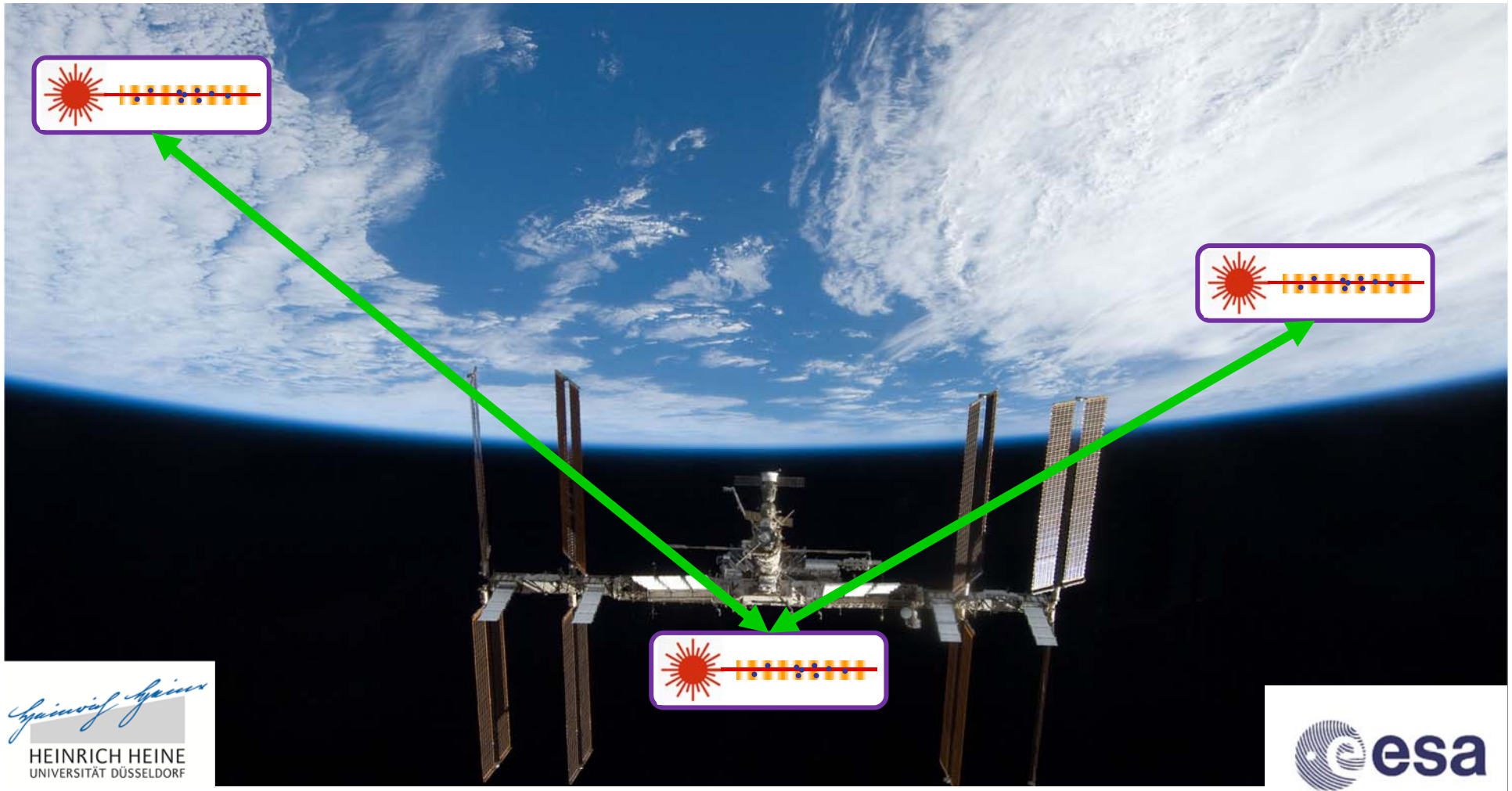
Mission I-SOC: an optical clock on the ISS

S. Schiller (Heinrich-Heine-Universität Düsseldorf)
and the **I-SOC science team**



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esa

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

- Introduction: quantum sensors
- ISOC mission: goals and methods
- ISOC: elegant breadboard demonstrator
- ISOC: the way forward
- Summary

Applications of cold-atom sensors

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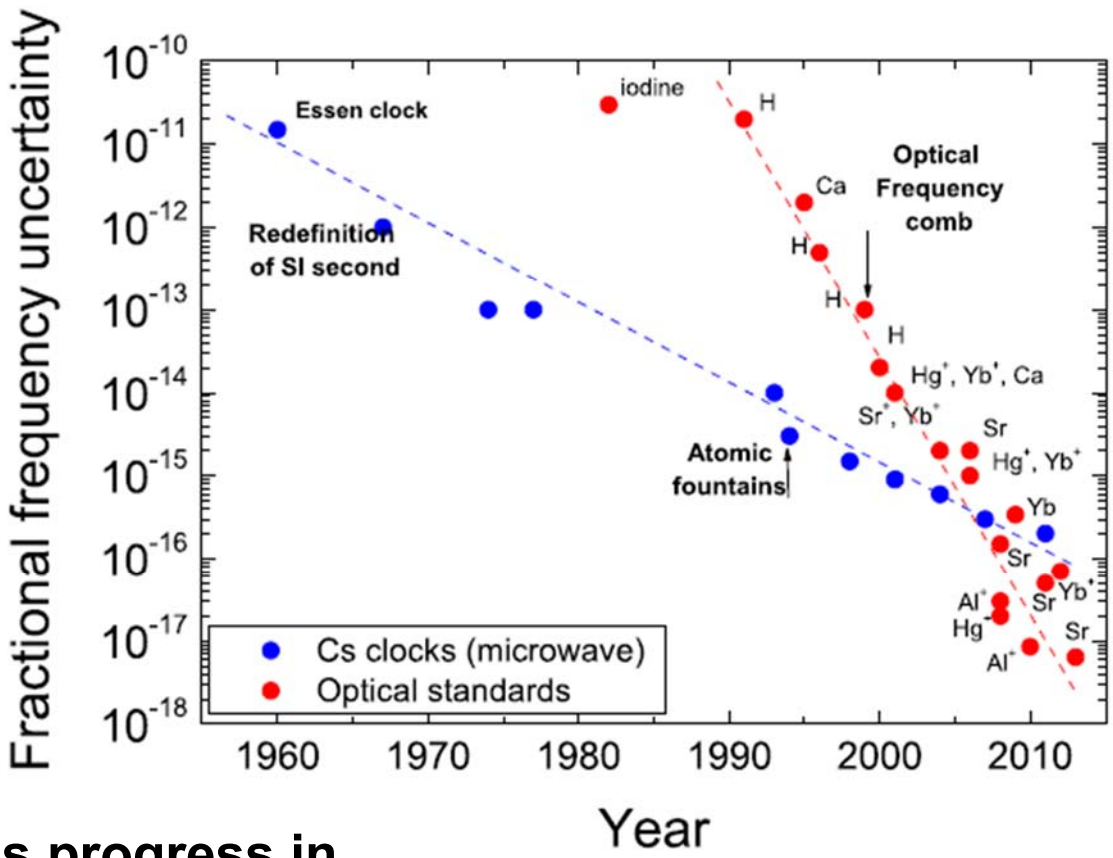
- Terrestrial applications

	Gravimeters	Clocks	Other
- fundamental physics	x	x	
- mining	x		
- construction	x		
- geodesy/geophysics	x	x	
- climate research	x	x	
- spacecraft navigation		x	
- medical studies & diagnostics			x

- Space applications

- fundamental physics	x	x	
- geodesy/geophysics		x	
- climate research	x	x	
- spacecraft navigation	x	x	

Cold-atom clocks



Reviews:
Poli et al.
Nuovo Cimento (2013);
Ludlow et al.
Rev. Mod. Phys. (2015)

