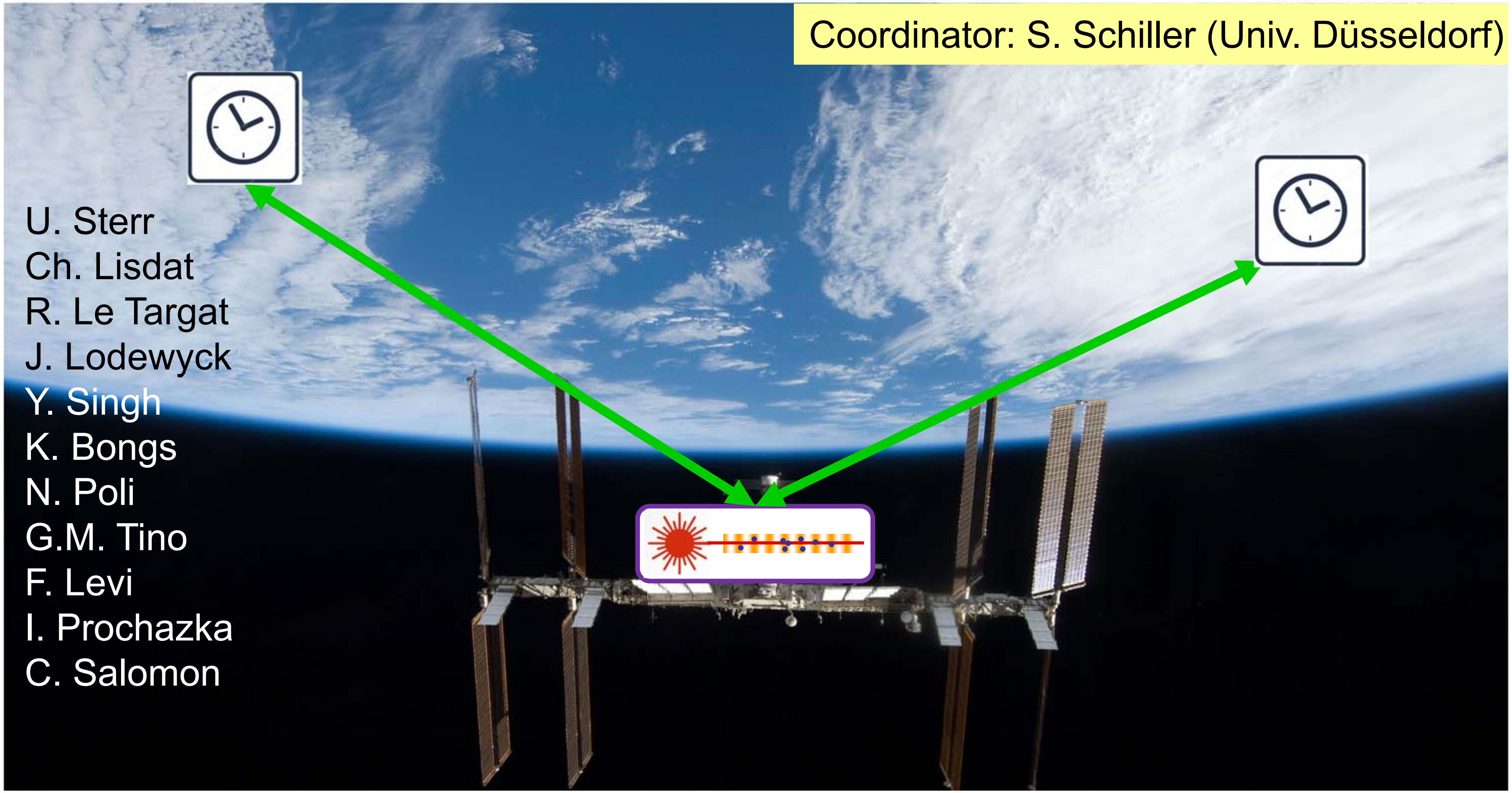
# Mission I-SOC:
## A world-wide frequency & time metrology network



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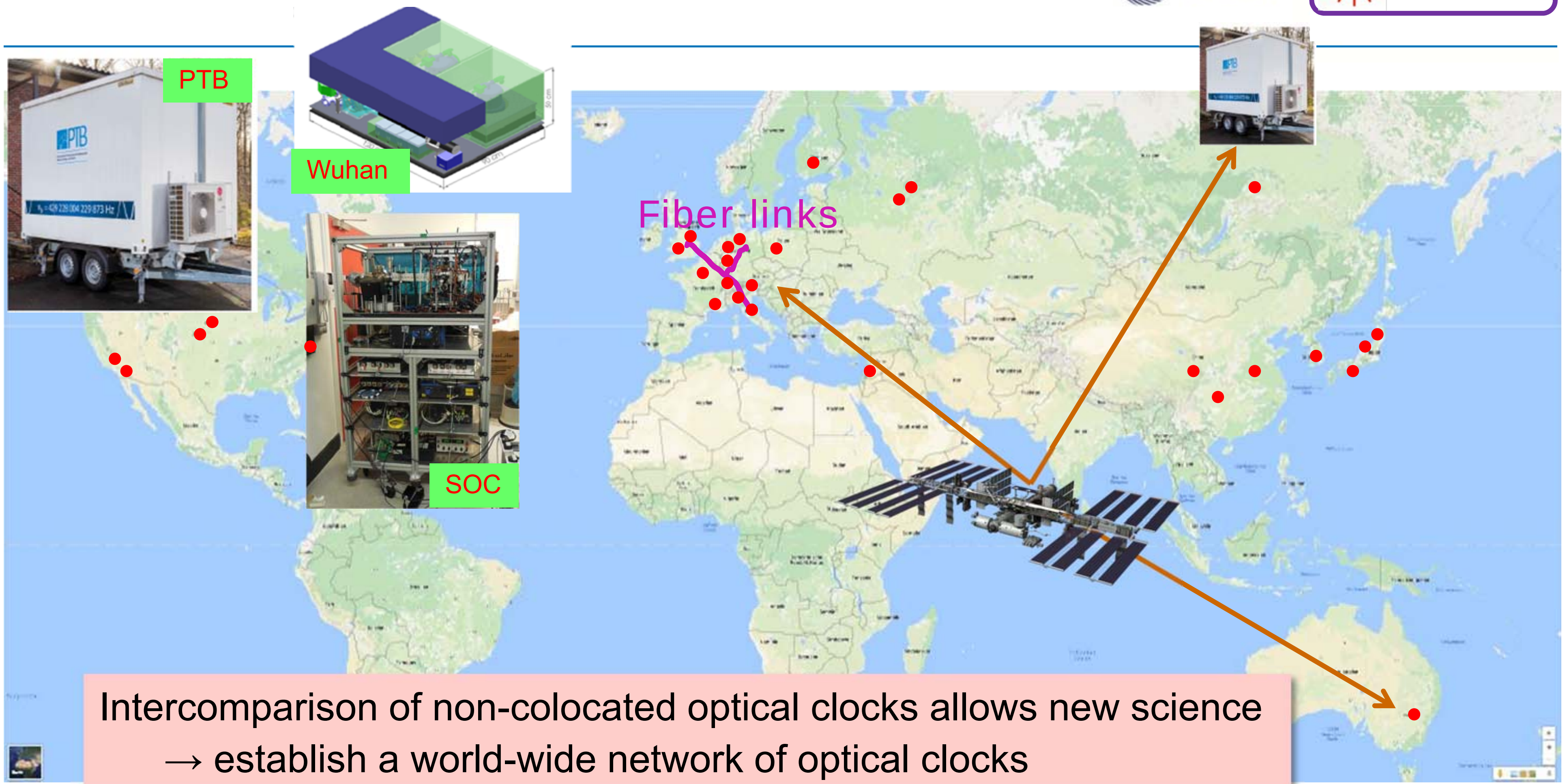
PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
l'Observatoire de Paris — SYRTE Systèmes de Référence Temps-Espace
INRIM Istituto Nazionale di Ricerca Metrologica
University of Birmingham
Università degli Studi Firenze
CTU Czech Technical University in Prague

# Contents

- I-SOC: Mission goals and methods
- I-SOC: Elegant breadboard demonstrator
- I-SOC: Preliminary space instrument design
- Perspectives

# Transportable optical clocks ; world-wide



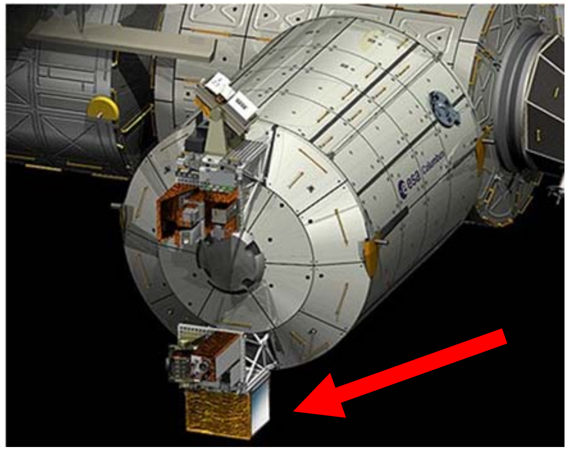

Intercomparison of non-colocated optical clocks allows new science
→ establish a world-wide network of optical clocks

Ca: NRC
USA: NIST, JILA, USNO, JPL, AOSense
Bra: U. Sao Carlos

I: INRIM, LENS
F: Obs. Paris, U. Marseille
CH: METAS
D: PTB, U. Düsseldorf, U. Hannover
UK: U. Birmingham, NPL
PL: FAMO
FIN: MIKES
A: Innsbruck. NL: V.U. Amsterdam

I: WIS
Rus: VNIFTRII, FIAN, ILP
J: NIMJ, RIKEN, U. Tokyo
K: KRISS
Ch: Wuhan IPM, NTSC, NIM….
Aus: U.West.Aust.

