Fundamental physics experiments using atomic clocks on the moon

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(Disclosure: Quantinuum Advisor)

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Optical atomic clocks

Why put optical atomic clocks in space?

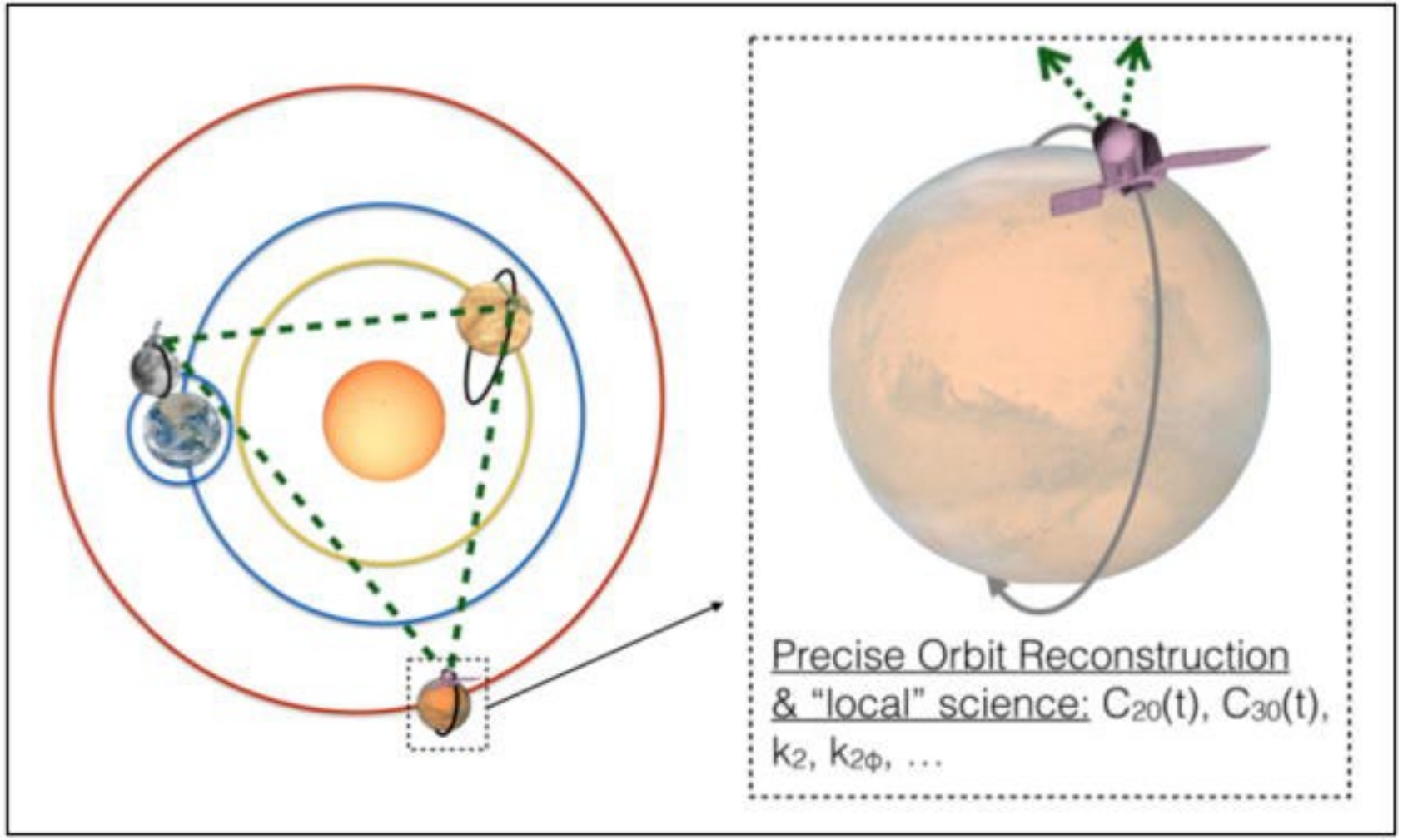
- 10^6 x improvement in planetary, lunar, and satellite ephemerides determination
  - Spacecraft navigation
  - Planetary defense (from asteroids)
  - Solar mass loss rate
  - Existence of planet 9
- 10^6 x improvement in VLBI resolution
  - Resolve the event horizon of black holes

Time/interferometry measurements

- μHz gravitational wave detection
  - Fill the gap between PTAs and LISA
  - Study black holes in the early universe, probe the geometry of the universe, search for the graviton
- 10^3 x improvement in Einstein equivalence principle violation searches
  - Predicted by *all* proposed theories that unify quantum mechanics with general relativity
- Dark matter searches
  - Ultralight and topological models

