Introduction to optical clocks

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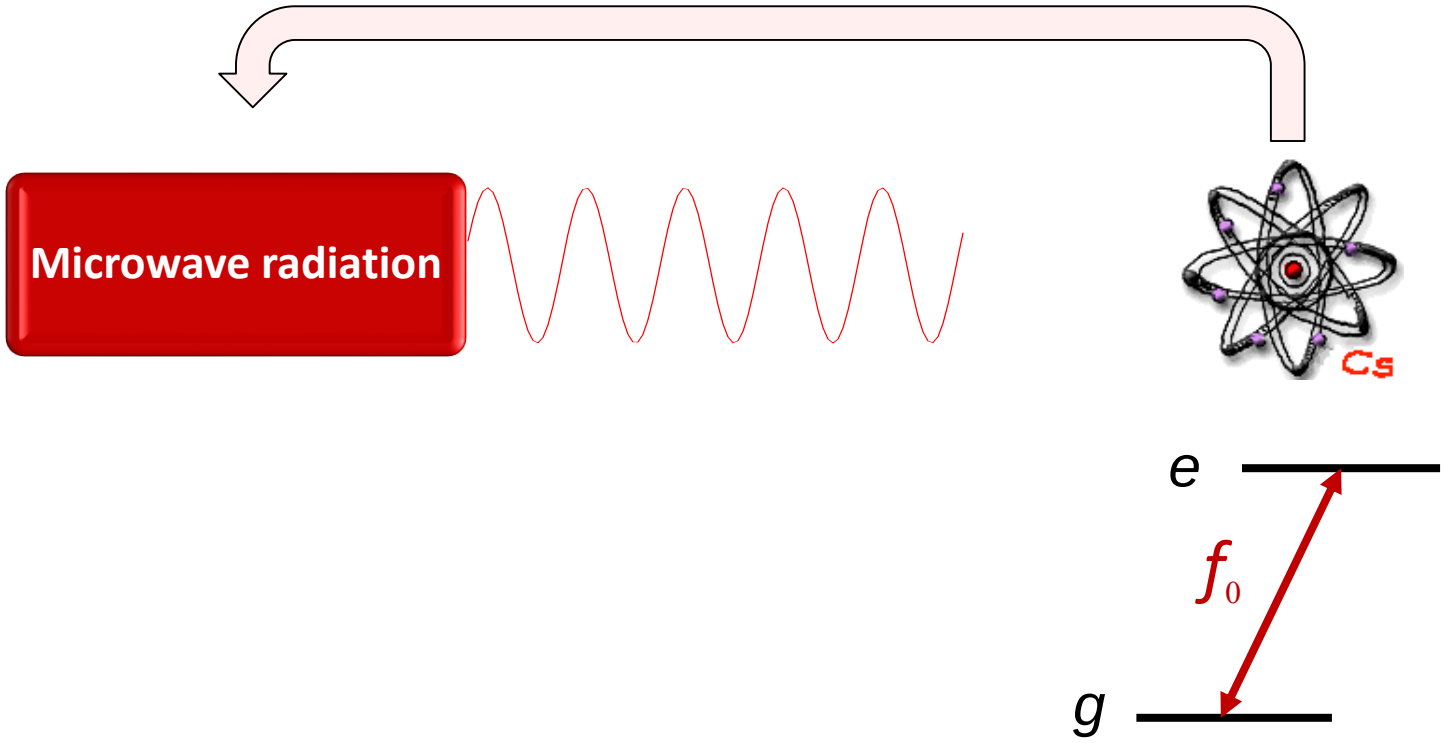
Outline

- ❑ What is an optical clock?
- ❑ How do optical clocks perform better than caesium clocks?
- ❑ State-of-the-art performance
- ❑ Future applications