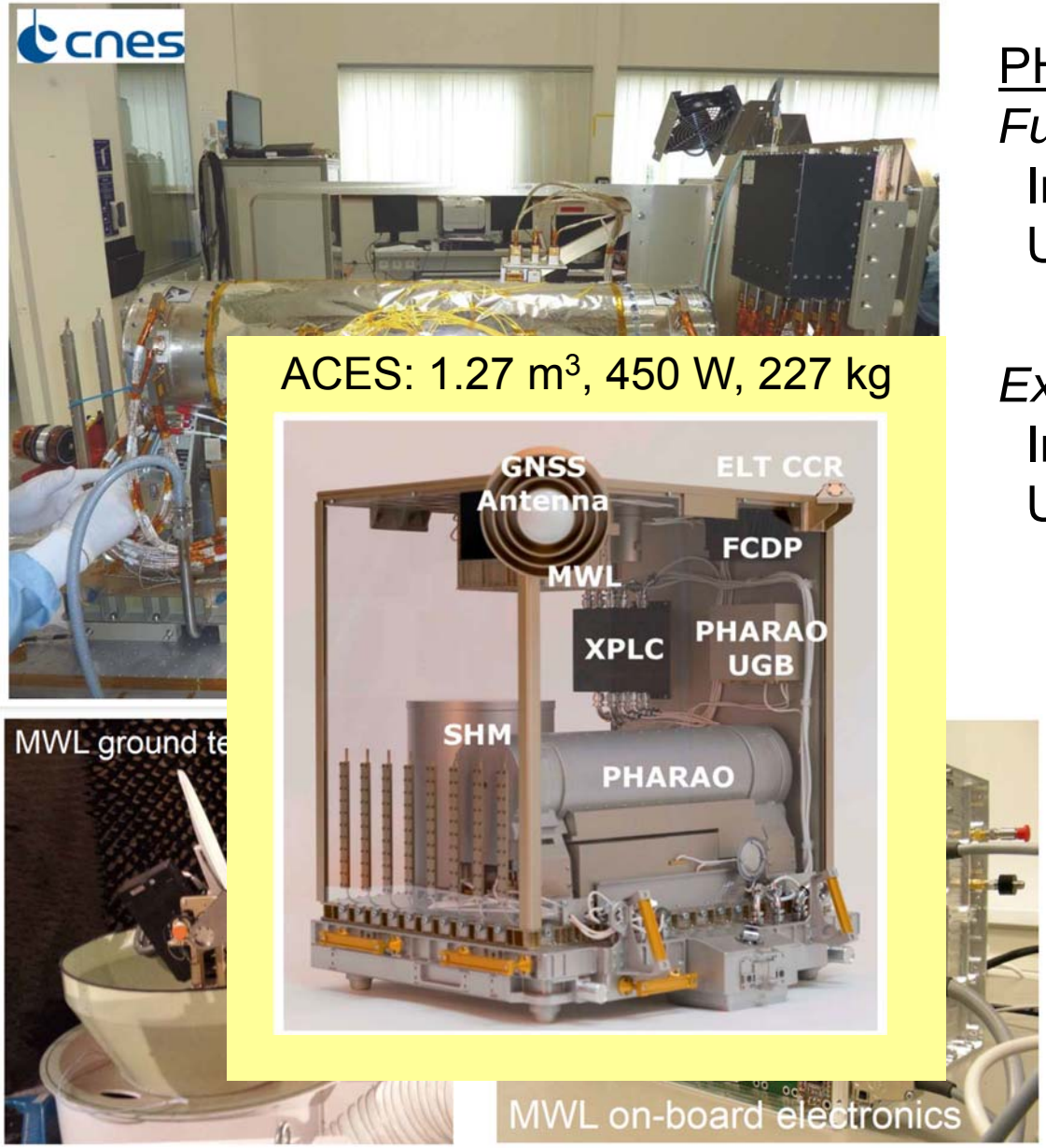
- **Continuous progress in atomic clock performance**
  - **Cold Cs microwave clock** (uncertainty, instability ~ 2 x 10^{-16})
  - **Cold atom/ion optical clocks** (unc. as low as 2 x 10^{-18}, instability ~ 1 x 10^{-18})

Cold-atom sensors in space: time line

- 1988 – 2003: invention of the basic principles
- In Europe since ca. 2000: proposals and developments of robust instruments for experiments in weightlessness (drop tower) and in space (satellites, space station)

  - **ISS Mission:** PHARAO/ACES on ISS (CNES/ESA, launch in 2018)

ACES: Clock for space (2018)



PHARAO: Laser-cooled Cs clock

Fully tested on ground:

Instability $3 \cdot 10^{-13}/\tau^{1/2}$

Uncertainty $1.4 \cdot 10^{-15}$

Expected in space:

Instability $1 \cdot 10^{-13}/\tau^{1/2}$

Uncertainty $<2 \cdot 10^{-16}$

Two-way microwave link:

capable of comparing ground clocks at 10^{-17} level

Cold-atom sensors in space: time line

- 1988 – 2003: invention of the basic principles
- In Europe since ca. 2000: proposals and developments of robust instruments for experiments in weightlessness (drop tower) and in space (satellites, space station)

  - **ISS mission:** PHARAO/ACES on ISS (CNES/ESA, launch in 2018)
  - **ISS mission (stopped)**: PARCS (NASA, stopped ca. 2005)
  - **Rocket missions:** QUANTUS, MAIUS, (DLR) …BEC on 23.1.2017
  - **ISS mission**: ISOC (ESA, launch goal: 2022)
  - **Medium-size satellite mission (study)**: STE-QUEST (ESA, natl. Agencies: 2010-13)
  - **ISS mission**: cold atom experimentation platform (NASA)
  - **CAI**: Atom interferometer technology development (ESA)
  - cold-atom satellite gravimetry (NASA)

- Ca 2020+: cold-atom sensors in space

Cold atom sensors in space: China

- The first cold atoms in space are Chinese!

  Laser-cooled Rb clock experiment on Tiang-Gong 2, 9/2016

- Announced: on future Tiang-Gong station in 2022+:
  - *a Sr optical clock (like ISOC),*
  - *a Cs cold atom clock*
  - *a H-maser*
  - *microwave and optical link*

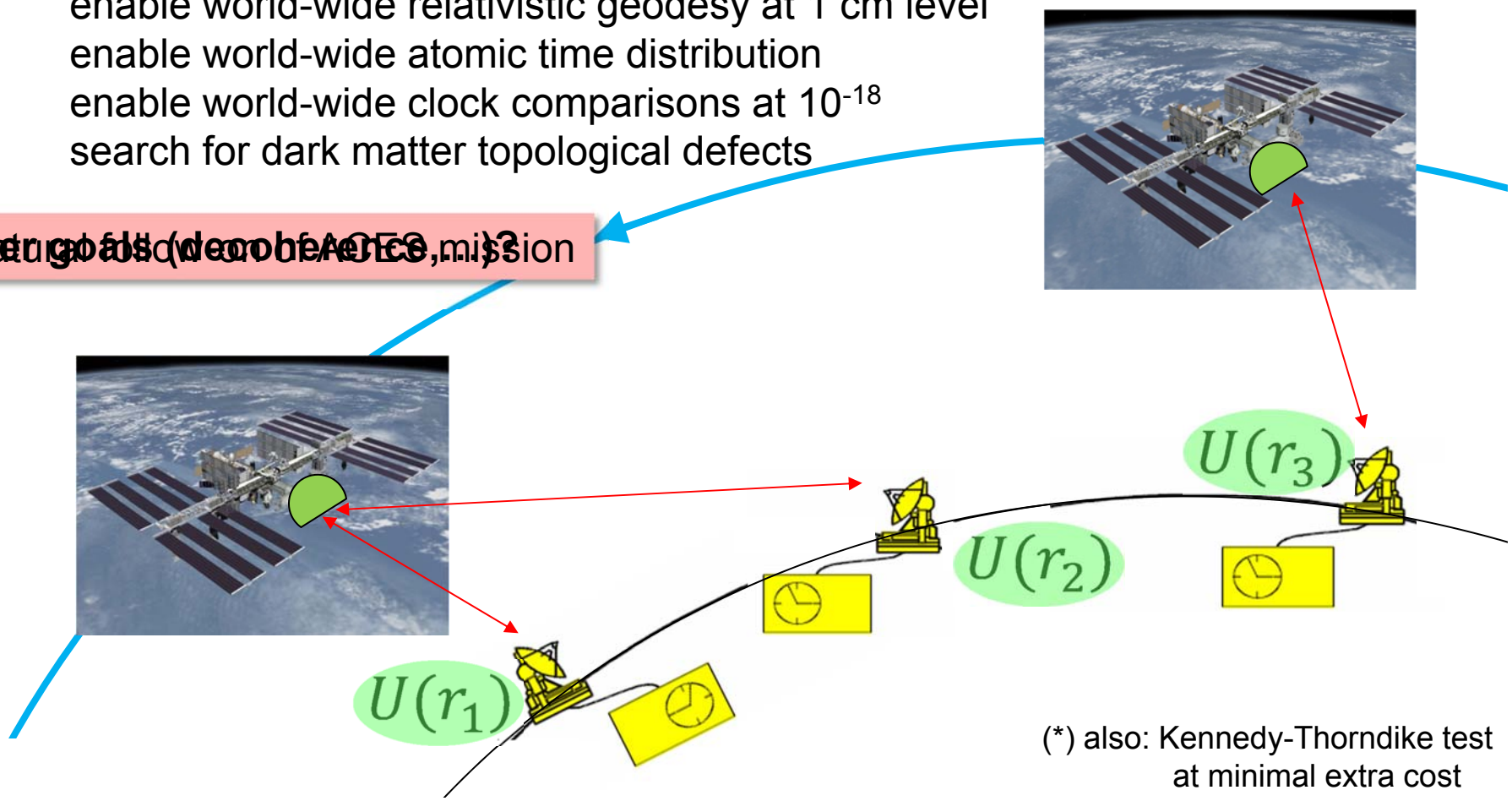
- Also 2016: first quantum communication satellite experiment

