Transportable optical clocks: Towards gravimetry based on the gravitational redshift

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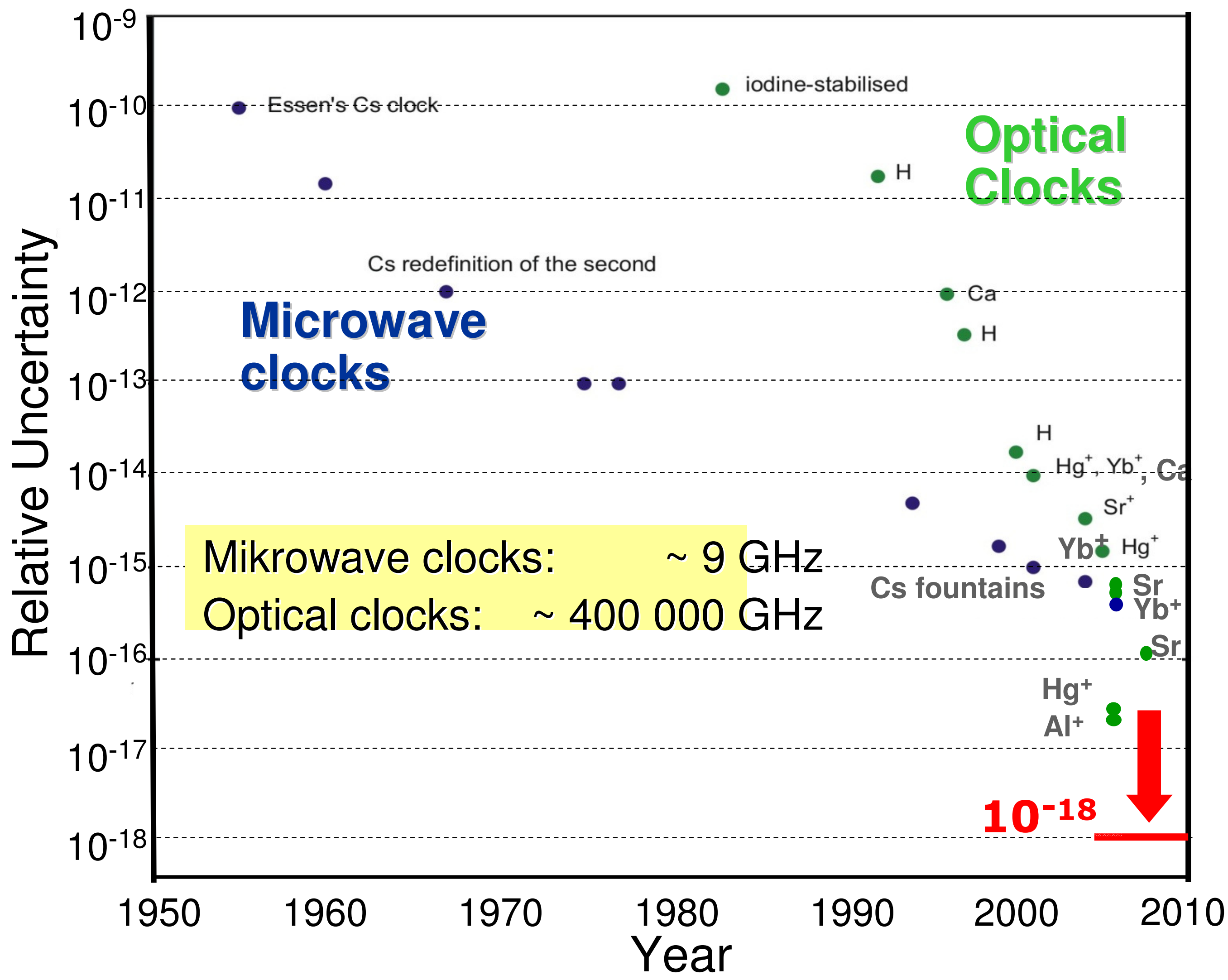
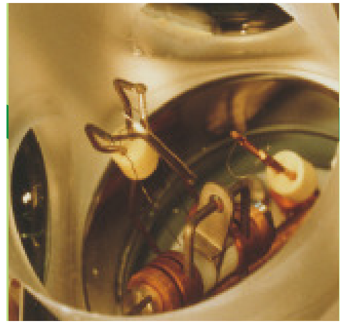
Towards a Roadmap for Future Satellite Gravity Missions, Graz 30.09 – 02.10. 2009

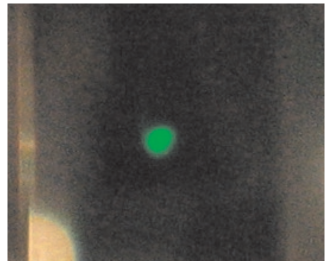
***Space Optical Clocks* (SOC)**

Evolution of atomic clocks





Single-ion trap (PTB)



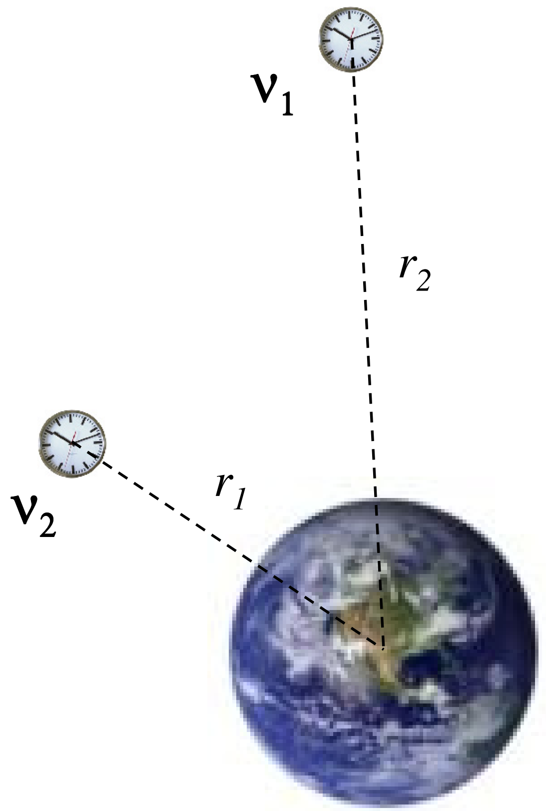
Neutral atom ensemble (HHUD)

Review: e. g. *P. Gill, Metrologia (2005)*

Applications of Optical Clocks

- Time and frequency distribution on earth (possibly „Master clock in space")
- Precision navigation in space, e.g. formation flying
- Ultraprecise tests of General Relativity
- Tests of time variation of fundamental constants
- Gravimetry

