The compact lattice optical clock `SOC2´: performance and perspectives for the ACES mission

S. Origlia, M. S. Pramod, S. Schiller (HHU Düsseldorf),

Y. Singh, K. Bongs (U. of Birmingham),

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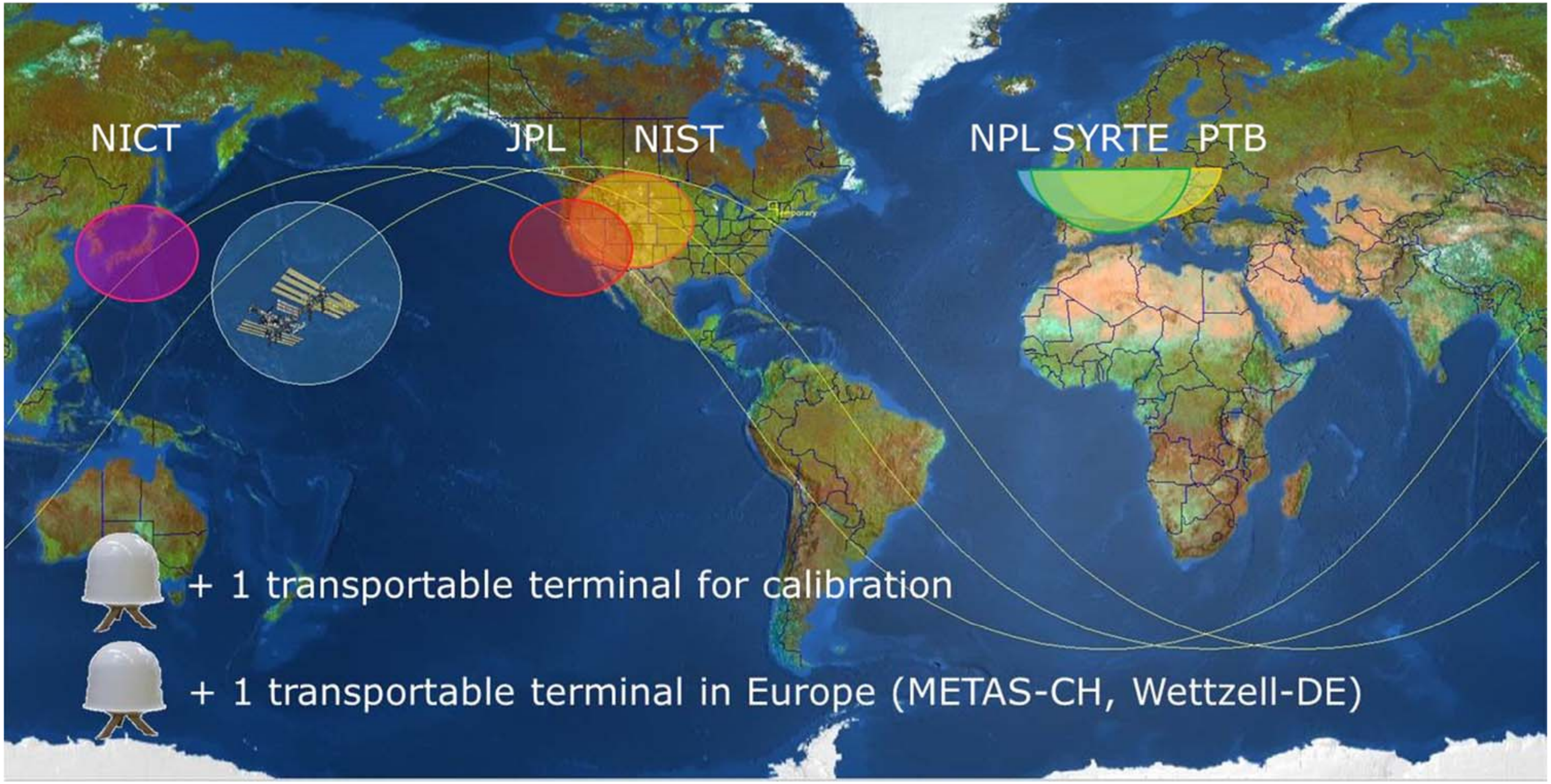
S. Häfner, U. Sterr, Ch. Lisdat (PTB Braunschweig)

Work funded under:
HHU, Behmenburg Schenkung, FP-7 ITN “FACT”, H2020-RISE “Q-Sense”, ESA “I-SOC”, CRC 1227 DQ-mat, RTG 1729, EMPIR 15SIB03 OC18.

Contents

- A transportable optical lattice clock for the ACES mission
- The breadboard demonstrator of the I-SOC clock
- Comments on I-SOC
- Plans and Conclusion

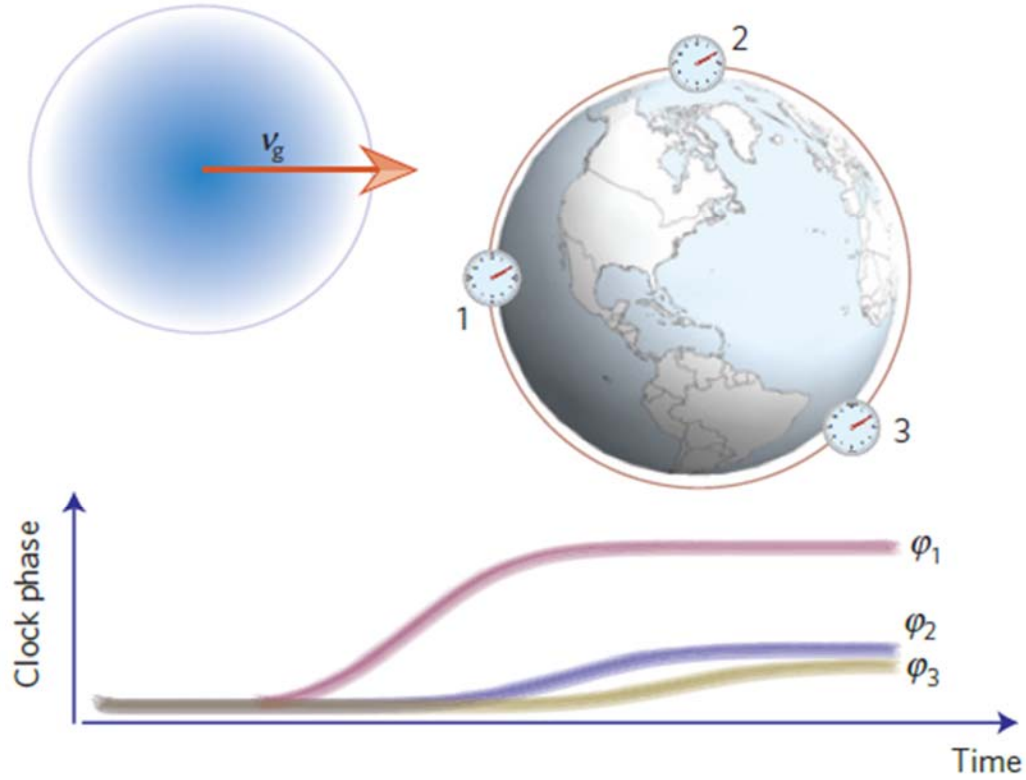
Intercontinental comparisons



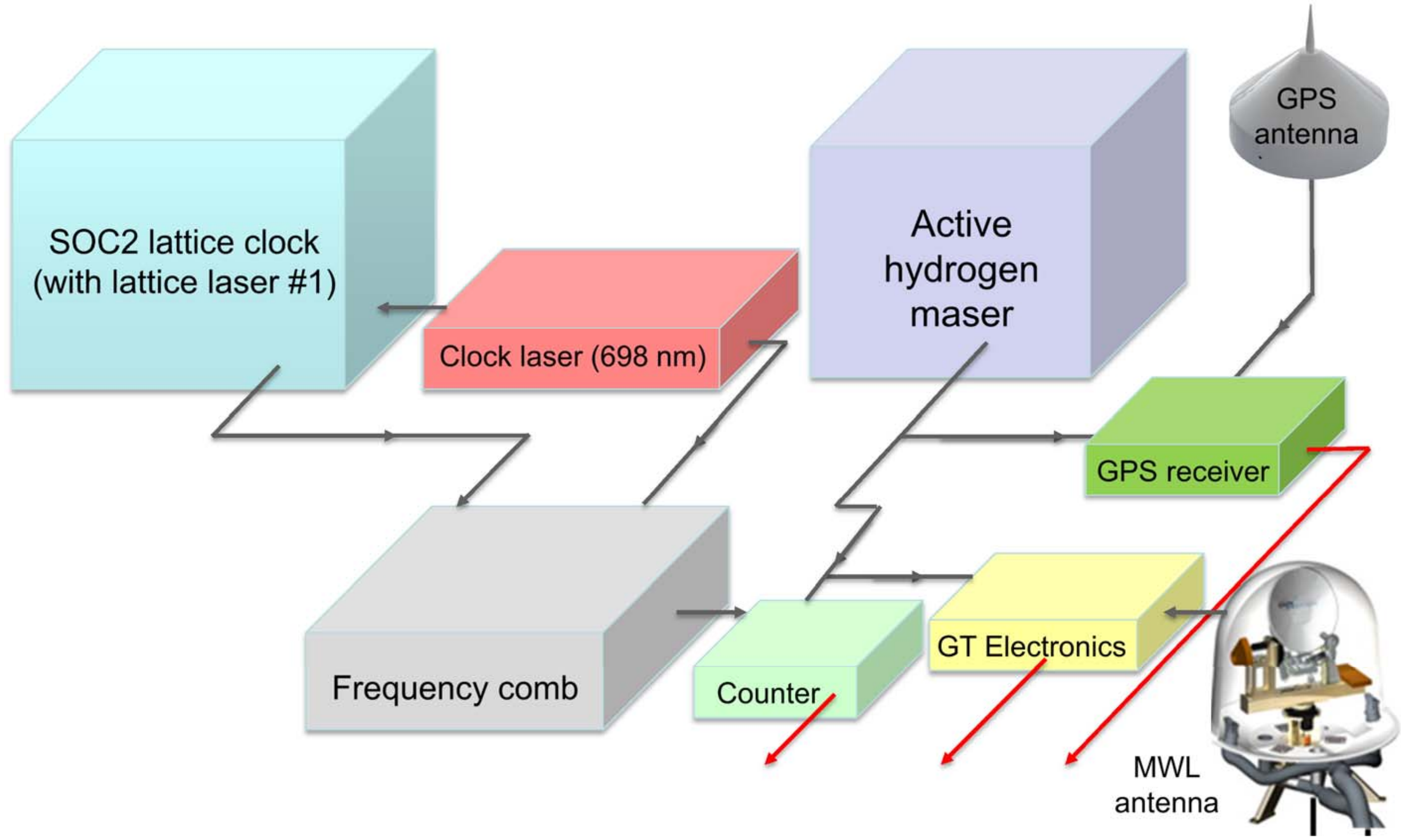
Comparing clocks in an Earth-scale network

- Search for dark matter topological defects crossing the Earth
  Derevianko & Pospelov, Nature Phys. 10, 933 (2014)