Mission ISOC (Space Optical Clock)

- Mission of ESA in ELIPS-4/SciSpace program; potential launch in 2022+
- Scientific goals: (*)

  measure Earth's gravitational time dilation at 2 x 10^{-7} level
  measure Sun's time dilation at 1 x 10^{-6} level
  measure Moon's time dilation at 2 x 10^{-4} level
  enable world-wide relativistic geodesy at 1 cm level
  enable world-wide atomic time distribution
  enable world-wide clock comparisons at 10^{-18}
  search for dark matter topological defects

- Other goals (beyond ACES, mission maturity)?



(*) also: Kennedy-Thorndike test
at minimal extra cost

Time dilation in the gravitational field (redshift)

Proper time of a clock

$$d\tau(r) = \sqrt{1 + 2\frac{U(r)}{c^2}}\, dt$$

Clock comparison

$$\frac{v_{clock1}\,(r)}{v_{clock2}\,(r)} \cong 1 + \frac{U(r_1) - U(r_2)}{c^2}$$

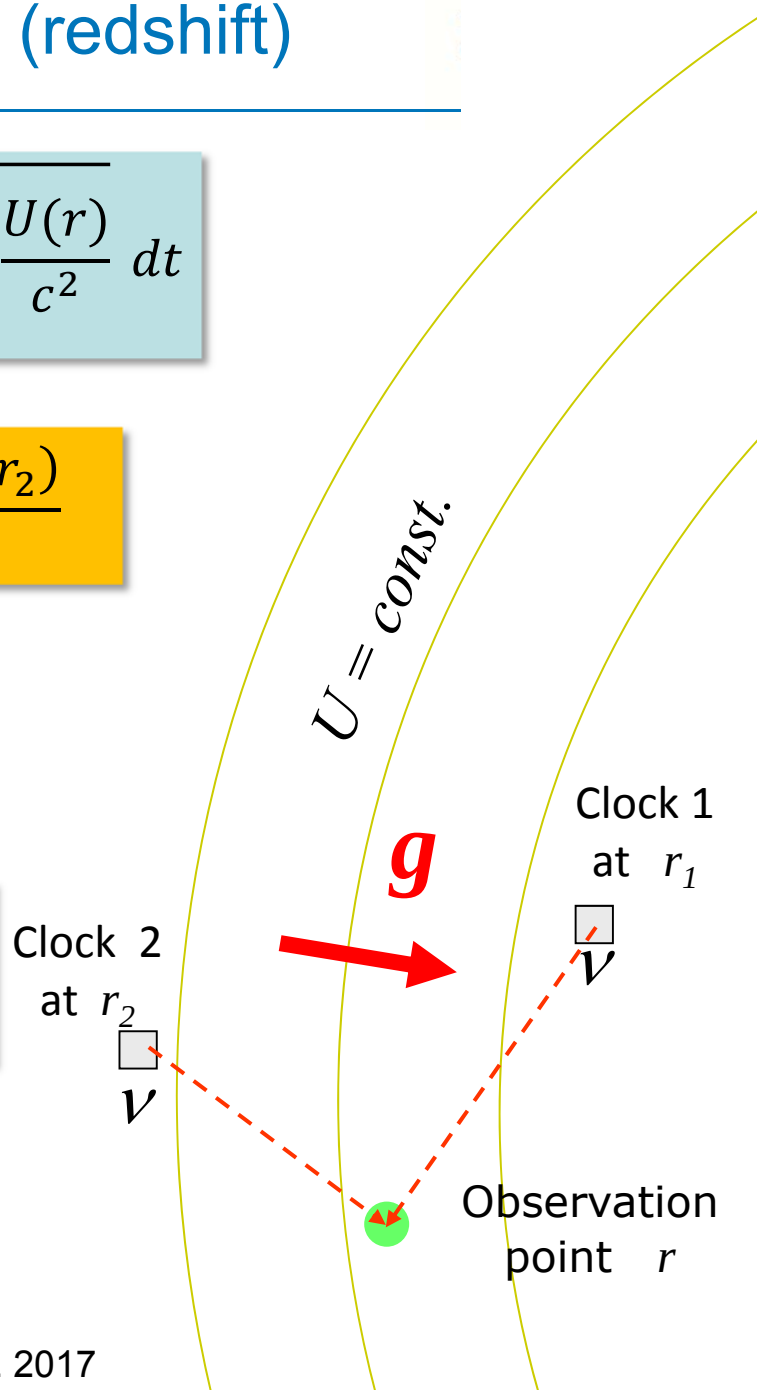
$$U(r) = -\frac{GM}{r} \quad ?$$

$$\frac{\nu_1 - \nu_2}{\nu} = (1 \times 10^{-16}) \times (\text{height difference in m})$$

Universally valid?

Independent of the type of clock ?

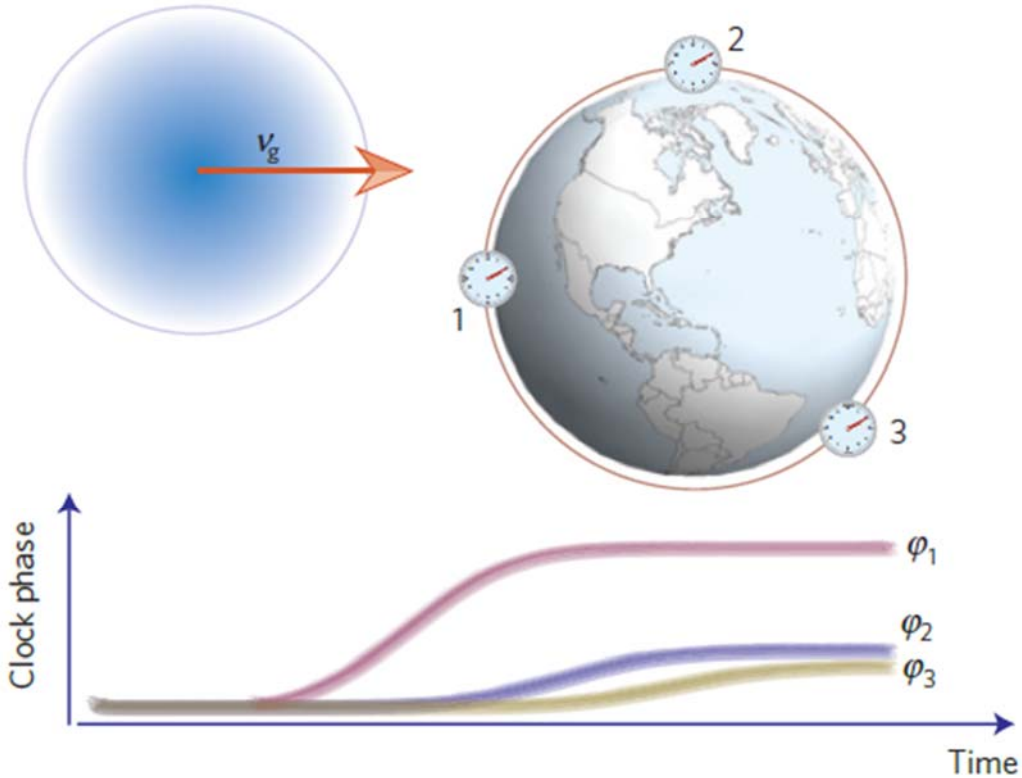
Independent of the type of mass ?



