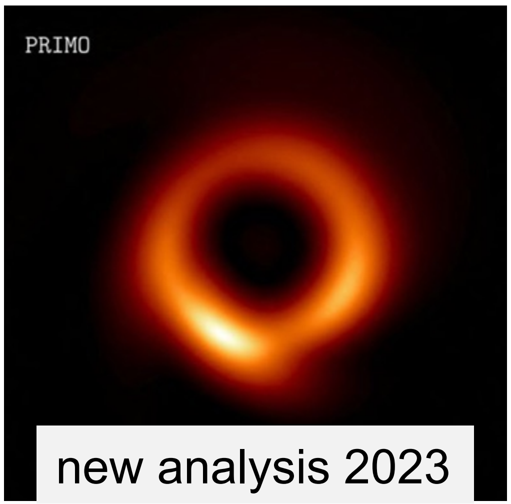
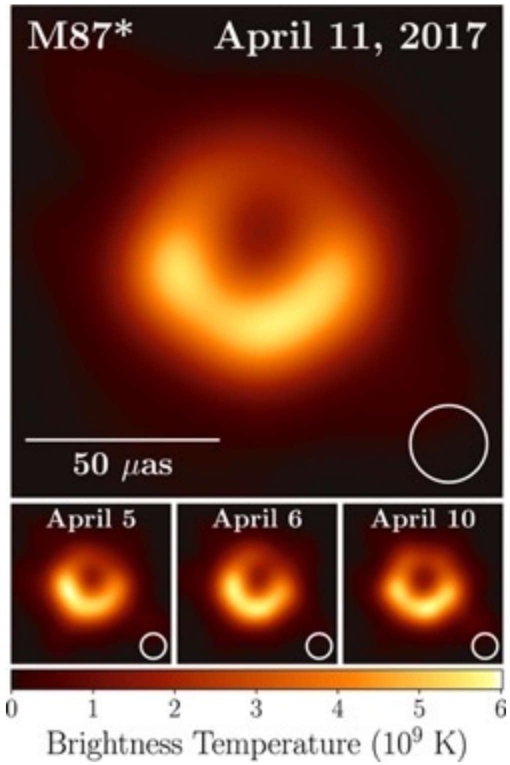
Quantum-Assisted Optical Interferometry for Precision Astrometry

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 et al

Astronomy picture of the decade





sensitive to features on angular scale

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

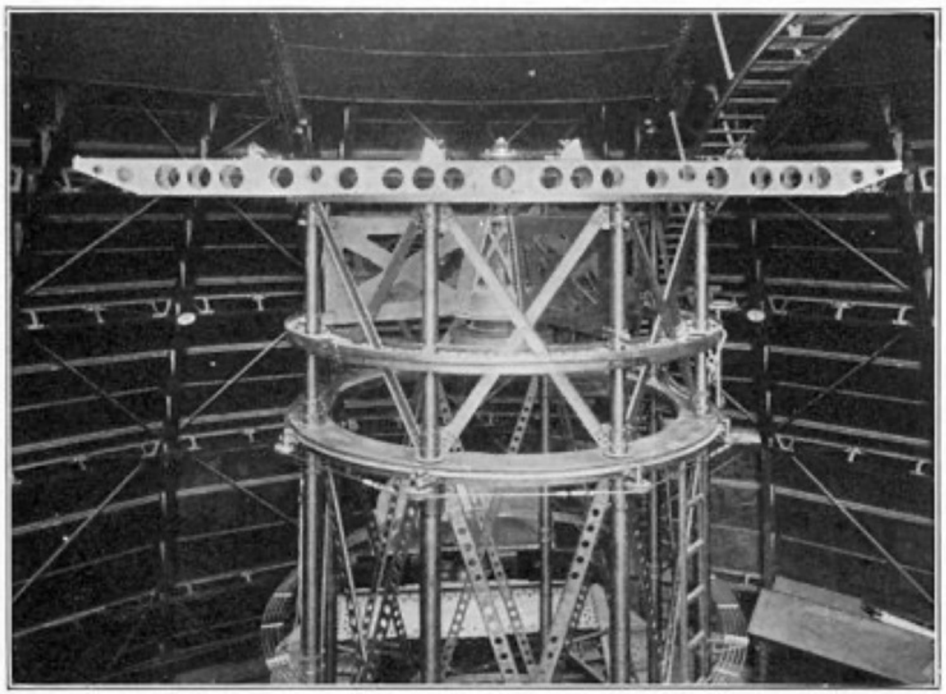
2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

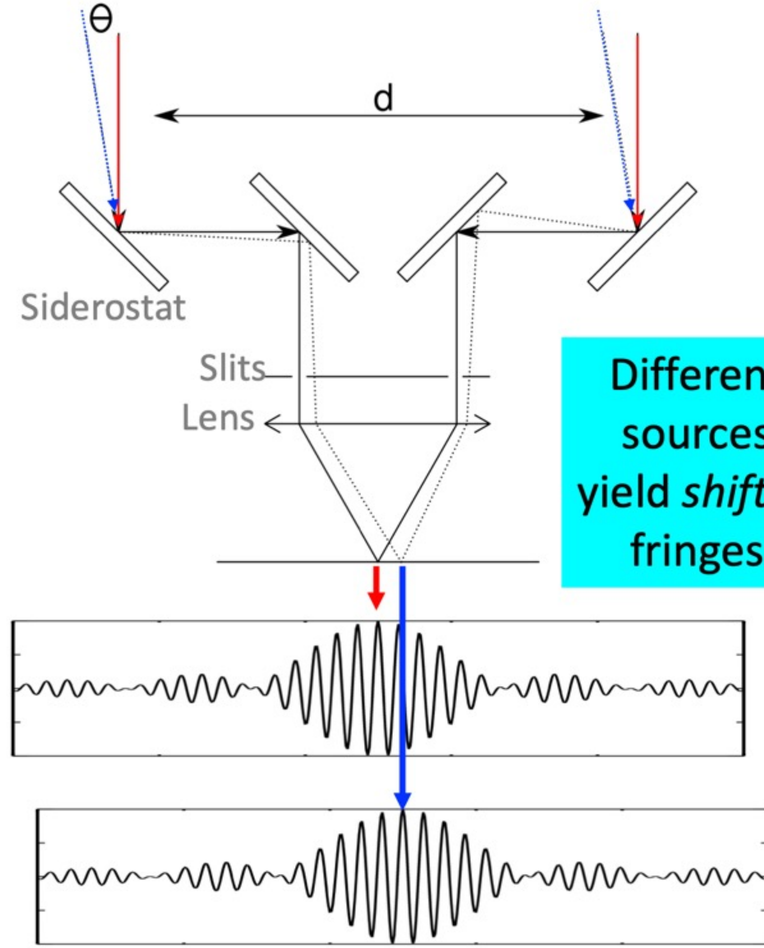
Achieved by radio interferometry with ~10000 km baselines

Classical interferometry

In classical times

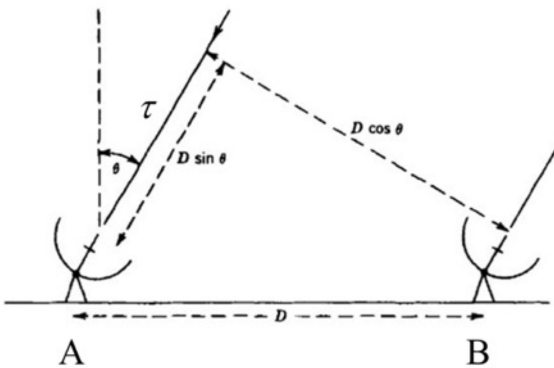


Michelson Stellar Interferometer at Mt. Wilson c. 1920,
after original idea by Michelson & Fizeau c. 1890



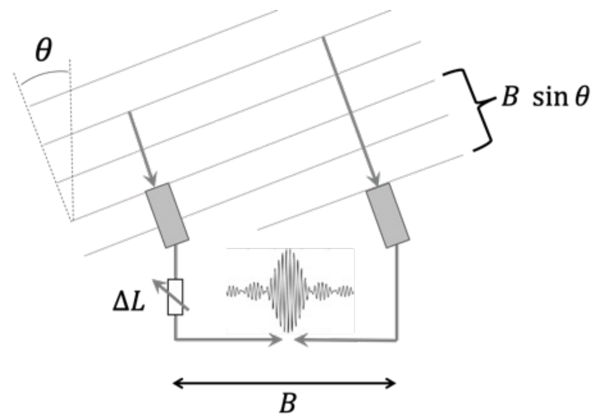
Different sources yield *shifted* fringes

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

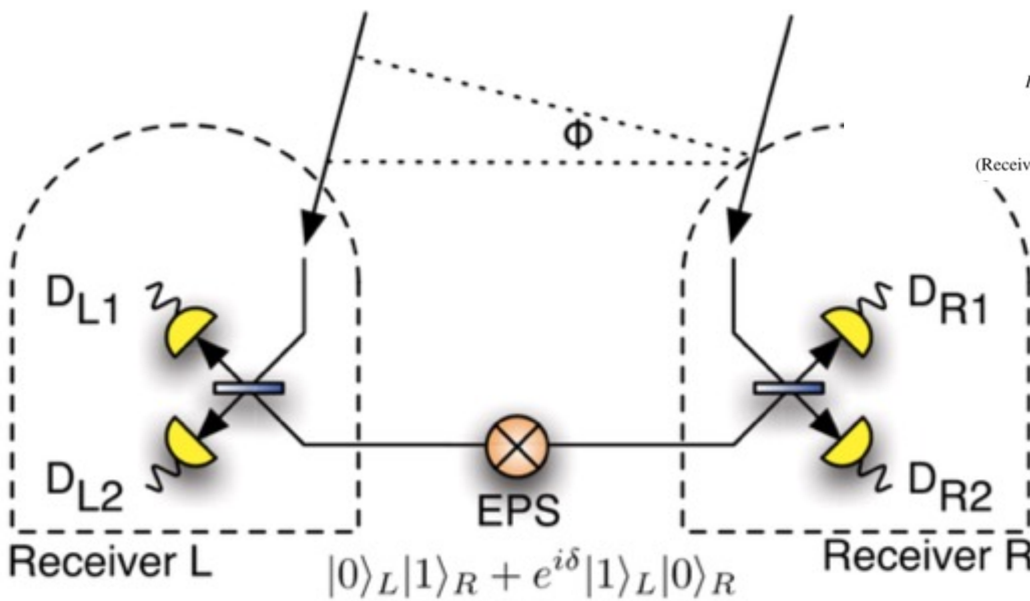
Accuracy ~ 1 mas

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)

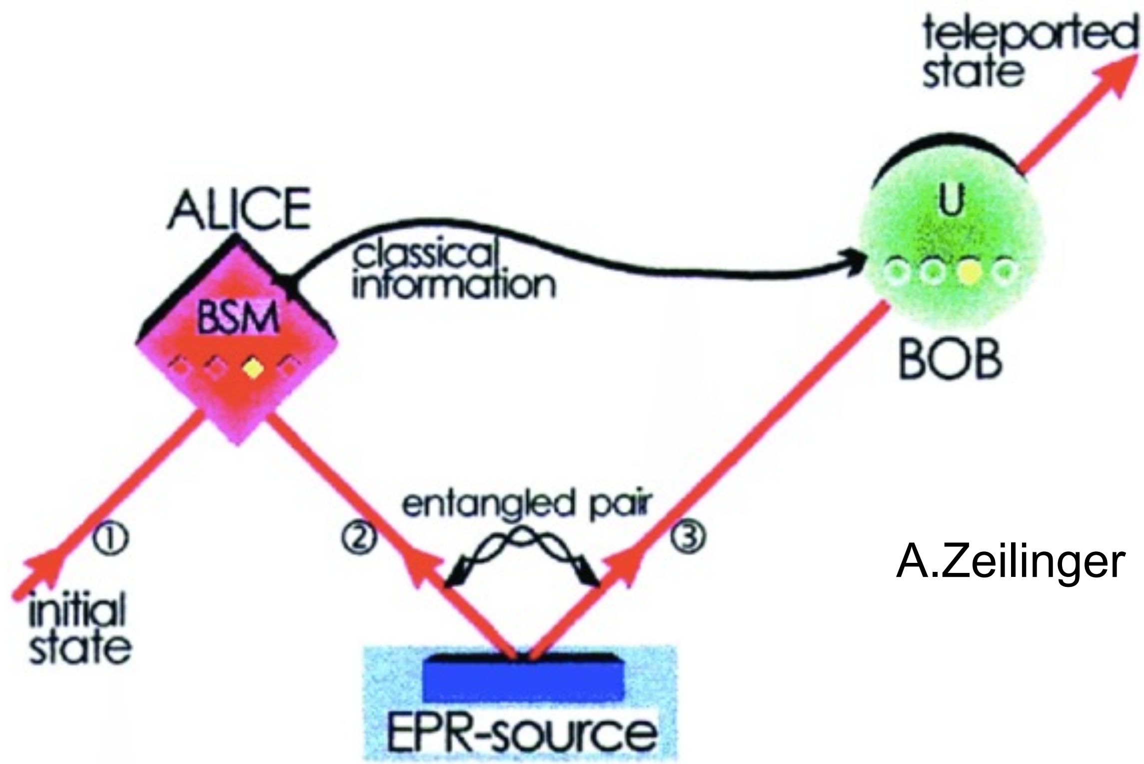
$$\Delta\theta \sim \frac{\lambda}{b}$$

- 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

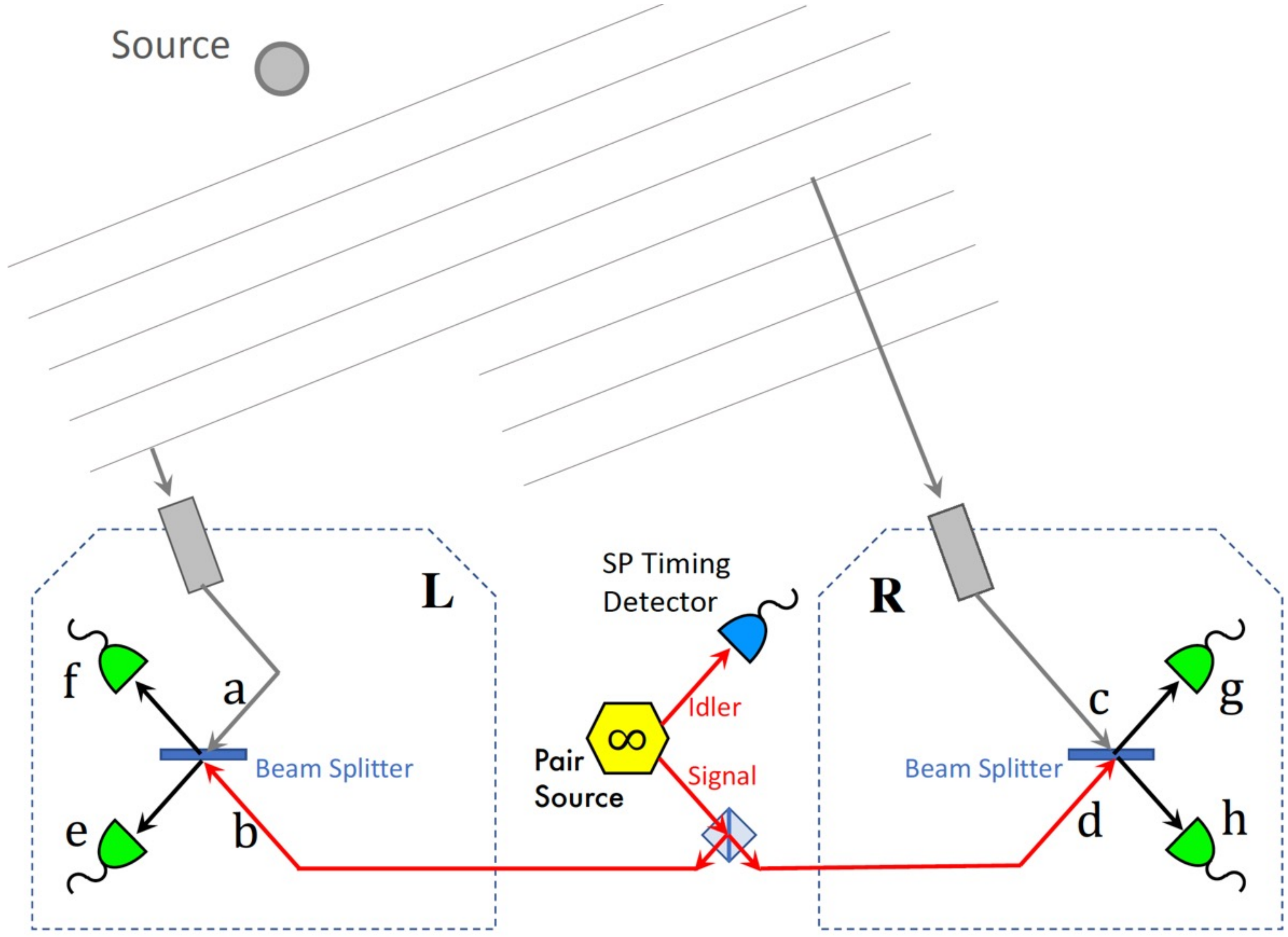
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- 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)

