Quantum-Enhanced Telescopy for HEP Science

Paul Stankus, BNL

CPAD 2023, RDC8 Nov 8, 2023

Brookhaven National Laboratory

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

“Keep watching the skies”

HEP Cosmological Frontier invests in observing photons from the sky

- Galaxy position, shape, photometric redshift
  - Tech: Low-noise CCD’s   Projects: DES, LSST/VRO
- Galaxy precision redshift
  - Tech: Low-noise spectrograph   Projects: BOSS, DESI
- Cosmic microwave background, incl polarization
  - Tech: TES   Projects: CMB-S4
- HI intensity mapping, including dark ages
  - Tech: RF spectrometers & interferometry   Projects: LuSEE Night

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- HI intensity mapping, including dark ages
    - Tech: RF spectrometers & interferometry Projects: LuSEE Night
- Precision *astrometry* of bright stars and binaries
    - Tech: Fast spectrograph, quantum optics Projects: TBD

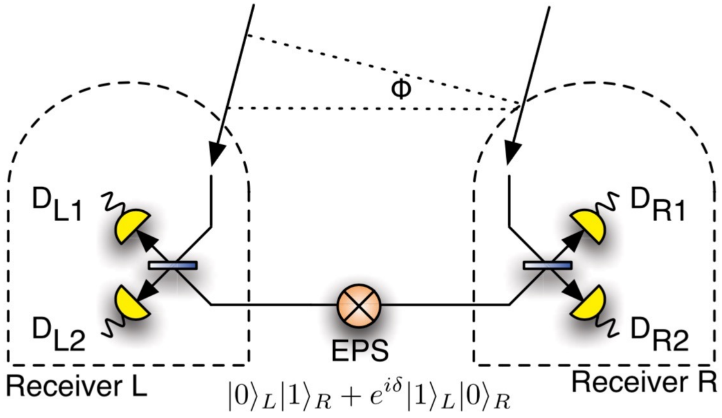
New!

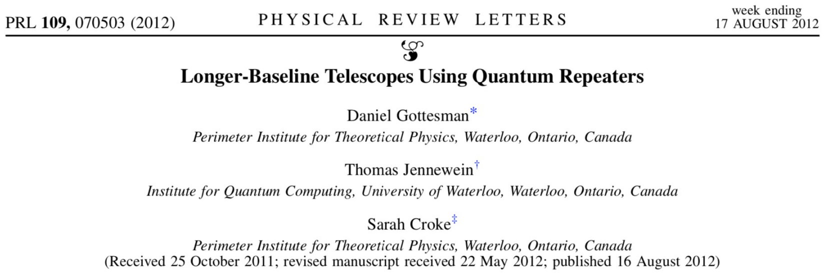
Idea: Quantum engineering can improve astronomical *interferometry*, both for high-resolution imaging and precision *astrometry*

Astrometry Measurement	Distance Ladder (H_0 tension)	Dark Energy	Dark Matter	GR Tests	Pre-CMB (relics)
Stellar parallax	✓	✓			
Proper motions			✓		
Binary orbit measure (independent distances)	✓	✓	✓		
Parallax with galaxies	✓	✓			
Microlensing in real time				✓	
Low-frequency (μHz) gravitational waves	✓	✓		✓	✓

Entanglement-Assisted Michelson

Quantum networks




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

Longer-Baseline Telescopes Using Quantum Repeaters

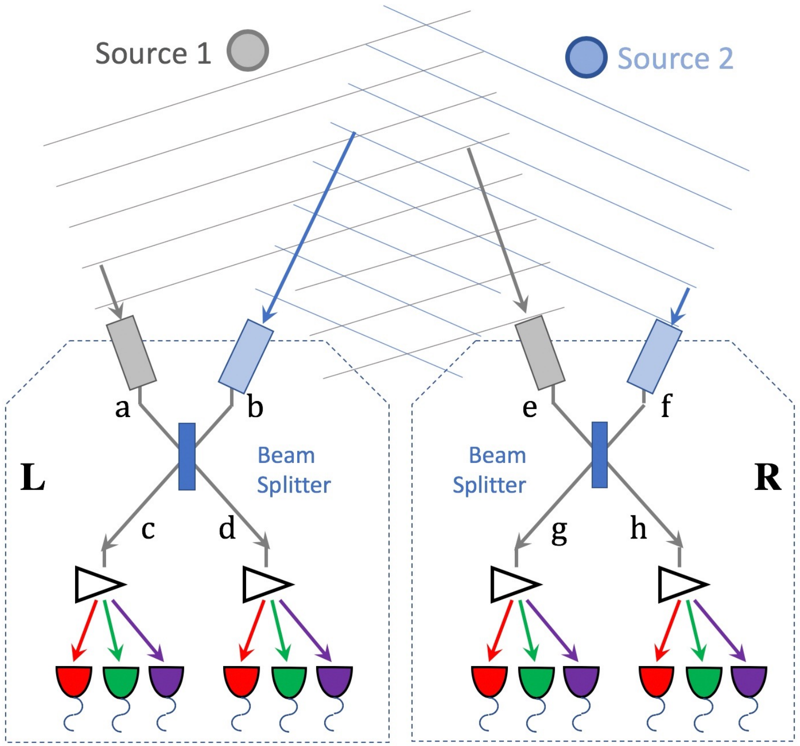
Daniel Gottesman[*]
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

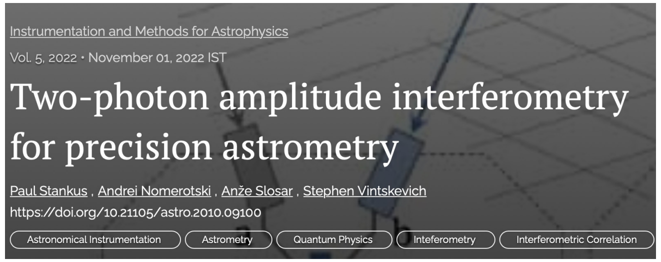
Thomas Jennewein[†]
Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

Sarah Croke[‡]
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

Two-source, generalized HBT

Arbitrary baselines




Instrumentation and Methods for Astrophysics

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Two-photon amplitude interferometry for precision astrometry

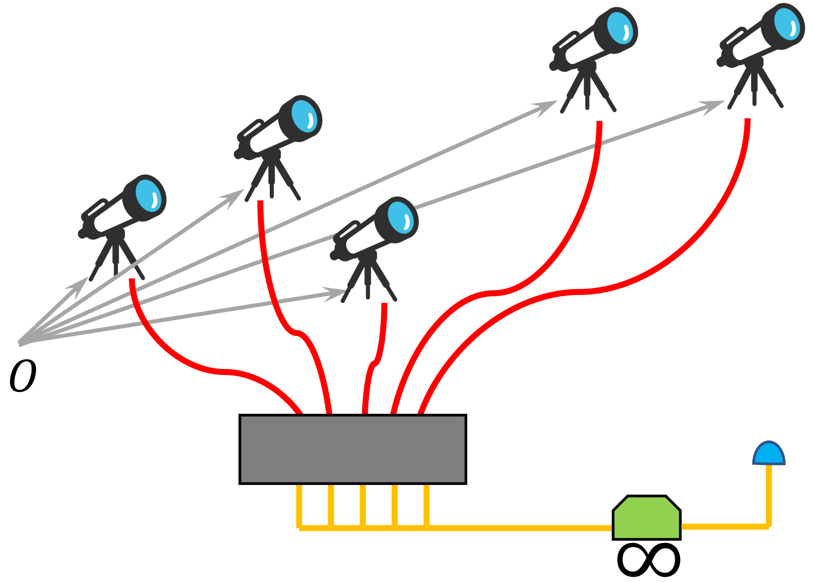
Paul Stankus , Andrei Nomerotski , Anže Slosar , Stephen Vintskevich

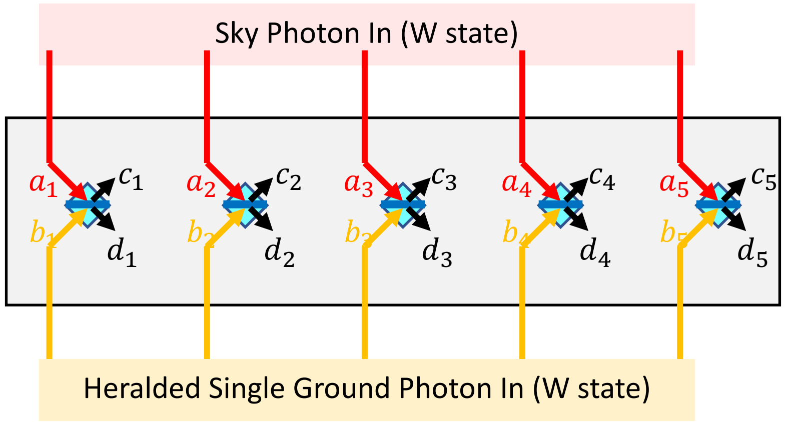
https://doi.org/10.21105/astro.2010.09100

Astronomical Instrumentation | Astrometry | Quantum Physics | Inteferometry | Interferometric Correlation

