Fast Two-Photon Interferometer Capable of Spectral Binning for Quantum Telescopy

Andrei Nomerotski, BNL

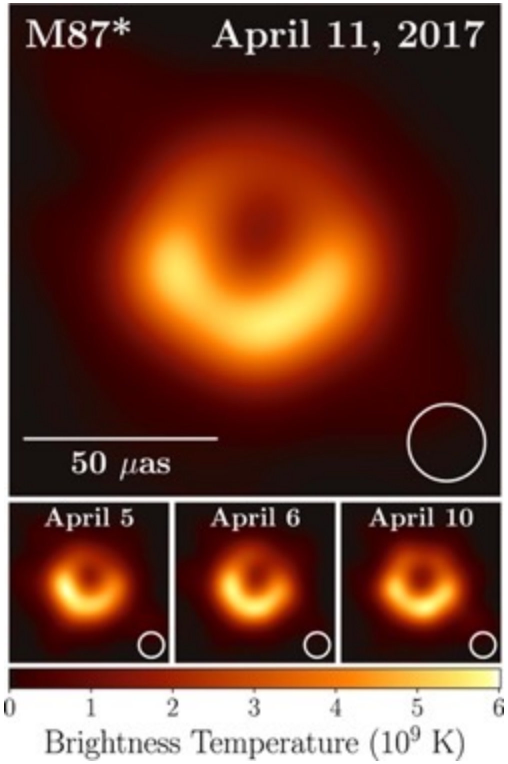
with Paul Stankus, Anze Slosar, Stephen Vintskevich, Raphael Abrahao, Jesse Crawford, Sergei Kulkov, Jakub Jirsa, Steve Bellavia, Michael Keach, Justine Haupt, Edoardo Charbon, Claudio Bruschini, Ermanno Bernasconi, Michal Marčišovský, Aaron Mueninghoff, Brianna Farella, Julian Martinez-Rincon et al

Optica Quantum 2.0 Conference and Exhibition

18 – 22 June 2023
Hybrid Event - Mountain Daylight/Summer Time (UTC - 06:00)

Hyatt Regency Denver at Colorado Convention Center
Denver, Colorado United States

Astronomy picture of the decade



2019 ApJL 875

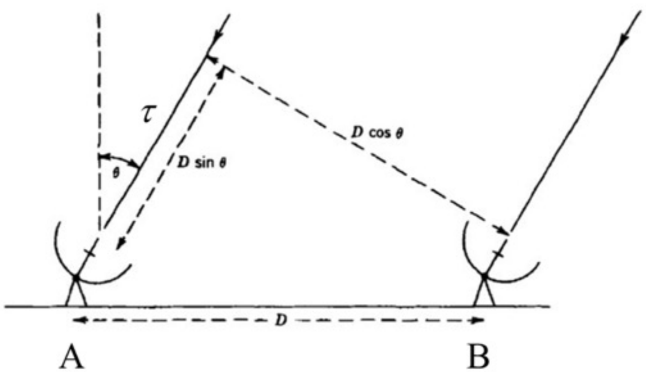
sensitive to features on angular scale

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

Black hole in the center of M87 imaged at 1.3mm

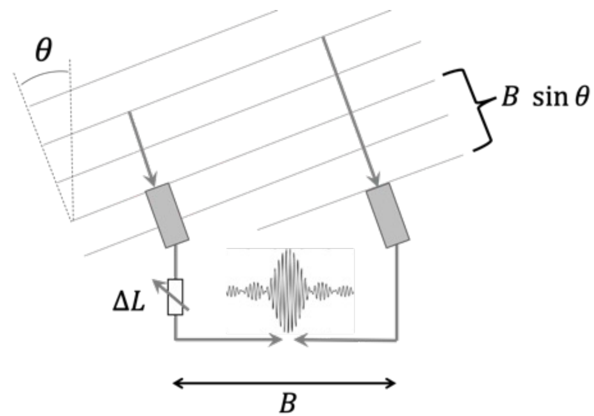
Achieved by radio interferometry with ~10000 km baselines

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

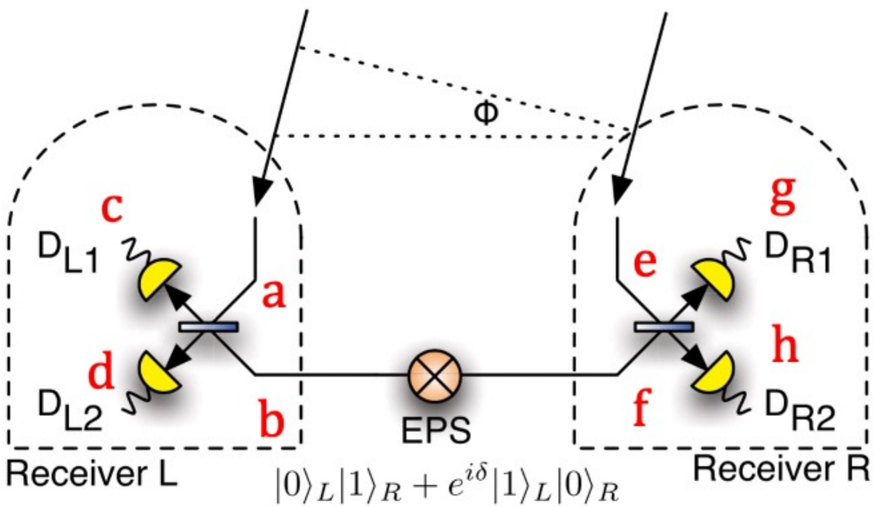
Accuracy ~ 1 mas

Max baselines to ~ 100 m

Two-photon techniques

Second photon for quantum assist

Quantum (two-photon) interferometer



PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

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(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

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

- Distribute path entangled photons
- Use photon counting

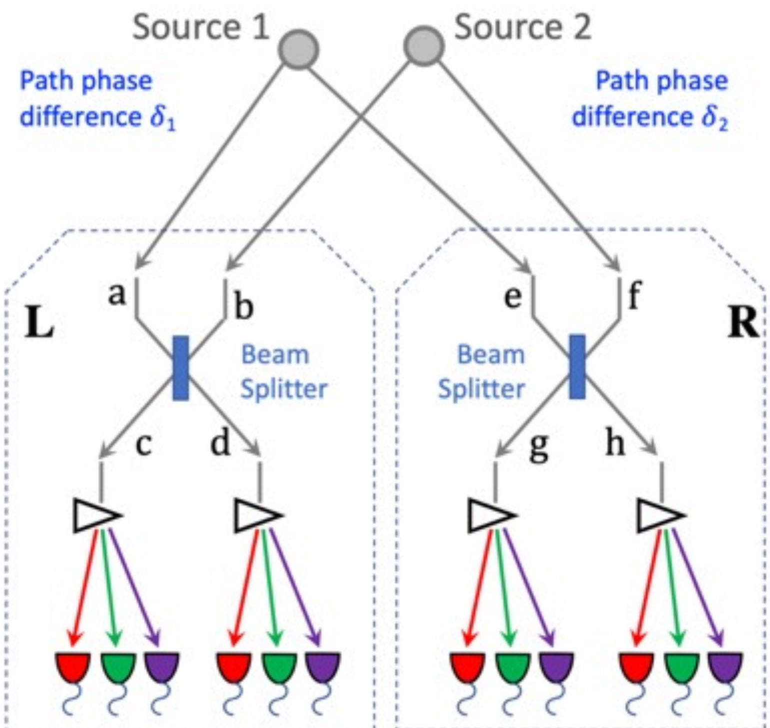
→ coincidences are sensitive to phase!

P(c g) = P(d h) = 1/8 (1 + cos(δ–φ))
P(c h) = P(d g) = 1/8 (1 - cos(δ–φ))

- Transfer the photon quantum state → can use quantum networks, this will allow long distances
- Enables long baselines and could improve astrometric precision by orders of magnitude
- Major impact on astrophysics and cosmology

Quantum Astrometry

Idea: use another star as source of coherent states for the interference



$$\begin{aligned} P(c^2) = P(d^2) = P(g^2) = P(h^2) &= 1/8 \\ P(cg) = P(dh) &= (1/8)(1+\cos(\delta_1 - \delta_2)) \\ P(ch) = P(dg) &= (1/8)(1-\cos(\delta_1 - \delta_2)) \end{aligned}$$

Full QFT calculation

$$N_c(xy) = \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

Rates HBT

$$A^2 \eta_1 \eta_2 T_r \left[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm \right.$$

$$\left. 2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B (\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right] \quad (30)$$

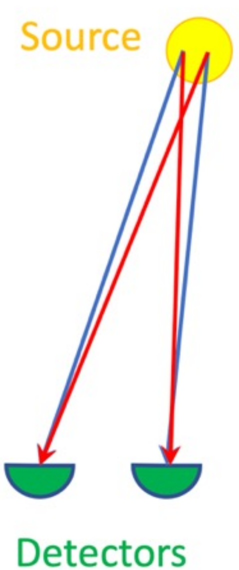
New oscillatory term!

