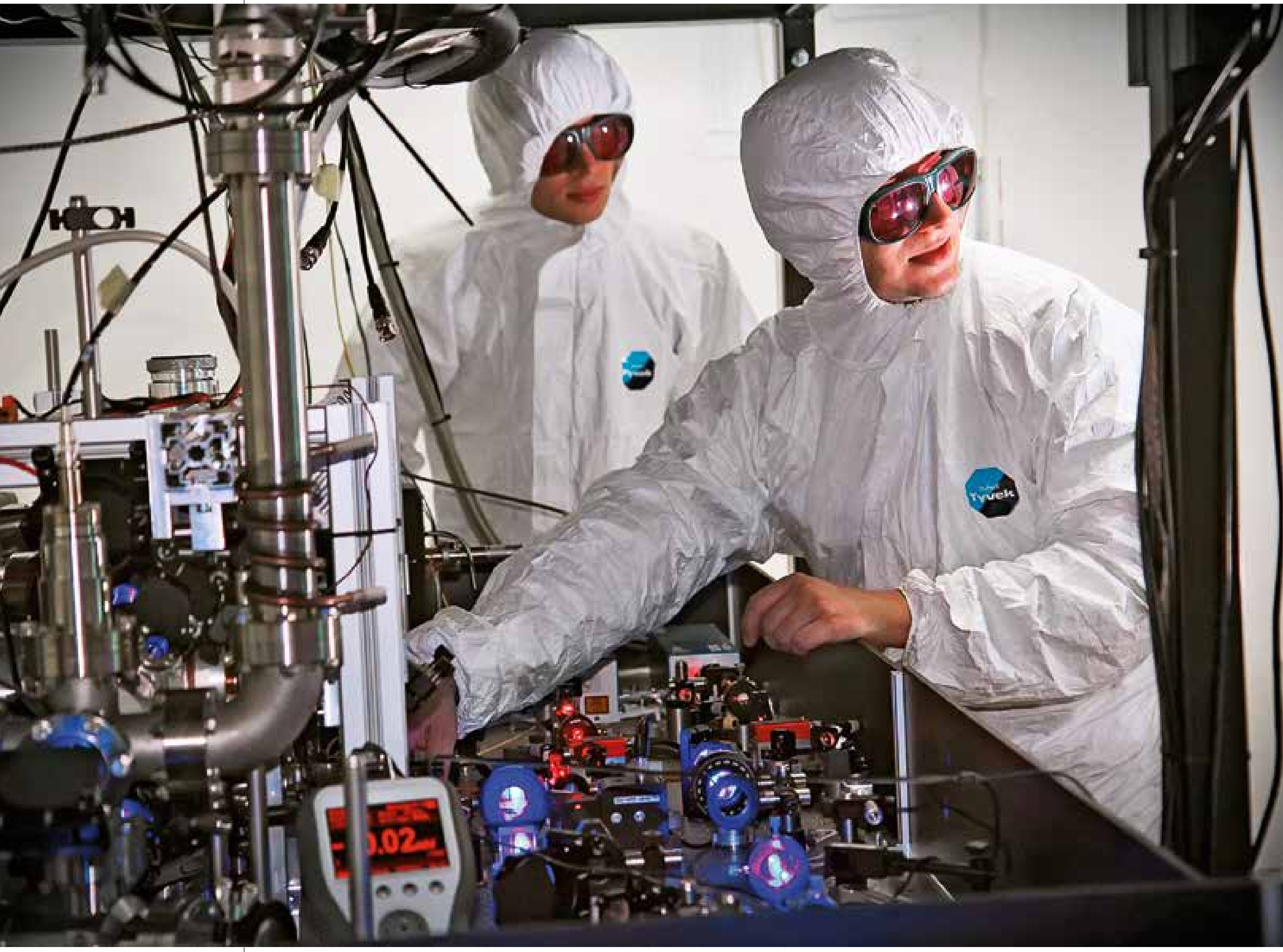

WAITING FOR DARK MATTER TO 'TICK'

Is dark matter real or just a convenient hypothesis? Although it was first proposed almost a century ago, physicists have yet to uncover its true nature. Scientists from the Nicolaus Copernicus University are investigating the phenomenon using atomic clocks.

