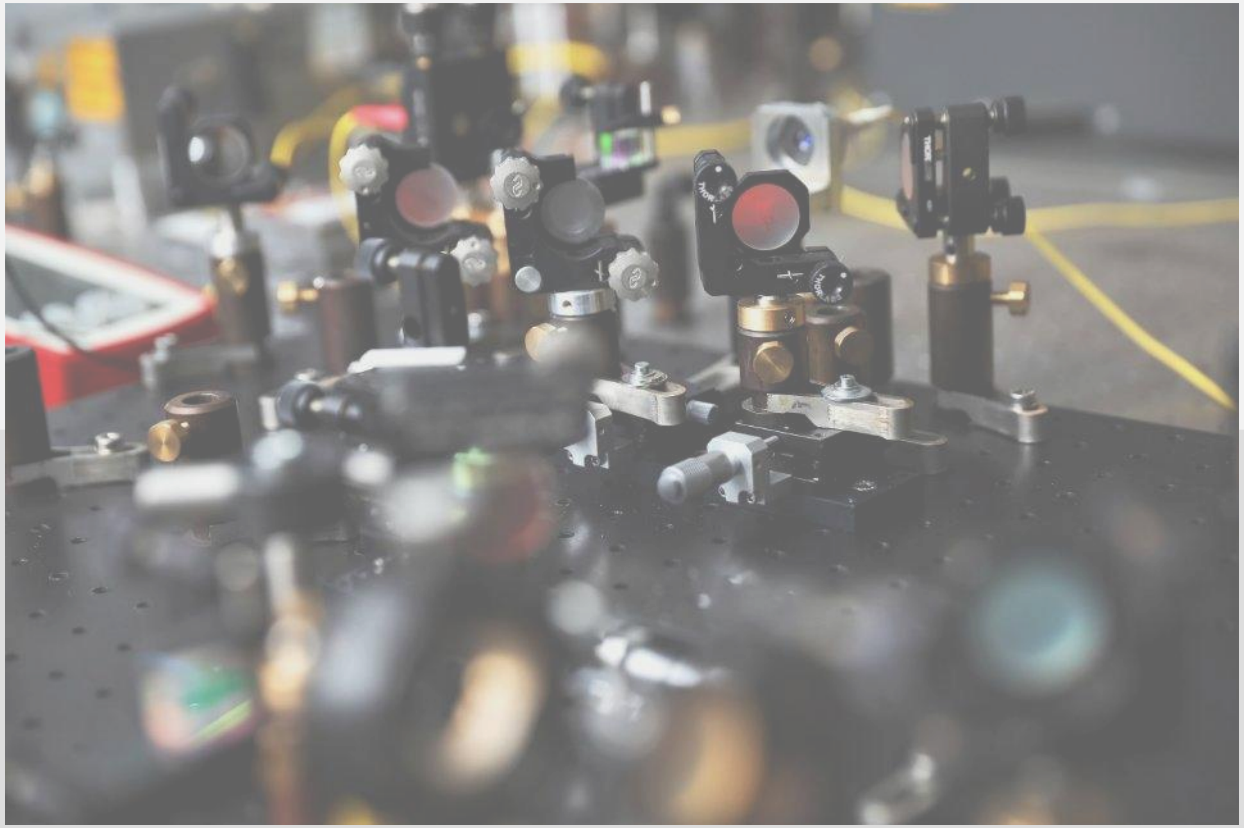
SEQUOIA

Sensing using quantum OCT with AI

Horizon Europe 101070062

https://sequoia-project.eu



SEQUOIA project overview

Jan-2026

Funded by the European Union

Presentation outline

- **Project summary**

  Consortium | Project overview | Objectives

- Theory and principles

  OAM control | Noise reduction

  QOCT | Sustainability

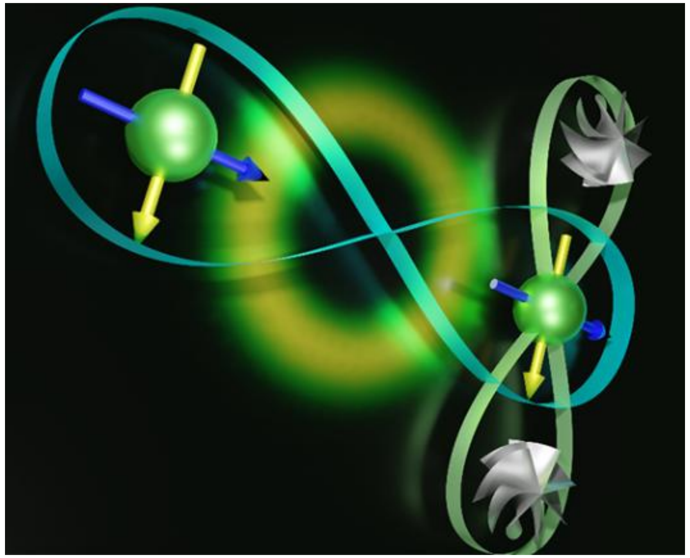
- Hardware

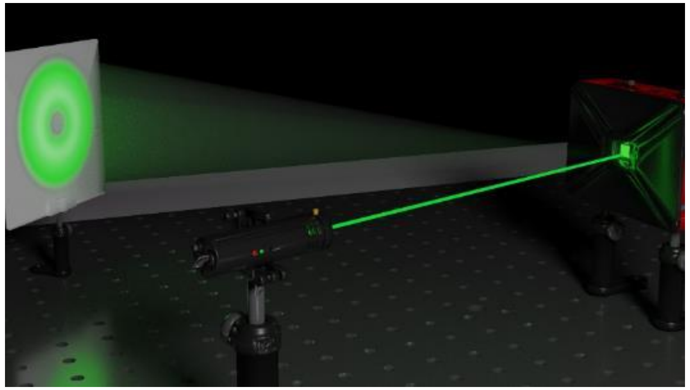
  Source | SPAD imager for QOCT

- Experiment

  Retinal studies | Characterisation and benchmarking

- Outlook





Project summary

- Horizon Europe project to develop optical coherence tomography (OCT) using quantum techniques
  - SEQUOIA: *Sensing using quantum OCT with AI*

- OCT is a non-contact high resolution 3D imaging technology
  - Highly successful in medical (especially retinal) imaging and industry
  - State-of-the-art OCT seems to have reached its limit at ~1 μm axial resolution (δz)

Theory suggests that:

1) Quantum OCT (QOCT) could:
   - Achieve 0.5 μm δz
   - Reduce dispersion

2) Control of the quantum property of orbital angular momentum (OAM) could:
   - Reduce noise
   - Improve edge and surface profile definition
   - Aid the discrimination of chiral objects

Project consortium

No.	Name	Country
1	NKT PHOTONICS A/S	DK
2	PHYSIKALISCH-TECHNISCHE BUNDESANSTALT	DE
3	MICRO PHOTON DEVICES SRL	IT
4	NORBLIS APS	DE
5	TECHNISCHE UNIVERSITEIT DELFT	NL
6	DANMARKS TEKNISKE UNIVERSITET	DK

No.	Name	Country
7	NICOLAUS COPERNICUS UNIVERSITY	PL
8	UNIVERSITAT POLITECNICA DE VALENCIA	ES
9	ARDITEC	FR
10	VIVID COMPONENTS GERMANY	DE
11	UNIVERSITY OF MÜNSTER	DE

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Classical vs. quantum optical coherence tomography

Classical OCT

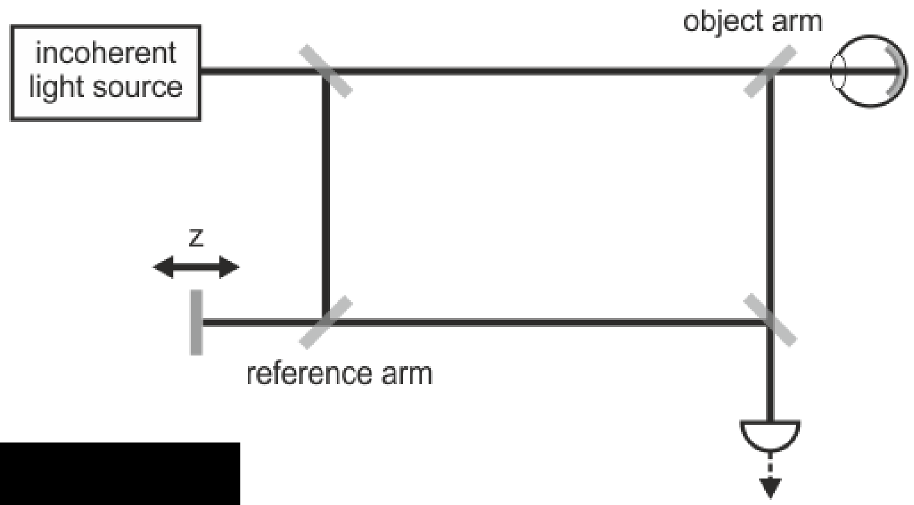
- Interference of EM field amplitudes
- White light interferometer

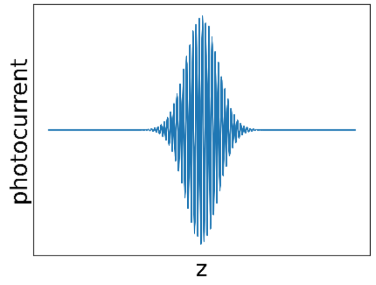
→Resolution limited by coherence length + dispersion

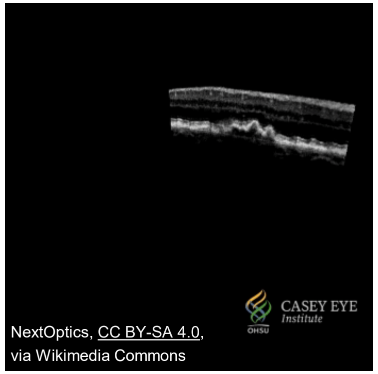
Quantum OCT

- Quantum interference of two indistinguishable photons
- Hong-Ou-Mandel interferometer

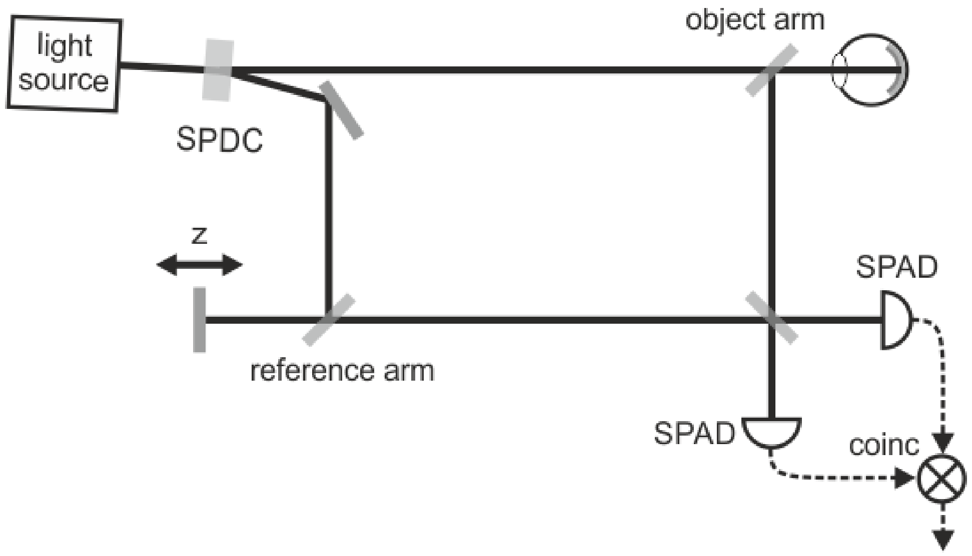
→Resolution limited by photon pair coherence length