# Clocks and space missions

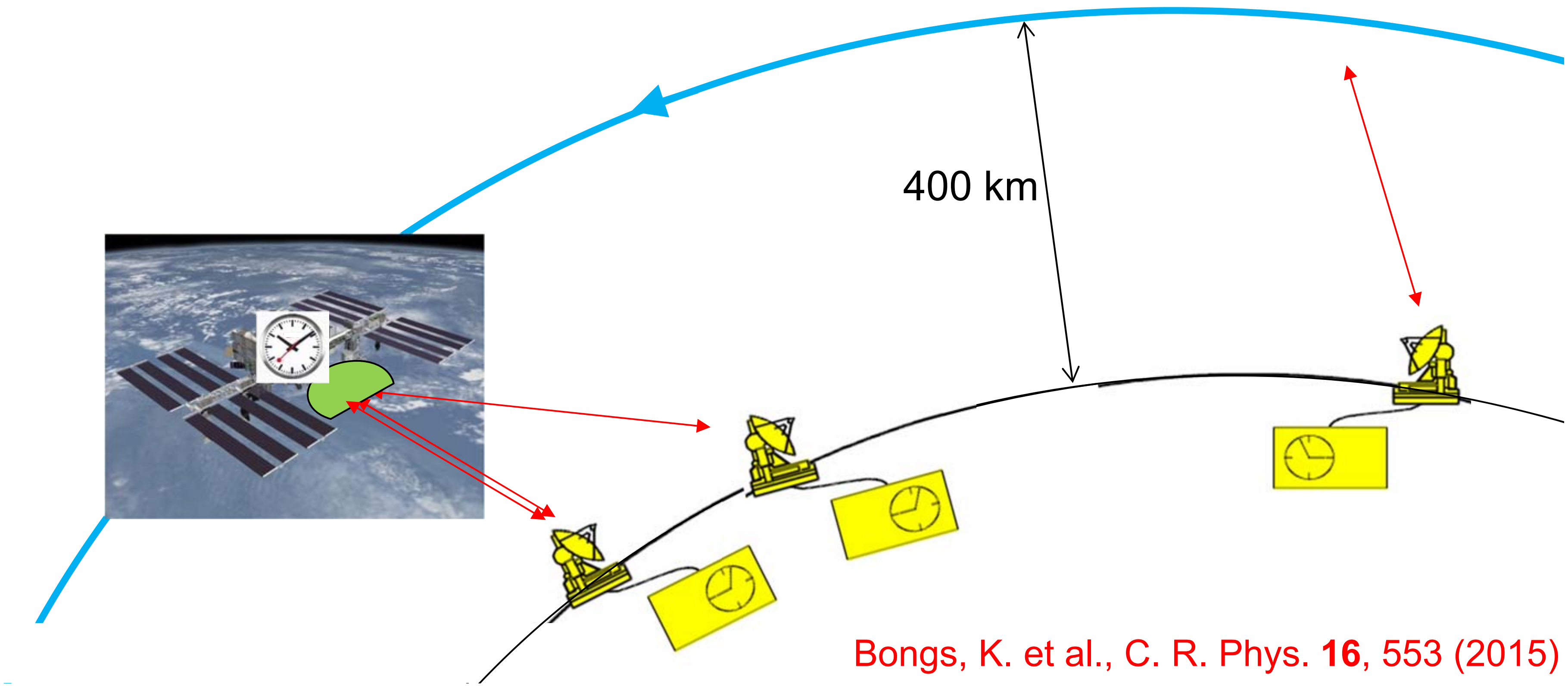


- In the upcoming ACES mission (~ 2020), optical ground clocks, combs and fiber links are a key mission component
- However, the impressive progress of ground clock performance calls for a post-ACES means of comparing them
- Improvements in ground and space technology (revolutionary & evolutionary) allow improvement by 10 – 100 in science output compared to ACES
- Can leverage on ACES heritage, BUT:
  Need to develop the I-SOC within a reasonable time of ACES, in order to maintain its know-how and heritage (technology, operations, data analysis, …)
- I-SOC can be the first and most realistic step towards future precision optical metrology space missions

- Proposed in 2004; part of the ISS utilization programme since 2006

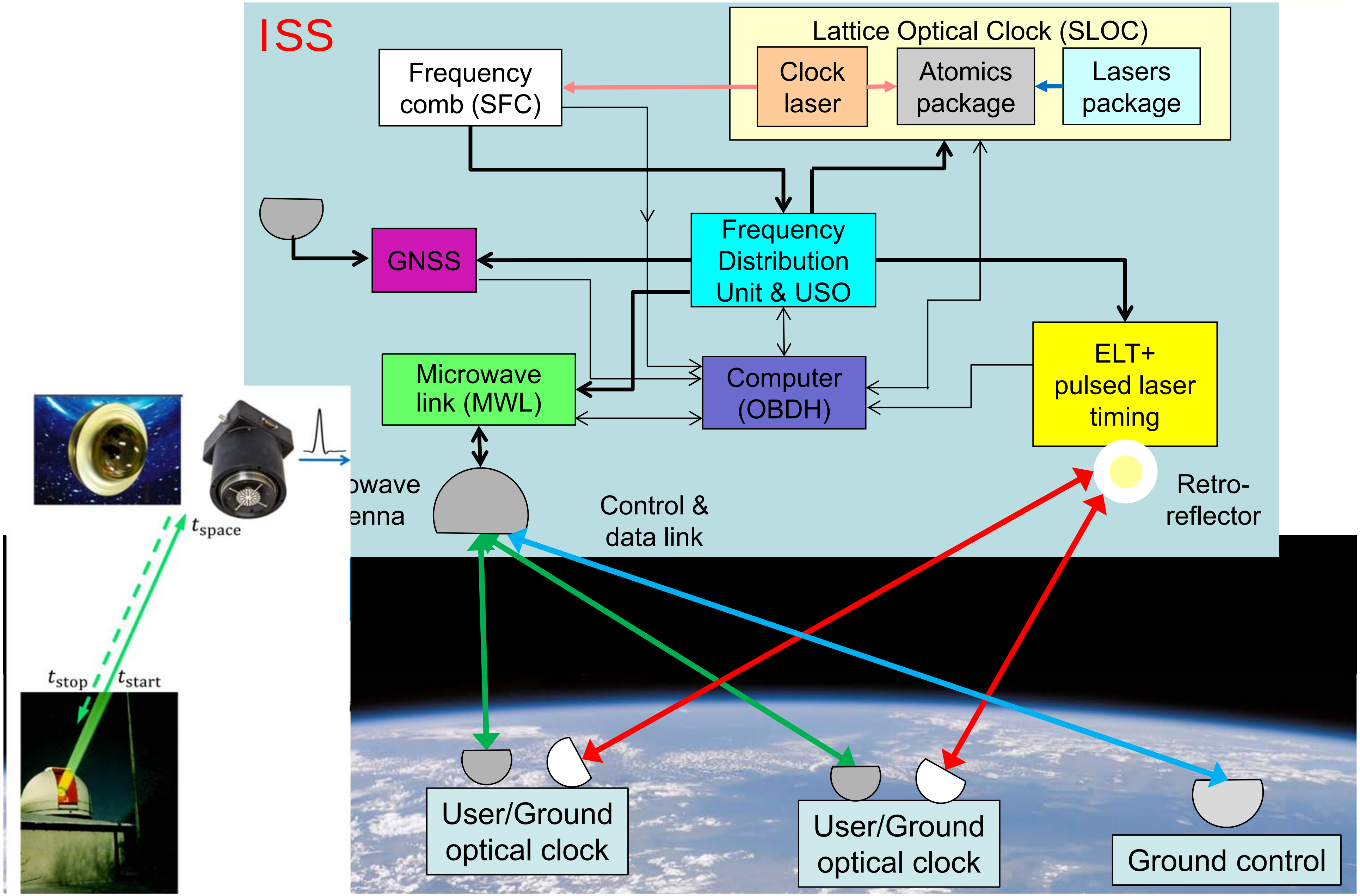
# How does it work?

- An on-board optical clock allows to transfer time/frequency between locations that are not in common-view of the ISS




Bongs, K. et al., C. R. Phys. **16**, 553 (2015)

# I-SOC payload: concept



# ACES and I-SOC

- ACES estimated performance vs. I-SOC requirements

| | ACES | I-SOC * | Improvem. |
|---|---|---|---|
| Clock instability | $1x10^{-13}/\tau^{1/2}$ | $8 \times 10^{-16}/\tau^{1/2}$ (up to $2\times10^{6}$ s) | x 100 |
| Clock inaccuracy | $1x10^{-16}$ | $1x10^{-17}$ | x 10 |
| MWL / MWL+ TDEV | 1.5 ps $\times(\tau/10\,000\text{ s})^{1/2}$ | 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 | |

- I-SOC clock signal shall be phase-coherent → requirement to comb and SLOC
- ELT+ supports reaching $1\times10^{-18}$ ground clock comparisons (or ground-to-space)
- I-SOC performance can be tested fully on the ground (*trapped* atoms)

* from I-SOC ESR document

** ground-to-space

# Science goals I: Comparing clocks in an Earth-scale network

- Most accurate direct measurements of Einstein's time dilation & Special Relativity

  *measure Earth's gravitational time dilation at 2 x $10^{-7}$ uncertainty level*
  *measure Sun's time dilation at 1 x $10^{-6}$ level*
  *measure Moon's time dilation at 2 x $10^{-4}$ level*
  *Kennedy-Thorndike test at 2 x $10^{-18}$ level*

