Quantum-assisted Optical Interferometry with Fast Time Stamping of Single Photons

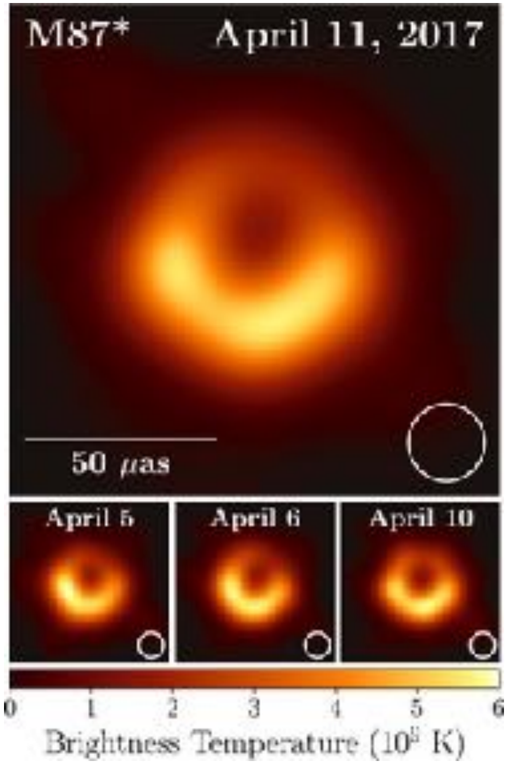
Andrei Nomerotski

Florida International Uni & Czech Technical Uni

SII workshop 2024

10 September 2024

Astronomy picture of the decade



sensitive to features
on angular scale

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

2019 ApJL 875

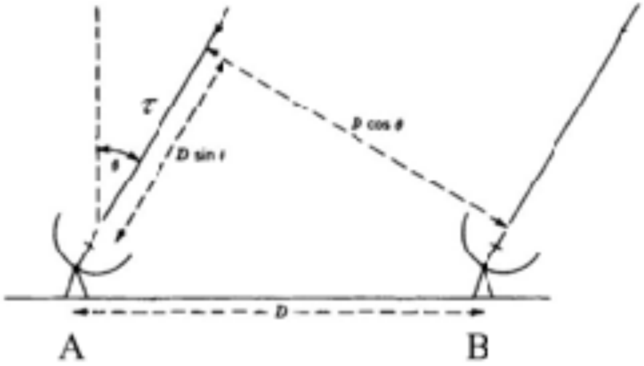
Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Radio

$\bar{n} \gg 1$

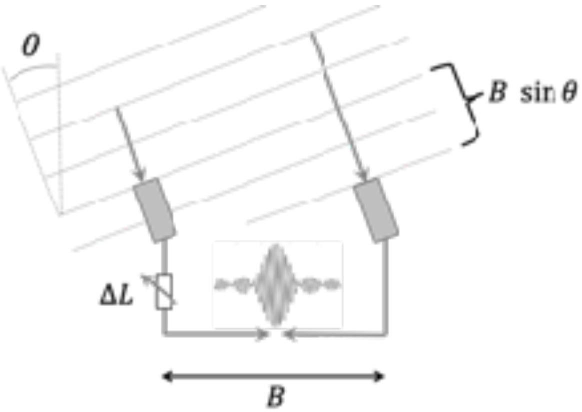
mode population



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

Optical

$\bar{n} \ll 1$ mode population



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

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

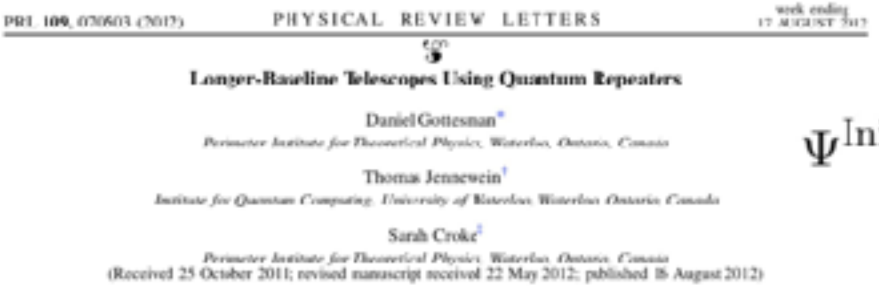
Need path length *stabilized* to better than λ

Accuracy ~ 1 mas

Max baselines to ~ 100 m

Two-photon techniques

Second photon for quantum assist

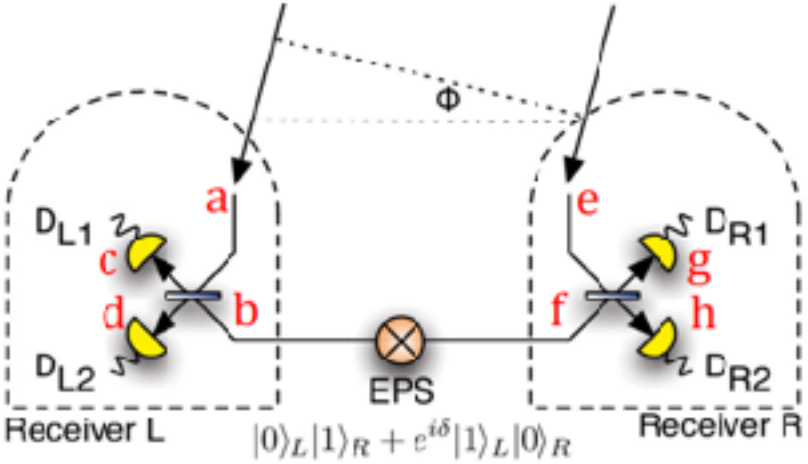


PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
Thomas Jennewein†
Institute for Quantum Computing, University of Waterloo, Waterloo Ontario Canada
Sarah Croke‡
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

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



$$|0\rangle_L|1\rangle_R + e^{i\delta}|1\rangle_L|0\rangle_R$$

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

Beam Splitters

$$\boxed{\begin{array}{ll} \hat{a}^\dagger \rightarrow (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} & \hat{b}^\dagger \rightarrow (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2} \\ \hat{e}^\dagger \rightarrow (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} & \hat{f}^\dagger \rightarrow (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2} \end{array}}$$

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

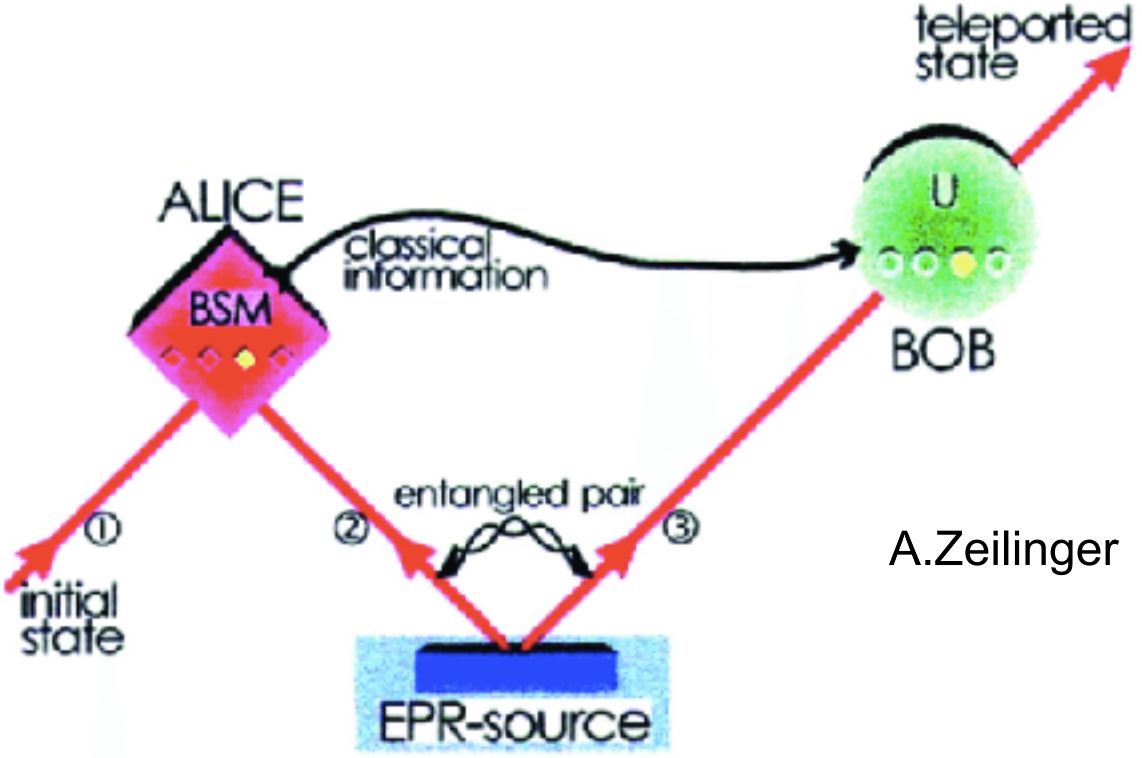
$$\boxed{\begin{aligned} P(c^2) = P(d^2) = P(g^2) = P(h^2) \quad &= \quad 1/8 \\ P(cg) = P(dh) \quad &= \quad (1/8)(1 + \cos(\delta_1 - \delta_2)) \\ P(ch) = P(dg) \quad &= \quad (1/8)(1 - \cos(\delta_1 - \delta_2)) \end{aligned}}$$

- Measure photon wave function at one station so effectively teleport the sky photon to the other station
- Need to transfer the photon quantum state → can use quantum networks, this will allow long distances

Quantum Network

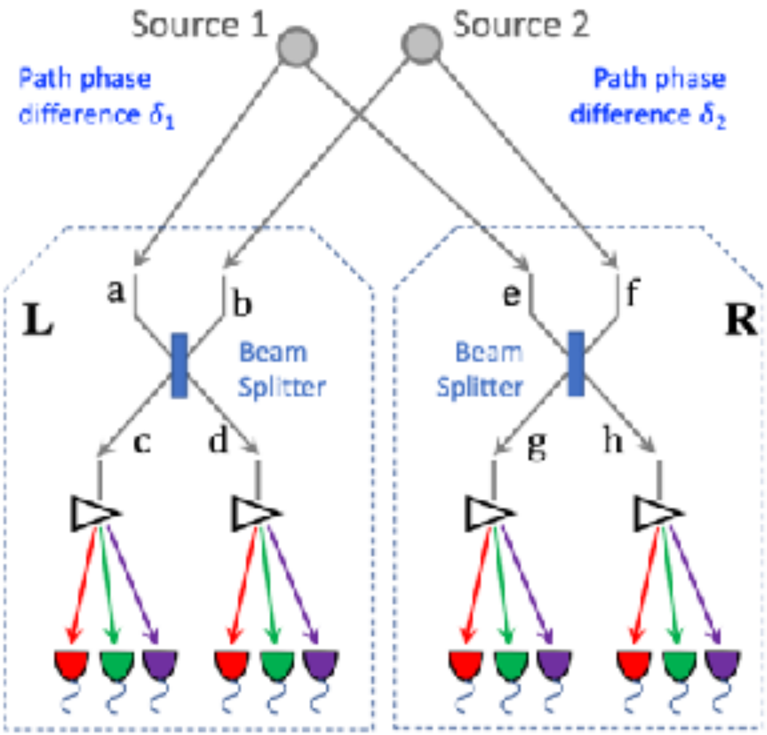
- Attenuation in fibers → need quantum repeater to reproduce qubits
  - Simple amplification will not conserve the quantum state

