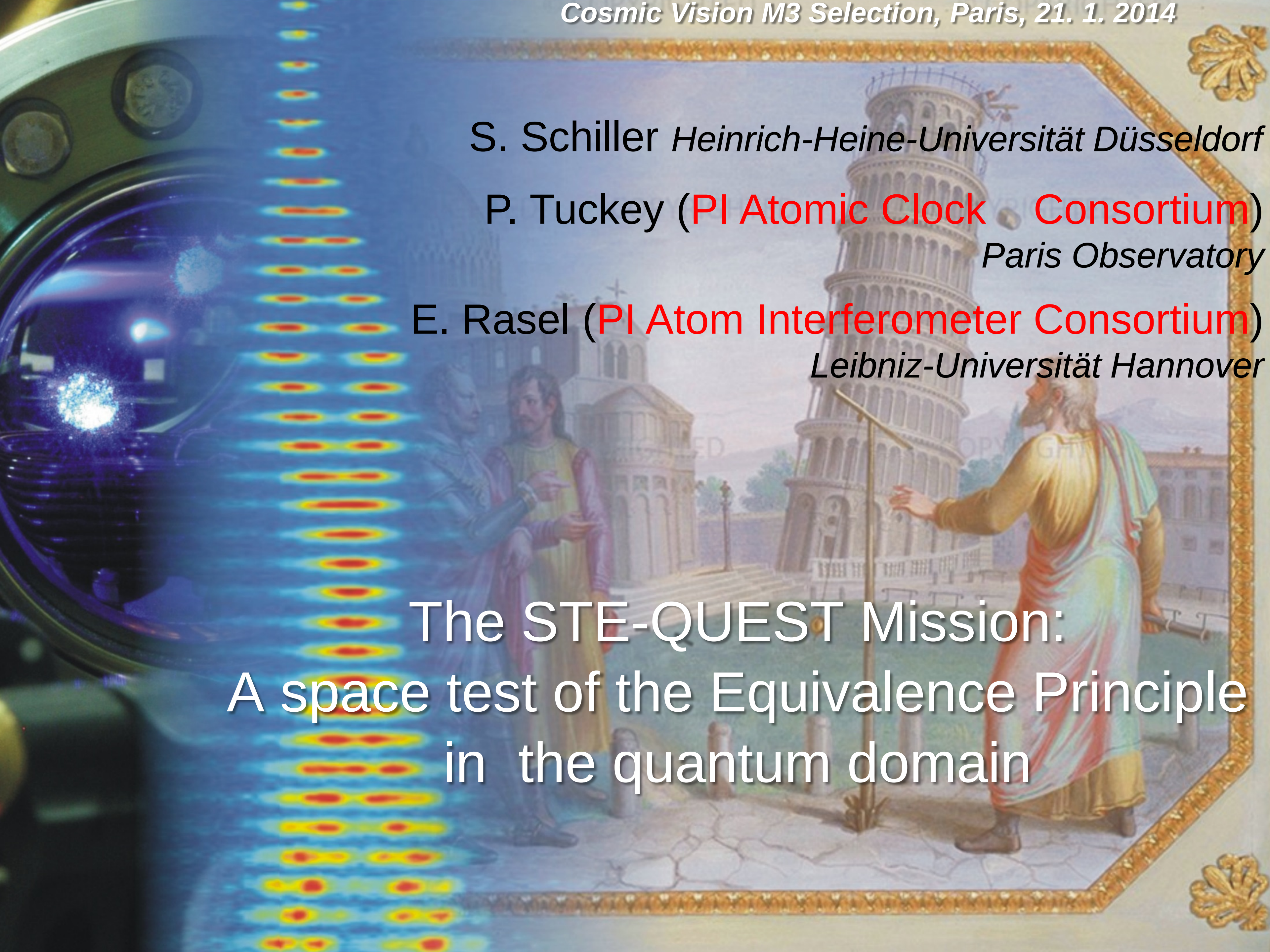

Cosmic Vision M3 Selection, Paris, 21. 1. 2014

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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:

SSO

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

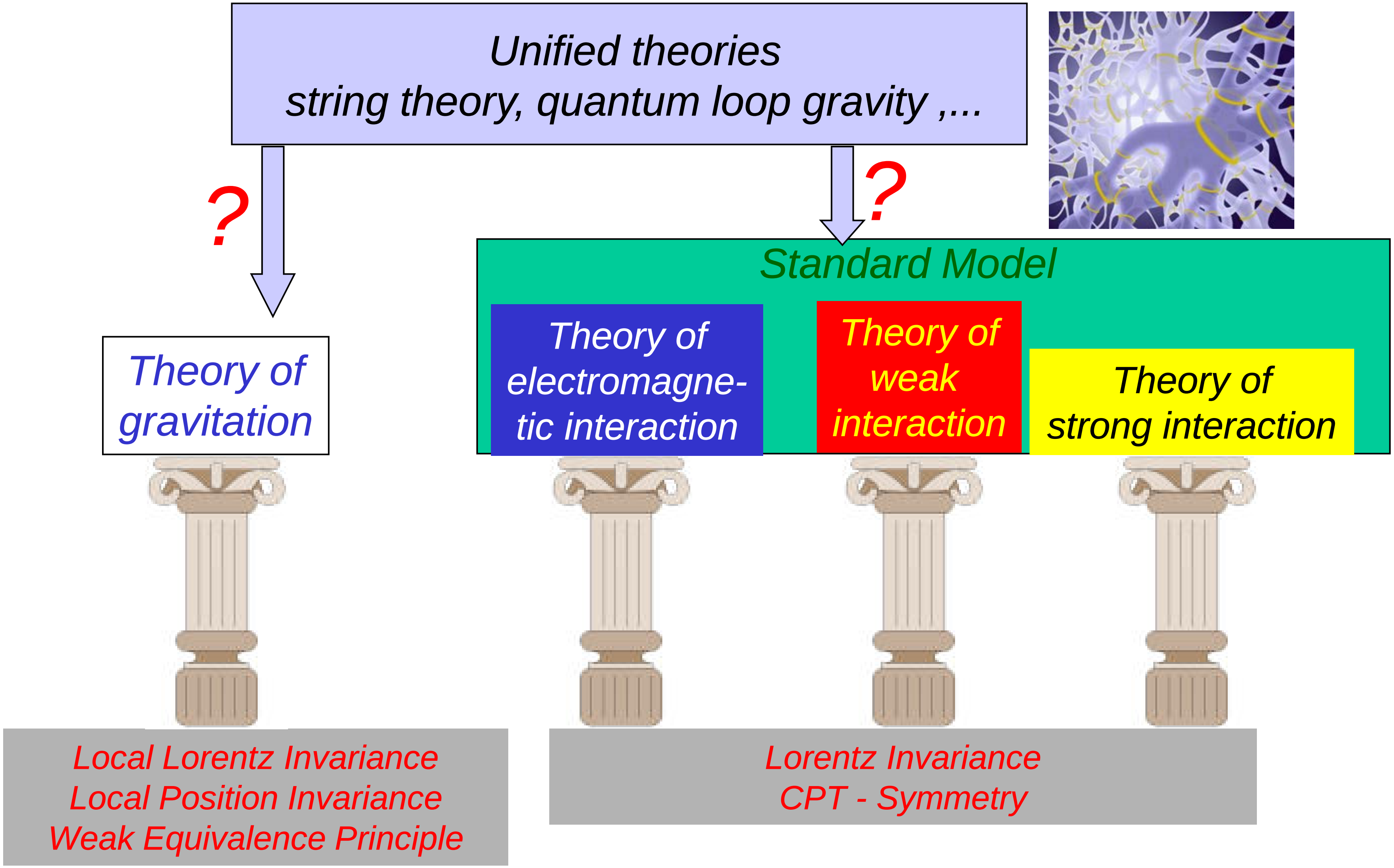
→ **Discovery of EEP violation would be a momentous event**

→ **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 ,...

?

?

Standard Model

Theory of gravitation

Theory of electromagnetic interaction

Theory of weak interaction

Theory of strong interaction

Local Lorentz Invariance
Local Position Invariance
Weak Equivalence Principle

Lorentz Invariance
CPT - Symmetry

exactly valid?

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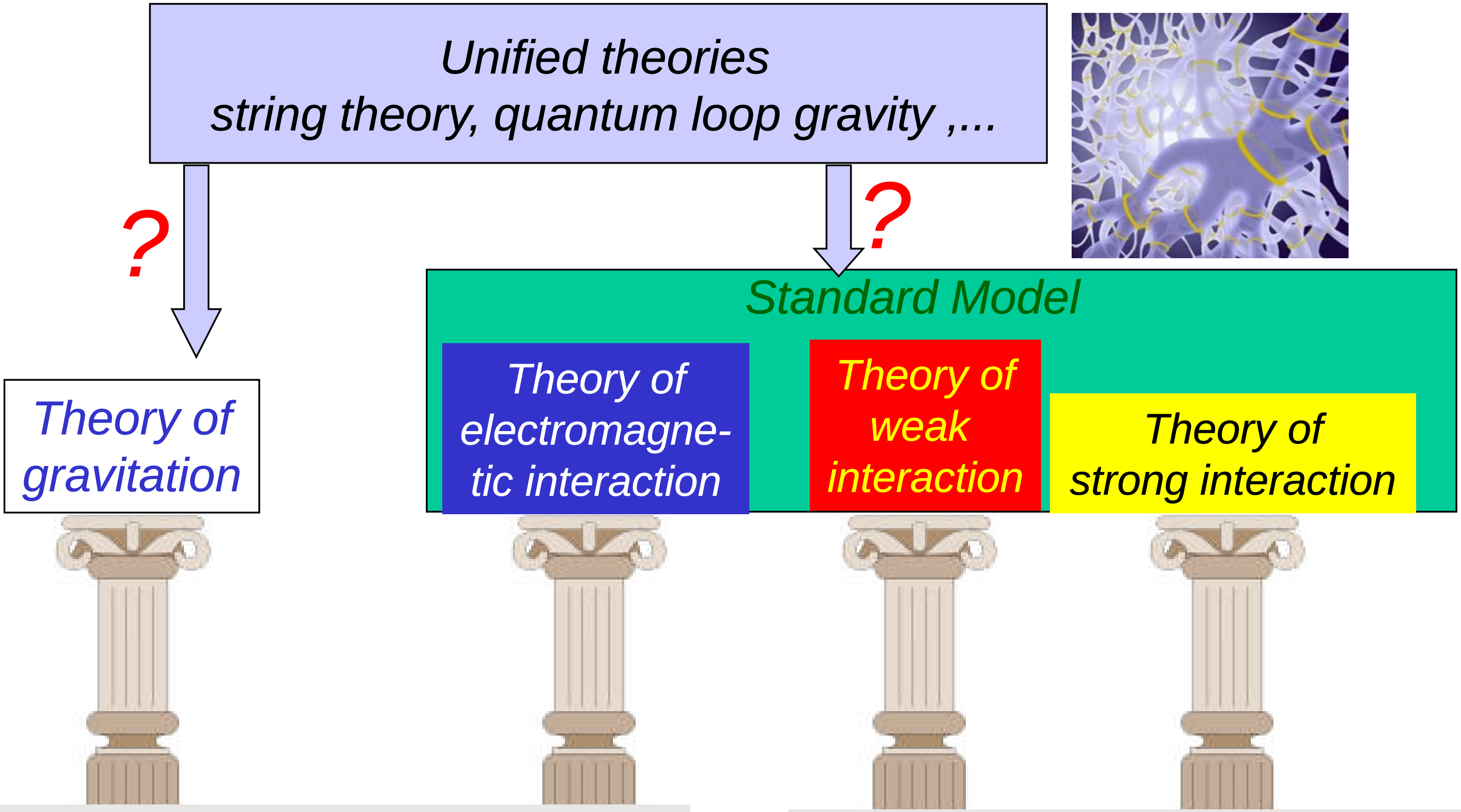
Motivation III



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

?

?

Standard Model

Theory of gravitation

Theory of electromagne-tic interaction

Theory of weak interaction

Theory of strong interaction

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

Lo
C

ctly

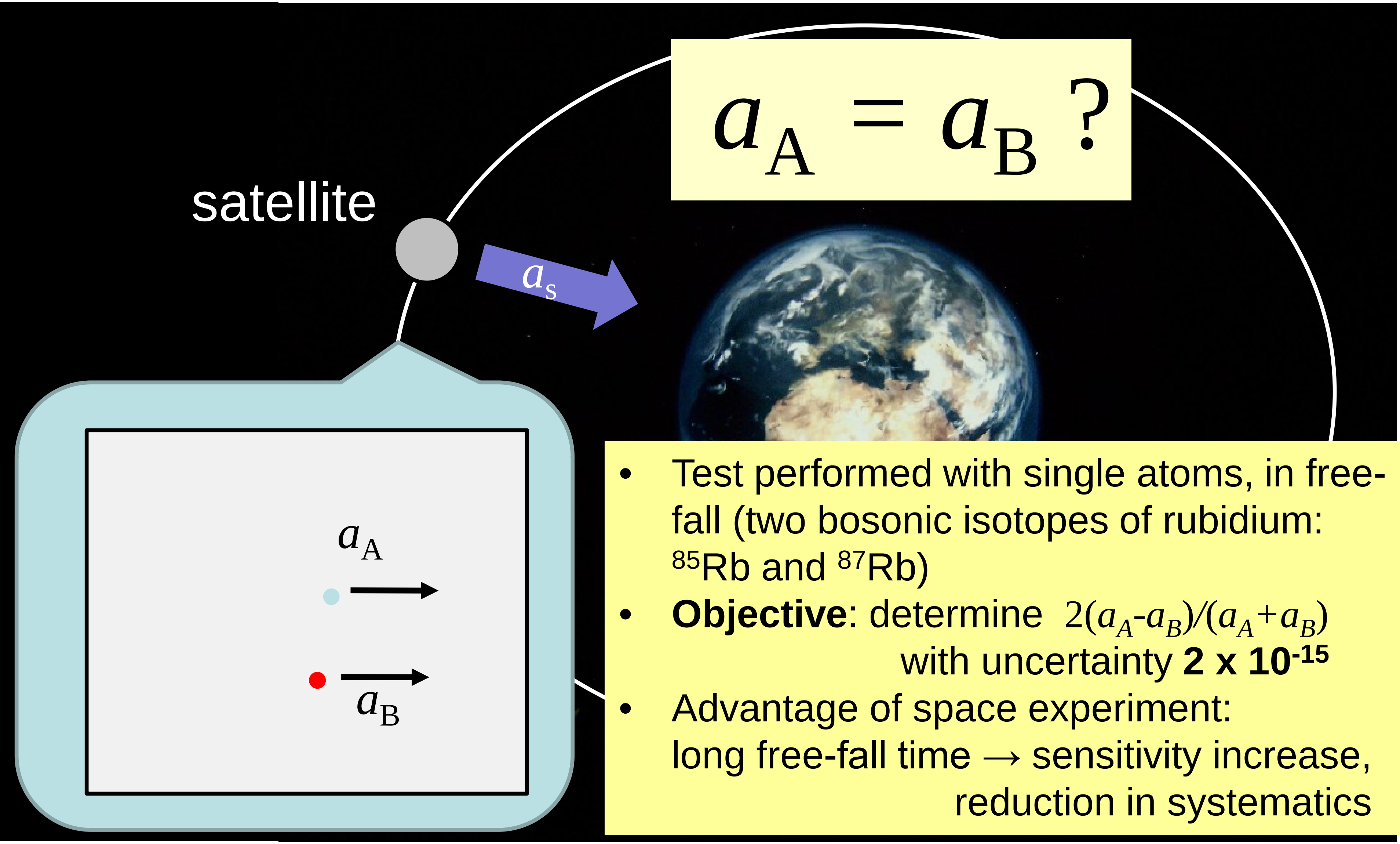
- LI tests (terrestrial experiments, astrophysical observations)
- CPT tests
- EDM searches

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?

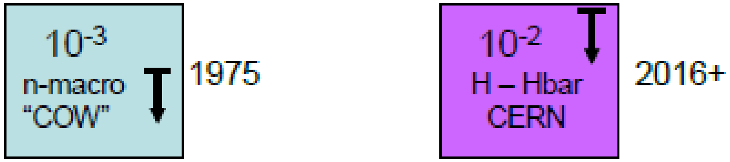


$$a_A = a_B \ ?$$

- 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 → sensitivity increase, reduction in systematics

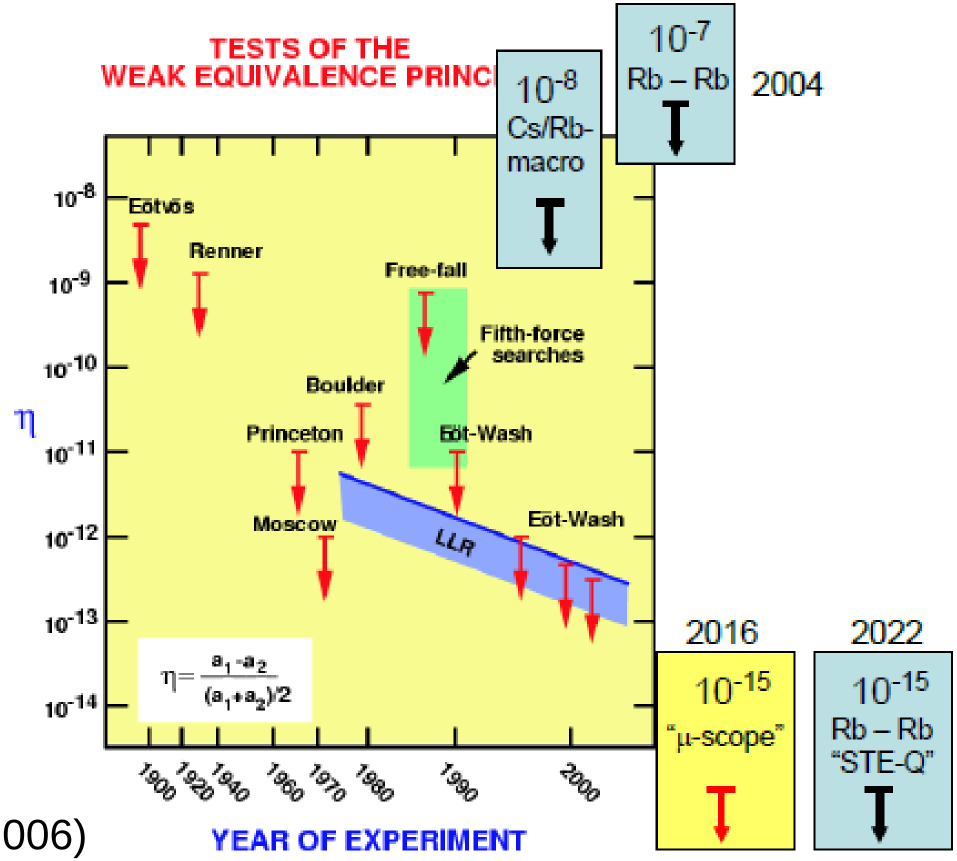
Complementarity to other experiments

- 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)

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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

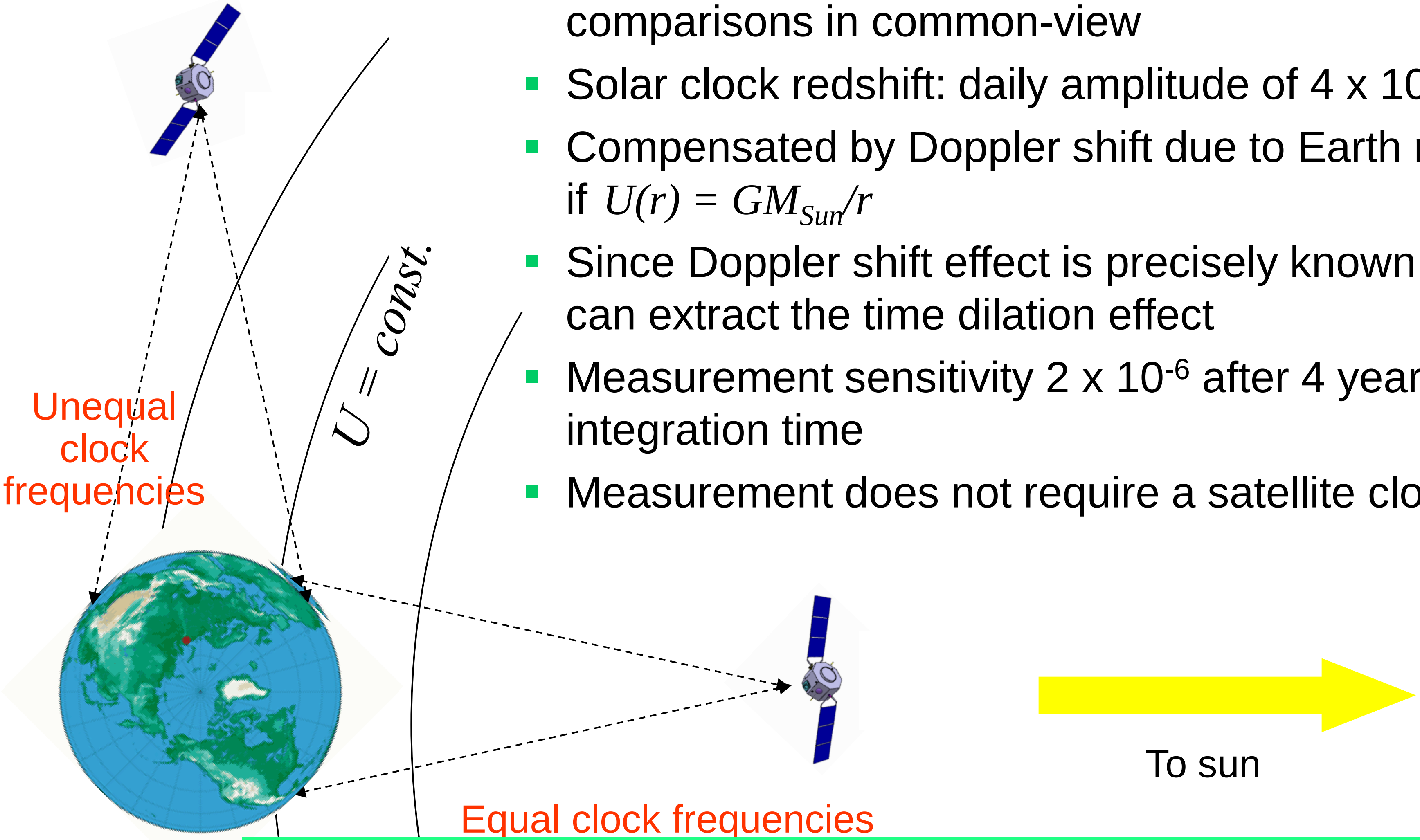
- the composition of the massive body?
- the type of clock?

