NEWSLETTER N.17, June 2022

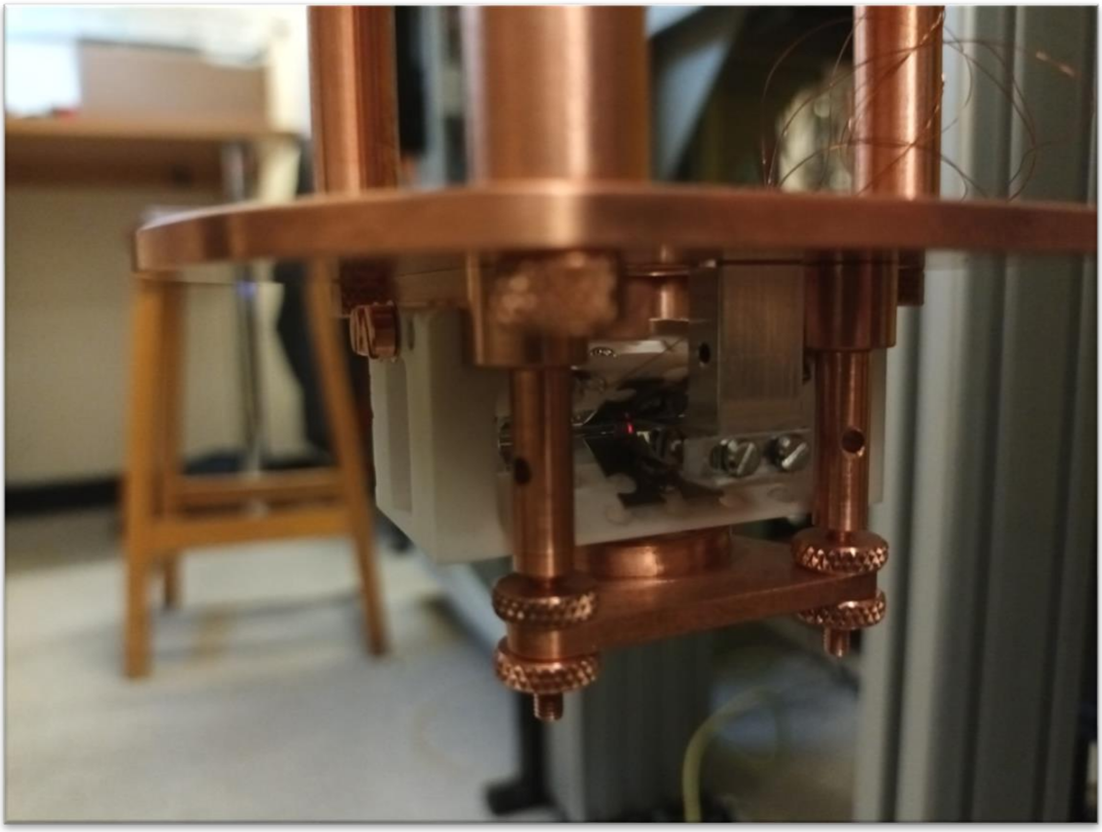

FIG. 1: TEQ PAUL TRAP ASSEMBLED AT SOUTHAMPTON WITH OPTICAL DETECTION AND PARTICLE SOURCE ASSEMBLY.

European Commission

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UPDATE OF WORK DONE

Work Package 1: Trapping

Yb:YLF nanocrystals (NCs) have the past years routinely synthesized and successfully trapped in traps of the UCL group. In the past reporting periods, focus has been on (1) controlling the size and shape of the NCs and (2) increasing their photoluminescence quantum yield (PLQY) to enable optical refrigeration to reduce the internal temperature of the NCs:

(1) The initial path to control the size and shape of the NCs by changing the temperature of the NC synthesis, which turned out to not be fully reproducible, have been substituted by a two-step synthesis. Here, relatively small NCs of well-defined bipyramidal shape are synthesized, and additional precursors are added to induce the growth of a shell of YLF or Yb:YLF around the NCs. During the reporting period, this method has been refined and led to an increased control of the size and shapes the produced NCs [Fig. 2].

(2) PLQYabove 97%, required for optical refrigeration have been achieved by coating Yb:YLF NCs by YLF shells without Yb. Essentially, the same high value of PLQY has been obtained in this way for any Yb doping concentrations of the core NC [Fig. 2].

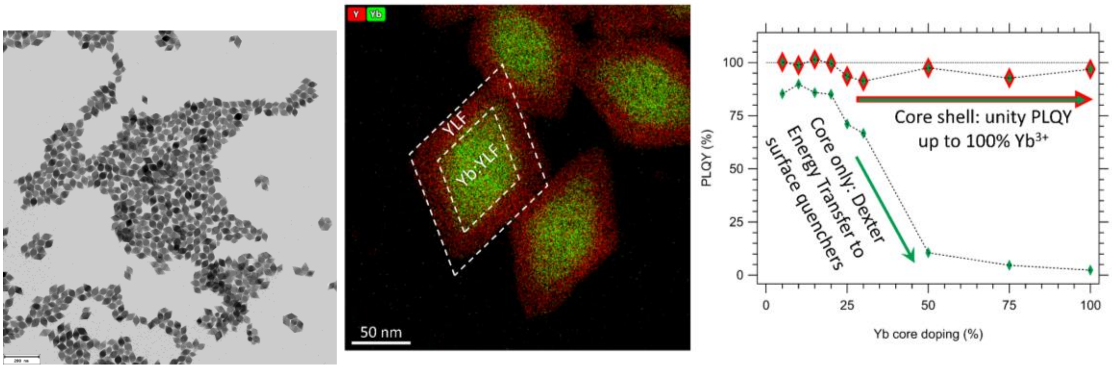


FIG. 2. LEFT: $LiY_{0.75}Yb_{0.25}F_4$(/$LiYF_4$) NANOCRYSTALS WITH LESS THAN 10% DISPERSION IN SIZES. MIDDLE: $LiYF_4$ COATED $LiY_XYb_{1-X}F_4$ NANOCRYSTALS. RIGHT: PLQY AS FUNCTION OF YB DOPING LEVEL OF THE CORE CRYSTAL.

