Astronomy with Quantum Assist: Precision Astrometry and More

Some forward-looking ideas and works in progress

https://www.quantastro.bnl.gov

Brookhaven National Laboratory

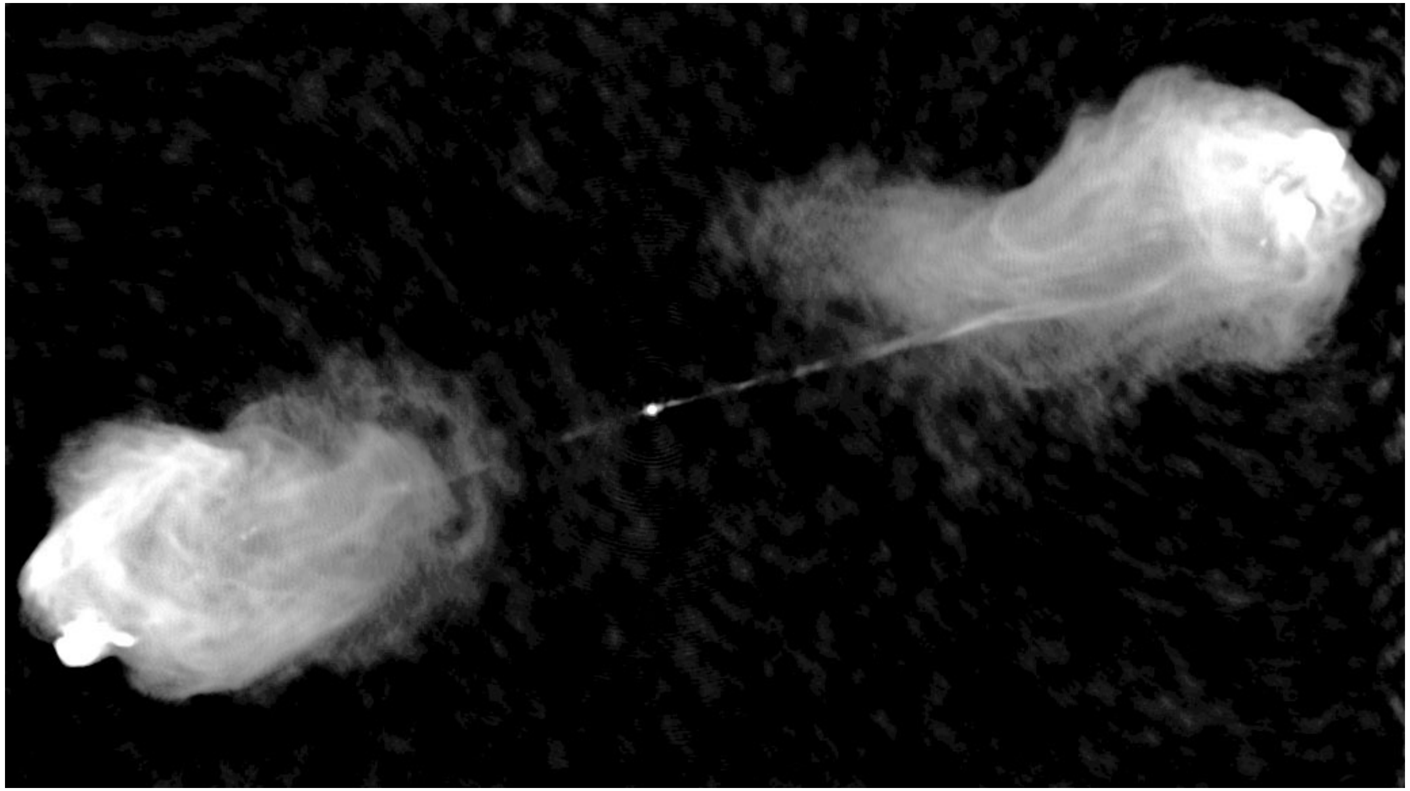
$\langle BNL|\hat{a}^{\dagger}|QIST\rangle$