STE-QUEST objective:

Test at the 2 x 10^{-6} level in the Sun‘s gravitational field
Test at the 4 x 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)

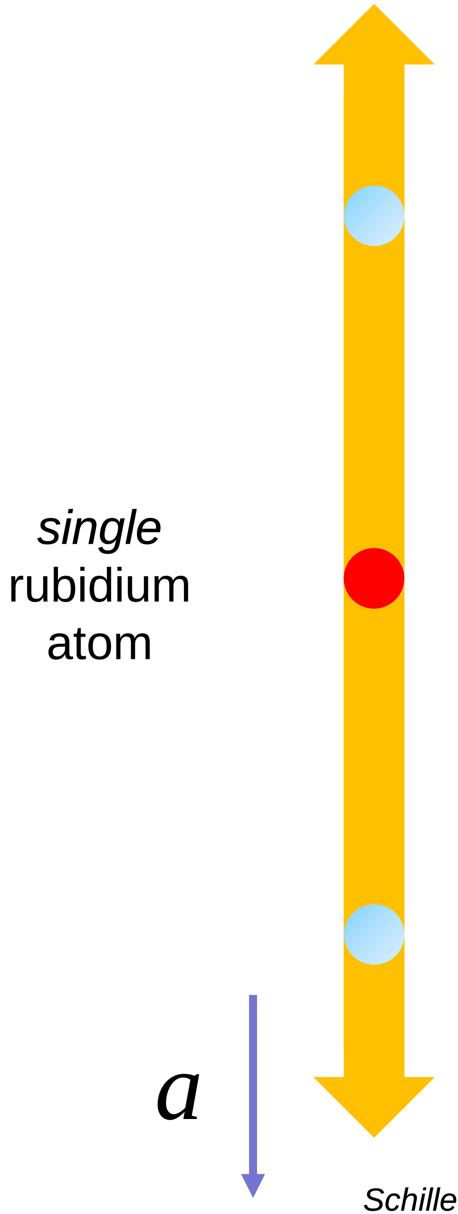
- Model: $\phi_{i,j}(r) \sim S_{i,j}/r$

  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 $S_{\mathrm{SUN},j}$, $S_{\mathrm{MOON},j}$

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 x 10^{-5}); ACES (ISS, 2016; 2 x 10^{-6}) → limits to S_{EARTH}
- Time dilation tests and WEP tests are related, but relationship is model-dependent → 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 ≈ 10^{21} times larger than for macroscopic test masses

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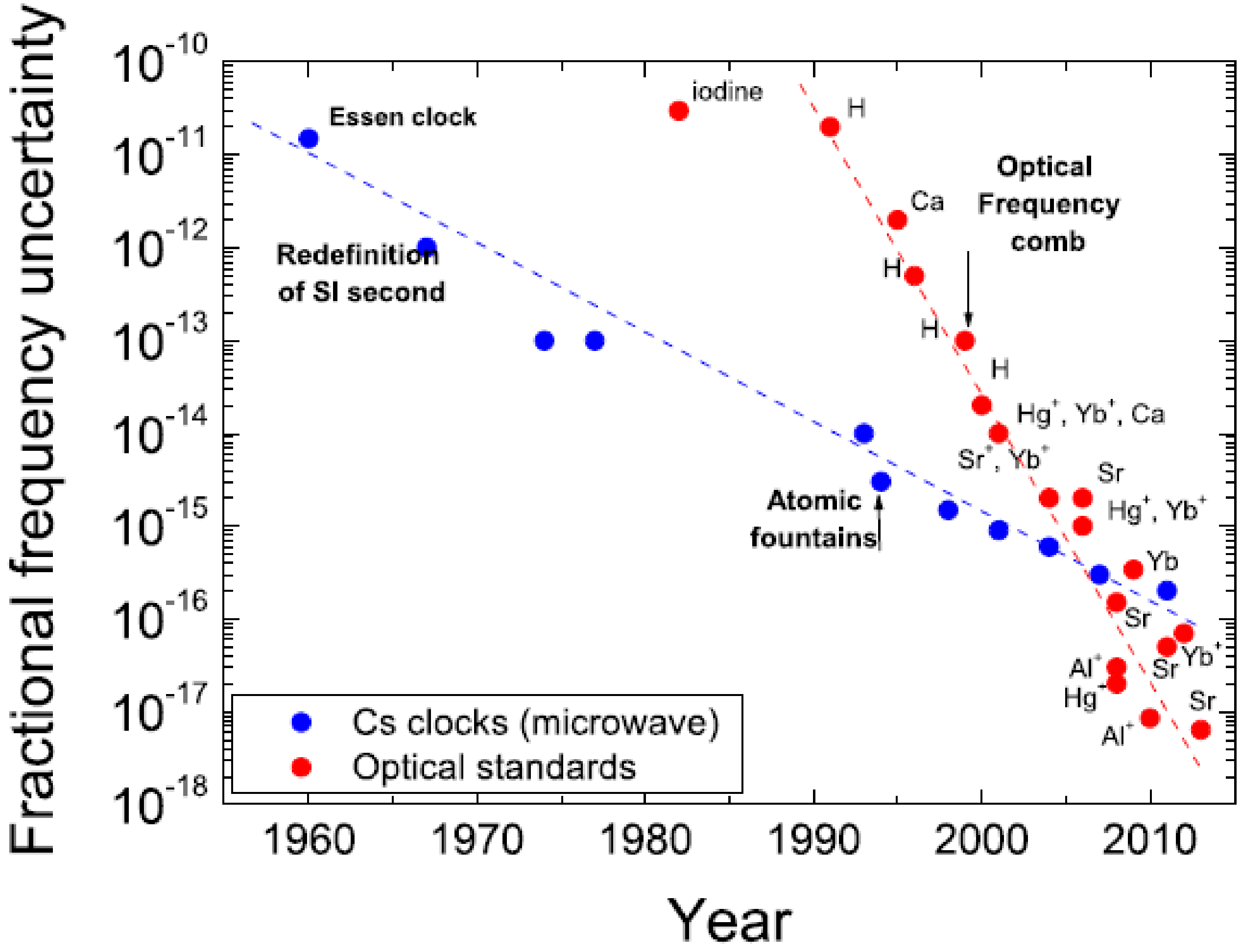
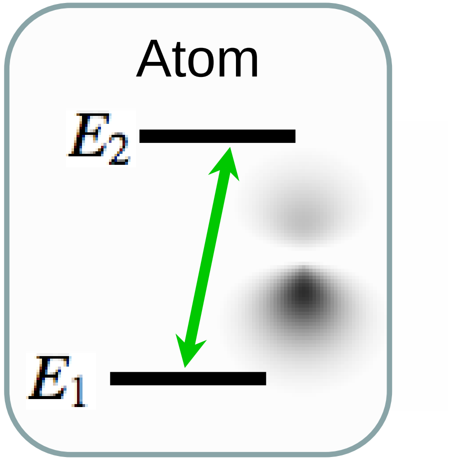
Instrument II: Atomic clocks and link





Hume et al. (2012)

Poli et al. (2013)

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

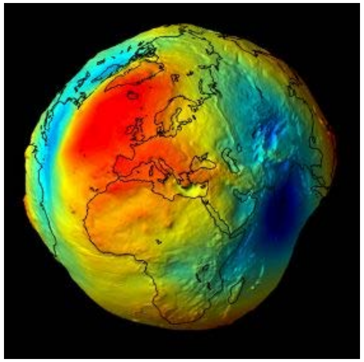
Secondary goals

- 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}** (x 10^{6} improvement)
  - Test time dilation in the solar and the lunar gravitational potential,
    accuracy: **2×10^{-6}**, **4×10^{-4}**, resp.
    (x 10^{4}, x 10^{3} improvement, resp.)

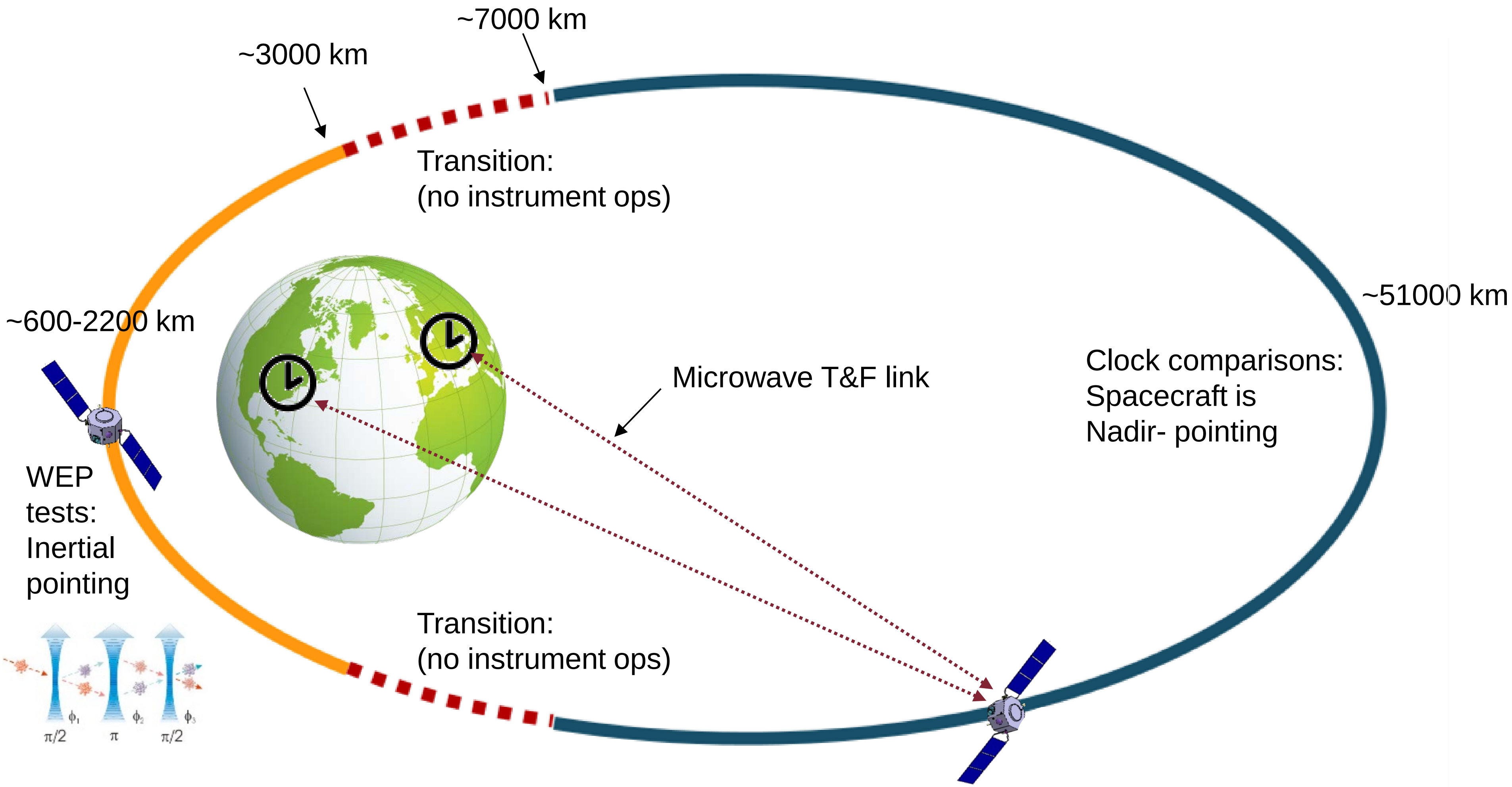
- **Application to other fields:**
  - Contribution to tests of time-variation of fundamental constants
  - Contribution to improved reference frame definitions
  - Distribution of time world-wide
  - Mapping of the gravitational potential of the Earth with high spatial resolution

- **Potential for enhancement of science objectives:**
  - Phase-coherence of microwave link between orbits
  - Optional laser link
  - Optional on-board clock

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



~7000 km

~3000 km

Transition:
(no instrument ops)

~600-2200 km

~51000 km

Microwave T&F link

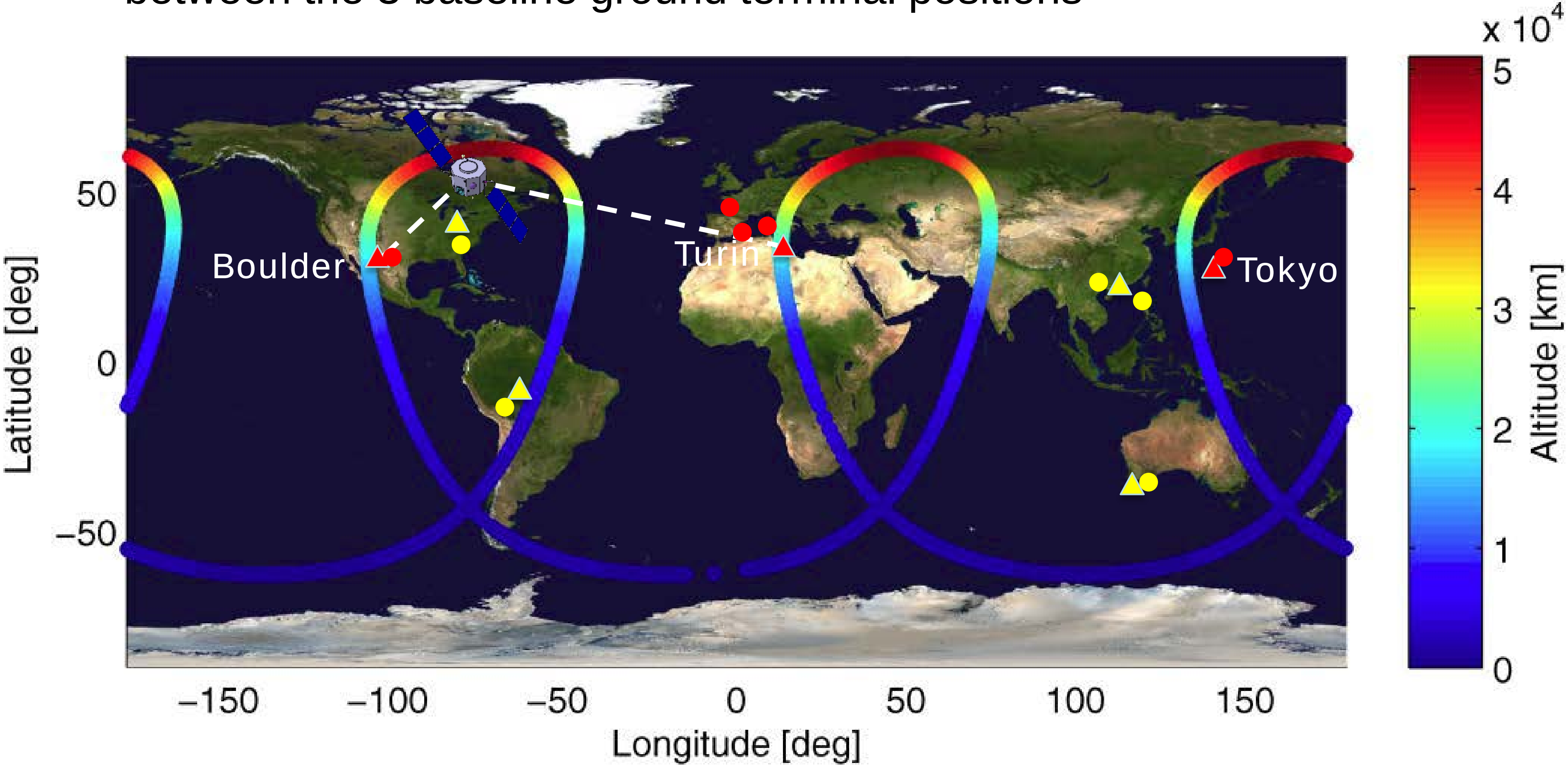
Clock comparisons:
Spacecraft is
Nadir- pointing

WEP
tests:
Inertial
pointing

Transition:
(no instrument ops)

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



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Microwave link

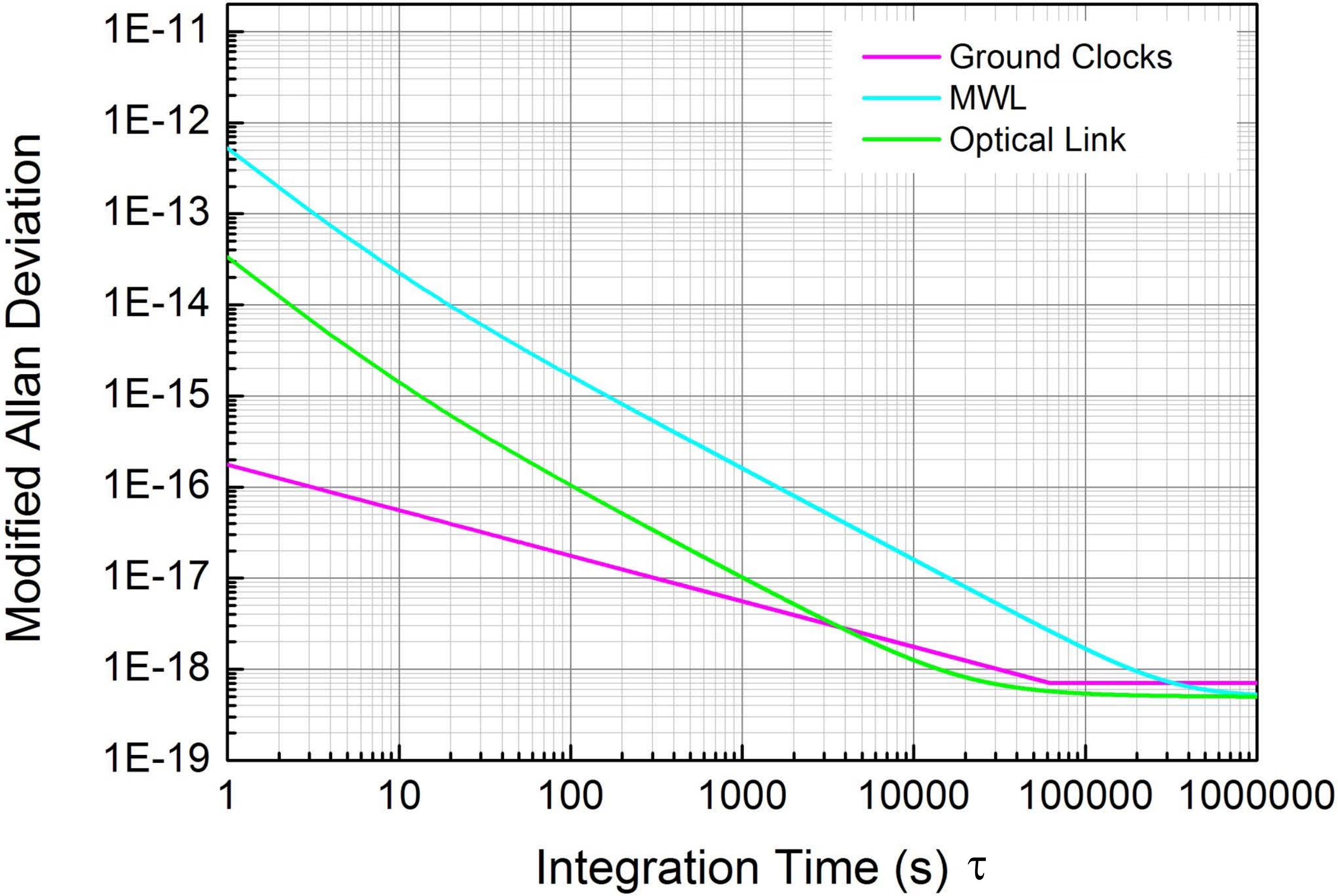
Operation:

- 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 $< 1 \times 10^{-18}$ (relative) after 2.5 days
- phase conserved across dead time between observations

Frequency stability requirements



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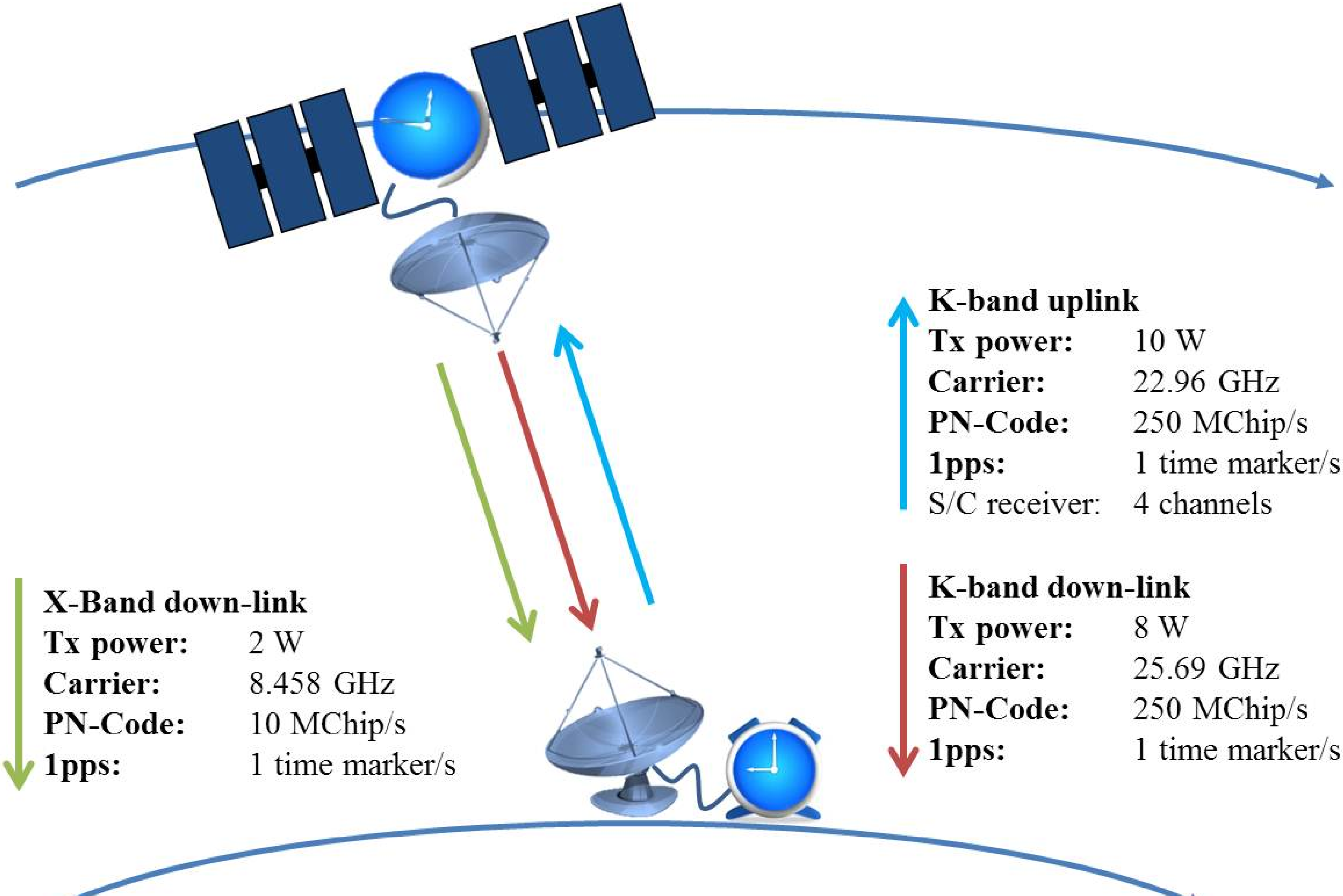
Microwave link design

Industrial study under ESA contract



K-band uplink

Tx power:	10 W
Carrier:	22.96 GHz
PN-Code:	250 MChip/s
1pps:	1 time marker/s
S/C receiver:	4 channels

X-Band down-link

Tx power:	2 W
Carrier:	8.458 GHz
PN-Code:	10 MChip/s
1pps:	1 time marker/s

K-band down-link

Tx power:	8 W
Carrier:	25.69 GHz
PN-Code:	250 MChip/s
1pps:	1 time marker/s

Microwave link ground terminal

Based on ACES ground terminal concept with upgrades.

Science ground segment

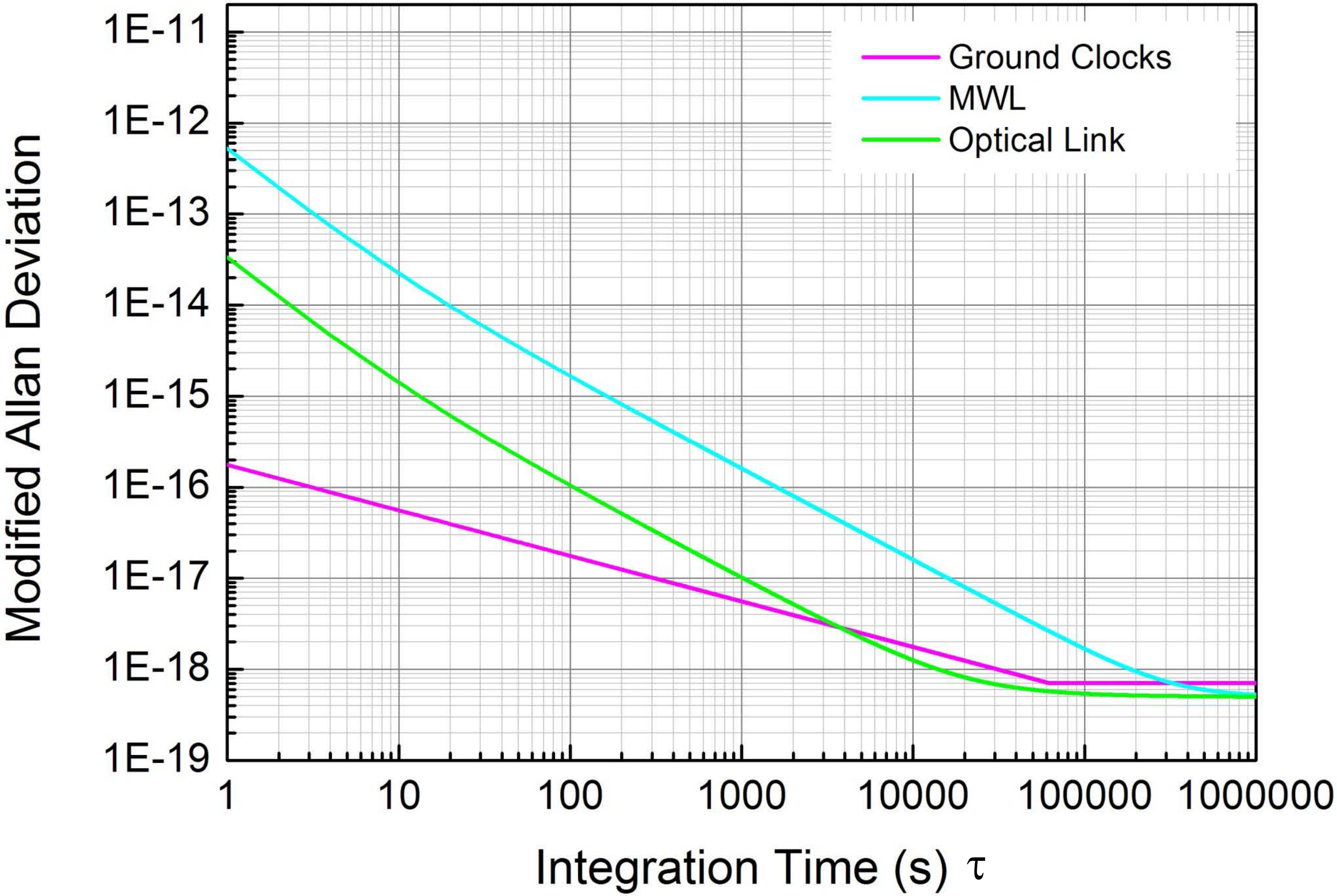
PI-provided

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



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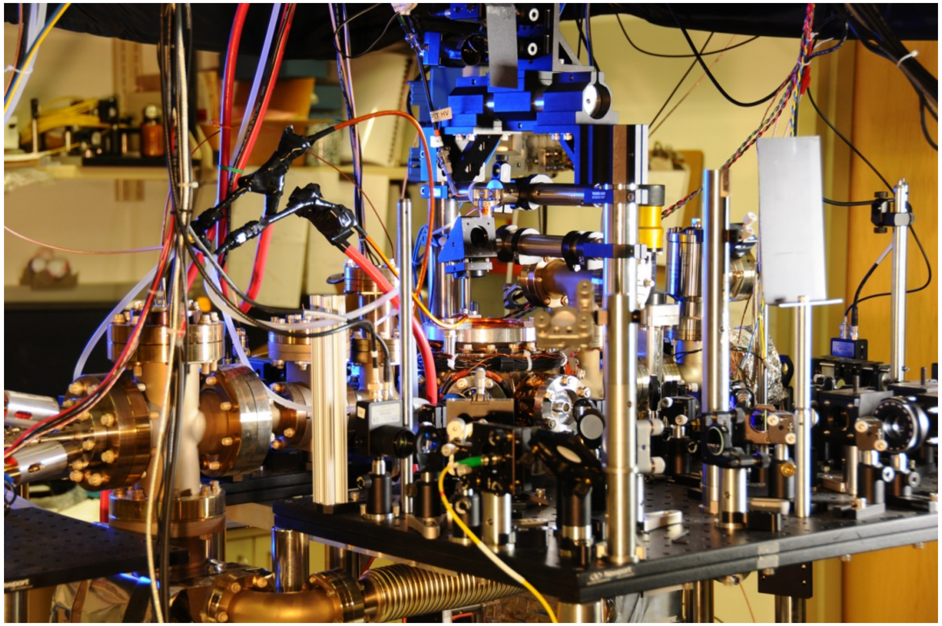
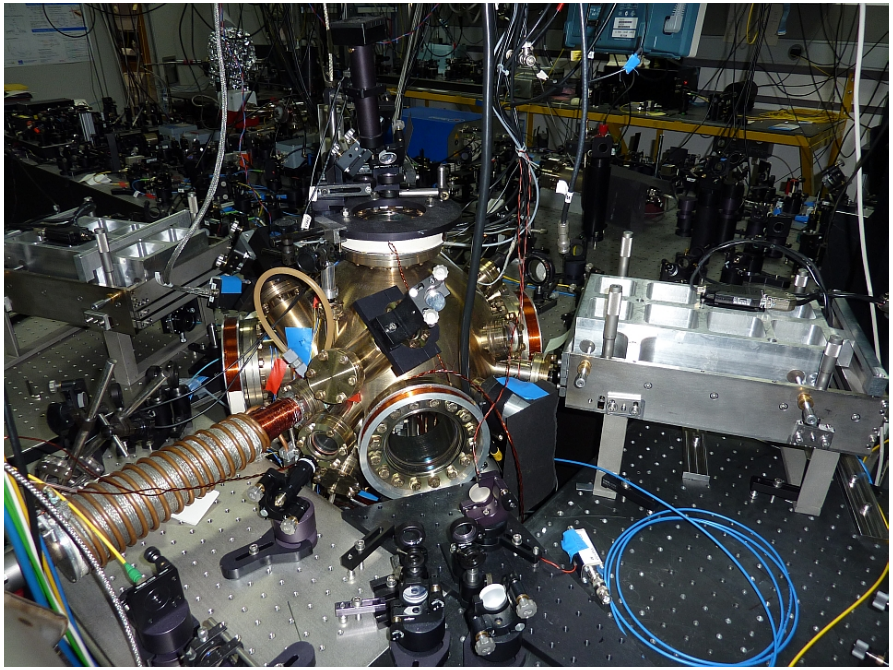
Examples of current ground optical clocks



NIST Yb lattice clock

stability 3.2 x $10^{-16}/\tau^{1/2}$



PTB Sr lattice clock

stability 4.5 x $10^{-16}/\tau^{1/2}$

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

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

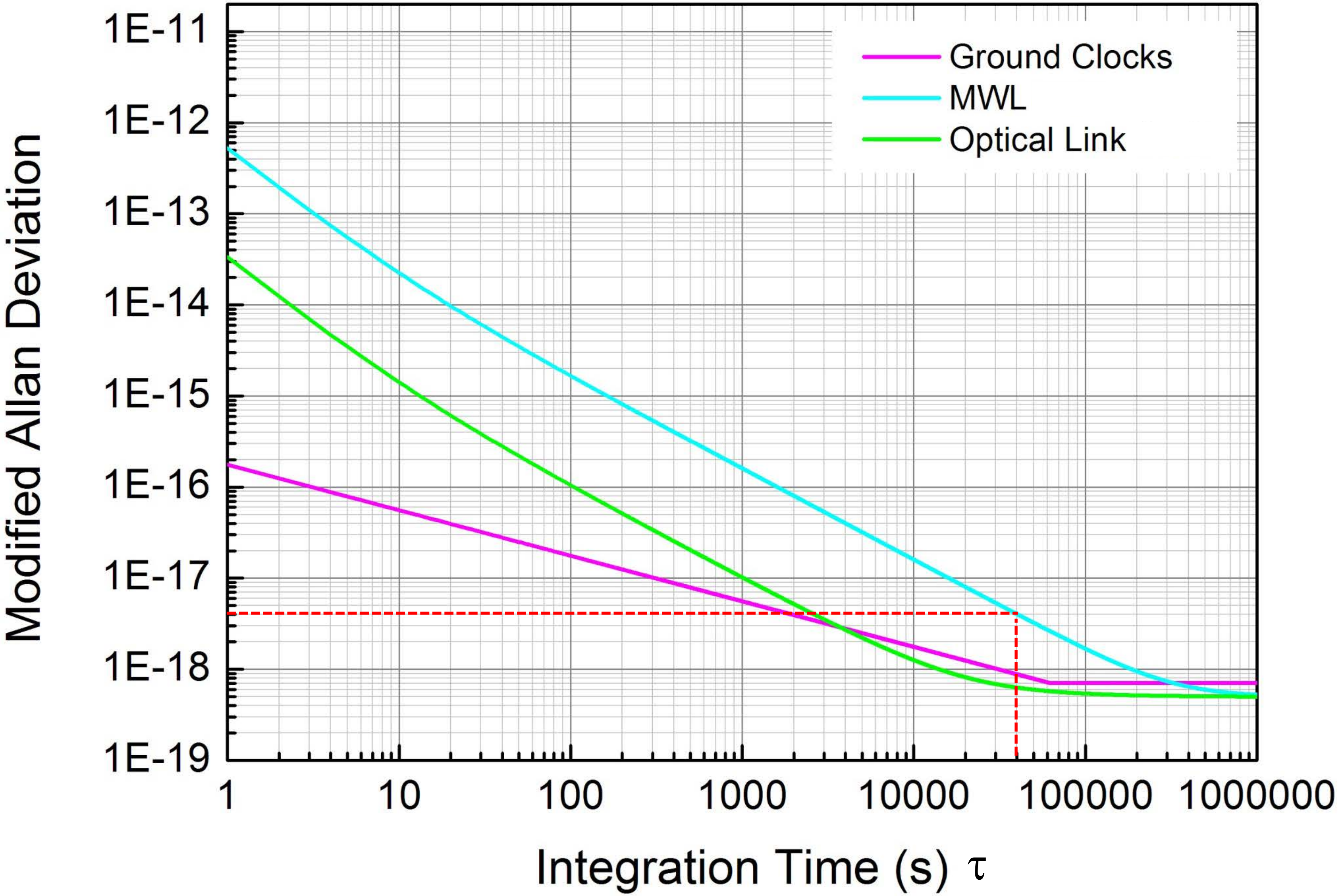
Ground-ground clock comparisons:

- time comparison accuracy < 50 ps
- typical link frequency noise of 4 x 10^{-18} after one comparison (~ 200 x better than current methods)
- link frequency noise falls below 1 x 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 x 10^{-5} after 2 days
- Moon redshift relative uncertainty ~ 170 x Sun
- geopotential uncertainty equivalent ~ 20 - 60 cm height after 1 comparison
- uncertainties average down to the science objective values over the mission lifetime, probably better.

