Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Towards international optical clock comparisons using optical fibers: current status and prospects

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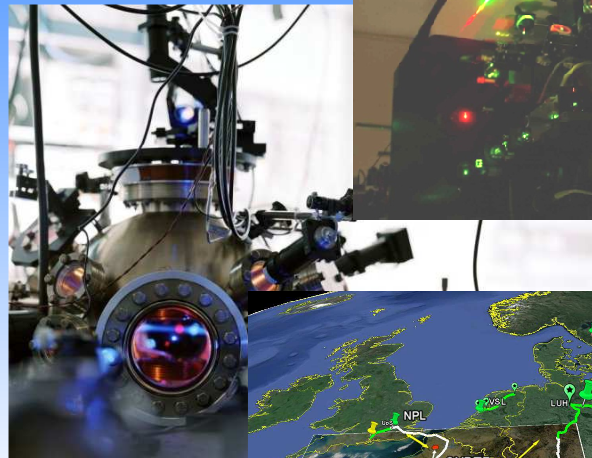
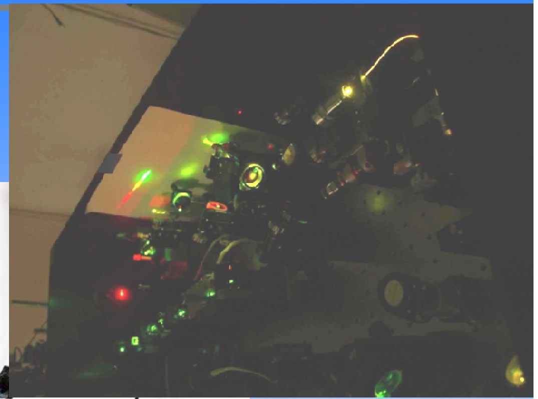
PTB, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Outline:

- **Atomic Clocks & Frequency Combs**

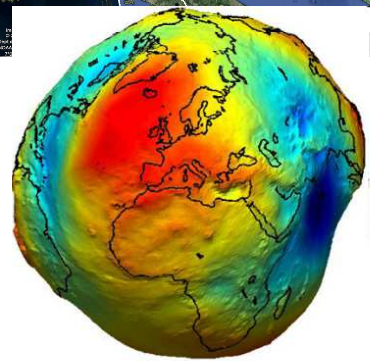




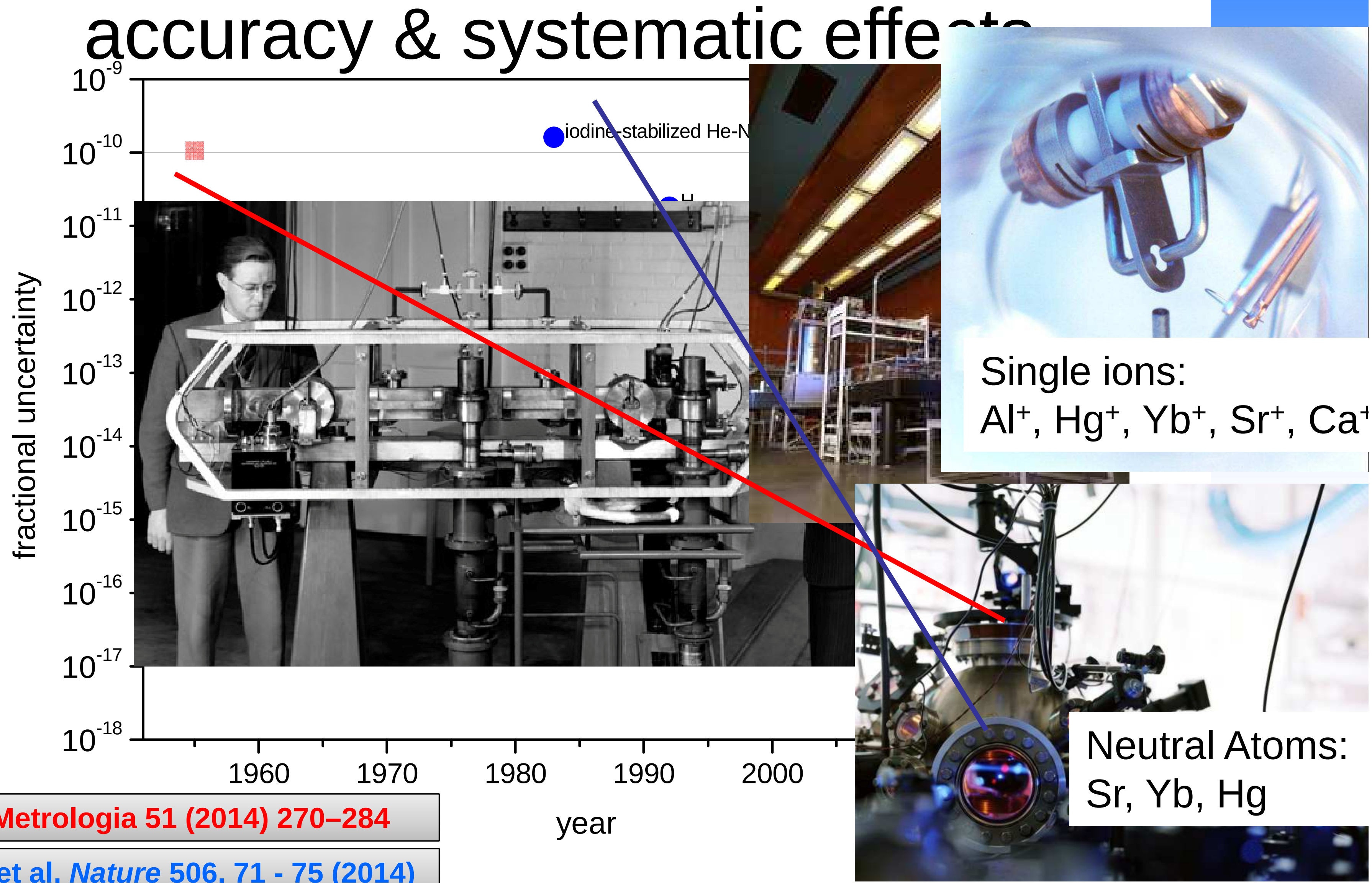
- **Optical Fiber Links**

- **Applications**

  Clocks for Relativistic Geodesy



Optical Atomic Clocks



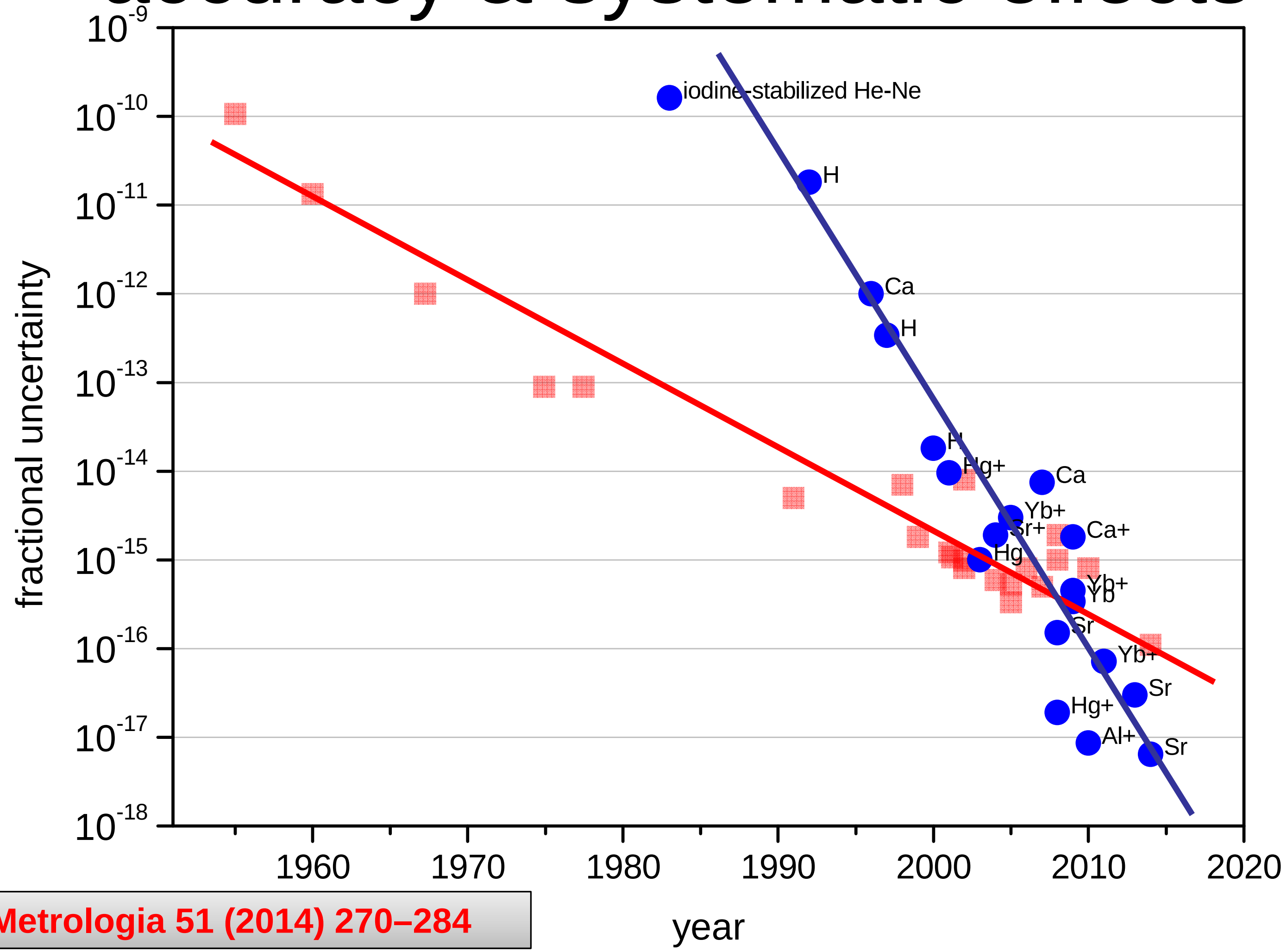
[1] F.Levi et al, Metrologia 51 (2014) 270–284

