Quantum Astrometry

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BNL Snowmass 2022 Retreat

Snowmass White Papers

1) Snowmass2021 - White Paper

Real-time Cosmology with High Precision Spectroscopy and Astrometry

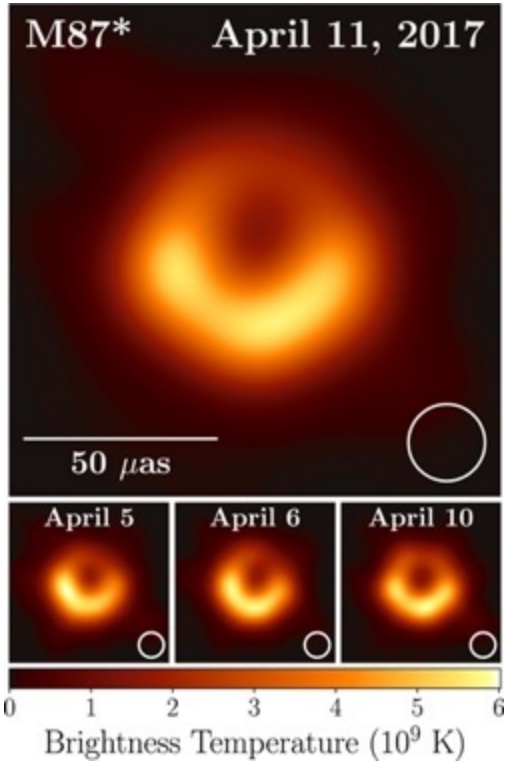
Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

2) Also will be contributing to White Paper:

Quantum Networks for HEP applications

Astronomy picture of the decade



2019 ApJL 875

53M light years away
δ ~ 10 μas (~ 10^{-11} rad)

sensitive to features on angular scale

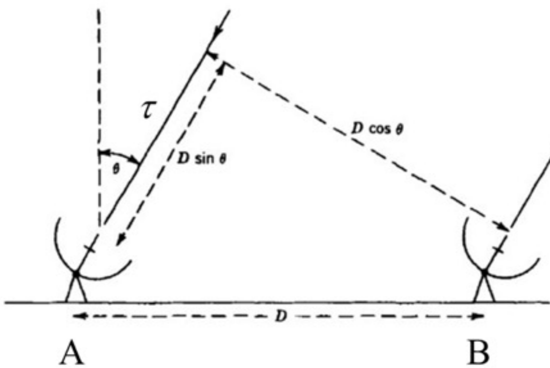
$$\Delta\theta \sim \frac{\lambda}{b}$$

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

Radio

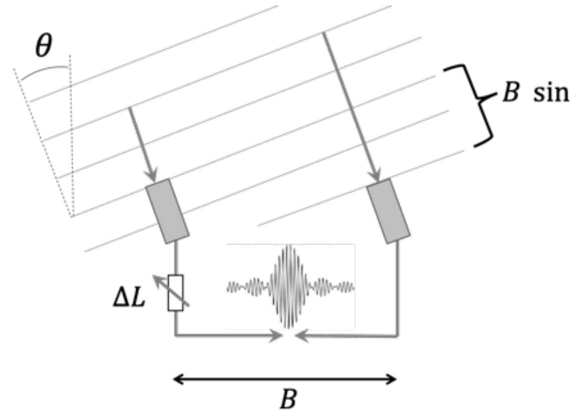
$\bar{n} \gg 1$



Can literally record entire waveform, 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

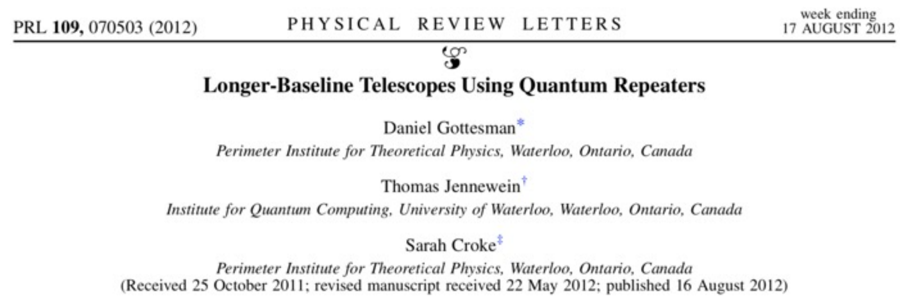
Need path length *stabilized* to better than λ