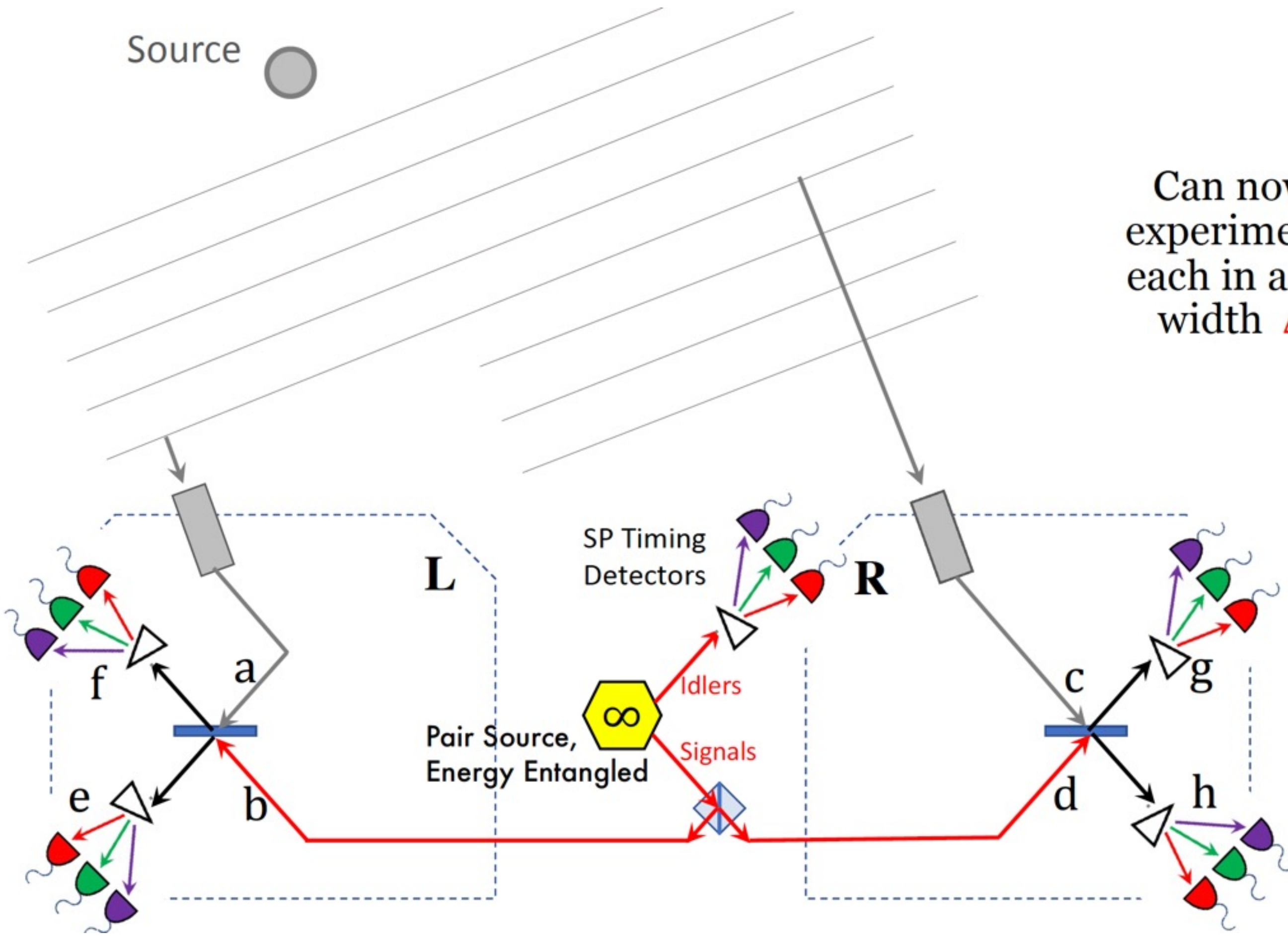


A.Zeilinger

with pair source

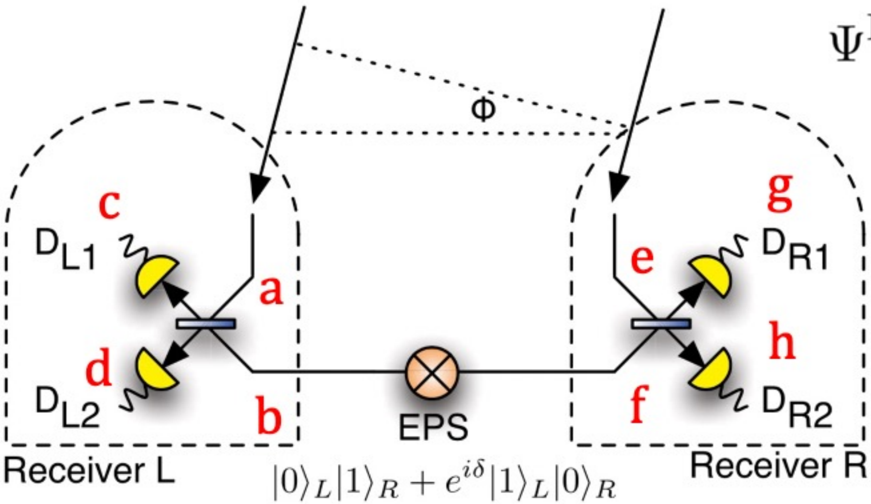


with pair source and spectral binning



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

What do we measure?



$$\Psi^{\text{Initial}} = \psi_1\psi_2 = \frac{1}{2}(\hat{a}^\dagger + e^{i\delta_1}\hat{e}^\dagger)(\hat{b}^\dagger + e^{i\delta_2}\hat{f}^\dagger)$$

Sky photon — Ground photon

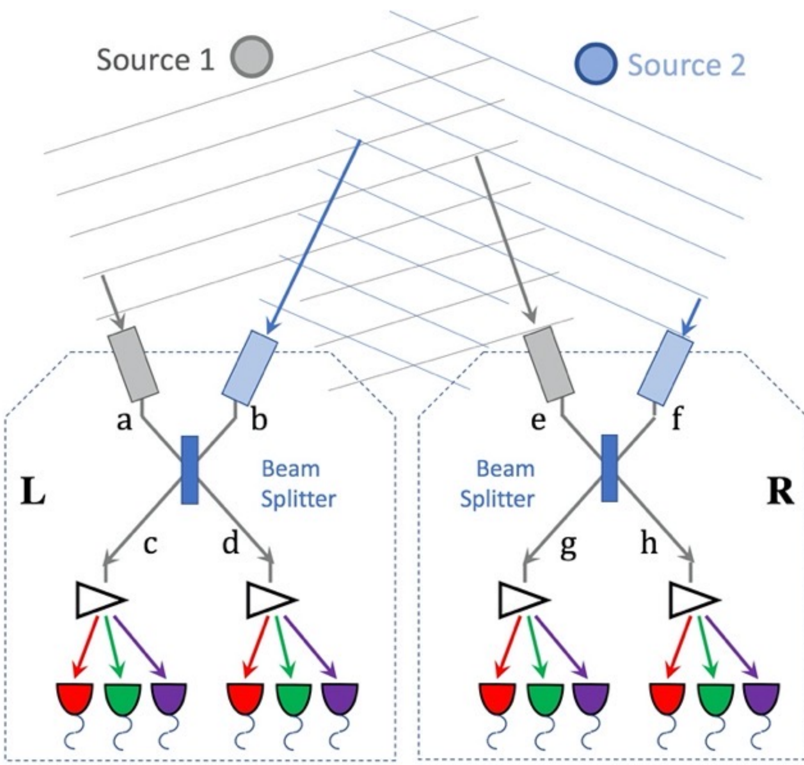
Beam Splitters

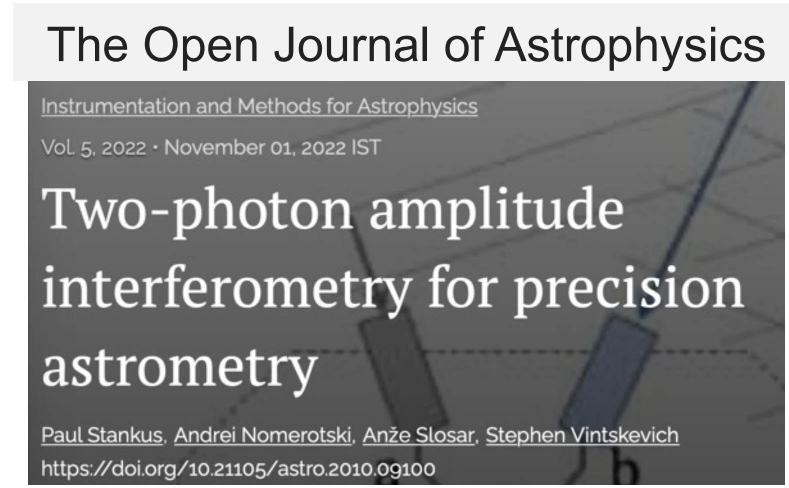
$$\hat{a}^\dagger \to (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} \qquad \hat{b}^\dagger \to (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2}$$
$$\hat{e}^\dagger \to (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} \qquad \hat{f}^\dagger \to (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2}$$

$$\begin{aligned}\Psi^{\text{Output}} = {} & (1/4)(\hat{c}^\dagger\hat{c}^\dagger - \hat{d}^\dagger\hat{d}^\dagger + e^{i(\delta_1+\delta_2)}(\hat{g}^\dagger\hat{g}^\dagger - \hat{h}^\dagger\hat{h}^\dagger) + \\ & (e^{i\delta_1} + e^{i\delta_2})(\hat{c}^\dagger\hat{g}^\dagger - \hat{d}^\dagger\hat{h}^\dagger) + (e^{i\delta_1} - e^{i\delta_2})(\hat{c}^\dagger\hat{h}^\dagger + \hat{d}^\dagger\hat{g}^\dagger))\end{aligned}$$

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

Idea: use two sky photons




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

Sensitive to *difference* in path length differences ☞ opening angle!

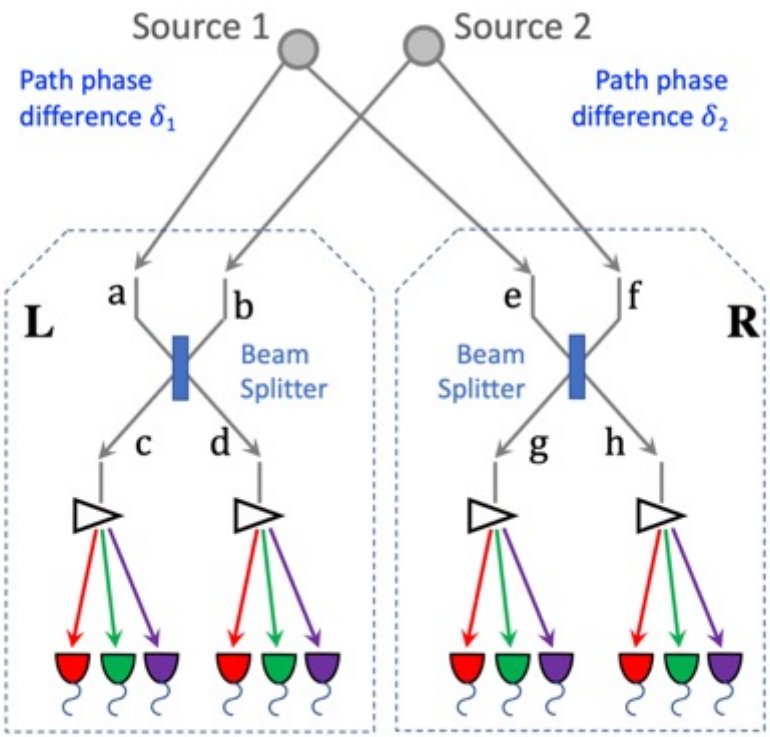
Does *not* require live optical link between stations; can use arbitrary baseline, similar advantage as HBT.

Does require coincidence of sky photons, similar drawback as HBT

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

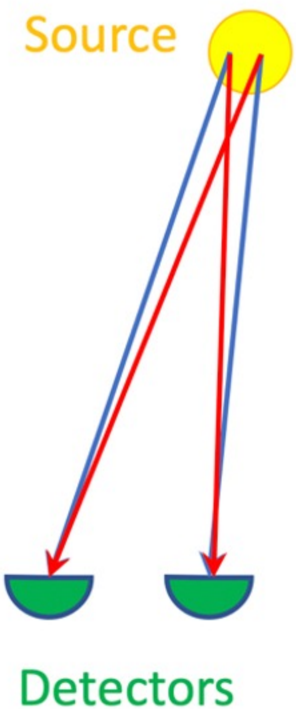
$$
A^2 \eta_1 \eta_2 T_r \Bigg[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm 2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B (\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \Bigg] \quad (30)
$$

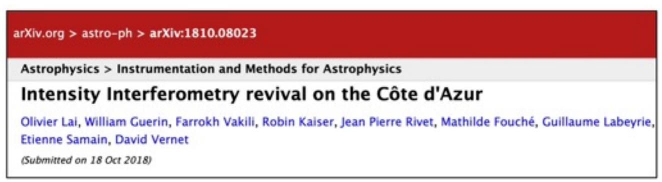
New oscillatory term!

- 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)

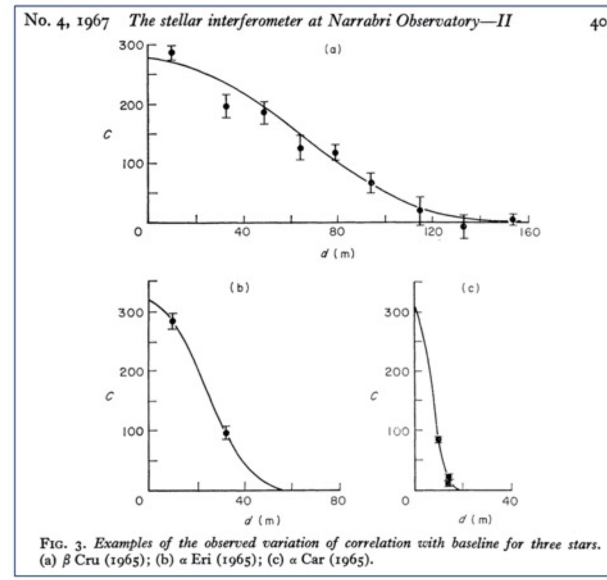
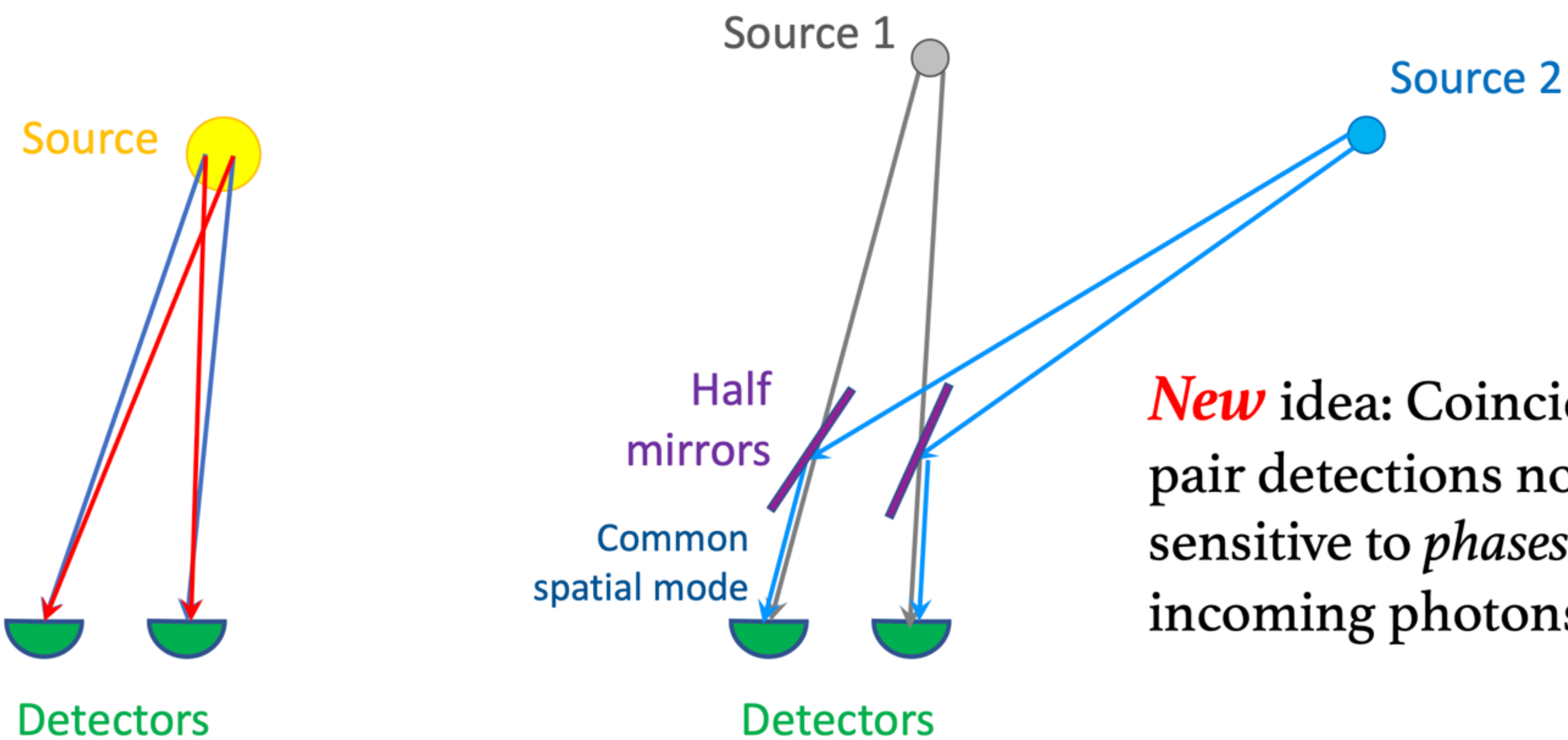


FIG. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

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

Hanbury Brown – Twiss Interferometry

HBT with two sources?

