Spectrometer based on SPAD linear array with sub-nanosecond timing resolution and single photon sensitivity for quantum-assisted optical interferometers.

CPAD 2022

11/30/2022 Stony Brook University

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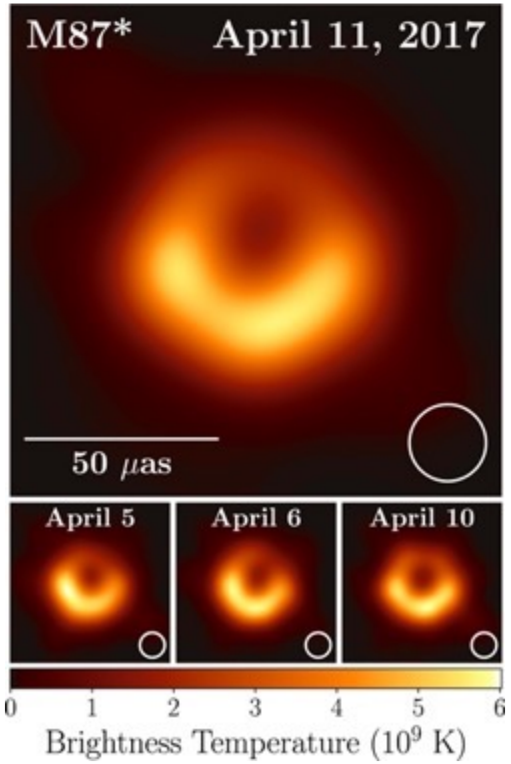
Czech TU: Jakub Jirsa, Sergei Kulkov, Michal Marcisovski

EPFL: Edoardo Charbon, Claudio Bruschini, Ermanno Bernasconi, Samuel Burri

Astronomy picture of the decade



sensitive to features on angular scale

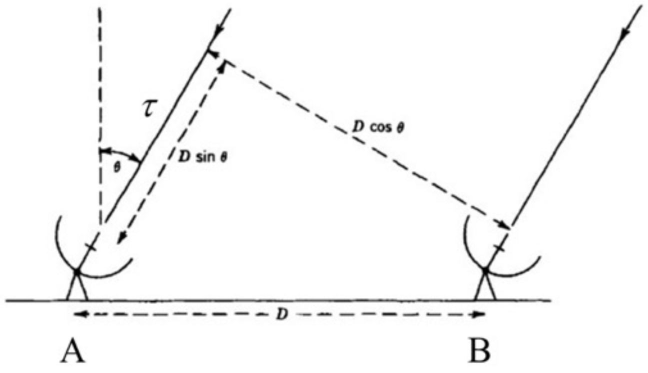
$$\Delta\theta \sim \frac{\lambda}{b}$$

2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

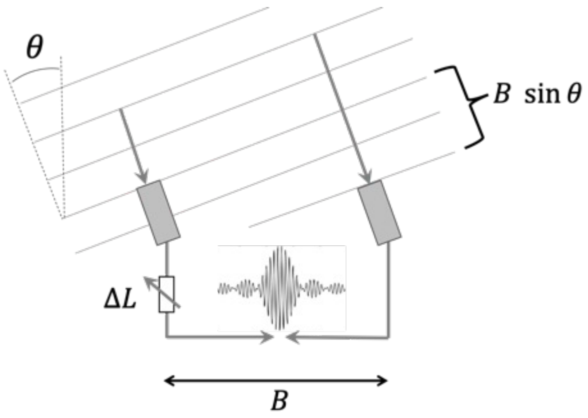
Achieved by radio interferometry with ~10000 km baselines

Radio $\bar{n} \gg 1$



Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline

$\bar{n} \ll 1$ Optical



One photon at a time! Need to bring paths to common point in real time

Need path length *compensated* to better than c/bandwidth

Need path length *stabilized* to better than λ

Accuracy ~ 1 mas

Max baselines to ~ 100 m

Two-photon techniques

Quantum Astrometry

DOE QuantISED project

- Measure photon phase difference teleporting it to another station, similar to quantum repeaters in quantum networks
- **Enables long baselines and could improve astrometrical precision by orders of magnitude**
- Great impact on astrophysics and cosmology

- Photons must be indistinguishable to interfere →

indistinguishable means: $\Delta E * \Delta t \sim h/2\pi$

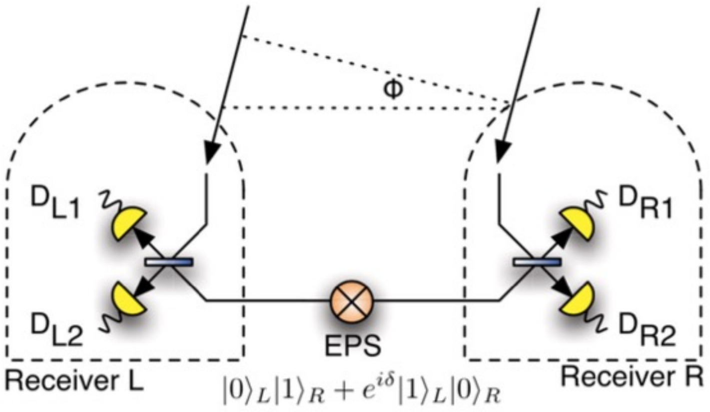
requires detectors with excellent time & spectral binning

$\Delta E * \Delta t \sim$ 0.1nm * 10ps

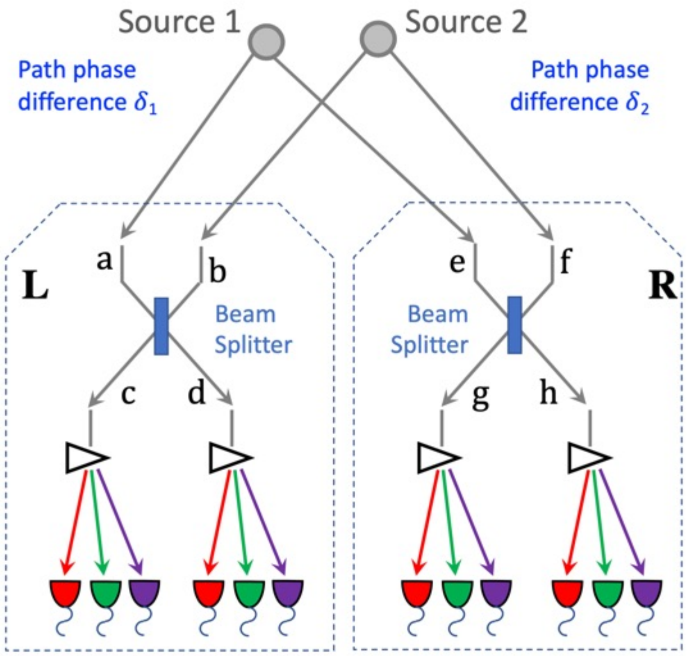
DOE QuantISED project

www.quantastro.bnl.gov

P.Stankus et al, arxiv:2010.09100
A.Nomerotski et al, arxiv:2012.02812, SPIE Proceedings
Y Zhang et al, Phys Rev A 101 (5), 053808 (2020)
P Svihra et al, Appl. Phys. Lett. **117**, 044001 (2020)
A.Nomerotski et al, arxiv: 2107.09229, TIPP Proceedings

