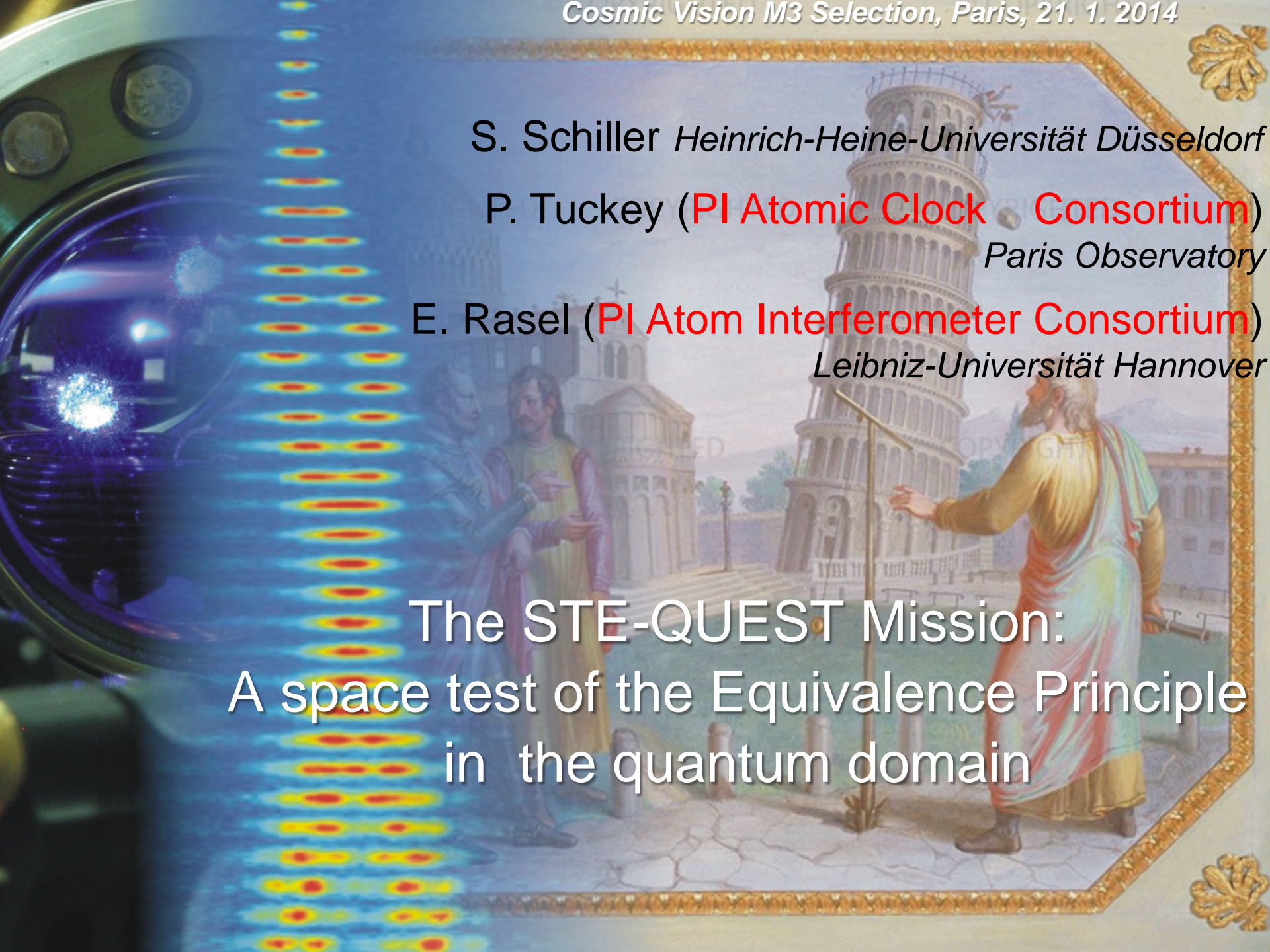


S. Schiller *Heinrich-Heine-Universität Düsseldorf*

P. Tuckey (**PI Atomic Clock Consortium**)
Paris Observatory

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Leibniz-Universität Hannover

The STE-QUEST Mission:
A space test of the Equivalence Principle
in the quantum domain



Contributors

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- Atom Interferometer Consortium

- Atomic Clock Consortium

- Time and Frequency Comparisons Ground Segment Working Group

- Science Working Group

- Reference Frames and Geodesy Working Group



Acknowledgement.



Motivation I

- Unified description of Gravity and Quantum Field Theory not achieved
- Nature of Dark Matter (DM): unknown
- Dark Energy – Cosmological constant: what is its nature?

- Models of unification and models of Dark Energy generally involve scalar fields that
 - couple to gravity
 - couple in different ways to different ordinary matter types and DM
- Fundamental constants are expectation values of scalar fields
- Such character can lead to time- and space-varying fundamental constants
- Recent detection of first fundamental scalar field (Englert-Brout-Higgs field)

Violation of EEP is a general consequence

Motivation II

Test the **Einstein Equivalence Principle**

- Weak EP (WEP): „In a gravitational field, pointlike particles move on trajectories defined by initial velocity, independent of their composition“
- Local Position Invariance (LPI): „The outcome of nongravitational experiments are independent of where and when they are performed“
(→ *Clocks measure proper time independent of their composition; fundamental constants do not vary*)
- Local Lorentz Invariance (LLI): „In freely falling frames, Lorentz Invariance holds“
- Past experimental confirmations of EEP have already strongly constrained theoretical proposals
- **Discovery of EEP violation would be a momentous event**
- **STE-QUEST tests will be performed in the quantum regime**

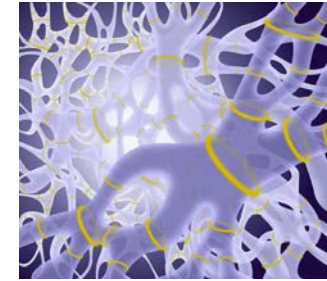
Quantum gravitational effects are few but of eminent importance:

(Primordial quantum fluctuations and inflation;

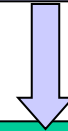
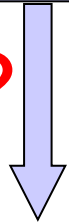
Far future of universe: quantum evaporation of black holes)...

Motivation III

*Unified theories
string theory, quantum loop gravity ,...*

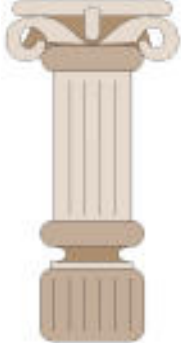


?



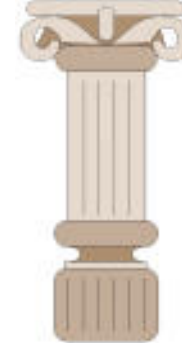
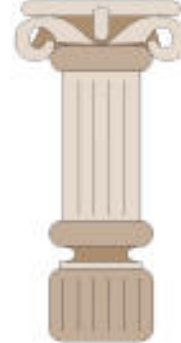
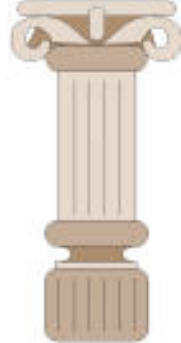
?

*Theory of
gravitation*



Standard Model

<i>Theory of electromagne- tic interaction</i>	<i>Theory of weak interaction</i>	<i>Theory of strong interaction</i>
--	---	---



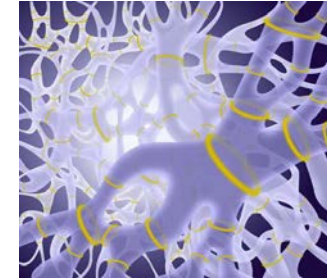
*Local Lorentz Invariance
Local Position Invariance
Weak Equivalence Principle*

*Lorentz Invariance
CPT - Symmetry*

exactly valid?

Motivation III

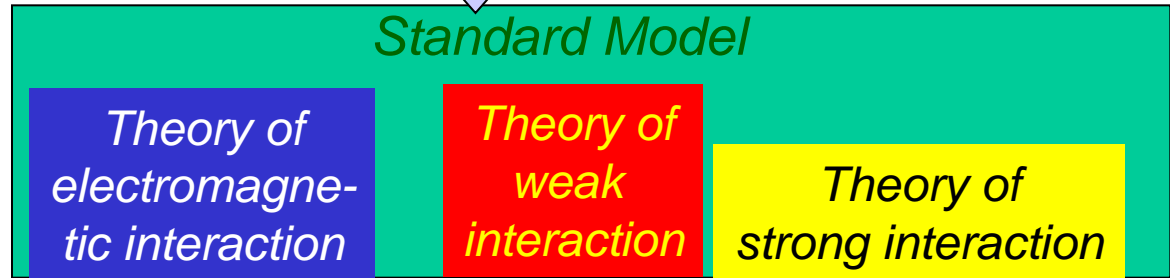
*Unified theories
string theory, quantum loop gravity ,...*



?

?

*Theory of
gravitation*



- Direct tests of GR predictions (pulsar binaries,)
- Antimatter – matter gravitational attraction (anti-hydrogen)

- LI tests (terrestrial experiments, astrophysical observations)
- CPT tests
- EDM searches

ctly

STE-QUEST ...

- ...searches for hints of non-standard physics in the gravitational sector (violations of metric gravitational theories)
- ...explores the foundations of the space-time description:
 - How does the presence of matter modify proper time?
 - How does gravity act on matter?
- ...uses quantum probes
- ...will push the accuracy of knowledge of fundamental laws further by several orders of magnitude in precision
- ...may discover deviations from established laws of physics

I. Test of the Weak Equivalence Principle: Is the gravitational acceleration universal?

satellite

$$a_A = a_B ?$$

a_s

a_A



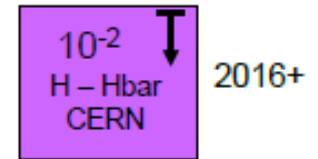
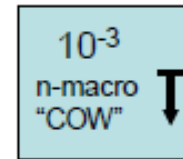
a_B

- Test performed with single atoms, in free-fall (two bosonic isotopes of rubidium: ^{85}Rb and ^{87}Rb)
- **Objective:** determine $2(a_A - a_B)/(a_A + a_B)$ with uncertainty 2×10^{-15}
- Advantage of space experiment: long free-fall time \rightarrow sensitivity increase, reduction in systematics

Complementarity to other experiments

- WEP test with **terrestrial experiments**

- Macroscopic masses, without/with spin (10^{-13})
- Cold atoms in free fall (Rb-Rb 10^{-7} , Cs/Rb-macro: 10^{-8})

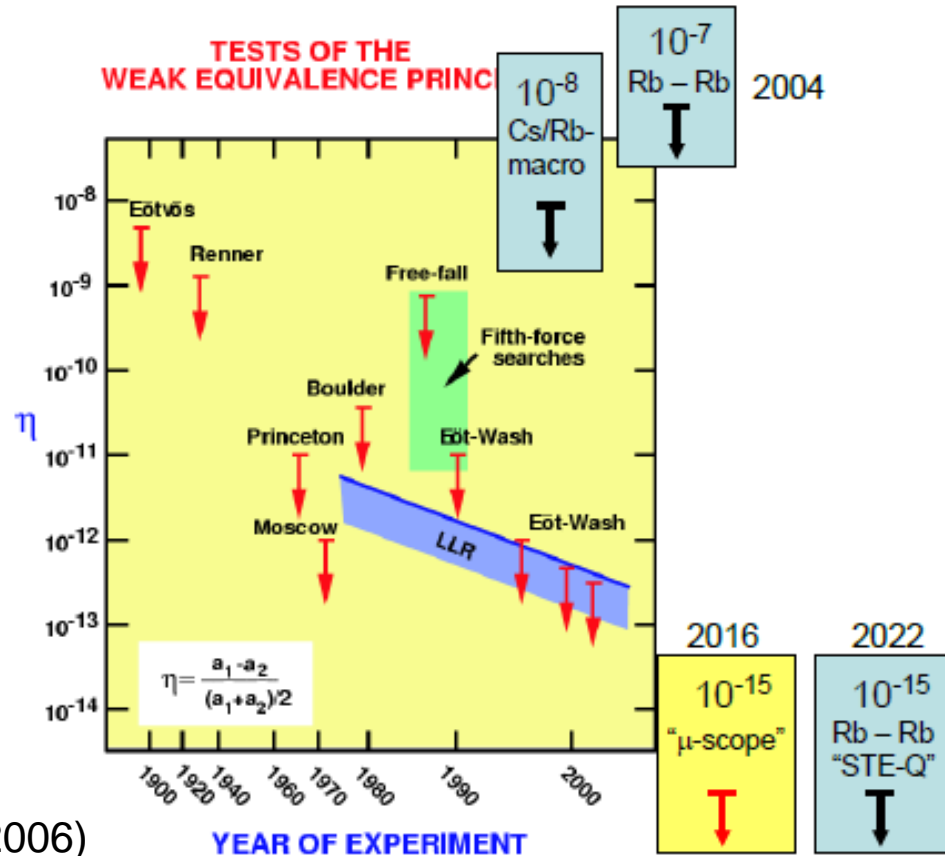


- WEP test **in space:**

(mission MICROSCOPE)
Titanium/Platinum test masses,
 10^{-15} level,
nuclear composition different from
STE-QUEST

- Strong EP** test (incl. self-gravity)

- in space:
- Lunar laser ranging of moon (in solar grav. field)
 - Pulsar timing



Will (2006)

II. Measurement of time dilation in gravitational field

Proper time:

$$d\tau(r) = \sqrt{1 + 2 \frac{U(r)}{c^2}} dt$$

$$U(r) = -\frac{GM}{r} \quad ?$$

Is this universal, i.e. independent of

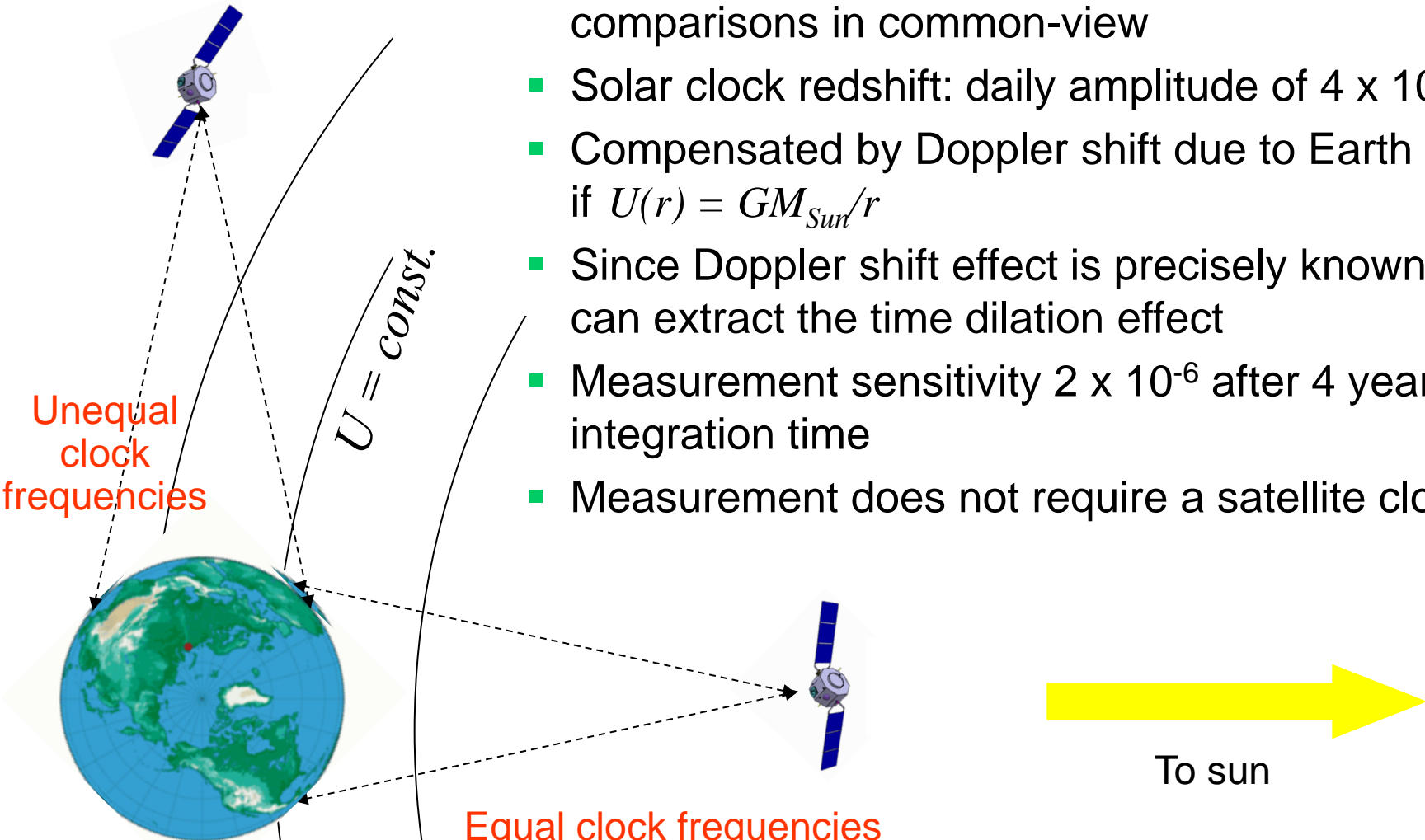
- the composition of the massive body?
- the type of clock?

