PREIN Workshop on Quantum Research & Technologies

13–15 April 2026, cruise boat Silja Serenade, conference center on Deck 6

Monday, April 13

13:00 *Meeting at Helsinki Olympiaterminaali harbour (Olympiaranta 1, 00140 Helsinki)*

15:00–15:15 *Opening words*

Session 1

15:15–16:00 **Tim Schröder (Plenary talk)**
Quantum physics with glamour: How diamond spin-photon interfaces make the quantum internet possible

16:00–16:20 **Kari Seppänen**
QDK - EuroQCI and national deployments

16:20–16:40 **Teemu Hakkarainen**
GaSb-based quantum light sources for fiber-based quantum communication

16:40–17:20 *Coffee break*

Session 2

17:20–17:40 **Xu Cheng**
All-van der Waals microcavities for ultralow-loss nonlinear photonics

17:40–18:00 **Sonia Alipour**
Quantum theory of third-harmonic generation in epsilon-near-zero materials

18:00–18:20 **Kimmo Luoma**
Gaussian wavepacket approach to trapped nanoparticle dynamics

18:20–18:40 **Emily Haughton**
Polariton squeezing in cavity optomechanical systems with exitons

18:40–20:00 **Poster Session and discussion**

21:00– *Dinner*

Tuesday, April 14

07:30– *Breakfast*

10:00 *Arrival to Stockholm*

15:00 *Return to ferry*

Session 3

15:55–16:40 **Michał Karpiński (Plenary talk)**
Quantum photonics in the time-energy domain

16:40–17:00 **Jaime Moreno**
Faking large amount of entanglement with small errors

17:00–17:20 **Martti Hanhisalo**
Coherence squeezing in optical double-slit interference

17:20–17:40 **José J. Gil**
Intrinsic structure of density matrices: population asymmetry, coherence asymmetry, and effective dimension

17:40–18:20 *Coffee break*

Session 4

18:20–18:40 **Sara Pourjamal**
Photonics in quantum pilot lines

18:40–19:00 **Patrik Rajala**
Ultra low threshold, single mode VCSELs for cryogenic optical links

19:00–19:20 **Elizabeth Pereira**
Machine-learning-enabled characterization of individual ring resonators in integrated photonic lattices

19:20–19:40 **Sergei Malykhin**
Nanoscale multimodal sensing with diamond needles

19:40–20:00 *Closing remarks*

21:00– *Dinner*

Wednesday, April 15

07:30– *Breakfast*

10:30 *Arrival to Helsinki*

Poster session

1. Santiago Agudelo Gomez (University of Jyväskylä)
Modelling strong light-matter coupling in plasmons nanocavities

2. Behnaz Fazlpour (University of Eastern Finland)
Polarization structures of quantized light in relativistic frames

3. Atri Halder (University of Eastern Finland)
Maximal influences of arbitrary unitary transformation on vector-light interference

4. Najirul Islam (University of Eastern Finland)
Polarization squeezed light from two entangled two-level atoms

5. Anna Jokiniemi (Tampere University)
Polarization-encoded quantum key distribution using on-demand quantum dot sources at telecom wavelengths

6. Lea Kopf (VTT Technical Research Centre of Finland)
PIC based QKD receiver

7. Oussama Korichi / Lucas Gehse (Tampere University)
Direct laser-written nanogratings for structured light manipulation

8. Tomi Leinonen (University of Eastern Finland)
Efficient yet accurate: Balancing calculations for carbene-metal-amides

9. Timo Leppälä (University of Turku)
Organic microcavity polariton emission with non-Markovian quantum state diffusion

10. Niladri Modak (Tampere University)
Polarization entangled spectral vector photons

11. Tian Ruijuan (Aalto University)
Observation of magnetically induced valley polarization in electroluminescence

12. Nikita Solonovich (University of Eastern Finland)
Time to space ghost imaging with classical and quantum light

13. Iuliia Zalesskaia (Tampere University)
High-purity amplification of circularly polarized orbital angular momentum modes in an active spun ring-core tapered fiber

14. Yufeng Zhang (Aalto University)
High-order optical tensor processing advantages for parallel quantum simulation

15:15–16:00 **Tim Schröder** (Humboldt-Universität zu Berlin, Ferdinand-Braun-Institut): *Quantum physics with glamour – How diamond spin-photon interfaces make the quantum internet possible*

Optically active spin defects in diamond are a promising resource for quantum communication and networking. Here I bridge ongoing work and concepts in the control, analysis and engineering of single spin defects for q-networking. I introduce work showing theoretically that error-corrected q-communication over 1000 km becomes achievable with solid-state spin qubits coupled to optical nanostructures. The coherent control of such defects has requirements beyond the current state-of-the-art. We focus on understanding the spin qubits' nano- and microscopic noise environment, coupling to nanostructures, and control schemes. I outline how we control single diamond spin qubits with optical SUPER pulses, enhance qubit-to-waveguide coupling with the Sawfish interface with efficiencies up to 99%, and mitigate noise to maintain photon coherence. Finally, I describe plans to generate multi-qubit entangled states with photonic hetero-integration.