Very Large Arrays

Higher rates, multipartite states





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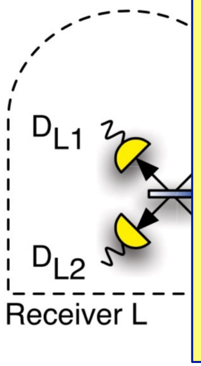
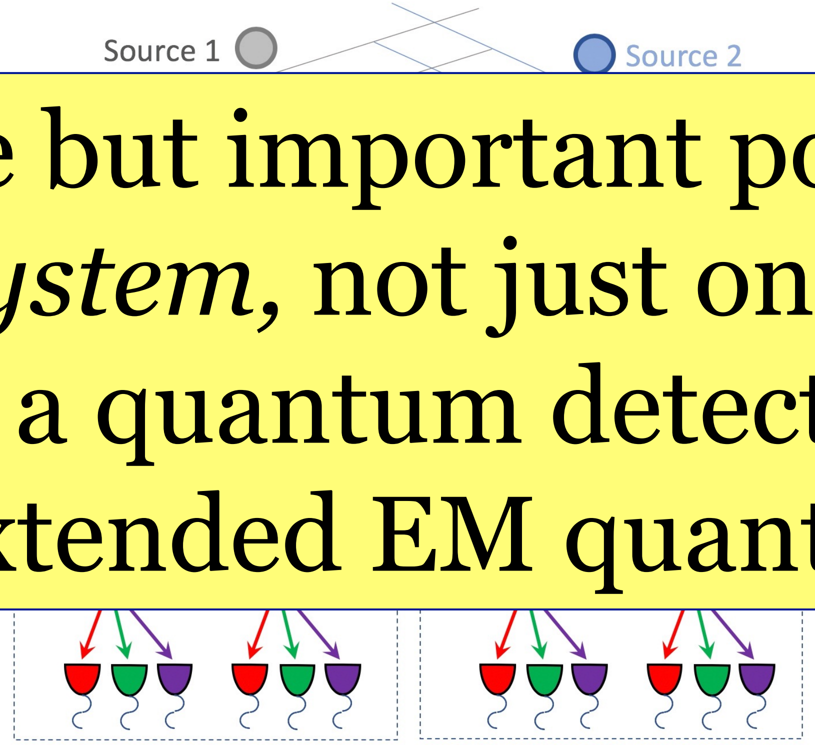
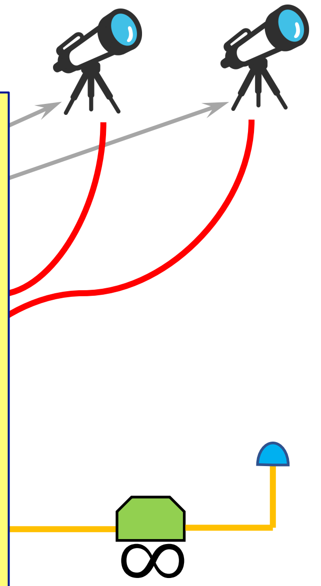
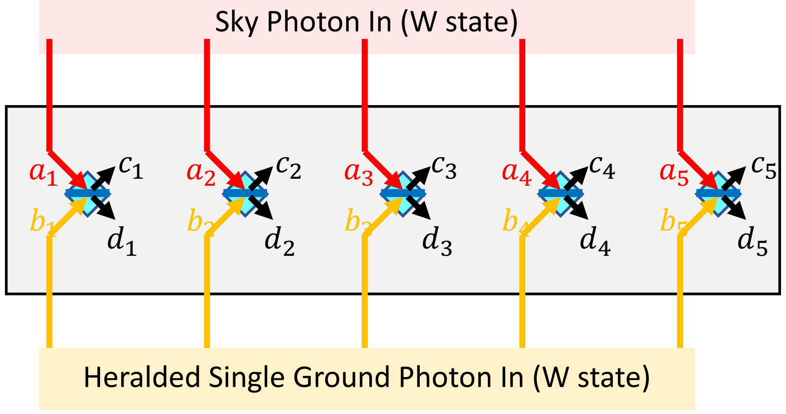
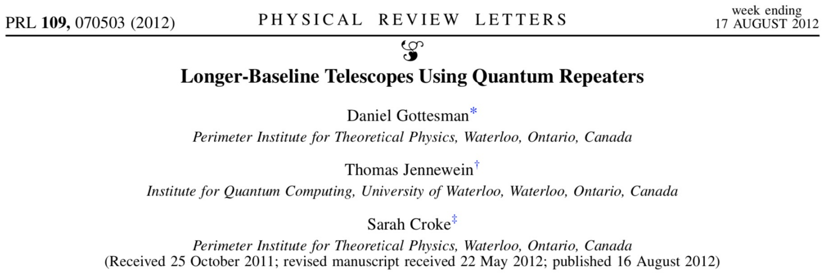






Subtle but important point:
The *entire system*, not just one device or sensor, is a quantum detector for a coherent extended EM quantum field.

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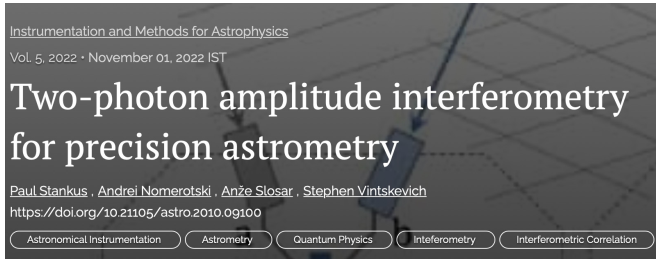
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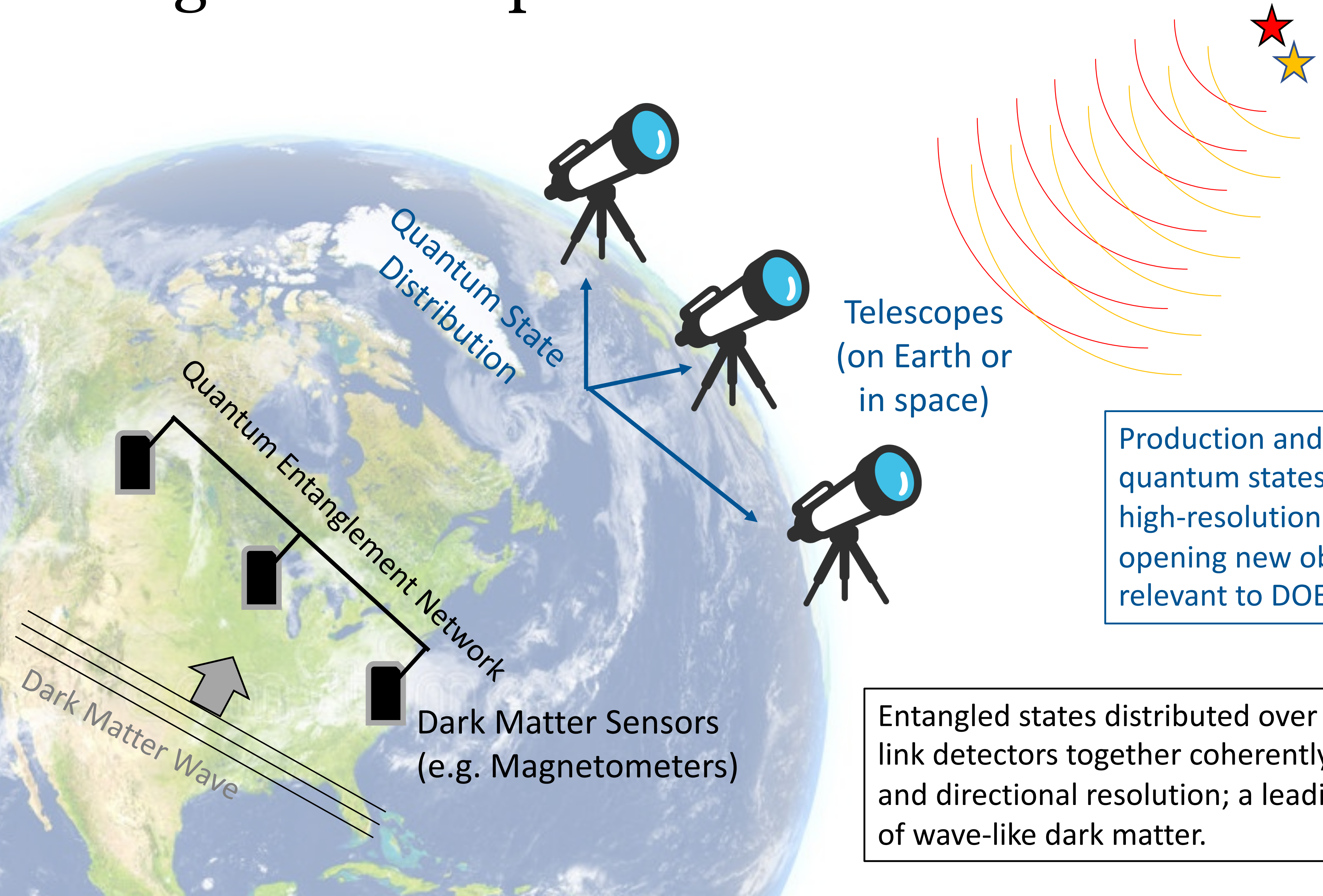
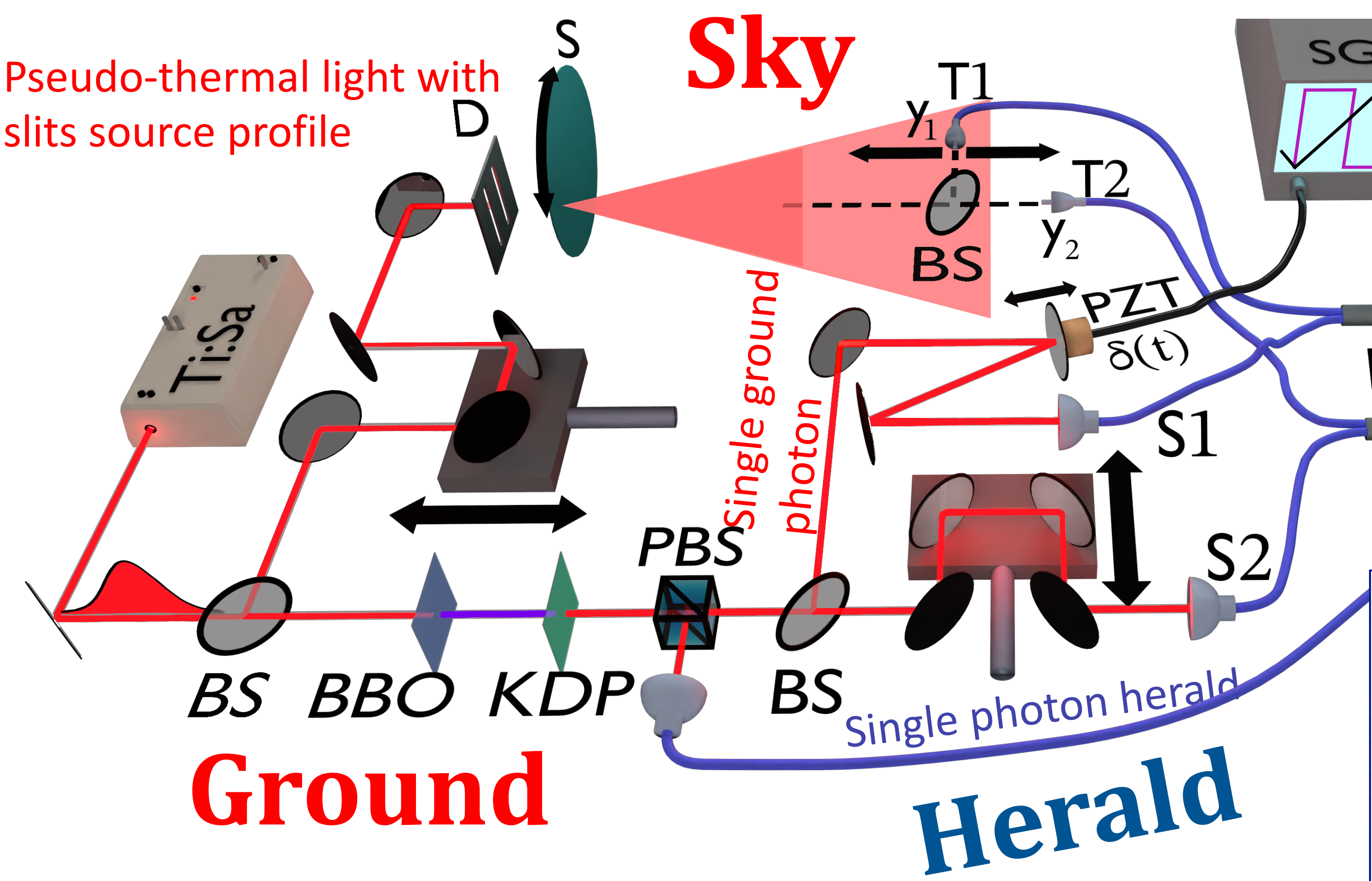
Long-distance quantum coherence



Interferometers are sensitive to very small details and differences in stars' positions.

