Fast Imaging of Single Photons for Astronomical Applications

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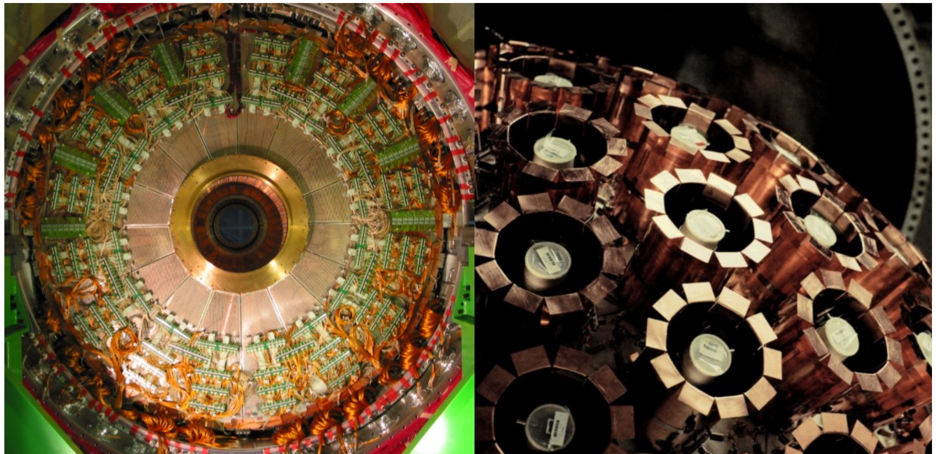
In collaboration with: Paul Stankus, Stephen Vintskevich, Anze Slosar, Michael Keach, Jonathan Schiff, Alex Parsells

International Conference
on Technology and
Instrumentation
in Particle Physics

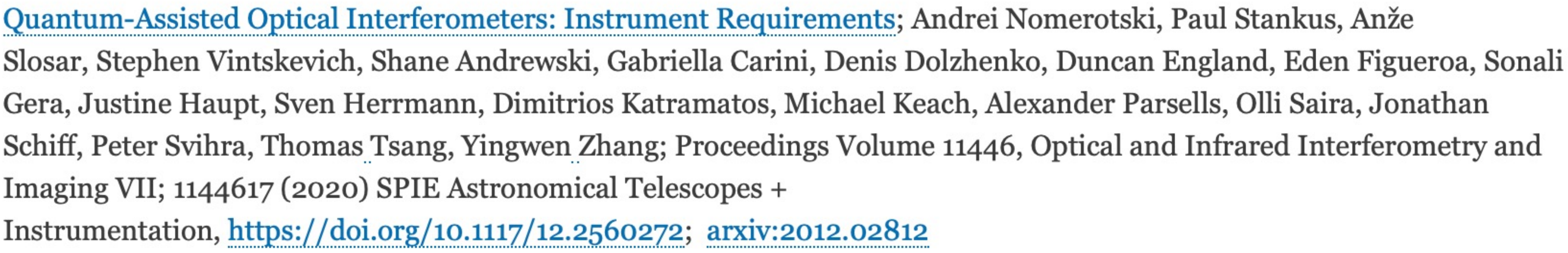
May 24-28, 2021 Online format



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

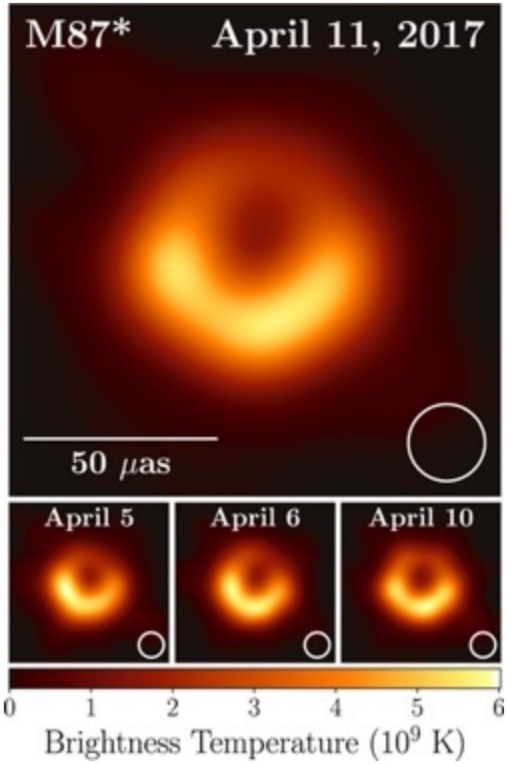
Two-photon amplitude interferometry for precision astrometry
Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich
https://arxiv.org/abs/2010.09100, under review in Phys. Rev. Research

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



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; 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

Astronomy picture of the decade



sensitive to features on angular scale

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

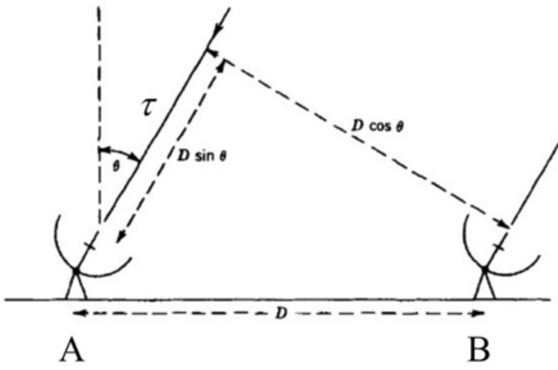
2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Radio

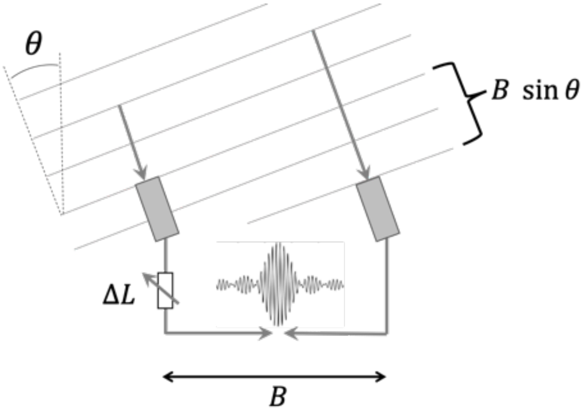
$\bar{n} \gg 1$



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

Optical

$\bar{n} \ll 1$



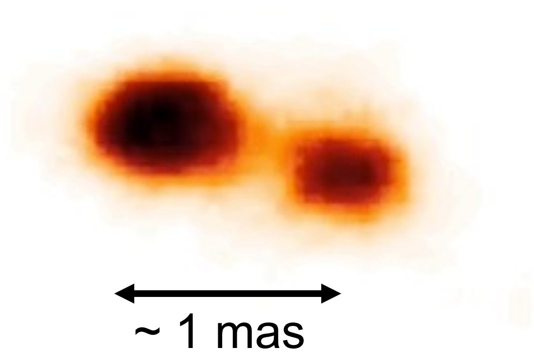
One photon at a time! Need to bring paths to common point in real time

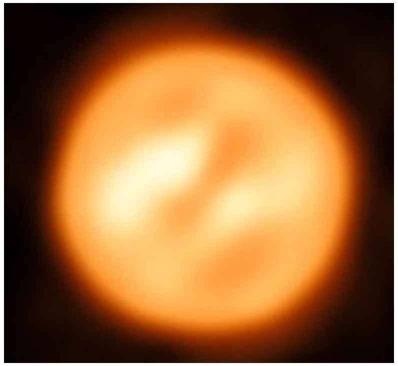
Need path length *stabilized* to better than λ

