Quantum Astrometry

Raphael Akel Abrahao

Department of Physics

Aug 25 2023

1. Introduce myself
2. An example of how quantum optics improves imaging
3. Quantum Astrometry
   A. Theory
   B. Proof-of-principle demonstration
   C. Spectrometer


Venezuela
Guyana
Colombia
Suriname
RR
AP
Ecuador
AM
PA
MA
CE
RN
PB
PI
PE
Brazil
AC
AL
Peru
RO
TO
SE
BA
MT
GO
Bolivia
MG
ES
MS
SP
RJ
Paraguay
PR
Chile
SC
RS
Uruguay
Argentina

Undergrad and Master’s

Electrical Engineering

UNICAMP

Spectral Analysis of five times ionized xenon

Atomic spectroscopy → Astronomy

PhD

Quantum Optics and Quantum Information

The University of Queensland
Australia

PostDoc

uOttawa

Brookhaven National Laboratory

I joined BNL in October 2022

Example: how quantum optics can improve spatial resolution of far away objects?

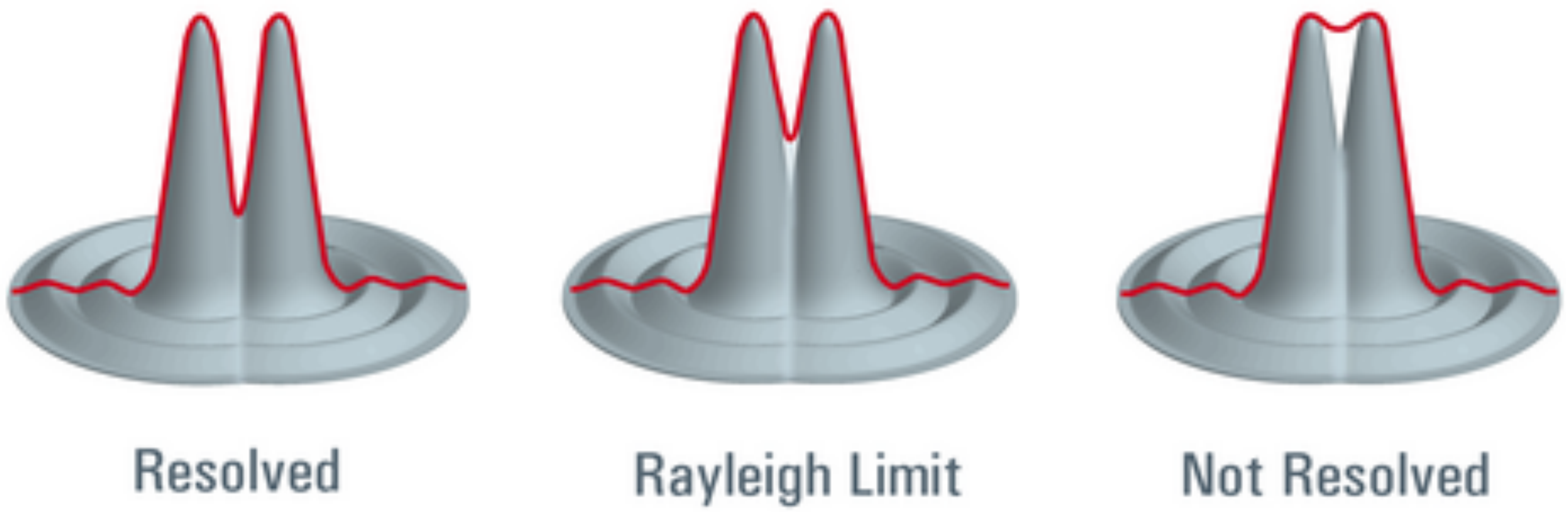
PHYSICAL REVIEW LETTERS **123,** 143604 (2019)

Optimal Imaging of Remote Bodies Using Quantum Detectors

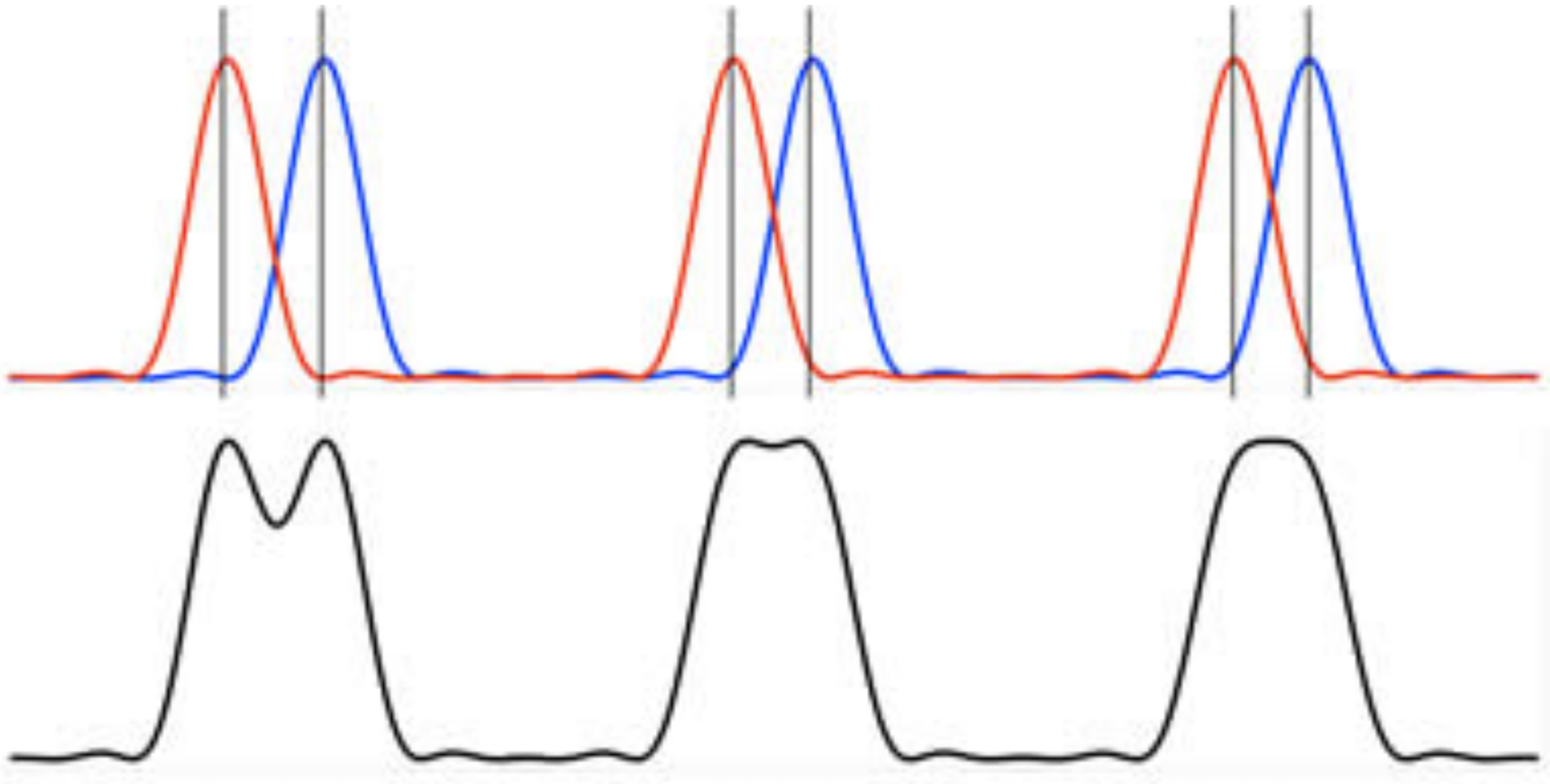
L. A. Howard,[1] G. G. Gillett,[1] M. E. Pearce,[2] R. A. Abrahao,[1] T. J. Weinhold,[1] P. Kok,[2] and A. G. White[1]
[1]*Centre for Engineered Quantum Systems, School of Mathematics and Physics, University of Queensland, 4072 Brisbane, Australia*
[2]*Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom*

Rayleigh, Abbe, and Sparrow limits

smallest resolvable feature
(laterally)



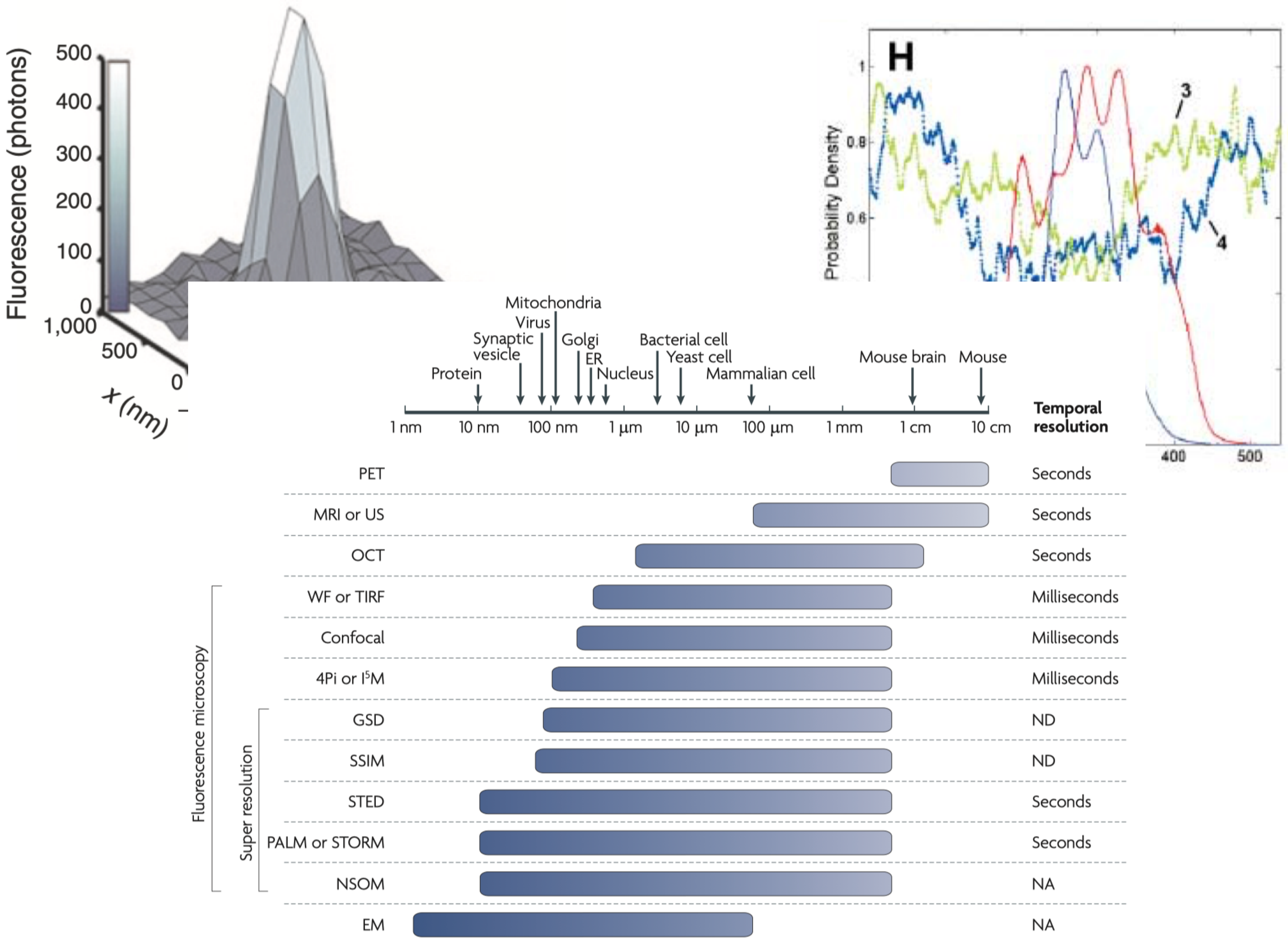
$$d = \frac{k}{2}\frac{\lambda}{n\sin\theta} = \frac{k}{2}\frac{\lambda}{\text{NA}}$$



$k = 1.22$	$k = 1$	$k = 0.94$
Rayleigh	Abbe	Sparrow

Circumventing the Rayleigh-Abbe limits

super-resolution techniques: exploit physical structure of the object



Rust, et al., *Nature Methods* **3**, 793 (2006)

Betzig, et al., *Science* **313**, 1642 (2006)

Fernández-Suárez et al.,
Nature Reviews Mol. Cell Bio. **9**, 929 (2008)

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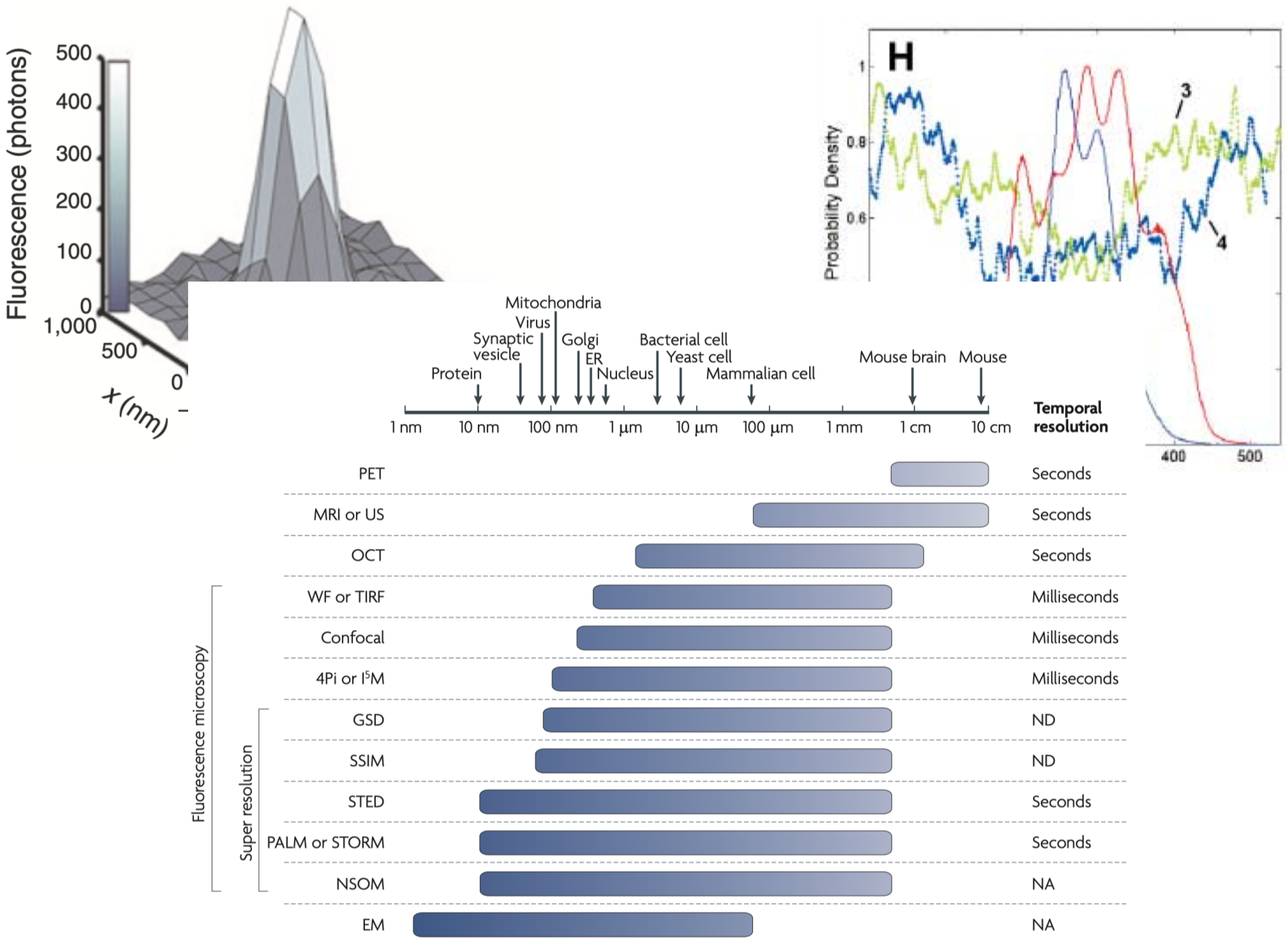

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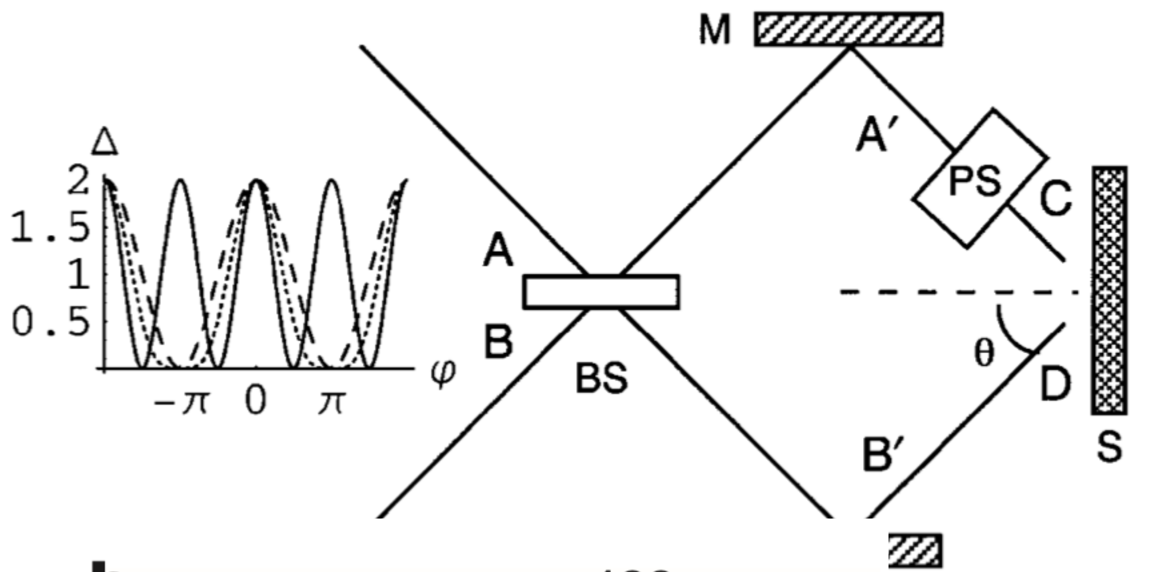
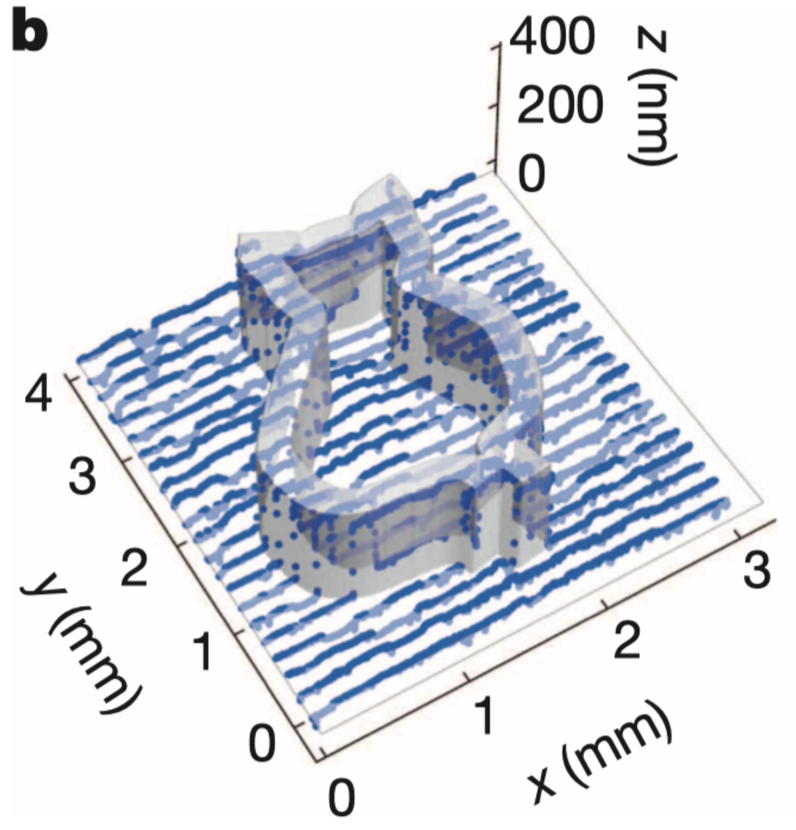
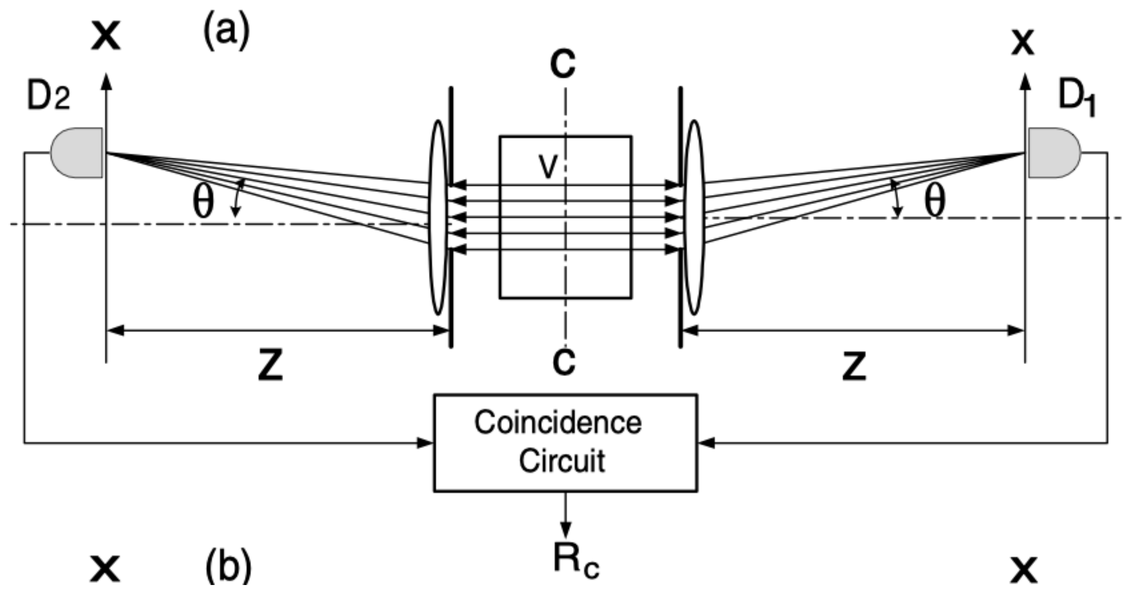
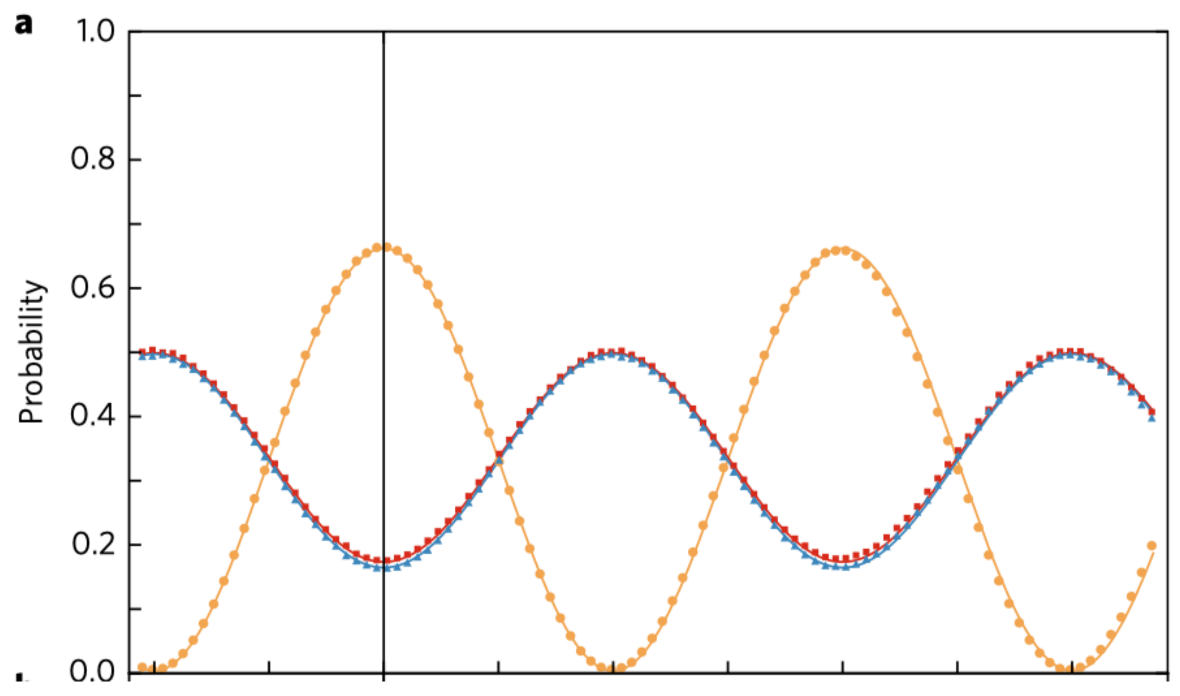
object illumination with entangled states of light