In parallel, silica nanoparticles have been successfully trapped at UCL, in the TEQ blade trap, at ambient pressure, room temperature and using the new low-noise digitally controlled electronics produced by INFN and AU. In particular, in the frequency range that the trapped nanoparticles oscillate, the new electronics have improved the voltage noise by about 2-4 orders of magnitude compared to previously used electronics at UCL. Most recently, a combined analog AC+DC power supply designed by INFN with voltage output of 350V, a 100 kHz bandwidth (for frequency tuning of the AC) and low noise (130nV/√Hz) has been completed [Fig. 3]. After first successful testes at UCL, the supply has been transferred to UoS and integrated in the final experiment under cryogenic conditions.

FIG. 3: PHOTOS OF THE COMBINED ANALOG AC+DC POWER SUPPLY DESIGNED AND TESTED AT UCL. LEFT: THE ACTUALLY PRODUCED ELECTRONIC CIRCUITS. RIGHT: THE INTERFACE FOR THE EXPERIMENTS.

The TEQ consortium initially investigated several different methods of loading nanoparticles into charged particle traps, including electrospray sources and nebulisation techniques. Eventually, we have ended up chosen laser desorption for loading the nanoparticles since during the past years this technique has been matured and constitute a very simple and robust way of particle loading even at low pressures and low temperatures.

With this method, silica nanoparticles have been successfully loaded and trapped at ambient pressure and room temperature at UoS in the cryogenic setup in a slightly modified blade trap originally designed by AU [Fig. 4].

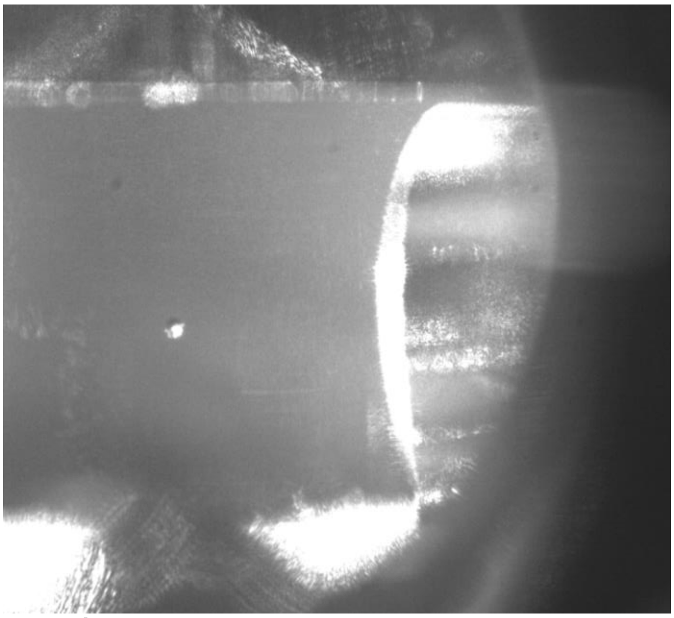


FIG. 4. A SILICA NANOPARTICLE TRAPPED IN THE BLADE TRAP AT UOS.

In parallel to the NC investigations, an experiment to test CSL models on a complementary few nm length scale has been finalized at AU. It consists of an electrospray source attached to a cryogenically cooled ion trap, in which a single laser-cooled Ba+ ion will enable sympathetic cooling of a co-trapped complex molecular ion species. Any CSL induced heating of the nm-sized molecular ion could be detected through motional heating of the combined atomic-molecular ion system. First, theoretical analysis of the sensitivity of this technique has been carried out together with other TEQ partners. These results indicate that improved bounds to CSL by this method will be challenging.

Work Package 2: Cooling

The work on WP2 is a combination of four parts as described in the DoA.

Low-noise electronics: The low noise electronics developed for the Paul trap, including the AC source produced by INFN, and the DAC system (Aarhus) for controlling the DC voltages on the Paul trap has been brought together and implemented into the trap at UCL. At INFN, there has been the need to increase the work effort to perform testing activity of the electronics in the lab for the qualification of the noise level. At this aim, a PostDoc was involved in the work: his effort is quantified as 5 Person-Months and his cost is not claimed in the Financial Report (see section 5 of this document).
First tests confirmed the required low noise at the trap frequencies. However, longer tests of this system where the motional noise/temperature were to measured were abruptly halted by the shutdown of UCL due to COVID-19. The labs were closed for approximately 6 months but in the last 5 months have been operating at full capacity.

