



Observatoire  
de Paris

PSL



SORBONNE  
UNIVERSITÉ  
CRÉATEURS DE FUTURS  
DEPUIS 1257

LABORATOIRE  
NATIONAL  
DE MÉTROLOGIE  
ET D'ESSAIS



# Chronometric Geodesy: Atomic clocks for levelling

## EUREF PARIS 2026

Rodolphe Le Targat

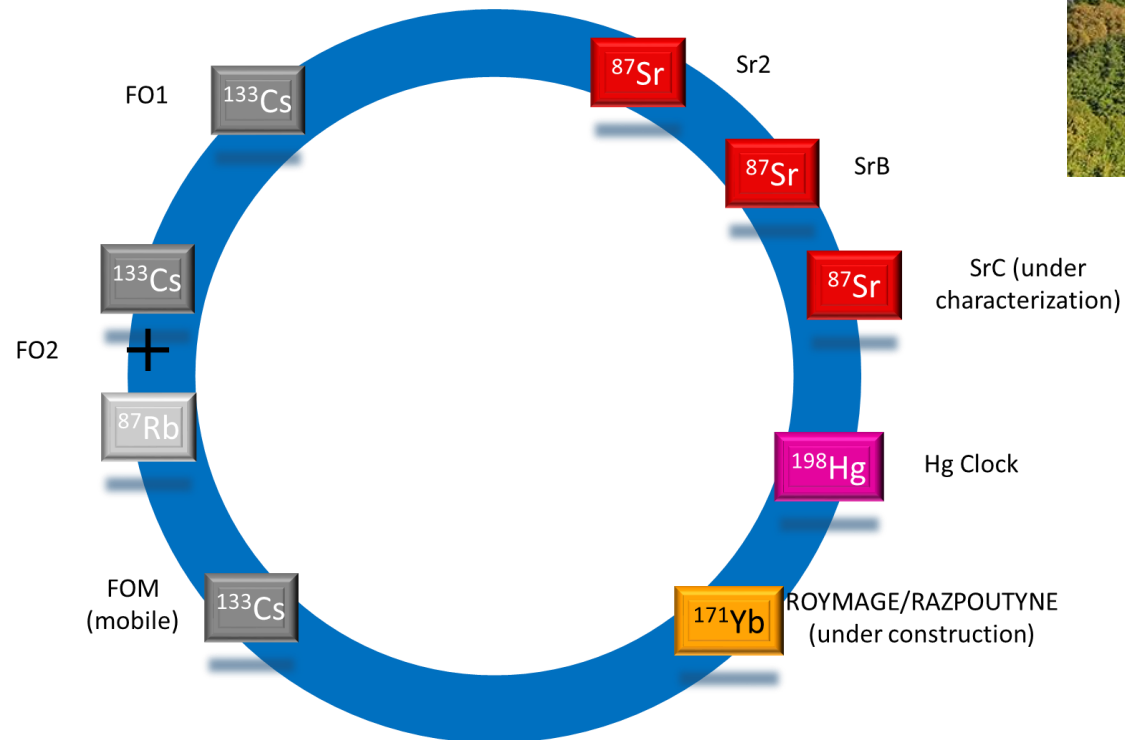
LTE (Laboratoire Temps-Espace),  
Observatoire de Paris

# Motivation

# What is an atomic clock?

## Time and Frequency missions of LTE (Laboratoire Temps-Espace)

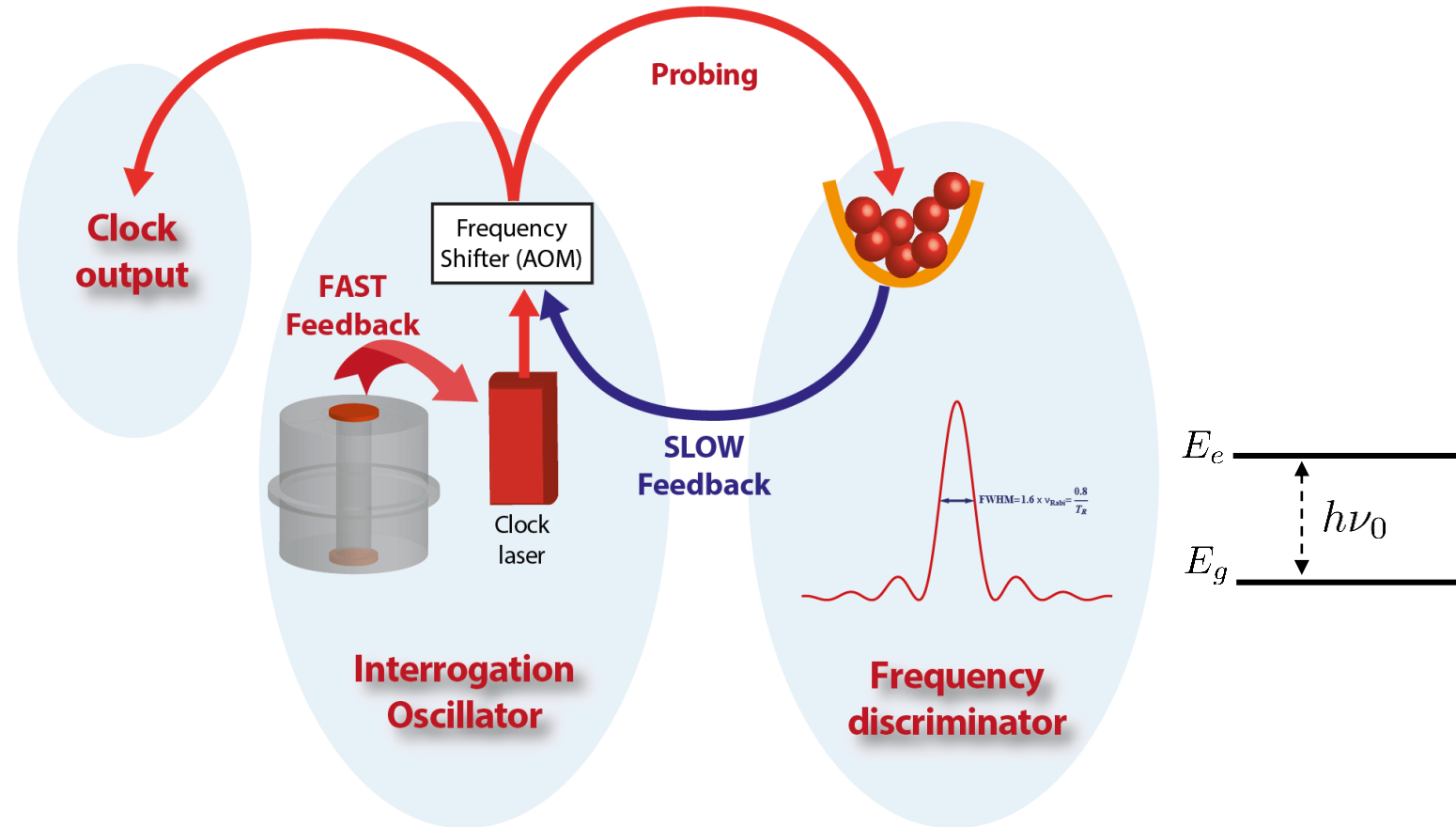
- Build and exploit **primary and secondary frequency standards**
- Realize and broadcast the **national time reference UTC(OP)**, base of the French legal time



# What is an atomic clock?

An atomic clock is the combination of:  
OSCILLATOR+  
DISCRIMINATOR

It provides a  
**FREQUENCY**  
reference



whose frequency  $\nu_\ell(t)$  is adjustable  
e.g.: Microwave source ( $10^{10}$  Hz)  
Laser source ( $10^{15}$  Hz)

Atomic transition  
(frequency  $\nu_0$ ) with  
high quality factor  
(hyperfine,  
intercombination or  
nuclear)

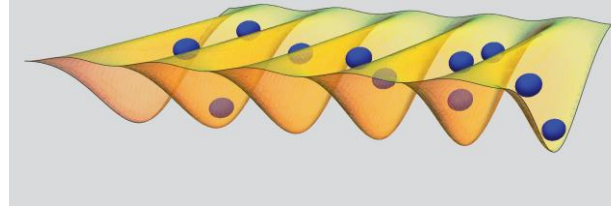
# Why do we need clocks?

Metrology: distribute frequency references, steer timescales

Test theories of fundamental Physics

Use the sensitivity of clocks to turn it into a detector

## Clocks



## Timescales

UTC

TAI

EAL

UTC(k)

Possible drift of fundamental constants ?

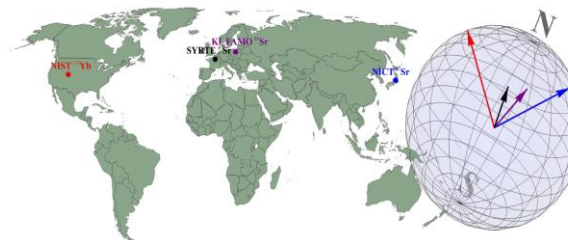
$$\frac{\delta(\nu_{Sr}/\nu_{Cs})}{\nu_{Sr}/\nu_{Cs}} = -2.77 \frac{\delta\alpha}{\alpha} - \frac{\delta\mu}{\mu}$$

Tests of Lorentz invariance

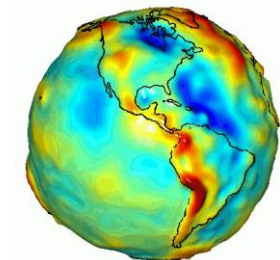
On Earth

Between Earth and space

Search for Dark matter



Earth Sciences (Chronometric Geodesy)



Geodesy – study of the Earth's shape and gravity field

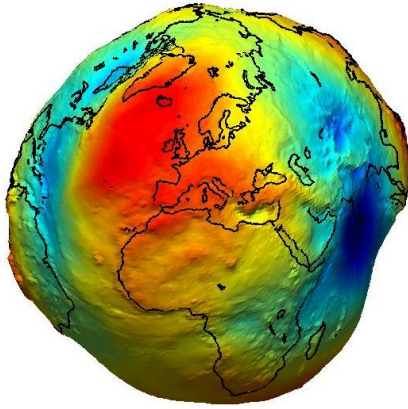


Image credit: ESA

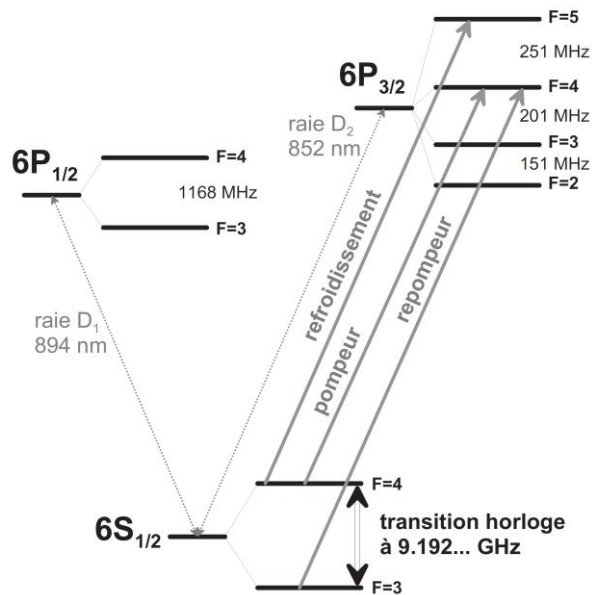
- ⇒ Gravitational time dilation was predicted by Einstein in 1907
- ⇒ The rate at which the time runs depends on the referential the clock is in
- ⇒ The referential is different between two different heights because of the geopotential
- ⇒ Therefore two clocks at different heights will have a different frequency when they are compared one to the other:

$$\frac{\Delta \nu}{\nu} = \frac{\Delta W}{c^2} \approx \frac{g \cdot \Delta h}{c^2}$$

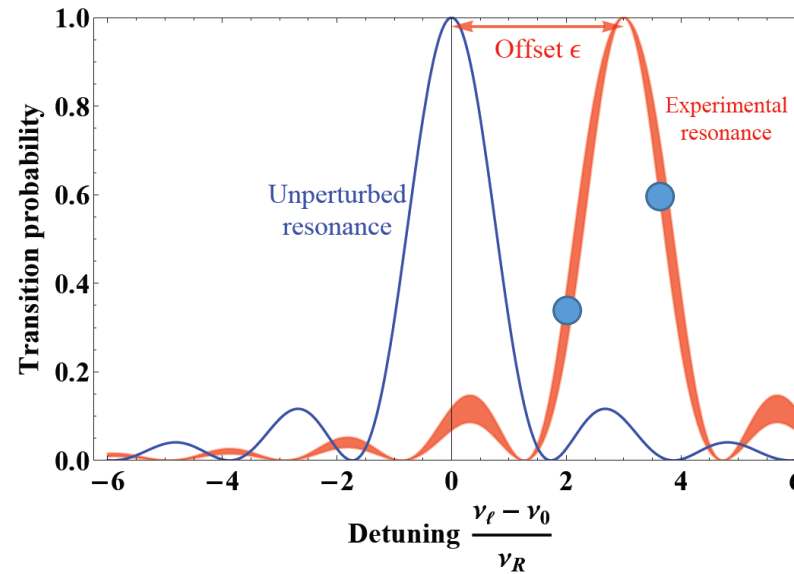
# Principle of Atomic clocks

# Caesium is the base of the present definition of the second

⇒ Narrow atomic transition in the microwave or optical domain



Atomic structure  
of Caesium



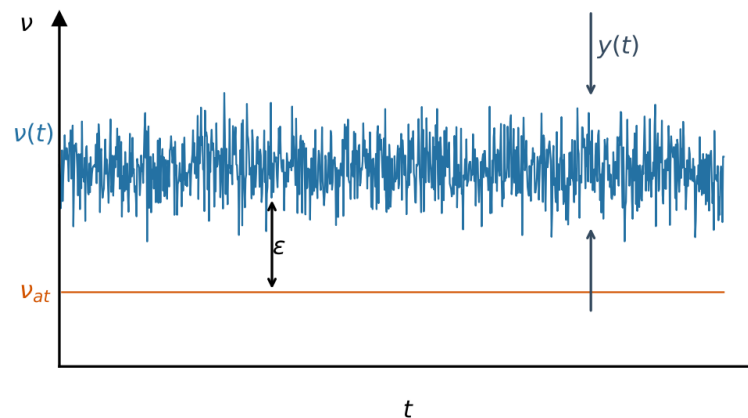
$$\nu_\ell(t) = \nu_0 \times [1 + \varepsilon + y(t)]$$

There is a list of systematic effects  
shifting the clock frequency  
(magnetic field effect, collisions ...)