Production and distribution of custom quantum states enables long-baseline, high-resolution optical interferometry, opening new observations directly relevant to DOE HEP science.

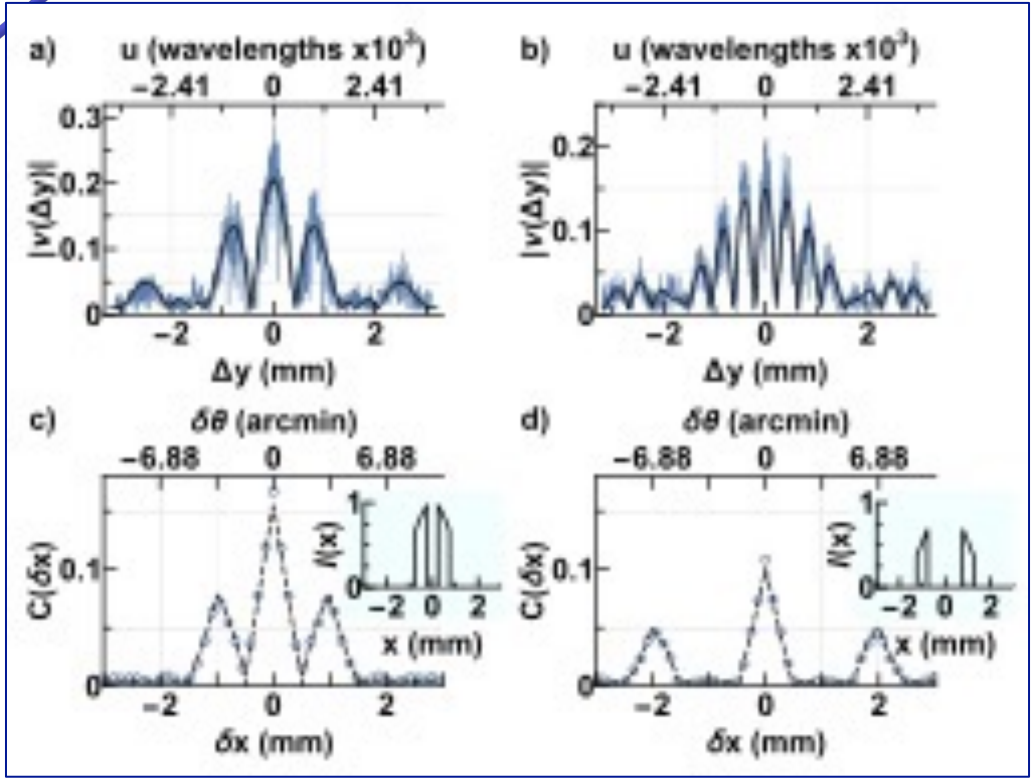
Entangled states distributed over quantum networks can link detectors together coherently, improving sensitivity and directional resolution; a leading example is detection of wave-like dark matter.



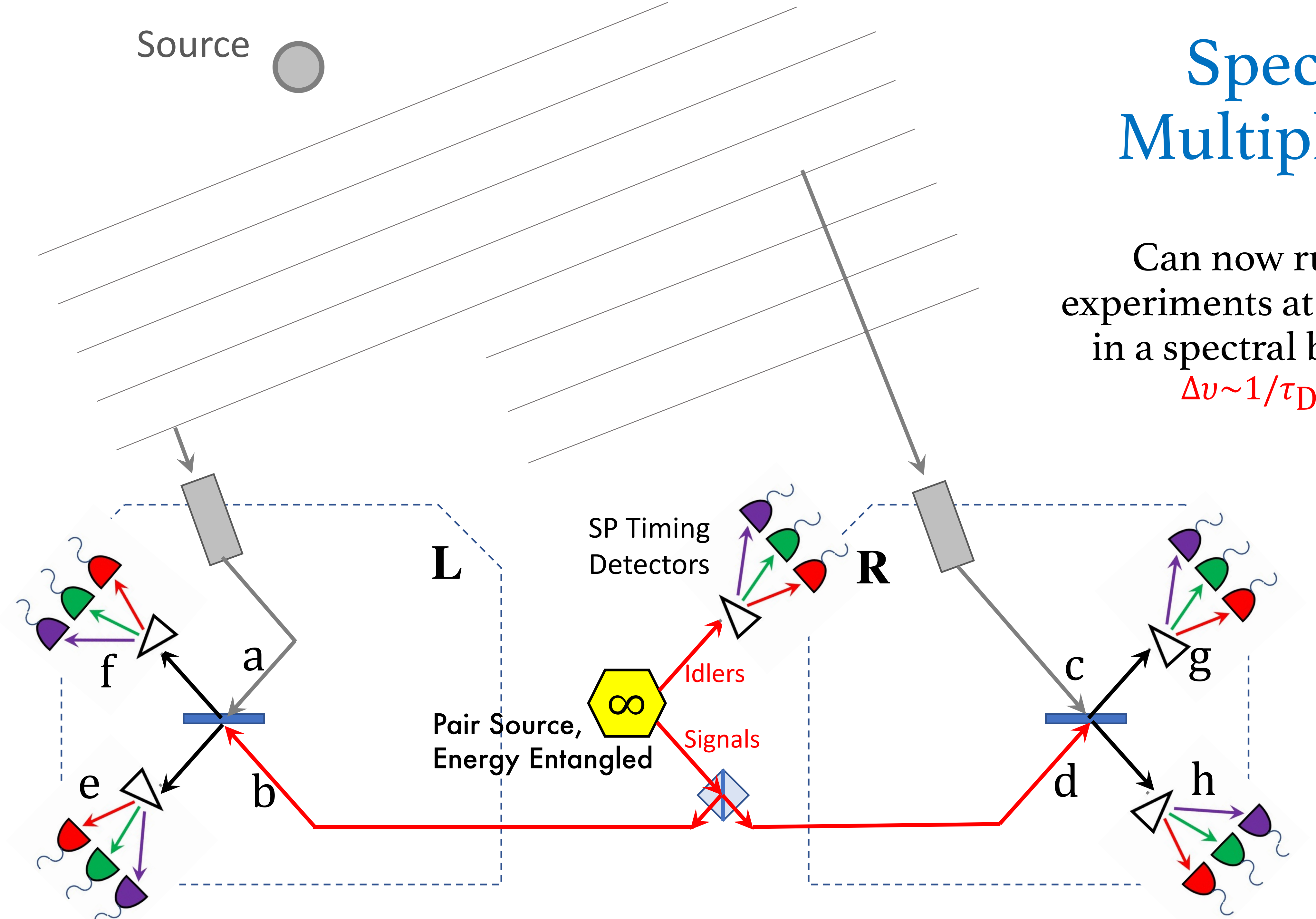
Interferometric imaging using shared quantum entanglement

Matthew R. Brown,[1] Markus Allgaier,[1] Valérian Thiel,[2] John
D. Monnier,[3] Michael G. Raymer,[1] and Brian J. Smith[1,*]
[1] *Department of Physics and Oregon Center for Optical, Molecular,*
and Quantum Science, University of Oregon, Eugene, Oregon 97403, USA
[2] *PASQAL, 7 rue Léonard de Vinci, 91300 Massy, France*
[3] *Department of Astronomy, University of Michigan, Ann Arbor, Michigan 48109, USA*

