Asteroids for μHz gravitational wave detection

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(Disclosure: Quantinuum Advisor)

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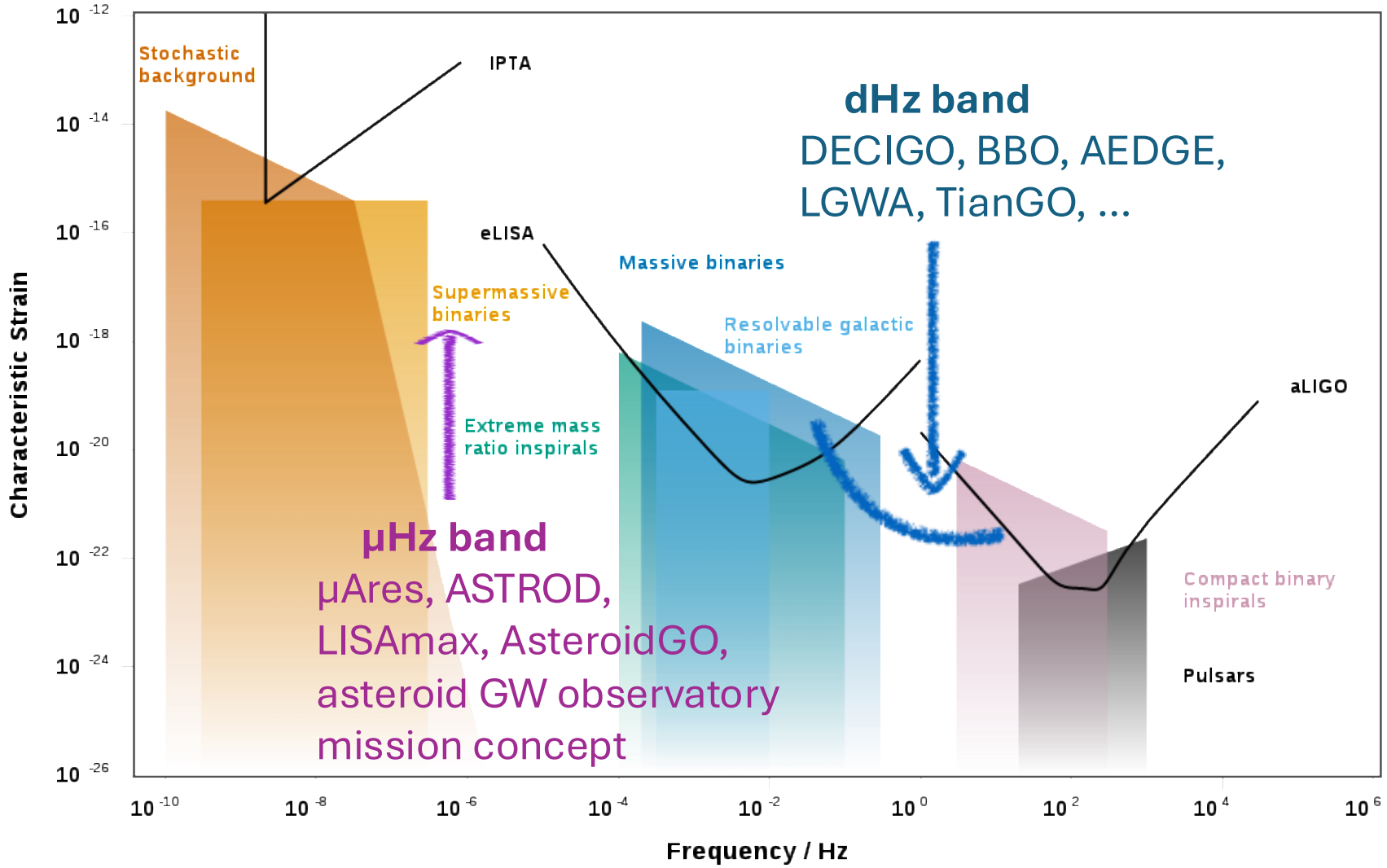
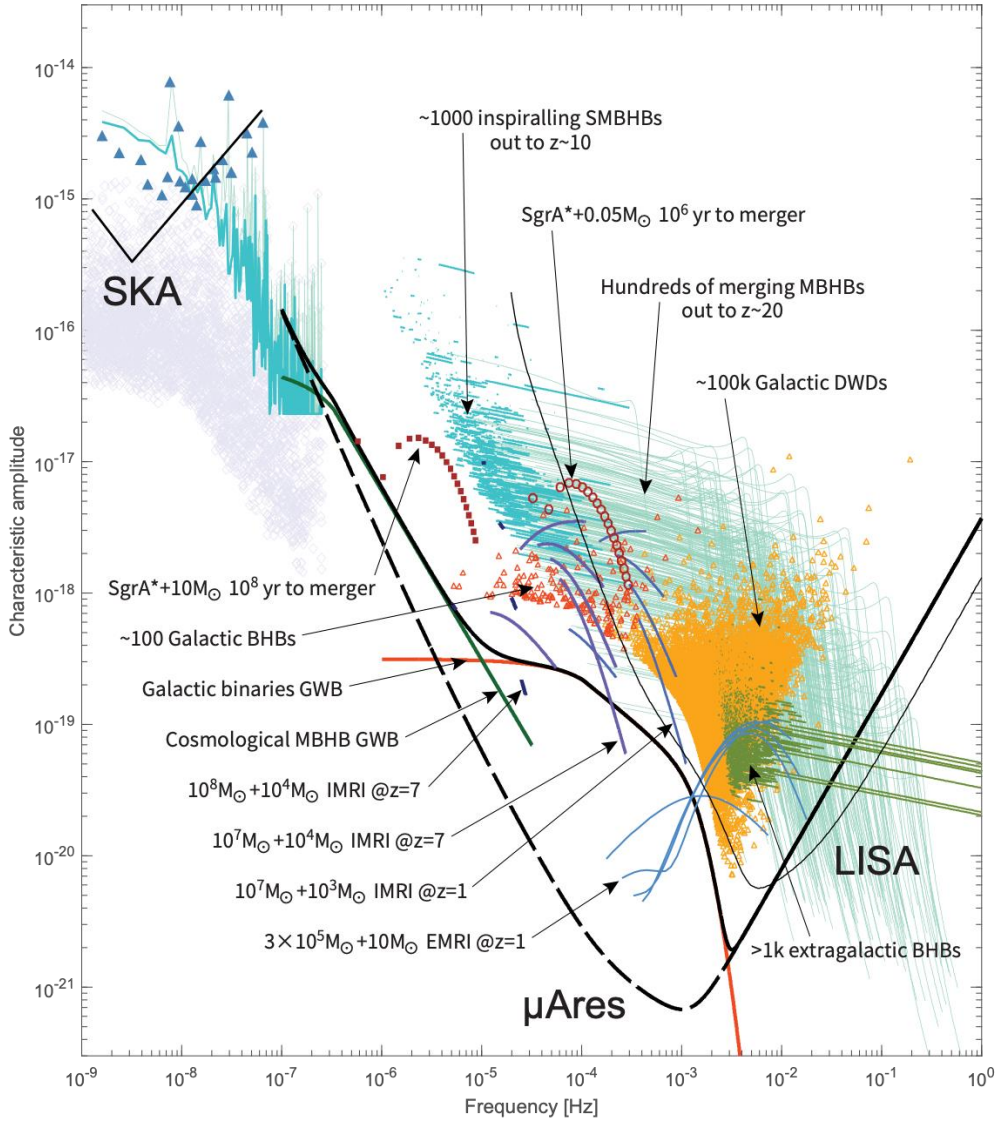
Pasadena, CA

