Quantum-Assisted Optical Interferometry for Astrometry and Precision Imaging

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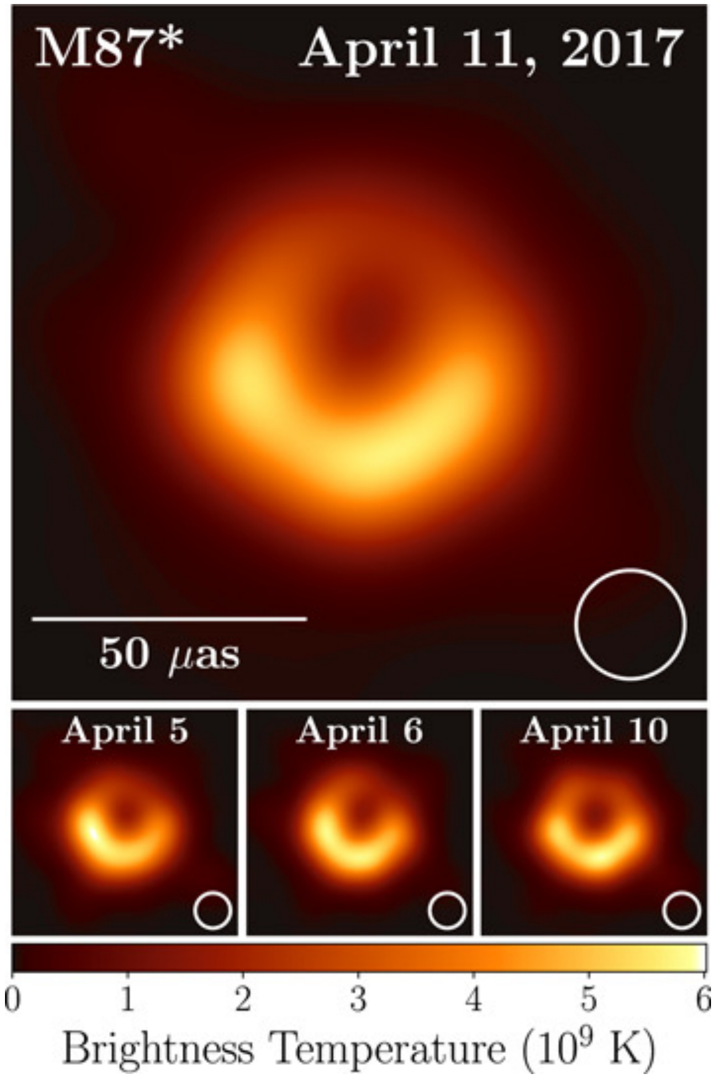
Quantum 2.0 Conference & Exhibition
Boston, 6/13/2022

Brookhaven National Laboratory

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

Stony Brook University

Interferometry: Imaging and Astrometry



High-resolution imaging is the most well-known use for long-baseline interferometry.

Interferometry can also be used for *precision astrometry*, measurement of the positions of objects on the sky

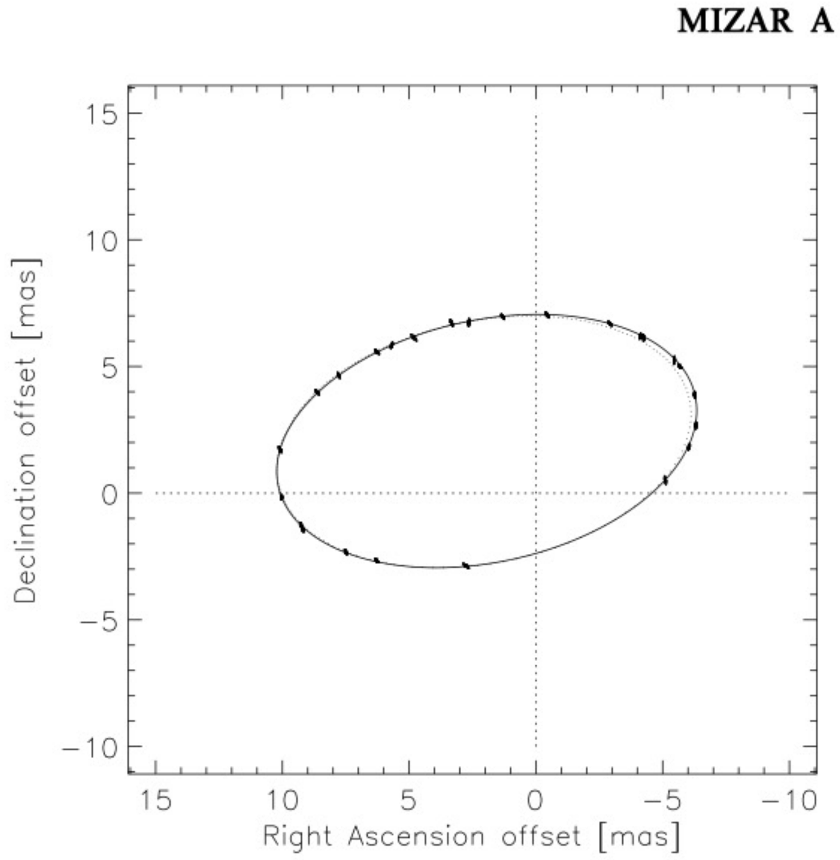


FIG. 11.—Apparent interferometric orbit of Mizar A with NPOI measurements. The dotted line is the orbit published by H95 based on Mark III observations, which did not cover the northwest quadrant.

Idea 0

Originally: Gottesman, Jennewein, Croke 2012
Demonstrated: Oregon & Illinois 2022

Matthew Brown, Valerian Thiel, Markus Allgaier, Michael Raymer, Brian Smith, Paul Kwiat, and John Monnier "Long-baseline interferometry using single photon states as a non-local oscillator", Proc. SPIE 12015, Quantum Computing, Communication, and Simulation II, 120150E (1 March 2022);

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

Longer-Baseline Telescopes Using Quantum Repeaters

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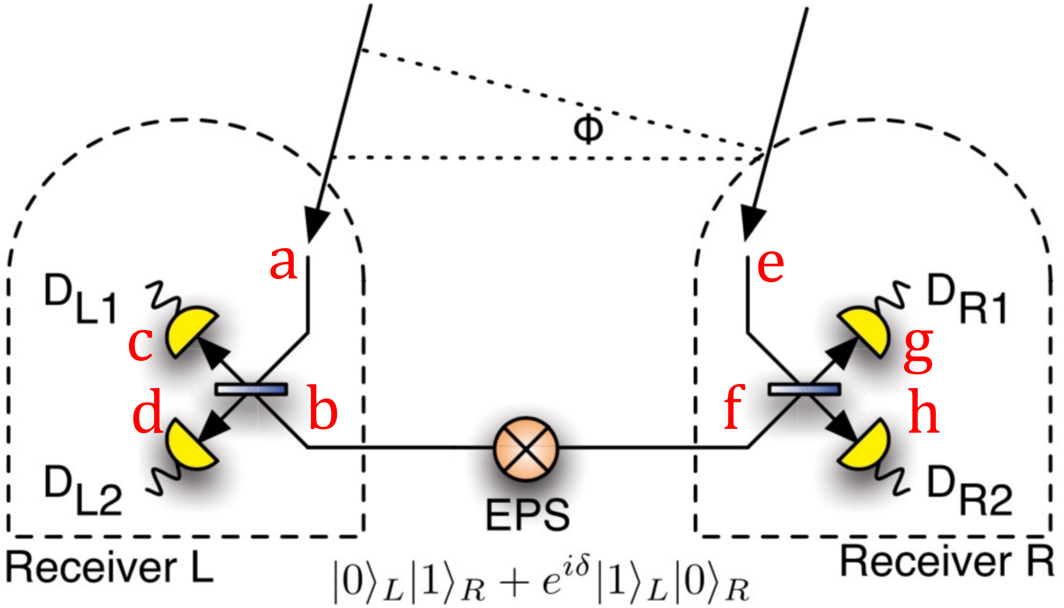
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)



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

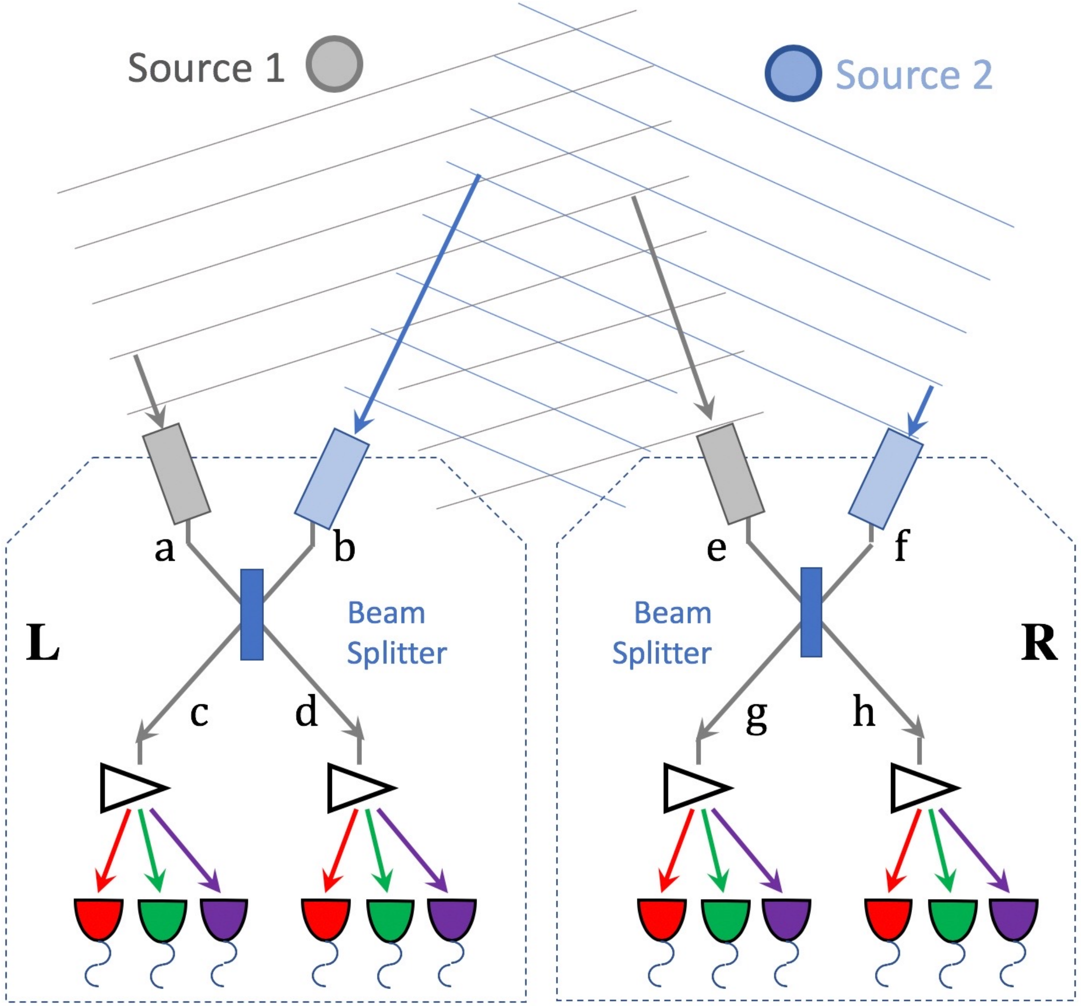
Beam Splitters

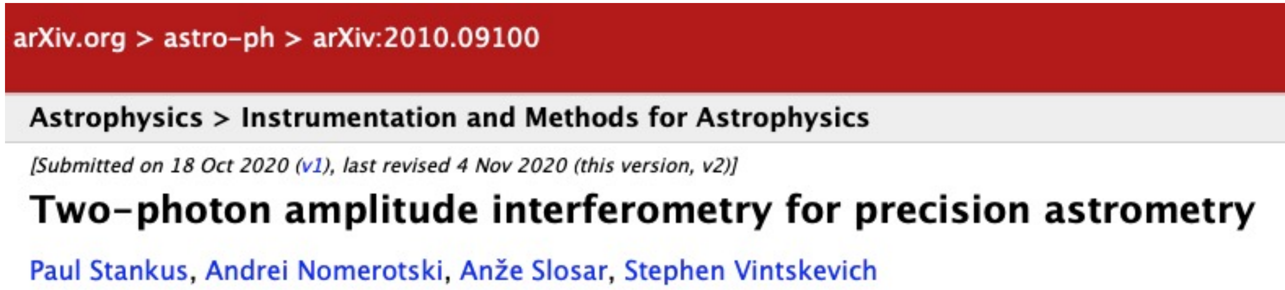
$$\hat{a}^\dagger \to (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} \qquad \hat{b}^\dagger \to (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2}$$
$$\hat{e}^\dagger \to (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} \qquad \hat{f}^\dagger \to (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2}$$

