Quantum-Assisted Optical Telescopes

Andrei Nomerotski, Brookhaven National Lab

28 September 2021

In collaboration with: Paul Stankus, Stephen Vintskevich, Anze Slosar, Ning Bao, Zhi Chen, Jonathan Schiff, Alex Parsells, Duncan England, Yingwen Zhang et al

Sensing with Quantum Light
SQL21

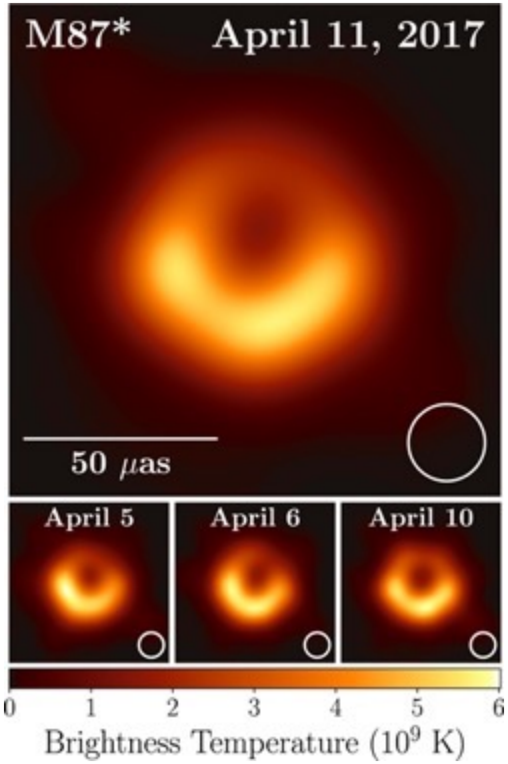
WE-Heraeus-Seminar, 26 Sep - 29 Sep 2021

Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Astronomy picture of the decade

53M light years away
$\delta \sim 10\ \mu as$ ($\sim 10^{-11}$ rad)



sensitive to features on angular scale

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

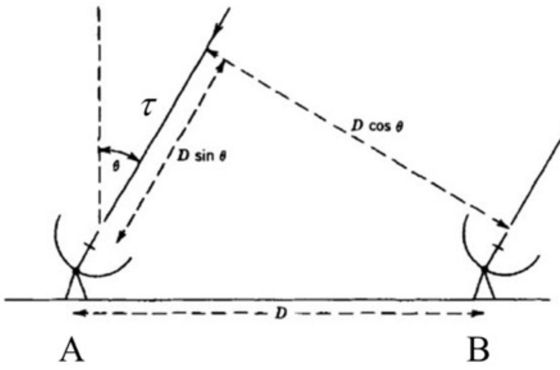
2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Radio

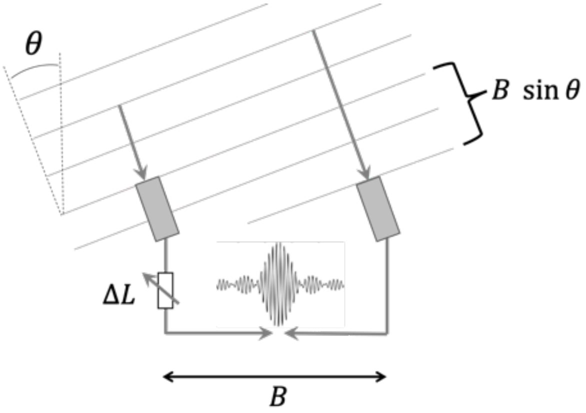
$\bar{n} \gg 1$



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

Optical

$\bar{n} \ll 1$



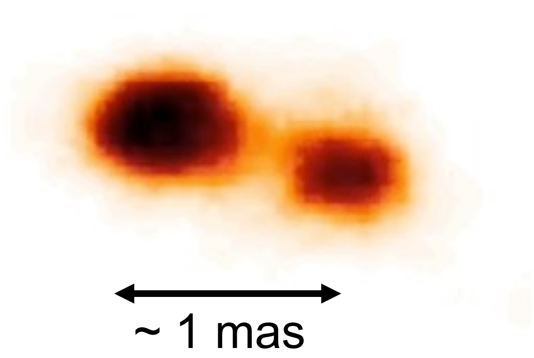
One photon at a time! Need to bring paths to common point in real time

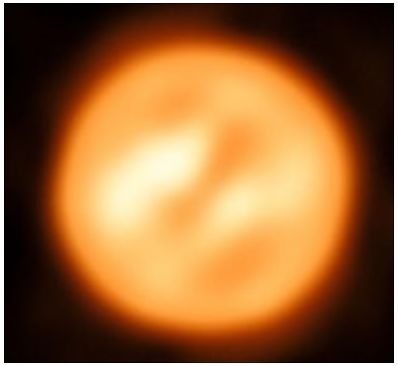
Need path length *stabilized* to better than λ

Accuracy ~ 1 mas (milliarcsecond)

Max baselines ~ 100 m

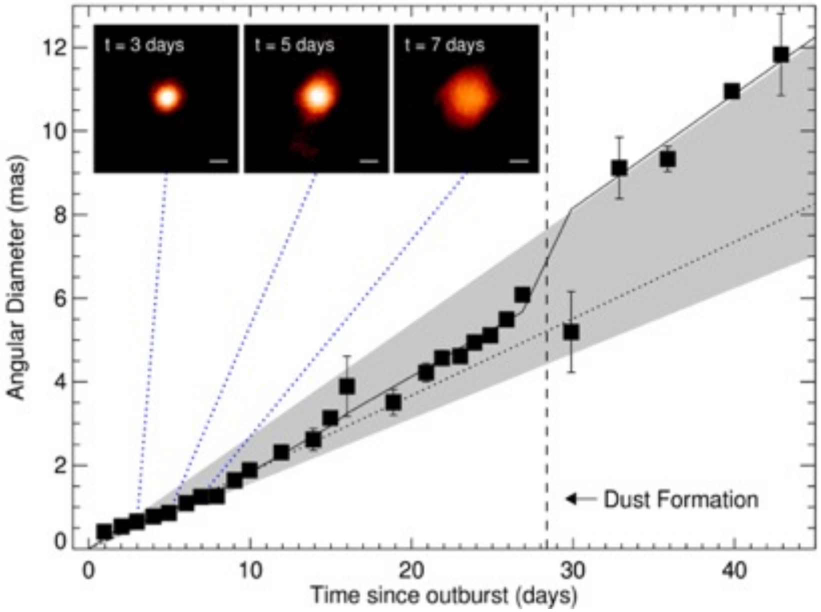
Optical interferometry examples





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.

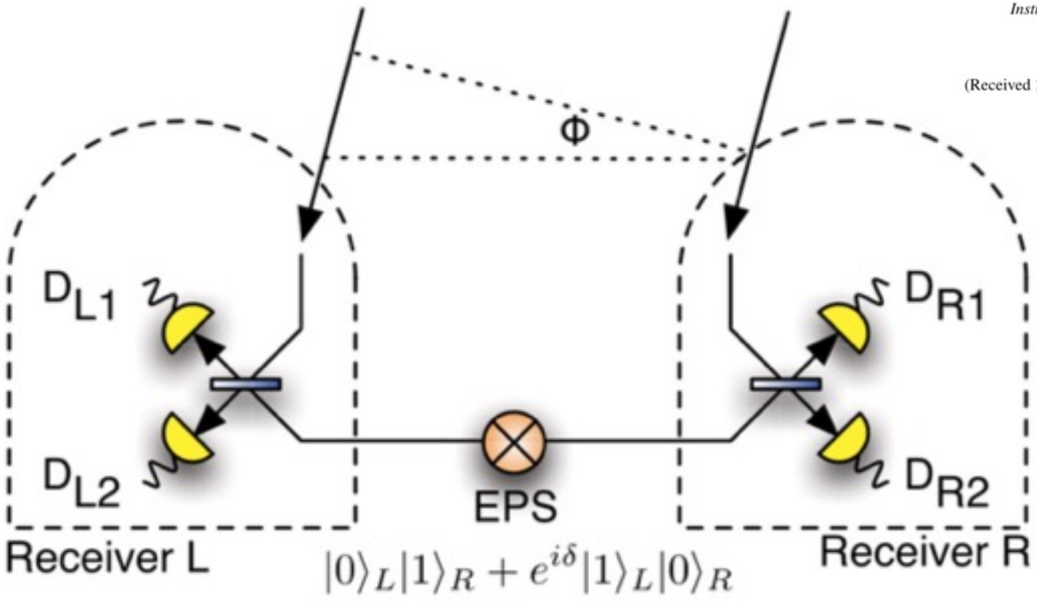


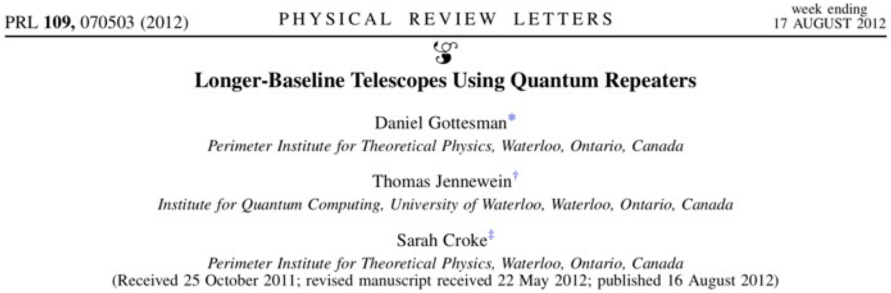
Nova in progress (CHARA)

