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Review

Astro-Particle Physics at INFN

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Abstract: In Italy, INFN coordinates the research in the field of astro-particle physics. The supported experimental activities include the study of the cosmic radiation, the search of gravitational waves, the study of dark universe, general and quantum physics, and the study of the neutrino properties. A rich program of experiments installed on the earth, in the space, and underground or underwater is being supported to provide a possible answer to some of the most relevant open questions of particle physics, astrophysics, and cosmology. A short overview of the ongoing effort is presented.

Keywords: particle physics; astrophysics; cosmology; dark energy; dark matter; neutrino; cosmic rays; gravitational waves

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1. Introduction

Astro-particle physics is a relatively young field of research at the intersection of particle physics, astronomy, and cosmology. It uses particle physics infrastructures and methods to detect a wide range of cosmic particles, including neutrinos, gamma rays, cosmic rays, dark matter, and gravitational waves. Indeed, it could be seen as a bridge between two standard models: the particle (SM) and the cosmology (ΛCDM) standard models. Both are crowned by the successful description of many processes but, in both cases, there is a long list of open questions. Just to to give an example, the former does not include gravity, while the latter has no explanation for dark matter and dark energy. Astro-particle physics assumes that these answers have a common root and is committed to study the cosmic background radiation, cosmic rays, neutrinos, gravitational waves, very-high-energy gamma rays, and other rare particles that could provide important clues to the unexplained questions. The possibility to observe cosmic phenomena by means of different messengers (e.g., neutrinos and gravitational waves) has opened new incredibly exciting perspectives. Indeed, the observation of gravitational waves is continuously unveiling new unexpected cosmic phenomena which complement (and often trigger) the observations with other cosmic messengers (e.g., the full electromagnetic spectrum). On the other hand, neutrinos have always represented a key to the discovery of new phenomena beyond the particle standard model, and the study of their properties is still central to astro-particle physics.

A long list of experiments is facing this challenge, in high mountains, underground and in the depth of the sea or ice, in large laboratories of particle physics, and in space. They use the universe as a natural accelerator or study rare events in deep laboratories protected from the cosmic radiation.

INFN [1] through a dedicated committee (CSN2 [2]) coordinates in Italy the research in the field of astro-particle physics. The supported experimental activities are subdivided into four main research lines: the study of the cosmic rays, the study of the dark universe, the search of gravitational waves, and general and quantum physics and the study of the neutrino properties. In the following sections, a brief summary is given of the INFN activities for each research line.

2. Cosmic Radiation

The discovery of energetic particles penetrating the Earth's atmosphere from the outer space dates back to 1912. The pioneering discovery of new elementary particles, like positrons, pions, and kaons, to be later identified as entirely new classes of particles, i.e., antimatter, mesons, and strange matter, was made through observations of cosmic-ray (CR) events, using the first, passive, ionizing-radiation detectors (bubble chambers and emulsions). With the advent of accelerator technologies that could produce such particles in controlled laboratory conditions and the invention of active sensors generating real-time electronic signals, the study of the basic building blocks of matter and their interactions was carried out in the second half of the 20th century. Conducted at increasing energies and collision rates to catch the most rare events, and developed in synergy with dedicated efforts in theoretical physics, a series of challenging and technologically complex particle physics experiments brought to the construction and verification of the Standard Model of particle physics. In parallel, observations of CR events focused on the properties and origin of cosmic radiation, searching for high energy particles, which (i) are the most informative messenger of the physics taking place in distant and exotic sources and (ii) have energies that can be tens of million times higher than the maximum achievable with man-made accelerators.

Experimental efforts have been developing along two complementary observational techniques: direct and indirect.

In the direct approach, primary CRs are captured before they enter the Earth atmosphere. This is obtained by means of radiation detectors operating on satellites and balloon-borne payloads, which allow to detect the radiation coming directly from cosmic sources, inferring their properties, (e.g., energy spectrum), chemical composition, and morphology. A complete information is obtained by detecting photons at various wavelengths (which can be tracked directly to their parent source) and charged particles (protons, electrons and ions) which are curved by magnetic fields permeating the deep space between galaxies, our own Milky Way, and the relatively nearby space of the solar system. This effort requires a combination of observatories designed to measure all these different cosmic radiations. Thanks to a longstanding experience in the development and construction of sophisticated detectors for the observation of the elementary particle phenomena, in the last 30 years, INFN has gained a primary role in this field by designing, assembling, and operating advanced detection systems that have enabled significant progress in the field. These include the first high-resolution satellite spectrometer for charged CRs, PAMELA, the largest silicon tracker operating in space on the Fermi Gamma-ray Space Telescope, the multiple particle identification systems of the AMS spectrometer onboard the ISS, and the silicon tracker of the CR electron imaging calorimeter DAMPE.