The uncertainty on  $\varepsilon$  is the  
uncertainty of the clock

Noise on the measurement of the frequency

Stability of the clock = says how the noise  
averages (or not) with time



# A few examples of systematic effects?

⇒ The **Zeeman effect** is the displacement of atomic levels under the influence of a magnetic field:

$$\nu_{\text{measured}} = \nu_0 + (m_e g_e - m_g g_g) \frac{\mu_B B}{h} + \text{higher orders}$$

Bohr magneton

Zeeman quantum numbers

Landé factors

Planck's constant

In this case, the trick is to either probe  $m_e = m_g = 0$  or alternate between  $m_e$  and  $m_g$  of opposite signs

⇒ The **collision effect** corresponds to a dependency of the frequency on the atomic density

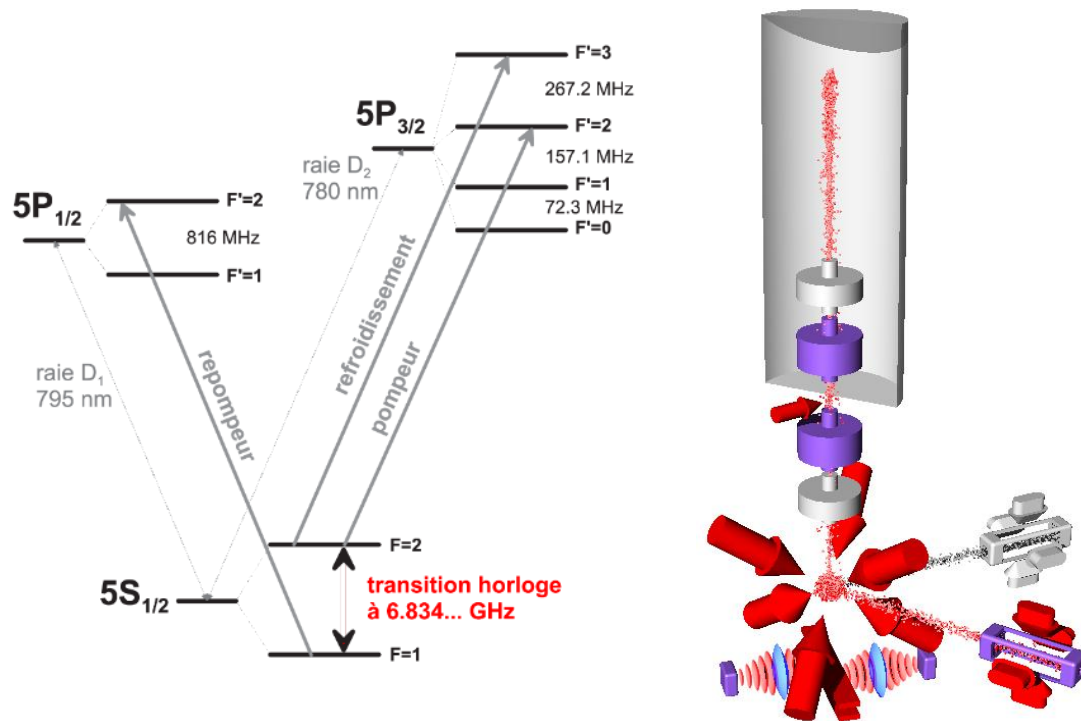
$$\nu_{\text{measured}} = \nu_0 + \alpha \cdot n_{\text{at}}$$

In this case, measured at various  $n_{\text{at}}$  allow extrapolating to  $n_{\text{at}} = 0$

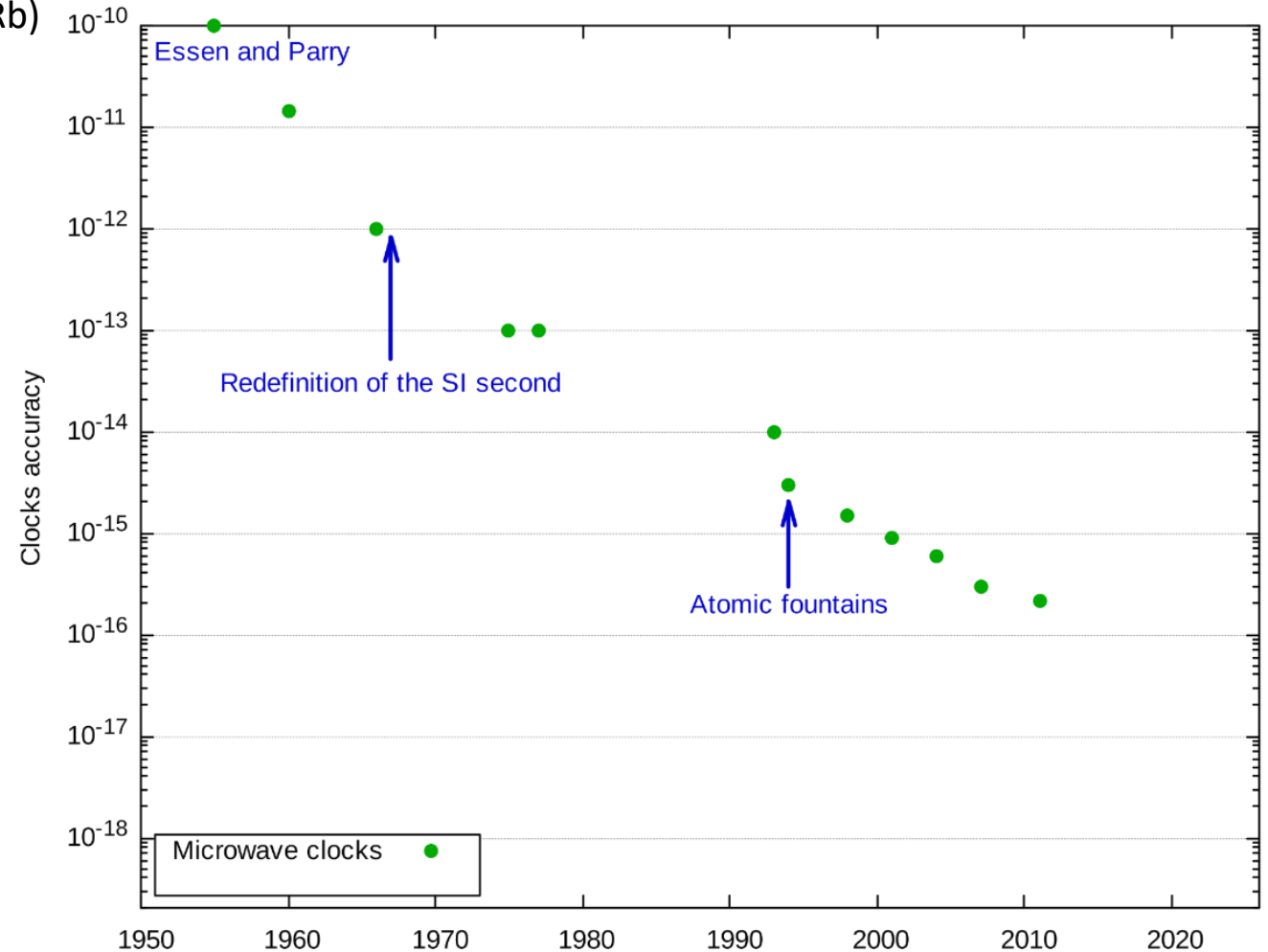
# The first atomic clocks

## Microwave clocks ( $\sim 10$ GHz)

- ⇒ Based on an hyperfine transition (9.2 GHz for Cs, 6.8 GHz for Rb)
- ⇒ Best microwave clocks feature an accuracy of  $1 - 2 \times 10^{-16}$



FO2 dual fountain,  
LTE



# State-of-the-art atomic primary frequency standards

Accuracy budget of the FO2 fountain :

|                                                                             | Corrections (in $10^{-16}$ ) | Uncertainty (in $10^{-16}$ ) |
|-----------------------------------------------------------------------------|------------------------------|------------------------------|
| Quadratic Zeeman shift                                                      | -1915.9                      | 0.3                          |
| Collisions and cavity pulling                                               | 112.0                        | 1.2                          |
| Spectral purity (spurious sidebands), leakage, synchronous phase modulation | 0                            | <0.5                         |
| Raby and Ramsey pulling                                                     | 0                            | <0.1                         |
| Background collisions                                                       | 0                            | 1.0                          |
| Black-body radiation shift                                                  | 168.0                        | 0.6                          |
| Distributed cavity phase shift (=Residual 1 <sup>st</sup> order Doppler)    | -0.9                         | 0.9                          |
| Microwave lensing (=microwave recoil)                                       | -0.7                         | 0.7                          |
| Second order Doppler shift                                                  | 0                            | 0.1                          |
| <b>Total</b>                                                                | <b>-1637.5</b>               | <b>2.1</b>                   |

The systematic effects can be classified in 3 categories:

→ Effects independent of the frequency

→ Effect tightly connected to the full atomic structure

→ Effects depending on the frequency

Guéna et al., Progress in Atomic Fountains at LNE-SYRTE, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 59, pages 391-420 (2012)

# Why go optical? ( $\sim 10^{15}$ Hz)

|                                                                                |
|--------------------------------------------------------------------------------|
|                                                                                |
| Quadratic Zeeman shift                                                         |
| Collisions and cavity pulling                                                  |
| Spectral purity (spurious sidebands),<br>leakage, synchronous phase modulation |
| Raby and Ramsey pulling                                                        |
| Background collisions                                                          |
| Black-body radiation shift                                                     |
| Distributed cavity phase shift<br>(=Residual 1 <sup>st</sup> order Doppler)    |
| Microwave lensing (=microwave recoil)                                          |
| Second order Doppler shift                                                     |
| Total                                                                          |

- ⇒ Because state-of-the art **optical oscillators (lasers) are more stable** than microwave sources
  - ⇒ Best lasers have a linewidth of 5-10 mHz
  - ⇒ D. Lee et al., arXiv:2509.13503
  - ⇒ D. G. Matei et al., PRL **118**, 263202 (2017)
- ⇒ Because of the availability of **very narrow atomic transitions**, that can be (nearly) resolved by the best optical oscillators
  - ⇒ 1 mHz large in neutral Sr 87
  - ⇒ 10 mHz large in neutral Yb 171
- ⇒ Because atoms are **less sensitive** in relative value to **most** external perturbations.
  - ⇒ Example: the Zeeman first order shift is:

$$\Delta\nu = (m'g' - mg)\frac{\mu_B B}{h}$$

# Optical clocks: why oh why?

Sounds easy peasy but ... 2 main difficulties:

1. Necessity to reach the **Lamb-Dicke regime**
2. Necessity to be able to **measure the frequency in 'Caesium Hertz'**

## 1. Necessity to reach the **Lamb-Dicke regime**

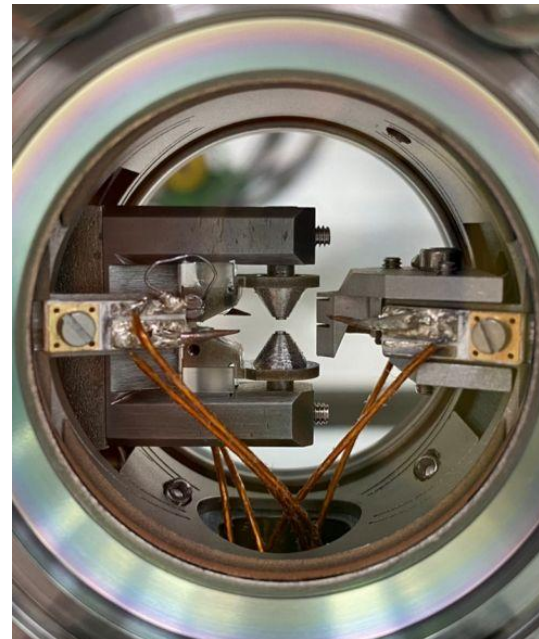
- ⇒ **Ion clocks: strong confinement mastered already in the 80's**
- ⇒ With neutral atoms ... it took until 2003 to find a solution



Wolfgang Paul



Hans Dehmelt



Yb+ clock NPL (courtesy of Rachel Godun)



Multi ion clock @PTB (courtesy of Tanja Mehlstaebler)

# Optical clocks: why oh why?

Sounds easy peasy but ... 2 main difficulties:

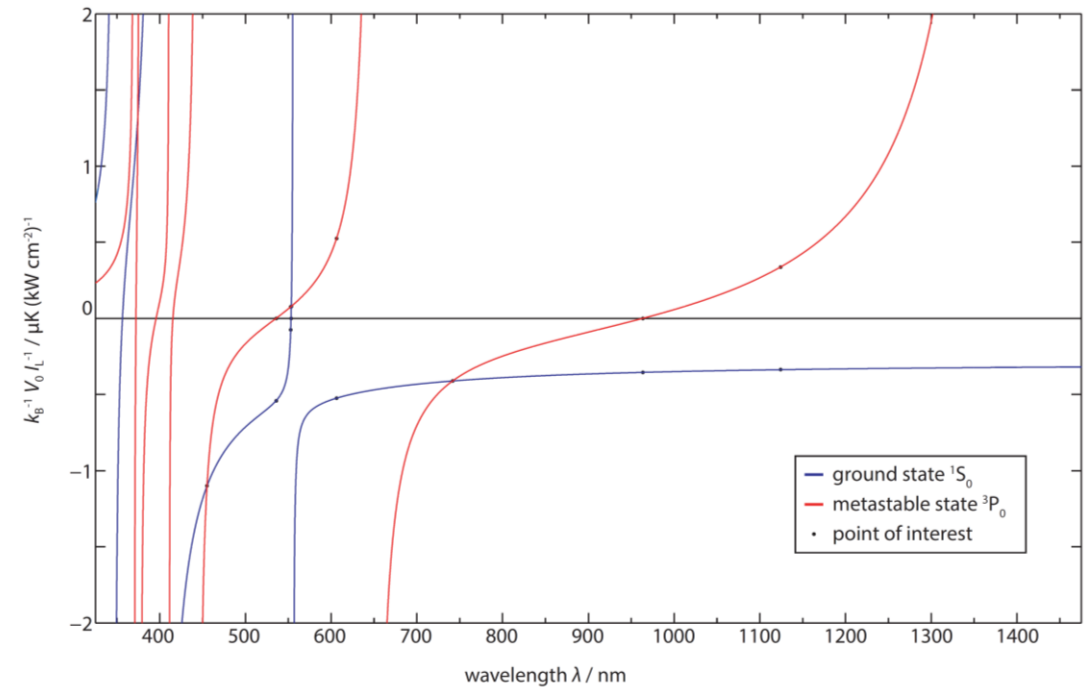
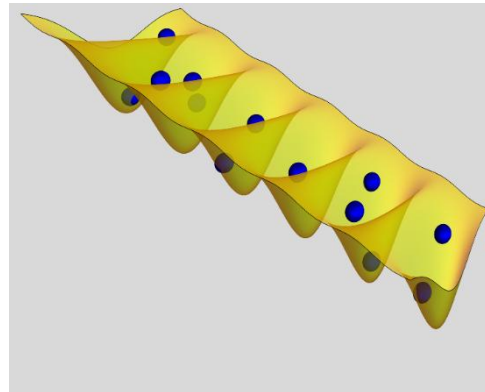
1. Necessity to reach the **Lamb-Dicke regime**
2. Necessity to be able to **measure the frequency in 'Caesium Hertz'**

## 1. Necessity to reach the **Lamb-Dicke regime**

- ⇒ **Ion clocks: strong confinement mastered already in the 80's**
- ⇒ With neutral atoms ... it took until 2003 to find a solution