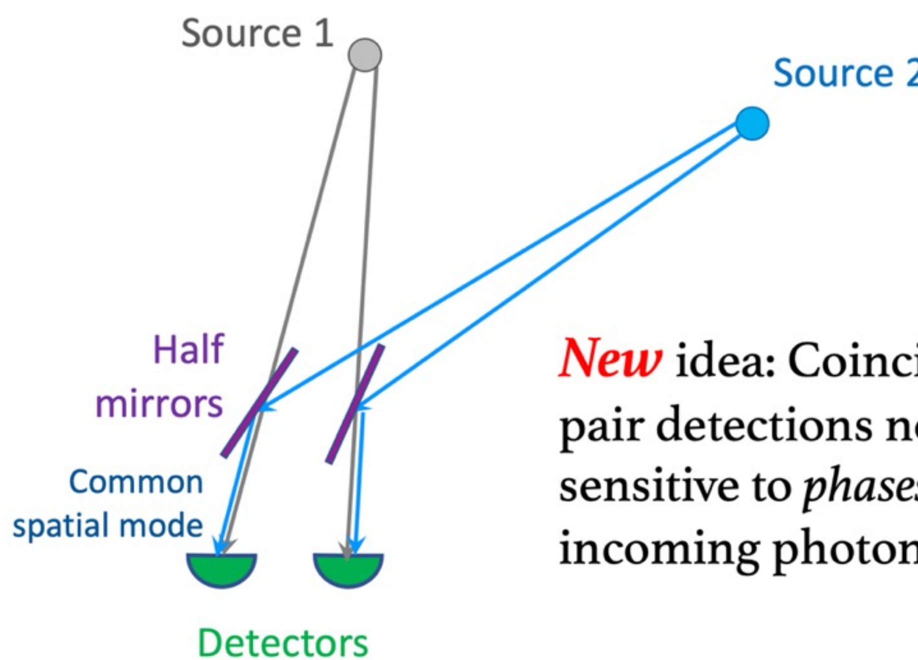
- Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and h
- Can provide 10 microarcsec resolution for bright stars https://arxiv.org/abs/2010.09100
- Perfect to start exploring this approach - no quantum sources, no connection between stations, otherwise same instrumentation

Hanbury Brown – Twiss Intensity Interferometry

Our technique can be considered as extension of standard SII

HBT with two separated sources





New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Possible impact on astrophysics and cosmology

https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder (Dark Energy)
- Proper star motions (Dark Matter)
- Microlensing, see shape changes (Dark Matter)

- Black hole imaging
- Gravitational waves in μHz – nHz: coherent motions of stars
- Exoplanets

Requirements for detectors

- Photons must be close enough in frequency and time to interfere → **temporal & spectral binning**: need ~ 0.01 nm * 20 ps

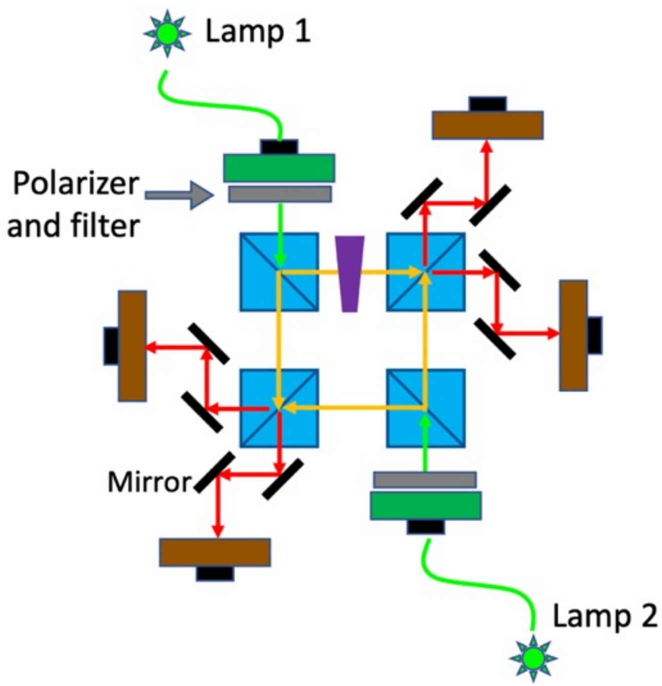
- Fast imaging techniques are the key
  - Several promising technologies: **SPADs** & SNSPDs

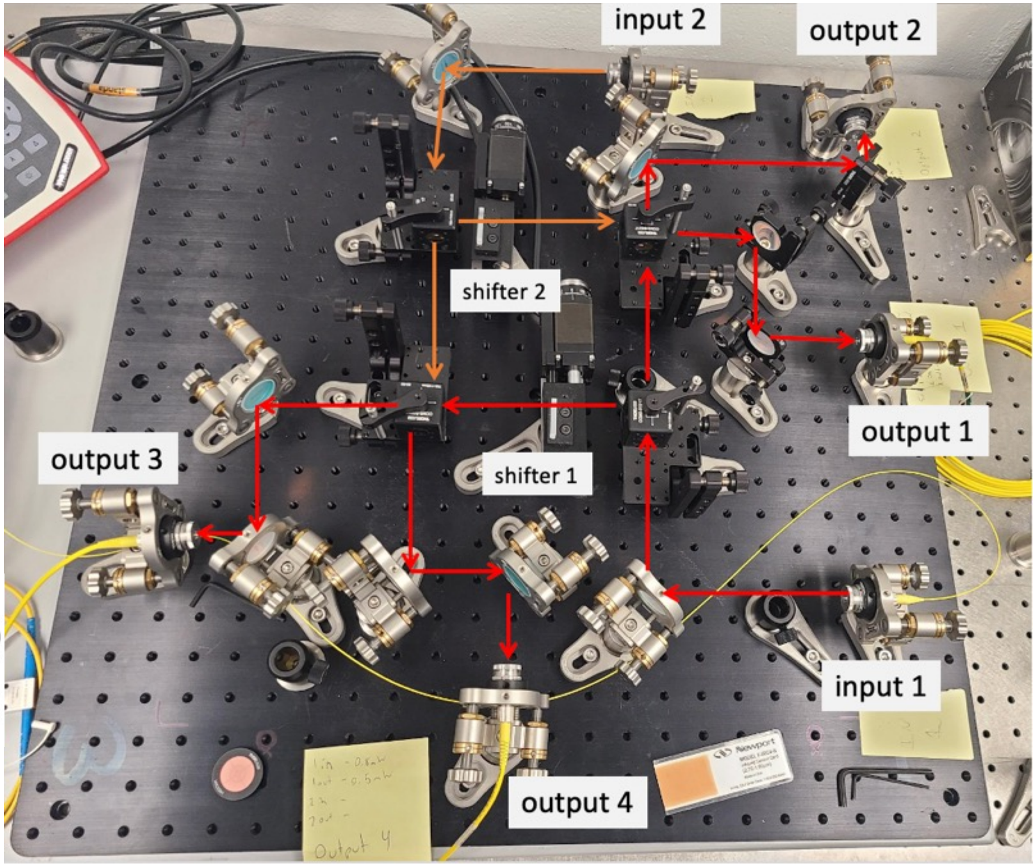
- Spectral binning: diffraction gratings, echelle spectrometers