Caesium clock basics

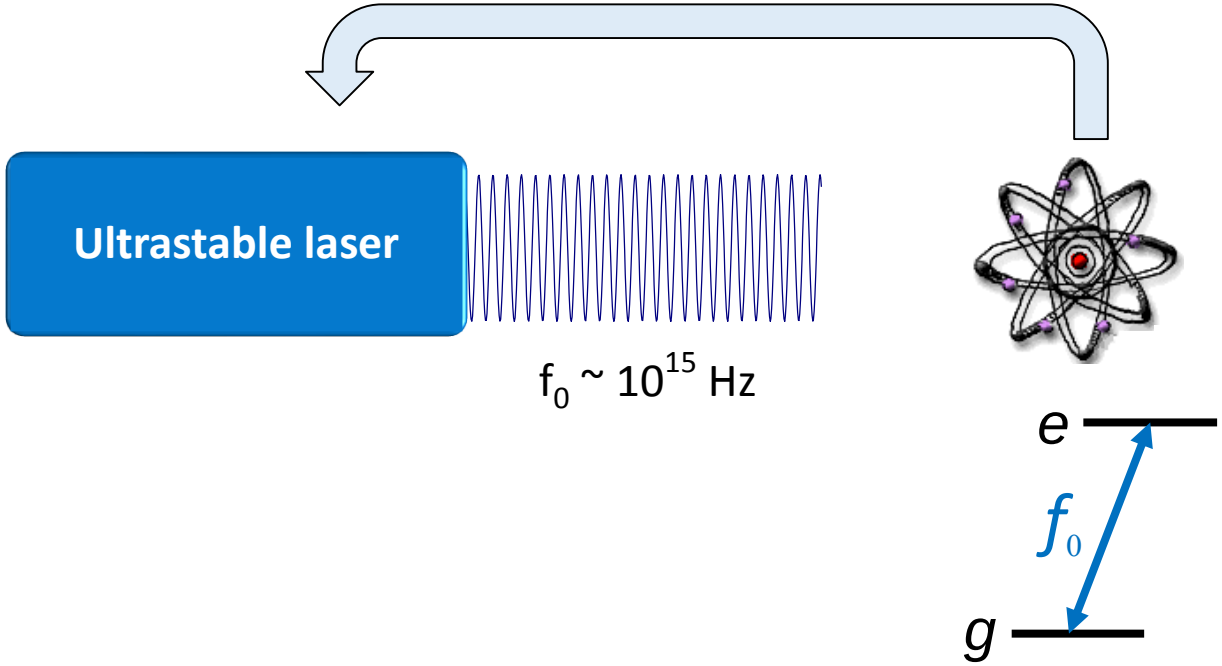


- Tune the frequency of the radiation to drive an atomic transition
- The radiation will then be at a specific frequency: 9.192 631 770 GHz

Caesium clocks are widely used

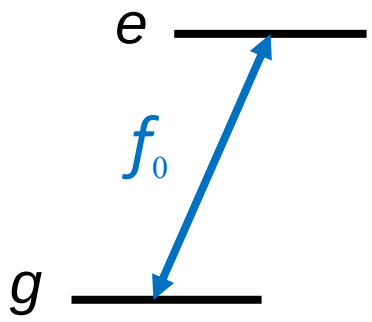
- International time scale
- Navigation
- Network synchronisation
- …