The gravitational wave spectrum



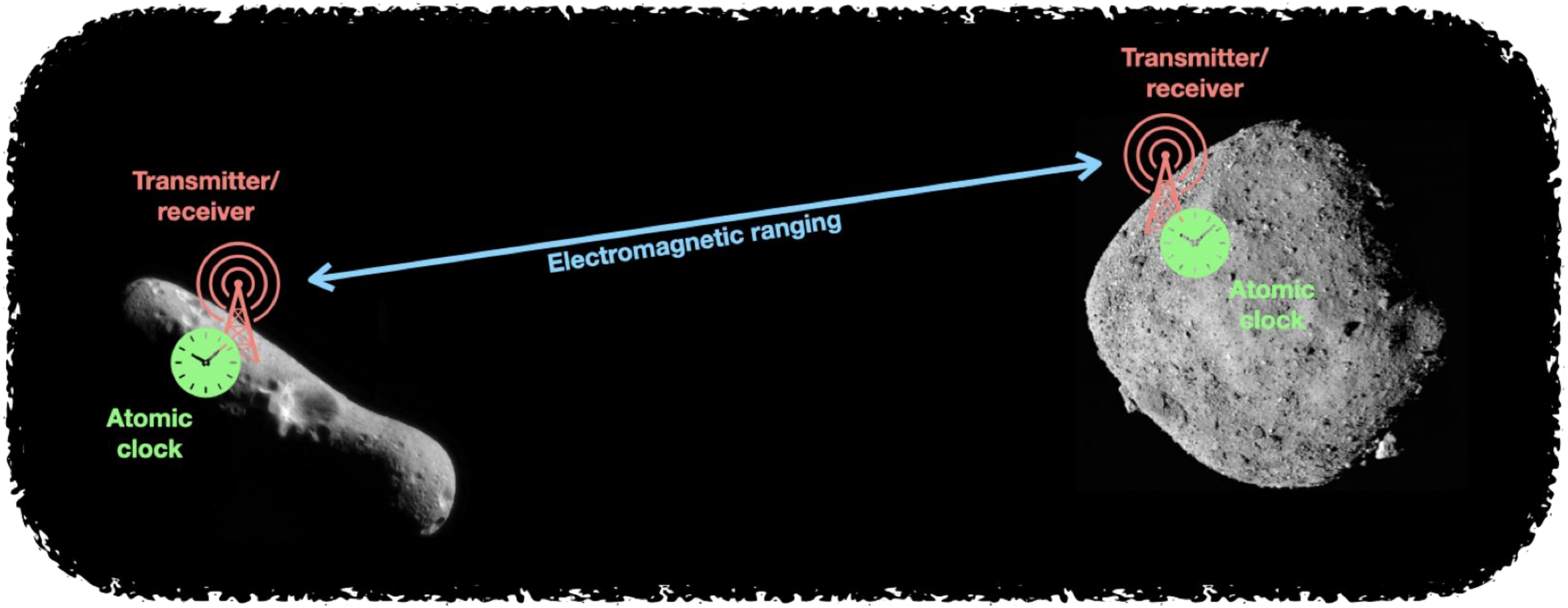
Gravitational wave science in the μHz band



- Trace the formation, growth, and mergers of the Universe's most massive black holes
- Localize massive-black-hole binaries years before merger, enabling multimessenger observations and standard-siren cosmology
- Probe early-Universe physics through stochastic backgrounds from primordial phase transitions, inflation, and cosmic strings
- Test general relativity, including graviton mass, nonlinear memory, black-hole spectroscopy, and dark-matter effects
- Study long-period Galactic binaries and compact objects orbiting the Milky Way's central black hole

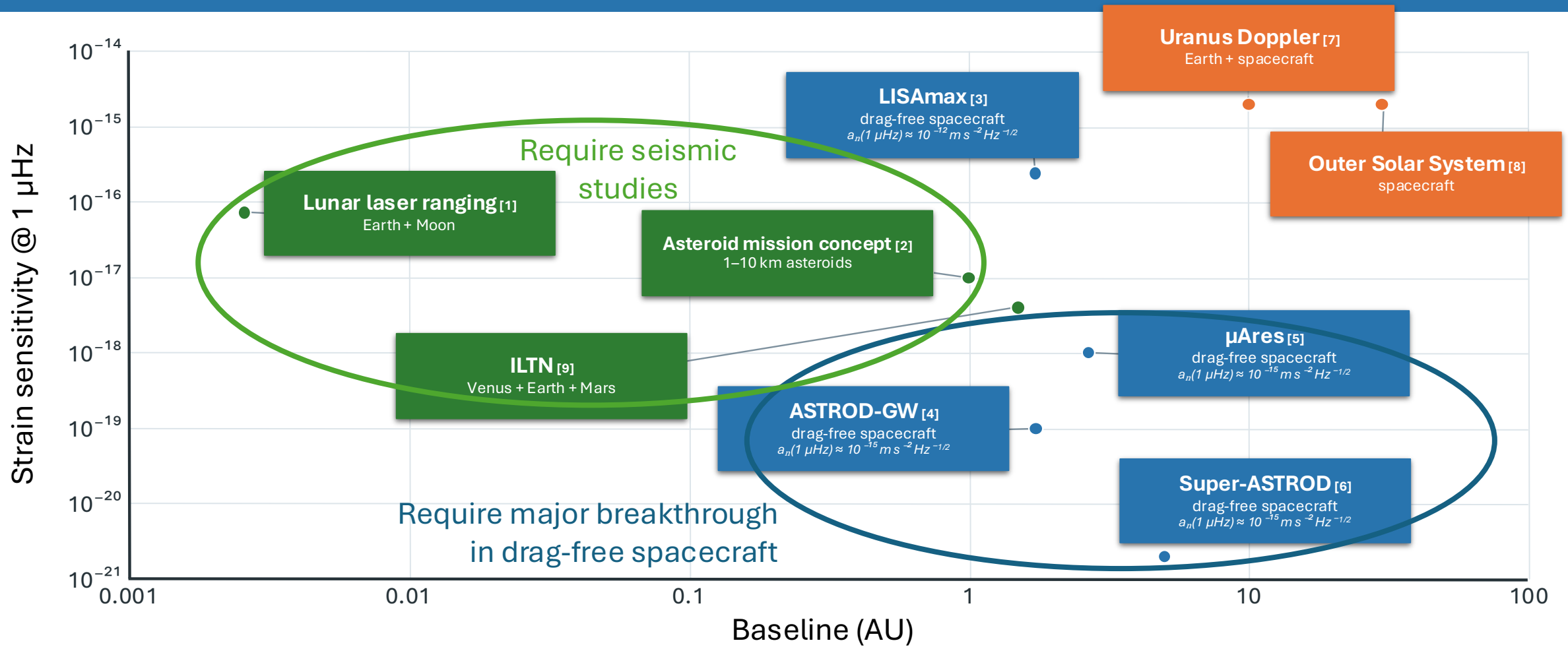
μAres concept paper, Exp. Astronomy **51**, 1333 (2021)