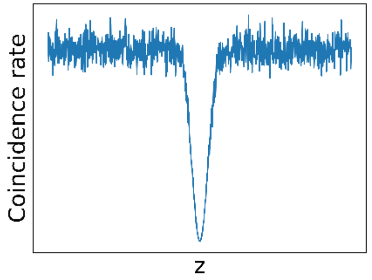






Volumetric classical OCT scan of human retina





→ Potential ×2 resolution improvement

→ Immune to even order dispersion

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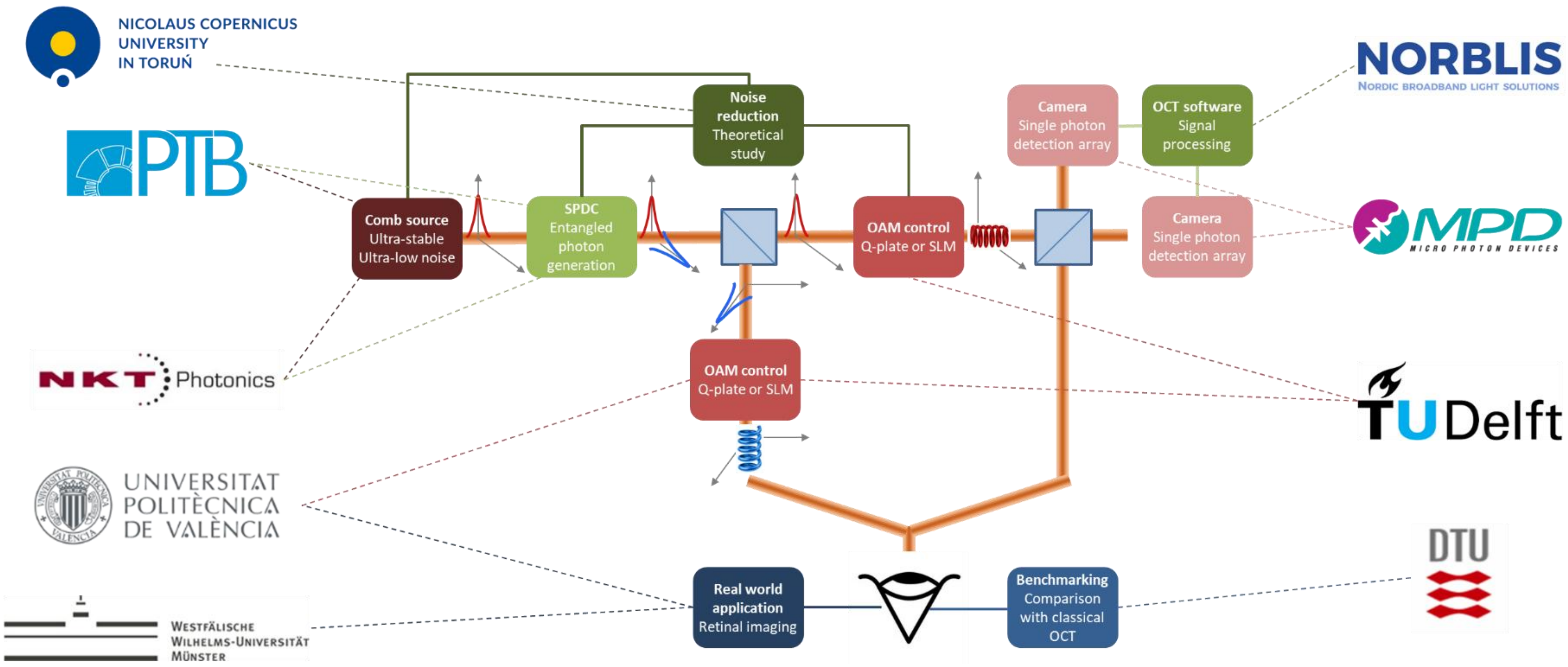
SEQUOIA overview



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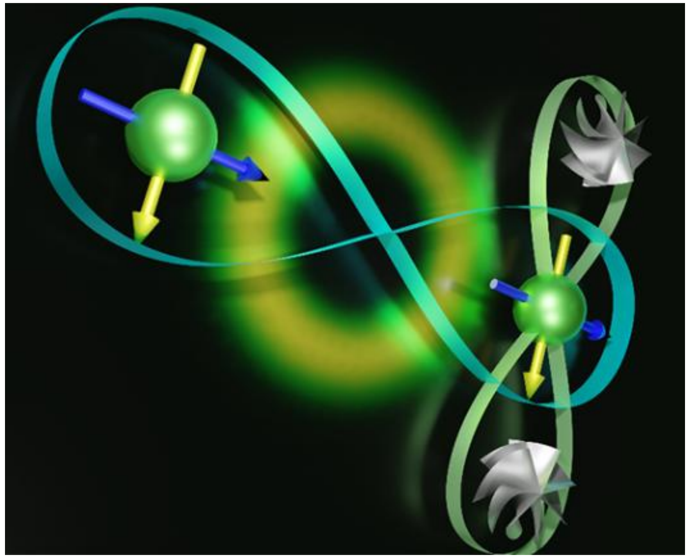

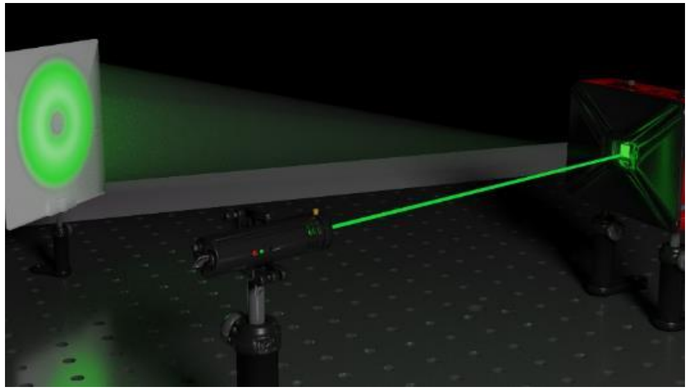

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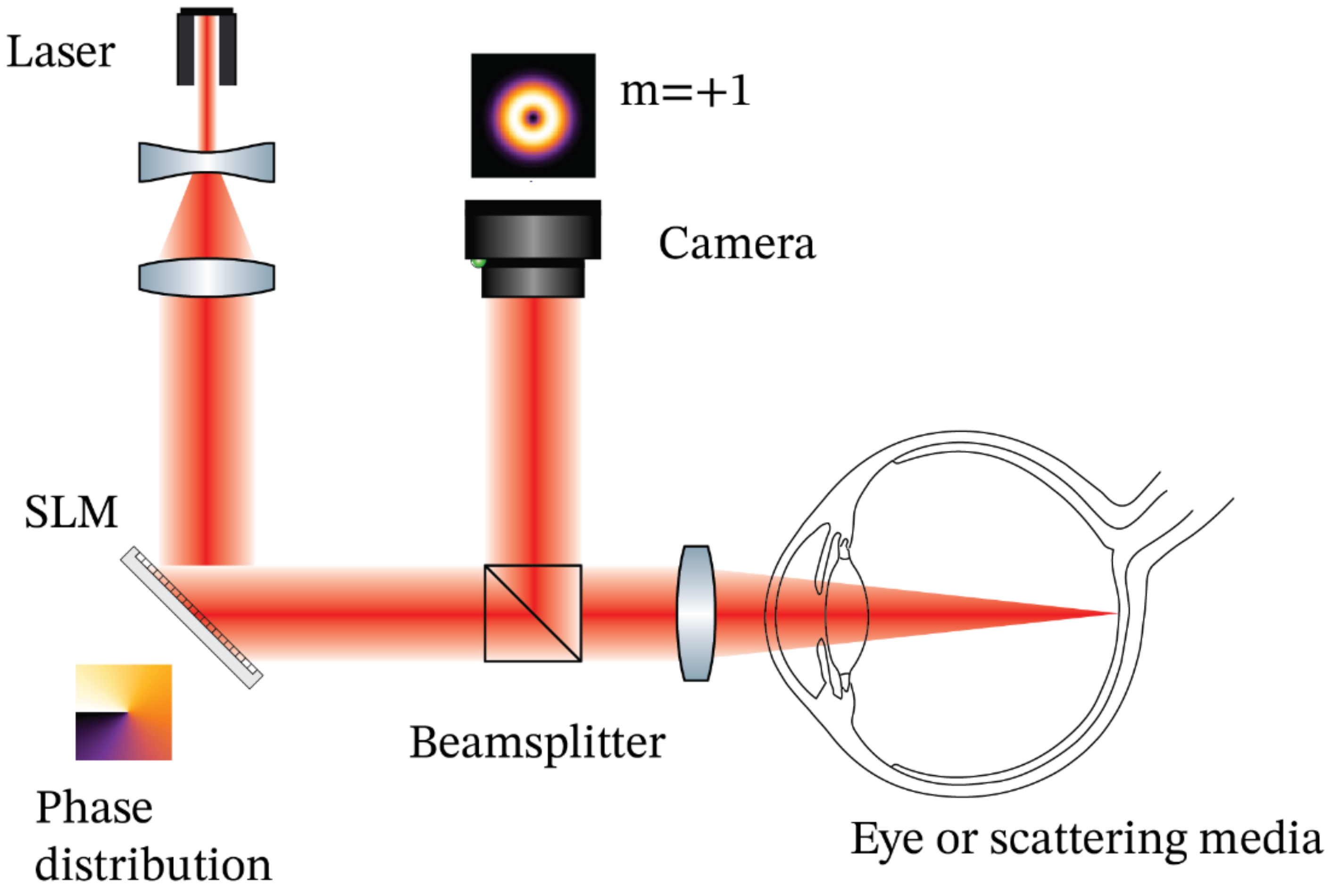
Orbital angular momentum: experiment



- Use of OAM offers protection from noise
  - It could bring other benefits:
    - Improved edge definition
    - Better surface profile distinction
    - Discrimination of chiral objects (*e.g.* in retinal structures)
- OAM is generated using a spatial light modulator (SLM)
- SEQUOIA will study the effects on OAM of propagation in a scattering media
  - Experiment and comparison with simulation
  - The eye may be approximated as a multilayer scattering media
- Train AI algorithm to recognise and control the type (order) of OAM

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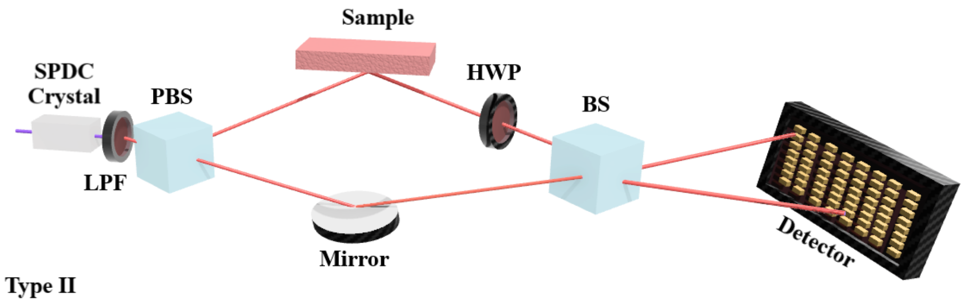
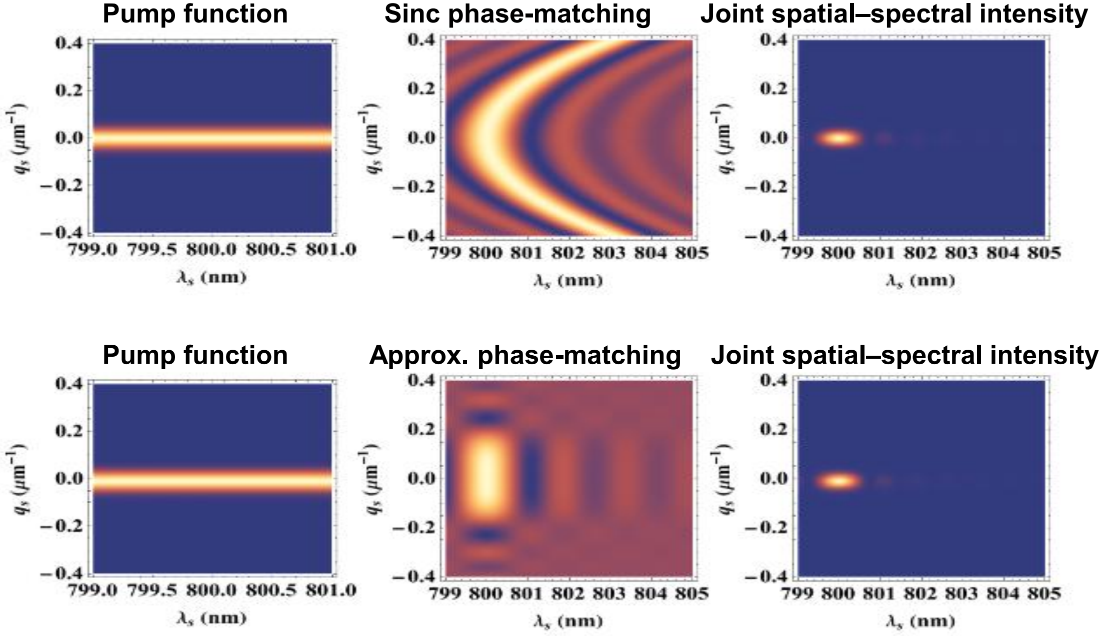
Identification and modeling of noise sources

- We model the main QOCT noise sources.
  - Optical losses in the interferometer: scattering and absorption;
  - SPAD camera imperfections: finite detection efficiency, dark counts, and optical crosstalk.
- High-quality signal demands no spatial-spectral correlations; our model embodies the SPDC-set bandwidth, avoiding external filters that would further deplete the signal.