Hidetoshi  
Katori

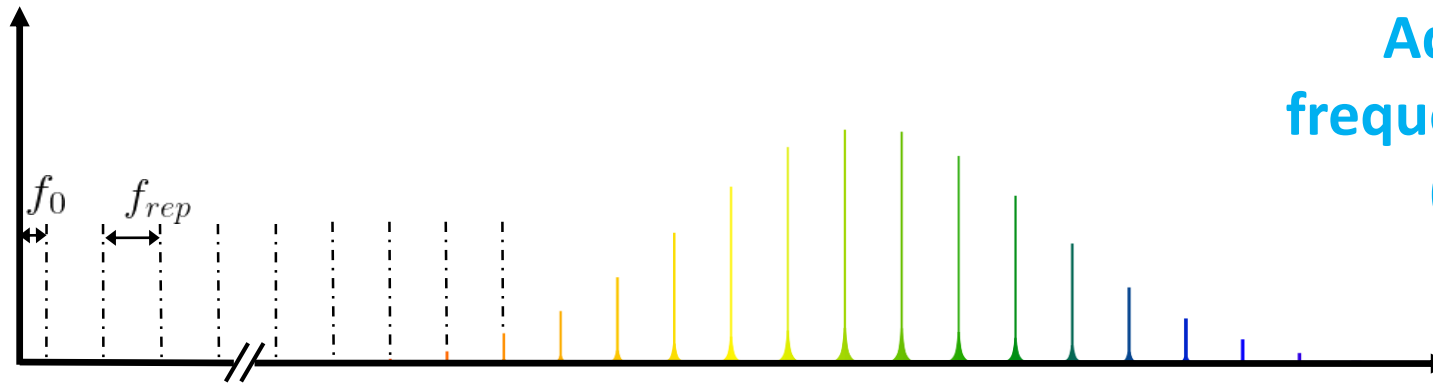


# Optical clocks: why oh why?

Sounds easy peasy but ... 2 main difficulties:

1. Necessity to reach the **Lamb-Dicke regime**
2. Necessity to be able to **measure the frequency in 'Caesium Hertz'**

**2.** Necessity to  
measure simply  
frequency ratios  
optical vs microwave



**Advent of  
frequency combs  
(2000)**

$$\nu_N = N f_{\text{rep}} + f_0$$

Both measurable  
vs microwave standards

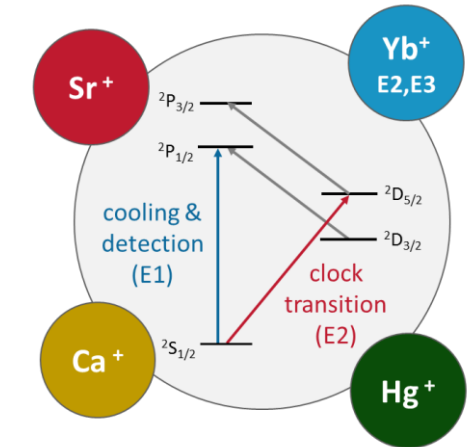
# Which atoms do feature a narrow optical transition?

## PERIODIC TABLE OF ELEMENTS

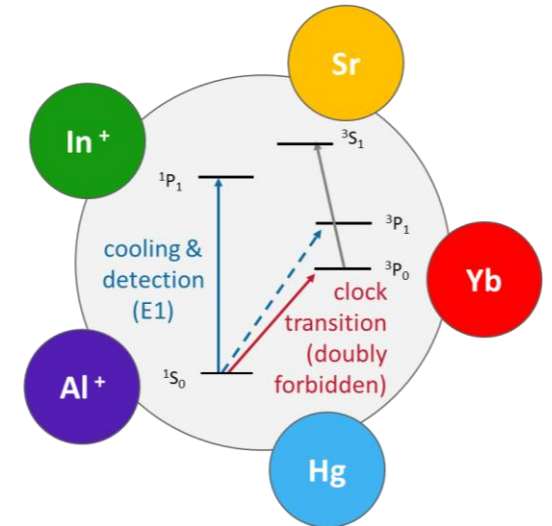
| GROUP  | 1                       | 2                        |                          |                              |                             |                           |                           |                          |                           |                             |                            |                            | 13                         | 14                       | 15                         | 16                         | 17                        | 18                       |
|--------|-------------------------|--------------------------|--------------------------|------------------------------|-----------------------------|---------------------------|---------------------------|--------------------------|---------------------------|-----------------------------|----------------------------|----------------------------|----------------------------|--------------------------|----------------------------|----------------------------|---------------------------|--------------------------|
| PERIOD | 1                       | 2                        | 3                        | 4                            | 5                           | 6                         | 7                         | 8                        | 9                         | 10                          | 11                         | 12                         | 13                         | 14                       | 15                         | 16                         | 17                        | 18                       |
| 1      | H<br>Hydrogen<br>1.008  |                          |                          |                              |                             |                           |                           |                          |                           |                             |                            |                            |                            |                          |                            |                            |                           | He<br>Helium<br>4.003    |
| 2      | Li<br>Lithium<br>6.94   | Be<br>Beryllium<br>9.012 |                          |                              |                             |                           |                           |                          |                           |                             |                            |                            | B<br>Boron<br>10.81        | C<br>Carbon<br>12.01     | N<br>Nitrogen<br>14.01     | O<br>Oxygen<br>16.00       | F<br>Fluorine<br>19.00    | Ne<br>Neon<br>20.18      |
| 3      | Na<br>Sodium<br>22.99   | Mg<br>Magnesium<br>24.31 |                          |                              |                             |                           |                           |                          |                           |                             |                            |                            | Al<br>Aluminium<br>26.98   | Si<br>Silicon<br>28.09   | P<br>Phosphorus<br>30.97   | S<br>Sulfur<br>32.06       | Cl<br>Chlorine<br>35.45   | Ar<br>Argon<br>39.95     |
| 4      | K<br>Potassium<br>39.10 | Ca<br>Calcium<br>40.08   | Sc<br>Scandium<br>44.96  | Ti<br>Titanium<br>47.88      | V<br>Vanadium<br>50.94      | Cr<br>Chromium<br>52.00   | Mn<br>Manganese<br>54.94  | Fe<br>Iron<br>55.85      | Co<br>Cobalt<br>58.93     | Ni<br>Nickel<br>58.69       | Cu<br>Copper<br>63.55      | Zn<br>Zinc<br>65.39        | Ga<br>Gallium<br>69.72     | Ge<br>Germanium<br>72.64 | As<br>Arsenic<br>74.92     | Se<br>Selenium<br>78.96    | Br<br>Bromine<br>79.90    | Kr<br>Krypton<br>83.79   |
| 5      | Rb<br>Rubidium<br>85.47 | Sr<br>Strontium<br>87.62 | Y<br>Yttrium<br>88.91    | Zr<br>Zirconium<br>91.22     | Nb<br>Niobium<br>92.91      | Mo<br>Molybdenum<br>95.96 | Tc<br>Technetium<br>(98)  | Ru<br>Ruthenium<br>101.1 | Rh<br>Rhodium<br>102.9    | Pd<br>Palladium<br>106.4    | Ag<br>Silver<br>107.9      | Cd<br>Cadmium<br>112.4     | In<br>Indium<br>114.8      | Sn<br>Tin<br>118.7       | Sb<br>Antimony<br>121.8    | Te<br>Tellurium<br>127.6   | I<br>Iodine<br>126.9      | Xe<br>Xenon<br>131.3     |
| 6      | Cs<br>Caesium<br>132.9  | Ba<br>Barium<br>137.3    | 57-71<br>Lanthanides     | Hf<br>Hafnium<br>178.5       | Ta<br>Tantalum<br>180.9     | W<br>Tungsten<br>183.9    | Re<br>Rhenium<br>186.2    | Os<br>Osmium<br>190.2    | Ir<br>Iridium<br>192.2    | Pt<br>Platinum<br>195.1     | Au<br>Gold<br>197.0        | Hg<br>Mercury<br>200.5     | Tl<br>Thallium<br>204.38   | Pb<br>Lead<br>207.2      | Bi<br>Bismuth<br>209.0     | Po<br>Polonium<br>(209)    | At<br>Astatine<br>(210)   | Rn<br>Radon<br>(222)     |
| 7      | Fr<br>Francium<br>(223) | Ra<br>Radium<br>(226)    | 89-103<br>Actinides      | Rf<br>Rutherfordium<br>(261) | Db<br>Dubnium<br>(268)      | Sg<br>Seaborgium<br>(271) | Bh<br>Bohrium<br>(270)    | Hs<br>Hassium<br>(277)   | Mt<br>Meitnerium<br>(276) | Ds<br>Darmstadtium<br>(281) | Rg<br>Roentgenium<br>(280) | Cn<br>Copernicium<br>(285) | Nh<br>Nihonium<br>(284)    | Fl<br>Flerovium<br>(289) | Mc<br>Moscovium<br>(288)   | Lv<br>Livermorium<br>(293) | Ts<br>Tennessine<br>(294) | Og<br>Oganesson<br>(294) |
|        |                         |                          | 57                       | 58                           | 59                          | 60                        | 61                        | 62                       | 63                        | 64                          | 65                         | 66                         | 67                         | 68                       | 69                         | 70                         | 71                        |                          |
|        |                         |                          | La<br>Lanthanum<br>138.9 | Ce<br>Cerium<br>140.1        | Pr<br>Praseodymium<br>140.9 | Nd<br>Neodymium<br>144.2  | Pm<br>Promethium<br>(145) | Sm<br>Samarium<br>150.4  | Eu<br>Europium<br>152.0   | Gd<br>Gadolinium<br>157.3   | Tb<br>Terbium<br>158.9     | Dy<br>Dysprosium<br>162.5  | Ho<br>Holmium<br>164.9     | Er<br>Erbium<br>167.3    | Tm<br>Thulium<br>168.9     | Yb<br>Ytterbium<br>173.0   | Lu<br>Lutetium<br>175.0   |                          |
|        |                         |                          | 89                       | 90                           | 91                          | 92                        | 93                        | 94                       | 95                        | 96                          | 97                         | 98                         | 99                         | 100                      | 101                        | 102                        | 103                       |                          |
|        |                         |                          | Ac<br>Actinium<br>(227)  | Th<br>Thorium<br>232.0       | Pa<br>Protactinium<br>231.0 | U<br>Uranium<br>238.0     | Np<br>Neptunium<br>(237)  | Pu<br>Plutonium<br>(244) | Am<br>Americium<br>(243)  | Cm<br>Curium<br>(247)       | Bk<br>Berkelium<br>(247)   | Cf<br>Californium<br>(251) | Es<br>Einsteinium<br>(252) | Fm<br>Fermium<br>(257)   | Md<br>Mendelevium<br>(258) | No<br>Nobelium<br>(259)    | Lr<br>Lawrencium<br>(262) |                          |

- Species suitable to **microwave** clocks
- Species suitable to **optical** clocks based on neutral **atoms**
- Species suitable to **optical** clocks based on **ions**

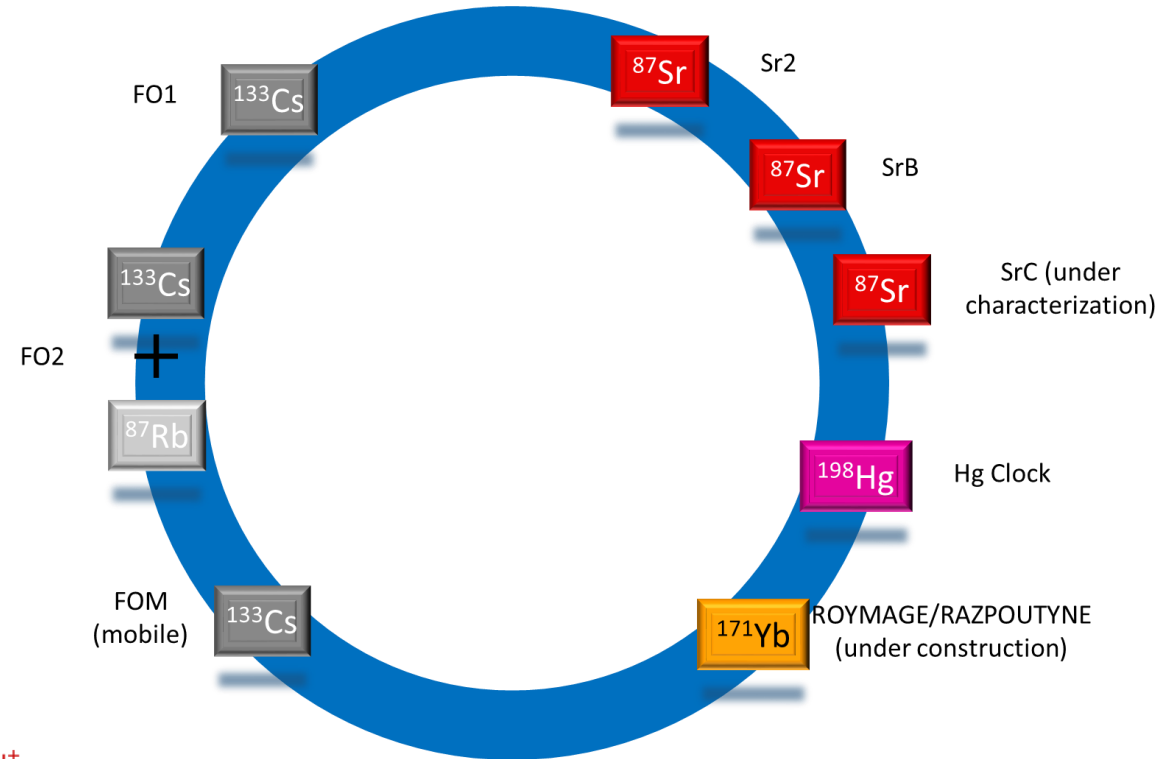
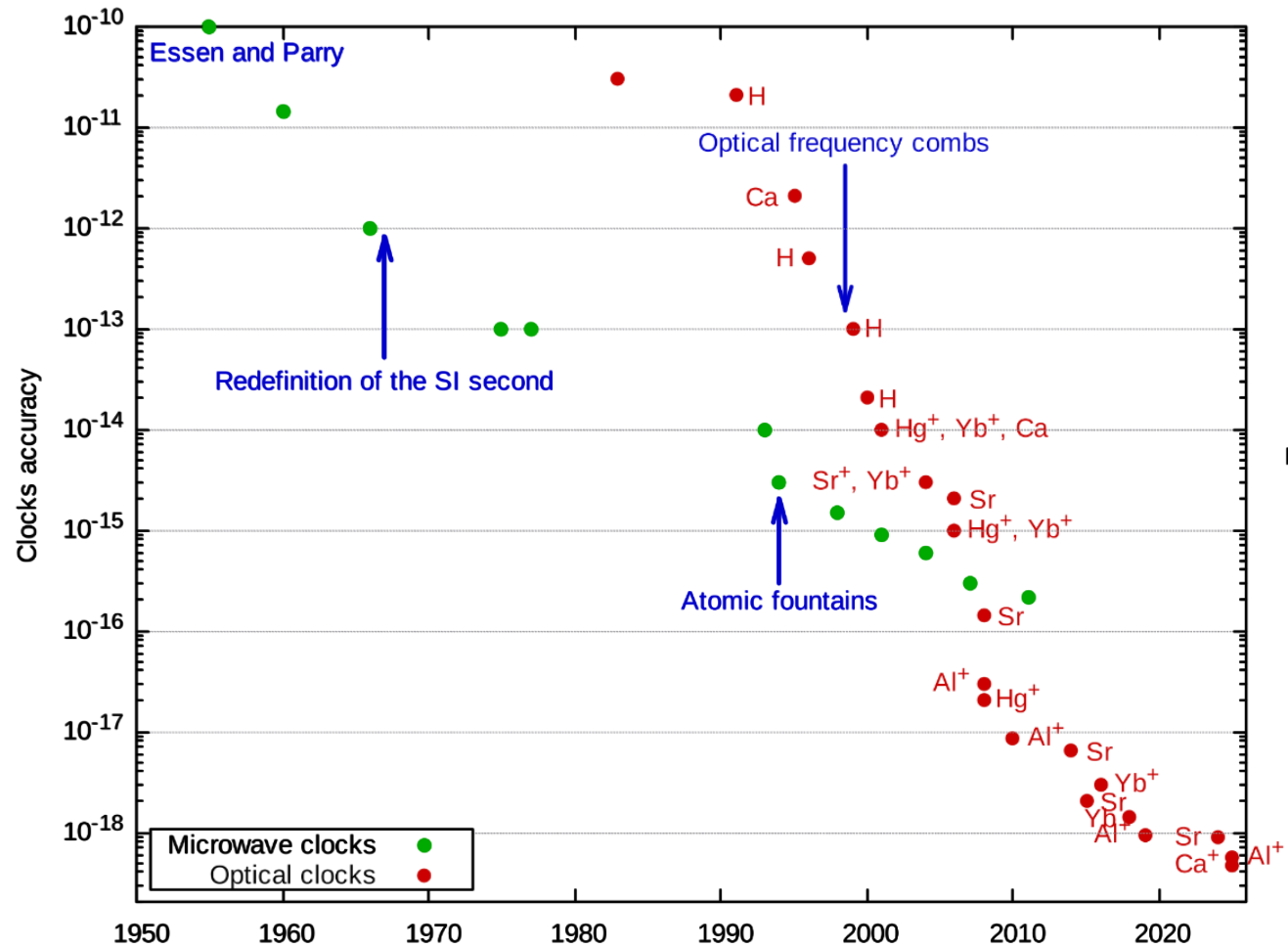
Alkali-like: one valence electron