Boto, et al., *PRL* **85**, 2733 (2000)

D'Angelo, et al., *PRL* **87**, 777 (2001)

Lloyd, *Science* **321**, 1463 (2008)

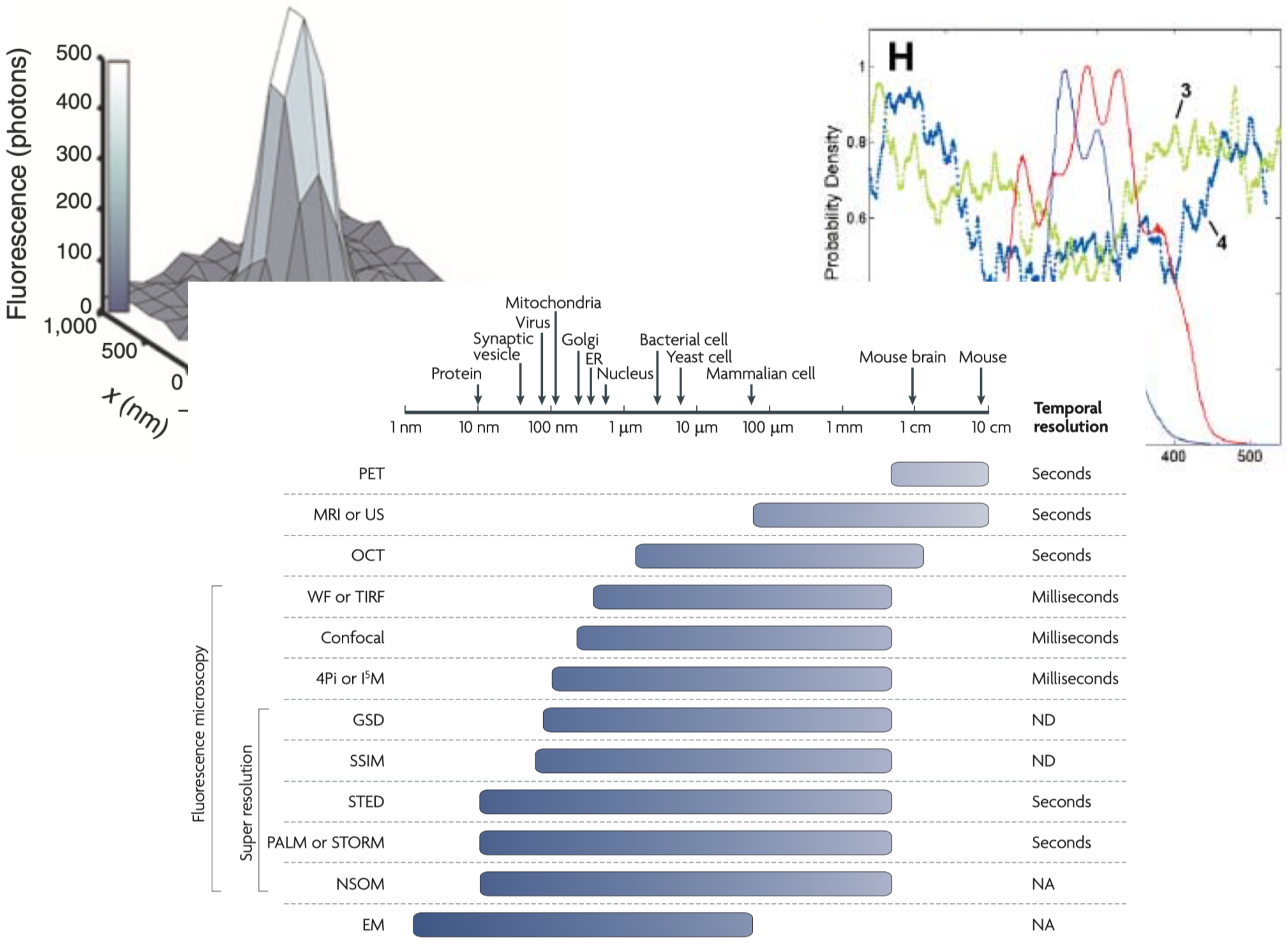
Lemos, et al., *Nature* **512**, 409 (2014)

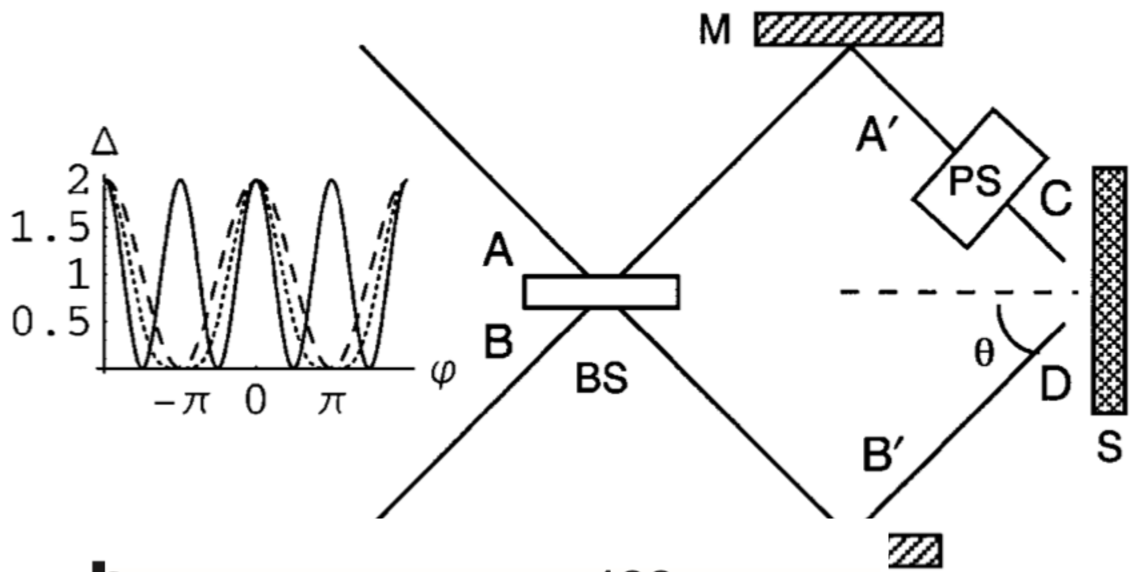
Slussarenko, *Nature Photonics* **11**, 700 (2017)

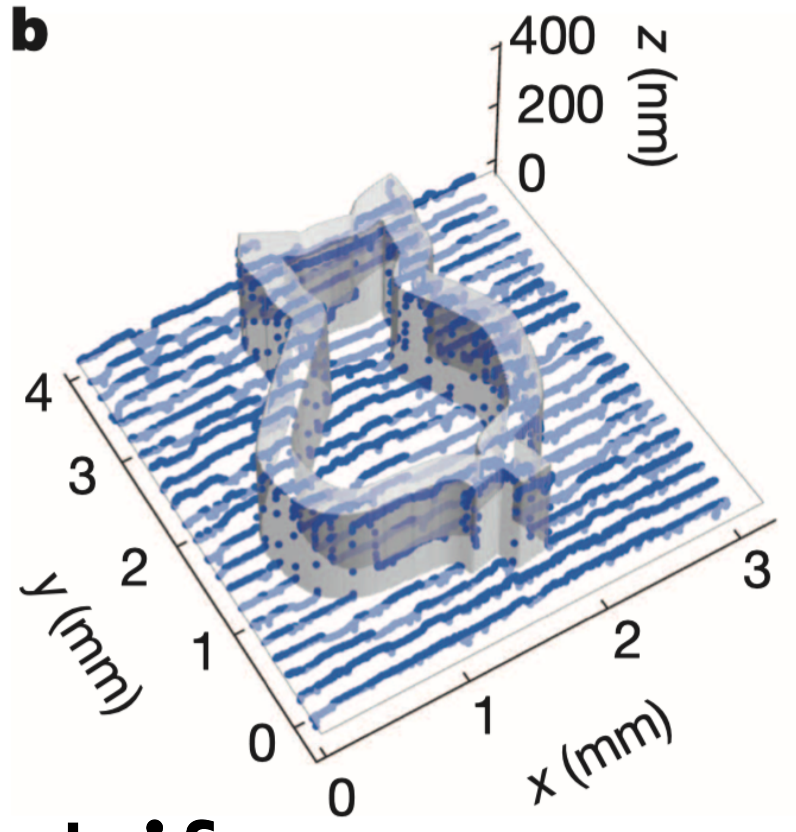
Circumventing the Rayleigh-Abbe limits

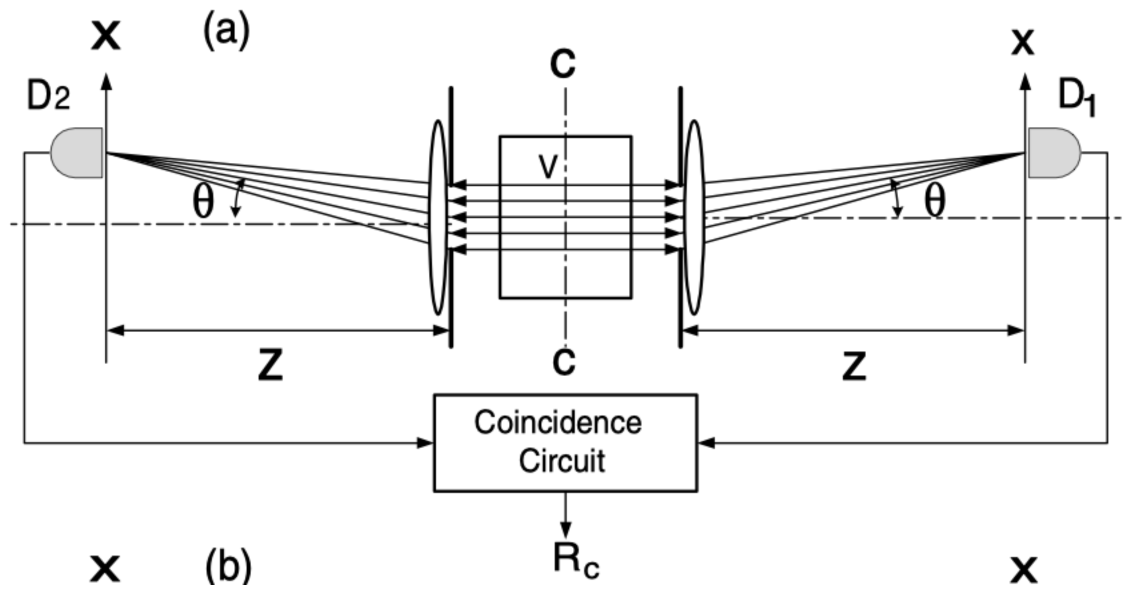
super-resolution techniques: exploit physical structure of the object

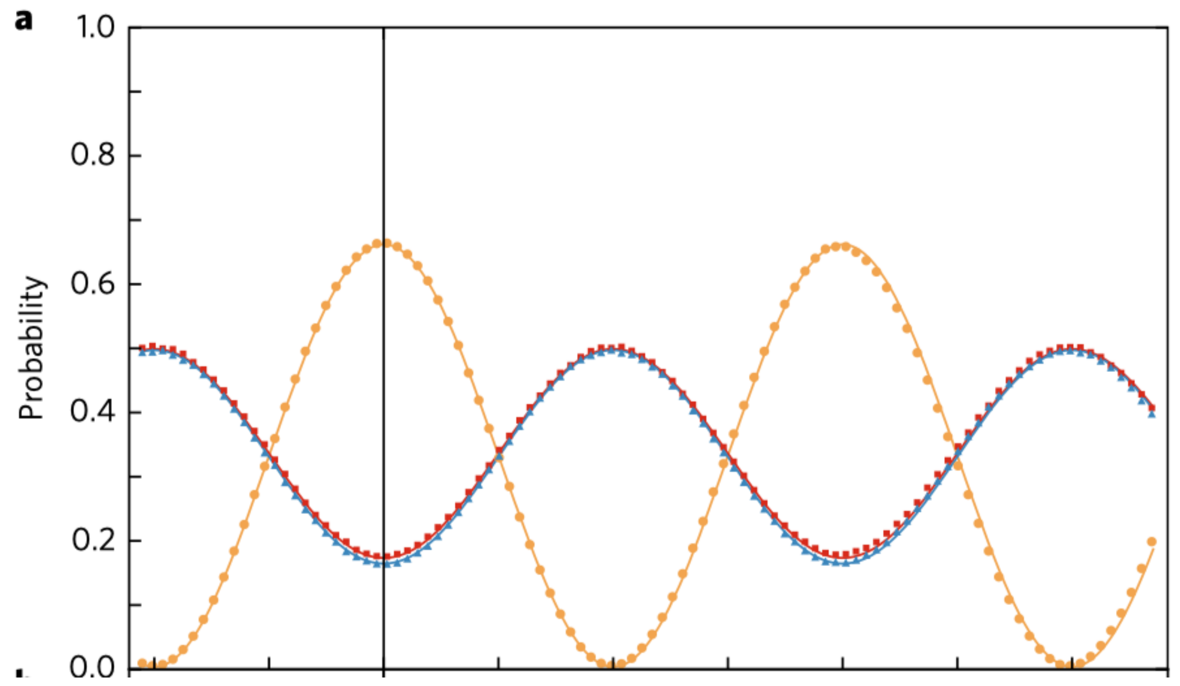
object illumination with entangled states of light











what if object is remote and unknown?

Rust, et al., *Nature Methods* **3**, 793 (2006)

Betzig, et al., *Science* **313**, 1642 (2006)

Fernández-Suárez et al.,
Nature Reviews Mol. Cell Bio. **9**, 929 (2008)

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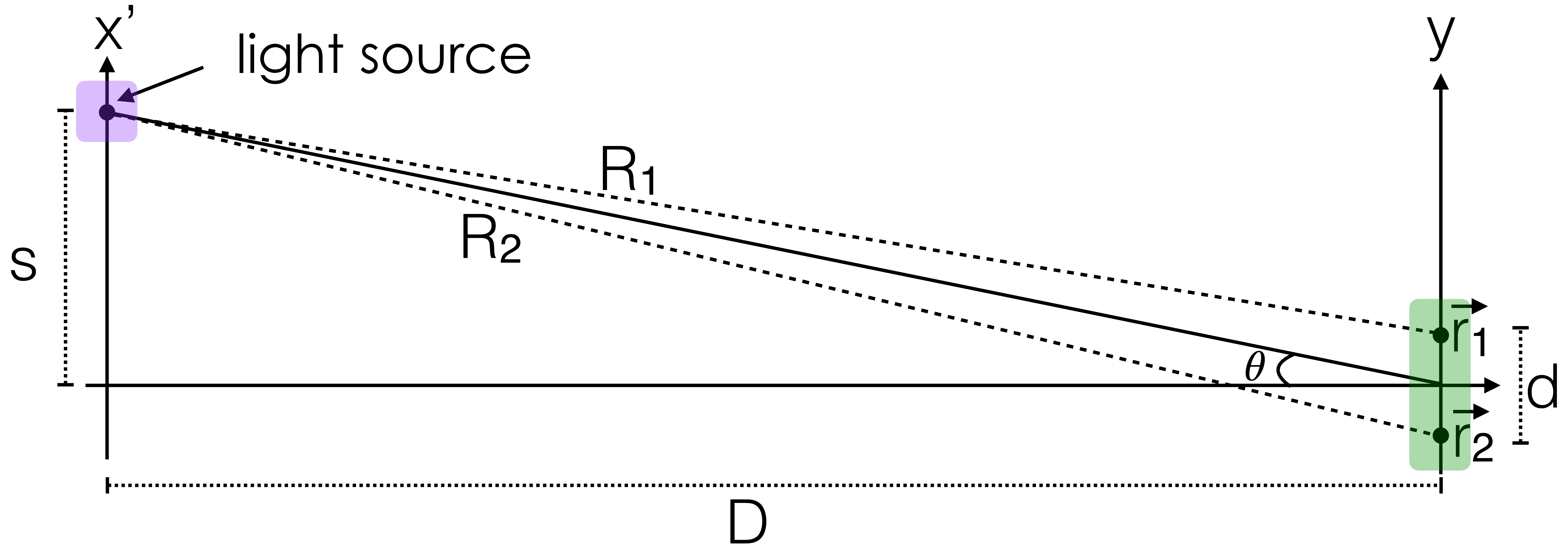
Lloyd, *Science* **321**, 1463 (2008)

Lemos, et al., *Nature* **512**, 409 (2014)

Slussarenko, *Nature Photonics* **11**, 700 (2017)

Complex degree of coherence

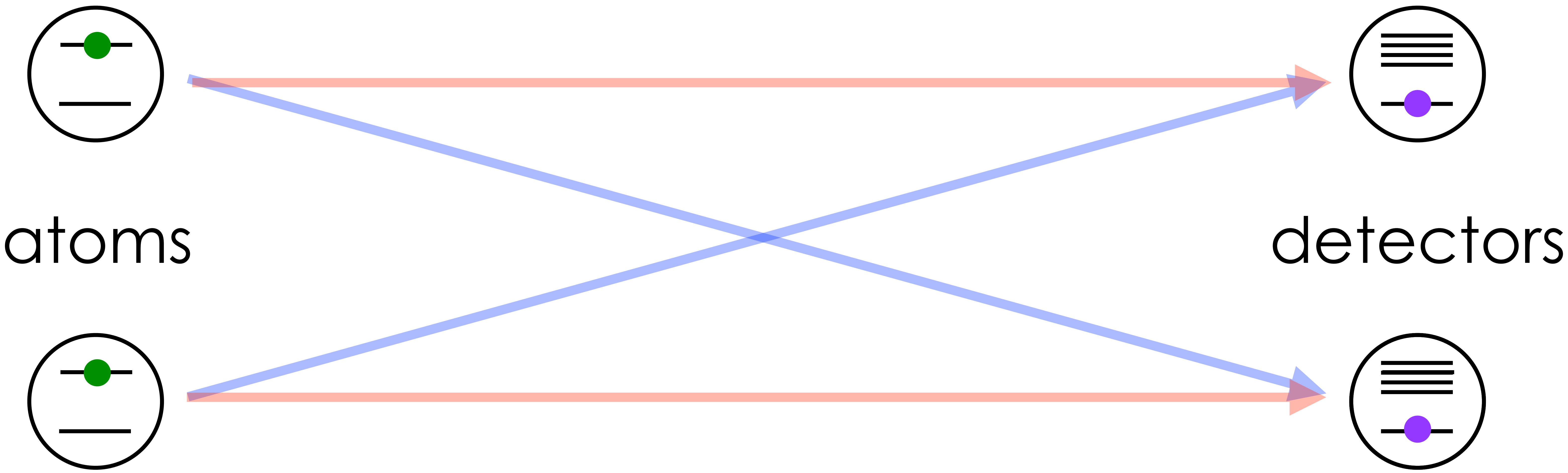
$$\gamma(\mathbf{r}_1, \mathbf{r}_2) = |\gamma| e^{i\phi}$$



van Cittert-Zernike theorem relates the CDC to the source distribution via a 2D Fourier transform

Measuring the CDC: Traditional method

Hanbury Brown — Twiss effect



two paths for light to go from atoms to detectors

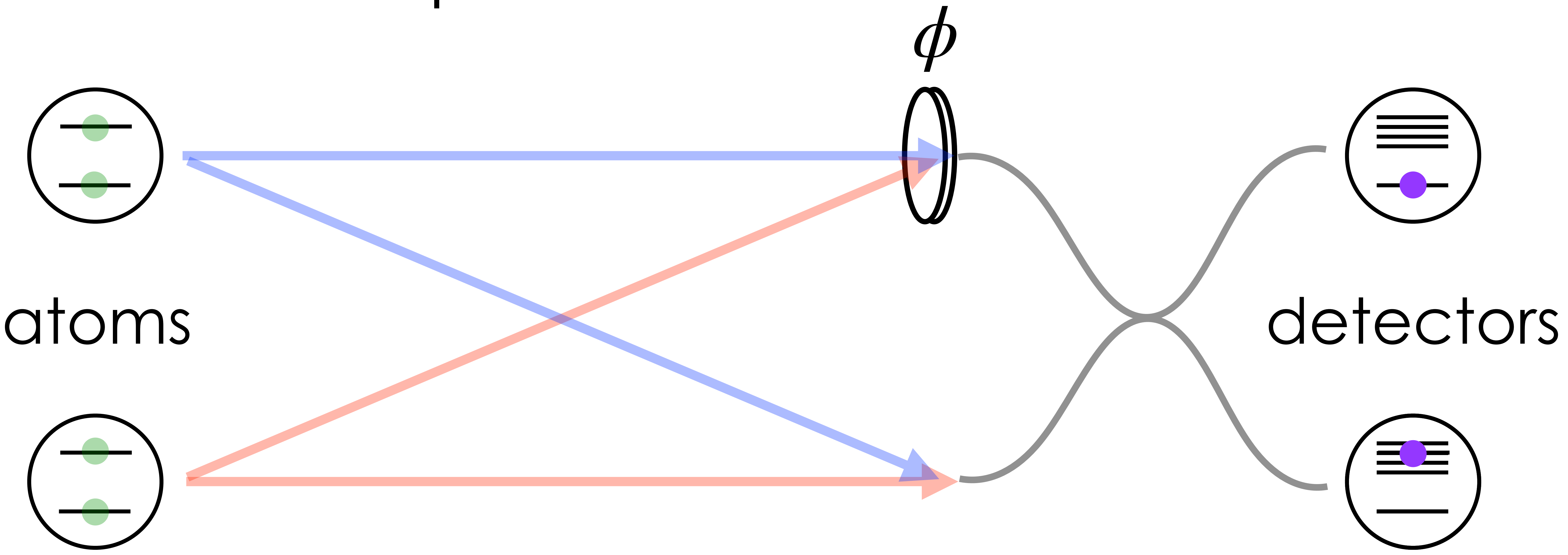
amplitudes of the two paths interfere

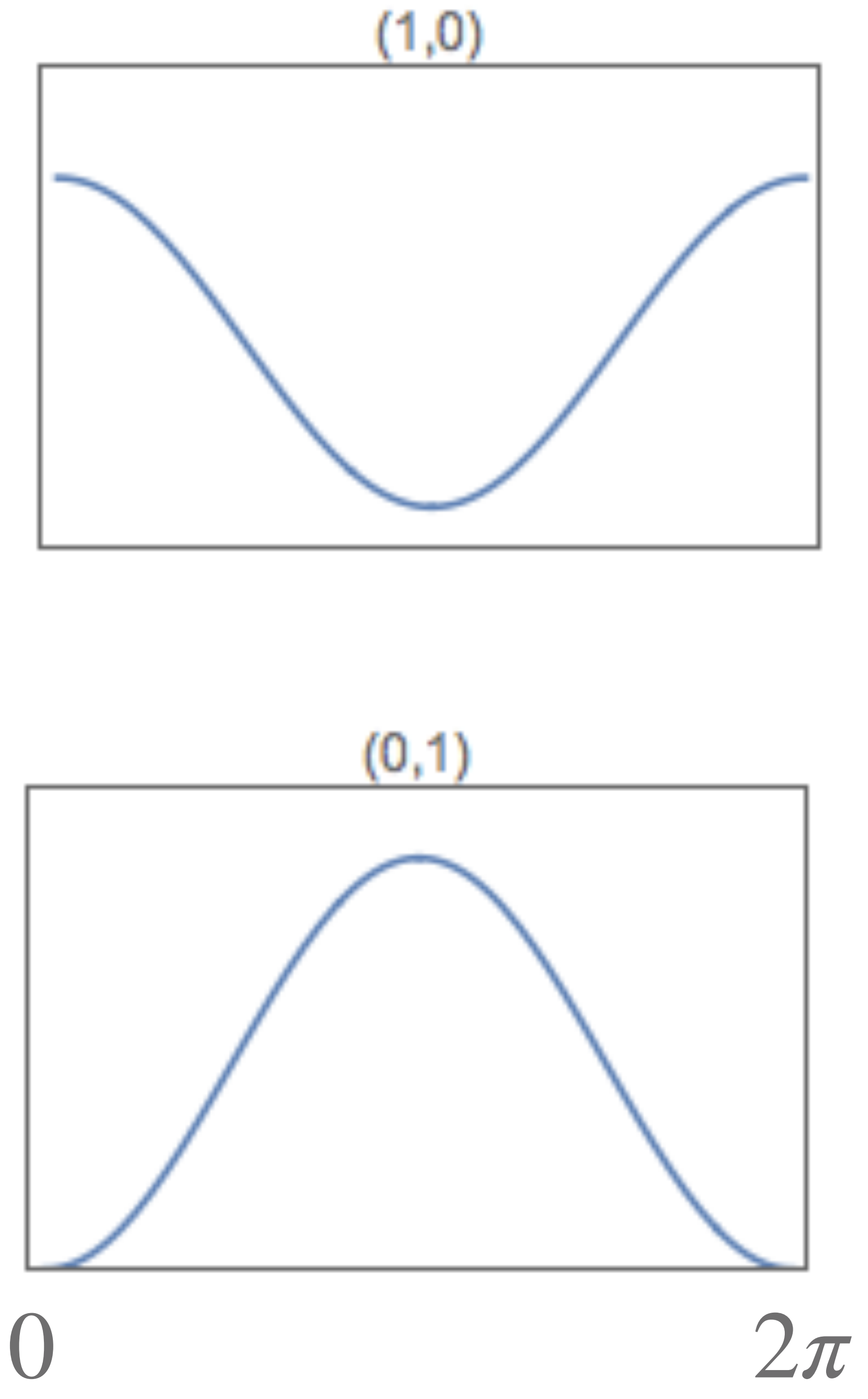
Fano, *American Journal of Physics* **29**, 539 (1961)