Frequency stability requirements



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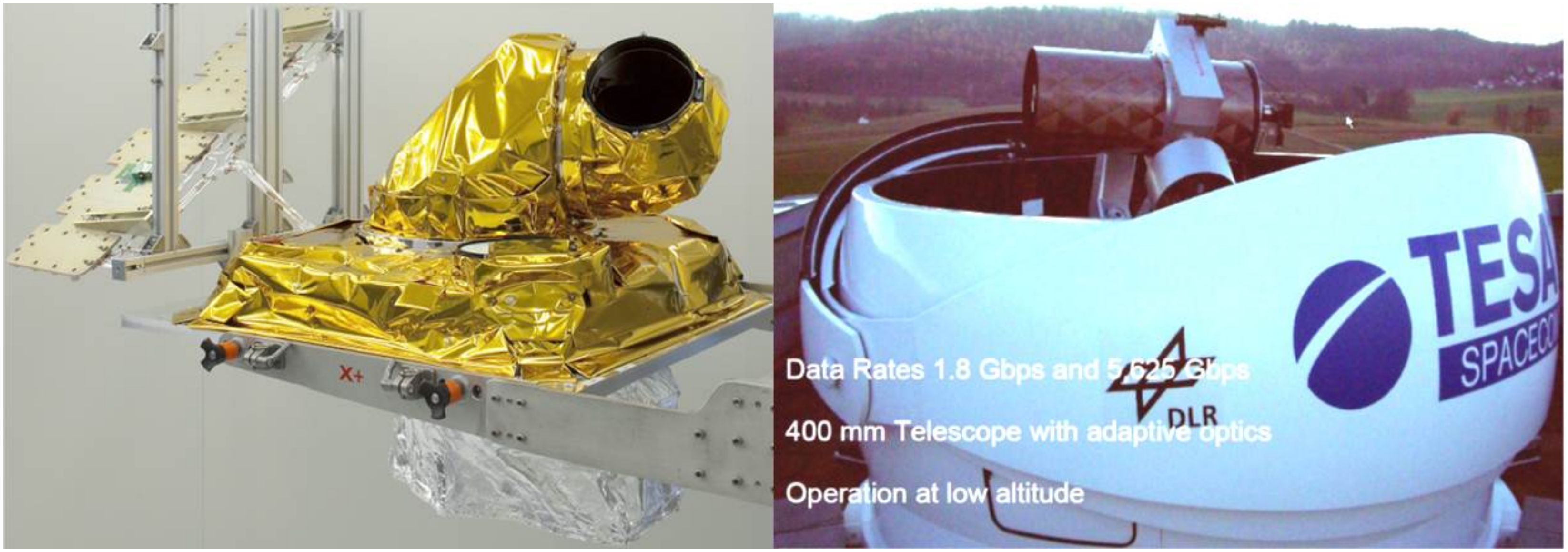
Optional instruments

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



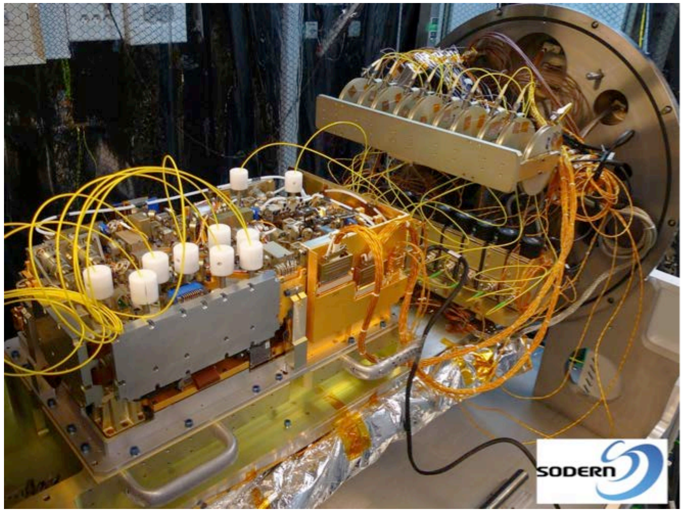
TESAT

Optional instruments

Space cold caesium clock:

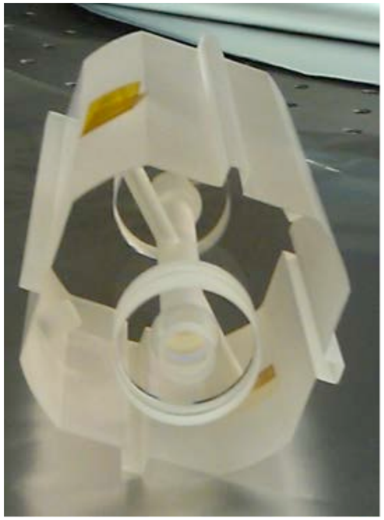
- copy of PHARAO cold Cs clock for ACES (2016)
- addition of an ultrastable oscillator based on a cavity-stabilized laser + femtosecond laser comb
- performances specification = PHARAO ultimate goal
  - frequency error < 1 x 10^{-16}
  - frequency noise < 8 x 10^{-14} / $\tau^{1/2}$ (to 8 days)
- enables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

PHARAO Optical Bench



SODERN

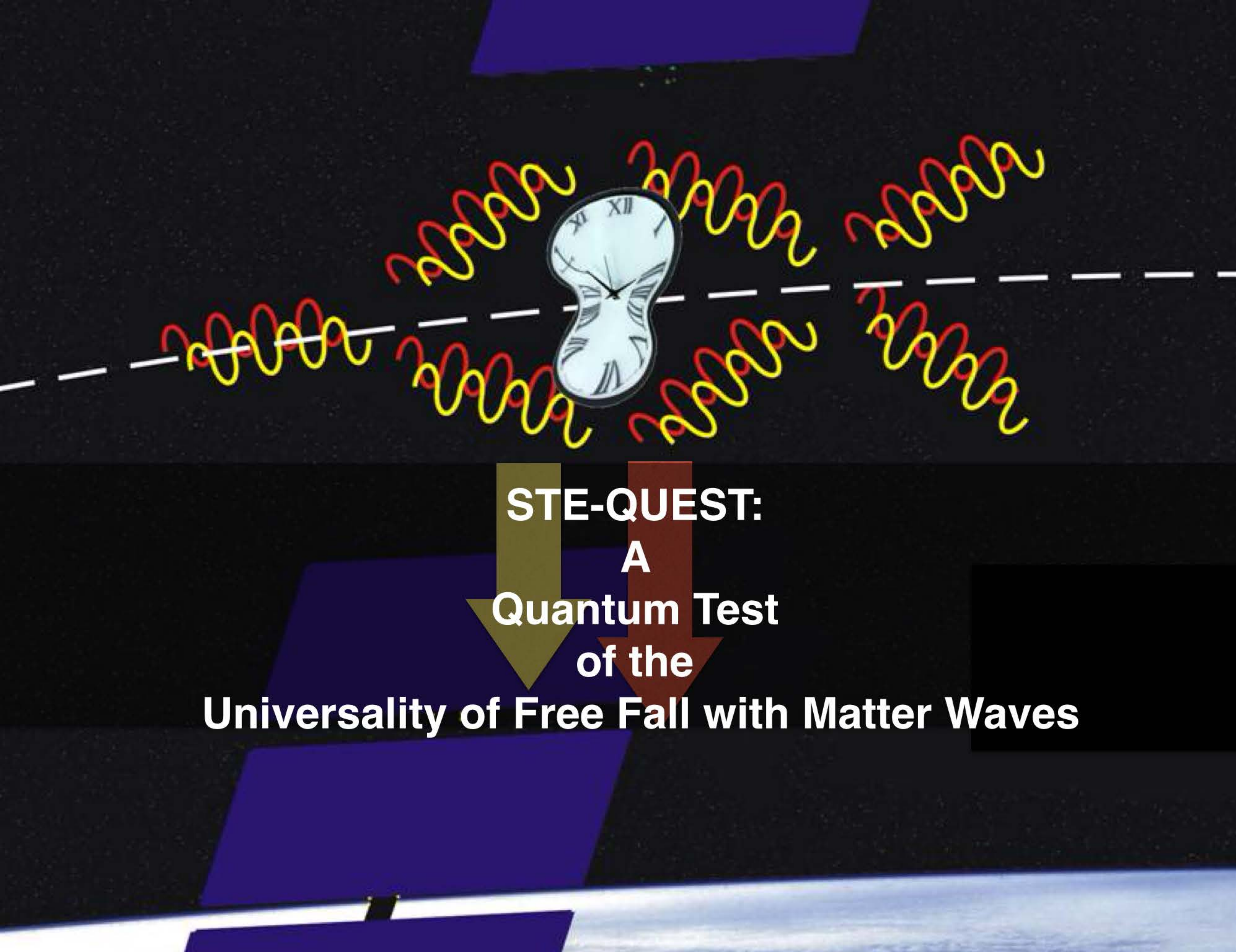
Ultra-stable cavity



HHUD/PTB

Femtosecond laser comb

MenloSystems



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

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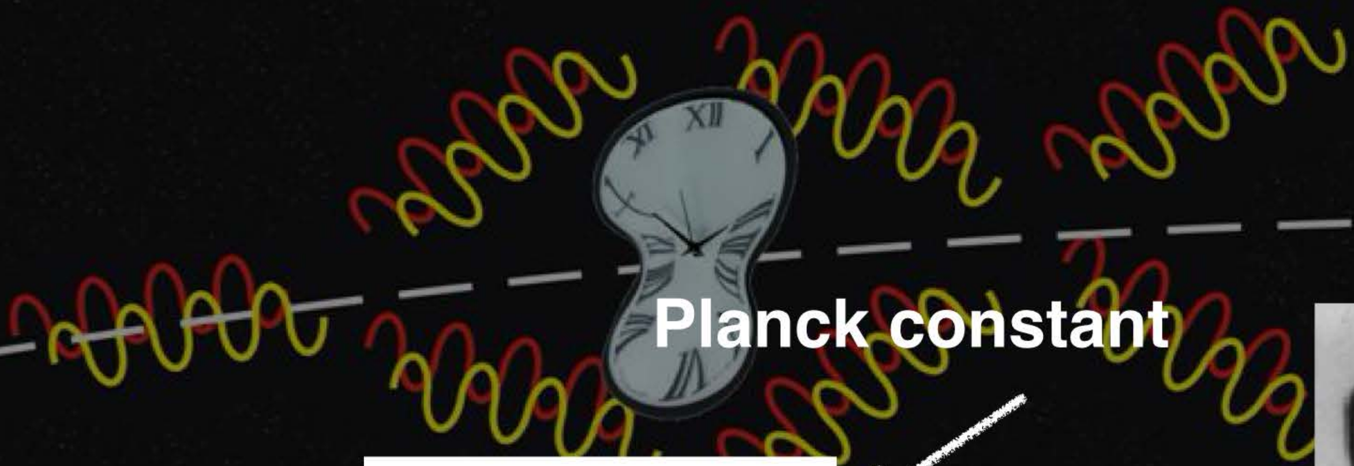
Matter forms Waves



Planck constant

Momentum

$$p = m \cdot v = \frac{h}{\lambda}$$

de Broglie wavelength

Louis Victor de Broglie
Nobel prize 1929

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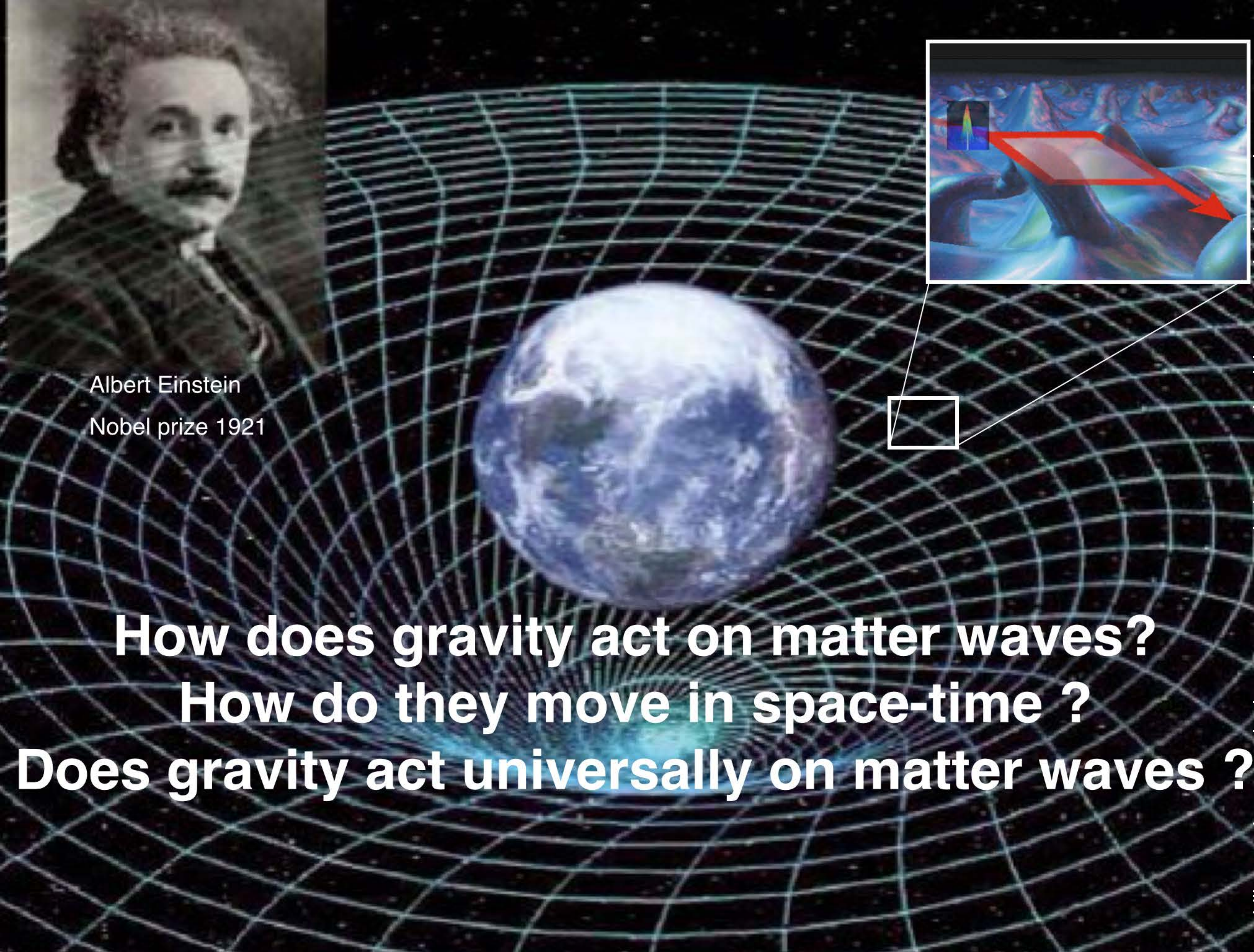

Albert Einstein

Nobel prize 1921

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

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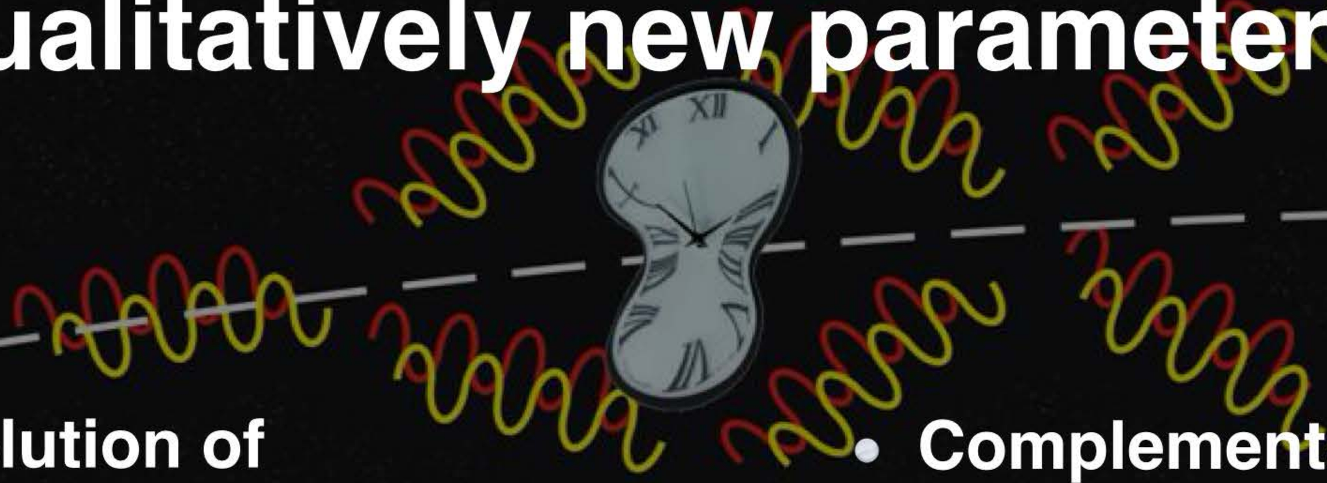
Quantum tests explore a qualitatively new parameter range



- Evolution of delocalised wave packets
- Macroscopic coherence length
- Pure isotopes
- Pure spin states

- Complementary to classical tests
- Atom sensors allow redshift & free fall tests

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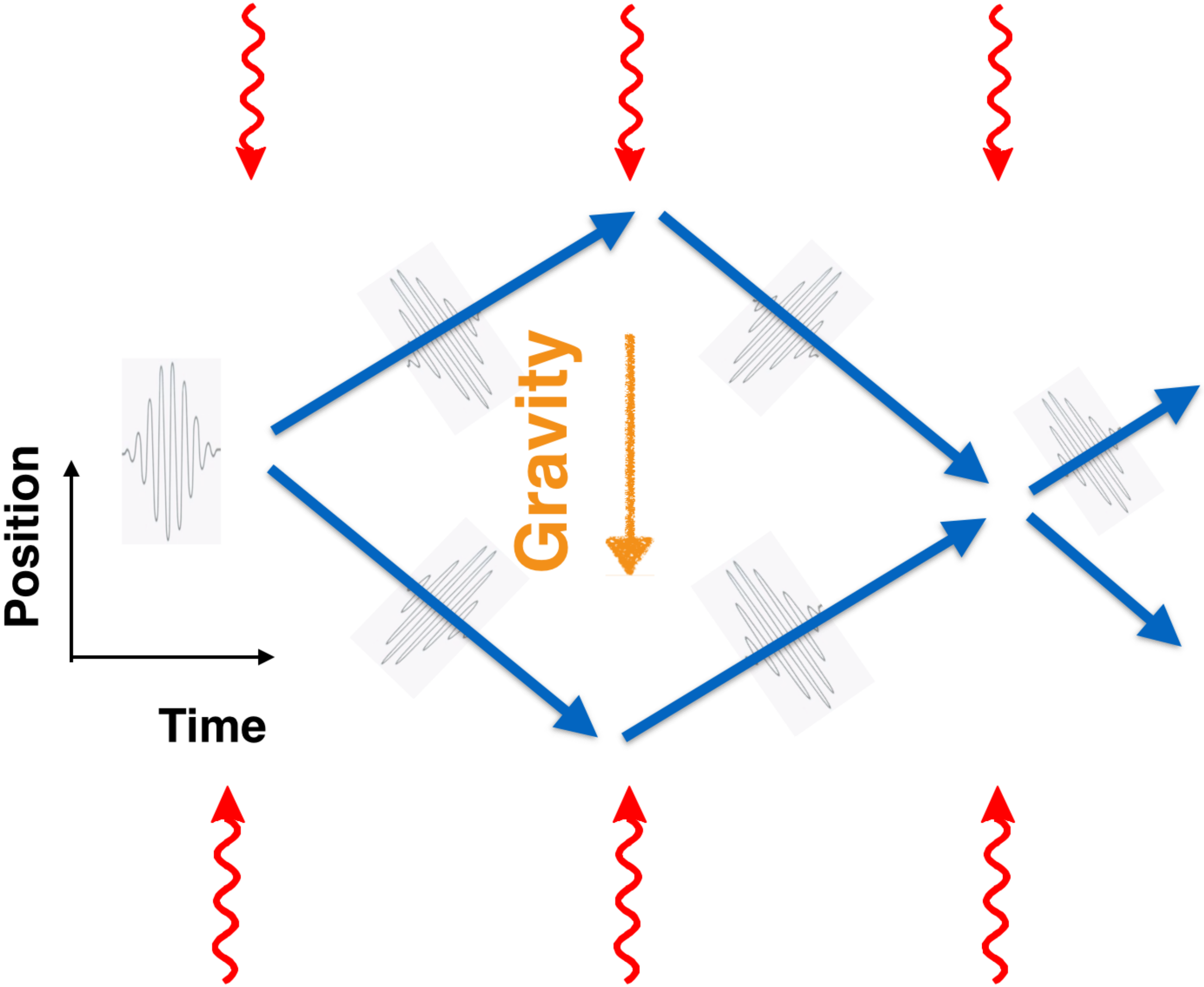
Probing matter waves with interferometry



