Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

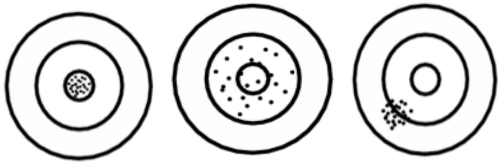
Transportable optical clocks

Christian Lisdat

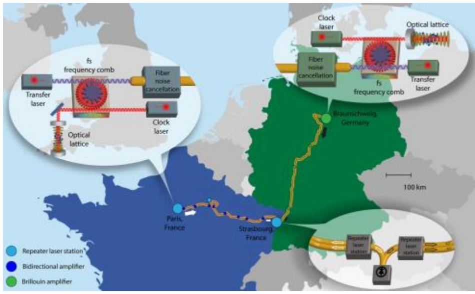
656th WE Heraeus Seminar 25.10.2017

Outline:

▶Clock basics, Vocabulary



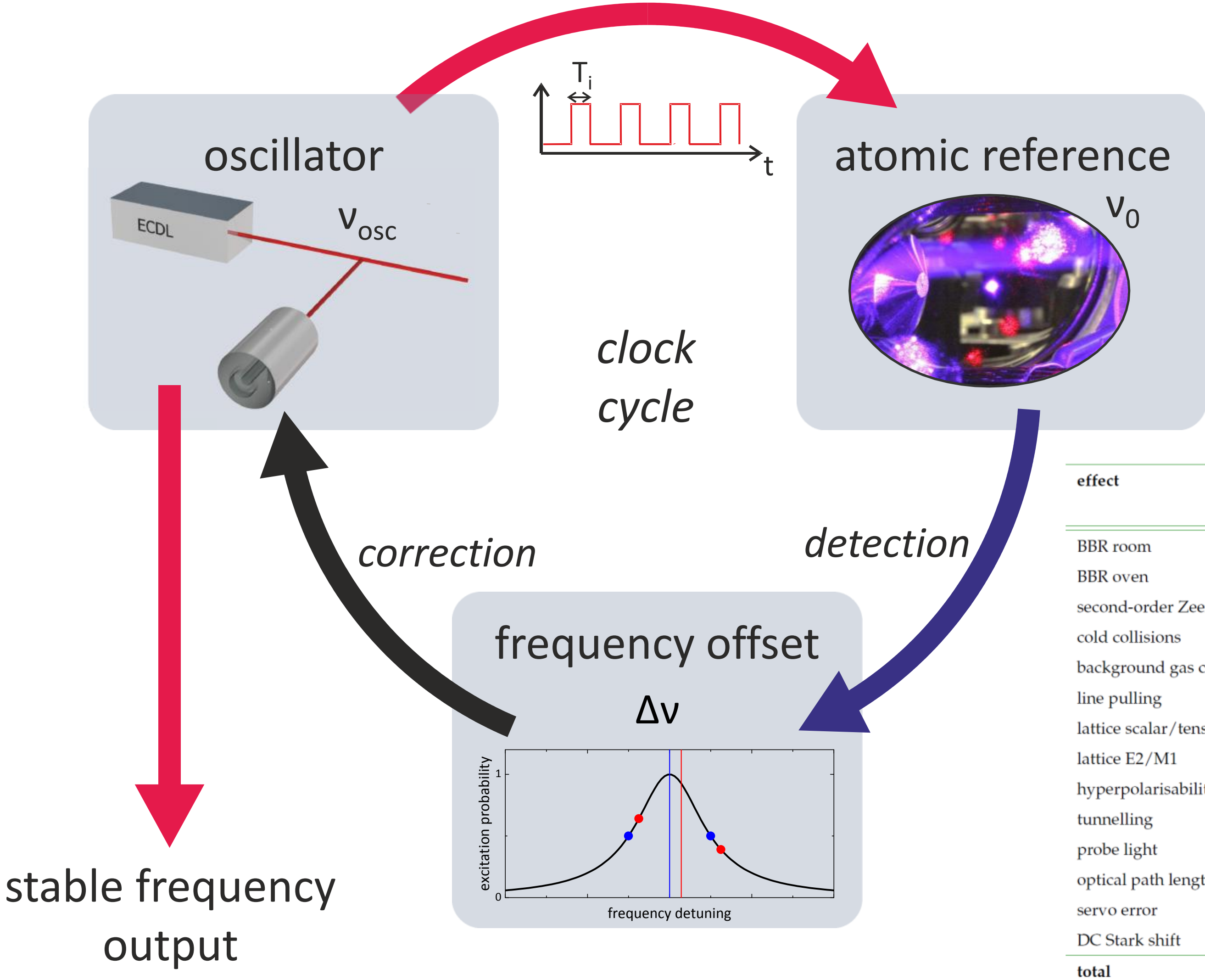
▶Clocks in the lab: examples of experiments



▶Transportable optical clocks on ground

▶Optical clocks in space

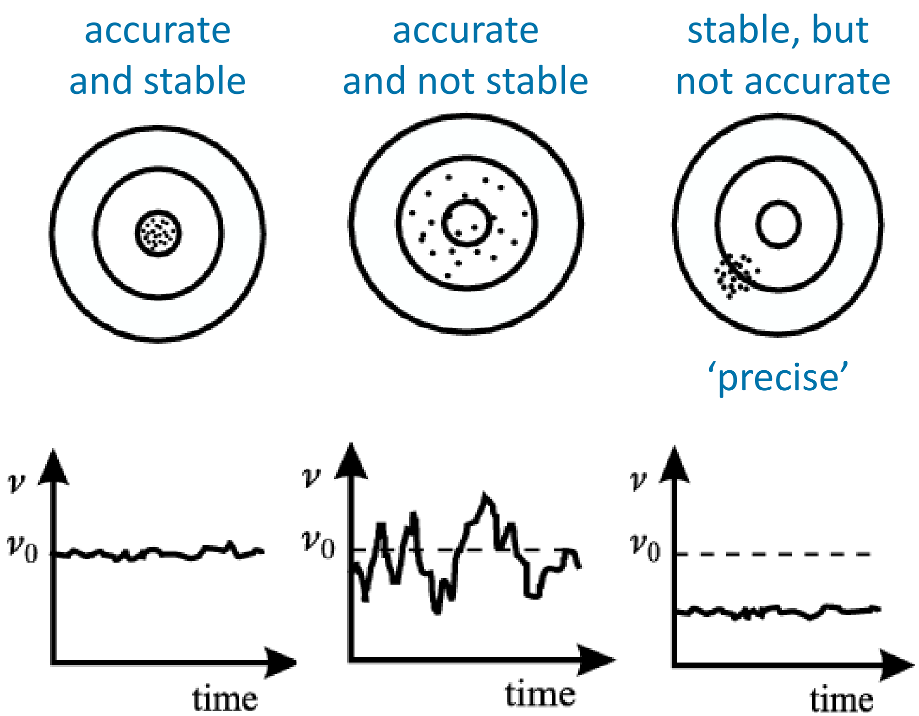
Principle of operation



effect	correction (10^{-17})	uncertainty (10^{-17})
BBR room	492.9	1.28
BBR oven	0.94	0.94
second-order Zeeman	3.6	0.15
cold collisions	0	0.08
background gas collisions	0	0.4
line pulling	0	0.01
lattice scalar/tensor	−0.7	0.9
lattice E2/M1	0	0.34
hyperpolarisability	−0.39	0.18
tunnelling	0	0.21
probe light	0	0.01
optical path length error	0	0.01
servo error	0	0.17
DC Stark shift	0	0.03
total	496.4	1.9

Performance of atomic clocks

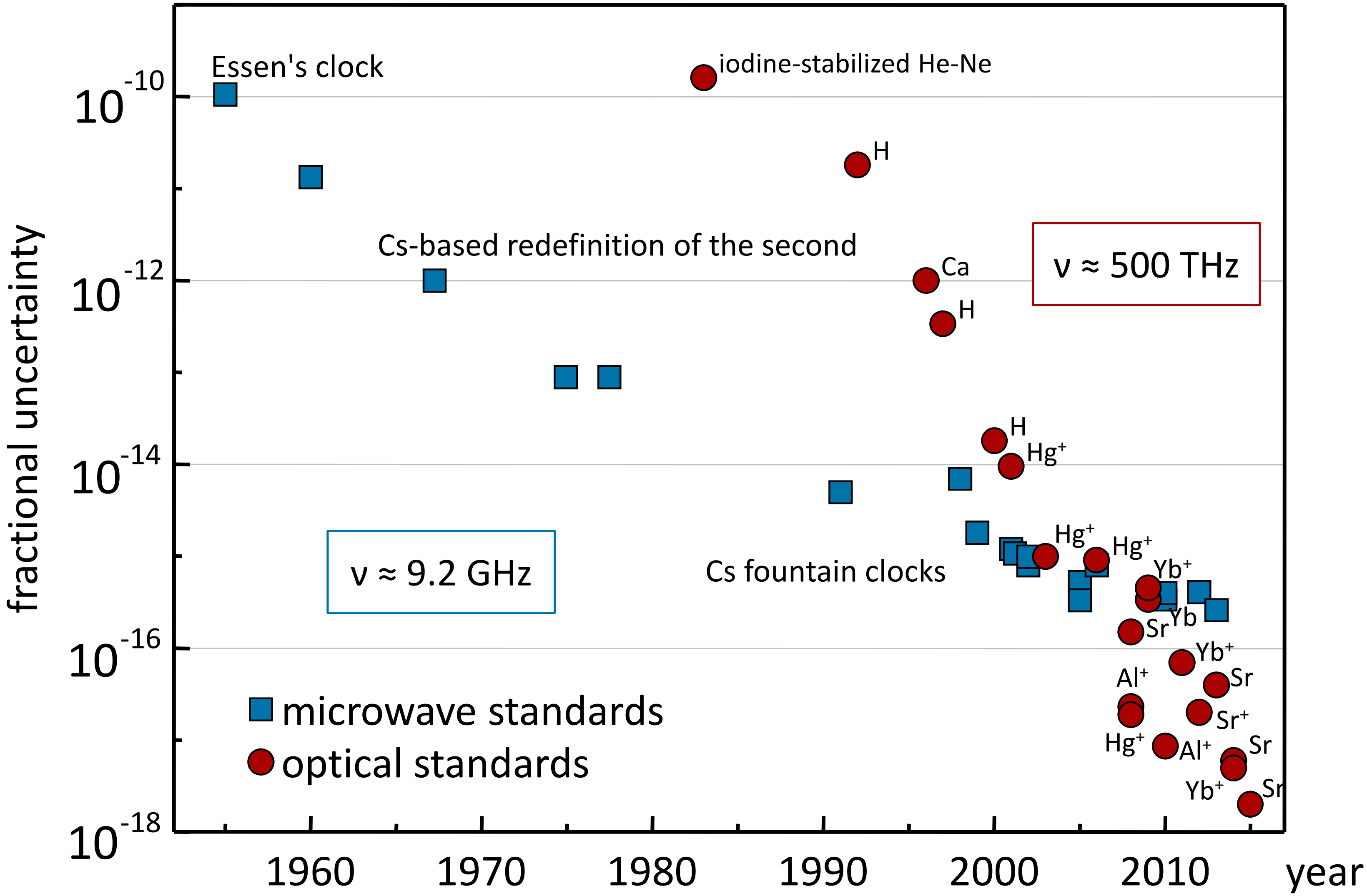
- Systematic uncertainty u_B
  - Suppress or control systematic frequency shifts.
- Instability $\sigma_y(\tau)$
  - Expressed by Allan deviation
  - $\sigma_y(\tau) \backsim \tau^{-1/2}$ for atomic clocks
  - Technical and physical limitations
- Reliability
  - Minimal interruptions
  - Practical long-term operation



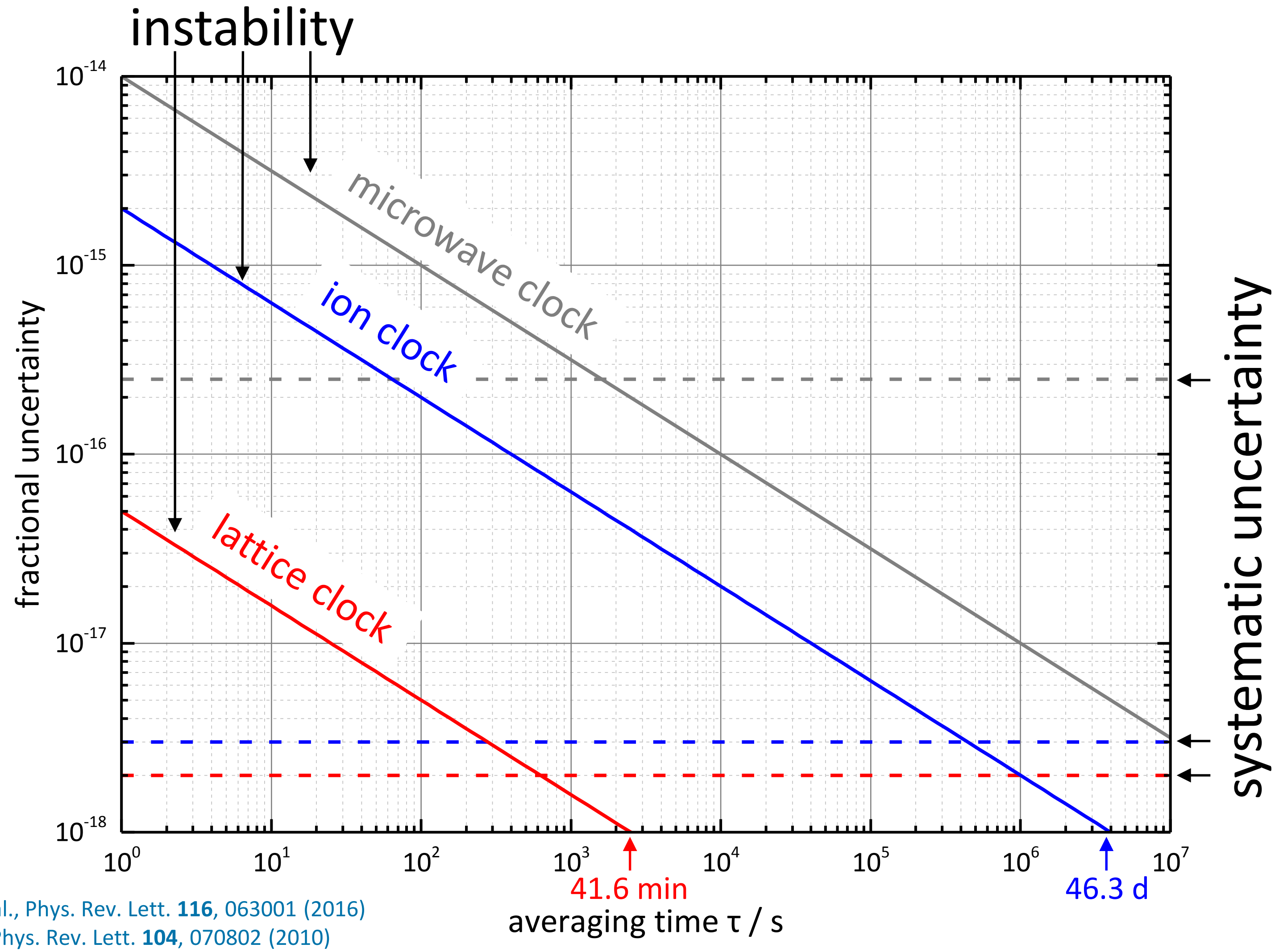
from: F. Riehle, Frequency Standards, Wiley VCH 2004

