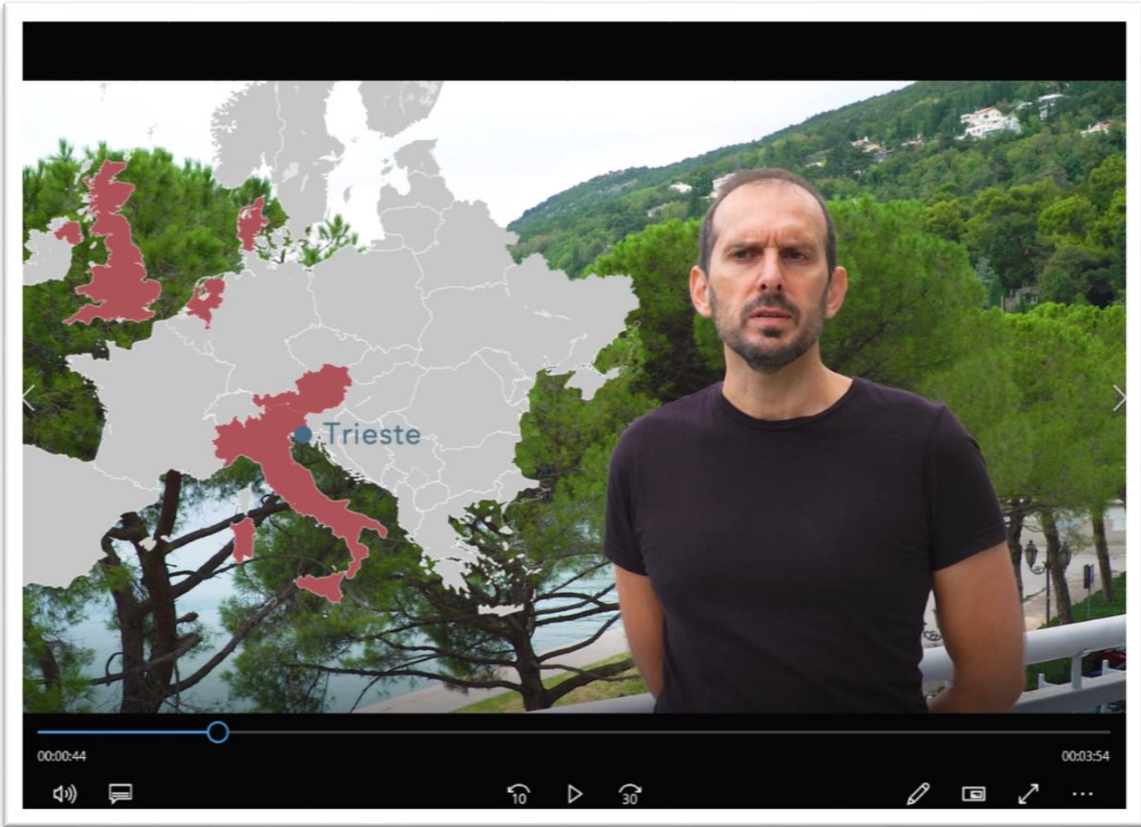
NEWSLETTER N.7, December 2019



A frame of the TEQ video developed as part of the project workplan.

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UPDATE OF WORK DONE

During the last months, at **UNITS**, we have applied our recently developed model for gravitationally induced decoherence of non-relativistic scalar bosonic particles to matter-interferometry experiments. Our aim is to determine whether current technology holds the potential to detect stochastic fluctuations of the metric like, for instance, those produced during inflation.
We have also been developing a model concerning the dynamics of the Maxwell field on weakly curved backgrounds in order to then quantify the gravitationally induced decoherence and the aberration effects in interferometric experiments.
Furthermore, we have investigated the spectral properties of the colored CSL model. We bounded the frequency spectrum from below in two ways: by considering a 'minimal' measurement setup, requiring that the collapse is completed within the measurement time; and in a measurement modelling-independent way, by requiring that the fluctuations average to zero before the measurement time.

The activity of the **LNF-INFN** group was mostly dedicated to the development and realisation of the low-noise electronics for UCL setup. In particular, a high voltage amplifier AC/DC/Mixer was developed after having decided the specifications in dedicated meetings and discussions with other experimental teams, in particular with the UCL group. The development of this component required a module of AC and DC amplification with an output dynamic range ±300V, and noise level lower than 200 nV. The module should deliver two outputs (AC and AC plus DC) with noise levels which should cancel when supplied to the experimental setup. The module was designed, realized and extensively tested at LNF-INFN in the dedicated electronics laboratory. The noise level which was reached is about 132 nV, well within the specifications and requirements. The modules were finally sent to UCL for the testing with the experimental setup.

