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Quantum Assisted SII: Unlocking Ultra-High-Resolution Astrophysical Phenomena

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Neutrinos, key messengers in high-energy astrophysics, provide valuable insights into extreme environments within astrophysical objects. However, their weak interactions limit spatial imaging, requiring neutrino telescope findings to be correlated with other observational methods. In recent years, intensity interferometry has emerged as a powerful tool for observing these regions with unprecedented accuracy.

Stellar Intensity Interferometry (SII) leverages correlations in chaotic light to achieve sub-milliarcsecond resolution, with aspirations of reaching nanoarcsecond precision. This advancement opens pathways to imaging accretion disks around compact objects, binary systems, and stellar explosions. First demonstrated in the 1960s at the Narrabri Observatory, SII was later abandoned due to technological constraints, such as limited mirror area and time resolution, restricting it to simple proofs of concept.

In recent years, Cherenkov telescopes like MAGIC, and soon the Large-Sized Telescopes (LSTs) for the CTAO, with their large mirror areas, have enabled SII to directly measure several stellar radii and aim to resolve smaller structures in the high-energy universe.

Additionally, the latest generation of light detectors—single-photon sensitive and operating with picoseconds timing—has made photon-counting mode SII feasible. These ultra-fast detectors measure photon arrival time differences, allowing precise determination of the second-order correlation function $g^{(2)}$ and the photon bunching phenomenon.

While several initiatives are ongoing, this work focuses on the SII activities of the MAGIC telescopes, active since 2021, which have achieved stellar radius measurements with milliarcsecond precision using a uniform disk model. We also highlight the Swiss QUASAR project, which aims to develop a spectrometer based on ultra-fast detectors capable of achieving nanoarcsecond resolution using large telescopes separated by distances of up to ten kilometers.

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1. Introduction

Amplitude interferometry in radio wavelengths has demonstrated its remarkable capabilities, exemplified by the Event Horizon Telescope (EHT) collaboration's achievement of capturing the first image of the environment surrounding a supermassive black hole (SMBH) in the M87 galaxy. This milestone achieved a resolution of 50 μas. Interferometry thus remains a powerful tool for imaging matter distribution in such regions, providing critical data to refine models of neutrino production. In recent years, advancements in interferometry have extended its applicability to optical wavelengths. By leveraging intensity correlations in chaotic light beams from astronomical sources, it is now possible to probe the spatial structures of these objects with increasing precision.

Rapid progress in light detector technology is expected to enable sub-microarcsecond resolution in the near future. This breakthrough will facilitate detailed imaging of accretion disks and provide an unprecedented window into the neutrino-producing regions of the extreme universe.

2. Stellar Intensity Interferometry

The Von Cittert-Zernike theorem states that the visibility (fringes contrast, in case of phase interferometry) is :

$$V(u,v) = \iint I(l,m)e^{-2\pi i(ul+vm)}dldm \tag{1}$$

Measuring the visibility of a source in the u-v plane, allow the reconstruction of an image of the source intensity distribution $I(l,m)$ (mapped in the cosines angles l and m) through its inverse Fourier transform. This procedure is known as aperture synthesis. Through HBT interferometry, SII measures the correlation of intensity fluctuations in chaotic light, which shows spatial and temporal correlations when detected at two locations within the coherence time and space, e.g., by two different telescopes separated by a time delay τ and a baseline $\Delta\mathbf{r}$. Intensity correlation is encoded in the second-order correlation function, which relates to the source's visibility as [2, 3]:

$$g^{(2)}(\tau,\Delta\mathbf{r}) = \frac{\langle I(t,\mathbf{r})I(t+\tau,\mathbf{r}+\Delta\mathbf{r})\rangle}{\langle I(t,\mathbf{r})\rangle\langle I(t+\tau,\mathbf{r}+\Delta\mathbf{r})\rangle} = 1 + |V(\tau,\Delta\mathbf{r})|^2 \tag{2}$$

The angular resolution of such system is determined by the distance between two telescopes or the baseline B, and the wavelength λ, i.e. $\Delta\theta = \frac{\lambda}{B}$. Increasing angular resolution thus requires longer baselines and shorter wavelengths (e.g., moving to the optical range).

The intensity correlations of chaotic light, explained through Quantum Mechanics by Glauber, is quantified by the second-order correlation function $g^{(2)}$, which reaches a maximum at zero delay ($\tau = 0$) between detections. Fano [5] showed that when two identical photons from a thermal source are detected by two closely placed detectors within their coherence time, the probability of simultaneous detection increases due to constructive interference between detection pathways.

Given two optical telescopes, the SNR of HBT effect over random coincidences can be computed through [3]:

$$\mathrm{SNR} = \mathrm{n}_\gamma \cdot \eta \cdot \mathrm{A} \cdot \sqrt{\frac{\mathrm{T}}{\tau_\mathrm{c} \cdot \sigma_\mathrm{T}}} \cdot \left|\mathrm{g}^{(1)}(\mathbf{r})\right|^2 \cdot \sqrt{\mathrm{N_{ch}}} \tag{3}$$

where n_γ is the photon flux, η is the optical and detector efficiency, A is the mirror area, T is the measuring time, τ_c is the coherence time (determined by the optical pass-band), σ_T is the time resolution and N_{ch} is the number of channels (in case of multichannel measurements). The coherence time is the time during which intensities are correlated and can be computed as $\tau_c \approx 1/\Delta\nu$, showing that this quantity depends on the used filter width.