- Differential phase shift between distant clocks

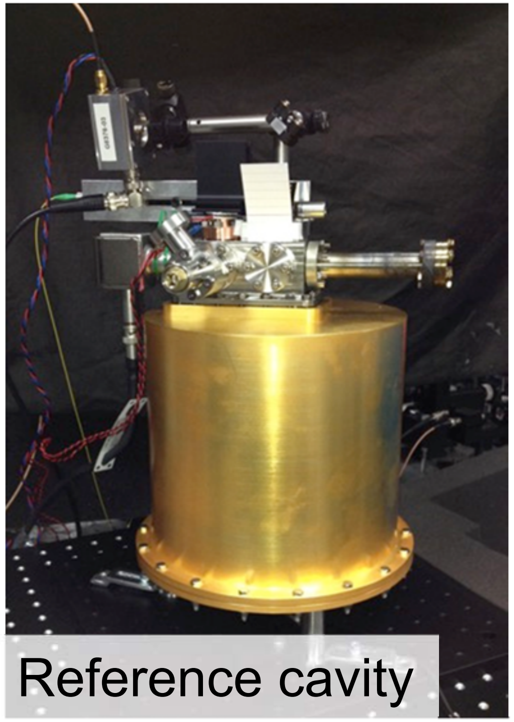


Configuration of SOC2 clock for ACES ground use

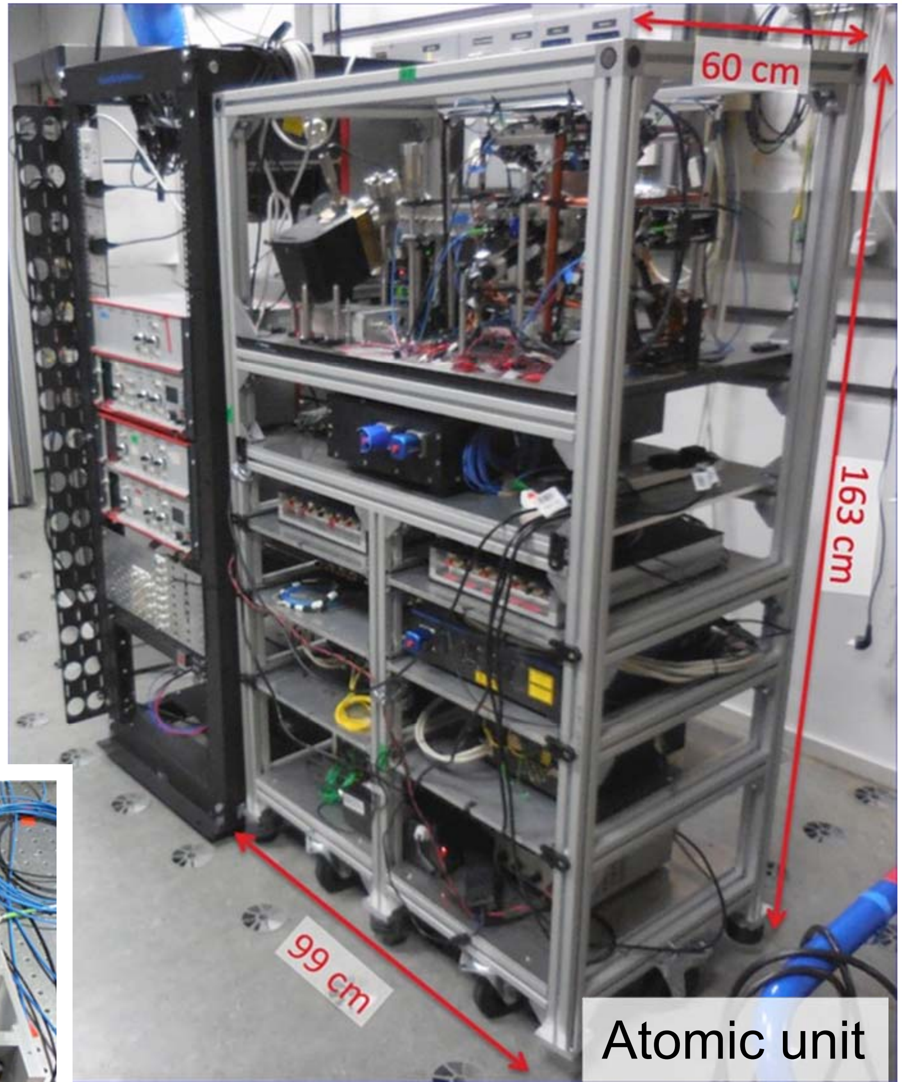


SOC breadboard demonstrator development (2010-15)

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF
PTB
Leibniz Universität Hannover
l'Observatoire de Paris – SYRTE
Systèmes de Référence Temps-Espace
INRiM – ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITY OF BIRMINGHAM
NPL National Physical Laboratory
TOPTICA PHOTONICS
KAYSER-THREDE
Ein Unternehmen der OHB Technology AG
EADS astrium
MenloSystems GmbH
KAYSER ITALIA
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LTF Université de Neuchâtel unine
csem centre suisse d'électronique et de microtechnique


Reference cavity

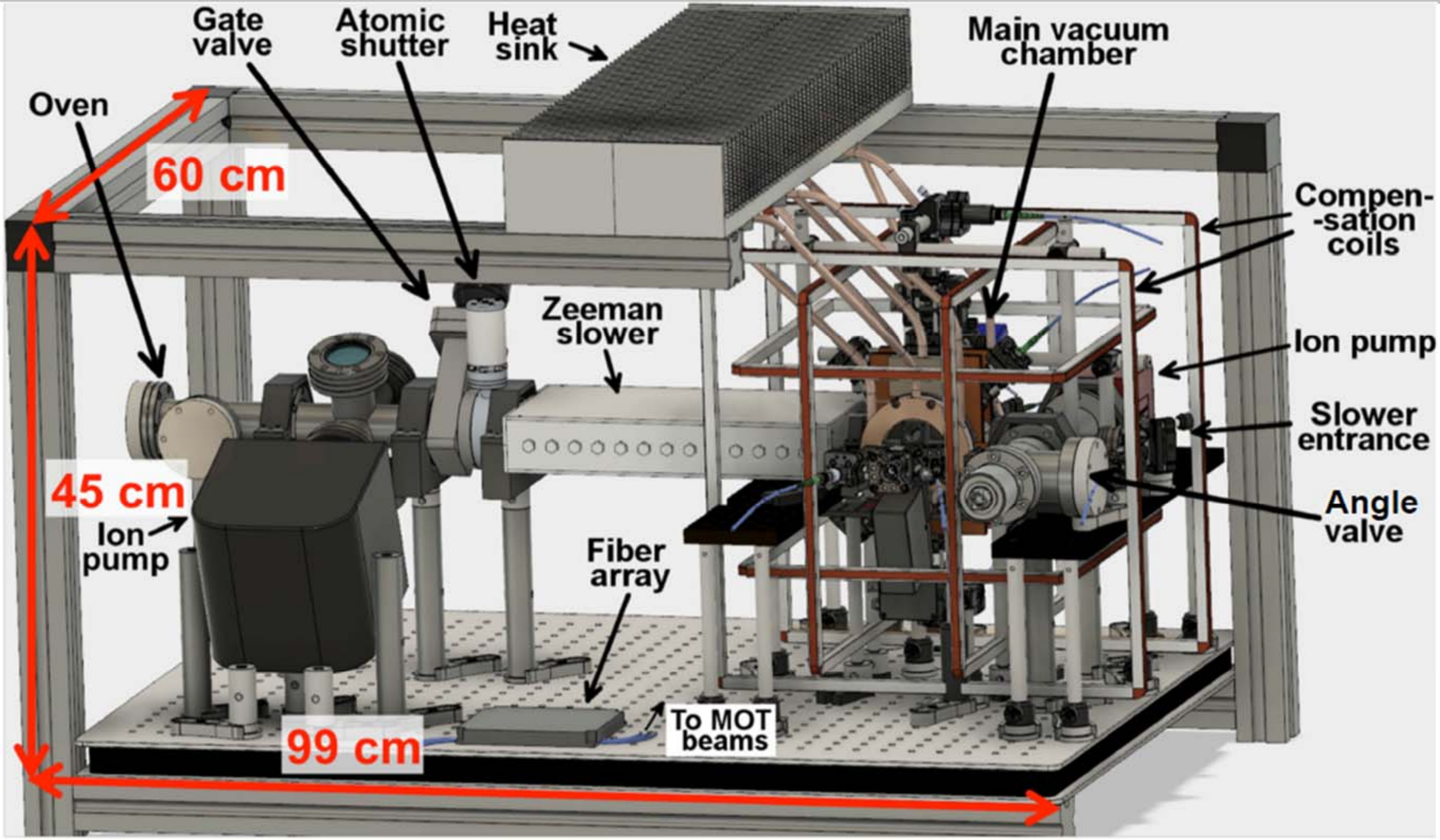
Clock laser breadboard

Atomic unit

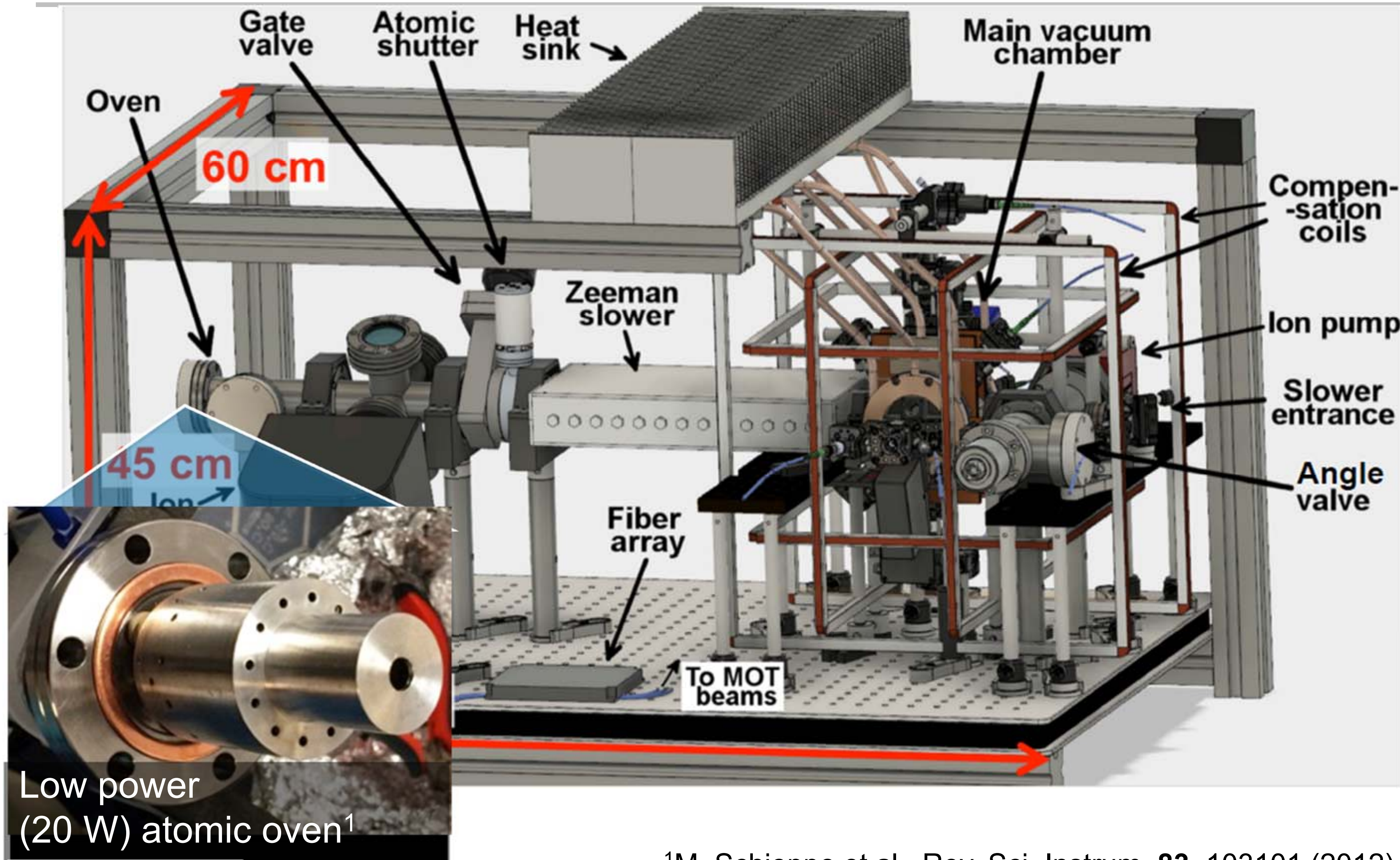
SEVENTH FRAMEWORK PROGRAMME
DLR
esa

Atomics Package



PTB
UNIVERSITY OF BIRMINGHAM
HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Atomics Package