The gravitational frequency shift



- Two clocks at different positions

$$\Rightarrow \quad \frac{\nu_1 - \nu_2}{\nu} = \frac{U(r_1) - U(r_2)}{c^2}$$

gravitational potential

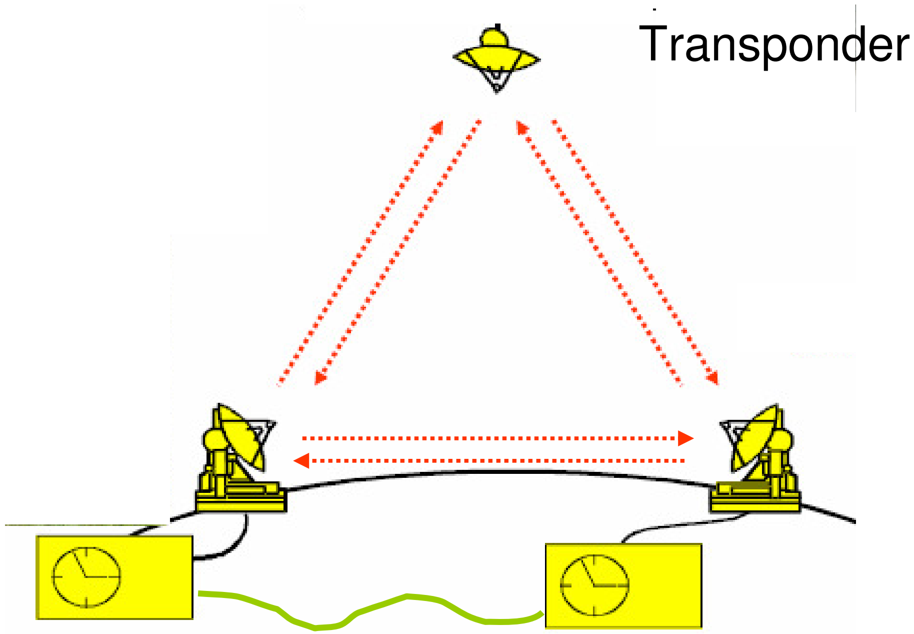
- On/near the earth surface

$$r_1 - r_2 = 1\ \text{cm} \ \Rightarrow \ \frac{\Delta\nu}{\nu} = 10^{-18}$$

- Optical clock as local probe of gravitational potential

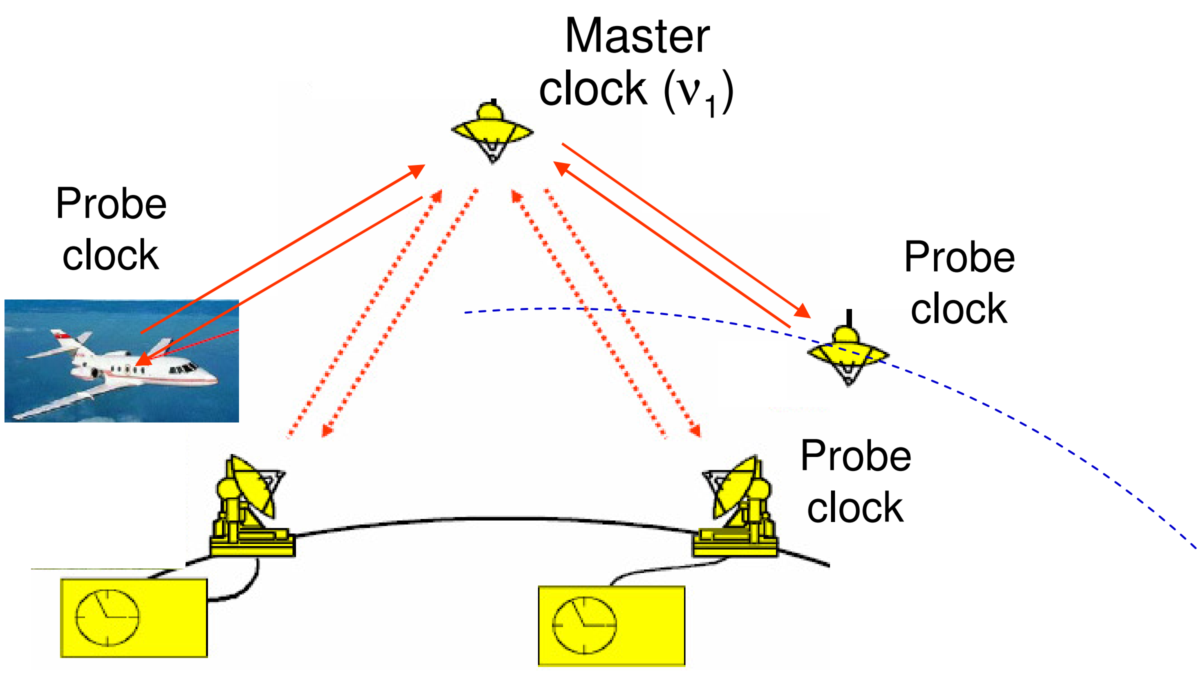
- Good time resolution (goal for clock uncertainty: $2 \times 10^{-16}\ \sqrt{s}$)