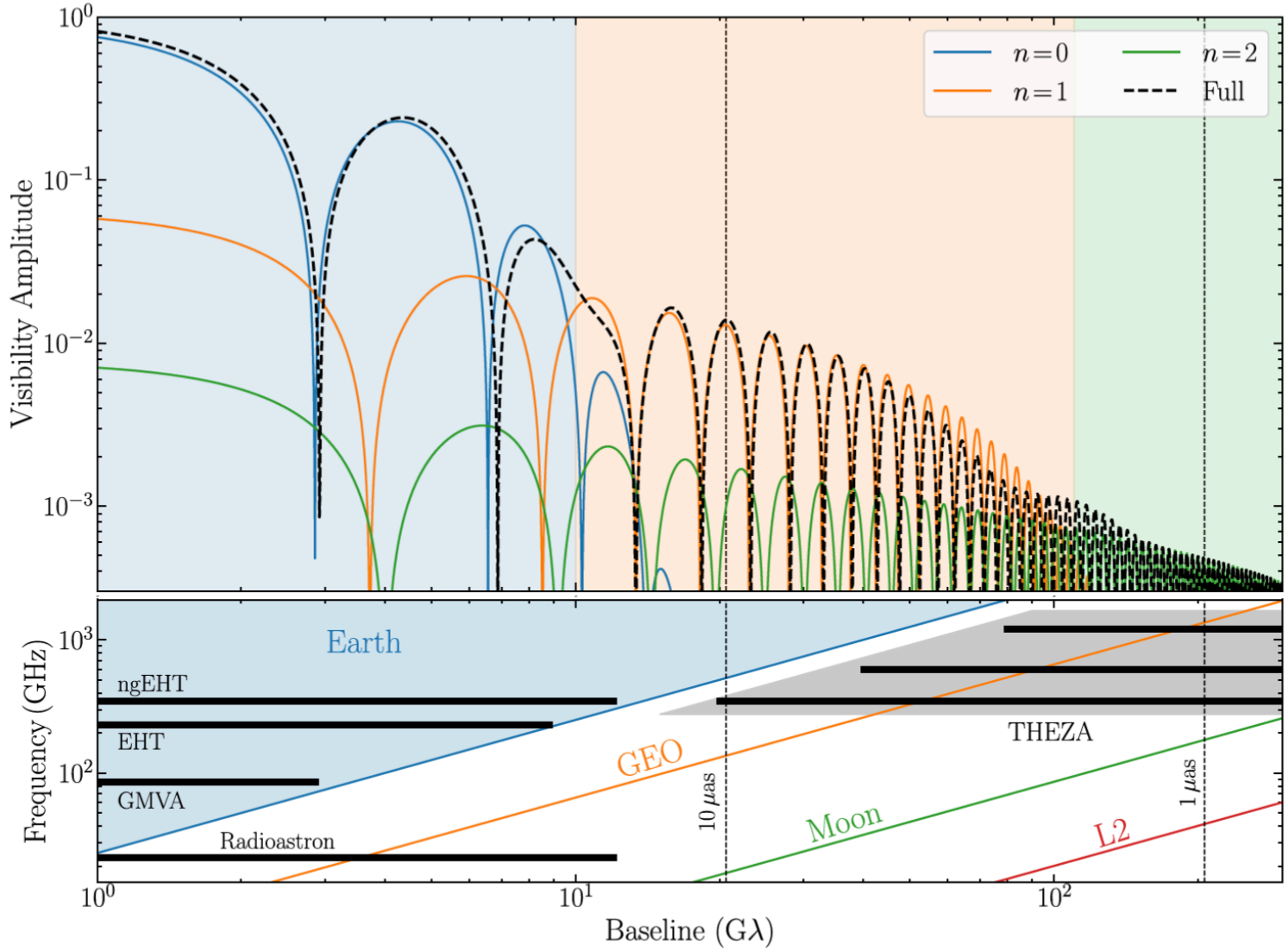
Frequency ratio measurements

Ephemerides (ILTN mission concept)



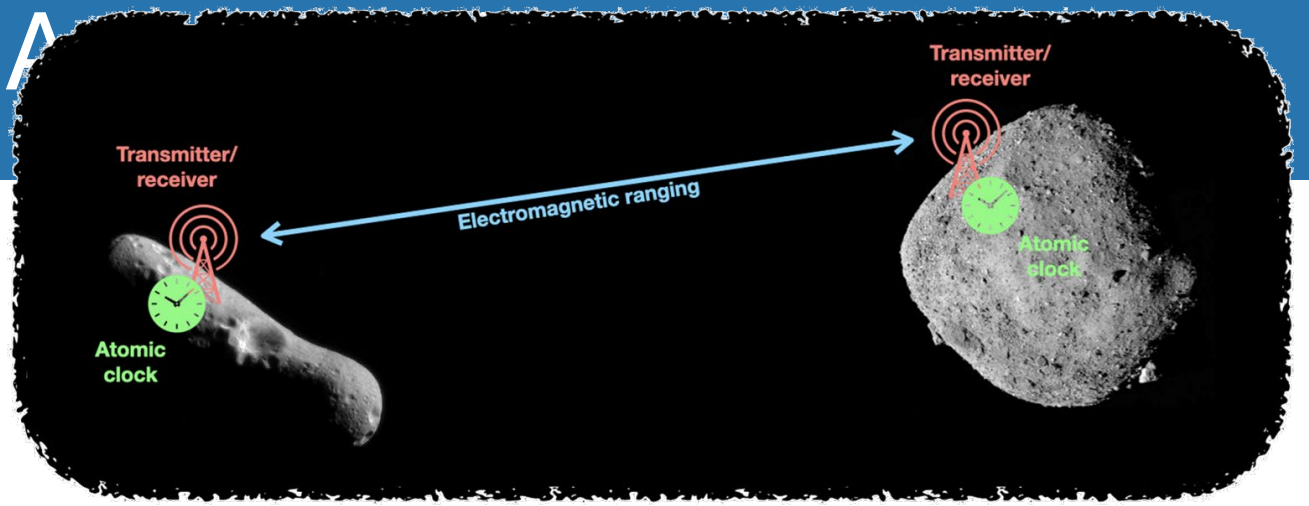
Smith ..., Planet Space Sci. **153**, 127 (2018)