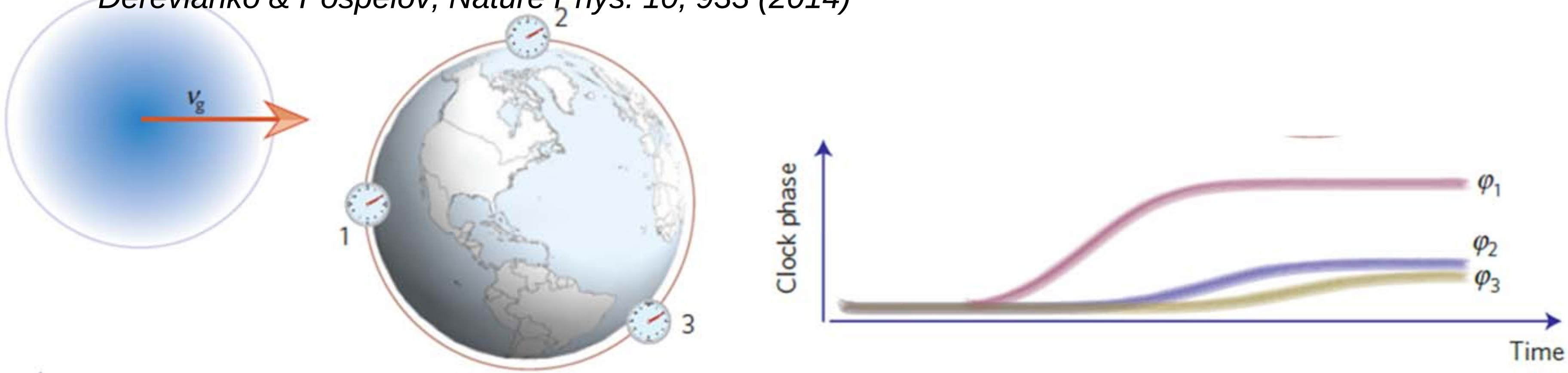
- Deliver time and frequency to users everywhere (universities, research centers, observatories)

  *world-wide atomic time distribution synchronized at few 10 picoseconds uncertainty*
  *world-wide clock comparisons with $10^{-18}$ fractional frequency uncertainty*

- Enable "new SI second";
  Support development of clocks and precision-optical measurements world-wide

- Enable fundamental physics studies: e.g. time-variability of fundamental constants

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

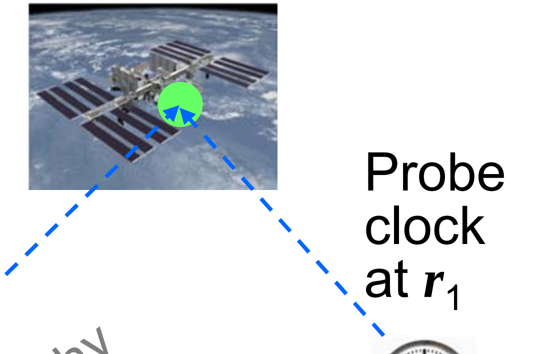


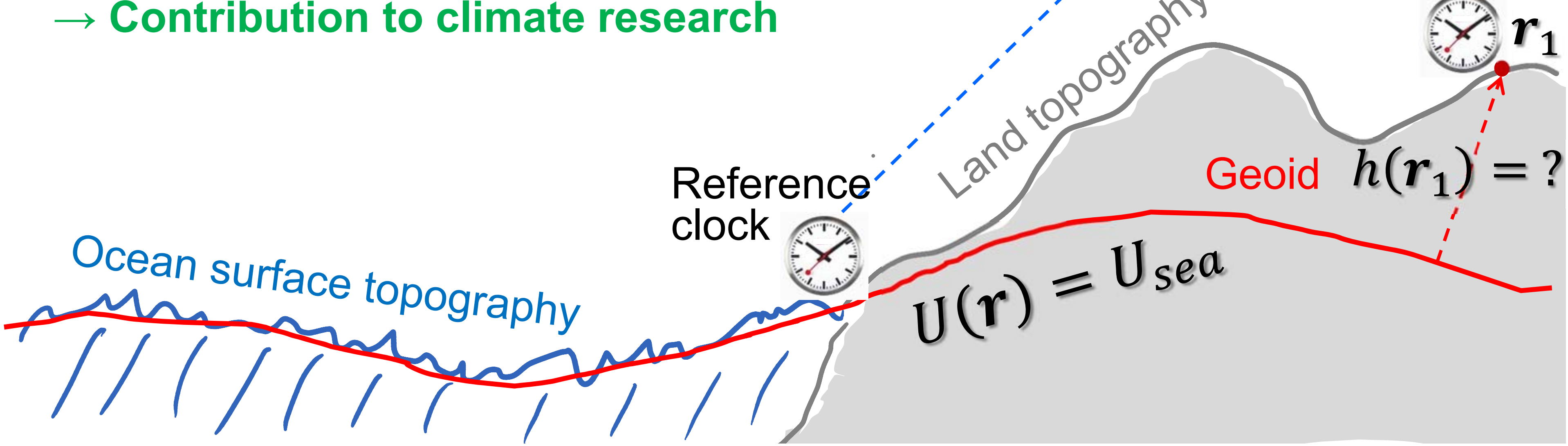
# Science goals II: Geodesy via Relativity

- Topography: determined using GPS
- Geoid surface: determined via transportable clock comparisons
  - Near-real time & local determination
  - 1 cm accuracy

Alternative & complementary to classic gravimetry

→ **Unification of national tidal height systems**
→ **Verfication & extension of satellite gravimetry models: time-dependence!**
→ **Contribution to climate research**



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- I-SOC: elegant breadboard demonstrator
- I-SOC: preliminary space instrument design
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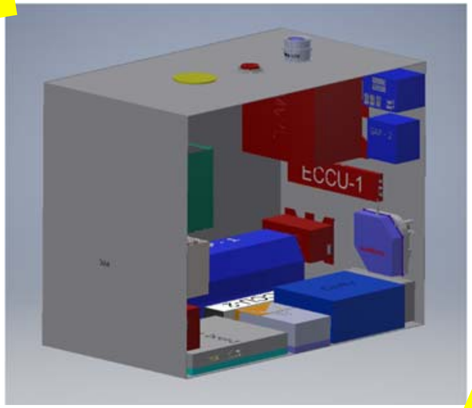
# From ACES to I-SOC

*Funded by: ESA & EU, DLR, DFG*
*Currently: ESA Co. 4000119716*
*(L. Cacciapuoti, C. Moratto)*

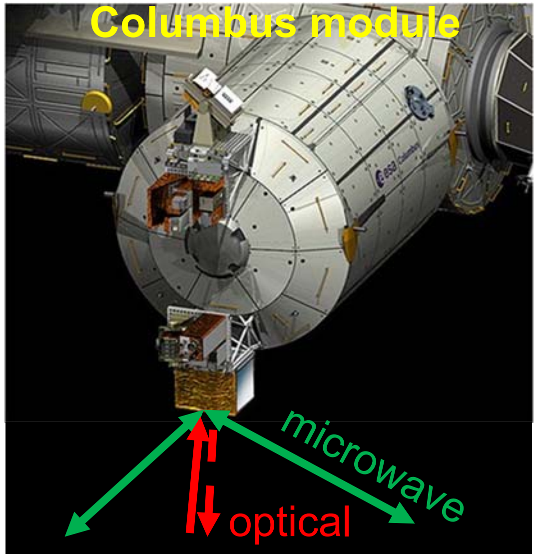
ACES
(being integrated)

Laser-cooled Cs clock ($f$ = 9.2 GHz) → Strontium optical lattice clock ($f$ = 429 THz)

Hydogen maser → optical reference cavity + frequency comb

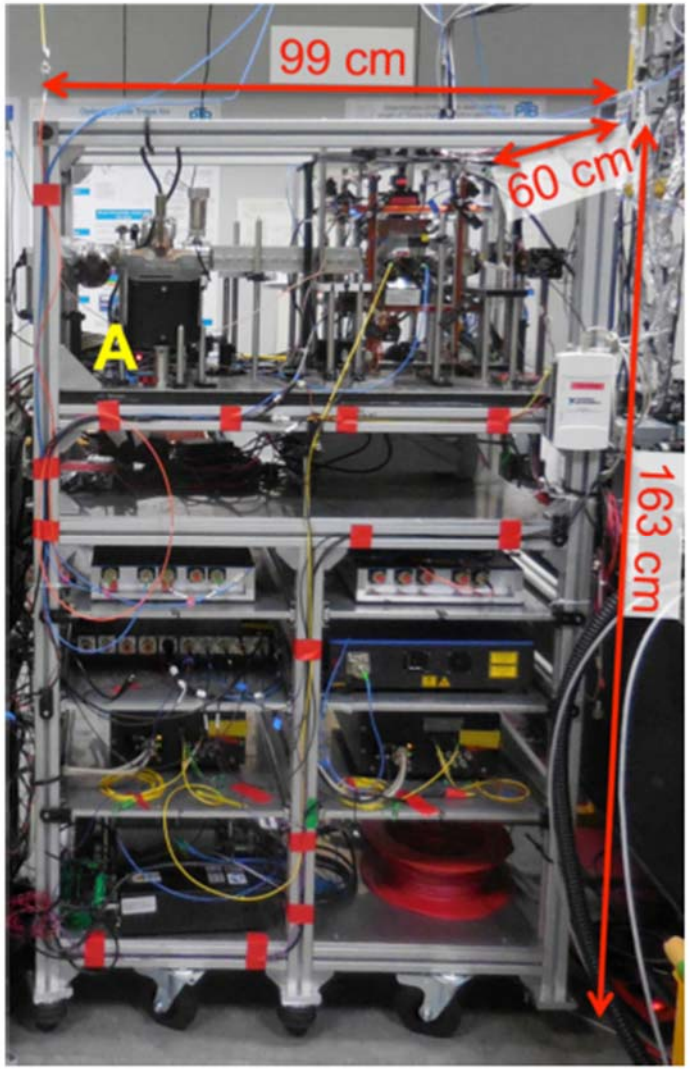



I-SOC
(prelim. design)



