Quantum-Assisted Optical Inteferometry

Some forward-looking ideas and works in progress

In collaboration with: Andrei Nomerotski, Stephen Vintskevich, Anze Slosar, Michael Keach, Olli Saira, Jonathan Schiff, Alex Parsells, Tom Tsang (BNL)

https://www.quantastro.bnl.gov

BROOKHAVEN NATIONAL LABORATORY

Paul Stankus, BNL

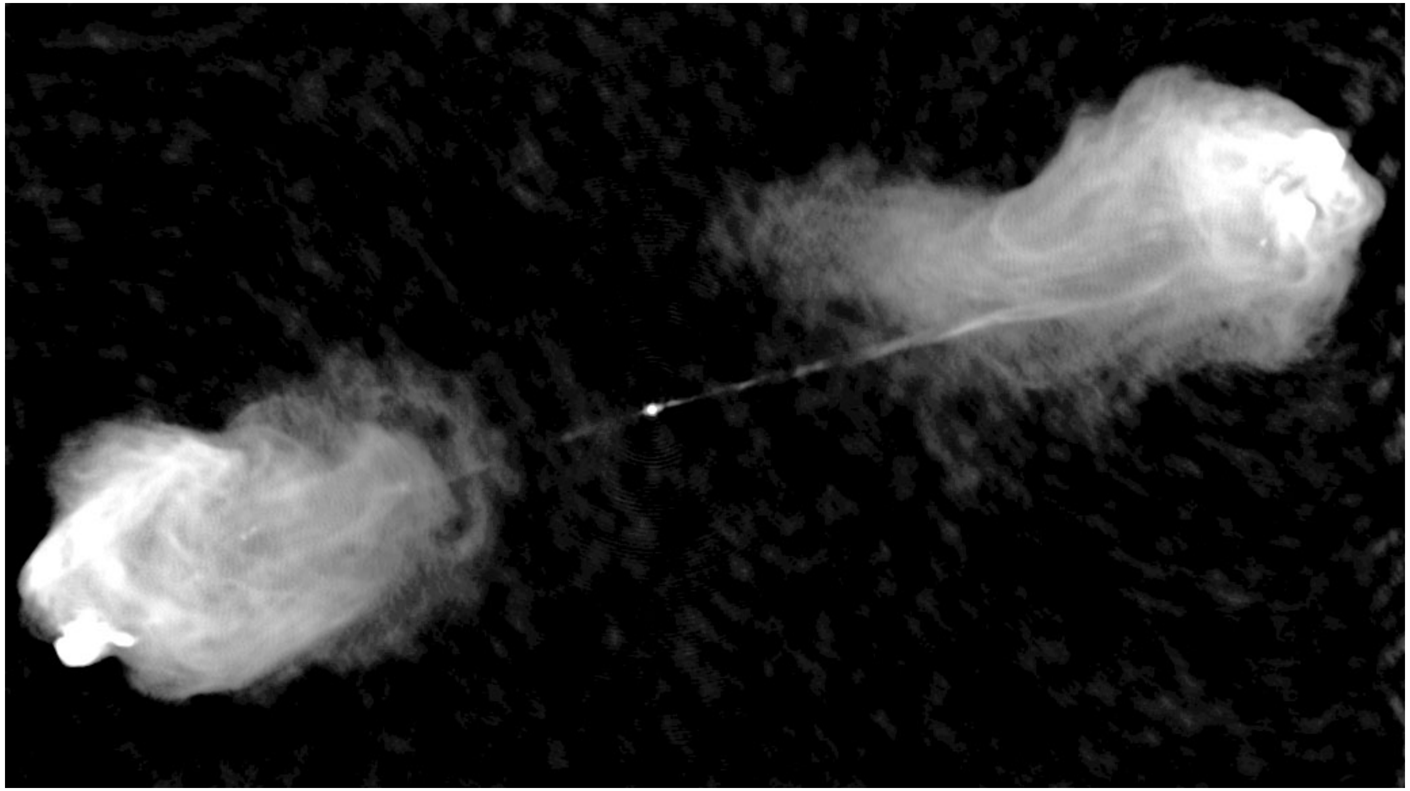
Harvard Lukin Group Seminar
9 April 2021

$$\langle BNL|\hat{a}^{\dagger}|QIST\rangle$$

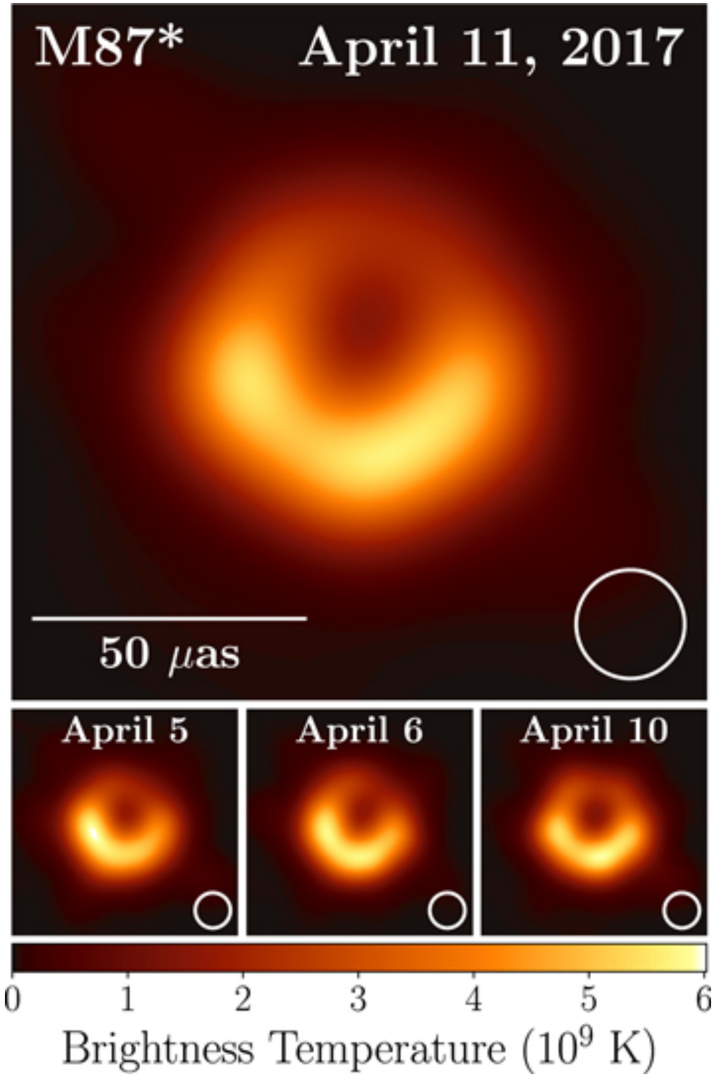
Agenda

- The glories of interferometry
- Single-photon methods (classical)
- Two-photon methods (quantum mechanical)
- Quantum assist; futuristic ideas
- New: two-photon interference for precision astrometry
- Astrophysical applications
- Experiments and detectors

