Quantum-Assisted Optical Interferometry for Precision Astrometry

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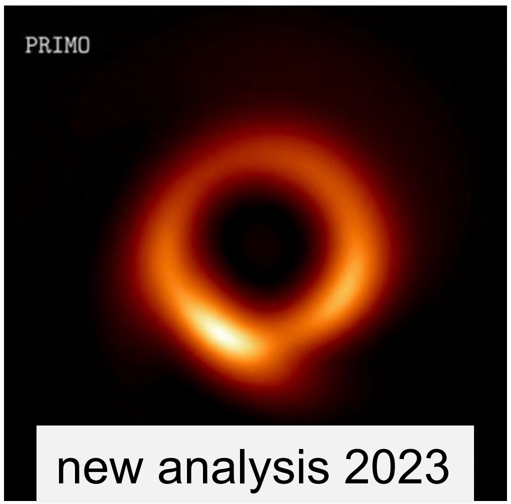
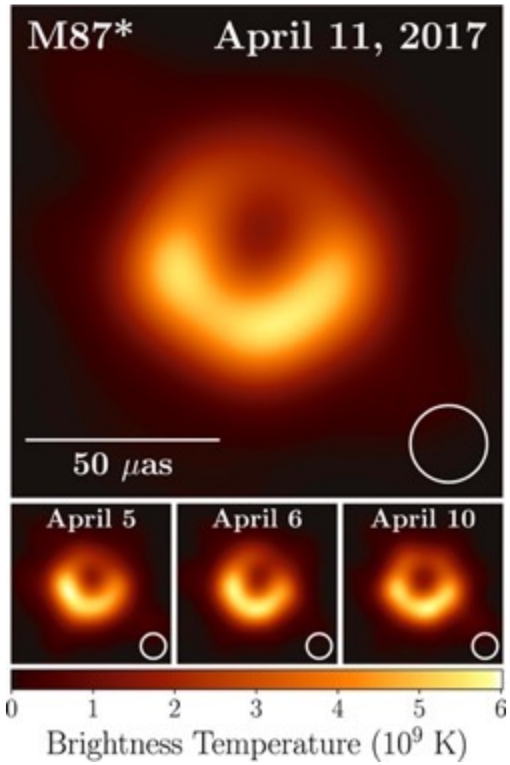
University of Geneva/ EPFL seminar

11-12 May 2023

Astronomy picture of the decade





sensitive to features on angular scale

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

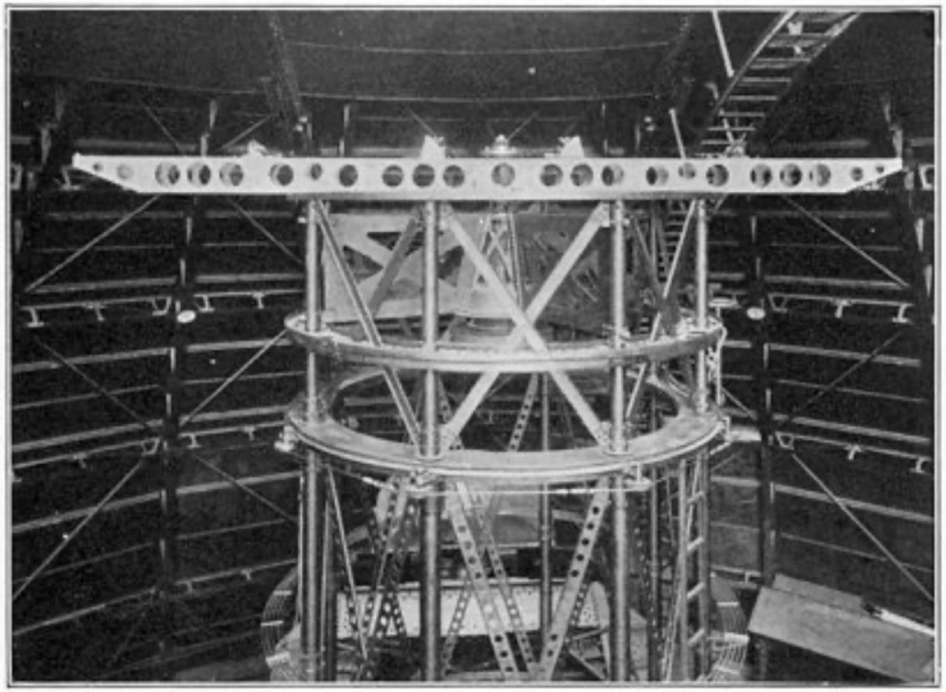
2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

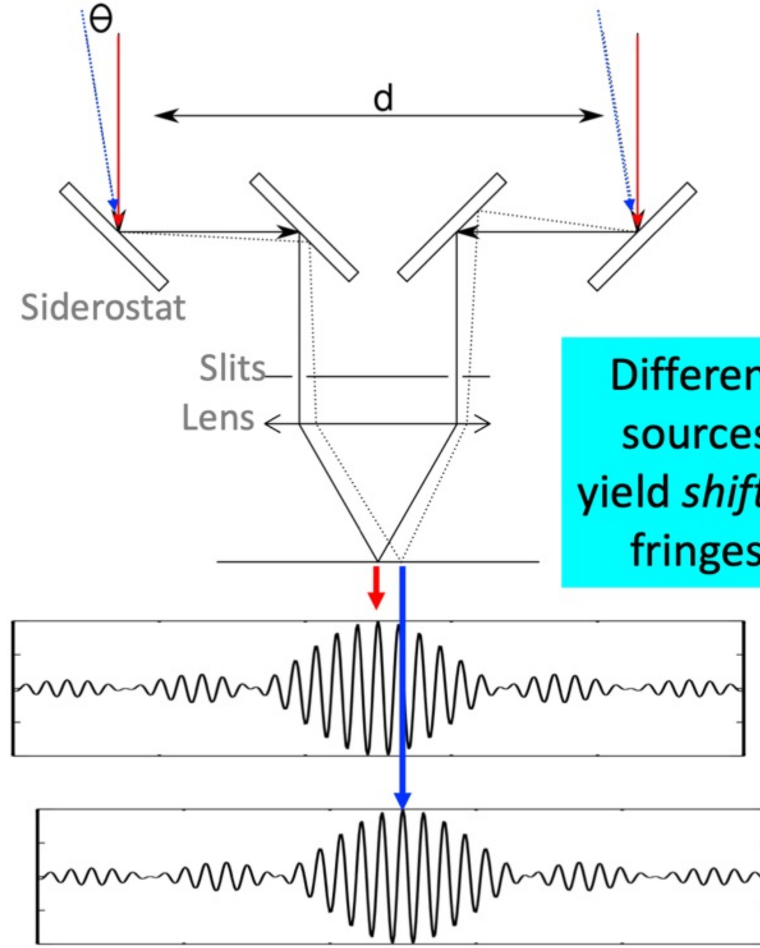
Achieved by radio interferometry with ~10000 km baselines

Classical interferometery

In classical times

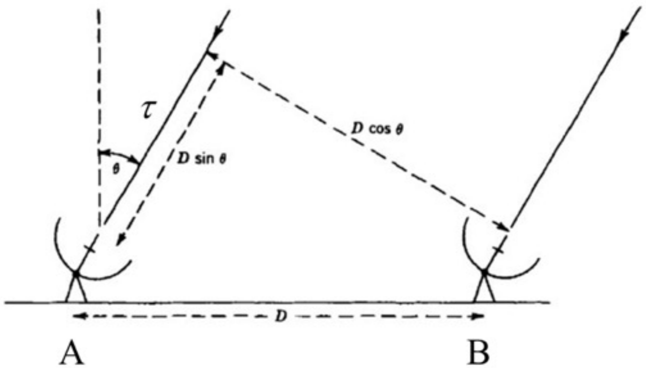


Michelson Stellar Interferometer at Mt. Wilson c. 1920, after original idea by Michelson & Fizeau c. 1890



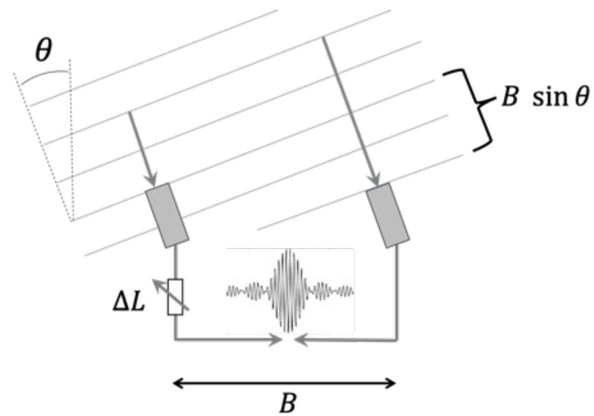
Different sources yield *shifted* fringes

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

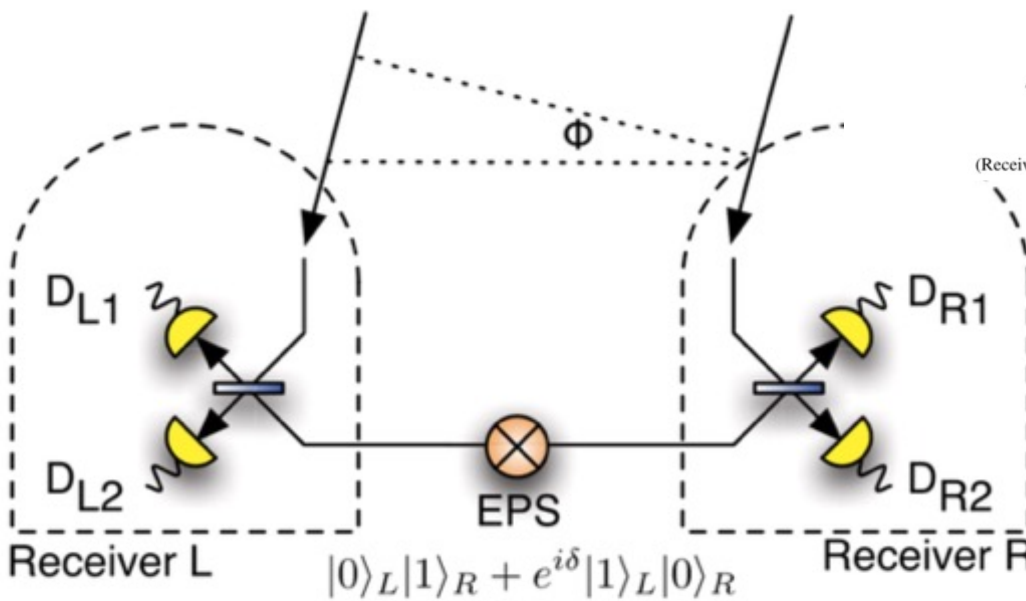
Accuracy ~ 1 mas

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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Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

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Sarah Croke‡
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

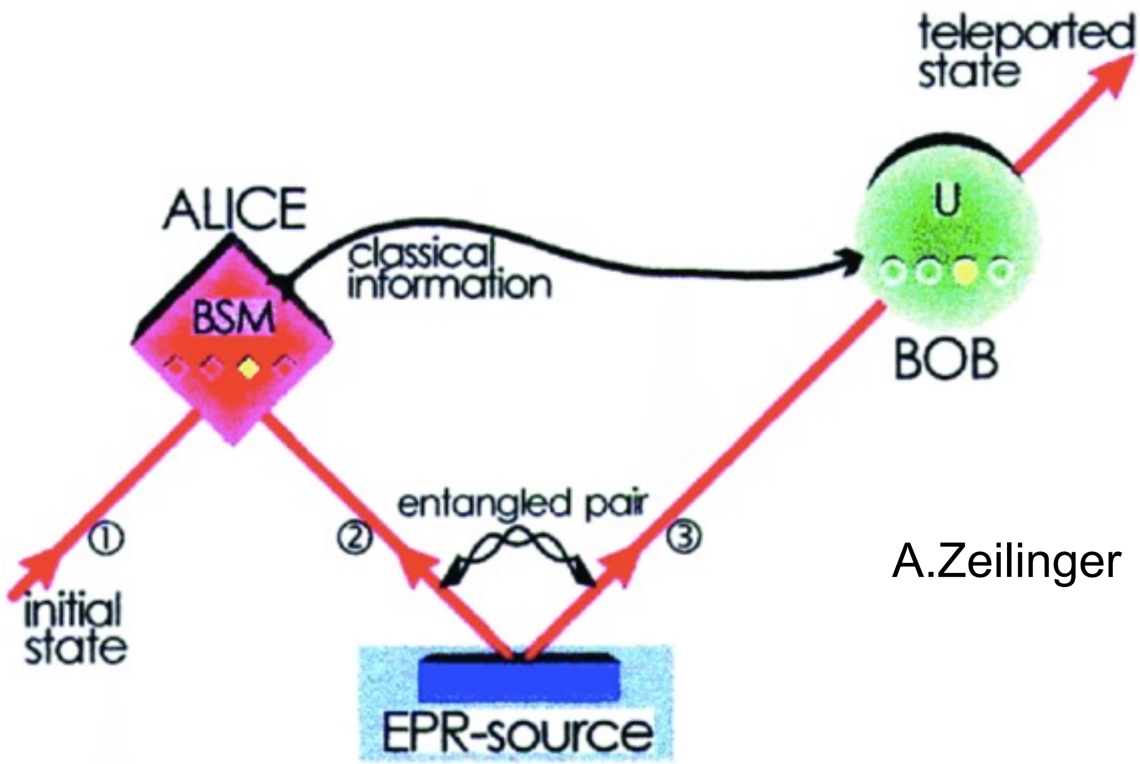
$$\Delta\theta \sim \frac{\lambda}{b}$$

- Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
- Need to 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 Network

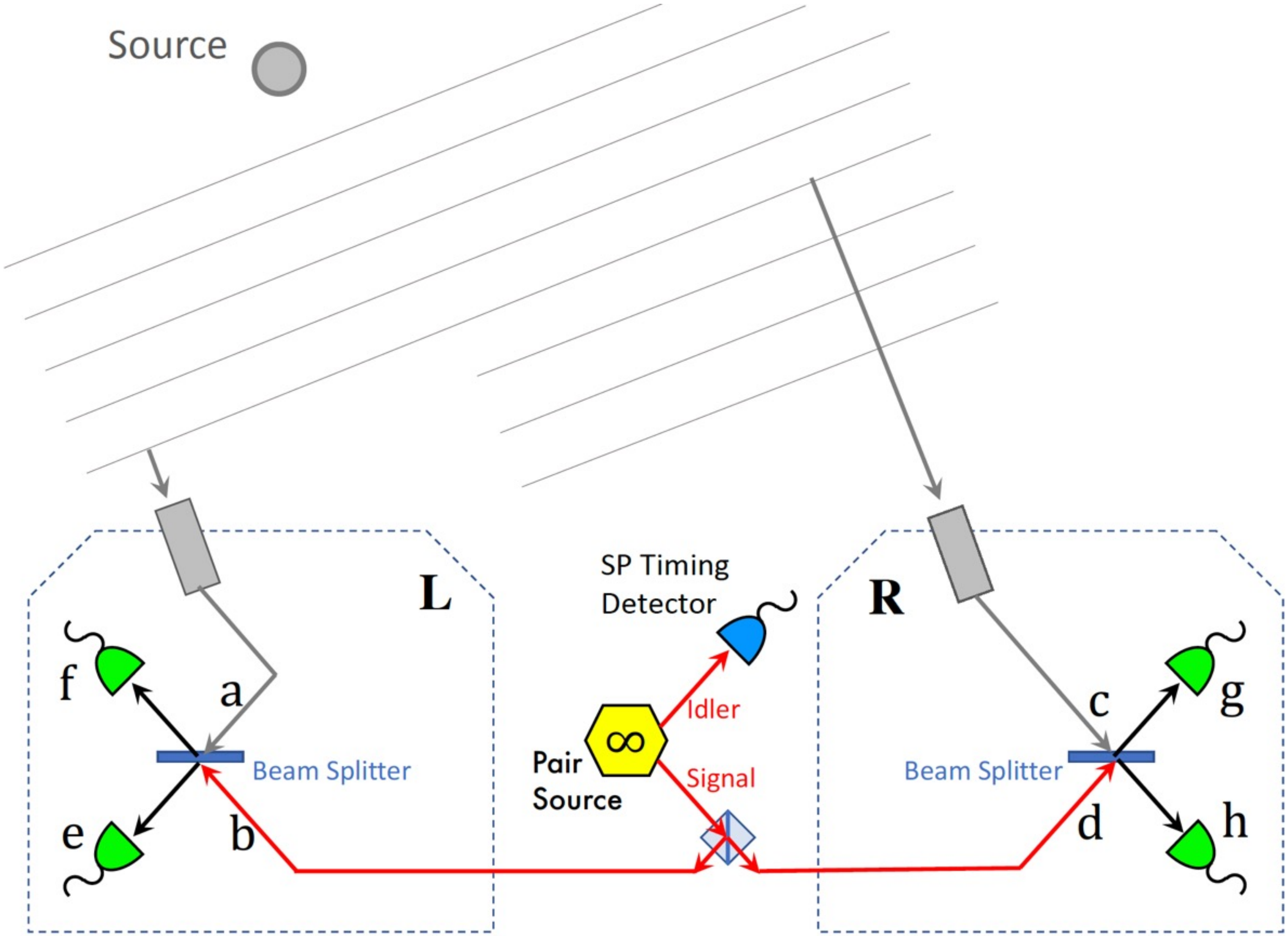
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- Qubit teleportation: produce entangled photons and send them to two locations
- Bell State Measurement (BSM) on one photon will collapse the wave function of the other one (or swap entanglement, or teleport photon)