Paul Stankus, BNL

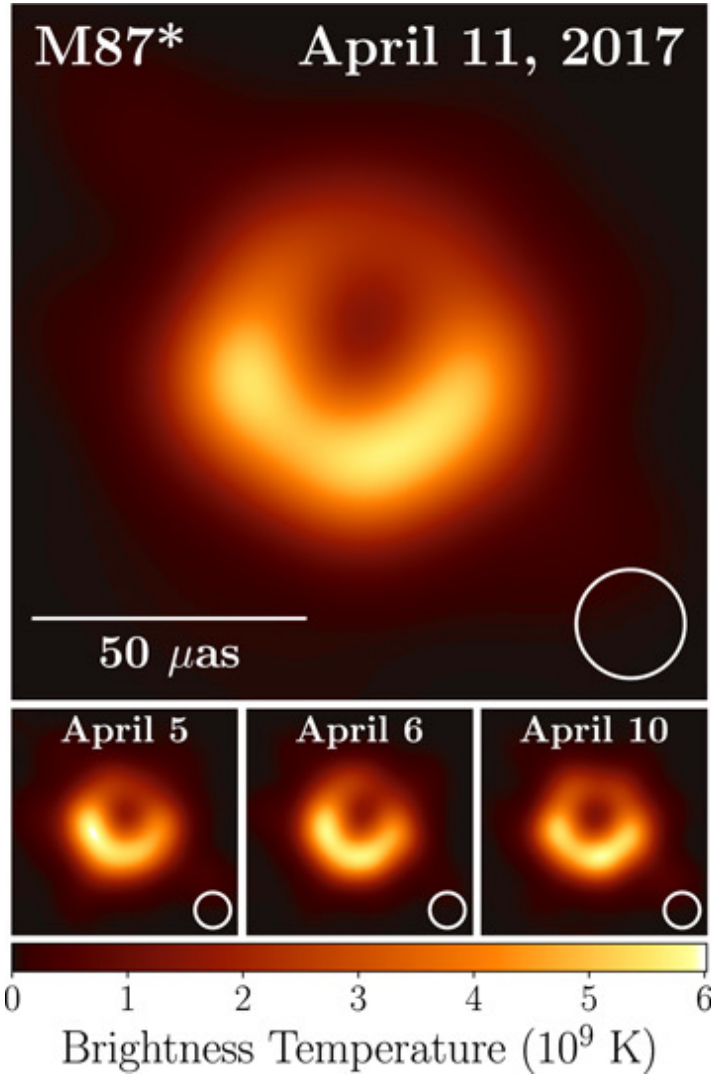
Southern CT State Seminar

27 Oct 2021

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



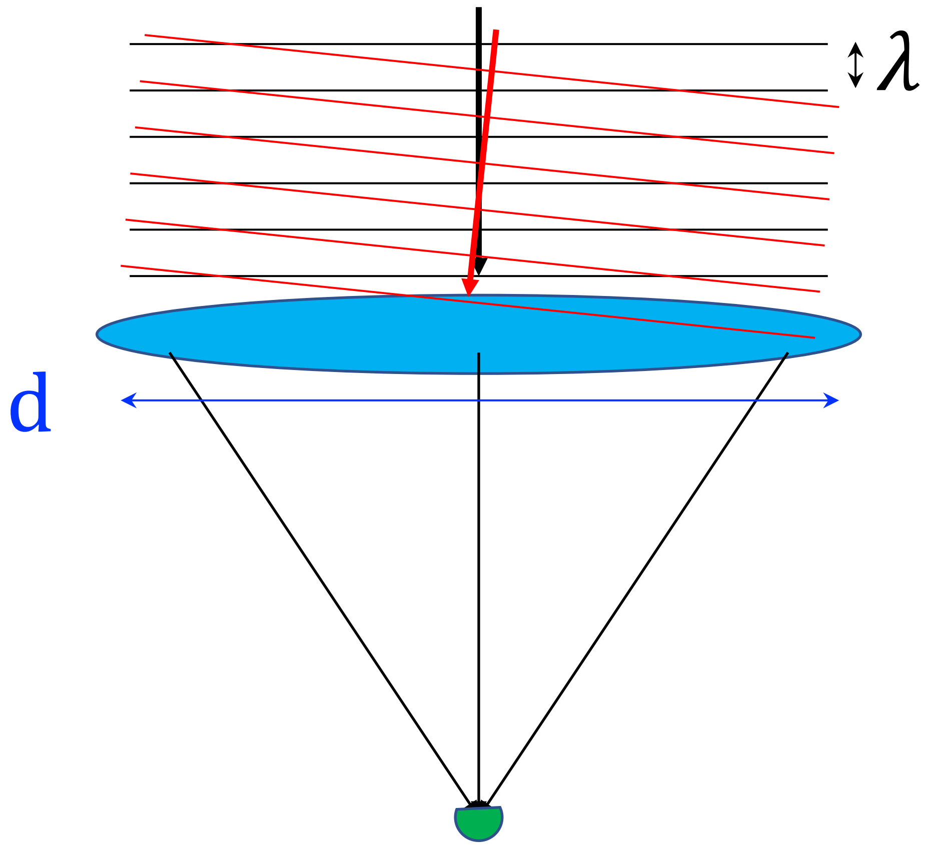
Radio source Cygnus A imaged at 6cm



Center of M87 imaged at 1.3mm

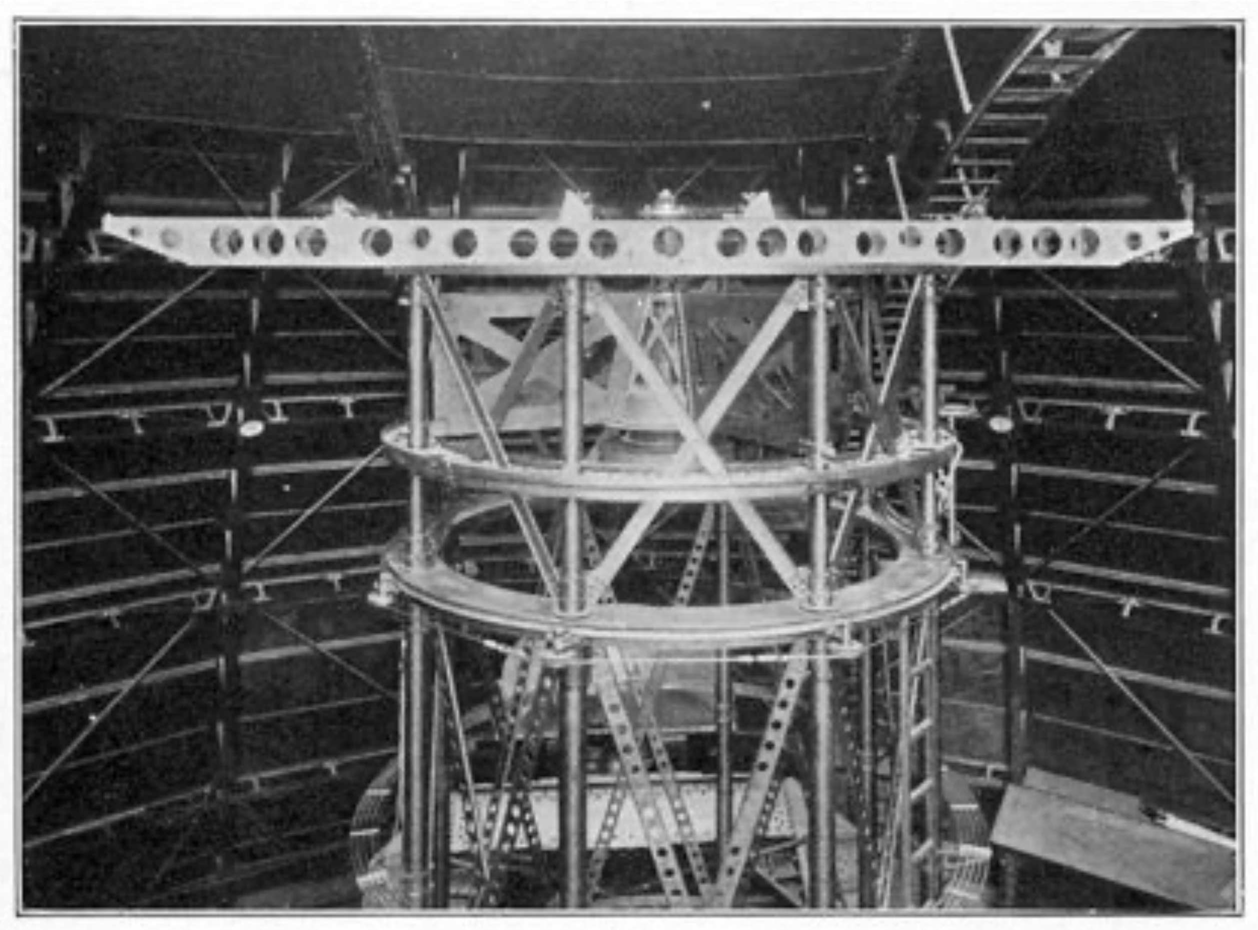
2019 ApJL 875

Single Aperture: Diffraction Limit

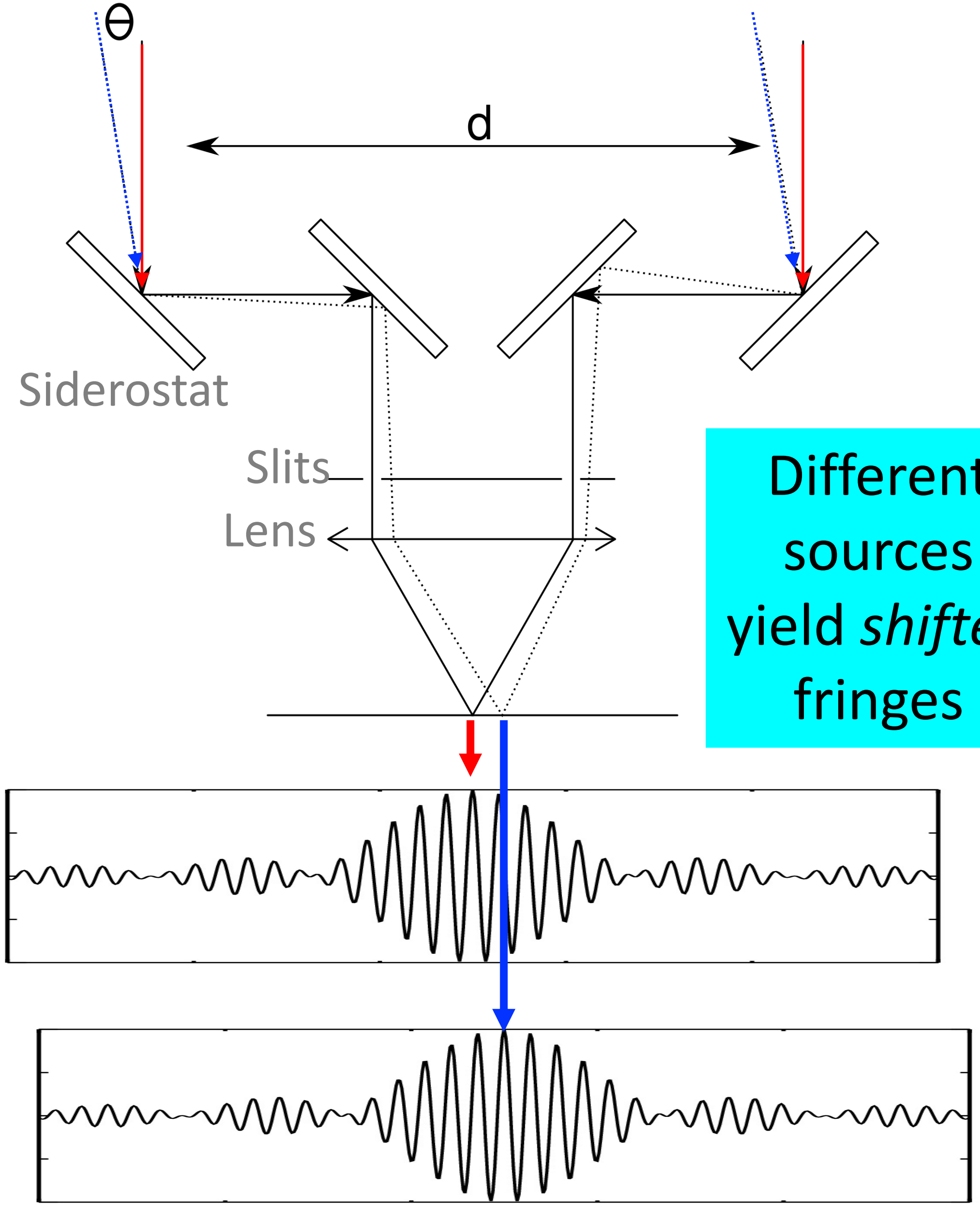


A single detector/pixel point will collect intensity from a range of angles. The limit of this angular range is $\Delta\theta \sim \lambda / d$ after which the wavefront will interfere with itself destructively across the aperture. Therefore any single-aperture telescope cannot resolve features with angular size smaller than λ / d

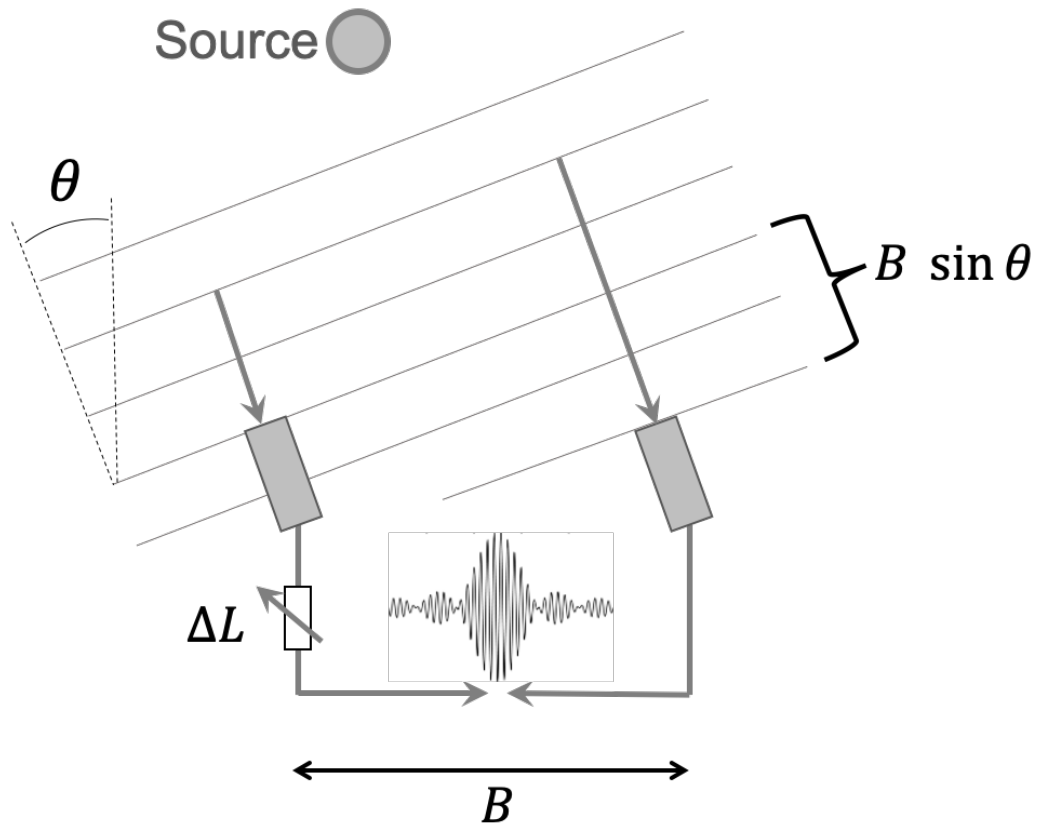
In classical times

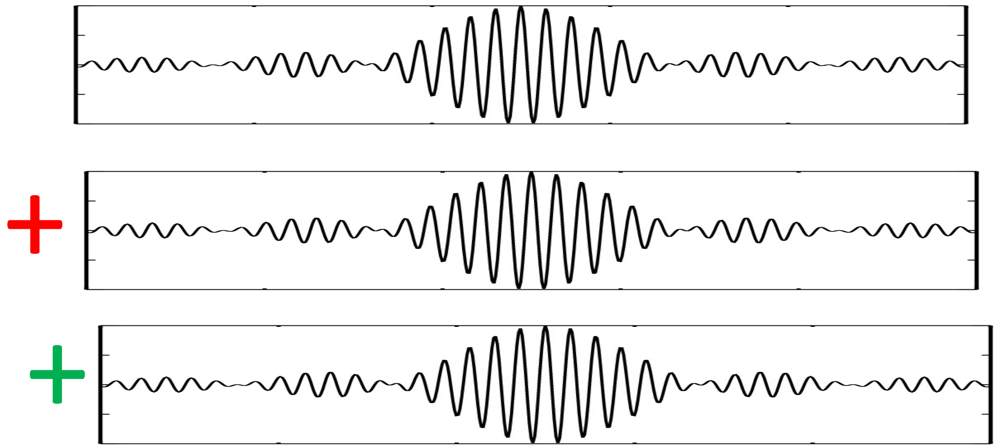


Michelson Stellar Interferometer at Mt. Wilson c. 1920, after original idea by Michelson & Fizeau c. 1890



Different sources yield *shifted* fringes

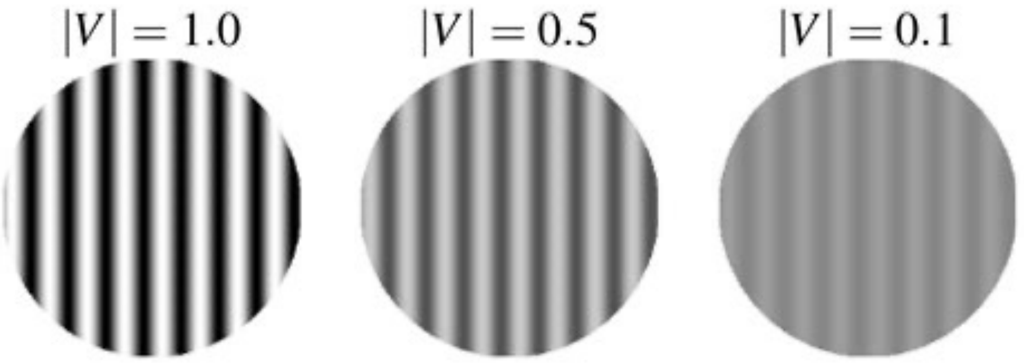




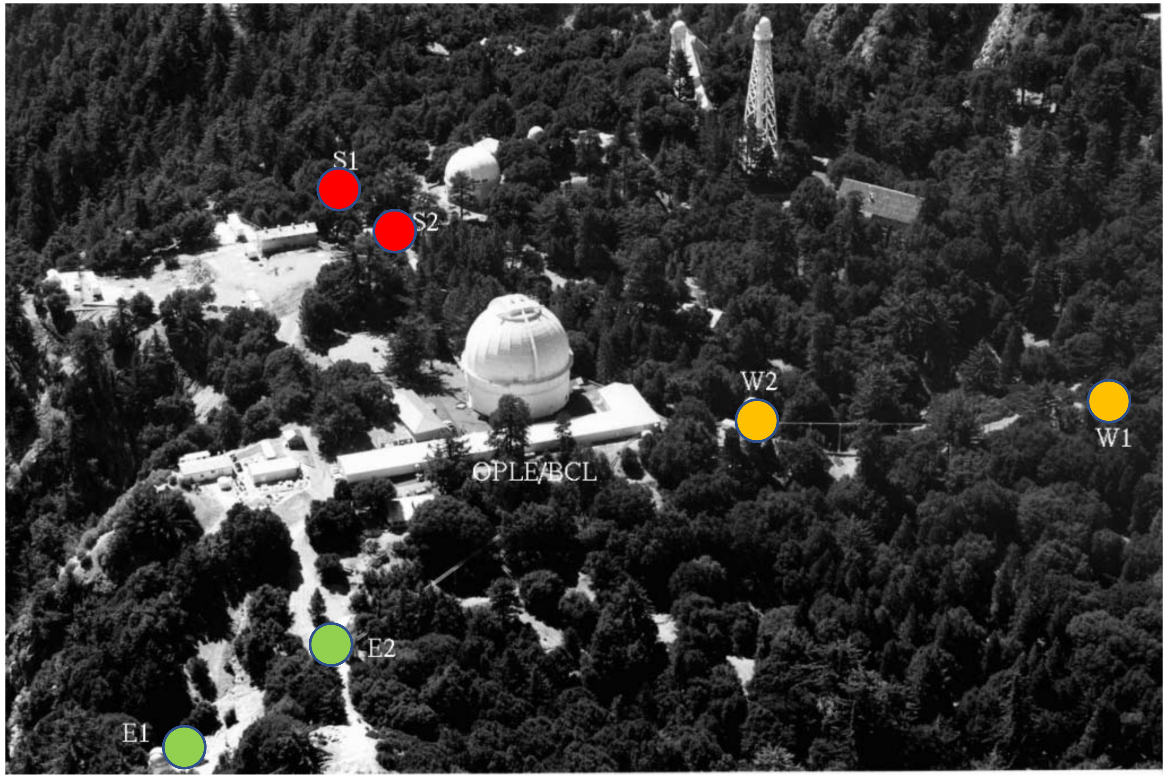
Each source i at sky position θ_i produces a fringe shifted by phase amount $\Delta\phi = 2\pi B \sin\theta_i/\lambda$

Intensity pattern is sum over all sources ☞ Fourier moment!