Astronomy pictures of the ~~day~~ ~~year~~ decade



Radio source Cygnus A imaged at 6cm

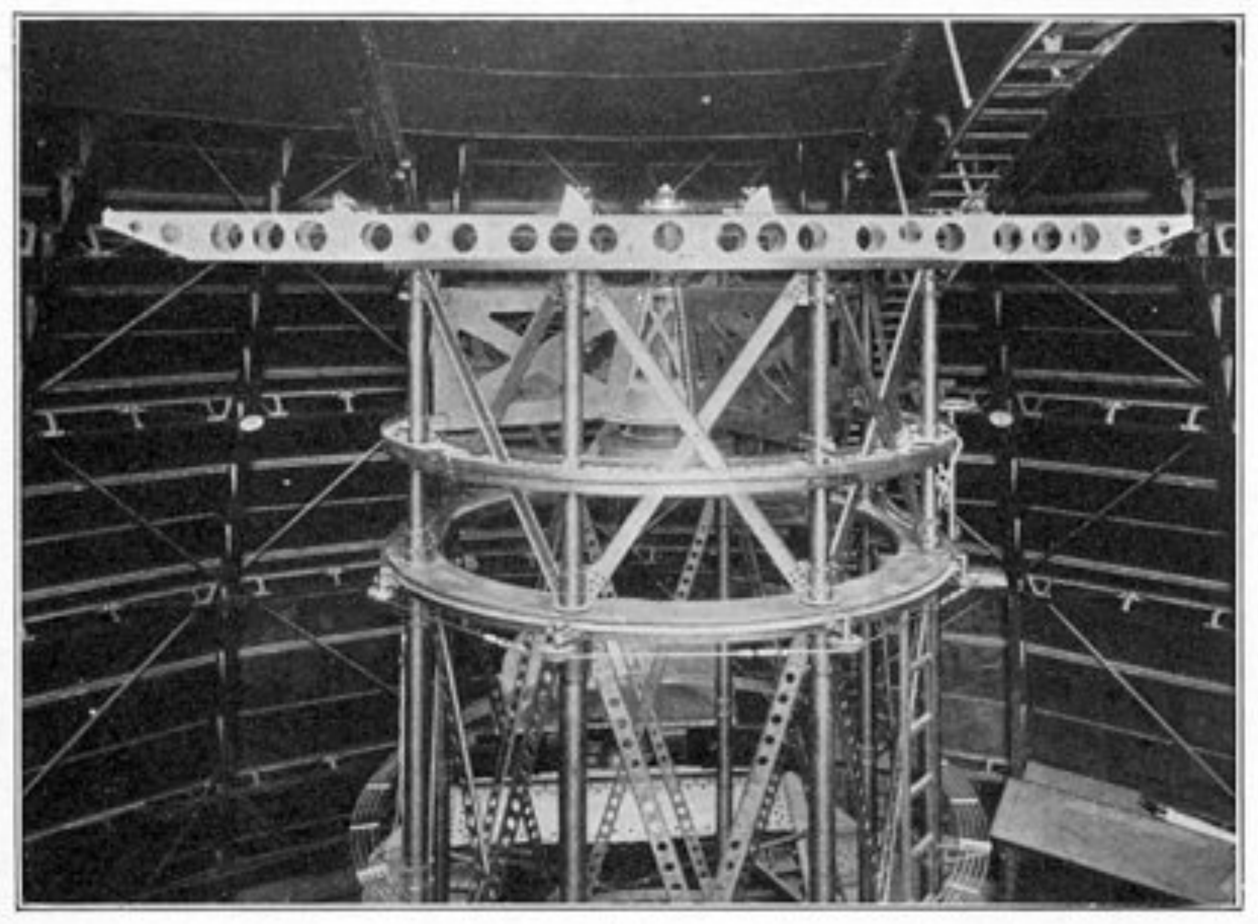


Center of M87 imaged at 1.3mm

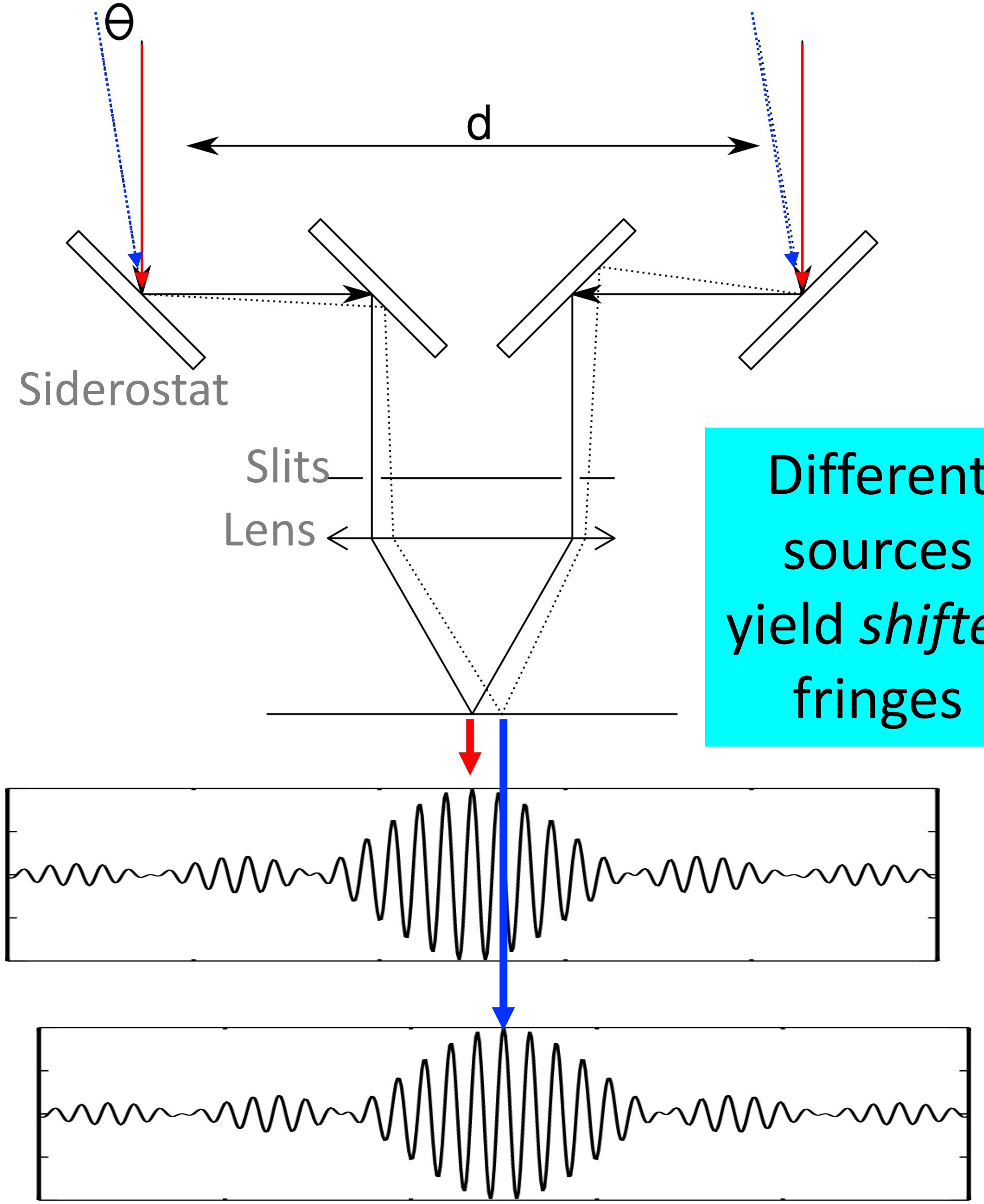
2019 ApJL 875

Single-photon techniques (classical)

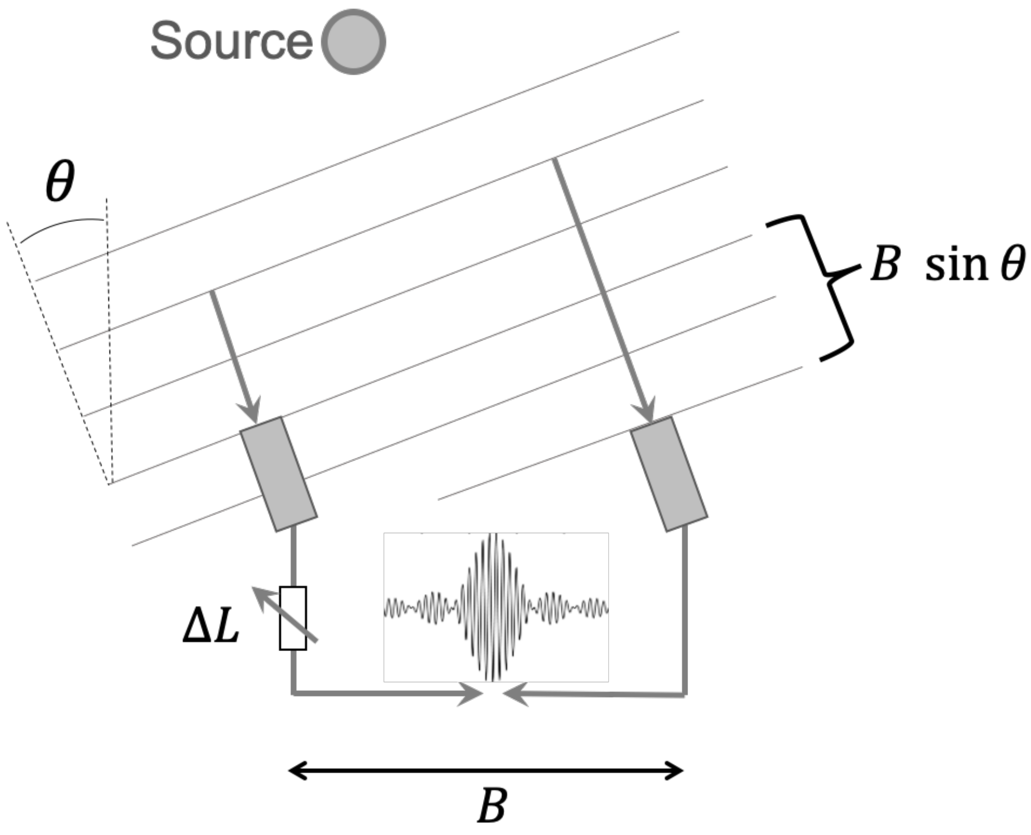
In classical times



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



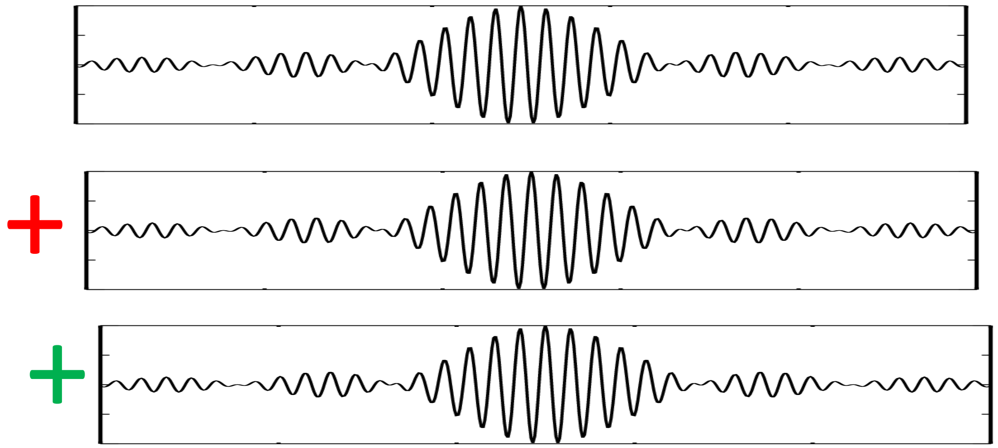
Different sources yield *shifted* fringes

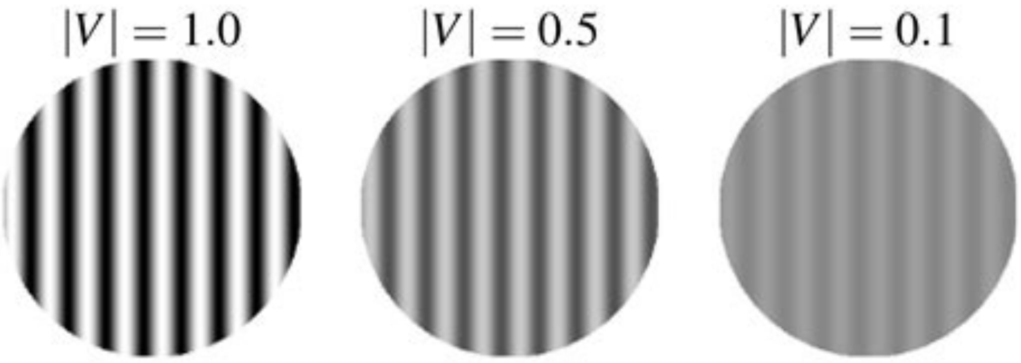


Each source i at sky position θ_i produces a fringe shifted by phase amount $\Delta\phi = 2\pi B \sin\theta_i/\lambda$

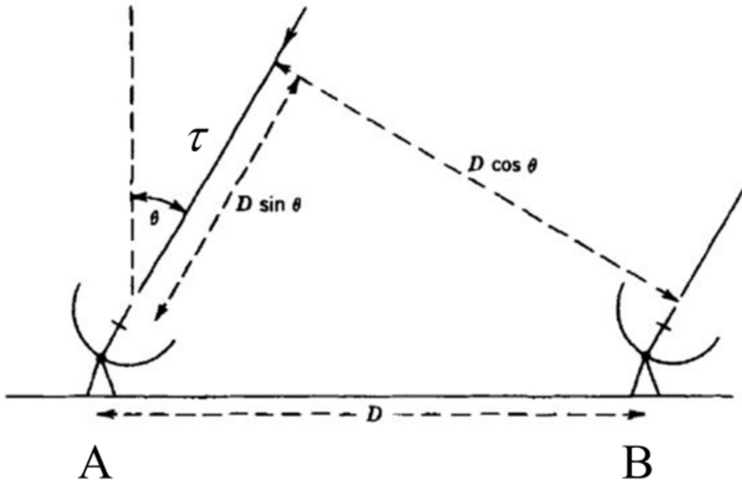
Intensity pattern is sum over all sources ☞ Fourier moment!

Fringe contrast(/visibility) measures <u>amplitude</u> of Fourier moment at wavenumber $k \approx 2\pi B/\lambda$



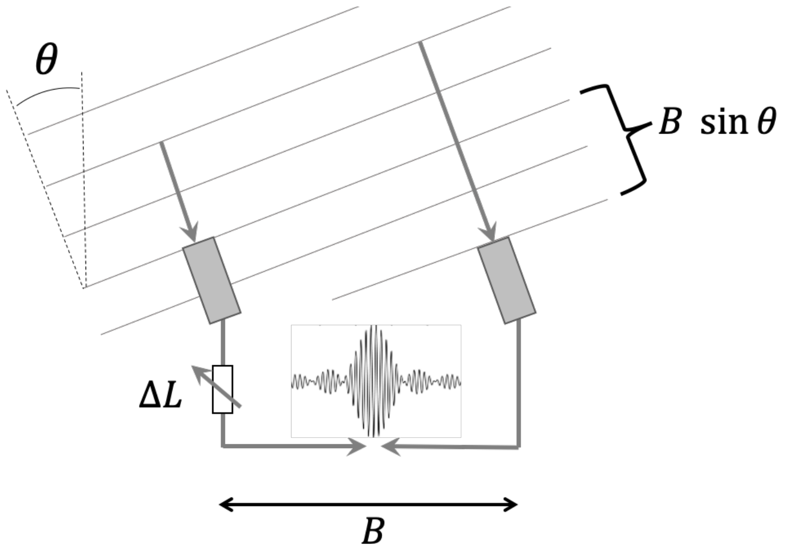


Radio $\bar{n} \gg 1$



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

Optical $\bar{n} \ll 1$

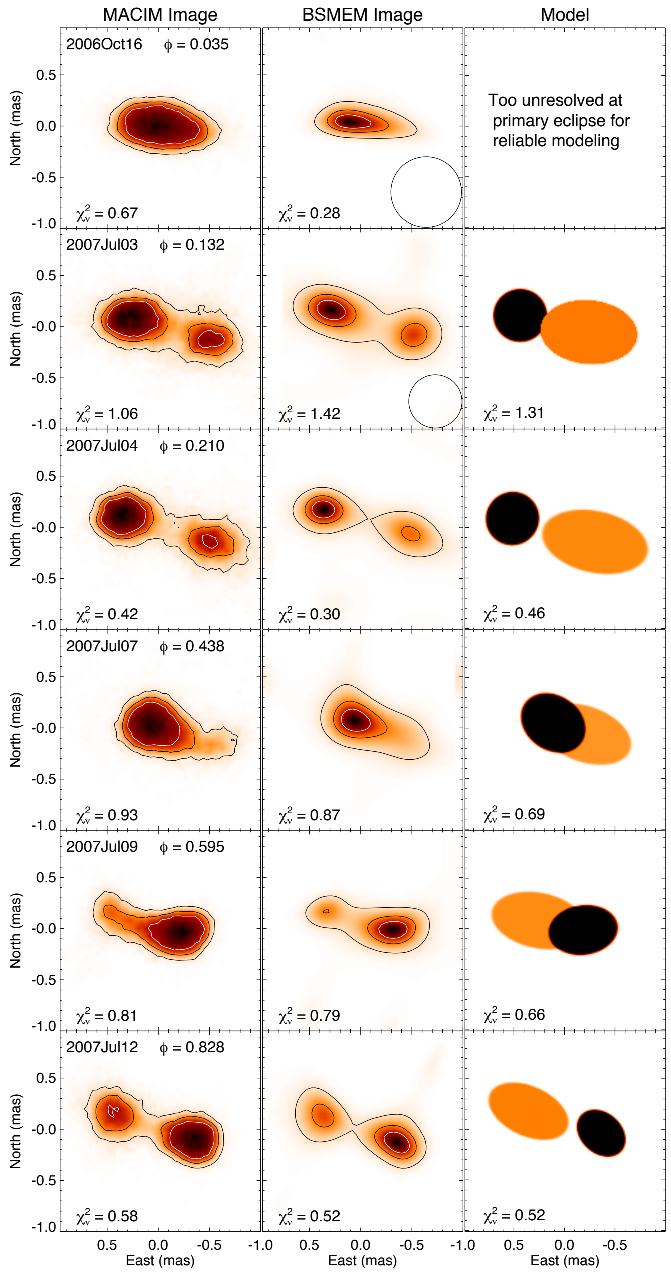


One photon at a time! Need to bring paths to common point in real time

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

Need path length *stabilized* to better than λ

How cool is this?