Alkaline earth-like: two valence electrons

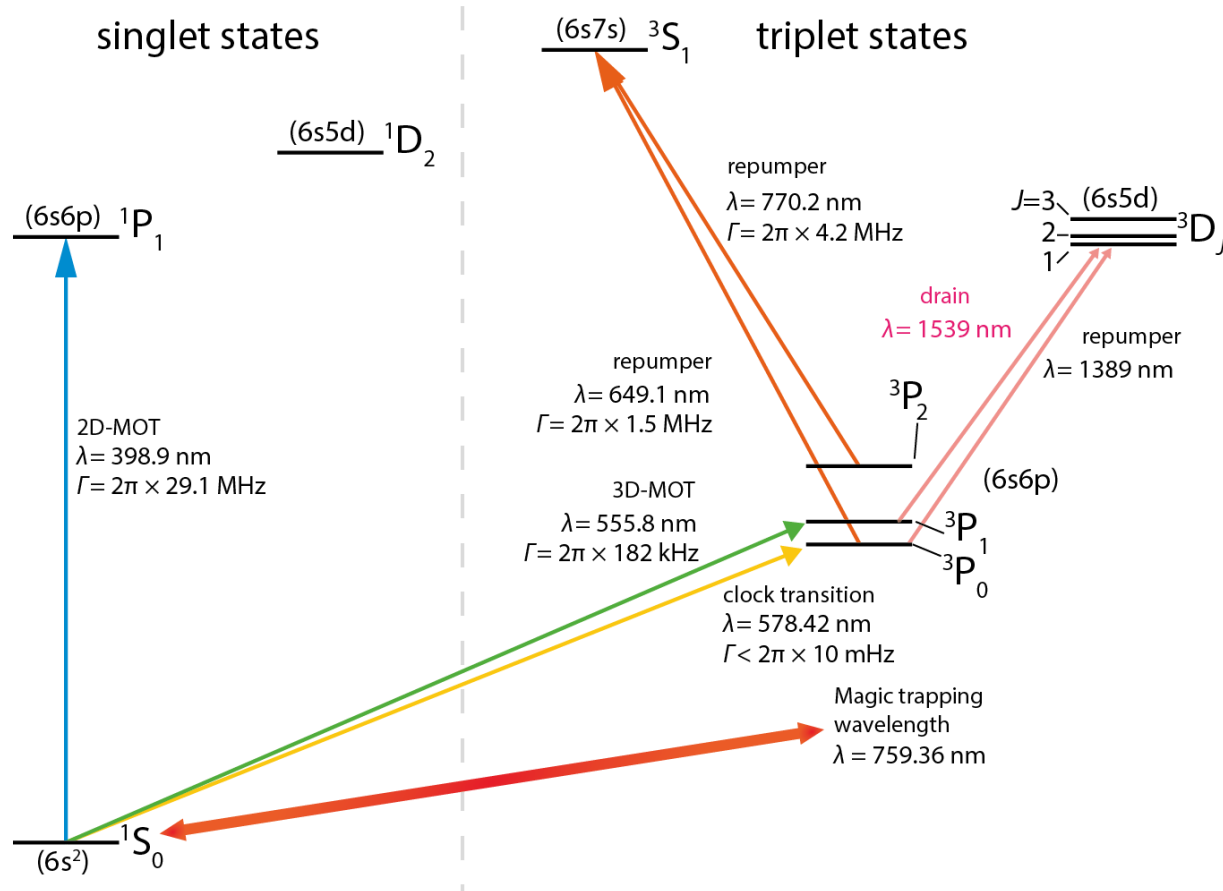


# Progress of optical clocks



# **Practical Operation of Atomic clocks**

# Optical clock: example of ytterbium (isotope 171)



Levels scheme of Yb 171

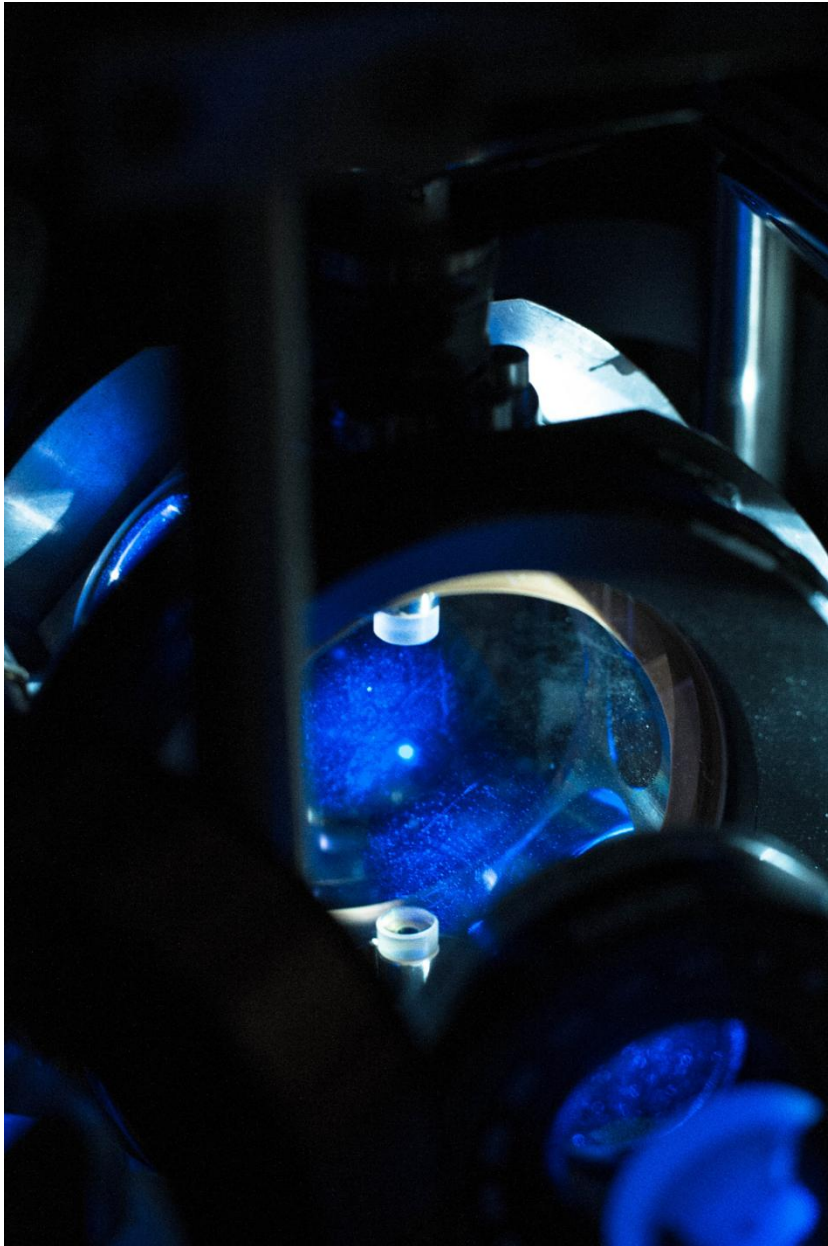
## PROS

- ⇒ Clocks based on a  $1S_0 \rightarrow 3P_0$  transition (Almost) forbidden transition: natural quality factor in the  $10^{-17}$  or even  $10^{-18}$  range!
- Very little sensitive to magnetic fields
- ⇒ Magic optical traps + spherical orbitals, very little sensitive to the polarization of the trap
- ⇒ Heavy atoms, favorable for the BBR shift

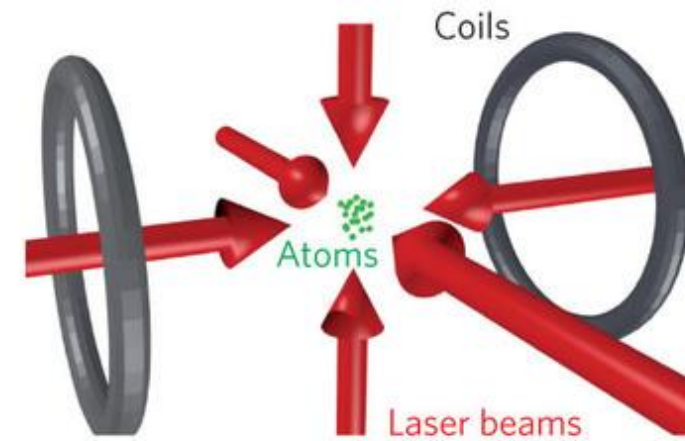
## CONS

- ⇒ Cooling is necessary to precool neutral atoms (neutrals are at a speed of  $\sim 400 \text{ m/s}$  at the output of an oven heated to  $500^\circ\text{C}$ )
- ⇒ Both for ion and neutrals: cooling in the trap is necessary to reach the motional ground state of the trapping potential
- ⇒ 5 or 6 different wavelengths necessary to manipulate the internal state of the atoms

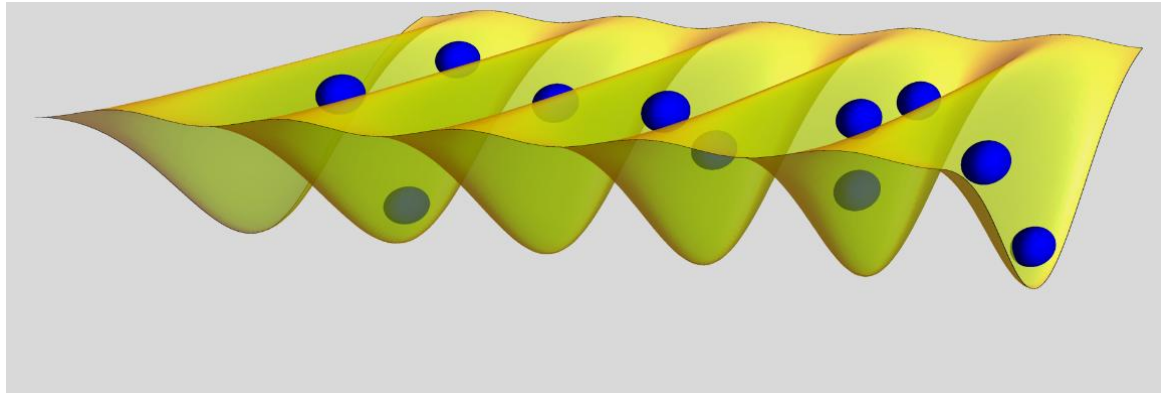
# Capture atoms with magneto-optical traps



Magneto-Optical trapping



# Optical lattices to reach the Lamb-Dicke regime



- Coupling occurs via the polarisability  $\alpha_g$ :

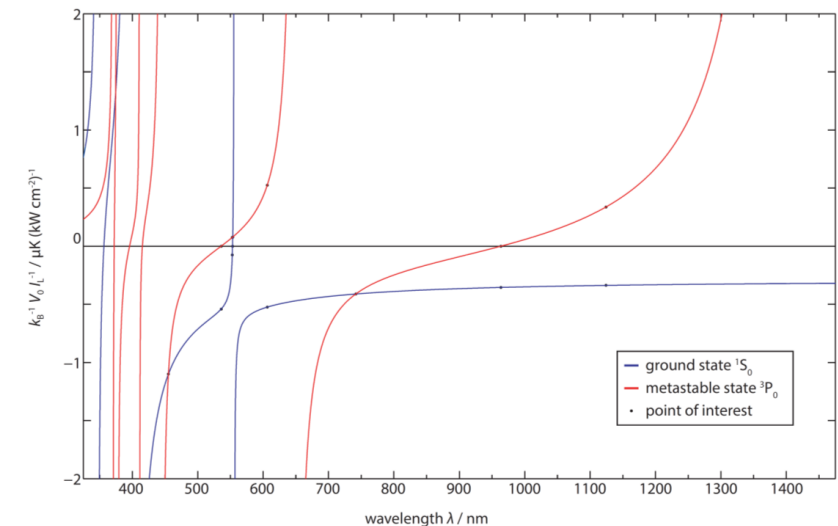
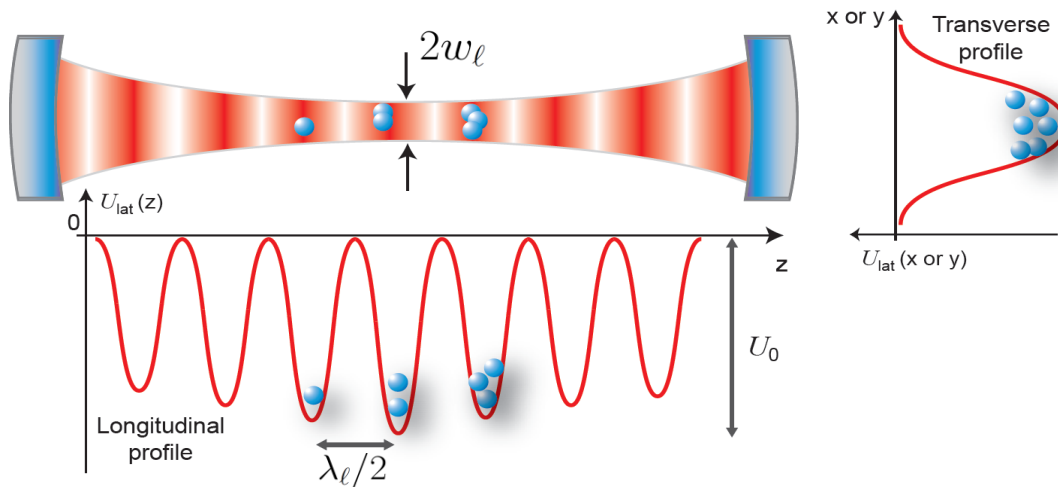
$$\text{Trapping potential} = -\frac{1}{2}\alpha_g I(\vec{r})$$