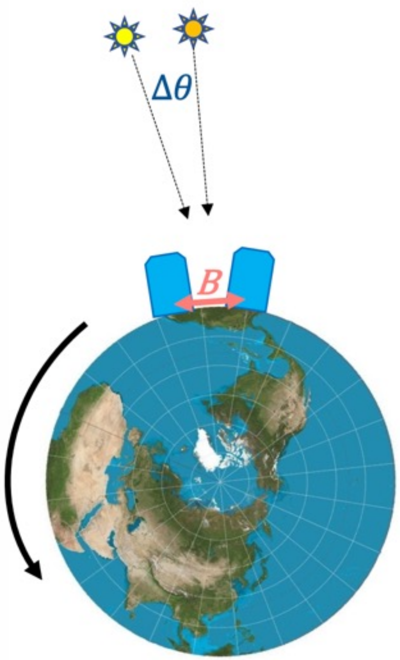


New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Earth rotation fringe scan

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

This will evolve as the Earth rotates



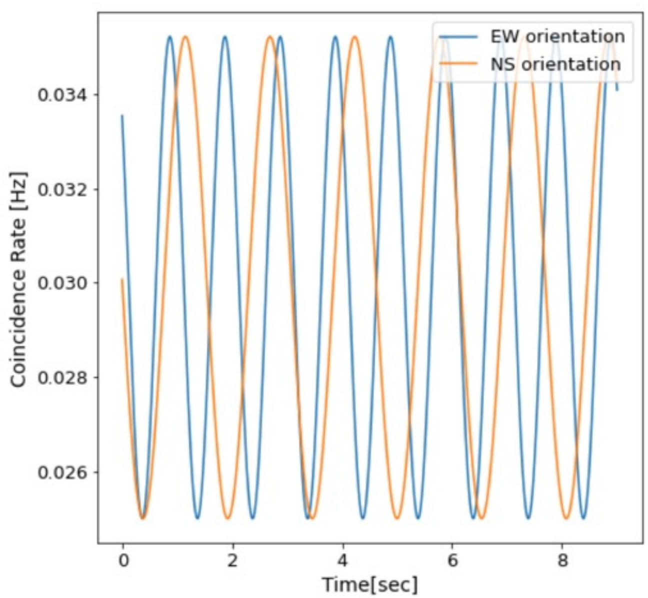
$$\langle N_{xy}\rangle(t) = \bar{N}_{xy}\left[1 \pm V\cos\left(\omega_f t + \Phi\right)\right]$$

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

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

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

Zhi Chen

Stony Brook University, Stony Brook, New York 11794, USA and Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

Andrei Nomerotski and Anže Slosar

Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

Paul Stankus

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, USA

Stephen Vintskevich

Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region 141700, Russia

World-competitive precision

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

$\bar{n}$ = 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

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

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

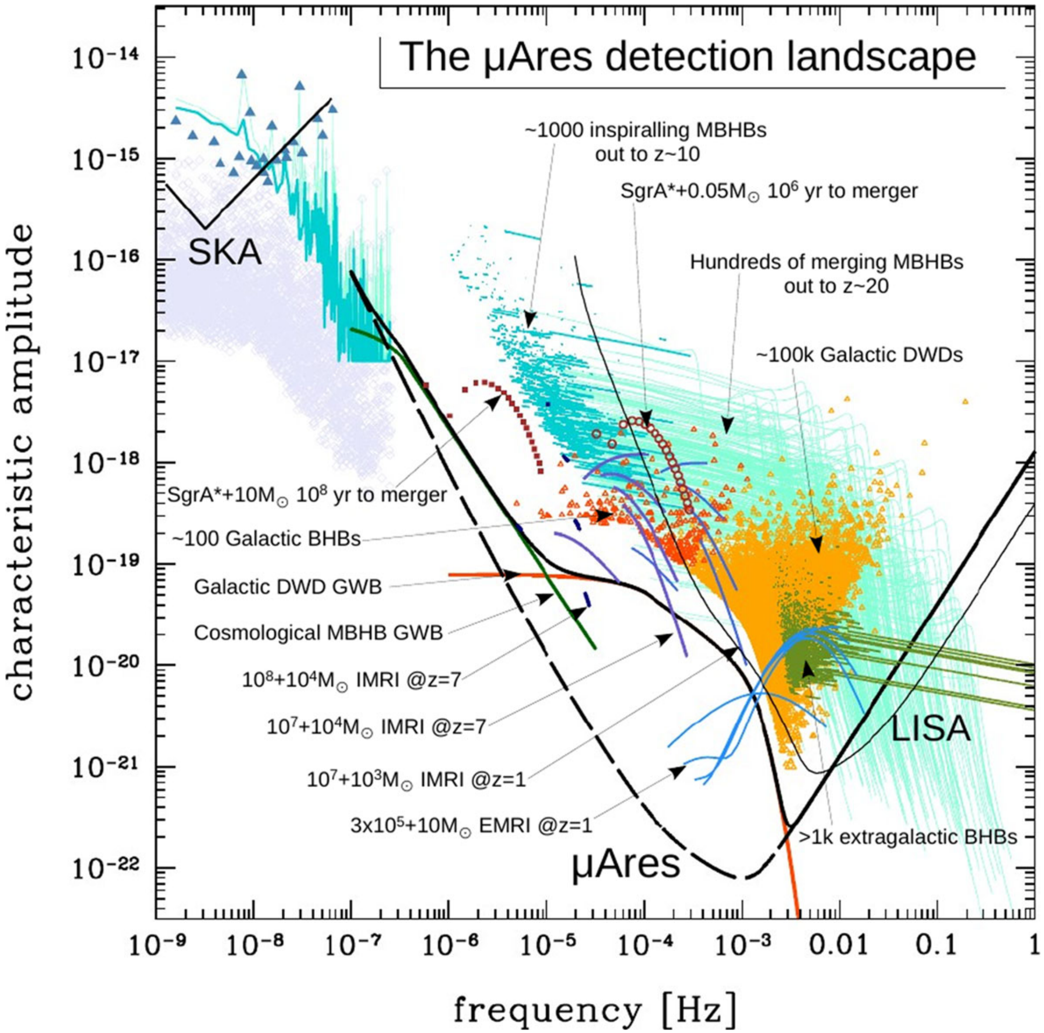
Possible impact on astrophysics and cosmology

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



Experimental Astronomy (2021) 51:1333–1383
https://doi.org/10.1007/s10686-021-09709-9

ORIGINAL ARTICLE

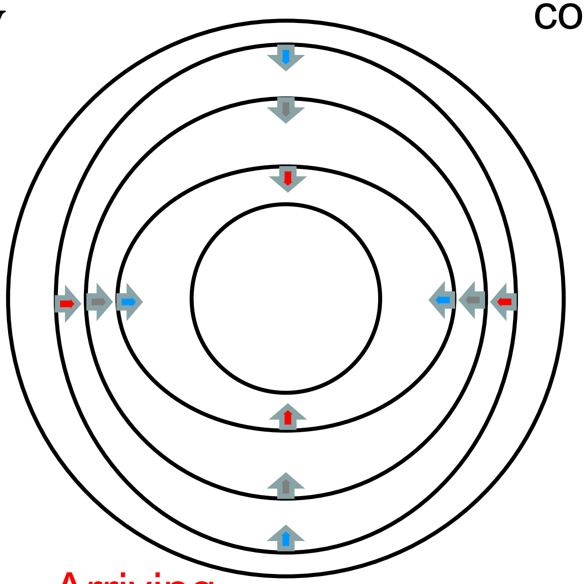
Unveiling the gravitational universe at μ-Hz frequencies

Paper is a proposal for a giant post-LISA space-based interferometer with 400MKm baselines. Very far future but contains many useful references on GW sources

LIGO

If we track individual arriving wave/pulse fronts then we see an alternating quadrupole pattern of early and late arrivals.

Surfaces of constant phase



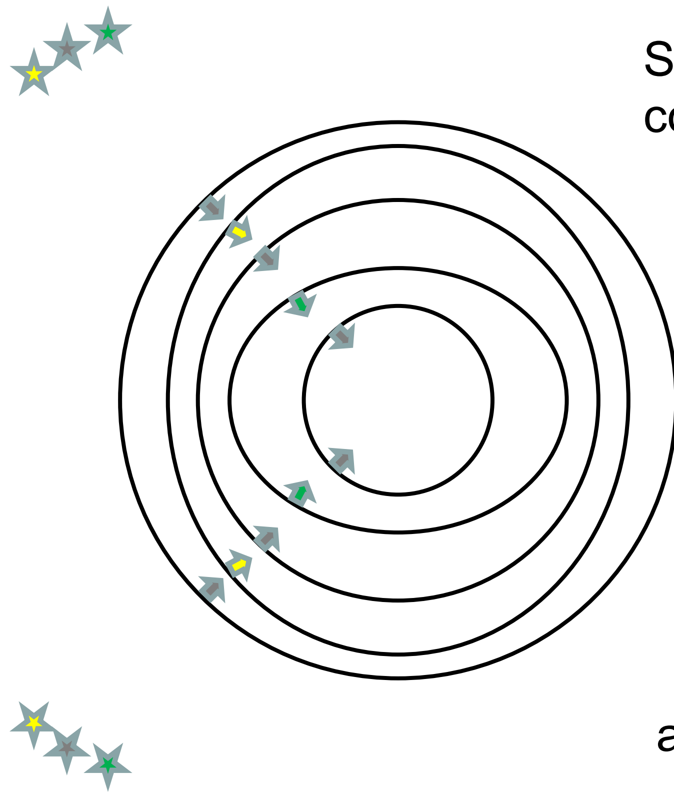
Arriving Early

Arriving Late

Pulsar Timing Method

The surfaces of constant phase are bent along the diagonal directions, which must correspond to a change in apparent incoming direction/sky position.

Surfaces of constant phase



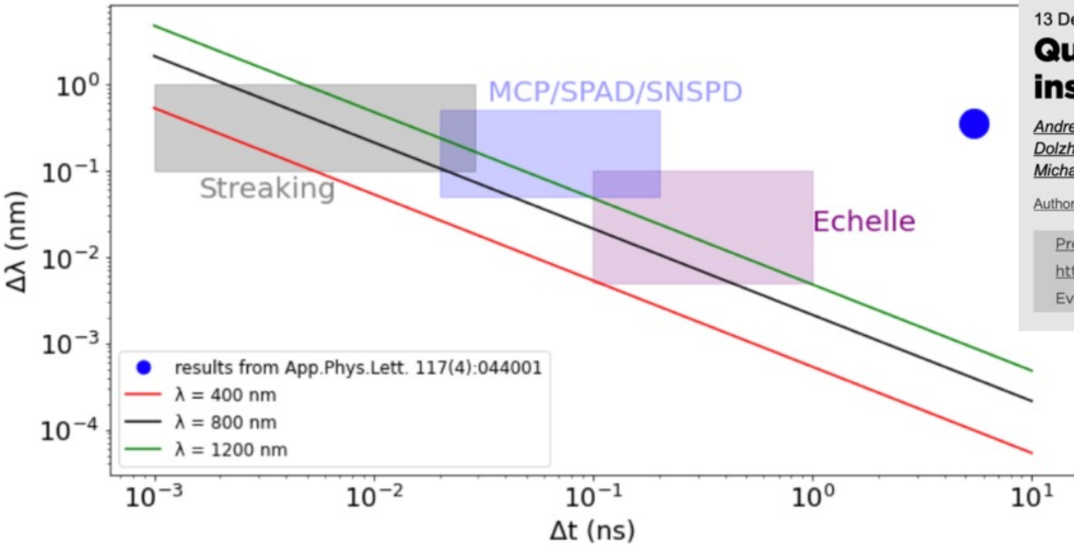
Astrometry Method

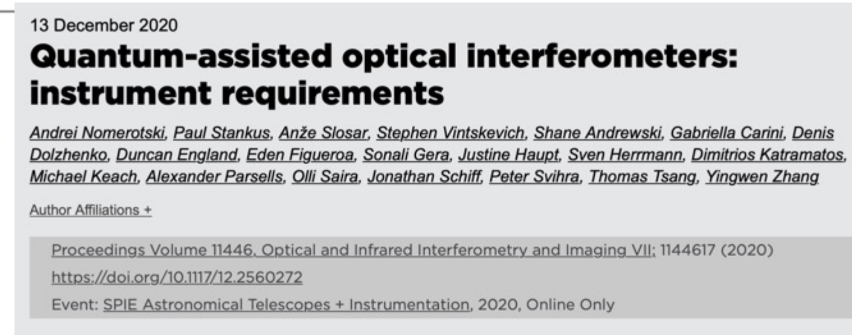
arxiv.org/2204.07677

Astrometric Gravitational-Wave Detection via Stellar Interferometry

Michael A. Fedderke[1,*] Peter W. Graham[2,3,†] Bruce Macintosh[3,‡] and Surjeet Rajendran[1,§]
[1]*The William H. Miller III Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA*
[2]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA*
[3]*Kavli Institute for Particle Astrophysics & Cosmology, Department of Physics, Stanford University, Stanford, CA 94305, USA*
(Dated: July 6, 2022)

Requirements for detectors




13 December 2020

Quantum-assisted optical interferometers: instrument requirements

Andrei Nomerotski, Paul Stankus, Anže Slosar, Stephen Vintskevich, Shane Andrewski, Gabriella Carini, Denis Dolzhenko, Duncan England, Eden Figueroa, Sonali Gera, Justine Haupt, Sven Herrmann, Dimitrios Katramatos, Michael Keach, Alexander Parsells, Olli Saira, Jonathan Schiff, Peter Svihra, Thomas Tsang, Yingwen Zhang

Author Affiliations +

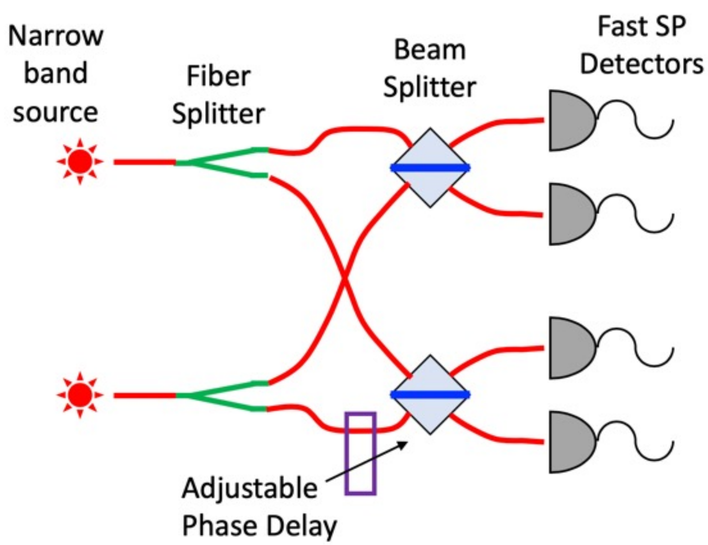
Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 1144617 (2020)
https://doi.org/10.1117/12.2560272
Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

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

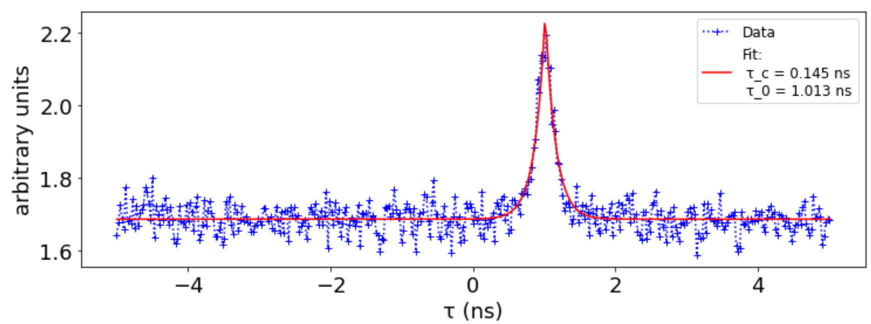
$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

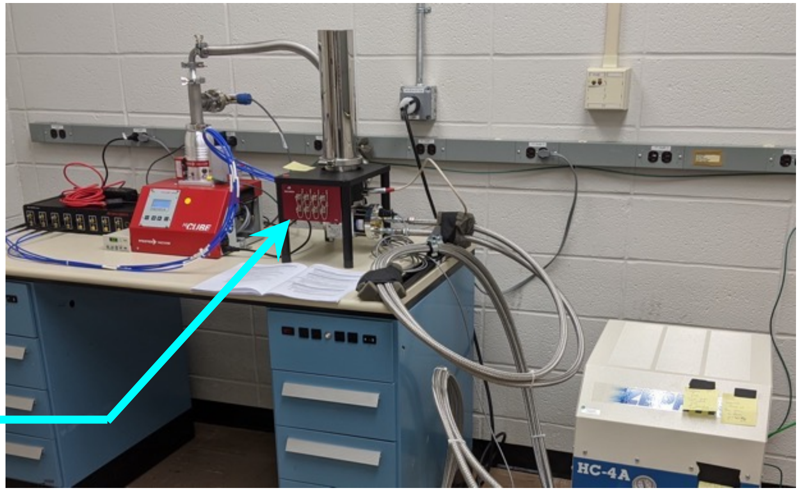
- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, **SPADs**, SNSPDs
  - Target sub-100 ps resolution
- Spectral binning: diffraction gratings, echelle spectrometers
- High photon detection efficiency

Experiments in progress



Strong HBT peak with single lamp





Bench-top model of two-photon interferometry

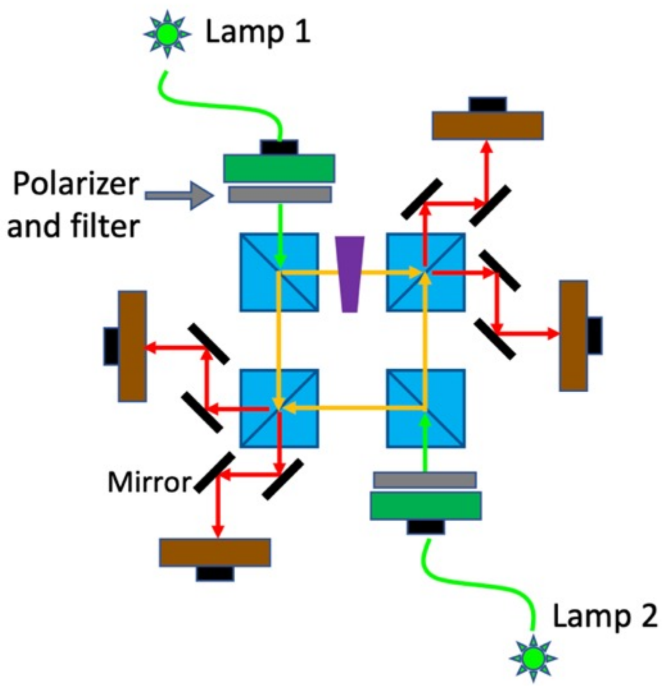
Ar vapor lamps with ultra-narrow band filters

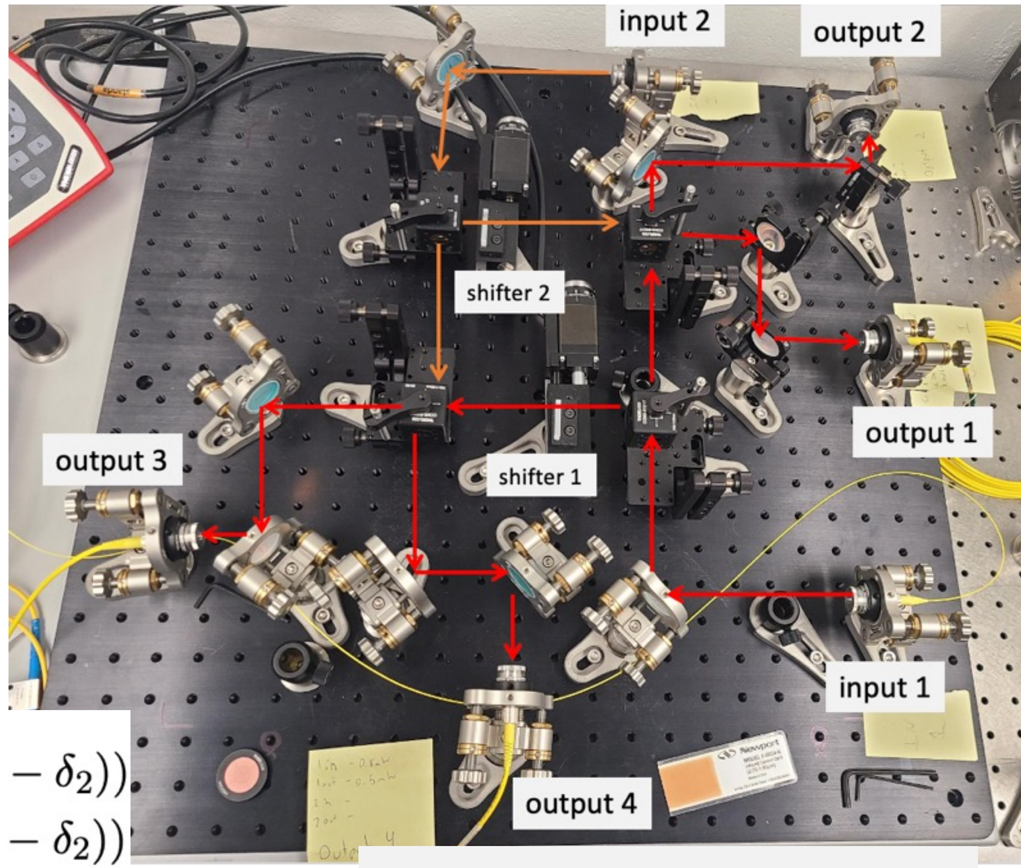
Superconducting nanowire single-photon detectors

