Towards Two-Photon Amplitude Interferometry and its Cosmological Applications

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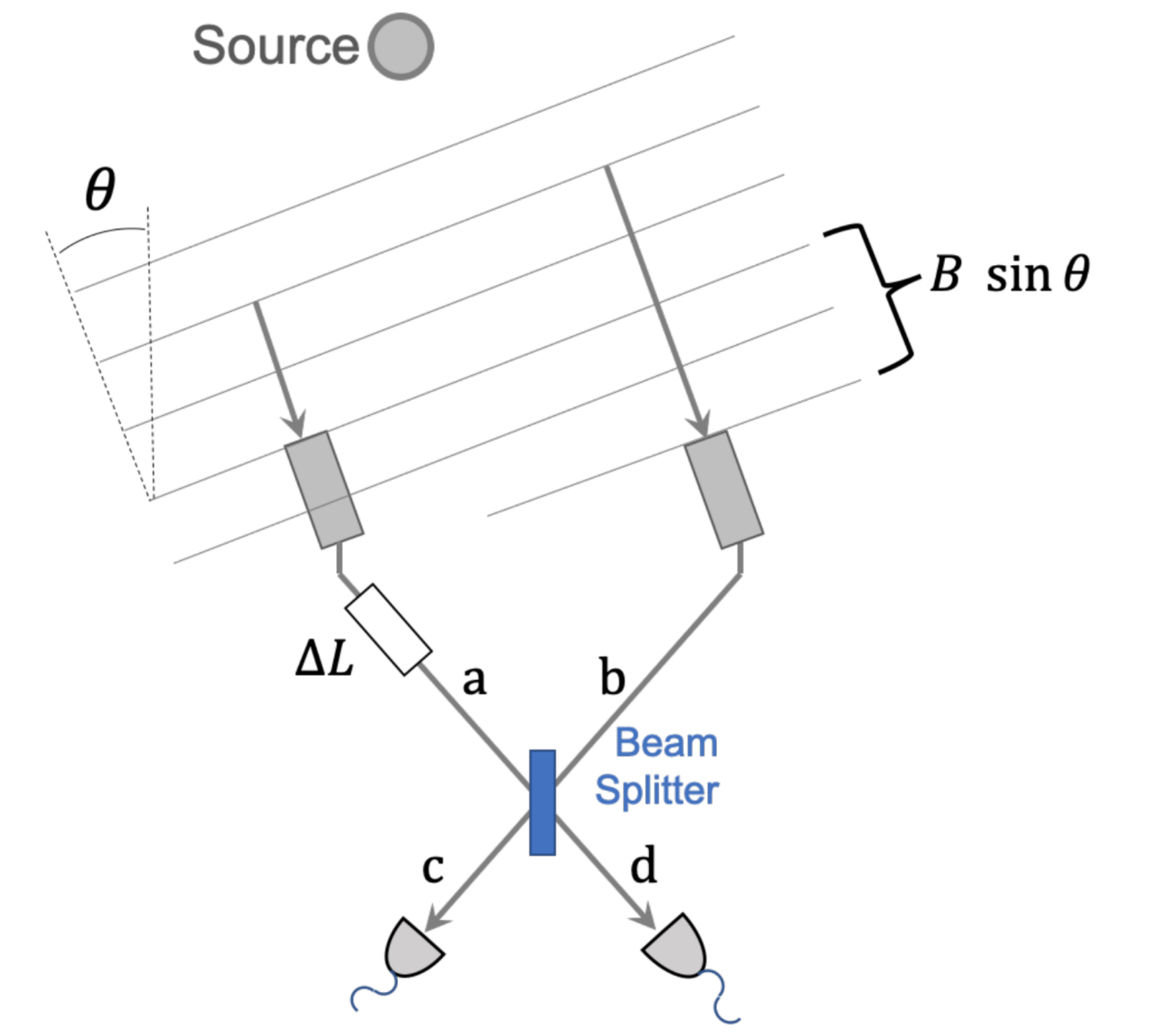
Interferometers