Glauber, *Physical Review Letters* **10**, 84 (1963)

Measuring the CDC: Count method

Now add a 50% beamsplitter





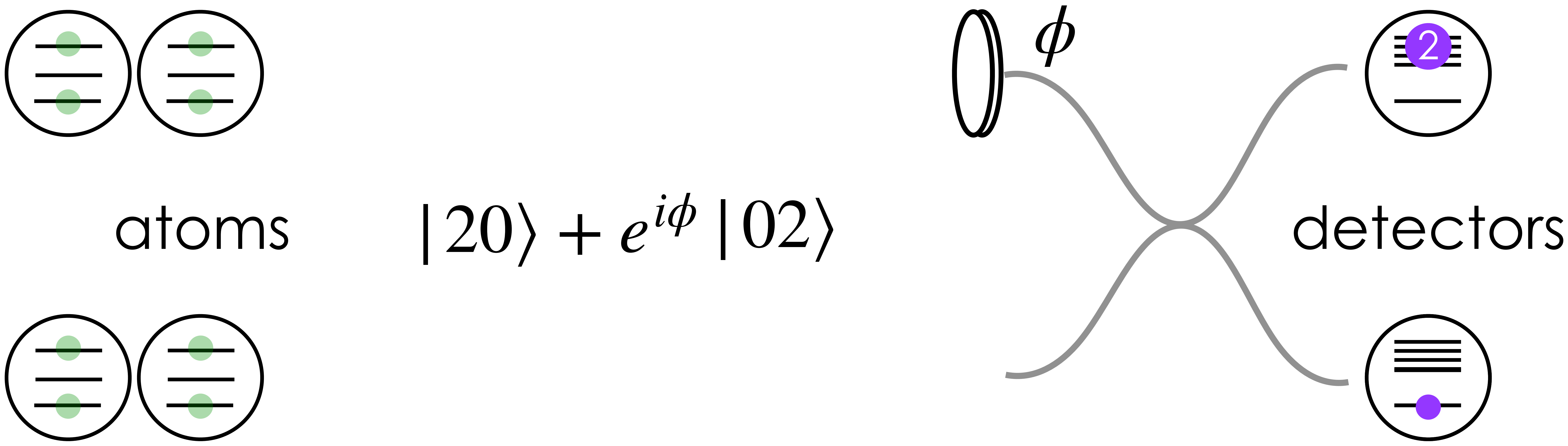
if one detector fires, which atom did it come from?

amplitudes of the two paths interfere

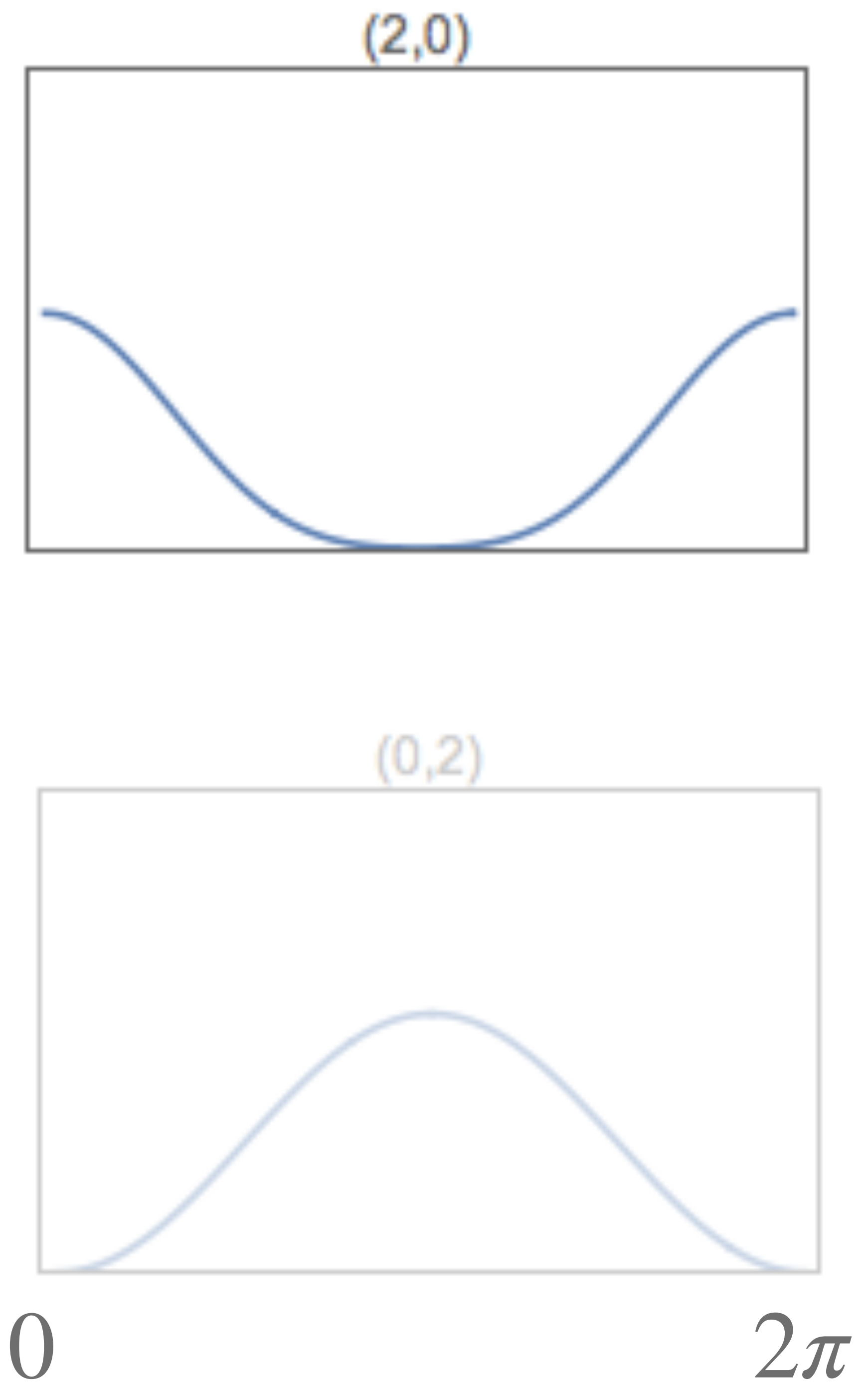
to see interference, add variable phase

Measuring the CDC: Count method

Now let two photons be emitted from … somewhere



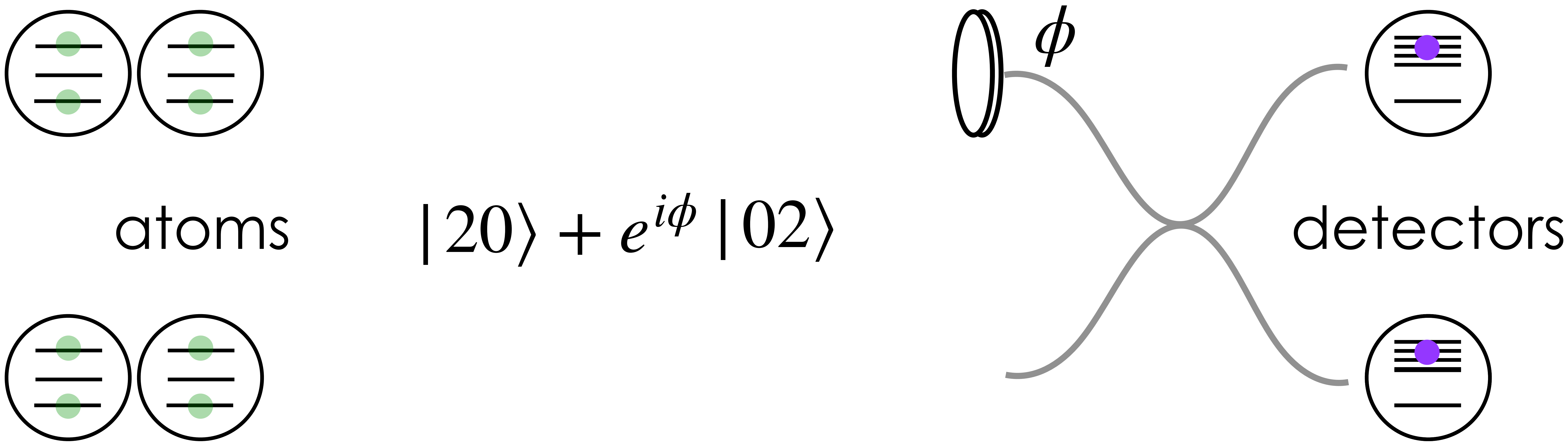
$$|20\rangle + e^{i\phi}\,|02\rangle$$



top detector can count two photons

Measuring the CDC: Count method

Now let two photons be emitted from … somewhere



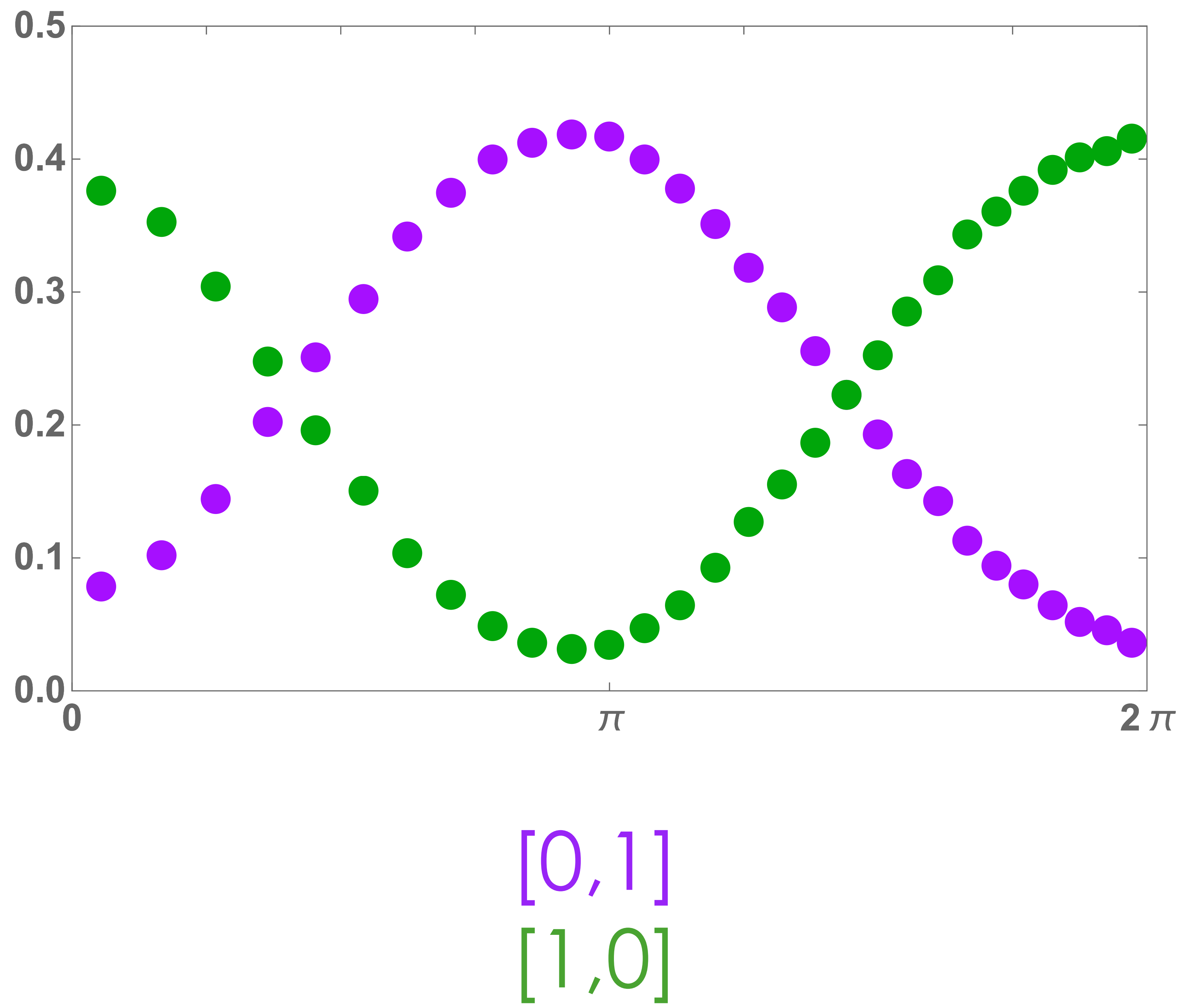
$$|20\rangle + e^{i\phi}|02\rangle$$

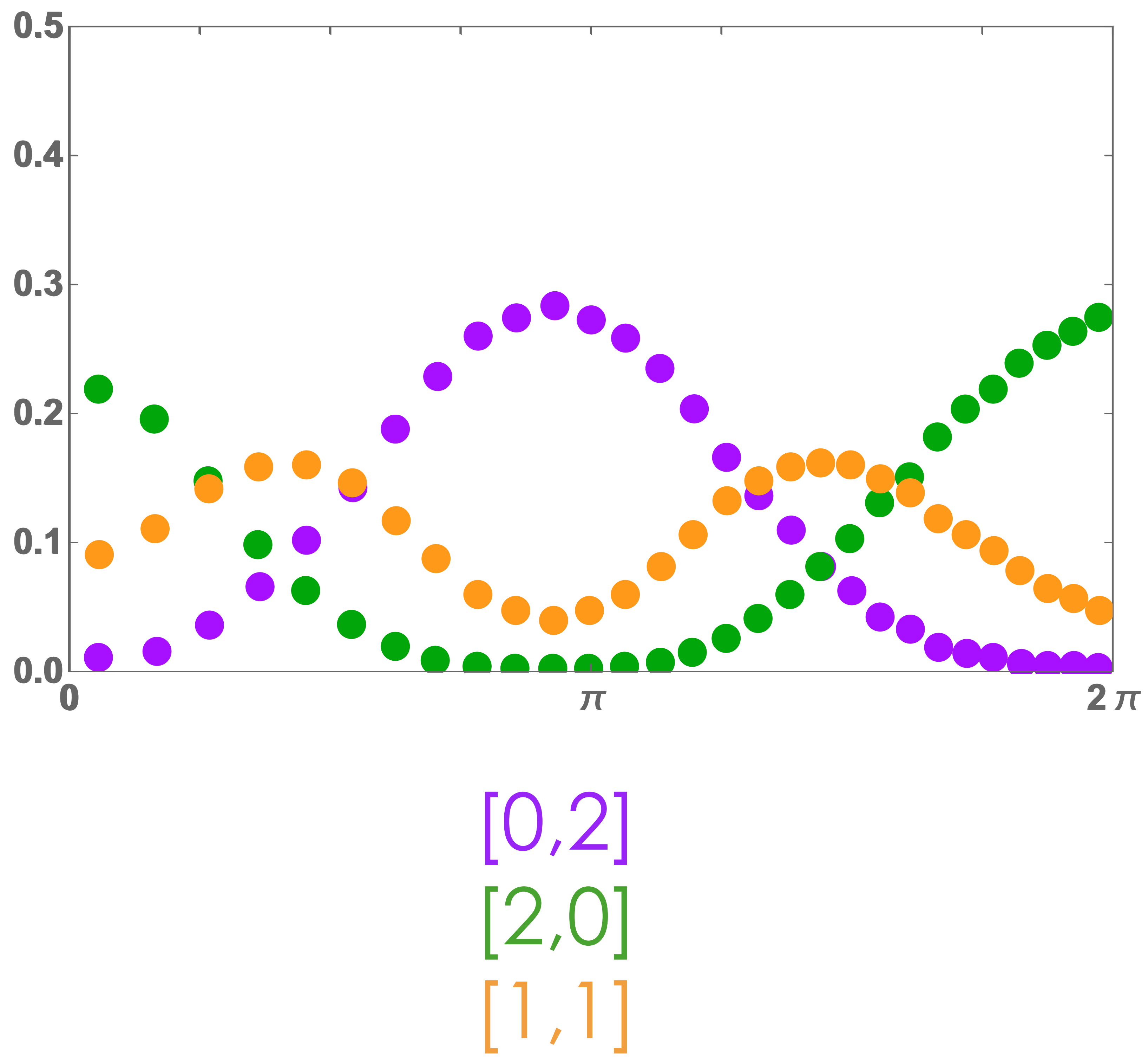
each detector can count one photon

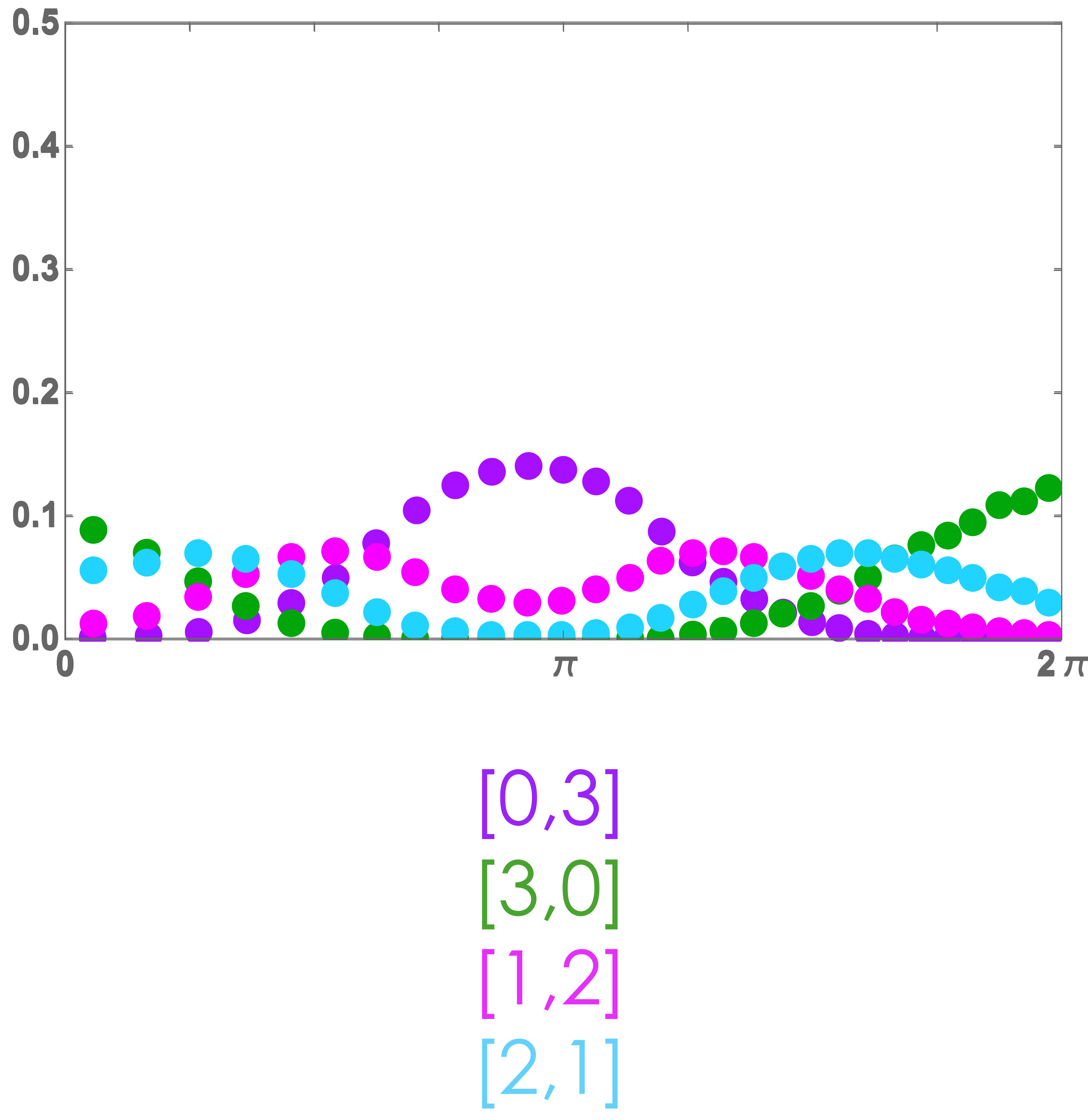
nonclassical interference: phase super-resolution

Check with coherent source

Probability x Applied Phase







Now with pseudothermal light

3 Methods:

Count: variable phase + photon-number resolution

Traditional: NO variable phase (subset of *Count*)

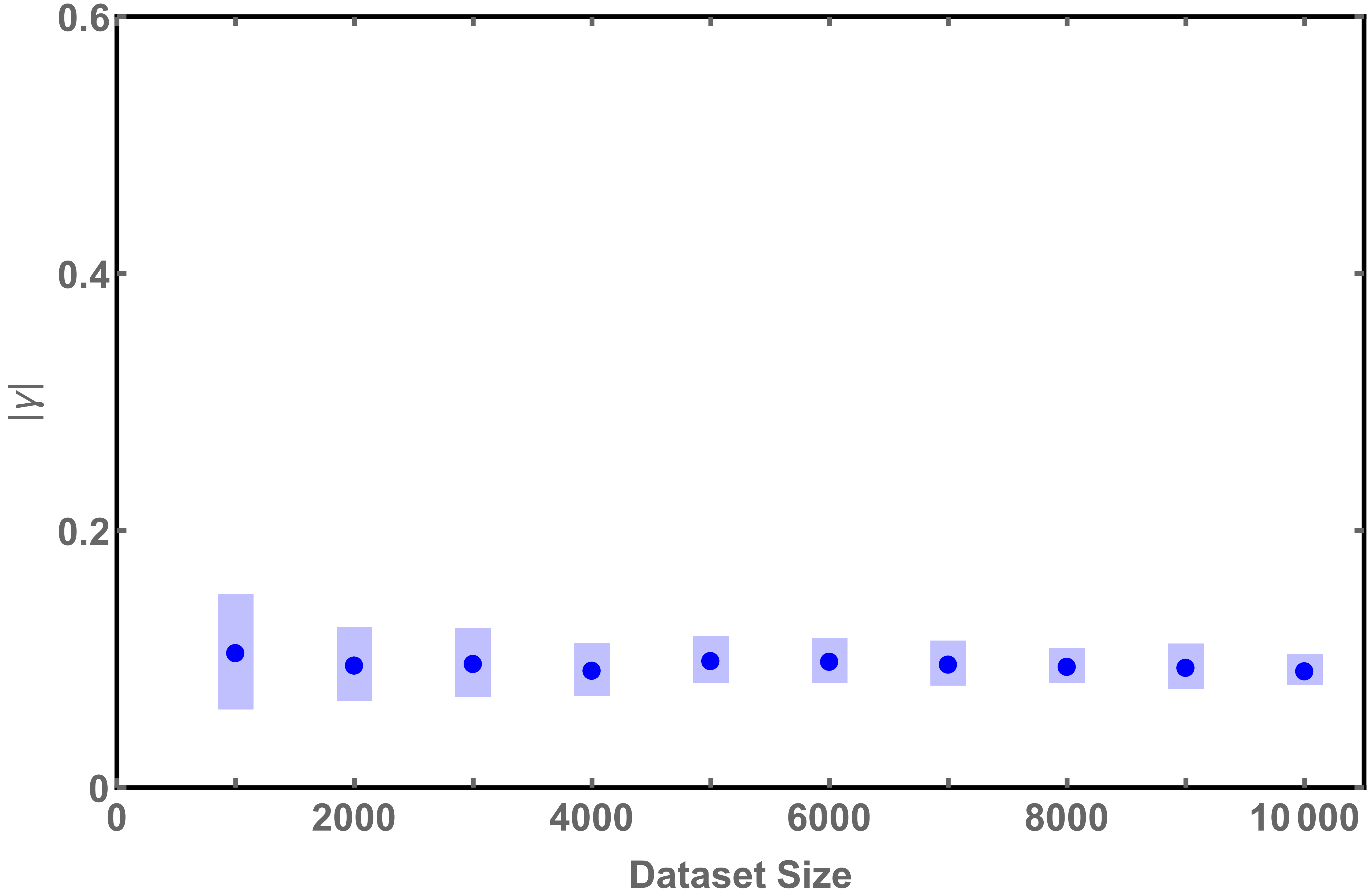
Click: variable phase, but NO photon-number resolution (click/ no click)