Accuracy ~ 1 mas

Max baselines to ~ 100 m

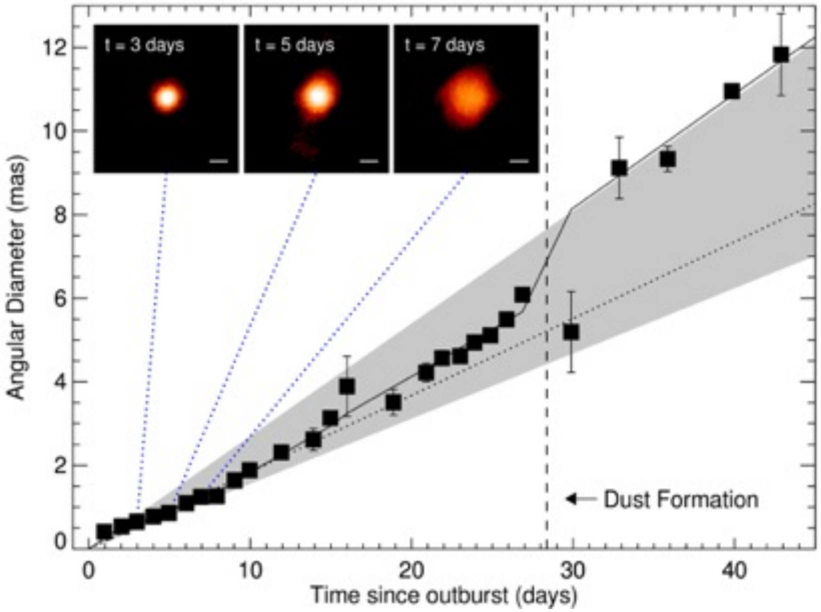
Optical interferometry examples





Dynamic convection on
Antares
(VLTI, ESO)

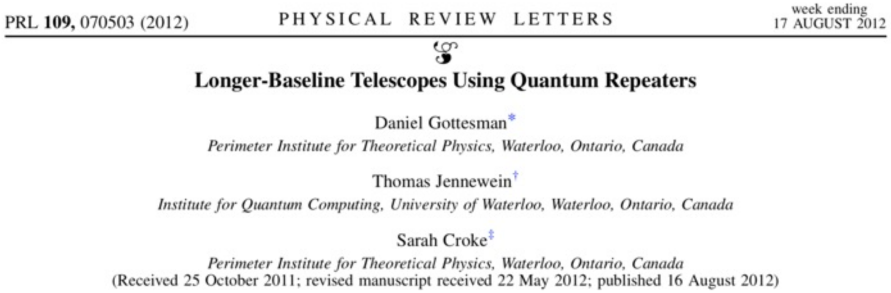
CHARA Collaboration, "First Resolved Images of the Eclipsing and Interacting Binary β Lyrae"; arXiv:0808.0932, The Astrophysical Journal, 684: L95–L98.



Nova in progress (CHARA)

Two-photon techniques

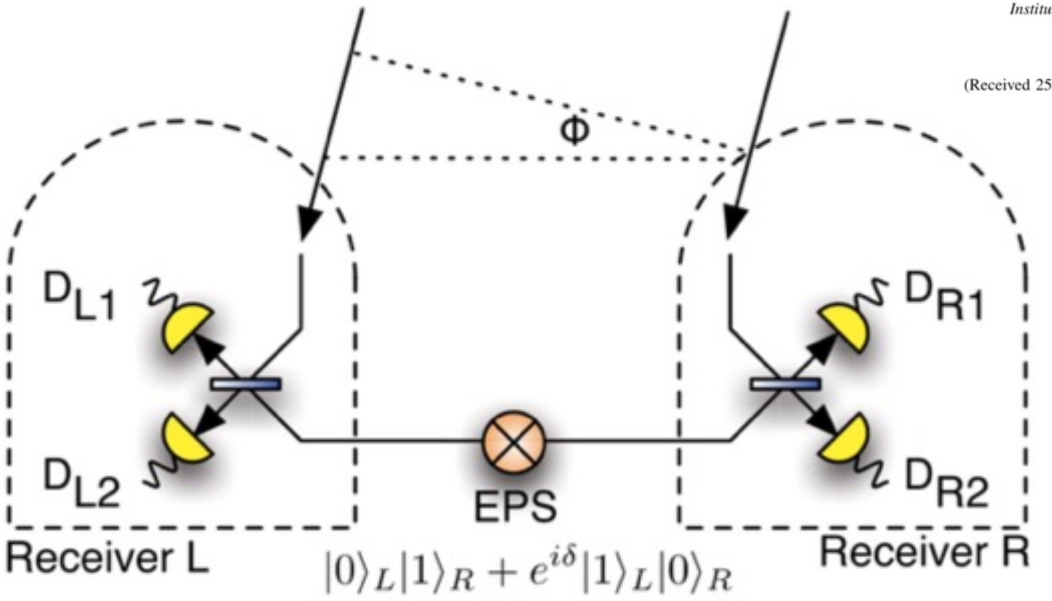
Second photon for quantum assist


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)

Quantum (two-photon) interferometer



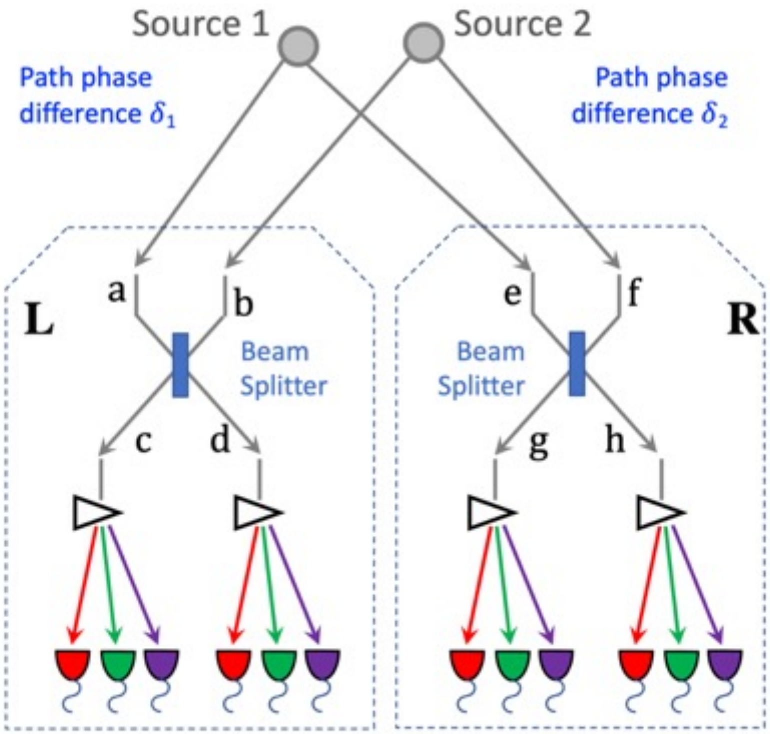
$$\Delta\theta \sim \frac{\lambda}{b}$$

- 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



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

Full QFT calculation

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

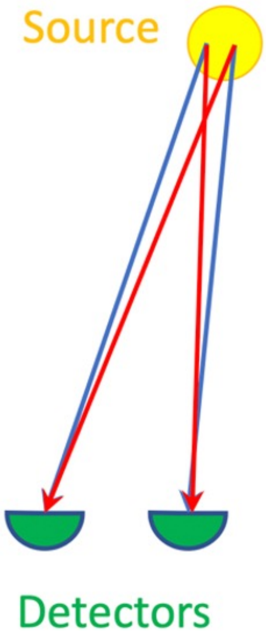
$$A^2\eta_1\eta_2 T_r\Bigg[\overset{\text{Rates}}{\boxed{(I_1+I_2)^2}} + \overset{\text{HBT}}{\boxed{I_1^2\frac{\tau_c g_{11}}{T_r} + I_2^2\frac{\tau_c g_{22}}{T_r}}} \pm$$

$$\underset{\text{New oscillatory term!}}{\boxed{2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B(\sin\theta_1-\sin\theta_2)}{c}+\frac{\omega_0\Delta L}{c}\right)}}\Bigg] \quad (30)$$