Two-photon techniques

Quantum-assisted telescopes

Quantum (two-photon) interferometer




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)

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

- 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
- Observables: measure coincidence rates of four single photon counters

Possible impact on astrophysics and cosmology

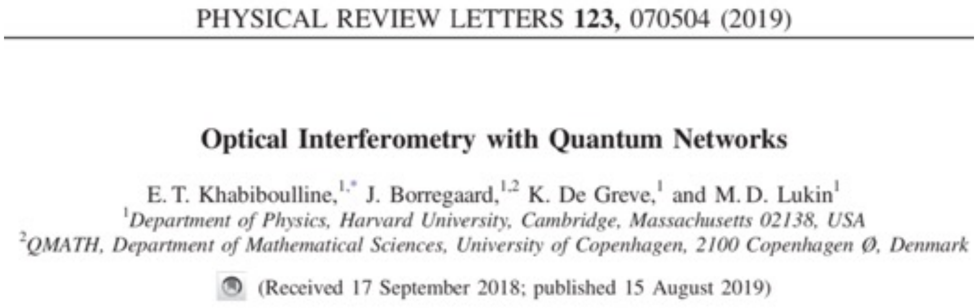
https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder
- Proper star motions
- Microlensing, see shape changes
- Gravitational waves, coherent motions of stars
- Exoplanets
- etc

More recent developments

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

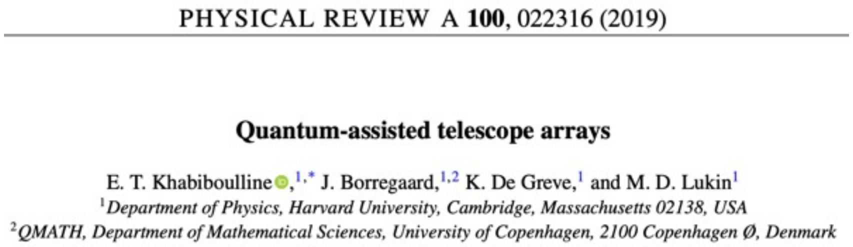


PHYSICAL REVIEW LETTERS **123**, 070504 (2019)

Optical Interferometry with Quantum Networks

E. T. Khabiboulline,[1,*] J. Borregaard,[1,2] K. De Greve,[1] and M. D. Lukin[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen Ø, Denmark*

(Received 17 September 2018; published 15 August 2019)



PHYSICAL REVIEW A **100**, 022316 (2019)

Quantum-assisted telescope arrays

E. T. Khabiboulline,[1,*] J. Borregaard,[1,2] K. De Greve,[1] and M. D. Lukin[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
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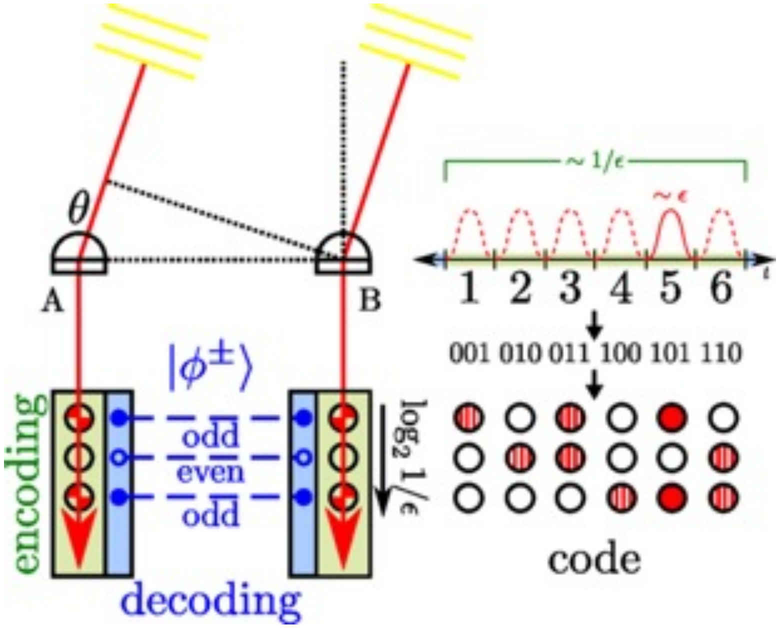


Idea: Efficient time-bin encoding of photon arrivals

More futuristic ideas

Quantum hard drives!

Scientific American Unlimited Learn More

OPINION PUBLICATIONS

PHYSICS

Quantum Astronomy Could Create Telescopes Hundreds of Kilometers Wide

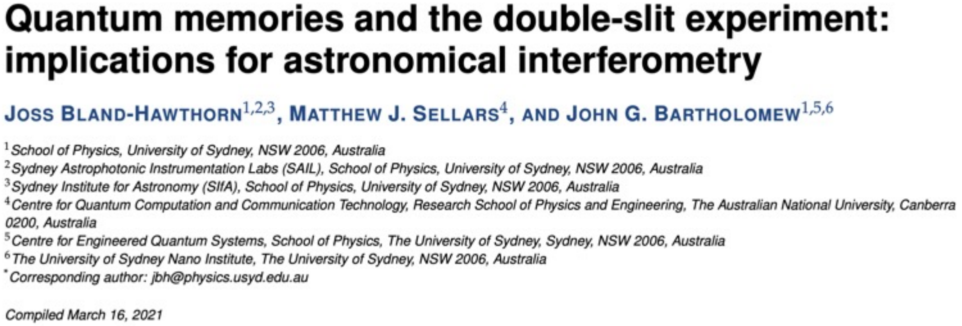
Astronomers hope to use innovations fr
large arrays

By Anil Anar

HOME › EXTREME › ASTRONOMERS WANT TO DESIGN QUANTUM TELESCOPES THAT SPAN THE GLOBE

Astronomers Want to Design Quantum Telescopes That Span the Globe

By Ryan Whitwam on April 26, 2021 at 7:30 am | Comments



Quantum memories and the double-slit experiment: implications for astronomical interferometry

Joss Bland-Hawthorn[1,2,3], **Matthew J. Sellars**[4], and **John G. Bartholomew**[1,5,6]

[1] *School of Physics, University of Sydney, NSW 2006, Australia*
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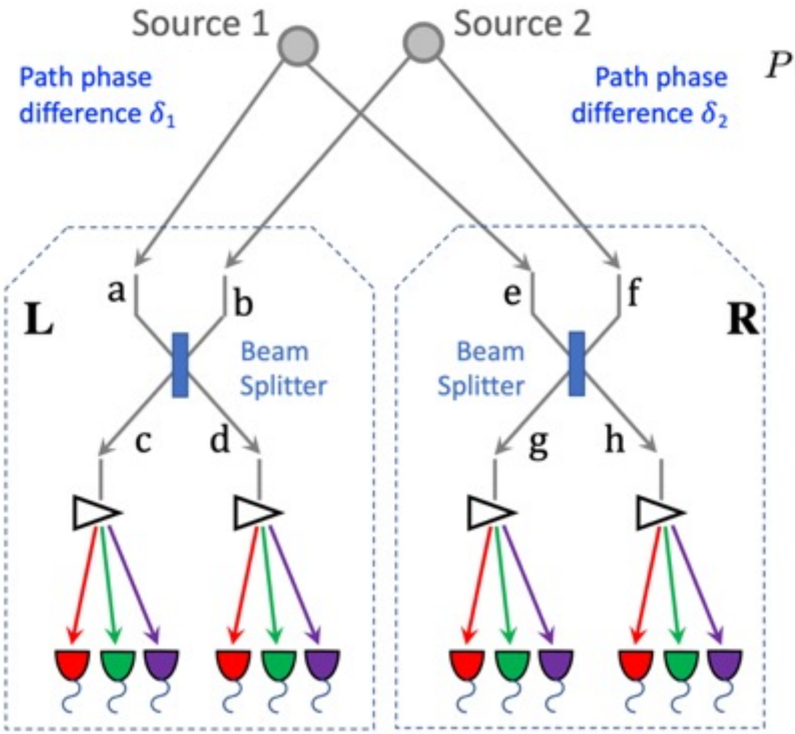
Compiled March 16, 2021