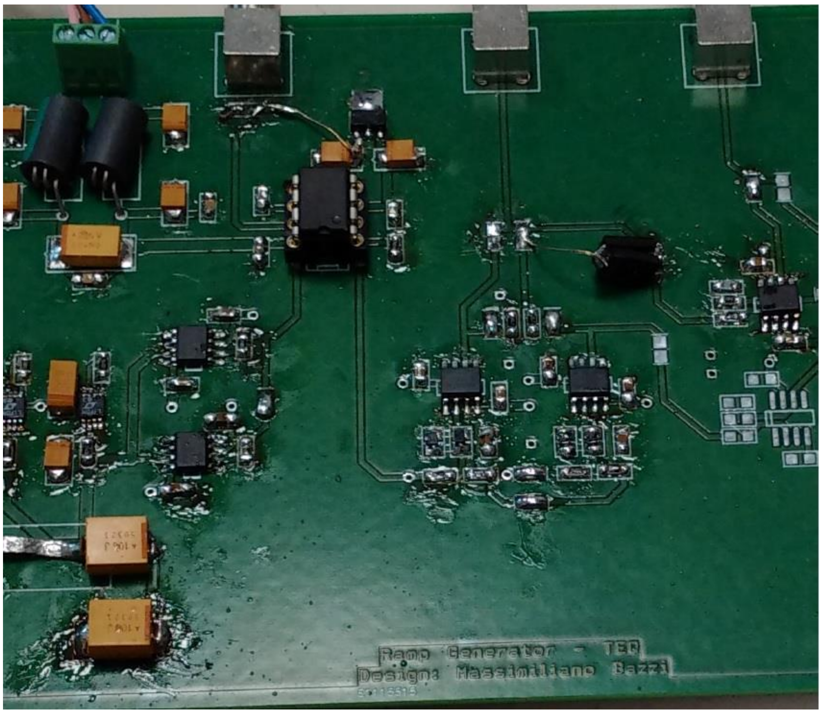


FIG. 5. TEQ DEDICATED ULTRA- LOW NOISE, 0 TO 5 VOLT RAMP GENERATOR DEVELOPED AT INFN

Centre-of-mass cooling: UoS and UCL have already demonstrated parametric feedback cooling, but more recently, UCL has also implemented and compared both velocity damping and parametric feedback in the Paul trap. This was undertaken to understand which of these schemes is better for cooling to the lowest ultimate temperatures in the TEQ trap. Our experiments have shown a ten-fold improvement using velocity damping and this is backed up by theoretical studies undertaken during the lockdown period when access to the labs has been prevented.. Both linear and quadratic cavity cooling of a silica nanosphere levitated in the Paul trap has been carried out. It was shown that the quadratic cooling is analogous to parametric feedback cooling where the feedback is automatically applied by the cavity. Similar temperatures in the mK range where obtained but non-thermal distributions are created by this type of cooling. Linear cooling in Paul trap is limited by frequency noise in the laser. Recent work has shown even strong cooling using coherent scattering.

We have reached temperature in the microkelvin range. Importantly we have also cooled all the rotational degrees of freedom of non-spherical nanoparticles down to mK temperatures.

Internal cooling: TUD has continued to develop methods for synthesis of doped Yb:YLF doped crystals. Their measurements have shown increasingly better quantum efficiencies which is required for internal-state cooling via spontaneous anti-Stokes fluorescence. While these particles are still shown to heat in the trap we have verified that undoped YLF particles do not heat and represent one of the few optically trapped particles that can potentially be taken into high vacuum without particle loss due to melting. UCL has implemented velocity damping feedback cooling on these particles but has shown that in an optical trap they become dynamically unstable and are lost from the trap. UCL has modelled this motion and identified the main dynamical features in both linear and circularly polarized light.

Analysis of decoherence and non-equilibrium: Experiments performed at the lowest pressures have confirmed that the primary source of decoherence for the Paul trap experiments is the motional heating due to electric field noise in the traps and this leads to non-equilibrium since the trapped particle do not come to a well-defined temperature. This has been addressed via the low noise electronics developed at INFN as well as the electronics at Aarhus. The final electronics has now been implemented and tested at UCL and it was shown to meet the original TEQ requirements and it was found that the trapped particle, even at the lowest temperatures maintain the ambient temperature set by the background environment. .

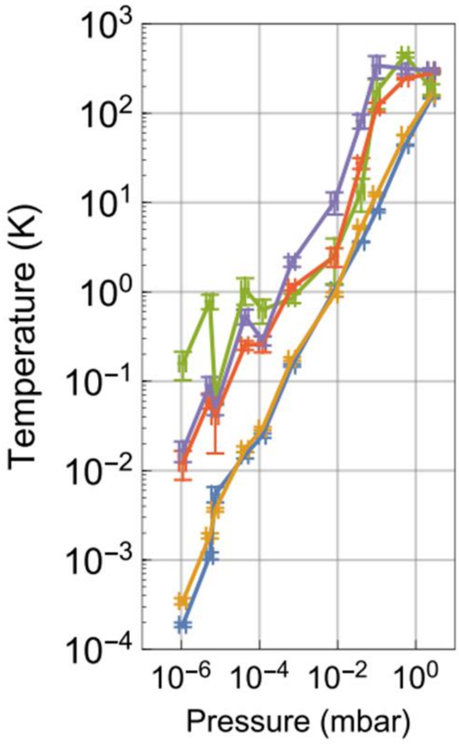


FIG 6. COOLING OF CENTER-OF-MASS AND ROTATION VIA CAVITY COOLING.

