Fundamental Physics Tests with Space Based Atomic Clocks

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September 20, 2021

Introduction to timekeeping

A clock keeps time by counting the cycles of a periodic oscillator

Counter:
Counts the cycles of the oscillator

Oscillator:
Provides a stable, periodic signal

Reference:
Provides a periodic calibration of the oscillation

[redacted]
$\Delta f/f \sim 10^{-8}$

The three main components of a clock are:
an **oscillator**, a **reference**, and a **counter**.

D. D. McCarthy and P. K. Seidelmann., Cambridge University Press, 2018.

Introduction to timekeeping

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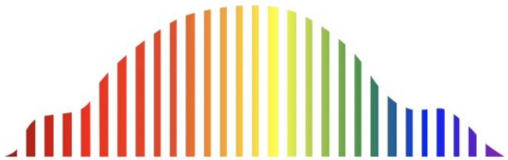
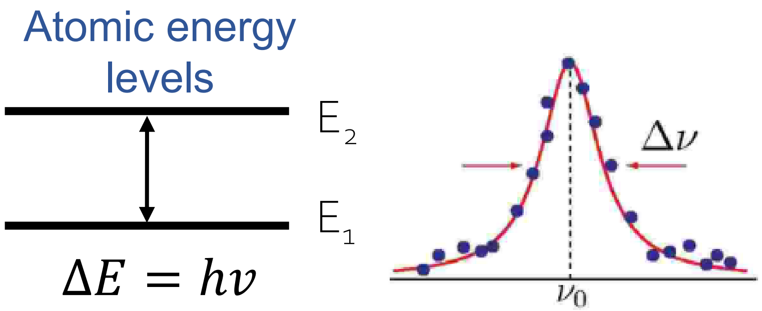
Counter



Optical Frequency Comb
or frequency counter

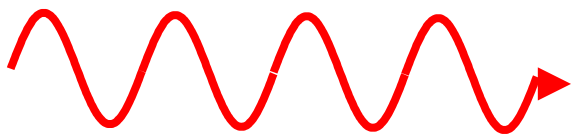
Reference:
Provides a periodic calibration of the oscillation frequency



Atomic reference

Oscillator:
Provides a stable, periodic signal

Electromagnetic Radiation



Light waves, microwaves

Accuracy
$\Delta f/f \sim 10^{-16}$-10^{-18}

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A. D. Ludlow, et al. *Reviews of Modern Physics* 87.2, 637 (2015).
N. Poli, et al, *Rivista del Nuovo Cimento*, 36.12, (2003)

Introduction to timekeeping

Definition of the SI second:
"The duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom"

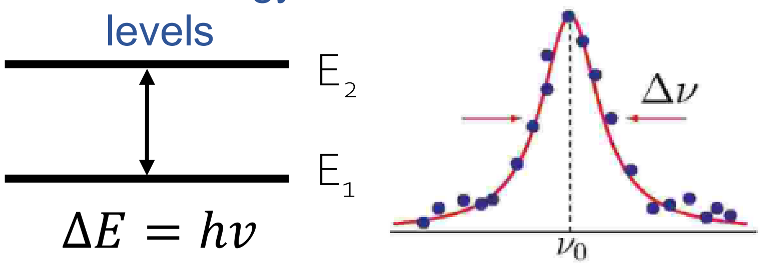
Counter:
Counts the cycles of the oscillator

Counter

Optical Frequency Comb or frequency counter

Reference:
Provides a periodic calibration of the oscillation frequency

Atomic energy levels



Atomic reference

Oscillator:
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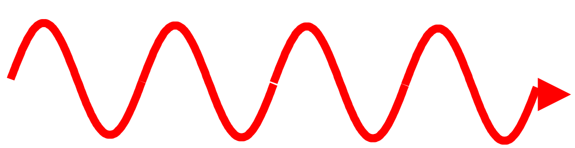

Light waves, microwaves

A. D. Ludlow, et al. *Reviews of Modern Physics* 87.2, 637 (2015).
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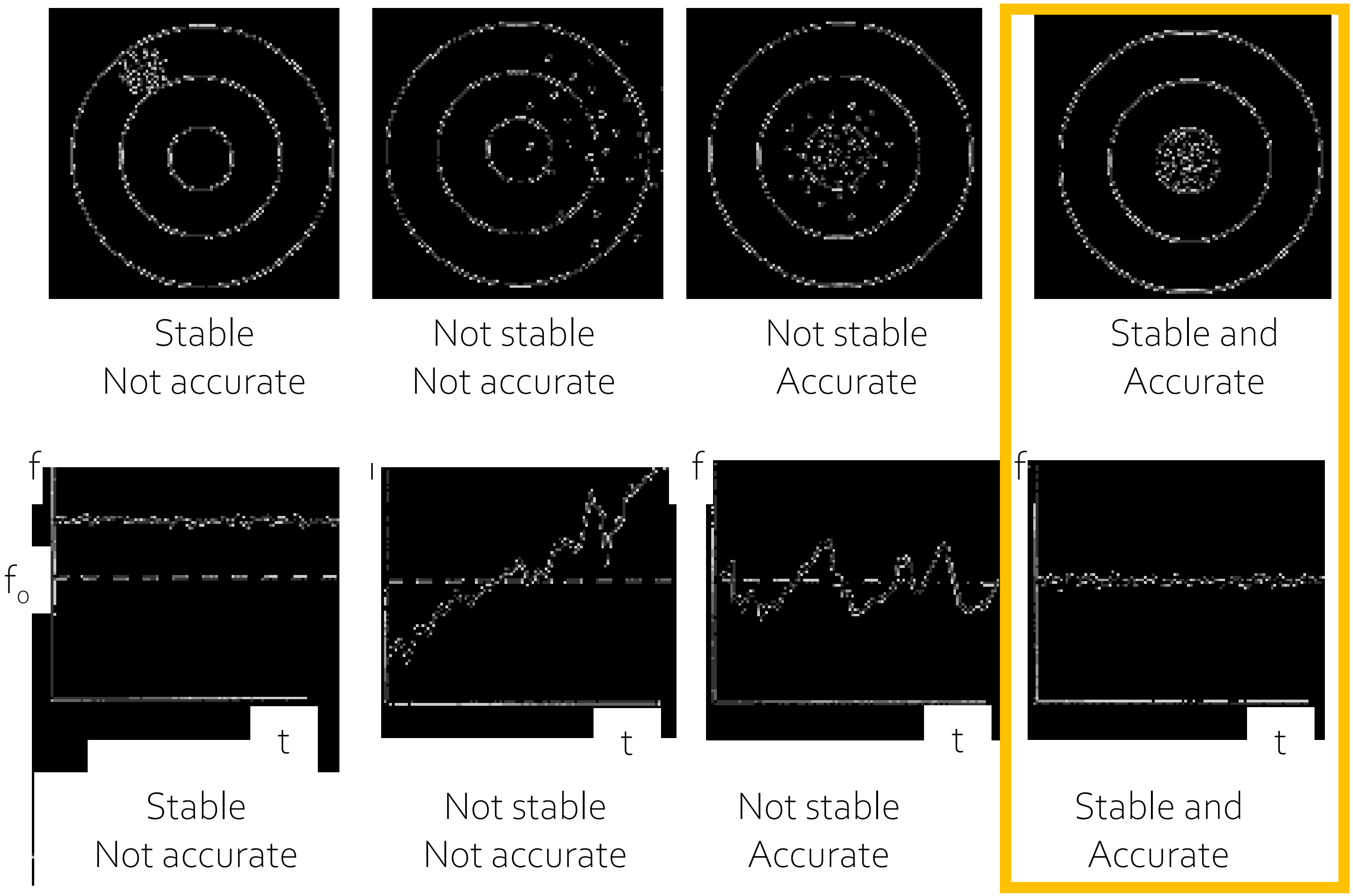
Evaluating Atomic Clocks



Best clocks are both stable and accurate!

