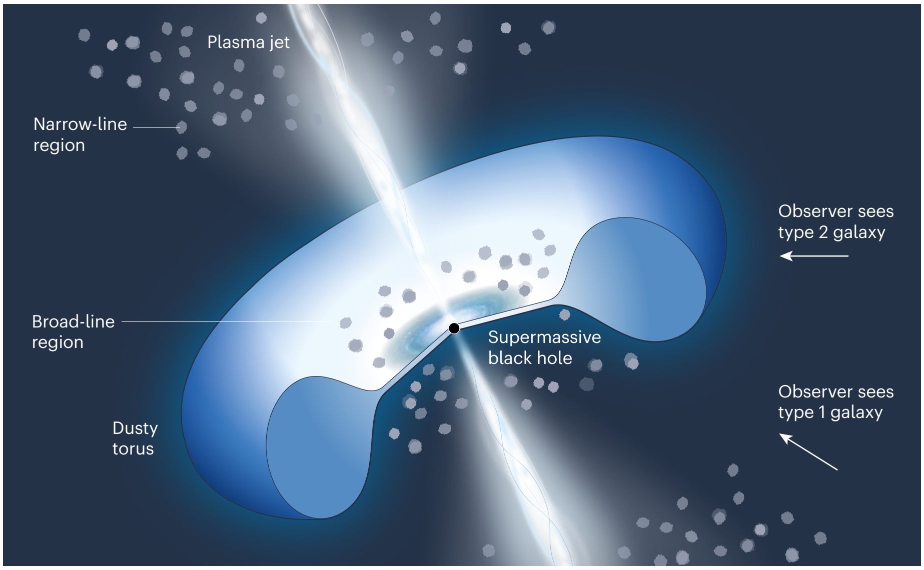

Figure 1 | Imaging the dust around an active galactic nucleus. Active galactic nuclei are the luminous centres of some galaxies, and are thought to be powered by supermassive black holes. The light emitted by such nuclei has key spectral features, including a broad-line region and a narrow-line region. Nuclei with spectra that show both regions are known as type 1 objects, whereas those that show only the narrow-line region are known as type 2 objects. The unified model suggests that this distinction arises because the line of sight to type 2 objects is obscured by a dusty torus of matter that feeds the black hole. This model is supported by observations of plasma jets emanating from the nuclei. Gámez Rosas *et al.*[1] imaged the dusty torus around an active galactic nucleus with very high sensitivity.

must lead to copious accretion onto the black hole, so the mass flow through the torus could power the whole magnificent edifice[7,8]. Better understanding requires imaging the torus.

Gámez Rosas and colleagues' data come from a powerful instrument called MATISSE, which combines data from the four units of the European Southern Observatory's Very Large Telescope Interferometer in Chile with sufficient angular resolution and sensitivity to identify the torus of an active galactic nucleus. The work also required great judgement, technical skill and astrophysical knowledge, because the dust is distributed in a complicated, weather-like way and it absorbs as well as emits.

In fact, similar data at slightly shorter wavelengths were previously presented by another group, who failed to identify the nuclear infrared source[9]. I disagreed strongly with their interpretation of their data, and the present authors rule it out. They do this in two principle ways, but we need to know a bit of physics first to understand how. As torus material works its way towards the black hole, it inevitably gets so hot that the dust evaporates, and the distance at which that occurs, the sublimation radius, is the inner edge of the dusty torus.

The present authors' data set includes spectral channels that specifically measure foreground absorption towards each location on the image. This breaks a degeneracy (ambiguity) between temperature and obscuration, showing that the hottest innermost dust is far from the location proposed previously[9].

Gámez Rosas *et al.* decisively confirmed the location of the black hole on the infrared images in an independent and robust manner. Their new maps obtained using radio interferometry can persuasively be aligned with the maps of infrared emission obtained previously[9]. In my opinion, this does confirm that the positional registration adopted by the first group is incorrect. With the correct registration, Gámez Rosas *et al.* found a compact infrared source at the black-hole position, which, generally speaking, answers the requirements for the active galactic nucleus torus. This is great work!

There is, however, a little unfinished business. The unified model was derived from the shadowing properties inferred from polarization, and their relation to the radio jet. Both of these observations indicate a torus extended very close to the east–west direction[10]. The structure Gámez Rosas and colleagues identified as the torus is tilted by 30° to where it must be to produce the scattered light. But it is also not straight. I predict that, with improved resolution, imaging will reveal that the torus is oriented east–west on the smallest scales.

Furthermore, the resolution of the authors' data is still at least several times too poor to resolve the crucial region where the dust grains sublimate. There are both observational and theoretical reasons to think that the torus swells and controls the shadowing at this very location[11].