16:00–16:20 **Kari Seppänen** (VTT Technical Research Centre of Finland): *QDK - EuroQCI and national deployments*

16:20–16:40 **Teemu Hakkarainen** (Tampere University): *GaSb-based quantum light sources for fiber-based quantum communication*

We present the development prospects, fabrication, and emission properties of GaSb quantum dots formed by filling droplet-etched nanoholes. These recently-demonstrated quantum-photonics building blocks emit at 1.5 µm enabling wavelength compatibility with fiber optics and Si-photonics.

17:20–17:40 **Xu Cheng** (Aalto University): *All-van der Waals microcavities for ultralow-loss nonlinear photonics*

17:40–18:00 **Sonia Alipour** (Tampere University): *Quantum theory of third-harmonic generation in epsilon-near-zero materials*

18:00–18:20 **Kimmo Luoma** (University of Turku): *Gaussian wavepacket approach to trapped nanoparticle dynamics*

Optically trapped nanoparticles are a versatile platform where questions of fundamental physics and applications can be investigated and developed By carefully controlling the environment of the trapped nanoparticle, dynamics of the particle can range from classical noisy dynamics described by Langeving equations to noisy quantum dynamics. In this work we present an approach based on Gaussian wavepackets which provides a framework for describing the dynamics both in the quantum and classical regime. We first present an exact approach which based on quantum state diffusion. We also generalize the theory to incorporate non-Markovian effects either in terms of the generalized Langevin equations or through non-Markovian extension of quantum state diffusion.

18:20–18:40 **Emily Haughton** (Aalto University): *Polariton squeezing in cavity optomechanical systems with exitons*

In this work, we investigate the generation of TMS in a driven optomechanical cavity. Starting from the standard linearized optomechanical interaction, we examine the generation of correlations between optical and mechanical modes under blue-detuned pumping and identify the regimes in which steady-state squeezing can be sustained. Beyond intracavity correlations, we investigate ponderomotive squeezing of the output cavity field, arising from correlations between optical amplitude and phase fluctuations mediated by the mechanical oscillator. To probe these effects, we consider a configuration in which the cavity is driven by two coherent tones, enabling controlled access to both parametric amplification and beam-splitter type interactions. Within this framework, we identify the optimal operating regimes in which optical fluctuations are suppressed the vacuum level. Our results therefore provide a realistic pathway toward strong continuous-variable entanglement for precision measurements

15:55–16:40 **Michał Karpiński** (University of Warsaw): *Quantum photonics in the time-energy domain*

The time-energy degree of freedom of light enables high-dimensional encoding of quantum information and the shaping of light pulses for efficient interfacing within quantum networks. I will discuss electro-optic and nonlinear optical methods to coherently manipulate the spectral-temporal properties of single-photon pulses emitted by both spontaneous parametric down-conversion and solid-state sources.

16:40–17:00 **Jaime Moreno** (Tampere University): *Faking large amount of entanglement with small errors*

Entanglement is a key resource for achieving quantum advantage in computation and enabling secure quantum communications. Consequently, many quantum information protocols depend on reliable entanglement certification. In this work, we propose a protocol where a fully separable state can surpass the non-separability boundary of a d-dimensional bipartite entanglement witness through the introduction of a slightly perturbed positive operator-value measure (POVM) whose deviation from the ideal POVM is smaller than the typical experimental crosstalk. The results show that a perturbation to the POVM of only 0.35%-well below the detection errors of 3%-enables violation of the non-separability boundary 1+1/. Strengthening the perturbation increases the value of the witness allowing to measure high Schmidt numbers indicating stronger entanglement. Notably, the perturbation magnitude required to surpass the non-separability boundary decreases with increasing the system dimensionality.