- High photon detection efficiency

Bench-top model of two-photon interferometry

- Use 794 nm Ar line
- SPAD and SNSPD readout

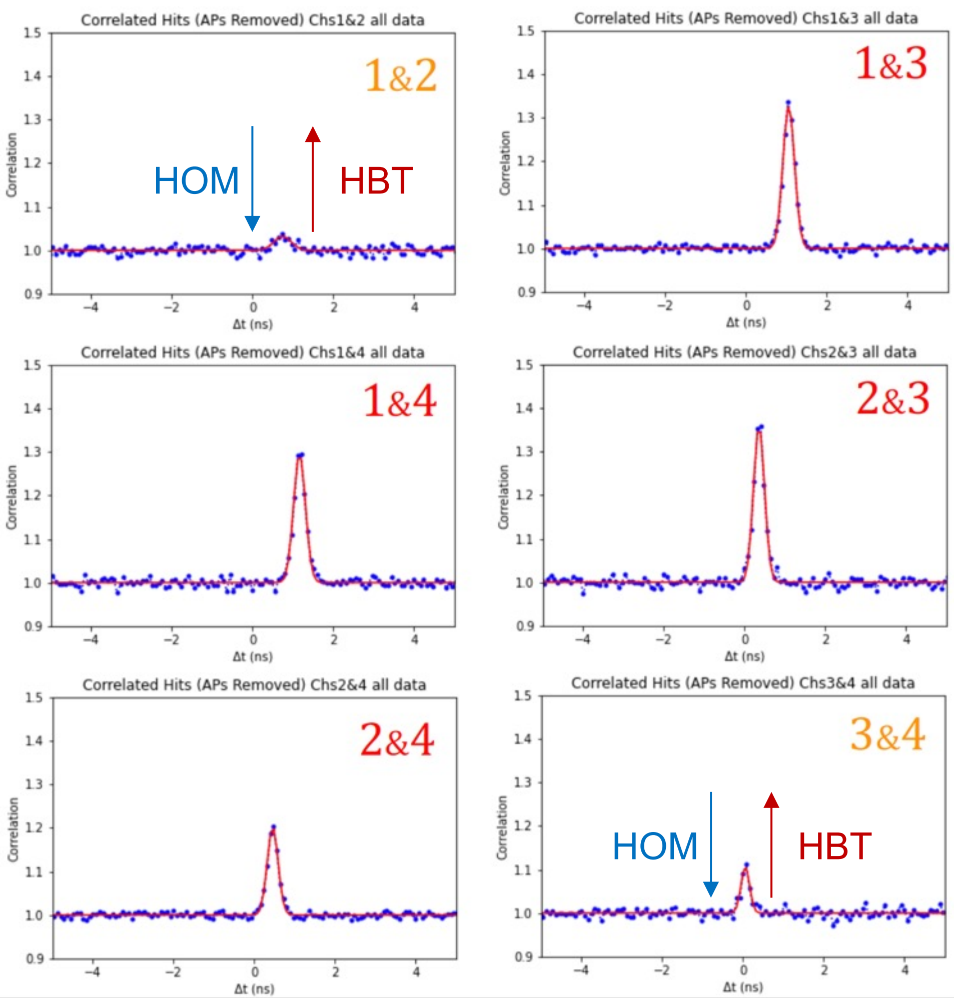


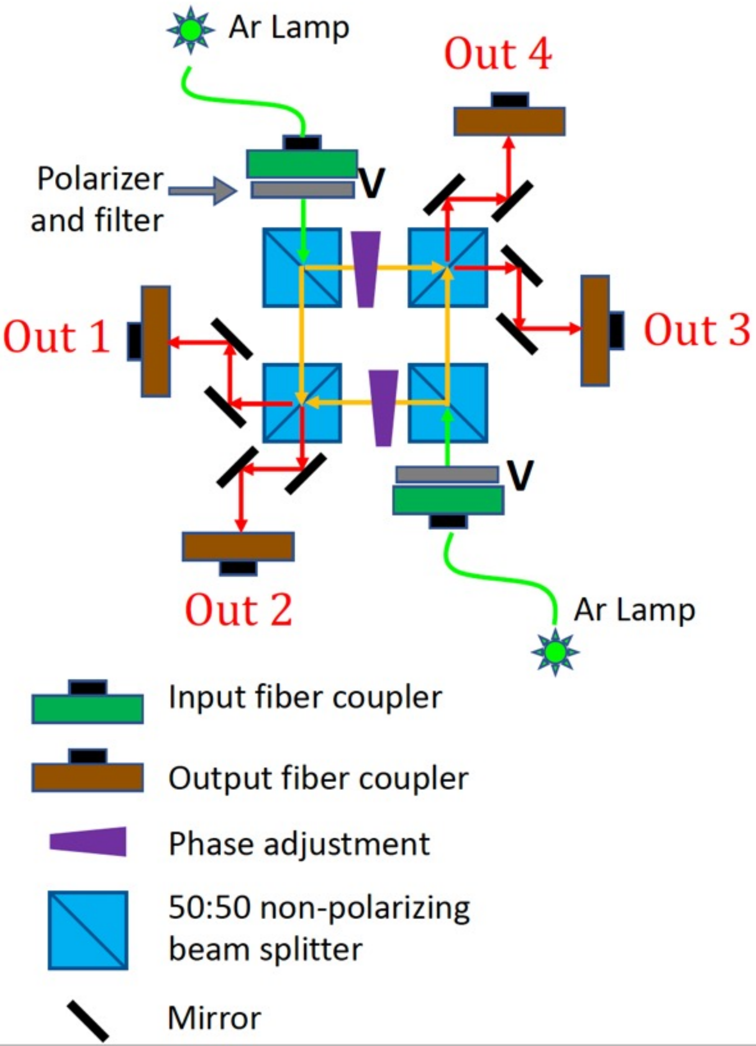


$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

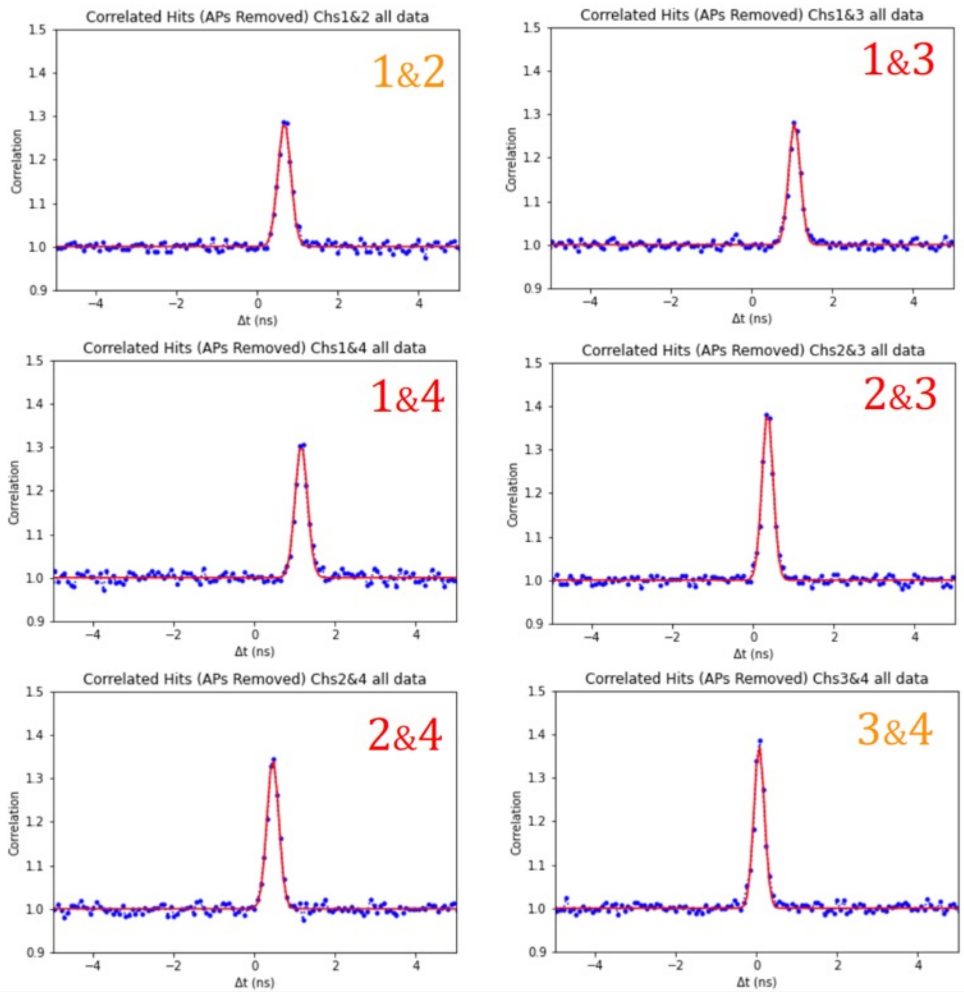
arxiv.org/abs/2301.07042

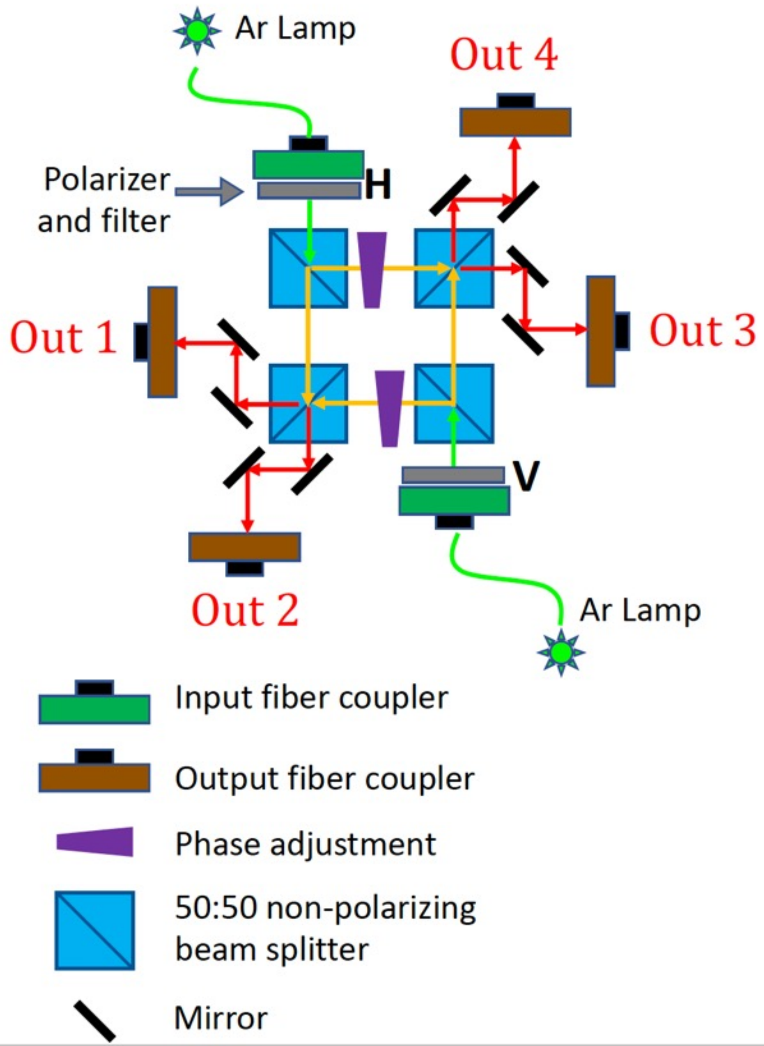
Polarized – V V



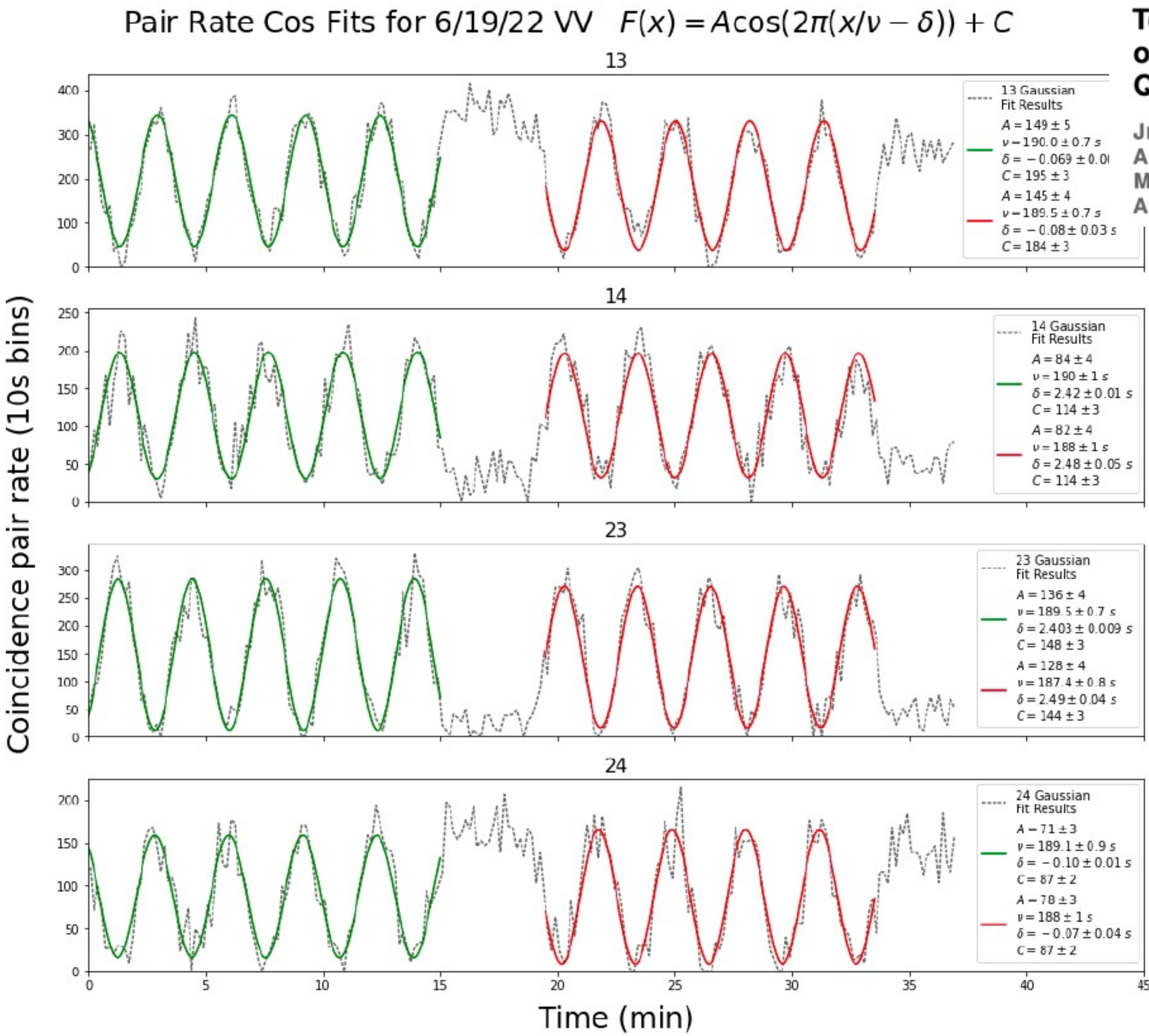


Polarized – V H





Phase dependence



phase oscillations confirmed!

Towards Quantum Telescopes: Demonstration of a Two-Photon Interferometer for Quantum-Assisted Astronomy