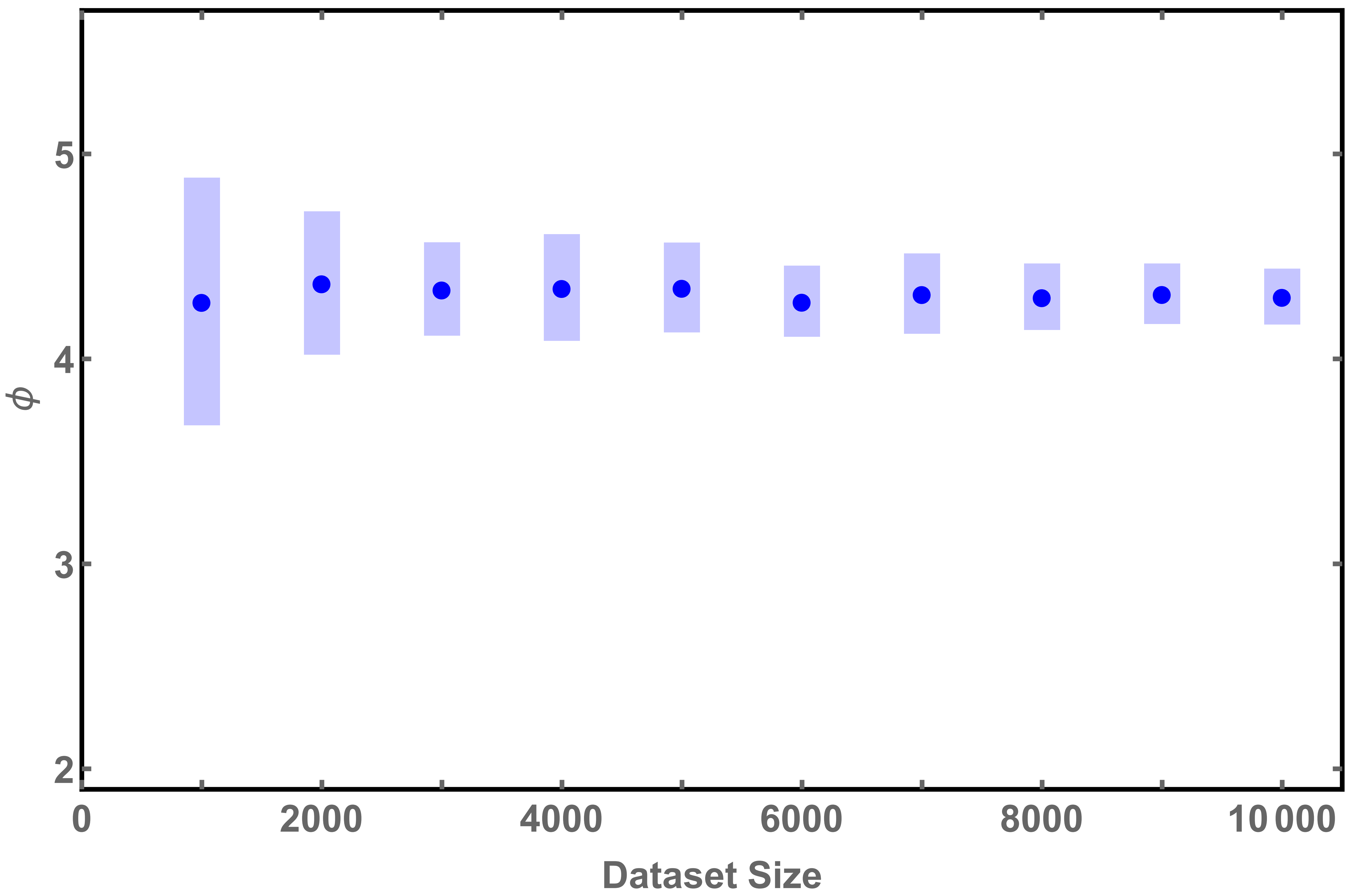
Incoherent source: traditonal scheme

$$\gamma(\mathbf{r}_1, \mathbf{r}_2) = |\gamma| e^{i\phi}$$

$\gamma = 0.20 \pm 0.16$ $\varphi = 4.50 \pm 1.0$

Incoherent source: count scheme





$\gamma = 0.20 \pm 0.16$

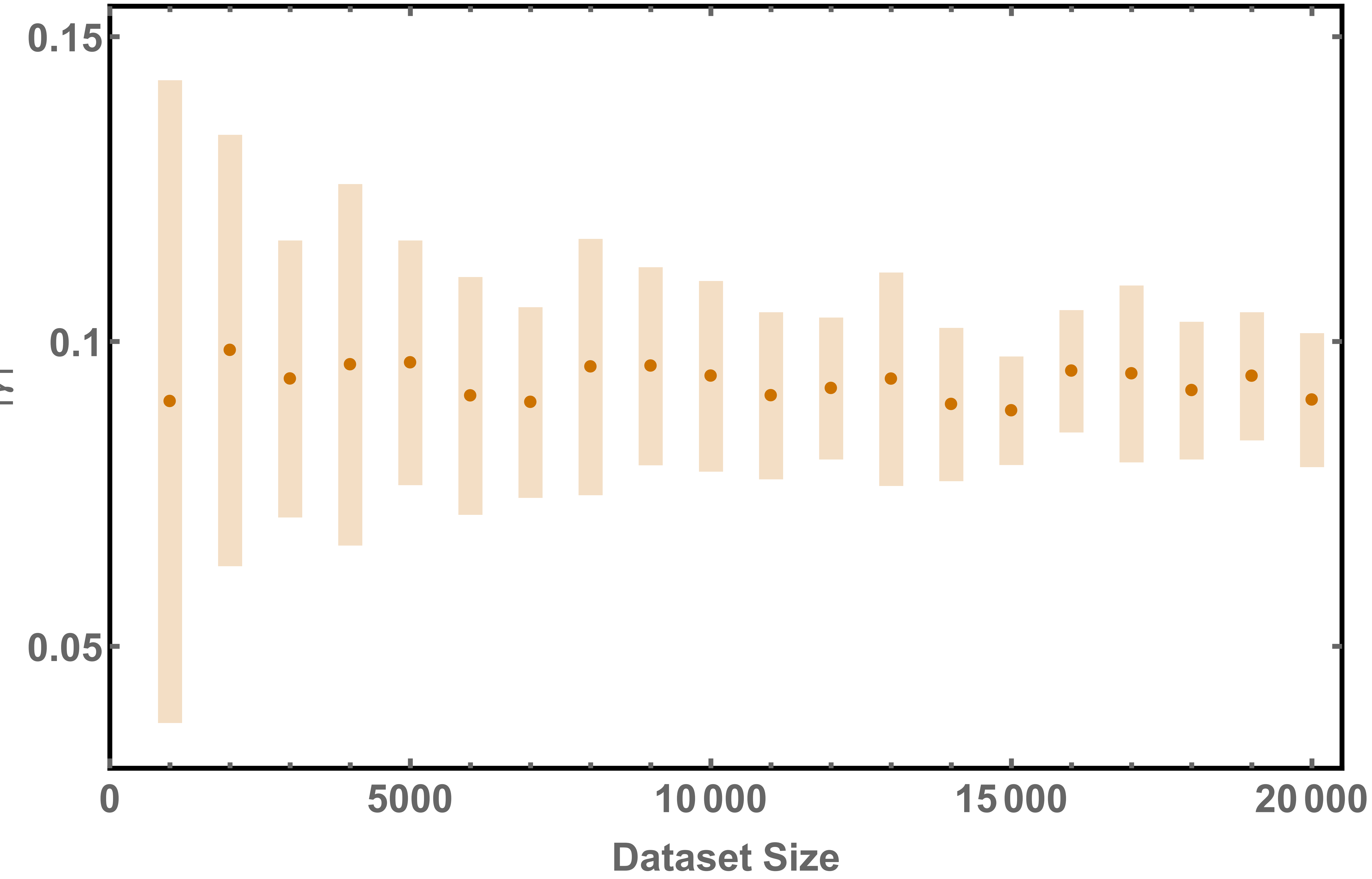
$\gamma = 0.096 \pm 0.022$

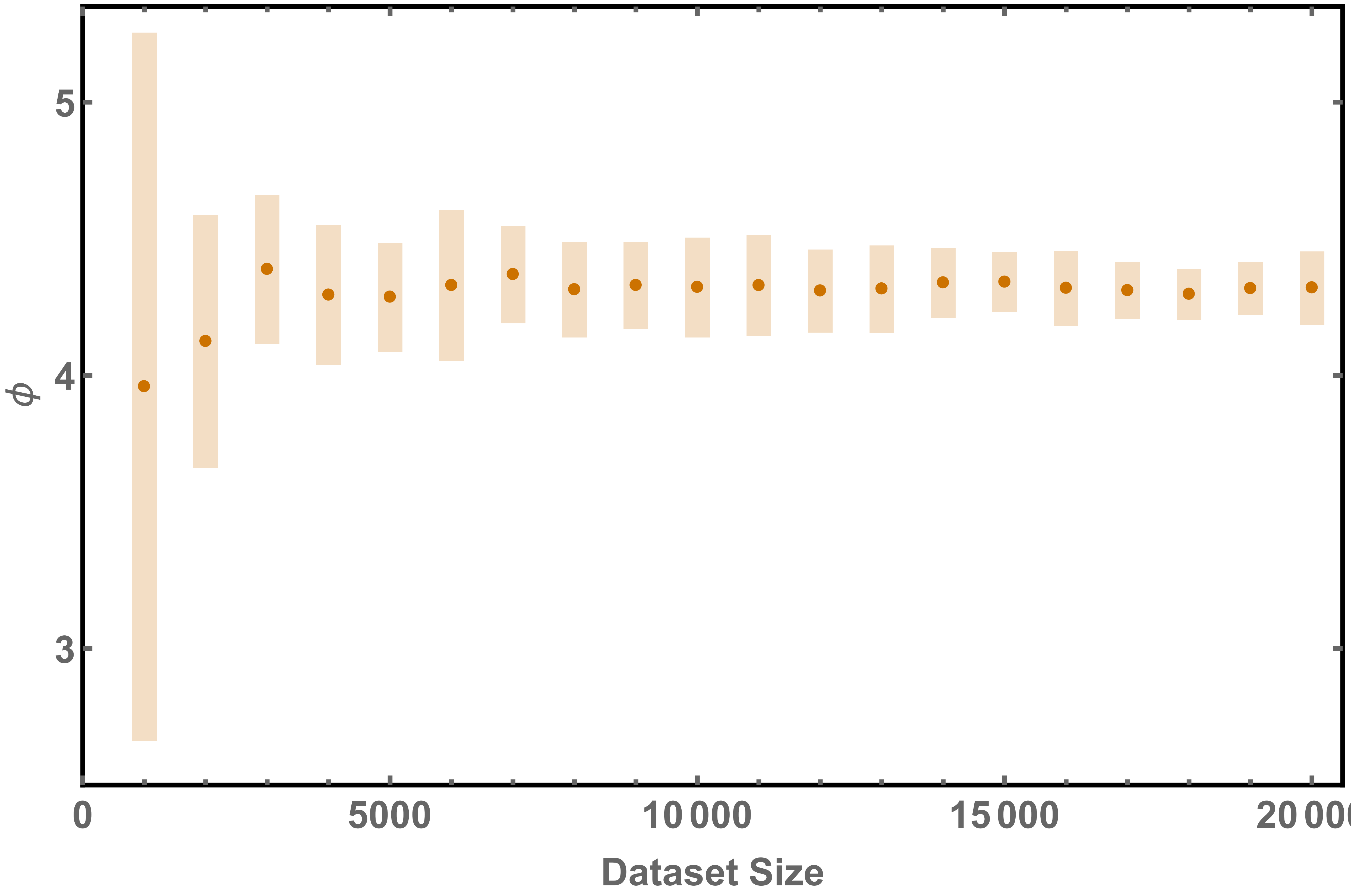
$\varphi = 4.50 \pm 1.0$

$\varphi = 4.32 \pm 0.25$

Incoherent source: click scheme

what if we don't count photons?





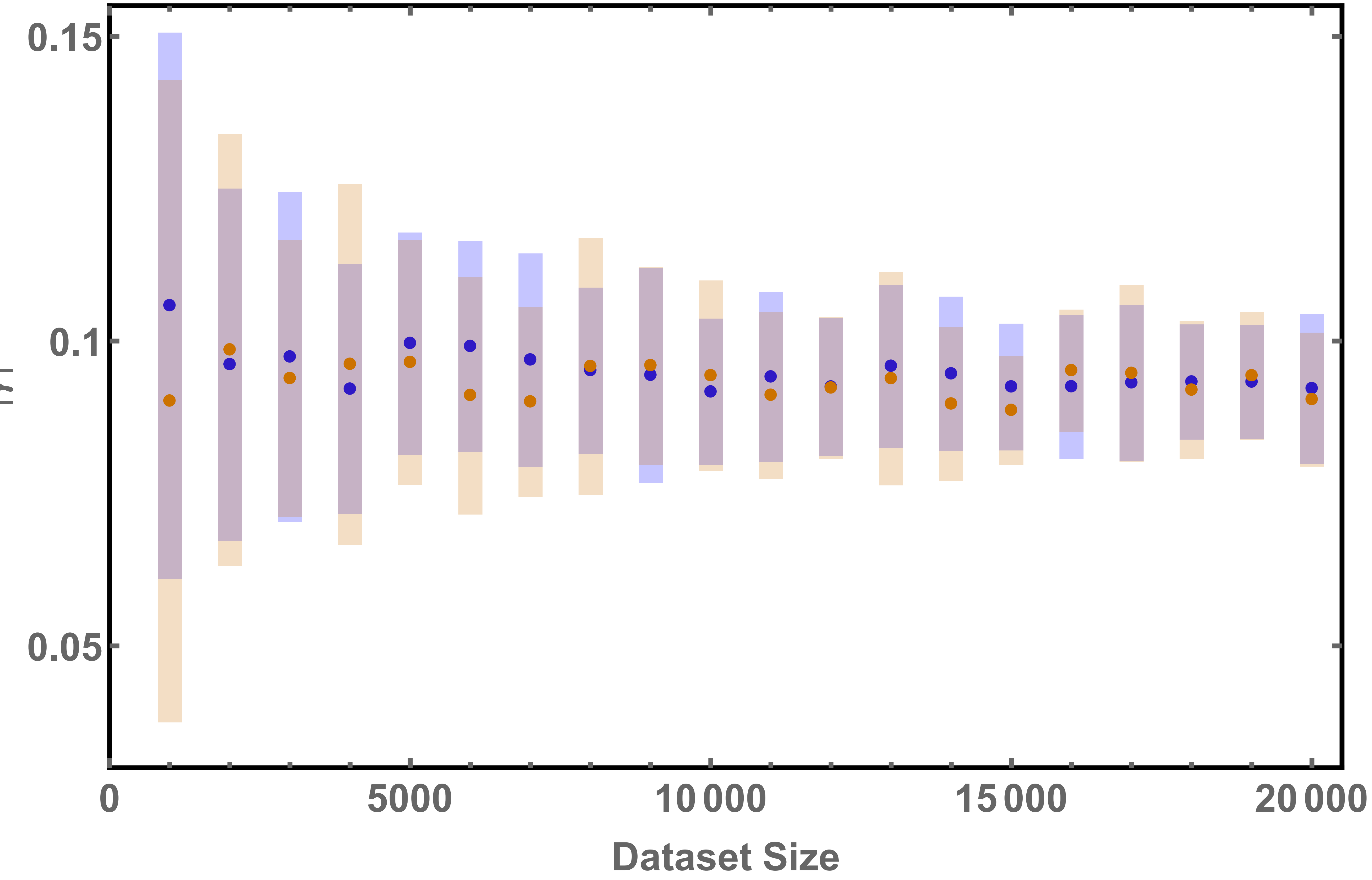
$\gamma = 0.20 \pm 0.16$

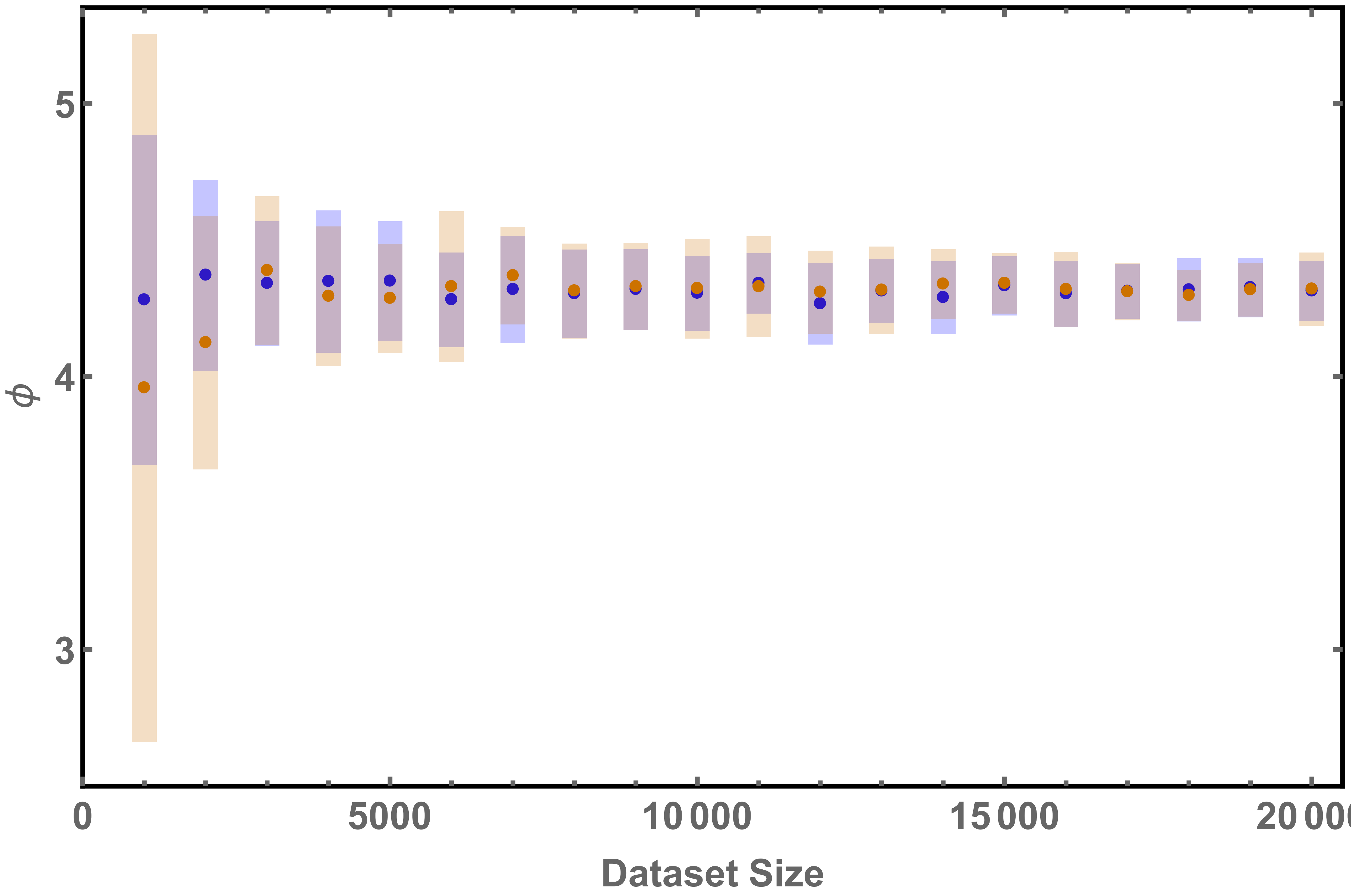
$\gamma = 0.095 \pm 0.025$

$\varphi = 4.50 \pm 1.0$

$\varphi = 4.29 \pm 0.35$

Click vs count schemes





$\gamma = 0.096 \pm 0.022$

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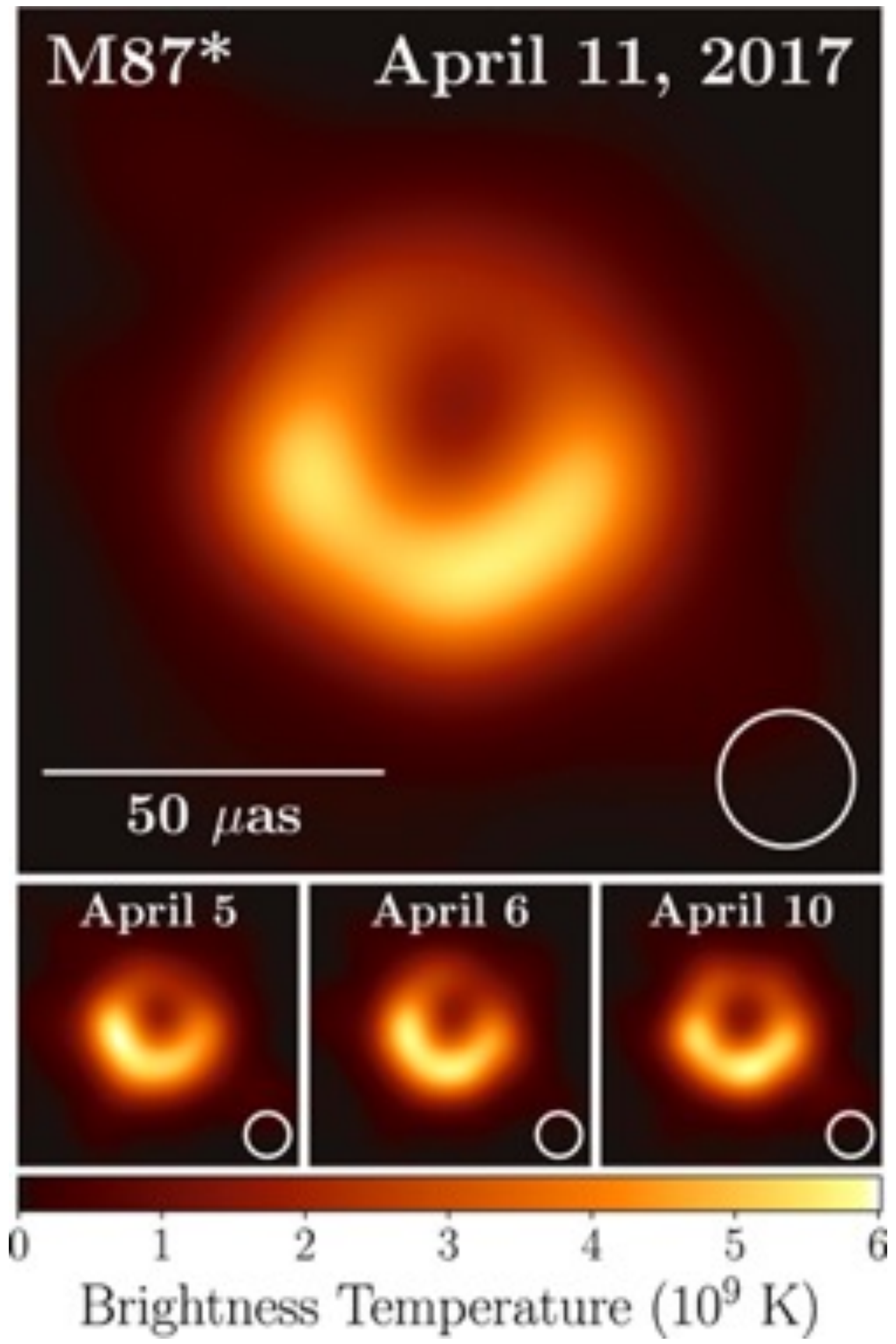
Quantum Astronomy



sensitive to features on angular scale

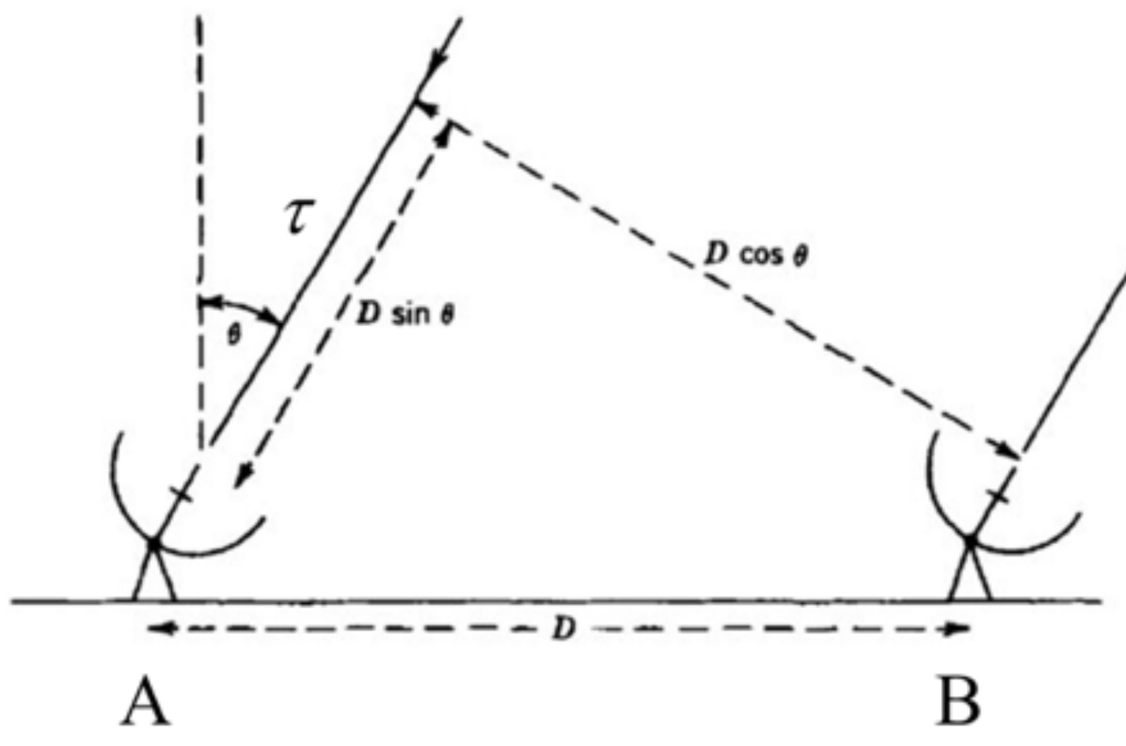
$$\Delta\,\theta \sim \frac{\lambda}{b}$$