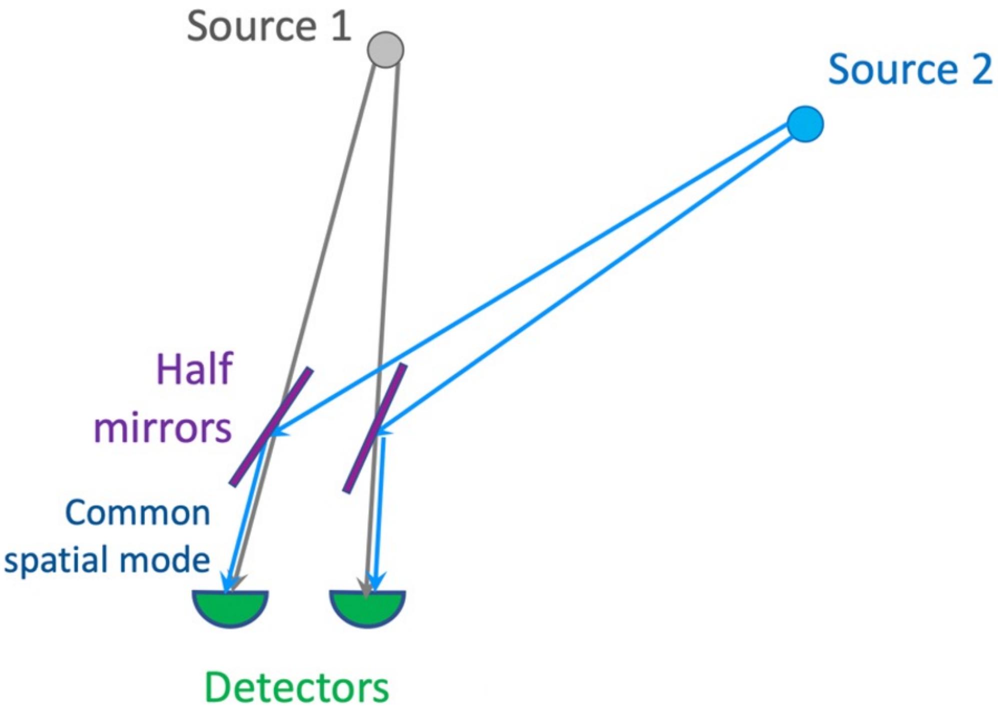
Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and f

Comparison to Hanbury Brown – Twiss Interferometry

Standard HBT



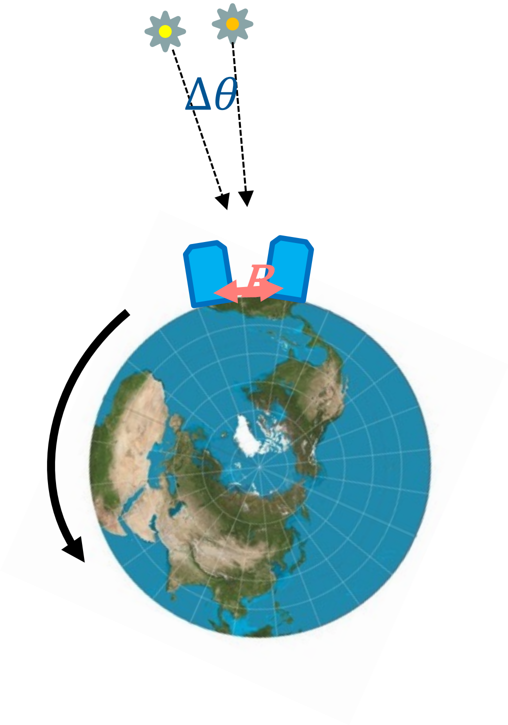
Quantum astrometry



Coincident pair detection sensitive to phase difference of two photons

Earth rotation fringe scan

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



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

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!

world competitive precision with a modest experiment

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

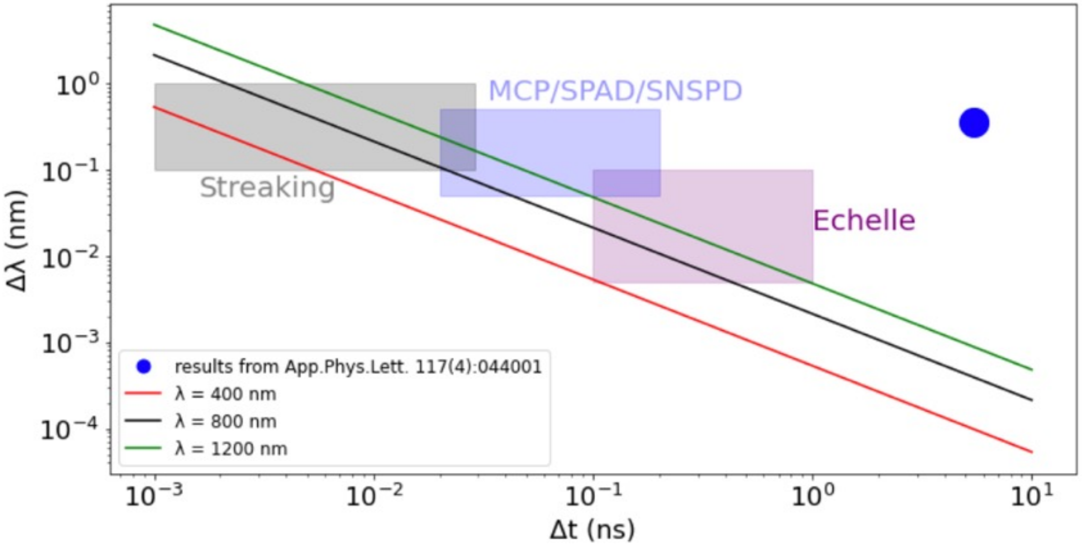
Possible impact on astrophysics and cosmology

https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with possible major impact on dark energy and dark matter studies

- Parallax: improved distance ladder
- Proper motions
- Microlensing, see motions and shape changes
- 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 ~ 0.01 ns * 0.2 nm for 800 nm

- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, SPADs, SNSPDs, streaking

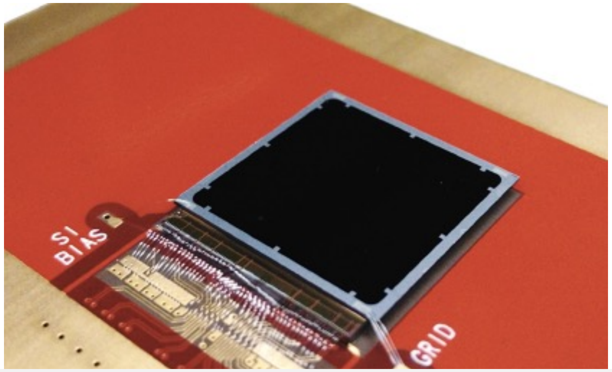
- Spectral binning: diffraction gratings, Echelle spectrometers