Jesse Crawford [A], Denis Dolzhenko [A], Michael Keach [A], Aaron Mueninghoff [B], Raphael A. Abrahao [A], Julian Martinez-Rincon [A], Paul Stankus [A], Stephen Vintskevich[C], Andrei Nomerotski [A]

arxiv.org/abs/2301.07042

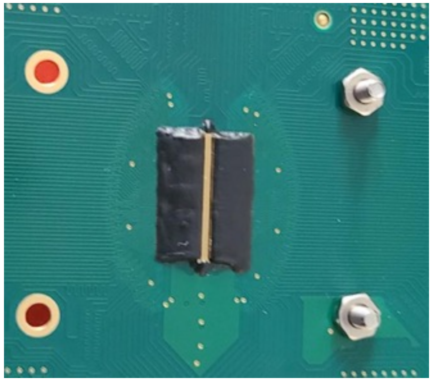
Next:

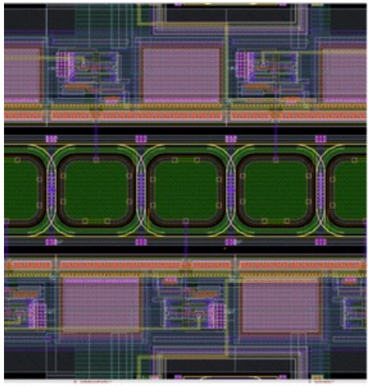
Replace one Ar lamp with SPDC source

Next step: 50 ps timing resolution

LinoSPAD2 linear SPAD array

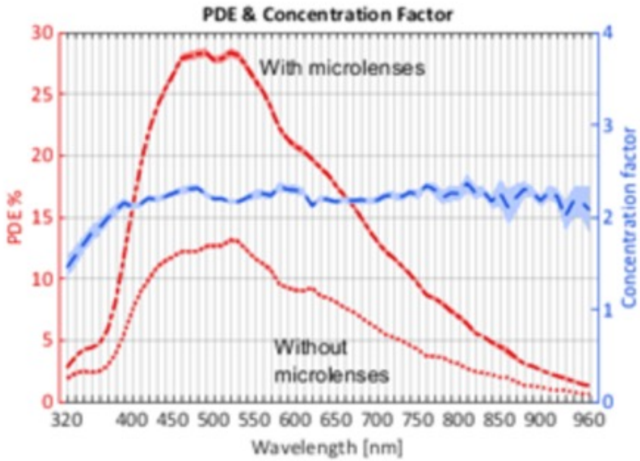
SPAD = single photon avalanche device
p-n junction with amplification