- 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

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

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

$$A^2\eta_1\eta_2 T_r\left[\overset{\text{Rates}}{\boxed{(I_1+I_2)^2}} + \overset{\text{HBT}}{\boxed{I_1^2\frac{\tau_c g_{11}}{T_r} + I_2^2\frac{\tau_c g_{22}}{T_r}}} \pm \underset{\text{New oscillatory term!}}{\boxed{2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B(\sin\theta_1-\sin\theta_2)}{c}+\frac{\omega_0\Delta L}{c}\right)}}\right] \quad (30)$$

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

Perfect to start exploring this approach

Instrumentation and Methods for Astrophysics

Vol. 5, 2022 • November 01, 2022 EST

Two-photon amplitude interferometry for precision astrometry

Paul Stankus, Andre Nomerotski, Anže Slosar, Stephen Vintskevich

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

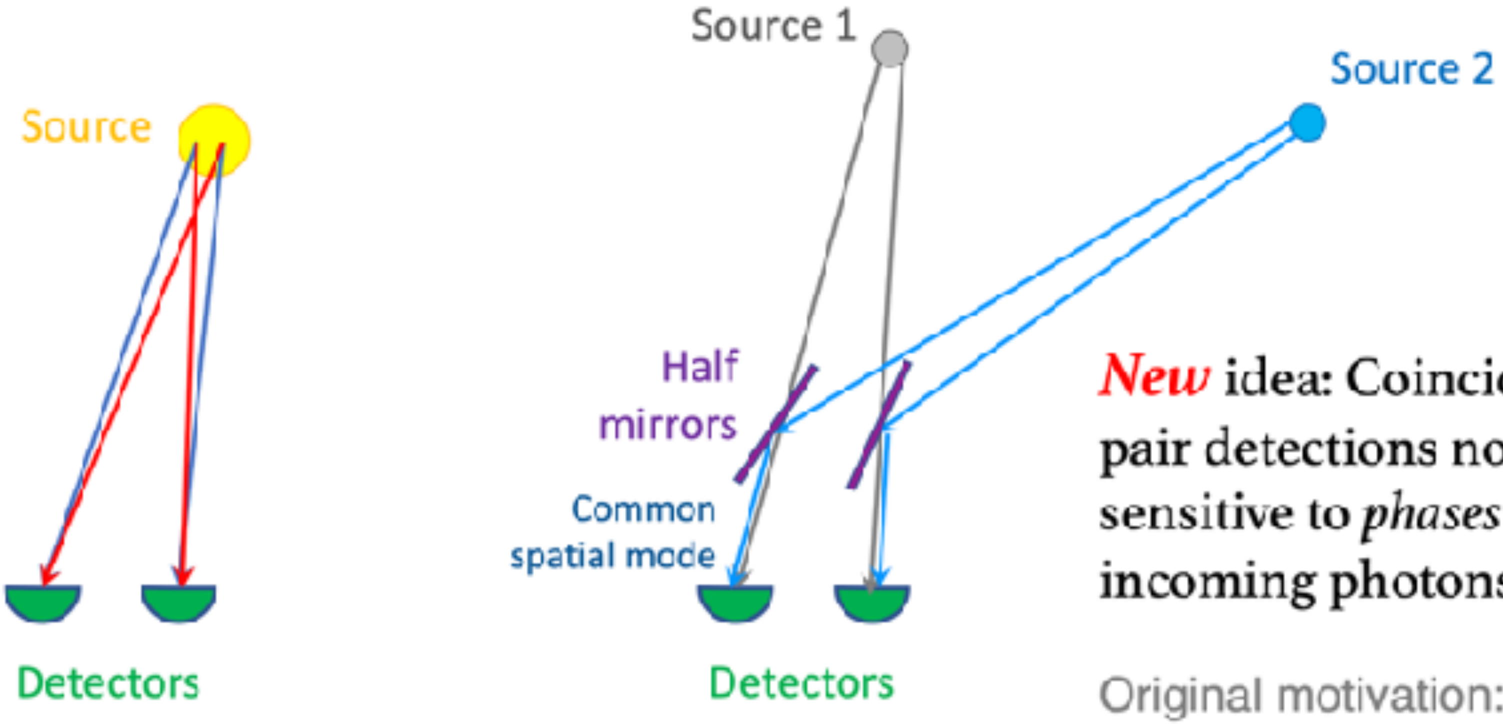
https://arxiv.org/abs/2010.09100

Hanbury Brown – Twiss Interferometry

If points are close enough two options of photons paths are coherent = photon phases not so different and they interfere

Interference produces photon bunching or HBT effect

HBT with two sources?



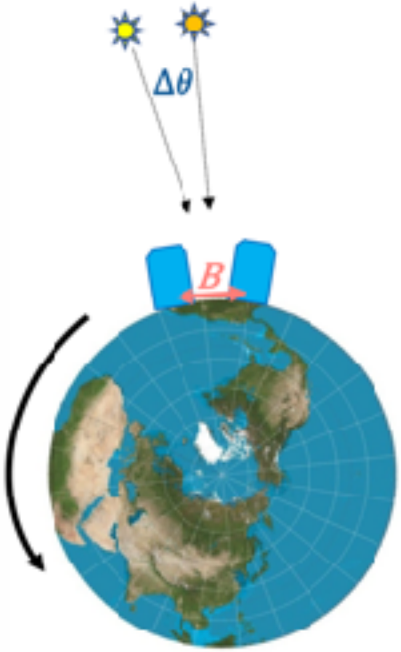
New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Original motivation: gravitational waves

Earth rotation fringe scan

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

This will evolve as the Earth rotates



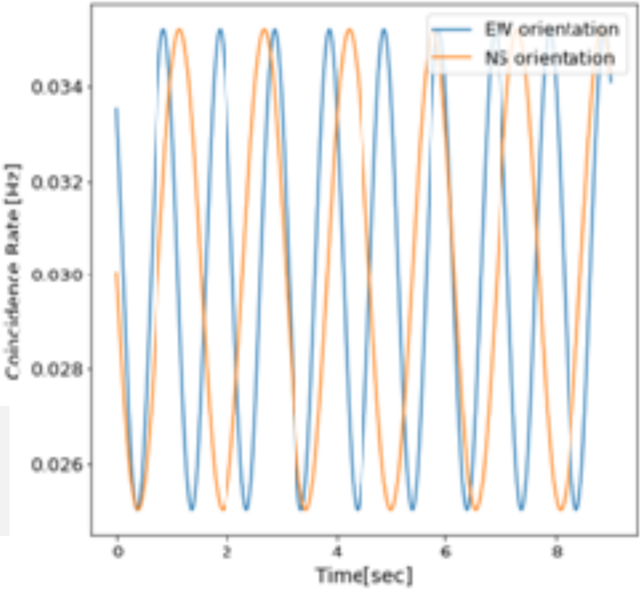
$$\langle N_{xy}\rangle(t) = \bar{N}_{xy}\left[1 \pm V\cos(\omega_f t + \Phi)\right]$$

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

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

doi.org/10.1103/PhysRevD.107.023015

Possible impact on astrophysics and cosmology

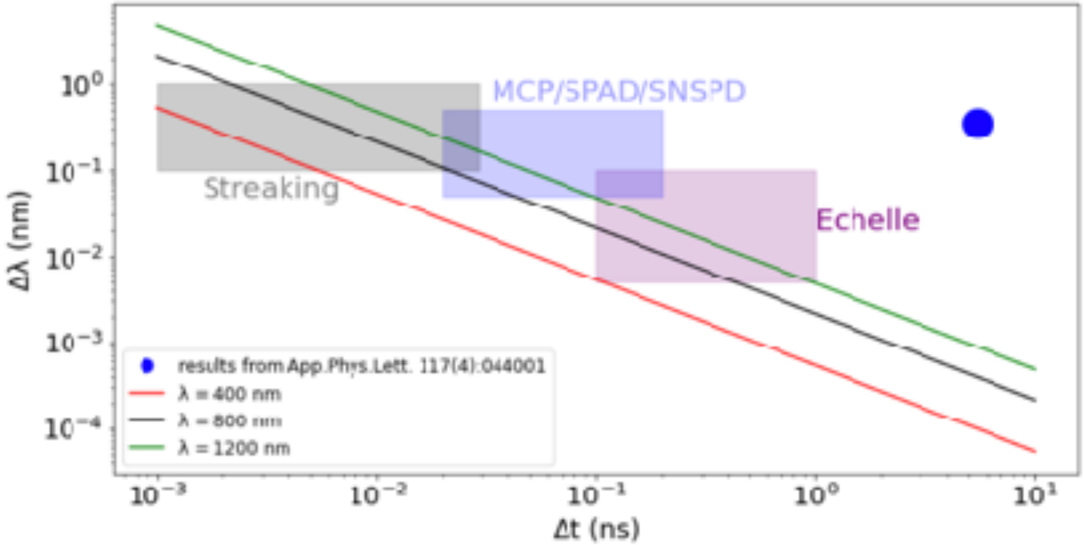
https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

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

- Black hole imaging
- Gravitational waves, coherent motions of stars - microHz range
- Exoplanets

Requirements for detectors



- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.1 nm * 10 ps

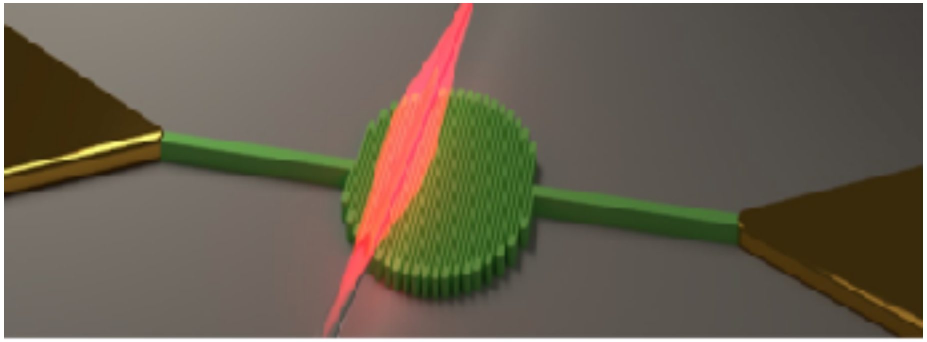
- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, **SPADs**, SNSPDs
  - Target 1-100 ps resolution
- Spectral binning: diffraction gratings, echelle spectrometers

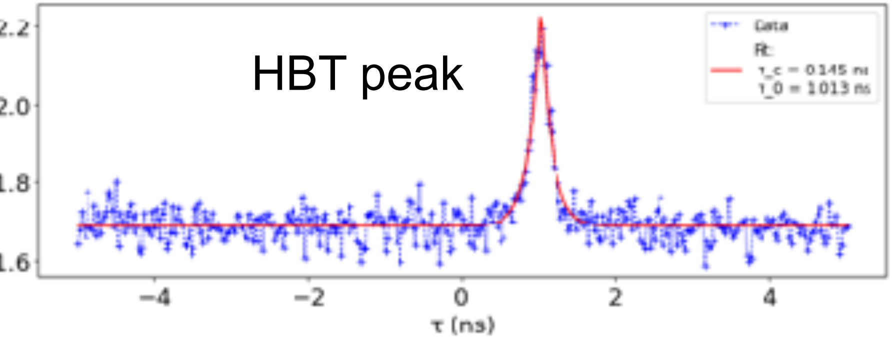
- High photon detection efficiency

Quantum-Assisted Optical Interferometers: Instrument Requirements; Andrei Nomerotski et al, Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 1144617 (2020) SPIE Astronomical Telescopes +Instrumentation, https://doi.org/10.1117/12.2560272; arxiv:2012.02812