Supported by DOE HEP QuantISED program

2022: benchtop verification

arxiv.org/abs/2301.07042

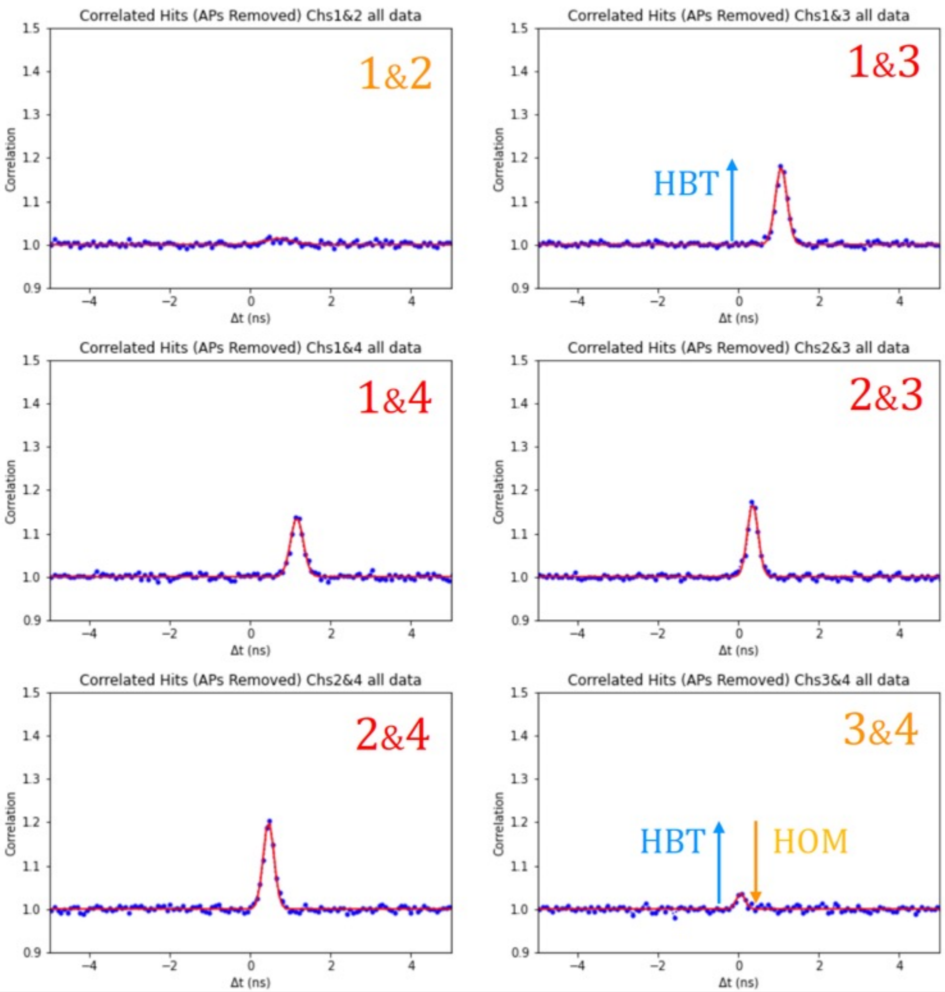


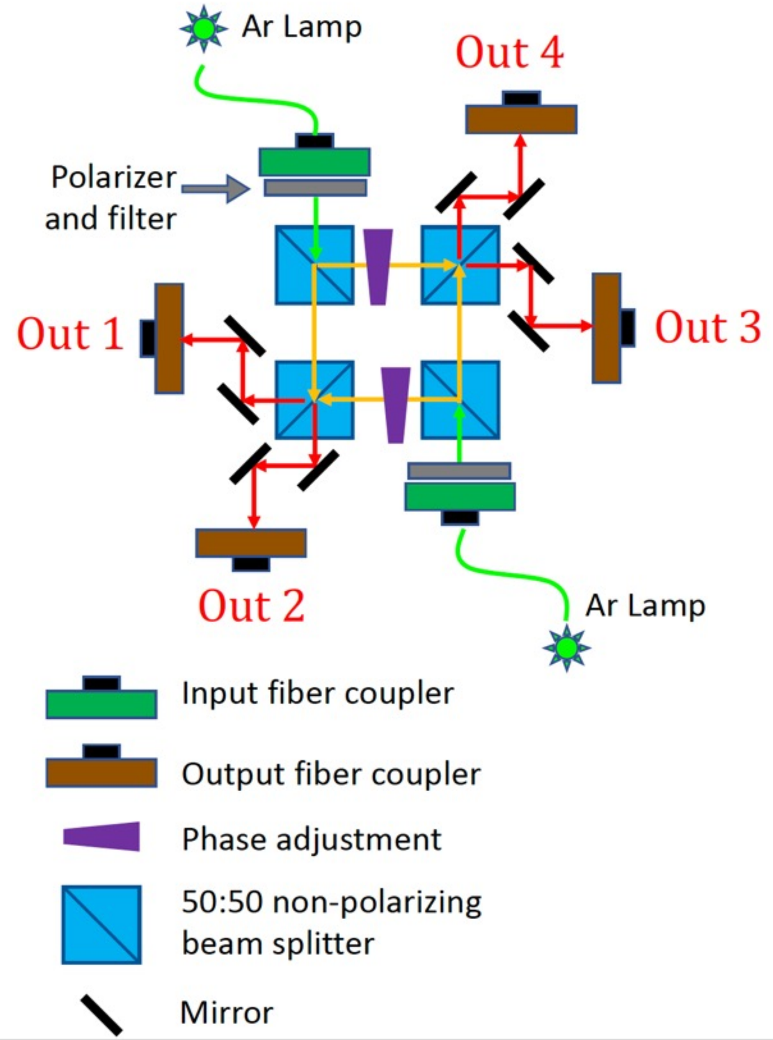


$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

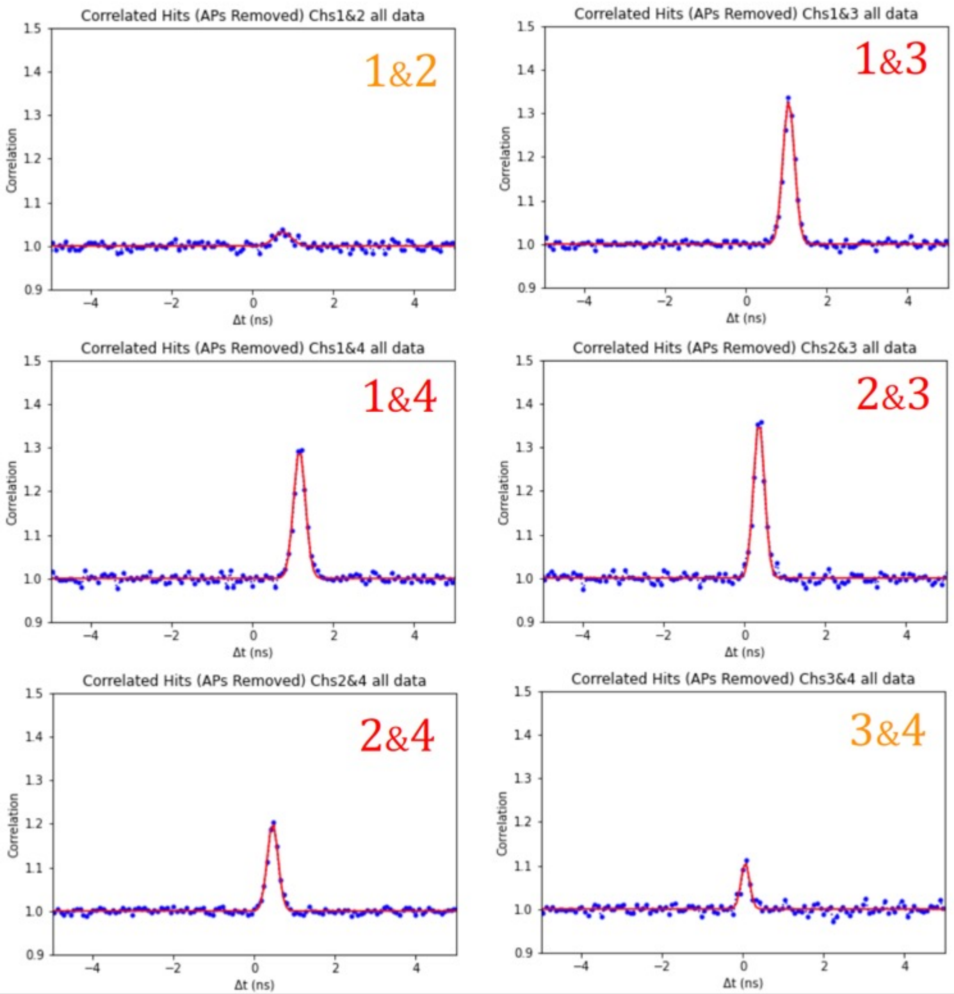
SPAD and SNSPD readout

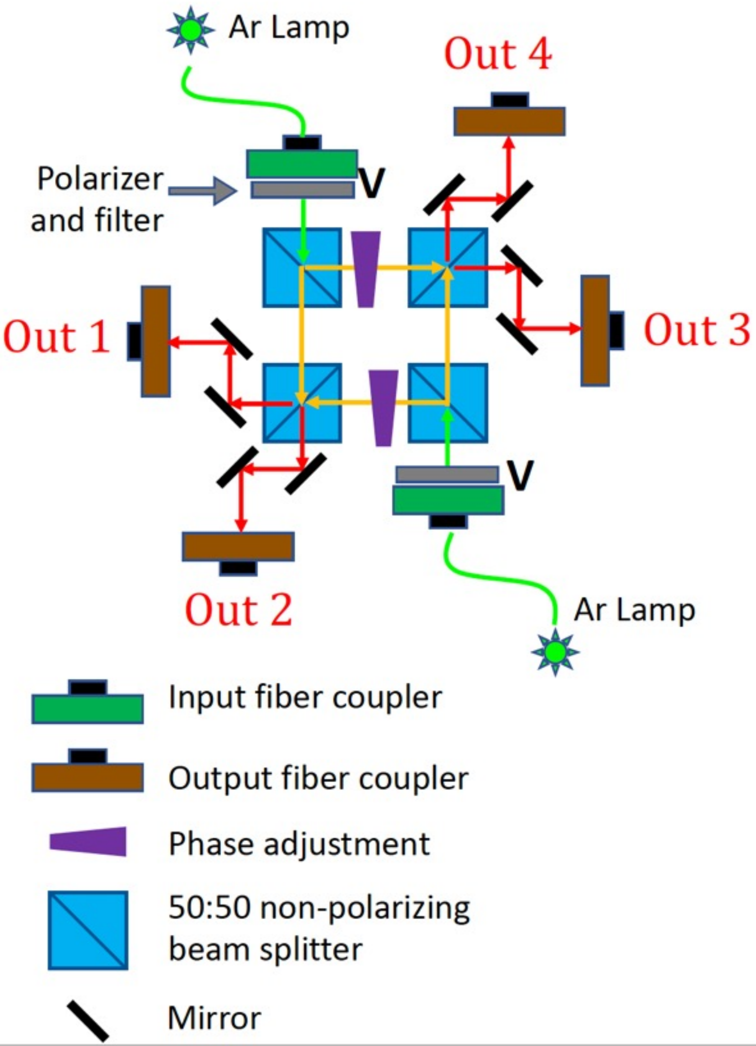
Unpolarized



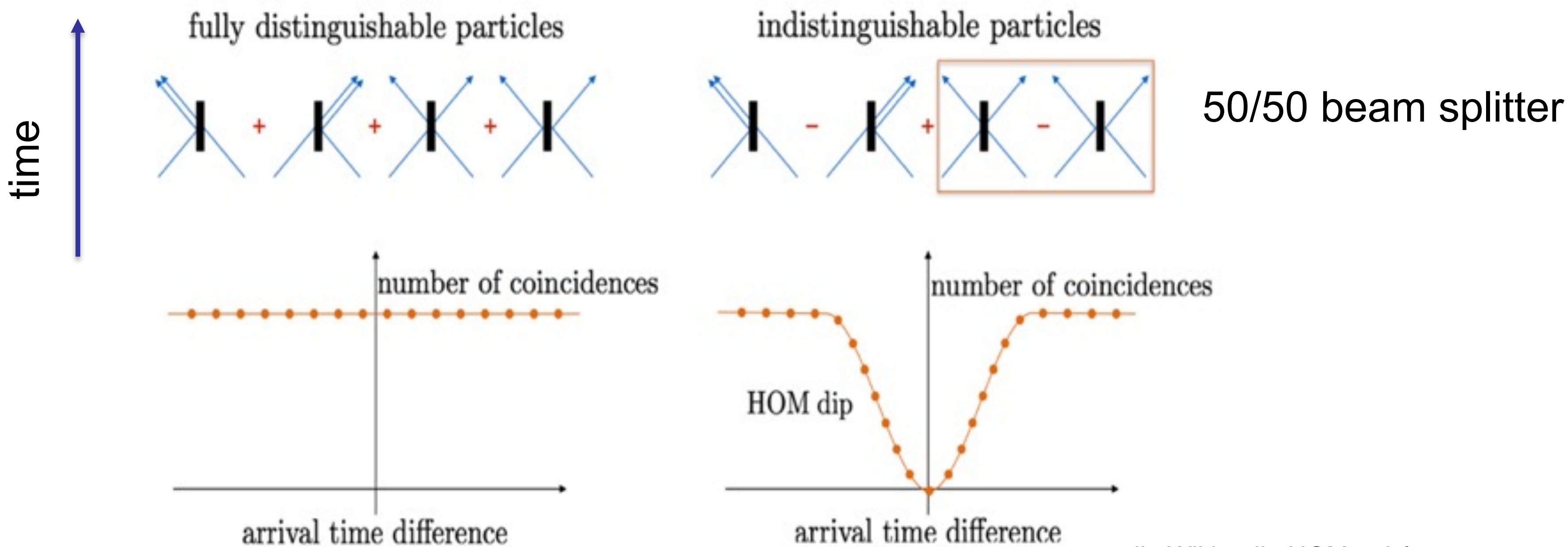


Polarized – V V





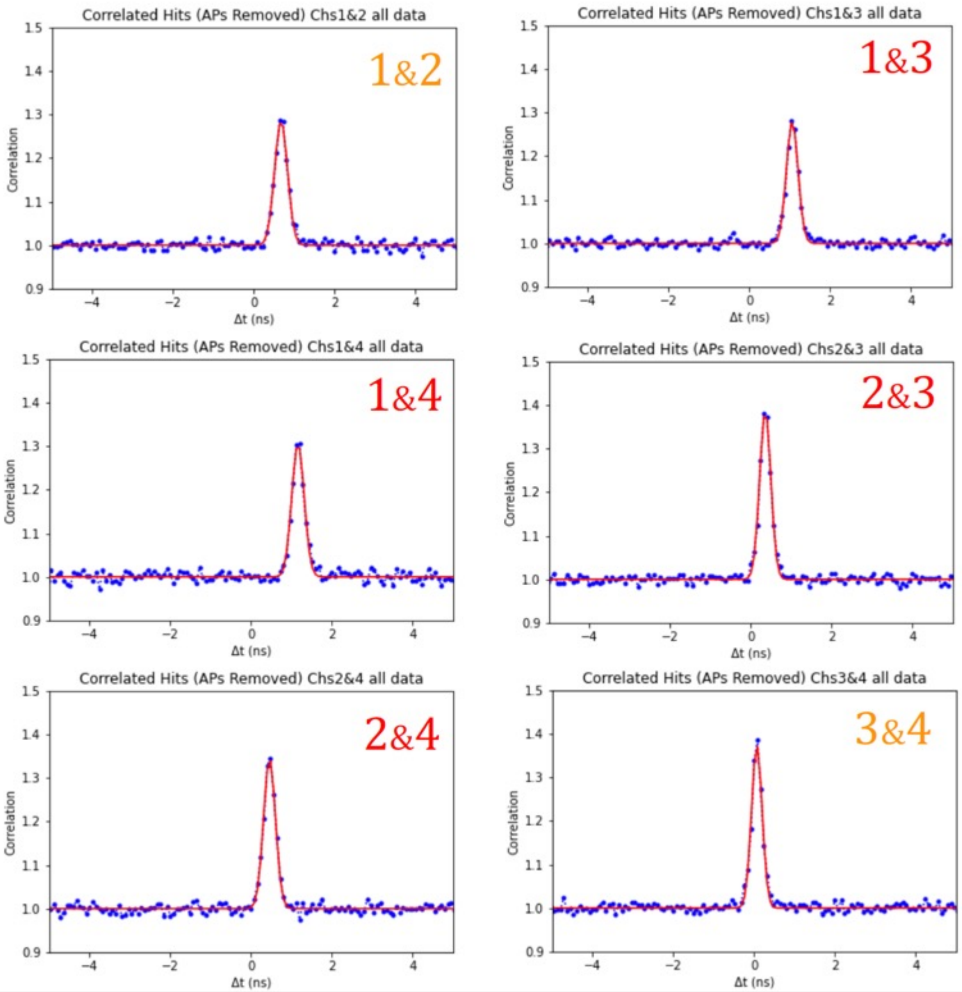
Hong-Ou-Mandel effect

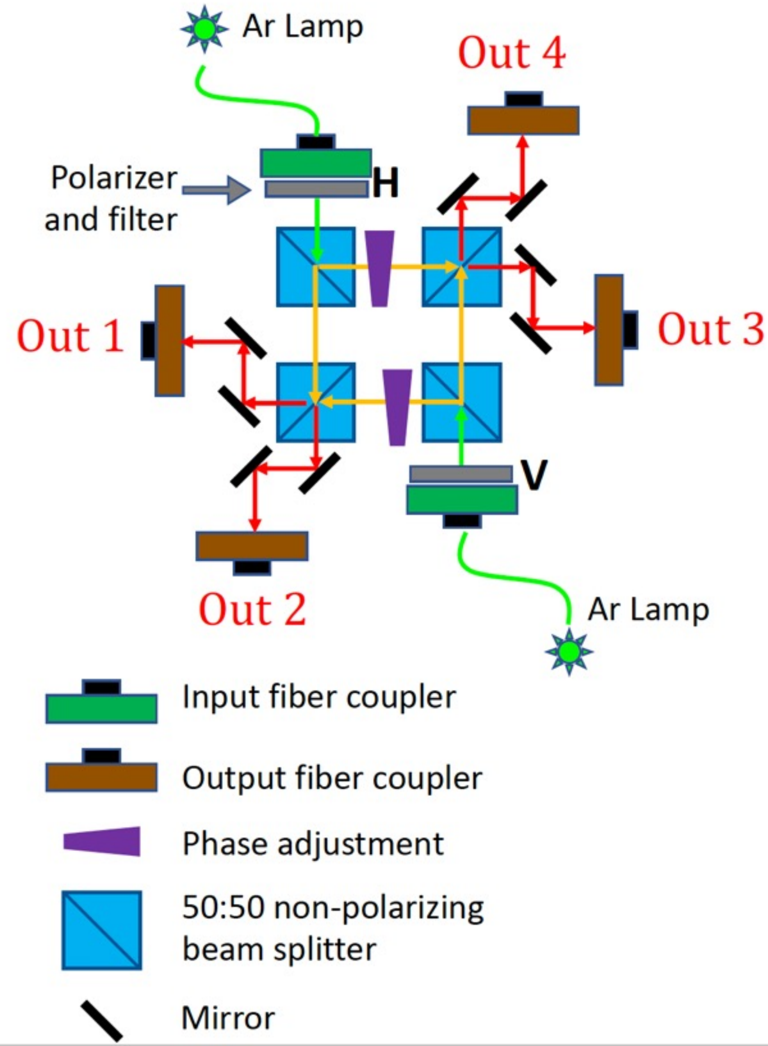


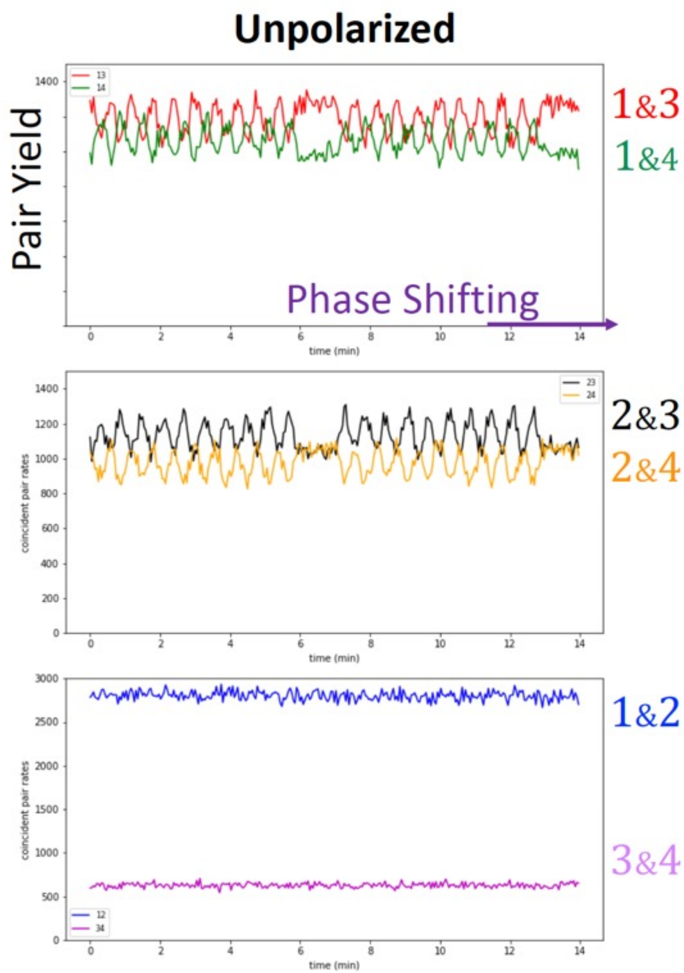
credit: Wikipedia HOM article

HOM dip for coincidences of two outputs

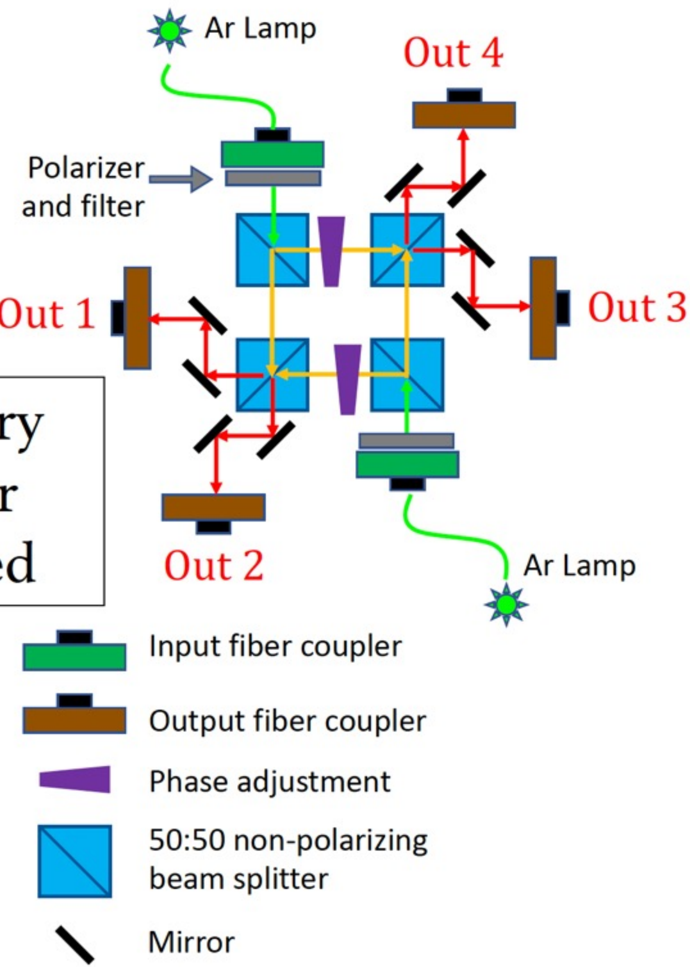