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

Classical summary

- EM waves interfere with themselves; single photons do same
- Interferometer sensitive to features on angular scale $\Delta\theta \sim \frac{\lambda}{B}$
- Drawbacks in ***optical***:
  - Need live optical link between stations
  - Need path length control precision on order $\lambda^2/\Delta\lambda$
  - Atmospheric effects enter at $O(1)$
  - Need to control polarization during transport
  - Practical limit on baselines ~ 100m

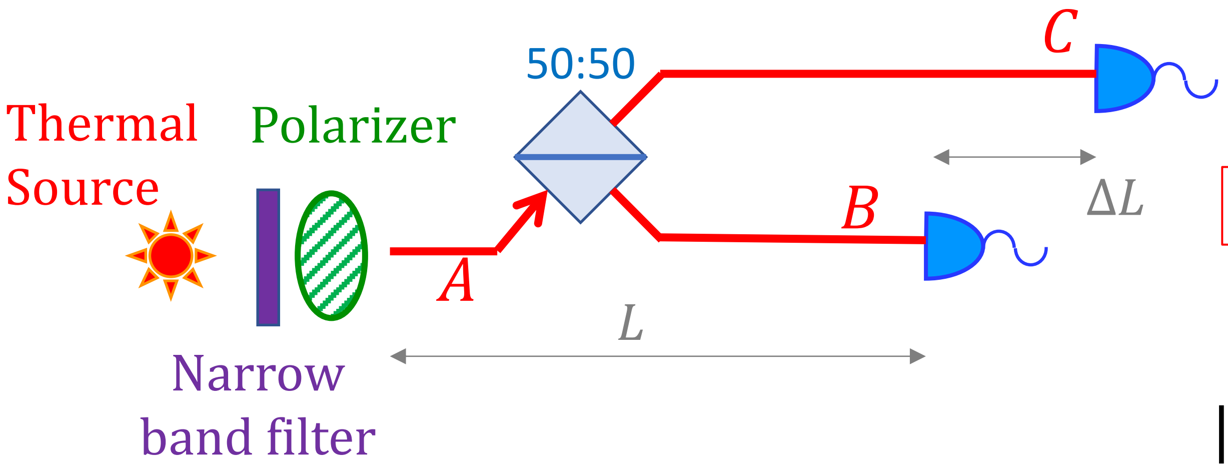
Two-photon techniques (quantum mechanical)

Prelude: Two-photon Intensity Interferometry

The curious HBT effect

"The birth of quantum optics"

Glauber theory of photodetection, c. 1963



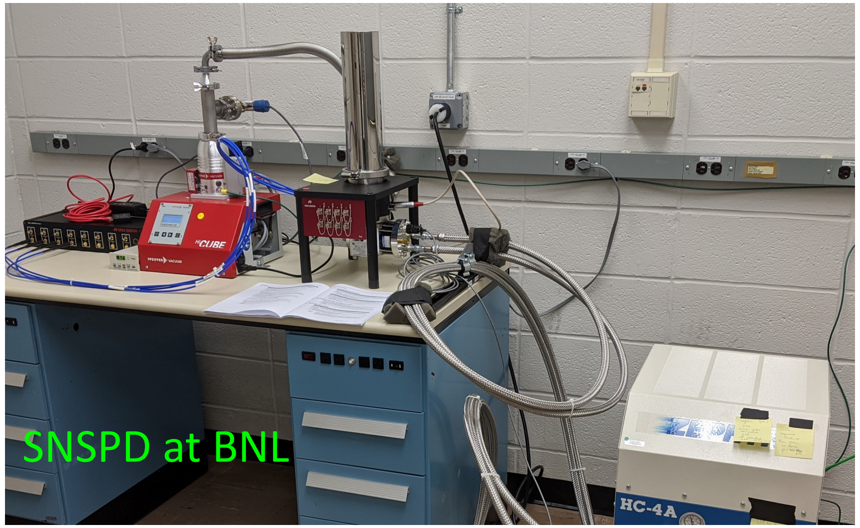
$$\text{Rate}^{BC}(t_B, t_C) \propto \|\hat{a}_B(t_B)\,\hat{a}_C(t_C)|\Psi\rangle\|^2$$

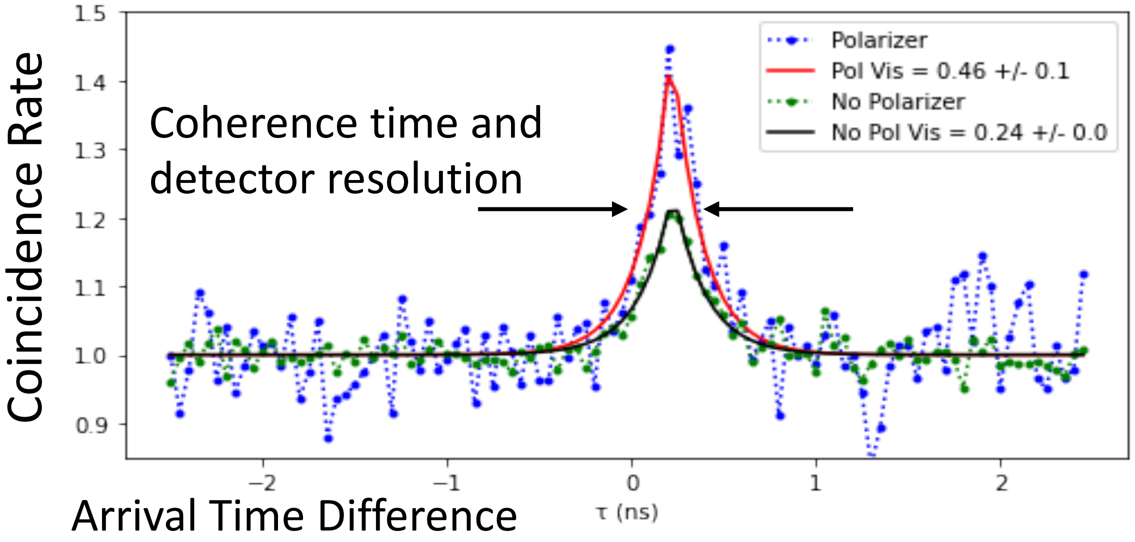
$$\propto \|\hat{a}_A(t_B - L/v)\,\hat{a}_A(t_c - (L+\Delta L)/v)|\Psi\rangle\|^2$$

$$\text{If } (t_B - L/v) = (t_c - (L+\Delta L)/v) = t_A$$

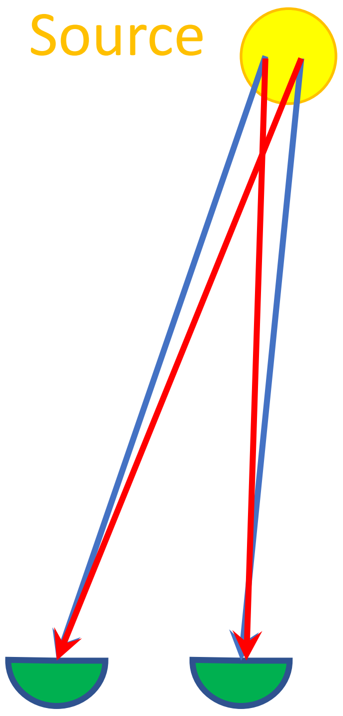
$$\text{then } \text{Rate}^{BC}(t_B, t_C) \propto \|\hat{a}_A(t_A)^2|\Psi_{Th}\rangle\|^2$$

$$\|\hat{a}_A(t_A)^2|\Psi_{Th}\rangle\|^2 = 2\|\hat{a}_A(t_A)\,\hat{a}_A(t_A')|\Psi_{Th}\rangle\|^2$$





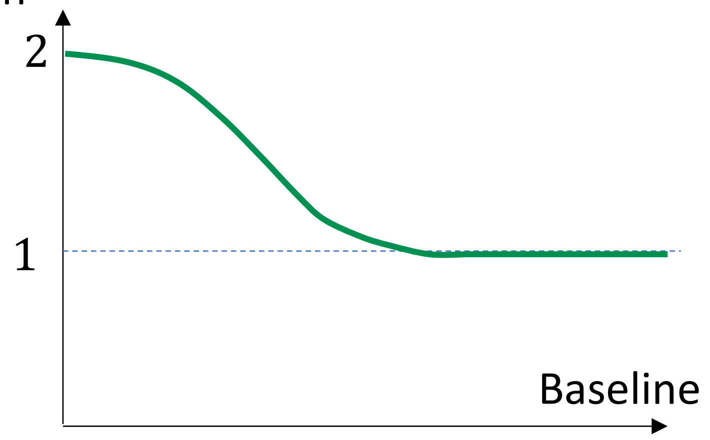
HBT and stellar sizes



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

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

Glauber theory of photodetection, c. 1963



(It works for other bosons, too.)

High ride of HBT, 1956-1974 ...and beyond?

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

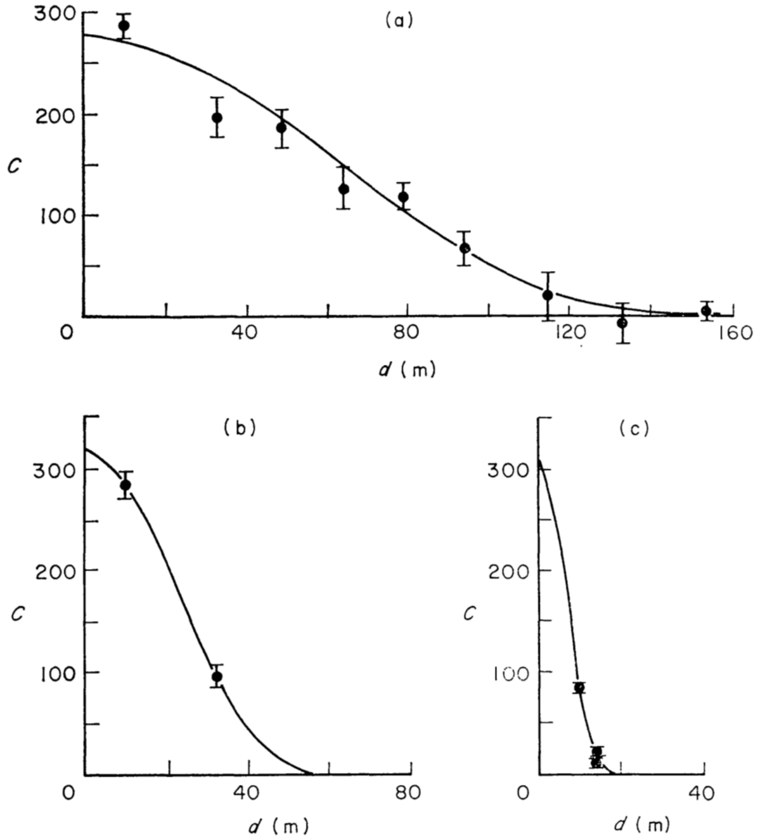


Fig. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

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

HBT track record

- Advantages:
  - Separate stations with only classical connection
  - Arbitrary baselines, set by desired angular scale
  - No path-length corrections needed
  - Immune to atmospheric effects (at leading order)

- Drawbacks:
  - Low rates! Need to see coincident photon pairs, only pairs with $\Delta\nu\ \Delta t < 1$ will show effect; but more & finer spectral bins will help
  - Sensitive to *square* of image Fourier moment, washes out fine details
  - Used (thus far) mainly for gross features of bright objects

Two-photon techniques (quantum mechanical)

New: Two-Photon Amplitude Interferometry

Improved single photon interference?