Laser pulse 1 Laser pulse 2 Laser pulse 3

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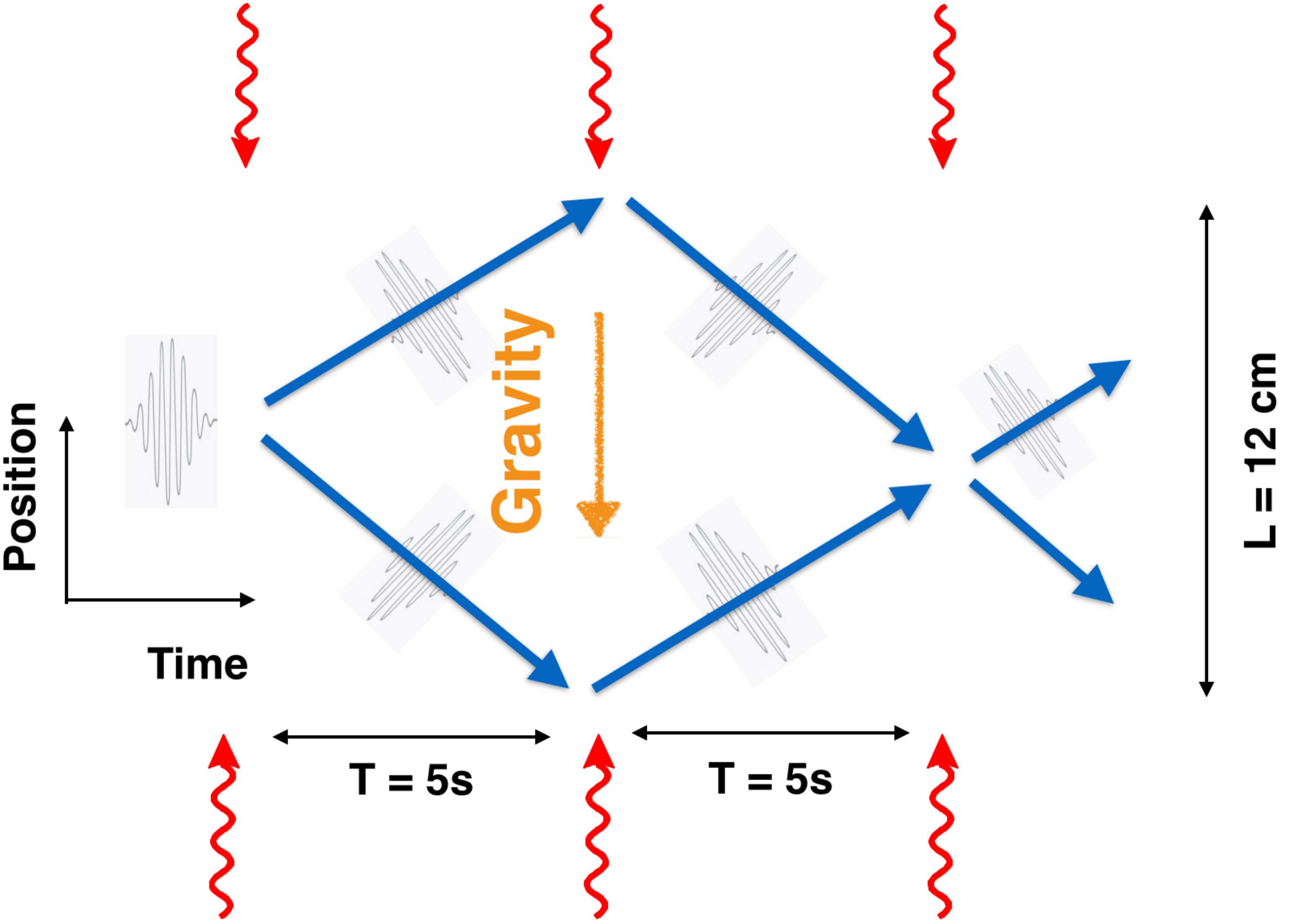
Probing matter waves on macroscopic scales



Laser pulse 1 **Laser pulse 2** **Laser pulse 3**

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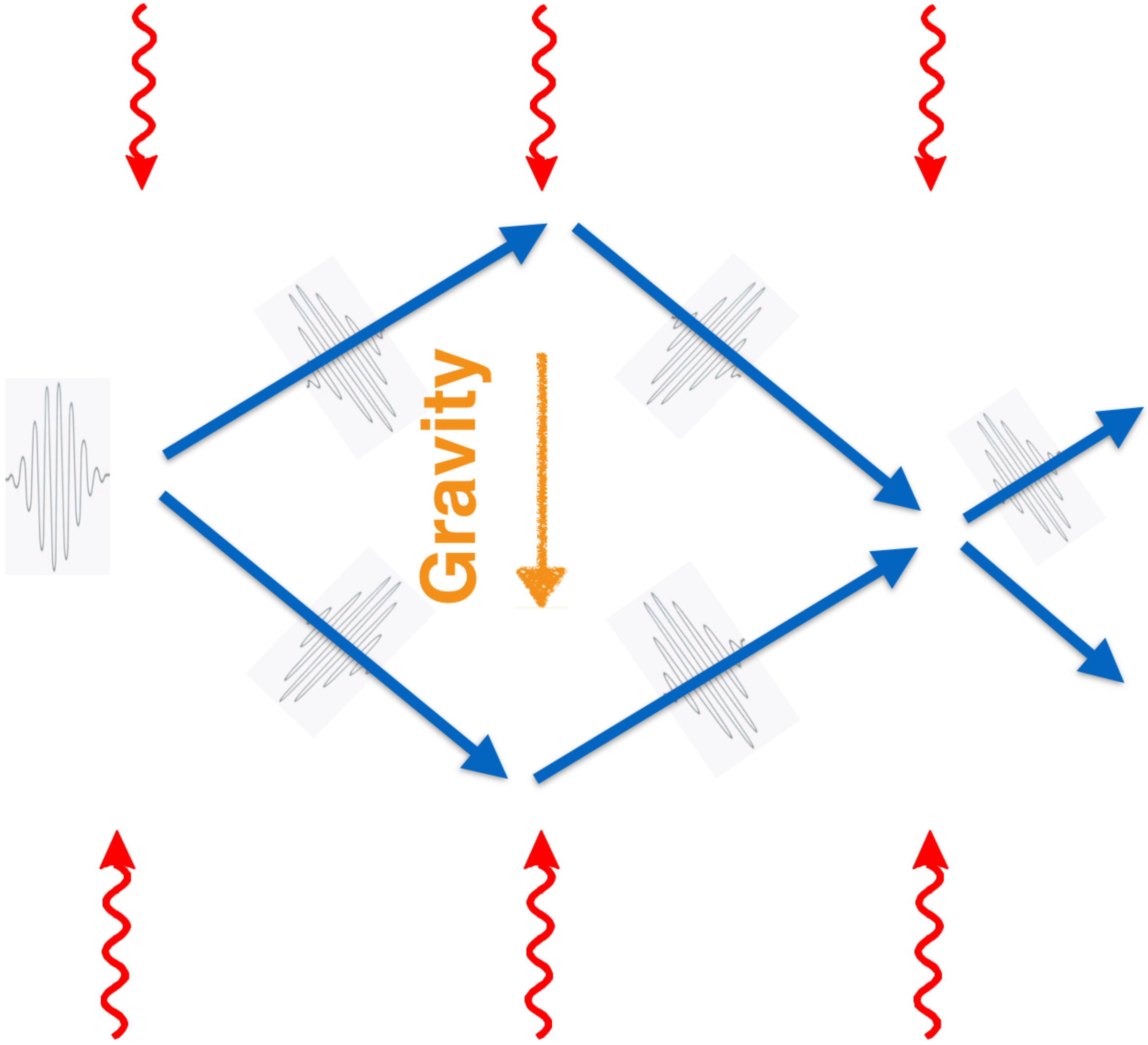
Gravity-induced phase shift



If QWEP holds
then mass drops out!

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

Sensitivity boost
through extended free fall

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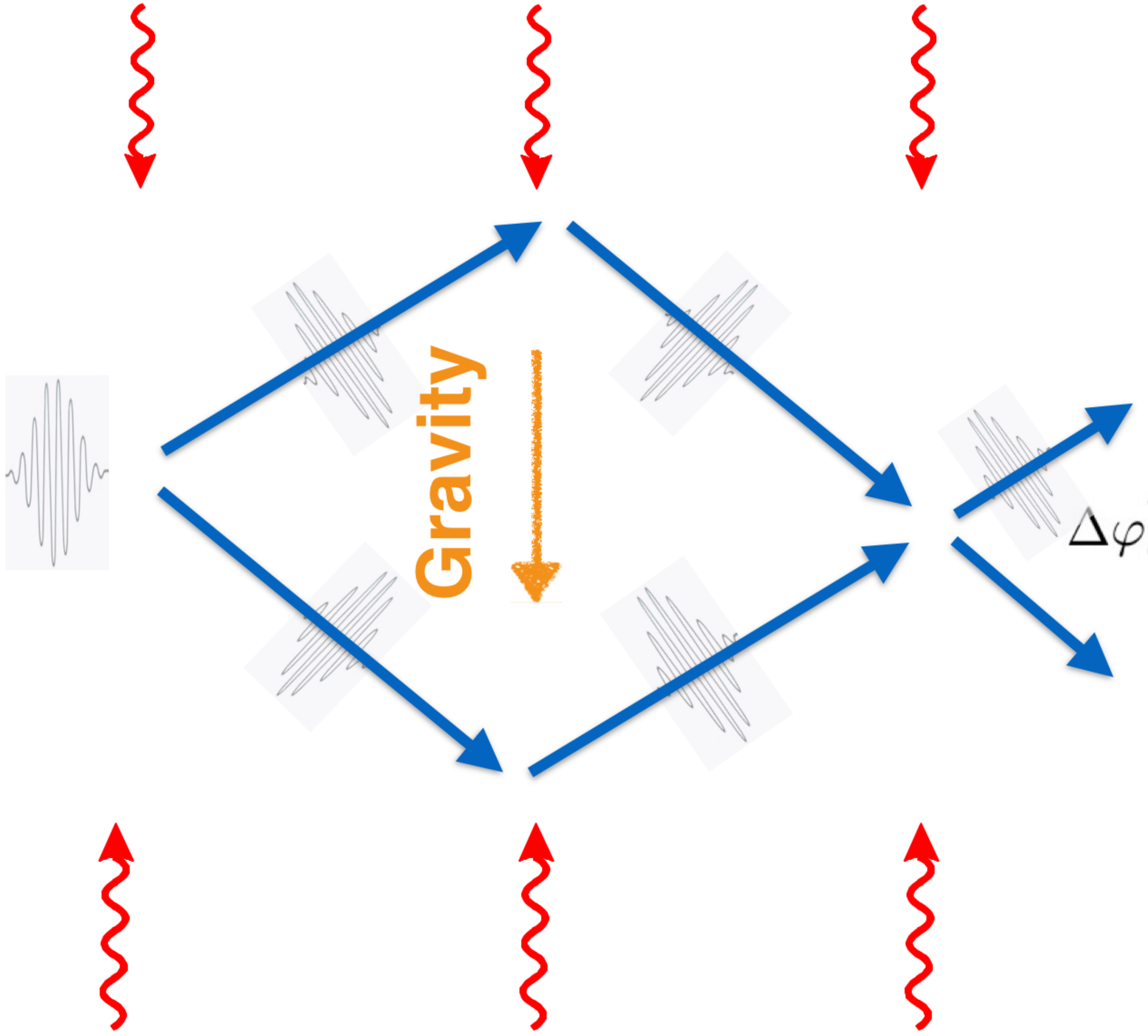
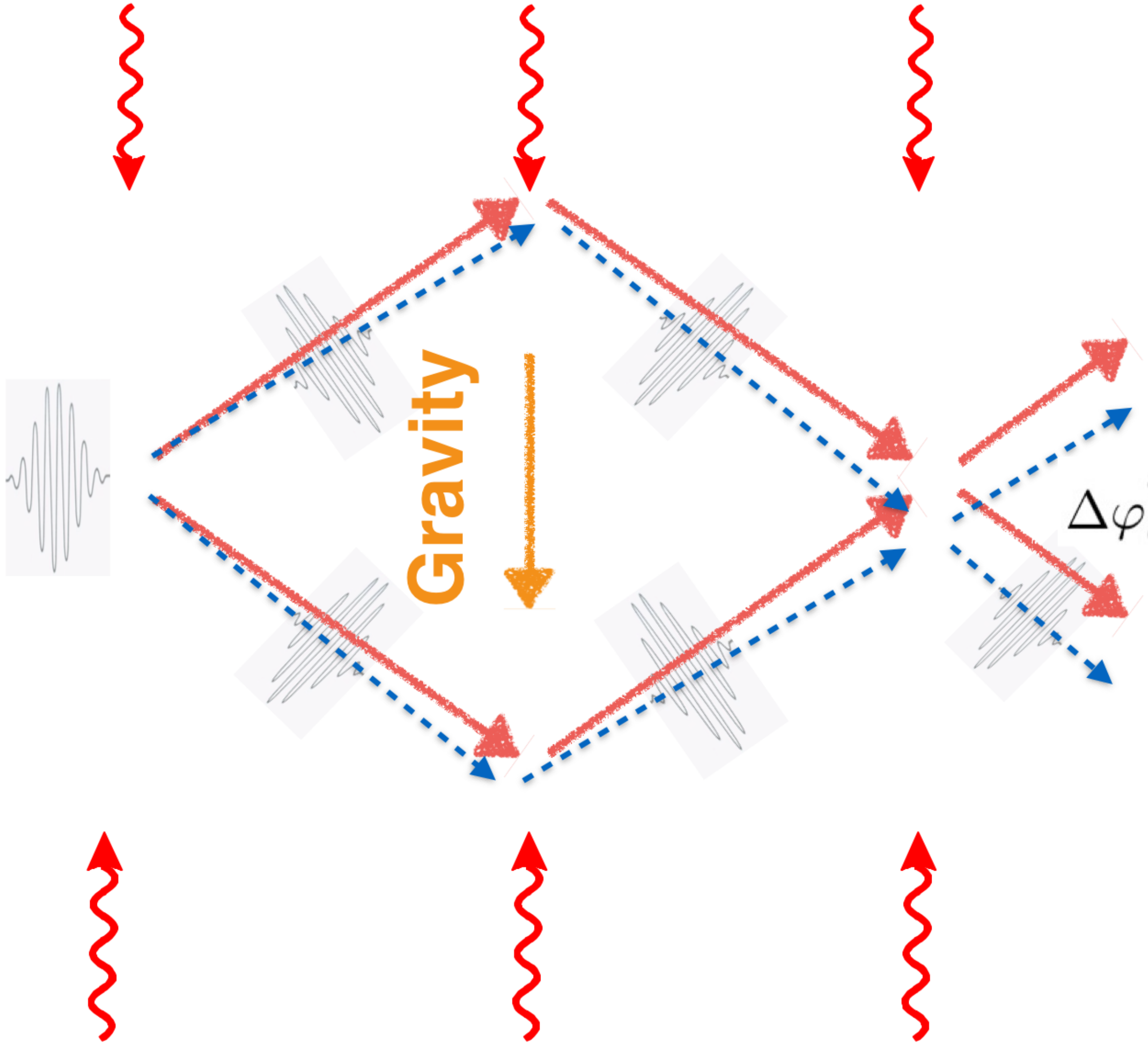
Comparing matter waves of ^{87}Rb and ^{85}Rb



^{87}Rb

$$\Delta\varphi_{acc}^{87Rb} = \vec{k}_{^{87}Rb} \cdot \vec{g}_{^{87}Rb} \cdot T^2$$

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



$$\Delta\varphi_{acc}^{85\,Rb} = \vec{k}_{^{85}Rb} \cdot \vec{g}_{^{85}Rb} \cdot T^2$$

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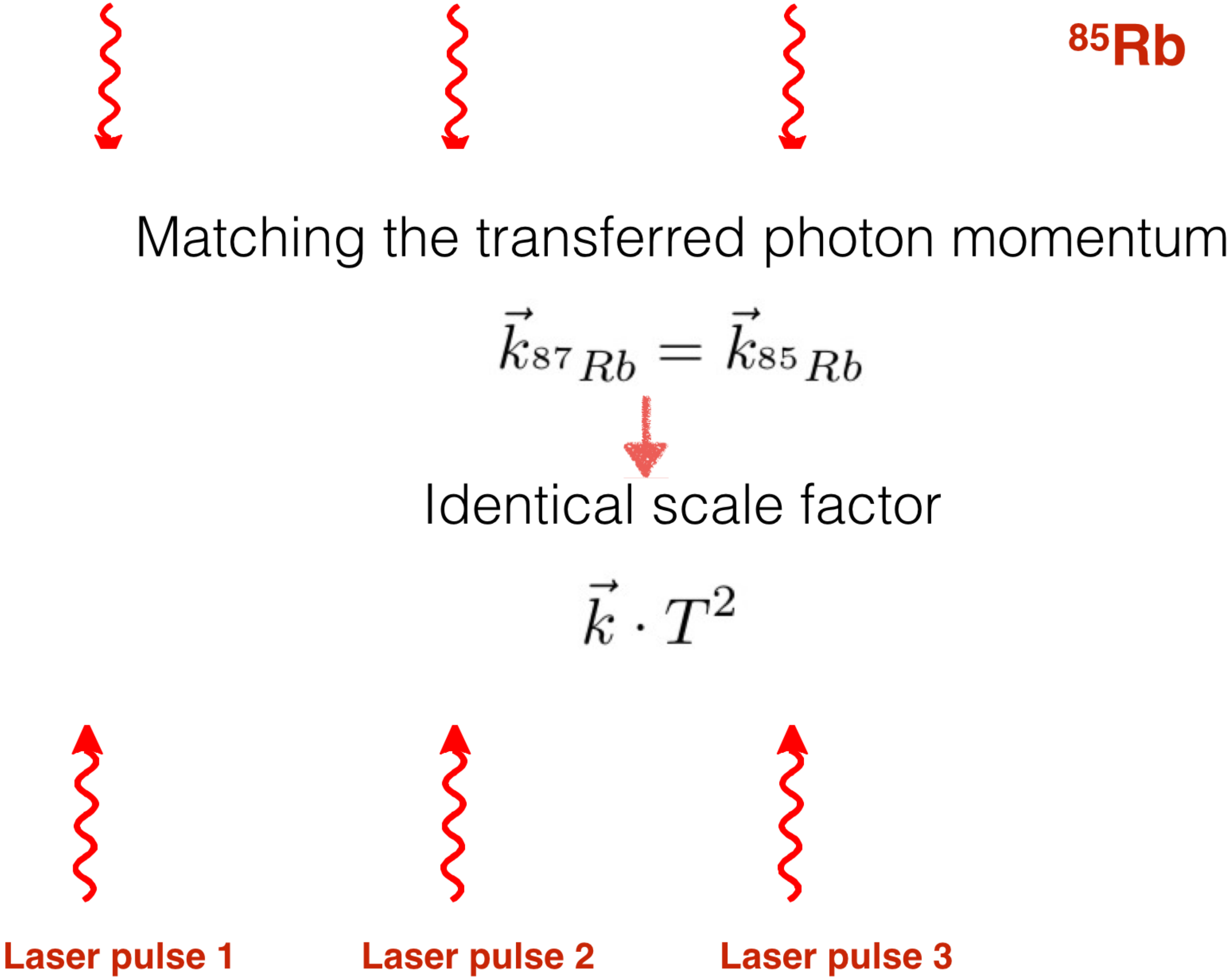
Comparing matter waves of ^{87}Rb and ^{85}Rb



Matching the transferred photon momentum

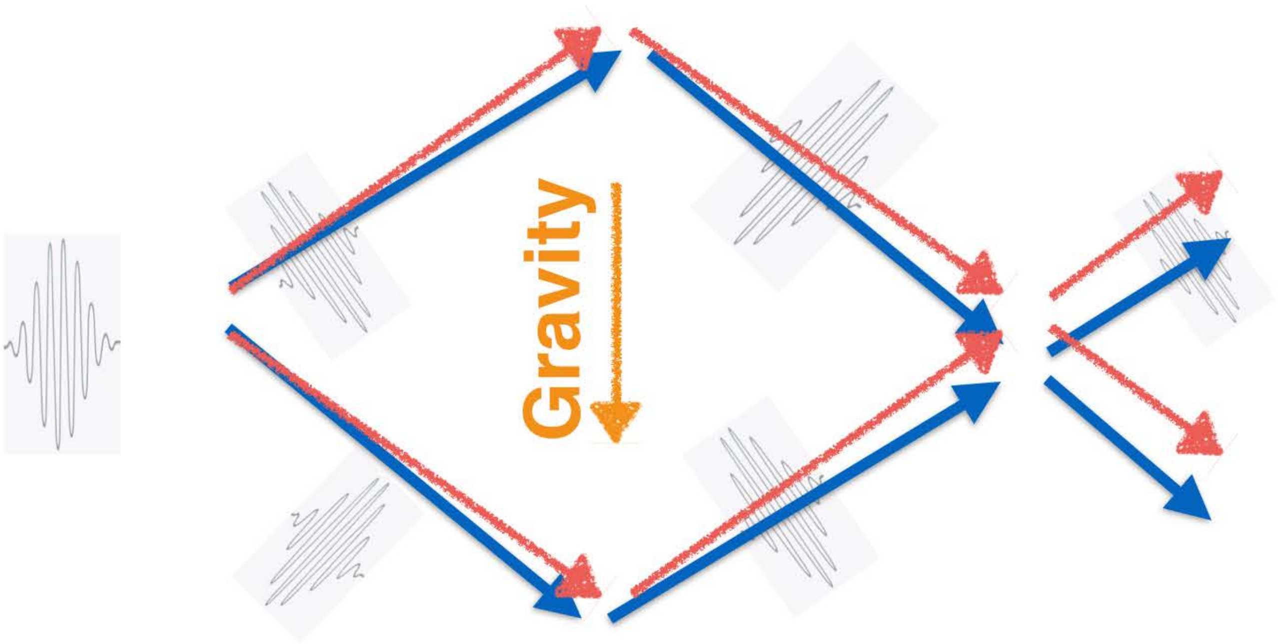
$$\vec{k}_{^{87}Rb} = \vec{k}_{^{85}Rb}$$