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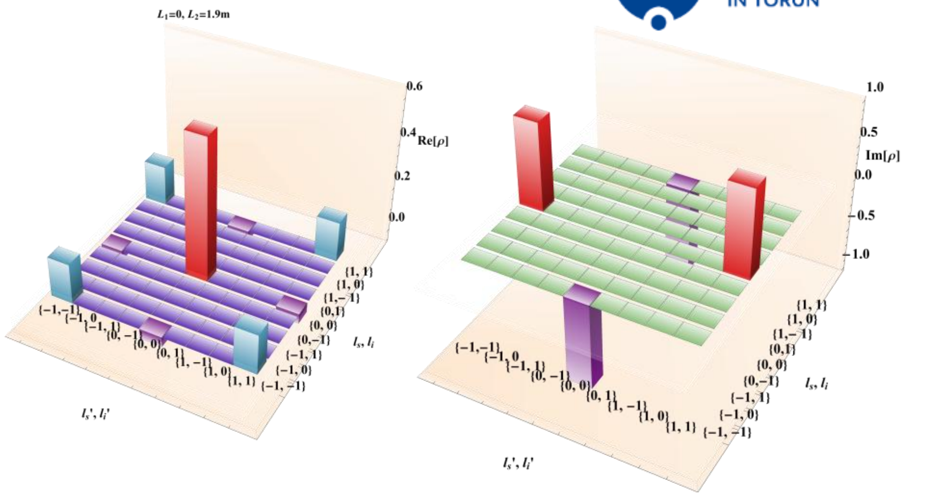
Model for OAM entangled photons in QOCT

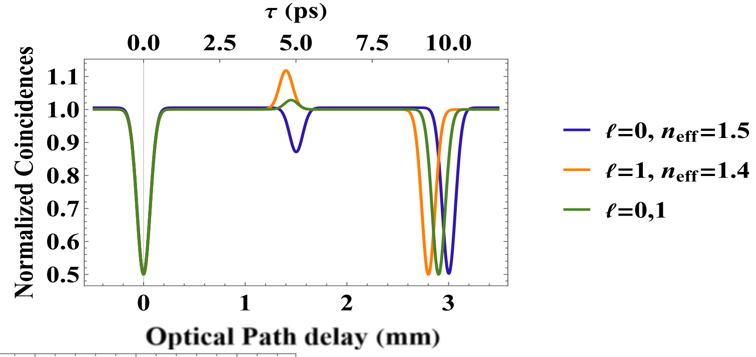
NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ



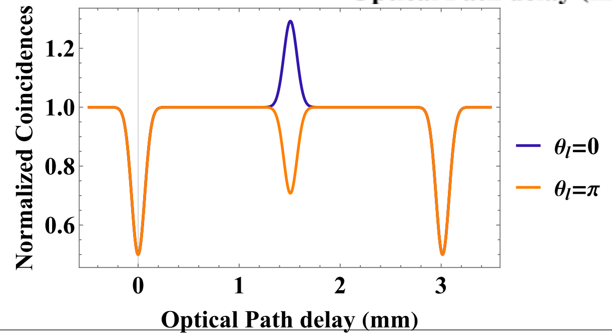
- Propagation of **only one** photon from an OAM-entangled SPDC pair irreversibly degrades the entanglement due to modal dispersion, information is lost to the medium.

- **In a QOCT interferometer**, the modal dispersion is symmetrically imprinted as phase and cancels from the coincidence signal.

- **QOCT with a waveguide sample:** each OAM mode experiences a different effective refractive index, thus probing a different effective depth in the sample.



- **OAM-resolved QOCT for artefact tracking** for a sample indifferent to the OAM mode.



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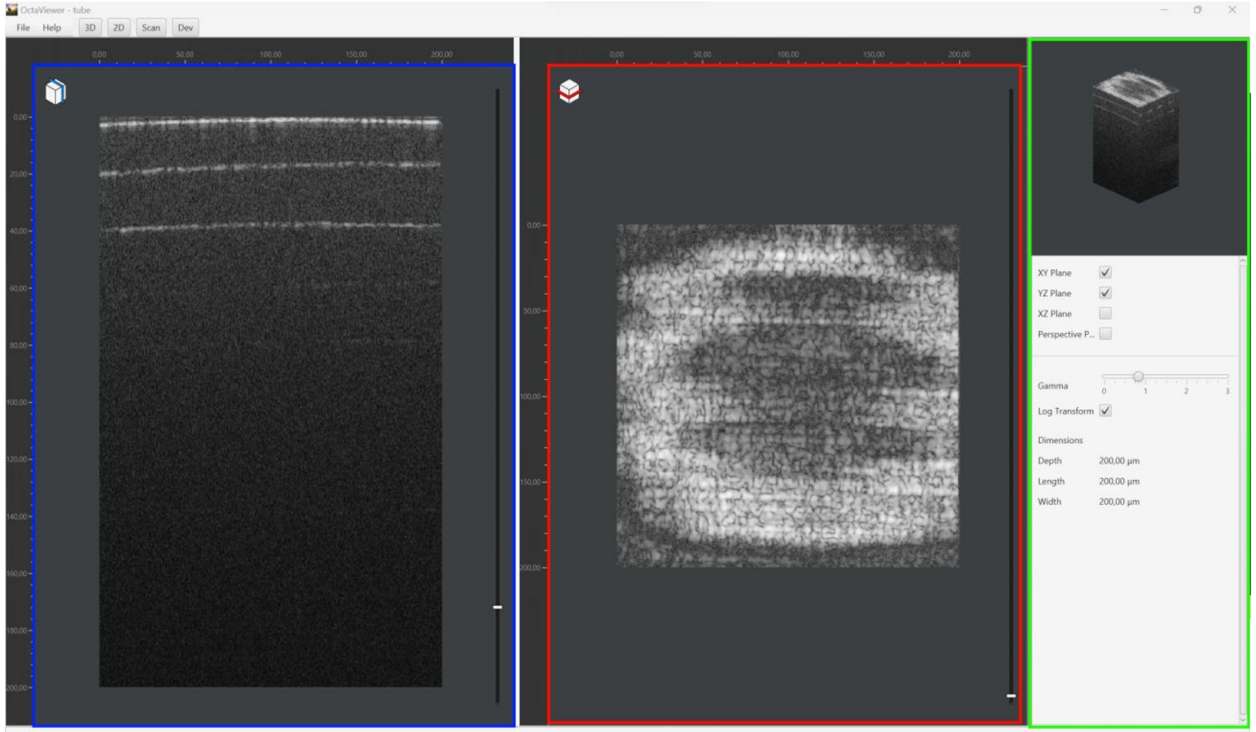
QOCT software - From classical to quantum imaging interfaces

- Tailor and optimise the existing state-of-the-art classical **spectral domain OCT** data acquisition and processing software to a **QOCT platform**

- Development of a user-friendly interface for time-domain QOCT – **single pixel** and **multi-pixel intensity correlations**

- Capability for visualisation and interactive image effects (depth, layers, *etc.*) including **spectrally resolved intensity correlations**

- Development of a novel swept source spectral domain **QOCT software supporting OAM analysis**



Example of visualisation of a volumetric scan. The blue and red regions show a B-scan and a C-scan, respectively. The green region is a control panel where the user can change how the volume is rendered.

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Potential applications for QOCT technologies

- Clinical applications
  - Surface imaging
    - Ophtalmology
    - Dermatology
    - Dentistry
    - Cochlear vibrometrie
  - Endoscopic imaging
    - Cardiovascular
    - Gastroenterology
    - Gynaecology Urology
    - Pulmonology
- Developmental Biology
  - Elastography
  - Cochlea Organ Tissue
  - Microvasculature
  - Skin
  - Nervous System
- Industrial application
  - Displays
  - Pharmaceuticals
  - Contact Lens Metrology
  - Packaging
  - Biofilm
  - Industrial Paints and Varnish
  - Thin Films
  - (Nano)membrane anti-fouling
  - CAD/CAM
  - 3D Printing
  - Composite Materials
  - Aerospace
  - Welding & Keyhole Mapping
  - Meat Quality Control
  - Art conservation

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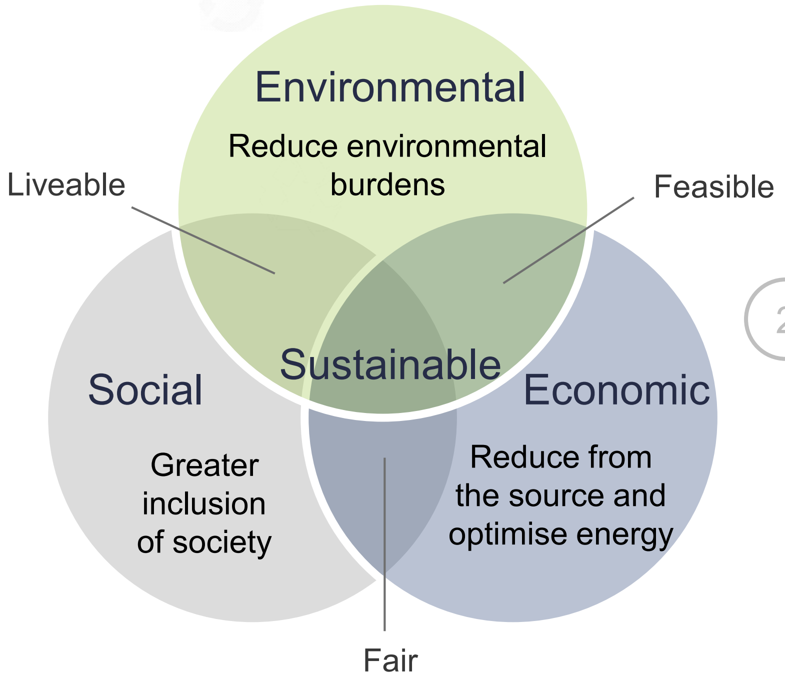
Techno-economic and social assessments of the potential for QOCT

1 Life Cycle Assessment (LCA)

3 Social Life Cycle Assessment (SLCA)



2 Techno-economic Assessment (TEA)

Life Cycle Costing (LCC)

