The Science of the PFaST (Probing the Fabric of Space-Time) Campaign

Andrei Derevianko

University of Nevada, Reno, USA

My background

Theoretical physicist working at the intersection of quantum technologies with foundational physics and cosmology

FOCOS mission: Modern orbiting clocks to confront Einstein's gravity (++)

Fundamental Physics with a State-of-the-Art Optical Clock in Space,   A. Derevianko, K. Gibble, L. Hollberg, N. R. Newbury, C. Oates, M. S. Safronova, L. C. Sinclair, and N. Yu, Quantum Science & Technology 7, 044002 (2022)

Outline

- Clouds hanging over 21st century physics
- Quantum sensors as exquisite listening devices
- Atomic clocks: human ingenuity on display
- Einstein's gravitational redshift is real and intriguing
- Einstein's gravity: trust but verify
- FOCOS mission: modern clocks in space
- FOCOS mission: decisively confronting Einstein
- FOCOS mission: other science and practical goals

Who invented iPhone?

Apple Inc.

or

Generations of scientists?

Key technologies - such as transistors and semiconductors - are the result of quantum mechanical principles

iPhone works. Is Physics dead?

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

iPhone works. Is Physics dead?

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

~ William Thomson (Lord Kelvin), 1900

iPhone works. Is Physics dead?

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

~ William Thomson (Lord Kelvin), 1900

Lord Kelvin: “cloud” hanging over 19th-century physics:
blackbody radiation and the ultraviolet catastrophe

iPhone works. Is Physics dead?

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

~ William Thomson (Lord Kelvin), 1900

Lord Kelvin: "cloud" hanging over 19th-century physics:
blackbody radiation and the ultraviolet catastrophe

Max Planck (1901) : blackbody spectrum $\longrightarrow$ quantization paradigm $\longrightarrow$ Planck constant $\hbar$ $\longrightarrow$ quantum revolution

iPhone works. Is Physics dead?

"There is nothing new to be discovered in physics now.
All that remains is more and more precise measurement."

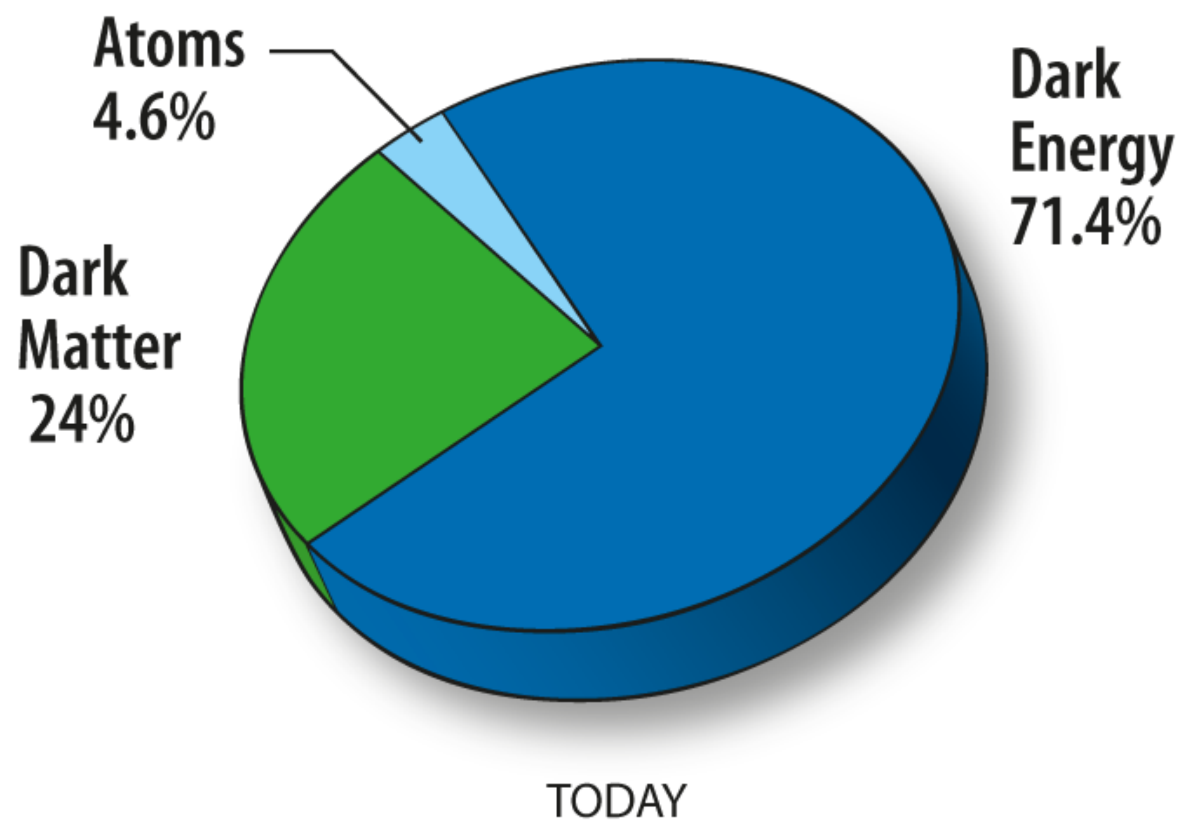
~ William Thomson (Lord Kelvin), 1900

Lord Kelvin: "cloud" hanging over 19th-century physics:
blackbody radiation and the ultraviolet catastrophe

Max Planck (1901) : blackbody spectrum $\longrightarrow$ quantization paradigm $\longrightarrow$ Planck constant $\hbar$ $\longrightarrow$ quantum revolution

$\longrightarrow$ iPhone

"Cloud" hanging over 21st-century physics



- Our beautiful equations can describe only 5% of what is out there
- Multiple internal inconsistencies in the established theoretical frameworks
- Does the Einstein theory of gravity hold? Alternatives can explain dark matter too!
- Intriguing discovery potential +

  basis of future technologies and motivating young generation of scientists

Quantum sensors as exquisite *listening* devices

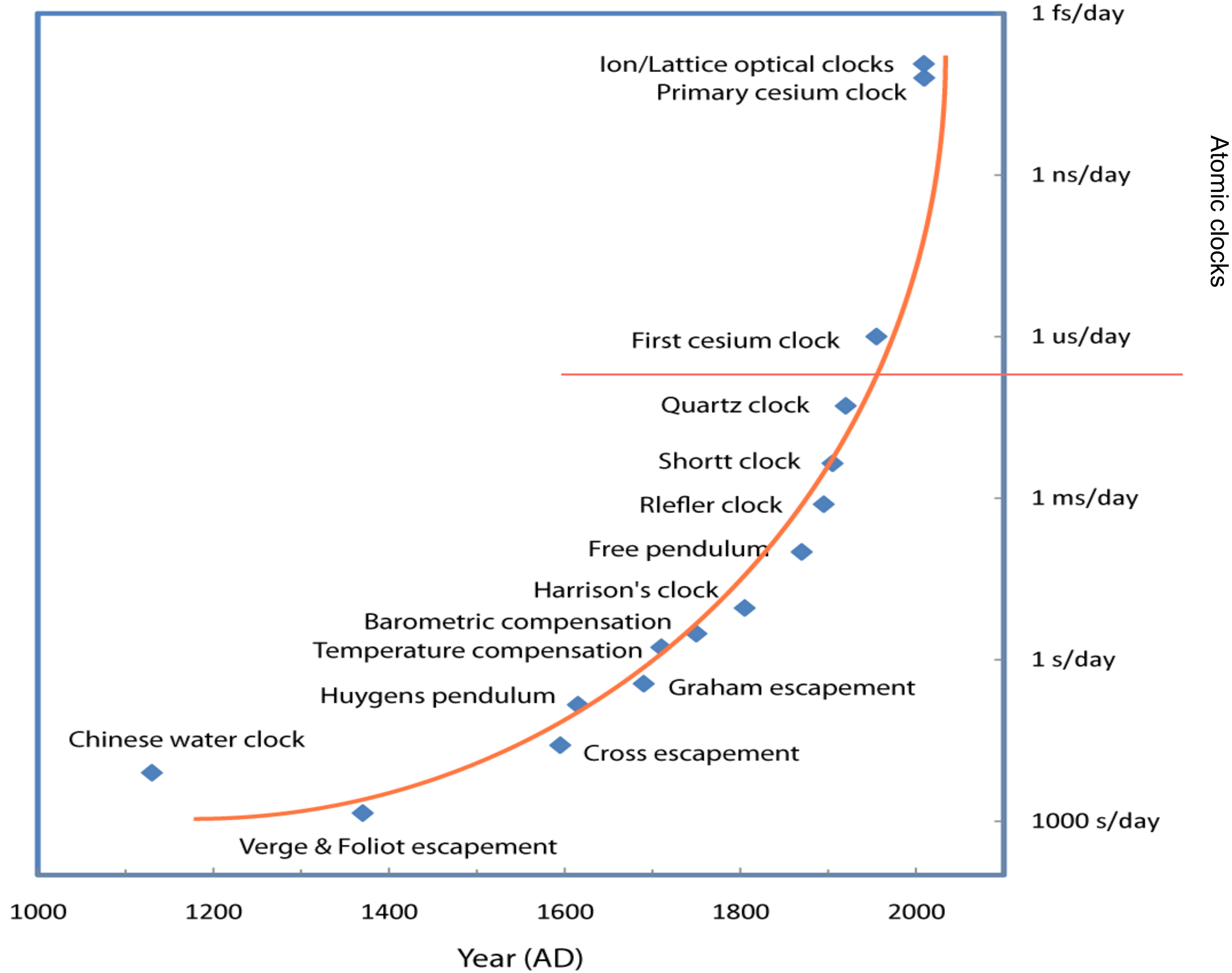
- atomic and nuclear clocks
- magnetometers (SQUIDs, NV-centers, etc),
- quantum gyroscopes,
- quantum accelerometers,
- quantum gravimeters,
- opto-mechanical sensors,
- optical and atomic interferometry