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

Longer-Baseline Telescopes Using Quantum Repeaters

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Sarah Croke[‡]
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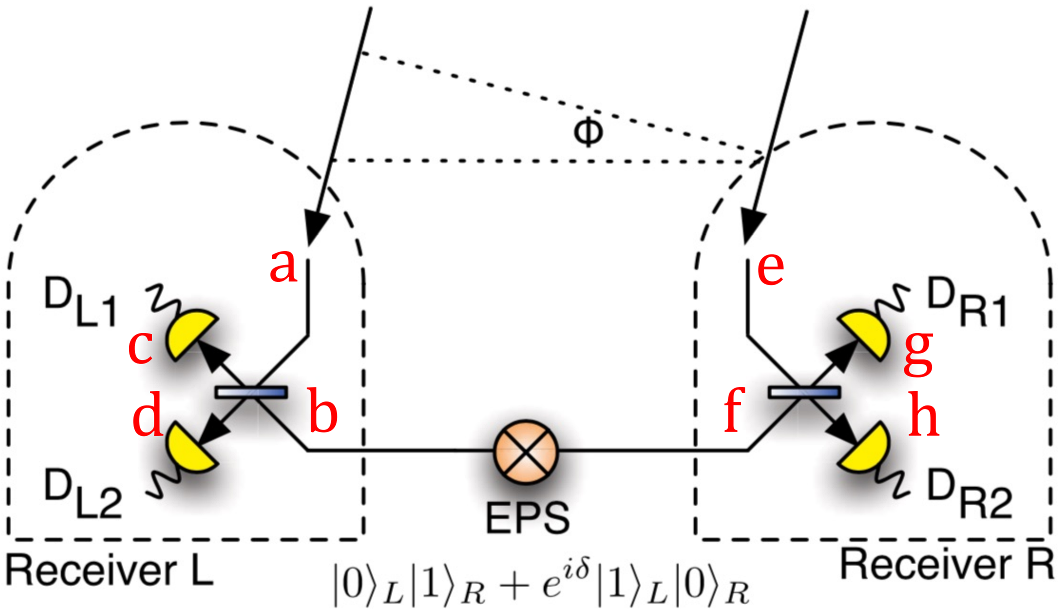
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)



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

Beam Splitters

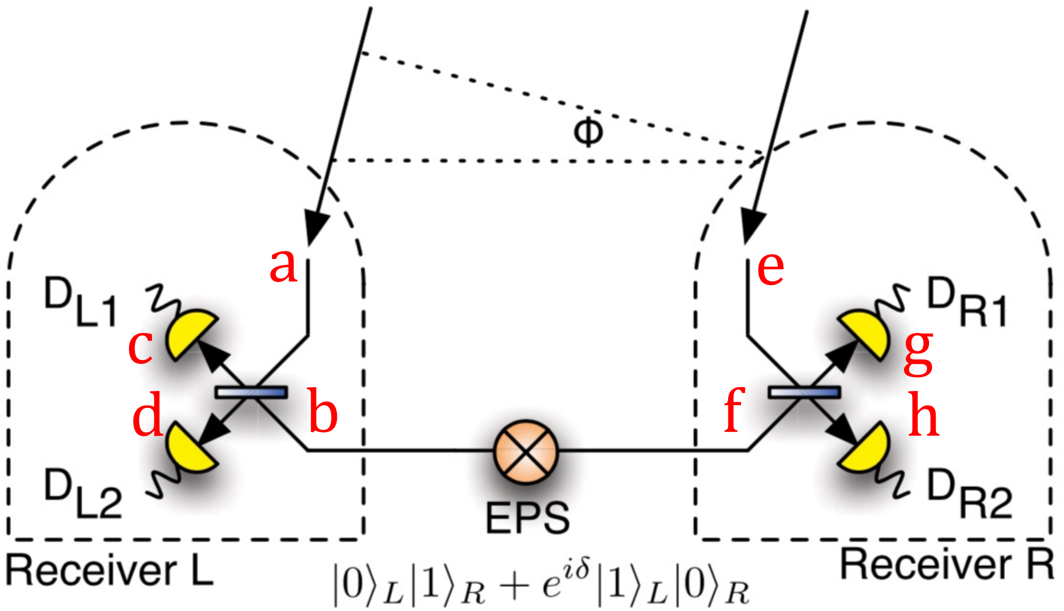
$$\hat{a}^\dagger \to (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} \qquad \hat{b}^\dagger \to (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2}$$
$$\hat{e}^\dagger \to (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} \qquad \hat{f}^\dagger \to (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2}$$

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

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

Two-photon amplitude interferometry

$$\frac{N(cg)+N(dh)-\big(N(ch)+N(dg)\big)}{N(cg)+N(dh)+N(ch)+N(dg)}$$



New visibility observable:

$$\frac{N(cg)+N(dh)-\big(N(ch)+N(dg)\big)}{N(cg)+N(dh)+N(ch)+N(dg)}$$

$$= \cos(\delta_1 - \delta_2)$$

$$= \cos\left(\frac{2\pi \sin\theta\, b}{\lambda} - \delta_{Ground}\right)$$

- Same measurement as single-photon interferometry, if ground photons are available
- Can be interpreted as *quantum teleportation* of sky photon from one station to the other

Let slip the quantum technology!

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

Optical Interferometry with Quantum Networks

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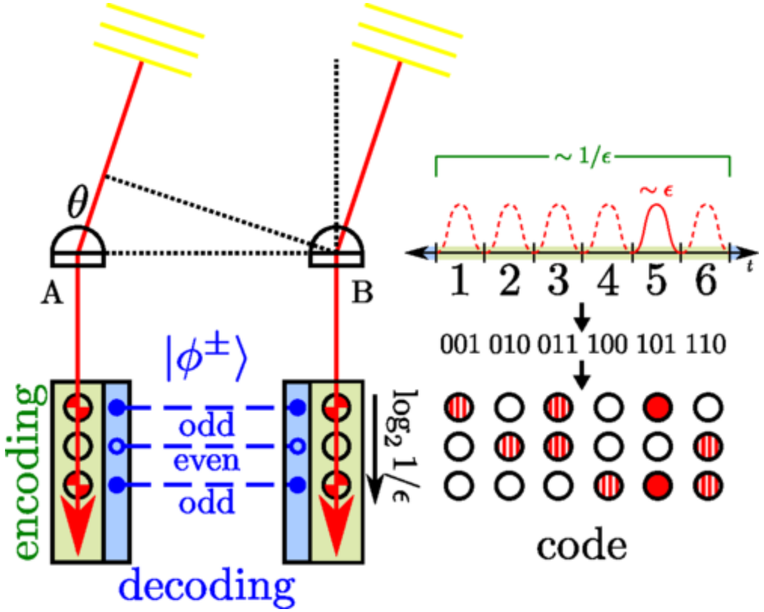
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen Ø, Denmark*

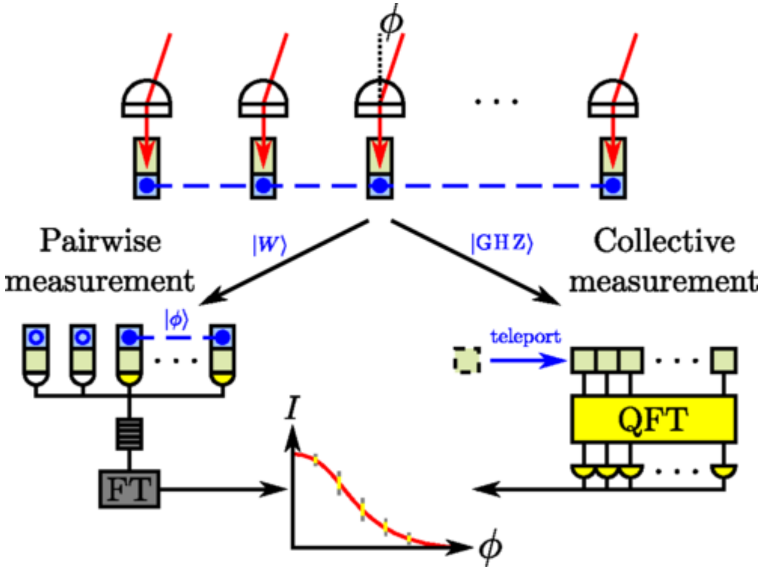
(Received 17 September 2018; published 15 August 2019)

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



Idea: Efficient time-bin encoding of photon arrivals

Idea: Use quantum Fourier transform (QFT) to directly invert pattern from array

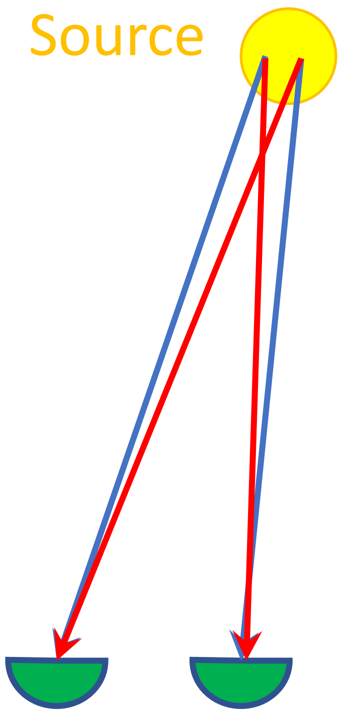


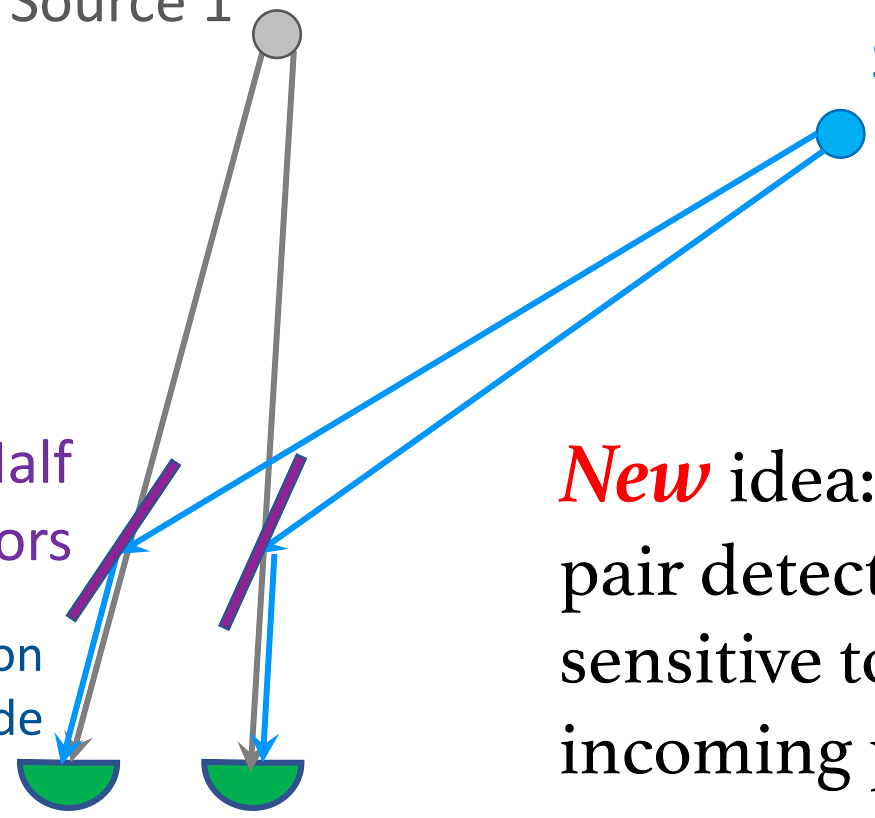
Two-photon spin-off technique

New: Two-Photon Amplitude Interferometry for *Astrometry**

* Astrometry = measurement of *positions* of objects on the sky

HBT with two sources?