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

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

Idea 1: Use two sky photons





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

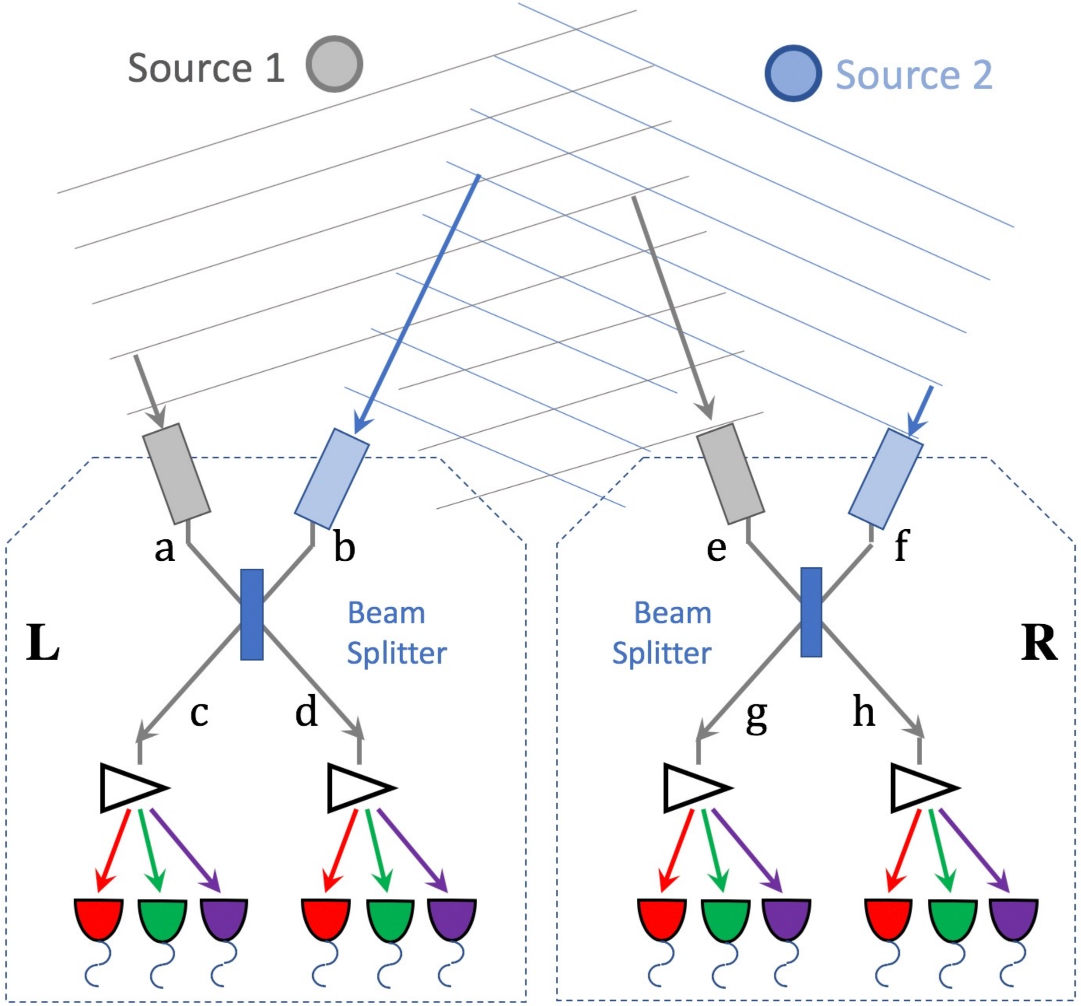
Sensitive to *difference* in path length differences ☞ opening angle!

Basis for precision astrometry; could achieve ~10microarcsec for bright objects

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

Does require coincidence of sky photons, similar drawback as HBT

Idea 1: Use two sky photons



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Base combinatoric pair rate

HBT enhancement

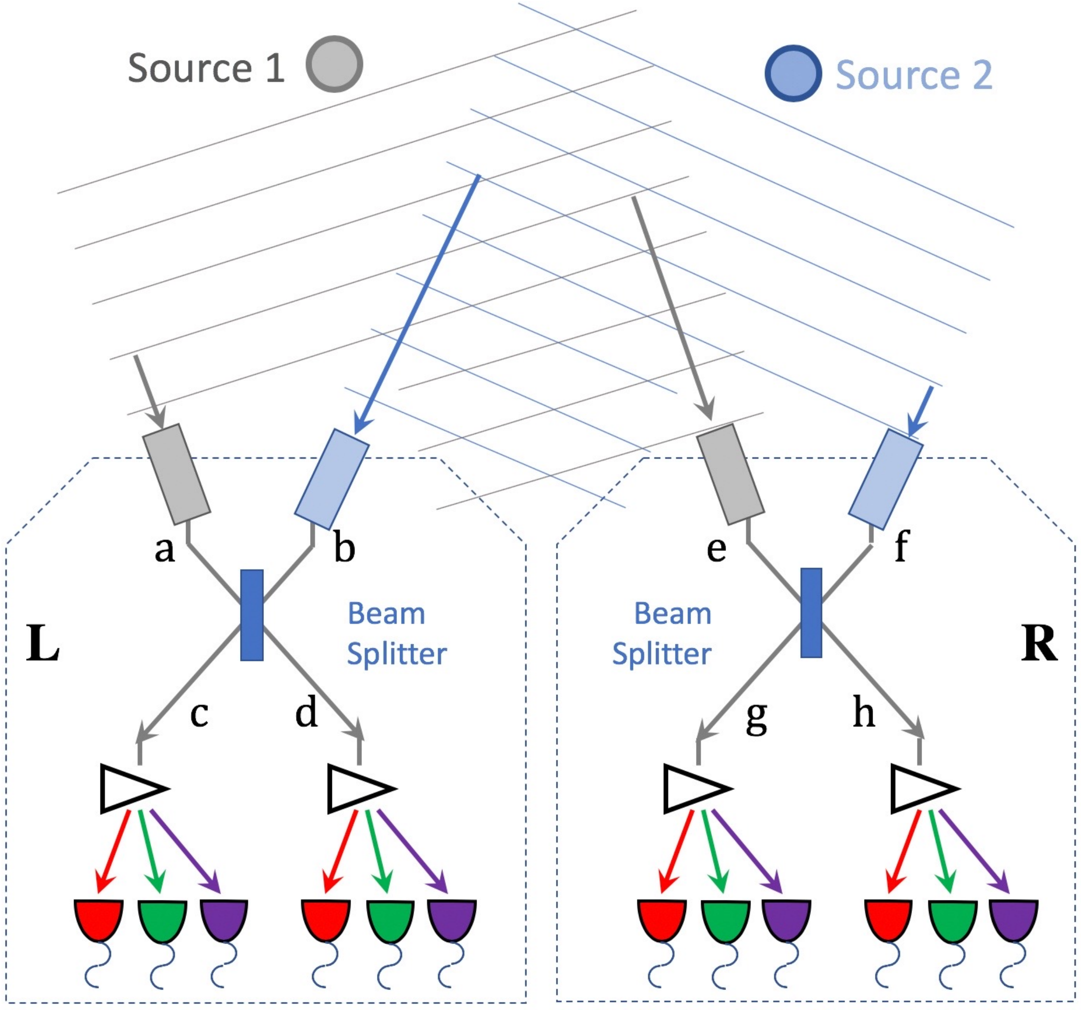
$$N_c(xy) = \eta_1\eta_2 A^2 \int_0^{T_r} P^{\text{two photons}}_{L,R,\tau}\, d\tau =$$

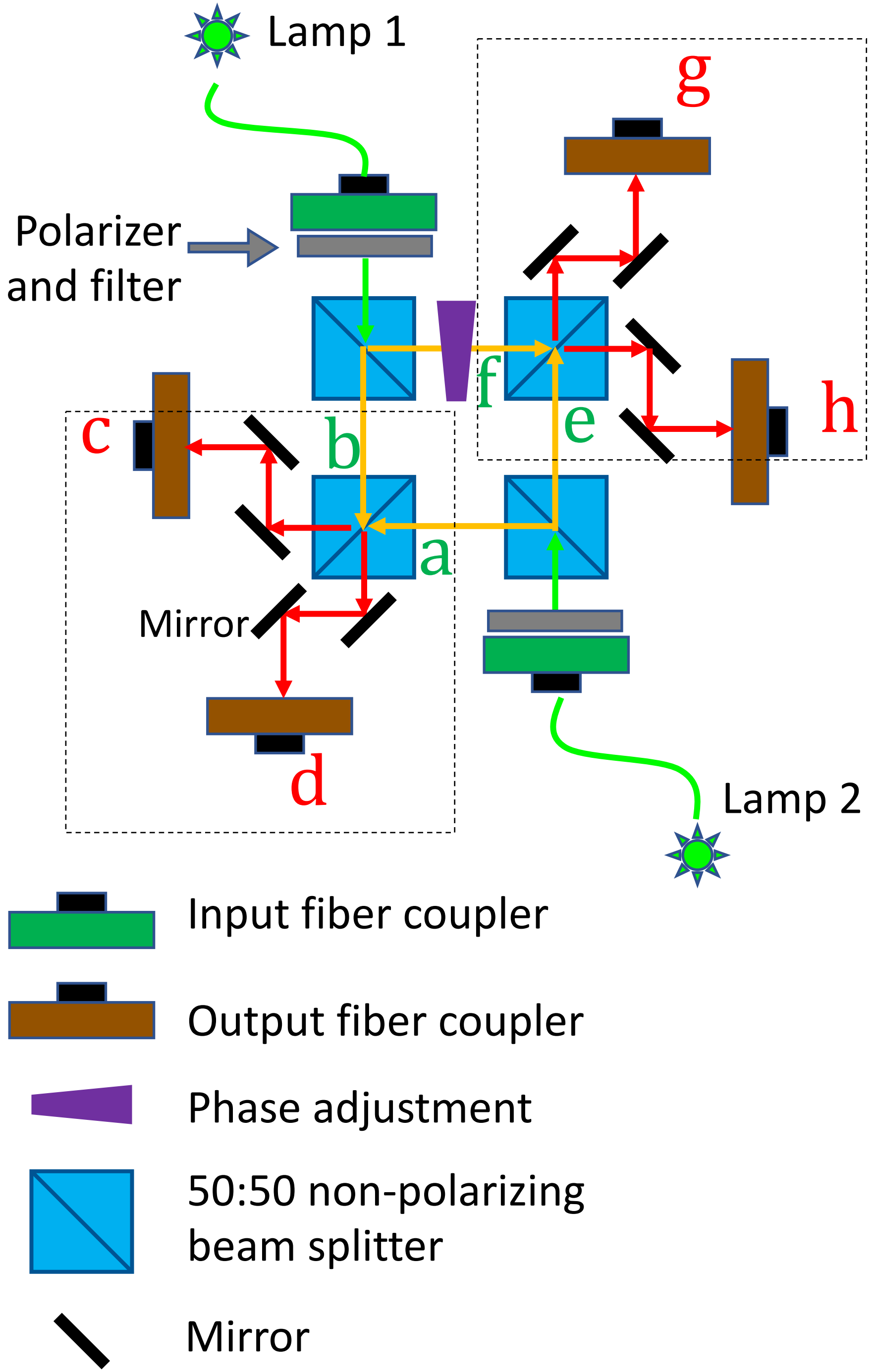
$$A^2\eta_1\eta_2 T_r \left[(I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm 2 I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos\left(\frac{\omega_0 B(\sin\theta_1 - \sin\theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right]$$