STE-QUEST objective:

Test at the 2×10^{-6} level in the Sun's gravitational field

Test at the 4×10^{-4} level in the Moon's gravitational field

Time dilation measurement in Sun field



- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Solar clock redshift: daily amplitude of 4×10^{-13}
- Compensated by Doppler shift due to Earth motion if $U(r) = GM_{Sun}/r$
- Since Doppler shift effect is precisely known, one can extract the time dilation effect
- Measurement sensitivity 2×10^{-6} after 4 years integration time
- Measurement does not require a satellite clock

Advantage of space experiment:

clocks separated by maximum distance can be compared

Interpretation of time dilation test results

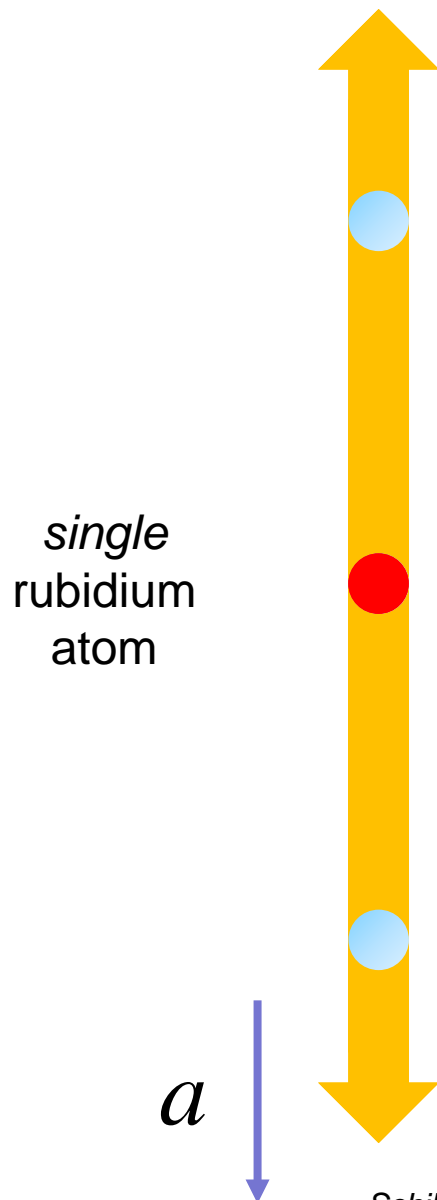
Search for existence of additional scalar fields ϕ emanating from constituents of Sun (protons) and Moon (protons, neutrons)

- Model:
$$\phi_{i,j}(r) \sim S_{i,j}/r$$
where S_{ij} may depend on
 - the particle species contained in source body i ;
 - the clock type j
- STE-QUEST will compare different clock types: atomic, hyperfine, ...
- STE-QUEST will set limits to $S_{\text{SUN},j}$, $S_{\text{MOON},j}$

Complementarity

- Test in the Sun field
 - Redshift of atomic lines (1991); quartz oscillator on GALILEO (1993): 2%
 - Clock-type independence well-tested using co-located Earth clocks (2012)
- Test in the Moon field: none so far
- Test in the Earth field:
 - Gravity-Probe A (1976; 7×10^{-5}); ACES (ISS, 2016; 2×10^{-6}) \rightarrow limits to S_{EARTH}
- Time dilation tests and WEP tests are related, but relationship is model-dependent \rightarrow both important

Instrument I: Atom interferometer

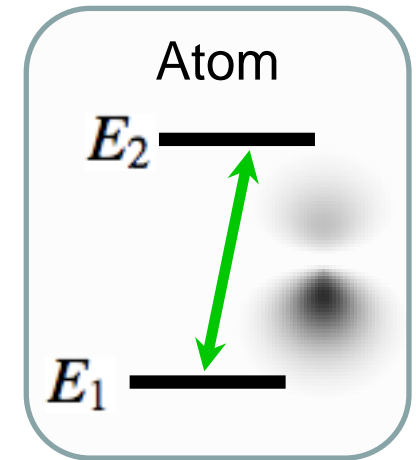
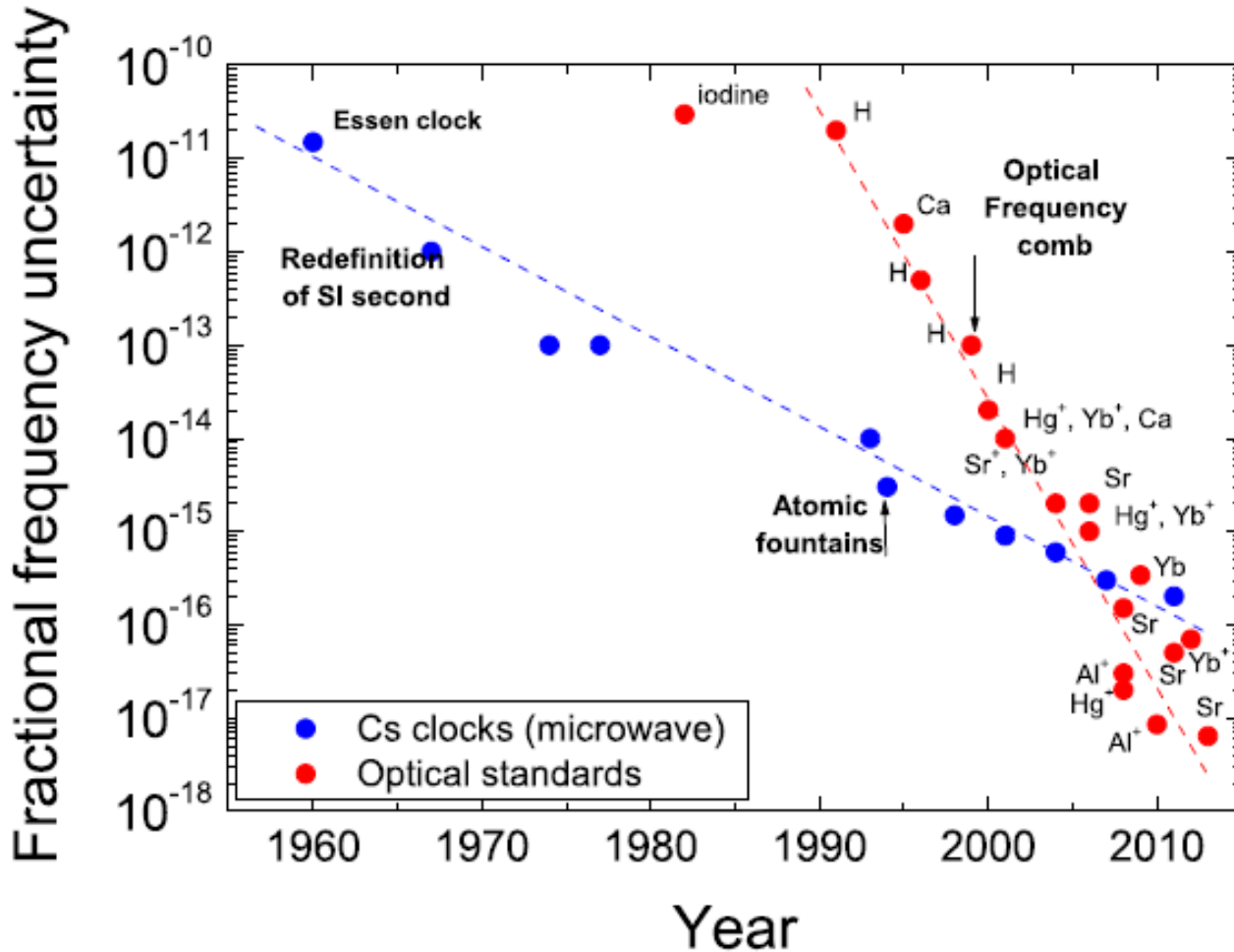


- Single-atom matter wave
- an atom interferes with itself; interference depends on acceleration

→ „The largest atoms in the universe“: **12 cm**

→ de Broglie wavelength $\approx 10^{21}$ times larger than for macroscopic test masses

Instrument II: Atomic clocks and link



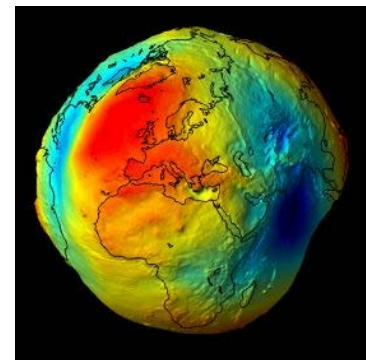
Hume et al. (2012)

Poli et al. (2013)

- Instability level 2×10^{-18} has already been demonstrated (NIST, 2013)
- STE-QUEST will make use of terrestrial atomic clocks having fractional instability and inaccuracy of 1×10^{-18} in 2024

Secondary goals

- Set limits to orientation-dependent and velocity-dependent (i.e. LI-violating) contributions to the time dilation
- *By tracking of STE-QUEST satellite on its highly elliptical orbit*
 - contribution to reference frame accuracy improvements and alignment between frames (terrestrial, celestial)
 - more precise data on Earth gravity field
 - improvement of GNSS orbit accuracies
 - contribution to Earth movement measurement
- *By comparison of atomic, molecular and nuclear clocks world-wide:*
 - Contribution to tests of time-independence of fund. constants,
 - Contribution to establishing a new definition of the Second
 - Contribution to dissemination of atomic time worldwide
- *By comparison of mobile terrestrial clocks with reference clocks:*
 - Contribution to geodesy, geophysics and climate studies



Summary

■ Science objectives:

Test the metric nature of the theory of gravitation,
search for physics beyond the Standard Model & General Relativity

- Test the Weak Equivalence Principle with matter waves,
accuracy : 2×10^{-15} ($\times 10^6$ improvement)
- Test time dilation in the solar and the lunar gravitational potential,
accuracy: 2×10^{-6} , 4×10^{-4} , resp.
($\times 10^4$, $\times 10^3$ improvement, resp.)

■ Application to other fields:

- Contribution to tests of time-variation of fundamental constants
- Contribution to improved reference frame definitions
- Distribution of time world-wide
- Mapping of the gravitational potential of the Earth with high spatial resolution

■ Potential for enhancement of science objectives:

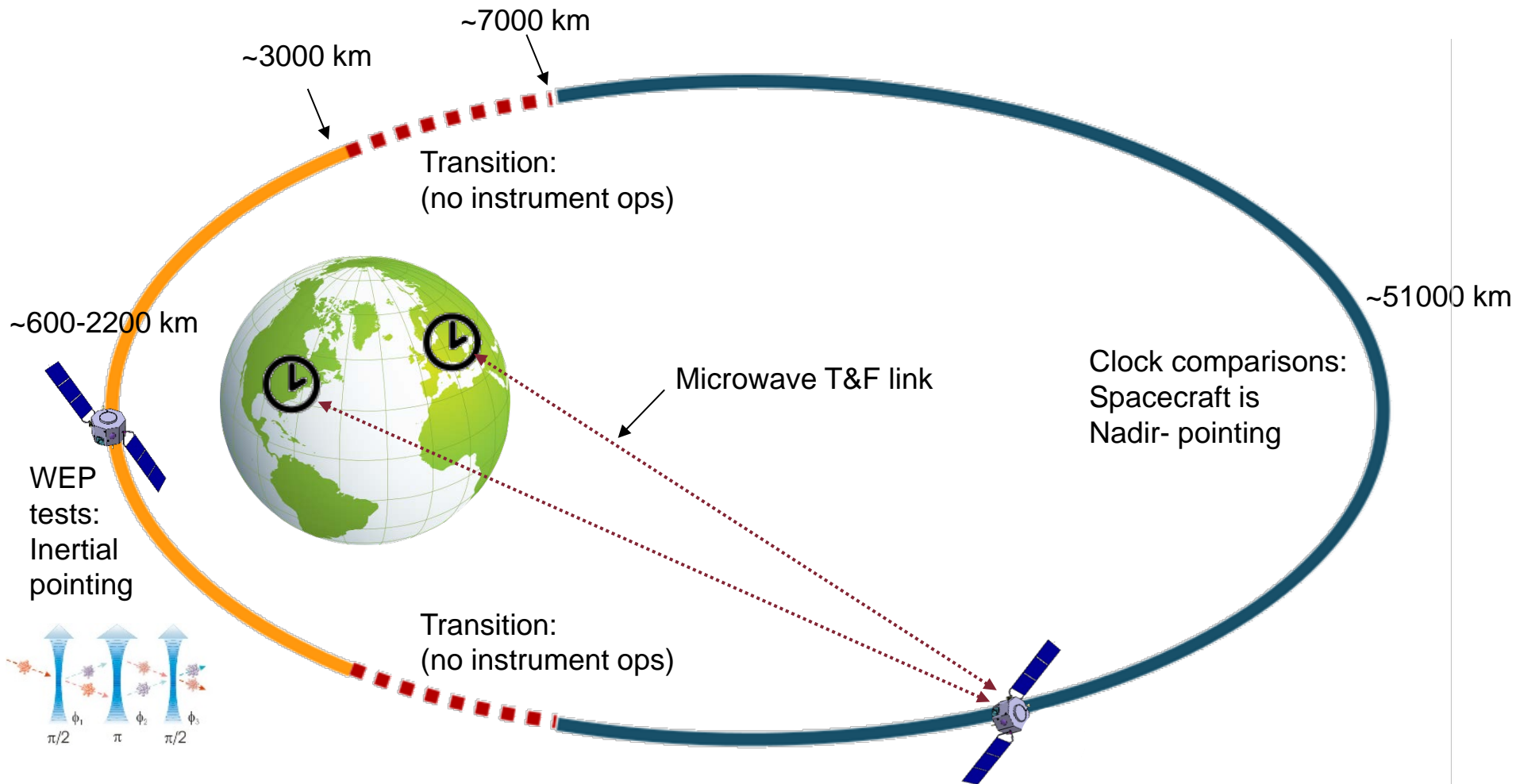
- Phase-coherence of microwave link between orbits
- Optional laser link
- Optional on-board clock

STE-QUEST

Time and frequency comparisons mission segment

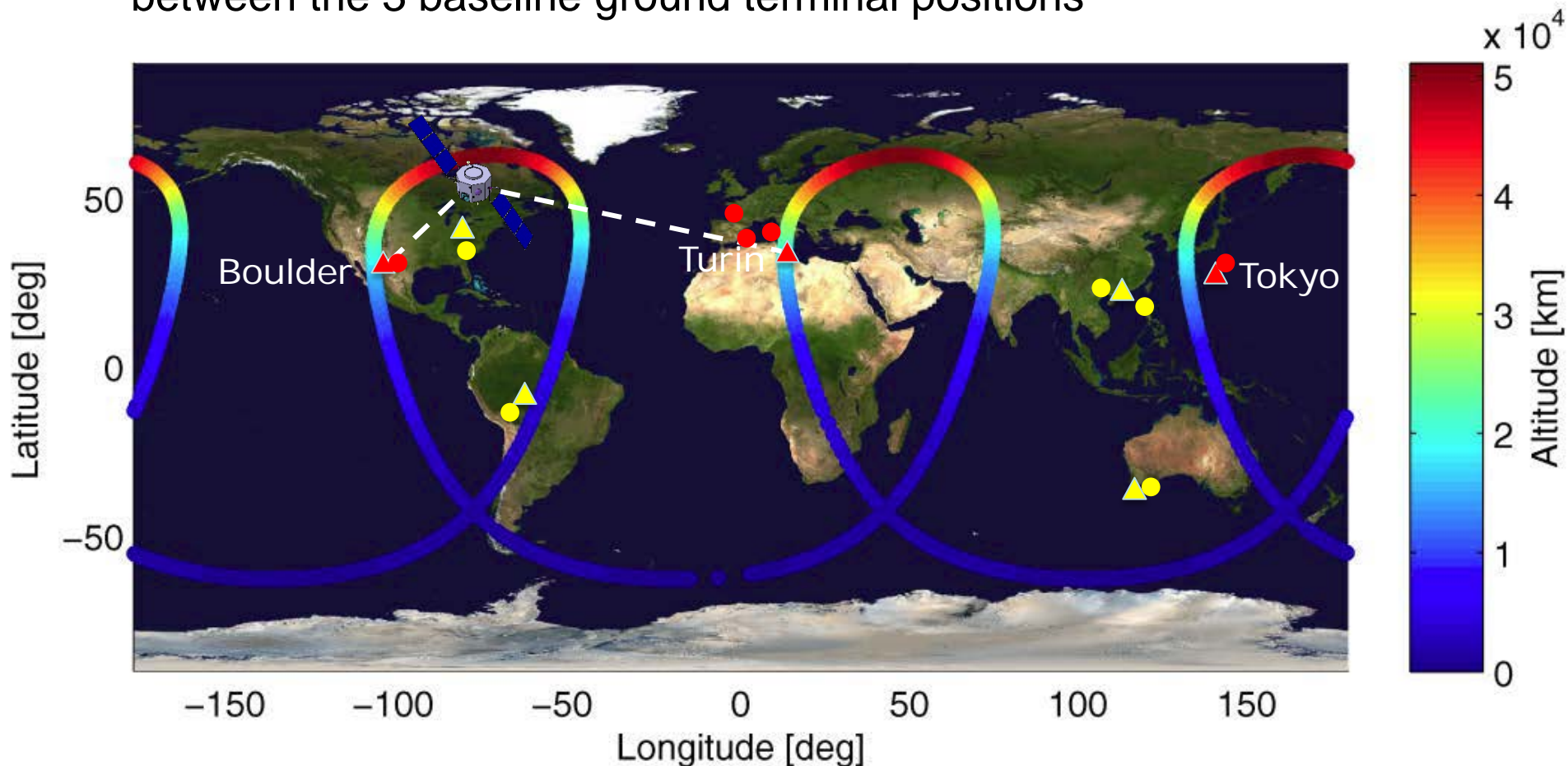
- Sun and Moon gravitational redshift tests
- Lorentz invariance tests
- Search for variations of fundamental constants
- Time and frequency metrology
- Clock-based relativistic geodesy
- Reference frames

Mission scenario



Mission scenario

- orbit inclination 63° , period 16 h
- ground track is “frozen”, repeats every 3 orbits / 2 days
- successive pairwise common-view comparisons of 11-12 h duration between the 3 baseline ground terminal positions



