Optical lattice clocks to see curved spacetime

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Spacetime Engineering Team, RIKEN Advanced Photonics
JST-Mirai Program (2018.11-2028.3)

Optical lattice clocks are becoming sensors of proper time in curved spacetime

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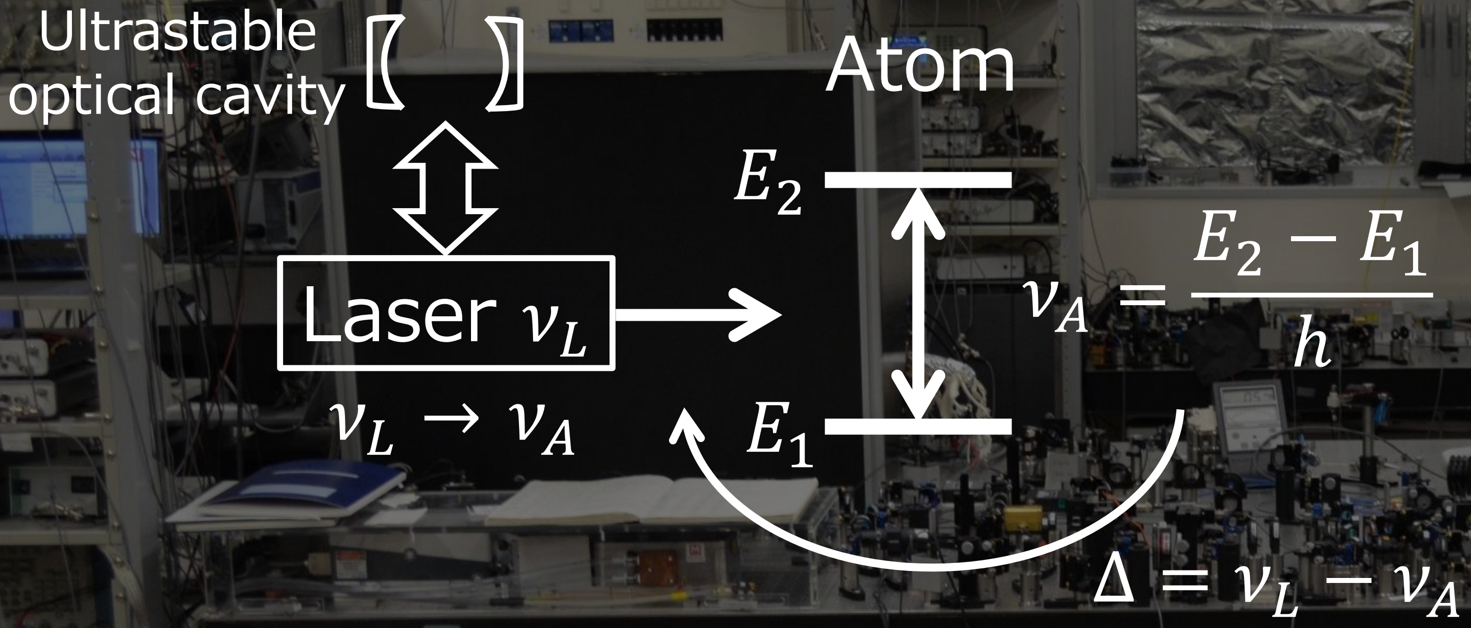
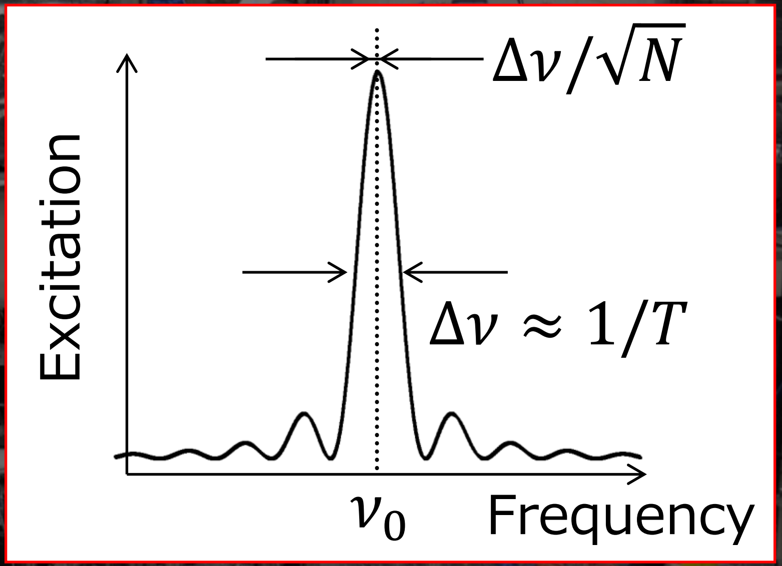
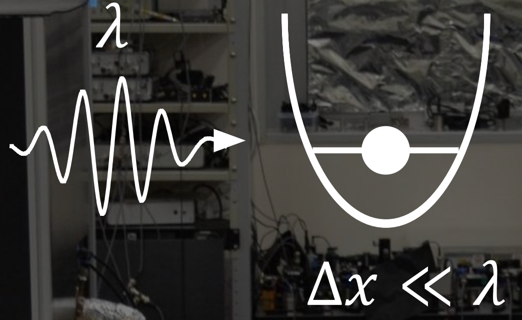


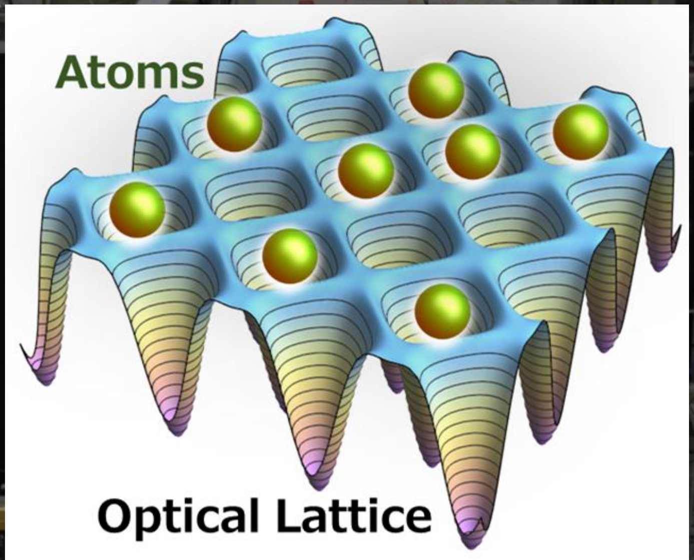


Atomic clock: Rely on the constancy of fundamental constants

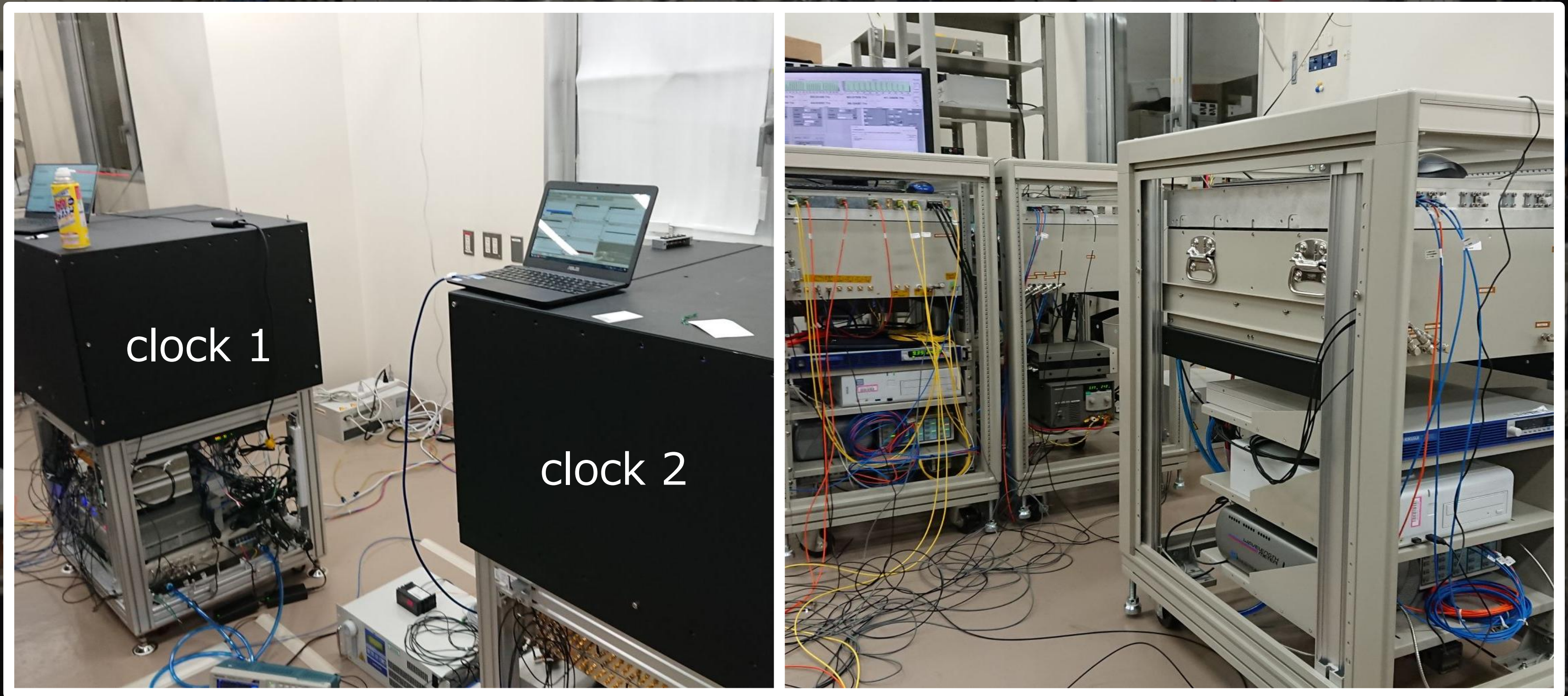
- Measure transition frequency as precise as possible
- Control laser frequency to be the atomic frequency.
- Long coherence time ($T > 1\ \mathrm{s}$) of atoms gives narrow spectrum width $\Delta\nu = 1/T < 1\mathrm{Hz}$, requiring ultrastable laser
- Quantum noise matters, many atoms N determines $\Delta\nu/\sqrt{N}$.



Atom confined in the Lamb-Dicke region is free from Doppler shift



- 2001: Proposal of an optical lattice clock, aiming at stability $\propto \Delta\nu/\sqrt{N}$ with an engineered light shift trap (magic wavelength).
- 2014: $\Delta\nu/\nu = 2 \times 10^{-18}$(=1s/10billion yrs) achieved
- 2018: Make lab-sized clocks transportable, relativistic sensing