Under certain conditions, if caught in an intense light beam (intensity  $I(\vec{r})$ ), atoms will seek the **maximum of intensity**

- Problem: results in possibly very large light shift on every energy level

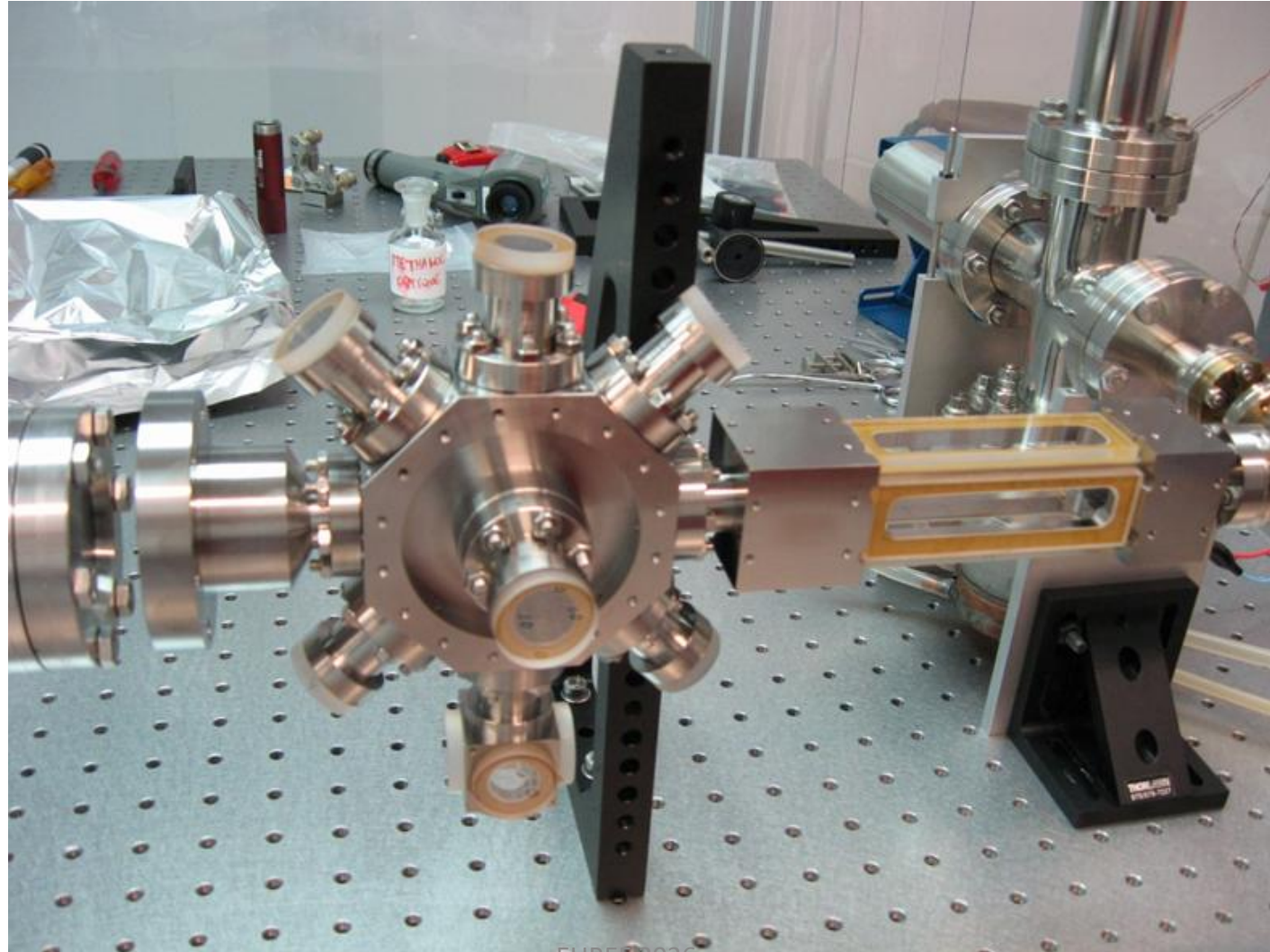
$$\nu_{\text{measured}} = \nu_0 - \frac{1}{2h}(\alpha_e - \alpha_g)I(\vec{r}) + \text{higher orders}$$

- But there are 'magic' crossings where the first-order shift is identical for both  $^1S_0$  and  $^3P_0$

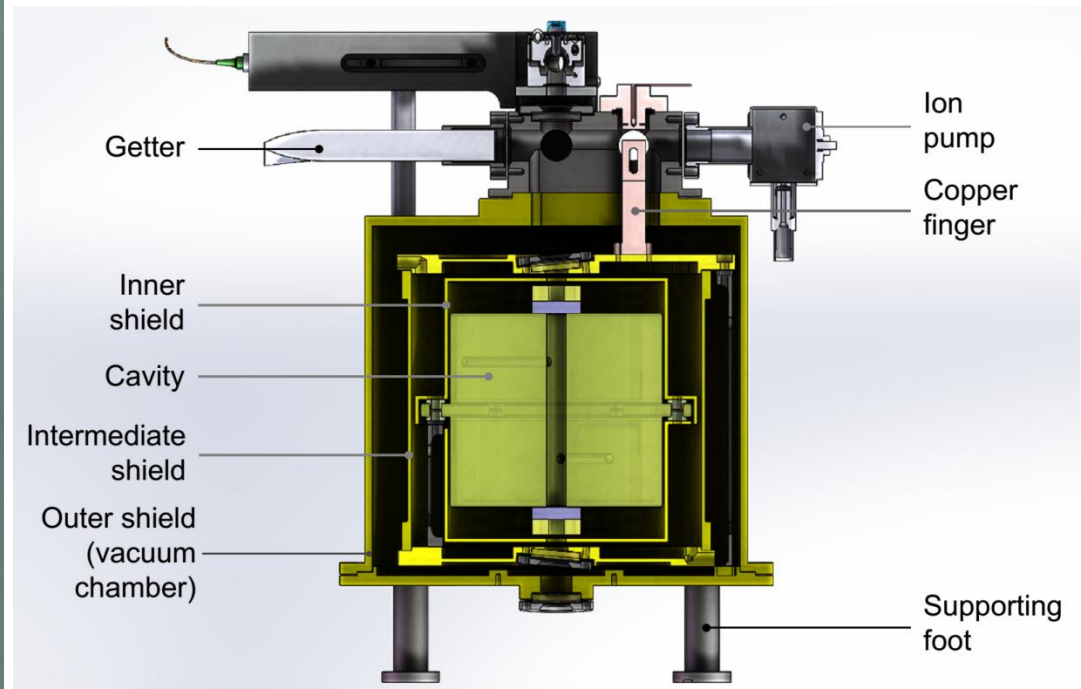
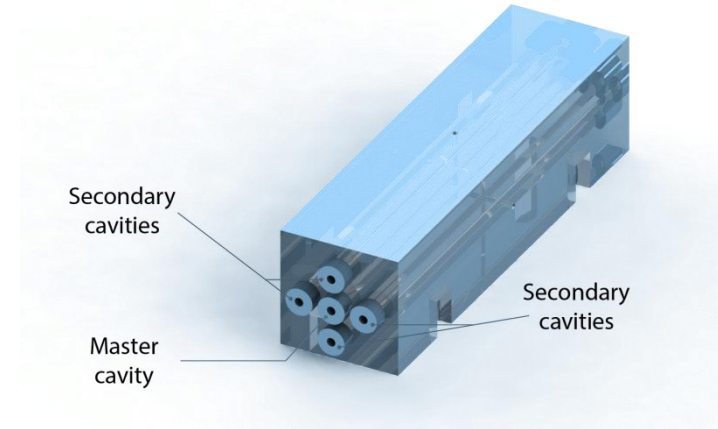
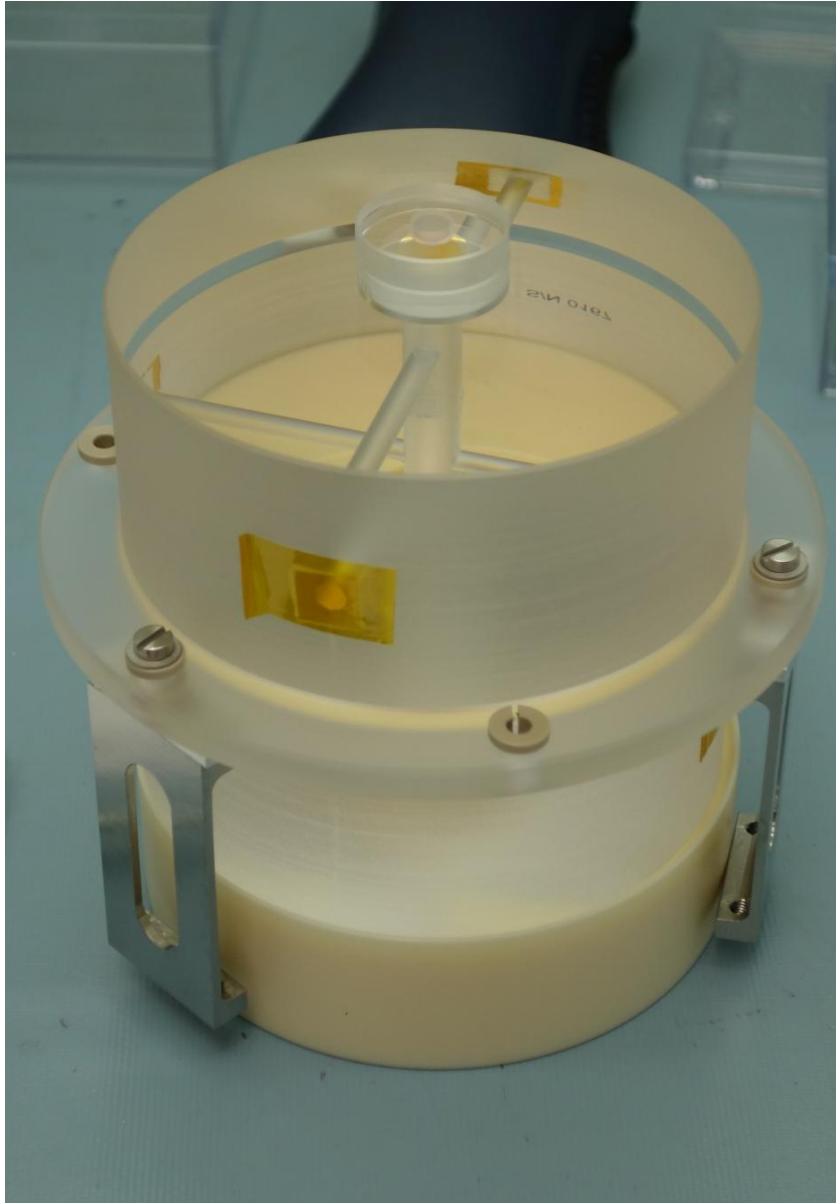


# Vacuum systems

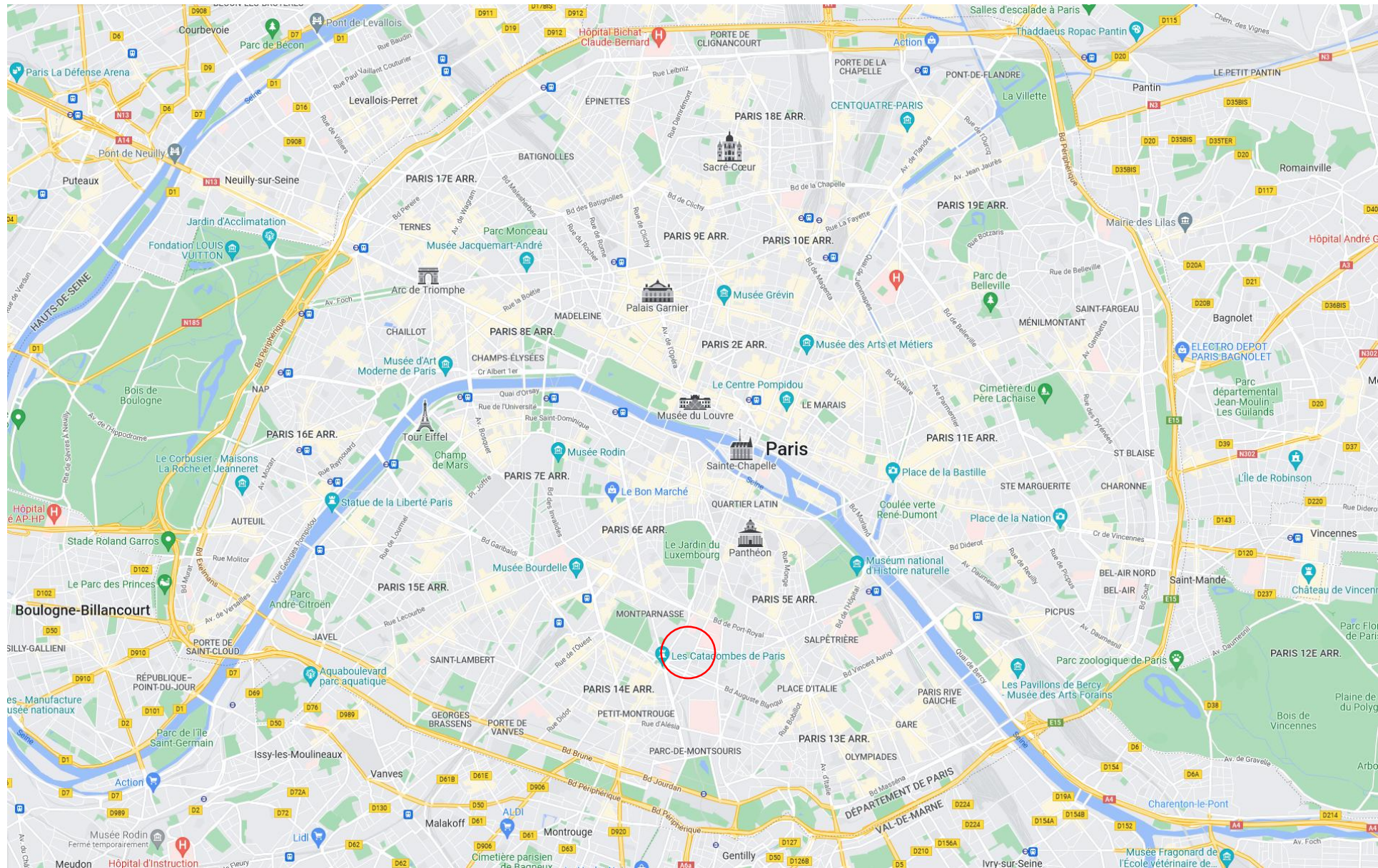
➔ We assemble vacuum systems able to reach vacuum as low as  $10^{-10}$  mbar