Microwave link

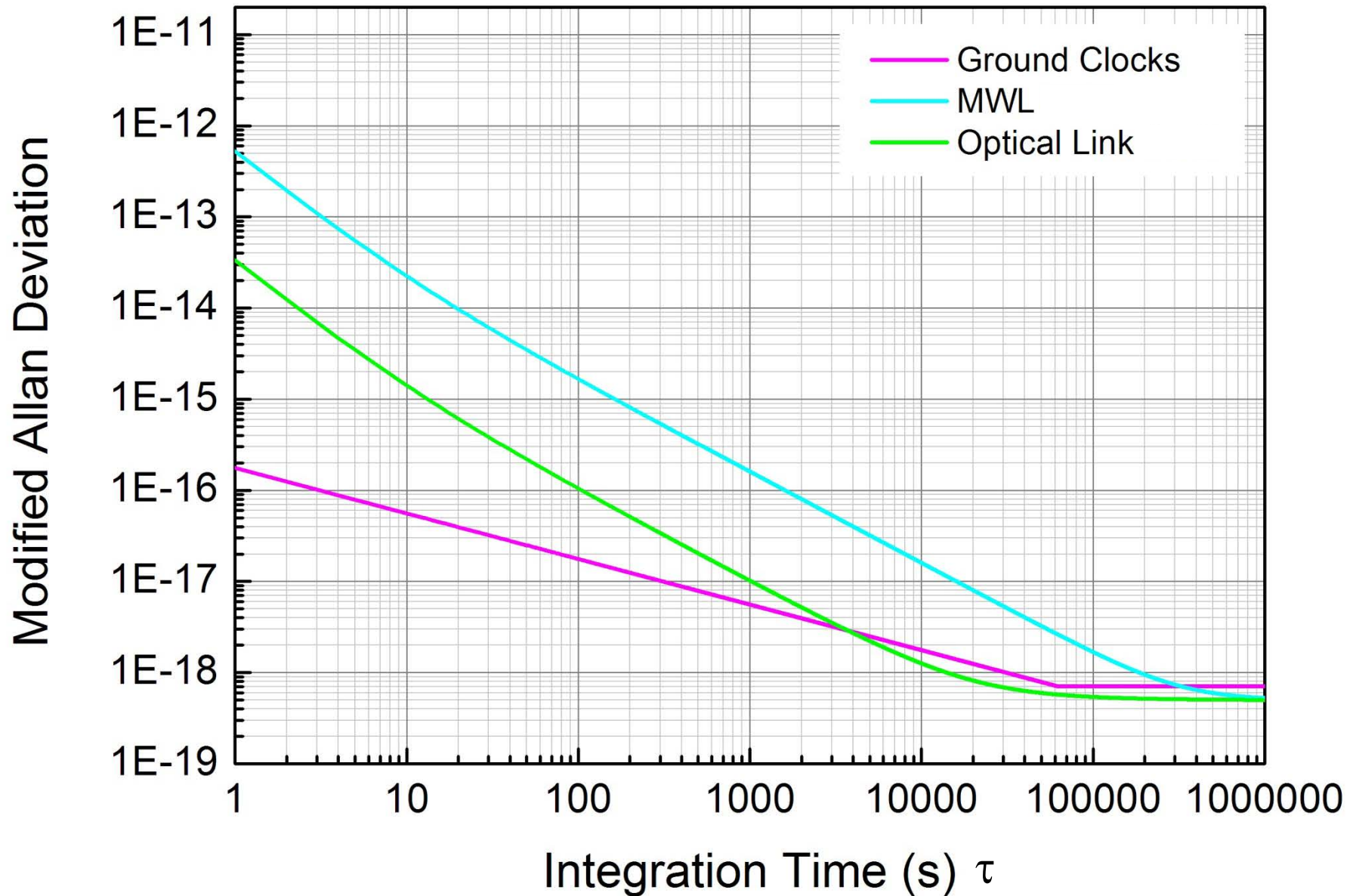
Operation:

- Composed of **flight segment** and **ground terminal(s)**
- Measures the time difference between a ground clock and spacecraft time, generated from an on-board oscillator.
- Two or more simultaneous ground–space comparisons can be combined to obtain **ground clock – ground clock comparisons** (spacecraft time cancels out).
- Time difference -> frequency comparison

Requirements:

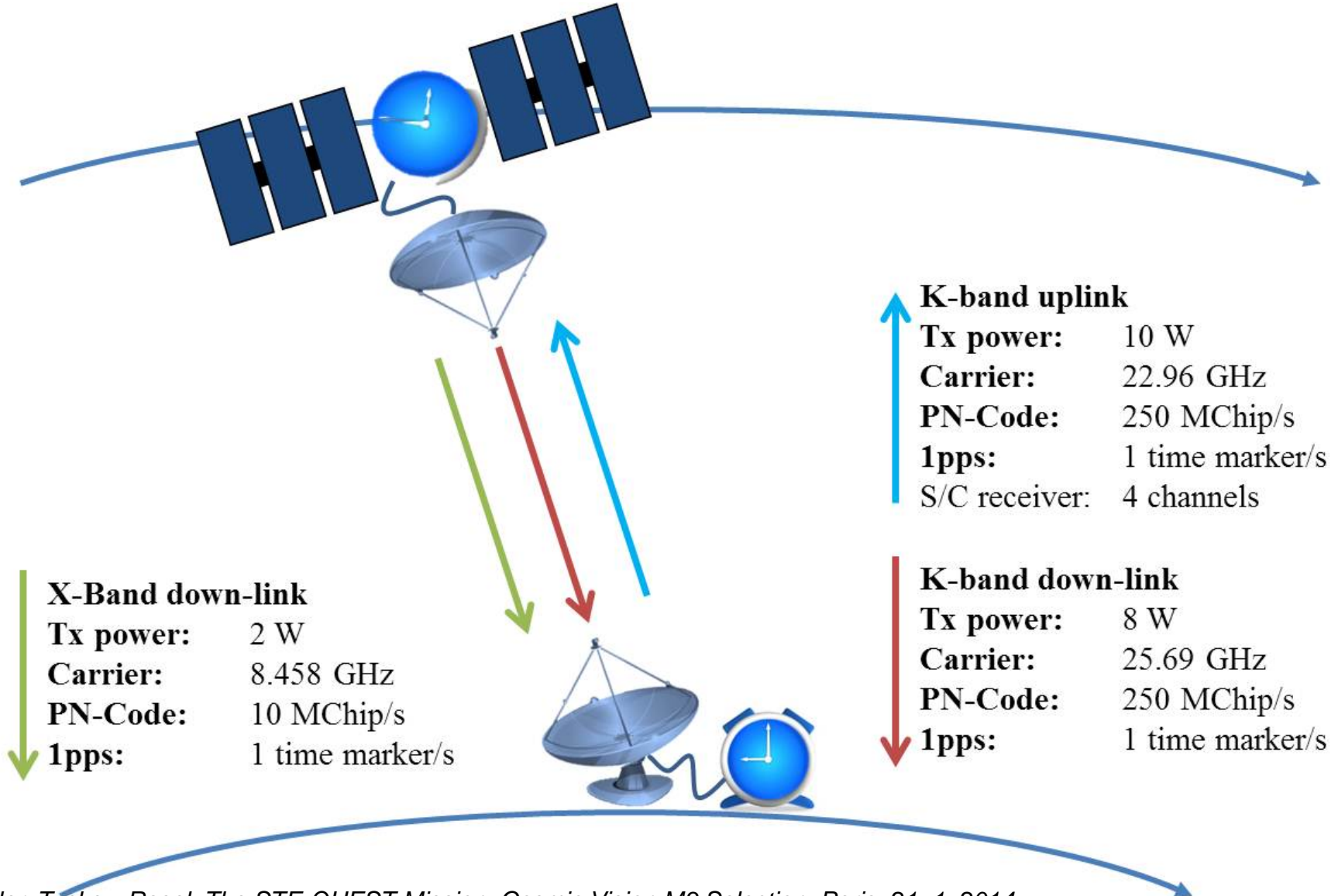
- 4 channels for simultaneous ground-space comparisons
- **ground-ground time comparisons:** error < 50 ps (calibration)
- **ground-ground frequency comparisons:** link noise < 1×10^{-18} (relative) after 2.5 days
- phase conserved across dead time between observations

Frequency stability requirements



Microwave link design

Industrial study under ESA contract



Microwave link ground terminal



Based on ACES ground terminal concept with upgrades.

Science ground segment

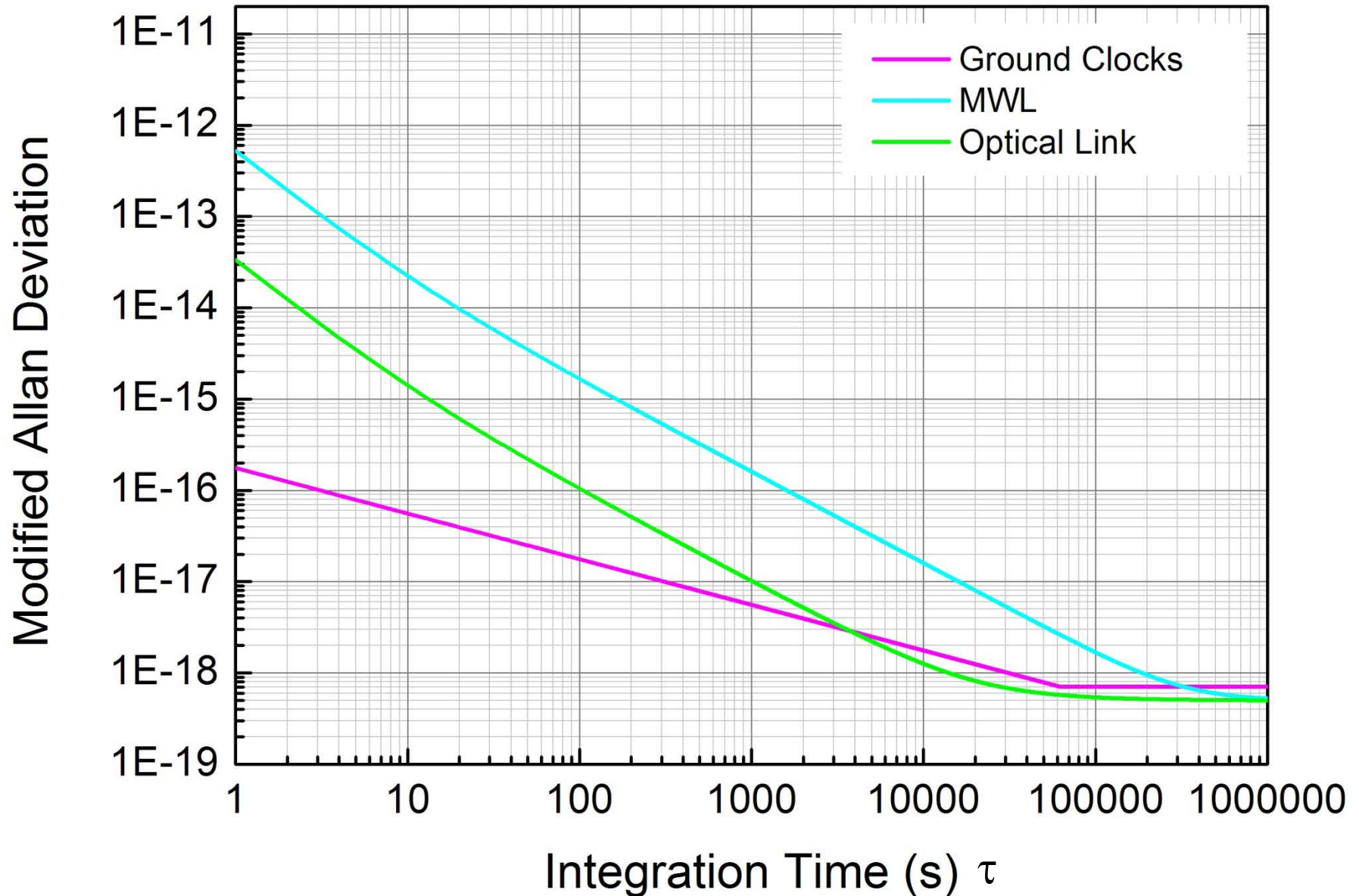
PI-provided

Baseline requirements:

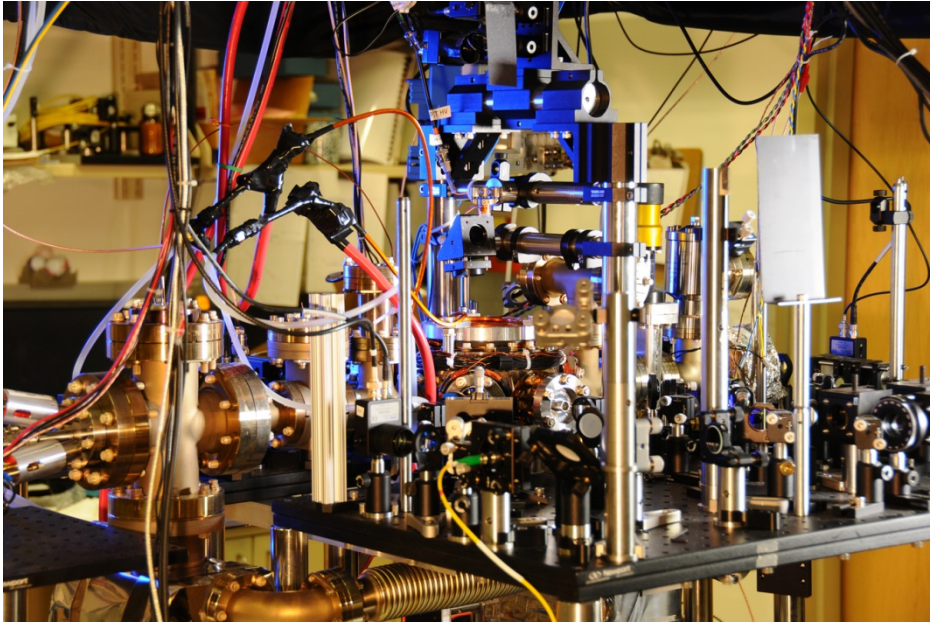
- **3 ground stations (Turin, Tokyo, Boulder)**
 - host the microwave link ground terminals
 - appropriately positioned around the world
- **high-performance ground clocks**
 - located at or connected to ground stations
 - frequency error $< 1 \times 10^{-18}$
 - frequency noise $< 2.5 \times 10^{-16} / \tau^{1/2}$ (up to 3 days)
- **2 data processing centres**
- **science data analysis centres (User segment)**

Strong similarities to the ACES ground segment and International Working Group, which we build on.

Frequency stability requirements



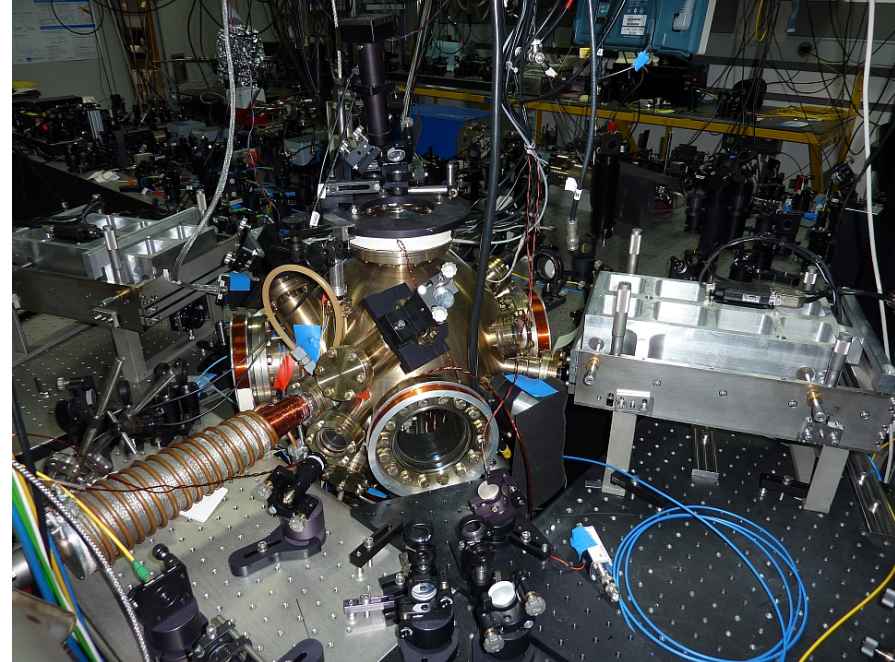
Examples of current ground optical clocks



NIST Yb lattice clock
stability $3.2 \times 10^{-16}/\tau^{1/2}$

PTB Sr lattice clock
stability $3.0 \times 10^{-16}/\tau^{1/2}$

STE-QUEST: $2.5 \times 10^{-16}/\tau^{1/2}$



Science ground segment

Baseline configuration:

Microwave link ground stations	
Asia: Tokyo	NICT (with U. Tokyo, NMIJ)
North America: Boulder	NIST
Europe: Turin	INRIM
Ground clocks	
Asia	NICT, NMIJ, U. Tokyo
North America	NIST, JILA
Europe	INRIM, NPL, PTB, LNE-SYRTE
Data processing centres	
DPC 1	LNE-SYRTE
DPC 2	NIST

- experienced ground stations (2 ACES sites)
- co-located clocks + access to others via regional fibre links
- data processing centres re-use ACES experience
- backup institutes identified for all functions
- optional additional sites/clocks for added science value
- 18 further groups/institutes for science analysis
- 38 groups/institutes in all
- MOC, SOC: moderate data volume, non-critical scheduling