Possible technologies: SNSPD

- Superconducting nanowires
  - Used Single Quantum SNSPD
  - 20 ps resolution for single photons using SPDC photon pair source
  - 3 ps devices reported




HBT peak

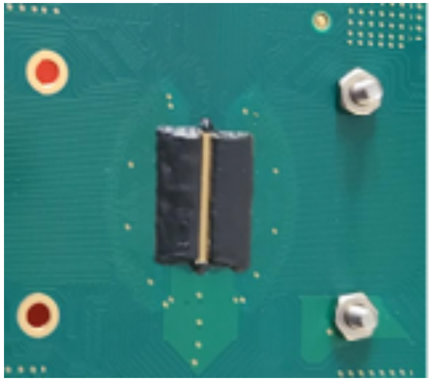
Possible technologies: SPAD

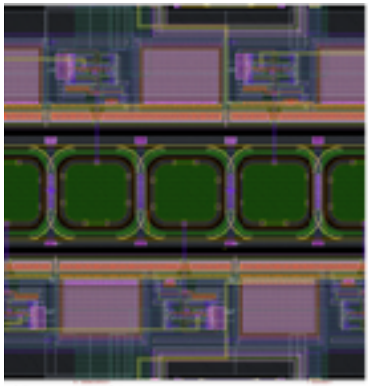
SPAD = single photon avalanche device
Semiconductor device: p-n junction with amplification

50 ps resolution

Developed in EPFL (E.Charbon et al)

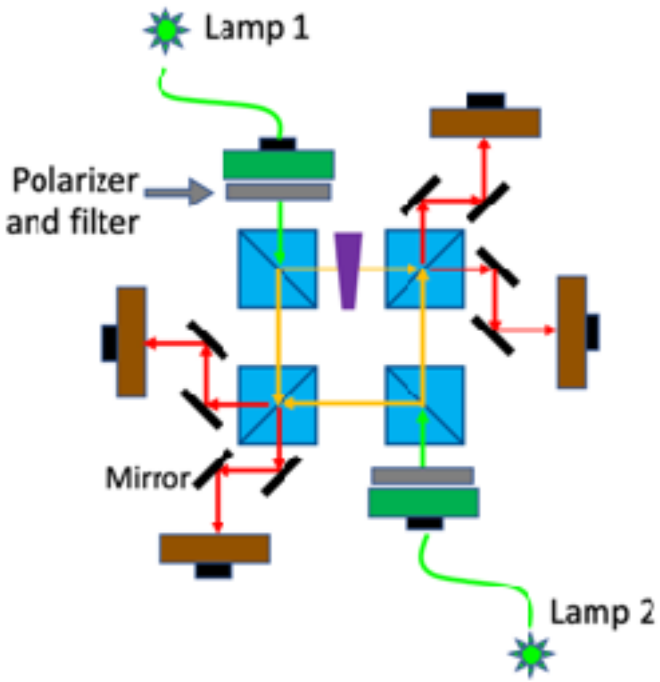
LinoSPAD2

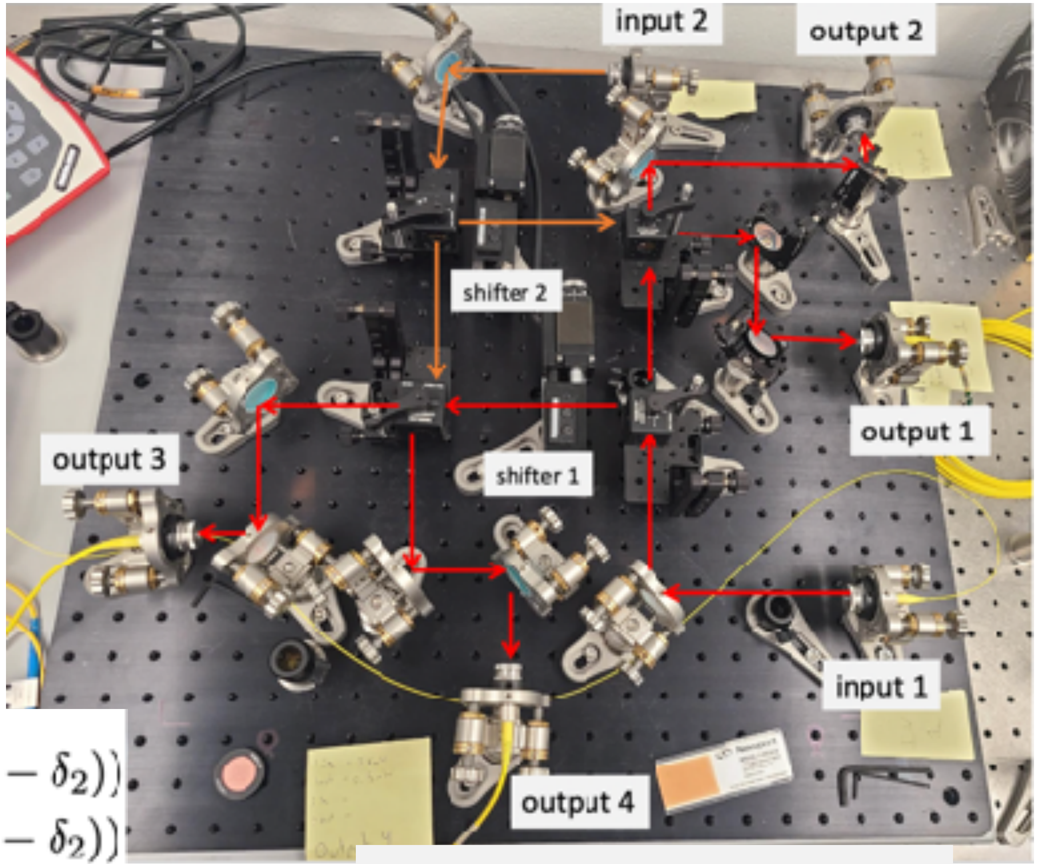




Close-up of SPADs

Benchtop Verification



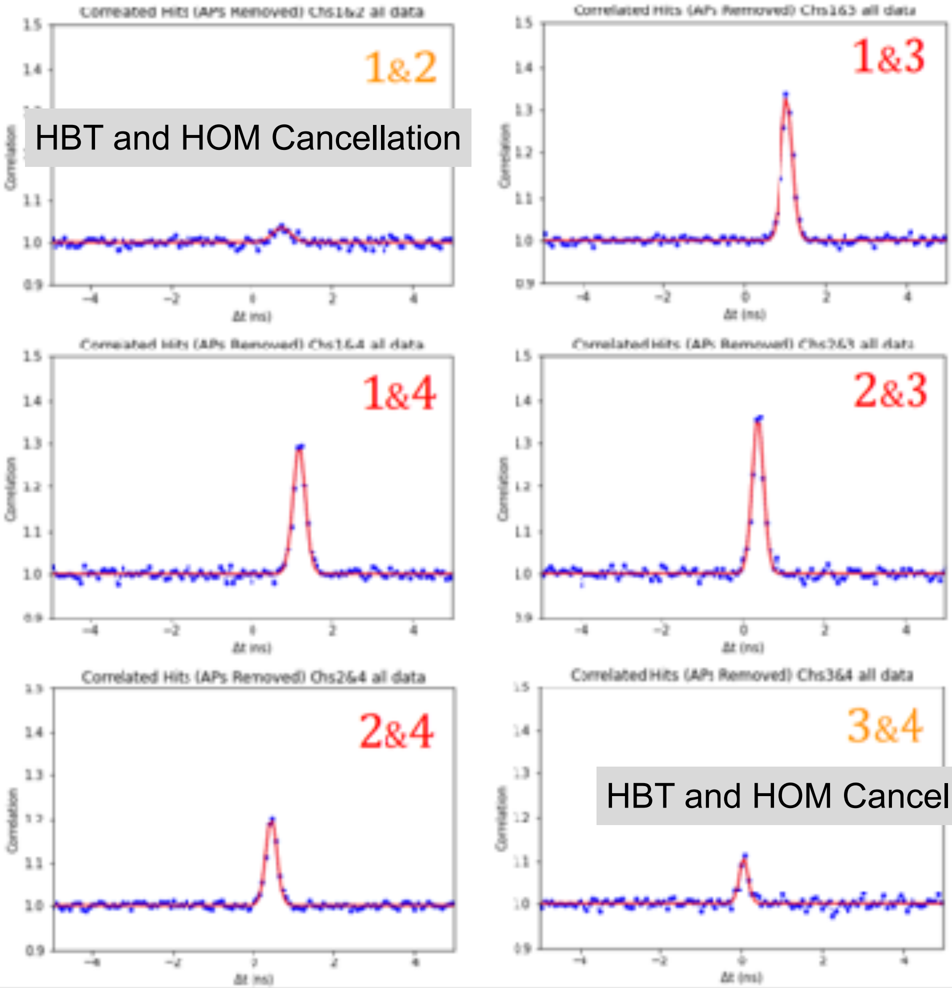


$$P(cg) = P(dh) = (1/8)(1+\cos(\delta_1-\delta_2))$$
$$P(ch) = P(dg) = (1/8)(1-\cos(\delta_1-\delta_2))$$

SPAD and SNSPD readout

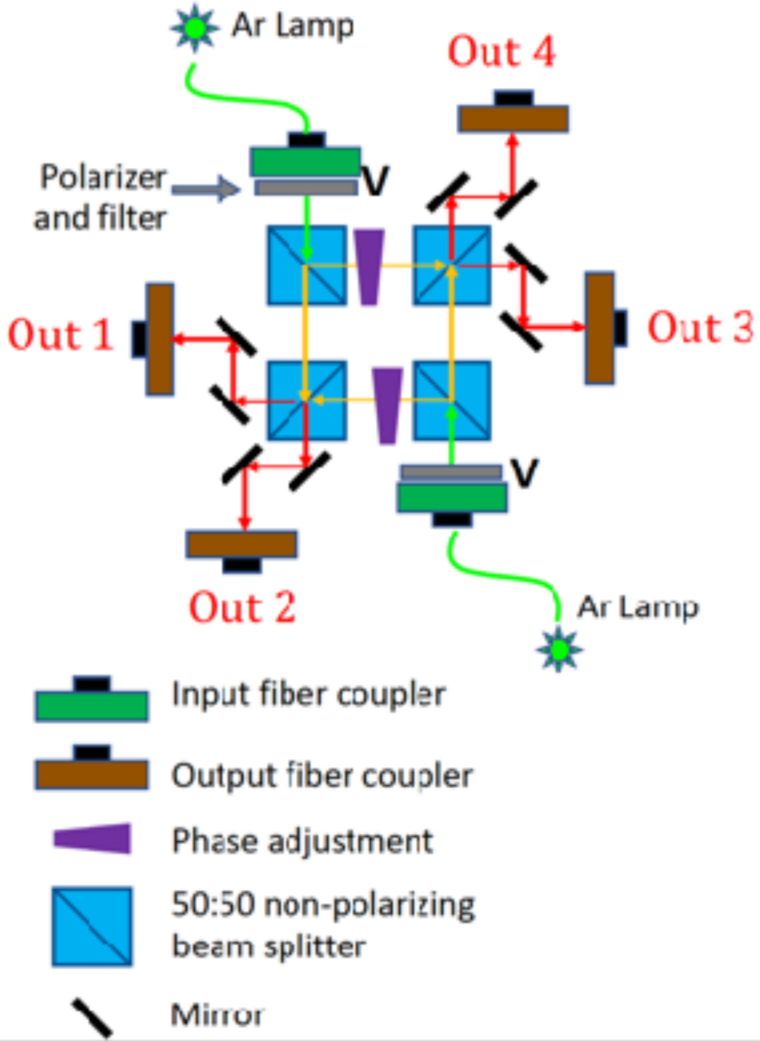
arxiv.org/abs/2301.07042
Optics Express 31, 44246-44258 (2023)