Differential measurement of the gravitational potential



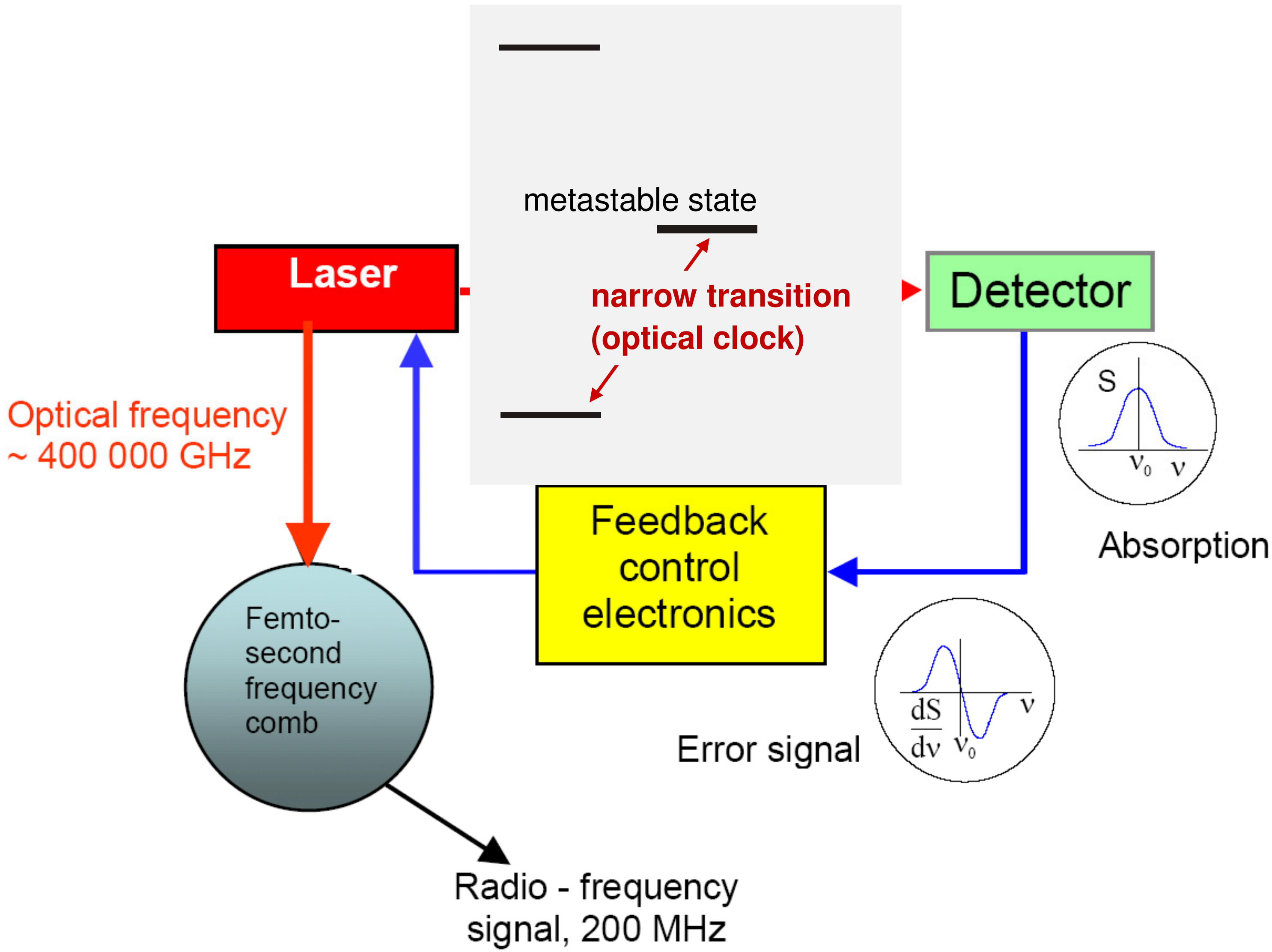
- Frequency comparison by: - Free-space link (~ 10 km)
  - Optical fiber (~ 100 km)
  - Transponder (any distance, intercontinental)
- Optical or microwave link possible
- Two-way link permits Doppler cancellation

Absolute measurement of the gravitational potential



- Comparison with a reference clock („master clock“)
- Possible location of „master clock“: geostationary orbit (low uncertainty of U)

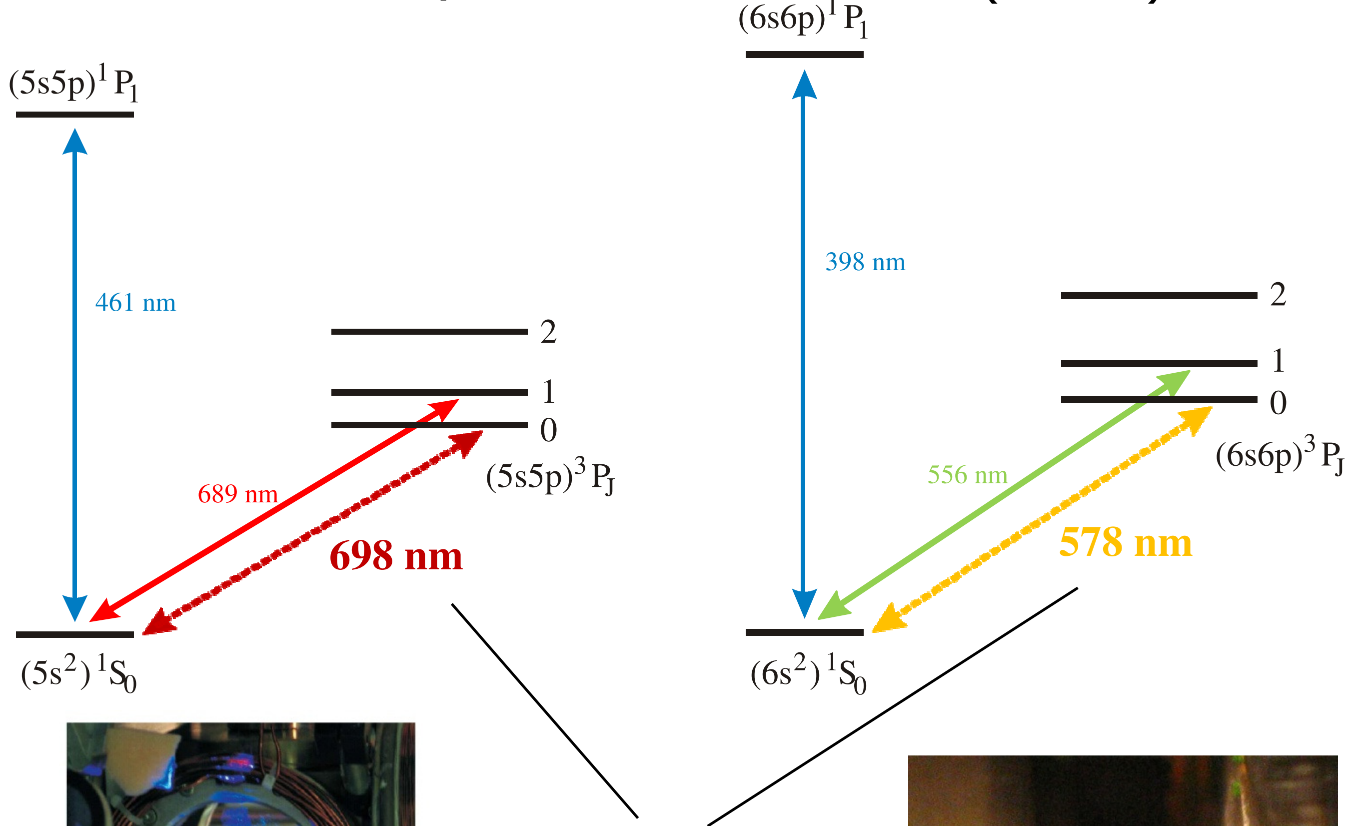
Optical lattice clock – operating scheme