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



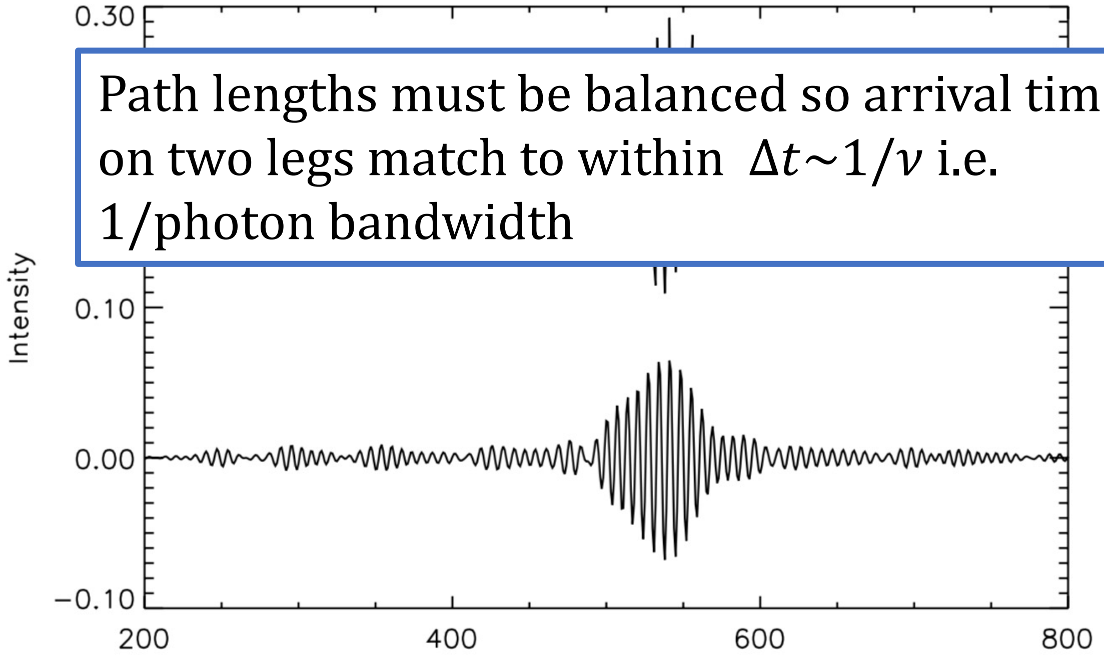
Back on Mt. Wilson



CHARA (Center for High Angular Resolution Astronomy) Observatory

The Astrophysical Journal, 628:453–465

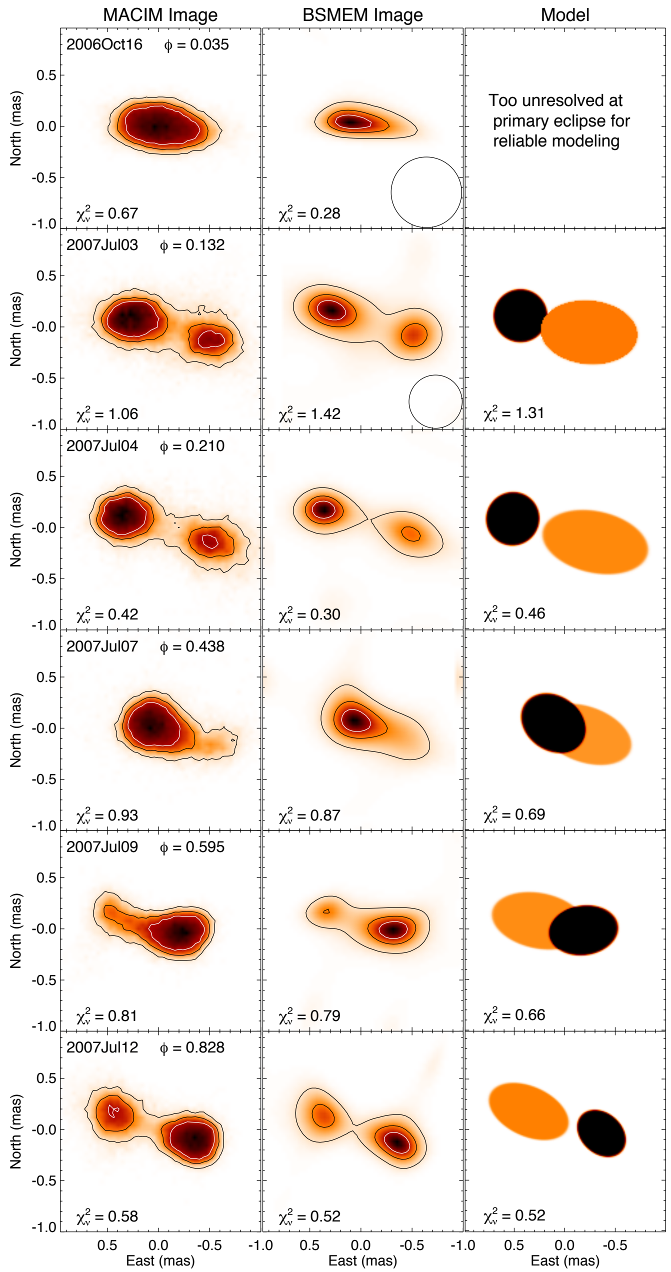
Beam line path length control at CHARA



Path lengths must be balanced so arrival times on two legs match to within $\Delta t \sim 1/\nu$ i.e. 1/photon bandwidth

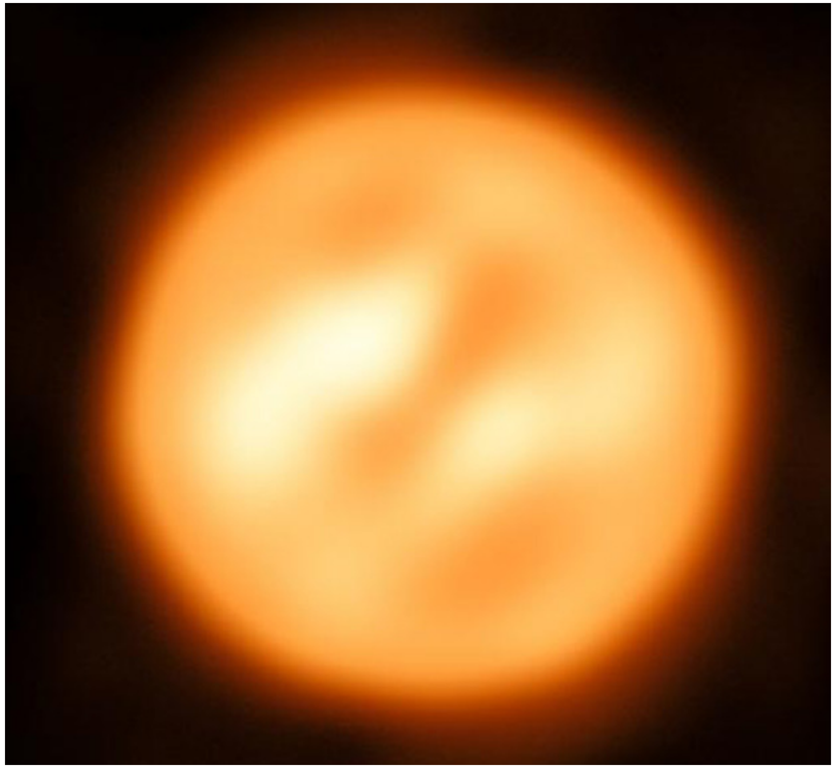
δ Path Length

How cool is this?

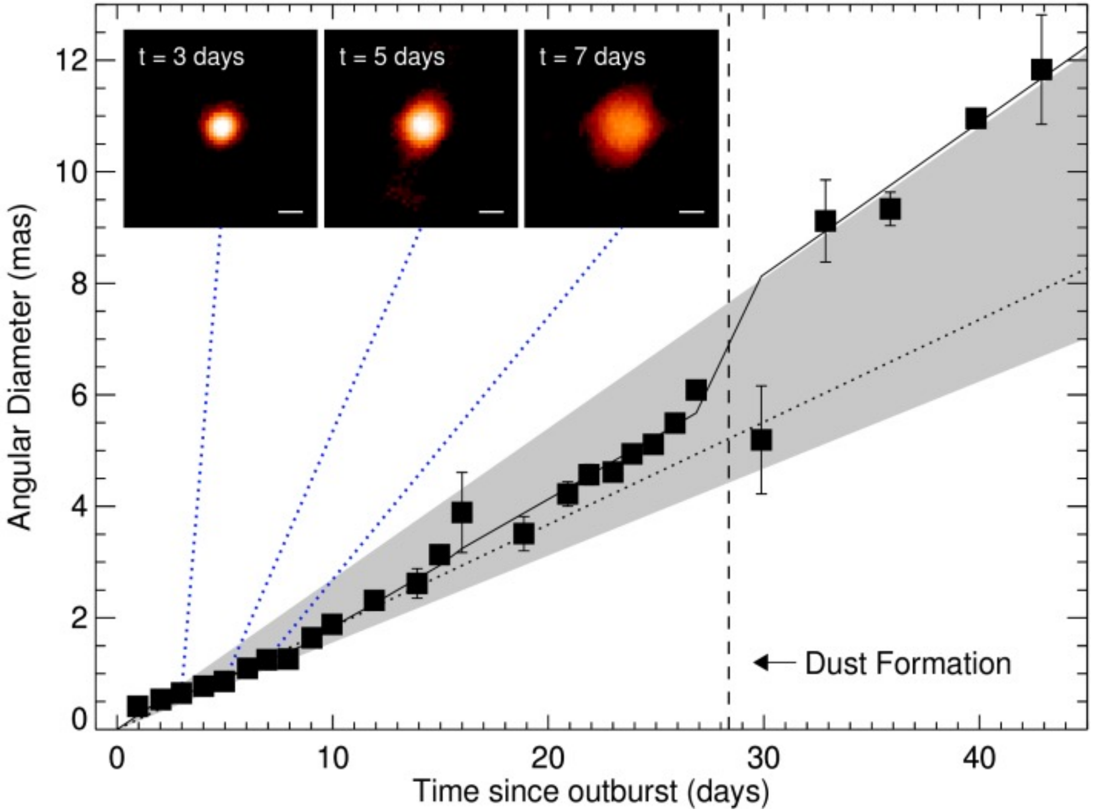


CHARA Collaboration, “First Resolved Images of the Eclipsing and Interacting Binary β Lyrae”; arXiv:0808.0932, The Astrophysical Journal, 684: L95–L98, 2008 September 10

Optical interferometry examples



Dynamic convection on Antares
(VLTI, ESO)

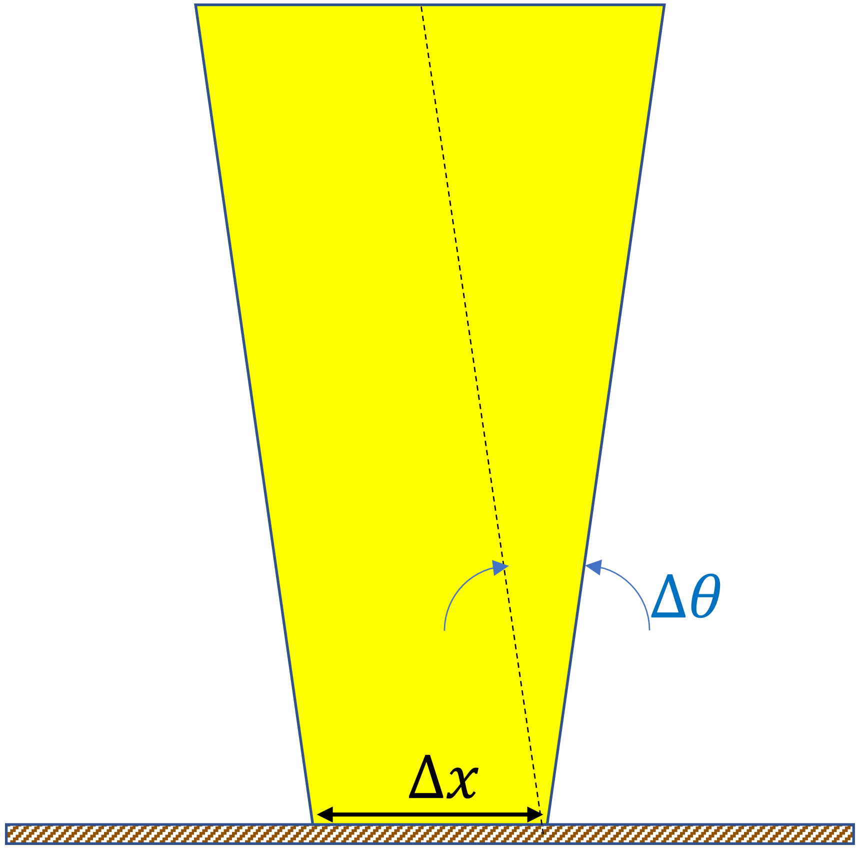


Nova in progress (CHARA)

So far, so classical

- 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

One spatial mode, with extent Δx along the ground and able to cover an angular range of $\Delta\theta$ on the sky



Photons ala mode

To move from classical to quantum optics we describe the EM field in terms of **modes**; then photons are **excitations** in one or more modes.

Two photons in different modes are independent
Two photons in the same mode can/will interfere with each other quantum mechanically.

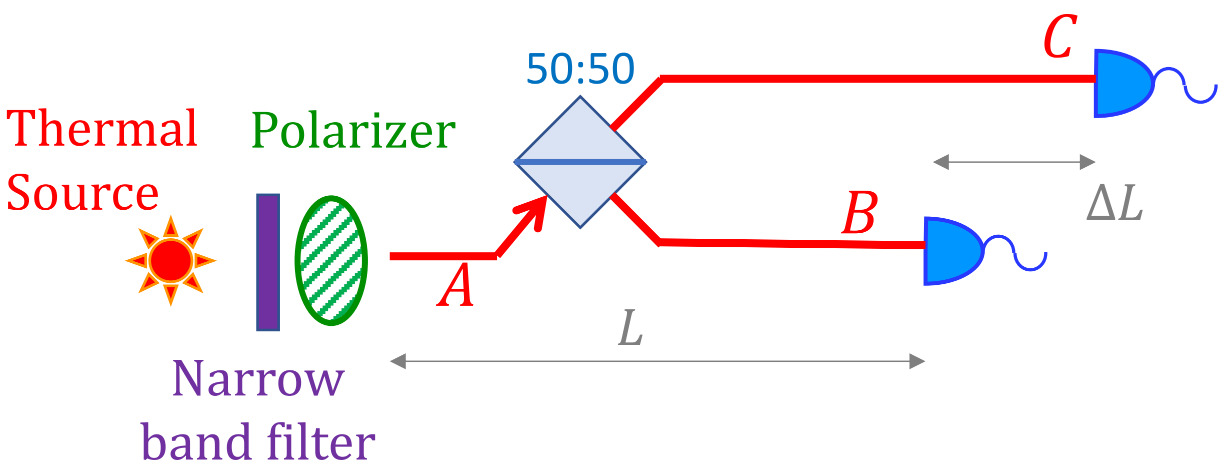
A *mode* is a region of 6-D phase space, 3-mom x 3-spatial, with total volume of $\hbar^3$.