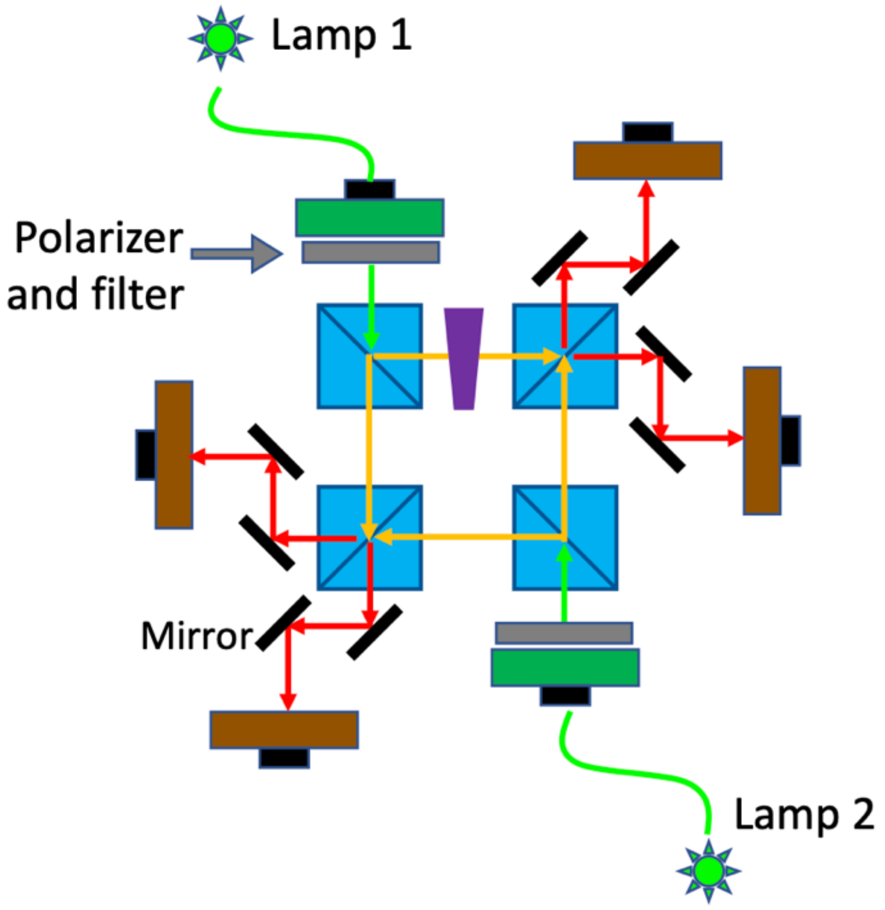


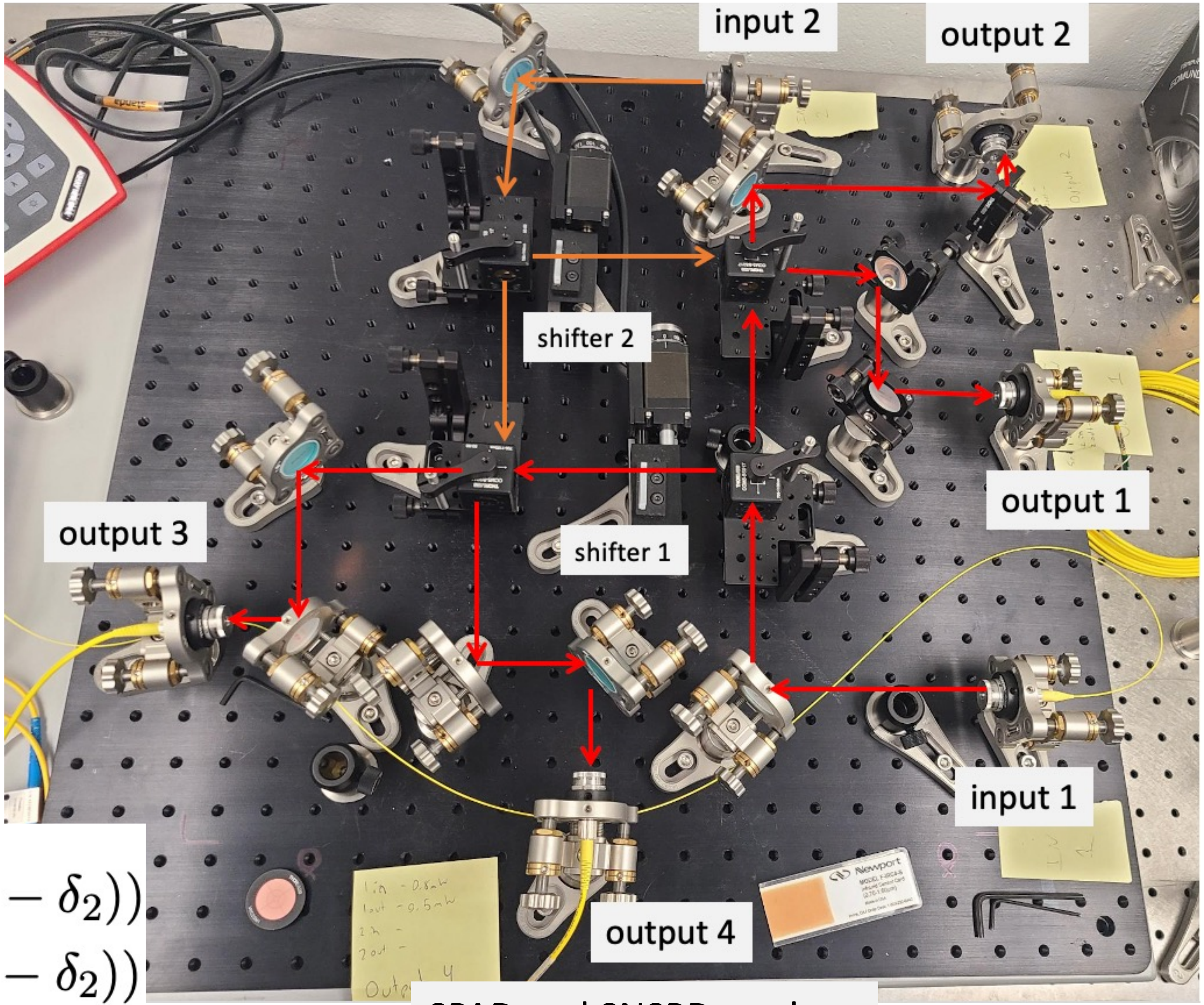
D.Gottesman et al Phys. Rev. Lett. 109, 070503 (2012)



relative phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and h

2022: benchtop verification





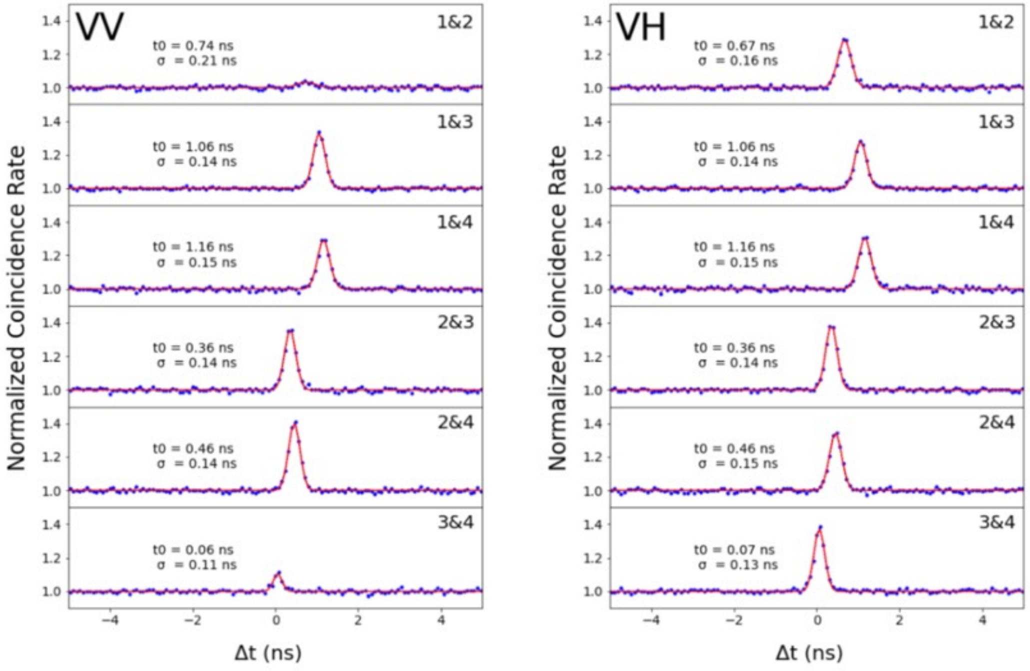
$$P(cg) = P(dh) = (1/8)(1+\cos(\delta_1-\delta_2))$$
$$P(ch) = P(dg) = (1/8)(1-\cos(\delta_1-\delta_2))$$