Beata Zjawin

Nicolaus Copernicus University in Toruń

Galaxies – vast systems of stars, gas and dust – have been fascinating people for centuries. Astronomers study our own Milky Way, our closest neighbor the Andromeda galaxy, and other galaxies found huge distances away. Since almost a century ago, scientists have been able to estimate the masses of individual galaxies based on observations. However, they soon encountered a problem: their experimental results didn't match theoretical predictions. Furthermore, in 1933, the Swiss astronomer Fred Zwicky noticed that clusters of galaxies move at significantly higher speeds than expected given their gravitational potential, as suggested by observations. According to basic laws of physics, at such vast speeds galaxies should spread away from one another in space, yet we can see that they remain clustered, as though held together by a mystery force. Zwicky posited that the force responsible is gravitational in nature, but that it originates not from visible matter but rather from some "dark" matter, comprised of unknown dark particles which do not emit or absorb photons. Zwicky's dark matter theory remains the most likely hypothesis, but it has yet to be observed in any direct way.

The difficulties involved in studying a phenomenon as mysterious as dark matter certainly haven't put astronomers off. This still-hypothetical kind of matter is the subject of research at various laboratories; for example, the Great Hadron Collider at CERN is used to attempt to create dark matter particles through a variety of processes. Observations of the sky are also used to try to capture the mysterious phenomenon. The OGLE project, initiated by Prof. Bohdan Baczyński in 1992, aimed to identify massive compact halo objects (MACHOs) – ordinary but hard to see matter, with a nature similar to that found in known stars or planets. If MACHOs do exist, the Polish telescope at the Las Campanas Observatory in Chile would have registered their presence by observing the phenomenon known as gravitational microlensing. The direction of light heading for Earth would change if it were to encounter a lensing body such as a MACHO. While Polish scientists haven't observed any signs confirming the existence of dark matter, their studies have revealed that its form likely doesn't resemble that of ordinary matter. We now suspect that dark matter could manifest as topological defects – regions of space distinct from ordinary space, probably formed at the very early stages of the Universe's existence, when it was extremely hot and compact and started to expand and cool rapidly.

Tick, tick, tock

Building dark matter detectors is extremely expensive, their design and execution taking many years. However, physicists suppose that highly sensitive optical atomic clocks could register dark matter, since their ticking is dictated by the standard model of elementary particle physics. This means that if such a clock encounters dark matter, its operation will be briefly altered. This should tell us the level at which dark matter interacts with ordinary matter, since it could effectively change the parameters of the standard model, as seen in experiments.

> If dark matter encounters an optical atomic clock along its path, the clock's operation will be briefly altered.

The concept of using optical atomic clocks to search for topological defects is not new, although it originally proposed comparing measurements taken by two clocks joined together with a fiber optic link.

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Since such experiments would be extremely expensive and difficult, Dr. Piotr Wcisło from the Institute of Physics at the Nicolaus Copernicus University proposed a similar experiment using a single clock. Instead of comparing results obtained by two instruments, it is possible to compare the behavior of two parts of the clock – ultracold atoms and the optical cavity – at the moment dark matter is encountered. The elements will respond differently to topological defects, and this difference in responses will reveal many properties of dark matter. Using this idea, a team of physicists from the Institute – Dr. Piotr Wcisło, Dr. Piotr Morzyński, Dr. Marcin Bober, Dr. Agata Cygan, Dr. Daniel Lisak, Prof. Roman Ciuryło and Prof. Michał Zawada – started studying the nature of dark matter using the university's optical atomic clock, without having to construct another expensive instrument.

> The measurements conducted at Nicolaus Copernicus University used two clocks relatively close to one another, about 10 meters apart.