Close-up of SPADs

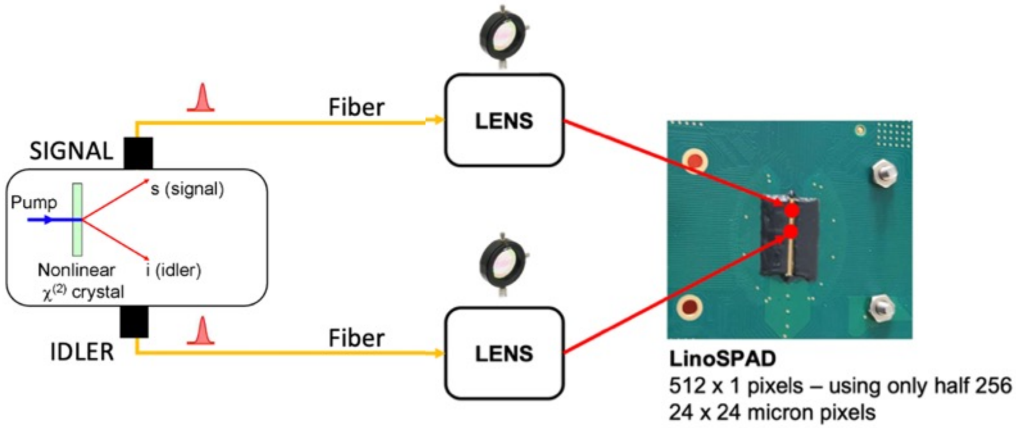
- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- Fill factor ~ 40%
- DCR ~ 30 Hz /pix @ room T
- Deadtime ~ 100ns
- Asynchronous readout of pixels

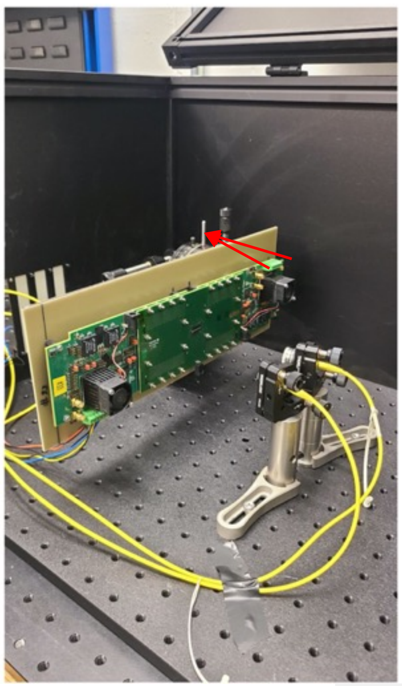


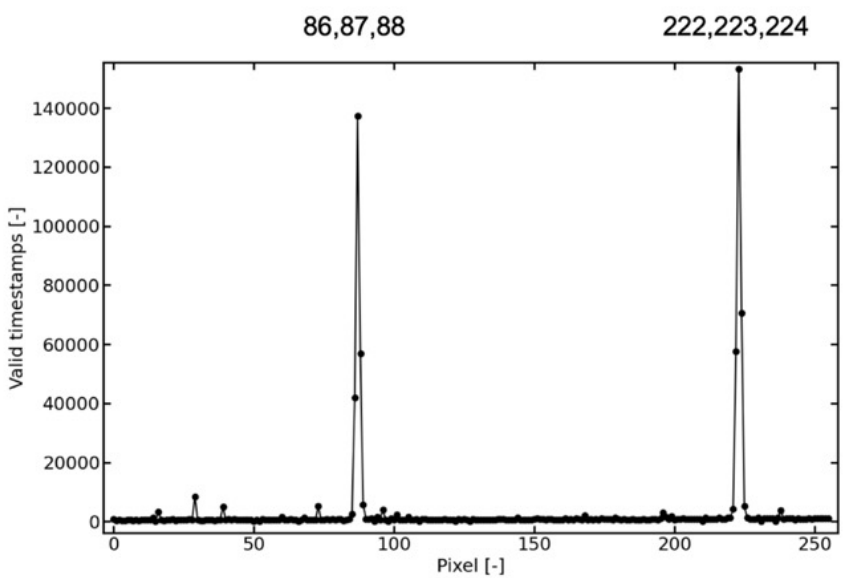
Developed by AQUA group in EPFL (Switzerland) E.Charbon et al

C. Bruschini, S. Burri, E. Bernasconi, T. Milanese, A. C. Ulku, H. Homulle, and E. Charbon, Linospad2: a 512x1 linear spad camera with system-level 135-ps sptr and a reconfigurable computational engine for time-resolved single-photon imaging, in *Quantum Sensing and Nano Electronics and Photonics XIX*, Vol. 12430 (SPIE, 2023) pp. 126–135.

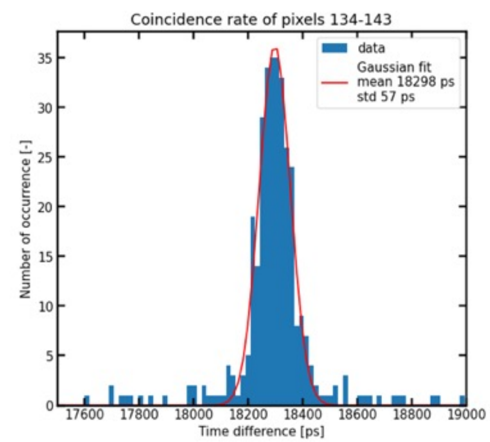
SPAD arrays with 50 ps resolution







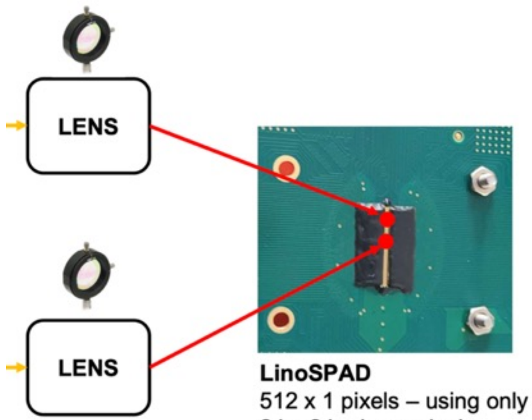
240k photons per peak



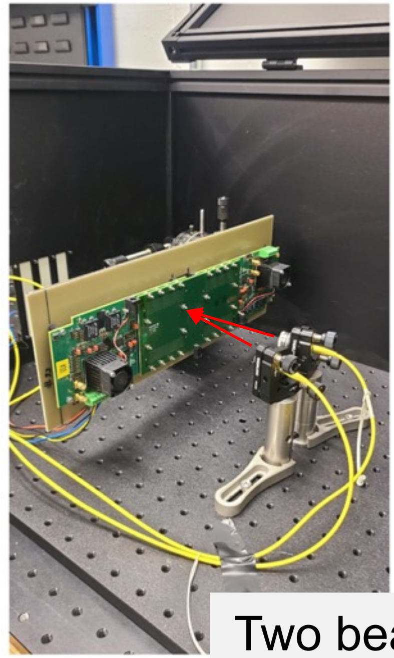
time difference, σ=57 ps
→ 40 ps per photon