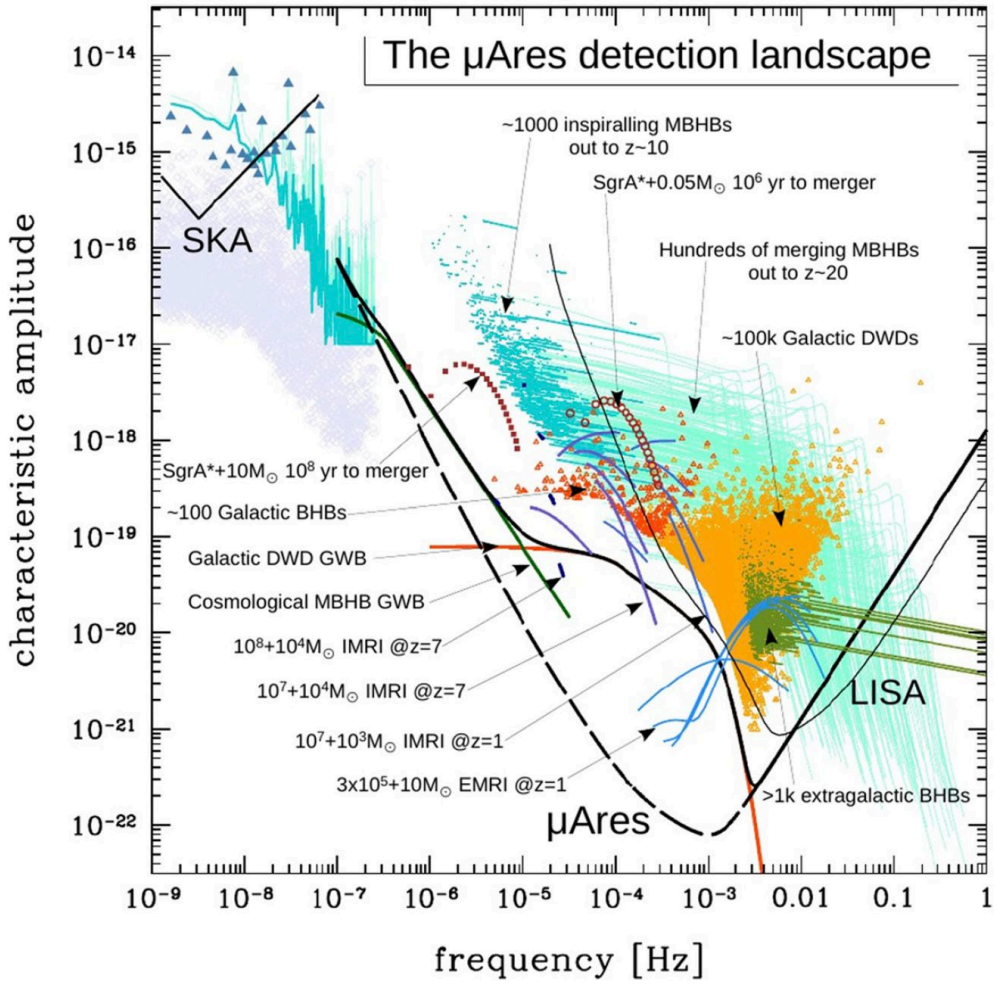
VLBI (THEZA mission concept)

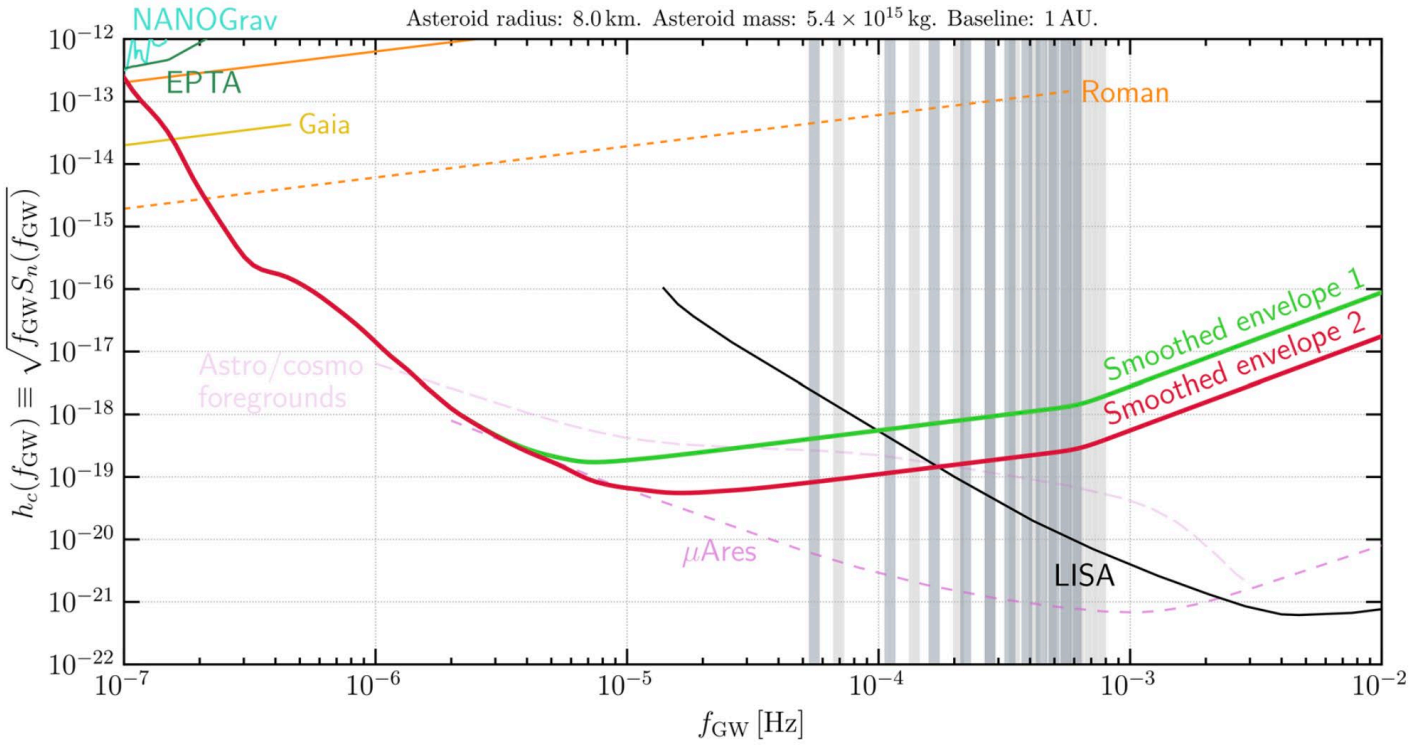


THEZA collaboration, Exp. Astron. **51**, 559 (2021); Acta Astronautica **196**, 314 (2022)

