

Community Science Ad ASTRA Workshop

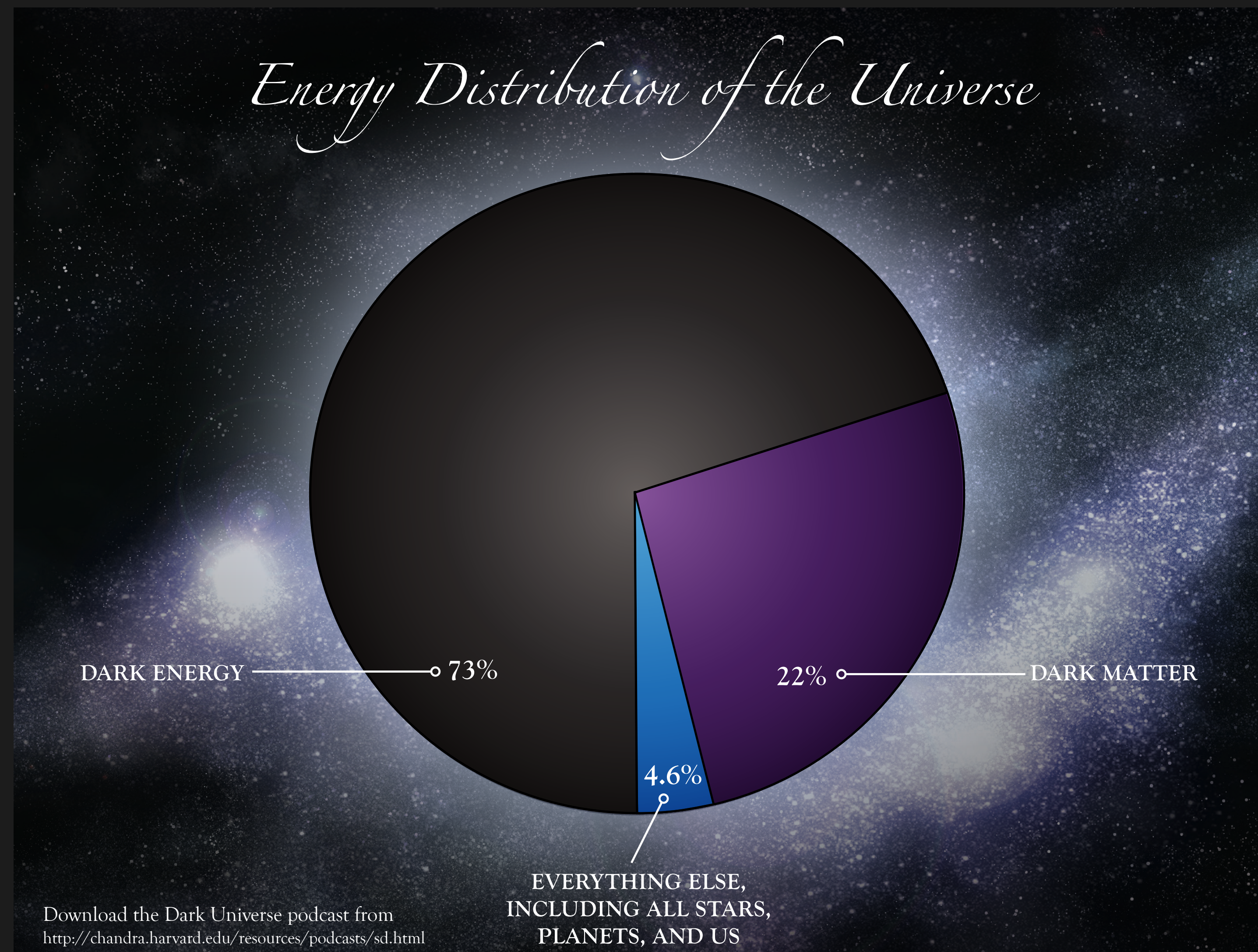
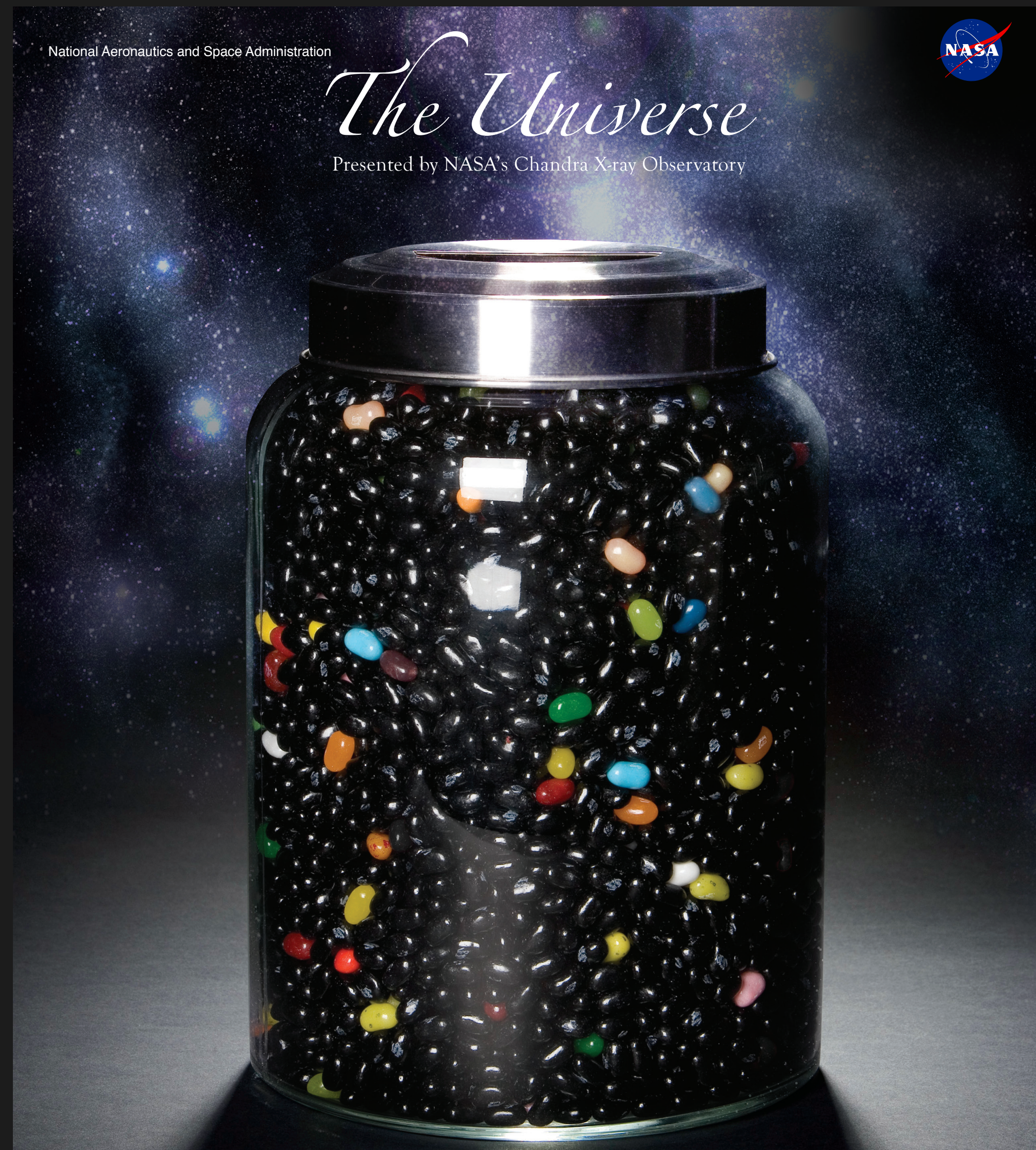
Atomic Experiment for Dark Matter and Gravity Exploration in Space

Naceur Gaaloul

Theory of Quantum Sensing
Institute of Quantum Optics
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We are missing most of the Universe