Image Credit: John R. Vig

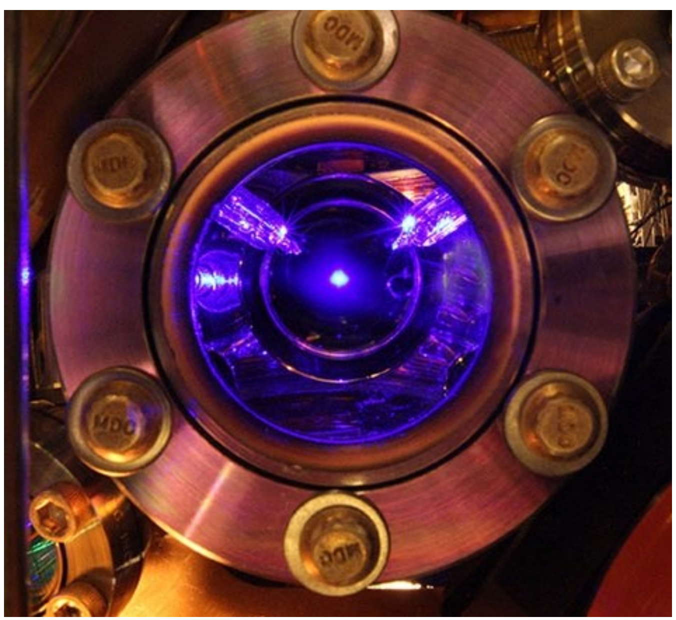
Optical Atomic Clocks

18 digits of resolution

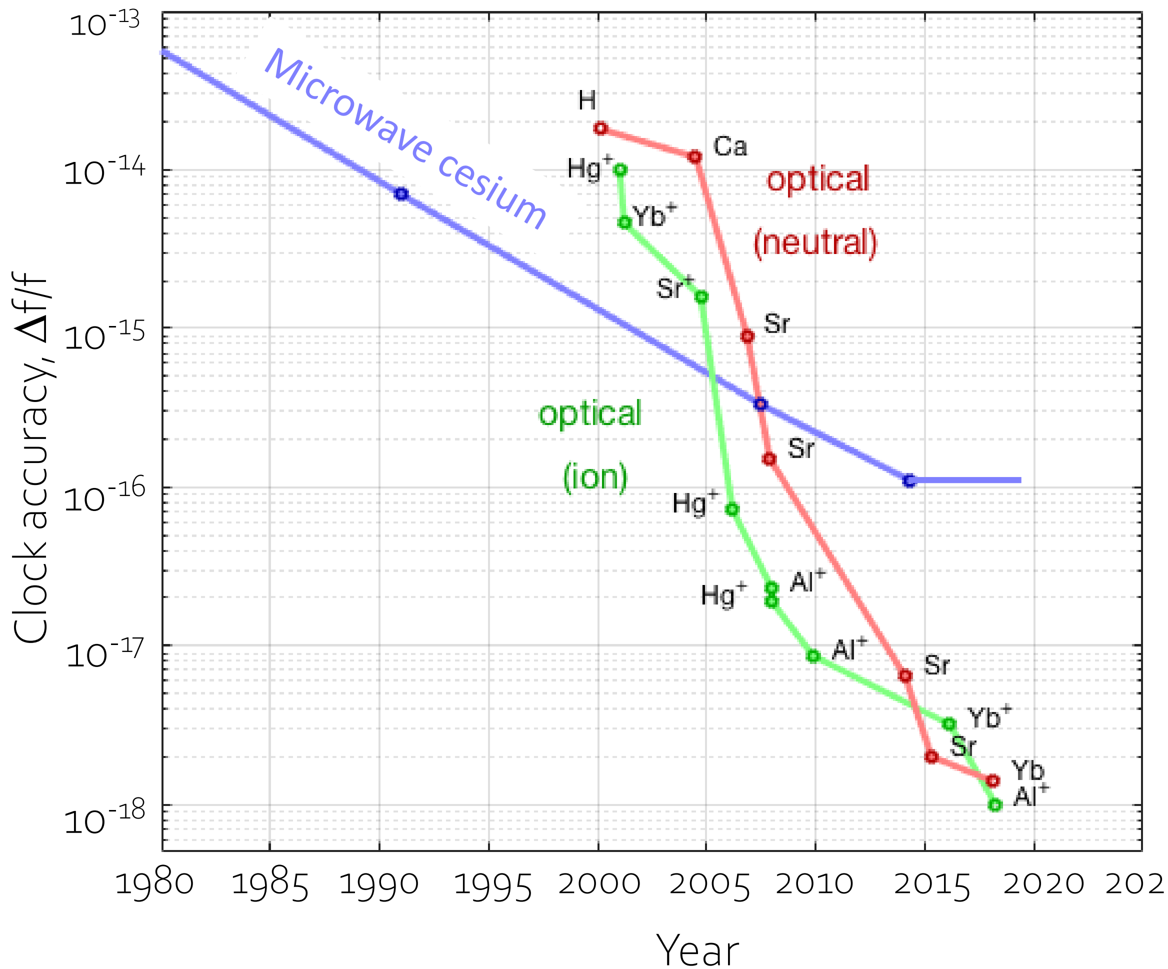
0.000 000 000 000 000 001 _

Optical frequencies oscillate 10^5 times faster than microwave frequencies

Second can be divided into finer segment

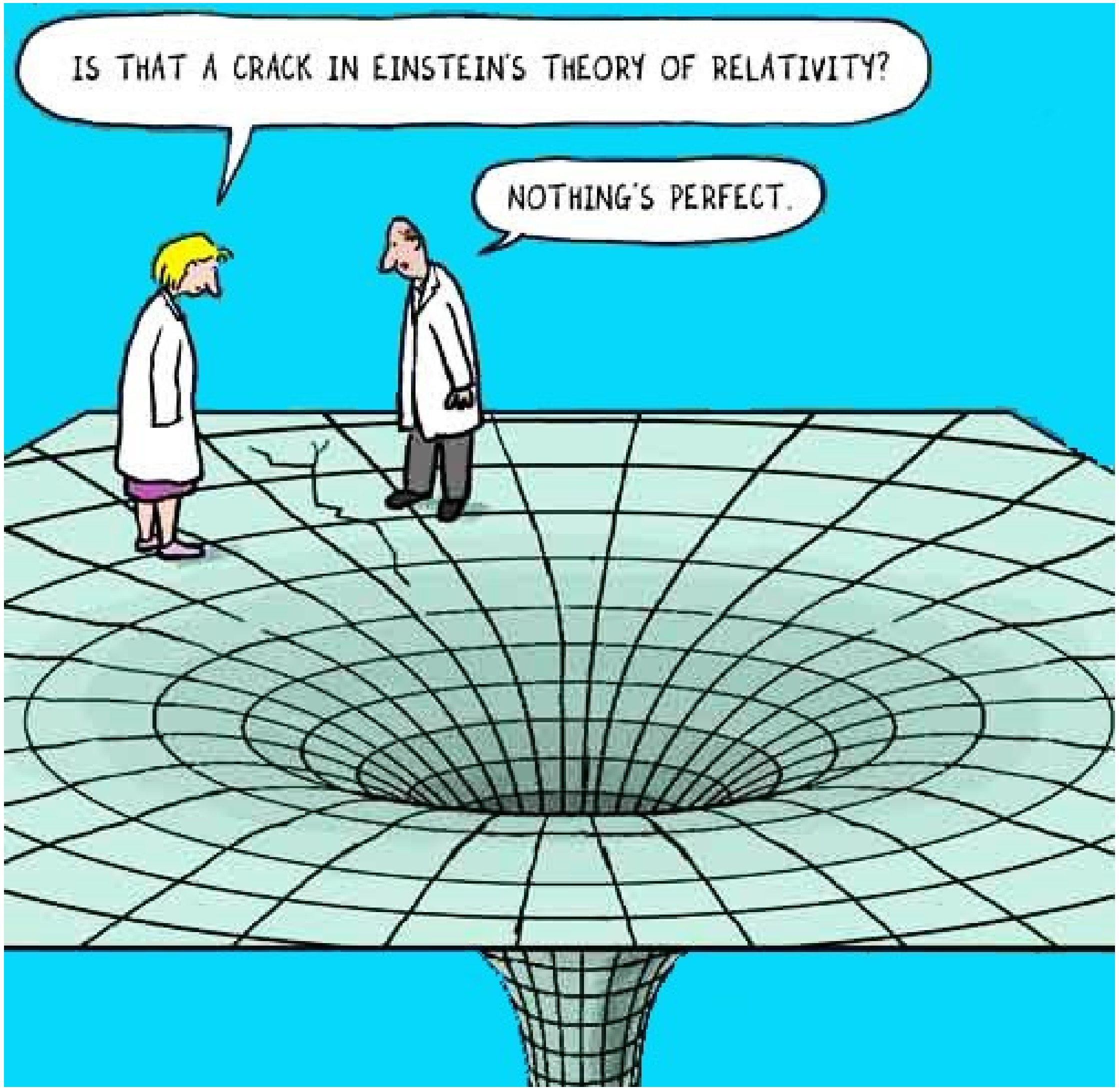


JILA Sr lattice clock



Atomic Clocks as Sensors

Atomic clocks can be used as sensors to probe fundamental physics.



Atomic clock frequencies very well known (10^{-16}-10^{-18})

- Sensitive to very small changes in transition frequency/energy levels
- Atomic transitions based on fundamental constants

Atomic clock measurements could give insight to:

- Unification Theory
- Dark Matter Detection
- Variations of Fundamental Constants
- Physics beyond the standard model