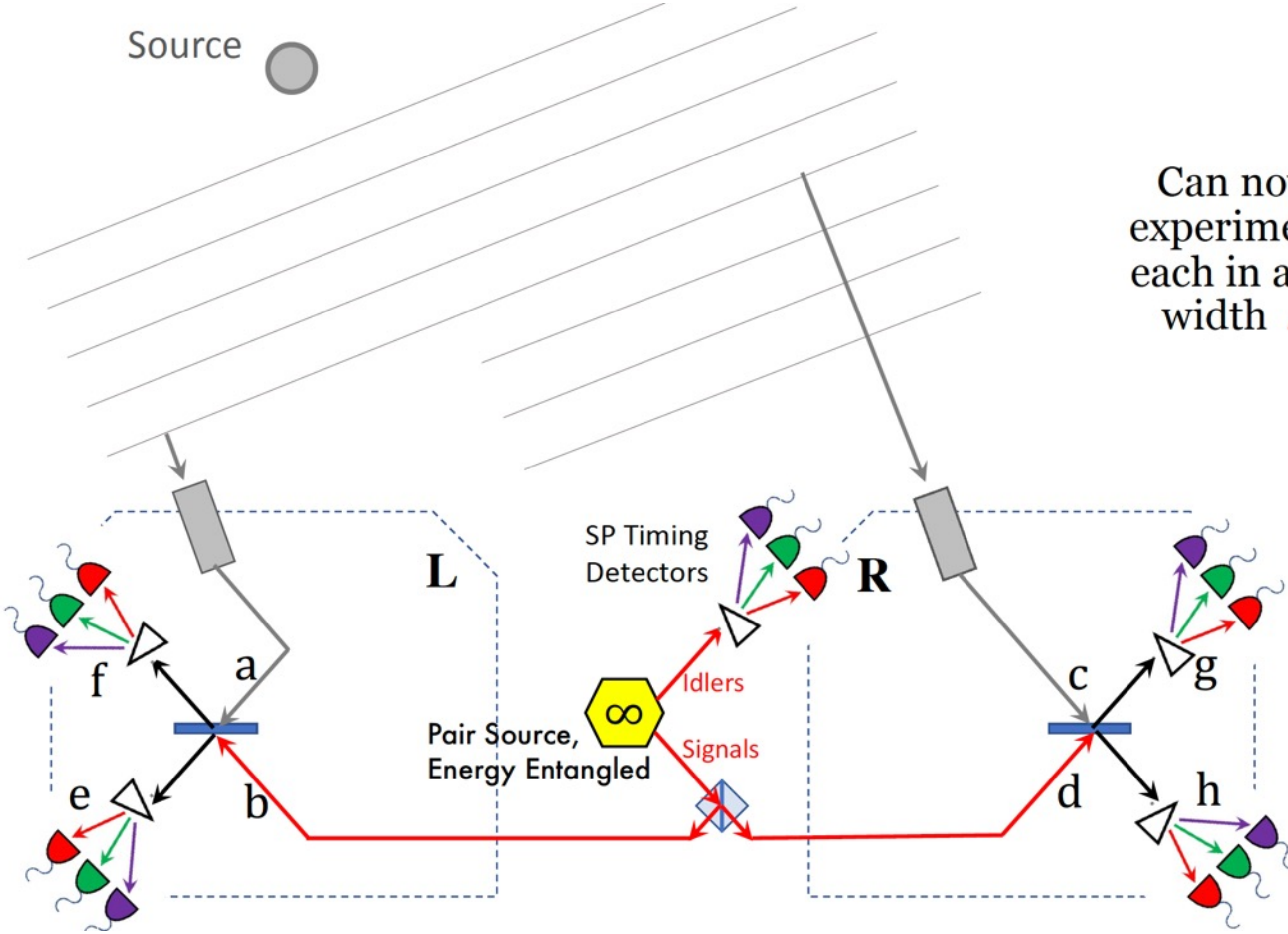


A.Zeilinger

with pair source



with pair source and spectral binning

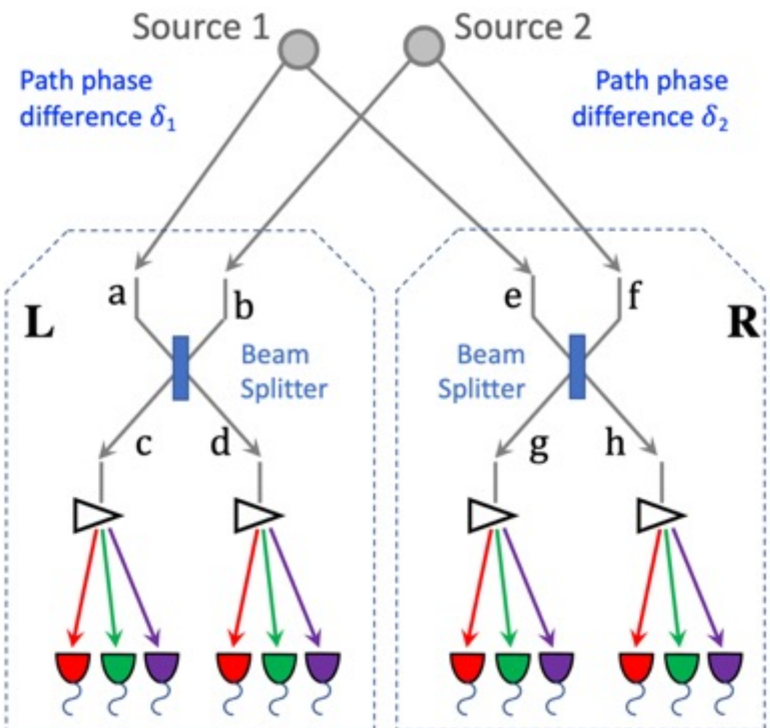


Can now run 10^3-10^4 experiments at once (!), each in a spectral bin of width $\Delta\upsilon \sim 1/\tau_{\text{Detector}}$

Quantum Astrometry

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

https://arxiv.org/abs/2010.09100



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

Full QFT calculation

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

Rates — HBT

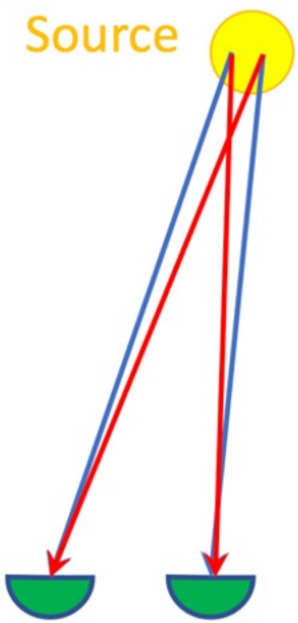
$$
A^2 \eta_1 \eta_2 T_r \left[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm 2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B (\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right] \quad (30)
$$

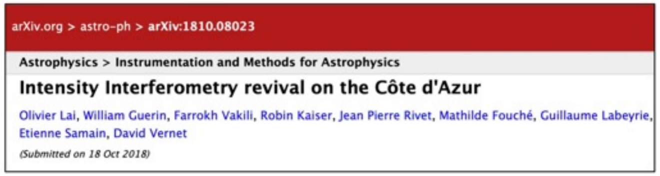
New oscillatory term!

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

- Can provide 10 microarcsec resolution for bright stars
- Perfect to start exploring this approach

Stellar Intensity Interferometry




arXiv.org > astro-ph > arXiv:1810.08023

Astrophysics > Instrumentation and Methods for Astrophysics

Intensity Interferometry revival on the Côte d'Azur

Olivier Lai, William Guerin, Farrokh Vakili, Robin Kaiser, Jean Pierre Rivet, Mathilde Fouché, Guillaume Labeyrie, Etienne Samain, David Vernet

(Submitted on 18 Oct 2018)

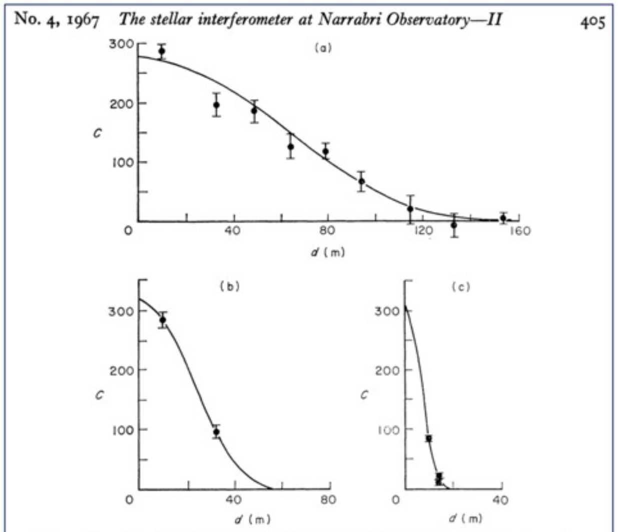
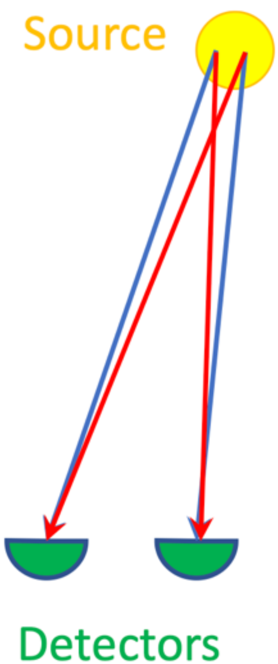

No. 4, 1967 *The stellar interferometer at Narrabri Observatory—II* 405

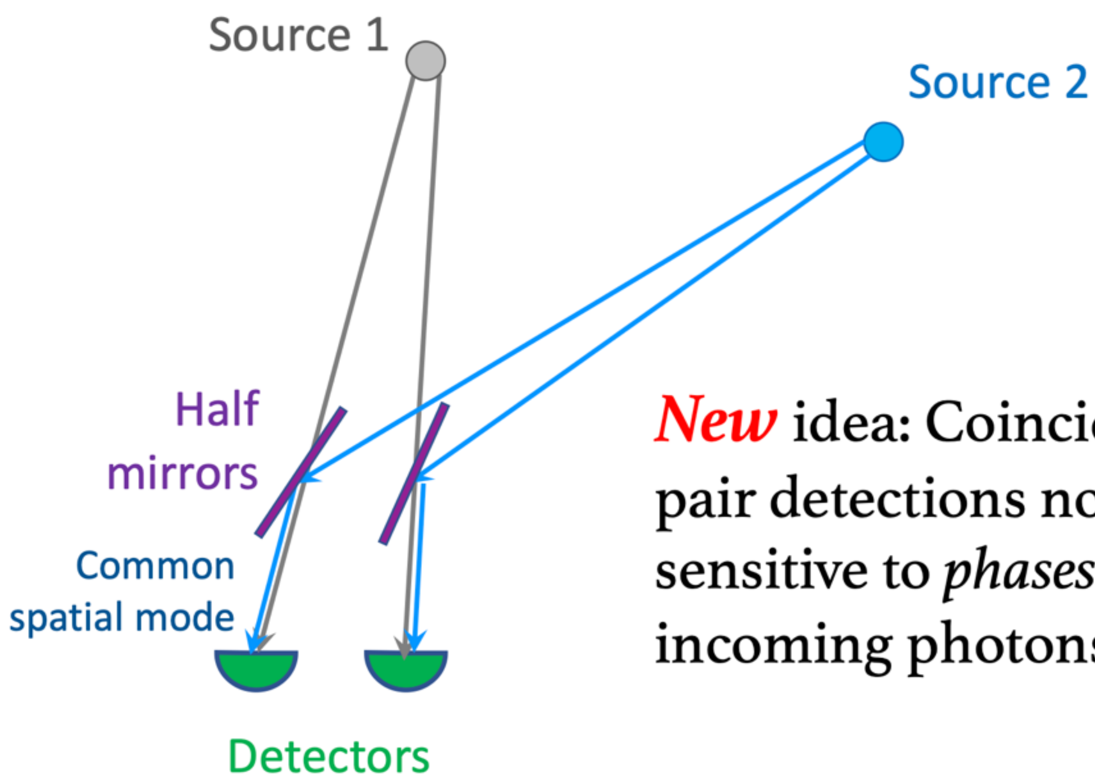
FIG. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

Hanbury Brown, Davis, Allen, Rome; MNRAS **137**, (1967) p393-417

Hanbury Brown – Twiss Interferometry

HBT with two sources?



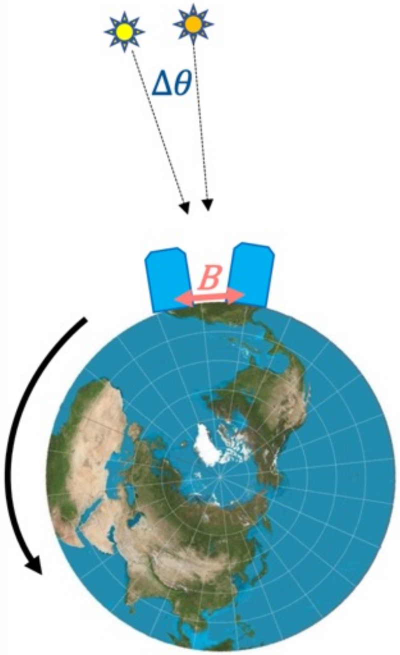


New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Earth rotation fringe scan

$$\langle N(xy)\rangle = \frac{k(S_1+S_2)^2}{8}\left[1 \pm V_{2PS}\cos\left[\frac{2\pi B}{\lambda}(\sin\theta_1 - \sin\theta_2) + \frac{2\pi \Delta L}{\lambda}\right]\right]$$

This will evolve as the Earth rotates



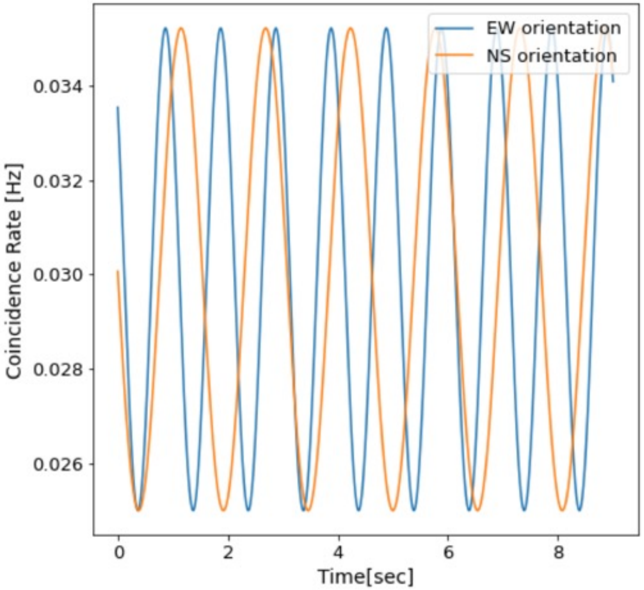
$$\langle N_{xy}\rangle(t) = \bar{N}_{xy}\left[1 \pm V\cos\left(\omega_f t + \Phi\right)\right]$$

Coincidence rates oscillate

$$\omega_f = \frac{2\pi B \Omega_\oplus \sin\theta_0}{\lambda}\Delta\theta$$

Fringe oscillation rate is a direct measure of sources' opening angle!