(Dated: June 19, 2023)
To appear in PRL



Spectral Multiplexing



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

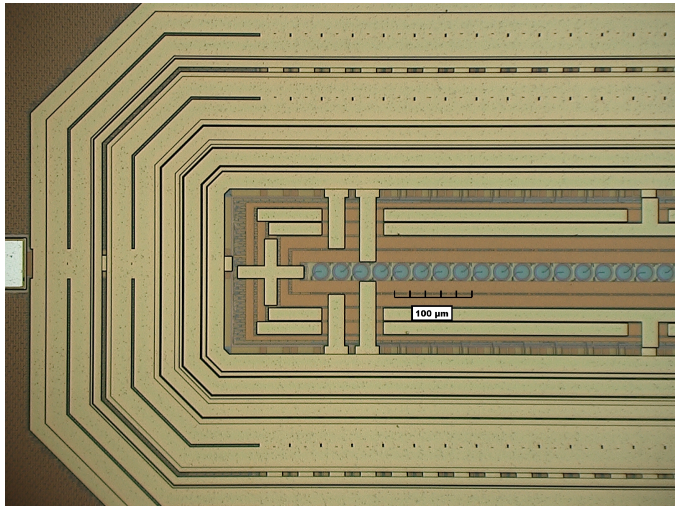
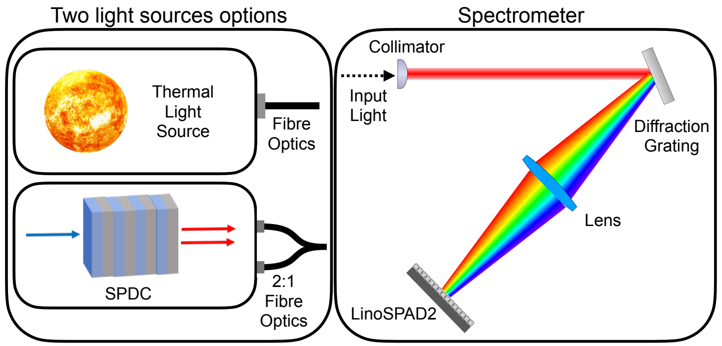
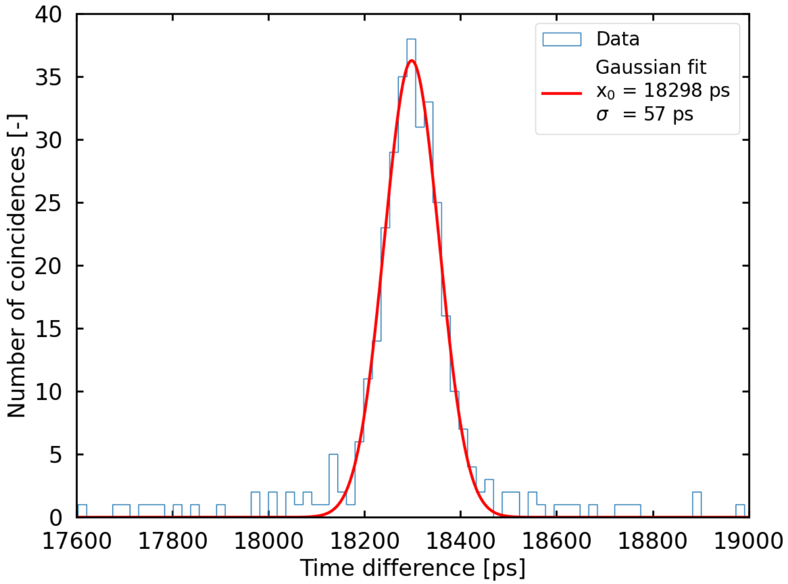
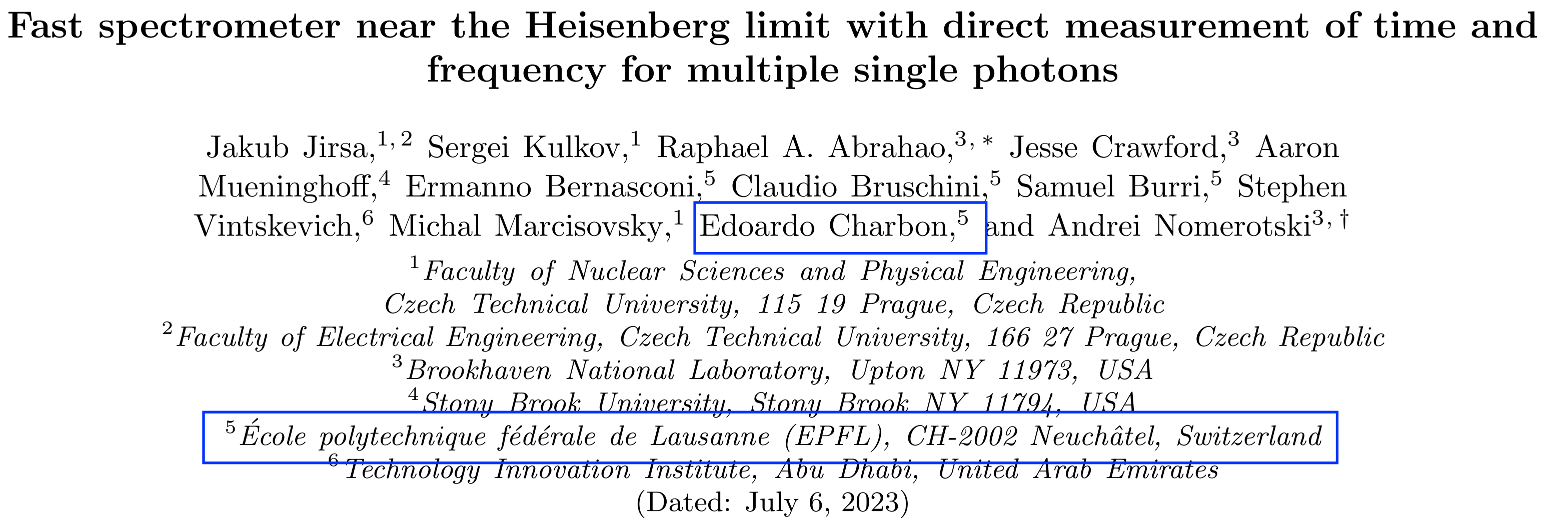


FIG. 2. Photograph of the LinoSPAD2 sensor edge. The line of pixels is in the centre, oriented horizontally.





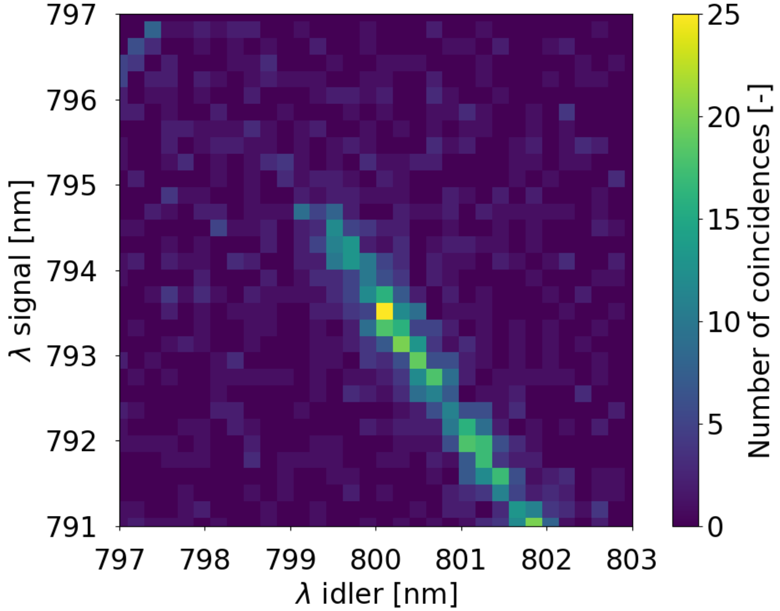


Fast spectrometer near the Heisenberg limit with direct measurement of time and frequency for multiple single photons

Jakub Jirsa,[1,2] Sergei Kulkov,[1] Raphael A. Abrahao,[3,*] Jesse Crawford,[3] Aaron Mueninghoff,[4] Ermanno Bernasconi,[5] Claudio Bruschini,[5] Samuel Burri,[5] Stephen Vintskevich,[6] Michal Marcisovsky,[1] Edoardo Charbon,[5] and Andrei Nomerotski[3,†]

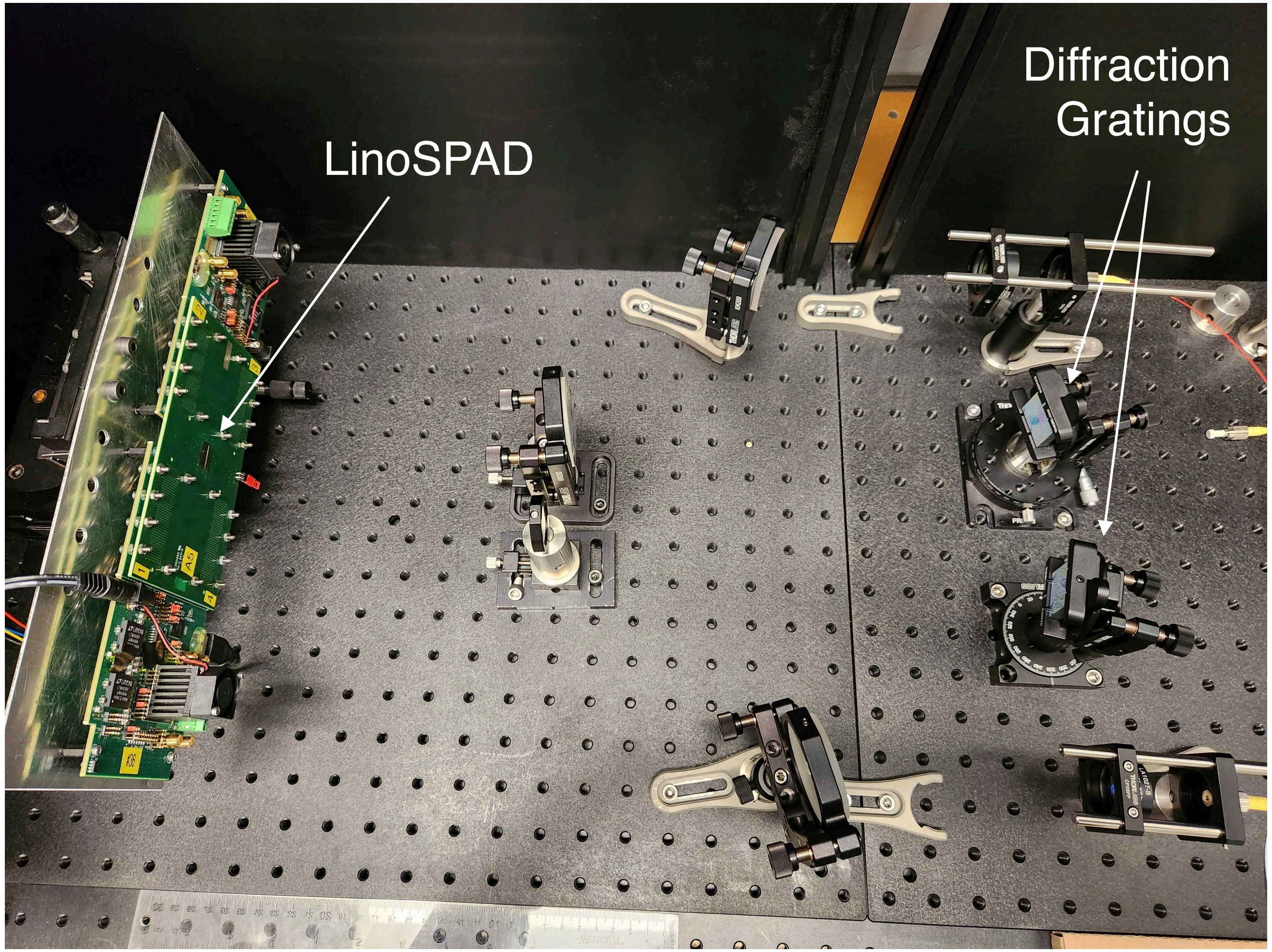
[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, 115 19 Prague, Czech Republic*
[2] *Faculty of Electrical Engineering, Czech Technical University, 166 27 Prague, Czech Republic*
[3] *Brookhaven National Laboratory, Upton NY 11973, USA*
[4] *Stony Brook University, Stony Brook NY 11794, USA*
[5] *École polytechnique fédérale de Lausanne (EPFL), CH-2002 Neuchâtel, Switzerland*
[6] *Technology Innovation Institute, Abu Dhabi, United Arab Emirates*