- Photon detection efficiency: high

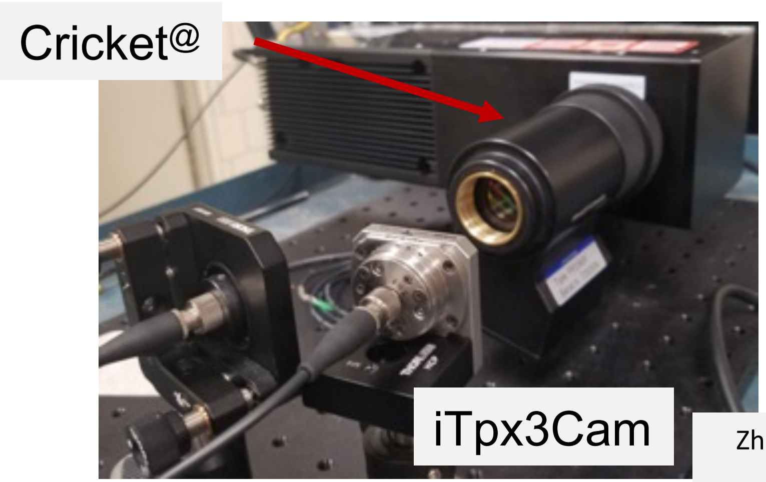
Intensified Timepix3 Camera

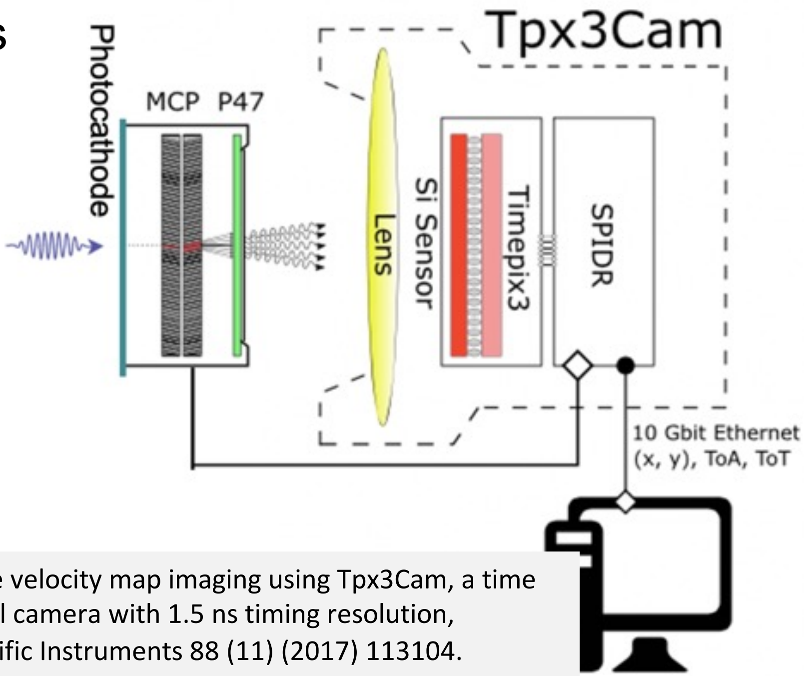
Camera = intensifier + sensor + ASIC + readout

- Optical sensor with high QE @ BNL
  - Sensor is bump-bonded to chip Timepix3
- Timepix3 ASIC @ CERN
  - 256 x 256 array, 55 x 55 micron pixel
  - 1.56 ns timing resolution, data-driven readout
- 10 Gbs readout SPIDR @ Amsterdam Scientific Instr
- Intensifier with GaAs photocathode @ Photonis



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

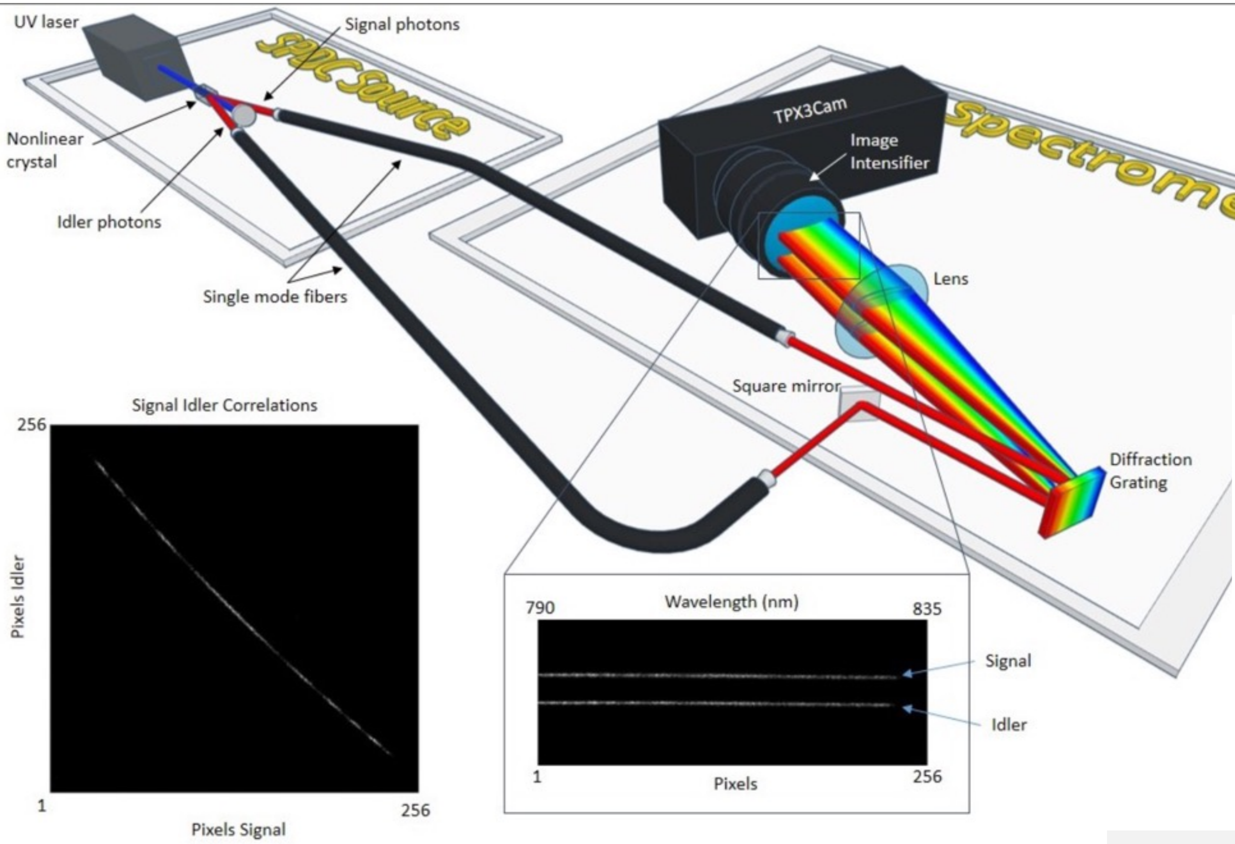




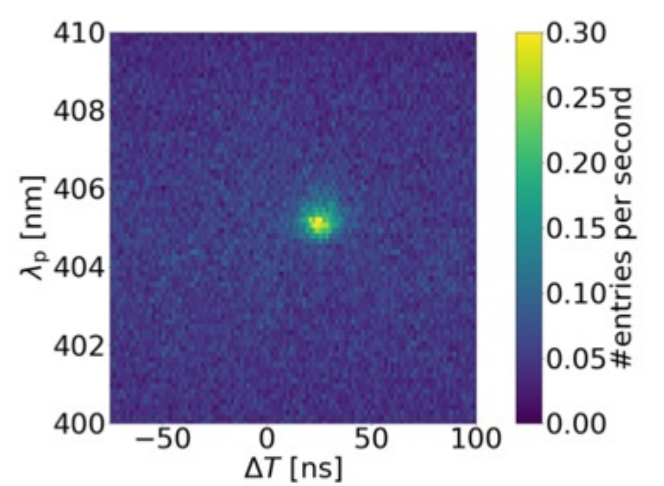
Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.