Can measure with high precision



example of oscillations for pair of stars

World-competitive precision

$$\sigma\left[\Delta\theta\right] = \sqrt{\frac{6}{\pi^2\kappa}}\,\frac{1}{V}\,\frac{\lambda}{B}\,\frac{1}{T\Omega_\oplus \sin\theta_0}\,\frac{1}{\sqrt{\bar{n}T}}$$

$\bar{n}$ = average pair rate
T = total observation time

A modest experiment:

- Bright stars, mag 2
- 1 m^2 collecting area
- 10^4 seconds observation
- 0.15 nsec time resolution
- 10^4 spectral channels

Idea: Dynamic Astrometry

Track day-over-day changes in $\Delta\theta$ to observe parallax, proper motion, orbital motion, gravitational lensing

$$\sigma[\Delta\theta] \sim 10\mu\text{as} \; (\sim 10^{-11}\,\text{rad})$$

1 mas HIPPARCOS (1989-1993)
7 μas GAIA (2013-)

Possible impact on astrophysics and cosmology

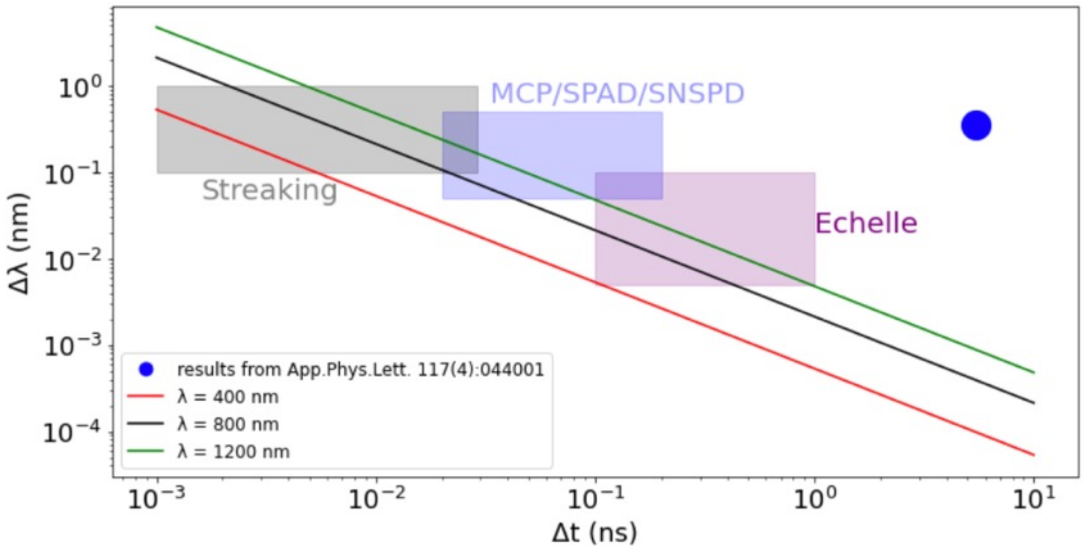
https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder (DE)
- Proper star motions (DM)
- Microlensing, see shape changes (DM)

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

Requirements for detectors

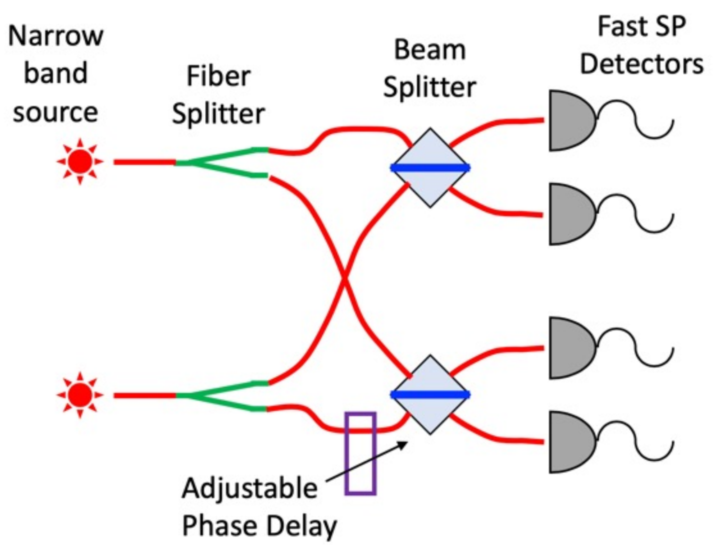


- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.05 nm * 20 ps

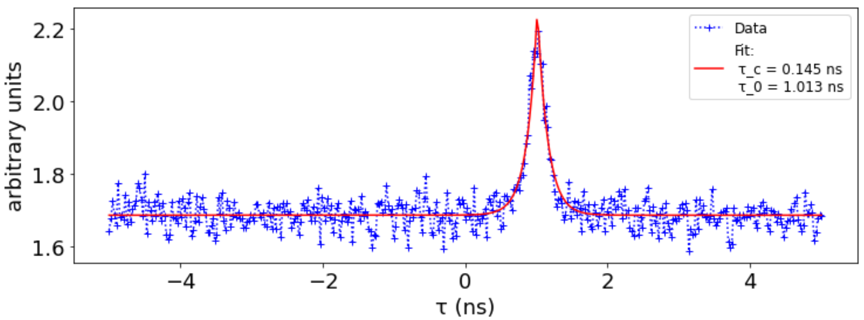
- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, **SPADs**, SNSPDs, streaking
  - Target 1-100 ps resolution
- Spectral binning: diffraction gratings, Echelle spectrometers

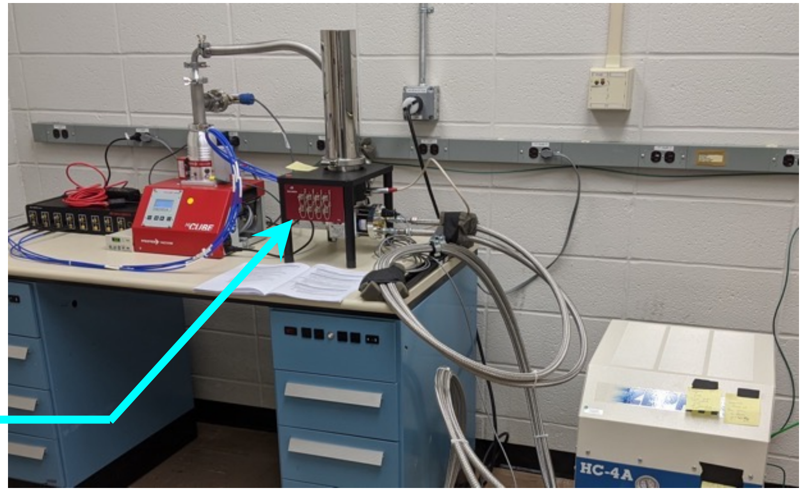
- High photon detection efficiency

Experiments in progress



Strong HBT peak with single lamp





Bench-top model of two-photon interferometry

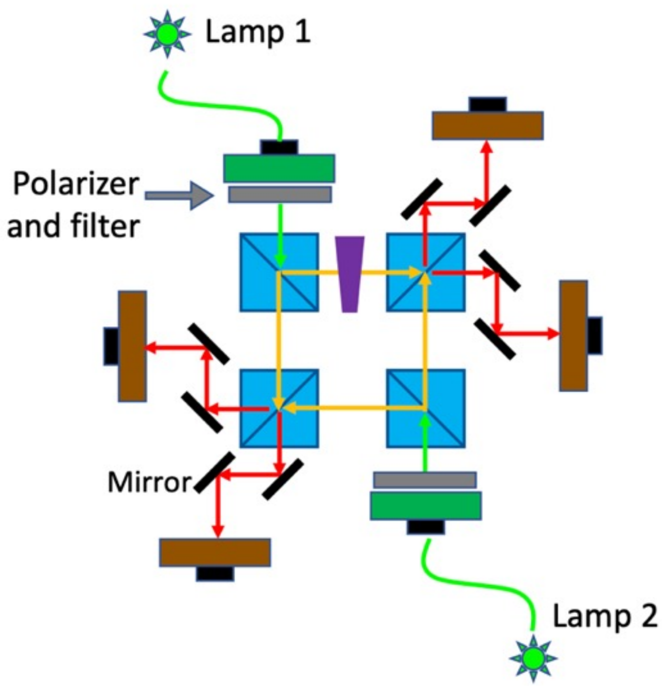
Ar vapor lamps with ultra-narrow band filters

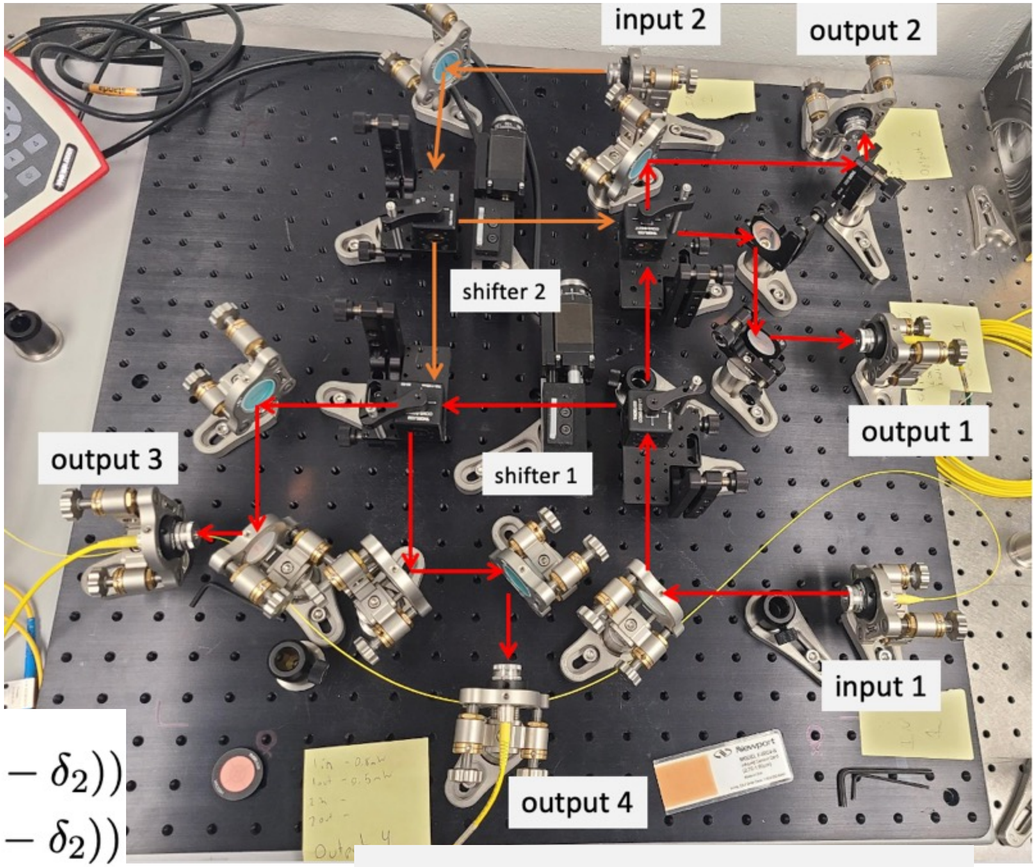
Superconducting nanowire single-photon detectors