17:00–17:20 **Martti Hanhisalo** (University of Eastern Finland): *Coherence squeezing in optical double-slit interference*

The recent notion of quantum optical coherence uncertainty reveals hidden fluctuations of light. Here, we extend it to two-slit interference and introduce the concept of coherence squeezing. We construct Hermitian operators that characterize the coherence at the slits. These operators define coherence uncertainty relations and a criterion for coherence squeezing. We also analyze specific states that exhibit such squeezing and show how it manifests in interferometric intensity fluctuations. Our work identifies coherence as a fundamental degree of freedom for squeezing, complementing phase, amplitude, and polarization, which could benefit quantum-enhanced interferometry.

17:20–17:40 **José J. Gil** (Independent researcher): *Intrinsic structure of density matrices: population asymmetry, coherence asymmetry, and effective dimension: Coherence squeezing in optical double-slit interference*

While density matrices are commonly analyzed through eigenvalues, rank, and spectral decomposition, this viewpoint does not by itself make explicit several structural properties of the represented state. A concise framework for general $n \times n$ quantum states is presented. The intrinsic description identifies two complementary sources of purity, linked to population asymmetry and coherence asymmetry, whereas the characteristic decomposition provides an independent route to nonregularity. The resulting physically relevant dimensionality is also analyzed. Possible applications to qutrits, state characterization, dimensionality-aware tomography, and quantum-channel analysis are briefly indicated.

18:20–18:40 **Sara Pourjamal** (VTT Technical Research Centre of Finland): *Photonics in quantum pilot lines*

18:40–19:00 **Patrik Rajala** (Tampere University): *Ultra low threshold, single mode VCSELs for cryogenic optical links*

Design, fabrication and characterization of ultra low threshold, single mode vertical-cavity surface-emitting lasers (VCSELs) for optical interfaces at cryogenic conditions are presented. A record low threshold of around 120 µA while maintaining single mode operation and mW-level output power at 4 K are demonstrated. In addition, the intra-cavity contact design of the VCSELs minimizes their thermal load. To this end, the VCSELs presented are highly desirable for optical links required for both single flux quantum (SFQ) and cryo-CMOS technologies.

19:00–19:20 **Elizabeth Pereira** (Aalto University): *Machine-learning-enabled characterization of individual ring resonators in integrated photonic lattices*

Photonic integrated circuits (PICs) integrate multiple optical components on a single chip, enabling compact and scalable control of light. However, determining their underlying physical parameters becomes increasingly difficult as device complexity grows. Inferring these parameters directly from spectral measurements offers an alternative to traditional calibration methods that rely on detailed device models. Here, we present a supervised machine-learning approach to infer onsite losses and resonant-frequency shifts in a coupled ring-resonator array from measured spectral power distributions. The networks recover these parameters with high accuracy across multiple experimental configurations and capture the spectral features governing device response. This approach provides a scalable and non-invasive route for parameter extraction and automated calibration in programmable photonic circuits.

19:20–19:40 **Sergei Malykhin** (University of Eastern Finland): *Nanoscale multimodal sensing with diamond needles*

Fluorescent diamonds provide a powerful platform for nanoscale biosensing thanks to their biocompatibility, bright emission, and exceptional photostability. Needle-shaped fluorescent diamond crystals offer further advantages by combining cell-penetrating thinness with a larger fluorescent volume than spherical nanoparticles. Diamond hosts a broad range of optically active point defects - color centers - that enable sensing of diverse physical parameters, and fluorescent diamonds have already been used to detect magnetic fields, temperature, pH, electric fields, and mechanical strain. Realizing multimodal nanoscale sensing, however, requires precise control over the spatial distribution of color centers within individual nanoparticles. In this work, we demonstrate the fabrication of diamond nanoneedles with controlled incorporation of NV and SiV centers throughout their volume and explore their potential for advanced multimodal sensing at the nanoscale.

Poster abstracts

1. Santiago Agudelo Gomez (University of Jyväskylä): *Modelling strong light-matter coupling in plasmons nanocavities*

Strong light–matter coupling enables control of photophysical and photochemical processes through polaritonic states formed by hybridising molecular excitations with cavity electromagnetic modes, reshaping energy surfaces and enhancing energy transfer. However, progress is limited by the lack of predictive theory. In Fabry–Pérot cavities, increasing the number of molecules leads to dark states that complicate excited-state dynamics. To reduce collective effects, surface plasmon nanocavities offer extreme field confinement, enabling single- or few-molecule strong coupling but requiring models beyond standard cavity QED. In my presentation, I focus on all-atom approaches to describe photonic properties of coupled molecular systems inside and outside cavities, aiming for more realistic simulations of strong-coupling regimes.