Spectroscopic binning

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



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

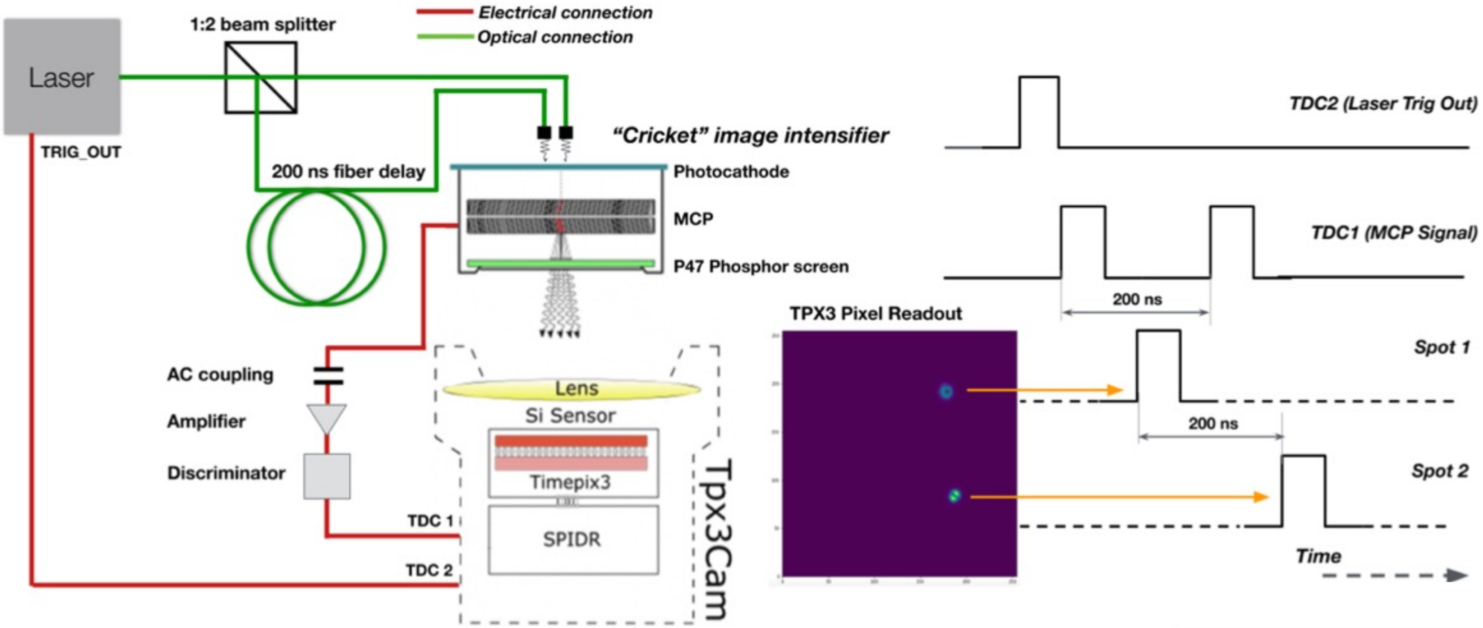


Pump photon wavelength vs time difference

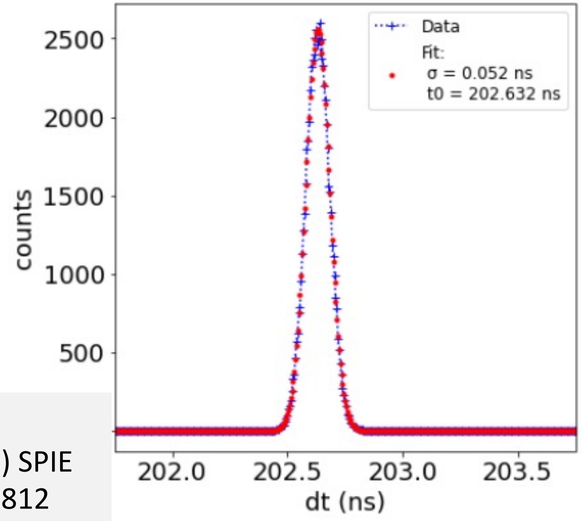
Y Zhang, D England, A Nomerotski, P Svihra et al, Multidimensional quantum-enhanced target detection via spectrotemporal-correlation measurements, Physical Review A 101 (5), 053808

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

MCP Timing Performance



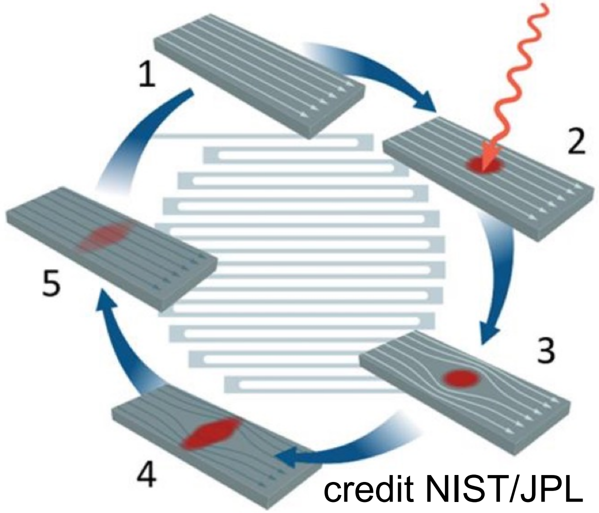
- Micro-channel plate (MCP) is fast
  - Demonstrated resolution < 30 ps
- MCP readout for Tpx3 camera
  - 50 ps, not for single photons yet



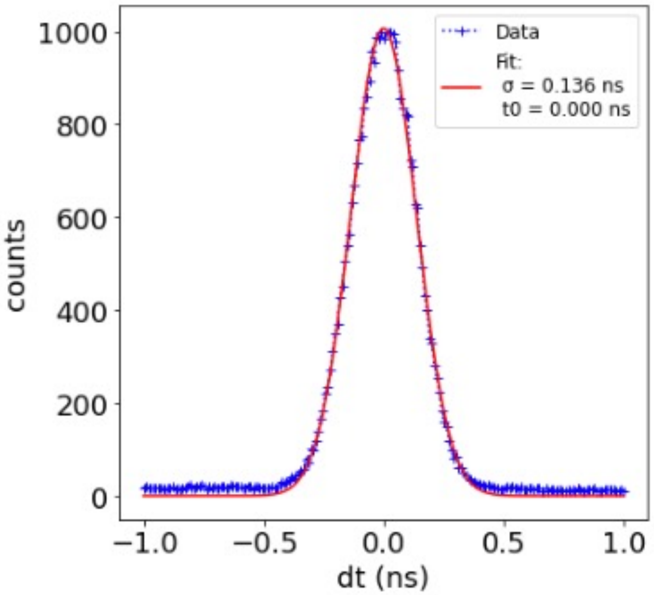
Quantum-Assisted Optical Interferometers: Instrument Requirements; Andrei Nomerotski et al, Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 1144617 (2020) SPIE Astronomical Telescopes +Instrumentation, https://doi.org/10.1117/12.2560272; arxiv:2012.02812