Quantum Astrometry

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

Quantum Astrometry

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



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

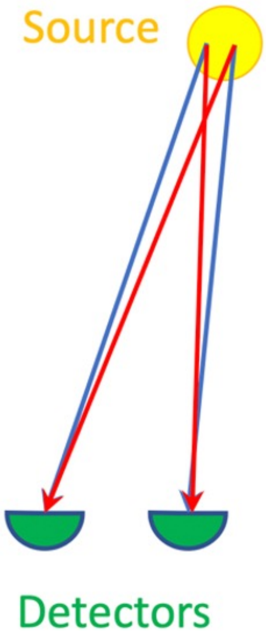
Full QFT calculation in https://arxiv.org/abs/2010.09100

$$
N_c(xy)=\eta_1\eta_2A^2\int_0^{T_r}P^{\text{two photons}}_{L,R,\tau}\,d\tau =
A^2\eta_1\eta_2T_r\left[\overset{\text{Rates}}{\boxed{(I_1+I_2)^2}}+\overset{\text{HBT}}{\boxed{I_1^2\frac{\tau_c g_{11}}{T_r}+I_2^2\frac{\tau_c g_{22}}{T_r}}}\pm
\underset{\text{New oscillatory term!}}{\boxed{2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B(\sin\theta_1-\sin\theta_2)}{c}+\frac{\omega_0\Delta L}{c}\right)}}\right] \quad (30)
$$

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

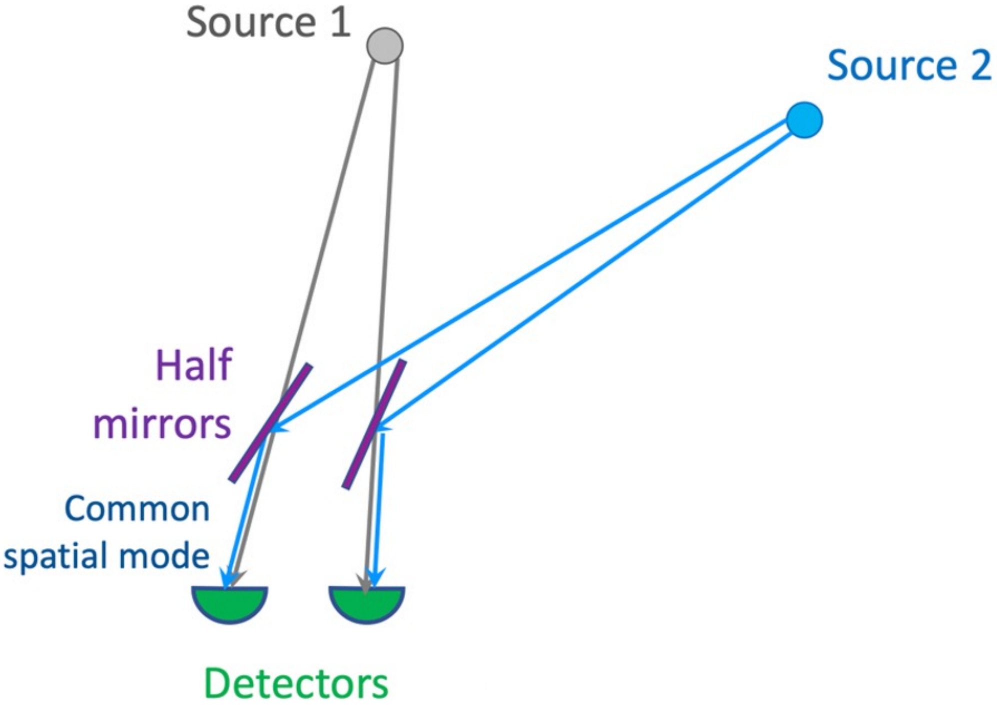
Comparison to Hanbury Brown – Twiss Intensity Interferometry

Standard HBT



Photon bunching if path difference is within coherence time

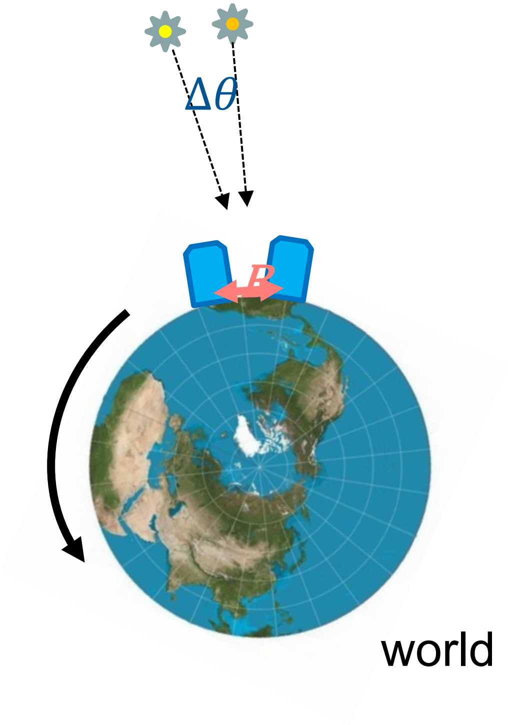
Quantum astrometry



Coincident pair detection sensitive to phase difference of two photons

Earth rotation fringe scan

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



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

Coincidence rates oscillate

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

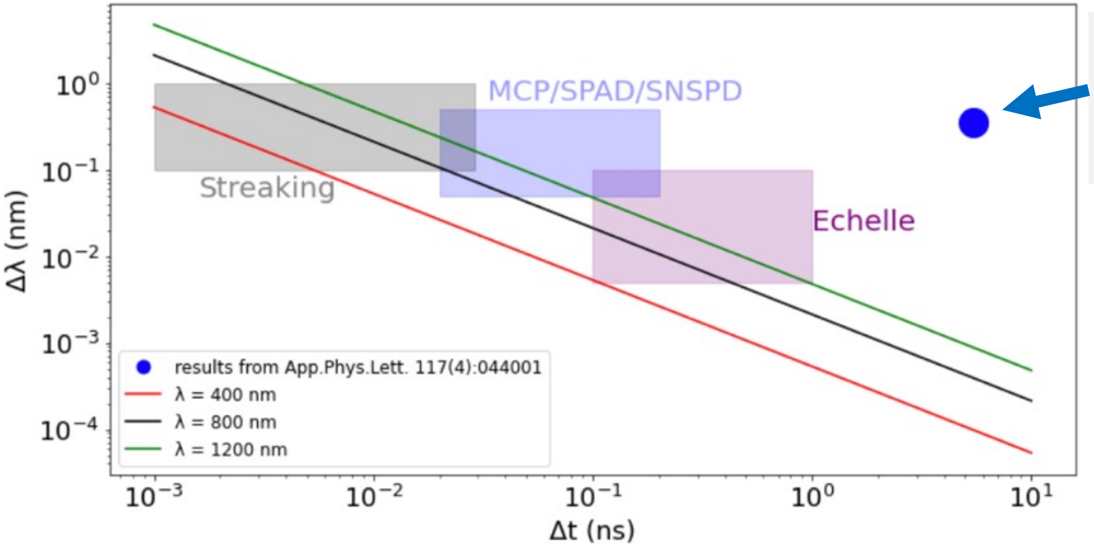
⇐ Fringe oscillation rate is a direct measure of sources' opening angle!

world competitive precision with a modest experiment (for bright stars)

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

https://arxiv.org/abs/2010.09100

Requirements for detectors



results from:

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

- 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
  - Need large number of bins

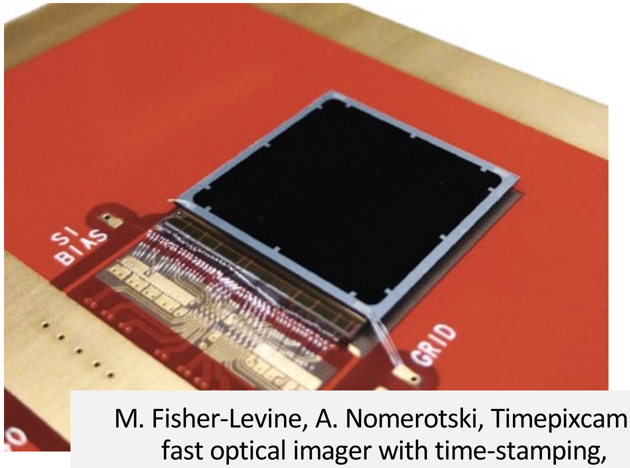
Quantum-Assisted Optical Interferometers: Instrument Requirements; Andrei Nomerotski et al, Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 1144617 (2020) SPIE Astronomical Telescopes +Instrumentation, https://doi.org/10.1117/12.2560272; arxiv:2012.02812

