Quantum Assisted Optical Interferometers: Instrument Requirements

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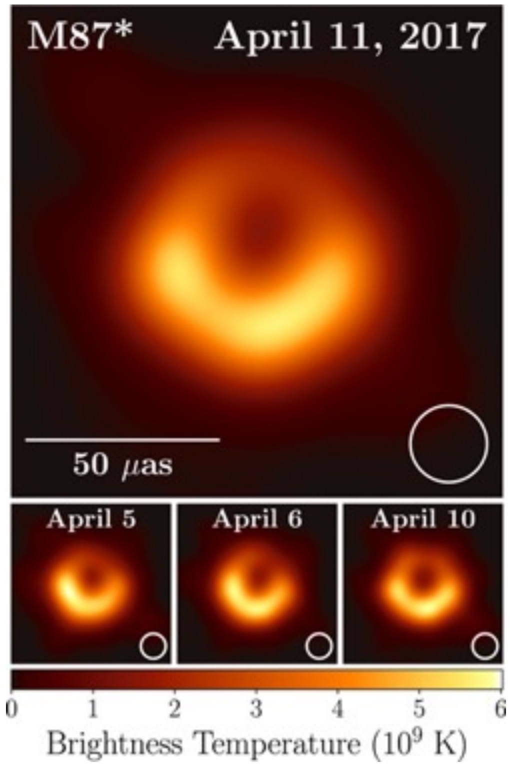
Idea: employ quantum entanglement to improve astrometrical precision of optical interferometers

Two-photon amplitude interferometry for precision astrometry
Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich
https://arxiv.org/abs/2010.09100

Will also discuss experimental implications: temporal and spectral resolutions required for implementation

Astronomy picture of the decade



sensitive to features on angular scale

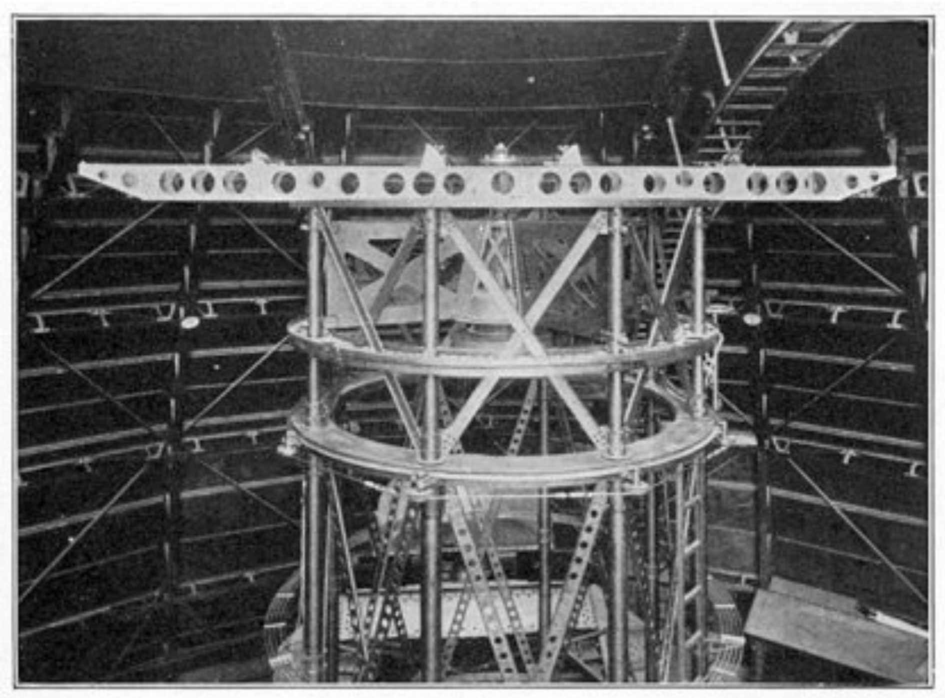
$$\Delta\theta \sim \frac{\lambda}{b}$$

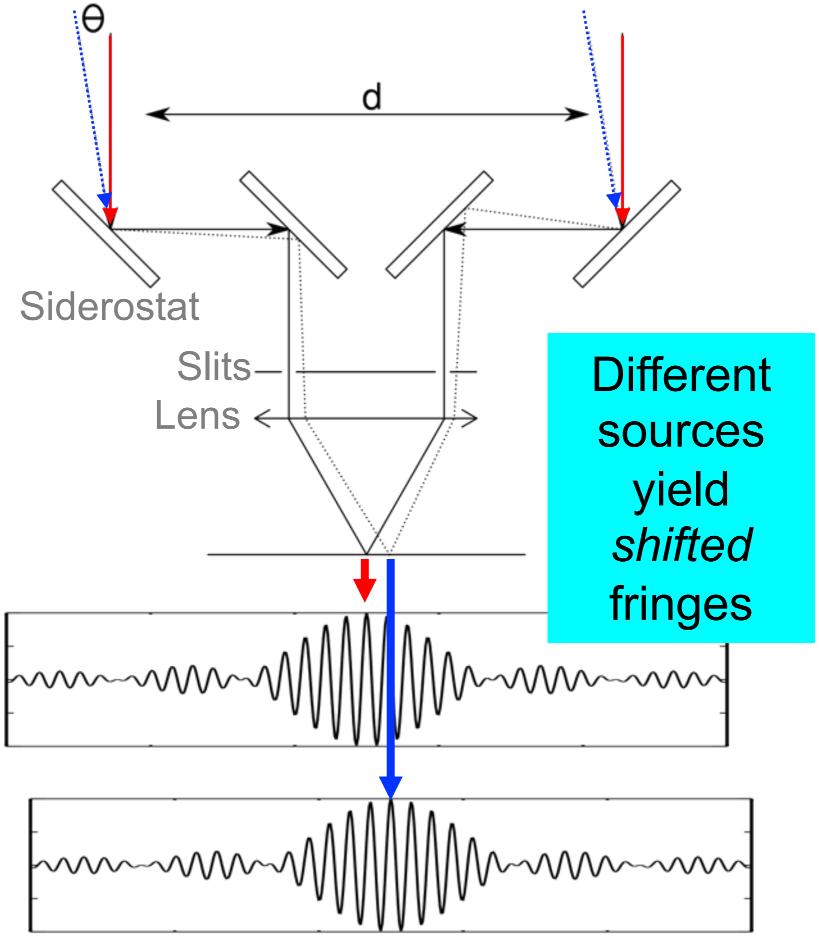
2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