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1. Gámez Rosas, V. *et al. Nature* **602**, 403–407 (2022).
2. Antonucci, R. *Nature* **495**, 165–167 (2013).
3. Tadhunter, C. & Tsvetanov, Z. *Nature* **341**, 422–424 (1989).
4. Ogle, P. M. *et al. Astrophys. J.* **482**, L37–L40 (1997).
5. Bock, J. J. *et al. Astron. J.* **120**, 2904–2919 (2000).
6. Lynden-Bell, D. *Nature* **223**, 690–694 (1969).
7. Krolik, J. H. & Begelman, M. C. *Astrophys. J.* **308**, L55–L58 (1986).
8. Krolik, J. H. & Begelman, M. C. *Astrophys. J.* **329**, 702 (1988).
9. Pfuhl, O. *et al. Astron. Astrophys.* **634**, A1 (2020).
10. Kishimoto, M. *Astrophys. J.* **518**, 676–692 (1999).
11. Krolik, J. H. *Astrophys. J.* **661**, 52–59 (2007).

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Metrology

Atomic clouds stabilized to measure dilation of time

Ksenia Khabarova

Tests of relativity once required accurate clocks separated by thousands of kilometres. Optical techniques have now made such tests possible in an atomic cluster measuring no more than one millimetre in size. **See p.420 & p.425**

As Albert Einstein predicted in his theory of general relativity, the gravitational field of a massive object distorts space-time, which causes time to move more slowly as one gets closer to the object. This phenomenon is known as gravitational time dilation, and it is measurable — particularly in the vicinity of a very massive object such as Earth. The measurement requires a sufficiently accurate clock, and, today, the most accurate timekeepers are atomic clocks, which keep time by detecting the transition energy between two

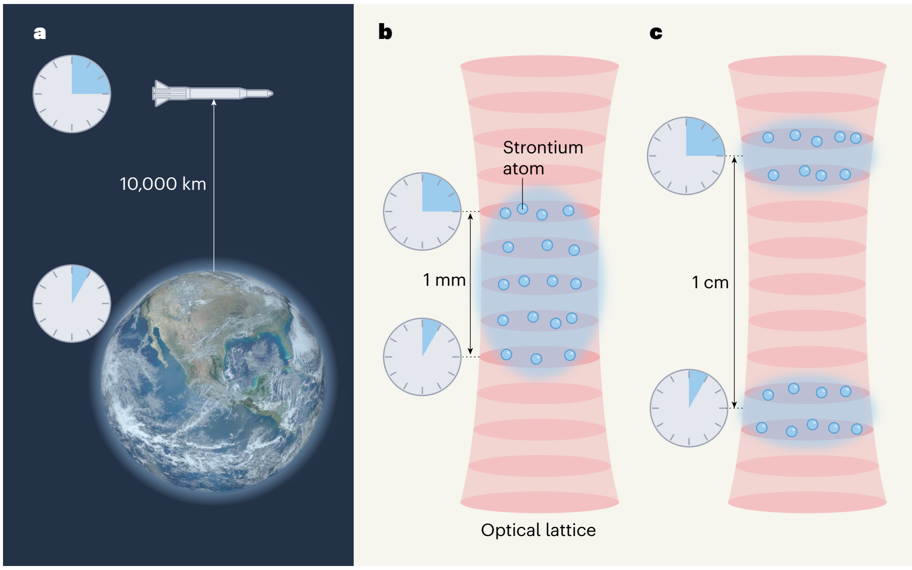

Figure 1 | Measuring time differences in vertically separated clocks. a, The Gravity Probe A experiment[3] measured gravitational redshift (a metric for how gravity changes time) using two clocks separated by a vertical distance of 10,000 kilometres – one was on a spacecraft and the other remained on Earth's surface. The clock on the spacecraft ran faster than the clock on Earth. **b**, Bothwell *et al.*[1] showed that it is possible to measure gravitational redshift even on the submillimetre scale, by probing the timing of electronic transitions in a single cloud of strontium atoms trapped in an optical lattice (formed by the interference pattern of lasers). This required the team to measure an effect that was 20 billion times less pronounced than that detected in the Gravity Probe A experiment. **c**, Zheng *et al.*[2] demonstrated a similar set-up for such measurements using clouds of strontium atoms separated by one centimetre.

electronic states in an atom. Bothwell *et al.*[1] (page 420) and Zheng *et al.*[2] (page 425) now report astounding progress in the stability of atomic clocks using ensembles of ultracold strontium atoms. Bothwell and colleagues even managed to measure the degree to which time is dilated by gravity – a quantity known as gravitational redshift – in a single atomic cloud.