INFN has also been developing a new generation of instruments that can open new observational windows on cosmic radiation, like gaseous detectors sensitive to polarized X-rays for the IXPE mission, 3D imaging calorimeters for the future HERD CR observatory, and large dynamic range electronics for the GAPS balloon anti-matter spectrometer. Obvious constraints on mass, power, and geometry limit the instruments designed to operate in space to dimensions of order m^2, masses at the ton scale, and overall power in the kWatt range, with obvious limits to the sensitivity, resolution, and precision of the corresponding measurements.

Indirect observations can overcome these limitations and exploit the interaction of cosmic particles with the atmosphere, which is effectively used as a very large area, passive target for incoming radiation. Particle showers are reconstructed by detectors on the ground at the appropriate altitude to intercept the shower development. Typically, two types of detectors are used: extended air shower arrays and fluorescence or Cherenkov telescopes. The former samples the energy, density, and arrival time of secondary particles with surface detectors placed at various distances from the shower axis, like in the AUGER Surface Detector in Argentina, the largest CR observatory in the world.

The latter measure the emission of light of different wavelengths associated with the particle shower development in the atmosphere, as in the AUGER Fluorescence Detector, and the MAGIC and CTA Cherenkov telescopes on the Canary Island of La Palma.

INFN has been deeply involved in the design, construction, and operation of these observatories, which are optimized to capture very rare energetic events (e.g., Ultra High Energy CRs in AUGER), events of potentially extragalactic origin, or above the highest energy covered by satellite observatories for the Cherenkov telescopes, with the aim to constrain the most powerful accelerators in the Universe. The strongest limitation of the indirect observations comes from the imperfect knowledge of the atmosphere composition along the shower development path, as well as from the model uncertainties in the primary interactions triggering the showers, which contribute to the systematic errors in the energy scale and particle identification.

Although lots of questions remain open in the quest for the origin and properties of the Cosmic Radiation, our knowledge has evolved considerably. In particular, thanks to gamma-ray observations, we have discovered that Super Novae accelerate protons and are likely to be the dominant source of galactic CRs. Moreover, thanks to UHECR observations, we have understood that the highest energy CRs have extragalactic origin and are suppressed above 10^{19} eV, either by transport effects (GZK cutoff) or by the acceleration processes inside sources. Finally, precise measurements of matter/anti-matter asymmetries have shown unexpected features that can provide a hint of new physics (e.g., signature of Dark Matter).

In recent years, new and key information on the cosmic phenomena has been coming from observatories that have reached remarkable sensitivity to other cosmic messengers, neutrinos, and Gravitational Waves (GW), therefore enabling regular and concurrent observations with direct and indirect CR telescopes. This multi-messenger observational context offers the most complete view of the dynamics taking place inside cosmic sources and promises to unlock the remaining mysteries on Cosmic Radiation, once again with crucial contributions from INFN to existing facilities, like Virgo and Antares, and future observatories (Einstein Telescope, Km3Net, LISA).

At the lowest extreme of the electromagnetic spectrum, we find the Cosmic Microwave Background Radiation (CMBR), which is often considered as an independent discipline, both because of its cosmological origin and for its strong influence on all the other aspects of astro-particle physics (e.g., cosmology, neutrinos, dark matter). Indeed, Planck and WMAP measurements have provided the most quoted balance of baryonic matter, dark matter, and dark energy, and (though strongly model dependent) have produced the most stringent limits on the sum of neutrino masses. Therefore, although CMBR studies have always been considered a subject of exclusive interest of astronomy and astrophysics, they have attracted the interest of INFN and have been recently included in its astro-particle program. The goal is to exploit INFN experience in the development of sensitive radiation detectors to support the observation of the CMBR polarization (B-modes). The choice is for a phased program starting with smaller scale experiments (QUBIC, LSPE), while preparing larger collaborations to more ambitious future programs (LiteBIRD).

3. Dark Universe

Astrophysical observations at galactic, cluster, and cosmological scales clearly demonstrate the existence of dark matter (DM) and dark energy in the Universe. Unfortunately, the nature of this DM is unknown, except for its supposed energy density, which indicates that DM constitutes about 85% of the total mass in galaxies and clusters of galaxies. Therefore, DM plays a dominant role in the dynamics of the Universe.