Science performances

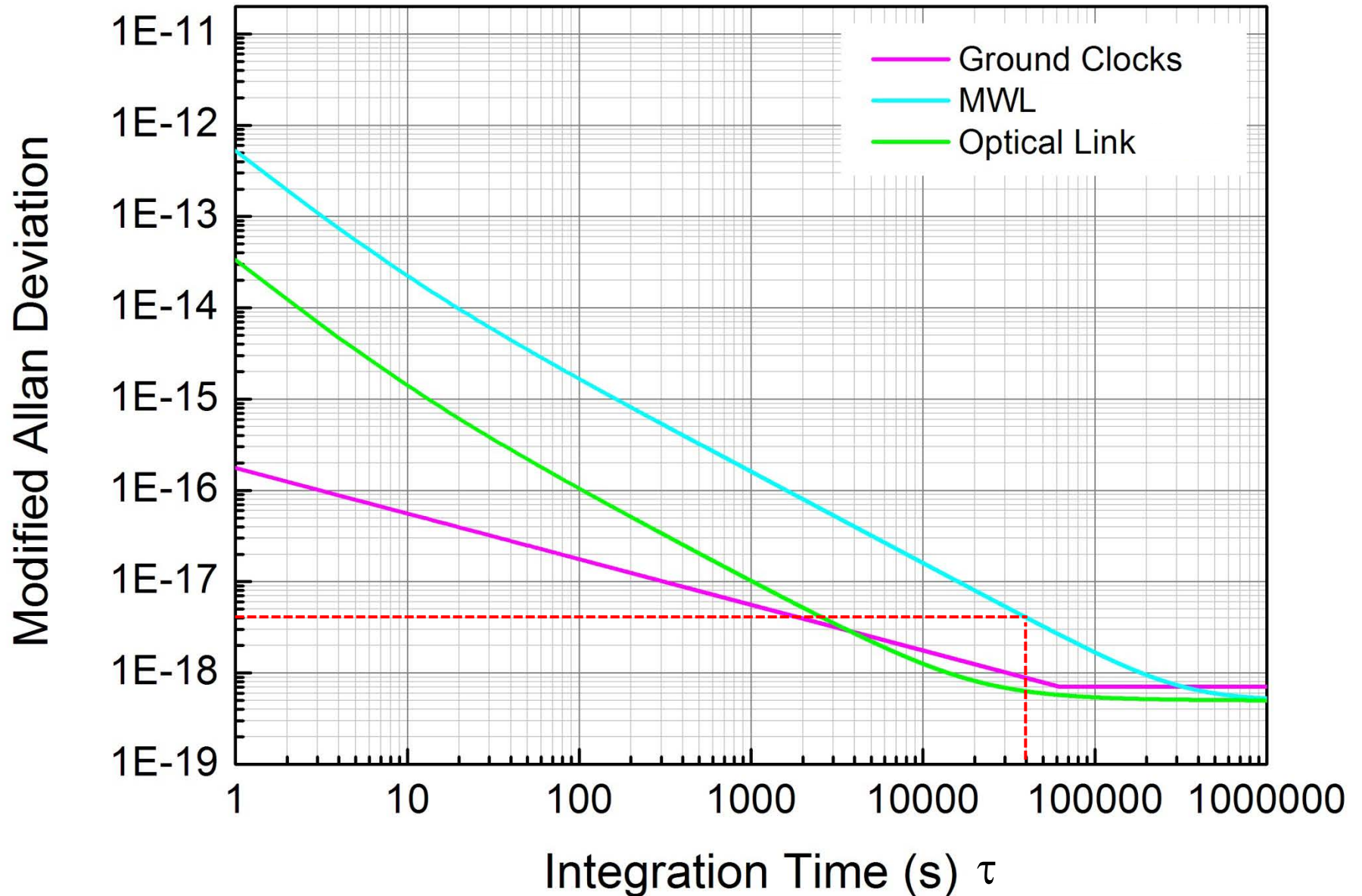
Ground-ground clock comparisons:

- time comparison accuracy < 50 ps
- typical link frequency noise of 4×10^{-18} after one comparison (~ 200 x better than current methods)
- link frequency noise falls below 1×10^{-18} after 3 days in nominal operation
- -> timescales, definition second, variations fund. constants

Gravitational redshift and geopotential measurements:

- extract time-varying (periodic) and constant terms from ground-clock frequency comparison series (MC modeling)
- **Sun redshift** relative uncertainty 6×10^{-5} after 2 days
- **Moon redshift** relative uncertainty ~ 170 x Sun
- **geopotential** uncertainty equivalent $\sim 20 - 60$ cm height after 1 comparison
- uncertainties average down to the science objective values over the mission lifetime, probably better.

Frequency stability requirements



Optional instruments

Optical link:

- based on an existing laser communications link with the addition of a time and frequency module
- independent of microwave link
- much lower noise – more rapid and flexible comparisons
- requires good weather conditions
- factor of 4 improvement on science goals



Data Rates 1.8 Gbps and 5,625 Gbps
400 mm Telescope with adaptive optics
Operation at low altitude

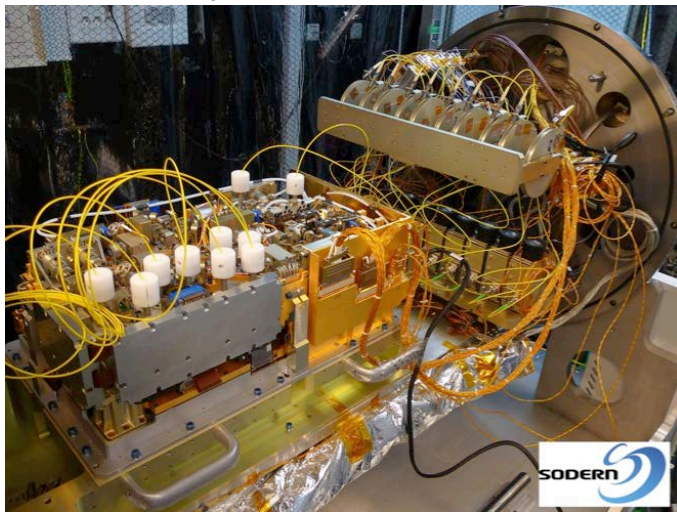
TESAT

Optional instruments

Space cold caesium clock:

- copy of PHARAO cold Cs clock for ACES (2016)
- addition of an ultrastable oscillator based on a cavity-stabilized laser + femtosecond laser comb
- performances specification = PHARAO ultimate goal
 - frequency error $< 1 \times 10^{-16}$
 - frequency noise $< 8 \times 10^{-14} / \tau^{1/2}$ (to 8 days)
- enables Earth gravitational redshift measurement at 2×10^{-7}

PHARAO Optical Bench



SODERN

Ultra-stable cavity

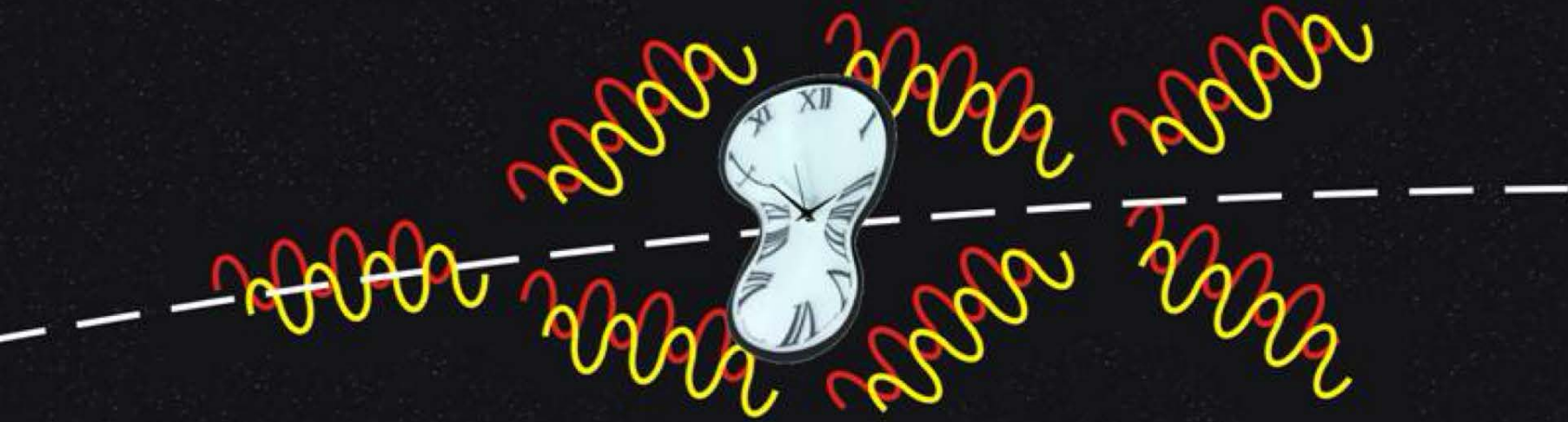


HHUD/PTB

Femtosecond laser comb

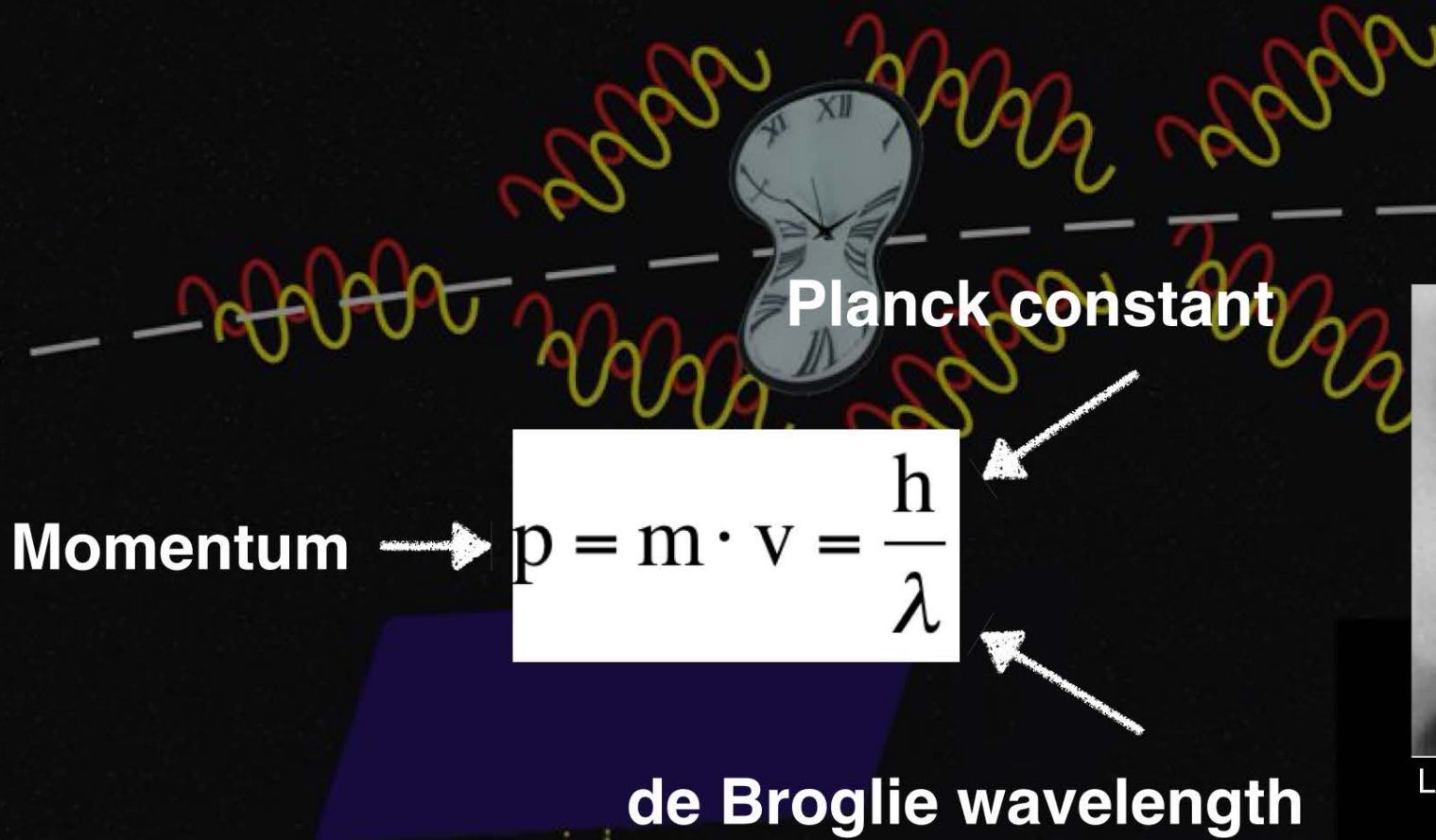


MenloSystems



**STE-QUEST:
A
Quantum Test
of the
Universality of Free Fall with Matter Waves**

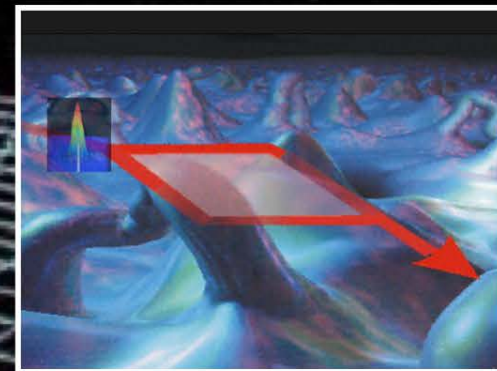
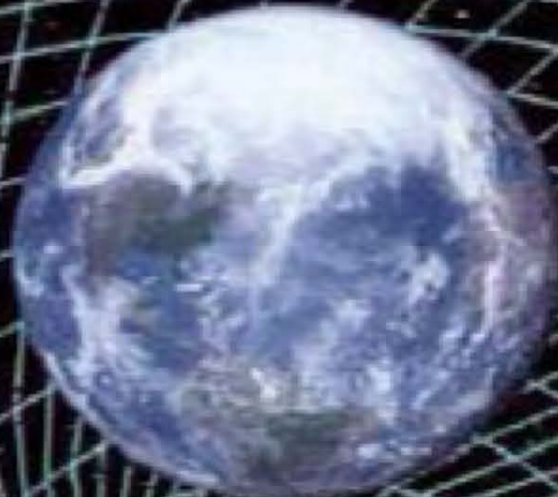
Matter forms Waves



Louis Victor de Broglie
Nobel prize 1929




Albert Einstein
Nobel prize 1921

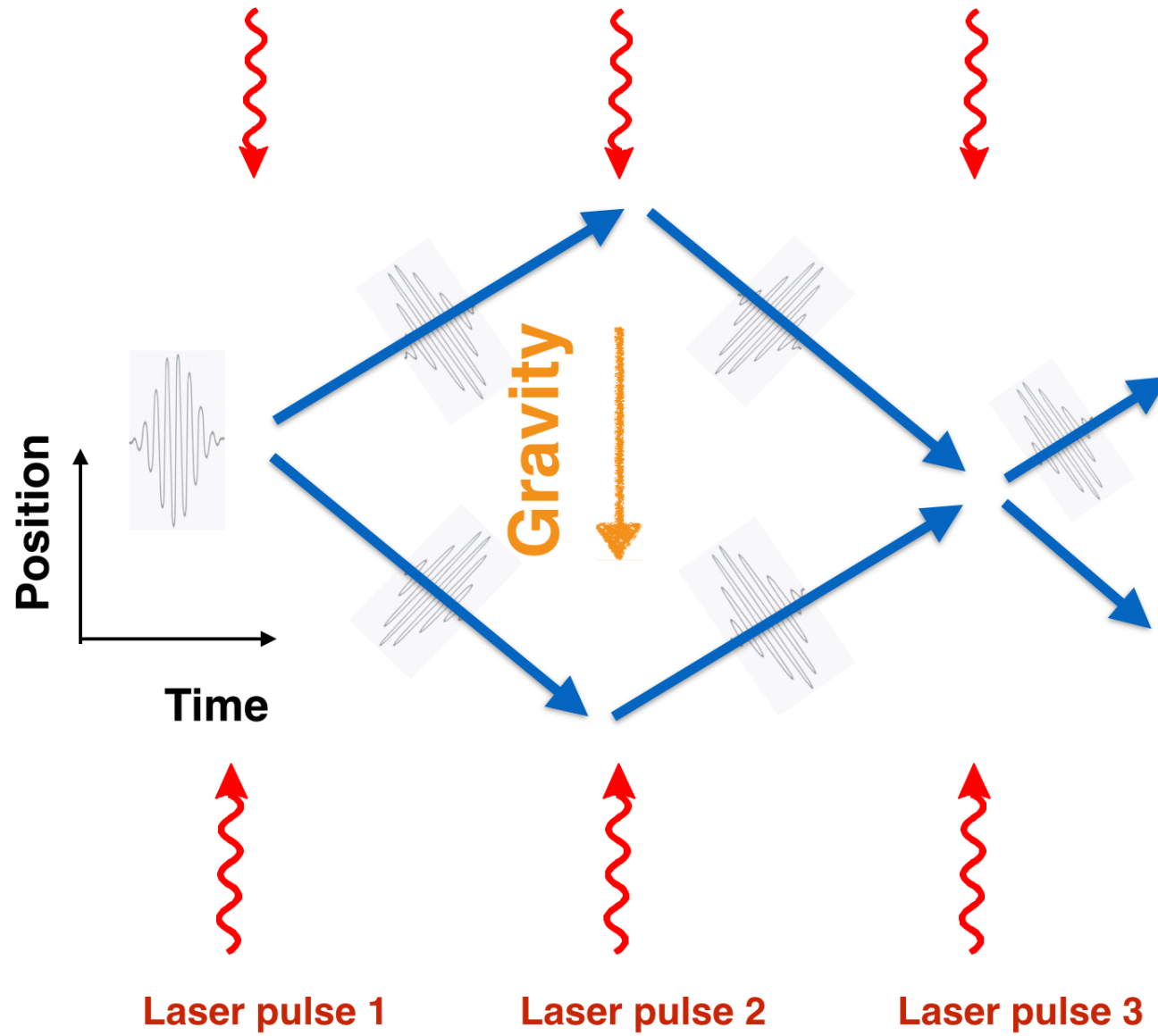


**How does gravity act on matter waves?
How do they move in space-time ?
Does gravity act universally on matter waves ?**