Accuracy ~ 1 mas (milliarcsecond)

Max baselines ~ 100 m

Two-photon techniques

Quantum-assisted telescopes


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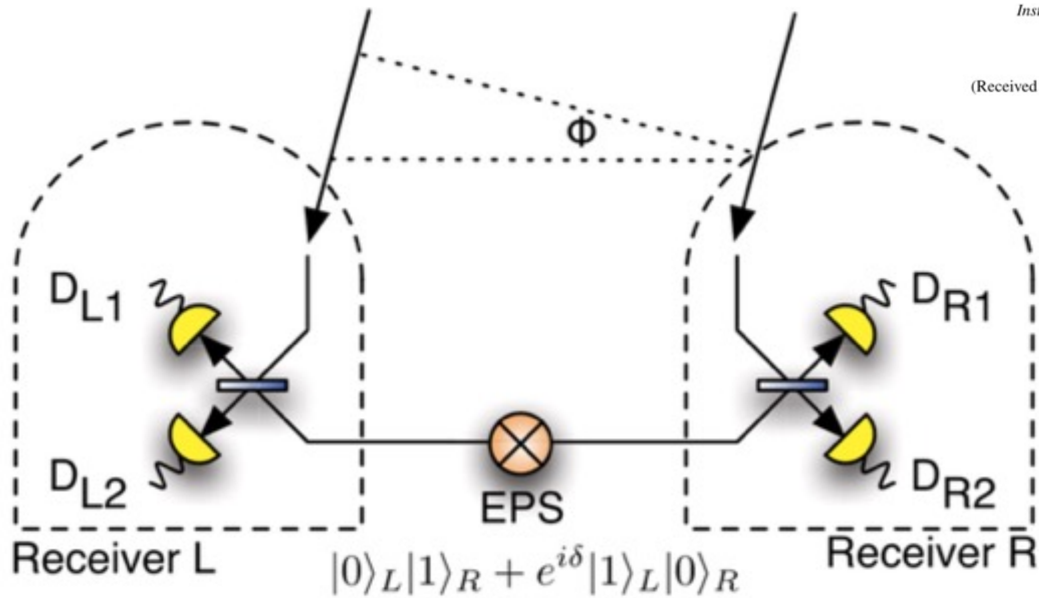
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

Quantum (two-photon) interferometer



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

- Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
- Enables long baselines and could improve astrometric precision by orders of magnitude
- Observables: measure coincidence rates of four single photon counters

Possible impact on astrophysics and cosmology

https://arxiv.org/abs/2010.09100

offers orders of magnitude better astrometry with major impact

DOE topics

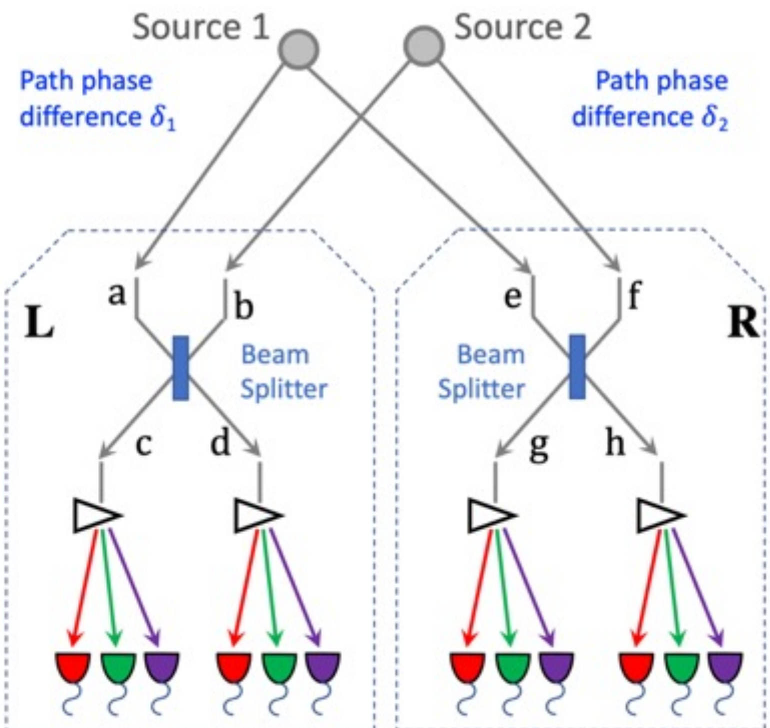
- Parallax: improved distance ladder (DE)
- Proper star motions (DM)
- Microlensing, see shape changes (DM)