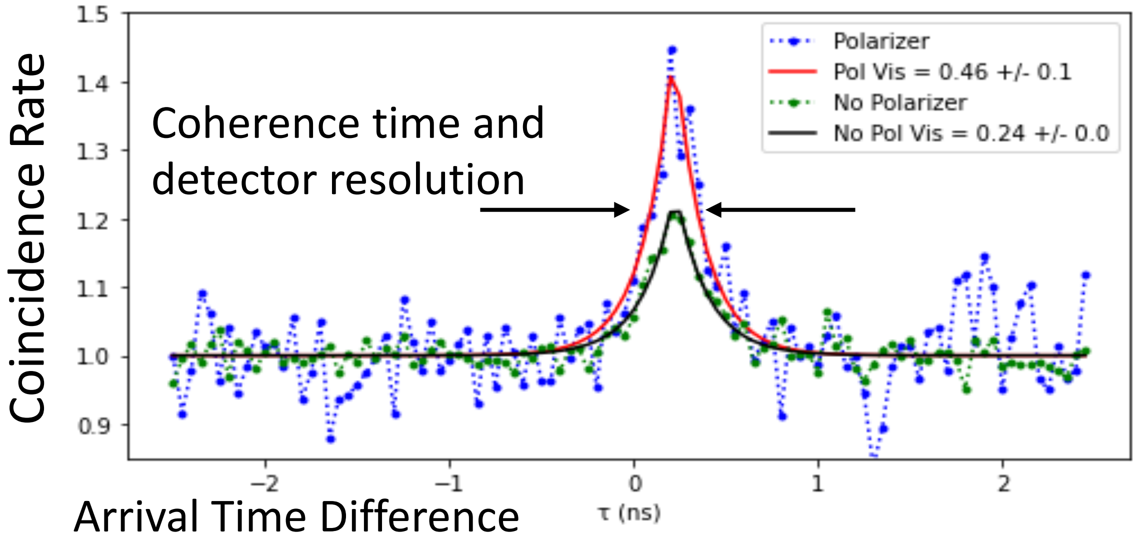
For a beam we can describe the transverse spatial and angular extents:

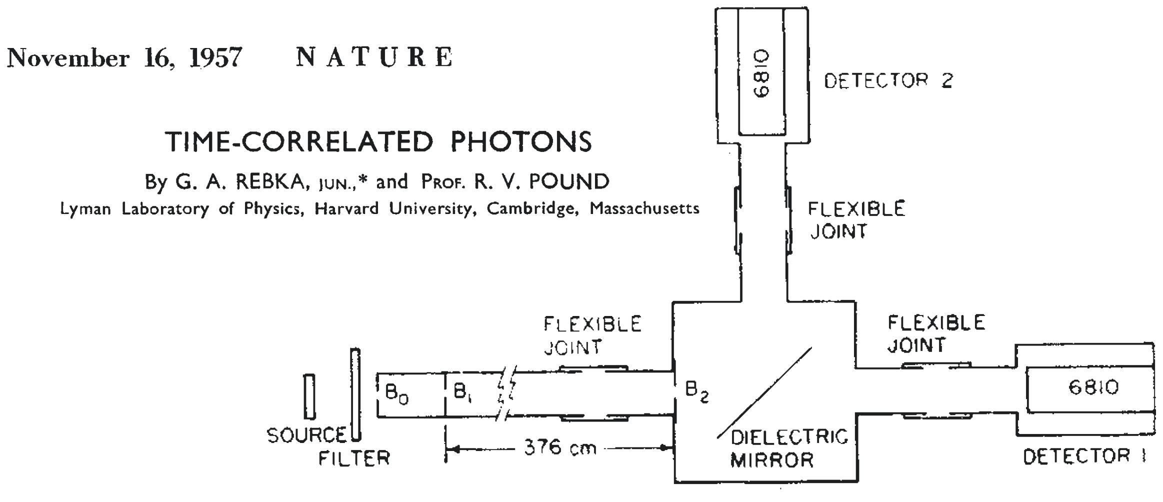
$$\hbar \sim \Delta x\, \Delta p = \Delta x\, p\, \Delta\theta = \Delta x \frac{\hbar}{\lambda} \Delta\theta \text{ and so } \Delta x\, \Delta\theta \sim \lambda$$

The curious HBT effect

"The birth of quantum optics"



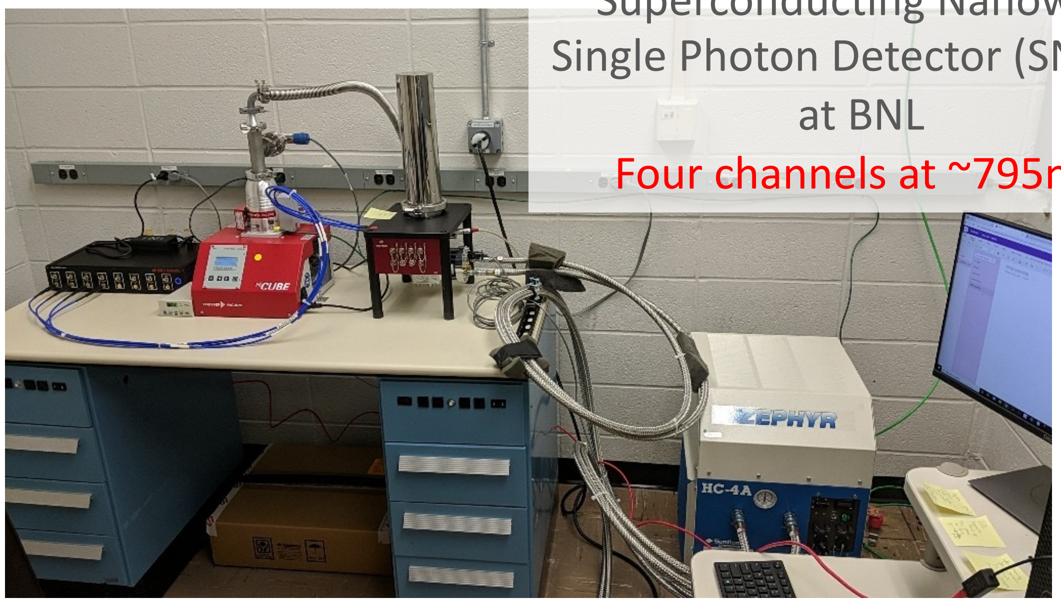



November 16, 1957 NATURE

TIME-CORRELATED PHOTONS

By G. A. REBKA, JUN.,* and PROF. R. V. POUND

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

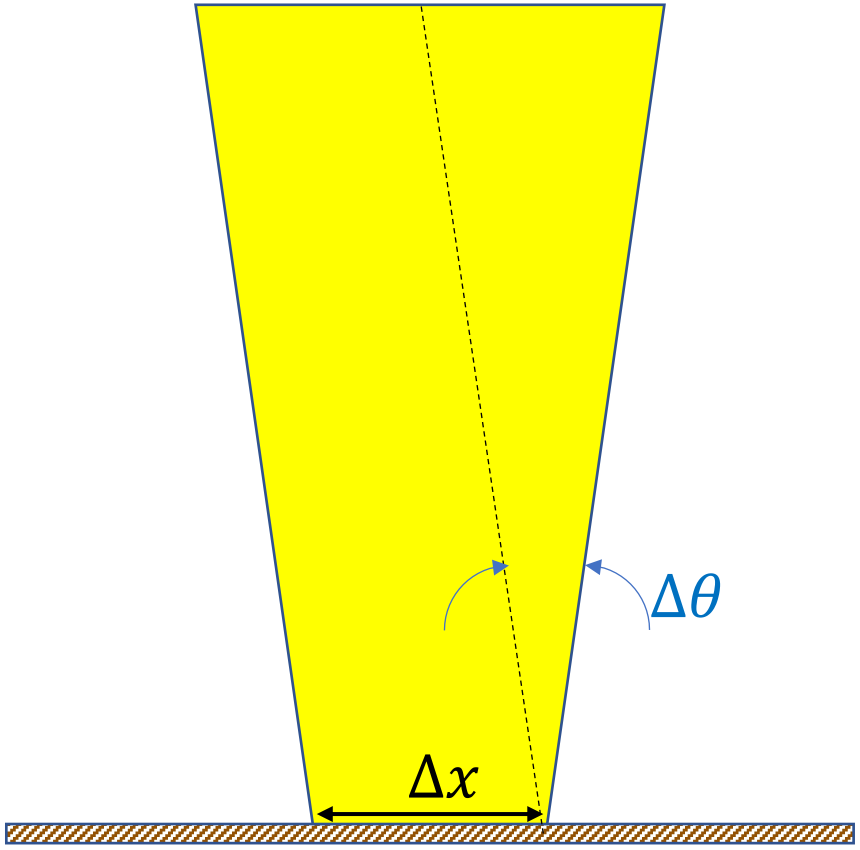


Superconducting Nanowire
Single Photon Detector (SNSPD)
at BNL

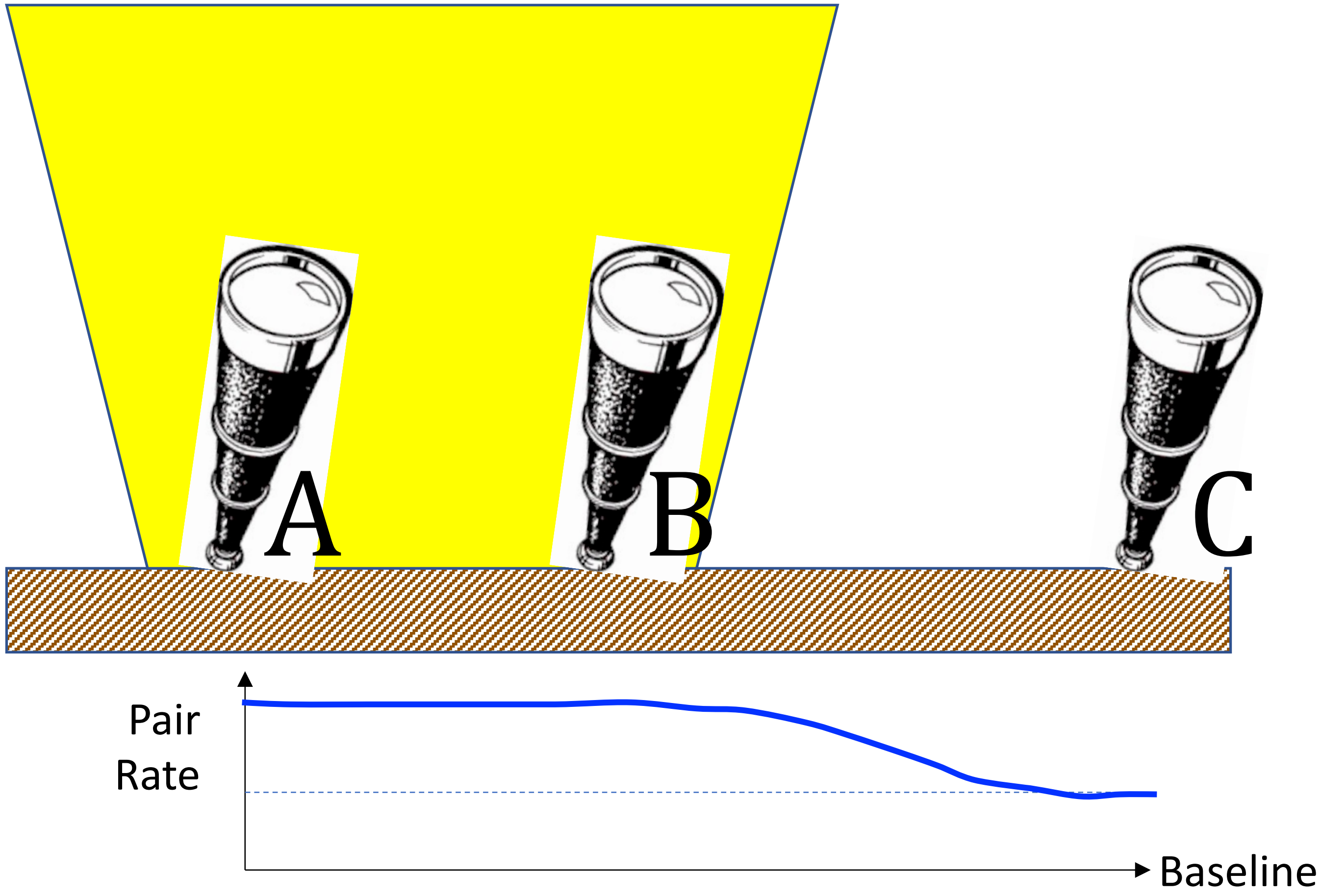
Four channels at ~795nm

HBT Intensity Interferometry

Telescopes $\boldsymbol{A}$ and B will detect the same mode from an object with angular size on the sky, and so will have an elevated coincidence rate



$$\Delta x \, \Delta\theta \sim \lambda$$



High ride of astro HBT, 1956-1974 … and again now

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

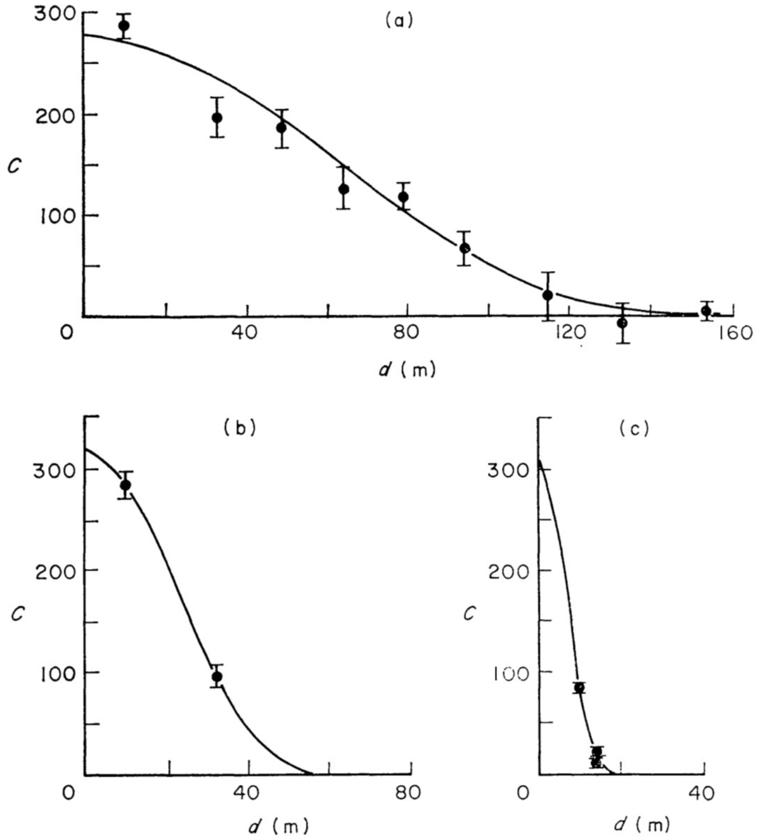


FIG. 3. *Examples of the observed variation of correlation with baseline for three stars.* (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).

