Honda Foundation Report No. 183
Commemorative Lecture at the 43rd Honda Prize
Award Ceremony on the 17th November 2022

From Curiosity-Driven Science to Future Technologies

Dr. Hidetoshi Katori

- Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo
- Chief Scientist, Quantum Metrology Laboratory /
  Team Leader, Space-Time Engineering Research Team, RIKEN Center for Advanced Photonics (RAP), RIKEN
- Program Manager, JST-MIRAI Program, Japan Science and Technology Agency

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- Program Manager, JST-MIRAI Program, Japan Science and Technology Agency

■Date of Birth

September 27, 1964, Japan

■Education and Qualifications

1988: B. Eng. in Applied Physics, Faculty of Engineering, The University of Tokyo
1990: M. Eng. in Applied Physics, Graduate School of Engineering, The University of Tokyo
1994: D. Eng. in Applied Physics, Graduate School of Engineering, The University of Tokyo

■Scientific Positions

1991: Research Associate, Department of Applied Physics, Faculty of Engineering, The University of Tokyo
1994: Guest Scientist, Max Planck Institute for Quantum Optics, Garching, Germany
1997: Group Leader, ERATO Gonokami Cooperative Excitation Project, Japan Science and Technology Corporation
1999: Associate Professor, Engineering Research Institute, Faculty of Engineering, The University of Tokyo
2005: Associate Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo
Principal Investigator, CREST, Japan Science and Technology Agency
2010～present: Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo
2010～2016: Research Director, ERATO Katori Innovative Space-Time Project, Japan Science and Technology Agency
2011～present: Chief Scientist, Quantum Metrology Laboratory, RIKEN
2014～present: Team Leader, Space-Time Engineering Research Team, RIKEN Center for Advanced Photonics (RAP), RIKEN
2014～2022: Distinguished Guest Professor, University of Tübingen
2018～present: Program Manager, Space-time information platform with a cloud of optical lattice clocks, JST-Mirai Program, Japan Science and Technology Agency

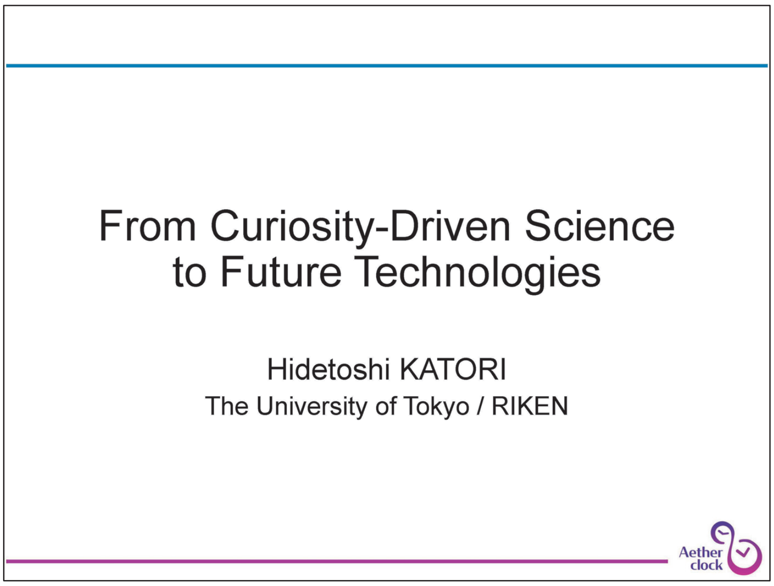
■Awards

2001: Marubun Research Award
2005: The European Frequency and Time Award
The 1st JSPS (Japan Society for the Promotion of Science) Prize
Julius Springer Prize for Applied Physics
2006: Marubun Special Science Award
The 20th IBM Japan Science Prize
2008: Rabi Award
2010: The 42nd Ichimura Academic Award, Special Prize
2011: The 12th Optics and Quantum Electronics Achievement Prize (Hiroshi Takuma Award)
The Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology, Prizes for Science and Technology, Research Category
The Philipp Franz von Siebold Prize
2012: Asahi Prize 2011
2013: The 53rd Toray Science and Technology Prize
The 54th Fujihara Award
Nishina Memorial Prize
2014: Medal with Purple Ribbon
2015: Japan Academy Prize
2016: JSAP (The Japan Society of Applied Physics) Outstanding Achievement Award 2015
2017: Leo Esaki Prize
2020: The 90th Anniversary Special Award from the Hattori Foundation
The Micius Quantum Prize 2020
2022: Breakthrough Prize in Fundamental Physics

■Academic Society

The Physical Society of Japan, The Japan Society of Applied Physics, The Laser Society of Japan, American Physical Society, The Engineering Academy of Japan

This report is the gist of the commemorative lecture at the 43rd Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 17th November 2022.



■ Introduction

I am deeply honored to receive the Honda Prize. I want to express my sincere gratitude to the people at the Honda Foundation and the selection committee members. I would also like to take this opportunity to thank Prof. Fujio Shimizu*[1], Prof. Makoto Gonokami*[2], and Mr. Kuraishi*[3] for their congratulatory speeches.

As I listened to Prof. Shimizu and Prof. Gonokami, my mind was filled with memories of the nearly 30 years since I was a student. In this lecture, I would like to talk about the origin of optical lattice clocks, including my student days.

As Prof. Shimizu mentioned, it is difficult when the talk goes into the details of my research; then, I will proceed based on the reactions of my colleagues. I will talk about my research in a cursory manner or what I thought about while doing my research.

The title is "From Curiosity-Driven Science to Future Technologies." I have been conducting research in a "curiosity-driven" manner and have enjoyed it very much as a researcher. After 20 years of enjoying my research this way, and as I get older, I think I would like to use this technology to benefit future society. That is precisely what I would like to talk about today.

■ Optical Lattice Clock calibrates Japan Standard Time

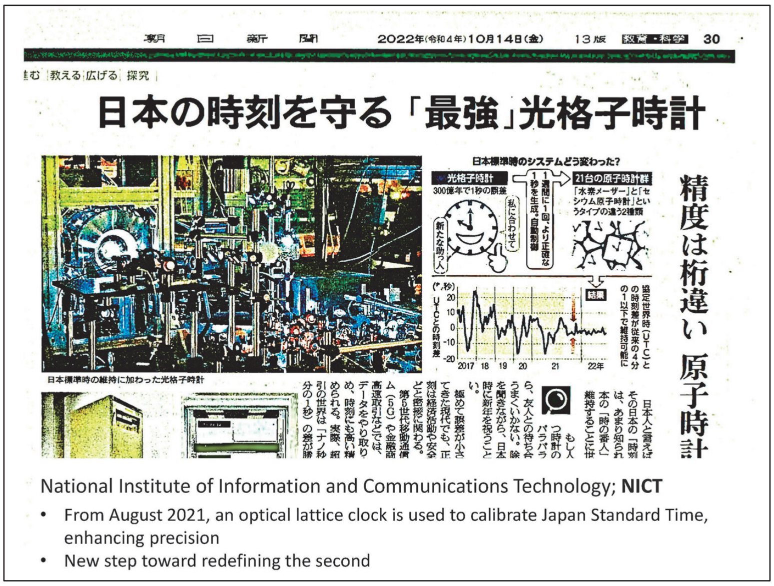


Fig. 1

〈Fig. 1〉 As I prepared for this speech, a newspaper article was published. Dr. Ido*4 and his colleague at NICT (National Institute of Information and Communications Technology) applied an optical lattice clock to maintain the Japanese standard time. This was my dream when I started working on the optical lattice clock. From the initial research stage, in which the research is driven mainly by curiosity, the technology is gradually developed, and finally, the technology properly contributes to society. It is my great honor to have encountered research connected from the beginning to the applications in this way.

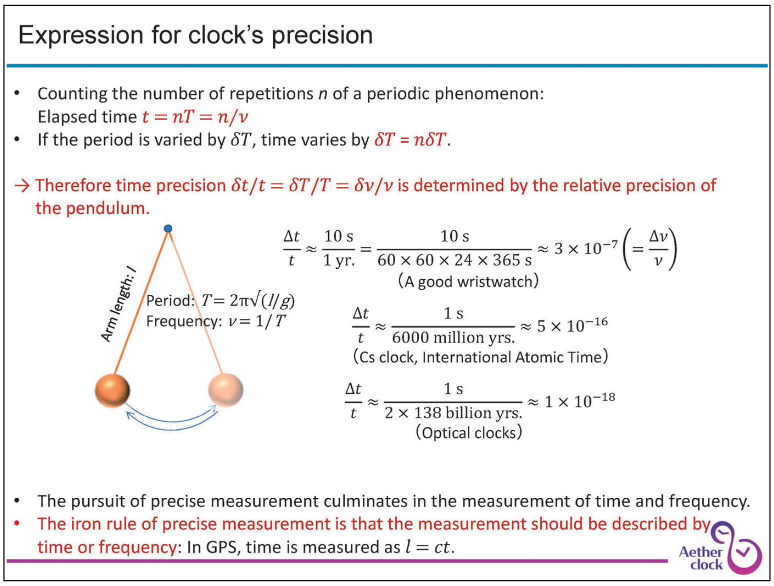


Fig. 2

〈Fig. 2〉 Let me explain how to express the precision of the clocks I will discuss. Time measurement is as simple as counting the number of repetitions, n, of a periodic phenomenon with period T. This is why the time measurement is so precise. If a periodic phenomenon is counted n times, the elapsed time is t = nT. If this period is varied by δT, the elapsed time is changed by n x δT. The key to accurate time measurement is accurate periodic phenomena. When you buy a wristwatch, you will see a specification that says, "This is a watch that may lose 10 seconds per year."

If the watch loses 10 seconds in one year, which is 60 x 60 x 24 x 365 seconds, we call it a relative accuracy of 7 digits by taking the power of an exponent of 10^{-7}(=10/(60 x 60 x 24 x 365)).

A cesium atomic clock would have a relative accuracy of about 15 digits and a half and lose one second every 60 million years.

The optical lattice clock I am about to discuss has 18-digit precision. When I started my research, I had the opportunity to write an appeal sentence for my laboratory: 10^{18} seconds correspond to two times 13.8 billion years, the age of the universe since the Big Bang. I gave the catchphrase "a clock that does not lose or gain even one second from the birth of the universe."

However, whether it deviates by one second in 30 billion years seems insignificant in daily life. In the latter half of the presentation, I will discuss how we can find applications for this precision.

■ A clock that reads one part in 10^{18}

I have been attracted by precision measurement science and wanted to do something extreme, which motivated me to study time and frequency measurements. The ironclad rule of precision measurement is to replace the quantity to be observed with time. A prime example is length measurement which is replaced with time measurement by defining the speed of light. For example, the distance from a GPS satellite to a specific location is determined by the time it takes for a radio wave to travel there. The atomic clock gives the foundation for this time measurement.

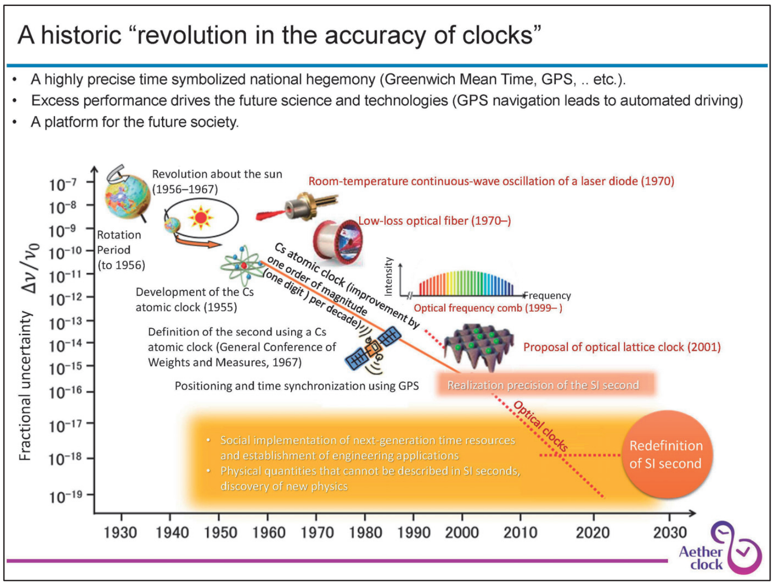


Fig. 3

〈Fig. 3〉 There should be no limits to the precision of clocks. Initially, a second was determined by the earth's rotation and revolution around the sun, which was redefined by the cesium atomic clock in 1967. The precision of "a second," which started with 10 digits, has now improved to 15 to 16 digits. Optical lattice clocks further enhance the precision by a factor of 100 to 1,000. I am excited to discover new physics and applications by precise clocks with 18-digit and even better.

The new definition of the second is expected in 2030.

The history of the development of clocks is equivalent to that of the evolution of human society. High-performance timekeeping has been a symbol of national hegemony. Nowadays, GPS plays a vital role as a social platform.

I look forward to seeing how the relativistic spacetime, which will be observable with optical lattice clocks, impacts future society.

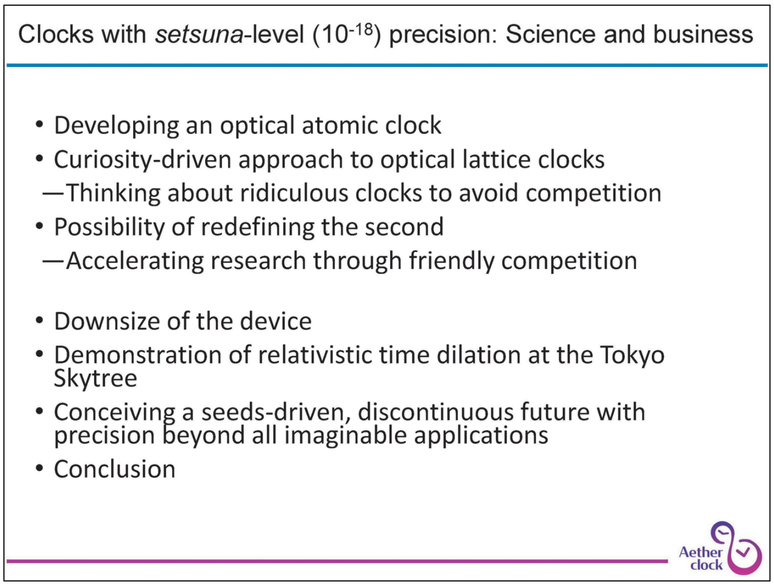


Fig. 4

〈Fig. 4〉 Google says an extremely small quantity of 10^{-18} is called "Setsuna" in Japanese. An optical lattice clock is a clock that reads "Setsuna." We will consider this science and its social implementation.