Possible technologies

- Superconducting nanowires (SNSPD)
  - by Single Quantum SNSPD
  - 100 ps resolution for single photons, high QE
  - 3 ps SNSPD devices reported



credit NIST/JPL



Other technologies

- Single Photon Avalanche Device (SPAD)
  - 30 ps resolution
- Streaking cameras
  - Use spatial information for time measurement
  - 1 ps resolution possible

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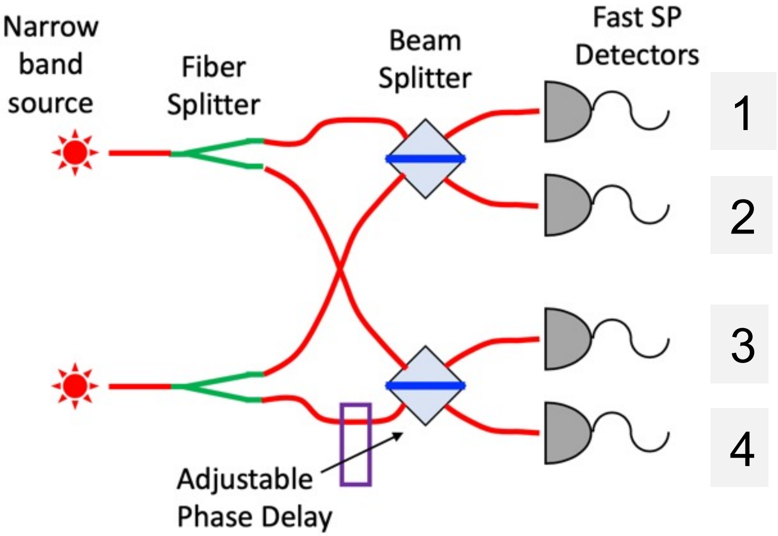
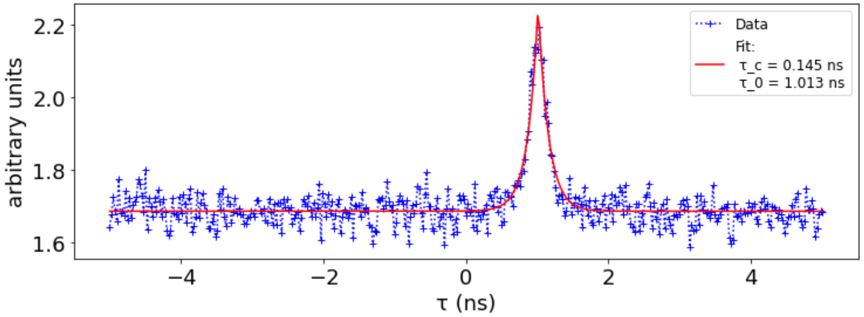
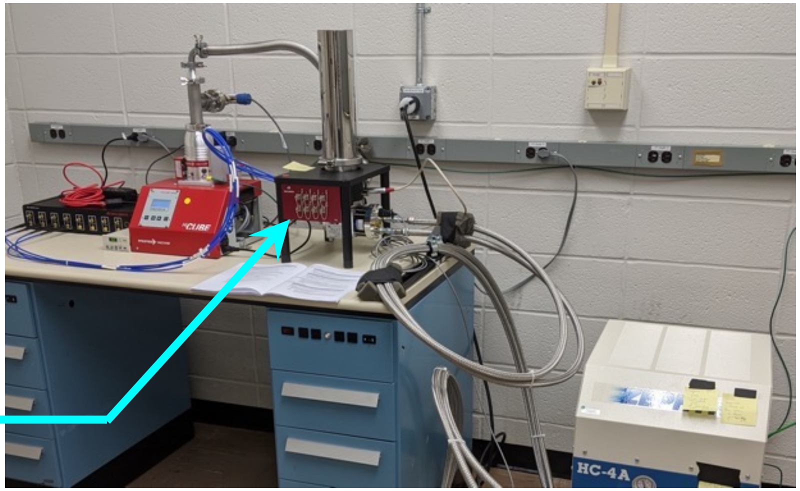
Experiments in progress



Strong HBT peak with single lamp





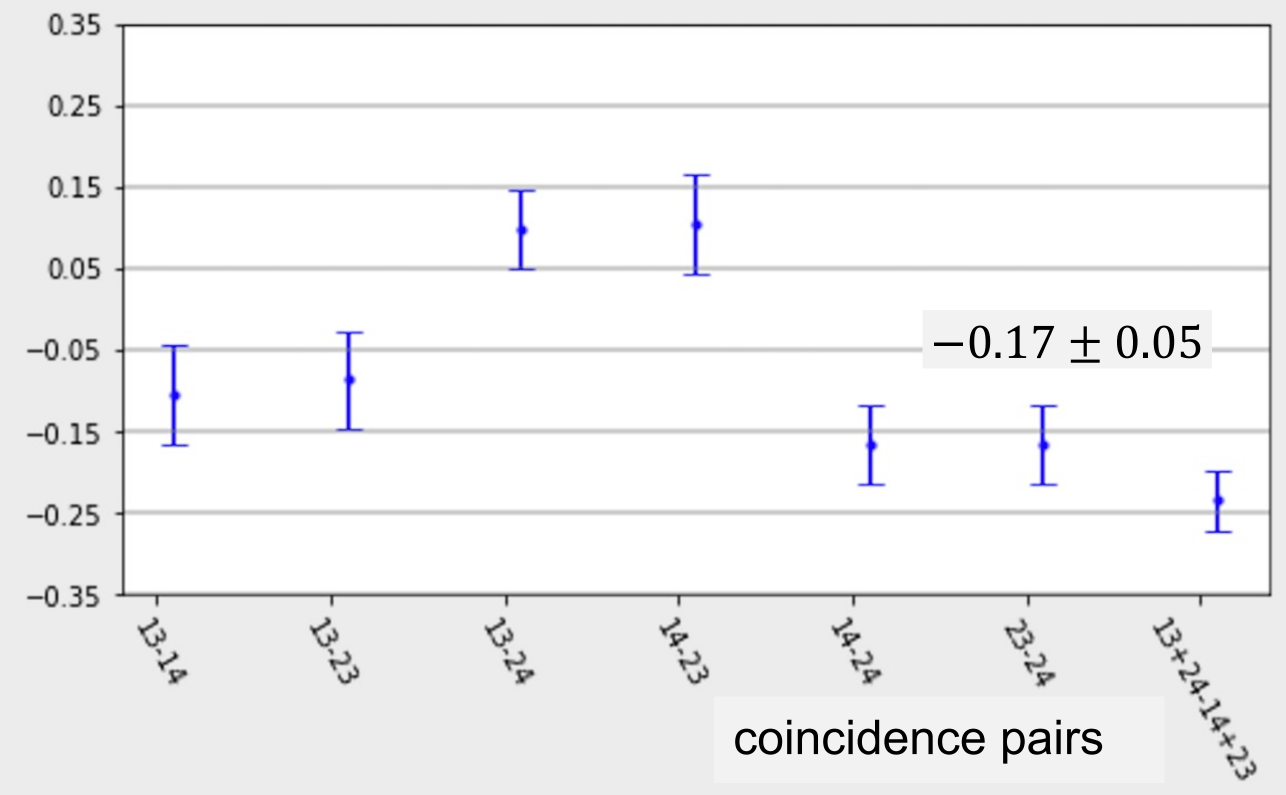
Bench-top model of two-photon interferometry