LIGO: optical interferometer sensitive
to 1/1600th proton diameter length change

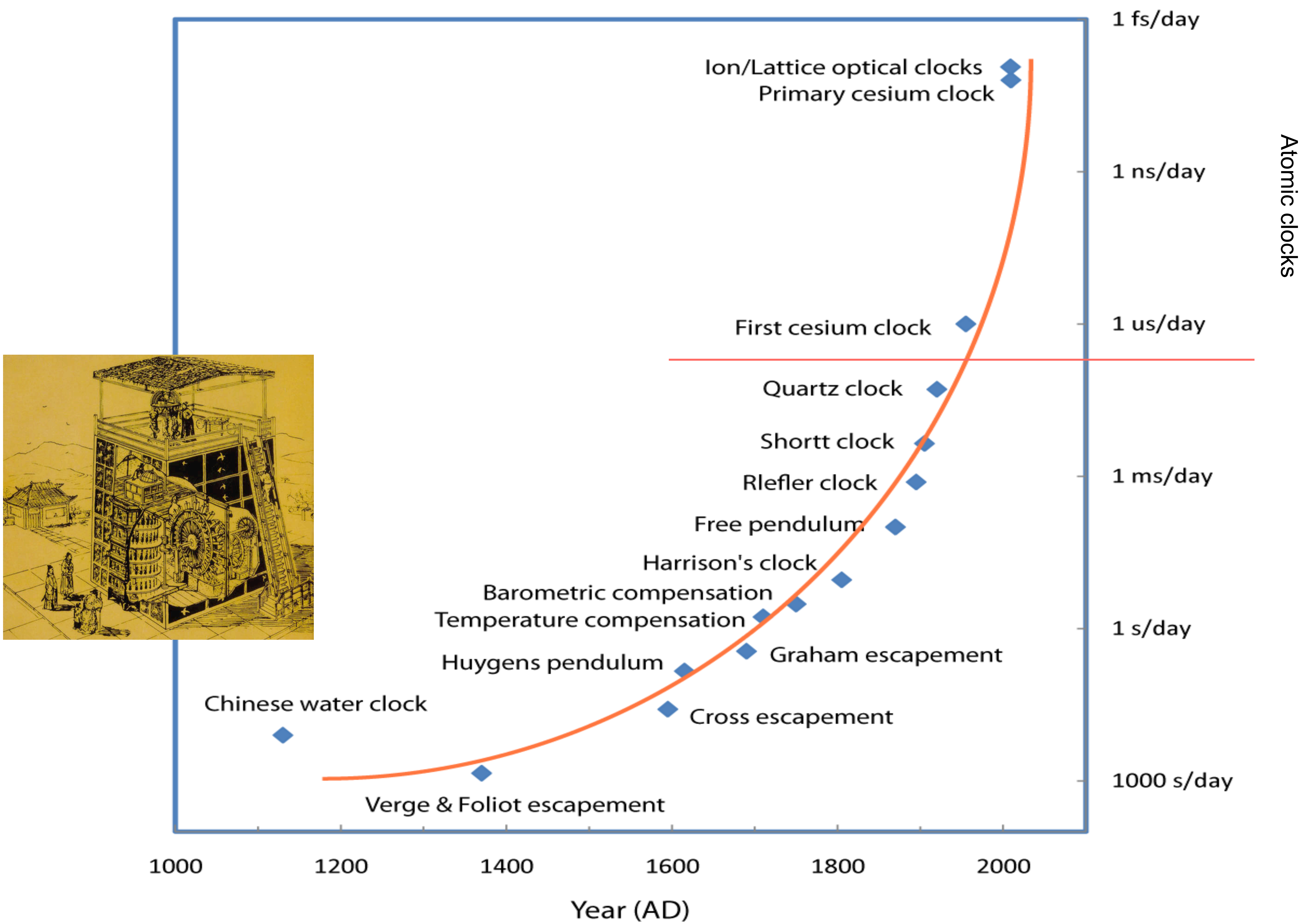
Quantum sensors as exquisite *listening* devices

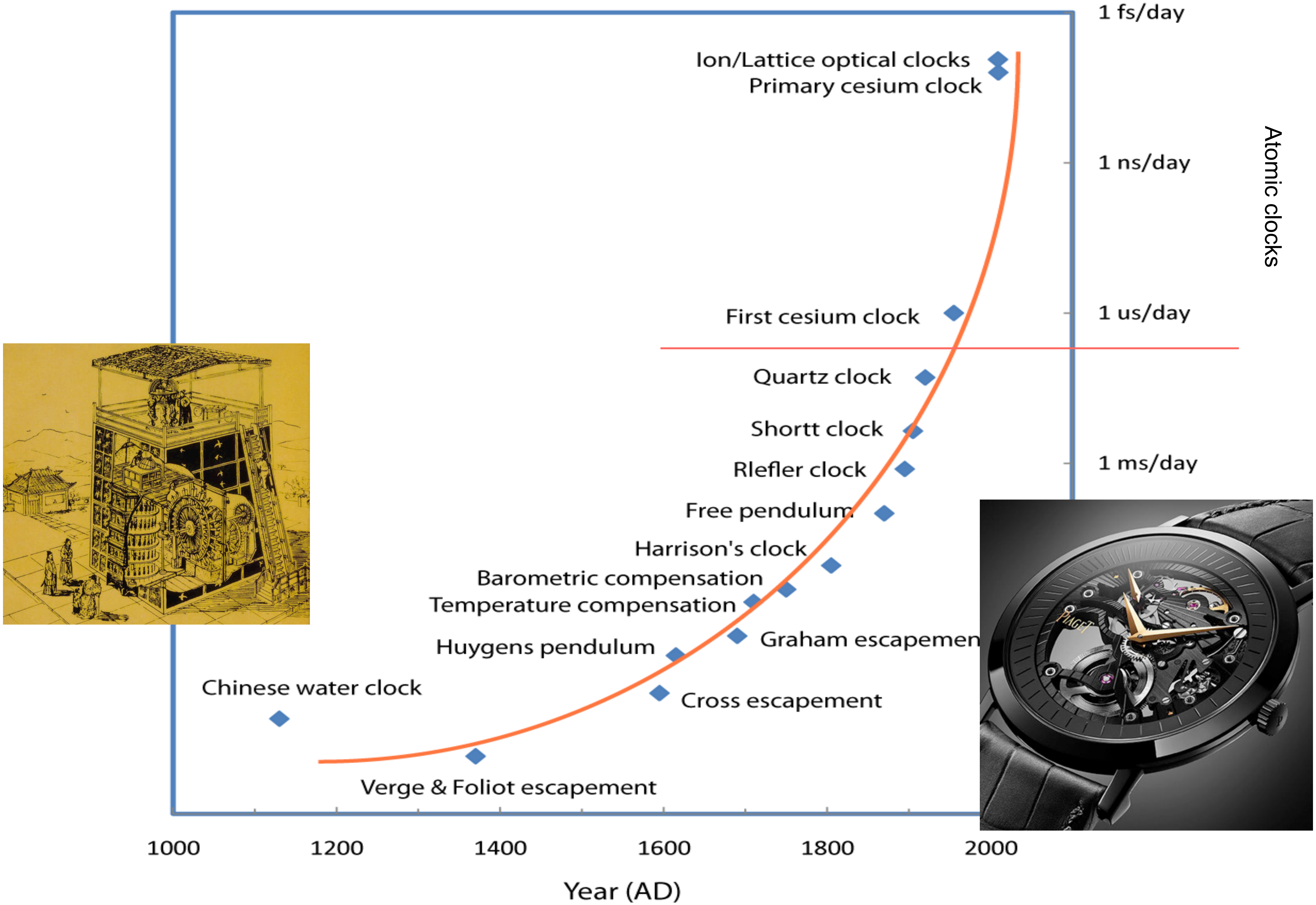
- atomic and nuclear clocks
- magnetometers (SQUIDs, NV-centers, etc),
- quantum gyroscopes,
- quantum accelerometers,
- quantum gravimeters,
- opto-mechanical sensors,
- optical and atomic interferometry