Polarized – V H

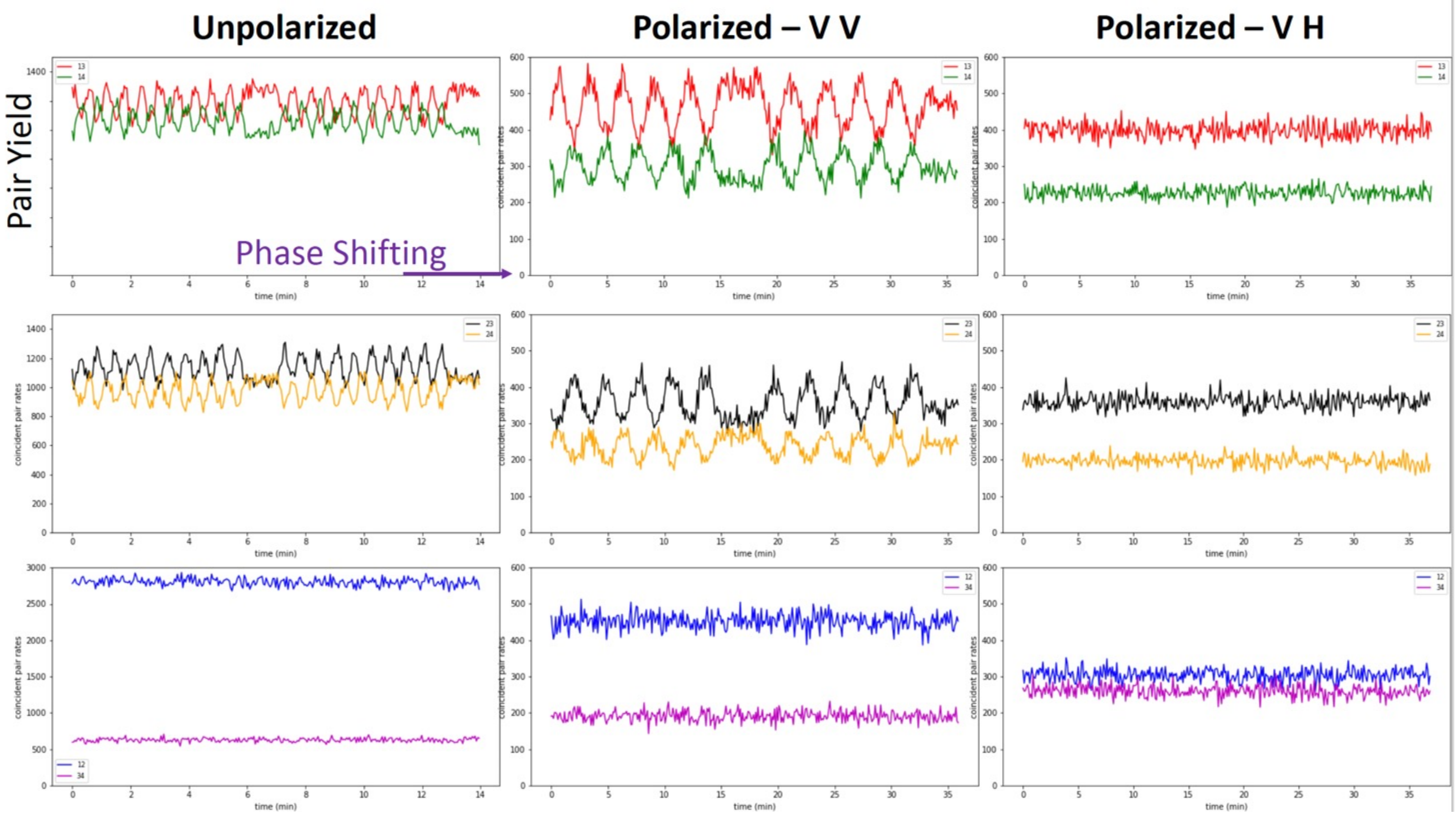






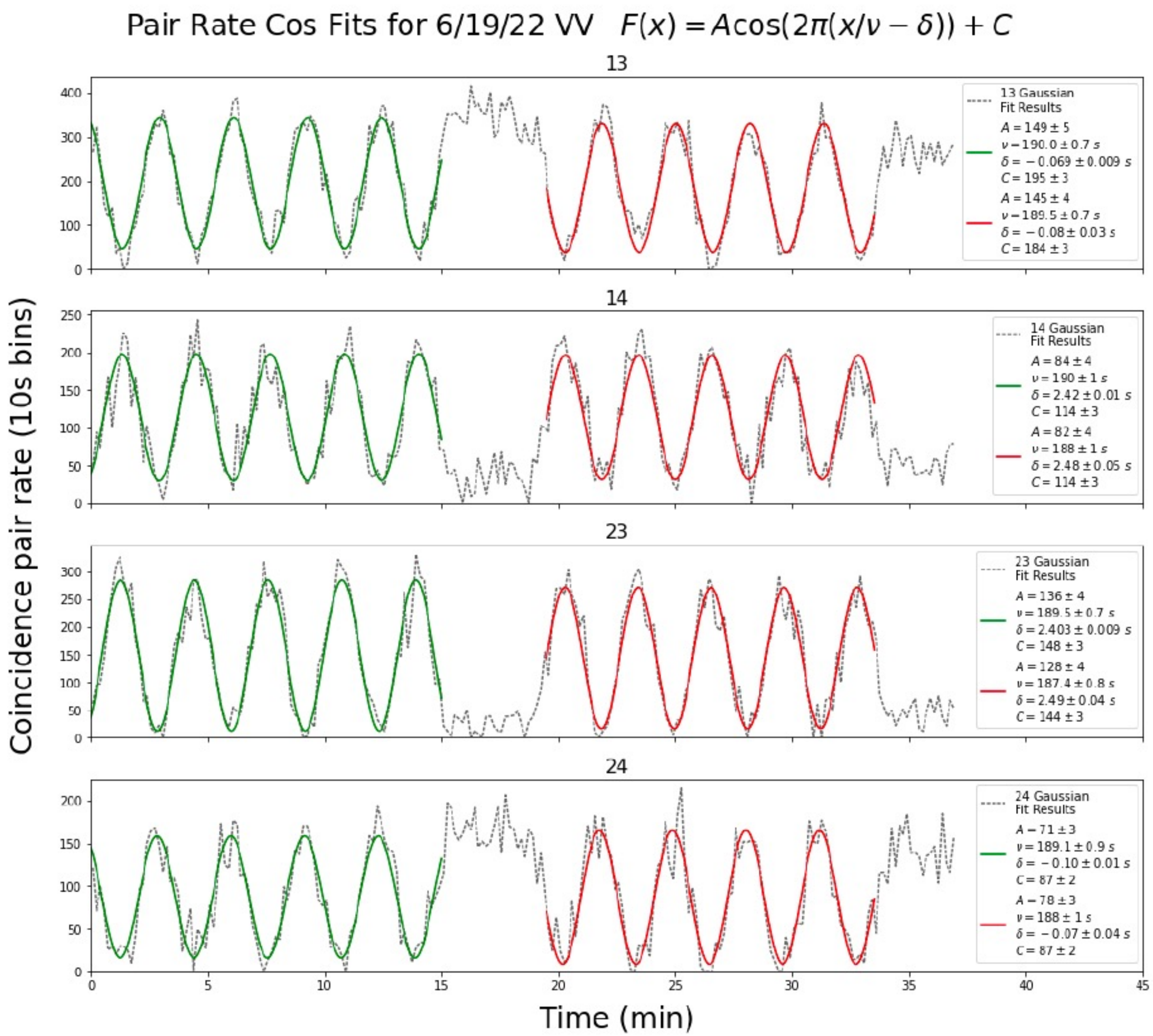
Oscillatory behavior confirmed





Unpolarized
Polarized – V V
Polarized – V H
Pair Yield
Phase Shifting
coincident pair rates
time (min)
13
14
23
24
12
34

Phase dependence



phase oscillations

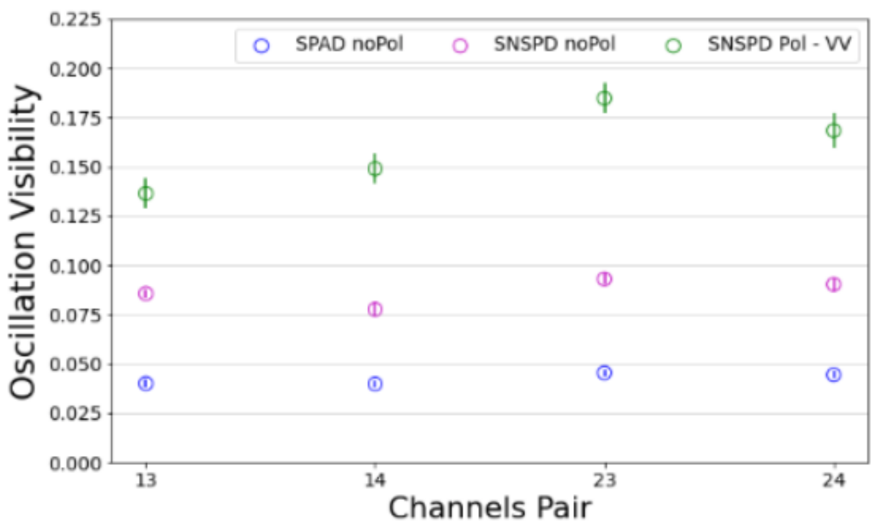
Visibility and phase

arxiv.org/abs/2301.07042

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

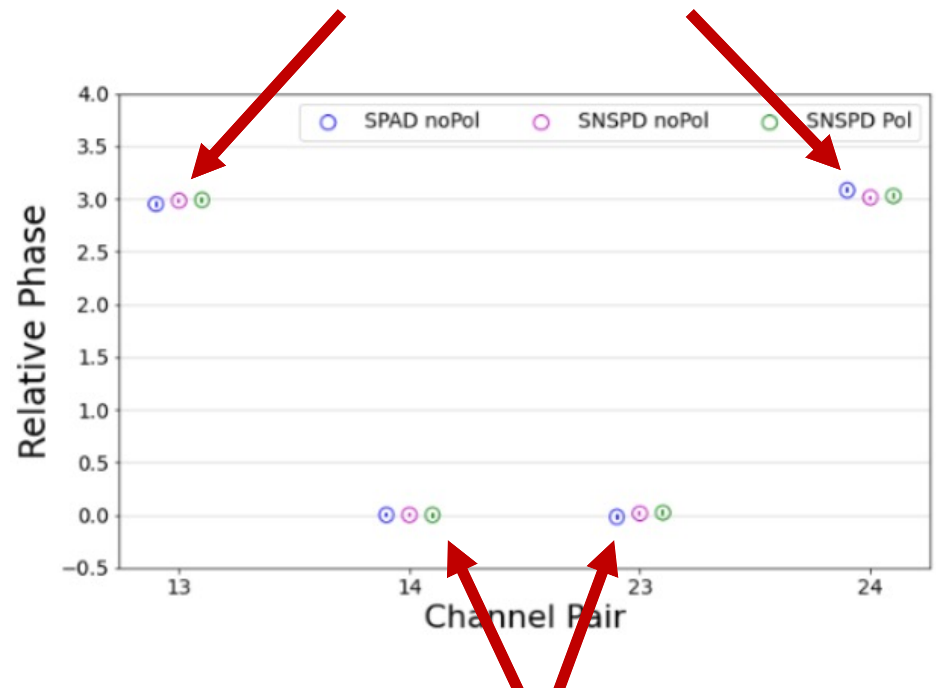
Jesse Crawford [A], Denis Dolzhenko [A], Michael Keach [A], Aaron Mueninghoff [B], Raphael A. Abrahao [A], Julian Martinez-Rincon [A], Paul Stankus [A], Stephen Vintskevich[C], Andrei Nomerotski [A]

