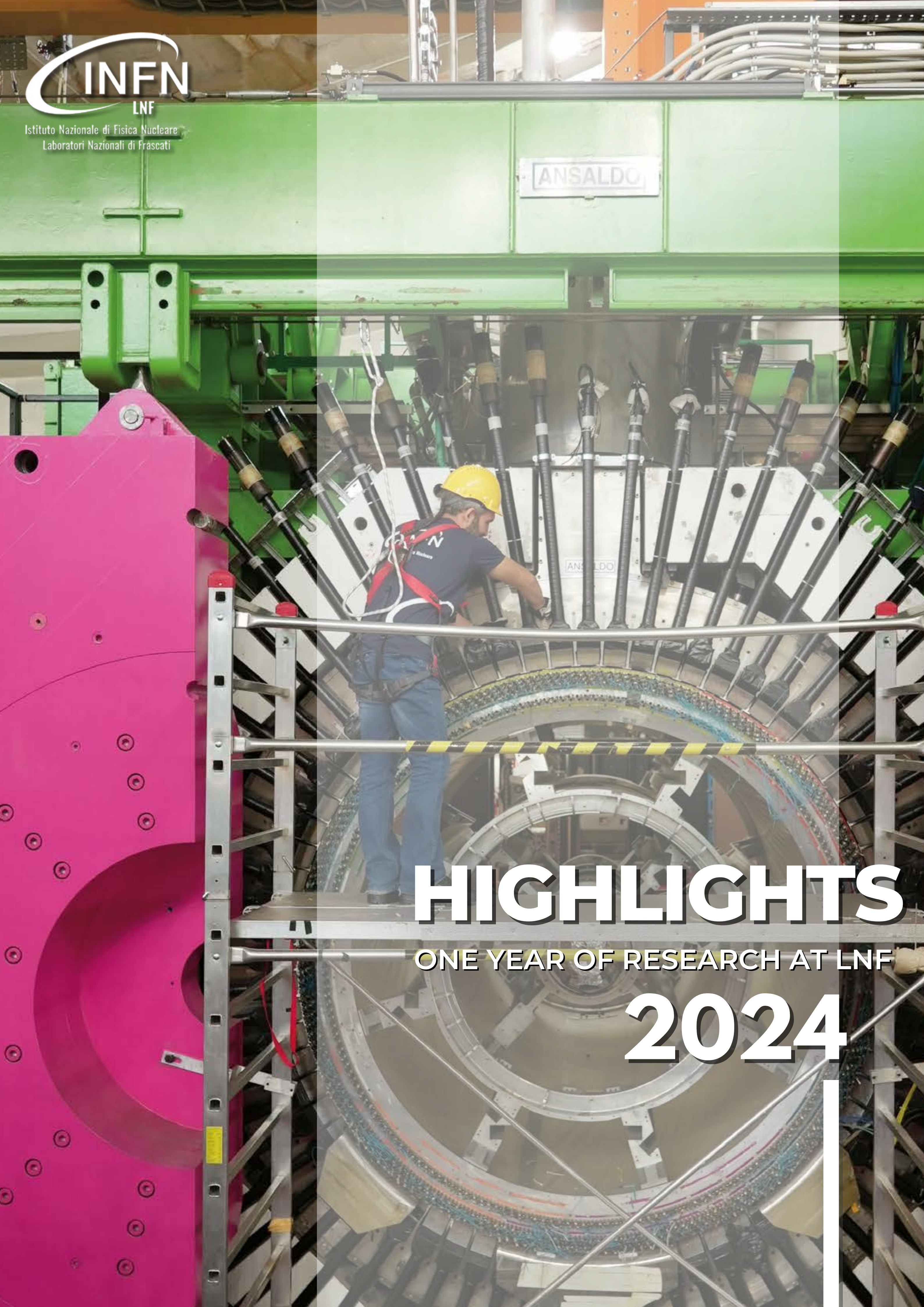
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

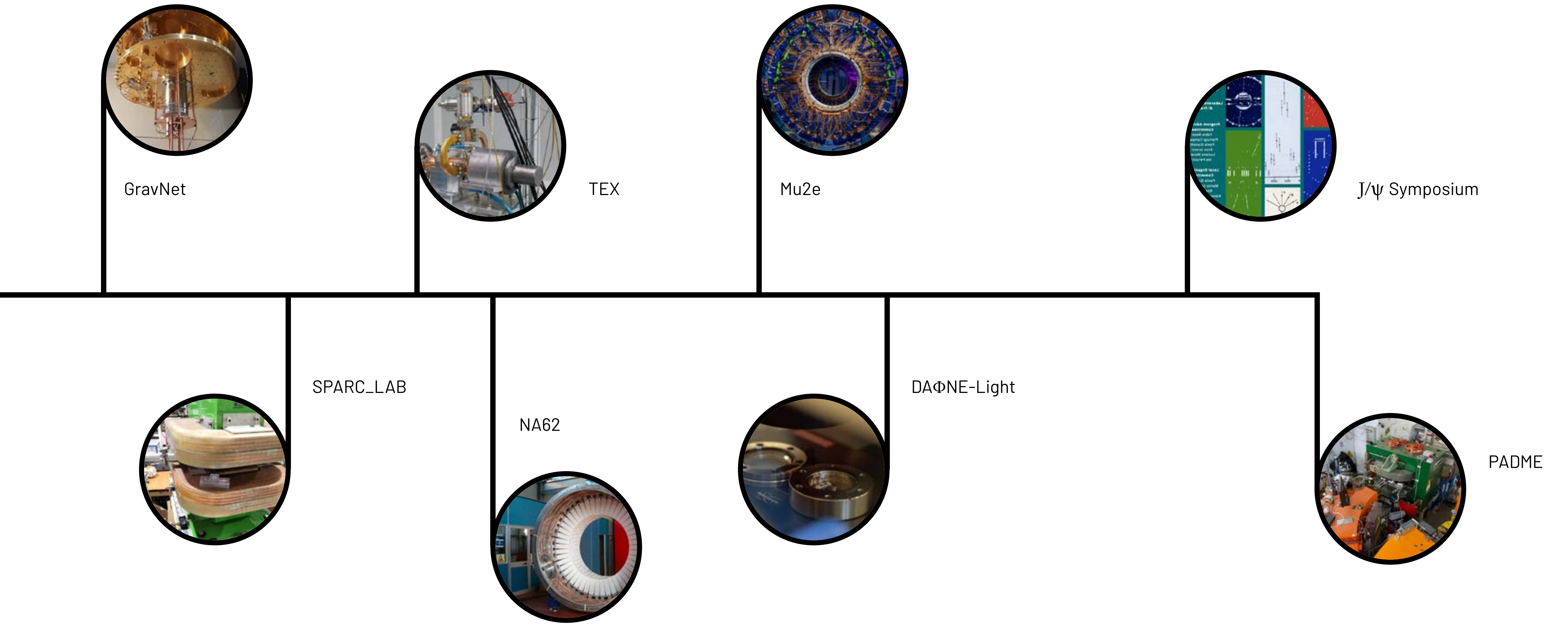


HIGHLIGHTS

ONE YEAR OF RESEARCH AT LNF

2024

Some LNF achievements during 2024



INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

ONE YEAR OF RESEARCH AT LNF

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SUMMARY

FOREWORD

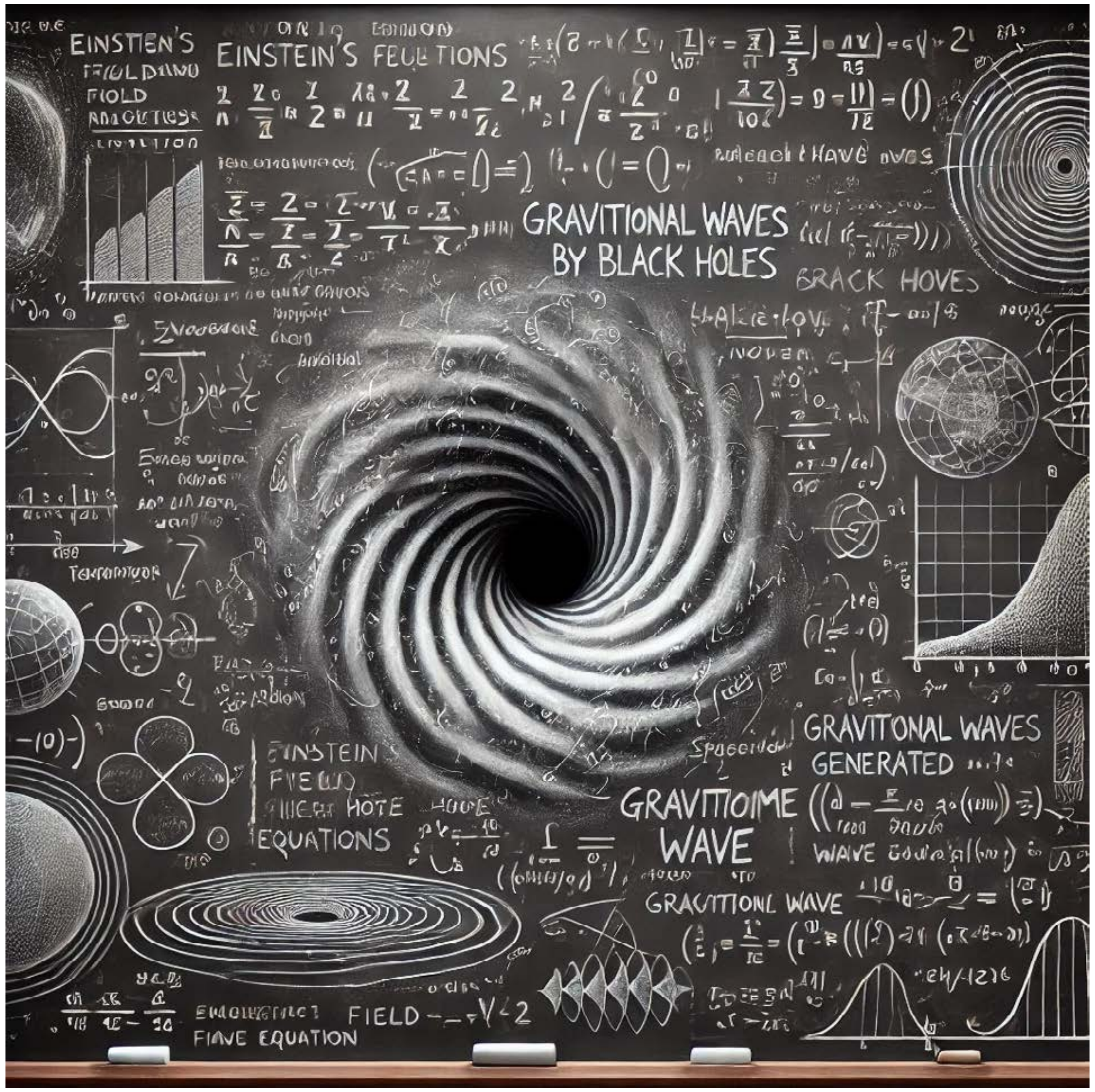
2024 has been a year of changes for our laboratories. Starting with the management, where from August 1st, I took office as the first female director of LNF. I am very proud of this achievement and hope to live up to the expectations and responsibilities that this role entails. It goes without saying that many of the results and successes achieved last year are not my merit, but the careful management of my predecessor Fabio Bossi, who, in addition to being an eminent researcher, proved to be an excellent manager. I thank him on behalf of all the laboratory employees for the work done over the past four years and hope to prove myself up to his standards.

The second change concerned our flagship project EuPRAXIA@SPARC_LAB, which, at the end of 2024, obtained additional funding from the Lazio Region to create a second line for users. The initiative is currently completing the design phases to start the construction of the new international research infrastructure from 2026. At the same time, the ancillary facilities of the project (EuAPS, TEX, SABINA), thanks to the funds provided under the aegis of the PNRR projects, have achieved important scientific and technological results.

Our researchers' commitments have always been divided between on-site activities and international collaborations at major laboratories around the world. Primarily at CERN in Geneva, where in 2024 tantalizing results in the quest for new physics did not come from the LHC experiments (ATLAS, CMS, ALICE, LHCb), but from the analysis of rare kaon decays studied by the NA62 collaboration. 2024 also saw the LNF group collaborating on the Mu2e experiment at Fermilab in the USA reaching an important milestone: the completion of an engineering marvel, an electromagnetic calorimeter made up of 1400 cesium iodide crystals.