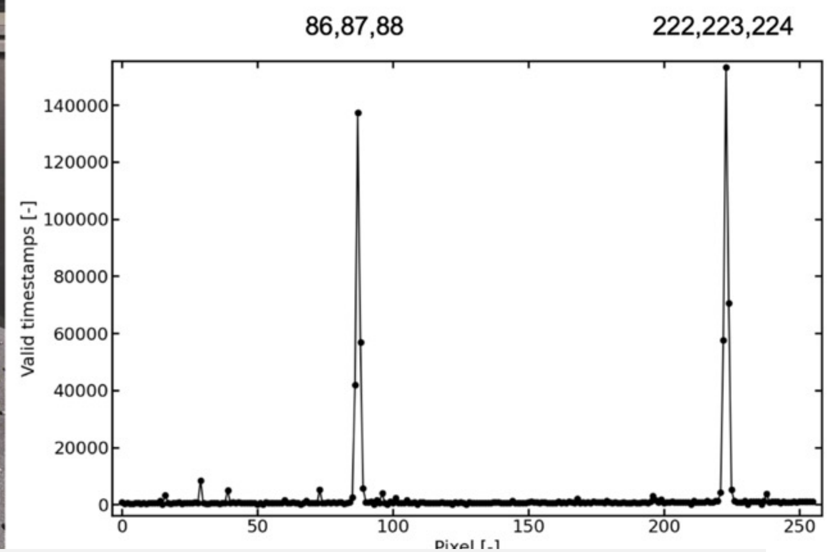
Two beams from SPDC source
Coincidence of two single photons

HBT peaks in LinoSPAD2

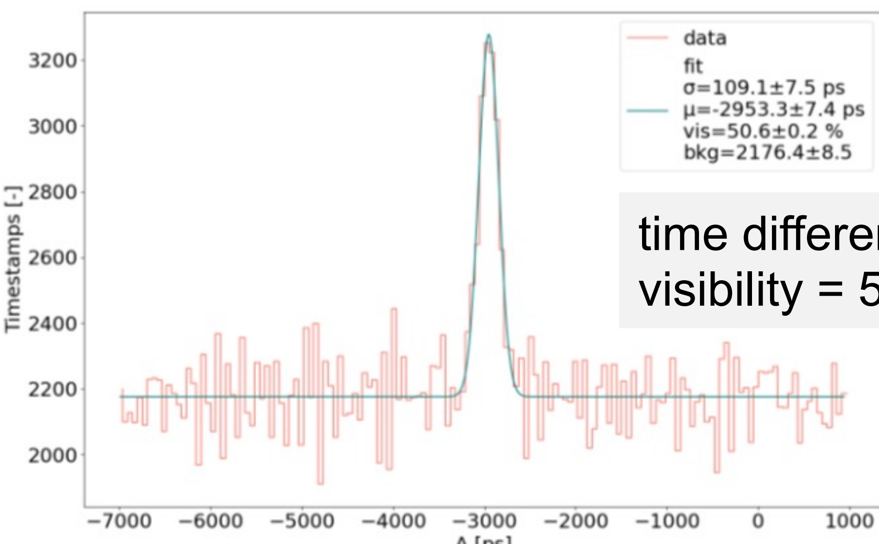


LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels





Two beams from Ar lamp + polarizer after beamsplitter



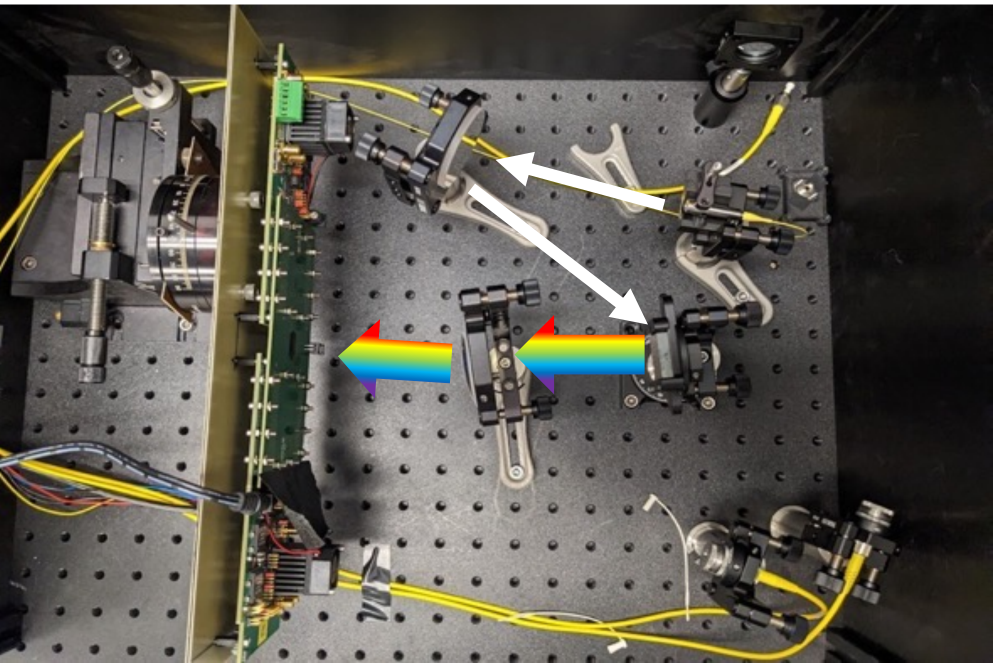
time difference, σ=110 ps
visibility = 50%

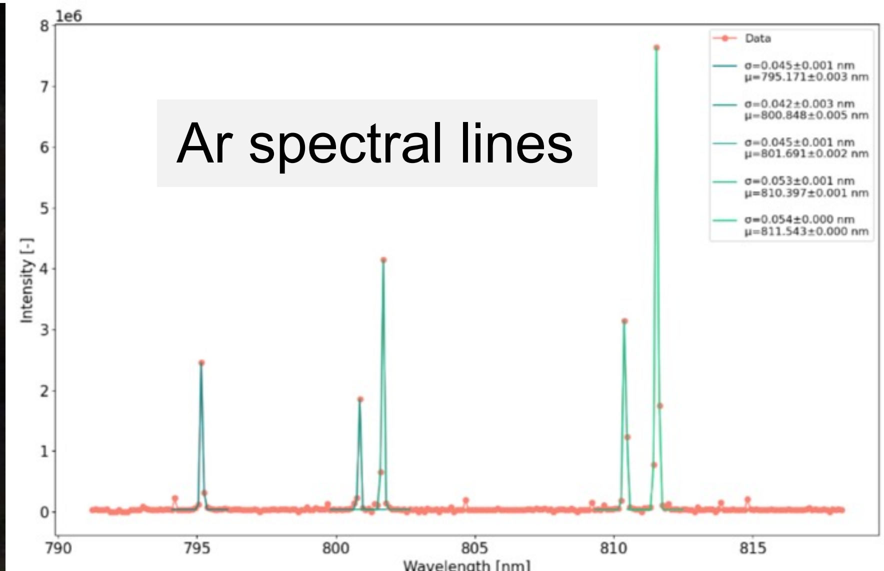
look for HBT = photon bunching,
natural coherence time > resolution

Next step: spectral binning

Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber



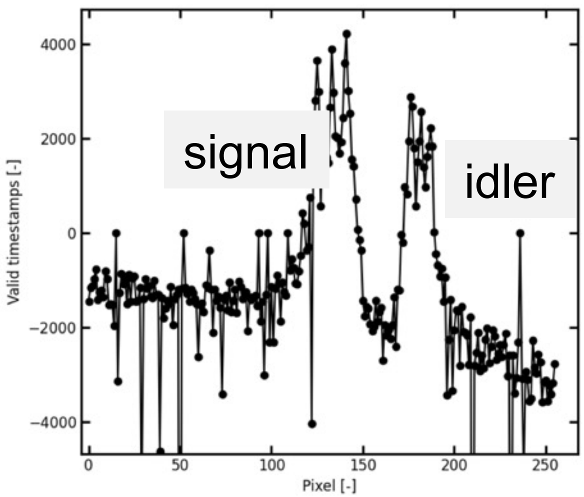


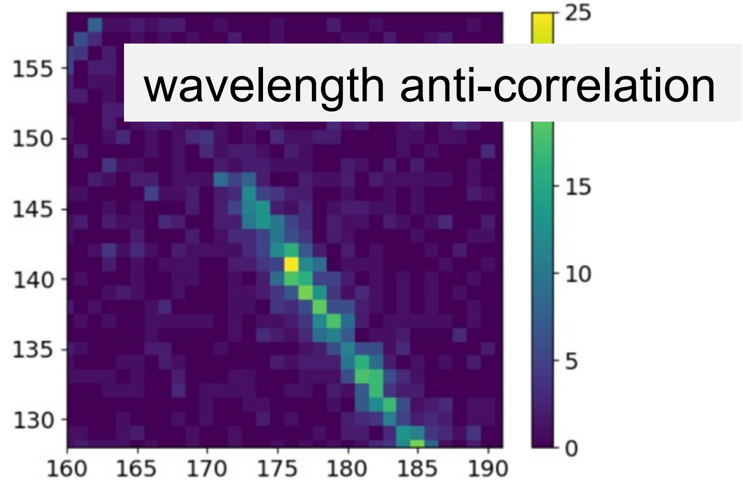
Achieved 0.04 nm spectral and 40 ps timing resolution

arxiv.org/abs/2304.11999

Wavelength anti-correlation in LinoSPAD2

- Combine signal and idler in single fiber so can use single spectrometer channel
- At 50 mW signal and idler spectra do not overlap