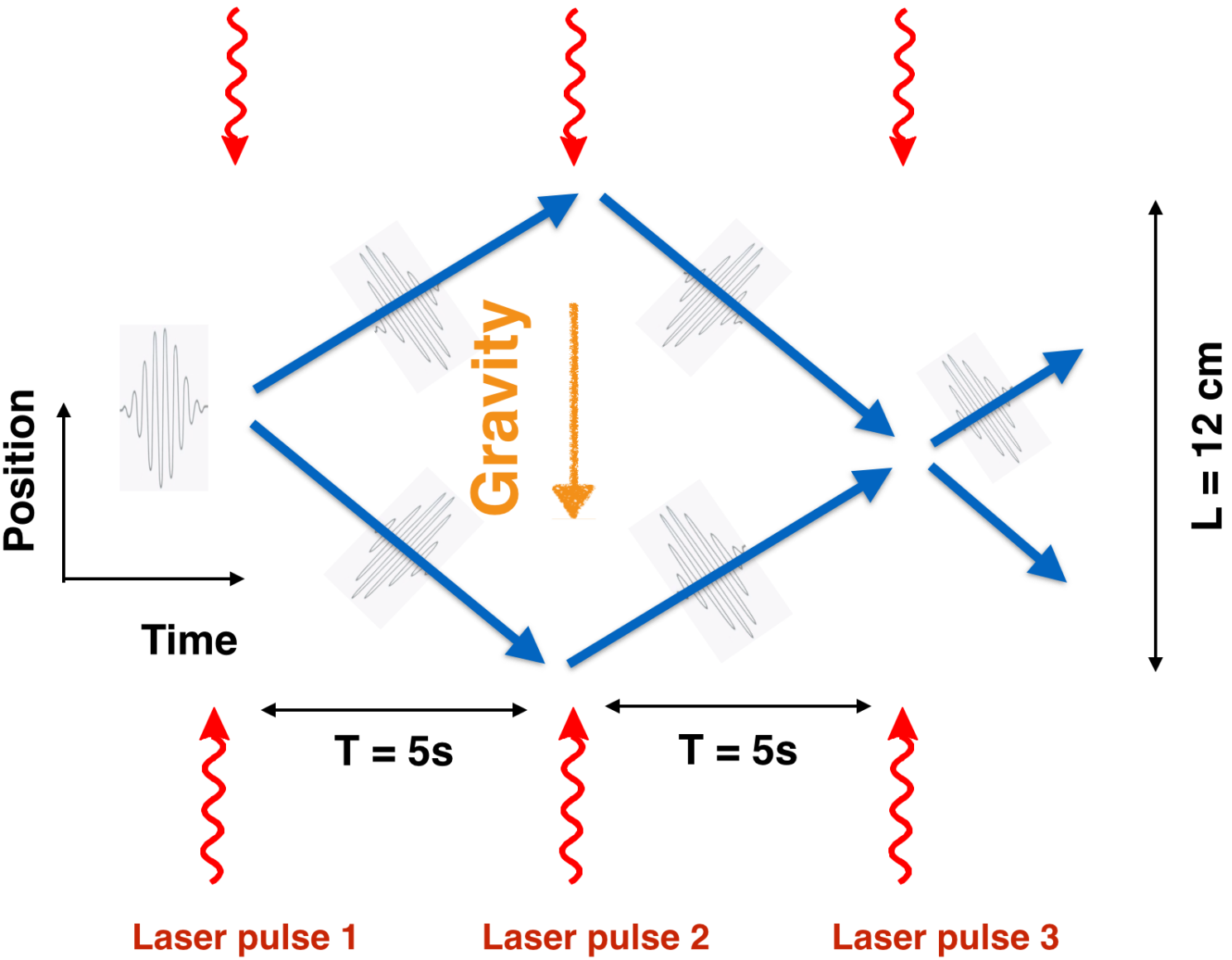
Quantum tests explore a qualitatively new parameter range

- 
- Evolution of delocalised wave packets
 - Macroscopic coherence length
 - Pure isotopes
 - Pure spin states
 - Complementary to classical tests
 - Atom sensors allow redshift & free fall tests

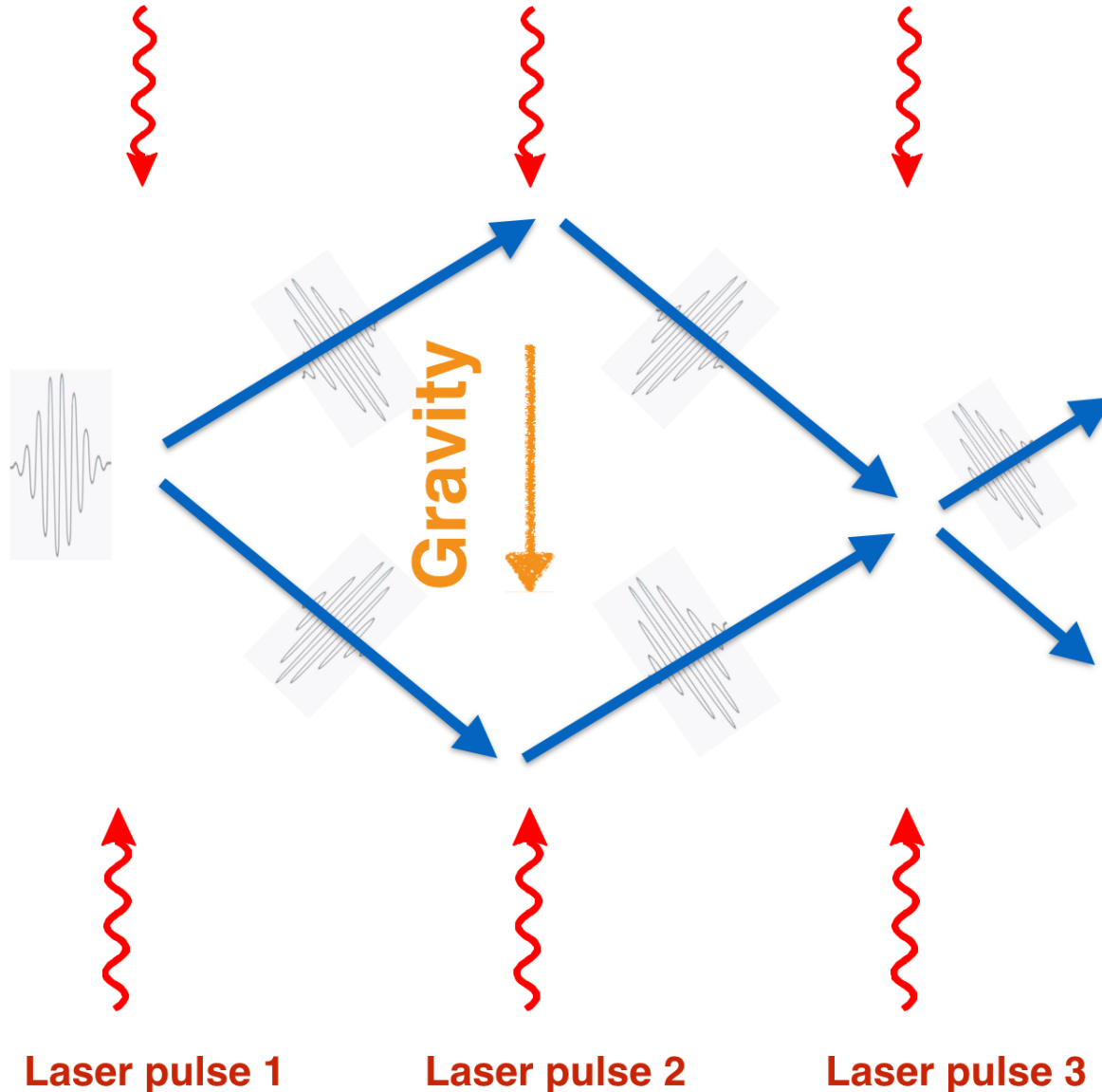
Probing matter waves with interferometry



Probing matter waves on macroscopic scales



Gravity-induced phase shift

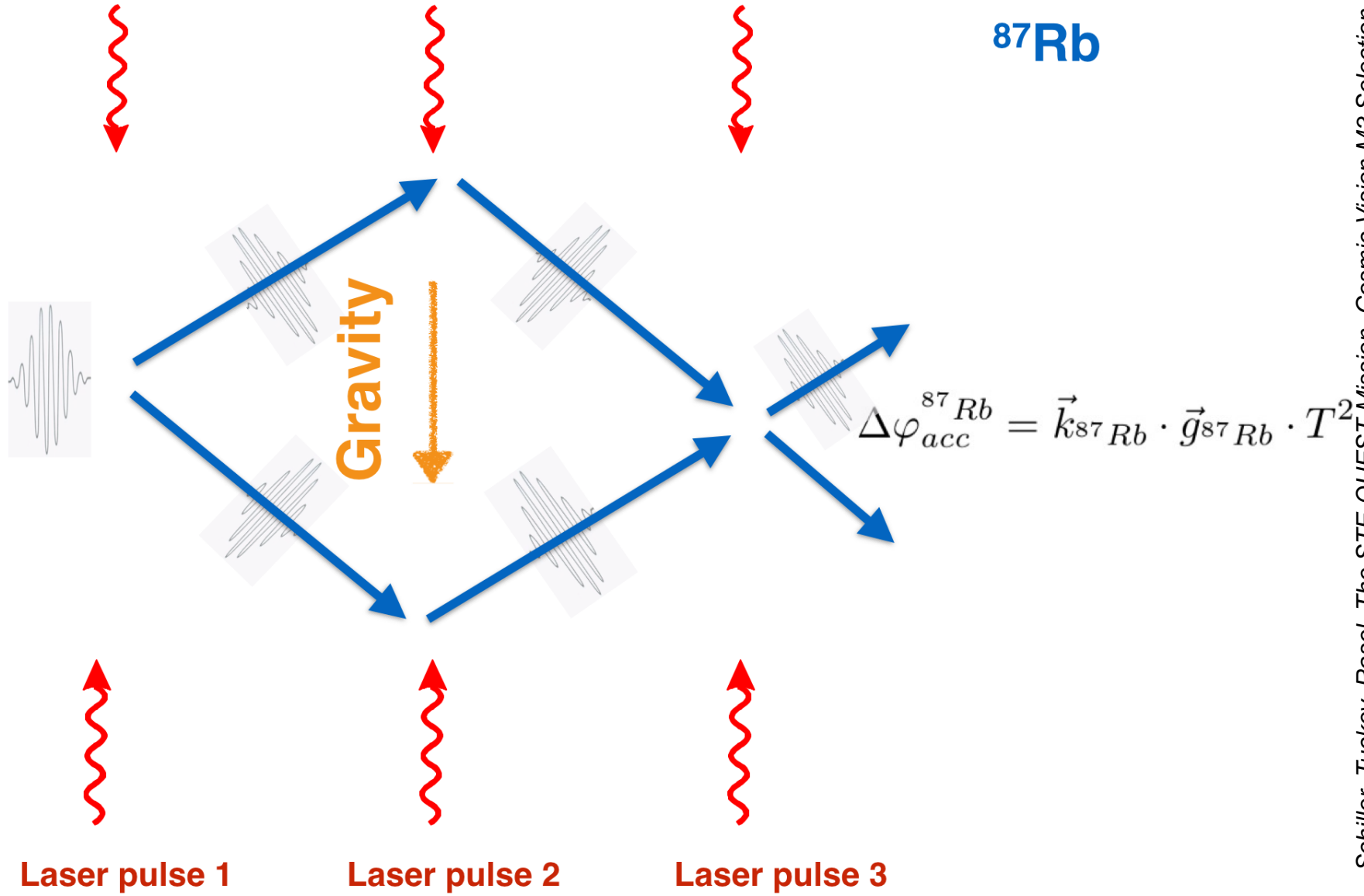


If QWEP holds
then mass drops out!

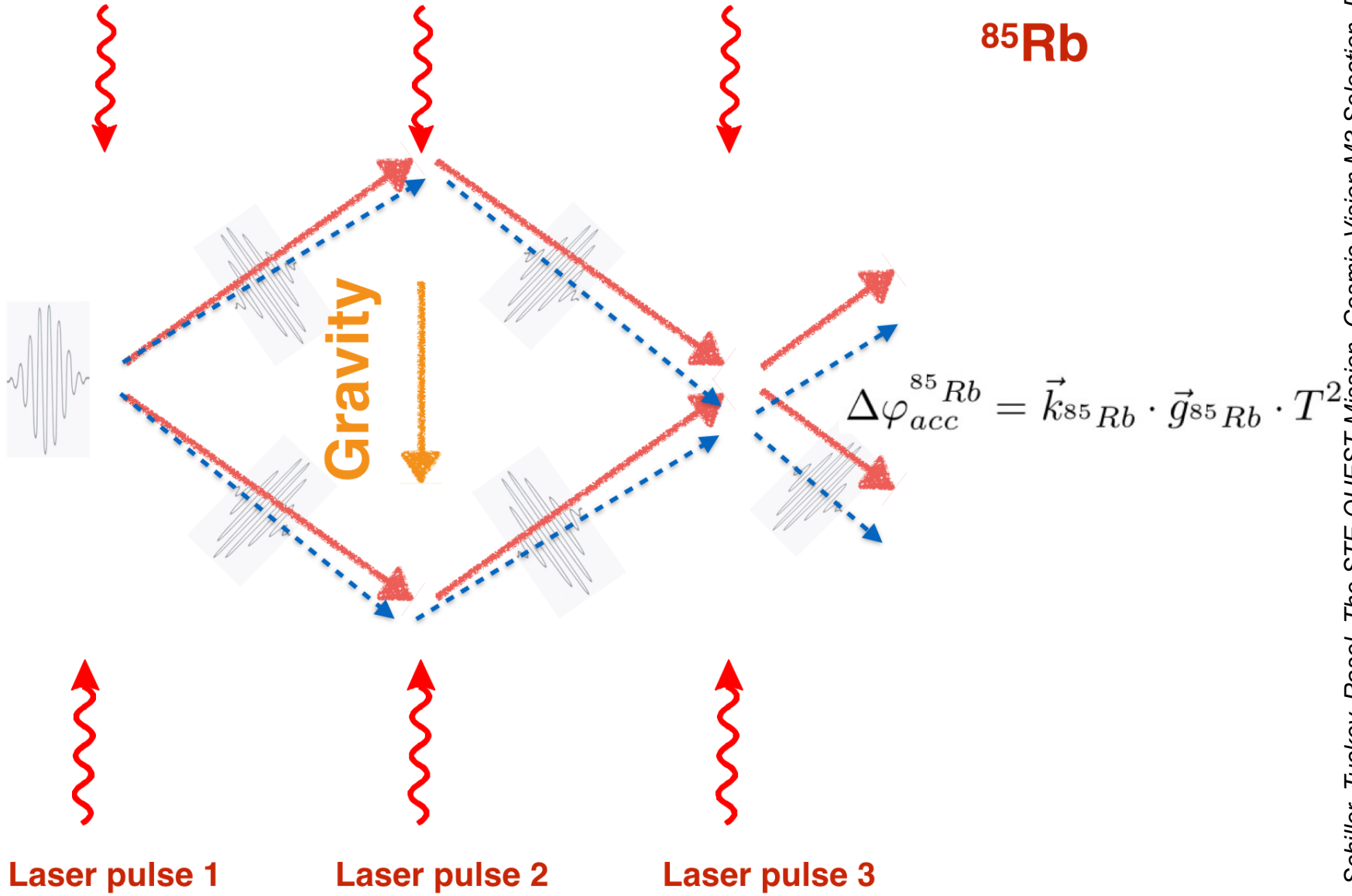
$$\Delta\varphi_{acc} = \vec{k} \cdot \vec{a} \cdot T^2$$

Sensitivity boost
through extended free fall

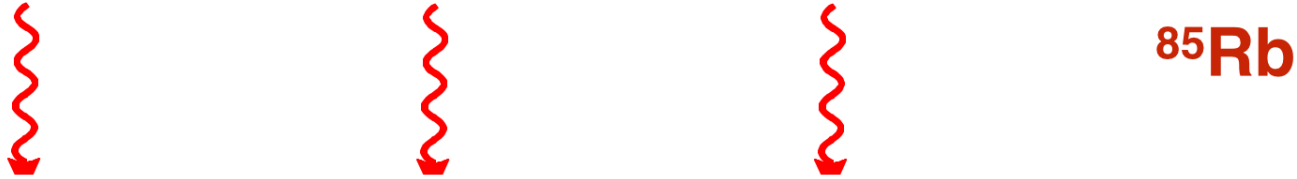
Comparing matter waves of ^{87}Rb and ^{85}Rb



