interactions of PBHs with Sun-like stars, and showing that they can, in principle, be detected. Figure 1 shows a snapshot of the radial velocities induced when a 10^{22} g PBH passes through the Sun on a radial orbit. These photospheric velocities can be measured through the Doppler shift of solar absorption lines. Oscillations driven by near-surface supersonic turbulence provide the dominant know n contribution to photospheric velocities, and hence act as a background for PBH searches. Kesden and Hanasoge have shown that the PBH-induced photospheric velocities can be distinguished from this background as their power spectra differ significantly.

Unless the dark-matter density in the solar neighbourhood is significantly higher than expected, the rate at which PBHs pass through the Sun is very small. However, the European Space Agency's CoRoT and NASA's Kepler satellites should be capable of detecting interactions between PBHs and other stars, albeit with a lower signal-to-noise ratio. In the future, NASA's proposed Stellar Imager may be able to resolve stellar disks, and hence achieve high signal-to-noise detections for other stars. If dark matter exists in the form of PBHs, these observations offer a powerful means of detecting it.

At present, the most popular dark-matter candidate is weakly interacting massive particles (WIMPs). These particles were

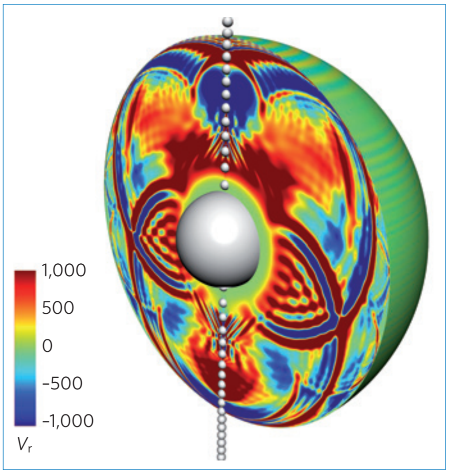

Figure 1 | The radial velocities (V_r) induced by the passage of a 10^{22} g primordial black hole through a Sun-like star on a radial orbit. Reproduced with permission from ref. 1, © 2011 APS.

generically produced in the early Universe with roughly the right abundance, and supersymmetry (the favoured extension to the standard model of particle physics) provides a concrete WIMP candidate in the form of the lightest supersymmetric particle. The search for WIMPs is already underway at the Large Hadron Collider, in dedicated lab-based direct detection experiments and, indirectly, using telescopes to detect their annihilation products. If WIMPs are not discovered in the next 5–10 years, then attention will turn to alternative dark-matter candidates[5].

PBHs have the advantage of requiring no new particle physics. There is, however, no known mechanism that naturally produces the correct abundance of PBHs. This number depends exponentially on the size of the density perturbations, which therefore has to be fine-tuned. Ultimately, the question of whether dark matter comprises WIMPs, PBHs or something else entirely will have to be answered experimentally. Kesden and Hanasoge's work suggests a way of probing a PBH mass window, about which we know very little. Even if PBHs in this mass range do not constitute dark matter, tightening the limits on their abundance will lead to improved constraints on the physics of the early Universe, particularly with respect to models of inflation. ❐

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QUANTUM PHYSICS

Environmental effects controlled

An open quantum system loses its 'quantumness' when information about the state leaks into its surroundings. Researchers now show how this decoherence can be controlled between two incompatible regimes in the case of a single photon.

Julio T. Barreiro

One of the major obstacles to realizing quantum computers and simulators is the environment, which disturbs quantum systems. In the ideal regime, information from the system leaks slowly to the environment. Such unidirectional flow of information in which the noise acts the same way at all times characterizes a Markovian process. However, soft- or condensed-matter systems are strongly coupled to the environment and this leads to a regime where information also flows back into the system; a non-Markovian process. Now, writing in *Nature Physics*[1], Bi-Heng Liu and co-workers report an all-optical experiment in which the flow of information between the system and environment is controlled and the system can be steered between these two regimes.

The open system considered by Liu *et al.* is deceptively simple, comprising just a single photon: the 'system' is its polarization and the 'environment' is its frequency spectrum. They considered the system's dynamical evolution as the photon passed through a quartz plate; different evolution times were studied by varying the thickness of the plate. The system–environment coupling is performed by the plate's birefringence: this adds a dynamical phase to the photon's state, the magnitude of which is dependent on both its polarization and frequency. More precisely, photons with ordinary and extraordinary polarization with respect to the crystal axis experience different phases. If the phase delay is longer than the coherence length of the photon, the frequency degree of freedom is essentially traced on detection, and superposition states of ordinary and extraordinary polarization will then experience decoherence[2].

At the heart of the experiment lies the preparation of an environment that can be tuned to exhibit either Markovian or non-Markovian character. The photon's frequency spectrum is initially prepared with two frequency peaks of the same Gaussian width but with adjustable relative amplitude (Fig. 1a) — all cleverly accomplished by an