Combs or rulers

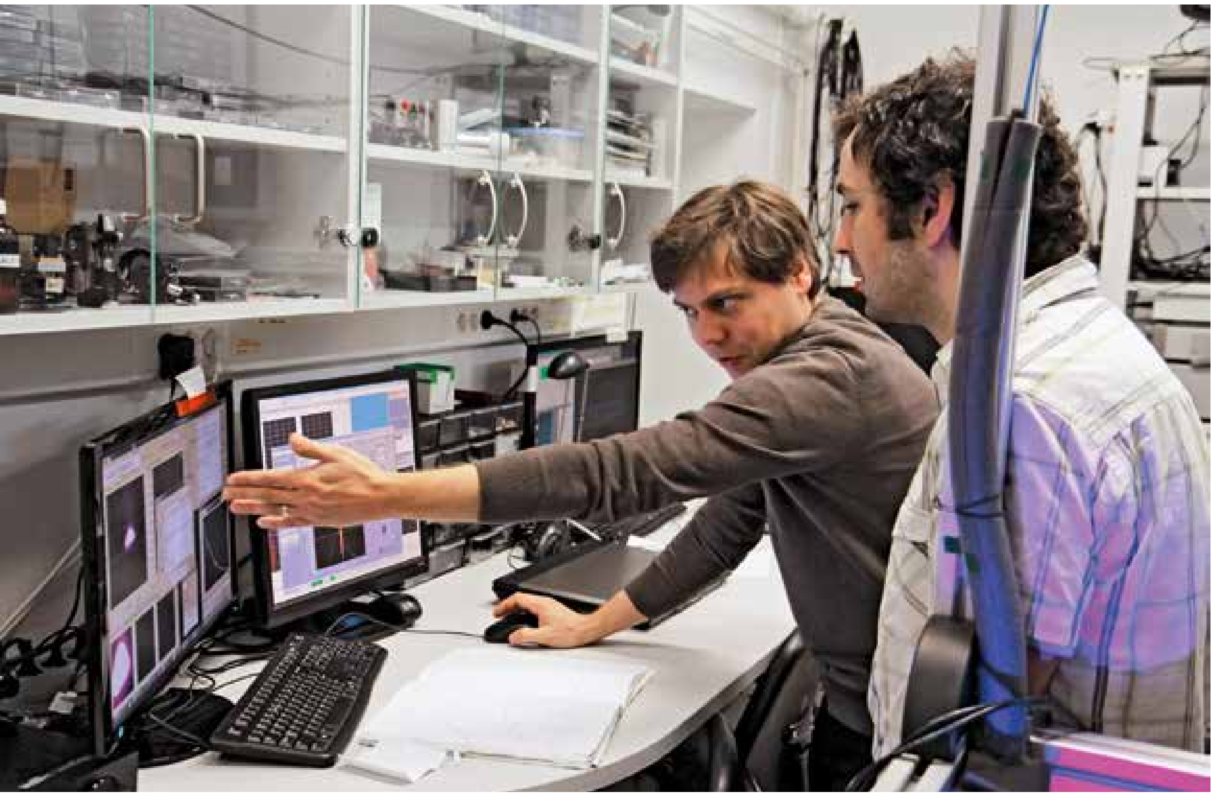
Time can be measured in a variety of ways, some of which are more accurate than others. When the optical atomic clock in Toruń was first brought online, its accuracy was one second per tens of billions of years. The instrument at the National Laboratory of Atomic, Molecular and Optical Physics was built by a consortium of the Jagiellonian University, the University of Warsaw and the Nicolaus Copernicus University as part of the Polish Optical Atomic Clock project of the Ministry of Science and Higher Education. It works like an ordinary clock: it measures time by counting the oscillations of an oscillator, but its very design ensures it does so with a high degree of precision. The oscillator is an ultrastable laser whose frequency is adjusted to the transitional frequency in strontium 88 atoms, while the counter is an optical frequency comb. The number of laser oscillations is so high that before it can be counted using electronic devices, it needs to be processed using the optical comb "ruler." The latter employs short, equal impulses generated by the femtosecond laser. The optical atomic clock at the National Laboratory of Atomic, Molecular and Optical Physics is connected to the OPTIME network, allowing scientists to refer to the coordinated universal time (UTC) provided to researchers by the Polish Academy of Sciences.