# I-SOC elegant breadboard

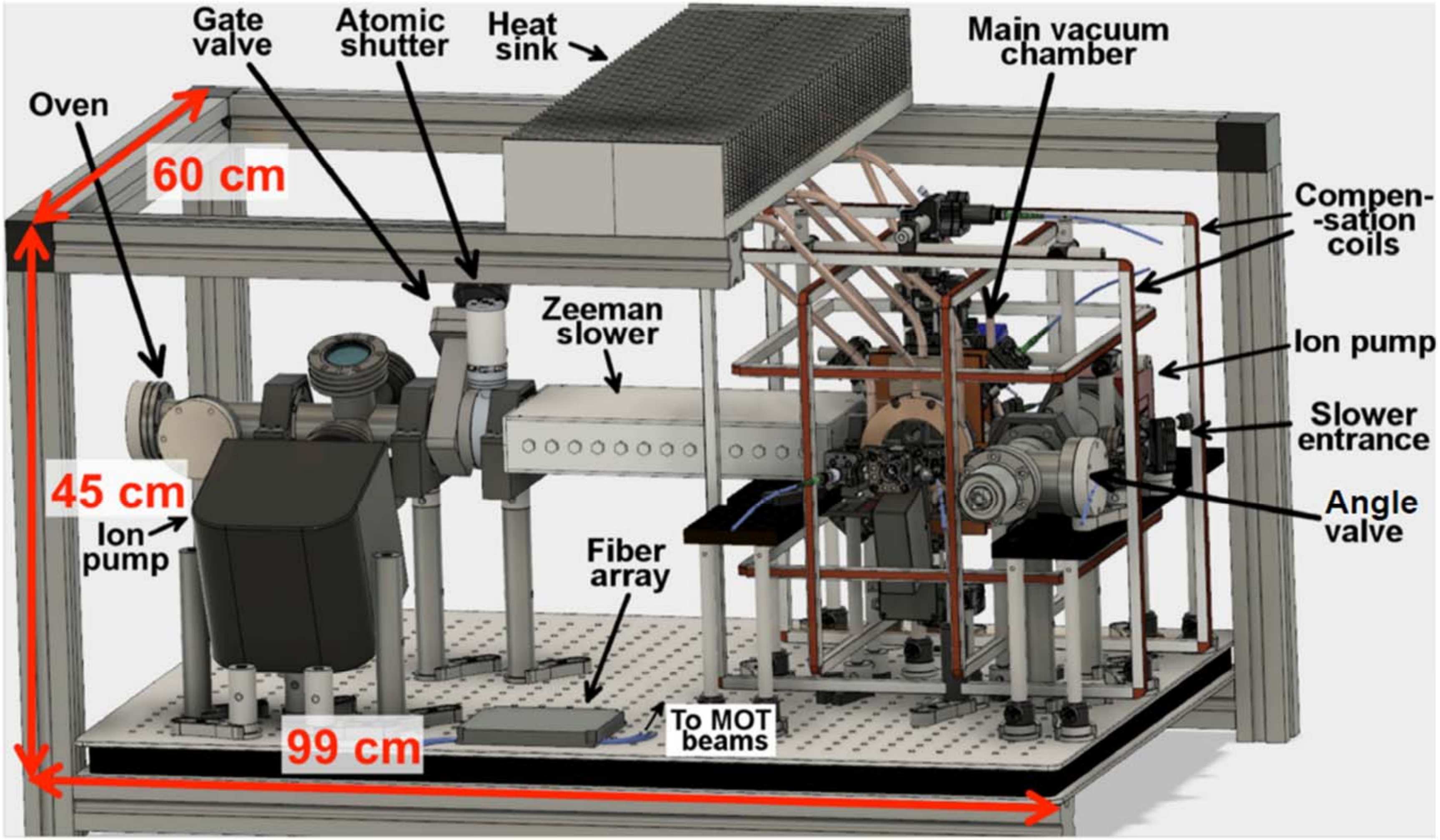
**Goal**: demonstrate a compact, robust system with goal performance, accessible technology, and modest mass, power, size




Atomics package

Laser package

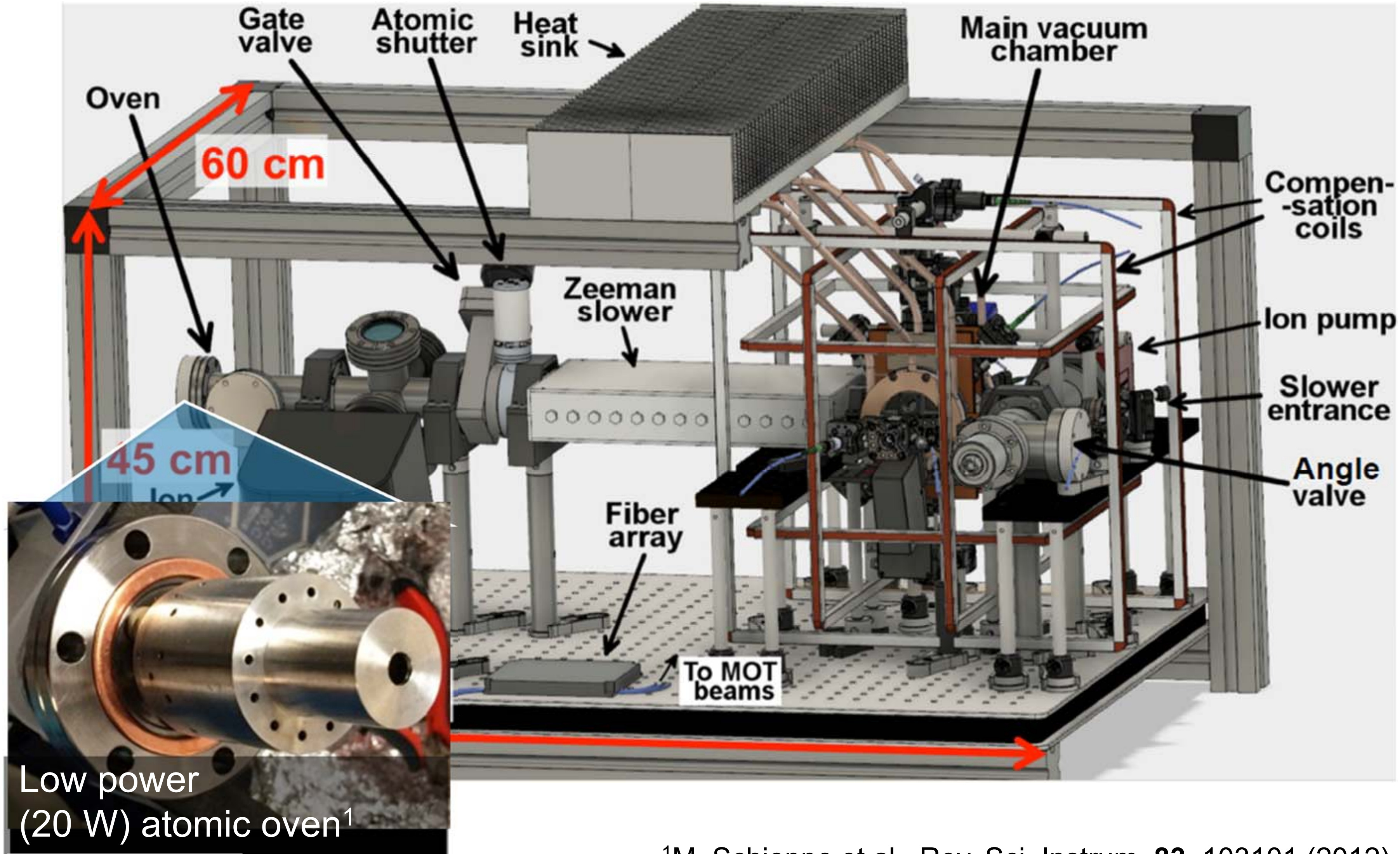
# Atomics Package



# Atomics Package

esa

I-SOC




Low power
(20 W) atomic oven[1]

UNIVERSITY OF BIRMINGHAM

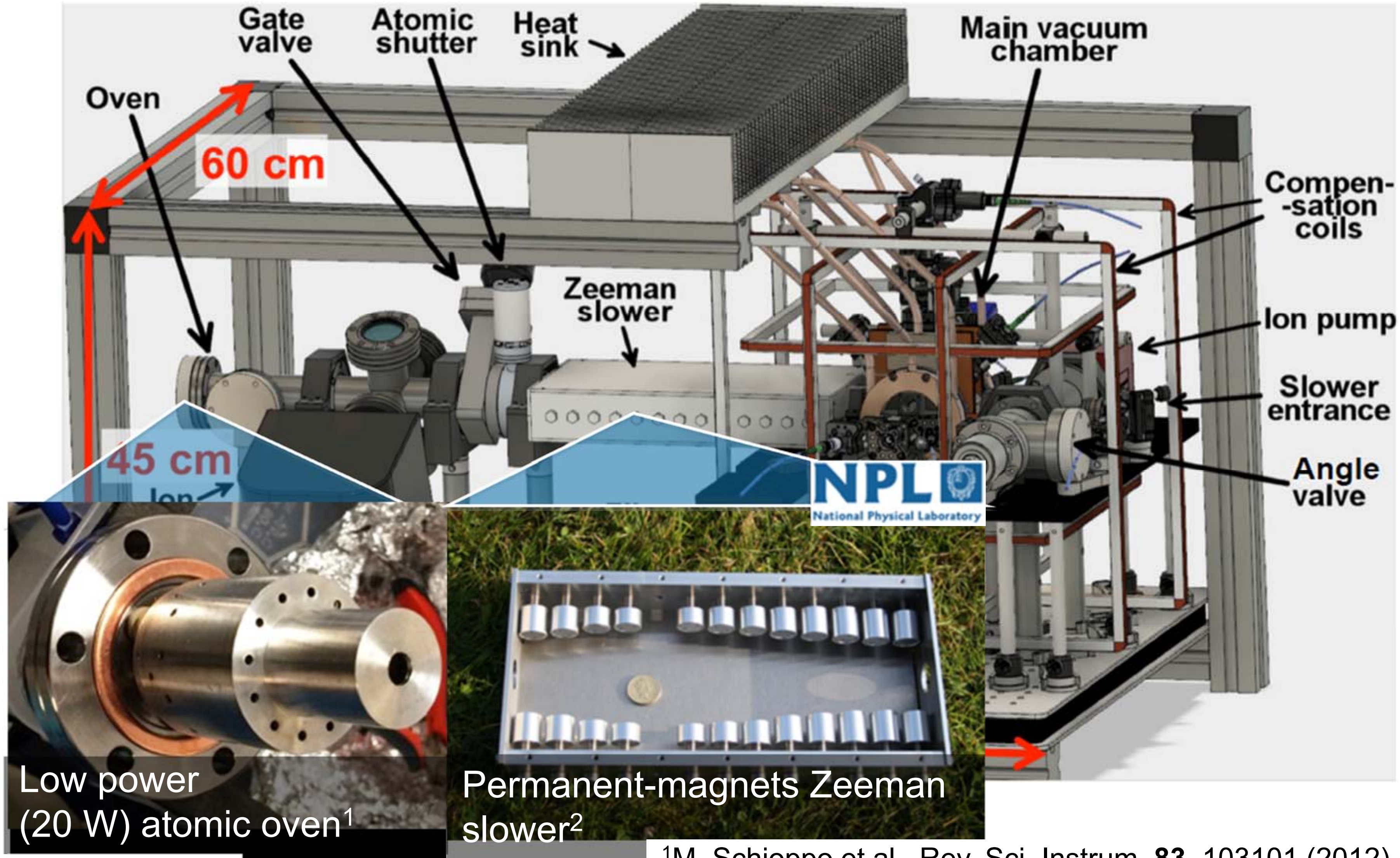
UNIVERSITÀ DEGLI STUDI FIRENZE

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

# Atomics Package

esa

I-SOC




Low power (20 W) atomic oven[1]