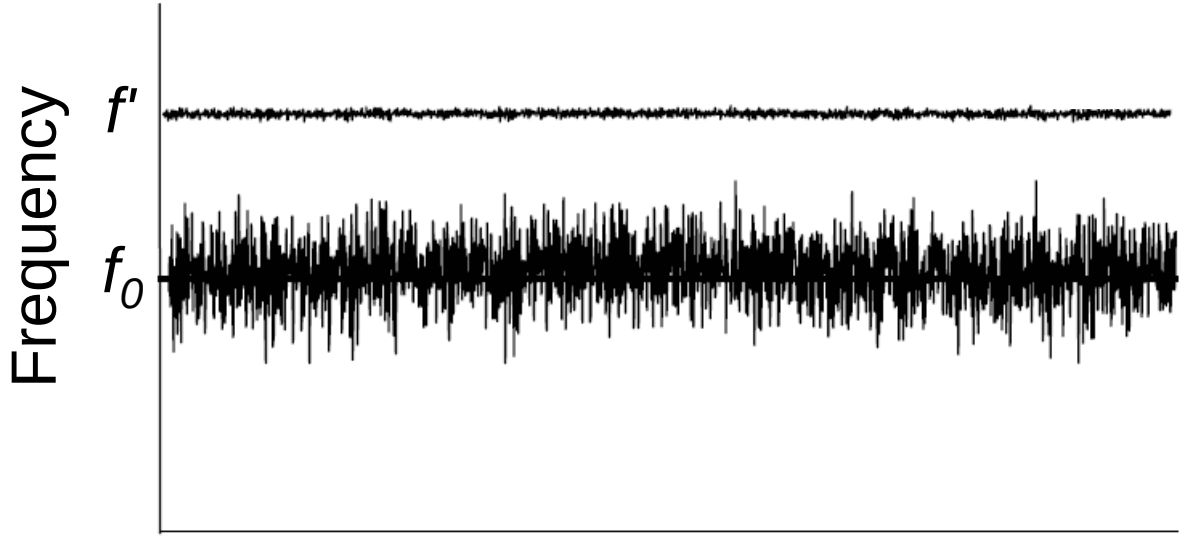
Optical clock basics



- Optical transition frequency

Performance of a frequency standard





Stability

Level of frequency fluctuations over time (statistical uncertainties)

Accuracy

Level of offset from correct frequency (systematic uncertainties)

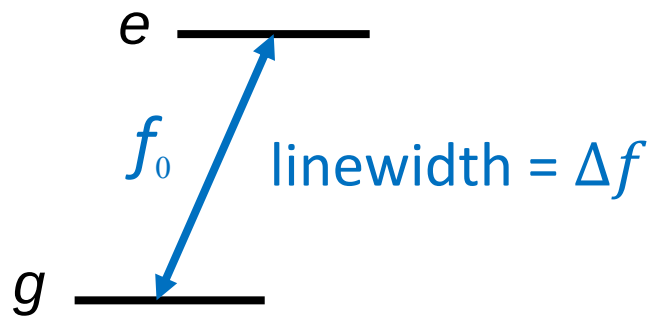
Advantage of optical frequency standards

Stability

Fractional instability $$\sigma(\tau) = \frac{\Delta f}{f_0}\frac{\eta}{(\mathrm{S/N})}\sqrt{\frac{t_c}{\tau}}$$

Δf	=	linewidth
f_0	=	optical frequency
(S/N)	=	signal-to-noise ratio
t_c	=	cycle time = $T_{probe} + T_{dead}$
τ	=	total averaging time
η ~ 1		depends on probing technique and shape of resonance

- Optical frequencies are 10^5 higher than microwave frequencies
- All other things being equal, expect optical clocks to have 10^5 better fractional instabilities