Among the on-site activities, for some years now, the laboratories have also been involved in the global effort of fundamental physics to identify signals of dark matter. At LNF, two complementary strategies are pursued: on one hand, the cryogenic technologies developed at the COLD_Lab are used to search for axion signals (very light particles of cosmic origin hypothesized by some theoretical models), and on the other, using the positrons from the DAΦNE complex linac, the PADME experiment searches for signals of new light particles... and some promising results seem to be coming from the analysis of the data collected in 2022. Just as in 1974, when LNF was the first non-USA laboratory to confirm the existence of the newly discovered charmed particle, the J/ψ, we hope that the hint from PADME identifying the X17 anomaly discovered by a series of nuclear physics experiments in Hungary will soon become a certainty that this is a never-before-seen particle.

Paola Gianotti / LNF Director



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GRAVNET
A GLOBAL NETWORK FOR THE SEARCH FOR HIGH-FREQUENCY GRAVITATIONAL WAVES

Gravitational waves represent ripples in the fabric of spacetime, first predicted by Einstein's General Relativity in 1915 and experimentally confirmed a century later. Their discovery opened an entirely new observational window onto the Universe, allowing scientists to study cosmic events that are essentially impossible to detect through electromagnetic radiation. While current gravitational wave observatories primarily operate at relatively low frequencies, detecting phenomena such as mergers of black holes and neutron stars, exploring high-frequency gravitational waves (HFGWs), in the MHz–GHz range, promises to reveal even more extraordinary and previously inaccessible astrophysical and cosmological phenomena.

HFGWs are especially intriguing because they may originate from entirely different and potentially more exotic sources compared to lower-frequency waves. These could include violent processes in the very early Universe such as phase transitions, cosmic inflation, or interactions involving novel particles beyond the Standard Model as well as certain dark matter candidates like primordial black holes and ultralight particles. Moreover, the MHz–GHz frequency range is largely unexplored, meaning that any detection in this band could represent a groundbreaking discovery, significantly reshaping our understanding of fundamental physics, cosmology, and astrophysics.

Investigating this uncharted territory of HFGWs is therefore not only an essential step toward completing the gravitational-wave spectrum, but also represents an exciting frontier in modern physics, potentially unveiling entirely new physics and changing our perception of the Universe itself.

This is the goal of GravNet, a global network of detectors for the search of high-frequency gravitational waves, which has just been funded by the European Research Council with a 10-million-euro Synergy Grant. The project, which will last six years, was proposed by a team of four researchers from institutes in three different European Union countries: the University of Bonn, the University Johannes Gutenberg in Mainz, the Institute De Fisica D'Altes Energies in Barcelona (IFAE) and the Frascati Laboratory of the Istituto Nazionale di Fisica Nucleare (INFN).

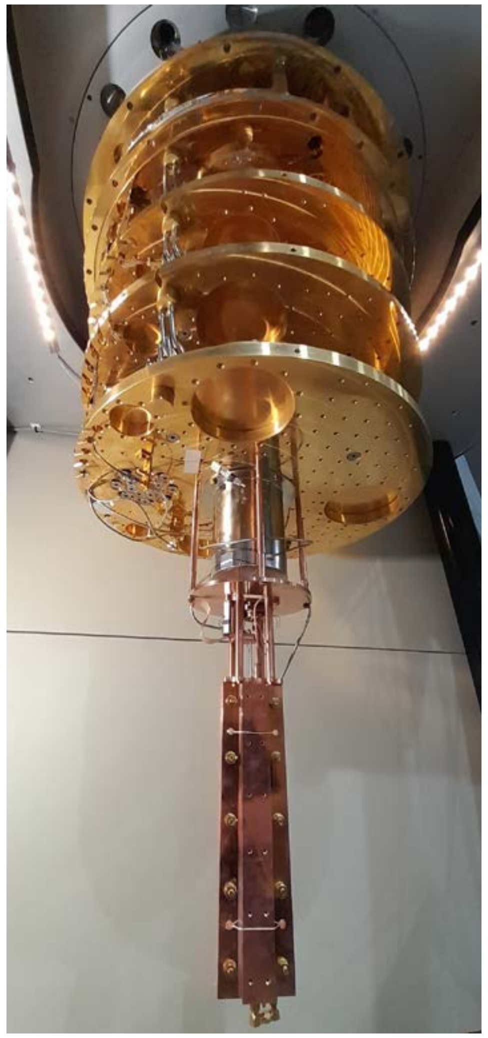
The research will be developed starting from a network of cryogenic detectors, called haloscopes, that are currently used to search for the presence of dark matter composed by hypothetical light particles called axions. These detectors will be synchronised, their shape and materials optimised and the network will be extended to other sites. In this way, GravNet will open up a new, vast parameter space for gravitational-wave searches and might be the enabling step towards the first detection of HFGWs.

LNF is already active in the search of axion dark matter and will contribute to the network with two haloscopes. A haloscope is an apparatus composed by a microwave cavity cooled down to cryogenic temperatures and placed inside a superconducting magnet. Here axions or HFGWs can convert to photons and be detected. The cavity resonance is tuned to different frequencies to probe the existence of axions with different mass or for different HFGW sources. The first LNF haloscope is already in operation within the QUAX experiment while the second, FLASH, will be constructed recycling the 3 m-bore magnet of the FINUDA experiment. In addition, the LNF team of the COLD_Lab[1] will develop new superconducting devices to increase the sensitivity of the detectors. These three activities are briefly described in the following.

The QUAX@LNF haloscope

QUAX is an INFN experiment designed to investigate the existence of axions with the two haloscopes in operation at the two national laboratories of INFN in Legnaro (LNL) and Frascati (LNF). The two haloscopes use resonant cavities with resonant frequency around 10 GHz, each slightly different from the other, and built using different technologies based on superconductors or dielectric materials to increase their quality factor.

In the last year the QUAX@LNF haloscope (Fig. 1) made its first data taking reaching the sensitivity required to detect dark matter axions[2], and now is increasing the sensitivity with the use of quantum amplifiers to extend the search to a broader range of frequencies. In the meantime, it will be connected and synchronised with GPS to the GravNet network to look for HFGWs.



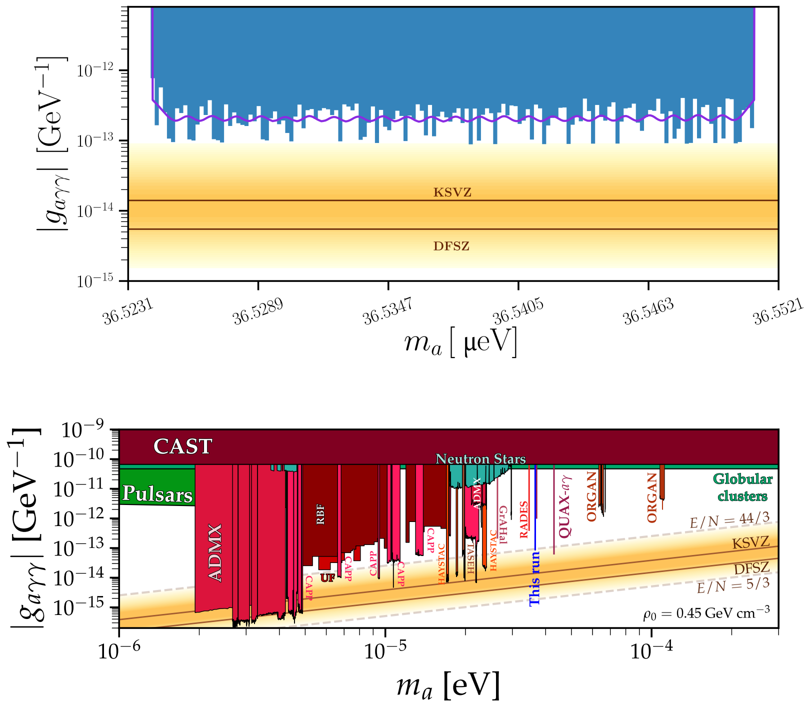


Figure 1: The QUAX haloscope. Right top: exclusion plot for the axion-photon coupling reached by the QUAX@LNF detector [2]. Right bottom: overall exclusion plot where the result of QUAX@LNF run (this run) is highlighted.

The FLASH haloscope

FLASH (Finuda magnet for Light Axion Search Haloscope) will use a large resonant cavity placed inside a strong static magnetic field, leveraging the superconducting magnet and cryogenic infrastructure from the FINUDA experiment at LNF[3]. FLASH will be sensitive to axions in the mass range from 0.49 to 1.49 micro-eV and high-frequency gravitational waves within the 100–300 MHz range. It will be the largest haloscope in the world, sensitive in a frequency range hardly reachable by other experiments.

In 2024 the decommissioning of the old FINUDA detector started and its removal from the magnet is foreseen by the end of 2025. Once freed from the old detector, a large cryostat with the resonant cavity inside will be inserted in its bore (Fig. 2). It will then take a few years for the technical design and the construction.

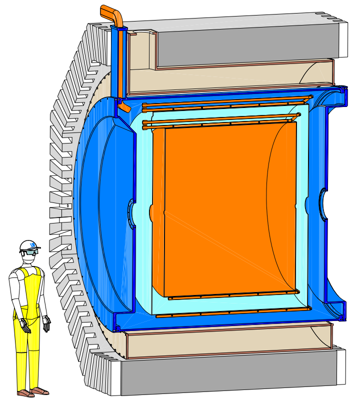


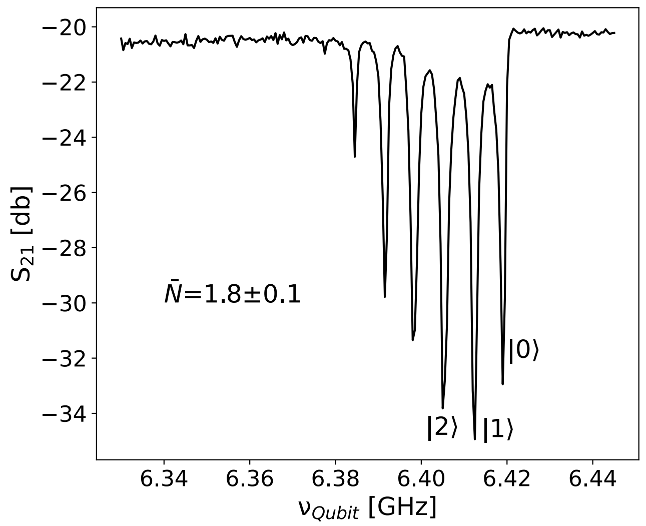
Figure 2: Sketch of the FLASH haloscope (credits C. Capoccia)

Quantum sensing with superconducting qubits

Quantum sensing is an exciting, emerging technology that uses the unique properties of quantum mechanics to measure phenomena with incredible precision. Unlike traditional sensors, quantum sensors exploit quantum effects such as superposition of states and entanglement, enabling the detection of extremely small electromagnetic radiation, phonons, magnons etc. These ultra-sensitive tools hold the potential to enable observations previously thought impossible.

Superconducting qubits based on Josephson junctions (JJs) stand out as particularly promising, as they can be manufactured on substrates like those used in conventional silicon electronics, allowing excellent scalability. JJs are extremely versatile superconducting devices, with applications ranging from microwave photon detection to parametric amplification and entangled photon emission.

The sensitivity of a superconducting qubit is exemplified by the spectrum in Fig. 3 (left), where individual Fock states (states with a given number of photons) are discriminated as different absorption peaks of the qubit.