Low power (20 W) atomic oven[1]

[1]M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

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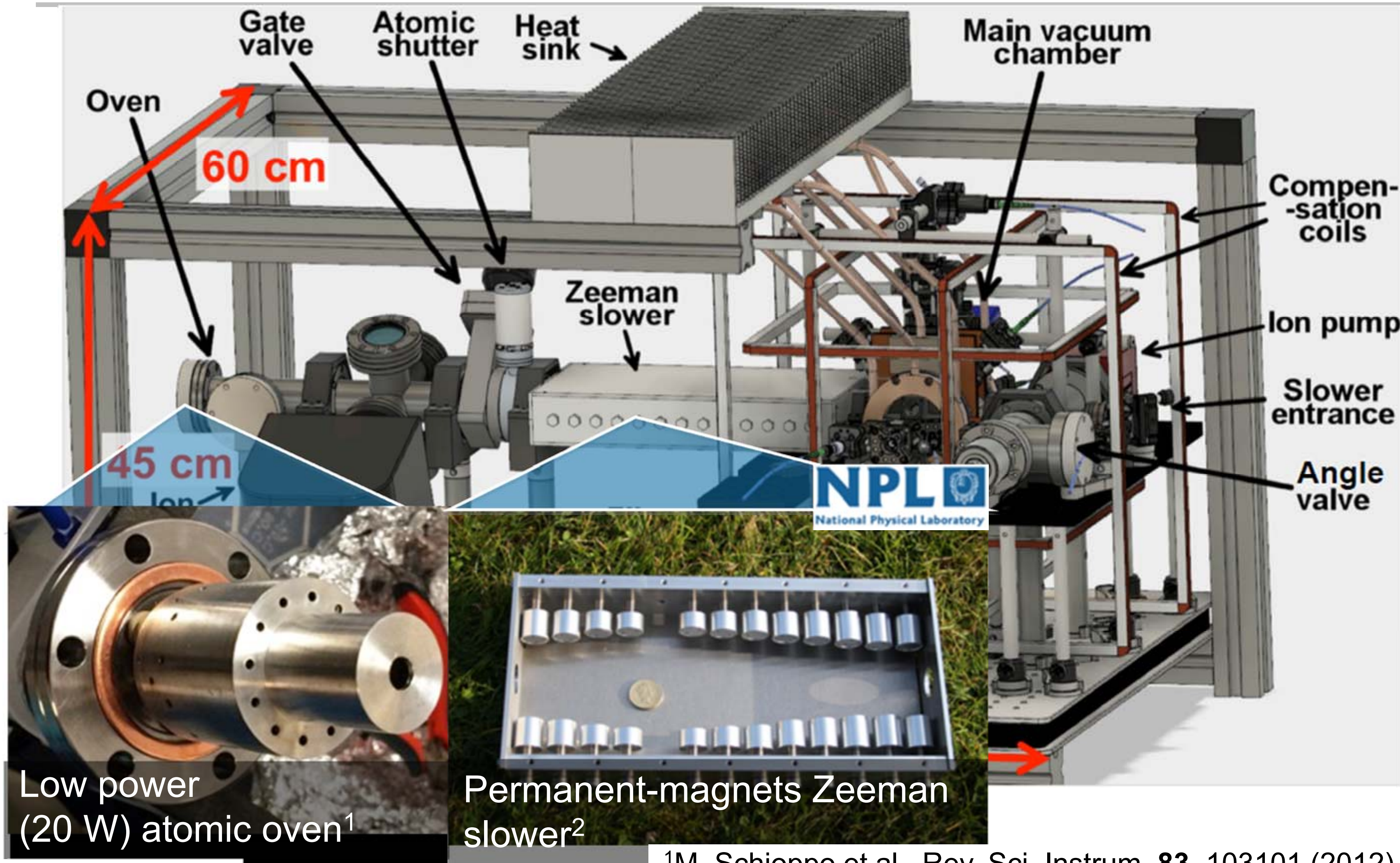
UNIVERSITÀ DEGLI STUDI FIRENZE

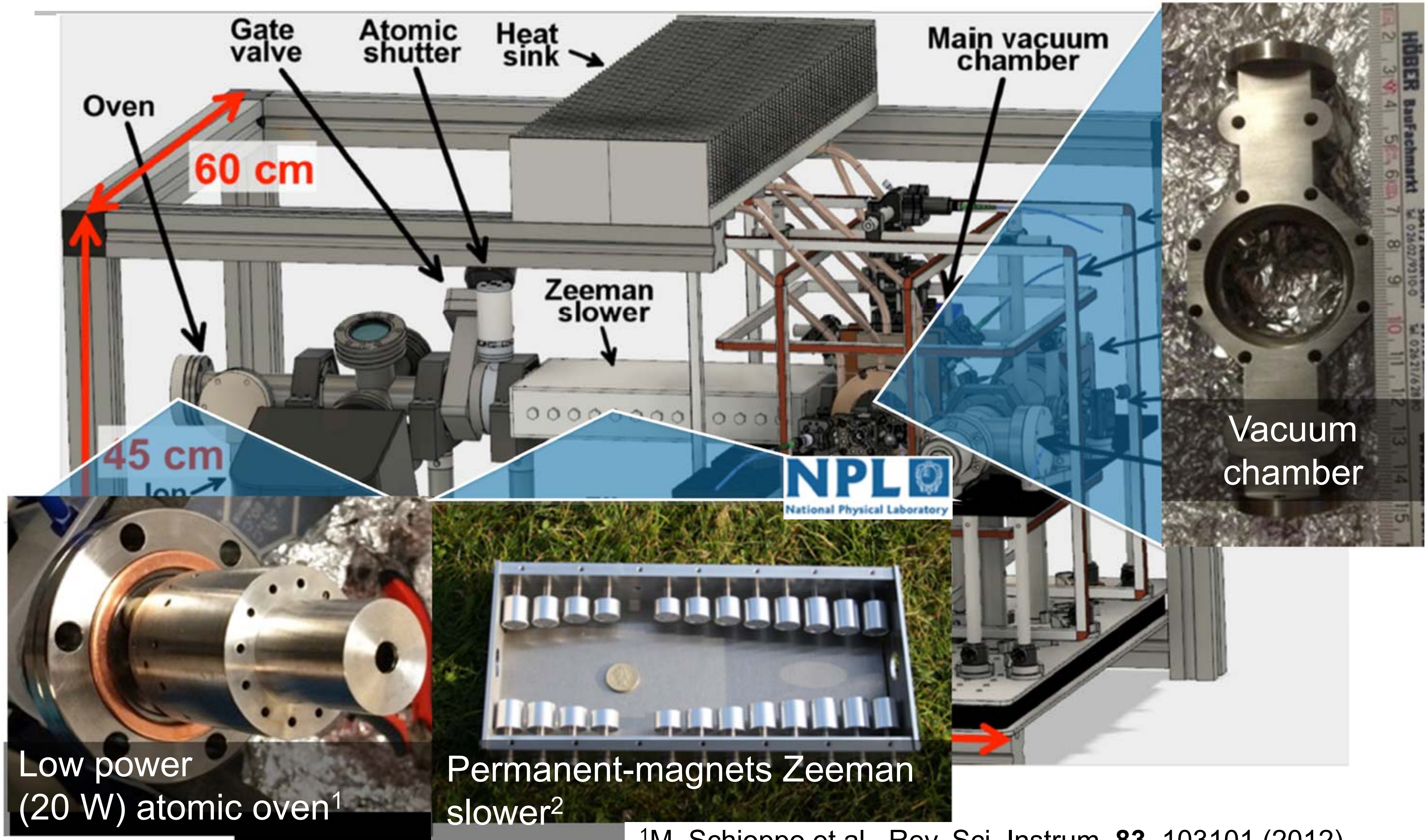
Atomics Package



[1]M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

[2]I. R. Hill et al., J. Phys. B **47**, 075006 (2014)

Atomics Package



Low power (20 W) atomic oven[1]

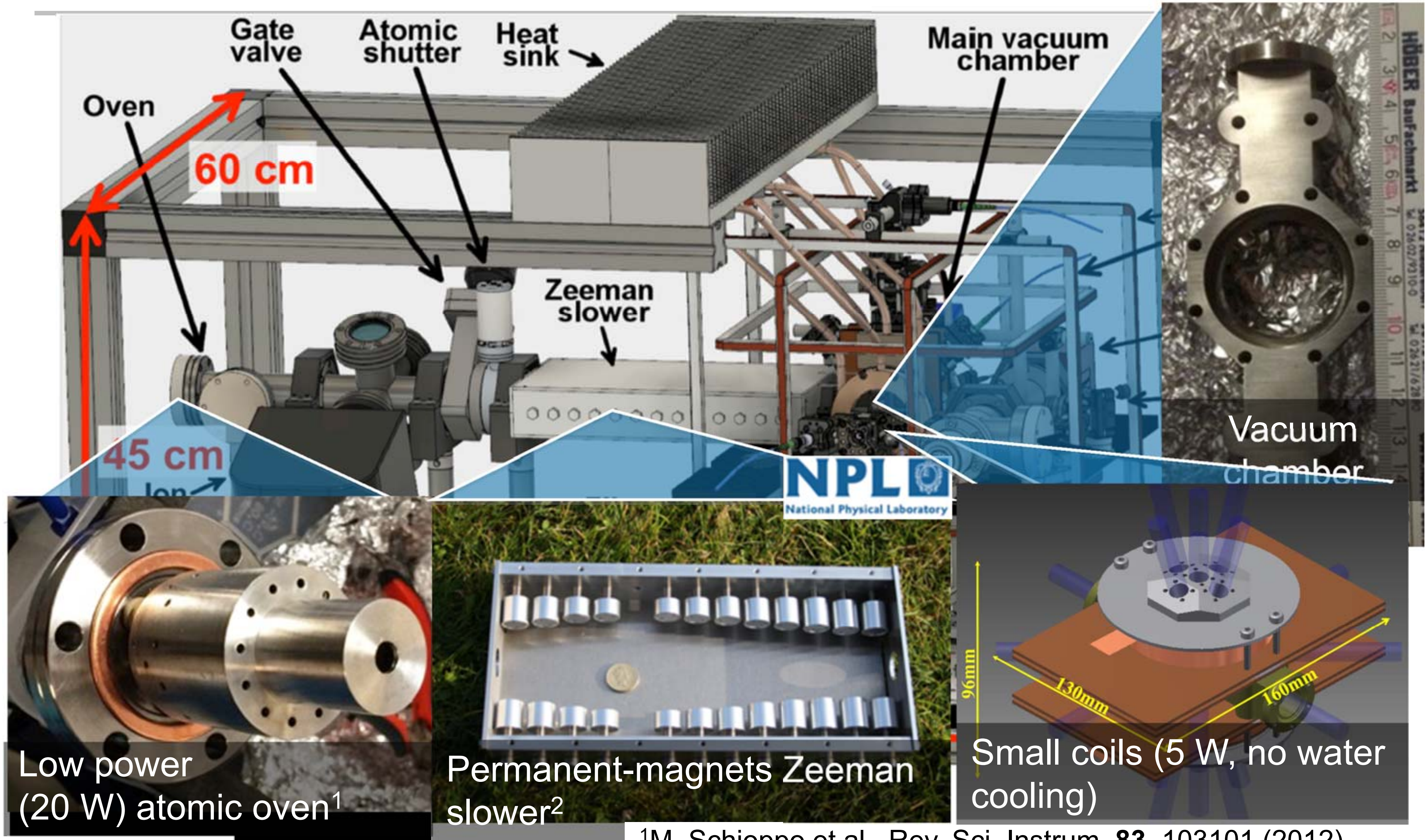
Permanent-magnets Zeeman slower[2]

Vacuum chamber

[1] M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

[2] I. R. Hill et al., J. Phys. B **47**, 075006 (2014)