State-of-the-art performance

Stability

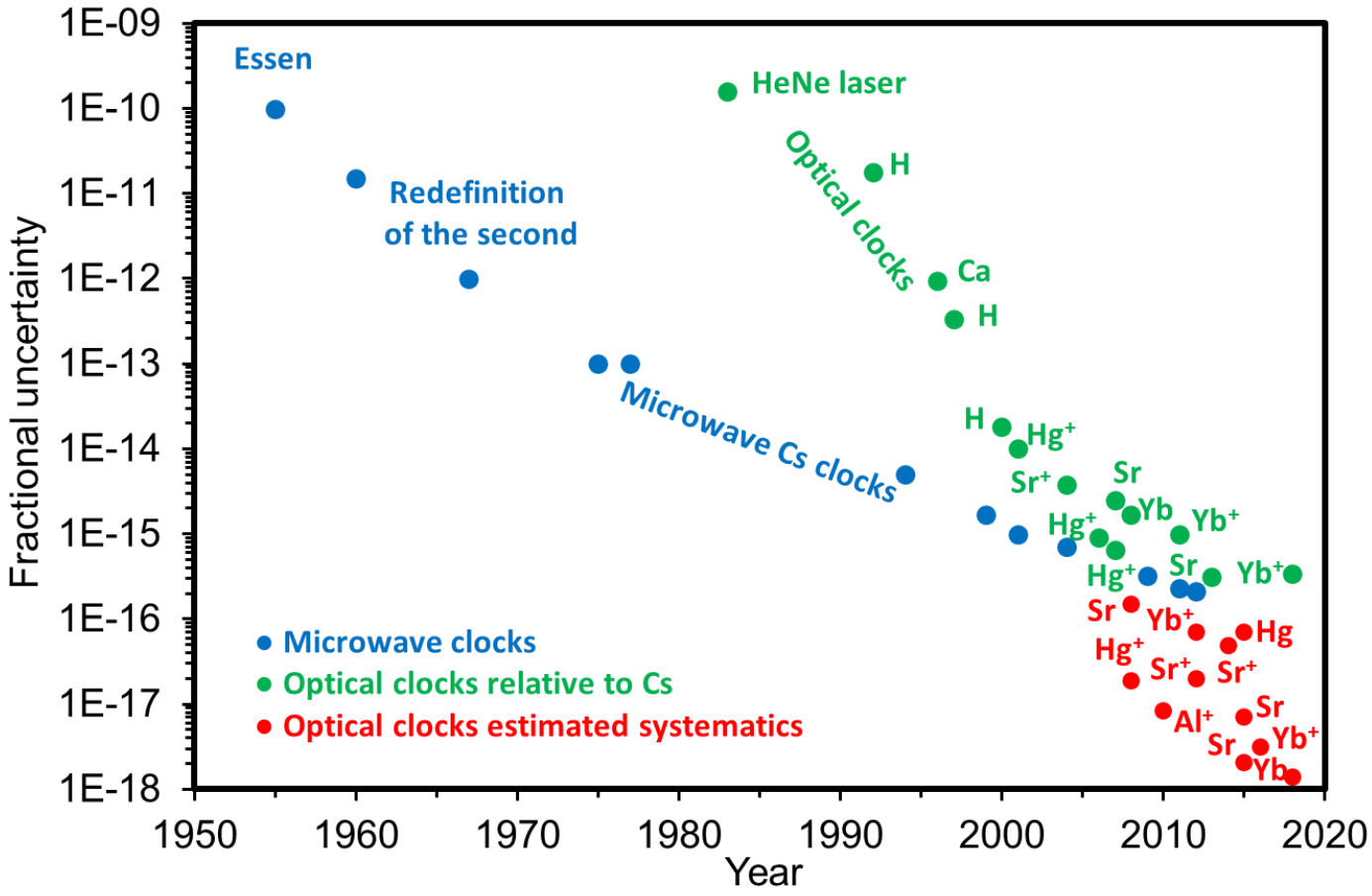
- Caesium clocks[1]

  $2 \times 10^{-14} / \sqrt{\tau}$

- Optical clocks[2]