Polarized – V V

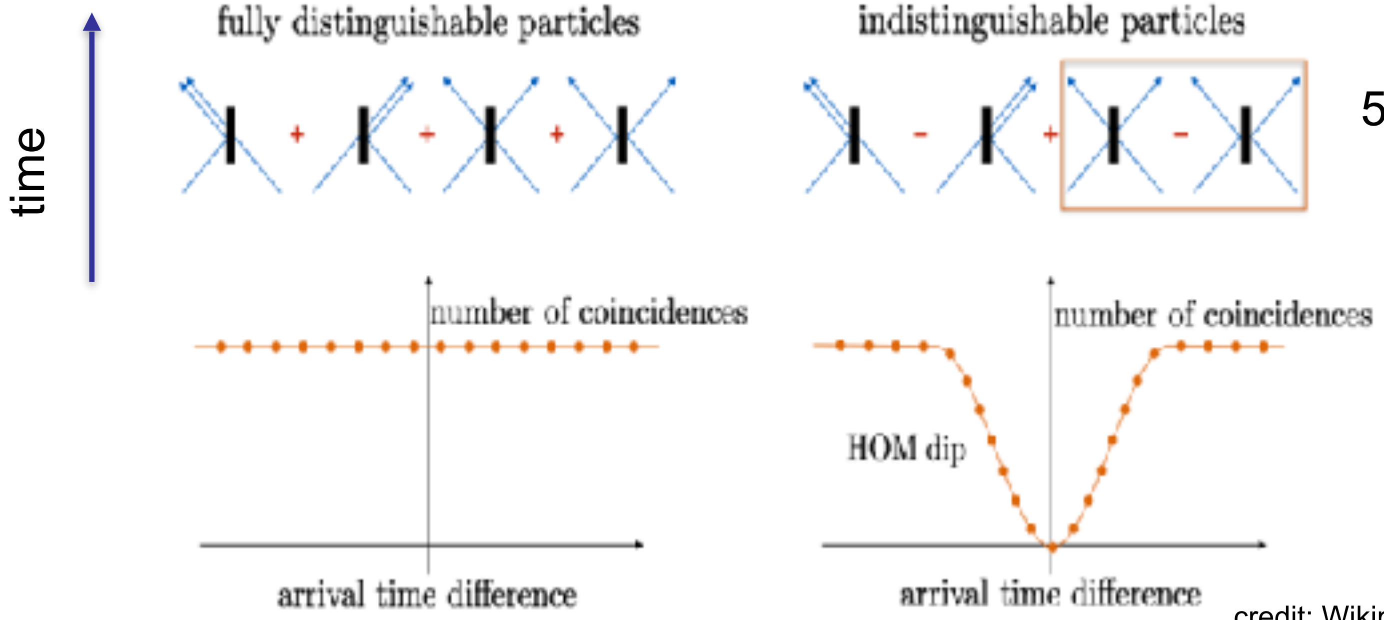


HBT and HOM Cancellation

HBT and HOM Cancellation



Hong-Ou-Mandel effect

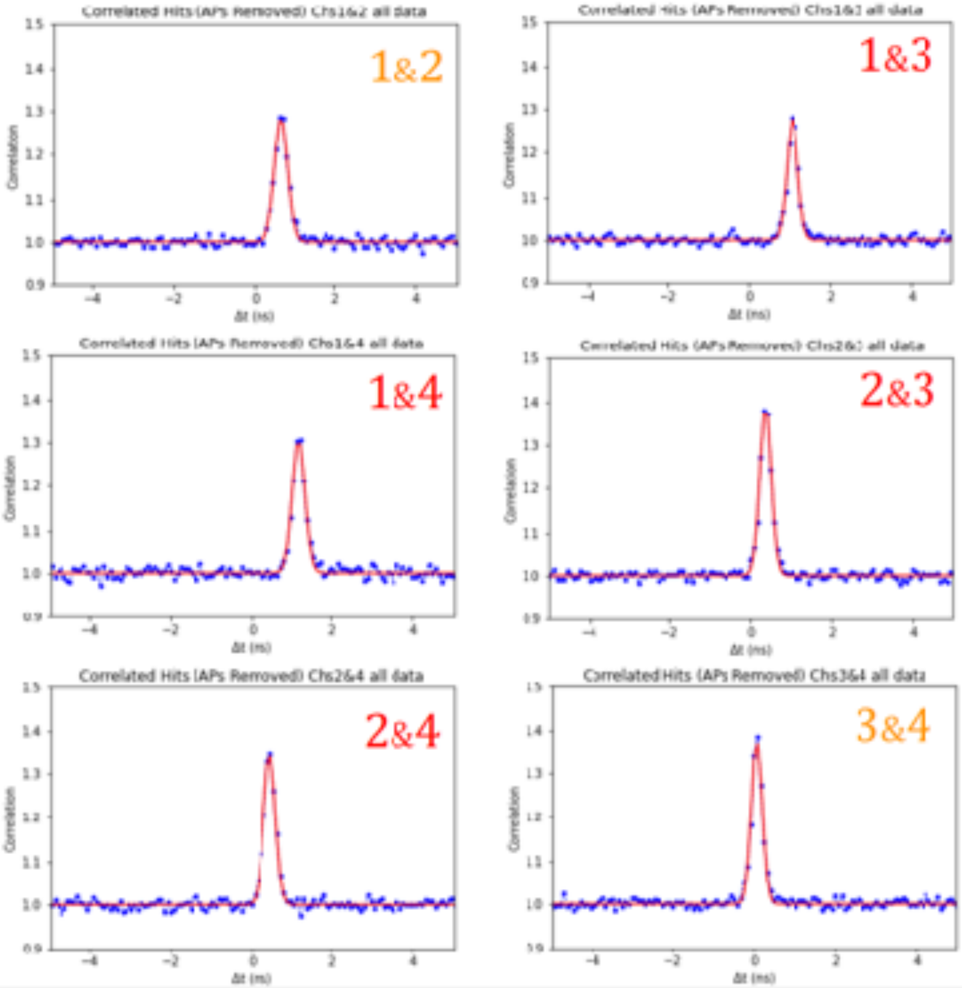


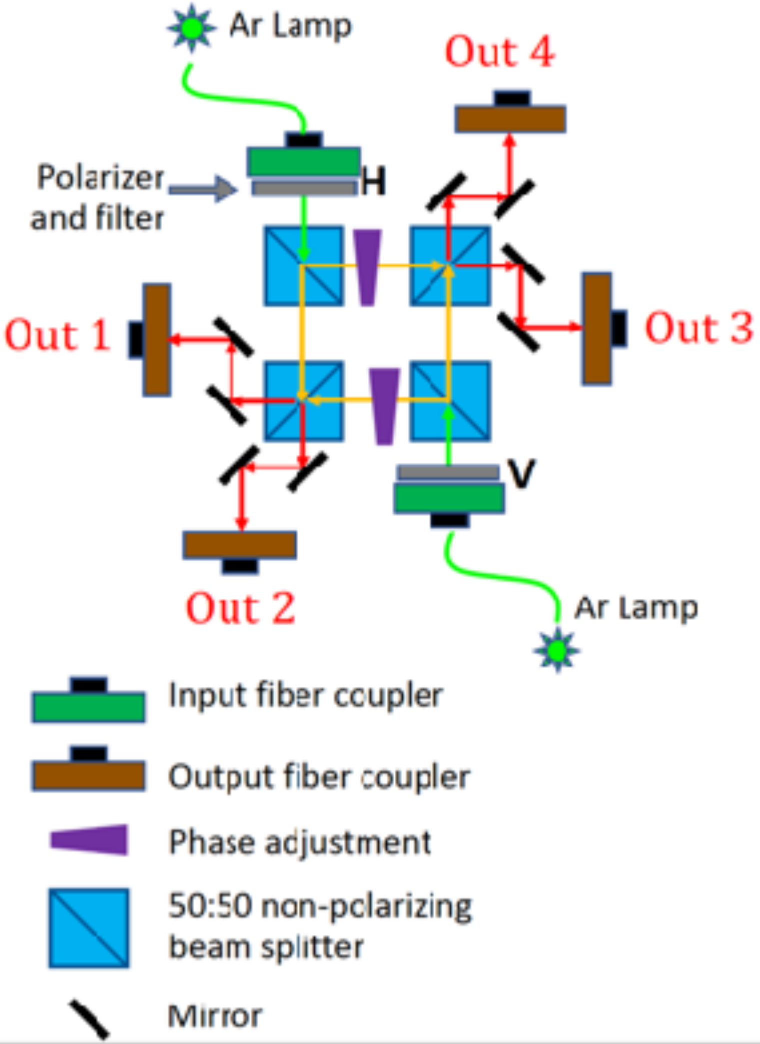
50/50 beam splitter

credit: Wikipedia HOM article

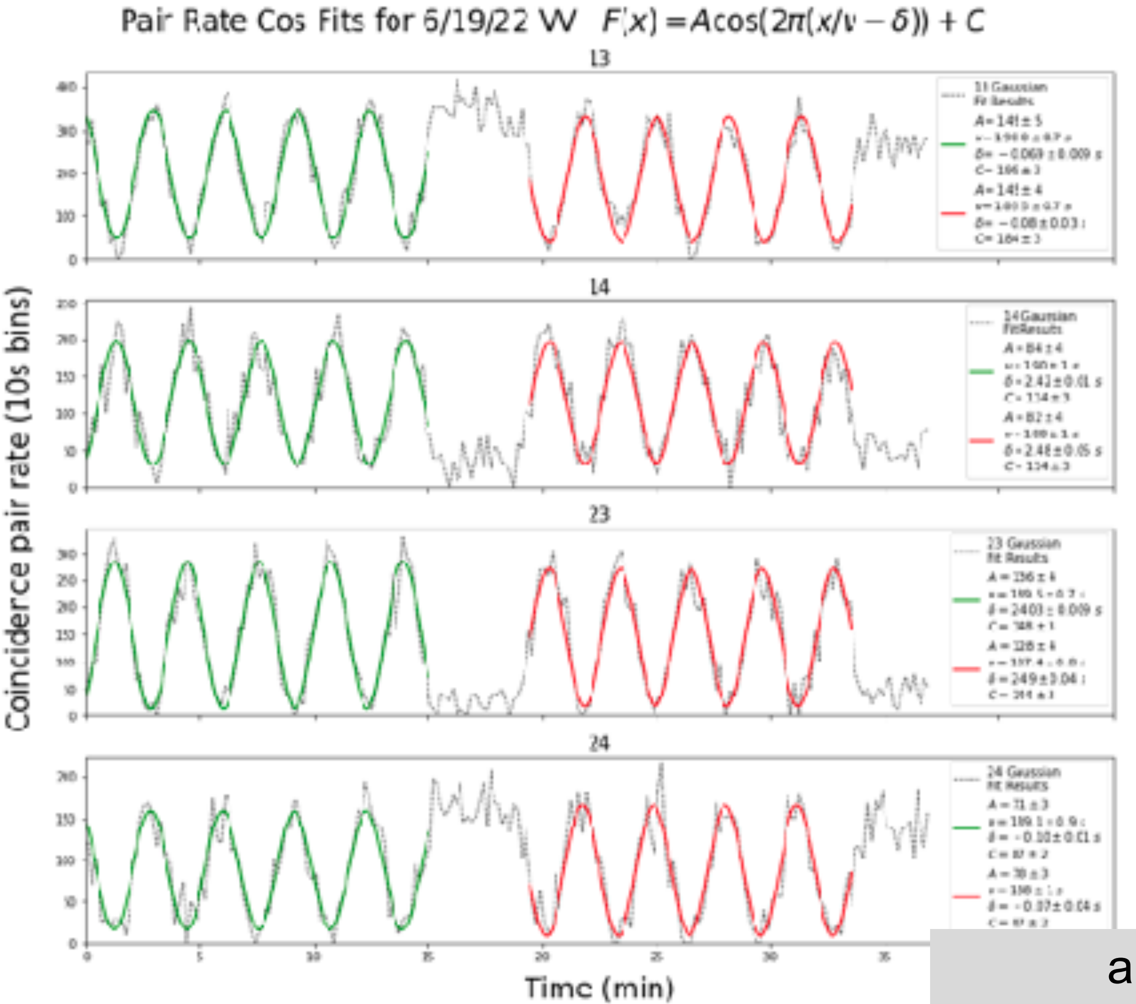
HOM dip for coincidences of two outputs

Polarized – V H





Phase dependence



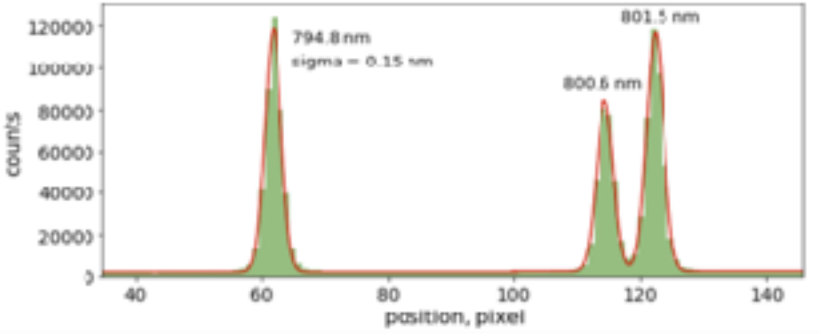
arxiv.org/abs/2301.07042
Optics Express 31, 44246-44258 (2023)

Population of HBT peaks as function of phase = phase oscillations