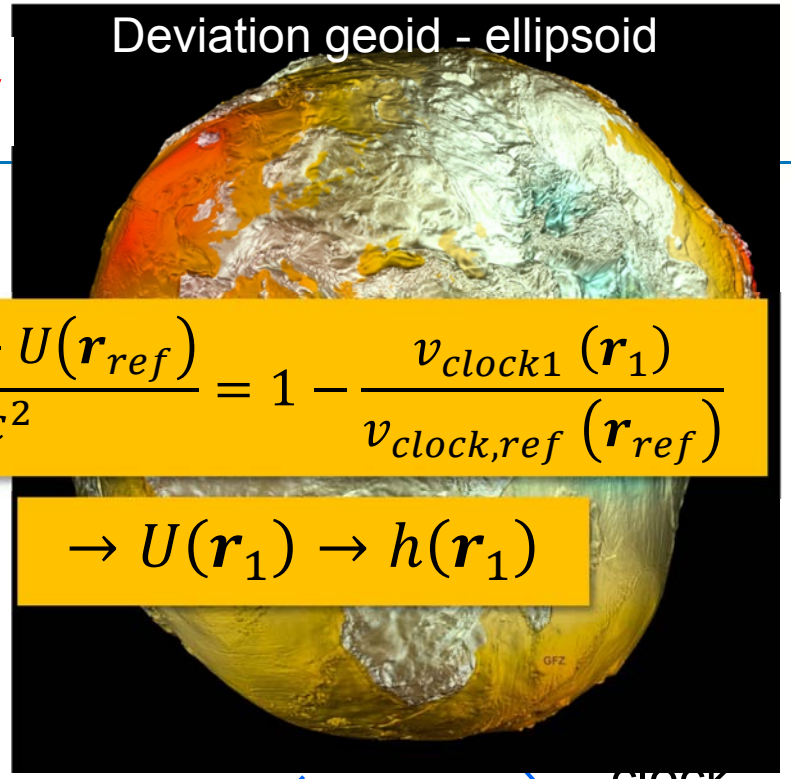
Comparing clocks in an Earth-scale network

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

- Differential phase shift between distant clocks



Geodesy via Relativity



- Topography: determined using GPS
- Geoid surface: determined via:
  - Gravimetric measurements
    slow; errors accumulate
  - Satellite gravimetry *slow (1 month), low-res (150 km), up to 30 cm inacc., bias*
  - Clock comparisons

$$\frac{U(\boldsymbol{r}_1) - U(\boldsymbol{r}_{ref})}{c^2} = 1 - \frac{v_{clock1}\,(\boldsymbol{r}_1)}{v_{clock,ref}\,(\boldsymbol{r}_{ref})}$$

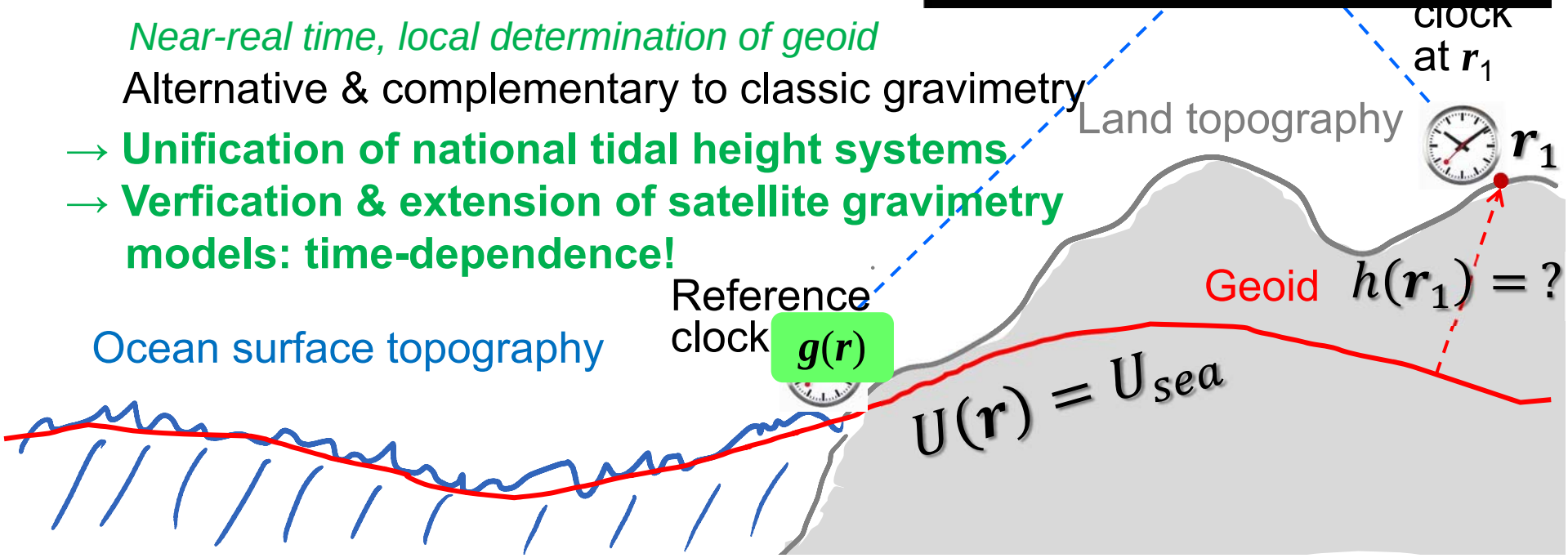
$$\rightarrow U(\boldsymbol{r}_1) \rightarrow h(\boldsymbol{r}_1)$$