Ar vapor lamps with ultra-narrow band filters
Superconducting nanowire single-photon detectors

Supported by DOE HEP QuantISED grant

First results with SNSPD data

- Effect can be seen in coincidence correlations between pairs of channels
  - not sensitive to phase instability (~ 10 sec)
- Results agree with predictions, correlations ~ 0.1-0.2 @ > 3 σ



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

Acknowledgements

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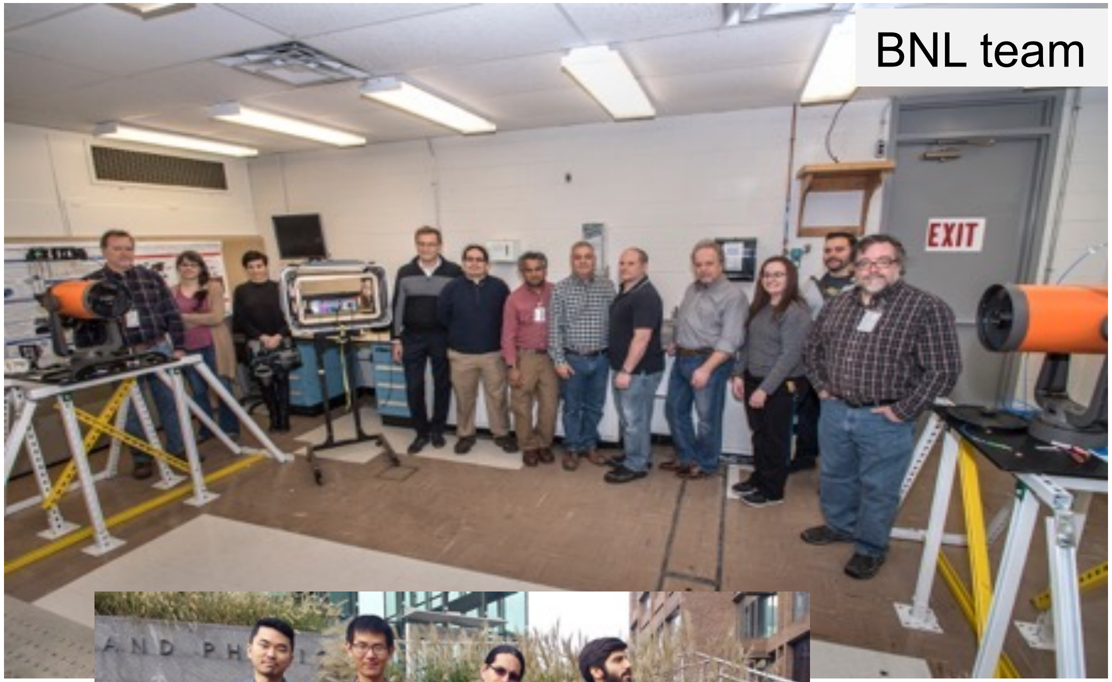
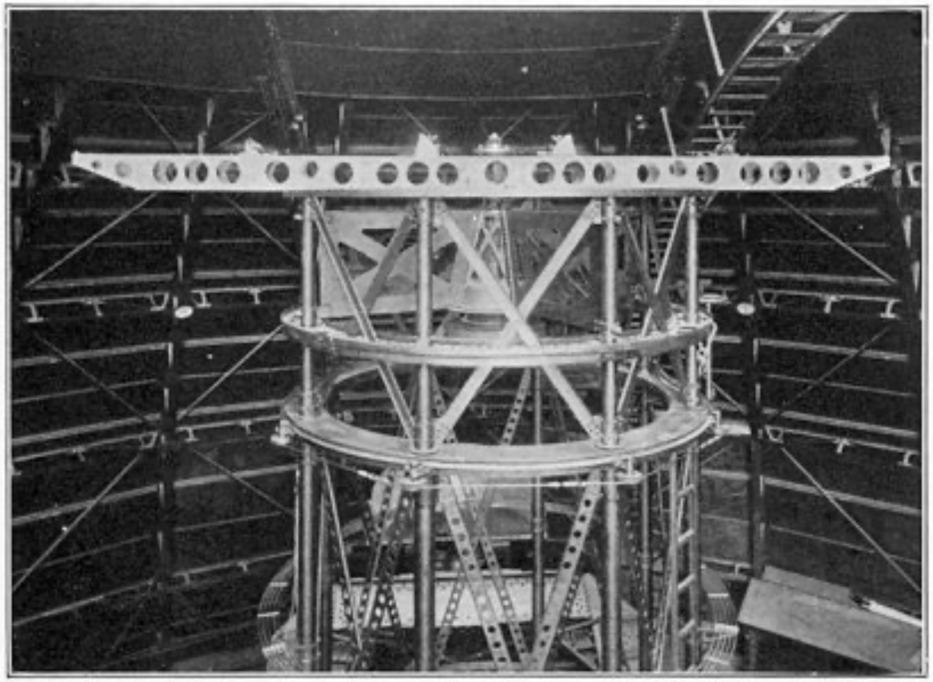
Bram Bouwens
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Peter Svihra