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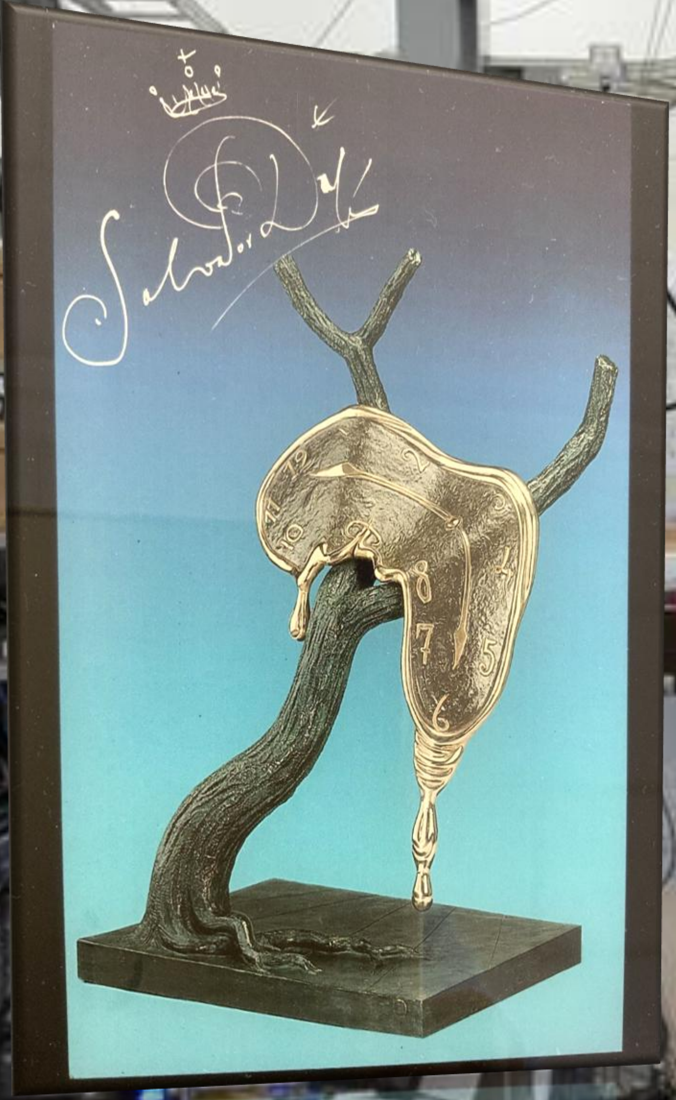
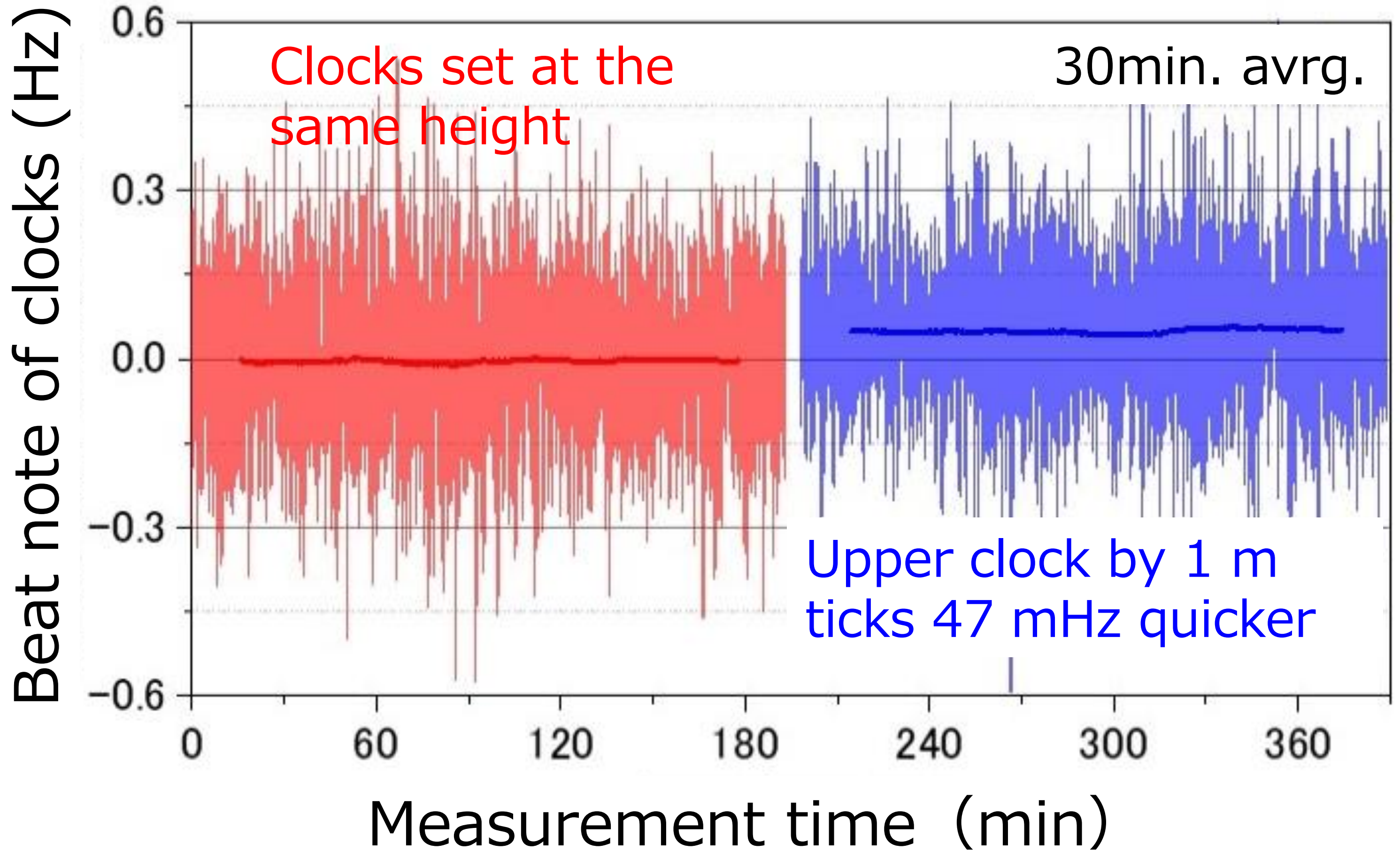
$$\Delta\nu/\nu_0 \approx g\Delta h/c^2 \approx 1.1 \times 10^{-18}\,\Delta h/\mathrm{cm}$$

Clocks measure 1cm height difference (after 3hs).





Dali's melting clocks became a reality.

The upper clock ticks faster (2018).

Reading 18th digits of strontium pendulums

SI allows describing 16-digit numbers

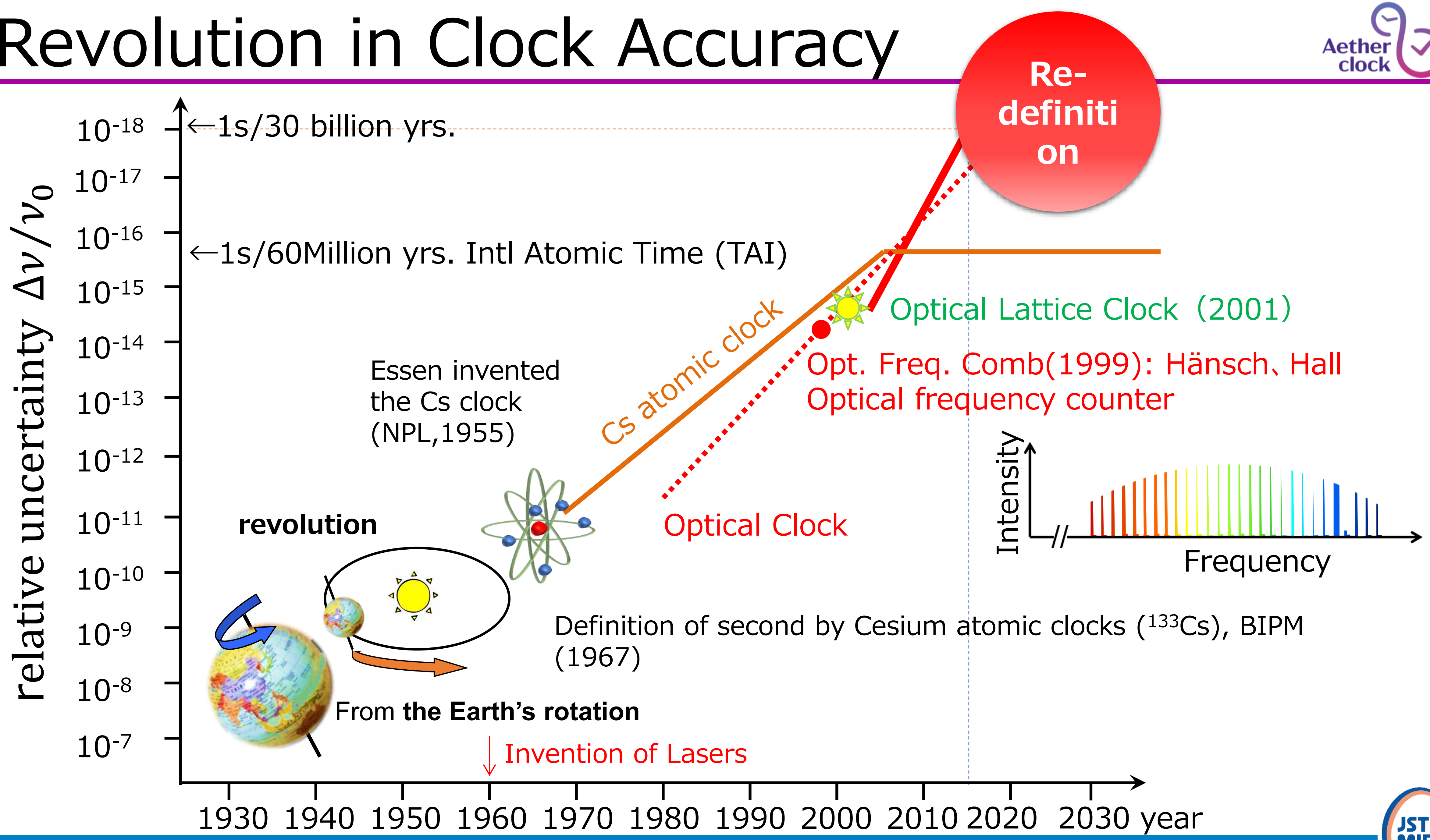
Upper clock: ν=429 228 004 229 873.037 Hz

Reference clock: ν=429 228 004 229 872.990 Hz

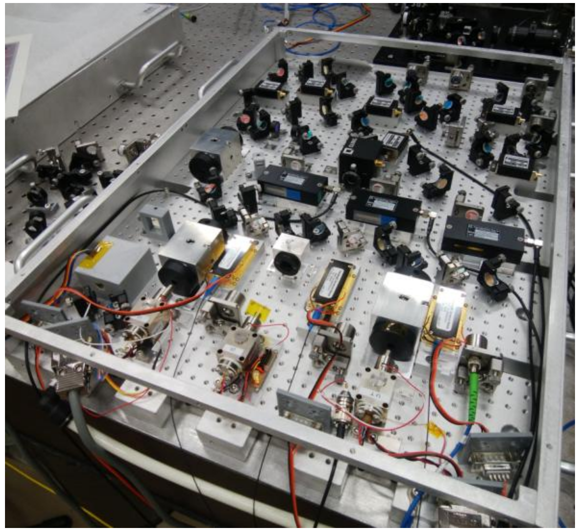
$\Delta\nu$ = 0.047 Hz

- Frequency beyond 16th digits indescribable with SI-second: Science in crisis.
- Motivates redefinition of the second.
- The international roadmap is moving toward a possible redefinition around 2030.

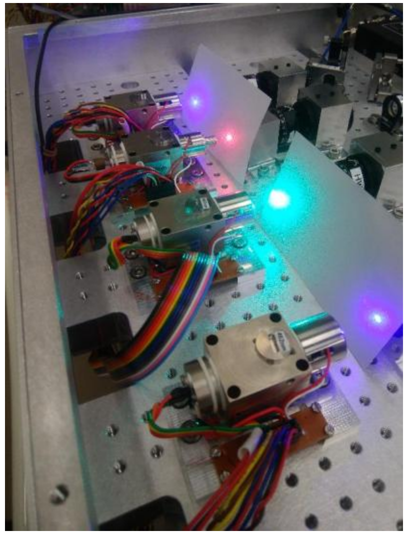
A Revolution in Clock Accuracy



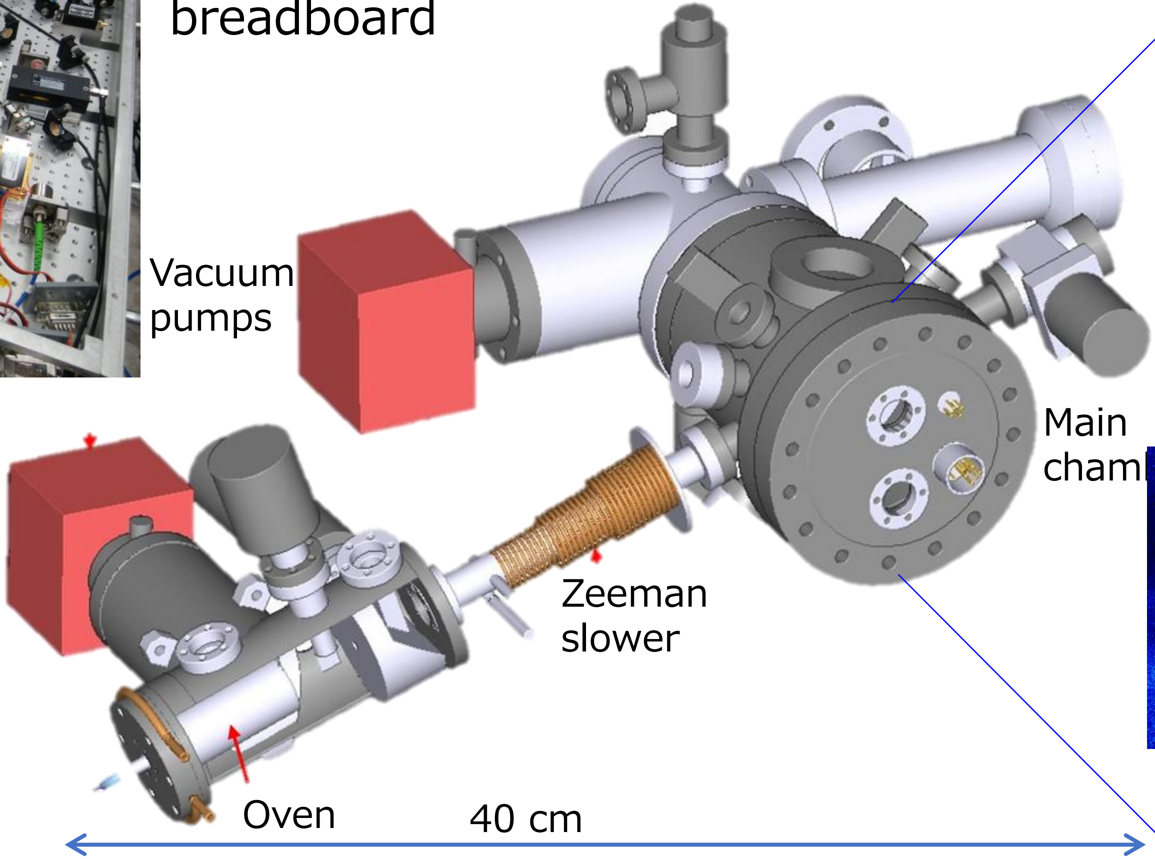
Inside of 1st Gen. ^{87}Sr transportable clock (2018)