Supported by DOE HEP QuantISED program

2022: benchtop verification

arxiv.org/abs/2301.07042

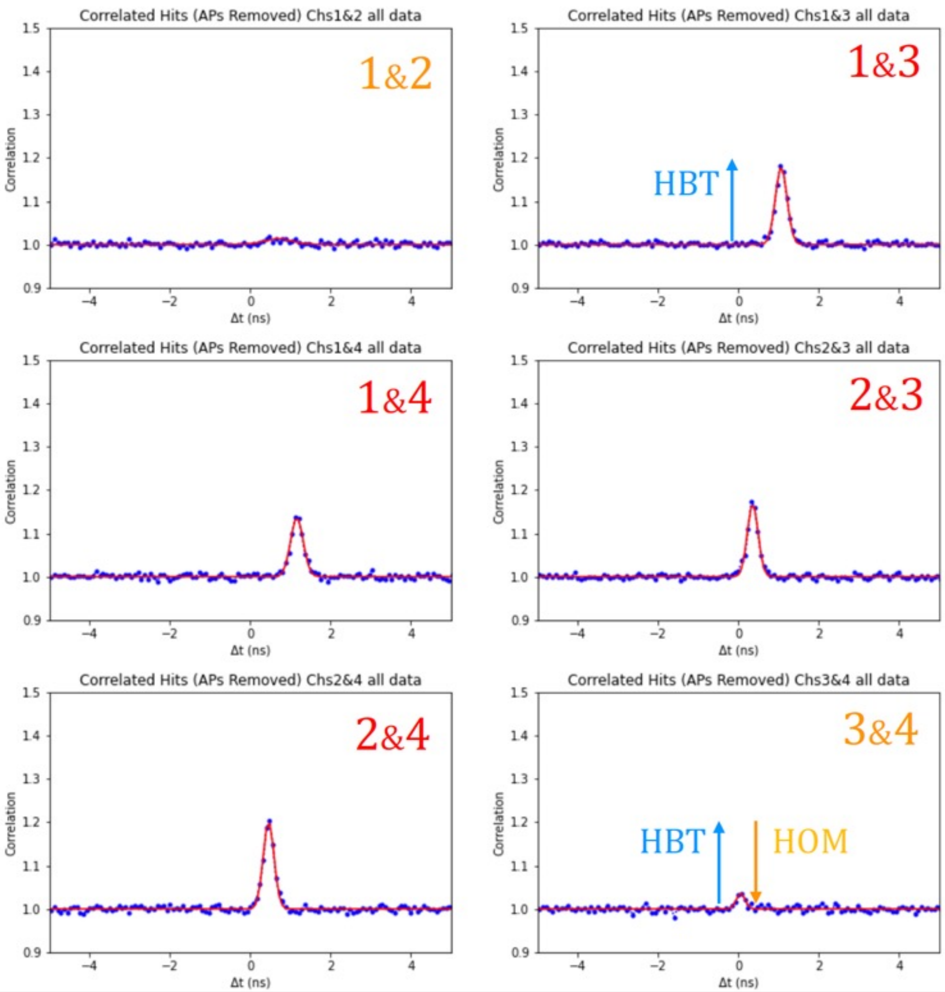


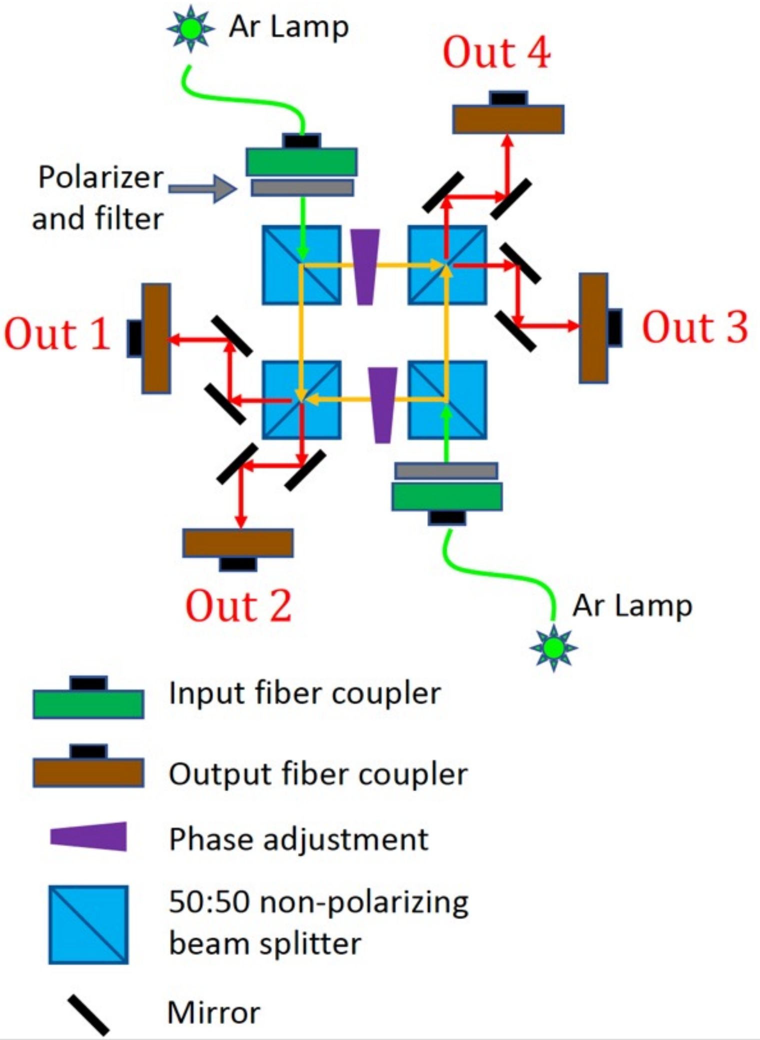


$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

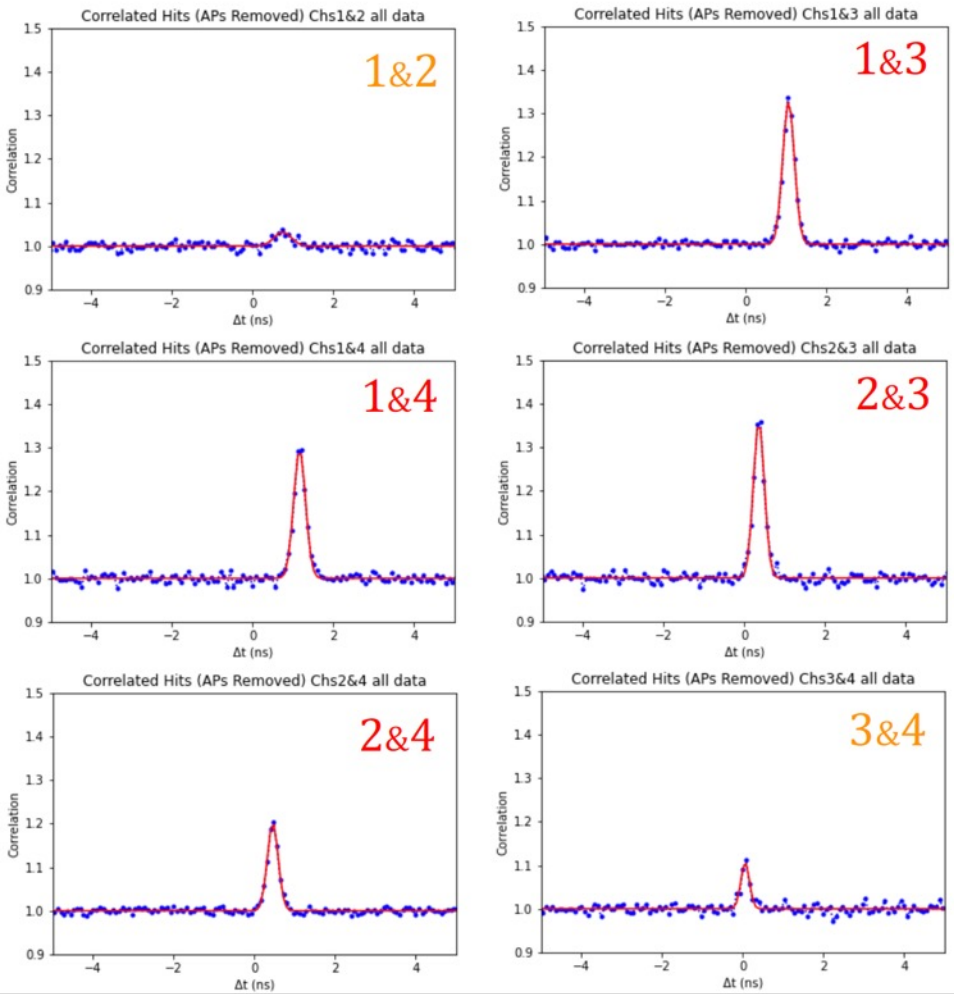
SPAD and SNSPD readout

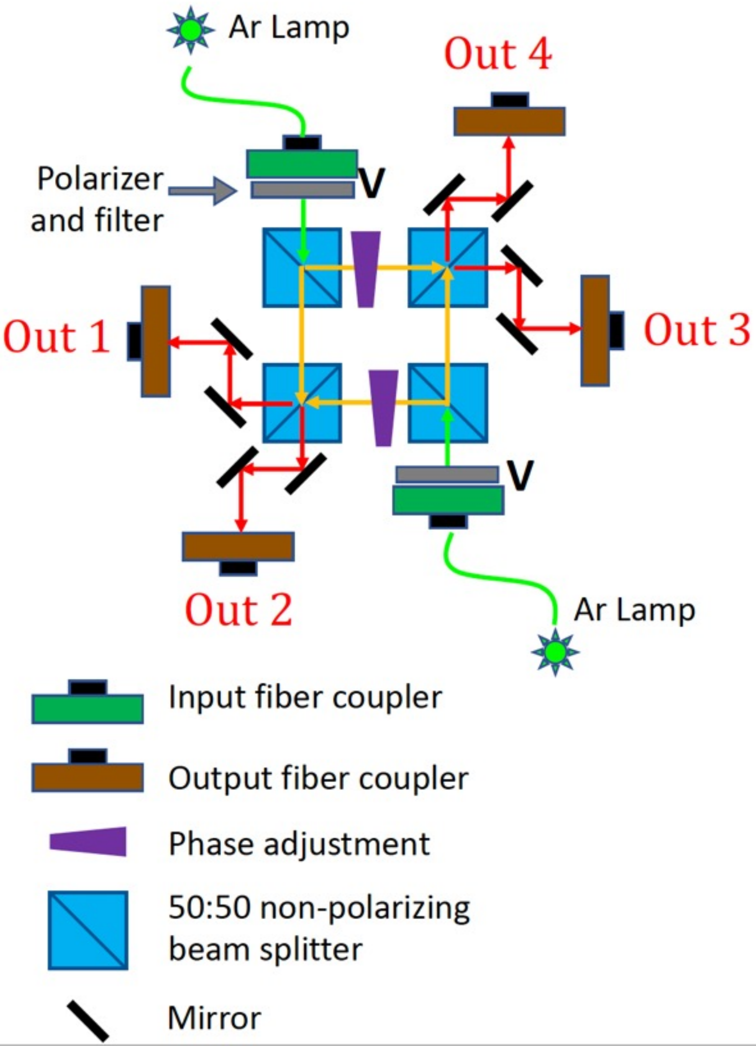
Unpolarized



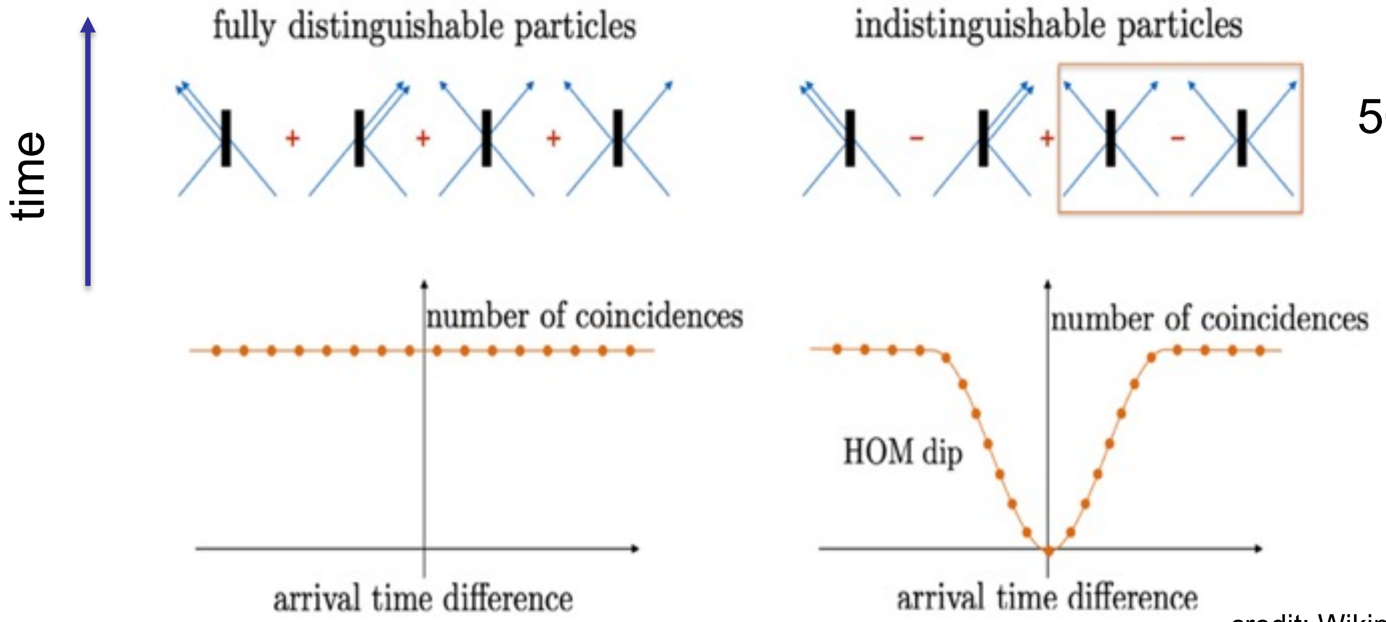


Polarized – V V





Hong-Ou-Mandel effect

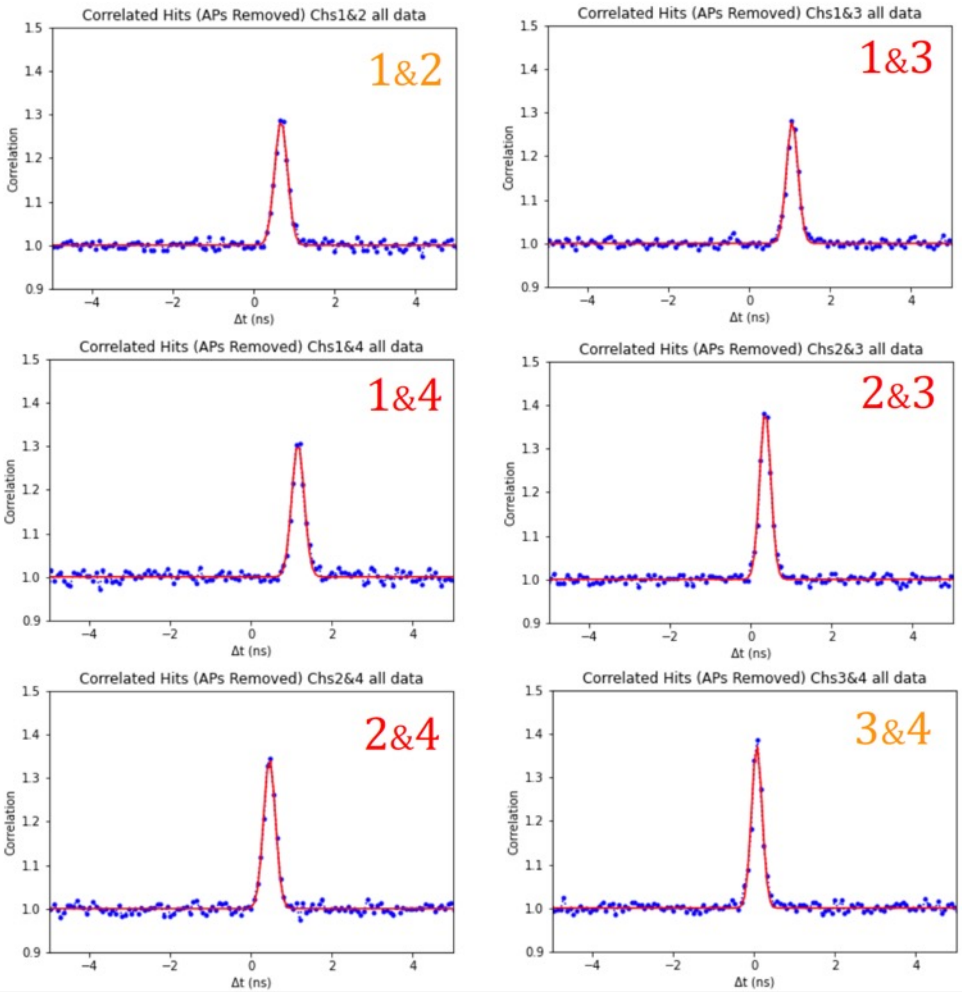


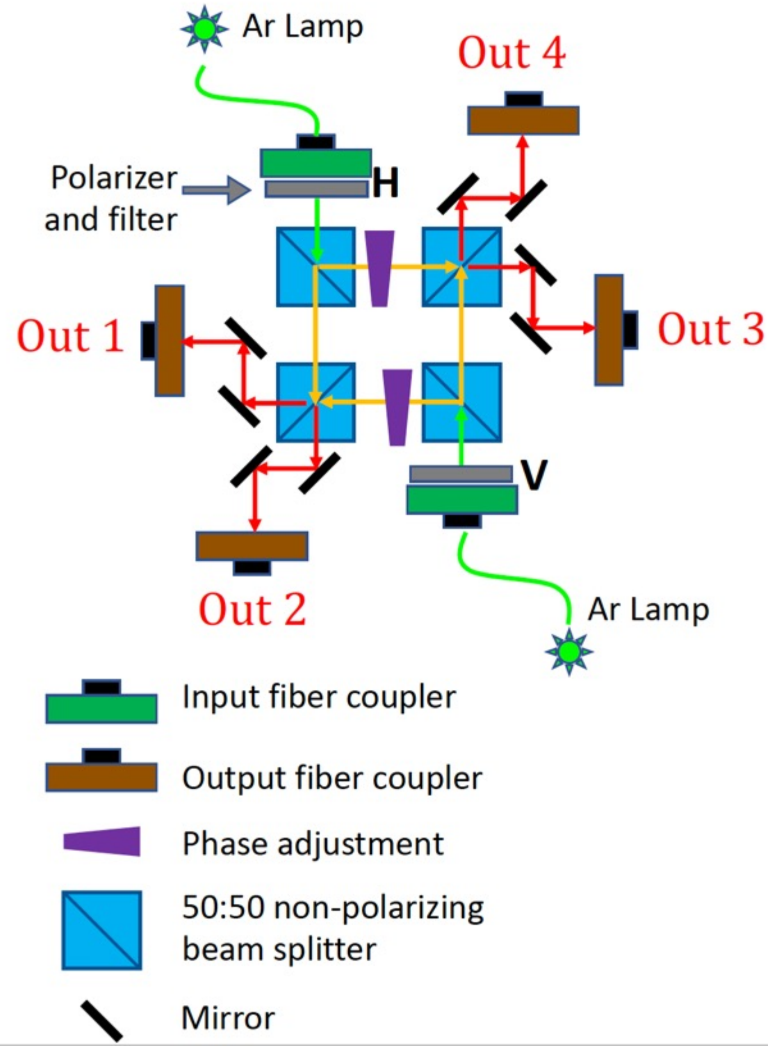
50/50 beam splitter

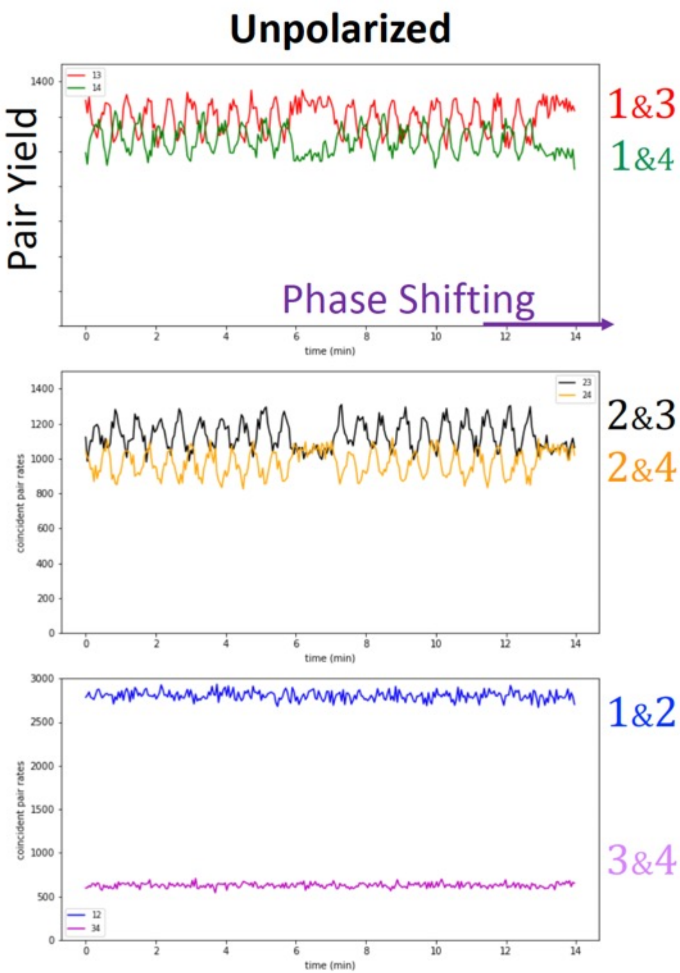
credit: Wikipedia HOM article

HOM dip for coincidences of two outputs

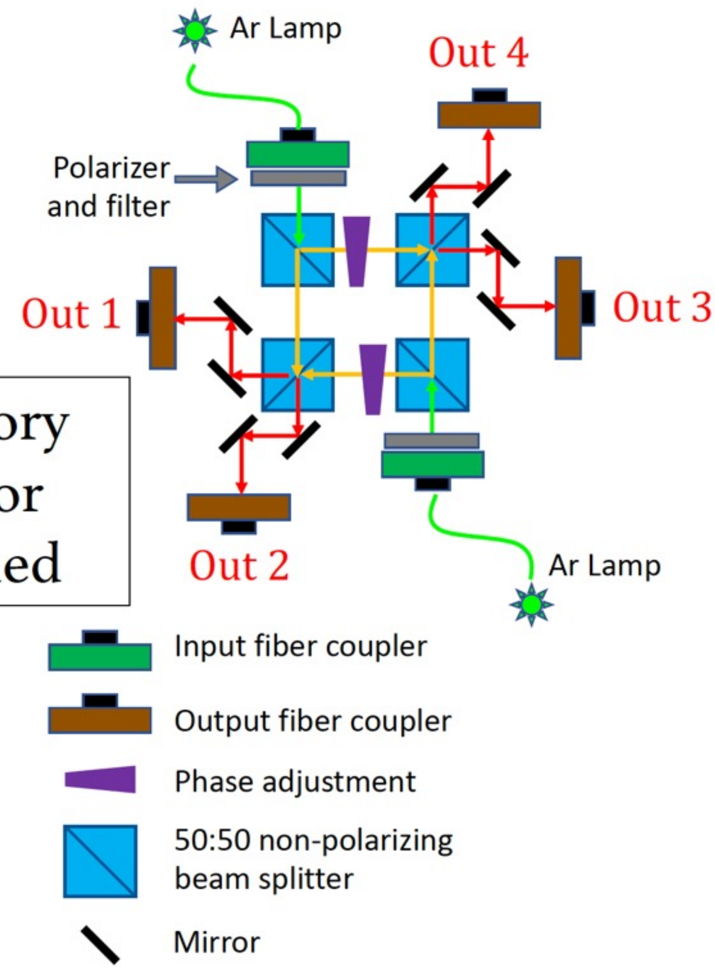
Polarized – V H



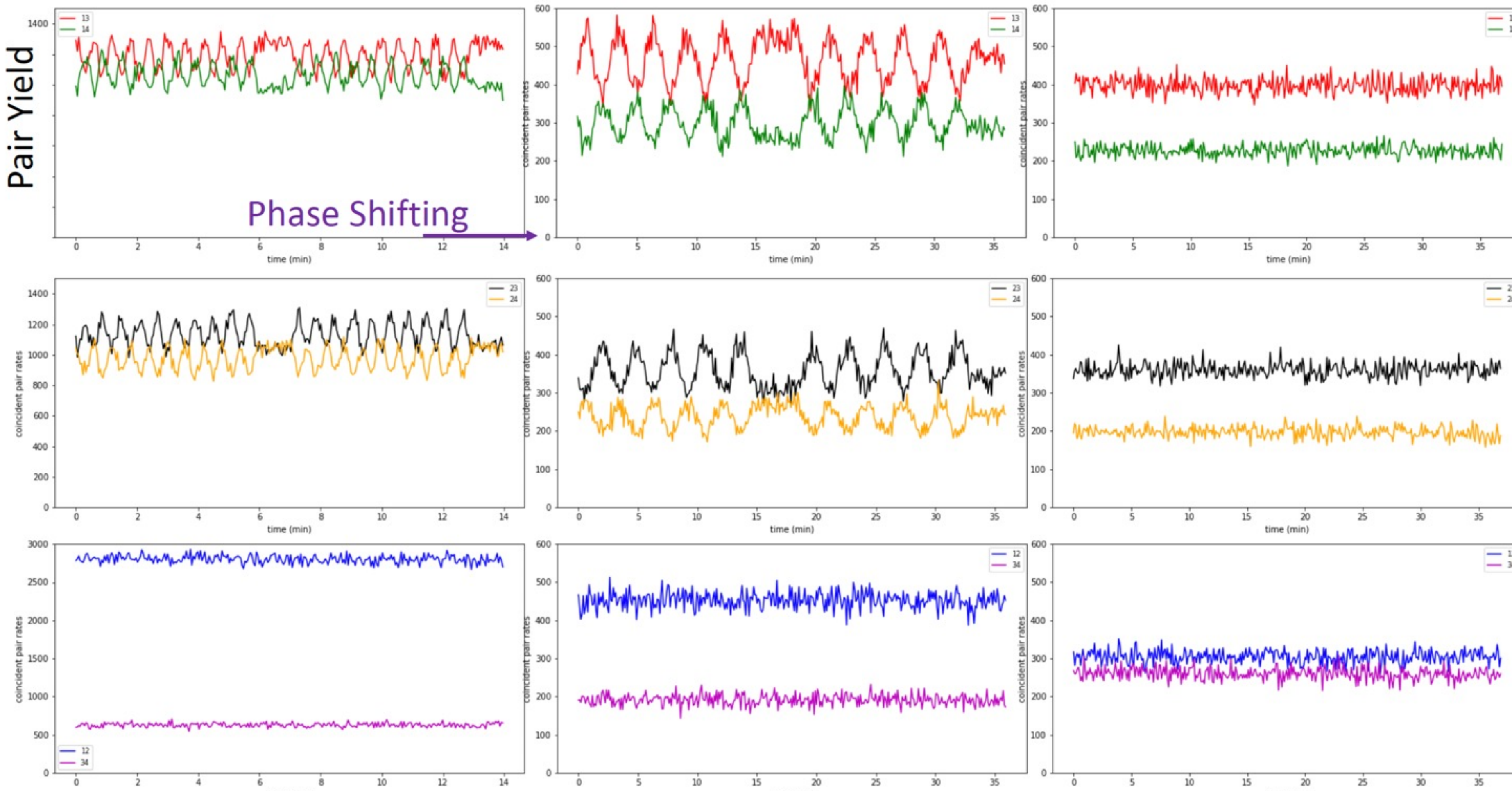




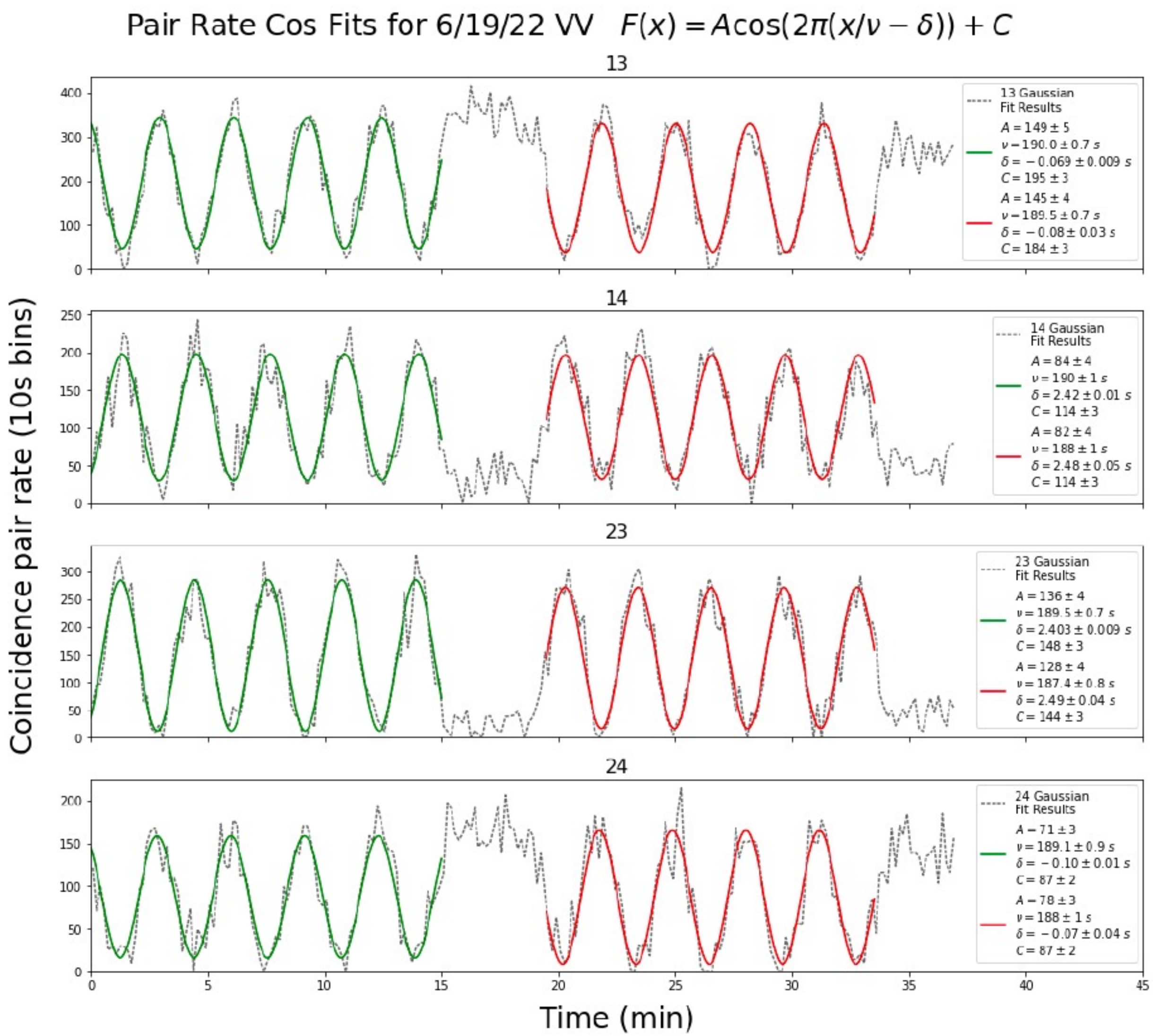
Oscillatory behavior confirmed



Unpolarized | Polarized – V V | Polarized – V H



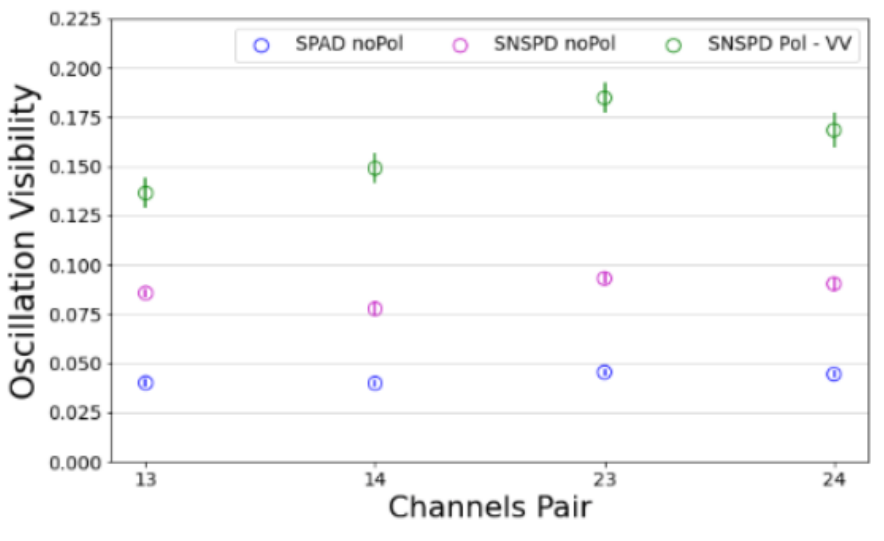
Phase dependence



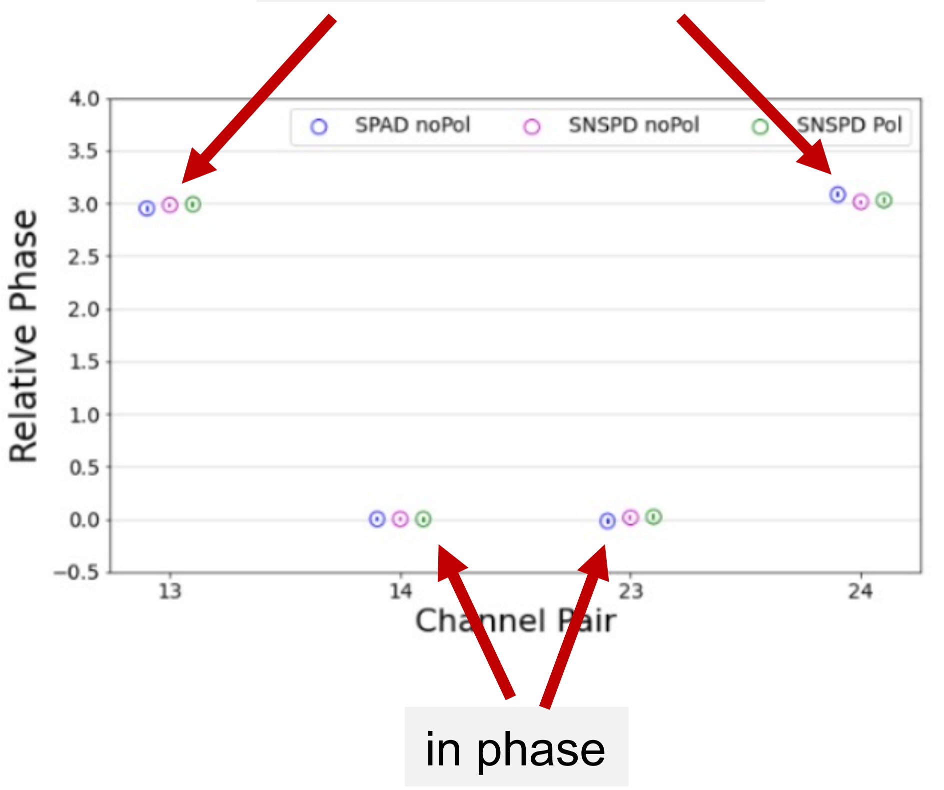