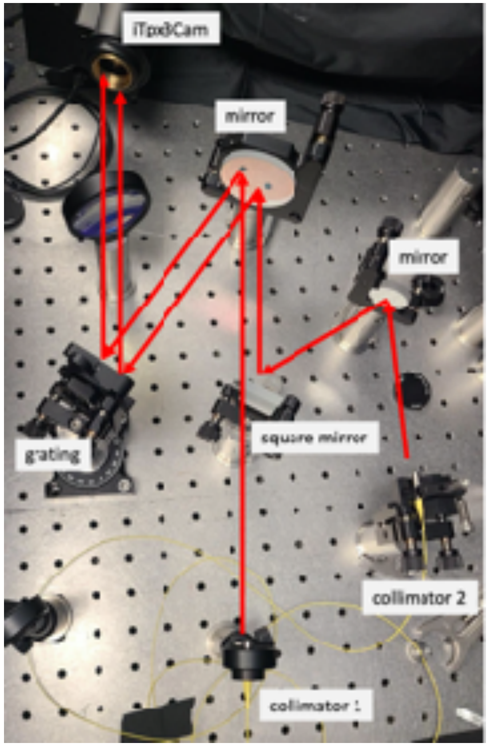
Next step: spectral binning

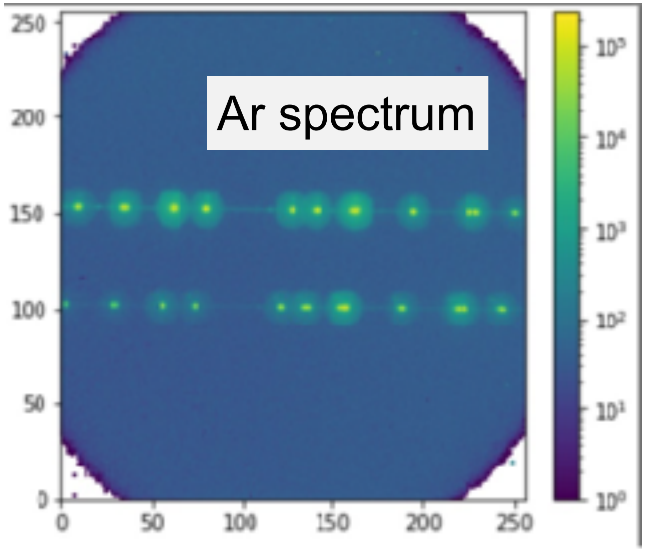
Spectral binning

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



spectral resolution for Ar lines ~0.15 nm




Ar spectrum

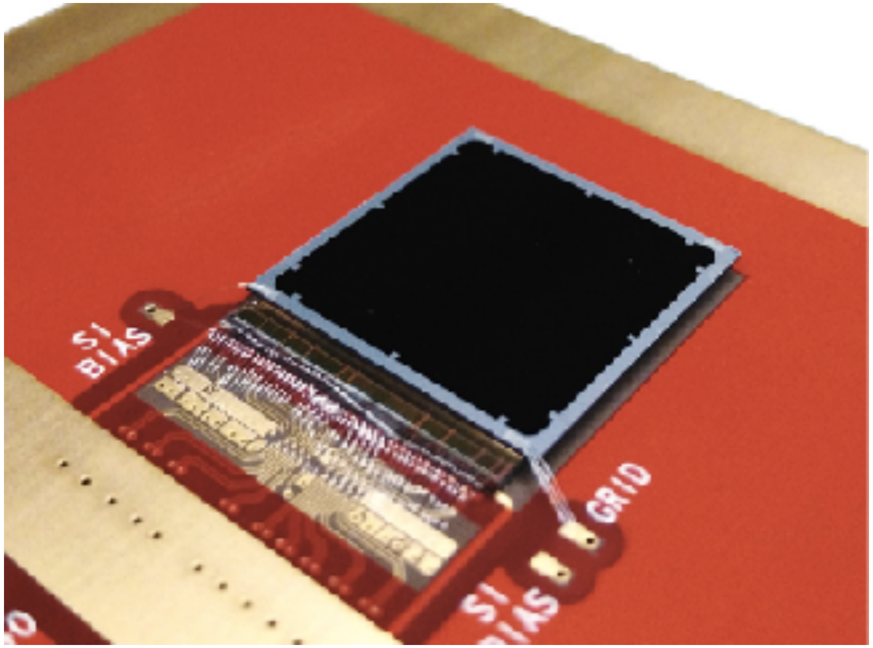
A.Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, published in JINST

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



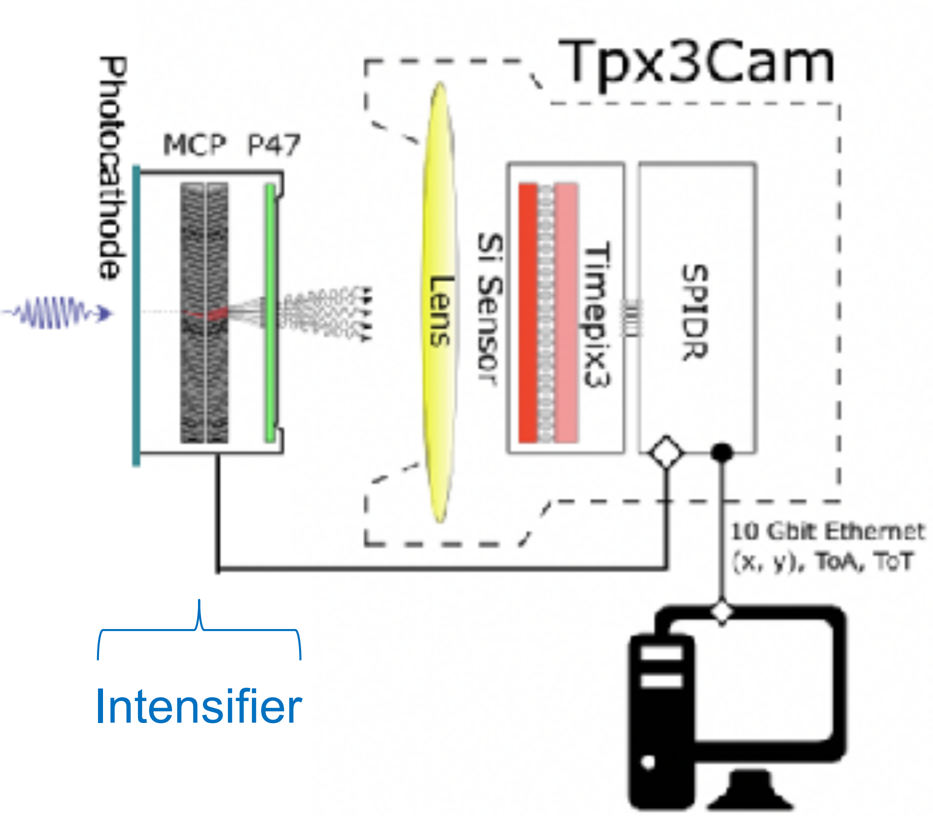
Sensor is bump-bonded to chip

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

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.