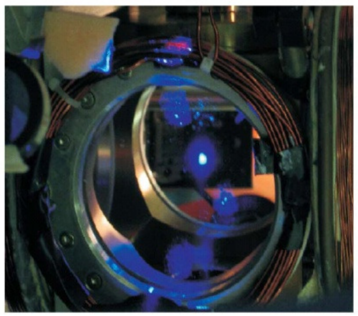
Optical lattice clock development within SOC

Strontium
(LENS, PTB, SYRTE)

Ytterbium
(HHUD)



clock transition



LENS

HHUD

Ultracold atom source

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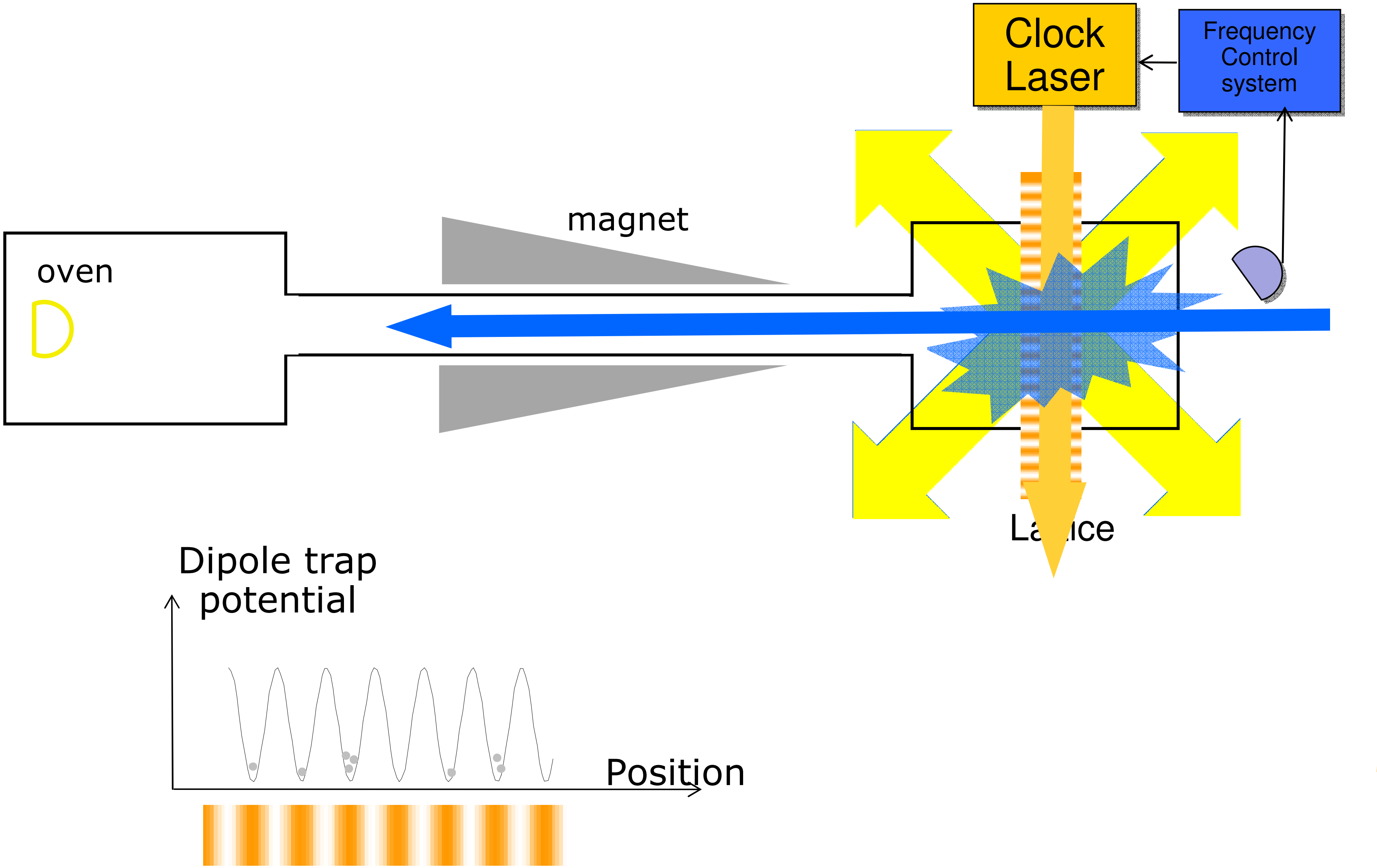
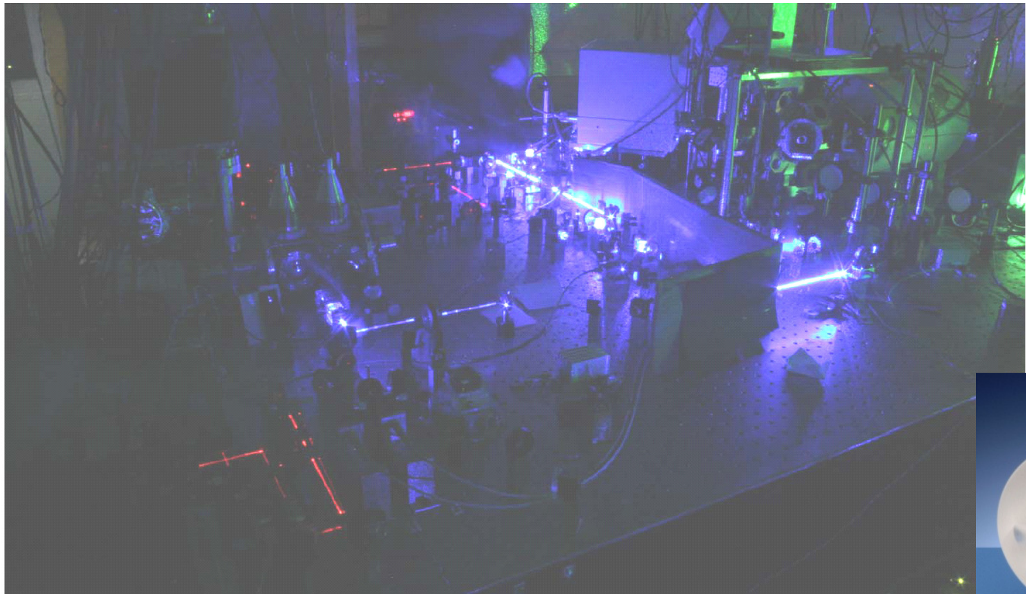