phase oscillations

Visibility and phase

- All as expected
- Paper submitted



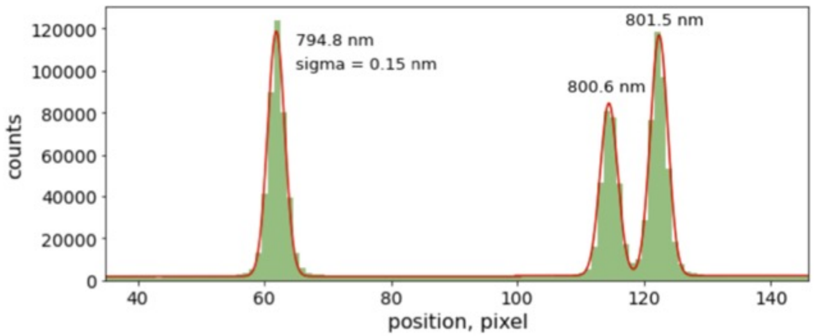
visibility



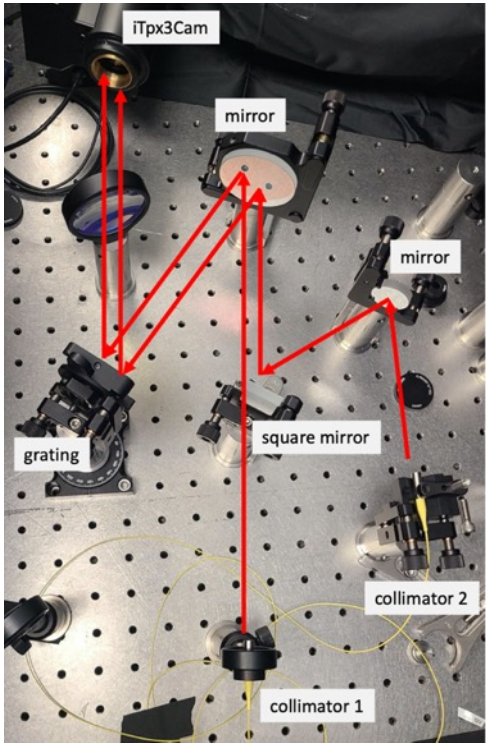
Next step: spectral binning

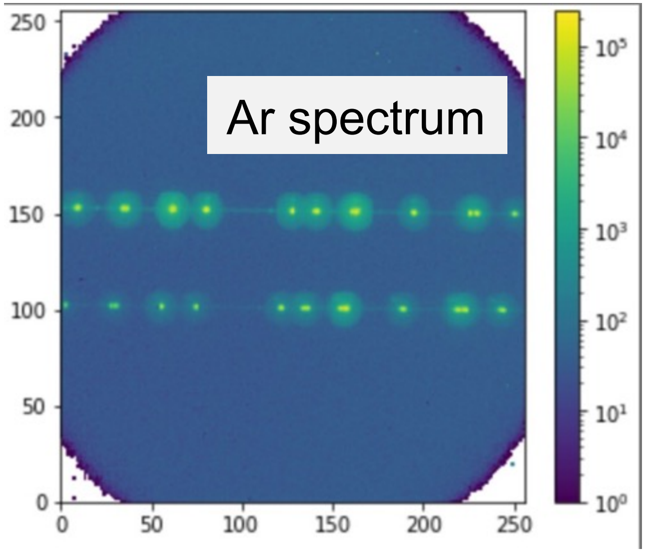
Spectral binning

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, published in JINST

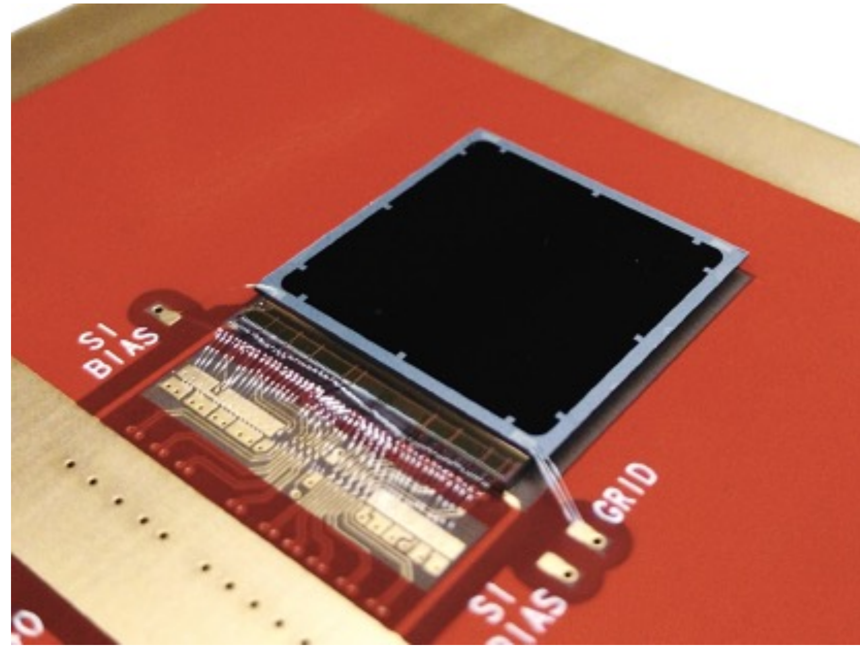
Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

Timepix3 ASIC:

- 256 x 256 array, 55 x 55 micron pixel
  - 14 mm x 14 mm active area
- 1.56 ns timing resolution
- Data-driven readout, 600 e min threshold, 80 Mpix/sec, no deadtime
- each pixel measures time and flux, ~1μs pixel deadtime when hit

T. Poikela et al, Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout, Journal of Instrumentation 9 (05) (2014) C05013.

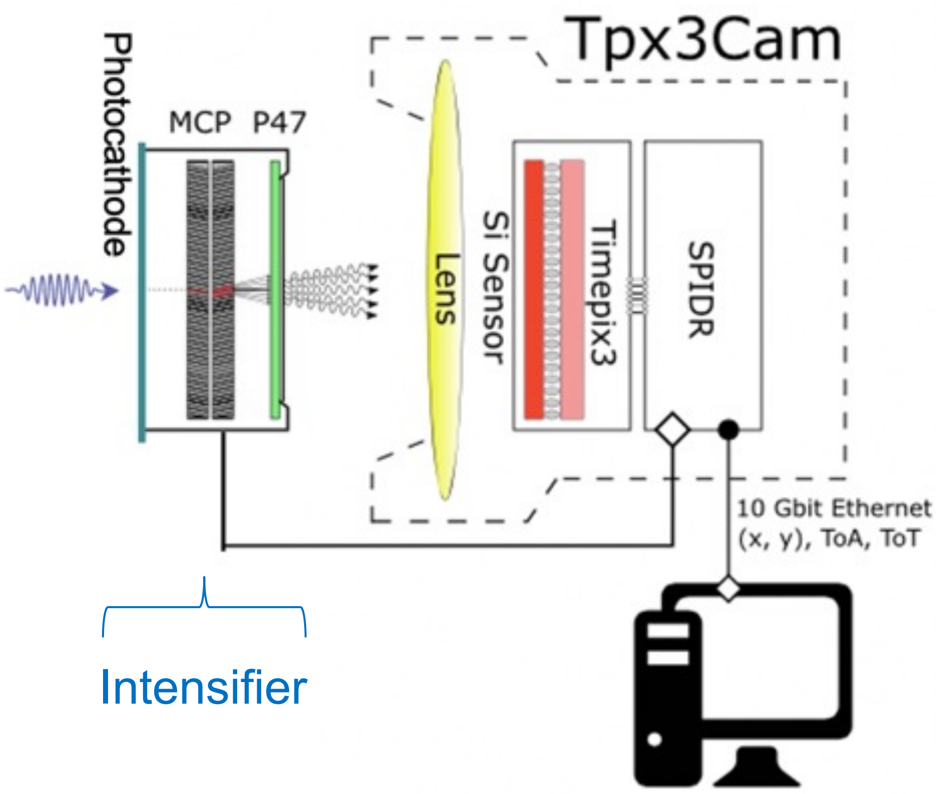


Sensor is bump-bonded to chip

Use existing x-ray readouts:
SPIDR (Nikhef & ASI)
www.amscins.com

Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.