NSF topics

- Black hole imaging
- Gravitational waves, coherent motions of stars
- Exoplanets

Quantum Astrometry

Idea: use another star as source of correlated states for the interference



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

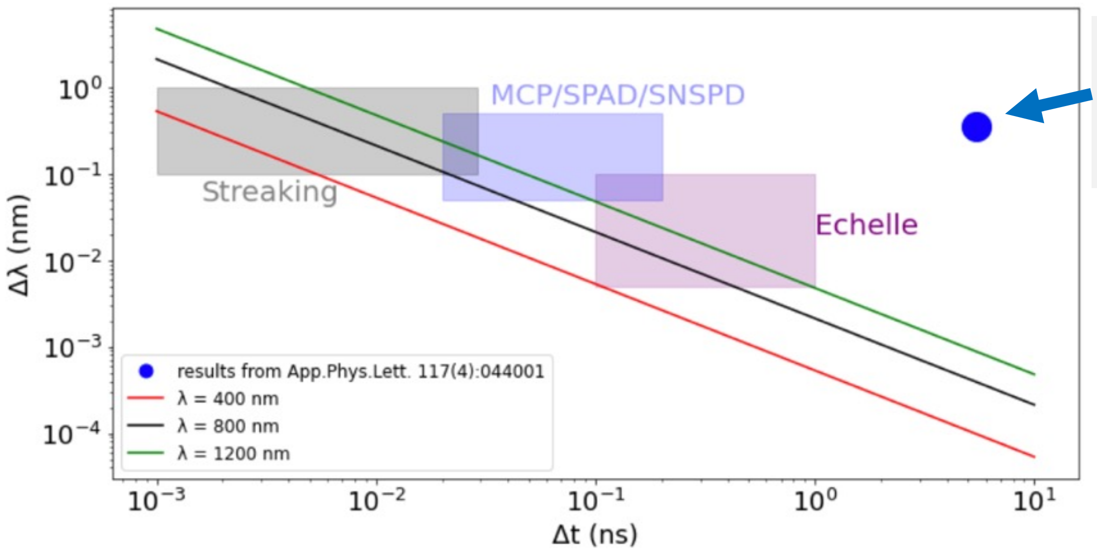
Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and f

world competitive precision with a modest experiment (for bright stars)

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

https://arxiv.org/abs/2010.09100

Requirements for detectors



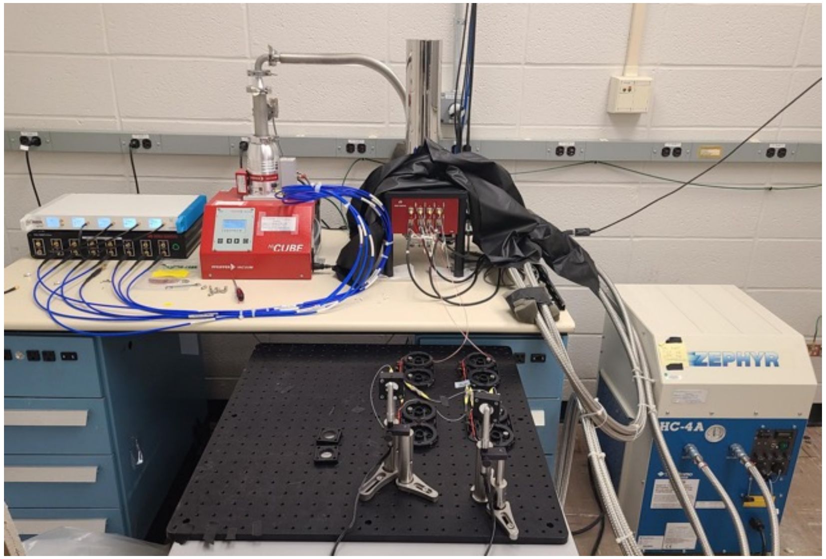
results from:

P Svihra et al, Multivariate Discrimination in Quantum Target Detection, Appl. Phys. Lett. **117**, 044001 (2020)

- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.01 ns * 0.2 nm for 800 nm
- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, SPADs, SNSPDs
- Spectral binning: diffraction gratings, Echelle spectrometers
  - Need large number of bins

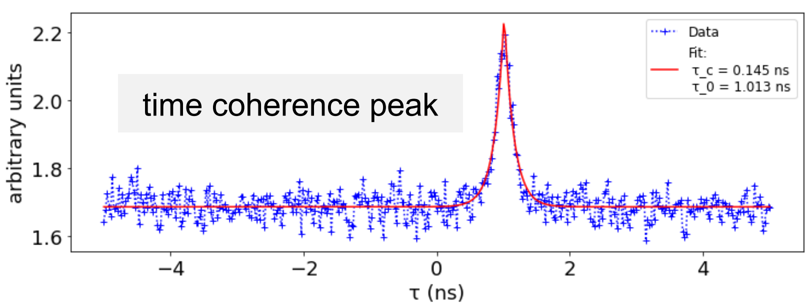
Quantum-Assisted Optical Interferometers: Instrument Requirements; Andrei Nomerotski et al, Proceedings Volume 11446, Optical and Infrared Interferometry and Imaging VII; 1144617 (2020) SPIE Astronomical Telescopes +Instrumentation, https://doi.org/10.1117/12.2560272; arxiv:2012.02812

Astrometry Experiments

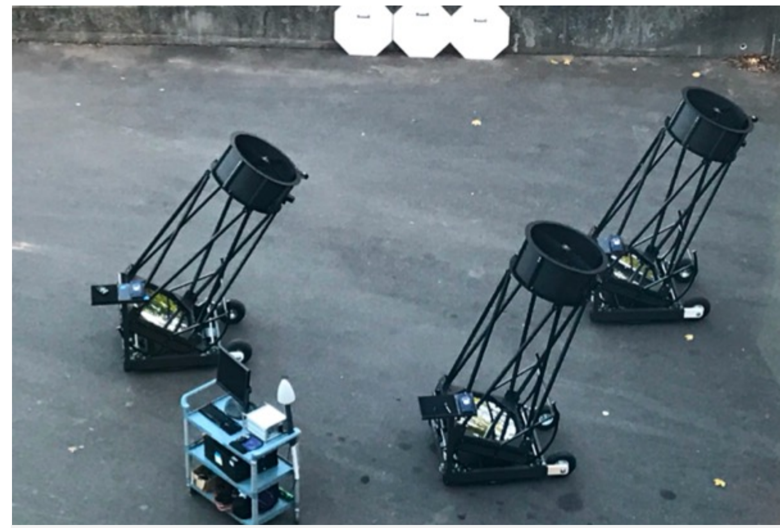


Bench-top experiments of two-photon interferometry

- Superconducting nanowire single-photon detectors
- Ar vapor lamp 794 nm line



- Collaboration with intensity interferometry astro community
  - overlap in instrumentation
- On-sky observations in summer 2022