Our instrument is calibrated to detect topological defects as they move through the Universe. Astronomers had previously searched for such topological defects in the cosmic microwave background, but they were unsuccessful.

The main features of optical atomic clocks are their precision and stability. The former is provided by atoms maintained under special conditions which minimize any environmental impact. For example, if the clock encounters a permanent temporal disturbance, it will no longer be as precise, but it will remain stable.

This is exactly the sort of clock required in searching for dark matter, due to the convergence of the frequency of ultrastable lasers and the atomic transition frequency. We know that the predicted disturbance would have two effects on the atom and laser components of the clock. By comparing the frequencies corresponding to atomic transition frequencies with laser frequencies, and assuming that dark matter will penetrate the clock, we can learn how it interacts with ordinary matter. Generally speaking, measurements suggested by physicists rely on comparing disturbances recorded by two clocks. The Polish scientists, on the other hand, have "split" their clock into two blocks with different sensitivities and are studying the disruptions to their stability.

The National Laboratory of Atomic, Molecular and Optical Physics holds two almost identical atomic clocks, both of which are used in the experiments. They both use strontium 88 atoms. Based on existing results of cosmological studies, physicists assume that the expected "wall" of dark matter has a width similar to Earth's radius (6378 km) and moves with a relative speed of 300 km/s, comparable to the velocity of the Sun in its journey through the center of our galaxy.



Employees of the National Laboratory of Atomic, Molecular and Optical Physics in one of the laboratories holding the optical atomic clock.

The readings of the two clocks are filtered to calibrate them to the expected parameters of this wall; the signals are then correlated. Experiments were conducted over 45,700 seconds in cycles lasting around 1 second, with each observation taking 2 seconds (two cycles). If a disruption was found, the laser (whose frequency fits the narrow spectral parameters of strontium 88) was adjusted. If no disruptions were found during a cycle – shown by the laser maintaining its frequency – it meant the laser is stable.

Waiting for a sign

In the experiment, the Polish scientists were the first in the world to test experimentally how an optical atomic clock coming into contact with a topological defect would affect the transitional frequency in strontium 88 atoms and the frequency of the ultrastable laser. Changes to the fine-structure constant, characterizing the strength of electromagnetic interactions, mark the boundaries of how dark matter interacts with ordinary matter.

Under perfect conditions, the experiment could be conducted using a single clock. Since creating such conditions is virtually impossible, Dr. Piotr Wcisło suggested an alternative way of improving accuracy, through the use of multiple clocks. Although the measurements conducted at the Nicolaus Copernicus University used two clocks, they were placed relatively close to one another, about 10 meters apart. In this instance, internal disturbances affected both clocks at the same time. A natural limitation of the experiment is the assumption that a topological defect with predicted parameters will happen to pass through Earth during the 45,700 seconds of the experiment. A solution to both these problems is conducting observations over the course of many years using several clocks placed large distances apart. Such an experimental program wouldn't require costly fiber optic connections or new equipment, since similar clocks are already in use in Japan and the US.

The method developed by Polish physicists and their experiment are therefore the first step on the way to creating a network of atomic clocks listening for signals of dark matter. It is a highly promising project, and scientists from the Institute of Physics at the Nicolaus Copernicus University are already working with other institutions which hold atomic clocks. More complex formats of future measurements bring new problems, such as the need to account for the distances between the clocks, their motion due to Earth's movement, and their motion across the galaxy in tandem with our entire solar system. Once these obstacles are overcome and astronomers begin analyzing results provided by individual clocks, we will await a single synchronized "tick" confirming the existence of dark matter. This will truly change how we see the world and our Universe.

Beata Zjawin
Photography by **Andrzej Romański**

Further reading:

Wcisło P., Morzyński P., Bober M., Cygan A., Lisak D., Ciuryło R. & Zawada M. (2016). Experimental constraint on dark matter detection with optical atomic clocks. *Nature Astronomy* 1.

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