- All as expected
- Paper submitted



visibility

sign flip, in anti-phase

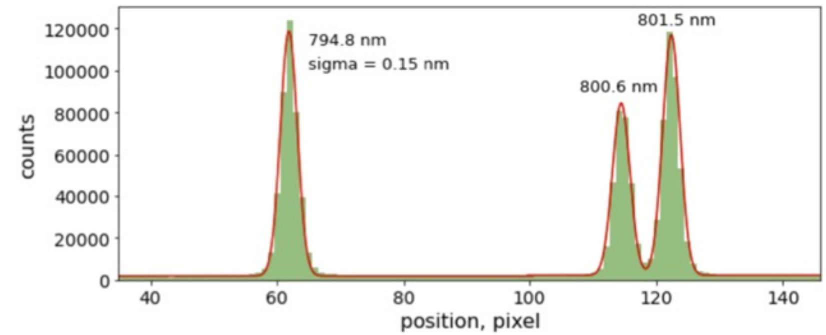


in phase

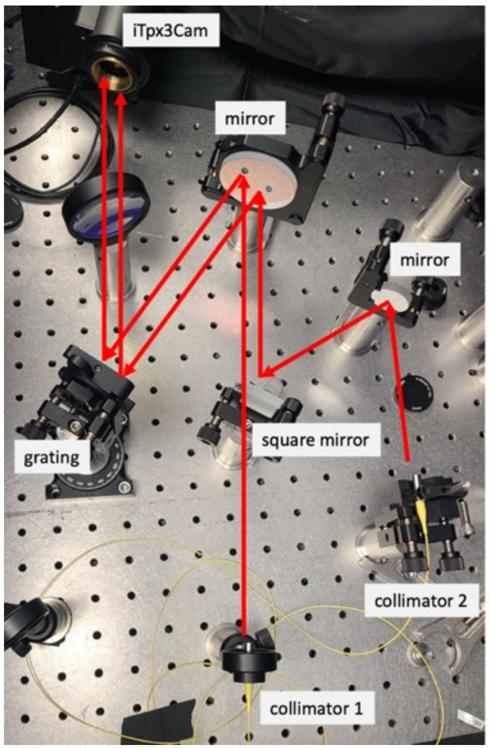
Next step: spectral binning

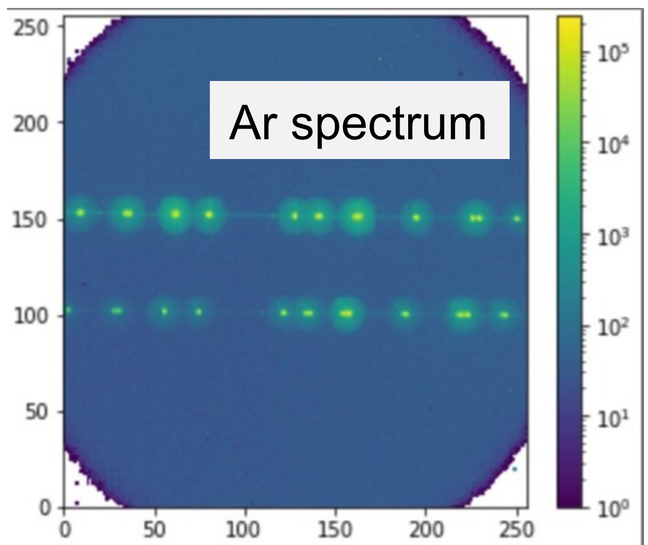
Spectral binning

Two beams → diffraction grating
Based on intensified Tpx3Cam, ns time resolution



spectral resolution for Ar lines ~0.15 nm





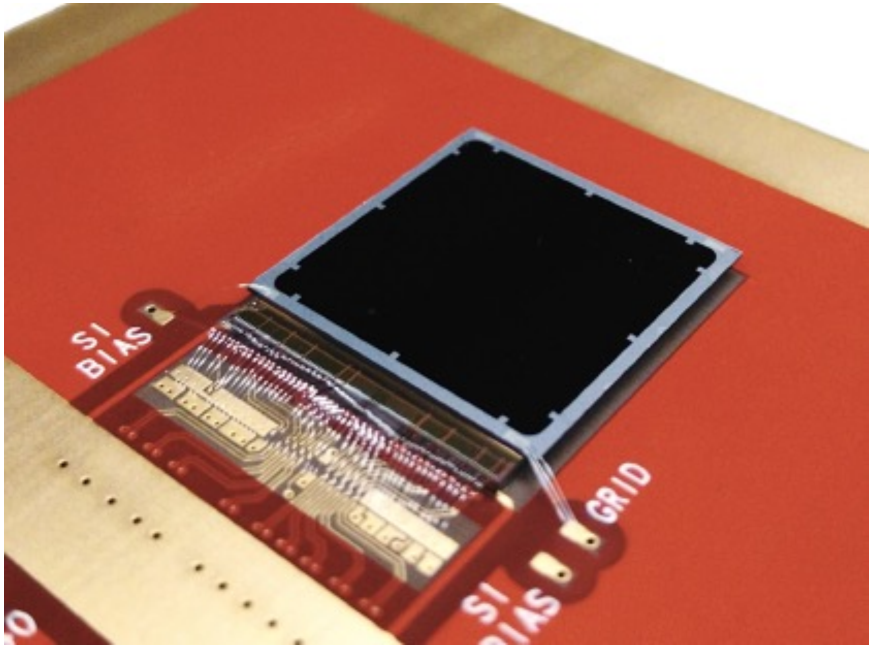
A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, published in JINST

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.

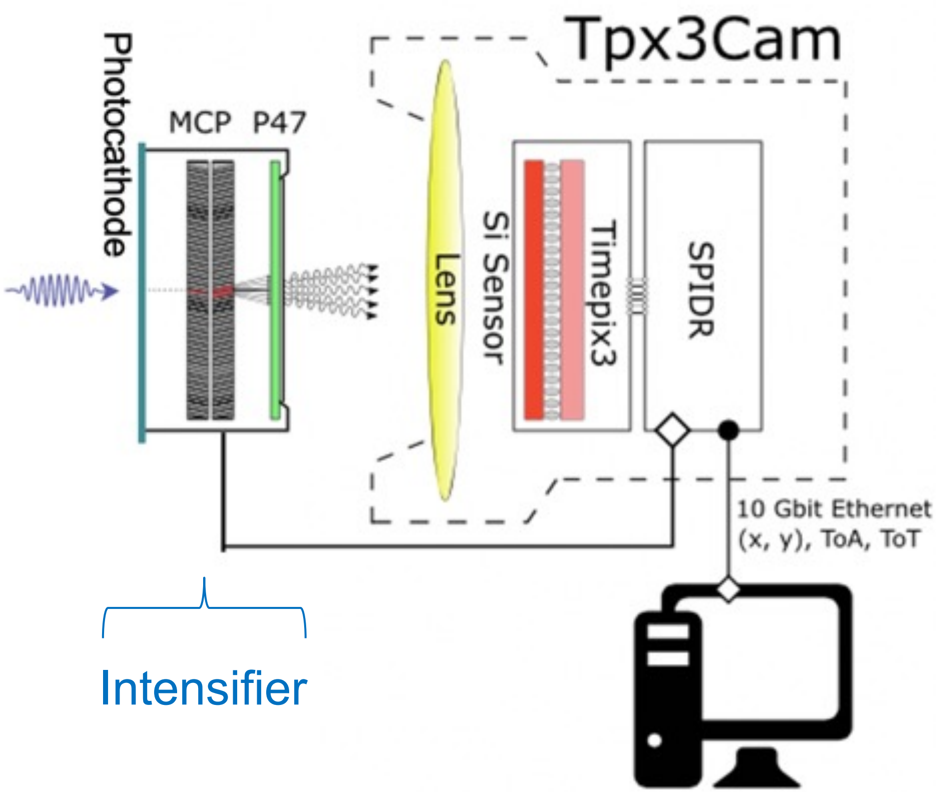


Sensor is bump-bonded to chip

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

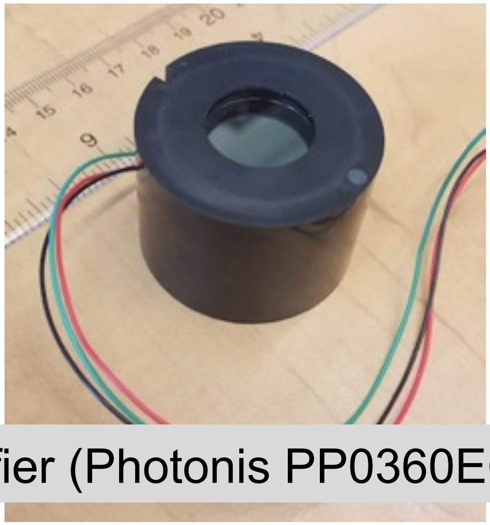
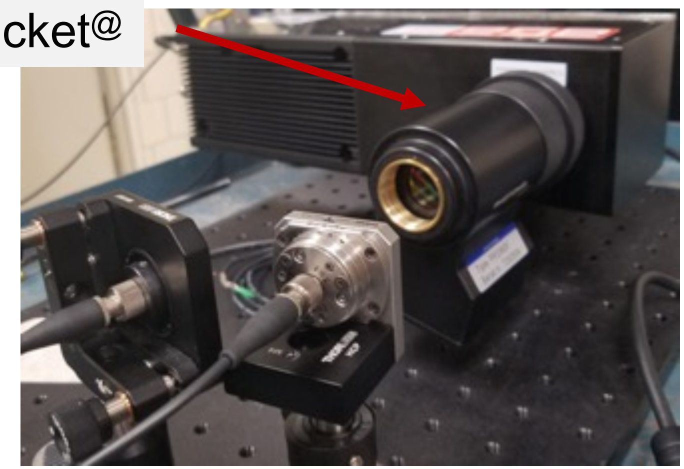


Image intensifier (Photonis PP0360EG)

Cricket@

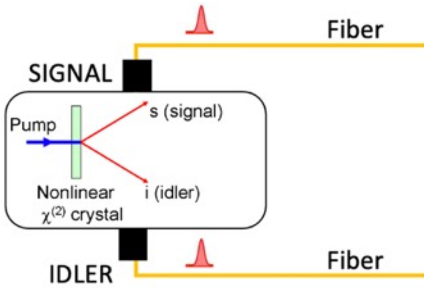


Intensified cameras are common:

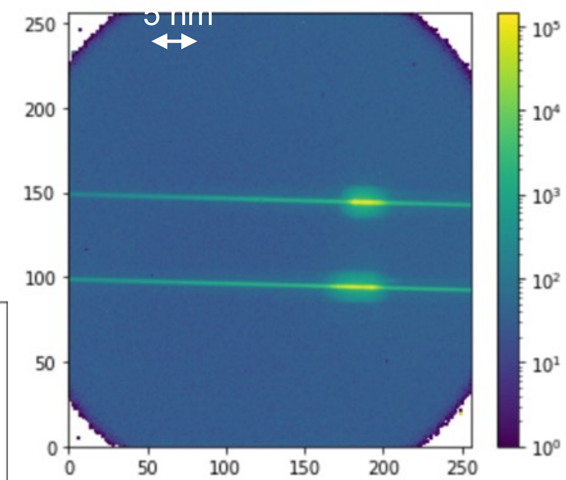
- iCCD
- iCMOS cameras

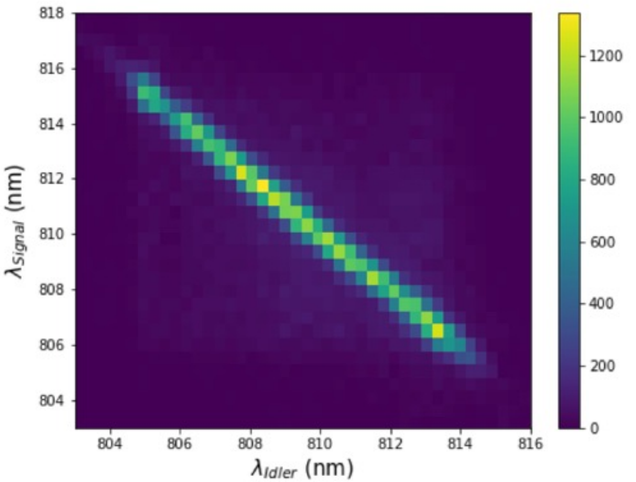
SPDC source in spectrometer

- 810 nm idler and signal
- no filter

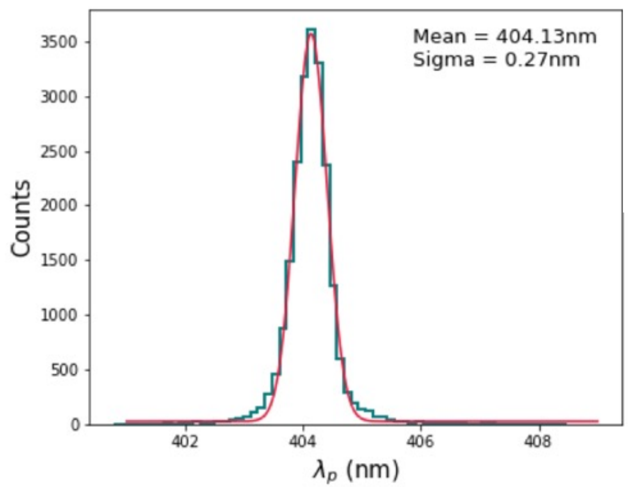


signal & idler in spectrometer

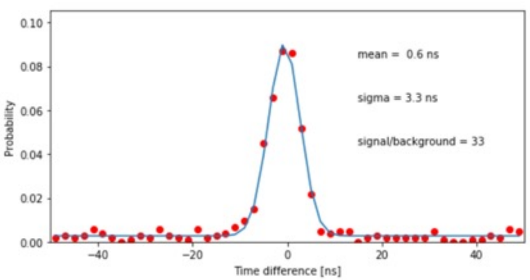




wavelength anti-correlation for photon pairs



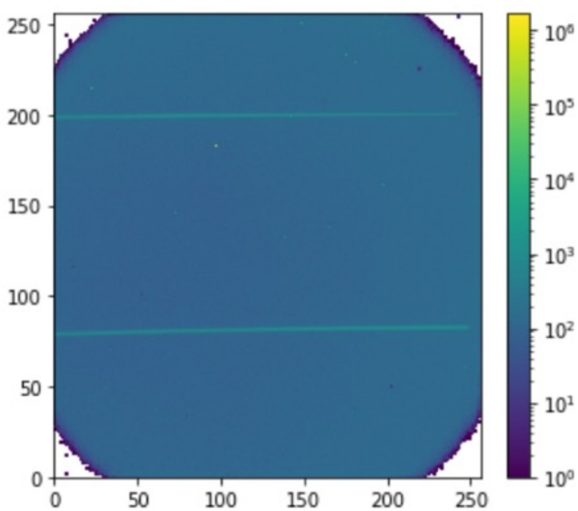
pump wavelength

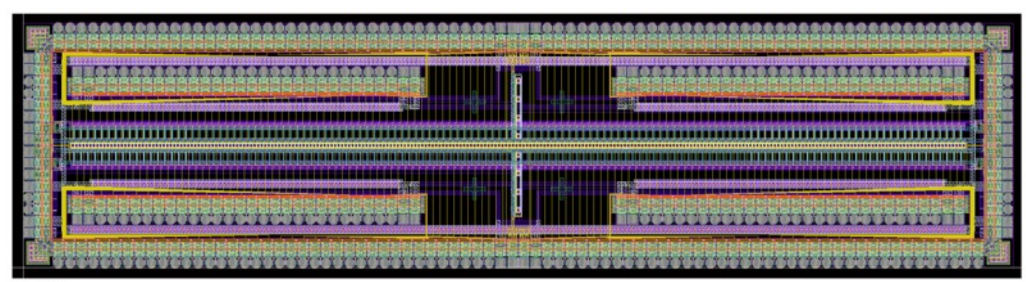


time coincidences

Next steps: spectrometer based on LinoSPAD2

Two diffracted photon stripes projected on to single linear array



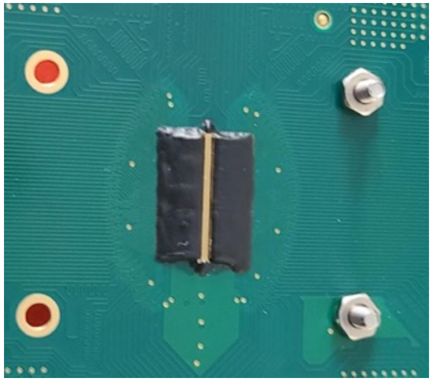


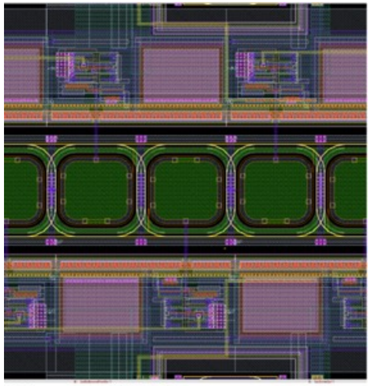
Spectrometer time resolution: ns → 50 ps

LinoSPAD2 linear SPAD array

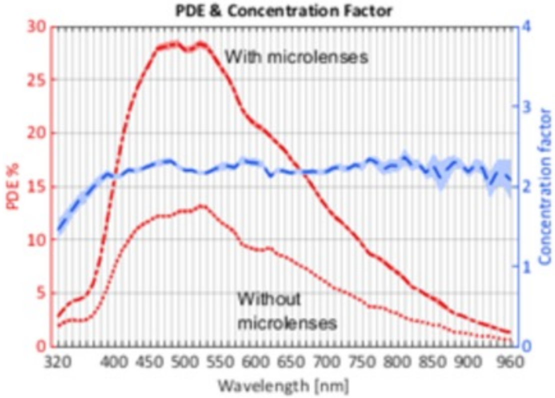
SPAD = single photon avalanche device
p-n junction with amplification

- 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





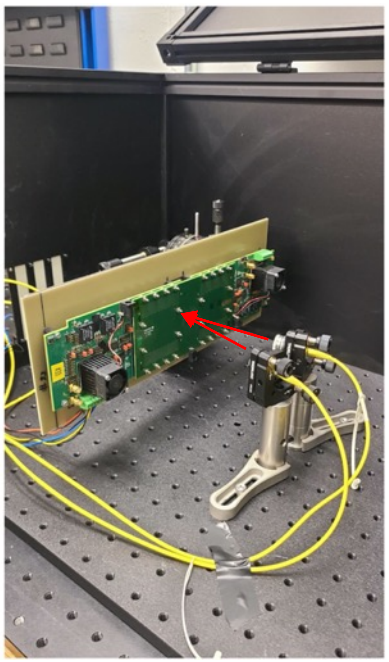
Close-up of SPADs

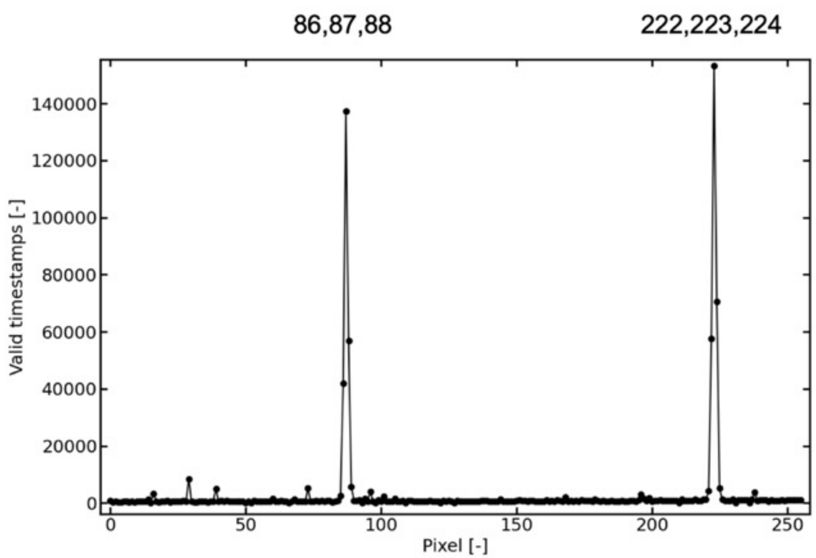


Developed by AQUA group in EPFL (Switzerland) E.Charbon et al

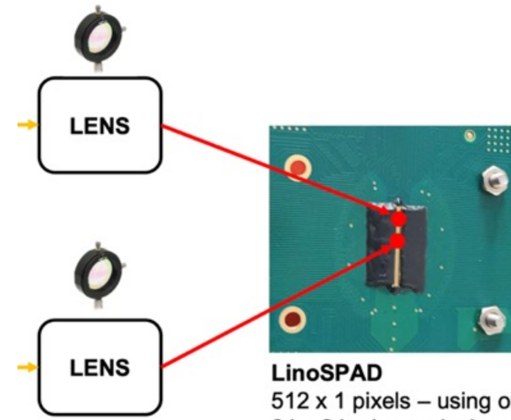
C. Bruschini, S. Burri, E. Bernasconi, T. Milanese, A. C. Ulku, H. Homulle, and E. Charbon, Linospad2: a 512x1 linear spad camera with system-level 135-ps sptr and a reconfigurable computational engine for time-resolved single-photon imaging, in *Quantum Sensing and Nano Electronics and Photonics XIX*,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