Here is the table of contents. First, I will describe the principle of an optical atomic clock. Then I will talk about when I was thinking about the concept of optical lattice clocks in a curiosity-driven way. Later, researchers worldwide started this research, which led to the possibility of redefining the second.

In the second half of the presentation, I will discuss how this technology can benefit society. I will talk about the downsize of the device and the demonstration of relativistic time dilation at the Tokyo Skytree.

What kind of applications is possible when further miniaturization is achieved? I would like to imagine a discontinuous future driven by the technology we have today.

■ Development of an Optical Atomic Clock

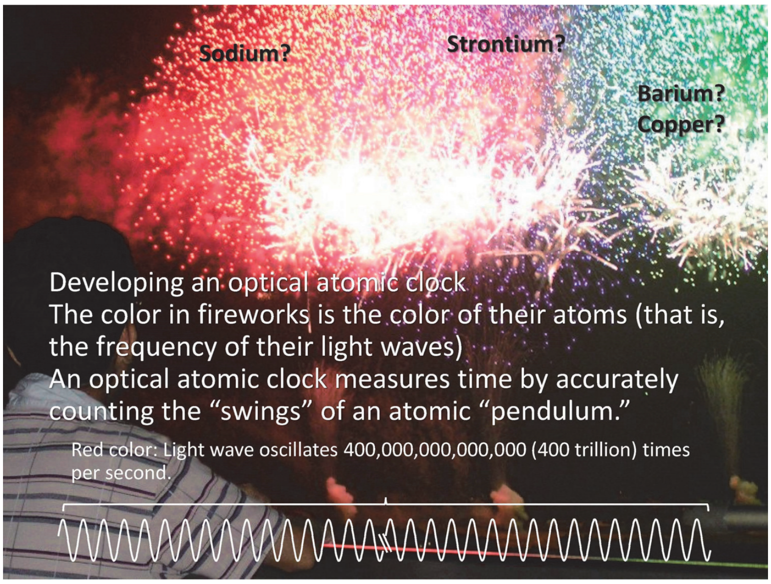


Fig. 5

〈Fig. 5〉 The color of fireworks on summer nights is based on the flame color reaction. If it is sodium, it glows orange. Barium and copper glow blue and green.

I will talk about strontium today, which is just around the purple area in this picture. Strontium has a strong blue and red spectrum. When we see red and blue simultaneously, we recognize them as purple.

We use the red spectrum, which oscillates about 400 trillion times per second, as the atomic pendulum in an optical lattice clock. Counting these vibrations 400 trillion times gives one second.

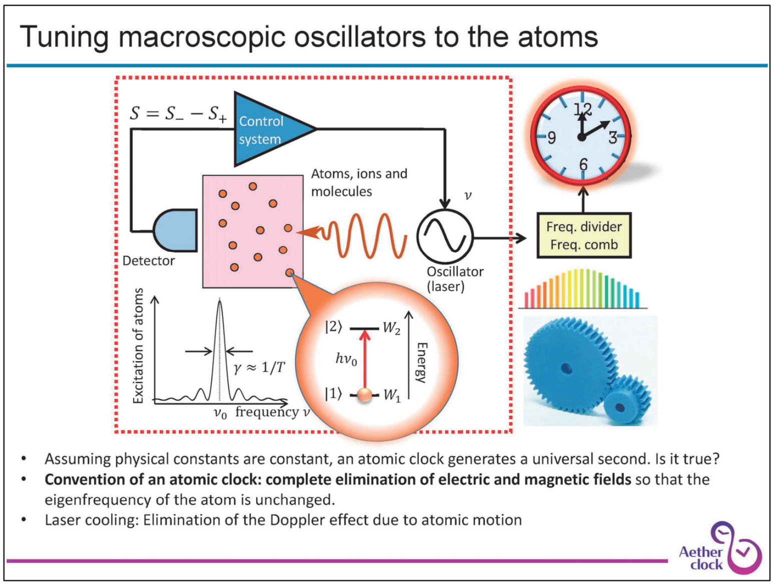


Fig. 6

〈Fig. 6〉 The vital thing in atomic clock development is to successfully copy the microscopic vibrations of atoms to the macroscopic vibrations of a laser (like the laser pointer I use).

One shines a light on the atoms and controls the frequency of the laser so that the atoms absorb the light most. Once a laser oscillator copies the transition frequency of the atom, its oscillation is divided using gears so that it gives one second.

What do physicists want to see at the end of a study like this?

They believe that physical constants are constant; therefore, the vibrations of atoms that are consisted of physical constants should also be constant. Thus, the atomic clock should allow us to share a universal second.

Physicists are wusses and want to challenge with common sense. By developing ultra-precise atomic clocks, we can ask ourselves, "are physical constants really constant?" "Is it constant over time and space?" would be verified. That is one of the prime motivations for our research. If they vary, there should be exciting new physics behind them.

Conventionally, the design rule for atomic clocks has been to thoroughly eliminate surrounding electric and magnetic fields so as not to alter the eigenfrequencies of atoms. Another cause of affecting the frequency of atoms is the Doppler effect due to the motion of the atoms. Laser cooling was invented to eliminate this. As Prof. Shimizu mentioned, I studied laser cooling as a student.

■ Manipulation of atomic motion by laser

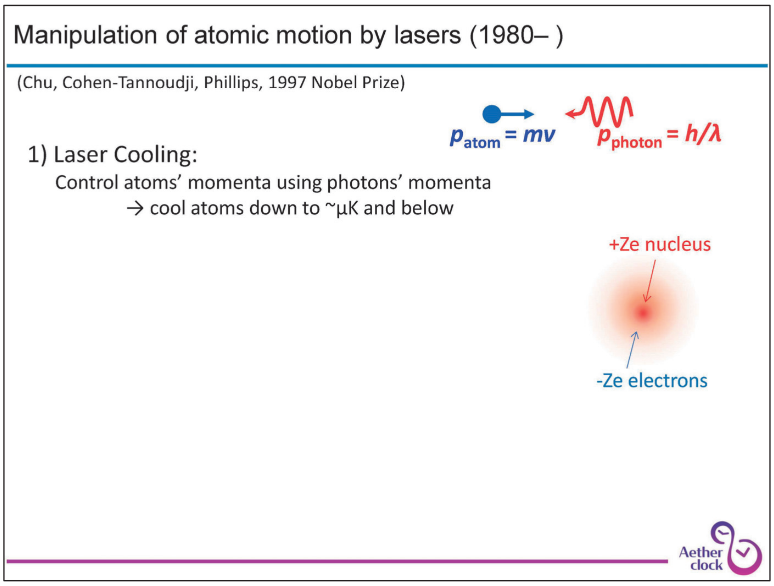


Fig. 7-1

〈Fig. 7-1〉 The study of laser cooling of atoms began around 1980. A moving atom has a momentum given by atomic mass times velocity. When light is shone on the atom from the opposite direction, the photon's momentum reduces the atomic momentum. If repeated many times, the atomic momentum decreases until the atom is almost at rest. This is about 1μK in terms of temperature, which is very close to absolute zero temperature.

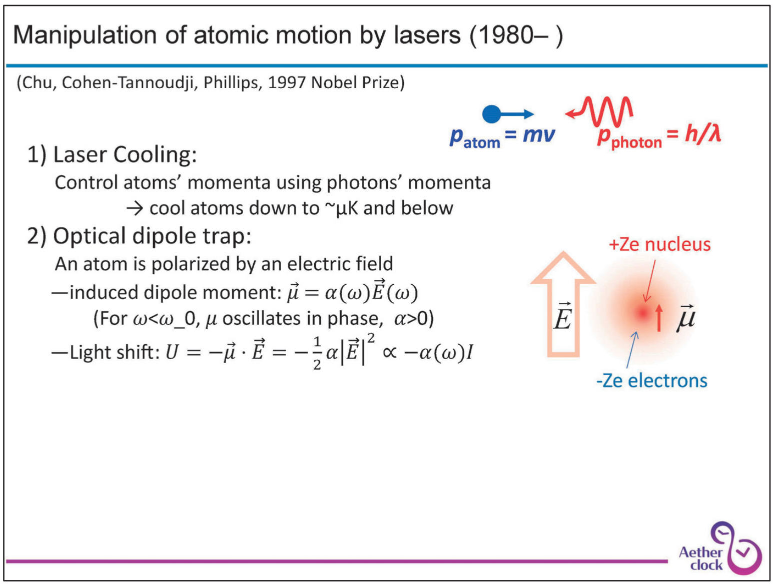


Fig. 7-2

〈Fig. 7-2〉 These cooled atoms can be optically trapped. When an electric field is applied to an atom, the atom is polarized by the slight displacement of its nucleus and electrons. The interaction of the polarized atom with the electric field changes the atom's energy.

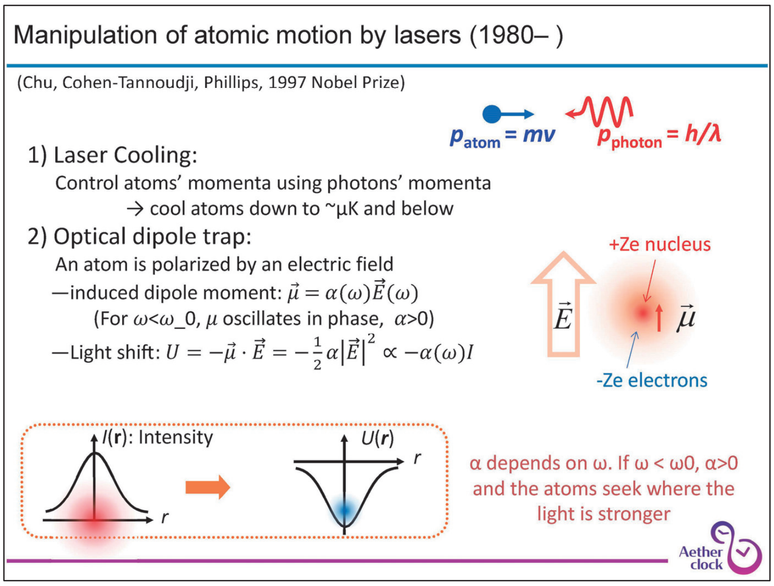


Fig. 7-3

〈Fig. 7-3〉 Generally, intensity varies spatially in a laser beam. The energy of atoms becomes minimum where the laser light intensity is highest, and atoms tend to gather at the point of minimum energy. This is the principle of trapping atoms with light.

For example, when static electricity is generated in an underlay, a hair, for example, is attracted to the underlay. This adsorption phenomenon is the same principle as optical trapping.

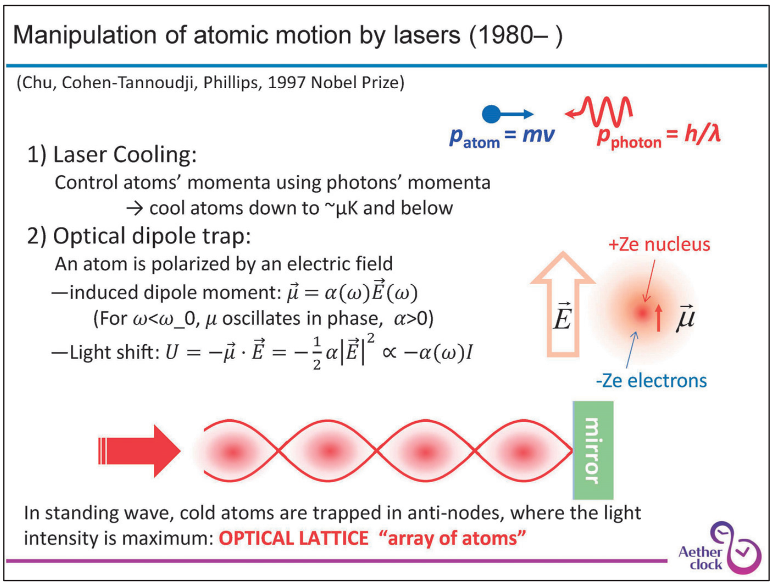


Fig. 8

〈Fig. 8〉 A standing wave is created by reflecting the light with a mirror. In the standing wave, the laser light intensity is maximum in the anti-nodes, where the atoms have the lowest energy. As a result, the atoms are trapped in the anti-nodes, forming an optical lattice in which the atoms are periodically lined up.

■ The starting point of the research, the 1990 Japan-U.S. Seminar at Mt. Hiei

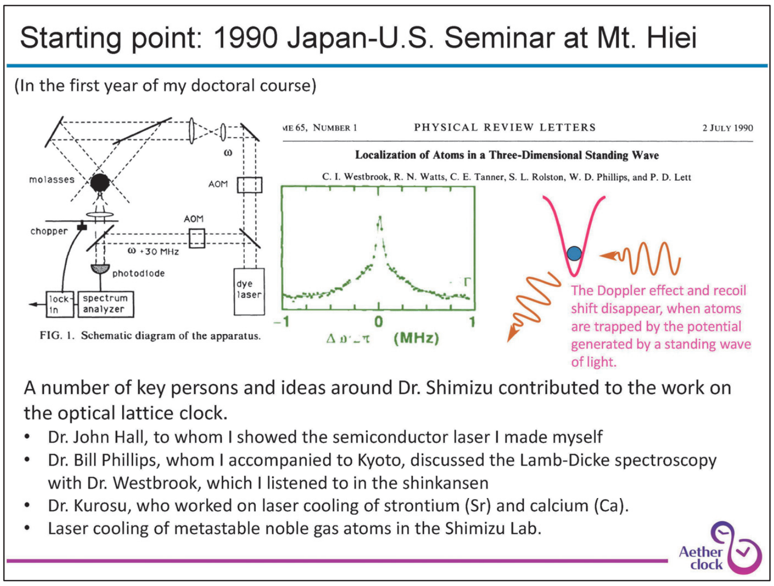


Fig. 9

〈Fig. 9〉 In 1990, Prof. Fujio Shimizu organized a Japan-US seminar at Mt. Hiei. It was when I was in the first year of a doctoral course. Prof. Shimizu said in his speech, "I did nothing," but there were many ideas and key persons that led me to the optical lattice clock around him. The Hiei seminar was the starting point of my series of research.