LIGO: optical interferometer sensitive
to 1/1600th proton diameter length change

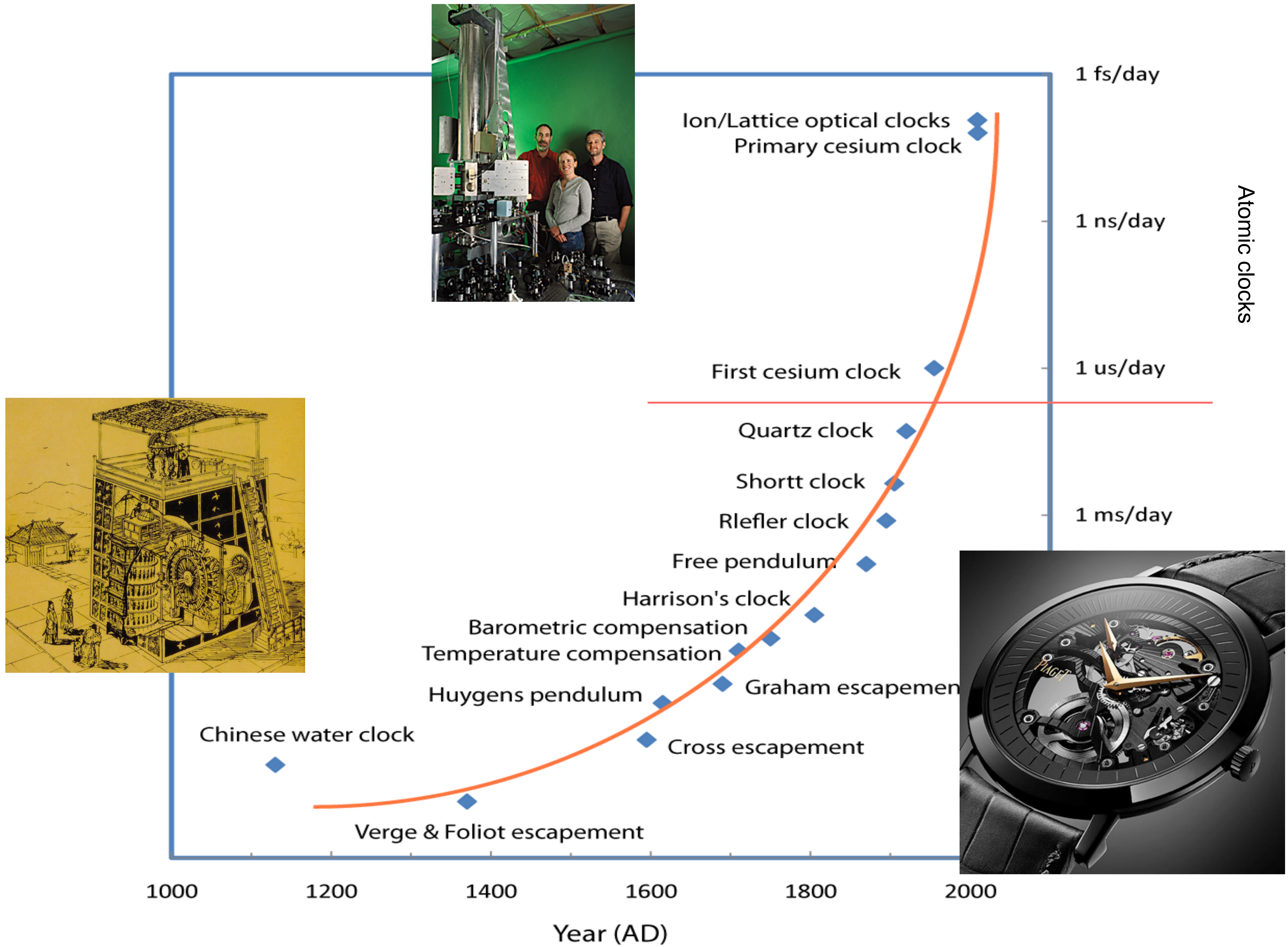


1 fs/day
1 ns/day
1 us/day
1 ms/day
1 s/day
1000 s/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapement
Huygens pendulum
Chinese water clock
Cross escapement
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)


1 fs/day
1 ns/day
1 us/day
1 ms/day
1 s/day
1000 s/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapement
Huygens pendulum
Chinese water clock
Cross escapement
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)

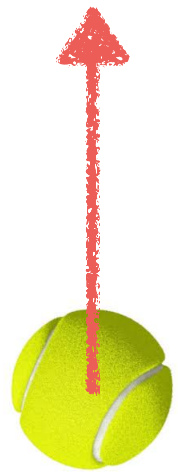


1 fs/day
1 ns/day
1 us/day
1 ms/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapemen
Huygens pendulum
Chinese water clock
Cross escapement
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)



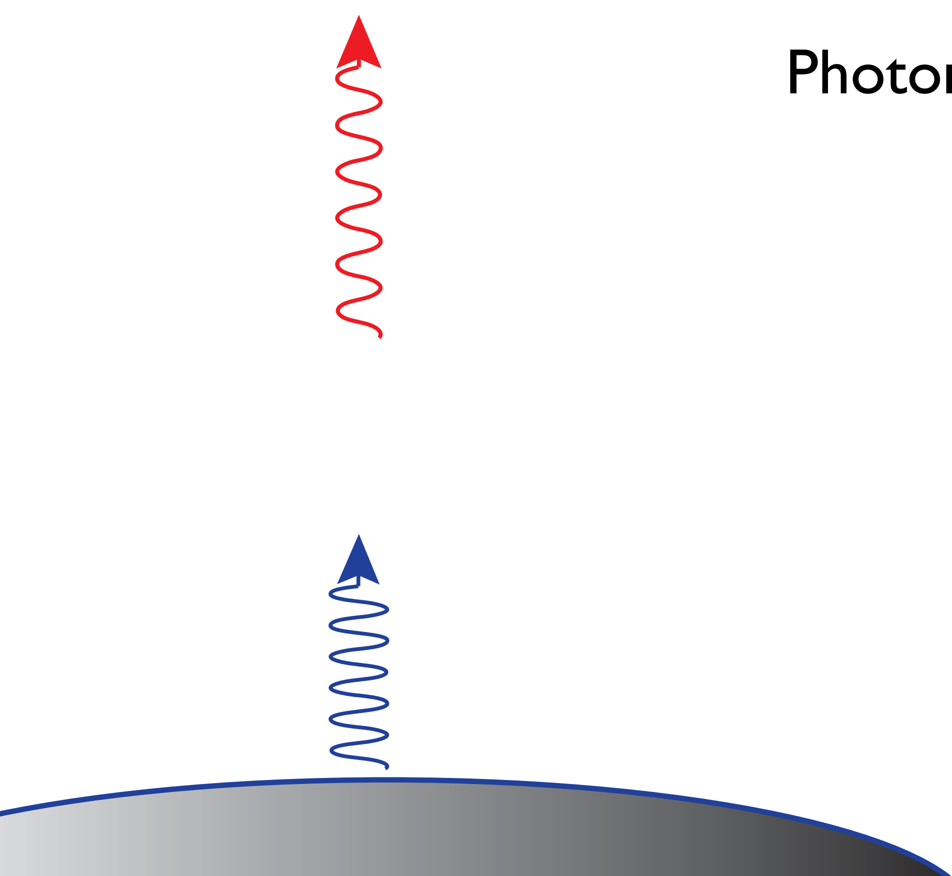
1 fs/day
1 ns/day
1 us/day
1 ms/day
Atomic clocks
Ion/Lattice optical clocks
Primary cesium clock
First cesium clock
Quartz clock
Shortt clock
Rlefler clock
Free pendulum
Harrison's clock
Barometric compensation
Temperature compensation
Graham escapemen
Huygens pendulum
Cross escapement
Chinese water clock
Verge & Foliot escapement
1000
1200
1400
1600
1800
2000
Year (AD)