  $6 \times 10^{-17} / \sqrt{\tau}$

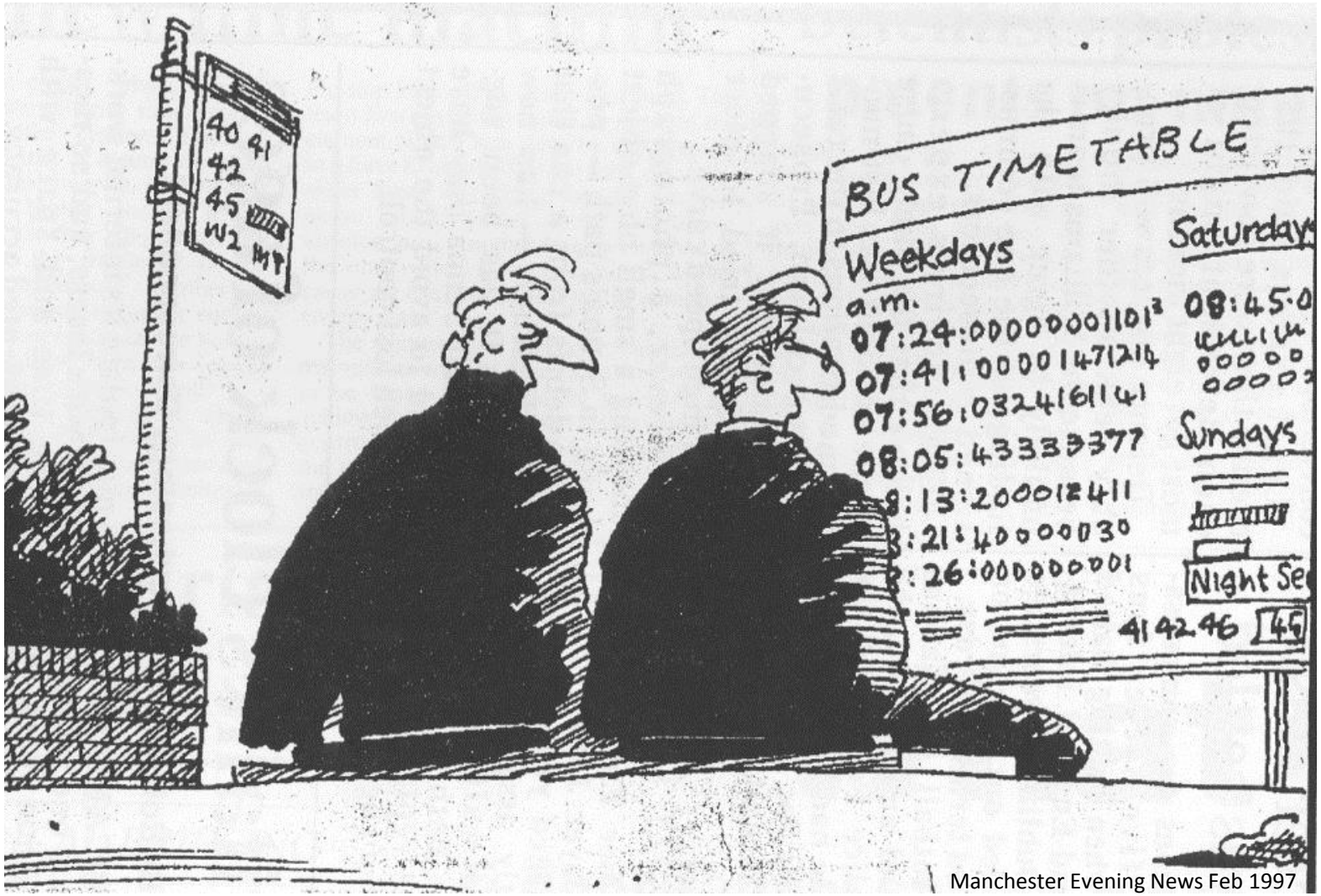
Accuracy



[1] C. Vian et al. IEEE Trans. Instrum. Meas **54**, 833 (2005)

[2] M. Schioppo et al. Nature Photonics **11**, 48 (2017)

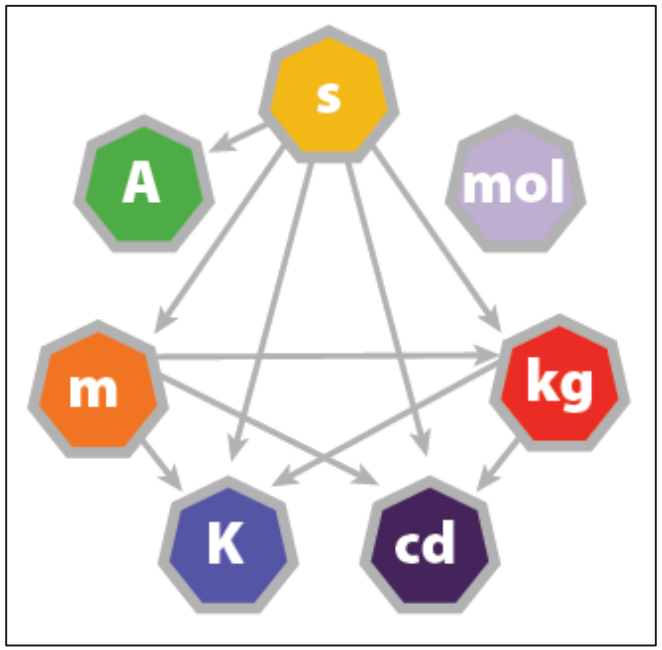
Who needs this?



Manchester Evening News Feb 1997

Applications - I

- Top level SI



- Contributing to TAI as secondary representation of SI second
- Preparing for an optical redefinition of SI second:
  - Need multiple optical clock comparisons between different institutes with fractional uncertainty better than 5×10^{-18}.