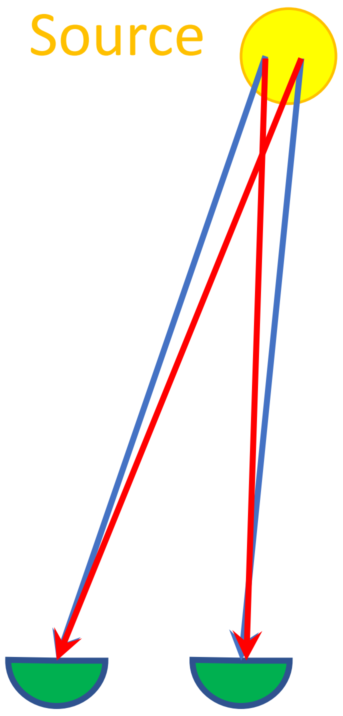
Hanbury Brown, Davis, Allen, Rome; MNRAS **137**, (1967) p393-417

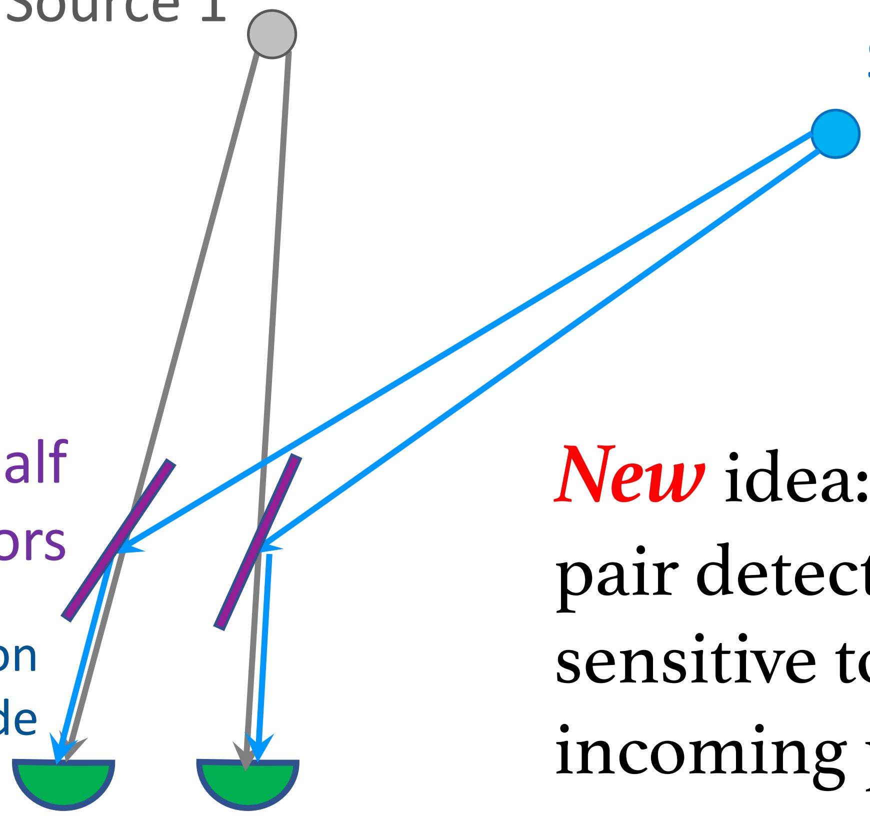
HBT track record

- 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

HBT with two, separated sources?

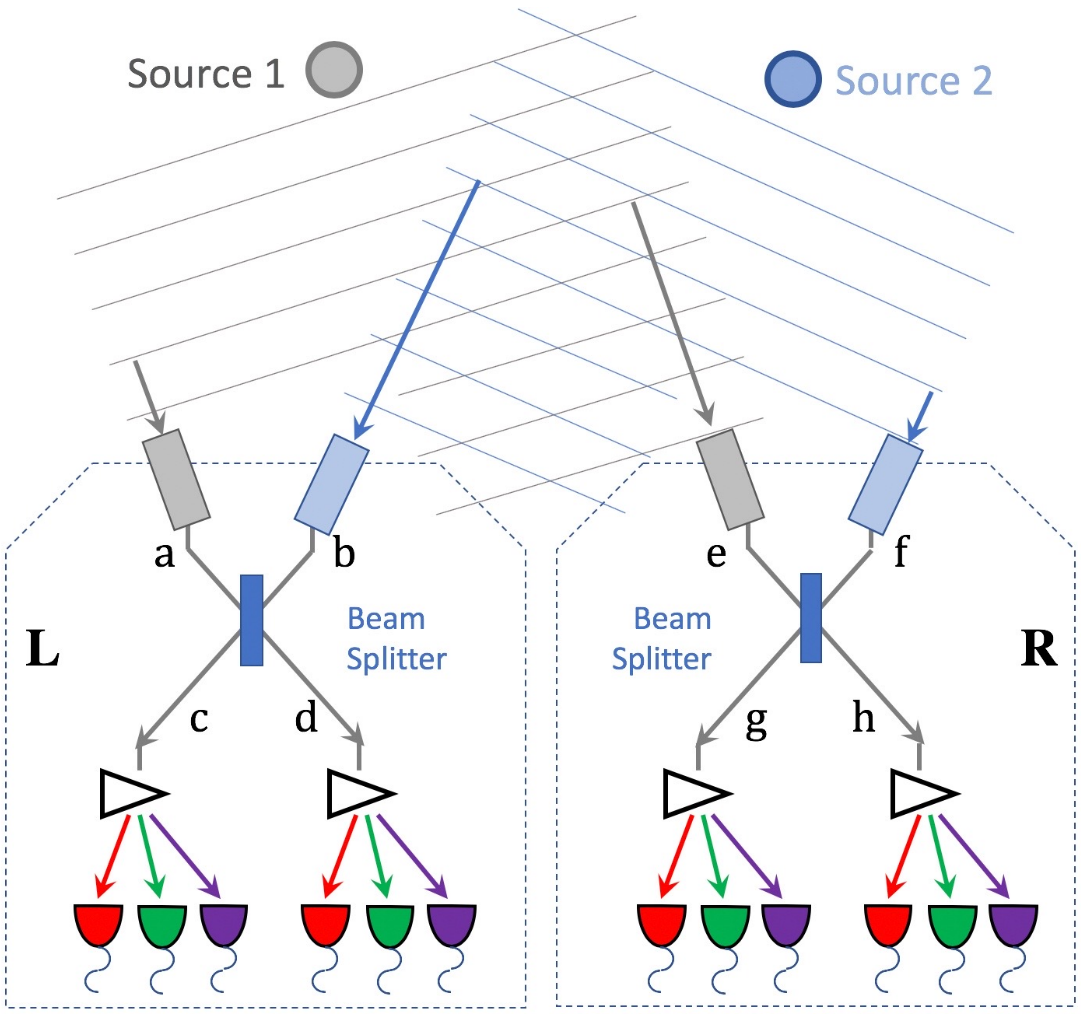




New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Original motivation: gravitational waves

Idea: two photons from two sky sources



arXiv.org > astro-ph > arXiv:2010.09100

Astrophysics > Instrumentation and Methods for Astrophysics

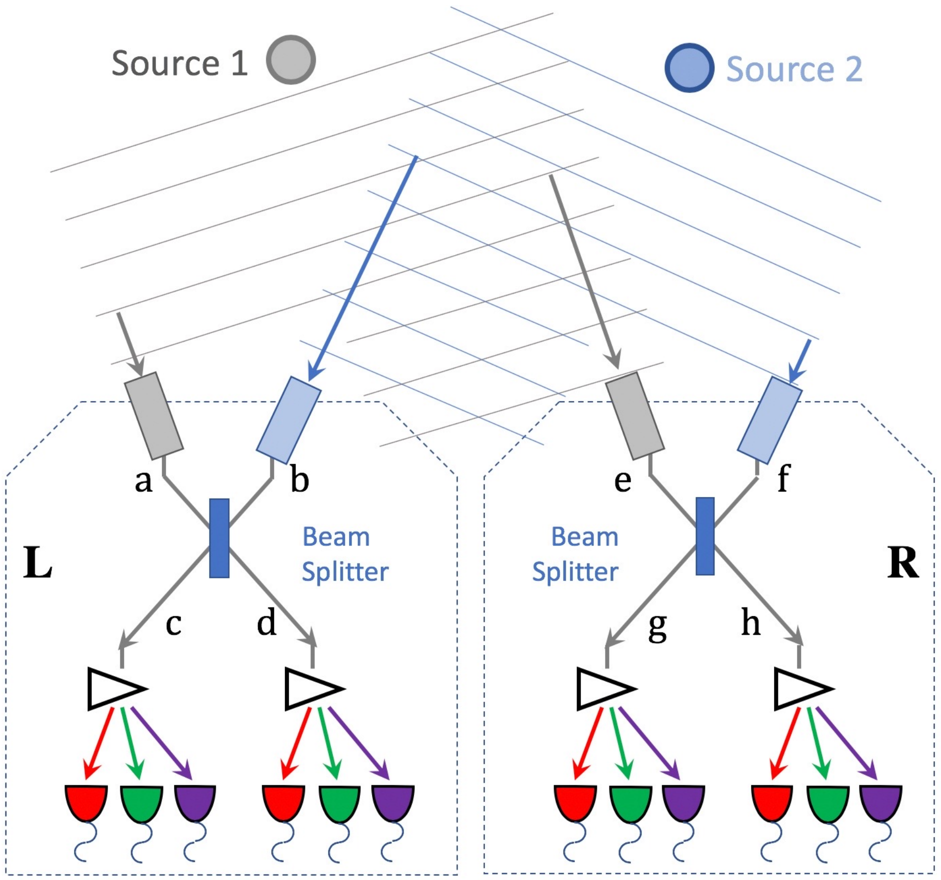
[Submitted on 18 Oct 2020 (v1), last revised 4 Nov 2020 (this version, v2)]

Two-photon amplitude interferometry for precision astrometry

Paul Stankus, Andrei Nomerotski, Anže Slosar, Stephen Vintskevich

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

Does *not* require live optical link between stations; can use arbitrary baseline, similar advantage as HBT.



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:

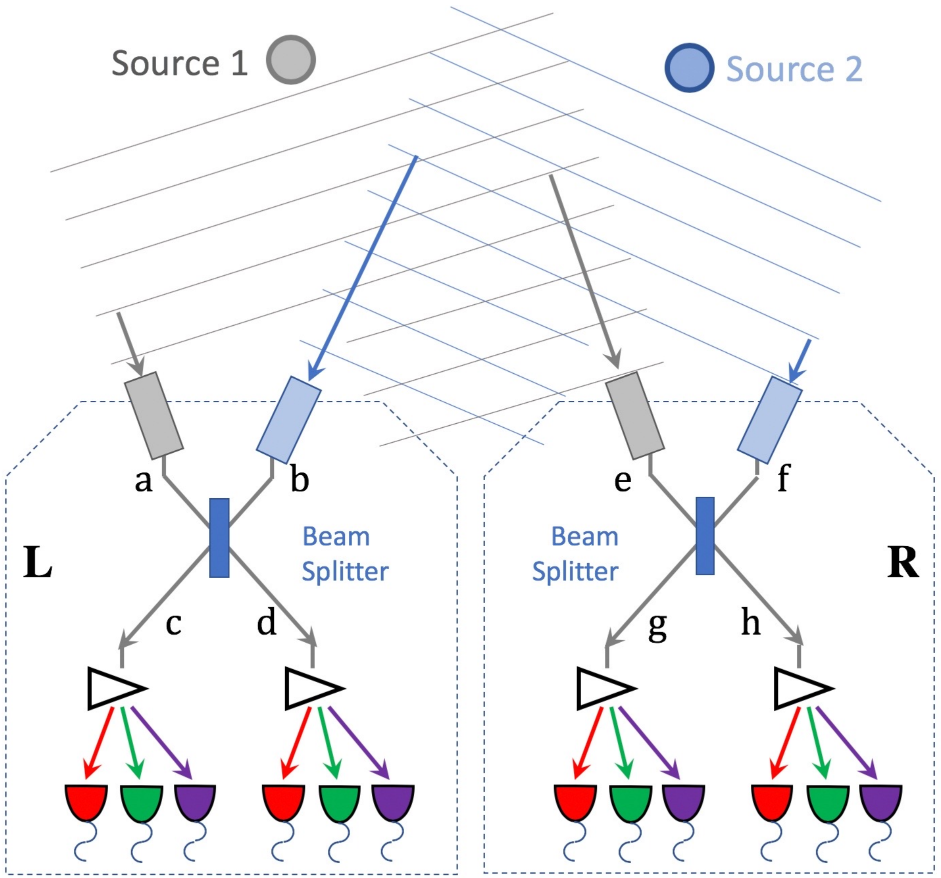
$$\langle N(xy)\rangle = \frac{k(S_1+S_2)^2}{8}\left[1 \pm V_{2\mathrm{PS}}\cos\left[\frac{2\pi B}{\lambda}(\sin\theta_1 - \sin\theta_2) + \frac{2\pi\Delta L}{\lambda}\right]\right]$$

Quantum field theory version; full:

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

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

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



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Base combinatoric pair rate

HBT enhancement

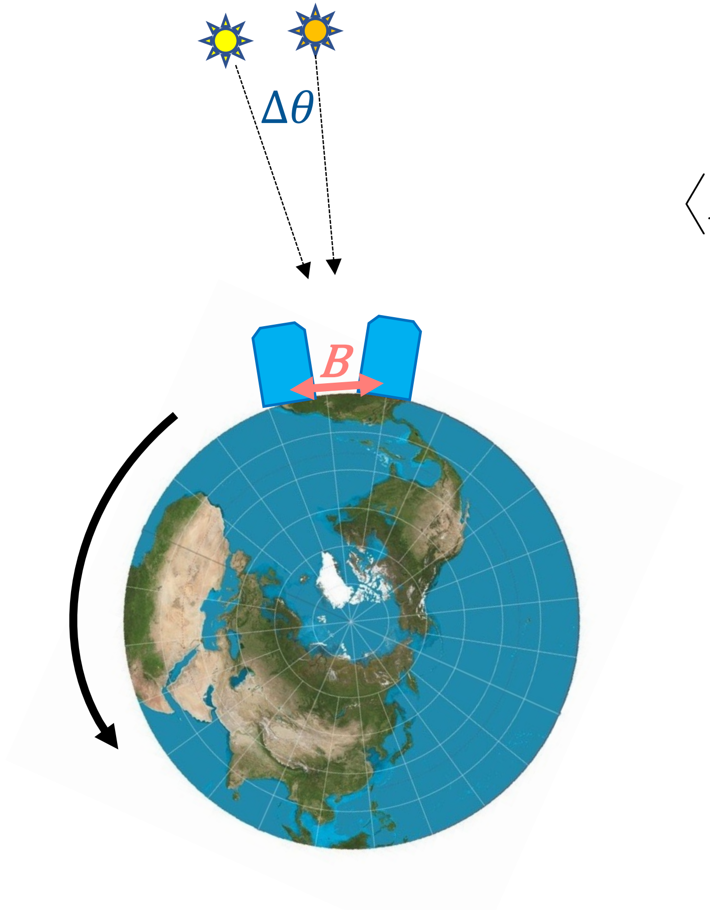
Oscillatory term, fringe passing

Has been seen on the bench

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

Idea: Dynamic Astrometry

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

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

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

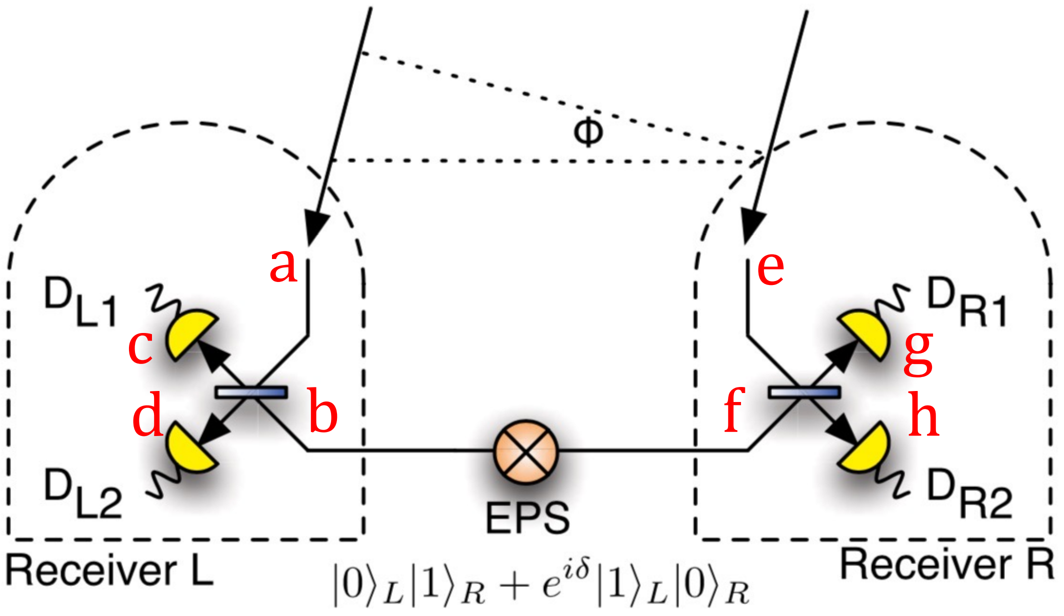
Further ideas are encouraged!

Quantum improved single photon interference?

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)



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

Sky photon: $(\hat{a}^\dagger + e^{i\delta_1}\hat{e}^\dagger)$ — Ground photon: $(\hat{b}^\dagger + e^{i\delta_2}\hat{f}^\dagger)$

Beam Splitters

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

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

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

Let slip the quantum technology!

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

Optical Interferometry with Quantum Networks

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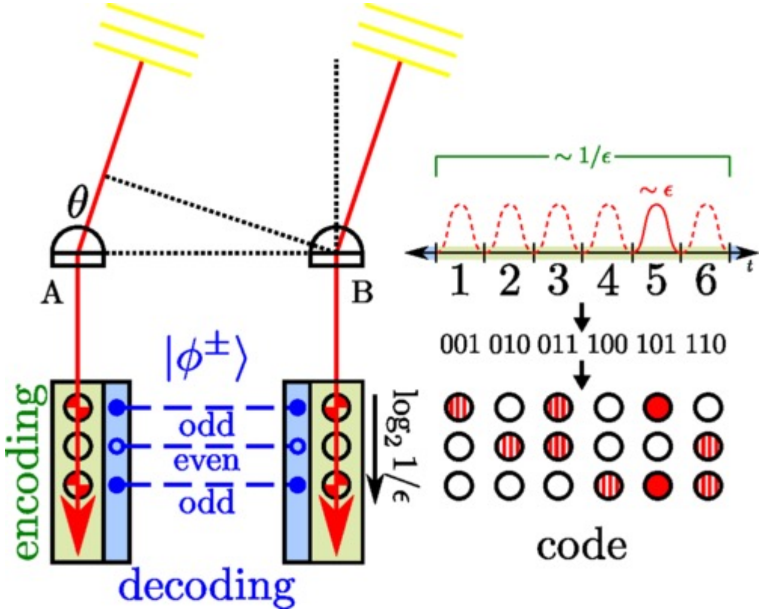
[2]*QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen Ø, Denmark*

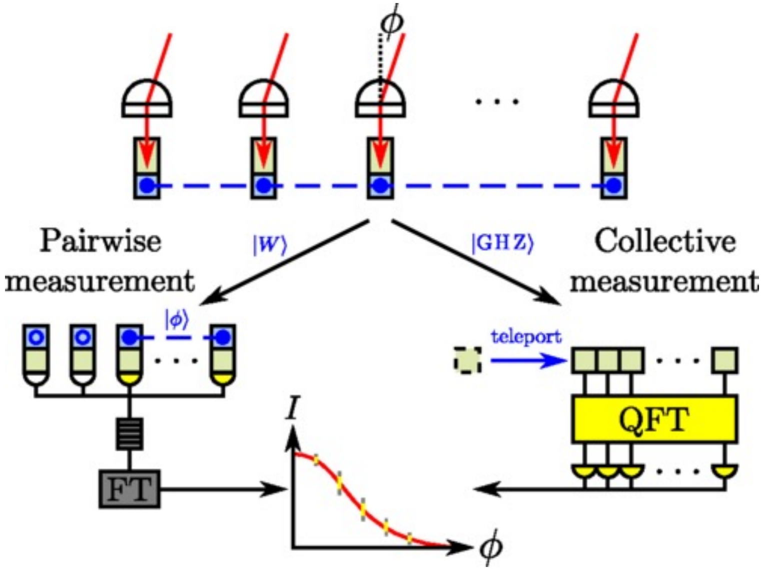
(Received 17 September 2018; published 15 August 2019)

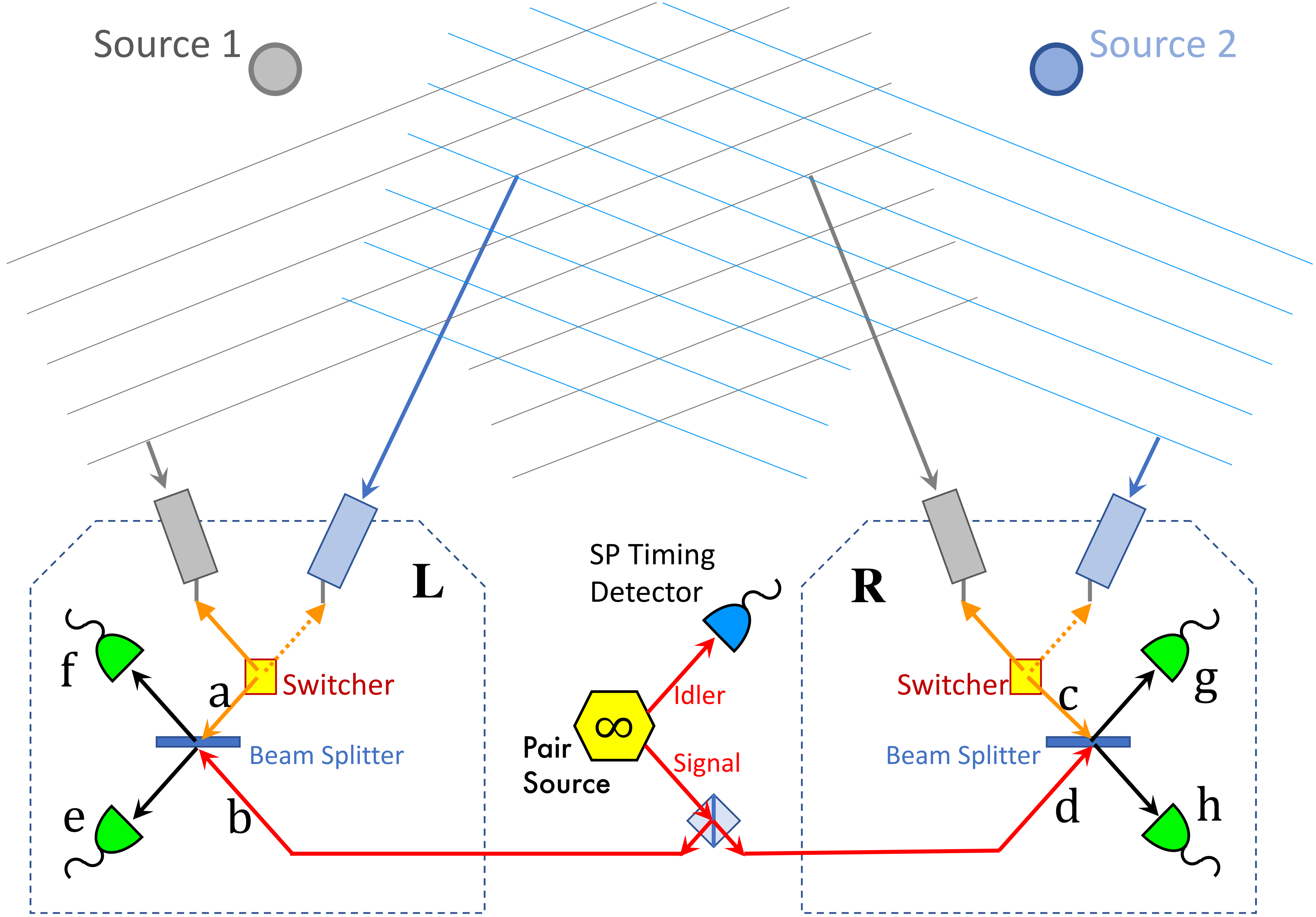
Idea: Capture and store sky photons in quantum memories, then teleport and measure as needed



Idea: Efficient time-bin encoding of photon arrivals

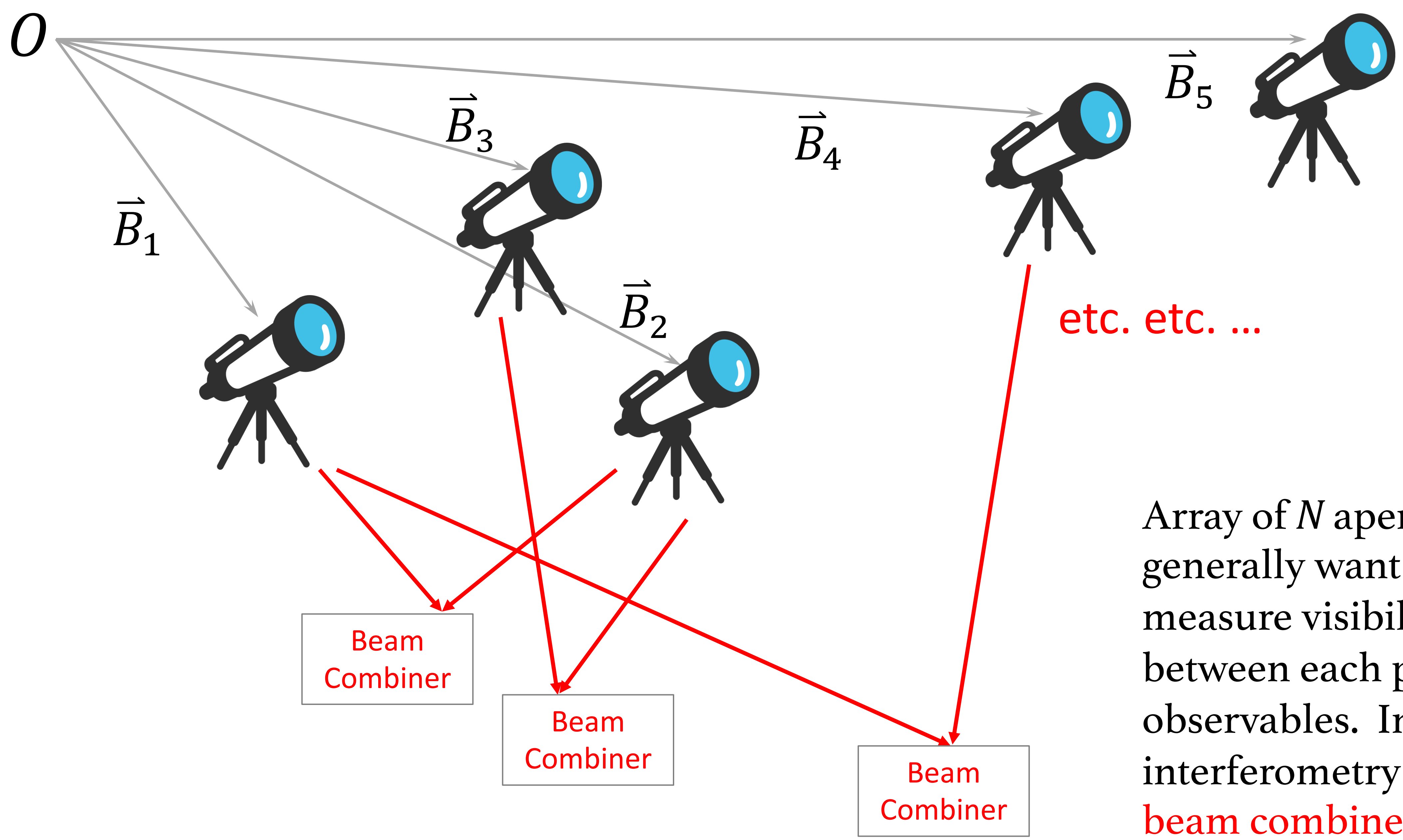
Idea: Use quantum Fourier transform (QFT) to directly invert pattern from array