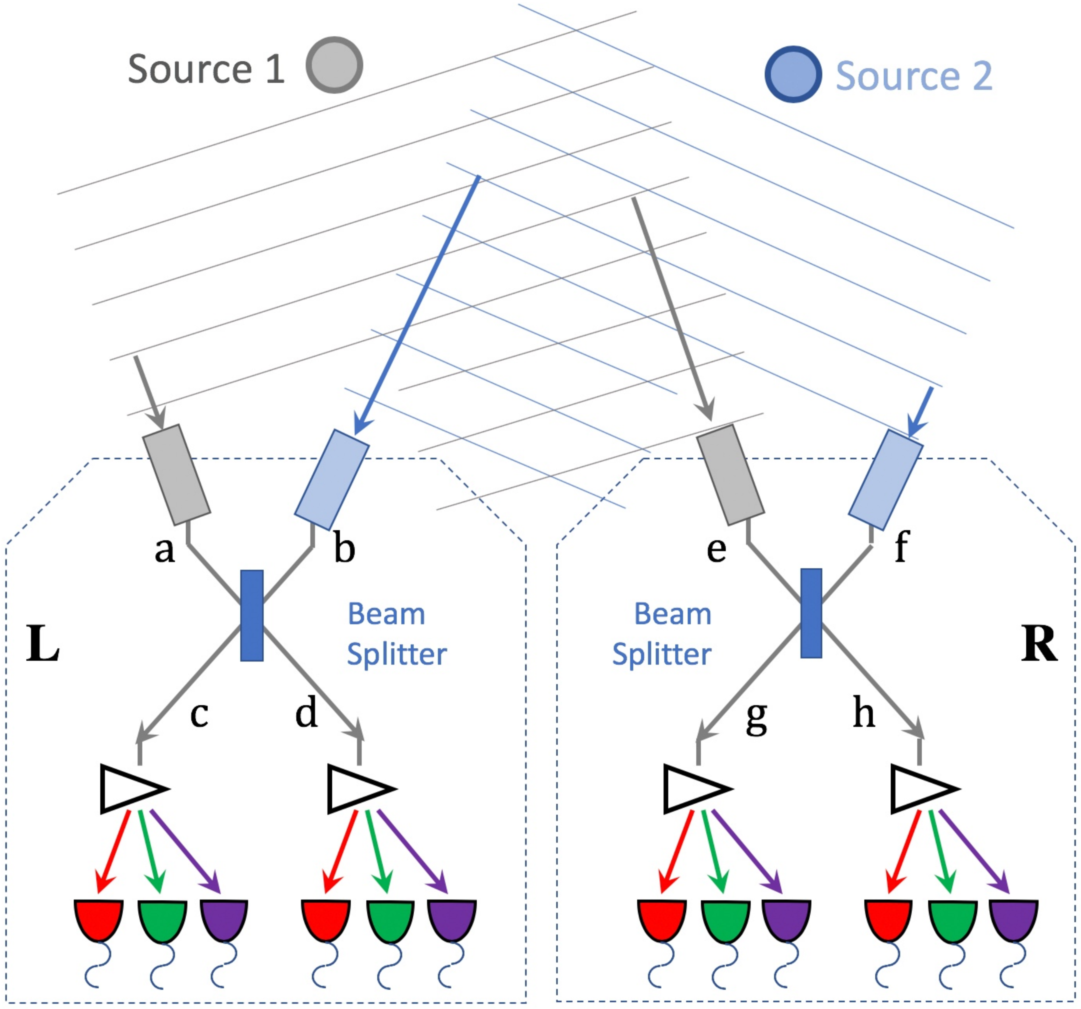




New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Original motivation: gravitational waves

Idea: two photons from two sky sources



arXiv.org > astro-ph > arXiv:2010.09100

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 18 Oct 2020 (v1), last revised 4 Nov 2020 (this version, v2)]

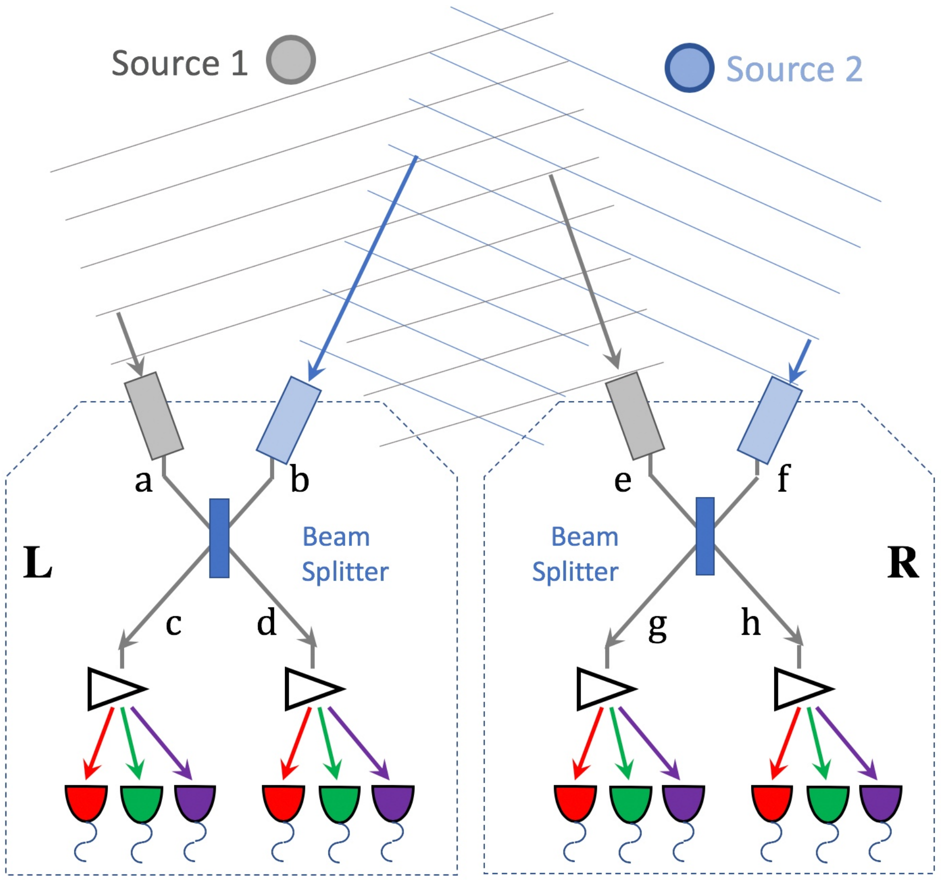
Two-photon amplitude interferometry for precision astrometry

Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich

Topology is equivalent to GJC(2012) but now with both photons from the sky, and from different objects

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

Does *not* require live optical link between stations; can use arbitrary baseline



Observable is the number/rate of coincidences *xy* = {*cg,dh*} or {*ch,dg*} at different stations.

(Can do many spectral bins in parallel.)

Quantum mechanics (Fock state) version; quickie:

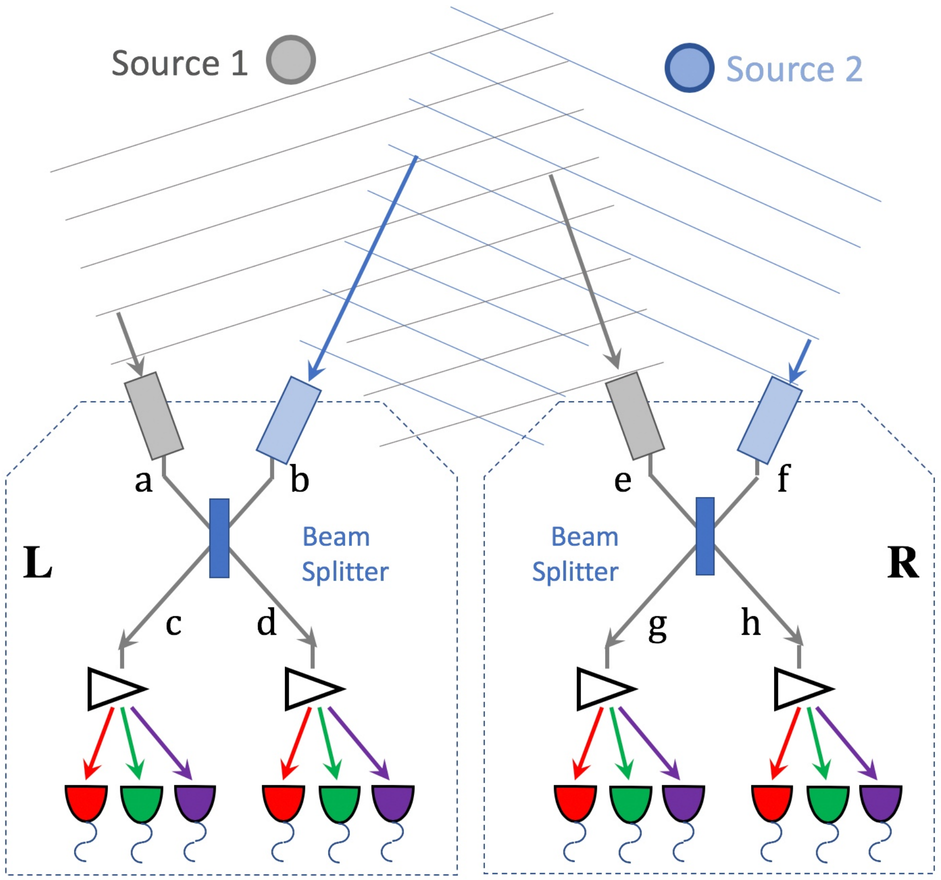
$$\langle N(xy)\rangle = \frac{k(S_1+S_2)^2}{8}\left[1 \pm V_{2\mathrm{PS}}\cos\left[\frac{2\pi B}{\lambda}(\sin\theta_1 - \sin\theta_2) + \frac{2\pi\Delta L}{\lambda}\right]\right]$$

Quantum field theory version; full:

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

$$A^2\eta_1\eta_2 T_r\left[(I_1+I_2)^2 + I_1^2\frac{\tau_c g_{11}}{T_r} + I_2^2\frac{\tau_c g_{22}}{T_r} \pm\right.$$

$$\left. 2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B(\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0\Delta L}{c}\right)\right]$$



Observable is the number/rate of coincidences *xy* = {*cg,dh*} or {*ch,dg*} at different stations.

(Can do many spectral bins in parallel.)