Permanent-magnets Zeeman slower[2]

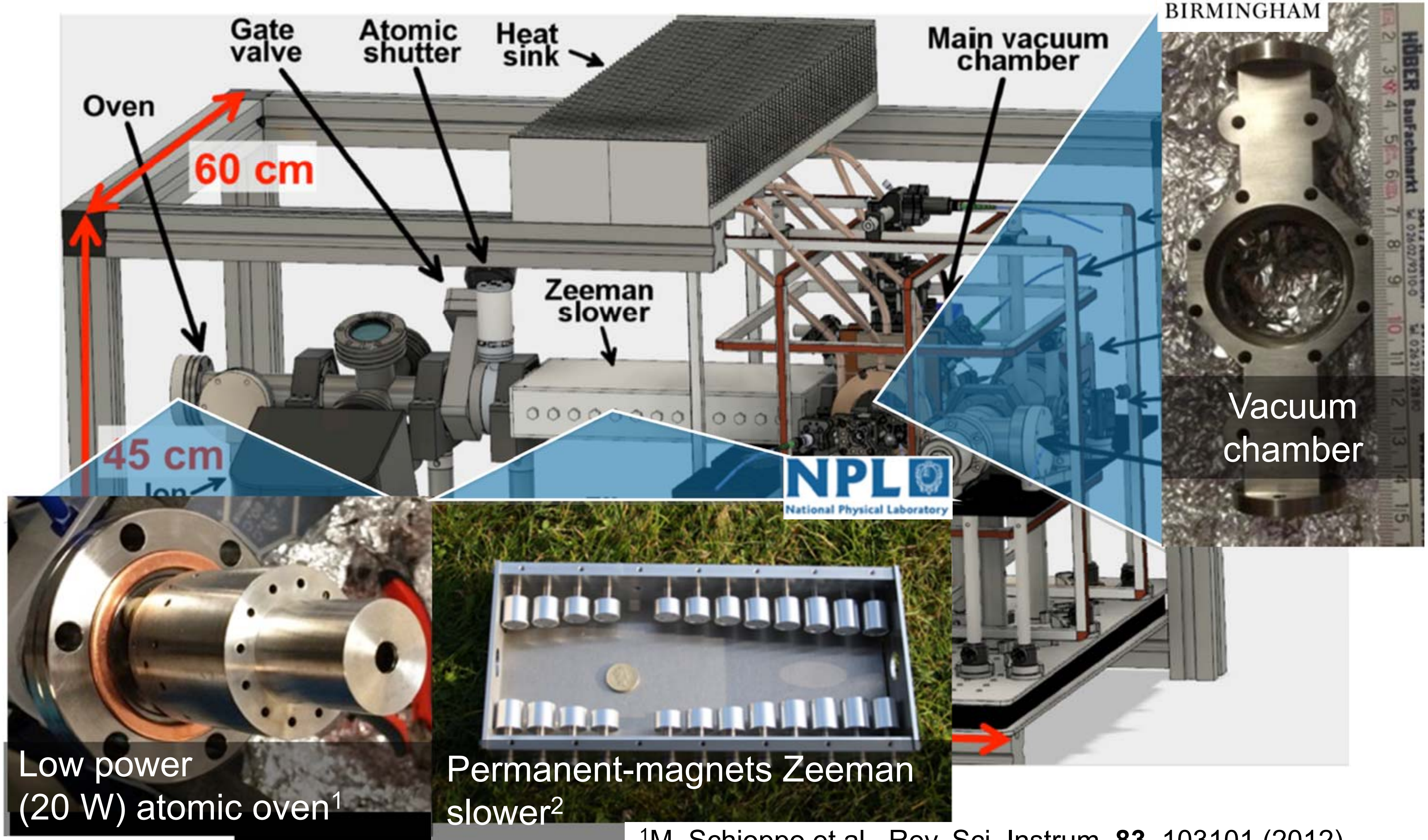
UNIVERSITY OF BIRMINGHAM

UNIVERSITÀ DEGLI STUDI FIRENZE

[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

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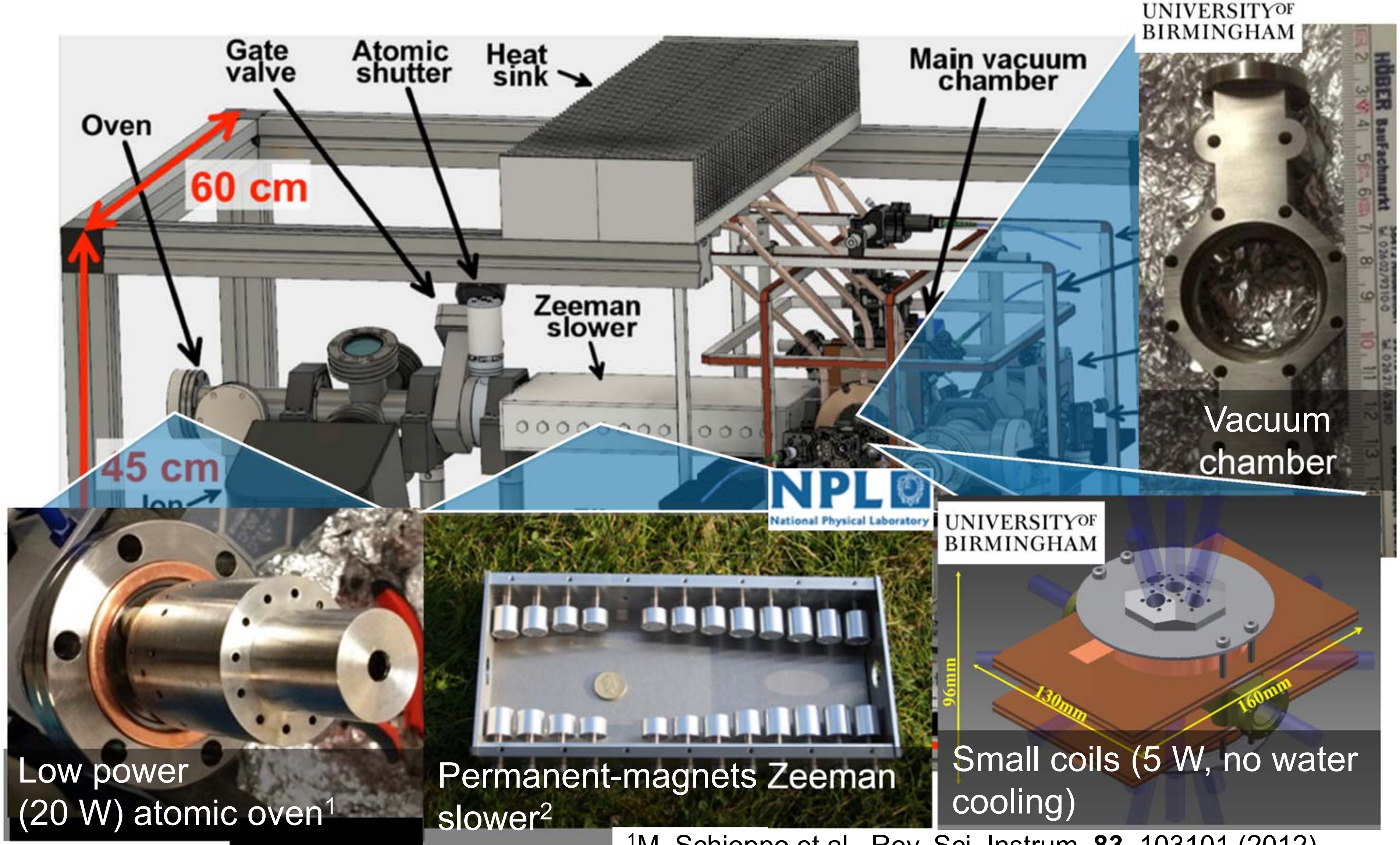
[1]M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

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

# Atomics Package

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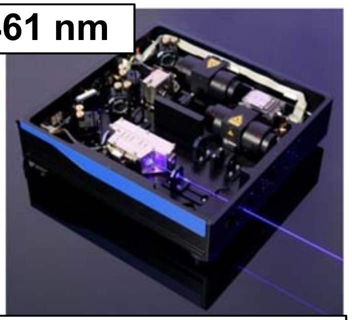
[1]M. Schioppo et al., Rev. Sci. Instrum. **83**, 103101 (2012)

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

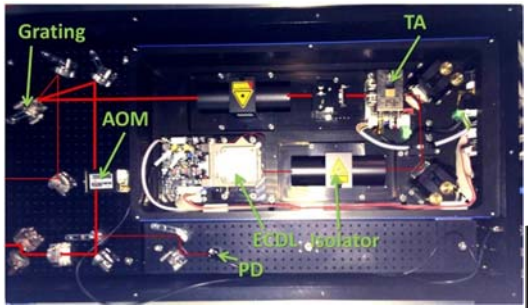
# I-SOC clock demonstrator: modular laser system