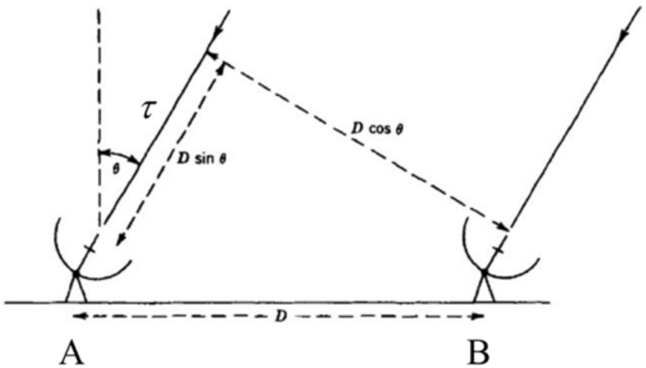
In classical times





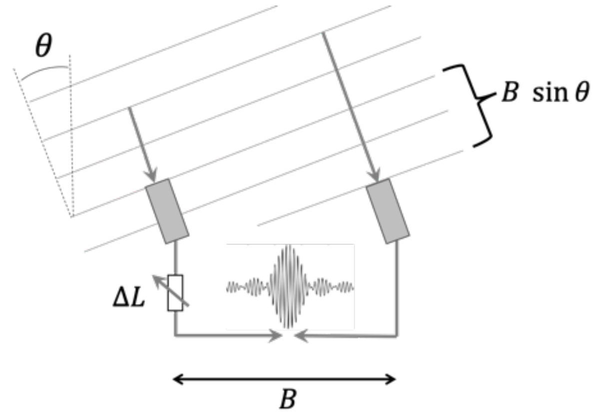
Michelson Stellar Interferometer at Mt. Wilson c. 1920, after original idea by Michelson & Fizeau c. 1890

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

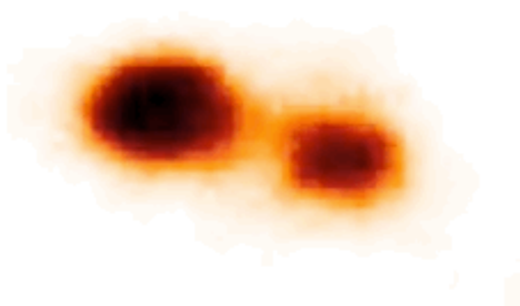


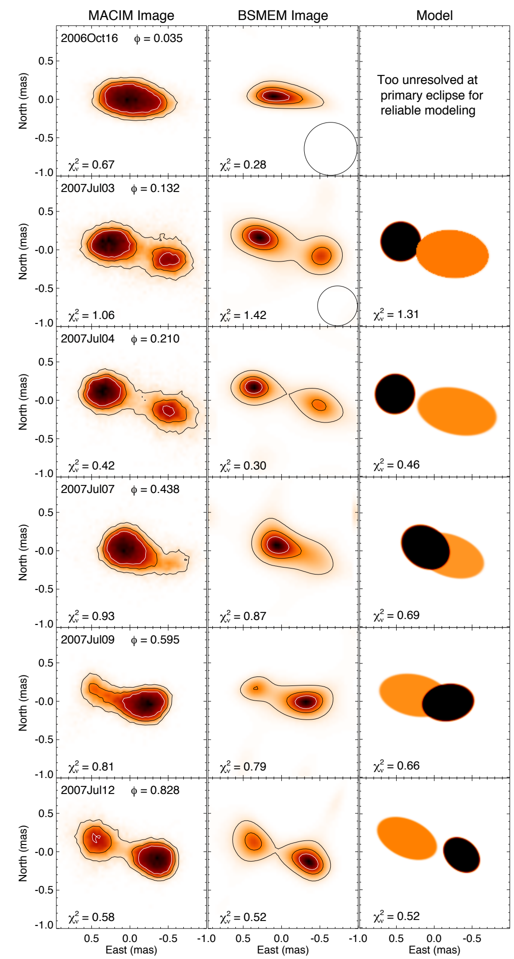
One photon at a time! Need to bring paths to common point in real time

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

Need path length *stabilized* to better than λ

Impressive results





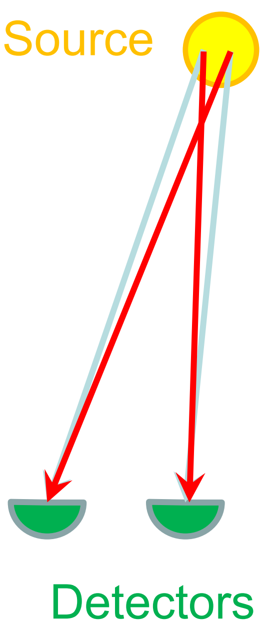
CHARA Collaboration, "First Resolved Images of the Eclipsing and Interacting Binary β Lyrae"; arXiv:0808.0932, The Astrophysical Journal, 684: L95–L98, 2008 September 10

Accuracy ~ 1 mas

Max baselines to ~ 100 m

Two-photon techniques

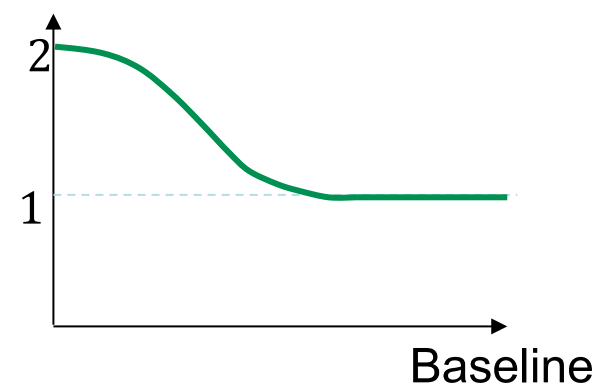
Intensity Interferometry



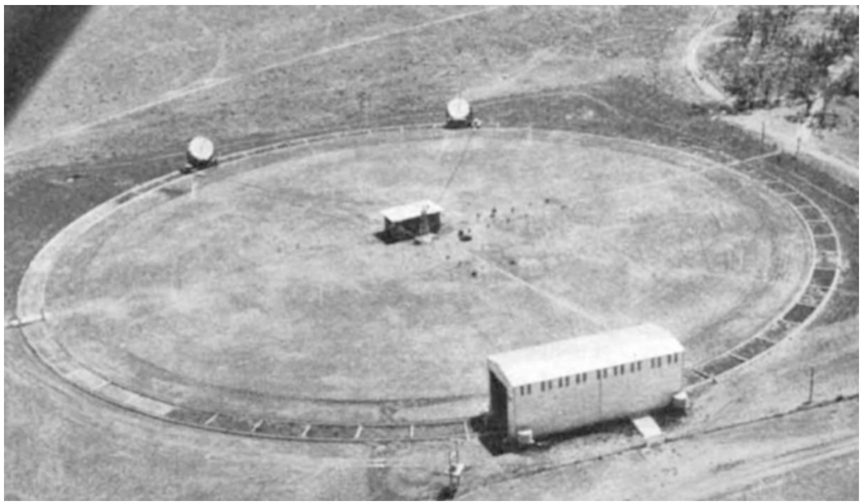
In Hanbury Brown & Twiss (HBT) **intensity interferometry**, the observable is the *correlation* between photon detections at two separate detectors

$$\frac{(Pairs)}{(Singles)(Singles)} = \frac{\left\| \hat{a}_{\overrightarrow{k1}} \hat{a}_{\overrightarrow{k2}} |\Psi\rangle \right\|^2}{\left\| \hat{a}_{\overrightarrow{k1}} |\Psi\rangle \right\|^2 \left\| \hat{a}_{\overrightarrow{k2}} |\Psi\rangle \right\|^2} = \begin{cases} 1 & \overrightarrow{k1} \neq \overrightarrow{k2} \\ 2 & \overrightarrow{k1} = \overrightarrow{k2} \end{cases}$$