The matching between the numerical simulations of structures growth and the astronomical observations requires that at least a large fraction of dark matter is cold, i.e., non-relativistic at the time of structure formation, thus allowing its capture in gravitational wells, contributing crucially to structure formation.

No particle in the Standard Model has the properties required to explain this dynamic behavior, including the neutrinos, which are too light and fast to fit the experimental observations.

The search for dark matter is a very active field of research that developed since the 1980s along three main paths: (i) the search of new particles produced at accelerator or beam dump experiments, (ii) the direct search of dark matter candidates interacting in low background underground detectors, and (iii) the indirect search of decay or annihilation products of dark matter particles in the Universe by searching for specific decays. Indirect searches have been already considered in the previous section since they are part of the research line on the cosmic radiation. On the other hand, the direct search experiments, where INFN is involved, have been historically performed at Laboratori Nazionali del Gran Sasso (LNGS), searching for nuclear or electron recoils by means of high mass, low background, and low threshold detectors, exploiting, in some cases, the annual modulation signature of the dark matter flux through the Earth, as well.

The energy deposited by nuclear and electronic recoils can be detected mainly in three channels: heat (bolometers), light (scintillation), and charge (ionization). Some experimental techniques are simultaneously sensitive to two of those detection channels, and can obtain information on the nature of the interaction by combining them.

Crystal detectors are used for DM search both at room and at cryogenic temperatures, using scintillation, bolometry, or ionization. INFN is currently involved in NaI(Tl) detectors, such as DAMA/LIBRA, SABRE, and COSINUS, while CRESST makes use of $CaWO_4$ crystals. Another technique is used in MOSCAB, with a superheated fluorine liquid. A different approach, dedicated to measuring the direction of nuclear recoils, is exploited in two experiments in R&D phase: NEWS, using films of nanometric nuclear emulsions, and CYGNUS, a low-pressure low-Z gaseous TPC.

Liquid noble-gas detectors offer large and homogeneous targets: in particular, liquid argon (LAr) and liquid xenon (LXe) are commonly used as detector media. Double-phase (liquid and gas) Time Projection Chambers enable detection of both the scintillation light and the charge signal from ionization produced by an energy deposition. The relatively high density of liquid argon and xenon (about 1.4 and 3 kg/L, respectively) can provide self-shielding for the analysis in the innermost region. In addition, xenon contains almost 50% of non-zero spin isotopes, ^{129}Xe and ^{131}Xe, providing additional sensitivity to spin-dependent WIMP interactions.

The DarkSide collaboration operated the DarkSide-50 experiment at LNGS with about 50 kg of LAr. Key features of the detector are the high light yield of the LAr-TPC and the presence of an active veto, based on a boron loaded scintillator, allowing a neutron tagging efficiency better than 99.5%. Operating with atmospheric argon (AAr), DarkSide-50 provided a powerful assessment of the performance of the pulse shape discrimination of the scintillation pulses in LAr. Indeed the experiment demonstrated that the pulse shape discrimination (PSD) of the primary scintillation signal guarantees a rejection factor better than one part in 1.7×10^7. DarkSide-50 also demonstrated the viability of an underground argon (UAr) target, which can be obtained with an ^{39}Ar content that is suppressed by a factor of more than 1400 with respect to atmospheric argon, drastically reducing the expected number of electron recoil events to be discriminated against. Building on the achievement obtained with DarkSide-50, the next step of the collaboration is the DarkSide-20 k program at LNGS. DarkSide-20 k, will perform a search for high-mass dark matter with a 20 tons (fiducial) depleted argon detector, located in the Hall-C of LNGS. It consists of two detectors: the inner detector and the veto detector, both hosted in a ProtoDUNE-like cryostat. The inner detector is a LAr TPC filled with UAr and readout by innovative SiPM-based photon detection modules (PDMs). The veto detector is based on the use of a plastic shell, loaded with Gd, surrounding the inner detector and immersed in the AAr. The scintillation light from the AAr will be detected using the same PDMs developed for the LAr TPC. A dedicated R&D is also studying the possibility to access the direction of the incoming DM candidate (RED).