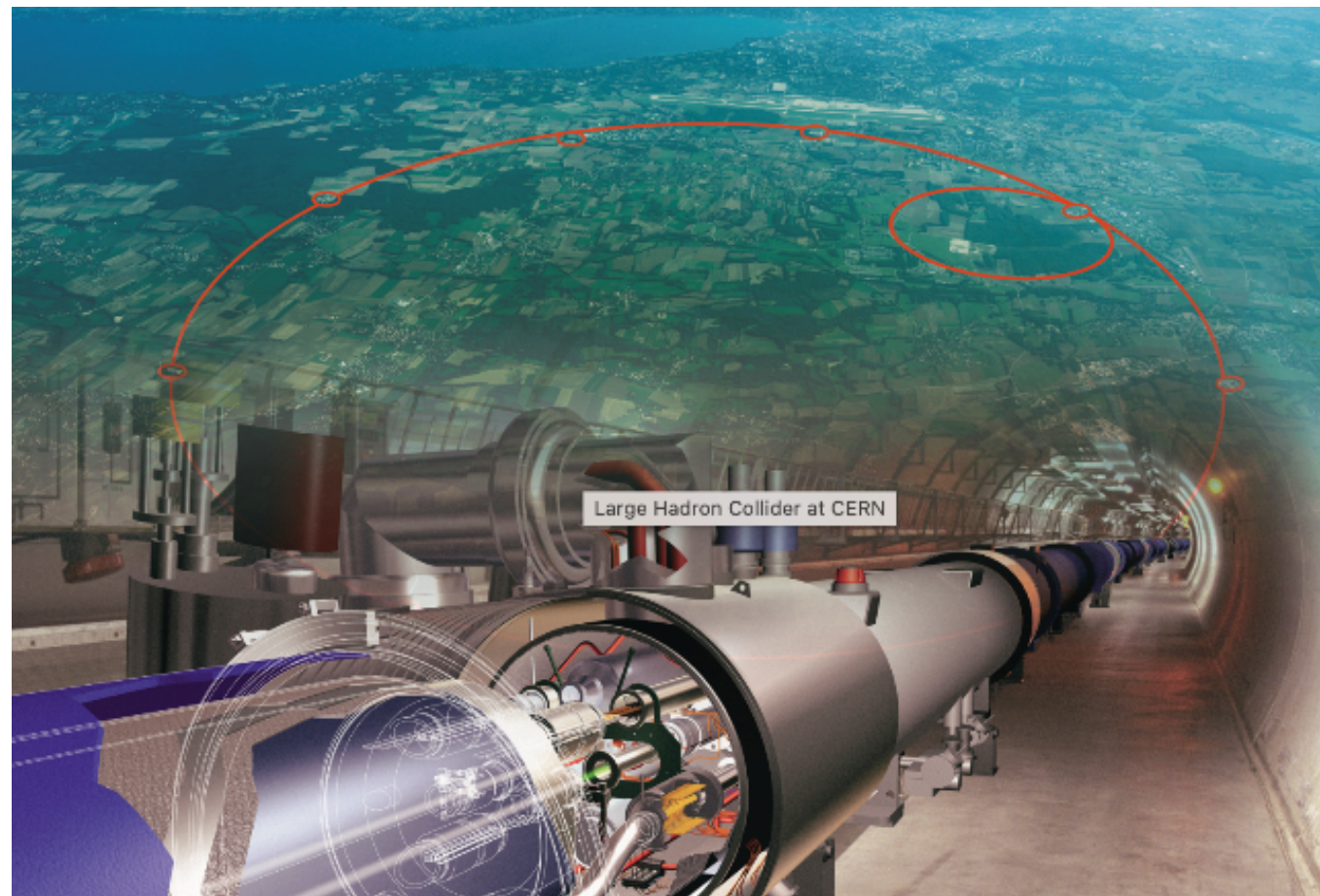


Signatures: Galaxies' rotation speed, Gas cluster collisions, CMB and formation of large structures...