BNL team

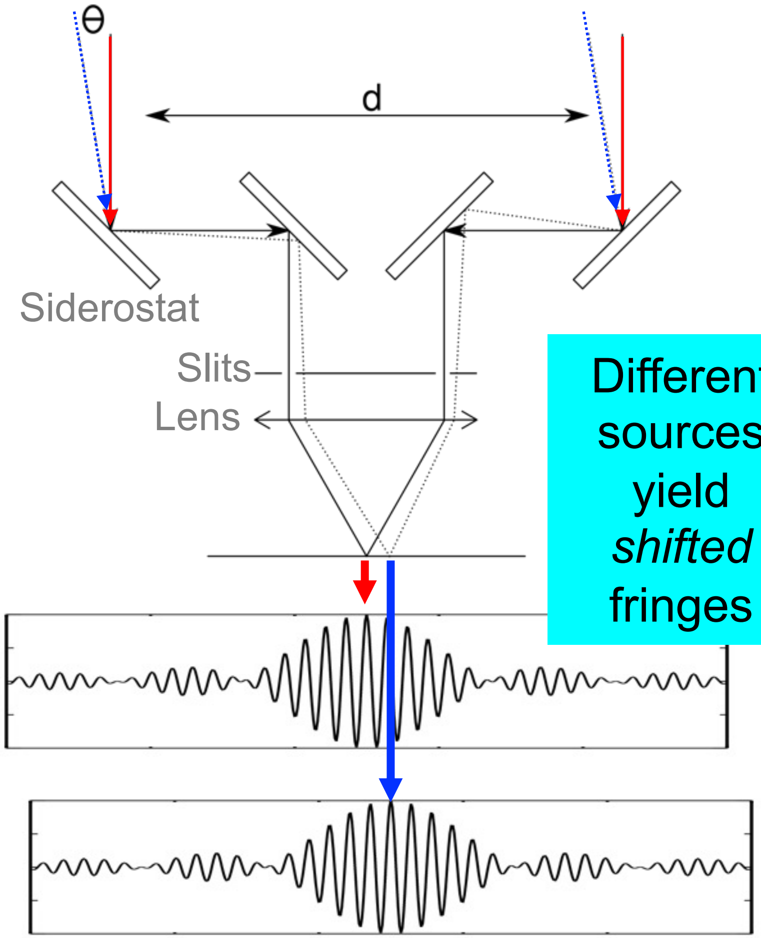

SBU team

spares

In the optical



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



Different sources yield *shifted* fringes

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

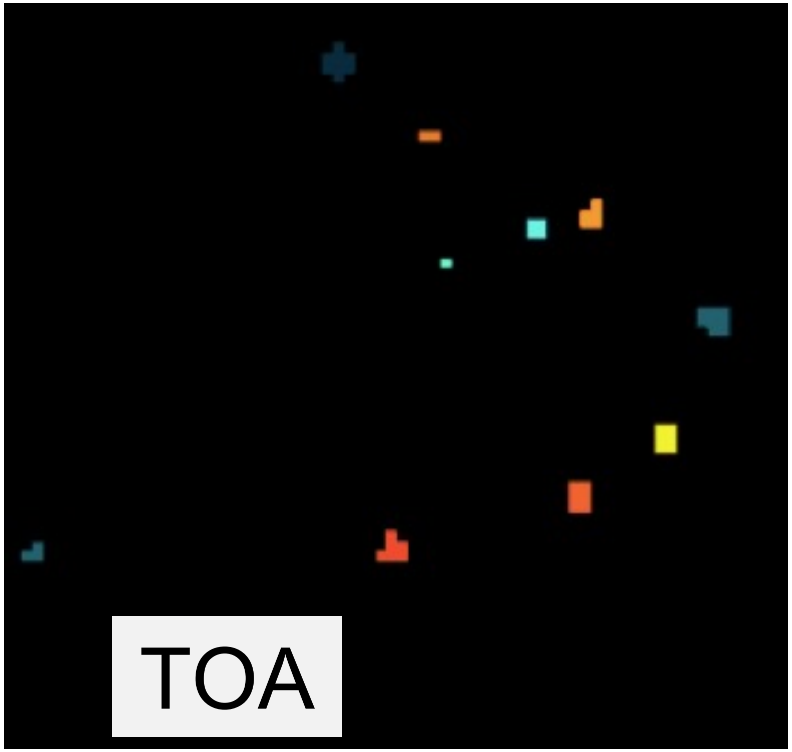
A modest experiment:

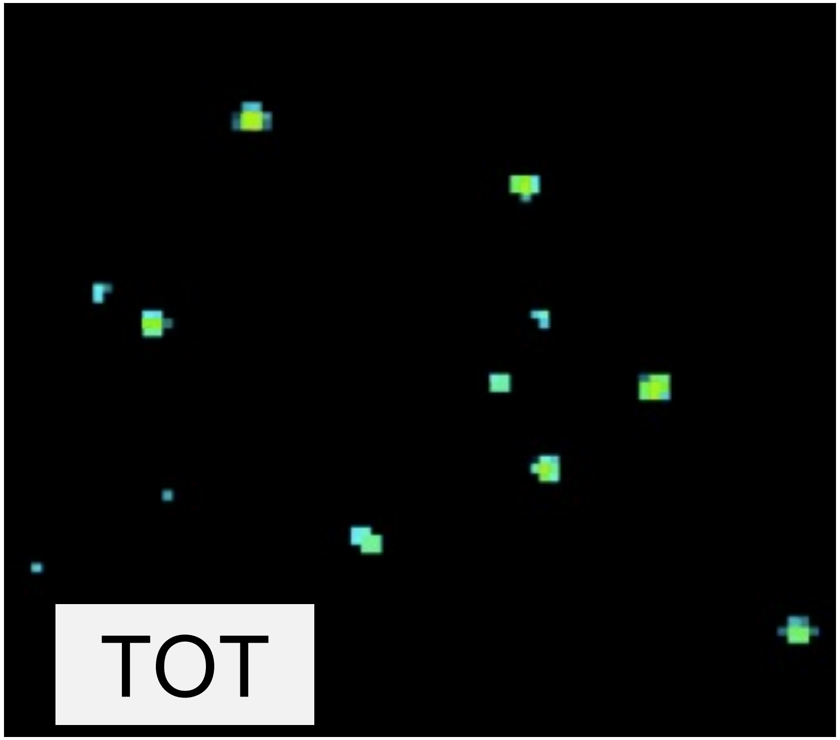
- Bright stars, mag 2
- 1 m^2 collecting area
- 10^4 seconds observation
- 0.15 nsec time resolution
- 10^4 spectral channels
- 200 m baseline

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

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

state of art: 7 μas GAIA (2013 -)



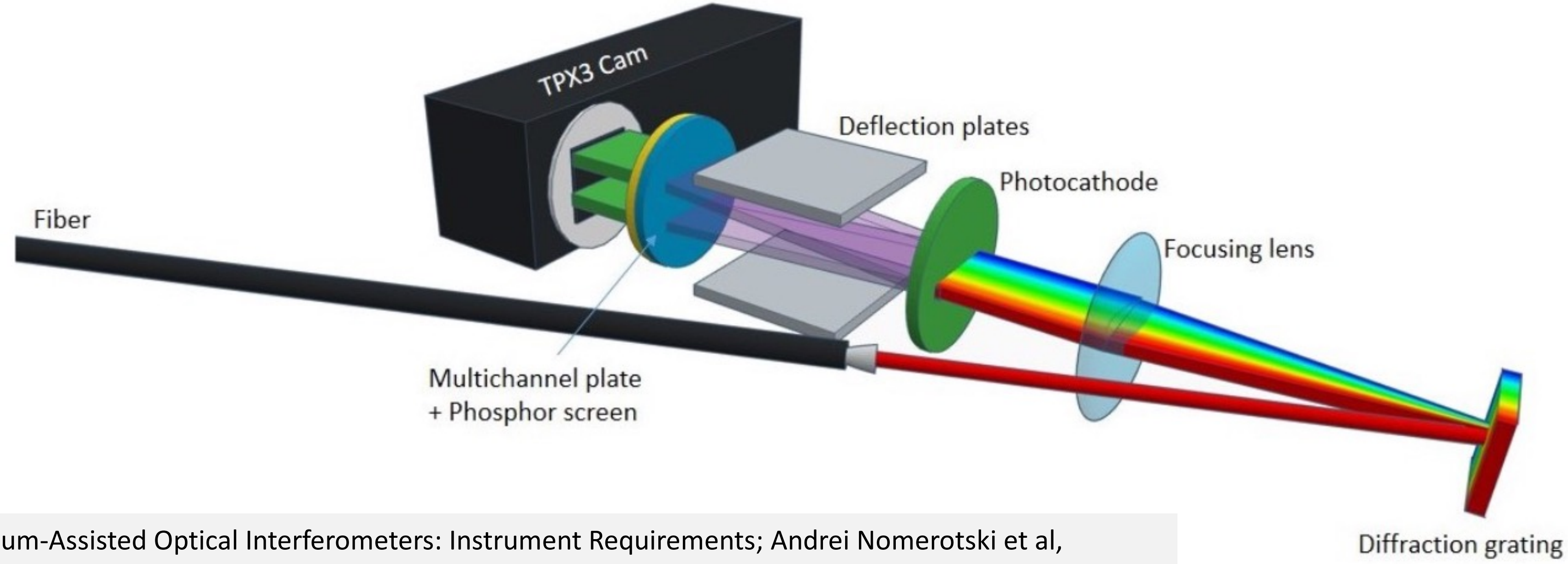


Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

Time resolution: 2 ns / photon

Possible technologies: Streaking

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



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