Quantum-Enhanced Telescopy for HEP Science

Paul Stankus, BNL
CPAD 2023, RDC8  Nov 8, 2023
“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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- 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**

<table>
<thead>
<tr>
<th>Astrometry Measurement</th>
<th>Distance Ladder ($H_0$ tension)</th>
<th>Dark Energy</th>
<th>Dark Matter</th>
<th>GR Tests</th>
<th>Pre-CMB (relics)</th>
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<td>Stellar parallax</td>
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<tr>
<td>Proper motions</td>
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<td>Binary orbit measure (independent distances)</td>
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<tr>
<td>Parallax with galaxies</td>
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<td>Microlensing in real time</td>
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<td>Low-frequency ($\mu$Hz) gravitational waves</td>
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<td>✓</td>
<td></td>
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</table>
Entanglement-Assisted Michelson Quantum networks

Two-source, generalized HBT Arbitrary baselines

Very Large Arrays
Higher rates, multipartite states
Entanglement-Assisted Michelson Quantum networks

Two-source, generalized HBT Arbitrary baselines

Very Large Arrays Higher rates, multipartite states

Subtle but important point: The *entire system*, not just one device or sensor, is a quantum detector for a coherent extended EM quantum field.
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.
Quantum entanglement-based imaging promises significantly increased resolution by extending the di

angle separation of apertures (the ‘baseline’) is motivated by angular resolution in the optical band by extending the detection apertures of an imaging system, an approach demonstrated by Michelson and Pease \cite{1}. The resolution of a single photon in the pulse.

The set of event phases are used to estimate the complex visibility measured by comparison to a phase-locked square voltage pulse used in our experiment to be (see Supplemental Materials \cite{35}). Theory predicts the estimated visibility measured by spectral-temporal-mode thermal-like state by passing through a double slit (D) and then a time-varying scatterer (S). The BS (FBS). The outputs of the FBSs are monitored by superconducting nanowire single-photon counting detectors (SNSPDs).

A polarizing BS separates the H and V fields, where the heralding e

Gaussian distribution of a simulated thermal light source is determined by interfering light collected at each aperture and coherently combining the collected fields at a beam splitter (BS) with a known relative phase (\(\phi\)). The spatially separated interference reference states (S1 and S2) are then time-tagged using a time-to-digital converter (TDC). The TDC time tags are used to decode the events based on the heralding photons arriving at the multi-mode fiber BSs (FBS). The FBS outputs are sent to SNSPDs.

SNSPDs & Time Taggers

Interferometric imaging using shared quantum entanglement

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(Dated: June 19, 2023) To appear in PRL
Can now run $10^3$-$10^4$ experiments at once (!), each in a spectral bin of width $\Delta v \sim 1/\tau_{\text{Detector}}$. 

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

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(Dated: July 6, 2023)
Double spectrograph prototype at BNL

Quantum enhancement (HBT) observed
Technology needs: **Fast Spectrograph**

Enabling technology for many quantum-enhanced telescropy 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, \(\sim 10^{3-5}\) 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 photodetectors, 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 $\mu$Hz 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.
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
A single detector/pixel point will collect intensity from a range of angles. The limit of this angular range is $\Delta \theta \sim \frac{\lambda}{d}$ 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 $\frac{\lambda}{d}$.
Idea: Separate apertures over long baselines
Michelson Stellar Interferometer ca. 1890

Interference fringe pattern sensitive to features of angular size $\Delta \theta \sim \lambda / B$
Contrast *visibility* measures Fourier component of source distribution at $k \sim B / \lambda$

https://xkcd.com/1922/
Idea: Separate functions of photon capture, photon transport, and photon interference

Standard Michelson
Single sky photon interferes with itself

\[
\frac{b \sin(\theta)}{\lambda} = \phi 
\]

Receiver L

\[ \theta; \]

Receiver R

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

GJC: Sky photon is mixed with a single “ground” photon at each station
Pattern of coincidences measured at L and R stations reveals phase difference of sky photon arriving in two places: interferometry

\[ \Psi_{\text{Initial}} = \psi_1 \psi_2 = \frac{1}{2} (\hat{a} + e^{i\delta_1} \hat{e})(\hat{b} + e^{i\delta_2} \hat{f}) \]

- **Beam Splitters**
  - \( \hat{a} \mapsto (\hat{c} + \hat{d})/\sqrt{2} \)
  - \( \hat{b} \mapsto (\hat{c} - \hat{d})/\sqrt{2} \)
  - \( \hat{e} \mapsto (\hat{g} + \hat{h})/\sqrt{2} \)
  - \( \hat{f} \mapsto (\hat{g} - \hat{h})/\sqrt{2} \)

\[ \Psi_{\text{Output}} = \frac{1}{4}(\hat{c} \hat{c} - \hat{d} \hat{d} + e^{i(\delta_1 + \delta_2)}(\hat{g} \hat{g} - \hat{h} \hat{h}) + (e^{i\delta_1} + e^{i\delta_2})(\hat{c} \hat{g} - \hat{d} \hat{h}) + (e^{i\delta_1} - e^{i\delta_2})(\hat{c} \hat{h} + \hat{d} \hat{g})) \]

- \( P(c^2) = P(d^2) = P(g^2) = P(h^2) = 1/8 \)
- \( P(ce) = P(ch) = (1/8)(1 + \cos(\delta_1 - \delta_2)) \)
- \( P(ce) = P(ch) = (1/8)(1 - \cos(\delta_1 - \delta_2)) \)
Enabling very large arrays

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 detectors.
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.