2019 ApJL 875

Black hole in the center of M87 imaged at 1.3mm

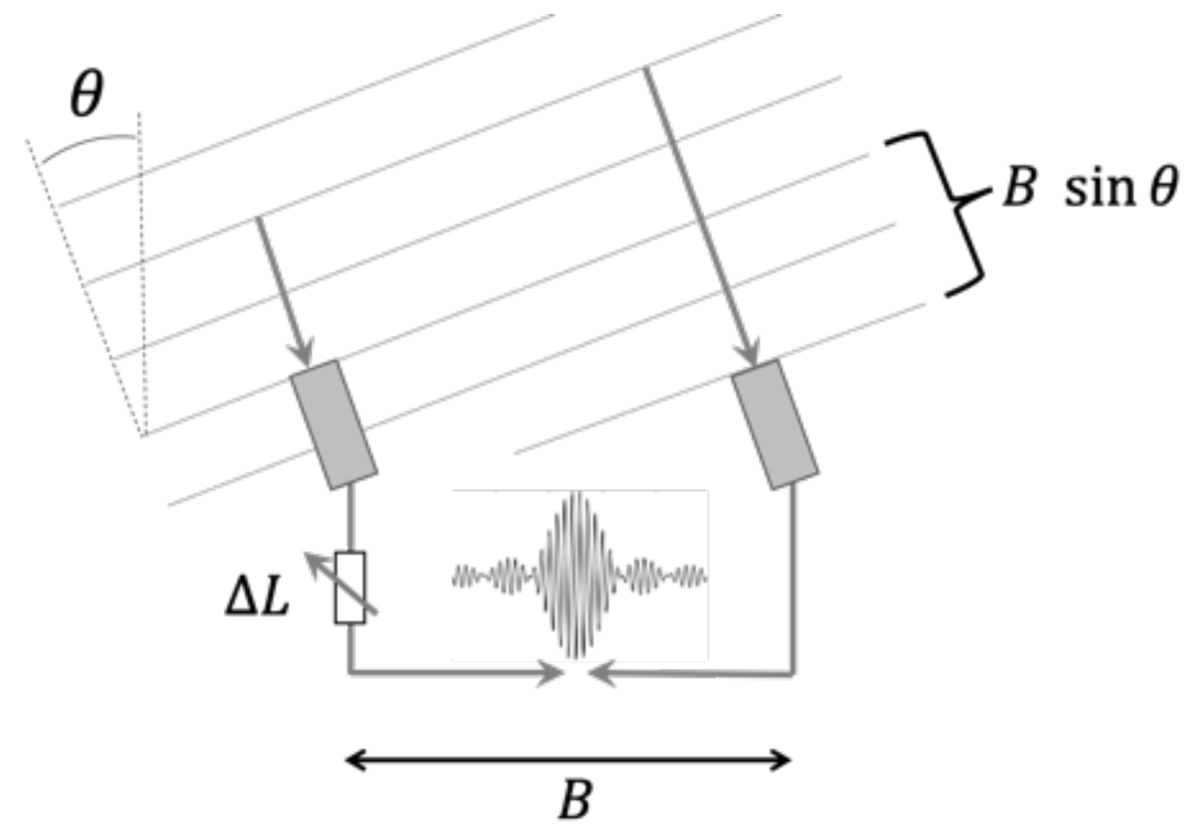
Achieved by radio interferometry with ~10000 km baselines

Radio $\bar{n} \gg 1$



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

$\bar{n} \ll 1$ Optical

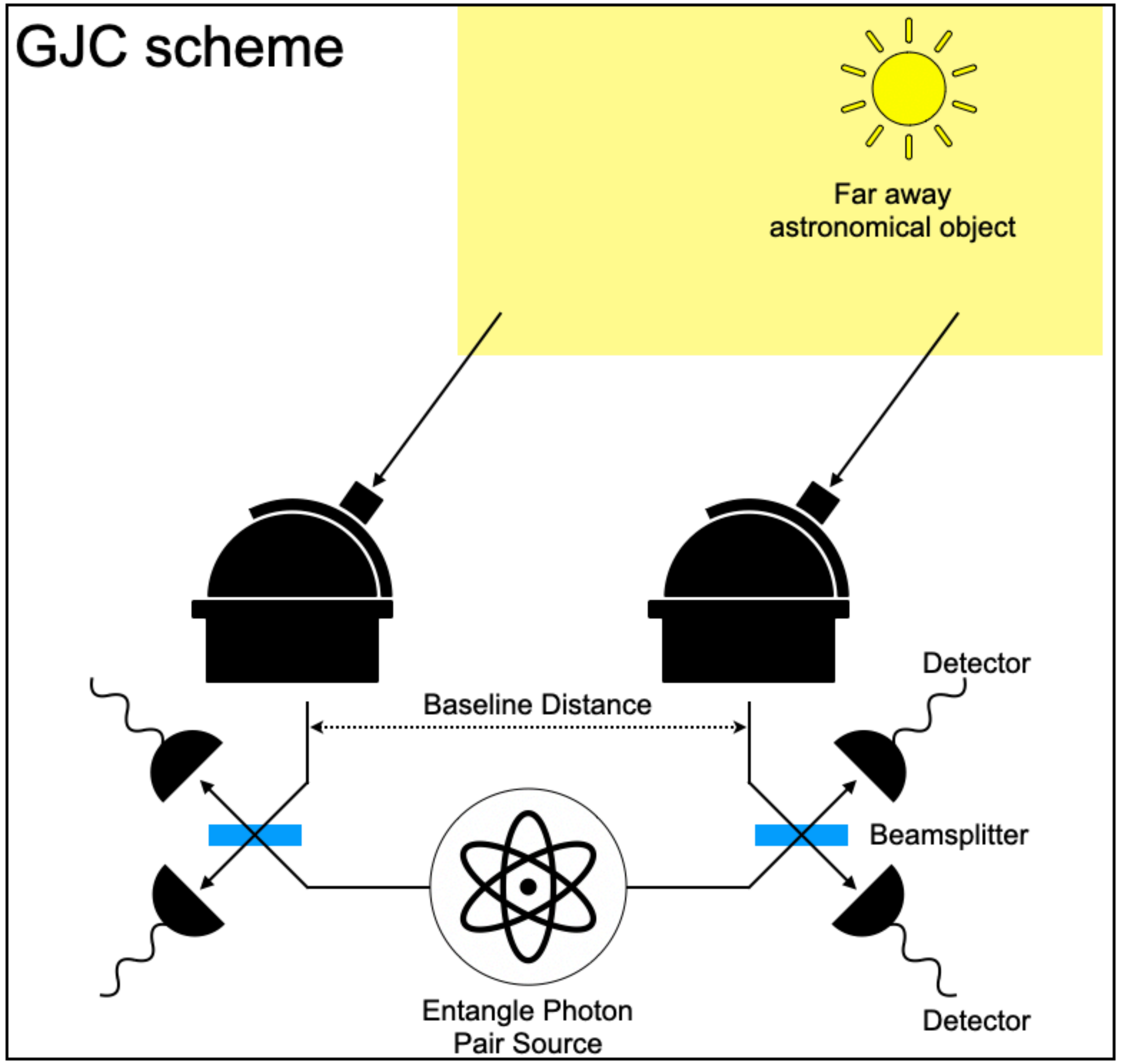


One photon at a time! Need to bring paths to common point in real time

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

Need path length *stabilized* to better than λ

Quantum Astronomy



Longer-Baseline Telescopes Using Quantum Repeaters

PRL 2012

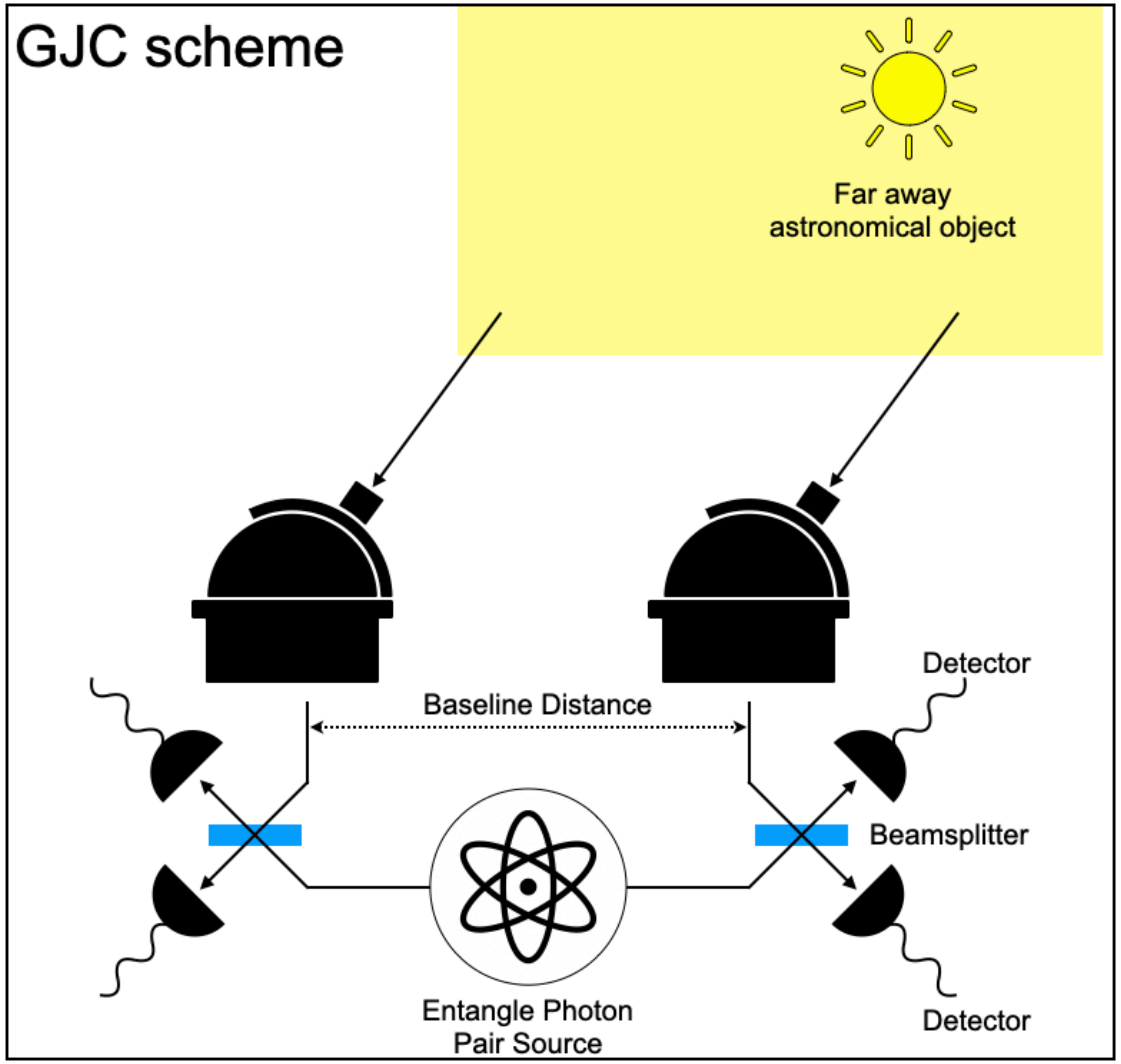
Seminal work in the field

Very interesting

Not feasible with current quantum technology

Cost? Scale?

Quantum Astronomy



Longer-Baseline Telescopes Using Quantum Repeaters

PRL 2012

Seminal work in the field

Very interesting

Not feasible with current quantum technolo

Cost? Scale?

Here comes BNL to the rescue!

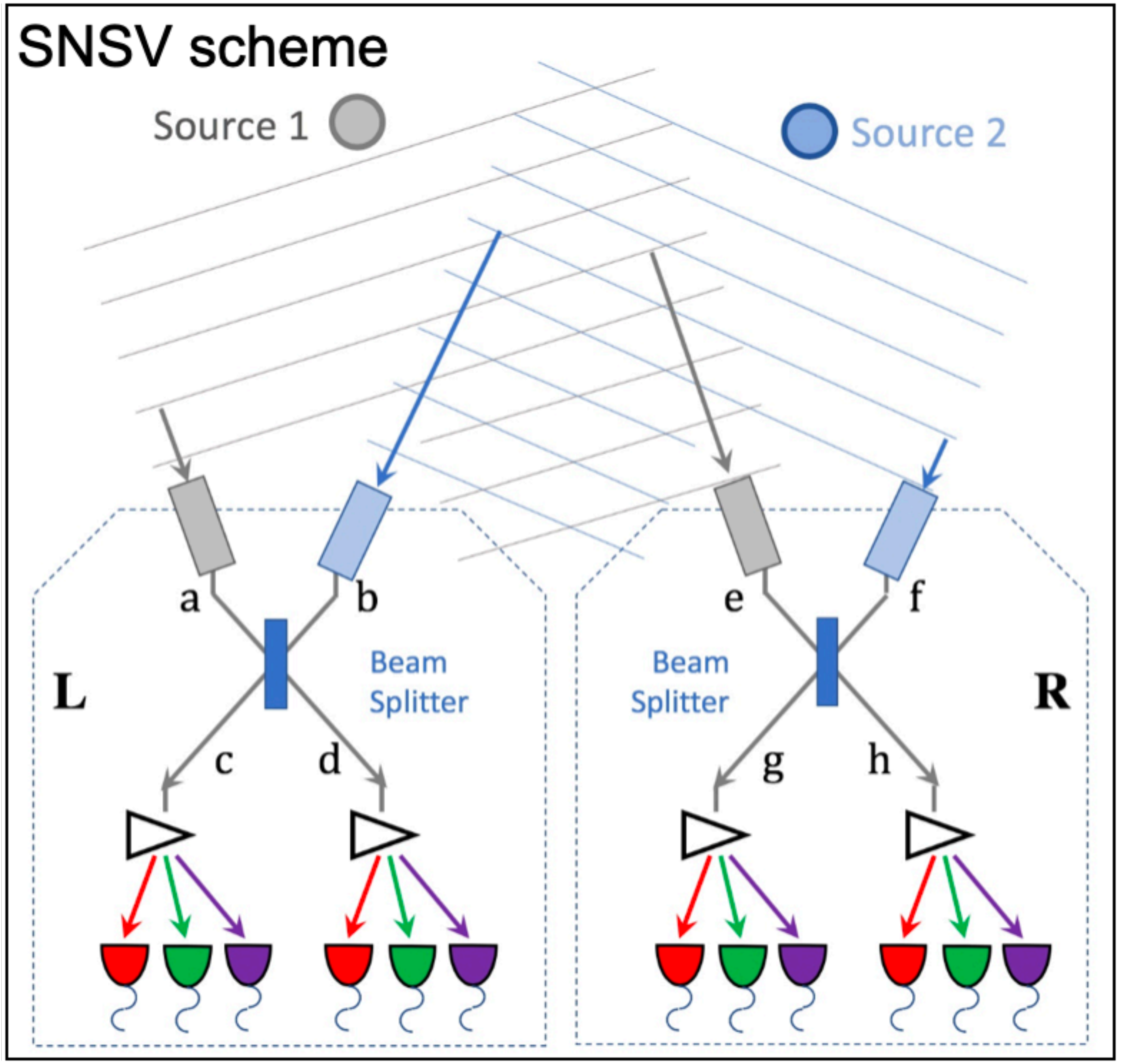
Quantum Astronomy

No need for connection between base stations

Enable long distance baseline

Many great impacts on Astrophysics and Cosmology

Gravitational Wave detection



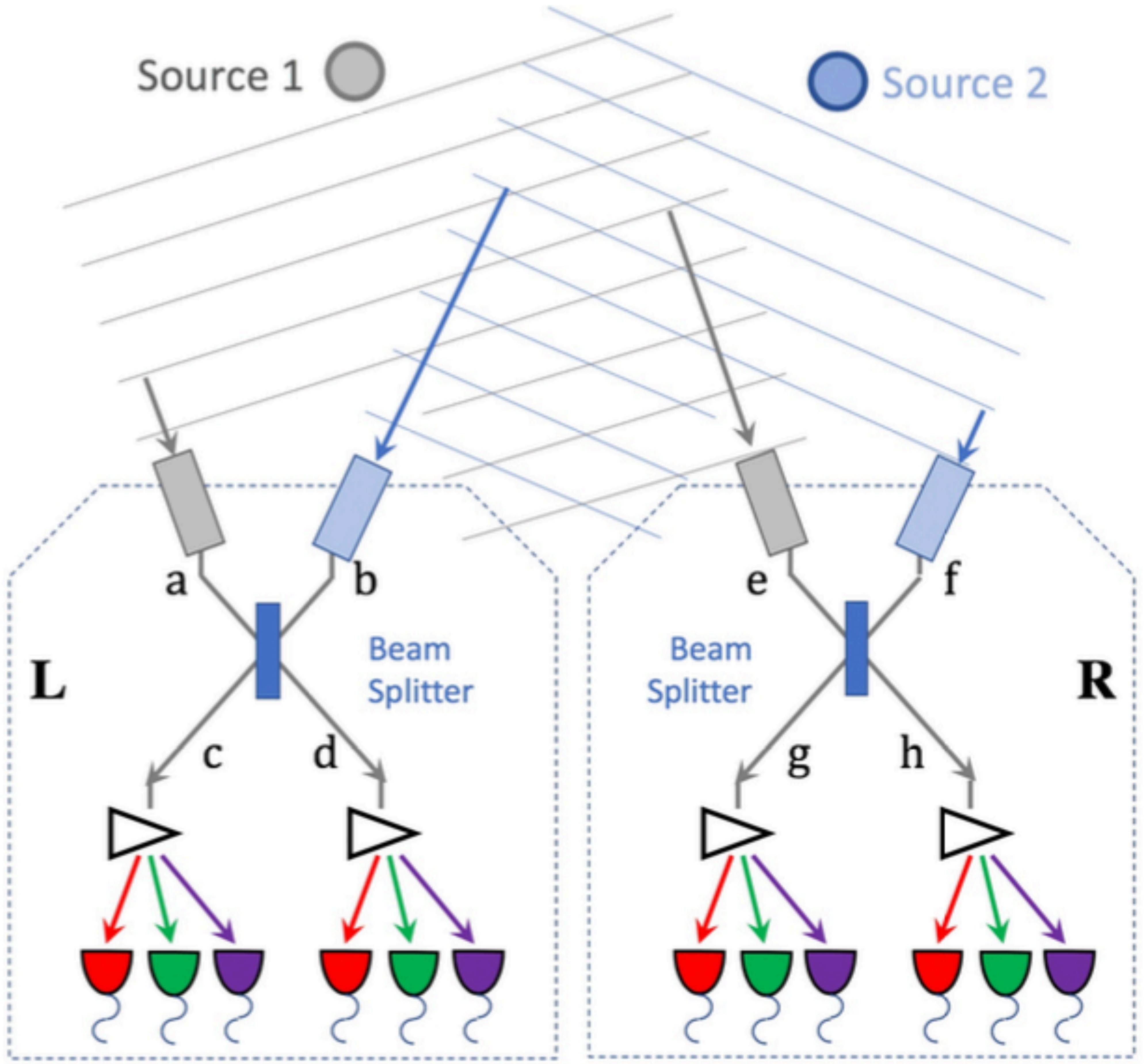
Two-photon amplitude interferometry for precision astrometry
The Open Journal of Astrophysics 2022

TWO-PHOTON AMPLITUDE INTERFEROMETRY FOR PRECISION ASTROMETRY

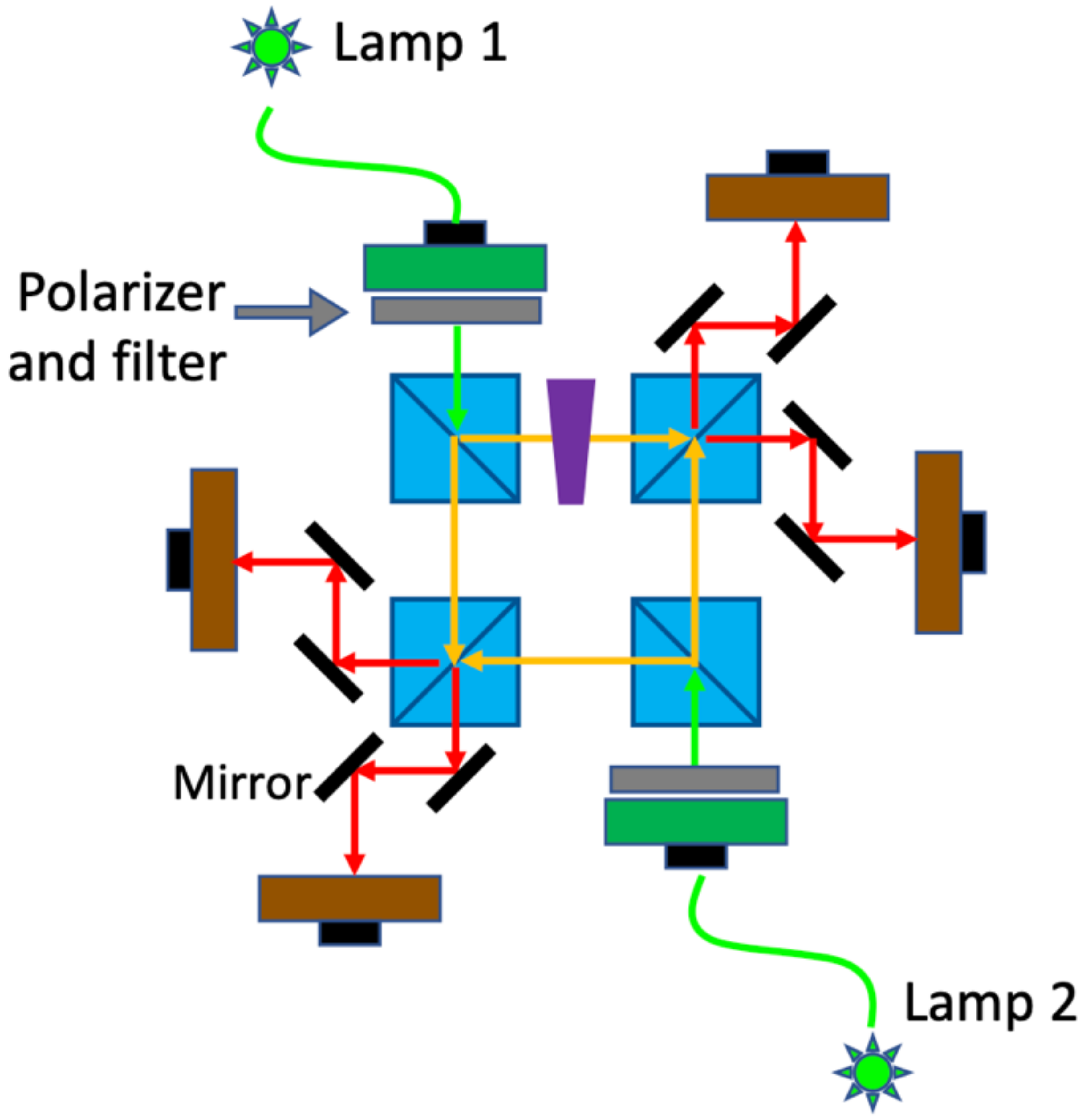
Paul Stankus, Andrei Nomerotski, Anze Slosar, and Stephen Vintskevich