Work Package 3: Testing

In WP3 we have been working to continue the realization of the ultimate TEQ experiment. This has multiple aspects and work was done together with TEQ partners from other WPs. Over the reporting period we have held weekly zoom meetings between partners at QUB, Aarhus, UCL and Southampton to coordinate progress with Paul trap, electronics, and detection method. At the same time the final design of the low-temperature experiment at Southampton has been finalized. By end of April 2022 the room-temperature tested Paul trap with the TEQ electronics was picked up at UCL and the Southampton team trained to operate the trap. The Paul trap was routinely loaded at UCL and the noise level have been characterized at room temperature (paper in preparation).

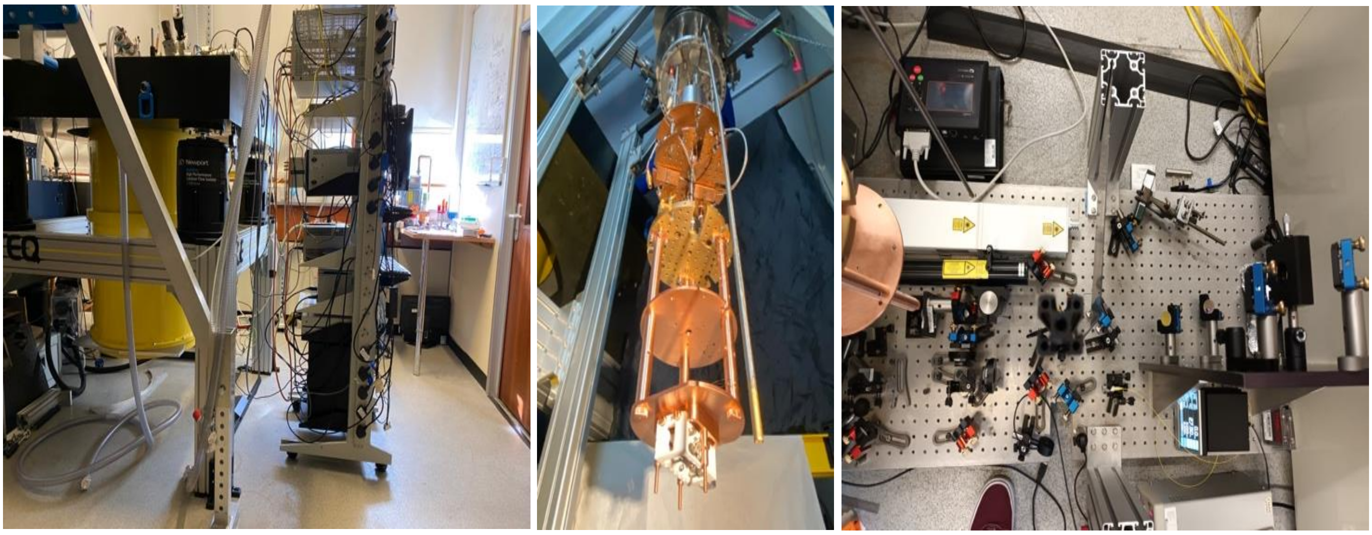


FIG. 7: LEFT: THE CRYOSTAT ENVIRONMENT AT SOUTHAMPTON WITH THE CONTROLLER RACK, MIDDLE: THE PAUL TRAP ASSEMBLED TO THE 300 MK CRYOSTAT. RIGHT: OPTICAL BREADBOARD WITH LIAD LOADING AND OPTICAL DETECTIONS.

The Paul trap has been installed at the 300 mK cryostat at Southampton with two optical detections: a high-resolution CMOS based imaging at high-speed (a method developed at UCL and papers have been published), and a pulsed homodyning detection at low laser power scattered by the trapped particle. The latter is key to avoid heating (generation of noise) by the detection itself at the high spatial and temporal resolution needed for the new TEQ detection (parameter estimation and dynamical model selection). A Laser Induced Acoustic Desorption (LIAD) technique has been implemented and tested at Southampton for trap loading (300 nm silica particles) at mbar pressure. Some pictures of the assembled trap and detection are shown in Fig. 7.
Other activities in order to achieve the TEQ objective of WP3 include, and to test CSL noise to the defined TEQ level (10^{-11} 1/s at 10^{-7} m):

- Magnetic levitation experiments have been implemented and performed as alternative to the TEQ Paul trap. Two papers have been published on results of the magnetic levitation in early and mid-2020. Since then, we have been optimizing magnetic levitation at 300 mK for magnets of 10 micrometre size and their loading into the Meissner traps, which remains a mayor experimental challenge. However, liberational modes of larger non-spherical ferromagnets is an alternative avenue which we are pursuing now, and ultra-low force noise measurements have been performed already together with external partners at Leiden at 10 mK. A paper is in preparation.

We have theoretically explored the possibility of using macro-molecules in 4 K Paul traps at Aarhus to test for CSL noise. The mass/size of such molecules is too small for a straightforward centre of mass motion CSL test, however the detailed analysis of specific effects of relative arrangements of different atomic species bound together in poly-aromatic molecules open a new avenue for testing CSL in a competitive way. A theory paper is in preparation.