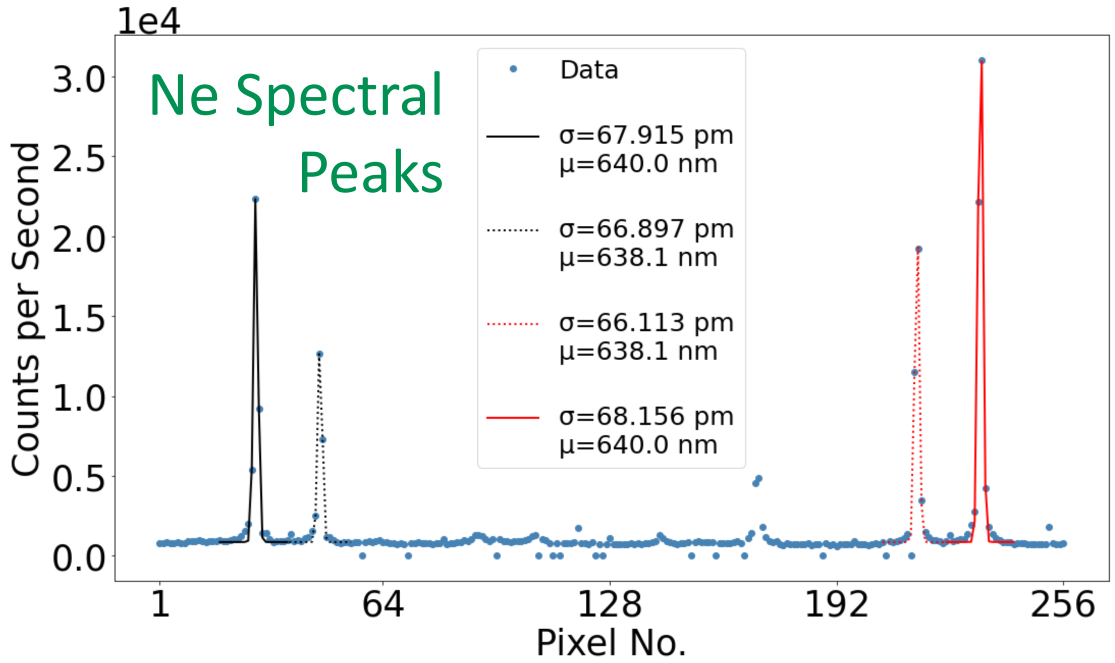
(Dated: July 6, 2023)

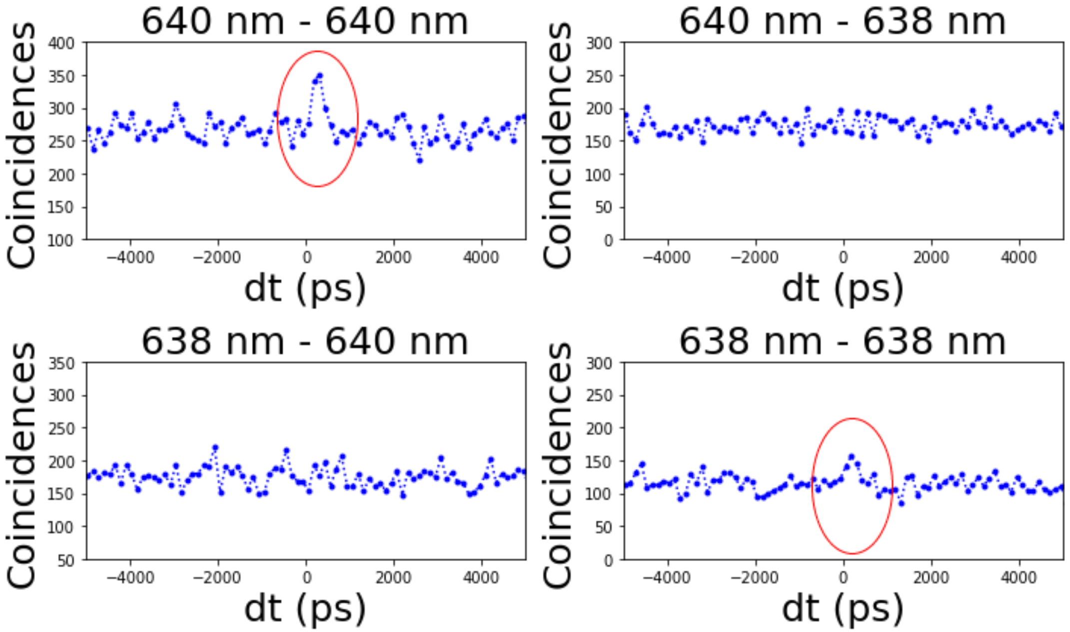


arXiv:2304.11999

Double spectrograph prototype at BNL







Quantum enhancement (HBT) observed

Technology needs: Fast Spectrograph

Enabling technology for many quantum-enhanced telescopy approaches

Very natural fit for HEP detector expertise

- Array of single-photon sensitive detectors to view a spectrographic spread of a single-mode beam – can be 1D or 2D (Echelle)
- Want reasonable QE (>50%) and good timing (<50ps, better is better)
- Many possibilities, SPAD's, SiPM's, SNSPD's
- Want many channels, ~$10^{3\text{-}5}$ in parallel ↔ low cost/channel
- Operational: Portable, durable, etc.

Is this a natural "work package"? or part of one?

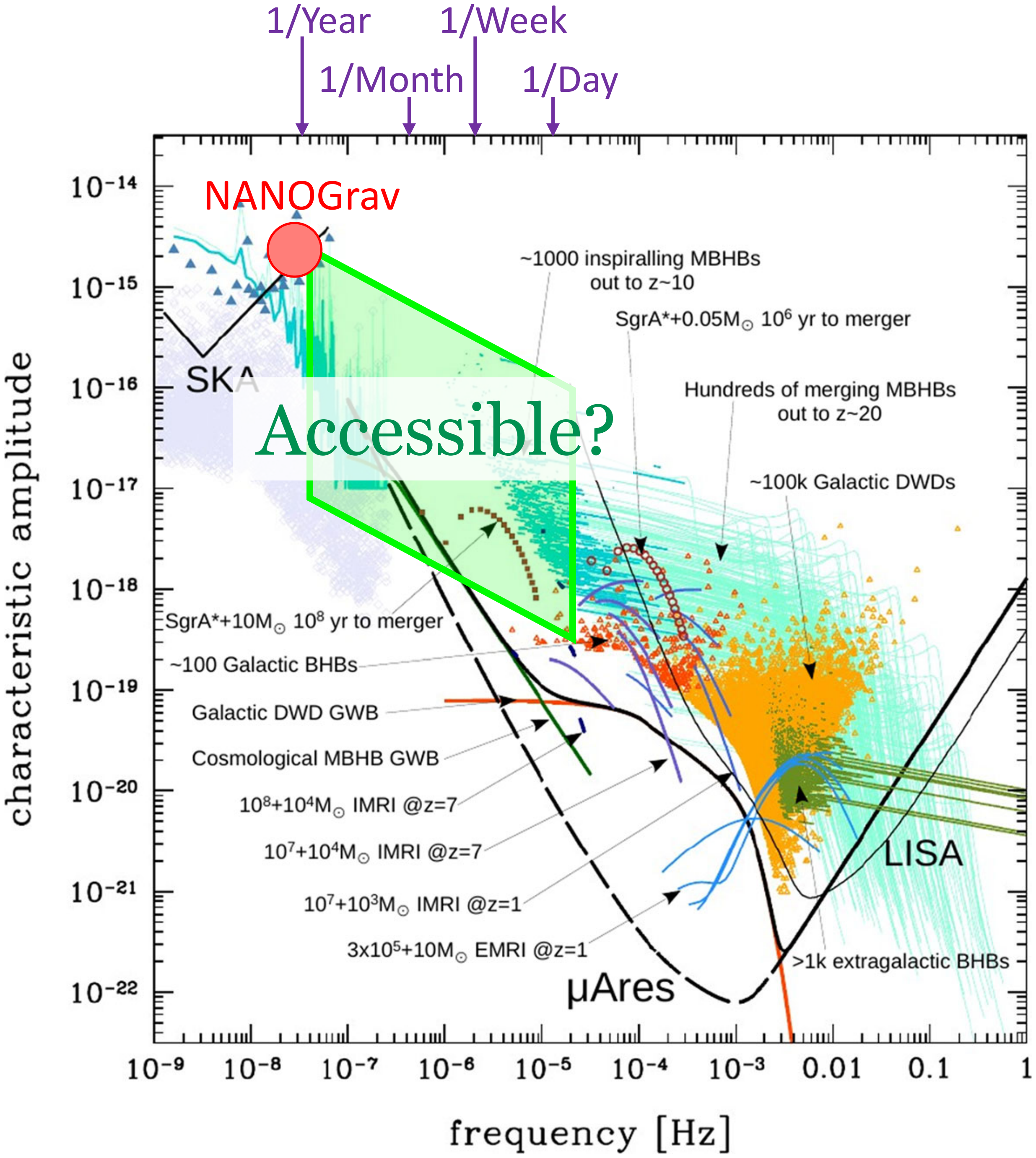
Technology needs: Quantum/Optics

New for HEP detector portfolio, but definitely some overlaps with traditional expertise

- Quantum entangled state creation, e.g. parametric down-conversion; higher rates, high brightness, custom lineshapes, etc.
- Photon transport, e.g. stabilizing long fiber runs
- Remote synchronization, ~psec across 10’s km
- **Futuristic:** long-distance quantum networks using repeaters, quantum memory storage, QND detection
- Collection optics, not usually an HEP specialty; but, air shower arrays -> HBT observatories for example

Summary

- Quantum devices can greatly improve optical interferometry; q-astro is a new and growing field independent of HEP
- *Precision astrometry* enabled by improved interferometers can be directly relevant to HEP Cosmic Frontier science
- A distributed array of detectors can act as a quantum sensor, even if individual pieces look like phototdetectors, e.g.
- Immediate technology path ahead, from very concrete HEP expertise to longer-range QIST capabilities



Science question: Are low-frequency gravitational waves part of the HEP Cosmological Frontier? Should they be?

