# LPHYS'22. PLENARY SPEAKERS:

## Quantifying Quantum Metrology: Noiseless Amplification, Precision Bounds For Open Systems, and Ghost Quantum Sensing

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**Abstract:**

Quantum metrology is one of the basic pillars of quantum information, together with quantum computation, quantum simulation, and quantum communication. It concerns the estimation of parameters, for which lower bounds to the precision of estimation are derived through a rigorous theoretical framework, established by Cramér, Rao, and Fisher for classical systems and generalized to quantum physics by Helstrom and Holevo. This framework yields simple expressions for the precision when dealing with parameter-dependent unitary evolutions in closed systems. Open systems, on the other hand, require more sophisticated techniques [1-4]. This talk reviews recent results on closed and open systems: the analysis of an experiment on noiseless quantum amplification of mechanical oscillator motion [5,6], and the demonstration that, for open systems, a procedure analogous to quantum ghost imaging may increase the precision of estimation.

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[6] G. S. Agarwal and L. Davidovich, Phys. Rev. Research 4, L012014 (2022).

## From Multi-Photon Entanglement to Quantum Computational Advantage

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**Abstract:**

Photons, the fast flying qubits which can be controlled with high precision using linear optics and have weak interaction with environment, are the natural candidate for quantum communications. By developing a quantum science satellite *Micius* and exploiting the negligible decoherence and photon loss in the out space, practically secure quantum cryptography, entanglement distribution, and quantum teleportation have been achieved over thousand kilometer scale, laying the foundation for future global quantum internet. Surprisingly, despite the extremely weak optical nonlinearity at single-photon level, an effective interaction between independent indistinguishable photons can be effectively induced by a multi-photon interferometry, which allowed the first creation of multi-particle entanglement and test of Einstein's local realism in the most extreme way. By developing high-performance quantum light sources, the multi-photon interference has been scaled up to implement boson sampling with up to 76 photons out of a 100-mode interferometer, which yields a Hilbert state space dimension of $10^{30}$ and a rate that is $10^{14}$ faster than using the state-of-the-art simulation strategy on supercomputers. Such a demonstration of quantum computational advantage is a much-anticipated milestone for quantum computing. The special-purpose photonic platform will be further used to investigate practical applications linked to the Gaussian boson sampling, such as graph optimization and quantum machine learning.

## Quantum Optics with Giant Atoms: Decoherence-Free Interaction between Giant Atoms in Waveguide Quantum Electrodynamics

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**Abstract:**

In quantum optics, atoms are usually approximated as point-like compared to the wavelength of the light they interact with. However, recent advances in experiments with artificial atoms built from superconducting circuits have shown that this assumption can be violated. Instead, these artificial atoms can couple to an electromagnetic field in a waveguide at multiple points, which are spaced wavelength distances apart. Such systems are called giant atoms. They have attracted increasing interest in the past few years (*e.g.*, see the review in [1]), in particular because it turns out that **the interference effects due to the multiple coupling points allow giant atoms to interact with each other through the waveguide** without losing energy into the waveguide (theory in [2] and experiments in [3]). This talk will review some of these developments. Finally, we will also show how a

giant atom coupled to a waveguide with varying impedance can give rise to chiral bound states [4].

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## Measuring the timing of the photoelectric effect

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### Abstract:

The generation of single isolated attosecond pulses in the extreme ultraviolet (XUV) together with fully synchronized few-cycle infrared (IR) laser pulses allowed to trace electronic processes on the attosecond timescale. A pump/probe technique, “attosecond streaking” [1], was used to investigate electron dynamics on surfaces and layered systems with unprecedented resolution. Photoelectrons generated by laser based attosecond extreme ultraviolet pulses (XUV), are exposed to a dressing electric field from well synchronized laser pulses. The energy shift experienced by the photoelectrons by the dressing field is dependent on the delay between the XUV pulse and the dressing field and makes it possible to measure the respective delay in photoemission between electrons of different type (core electrons vs. conduction band electrons). The information gained in such experiments on tungsten [2] triggered many theoretical activities leading to different explanations on the physical reason of the delay. Attosecond streaking experiments have been performed on different solids [3,4], layered structures and liquids, resulting in different delays – also depending on the excitation photon energy. These measurements lead to a stepwise increase of the understanding of different physical effects contributing to the timing of photoemission. In this presentation, an overview on the different physical contributions to attosecond time delays in photoemission will be given. The “absolute” time delay, i.e. the delay between the instant of ionization and the emission of a photoelectron will be discussed and new measurements will be presented.