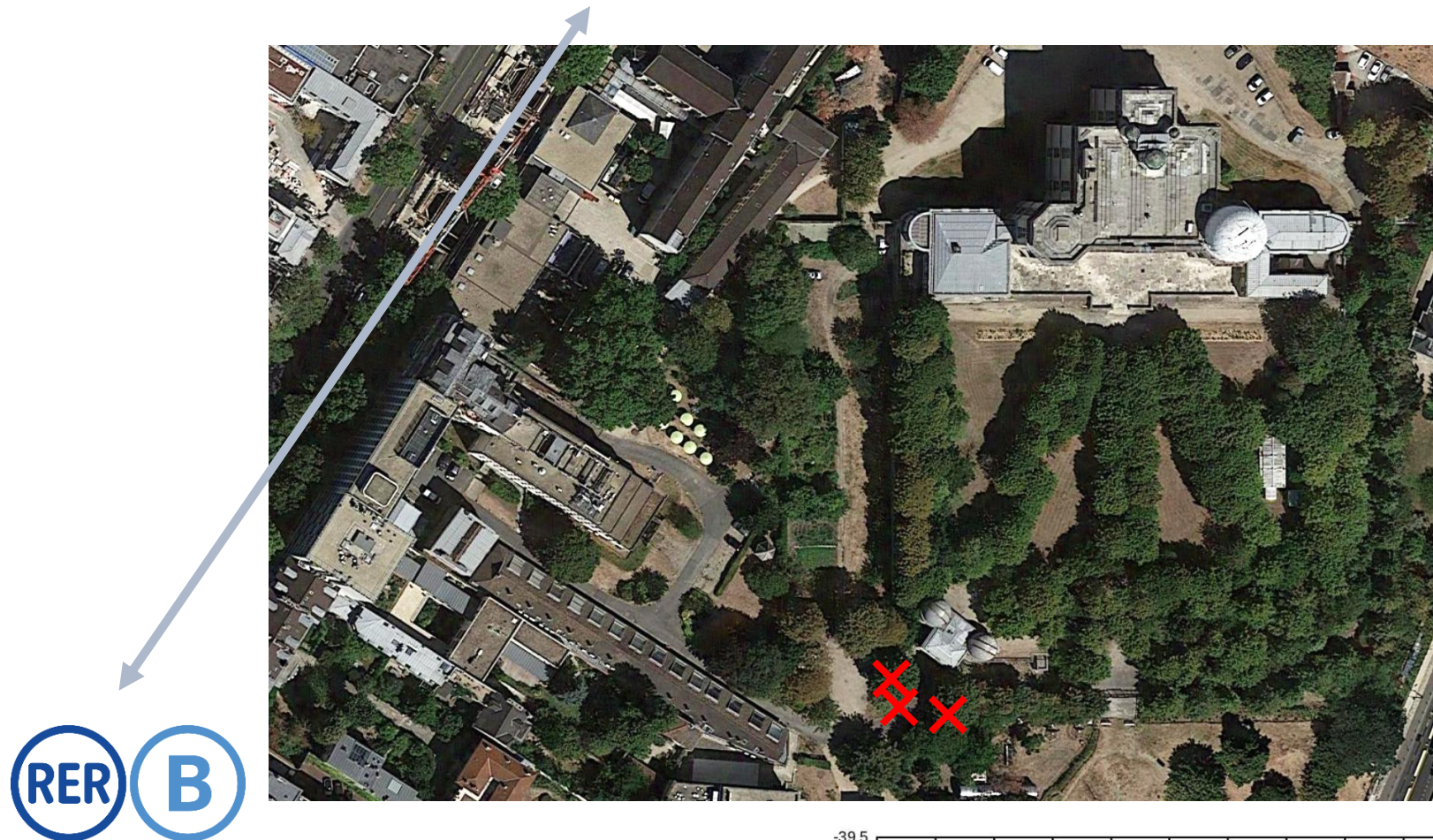
# High finesse optical cavities



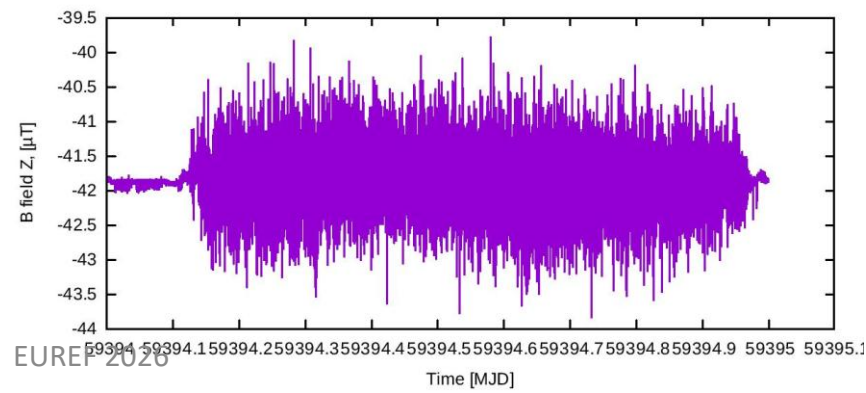
# Exemple de perturbation : champ magnétique du métro de Paris



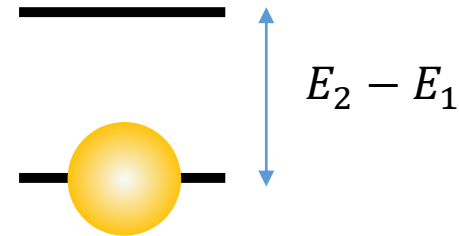
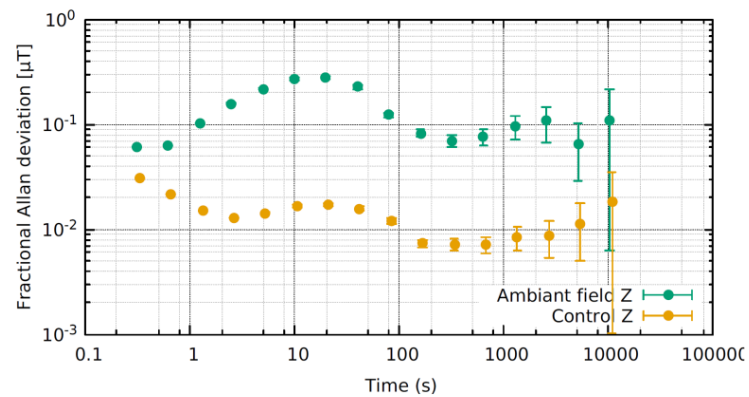
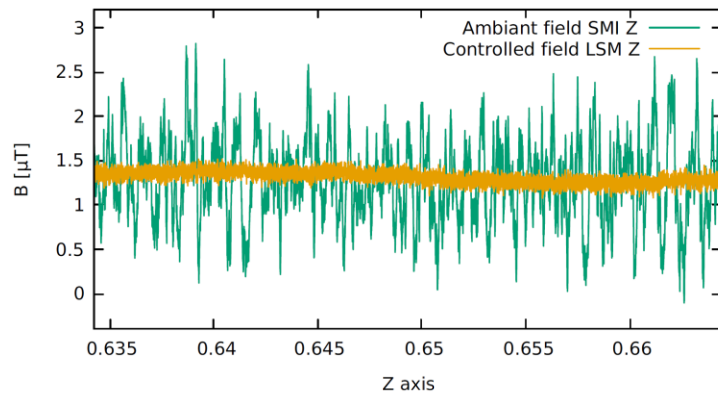
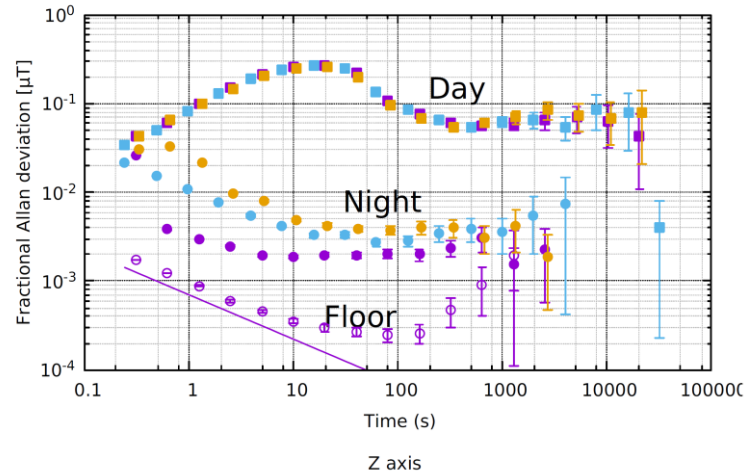
# Exemple de perturbation : champ magnétique du métro de Paris



⇒ Drastic change night/day



# Exemple de perturbation : champ magnétique du métro de Paris



⇒ La fréquence de l'horloge dépend (légèrement !) du champ magnétique

$$\nu = \nu_0 + \frac{\mu_B g_F m_F}{h} \mathbf{B} + \gamma \mathbf{B}^2$$

⇒ Flux gate magnetometer



# Applications of Atomic clocks

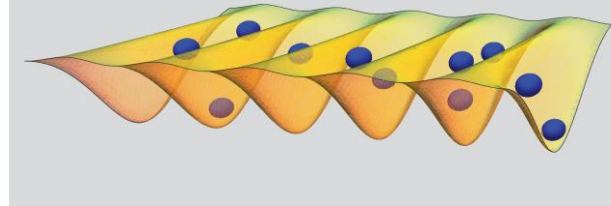
# Why do we need clocks?

Metrology: distribute frequency references, steer timescales

Test theories of fundamental Physics

Use the sensitivity of clocks to turn it into a detector

## Clocks



## Timescales

UTC

TAI

EAL

UTC(k)

Possible drift of fundamental constants ?

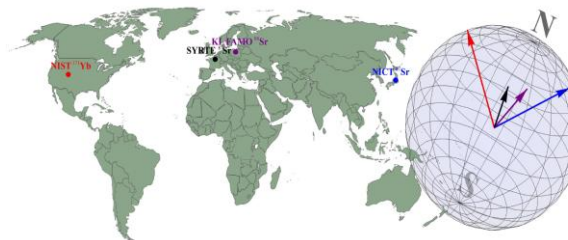
$$\frac{\delta(\nu_{Sr}/\nu_{Cs})}{\nu_{Sr}/\nu_{Cs}} = -2.77 \frac{\delta\alpha}{\alpha} - \frac{\delta\mu}{\mu}$$

Tests of Lorentz invariance

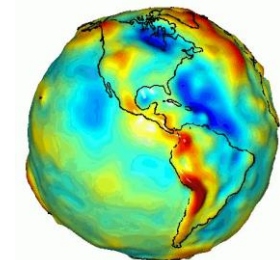
On Earth

Between Earth and space

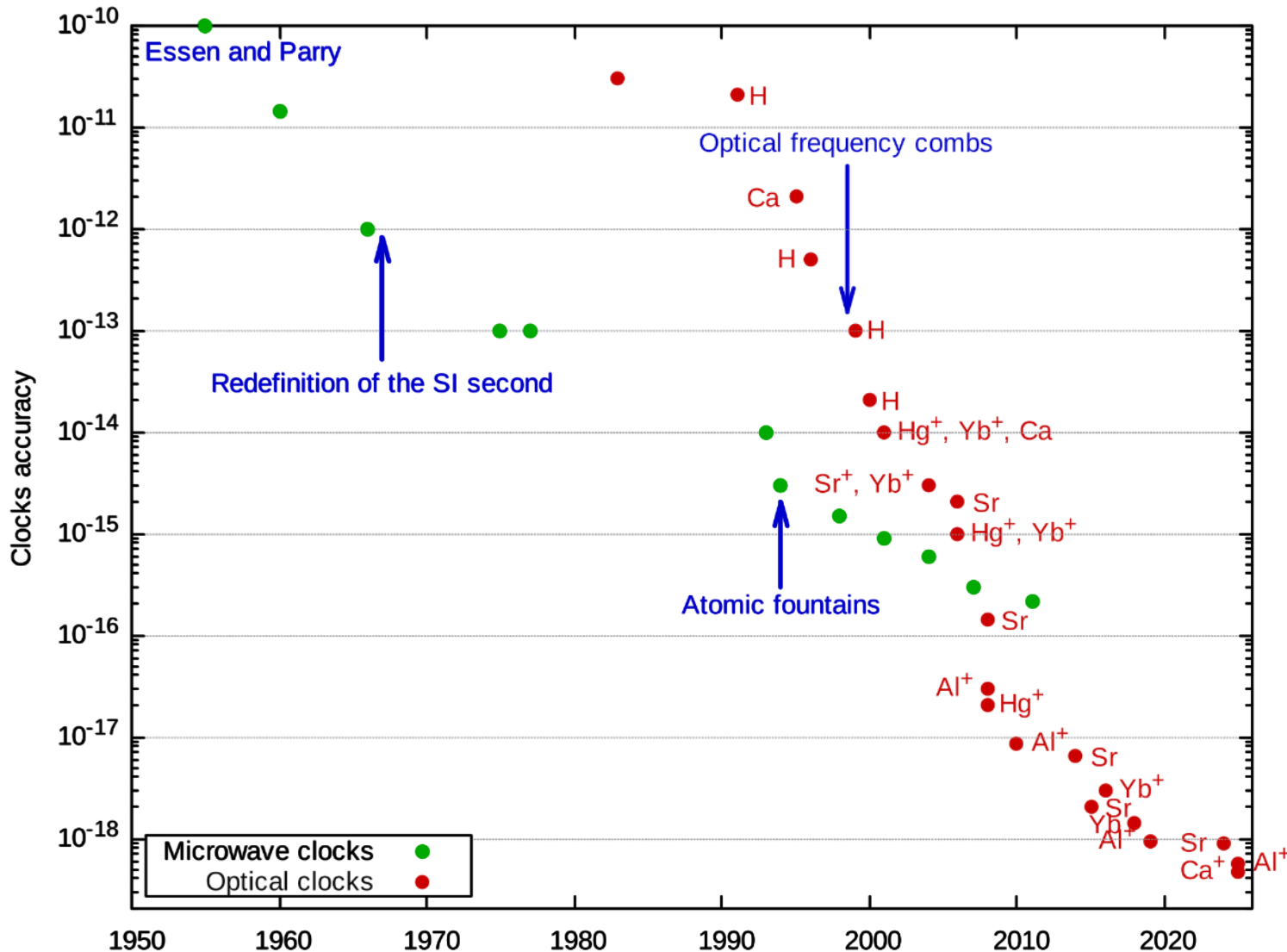
Search for Dark matter



Earth Sciences (Chronometric Geodesy)



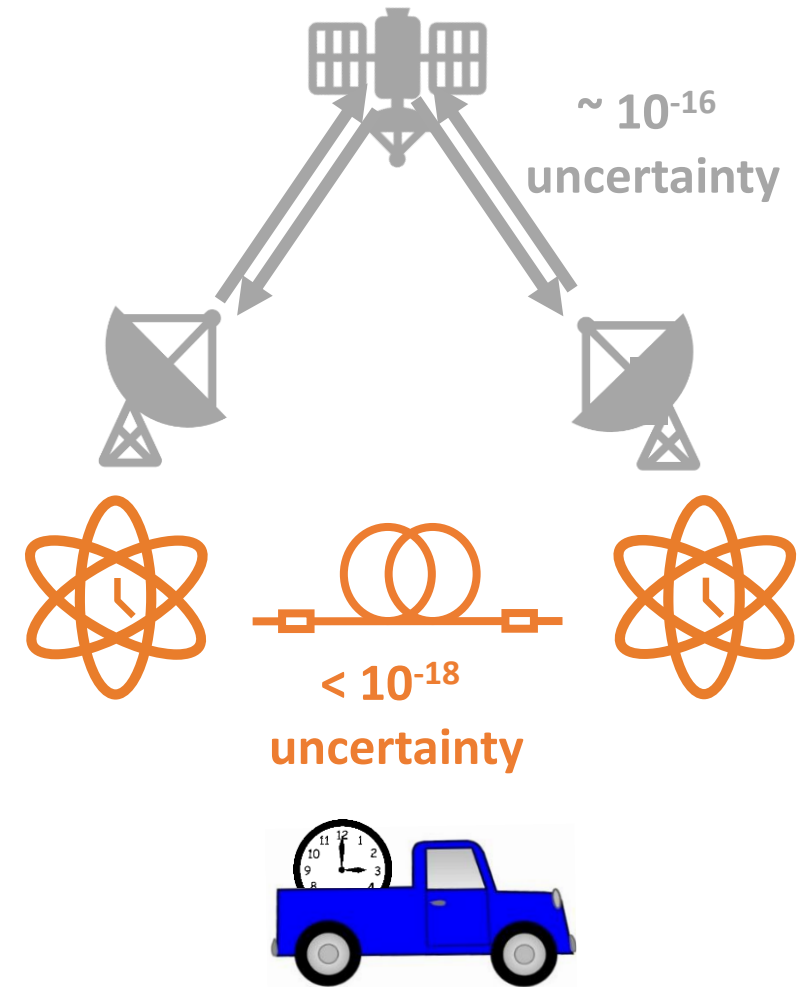
# Next definition of the second?