Near-real time, local determination of geoid

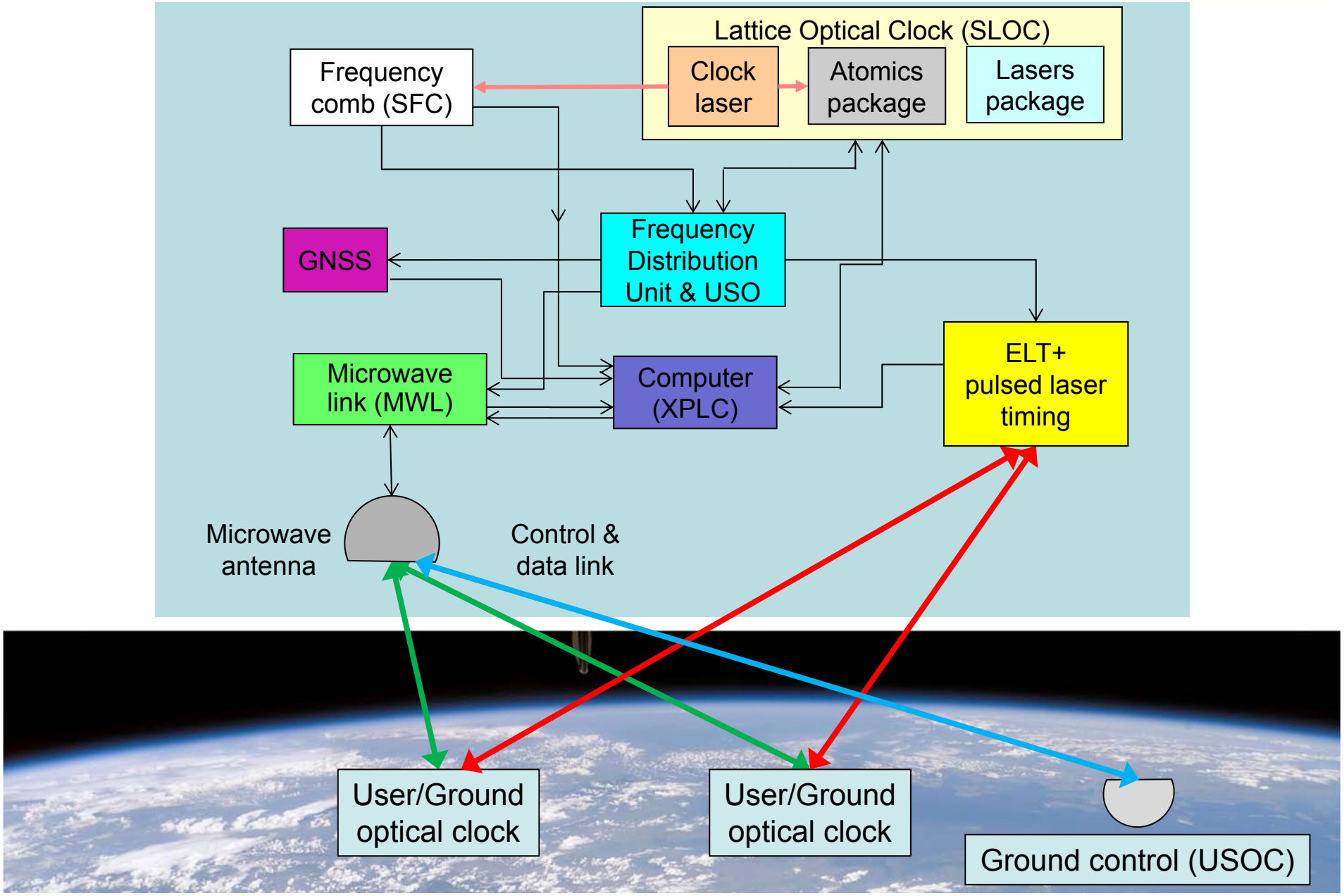
Alternative & complementary to classic gravimetry

→ **Unification of national tidal height systems**

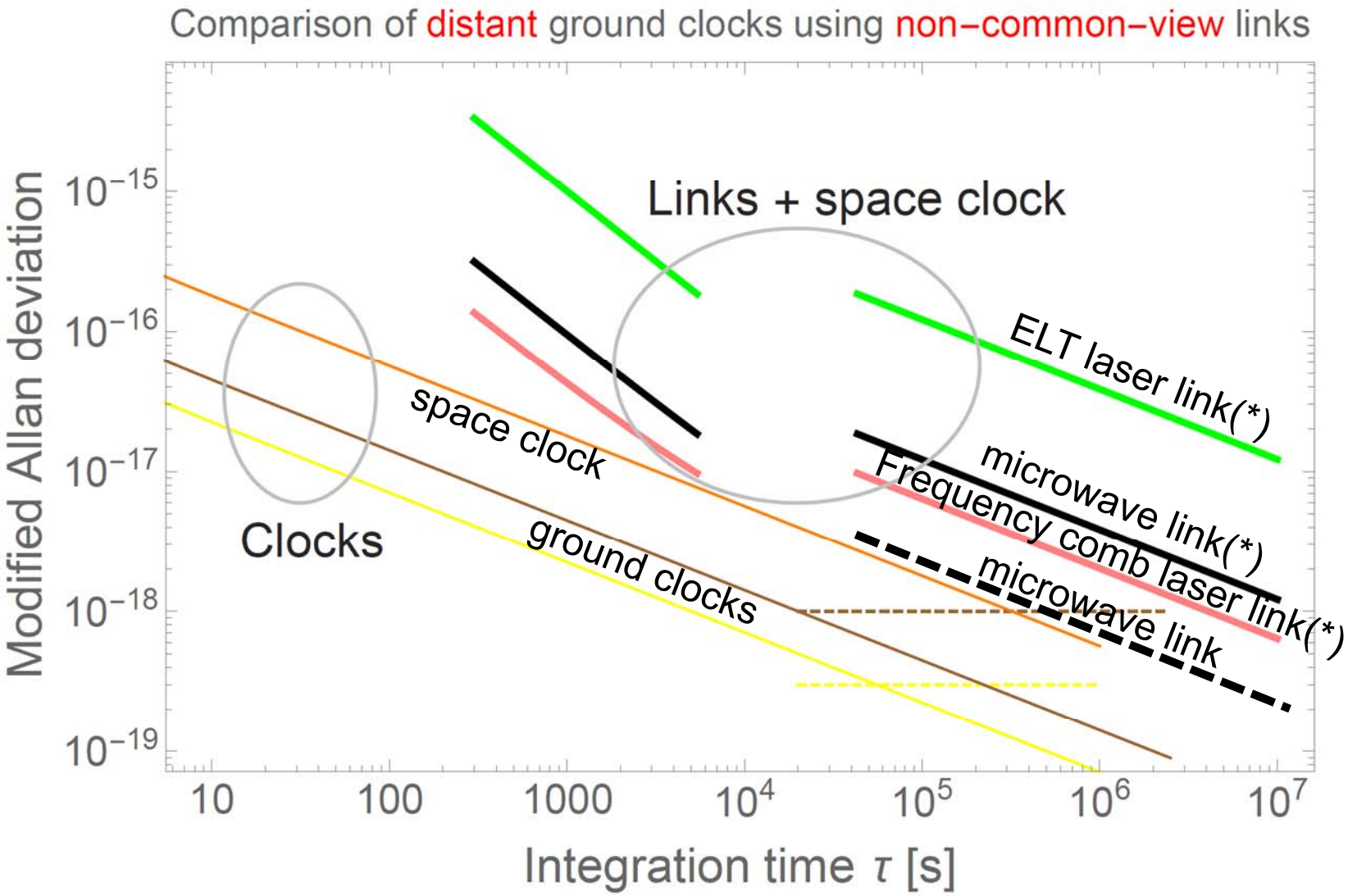
→ **Verfication & extension of satellite gravimetry models: time-dependence!**



I-SOC payload: concept



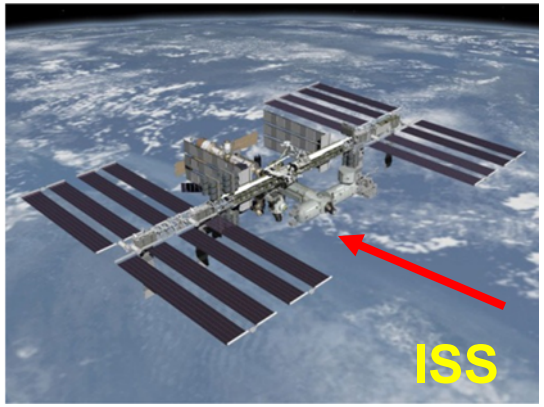
Specifications for clocks and links

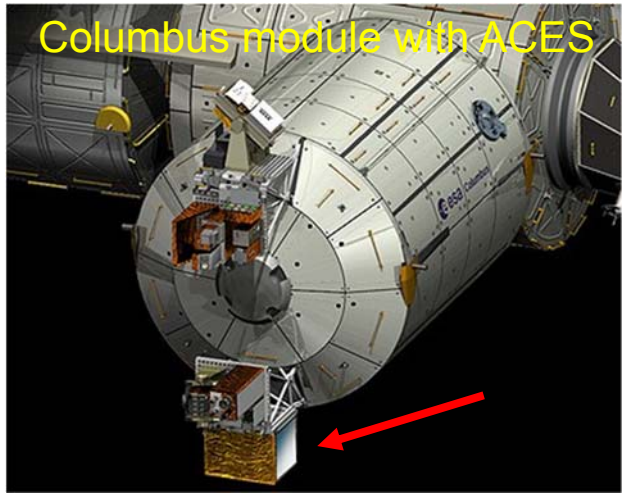


(*) Conservative assumption: no coherence for $\tau > 2$ h

Requirements on instrument

- Performance: 1×10^{-17} inaccuracy, $8 \times 10^{-16}/\tau^{1/2}$ instability (15 x, 120 x lower than PHARAO)
- External payload on ISS
- Clock physics package: mass <100 kg,
  power consumption < 250 W, volume < 0.5 m^3
- Automatic operation, remote diagnostics & control
- Operation in vacuum environment, radiation
- Operation in „noisy“ ISS environment
- (Near-) continuous operation for 2 years
- In nonoperational mode, must withstand:
  - temperature cycling from -40 to + 40 °C while awaiting launch
  - Shocks/vibrations: 30 g during launch
- Ground-space links of corresponding perfomance