Glauber theory of photodetection, c. 1963



HBT for astronomy



Stellar intensity interferometer
at Narrabri, Australia, 1968

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

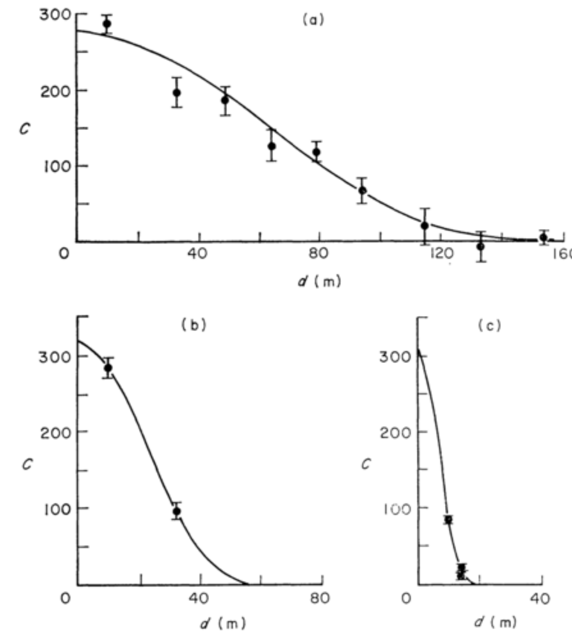
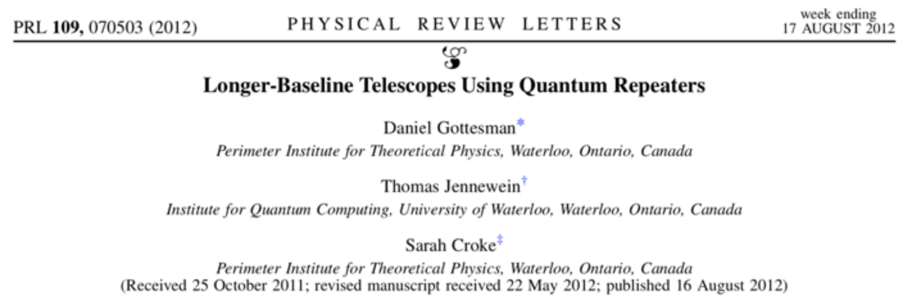


Fig. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

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

Two-photon amplitude techniques (quantum mechanical)

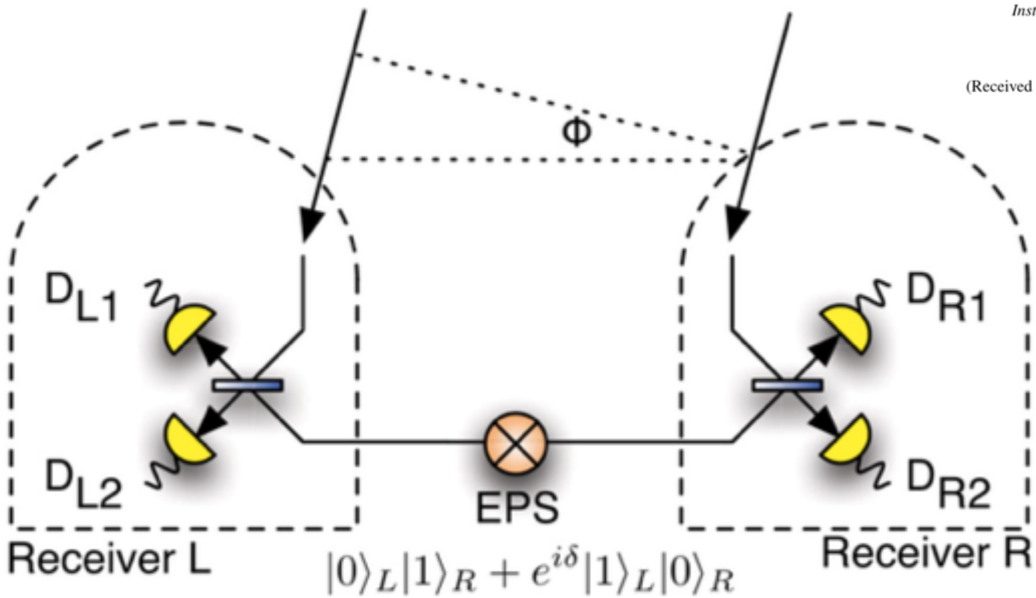
Second photon for quantum assist


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)

Quantum (two-photon) interferometer



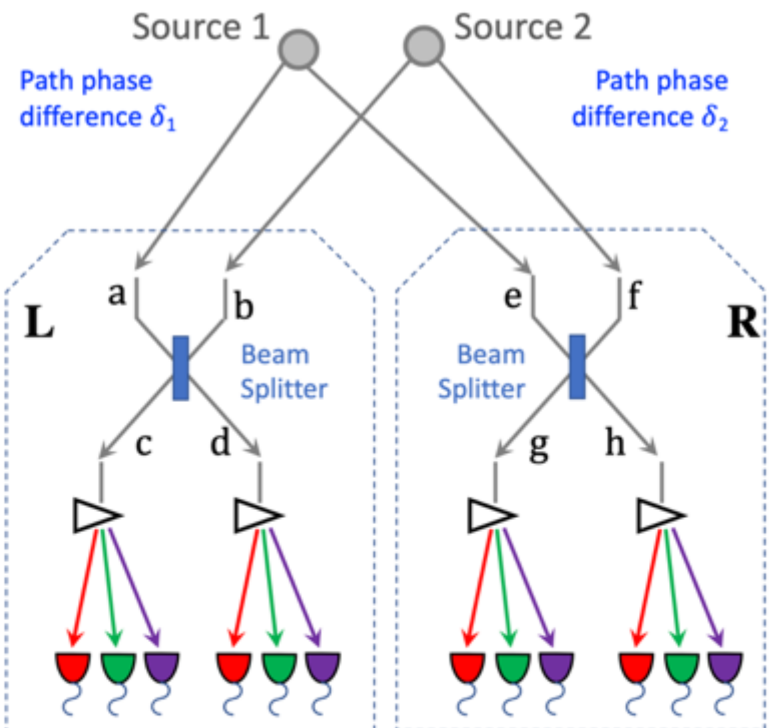
$$\Delta\theta \sim \frac{\lambda}{b}$$

- Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
- Enables long baselines and could improve astrometric precision by orders of magnitude

Quantum Astrometry

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

https://arxiv.org/abs/2010.09100



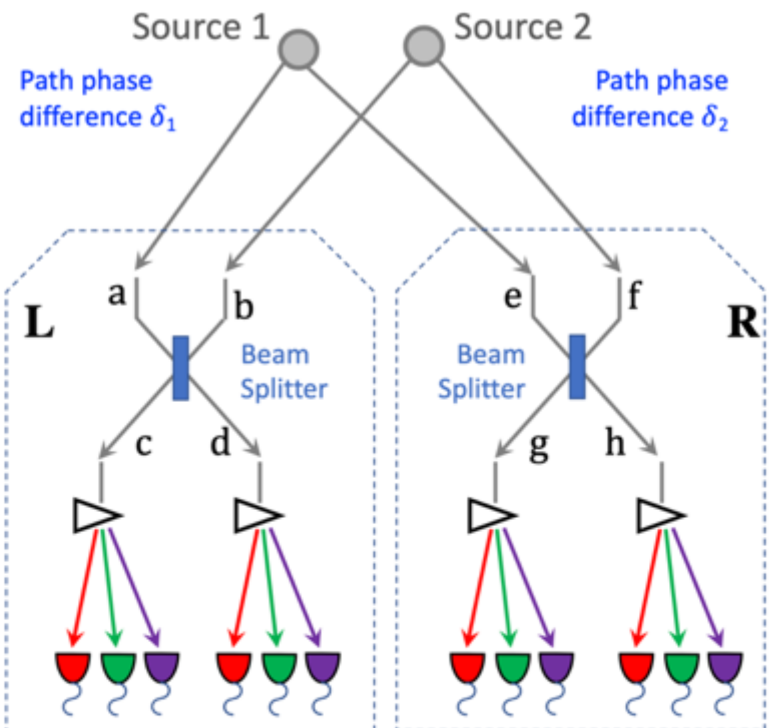
$$
\begin{aligned}
P(c^2) = P(d^2) = P(g^2) = P(h^2) &= 1/8 \\
P(cg) = P(dh) &= (1/8)(1 + \cos(\delta_1 - \delta_2)) \\
P(ch) = P(dg) &= (1/8)(1 - \cos(\delta_1 - \delta_2))
\end{aligned}
$$