Vocabulary in International Metrology (BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML)
https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

Evolution of atomic clocks



Best clock performances



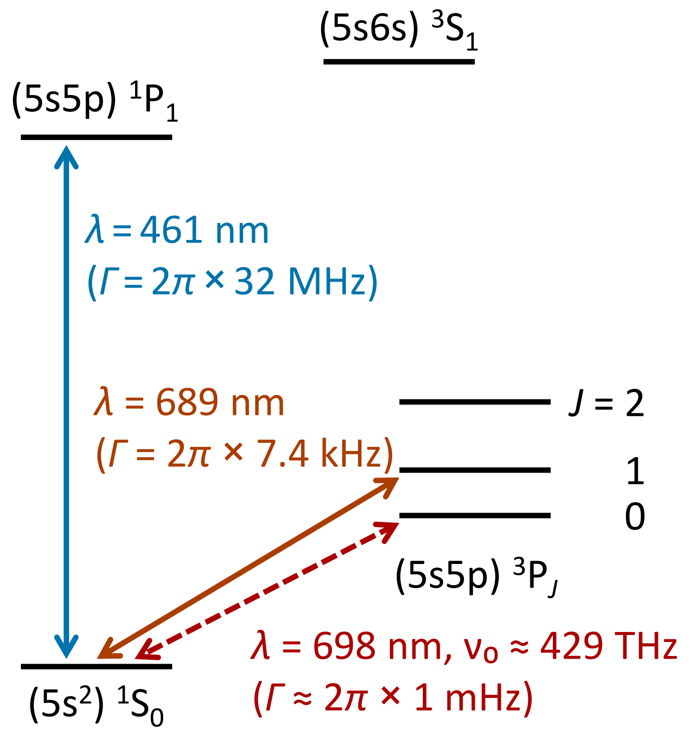
N. Huntemann et al., Phys. Rev. Lett. **116**, 063001 (2016)
C. W. Chou et al., Phys. Rev. Lett. **104**, 070802 (2010)
T. Nicholson et al., Nature Com. **6**, 6896 (2015)
M. Schioppo et al., Nature Photonics **11**, 48 (2017)

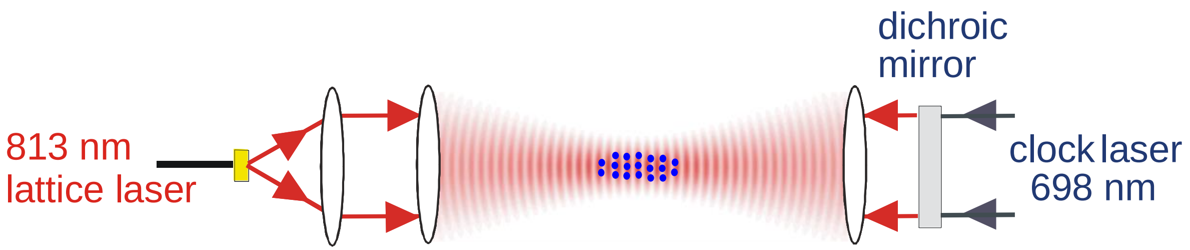
Strontium lattice clock

Experimental sequence

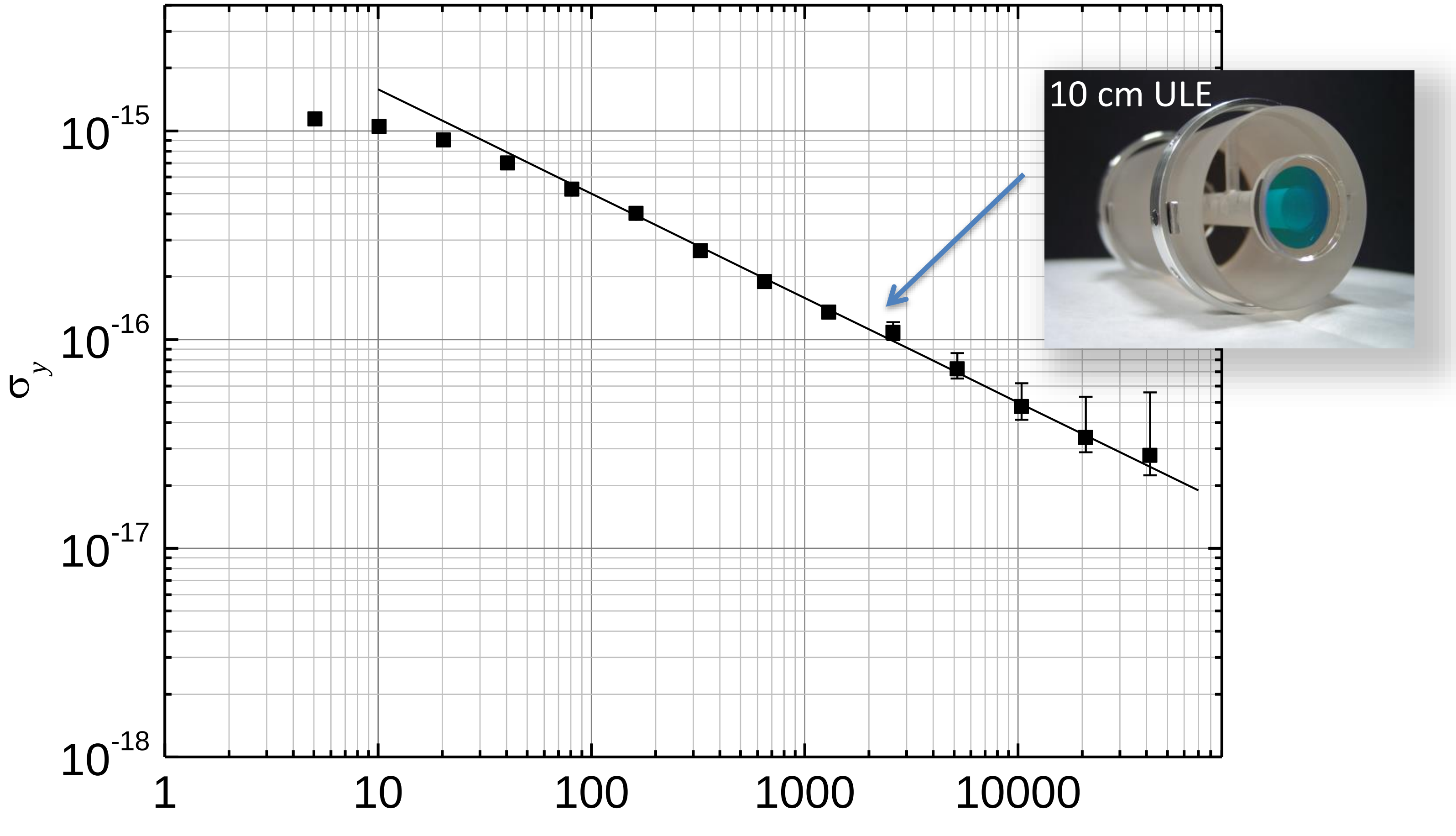
200 ms	Zeeman slower 1st stage MOT (461 nm), $T \backsim$ mK
90 ms	2nd stage MOT (689 nm)
90 ms	3rd stage MOT (689 nm), $T \backsim$ µK
65 ms	state preparation in 1D optical lattice
0.8 s – 2.6 s	Rabi interrogation (698 nm) in 1D optical lattice
	balanced detection

Partial level diagram





Importance of the clock laser



St. Falke *et al.*, Metrologia **48** (2011) 399 ,
Ch. Hagemann *et al.*, IEEE Trans. Instr. Meas. **62** (2013) 1556
A. Al-Masoudi *et al.*, PRA **92**, 063814 (2015)

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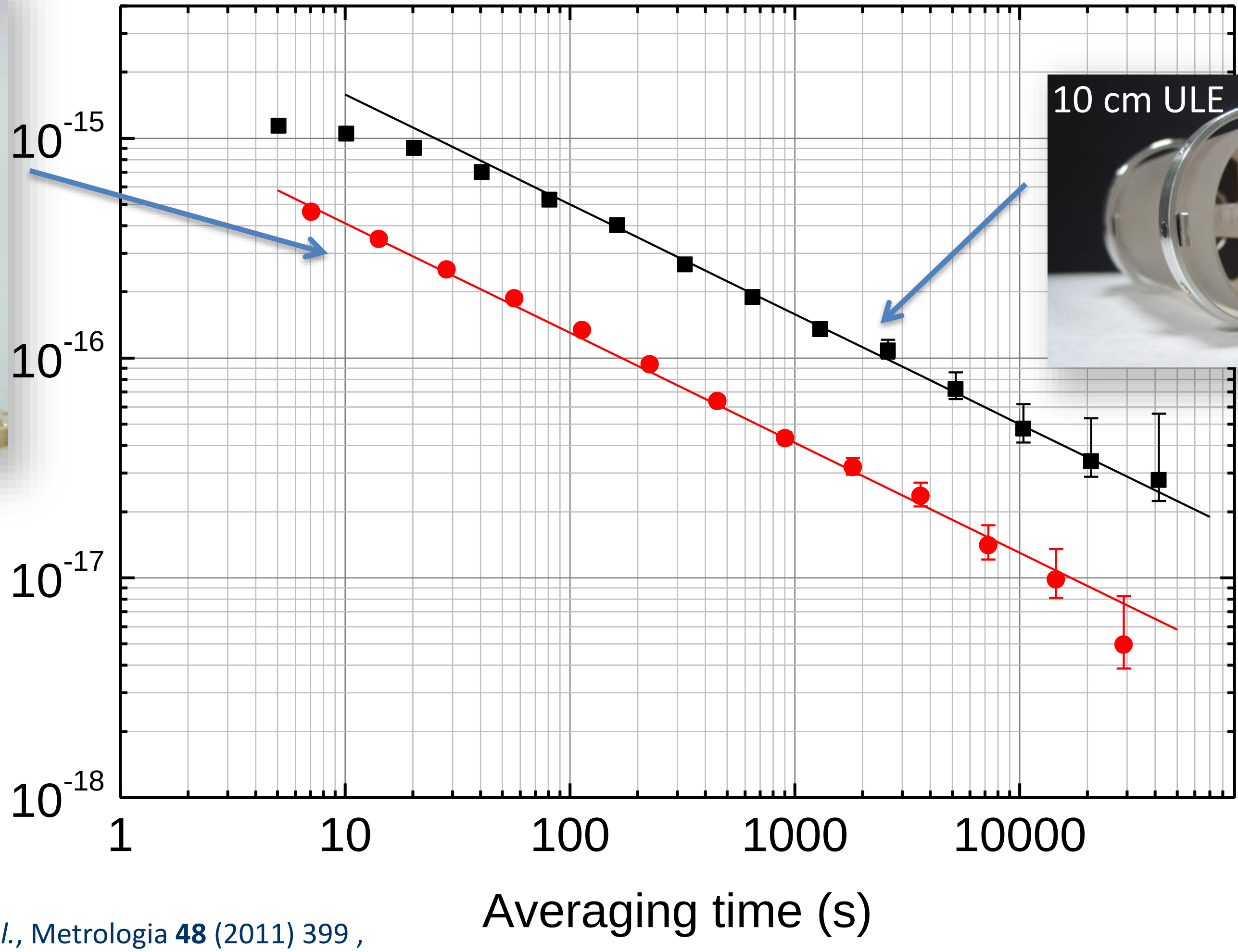