SPAD arrays with 50 ps resolution

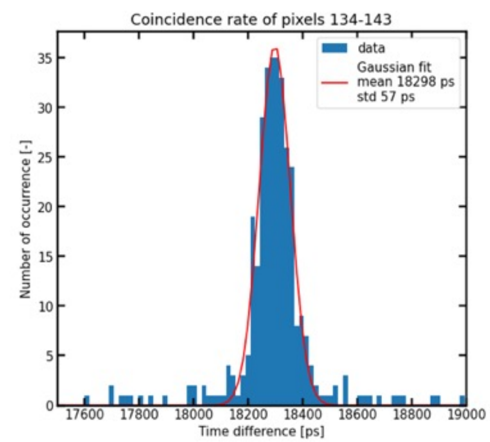




Two beams from SPDC source
Coincidence of two single photons

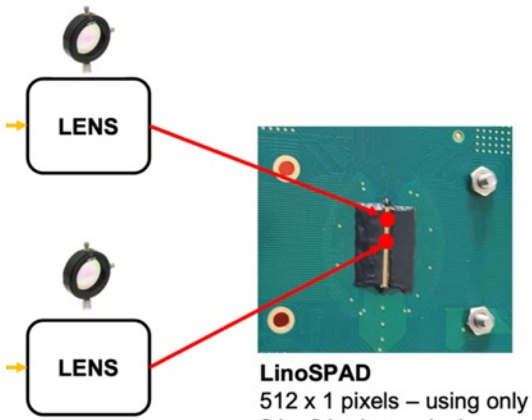


LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels

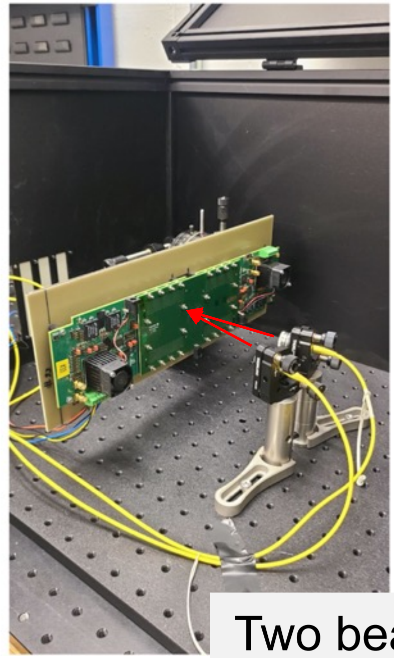


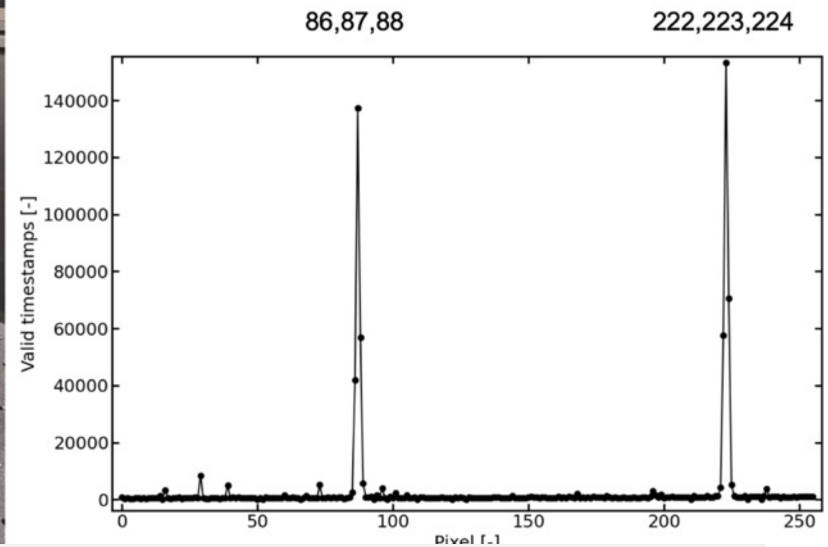
time difference, σ=57 ps
→ 40 ps per photon

HBT peaks in LinoSPAD2

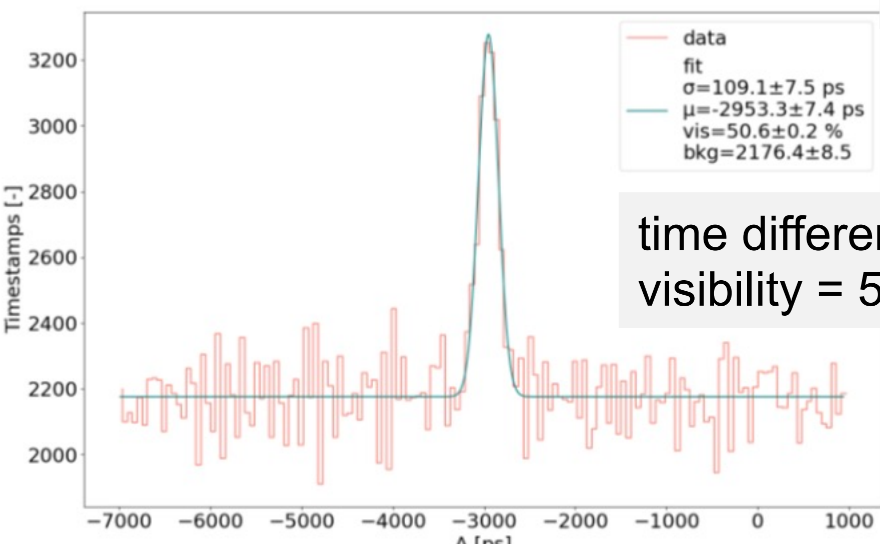


LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels





Two beams from Ar lamp + polarizer after beamsplitter

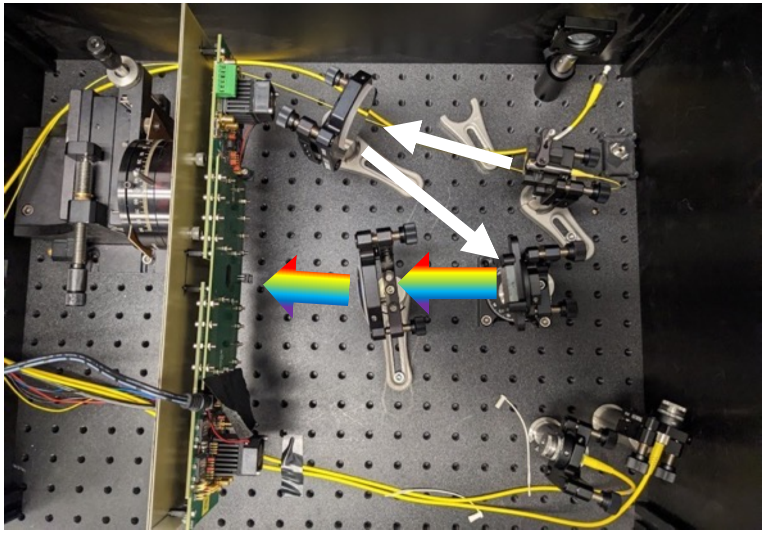


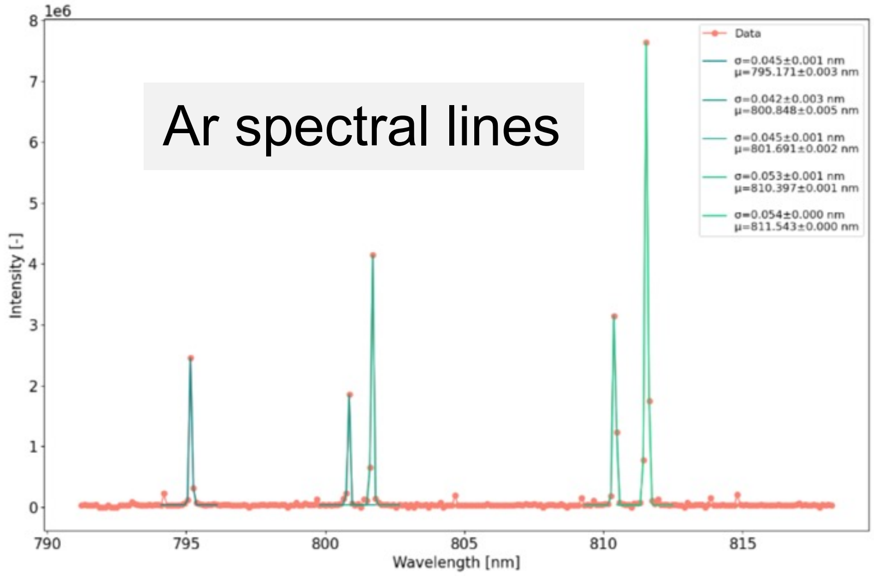
time difference, σ=110 ps
visibility = 50%

look for HBT = photon bunching,
natural width > resolution

Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber



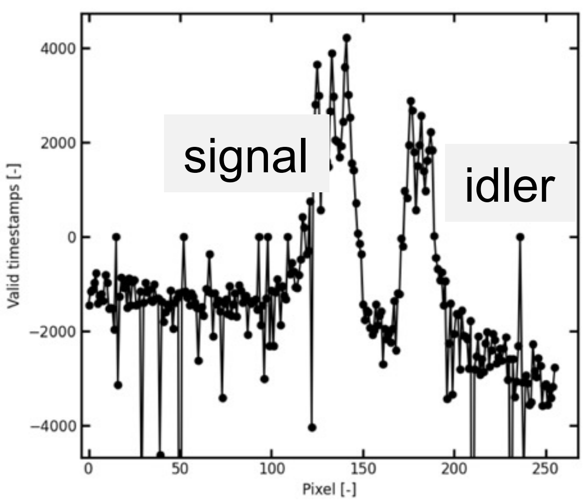


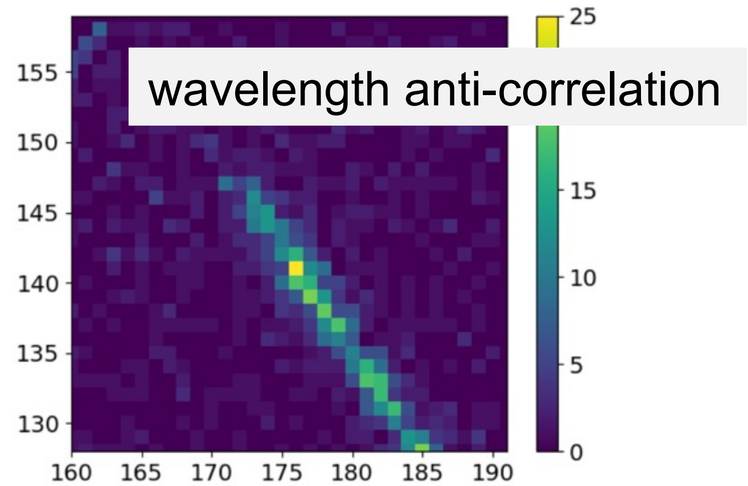
Achieved 0.04 nm spectral and 40 ps timing resolution (only x10 above Heisenberg hbar/2 limit)

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

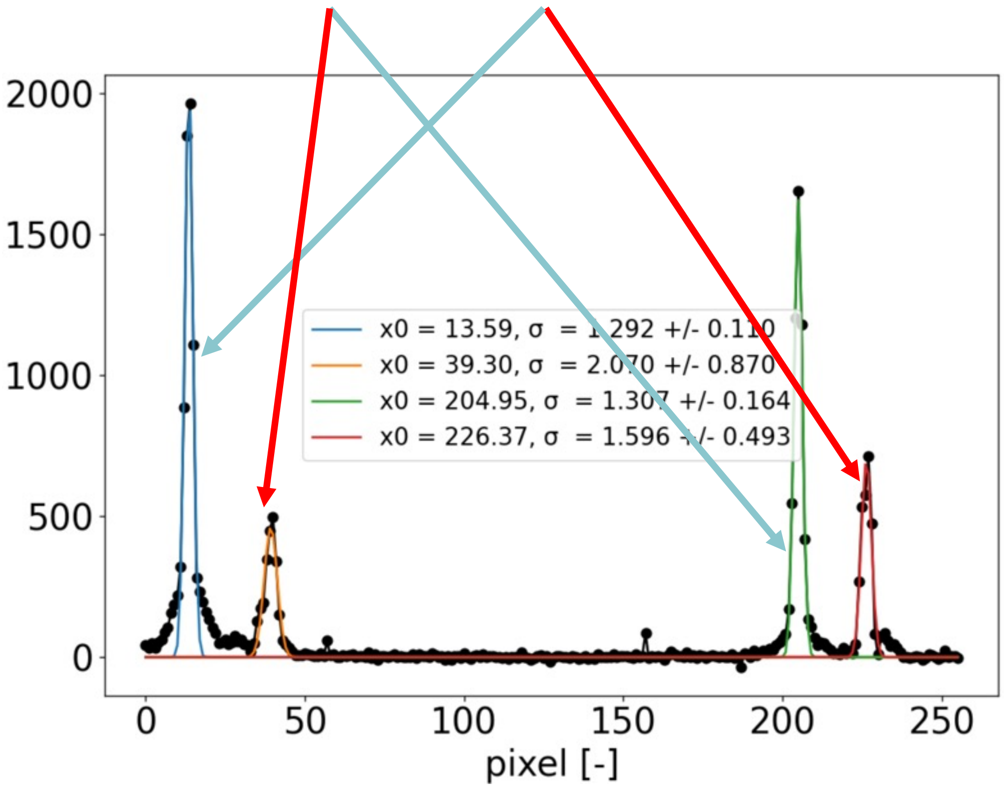


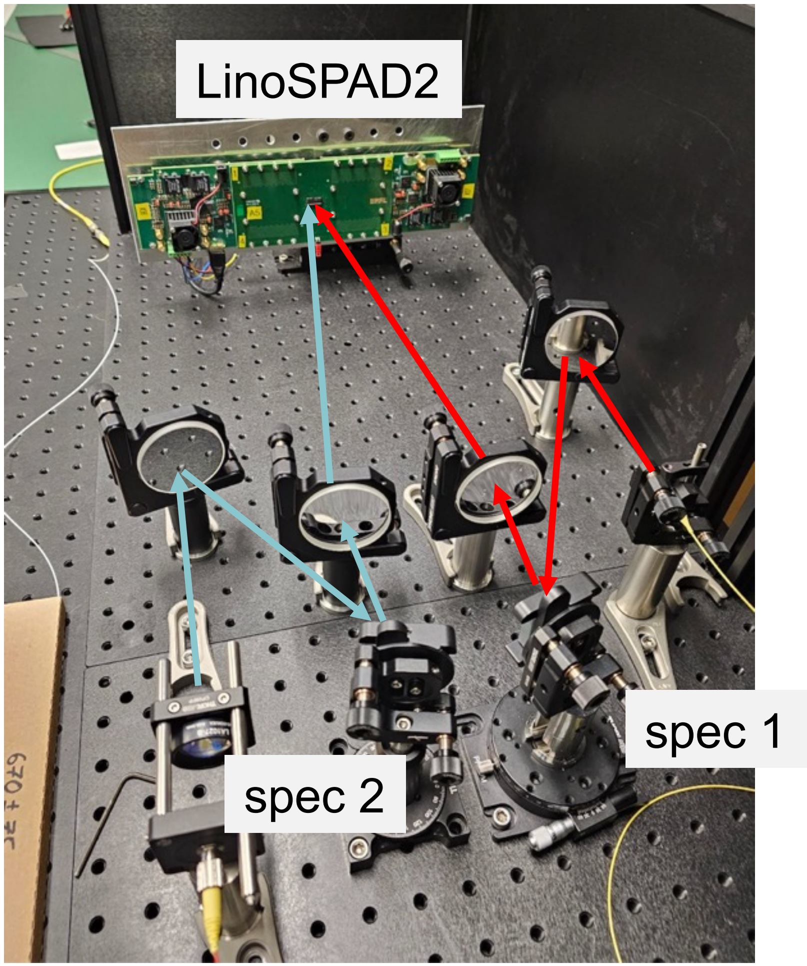


Spectrometer with 0.04 nm and 40 ps resolutions → near Heisenberg limit

Dual spectrometer

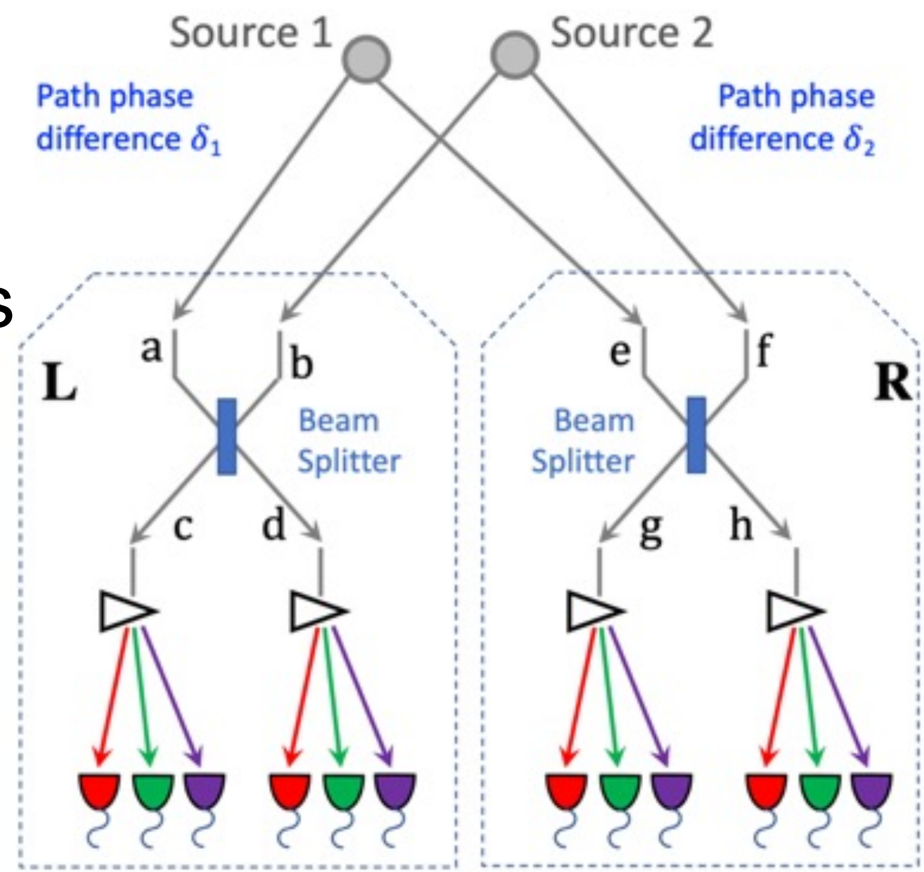
- Can see two Ne spectra
- Chasing spectral resolution
  - Increased scale, now 20 pix/nm → 13 nm range for 256 pixels
  - Neon 693 and 703 nm lines