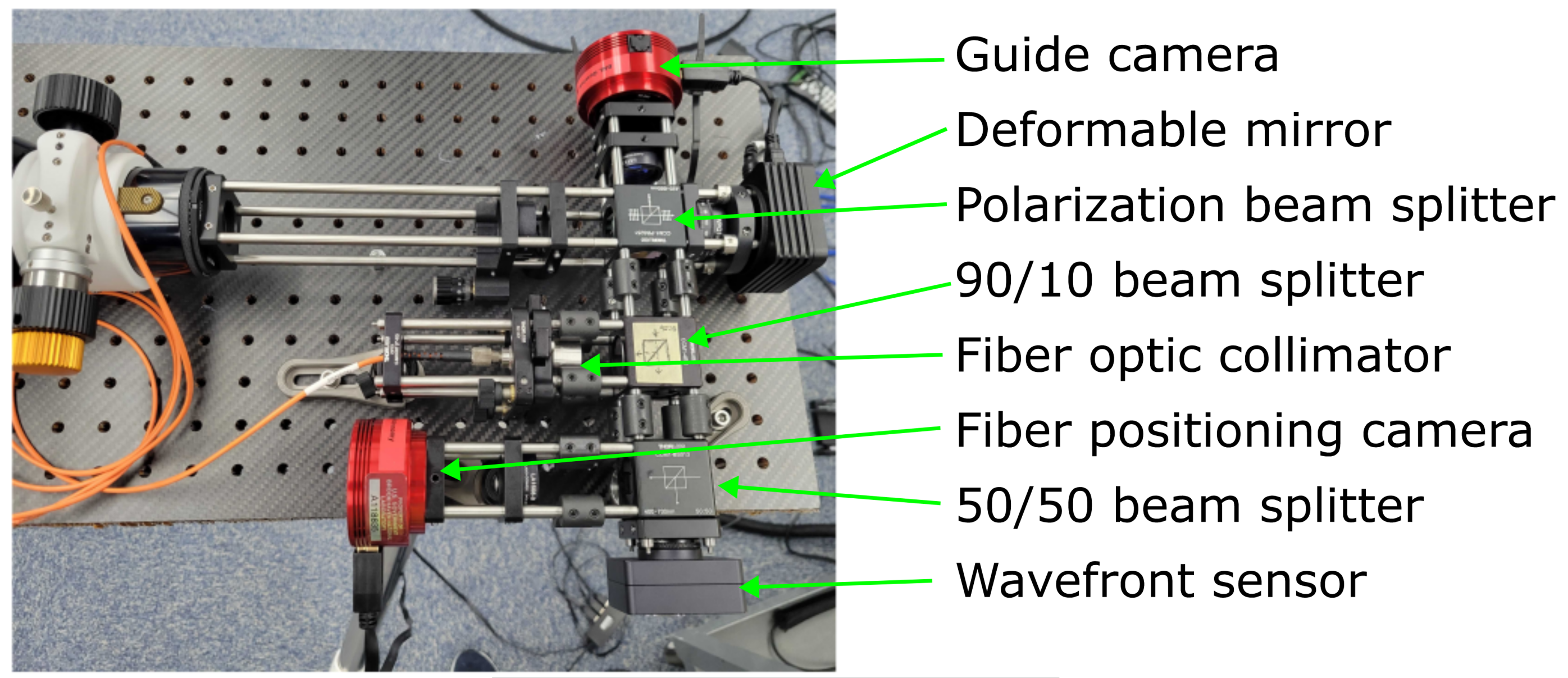
Interferometry is an astronomical observation method in which photons from a single source enter two (or more) apertures and are then brought together to interfere. The resulting signal will experience boson bunching due to the Hanbury-Brown-Twiss (HBT) effect, increasing the rate of coincident counts on the detectors. The coincidence rate is sensitive on angular scales of $\Delta\theta \sim \lambda/B$ where λ is the wavelength of the photons and B is the distance between the two apertures, called the baseline.