Work Package 4: Enabling

The third reporting period has seen the TEQ team working through the extension of the collapse-model framework via the formulation and test of energy-conserving Continuous Spontaneous Localisation (eCSL) mechanisms. UCL and Southampton have studied experimentally such model through the use of both a magnetically levitated microsphere with ultralow damping and a levitated nano-particle in a linear Paul trap, establishing new, previously unforeseen bounds on eCSL. The data gathered from the experiments allow the exclusion of a significant portion of the parameter space. The achievement of the goals of TEQ passes through the carefully crafted interplay between coherent dynamics and incoherent mechanisms for localisation and thermalisation, which is possible only through a careful quantification of the effects of sources of decoherence affecting our experimental platforms. QUB has performed such quantitative characterisation using a non-equilibrium perspective by focussing on the characterisation of the entropy production resulting from such non-equilibrium dynamics. We have successfully analysed the open-system dynamics of the nanoparticles at the core of TEQ highlighting the relative weight of thermalisation and localisation in the determination of the steady-state features of the system. Working together, UCL, Southampton and QUB have explored the energetic bounds to the macroscopicity of the state of the mechanical oscillator achieved by subjecting it to either continuous or time-gate measurements, and the consequent capability of inferring the parameters of a potential CSL mechanism with an uncertainty that does not hinder the infer process itself. The results of our study have highlighted the extreme sensitivity of the experimental platform to the backaction induced by the measurements performed on the mechanical system, whose motional state would be quickly ‘buried’ by significant thermal excitations, and thus rendered fully classical. UniTs and Southampton have then furthered the work pioneered by the TEQ consortium on the possibility to enhance the CSL noise through groundbreaking experimental effort. Using a multilayer test mass attached on a high quality factor microcantilever specifically designed to enhance the effect of CSL noise, the team has shown agreement with pure thermal motion for temperatures down to 100 mK, thus establishing a new bound on the collapse rate of the model and challenging a significant region of the CSL parameter space proposed by Adler.

A significant step made towards the “ruling out’ objectives of WP4 has been embodied by the critical assessment of the model proposed by Diósi and Penrose for the collapse of a spatial quantum superposition due to a back-reaction from spacetime (suggestive of a gravity-related wave function collapse). A careful computation of the radiation emission rate resulting from the collapse of a mass density of charged particles allowed an experimental investigation, performed within through the collaboration between UniTs and INFN, allowed to establish a bound about three orders of magnitude larger than previous known ones, thus ruling out the natural parameter-free version of the Diósi-Penrose model. Furthering these efforts, the UniTs team has critically assessed models formulated by Kafri, Taylor, and Milburn and by Tilloy and Diósi to describe gravitational interaction through a continuous measurement and feedback protocol, proposing a dissipative generalization of these models that shows long-time thermalization effects to an effective finite temperature.

OEAW has continued the critical assessment of the formulation of the Principle of Equivalence by challenging the assumptions, upon which the principle stems, that reference frames are abstracted from classical systems (classical rods and clocks) and the spacetime background is well defined. Quantum theory explicitly allows for superposition of the state of systems and, potentially, classical spacetime structures. The OAEW team has tackled both questions by introducing a relational formalism to describe quantum systems in a superposition of curved spacetimes, which allowed them to argue that the formulation of the Equivalence Principle can be generalised so that it holds for reference frames that are associated to quantum systems in a superposition of spacetimes. This procedure reconciles the principle of linear superposition in Quantum Theory with that of general covariance and the Equivalence Principle of General Relativity, thus ruling out the need for a gravity-induced spontaneous state reduction when a massive body is prepared in a spatial superposition.