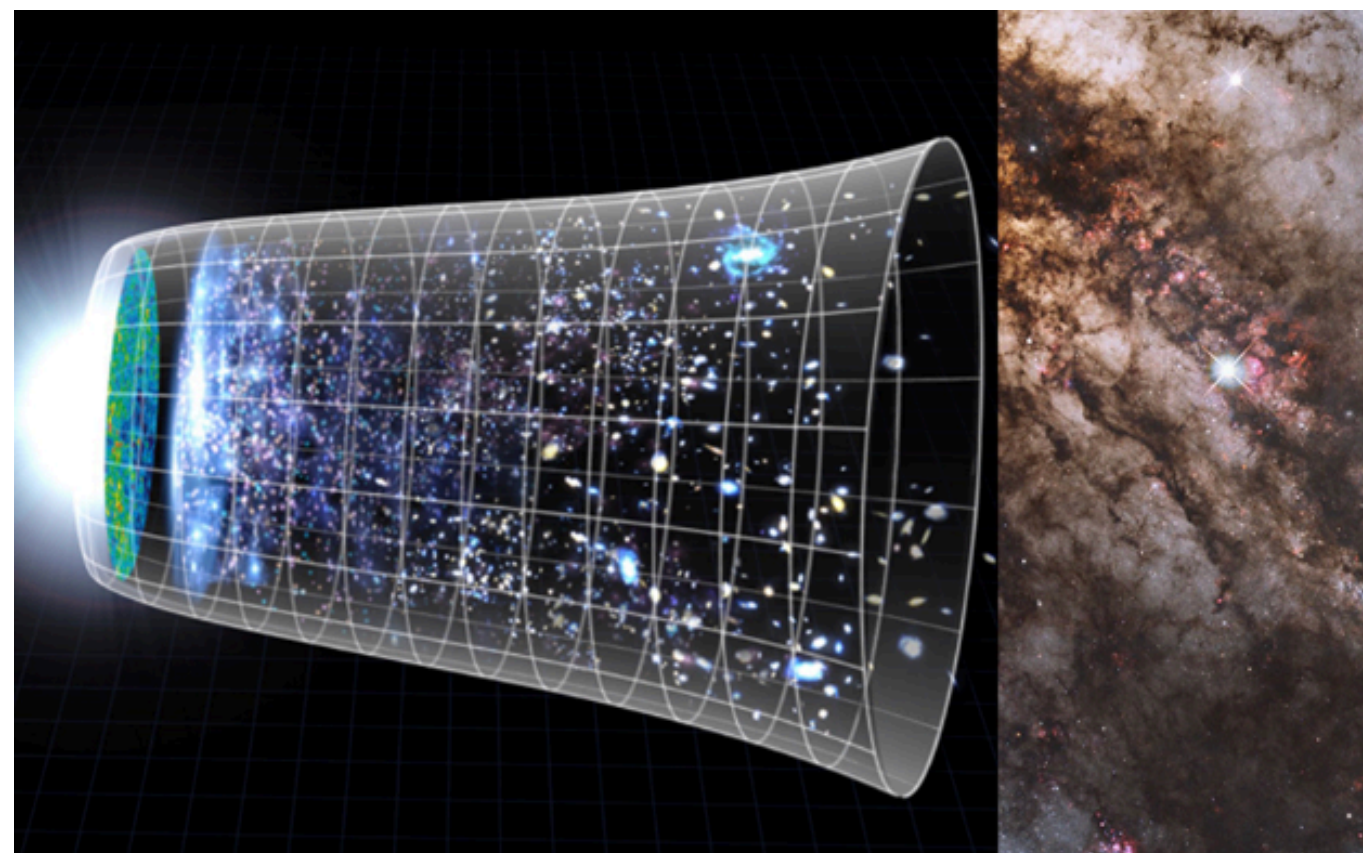
Probes of New Physics

High-energy Scale

Colliders



Astrophysical
Observations



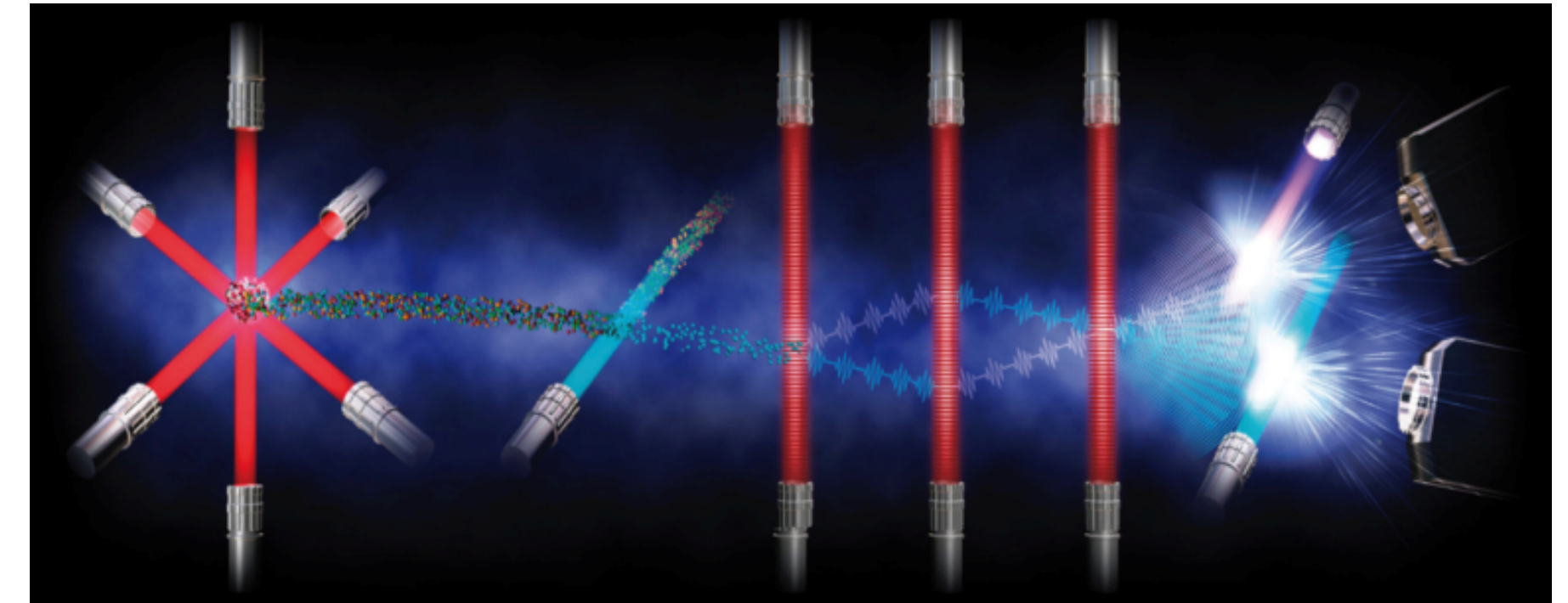
Probes of New Physics — Quantum Sensors

Low-energy Scale

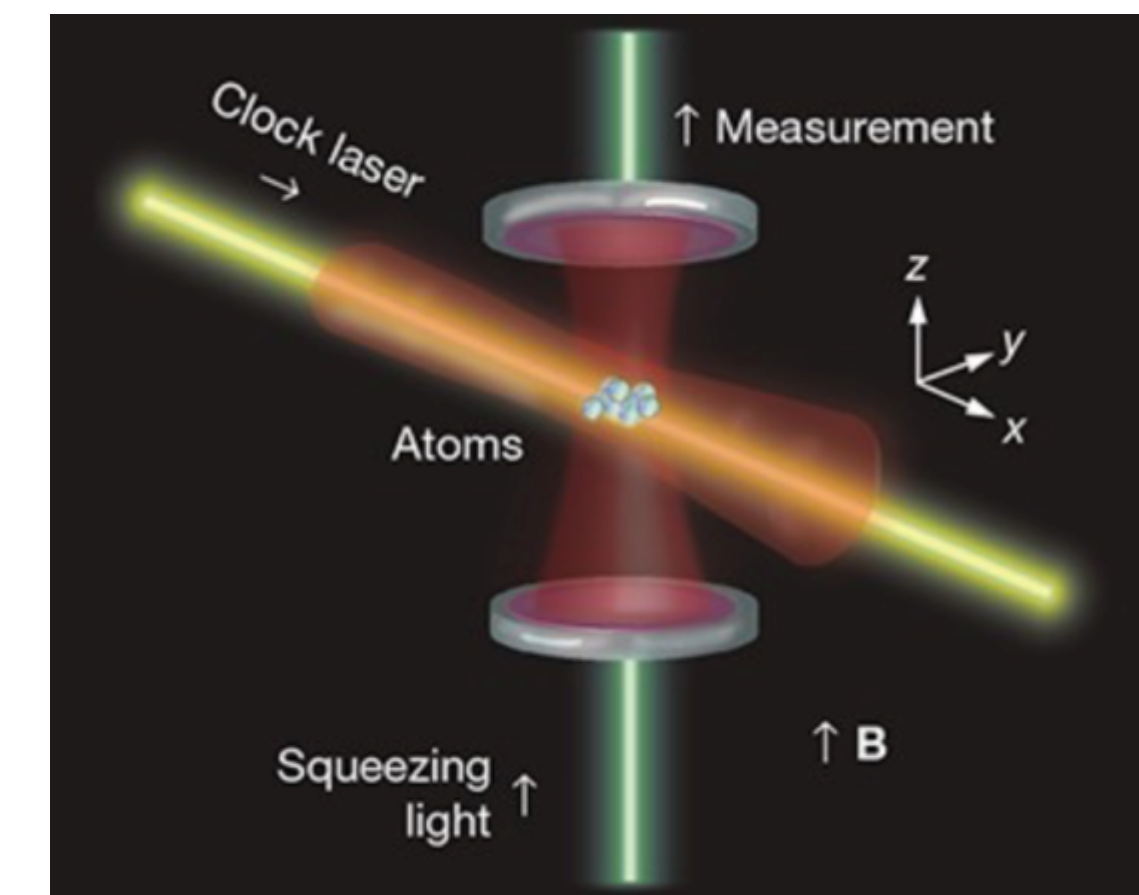
« "Quantum sensing" describes the use of a quantum **system**, quantum **properties** or quantum **phenomena** to perform a **measurement of a physical quantity**... »