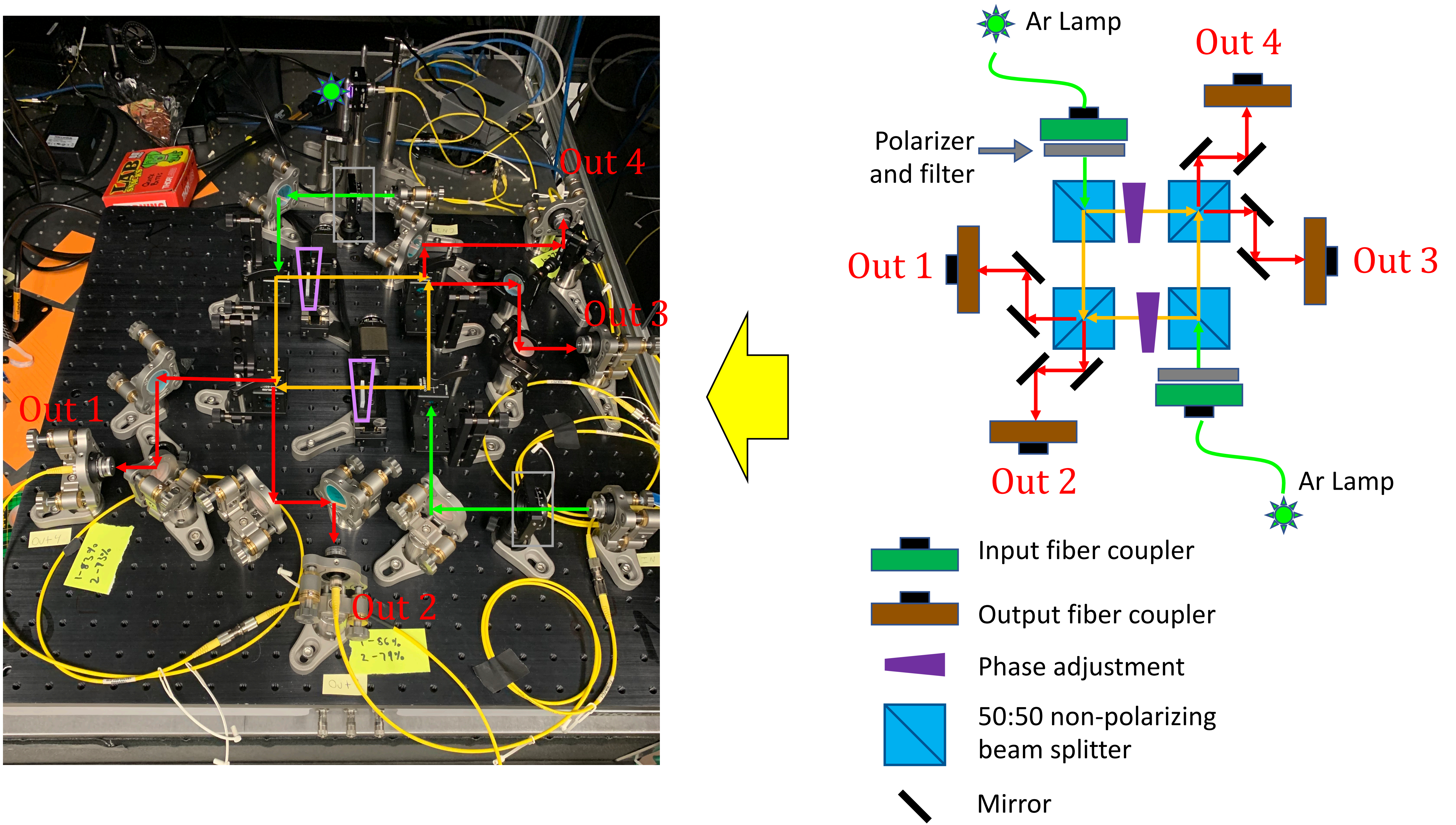
Oscillatory term, fringe passing

See "Astrometry in two-photon interferometry using Earth rotation fringe scan" Zhi Chen, et.al. https://arxiv.org/abs/2205.09091

Bench analog

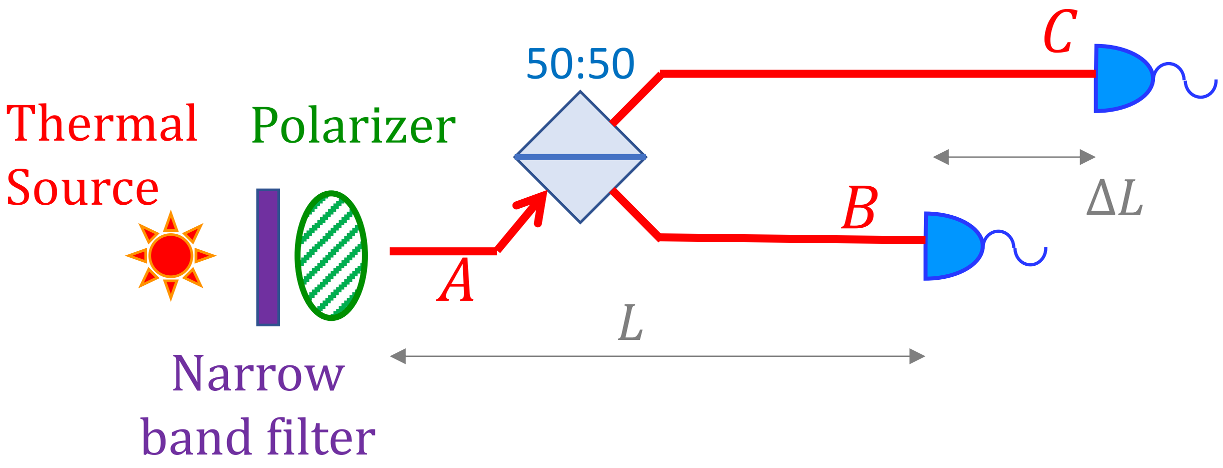


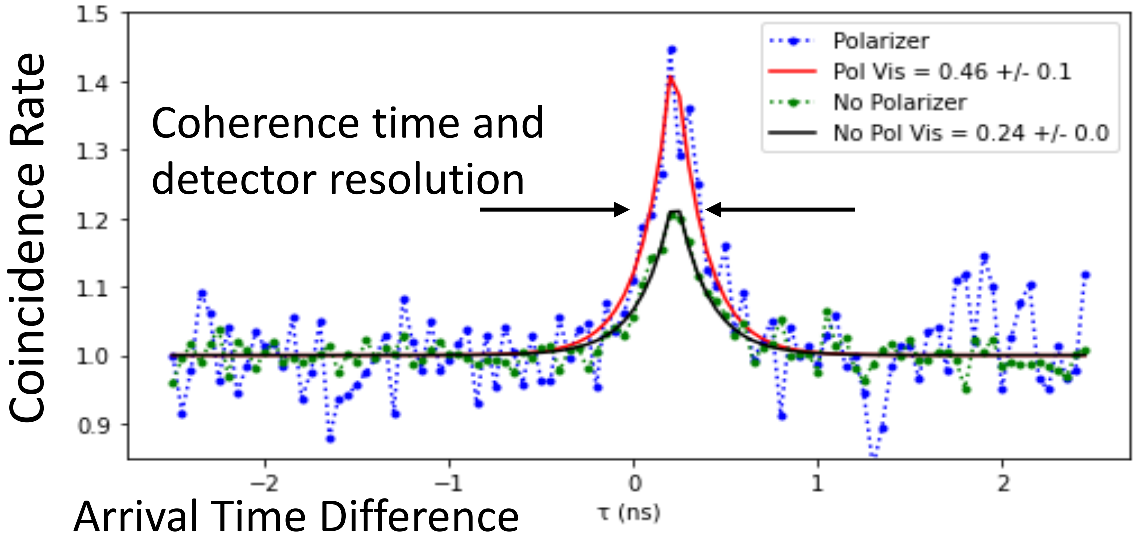


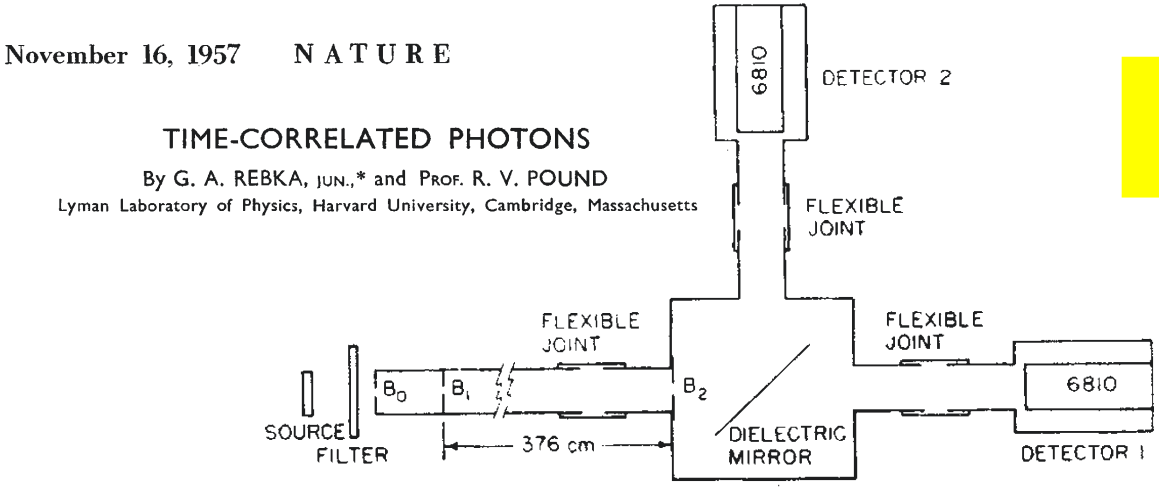

Out 4
Out 3
Out 1
Out 2
Ar Lamp
Out 4
Polarizer and filter
Out 1
Out 3
Out 2
Ar Lamp
Input fiber coupler
Output fiber coupler
Phase adjustment
50:50 non-polarizing beam splitter
Mirror

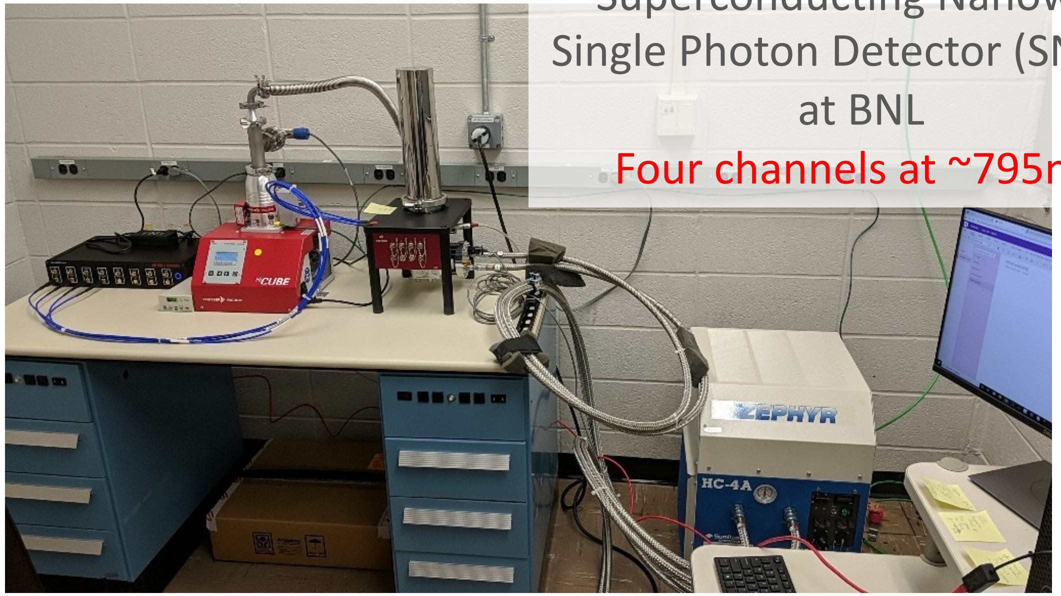
Reminder: HBT effect

"The birth of quantum optics"