Intensified camera: use off-the-shelf image intensifier



Intensifier

Intensified cameras are common:

- iCCD
- iCMOS cameras

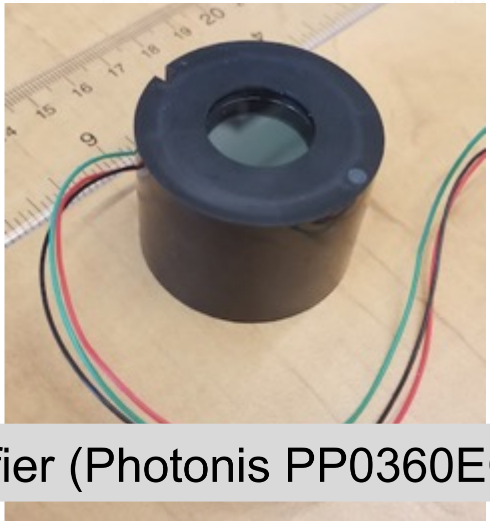
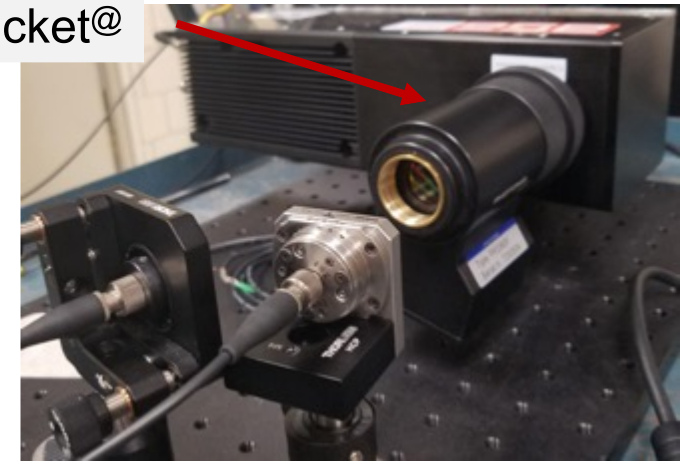
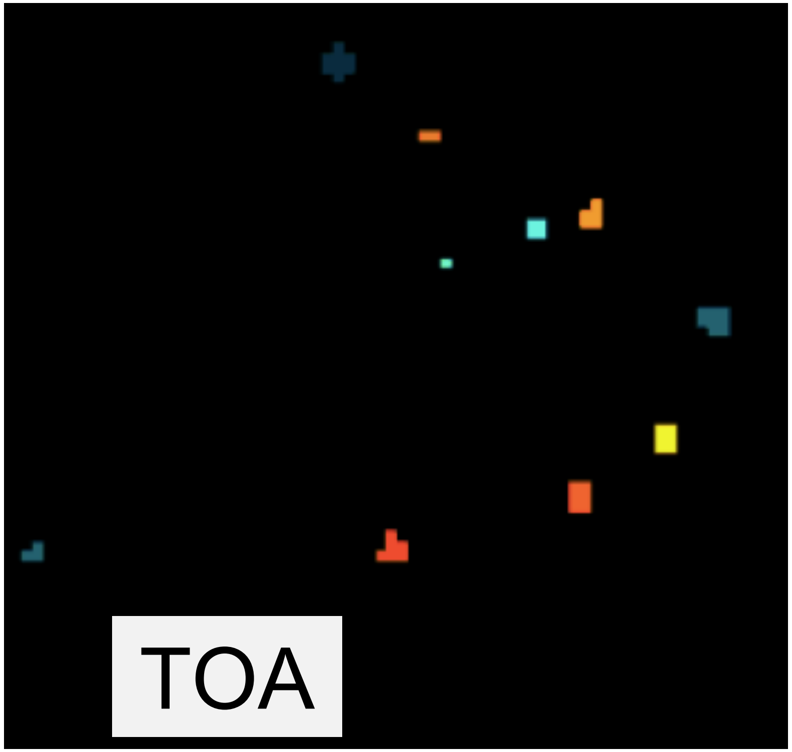
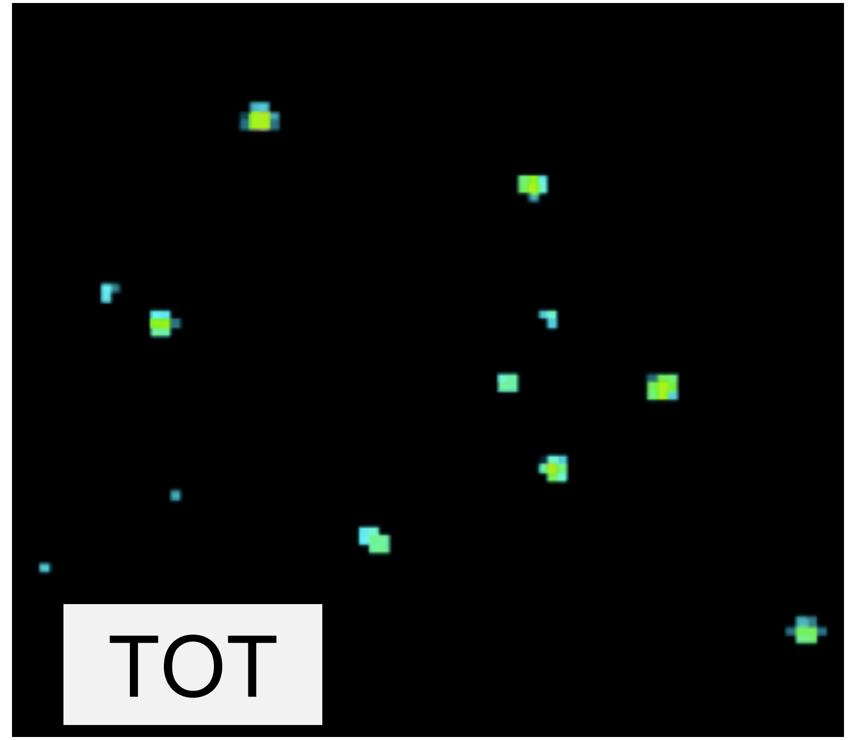


Image intensifier (Photonis PP0360EG)

Cricket@







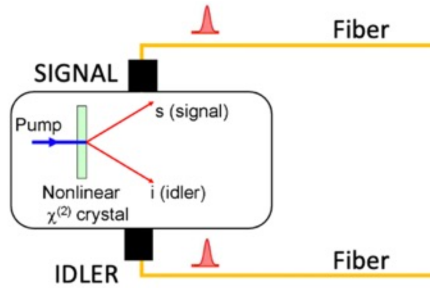
Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

Spatial resolution: 0.1 pixel / photon

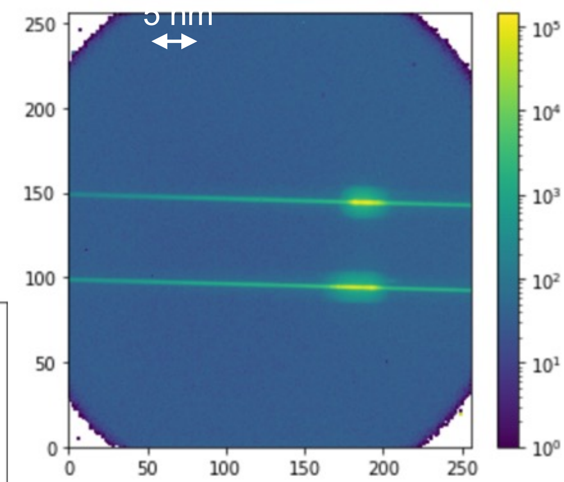
Time resolution: < 1 ns / photon

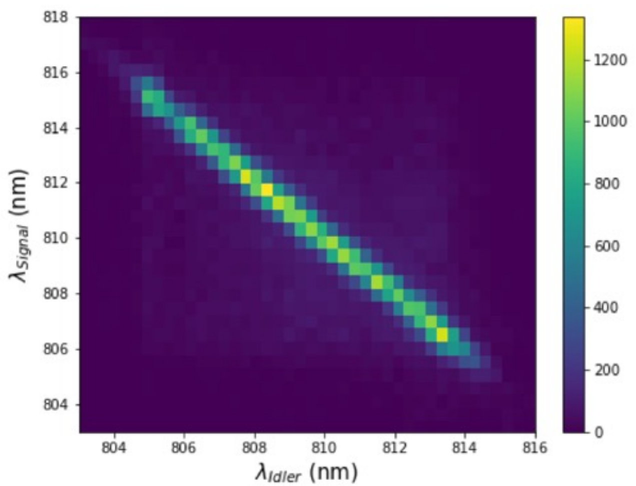
SPDC source in spectrometer

- 810 nm idler and signal
- no filter

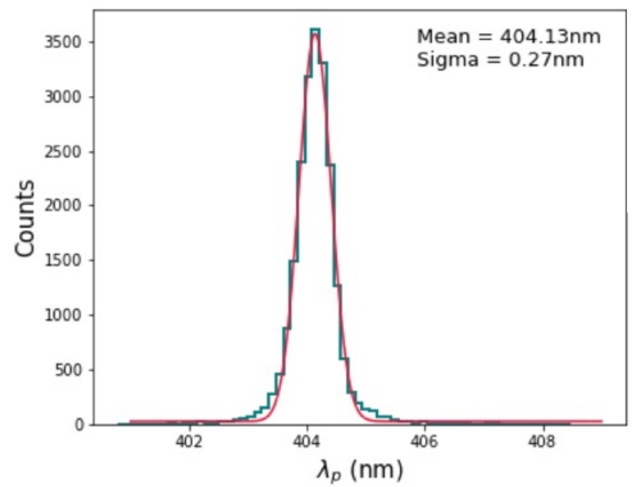


signal & idler in spectrometer

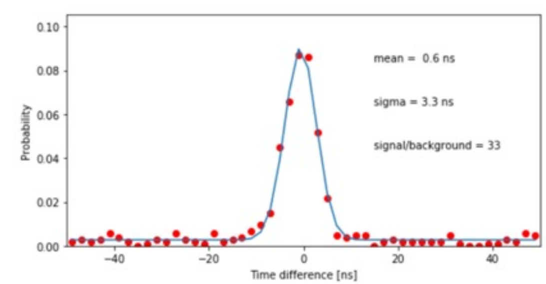




wavelength anti-correlation
for photon pairs



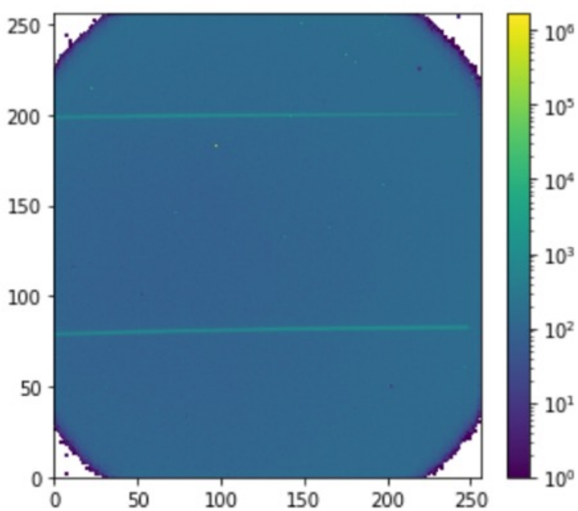
pump wavelength

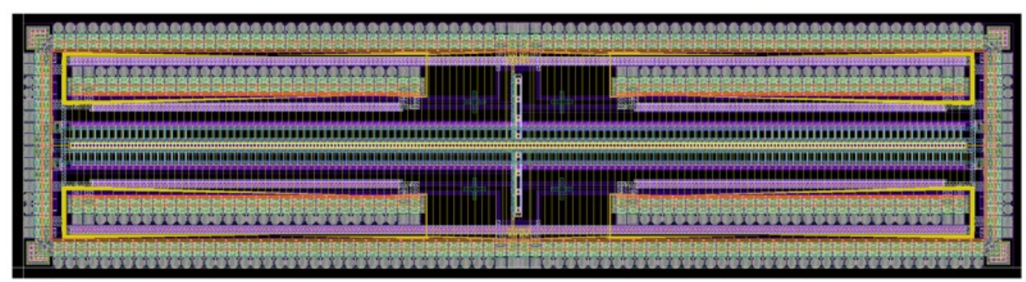


time coincidences

Next steps: spectrometer based on LinoSPAD2

Two diffracted photon stripes projected on to single linear array





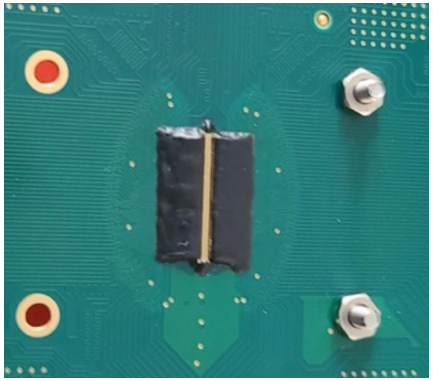
Spectrometer time resolution: ns → 100 ps

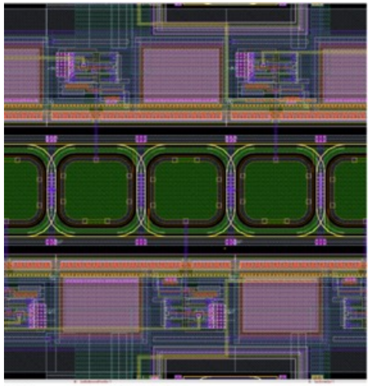
LinoSPAD2 linear SPAD array

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

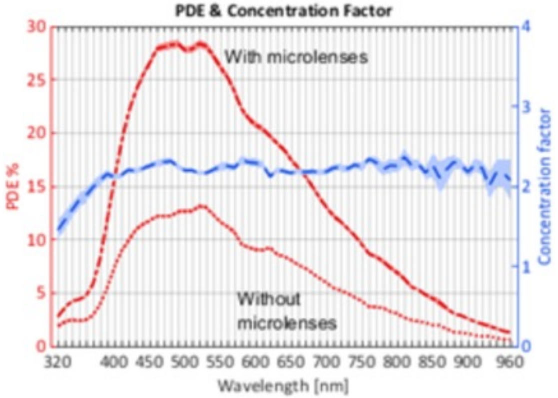
- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- Fill factor ~ 40%
- DCR ~ 30 Hz /pix @ room T
- Deadtime ~ 100ns
- Asynchronous readout of pixels