Gravitational waves (μA

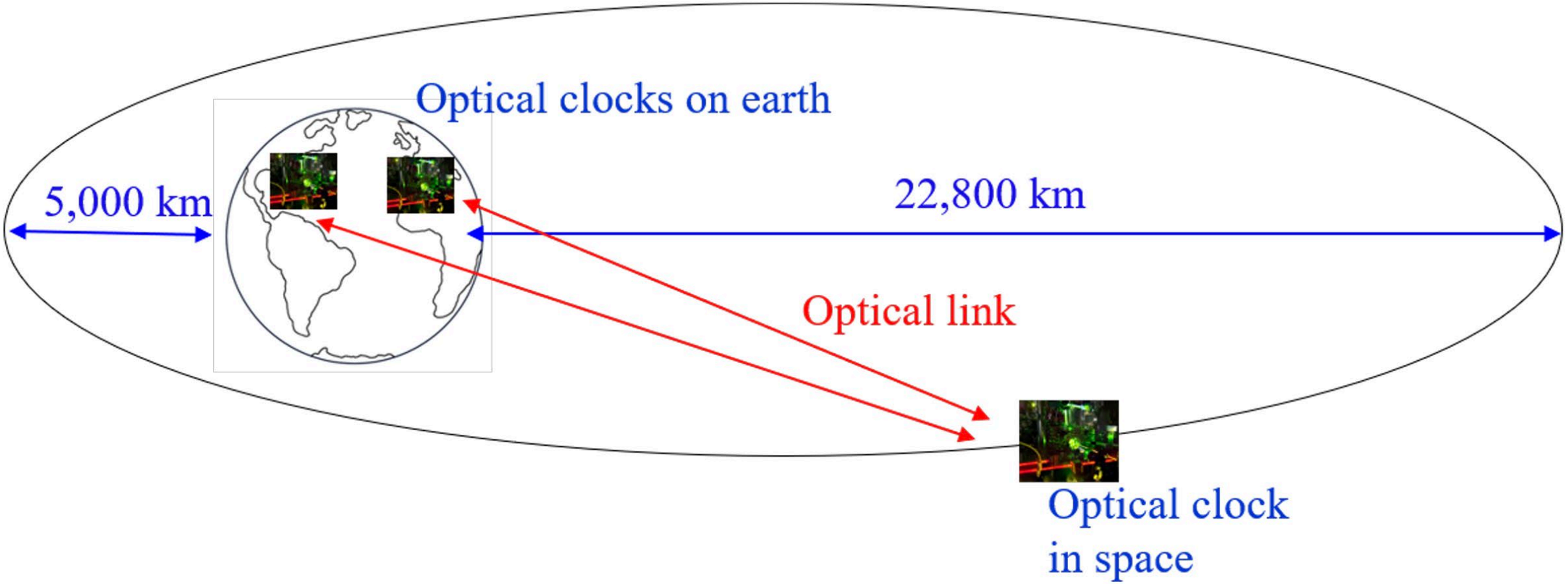






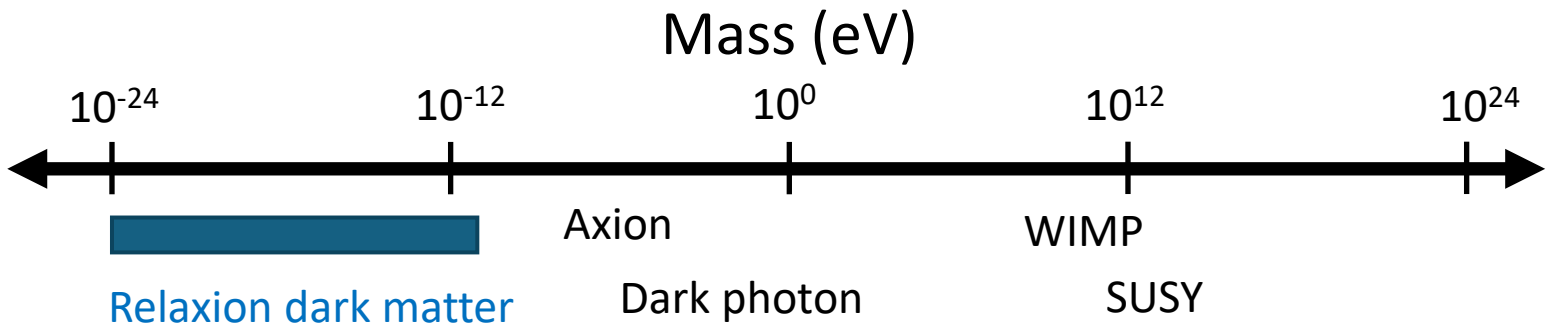
μAres collaboration, Exp. Astron. **51**, 1333 (2021); Fedderke, Graham, Rajendran, PRD **105**, 103018 (2022)

Equivalence principle (FOCOS mission concept)



Derevianko ..., Quantum Sci. Technol. **7** 044002 (2022)

Dark matter



Relaxion dark matter
Dilaton dark matter
Fuzzy dark matter
Wave dark matter
Ultralight bosonic dark matter
Ultralight virialized fields
…

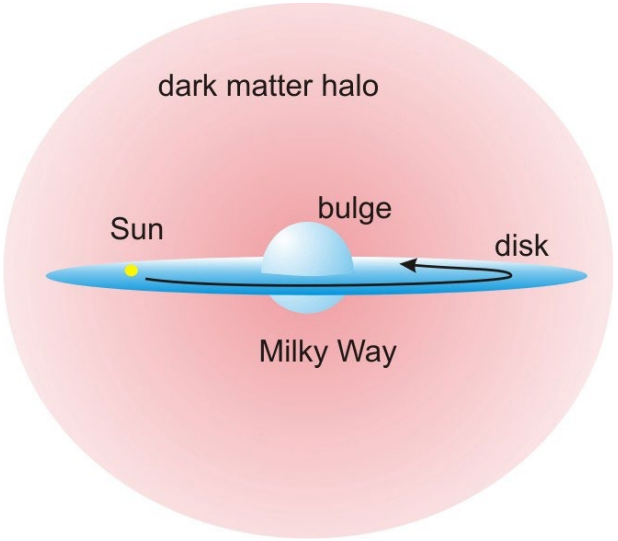
"Crazy ideas, responsibly talked about, are something we need more of in physics today"
- Jan Hall (paraphrased)

If it is an ultralight particle, what DO we know?