Dr. John Hall is an expert in laser stabilization. He often came to Shimizu laboratory, and we discussed the stabilization of semiconductor lasers.

When Dr. Bill Philips, who won the Nobel Prize for laser cooling in 1997, came to the lab, Prof. Shimizu asked me, "You should accompany him to Kyoto." In this way, I sat next to him on the bullet train listening to his discussion.

Dr. Phillips and Dr. Westbrook discussed their recent experiment that indicates atoms being trapped by the standing waves of light. The disappearance of the Doppler shift from the scattered light should be evidence. It was just when their paper was published, and they were very excitedly discussing the Lamb-Dicke effect.

Dr. Kurosu worked on laser cooling Sr (strontium) and Ca (calcium). Moreover, there were traditional experiments on laser cooling of metastable noble gas atoms in the Shimizu Lab.

All of these backgrounds were successfully combined and gave me the inspiration for the optical lattice clock.

■ When I thought of an optical lattice clock in a curiosity-driven way

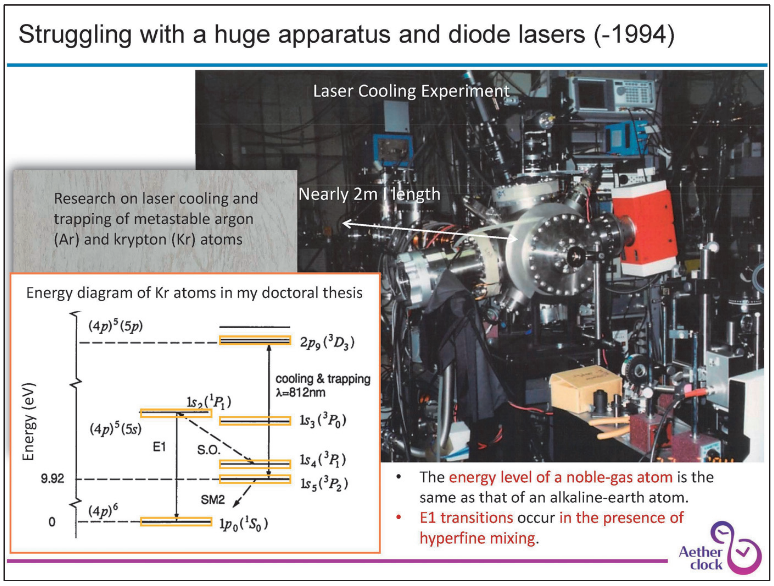


Fig. 10

〈Fig. 10〉 In my Ph.D. research, I struggled with a huge vacuum apparatus that was 2 meters long for laser-cooling krypton gas. The energy diagram of the noble gas I studied in my doctoral thesis is the same as that I now use for the optical lattice clock. Thanks to this, what I was thinking about when writing my Ph.D. thesis became exactly what I am doing now.

One of the central ideas for optical lattice clocks is to derive electric-dipole transitions by hyperfine mixing. This is also something I had already experienced while working on my Ph.D. thesis. The doctoral course study at Shimizu Lab gave me great fruits.

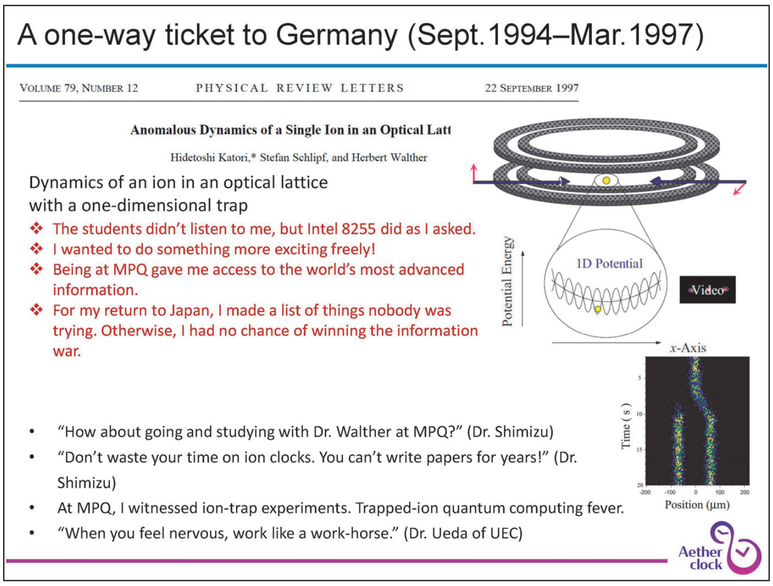


Fig. 11

〈Fig. 11〉 As Prof. Shimizu mentioned, I worked at the Max Planck Institute after finishing my Ph.D. One day he told me, "What will you do next? If you haven't thought about it, how about going to Max Planck?" I followed his advice.

When I told Prof. Shimizu that I wanted to work on an atomic clock which was among the research proposed by Prof. Walther at the Max Planck Institute, Prof. Shimizu said, "It's better not working on atomic clocks. If you start doing that, you won't be able to find a job because you won't be able to write papers for years."

If you are told not to do something, it is human nature to want to do it more. I was watching an experiment on atomic clocks using ion traps carried out in a neighboring laboratory at Max Planck. At that time, I worked on my research to observe the dynamics of an ion moving in an optical lattice.

Persuading students to proceed with experiments took much work for me as a newcomer. The most reliable guys which listened to me were electronics and computers. This was when my desire to conduct exciting research freely was at its peak.

At the Max Planck Institute, excellent seminars were held weekly by top researchers from around the world presenting their latest data. I realized that European and U.S. researchers exchange information closely and promote their research. It was easy to imagine how difficult conducting such a research style in Japan would be. I thought that the only way to compete in Japan was to do something that no one thought about in the rest of the world. This is why I devoted myself to listing "things that are not being done in the world." This led to the idea of an optical lattice clock.

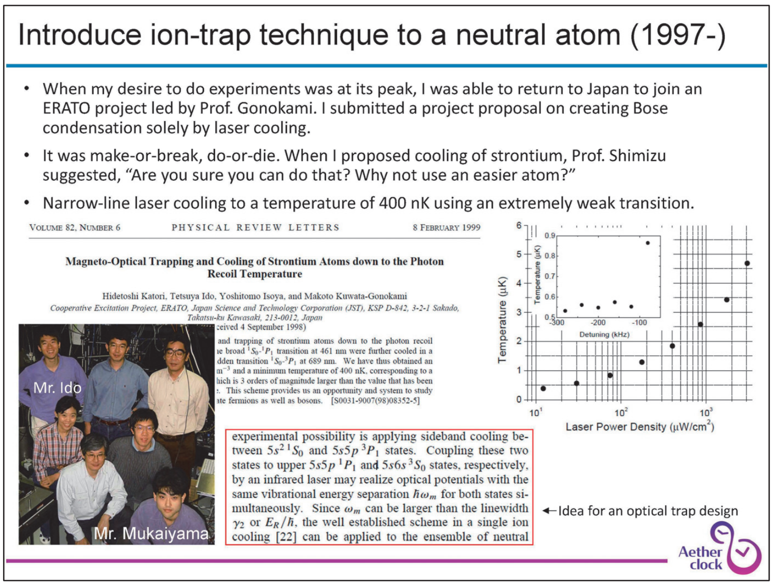


Fig. 12

〈Fig. 12〉 Around that time (the end of 1996), I was contacted by Prof. Gonokami, who told me that he was going to conduct an ERATO project and that I should propose any research that I liked, which is preferably a system that macroscopic quantum phenomena such as Bose condensation emerges.

At that time, I proposed to create Bose condensation solely by laser cooling, research that had yet to be done by anyone else in the world. This was very ambitious research at that time.

Prof. Shimizu, who usually told me to be more ambitious, was concerned and asked me, "Can you really do that?" He said, "Why don't you use a more accessible atom?" I remember the conversations and his kind concern fondly.

In this ERATO research, I worked with Dr. Ido and achieved excellent results in a brief period of a year. We could cool strontium atoms down to 400 nK, close to the energy received by the recoil of a single photon, by laser cooling using a very narrow transition formally known as a clock transition.

While working on this study, I wanted to extend the system into an experiment that would introduce the idea of an ion trap next.

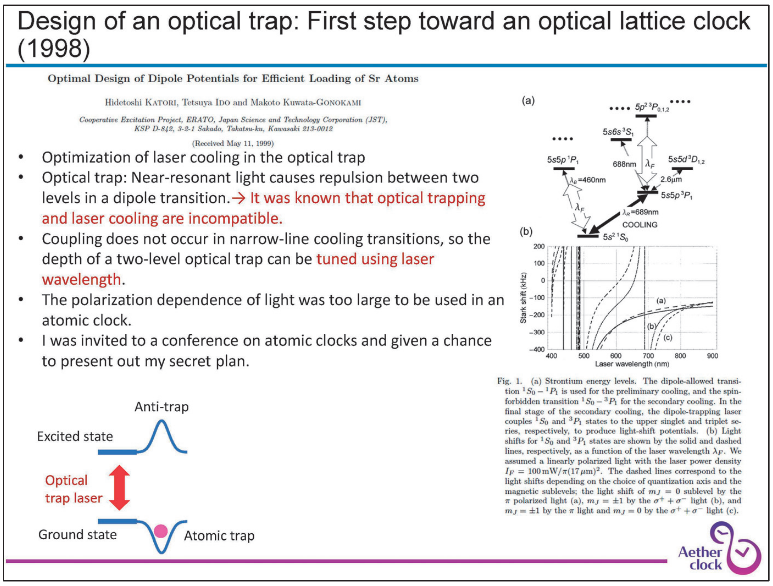


Fig. 13-1

〈Fig. 13-1〉 Cooling in an optical trap was necessary to create Bose condensation, but it was known that optical trapping and laser cooling are incompatible. As a student, I read a textbook by Steven Chu that explained laser cooling in optical traps. It was written that cooling and trapping could not coexist because the excited state is anti-trap in optical traps.

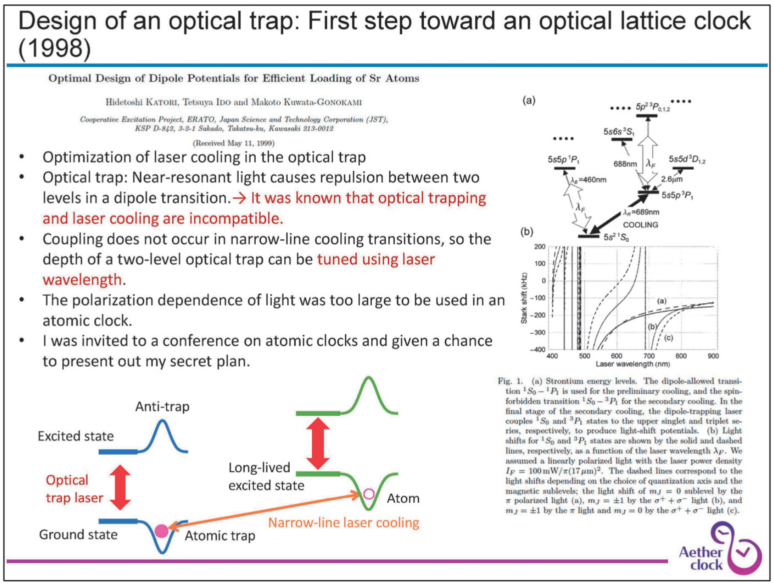


Fig. 13-2

〈Fig. 13-2〉 However, in the laser cooling with spin-forbidden transitions that we worked with, the trap-laser coupled the upper level of the cooling transition to the other upper level. Therefore, by changing the trapping laser's wavelength, we could freely tune the depth of the optical trap for the upper and lower levels used for laser cooling. We wrote a paper on the optimal design of optical traps with preliminary experimental data.

As Prof. Shimizu mentioned, there are many ideas like this. The crucial thing is how to realize the idea experimentally.

The new system looks nice for an atomic clock because it resembles an ion trap. However, we soon realized that the light polarization dependence is too significant to be used as an atomic clock. Is there a way to make this an atomic clock?

■ An atomic clock not considered so far

Fig. 14

〈Fig. 14〉 An excellent opportunity to advance my thinking came in 2001 when I was invited to an international conference on atomic clocks, held every seven years. This is a photo from the Proceedings of the conference. Many Nobel Prize winners (in late years), such as Dr. John Hall and Dr. Wineland, were invited to the conference.

When a young researcher is invited to a conference full of such authorities, he cannot compete with them regarding experimental results. So I thought I should present some wacky, youthful ideas. Conventionally, atomic clocks have been designed to eliminate electromagnetic fields as much as possible. I suggested that there should be a new design rule for atomic clocks based on well-engineered electromagnetic fields.

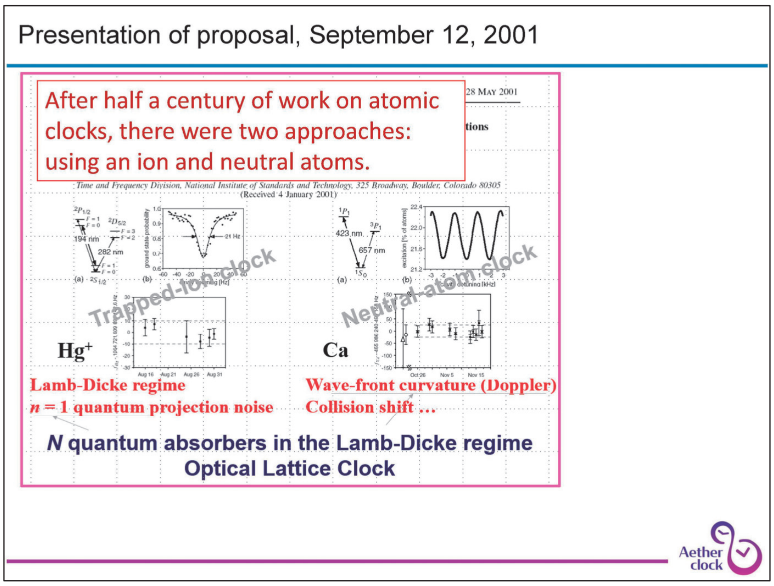


Fig. 15-1

〈Fig. 15-1〉 At that time, there were two types of atomic clocks: 1) single ion optical clocks, which observed a single ion, and 2) neutral atom optical clocks, which observed many neutral atoms in free fall. The optical lattice clock was conceived to adopt the best of both ion-based and neutral atom-based clocks.