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



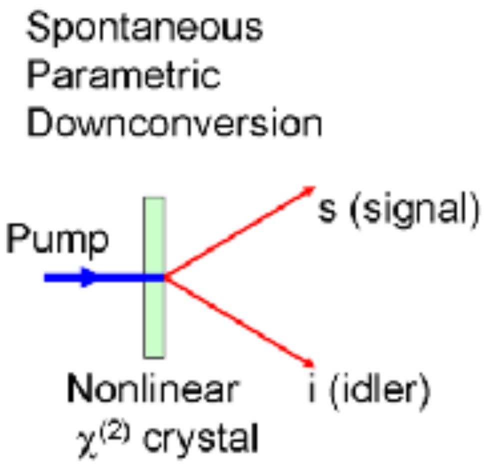
Intensifier

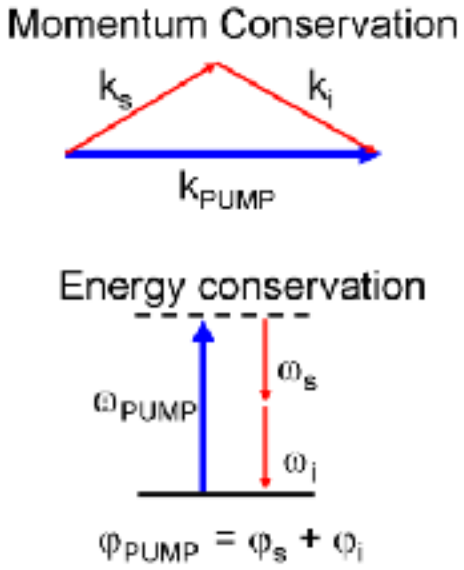
Intensified cameras are common:
- iCCD
- iCMOS cameras

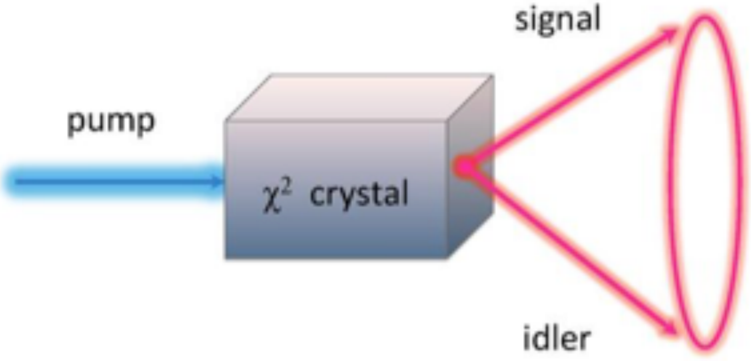
Image intensifier (Photonis PP0360EG)

Cricket@

Quantum photon sources - spontaneous parametric down-conversion (SPDC) sources





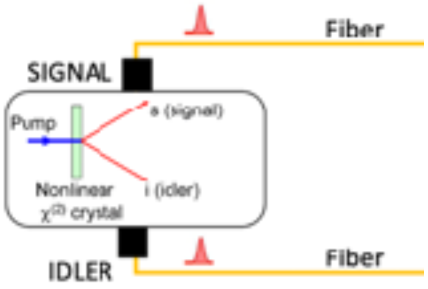


Produce two photons correlated (sometimes entangled) in

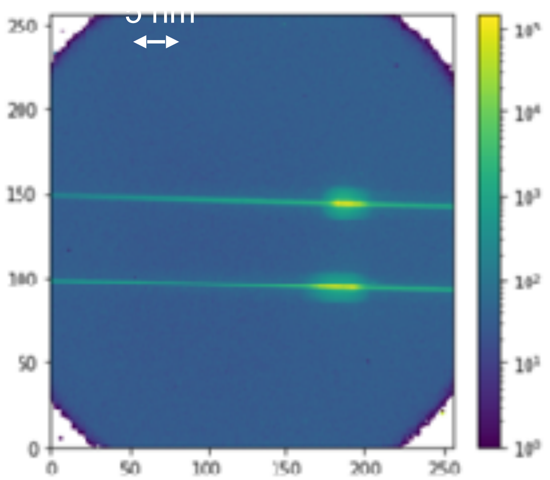
1. Time
2. Position
3. Energy

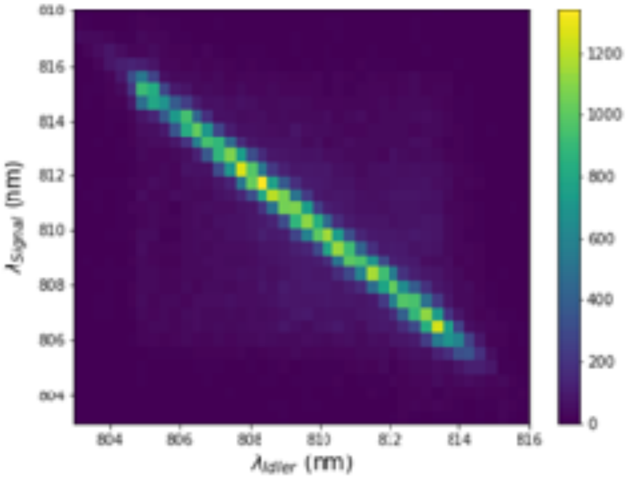
SPDC source in spectrometer

- 810 nm idler and signal
- no filter

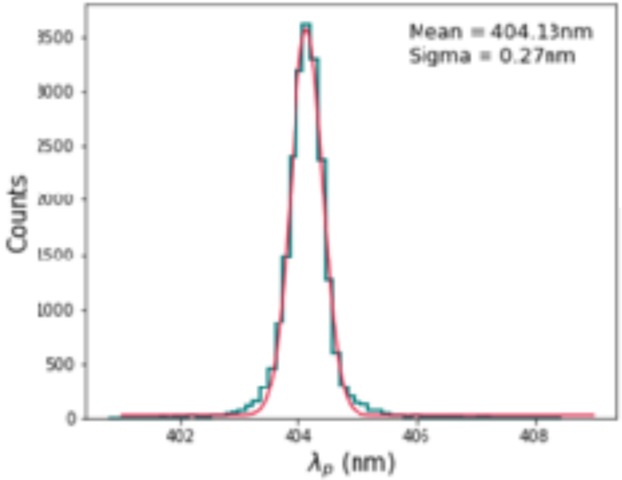


signal & idler in spectrometer

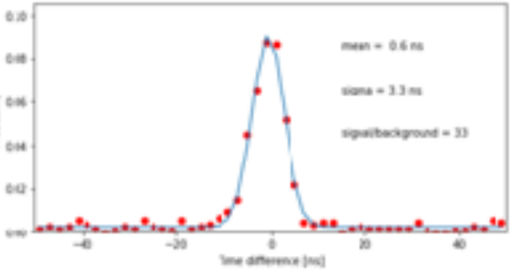




wavelength anti-correlation
for photon pairs



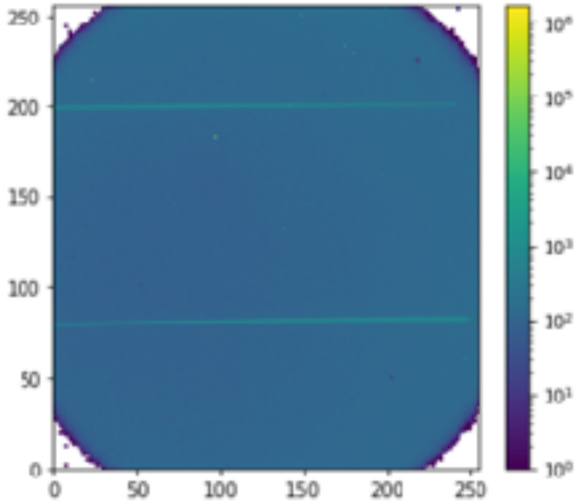
pump wavelength

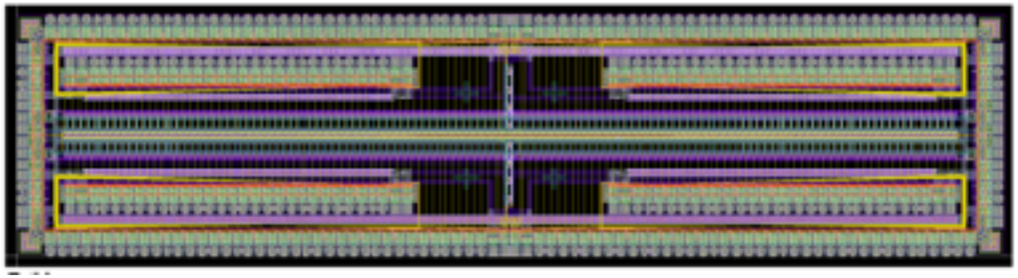


time coincidences

Next steps: spectrometer based on LinoSPAD2

Diffracted photon stripe projected on to linear array





Spectrometer time resolution: 5 ns →100 ps

Sergei’s slides

Fast spectrometers at Heisenberg limit

For a single photon uncertainties are bounded by Heisenberg uncertainty principle

$\Delta t * \Delta E \geq \hbar/2$ 0.03 nm * 10 ps

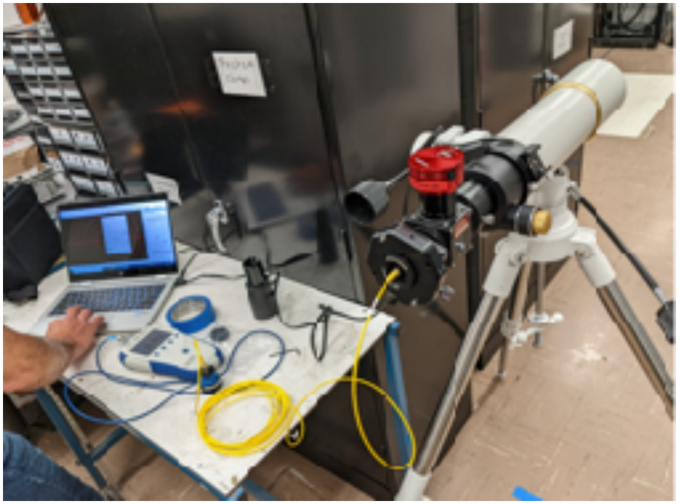
Achieved 0.04 nm spectral and 40 ps timing resolution

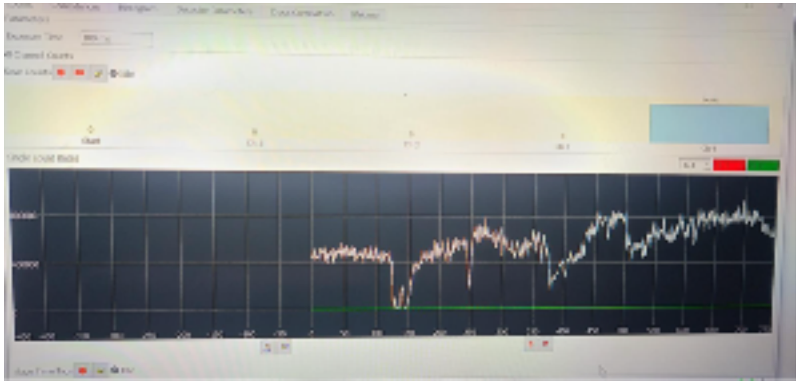
only x10 more than $\Delta t * \Delta E \geq \hbar/2$