Atomics Package



Low power (20 W) atomic oven[1]

Permanent-magnets Zeeman slower[2]

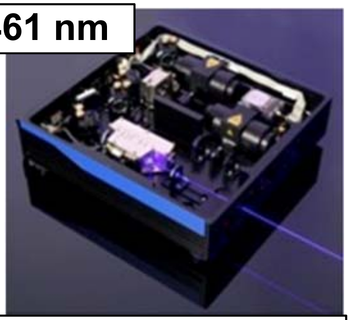
Small coils (5 W, no water cooling)

[1]M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

[2]I. R. Hill et al., J. Phys. B **47**, 075006 (2014)

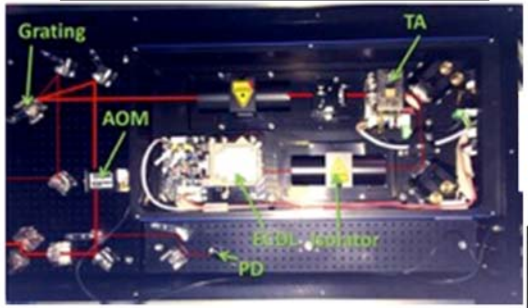
Modular laser system

461 nm

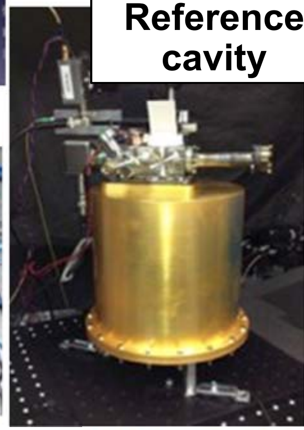


461 nm distribution

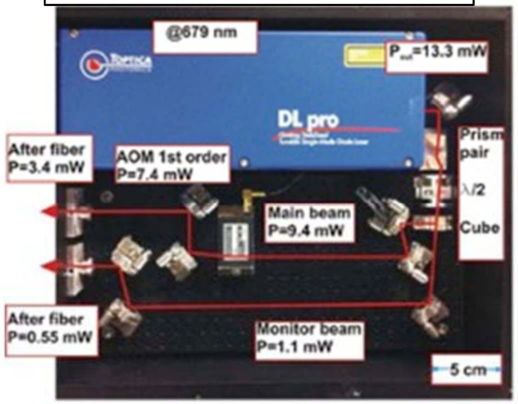
813 nm lattice



Reference cavity



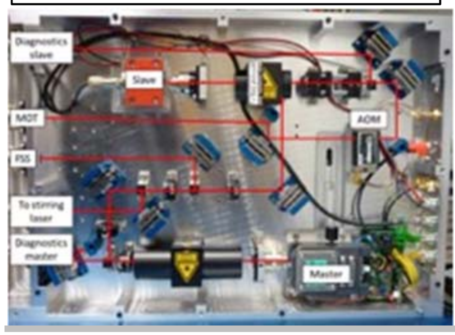
Repumper 679 nm



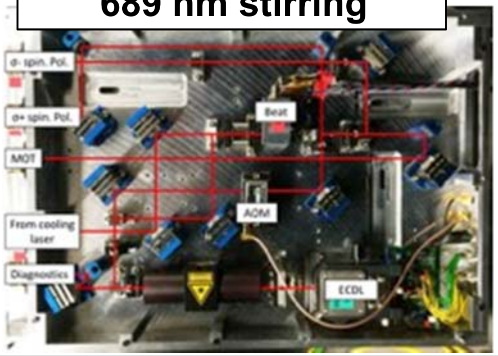
Repumper 707 nm

698 nm clock laser

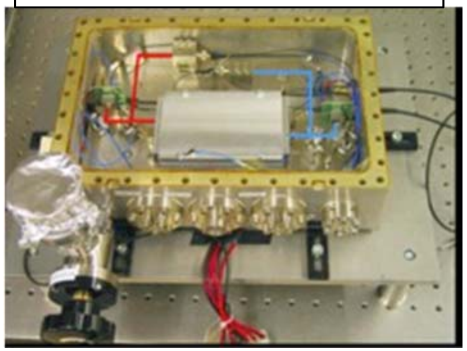
689 nm cooling



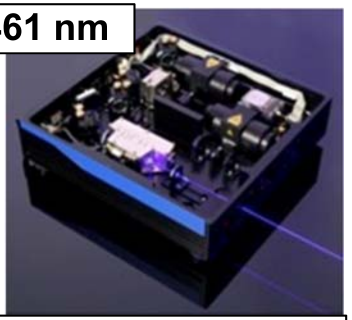
689 nm stirring

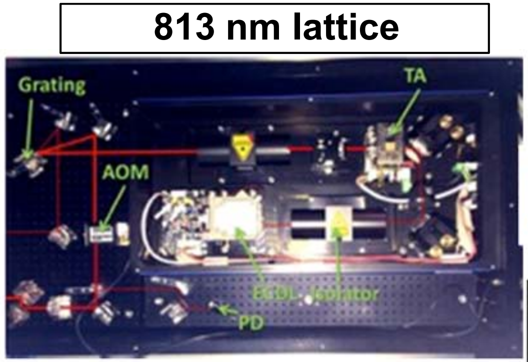


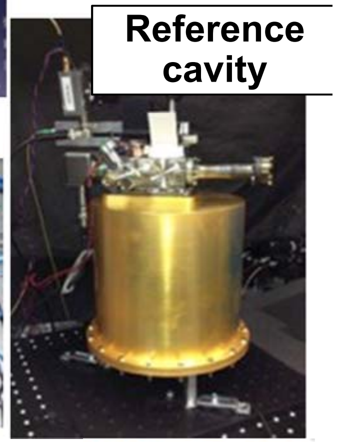
461, 689, 813 nm stabilization unit



Modular laser system



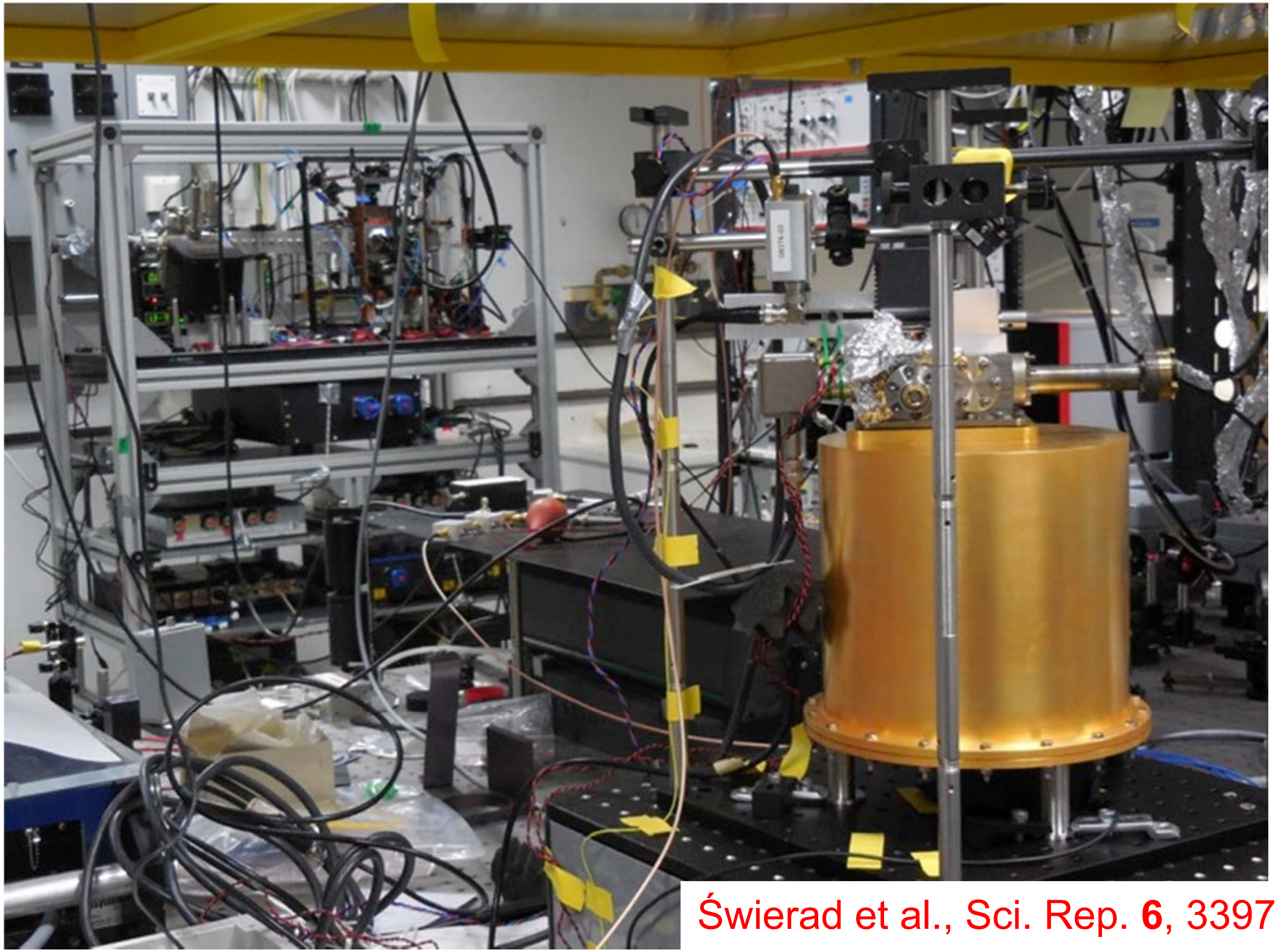




- Relies on robust, mostly COTS, laser technology
- Units are exchangeable with improved ones

Bongs, K. et al., “Development of a strontium optical lattice clock for the SOC mission on the ISS”, C. R. Phys. **16**, 553 (2015)

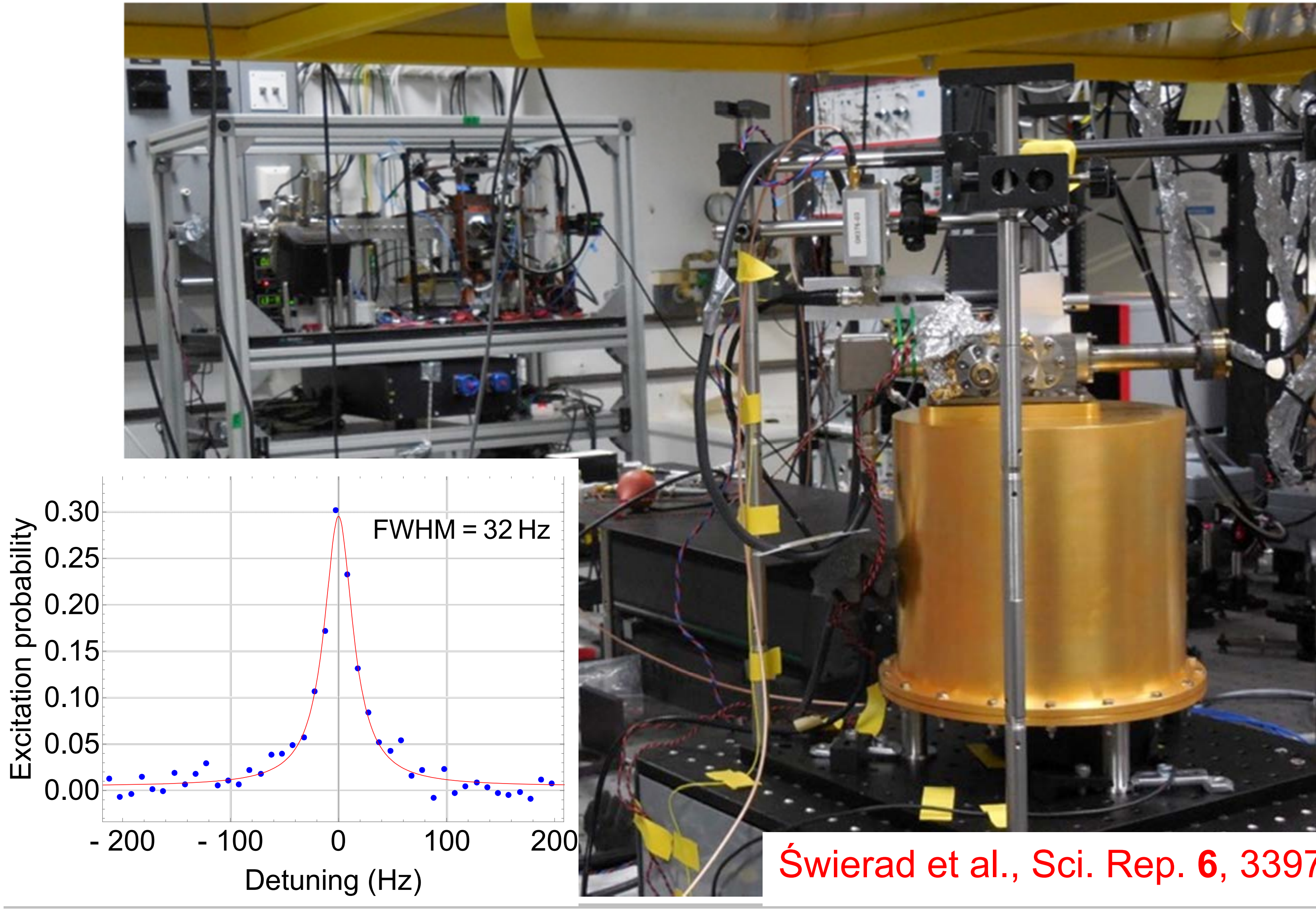
Clock laser integration



Świerad et al., Sci. Rep. **6**, 33973 (2016)