The **QUB** node worked on the development of a framework for the time-resolved assessment of the effects of collapse models in cavity optomechanics, including an ab initio quantum formulation of the process of thermalisation and relaxation that makes use of the tools of non-equilibrium quantum (thermo-)dynamics.
More recently, the team has started addressing the inference of the effects of collapses through the formalism of quantum hypothesis testing.

At **UoS** we worked on the installation and testing of the 300 mK cryostat which will host the low noise TEQ experiment. In late summer we were facing difficulties with the performance of the cryostat, which did not reach the defined specifications. We had to send the equipment back to the manufacturer. Together with the manufacturing company we achieved an improvement of the performance of the cryostat to fulfil the specification and in mid-September the full cryostat was installed in the laboratory at Southampton on a vibration isolation platform. In the mean time we have been working on new ways to trap particles at low temperature and in low-noise environments (low pressure, low vibrations, low electrical and magnetic noise) and have developed a magnetic trap which is using a type 1 superconducting lead trap to levitate a permanent magnet. We have performed experiments of magnetic trapping at 4K and in early December have transferred the magnetic trap to the 300 mK cryostat. In the cryostat we will use the magnetic trapping to test the low noise conditions, especially vibrations. Such measurement will inform our decision to implement further vibration isolation technology (and at which frequencies), if needed. We further had two meetings with TEQ experiment partners to discuss the joint effort, progress and next steps.

In addition to previous studies of charge particle heating by voltage noise originating from DC trapping sources, AU has studied the impact of voltage noise from the radio-frequency (RF) source on the trapping and heating of a single trapped atomic ion. It was found that such noise at the trap frequency ω_z can contribute to heating of the trapped particle, while the ion is extremely immune to noise at sidebands at multiple times ω_z from the RF drive frequency (see Fig. 1). Compared to the DC noise spectral density $S_V^{DC}(\omega_z)$, the RF one, $S_V^{RF}(\omega_z)$, contributes more than 5000 times weaker to heating of the particle. While S_V^{RF} around the drive frequency ω_{RF} does not lead to heating, it still though can affect the loading. A phase noise < -70 dBc is required for good loading of the ion. The reason for this is not yet pinned down, but probably it is related to parametric heating in the plane perpendicular to the trap axis z, something to be investigated in the near future