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

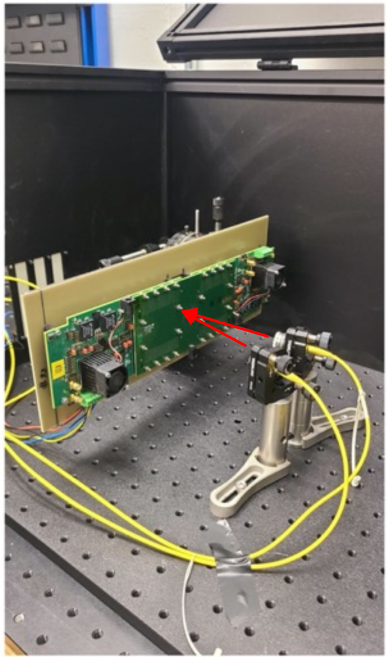


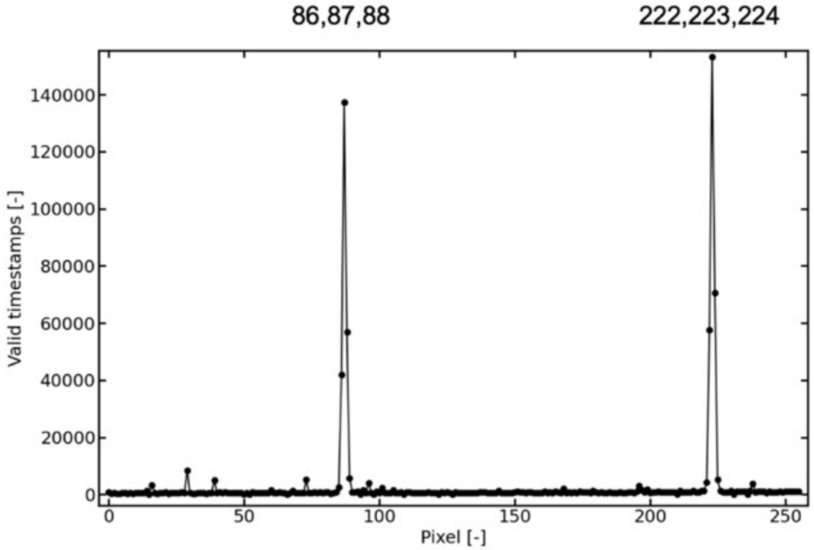


Close-up of SPADs

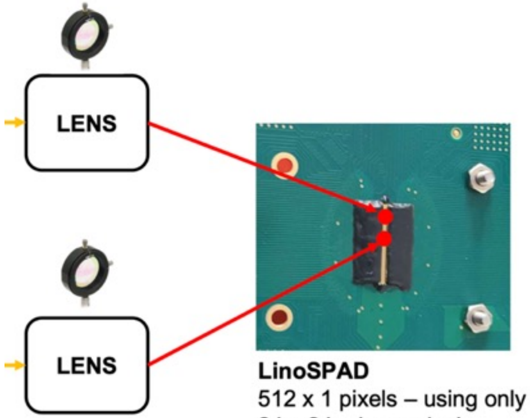


SPAD arrays with 50 ps resolution

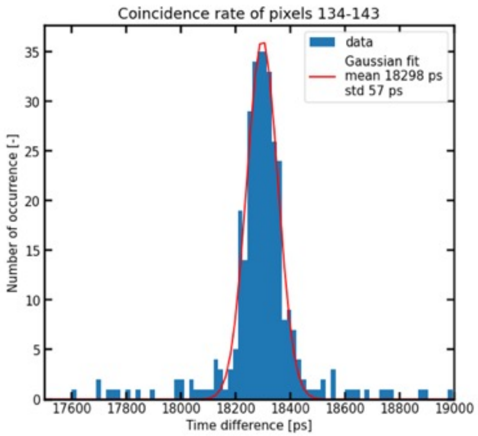




Two beams from SPDC source
Coincidence of two single photons

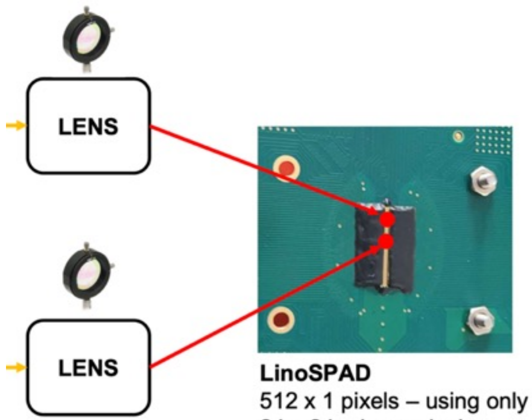


LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels

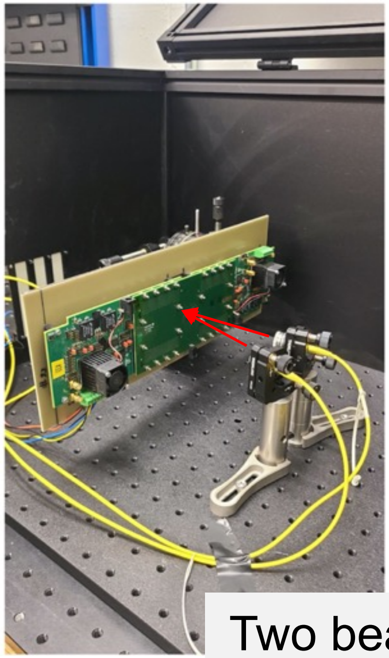


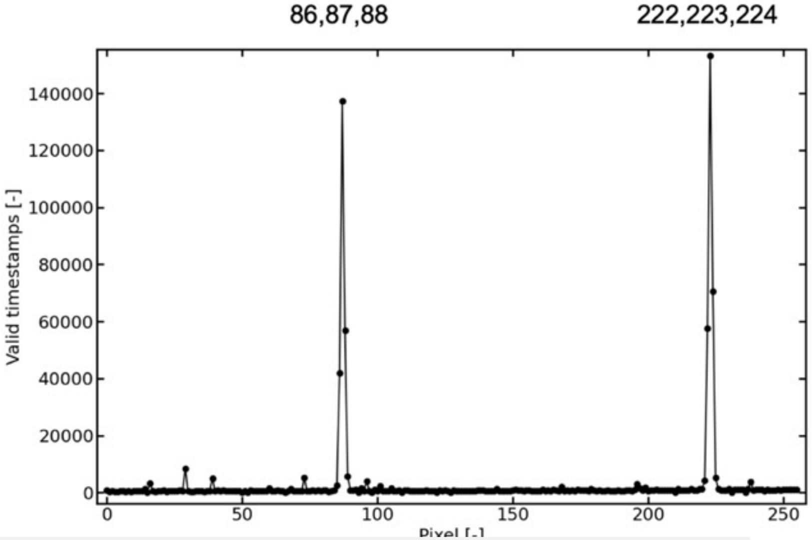
time difference, σ=57 ps

HBT peaks in LinoSPAD2

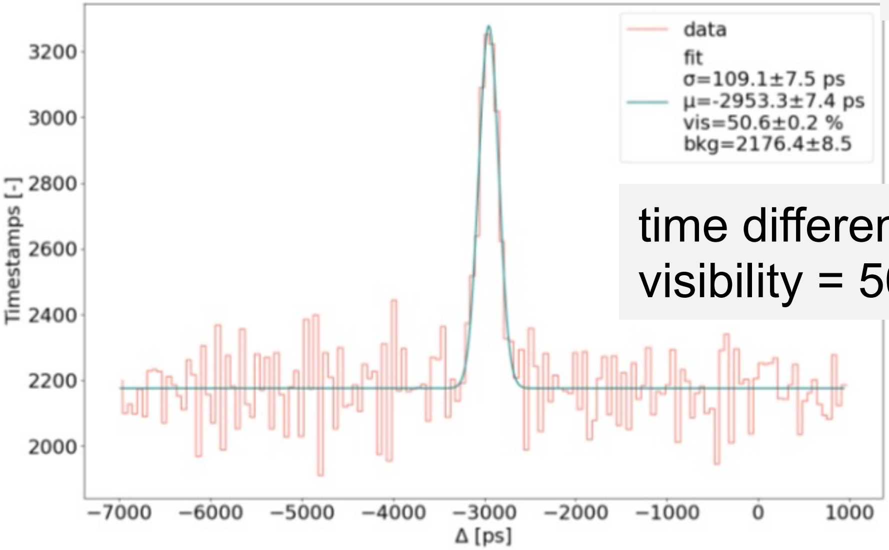


LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels





Two beams from Ar lamp + polarizer after beamsplitter

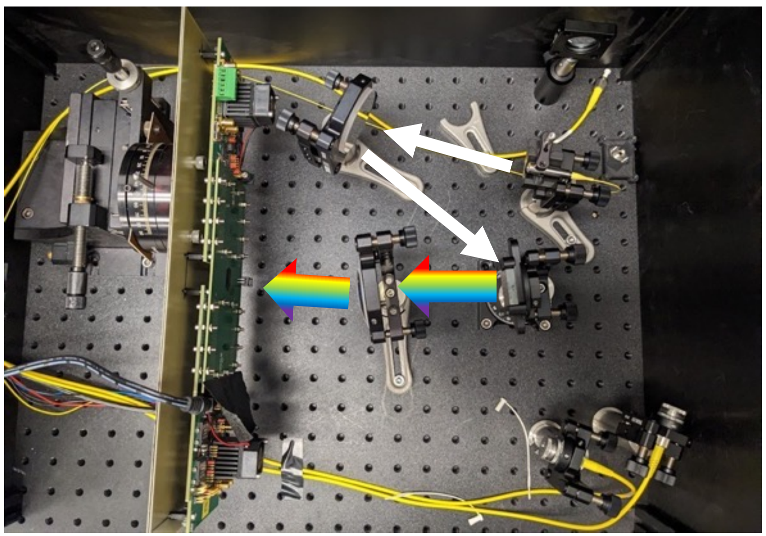


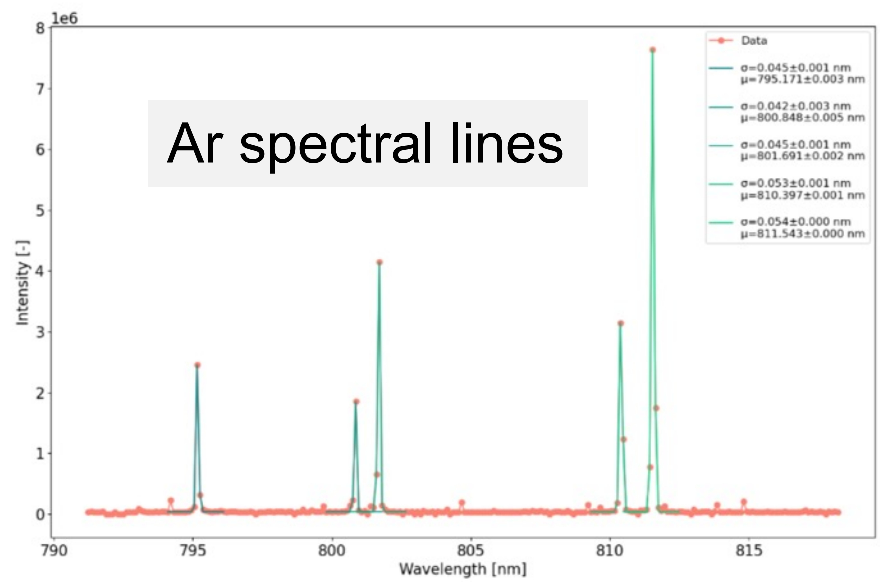
time difference, σ=110 ps
visibility = 50%

look for HBT = photon bunching, natural width > resolution

Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber



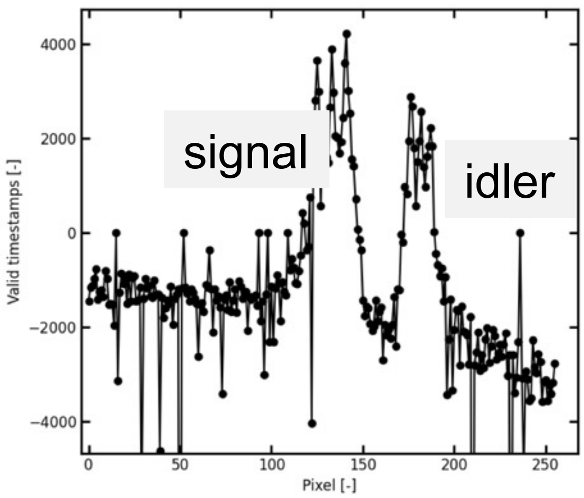


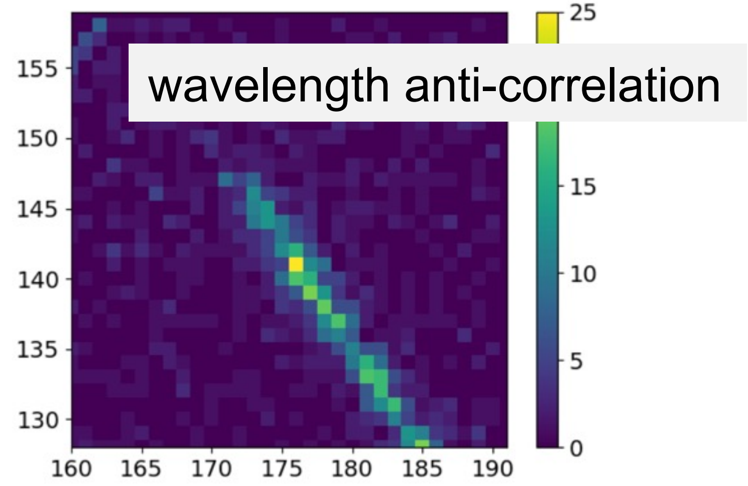
Achieved 0.04 nm spectral and 40 ps timing resolution

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

Wavelength anti-correlation in LinoSPAD2

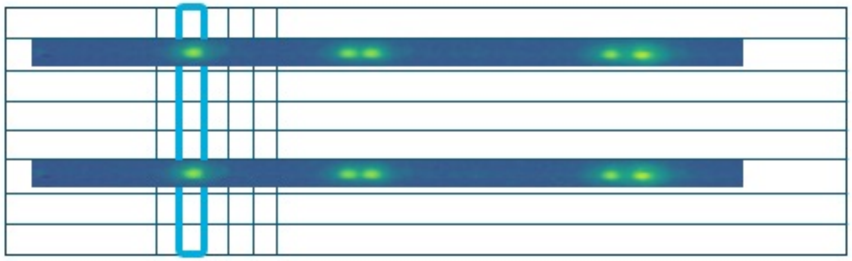
- Combine signal and idler in single fiber so can use single spectrometer channel
- At 50 mW signal and idler spectra do not overlap





Spectrometer with 0.04 nm and 40 ps resolutions → near Heisenberg limit

Fast sensor R&D



- 8*512 pixel array where each column is 8-pixel SiPM

SiPM approach

- Collaboration with EPFL, CzTU and FIU groups

- Wide sensor: easy to align, can be mass produced and used in field
- Time resolution is preserved or improved (goal 10 ps)
- Can count photons: detect coincidences in dual spectrometer, in spectral bins

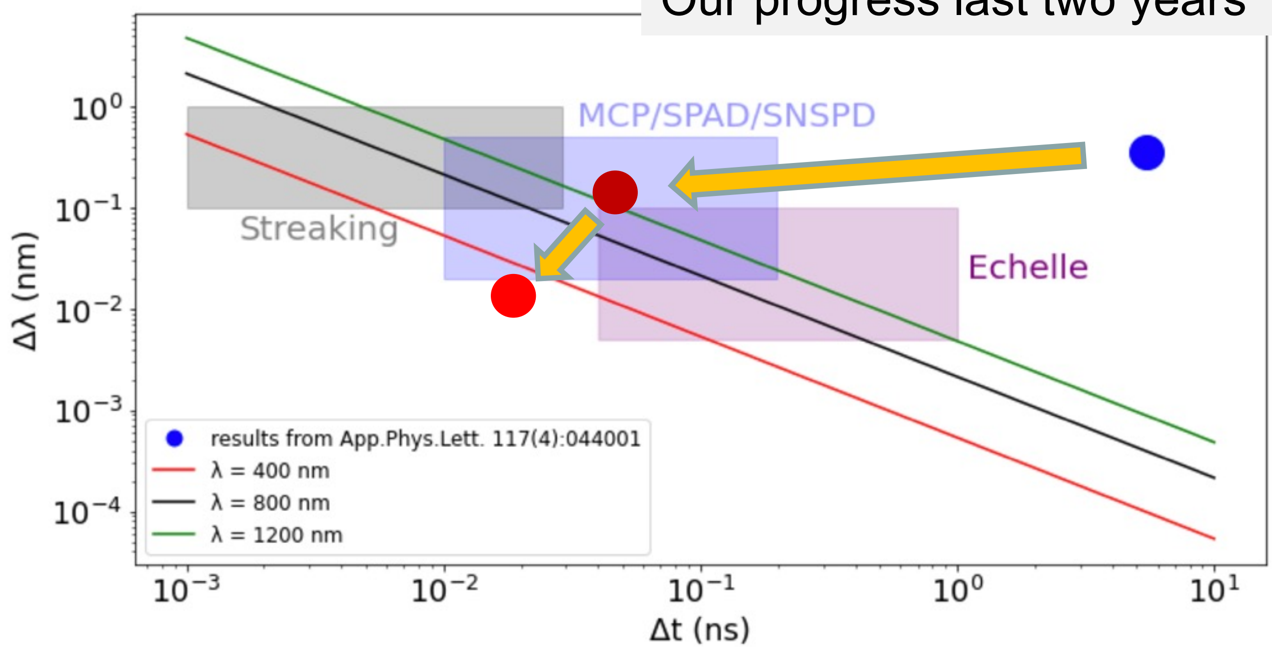
Fast spectrometers at Heisenberg limit

For a single photon uncertainties are bounded by Heisenberg uncertainty principle

$$\Delta t * \Delta E \;\geq\; \hbar/2$$

0.01 nm * 20 ps

Our progress last two years

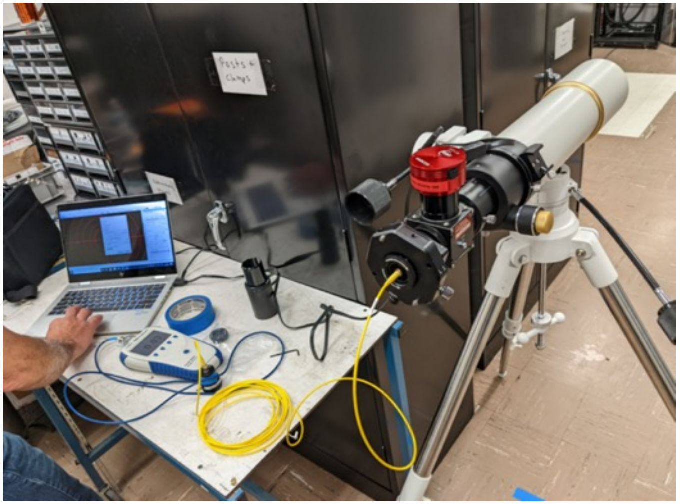


A.Nomerotski et al, Quantum-assisted optical interferometers: instrument requirements, in SPIE Proceedings on Astronom. Telescopes (2020), arxiv: 2012.02812