Gravitational redshift



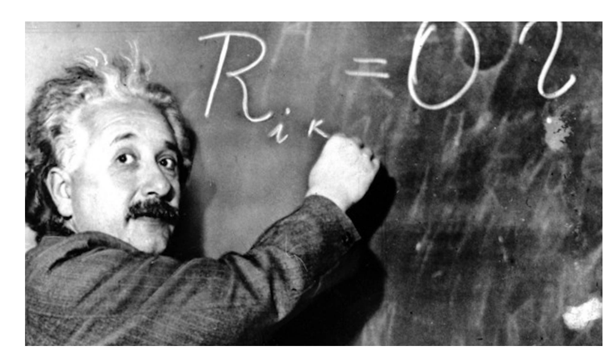
Kinetic energy is reduced by converting it into gravitational energy

Photon energy ($\hbar\omega$) is reduced by converting it into gravitational energy



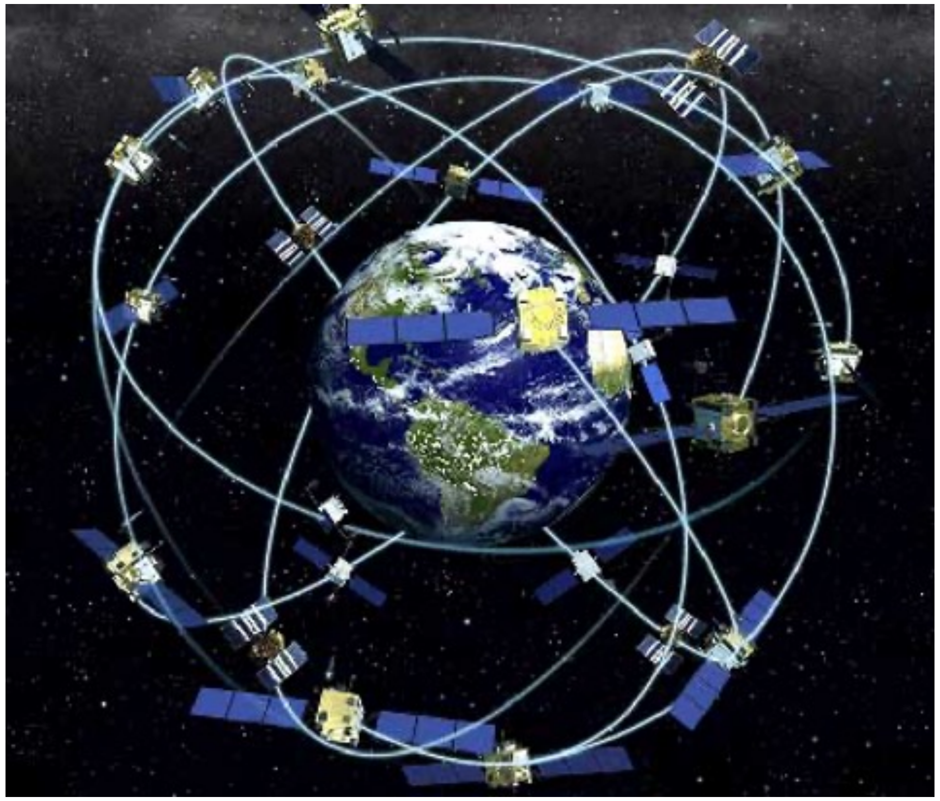
$$\frac{\Delta\omega}{\omega} = \frac{GM_{\text{Earth}}}{c^2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \cdots$$

=> Rate of the flow of time => clocks



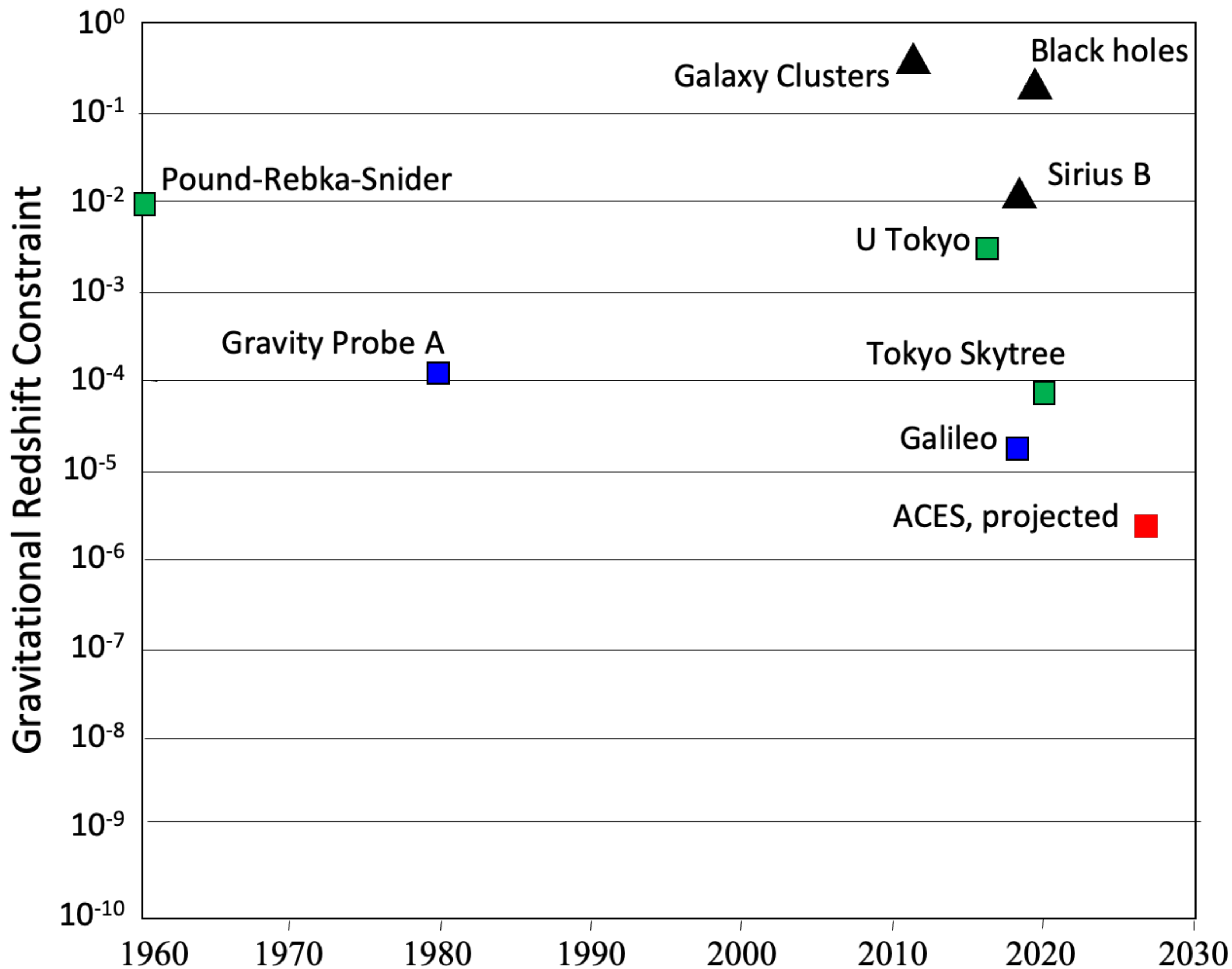
Gravitational redshift is real

In GPS, neglecting gravitational redshift leads to
positioning errors growing at a rate of ~10 kilometers per day