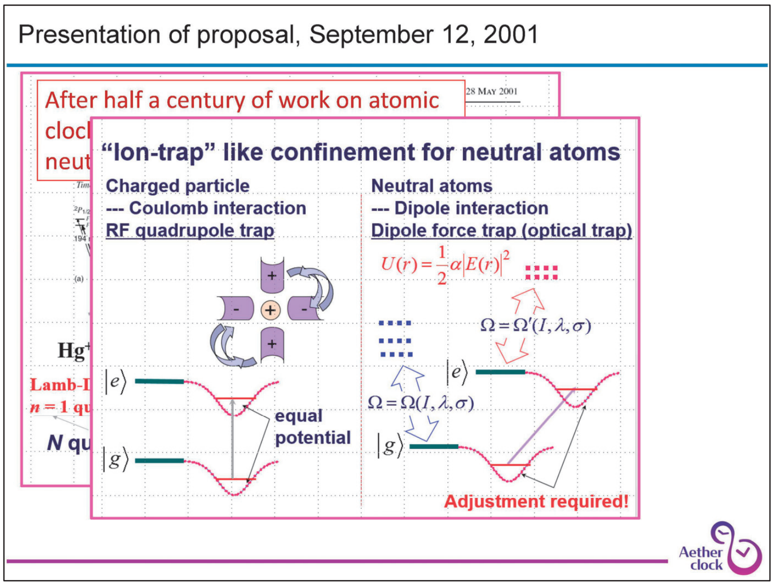


Fig. 15-2

〈Fig. 15-2〉 Ion traps provide the same trapping depth for the ground and excited states. However, such a trap does not exist for neutral atoms. The idea of tuning the trap depth of the upper and lower levels for the forbidden transitions mentioned earlier is applied here to achieve ion trap-like confinement.

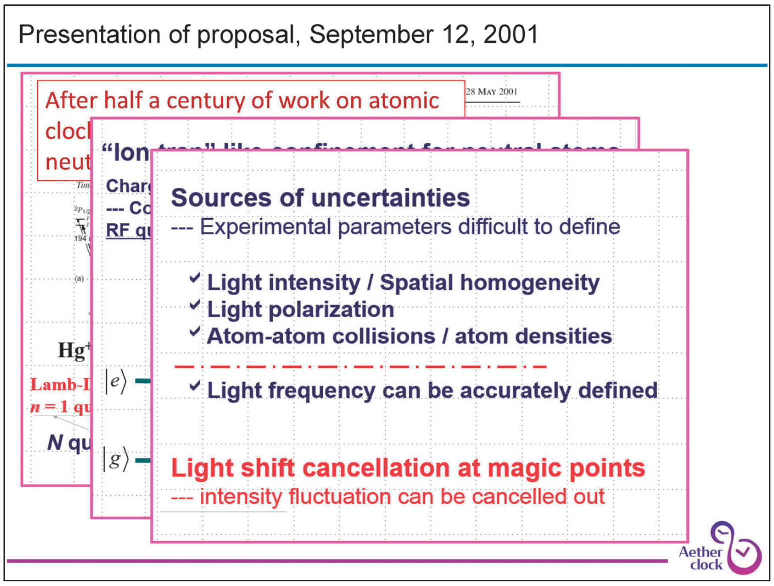


Fig. 15-3

〈Fig. 15-3〉 This is where I wrote the idea of magic wavelengths. The magic points would equalize the energy of the trap depths.

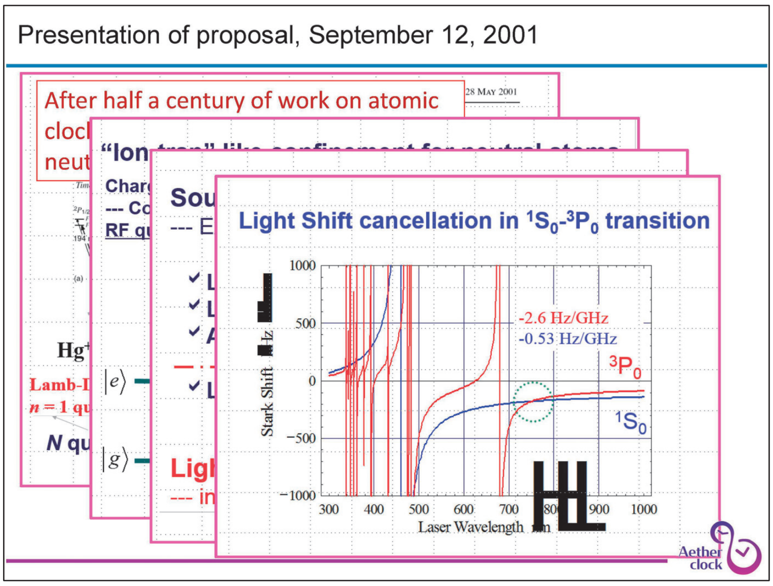


Fig. 15-4

〈Fig. 15-4〉 Using a scalar state with zero orbital angular momentum would be an ideal way to control the light shift since the polarization dependence would not come in. This is the essential idea for an optical lattice clock using a magic wavelength.

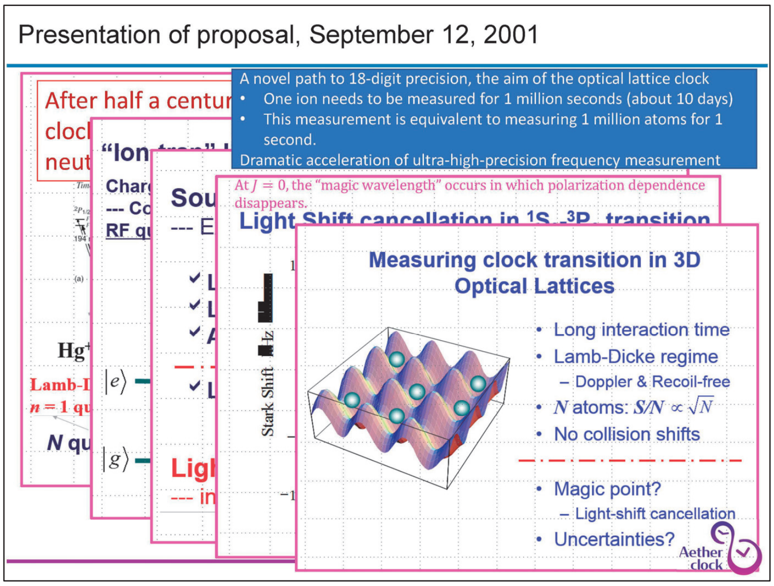


Fig. 15-5

〈Fig. 15-5〉 A scenario for the 18-digit measurement by the optical atomic clocks was to measure a single ion a million times, which would take a million seconds or 10 days. Instead, if we could measure a million atoms trapped in an optical lattice, we would reach 18-digit precision a million times faster than working on a single ion clock. The optical lattice clock attempts to achieve an overwhelmingly quick time measurement.

Fig. 16

〈Fig. 16〉 I was considering the idea of such an optical lattice clock around the end of Prof. Gonokami's ERATO project. Looking at the commemorative photo at the end of the project, everyone has a friendly smile. It was a very successful project.

Prof. Gonokami is an excellent mentor and educator: He asked me, "Is this ERATO the culmination of your research?" He says words that ignite my fighting spirit. His word motivates me to do more outstanding research than ever before.

When I was a student, Prof. Shimizu often said to me, "A researcher must be a trailblazer," which came to my mind. As a researcher, I must be ambitious and find new research sources.

■ Possible redefinition of seconds

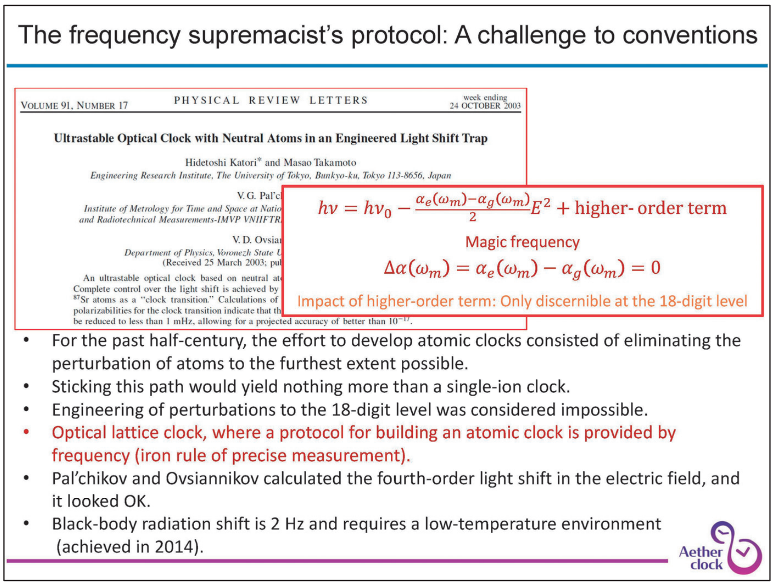


Fig. 17

〈Fig. 17〉 Afterward, I made an official proposal with an uncertainty budget for optical lattice clocks. The central concern in developing atomic clocks was eliminating the electric and magnetic fields that perturb atoms, leading to conventional singly trapped ion-based clocks. At that time, no one believed that perturbations applied to atoms could be successfully engineered at the 18-digit level.

As I mentioned at the beginning of this talk, the iron rule of precision measurement was to replace measurement with frequency. If one follows this iron rule and gives the perturbation specified by a frequency, there would be a chance, which led to the idea of a “magic frequency or wavelength.” There were higher-order effects that the magic frequency protocol could not eliminate. The theory collaborators calculated that higher-order effects would appear in the 18th digit. We, therefore, propose an optical lattice clock aiming at 18-digit accuracy.

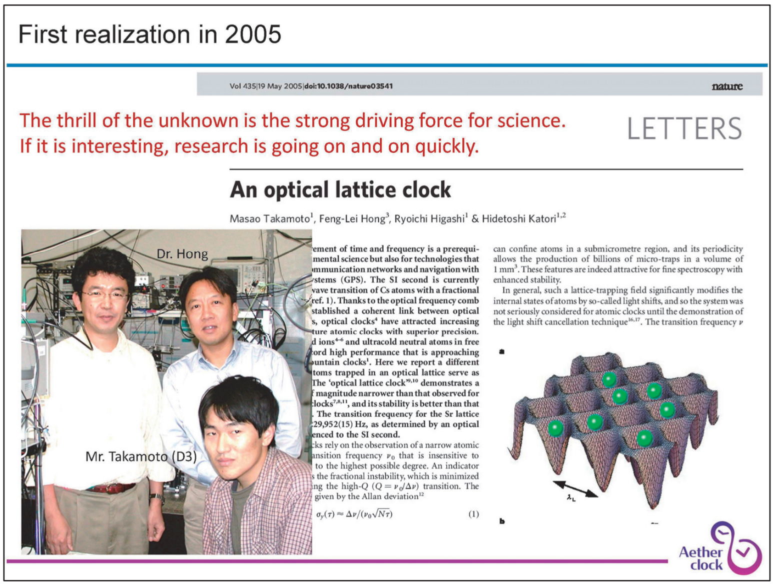


Fig. 18

〈Fig. 18〉 At that time, Dr. Takamoto was in a doctoral course. He played a significant role in realizing an optical lattice clock for the first time. Dr. Hong, who was at AIST, brought the measurement equipment to the University of Tokyo to measure the frequency of the optical lattice clock. We thus demonstrated the first optical lattice clock.

The driving force for science is the excitement for new physics. This kind of exciting research continues, even if it is difficult.

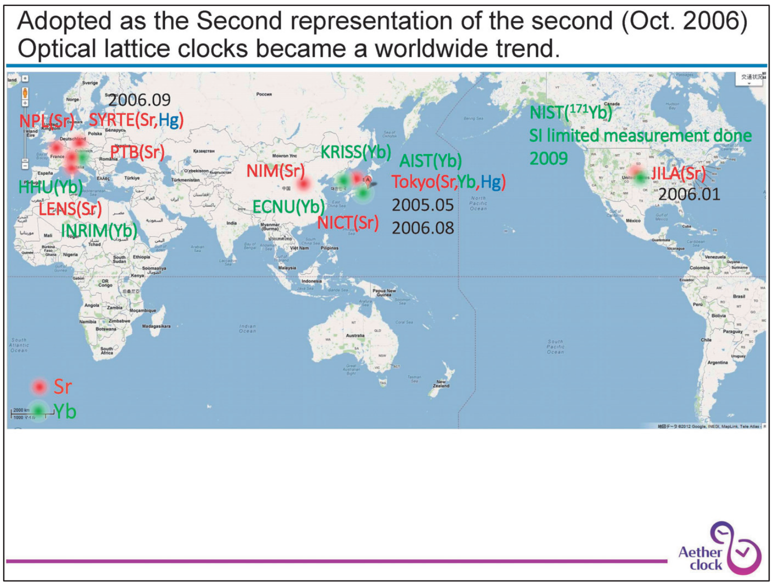


Fig. 19-1

〈Fig. 19-1〉 We thought we were the only ones working on optical lattice clocks, but six months after we realized ours, a group in the U.S. and later a group in France also demonstrated theirs. We were relieved that we were the first to demonstrate this clock. Once the idea is proposed and the research starts, researchers pursue the same direction.

Since then, research on optical lattice clocks has spread worldwide. Today, nearly 30 groups are working on this research.