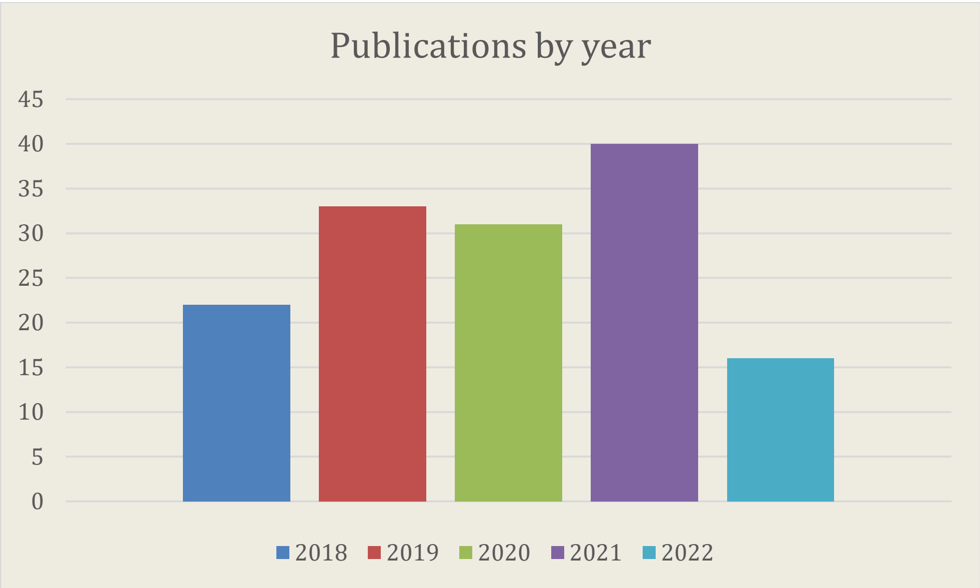
PUBLICATIONS

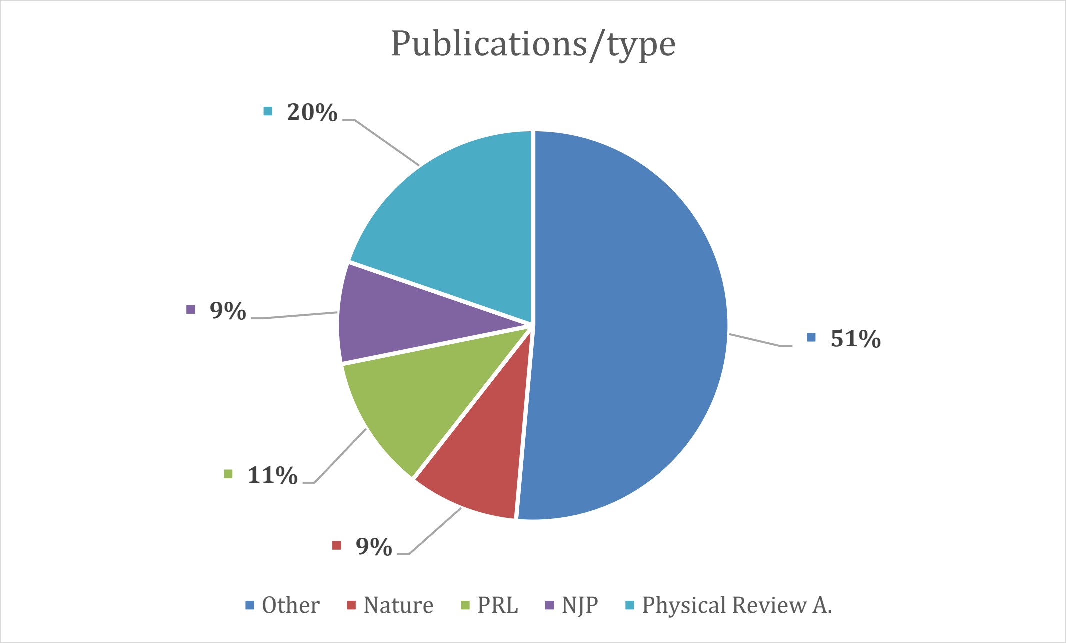
Here below the list of the publications of the last 3 months.

Authors	Title	Journal	Volume	Pages	Year
Renner, Martin J., and Časlav Brukner	Computational Advantage from a Quantum Superposition of Qubit Gate Orders	Phys. Rev. Lett.	128	230503	2022
Rubino, Giulia, Gonzalo Manzano, Lee A. Rozema, Philip Walther, Juan M. R. Parrondo, and Časlav Brukner	Inferring work by quantum superposing forward and time-reversal evolutions	Phys. Rev. Research	4	013208	2022
Derakhshania, Maaneli, Matthias Laubensteind, Kristian Piscicchia, Lajos Diósi, and Catalina Curceanu	At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory	Physics of Life Reviews	42	8-14	2022
Napolitano, F., et al.	Testing the Pauli Exclusion Principle with the VIP-2 Experiment	Symmetry	15(5)	893	2022
Curceanu, Catalina, et al.	Underground tests of Quantum Mechanics at Gran Sasso	PoS DISCRETE2020-2021	405		2022

De Paolis, L., et al.	Testing Pauli Exclusion Principle for electrons at the LNGS underground laboratory: The VIP-2 experiment	PoS PANIC 2021	380		2022
Porcelli, A., and et al.	Analysis methods used and planned for VIP-2	EPJ Web of Conferences	262	01022	2022

In its 54 months of life, TEQ partners have produced a collection of 142 publications.





To explore all publications, visit Publications | TeQuantum.

DISSEMINATION ACTIVITIES

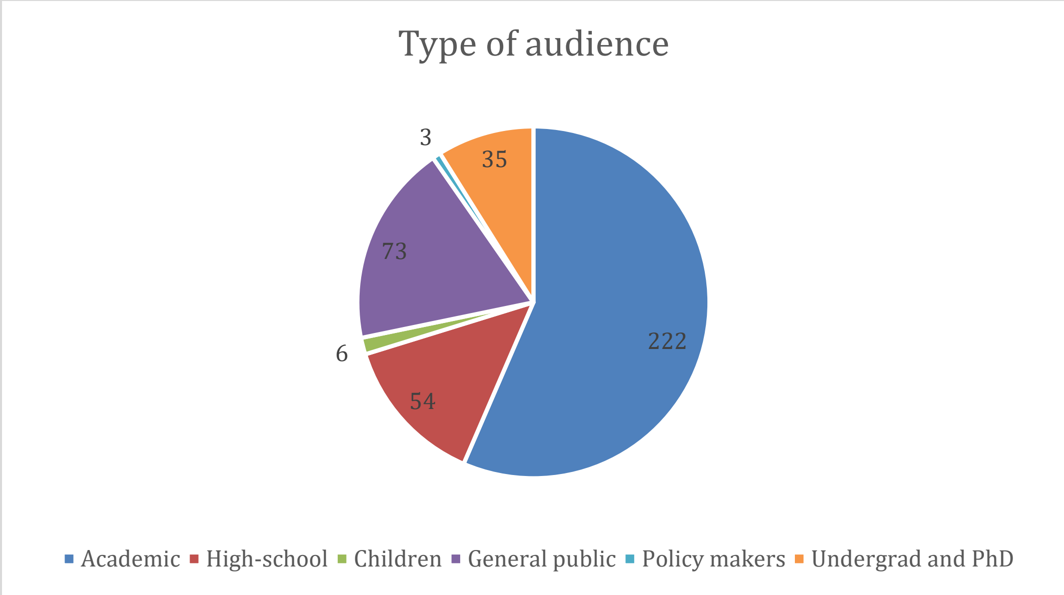
In the last 3 months, TEQ members delivered seminars and talks to over 1.500 people in audience:

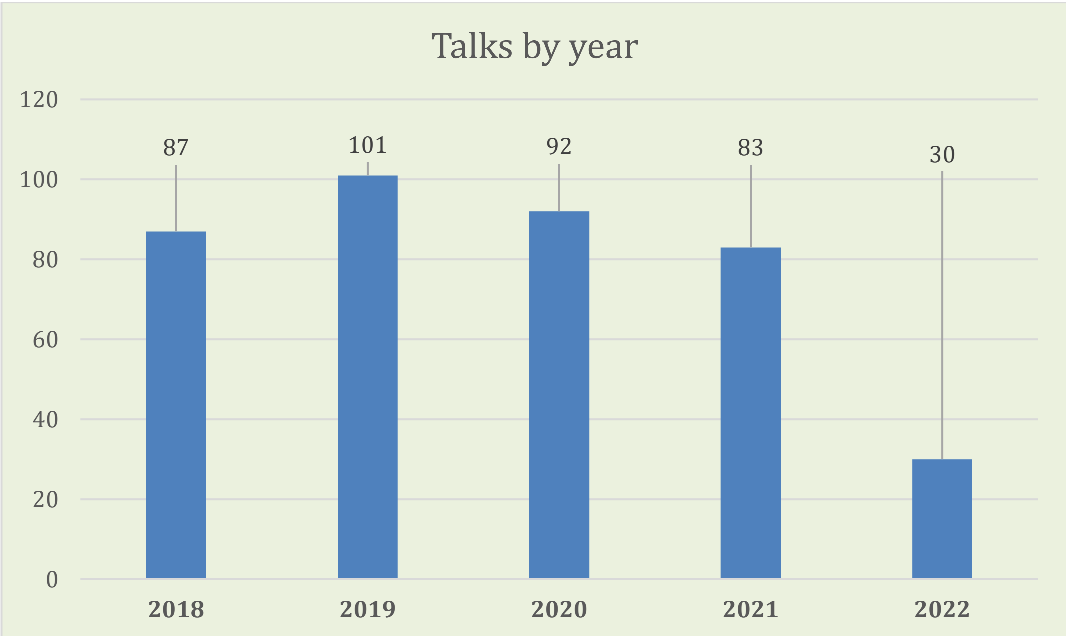
Who	What	Where	When
Catalina Curceanu	De la stelele de neutroni la mecanica cuantica	Caravana Stiintei si Imaginetiei	March, 2022
Caslav Brukner	Falling through masses in superposition: quantum reference frames for indefinite metrics	DPG Tagung – Hauptvortrag, Fachverband Theoretische und Mathematische Grundlagen der Physik	March, 2022
Angelo Bassi	Oltre i confini della fisica	Log@Ritmi	March, 2022
Angelo Bassi	Seven non-standard models coupling quantum matter and gravity	Testing Quantum Aspects of Gravity in a Laboratory	March, 2022

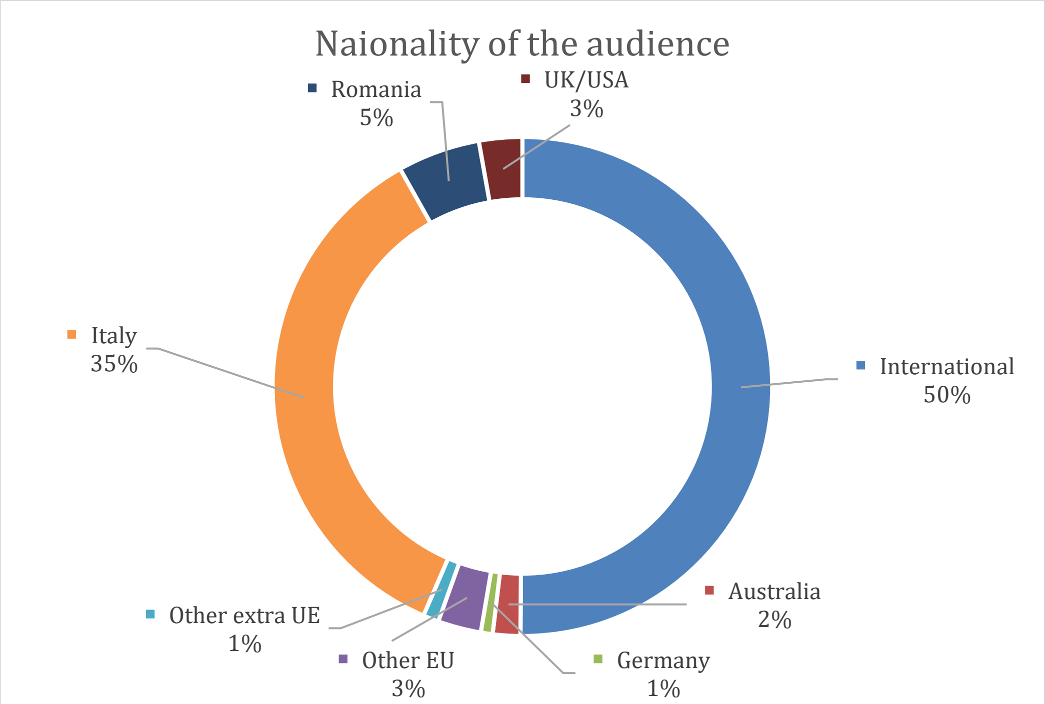
Catalina Curceanu	Underground tests of Quantum Mechanics - Collapse models and Pauli Exclusion Principle	Lorentz Center, Testing Quantum Aspects of the Gravity in a Laboratory Workshop	March, 2022
Catalina Curceanu	Dal gatto di Schroedinger al computer quantistico	Visioni scientifiche sul futuro dell'umanità	March, 2022
Catalina Curceanu	De la stelele de neutroni la mecanica cuantica	Caravana Stiintei si Imaginetiei	March, 2022
Caslav Brukner	Quantum causal structures	International Network on Acausal Quantum Technology	March, 2022
Angelo Bassi	Quantum communication	Italian Quantum Weeks	April, 2022
Catalina Curceanu	Underground tests of Quantum Mechanics - Collapse models and Pauli Exclusion Principle	INFN2022 Conference	May, 2022
Arjan Houtepen	Nanoscale charge transport	Ghent seminar on nanoscience	May, 2022
Caslav Brukner	Falling through masses in superposition: Quantum reference frames for indefinite metrics	Seminar at University College London	May, 2022
Angelo Bassi	Siamo tutti connessi	La via delle scienze	May, 2022
Catalina Curceanu	Underground tests of Quantum Mechanics - Collapse models and Pauli Exclusion Principle	INFN2022 Conference	May, 2022
Angelo Bassi	Spontaneous wave function collapse models: an update	Mind and Agency in the Foundations of Quantum Physics	May, 2022