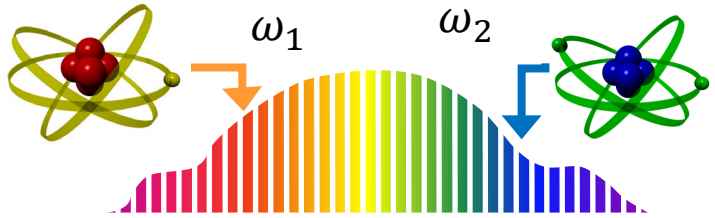
- de Broglie wavelength shorter than size of dwarf galaxies
- Density ~0.3 GeV/cm^3
- Bosonic (as many as 10^{100} particles in a cubic de Broglie wavelength)
- Acts like a scalar field oscillating at the Compton frequency $\omega_{DM} = \frac{m_\phi c^2}{\hbar}$
- Coherence time ~10^6 oscillation periods

Arvanataki …, PRD **91**, 015015 (2015); Snowmass Review, arXiv:2203.14915

Dark matter



Non-gravitational coupling to standard model:



$$R(t) = \frac{\omega_1(t)}{\omega_2(t)} = R_0 + R_{DM}\sin(\omega_{DM}\, t + \theta_{DM})$$

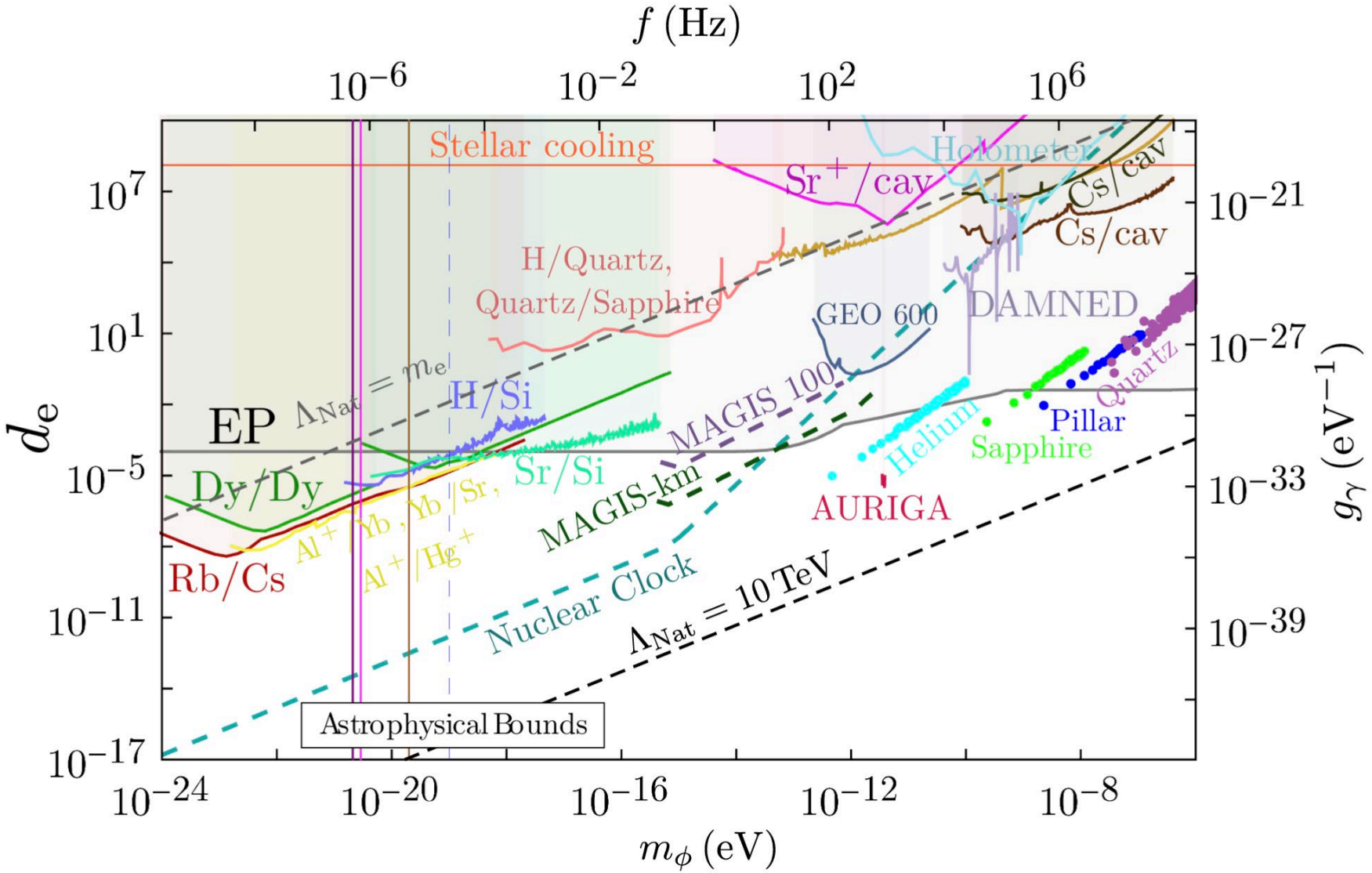
$$\mathcal{L}_{int}^{lin} = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \sum_f \frac{\phi}{\Lambda_f}\bar{f}f$$

$$\alpha \to \alpha\left(1 + \frac{\phi}{\Lambda_\gamma}\right), m_f \to m_f\left(1 + \frac{\phi}{\Lambda_f}\right)$$

Atom, transition	A
$^{27}Al^+$, $^1S_0 \to {}^3P_0$	+ 0.01
^{87}Sr, $^1S_0 \to {}^3P_0$	+ 0.06
$^{40}Ca^+$, $^2S_{1/2} \to {}^2D_{5/2}$	+ 0.15
^{171}Yb, $^1S_0 \to {}^3P_0$	+ 0.31
$^{88}Sr^+$, $^2S_{1/2} \to {}^2D_{5/2}$	+ 0.43
$^{176}Lu^+$, $^1S_0 \to {}^3D_1$	- 2.52
$^{226}Ra^+$, $^2S_{1/2} \to {}^2D_{5/2}$	+ 2.77
$^{199}Hg^+$, $^2S_{1/2} \to {}^2D_{5/2}$	- 2.94
$^{171}Yb^+$, $^2S_{1/2} \to {}^2D_{3/2}$	+ 0.88
$^{171}Yb^+$, $^2S_{1/2} \to {}^2F_{7/2}$	- 5.95
$^{229}Th^{3+}$, $\frac{5^+}{2}[633] \to \frac{3^+}{2}[631]$	~10^4

Arvanataki ..., PRD **91**, 015015 (2015); Snowmass Review, arXiv:2203.14915

Dark matter



Arvanataki ..., PRD **91**, 015015 (2015); Snowmass Review, arXiv:2203.14915

Why/where on the moon?

	Earth
Baseline	10^4 km
No atmosphere	✗
Ephemeris drift due to drag can be well known	✓
Time dependent gravitational potentials can be well known	✗
Visibility for ephemerids determination	better
No radiation	✓

Why/where on the moon?