Quantum mechanics (Fock state) version; quickie:

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

Quantum field theory version; full:

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

$$A^2\eta_1\eta_2 T_r\left[(I_1+I_2)^2 + I_1^2\frac{\tau_c g_{11}}{T_r} + I_2^2\frac{\tau_c g_{22}}{T_r} \pm 2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B(\sin\theta_1-\sin\theta_2)}{c} + \frac{\omega_0\Delta L}{c}\right)\right]$$

Base combinatoric pair rate

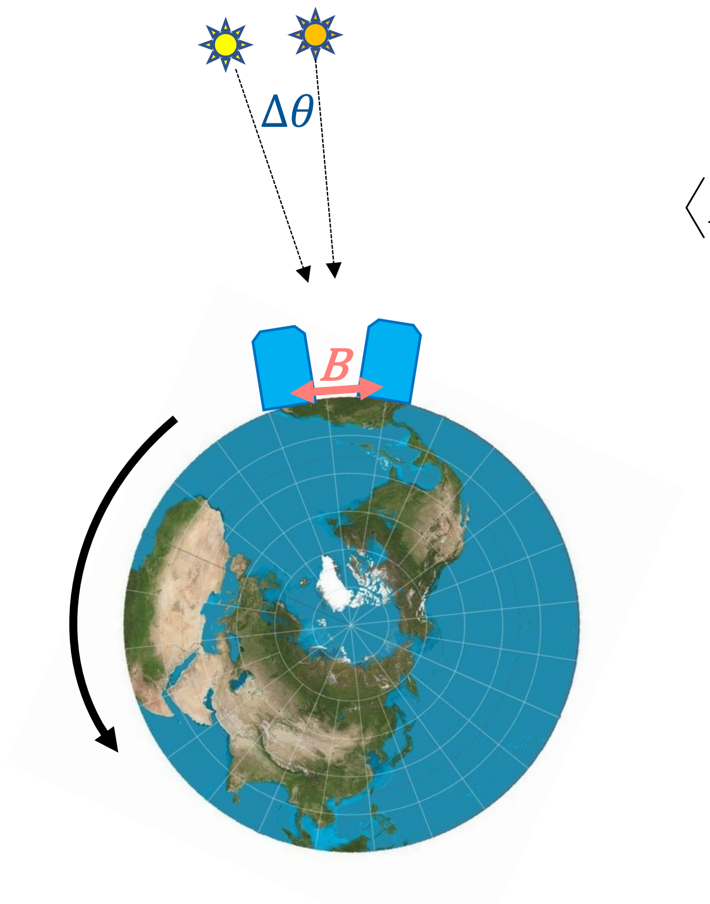
HBT enhancement

Oscillatory term, fringe passing

Idea: 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

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

Idea: Dynamic Astrometry

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

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

Astrophysics topics in dynamic astrometry

- Parallax: improved distance ladder
- Proper motions: local dark matter patterns
- Microlensing, see motions and shape changes
- Gravitational waves at mid-frequency
- Quantum applications, e.g. quantum key distribution

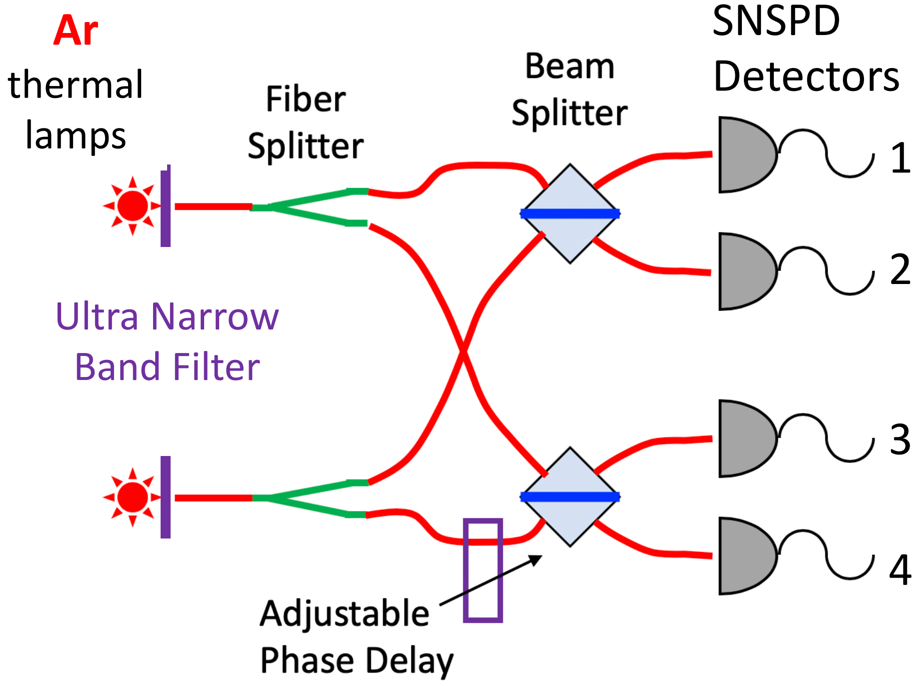
Further ideas are encouraged!

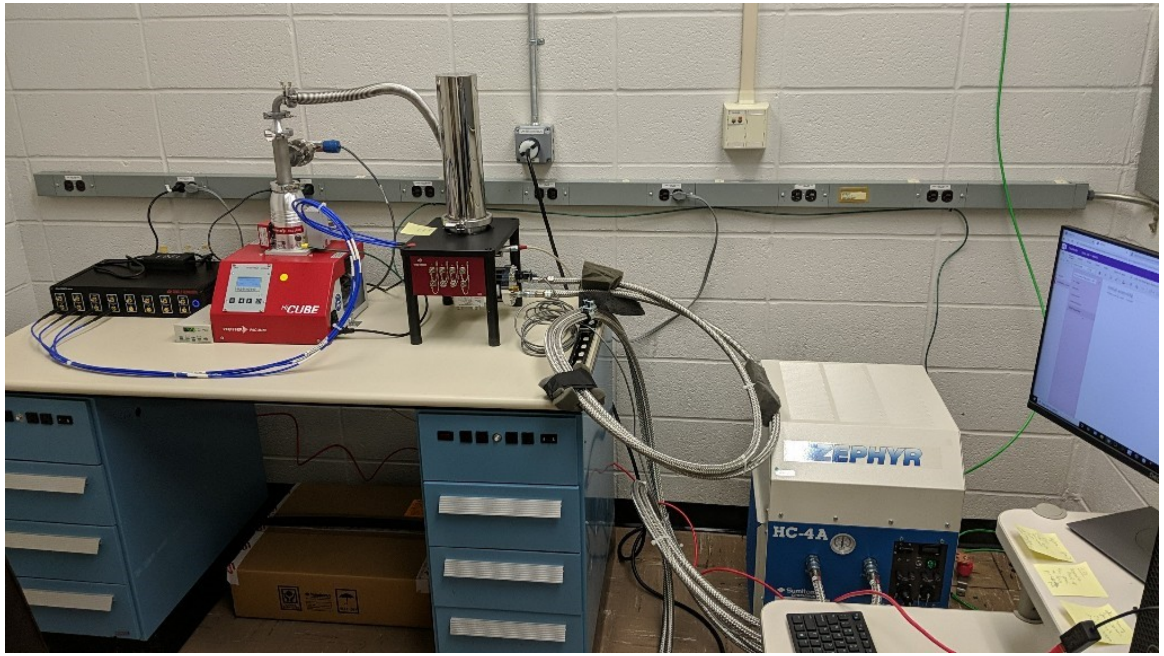
Experiments and Detectors

What are we going to need?

Experiments in progress

Supported at BNL by DOE HEP
QuantISED grant 2020-21

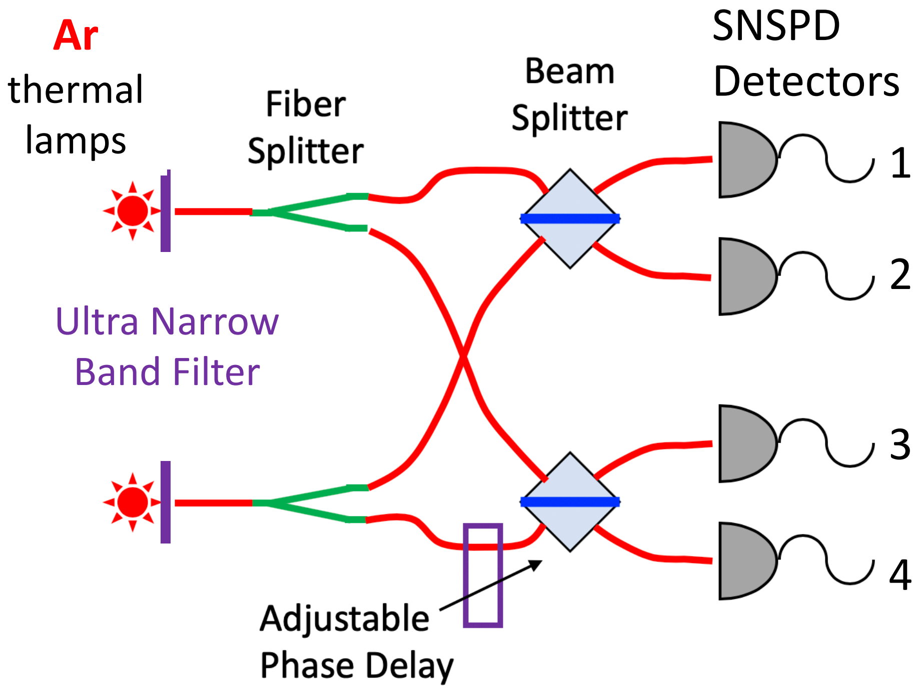


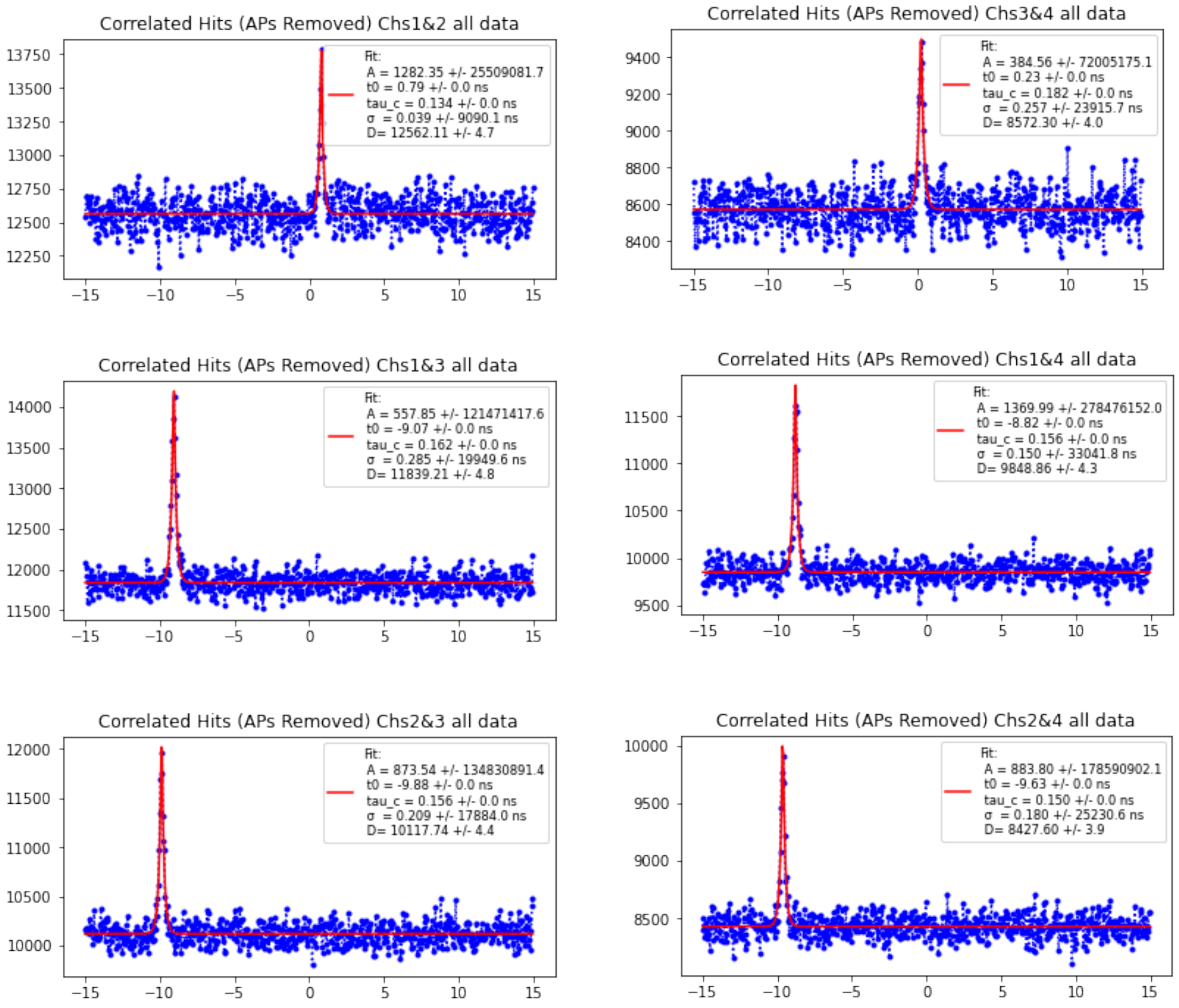


Superconducting Nanowire
Single Photon Detector
(SNSPD) at BNL
Four channels at ~795nm