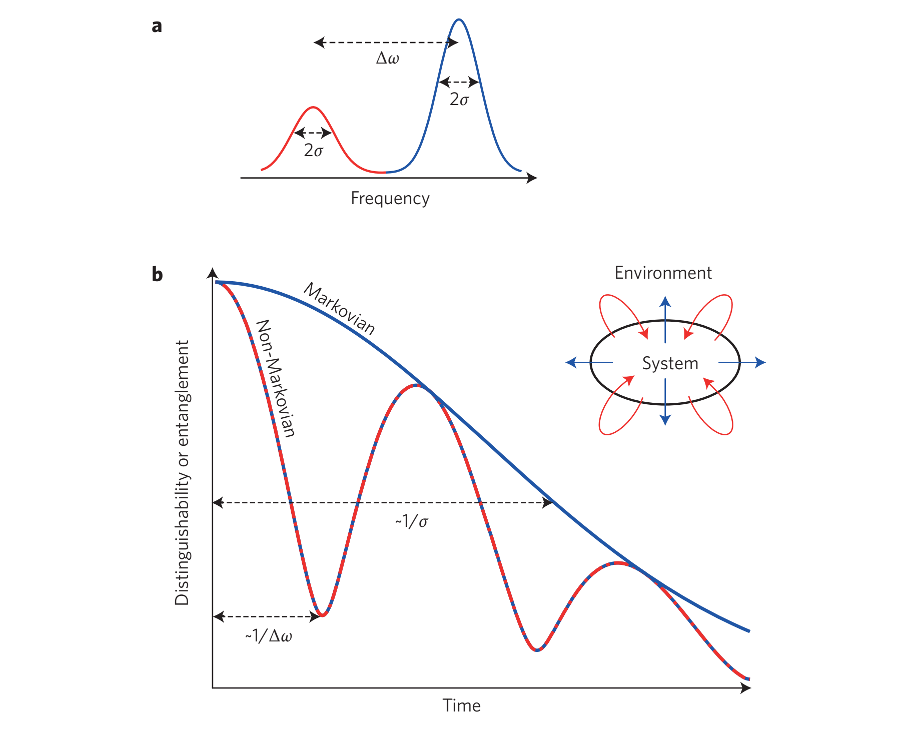

Figure 1 | Driving an open system from the Markovian to the non-Markovian regime. **a**, The photon's frequency spectrum (environment) is initially prepared into two frequency peaks separated by $\Delta\omega$ and with equal Gaussian width σ, but with an adjustable relative amplitude. **b**, In the Markovian regime with a single frequency in the spectrum, the flow of information goes only from the system (polarization) into the environment (blue arrows), and both the distinguishability of any pair of states and the entanglement with an ancilla decrease monotonically. In the non-Markovian regime, in contrast, information also flows back into the system (red arrows) and a revival of those properties can be observed in the time evolution.

etalon with adjustable tilt. When the tilt is such that the spectrum consists of a single frequency, the system shows a Markovian dynamical evolution. However, as soon as two frequencies are present, the polarization and frequency interplay during the dynamical evolution in the quartz plate and this leads to a non-Markovian behaviour.

To understand and ultimately control an arbitrary open quantum system, one first needs to gain some knowledge of the nature and strength of the coupling to the environment. Sometimes this is the only viable information, not only because the evolution may be complicated, but also because an accurate microscopic model of the system–environment interactions may be unfeasible, such as in many-body systems. Recently, several ideas have been proposed to determine if a system is non-Markovian and to quantify it without looking at the environment. One such measure is based on the distinguishability of a pair of states of the system[3]. During a Markovian process, the distinguishability tends to monotonically decrease for any pair. Memory effects during a non-Markovian process, however, can temporarily increase it for some pairs. Finding a pair of states with such revival behaviour gives away non-Markovianity. Full knowledge of their open system enabled Liu and the team to prepare such a pair of states. In the Markovian regime, they observed a distinguishability decaying at a rate proportional to the width, σ, of the single frequency peak (Fig. 1). As the environment was tuned towards non-Markovianity, the distinguishability decayed faster but was interrupted by a revival at a time determined by the difference of the two frequencies, $\Delta\omega$. This measure has also been recently applied on a similar system where the environment consists of the photon's momentum[4].

This non-Markovianity measure, however, generally relies on finding a particular pair of states. This issue was addressed by another measure that instead keeps track of the entanglement of the system with an ancilla[5]. Any indication of a non-monotonic decay of the entanglement heralds non-Markovianity and the magnitude of such revival quantifies it. Liu *et al.* theoretically show and experimentally confirm that both distinguishability- and entanglement-based measures are equivalent for their open system. Although the experiments using the distinguishability measure above can be reproduced with a classical light source such as an attenuated laser, the second characterization requires a truly quantum mechanical source of entangled states. For this reason, in both experiments a source of arbitrary two-photon states based on spontaneous parametric down-conversion was used. In the present experiment, the non-Markovianity measure of Rivas *et al.*[5] was evaluated through a full quantum-state reconstruction. However, given that the ancilla was already present and entangled with the system, a direct characterization of non-Markovianity should be possible following earlier ideas[6].

A non-monotonic behaviour of the degree of entanglement as a signature of non-Markovianity has also been observed for models and experiments in quantum biology. For example, in the 'radical-pair mechanism' model of the magnetic compass in birds, the entanglement of the radical pair shows a revival[7]. Similarly, in experiments of photosynthetic energy transfer, excitons display coherence oscillations[8,9]. The challenge, of course, remains not only in finding experimental techniques to apply the above measures of non-Markovianity to such non-engineered systems, but also in controlling the environment. Recently, experimental steps towards a more complex engineering of the environment have been taken, from a toolbox for the controllable simulation of open systems[10] to a proposal modelling photosynthetic energy transfer[11].

The above non-Markovianity measures and environment engineering are easy to realize for one qubit, but no equivalent is available for many-body systems. Further ideas are necessary to implement these results into more general systems. ❐

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