Why go to Space?

Space provides a unique environment:

- Microgravity
- Long baselines
- Large aperture networks
- Not limited by seismic noise
- Low-noise environment Reduced atmospheric interference on optical signals – optical links

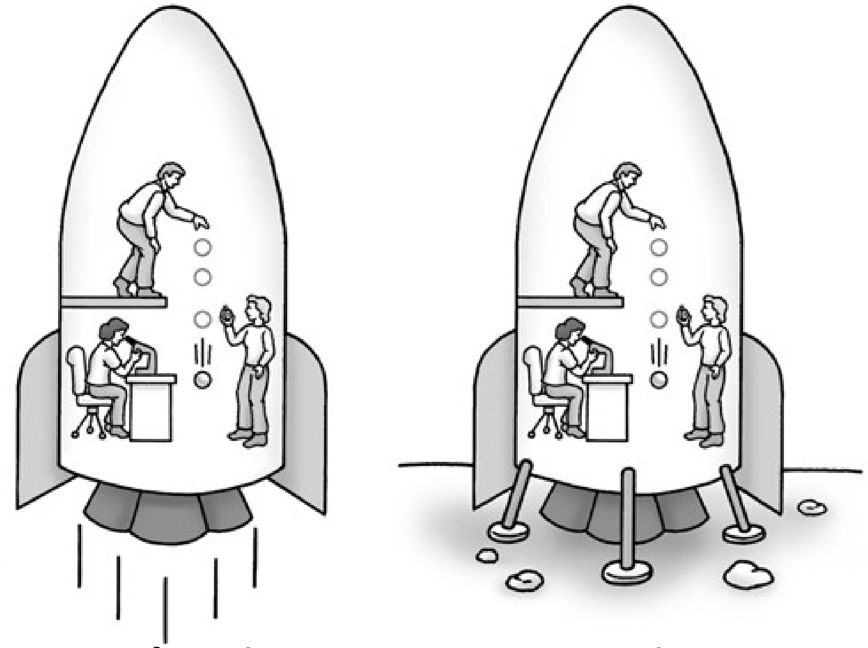
Einstein Equivalence Principle

Comparing atomic clocks can test Einstein Equivalence Principle!

1. Weak Equivalence Principle –
   - Objects fall at the same rate regardless of composition.

2. Local Lorentz Invariance –
   - Outcome of any non-gravitational experiment is independent of the velocity and orientation (freely falling) apparatus.

3. Local Position Invariance –
   - Outcome of any non-gravitational experiment is independent of where and when in universe it was performed.
   - Fundamental constants do not vary in time.