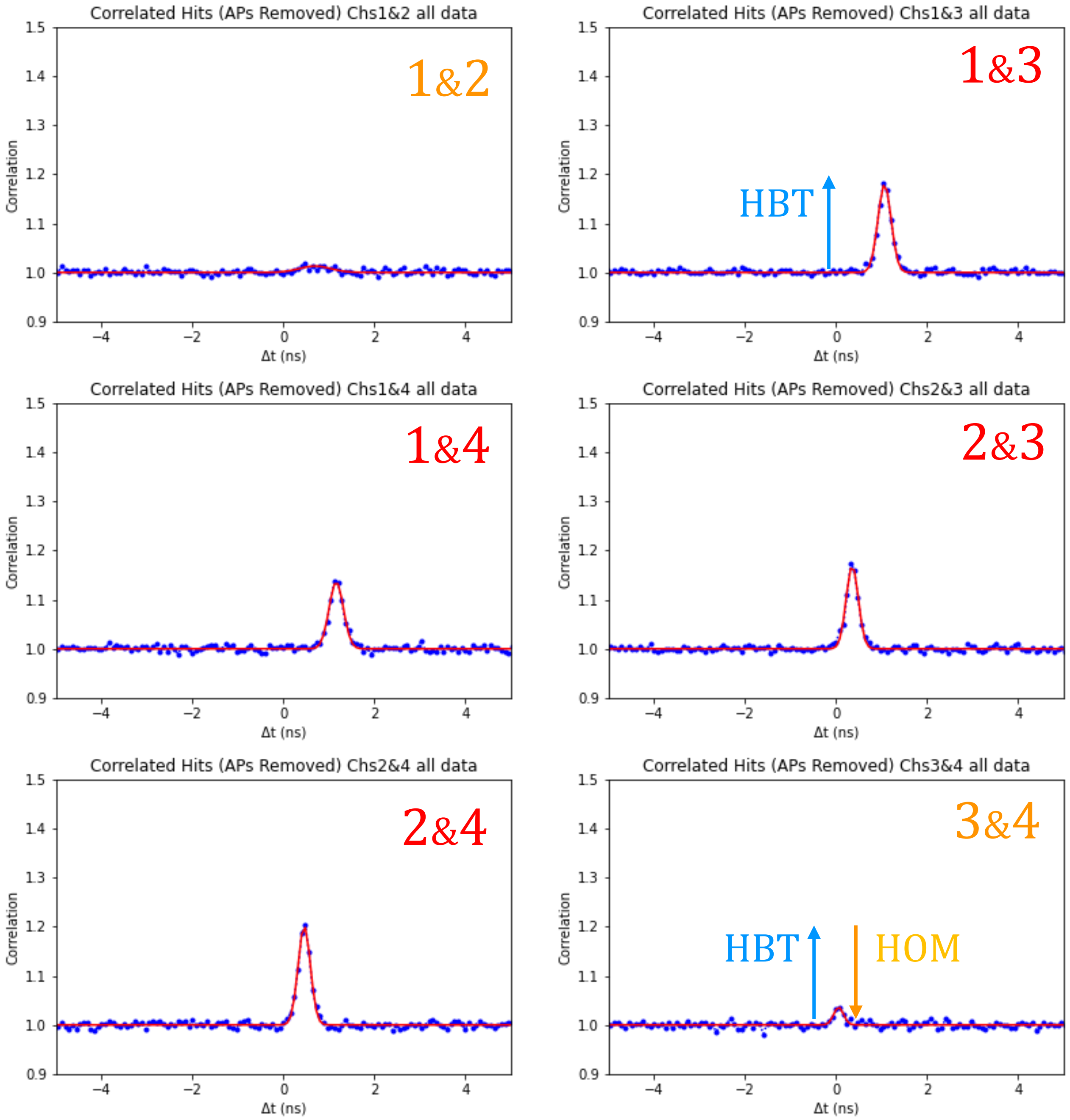


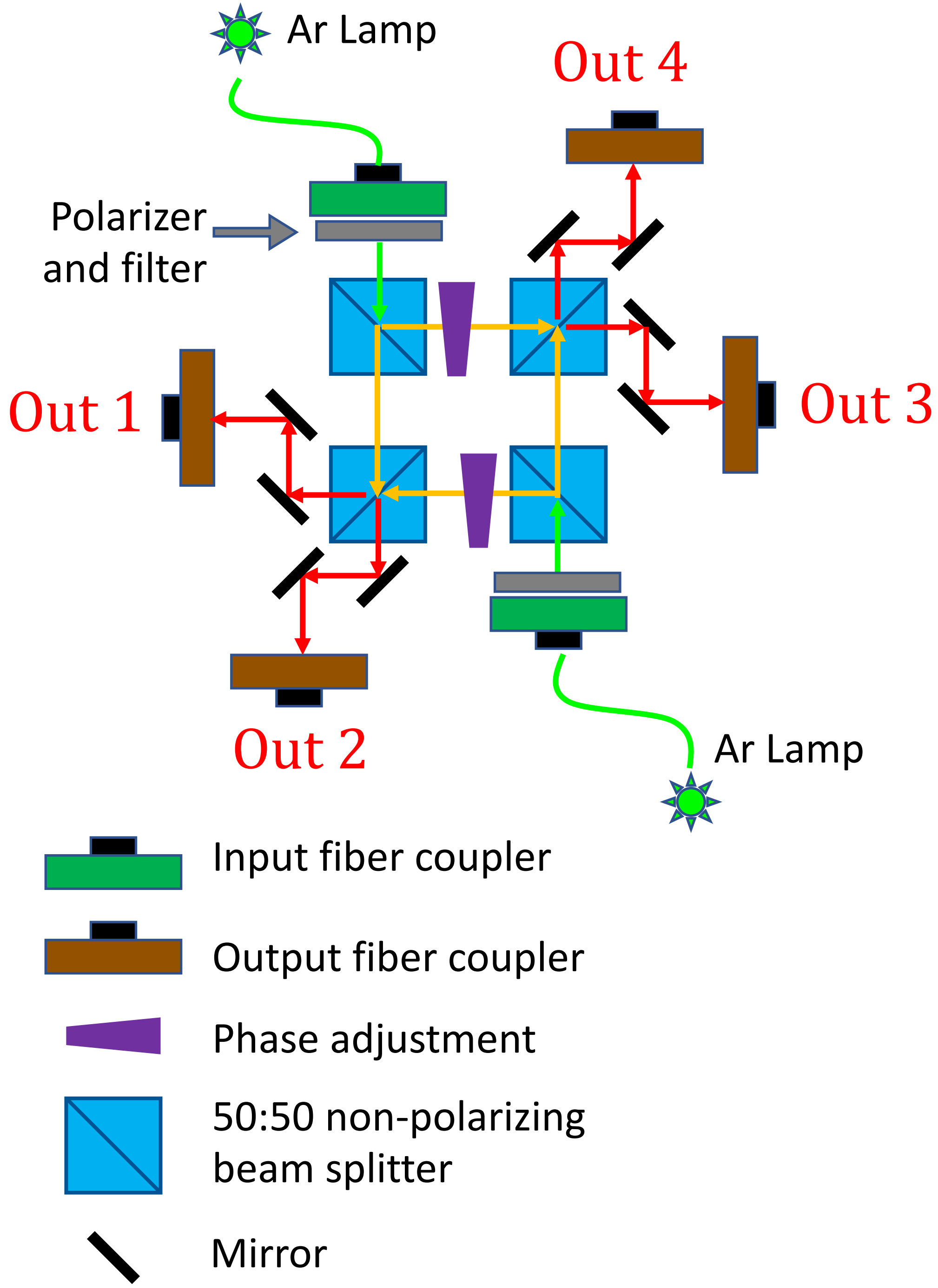


Superconducting Nanowire Single Photon Detector (SNSPD) at BNL

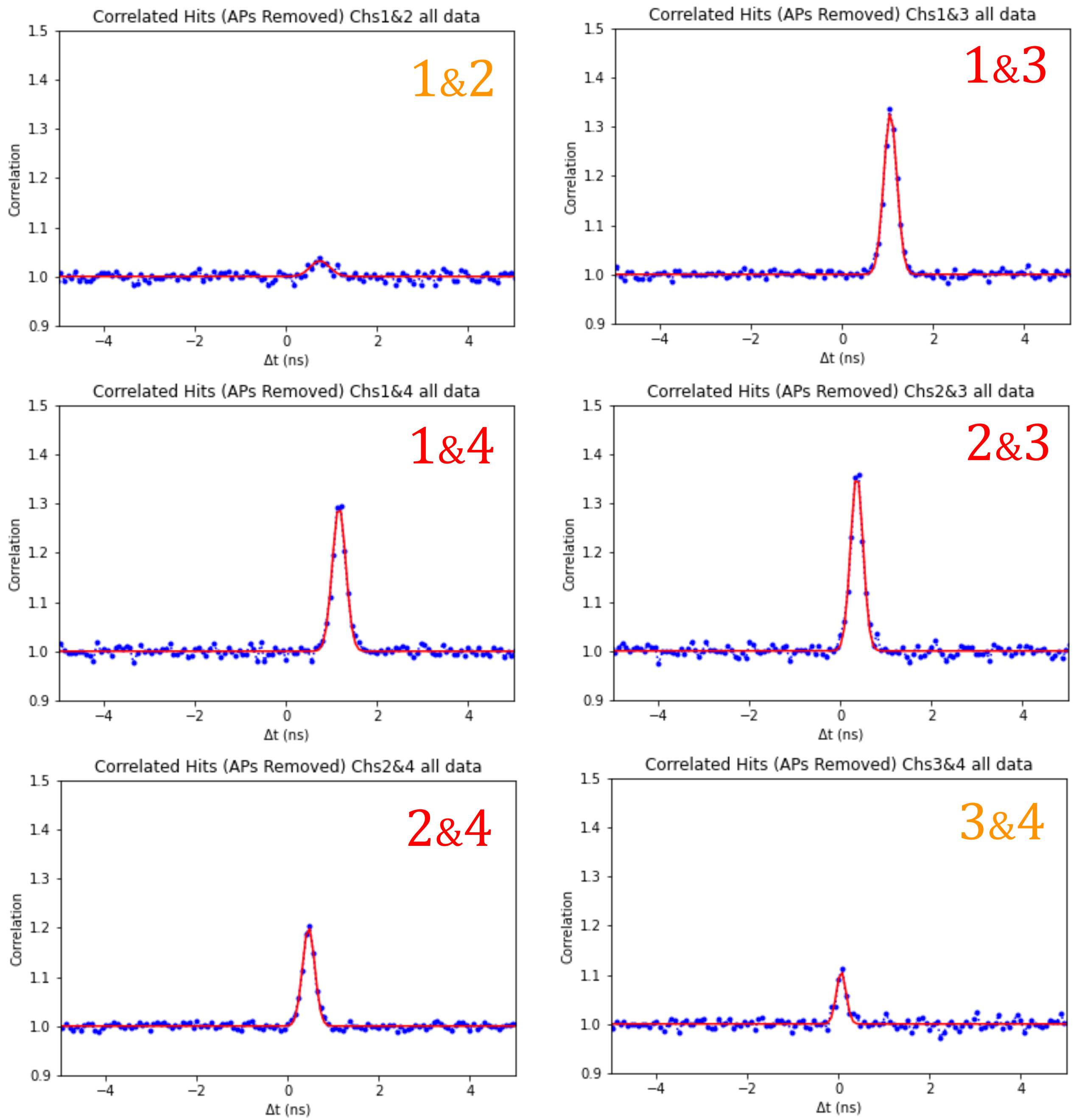
Four channels at ~795nm

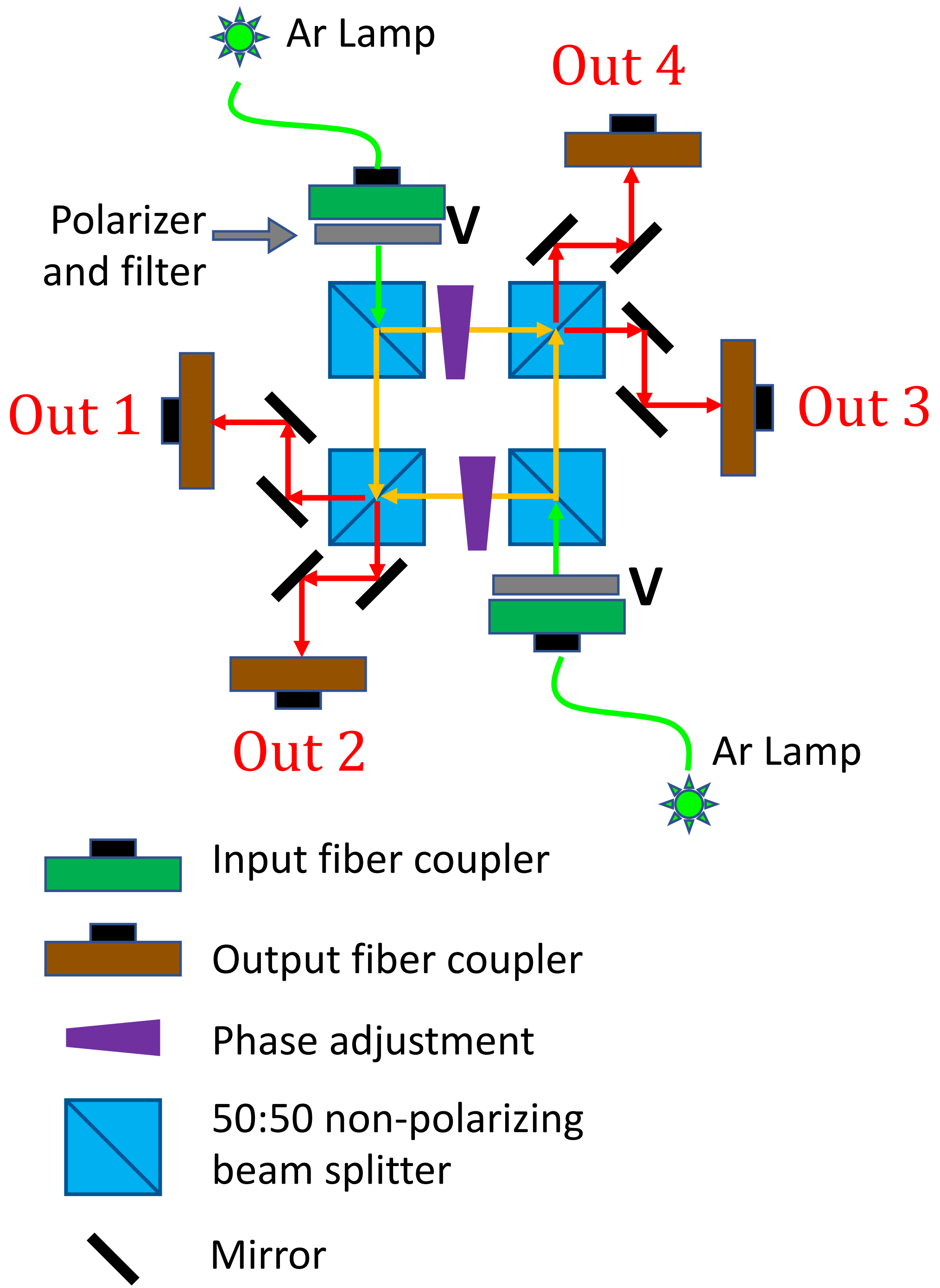
Unpolarized



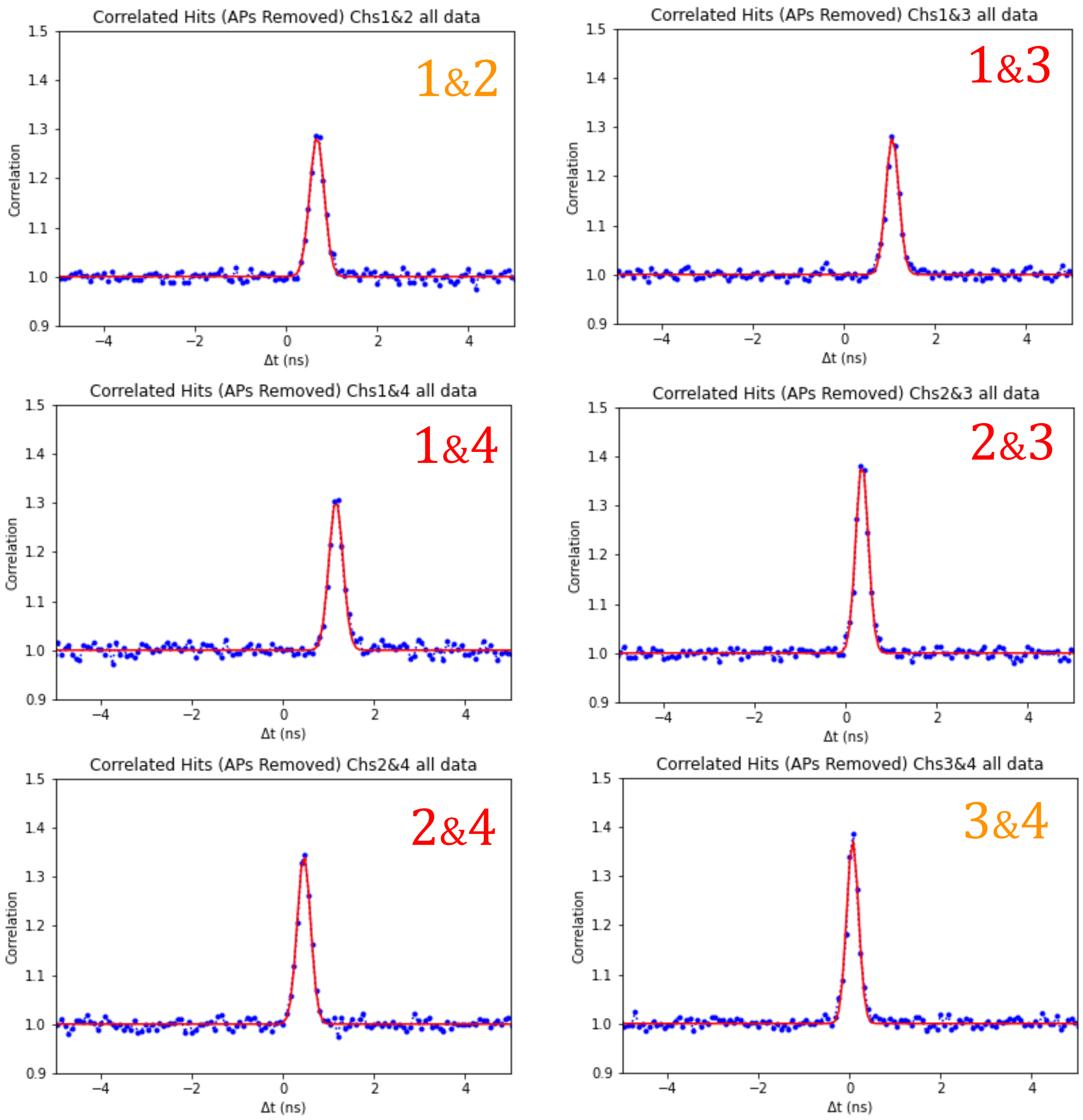