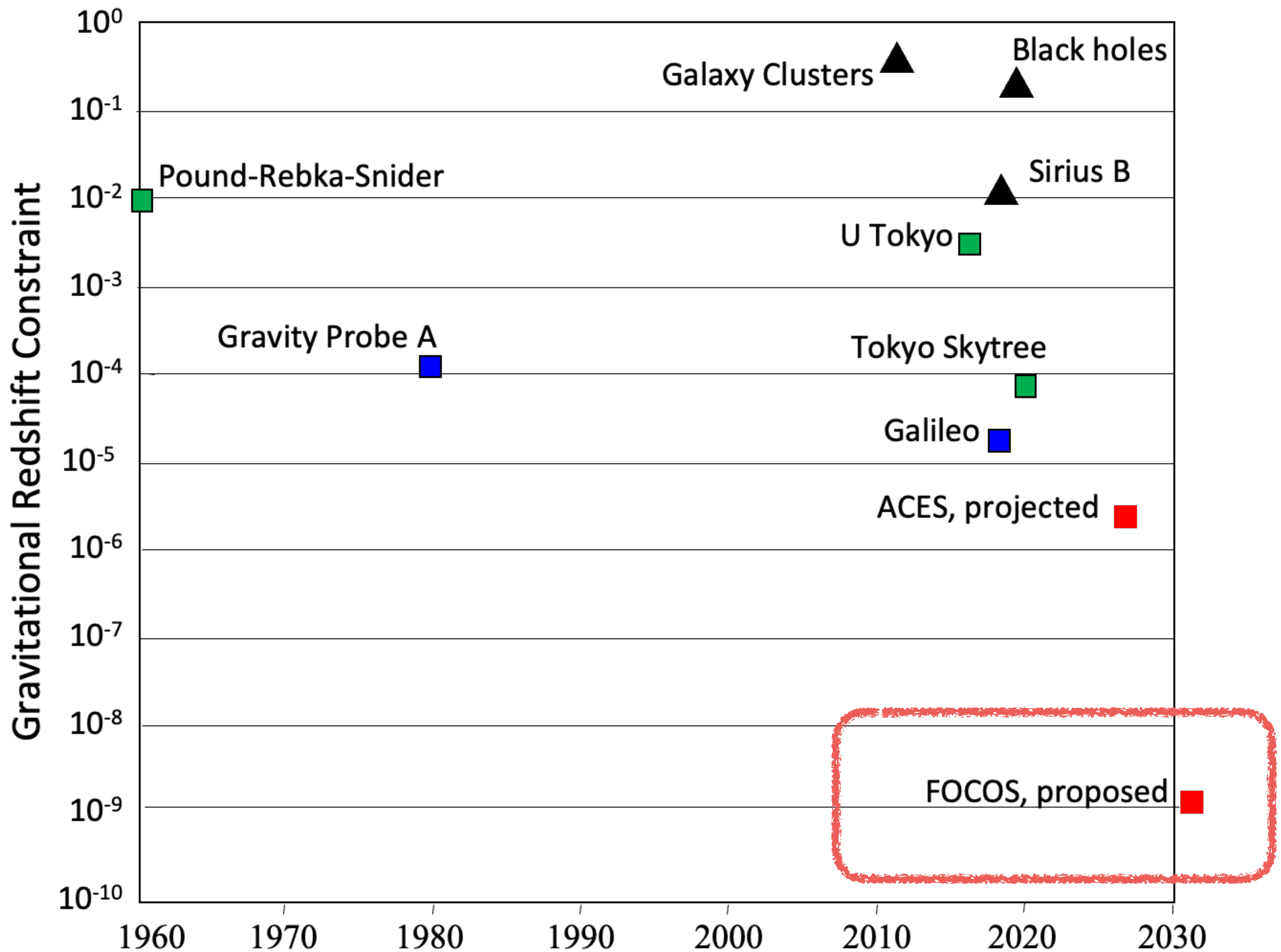
Tests of the Gravitational Redshift

- Does the Einstein theory of gravity hold? Alternatives can explain Dark Matter too



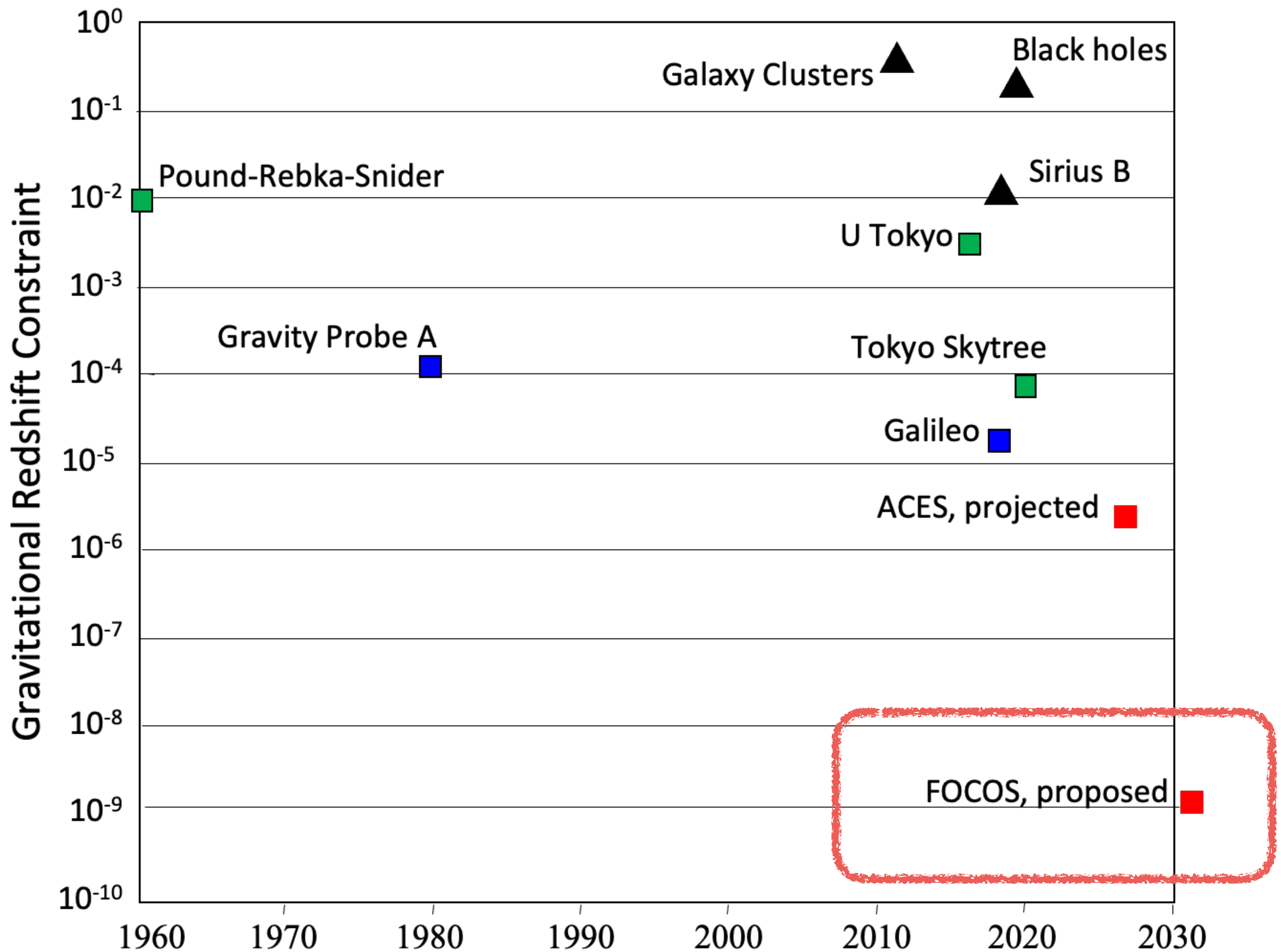
Tests of the Gravitational Redshift

- Does the Einstein theory of gravity hold? Alternatives can explain Dark Matter too



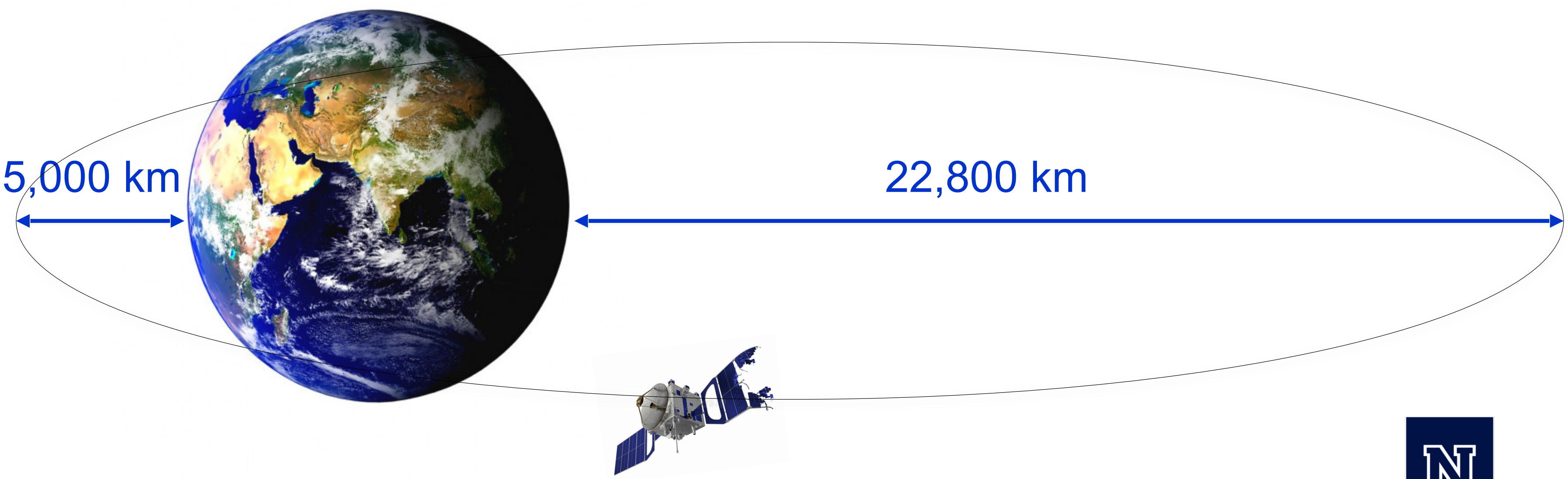
Tests of the Gravitational Redshift

- Does the Einstein theory of gravity hold? Alternatives can explain Dark Matter too