**461 nm**

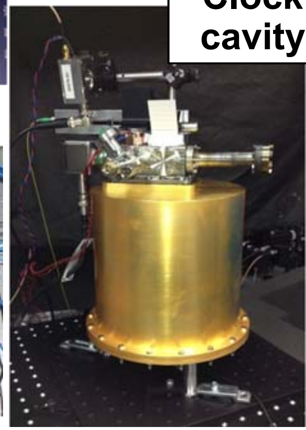


**461 nm distribution**

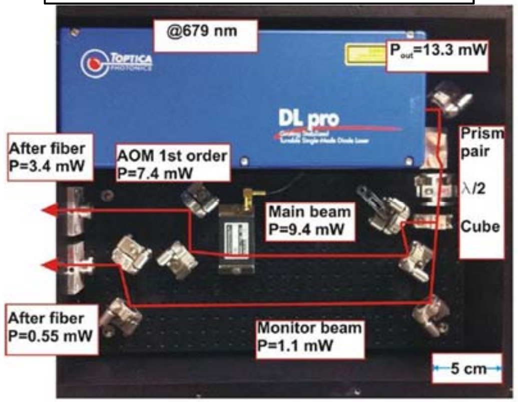
**813 nm Lattice**



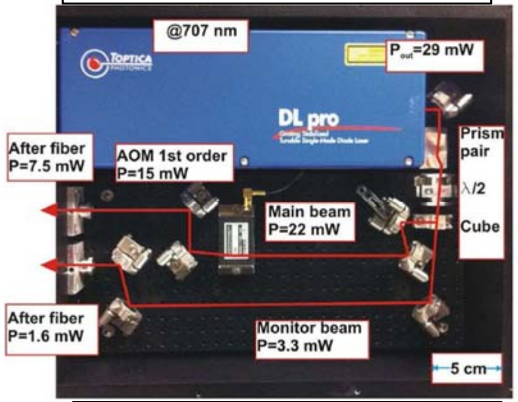

**Clock cavity**



**Repumper 679 nm**

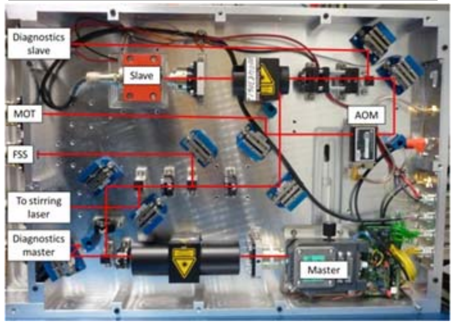



**Repumper 707 nm**

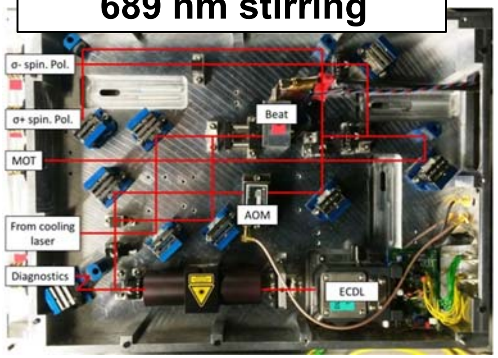



**698 nm clock**

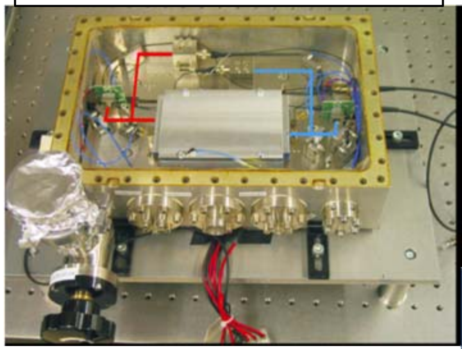
**689 nm cooling**




**689 nm stirring**



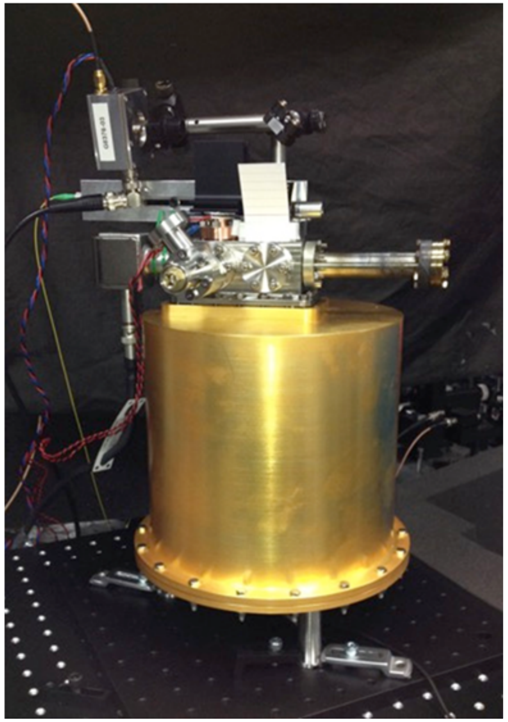

**461, 689, 813 nm stabilization unit**



l'Observatoire de Paris — SYRTE (Systèmes de Référence Temps-Espace)
TOPTICA PHOTONICS
PTB
Università degli Studi Firenze
Leibniz Universität Hannover
University of Birmingham
NPL National Physical Laboratory
Heinrich Heine Universität Düsseldorf


Bongs, K. et al., C. R. Phys. **16**, 553 (2015)
Nevsky, A. et al., Opt. Lett. **38**, 4903 (2013)
Świerad, D. et al., Sci. Rep. **6**, 33973 (2016)

# Robustness of breadboard components



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

Ultra-high reflectivity mirrors
are **radiation** resitant:
*Chen et al., Appl. Phys. B 116, 385 (2014)*


June 2015: Birmingham, UK → Braunschweig, D

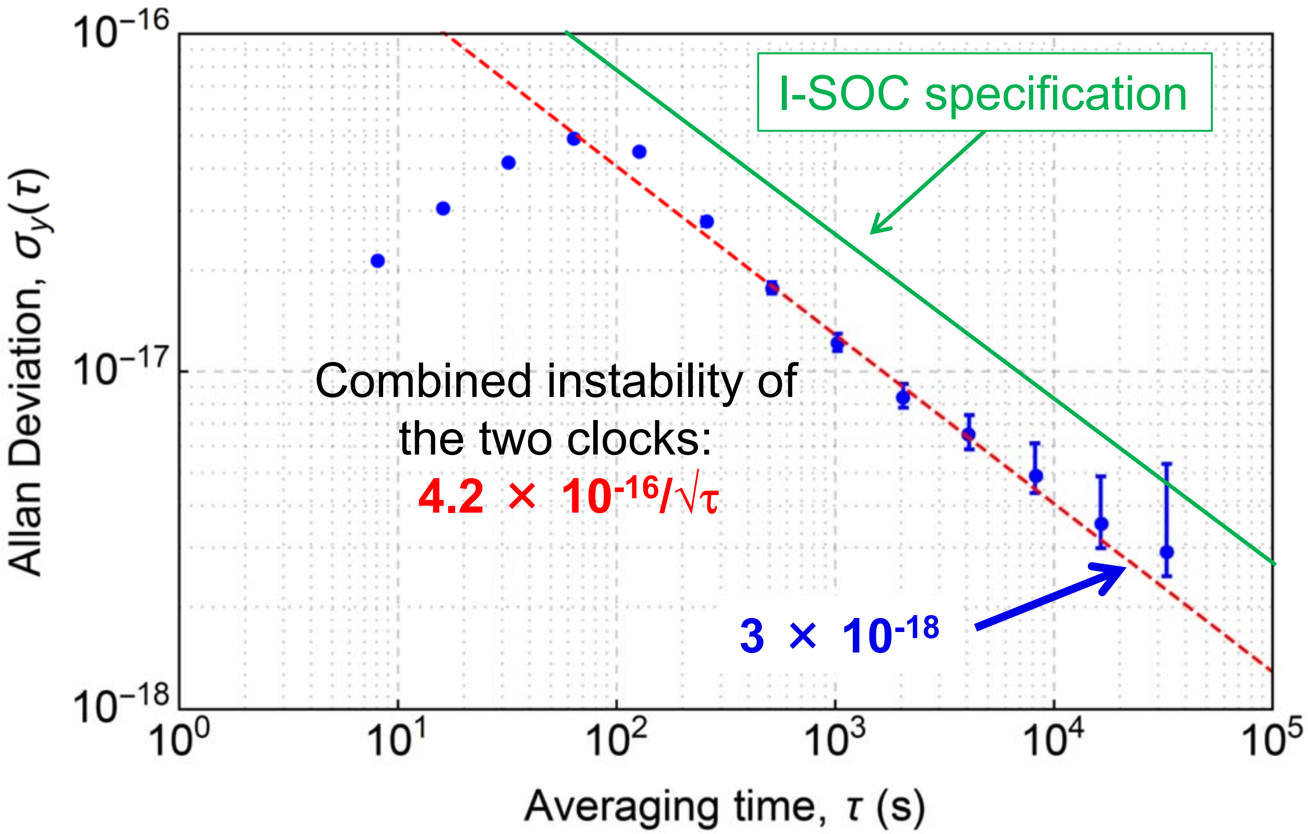
- 1st stage MOT obtained within 2 days of arrival
- Atoms trapped in lattice within 3 weeks of arrival

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

# Breadboard clock instability

*Origlia et al., Phys. Rev. A, 98, 053443 (2018)*

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)

# Breadboard clock inaccuracy

*Origlia et al., Phys. Rev. A, 98, 053443 (2018)*

I-SOC breadboard: $^{88}$Sr clock — PTB stationary clock: $^{87}$Sr clock

| Effect | $^{88}$Sr clock $\Delta\nu/\nu$ | $^{88}$Sr clock $u/\nu$ | $^{87}$Sr clock $\Delta\nu/\nu$ | $^{87}$Sr clock $u/\nu$ |
|---|---|---|---|---|
| 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 |
| Second-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 |

**All numbers: $\times 10^{-17}$**

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

Lattice laser:

Both Ti:Sapphire and diode laser give similar performance

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

*Origlia et al., Phys. Rev. A 98, 053443 (2018)*

I-SOC breadboard

PTB stationary clock

$$f(^{88}\mathrm{Sr}) - f(^{87}\mathrm{Sr}) = 62\,188\,134.027(12)\ \mathrm{Hz}$$

$$f(^{88}\mathrm{Sr}) / f(^{87}\mathrm{Sr}) = 1.000\,000\,144\,883\,682\,831\,(28)$$

At the time (2018), probably the most accurate measurement of a property of nature

In agreement with an independent measurement in Japan
*Takano et al., Applied Physics Express 10, 072801 (2017)*