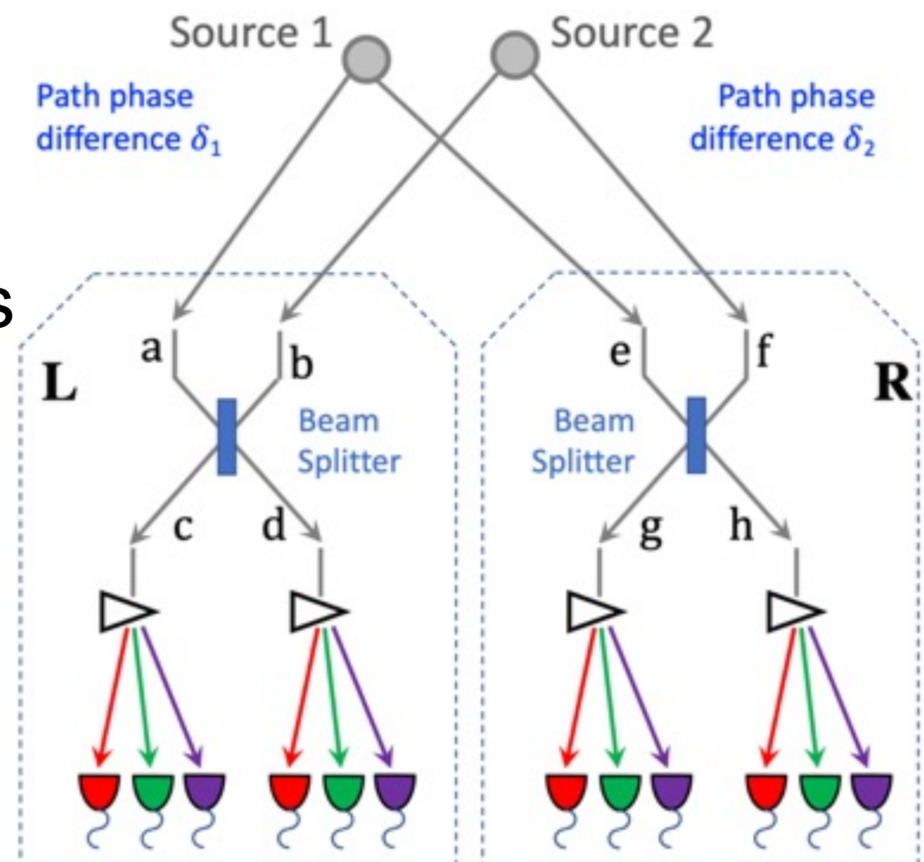
Spectrometer with 0.04 nm and 40 ps resolutions

only x10 above Heisenberg hbar/2 limit

arxiv.org/abs/2304.11999

Next step: broadband HBT

- Each spectral line is a separate experiment
- Step 1: interfere neon lines
- Step 2: interfere spectral bins, this is what we need for quantum-assisted astrometry



7.5 ps superSPAD sensor

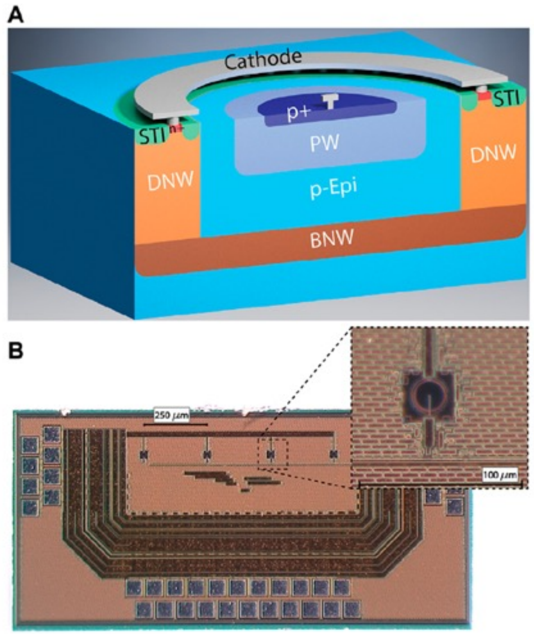
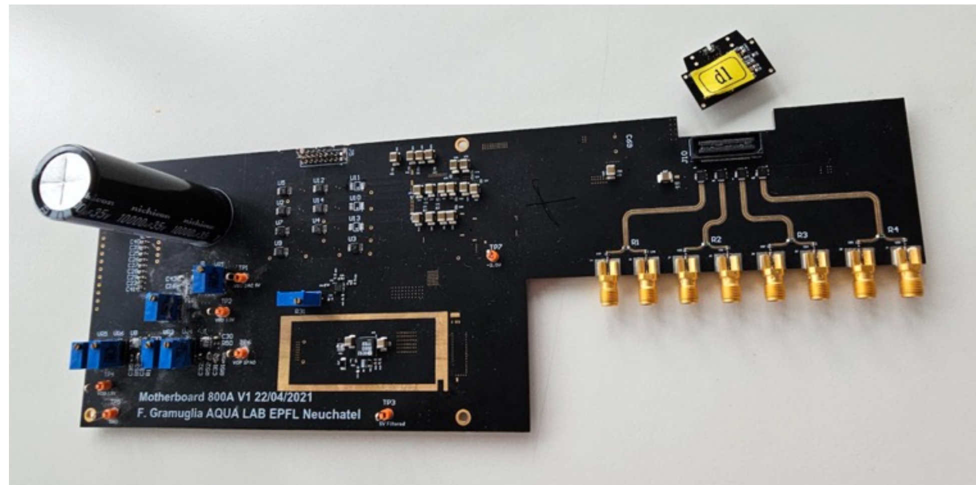


FIGURE 1 | (A): SPAD cross section. **(B)**: Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [21].



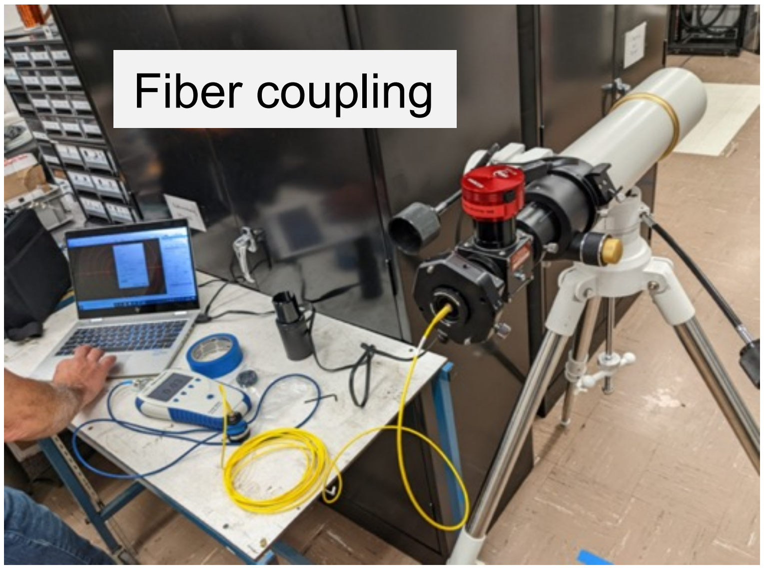
- Developed in AQUA group in EPFL
- 7.5 ps FWHM time resolution
- Starting tests at BNL

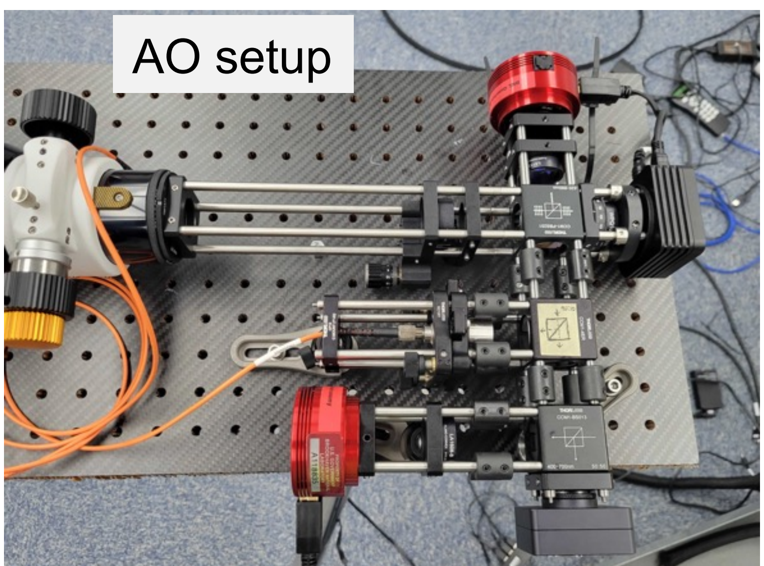
F. Gramuglia, M.-L. Wu, C. Bruschini, M.-J. Lee, and E. Charbon, A low-noise CMOS SPAD pixel with 12.1 ps SPTR and 3 ns dead time, IEEE Journal of Selected Topics in Quantum Electronics **28**, 1 (2022).