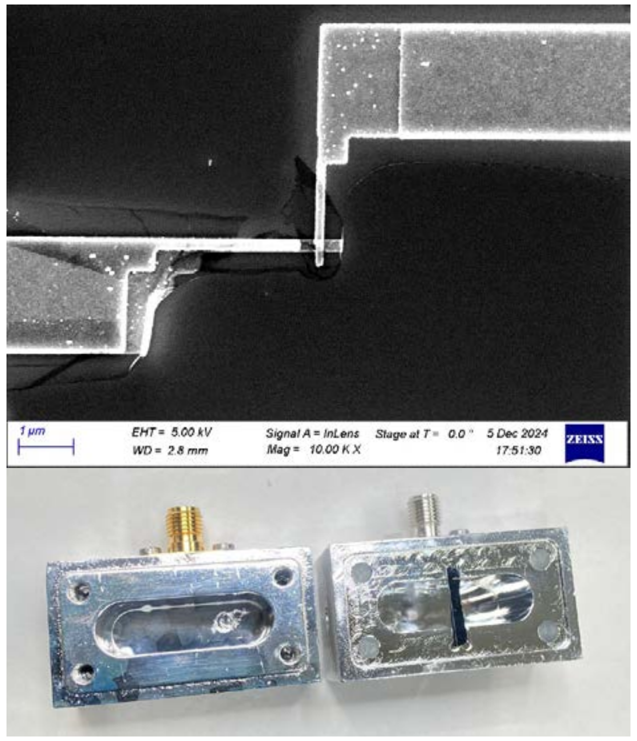


Figure 3: Left: Absorption spectrum of a qubit inserted in a cavity populated with an average number of photons . The different Fock states can be discriminated as individual absorption peaks. Right: SEM and optical image of the 3D Al qubit fabricated at IFN-CNR and assembled and tested at LNF.

The spectrum was measured at the COLD_Lab [4] with a qubit fabricated at the Technology Innovation Institute in Abu Dhabi (TII) [5].
In collaboration with partners in the INFN-QubIT project and in PNRR projects NQSTI and ICSC, both planar and "3D" qubits have been realized. The latter (Fig. 3 right) is composed of a qubit fabricated at CNR-IFN in Rome and a superconducting cavity fabricated at LNL. The device was assembled and characterised in a dilution refrigerator at LNF COLD_Lab.

To reduce the ubiquitous presence of noise hampering the detection of single photons, the device under study for GravNet will be based on the coincidence of quantum non-demolition (QND) measurements of the photon done with two different qubits. In other words, a qubit can sense the arrival of a photon without destroying it allowing repeated or simultaneous measurements with more qubits. This is possible because the photon is not absorbed by the qubits but, as it passes, it leaves its imprint on the phase of their quantum states as shown in Fig. 4.

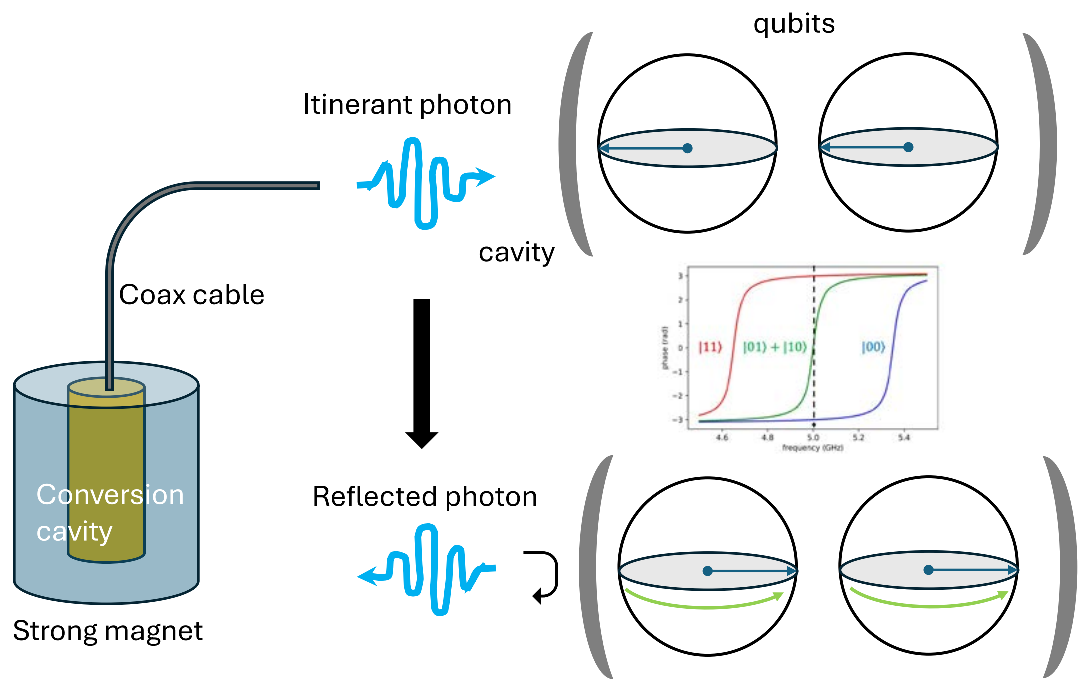


Figure 4: Sketch illustrating the working principle of the QND measurements operated with the two-qubit device.

New materials for resilient qubits

The presence of strong magnetic fields in haloscopes, prevents to place the superconducting qubits close to the detector, thus increasing the losses during the transport and making the quantum protocol more complicated. To overcome this obstacle, JJs have been fabricated using niobium diselenide (NbSe2) within the INFN project RESILIENCE, a collaboration between LNF, CNR-IFN and the University of Camerino. This material, that belongs to the van der Waals (vdW) family, can withstand strong magnetic fields up to 30 T. A JJ constructed from NbSe2 would thus inherit this remarkable resilience to magnetic fields and be used to sense single photons even when placed close to the detector area.
To fabricate the qubits, a NbSe2/NbSe2 homojunction was assembled on the contacts of a small antenna made by two circular aluminium-pads and placed inside an aluminium 3D cavity (Fig. 5 left). The quantum mechanical behaviour of the device is highlighted by the measurement, carried out at the COLD_Lab, of its temporal evolution under an appropriate excitation, which shows the typical pattern of Rabi oscillations (Fig. 5 right). Its remarkable relaxation time of about 7 microseconds represents a two-orders-of-magnitude improvement in coherence time compared to previously reported quantum devices based on other vdW materials.
To our knowledge, this work represents the first successful fabrication and characterisation of a qubit based on a NbSe2 JJ.
In conclusion, GravNet is a pioneering initiative that could unlock a completely new window onto the Universe by searching for high-frequency gravitational waves, an area still largely unexplored, allowing at the same time to continue the search for light dark-matter candidates.

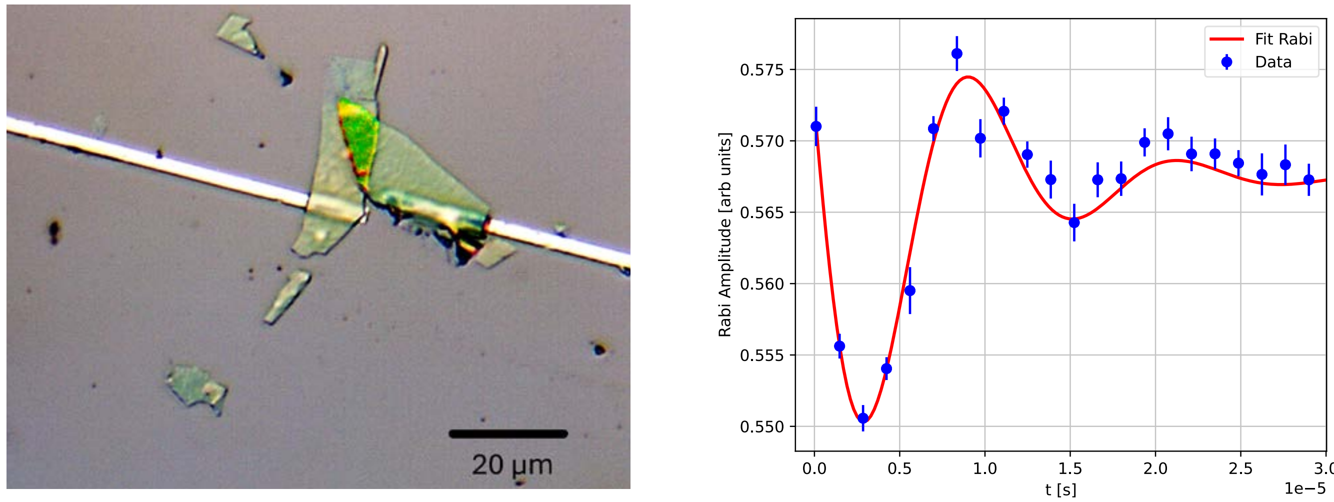


Figure 5: Left: Optical image of the NbSe2/NbSe2 JJ. The JJ area is reported in false color to enhance its visibility. Right: Rabi oscillation of the NbSe2 JJ.

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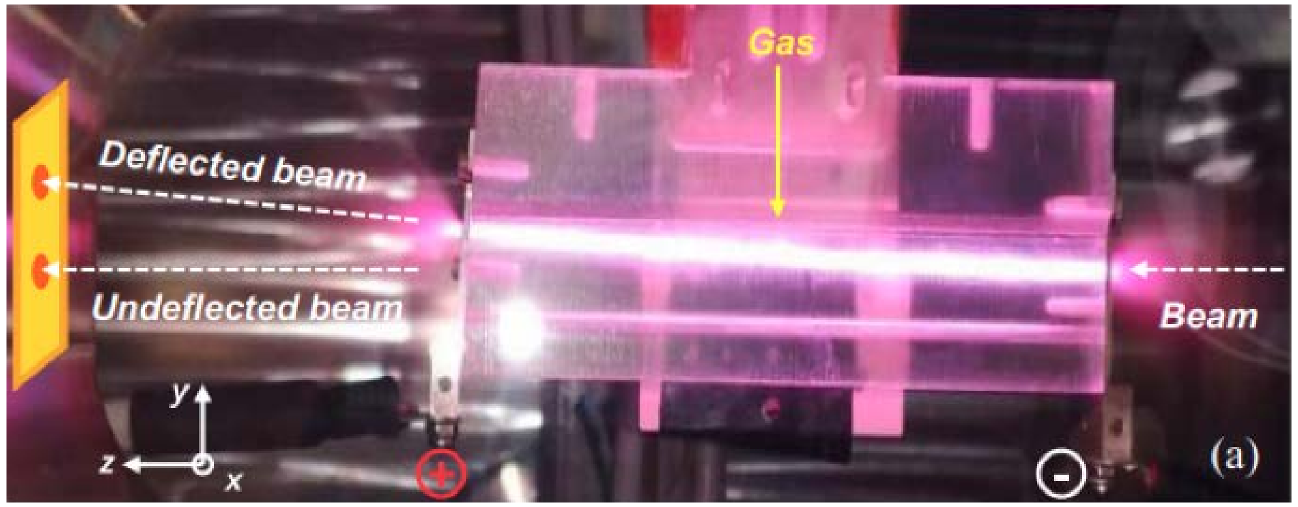
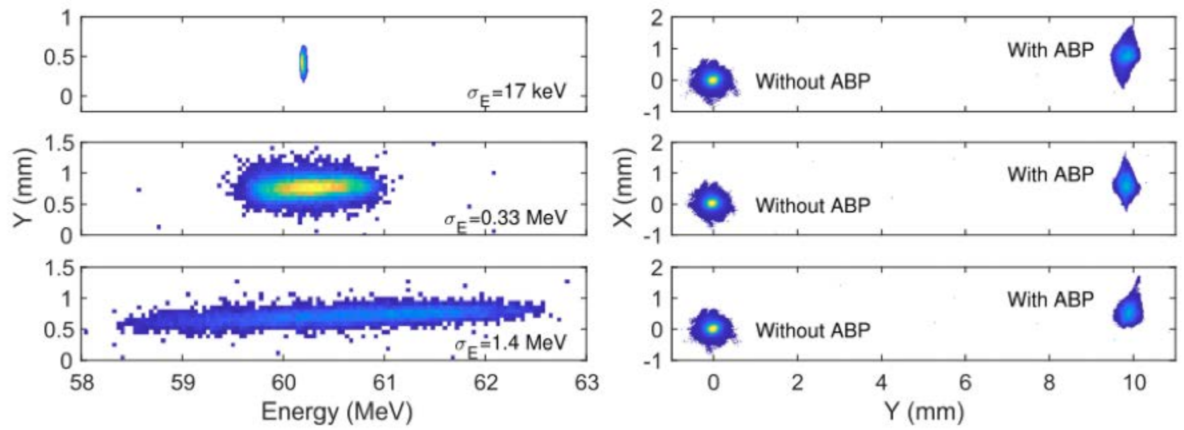


Figure 1: The high-voltage discharge current is applied to the two electrodes of the curved capillary to produce the plasma. The beam is measured on a scintillating screen located 10 cm downstream of it. The orientation of the x-y-z axes is also indicated.