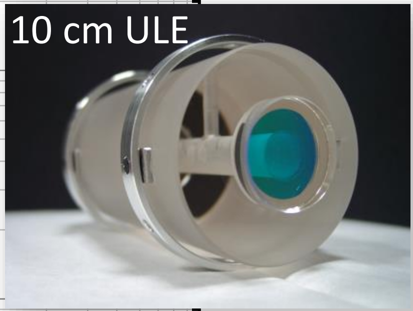

St. Falke *et al.*, Metrologia **48** (2011) 399 ,
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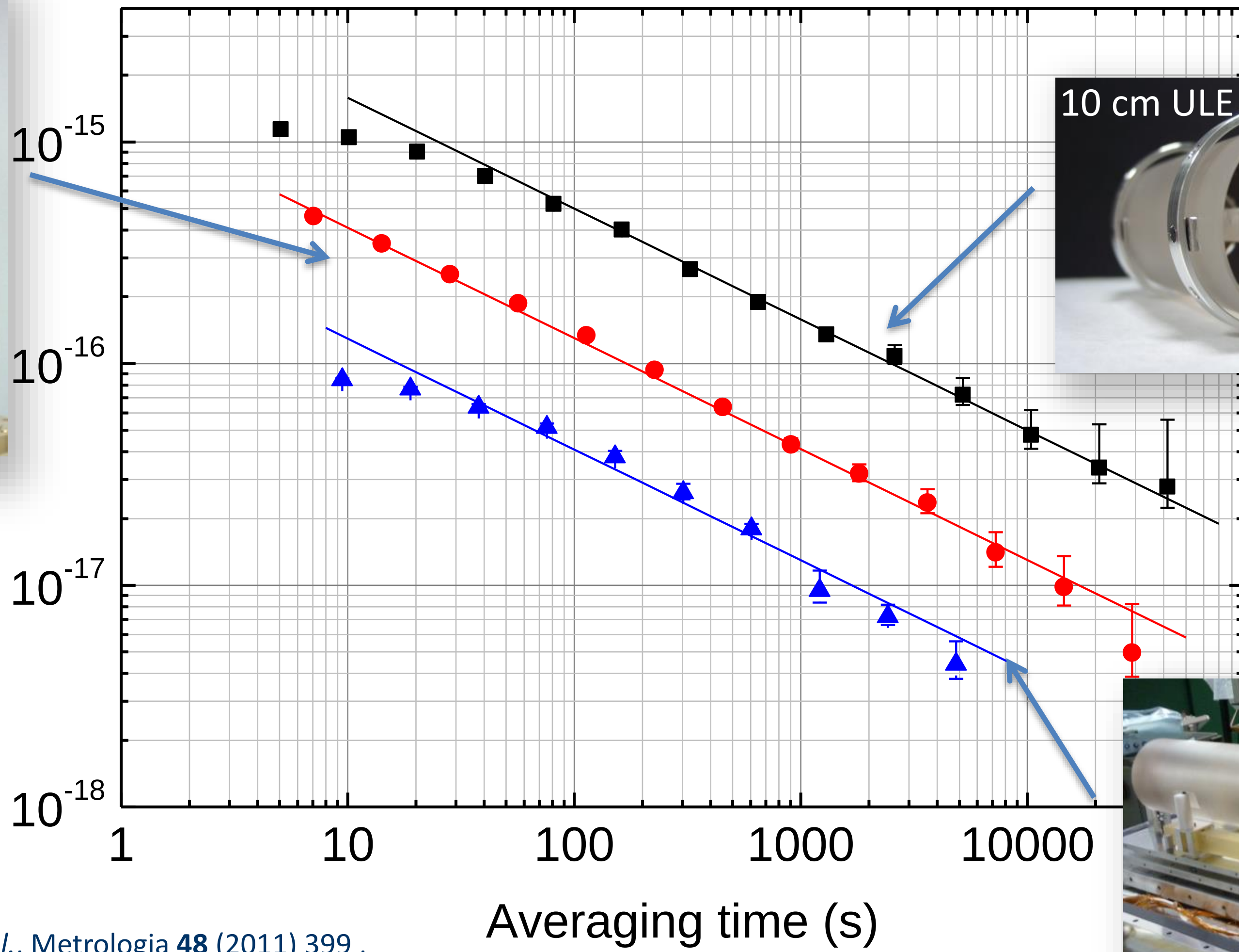

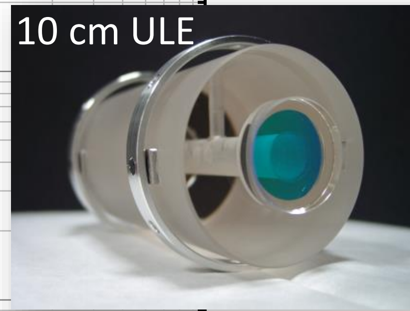

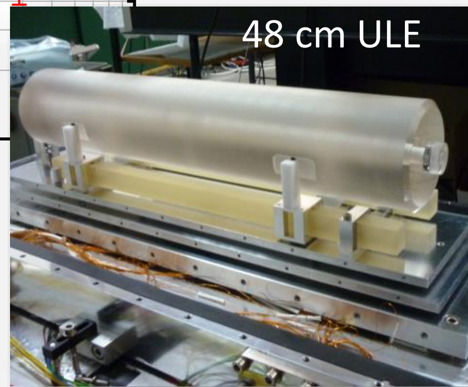

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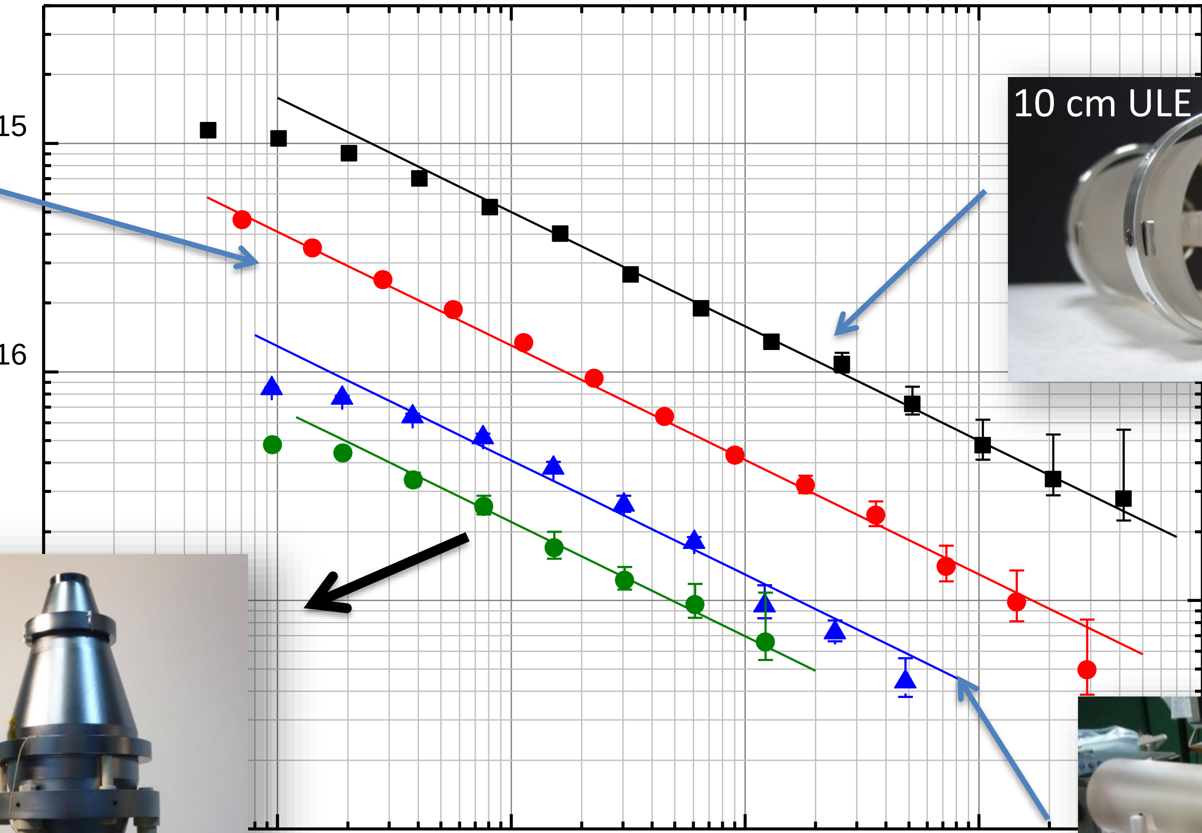
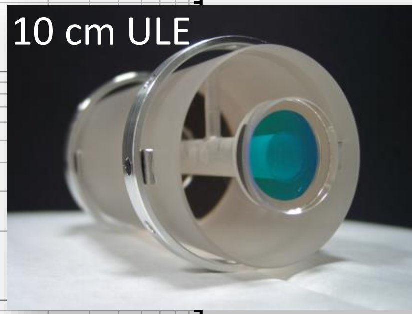
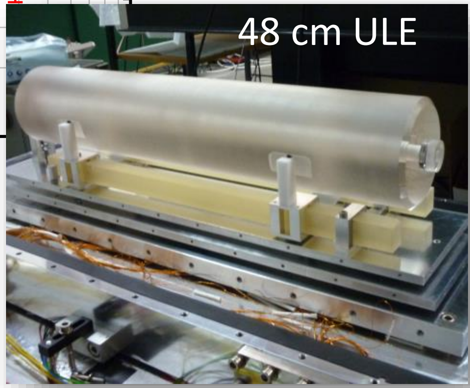






St. Falke e… 99 ,
Ch. Hagen… Meas. **62** (2013) 1556
A. Al-Masoudi *et al.*, PRA **92**, 063814 (2015)

Importance of the clock laser

FEM optimized cavity shape for minimal vibration sensitivity

expected thermal noise limit at T =123.5 K:

mod $\sigma_y \approx 4\times10^{-17}$

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta L}{L}$$

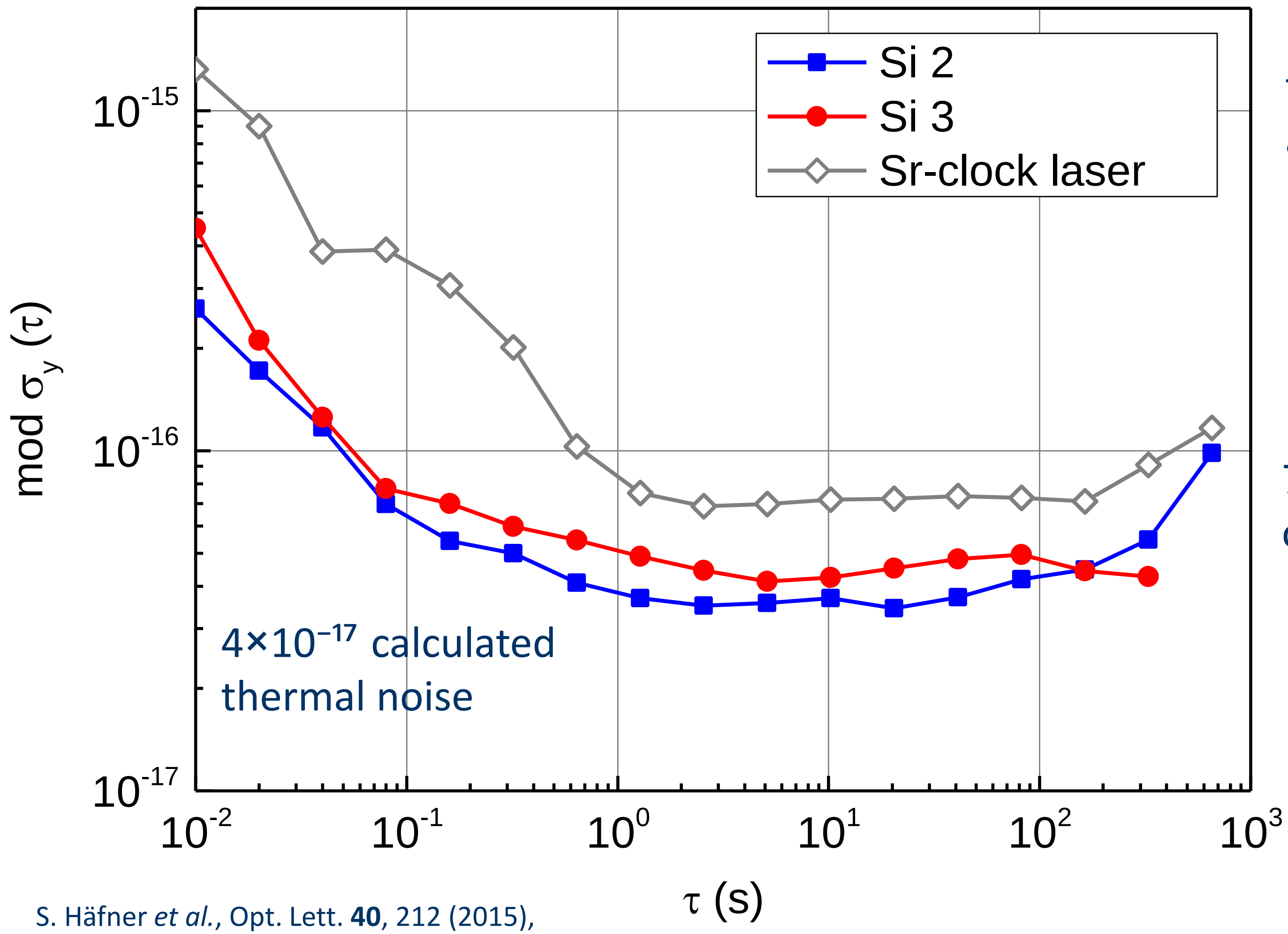
absolute length fluctuations $\approx 8.5\times10^{-18}$ m

dominated by mirror coatings!

proton diameter ≈ 0.85 fm = 850×10^{-18} m

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

Importance of the clock laser



linear drift removed from Si 3 – Si 2 and Sr – Si 2 beats

7×10^{-17} thermal noise of ULE cavity

S. Häfner *et al.*, Opt. Lett. **40**, 212 (2015),
T. Kessler *et al.*, Nature Phot. **6**, 687 (2012),
D. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