50,000 fold improvement! Exquisite accuracy to confront Einstein's gravity

FOCOS Mission Concept – Fundamental physics with an Optical Clock Orbiting in Space



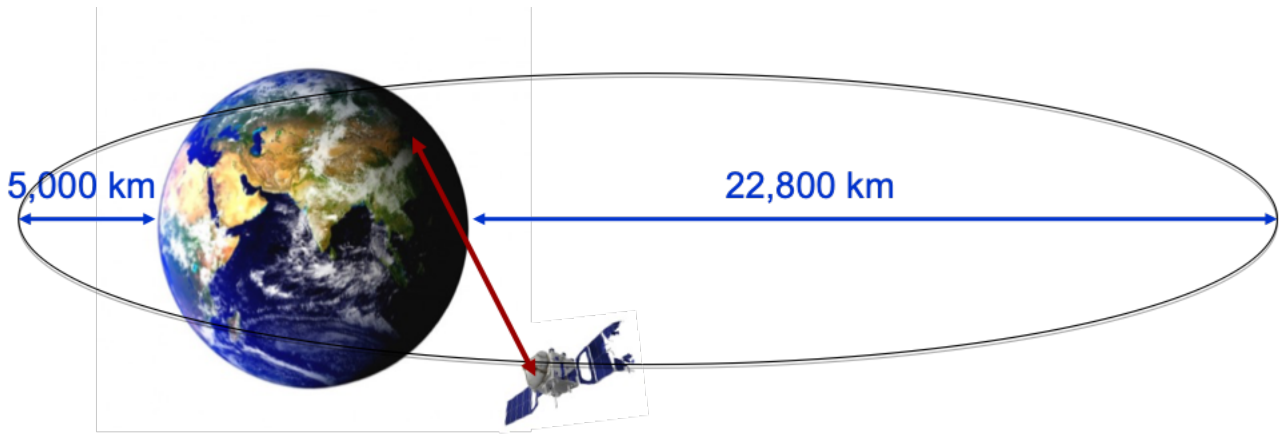
Andrei Derevianko, U. of Nev.-Reno
Kurt Gibble, Penn State U.
Leo Hollberg, Stanford U.
Nate Newbury, NIST
Marianna Safronova, U. of Del.
Laura Sinclair, NIST
Nan Yu, JPL
(Chris Oates, NIST)

University of Nevada, Reno
PennState
SCPNT Stanford Center for Position, Navigation and Time
NIST
University of Delaware
NASA
Jet Propulsion Laboratory
California Institute of Technology

Quantum Science and Technology 7, 044002 2022

FOCOS Mission concept

A high-performance optical clock in an elliptical orbit

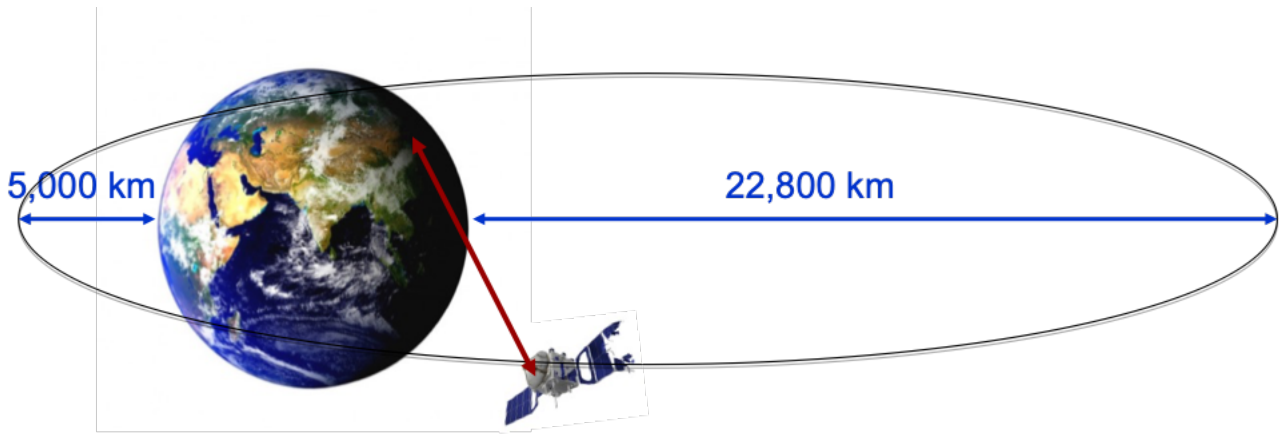


$$\frac{\Delta\omega}{\omega} = \frac{GM_{\mathrm{Earth}}}{c^2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \cdots$$

Courtesy of Kurt Gibble

FOCOS Mission concept

A high-performance optical clock in an elliptical orbit



$$\frac{\Delta\omega}{\omega} = \frac{GM_{\text{Earth}}}{c^2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \cdots$$

Optical clock performance: $1 \times 10^{-16}\ \tau^{-1/2}$, 1×10^{-18} uncertainty

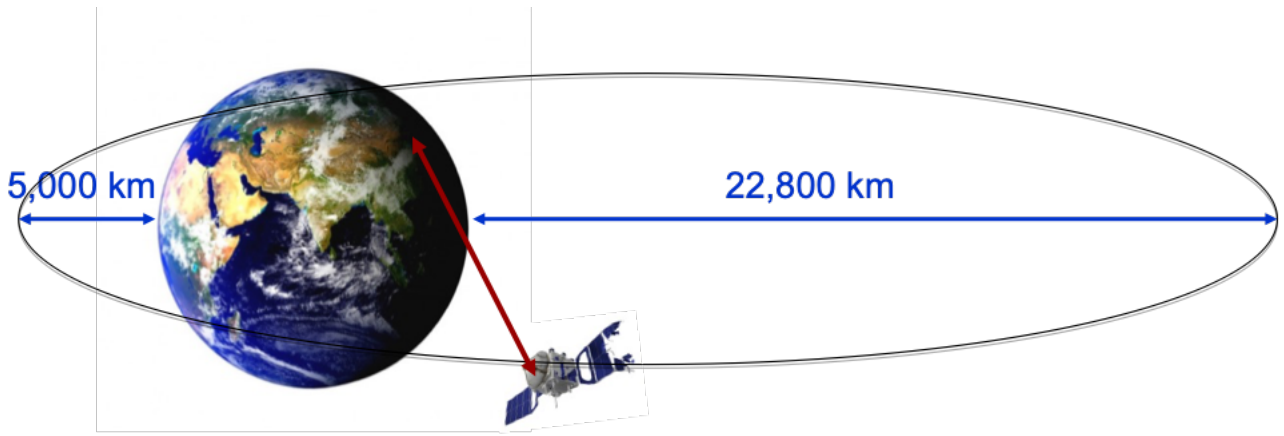
Optical link: $<1 \times 10^{-16}\ \tau^{-1}$, $< 5 \times 10^{-19}$ bias

Range at periapsis known to 1mm (two-way Doppler link) and velocity to 1μm/s.

Courtesy of Kurt Gibble

FOCOS Mission concept

A high-performance optical clock in an elliptical orbit



$$\frac{\Delta\omega}{\omega} = \frac{GM_{\text{Earth}}}{c^2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \cdots$$

Orbit modulates gravitational potential: 2.4 x 10^{-10} variation => Gravitational redshift.

Optical clock performance: 1 x 10^{-16} $\tau^{-1/2}$, 1 x 10^{-18} uncertainty

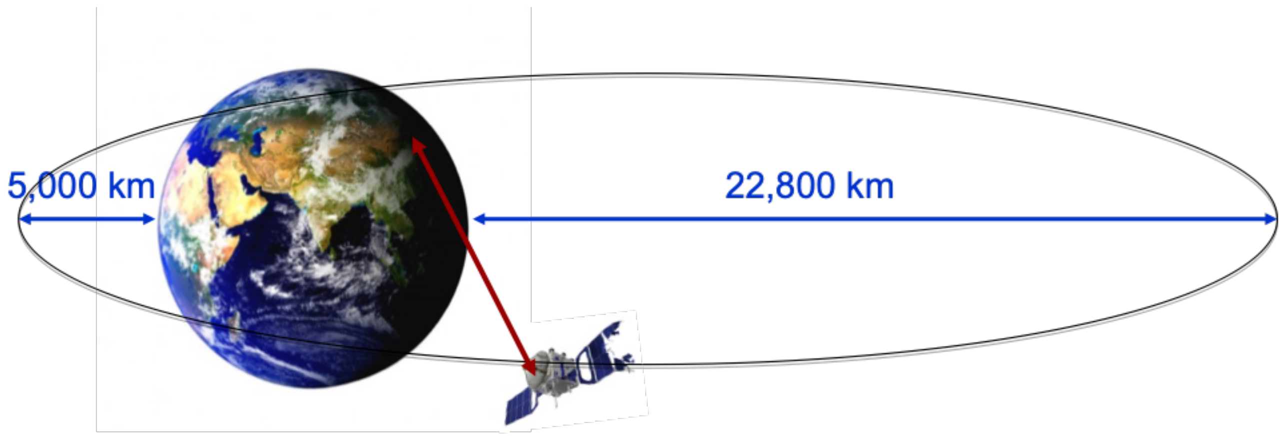
Optical link: <1 x 10^{-16} τ^{-1}, < 5 x 10^{-19} bias

Range at periapsis known to 1mm (two-way Doppler link) and velocity to 1µm/s.

