Snowmass2021 - Letter of Interest

Extreme Precision Astrometry using Two-Photon Amplitude Interferometry

Thematic Areas:

■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors

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Abstract: Two-photon amplitude interferometry is a new quantum technique that would enable practically arbitrarily large synthesized apertures in optical interferometers, opening completely new windows into astrophysical phenomena. We will discuss a few examples on how this can be deployed for cosmological and astronomical measurements derived from precise astrometry of stars and galaxies. We also describe possible proof-of-principle experiments, showcasing the observational methods assisted by entanglement of photons.

Idea: Observations using optical interferometers provide sensitivity to features of images on angular scales much smaller than any single telescope, on the order of $\Delta\theta \approx \lambda/d$ where d is the interferometric baseline. While very successful in radio frequency domain the large baseline interferometry struggles in the optical domain. The cost of building and maintaining an optical path which is stable at the sub-wavelength level limits present-day interferometers to maximum baselines on the order of a hundred meters, which for the visible wavelength range corresponds to angular resolutions on the order of a milli-arcsecond[1–3].

Present-day optical interferometers are essentially classical, interfering single photons with themselves. However, there is a new wave of interest in interferometry using multiple photons, whose mechanisms are inherently quantum mechanical, which offer the prospects of increased baselines and hence finer resolutions, among other advantages. We will discuss recent ideas for quantum-assisted interferometry using the resource of entangled pairs, and specifically a two-photon amplitude technique aimed at improved precision in astrometry.

It was pointed out by Gottesman, Jennewein and Croke[4] in 2012 that optical interferometer baselines could be extended, without an optical connecting path, if a supply of entangled Bell states between the two stations could be provided. If these states could then be interfered locally at each station with an astronomical photon that has impinged on both stations, the outcomes at the two stations would be correlated in a way that is sensitive to the phase difference in the two paths of the photon, thus reproducing the action of an interferometer. Equivalently, this can be seen as using a Bell state measurement at one station to teleport the state of that station's astronomical photon to the other station, and interfering it with its counterpart there. This teleportation technique would allow to uncouple the two observing stations, in principle then allowing arbitrary baselines and much finer angular resolution scales, down to the micro-arcsecond level or below.

Impact: While it is impossible to foresee all the scientific opportunities offered by an instrument that would enable orders of magnitude better resolution compared to current instruments, it is clear that this would open completely new windows into astrophysical phenomena. We list just a few examples relevant to the high energy physics, but many more can be imagined.

- **Precision parallax and cosmic distance ladder:** An improvement in the astrometric precision by several orders of magnitude proposed here should allow us to completely sidestep the Cepheids in the distance ladder calibration and use parallax directly on galaxies with supernovae Type Ia, potentialy providing a landmark advance in H_0 measurements.

- **Mapping microlensing events:** Improving the astrometric precision of the measurements will allow decrease in the detection thresholds, dramatically increasing the statistics hence the sensitivity to the DM subhalos[5;6]. The astrometric approach is also more straightforward to interpret in terms of the lens mass and its spatial distribution. An interesting novel possibility here would be to constrain astrometric jitter that would in turn constrain the presence of a population of small microlenses in a statistical manner.

- **Peculiar motions and dark matter:** Measurement of the full 3D velocity vector for a significant portion of the stars across the Galaxy would allow to infer the gravitational potential for the galactic halo and would be transformative. It will give us a census of merging events in the history of the milky way halo and it would directly probe dark matter self-interaction, its interactions with baryons and other exciting possibilities[7].

- **Direct imaging of black hole accretion discs** would open completely new avenues in study of theories of modified gravity that could potentially have large impacts on our understanding of dark energy.

Current Work: In our work we extended the original idea to employ a quantum network to connect the telescopes to the use of the second photon produced by another astronomical sky source with basic arrangement shown in Figure 1. The path length difference between the two photons leads to a phase offset and if the two photons are close enough together in both time and wavelength, then due to quantum mechanical interference in the beam splitters the pattern of coincidences will be sensitive to the phase differences, and this in turn will be sensitive to the relative opening angle between the two sources. In this scheme no optical connection path is needed between the two stations, a major simplification of the original idea; and the measurement can be carried out in many spectroscopic bins simultaneously. Excellent timing and position resolution of the imaging sensors will be required to enable spectroscopic binning of the incoming photons with enough granulation to efficiently interfere [8;9].

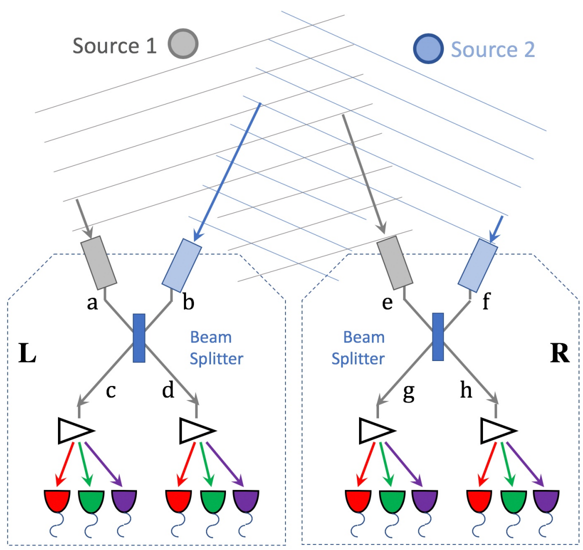

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Figure 1: The two-photon amplitude interferometer. The pattern of coincidences between measurements at "c" and "d" in **L** and "g" and "h" in **R** will be sensitive to the difference in phase differences $(\delta_1 - \delta_2)$; and this in turn will be sensitive to the relative opening angle between the two sources.

We already started experiments in the lab on practical implementations of the technique employing narrow-band photon sources to demonstrate two-photon amplitude interference [9;10]. This work is carried out within the DOE QuantISED QIS-HEP program with the goal to demonstrate how this can be deployed for astronomical measurements derived from precise astrometry of stars and galaxies.

Outlook and Path to Small Experiment: The main priority now is to prepare and perform on-sky observations to demonstrate the viability of the technique in practical setting. Separately, we intend to explore potential impact on the fields of cosmology and astrophysics in more detail to motivate larger scale experiments. We view the on-sky measurements of several bright enough binary systems with small separations as a key milestone to determine a path to small demonstrator experiment targeting HEP science.

On the QIS front we are going to experimentally explore synergies with the quantum network/internet programs since the teleportation of entangled photons [11–13] and the sources to produce such photons together with quantum memories [14] to store them while waiting for arrival of the sky photon is an important extension of our approach. This project would aspire to become one of early science applications of quantum internet.

We are also going to explore novel theoretical ideas to generalize the interference effects of simple Bell-type entanglement to interference patterns of GHZ and other types of multipartite entanglement. This could potentially be useful in probing the underlying entanglement structure of cosmological features. Another interesting direction would be to use the telescope interferometric properties to study cosmic Bell violations by probing quantum correlations in the sky. Both could be valuable in extending possible measurements to higher multi-point correlation functions in the sky that can be related to various inflationary models.

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