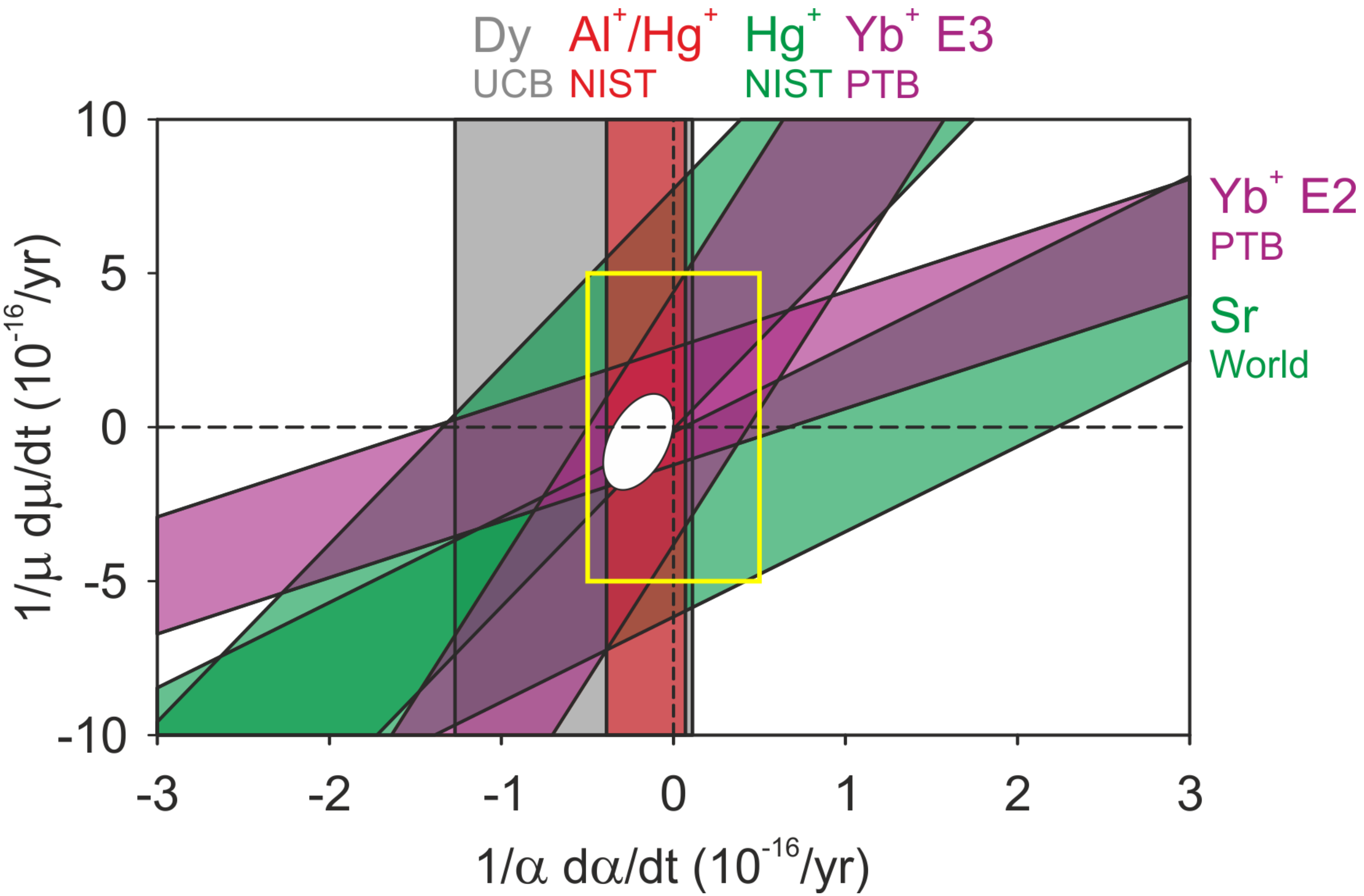
What can you do?

Yb$^+$ single ion clock

building A building B

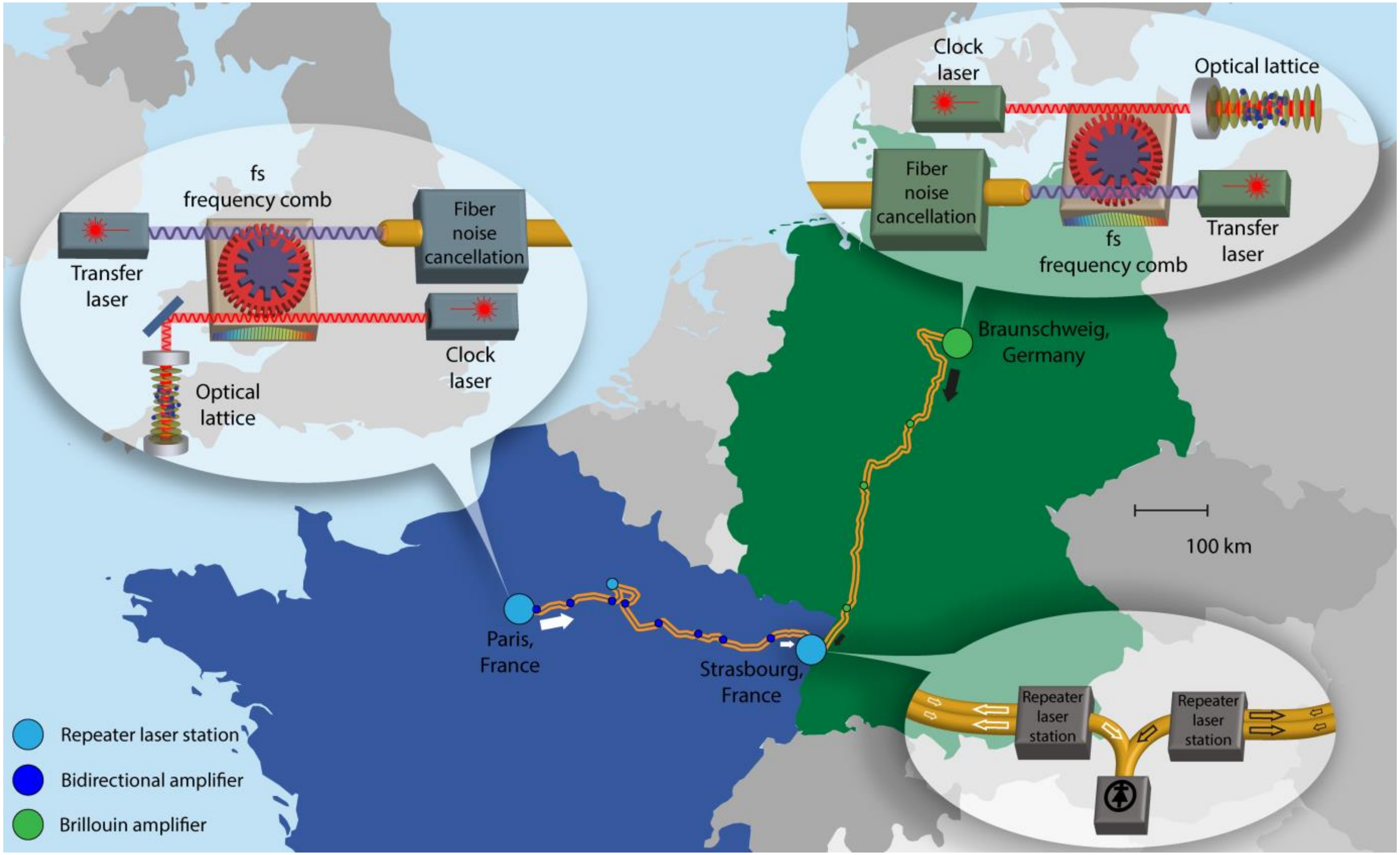
Sr lattice clock

Repeated comparisons – interpretation



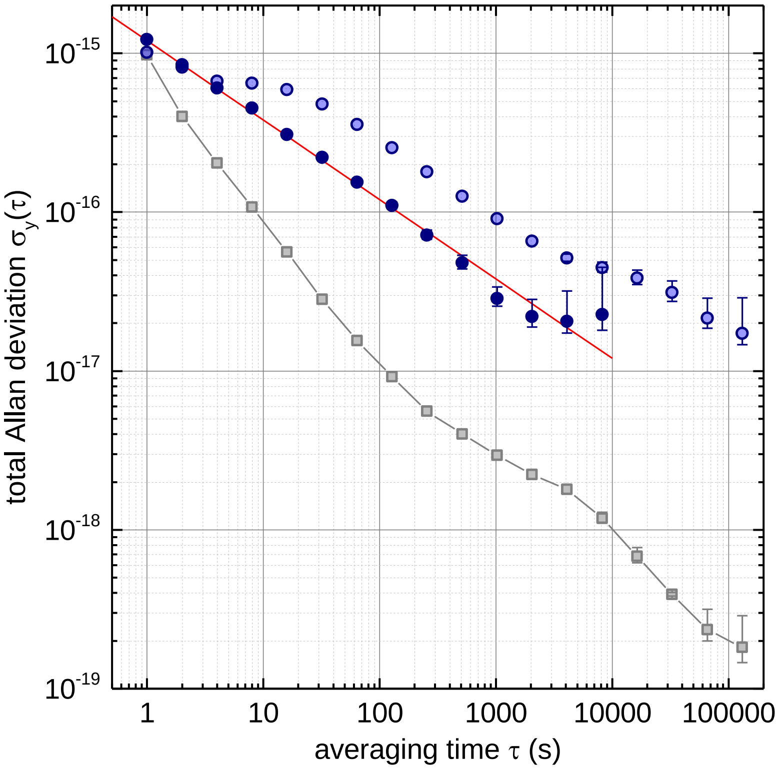
N. Huntemann *et al.*, Phys. Rev. Lett. **113**, 210802 (2014)
R. Godun *et al.*, Phys. Rev. Lett. **113**, 210801 (2014)
T. Rosenband *et al.*, Science **319**, 1808 (2008)

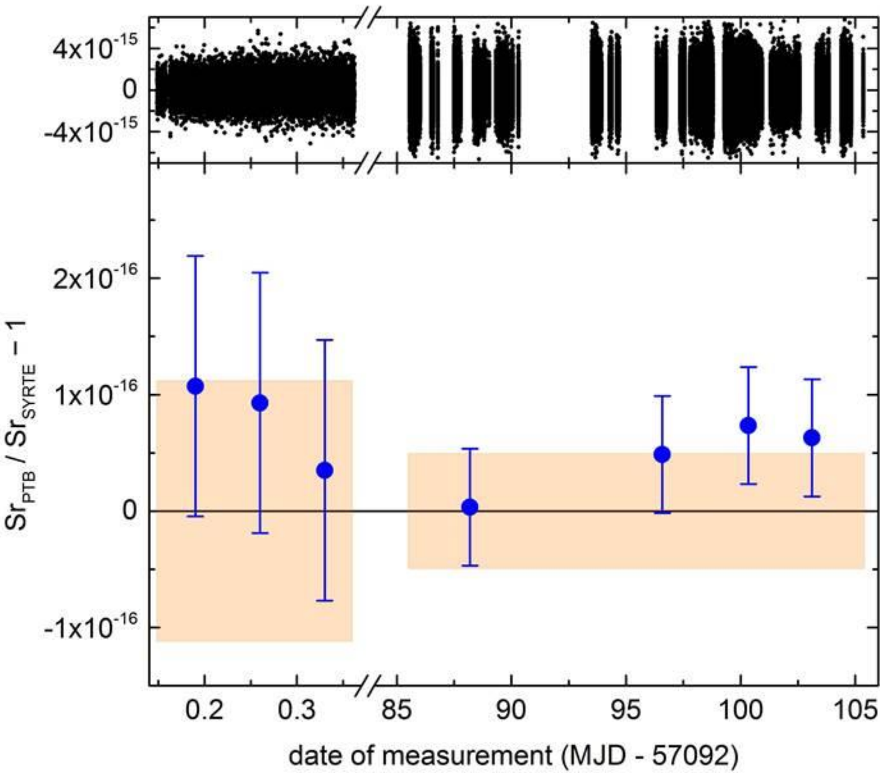
Clock comparisons – local and non-local



Ch. Lisdat *et al.*, Nature Comms. **7**, 12443 (2016)

Clock comparisons – Paris & Braunschweig



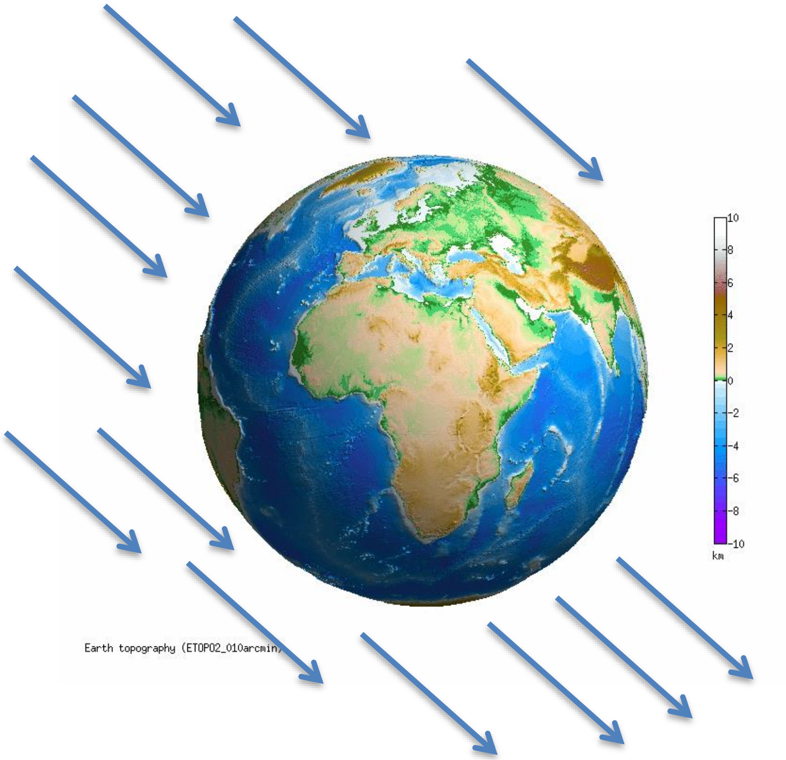


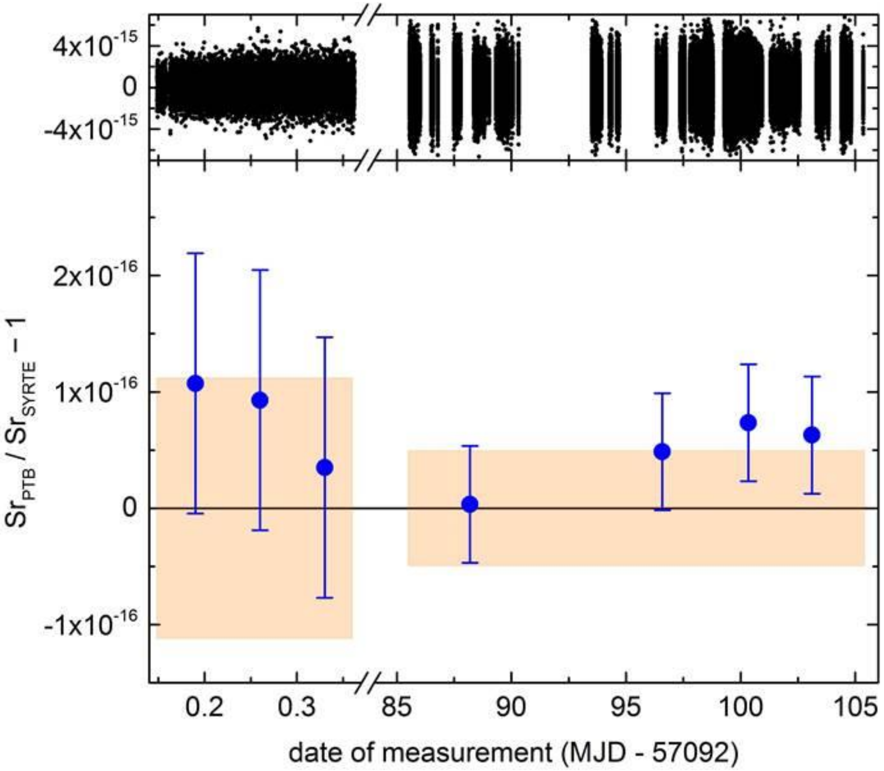
Gravity potential correction
$-247.2(4)\times10^{-17}$