Acceleration = Gravity

We can compare:

- Different atomic species
- Clocks on ground and in orbit
- Clocks at different points in orbit
- Clocks over extended periods of time

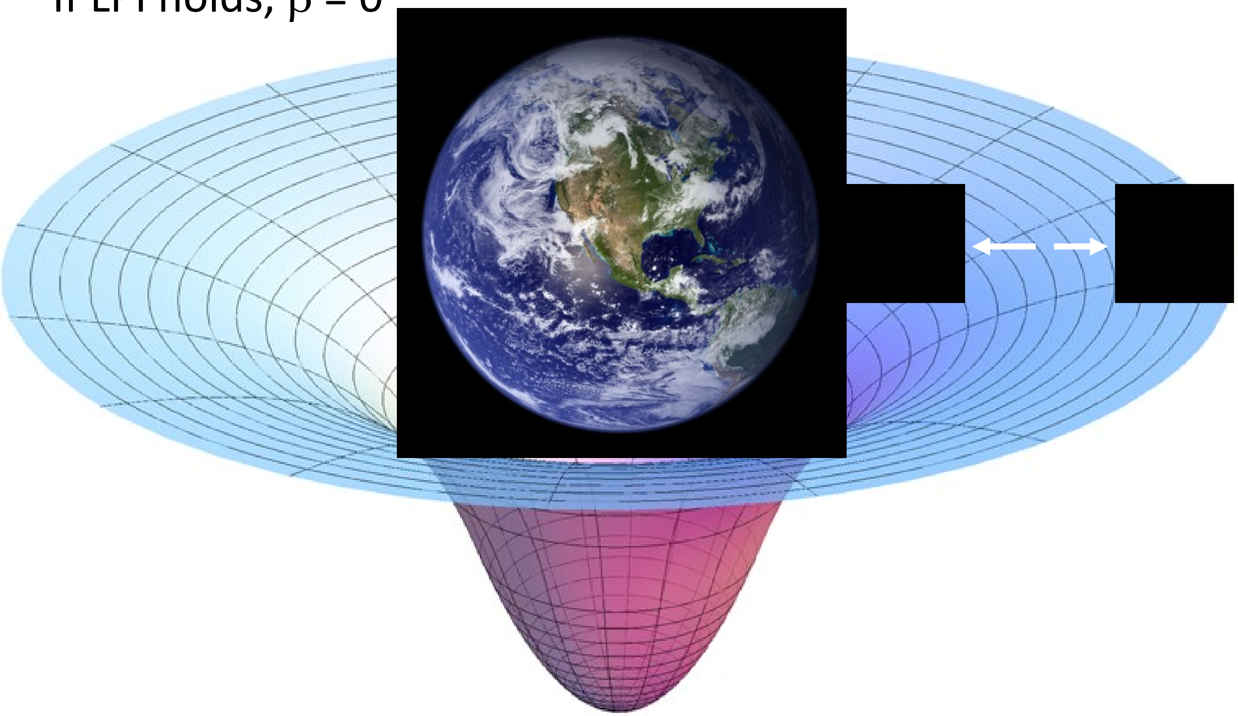
Testing Universal Gravitational Redshift

Gravitational redshift measurements test Local Position Invariance

$$Z = (1+\beta)\frac{\Delta U}{c^2}$$

If LPI holds, $\beta = 0$

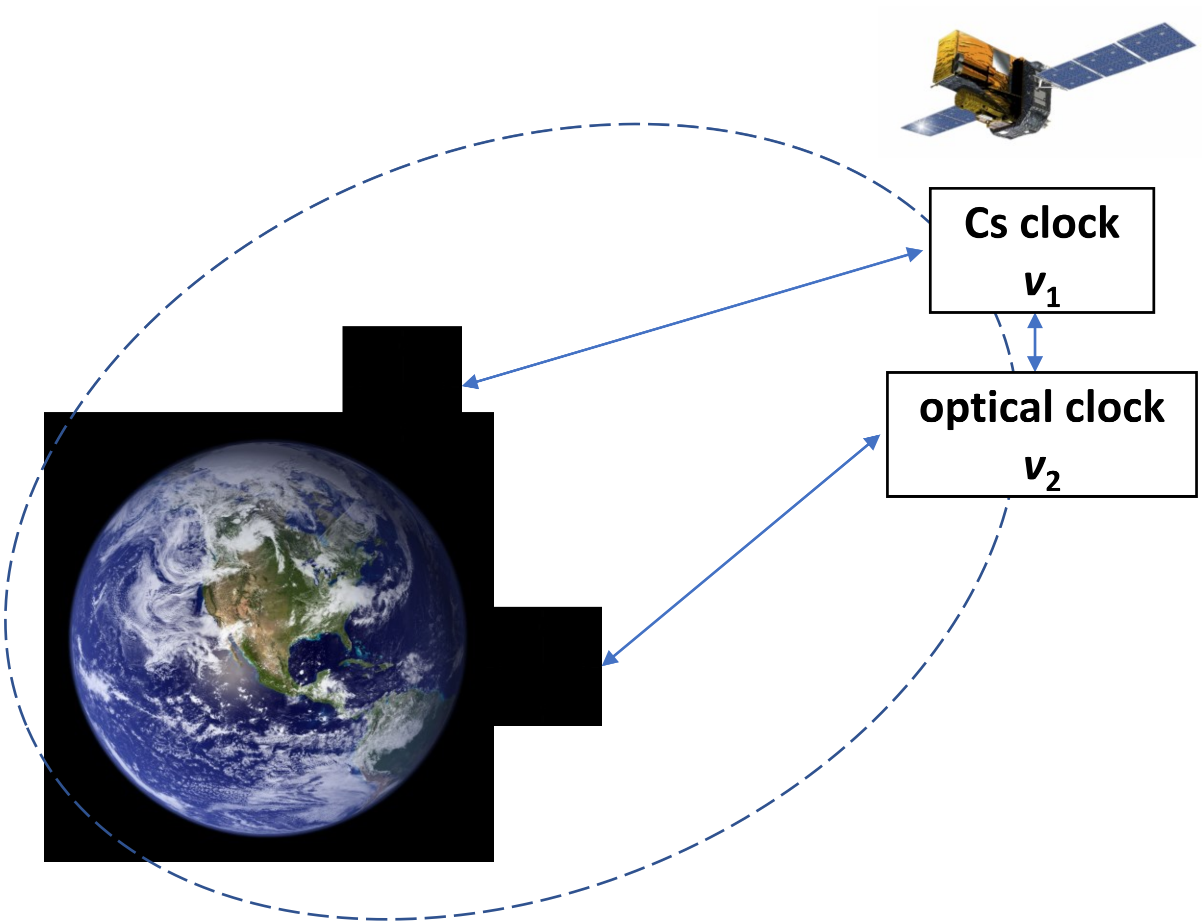
Clock frequency shift due to change in gravitational potential ΔU



- Clocks run slower closer to massive objects
  - Gravitational redshift
- Compare identical clocks at different gravitational potentials
- Precision measurement of the Earth and Sun gravitational potentials
- Constrain β at 10^{-6} level by comparing 10^{-16} clocks

Schiller., et al., *Nuclear Physics B-Proceedings Supplements* 166 (2007)
Gill, et al, *National Physical Laboratory* (2008)

Ground-to-Space Clock Comparisons



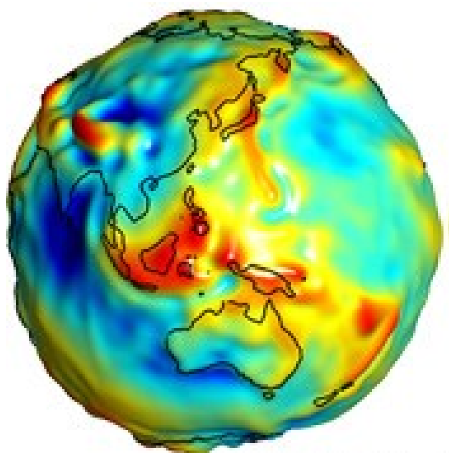
- Compare ratios of different atomic species in orbit. –
  - Weak Equivalence Principle (WEP) tests
- Compare different atomic clocks
  - Does the ratio of atomic clocks change in orbit?
- Variations of fundamental constants – Local Lorentz Invariance test
  - Is the speed of light constant and isotropic?