Intensified Timepix3 Camera

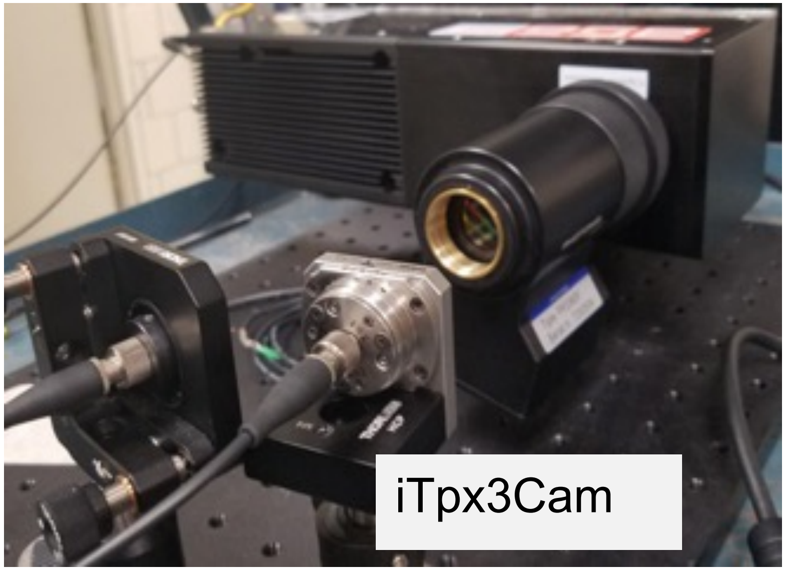
time-stamps single photons with ns resolution

Camera = intensifier + sensor + ASIC + readout

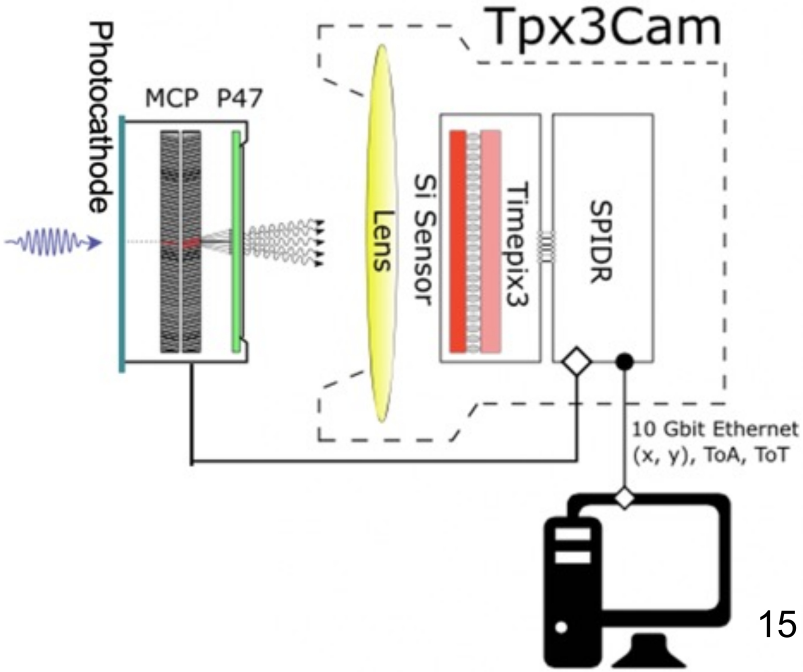
- 256 x 256 array
- 1.6 ns time bin, data-driven readout



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



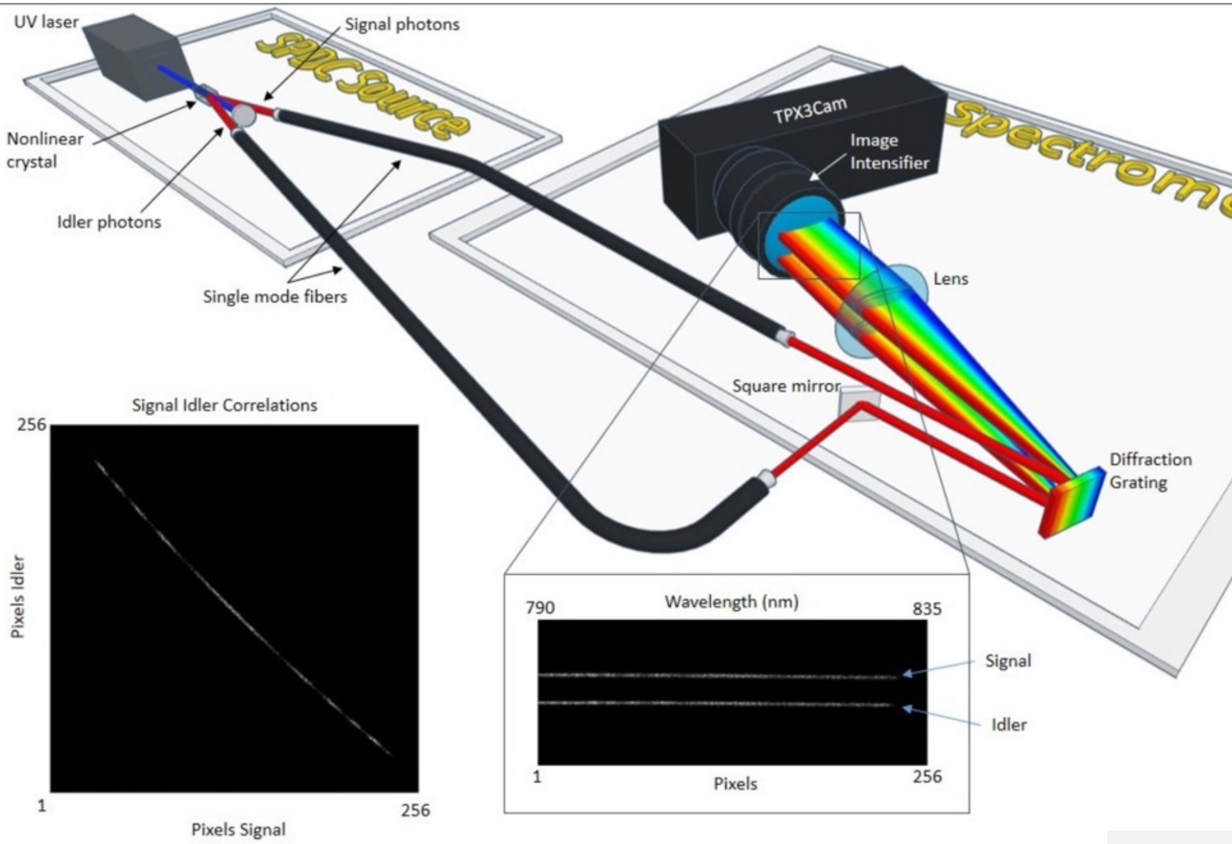
iTpx3Cam



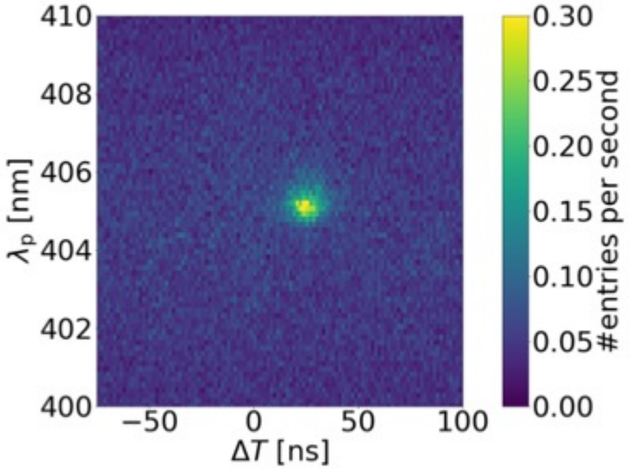
arxiv.org/abs/1902.01357

Spectral 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

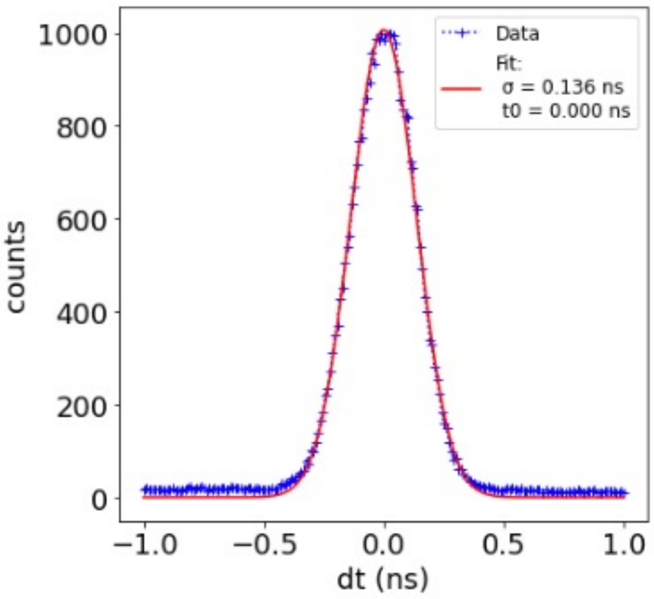
arxiv.org/abs/2105.09431

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)