telescopes

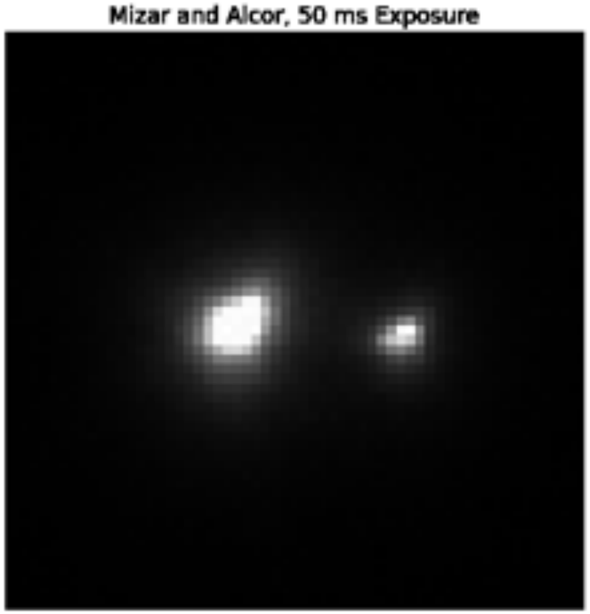
On-sky measurements

- Experimenting with SM fiber coupling
- Trying adaptive optics





On-sky measurements



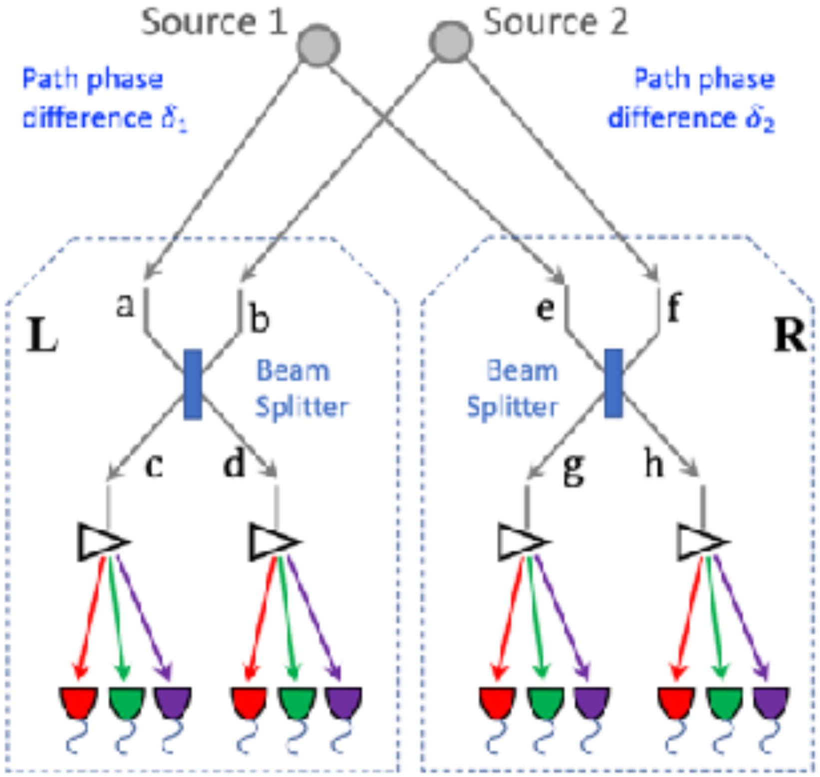
Mizar A & B

- 50 ms exposure
- 15 arcsec separation

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

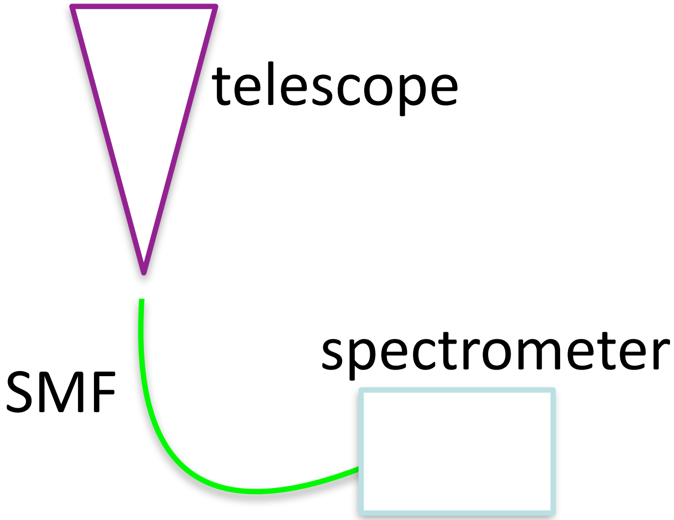
Important point for discussion

- For amplitude two-photon interferometry light needs be coupled to SMF
- This is difficult! 5-10 micron spot, highly non-trivial adaptive optics
- If achieved then interference and spectrometers are easy



Two possible geometries

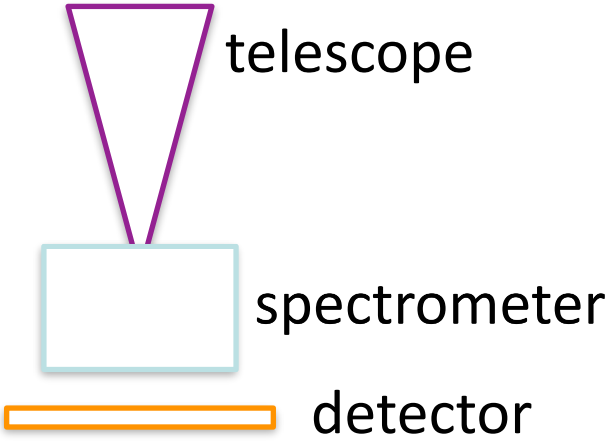
1)



collect telescope light to SMF and send to spectrometer/interferometer

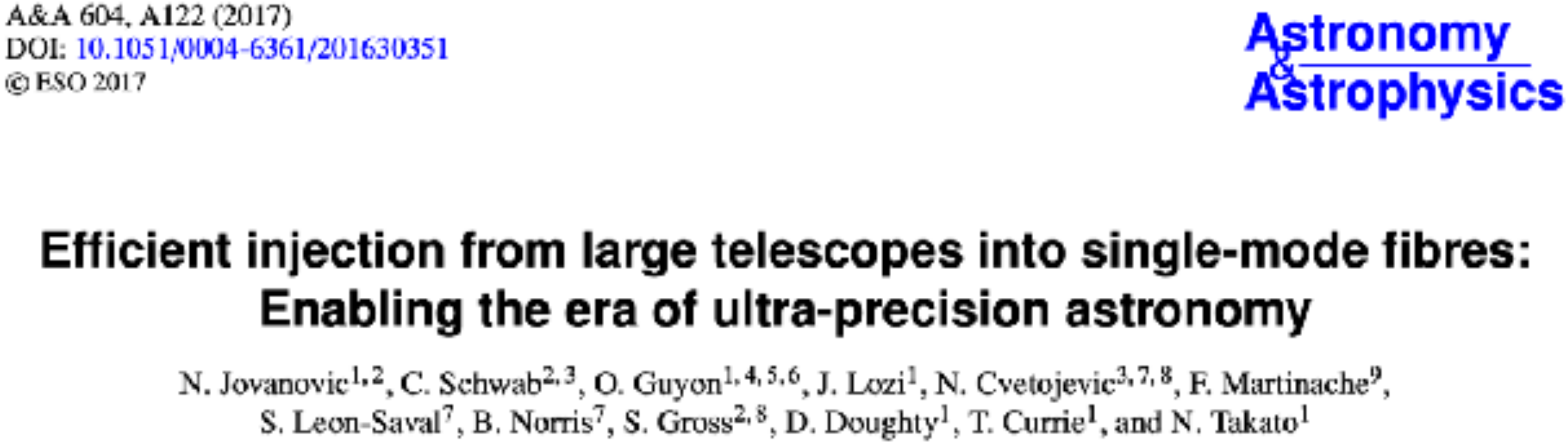
- Difficult, 5-10 um spot, new adaptive optics - collection efficiency?

2)



send telescope light directly to (existing) spectrometer

- Need new detectors



A&A 604, A122 (2017)
DOI: 10.1051/0004-6361/201630351

Astronomy & Astrophysics

Efficient injection from large telescopes into single-mode fibres: Enabling the era of ultra-precision astronomy

N. Jovanovic[1,2], C. Schwab[2,3], O. Guyon[1,4,5,6], J. Lozi[1], N. Cvetojevic[3,7,8], F. Martinache[9],
S. Leon-Saval[7], B. Norris[7], S. Gross[2,8], D. Doughty[1], T. Currie[1], and N. Takato[1]

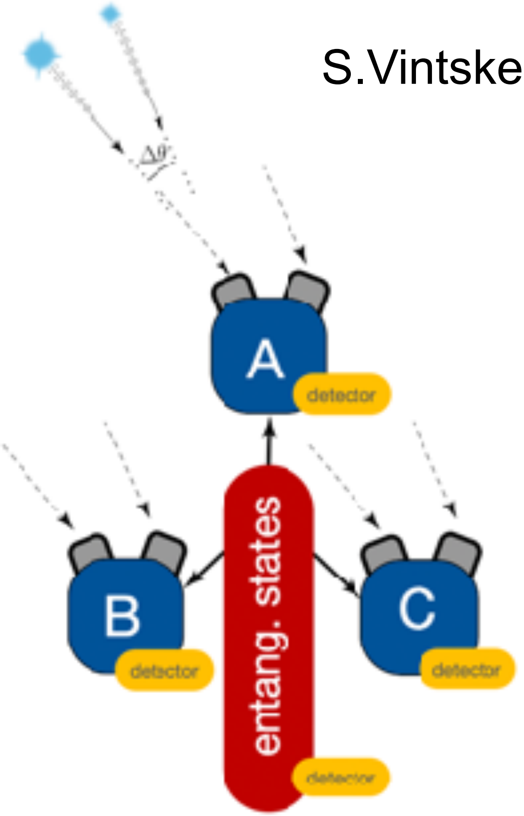
coupling efficiency in J - H bands ~ 50%

There is hope!

Developing the quantum

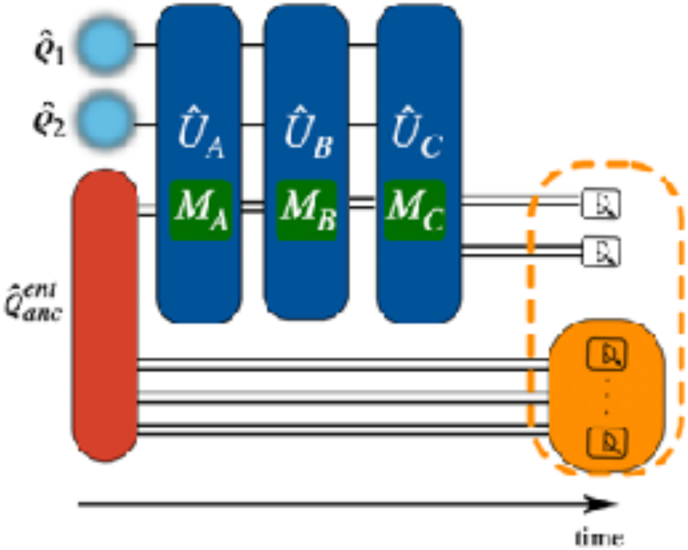
Use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations and quantum protocol to process information in noisy environment

S.Vintskevich et al



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

Quantum protocol circuit



detectors

Quantum protocol evaluates experimental observables

Common approaches with quantum sensing and quantum metrology

Classification of four-qubit entangled states via machine learning

S. V. Vintskevich, N. Bao, A. Nomerotski, P. Stankus, and D. A. Grigoriev
Phys. Rev. A **107**, 032421 – Published 23 March 2023