  - Need to gather more frequency ratio data to determine optimised values of the frequencies
  - Need to demonstrate regular contributions to TAI

Applications - II

- Fundamental physics

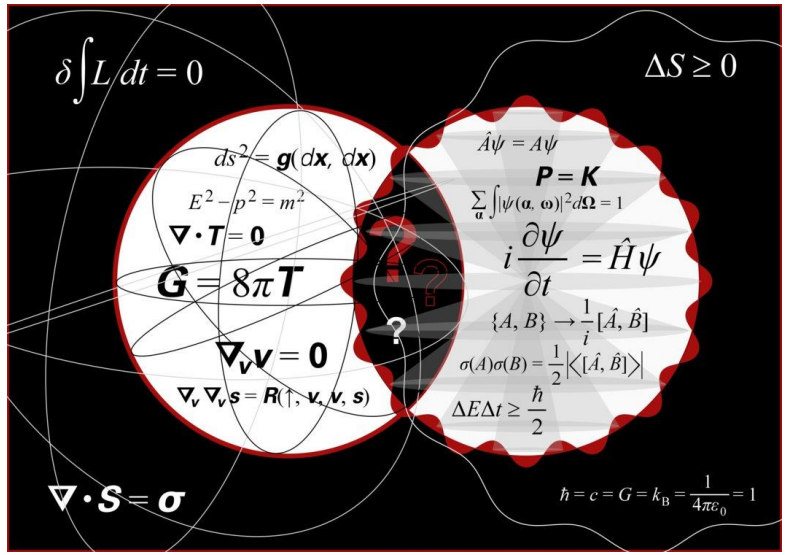


Image: DeviantArt/Maschen

- Optical clocks can make measurements at unprecedented levels
- High-precision spectroscopy can reveal effects beyond the Standard Model
  - Variation of fundamental physical constants
  - Tests of Lorentz Invariance
  - Searches for Dark Matter