Ch. Lisdat *et al.*, Nature Comms. **7**, 12443 (2016)

Clock comparisons – Paris & Braunschweig

Local Lorentz invariance: search for daily modulation due to motion wrt. background

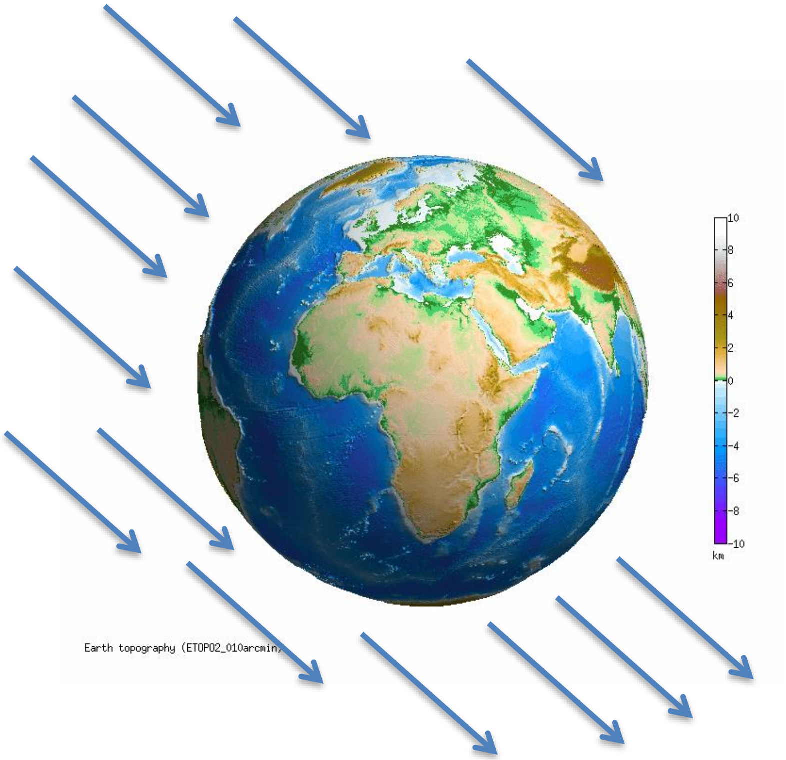




animation: A. Bezdek and J. Sebera, Computers & Geosciences **56**, 127 (2013), data set: ETOPO2 / EGM2008

Clock comparisons – Paris & Braunschweig

Local Lorentz invariance: search for daily modulation due to motion wrt. background



was done with Rb clocks (GPS)
P. Wolf & G. Petit, Phys. Rev. A **56**, 4405 (1997)

$|\alpha| \leq 10^{-6}$

LLI test also with fast ion beams
B. Botermann *et al.*, Phys. Rev. Lett. **113**, 120405 (2014)

$|\alpha| \leq 2 \times 10^{-8}$

Sr clocks London, Paris, Braunschweig
P. Delva *et al.*, Phys. Rev. Lett. **118**, 221102 (2017)

$|\alpha| \leq 1.2 \times 10^{-8}$

animation: A. Bezdek and J. Sebera, Computers & Geosciences **56**, 127 (2013), data set: ETOPO2 / EGM2008

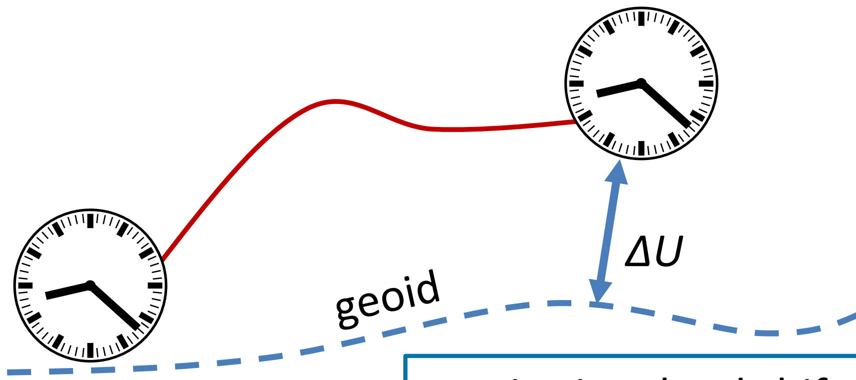
Transportable optical clocks

Leaving the lab:
Transportable clocks

- ► flexibility of clock pairs
- ► choose operation sites
  to probe the gravity potential
- ► first step towards space

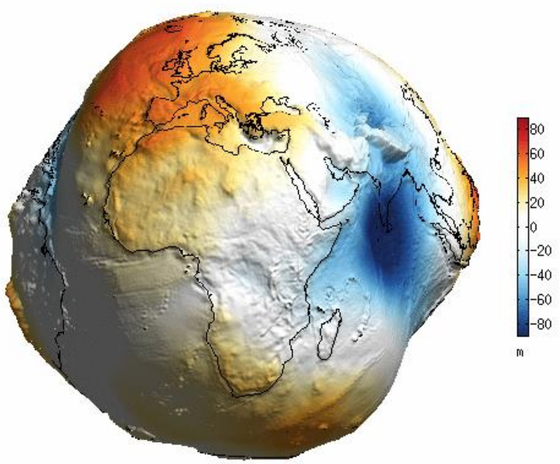
Transportable optical clocks

- Optical clocks as sensors:
  - Directly measure potential differences.
  - Vision: Realize geoid by clocks.



gravitational red shift:
$\Delta\nu/\nu = \Delta U/c^2$

Earth topography (ETOPO2_010arcmin)

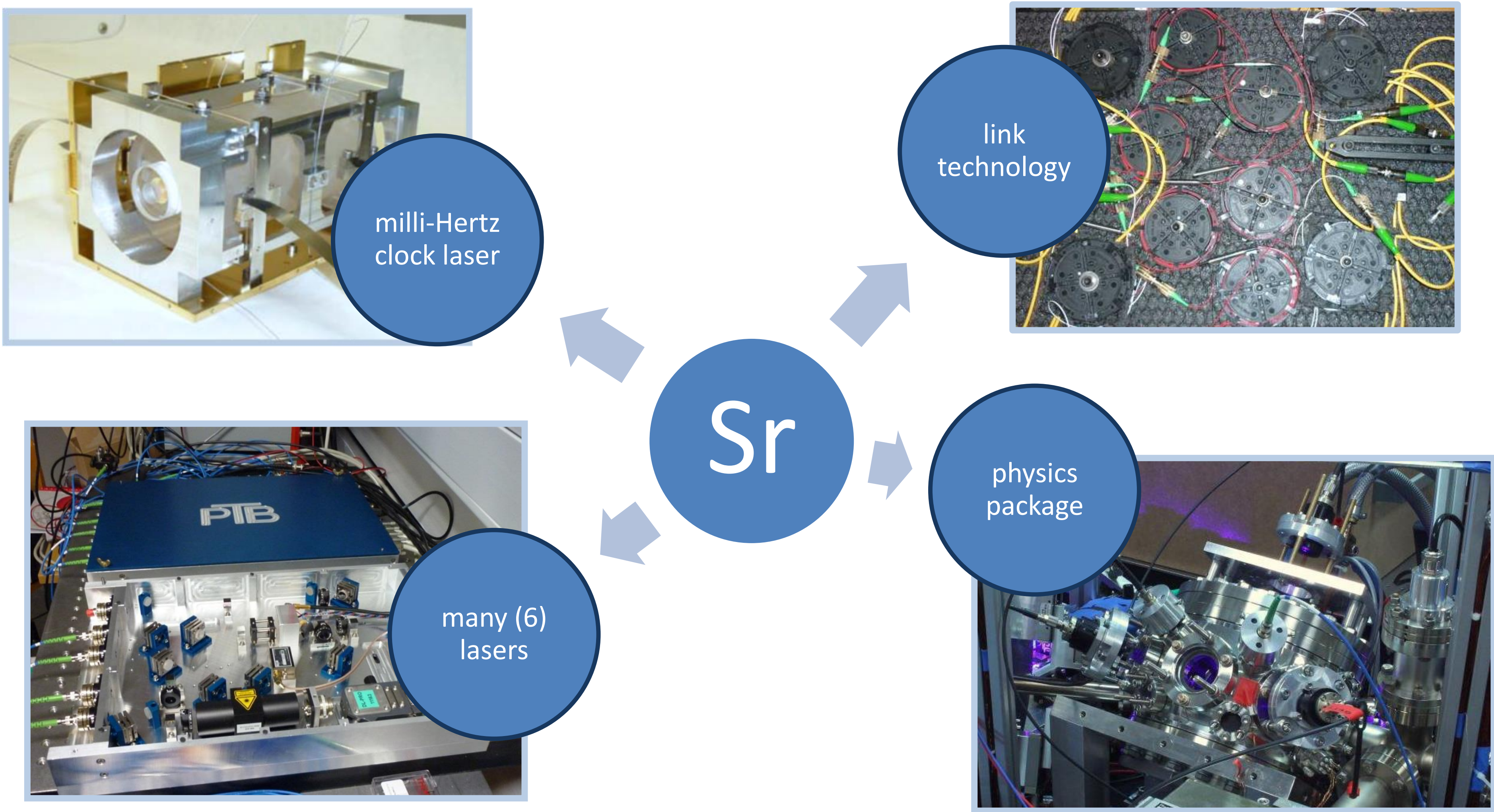


Geoid height (EGM2008, nmax=500)