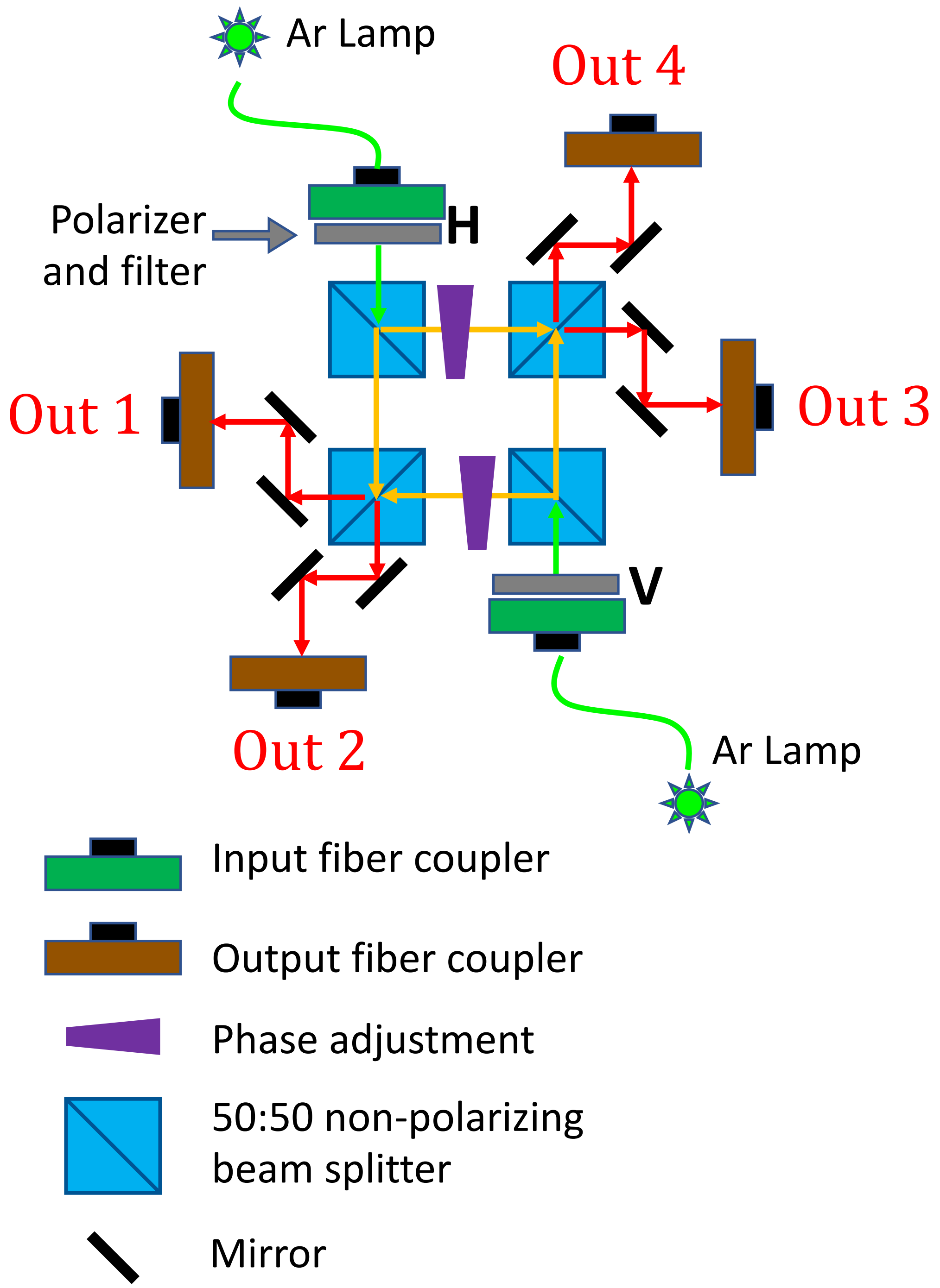
Polarized – V V



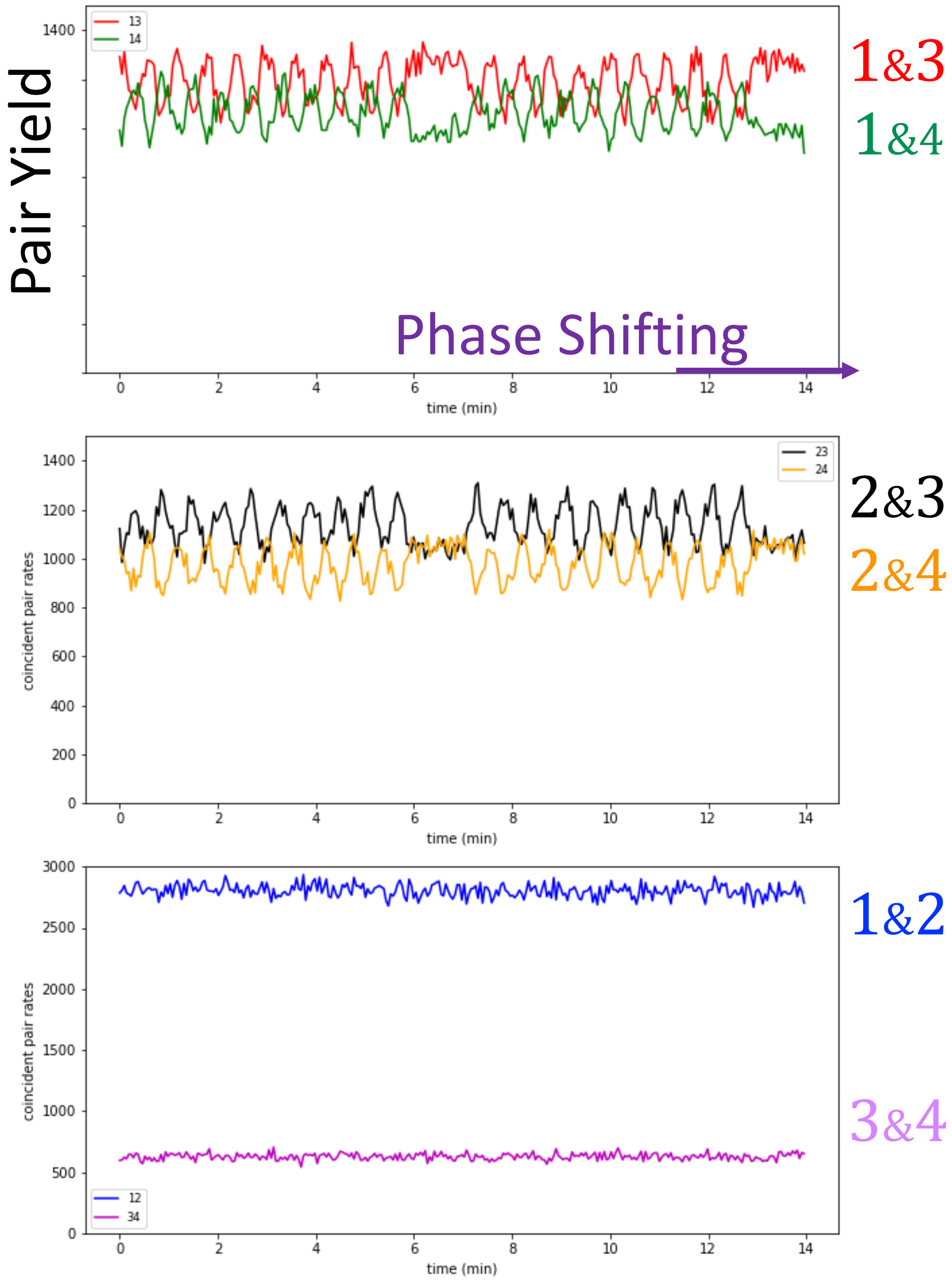


Polarized – V H

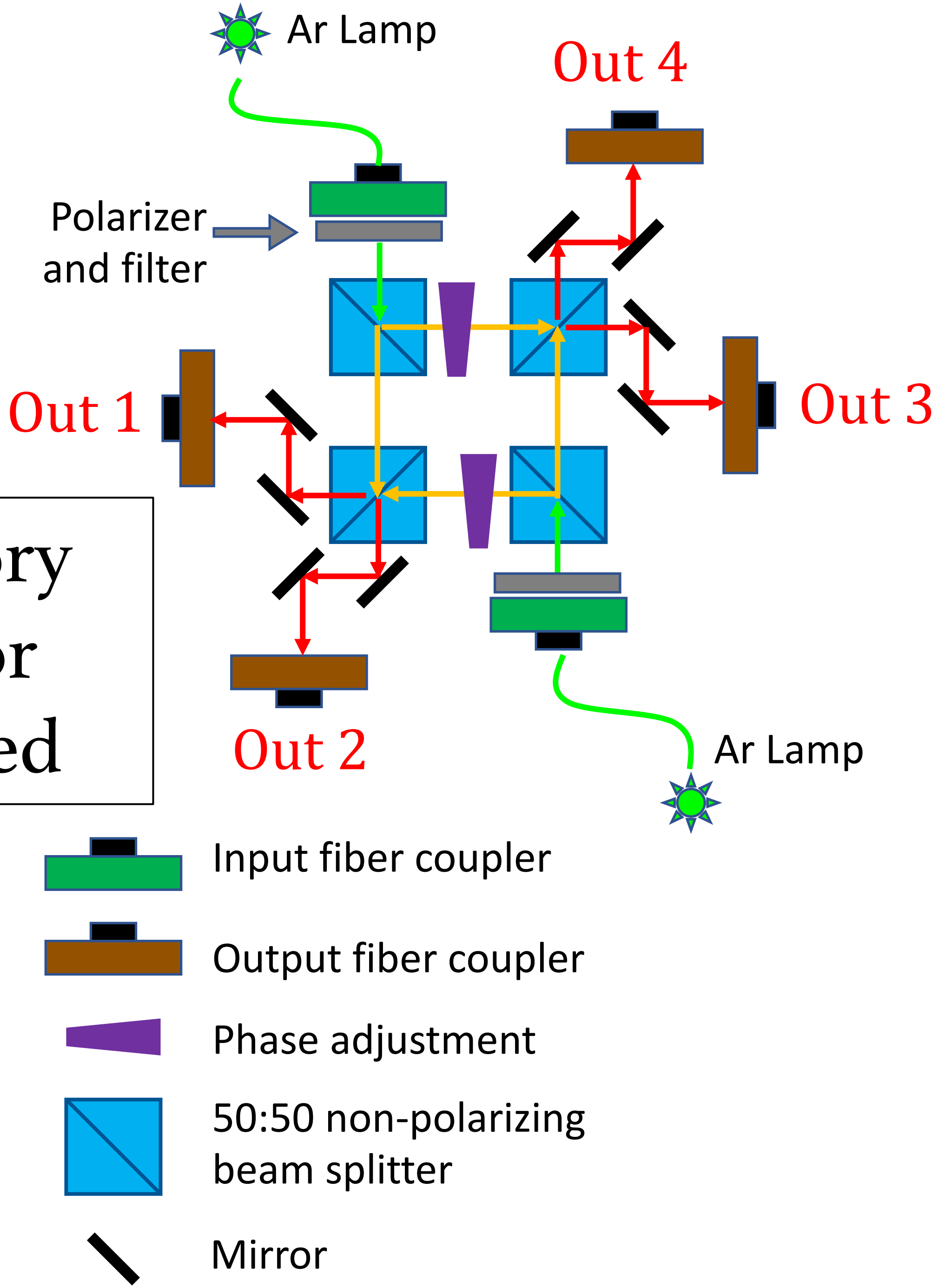




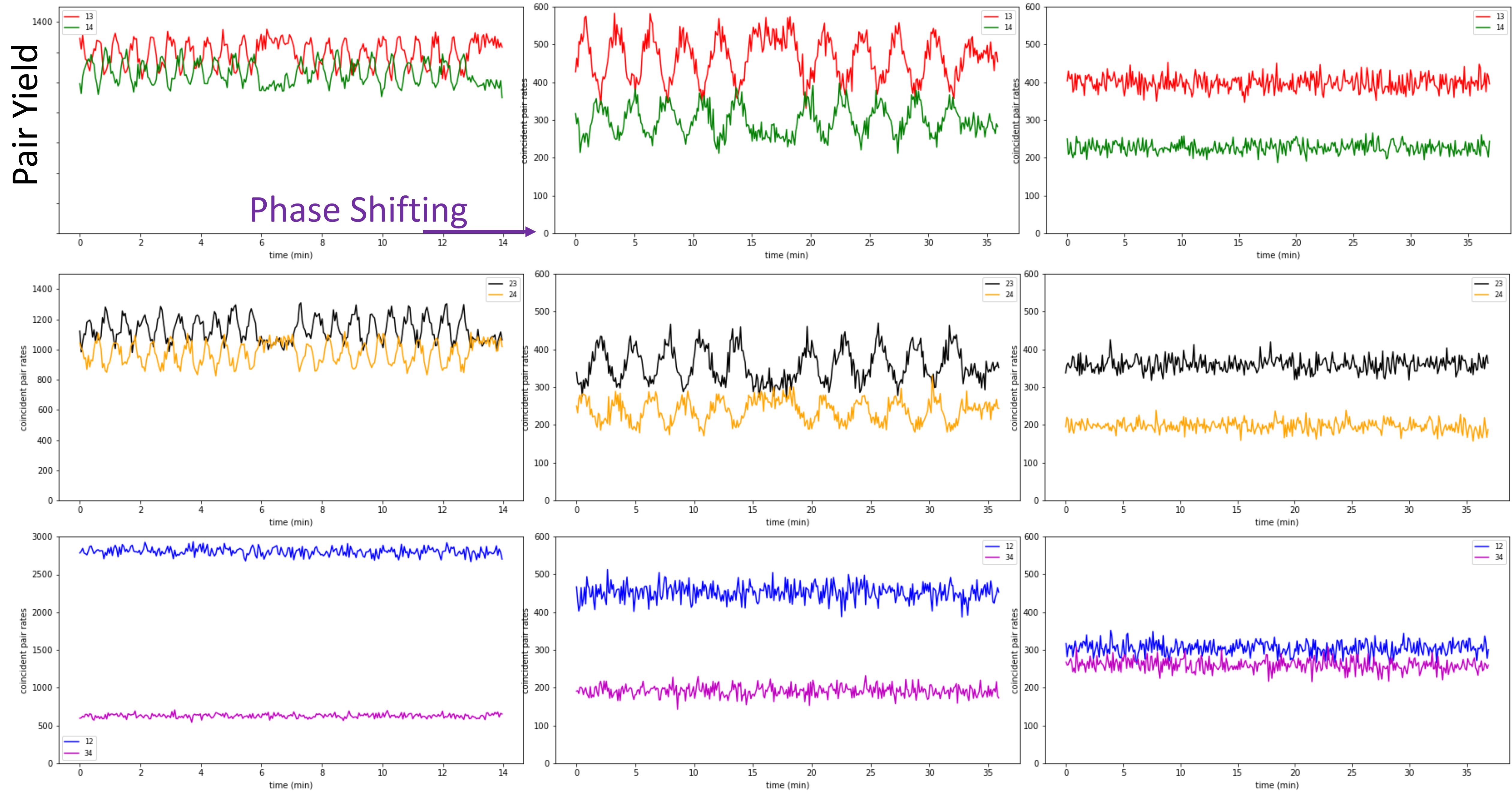
Unpolarized



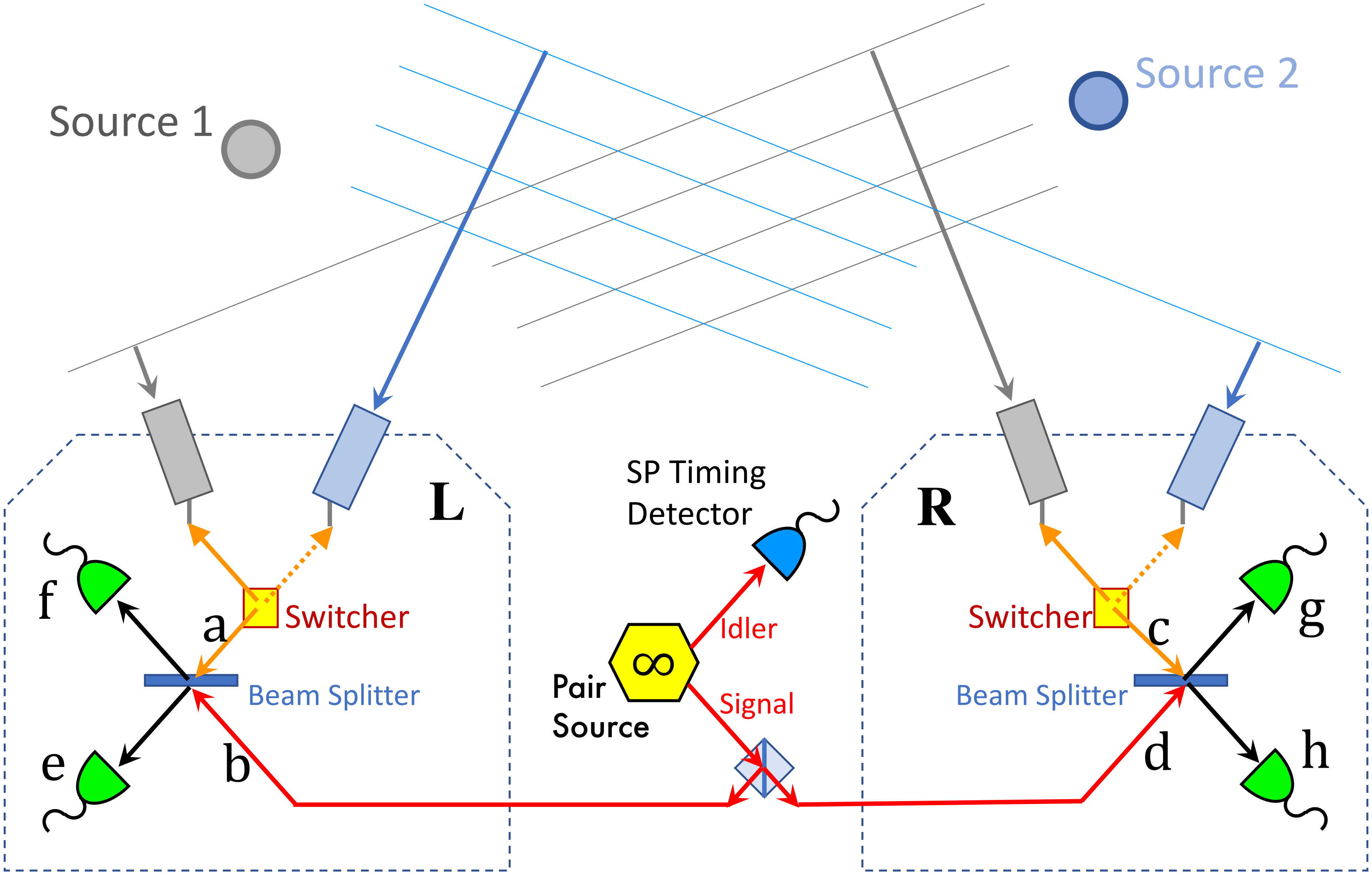