SPAD and SNSPD readout

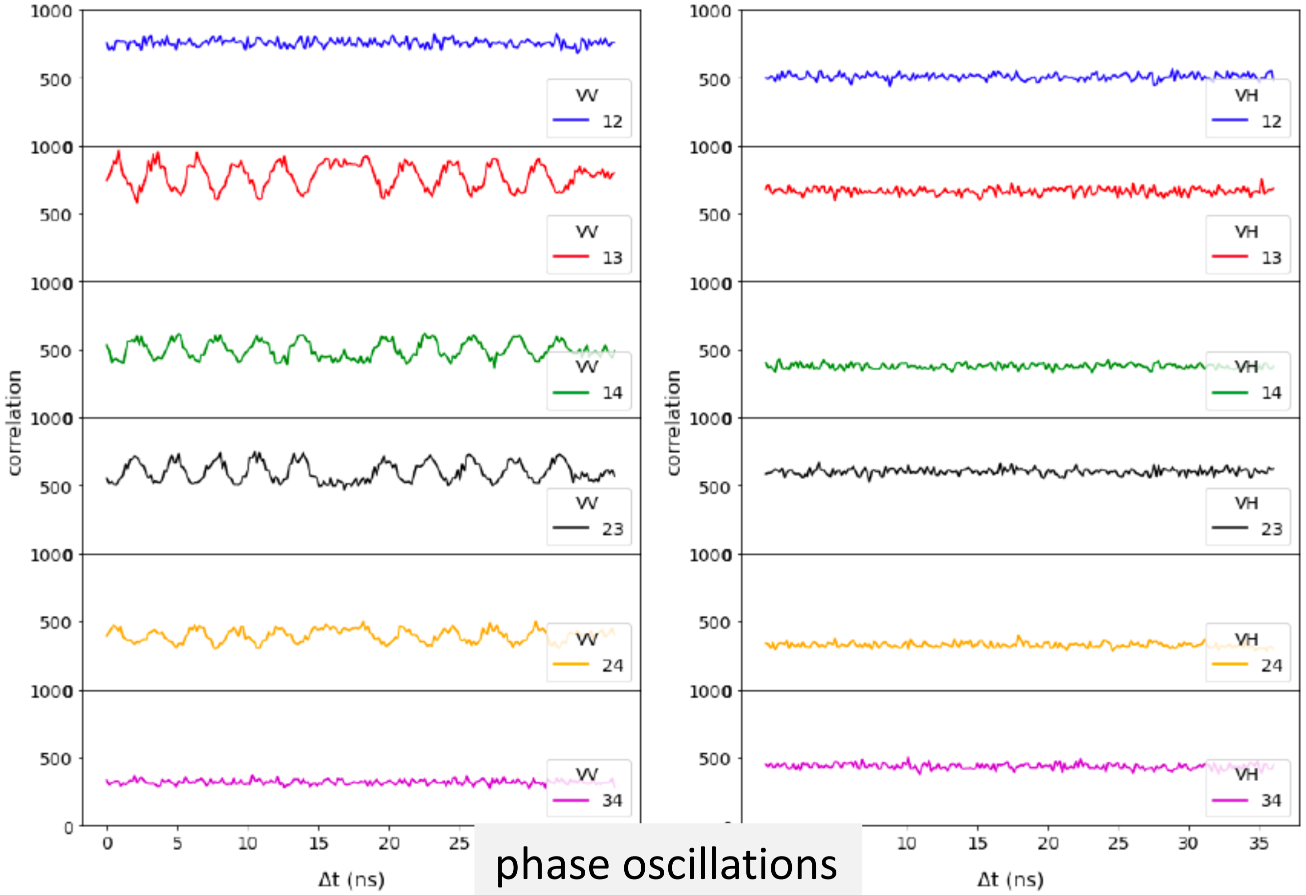
Phase dependence

- Stable setup
- See expected behavior

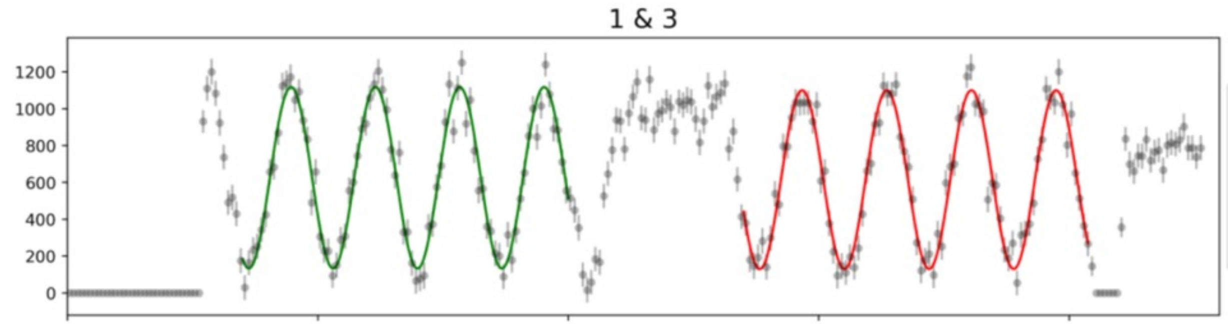
- Time resolution ~ 100 ps



HBT peaks with SNSPDs

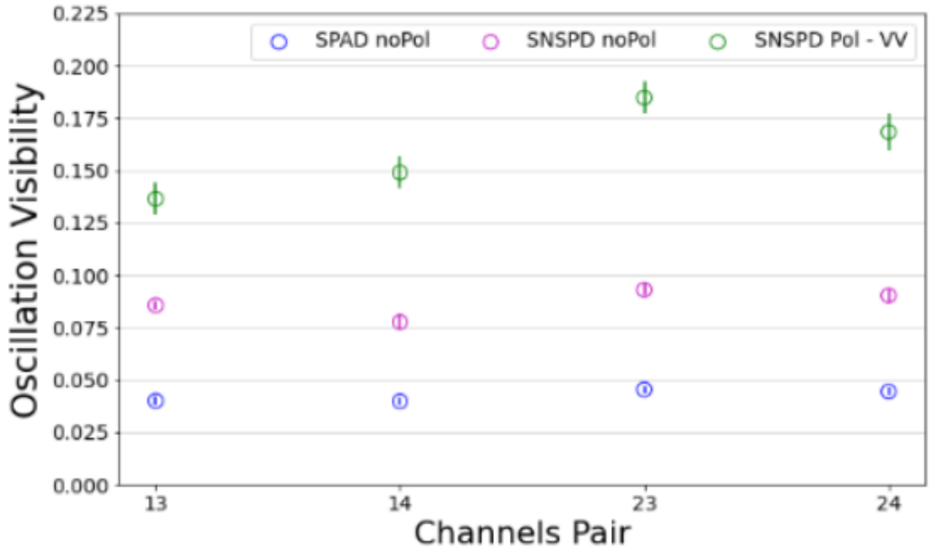


phase oscillations

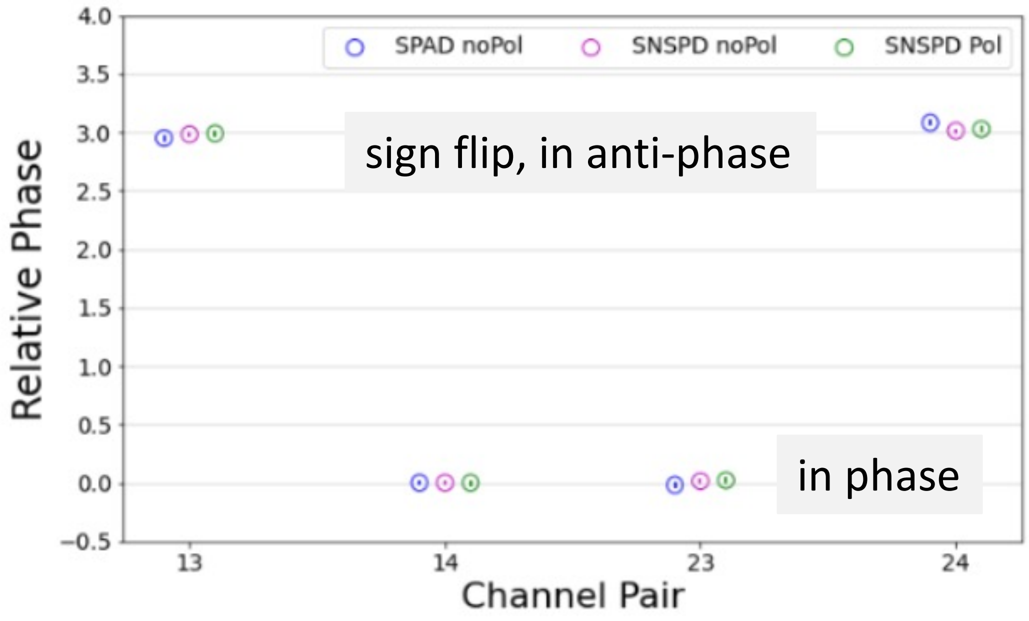


Visibility and phase

- All as expected
- Paper in preparation

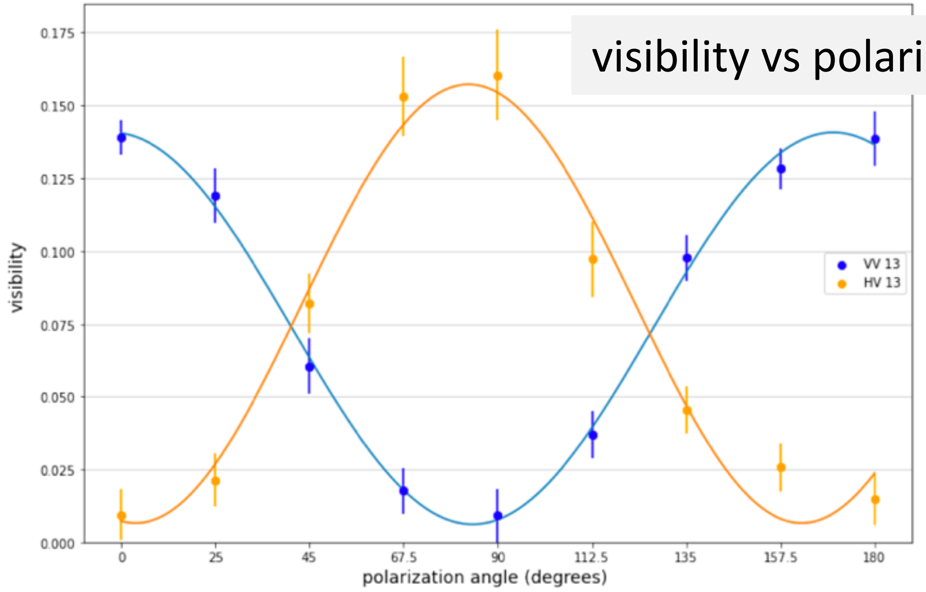


visibility



sign flip, in anti-phase

in phase