- Introduction: quantum sensors
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- Status: elegant breadboard demonstrator for ISOC
- ISOC: the way forward
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Principle of an optical atomic clock

Time data

Counter (Frequency comb)

f_L

Clock laser

Frequency controller

f_L Excitation beam

f_0

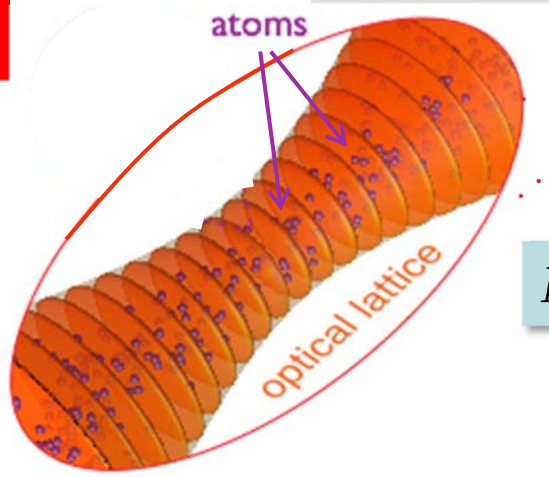
atoms

Detection laser beam

Oscillator

- Oscillator: Laser
- Reference: a single or many identical atoms
- Laserwave excites atoms
- Controller maintains laser frequency on the atomic transition frequency
  → referenced oscillator

$$f_L = f_0$$

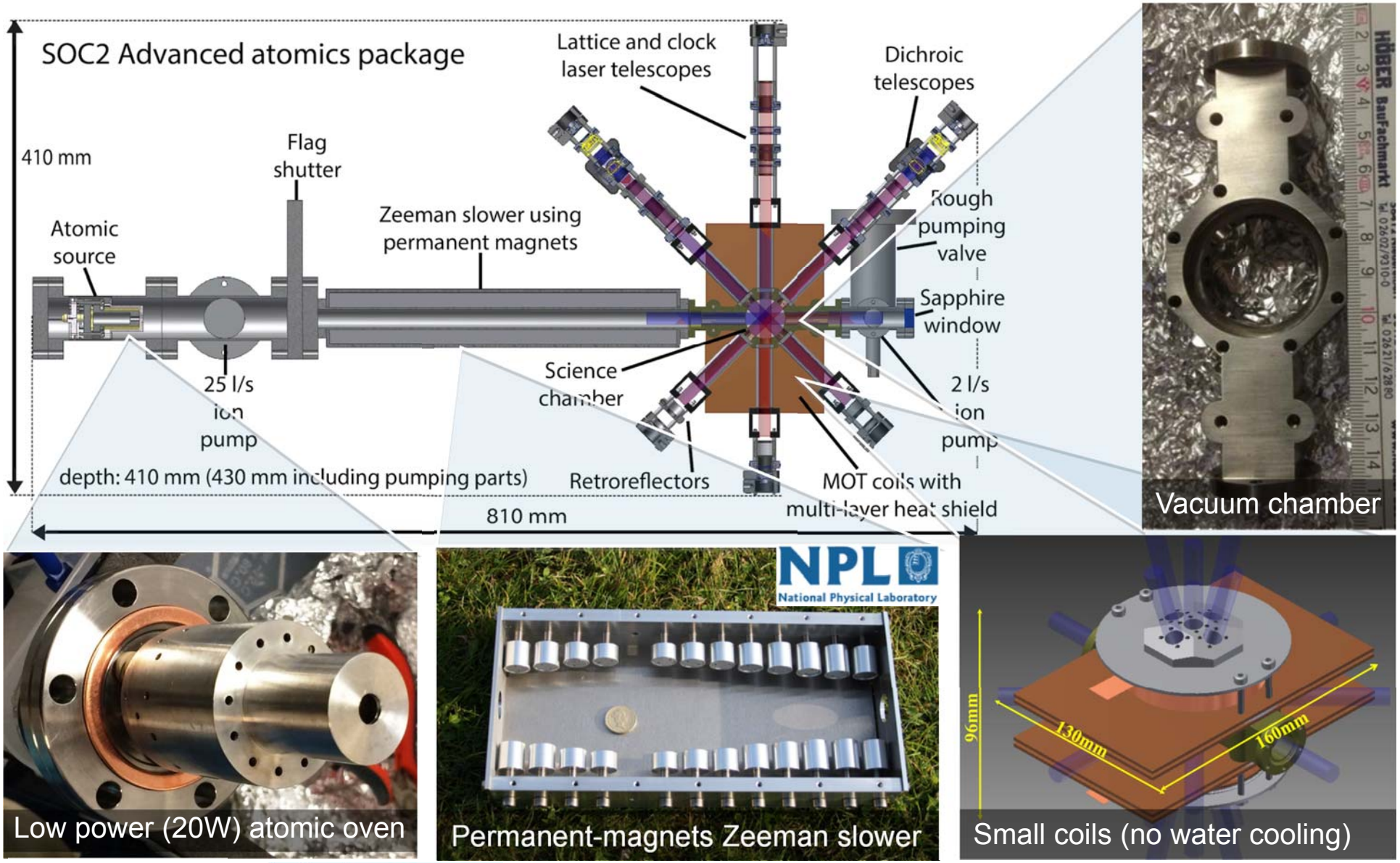


- **Lattice optical clock**
- Permits highest stability and accuracy

$N \approx$ few 1000 atoms

Other studies (decoherence,…)?

I-SOC clock demonstrator: compact physics package



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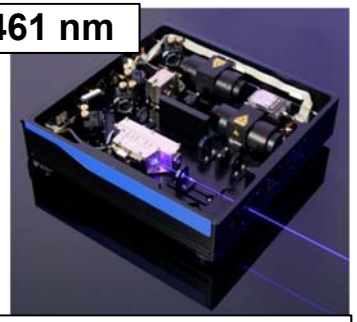
Hill, I.R. et al., J. Phys. B **47**, 075006 (2014)

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

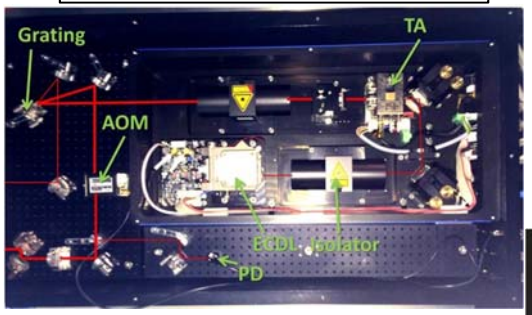
I-SOC clock demonstrator: modular laser system