	Earth	Free-flying satellite
Baseline	10^4 km	10^4 - 10^8 km
No atmosphere	✗	✓
Ephemeris drift due to drag can be well known	✓	✗ *
Time dependent gravitational potentials can be well known	✗	✓
Visibility for ephemerids determination	better	best
No radiation	✓	✗

* ✓ with drag free satellite

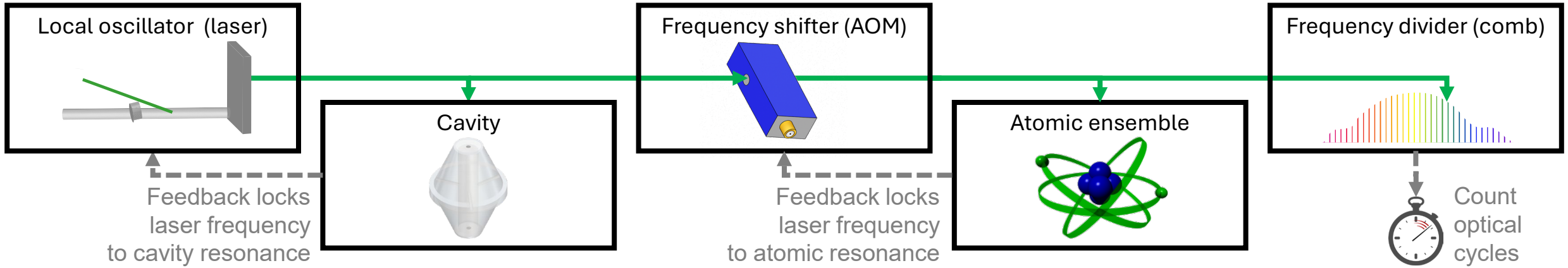
Why/where on the moon?

	Earth	Free-flying satellite	Polar location on Moon	Non-polar location on Moon
Baseline	$1x10^4$ km	10^3 - 10^8 km	$4x10^5$ km	$4x10^5$ km
No atmosphere	✗	✓	✓	✓
Ephemeris drift due to drag can be well known	✓	✗ *	✓	✓
Time dependent gravitational potentials can be well known	✗	✓	✓ ?	✓ ?
Visibility for ephemerids determination	better	best	worst	ok **
No radiation	✓	✗	✓ (bury under regolith)	✓ (bury under regolith)

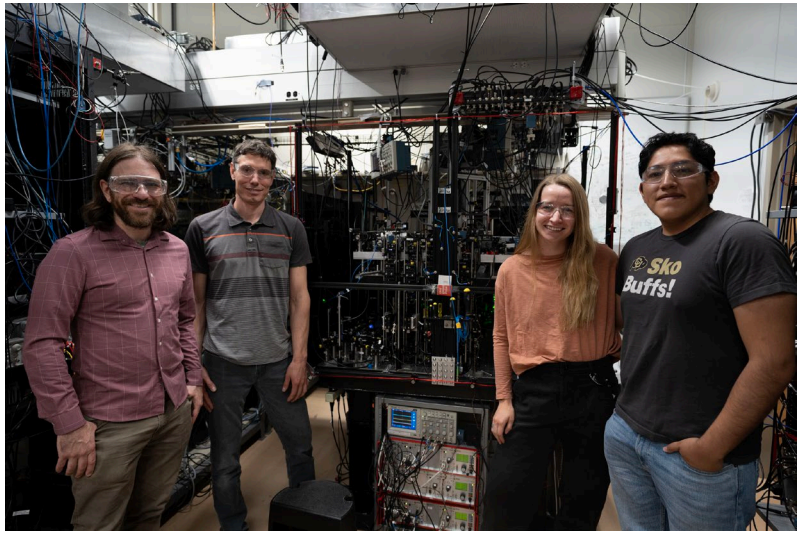
* ✓ with drag free satellite
** best with multiple sites

UCLA

Optical atomic clocks 101



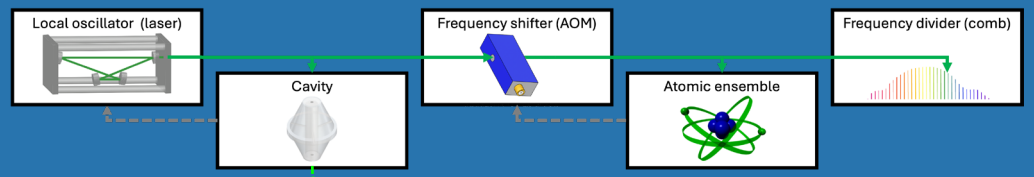
NIST cryogenic sapphire cavity
Valencia ... Leibrandt, Hume,



NIST Al^+ clock
Marshall ... Leibrandt, Hume, PRL **135**, 033201 (2025)
https://www.nist.gov/news-events/news/2025/07/nist-ion-clock-sets-new-record-most-accurate-clock-world

UCLA

Optical atomic clocks 101



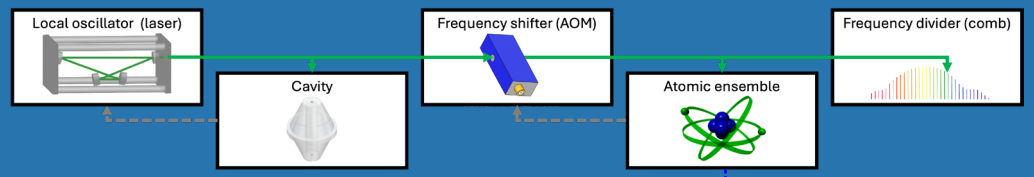
Vibrations

Thermal expansion

Thermal noise

Numata, … PRL **93**, 250602 (2004)

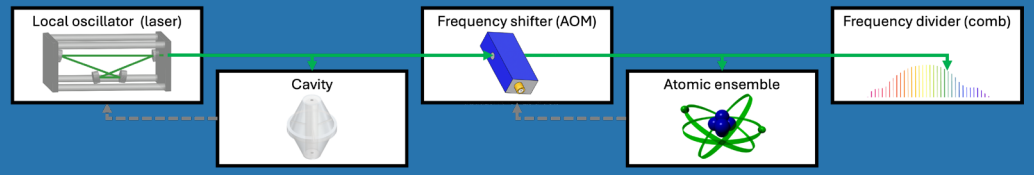
Optical atomic clocks 101



Quantum projection noise
Itano, … PRA **47**, 3554 (1993)