Courtesy of Kurt Gibble

FOCOS Mission concept

A high-performance optical clock in an elliptical orbit



$$\frac{\Delta\omega}{\omega} = \frac{GM_{\text{Earth}}}{c^2}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \cdots$$

Orbit modulates gravitational potential: 2.4 x 10^{-10} variation => Gravitational redshift.

Optical clock performance: 1 x 10^{-16} $\tau^{-1/2}$, 1 x 10^{-18} uncertainty

Optical link: <1 x 10^{-16} τ^{-1}, < 5 x 10^{-19} bias

Range at periapsis known to 1mm (two-way Doppler link) and velocity to 1µm/s.

Average 100 orbits to reach 2.4 ppb in gravitational redshift measuremet.

Courtesy of Kurt Gibble

FOCOS science goals

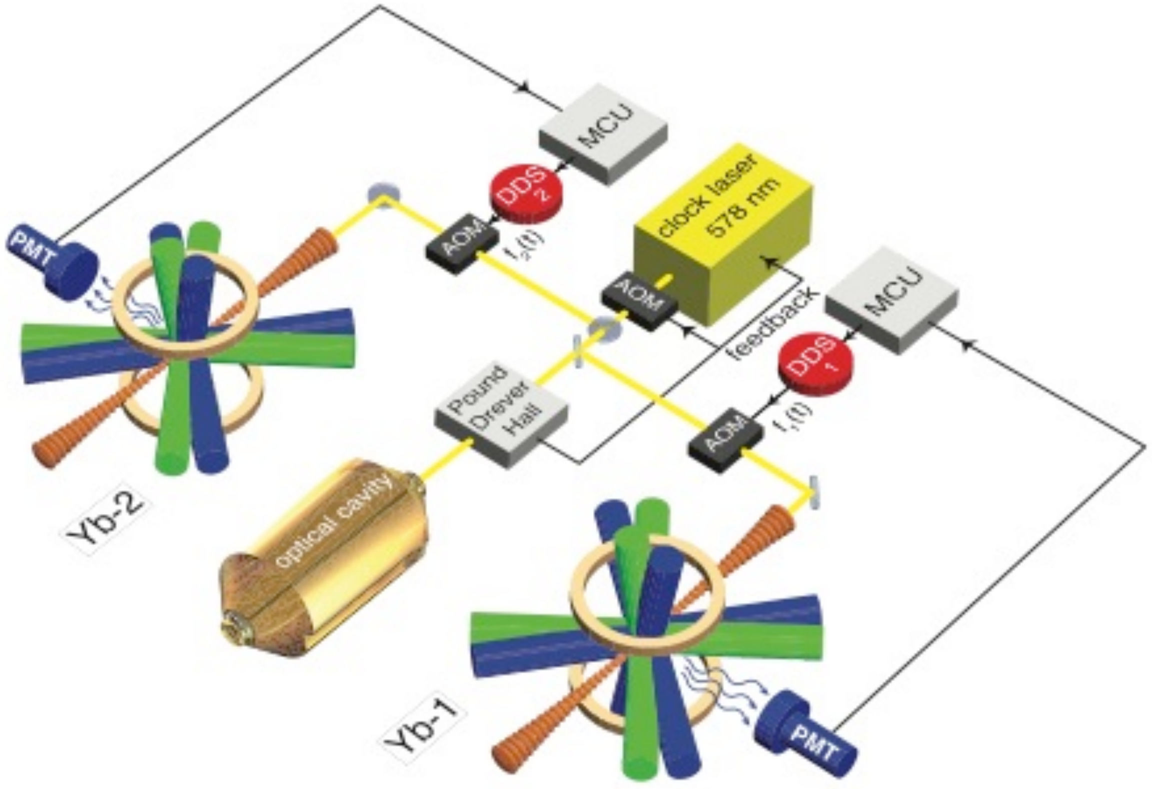
Fundamental physics:

1. Gravitational Redshift – improve the uncertainty by 50,000x to 1ppb.

2. Local Lorentz Invariance (foundation of quantum field theory)

Cavity-clock comparisons - orientation and velocity

Large expected gains in sensitivity.



Courtesy of Kurt Gibble

FOCOS science goals

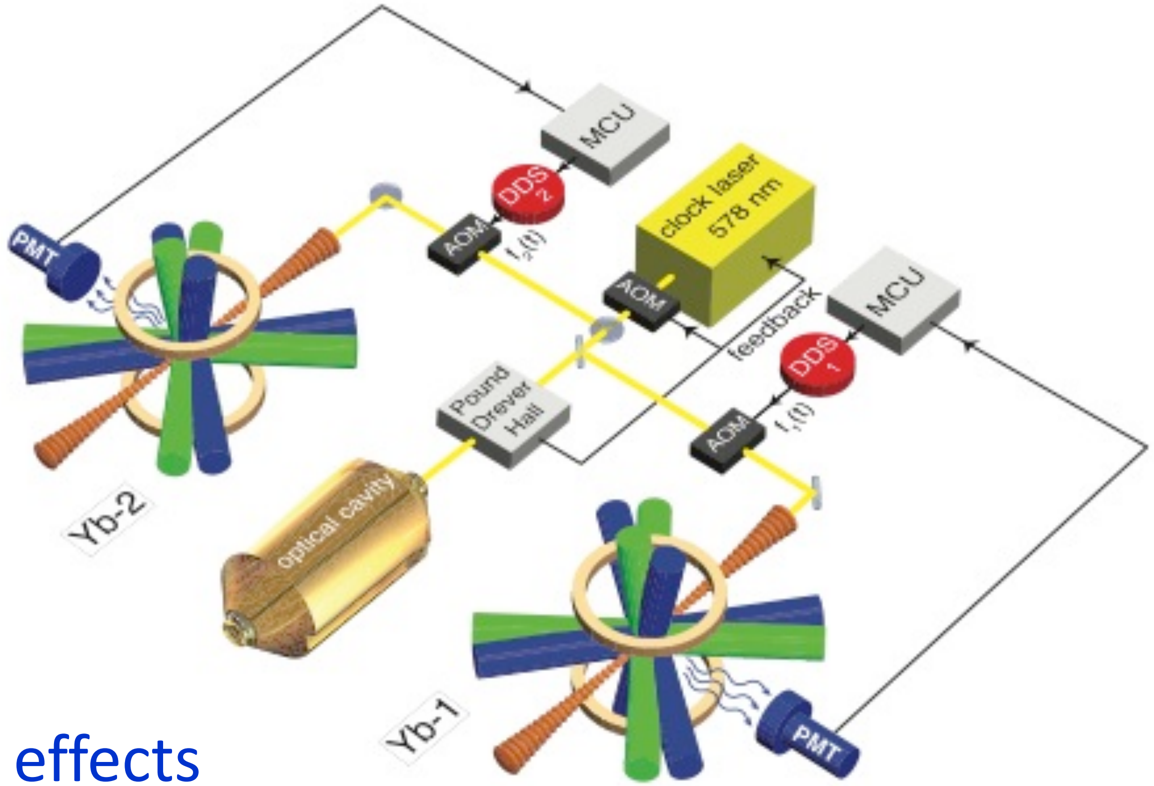
Fundamental physics:

1. Gravitational Redshift – improve the uncertainty by 50,000x to 1ppb.

2. Local Lorentz Invariance (foundation of quantum field theory)

   Cavity-clock comparisons - orientation and velocity

   Large expected gains in sensitivity.