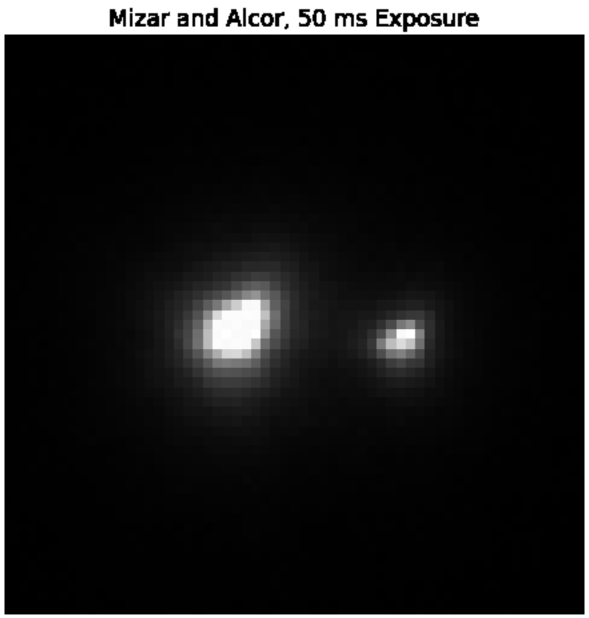
telescopes

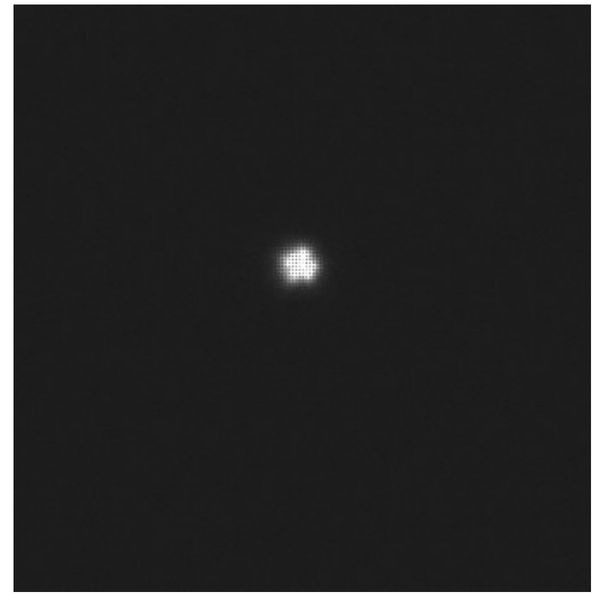
On-sky measurements

- Experimenting with SM fiber coupling
- Trying adaptive optics



On-sky measurements





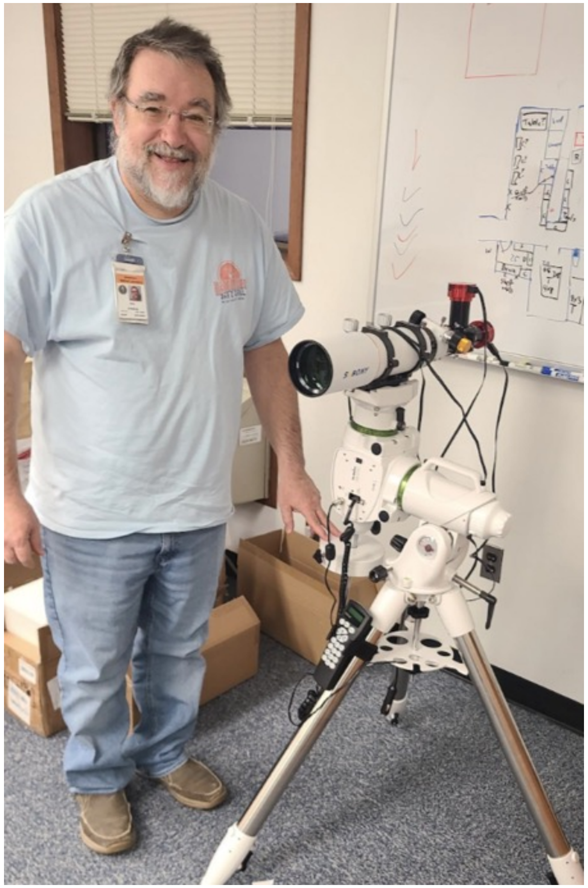
Mizar A & B

- 50 ms exposure
- 15 arcsec separation

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

Future steps

- Setting up 4 telescopes
- Exploring options for adaptive optics (AO)
  - Coupling starlight to SMF will require this (due to atmosphere)
- Exploring tradeoffs of MMF
  - Easier to collect light, may not need AO
  - More difficult to focus in spectrometer



On-sky Experiments

- Collaboration with intensity interferometry astro community
  - overlap in instrumentation

Intensity interferometer in SCSU

Goal: propose a small experiment with HEP scope in 2024

Supported by DOE HEP QuantISED grant

Special Events

- Quantum-Enhanced Telescopy Workshop

Quantum-Enhanced Telescopy Workshop

Sunday, 18 June 09:00 – 17:00

Organizers:
Paul Kwiat, *University of Illinois at Urbana-Champaign, USA*
Andrei Nomerotski, *Brookhaven National Laboratory, USA*
Brian Smith, *University of Oregon, USA*

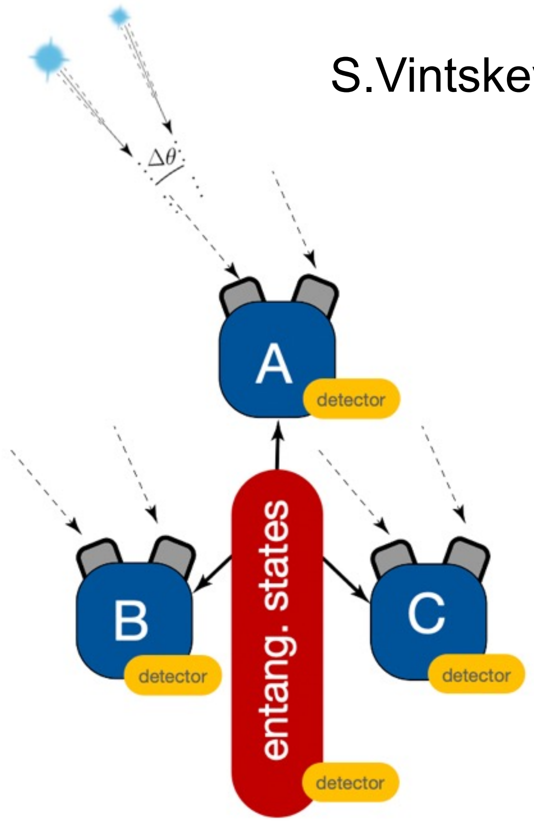
The angular resolution of conventional very long-baseline interferometry (VLBI) in the optical (visible and near-infrared) spectrum is currently limited by the need to combine coherent optical fields collected by separated telescopes. This becomes impractical over more than a few hundred meters. Recent proposals that utilize quantum resources, such as quantum memories and entanglement, have shown promise to obviate the need to directly combine the signals from separated telescopes and thus enable significantly longer baselines, leading to greatly increased resolution.

The workshop aims to bring together astronomers and quantum information scientists to discuss the emerging role of quantum technologies for improved astronomical observations. It will highlight current experimental and theoretical progress as well as future areas of research.

Developing the quantum

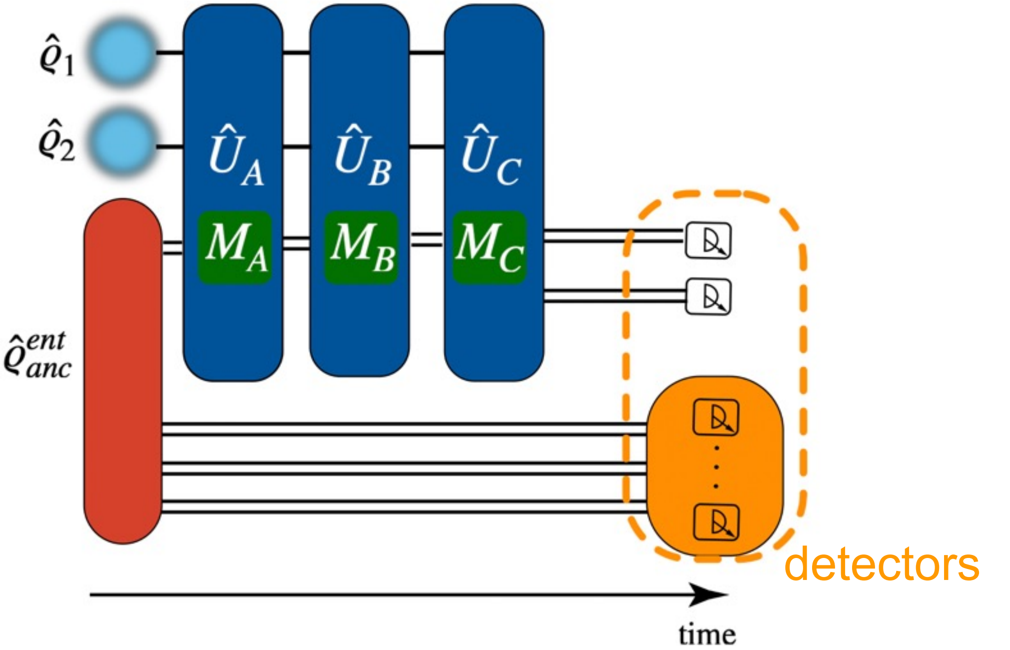
Use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations and quantum protocol to process information in noisy environment

S.Vintskevich et al



Geometry: 2 stars + A,B,C telescope stations + source of entangled photon states + detectors

Quantum protocol circuit



- Density operators ρ
- Multi-partite entanglement is distributed over multiple stations
- Quantum protocol evaluates experimental observables
- Paper in preparation

Multipartite Entanglement for Quantum Astrometry

- Strategy: discover and classify multipartite entangled states on few qubits to design interferometry patterns optimized for studying specific quantities

Machine Learning Multipartite Entanglement

- Strategy of classifying entanglement: entanglement witnesses
- Positive expectation value for specific patterns of entanglement
- Nonpositive expectation for separable states
- Equivalent to finding separating hyperplanes in Hilbert space
- Ideal for support vector machine methods in machine learning (optimized for finding separating hyperplanes)

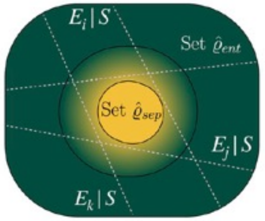


FIG. 2. Schematic representation of results obtained with the SVM approach. The decision boundaries between the set of separable states S and each class of entangled states E_i are represented by dashed lines. Each line corresponds to a particular class and is specified by a vector representation $\vec{w}_i$ of the entanglement witness operator $\hat{W}_i$ in accordance with Eqs. (1) and Eqs. (3).

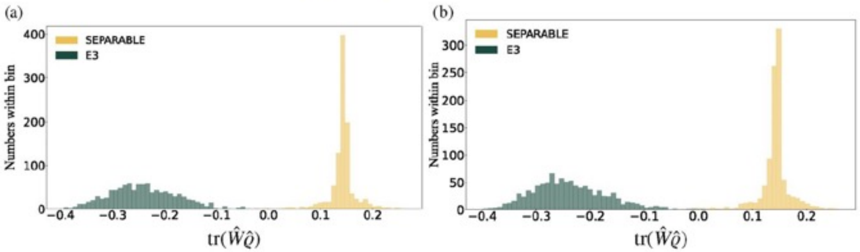


FIG. 3. Distribution of $\mathrm{tr}(\hat{\varrho}\hat{W})$, mean value of the entanglement witness for (a) validation set and (b) test set of the trained EW model via linear SVM algorithm in the case of E_3 family of states. Both test set and validation set consist of 2000 samples: 1000 separable states and 1000 entangled states of E_3 family. For both validation and test sets there were only few ($\leqslant 5$) miss-classifications of entangled states and zero miss-classifications for separable states. Note that the training data set included mixed Werner states to achieve better generalization.

Classification of four-qubit entangled states via Machine Learning; S. V. Vintskevich, N. Bao, A. Nomerotski, P. Stankus, D.A. Grigoriev; published in Phys Rev A doi.org/10.1103/PhysRevA.107.032421

more quantum

PHYSICAL REVIEW LETTERS **123,** 070504 (2019)

Optical Interferometry with Quantum Networks

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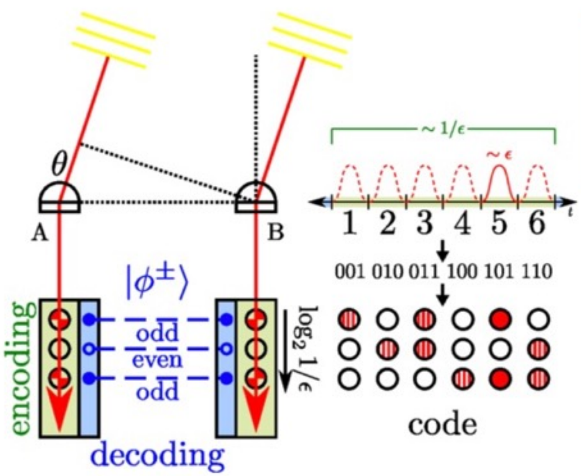
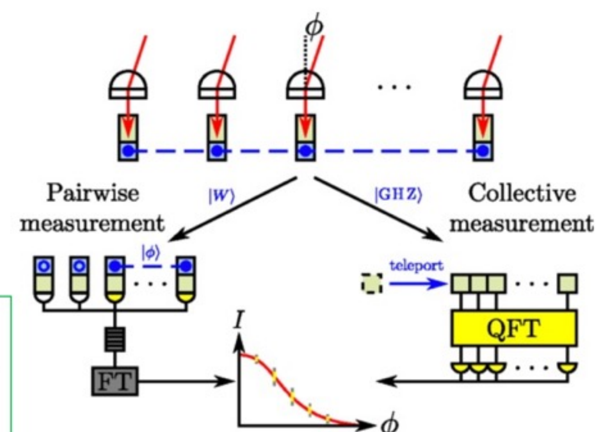
(Received 17 September 2018; published 15 August 2019)

Idea: Capture and store sky photons in quantum memories, then teleport and measure as needed



Idea: Efficient time-bin encoding of photon arrivals

Idea: Use quantum Fourier transform (QFT) to directly invert pattern from array



To sum up

Main points to take home

- Classical, 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
- One specific two-photon technique addresses dynamic astrometry, which will have interesting astrophysics applications
- There is a potentially broad program in quantum-assisted optical interferometry ahead

Main publications

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]

PHYSICAL REVIEW A **00**, 002400 (2023)

Classification of four-qubit entangled states via machine learning

S. V. Vintskevich,[1] N. Bao,[2] A. Nomerotski,[2] P. Stankus,[2] and D. A. Grigoriev[3]
[1]*Technology Innovation Institute, Abu Dhabi, Masdar City 9639, United Arab Emirates*
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(Received 6 July 2022; accepted 2 March 2023; published xxxxxxxxxx)

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Increasing baselines and precision of optical interferometers using two-photon interference

PHYSICAL REVIEW D **107**, 023015 (2023)

Astrometry in two-photon interferometry using an Earth rotation fringe scan

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Andrei Nomerotski and Anže Slosar
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Stephen Vintskevich
Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region 141700, Russia

The Open Journal of Astrophysics

Instrumentation and Methods for Astrophysics

Vol. 5, 2022 • November 01, 2022 IST

Two-photon amplitude interferometry for precision astrometry

Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich

https://doi.org/10.21105/astro.2010.09100

www.quantastro.bnl.gov

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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Zhi Chen
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Aarom Mueninghoff

Jingming Long
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Bram Bouwens
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Jord Prangsma
Duncan England
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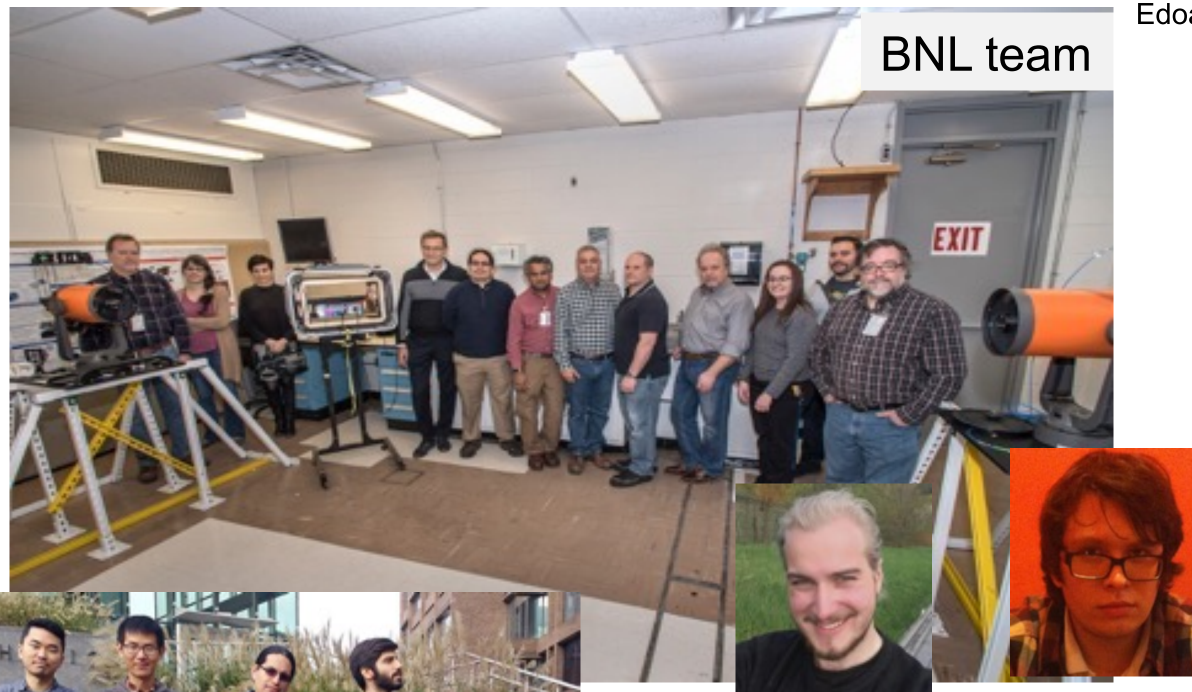
Boris Blinov
Mila Zhukas
Maverick Millican
Alex Kato
Peter Svihra
Michal Marcisovsky
Sergei Kulkov
Jakub Jirsa
Raphael Abrahao
Brianna Farella
Ryan Mahon

Ermanno Bernasconi
Claudio Bruschini
Samuel Burri
Tommaso Milanese
Edoardo Charbon



BNL team


SBU team

Questions?