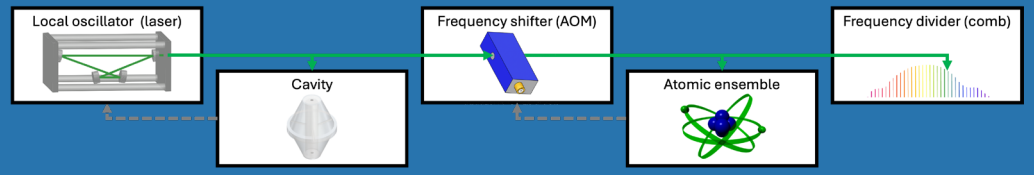
Fluctuating systematic shifts

Optical atomic clocks 101



Cryogenic silicon cavity
Oekler … Ye, Nat. Photonics **13**, 714 (2019)

Optical atomic clocks 101



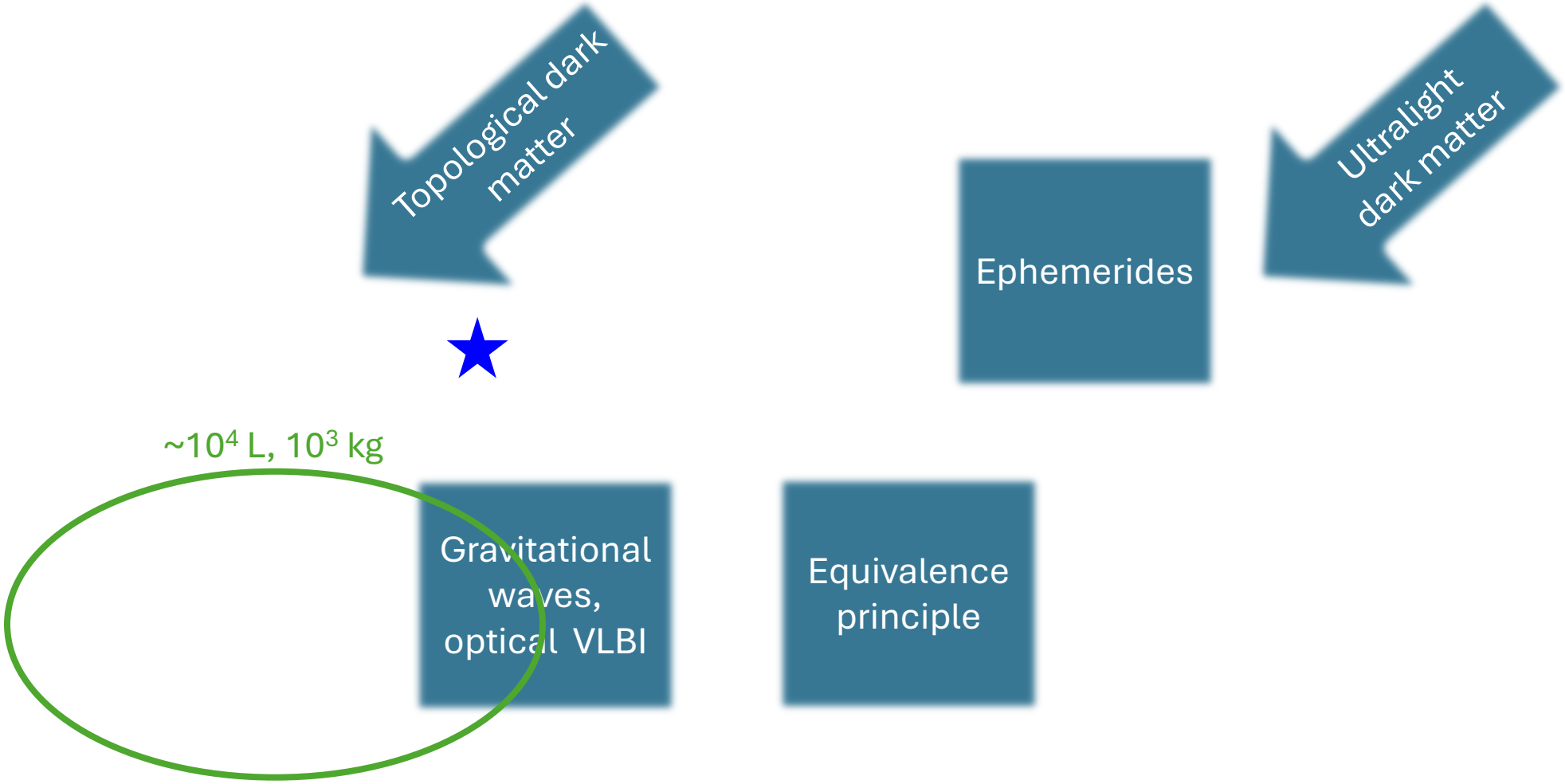
Cryogenic silicon cavity
Oekler … Ye, Nat. Photonics **13**, 714 (2019)

Sr lattice clock
Stability: Oekler … Ye, Nat. Photonics **13**, 714 (2019)
Accuracy: Aeppli … Ye, PRL **133**, 023401 (2024)

Optical atomic clocks 101

Optical atomic clocks 101

THz
VLBI



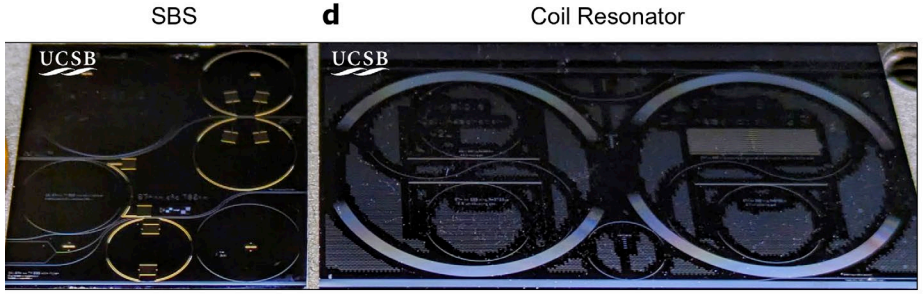
COTS optical clocks

- Shimadzu Corporation “Aether clock OC 020”
- Product launch March 2025
- 250 L, 200 kg
- $3.4M

https://www.shimadzu.co.jp/news/2025/-oqneexd8997ms8u.html

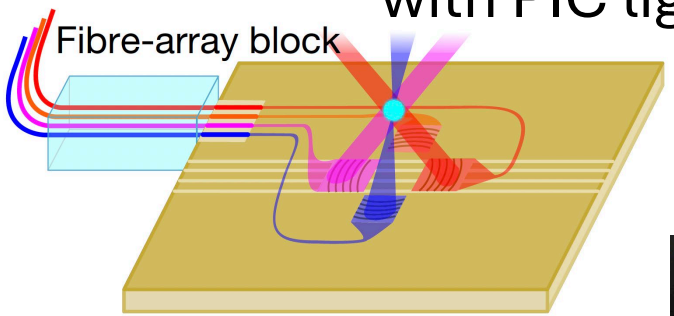
Miniaturization & ruggedization – PIC ion clocks