- 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

- Different from Hanbury Brown Twiss intensity interferometry, can produce both negative and positive rate oscillations → **amplitude interferometry**

Quantum Astrometry

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



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

Full QFT calculation https://arxiv.org/abs/2010.09100

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

Rates HBT

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

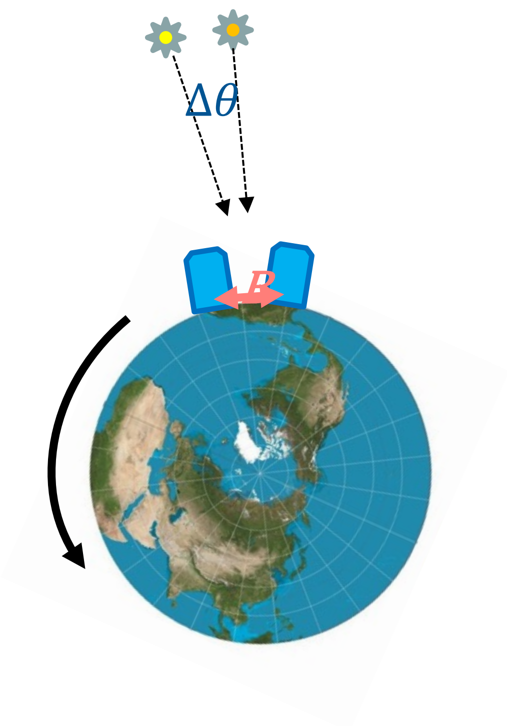
New oscillatory term!

- 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
- Different from Hanbury Brown Twiss intensity interferometry, can produce both negative and positive rate oscillations → **amplitude interferometry**

Earth rotation fringe scan

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

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

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

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

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

state of art: 7 μas GAIA (2013 -)

Possible impact on astrophysics and cosmology

So far a blue-sky research

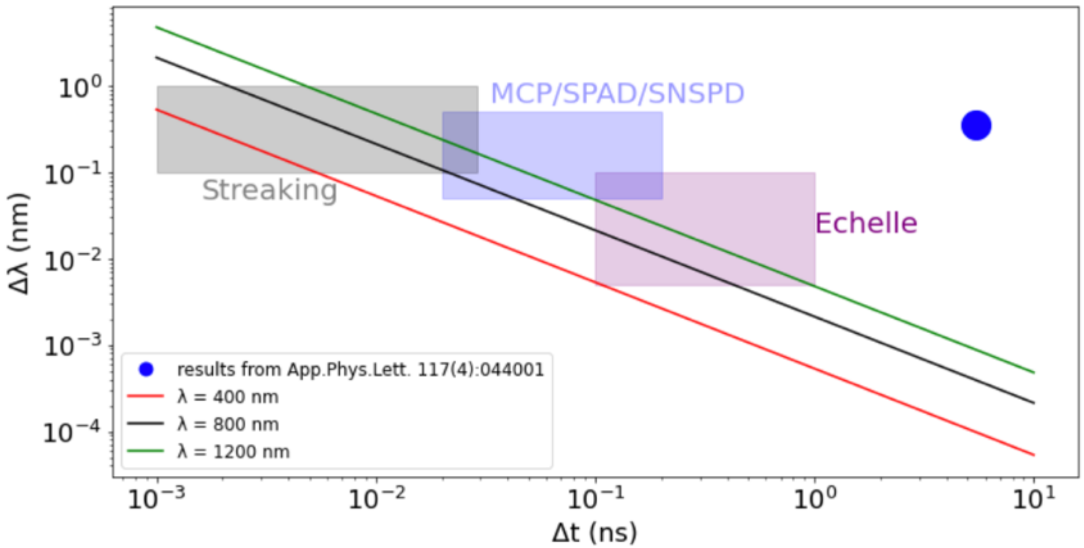
https://arxiv.org/abs/2010.09100

BUT if successful : orders of magnitude better astrometry

- Parallax: improved distance ladder → SN science → Dark Energy
- Proper motions: local Dark Matter patterns
- Microlensing, see motions and shape changes, Dark Matter hunting

- Gravitational waves, coherent motions of stars
- Exoplanets
- etc

Requirements for detectors



- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 1 ns * 0.002 nm for 800 nm

- 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
  - Fringe rate resolution doesn't depend on bin width - wider spectral binning gives lower visibility but same statistical precision

  → what's important is # of spectral channels
- Photon detection efficiency: high

Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

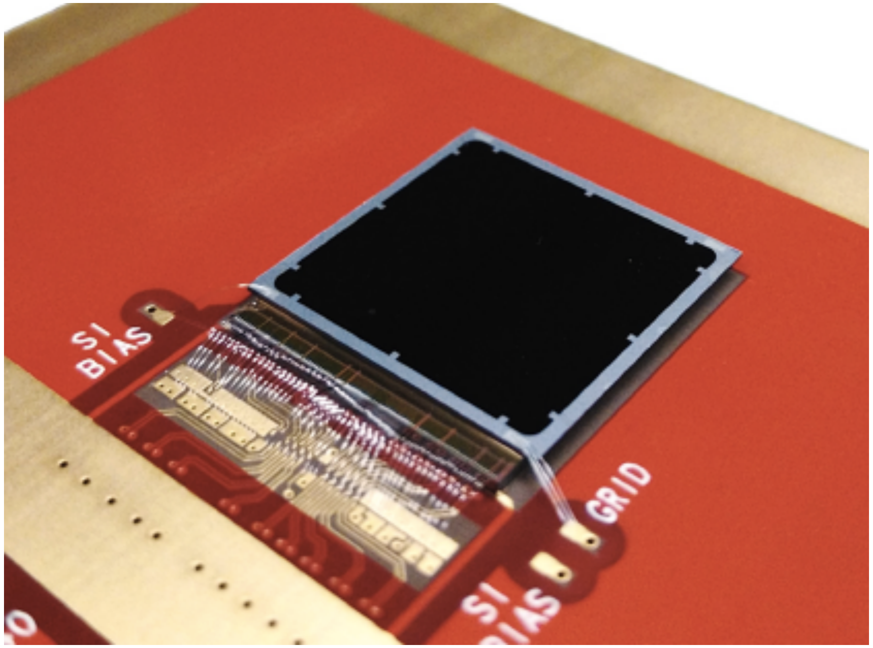
Optical sensor with high QE developed at BNL