- ⇒ Absolute frequencies are still measured in units of Hz, i.e. relative to Cs (primary frequency standards)
- ⇒ Some transition are obviously better controlled than the best realizations of the current SI second
- ⇒ Time to choose a new definition !

# What's the plan?

- ⇒ International metrology community is **targeting 2030** for an optical redefinition
- ⇒ Series of milestones to meet before redefinition, including:
  - ⇒ Improve systematic **uncertainty budgets**
  - ⇒ **Verify performance** by comparing optical clocks globally
  - ⇒ Have more optical clocks **contributing to the international time scale**
  - ⇒ **Choose which atom or atoms** to include in the new definition



Slide provided by Rachel Godun, NPL, UK

Geodesy – study of the Earth's shape and gravity field

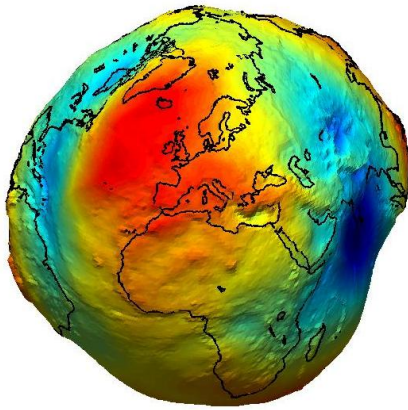


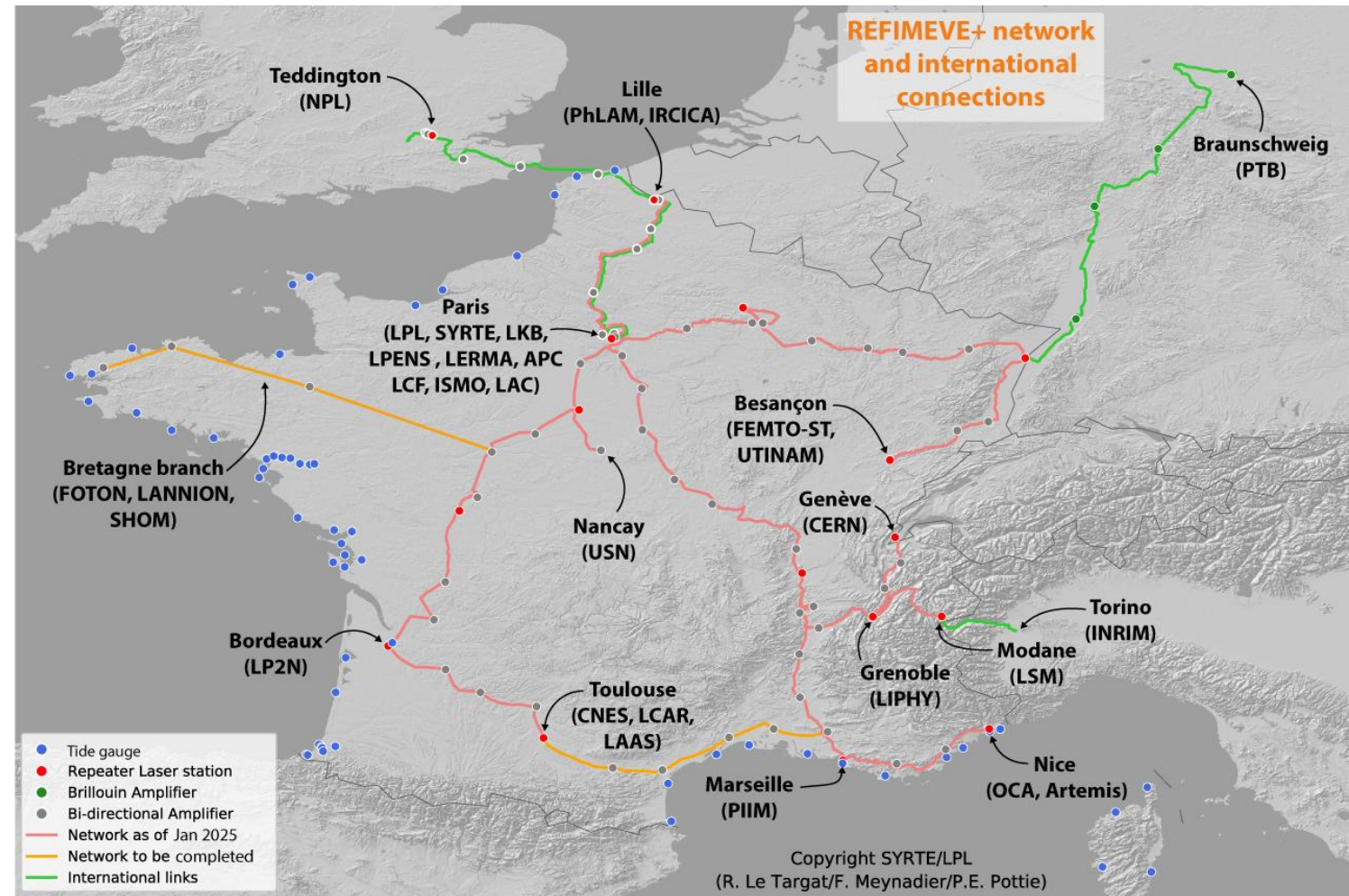
Image credit: ESA

- ⇒ Gravitational time dilation was predicted by Einstein in 1907
- ⇒ The rate at which the time runs depends on the referential the clock is in
- ⇒ The referential is different between two different heights because of the geopotential
- ⇒ Therefore two clocks at different heights will have a different frequency when they are compared one to the other:

$$\frac{\Delta \nu}{\nu} = \frac{\Delta W}{c^2} \approx \frac{g \cdot \Delta h}{c^2}$$

# Chronometric geodesy

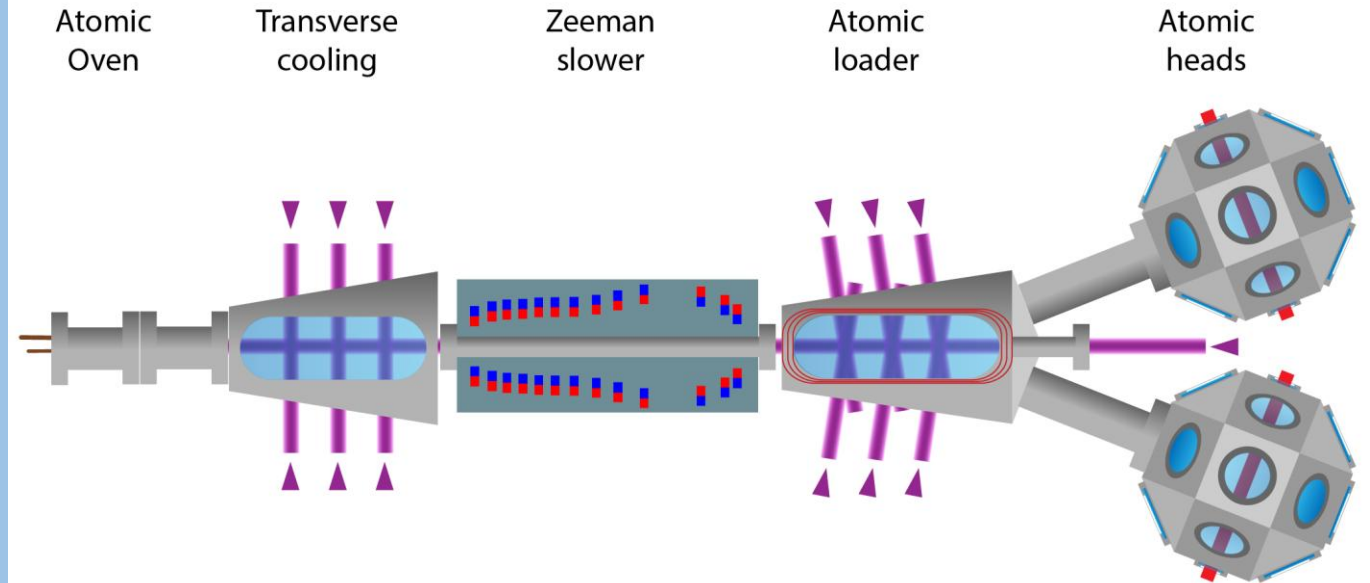
- ⇒ Remote comparisons between clocks provides a direct access to  $\Delta h$
- ⇒ Clocks measure directly the potential ( $\propto 1/r$ ), complementary to measurements performed by gravimeters (measure of the field,  $\propto 1/r^2$ )
- ⇒  $10^{-18}$  corresponds to  $\Delta h = 1 \text{ cm}$
- ⇒ Competitive with traditional leveling techniques
- ⇒ LTE started a transportable Yb clock in 2021, meant to be connected to the relevant part of the ~60 outputs of the REFIMEVE+ infrastructure to compare remotely to the ~12 European stationary optical clocks.



# Construction of two apparatus in parallel

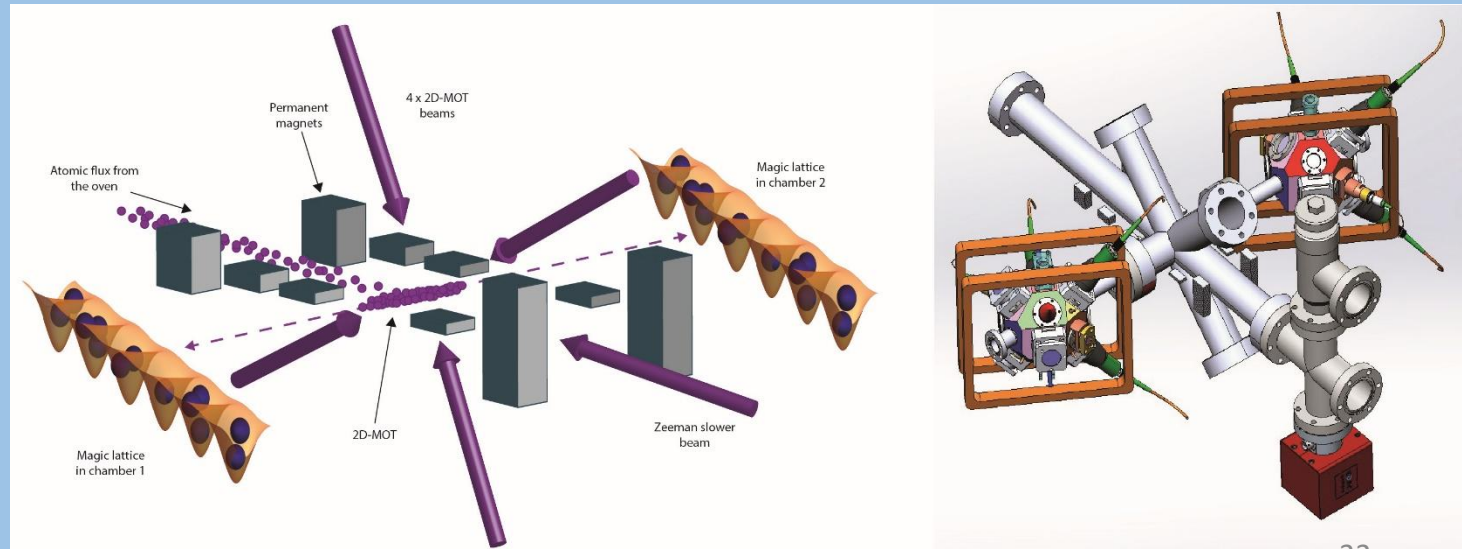
## ROYMAGE

(hoRloge Optique à Ytterbium Mobile  
Appliquée à l'exploration GEodésique)