Experiments in progress

Supported at BNL by DOE HEP
QuantISED grant 2020-21



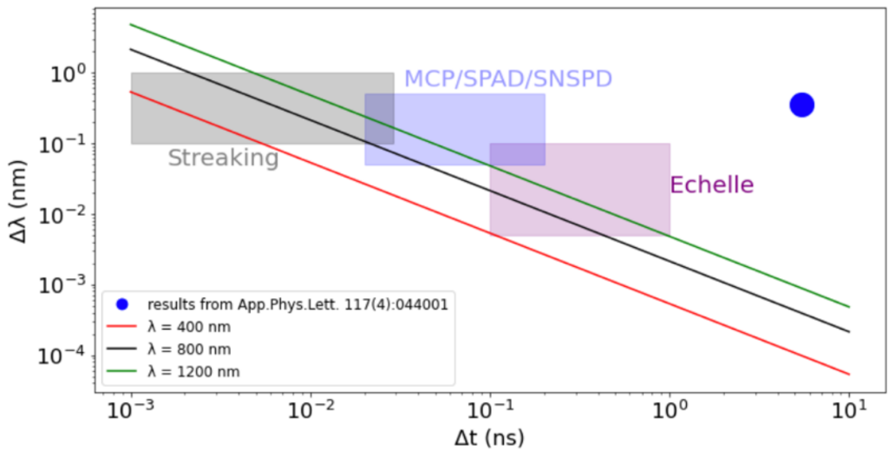


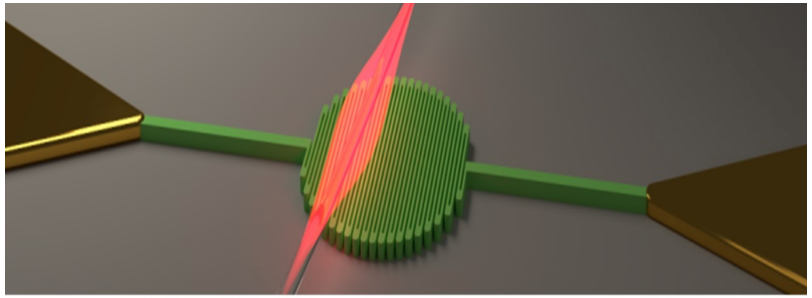
Check: We can see HBT coincidence enhancement peak in all channel combinations

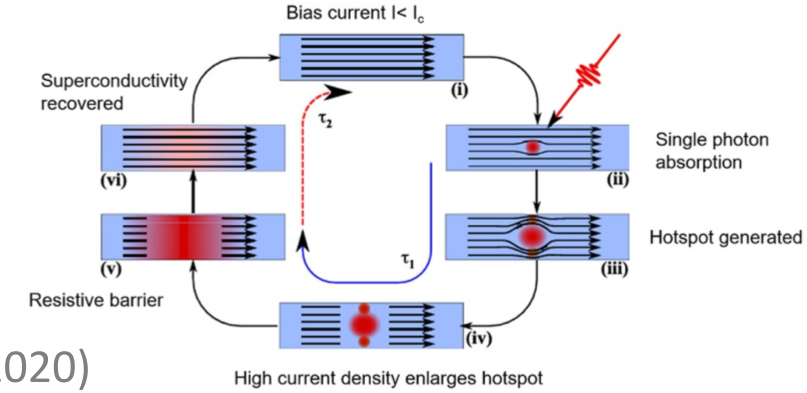
Future detector requirement

- Two essential figures of merit:
  - Number of detectors/spectroscopic channels (more pairs)
  - Detector time resolution (wider spectroscopic bins, more pairs per detector)

- Fast pixel array (Timepix) + dispersive spectrograph (Echele?)
- Very fast single photon detectors – improved SNSPD? Timing, QE, many channels

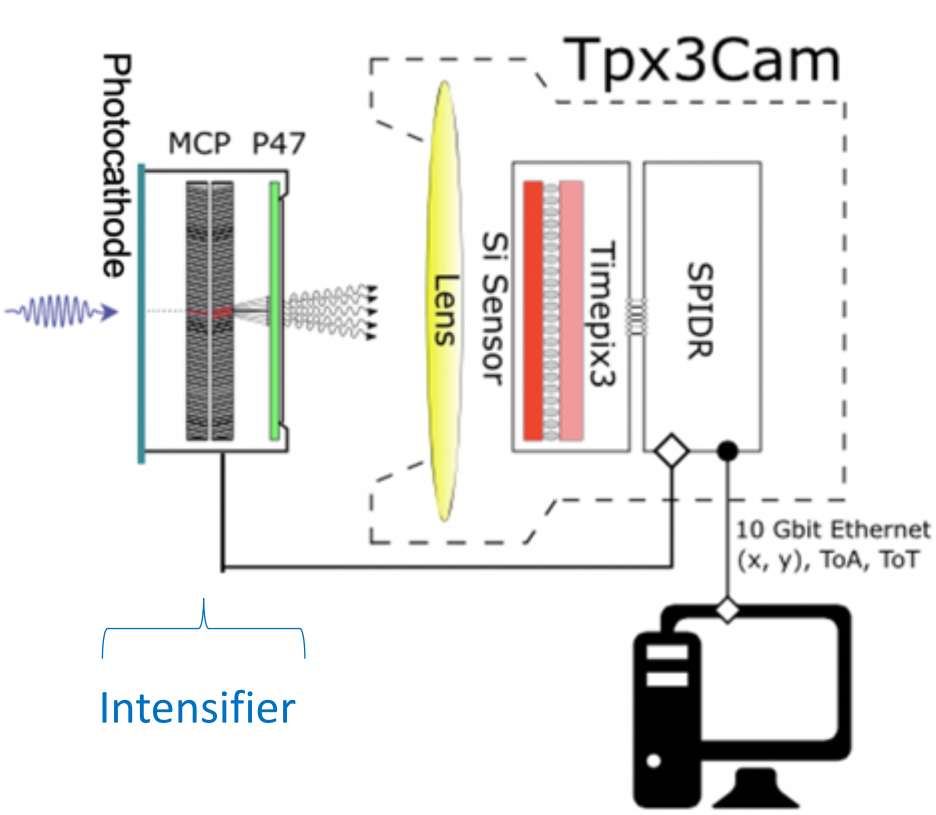






A. Nomerotski, SPIE (2020)

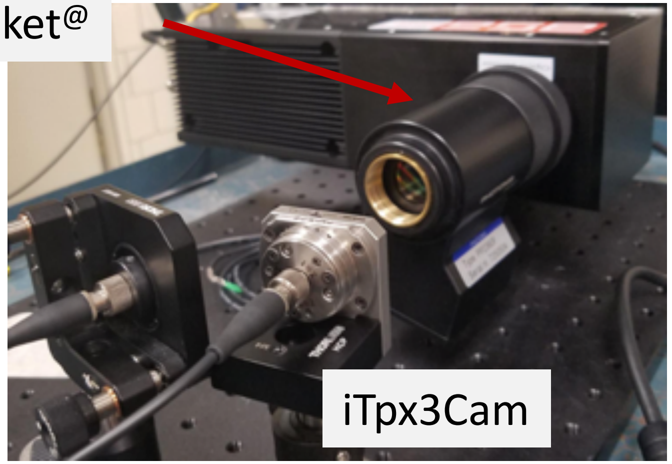
Intensified camera is single photon sensitive



Intensifier

Image intensifier (Photonis PP0360EG)

Cricket@



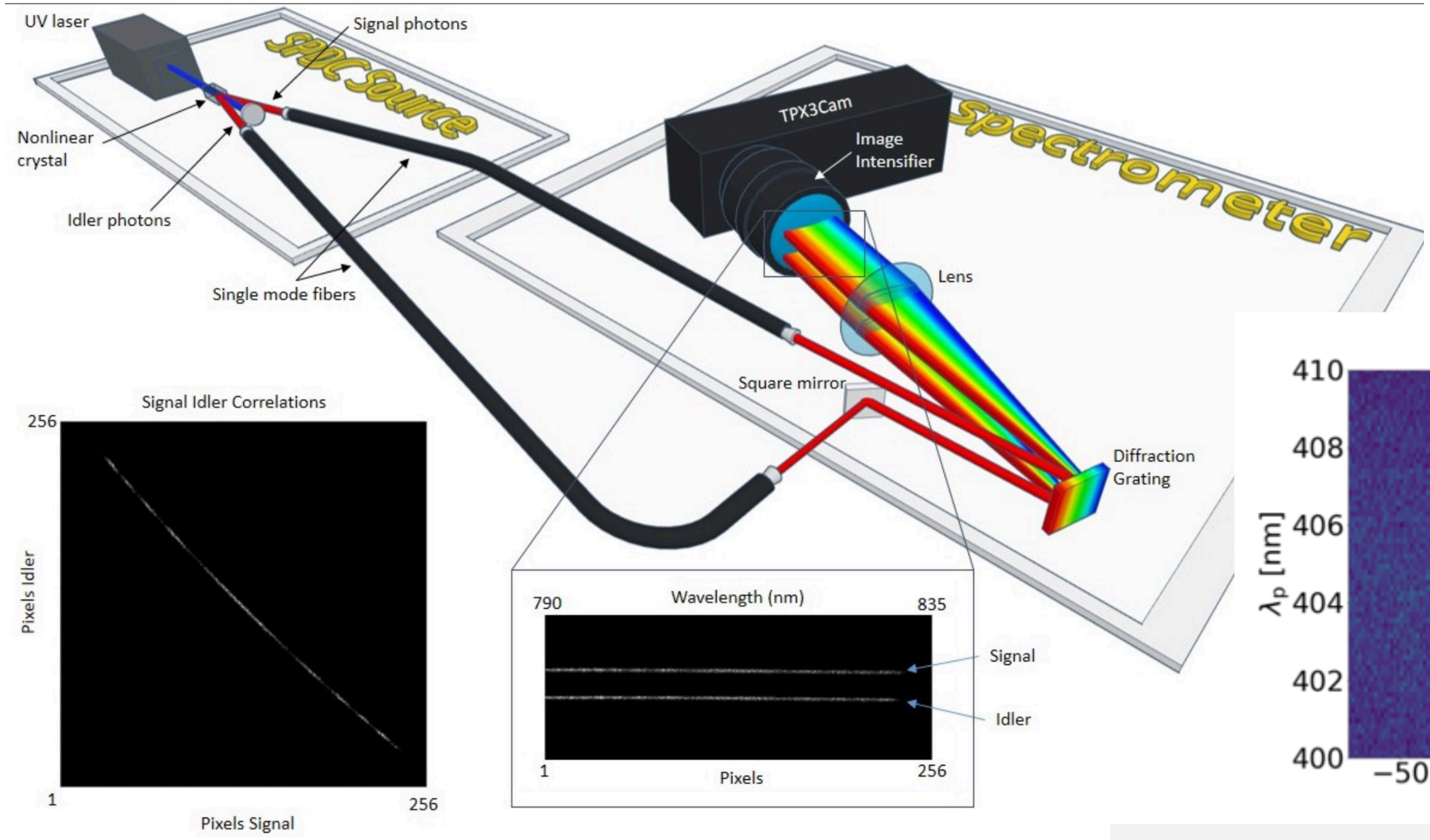
iTpx3Cam

Quantum efficiency ~ 30%

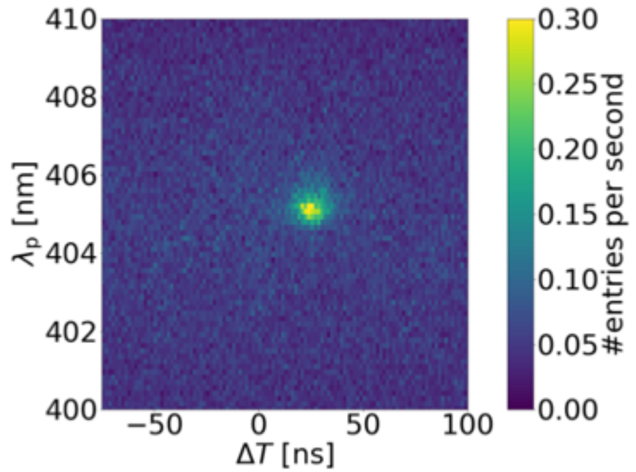
A.Nomerotski, Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, NIM **A** 937 (2019) 26