Fast timing technologies

- Superconducting nanowires (SNSPD)
  - In our measurements: 100 ps resolution for single photons, high QE
  - 3 ps SNSPD devices reported



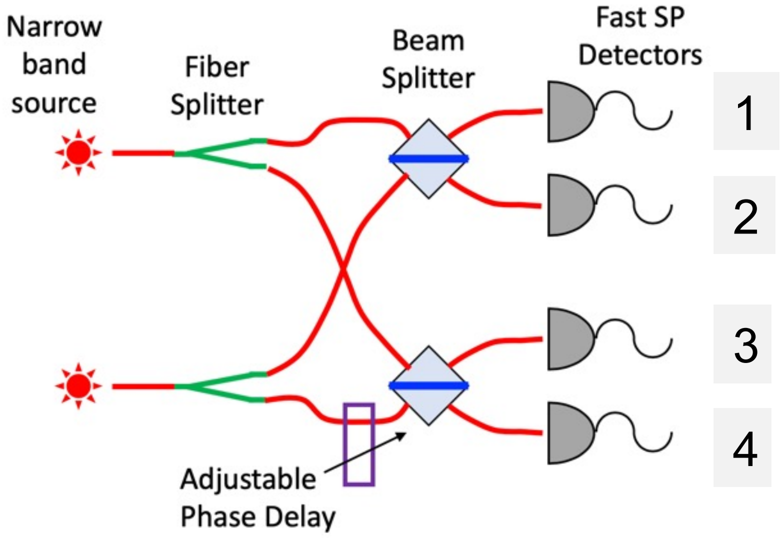
SPDC pairs in SNSPD

Other technologies under evaluation

- Single Photon Avalanche Device (SPAD)
  - 10 ps resolution possible
  - Scalable: 1D and 2D matrices
- Streaking cameras
  - Use spatial information for time measurement
  - 1 ps resolution possible

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

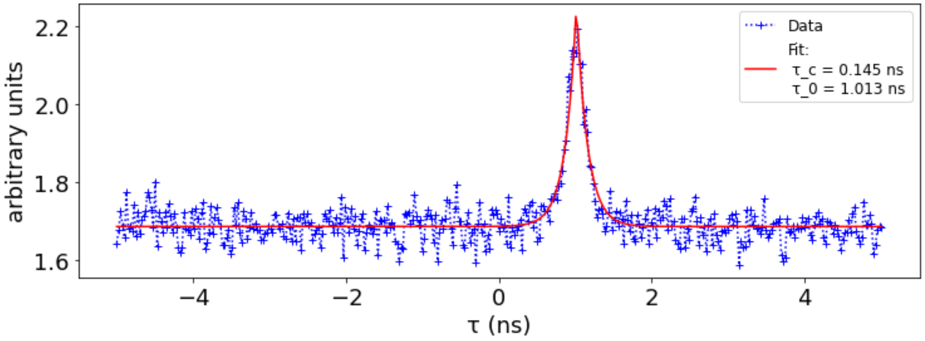
Experiments in progress

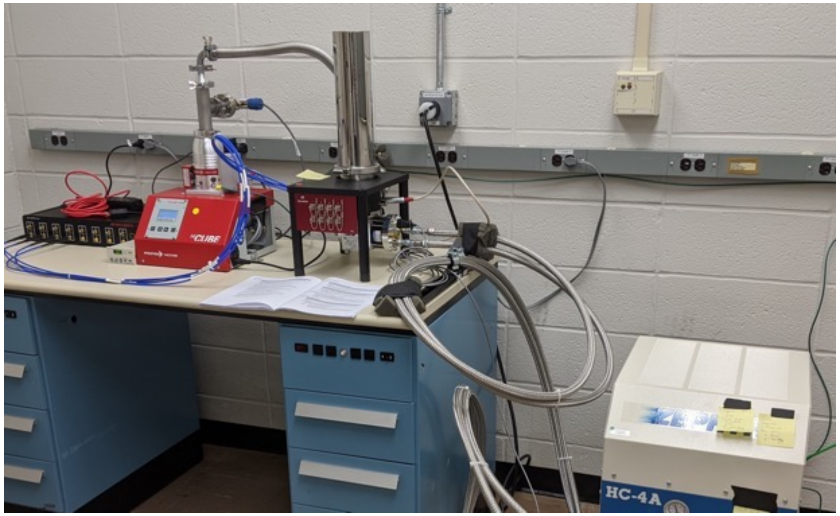


Bench-top model of two-photon interferometry

Ar vapor lamps (794 nm line) with narrow band filters
Superconducting nanowire single-photon detectors (Single Quantum)

Strong HBT peak with single lamp



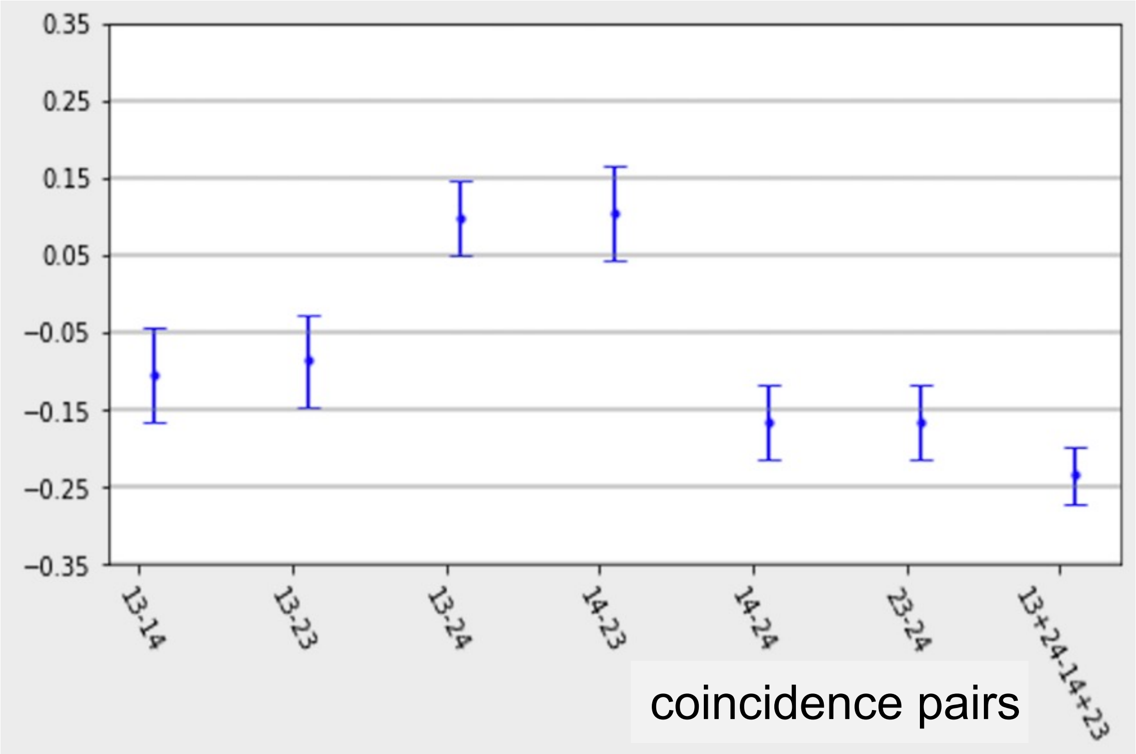


arxiv.org/abs/2012.02812

Supported by DOE HEP QuantISED grant

First results

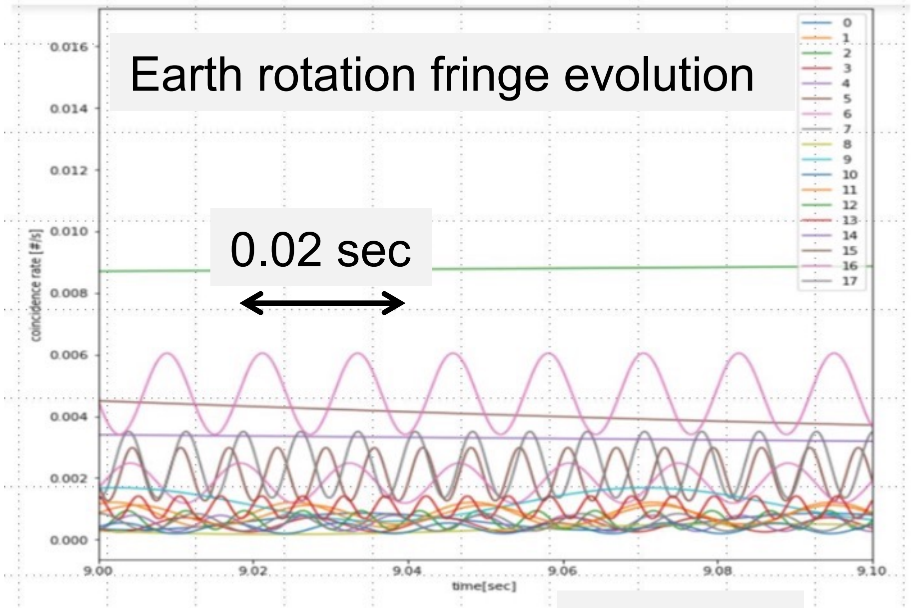
- Effect can be seen in coincidence correlations between pairs of SNSPD channels
  - Technique is less sensitive to phase instability (~ 10 sec)
- Results agree with predictions, correlations ~ 0.1-0.2 @ > 3 σ