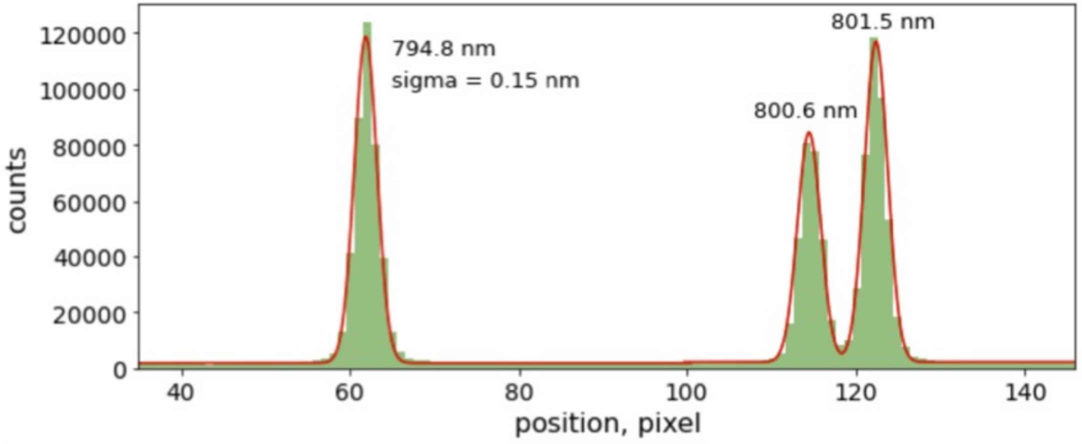
visibility vs polarization

Next step: spectral binning

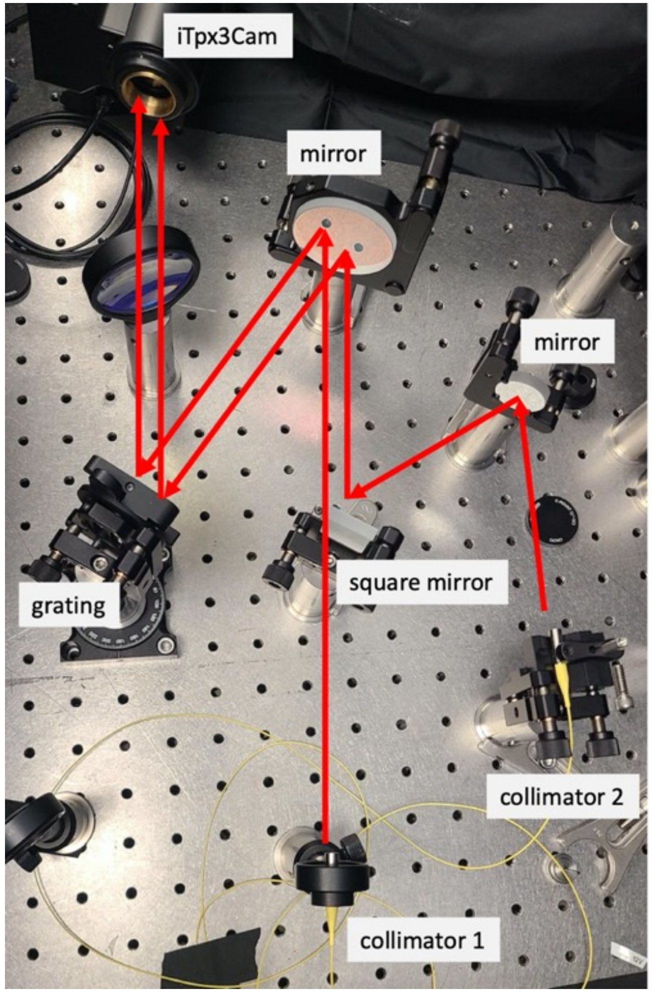
Spectral binning

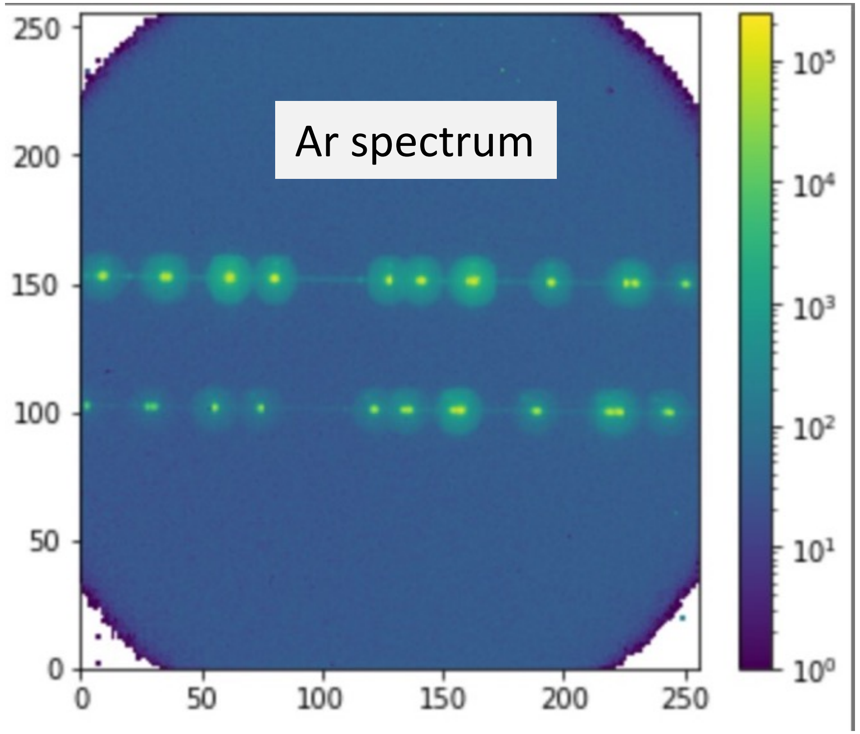
Two beams → diffraction grating

Based on intensified Tpx3Cam, ns time resolution



spectral resolution for Ar lines ~0.15 nm

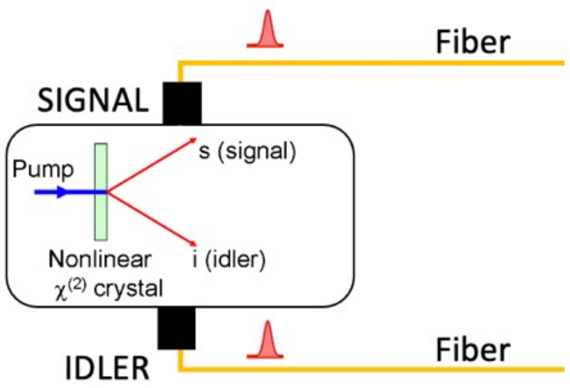




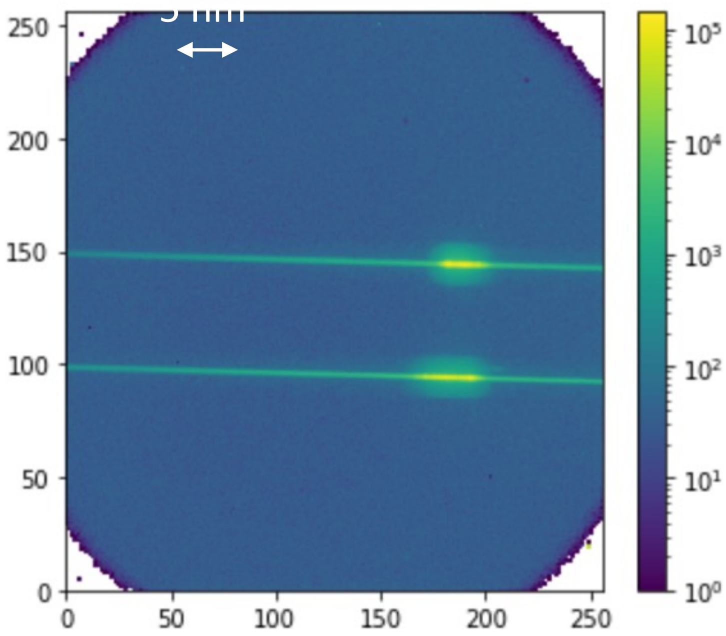
A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, accepted to JINST