C. L. Degen et al., Quantum Sensing, Rev. Mod. Phys. 89, 035002 (2017)

Atom Interferometers

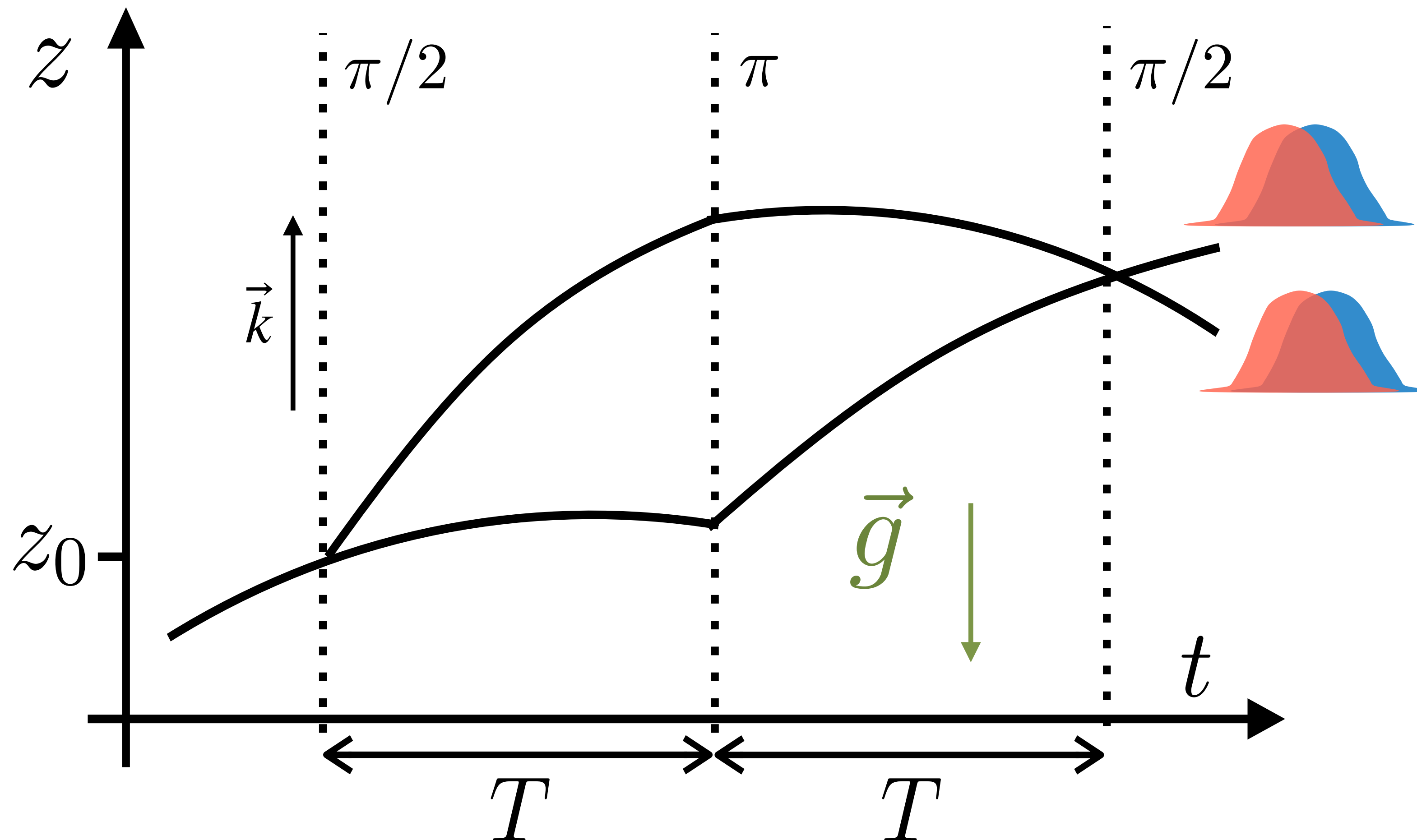


Atomic Clocks



Sensing external potentials with atom interferometry

Mach-Zehnder-type Atom-interferometer



Population in output port

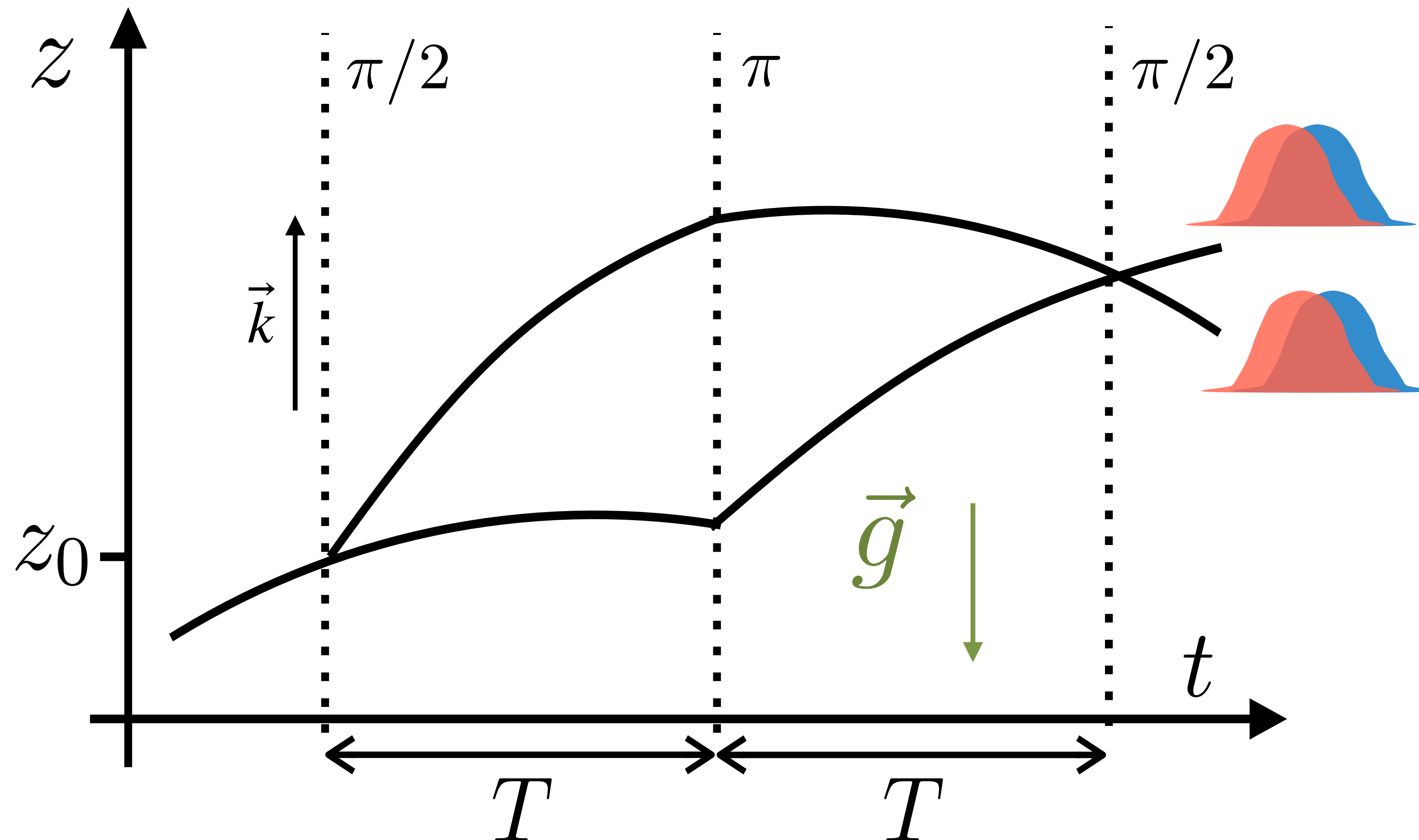
$$P \propto \cos(\Delta\phi)$$

phase difference

$$\Delta\phi = \vec{k} \cdot \vec{g} T^2$$

Sensing external potentials with atom interferometry

Mach-Zehnder-type Atom-interferometer



Population in output port

$$P \propto \cos(\Delta\phi)$$

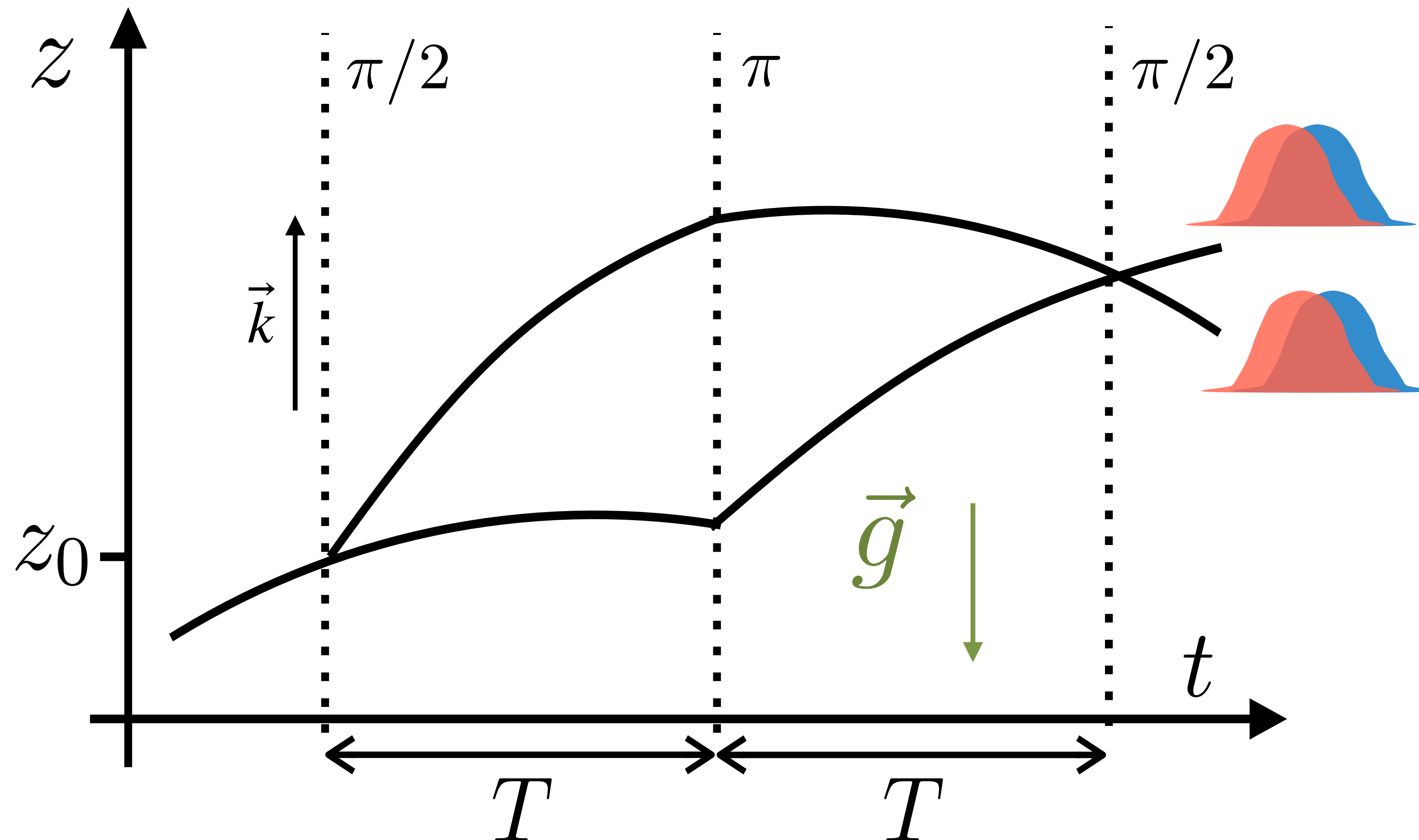
phase difference

$$\Delta\phi = \vec{k} \cdot \vec{g} T^2$$

Large-baselines

Sensing external potentials with atom interferometry

Mach-Zehnder-type Atom-interferometer



Population in output port

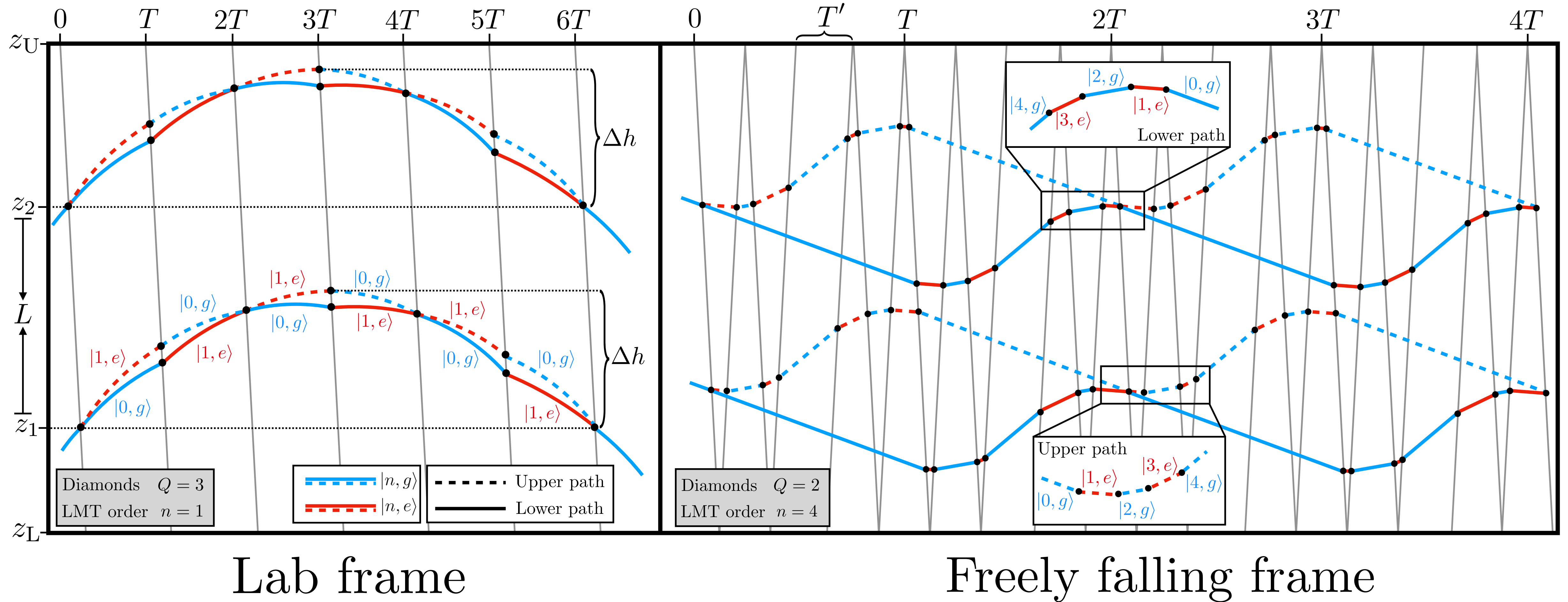
$$P \propto \cos(\Delta\phi)$$

phase difference

$$\Delta\phi = \vec{k} \cdot \vec{g} T^2$$

**Microgravity
and Space**

Gravitational Wave Detection



Werner et al. - "Terrestrial Gravitational Wave Detection with Atom Interferometers" (2026)

Propagation phase

Influence of other potentials which affect atoms

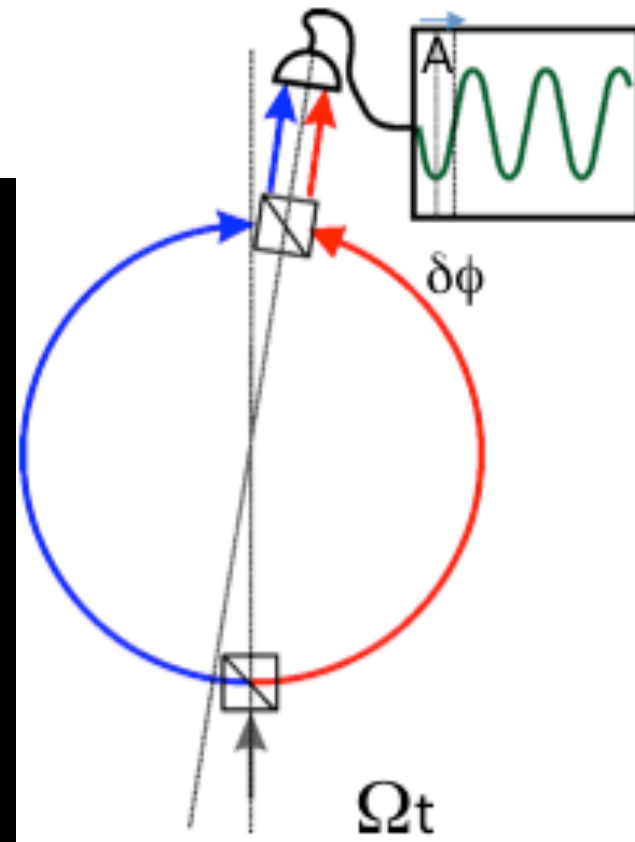
TABLE V Potentials in atom optics. Examples are for sodium atoms in the ground $3S_{1/2}|F = 2, m_F = 2\rangle$ state.