3. Test higher-order relativistic and gravitational effects

   Requires precision orbit determination

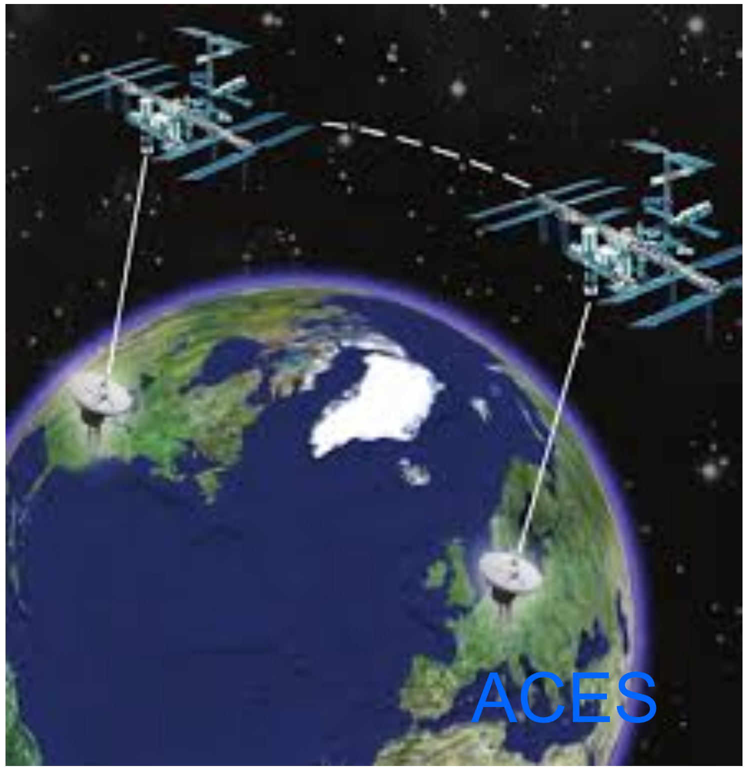
   GRACE, etc. for the gravitational field

4. Post-Newtonian effects on the satellite orbit (through two-way link data)

Courtesy of Kurt Gibble

FOCOS Science Goals – International Clock Network

Improved network of earth clocks – a step towards a space network.



Quantum Science and Technology 7, 044002 2022

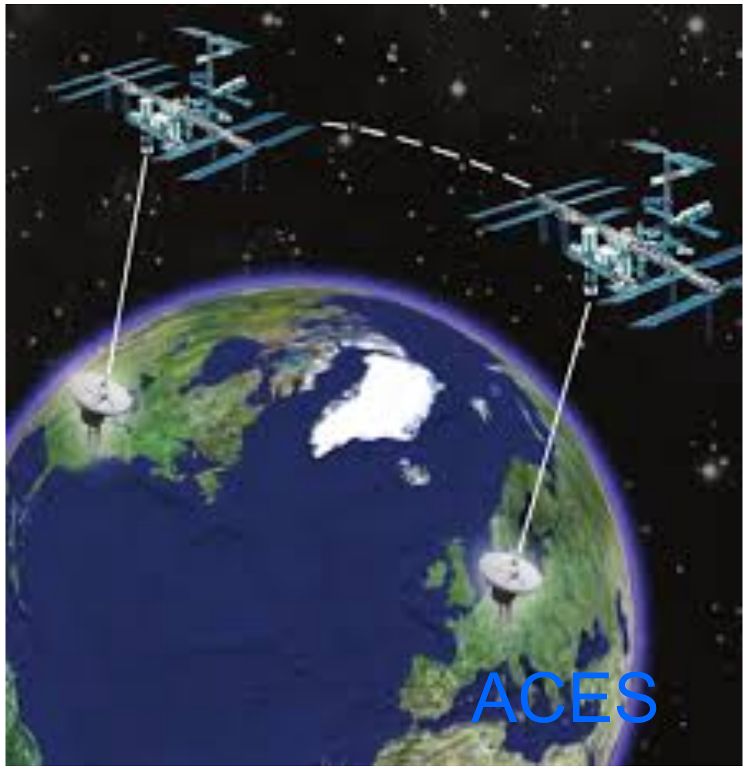
Courtesy of Kurt Gibble

FOCOS Science Goals – International Clock Network

Improved network of earth clocks – a step towards a space network.

Fundamental physics:

5. Dark Matter searches in space and on Earth
   – 100 to 1,000× improvement



Courtesy of Kurt Gibble

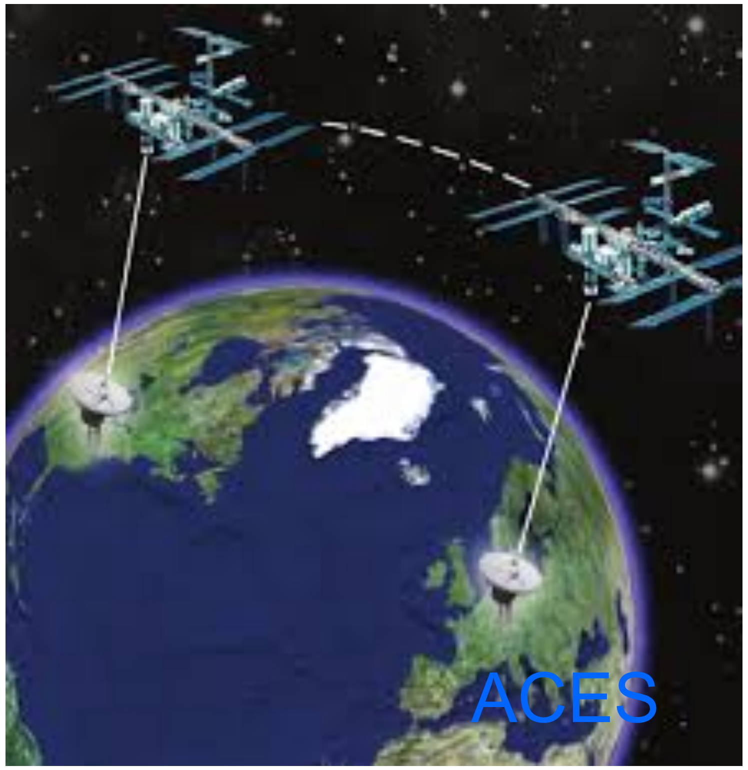
FOCOS Science Goals – International Clock Network

Improved network of earth clocks – a step towards a space network.

Fundamental physics:

5. Dark Matter searches in space and on Earth
   – 100 to 1,000× improvement

6. LPI tests – e.g., drifts of fundamental constants



Quantum Science and Technology 7, 044002 2022

Courtesy of Kurt Gibble

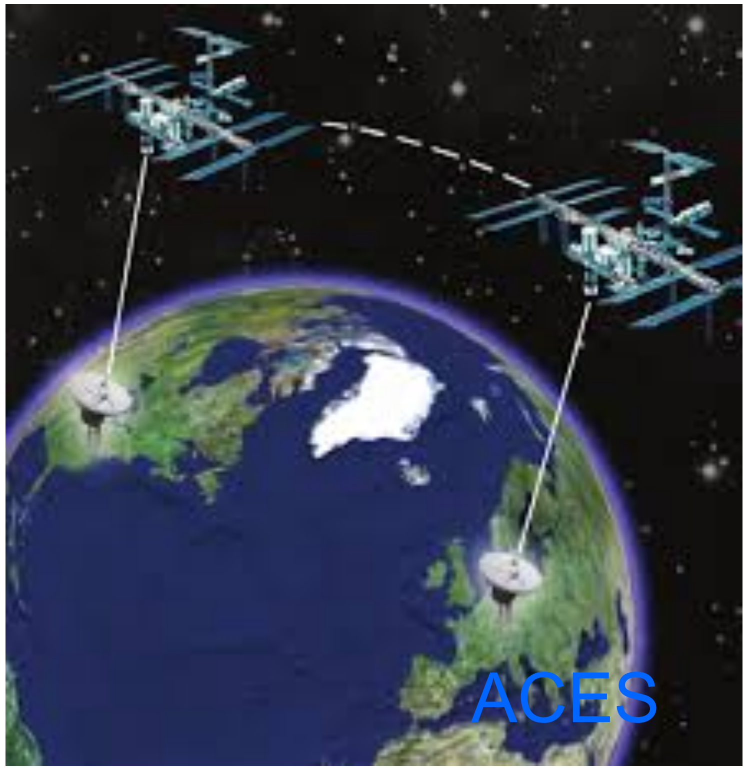
FOCOS Science Goals – International Clock Network

Improved network of earth clocks – a step towards a space network.

Fundamental physics:

5. Dark Matter searches in space and on Earth
   – 100 to 1,000× improvement

6. LPI tests – e.g., drifts of fundamental constants



Timing (practical) applications:

7. Worldwide timing: ns to ps level

8. Precision geodetic referencing at the mm-level

9. Space-time reference

Pathfinder-style mission for future atom interferometry (Equivalence Principle), clock constellation in space, laser/atom-based gravity wave detection

Quantum Science and Technology 7, 044002 2022

Courtesy of Kurt Gibble