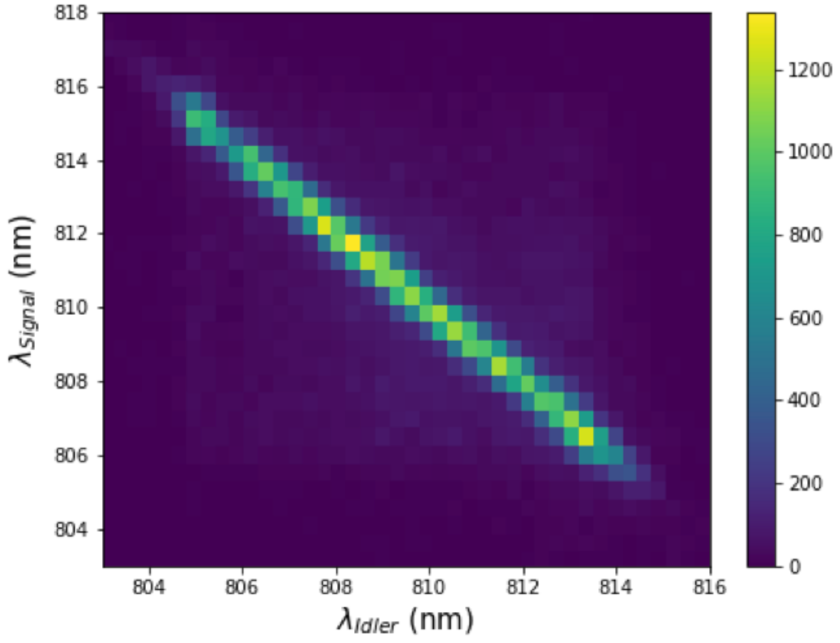
SPDC source in spectrometer

- 810 nm idler and signal
- no filter

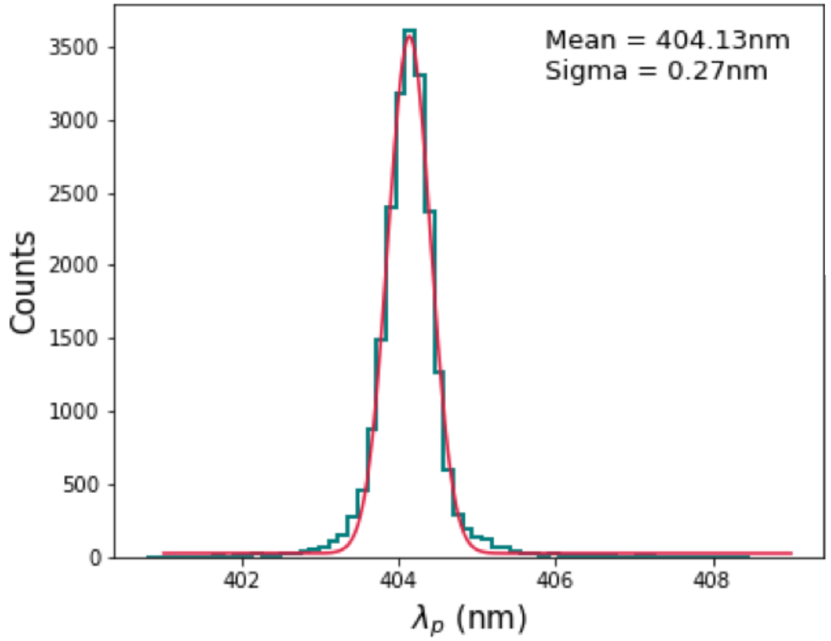


signal & idler in spectrometer

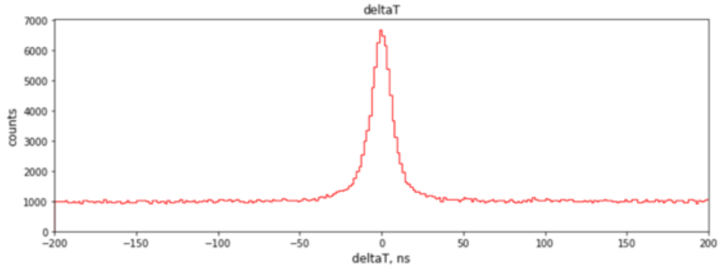




wavelength anti-correlation for photon pairs

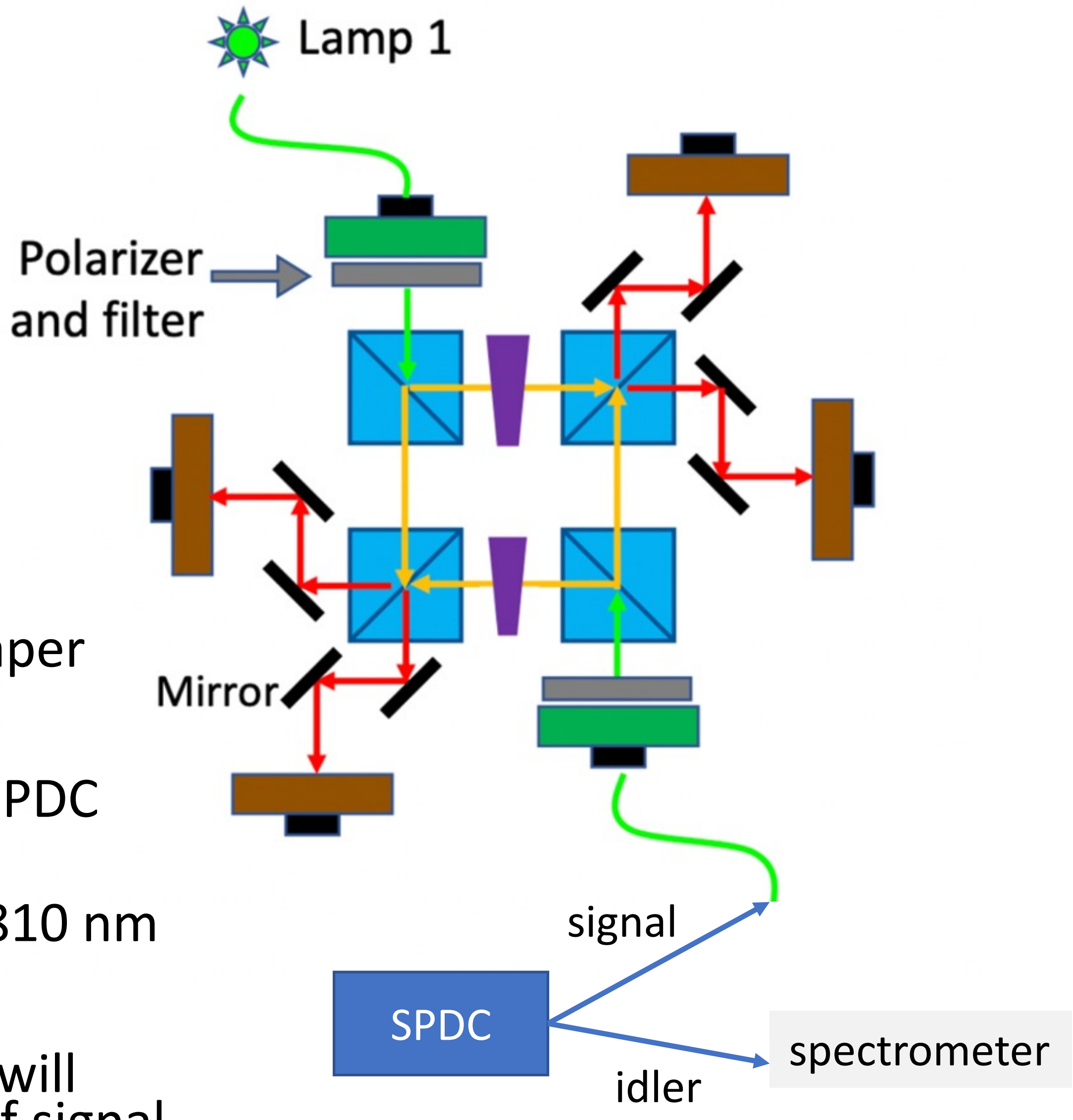


pump wavelength



time coincidences

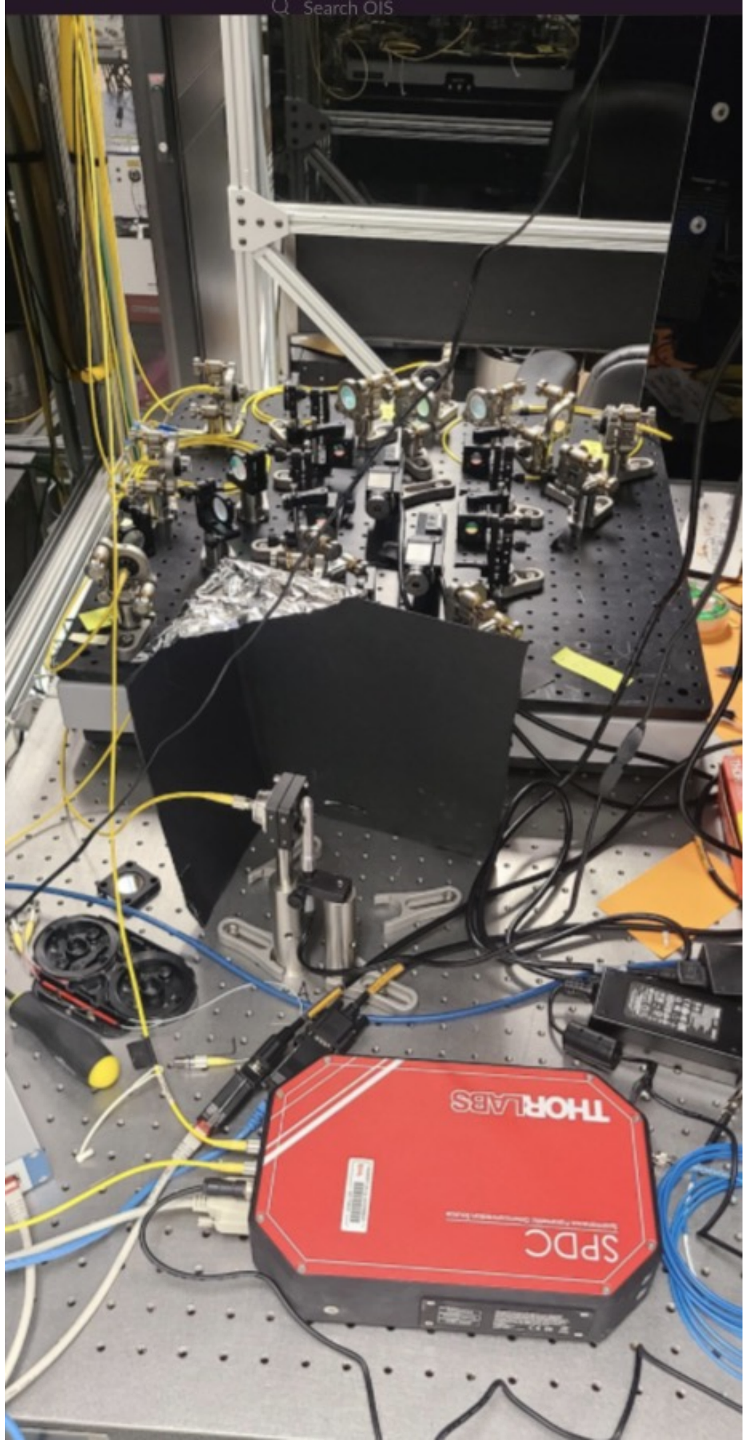
Adding SPDC instead of one lamp



- As in original GJC2012 paper