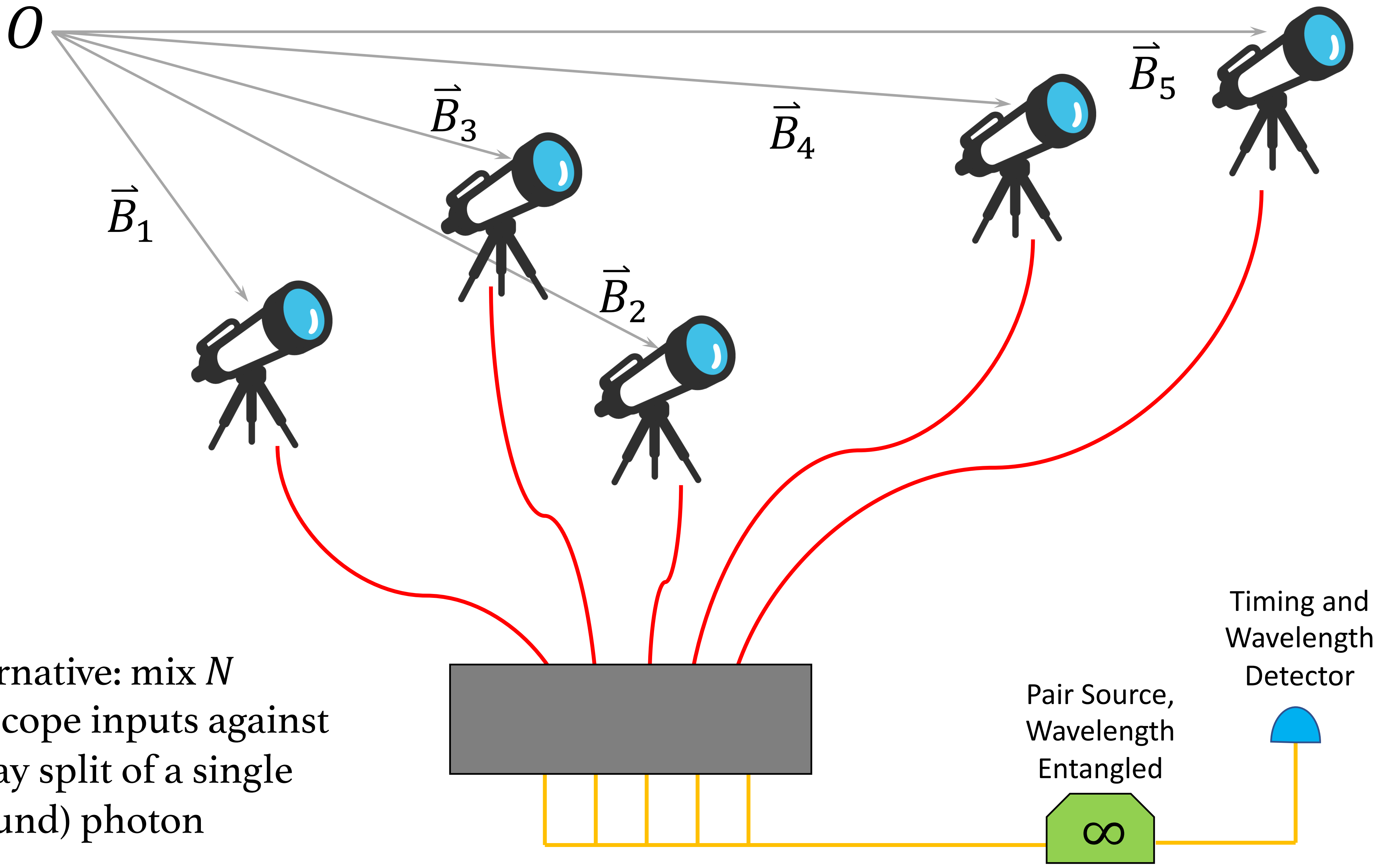


"Switched" configuration using single photon source does not require a coincidence from two sky objects .

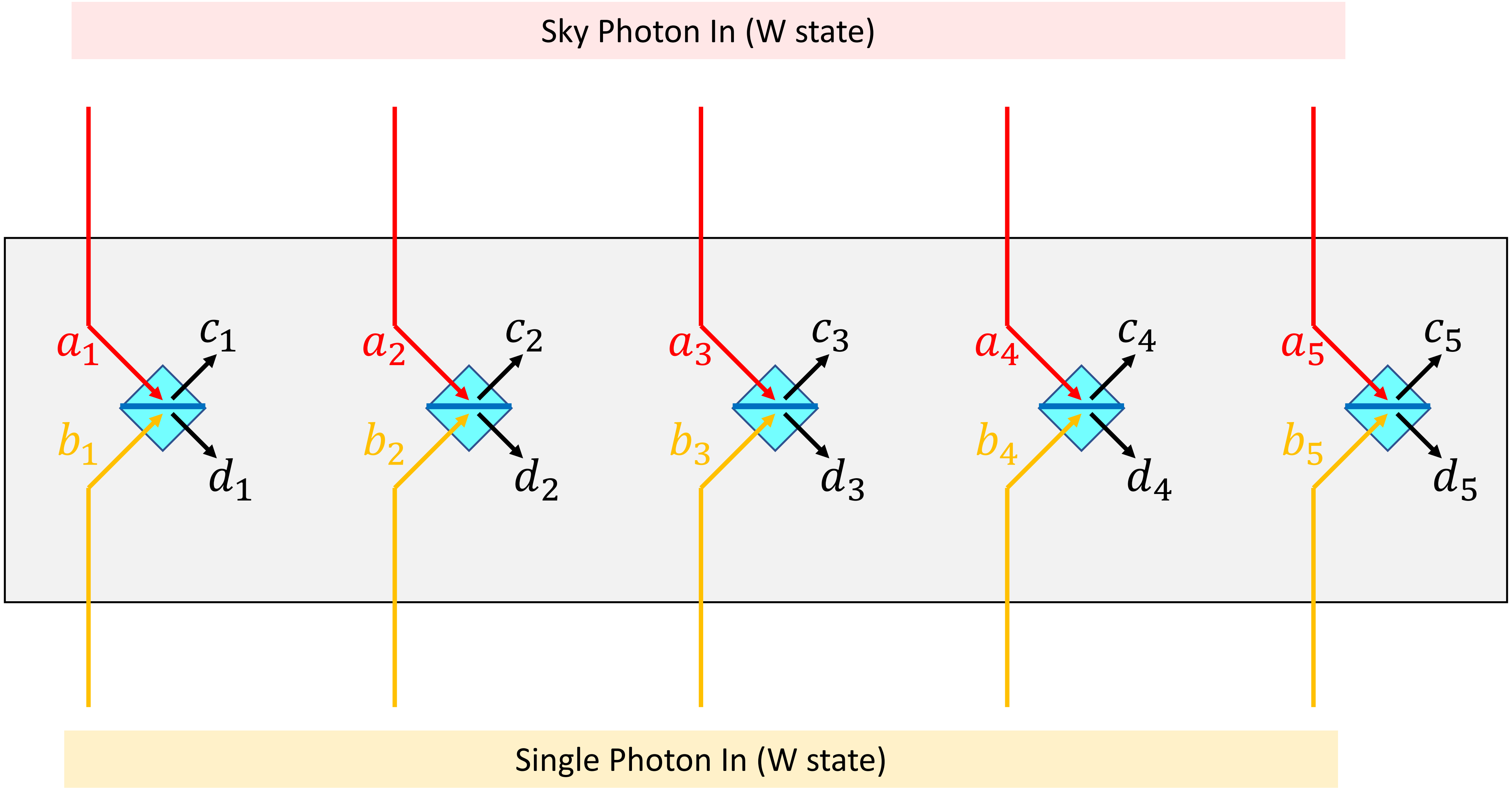
Great improvement possible for faint sources if photon pairs are available.



Array of N apertures, generally want to measure visibility between each pair, ie N^2 observables. In standard interferometry need N^2 beam combiners.



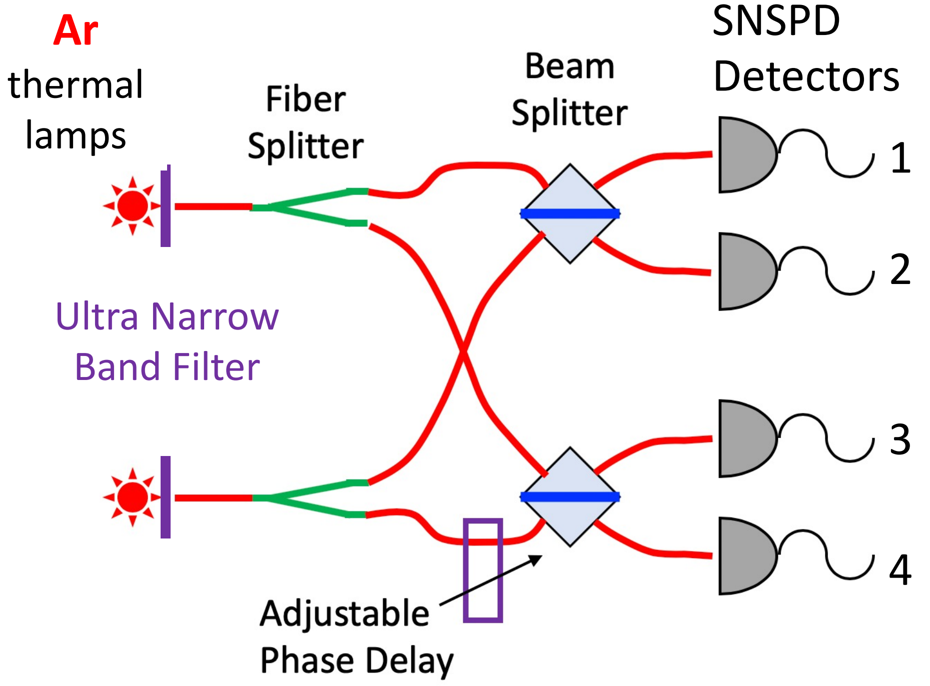
Alternative: mix N telescope inputs against N-way split of a single (ground) photon

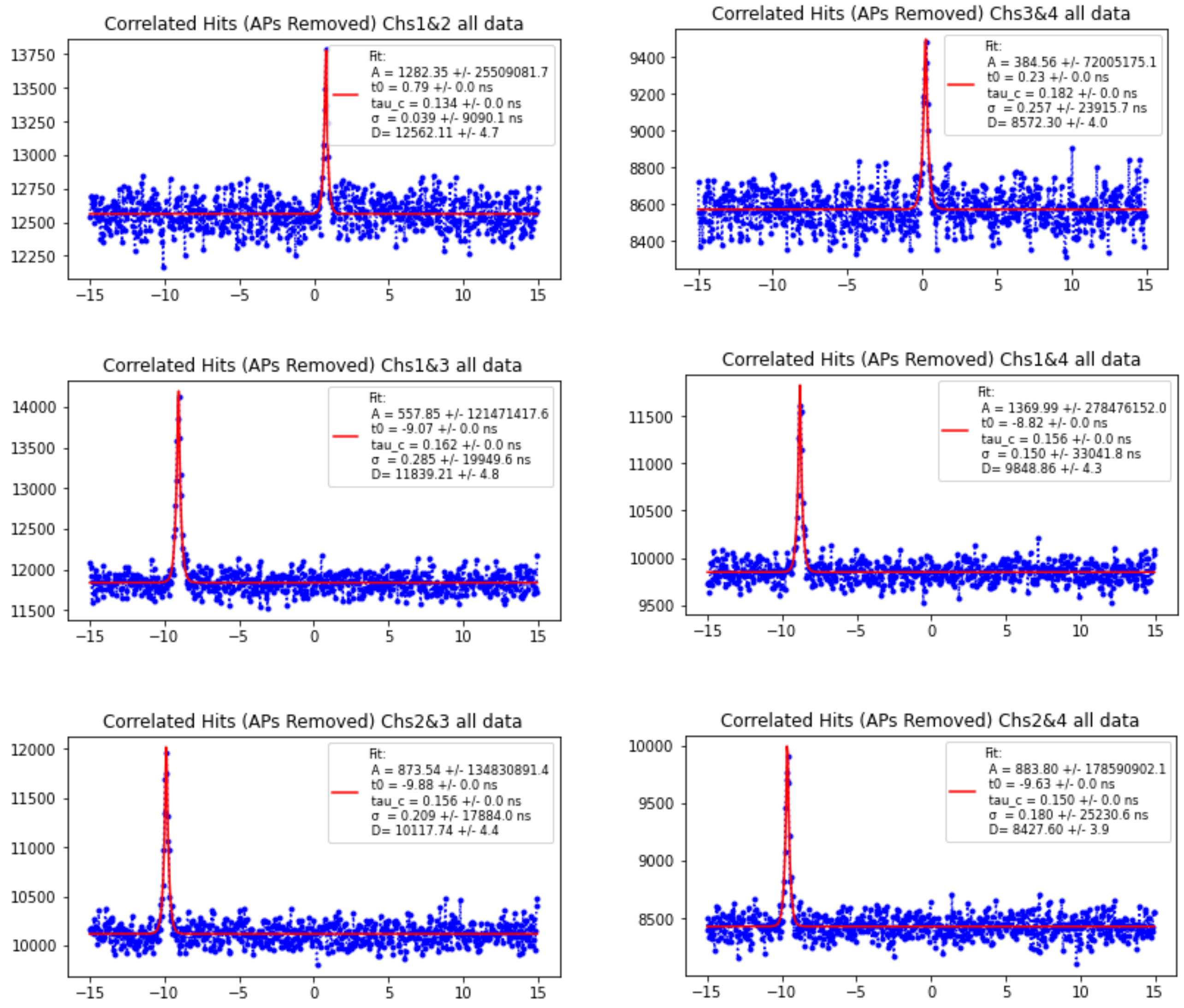


Repeated GJC arrangement, once for each telescope and each split off the ground single photon; cost & complexity grows linearly with array size.