Comparing matter waves of ^{87}Rb and ^{85}Rb



Comparing matter waves of ^{87}Rb and ^{85}Rb



Matching the transferred photon momentum

$$\vec{k}_{87\text{Rb}} = \vec{k}_{85\text{Rb}}$$



Identical scale factor

$$\vec{k} \cdot T^2$$



Laser pulse 1

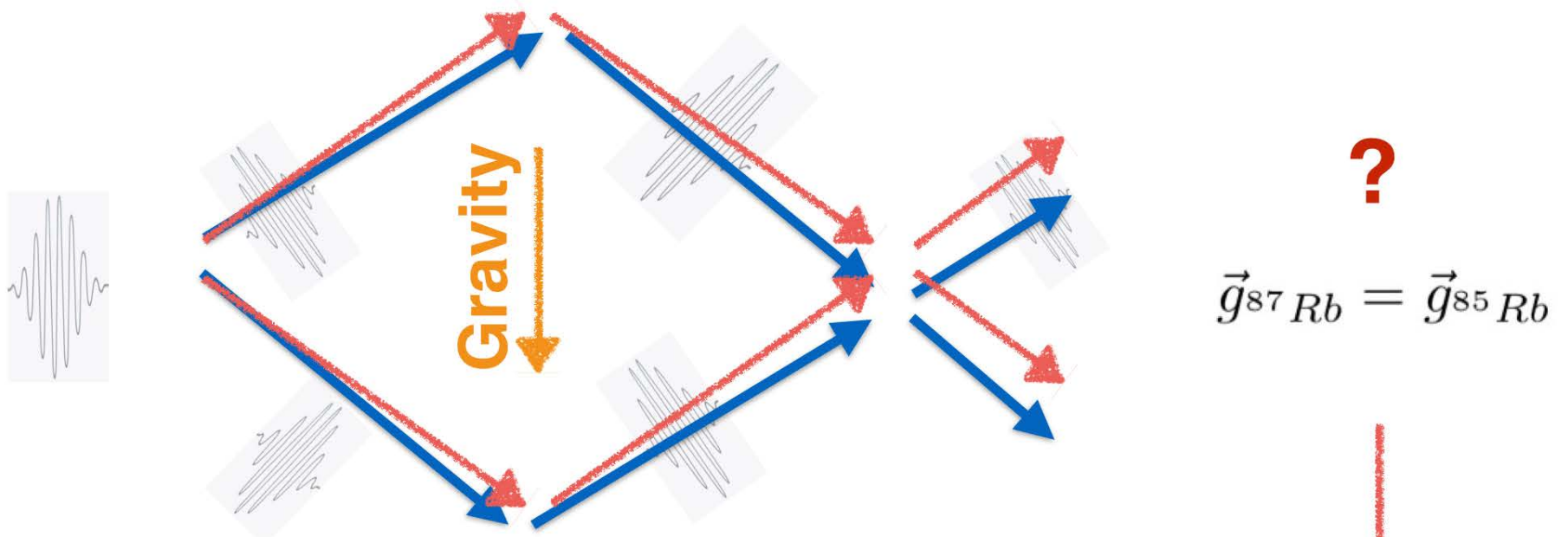


Laser pulse 2



Laser pulse 3

Determination of the Eötvös ratio

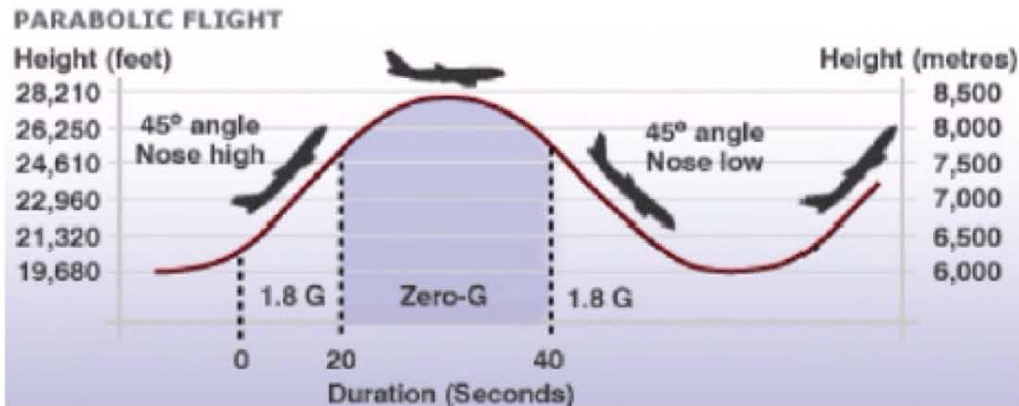


Eötvös ratio

$$\eta(87, 85) = \frac{|\vec{g}_{87 Rb}(\vec{r}) - \vec{g}_{85 Rb}(\vec{r})|}{|\vec{g}(\vec{r})|} = \frac{|\Delta\vec{g}_{87 Rb/85 Rb}(\vec{r})|}{|\vec{g}(\vec{r})|}$$

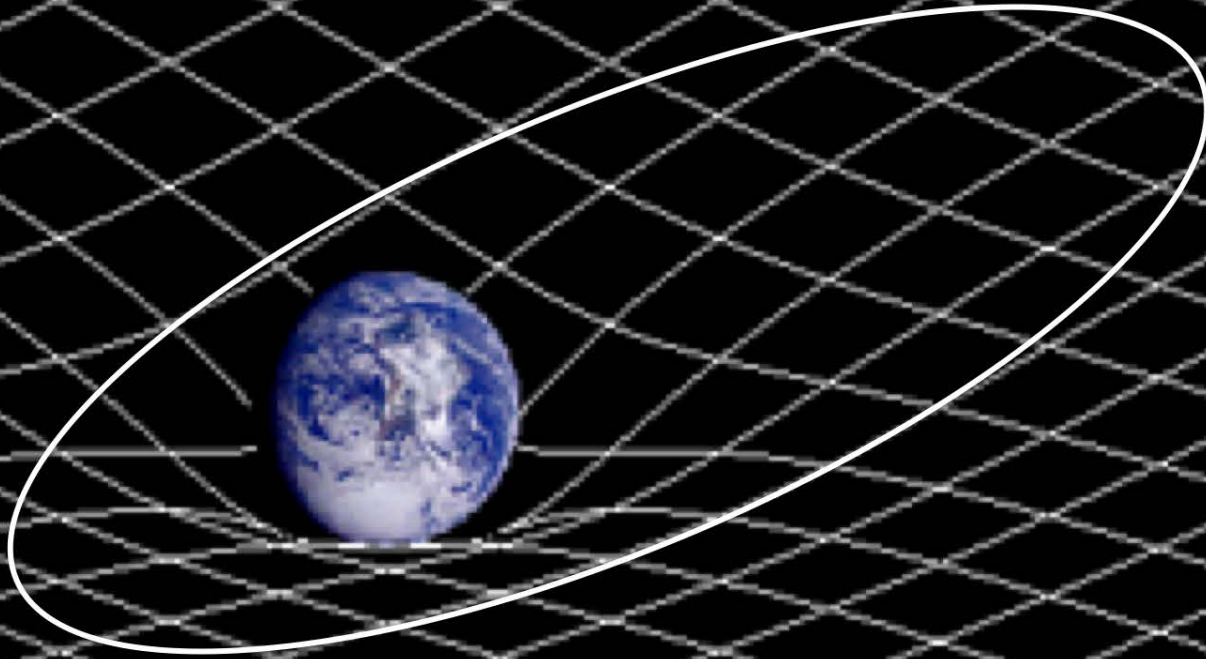
Demonstration of atom interferometers in microgravity

First tests in March 2007 : 500 parabolas since then.



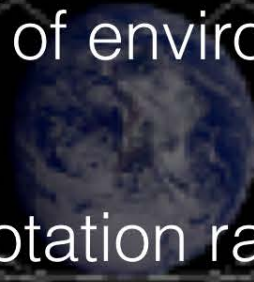
R. Geiger et al., Nat. Comm. 2011

Unique advantages of space

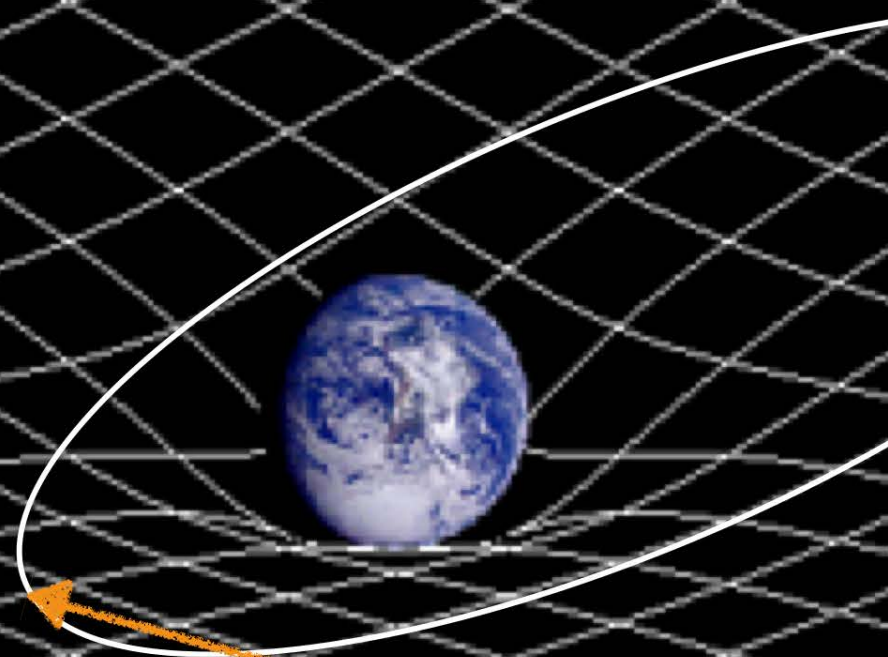


Unique advantages of space

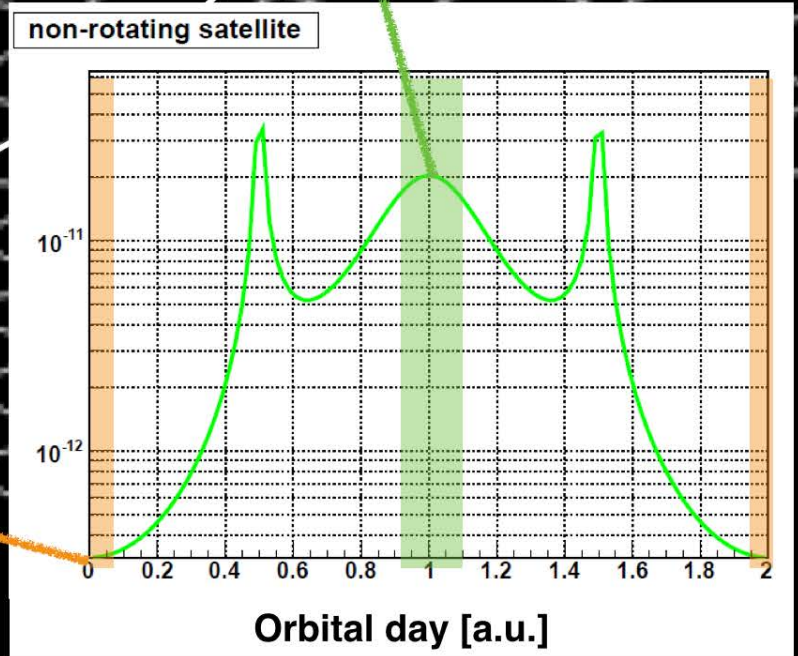
- Infinitely long and unperturbed “free fall” conditions
Long measurement times
- Absence of environmental noise (seismic, Newtonian ...)
- Low rotation rates compared to Earth (100 times)
- Large variations of the gravitational potential.



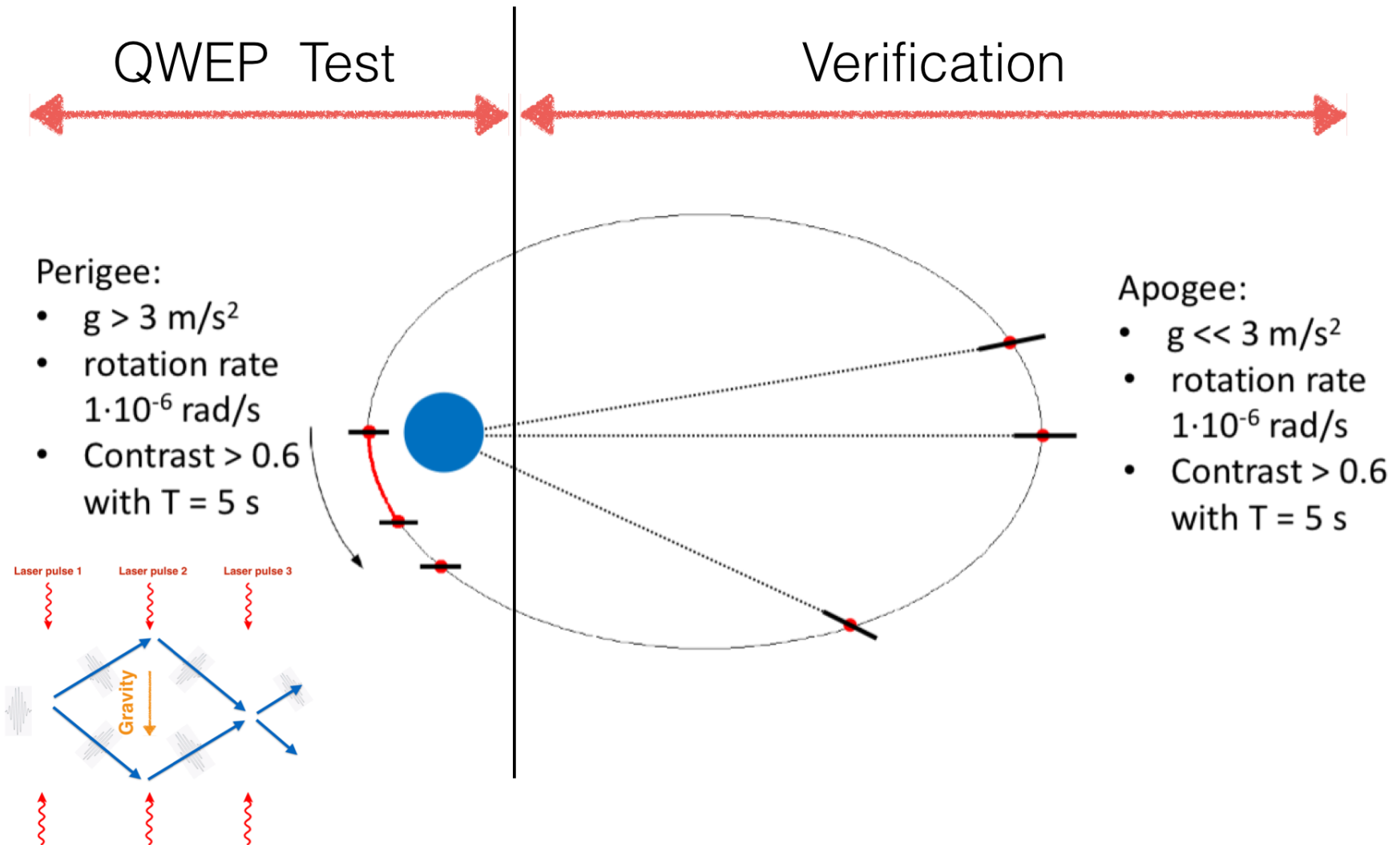
Unique signal due to gravity



$$\frac{|\Delta \vec{g}_{87\text{Rb}/85\text{Rb}}(\vec{r})|}{|\vec{g}(\vec{r})|}$$

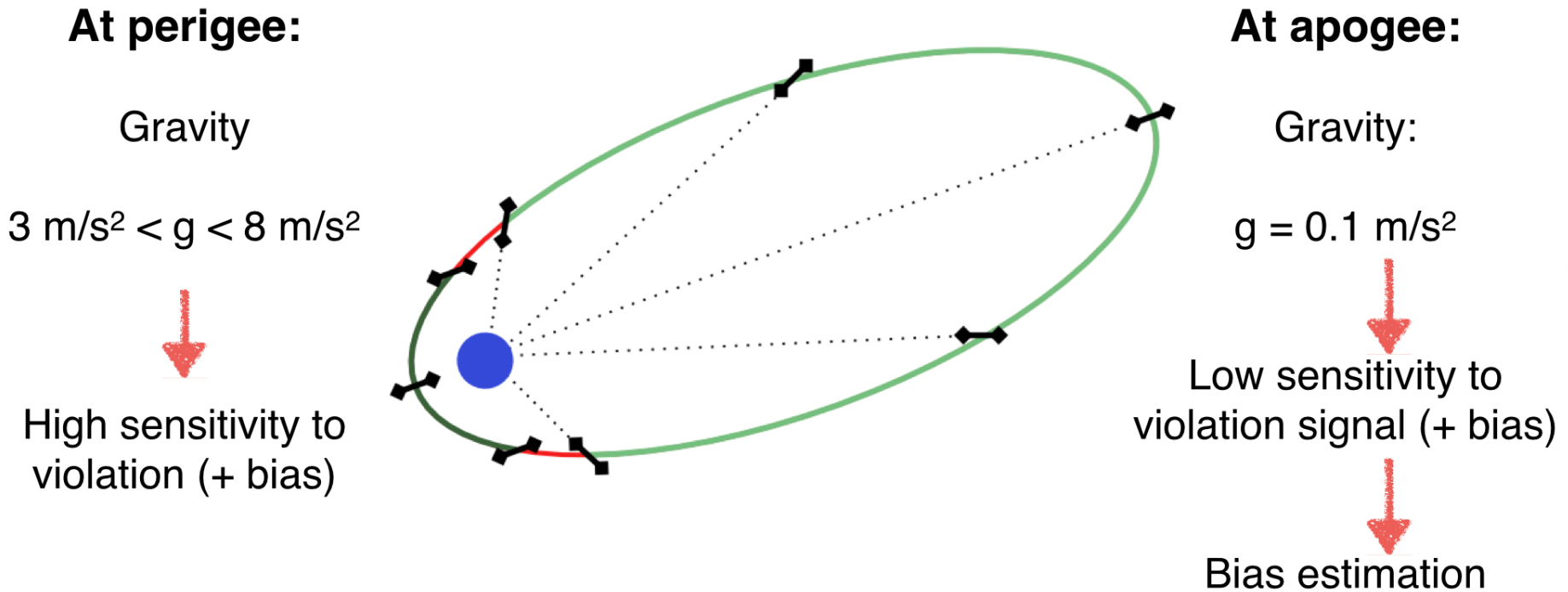


STE-QUEST Measurement strategy



Estimating the bias due to self-gravity and other effects (independent of the Earth's gravity)

Bias determined at apogee (null measurement)
Subtracted from perigee measurement

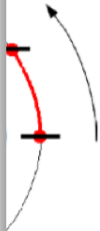


Assumption: bias Δa stable during time / orbit

STE-QUEST QWEP Measurement

Perigee:

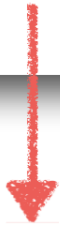
- $g > 3 \text{ m/s}^2$
- rotation rate $1 \cdot 10^{-6} \text{ rad/s}$
- Contrast > 0.6 with $T = 5 \text{ s}$