HOLISTIC APPROACH - 3 pillars of sustainability

Tasks performed within the scope of SEQUOIA Project

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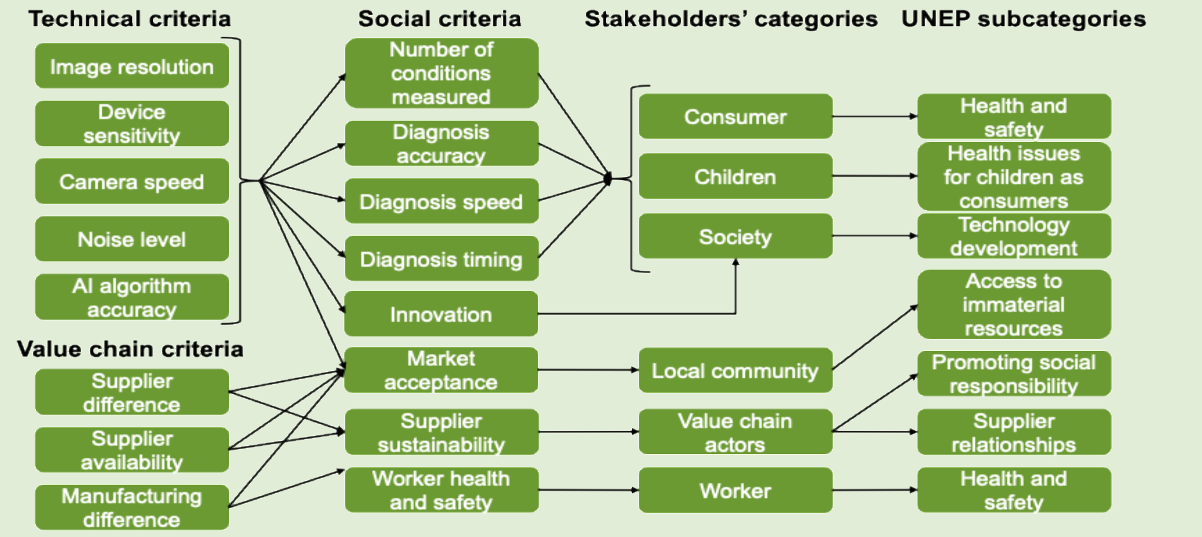
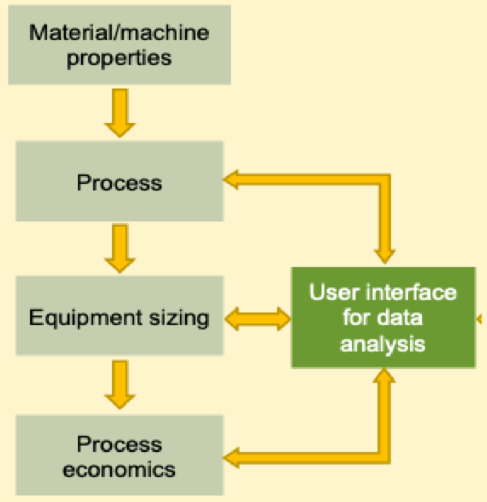
Social (SLCA) and Techno-economic assessment (TEA) of QOCT

ARDITEC

SOCIAL



TEA



Evaluate new device for components sizing (potential scale-up) and current energy requirements.

Identify capital CAPEX, operational costs OPEX and identify cost optimisation opportunities.

Identify and eliminate supply-chain and market bottlenecks, including devices and material prices volatility compared to expected costs.

Main findings

- Diagnosis accuracy and diagnosis timing are the most important social aspects
- Traditional OCT scores higher in ophthalmology than dermatology
- Compared with traditional OCT, QOCT in ophthalmology and dermatology is expected to have an average improvement in the social score of 13 % and 25 %, respectively.

Main findings

- QOCT enables early detection, reducing late-stage treatment costs and social security/health expenses for glaucoma, RVO, and AMD.
- QOCT energy costs are minor in OPEX; staffing is the main driver.
- QOCT components should last +10k hours to keep replacement and levelised imaging costs low.
- SEQUOIA QOCT already shows strong social/economic impacts, especially if used >2k times or >8,000 images p.a.
- QOCT components are well mastered by the consortium

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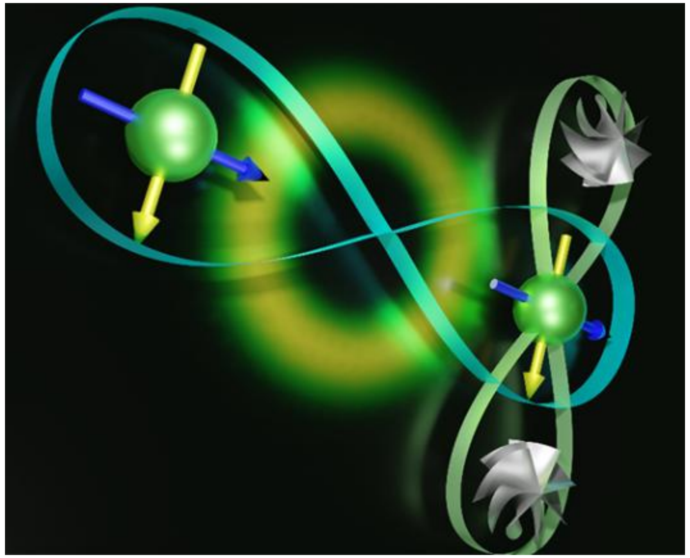

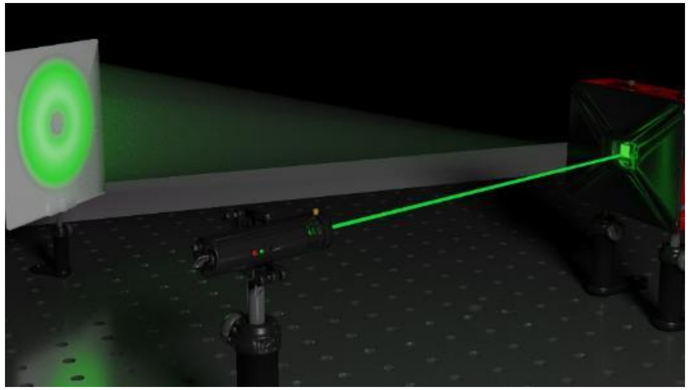

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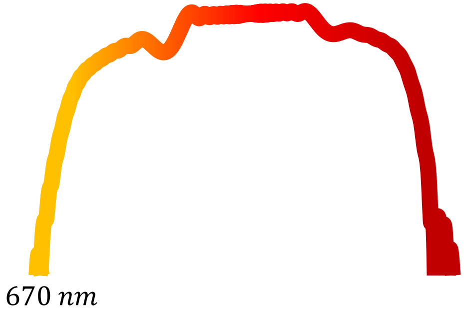
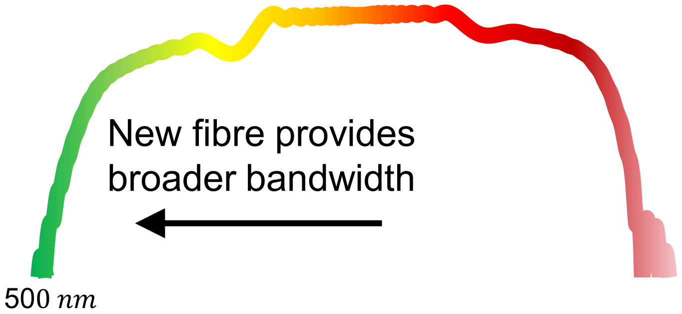
Aim: Broadband spectral coverage supercontinuum with low noise

NKT Photonics

- **Motivation:** OCT axial resolution is improved by a wider bandwidth source: spectroscopic and other functionalities can be exploited at VIS wavelengths
- **To make visible entangled photons, requires UV supercontinuum (SC):** A new fibre design will first be created and drawn at NKT Photonics to extend the SC bandwidth to reach short wavelengths
- **To make a true comb, the SC must be stabilised.** PTB will use feedback mechanisms to stabilise the repetition frequency and drift of the carrier phase



Coherent SC →



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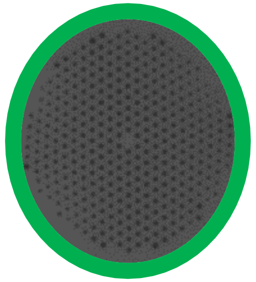
SEQUOIA ultra-stable source objective

- NKT will generate a low noise broadband comb source using coherent SC
- For the SC to be considered a comb, advanced stabilisation techniques are required
    - An octave spanning spectrum is required for carrier phase stabilisation
    - Relative intensity noise (RIN) of <0.6 % in Stage 1 and 0.2 % in Stage 2

NKTP fs laser

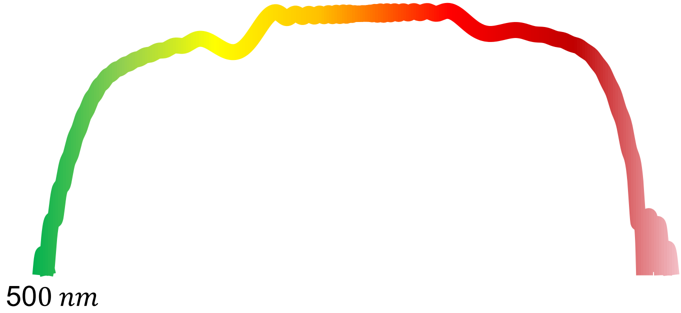
+



All-normal fibre

+

Advanced stabilisation with PTB



Octave spanning SC

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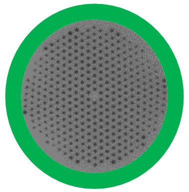
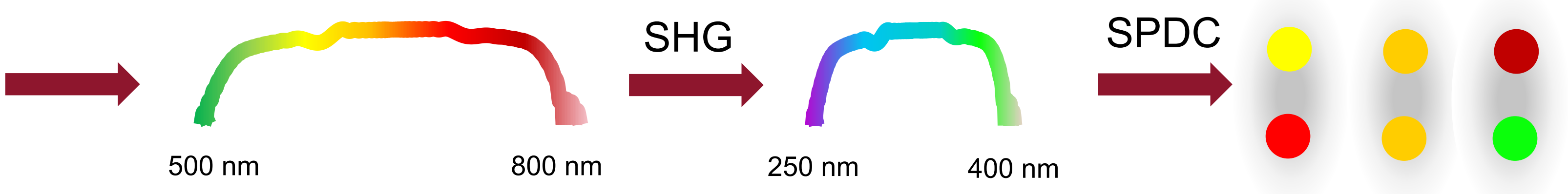
Light sources development: fs laser + SC fiber + SHG + SPDC