M. Vermeer, Rep. of the Finnish Geod. Insti. **83**, 1 (1983)

A. Bjerhammar, Bull. Geodesique **59**, 207 (1985)

Transportable optical clocks

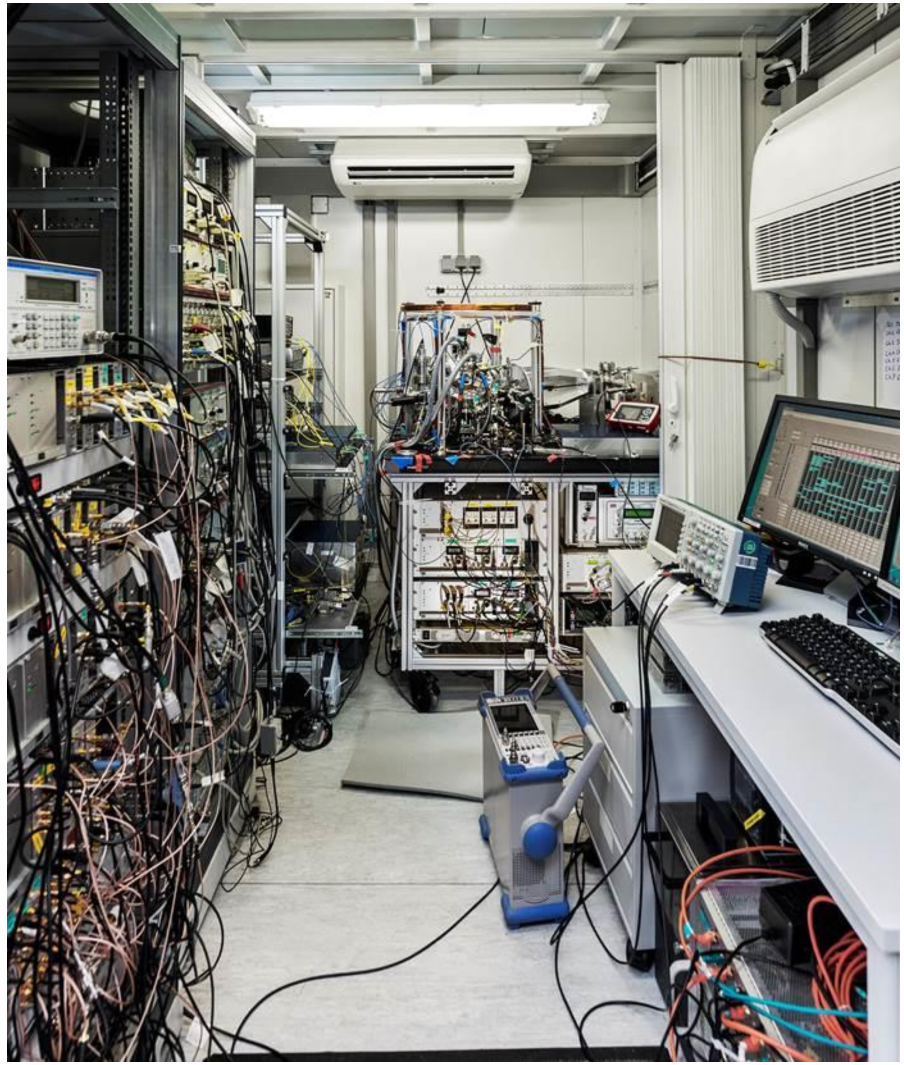


Transportable optical clocks

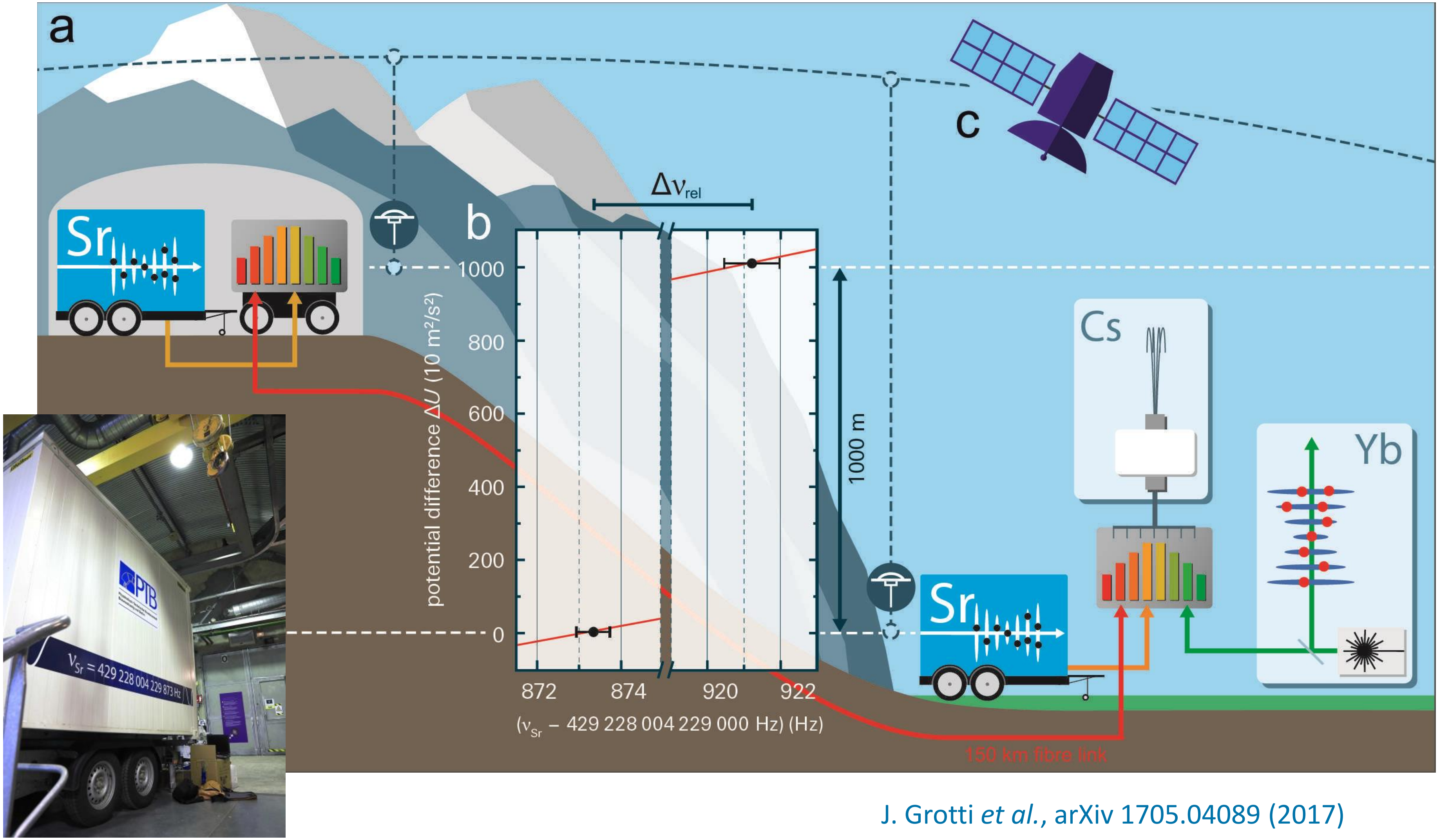
Car trailer housing the clock

S. Koller *et al.*, Phys. Rev. Lett. **118**, 073601 (2017)

View into the car trailer ►

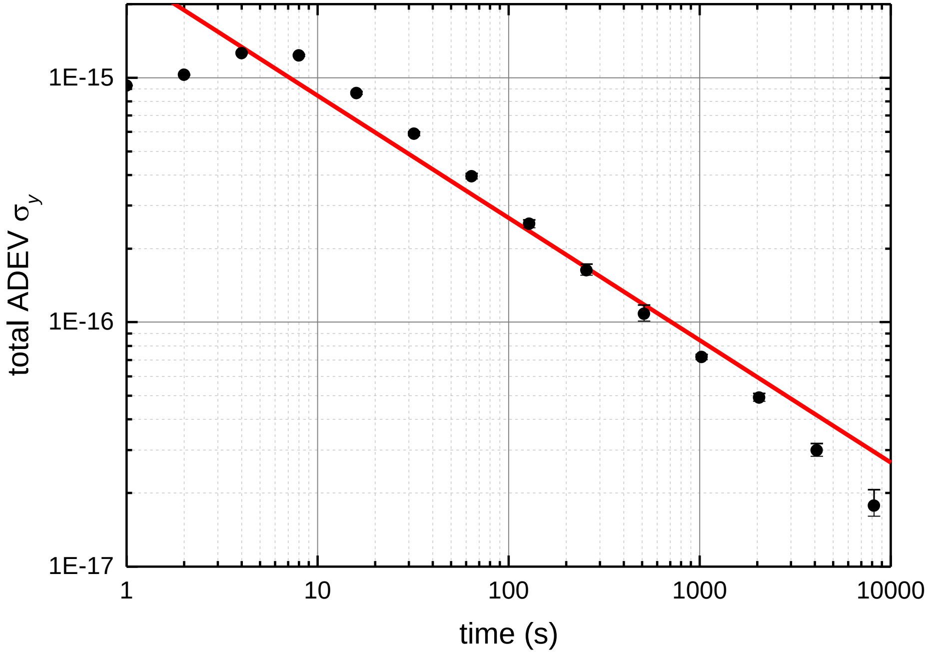


First time off-campus: Modane – Torino 2016



J. Grotti *et al.*, arXiv 1705.04089 (2017)

Second campaign: Paris – Braunschweig 2017



Combined uncertainty ≈ 3×10^{-17} or 30 cm in 3 hours.

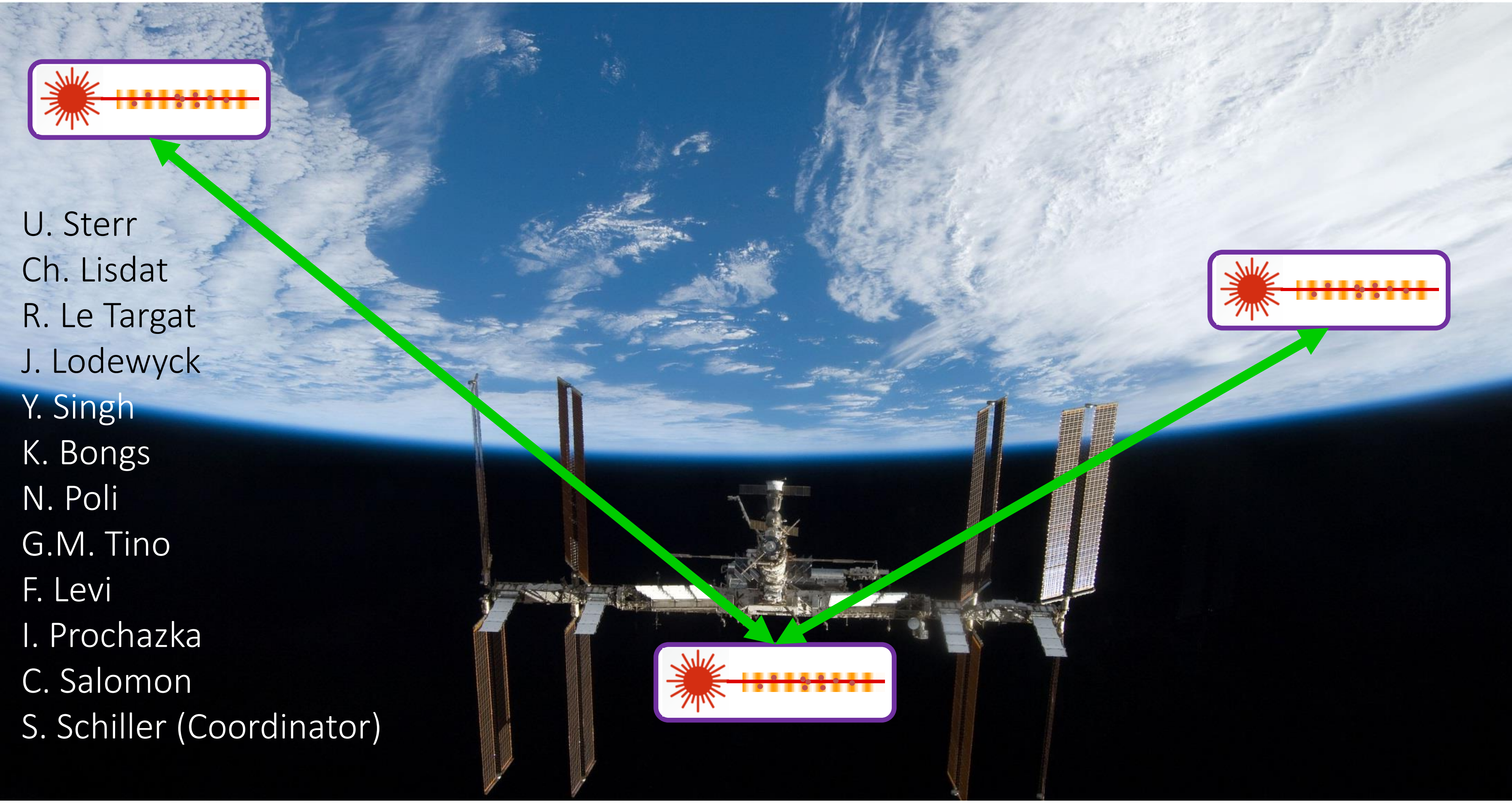
Gravity potential correction from geodesy: $-247.2(4)\times10^{-17}$

unfortunately: ‘anomaly’ in the second half of the campaign

Status PTB's transportable lattice clock

- Approaching design uncertainty of 1×10^{-17}
- Reliability is still a problem
  – but it is obvious that you can do better
- Balance design/construction effort with salary of PhD student
- Next generation: lower uncertainty (1×10^{-18}?)
  more 'user friendly'
  as heavy and power hungry

Mission I-SOC:
An optical clock on the ISS



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

Science goals of I-SOC

Explore the limits of our physical laws:

- Test Einstein's prediction of time dilation (*Earth, Sun, Moon*)
- Test of the gravitational-potential independence of fundamental constants
- Kennedy-Thorndike experiment
- Support search for dark matter topological defects

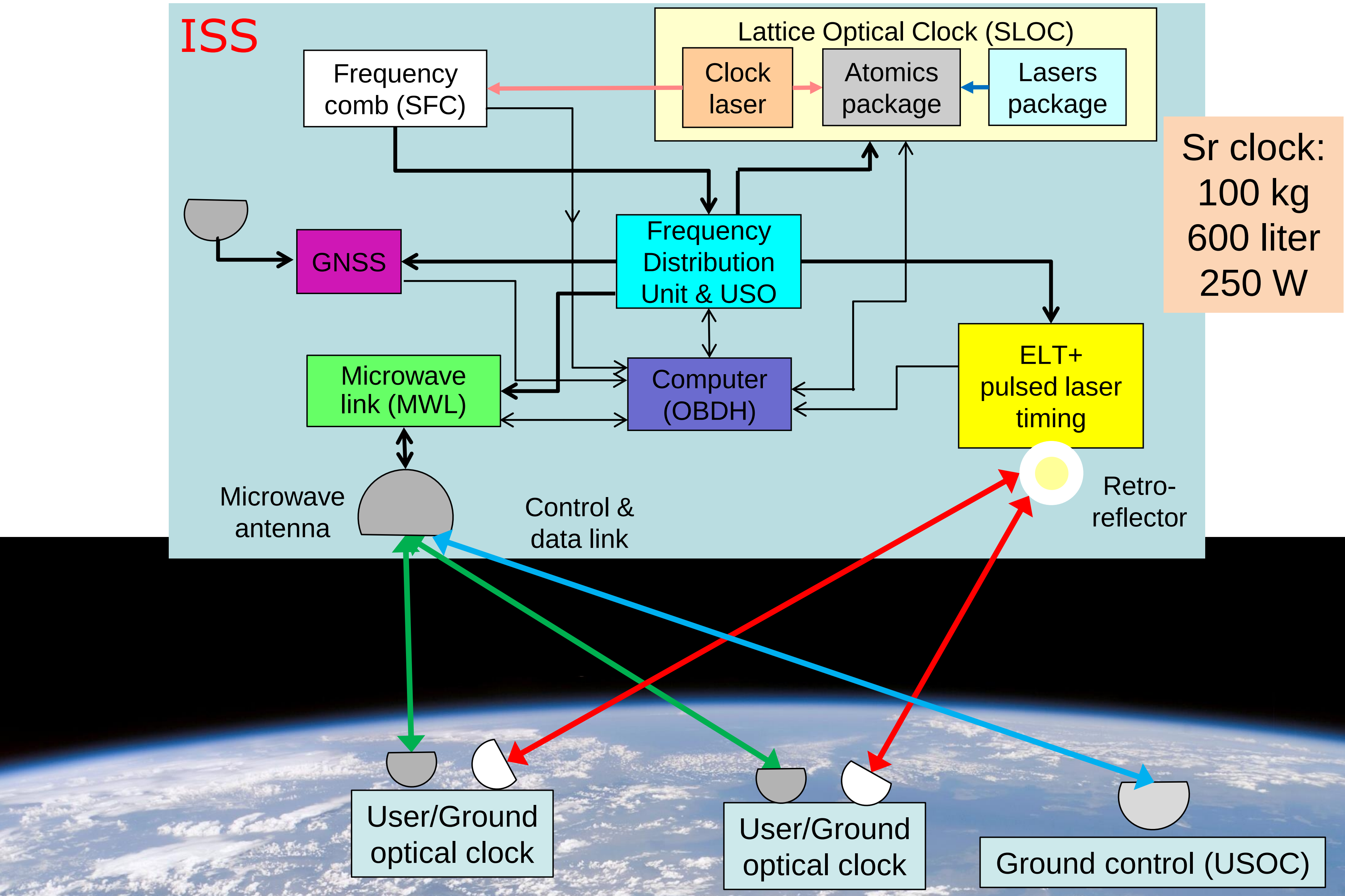
Frequency links + high-performance clock in space:

- Timekeeping: comparison of distant terrestrial clocks
- Relativistic geodesy: determination of the local gravity potential at 1 cm equivalent level within 1 day measur'.t time

Master clock in space:

- Delivery of atomic time to ground and (optionally) to spacecrafts

I-SOC payload: concept



Sr clock:
100 kg
600 liter
250 W

ACES and I-SOC

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

	ACES	I-SOC *	Improvem.
Clock instability	$1x10^{-13}/\tau^{1/2}$	$8x10^{-16}/\tau^{1/2}$ (τ up to 2×10^{6} s)	x 100
Clock uncertainty	$1x10^{-16}$	$1x10^{-17}$	x 10
MWL / MWL+ TDEV	1.5 ps $\times(\tau/10\ 000\ s)^{1/2}$	0.03 ps ** $\tau > 1000$ s	x 150 @ 1 day
ELT / ELT+ TDEV	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> SLOC
- ELT+ supports reaching 1×10^{-18} 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

I-SOC: way forward

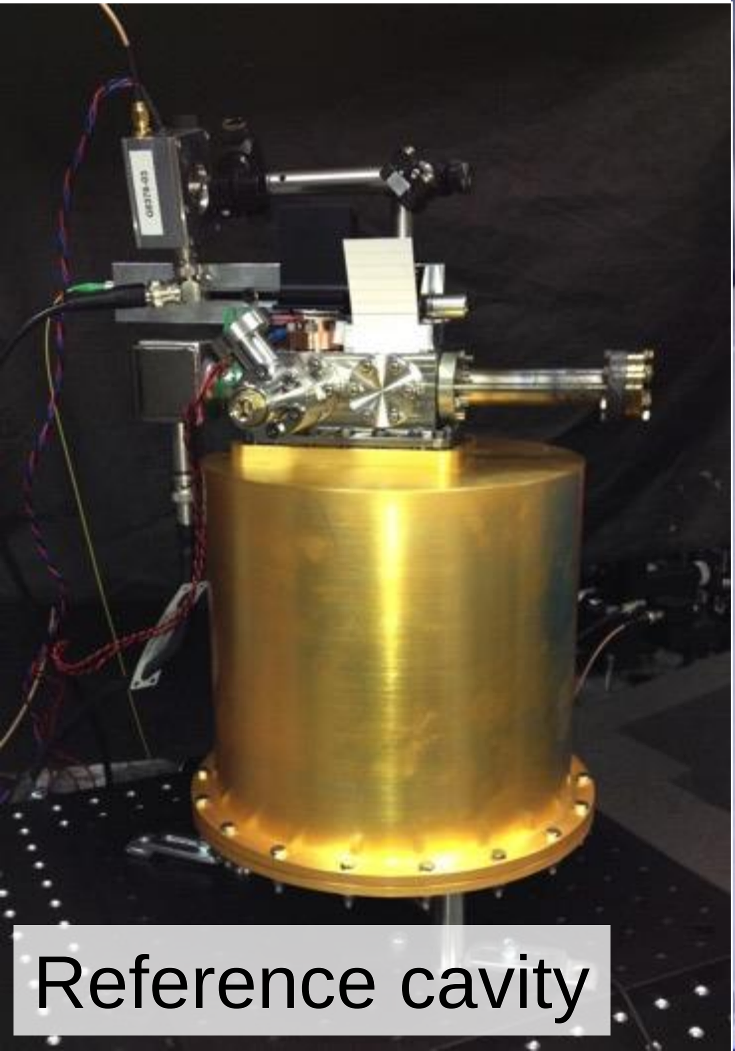
New approach by ESA:
Science team is strongly involved in all phases of mission development

1) ESA technology developments 2016-2018:
- *462 nm, 689 nm lasers* *[Fraunhofer UK, TopGaN,CNR,HHU]*
- *CCU: laser frequency stabilization system* *[NPL UK, PTB]*
- *813 nm lattice laser* *[Fraunhofer UK, SYRTE]*
- *Clock laser reference cavity (1397 nm)* *[Airbus F'hafen, NPL, SpaceTech, PTB]*
- *Two-way microwave link* *[Timetech, DLR Oberpf., SYRTE]*

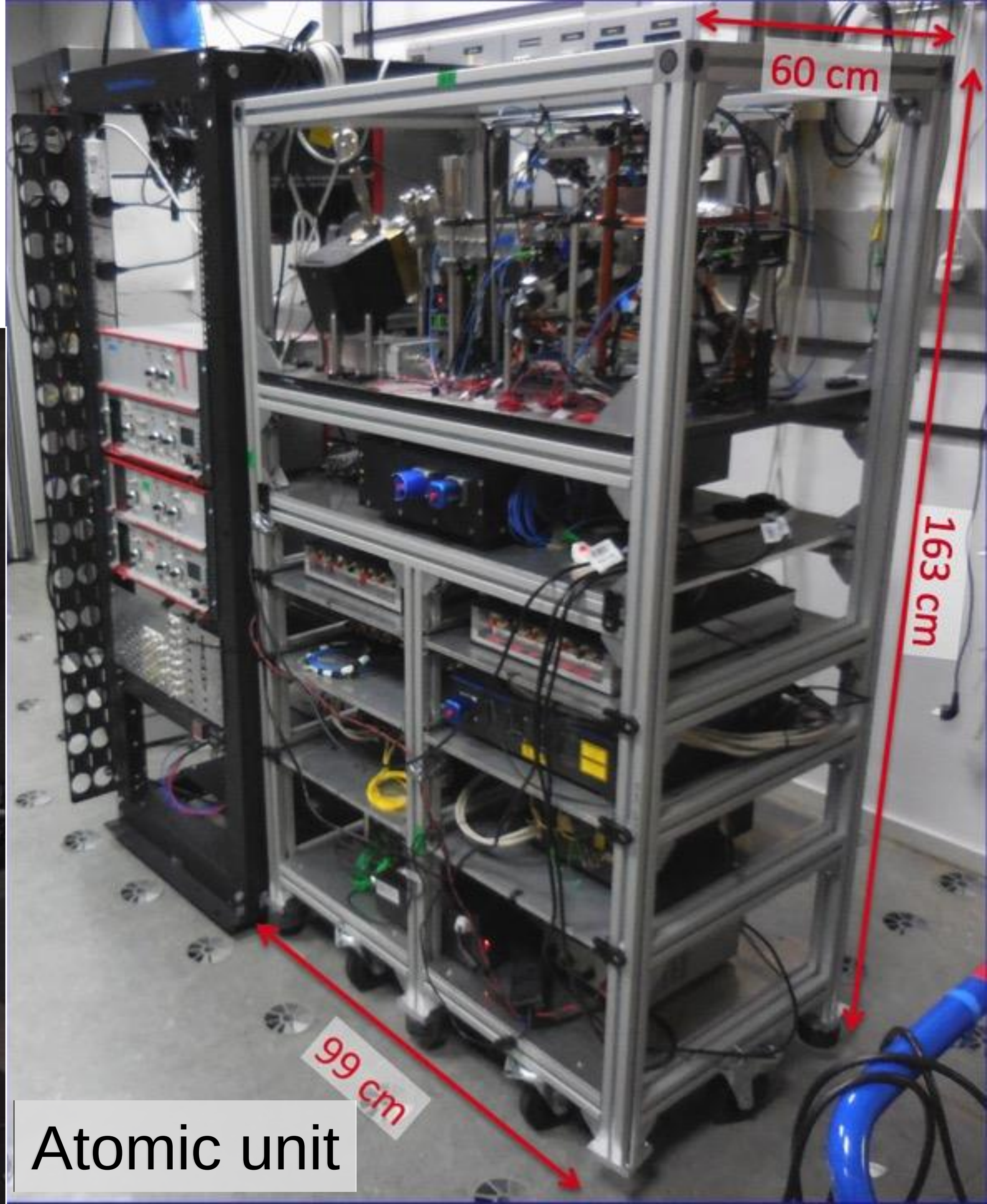
2) Experiment Science Document	2/2017	*[Science team]*
3) Phase-A study, scientific part	2017	*[Science team]*
4) Phase-A study, industrial part	2018	*[space industry, Science team]*
5) Phases B, C	2019+	*[space industry, Science team]*

Mission **2022+**

I-SOC:
Sr lattice clock demonstrator

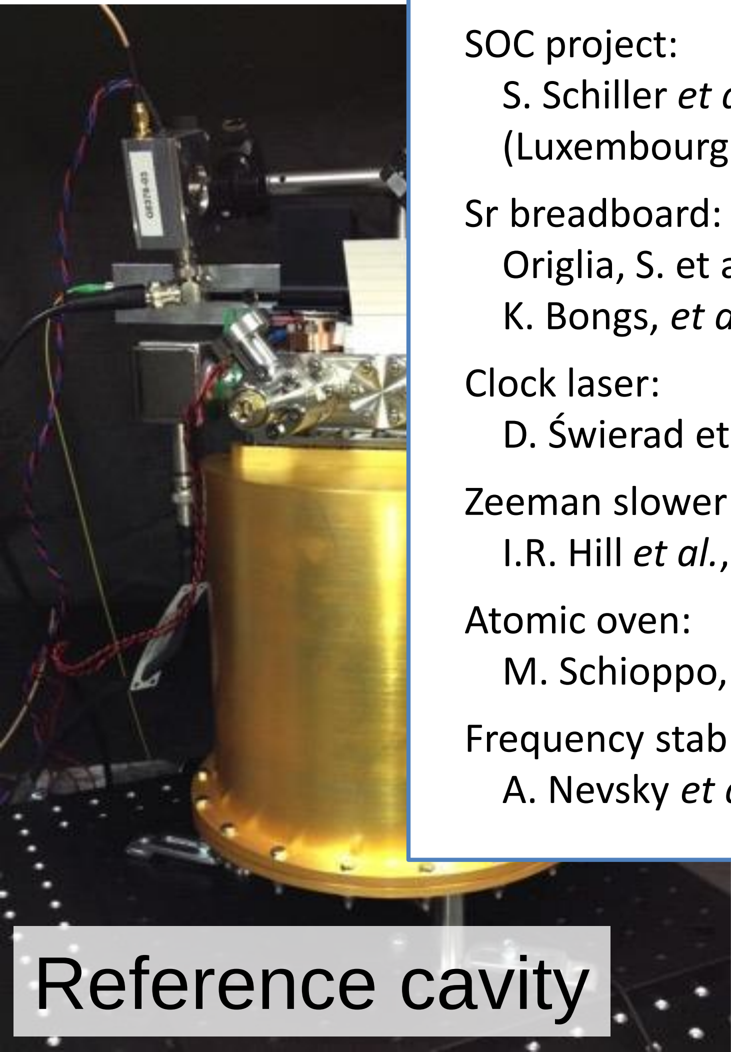


Reference cavity

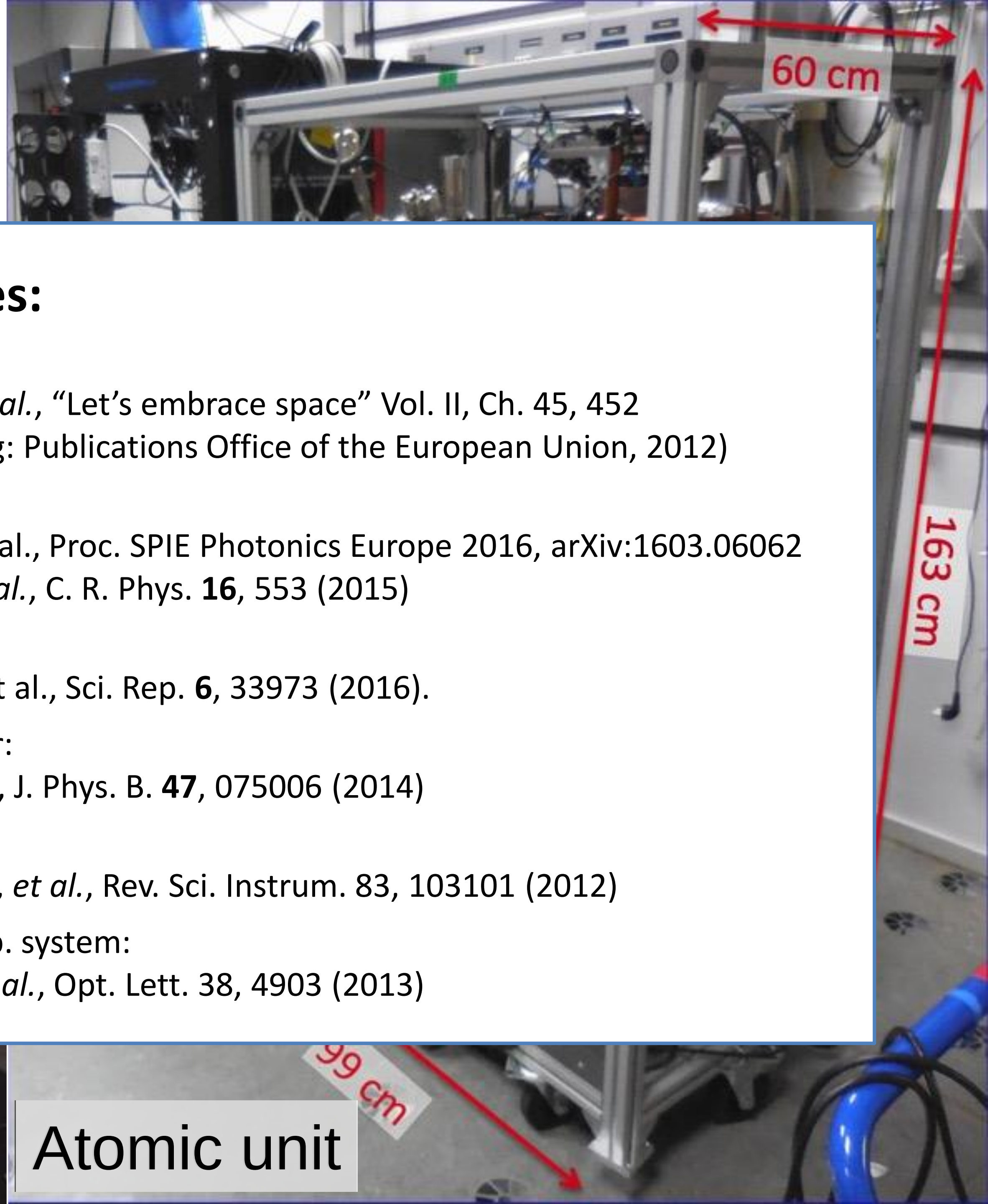


Atomic unit

I-SOC:
Sr lattice clock demonstrator



Reference cavity



Atomic unit

References:

SOC project:
- S. Schiller *et al.*, "Let's embrace space" Vol. II, Ch. 45, 452 (Luxembourg: Publications Office of the European Union, 2012)

Sr breadboard:
- Origlia, S. et al., Proc. SPIE Photonics Europe 2016, arXiv:1603.06062
- K. Bongs, *et al.*, C. R. Phys. **16**, 553 (2015)

Clock laser:
- D. Świerad et al., Sci. Rep. **6**, 33973 (2016).