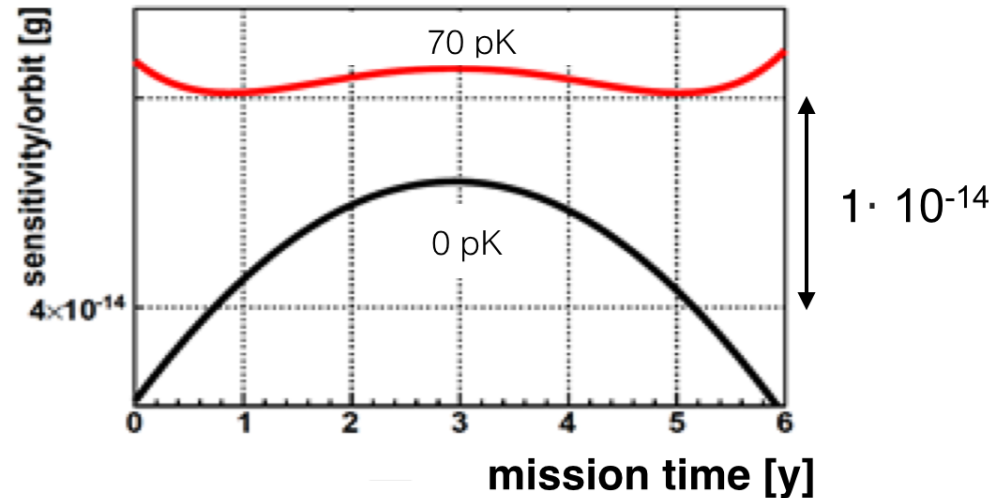
Sensitivity: $\sigma_{\Delta a} = 2.92 \cdot 10^{-12} \text{ m/s}^2$
 (single shot, differential, 60 % contrast at 700 km altitude)

integration to reach $\eta = 2 \cdot 10^{-15}$

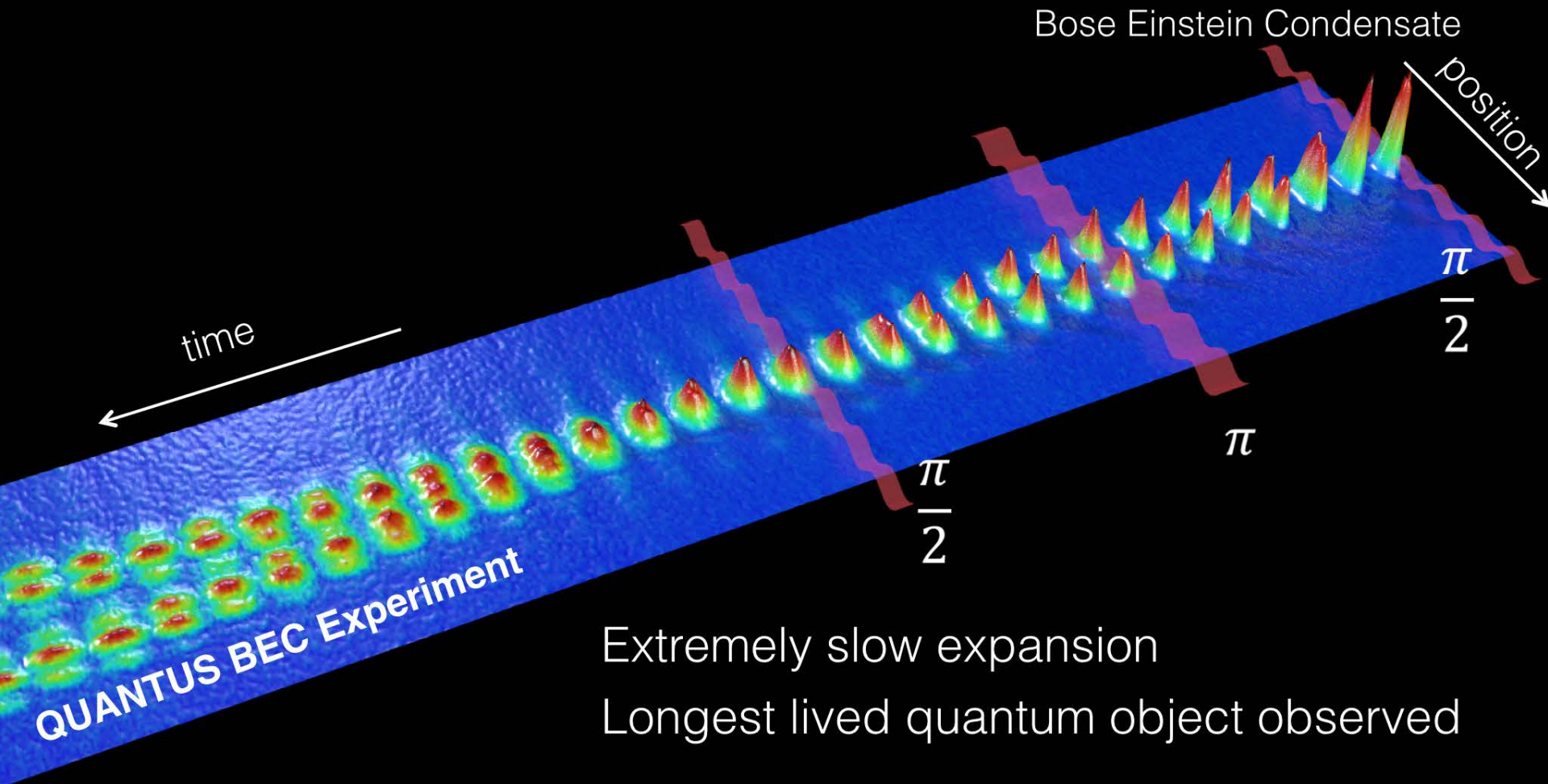
$$\sigma(\eta) = 5 \cdot 10^{-14} \text{ per orbit} \rightarrow 625 \text{ orbits} \rightarrow 1.2 \text{ y}$$



**Need for
 Ultracold Atoms
 Bose-Einstein Condensate**



Bose-Einstein condensates - ideal macroscopic wave packets



Extremely slow expansion

Longest lived quantum object observed

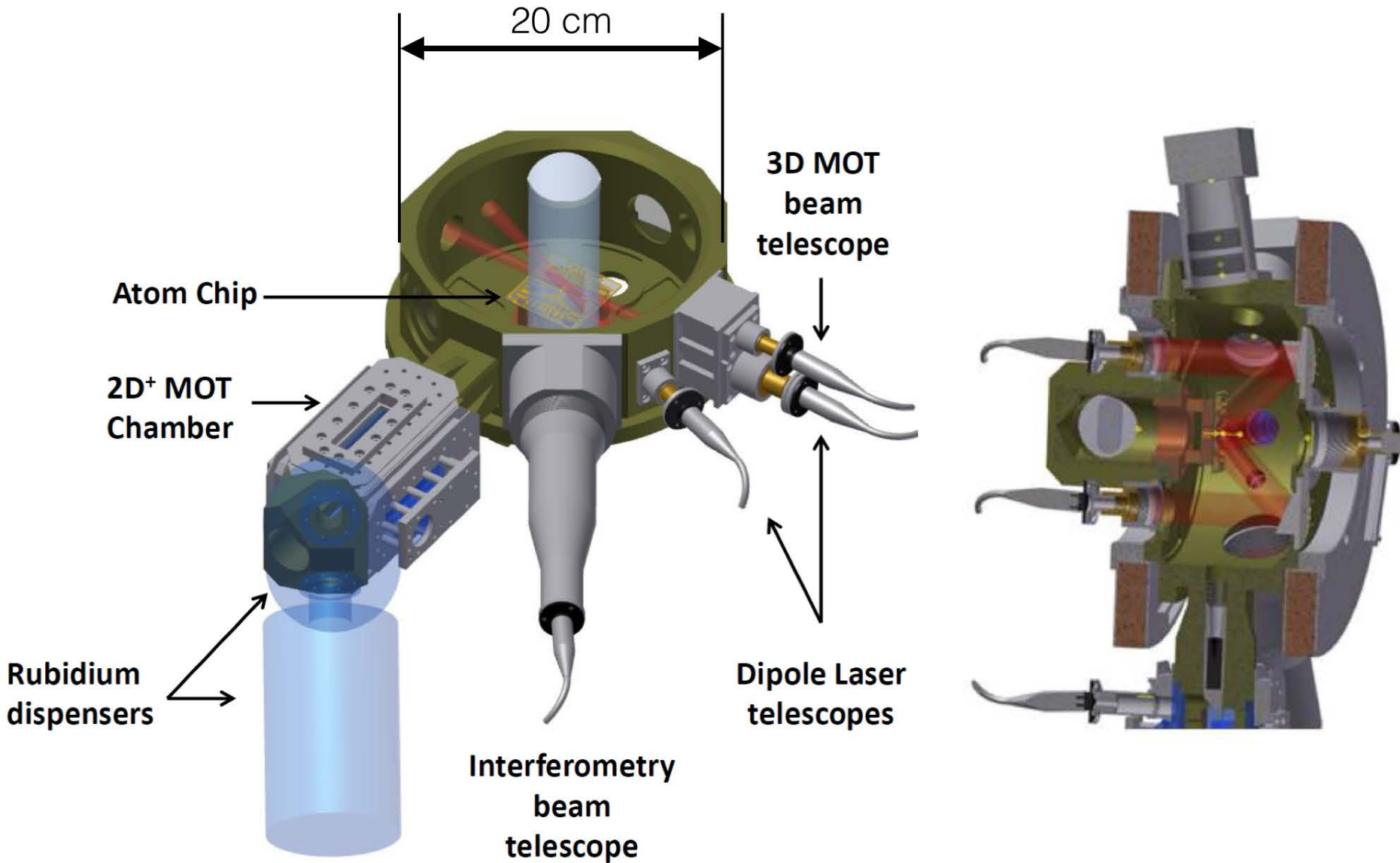
Muentinga et al., PRL 2013

Schiller, Tuckey, Rasel, The STE-QUEST Mission, Cosmic Vision M3 Selection, Paris, 21. 1. 2014

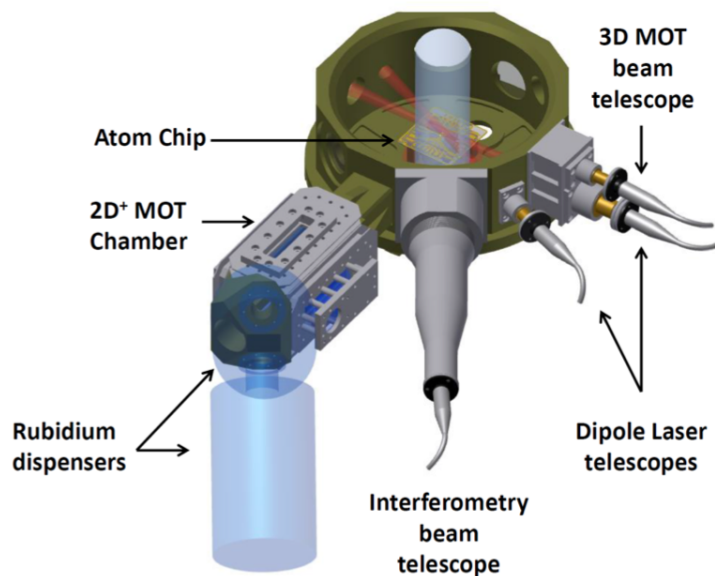


Dual species BEC source

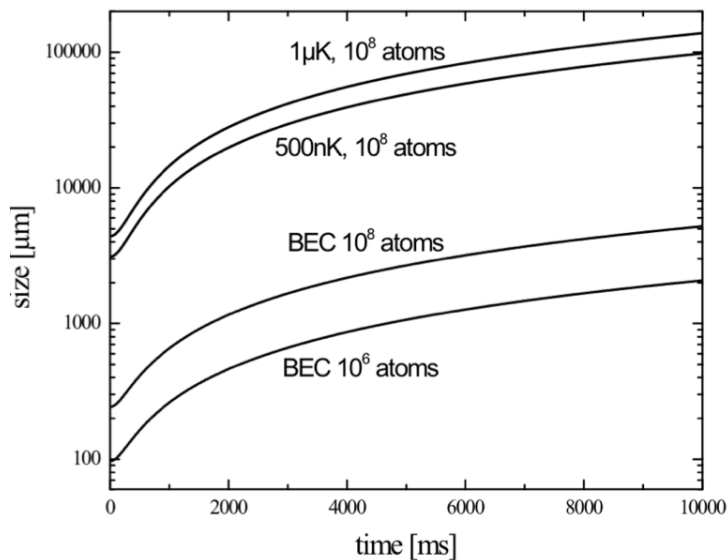
^{87}Rb and ^{85}Rb BEC source



Performance of ^{87}Rb and ^{85}Rb BEC source

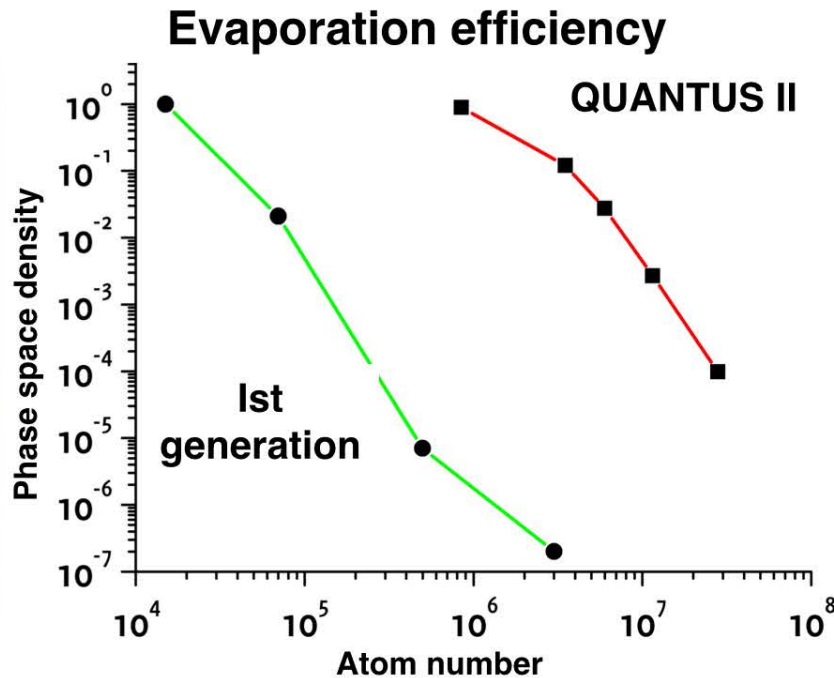


- 10^6 atoms of ^{87}Rb & ^{85}Rb
- Hybrid trap:
magnetic and dipole trap
- Macroscopic wave packets
- Equiv. temperature 0.07 nK
(Delta kick cooling)
- 10 s generation time
- 20 s total experimental cycle
(Generation & interferometry)
- High contrast



Atom chips tested in the ZARM drop tower (over 400 drops)

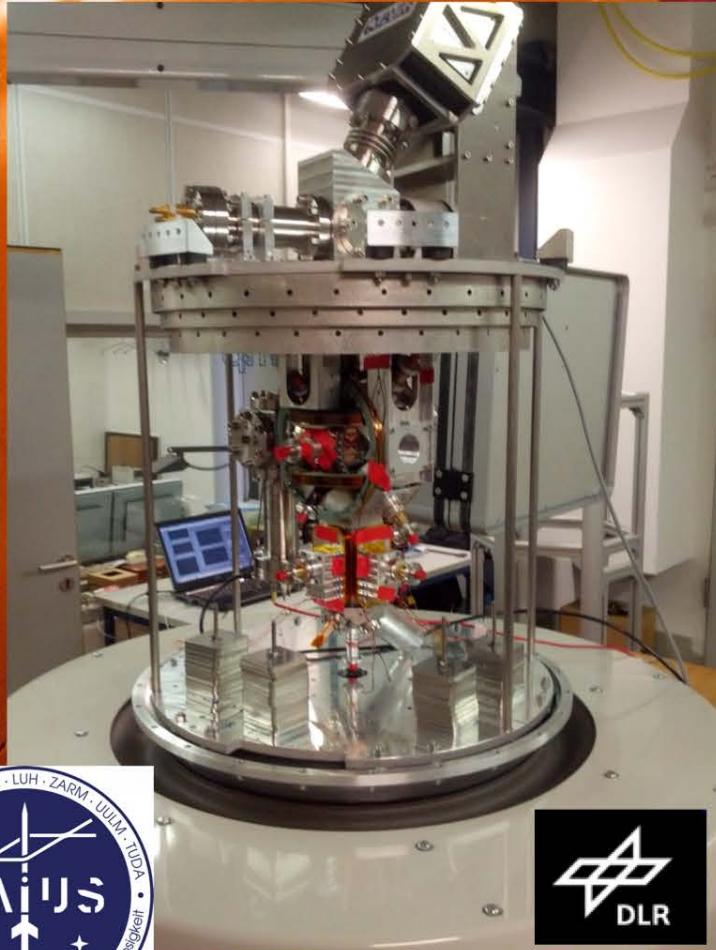
- Largest BEC: 4×10^5 atoms in 1.6s
- Typical BEC: 1×10^5 atoms in 1.1s
- Fastest BEC: 4×10^4 atoms in 0.85s



QUANTUS

DLR

Atom chips tested in the ZARM drop tower & on a rocket (2014/15)