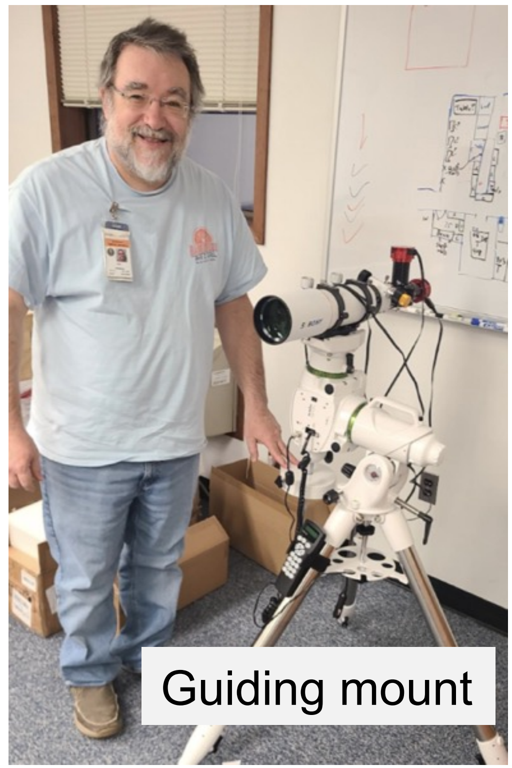
telescopes

On-sky measurements

Experimenting with SM fiber coupling and adaptive optics



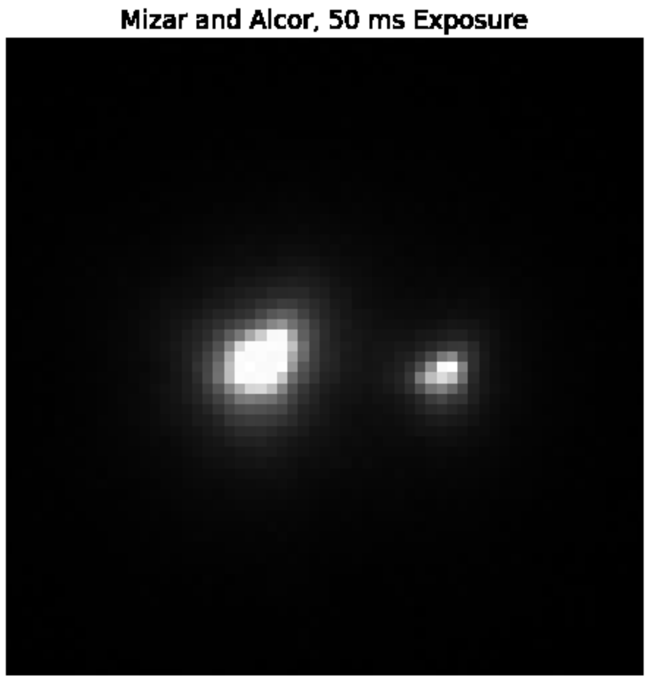




Next:

- 2 telescopes
  - demo of SII
- 4 telescopes
  - demo of quantum astrometry
- spectral binning demo

On-sky measurements



Mizar A & B

- 50 ms exposure
- 15 arcsec separation

Jitter of two stars is correlated and could cancel in differential measurement

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Special Programs

- Quantum-Enhanced Telescopy Workshop
- Nobel Symposium: Foundations on Quantum Physics

Quantum-Enhanced Telescopy Workshop

Sunday, 18 June 09:00 – 17:30

Speakers

Summary

- Single-photon interferometry reaches much higher resolutions than single telescopes; but practical issues limit maximum baselines

- Two-photon interferometry can permit independent stations over longer baselines

- Two-photon techniques are in general quantum mechanical; new ideas suggest quantum technology can enhance interferometry

- Bench-top demonstration of new ideas for quantum astrometry with temporal and spectral binning

Broad program in quantum-assisted optical interferometry ahead

Main publications

- Original idea: https://doi.org/10.21105/astro.2010.09100
- Earth rotation fringe scanning: doi.org/10.1103/PhysRevD.107.023015
- Experimental proof of principle: https://arxiv.org/abs/2301.07042
- Fast spectrometer: https://arxiv.org/abs/2304.11999

- See https://www.quantastro.bnl.gov/node/3 for the full list

- Our web site

www.quantastro.bnl.gov

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Stepan Vintskevich
Anze Slosar
Zhi Chen
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Aarom Mueninghoff

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Bram Bouwens
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Boris Blinov
Mila Zhukas
Maverick Millican
Alex Kato
Peter Svihra
Michal Marcisovsky
Sergei Kulkov
Jakub Jirsa
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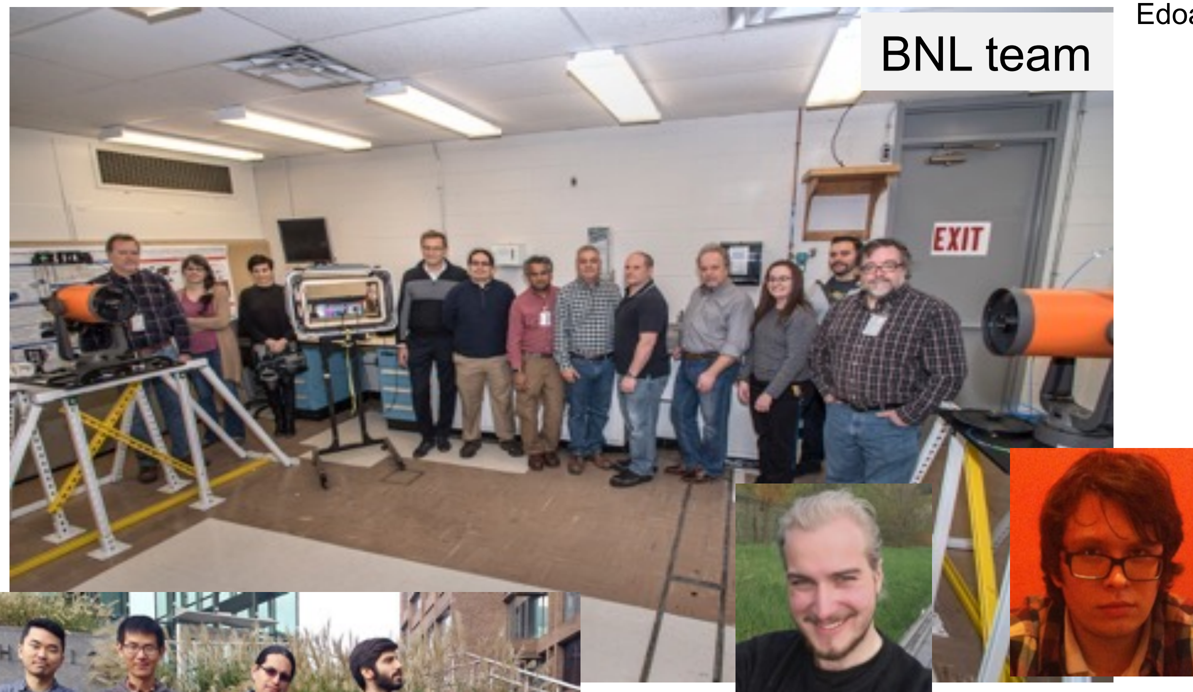

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