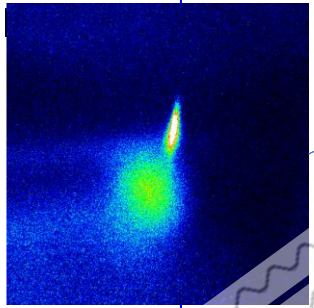


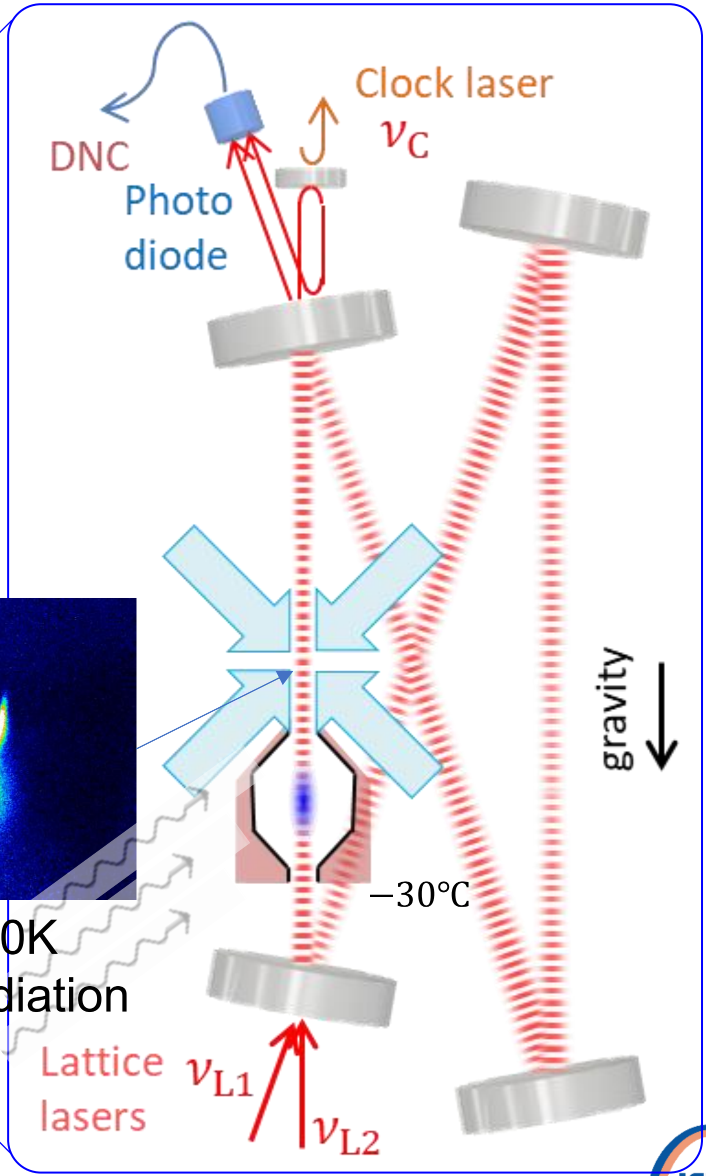
Temperature stabilized breadboard



Physics package







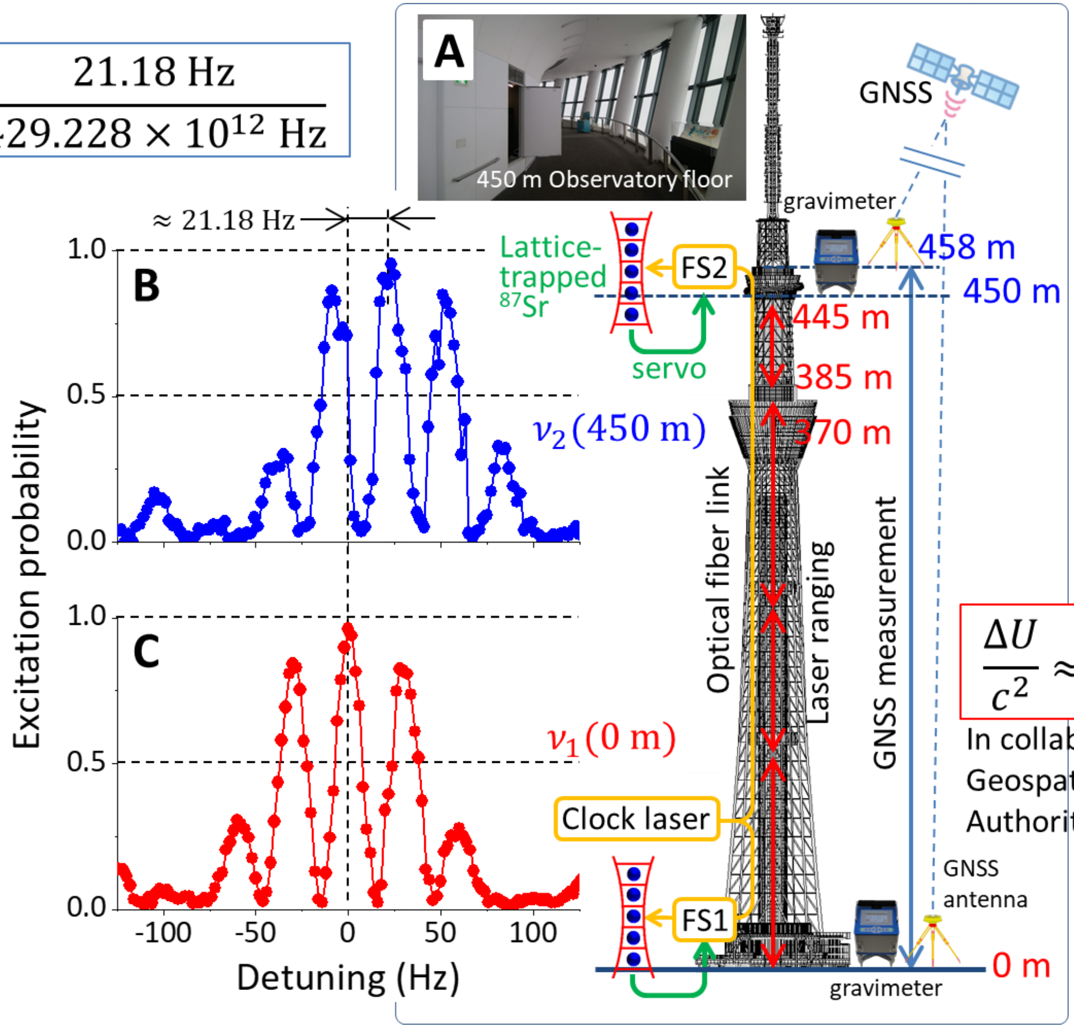
N. Ohmae et al., Transportable Strontium Optical Lattice Clocks Operated Outside Laboratory at the Level of 10^{-18} Uncertainty. Adv. Quant. Tech., 2100015 (2021).

Blackbody radiation shield: a key to 10^{-18} uncertainty.

Demonstration at Tokyo SkyTree (2019)

gravitational redshift $\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$ Geopotential difference

$$\frac{\Delta\nu}{\nu} \approx \frac{21.18\ \text{Hz}}{429.228 \times 10^{12}\ \text{Hz}}$$



- The best gravitational redshift test $\alpha = 1.4(9.1) \times 10^{-5}$ on the ground $\delta h \approx 450$ m.
- Combined with satellite experiments*, gravitational redshift tested at 10^{-5} level over 500 m-10,000 km range.
- The first demonstration of 10^{-18} level clocks operated outside the laboratory. An important step toward future applications.

$$\frac{\Delta U}{c^2} \approx \frac{g \times 452.6\text{m}}{c^2}$$

In collaboration with Geospatial Information Authority of Japan

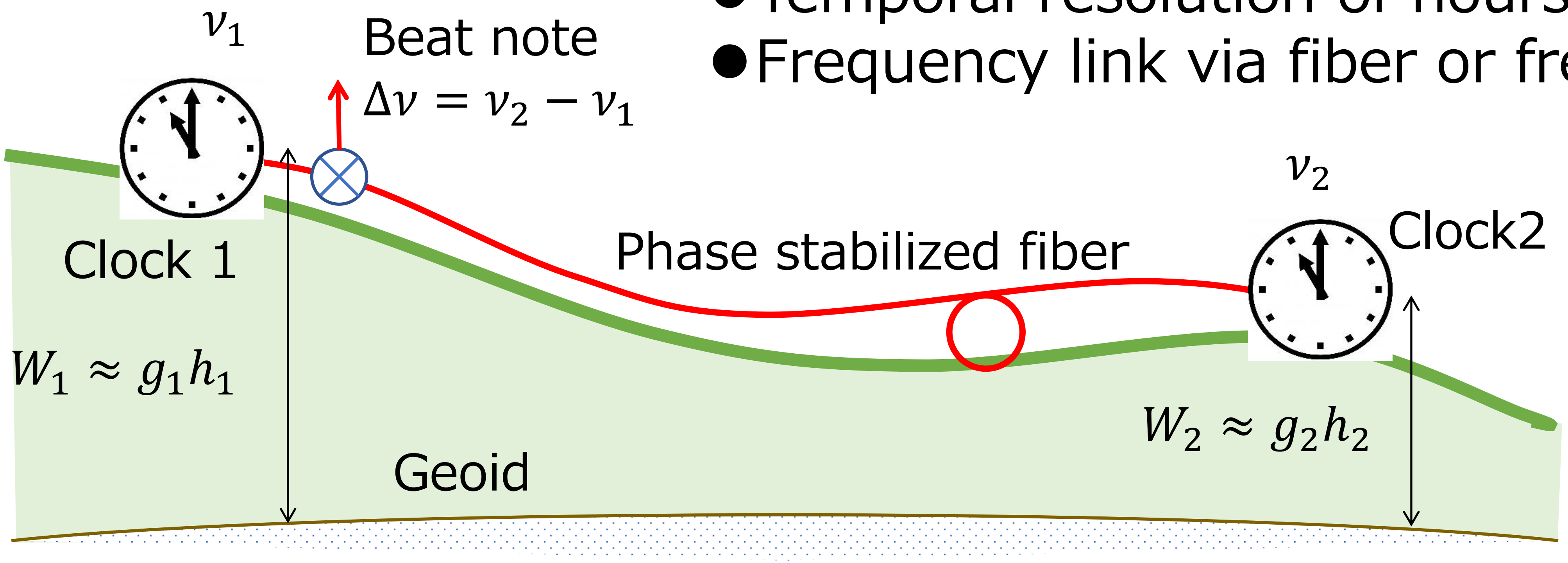
*Galileo satellites with elliptic orbits of height difference Δh≈8,500 km measure α=(0.19±2.48)×10^{-5}, (4.5±3.1)×10^{-5} Phys. Rev. Lett. 121, 231101/231102 (2018).
M. Takamoto, et al., Test of general relativity by a pair of transportable optical lattice clocks, Nat. Photon. (2020).