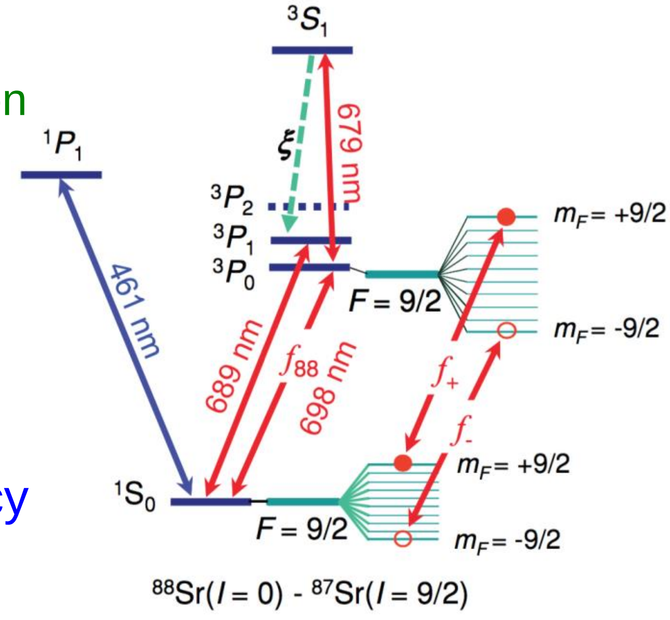
Zeeman slower:
- I.R. Hill *et al.*, J. Phys. B. **47**, 075006 (2014)

Atomic oven:
- M. Schioppo, *et al.*, Rev. Sci. Instrum. 83, 103101 (2012)

Frequency stab. system:
- A. Nevsky *et al.*, Opt. Lett. 38, 4903 (2013)

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

^{88}Sr	^{87}Sr
Isotopic aboundance: 83%	Isotopic aboundance: 7%
Laser cooling easier	Nuclear spin (I = 9/2): laser cooling more complicated (1 more laser)
Shorter cycle time (2 interrogations)	1st order Zeeman shift (4 interrogations)
Insensitive to vector and tensor light shift	Sensitive to vector and tensor light shift
Need for magnetically induced spectroscopy: 1) Large magnetic field 2) Large clock laser beam intensity	Hyperfine interaction allows $^1S_0$-$^3P_0$ transition
s-wave collisions	Only p-wave collisions
May have advantages in terms of simplicity and for transportability	Better for accuracy



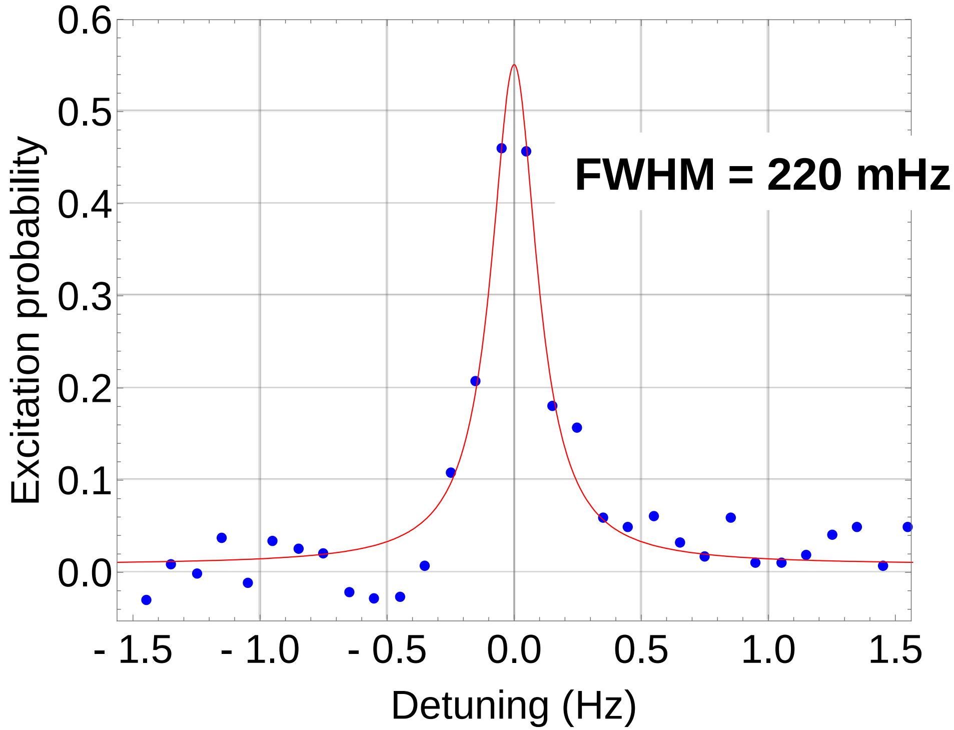
I-SOC Clock transition line in ^{88}Sr (698 nm)

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

$$|\boldsymbol{B}| = 0.20\ \mathrm{mT} \qquad \Delta\nu_B \approx 0.9\ \mathrm{Hz}$$

$$I = 14\ \mathrm{mW/cm^2} \qquad \Delta\nu_I \approx 0.5\ \mathrm{Hz}$$

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



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)

I-SOC clock demonstrator instability

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

PTB

UNIVERSITY OF BIRMINGHAM

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

Combined instability of the two clocks:

$4.2 \times 10^{-16}/\sqrt{\tau}$

Lowest instability:

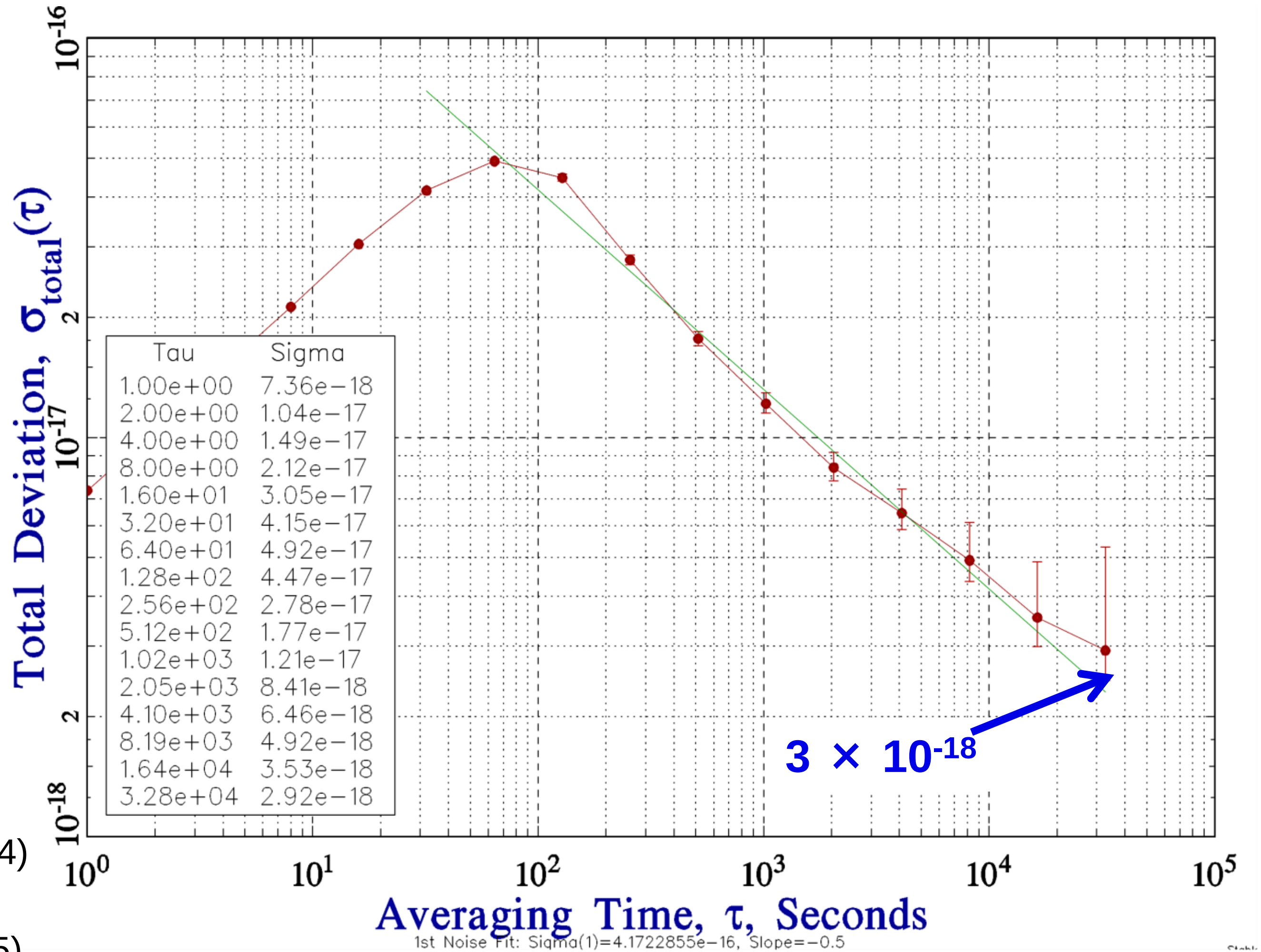
3×10^{-18} at

$\tau = 2 \times 10^{4}$ s

Tot. averaging time:

102 000 s

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



Tau	Sigma
1.00e+00	7.36e−18
2.00e+00	1.04e−17
4.00e+00	1.49e−17
8.00e+00	2.12e−17
1.60e+01	3.05e−17
3.20e+01	4.15e−17
6.40e+01	4.92e−17
1.28e+02	4.47e−17
2.56e+02	2.78e−17
5.12e+02	1.77e−17
1.02e+03	1.21e−17
2.05e+03	8.41e−18
4.10e+03	6.46e−18
8.19e+03	4.92e−18
1.64e+04	3.53e−18
3.28e+04	2.92e−18

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

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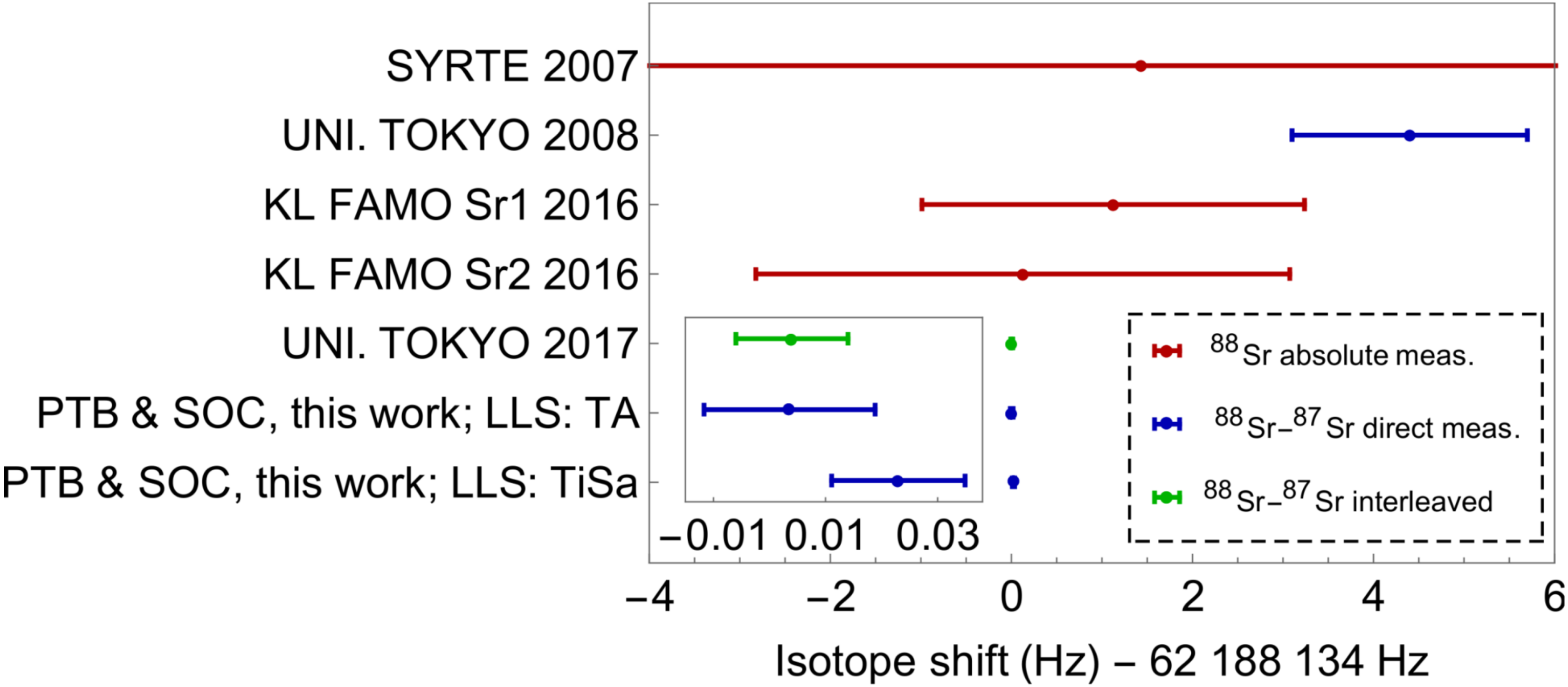

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- ► test system for components
- ► very good optical clock
- ► transportable clock laser…

In conclusion:

- ►Optical clocks are pretty accurate/stable/cool.
  We are getting closer to uncertainties of 10^{-18}.

- ►All fits into a car trailer,
  low-10^{-17} uncertainties have been demonstrated.

- ►Space seems possible!
  Many building blocks are there (ACES, Lisa pathfinder, combs…)

- ►Why space?
  many fundamental experiments are ‘easier’
  a new SI-second will need intercontinental links
  Earth observation: long-term stable height reference

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