Oscillatory behavior confirmed



Unpolarized | **Polarized – V V** | **Polarized – V H**



Idea 2: “Switched” config for astrometry

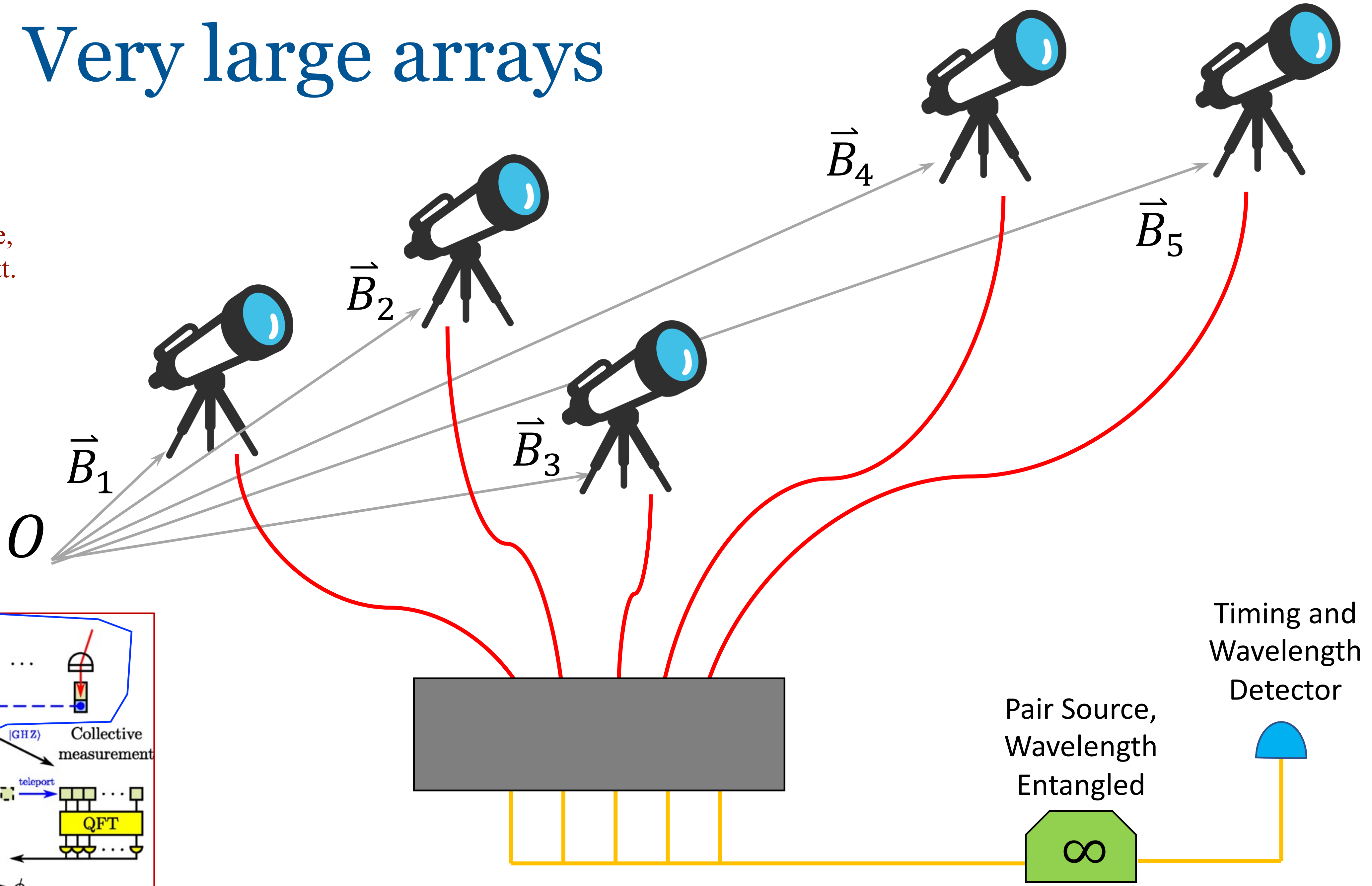


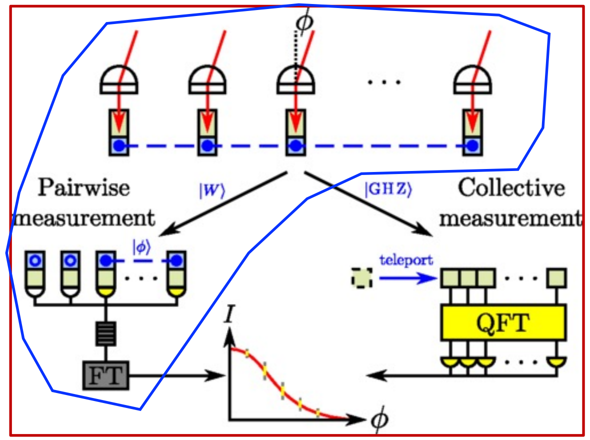
Does *not* require a coincidence from two sky objects; great improvement for faint sources.