The XENON collaboration operated a series of LXe TPC of increasing mass and reduced background at LNGS since 2004: XENON10, XENON100, and, recently, XENON1T. All of them provided, at the time, the best sensitivity in the WIMP search. XENON1T has been operated at LNGS since 2016. It consisted of 3.2 t (1.3 t fiducial mass) of LXe, surrounded by an active water Cherenkov muon veto system. Data collected in an exposure of 1 t $\times$ yr showed an ultra-low world-record electron recoil background rate in the low energy region of interest for WIMP search. No significant excess over background was found, and this allowed for setting limits on elastic scattering cross-section for WIMP-like masses above 1 GeV/c^2 that still lead the field. Many of the subsystems of XENON1T have been designed such that they can be used for an upgraded larger phase of the experiment, XENONnT, containing about 8 tons of LXe. Due to the improved self-shielding and capability to detect multiple scatters in the larger detector, to the addition of a novel Gd-loaded water-Cherenkov neutron veto around the cryostat, and to new techniques developed to further improve the purification of the LXe target from the intrinsic contaminants ^{222}Rn and ^{85}Kr, the overall background can be decreased by a factor 10. With a total exposure of 20 t $\times$ yr, XENONnT is, therefore, expected to achieve a sensitivity for spin-independent WIMP-nucleon cross section better by an order of magnitude with respect to XENON1T. The installation of the enlarged TPC and the improved ancillary systems is complete, and the detector is presently being commissioned in Hall-B at LNGS.

Introduced as a possible solution to the strong CP problem, axions have been recently gaining interest as possible dark matter candidates. Their coupling to the electromagnetic field characterizes most of the experimental searches, in which an excess of photons is searched in microwave cavities under a static magnetic field (inverse Primakoff effect). Experimental searches focus both on astrophysical sources (e.g., the Sun) and the galactic halo. Besides the original study of QCD vacuum polarization and the search for axion-like particles (ALPs), INFN has thus decided to enlarge the dark matter program, including the construction of a haloscope based on quantum technologies to search for dark matter axions (QUAX).

Dark energy is even more mysterious than dark matter. By late 1990, supernova surveys by two independent teams showed that measured luminosities were on the average 25% less than anticipated, providing indication for accelerating cosmic expansion. Over the past 15 years, the observational evidence for cosmic acceleration has continued to grow. Among the proposed explanations, there is an evolving scalar field that fills space (like the Higgs field or the inflaton field that drove the rapid early expansion of the Universe). All the evidence for Dark Energy uses the equations of general relativity to interpret our observations of the Universe's expansion and evolution. Hence, as an alternative solution, instead of introducing a new energy component, one could attempt to modify gravity in a way that leads to accelerated expansion. Future observations will measure the relationship between distance and redshift and the growth rate of structures. If general relativity is valid on cosmological scales, then these two measurements should be consistent. Ambitious projects are in preparation, as EUCLID, a medium class space mission of the ESA dedicated to Cosmology. The Euclid satellite will carry a sophisticated telescope with a visible imager (VIS) and a near-infrared photometer combined with a medium resolution spectrometer (NISP). These instruments will explore the expansion history of the Universe and the evolution of cosmic structures by measuring shapes and redshifts of galaxies over a large fraction of the sky. The precision of these measurements will be sufficient to disentangle the effect of various Dark Energy models and will provide a strong sensitivity to neutrino mass. Euclid will be launched in 2022 and then will travel to the L2 Sun-Earth Lagrangian point. In 6 years of operation, a survey of about 15,000 square degrees of the extragalactic sky will be achieved, allowing the reconstruction of the spatial distribution of more than 50 million galaxies and the "shape" of nearly 2 billion galaxies. Reconstructing the history of the cosmos of the past 10 billion years, Euclid could study how cosmic acceleration has modified the expansion and the distribution of matter in the Universe. This will be achieved by combining different and independent cosmological probes, from weak lensing produced by large-scale structures to galaxy clustering to track baryon acoustic oscillations.

4. Neutrino Physics

Neutrinos are the most elusive particles in the Universe. Billions are passing through the earth every second because they interact very feebly with matter. This is why decades of experimental efforts were necessary to detect them and understand their features. They are neutral fermions which interact only through weak forces, exist in 3 different types, can oscillate among them, and have a not-vanishing (although very small) mass.

Nonetheless, there are fundamental properties we still ignore: (i) the exact value of their mass and their ordering among the different eigenstates, (ii) if they coincide with their own antiparticle (Majorana fermions), and (iii) the role played in the creation of a matter dominated universe. There are also hints that other types of neutrinos, not interacting at all and, therefore, known as sterile, could exist. Finally, a large amount of very low energy relic neutrinos produced just after the big bang is expected to represent the analog of the cosmic microwave background radiation but has never been observed.