+

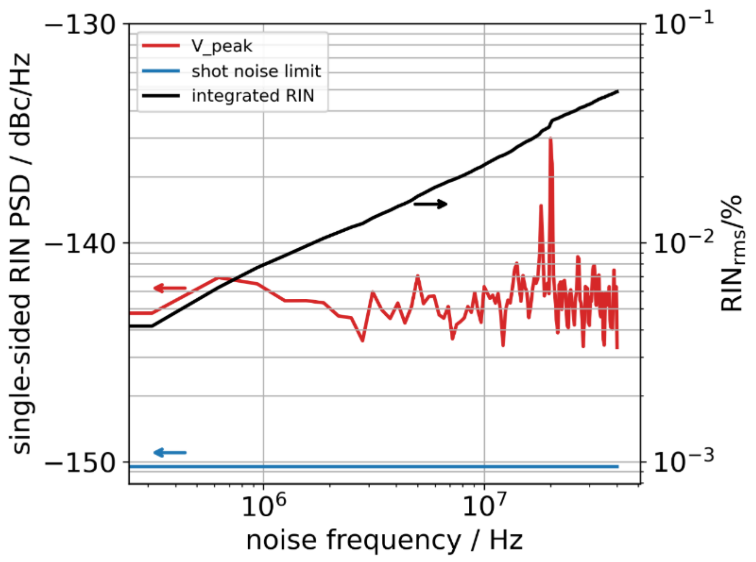




NKTP fs laser

All-normal Dispersion fibre

entangled / correlated photon pairs 500nm – 800 nm



- Record low integrated RIN for a supercontinuum source observed: 0.055 %

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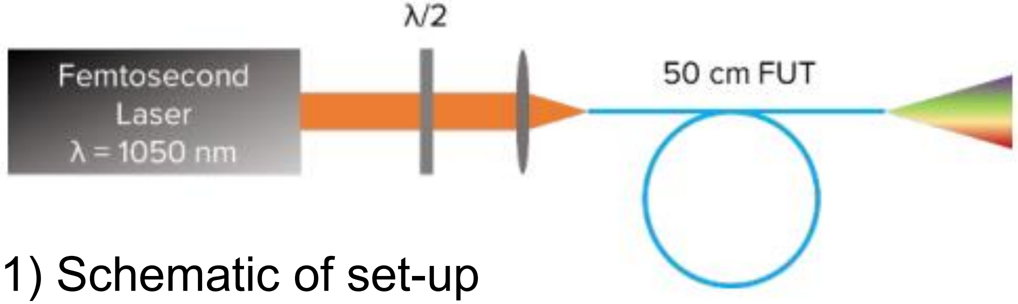
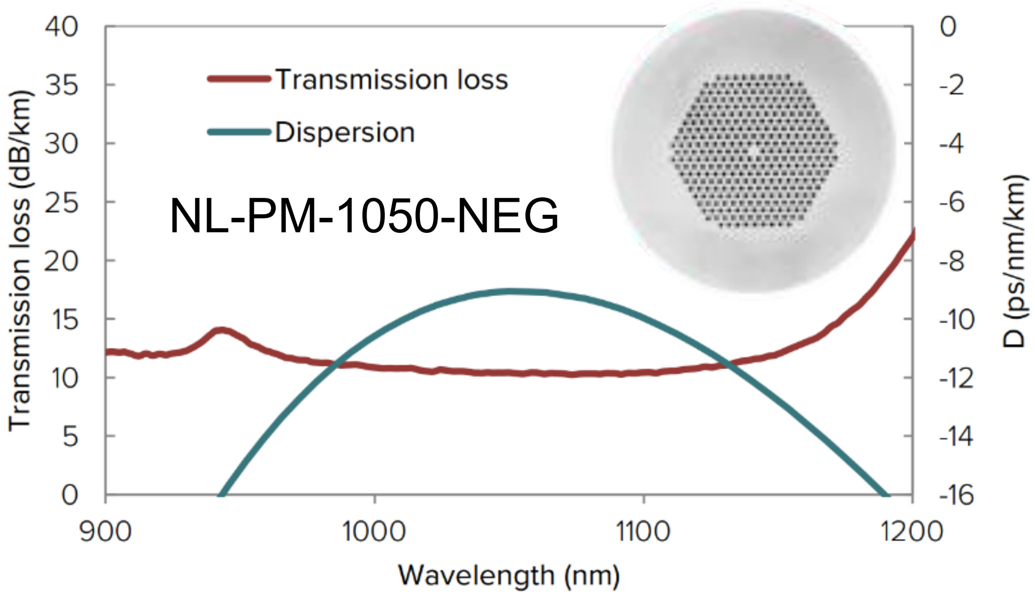
Advantage for OCT: a spectrally-flat light source

NKT Photonics

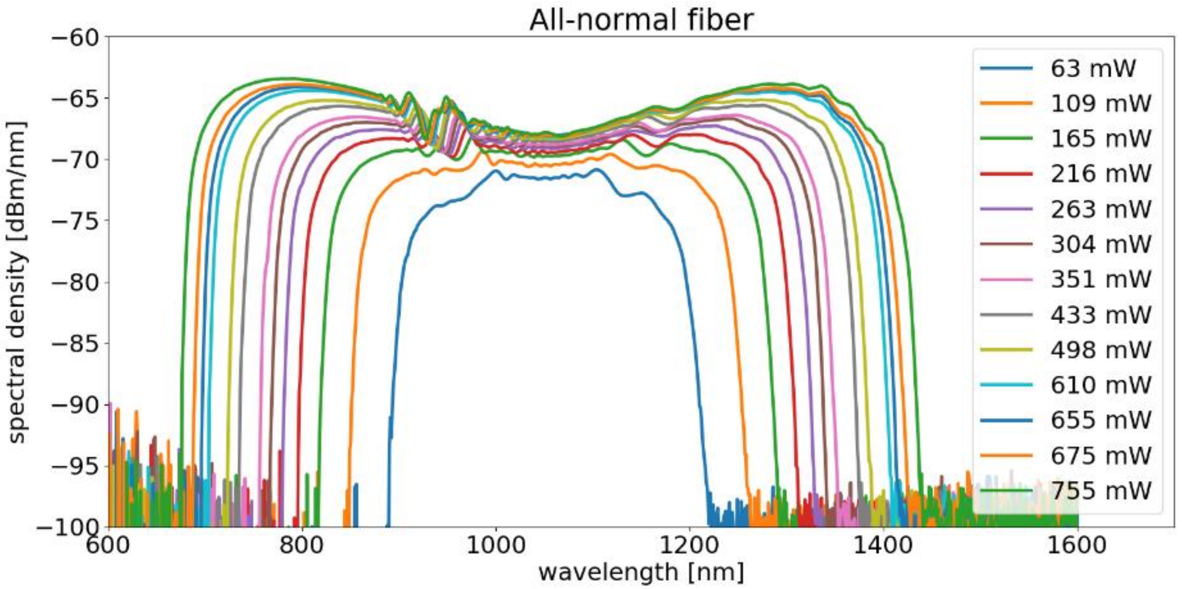
- All normal dispersion SC provides greater spectral flatness than typical SC
- The fibre is pumped using a 130 fs, 80 MHz NKTP Origami 10HP laser
- The result is an octave spanning SC, with a spectral flatness of 5 dB



1) Schematic of set-up



2) Fibre loss and dispersion



3) Spectrum at several pump powers (pumping fast axis)

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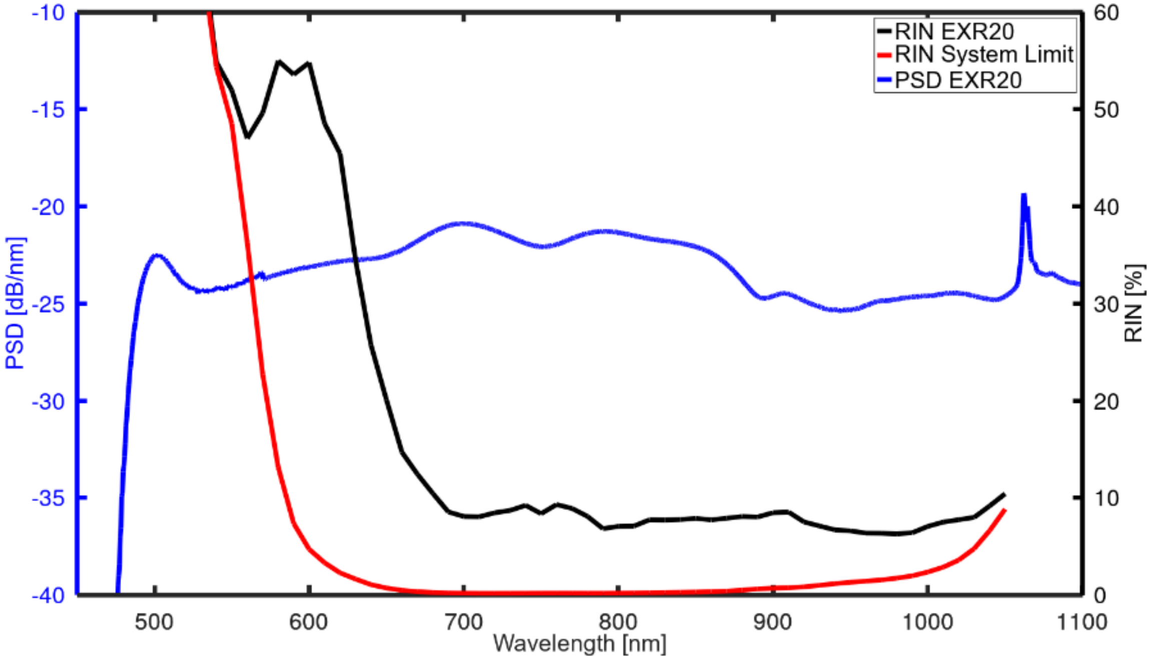
Advantage for OCT: low RIN

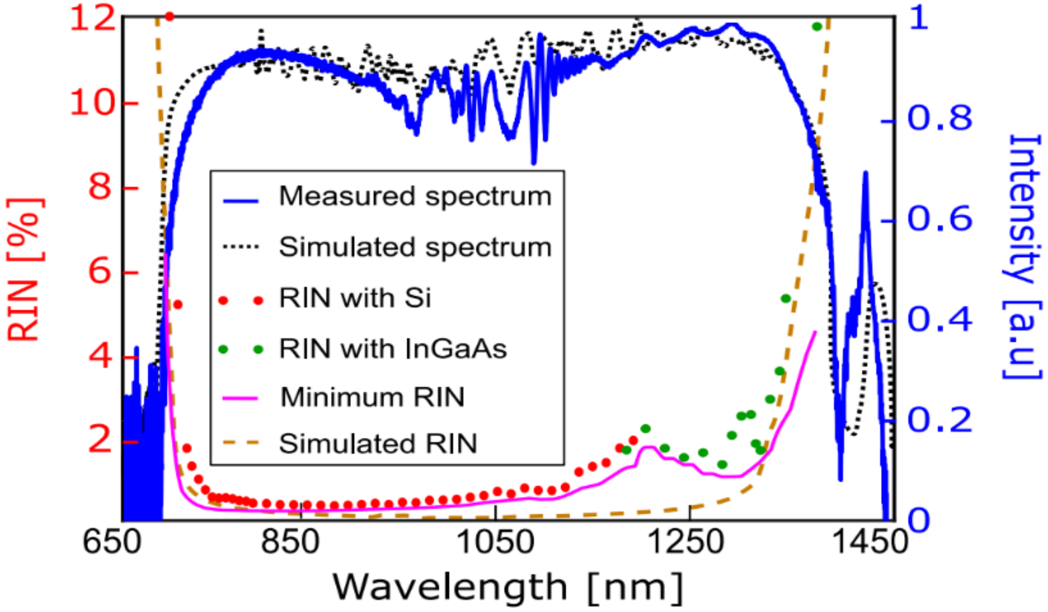
- Due to high temporal coherence, pulse-to-pulse fluctuations are very low
- Standard SC sources are characterised by RIN > 8 %
- Preliminary ANDi results suggest a possibile >10× improvement (<0.6 %)
- This can allow an OCT system to reach shot-noise limited sensitivity (>100 dB)

Anomalous supercontinuum



1) RIN of standard SuperK sources

All-normal supercontinuum



2) RIN of the SEQUOIA all-normal SC

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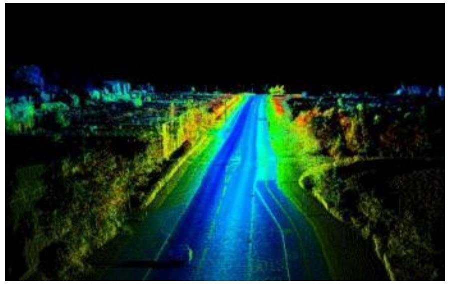
SPAD Imager for QOCT: Concept

Single-Photon Avalanche Diodes (SPADs) can **detect single photons**, can be **integrated** in silicon chips, and provide **excellent time resolution**, but current SPAD imager development is driven by LIDAR:

- High photon flux → Detector **noise is not important for LIDAR**
- Time resolution of a few ns is enough for distance sensing



MPD's SPAD cameras were already successfully employed for detecting entangled photon pairs* but were not designed for this application.