Experiments in progress

Supported at BNL by DOE HEP
QuantISED grant 2020-21



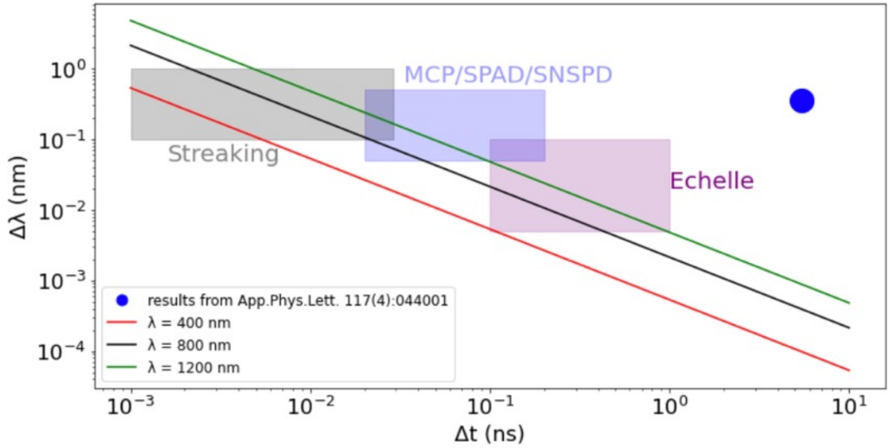


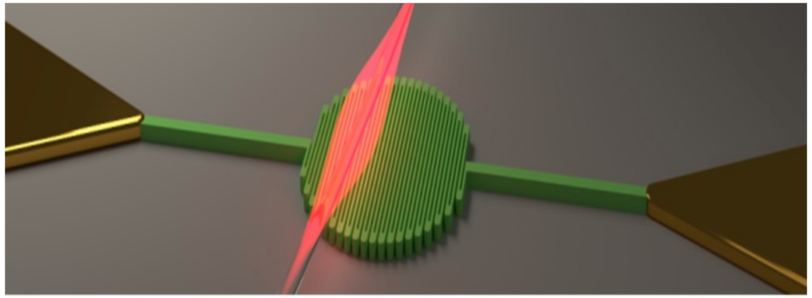
Check: We can see HBT coincidence enhancement peak in all channel combinations

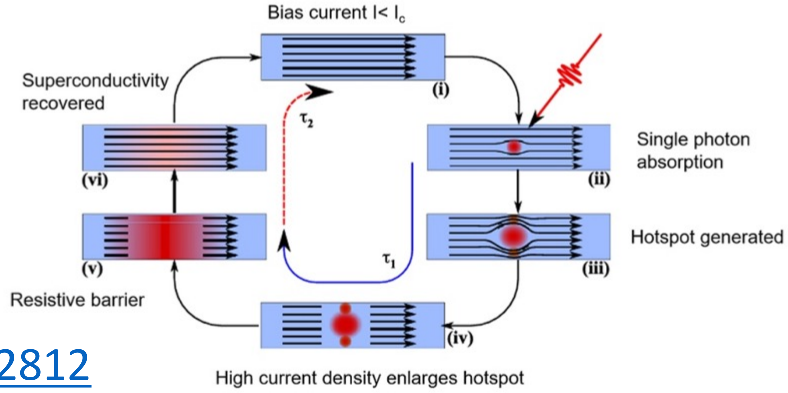
Future detector requirement

- 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

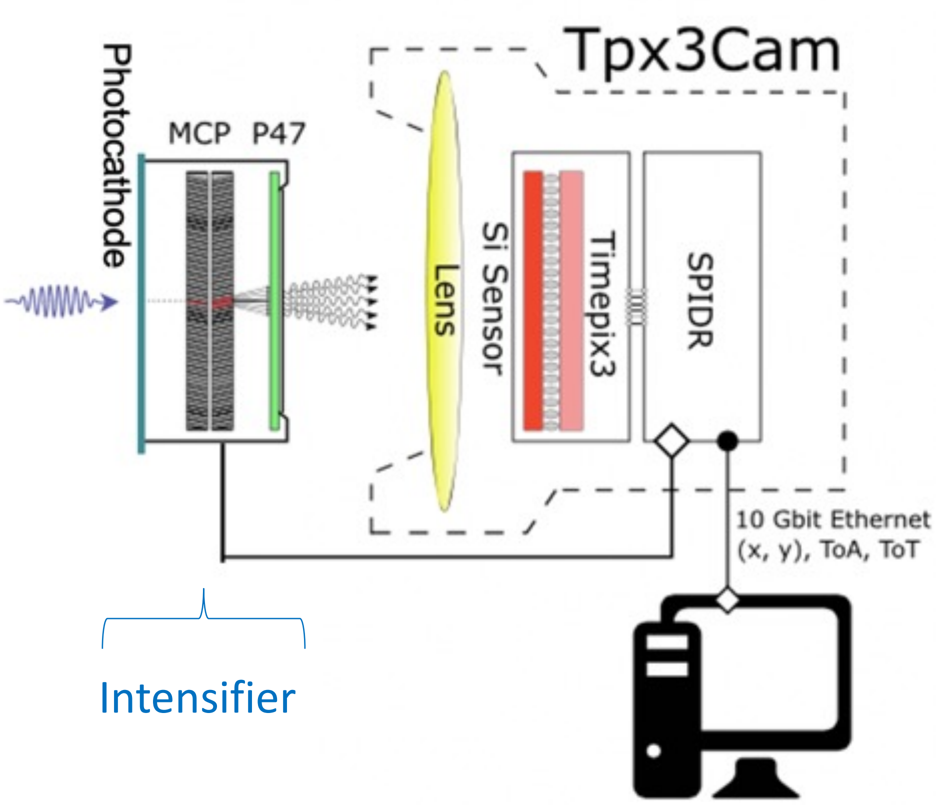






A. Nomerotski, SPIE (2020)
https://arxiv.org/abs/2012.02812

Intensified camera is single photon sensitive



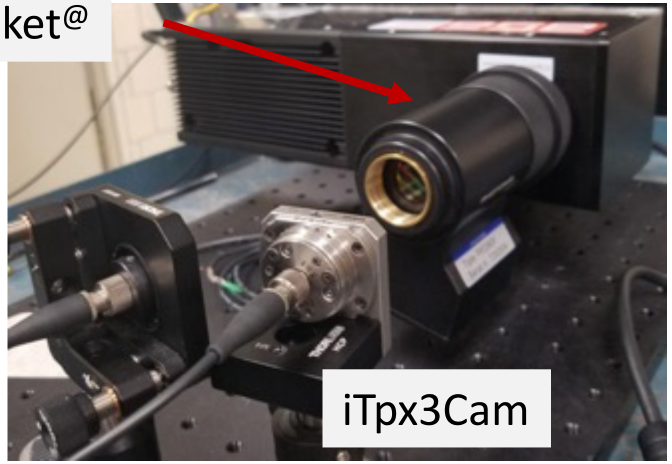
Intensifier

Quantum efficiency ~ 30%

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

Image intensifier (Photonis PP0360EG)

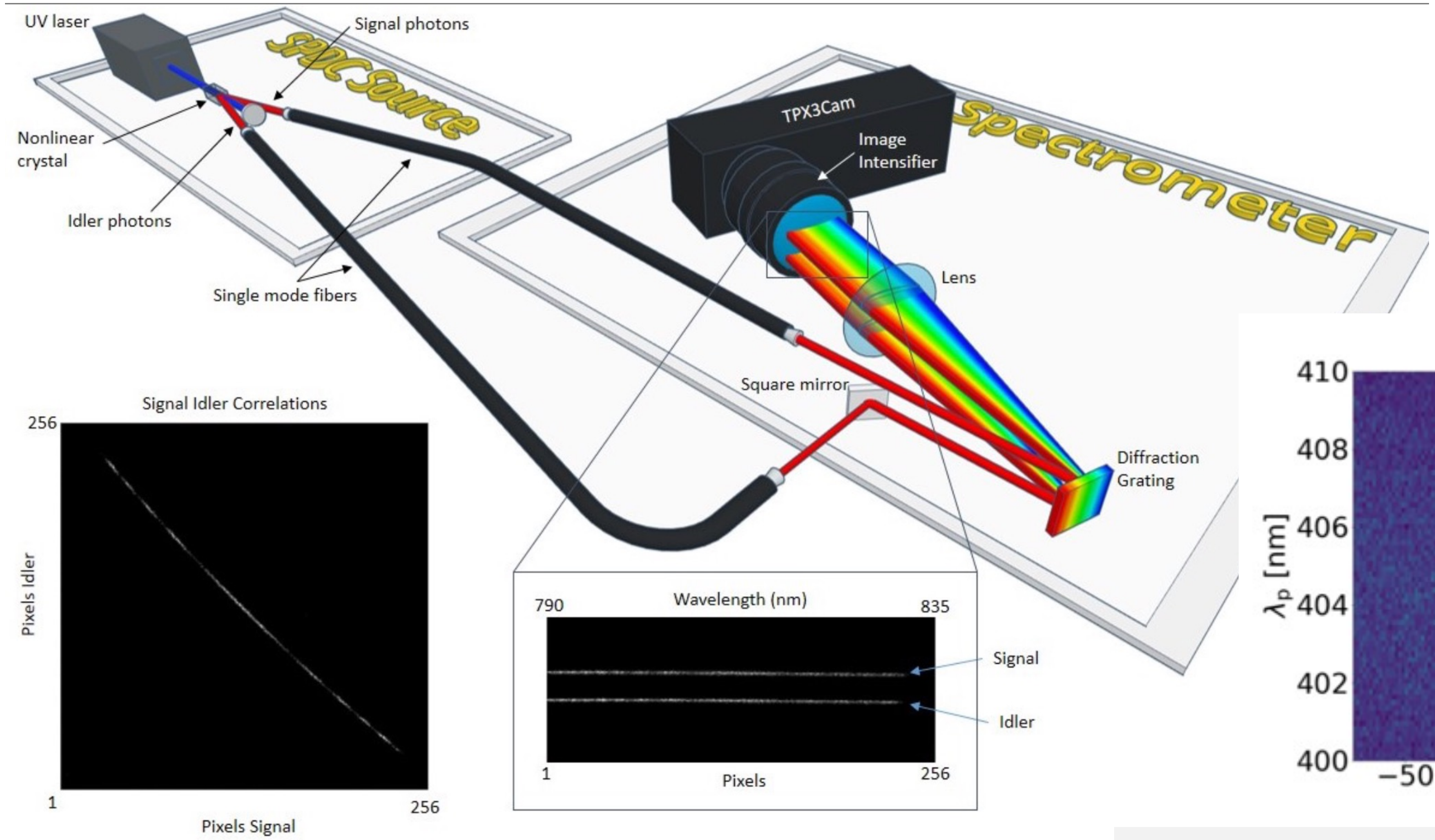
Cricket@



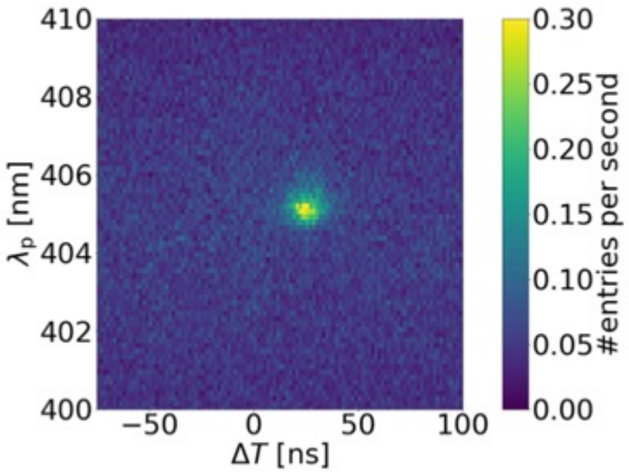
iTpx3Cam

Spectroscopic binning already demonstrated

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



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



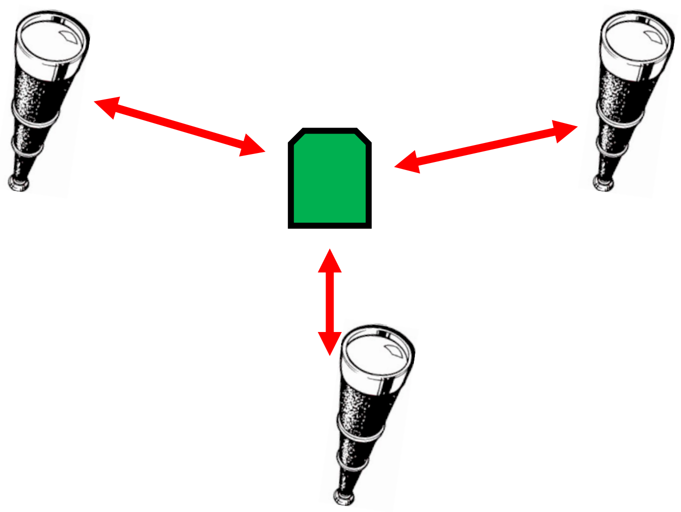
Pump photon wavelength vs time difference

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)

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