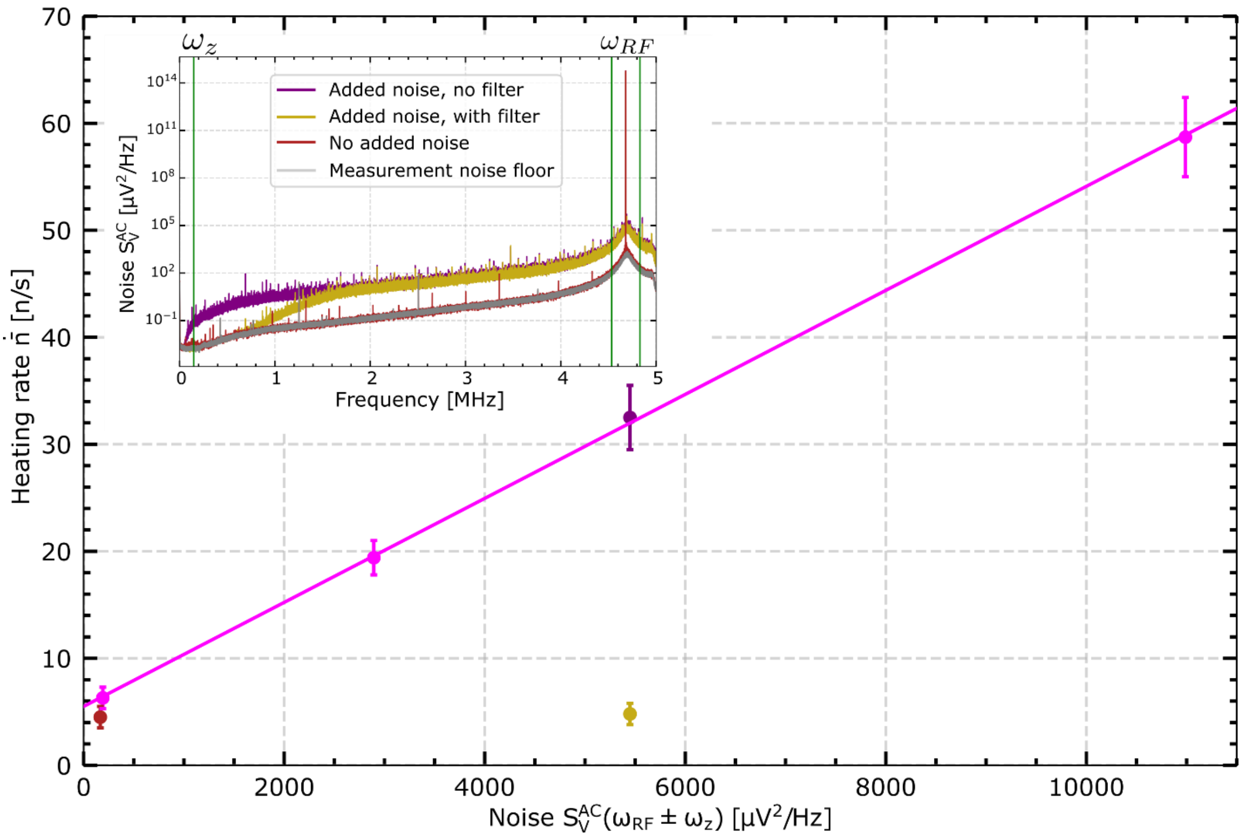

FIGURE 1: HEATING RATES OF A SINGLE ATOMIC ION FOR DIFFERENT NOISE SPECTRAL DENSITIES OF THE RF SOURCE. INSET: VARIOUS SPECTRAL DENSITY OF THE RF SOURCE WITHOUT (PURPLE) AND WITH (YELLOW) A HIGH-PASS FILTER WITH INDICATION FREQUENCIES ω_z AND $\omega_{RF} +/- \omega_z$. PINK POINTS CORRESPOND TO MEASUREMENTS WITHOUT FILTER (PURPLE TO THE PURPLE CURVE IN THE INSET), THE YELLOW POINT CORRESPONDS TO THE MEASUREMENT WITH FILTER.

With respect to the first TEQ blade trap, the first coating run had some problems with the gold coatings at the edges pointing directly towards the particles to be trapped. This problem has been solved by a new coating run, and the trap is now ready for first NC trapping at UCL (see figure 2). All the needed low noise electronic for trapping of NCs developed by INFN and AU is in the final stage of production, and first trapping of NCs in the trap is expected in early 2020 [D 1.1 (Rf trap for NCs)]

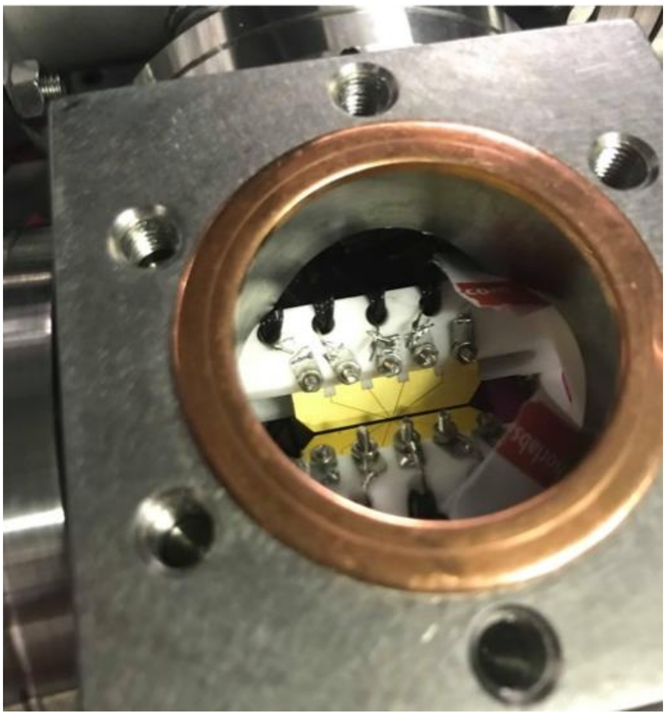

Figure 2: Picture of the first TEQ blade trap mounted inside a vacuum chamber at UCL.