Sensor R&D

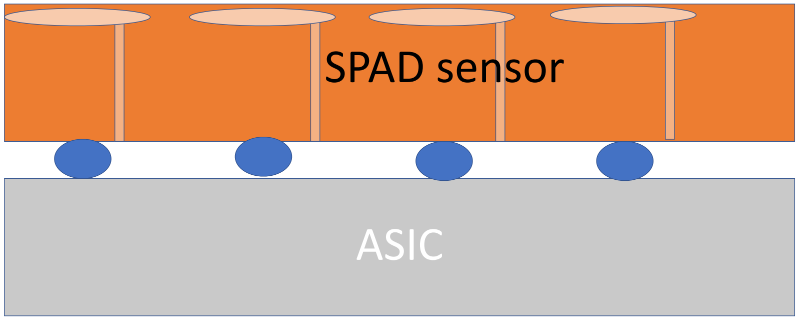
New ideas for 2d imaging sensors which can provide 20 ps resolution

20 ps timing

- 20 ps timing is needed for next round of CERN experiments in 10 years, there will be lots of investment in fast ASICs

- examples:
- Timepix4 chip: 200 ps
- Timespot1 chip: 50 ps

- Hybrid detector: SPAD + 20 ps chip



Timespot1: A 28 nm CMOS Pixel Read-Out ASIC for 4D Tracking at High Rates

---

Sandro Cadeddu,[a,1] Luca Frontini,[b,c] Adriano Lai,[a] Valentino Liberali,[b,c]
Lorenzo Piccolo,[d] Angelo Rivetti,[d] Jafar Shojaii,[e] Alberto Stabile[b,c]
[a] INFN Sezione di Cagliari, 09042 Monserrato, Italy
[b] Università degli Studi di Milano, Dipartimento di Fisica, 20133 Milano, Italy
[c] INFN Sezione di Milano, 20133 Milano, Italy
[d] INFN Sezione di Torino, 10125 Torino, Italy
[e] Swinburne University of Technology and University of Melbourne, Victoria, Australia

E-mail: sandro.cadeddu@ca.infn.it

Abstract: We present the first characterization results of Timespot1, an ASIC designed in CMOS 28 nm technology, featuring a 32 × 32 pixel matrix with a pitch of 55 µm. Timespot1 is the first-born small-size prototype, conceived to read-out fine-pitch pixels with single-hit time resolution below 50 ps and input rates of several hundreds of kilohertz per pixel. Such experimental conditions will be typical of the next generation of high-luminosity collider experiments, from the LHC run5 and beyond. Each pixel of the ASIC has been endowed with a charge amplifier, a discriminator, and a Time-to-Digital Converter with time resolution around 30 ps and maximum read-out rates (per pixel) of 3 MHz. To respect system-level constraints, the timing performance have been obtained keeping the power budget per pixel below 40 µW. The ASIC has been tested and characterised in laboratory concerning its performance in terms of time resolution, power budget and sustainable rates. The ASIC will be hybridized on a matched 32 × 32 pixel sensor matrix and will be tested under laser beam and Minimum Ionizing Particles in the laboratory and at test beams. In this paper we present a description of the ASIC operation and the first results obtained from characterization tests concerning its performance in tracking measurements.

Keywords: Front-end electronics for detector readout, Timing detectors, VLSI circuits

---

[1] Corresponding author.

5 ps timing

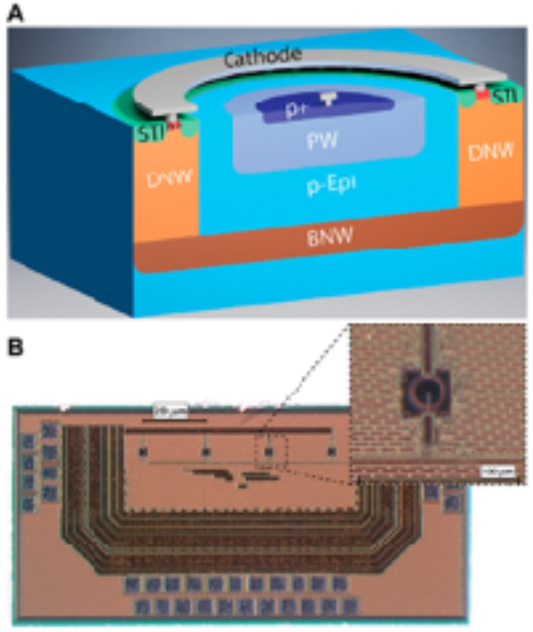
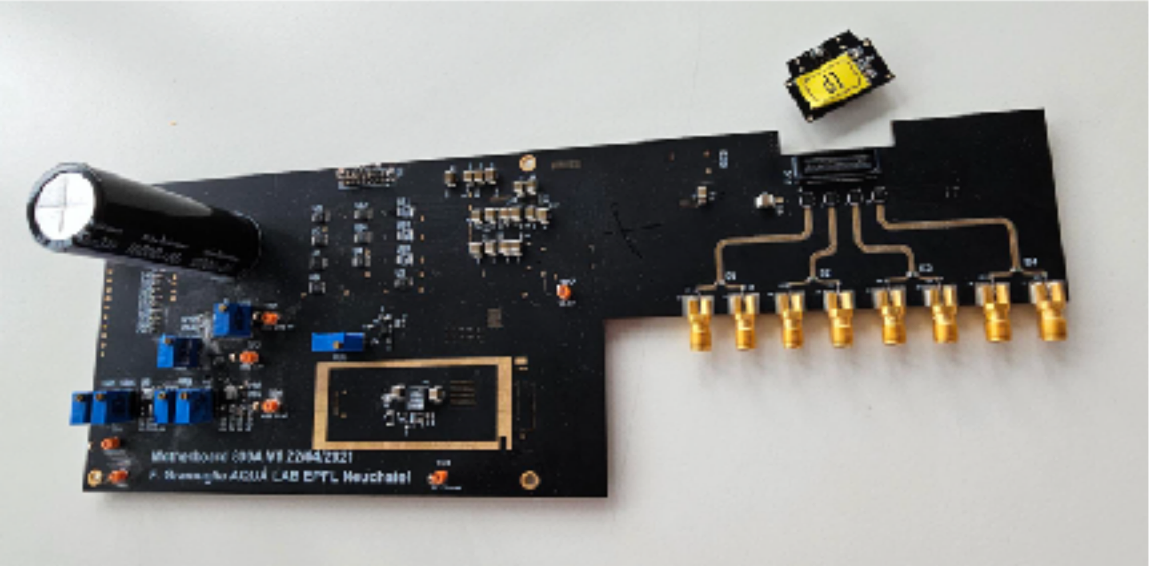


FIGURE 1 | (A): SPAD cross section. **(B):** Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [21].



- SuperSPAD sensor
    - 4 single devices so far
- Developed in AQUA group in EPFL
- 7.5 ps FWHM time resolution
- Starting tests

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).

Main points to take home

- Two-photon interferometry can permit independent stations over long baselines
- New ideas suggest quantum sensing technology can dramatically enhance astrometric precision, requires single photon cameras with 10 ps resolution

- Promising results with 50 ps spectrometers

Broad program in quantum-assisted optical interferometry ahead, efforts underway to develop new timing technologies

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

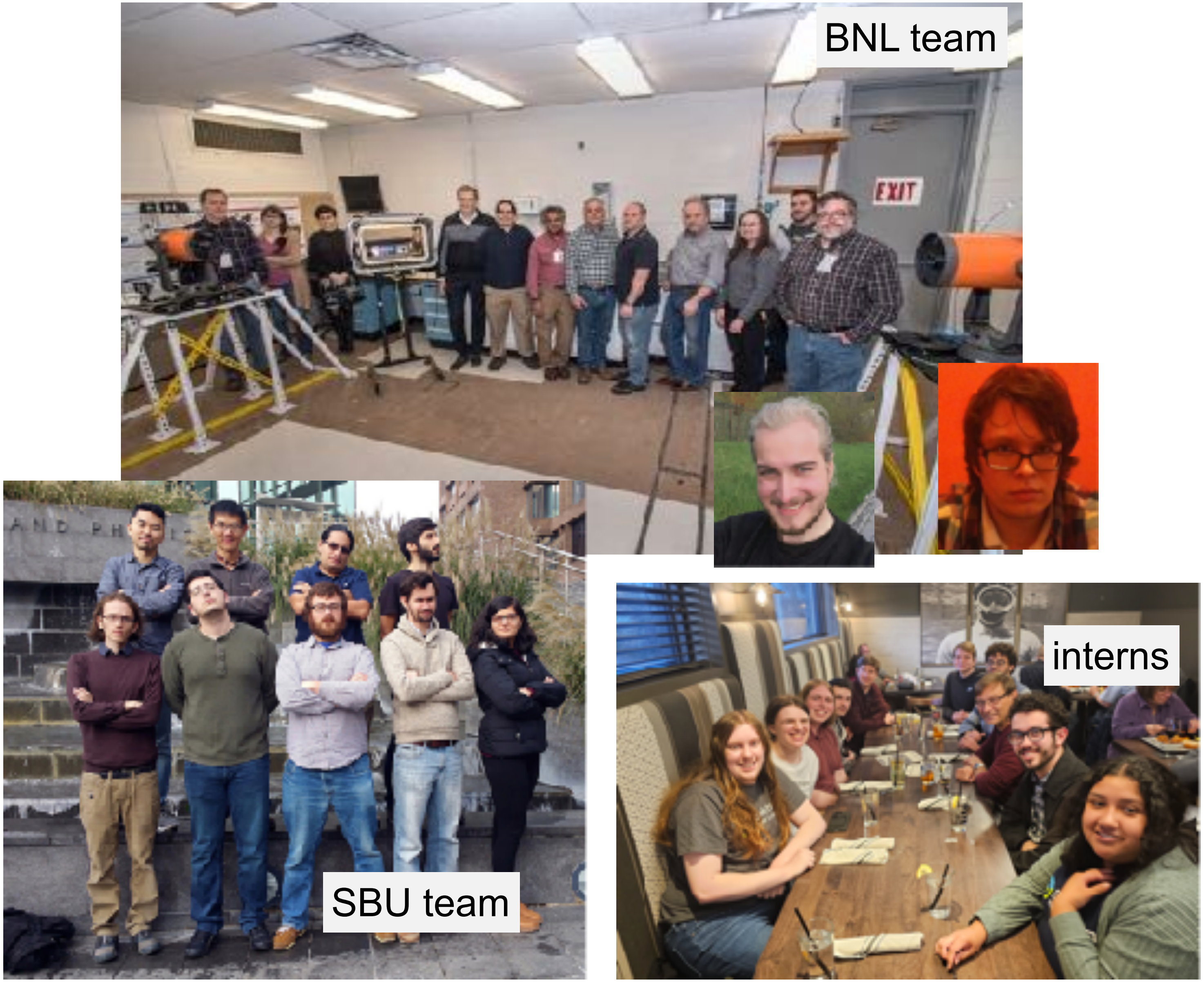
Eden Figueroa
Paul Stankus
Tom Tsang
Justine Haupt
Mael Flament
Guodong Cui
Sonali Gera
Dimitros Katramatos

Michael Keach
Steven Paci
Alex Parsells
Jonathan Schiff
Denis Dolzhenko
Stepan Vintskevich
Anze Slosar
Zhi Chen
Jesse Crawford
Aaron 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

Edoardo Charbon
Tommaso Milanese
Ermanno Bernasconi
Claudio Bruschini

Acknowledgements



Questions?

www.quantastro.bnl.gov