SEQUOIA needs improved SPAD imagers with:

- **Low noise**
- Good efficiency in 500-800 nm range
- **Coincidence detection** (sub-ns) with optimised readout
- **Thousands of pixels**

*Ndagano *et al.*, "Imaging and certifying high-dimensional entanglement with a single-photon avalanche diode camera," NPJ Quan. Inf **6**, 94 (2020). https://doi.org/10.1038/s41534-020-00324-8

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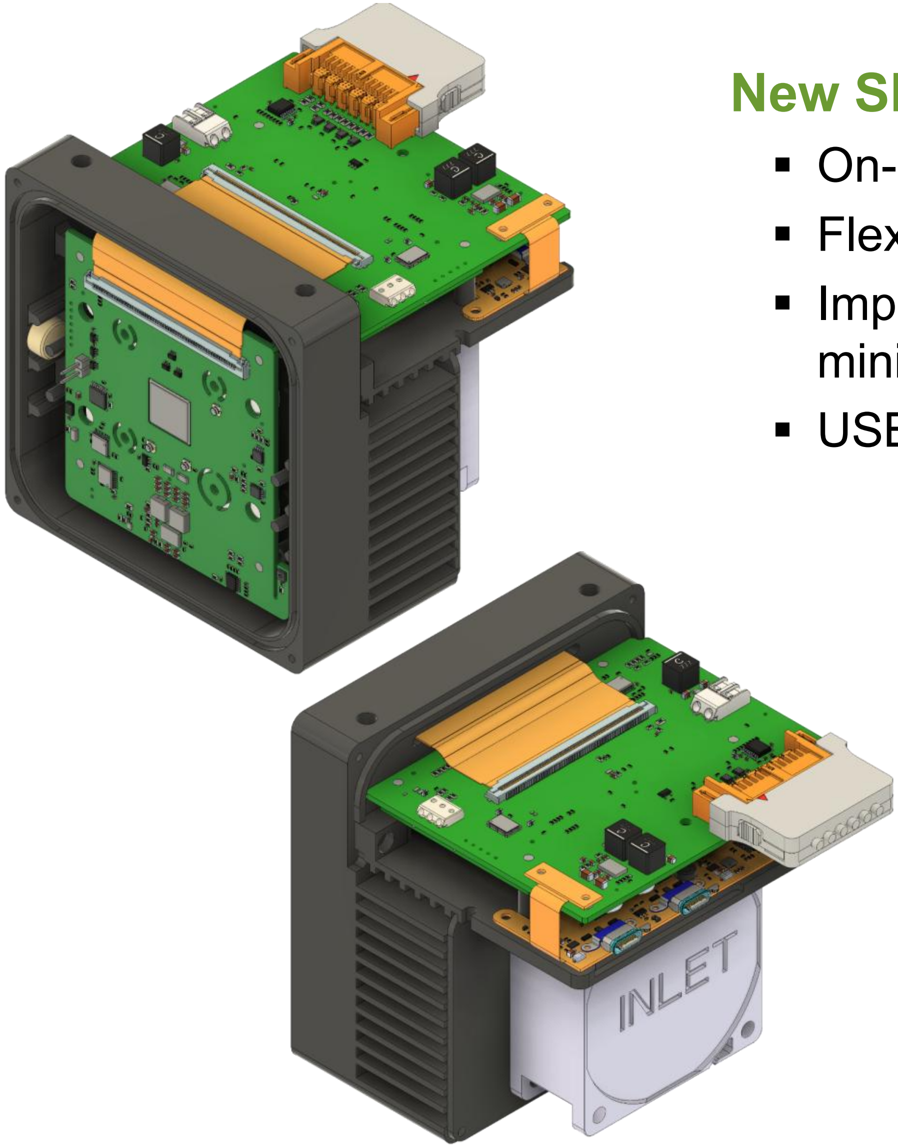
SPAD Imager for QOCT: Camera development and challenges



New SPAD camera design

- On-camera data processing to minimize data transfer overhead
- Flexible I/Os to interface with external instrumentation
- Improved thermal management with sub-ambient detector cooling, to minimise noise and improve stability
- USB Type-C power delivery and data transfer

Future steps:

- Camera prototype ready by M43
- Characterization in a QOCT setup before the end of the project
- Samples provided to partners and academic institutions for beta testing soon after the project closes
- Camera enters MPD catalogue after validation is successful

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  - Sustainability
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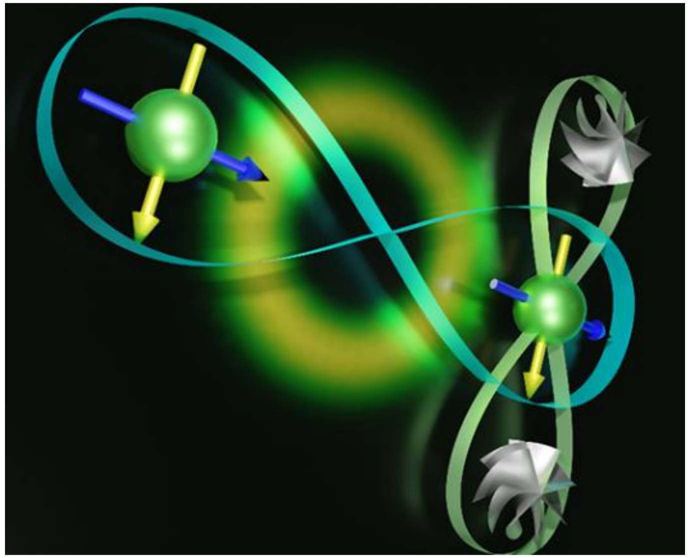

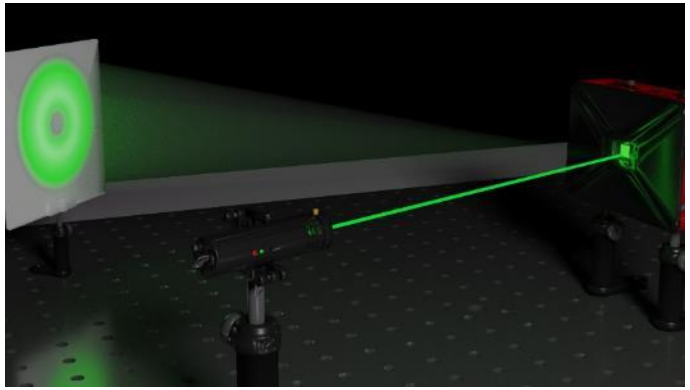

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QOCT for retinal imaging

- **Key objectives:**
  - **Demonstrate QOCT** in a real-world application (retinal imaging)
  - **Automated image analysis** showing increased resolution and contrast for retinal specimens

- **Stepping stone sub-objectives**
  - Establish **durable test standards** from rodent eyes with optical properties similar to native tissue
  - Acquire **reference OCT images** for training and testing ML-based image evaluation algorithms
  - Creation of **curated QOCT retinal imaging and databases** from rodent eye test standards
  - Semantic segmentation algorithms based on deep learning for **retinal layer delineation**
    - Compare algorithm performance of QOCT and state-of-the-art OCT
  - Deep learning-based framework for the **localisation and identification** of key retinal enantiomers

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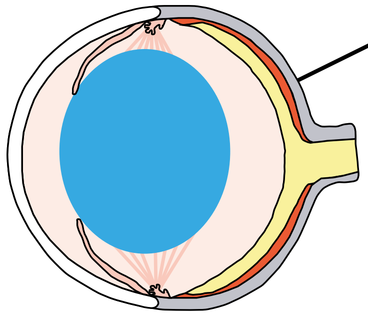
Durable test standards

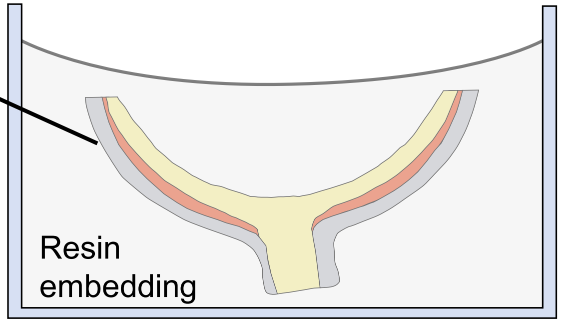
- Establishment of durable retina models for QOCT performance testing

***Ex vivo* rodent eye**

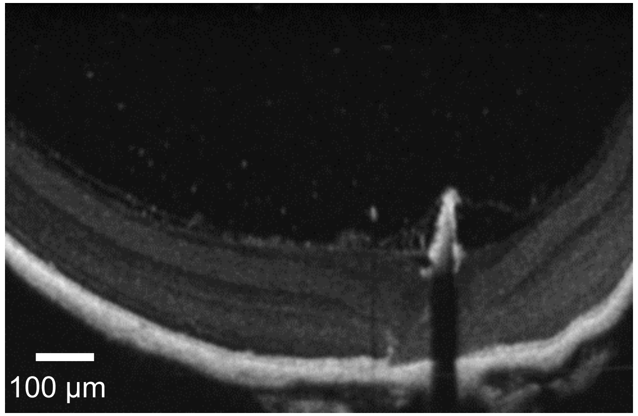
Retina



Tissue fixation + resin embedding

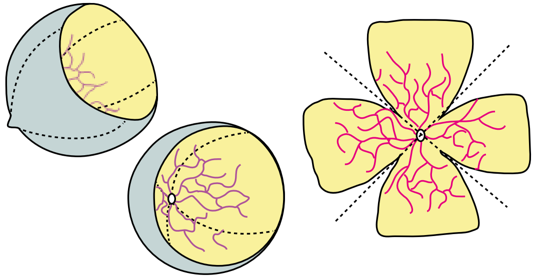


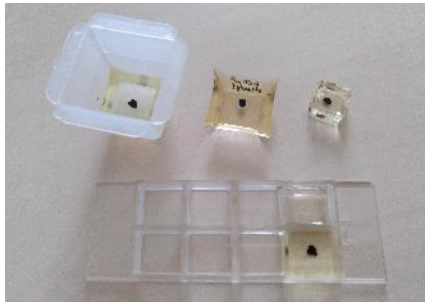
OCT measurements

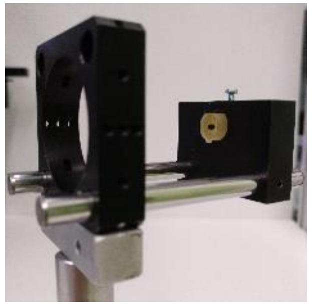


OCT B-scan (embedded mouse retina)

Dissected retina







Different embedding and mounting concepts

Á. Barroso, S. Ketelhut, G. Nettels-Hackert, P. Heidushka, R. del Amor, V. Naranjo, B. Kemper, J. Schnekenburger
Durable 3D murine ex vivo retina glaucoma models for optical coherence tomography
Biomed. Opt. Express **14**, p. 4421-4438 (2023) https://doi.org/10.1364/BOE.494271

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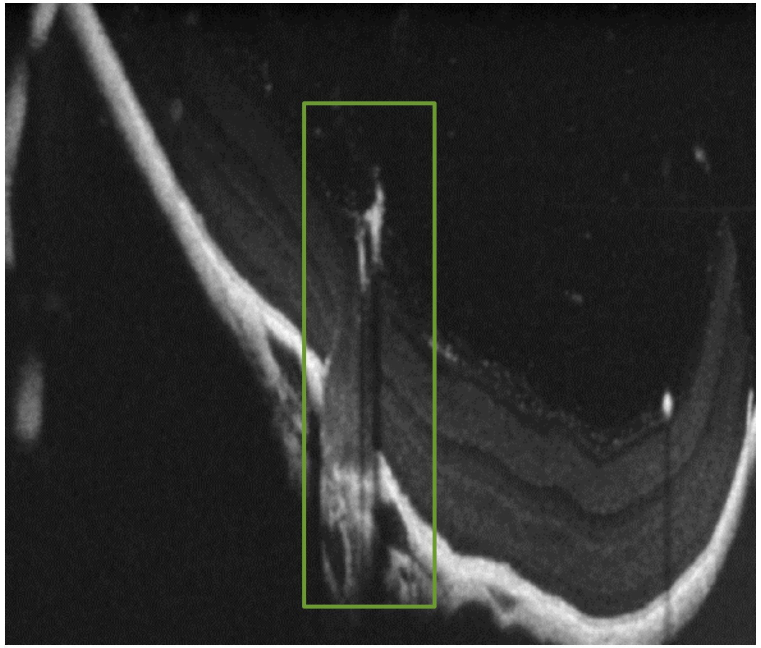
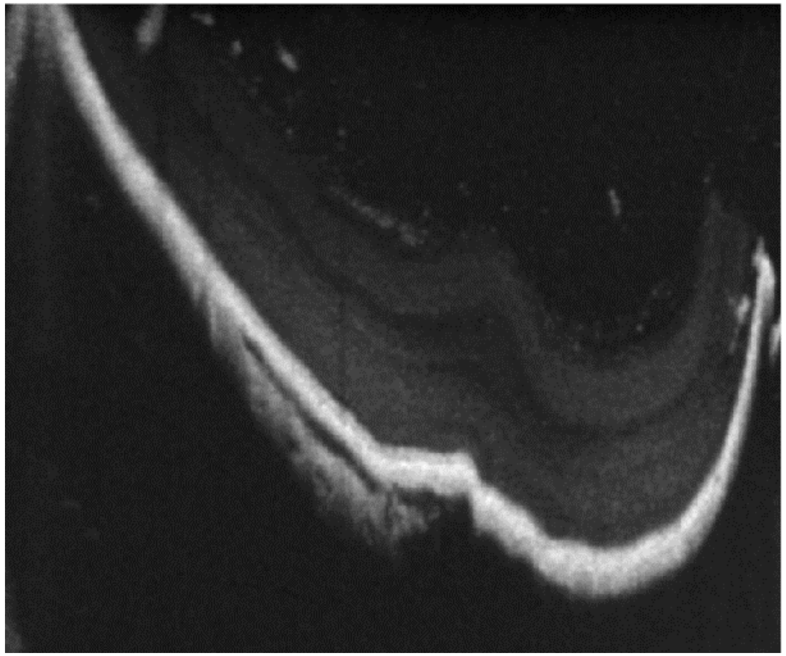
Artefact detection

