selected – people who carried them survived more often than those who did not, and left more descendants who inherited the protective genetic variants. In turn, these descendants would have had more protection during subsequent waves of disease, which occurred every few years for the next four centuries. Indeed, these subsequent waves were typically less deadly than the Black Death[4].

The narrow time window from which samples were taken, and the large number of samples analysed, are selling points of the study, allowing Klunk *et al.* to accurately date natural selection. The authors achieved this using historical records and radiocarbon dating, among other approaches. Even though evolutionary biologists had previously wondered about the possibility of natural selection during the Black Death, proper investigation was not possible without this precise dating of many samples.

Klunk and colleagues found that a striking number of genetic variants were selected for in genes that govern immune defence against pathogens. In just a few generations, tens to hundreds of genetic variants that might potentially be protective against the plague became more common in a detectable way. The authors also found that the four that became most common were selected for at a speed and an intensity never observed before in human genomes. Individuals who carried some or all of these variants probably had immune defences that responded efficiently to *Y. pestis*, and, as a result, had much better odds of surviving infections.

Klunk *et al.* then infected cultures of human cells carrying different genetic variants with *Y. pestis*. These experiments confirmed that the gene variants that were most highly selected for did indeed confer robust immune defences – the cells with those variants were more resistant to *Y. pestis* infection than were cells that did not carry these variants.

It is worth noting that such rapid and strong selection is highly unlikely to occur for human traits other than immune defence. No other set of traits is under such strong evolutionary pressure. Furthermore, the evolution of the immune defence system is unique in the sense that, until the advent of systematic vaccination of the population in the past century, humans had very little control over pathogens. Klunk and colleagues' results therefore cannot be extrapolated to the rest of the human genome.

Finally, there is evidence that the speed at which natural selection occurred during the Black Death might have come at a cost that is still being paid today. Some of the genetic variants identified by the authors increase the risk of autoimmune diseases such as rheumatoid arthritis[5]. Perhaps this increased risk simply did not matter during the Black Death – the urgency of the pandemic might have made the trade-off an inevitable one.

Although the study provides evidence of rapid selection of immune-defence variants, there are caveats to consider. Sequencing DNA from historical samples is challenging, so the authors had to restrict their sequencing efforts to prominent immune-defence genes. Such genes are involved in the response to many other pathogens, and it is still unclear whether any of these could have contributed to the strong natural selection observed. A possible future research avenue will be to sequence entire genomes, to further establish that the burst of natural selection was indeed specific to *Y. pestis*. This could be achieved by showing that natural selection occurred at a specific combination of genes whose modulation as a group is affected only by *Y. pestis*.

Going forward, more studies of ancient DNA could also enable a better understanding of the evolutionary origins of autoimmune diseases. Population migrations can shape the risk of such diseases through 'founder' events, in which, by chance, the founders of a given population happen to carry specific disease-associated variants[6]. Klunk and colleagues' inferences – together with a study by my group that identified a historical epidemic through the natural selection it drove in host genomes[7] – indicate that ancient epidemics are also a force to consider.

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Quantum physics

Superfluid system hosts early-Universe dynamics

Silke Weinfurtner

A fluid of ultracold atoms has exhibited quantum dynamics similar to those thought to have existed moments after the Big Bang – ushering in a new era of laboratory exploration of the early Universe. **See p.260**

The idea that the early Universe underwent a phase of rapid inflation was originally proposed to address some of the outstanding puzzles of the Big Bang[1]. But scientists soon realized that this theory of inflation could also explain the very origin of the Universe's cosmic structure[2]. Like all events that occurred in the early Universe, the inflationary phase has long been inaccessible to direct experiments, but that doesn't necessarily preclude exploration of the physics involved. On page 260, Viermann *et al.*[3] report a set of neat laboratory experiments that offer a peek at a small segment of inflationary history by examining the dynamics in a system of supercooled potassium-39 atoms.

By cooling the atoms down to just tens of nanokelvin, the authors achieved a state known as a superfluid, which can be thought of as an ideal fluid with zero viscosity. Superfluids exhibit excitations, called phonons, consisting of sound waves that are restricted to discrete energy levels[4]. Viermann and colleagues' superfluid was shaped like a pancake, so the phonons propagated in two dimensions. Once excited, they were free to roam through the superfluid, and their speed determined how long it took them to propagate from one side of the pancake to the other. The authors manipulated this speed, and the shape of the pancake, to mimic wave propagation in a particular space-time geometry (known as the Friedmann–Lemaître–Robertson–Walker, or FLRW, geometry). This geometry encodes the gravitational field of the whole Universe, meaning that it can represent different cosmological scenarios, including inflation[5].