Stochastic GW background in nHz range has recently been observed (NANOGrav)

Observation in μHz range are do-able through precision astrometry

Main source is SMBHB mergers, possibly following galaxy major mergers; informs structure formation, cosmology, dark matter; also possibly see pre-CMB relics

LIGO

Extras

1990's: Parody
2020's: Solid Advice

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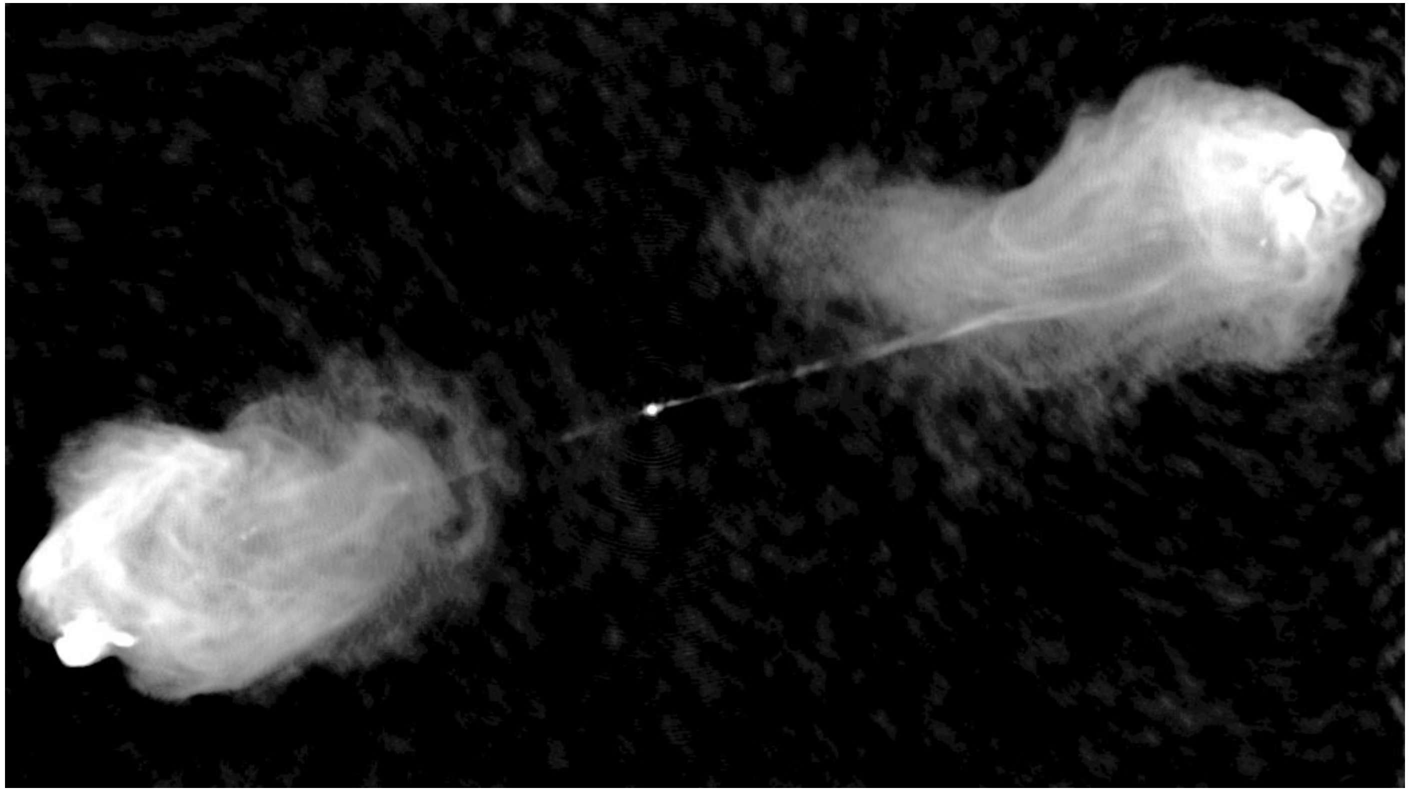
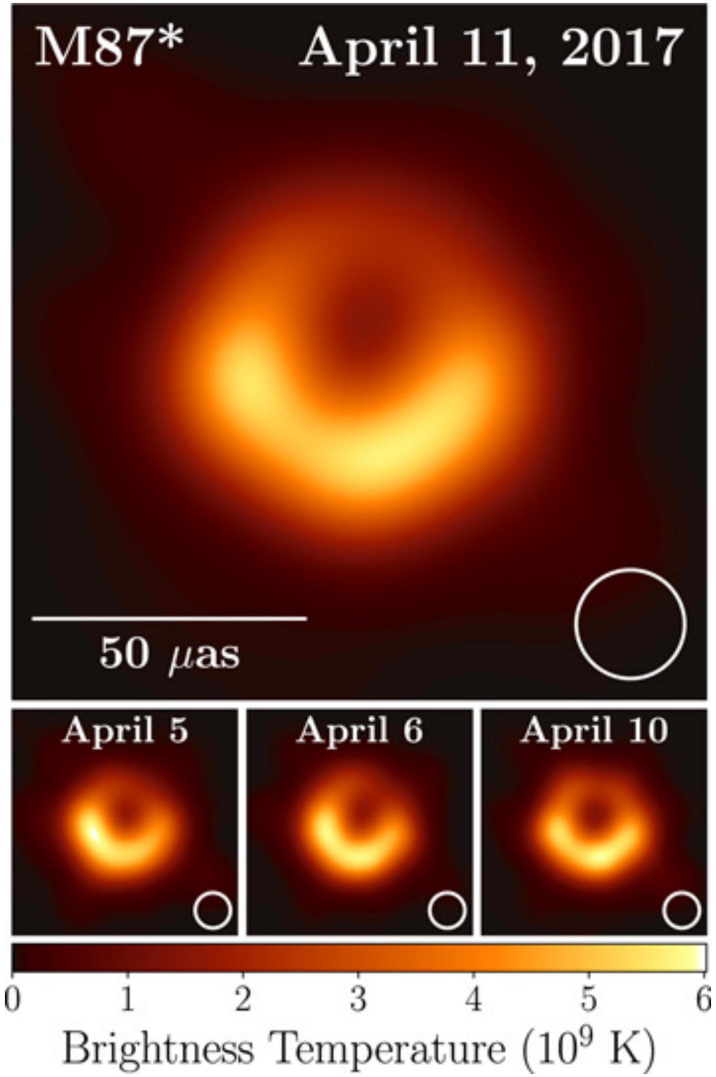
Interferometry is good