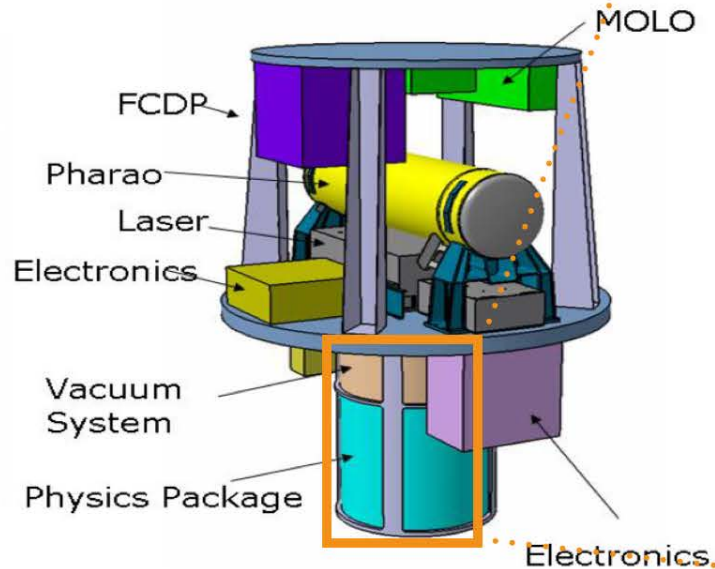


Atom interferometer physics package

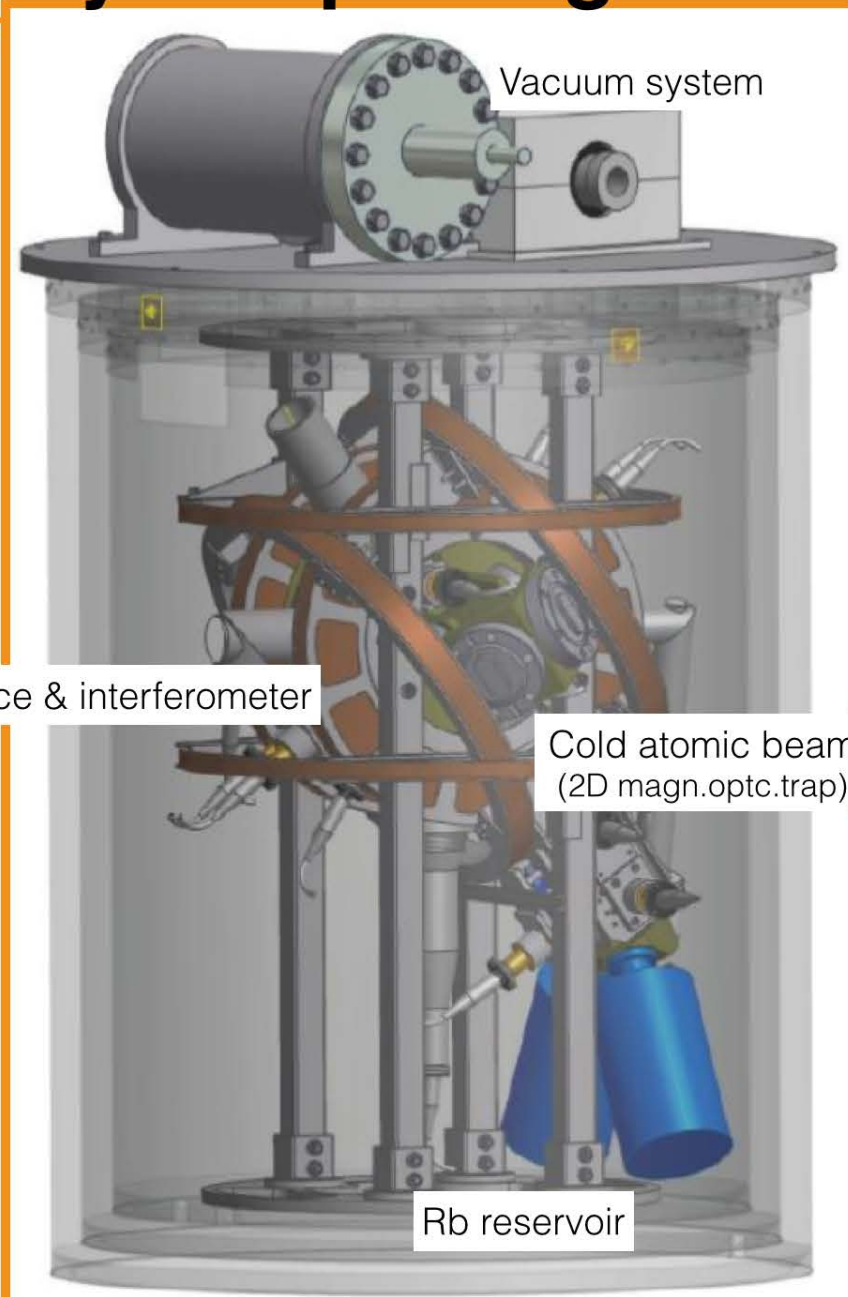
Size:	600 mm x 1000 mm
Volume:	342 l
Weight:	112 kg
Power:	61 W average / 130 W peak

(w.o. margins)

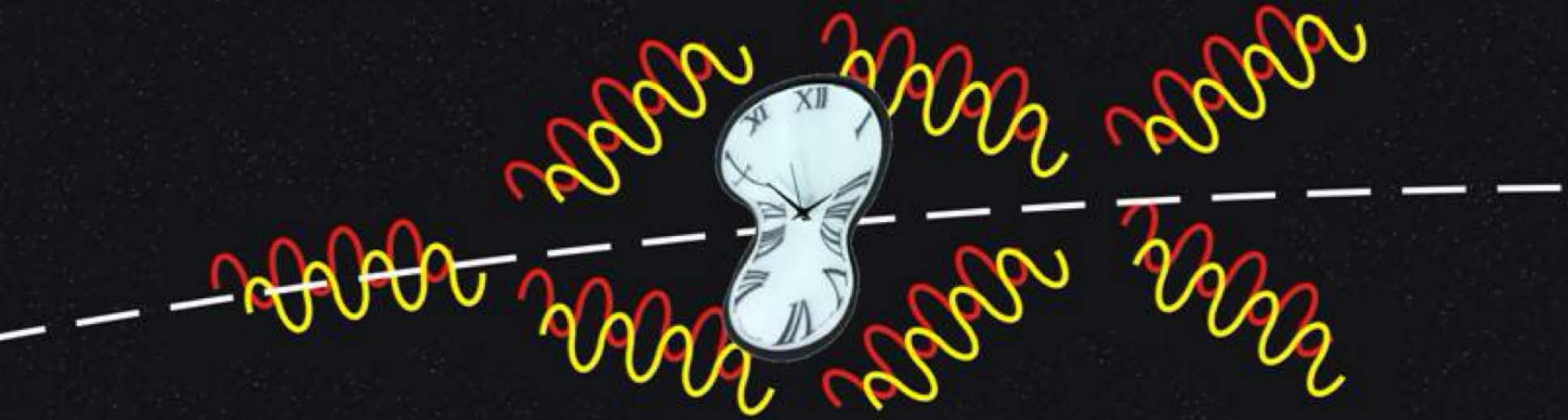
Satellite accommodation



Source & interferometer



Resulting uncertainty in Eötvös ratio η



- Uncertainty in bias acceleration Δa divided by projection of local gravitational acceleration g onto sensitive axis

$$\eta = \Delta a / g < 2 \cdot 10^{-15}$$

- Δa and projection of g change during orbit, compatible with $\eta < 2 \cdot 10^{-15}$

Error budget leading to $\Delta a/g = 2 \cdot 10^{-15}$

Error source	Error term $\Delta a = \Phi_{\Delta a}/(kT^2)$	Conditions	Bias in 10^{-15} m/s^2
Gravity gradient	$-T_{zz} \Delta z$	$\Delta z = 1.1 \cdot 10^{-9} \text{ m}$	2.6
	$-TT_{zz} \Delta v_z$	$\Delta v_z = 3.1 \cdot 10^{-10} \text{ m/s}$	3.5
Coriolis acceleration	$-2\Omega_y \Delta v_x$	$\Delta v_x = 3.1 \cdot 10^{-10} \text{ m/s}$	$-6.3 \cdot 10^{-1}$
	$-2\Omega_x \Delta v_y$	$\Delta v_y = 3.1 \cdot 10^{-10} \text{ m/s}$	$-6.3 \cdot 10^{-1}$
Other terms (rotations / gradients)	$-(\Omega_{\text{orb}}^2 - \Omega_c^2) \Delta z$	$\Delta x = 1.1 \cdot 10^{-9} \text{ m}$	$-3.2 \cdot 10^{-3}$
	$-T(6\Omega_c \Omega_{\text{orb}} - 3\Omega_{\text{orb}}^2 - 3\Omega_c^2) \Delta v_z$	$\Delta y = 1.1 \cdot 10^{-9} \text{ m}$	$< 10^{-3}$
	$T(2\Omega_{\text{orb}}^3 + \Omega_c^3) \Delta x$	$T_{zz} = -2GM_e/R^3 = -2.26 \cdot 10^{-6} \text{ s}^{-2}$	$4.9 \cdot 10^{-2}$
	$TT_{xx} \Omega_{\text{orb}} \Delta x$	$\Omega_c \approx \Omega_{\text{orb}} = 1.4 \text{ mrad/s}$,	$9.1 \cdot 10^{-3}$
	$-7/6 \cdot T^2 T_{zz} \Omega_{\text{orb}} \Delta v_x$	$\Omega_c - \Omega_{\text{orb}} \approx \Omega_x = \Omega_y = 1 \mu\text{rad/s}$	$2.9 \cdot 10^{-2}$
	$-7/6 \cdot T^2 T_{xx} \Omega_{\text{orb}} \Delta v_x$	$T_{xx} = T_{yy} = -T_{zz}/2$	$-1.5 \cdot 10^{-2}$
	$-\Omega_{\text{orb}} \Omega_z \Delta y$		$-1.6 \cdot 10^{-3}$
Photon recoil	$T^4 T_{zzz} \hbar^2 k^2 / 16 (m_{87}^{-2} - m_{85}^{-2})$	$T_{zzz} = 6GM_e/R^4 = -9.57 \cdot 10^{-13} \text{ m}^{-1} \text{ s}^{-2}$	$3.9 \cdot 10^{-2}$
Self-gravity		Apogee measurement - subtraction	1
Magnetic field gradients	$B_0 \delta B \hbar (K_{87}/m_{87} - K_{85}/m_{85})$	$B_0 = 100 \text{ nT}$, $\delta B < 0.1 \text{ nT/m}$, $K_{87} = 575.15 \text{ Hz/G}^2$, $K_{85} = 1293.98 \text{ Hz/G}^2$	1
Effective wave front (beam splitter lasers)	$(T_{\text{at},87}/m_{87} - T_{\text{at},85}/m_{85}) k_B/R_e$	$\lambda/300 \text{ mirror} \rightarrow R_e > 250 \text{ km}$, $T_{\text{at}} = 0.07 \text{ nK}$,	$6.3 \cdot 10^{-1}$
		collimation $R_i \sim 400 \text{ m} \rightarrow R_e > 250 \text{ km}$, $T_{\text{at}} = 0.07 \text{ nK}$	$2.8 \cdot 10^{-1}$
Mean field	$\int_0^{2T} dt [\mu V(0) / (\hbar V(t) N^{-1/2})]$	BEC radius at first beam splitter $300 \mu\text{m}$, expansion rate $82 \mu\text{m/s}$, tuned atom numbers uncertainty of 1000	$2 \cdot 10^{-5}$
Spurious accelerations	$\text{CMRR} \cdot a_{\text{spur}}$	$\text{CMRR} = 2.5 \cdot 10^{-9}$, $a_{\text{spur}} = 4 \cdot 10^{-7} \text{ m/s}^2$	1
Detection efficiency		$ \eta - 1 < 0.003$	< 1

Correlated Errors
w.r.t. wave packet overlap

Uncorrelated Errors

[Yellow book; Aguilera et al., arXiv:1312.5980 (2013); Schubert et al., arXiv:1312.5963 (2013)]

Effects mimicking a QWEP violation

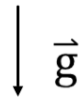
Imperfect overlap & differential velocities of ^{87}Rb and ^{85}Rb BECs in combination with gravity gradient cause differential acceleration

$$\Delta a = -T_{zz} \Delta z$$

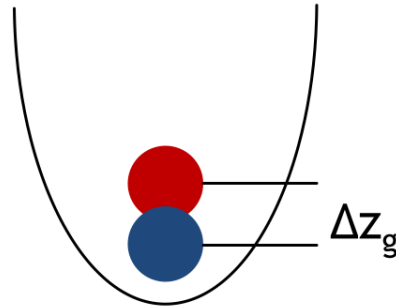
$$\Delta a = -T T_{zz} \Delta v_z$$

Displacement Δz , differential velocity Δv_z , T_{zz} gravity gradient

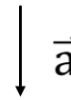
on ground:



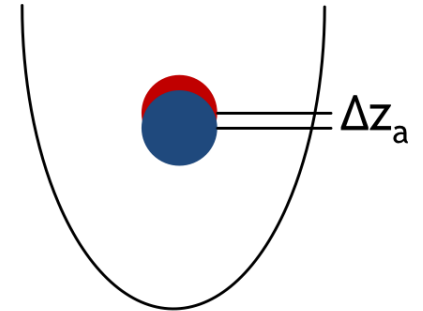
$g = 9.81 \text{ m/s}^2$



STE-QUEST:

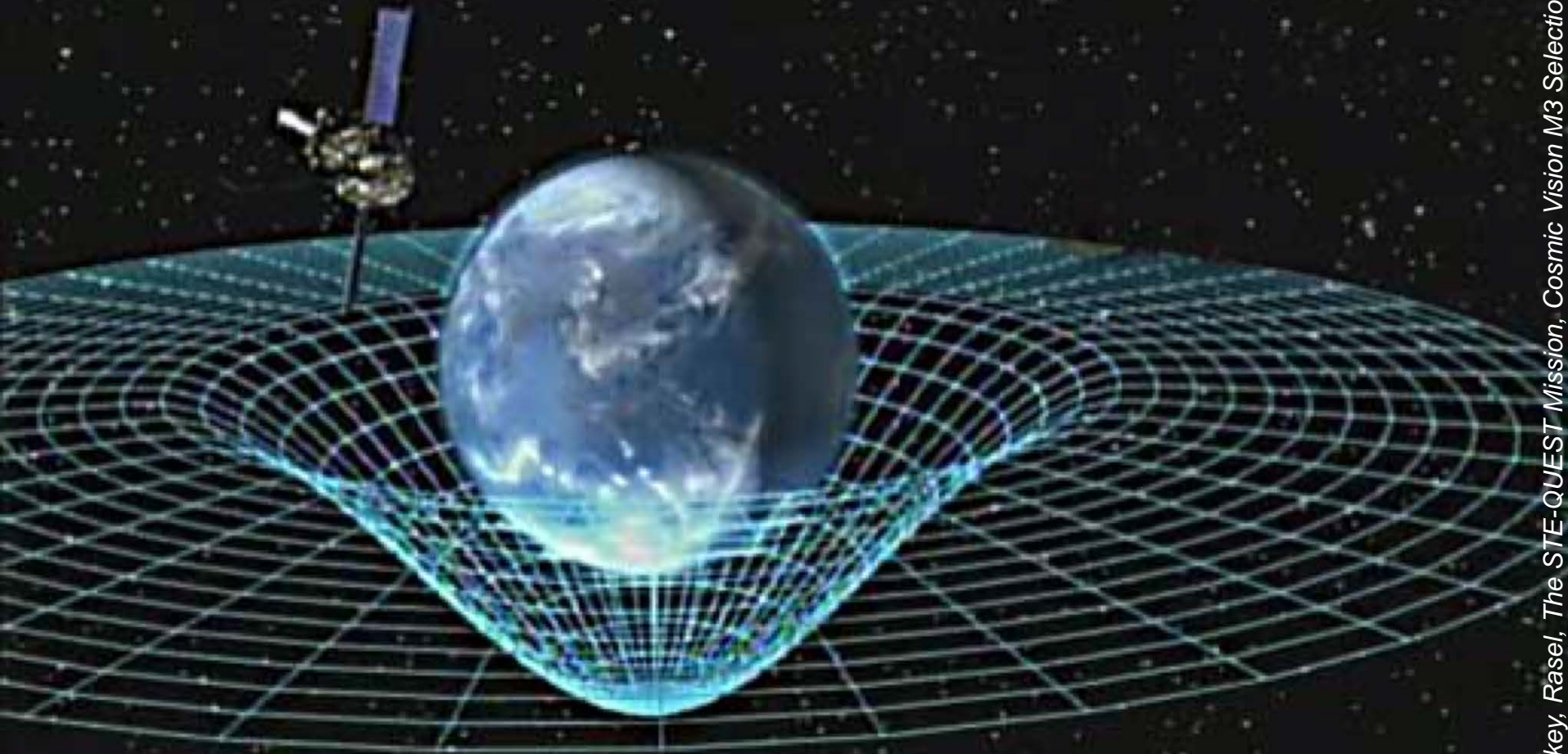


$a = 0.4 \mu\text{m/s}^2$



Effects causing displacements Δz	Gravitational sag in ODT
	Magnetic field gradients
	Rotations / gravity gradients and distance to center of mass of the satellite
Effects causing differential velocities Δv_z	Magnetic field gradients after release
	Strong electric fields

Advantages of Space for QWEP



Advantages of Space for QWEP

- Extended free fall (large scaling factor)
- On ground: scale factor has to be controlled better than 10^7
- Experiment in free fall:
Severe systematics reduced
(Smaller gravitational sag / enhanced quantum miscibility / better collocation of wave packets)
- Low rotation rates (strong suppression of systematics, factor 100)
- Strong modulation of gravity / unique signature of EP signal
- Calibration inaccessible on ground
- Low inertial perturbations
- Weightlessness allows for high sensitivities in a compact set-up

Summary

■ Science objectives:

Test the metric nature of the theory of gravitation,
search for physics beyond the Standard Model & General Relativity

- Test the Weak Equivalence Principle with matter waves,
accuracy : 2×10^{-15} ($\times 10^6$ improvement)
- Test time dilation in the solar and the lunar gravitational potential,
accuracy: 2×10^{-6} , 4×10^{-4} , resp.
($\times 10^4$, $\times 10^3$ improvement, resp.)

■ Application to other fields:

- Contribution to tests of time-variation of fundamental constants
- Contribution to improved reference frame definitions
- Distribution of time world-wide
- Mapping of the gravitational potential of the Earth with high spatial resolution

■ Potential for enhancement of science objectives:

- Phase-coherence of microwave link between orbits
- Optional laser link
- Optional on-board clock

Image credits

Photos and diagrams are contributed by members of the consortia and working groups (see Yellow Book) or from people/companies as indicated on the slides. Additionally:

- MWL ground terminal (ESA Contract No: 4000102471/10/D/SR; TimeTech (D), Astrium (D) et al.)
- Yb clock: Burrus/NIST" (<http://www.nist.gov/pml/div688/clock-082213.cfm>; N. Hinkley, et al. Science Express, Aug. 22, 2013)
- Sr lattice clock: U. Sterr, C. Lisdat, PTB
- Frequency comb flight model: MenloSystems GmbH (D)/DLR project FOKUS

Other figures:

<http://en.wikipedia.org/wiki/Spacetime>

http://www.ws5.com/spacetime/162571main_GPB_circling_earth3_516.jpg

http://www.fromquarkstoquasars.com/wp-content/uploads/2014/01/vortex1_crop.jpg