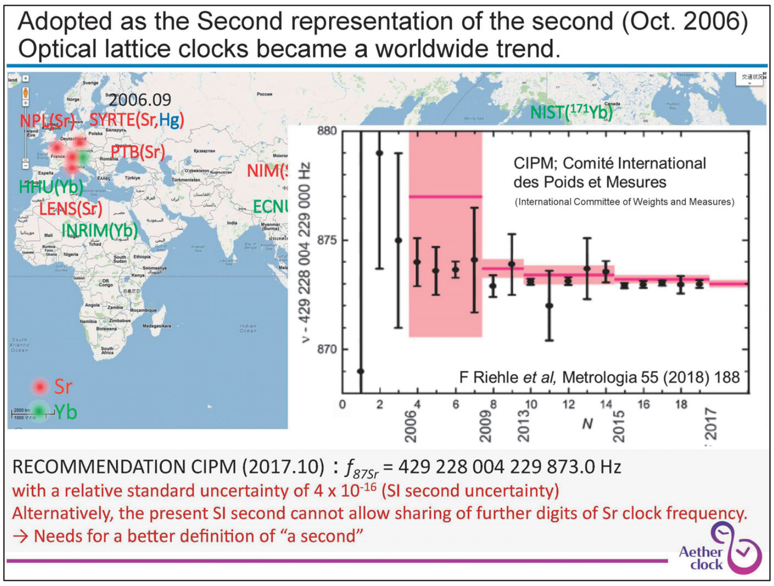


Fig. 19-2

〈Fig. 19-2〉 With the entry of many research groups, the race became more competitive to see how accurately the transition frequency of strontium could be measured. As a result, the measurement uncertainty became smaller over these 10 years, up to 16 digits, which is determined by the uncertainty in the definition of one second. In other words, due to the definition of the SI second by the cesium atom, we cannot share any more frequency information, which motivates the redefinition of the second.

■ Making optical lattice clocks more compact

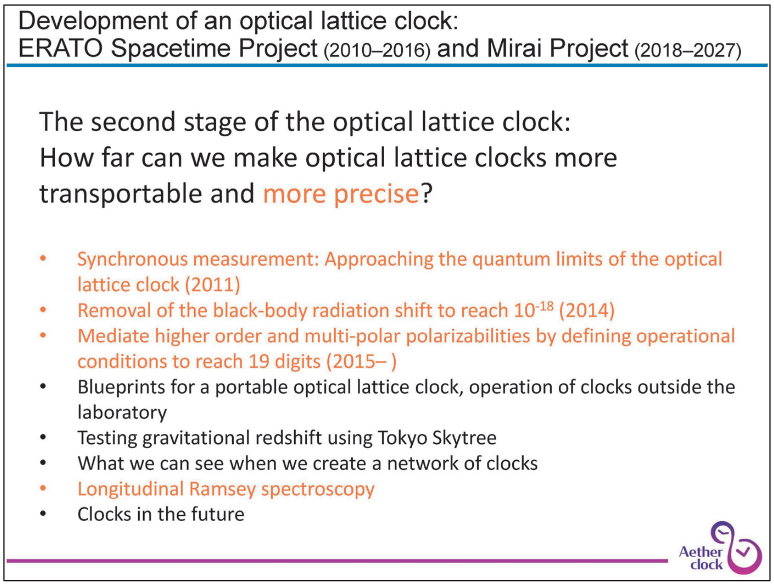


Fig. 20

〈Fig. 20〉 In the second half of this presentation, I will discuss the development of optical lattice clocks in my ERATO Spacetime Project, which began in 2010, and the Mirai Project in 2018.

In the second stage of the optical lattice clock, we are more interested in their miniaturization, portability, and precision. The orange-colored items correspond to the precision, whose target is 19 digits. The critical concepts for achieving high precision have been developed, and we are now testing them. In the last part of the presentation, I will focus on promoting miniaturization and social implementation of our clocks.

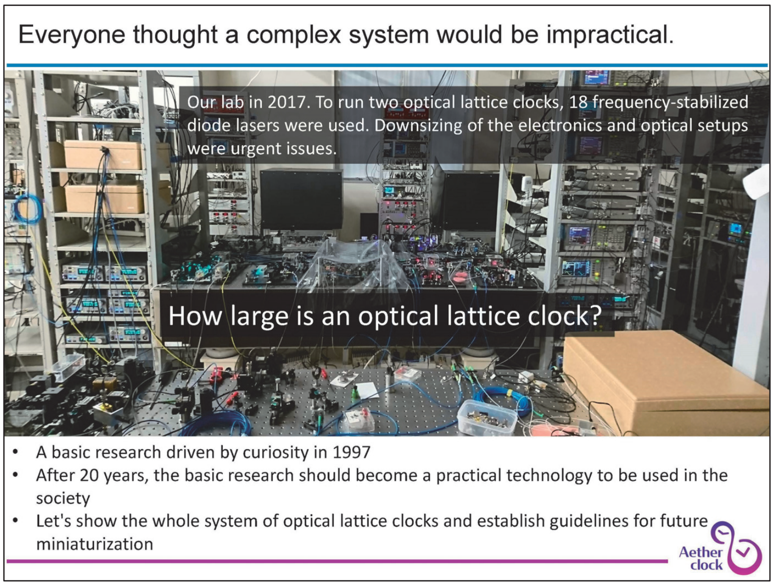


Fig. 21

〈Fig. 21〉 We started basic research in 1997 and added more equipment and ideas. When we compared two clocks with an uncertainty of 10^{-18}, the experimental apparatus occupied the whole laboratory of 40 m². After 20 years of basic research, I felt strongly that we should aim for the social implementation of quantum technology as we had promised at the beginning of the research.

First, I thought we should show the overall picture of the device to think about guidelines for future miniaturization. If we keep adding pieces of equipment, the system will become more and more complicated and eventually fail, so it will not be sustainable research. To advance research, it is necessary to black-box the technology as much as possible.

The device in this photo looks like an old-fashioned computer in the age of vacuum tubes. I wanted to make the experiment more modern and confront it with technology that could withstand practical use.

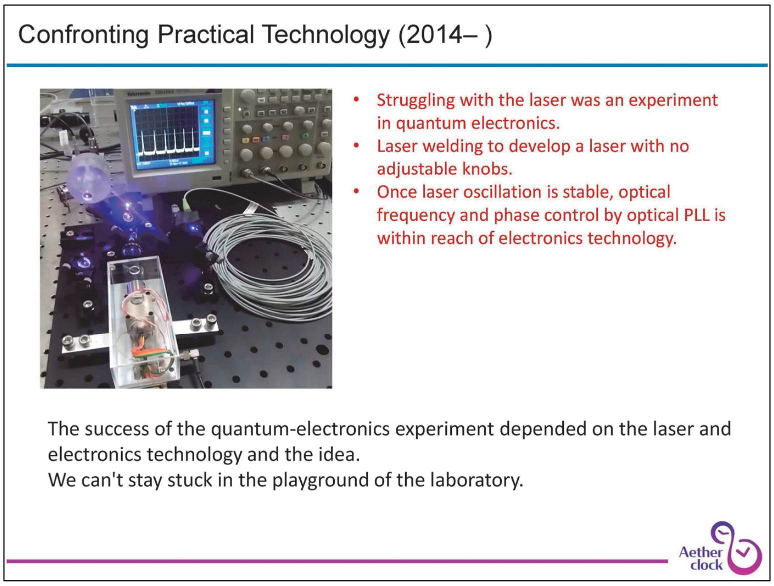


Fig. 22

〈Fig. 22〉 In the past, in precision laser spectroscopy experiments, researchers have fought with the lasers all day, as was the case since my student days 30 years ago. The experiment would not be proceeded or be slowed down if one is tired from struggling with the lasers. Thus, we started making a laser that requires no adjustment.

In the photo's foreground, a laser oscillates at a single frequency, whose oscillation is not disturbed even if you tap the optical table with a screwdriver. We started to develop an adjustment-free laser by using laser welding to fix the part that required fine-tuning.

Then, with the ease of making a phase-locked loop (PLL) for a crystal oscillator, we can make an optical PLL for the laser oscillator and control the frequency and phase of the light at will. I began to envision experiments in which the frequency of light would be exploited as easily as conventional electronics.

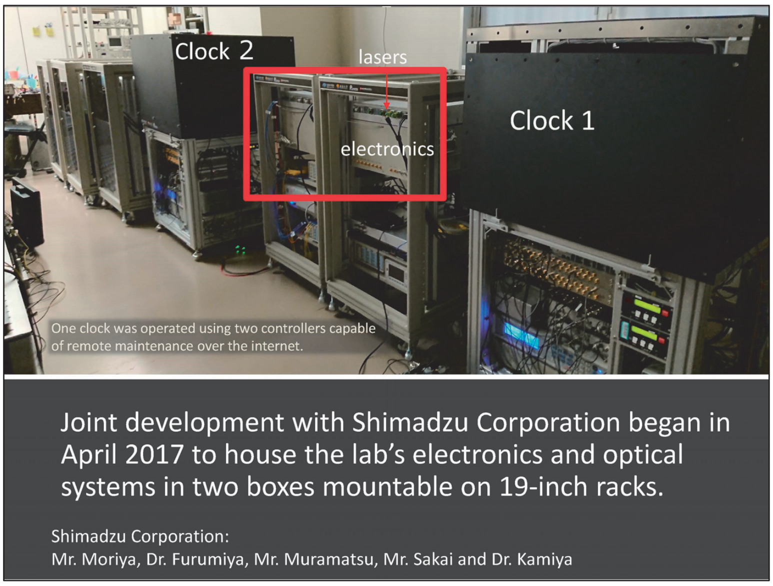


Fig. 23

〈Fig. 23〉 At that time, I had a chance to collaborate with Shimadzu Corporation. With the Shimadzu group, we put our electronics spread all over the lab into the two boxes framed in red. Optical systems such as lasers were placed on top of these boxes. The black box on the right side is the physics package of the optical lattice clock. This small apparatus realized the 18-digit-accurate clock.

■ Verifying Relativity at Tokyo Skytree

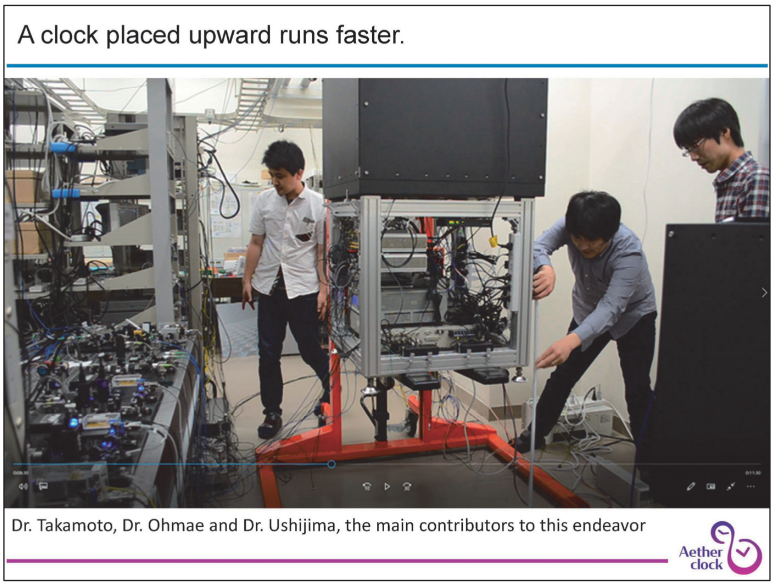


Fig. 24

〈Fig. 24〉 Now that the clocks are made smaller, we can test relativity by changing the height of the clocks. What would happen if we lifted one of the clocks by 1 meter? According to relativity, an upper clock ticks faster. We experimented with the cooperation of Dr. Takamoto, Dr. Ohmae, and Dr. Ushijima.

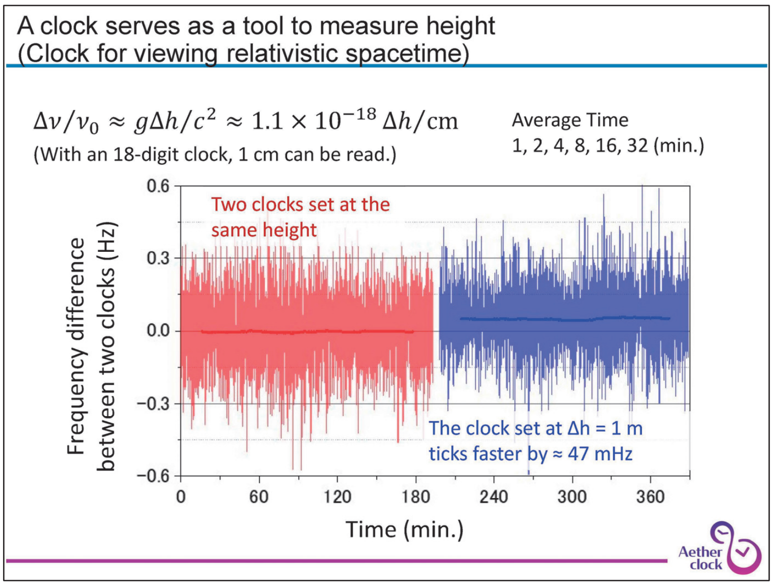


Fig. 25

〈Fig. 25〉 We monitor the beat frequency for the clocks placed at the same height and those with a 1-meter height difference. While the raw data is too noisy to tell, the solid red and blue lines are averaged for 30 minutes. Clocks at the same height agree up to the 18th digit precision, and the frequency difference is zero, but a frequency difference of about 40 mHz is observed for the clocks with a 1-meter height difference.

As Prof. Gonokami mentioned, the 18th digit of the clock will tick faster than the other for each centimeter on the ground. Then, a clock that reads the 18th digit would read the height difference of 1 cm on the ground. The clock, which used to be a tool for sharing time, becomes a sensor for exploring spacetime.

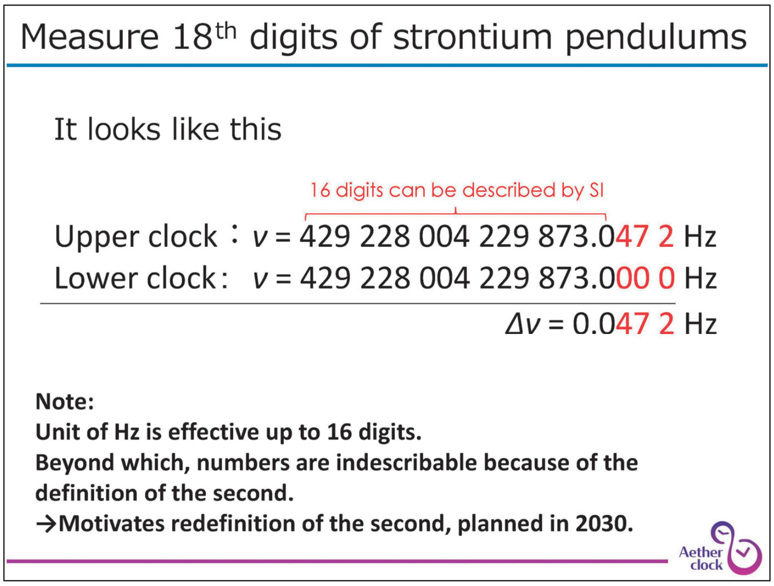


Fig. 26

〈Fig. 26〉 This is an image of measurement. 16 digits numbers can be described by the definition of one second. However, there is no way to describe the 17th and 18th digit numbers. This clock experiment is an example of new applications hidden in numbers that cannot be described by the current definition of a second. With this digit, a height difference of 1 cm can be read.