…

Applications - III

- Geodesy

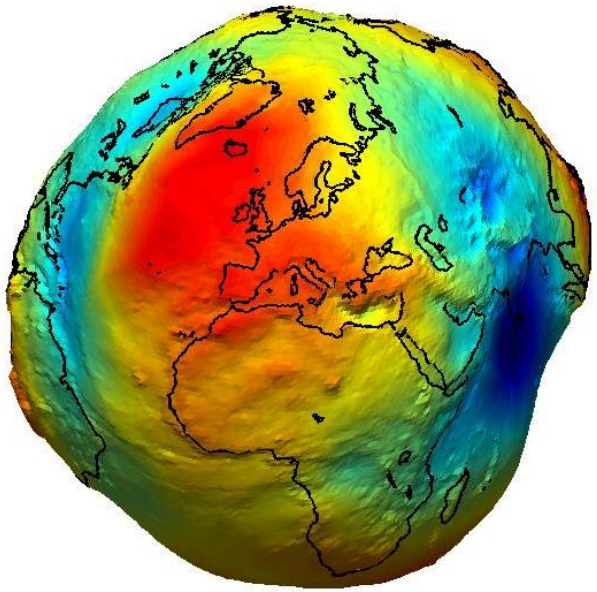


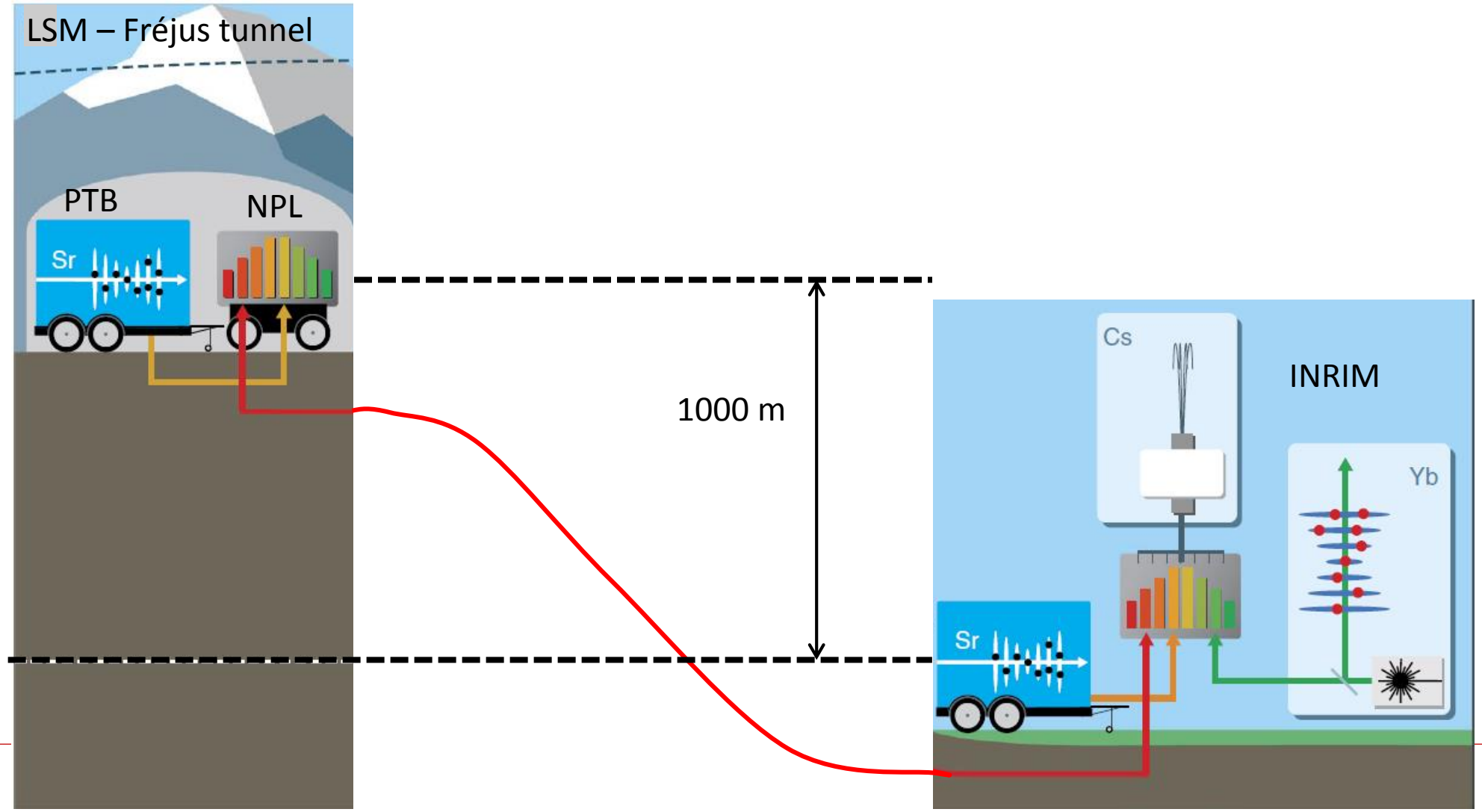
Image: ESA

- General Relativity tells us that time runs faster in weaker gravity potentials
- 10^{-18} frequency resolution equivalent to 1 cm height resolution
- Could use optical clocks as sensors for
  - Aligning national height reference systems
  - Monitoring ocean currents and sea-level rise
  - Monitoring volcanic activity