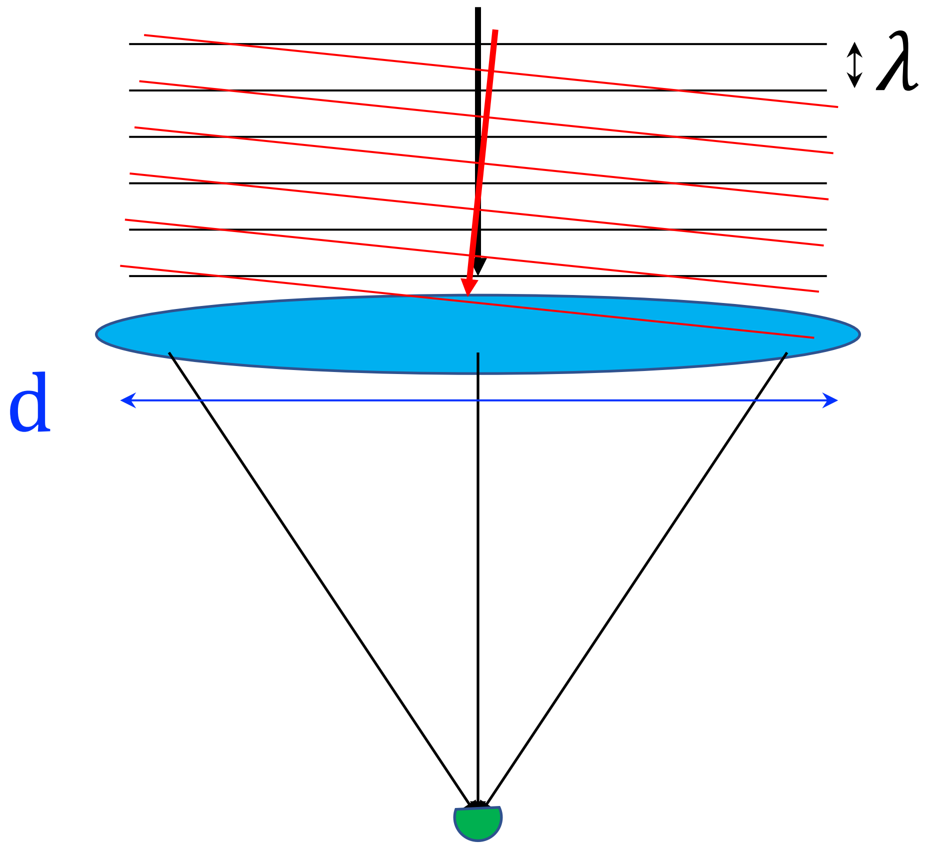
Radio source Cygnus A imaged at 6cm



Center of M87 imaged at 1.3mm

2019 ApJL 875

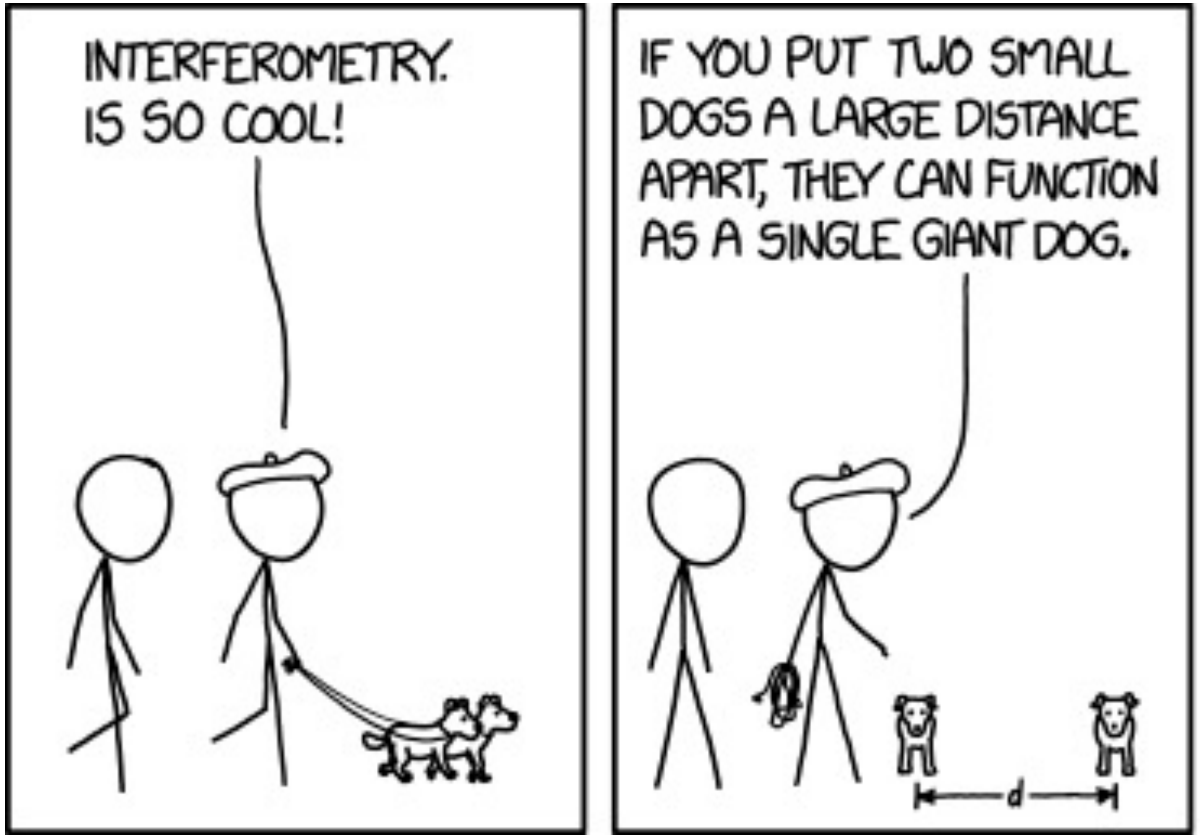
Single Aperture Diffraction Limit



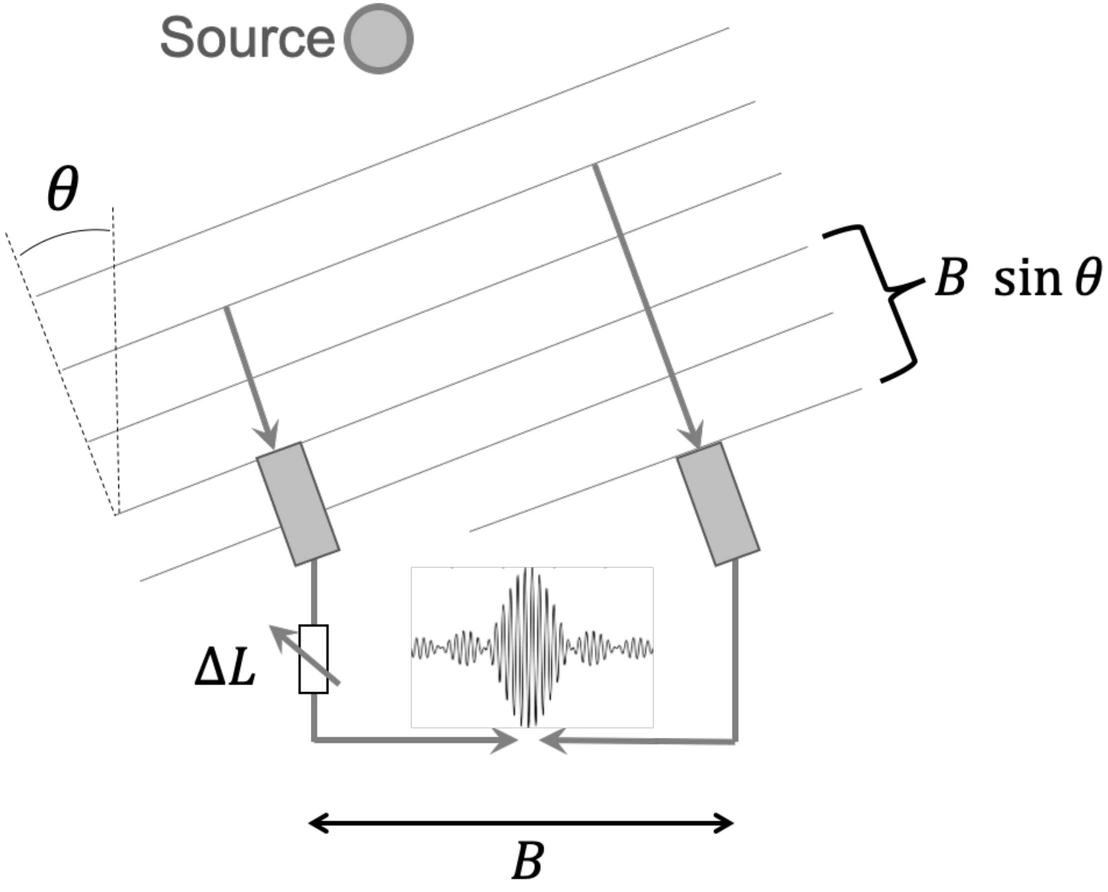
A single detector/pixel point will collect intensity from a range of angles. The limit of this angular range is $\Delta\theta \sim \lambda/d$ after which the wavefront will interfere with itself destructively across the aperture. Therefore any single-aperture telescope cannot resolve features with angular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

Idea: Separate apertures over long baselines

Michelson Stellar Interferometer ca.1890



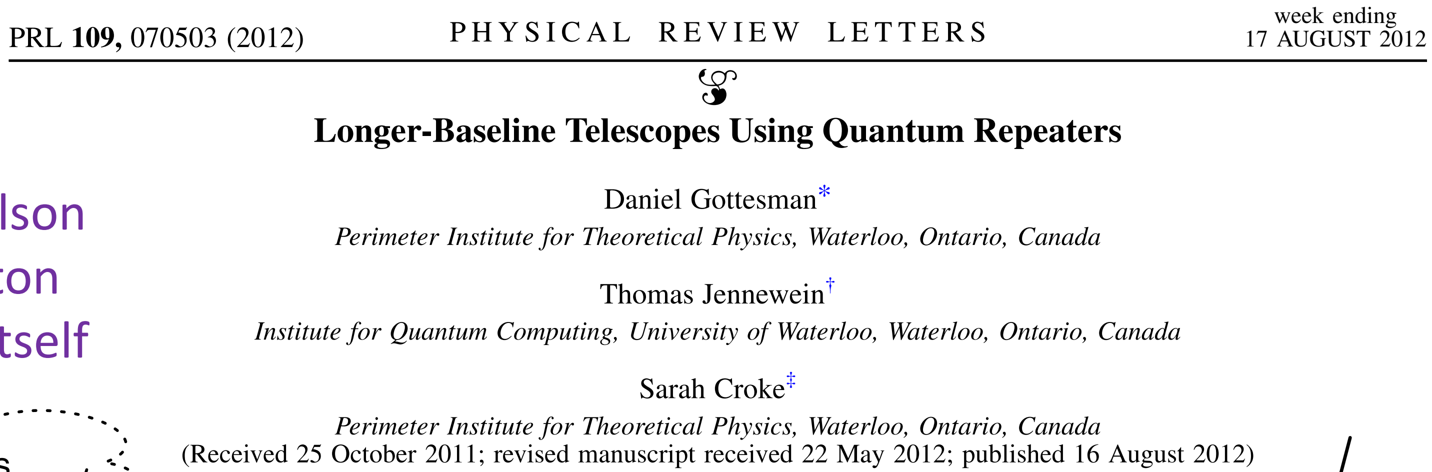
https://xkcd.com/1922/



Interference fringe pattern sensitive to features of angular size $\Delta\theta \sim \lambda/B$

Contrast *visibility* measures Fourier component of source distribution at $k \sim B/\lambda$

Idea: Separate functions of photon capture, photon transport, and photon interference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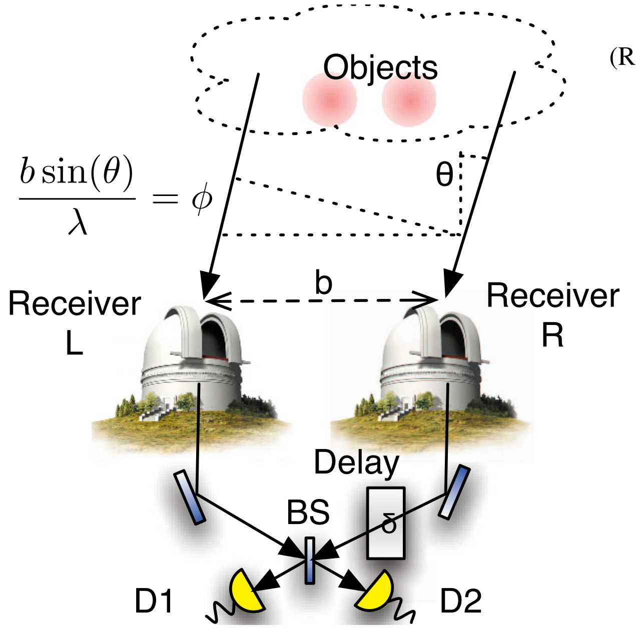
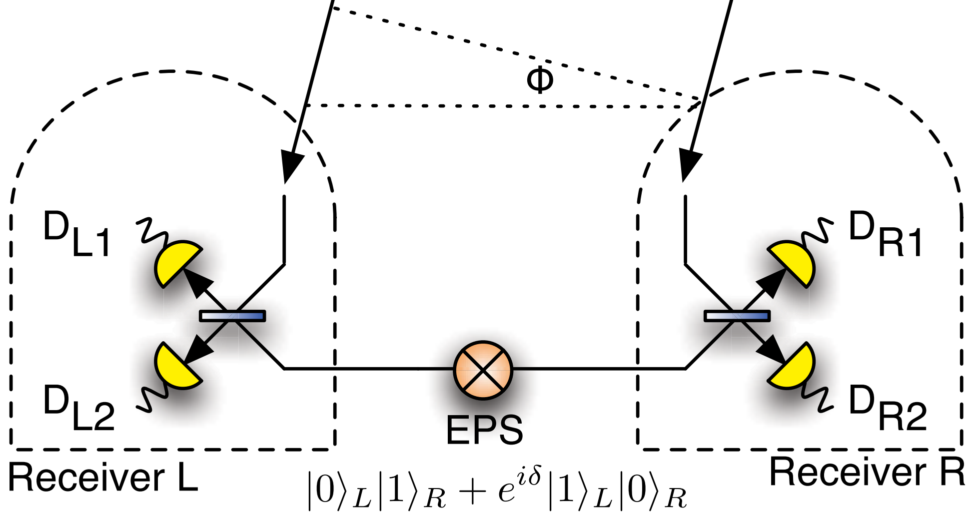
Standard Michelson
Single sky photon
interferes with itself



GJC: Sky photon is mixed with a single "ground" photon at each station



The single ground photon is assumed delivered through a *quantum network* which can provide entanglement on demand

Pattern of coincidences measured at L and R stations reveals phase difference of sky photon arriving in two places: interferometry