arxiv.org/abs/2107.09229

Next steps

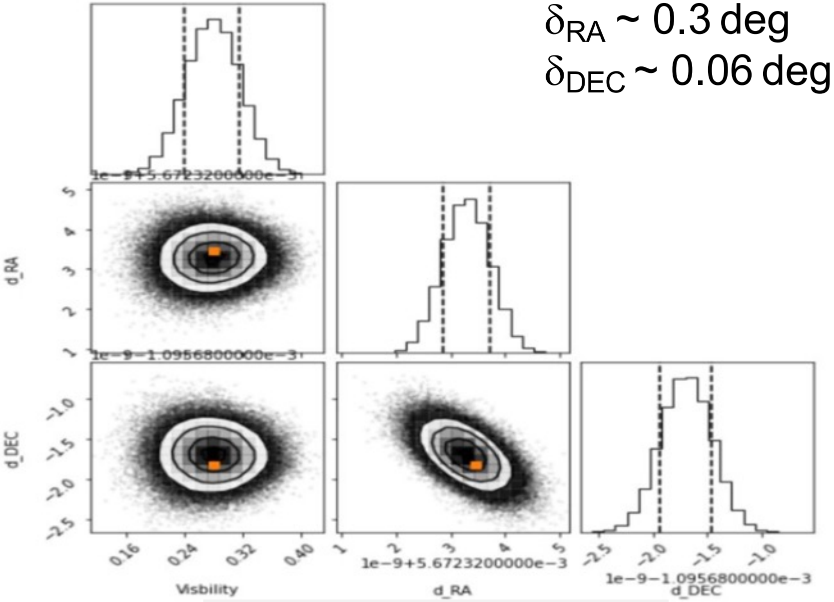
Preparations for on-sky experiments



Earth rotation fringe evolution

0.02 sec

Time, sec



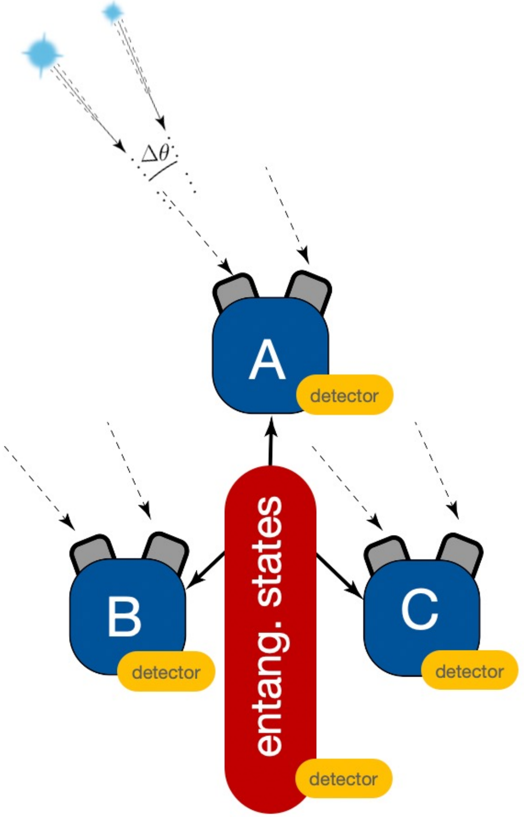
δ_{RA} ~ 0.3 deg
δ_{DEC} ~ 0.06 deg

Visibility, δ_{RA} , δ_{DEC}
MCMC fit results

- Star pair selection for fringe scans
  - Used catalog of bright stars visible from BNL site
- Modeled reconstruction of fringes to evaluate experimental errors
- Paper in preparation

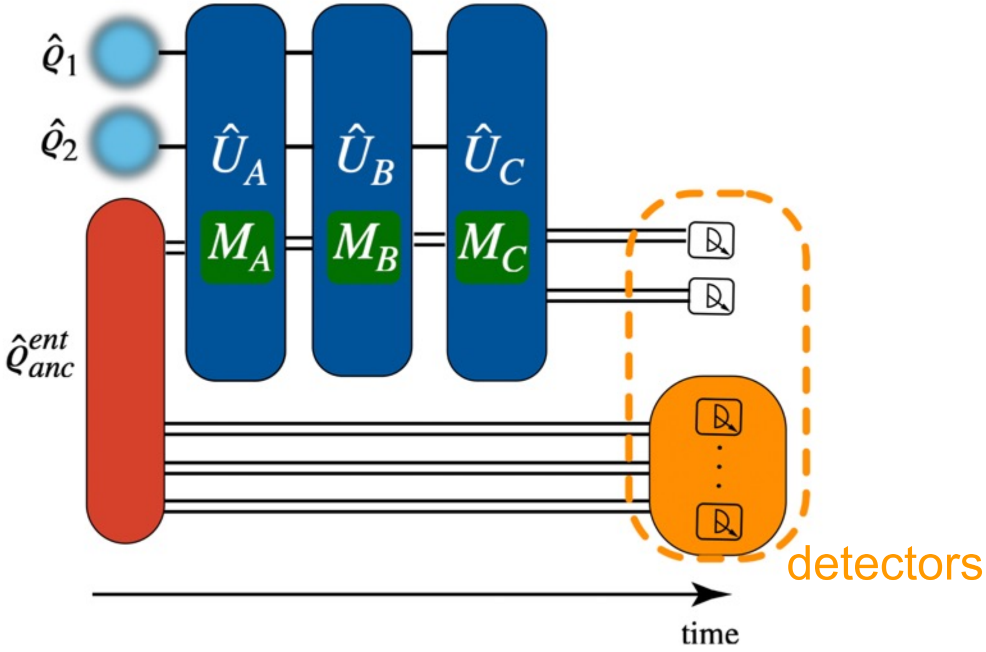
Developing the quantum

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



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

Quantum protocol circuit



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

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

- Planning on-sky measurements
- Developing theoretical framework, looking for new observables

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Jonathan Schiff
Alex Parsells
Zhi Chen
Anze Slosar
Olli Saira
Denis Dolzhenko
Stephen Vintskevich
Ning Bao

Jingming Long
Martin van Beuzekom
Erik Maddox
Jord Prangsma
Duncan England
Yingwen Zhang
Peter Svihra


BNL team


SBU team

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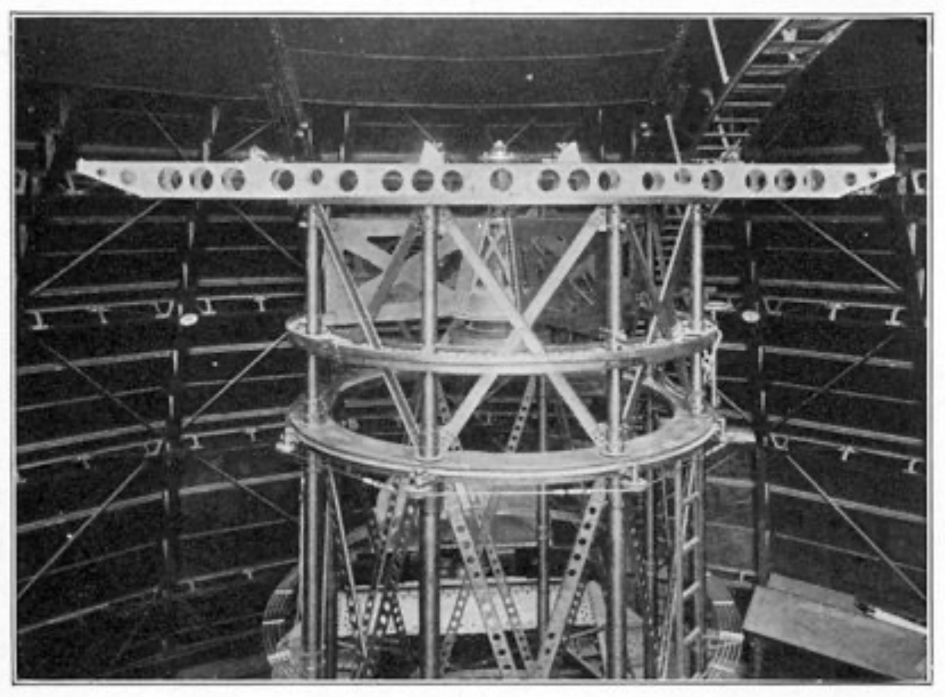
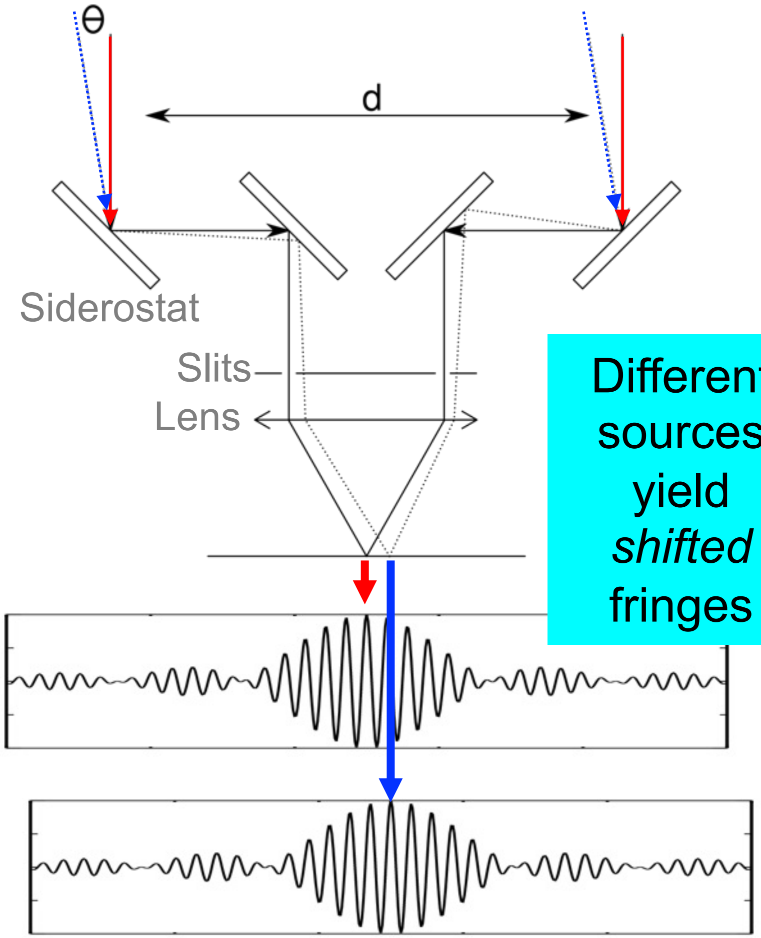
spares