Applications of clocks and next challenges

- Clocks to measure spacetime, test, and use relativity. **CHRONOMETRIC LEVELLING.**
- Optical Lattice Clock with **CONTINUOUS interrogation**
- Translate laboratory technology into robust **black-box** systems with industry partners. **COMMERCIAL CLOCKS** available.
- Dreaming of **FUTURE MOBILE ATOMIC CLOCKS**

Chronometric leveling, relativistic geodesy

- Geopotential mapping at cm-level
- Temporal resolution of hours
- Frequency link via fiber or free space



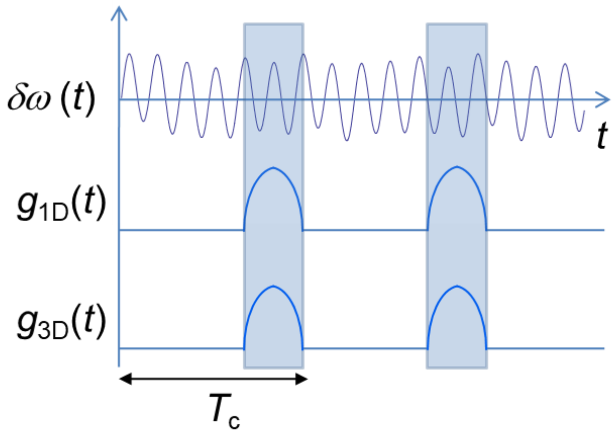
$$\frac{\Delta\nu}{\nu_1} = \frac{W_2 - W_1}{c^2} \approx \frac{g\Delta h}{c^2} = 1.1 \times 10^{-18}\, \Delta h/\mathrm{cm}$$

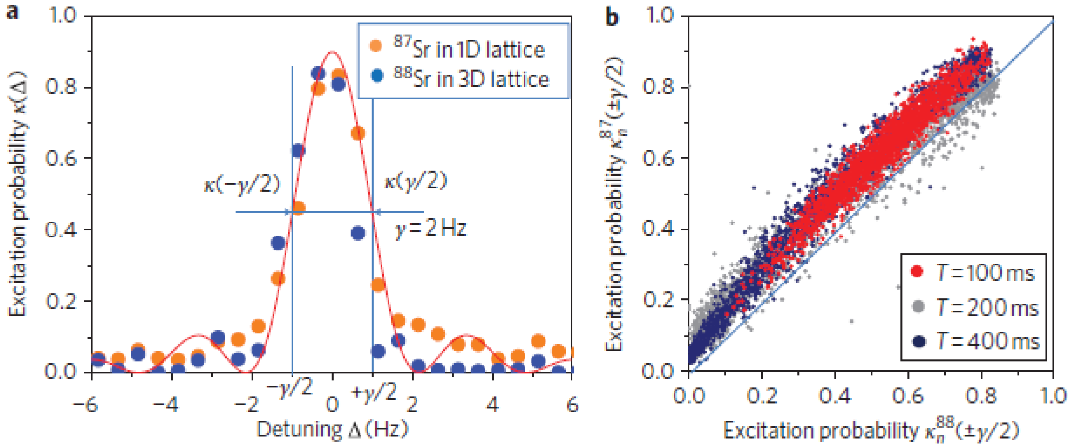
Why continuous clocks matter for spacetime sensing

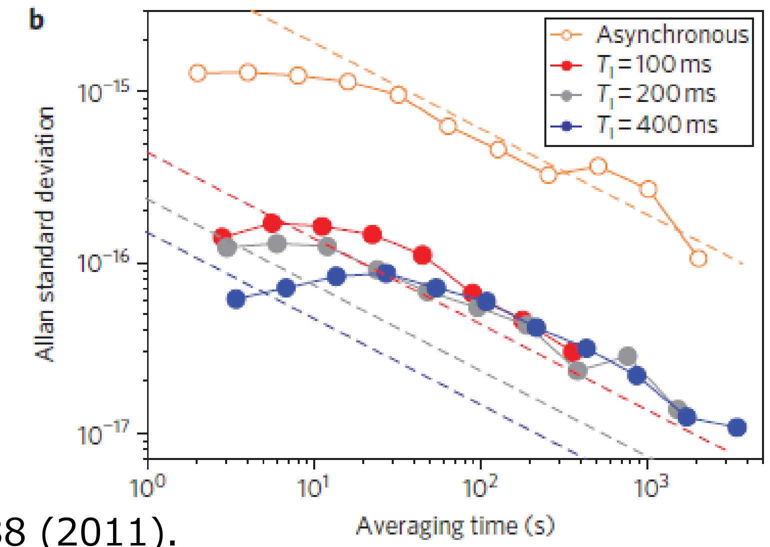
- standalone clocks as sensors of proper time
- faster access to the quantum limit
- robust operation outside the laboratory

Laser Frequency Noise: A Persistent Challenge

1. Optical lattice clocks marked a revolution in clock stability.
2. Synchronous comparison (2011) approached the **QPN limit by rejecting laser noise** for two lab-based clocks.
3. However, for long-distance, it is not applicable due to link noise.
4. The clock stability relied on the **clock laser stability**, offered by the **“excellent and delicate” optical cavity**.
5. Think about **“mobile and robust” system with QPN-limited stability**, including space applications.

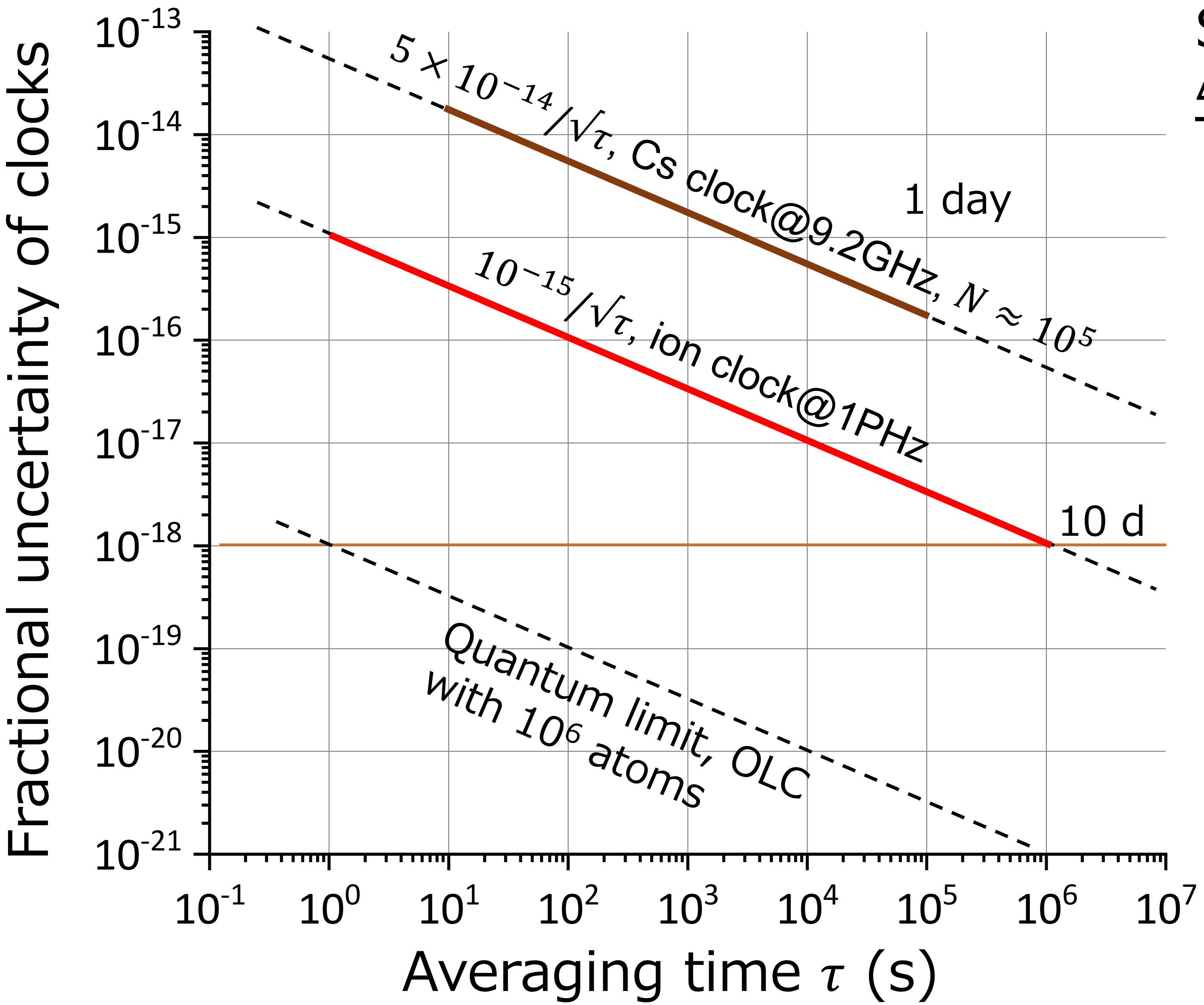






M. Takamoto, T. Takano, and H. Katori, Nat. Photon. 5, 288 (2011).

Next challenge: Access the quantum limit faster

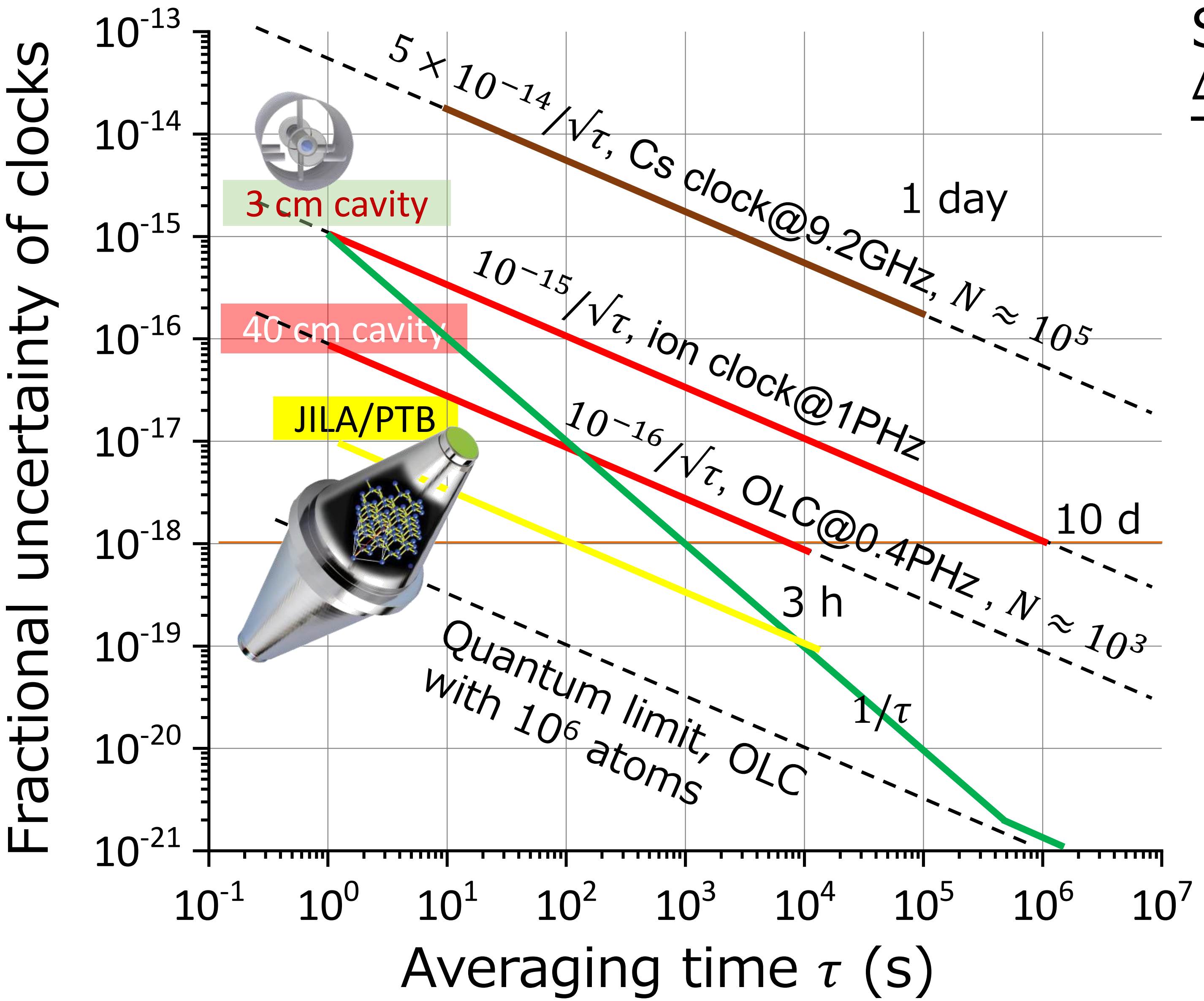


Statistical improvement of clocks

$$\frac{\Delta\nu_0}{\nu_0} = \underbrace{\frac{1}{\nu_0}\frac{1/T}{\sqrt{N}}}_{\text{Quantum noise limit}} \underbrace{\frac{1}{\sqrt{\tau/T_c}}}_{\text{Repeat measurements}}$$

- An optical lattice captures millions of atoms, significantly speeding up the measurements,
- But, the flywheel laser stability matters!