- Sensor is bump-bonded to chip Timepix3

Timepix3 ASIC:

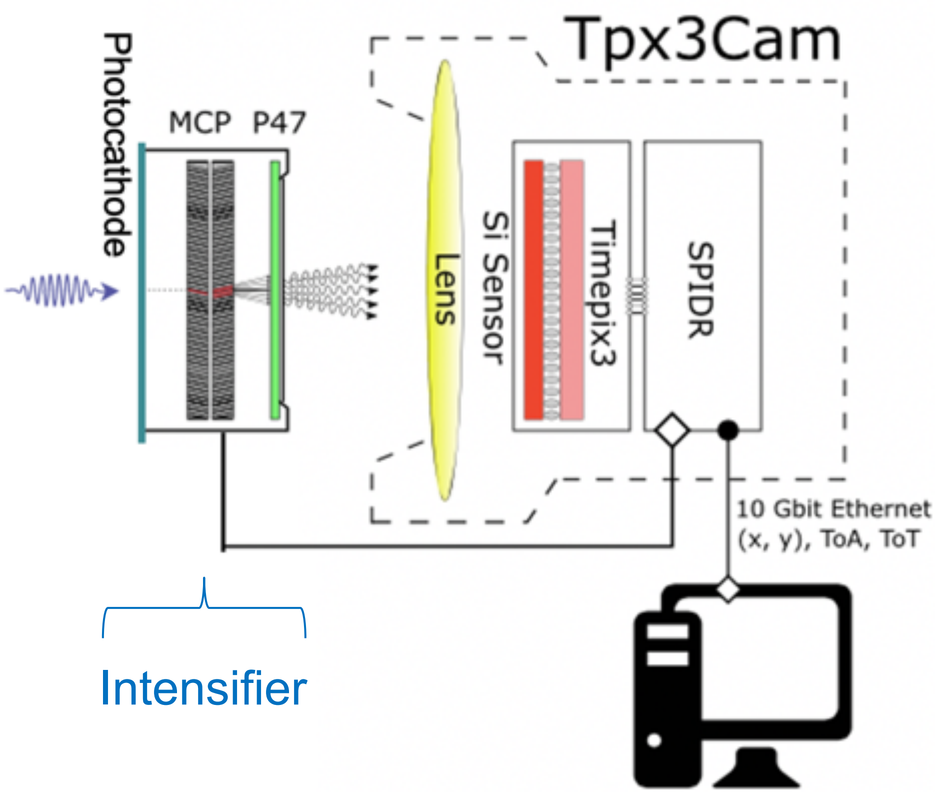
256 x 256 array, 55 x 55 micron pixel

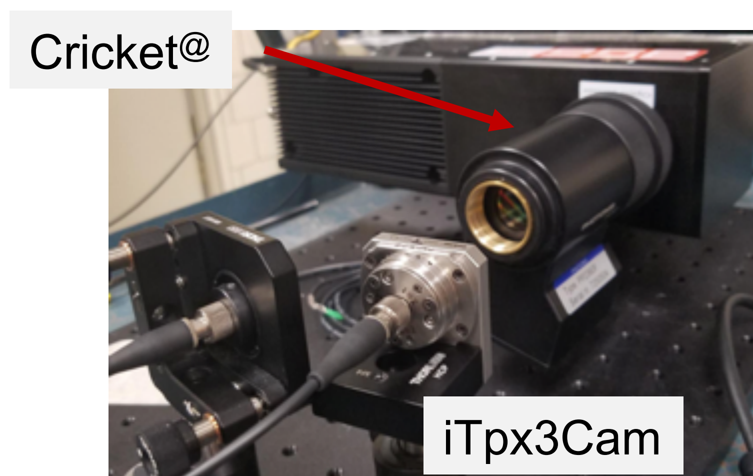
- 1.56 ns timing resolution
- data-driven readout, 80 Mpix/sec, no deadtime



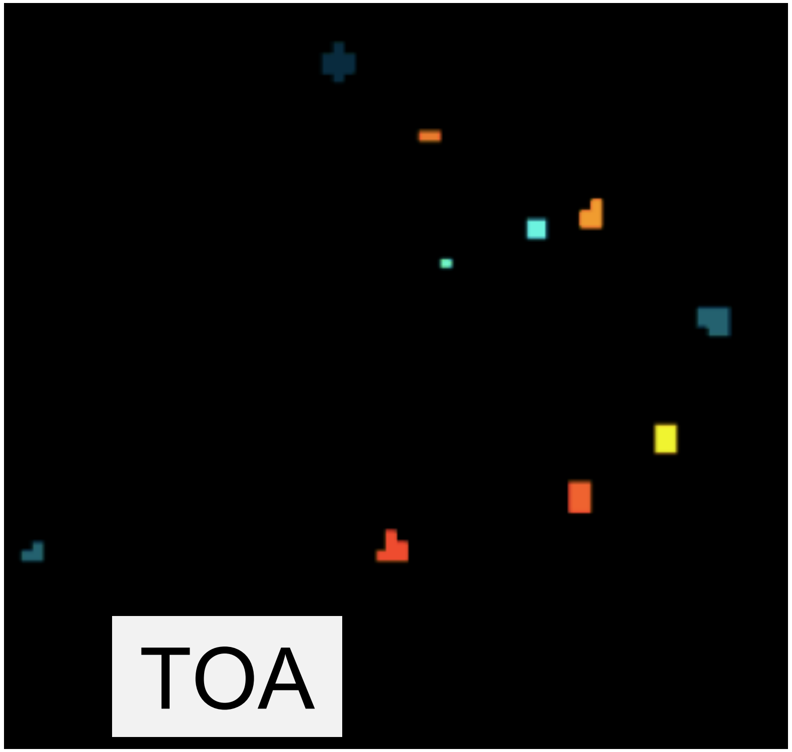
M. Fisher-Levine, A. Nomerotski, Timepixcam: a fast optical imager with time-stamping,
Journal of Instrumentation 11 (03) (2016) C03016.

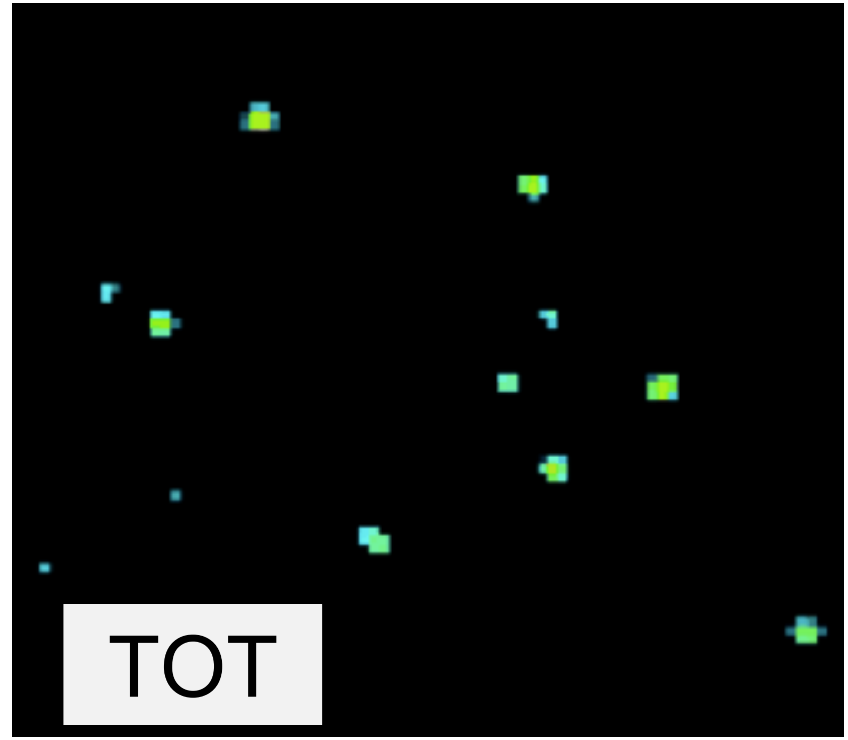
Intensified camera is single photon sensitive