Identical scale factor

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

Laser pulse 1 **Laser pulse 2** **Laser pulse 3**

Determination of the Eötvös ratio



?

$$\vec{g}_{^{87}Rb} = \vec{g}_{^{85}Rb}$$

Eötvös ratio

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

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

Demonstration of atom interferometers in microgravity

First tests in March 2007 : 500 parabolas since then.

cnes

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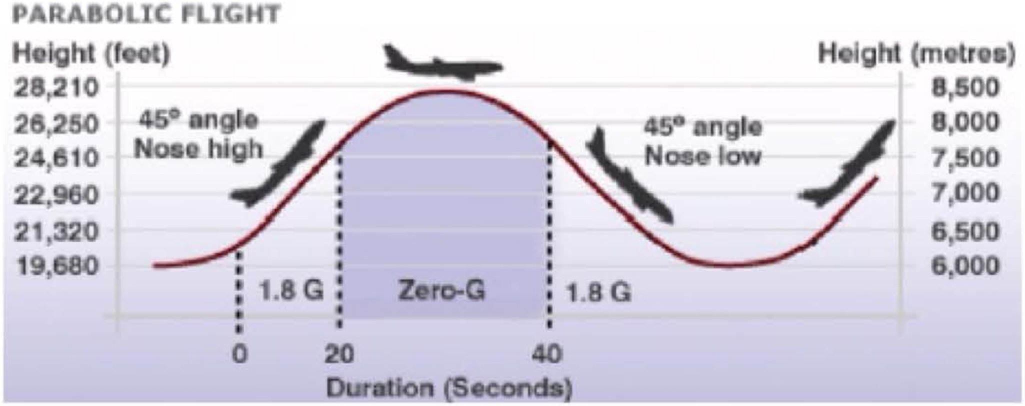
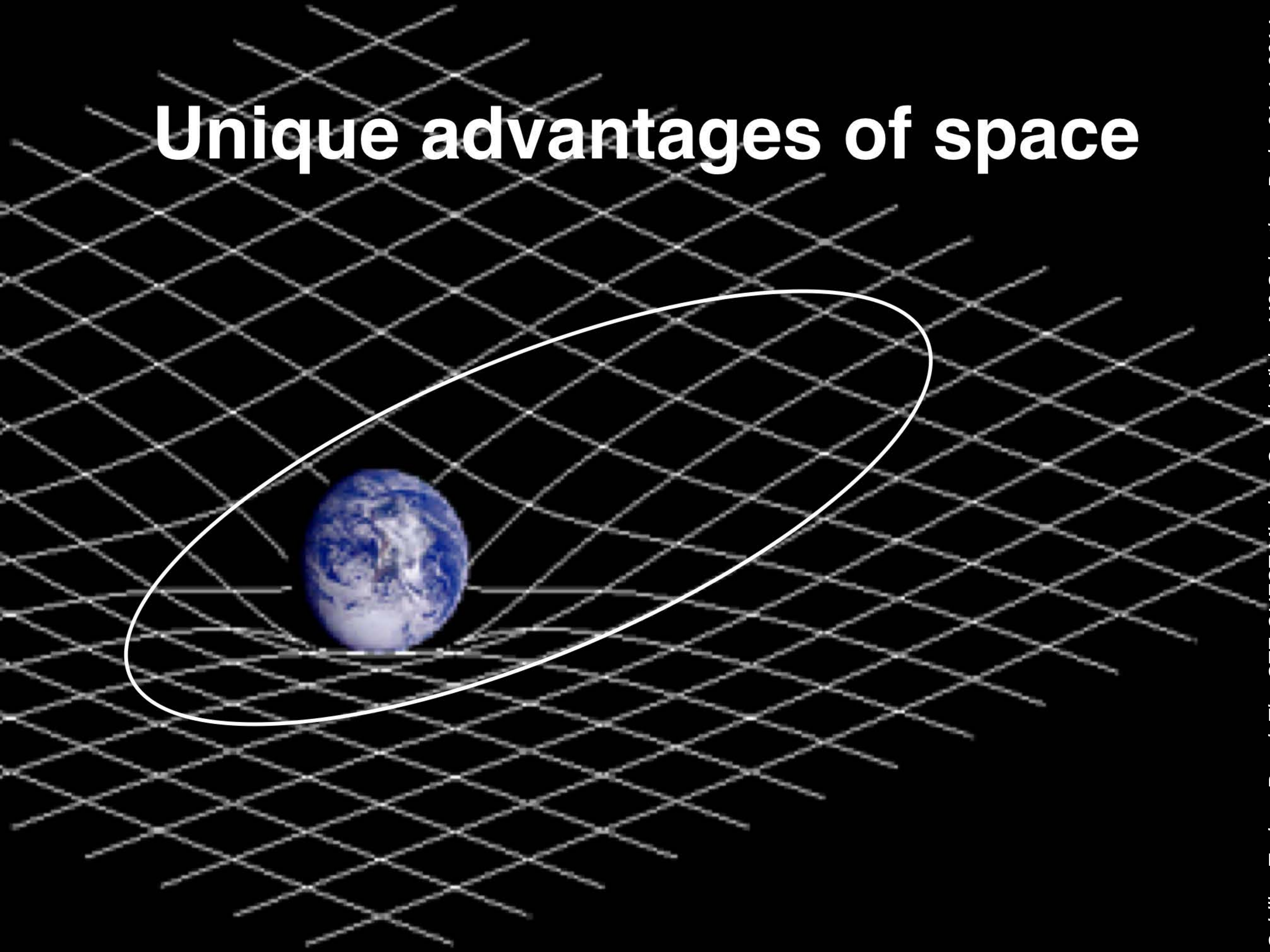
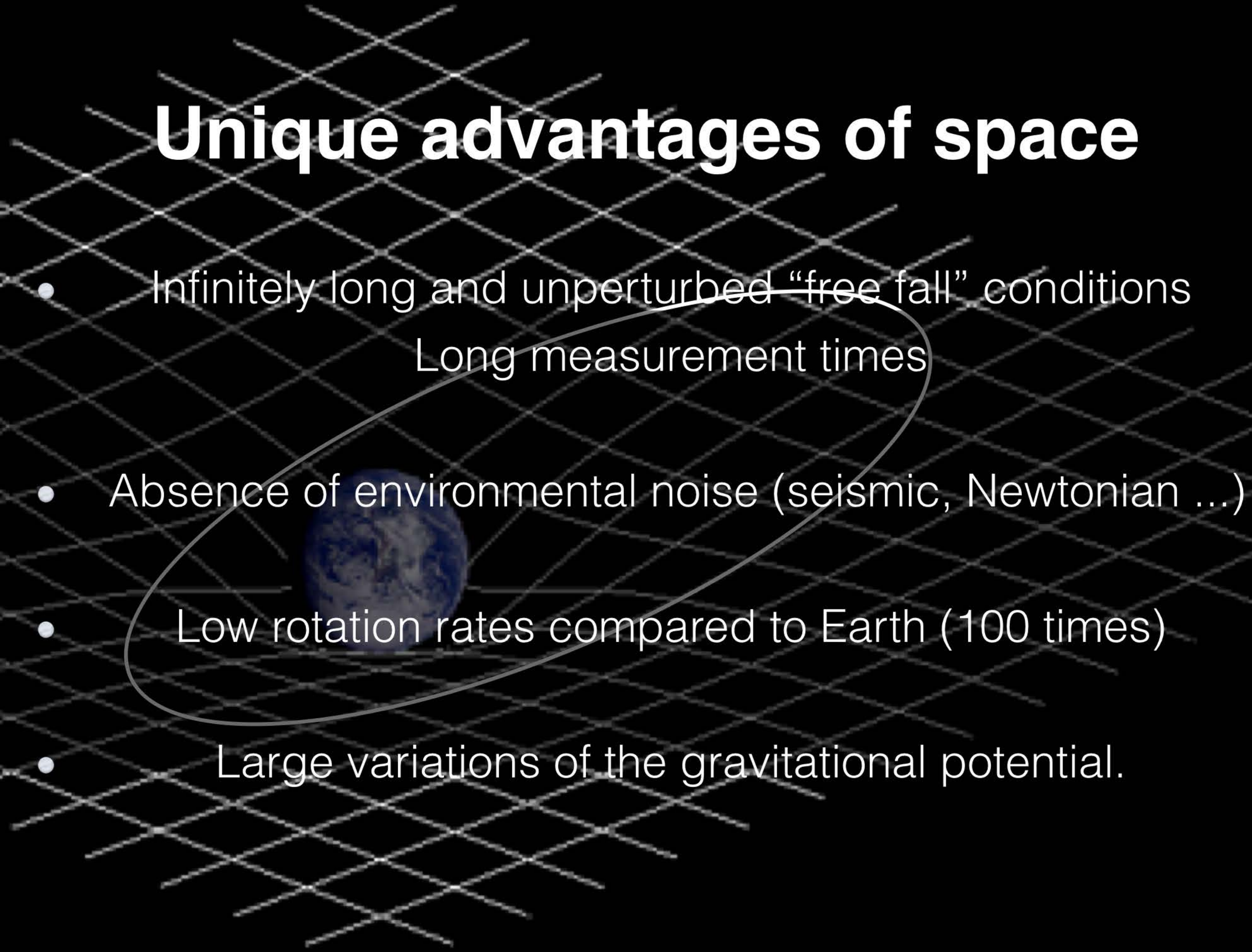


R. Geiger et al., Nat. Comm. 2011

Unique advantages of space



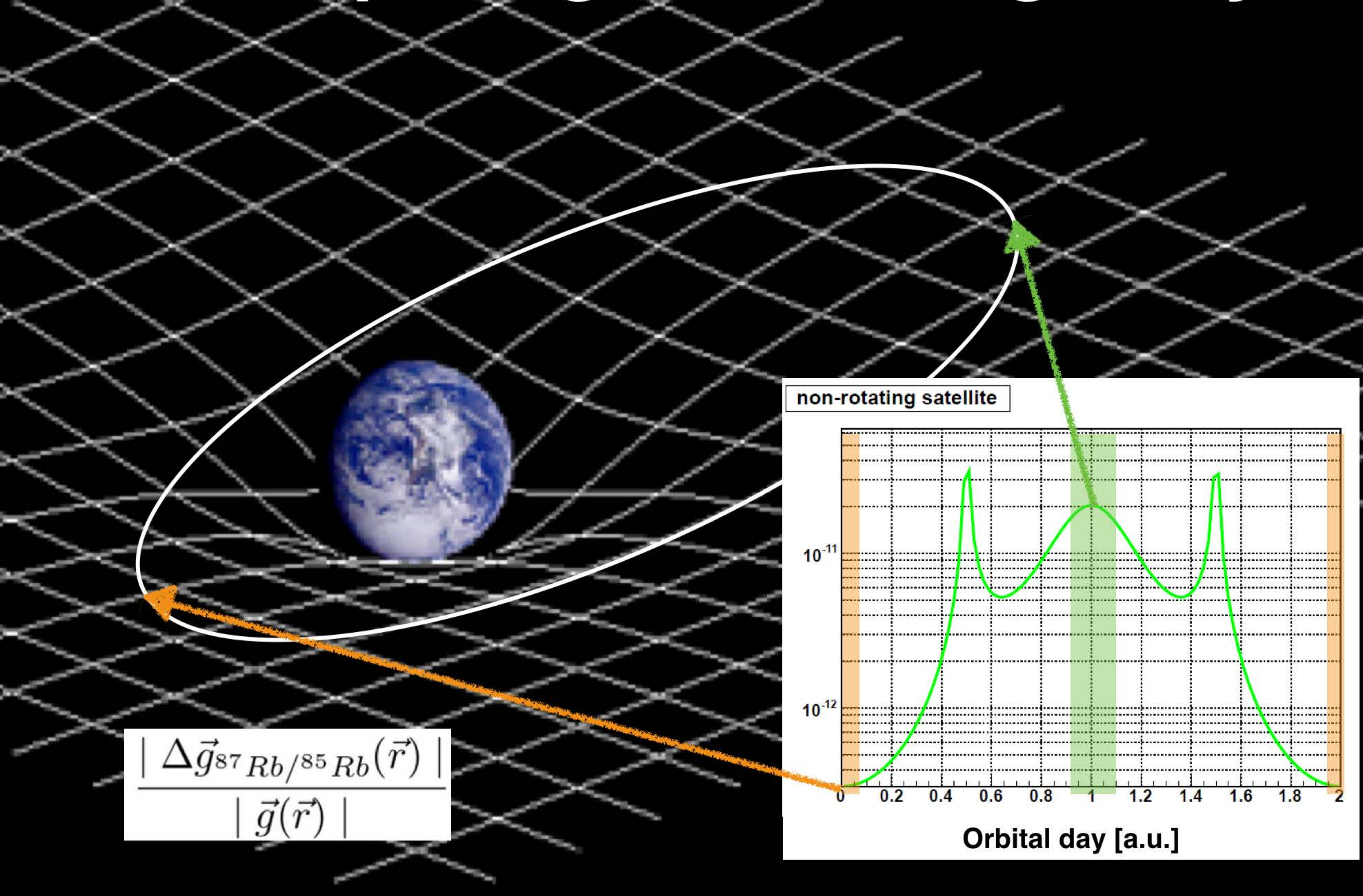
Unique advantages of space



- 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.

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

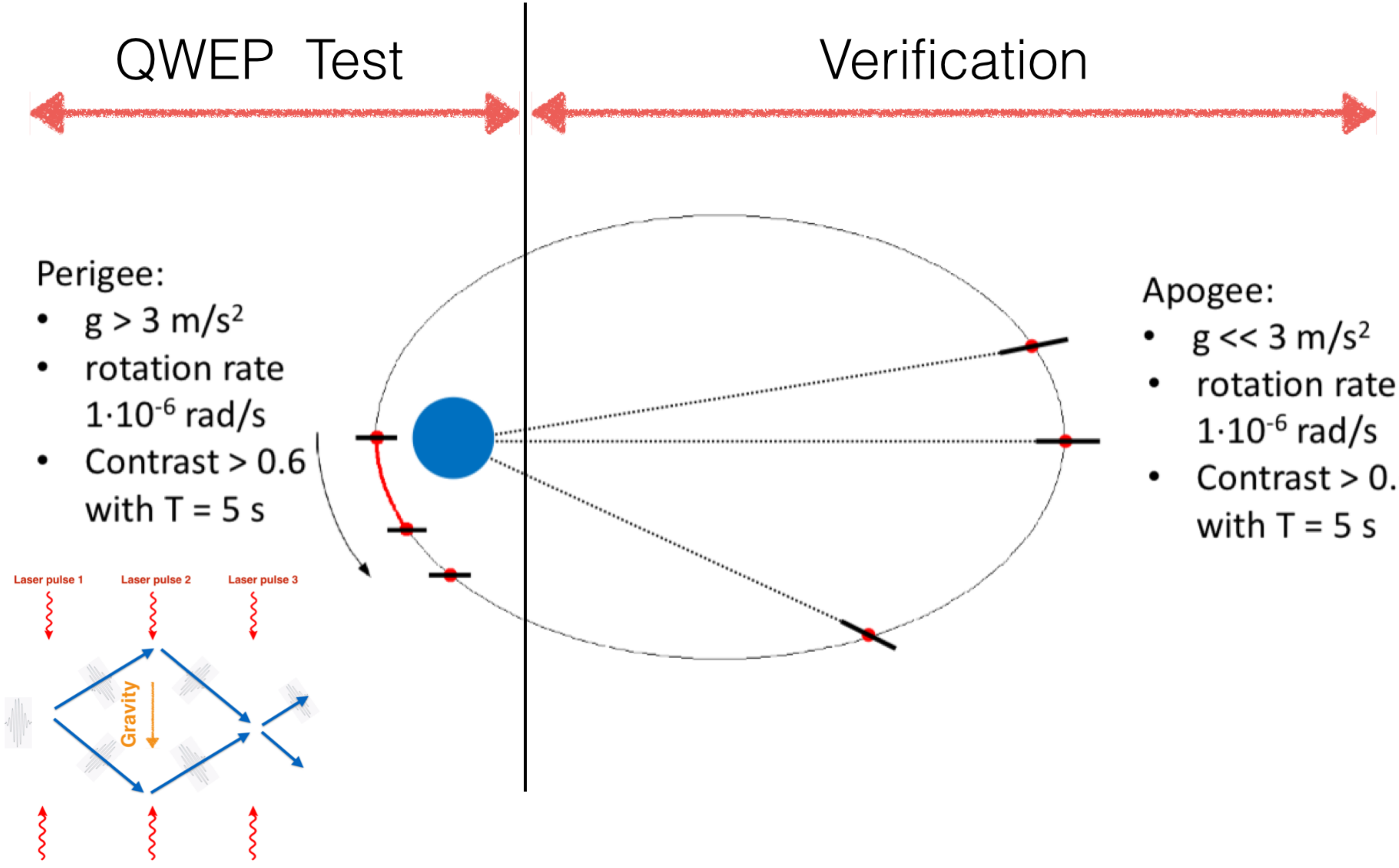
Unique signal due to gravity



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

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

STE-QUEST Measurement strategy



QWEP Test

Verification

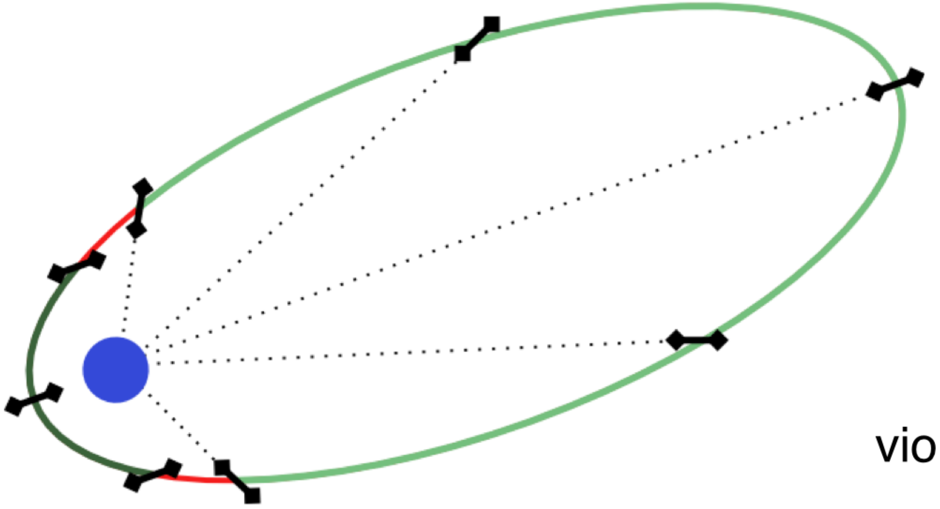
Perigee:
- $g > 3$ m/s^2
- rotation rate $1 \cdot 10^{-6}$ rad/s
- Contrast > 0.6 with T = 5 s

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

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

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



At perigee:

Gravity

$3\ \text{m/s}^2 < g < 8\ \text{m/s}^2$

↓

High sensitivity to violation (+ bias)

At apogee:

Gravity:

$g = 0.1\ \text{m/s}^2$

↓

Low sensitivity to violation signal (+ bias)

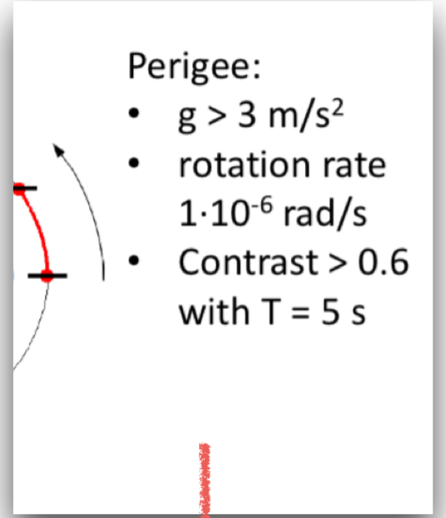
↓

Bias estimation

Assumption: bias Δa stable during time / orbit

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

STE-QUEST QWEP Measurement



Perigee:

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

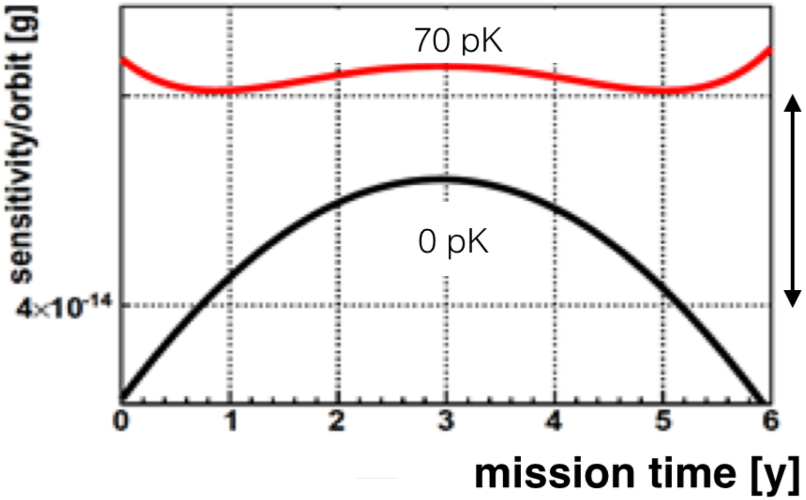
Sensitivity: $\sigma_{\Delta a} = 2.92 \cdot 10^{-12}\ \mathrm{m/s^2}$

(single shot, differential, 60 % contrast at 700 km altitude)

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

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

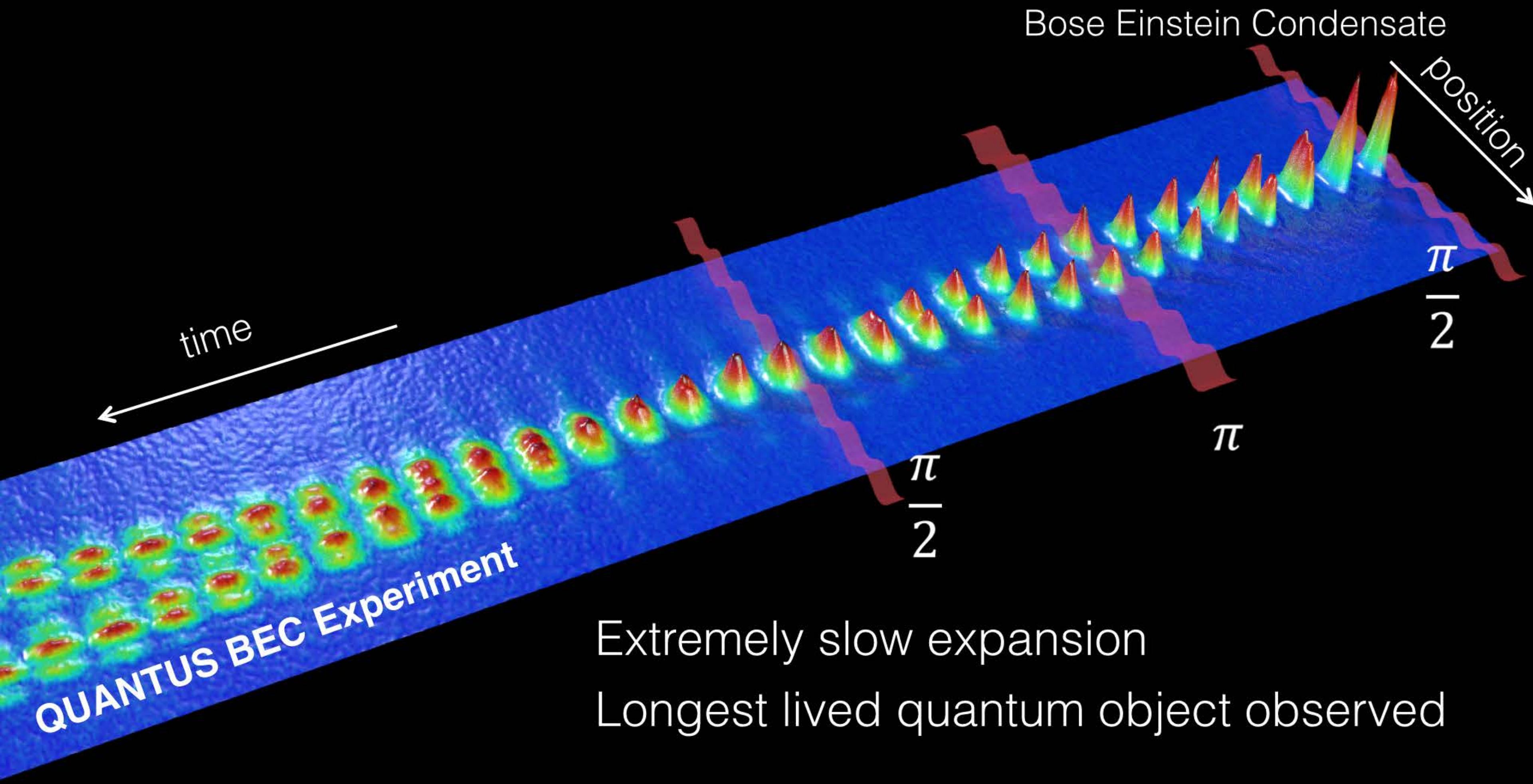
Need for Ultracold Atoms Bose-Einstein Condensate



$1 \cdot 10^{-14}$

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

Bose-Einstein condensates - ideal macroscopic wave packets

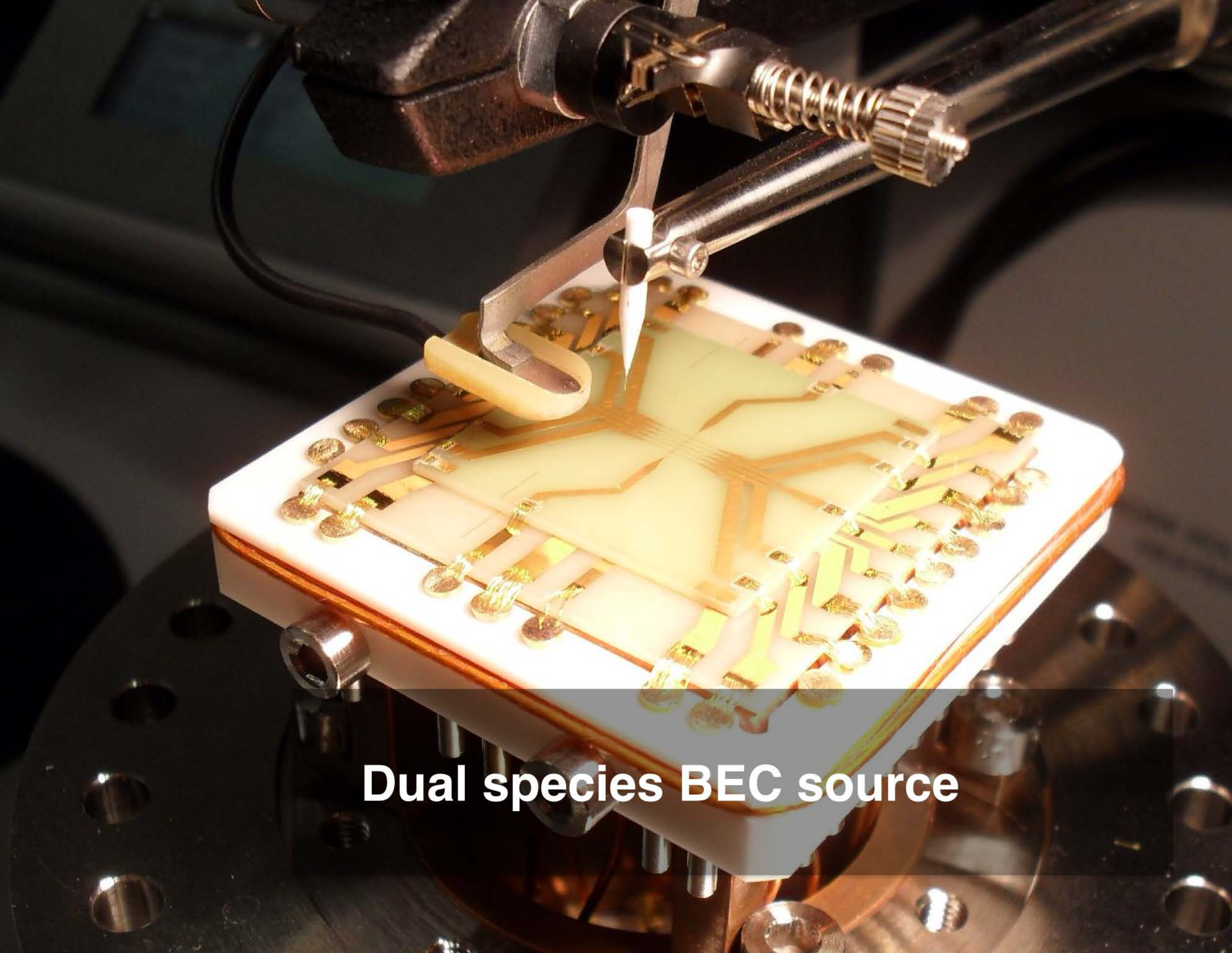


Extremely slow expansion

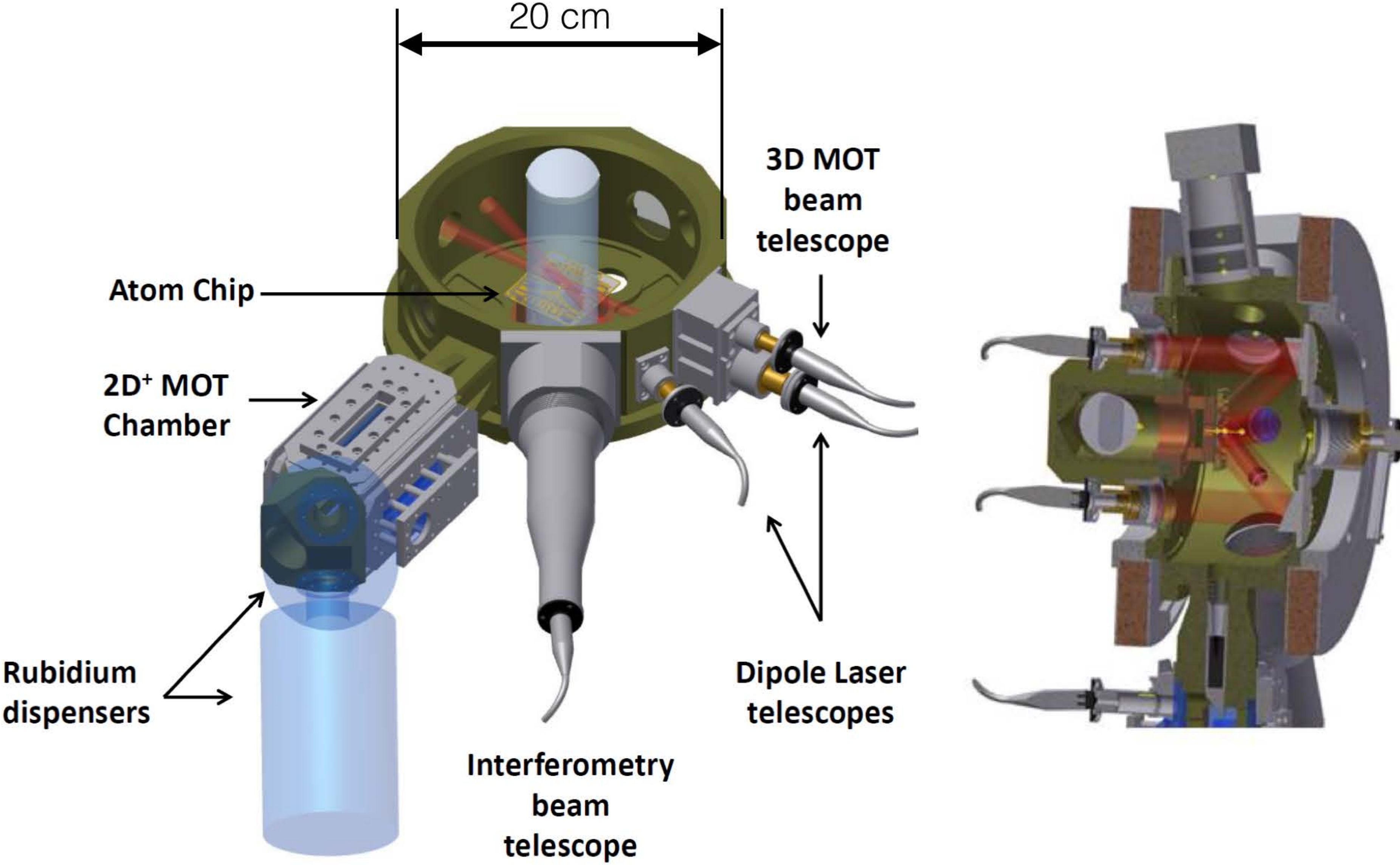
Longest lived quantum object observed

Muentinga et al., PRL 2013

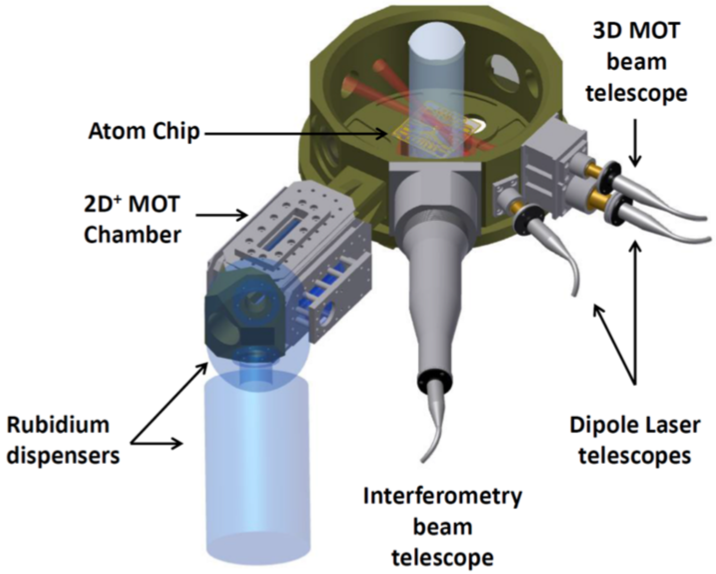
Dual species BEC source

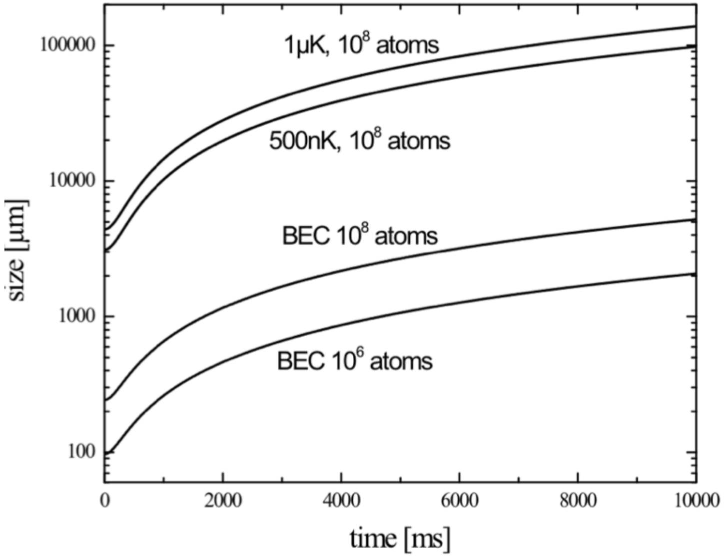


^{87}Rb and ^{85}Rb BEC source



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





- **10⁶** atoms of ^{87}Rb & ^{85}Rb
- Hybrid trap:

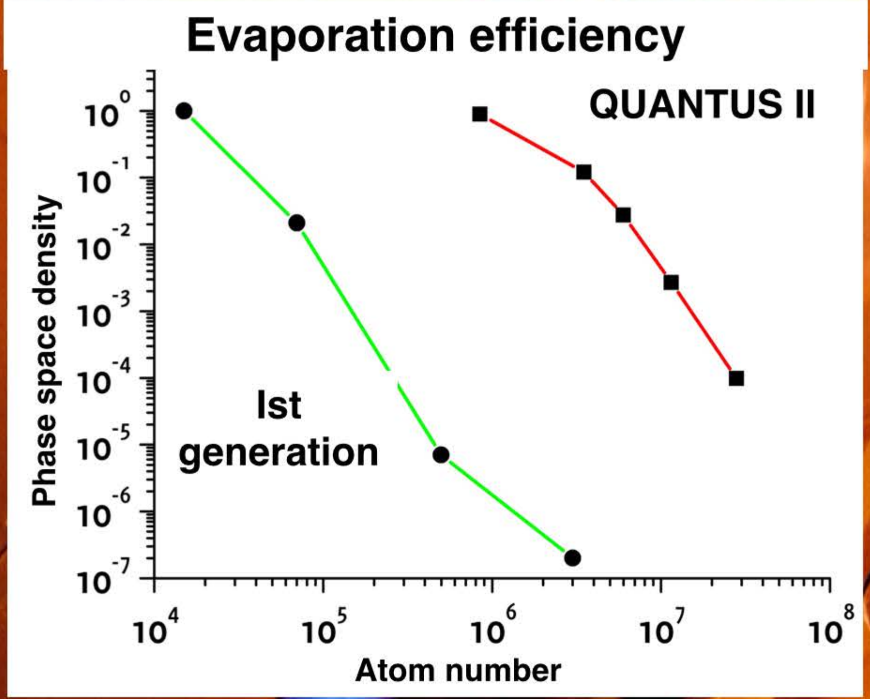
  magnetic and dipole trap
- Macroscopic wave packets
- Equiv. temperature 0.07 nK

  (Delta kick cooling)
- 10 s generation time
- 20 s total experimental cycle

  (Generation & interferometry)
- High contrast

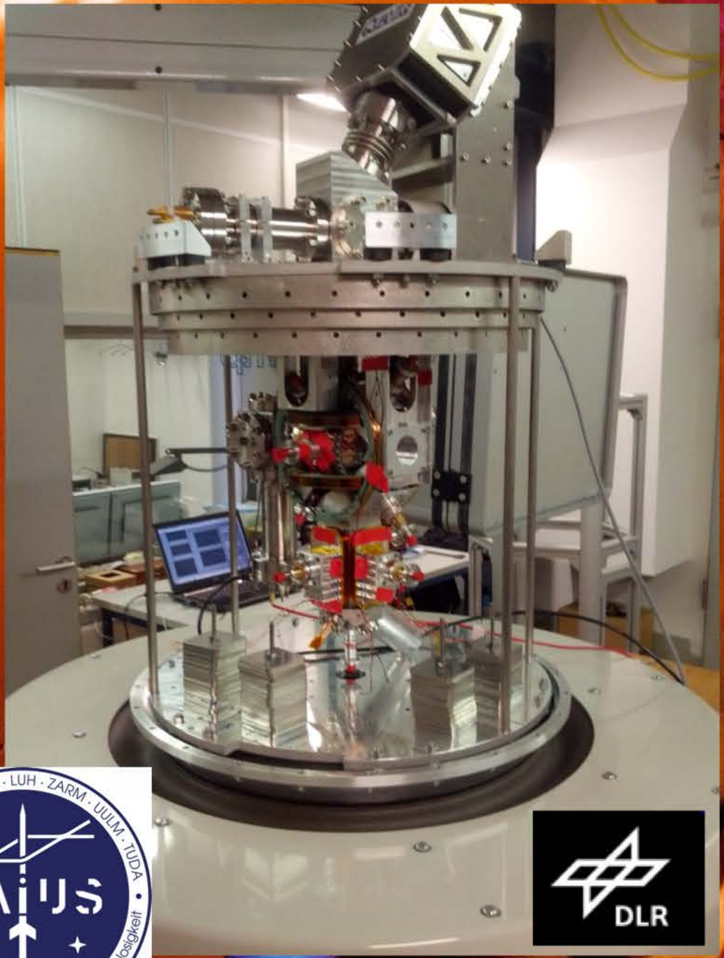
Atom chips
tested in the ZARM drop tower (over 400 drops)

- 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

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



UHH · FBH · HUB · DLR · LUH · ZARM · UULM · TUDA
MAIUS
Materiewelleninterferometer unter Schwerelosigkeit