PIC cavities for laser stabilization

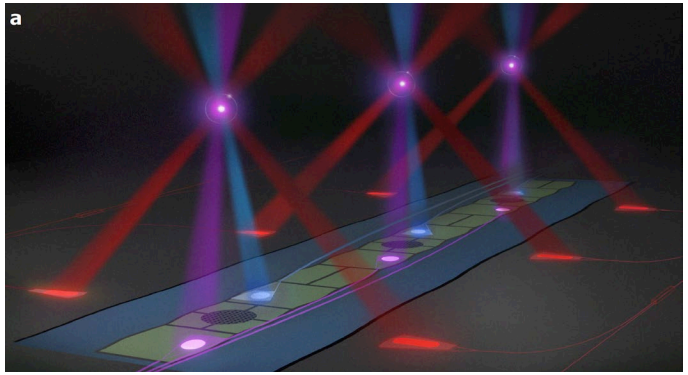


UCSB/UMass Sr^+ 674 nm clock laser
… Niffenegger, Blumenthal, arXiv:2402.16742 (2024)

Microfabricated ion traps with PIC light delivery

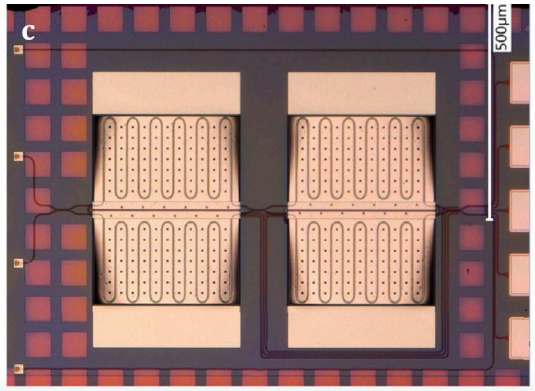


MITLL Sr^+ (single site)
Niffenegger … Chiaverini,
Nature **586**, 538 (2020)



Sandia Yb^+ (multiple sites)
Kwon … McGuinness,
Nat. Commun. **15**, 3709 (2024)

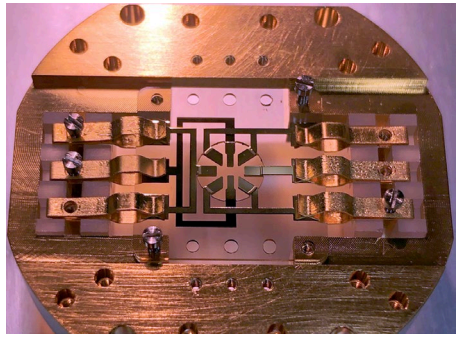
PIC modulators for light control



Sandia Ca^+ 729 nm clock laser
Hogle … Stick, npj Quantum Inf. **9**, 74 (2023)

SWaP for deployed sensors

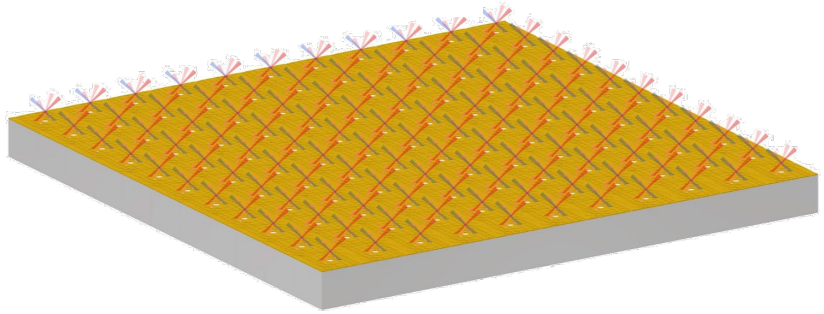
Single ion Ca^+ space clock



Stability: $1 \times 10^{-15}/\tau^{1/2}$
Accuracy: 1×10^{-18}

Component	Volume (L)	Mass (kg)	Power (W)
Frequency comb	1.0	1.0	10
Laser sources (4x)	1.4	2.0	32
Modulators (4x)	0.4	0.4	16
Clock laser cavity	3.5	2.4	7
Ion trap package	1.0	2.5	11
Control electronics	1.0	1.0	2
Mechanical packaging	4.0	2.0	0
Radiation shielding	2.0	2.0	0
Total	14.3	15.3	83

256 ion Ca^+/Ra^+ space clock



Stability: $1 \times 10^{-16}/\tau^{1/2}$
Accuracy: 1×10^{-18}

Component	Volume (L)	Mass (kg)	Power (W)
Frequency comb	1.0	1.0	10
Laser sources (8x)	2.8	4.0	64
Modulators (262x)	0.4	0.4	262
Clock laser cavity	3.5	2.4	7
Ion trap package	1.0	2.5	11
Control electronics	4.0	1.0	100
Mechanical packaging	4.0	2.0	0
Total	16.7	13.3	454

Perspective

- Optical clocks in space would enable revolutionary science
  - Ephemerides determination
  - VLBI
  - μHz gravitational waves
  - EEP violation searches
  - Dark matter searches
- The moon is a good location
  - Long baseline to Earth
  - Low-noise environment?
  - Astronauts could perform deployment & maintenance if required?
- A $1x10^{-15}/\tau^{1/2}$, $1x10^{-18}$, 20 L, 20 kg, 100 W single ion clock would meet the requirements of almost all science goals
- A geostationary optical clock mission would be a good pathfinder

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