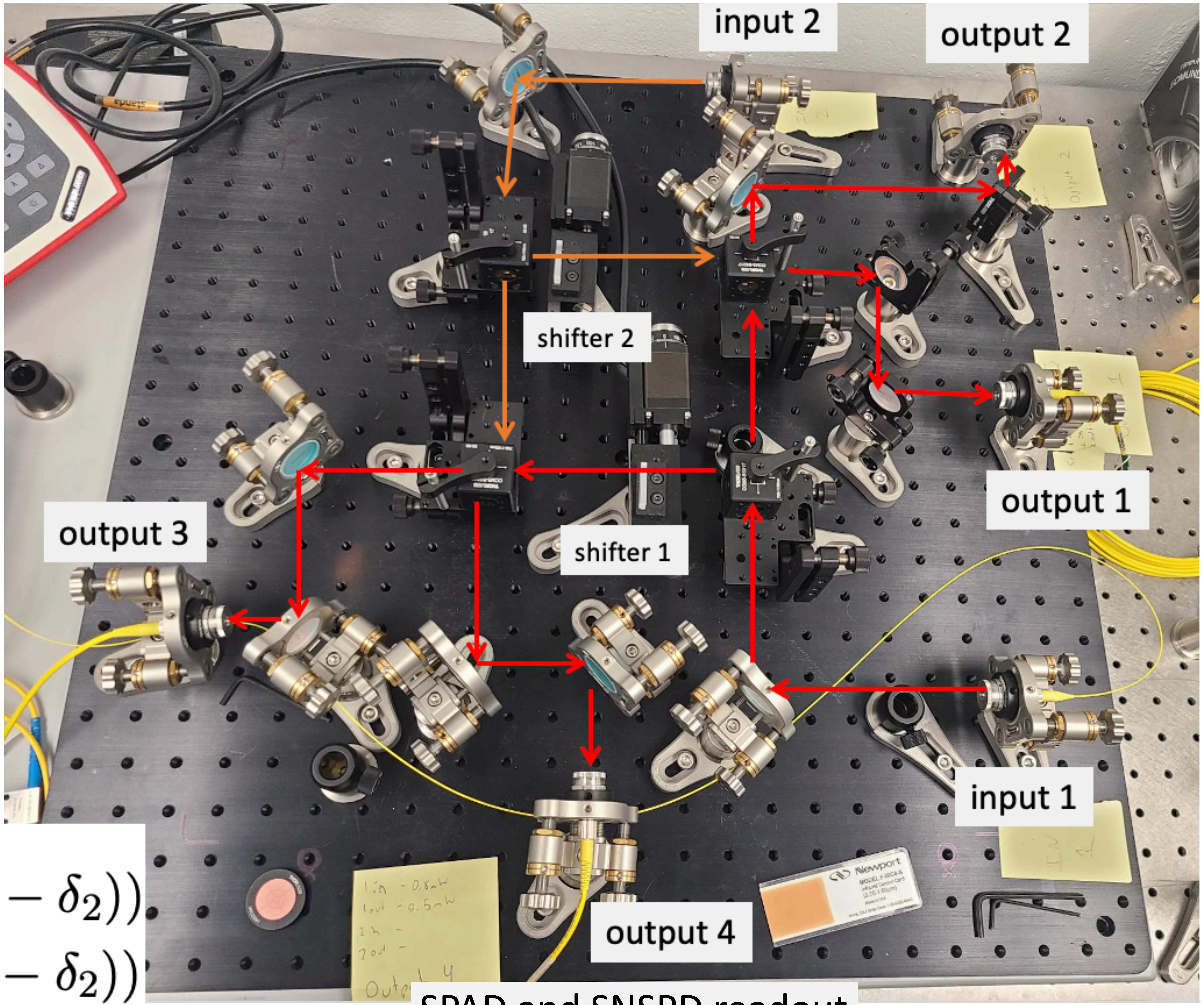
The Open Journal of Astrophysics

Published in November 2022



Proof-of-principle demonstration (2022)



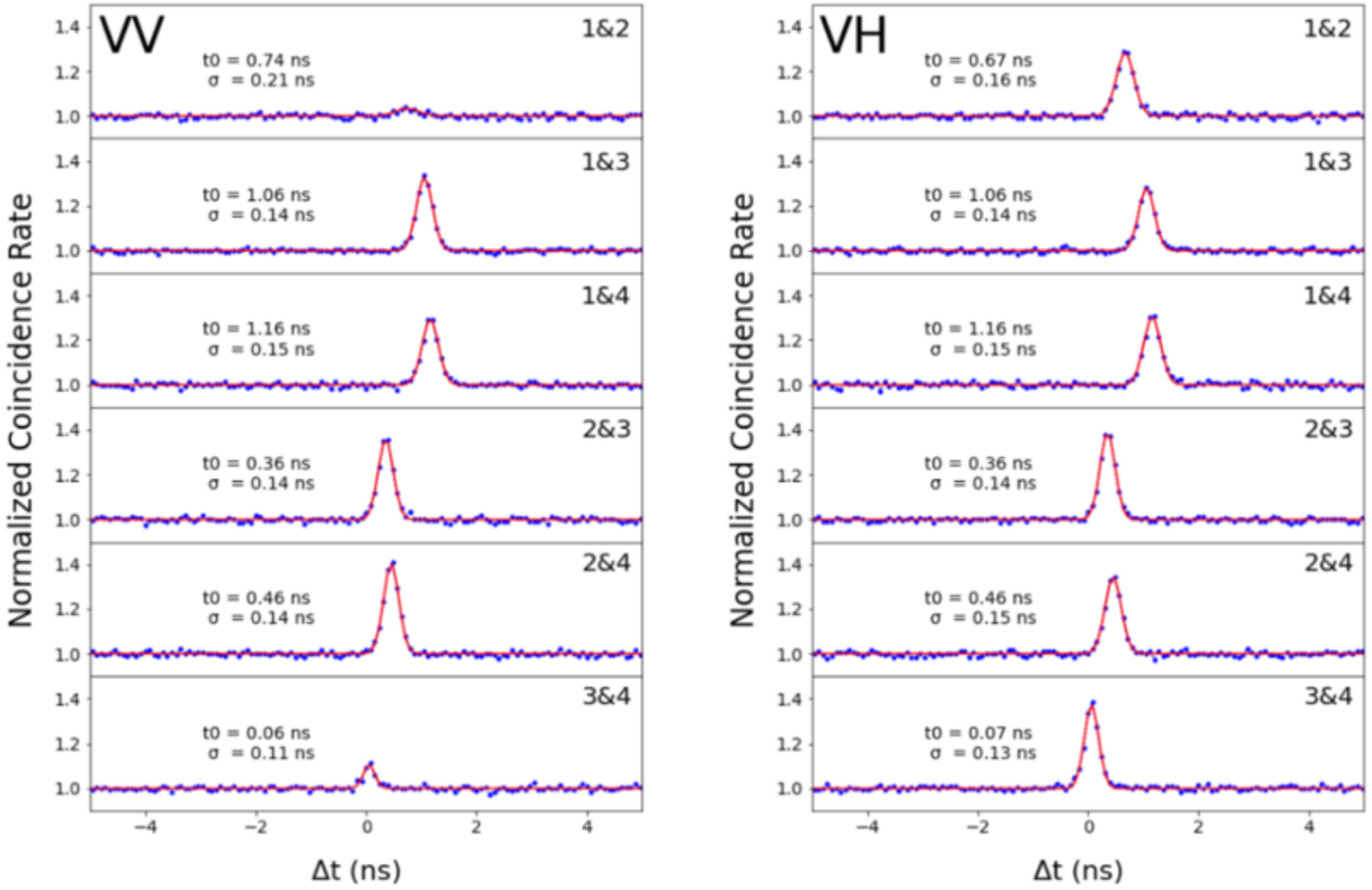


SPAD and SNSPD readout

$$P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2))$$
$$P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2))$$

Phase dependence

- Stable setup
- See expected behavior
- Time resolution ~ 100 ps



HBT peaks

Phase dependence

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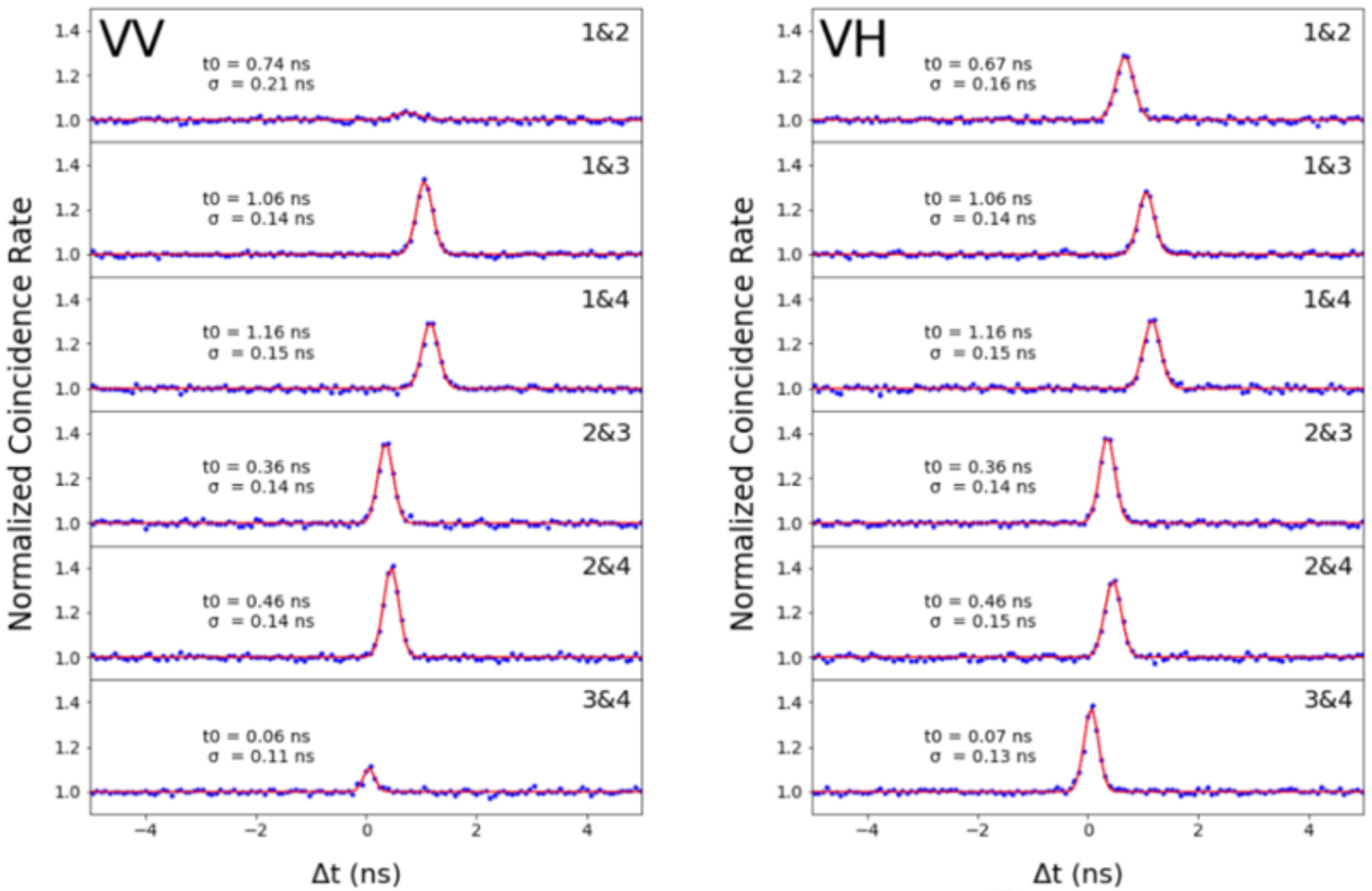

HBT peaks

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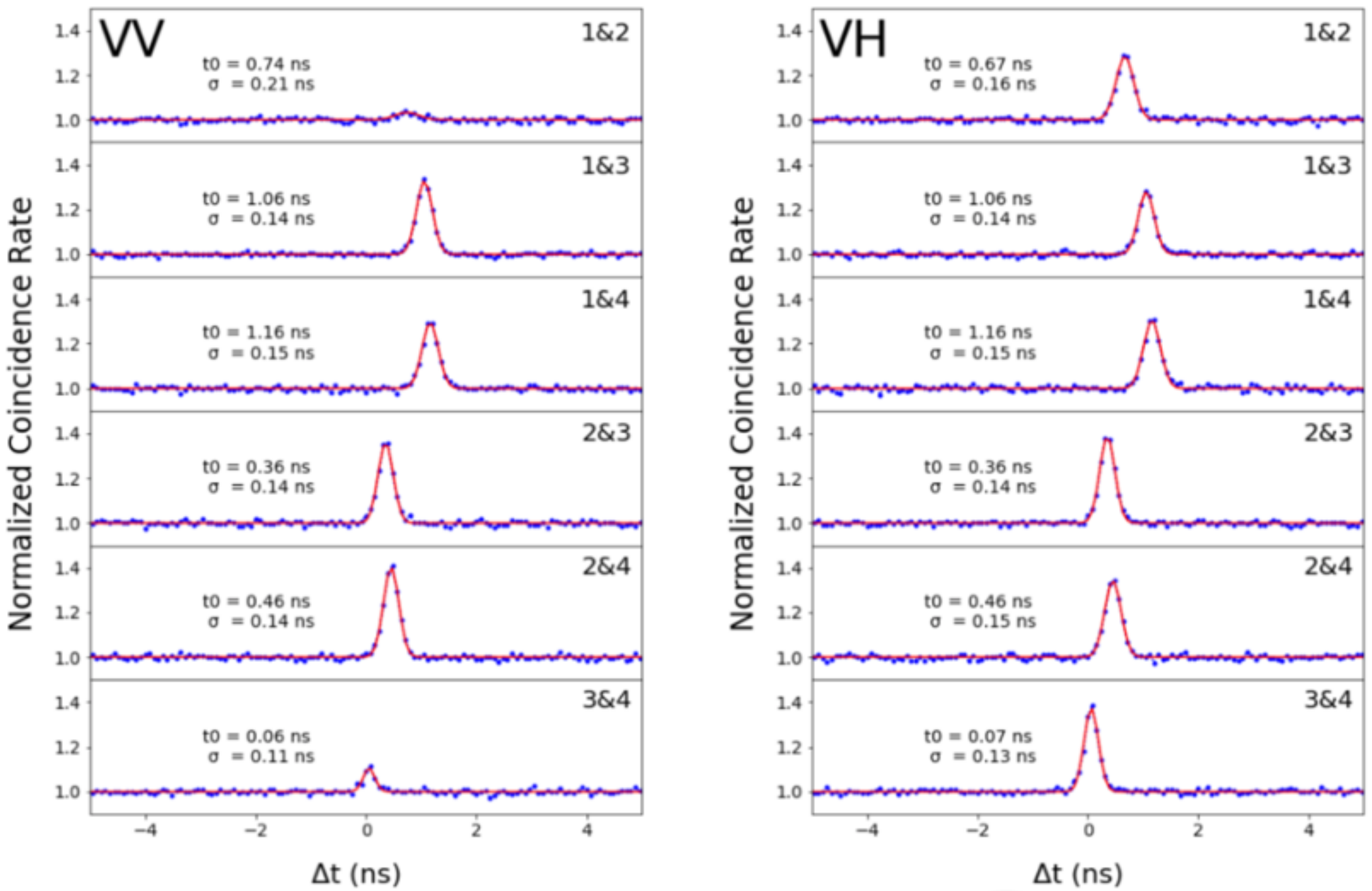
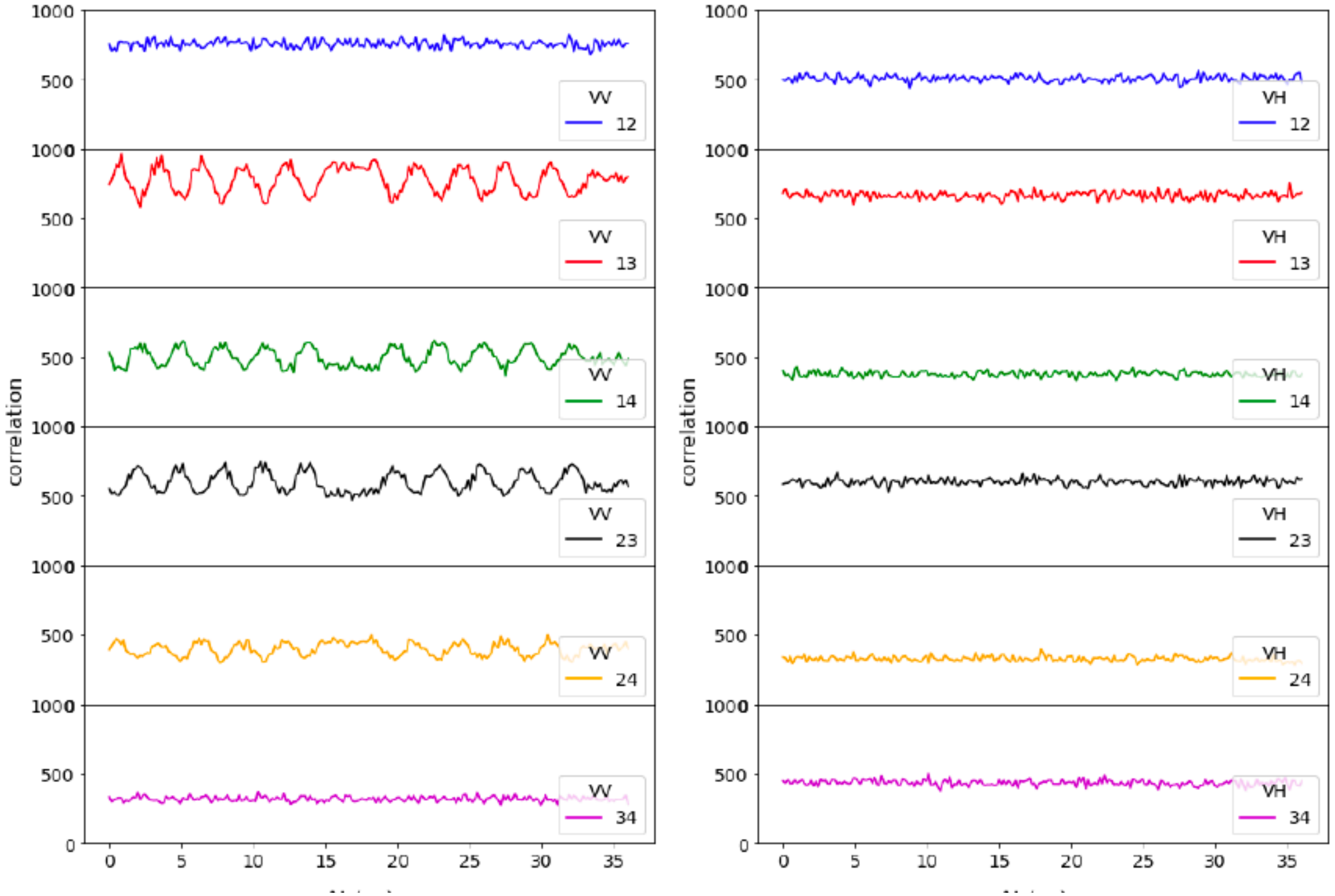
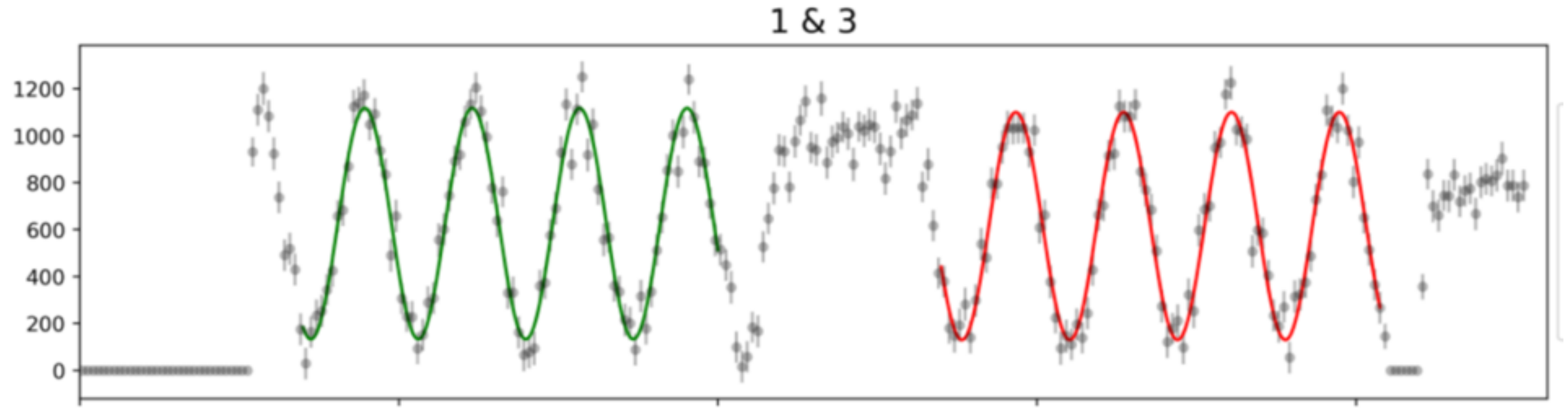