2.1 Continuous mode SII (MAGIC-CTAO)

Cherenkov telescopes revived SII thanks to their large mirror area and time resolution in the order of nano-seconds, which strongly increase the SNR of HBT interferometry shown in Equation 3. For this reason, all main Cherenkov Telescope collaborations (MAGIC, LST, VERITAS, and HESS) have already implemented an SII system within their experiments.

When pointing at a target star, SII is performed continuously by correlating PMTs' signals on the two telescopes in real-time. The star's movement during the night allows us to explore several projected baselines and hence observe how intensity correlation varies after changing the optical path between the two telescopes. In case of a radially symmetric star (Uniform disk model), the expected visibility is:

$$|g^{(1)}(R)|^2 = \left|\frac{2J_1(\pi R\theta_S/\lambda)}{\pi R\theta_S/\lambda}\right|^2 \tag{4}$$

where R is the projected baseline onto the two telescopes. The MAGIC collaboration developed an SII program in 2021 and has already measured the angular diameters of several stars with a resolution of milli arc-seconds [4]. More complex visibility models will allow us to explore stars' limb darkening, determine binary systems' orbits, and, in the future, resolve complex structures such as accretion disks. The first large-size telescope (LST) for CTAO has been built in the same observatory on La Palma island, and three more are under construction. These telescopes will offer an increased number of baselines (15 in total, including the two MAGIC telescopes), larger collecting areas (with a diameter of 23m), and timing resolutions below the ns scale.

2.2 Photon-counting mode SII (QUASAR project)

Another approach to SII is known as photon-counting mode. This method typically uses optical telescopes with smaller mirrors but employs ultra-fast photon detectors. In this setup, each photon's arrival time is measured at each telescope. The histogram of normalized coincidence between the two telescopes thus provides the $g^{(2)}$ distribution in time-lag space.

The QUASAR project [1], funded by the Swiss National Fund, aims to construct an array using ultra-fast SPAD detectors capable of timing jitter in the tens of picoseconds, dramatically enhancing the SNR. Using a spectrometer to perform HBT interferometry across multiple spectral bands simultaneously, the project seeks to increase N_{ch} and amplify the SNR further.

The instrument is designed for deployment on several optical telescopes worldwide and could be integrated with the next generation of Cherenkov telescopes. QUASAR aims to probe the smallest resolved scales in optical astronomy by utilizing sufficiently large baselines. Increased SNR will also enable the observation of fainter objects down to magnitude $m = 8$. For instance, deploying the instrument on telescopes across La Palma (such as the GTC, TNG, and WHT) would achieve baselines exceeding 1 km, enabling resolutions below 100 μas.

A potential evolution involves using the Very Large Telescope (VLT) and the forthcoming Extremely Large Telescope (ELT) at Paranal, with a 20 km baseline, to achieve μas-scale resolution. This high-precision astrometry could facilitate observations of accretion disks, supernova

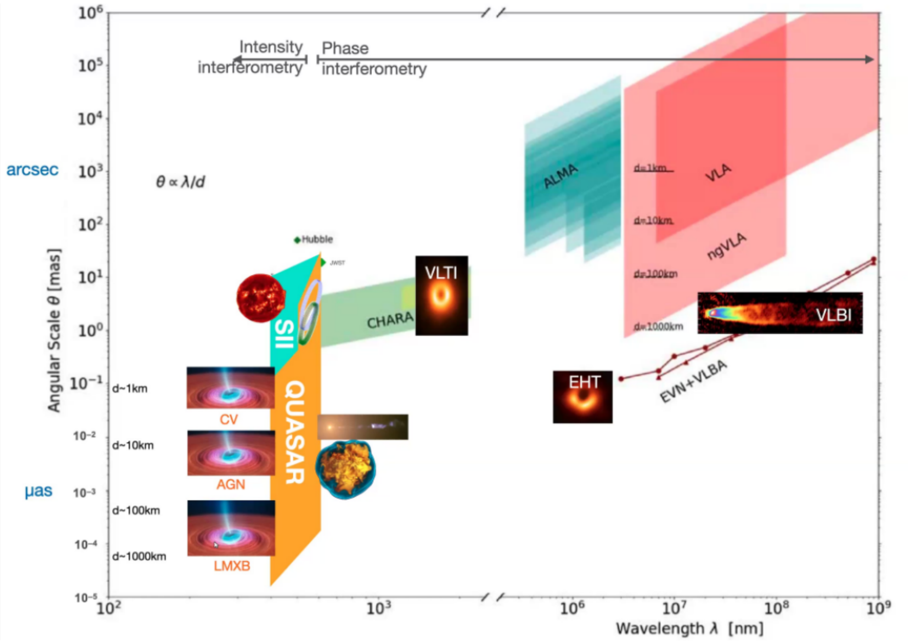

Figure 1: Left: Angular size of sources resolved by different interferometric approaches and collaborations. QUASAR aims to resolve sources in the optical band down to the micro-arcsec scale.

explosions, cataclysmic variables, and other potential sources of cosmic rays, high-energy gamma rays, and neutrinos. The project faces significant challenges, particularly regarding detector complexity and speed, as well as the synchronization of timing between telescopes, which must achieve picosecond-level stability. Current laboratory tests suggest that the ambitious goal of 20 km synchronization may be achievable.

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