A worldwide effort is ongoing to shed light on these questions, which are considered at the forefront of the particle physics.

A large variety of experimental techniques are in use, which share a common feature: a massive detector and a clean environment. The former is needed to have a measurable signal, the latter to disentangle any possible fake event (background) that could mimic the signal and spoil the experimental sensitivity. To reduce the background induced by cosmic rays, the majority of the experiments are placed underground, immersed in the so-called cosmic silence.

After more than 80 years from the introduction of the Majorana description, the observation of neutrinoless double beta decay (NDBD) still represents the only practical way to test if it describes the true nature of neutrinos. INFN is committed to this experimental search since the 1960s. A long series of experiments have been devoted to this search exploiting different detection techniques. Indeed, the use of both germanium diodes and bolometers was pioneered by INFN and LNGS has hosted some of the most sensitive experiments (Heidelberg-Moscow, GERDA, Cuoricino) and is actually supporting the operation of CUORE and the preparation of LEGEND-200. The goal of these experiments is to assess if neutrinos are Majorana particles. In such a case, the hypothetical decay $(A, Z) \rightarrow (A, Z + 2) + 2e^-$ would be possible. Unfortunately this occurrence has never been observed, with limits on the lifetime of this exceedingly rare decay greater than 10^{26} years: roughly 10^{15} times the age of the universe. Extremely pure environments and sophisticated techniques are needed. Apart from the well known use of germanium detectors, very promising is the use of bolometric detectors, which are characterized by excellent energy resolutions and an almost free choice of the material under investigation. The successful operation of CUORE has demonstrated that the stable operation of ton-sized calorimeters is possible on scales of the order of years. Indeed, CUORE consists of about 750 kg of tellurite crystals in operation at LNGS since 2017. The coupling of the information on the main background sources with the successful development of scintillating bolometers has paved the road to CUPID, a new proposal which aims to exploit the CUORE infrastructure while lowering the background contribution. CUPID will fill the CUORE experimental volume with isotopically enriched $Li^{100}MoO_4$ scintillating bolometers after the completion of the CUORE scientific program.

For about 20 years, LNGS has also hosted the operation of Borexino, whose sensitive part consists of a large volume of organic scintillator to detect the neutrinos arriving from the Sun or the Earth, to investigate their properties and other processes, otherwise inaccessible, as the ones that happen in the core of the stars. Borexino has successfully unveiled the details of the mechanism of energy production in the Sun, the modifications of the neutrino properties in their propagation to the earth, and the role of the radioactivity of the earth mantle in the heat dynamics of our planet.

Neutrino experiments at accelerator are also supported by INFN CSN2. After its successful operation in the CNGS program, the ICARUS experiment, a 20-m long (760 ton weight) Time Projection Chamber, has been finally moved to Fermilab (FNAL), where it is going to be operated as the far detector in the short baseline program (SBL), along the Booster Neutrino Beam, to search for a possible signal of new physics that may point to the sterile neutrino.

INFN is also collaborating with the DUNE program, a long baseline experiment from FNAL to the SURF underground laboratory (South Dakota) aiming to determine the neutrino mass ordering and measure the value of the CP-violating phase in the PNMS mixing matrix of the neutrinos. Based on the same technology pioneered by ICARUS, DUNE will see a strong involvement of the INFN groups in the design and construction of the near detector (SAND), which will be crucial to get rid of most systematic effects.

Besides a longstanding collaboration with the T2K experiment, INFN is presently also considering the participation to the HyperKamiokande (HK) program which, apart from the goal of determining the missing neutrino parameters, will be characterized by a rich program of physics beyond th Standard Model (in particular, proton decay).

Consisting of a 35 m acrylic sphere filled with a 20,000 tons of liquid scintillator, the JUNO experiment is under construction at Kaiping in China. Its main goal is the measurement of the neutrino mass hierarchy and the precise evaluation of the oscillation parameters studying neutrinos, mainly from the 50 km nuclear power plants but also that ones coming from the sun, the earth, the atmosphere, and supernova neutrinos.

Direct (or kinematic) measurements of the neutrino mass are particularly important since they represent the only model independent approach to the problem. So far, mass spectrometry has provided the best sensitivities, but the latest experiment of the saga, KATRIN, which is characterized by a sensitivity as low as 0.2 eV, is believed to have no successors. INFN immediately recognized the importance to develop new experimental approaches and has supported a number of R&D projects since the 1990s (MANU, MIBETA, MARE) based on the use of arrays of micro-bolometers. The latest development is the HOLMES experiment, which aims at demonstrating the feasibility of a large array of TES-based bolometers to investigate the electron capture (EC) of ^{163}Ho. The same technology could be used also in PTOLEMY, a project aiming at the first observation of the neutrino cosmic background.