Sky direction

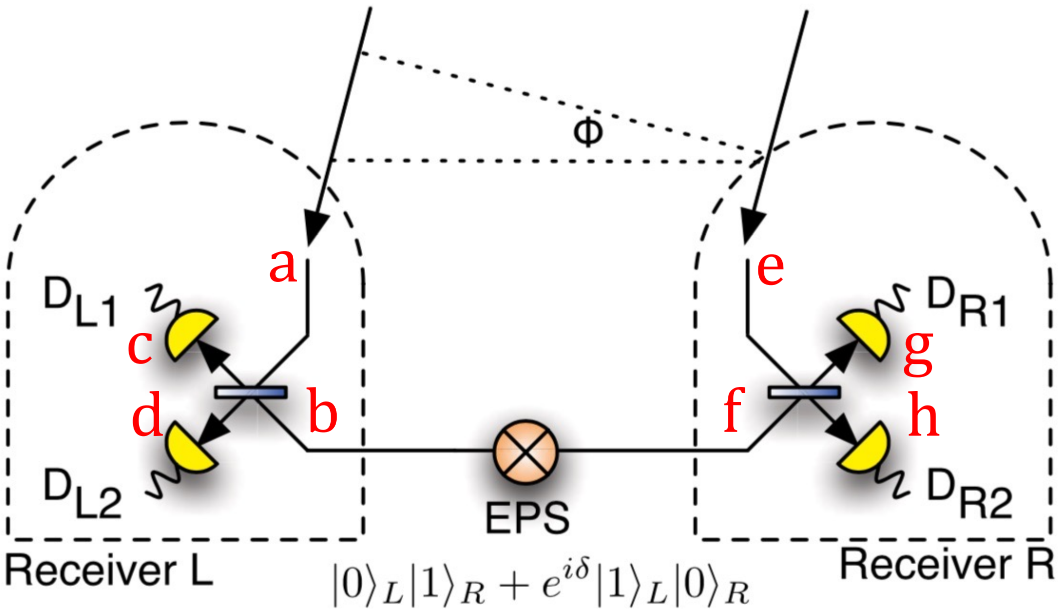
$$\Psi^{\text{Initial}} = \psi_1\psi_2 = \frac{1}{2}\underbrace{(\hat{a}^\dagger + e^{i\delta_1}\hat{e}^\dagger)}_{\text{Sky photon}}\underbrace{(\hat{b}^\dagger + e^{i\delta_2}\hat{f}^\dagger)}_{\text{Ground photon}}$$

Beam Splitters

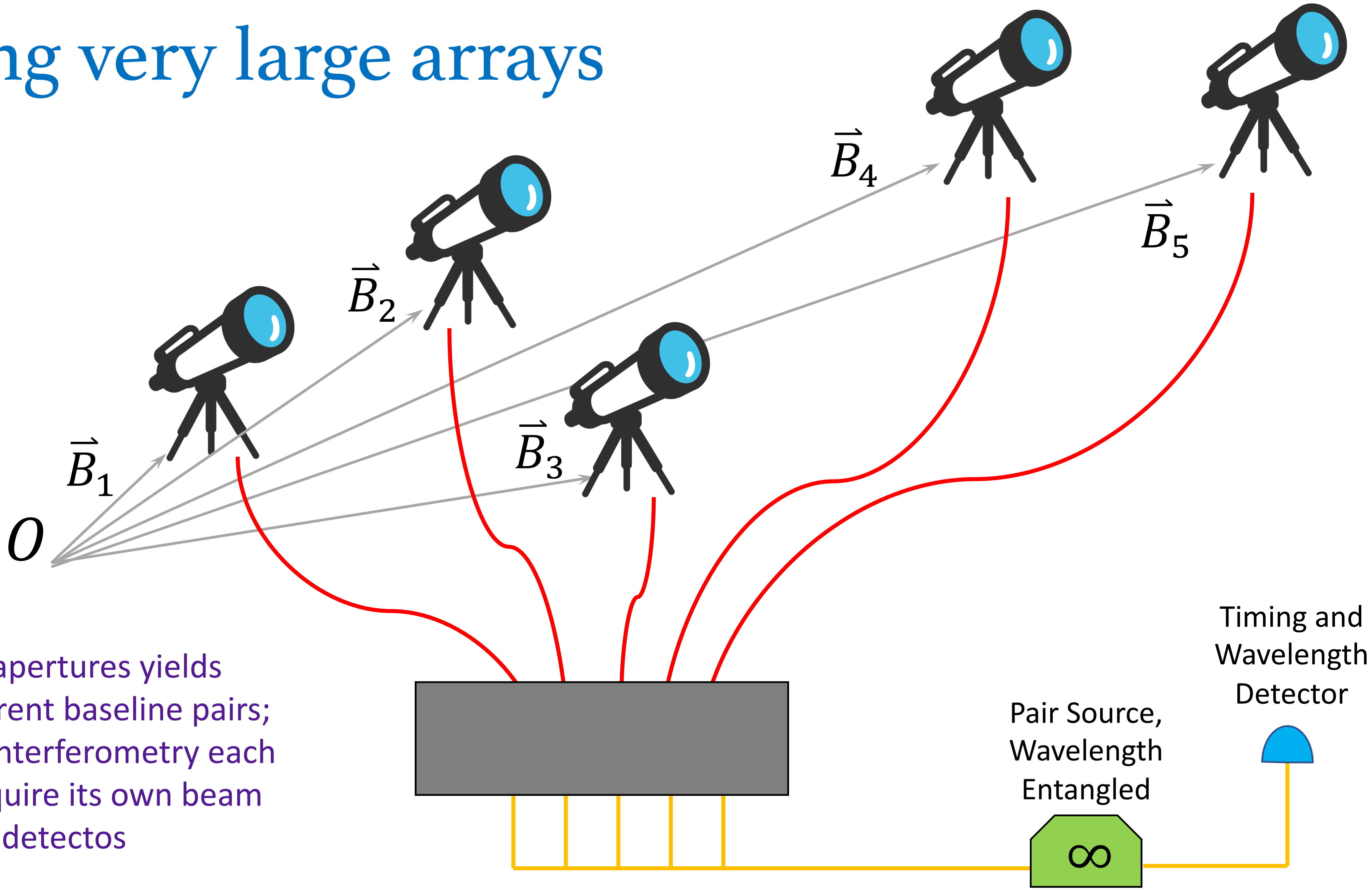
$$\begin{array}{ll} \hat{a}^\dagger \to (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} & \hat{b}^\dagger \to (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2} \\ \hat{e}^\dagger \to (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} & \hat{f}^\dagger \to (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2} \end{array}$$

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

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



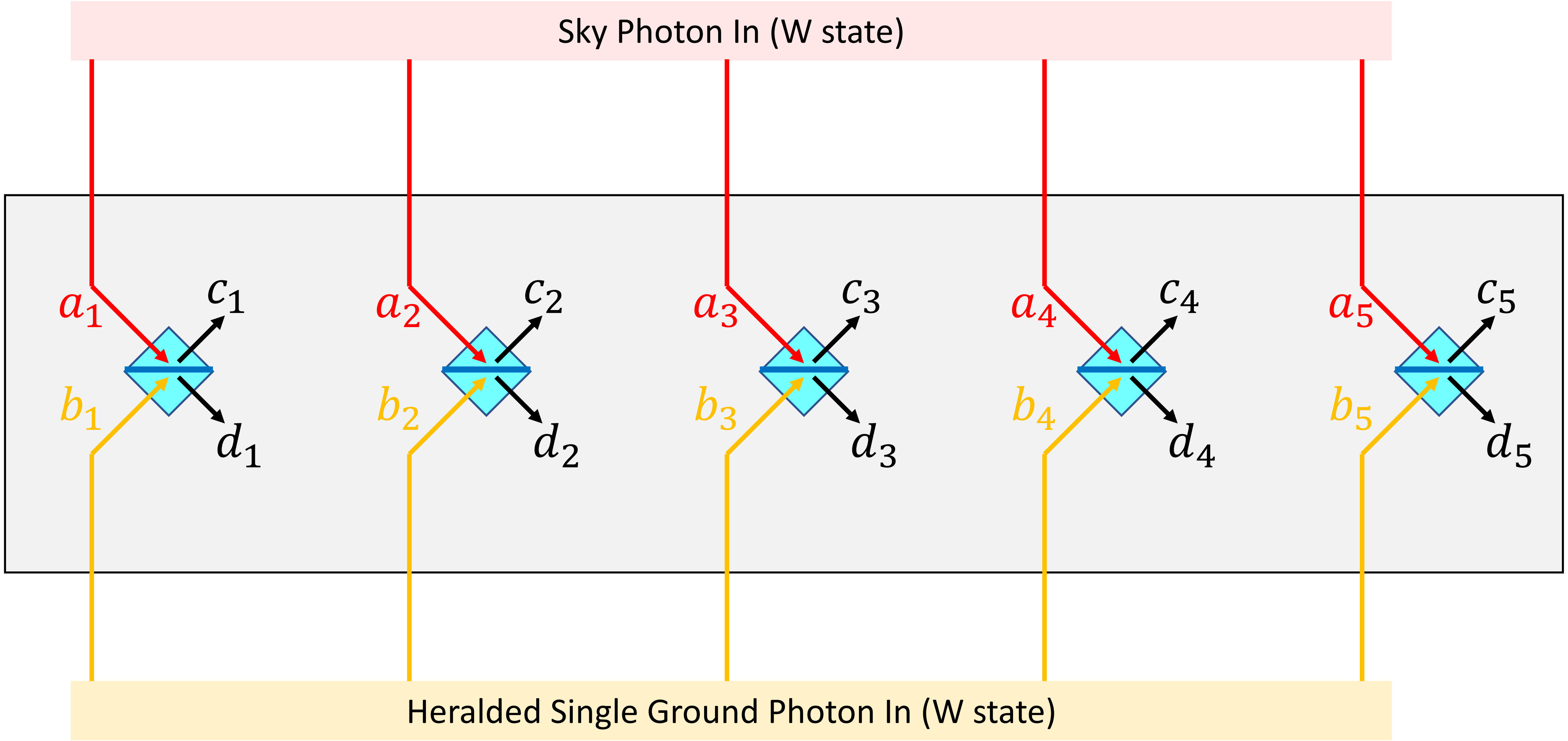
Enabling very large arrays



Timing and Wavelength Detector

Pair Source, Wavelength Entangled

An array of N apertures yields N(N-1)/2 different baseline pairs; in Michelson interferometry each pair would require its own beam combiner and detectos



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.