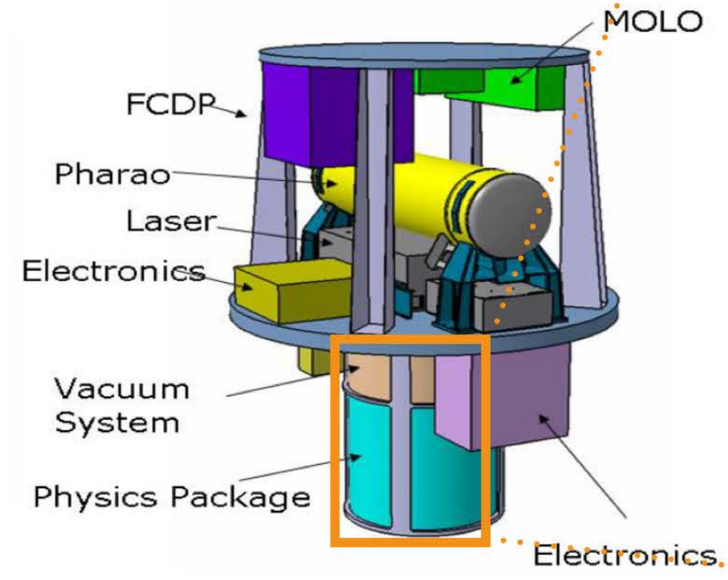
QUANTUS

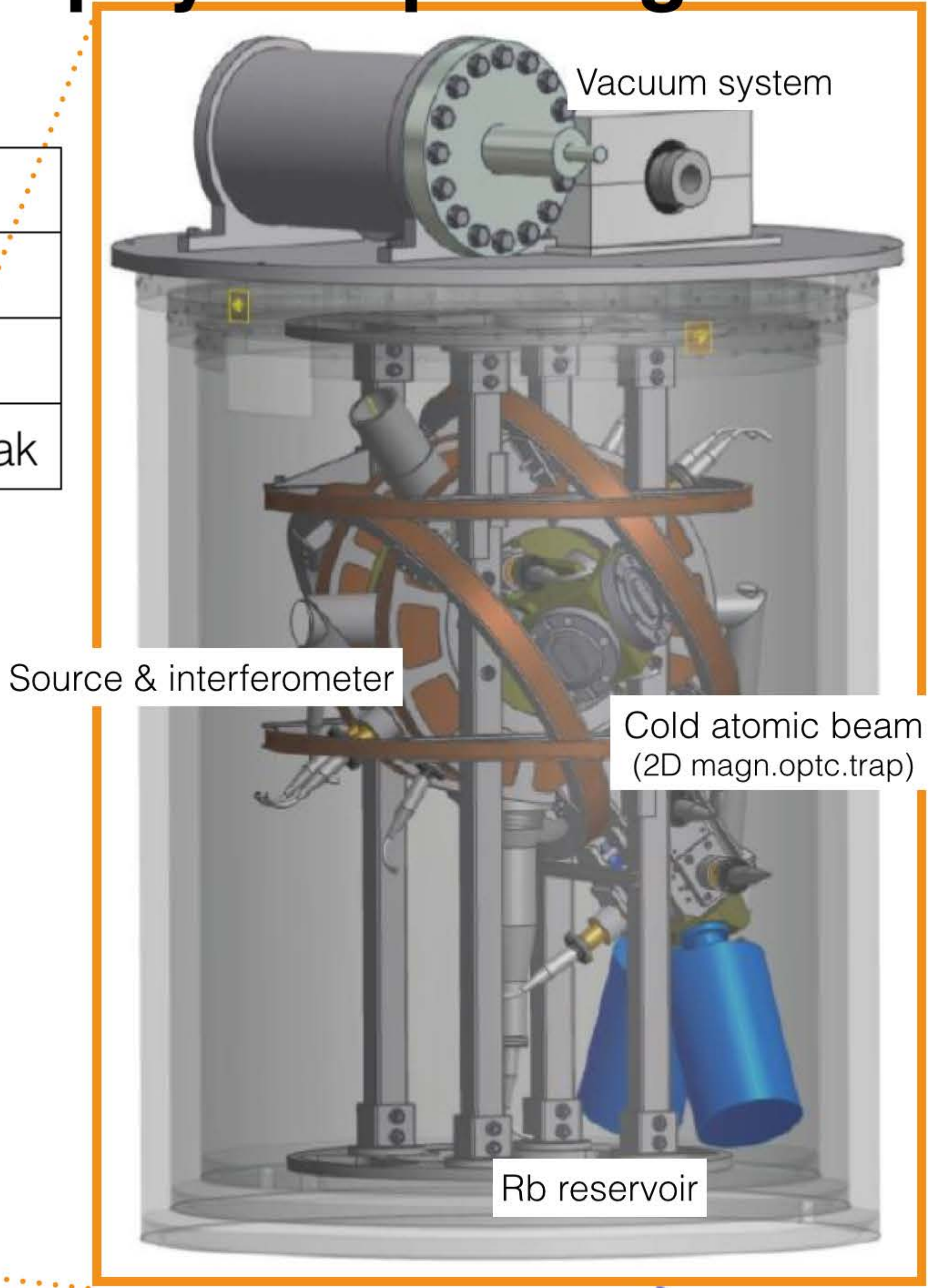
Atom interferometer physics package

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

(w.o. margins)

Satellite accommodation





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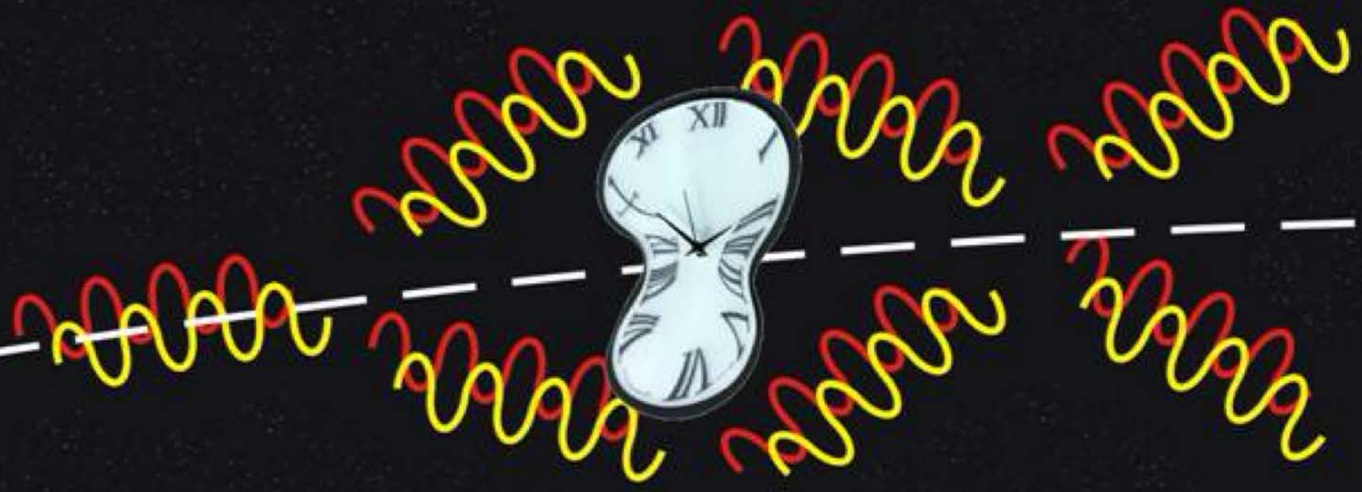
Resulting uncertainty in Eötvös ratio η



- 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	$-T_{zz}\ \Delta z$	$\Delta z = 1.1 \cdot 10^{-9}$ m	2.6	**Correlated Errors w.r.t. wave packet overlap**
	$-TT_{zz}\ \Delta v_z$	$\Delta v_z = 3.1 \cdot 10^{-10}$ m/s	3.5	
Coriolis acceleration	$-2\Omega_y\ \Delta v_x$	$\Delta v_x = 3.1 \cdot 10^{-10}$ m/s	$-6.3 \cdot 10^{-1}$	
	$-2\Omega_x\ \Delta v_y$	$\Delta v_y = 3.1 \cdot 10^{-10}$ m/s	$-6.3 \cdot 10^{-1}$	
Other terms (rotations / gradients)	$-(\Omega_{orb}^2 - \Omega_c^2)\ \Delta z$	$\Delta x = 1.1 \cdot 10^{-9}$ m	$-3.2 \cdot 10^{-3}$	
	$-T(6\Omega_c\Omega_{orb} - 3\Omega_{orb}^2 - 3\Omega_c^2)\ \Delta v_z$	$\Delta y = 1.1 \cdot 10^{-9}$ m	$< 10^{-3}$	
	$T(2\Omega_{orb}^3 + \Omega_c^3)\ \Delta x$	$T_{zz} = -2GM_e/R^3 = -2.26 \cdot 10^{-6}\ s^{-2}$	$4.9 \cdot 10^{-2}$	
	$TT_{xx}\Omega_{orb}\ \Delta x$	$\Omega_c \approx \Omega_{orb} = 1.4$ mrad/s,	$9.1 \cdot 10^{-3}$	
	$-7/6 \cdot T^2 T_{zz}\Omega_{orb}\ \Delta v_x$	$\Omega_c - \Omega_{orb} \approx \Omega_x = \Omega_y = 1\ \mu$rad/s	$2.9 \cdot 10^{-2}$	
	$-7/6 \cdot T^2 T_{xx}\Omega_{orb}\ \Delta v_x$	$T_{xx} = T_{yy} = -T_{zz}/2$	$-1.5 \cdot 10^{-2}$	
	$-\Omega_{orb}\Omega_z\ \Delta y$		$-1.6 \cdot 10^{-3}$	
Photon recoil	$T^4 T_{zzz}\hbar^2 k^2/16\ (m_{87}^{-2} - m_{85}^{-2})$	$T_{zzz} = 6GM_e/R^4 = -9.57 \cdot 10^{-13}\ m^{-1}s^{-2}$	$3.9 \cdot 10^{-2}$	**Uncorrelated Errors**
Self-gravity		Apogee measurement - subtraction	1	
Magnetic field gradients	$B_0\ \delta B\ \hbar\ (K_{87}/m_{87} - K_{85}/m_{85})$	$B_0 = 100$ nT, $\delta B < 0.1$ nT/m, $K_{87} = 575.15$ Hz/G^2, $K_{85} = 1293.98$ Hz/G^2	1	
Effective wave front (beam splitter lasers)	$(T_{at,87}/m_{87} - T_{at,85}/m_{85})\ k_B/R_e$	λ/300 mirror → $R_e > 250$ km, $T_{at} = 0.07$ nK,	$6.3 \cdot 10^{-1}$	
		collimation $R_i \sim 400$ m → $R_e > 250$ km, $T_{at} = 0.07$ 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 μm, expansion rate 82 μm/s, tuned atom numbers uncertainty of 1000	$2 \cdot 10^{-5}$	
Spurious accelerations	CMRR · a_{spur}	CMRR = $2.5 \cdot 10^{-9}$, $a_{spur} = 4 \cdot 10^{-7}$ m/s^2	1	
Detection efficiency		$\lvert \eta - 1 \rvert < 0.003$	< 1	

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

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

Effects mimicking a QWEP violation

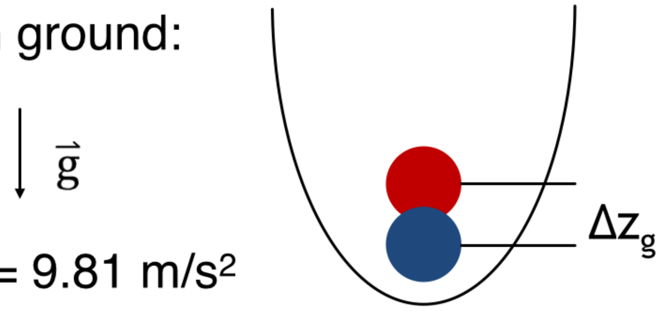
Imperfect overlap & differential velocities of ^{87}Rb and ^{85}Rb BECs in combination with gravity gradient cause differential acceleration

$$\Delta a = -T_{zz}\,\Delta z \qquad \Delta a = -TT_{zz}\,\Delta v_z$$

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

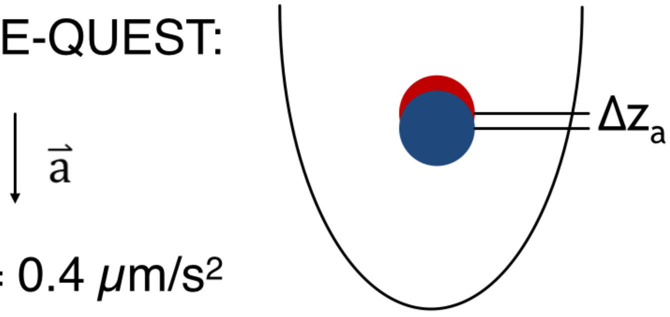
---

on ground:



$g = 9.81$ m/s²

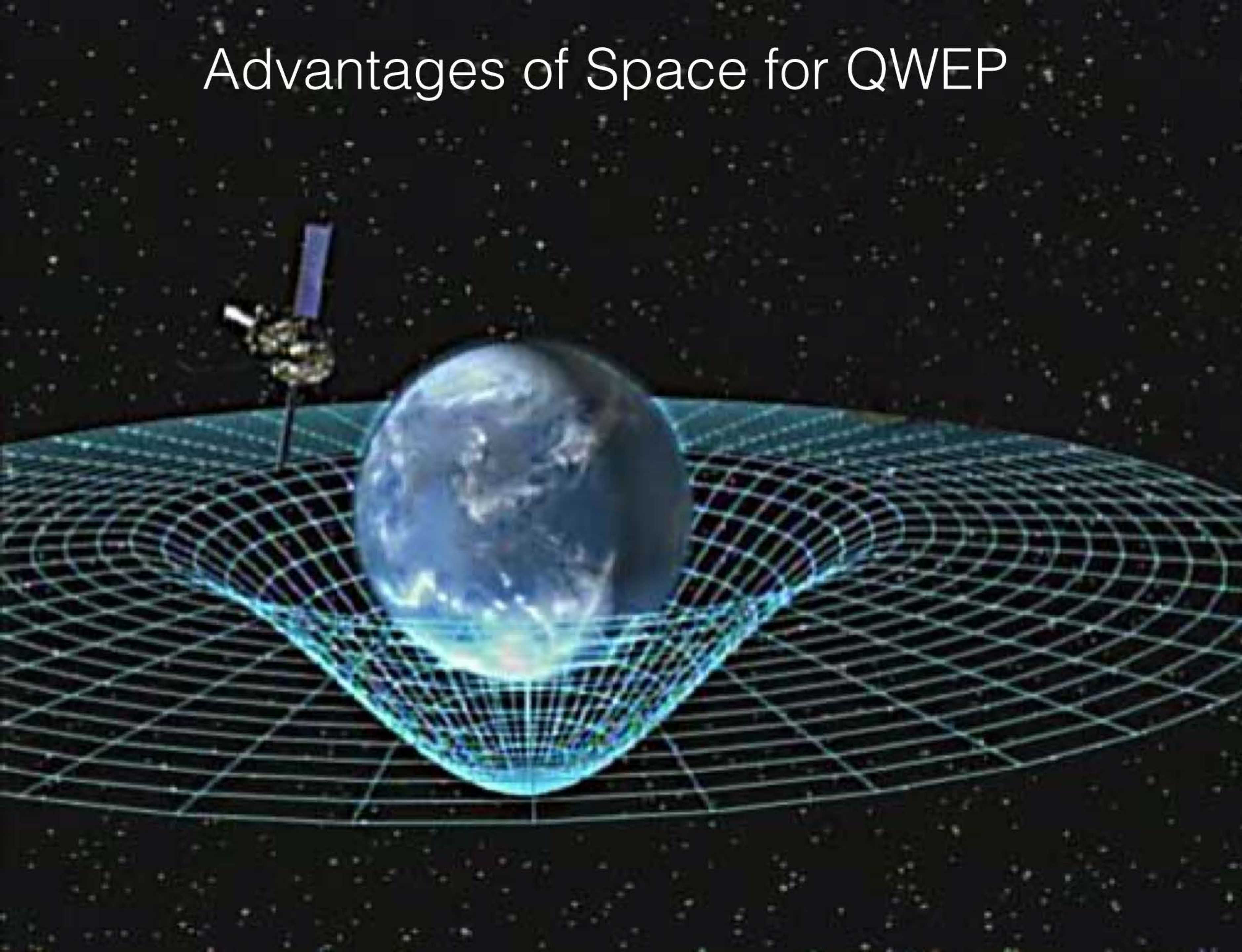
STE-QUEST:



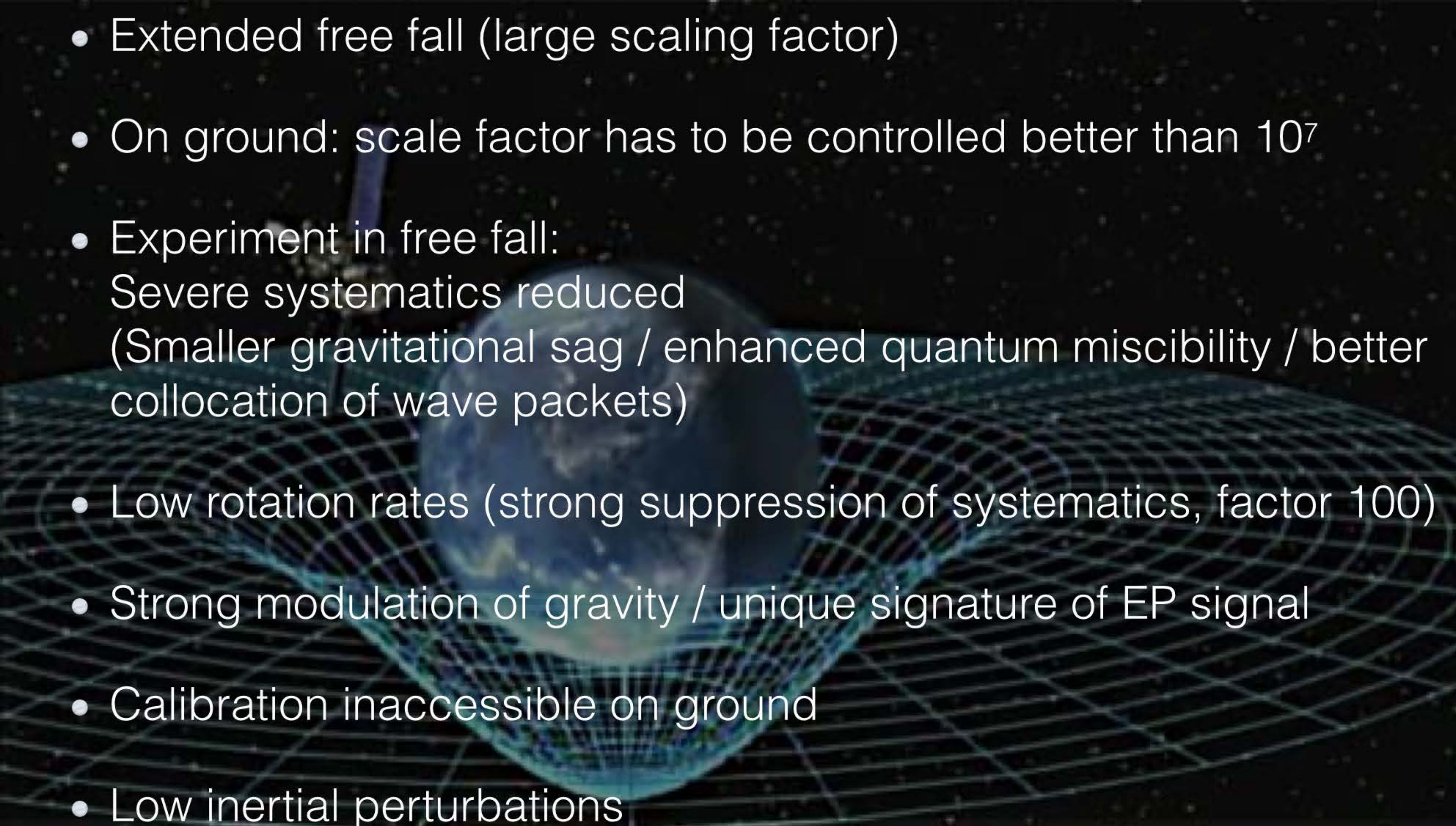
$a = 0.4\ \mu$m/s²

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 x 10^{-15}** (x 10^{6} improvement)
  - Test time dilation in the solar and the lunar gravitational potential, accuracy: **2 x 10^{-6}**, **4 x 10^{-4}**, resp.
    (x 10^{4}, x 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: Sterr/PTB (C. Hagemann et al., IEEE Trans. Instrum. Meas. 62, 1556-1562 (2013))

- 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