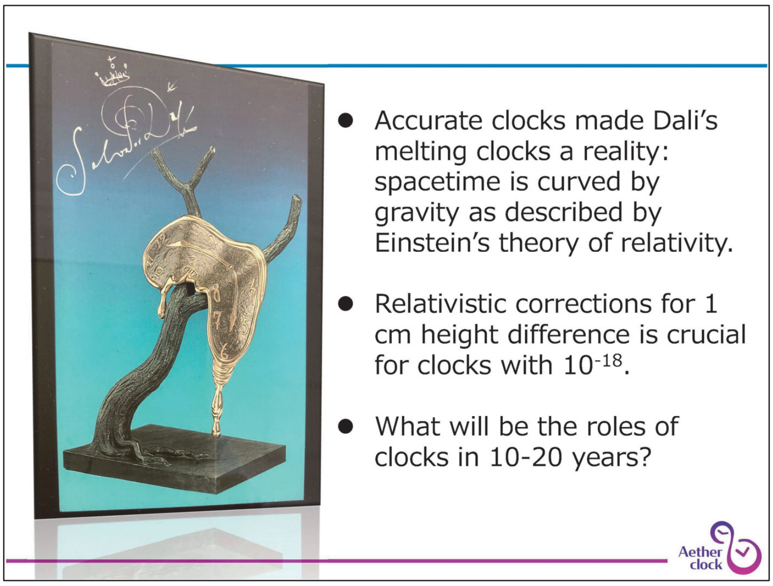


Fig. 27

〈Fig. 27〉 Such experiments remind me of Dali's clock I saw in junior high school. Inspired by Einstein's relativity theory, Dali painted melting clocks like Camembert cheese entitled "persistence of memory" in 1931. When I first saw this painting, I had no idea what it indicated. Now this clock has become a reality in the laboratory.

What will the role of clocks be in the next 10 or 20 years when we see curved space-time by gravity on a personal scale? The time will come when relativity will be used in the real world. As the first demonstration outside the laboratory, we conducted a field test of our clocks at Tokyo Skytree.

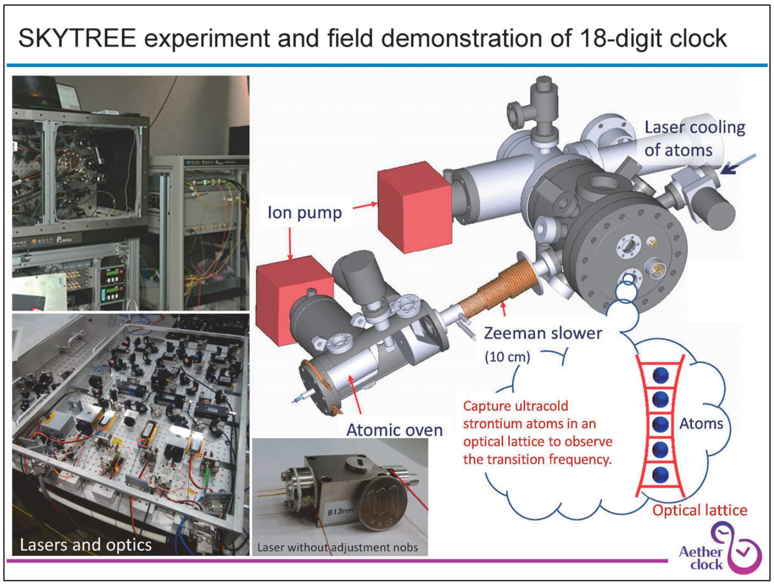


Fig. 28

〈Fig. 28〉 This is the device we used in the Skytree experiment. We set optics and the adjustment-free lasers I mentioned earlier on a breadboard. The main body of the optical lattice clock is contained in a magnetic shield of a cube about 60 cm on each side. In the vacuum apparatus on the right side of the figure, atoms are trapped in the optical lattice, and the transition frequencies of the atoms are measured.

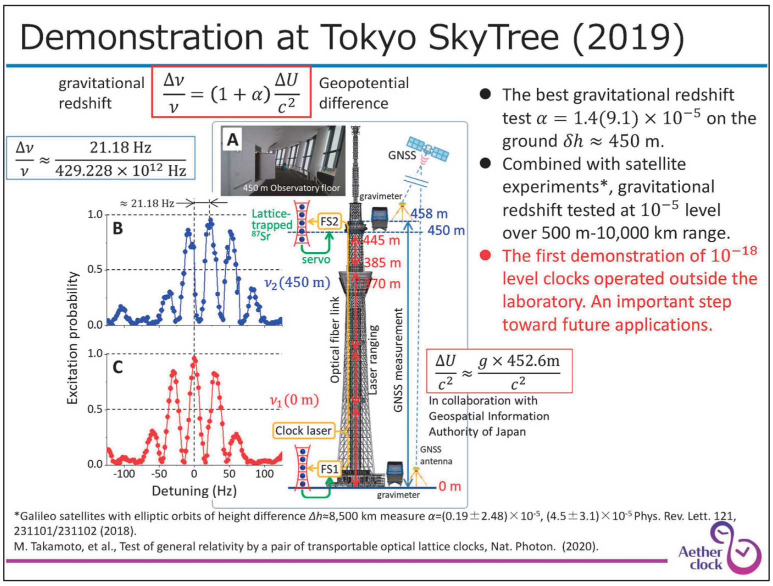


Fig. 29

〈Fig. 29〉 We installed the first clock in a meeting room at the ground level of the Tokyo Skytree and were allowed to set the second clock in a small room in the observation deck at 450 m. The height difference of 450 m gives clocks the gravitational redshift of 21 Hz.

The critical part of this experiment is to precisely verify the agreement between the gravitational redshift of the clocks and the actual gravitational potential difference. For this purpose, we asked the GSI (Geospatial Information Authority of Japan) to perform leveling, laser ranging, and GNSS ranging to measure the height difference.

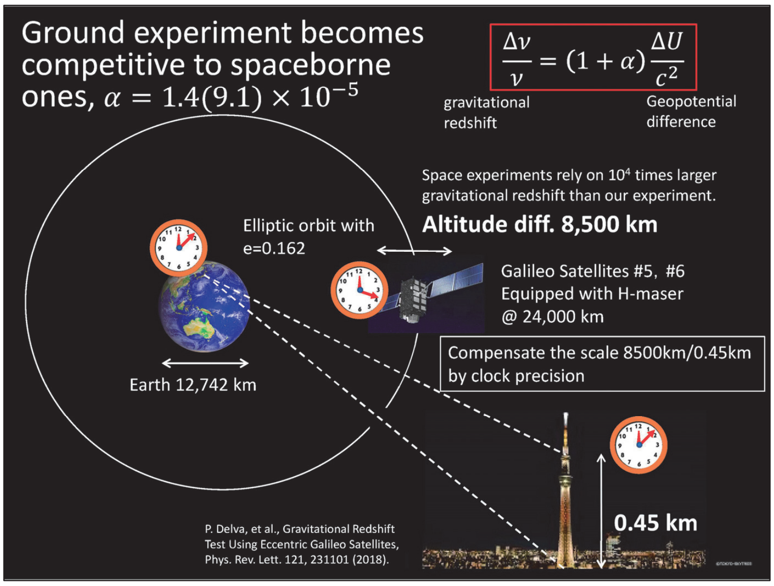


Fig. 30

〈Fig. 30〉 The results showed that the gravitational redshift and gravitational potential difference agreed with an uncertainty of 10^{-5}.

This kind of experiment was conventionally conducted using satellites and rockets to give a height difference of 10,000 km. However, we showed it is possible to conduct investigations of similar uncertainty with an altitude difference of only 450 m. This experiment also demonstrated that relativistic effects could be used as a new sensing tool on the ground using high-precision clocks.

■ Clocks for measuring spacetime

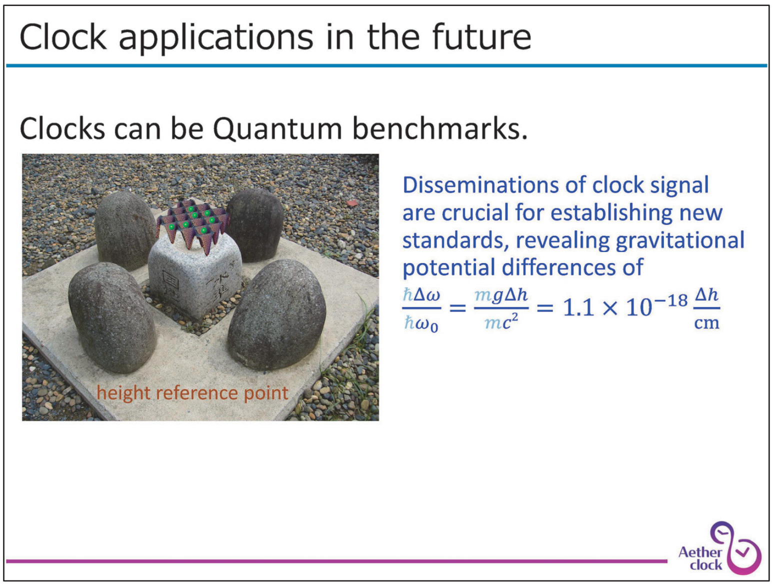


Fig. 31

〈Fig. 31〉 Clocks can be used for relativistic sensing. In particular, optical lattice clocks are suitable for geodetic applications because they can measure the frequency in a short time thanks to a large number of atoms. One day in the future, optical lattice clocks will replace benchmarks.

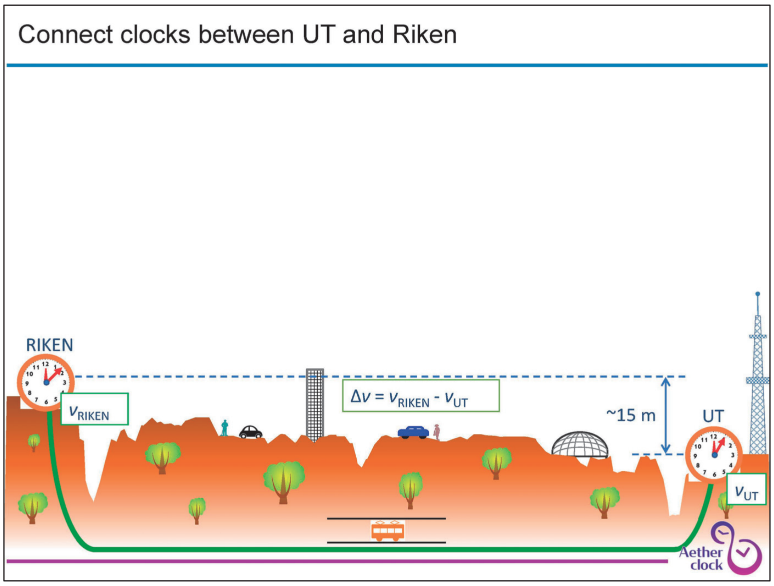


Fig. 32-1

〈Fig. 32-1〉 This is an experiment comparing 18-digit clocks. We prepared optical lattice clocks in the University of Tokyo and RIKEN labs. We connected them with an optical fiber to compare the frequency difference in their clock signals.

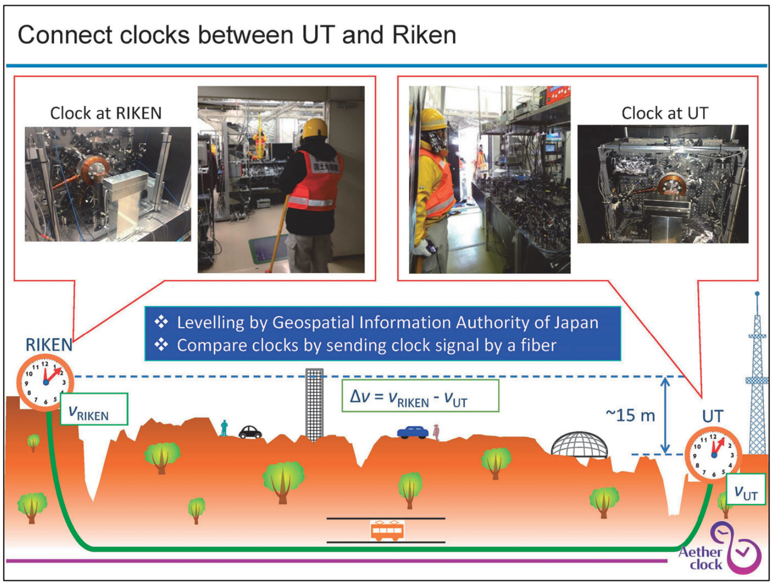


Fig. 32-2

〈Fig. 32-2〉 Again, the GSI measured the difference in elevation by level surveying while we measured the difference in clock frequencies.

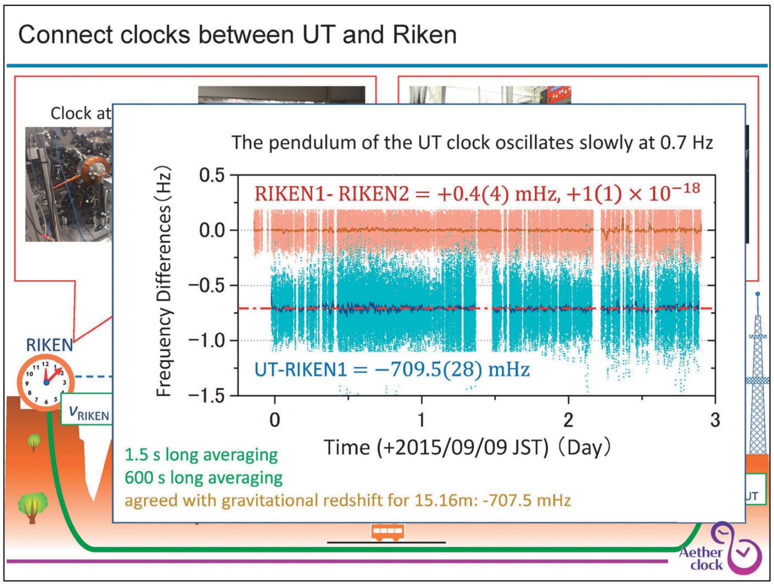


Fig. 32-3

〈Fig. 32-3〉 At RIKEN, the two clocks on the same optical table agreed up to 18 digits (orange in the plot), while the clock at the University of Tokyo oscillates slowly by 700 mHz (light blue in the plot). This suggests that the university lab is located 15 m lower in elevation than the RIKEN lab, consistent with the leveling results. This is a demonstration, but the time will come when this will be used in the real world.