The past year AU has as well built up an electrospray source to be attached to an existing cryogenically cooled ion trap (See Fig. 3). This system will enable the trapping and sympathetic laser-cooling of complex molecular ion species, and might within TEQ be used to study effect of quantum mechanics on a complementary length scale of a few nm scale.

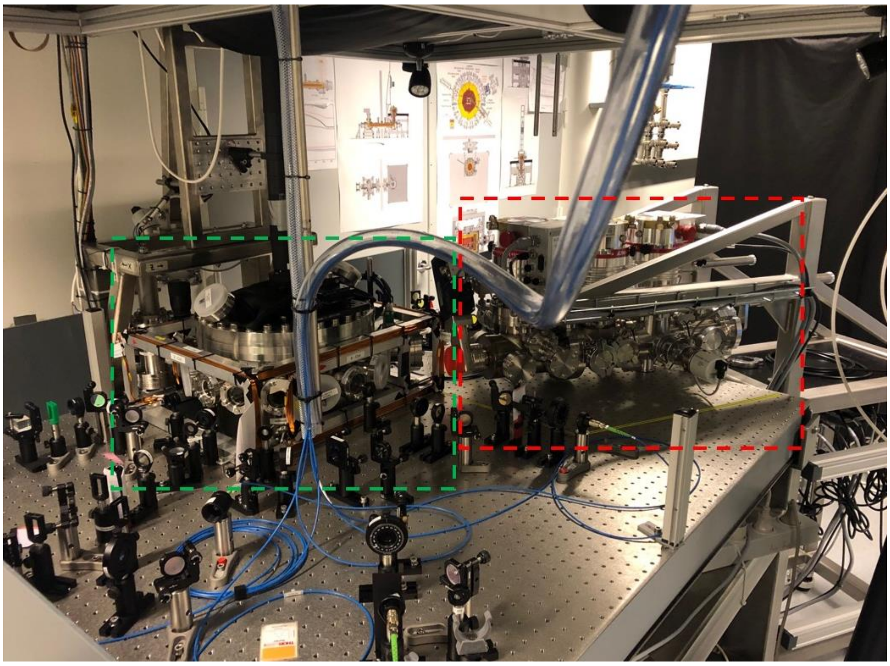

Figure 3: Cryogenically cooled ion trap (green square) and electrospray source (red square) to be used for experiments with complex molecular ions. Also shown are various optical elements used to deliver the light needed to laser cool a co-trapped atomic ion (Ba).

TU Delft has been working on improving the synthesis and optical properties of the Yb:YLF nanocrystals (NCs) that are used in the TEQ experiments. Since last year, the synthesis is greatly improved and reproducibly gives the same particles with good optical properties. Growing shells around the core NCs improves the photoluminescence quantum yield (PLQY) to a large extend, however the procedure of this synthesis part still needs to be optimized. Analysis and experiments at UCL on undoped YLF NCs indicated that currently, the largest improvements need to be made on increasing the PLQY of the emitting Yb ions, to change from heating the NC upon photoexcitation to cooling. This will however require a PLQY of >97%. The main question remains whether this will be experimentally possible for Yb:YLF NCs made by any wet chemical synthesis method. The analysis of the emission spectra of the NCs is improved and furthermore time resolved photoluminescence (TRPL) and temperature dependent photoluminescence (TDPL) experiments can be performed. From this, we can extract more data, and analyse amongst others the (relative) PLQY in a more reproducible way.

During the last six months, at UCL, we have continued the development of loading and cooling methods in the linear Paul test trap developed at UCL and have very recently commissioned the TEQ Blade Paul trap constructed by Aarhus at UCL. We have shown that using optical detection at pressures down to 10^-7 mbar that we do not internally heat the particles or increase their center-of mass motion through photon recoil heating. We have developed direct imaging of the motion of the trapped particles in all 3 dimensions using two CMOS cameras with framing rates up to 3 kFPS. Imaging the nanoparticles in this way has allowed us to calibrate particle displacement in the trap in a straightforward way and to perform super-resolution imaging of the trapped particles [https://doi.org/10.1063/1.5108807]. The measurement of displacement sensitivities lower than