- Detect the main artefacts in the *ex vivo* samples to eliminate them from the study

Optical nerve



Out of focus



Retina damage

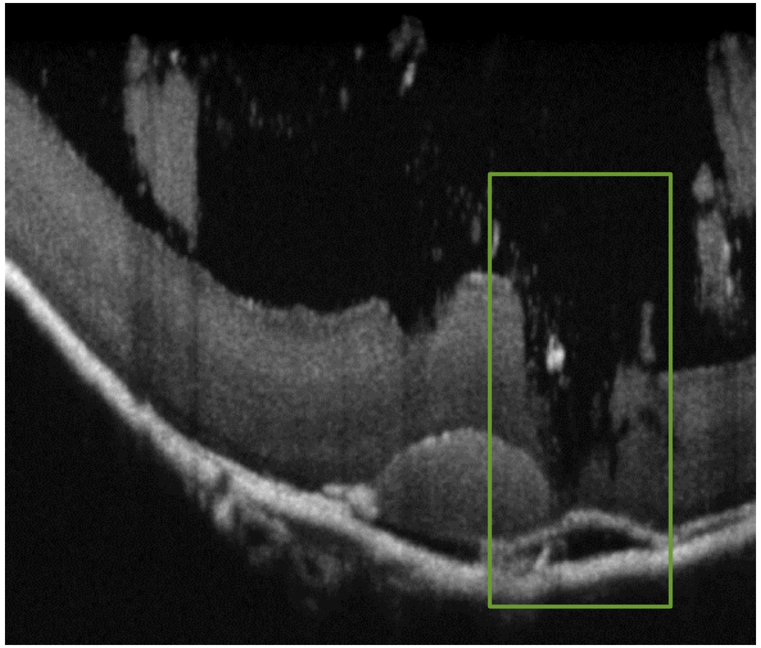


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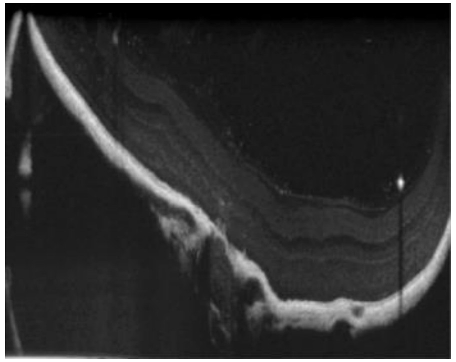
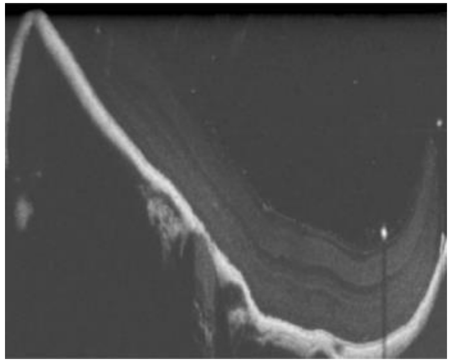
Image registration

- Objective: test the differences between the rotations of a sample using image registration

→ The samples with differences between them can be considered independent and will be included in the study

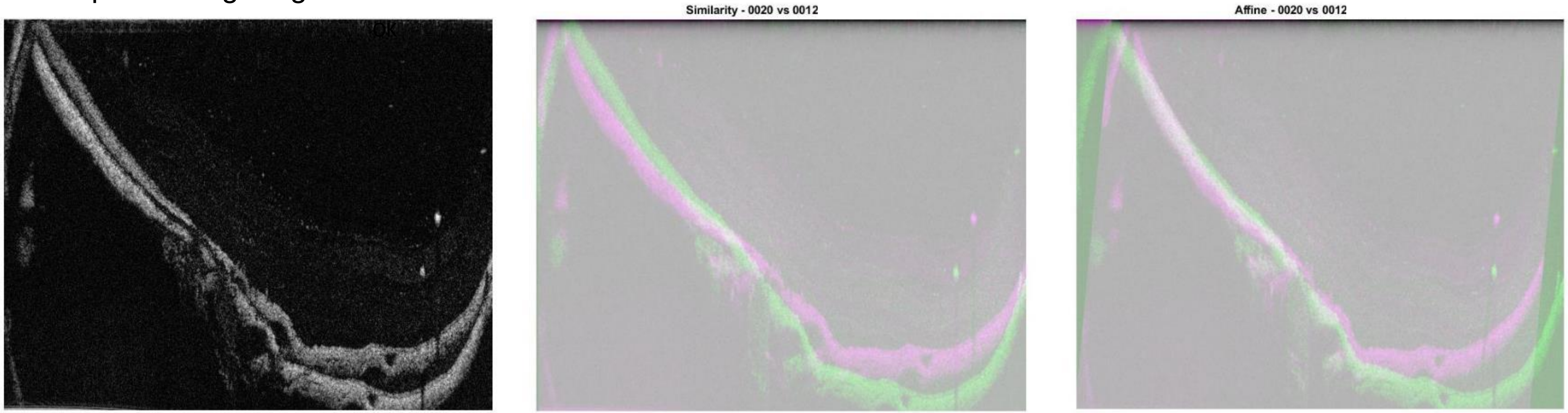


0012



0020

Example of image registration:



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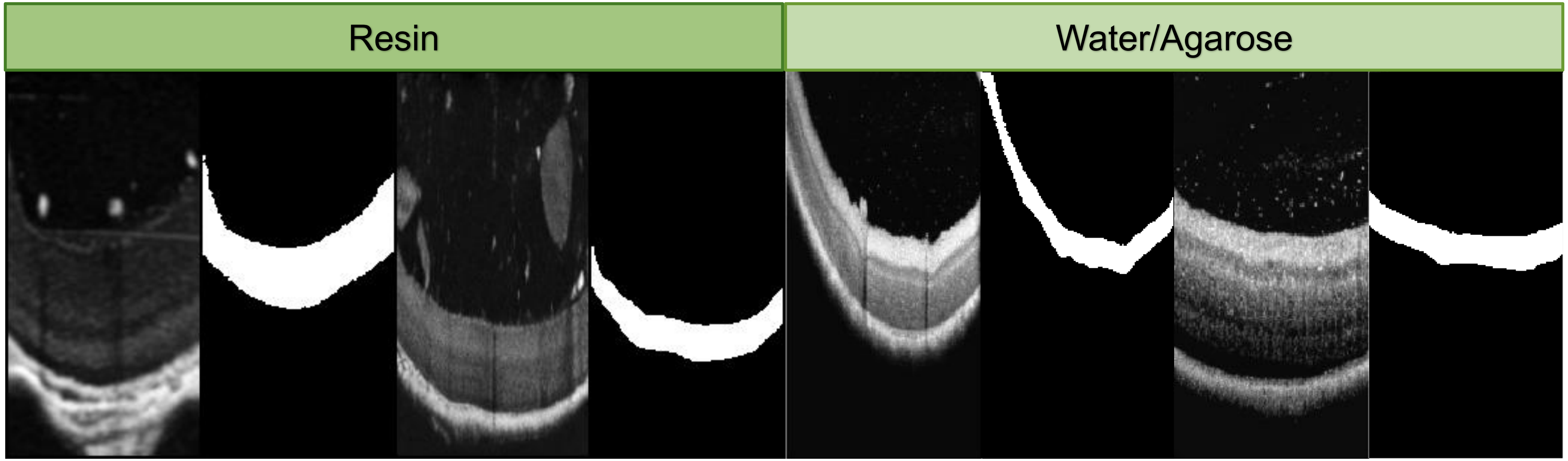
Data synthesis using generative models

- Objective: extend the amount of annotated OCT data for training robust deep learning segmentation models.

→ Generation of OCT images of the retina embedded in two different media (solid resin or water/agarose) and the corresponding upper retinal cell layer segmentation masks.



García-Torres, F., del Amor, R., Morales-Martínez, S., Barroso, Á., Kemper, B., Schnekenburger, J., & Naranjo, V. (Nov-2024). Using Diffusion Models for Data Augmentation on Limited Rodent OCT Datasets. In *International Conference on Intelligent Data Engineering and Automated Learning.* Cham: Springer Nature Switzerland.

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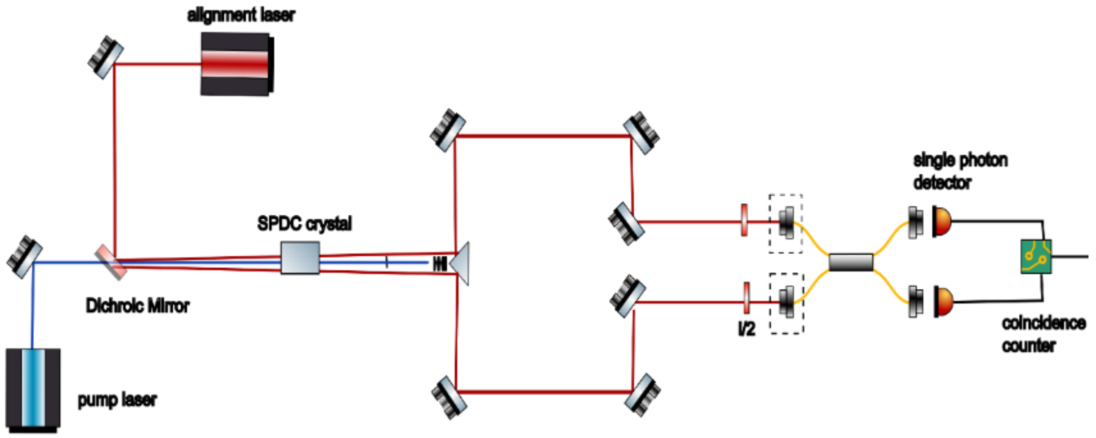
Characterisation and benchmarking

- **Developing a quality metric for imaging QOCT**

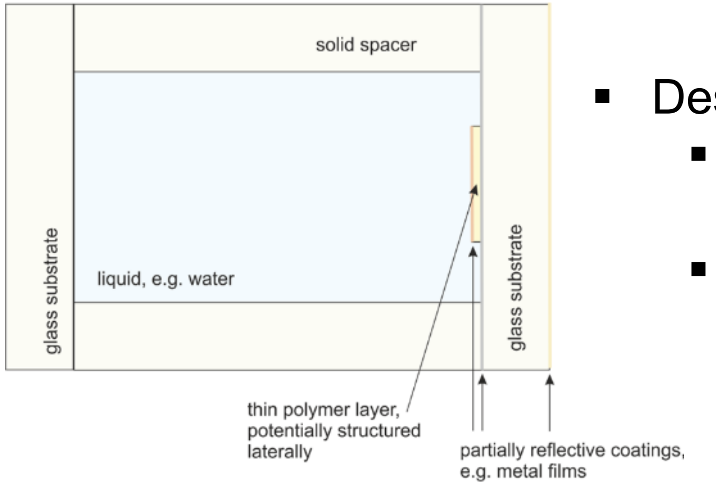
- Identification, modelling and characterisation of noise processes