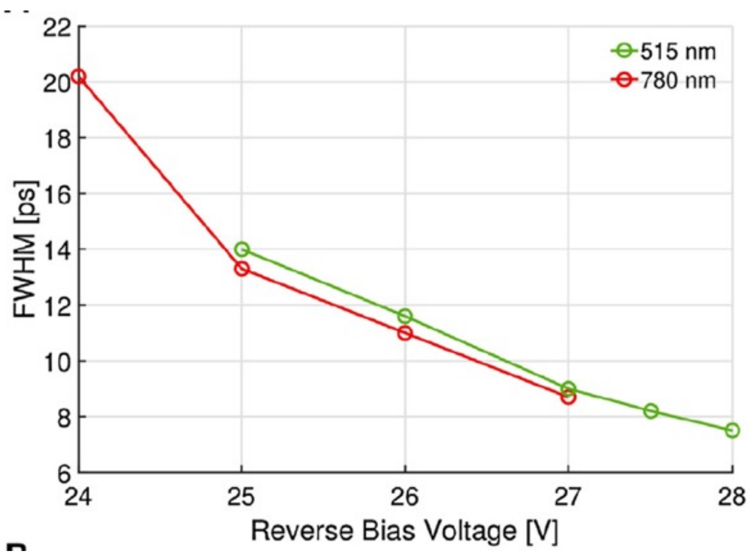


Next step: broadband HBT

- 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



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).

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

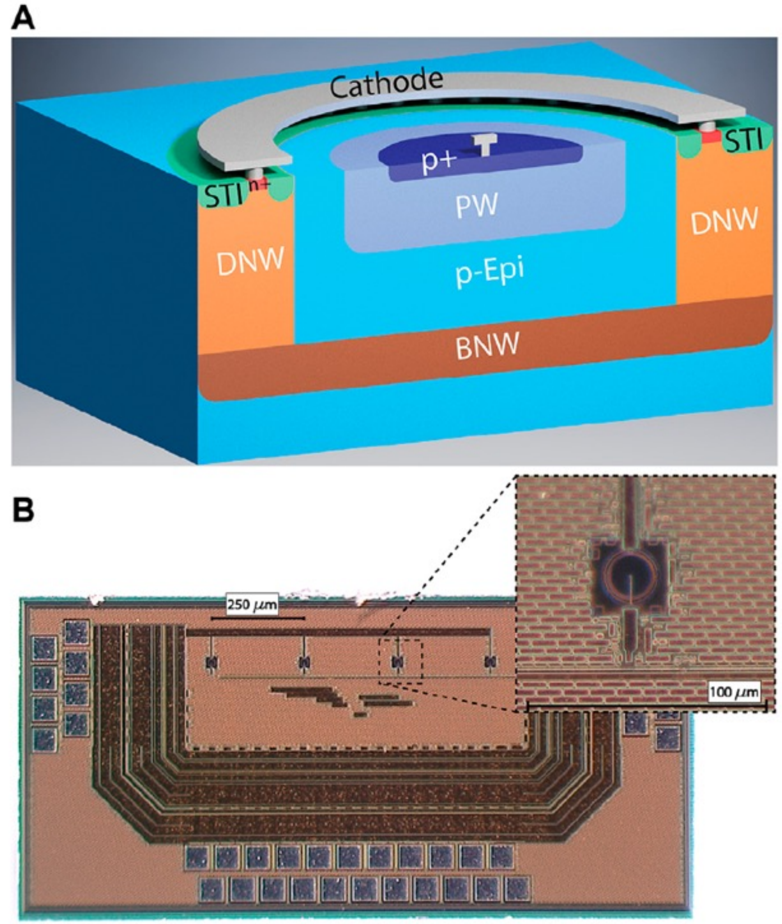
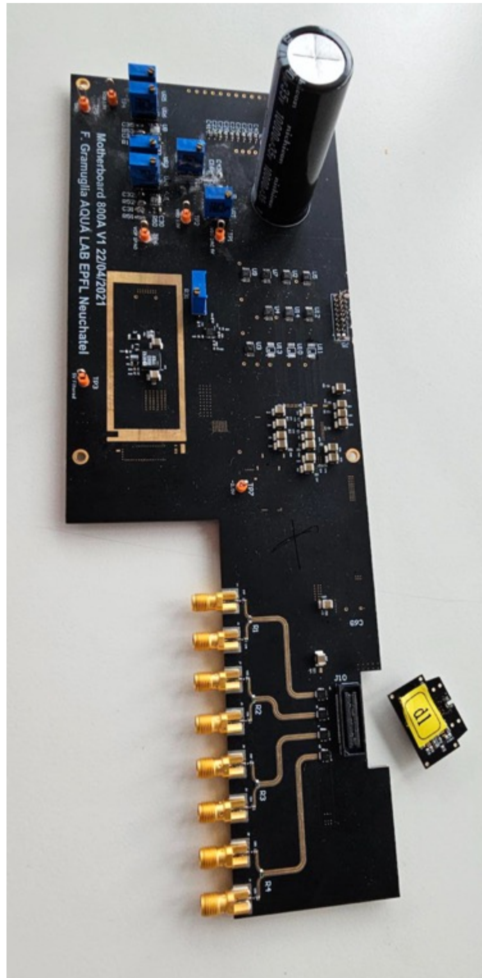
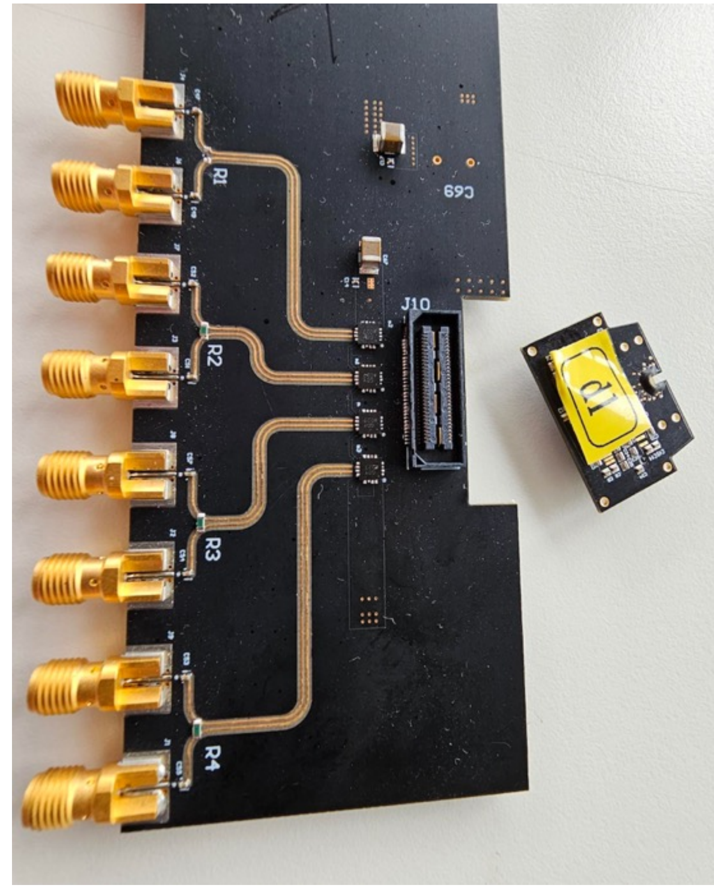


FIGURE 1 | (A): SPAD cross section. **(B)**: Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [21].

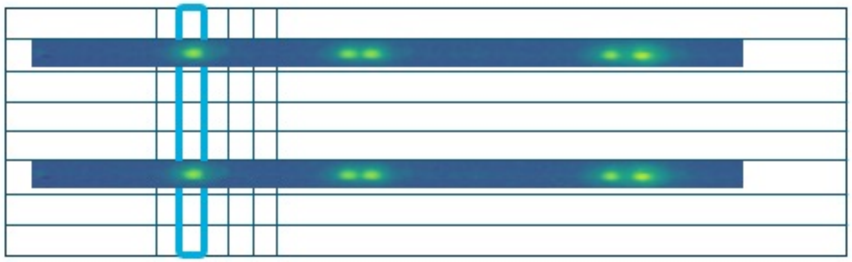
superSPAD

4-channel sensor





Ideas for fast sensor R&D



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

SiPM approach

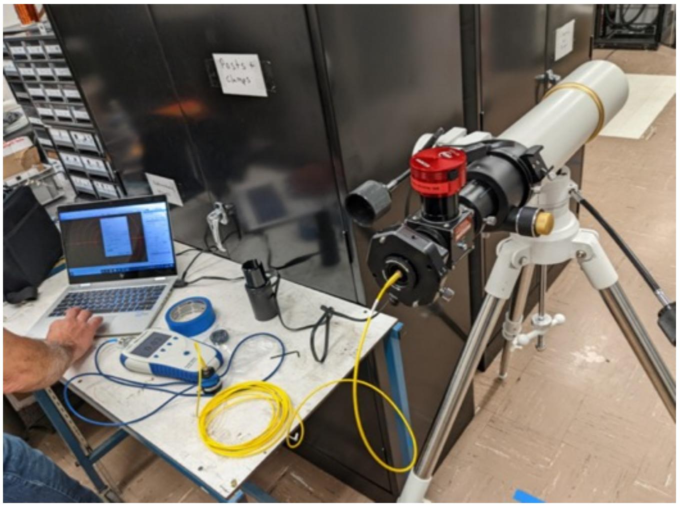
- Collaboration with EPFL, CzTU and FIU groups

- 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

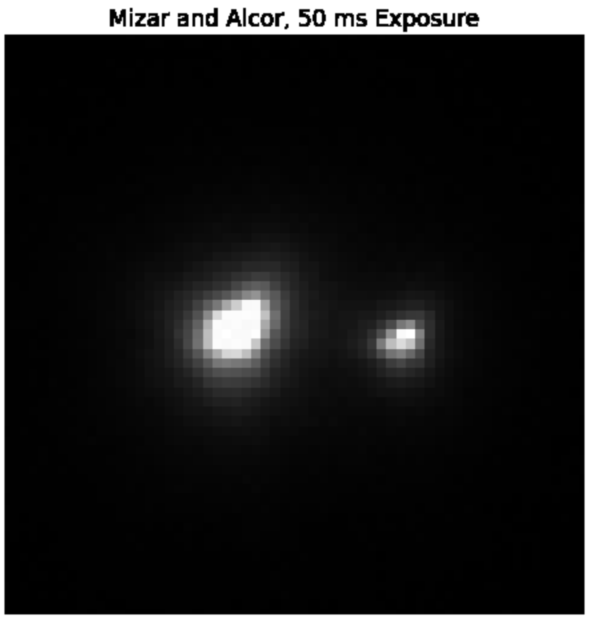
telescopes

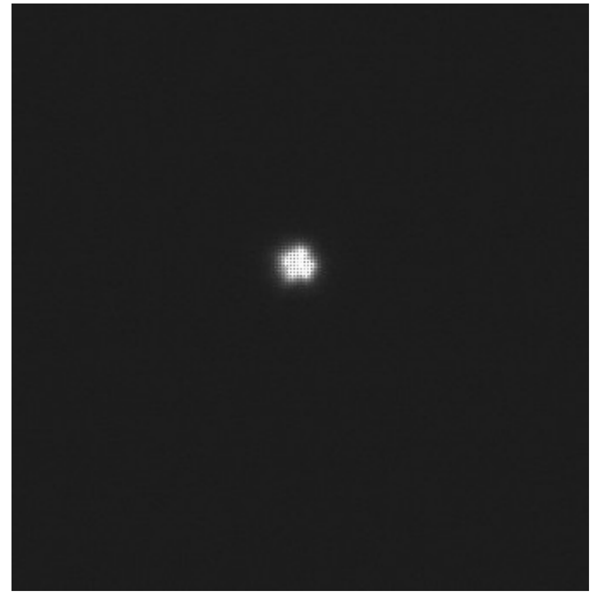
On-sky measurements

- Experimenting with SM fiber coupling
- Trying adaptive optics



On-sky measurements



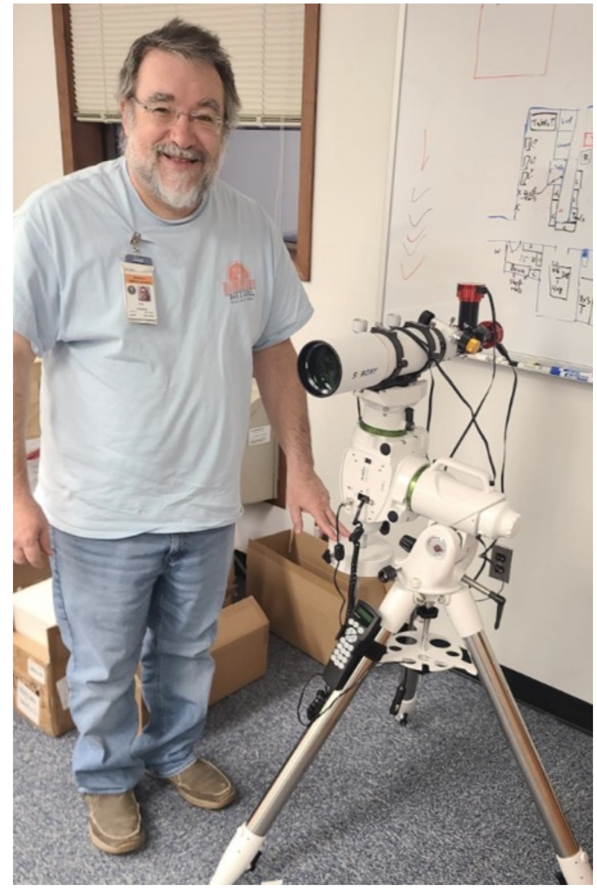


Mizar A & B
- 50 ms exposure
- 15 arcsec separation

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



Special Programs

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

Quantum-Enhanced Telescopy Workshop

Sunday, 18 June 09:00 – 17:30

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.

Registration for the workshop is included with the free Events and Exhibits Pass. Please see the Registration page for details.

Organizers

Paul Kwiat, *University of Illinois at Urbana-Champaign, USA*
John Monnier, *University of Michigan, USA*
Andrei Nomerotski, *Brookhaven National Laboratory, USA*
Mike Raymer, *University of Oregon, USA*
Brian Smith, *University of Oregon, USA*

Speakers

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
- Collaboration with intensity interferometry astro community, overlap in instrumentation

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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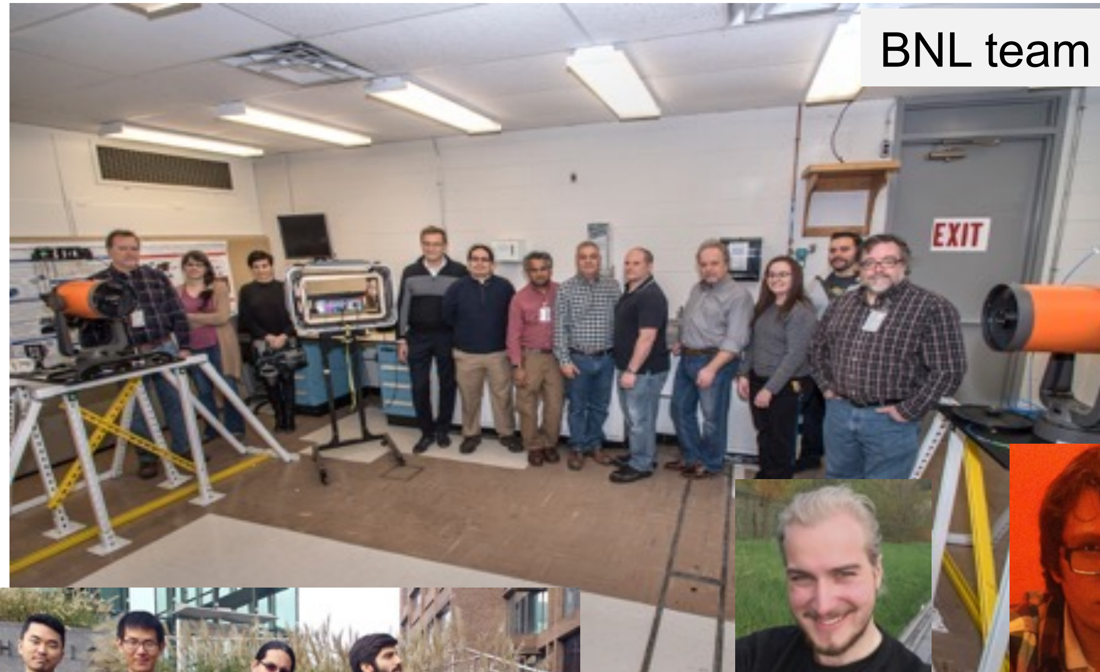
Alex Parsells
Jonathan Schiff
Denis Dolzhenko
Stepan Vintskevich
Anze Slosar
Zhi Chen
Jesse Crawford
Aarom Mueninghoff

Jingming Long
Martin van Beuzekom
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
Raphael Abrahao
Brianna Farella
Ryan Mahon

Ermanno Bernasconi
Claudio Bruschini
Samuel Burri
Tommaso Milanese
Edoardo Charbon



Questions?