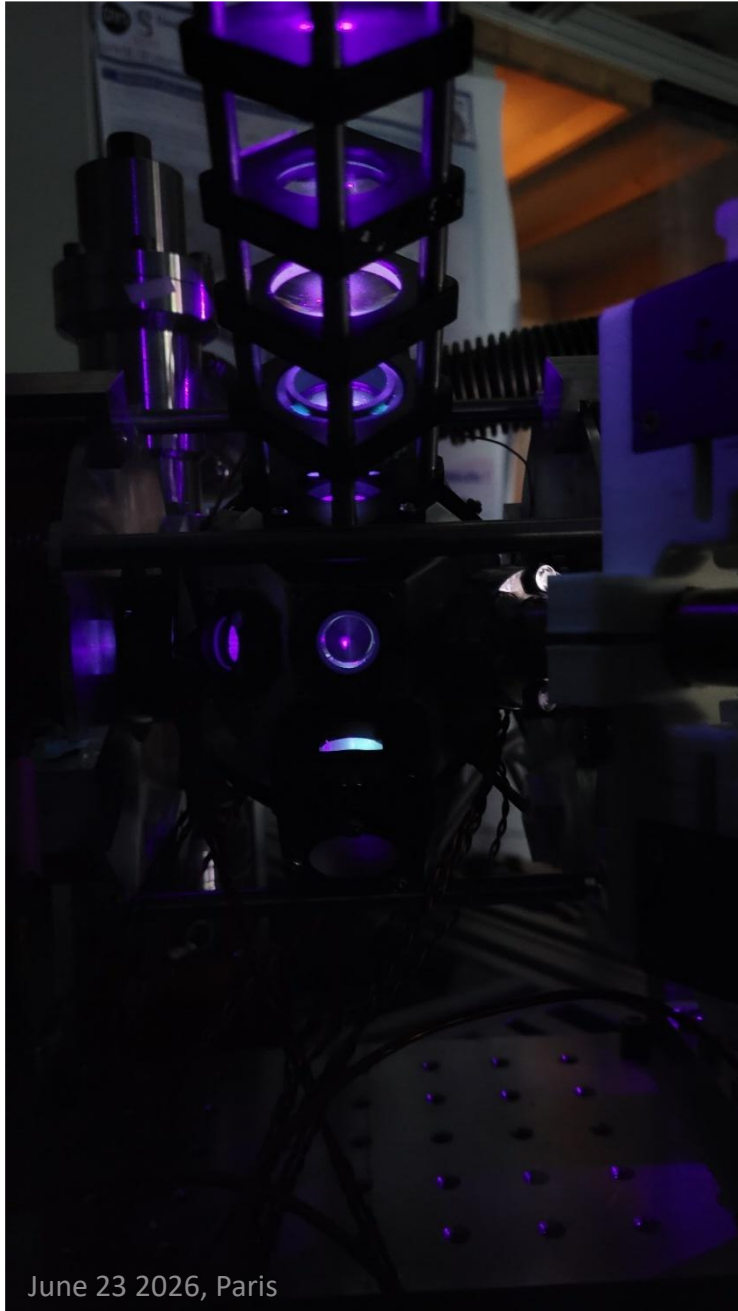


## RAZPOUTYNE

(RAlentisseur Zeeman et Piège  
magnéto-Optique Unifiés pour  
capTurer l'Ytterbium NEutre)

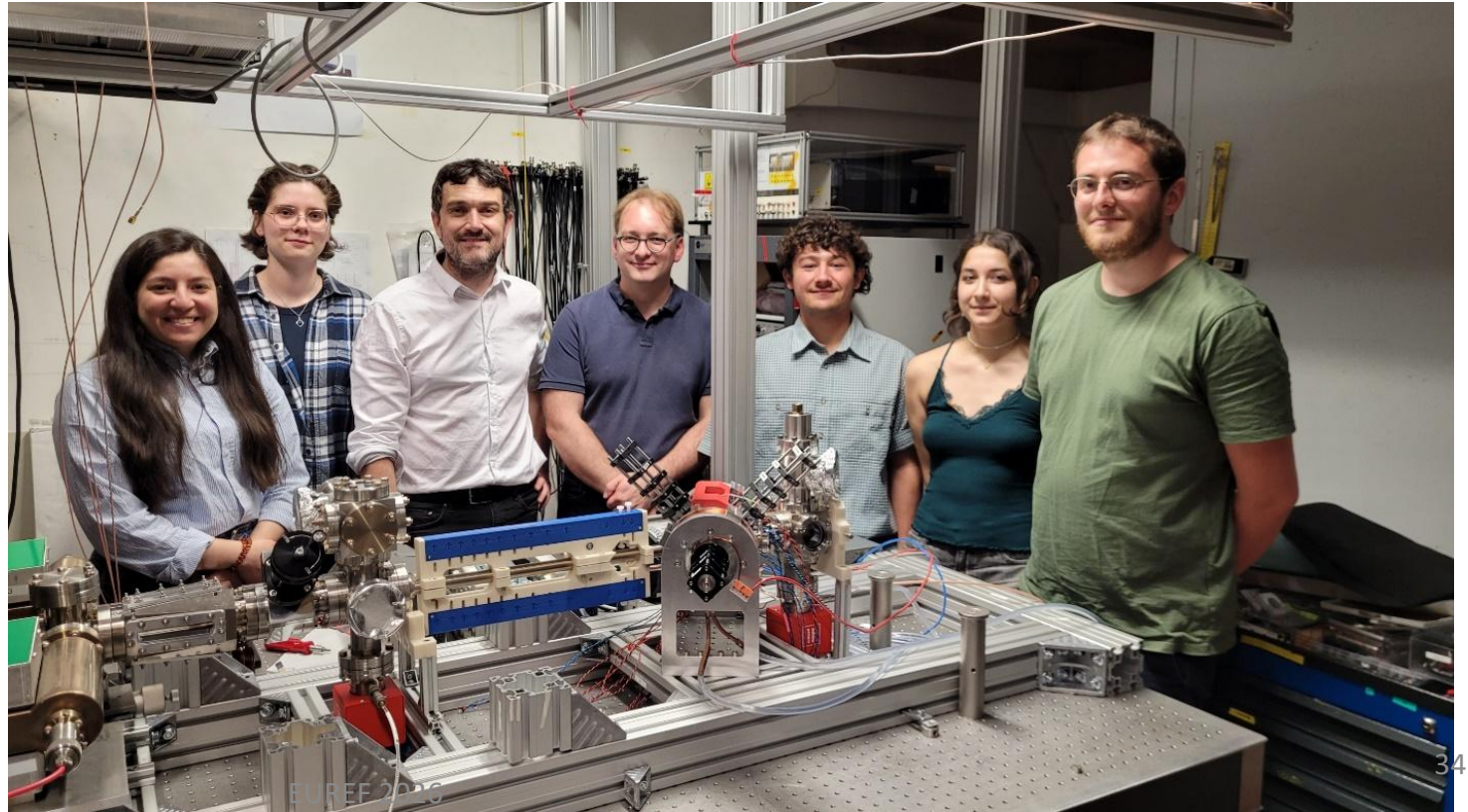


# First cold atoms on ROYMAGE



⇒ First 3D 399 nm Yb MOT in March 2025

Loading time estimated  
to 168 ms  
Number of atoms  $3 \times 10^7$   
with Zeeman slower

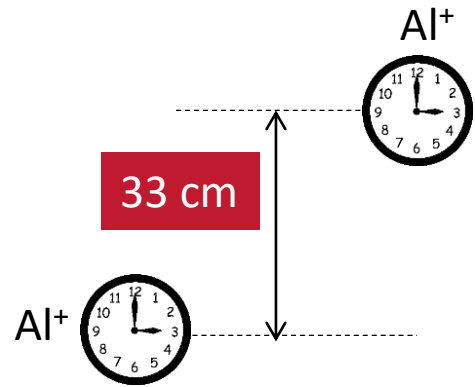


June 23 2026, Paris

EUREF 2026

# Using optical clocks to measure height differences

## NIST (Boulder)

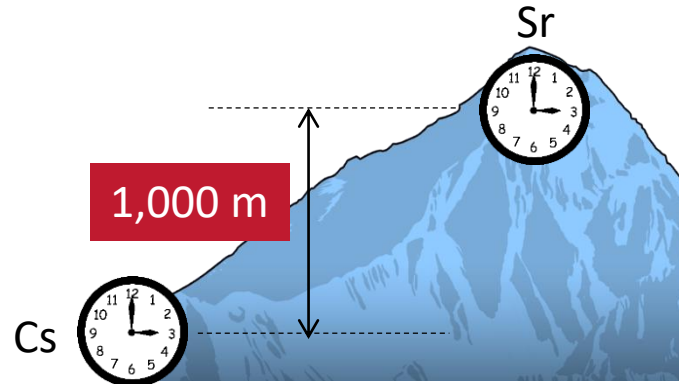


- Laboratory-based Al<sup>+</sup> clocks
- $\Delta\nu/\nu_0 = (4.1 \pm 1.6) \times 10^{-17}$

C. W. Chou *et al.*  
Science **329**, 1630 (2010)

- Ongoing work in the Colorado by the Yb team

## INRIM, PTB, NPL, LUH, LSM (The Alps)

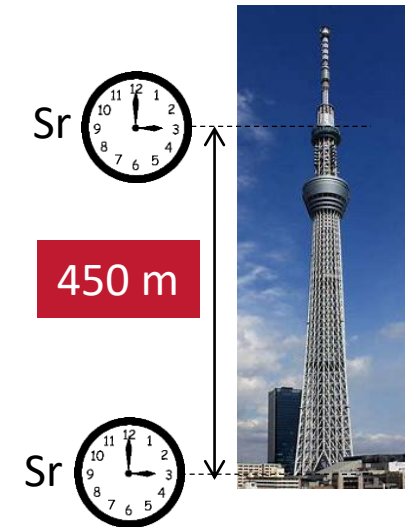


150 km optical fibre link connecting

- Transportable Sr clock at Modane
- Cs laboratory clock at INRIM
- $\Delta\nu/\nu_0 = (111.6 \pm 1.9) \times 10^{-15}$

J. Grotti *et al.*  
Nature Physics **14**, 437 (2018)

## RIKEN, Tokyo, Osaka, GIAJ (Tokyo)

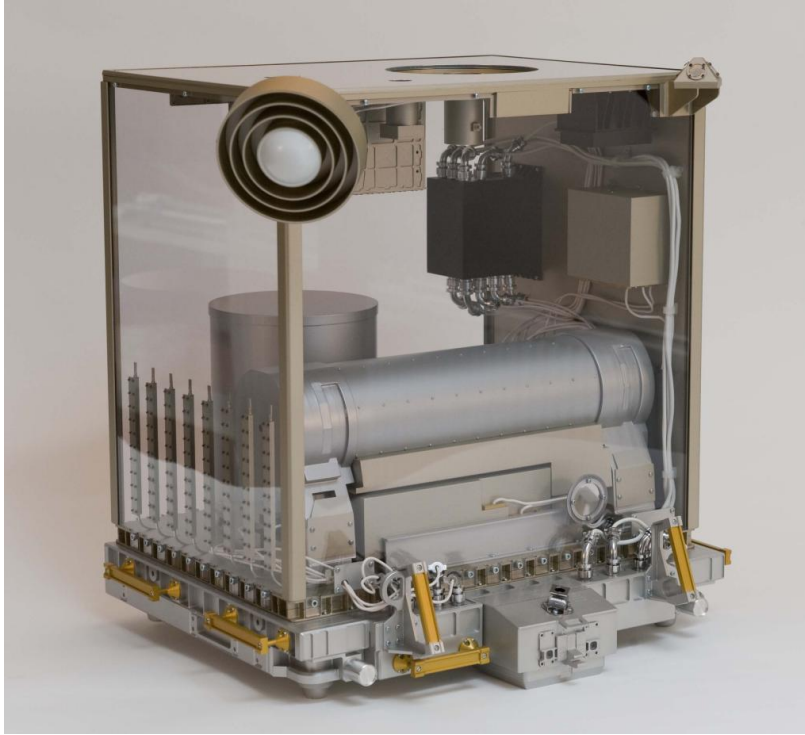


- Transportable Sr clocks at Skytree broadcasting tower
- $\Delta\nu/\nu_0 = (49,337.8 \pm 4.3) \times 10^{-18}$

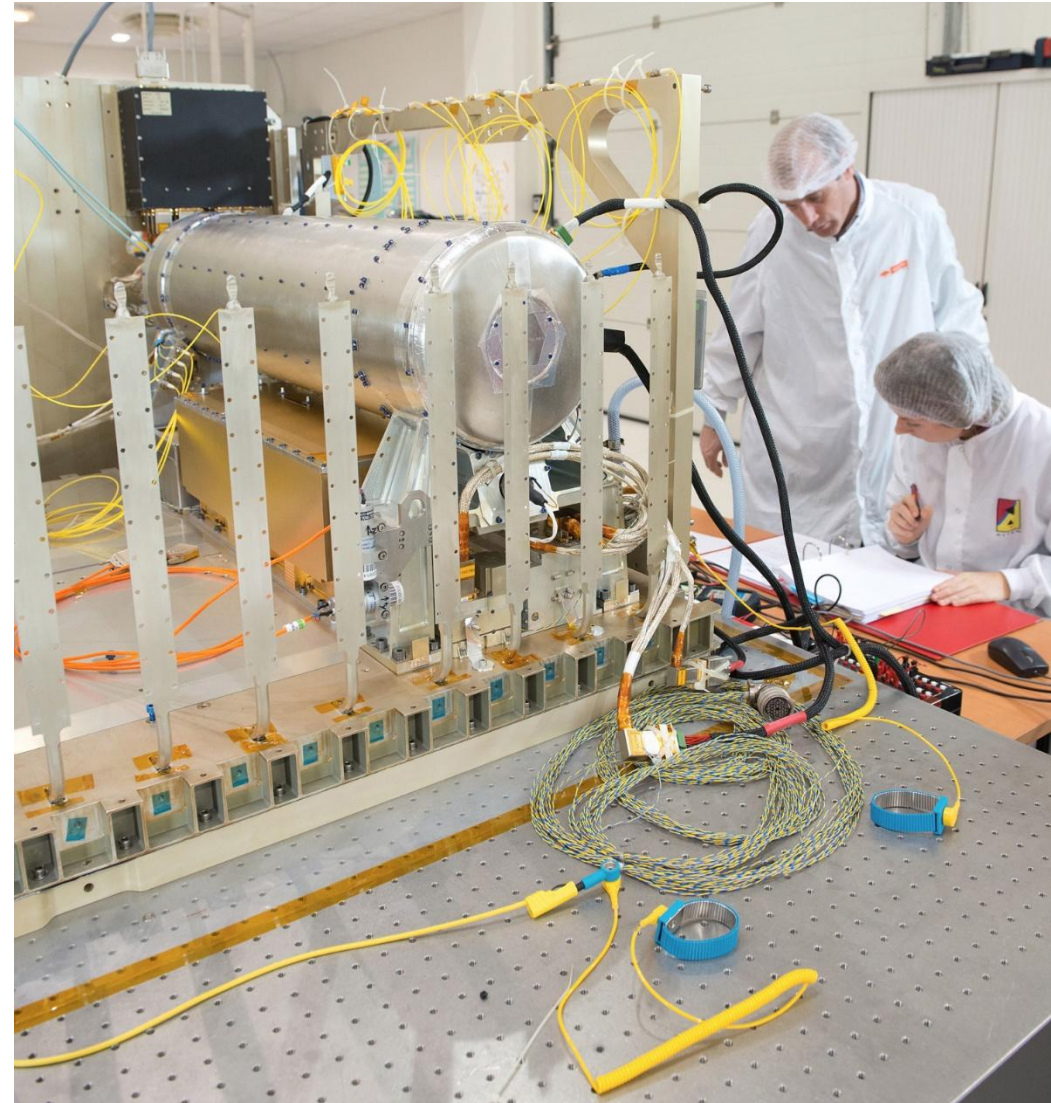
M. Takamoto *et al.*  
Nature Photonics **14**, 411 (2020)

Slide provided by Rachel Godun, NPL, UK

# PHARAO-ACES: a microwave clock in the ISS



- Cs clock in the space station
- Finally Launched in 2025
- Lifetime = 3 years+
- Tests of gravitational red-shift
- Many technical difficulties since ... 1995



# Take home messages

- ⇒ Atomic clocks based on optical transitions have reached a level of control of 18 digits
- ⇒ A redefinition of the second is drawing near: Sr, Yb, Hg, Yb+, Al+, Sr+ ...
- ⇒ 18 digits  $\leftrightarrow$  1 cm height difference
- ⇒ Complementary with traditional geodesy techniques, does not depend on the distance
- ⇒ Measure the potential, while gravimeters measure the field