Catalina Curceanu	Testing Quantum Mechanics Underground: Sneaking a look at God's cards	Mind and Agency in the Foundations of Quantum Physics (Chapman University, USA)	May, 2022
Arjan Houtepen	Nanoscale charge transport	Ghent seminar on nanoscience	May, 2022
Angelo Bassi	Siamo tutti connessi	La via delle scienze	May, 2022
Arjan Houtepen	Finding the weakest link - surface electrochemistry of nanomaterials	EMRS Spring meeting 2022	May, 2022
Catalina Curceanu	Experimental tests of QM from collapse models to the Pauli exclusion principle	IAP 2022 Conference	June, 2022
Angelo Bassi	Status of Collapse Models	When hbar meets G	June, 2022
Caslav Brukner	Objectivity "Bubble"	The Quantum Information Structure of Spacetime Conference	June, 2022
Fabrizio Napolitan o	Experimental tests of Quantum Mechanics: from collapse models to the Pauli Exclusion Principle	Quantum Information and Probability: from Foundations to Engineering (QIP22)	June, 2022
Catalina Curceanu	Testing Quantum Mechanics Underground	Invited Colloquium Rutgers University USA	June, 2022

In its 54 months of life, TEQ partners have produced an incredibly rich collection of 393 talks and reached out to almost **50.000 people**. Here below a graphic view of the dissemination results of the project:







A detailed list of all talks can be found at [Talks | TeQuantum.]()

ANY OTHER RELEVANT INFORMATION

INSPYRE 2022

The school Inspyre 2022 that took place from April 4th – 8th , 2022 (Frascati, Italy) was dedicated to interactive presentations of the most recent and exciting results in the particle physics and studies of the Universe, both from theoretical and experimental points of view. Quantum physics and gravity, the two pillars of our understanding of Nature and Universe, dark matter and dark energy, together with experimental possible signatures of physics beyond standard model was addressed by enthusiastic experts in the field – happy to share with you their wisdom. Participants were also invited on virtual visits in Laboratori Nazionali di Frascati of INFN Visitor Center and to main infrastructures, including the unique DAFNE accelerator where stars meet particle and nuclear physics.

Prof. Drewsen (AU) gives talk in Trieste

On Friday 13th May, Prof. Michael Drewsen (Aarhus University) was hosted by colleagues at the University of Trieste for a talk on the latest developments of his teams' research. Michael Drewsen is a Full Professor at the Department of Physics and Astronomy, Aarhus University. He is an Elected member of the Royal Danish Academy of Sciences and Letters and an Elected fellow of the American Physical Society.

Title of the talk:

Bounds to the coupling of bosons beyond the Standard Model to atoms through precise isotope shift measurements

Abstract:
By combining high-resolution spectroscopy of the 3d 2D3/2 − 3d 2D5/2 interval with an accuracy of ~20 Hz using direct frequency-comb Raman spectroscopy with isotope shift measurements of the 4s 2S1/2 ↔ 3d 2D5/2 transition in all stable even isotopes of ACa+ (A = 40, 42, 44, 46, and 48), we have been able to carry out a King plot analysis with unprecedented sensitivity to coupling between electrons and neutrons by bosons beyond the Standard Model. Furthermore, we estimate that by improved spectroscopic techniques available, King plots based on data from spectroscopy on either Ca+, Ba+ and Yb+ ions should be able to produce sensitivity to such potentially new bosons, which surpass other current methods in a broad mass range of 10 to 108 eV/c2.

The seminar, that took place in the ICTP premises in Trieste, involved around 10 participants from the Bassi Research Group, Italian and international PhD students, post-docs and researchers.