10^{-16} m2/Hz was also demonstrated using this technique. This publication was chosen as an Editor's pick for the journal. We have also studied both velocity feedback cooling and parametric feedback cooling and shown for our traps that lower temperatures can be achieved in the same trap using velocity damping.
The frequency and temperature stability of single trapped particles was measured over several weeks allowing us to identify the major sources of trap and environmental fluctuations. We measured overall frequency stability of 2 ppm/hr and a temperature stability of more than 5 hours via the Allan deviation. Our results have shown that the charge on the trapped particles was stable over a timescale of at least two weeks which is important for the final TEQ experiments. As we can measure the mass of the trapped particles with 3 % uncertainty we have shown that we can distinguish between the trapping of a single nanosphere and a nano-dumbbell formed by a cluster of two nanospheres [arXiv:1906.09580]. At the lowest pressures, secular frequencies with line widths of tens of µHz were measured. These linewidths were shown to be only limited by the residual gas pressure at high vacuum. These set of measurements allowed us to put new experimental bounds on dissipative models of wavefunction collapse including continuous spontaneous localisation (CSL) and Diósi-Penrose and to characterise the electronic noise in the Paul trap. These measurements illustrated the utility of this system for the final TEQ experiment that will put new limits on conventional CSL models [arXiv:1907.06046].
An important outcome of this work was a study into the effects of electronic noise on trapping in the Paul traps and the characterisation of electronics that were used in these initial test traps. This work showed that electronic noise, estimated to be 10 mV/Sqrt[Hz], increased the temperature of the trapped particles above 300 K below pressures of approximately 10-5 mbar without additional center-of-mass-cooling. This further highlighted the need for the lower noise DC electronics developed by INFN and Aarhus that have recently been commissioned at UCL.
In collaboration with Trieste (A. Bassi), D. Goldwater who is now at Nottingham and S. Donadi (Frankfurt) we have explored the use of a tunable oscillator such as levitated nanoparticle in a Paul trap for a spectrometer for quantum noise. This was recently published in Physical Review Letters (PRL, 123 230801 (2019)).
Finally, we have continued to characterise the Yb:YLF nanocrystals supplied by TU Delft. We have measured significantly lower heating of more recently fabricated YLF crystals in an optical trap such that they can be held in vacuum within an optical without feedback cooling down to 10^-2 mbar.

In close collaboration with UCL, **MSquared** 's main task has been to perform maintenance on the laser at UCL labs.

In the last 6 months the **Vienna node** has concentrated on two projects: (i) on the time reference frames and gravitating quantum clocks, and (ii) generalized probability rules from a timeless formulation of Wigner's friend scenarios.
The standard formulation of quantum theory relies on a fixed space-time metric determining the localisation and causal order of events. In general relativity, the metric is influenced by matter, and it is expected to become indefinite when matter behaves quantum mechanically. We have explored the problem of operationally defining events and their localisation in the presence of gravitating quantum systems. We develop a framework for "time reference frames," in which events are defined in terms of quantum operations with respect to a quantum clock. We find that, when clocks and quantum systems interact gravitationally, the temporal localisability of events becomes relative, depending on the time reference frame. We argue that the impossibility to find a reference frame in which all events are localised is a signature of an indefinite metric, which might yield an indefinite

causal order of events. Even if the metric is indefinite, for any event we can find a time reference frame with respect to which the event is localised in time, while other events may remain delocalised. In this frame, time evolution takes its standard (Schrödinger) form, including the unitary dilation of the quantum operation defining the event. In addition, this form is preserved when moving from the frame localising one event to the frame localising another one, thereby implementing a form of covariance with respect to quantum reference frame transformations. (arXiv:1908.10165)

The quantum measurement problem can be regarded as the tension between the two alternative dynamics prescribed by quantum mechanics: the unitary evolution of the wave function and the state-update rule (or "collapse") at the instant a measurement takes place. The notorious Wigner's friend gedankenexperiment constitutes the paradoxical scenario in which different observers (one of whom is observed by the other) describe one and the same interaction differently, one --the Friend-- via state-update and the other --Wigner-- unitarily. This can lead to Wigner and his friend assigning different probabilities to the outcome of the same subsequent measurement. We applied the Page-Wootters mechanism (PWM) as a timeless description of Wigner's friend-like scenarios. We showed that the standard rules to assign two-time conditional probabilities within the PWM need to be modified to deal with the Wigner's friend gedankenexperiment. We identified three main definitions of such modified rules to assign two-time conditional probabilities, all of which reduce to standard quantum theory for non-Wigner's friend scenarios. However, when applied to the Wigner's friend setup each rule assigns different conditional probabilities, potentially resolving the probability-assignment paradox in a different manner. Moreover, one rule imposes strict limits on when a joint probability distribution for the measurement outcomes of Wigner and his Friend is well-defined, which single out those cases where Wigner's measurement does not disturb the Friend's memory and such a probability has an operational meaning in terms of collectible statistics. Interestingly, the same limits guarantee that said measurement outcomes fulfil the consistency condition of the consistent histories framework. (arXiv:1911.09696)