Quantum efficiency ~ 30%



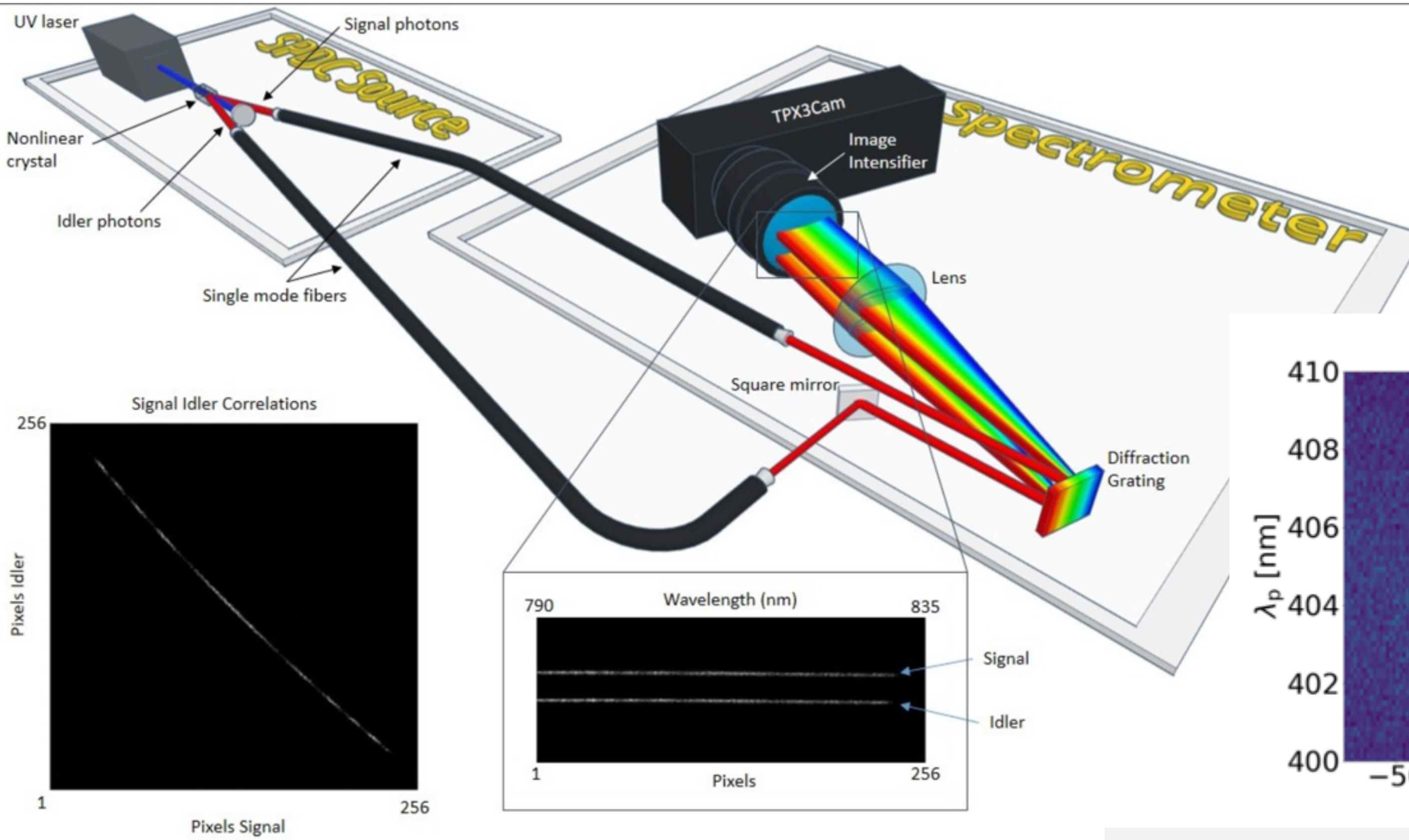


Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

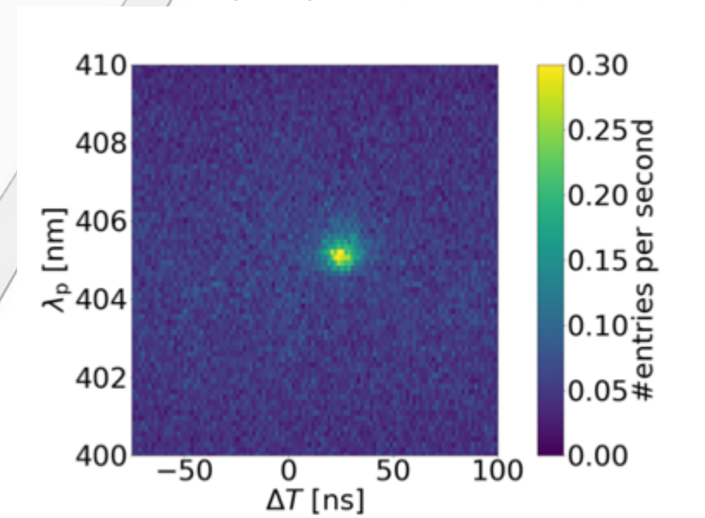
Time resolution: 2 ns / photon

Spectroscopic binning

In collaboration with NRC (Ottawa) D.England, Y.Zhang et al



$\delta\lambda * \delta t \sim 5$ ns * 0.5 nm

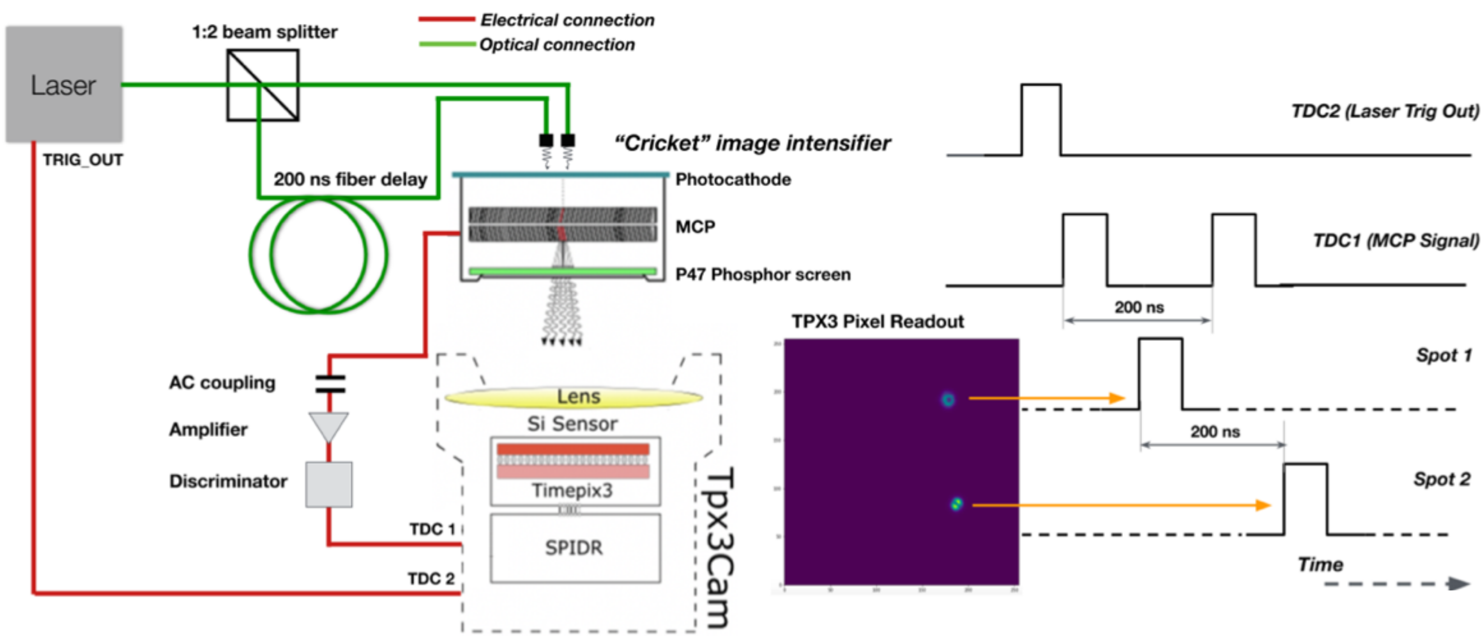


Pump photon wavelength vs time difference

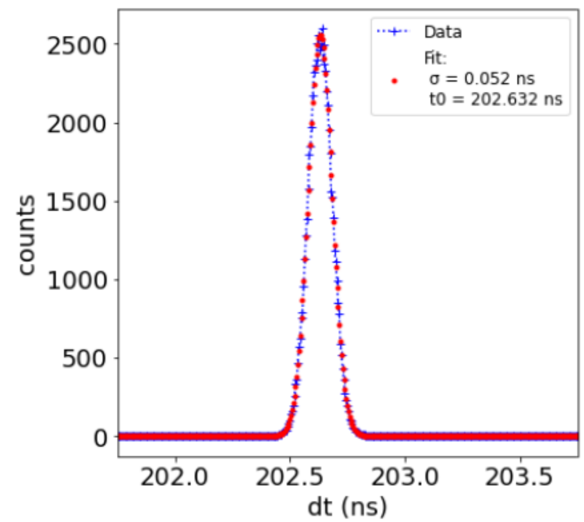
Y Zhang, D England, A Nomerotski, P Svihra et al, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808