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## Massive matter-wave interferometers on the atom chip with nano-diamonds: a roadmap

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### Abstract:

Matter-wave interferometry provides an excellent tool for fundamental studies as well as technological applications. Looking to the future, a spatial superposition of massive objects has long been sought after due to the potential for new insight into the foundations of quantum mechanics (QM), the interface of QM and gravity, and as a tool for testing exotic theories. In our group, several interferometry experiments have been conducted with a BEC on an atom chip. I will briefly present realized interferometric schemes based on Stern-Gerlach interferometry (SGI), and mainly focus on plans to use this unique SGI to put a nano diamond in a state of spatial superposition.

## Opportunities for quantum biosensing with fluorescent diamond and phosphor nanoparticles

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### Abstract:

Fluorescent nanoparticles can probe biological processes on the nanoscale, sometimes with the potential for quantum-enhanced sensing. I will give a brief overview of the field with emphasis on opportunities for hybrid integration of diamond and upconversion phosphor particles. In particular, I will discuss some experimental examples of using both types of particles as biological probes. I will also discuss opportunities to use the quantum nature of some of the fluorescent particles to improve sensitivity.

## Absolute quantum advantage in imaging: quantum correlations allow imaging of otherwise unobservable biological structures

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### Abstract:

It has been recognised since the 1980s that quantum light sources have the potential to improve the performance of microscopes, enhancing the information that can be extracted from biological systems at fixed photon budget [1]. Indeed, today state-of-the-art microscopes use intense lasers that can severely disturb biological processes, function and viability. This introduces hard limits on performance that only quantum photon correlations can overcome [2]. As such, the development of photodamage evading microscopes is widely considered as a key milestone in quantum technology roadmaps (e.g. [3]).

In this talk I will report work which demonstrates absolute quantum advantage in biological imaging [3]. We show that quantum correlations enable signal-to-noise beyond the photodamage-free capacity of conventional microscopy. Broadly, this represents the first demonstration that quantum correlations can allow sensing beyond the limits introduced by optical intrusion upon the measurement process. We achieve this in a coherent Raman microscope, which we use to image molecular bonds within a cell with both quantum-enhanced contrast and sub-wavelength resolution. This allows imaging of biological structures that are inaccessible using classical light. Coherent Raman microscopes allow highly selective biomolecular finger-printing in unlabelled specimens, but photodamage is a major roadblock for many applications. By showing that this roadblock can be overcome, our work provides a path towards order-of-magnitude improvements in both sensitivity and imaging speed.

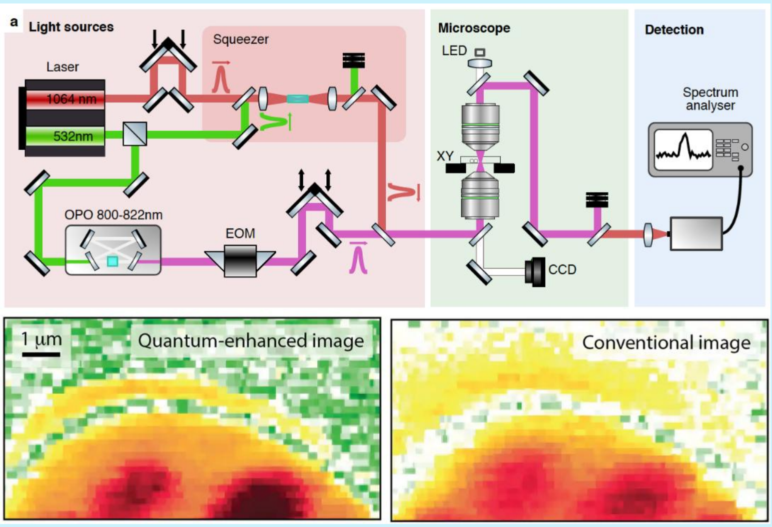


**Fig. 1 Quantum-enhanced stimulated Raman microscope.** *Top:* microscope design. *Bottom:* comparison of quantum-enhanced and conventional images.

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[2] Taylor, M. A. & Bowen, W. P. 2016. Quantum metrology and its application in biology. Phys. Rep. 615, 1–59.
[3] Casacio, C. A. et al., Quantum-enhanced nonlinear microscopy. 2021. Nature 594 201–206.