    …

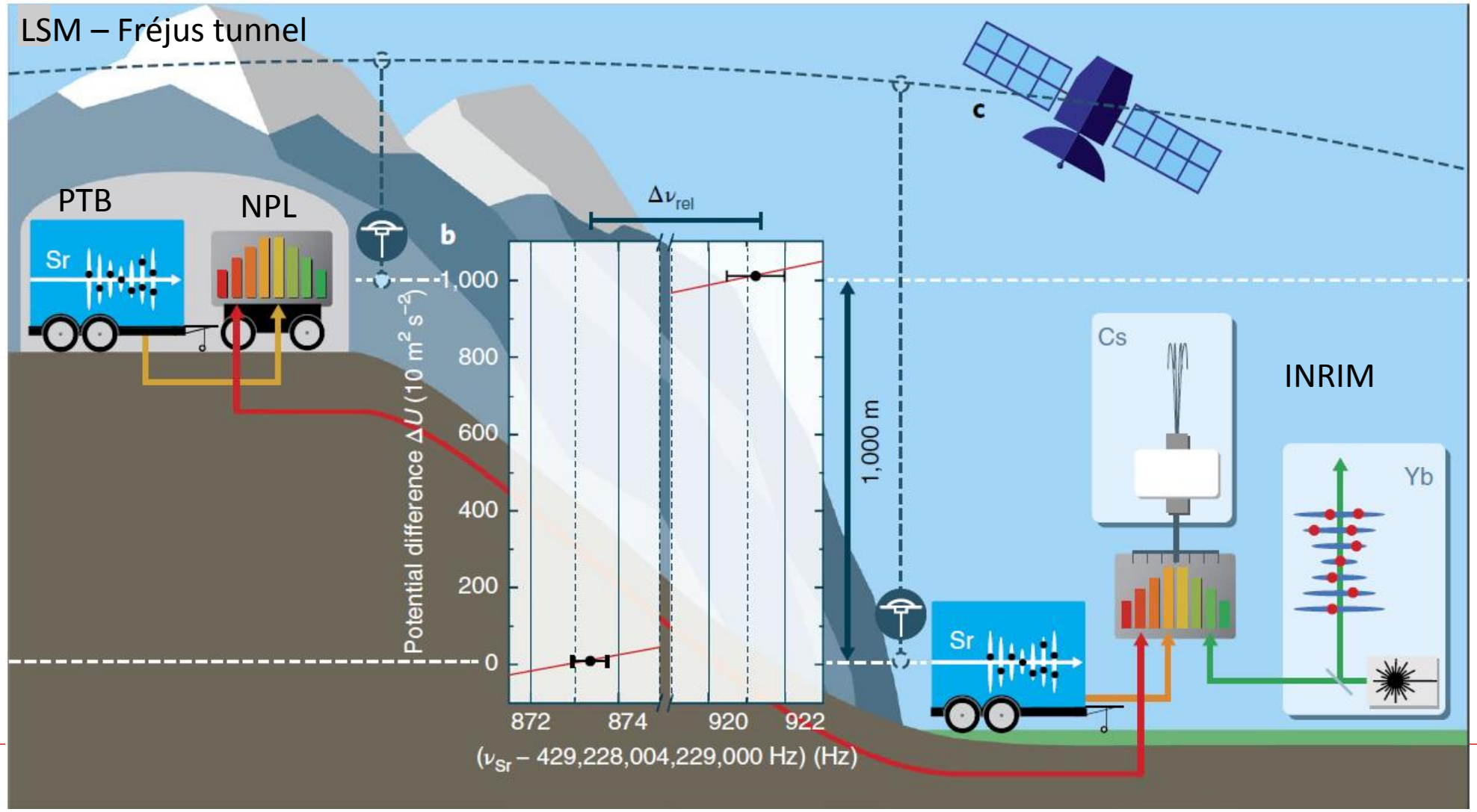
Applications - III

- Proof-of-principle measurement of gravity potential difference



Applications - III

- Proof-of-principle measurement of gravity potential difference



J. Grotti *et al.*
Nature Phys (2018)

Summary

Measured height diff. consistent with GNSS/geoid

Uncertainty = 18 m

Freq. uncertainty = 1.8×10^{-15}

Applications - IIII

- Longer term

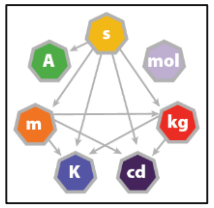
- The low instability of optical clocks may also be useful for:
  - Very long baseline interferometry
  - Global navigation satellite systems

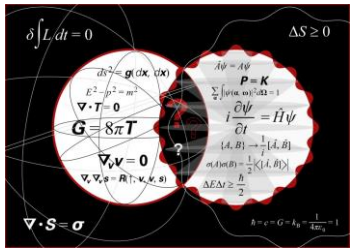
    …

Summary

- Optical clocks can outperform Cs primary standards by almost two orders of magnitude in **Stability** and **Accuracy**

- Opens up many new applications for the future
  - Top level SI
  - Fundamental physics
  - Geodesy
  - Navigation systems





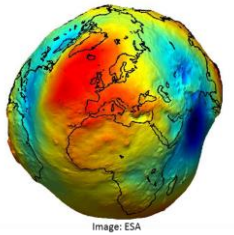


Image: ESA

Thank you for your attention

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CLONETS – CLock NETwork Services

Strategy and innovation for clock services over optical-fibre networks

Proposal ID: **731107**
Topic: **INFRAINNOV-2016**
Duration: **30 months**
Start date: **1st January 2017**
Web page: **http://www.clonets.eu**

Coordinator

Participants

Third Parties