SPARC_LAB DEMONSTRATES THE DEFLECTION OF A PARTICLE BEAM WITH A CURVED PLASMA-DISCHARGE CAPILLARY

With an experiment carried out in the late 2023, the SPARC_LAB group presented a novel method for deflecting and guiding relativistic electron beams along curved paths using magnetic fields generated within plasma-discharge capillaries. This pioneering approach promises to significantly mitigate the chromatic dispersion effects commonly encountered with conventional bending magnets, marking a substantial leap forward in the field.

The experimental results, published in Physical Review Letters[1] and highlighted on its May 2024 cover, demonstrate that the guiding of electron beams through plasma-discharge capillaries is notably less influenced by chromatic dispersion, a phenomenon where particles of different energies follow slightly different paths, compared to traditional bending magnets. Enhanced numerical simulations support these findings, indicating that by increasing the discharge currents, the technique can be rendered nearly achromatic.

Figure2: Proofs of beam deflection. Left column: energy spectra of the beam obtained for three different working points of the linac. The corresponding energy spread σ_E is indicated in each plot. Right column: deflected and undeflected transverse spot sizes downstream of the curved capillary. Each plot is obtained by overlapping a single shot of the undeflected beam (capillary out of the beam path) with a single shot of the deflected one (capillary inserted and discharge current set to ID ≈ 1.57 kA). The energy spread is the same as in the corresponding spectrum on the left.

These results follow previous studies at SPARC_LAB on (straight) active-plasma lenses and show that the same working principle can be applied to curved geometries with the goal to guide and bend relativistic particle beams by means of a plasma-based device. For this purpose, a high-current discharge flowing within a curved capillary simultaneously with the beam was used. Significant R&D was needed to develop the high-current discharge pulser that can reach 2.2 kA peak current. The results show that the guiding was correctly obtained and, unlike conventional bending magnets, it can be made achromatic (i.e., not affected by the beam energy spread) by tuning the discharge current.

The proof-of-principle experiment used a curved plasma-discharge device to bend and guide a 60 MeV electron beam. Such a device, shown in Fig. 1, consists of a capillary filled up with nitrogen gas with length 10 cm and 1.6 m bending radius. The deflection is obtained by applying a high-voltage discharge current to the two electrodes connected at its ends. The discharge generates the plasma and, in turn, the poloidal magnetic field that simultaneously focuses and guides the beam over the curved path providing an overall 4° deflection in the vertical plane.

The beam guiding along the curved capillary is demonstrated by testing its operation with three different beam configurations. The RF linac was tuned to produce a low (17 keV), medium (0.33 MeV), and large (1.4 MeV) energy spread while keeping fixed the average beam energy. Figure 2 (left column) shows the energy spectra of such beams measured with a magnetic spectrometer and the resulting beam spot sizes (right column) obtained on the scintillating screen downstream of the capillary. The deflection is achieved by applying a discharge current ~1.57 kA. To compare the undeflected and the deflected beams, two single-shot images, obtained without and with the device, have been overlapped. The plots show that the beam is guided along the curved path and, after traveling on the following drift, reaches the screen with an overall displacement of ~9.9 mm.

This study highlights the potential for this innovative method to pave the way for next-generation table-top particle accelerator facilities. If compared to state-of-the-art bending magnets technology (Fig. 3), its practical implementation would be very affordable in terms of size and costs. Active-bending plasma represents therefore an innovative solution to develop ultra-compact beam lines for existing or next-generation accelerator facilities. This development marks a promising step towards more compact, versatile, and economically feasible particle acceleration technologies.

Figure 3: The active bending plasma device compared with a conventional bending magnet.

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GOOD NEWS FROM TEX FACILITY: FIRST HIGH-POWER TEST OF THE EUPRAXIA X-BAND STRUCTURE PROTOTYPE

Since its commissioning at the end of 2022, the TEX (TEst stand for X-band) facility, located at LNF, has served as a strategic infrastructure dedicated to the development, qualification, and test of high-gradient X-band RF technology. Established within the framework of the LATINO project, and closely aligned with the roadmap of the EuPRAXIA@SPARC_LAB initiative, TEX has become a national reference point for advanced linear accelerator research. Specifically designed to support the realisation of the compact 1 GeV high-brightness EuPRAXIA linac based on X-band technology, TEX plays a central role in the R&D of RF components, accelerating structures, control systems, vacuum and conditioning procedures. The importance of TEX lies in its capability to reproduce the operational conditions of future high-gradient linacs. Equipped with multiple high-power RF sources, a state-of-the-art control system, advanced LLRF diagnostics, and AI-assisted conditioning routines, TEX provides a comprehensive environment for both component development and system-level integration. Moreover, TEX also supports collaborations with industry and international research institutes, particularly through component testing for CERN's CLIC project and high-power testing of RF components developed at PSI, further underscoring its international relevance.

A major milestone achieved in 2024 was the high-power RF test of the first X-band accelerating structure prototype for EuPRAXIA@SPARC_LAB. This initial 21-cell prototype (Fig.1) is a constant impedance, scaled version of the final structure. It was developed entirely in-house at LNF, from electromagnetic and thermo-mechanical design to brazing, using the vacuum furnace available at LNF. Following brazing and extensive low-power RF characterisation, the structure underwent its first high-power conditioning campaign at TEX in spring 2024. In just 12 days of conditioning, the prototype reached input pulses of 35 MW with a 100 ns pulse length at a repetition rate of 50 Hz. This corresponds to an average accelerating gradient of 74 MV/m and a peak gradient at the structure input of approximately 80 MV/m. These values exceed the nominal EuPRAXIA design gradient of 60 MV/m, confirming the excellent performance of the structure in terms of breakdown rate, thermal stability, and mechanical robustness. The test also validated the performance of the entire RF chain, including the waveguide network, vacuum system and LLRF system.

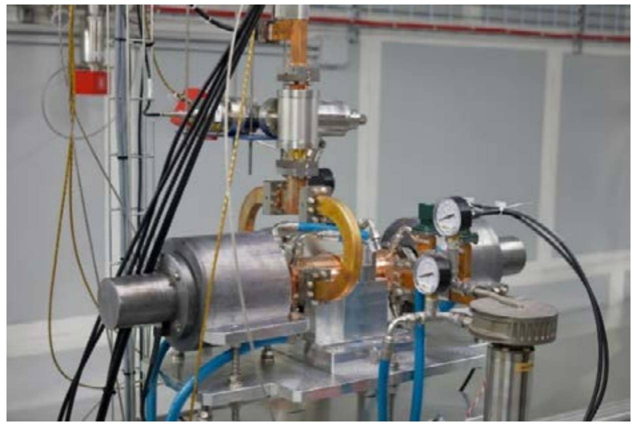

Figure 1: First X-band 21-cell RF accelerating structure prototype mounted in the TEX bunker for the high-power test.

This achievement represents the culmination of a broader prototyping effort, which included the fabrication of two full-scale mechanical structures, comprehensive of brazing and alignment tests, and detailed vacuum modelling. It marks a significant advancement in demonstrating the technological readiness of the X-band accelerating structures for the EuPRAXIA booster linac.

Another major highlight of 2024 was the completion of a substantial upgrade to the TEX facility through the installation of two high-repetition-rate RF power sources (Fig. 2). A 25 MW X-band source (Canon E37119) and a 20 MW C-band source (Canon E37217), both operating at up to 400 Hz, were successfully integrated into the facility's infrastructure. These additions will double TEX's capacity for X-band testing and expand its capabilities to include high-gradient C-band experiments, particularly relevant for medical accelerator developments and compact photoinjector applications. This expansion significantly broadens TEX's technical capabilities, establishing it as a unique hub in Europe for RF technology validation across both X-band and C-band frequency regimes.

With these upgrades and successful experimental campaigns, TEX and its team (Fig. 3) continue to be a strategic asset for INFN and the wider EuPRAXIA community, paving the way for the next generation of high-gradient linear accelerators through experimental validation, technological innovation, and collaborative development.

Figure 2: The new X-band and C-band high average power RF sources integrated in the TEX modulator area.

Figure 3: First RF X-band prototype mounted in the TEX bunker. In the picture, left to right, are Gabriele Santucci, Giorgio Scarselletta, Claudio Di Giulio, Marco Bellaveglia, Luca Piersanti, Simone Bini, David Alesini, Alessandro Gallo, Enrico De Pasquale, Fabio Cardelli, Stefano Pioli, Andrea Liedl, Luisa Spallino, Paolo Chimenti, Giulia Latini and Beatrice Serenellini.

THE NA62 EXPERIMENT AT CERN OBSERVES THE RAREST DECAY EVER

The Standard Model of particle physics developed in the latter half of the twentieth century has been enormously successful at predicting the results of experiments. Yet, it is known to be incomplete. It doesn't describe the nature of dark matter, for example, nor does it explain why the universe is made mostly of matter and contains very little antimatter.

Figure 1: The NA62 experiment at the CERN SPS.

Experimental particle physics today is essentially a quest to observe phenomena that cannot be explained by the Standard Model. Experiments at the largest colliders, such as those at the Large Hadron Collider at CERN, collide particles at higher and higher energies in the hope to find never-before-observed particles. However, there are technological limits on the energies that can be reached. Nevertheless, new phenomena that become visible at the highest energies are also present at lower energies, even if their effects at low energies are tiny. For example, the existence of new, unobserved particles could cause a well-known particle to occasionally decay to a combination of lighter particles that is forbidden in the Standard Model. This would happen exceptionally rarely, but if an experiment could observe enough decays, it would eventually see the forbidden decay, uncovering evidence of the new physics at work.

The NA62 experiment at CERN[1] was proposed twenty years ago to observe a particularly rare decay of the K^+ meson to a π^+ meson and a neutrino-antineutrino pair ($\nu\bar{\nu}$). Physicists around the world have been trying to measure the frequency of this particular decay, $K^+ \to \pi^+\nu\bar{\nu}$ since the early 1990s. This decay is not completely forbidden in the Standard Model, but it happens so rarely — for every 10 billion K^+ decays, less than one is to $\pi^+\nu\bar{\nu}$ — that even a small contribution to the frequency of this decay from new physics would increase its apparent rate dramatically. Prior to the start of NA62 data taking, only one experiment, at Brookhaven National Laboratories, in the United States, had ever claimed to have seen possible $K^+ \to \pi^+\nu\bar{\nu}$ decays.