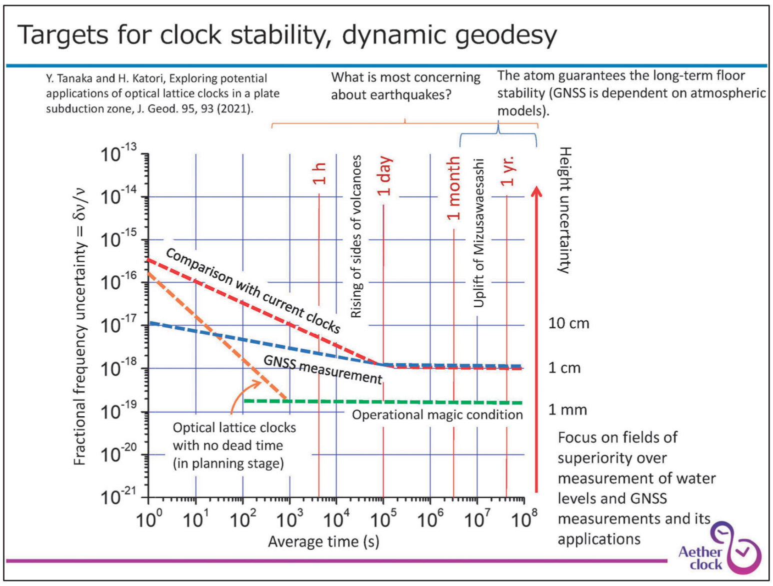


Fig. 33

〈Fig. 33〉 We are considering targets for such geodetic applications. In the previous experiment, a few centimeters of height difference could be read in a few hours. With GNSS surveying, a centimeter can be determined in about a day. However, it is difficult to determine absolute values due to atmospheric pressure fluctuations and geoid models.

The prime advantage of using an optical lattice clock is that the atoms guarantee long-term stability. Moreover, if the clock has high stability, it is perfect. We are developing a "zero-dead-time optical lattice clock" to achieve higher stability. We want to build a clock that reads 19 digits quickly, say 1000 seconds, or mm in height difference. If we add the protocol of operational magic condition to the optical lattice clock, we will be ready to read 10^{-19}. With these two ideas, I would like to proceed with future experiments.

Once we have a target for clock development in this way, the next step is to look for applications using it. What kind of target should we have for predicting volcanic eruptions or earthquakes? We started discussing such things with geophysicists.

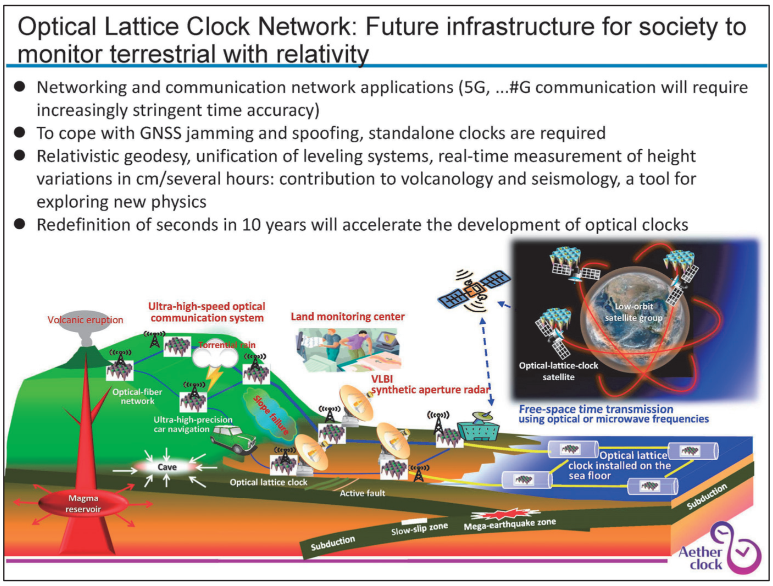


Fig. 34

〈Fig. 34〉 When optical lattice clocks are miniaturized and networked, we can tell what is going on underground by the signals of the clocks. Ultra-high-performance atomic clocks will be the tool to see the earth's softness. Once we have a robust time base of atomic clocks, we will find a wide range of applications, just as GPS did.

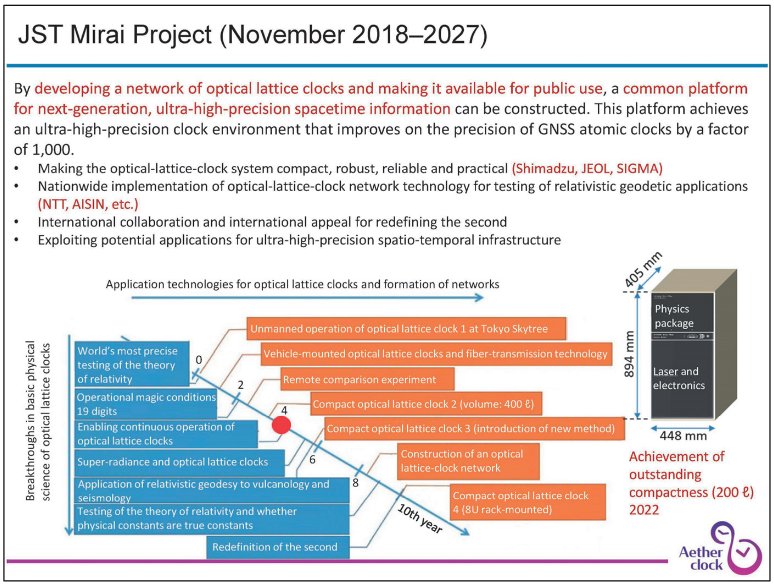


Fig. 35

〈Fig. 35〉 We are now in the middle of the Mirai Project, which aims to implement optical lattice clocks in society. We are working with companies including Shimadzu, JEOL, Sigma Koki, and NTT to develop real-world technologies and applications.

Four years after the project started, the volume of the optical lattice clock became 200 liters, which is about the size of a small refrigerator. Now, if we can improve the durability of the clock, we will be close to the commercialization of the clock.

■ New developments in optical lattice clocks

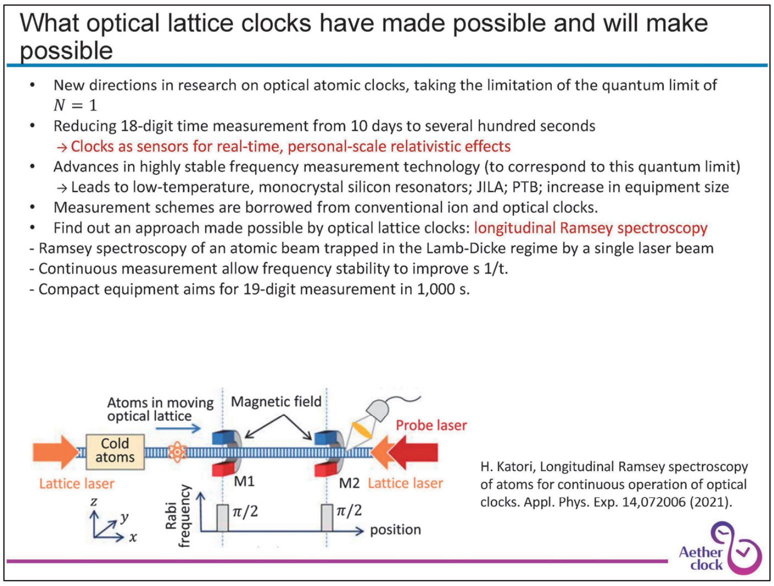


Fig. 36

〈Fig. 36〉 I will review the past and summarize what optical lattice clocks have made possible and will make possible in the future. The achievement of optical lattice clocks is that they have given a new guideline for designing atomic clocks. The quantum limit associated with a single atom had previously limited atomic clocks. However, we successfully break this limit. As a result, 18-digit-accurate time measurements, which would have taken 10 days, can be conducted in hours.

We are now in an era in which we can see relativistic effects on a personal scale by observing height differences of 1 cm in hundreds of seconds or hours. We will eventually be able to take advantage of these effects.

As a result of the realization of the highly stable optical lattice clocks, relevant laser techniques have made significant progress in the past 10 years or so. Although optical lattice clocks have worked well, I regret that we still follow the traditional technique developed for ion-based optical clocks at the fundamental level.

I want to develop a new measurement technique that fully utilizes an optical lattice clock. I will not go into details, but last year I published a paper on a new design named longitudinal Ramsey spectroscopy. With this method, we aim to develop a new kind of optical lattice clock that measures the 19th decimal place in 1000 seconds.

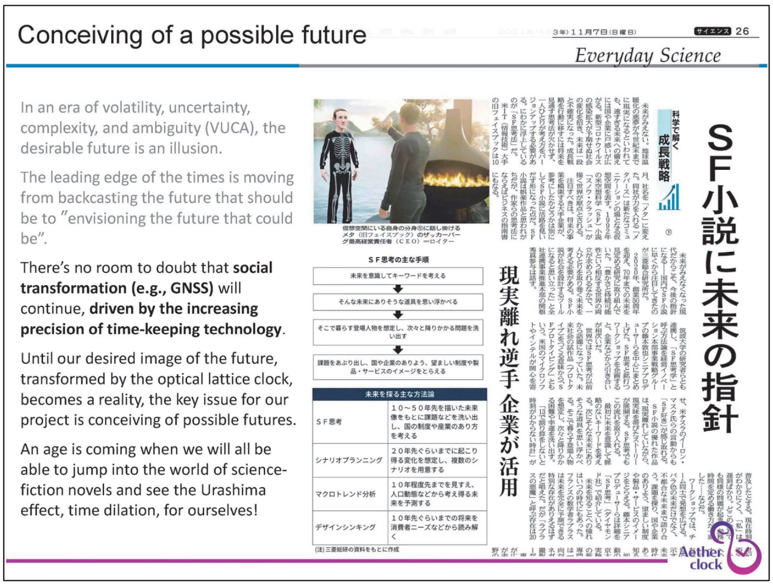


Fig. 37

〈Fig. 37〉 The advances in time measurement technology I have been discussing are endless. These advances in time measurement technology have changed human society in the past. This is exactly what the current world of GPS navigation is all about. As a result, we are on the verge of a world of automated driving, which was once thought to be a distant future.

It is time to start envisioning the future in a relativistic spacetime as seen by optical lattice clocks. We are about to enter a world that would be science fiction, where time is delayed by moving clocks, and the Urashima effect can be seen.

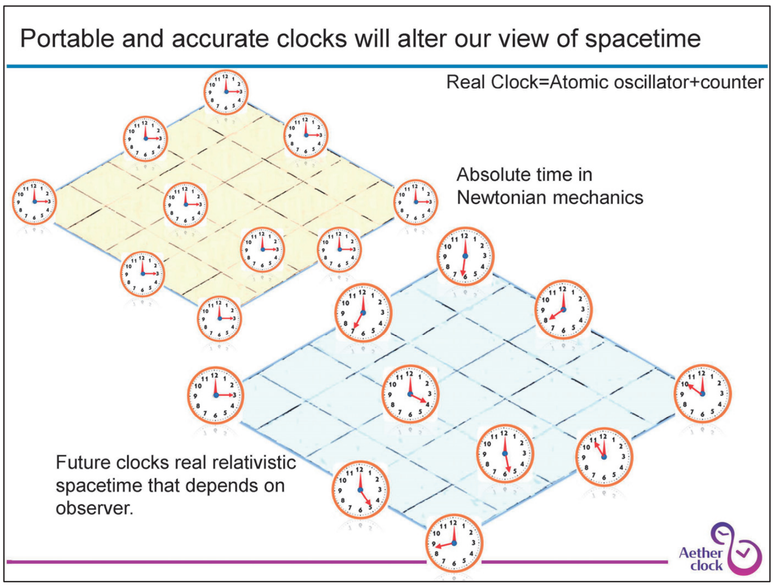


Fig. 38

〈Fig. 38〉 From the viewpoint of the functional value of a clock, the accuracy of a wristwatch is okay for us in our daily lives. Still, our consciousness is governed by Newtonian absolute time. Because of this, we feel unsettled when all clocks are not synchronized to a high degree of precision.

However, as more and more high-precision clocks are developed, one will believe that clocks are not devices to be synchronized. The role of clocks in the future will be to give a relative relationship between one clock and the others, with a time dilation effect when the clock moves or gravitational potential varies.

■ Thoughts open up a future beyond imagination

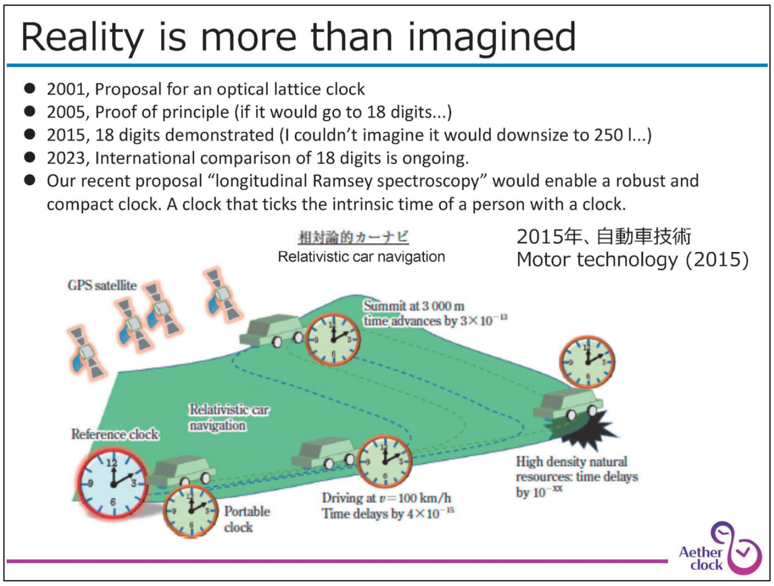


Fig. 39

〈Fig. 39〉 Looking back on my research, the future has always been beyond my imagination. Persistent thinking about research has always paved the way for the future.