Clock laser integration

l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace
PTB
UNIVERSITY OF BIRMINGHAM
HEINRICH HEINE UNIVERSITÄT DÜSSELDORF



Świerad et al., Sci. Rep. **6**, 33973 (2016)

Atomic package transport (6/2015)

- 1st stage MOT obtained within 2 days of arrival
- Atoms trapped in lattice within 3 weeks of arrival

Birmingham → Eurotunnel → Braunschweig (PTB)

^{88}Sr (boson) vs. ^{87}Sr (fermion)

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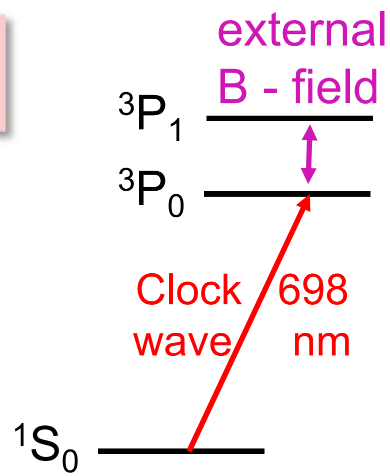
^{88}Sr



Isotopic abundance:
83%

Laser cooling: easier

Cycle time: Shorter
(2 interrogations)

Vector and tensor light shift: insensitive

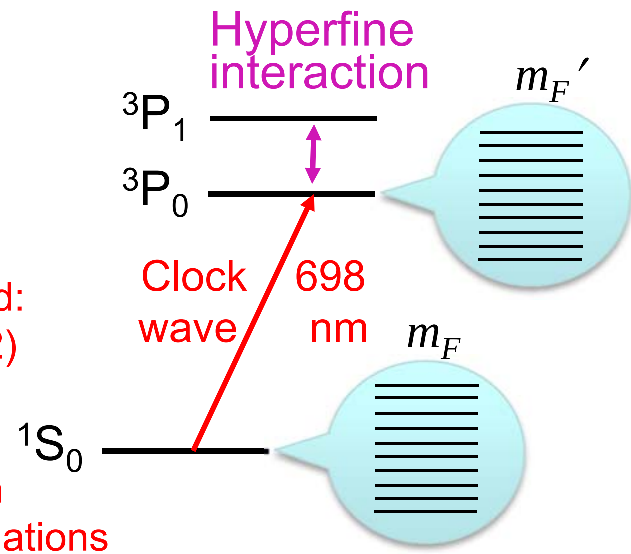
Spectroscopy:
magnetically induced :

1) Large magnetic field
2) Large clock laser beam intensity

Collisions: s-wave

May have advantages in terms of simplicity and for transportability; furnishes additional isotope shifts

^{87}Sr



7%

more complicated:
nucl. spin (I = 9/2)
→ 1 more laser

1st order Zeeman shift → 4 interrogations

Sensitive

Hyperfine interaction allows $^1S_0$ - $^3P_0$ transition

Only p-wave collisions

Better for accuracy

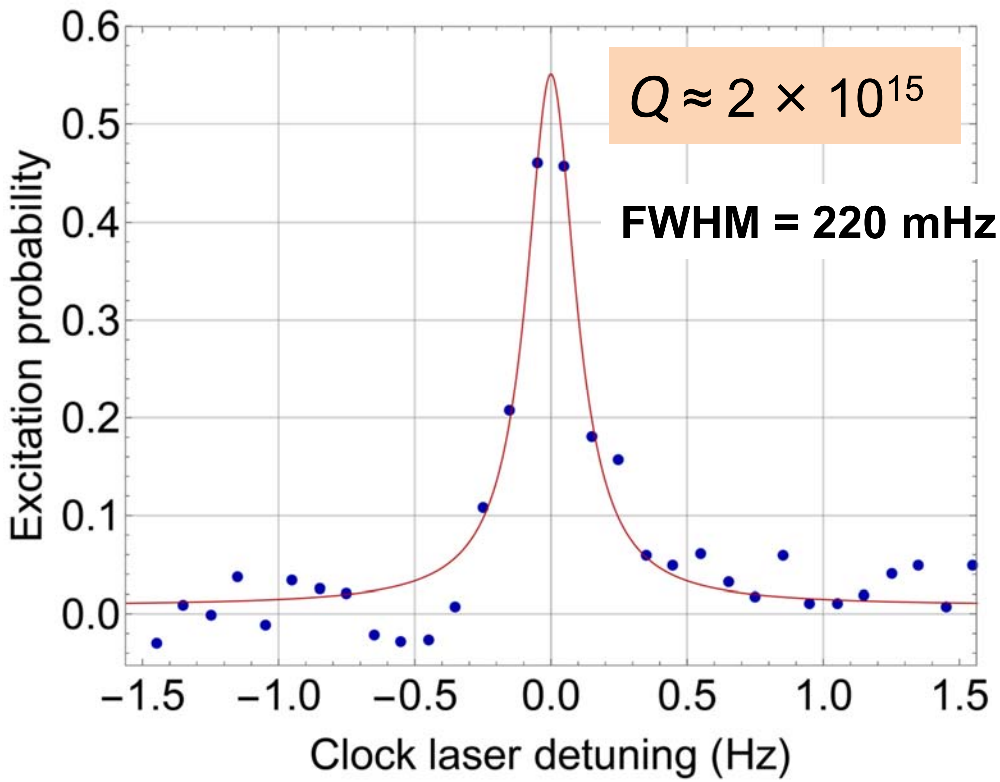
Clock transition line in ^{88}Sr (698 nm)

$$\frac{(\Delta\nu_B + \Delta\nu_I)_{min}}{\nu_0} = \frac{-7.7 \times 10^{-15}}{T_\pi/s}$$

Clock transition line in ^{88}Sr (698 nm)

$$\frac{(\Delta\nu_B + \Delta\nu_I)_{min}}{\nu_0} = \frac{-7.7 \times 10^{-15}}{T_\pi/s}$$

Long interrogation time:
4 s (Fourier-limited linewidth)



By stabilizing the clock laser to a cryogenic silicon cavity[1,2] (PTB), using a transfer-lock scheme

[1]D. G. Matei et al., J. Phys. Conf. Ser., 723, 012031 (2016)
[2]D. G. Matei et al., PRL 118, 2632202 (2017)

Clock transition line in ^{88}Sr (698 nm)

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HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

$$\frac{(\Delta\nu_B + \Delta\nu_I)_{min}}{\nu_0} = \frac{-7.7 \times 10^{-15}}{T_\pi / s}$$

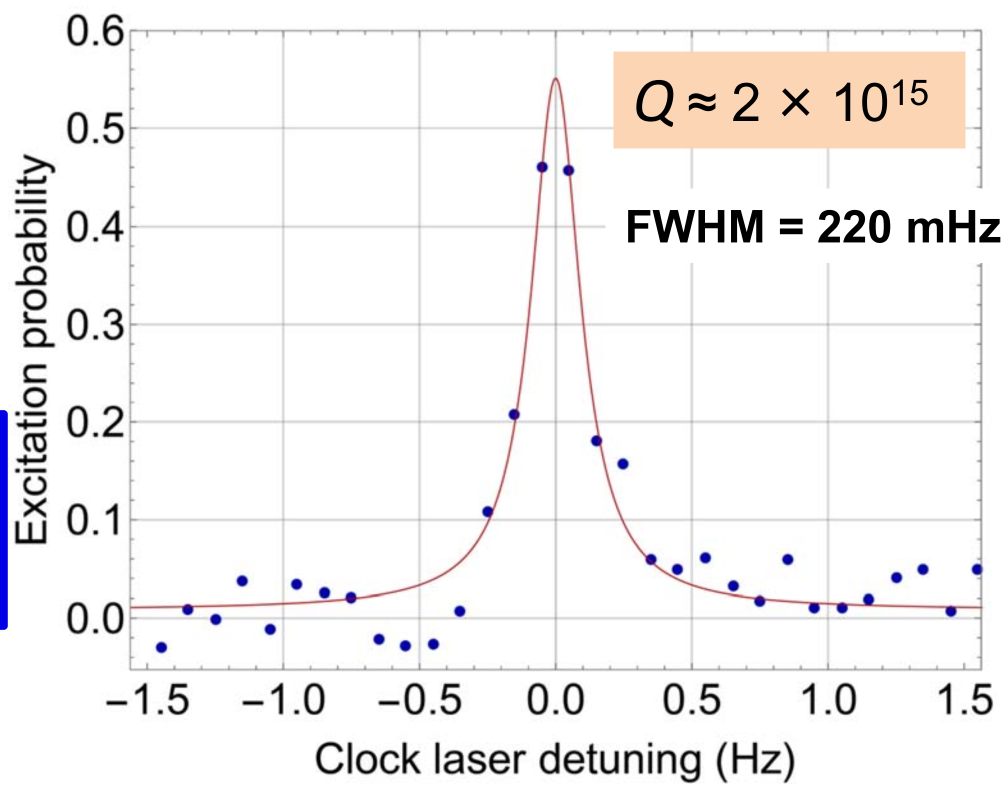
Long interrogation time:
4 s (Fourier-limited linewidth)

$$|\boldsymbol{B}| = 0.21\,\mathrm{mT} \qquad \Delta\nu_B \approx -1.0\,\mathrm{Hz}$$
$$I = 28\,\mathrm{mW/cm^2} \qquad \Delta\nu_I \approx -0.25\,\mathrm{Hz}$$

$$\frac{\Delta\nu_B + \Delta\nu_I}{\nu_0} = -3.1 \times 10^{-15}$$

For < 10^{-17} fractional instability,
I and B have to be stabilized

For 10^{-17} fractional inaccuracy,
shifts have to be measured



By stabilizing the clock laser to a cryogenic silicon cavity[1,2] (PTB), using a transfer-lock scheme

[1]D. G. Matei et al., J. Phys. Conf. Ser., 723, 012031 (2016)
[2]D. G. Matei et al., PRL 118, 2632202 (2017)

Characterisation of clock

^{87}**Sr lattice clock (PTB)**

A. Al-Masoudi *et al.*,
PRA **92**, 063814 (2015)

λ_1 = 698 nm

^{88}**Sr lattice clock (SOC)**

λ_2 = 698 nm

K. Bongs et al. C. R. Physique 16, 553 (2015)
S. Origlia et al., arxiv 1603.06062 (2016)

Silicon reference cavity (PTB)