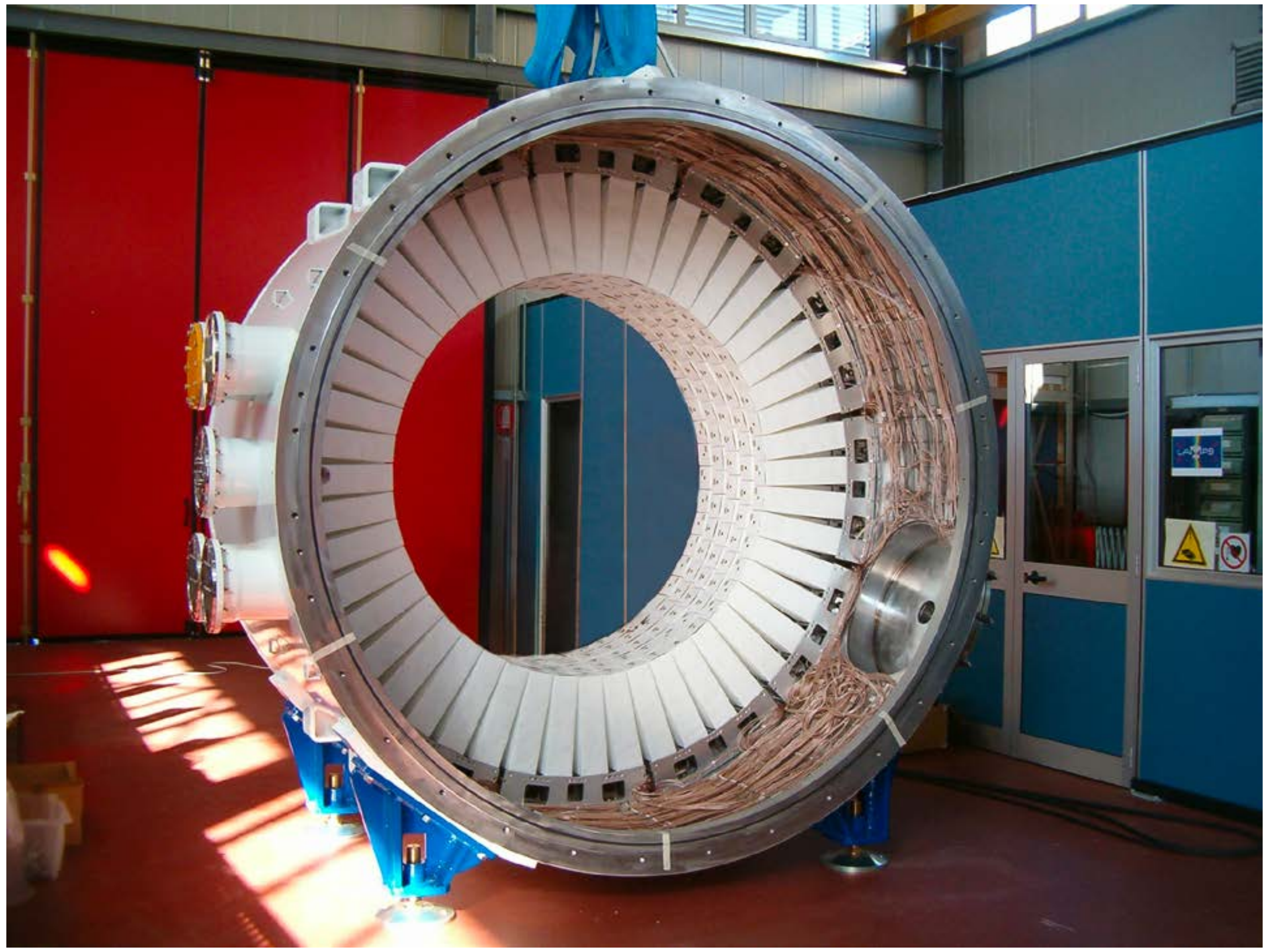

Figure 2: An NA62 large-angle photon veto detector in the assembly hall at LNF.

From 7 candidate events, the Brookhaven experiment estimated that the decay occurs 17.3 times per 100 billion K^+ decays[2]. This is about twice the rate expected from the Standard Model, but the uncertainty on the Brookhaven measurement was large, about ±70%.

To observe the $K^+ \to \pi^+\nu\bar{\nu}$ decay, the NA62 experiment starts with an intense beam of protons from the Super Proton Synchrotron (SPS), the same machine that provides the protons for the LHC. More than 2 trillion protons per second arrive on the NA62 primary target, creating an enormous shower of particles, among which 30 million K^+ mesons per second that enter the NA62 experiment (Fig. 1). One by one, these K^+ mesons are tracked and their momenta are measured; the Cherenkov light that they produce in a special, gas-filled tank confirms their identity as K^+ mesons. Then, these K^+ mesons travel through a 120-m long vacuum tank, inside of which about 10% decay. The very few that decay to $\pi^+\nu\bar{\nu}$ are identified by tracking the π^+, measuring its momentum, and confirming its identity as a π^+ with a ring-imaging Cherenkov counter and a system of calorimeters. The neutrino-antineutrino pair cannot be detected, which makes the identification of the $\pi^+\nu\bar{\nu}$ decay particularly challenging. The vast majority of K^+ mesons decay to combinations such as a muon and a muon neutrino ($\mu^+\nu_\mu$) or a charged and a neutral π meson ($\pi^+\pi^0$). In either case, the momentum of the charged track (μ^+ or π^+) takes on characteristic values in relation to its angle with the initial K^+ meson. This fact can be used to identify and reject most of these two body decays.

However, the decay $K^+ \to \pi^+\pi^0$ is 2 billion times more common than $K^+ \to \pi^+\nu\bar{\nu}$, and the rejection based on momentum alone is not sufficient. This decay can be confused for a $\pi^+\nu\bar{\nu}$ decay if for some reason the two photons from the subsequent decay of the π^0 go undetected. In this case, the charged track is in fact a π^+ meson, just as in $\pi^+\nu\bar{\nu}$ decay, so the particle-identification systems are useless. It is therefore critical to detect any photons from π^0 decays with extremely high efficiency. Most of these photons go down the beamline and are detected in the NA62 calorimeter, but some exit through the side walls of the decay tank or through the hole at the downstream end of the experiment through which the undecayed particles in the beam exit.

This is where the LNF team stepped in. Building on experience gained at LNF with the construction and operation of the calorimeter from the KLOE experiment, from the moment of the NA62 proposal in 2005, the LNF team took charge of the development of the massive system of highly efficient photon detectors to enclose the entire decay tank, to make sure that any photons, for example, from π^0s in $K^+ \to \pi^+\pi^0$ decays, have a very high probability of being detected, so that these decays are not confused with the elusive $K^+ \to \pi^+\nu\bar{\nu}$ events.

By far the largest detector in NA62, the Large Angle Veto (LAV) system consists of 12 separate ring-shaped detectors (Fig. 2), with diameters ranging from 2 to 3 m each, and each weighing between 8 and 20 tons, positioned at intervals of 6 to 10 m along the decay tank. Before starting construction, LNF team members spent 3 years creating prototype detectors with different technologies and testing their performance at the Frascati Beam-Test Facility (BTF). Working with other INFN team members from the Napoli and Pisa sections, the LNF team confirmed that the lead-glass blocks and photomultiplier tubes from the OPAL experiment at CERN's Large Electron Positron collider, decommissioned in 2001, could be reused for the construction of the LAV system. Construction and testing at CERN of two complete LAV detector prototypes began in 2008 and took another two years. Finally, the remaining stations were constructed between 2010 and 2014. The last station was delivered to CERN in August 2014, just in time to be installed for the first shakedown run of the NA62 experiment in October. The first data from the experiment confirmed that the photon veto system was performing exactly as designed, detecting π^0s with an inefficiency of just 2 π^0s lost per 100 million $K^+ \to \pi^+\pi^0$ decays [3, 4].

With only a single two-year pause for maintenance and upgrades, NA62 has been taking data ever since, with the dedicated participation of LNF team members not only for the maintenance and operation of the Large Angle Vetoes, but in all aspects of the experiment, including data reconstruction, simulation, and analysis. In recent years, INFN groups, and the LNF group in particular, have played increasingly important roles in the measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay probability: one of the principal data analysts, Dr. Joel Swallow, is a post-doctoral researcher at LNF. In a seminar at CERN in September 2024, Swallow presented the latest results from NA62, based on analysis of data collected in 2021 and 2022, when the experiment resumed data taking after the pause for upgrades. After the application of all of the criteria to select $K^+ \to \pi^+ \nu\bar{\nu}$ events and reject events of all other types based on information from the NA62 tracking detectors, particle-identification detectors, and calorimeters, as well as from the photon veto detectors designed and constructed at LNF, 31 candidate $K^+ \to \pi^+ \nu\bar{\nu}$ events were found. Of these, between 9 and 13 are expected to arise from mistakes in identifying more common events, so the experiment claims to have probably seen about 20 signal events, or about twice as many as predicted by the Standard Model. Adding these events to those previously found by NA62 in data collected in the years 2016 to 2018[5, 6], NA62 measures that the decay occurs 13.0 times for every 100 billion K^+ decays, with an uncertainty of about 25%[7], while the Standard Model predicts this decay to occur only about 8.4 times, with an uncertainty of about 12%. This is the rarest decay ever to be observed, in the sense commonly used by particle physicists (i.e., with a statistical significance of 5σ). The NA62 result is tantalizing but not conclusive: in statistical terms, the NA62 result is 1.7σ higher than the Standard Model prediction and therefore still compatible with it, even though the NA62 result itself is nearly 50% larger than the Standard Model value. What can be said for now is that if there are effects from new physics in the $K^+ \to \pi^+ \nu\bar{\nu}$ decay, they only have a modest effect on the decay rate, and this observation alone is enough to exclude numerous hypothetical scenarios for new physics. NA62 will continue to take data in 2025 and 2026, allowing the uncertainties on its result to be reduced to less than 20%. Meanwhile, by developing the techniques to make this extremely challenging measurement a reality, the NA62 collaboration, with critical inputs from the LNF team members particularly in the design, construction, and operation of the LAV system (Fig. 3), has paved the way for even better measurements by future experiments.

Figure 3: Members of the NA62 LNF team celebrating the completion of the construction of the last of the 12 LAV stations, in preparation for shipment from LNF to CERN.

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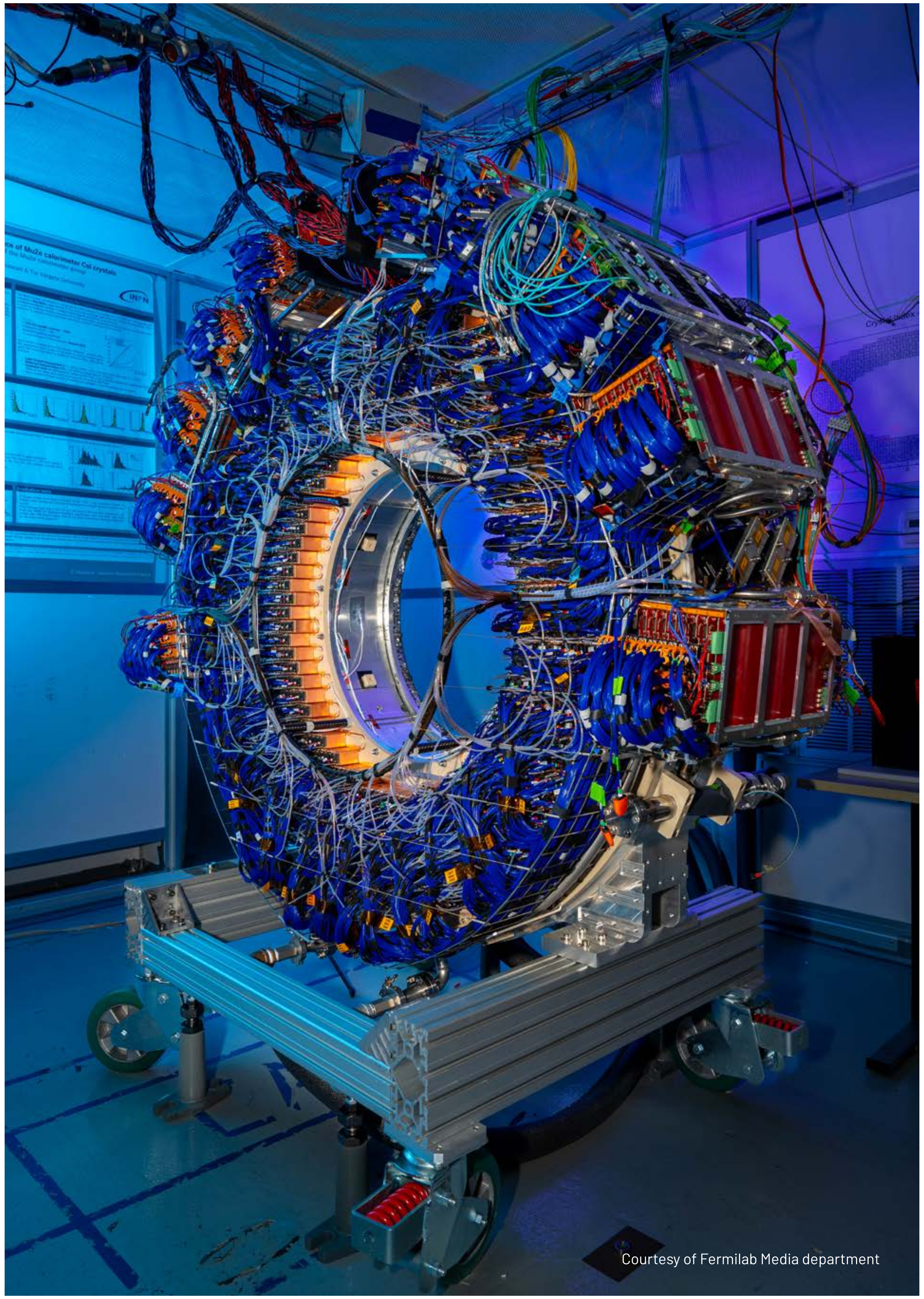

THE ELECTROMAGNETIC CALORIMETER OF THE MU2E EXPERIMENT AT FERMILAB

The Mu2e experiment[1] at Fermilab searches for the coherent, neutrino-less conversion of a μ^- to an e^- in the Coulomb field of aluminum atoms, representing one of the cleanest Charged Lepton Flavor Violating (CLFV) processes for exploring Beyond the Standard Model (BSM) physics. If detected, this would show up as electrons with a specific energy just below the muon rest mass, standing out from the usual electron energy spectrum from normal muon decays in orbit around the nucleus. Observing few of these electrons would be a clear discovery of new physics phenomena [2-3].