To establish the link between wave propagation in their superfluid pancake and the dynamics of the early Universe, Viermann *et al.* carried out two kinds of test. First, they excited short bursts of sound waves (wavepackets) in the centre of their superfluid, and studied how these wavepackets spread out when the wave speed was manipulated to simulate an inflationary Universe (Fig. 1). The sound speeds were modified by varying external magnetic fields, which influenced the interactions between atoms. The authors found that the wavepackets propagated in an

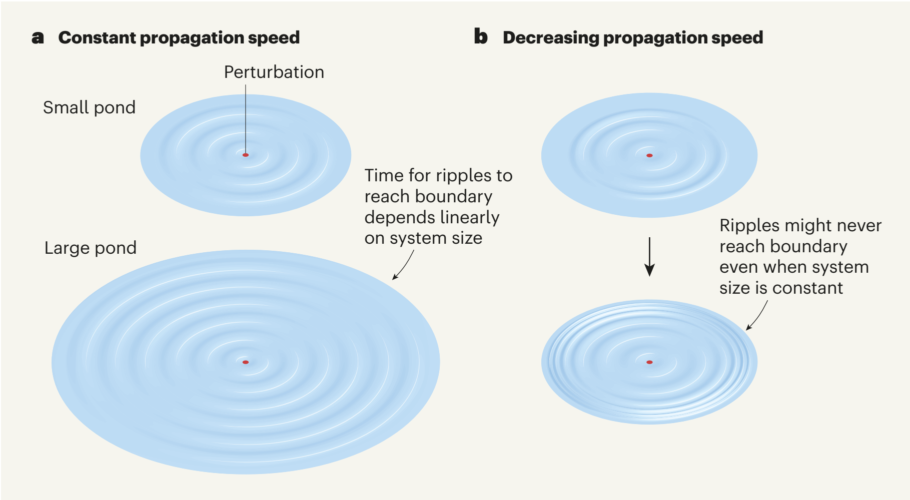

Figure 1 | Simulating the early Universe. The Universe is thought to have undergone a phase of rapid inflation after the Big Bang. This can be explored using an analogy with fluids[6]. **a**, A perturbation in a fluid propagates with constant speed, creating ripples in a pond's surface. The time it takes these ripples to reach the pond's boundary can be used to measure the size of the pond. **b**, Viermann *et al.*[3] simulated the expansion of the Universe using a superfluid (an ideal fluid with zero viscosity) by exciting short bursts of sound waves (wavepackets) and studying how these wavepackets spread out over a period of milliseconds. The properties of the superfluid allowed them to progressively decrease the wave speed so that the wavepackets never reached the boundary. This meant that they could mimic inflation even though the actual size of the superfluid remained constant.

effective FLRW geometry. Furthermore, by changing the shape of the pancake, they could implement FLRW-type universes with different spatial geometries.

Second, the team studied what happens to quantum waves during an inflationary phase. Such quantum waves naturally arise in a superfluid as the smallest possible excitations in the system. They are omnipresent, but only affect systems that are so cold that no other excitations (such as thermal excitations) dominate. The commonly held theory is that the Universe was devoid of everything except quantum excitations at the beginning of inflation. These excitations are therefore a particularly intriguing starting point for studying inflationary dynamics. Viermann *et al.* showed that quantum fluctuations imprint a distinct time-dependent pattern in the superfluid, as predicted by the theory of inflation.

Fluids have been used to explore the quantum dynamics of the Universe since 1981, when Canadian physicist William Unruh developed a theoretical mapping between fluids and the conditions under which black holes evaporate[6]. This framework sparked a new line of research, in which scientists sought to mimic the conditions of these black holes in 'analogue gravity' experiments[7,8], also known as gravity simulators.

It took several decades for these experiments to prove successful, but many black-hole effects have now been realized in different physical systems acting as gravity simulators[9]. Although early efforts focused on simulating black holes, theoretical work[10,11] eventually prompted researchers to explore the possibility of using gravity simulators to reproduce the physics of the early Universe.

In 2018, researchers demonstrated that an expanding doughnut-shaped superfluid exhibits phonon dynamics resembling those of an inflationary Universe[12]. The fast expansion of the doughnut was related to a rapid change in the speed of sound, and this made the phonons' motion seem as though it was damped — an effect that was shown to be caused by the FLRW geometry. Then, earlier this year, quantum-fluid experiments revealed the spontaneous production of particles mimicking those appearing in the Universe's infancy[13].

Viermann and colleagues' work marks a crucial step in the development of these early Universe simulators. The authors achieved exquisite temporal and spatial control in their experiments, and produced powerful detection methods. Together, these advances offer a first glimpse of the insights that gravity simulators will make possible in years to come.

As is often the case, skilful implementations raise expectations. For example, one might wonder why Viermann *et al.* were only able to sample such a small segment of inflation. The 'pancake Universe' in their experiments merely tripled in size — a far cry from the factor of 10^{26} that the theory of inflation predicts. In fact, the expansion is too small to see any imprints of the dynamics that are suggested to have been the origin of the Universe's large-scale structure. Increasing expansion rates sufficiently to see this effect is a key goal for future experiments[14].

Cosmologically interesting scenarios beyond inflation might also be accessible with these experiments. For example, could gravity simulators be used to explore what happened before the Big Bang? One promising idea is that the Universe was in a metastable state and underwent a phase transition, known as false-vacuum decay. Modelling efforts predict that this transition could be implemented in experiments using ultracold atoms[15,16].

What about post-inflation processes? After sufficiently long periods of inflation, all excitations will be frozen and merely dragged along with the rapidly expanding fabric of space-time. Hence, the idea of an inflationary Universe requires a mechanism that could amplify and thaw these frozen excitations[17]. A first proof-of-principle experiment has been carried out to demonstrate that gravity simulators can mimic the intricate details of such a cosmological heating mechanism[18], and Viermann and colleagues' set-up could, in principle, be used to probe this question.

Gravity simulators offer a window into the otherwise inaccessible quantum dynamics of the early Universe. The ultimate goal is to use these simulators to venture beyond what we can calculate, and to foster an exchange of ideas between the theorists who predict the dynamics of the early Universe and the experimentalists who work on quantum systems. Viermann and colleagues' work is a crucial step in this direction.

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