→ Initial noise characterisation in a Hong-Ou-Mandel set-up

- Establish a metrological framework for entangled sources
- Benchmarking of the QOCT system against classical OCT

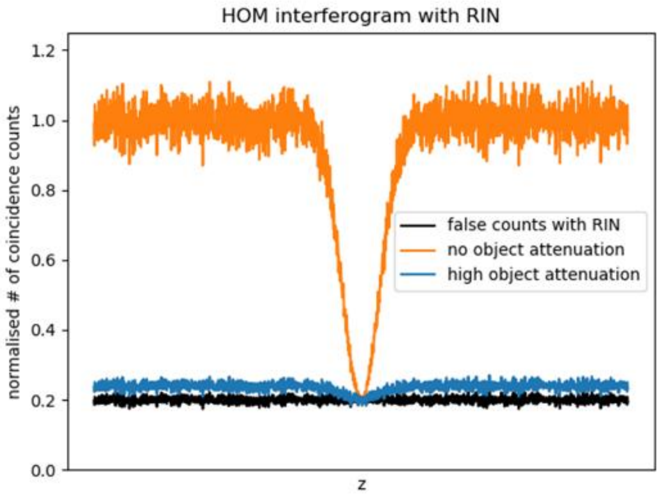


HOM set-up for noise characterisation



Multilayer sample

- Design of QOCT technical standard samples:
  - Multilayer samples with well-defined properties
  - Thickness, reflectivities, absorption, scattering and dispersion



Effect of RIN on HOM dip

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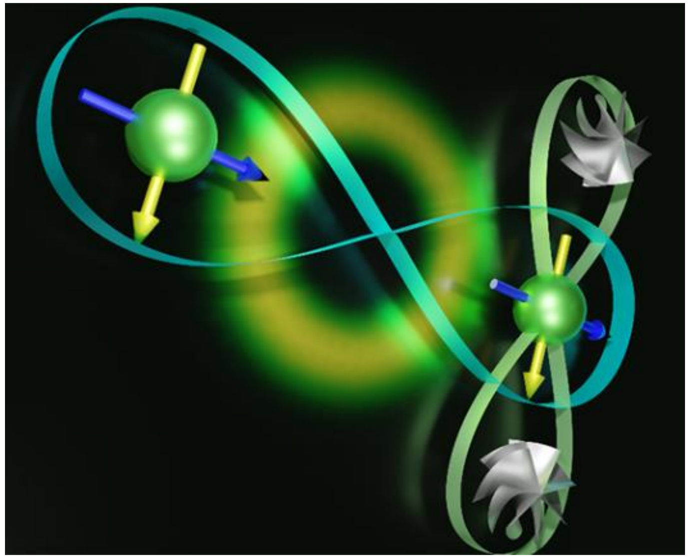
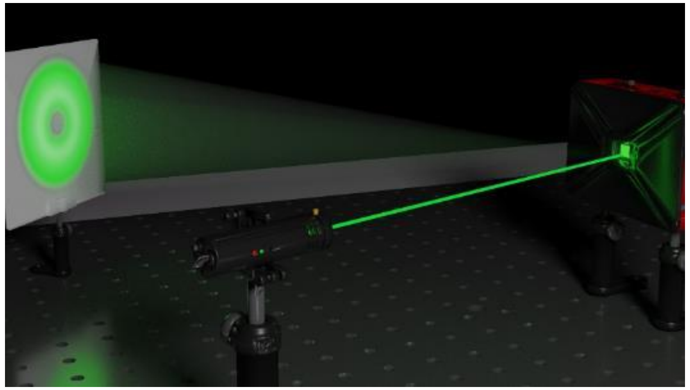
Presentation outline

- Project summary
  - Consortium
  - Project overview
  - Objectives
- Theory and principles
  - OAM control
  - Noise reduction
  - QOCT
  - Sustainability
- Hardware
  - Source
  - SPAD imager for QOCT
- Experiment
  - Retinal studies
  - Characterisation and benchmarking
- **Outlook**





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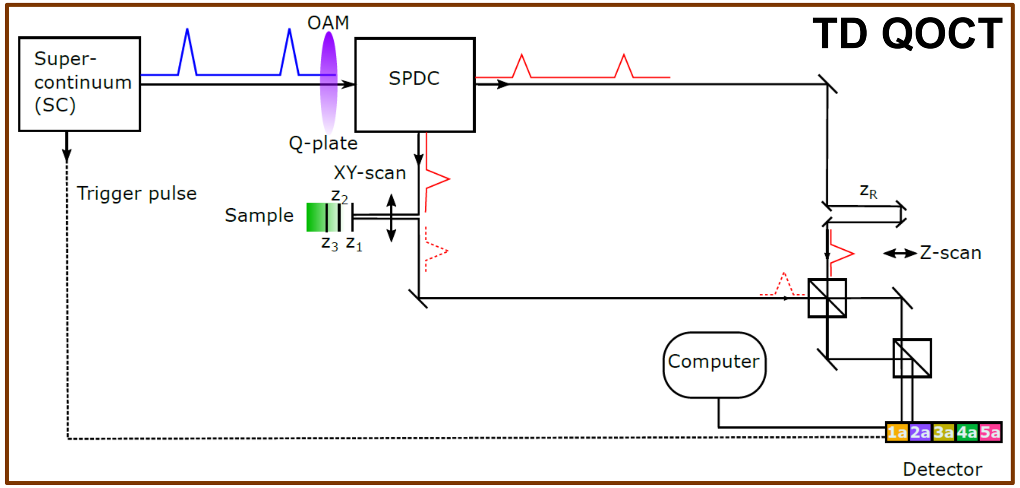
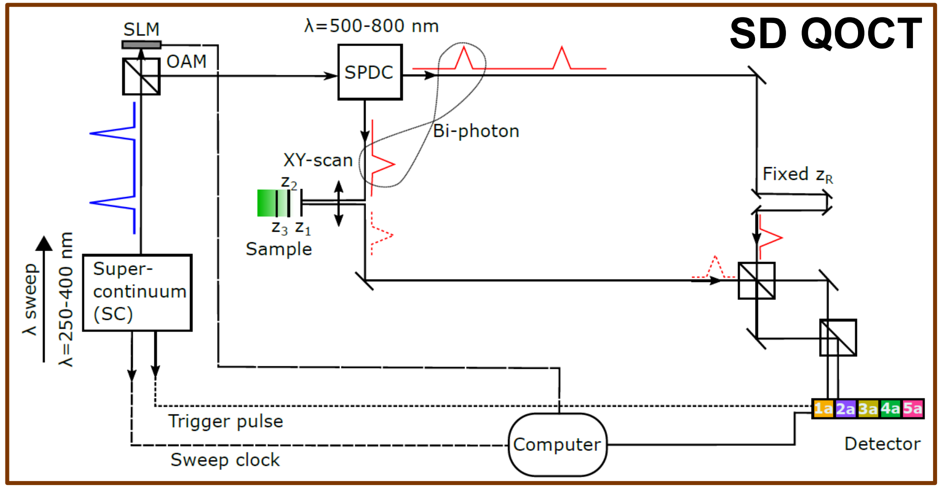
Experimental SEQUOIA goals

- **Objectives:**
  - Initial TD QOCT system for evaluation and delivery of training data for the machine learning
  - Swept source SD QOCT system using AOTF and SLMs
- **Experimental goals**:
  - Operational TD QOCT system with Q-plate and axial resolution (<1 μm)
  - 250-400 nm swept frequency comb synchronised to SLMs
  - Swept source 500-800 nm SD QOCT system with axial resolution <500 nm





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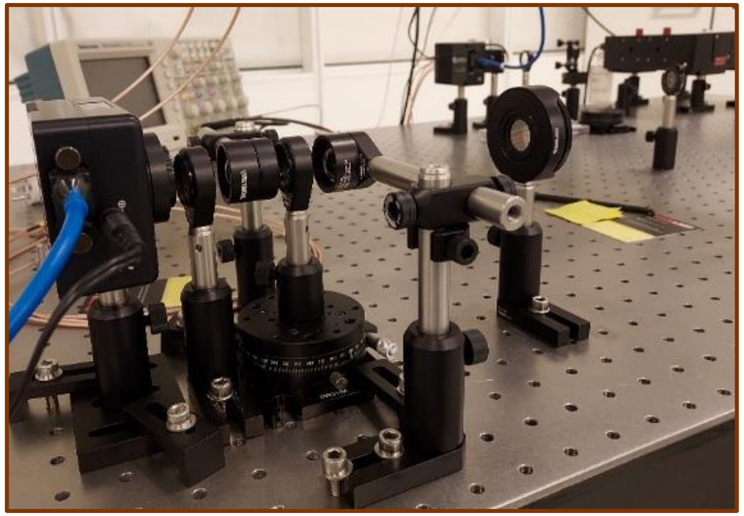
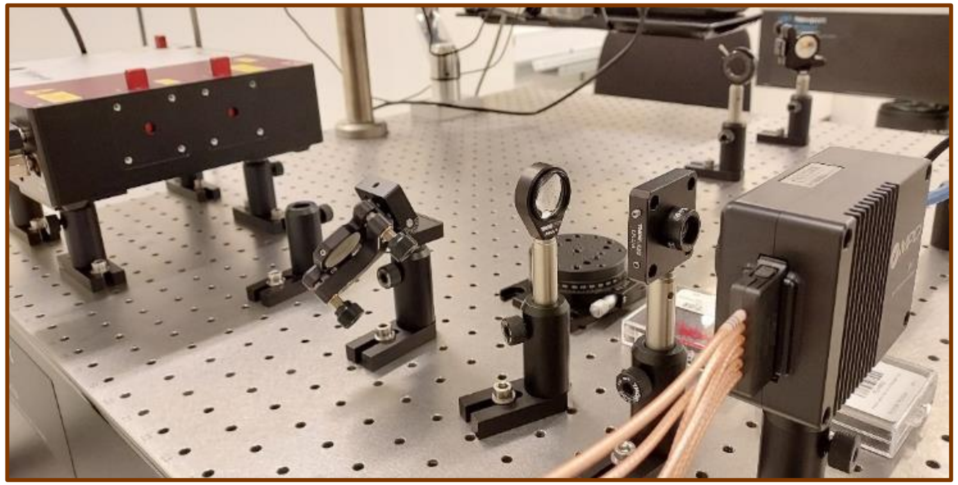
Experimental development of QOCT in SEQUOIA

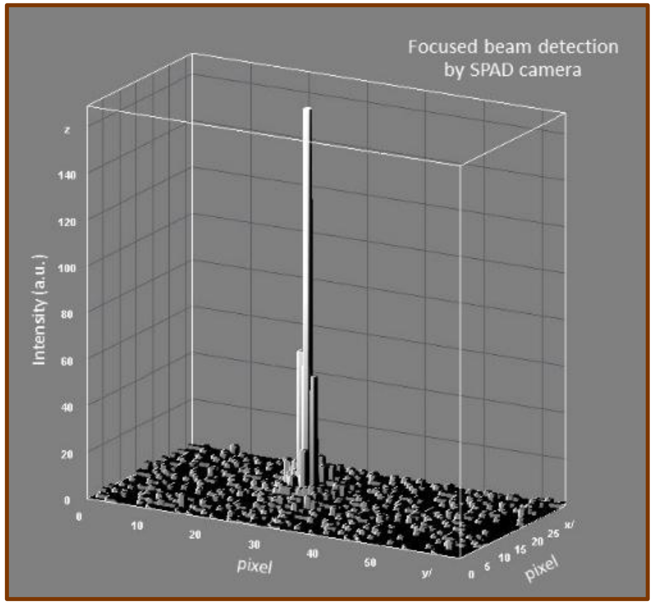
- **Status:**
  - A new Quantum Imaging Lab is established at DTU Electro
  - Focusing beam to a single pixel in an MPD SPAD camera achieved using lens combination
  - Experiment started to generate SPDC photon pairs



SPDC set-up



Set-up for focusing beam to a single pixel



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Thank you for your attention!

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https://sequoia-project.eu

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