Next challenge: Access the quantum limit faster



Statistical improvement of clocks

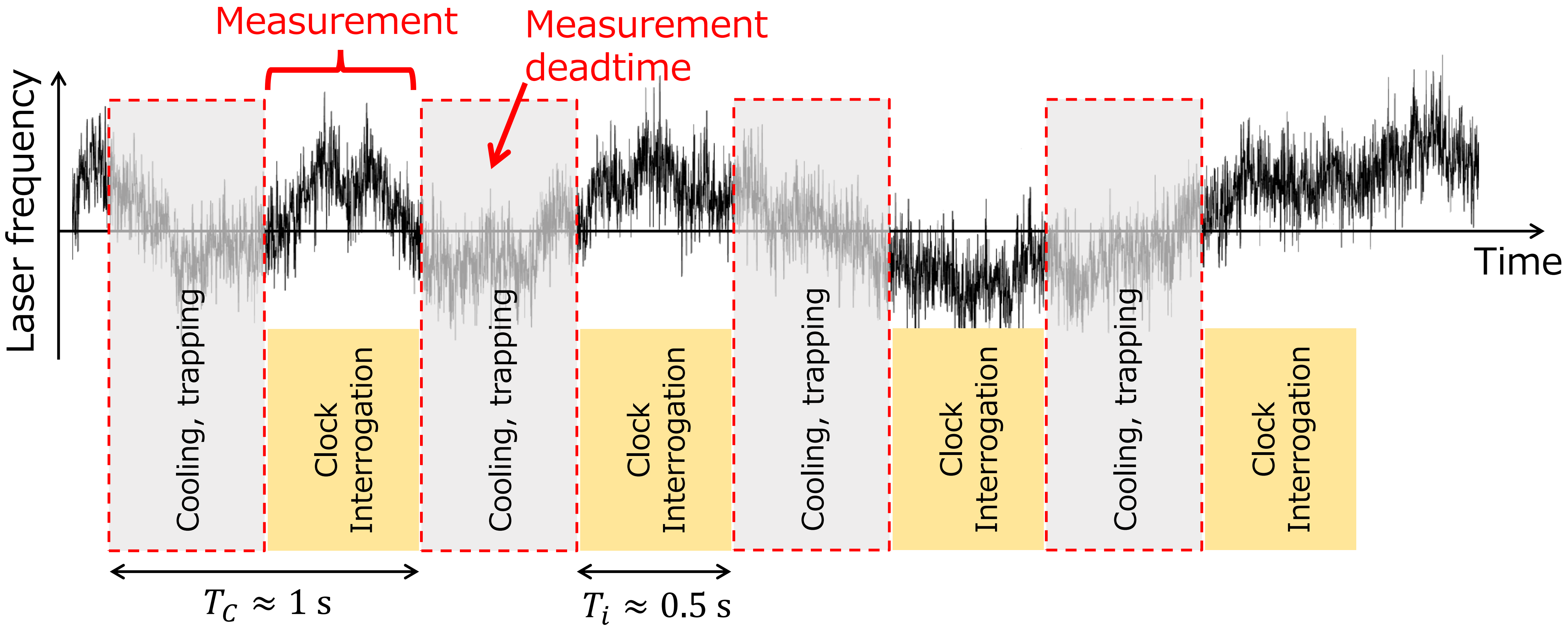
$$\frac{\Delta\nu_0}{\nu_0} = \frac{1}{\nu_0}\frac{1/T}{\sqrt{N}}\frac{1}{\sqrt{\tau/T_c}}$$

Quantum noise limit — Repeat measurements

- Stability of OLC is not limited by the Quantum limit, but by the clock lasers.
- JILA/PTB take advantage of ultrastable laser with cryogenic Si cavity.

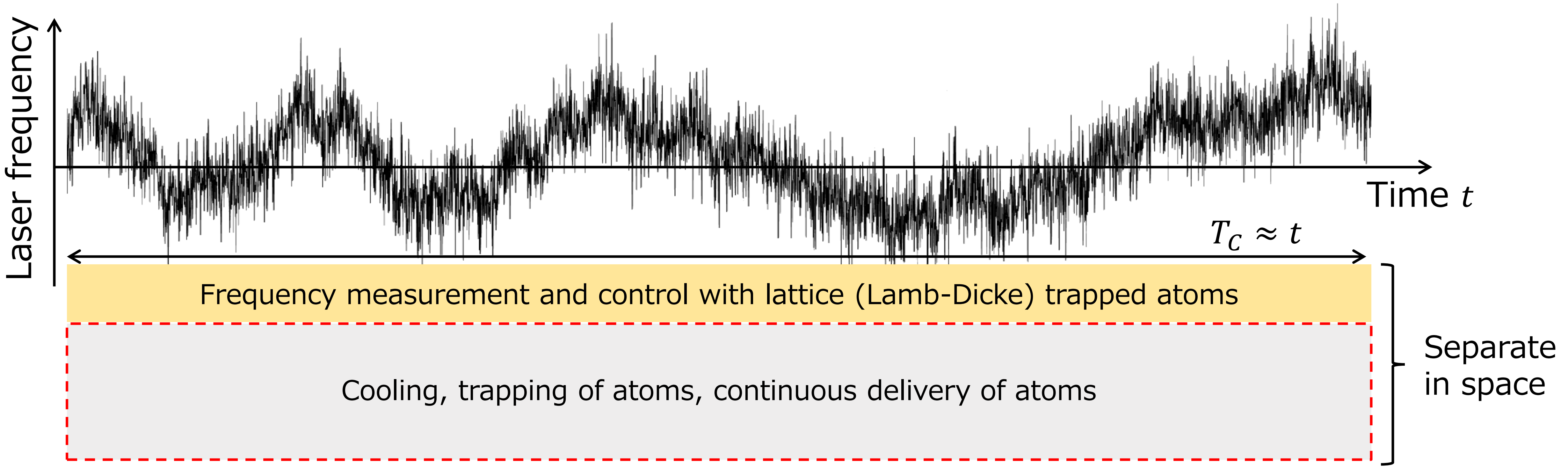
Dick effect arising from intermittent interrogation

- Periodic meas. of ν_L & statistical average over $n = t/T_c$ improves as $\sigma_y \propto 1/\sqrt{t/T_c}$.
- Measurement deadtime further degrades the stability (Dick effect, 1990).
- $\sigma_{\mathrm{Dick}} = \frac{\delta\nu}{\nu_0}\frac{1}{\sqrt{t/T_c}} \sim \frac{10^{-15}}{\sqrt{t/s}}$: no advantage of many atoms to reduce quantum noise



Continuous clock interrogation with a single clock

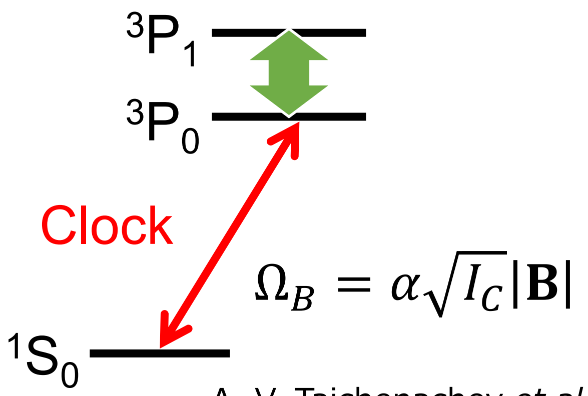
- Continuous measurement and control of laser frequency over $T_C \approx t$.
- Frequency measurement in the Fourier limit $\delta\nu \sim 1/T_C = 1/t$
- $\sigma_{\mathrm{Cont.}} = \frac{\delta\nu}{\nu_0} \approx \frac{10^{-15}}{t/\mathrm{s}}$ until reaching σ_{QPN} (cf. $\sigma_{\mathrm{Dick}} = \frac{\delta\nu}{\nu_0}\frac{1}{\sqrt{t/T_C}} \sim \frac{10^{-15}}{\sqrt{t/\mathrm{s}}}$)



So far, synthesizing two clocks, Kasevich, Ludlow, Jian-Wei Pan

Combining developed elements

① Continuous atom source & Moving optical lattice
② Clock laser to probe atoms in the Lamb-Dick regime (Longitudinal excitation geometry, Katori 2021)
③ Spatially localized excitation by B-field mixing on ^{88}Sr (define pulse area, i.e., π-pulse excitation)
④ State-selective detection



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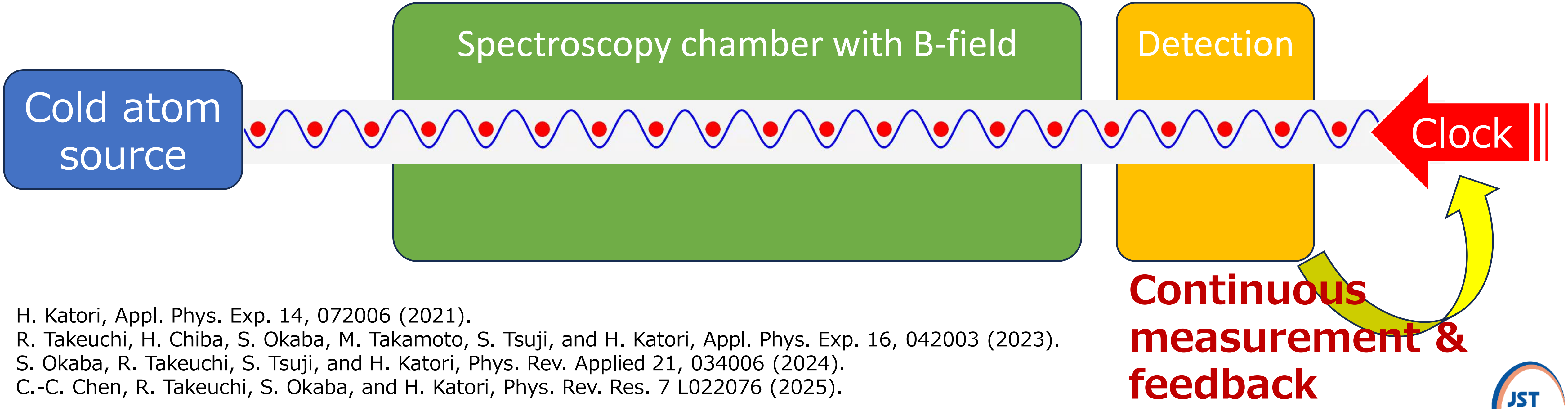

