Project title: Non-local imaging through scattering media.

Context: Imaging through scattering media is a major challenge in optical microscopy. For instance, when light scatters in biological tissues, it reduces how deep we can image inside. This limitation usually confines microscopy to areas like the eyes (transparent) and the top layer of the skin (~100µm depth). Over the past decades, many techniques have emerged to tackle optical scattering. One notable advancement involves wavefront shaping methods, made possible by the development of spatial light modulators (SLMs). They enable the coherent control of scattered light to re-focus and image through scattering media [1]. However, despite the progress made, these approaches remain quite limited: they are far from perfectly correcting the scattering effects and only work in very specific imaging configurations.

In parallel with these developments, a handful of research teams have also explored the propagation of non-classical states of light through scattering media. The initial targeted applications were for quantum communications. For example, researchers have successfully used wavefront shaping to preserve entanglement between pairs of photons propagating through a multimode fiber [2] and a scattering layer [3], ensuring the establishment of a quantum link between an emitter and a receiver. Building on these concepts, our team investigates the potential of non-classical light for **imaging in scattering environments.**

In this respect, we have recently developed a quantum imaging approach that leverages entanglement between photon pairs to correct optical aberrations with an SLM [4]. This approach, however, only operates in the presence of weak aberrations, such as those caused by a very thin biological tissue or a translucent medium. It becomes ineffective when the medium is too thick or overly complex. To delve deeper into the scattering regime, both technological advancements and conceptual progress are essential. Building on [4], this PhD project aims to explore a novel quantum imaging configuration and develop specific wavefront shaping approaches to combat scattering, potentially surpassing classical methods.

Objective: In this doctoral project, the student will investigate the problem of **quantum imaging through scattering media using a non-local imaging configuration.** Indeed, quantum non-locality allow us to approach the problem of imaging through scattering media from a new perspective. Instead of trying to undo scattering using SLMs positioned before and/or after a scattering medium, as done in classical imaging configurations (Fig.1a), entangled photons allow us to achieve that in a non-local way. Figure 1b illustrates this disruptive concept. One photon of an entangled pair is sent towards an imaging system (e.g. a microscope) where it illuminates an object whose image is blurred due to aberrations and scattering – this is the imaging path. Simultaneously, its twin is sent towards an independent optical path, called the reference path. This optical path can be very complex and contain numerous optics, including multiple SLMs. At the output, spatial correlations between entangled photons are measured with two single-photon sensitive cameras. In such a configuration, acting on the photon in the reference path directly influences the behavior of the photon in the imaging path. In particular, one can show in theory that it is possible to use the SLMs in the reference path to **non-locally compensate for scattering** in the imaging path. By doing this, one could retrieve a clear image of the object at the output by measuring the correlations, without ever touching the imaging path. Such a non-local configuration offers practical advantages compared to those where both photons pass through the imaging system, including a significant reduction in losses. Additionally, it explores the

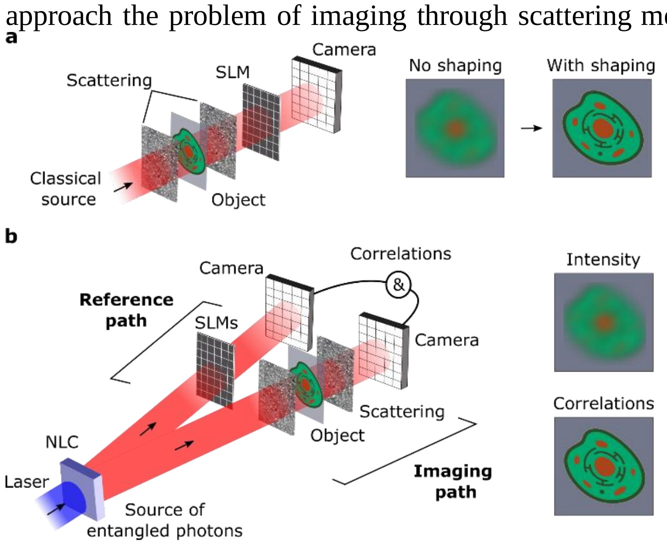

Figure 1. **a.** Simplified scheme illustrating the concept of classical wavefront shaping. A SLM shapes the scattered light coming from the object to undo scattering and retrieve its image. The approach is limited to weak scattering and works only in specific imaging configurations. **b.** Simplified scheme illustrating the concept of non-local wavefront shaping for imaging. SLMs positioned in the reference path act in a non-local way to compensate scattering in the imaging path and retrieve an image via correlation measurement.