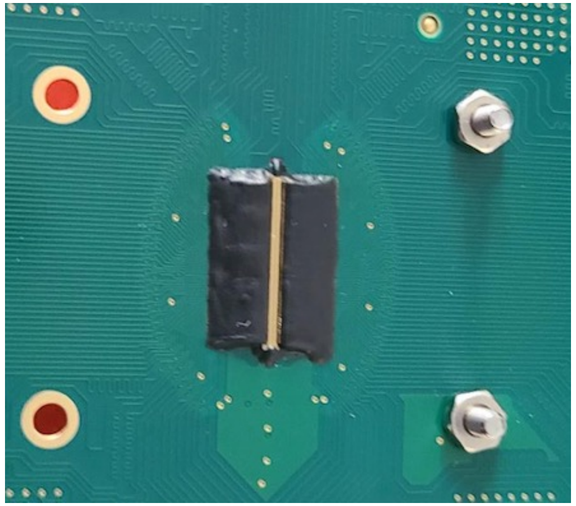
- one Ar lamp + Thorlabs SPDC source
- Thorlabs source 1 MHz, 810 nm

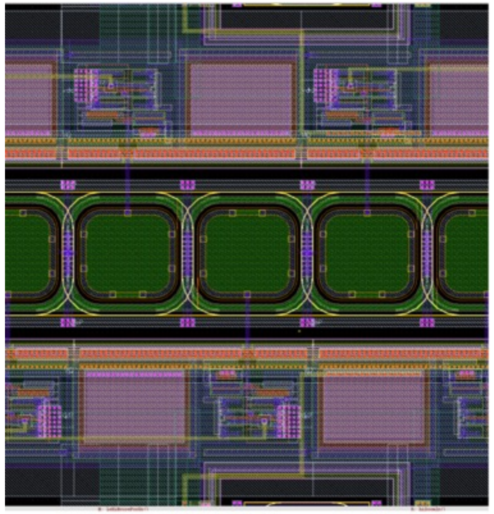
- Spectral analysis of idler will post-select wavelength of signal photon



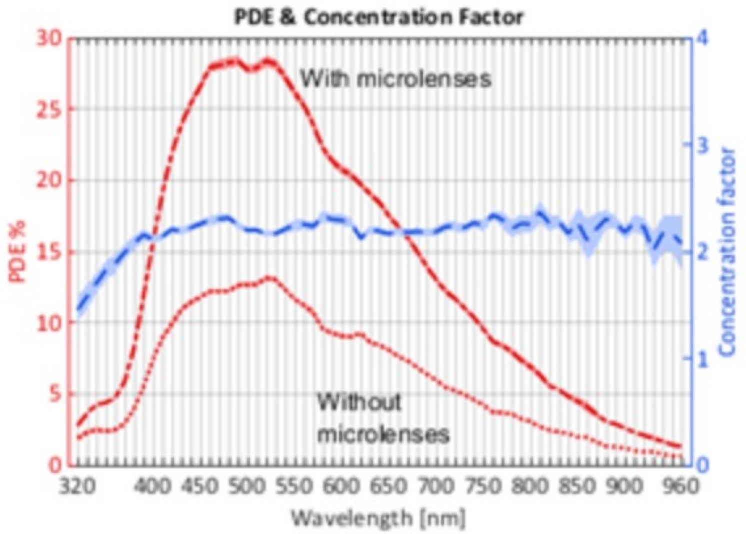
LinoSPAD2 linear SPAD array

- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- Fill factor ~ 40%
- DCR ~ 30 Hz /pix @ room T
- Deadtime ~ 100ns
- Asynchronous readout of pixels