Interaction	$V =$	Example Condition	Potential in [eV]
Static E	$-\frac{1}{2}\alpha(0)\mathbf{E}^2$	$\mathbf{E}=1\text{kV/mm}$	7×10^{-10}
Static B	$-\mu_B \cdot \mathbf{B}$	$\mathbf{B}=100 \text{ Gauss}$	6×10^{-7}
Near resonant $\mathbf{E}(\omega)$	$-\frac{1}{2}\alpha(\omega)\mathbf{E}^2 = \pm \frac{\hbar \Omega_1 ^2}{4\Delta}$	$I = 12 \text{ mW/cm}^2, \Delta = 100\Gamma$	1×10^{-10}
Nearby surface	$-C_3/r^3 \quad (r < 100 \text{ nm})$	$r = 10 \text{ nm}$	5×10^{-6}
Nearby atom	$-C_6/r^6 \quad (a_0 < r < 100 \text{ nm})$	$r = 10 \text{ nm}$	7×10^{-10}
Gravity (g)	mgh	$h = 1 \text{ mm}$	3×10^{-9}
Nearby mass	GmM'/r	$M' = 200 \text{ kg}, r=1 \text{ m}$	2×10^{-15}

1000 rad !!!

- Sensitivity of matter waves to external potentials can be exploited to measure
- atomic polarizability and/or electric fields
 - magnetic fields
 - light shifts
 - short range forces (Van der Waals, Casimir Polder)
 - gravity

Sagnac effect



$$\delta\phi_{\text{Sagnac}} = \frac{4\pi}{h} \frac{E}{c^2} \vec{A} \cdot \vec{\Omega}$$

$$\text{light: } \delta\phi_{\text{Sagnac}} = \frac{4\pi}{\lambda c} \vec{A} \cdot \vec{\Omega}$$

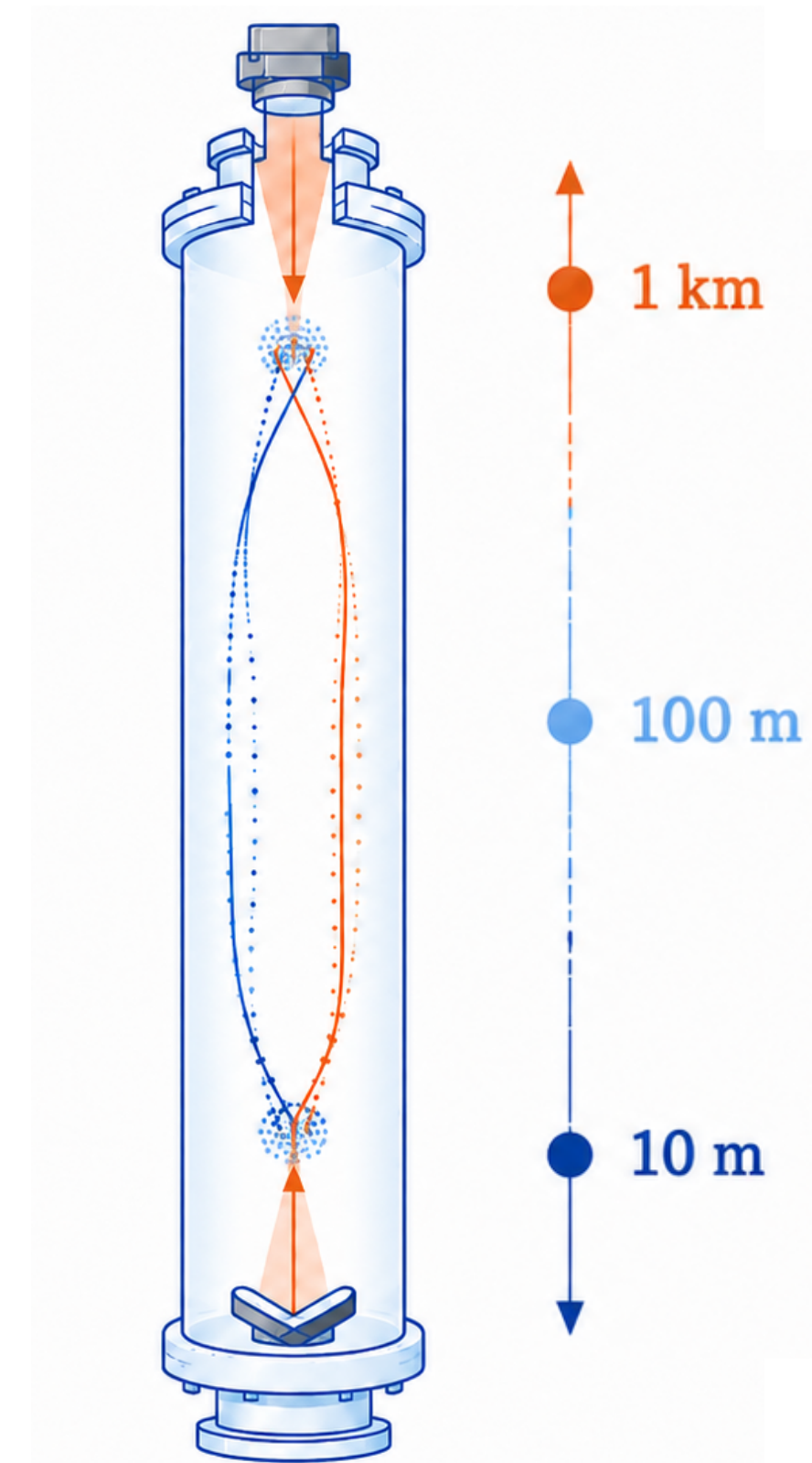
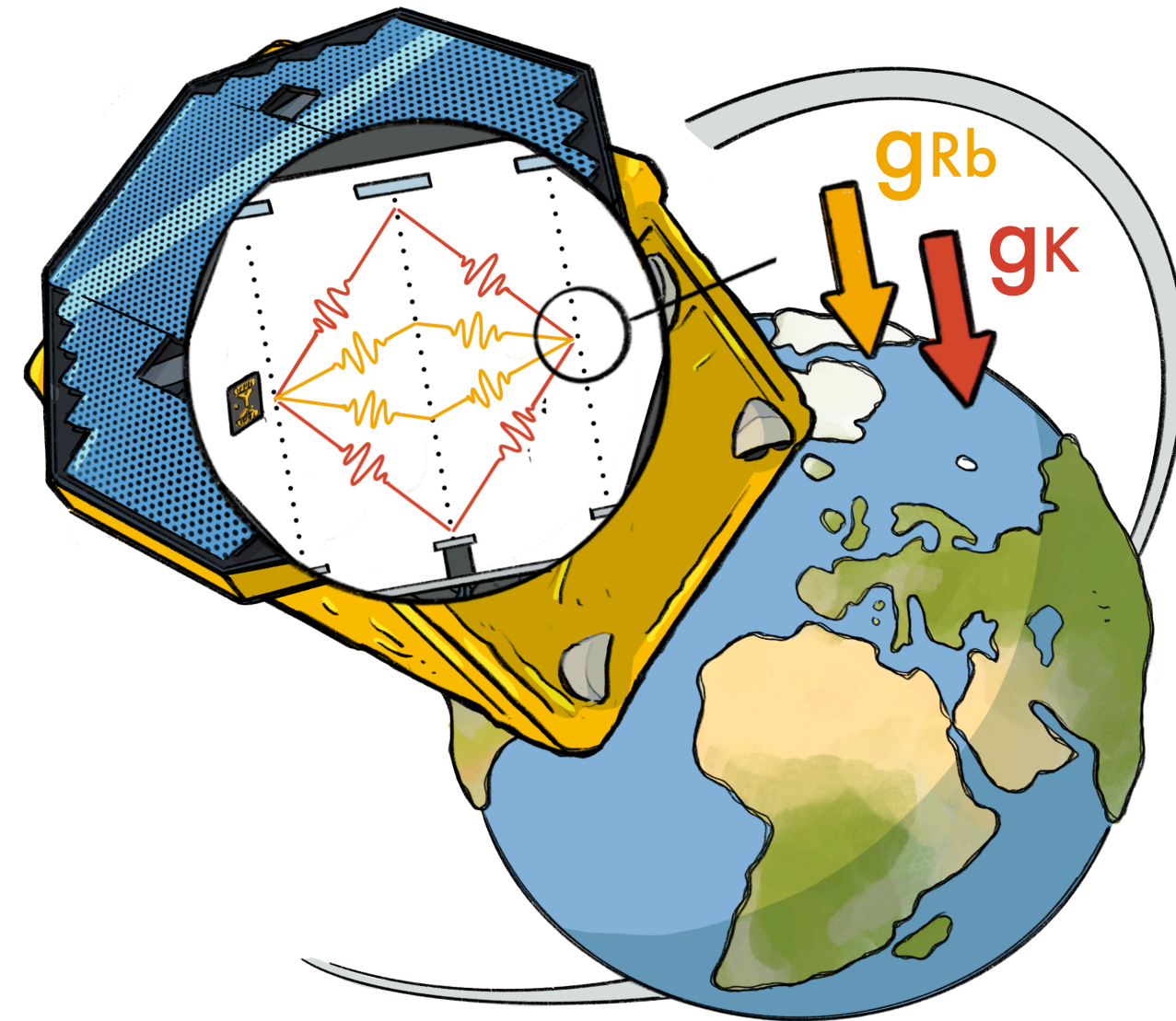
$$\text{matter: } \delta\phi_{\text{Sagnac}} = \frac{4\pi}{h} m_{\text{at}} \vec{A} \cdot \vec{\Omega}$$