P Svihra et al, Multivariate Discrimination in Quantum Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

MCP Timing Performance

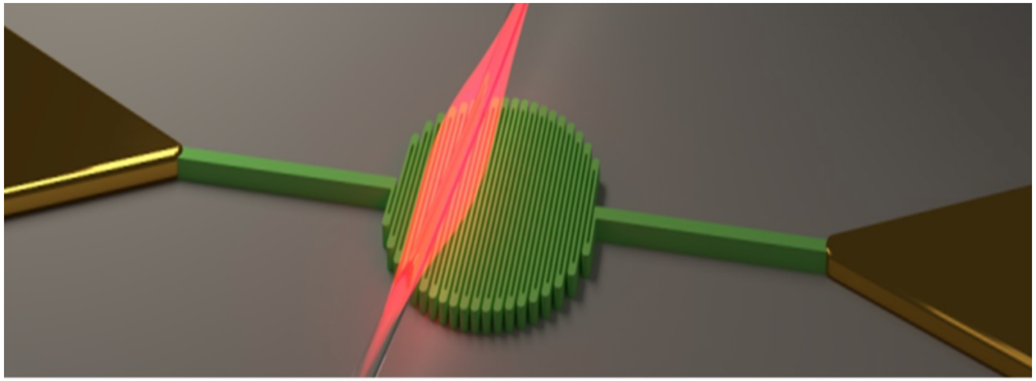


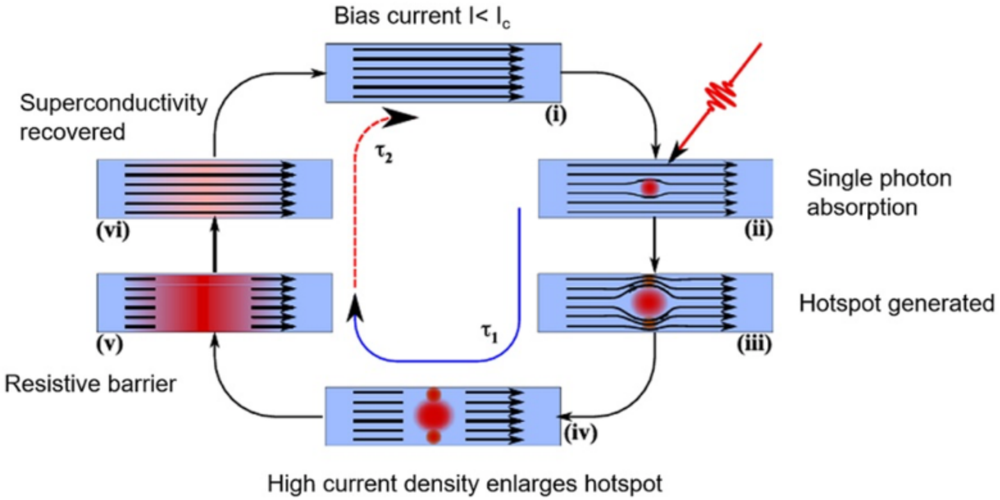
- Micro-channel plate (MCP) is fast
  - Demonstrated resolution < 30 ps
- MCP readout for Tpx3 camera
  - 50 ps, not for single photons yet

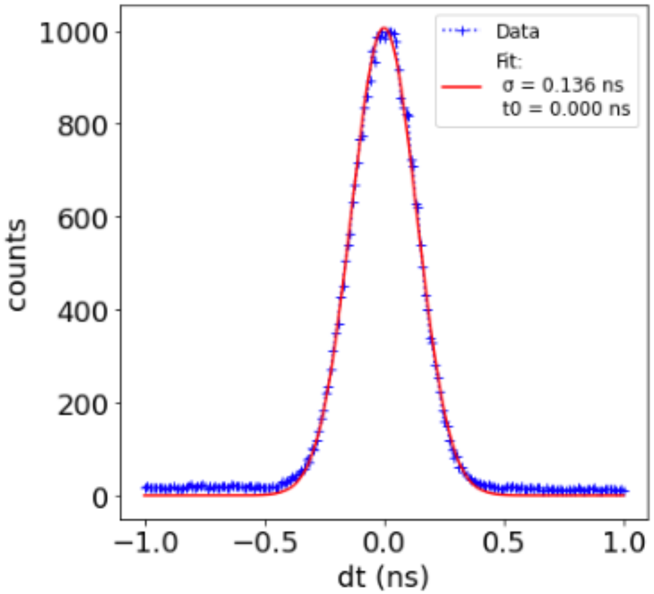


Possible technologies: SNSPD

- Superconducting nanowires
  - Used Single Quantum SNSPD
  - 100 ps resolution for single photons using SPDC photon pair source