The asteroid GW observatory mission concept



Fedderke, Graham, Rajendran, PRD **105**, 103018 (2022)

μHz GW observatory mission concepts



[1] Turyshev, arXiv:2605.04110; [2] Fedderke et al., PRD 105, 103018 (2022); [3] Martens et al., CQG 40, 195022 (2023); [4] Ni, IJMPD 22, 1341004 (2013); [5] Sesana et al., Exp Astron 51, 1333 (2021); [6] Ni, CQG 26, 075021 (2009); [7] Zwick et al., PRD 112, 083029 (2025); [8] McQuinn & McGrath, ApJ 991, 106 (2025); [9] ILTN KISS report (2026)

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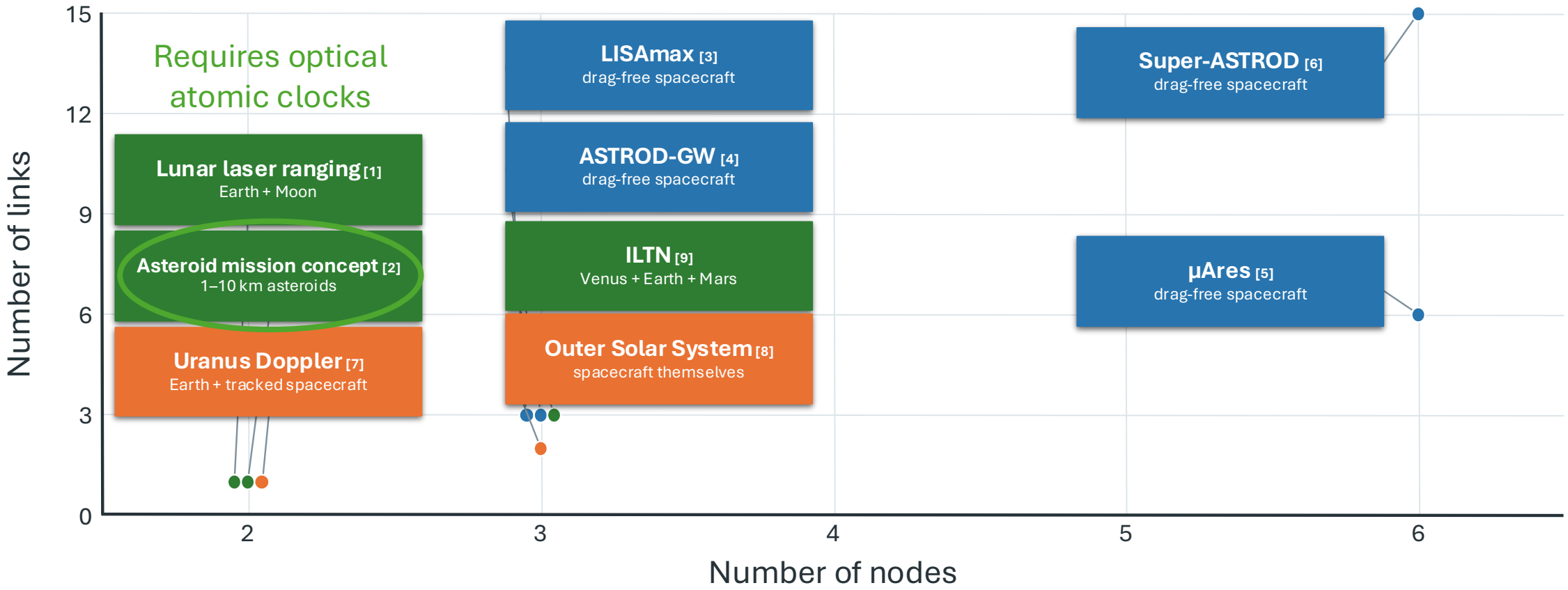
uHz GW observatory architectures