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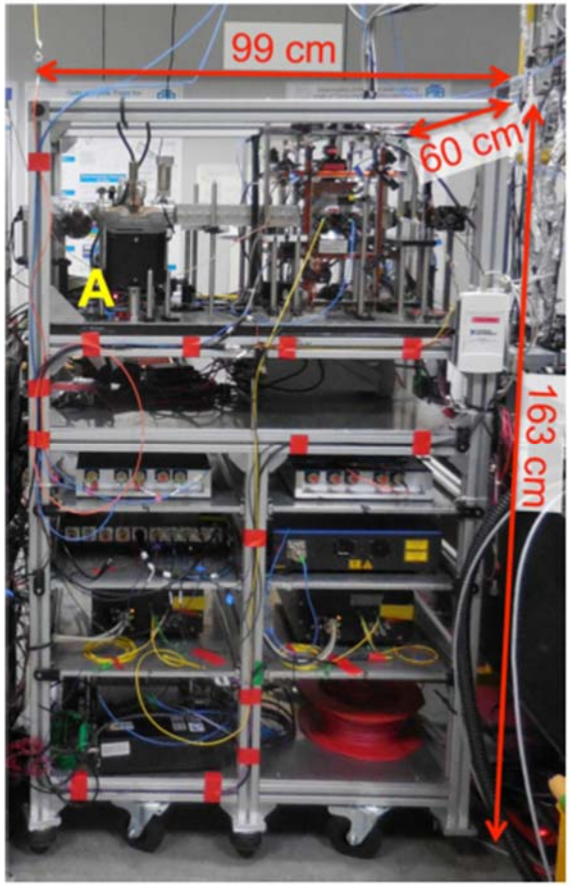
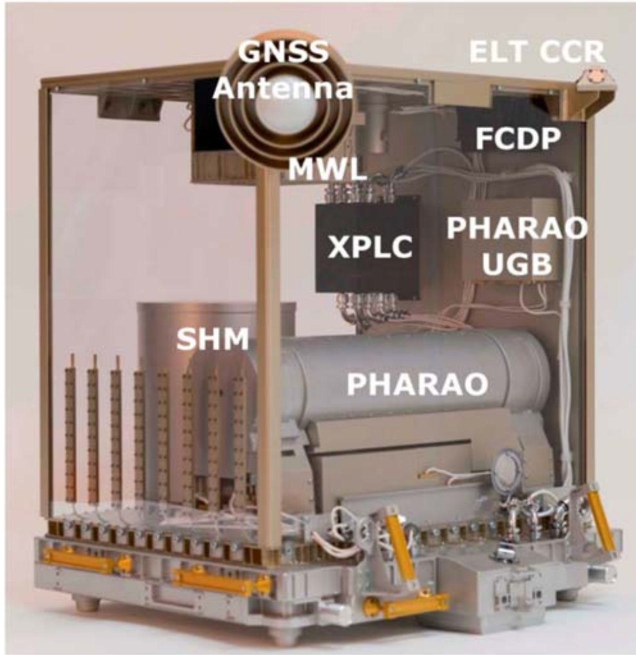
# From elegant breadboard to space instrument




?

ACES




**Accomodation requirements of complete space instrument:**

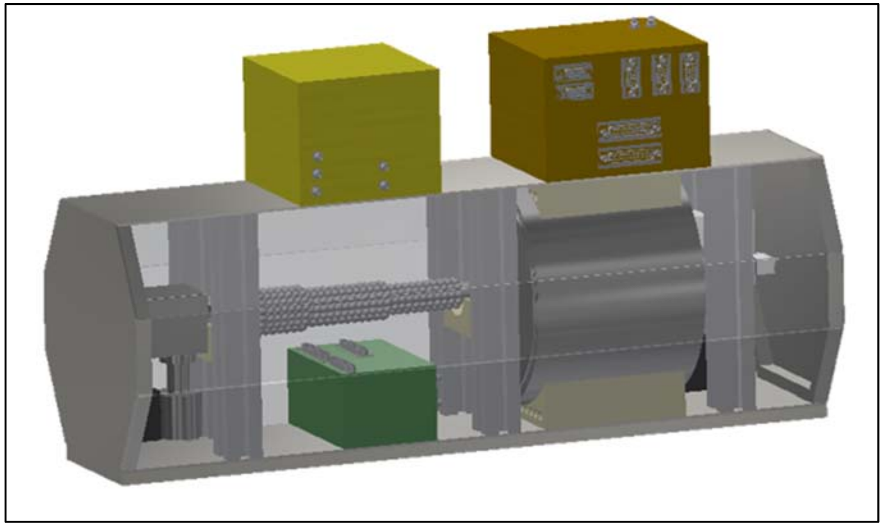
< **100 kg**

< **250 W**

< **480 liter** (< 1 m x 0.6 m x 0.8 m)

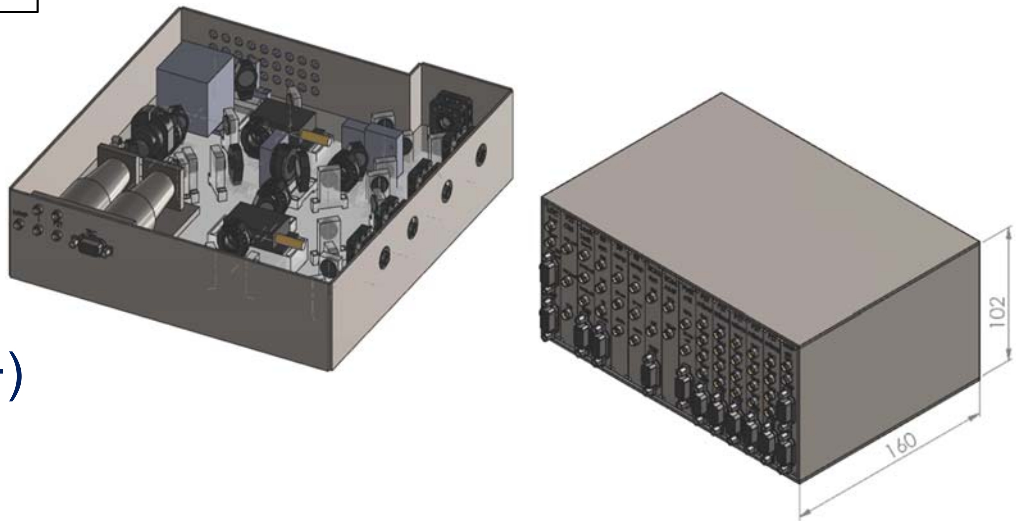
(Complete payload: 1.17 m$^3$, 400 W, 226 kg)

# Preliminary design of sub-systems: examples

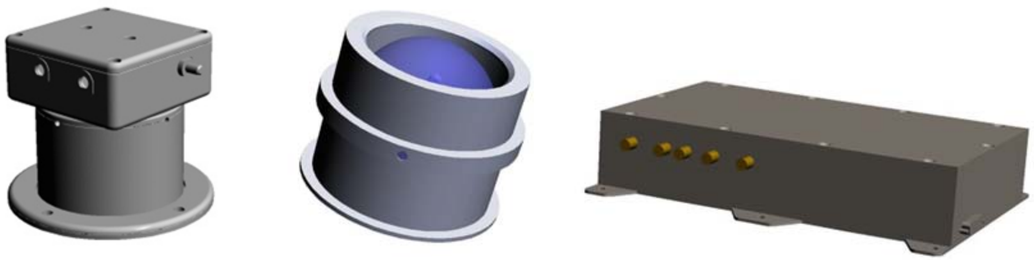


Atomics package

2nd-stage cooling laser (689 nm)




Single-photon time transfer (ELT+)



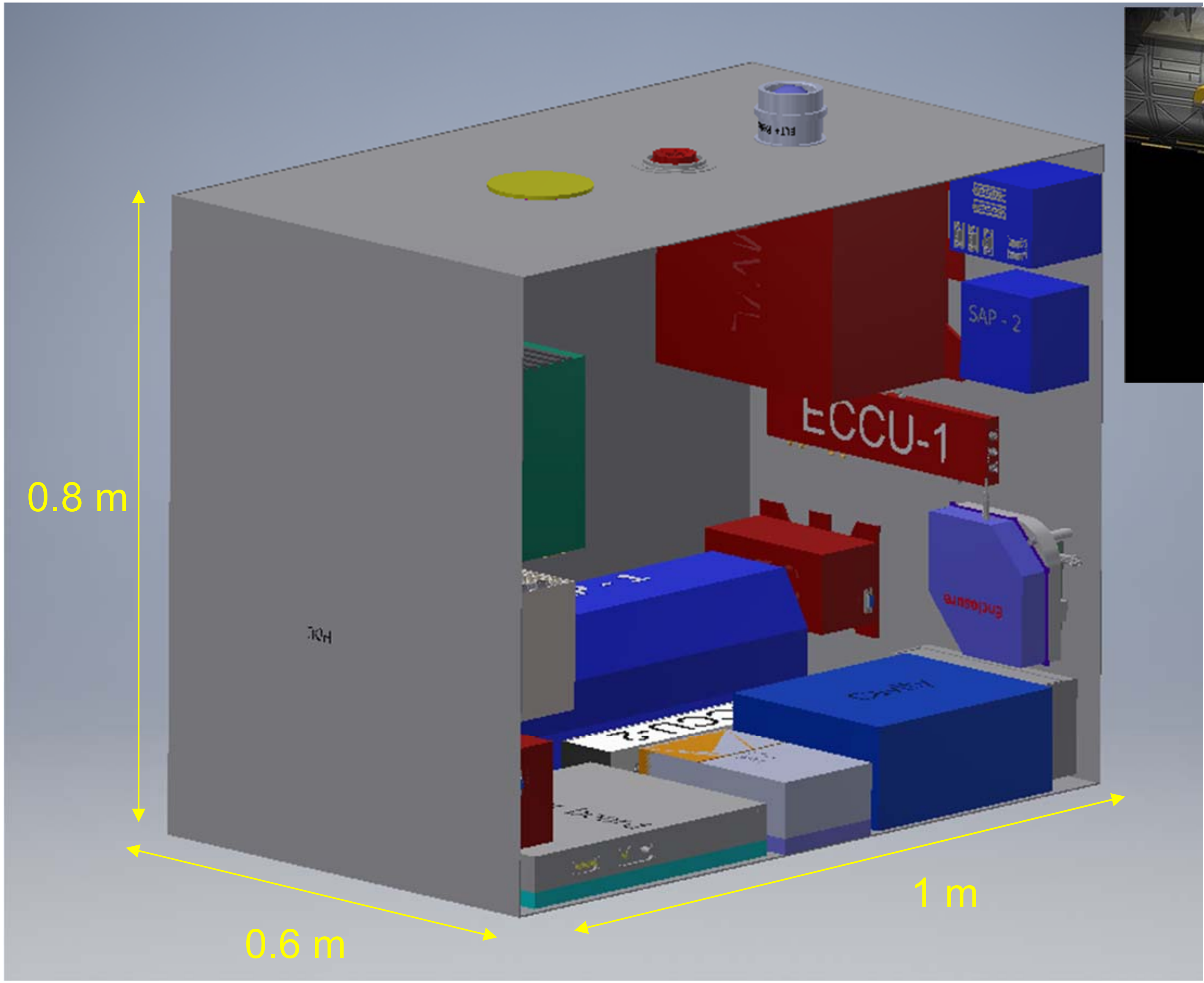
# Physical parameters (preliminary)