PUBLICATIONS

(for more info, please go to www.tequantum.eu, in 'Documents' → 'Dissemination')

Authors	Title	Journal	Volume	Pages	Year
Vinante, Andrea	Testing spontaneous collapse models with mechanical experiments	J. Phys.: Conf. Ser.	1275	012015	2019
Belenchia, Alessio, Giulio Gasbarri, Rainer Kaltenbaek, Hendrik Ulbricht, and Mauro Paternostro	Talbot-Lau effect beyond the point-particle approximation	Phys. Rev. A	100	033813	2019
Setter, Ashley, Jamie Vovrosh, and Hendrik Ulbricht	Characterization of non-linearities through mechanical squeezing in levitated optomechanics	Appl. Phys. Lett.	115	153106	2019

Timberlake, Chris, Giulio Gasbarri, Andrea Vinante, Ashley Setter, and Hendrik Ulbricht	Acceleration sensing with magnetically levitated oscillators above a superconductor	Appl. Phys. Lett.	115	224101	2019
Carlesso, M, A Bassi, M Paternostro, and H Ulbricht	Testing the gravitational field generated by a quantum superposition	New J. Phys.	21	093052	2019
Bullier, N. P., A. Pontin, and P. F. Barker	Super-resolution imaging of a low frequency levitated oscillator	Review of Scientific Instruments	90.9	093201	2019

DISSEMINATION ACTIVITIES

(for more info, please go to www.tequantum.eu, in 'Documents' → 'Dissemination')

In the second year of TEQ's lifetime (from January to December 2019), the dissemination activities held were a total of 79, addressing a total of more than 6 000 people. 45 talks were given to academic audiences, 14 lectures were given to high-school students while 20 presentations were delivered to the general public. The numbers of the first year of TEQ are very similar having the TEQ members in 2018 given a total of 83 talks for more than 5 000 people.
A detailed list of all talks can be found on the TEQ Website.

ANY OTHER RELEVANT INFORMATION

Outreach activities
Dr Catalina Curceanu gave a talk at the TEDxFrascati event: https://www.youtube.com/watch?v=f5FqZqoaYYw&t=130s,
which also included the TEQ activity.
Moreover, Dr Curceanu spent as visiting scientist a period at the Griffith University (Australia) in August 2019, where she gave various lectures, at the University, school and public, the last one being given at Griffith's QCA Lecture Theatre South Bank.
https://news.griffith.edu.au/2019/08/09/from-the-schrodinger-cat-to-quantum-computers/

TEQ Video
As part of the broader communication strategy of the project, the project consortium developed a video trailer explaining the TEQ project and aiming at: the general public with a general knowledge of science and physics; the scientific community interested in knowing what is the project about; funding agencies potentially interested in financing further research connected to TEQ.
The preparation of the video was fairly shared among the Consortium members and the final result was delivered at the end of November. The video was planned to be a balanced combination of structured explanations of the phases of the project involving the PI and the WP leaders.

The final product is shared with the partners for dissemination through their institutional channels (websites, presentations, talks, etc.) and is posted on TEQ's Youtube channel, on the TEQ Website and on TEQ's social media accounts. The Consortium members are engaged to give maximum dissemination to the video to the scientific community, to the general public and to potential funding agencies.

"The Quantum and the Cosmos"

TEQ will co-fund the workshop "The Quantum and the Cosmos" taking place from March 23 to 26, 2020 in Trieste, Italy. The workshop will bring together experts in quantum mechanics, cosmology and quantum gravity, to discuss questions like: Does gravity need to be quantum? What are the possible routes to quantum gravity? What are the possible quantum effects in cosmology? Does quantum gravity eliminate space-time singularities like a big bang? Is space-time relational? Can alternatives to quantum mechanics be tested by cosmological observations?
Roughly 100 participants are expected to attend the workshop.
More information can be found at http://www.qtspace.eu/?q=quantum-cosmos