Constrain variations in fundamental constants and the WEP via clock comparisons

Schiller., et al., *Nuclear Physics B-Proceedings Supplements* 166 (2007)
Gill, et al, *National Physical Laboratory* (2008)

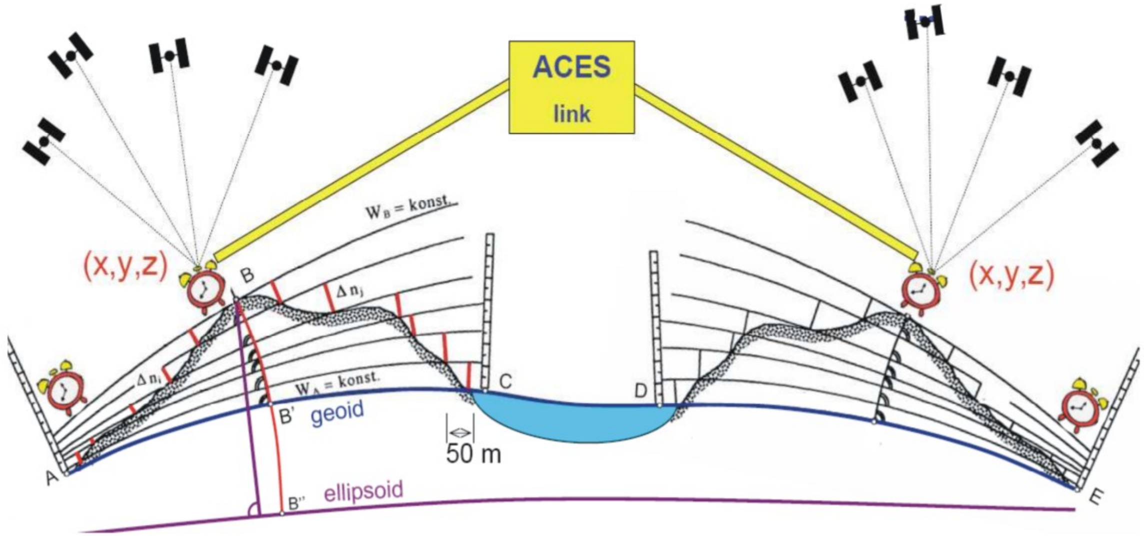
Relativistic Geodesy

Use atomic clocks to improve local geodesic measurements



Map Earth's geopotential at the cm-level with 10^{-18} clocks

Measure differential redshift between clocks on ground and in orbit – measure Earths geopotential

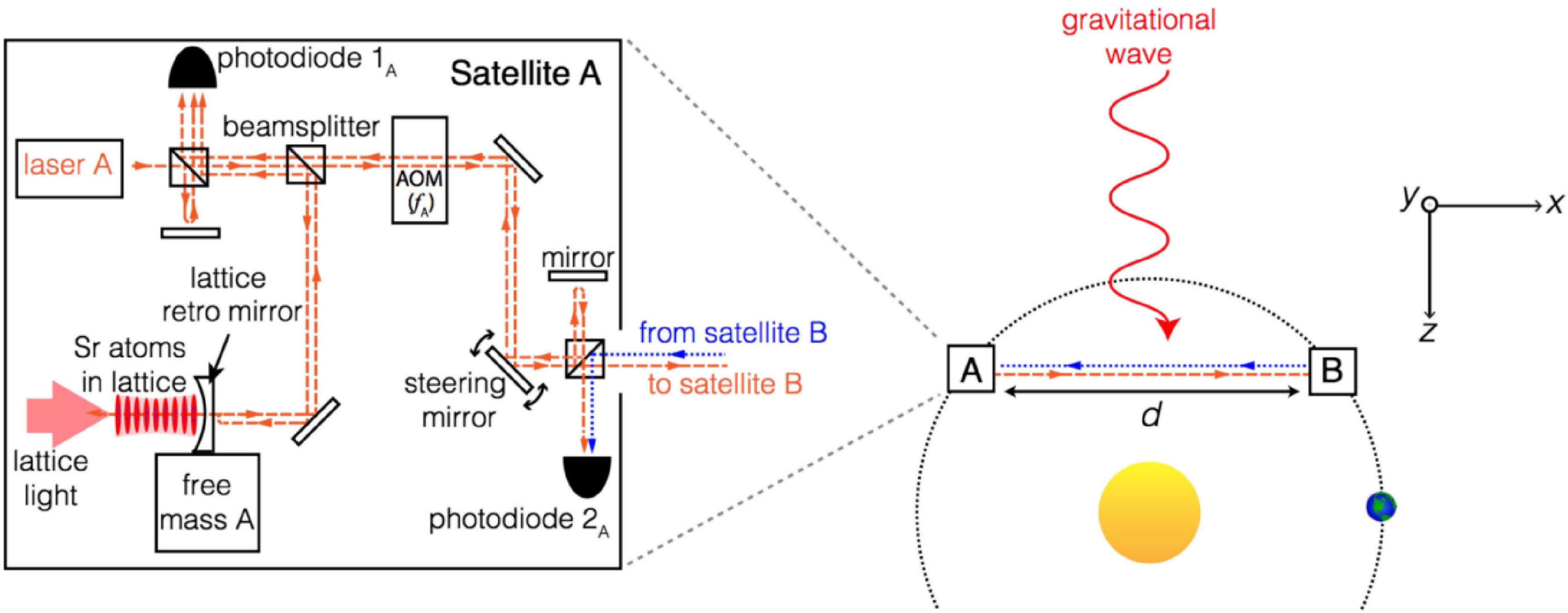


- Study variations in Earth's geopotential
- Map water/ice flows
- Establish unified height datum

Mehlstäubler et al 2018 Rep. Prog. Phys. 81 064401

Gravitational Wave Detection

GW induces doppler shift between identical atomic clocks.