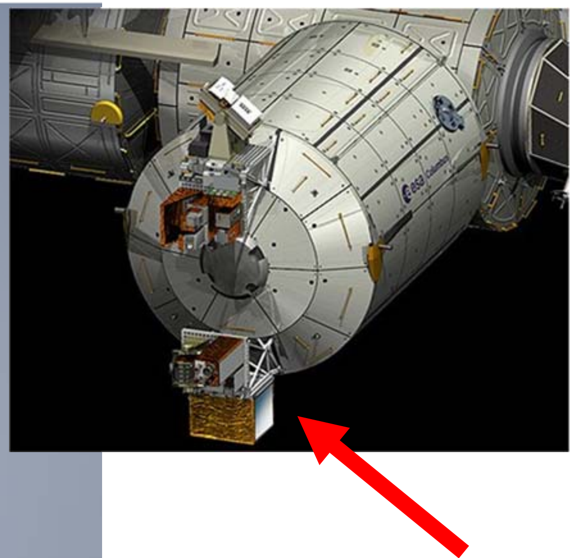
| Subsystem | Mass (kg) | Volume (liter) | Elec. Power (W) |
|---|---|---|---|
| Atomics package (SAP) with optics | 31.3 | 28 | 29.8 |
| Blue cooling laser (BCL) + distribution module (DBL) | 7.2 + 2.2 | 6.2 + 2.6 | 10 + 1.4 avg. 2.2 pk |
| Red cooling and stirring laser (RCL, 689 nm) | 7.9 | 5.7 | 10.3 |
| Repumpers (RLS, 707 and 679 nm) | 4.0 | 2.9 | 4.8 |
| Lattice laser (LLS, 813 nm) | 6.1 | 4.4 | 6.2 |
| Frequency stabilization system (ECCU) | 6.3 | 4.7 | 9.3 |
| **Subtotal atomics unit (with electronics)** | **65** | **57.1** | **71.8** |
| CLS-1: Clock laser cavity (OSRC specifications) | 10.5 | 10 | 15 |
| CLS-2: Clock laser vibration isolation unit | n/a | n/a | n/a |
| CLS-3: Clock laser breadboard + SHG | 10.3 | 10 | 14.3 |
| Clock monitoring unit (CMU) | 5 | 7.3 | 15 avg. 25 pk. |
| **Total clock (SLOC) (with electronics)** | **90.8** | **84.4** | **116.1** |
| Frequency comb (SFC) | 10 (est.) | 10 (est.) | 35 (est.) |
| Frequency distribution package (FDP) | 2 | 2 | 17.6 |
| Microwave link (MWL) | 10.4 | 14.4 | 31 |
| Laser timing (ELT+) | 3.1 | 4.5 | 15 |
| GNSS receiver (GNSS) | 4.5 (est.) | 2 (est.) | 15 (est.) |
| **Total I-SOC instrument** | **120.8** | **117.3** | **229.7 avg.** |

| | | | |
|---|---|---|---|
| **ISS accomodation Physical Requirements** | **< 100 kg** (no margin considered) | **< 480 liter** plus margin (< 1 x 0.6 x 0.8 $m^3$) | **< 250 W** (no margin considered) |

Status: March 2018

# Accomodation



Accomodation
is possible
(with large margin)

# I-SOC Phase A1: Documentation


~ 500 interfaces

# I-SOC: Status

**Delivered**:

1) Experiment Science Document — 2/2017 *[Science team]*
2) Phase A1: preliminary clock design — 3/2018 *[Science team]*
3) Elegant Breadboard — 11/2018 *[Science team]*

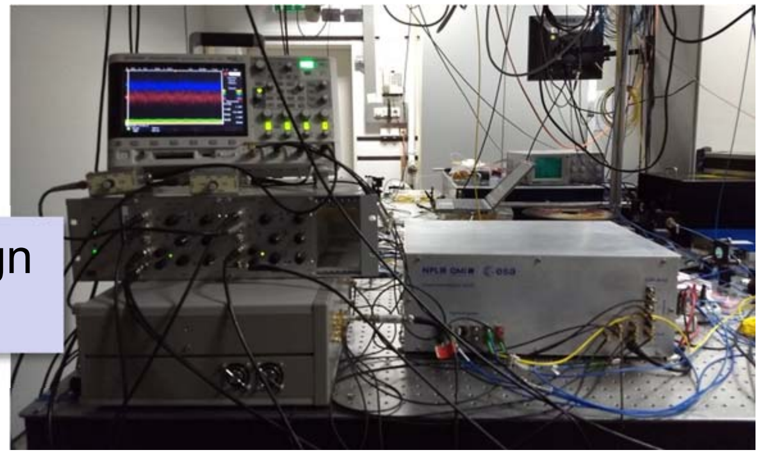
**Ongoing:**

4) Further tests and enhancements on breadboard
5) ESA-funded technology developments 2016-2019:

- *462 nm laser, 689 nm laser* — *[Fraunhofer CAP, TopGaN,CNR,HHU]*
- *CCU: laser frequency stabilization system* — *[NPL, PTB]*
- *813 nm lattice laser* — *[Fraunhofer CAP, SYRTE]*
- *OSRC: reference cavity* — *[ADS, NPL, SpaceTech,…, PTB]*
- *Two-way microwave link „HERO"* — *[TAS, Wiser, DLR, SYRTE]*

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

Project is ready to enter next phase: detailed design and building of atomics and other subsystems



CCU @ *PTB*

# Cost estimate

Cost after Completion (CAC) = **A** + **B** + **C**

**A**: subsystems with high TRL → only FM cost included

**B**: other subsystems

engineering model (EM) cost = breadboard model (BB) cost × 2.5
flight model (FM) cost = BB cost × 5

**C**: other (ground terminals upgrade, assembly, intergration, testing;
product assurance; ground segment; flight operations;
assumed personell costs: 0.2 M€ per person-year)

**Total CAC (1 EM + 1 FM + Part C), incl. 20% margin:**

*Note: BB cost not included, since already built*

# Options for cost control / cost reduction

I-SOC

- **#1:** Some subsystems are national contributions, i.e. agency-furnished items.

- **#2:**
  - Involvement of research institutes in the technology development and testing activities ($\rightarrow$ experience, lower labor costs, instrumentation)

  - Implement technology development phase with joint work of research institutes and industries

  - Involvement of scientists and their expertise for the evaluation of proposals submitted in response to ESA announcement of opportunities.

Capitalize on the increasing quantum technology know-how

# I-SOC pathfinder

I-SOC

- Less complex, reduced science reach; earlier launch: 2024-5
- **Scientific goal: <u>common-view</u> comparison of ground clocks, time-transfer, relativistic geodesy**

*4 options;*

- MWL(extension of ACES) **9 M€**
- **OR:** MWL+ (= HERO, improved performance: $10^{-18}$ level) **12.6 M€**
- **ADDITIONALLY:** ELT-plus (improved performance: $10^{-18}$ level @ long integration time) **8.5 M€**
- **ADDITIONALLY:** Technology demonstration + Test of Lorentz Invariance: high-performance cavity-stabilized laser + frequency comb **17 M€**

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
Nicolaus Copernicus University in Toruń
l'Observatoire de Paris — SYRTE Systèmes de Référence Temps-Espace
TUM Technische Universität München
University of Birmingham
Universität Zürich UZH
ETH zürich
CTU Czech Technical University in Prague

# I-SOC implementation

- ESA member state ministers will decide on ESA budget in November 2019;
- The ISS utilization programme SpaceSciE will receive a fraction of that budget
- If total allocated ESA budget is large enough, there will be funds to implement new experiments, such as I-SOC pathfinder

**It is important that as many national agencies as possible support strong funding of the SpaceSciE programme!**

**To get them to do so, the scientists have to express their support of experiments on the ISS, incl. I-SOC/I-SOC pathfinder**

# I-SOC: Key points

I-SOC

- I-SOC will enable continued and improved science results in fundamental physics, and the establishement of a new geodetic frame (via time)
- … will provide opportunities to test key subsystems in a realistic environment
- … will capitalize on developments done so far
- … will keep momentum on time & frequency metrology technology also after ACES
  – not leaving the field only to Chinese
- … will be an important (essential?) step towards future far-reaching missions on satellites requiring optical clock technology

**If you wish to participate in I-SOC or help support it, please contact me:**

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# Strategic considerations: opinion


If a mission such as AEDGE is ever to fly during our lifetime ….

- the interested scientific community needs to develop a **roadmap**
- Devote a **fraction** of their resources (time, funds) to cooperative efforts towards implementing it
- Proceed by **incremental** steps, FOKUS, ACES, CAL, … I-SOC (Strontium!), gaining experience with space missions, technology development, and science
- Support such experiments by **actively** seeking support from national agencies
- **Involve** as many member states of ESA, also smaller countries
- Find a **compromise** between efforts towards ground-based devices (duplications!) and towards technology development for space
- Invent ways of cooperating as in CERN!