Mu2e aims to improve previous results by four orders of magnitude to reach a single event sensitivity of $3x10^{-17}$. To do this, the experiment will use the highest intensity pulsed muon beam in the world, with up to $6x10^9$ stopped muons/sec, and a data taking of at least 3 years to collect $6x10^{17}$ muons, which is as large as the number of grains of sand on Earth. This will be achieved by using the Fermilab proton beam and a unique 25 m long superconducting solenoidal system to produce and guide the muons to the aluminum stopping target (Fig.1). A high-resolution straw tracker and a fast crystal calorimeter will identify the conversion electron inside the last solenoidal section (DS).

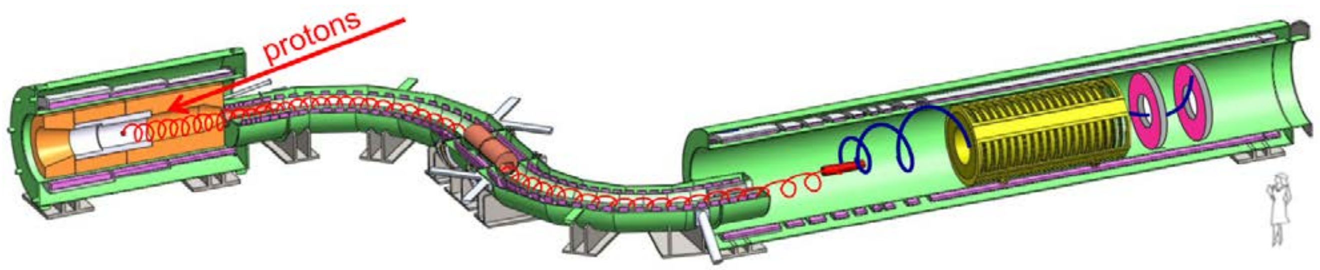

Figure 1: Mu2e experimental layout. From left to right, the PS, TS and DS solenoids. Inside the DS, the muon beam is stopped on an aluminum target. The tracks spiral with increasing radius in a gradient B-field until reaching a uniform region (1 Tesla B-field), where the 3 m long straw tracker (yellow cylinder) and the two calorimeter disks reside.

The Mu2e LNF team plays a significant leadership role in the experiment, both in collaboration management and in the realization and commissioning of the electromagnetic calorimeter[4]. Although the calorimeter cannot compete in precision with the straw tracker, it complements it with a powerful (200:1) muon-to-electron rejection capability and a filter for pattern recognition that rejects out-of-time hits. To achieve these goals, a crystal calorimeter with silicon photomultipliers (SiPM) readout has been designed, with better than 10% energy and 500 ps time resolutions at 105 MeV. The calorimeter is expected to maintain this performance when operating in a demanding, space-like, environment, running for one-year-long periods in an evacuated region (10^{-4} Torr), in the presence of 1 Tesla axial B-field, and in a strong radiation field.

The calorimeter design and construction have gone through a long R&D process, leading to the final baseline choice [5] of pure CsI crystals readout with large arrays of UV-extended SiPMs (Fig.2 left). The final Mu2e calorimeter [4] consists of two identical annular disks (Fig.2 right), each composed by 674 crystals readout by units (ROU) composed of 2 SiPMs and 2 FEE boards, 68 digital boards, a mezzanine (MZB) board for controlling and monitoring the sensors, and a DIRAC board for digital readout at 200 Msps. The mechanics consists of two large aluminum support disks, two carbon fiber inner rings, two carbon fiber front plates, two ROU's cooling plates in PEEK, and 20 custom-made crates for cooling the digital boards.

Since the start of construction in 2016, the LNF group has procured, fabricated and quality controlled: 1500 CsI crystals, 4000 SiPMs, 3500 FEE boards,1500 ROUs, 170 mezzanine and DIRAC boards, realized and assembled all mechanical parts, stacked crystals in the mechanical frame, inserted the ROUs in the cooling plates, inserted all digital electronics and routed cables. The overall cost of the assembled disks is approximately 3 million euros for the core INFN construction, with an additional 6.5 million USD for the US estimated cost of the remaining material and person power. This work was carried out by the LNF team in collaboration with other INFN units (Pisa, Trieste, Ferrara and Lecce), JINR (RU) and California Institute of Technology (USA) teams. The calorimeter team faced many challenges along the way, all of which were overcome thanks to the perseverance and capabilities of the team, especially with the support received from LNF.

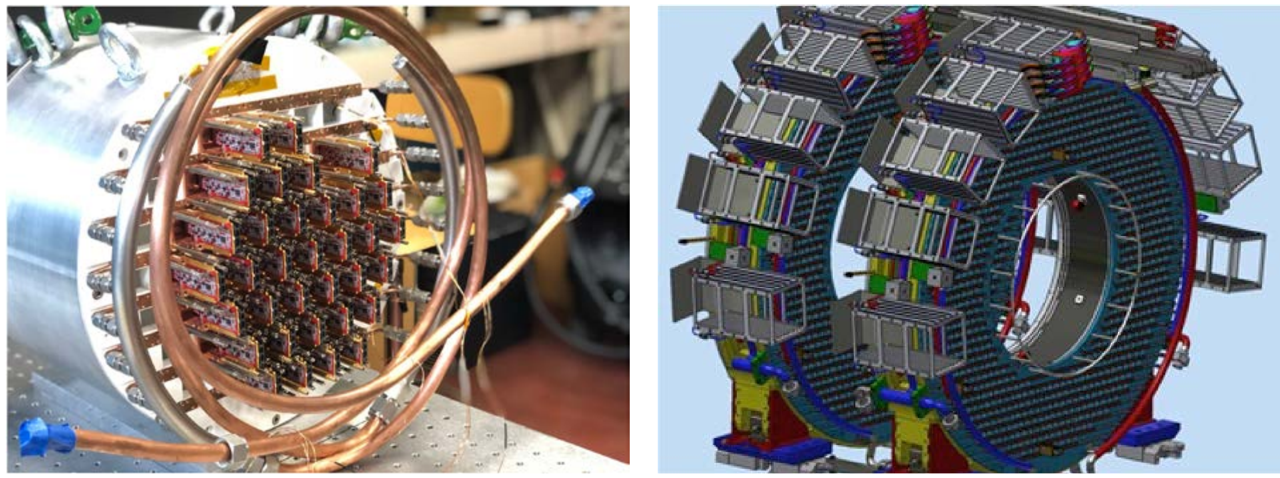

Figure 2: (Left) Modulo-0 calorimeter prototype, (Right) calorimeter CAD model.

The COVID-19 pandemic disrupted travel to Fermilab at beginning of 2020 and required a dramatic change in strategy. By then, the Mu2e team had already completed the production of crystals and SiPMs and planned to ship the first aluminum disk to Fermilab for final assembly with the ROUs. Instead, all SiPMs were shipped back in Italy and the fabrication plan was moved to LNF for both assemblying the ROUs and performing a dry run of the mechanical assembly. In parallel, a long, exhaustive R&D program for radiation hardness was conducted to improve the functionality of SiPMs, FEE, MZB boards, and other

components by exposing them to ionization doses of up to 100 krad, neutron fluxes of up to 10^{12} n/cm^2 and protons of 60-200 MeV/c of up to few 10^{10} p/cm^2. Due to the Ukraine-Russia conflict, 800 FEE units were lost, but they were produced and tested anew.

Overall, the production of all components and their testing was completed by the end of 2023. Assembly of the mechanical parts began in mid-2022, when travel to Fermilab was resumed officially. In the last 2.5 years, systematic assembly of all parts for both disks was carried out, which was completed in early 2025. The result of such an incredible journey is shown in the picture of Figure 3.

The calorimeter disks are now undergoing final acceptance commissioning runs in the assembly clean room, which follow the startup tests performed in 2024. In Figure 4, an example of a cosmic ray track as seen from the downstream calorimeter disk is shown. Preparation for transportation to the Mu2e experimental hall is well underway, with the first disk expected to be ready by mid-May 2025. Soon after installation on the rails, a 1.5-year-long commissioning phase[6] with cosmic rays will take place while waiting for the final installation and operation inside the DS. Beam operations are planned to begin in early 2027.

The completion of the Mu2e electromagnetic calorimeter is a great success of the whole LNF. In all phases, the dedicated efforts of the local Mu2e team and the support of many people from various LNF services have been, and continue to be, fundamental. The electronics, mechanics and detector development units, the vacuum service, and the mechanical workshop have supported both the R&D, design, fabrication, assembly, and final tests with great expertise and dedication, all celebrated in Figure 5.

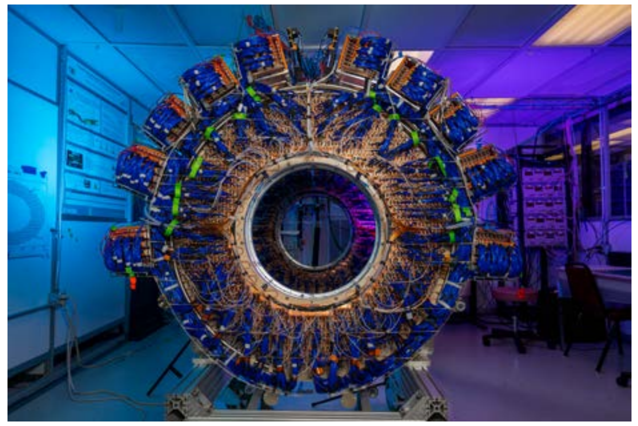

Figure 3: picture of the downstream calorimeter disk as of December 2024 (courtesy of Fermilab Media department).

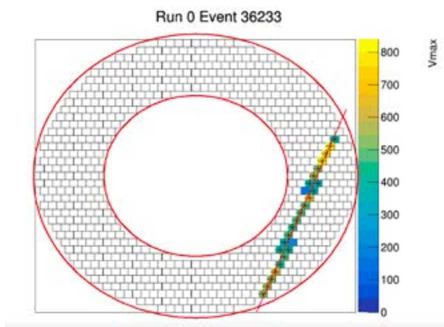

Figure 4: Event display of a cosmic ray track reconstructed by the calorimeter.

Figure 5: A collection of pictures during various construction phases.

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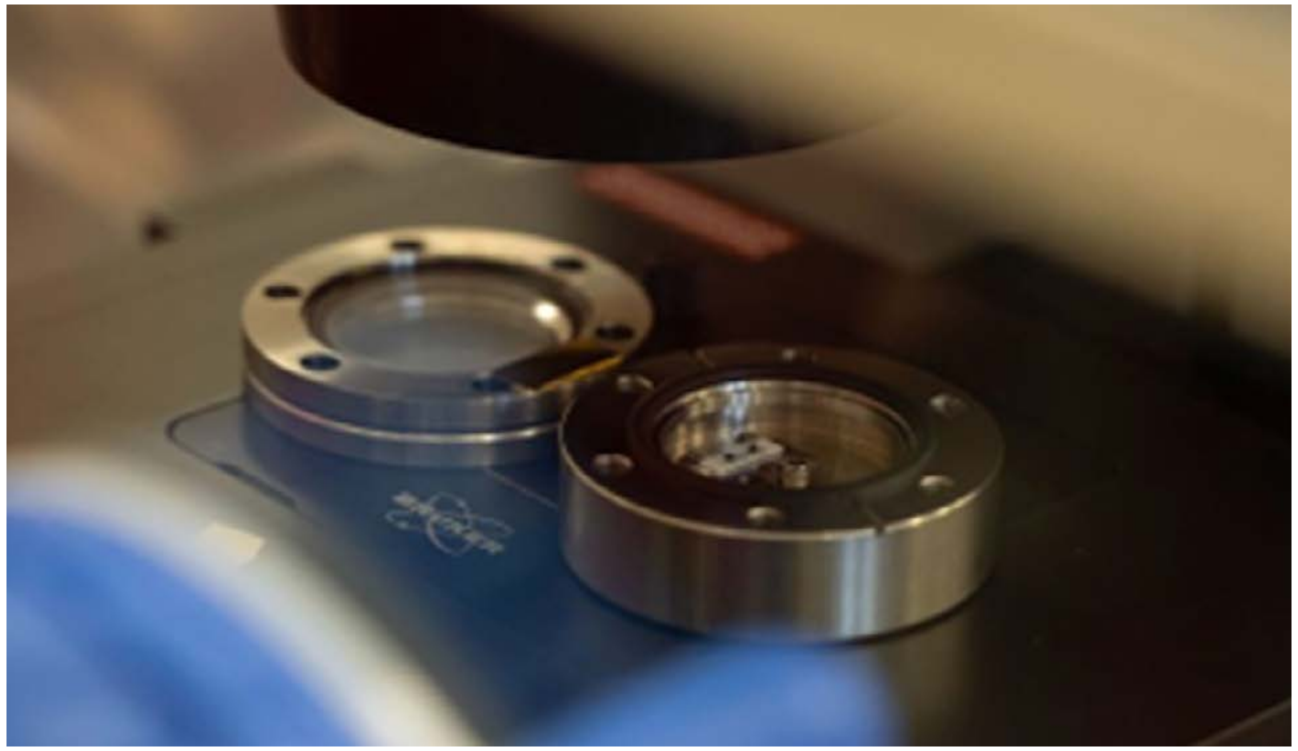


Figure 1: Image of two Ryugu asteroid grains inside their vacuum chambers, maintaining a controlled environment for FT-IR microscopic analysis.