T. Kessler *et al.*, Nature Phot. **6**, 687 (2012),
D. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

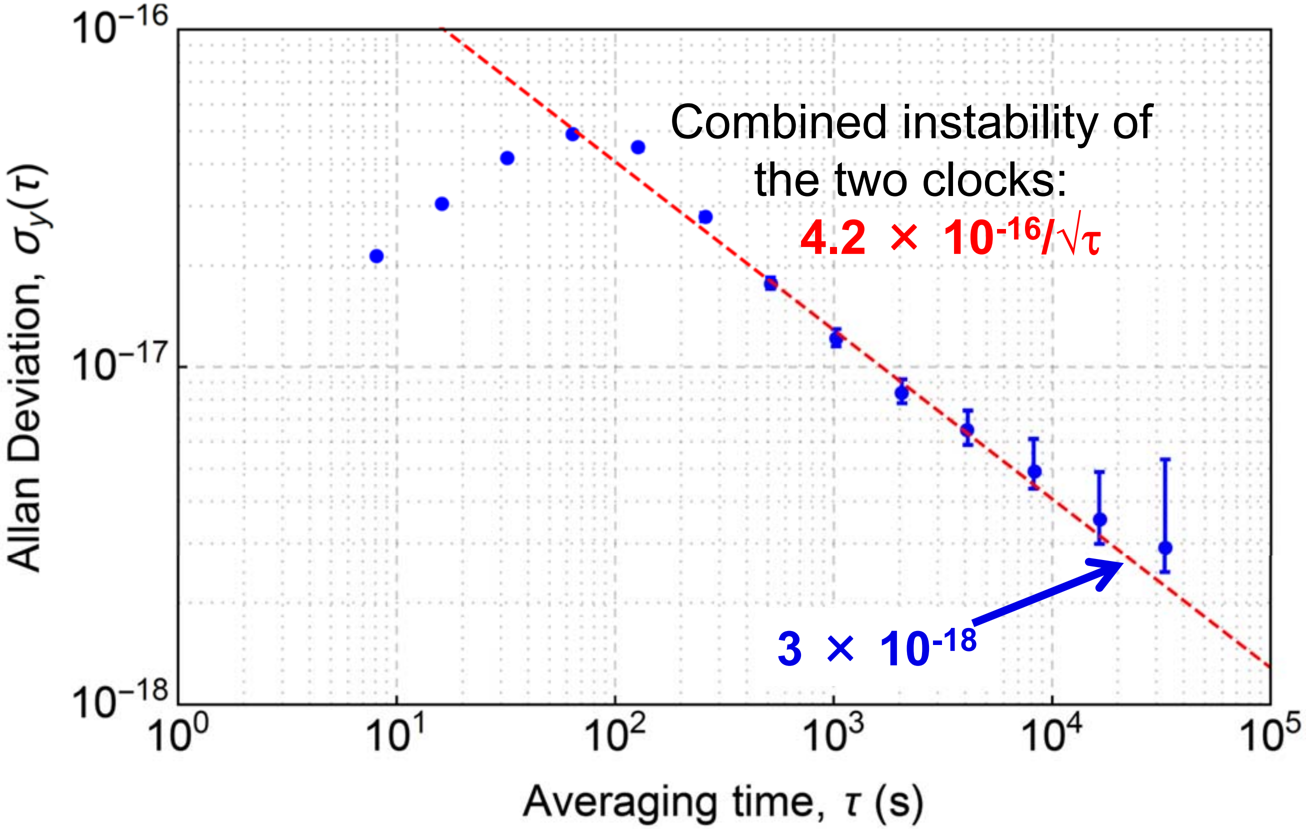
λ_3 = 1542 nm

Clock instability

Instability determined by comparison with ^{87}Sr clock at PTB[1,2]

Total averaging time:
102 000 s

SOC clock locked continuously to atoms for **74 hours**!



[1]S. Falke et al., New J. Phys. 16, 073023 (2014)

[2]A. Al-Masoudi et al., Phys. Rev. A 92, 063814 (2015)

SOC clock accuracy

	SOC2		PTB stationary	
	^{88}Sr clock		^{87}Sr clock	
Effect	$\Delta\nu/\nu$	u	$\Delta\nu/\nu$	u
BBR shift	-523.4	0.8	-492.2	1.5
BBR oven shift	0	0	-0.9	0.9
Lattice shift ($\Delta\nu_L$)	-1.8	1.1	-0.9	0.4
Probe light shift ($\Delta\nu_P$)	-96.1	1.3	0.0	0.0
Cold collision shift ($\Delta\nu_{LP}$)	-0.6	0.3	0.0	0.2
2^{nd}-order Zeeman shift ($\Delta\nu_B$)	-209.7	0.5	-3.4	0.1
Tunneling	0	0	0.0	0.3
Background gas collision shift	-0.13	0.13	-0.8	0.8
DC-Stark shift	-0.2	0.2	-0.2	0.1
Gravitational shift	+5.1	0.1	0.0	
Total shift	-826.9	2.0	-498.4	2.0
	$\times 10^{-17}$	$\times 10^{-17}$	$\times 10^{-17}$	$\times 10^{-17}$

Lattice laser: Ti:Sapphire

The SOC breadboard demonstrator is as accurate as the most accurate European lattice clocks

Origlia et al., arxiv.1803.03157; Phys. Rev. A, to appear

Comparison SOC(^{88}Sr) and Sr-PTB(^{87}Sr)

PTB

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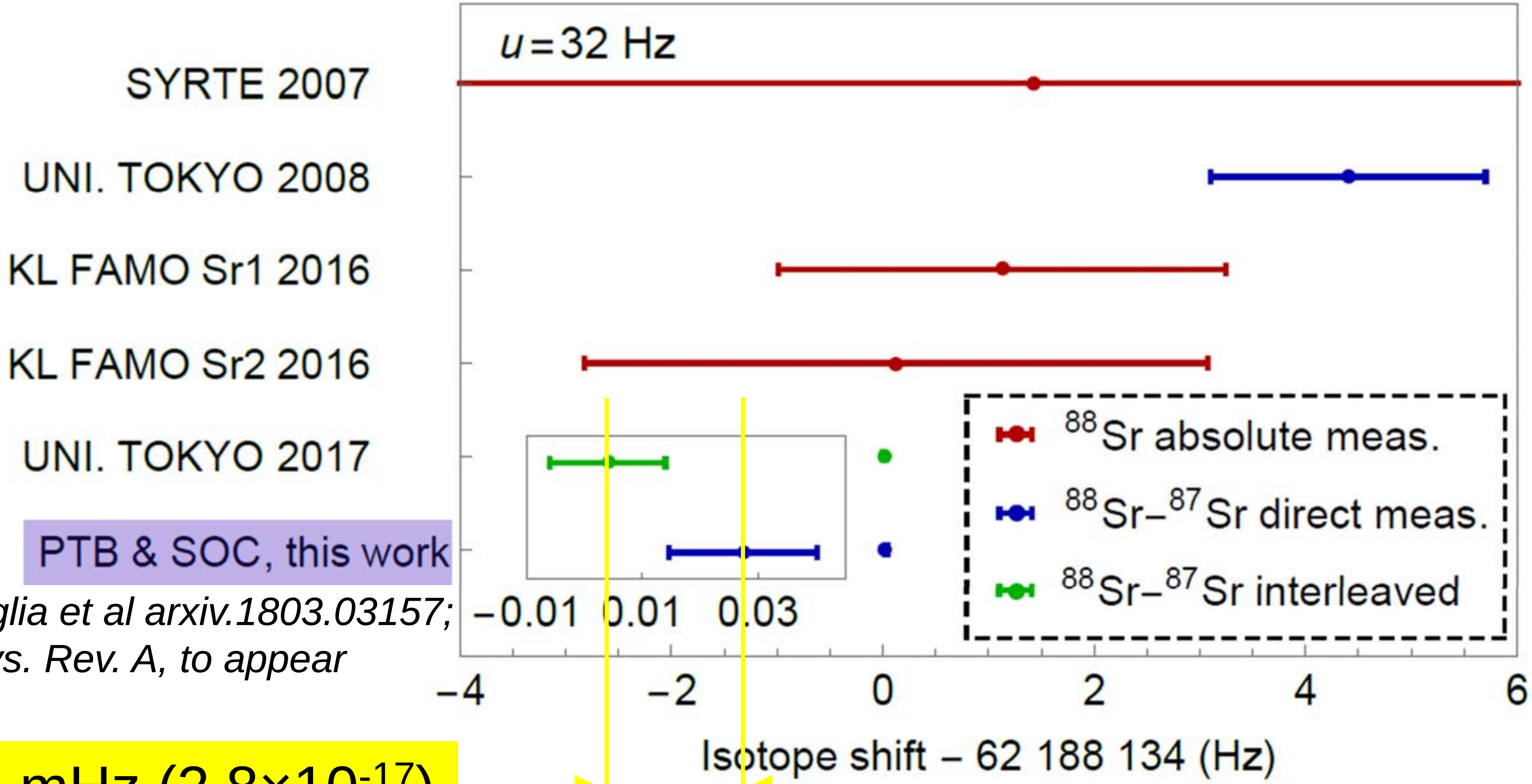
ν(^{88}Sr) – ν(^{87}Sr) = 62 188 134.027(12) Hz (uncertainty ^{87}Sr: 2.0×10^{-17})



Origlia et al arxiv.1803.03157; Phys. Rev. A, to appear

12 mHz (2.8×10^{-17})

X. Baillard *et al.*, Opt. Lett. **32**, 1812 (2007)
T. Akatsuka *et al.*, Nature Phys. **4**, 954 (2008)
P. Morzynski *et al.*, Sci. Rep. **5**, 17495 (2015)
C. Radzewicz *et al.*, Phys. Scr. **91**, 084003 (2016)
T. Takano *et al.*, Appl. Phys. Expr. **10**, 072801 (2017)