## Efficient sampling from the quantum state space

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**Abstract:**

A random sample of quantum states with specific properties is useful for various applications. Since the quantum state space has highly complicated boundaries in high dimension due to the positivity constraint, it is challenging to incorporate the specific properties into the sampling algorithm. The Sequentially Constraint Monte Carlo (SCMC) algorithm is a powerful method for sampling quantum states in accordance with any desired properties that can be described by inequalities. For illustration, we apply this method to the sampling of quantum states with bound entanglement, high-dimensional quantum states with a desired target distribution, and uniformly distributed quantum states in regions bounded by values of the problem-specific target distribution. These examples demonstrate that the SCMC sampler is efficient and reliable; perhaps, it also overcomes the curse of dimensionality. (Based on arXiv:2109.14215)

## Capitalizing on Schrödinger

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**Abstract:**

The superposition principle is a cornerstone of quantum mechanics and results from the linearity of the Schrödinger equation. In this talk we motivate the non-linear wave equation of classical statistical mechanics as well as the linear Schrödinger equation of quantum mechanics from a mathematical identity. Moreover, the linearity is crucial for the use of matter wave interferometers as sensors for rotation and acceleration. We show that the phase in a Kasevich-Chu atom interferometer measures the commutator of two unitary time evolutions and thus the acceleration. In addition, we report the observation of the Kennard phase using water waves and the realization of a Kennard interferometer with a scaling superior to the Kasevich-Chu interferometer.

## Programmable Quantum Simulation with Trapped Ions

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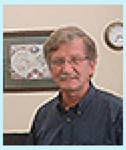
**Abstract:**

Trapped ions provide a prominent platform to implement quantum information processing tasks, including quantum computing and quantum simulation with tens of qubits. The ability to precisely engineer many-body Hamiltonians and to perform single-site and single-shot readouts have seen trapped ions evolve into a new generation of programmable quantum simulators, which combine a certain amount of programmability with scalability to

large particle numbers. In this talk we first introduce the core idea of collective phonon modes that allow to generate controlled entanglement in a chain of ultracold ions. Then we move on to discuss recent results obtained on a trapped ion platform with up to fifty qubits/spins, with the goal to develop and demonstrate quantum protocols, addressing questions from the fundamental to the practical. Examples include variational ground state engineering, measurement protocols revealing the entanglement structure of the many-body wavefunction, and implementing 'optimal' quantum metrology with variational quantum circuits.

## 100 years of complementarity



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**Abstract:**

Einstein in 1905, in his explanation of the photoelectric effect, postulated that light, the quintessential wave, had to possess particle-like properties. In the course of 1923-24, de Broglie, analyzing electron scattering from metal surfaces, postulated that electrons, the quintessential particles, must possess wave-like properties. In 1928, Bohr made the first attempt to reconcile the two viewpoints and introduced the concept of complementarity (or, in a more restricted sense, wave-particle duality), and thus the by now nearly 100 years history of complementarity has started. We will overview the history [1-5] and present recent results [6-12], highlighting that to complete complementarity, beside wave and particle features (which have classical counterparts), a third, truly quantum, reality, entanglement, must be included.

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# Compact widely tunable room temperature Terahertz Molecular Lasers from 250 GHz to 4.6 THz

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**Abstract:**

Quantum cascade lasers (QCLs) are the dominant source in the mid-IR and have found a wide range of applications in chemical sensing, trace gas monitoring, biomedical and spectroscopy. However, their performance falls short in the Terahertz gap. Other THz lasers, such as molecular lasers, have similar limitations in addition to a large footprint. We have realized a compact, room temperature, widely frequency-tunable, bright THz QCL pumped molecular laser (QPML) based on rotational population inversion. By identifying the essential parameters that determine the suitability of a molecule for a terahertz laser, almost any rotational transition of almost any molecular gas can be made to lase. Using Nitrous oxide (N2O) as the gain medium we demonstrated tunability over 37 lines spanning 0.251 to 0.955 terahertz, each with kilohertz linewidths [1]. We have recently achieved lasing in methyl fluoride (CH3F) QPML, where we showed laser operation between 250 GHz and 1.255 THz – line tunable over more than 1 THz [2]. We additionally measured the emission frequencies of more than 70 individual laser lines between 300 GHz and 755 GHz. The CH3F QPML was shown to exhibit a low lasing threshold (reduced by a factor 7 compared to our previous work with nitrous oxide), thus making methyl fluoride a promising gain medium for many QPML applications. Finally, we have recently reported explored the potential of the ammonia QPMLs to produce powerful, broadly tunable terahertz frequency lasing on rotational and pure inversion transitions [3]. After theoretically predicting possible laser frequencies, pump thresholds, and efficiencies, we experimentally demonstrated unprecedented tunability — from 0.763 to 4.459 THz — by pumping Q- and R-branch infrared transitions. with widely tunable quantum cascade lasers. We additionally demonstrated two types of multi-line lasing: simultaneous pure inversion and rotation– inversion transitions from the same pumped rotational state and cascaded lasing involving transitions below the pumped rotational state. We report single frequency power levels as great as 0.45 mW from a low volume laser cavity.

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