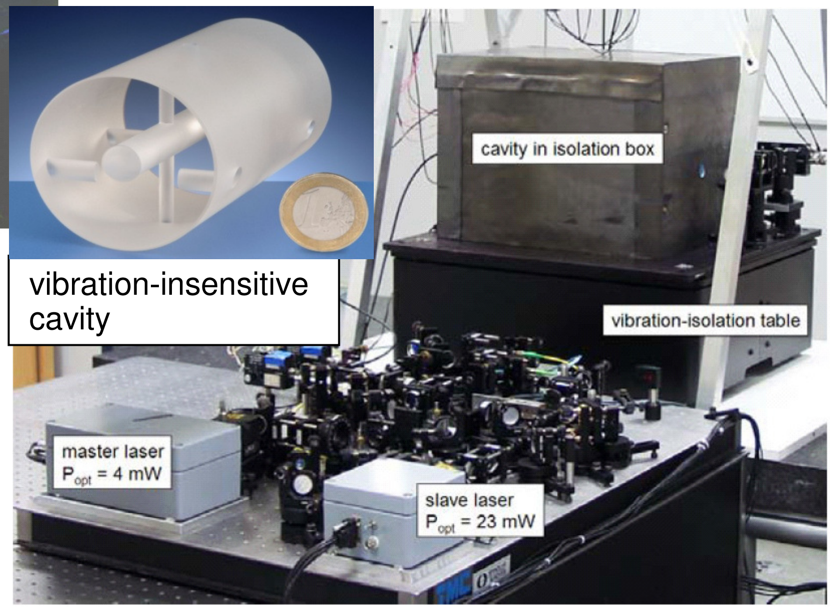
Strontium optical lattice clock - setup

Laboratory source of
ultracold atoms (partial view)