$f_{88}/f_{87} = 1.000\,000\,144\,883\,682\,831\,(28)$

One of the most accurate measurements of a property of nature

Contents

A transportable optical lattice clock for the ACES mission

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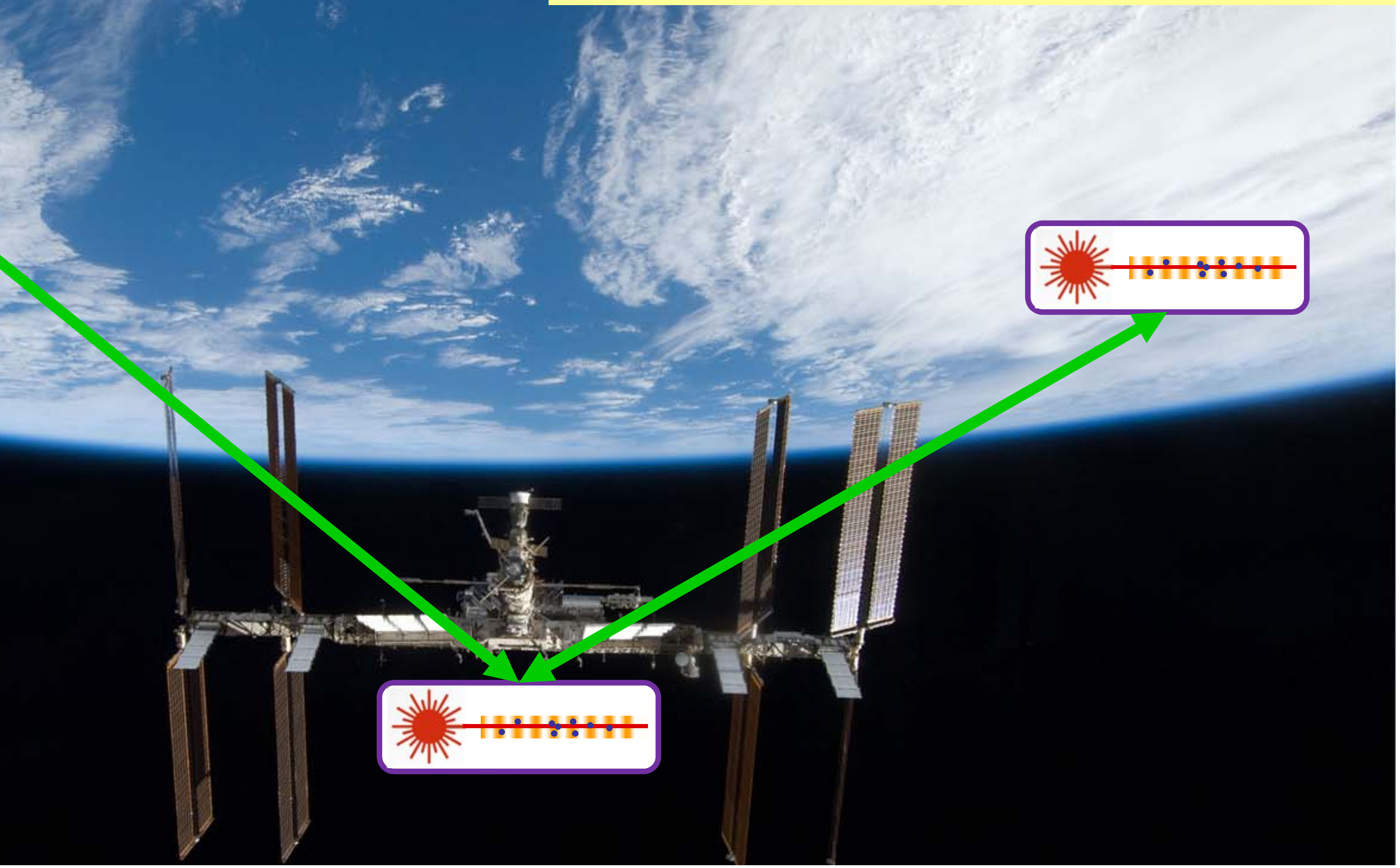
Mission I-SOC:
An optical clock on the ISS

Coordinator: S. Schiller (Univ. Düsseldorf)



U. Sterr
Ch. Lisdat
R. Le Targat
J. Lodewyck
Y. Singh
K. Bongs
N. Poli
G.M. Tino
F. Levi
I. Prochazka
C. Salomon

ACES and I-SOC

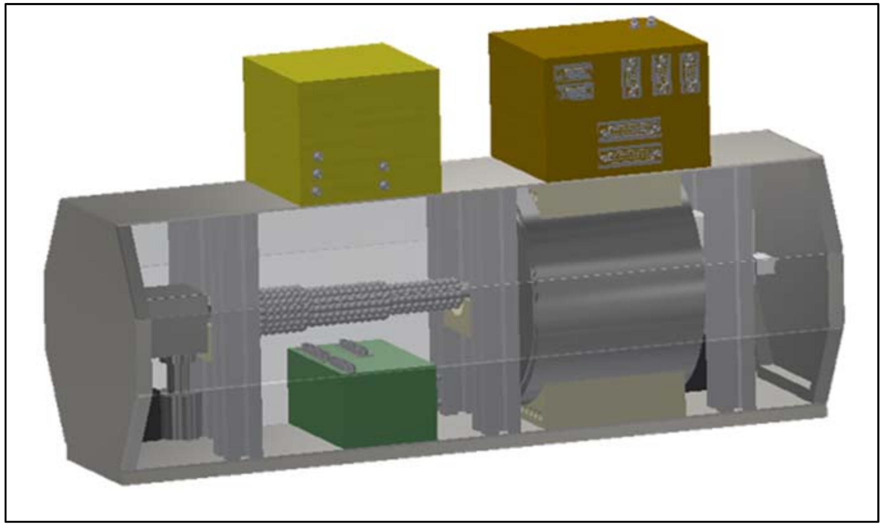
- ACES actual/estimated performance vs. I-SOC requirements

	ACES (MWL, ELT)	**I-SOC** (MWL+, ELT+) *	**Improvem.**
Clock instability	$1\text{x}10^{-13}/\tau^{1/2}$	$8 \text{ x } 10^{-16}/\tau^{1/2}$ ($\tau \leq 2{\times}10^{6}$ s)	x 100
Clock inaccuracy	$1\text{x}10^{-16}$	$1\text{x}10^{-17}$	x 10
TDEV – MWL/MWL+	1.5 ps $\times(\tau/10\,000 \text{ s})^{1/2}$	0.03 ps **, $\tau > 1000$ s	x 150 @ 1 day
TDEV – ELT/ELT+	8 ps @ 10^{6} s	1 ps @ 10^{6} s	x 8
Phase coherence	yes	yes, minimum 12 h; up to 10 days (25 times)	

- I-SOC clock signal shall be phase-coherent
  → requirement to comb <u>and</u> clock
- ELT+ supports reaching $1{\times}10^{-18}$ for
  ground clock comparisons (or ground-space)
- I-SOC performance can be tested fully on
  the ground (*trapped* atoms)

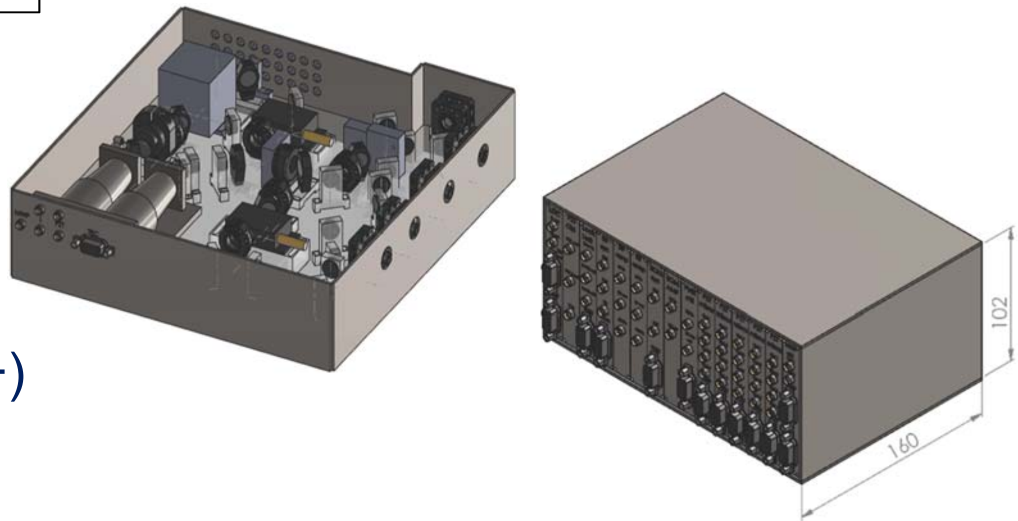
* from I-SOC ESR document   ** ground-to-space

Preliminary design of sub-systems

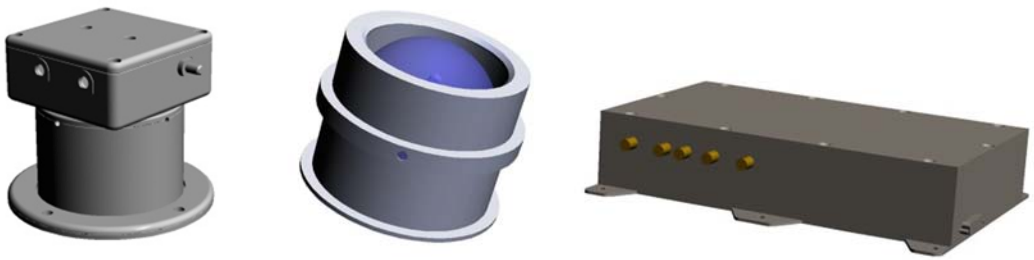


Atomics package

2nd-stage cooling laser (689 nm)

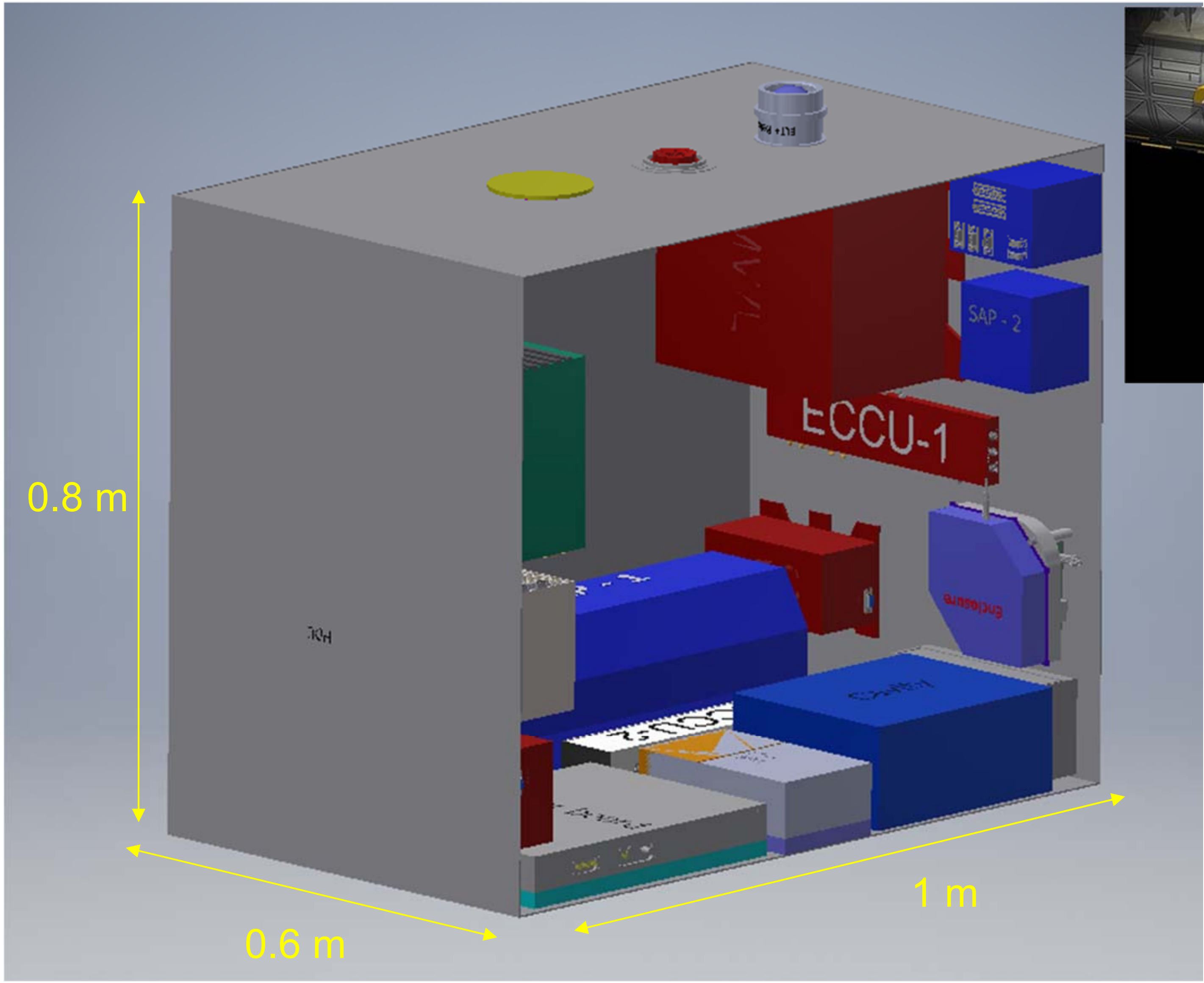


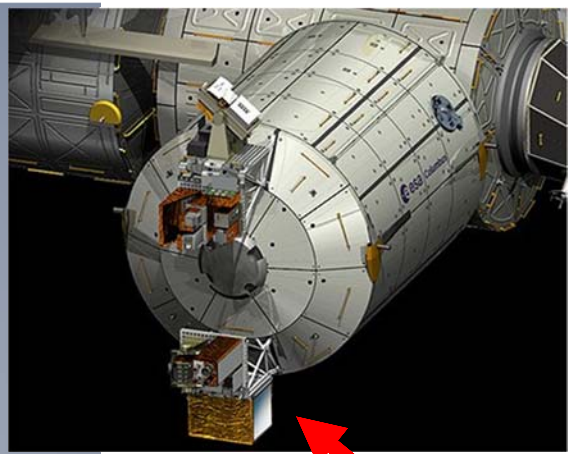
Single-photon time transfer (ELT+)