FROM MICROSCOPIC TO MACROSCOPIC: FT-IR SPECTROSCOPY FOR INVESTIGATING FUNDAMENTAL ORIGINS

The SINBAD-IR beamline at the DAΦNE-Light synchrotron radiation laboratory, utilizing both synchrotron radiation and conventional sources, enables advanced Fourier Transform Infrared (FT-IR) micro-imaging and spectroscopy. This versatile technique finds broad application across diverse scientific domains. In material science, it characterizes advanced materials; in biology and radiobiology, it investigates cellular processes and radiation effects, including the monitoring of dynamic changes in living cells. FT-IR spectroscopy also plays a crucial role in studying the composition of cosmic materials like meteorites and asteroids, and in the cultural heritage field, it aids in the analysis of artwork materials through dedicated setups.

In January 2024, the DAΦNE-Light laboratory employed FT-IR spectroscopy to investigate the origins of two different phenomena: the formation of our solar system and the creative processes of artists. These investigations, though operating on vastly different scales, are united by a common goal: to decipher the fundamental materials that play a role in the cosmic evolution, in one case, and that participate to the artistic creation of an artwork in the other case.

Unlocking the secrets of the early solar system

The first set of investigations focused on microscopic fragments from the Ryugu asteroid, precious samples returned to Earth by the Hayabusa-2 mission. By meticulously analysing these samples, scientists from the National Institute for Astrophysics (INAF-IAPS), the University of Firenze (UNIFI), and the National Institute for Nuclear Physics (INFN-LNF) aim to gain critical insights into the primordial conditions of the solar system. Their research seeks to illuminate its formation, the processes leading to the accretion of planetary bodies, and the nature of organic materials that may have contributed to the emergence of life on Earth. Two valuable asteroid grains, designated C0242 and A0226 (renamed Kiki and Totoro, respectively, by the Italian team in a nod to Japanese anime culture), were received in May 2023 following an international call for analysis of Hayabusa-2's cosmic cargo (Fig. 1).

The Japan Aerospace Exploration Agency (JAXA) Hayabusa-2 mission provided unprecedented access to the Ryugu asteroid. The spacecraft meticulously imaged its surface and, through a controlled impact, excavated subsurface material preserved for billions of years. Two collection chambers recovered both surface and subsurface fragments from two distinct sites, ensuring the pristine nature of the latter. The re-entry capsule carrying approximately five grams of this invaluable material was recovered in Australia in December 2020. This marks the first collection from a C-type asteroid, a class considered highly primitive and representative of the building blocks of the early solar system and Earth.

At the DAΦNE-Light laboratory, a specially designed controlled-environment glove box designed by the technical staff facilitated the analysis of these delicate Ryugu fragments. FT-IR analysis yielded crucial information about the physical-chemical interactions between organic molecules, minerals, and volatile compounds. These interactions are potentially pivotal in the origin of life within our solar system and beyond. The results of these analyses are currently being processed.

New discoveries into an unknown version of "Lo Spasimo di Palermo"

The second set of investigations shifted focus to an unknown version "Lo Spasimo di Palermo", very similar to Raphael's Renaissance masterpiece exhibited at the Prado Museum. Here, the objective was to unravel the intricacies of the artistic process by identifying the materials, techniques, and artistic choices employed. Through the application of FT-IR spectroscopy and other advanced imaging technologies, researchers from the INFN-Cultural Heritage Network (CHNet), the University of Roma Tre and the Accademia delle Belle Arti di Roma explored the pictorial layers of the painting. Their analysis aims to reveal the artist's working methods, identify potential restorations, and contextualize the artwork within its historical period.

This previously unstudied version of "Lo Spasimo di Palermo" was hosted at the DAΦNE-Light laboratory to undergo a comprehensive diagnostic campaign (Fig. 2). Like the well-known original, stored at the Prado Museum, this painting has a complex history marked by wars and numerous relocations, raising significant questions about its creation and commissioning.

The study of Cultural Heritage (CH) materials necessitates the application and development of cutting-edge technologies, often linked to accelerator science. It also requires carefully tailored sample preparation procedures and the need to non-invasive and minimally interactive analysis methods to safeguard the artworks. The INFN-CHNet, an INFN network dedicated to the study of CH materials, addresses these needs by developing innovative instrumentation and fostering collaborations with CH professionals for expert data interpretation.

To address the specific diagnostic questions posed by art historians, a suite of advanced technologies was employed. A profilometer scanner, developed at the University of Roma Tre as part of the PERSEPOLY project, mapped the painting's surface topography, identifying detachments, overpainting, and fractures. Multispectral imaging, spanning the UV-VIS-NIR to SWIR spectral ranges, was used to investigate preparatory drawings, restoration efforts, and degradation products. Furthermore, X-ray fluorescence spectroscopy and FT-IR spectroscopy provided elemental and molecular information crucial for reconstructing the artist's palette (Fig. 3). Micro-samples will undergo further analysis at the DAΦNE-Light synchrotron radiation laboratory to determine the stratigraphy of the paint layers.

Figure 2: INFN-CHNet researchers and instrumentation during the diagnostic campaign of the "Spasimo di Palermo" painting.

Finally, the ARTEMISIA project's new multi-technique scanner, developed at LNF, characterized the composition and the superficial varnishes.

These scientific investigations successfully recovered an inscription revealing the year of the painting's creation. This crucial finding, combined with other analytical data, could provide definitive confirmation of its 19th-century royal commission. The comprehensive results will enable the reconstruction of the artist's pictorial technique, the identification of the materials used, and the detection of any past restoration treatments. This information is invaluable for art historians seeking to reconstruct the complete history of this significant painting. This research exemplifies the fruitful collaboration between researchers, art historians and restorers. Preliminary results of this work were presented in October 2024 at a dedicated workshop organized in Frascati by the the DAΦNE-Light team (M. Romani, L. Pronti), as shown in Fig. 4.

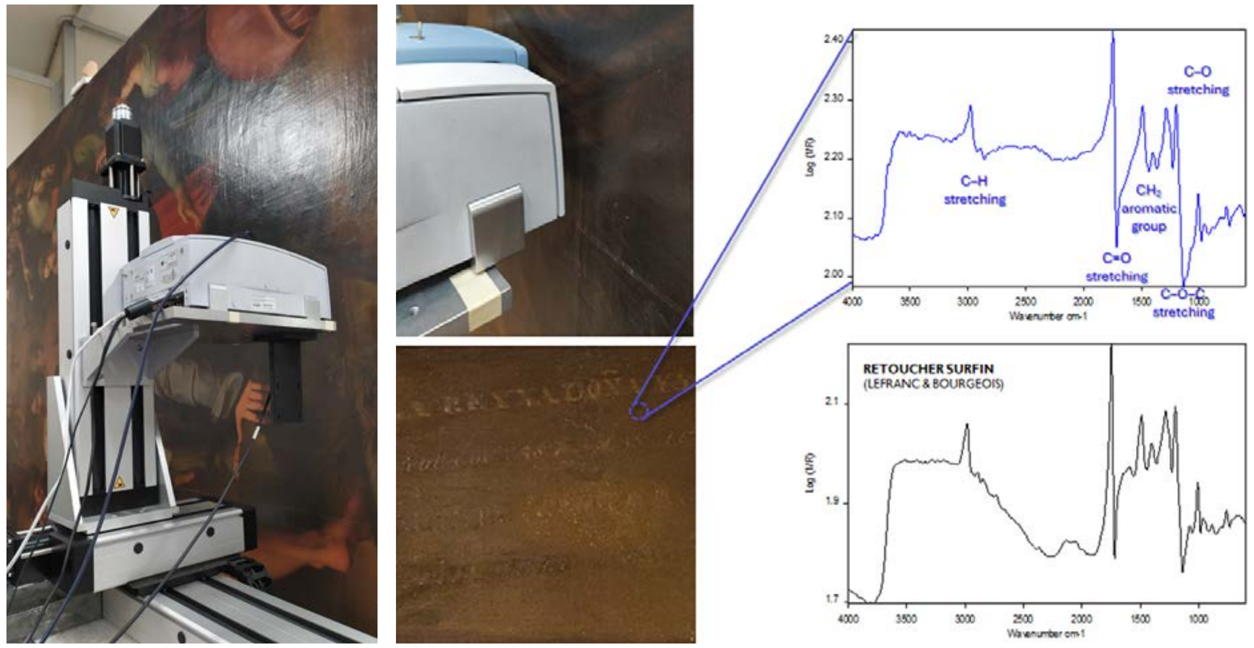


Figure 3: FT-IR measurements obtained with a Macro FT-IR scanner, demonstrating the identification of modern varnish on the artwork.

Figure 4: Workshop flyer from the event held in October 2024 at LNF.

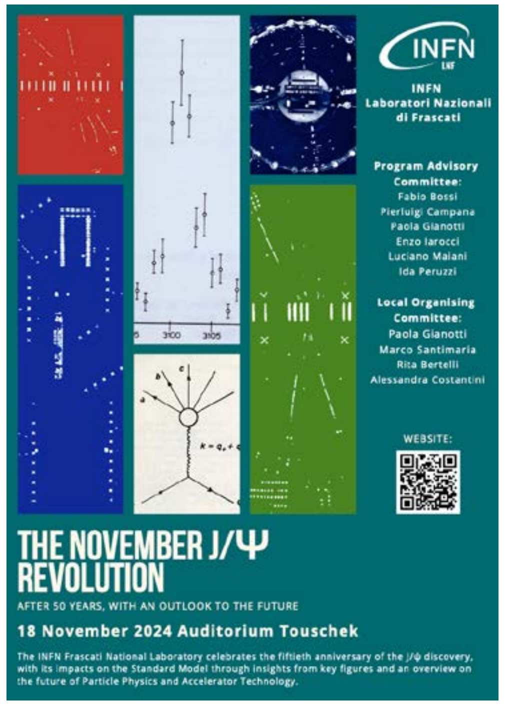


Figure 1: The promotional poster of the event.

Figure 2: A picture taken during the symposium.

Figure 3: One of the exhibition panels featuring the article from the New York Times, on the left, and a summary to facilitate reading, on the right.

THE NOVEMBER J/ψ REVOLUTION

On November 18th, 2024, on the occasion of the 50th anniversary of the discovery of the J/ψ particle, the Frascati National Laboratory of INFN organised a full-day celebration of this extraordinary event, of which they were among the key players.

It is common opinion that the discovery of the J/ψ has been a fundamental milestone in the history of particle physics. The existence of such a heavy particle with an unusually large lifetime was not foreseen by almost all of the main popular models of the time; only a paper by Glashow, Iliopoulos and Maiani predicting the existence of a fourth type of quark, the charm quark, could in fact explain the observation. After the discovery, the idea of the existence of many "families" of quarks and leptons, the fundamental building blocks of matter, became a key concept of the so-called Standard Model of particle physics.