[1] Turyshev, arXiv:2605.04110; [2] Fedderke et al., PRD 105, 103018 (2022); [3] Martens et al., CQG 40, 195022 (2023); [4] Ni, IJMPD 22, 1341004 (2013); [5] Sesana et al., Exp Astron 51, 1333 (2021); [6] Ni, CQG 26, 075021 (2009); [7] Zwick et al., PRD 112, 083029 (2025); [8] McQuinn & McGrath, ApJ 991, 106 (2025); [9] ILTN KISS report (2026)

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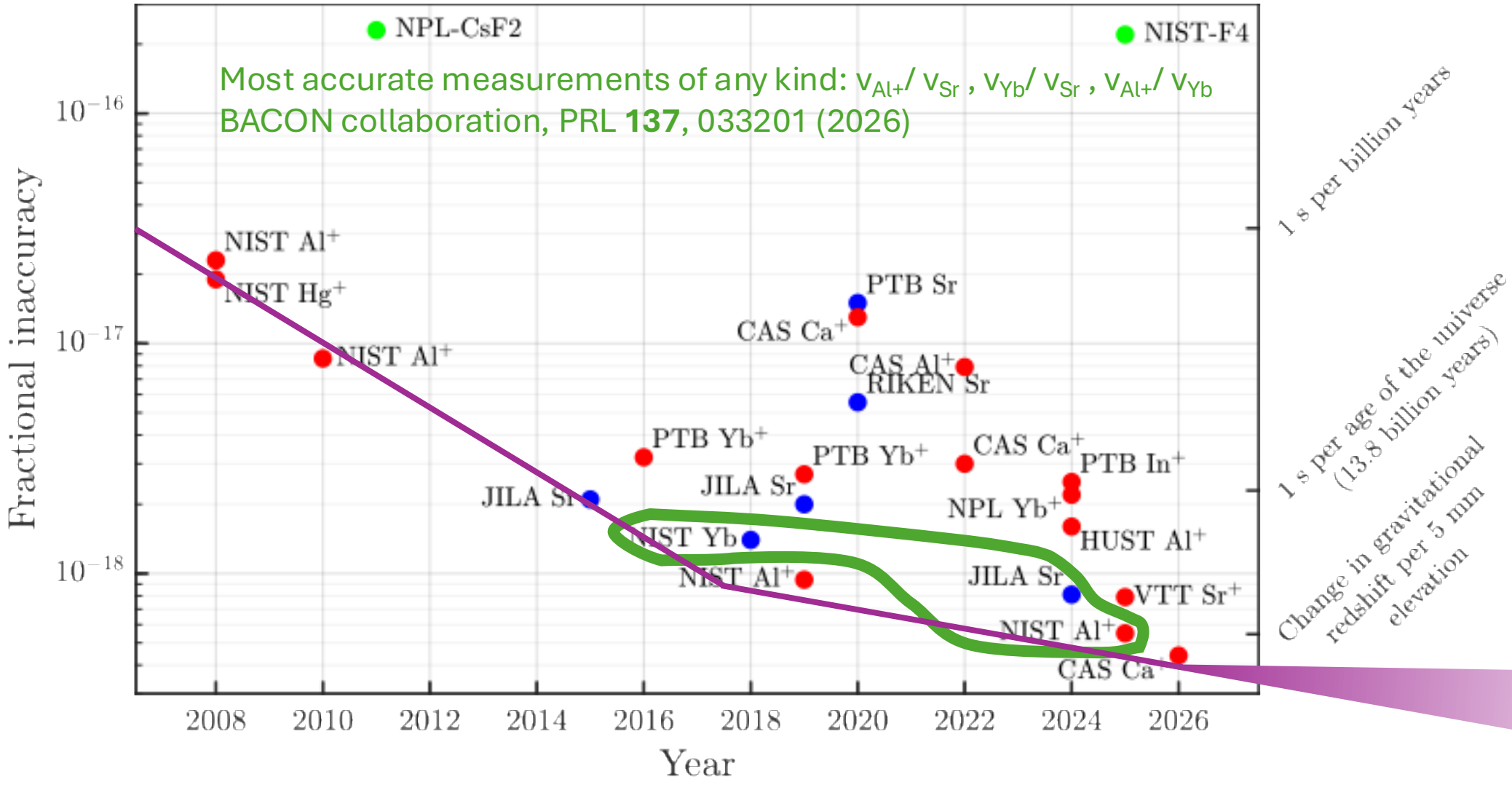
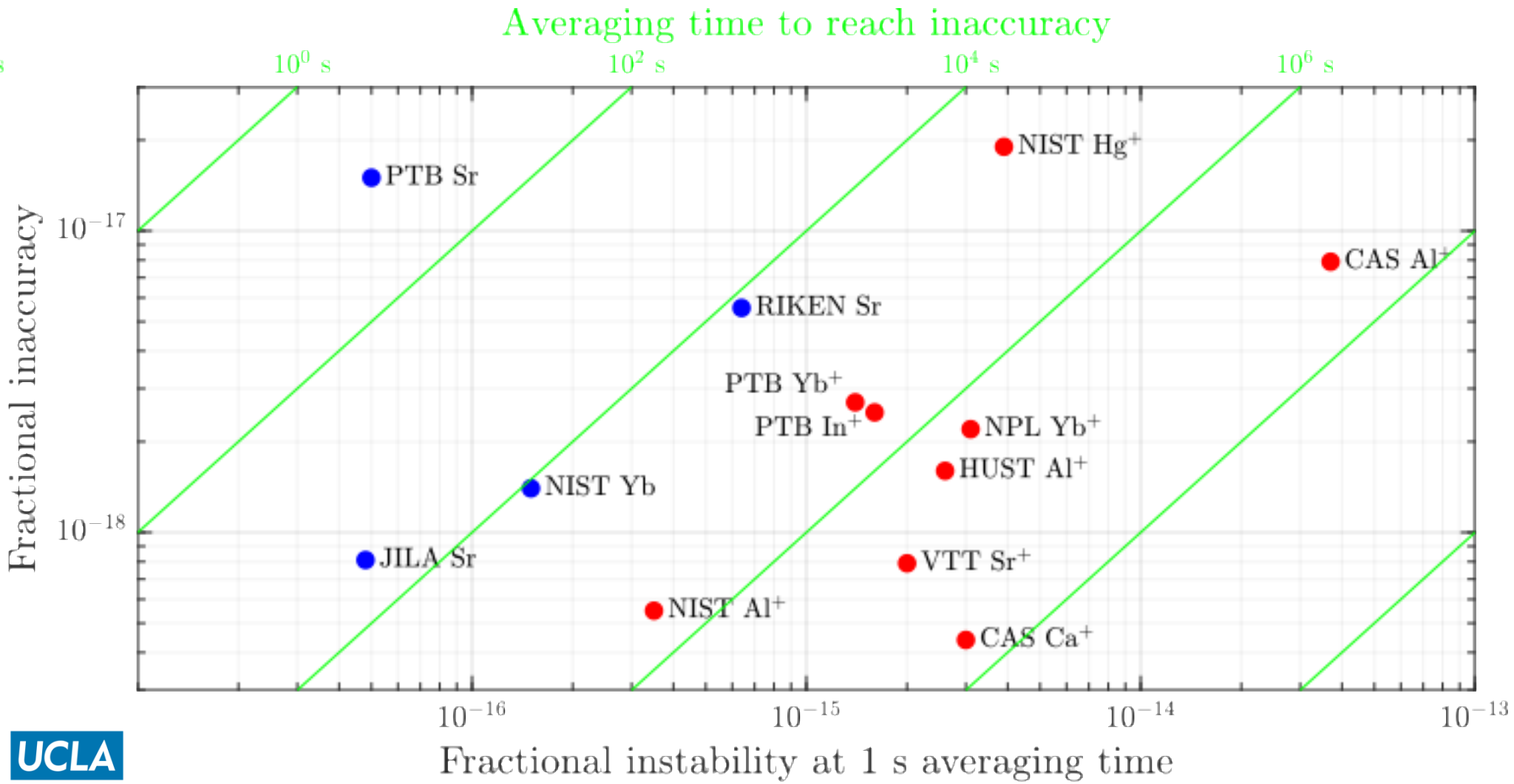
Optical atomic clocks