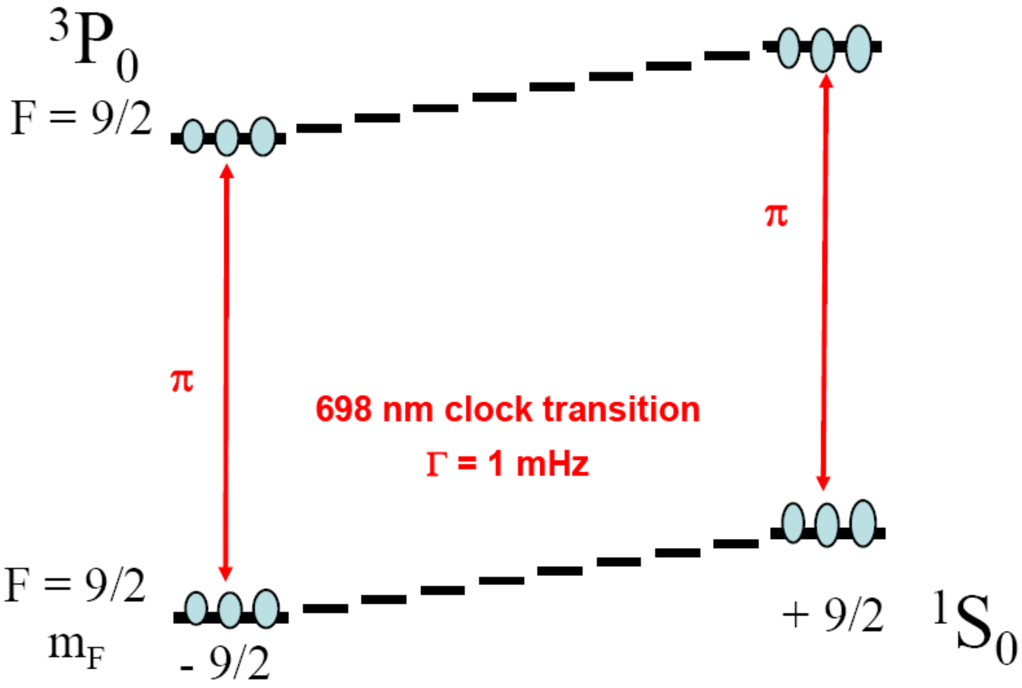
SYRTE

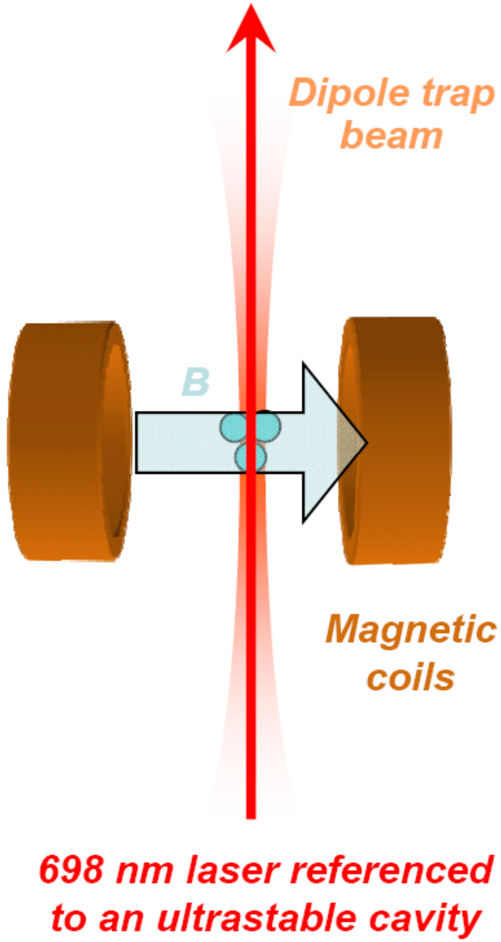
Clock laser



PTB

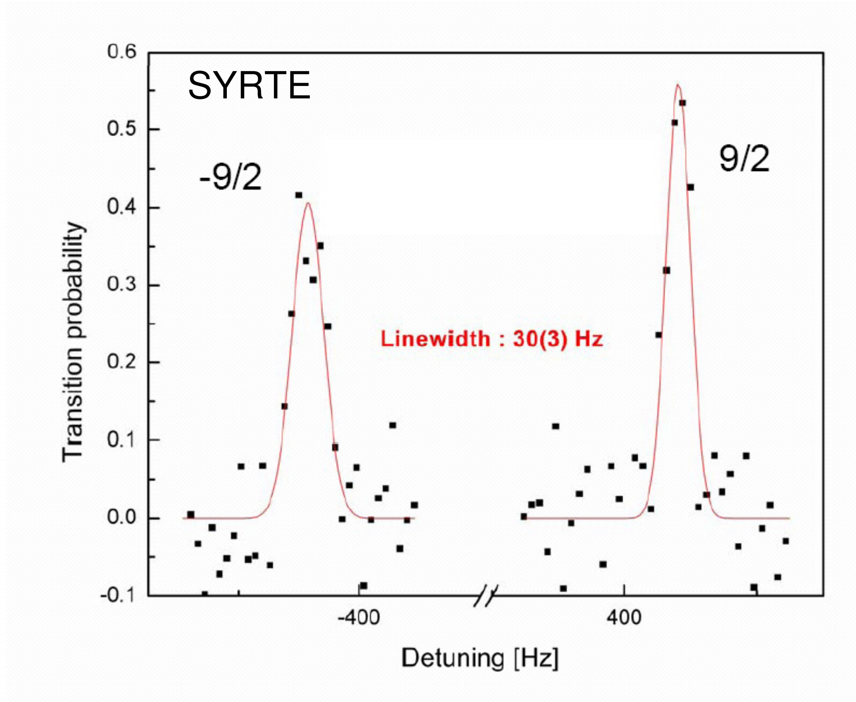
Clock transition spectroscopy



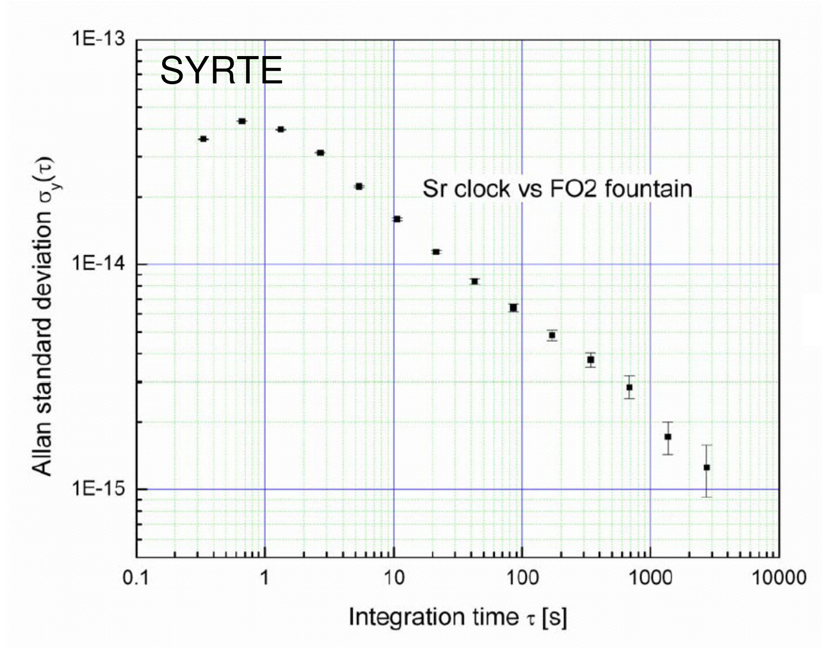


Strontium optical lattice clock - performance

Experimental resonance:



Frequency stability:



Sr clock frequency:

429 228 004 229 873.6 Hz

Lowest systematic uncertainty:

1 x 10^{-16} (JILA/NIST)

Ludlow et al., Science (2008)

Strontium optical lattice clock - accuracy budget

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Effect	Correction (Hz)	Uncertainty (Hz)	Fractional Uncertainty (10^{-15})
Zeeman	0.1	0.1	0.2
Probe laser Stark shift	0.1	0.1	0.2
Lattice AC Stark shift (100 Er)	0	0.1	0.2
Lattice 2nd order Stark shift (100 Er)	0	0.1	0.2
Line pulling (transverse sidebands & mF)	0	0.5	1.1
Cold collisions	0	0.1	0.2
BBR shift	2.39	0.1	0.1
Scatter of series #3	0	1	2.3
Fountain accuracy	0	0.2	0.4
Total	**2.59 Hz**	**1.1 Hz**	**2.6 10^{-15}**