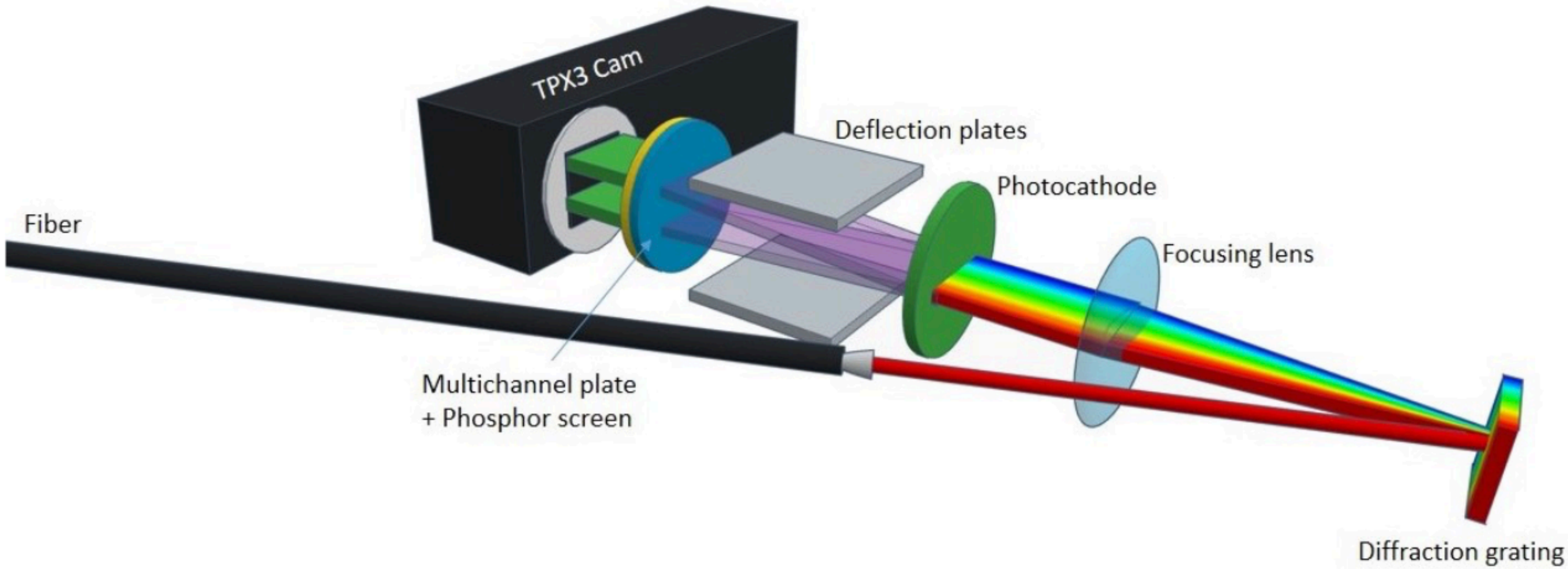




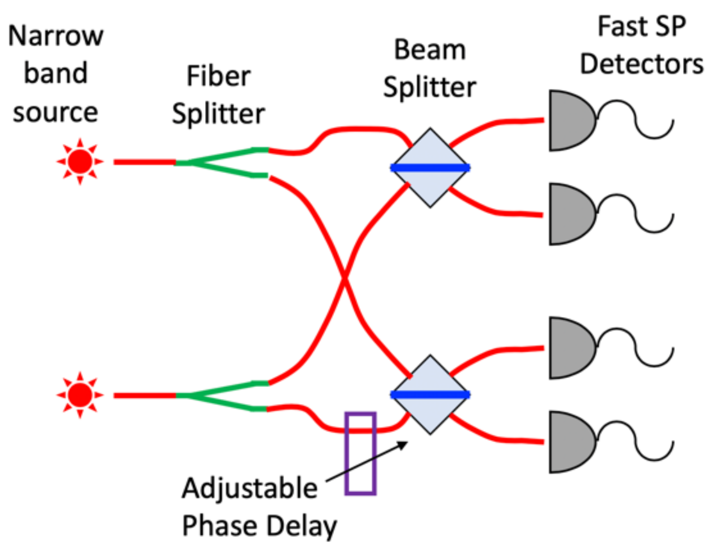


Possible technologies: Streaking

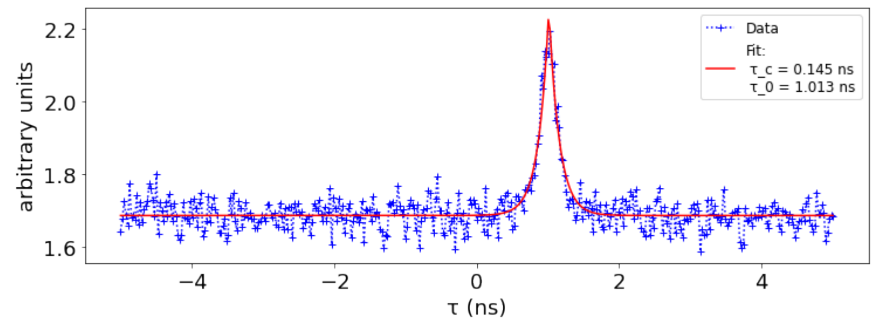
- Streaking: use a spatial coordinate for time measurement
  - Deflect photoelectrons by oscillating field
  - 1 ps resolution possible

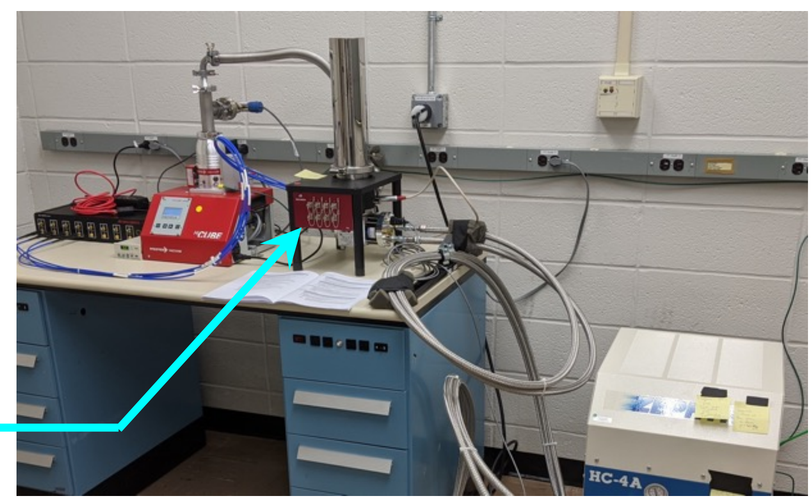


Experiments in progress



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 at BNL by DOE HEP QuantISED grant 2020-21

Summary

- Two-photon amplitude interference can be used to improve astrometrical precision by orders of magnitude
  - Application of quantum entanglement and teleportation techniques to astronomy with great potential

- Not far from practical implementation with existing technologies
  - Motivates new technologies for fast single photon detection with sub-ns resolution