Microwave clocks Trapped-ion optical clocks Optical lattice clocks

Optical atomic performance & applications

Trapped-ion optical clocks Optical lattice clocks

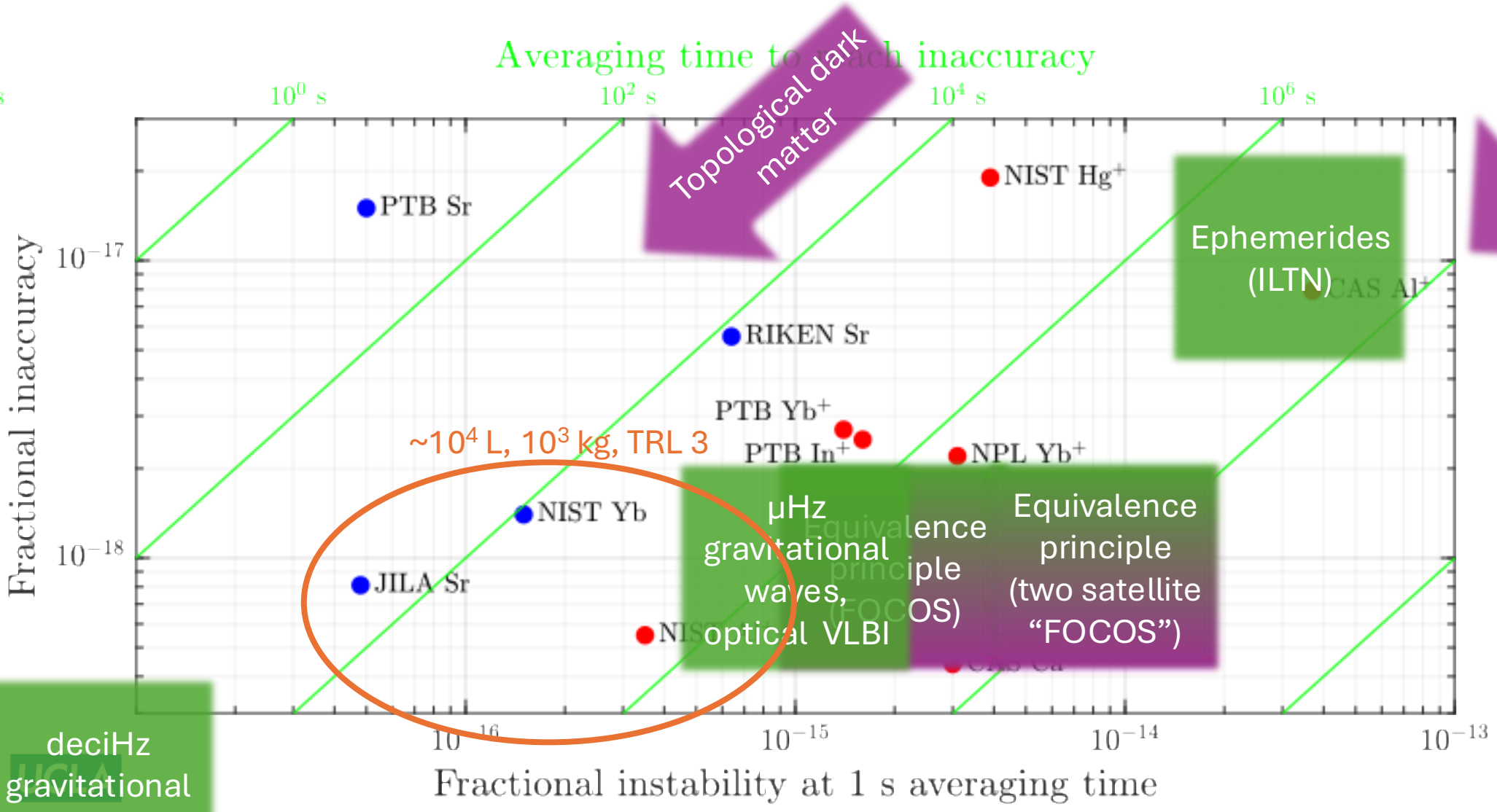


Optical atomic performance & applications

Ground clock comparisons

THz VLBI (THEZA)

Trapped-ion optical clocks Optical lattice clocks



The space optical clock trade space

	Current tech single-ion clock (e.g., $^{40}Ca^{+}$, $^{88}Sr^{+}$, $^{226}Ra^{+}$)
Complexity	2-4 direct DBR diode lasers, 1 mW each 10^{-15} FP cavity No modulators
SWaP	30 L, 30 kg, 100 W
Statistical uncertainty	$2x10^{-15}/\tau^{1/2}$
Systematic uncertainty	10^{-18}
DM sensitivity	~ 1
Estimated flight-ready date	t_0 + 5 years