HBT peaks

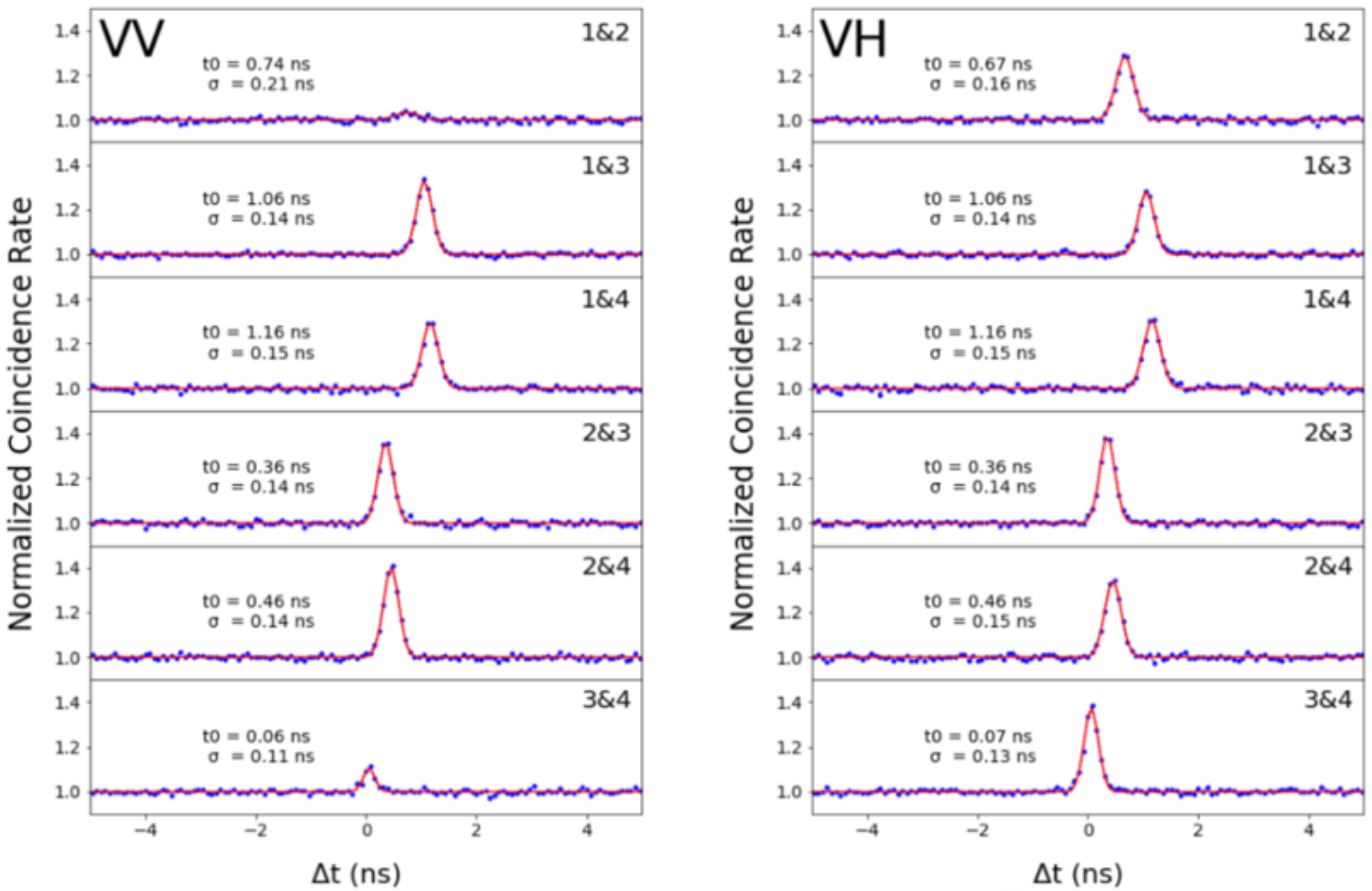




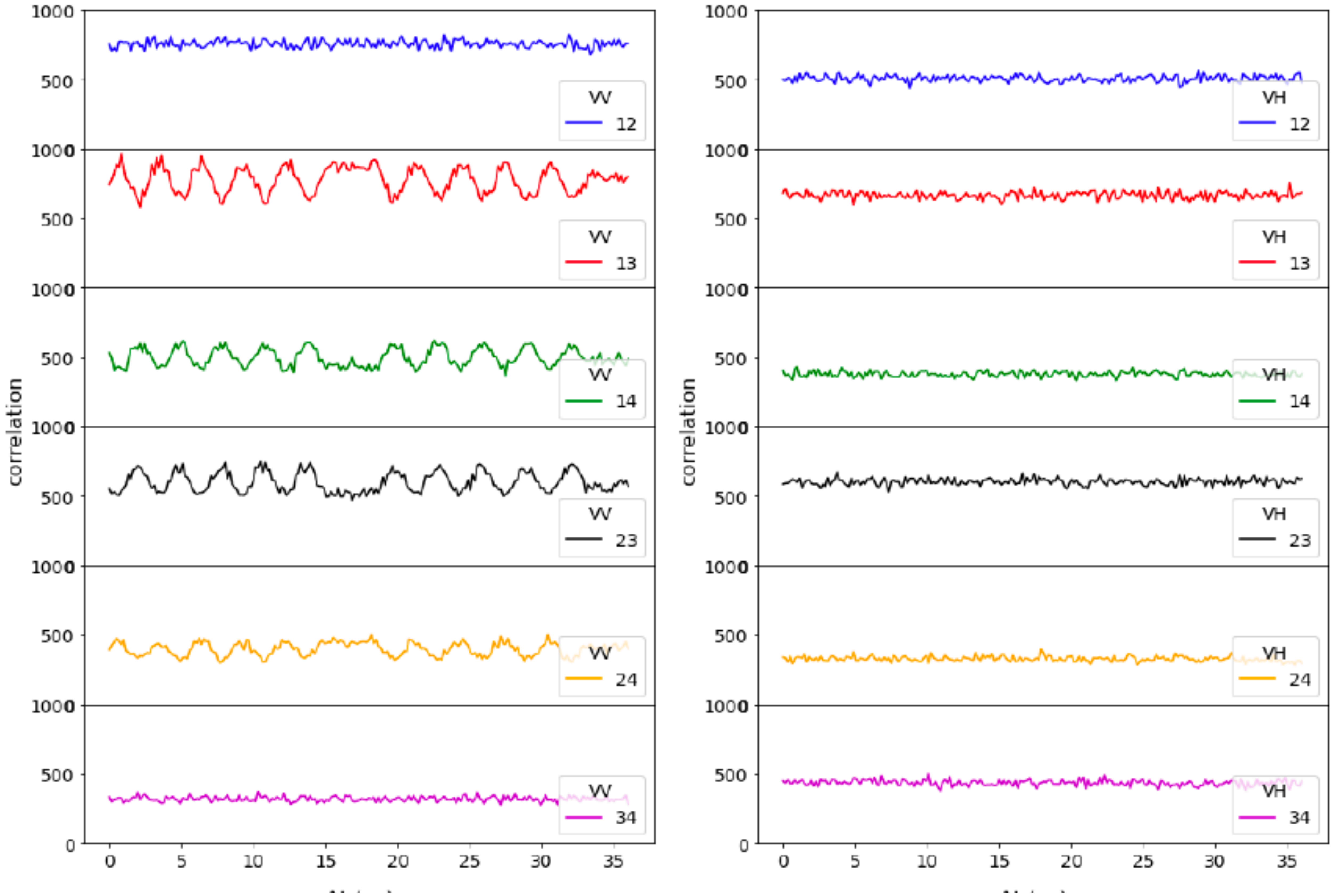
Phase Oscillations

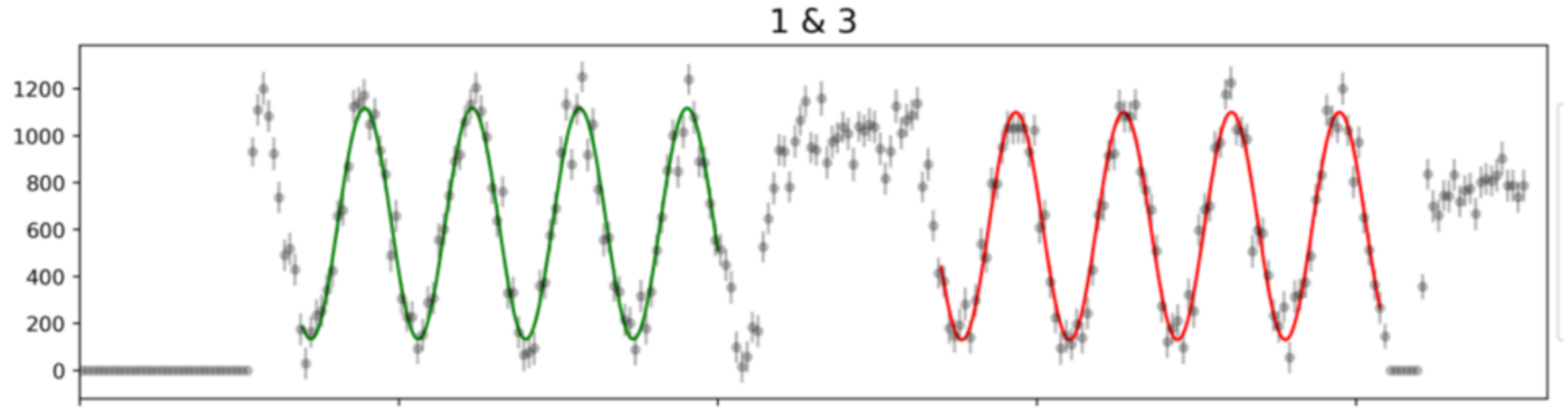
Phase dependence

- Stable setup
- See expected behavior
- Time resolution ~ 100 ps

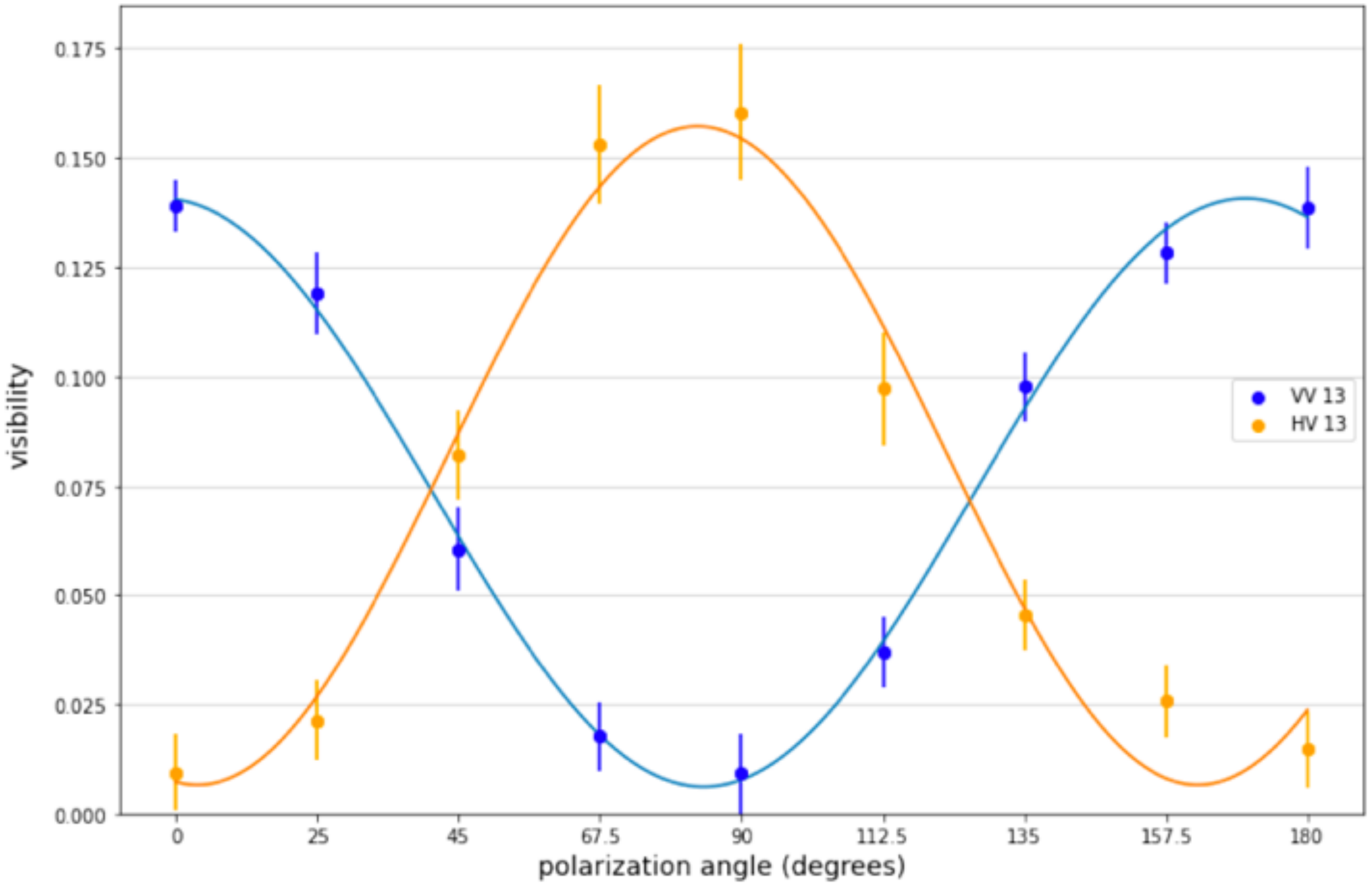


HBT peaks

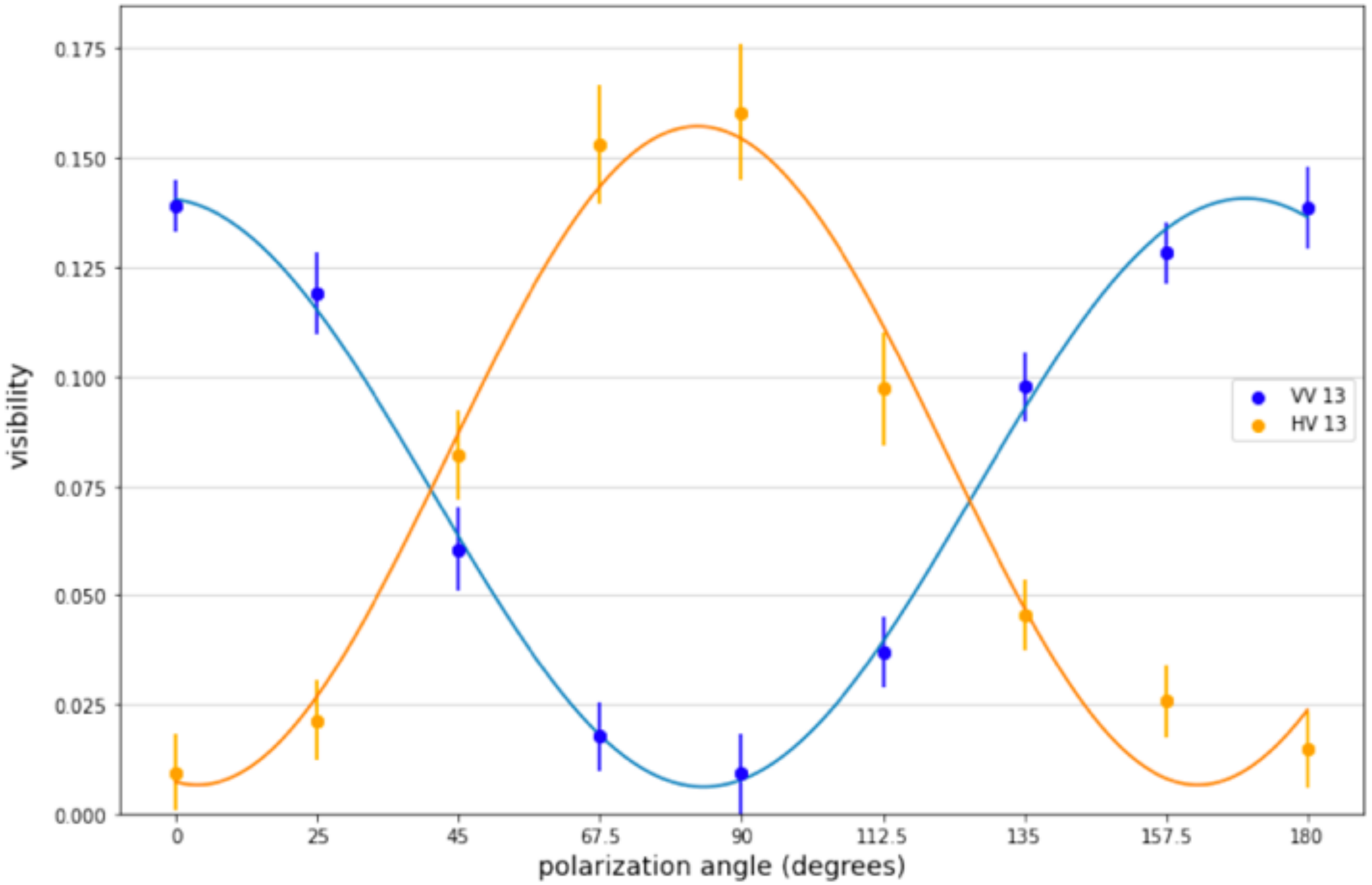




Phase Oscillations


0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
visibility
0
25
45
67.5
90
112.5
135
157.5
180
polarization angle (degrees)
VV 13
HV 13

Visibility


0.175
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0.050
0.025
0.000
visibility
0
25
45
67.5
90
112.5
135
157.5
180
polarization angle (degrees)
VV 13
HV 13

Visibility

Towards Quantum Telescopes: Demonstration of a Two-Photon Interferometer for Quantum-Assisted Astronomy