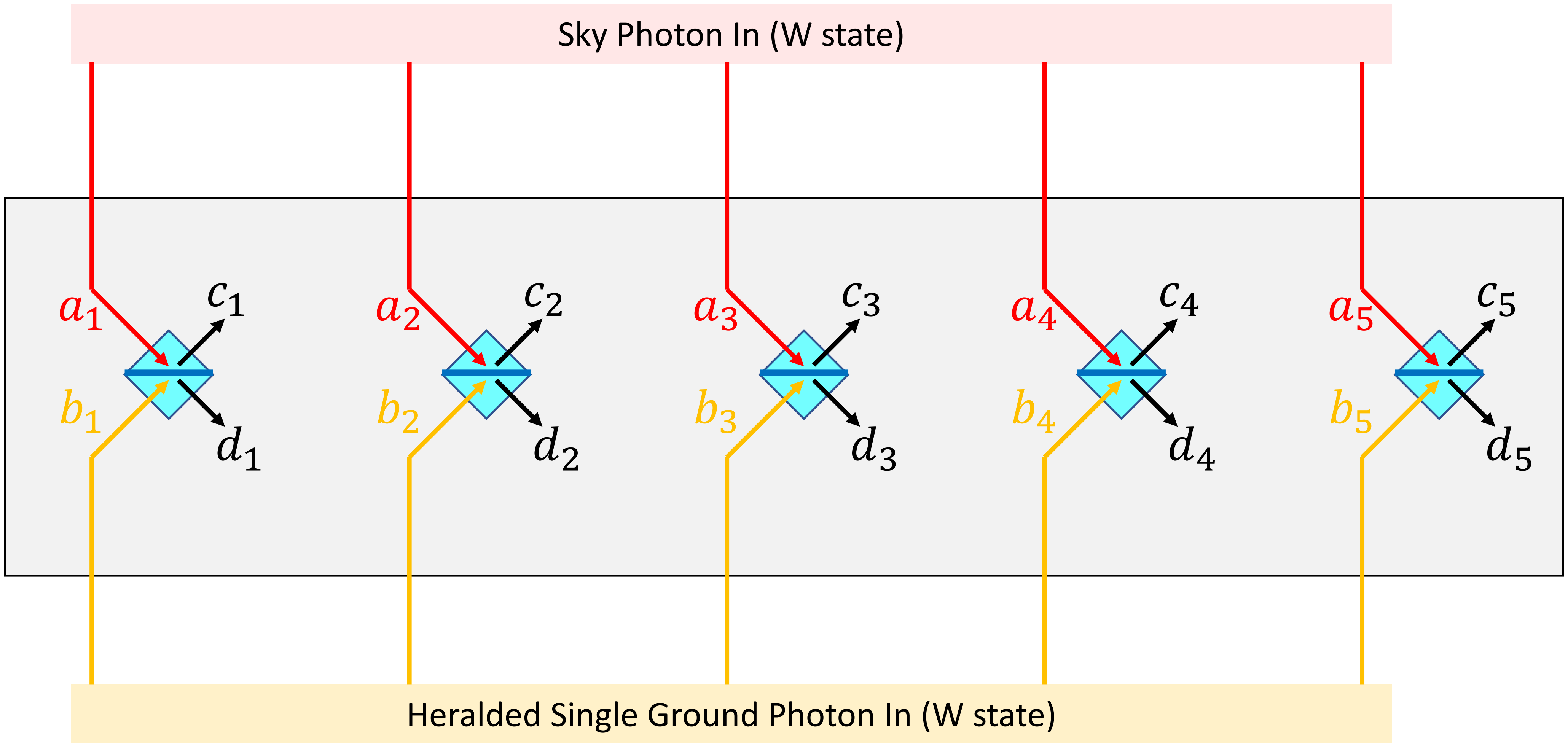
Stable against (slow) ground path changes.

Idea 3: Very large arrays

GJC; see also Khabiboulline, Borregaard, De Greve, Lukin, Phys. Rev. Lett. 123, 070504 (2019)







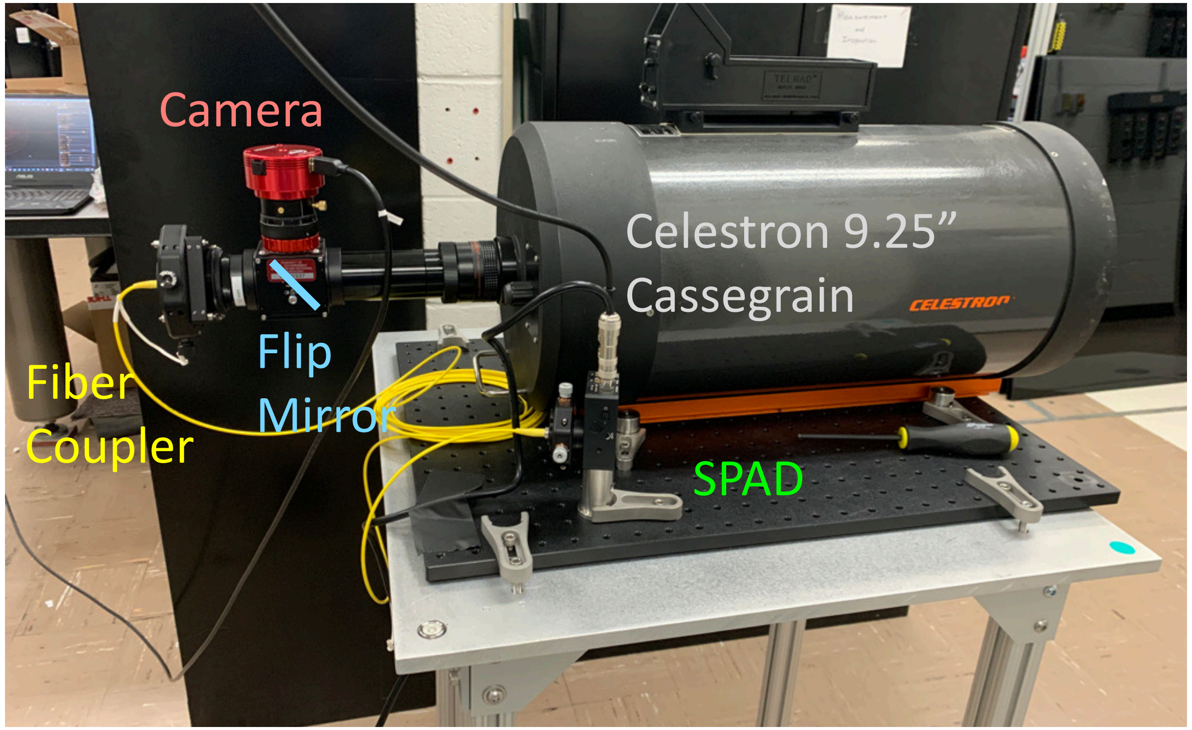
Quantum Advantage! Each coincidence between i and j reflects interferometric visibility on baseline $\vec{B}_i - \vec{B}_j$; achieve an N-aperture interferometer with only N beam combiners, rather than $O(N^2)$ that would be required classically.

Shopping list

- Field-deployable single photon detectors with ~nanosecond resolution
- Arrays of nanosecond SPD's with spectrographic separation
- Telescopes able to focus stably into single mode (e.g. SM fiber)
- High-rate source of energy-entangled photon pairs

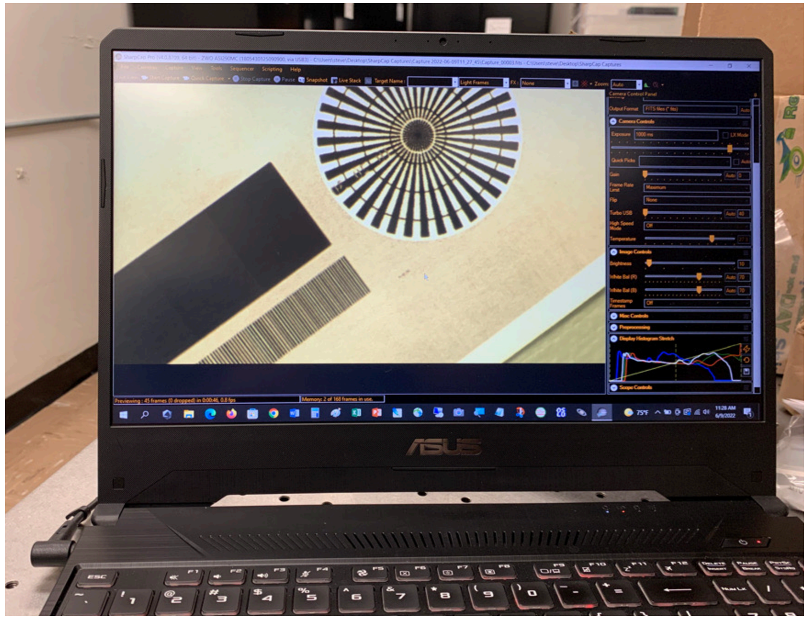
Not a dream but realistic IMO: everything either available now or can be soon.

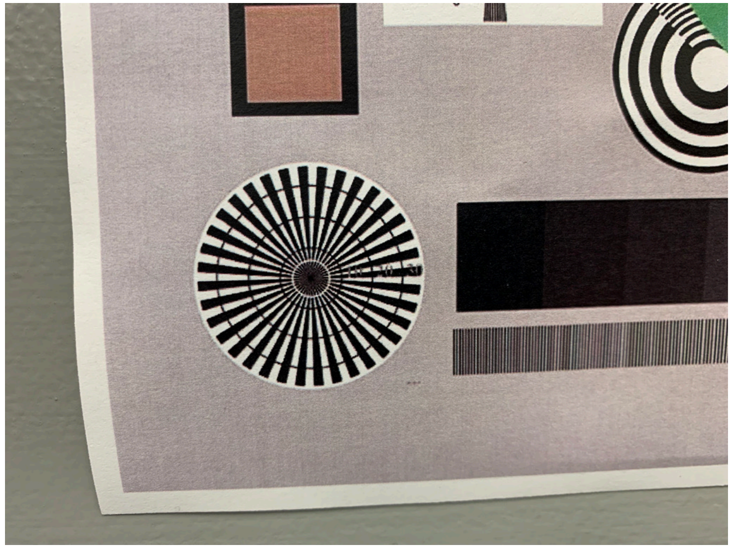
We can build an on-sky experiment with demonstrated quantum advantage for astronomy in the next few years.

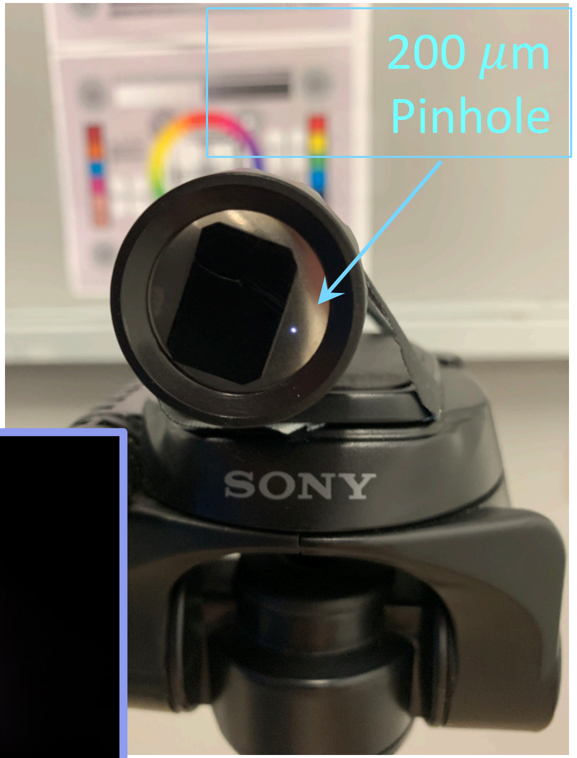


Testing point source to fiber coupling through small telescope in the lab.