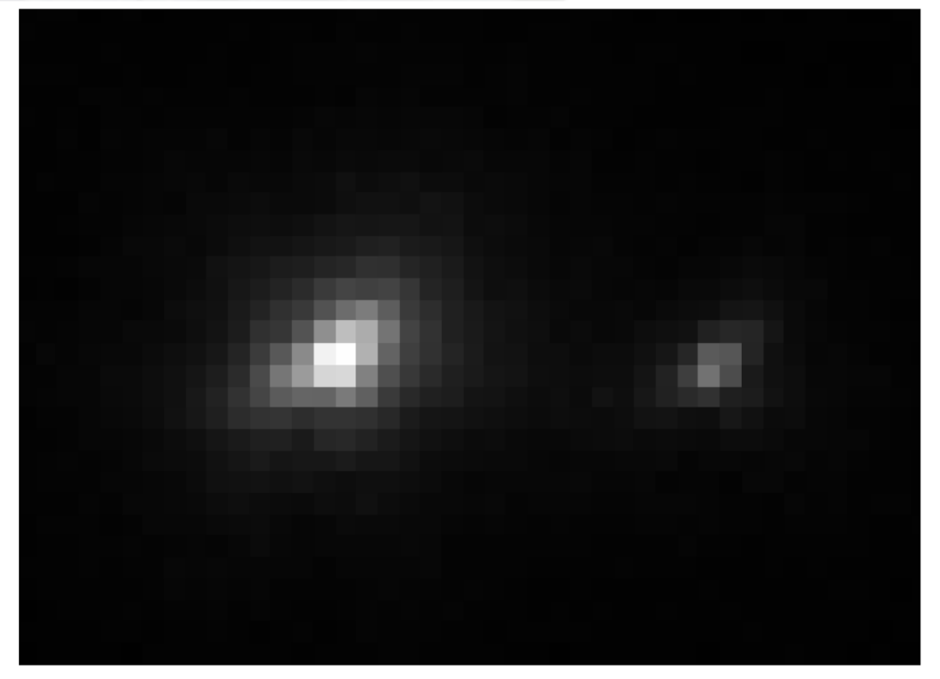


Schematic of a single-photon interferometer, with a variable path length, a beam splitter, and single-photon detectors. Figure 2 from Stankus et al. (2022, arXiv:2010.09100v6)

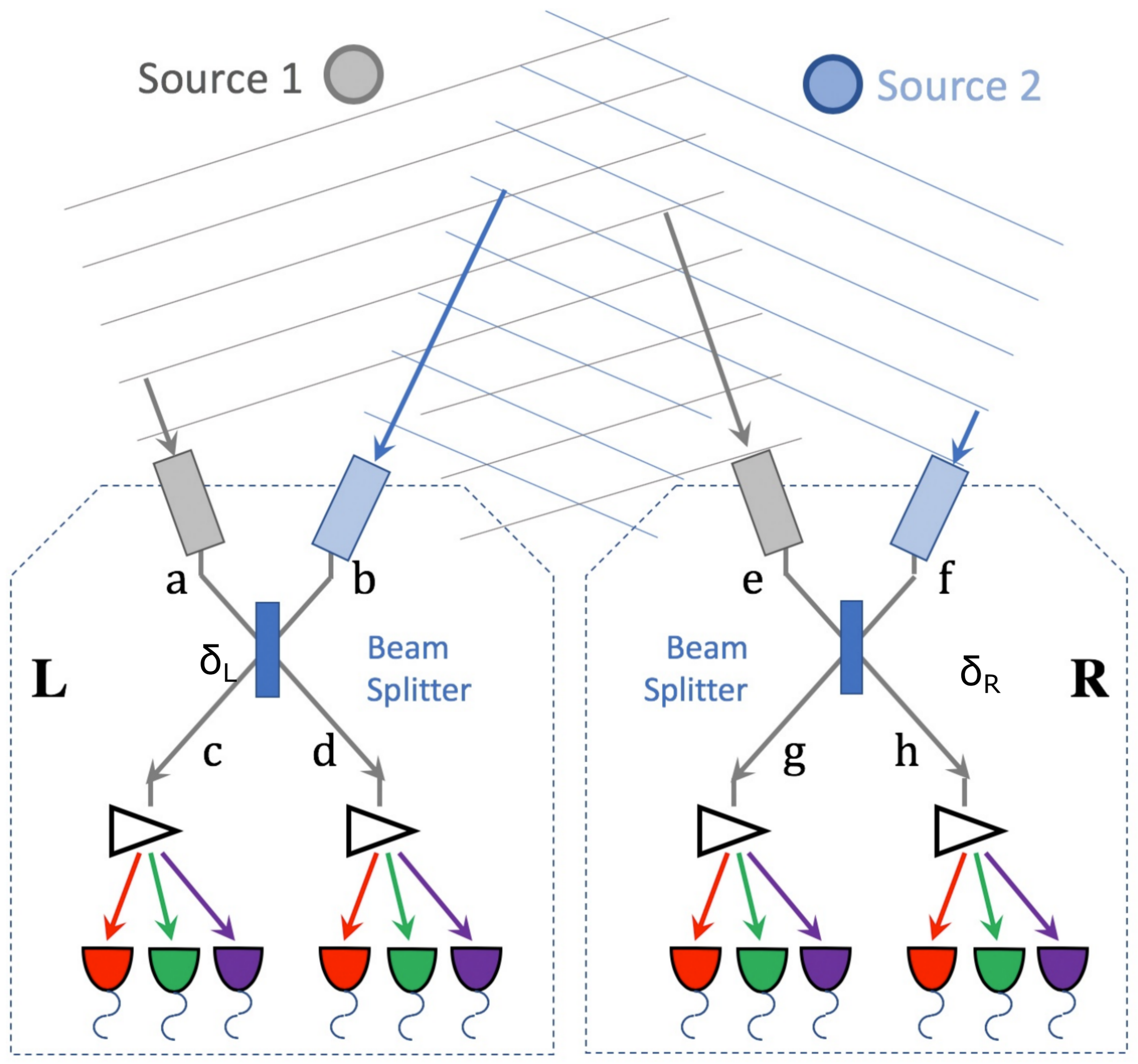
Unfortunetaly, this requires an optical connection from the apertures to the detectors that has sub-wavelength stability. This restricts the largest optical interferometers to baselines of a few 100 meters. A quantum enhancement of the optical interferometer design that does not require an optical connection between the apertures would allow for much longer baselines, and therefore much higher angular resolution.