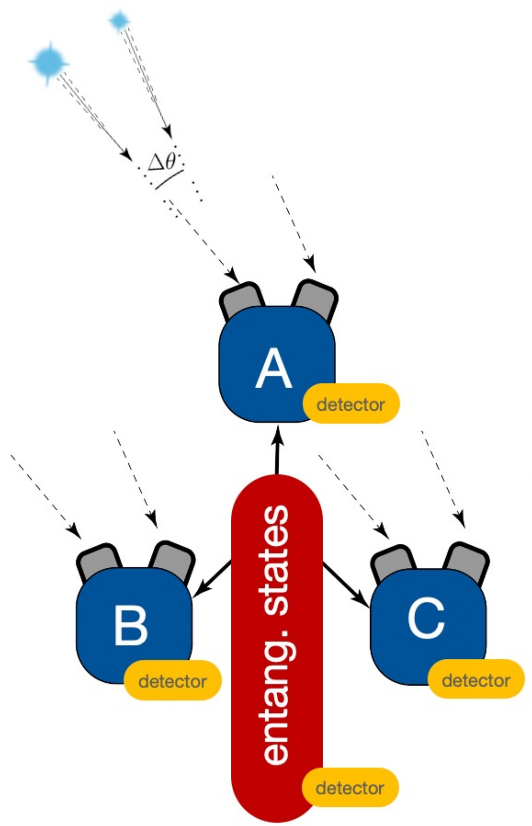
Intensity interferometer in SCSU

Goal: propose a small experiment with HEP scope in 2024

Supported by DOE HEP QuantISED grant

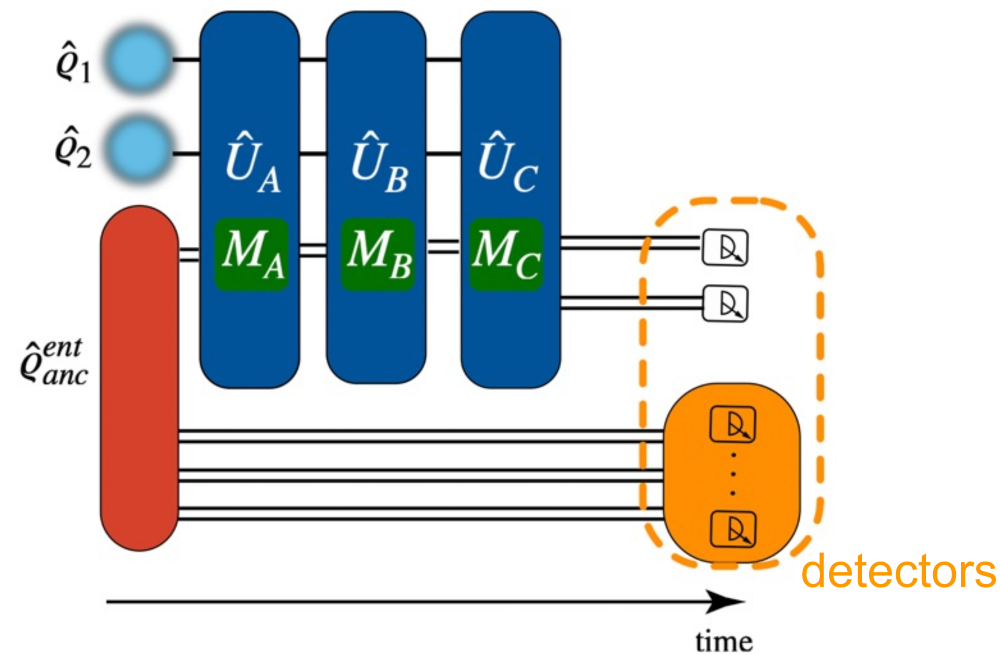
Developing the quantum

Use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations and quantum protocol to process information in noisy environment



Geometry: 2 stars + A,B,C telescope stations + source of entangled photon states + detectors

Quantum protocol circuit



Considerable scope for theoretical development

Also to be sensitive to faint sources (ex galaxies)

- Need high intensity entangled photon sources
- Need quantum repeaters and memories

Synergy with quantum internet roadmap

Summary

- Two-photon interference can be used to improve astrometrical precision by orders of magnitude
- Not far from practical implementation with existing technologies
  - Motivates new technologies for fast single photon detection with sub-ns resolution
- Synergetic with quantum networks

- **Goal for Snowmass:** advertise, find collaborators and ideas for a small experiment with HEP scope within next decade