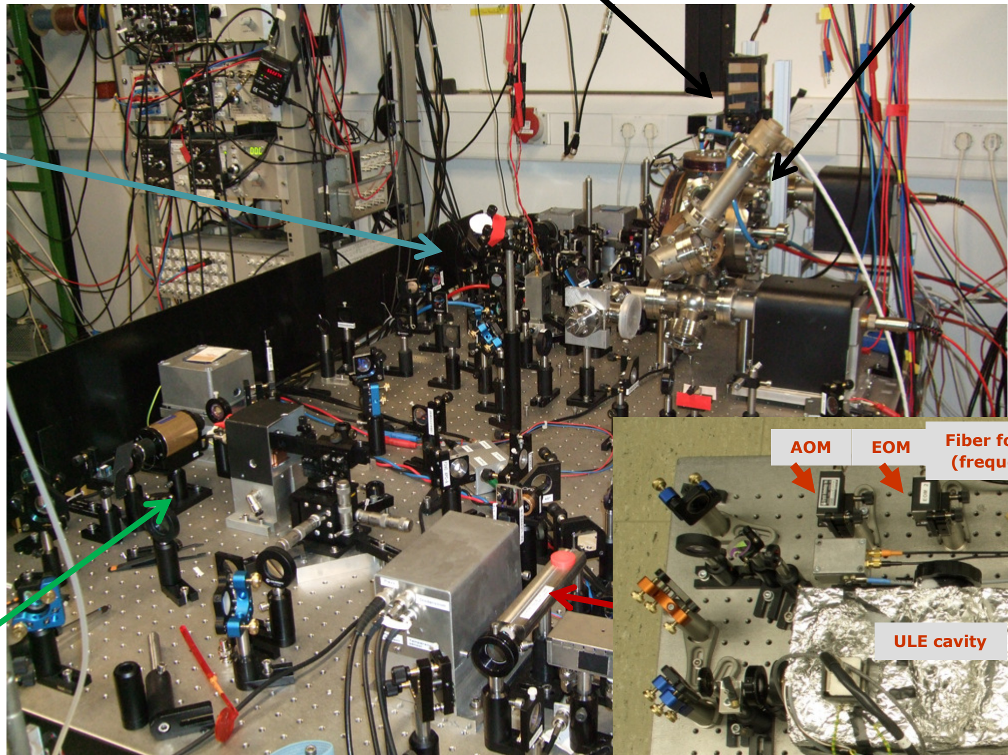
Compact clock apparatus - Yb

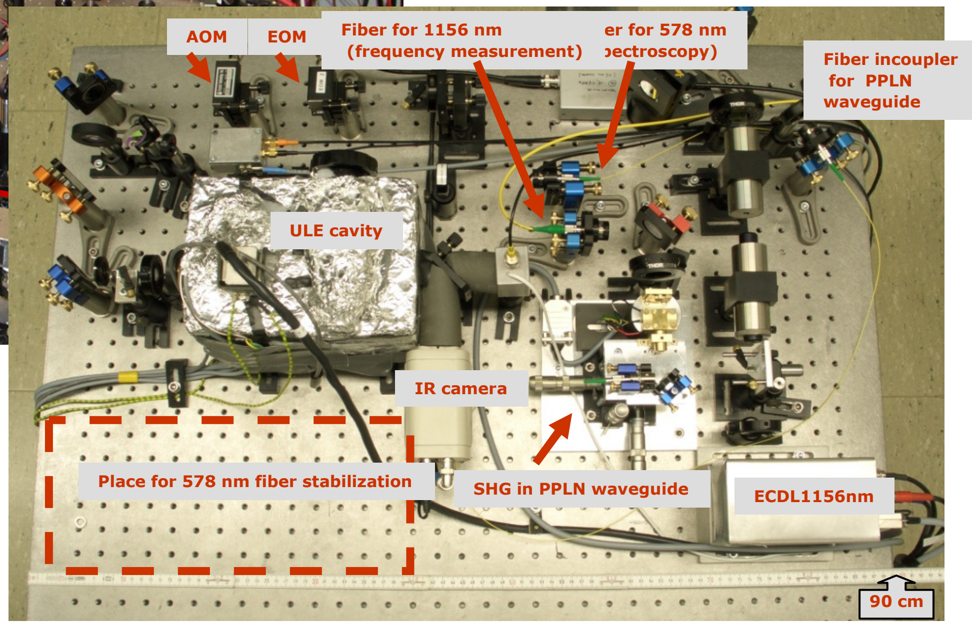
Spectroscopy beam

Main chamber

„Blue“ laser system (399 nm)

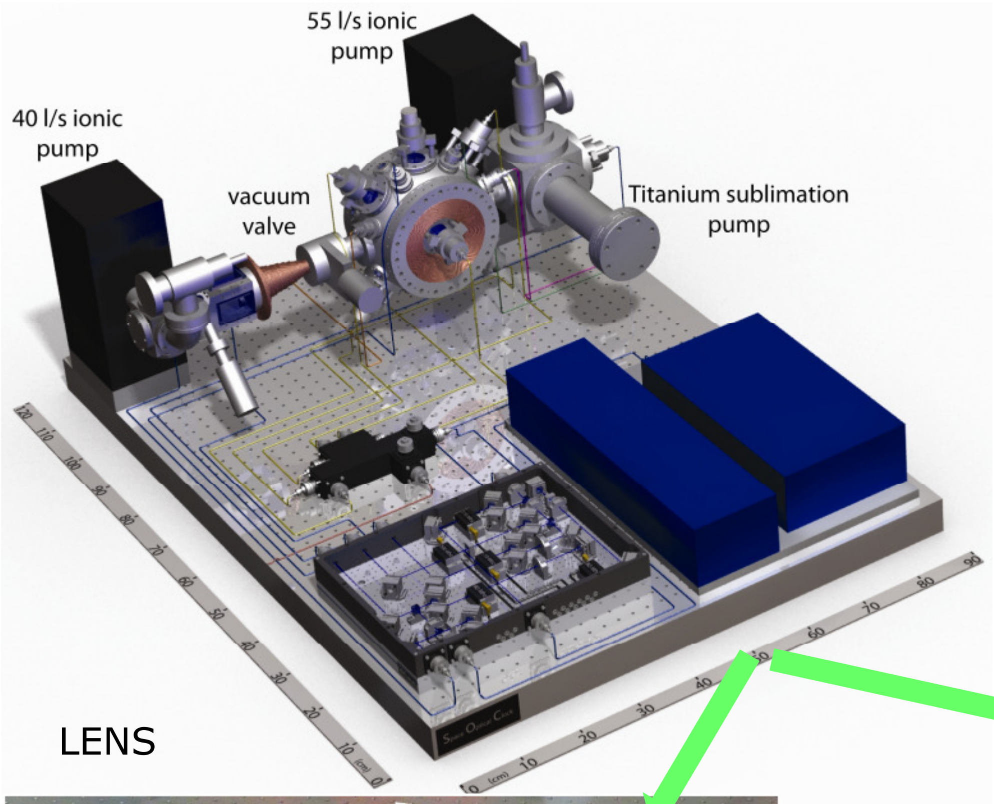
„Green“ laser (556 nm)

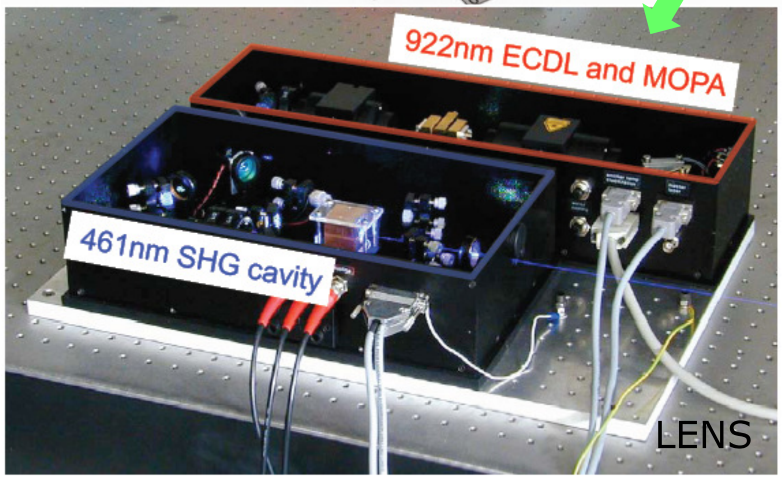


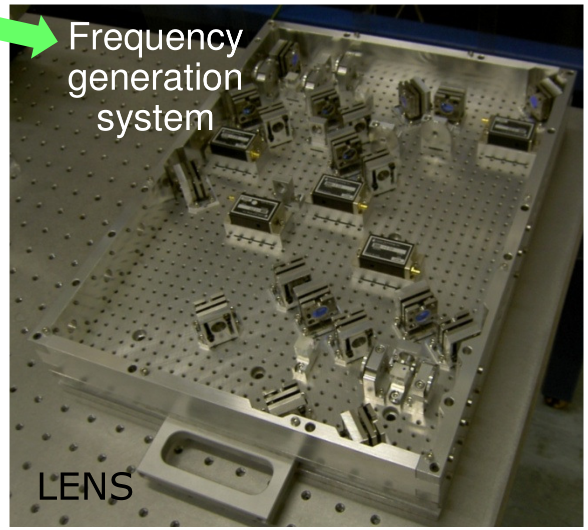


Transportable source - Sr

- Small footprint (110 x 90 cm)
- Low power consumption
- High-power diode laser system for 1st stage cooling
- Move from Florence to Braunschweig in January 2010