5. Gravitational Waves, Fundamental, and Quantum Physics

The observation of gravitational waves by the Advanced LIGO and Virgo detectors has opened an entirely new window on the study of the universe and can be considered one of the greatest scientific achievements of all times, confirming a century-old prediction of Albert Einstein's Theory of General Relativity (GR) and marking the birth of a new era in astronomy, astrophysics and fundamental physics.

Another decisive event also took place in the same time frame, the launch and successful operation of LISA Pathfinder by the European Space Agency. It is the precursor mission to the space-based gravitational wave observatory, which is foreseen as the third large scientific mission in its current planning.

The first two observing runs by the joint LIGO and Virgo collaborations, besides providing further confirmation to the theory of General Relativity, have already influenced several areas of astrophysics, from cosmology to high-energy astrophysics and nuclear physics, and are continuing to produce a series of unexpected and surprising results.

At present, gravitational waves have been detected from mergers of binary black holes and binary neutron stars, and different types of gravitational-wave signals from other sources await to be detected, e.g., core-collapse supernovae, spinning neutron stars, white-dwarf binary mergers, and even stochastic backgrounds of astrophysical or cosmological origin.

The third observing run of LIGO and Virgo, just concluded in Spring 2020, after almost one year of observation, is rewarding the scientific community with a large number of candidate signals of gravitational waves.

After the first detection of gravitational waves, detailed plans for the development of enhanced versions of the existing interferometers and for the design of a new generation of instruments are being actively pursued in several countries.

Indeed, the INFN community is strongly committed and played a major role in the development of the "Einstein Telescope" (ET), a European effort supported by the European Commission under the 7th Framework Program.

The detection of gravitational waves is, first of all, a technological challenge, whose achievement comes after more than half a century of experimental efforts, finalized in the last two decades with the conception, design, and realization of large interferometric detectors.

Gravitational waves are opening a new window on the catastrophic astrophysical events where huge gravitational fields are at work. It is, therefore, a unique opportunity to test General Relativity in extreme conditions. This is still one of the primary interests of INFN, although the unique opportunity of gathering (often triggering) independent observations to observe a number of astrophysical events under a different and more complete perspective is certainly affecting an increasing community of physicists. Multi-messenger astrophysics is now a reality, and gravitational waves are an irreplaceable ingredient.

Nevertheless, the tests of General Relativity in the weak field of the solar system continue to maintain their importance. Indeed, despite the fact that the sought effects are much weaker, the environment is well known, and calculations are affordable and reliable. In fact, the difficulties in the theoretical description of GR effects under strong fields still make the connection between the two categories of measurements difficult. In this framework, INFN is continuing the support to measurements on the earth (Gingerino) and satellites (SATOR_G, MOONLIGHT), which, besides the fundamental physics goals, attract the interest of other scientific and technological disciplines (e.g., seismology and geodesy).

The investigation of the limits of validity of General Relativity is only one of the aspects of the program of fundamental and quantum physics supported by INFN. Indeed, the development of quantum technologies to search for small quantum effects has been always a feature of the INFN astro-particle community (MIR, PVLAS, MAGIA, GGG, MICRA, etc.) and is presently continuing with a number of table-top measurements (SUPREMO, FISH, MEGANTE, ARCHIMEDES) which are paving the road, among the others, to important technological developments.

6. Conclusions

Interest in astro-particle physics has been constantly increasing in the past few decades. The discovery of neutrino oscillations and the observation of gravitational waves, as well as the precise measurements of the CMBR radiation, have triggered a huge international experimental effort aiming at providing answers to some of the most longstanding questions of particle physics and cosmology. INFN is strongly committed to this program and, where possible, participates in the international effort contributing its unique experience in the development and construction of sensitive particle detectors. The interests span a large number of subjects, sometimes considered as a risk of fragmentation of the research program. The adopted general strategy is to maintain a balance between large and well-established projects and new initiatives and R&D projects. For each research line, therefore, we have one or two main projects taking data and producing results, an equivalent number of projects under construction and a larger number of smaller projects or R&Ds. In all cases (i.e., regardless of the entertainment of the project or collaboration), the INFN intellectual contribution is always evident. As a result, the INFN astro-particle community is constantly increasing in size.

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