Accomodation

esa ISOC





I-SOC Phase A1: Documentation

~ 500 interfaces

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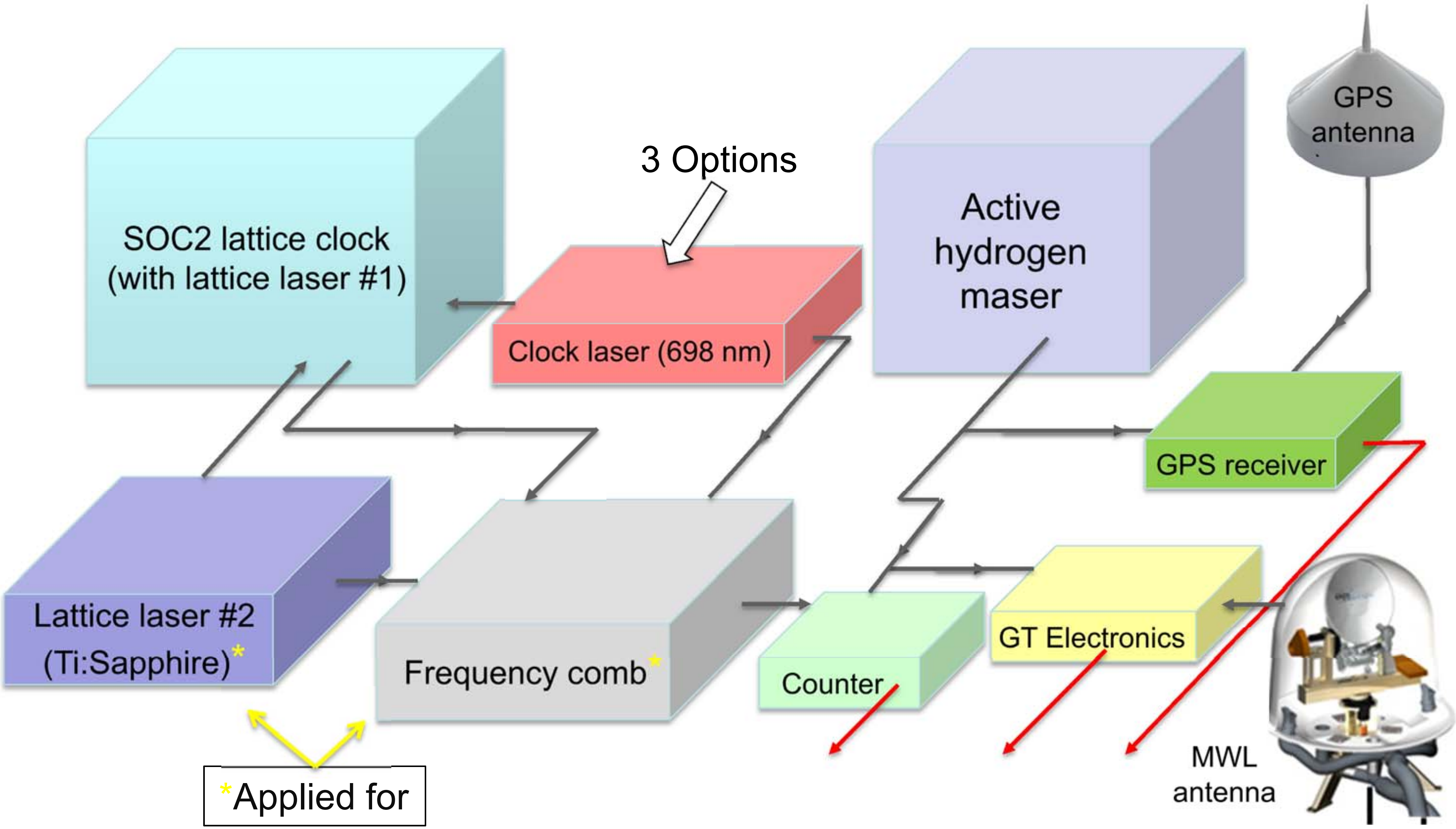
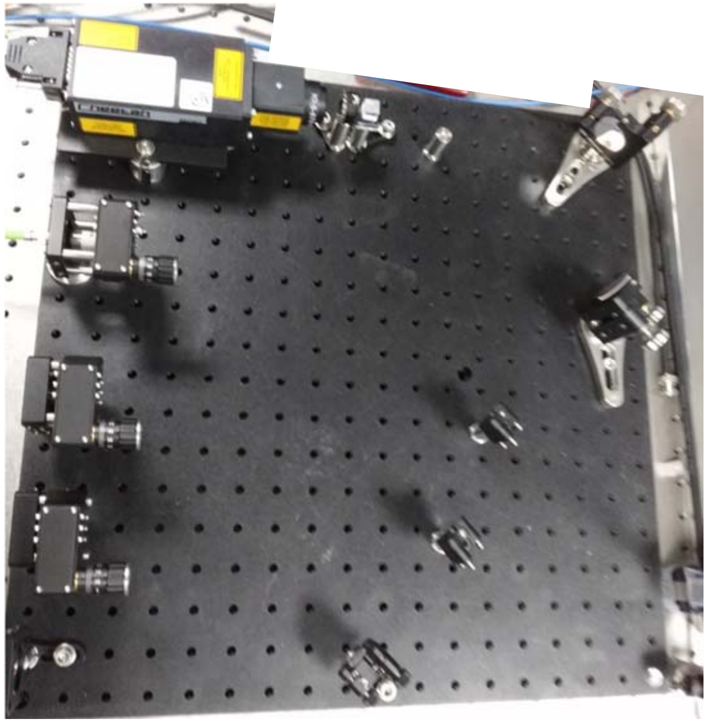
Configuration of SOC2 clock for ACES ground use



Transportable clock laser development

Ceramic cavity spacer
(NEXCERA)

New-generation 698 nm laser;
15 mW out of fiber



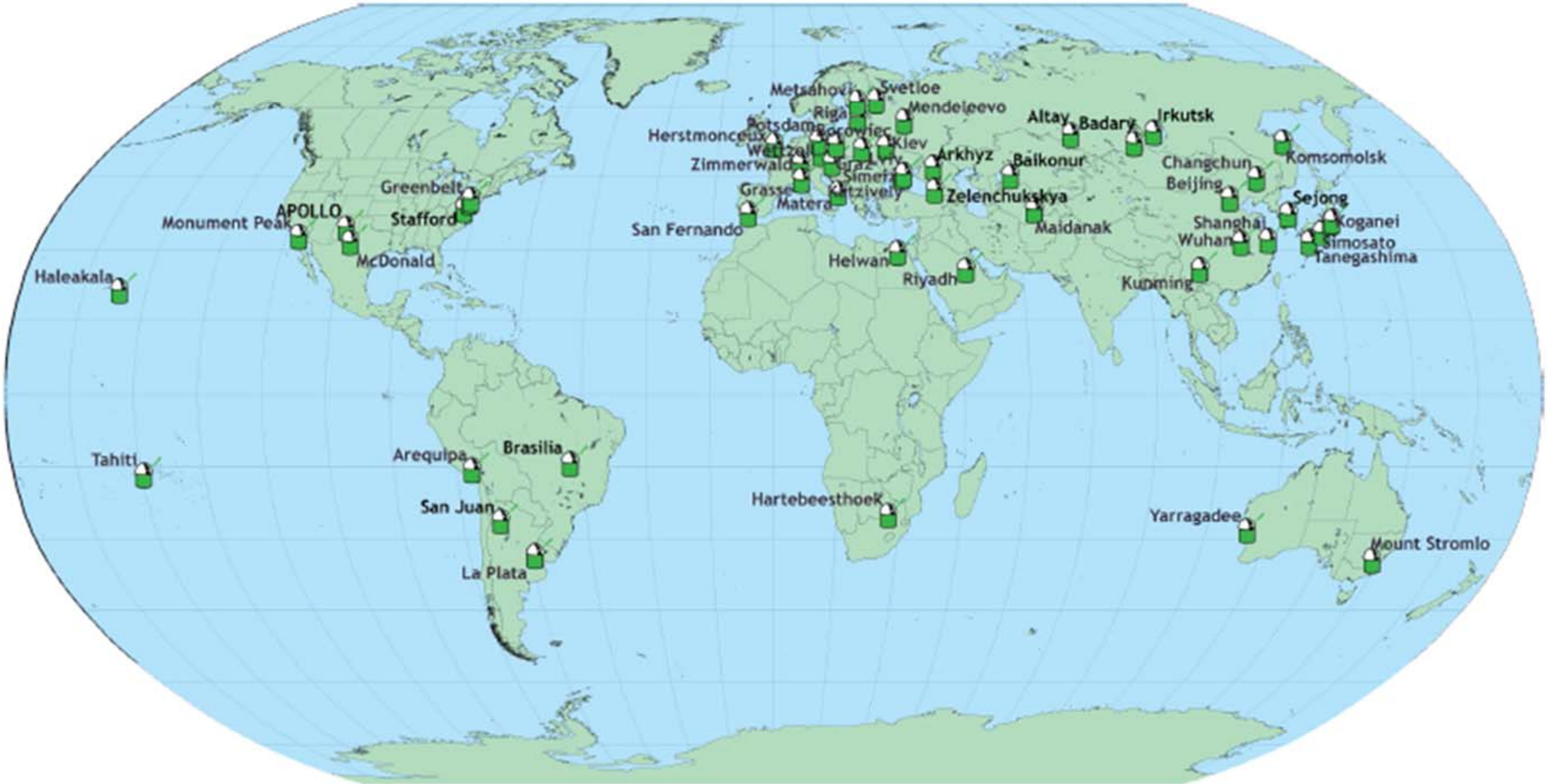
C. J. Kwong, M.G. Hansen, J. Sugawara, S.S.
Meas. Sci. Technol. **29** 075011 (2018)

See also: I. Ito et al. *Opt. Express* **25** 26020 (2017)

Candidate location

- Goal: unification of height systems in S. America
  → 5 cm clock uncertainty desirable
- Brazilian geodesists expressed interest (G. do Nascimento Guimaraes, A. C. Oliveira Cancoro de Matos, and D. Blitzkow)
- Possible site: Valinhos Astronomical Observatory, 115 km from Sao Paulo Int.l Airport
- Possible partners: Quantum optics group at Univ. Sao Paulo
  [part of ETN 721465 ColOpt Consortium]
- Country knowledge available

ILRS Network of SLR Stations



ACES submitted to ILRS as target: Wettzell, the ACES primary station already calibrated; Gratz and Herstmonceaux will follow; other stations can join provided they comply with ISS safety requirements.

Development plan

- Switch to ^{87}Sr (fermionic atoms)
- Key technical personell: 2 experienced Ph.D. students, 1 technician
- Many technical details, e.g. transportable thermally stabilized enclosure
- Field test in 2019: INRIM (Torino)
- Home base: PTB (characterizations)

Conclusions

- Providing a lattice clock system (low 10^{-17} uncertainty) for use during the ACES mission appears feasible
- Candidate location identified
- better/more locations?

Thanks to:

- C. Klempt, I. Kruse (LUH),
- D. Iwaschko, U. Rosowski (HHU),
- M. Misera, A. Koczwara, A. Uhde, T. Legero, D.G. Matei, E. Benkler, and C. Monte (PTB);
- SOC2/I-SOC consortium members;
- L. Cacciapuoti (ESA)