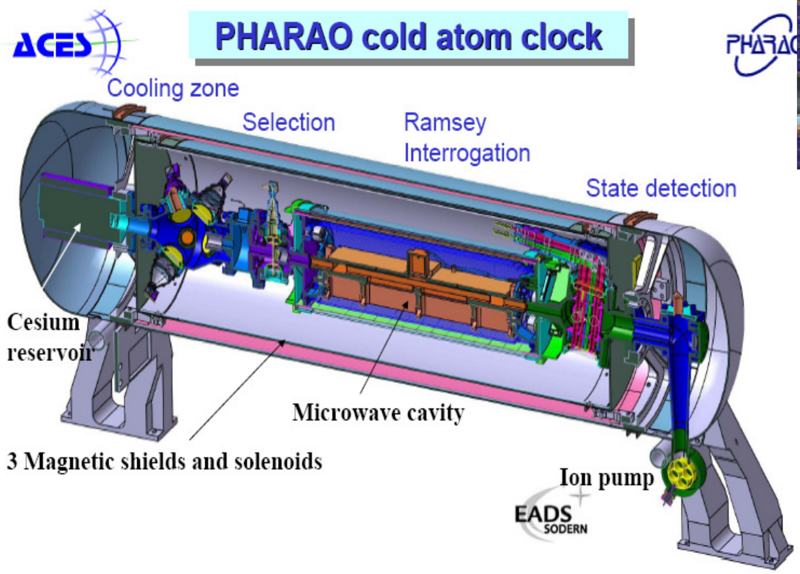


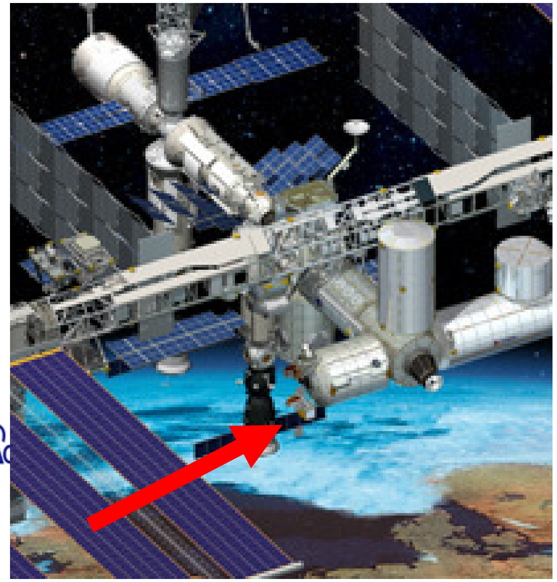




Atomic clocks for space - ACES

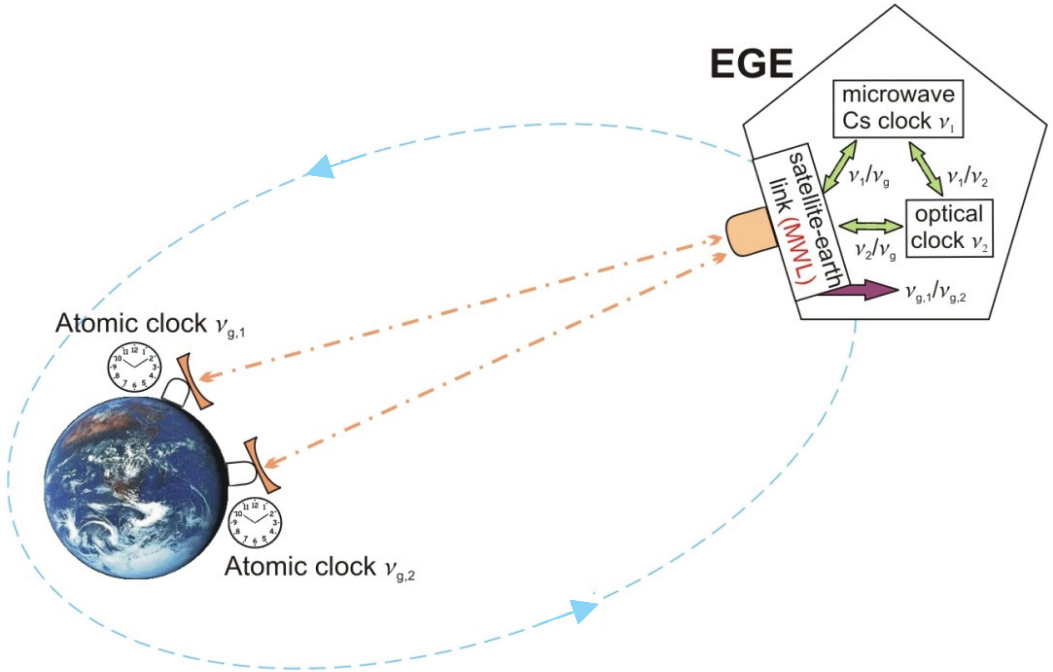
- Projected launch: ~ 2014
- PHARAO: cold atom microwave clock
- instability $1 \cdot 10^{-13}$ at 1 s, $4 \cdot 10^{-16}$ at 50 000 s
- accuracy ~ $1 \cdot 10^{-16}$
- technology demonstrator
- world-wide time dissemination and comparisons
- test of special and general relativity





Future applications of transportable optical clocks: Einstein Gravity Explorer

- Proposal within *Cosmic Vision*
- Ultrahigh stability optical clock (Ion and/or neutral atom)
- Primary objective: Fundamental tests of general relativity



- Projected resources: 200 W, 155 l, 125 kg (clock + frequency comb only)

Status and Perspectives

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- Optical Clocks of 10^{-16} accuracy could be turned into transportable or space instruments within ~ 5 years
- More than 15 research groups work on advanced optical clocks (natl. metrology labs, university groups)
- Developments in quantum information/atom interferometry help advancing technological development
- ESA support for several studies on optical clocks, including demonstrator developments („**Space Optical Clocks**")
- Transportable demonstrator(s) ready by 2010
- Clocks of 10^{-18} accuracy within 15 years possibly available
- Projected (minimal) resources: ~ 200 W, 155 l, 125 kg