arXiv:2301.07042

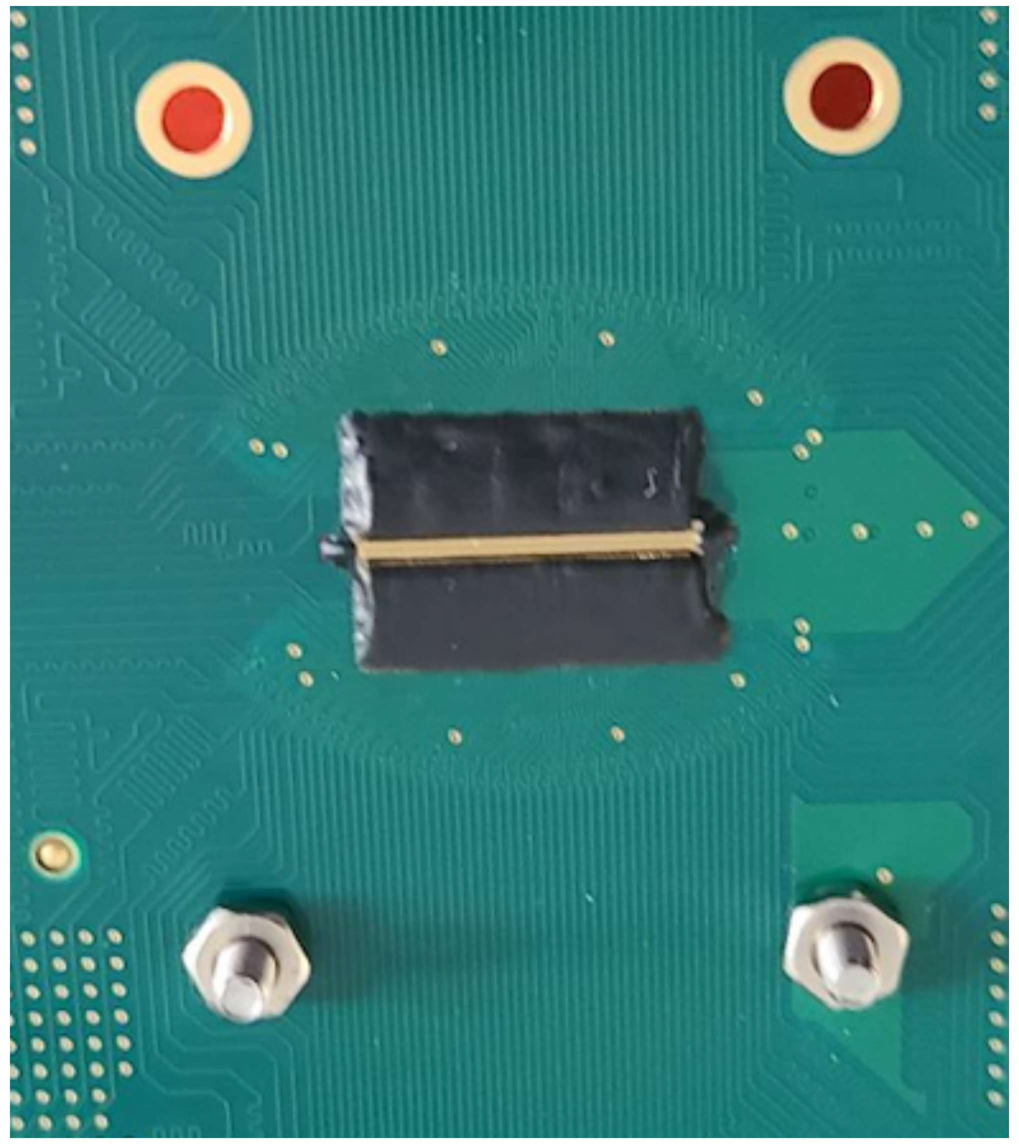
Expanding the tool box

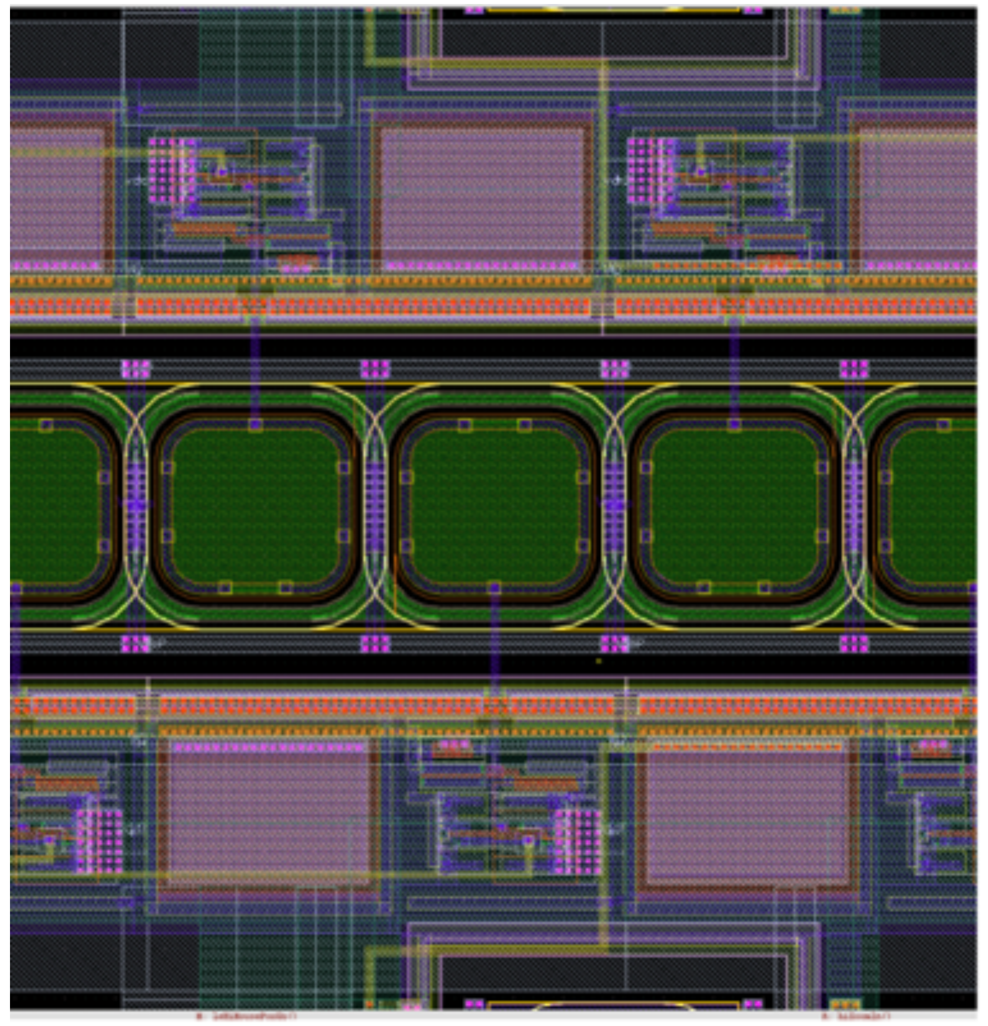
+

Spectral binning

LinoSPAD2: linear SPAD array

- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%

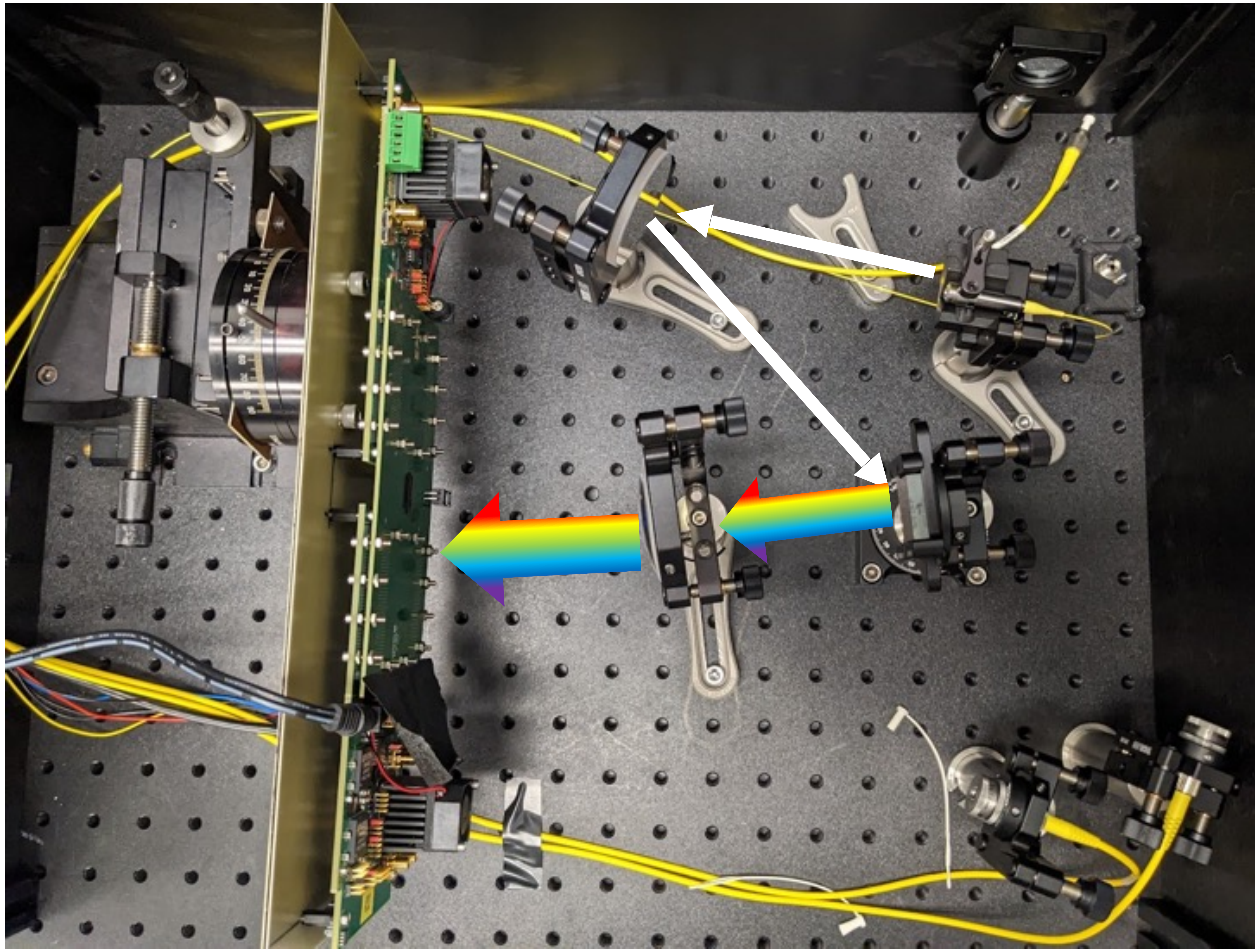


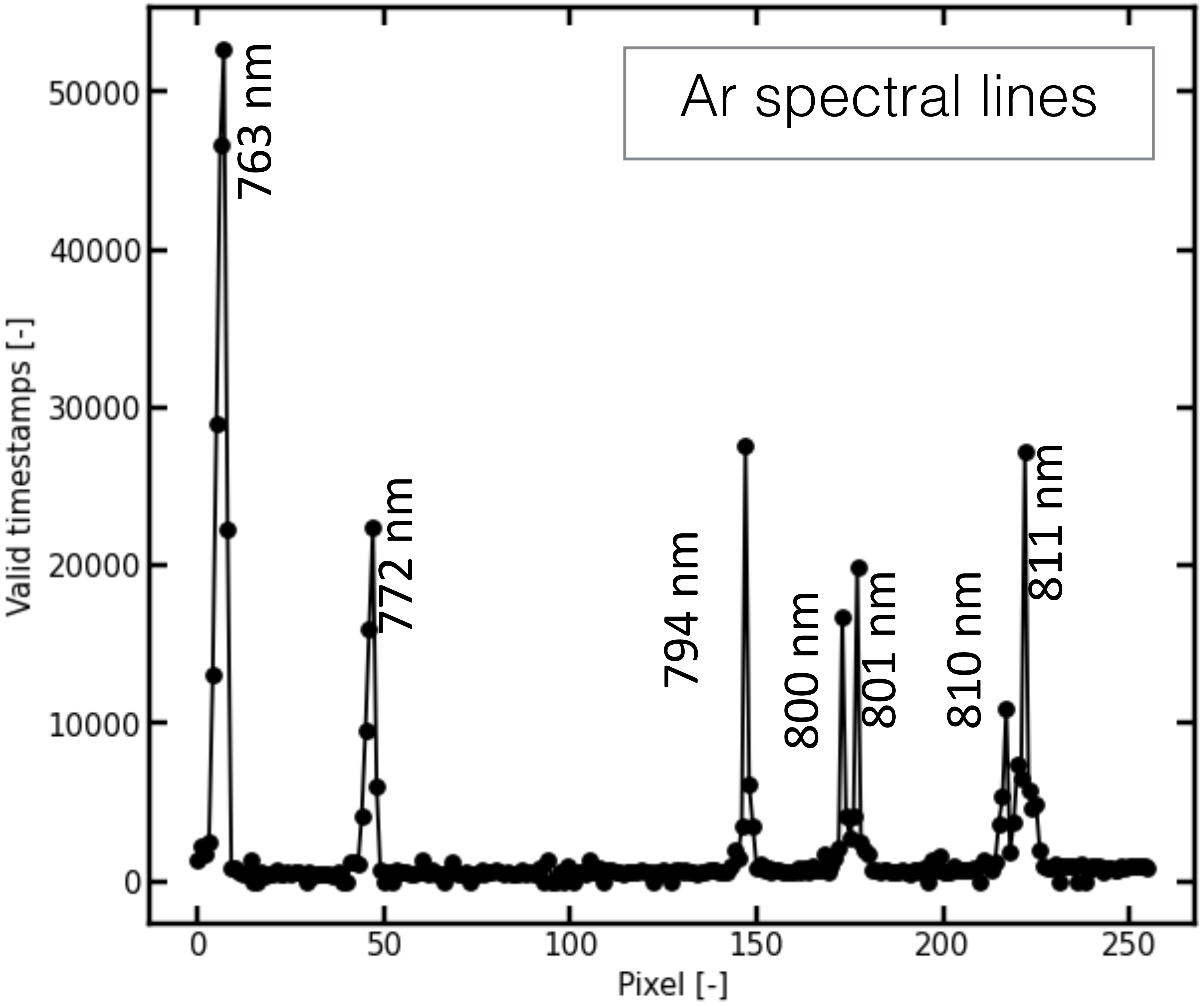


Close-up of SPADs

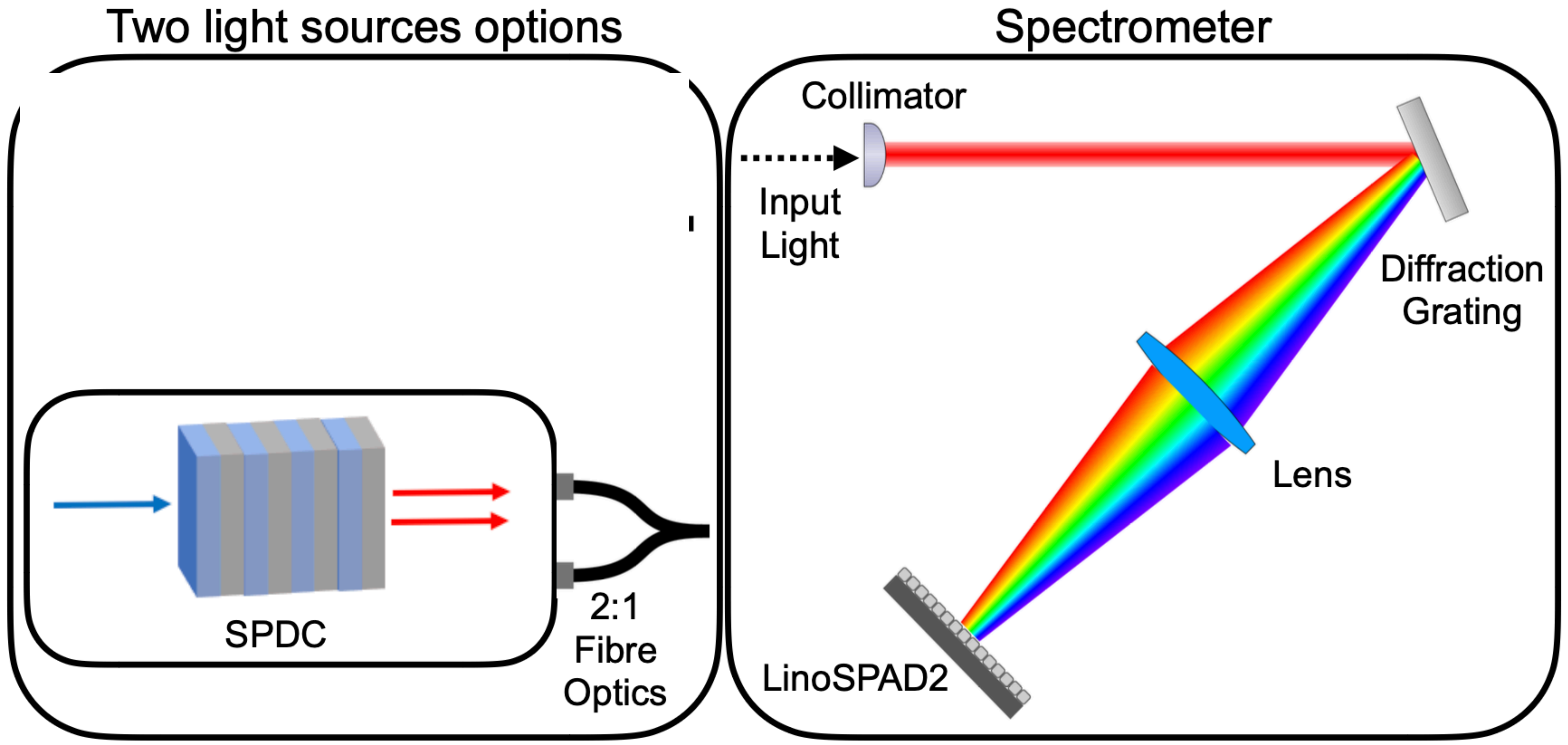
Spectrometer with LinoSPAD2

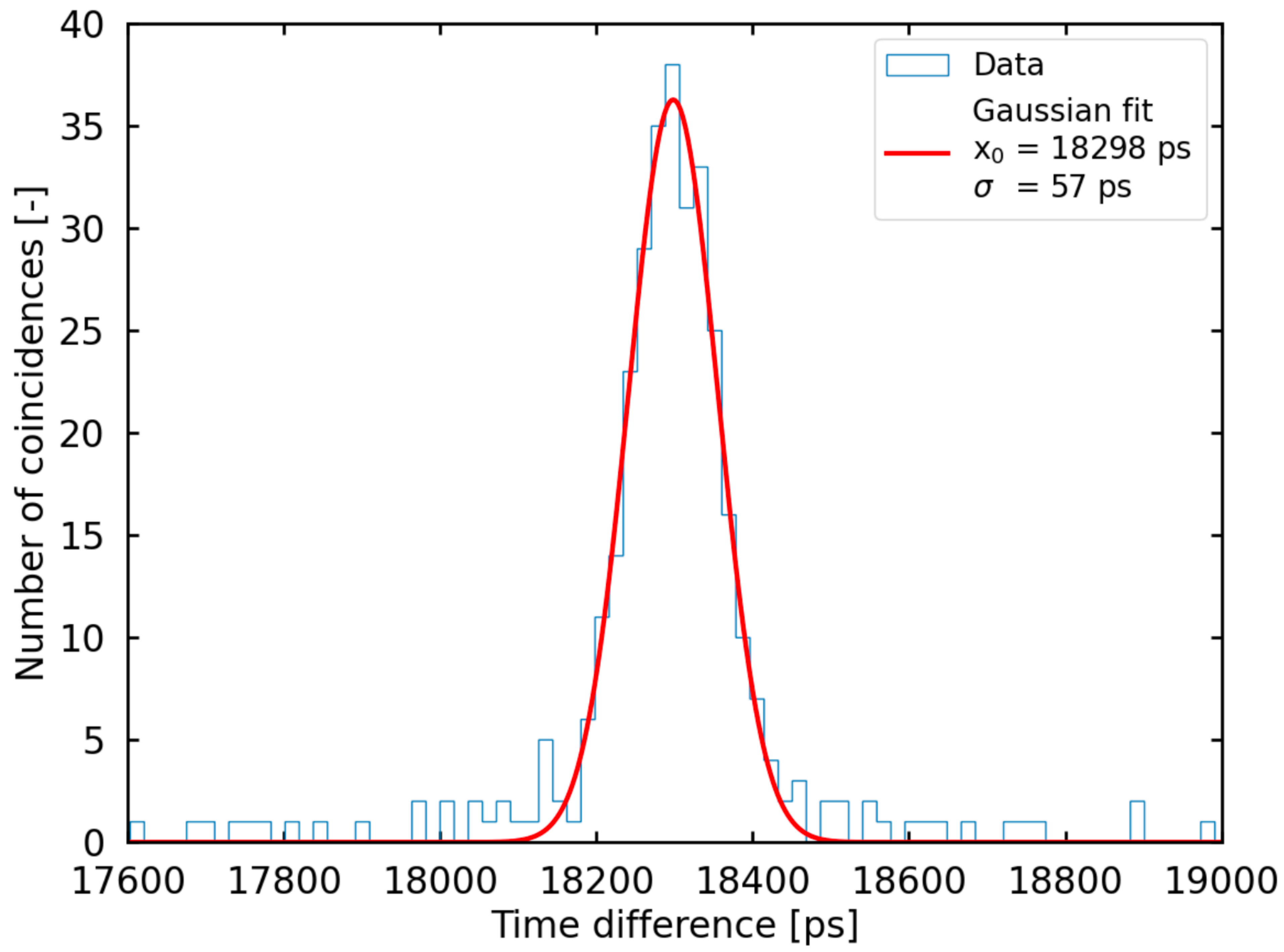
Used Ar lamp coupled to SM fiber

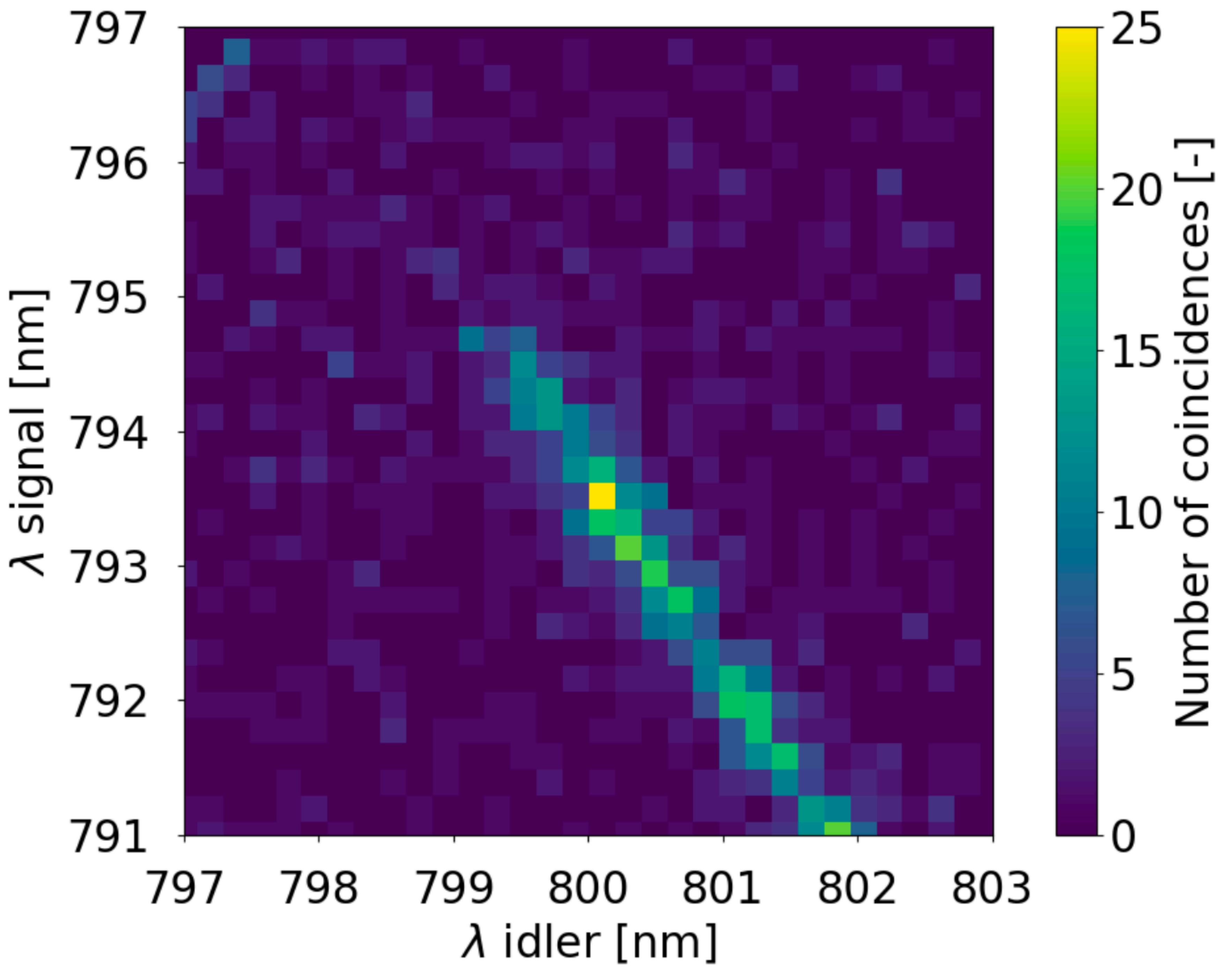




Two light sources options
Thermal
Light
Source
Fibre
Optics
Spectrometer
Collimator
Input
Light
Diffraction
Grating
Lens
LinoSPAD2
1e6
Counts [-]
Wavelength [nm]
Data
σ=0.045 nm
λ=794.932 nm
σ=0.042 nm
λ=800.607 nm
σ=0.045 nm
λ=801.451 nm
σ=0.053 nm
λ=810.154 nm
σ=0.054 nm
λ=811.299 nm


Two light sources options
Spectrometer
Collimator
Input Light
Diffraction Grating
Lens
LinoSPAD2
SPDC
2:1 Fibre Optics


Data
Gaussian fit
x_0 = 18298 ps
σ = 57 ps
Number of coincidences [-]
Time difference [ps]
0
5
10
15
20
25
30
35
40
17600
17800
18000
18200
18400
18600
18800
19000


λ signal [nm]
λ idler [nm]
Number of coincidences [-]
797
796
795
794
793
792
791
797
798
799
800
801
802
803
0
5
10
15
20
25

Benchmark

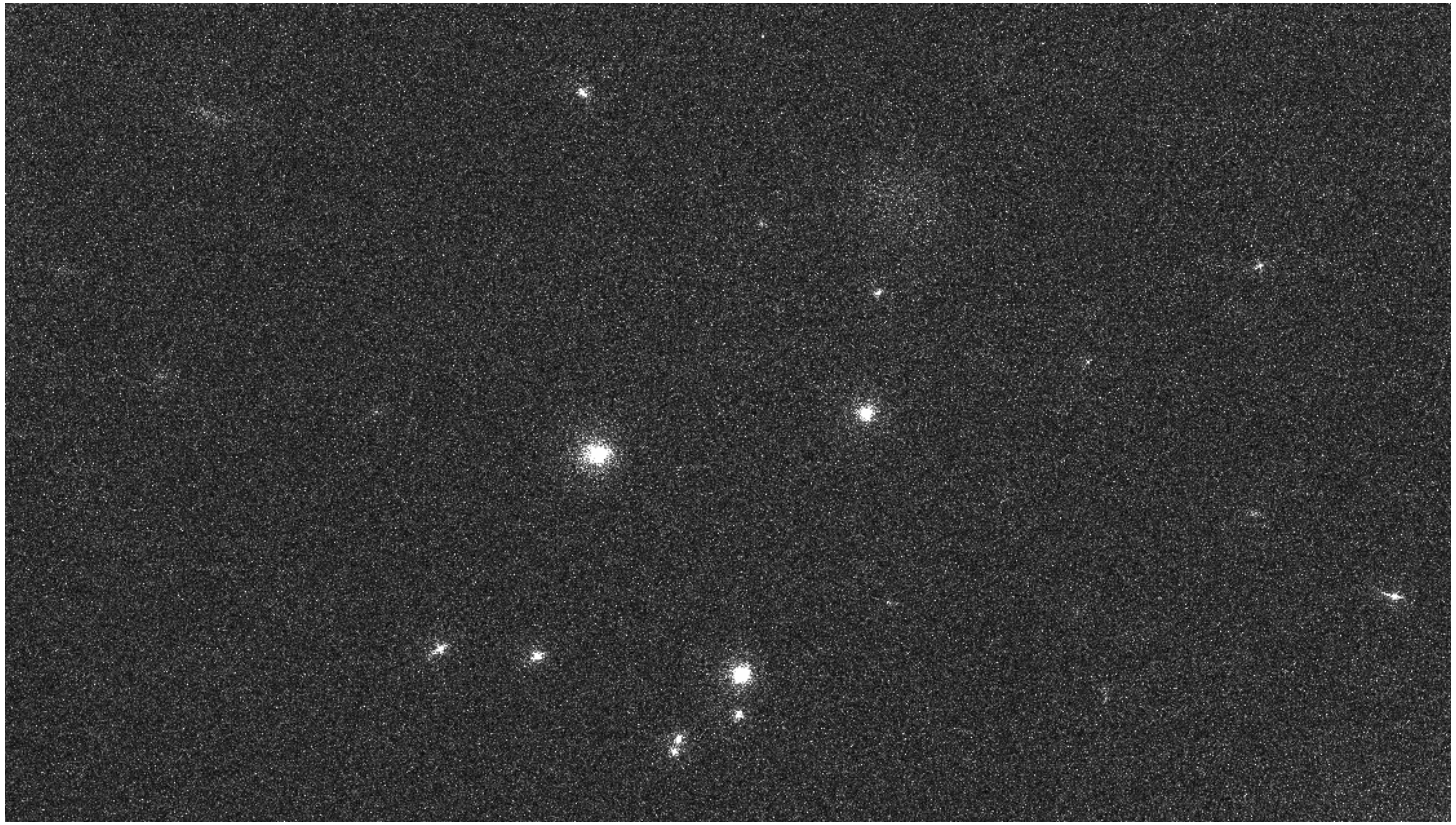
Heisenberg $$\Delta E \Delta t \geq \frac{\hbar}{2}$$

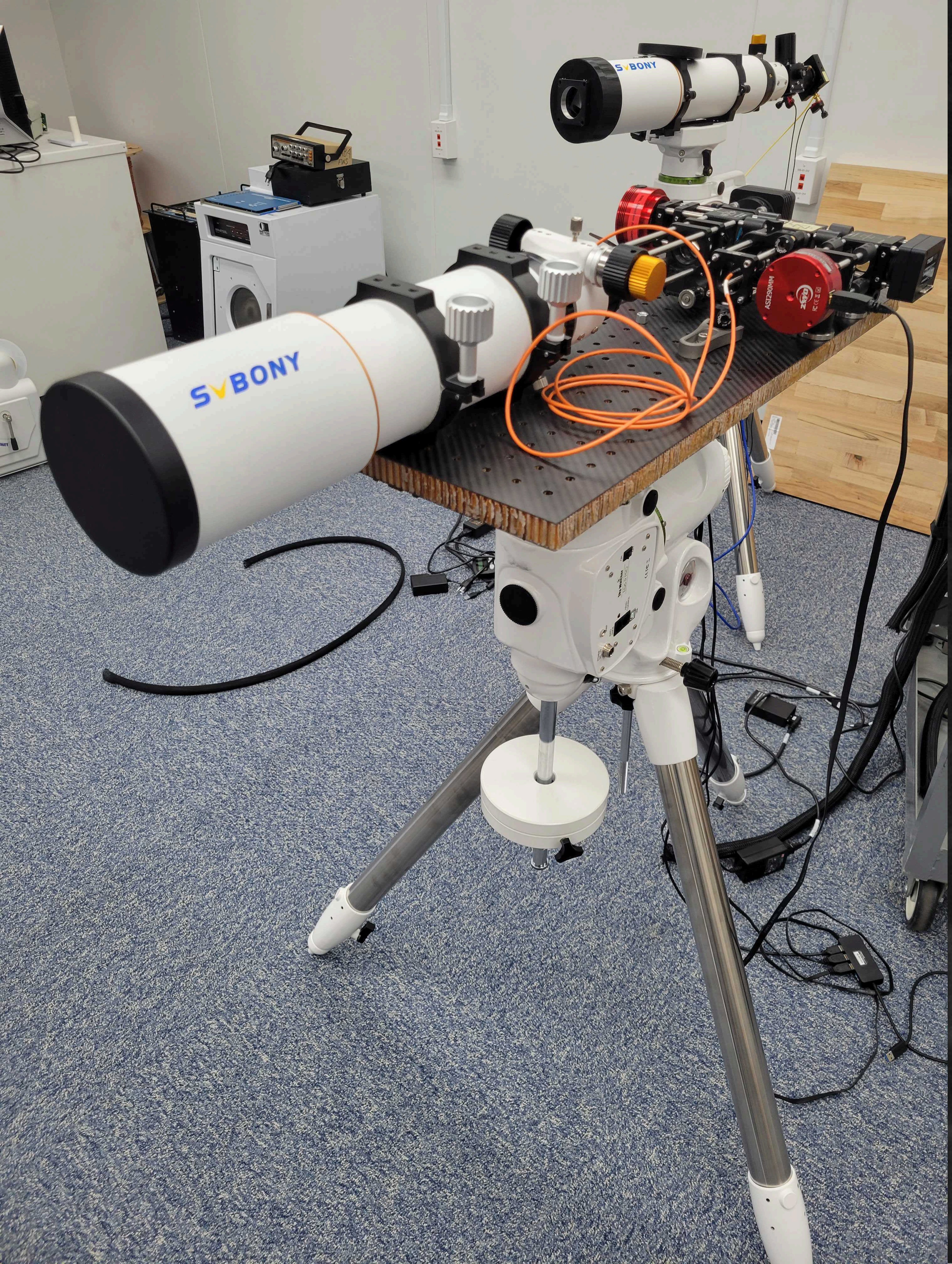
Our experiment $$(\Delta E \Delta t)/(\hbar/2) \approx 10$$

Fast spectrometer near the Heisenberg limit with direct measurement of time and frequency for multiple single photons

arXiv:2304.11999

We started testing with starlight on nights!!!!

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