2. Behnaz Fazlpour (University of Eastern Finland): *Polarization structures of quantized light in relativistic frames*

We study polarization of quantized light in Lorentz transformations. We derive general expressions for the Lorentz-transformed quantum polarization fluctuations and their uncertainty relations of a plane wave. It is demonstrated how the transformed quantum polarization fluctuations depend on the velocity when the field in the rest frame is in a coherent state and a number state. We also show that the degree of 3D polarization of blackbody radiation, and thus of 3D fields in general, is not preserved under Lorentz transformations. This property is in striking contrast to the Lorentz invariance of the degree of 2D polarization of transverse fields. A moving observer will experience the initially fully 3D unpolarized blackbody radiation as a partially polarized 3D field, and ultimately as an unpolarized 2D planar field when approaching the speed of light.

3. Atri Halder (University of Eastern Finland): *Maximal influences of arbitrary unitary transformation on vector-light interference*

In Young's setup, vector-light interference is governed by two fundamental relations, where the intensity (Stokes) distinguishability and the Stokes (intensity) visibility are complementary. These complementarity relations are manifestations of the two fundamental wave–particle (wave–ray) dualities of classical or quantum vector-light fields in Young's two-pinhole setup. We investigate how a 4×4 unitary operation may alter the four complementary elements (CEs). We find the upper and lower bounds of all CEs under arbitrary unitary transformations for any given pair of partially coherent and partially polarized beams, identify a class of unitary matrices that achieve those limits, and discuss several consequences. Our findings set limits on interferometric quantities under arbitrary unitary transformations, which play essential roles in research involving linear optical networks, such as photonic computing, optical neural networks, quantum computing, and related areas.

4. Najirul Islam (University of Eastern Finland): *Polarization squeezed light from two entangled two-level atoms*

We theoretically demonstrate polarization squeezing in the far-field radiation emitted by two non-degenerate two-level atoms. Using the transverse-field quantization of the electromagnetic field, we construct the Stokes operators for the total far field. We show that polarization squeezing occurs only when the atomic dipole moments are unequal. Within the single-excitation manifold, the atomic dipoles become entangled, and interference between the polarization amplitudes and the dipole geometry generates squeezing. These results show that non-classical polarization states can arise from a minimal two-emitter system.

5. Anna Jokiniemi (Tampere University): *Polarization-encoded quantum key distribution using on-demand quantum dot sources at telecom wavelengths*

Most commercial QKD implementations use weak coherent pulses that require decoy states to detect possible attacks. Such systems are efficient, but they cannot be extended to quantum repeater architectures or device-independent QKD. This limits their use to quantum networks constructed using entangled-photon sources, single photon detectors, quantum memories and memories connected by fiber or satellite links. To be compatible with a quantum network, we need to develop a QKD based on on-demand quantum dot sources operating at 1550 nm telecom wavelength. In this wavelength, propagation losses are low for both fiber-based and atmospheric free-space transmission. In this project, we will implement polarization encoded QKD with one-demand quantum dot source operating at 1550 nm, which will be compatible with quantum memory and repeater technology.

6. Lea Kopf (VTT Technical Research Centre of Finland): *PIC based QKD receiver*

7. Oussama Korichi / Lucas Gehse (Tampere University): *Direct laser-written nanogratings for structured light manipulation*

We present a compact and efficient realization of Multi-Plane Light Conversion (MPLC) for full vectorial light modulation, enabling control over polarization, phase, and amplitude. Conventional MPLC implementations based on phase-only modulation suffer from losses and limited polarization control, while metasurface-based solutions require complex nanofabrication processes. Our approach employs laser-written birefringent waveplates in silica slides, each with fixed retardance and a spatially varying optical axis orientation. The structures are fabricated using direct laser writing of nanogratings in silica, achieving ≈90% transmission and 1–2 μm spatial resolution. We demonstrate high-dimensional quantum gates and a polarization-controlled single-photon CNOT gate using spatial and polarization degrees of freedom. We further study how laser-written nanogratings can used to custom-tailor standard single mode Telecom fibers to emit structured light.