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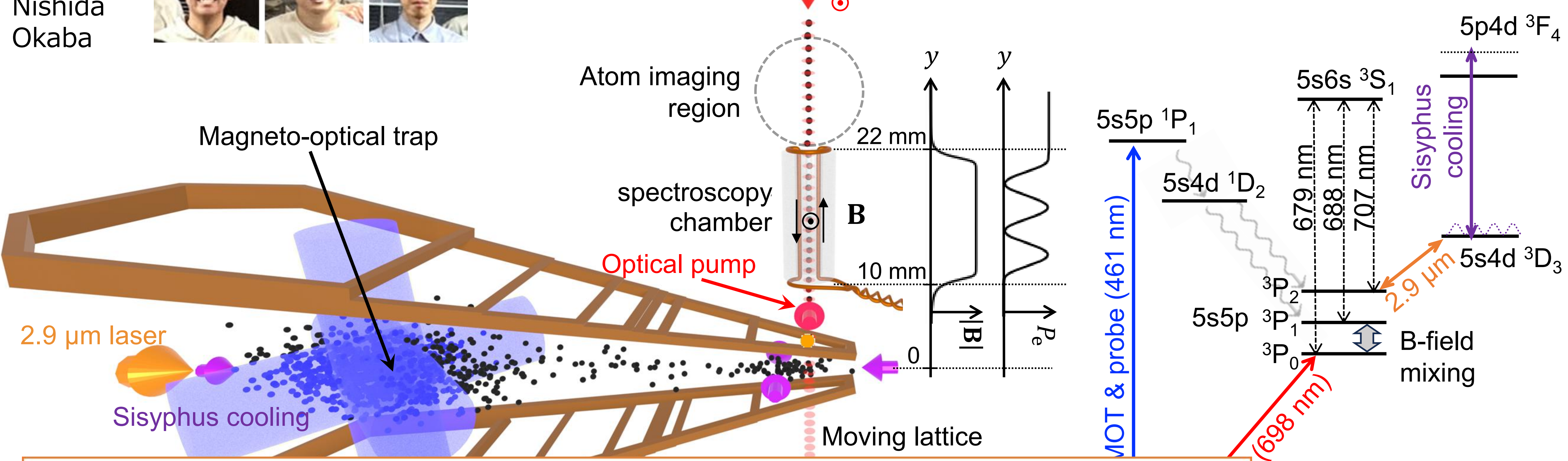
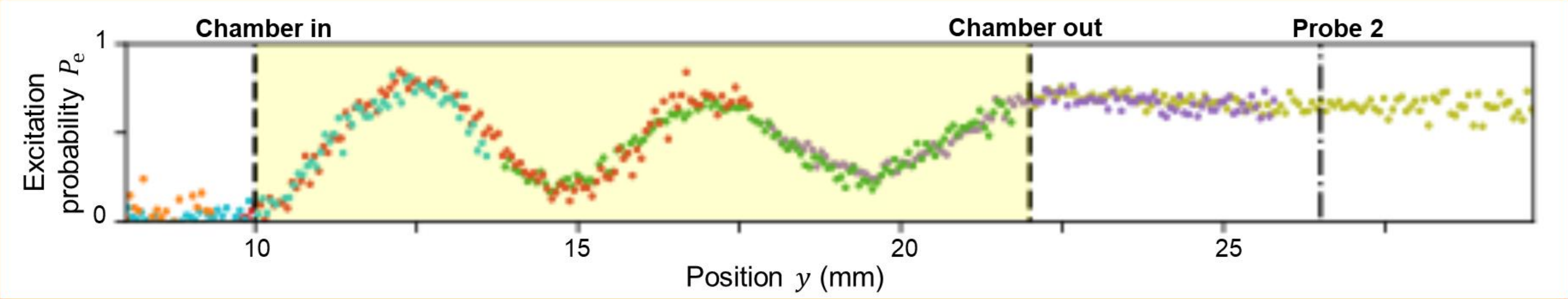
S. Okaba, R. Takeuchi, S. Tsuji, and H. Katori, Phys. Rev. Applied 21, 034006 (2024).
C.-C. Chen, R. Takeuchi, S. Okaba, and H. Katori, Phys. Rev. Res. 7 L022076 (2025).

Cont. Cooling, Moving Lattice, and interrogation

Thanks to
Takeuchi
Nishida
Okaba

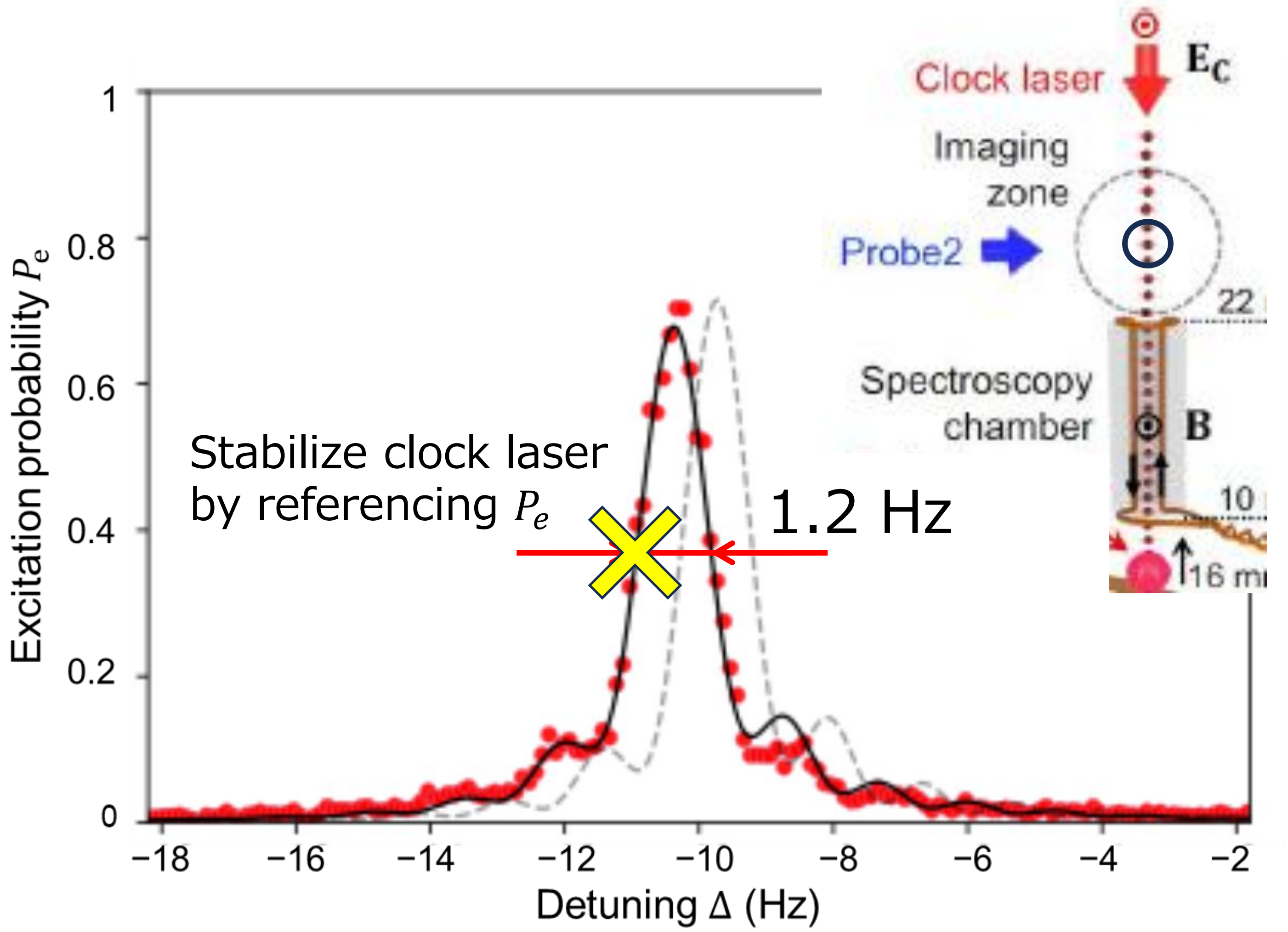




B-field induced transition

$$\Omega_B = \alpha\sqrt{I_C}|\mathbf{B}|\cos\theta$$

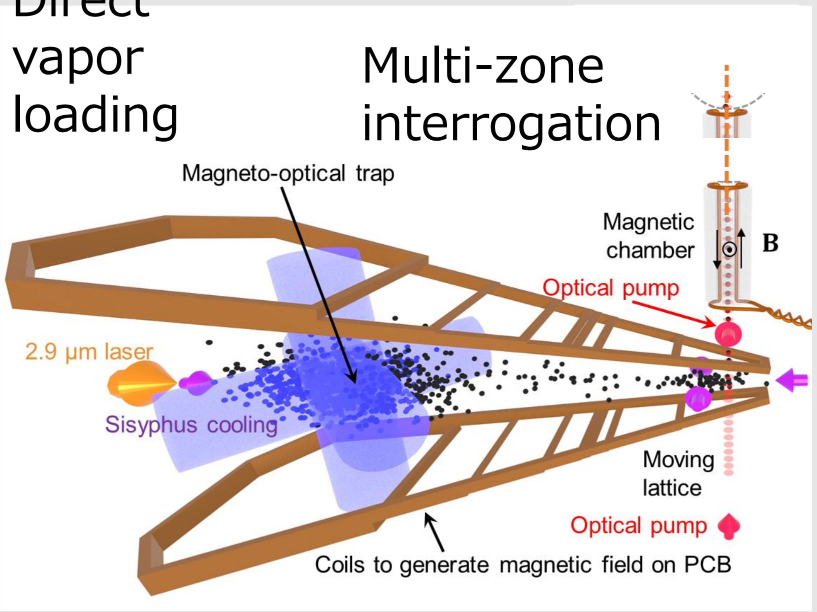
Fourier-limited longitudinal Rabi spectroscopy

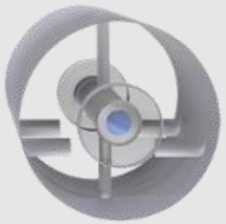


- Doppler shift of the moving lattice ≈23 kHz compensated
- Transit time 12mm/(16mm/s)=0.75s gives $\sqrt{3}/(2\tau) = 1.15\ \mathrm{Hz}$
- Detuning from ^{88}Sr resonance, ≈10 Hz includes Zeeman, light shift, BBR
- **Ready for continuous measurement and feedback.**
- Continuous superradiance···

Future compact mobile clocks in scope

- Compact physics package 20L





3-cm-long
ULE cavity or
solid etalon

- Compact clock laser (1L) without relying on half-a-meter long cavities
- ZDT interrogation allows achieving $10^{-15}/\tau$ stability
- Multi-zone measurements allow a wide frequency capture range.

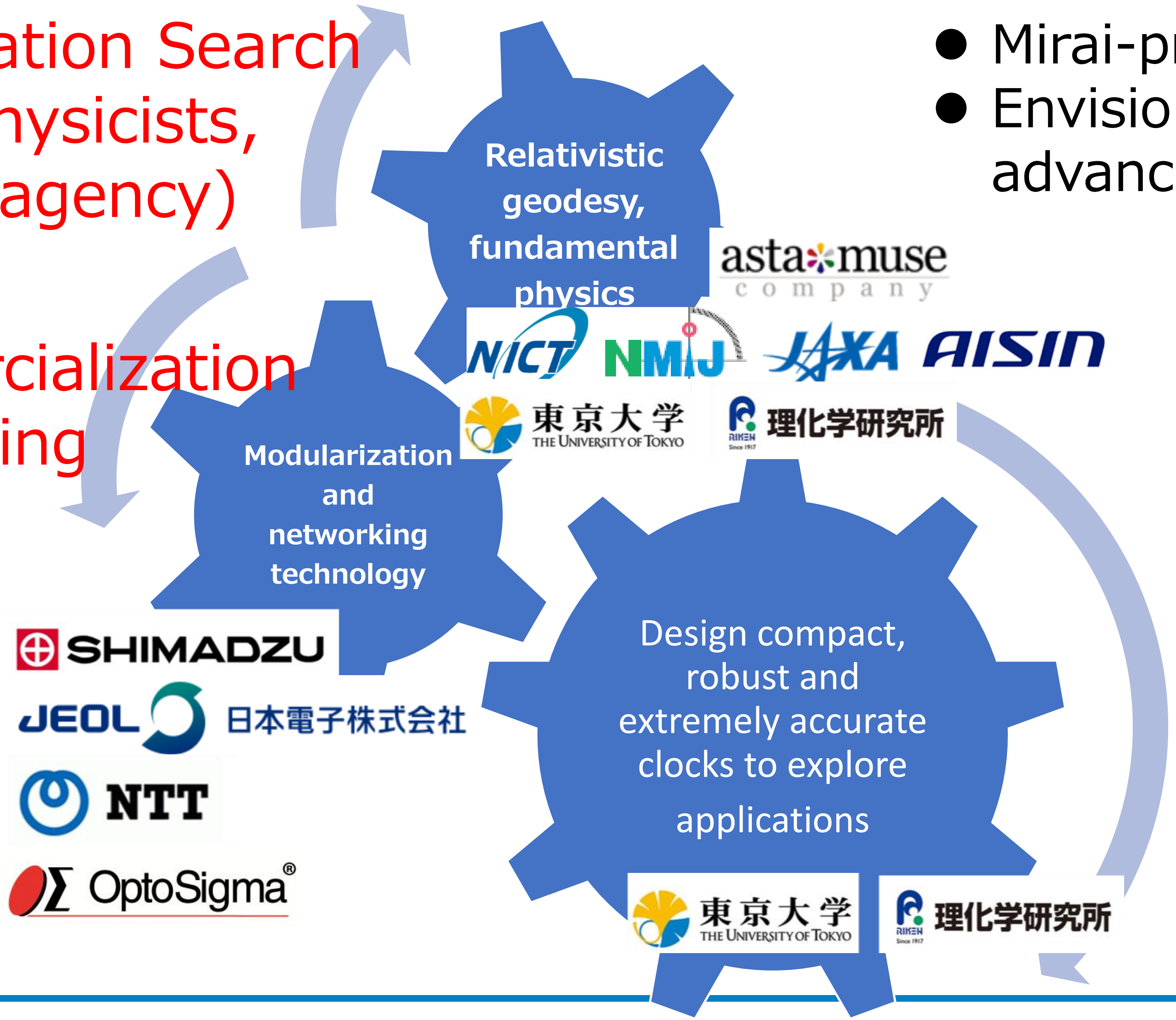
Transferring our technology to industry

Aether clock

- Mirai-project: 2018.11(-2028)
- Envision future society with advanced clocks.