When I proposed the optical lattice clock in 2001, I thought that although I had proposed it, it would be challenging to demonstrate it.

In 2005, we succeeded the proof-of-principle demonstration. A newspaper reporter asked me, "When will you reach 18 digits?" I said, "About 10 years," as there were too many issues to be solved before it. In 2015, when we were able to demonstrate the 18-digit clocks, I was asked, "How big is the clock?" and I was at a loss for a response, but after five years, we had the 200L device, as I mentioned earlier.

Furthermore, using longitudinal Ramsey spectroscopy, we can make a small clock to measure height differences in mm.

For example, if you put a clock on a car, the clock will be delayed as the car moves. The time may come when you will be fined for speeding because of the delay of your clock. You can then go up a mountain to advance your clock.

In 2015, I wrote an essay for an automotive magazine, which may be realized next. In this way, the role of the small optical lattice clock would be to count the proper time of the clock holder.

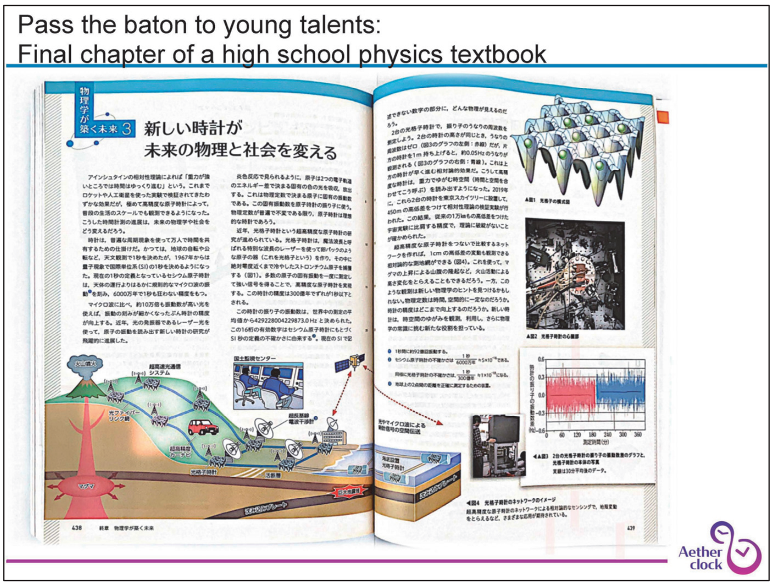


Fig. 40

〈Fig. 40〉 Last year, I was asked to write an article for the final chapter of a high school physics textbook. If we implement the network of optical lattice clocks that I talked about today, we may be able to see crustal deformation or gain new insights into physics that have not been discovered before.

If high school students know that relativity is something they can see daily, they will find real applications when they become university students or businesspeople. I am now entering a generation to pass the baton to young talents.

■ Envisioning the future driven by technological seeds

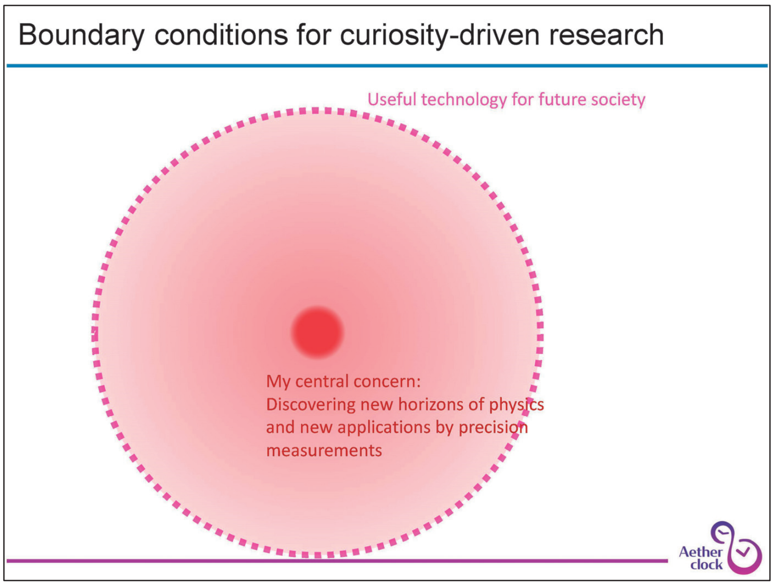


Fig. 41-1

〈Fig. 41-1〉 I would like to reflect on how my research has progressed.

My main interest has been "to investigate precision measurement." I have continued my research with the hope of exploring new horizons of physics by improving measurement precision and exploring new applications. And finally, I wanted to make it a useful technology.

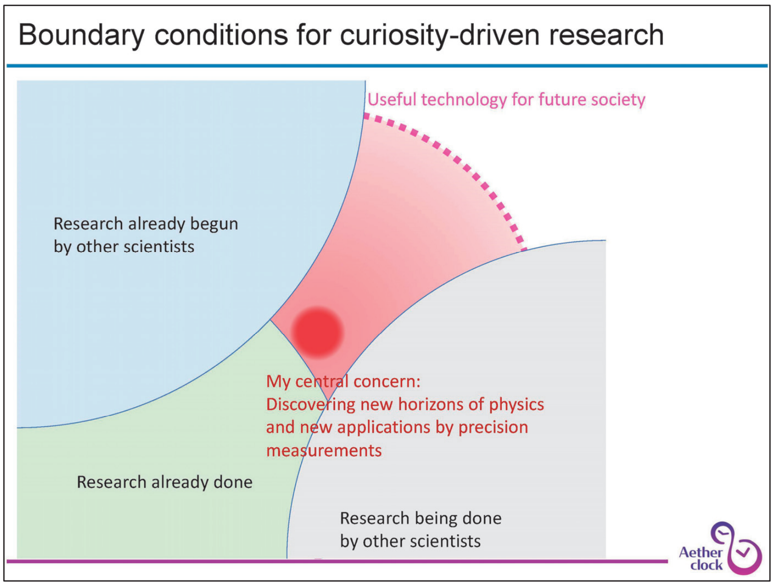


Fig. 41-2

〈Fig. 41-2〉 There are possibilities in all directions. However, there is no need to study what has already been studied or what other researchers are working on. Furthermore, it is not necessary to do what other researchers are thinking about to start. In this way, the direction of my research becomes more and more focused.

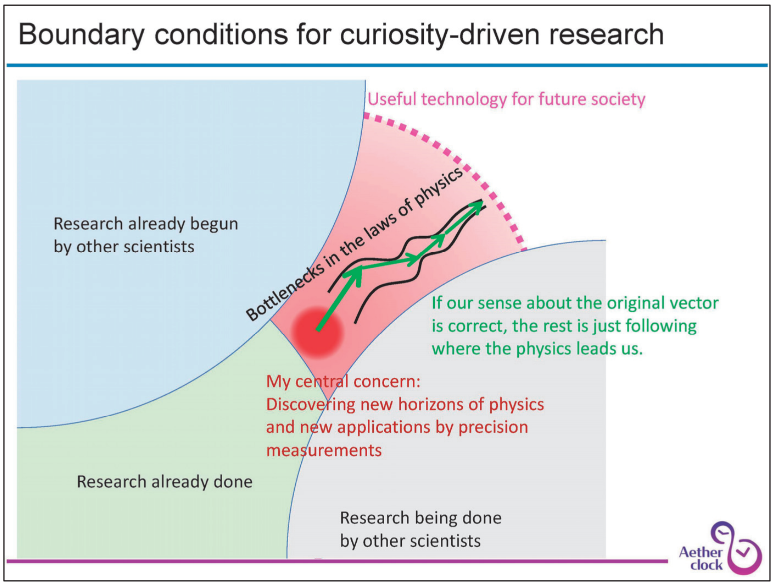


Fig. 41-3

〈Fig. 42-3〉 Once the initial research direction was correct, the rest of this series of studies was guided by the laws of physics. First, we come up with the initial idea, we conduct an experiment, and when a problem arises, we happily devise a protocol to circumvent the problem. The repetition of this process has brought us to this point.

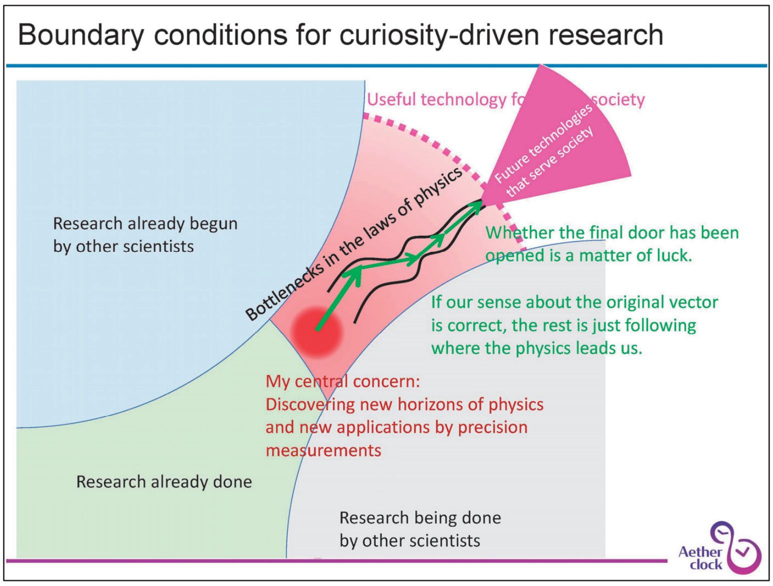


Fig. 41-4

〈Fig. 41-4〉 Finally, whether the door to future technology is open or not will be up to luck and the progress of research, which I look forward to.

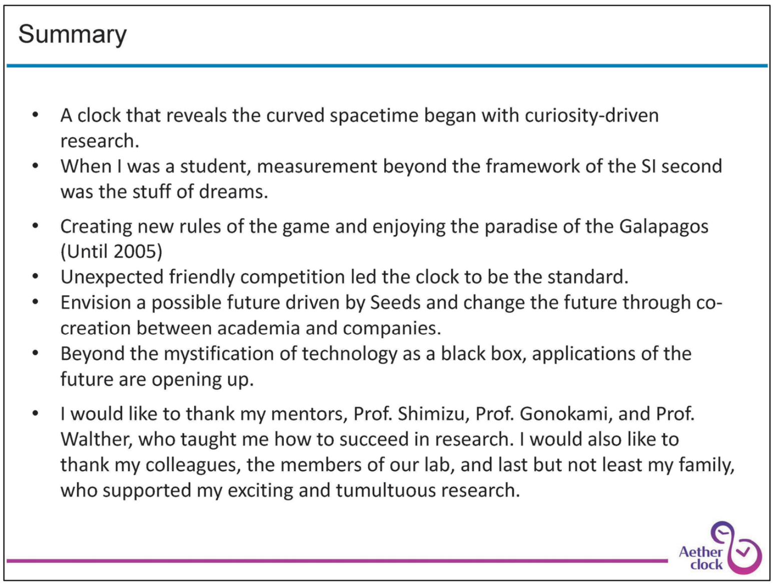


Fig. 42

〈Fig. 42〉 This has been a long time coming, but here is the last slide.

My research on clocks that reveal curved space-time started in a curiosity-driven way.

As a student, I never dreamed of conducting measurements beyond the reach of SI seconds.

We created a new set of rules to play a new game of atomic clocks, such as magic wavelength-based optical lattice clocks, a research paradise for us to enjoy.

Contrary to my expectations, many researchers entered this non-competitive research paradise, and thanks to the friendly competition among researchers, a roadmap that led to future standards was established.

I want to envision a future driven by the technological seeds we have developed. We now collaborate with industry partners to implement our research results in our society.

For this purpose, the first step is to pack the technology into a black box. Once a convenient black box like the iPhone has been developed, people gather and conceive endless applications. I look forward to optical lattice clocks becoming a core technology for the future society.

I want to thank Prof. Shimizu, Prof. Gonokami, and Prof. Walther, who taught me how to proceed with research. I would like to express my sincere gratitude to my colleagues who have supported very exciting and joyful research over the past 20 years,

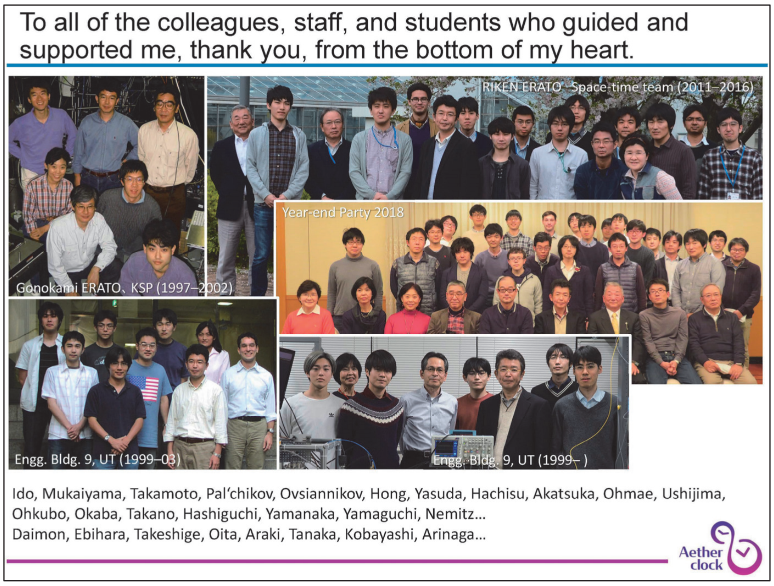


Fig. 43

〈Fig. 43〉 Finally, I would like to end with pictures of those who have shared our excitement about the research. Thank you very much for your kind attention.

Note: Affiliation, position, and profile content were current at the time of the award ceremony.

*1: Prof. Fujio Shimizu, Former Professor, Institute for Laser Science Research Center, The University of Electro-Communications

*2: Prof. Makoto Gonokami, President, RIKEN

*3: Mr. Seiji Kuraishi, Chairman and Director, Honda Motor Co., Ltd.

*4: Dr. Tetsuya Ido, Director, Space-Standards Laboratory, Radio Research Institute, National Institute of Information and Communications Technology

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