The meeting in Frascati had therefore a twofold purpose: reviving the memories of those exceptional days and making the point on the state of health of the Standard Model, and on the present and the future of our field of research.

In the first part of the meeting, Sam Ting, Martin Breindenbach and Enzo Iarocci reconstructed the history of the discovery and confirmation of the new particle, as seen from the laboratories of Brookhaven, SLAC and Frascati. Luciano Maiani, then, described the theoretical context and explained how the event dramatically changed our understanding of particle physics. In the afternoon session, Catia Milardi and Massimo Ferrario talked about the present and future accelerator projects of our laboratory; Gino Isidori gave a comprehensive review of flavour physics and Gian Francesco Giudice discussed the present challenges of particle physics and presented the world-wide projects aimed at building new powerful accelerators in the near future. To conclude the day happily but with a hint of nostalgia, a recollection of memories from young (at the time) physicists of the various experiments of Frascati, properly introduced and coordinated by Mario Greco, was held.

Following the suggestion of Enzo Iarocci and Corrado Mencuccini, both former directors of LNF, an exhibition featuring articles from many national and international newspapers, published soon after the announcement of the discovery, has been organised. The exhibition was also enriched by various photos and videos taken from different sources. The contents are displayed on exhibition panels and a specific visual identity was realised to valorise them. It aimed to revive those moments of excitement and anticipation, to inform and engage visitors, sharing the importance of the discovery and celebrating the scientific contributions associated with it. A connection between the past and present of research was created, inviting participants to reflect on the achievements and challenges of science. The visit pathway, designed for free exploration, invites attendees to take a leap back in time, bringing them to the year 1974 with a narrative that highlights scientific events and social and cultural facts. It is planned to further enrich it, in coincidence with the 70th anniversary of the foundation of the laboratory, that will be held in 2027.

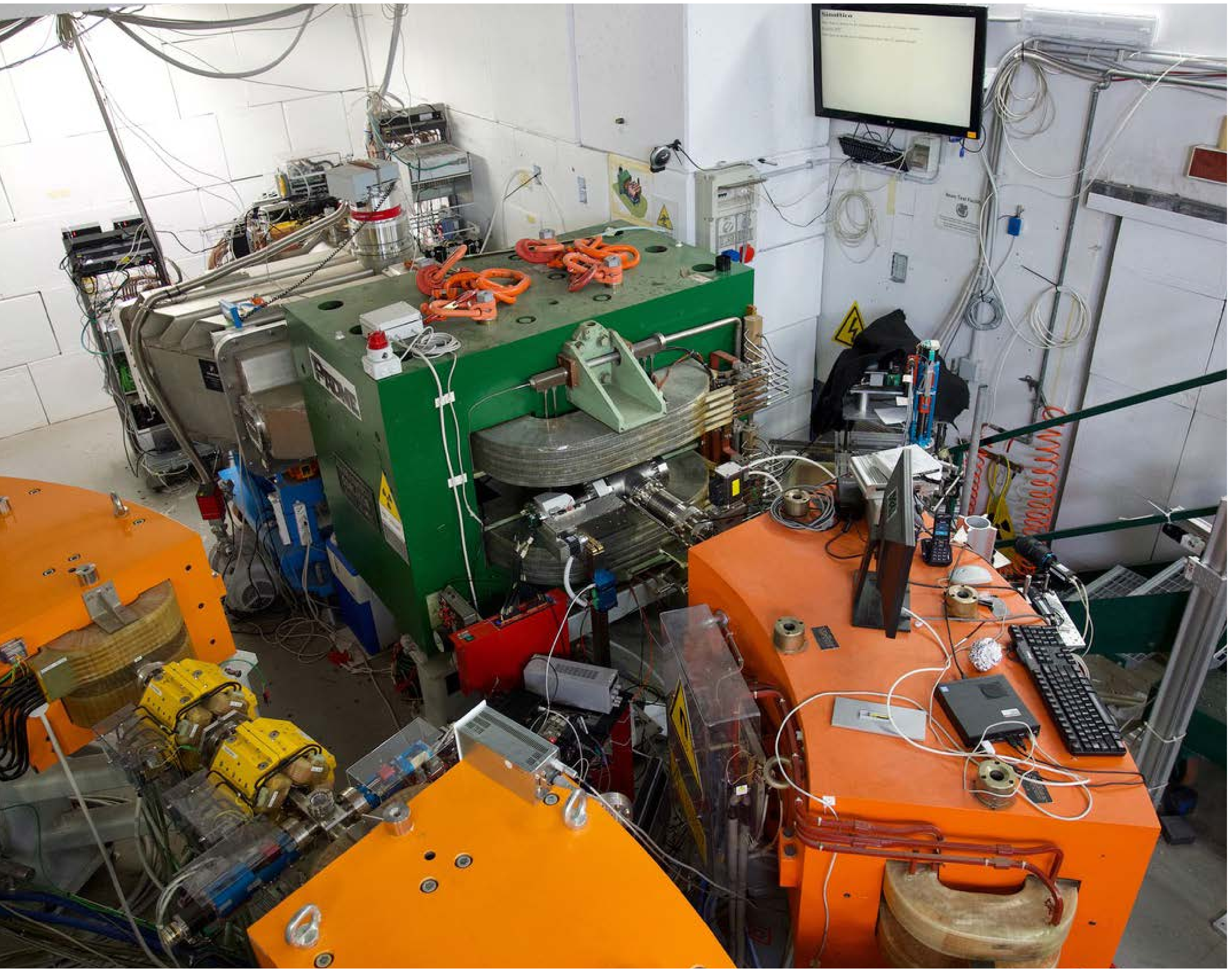


Figure 1: The PADME experiment at the DAΦNE LINAC.

NEW RESULTS FROM THE PADME EXPERIMENT IN THE SEARCH FOR THE X17 PARTICLE

After two years of hard work, the scientific collaboration of the PADME experiment (Fig. 1) has presented the results of the analysis of data collected in 2022, during the third data-taking phase (Run 3). The analysis presents a promising result in the search for the hypothetical particle known as X17.

In 2022, PADME collected data aimed at verifying the existence of a new particle with a mass of approximately 17 MeV/c^2, proposed to explain certain anomalies observed in a nuclear physics experiment conducted at the ATOMKI laboratory in Debrecen, Hungary, and named "X17." For this purpose, physicists of the LNF Accelerator Division have modified the set up of the LINAC of the DAΦNE complex, such as to provide a positron beam of variable energy, between 262 and 299 MeV, that hits the thin diamond target of PADME. The idea of the experiment is to see if, for some specific value of the energy, the rate of electron-positron pairs produced in the collisions between the beam and the target increases significantly with respect to the one measured at the other energy values: this would signal a so called "resonant production" of a particle with mass equal to the center of mass energy of the collisions.

Thanks to over 500 billion acquired events, analyzed using advanced statistical techniques, the PADME researchers have identified an excess corresponding to the mass indicated by the ATOMKI experiment (Fig. 2). The observed signal has a statistical significance of 2σ: an interesting indication, but not yet conclusive, which will guide the new data acquisition campaign planned very soon. With additional data and an enhancement of the experimental apparatus, the PADME collaboration aims to determine whether the observed excess is indeed due to the production of the X17 particle or simply a statistical fluctuation.

PADME, acronym for Positron Annihilation into Dark Matter Experiment, is an experiment at the Frascati National Laboratory. The collaboration includes the INFN Unit of Roma, the Physics Departments of Sapienza University of Roma, and the University of Sofia. Its main objective is the search for signals of new particles, candidates for composing the mysterious dark matter.

The improved detector will profit of the insertion of a new tracking device, which will allow PADME physicists to better characterize the final state events and of a stronger collaboration, thanks to the involvement of experienced colleagues from the INFN units of Roma, Napoli, and LNF.

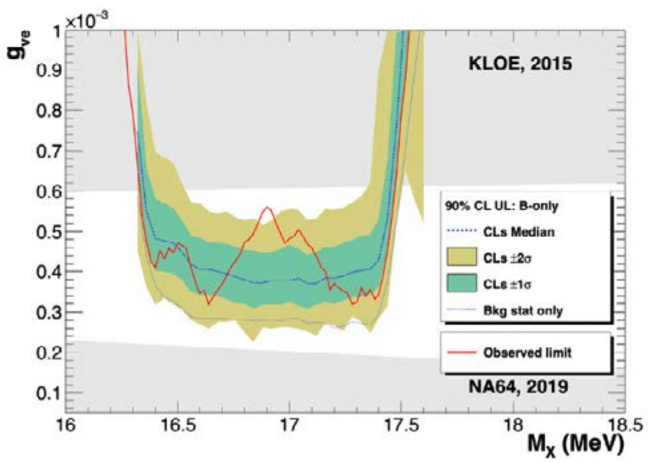


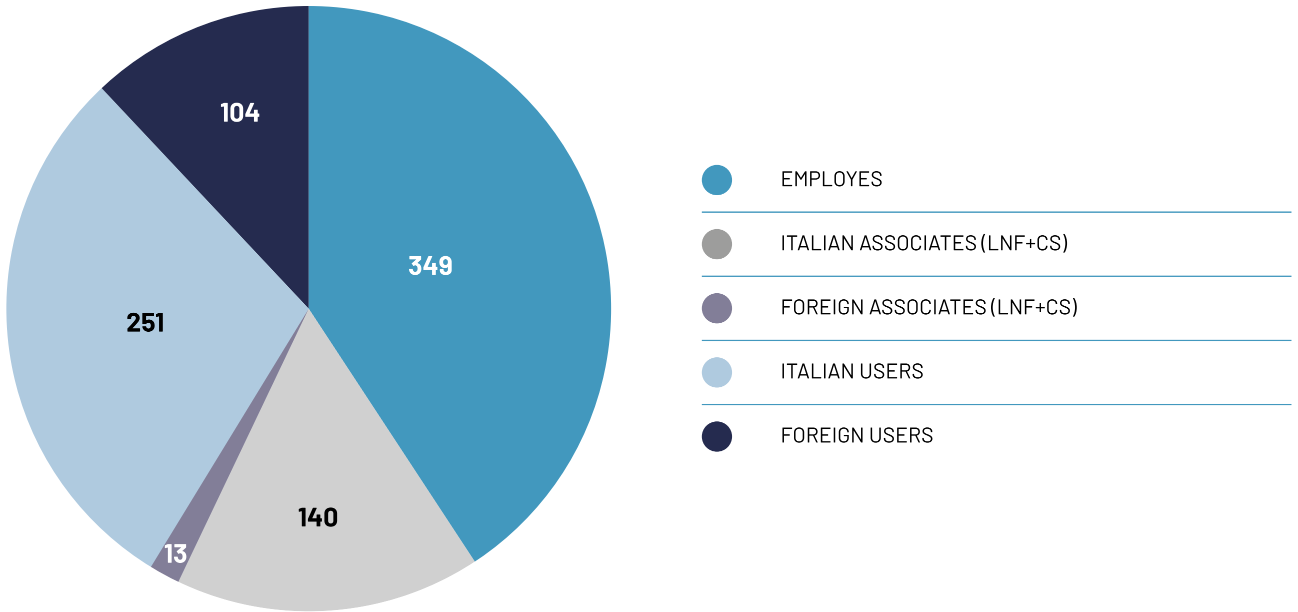
Figure 2: PADME result on X17 search: 90% CL upper limit on the coupling strength versus the particle mass; colored bands indicate the 1 and 2σ expected intervals, the red line indicates the observed limit, which has an excess around 16.9 MeV/c^2.

LNF IN NUMBERS

The LNF personnel, at the end of 2024, consists of 349 units, including 47 with a fixed term contract, plus 153 associate members. Among these, theare are university and PhD students, young post-Docs and employees from universities or other research institutions. Associate members work alongside staff members and likewise take part in the Laboratory's activities. Tab. 1 shows the division of the LNF personnel among the different profiles.

	STAFF	TEMP.	TOT.
RESEARCHER	70	0	70
ENGINEER	78	22	100
ADMINISTRATIVE	48	4	52
TECHNICIAN	106	21	127
TOT.	302	47	349

Table 1.
Snapshot of the LNF personnel at December 2024.



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HIGHLIGHTS

ONE YEAR OF RESEARCH AT LNF

2024

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