$$\frac{\Delta\Phi_{\text{atoms Sagnac}}}{\Delta\Phi_{\text{light Sagnac}}} = \frac{m_{\text{at}} \cdot \lambda \cdot c}{h} \approx 10^{11}$$

Fundamental Physics crisis

Extreme sensitivity of quantum sensors unveils...

Violations of General Relativity postulates



Atom Interferometry in Orbit

Overview

- Bragg diffraction with 785 nm wavelength
- Beam path through chip window
- Three PI-teams working on interferometry
- J. Williams (JPL)

Geometries used so far by CUAS

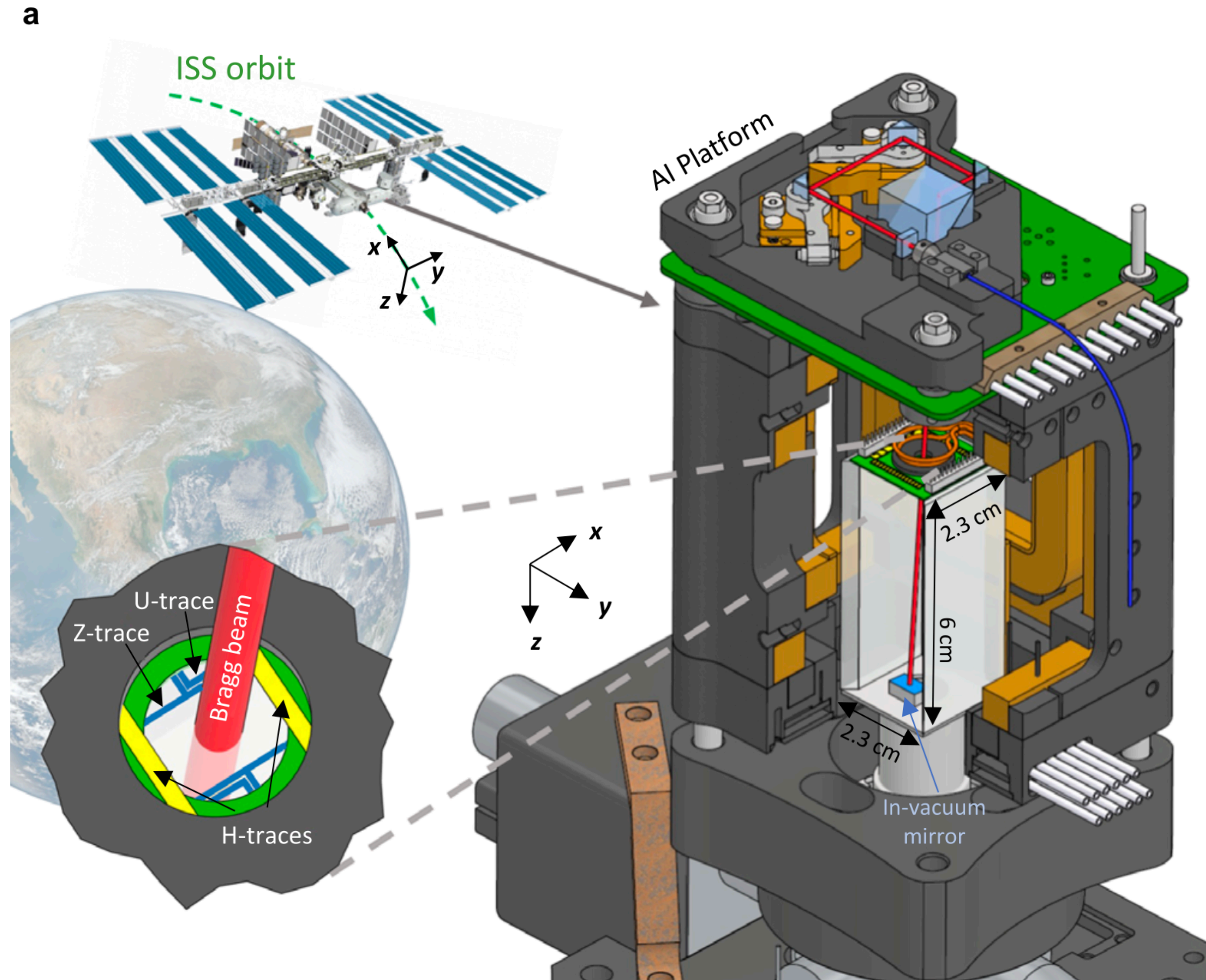
- 2-pulse shear-Ramsey
- 3(4)-pulse (differential) Mach-Zehnder
- 5-pulse differential butterfly

Nature Comm. **13**, 7889 (2022)

Nature **623**, 502 (2023)

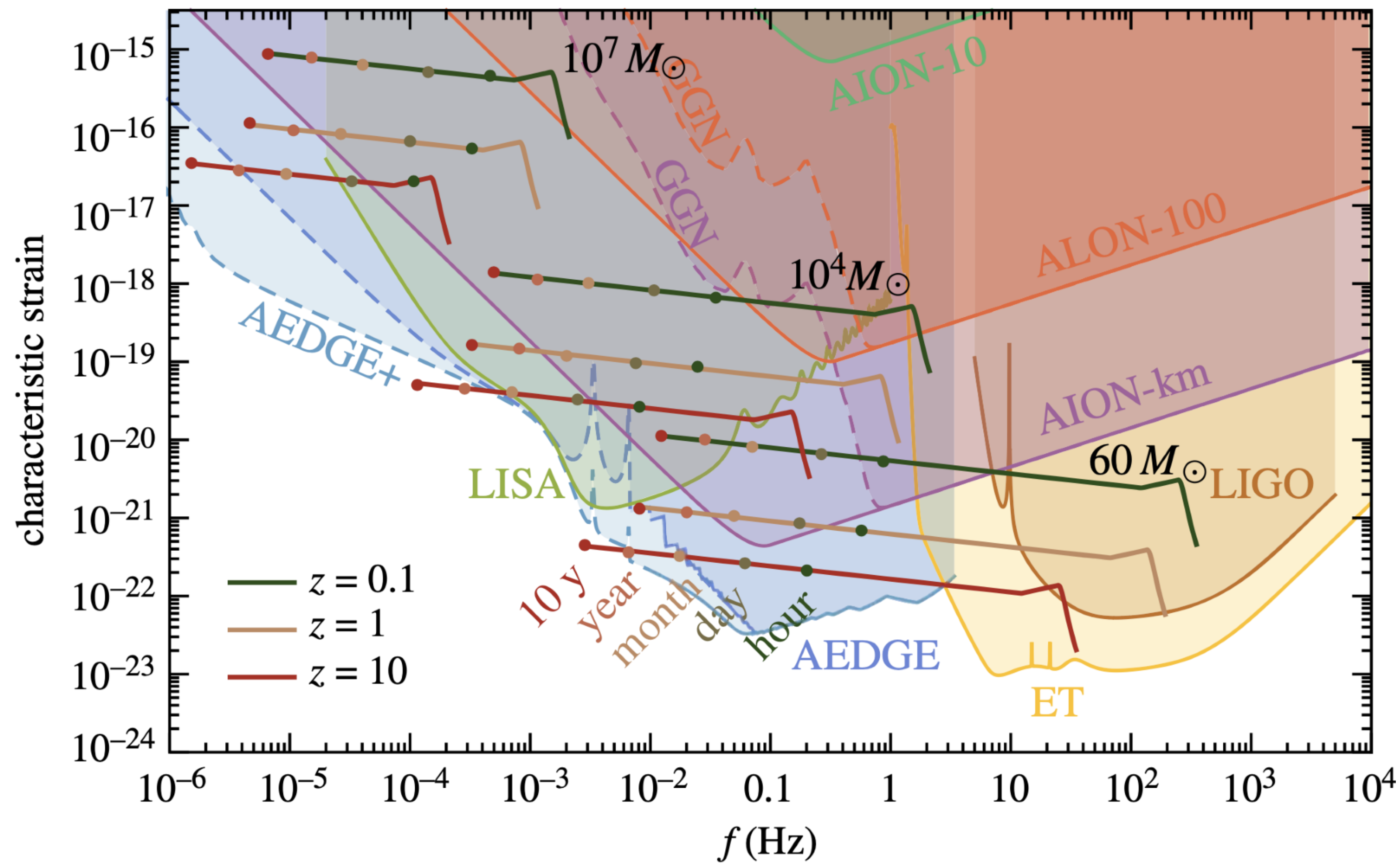
Nature Comm. **15**, 6414 (2024)