The Adaptive Optics Light-collection Setup





Mizar A&B, separated by 14.4 arcsec, taken with the non-AO setup, exposure time of 5ms. The asymetry seen in each star is the result of atmospheric seeing effects.



Schematic of the amplitude interferometry setup. Coincidence rates between the detectors of the two stations are sensitive to the angle between the sources. Figure 3 from Stankus et al. (2022, arXiv:2010.09100v6).

Amplitude Interferometry

The two-photon amplitude interferometry technique, first introduced in Stankus et al. (2022), consists of two stations, each an interferometer with two apertures. This is a generalization of HBT intensity interferometry from a single source to two sources. The coincidence rates for pairs of detectors from different stations, namely *cg*, *ch*, *dg*, *dh*, are sensitive to the *difference* in differences in path lengths, or the opening angle between the two sources.

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

Here, δ_L, δ_R are the phase difference in the paths at the Left and Right stations, respectively.

By changing the difference in path lengths at a station (with a glass wedge, for example) one would observe a sinusoidal signal in the rate of coincidences for a constant-baseline setup. Zhi et al. (2023) showed that the changing of the baseline relative to the sources due to the rotation of the Earth results in even tighter constraints. Zhi et al. estimate that, with a total collecting area of ~4m^2, the astrometric separation of certain pairs of sources could be determined with ~100 μarcsec precision with only a few hours of observation.

Light-Collection Setup

We are using off-the-shelf hobby telescopes from SVBONY, with apertures of 102mm and 70mm. The light-collection setup is designed to send starlight from a telescope into a single-mode fiber (SMF). The basic setup involves a 90/10 mirror allowing the use of a camera for guiding, and a SMF plugged into an XYZ stage. However, the collecting area of a SMF is only ~9 microns, so atmospheric effects drastically reduce the efficiency, both by moving star positions and changing star spot shapes (see lower-left). We are working on an Adaptive Optics (AO) setup (see upper-left) that uses a THORLABS AO kit to combat some of the atmospheric effects. The AO setup uses a wavefront sensor to determine the shape of the incoming wavefronts. The deformable mirror then tries to counteract atmospheric effects on the shape of the wavefronts. We use a polarizing beam splitter to send light to a guiding camera.

We are also experimenting with using a photonic lantern to increase our collecting area to ~25 micron diameter while still mainting SMF output.

Cosmological Applications

- Being able to measure changes in objects' positions on the order of ~100 μarcsec would provide parallax distance measurements out to ~10 kpc. This would be a major extension of the first rung of the cosmic distance ladder, and could allow for better calibration of Cepheid variable stars.

- A μHz to nHz frequency gravitational wave passing through Earth should squish space in one direction and stretch space in an orthogonal direction, changing the relative position of stars separated by large angles (90°) over the course of a period (weeks to months) (Zhi et al 2022). This could be detected with sufficient angular resolution and observation time.

Two-photon amplitude interferometry for precision astrometry
The Open J. Astrophys. 5 (2022).

Astrometry in two-photon interferometry using Earth rotation fringe scan
Phys. Rev. D 107, 023015 (2023)

Astrometric Gravitational-Wave Detection via Stellar Inteferometry
Phys. Rev. D 106, 023002 (2022)

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