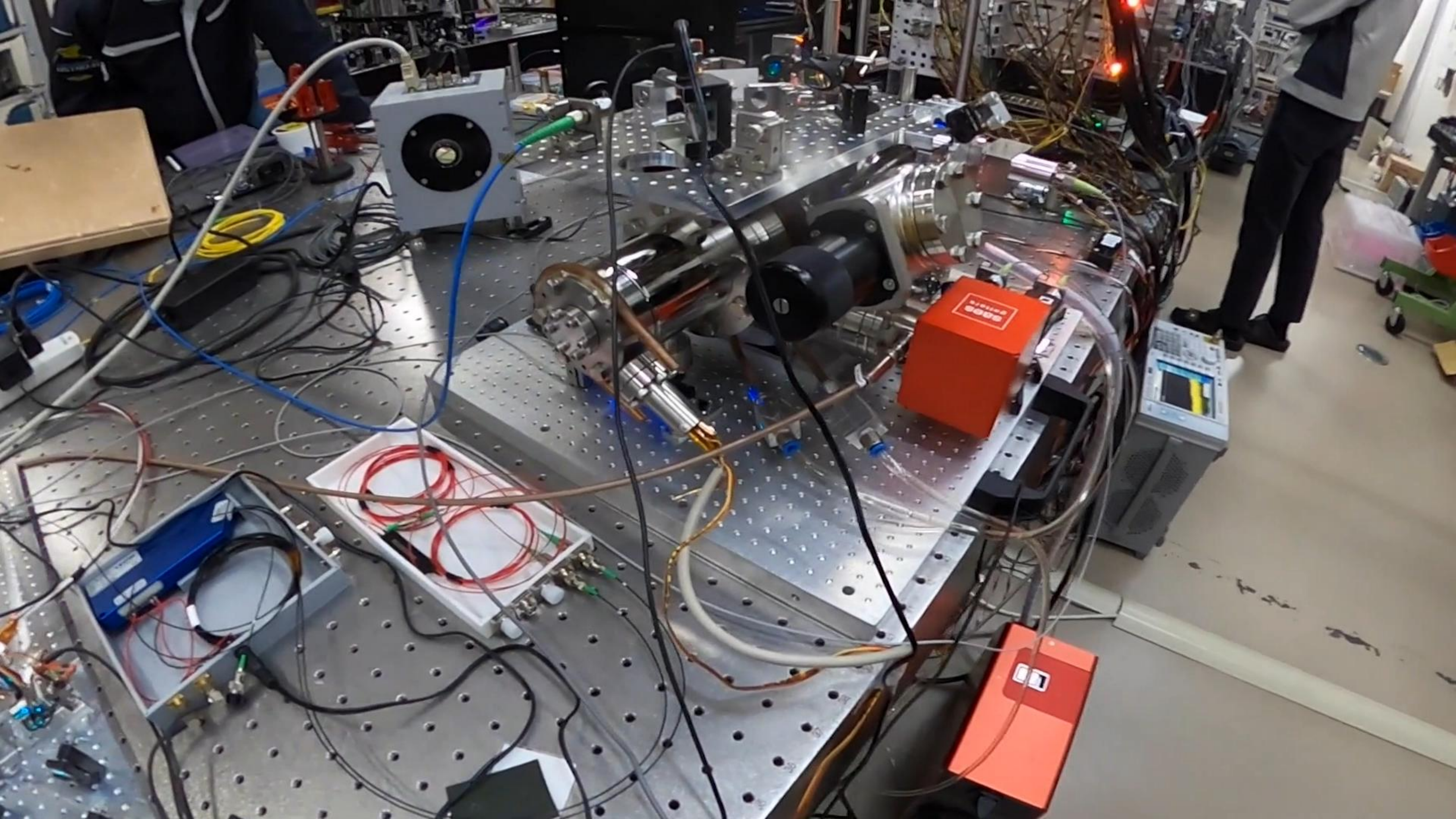
Application Search (Geophysicists, space agency)

Commercialization Networking



Fundamental Physics
New ideas
Technologies

JST MIRAI



Strontium Optical Lattice Clock

SHIMADZU Aether clock

Application

- ✓ Optical frequency standards for time keeping
- ✓ Reference clocks for next generation telecommunication
- ✓ Gravitational potential-meter

Feature

- ✓ Level of 10^{-18} systematic uncertainty
- ✓ Compact (W 1140 mm × H 1093 mm × D 650 mm*)
- ✓ Robust laser optics
- ✓ Easy maintenance
- ✓ Automatic operation (laser locking)
- ✓ Embedded reference cavity of $< 2 \times 10^{-15}$ (1s) stability

Pity cavity cannot fully utilize thousands of atoms.
Continuous operation will help.

Contact

Corporate Communication Department
Shimadzu Corporation pr@group.shimadzu.co.jp

Designed to fit within JEM (Kibo) payload constraints on the ISS.

JST MIRAI

Release from Shimadzu to start taking orders

誤差100億年に1秒 「光格子時計」実用化

島津製作所が販売する光格子時計「イーサクロック」(5日午後、京都府精華町の島津製作所みらい共創ラボで)＝川崎公太撮影

つことが期待されている。

香取教授は取材に対し、「最先端の時計の量産体制を世界に先駆けて整えた意義は大きく、社会実装の第一歩を踏み出せたことは非常に感慨深い。世界各国で活用が大きく進むきっかけになると思っている」と話している。

6, March, 2025, Yo

Japan Puts World's Most Accurate Clock On Sale For $3.3m

The machine, a box around a metre (three feet) tall, and volume of around 250 litres, can also be used in research fieldwork.

By Channels Television

Updated March 5, 2025

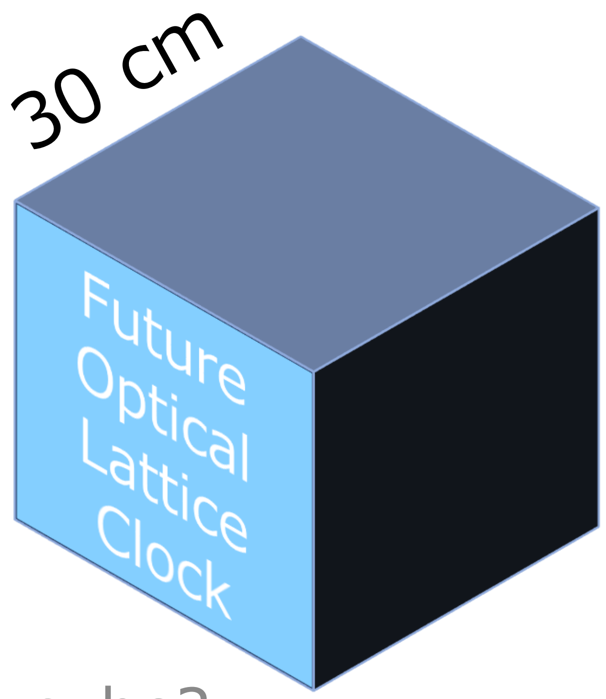
Resembling a squat, wide fridge, the world's most accurate clock went on sale for $3.3 million in Japan on Wednesday.

The "Aether clock OC 020" is so precise that it would take 10 billion years for it to deviate by one second, according to its Kyoto-based manufacturer Shimadzu Corp.
Known as a "strontium optical lattice clock", it is 100 times more accurate than caesium atomic clocks, the current standard for defining seconds, the precision-equipment producer said in a statement.
The machine, a box around a metre (three feet) tall, is small for its kind with a volume of around 250 litres. It can also be used in research fieldwork.
Shimadzu is aiming to sell 10 of its clocks over the next three years and hopes its customers will use them to advance scientific research in areas such as the observation of tectonic activity.
Optical lattice clocks have previously been installed in Tokyo's famous Skytree to test the general theory of relativity, which states that "time flows more slowly in places with strong gravity".
AFP

https://www.channelstv.com/2025/03/05/japan-puts-worlds-most-accurate-clock-on-sale-for-3-3m/

Summary of transportable clocks

Year	Group	Species	**Physics Pkg.**	Optics	Electronics	**Uncertainty**	**Ref.**
2014	LENS/PTB	^{88}Sr	< 2000 L		648 L	7×10^{-15}	Poli (2014)
2015	ESA	^{88}Sr	970 L		590 L	(Target) 5×10^{-17}	Bongs (2015)
2017	PTB	^{87}Sr	Trailer-Mounted (640L , ~50L , -)			5×10^{-17}	Koller (2017)
2018	HHU/UoB/PTB	^{88}Sr	1000 L		-	2×10^{-17}	Origlia (2018)
2020	CAS	^{87}Sr	650 L		-	-	Kong (2020)
2020	UTokyo/RIKEN	^{87}Sr	300 L	620 L		4×10^{-18}	Takamoto (2020)
2021	CAS	^{87}Sr	62 L	-	-	(Target) 6×10^{-17}	Guo (2021)
2022	UoB	^{88}Sr	121 L		-	-	Kale (2022)
2024	CAS	^{87}Sr	63 L + 50 L (partial)			-	Chen (2024)
2025	NIST	^{171}Yb	120 cm height rack ×3			-	Bothwell (2025)
2025	PTB	^{87}Sr	Trailer-Mounted (Total 700 kg)			2.1×10^{-18}	Nosske (2025)
This work	UTokyo/RIKEN/JST	^{87}Sr	**49 L**	**200 L**		$\mathbf{1.9\times10^{-18}}$	
2017	CAS	$^{40}Ca^{+}$	540 L		-	8×10^{-17}	Cao (2017)
2021	Opticlock	$^{171}Yb^{+}$	19" rack ×2			(Target) 2×10^{-17}	Stuhler (2021)
2022	CAS	$^{40}Ca^{+}$	330 L		-	1×10^{-17}	Cao (2022)
2023	JPL	$^{202}Hg^{+}$	1.1 L			(Stability) 1×10^{-14}	Hoang (2023)



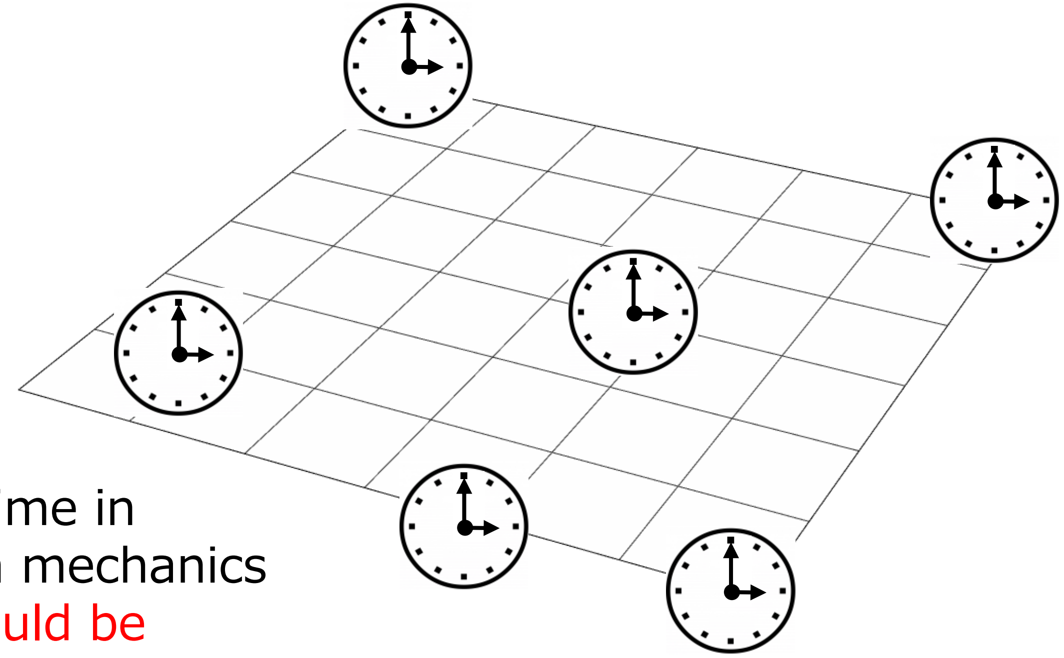
Dreaming beyond miniaturization of clocks

What if an optical lattice clock could fit inside a 30-cm cube?