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The space optical clock trade space

	Current tech single-ion clock (e.g., $^{40}Ca^+$, $^{88}Sr^+$, $^{226}Ra^+$)	**Future tech PIC multi-ion clock (e.g., $^{40}Ca^+$, $^{226}Ra^+$, $^{176}Lu^+$)**
Complexity	2-4 direct DBR diode lasers, 1 mW each 10^{-15} FP cavity No modulators	4-6 direct diode lasers, 10 mW each 10^{-15} FP cavity PIC development needed! Synergy with QC
SWaP	30 L, 30 kg, 100 W	3 L, 3 kg, 100 W
Statistical uncertainty	$2x10^{-15}/\tau^{1/2}$	$1x10^{-16}/\tau^{1/2}$
Systematic uncertainty	10^{-18}	10^{-19}
DM sensitivity	~ 1	~ 1
Estimated flight-ready date	t_0 + 5 years	t_0 + 10 years ?

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The space optical clock trade space

	Current tech single-ion clock (e.g., $^{40}Ca^+$, $^{88}Sr^+$, $^{226}Ra^+$)	Future tech PIC multi-ion clock (e.g., $^{40}Ca^+$, $^{226}Ra^+$, $^{176}Lu^+$)	Current tech lattice clock (e.g., ^{87}Sr, ^{171}Yb)
Complexity	2-4 direct DBR diode lasers, 1 mW each 10^{-15} FP cavity No modulators	4-6 direct diode lasers, 10 mW each 10^{-15} FP cavity PIC development needed! Synergy with QC	5-6 lasers, Not all direct diode, Up to 1 W each 10^{-16} FP cavity
SWaP	30 L, 30 kg, 100 W	3 L, 3 kg, 100 W	300 L, 300 kg, 1 kW
Statistical uncertainty	$2x10^{-15}/\tau^{1/2}$	$1x10^{-16}/\tau^{1/2}$	$1x10^{-16}/\tau^{1/2}$
Systematic uncertainty	10^{-18}	10^{-19}	10^{-18}
DM sensitivity	~ 1	~ 1	~ 0.1
Estimated flight-ready date	t_0 + 5 years	t_0 + 10 years ?	t_0 + 15 years ?

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The space optical clock trade space

	Current tech single-ion clock (e.g., $^{40}Ca^+$, $^{88}Sr^+$, $^{226}Ra^+$)	Future tech PIC multi-ion clock (e.g., $^{40}Ca^+$, $^{226}Ra^+$, $^{176}Lu^+$)	Current tech lattice clock (e.g., ^{87}Sr, ^{171}Yb)	Future tech lattice clock (e.g., ^{87}Sr, ^{171}Yb)
Complexity	2-4 direct DBR diode lasers, 1 mW each 10^{-15} FP cavity No modulators	4-6 direct diode lasers, 10 mW each 10^{-15} FP cavity PIC development needed! Synergy with QC	5-6 lasers, Not all direct diode, Up to 1 W each 10^{-16} FP cavity	5-6 lasers, Not all direct diode, Up to 1 W each 10^{-17} FP cavity
SWaP	30 L, 30 kg, 100 W	3 L, 3 kg, 100 W	300 L, 300 kg, 1 kW	300 L, 300 kg, 1 kW
Statistical uncertainty	$2\times10^{-15}/\tau^{1/2}$	$1\times10^{-16}/\tau^{1/2}$	$1\times10^{-16}/\tau^{1/2}$	$2\times10^{-19}/\tau^{1/2}$?? Two orders of magnitude beyond best lab clocks!
Systematic uncertainty	10^{-18}	10^{-19}	10^{-18}	10^{-20} ?? Two orders of magnitude beyond best lab clocks!
DM sensitivity	~ 1	~ 1	~ 0.1	~ 0.1
Estimated flight-ready date	t_0 + 5 years	t_0 + 10 years ?	t_0 + 15 years ?	t_0 + 30 years ??

Perspective

- The μHz GW domain is rich with sources
- μHz GW mission concepts fall into broad categories based on
  - Baseline lengths
  - What is used as proof masses
  - Numbers of nodes and links
- Next steps for the asteroid GW mission concept
  - Mission architecture study
    - 2 vs. 3 asteroids, orbiter vs. lander, pulsed laser vs. optical heterodyne link
  - Asteroid seismic studies
    - Can piggyback planned asteroid missions
  - Optical clock technology maturation
    - Current high-performance clocks are TRL ~ 3
    - DRL's recommendation: develop a single-ion optical clock and deploy it on the Moon

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The end