Next step: outdoors.

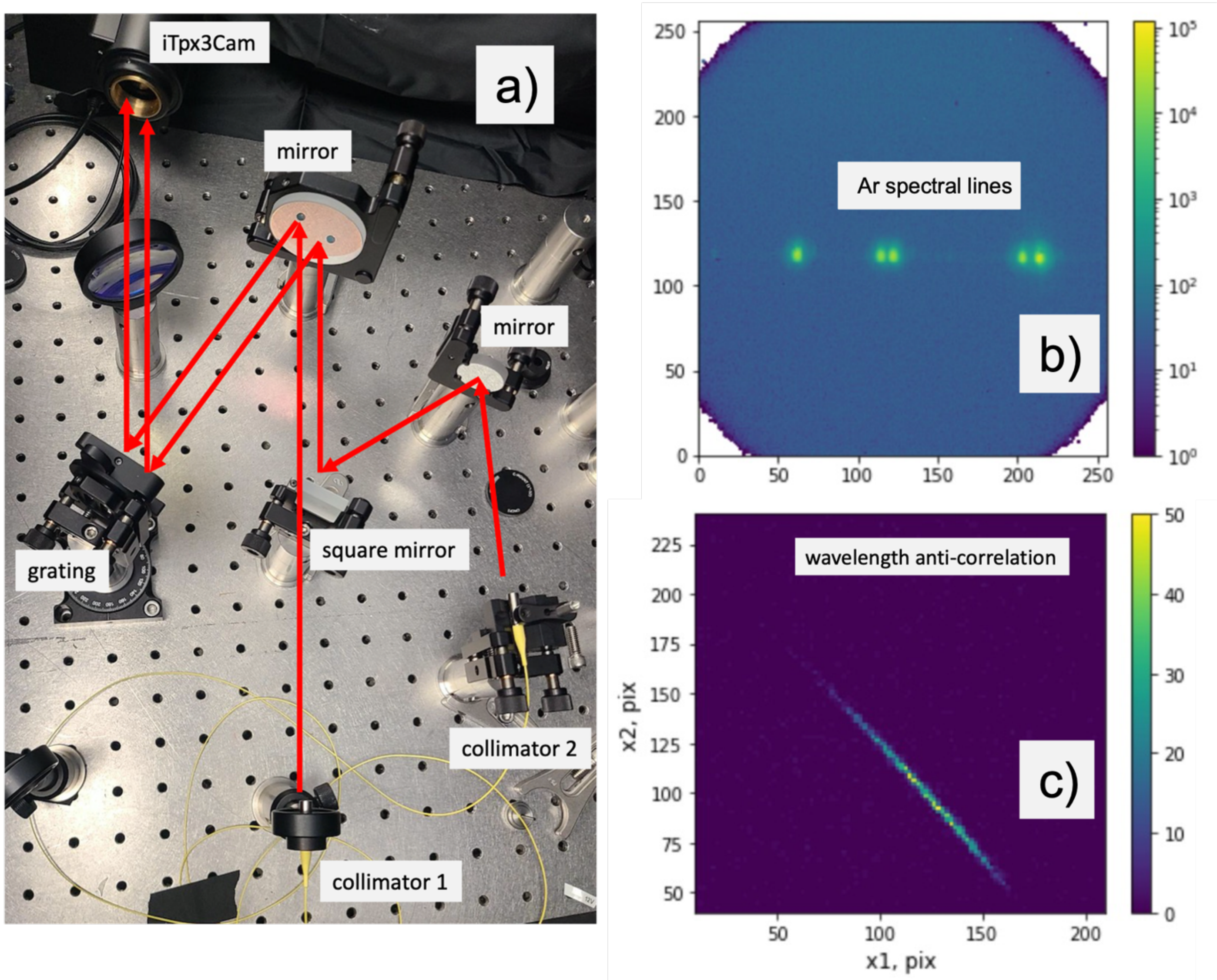






Spectrographic fast pixels

Single-mode fiber-fed twin spectrograph onto fast Si pixel array camera (256x256, ~nsec)



Spread of Ar spectral lines near 795nm

Anticorrelation between wavelengths of SPDC pairs

Impacts for cosmology and astrophysics

Qualitatively better astrometric precision can yield:

- Improved parallax-based distance measurements; H_0 tension
- Mapping orbits of binaries; independent distance measurements
- Improved proper motions, relevant to galactic dark matter

Astrometry and imaging on faint objects:

- Parallax with galaxies
- Microlensing in real time

And more:

- Gravitational wave detection through coherent stellar motion
- Exoplanet spectra through precision nulling

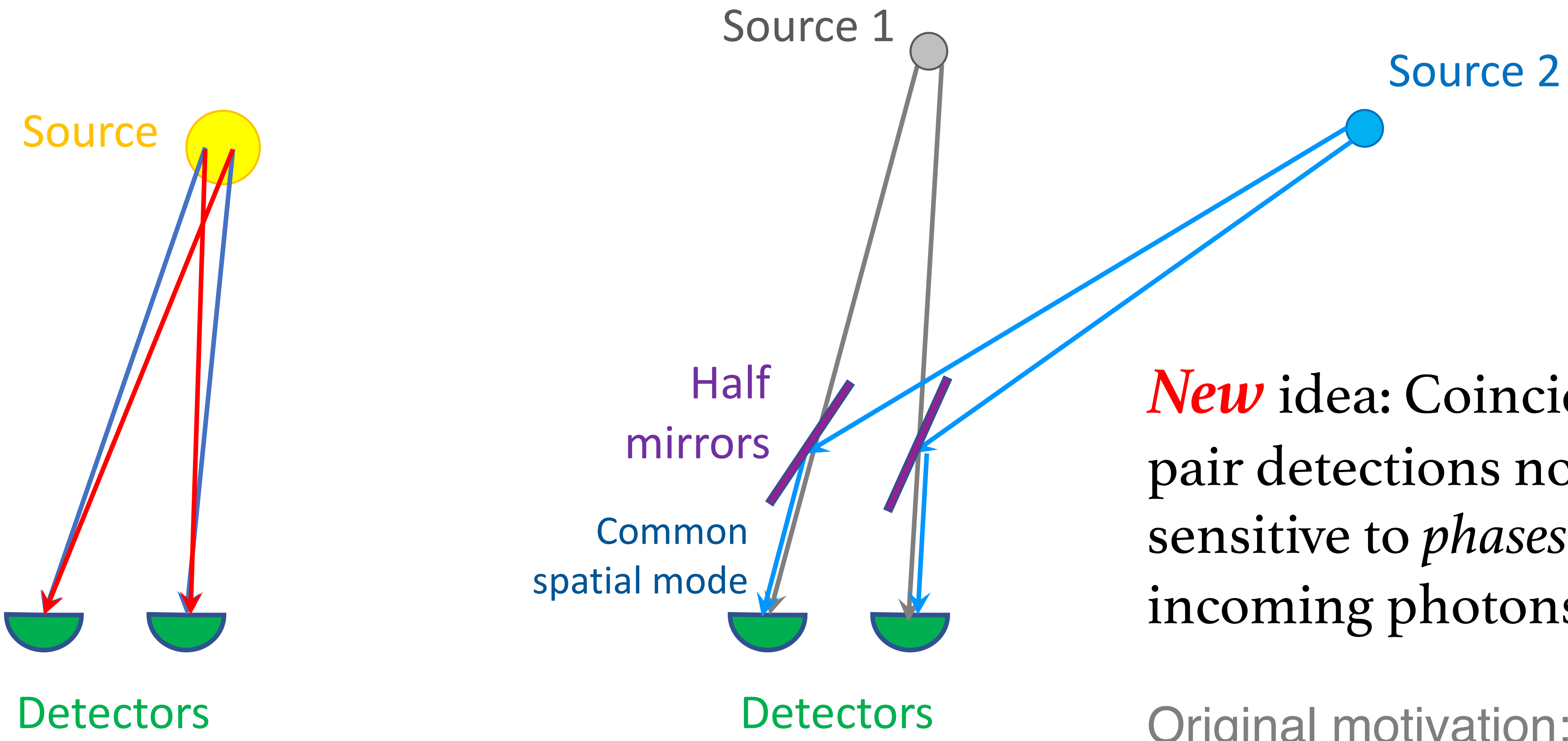
Summary

- Long-baseline, high-resolution optical interferometry has great scientific -- and possibly also commercial? – value
- Long baseline inteferometers can gain *quantum advantage* from (i) single photon generation, (ii) long-distance entanglement preparation/teleportation, (iii) quantum memory storage
- Two–photon technique of GJC now extended to use two sky photons for quantum-assisted *astrometry* science application; bench demonstrations shown, on sky soon
- Very promising development path immediately ahead: switching, energy entangled pairs, *W* state distribution, very large arrays

BNL effort supported by DOE HEP QuantiSED grant; see our work at
https://www.quantastro.bnl.gov

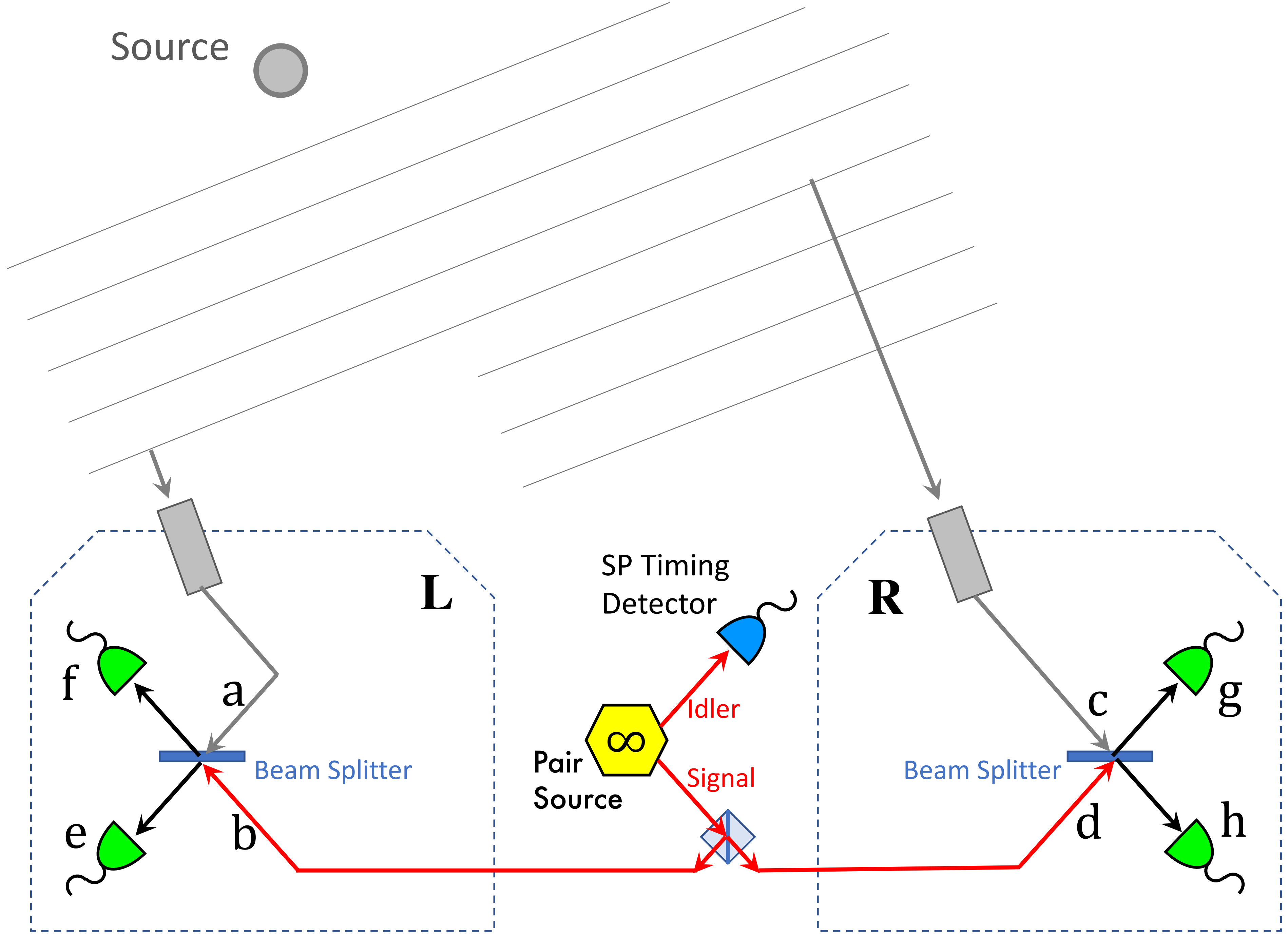
Backup

HBT with two, separated sources



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

Original motivation: gravitational waves


Source
L
R
SP Timing
Detector
Idler
Pair
Source
Signal
f
a
e
b
Beam Splitter
Beam Splitter
c
g
d
h

Idea 0.5

Can now run 10^3-10^4 experiments at once (!), each in a spectral bin of width $\Delta\upsilon \sim 1/\tau_{Detector}$