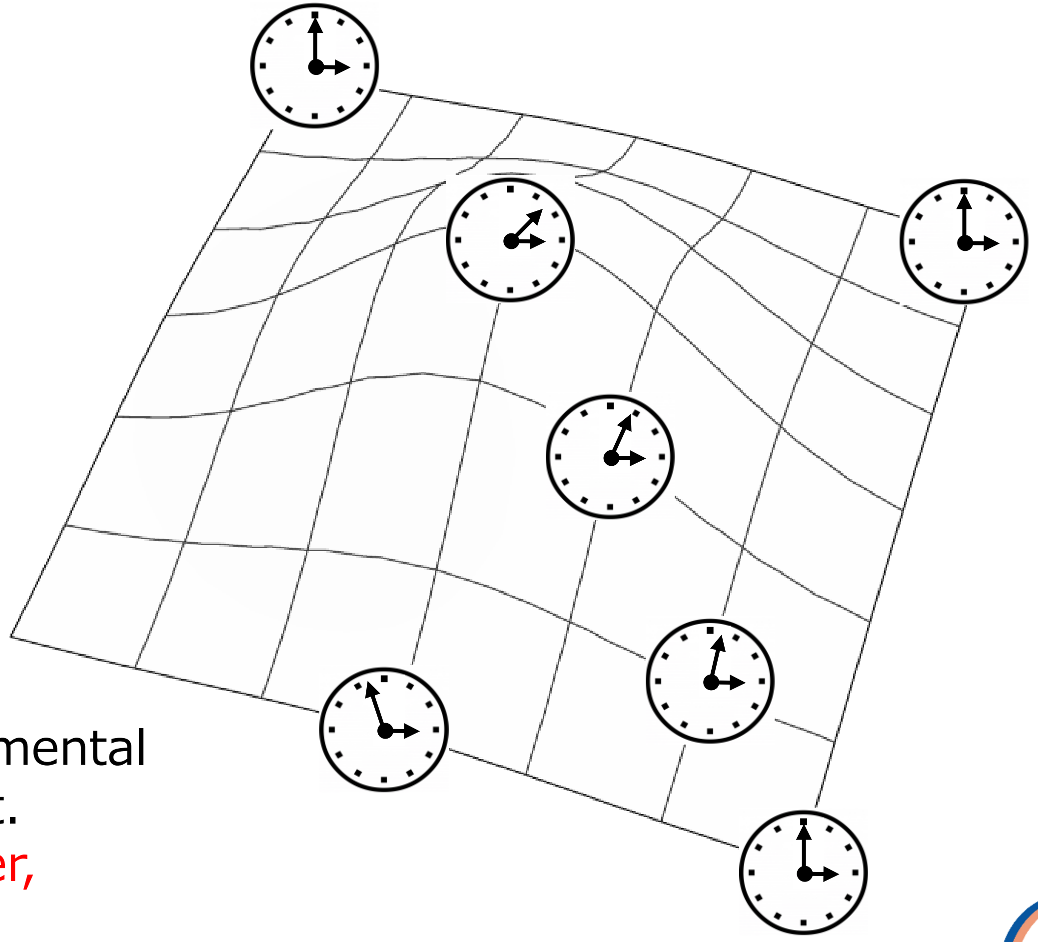
SEED-DRIVEN VISION FOR FUTURE CLOCKS

Black-boxed clocks alter our view of spacetime

Clocks will be further downsized and more robust by continuous scheme. A portable standalone clock is in scope.



Absolute time in Newtonian mechanics
Clocks should be synchronized.

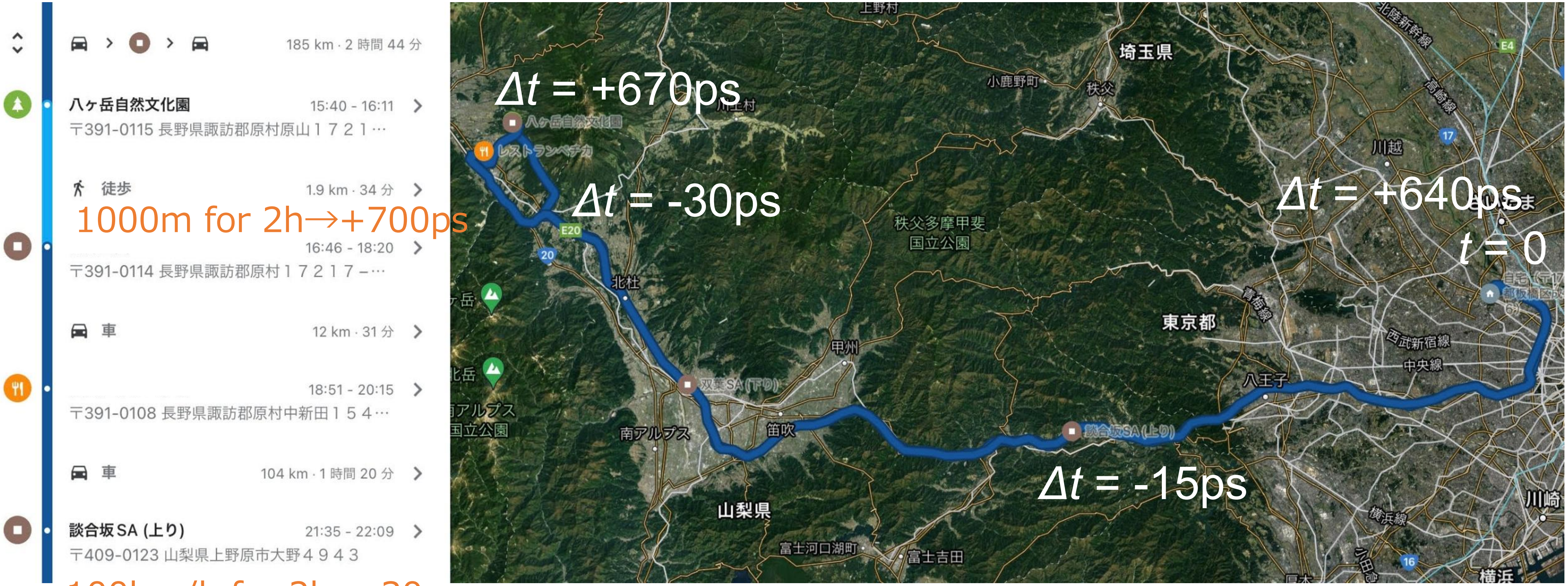


With 10^{-18} clocks, if you rely on the constancy of fundamental constants, losing less than 30 ps/yr without adjustment.
Standalone clocks measure the proper time of the owner, functioning as sensors for spacetime

If we go for a drive with an Optical Lattice Clock

- What would happen if optical lattice clocks were linked to Google timelines?
- Relativistic time delay (advance) linked to location information
- Return to RIKEN and measure relativistic time delay/advance. Your colleagues stay in the past (a bit).

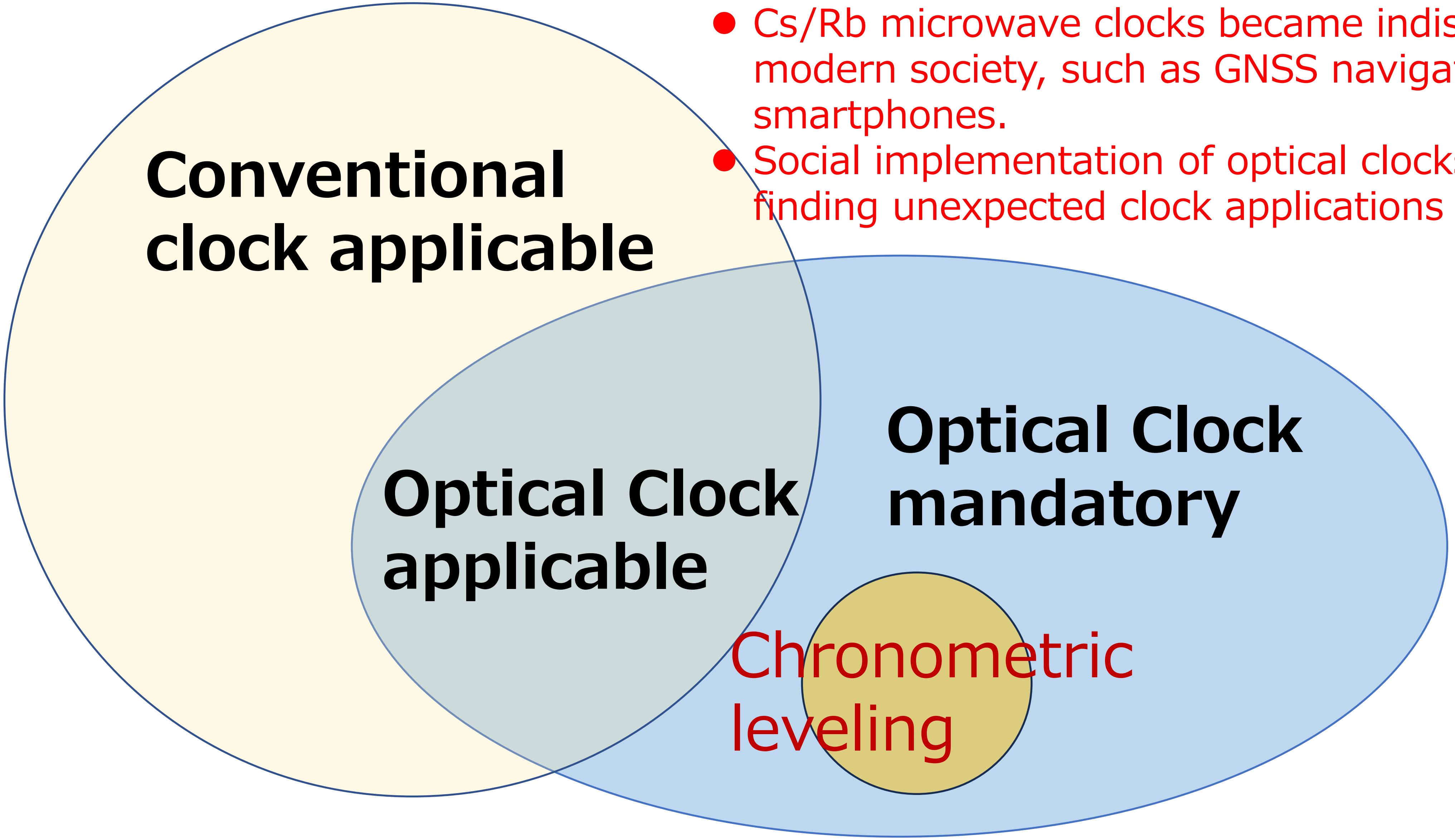
100km/h for 2h→-30ps



100km/h for 2h→-30ps

Find targets that only optical clocks can access

- Cs/Rb microwave clocks became indispensable to modern society, such as GNSS navigation with smartphones.
- Social implementation of optical clocks allows finding unexpected clock applications in the future.



Many thanks to The team:

Aether clock

M. Takamoto, I. Ushijima, N. Ohmae, Y. Takahashi, M. Kokubun, S. Okaba, R. Takeuchi, K. Nishida, K. Suekane, S. Yo, R. Yamashita, H. Chiba, S. Tsuji, T. Muramatsu, T. Hiroki, Y. Sakai, T. Takahashi,…

東京大学 THE UNIVERSITY OF TOKYO

RIKEN Since 1917 理化学研究所

SHIMADZU

JEOL 日本電子株式会社

JST MIRAI

Summary and outlook

Final Chapter of a High School Physics Textbook: Physics and the Future.
Novel quantum clocks alter future physics and society.

- OLCs demonstrate Dali's melting clocks.
- Continuous spectroscopy demonstrated. Toward $1/\tau$ stability compact clock.
- OLCs commercialized.
- Envision unexpected applications with clock precision: The untouched science/business platform with "Quantum & Relativity."