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

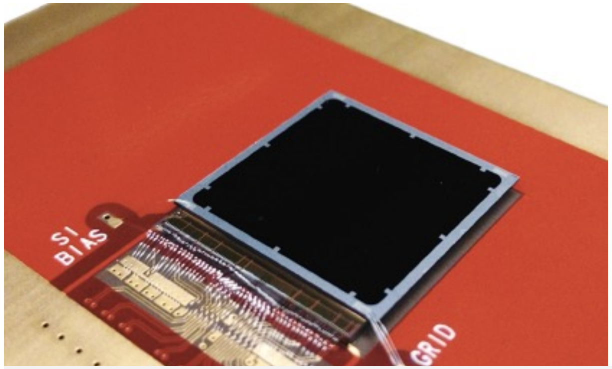
Track day-over-day changes in $\Delta\theta$ to observe parallax, proper motion, orbital motion, gravitational lensing

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

state of art: 7 μas GAIA (2013 -)

Intensified Timepix3 Camera

time-stamps single photons with ~ ns resolution

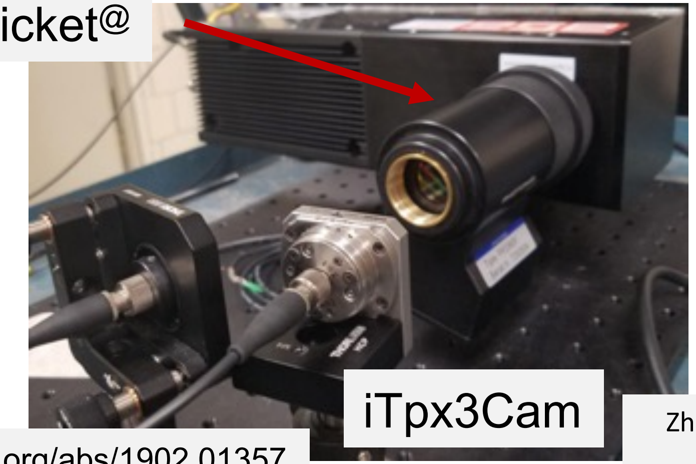


M. Fisher-Levine, A. Nomerotski, Timepixcam: a fast optical imager with time-stamping, Journal of Instrumentation 11 (03) (2016) C03016.

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
  - 1.6 ns timing resolution, data-driven readout
- 10 Gbs readout SPIDR @ Amsterdam Scientific Instruments
- Intensifier with GaAs photocathode @ Photonis