Gravity Probe A was the first such experiment sensitive enough to measure gravitational redshift[3]. In 1976, a spacecraft carrying a maser (the microwave equivalent of a laser) reached a height of 10,000 kilometres above Earth's surface (Fig. 1a). At this height, the highly accurate signal produced by the maser, which acts as a clock, was expected to be faster than an equivalent clock on Earth by around one second every 73 years. The Gravity Probe A team found that the clock on the spacecraft differed from the one on Earth by the predicted amount to an accuracy of 70 parts per million. Although this might seem a very small difference, an error of this magnitude would cause a GPS navigation system to calculate the wrong coordinates, so the GPS clocks on satellites flying 20,000 kilometres above Earth are corrected for the gravitational redshift.

The transitions between two electronic states in an atom that are the basis for an atomic clock are known as clock transitions, and they are typically induced by the oscillating light wave of a laser. In the case of neutral atomic clocks, a large ensemble of atoms is trapped in the interference patterns of oppositely propagating laser light, known as an optical lattice. The atoms are then exposed to a laser that is generating electromagnetic waves with an ultrastable frequency. State-of-the-art optical clocks can achieve a performance corresponding to an error of less than one second over the lifetime of the Universe[4].

Such accuracy has become possible through exquisite control of experimental conditions, effectively extending the time over which the quantum behaviour of the atomic ensemble can be predicted, which is known as the quantum coherence time. The longer the coherence time, the more stable and accurate the clock. Pioneering research in 2010 showed that a comparison of two atomic clocks separated in height enables the gravitational redshift to be measured on a scale of less than one metre[5]. The advance reported by Zheng *et al.* improves on this approach – and Bothwell and co-workers even bring it below the millimetre scale – with the help of record coherence times in ensembles of ultracold strontium atoms.

Bothwell and colleagues trapped strontium atoms in an optical lattice, forming a millimetre-scale atomic sample that was oriented along the direction of gravity (Fig. 1b). The authors succeeded in imaging the entire atomic ensemble *in situ*, with layer-by-layer spectroscopy that resulted in a resolution of 6 micrometres, corresponding to approximately 15 lattice sites. This approach allowed them to mitigate experimental errors and construct a map of atomic-transition frequencies across the cloud. The measured frequency gradient was consistent with the gravitational redshift predicted for two identical clocks separated vertically near Earth's surface.

To detect the redshift in a single atomic sample measuring only one millimetre in size, Bothwell and colleagues needed to measure an effect that was 20 billion times less pronounced than the gravity-induced frequency shift that the Gravity Probe A team had discerned. This is also a remarkable leap beyond previous measurements in ytterbium optical lattice clocks on a subcentimetre scale[6].

Zheng *et al.* also used strontium atomic ensembles trapped in an optical lattice, but in this case the clouds were vertically separated by one centimetre (Fig. 1c). They showed that up to six strontium atomic ensembles can be compared at the same time. Even more remarkably, they found that the ensembles can consist of different isotopes. The work is a feat of engineering, presenting a multiplexed optical-lattice-clock configuration that enables record quantum coherence times of up to 26 seconds – providing extraordinary clock stability. The authors minimized the effects of noise associated with the phase and amplitude of the laser by inducing and measuring transitions simultaneously.

Although Zheng *et al.* achieved excellent quantum coherence times and clock stability, factors preventing accurate measurement of gravitational redshift still need to be assessed before the authors' multiplexed optical-lattice clock can offer subcentimetre-scale precision. For example, the behaviour of different strontium isotopes can vary, even if the conditions are held constant. The conditions in Zheng and co-workers' set-up differ across the lattice, and it can be difficult to control the effect that this has on the behaviour of the isotopes.

These two papers show that progress in the stability and accuracy of atomic clocks has not stopped since Gravity Probe A first launched more than 40 years ago. The reported improvements in measurement precision offer new opportunities for the development of clock-based detectors and extremely sensitive quantum sensors.

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1. Bothwell, T. *et al. Nature* **602**, 420–424 (2022).
2. Zheng, X. *et al. Nature* **602**, 425–430 (2022).
3. Vessot, R. F. C. *et al. Phys. Rev. Lett.* **45**, 2081–2084 (1980).
4. Brewer, S. M. *et al. Phys. Rev. Lett.* **123**, 033201 (2019).
5. Chou, C.-W., Hume, D. B., Rosenband, T. & Wineland, D. J. *Science* **329**, 1630–1633 (2010).
6. McGrew, W. F. *et al. Nature* **564**, 87–90 (2018).

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