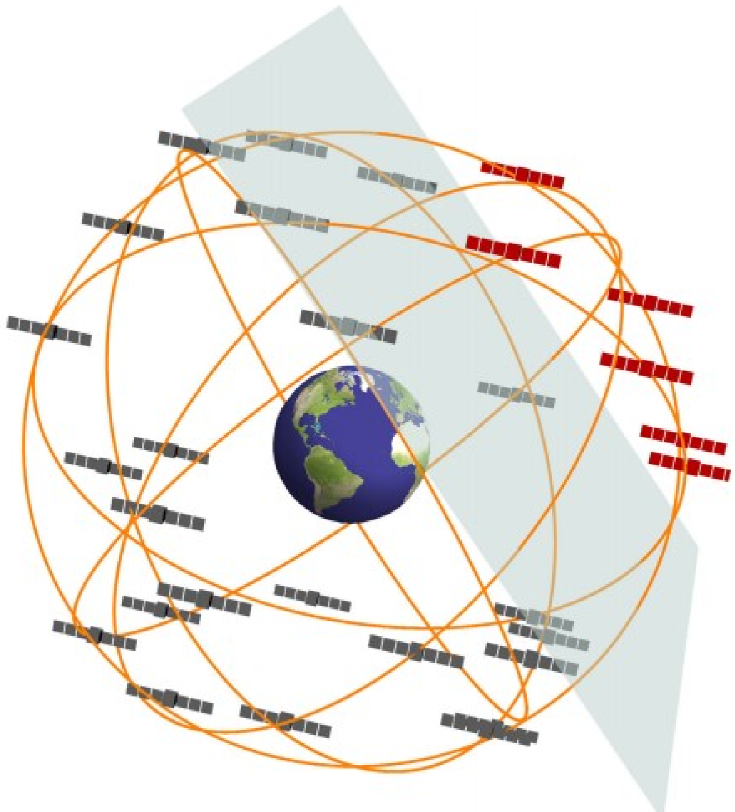


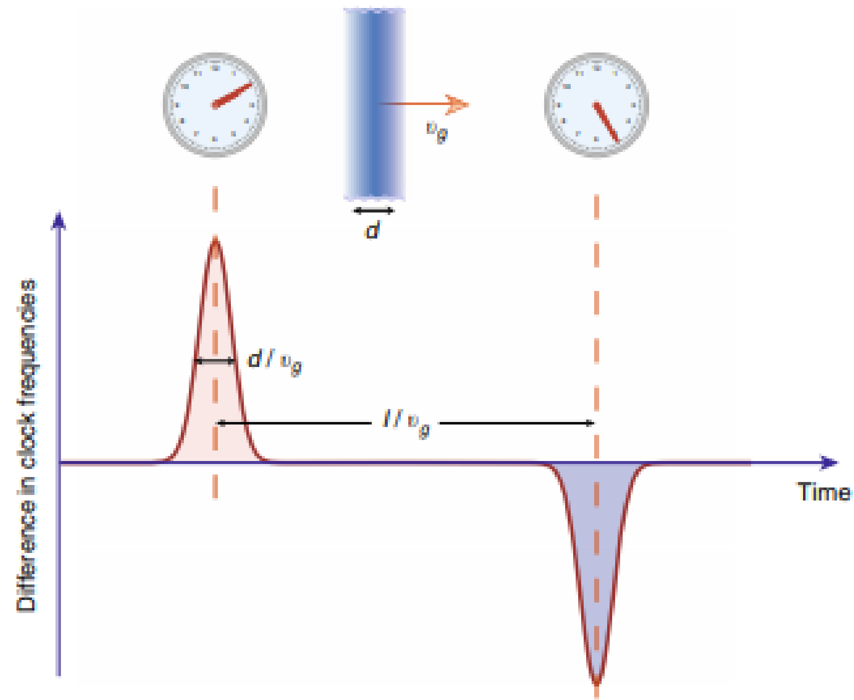
- Compare atomic clocks on independent satellites with a shared clock laser
- GW changes apparent distance between clocks
- Causes doppler shift between clocks
  - Clock B no longer on frequency
- Space based GW detector not limited by seismic noise
- Sensitive to Broad frequency of GW
  - mHz – 10's Hz
- Investigate new sources of GW waves
  - Inspiraling black hole mergers

S. Kolkowitz, Gravitational wave detection with optical lattice atomic clocks, Phys. Rev. D **94**, 124043 2016.

Dark Matter Detection

Clock networks can be used to detect and constrain models of dark matter.





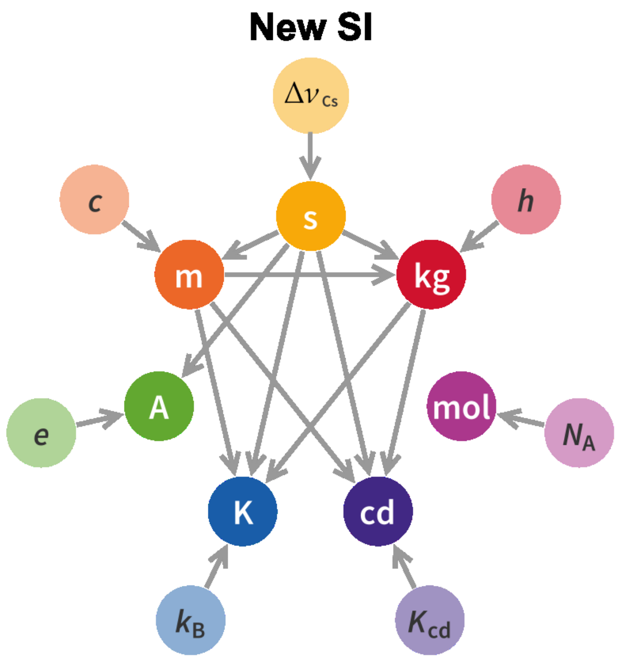
- GPS network provides distributed aperture for sensing DM
- Rb and Cs clocks have different coupling strengths
  - Independent networks

- Ultralight topological Dark Matter couple to fundamental constants
- Transient change in atomic transition frequency as domain wall passes through
- Velocity of DM signatures –~ 300 km/s

Roberts, *et al.* Search for domain wall dark matter with atomic clocks on board global positioning system satellites. *Nat Commun* **8,** 1195

Optical Time Dissemination

Redefinition of SI second



- On orbit atomic clock to compare against remote clocks on the ground
- Optical and microwave links to compare and disseminate timing data
- Improved atomic timescale

Requires:

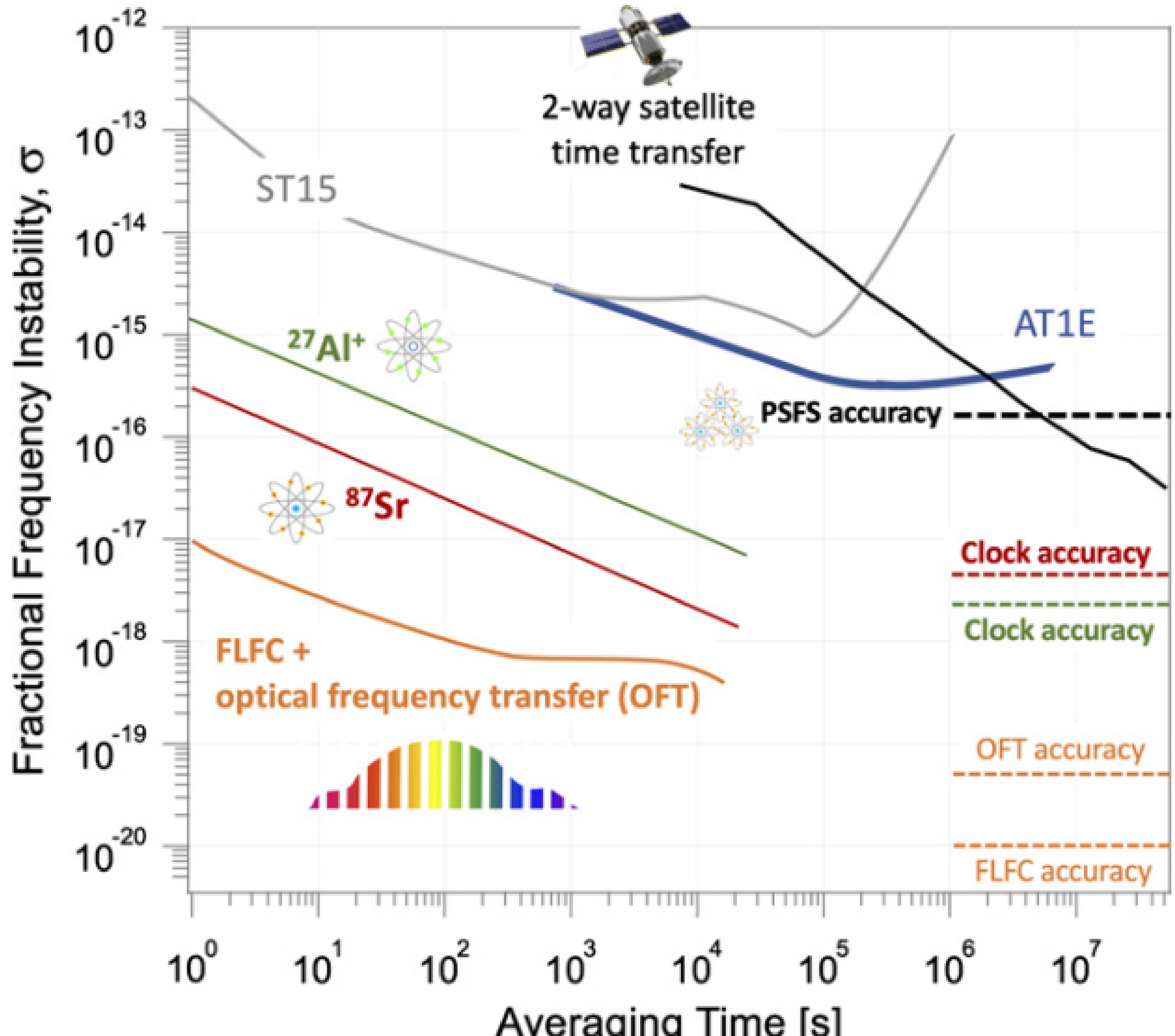
- Improved time transfer links

Optical second would improve realization of SI second by 2 orders of magnitude.

F. Riehle, et. al., *Metrologia* 55.2 188 (2018).

Performance of clocks and links

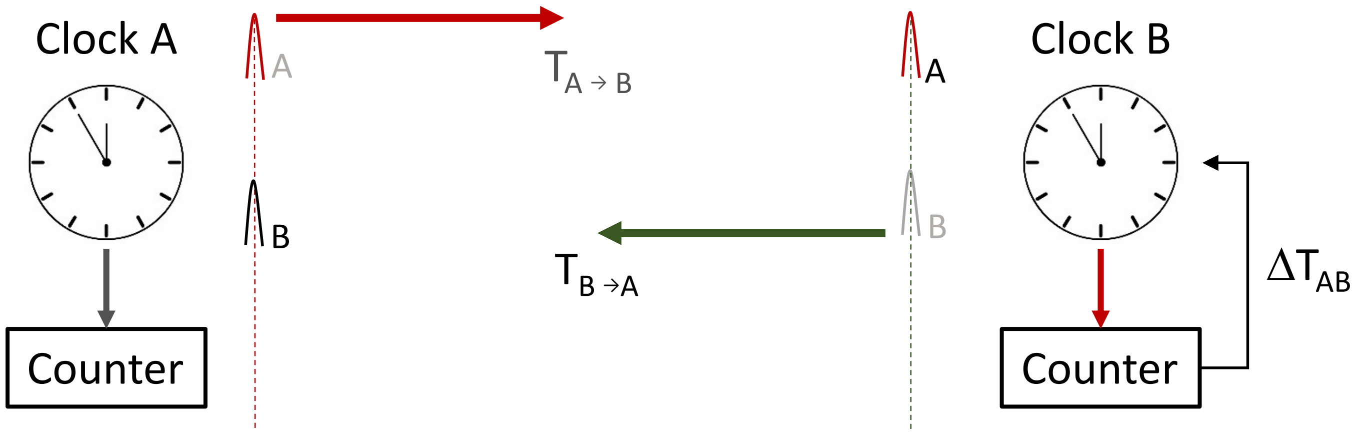
Optical time transfer links can support optical clock performance.



Leopardi et al, Metrologia (2021)

Two-way time transfer

Two clocks emit a pulse at the same local time.
Measure the time of arrival at the other site.
Apply timing correction to synchronize clocks.



$T(A) = T_{B \to A} + \Delta T_{AB}$ $\quad$ $T(B) = T_{A \to B} - \Delta T_{AB}$

$$\Delta T_{AB} = \tfrac{1}{2}\,(T(A) - T(B)) + \tfrac{1}{2}\,(T_{A \to B} - T_{B \to A})$$