challenge of imaging through scattering media from an angle not previously studied. This will result in the development of novel wavefront shaping approaches adapted to this configuration, potentially more effective than classical ones. **The student's objective will be to develop such an experiment, together with the associated wavefront shaping algorithms, theory, and numerical simulations.**

Scientific approach: This research project will be conducted in three stages: (1) Developing a non-local imaging system using entangled photon pairs (no scattering); (2) Introducing optical aberrations in the imaging path and correcting them using non-local adaptive optics; (3) Implementing non-local imaging through a scattering medium. To achieve this, the student will rely on the expertise developed within the team in terms of generation, manipulation, and imaging of entangled photon pairs.

Stage 1 (0-1st year): The student will develop a new quantum imaging experiment from scratch combining a source of entangled photon pairs and a single-photon sensitive camera, inspired from the setup implemented in our prior work [5]. In particular, correlation images will be reconstructed using a camera-based coincidence counting algorithm, a strong expertise in our team [6-8]. The student will also receive training on the basic experimental techniques and simulation methods used within the team.

Stage 2 (1st -1.5 year): Building on the team's expertise in adaptive optics [4], the student will introduce weak optical aberrations into their imaging system (e.g. parafilm layer, PDMS) along with an SLM on the reference arm. Under these simple conditions, the goal will be to experimentally demonstrate the feasibility of compensating for aberrations in a non-local way. This involves developing adaptive optics algorithms specifically designed for this quantum configuration.

Stage 3 (1.5 - 3rd year): In the final stage, the student will explore increased disorder by progressively thickening the scattering medium (e.g., multiple layers) and developing corresponding wavefront shaping algorithms. The system will be tested to determine its functionality up to a certain complexity. Depending on performance, it may be considered to replace the artificial scattering medium with a static layer of biological tissue. In case the system encounters challenges with the scattering medium (e.g., too low transmission…), the risk will be mitigated by reverting to a system with weak but natural aberrations.

Potential impact: Quantum non-locality opens the door to a novel imaging concept: non-local imaging. In this PhD thesis, we aim to leverage this for imaging through scattering media. Beyond its fundamental implications, this non-local approach can have a real impact in practice for optical imaging, especially in microscopy. Currently, implementing wavefront shaping in a classical microscope involves the integration of the SLM, which is difficult with compact, pre-designed commercial microscopes. With our approach, only sending one photon into the microscope and utilizing an optical table to control its twin photon can achieve aberration and scattering correction, simply and efficiently. Furthermore, other modalities could also be added to the microscope simply by tailoring the reference path accordingly (e.g., phase, hyperspectral, ...). The project results could thus influence the development of future real-world microscopes, with significant potential economic implications.

Suitability to the initiative and institute: The project fits perfectly into the Doctoral Program Initiative in quantum information launched by the Sorbonne Quantum Information Center. Indeed, it has potential for impact in the broad field of quantum information, especially for quantum imaging. It involves developments related to the physics of high-dimensional entangled states (theoretical and experimental) but has also an important computational dimension since advanced data processing algorithms will have to be developed for scattering correction and efficient photon coincidence detection with a camera. In addition, this project will enrich the scope of research of the institute, since quantum imaging using entangled states in the discrete variable regime is not explored there. In return, it will also strongly benefit from the expertise of other researchers in Sorbonne University, especially from those exploring multimode quantum optics in the continuous variable regime (Prof. N.Treps) and optics in complex media (Prof. S. Gigan).

Research environment: The student will join a dynamic research team led by H. Defienne in the Paris Institute of Nanoscience (INSP). It is currently composed of 2 PhD students and 1 post-doctorate. Lab and office space will be provided to the student upon arrival.

References: [1] PRL 104, 100601 (2010); [2] Nat.Phys.16,1112-1116 (2020). [3] PRX Quantum, 4, 010308 (2023). [4] Science 2024 (in press, arXiv:2308.11472); [5] Nat.Phys.17, 591-597 (2021). [6] OL,48(13),3439-3442(2023); [7] npj Quant. Info., 6(1), 94 (2020) [8] PRL 120, 203604 (2018).