8. Tomi Leinonen (University of Eastern Finland): *Efficient yet accurate: Balancing calculations for carbene-metal-amides*

Carbene-metal-amide (CMA) type OLED emitters have been investigated for nearly a decade due to their excellent tunability and photophysical properties. Quantum chemical calculations have been an invaluable tool for understanding the properties of the emitters but the computational demands have increased as the molecular size of the emitters have grown. This work evaluates several DFT functionals to address this issue, balancing between efficiency and accuracy. Both ground state and excited state properties of the available CMA structures are compared to DFT results. The preliminary results suggest that meta-GGA functionals are the best for describing the structure while global hybrids yield the most accurate properties.

9. Timo Leppälä (University of Turku): *Organic microcavity polariton emission with non-Markovian quantum state diffusion*

The collective light-matter coupling between the electronic states of a large number of organic molecules and the electromagnetic field in a cavity results in hybrid light-matter states called polaritons. The electronic states of the molecules and the cavity modes form an open quantum system that interacts with the molecular vibrations and loses photons through the imperfect cavity mirrors. We model the environment interactions with non-Markovian quantum state diffusion and calculate the evolution of the system with hierarchy of pure states. We fit the emission spectrum of the bare molecules calculated from this model to experimental data to get realistic parameter values for the molecules. Then we add the cavity and calculate the emission spectrum of the whole polariton system. Multiple cavity modes are included which allows us to calculate the emission at different angles.

10. Niladri Modak (Tampere University): *Polarization entangled spectral vector photons*

In the quantum domain, structuring the shape of single photons has been studied, e.g., in applications such as high-dimensional quantum communications, simulations, imaging, quantum metrology and so on. In this work, we experimentally demonstrate spectral vector photons (SVPs) with complex polarization patterns across their wavelength spectrum. By utilizing polarization-entangled photon pairs, we remotely prepare such SVPs and confirm entanglement via Bell-inequality violations.

11. Tian Ruijuan (Aalto University): *Observation of magnetically induced valley polarization in electroluminescence*

Valley polarization in two-dimensional transition metal dichalcogenides (TMDs) has attracted significant interest due to its potential applications in valleytronic and optoelectronic devices. Electrical generation and control of valley polarization remain important challenges for practical device implementations. In this work, we fabricate graphene/hBN/graphene tunneling heterostructures incorporating $WSe_2/MoSe_2$ heterostructure and observe exciton-assisted electroluminescence. Upon applying a magnetic field, the tunneling current exhibits a clear magnetic-field dependence. Concurrently, valley-polarized electroluminescence is observed, suggesting that the magnetic field modulates the tunneling process and enables valley polarization in the emitted light. These results demonstrate a viable approach for electrically driven and magnetically controllable valley polarization in TMD-based heterostructures, providing insight for future valleytronic devices.

12. Nikita Solonovich (University of Eastern Finland): *Time to space ghost imaging with classical and quantum light*

We study spatio-temporal ghost imaging with classical partially coherent light. We introduce the spatio-temporal Gaussian Schell model for pulsed light. We also describe a way to generate an STGSM light. The key advantage of considerable scheme is its ultrafast resolution (100 fs), which is two orders of magnitude faster than conventional temporal ghost imaging. Possible realization of two color ghost imaging with quantum light is also discussed.

13. Iuliia Zalesskaia (Tampere University): *High-purity amplification of circularly polarized orbital angular momentum modes in an active spun ring-core tapered fiber*

Structured light, optical fields engineered in their spatial, polarization, or phase degrees of freedom, has become a key resource across advanced communication, sensing, imaging, and quantum technologies. Optical fibers nowadays play an essential role in this landscape, providing stable and scalable platforms for guiding and amplifying complex modes such as vector and orbital angular momentum (OAM) beams. In this work, we demonstrate an active spun ring-shaped tapered fiber as a gain medium for efficient amplification of OAM modes preserving their modal purity and polarization topology. OAM beams with topological charges $\ell = 1$ and $\ell = 2$ carrying 60 ps pulses at 15 MHz repetition rate at 1030 nm wavelength are amplified over 1.2 W average power with modal purity over 95%. The spatially resolved measurement of the OAM beam polarization topology revealed small distortion due to the coupling in to neighbor modes. These results demonstrate the high potential of active spun ring-shaped tapered fibers for power scaling of complex beams, preserving their phase and polarization structure simultaneously.

14. Yufeng Zhang (Aalto University): *High-order optical tensor processing advantages for parallel quantum simulation*

I will also describe the electro-optic spectral shifting of single photons from semiconductor quantum dots, a key step for tuning solid-state emitters to network specifications. Finally, I will highlight how these time-frequency domain tools can be extended to high-dimensional quantum key distribution, utilizing the temporal Talbot effect for robust and resource-efficient information processing.