Time offset between clocks

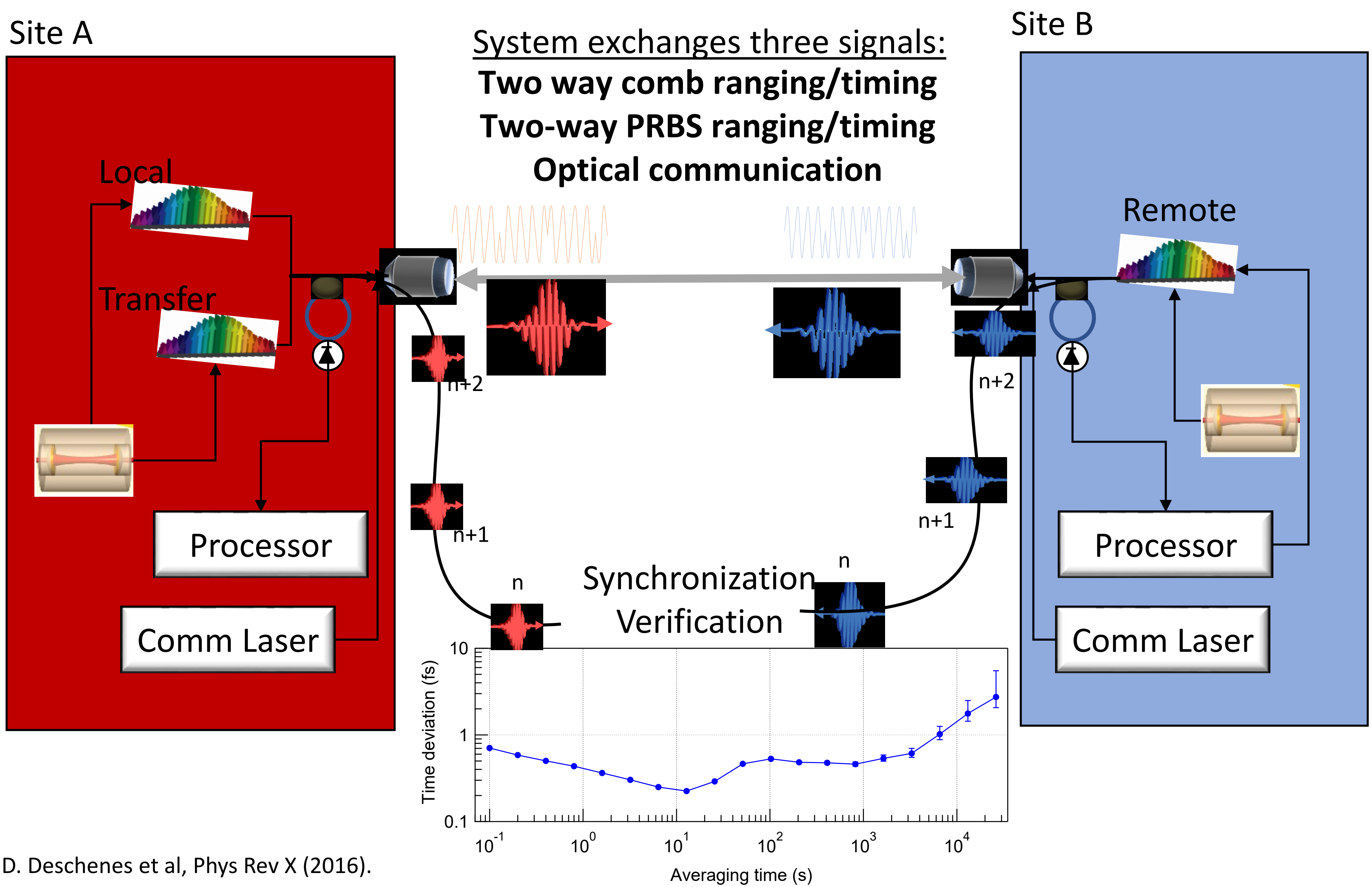
Time of arrival of pulses

Path delay across the link

Clocks are synchronized when the pulses arrive at each site at the same time!

Coherent time transfer with combs

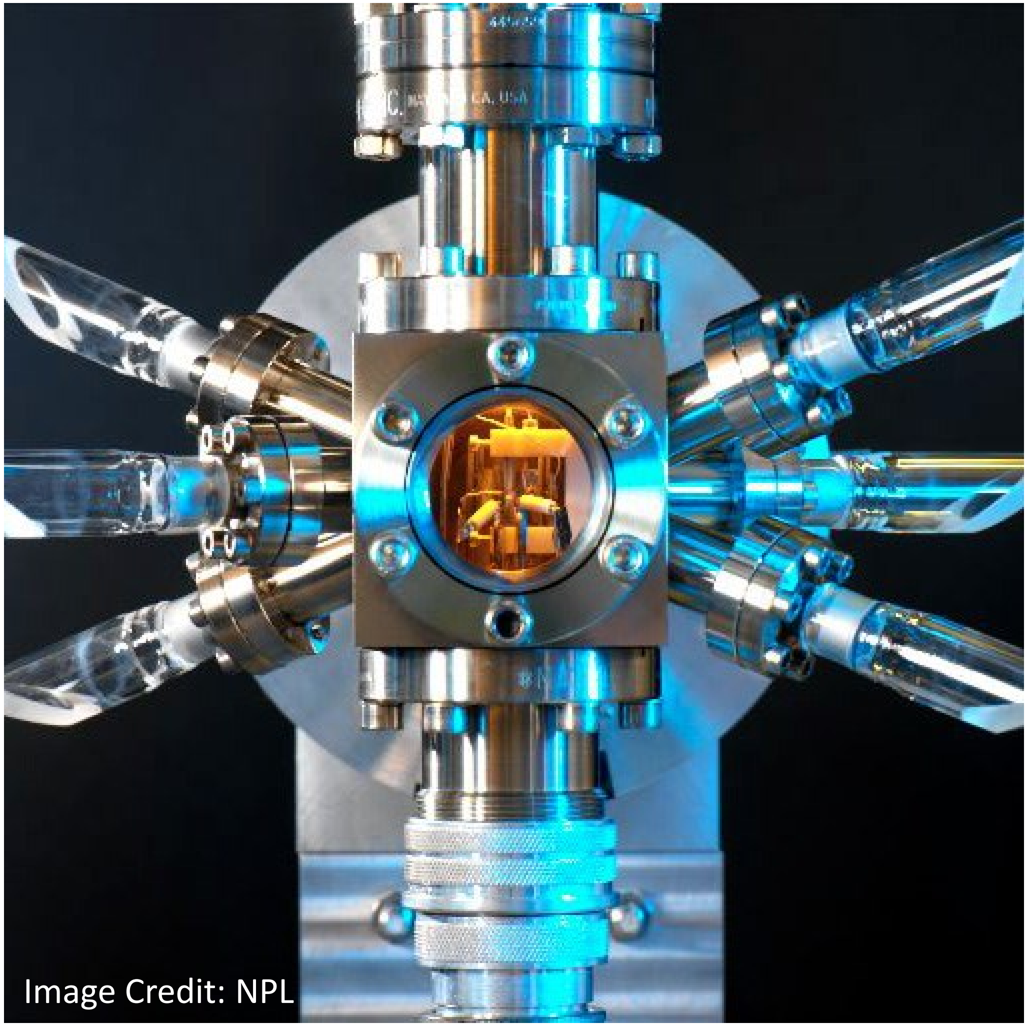
Frequency combs can transfer time by comparing and synchronizing pulse trains



J.D. Deschenes et al, Phys Rev X (2016).

Conclusion

- State of the Art optical Atomic clocks perform at 10^{-18} level
  - Precise sensors
- Comparing atomic clocks enables tests of fundamental physics
  - Einstein's Equivalence Principle
  - Dark Matter searches
  - Gravitational waves
  - Relativistic geodesy
  - Redefinition of SI second
- Free space optical time transfer links based on frequency combs



Thank you!

References

J.D. Deschenes, et. al., Phys Rev X (2016).

Leopardi et. al., Metrologia (2021)

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Roberts, *et. al., Nat Commun* **8,** 1195 (2017).

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