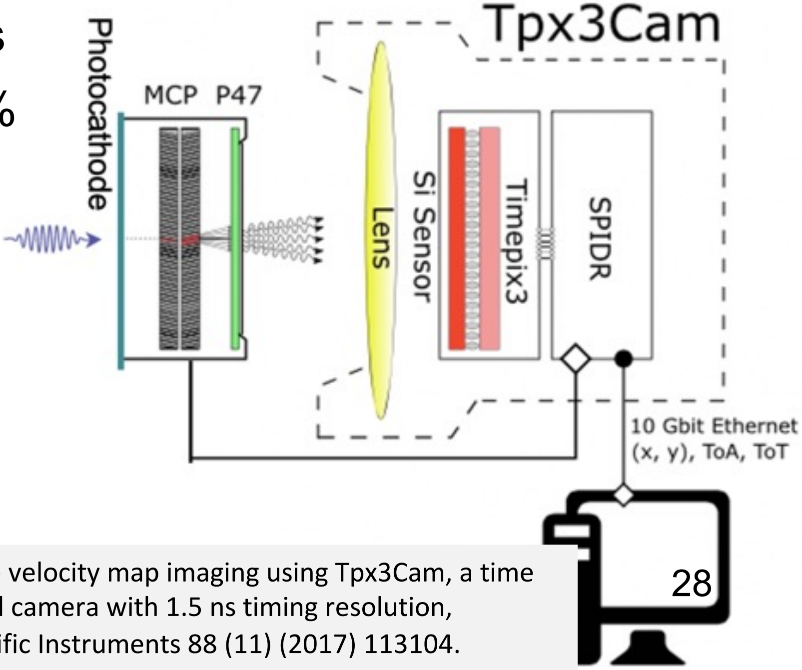
QE ~ 30%



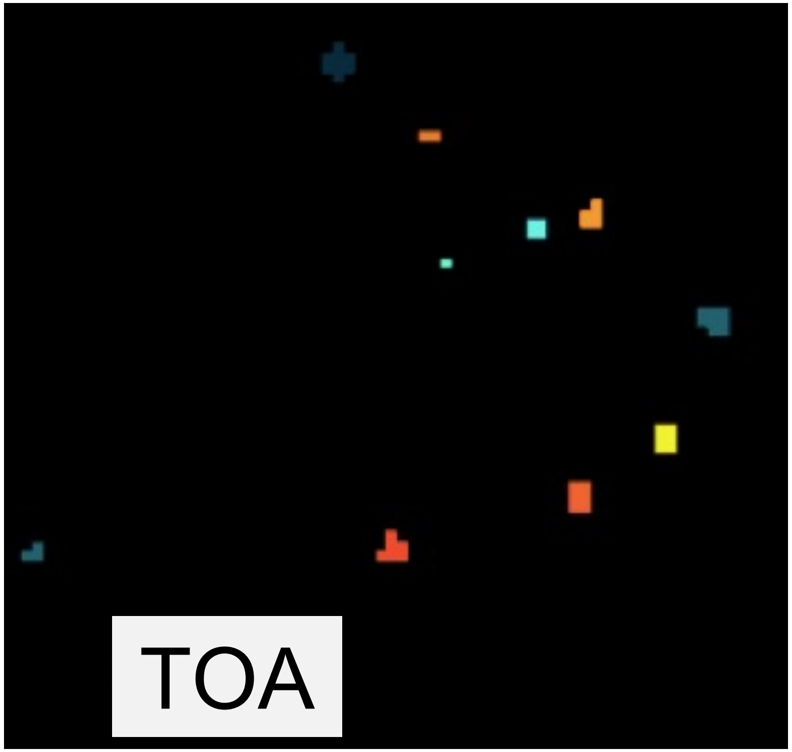
Cricket@

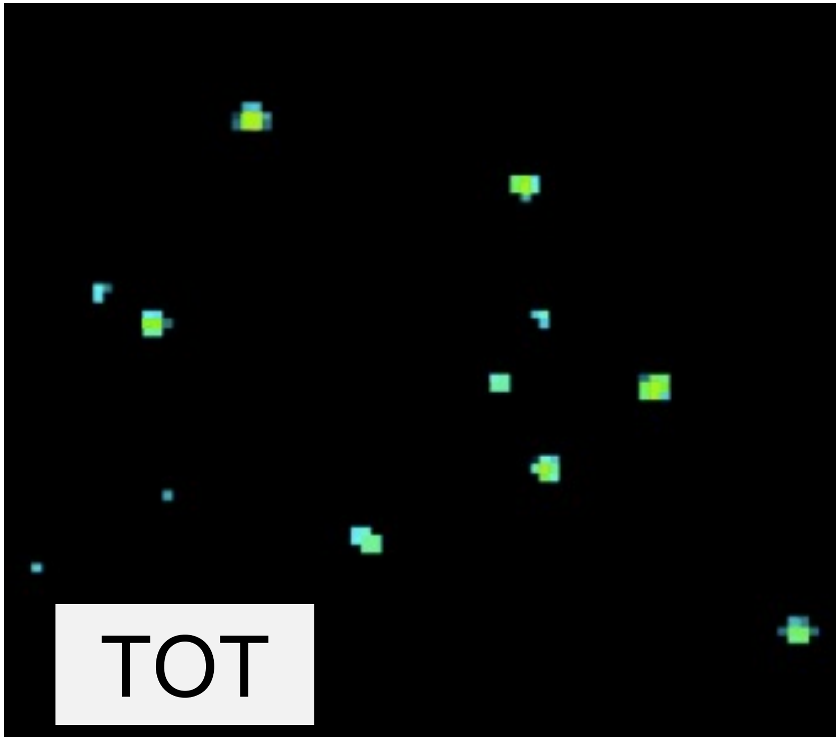
iTpx3Cam

arxiv.org/abs/1902.01357



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.



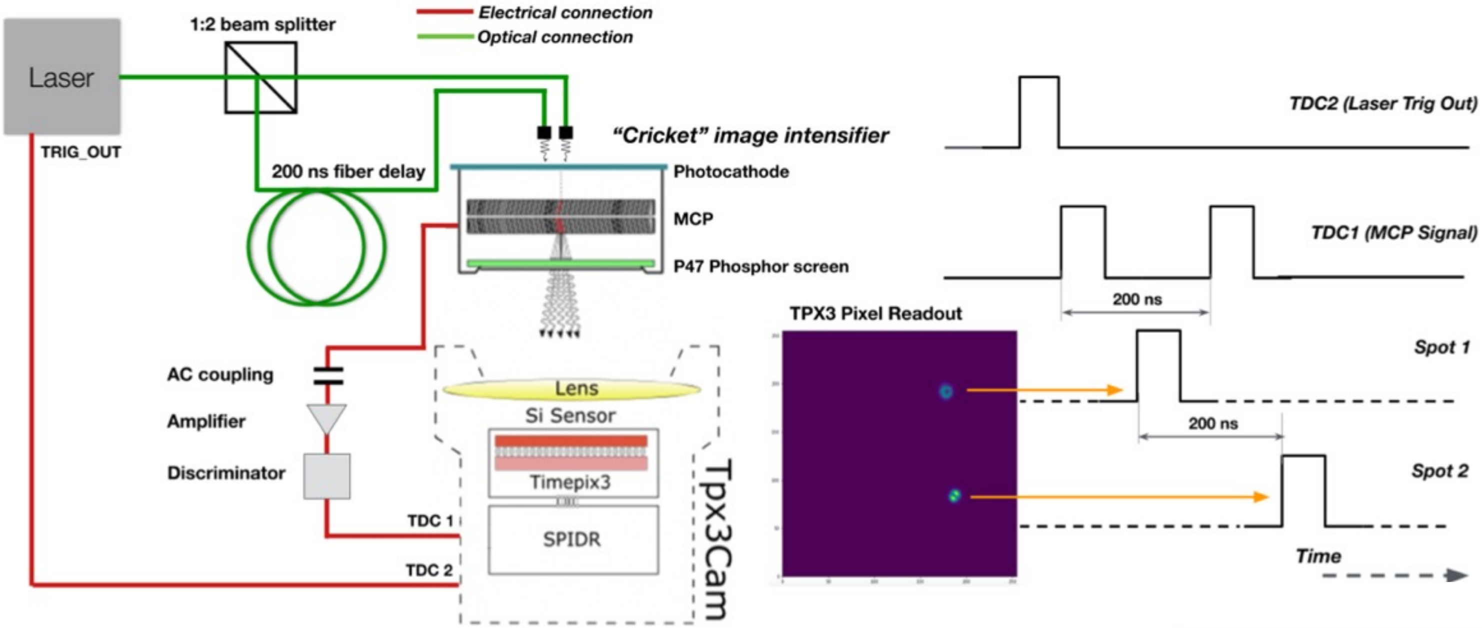


Each photon is a cluster of pixels
→ 3D (x,y,t) centoiding

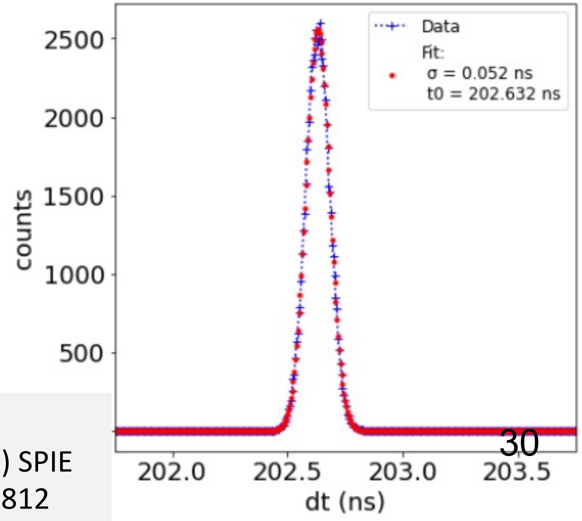
Time resolution: 2 ns / photon

A.Nomerotski, Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, Nuclear Instruments and Methods Sec A, Volume 937 (2019) pp 26-30

MCP Timing Performance



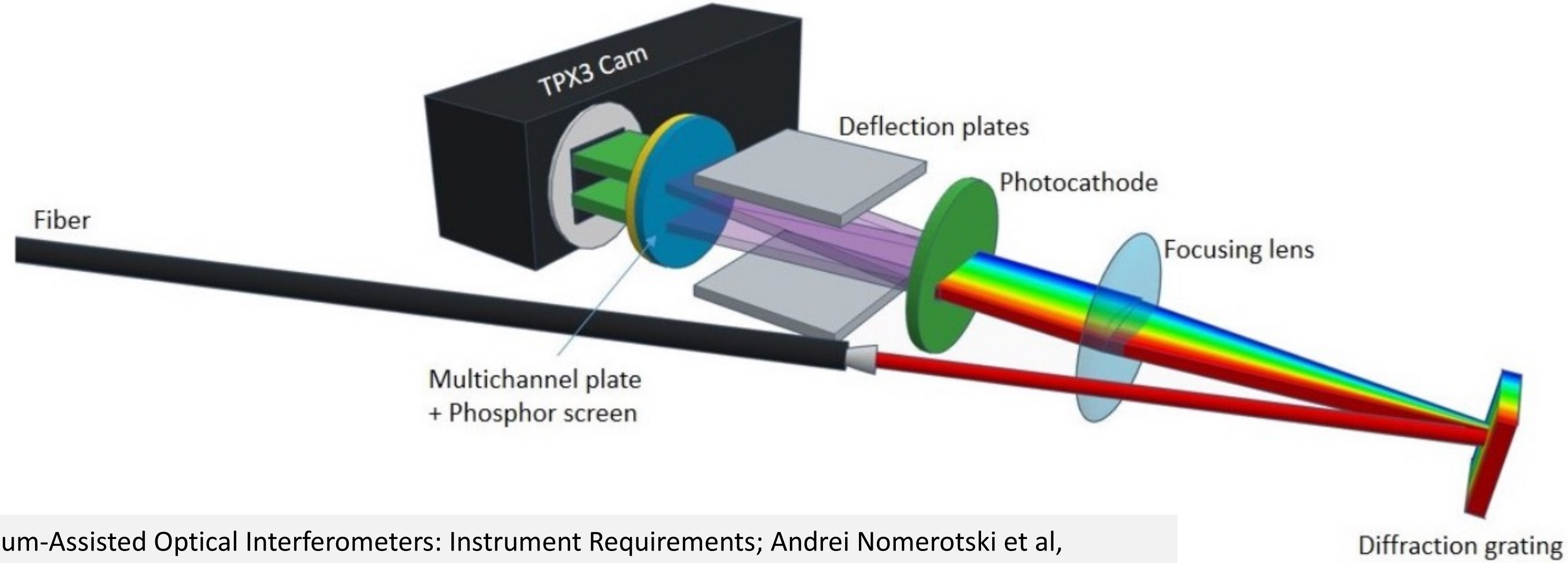
- Micro-channel plate (MCP) is fast
  - Demonstrated resolution < 30 ps
- MCP readout for Tpx3 camera
  - 50 ps, not for single photons yet



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: Streaking

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



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