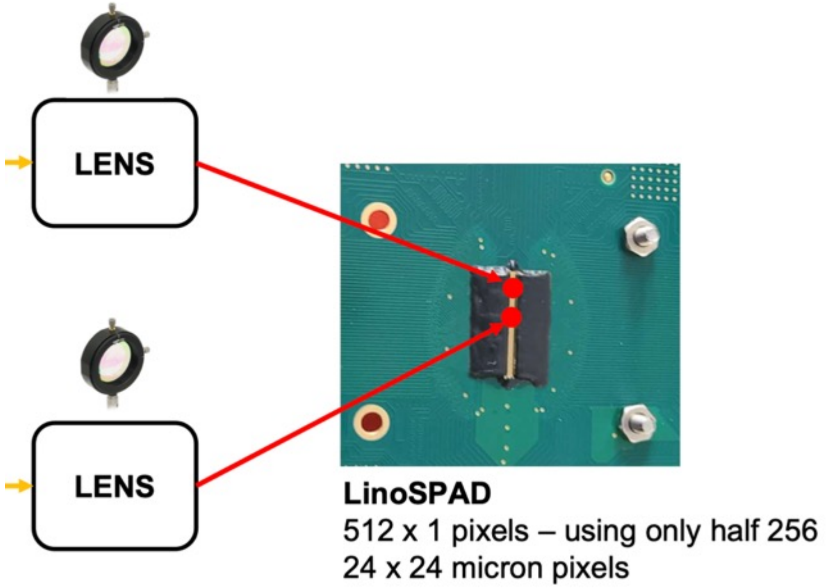


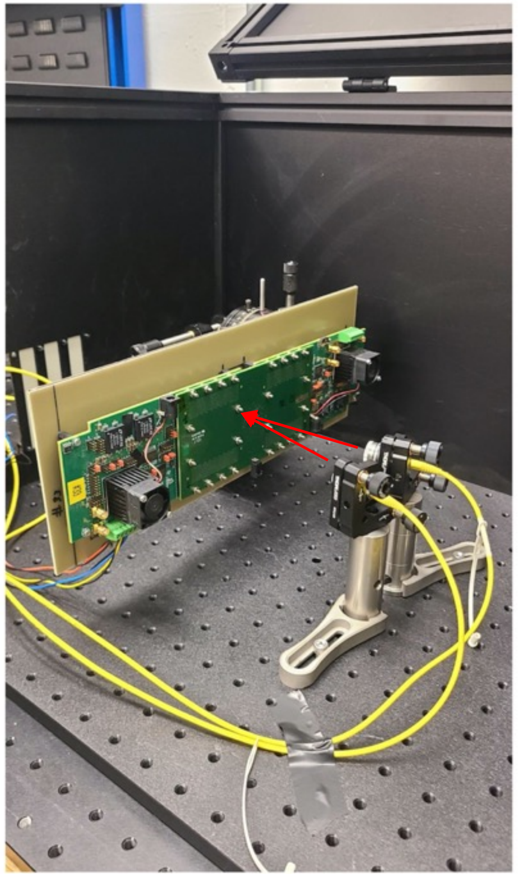
Close-up of SPADs

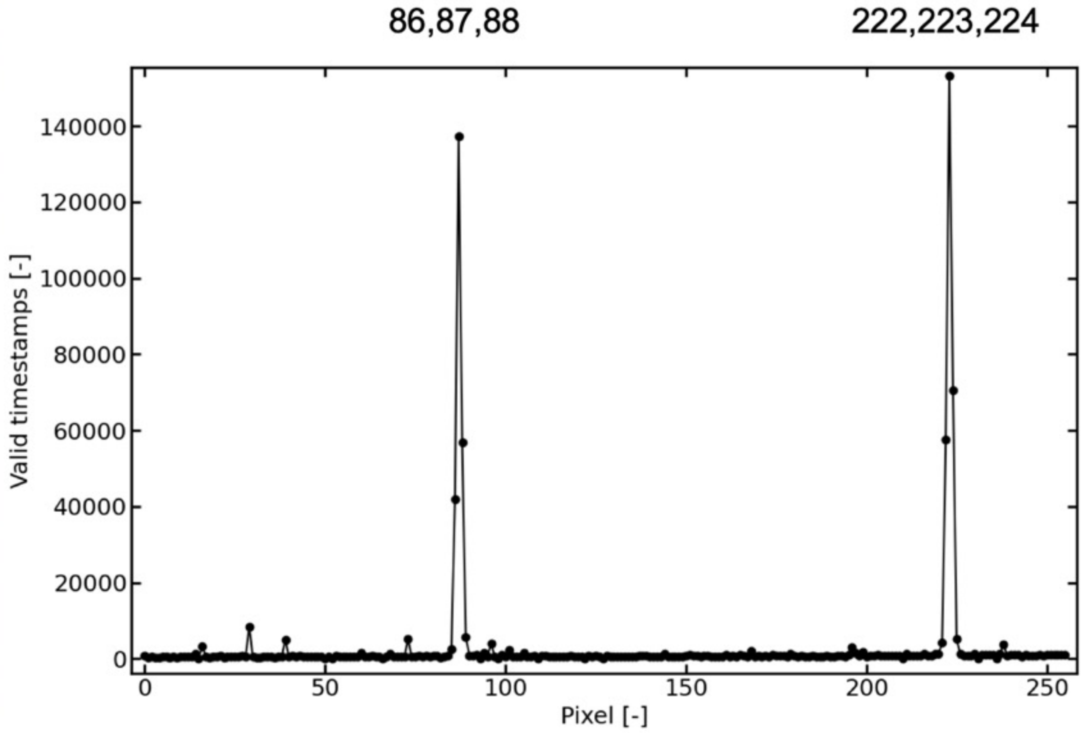


Developed by AQUA group in EPFL (Switzerland)
E.Charbon et al

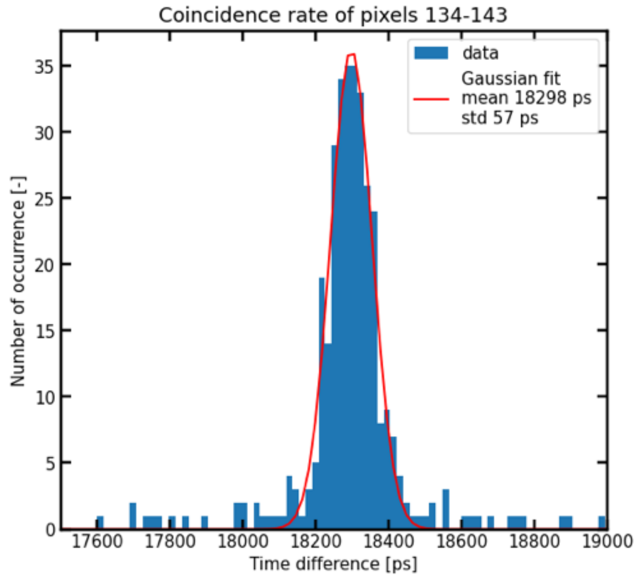
SPAD arrays with 50 ps resolution







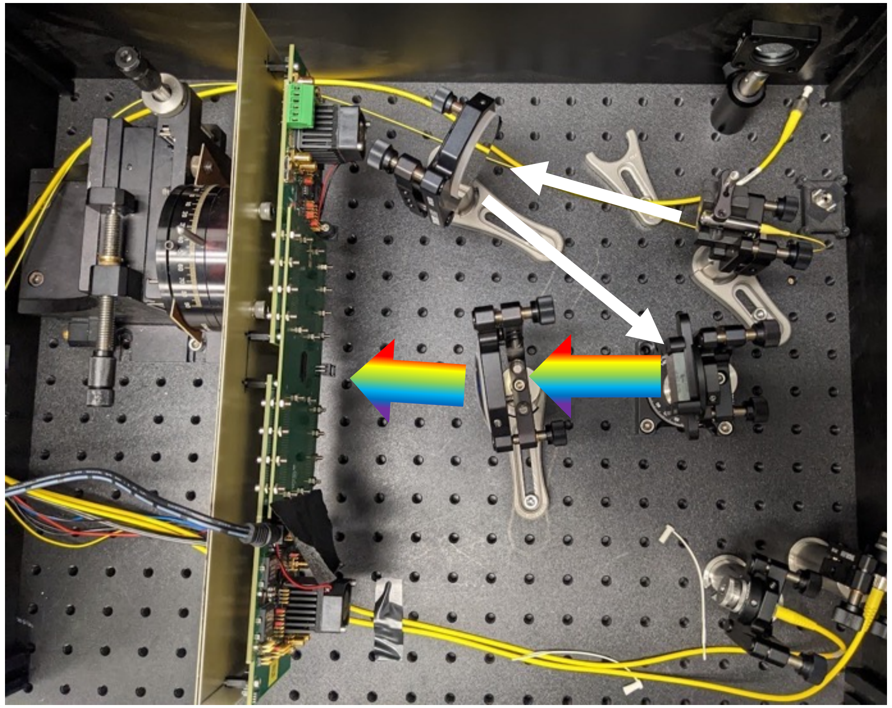
Two beams from SPDC source

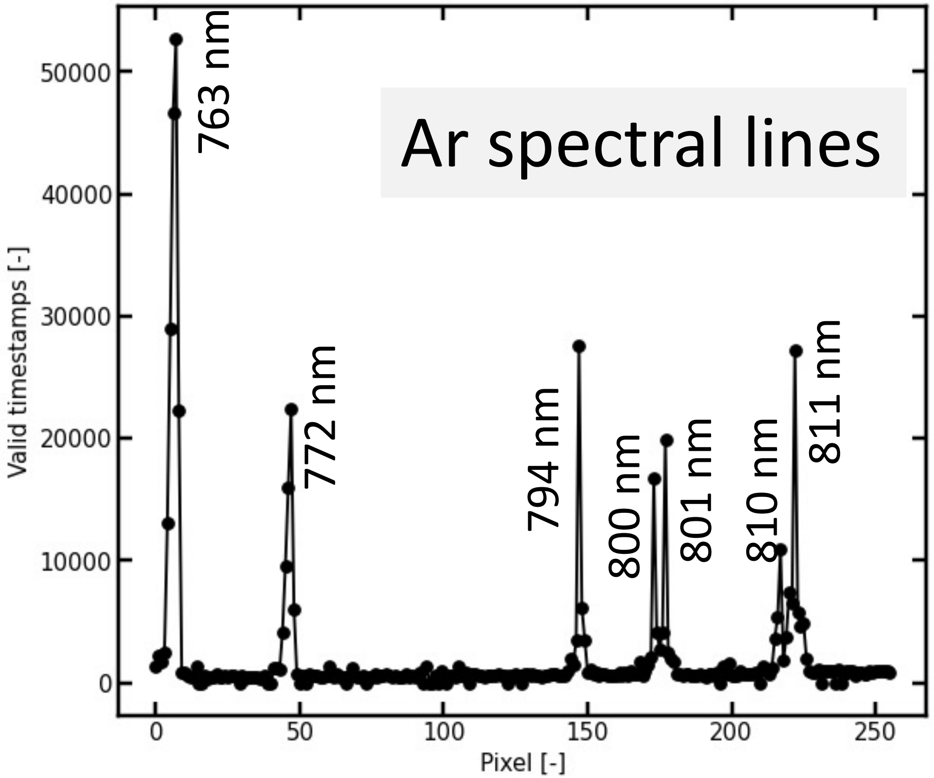


time difference, σ=57 ps

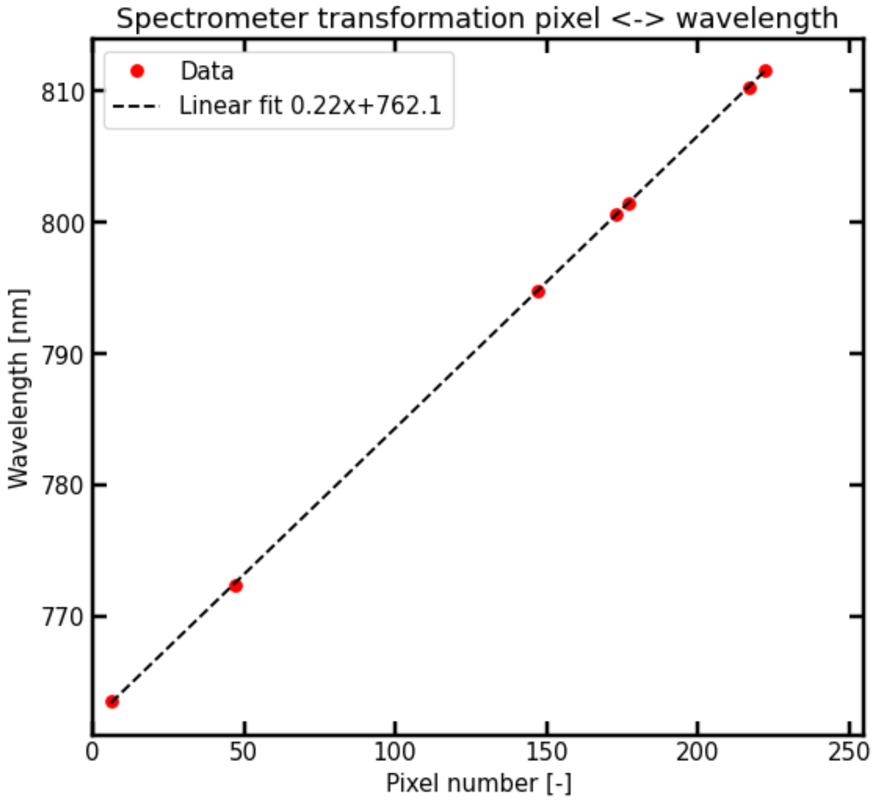
Spectrometer with LinoSPAD2 (1)

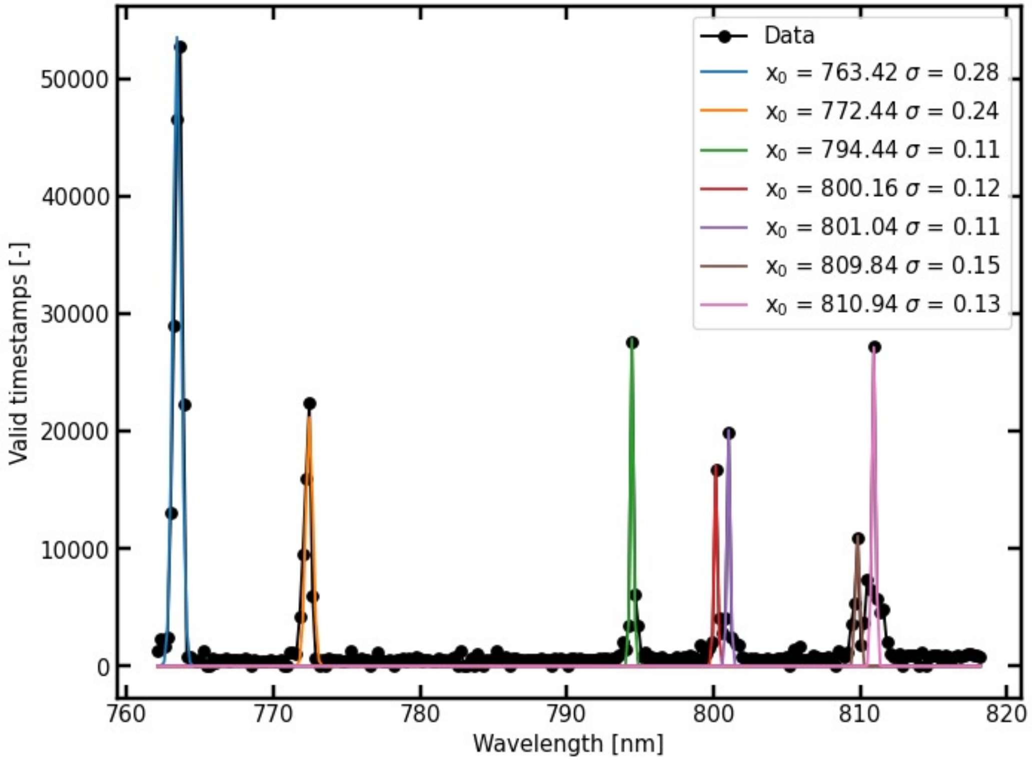
Used Ar lamp coupled to SM fiber





Spectrometer with LinoSPAD2 (2)



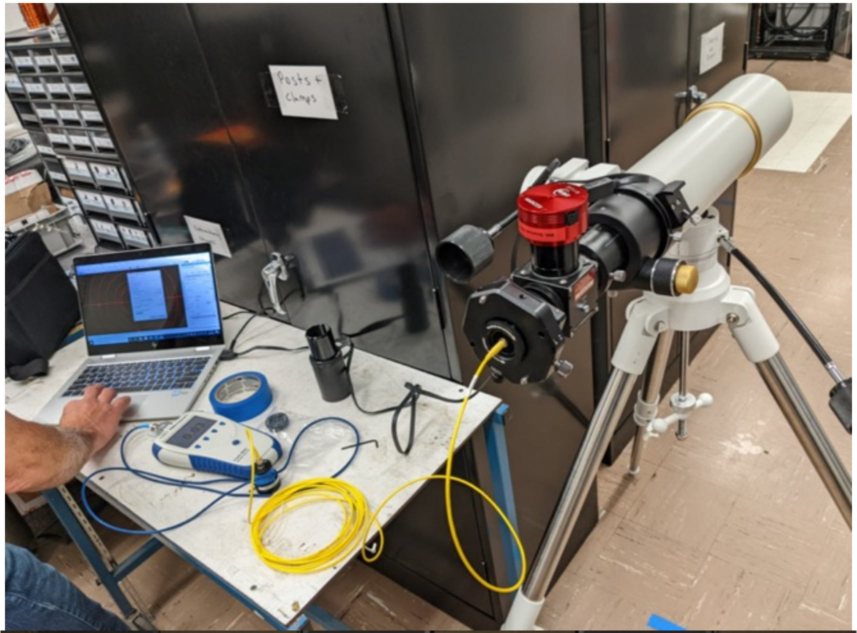


Achieved 0.1 nm spectral and 50 ps timing resolution

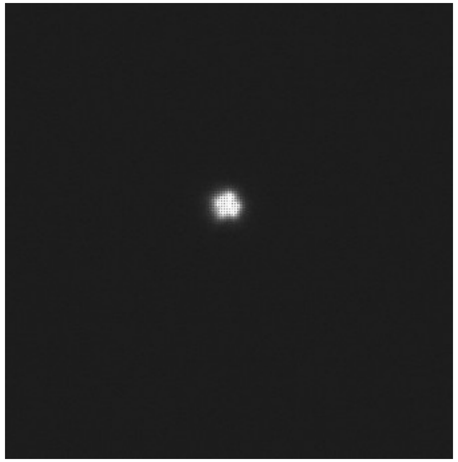
Next: demonstrate HBT peaks (photon bunching) for spectral binning

On-sky measurements

- Experimenting with SM fiber coupling
- Trying adaptive optics



with active participation of BNL & SBU



Summary and outlook

- Demonstrated the idea of quantum telescopes on the bench, closing in on required instrument parameters

- Collaborative effort: BNL, SBU, U Oregon, U Illinois, SCSU, EPFL, Czech TU, NRC Ottawa
- Quantum Telescopes: one day workshop in June 2023
  - Companion meeting at Quantum 2.0 in Denver CO

- Next: sky observations, demonstration of the original idea with stars

- To be sensitive to faint sources
  - Need high intensity entangled photon sources
  - Need quantum repeaters and memories

Synergy with quantum internet roadmap

P.Stankus et al, arxiv:2010.09100
A.Nomerotski et al, arxiv:2012.02812, SPIE Proceedings
Y Zhang et al, Phys Rev A 101 (5), 053808 (2020)
P Svihra et al, Appl. Phys. Lett. **117**, 044001 (2020)
A.Nomerotski et al, arxiv: 2107.09229, TIPP Proceedings

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