461 nm

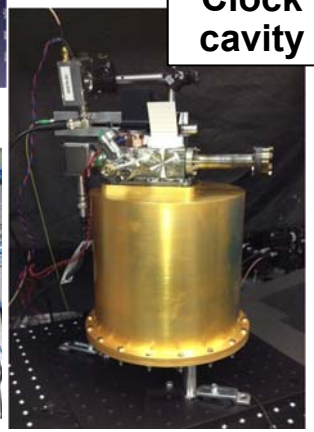


461 nm distribution

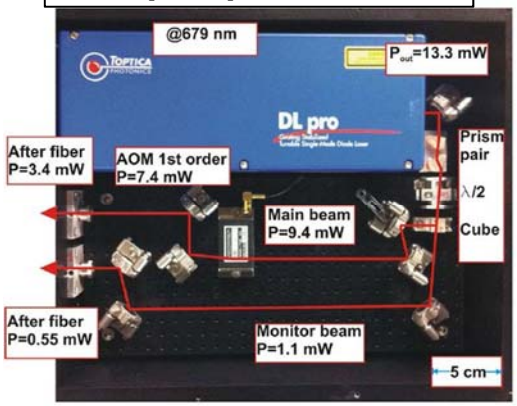
813 nm Lattice



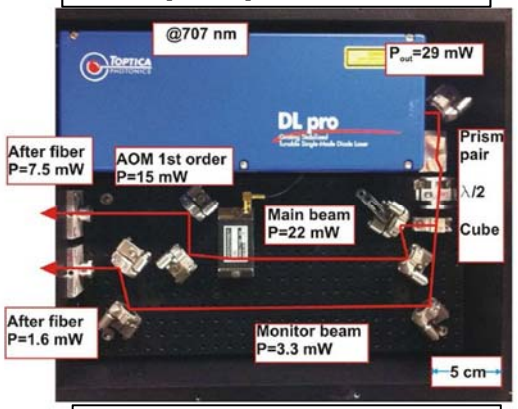
Clock cavity



Repumper 679 nm

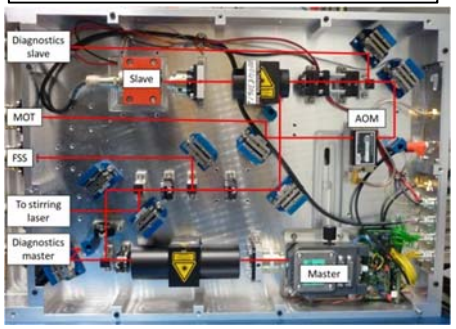


Repumper 707 nm

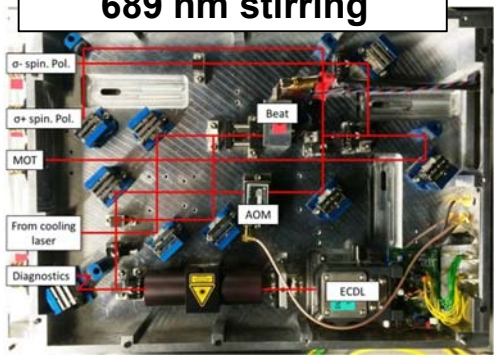


698 nm clock

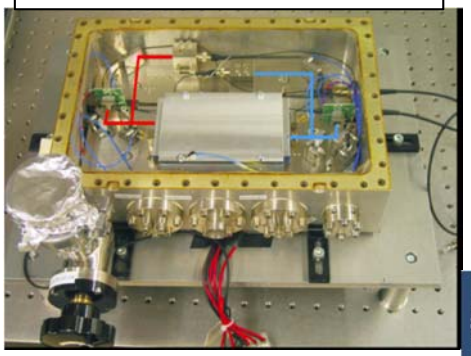
689 nm cooling



689 nm stirring



461, 689, 813 nm stabilization unit



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TOPTICA PHOTONICS

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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)

Leibniz Universität Hannover

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NPL National Physical Laboratory

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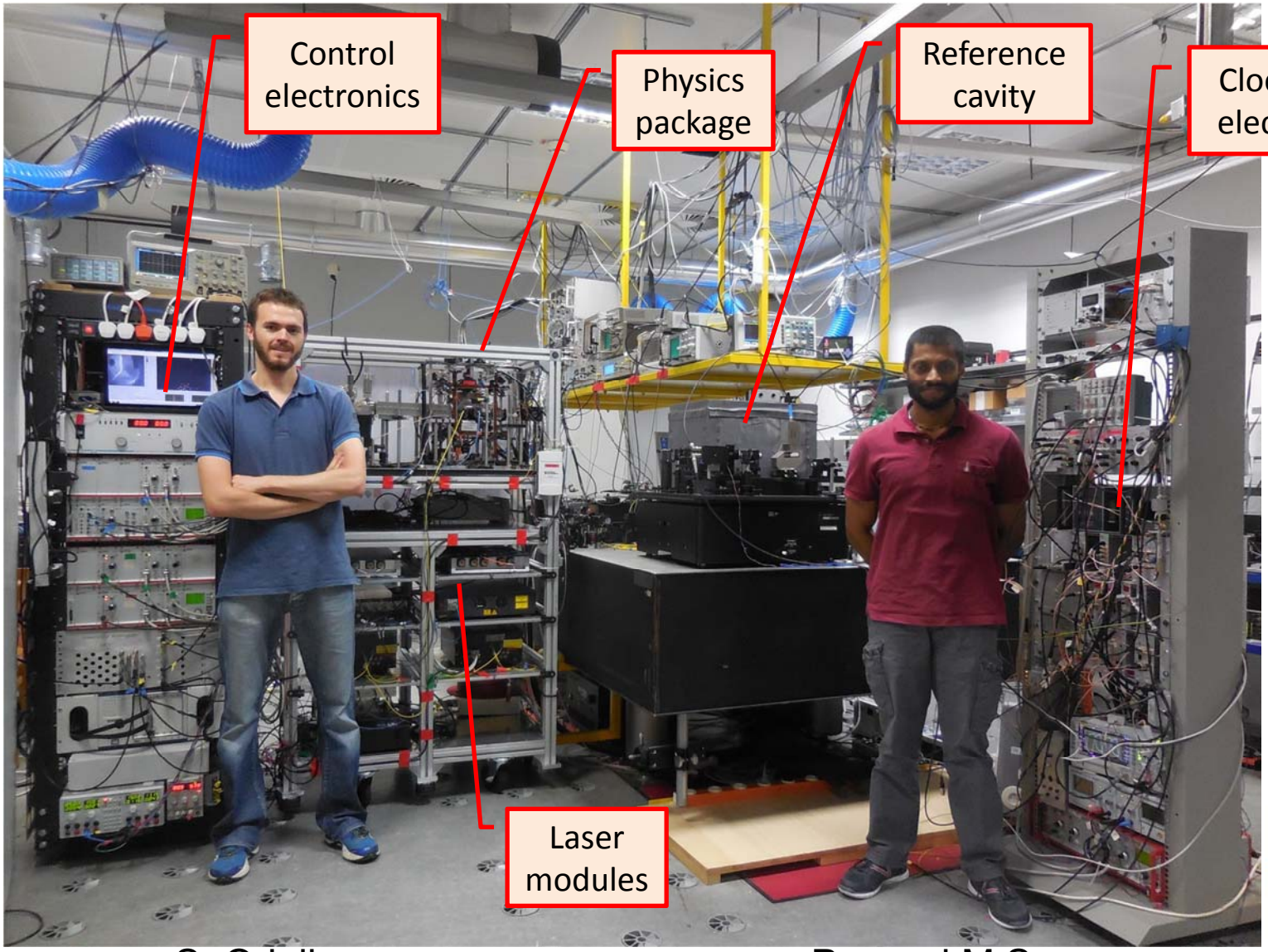
I-SOC clock breadboard demonstrator: current set-up



470 kg
1.1 kW,
2000 liter

S. Origlia

Pramod M.S.