Nature Comm. **17**, 6089 (2026)



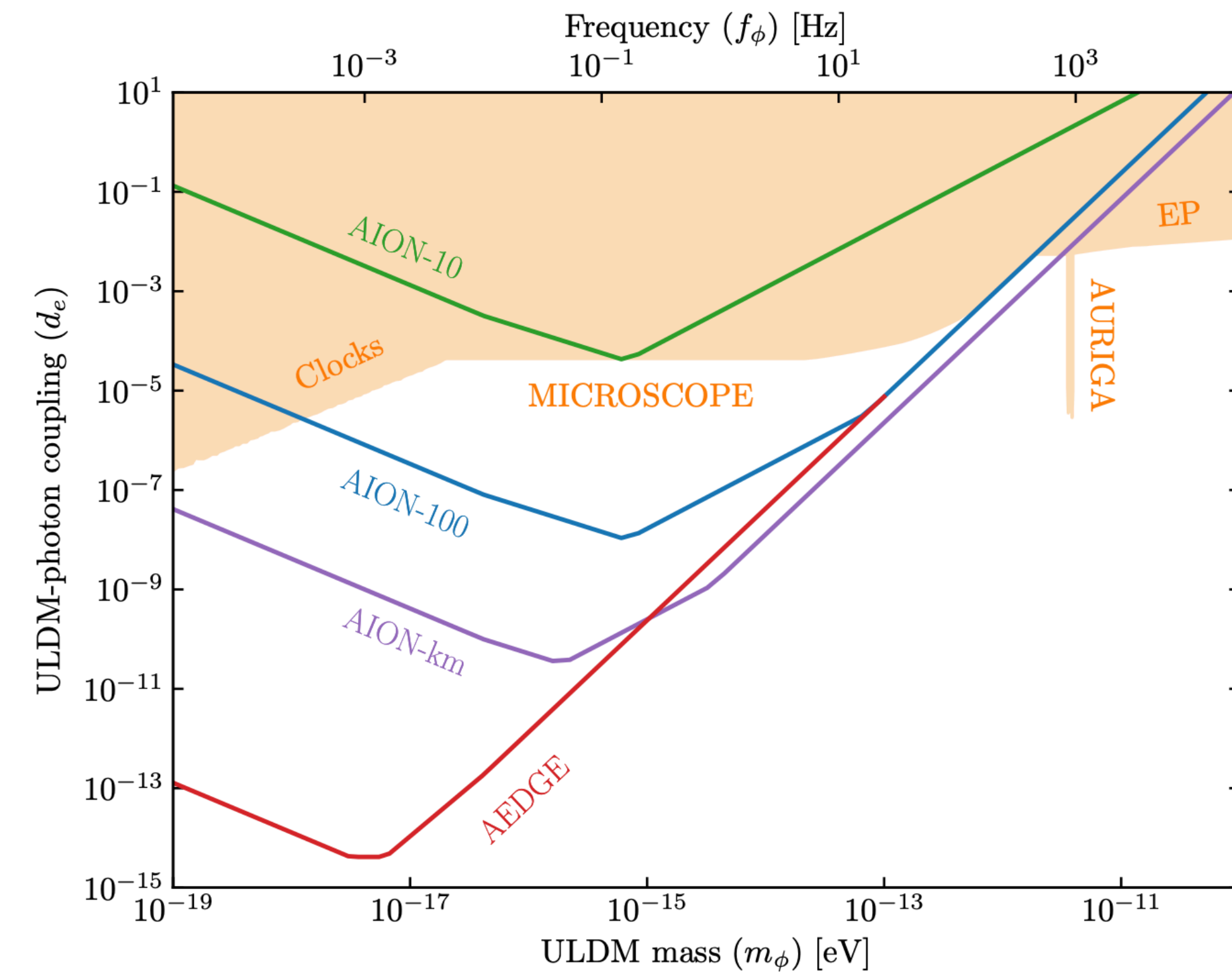
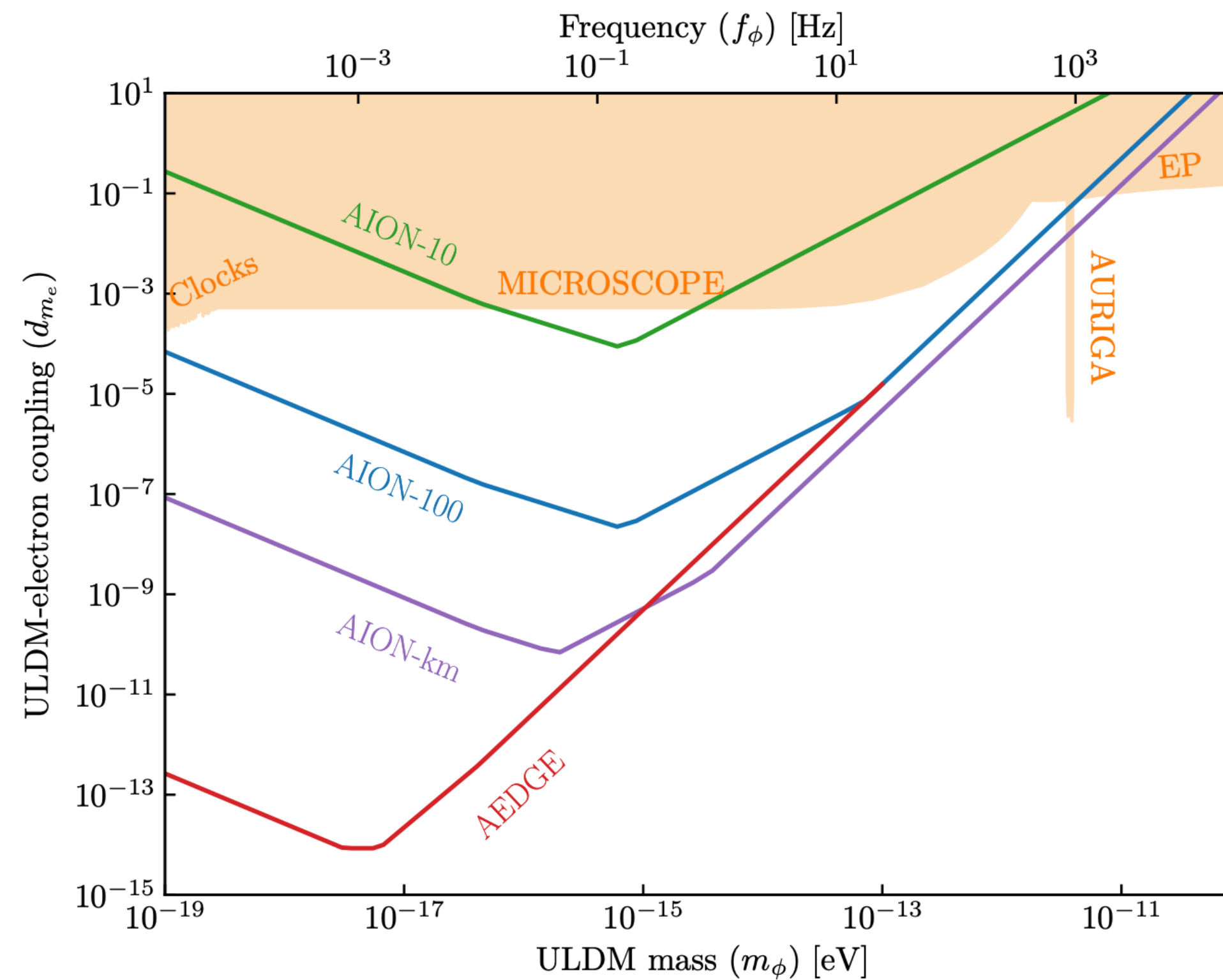
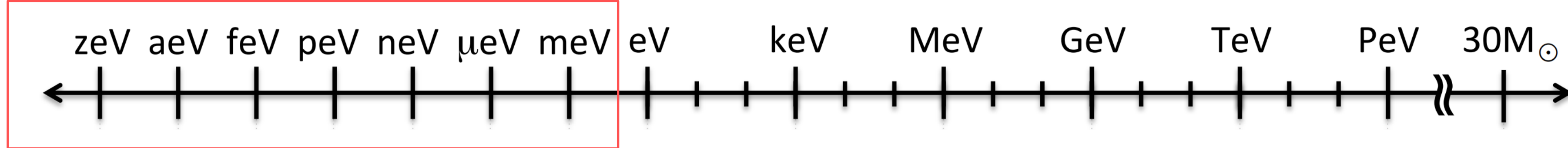
Gravitational Wave Detection

❖ ‘Mid-band’ sensitivity between LIGO and LISA.