Spectroscopic binning already demonstrated

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



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



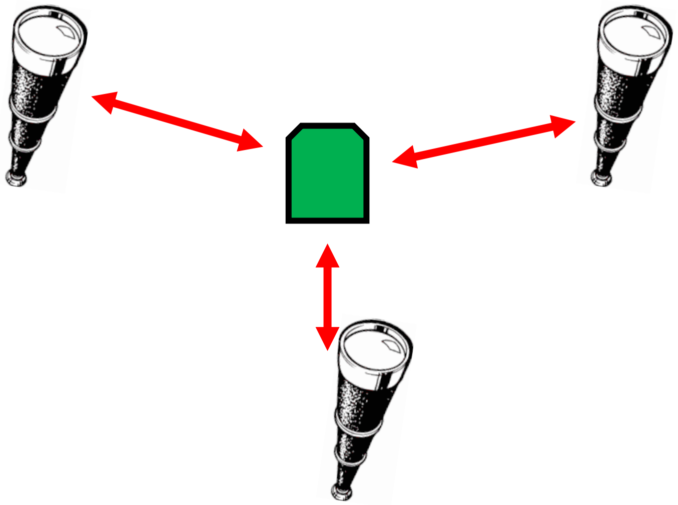
Pump photon wavelength vs time difference

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)

Just the beginning! A broad future program

- Observations with >2 receivers and >2 objects; phase closure?
- More complicated quantum states (GHZ, etc.)
- New kinds of entanglement distribution (polarization qubits, e.g.)
- Involvement of quantum memories to enhance pair rates; local expertise (SBU) with ^{87}Rb vapor room-temp QM's
- Atmospheric effect compensation
- On-sky experiments possible soon!



Points to take home

- Classical, single-photon interferometry reaches much higher resolutions, order milli-arcsec, than single telescopes; but practical issues limit maximum baselines
- Two-photon interferometry can permit independent stations over longer baselines; historical HBT is one example
- Two-photon techniques are in general quantum mechanical; new ideas suggest quantum technology can enhance interferometry
- One specific two-photon technique addresses dynamic astrometry, which will have interesting astrophysics applications
- There is a potentially broad program in quantum-assisted optical interferometry ahead

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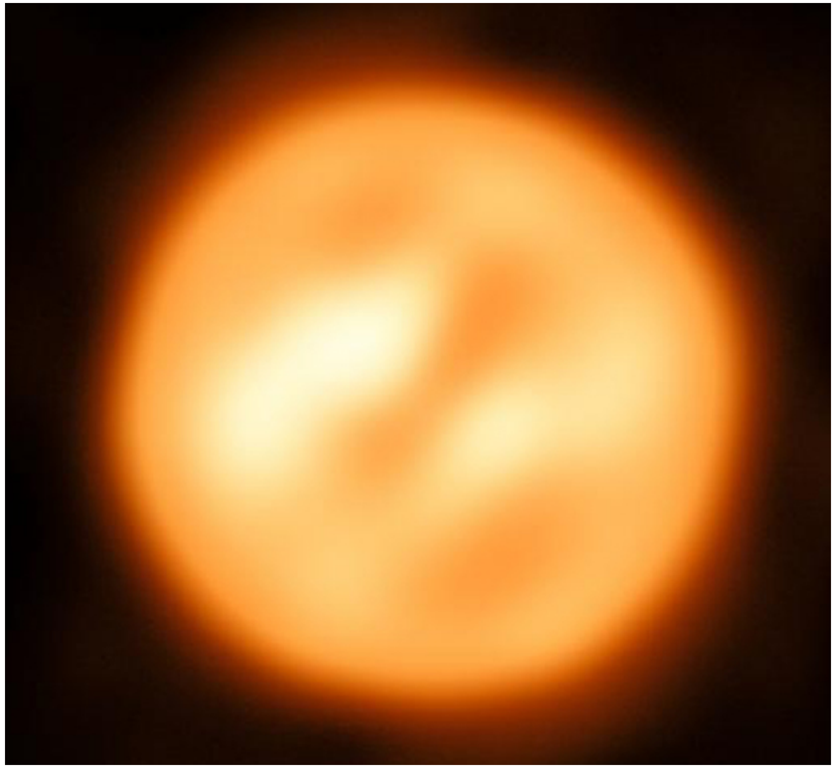
Backups



Dynamic convection on Antares
(VLTI, ESO)

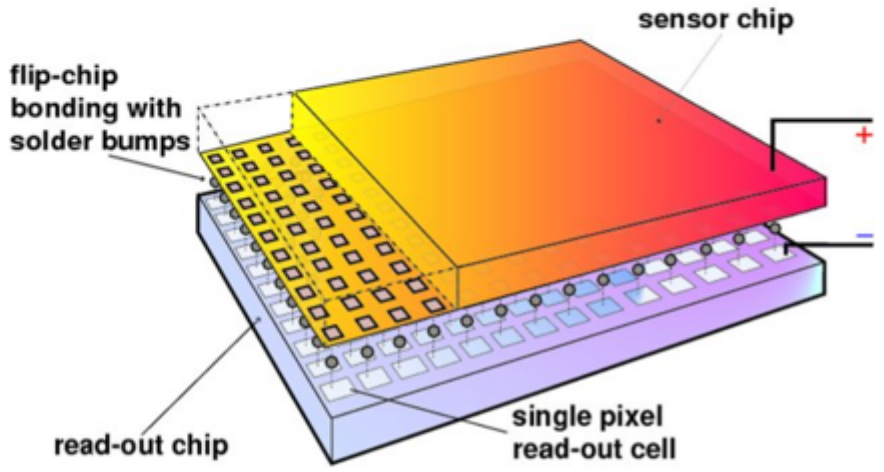
Each fringe observation measures *amplitude* and *phase* of Fourier moment along baseline vector at specific wavenumber.

Repeat for many different baselines/wavenumbers and invert to reconstruct original image.
(Note Earth rotation synthesis)

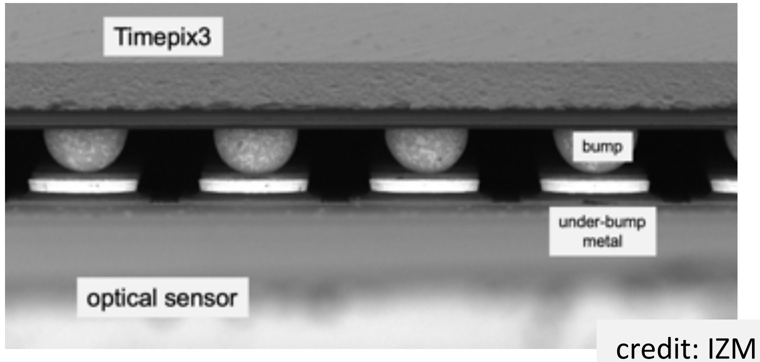
Measurement at baseline B sensitive to source features with angular size $\Delta\theta \sim \lambda/B$

Hybrid pixel detectors

Have roots in R&D for LEP/LHC vertex detectors



Lukas Tlustos and Erik H. M. Heijne, Performance and limitations of high granularity single photon processing X-ray imaging detectors, in CERN proceedings (2005)



credit: IZM

- Decouple readout chip and sensor
- Optimize technologies for chip and sensor separately

Use different sensors with same readout, versatile approach for x-rays (Si, CZT)

→ we will use OPTICAL sensors

Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

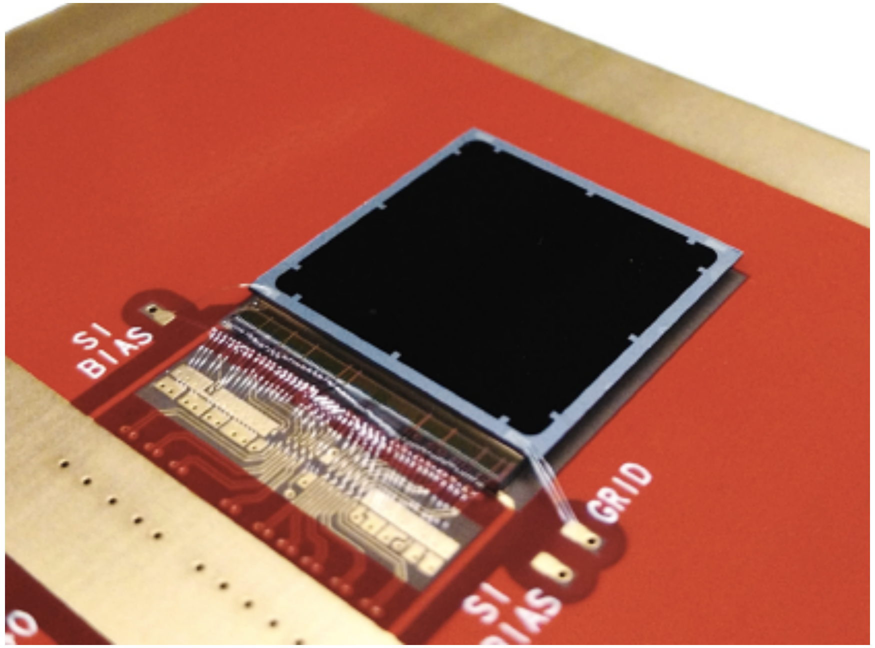
Optical sensor with high QE developed at BNL

- Sensor is bump-bonded to chip Timepix3

Timepix3 ASIC:

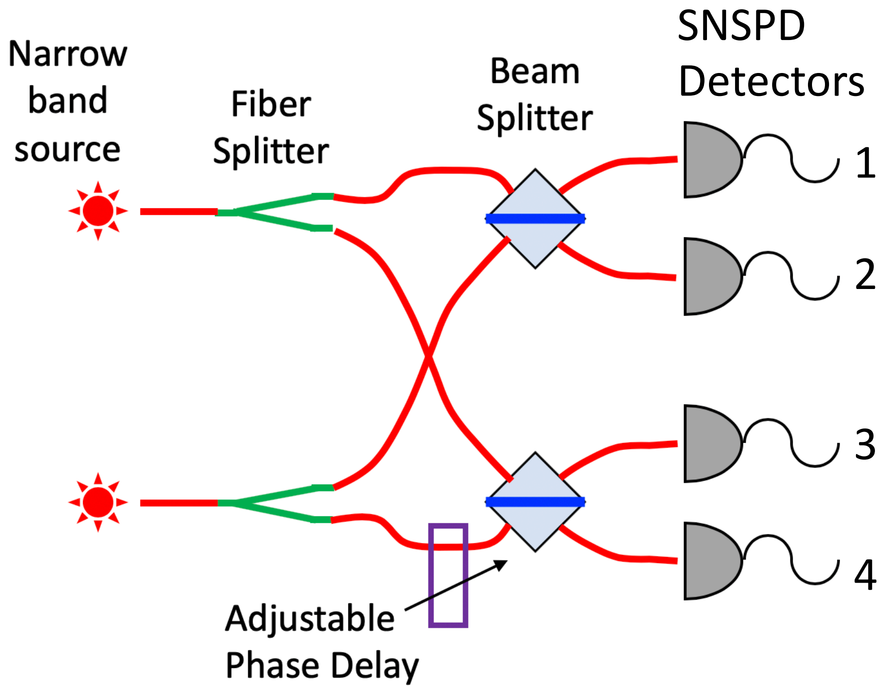
256 x 256 array, 55 x 55 micron pixel

- 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.

Pre-preliminary



(Pre-)Preliminary observation of **anti-correlation** between 1&3+2&4 pairs against 1&4+2&3 pairs, with random length/phase changes