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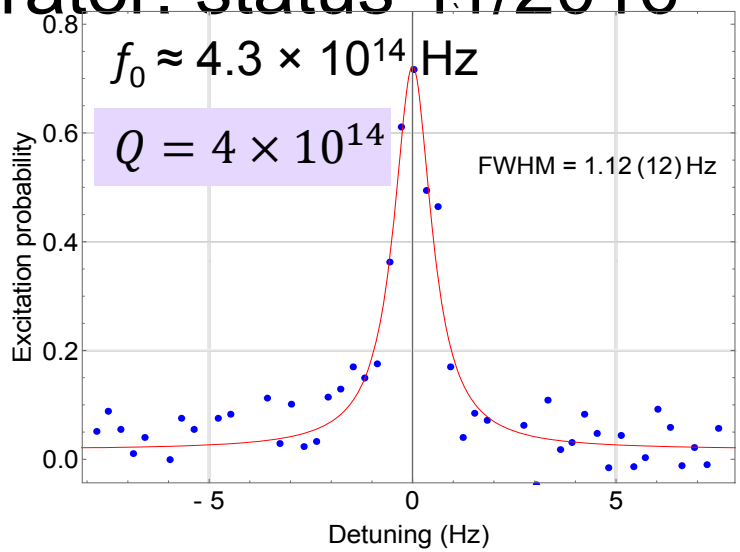
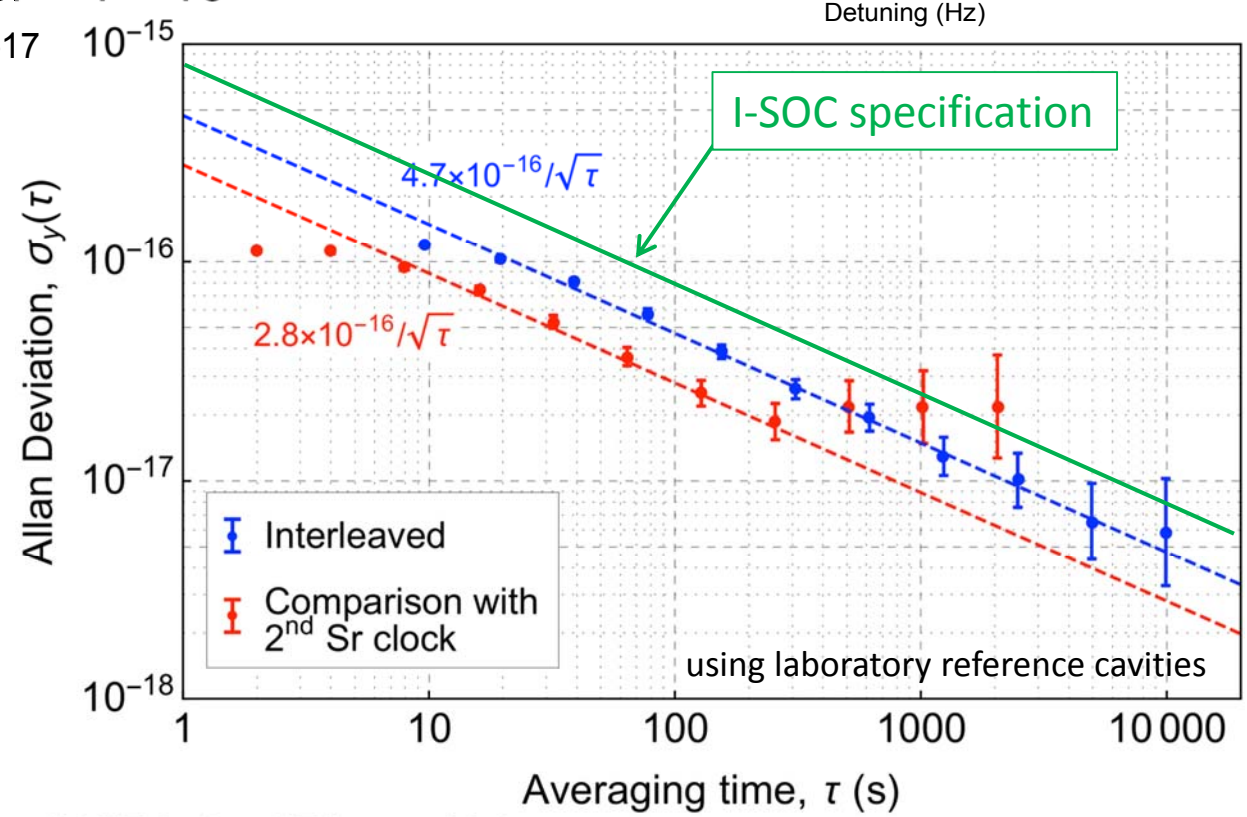
S.Origlia et al., Proc. SPIE 9900, 990003 (2016);http://arxiv.org/abs/1603.06062

I-SOC clock breadboard demonstrator: status 11/2016



Routinely operates with ^{88}Sr

- Clock transition linewidth:
  1.1 Hz (with laboratory ref. cavity)
  32 Hz (with compact ref. cavity)
- Rabi oscillations with 400 ms coherence time
- Zeeman shift uncertainty < 5×10^{-16}
- Clock laser light shift unc. < 1×10^{-16}
- Density shift unc. 2×10^{-17}



Upcoming:

d.c. Stark shift control
Blackbody shift control
Lattice light shift control
Operation with ^{87}Sr

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I-SOC clock demonstrator: transport

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

June 2015: Birmingham, UK → Braunschweig, D

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Europe: strong technology heritage

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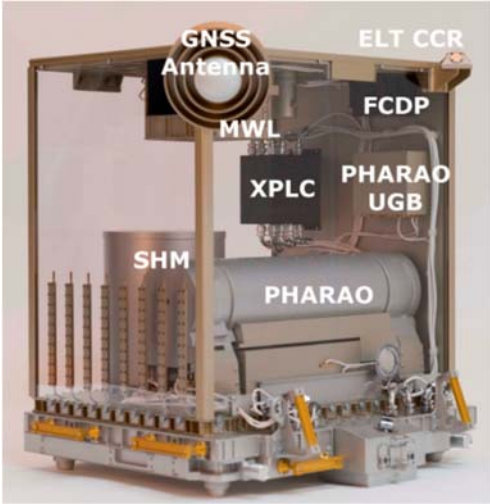
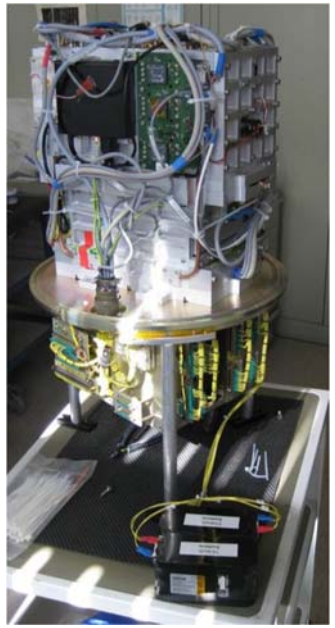
- Scientific know-how available
  (8 institutions have developed lattice clocks and ultrastable lasers @ 10^{-17} level, incl. transportable units)
- Cold Cs atoms microwave space clock fully developed in Europe: flight model ready
- Microwave link technology developed in Europe: flight model ready
- Frequency comb invented & commercialized in Germany
- Frequency combs prototypes tested in rocket flights (Menlo Systems, DLR)
- Critical laser technologies for ISOC under development under ESA funding
- Nearly complete demonstration breadboard of optical lattice clock





Mission SOC (Space Optical Clock)

- 2004 Proposed in response to the AO of the Microgravity Applications Programme of ISS
- 2005 selected for the ELIPS-3 programme (reviewed as outstanding)
- 2007-15: pre-phase-A development project (funded by ESA, EU, DLR,…
- 2013-16: following positive review, maintained in ELIPS-4 programme
- 2016: strongly recommended by HISPAC and PSWG: identified as a strategic project

Many European contributors, and strongly based in D, F, I, UK

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 CAP,HHU]*
   - *CCU: laser frequency stabilization system* *[NPL UK, PTB]*
   - *813 nm lattice laser* *[Fraunhofer CAP, SYRTE]*
   - *OSRC: reference cavity* *[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: clock design 2017 *[Science team]*
4) Phase A: mission design & costing 2018 *[space industry, Science team]*

5) Phases B, C (funding not yet decided) 2019+ *[space industry, Science team]*

Mission **2022+**

Summary

- ISOC has a very strong science case
- ISOC is technically feasible

Fundamental physics, **geophysics/geodesy**, **metrology**

- ISOC is a test bed for quantum sensors, future clocks and links: Europe can remain state-of-the-art in QT in space and its applications
- ISOC is strategic
  - *will provide a scientific infrastructure usable world-wide*
  - *will generate new research opportunities for a world-wide community of scientists across fields*
  - *will introduce a new technology step*
  - *future clocks will be based on its technology (upgrade/downgrade of performance can be traded off with mass, power, volume)*
  - *is part of a long roadmap of quantum technology in space (10 x improvements in accuracy, lifetime, distance ea. 10 years)*
- ISOC is cross-disciplinary & cross-directorate within ESA
- Important: committment of *national* space agencies for all phases needed