L. Badurina et al. arXiv: 2108.02468

Ultra-light Dark Matter

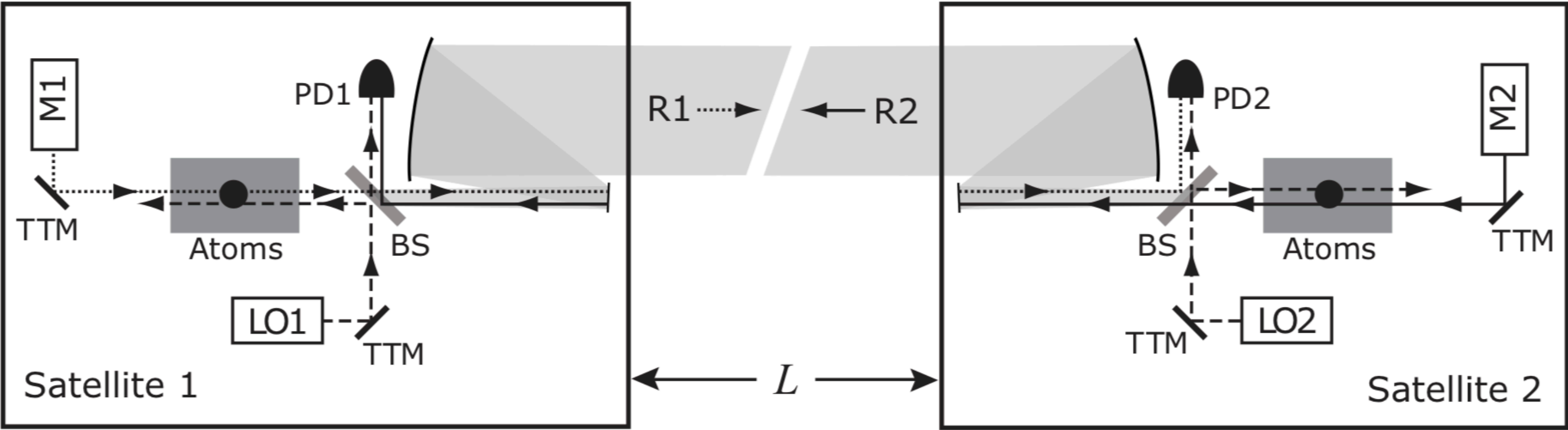
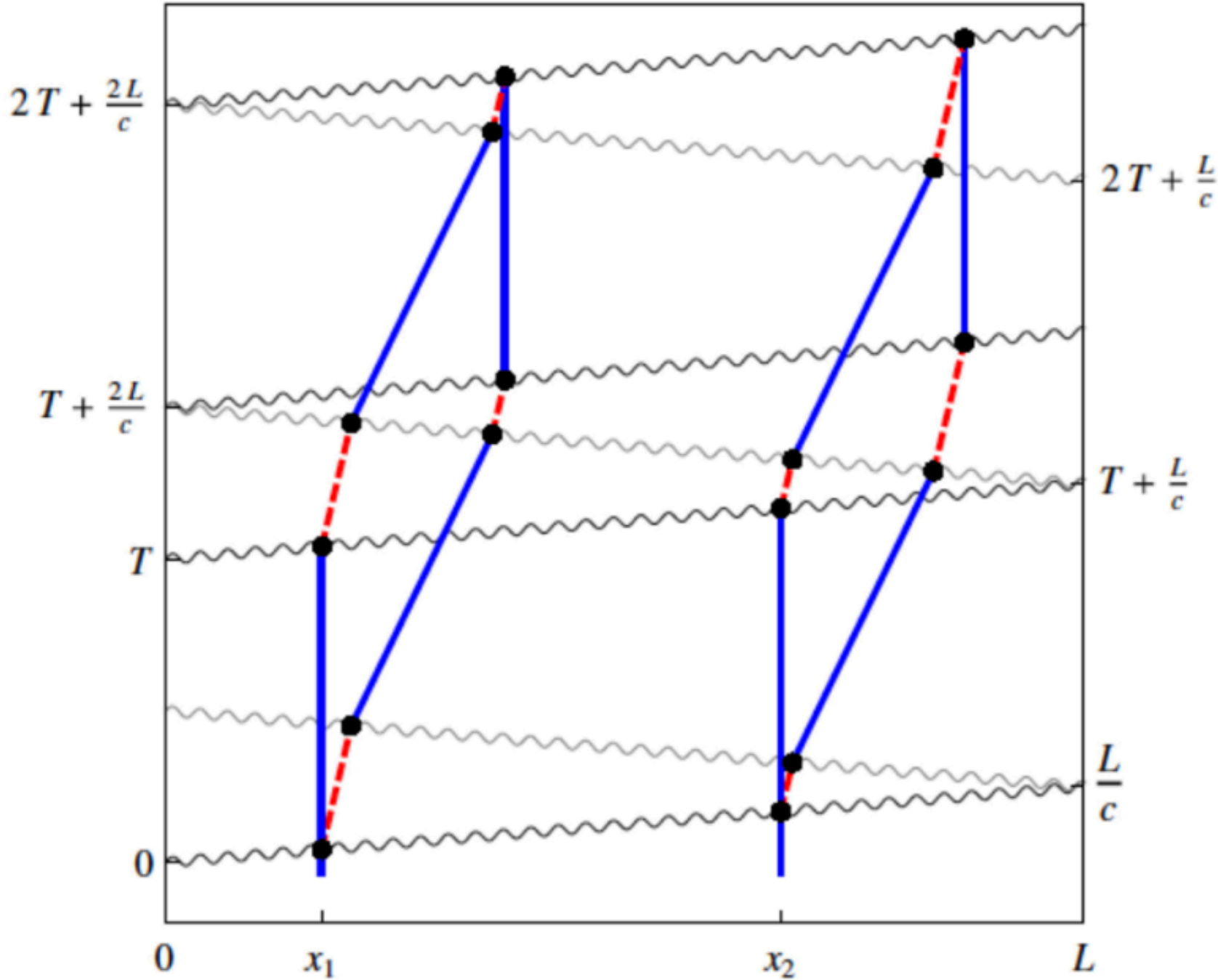


Ultralight mass means a high occupation number

Can describe as a classical field

$$\varphi(t, \mathbf{x}) \sim \cos(\omega_{\varphi} t - \mathbf{k}_{\varphi} \cdot \mathbf{x})$$

Mission Concept



	Parameter	Constraint	Notes
Spacecraft	Satellite longitudinal acceleration noise	$10^{-9} \frac{\text{m/s}^2}{\sqrt{\text{Hz}}} \left(\frac{f}{0.03 \text{ Hz}} \right)^4$	Residual gravity gradient $T_{zz} < 10 \text{ E}$
	Satellite transverse acceleration noise	$3 \times 10^{-10} \frac{\text{m/s}^2}{\sqrt{\text{Hz}}} \left(\frac{f}{0.03 \text{ Hz}} \right)^2$	$\lambda/100$ wavefront at $\Lambda = 1 \text{ cm}$
	Satellite pointing stability	$1 \mu\text{rad}/\sqrt{\text{Hz}}$	
Payload	Telescope aperture	30 cm	$\lambda/100$ wavefront aberration
	Laser pointing stability	$10 \text{ nrad}/\sqrt{\text{Hz}}$	Tip-tilt mirror servo; atom positioning $\Delta x < 1 \mu\text{m}$
	Laser power	2 W	Primary interferometry laser; one per spacecraft
	Interrogation region length	1 m	Length of UHV vacuum chamber
Atom Interferometry	Maximum interferometer duration	$2TQ < 300 \text{ s}$	Limited by vacuum, spontaneous emission
	Maximum atom optics pulses	$n_p < 10^3$	Includes all LMT and resonant enhancement
	Maximum wavepacket separation	$\frac{n\hbar k}{m} T < 1 \text{ m}$	
	AI readout noise	$10^{-4} \text{ rad}/\sqrt{\text{Hz}}$	Requires flux of 10^8 atoms/sec

Thank you very much

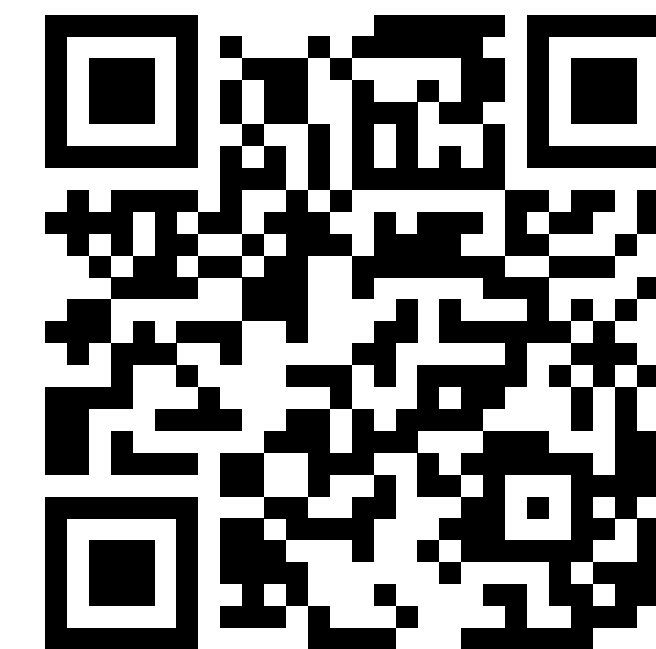


Theory of Quantum Sensing

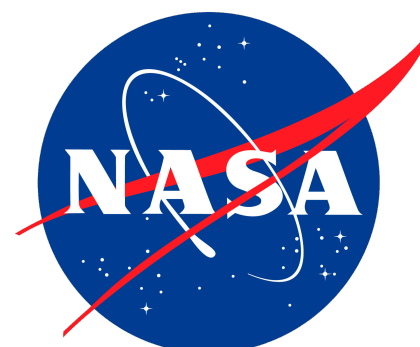


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Codes and contact!



- AEDGE collaboration
- STE-QUEST consortium (ESA)
- The CARIOQA consortium (EU)
- The CAL consortia (NASA)



Deutsche
Forschungsgemeinschaft
German Research Foundation



IQ



Naceur Gaaloul