[2] B. J. Bloom et al, *Nature* 506, 71 - 75 (2014)

Optical Atomic Clocks

PTB

accuracy & systematic effects



2.3×10^{-16}

6.4×10^{-18}

[1] F.Levi et al, Metrologia 51 (2014) 270–284

[2] B. J. Bloom et al, *Nature* 506, 71 - 75 (2014)

Basic Principle of Atomic Clocks

Narrow linewidth absorber:
ions, neutral atoms, molecules

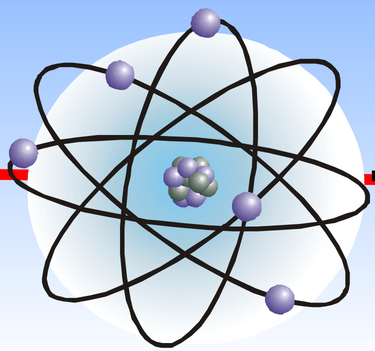
Ultrastable Laser
with reference cavity

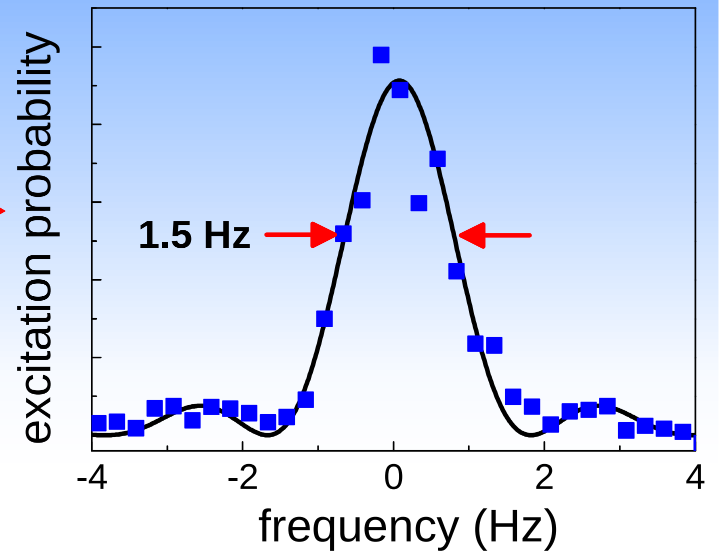
ν_0

absorption signal

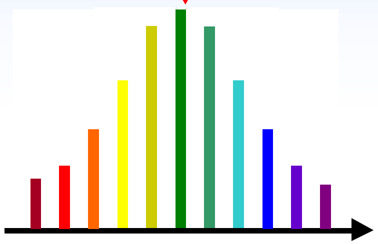
500 THz

Laser





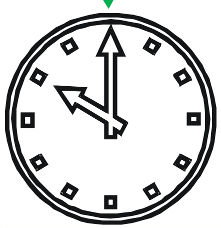
ν_{out}



Servo

Accuracy: How accurately agrees ν_{out} with ν_0?

Stability: To what extent fluctuates ν_{out} around ν_0?



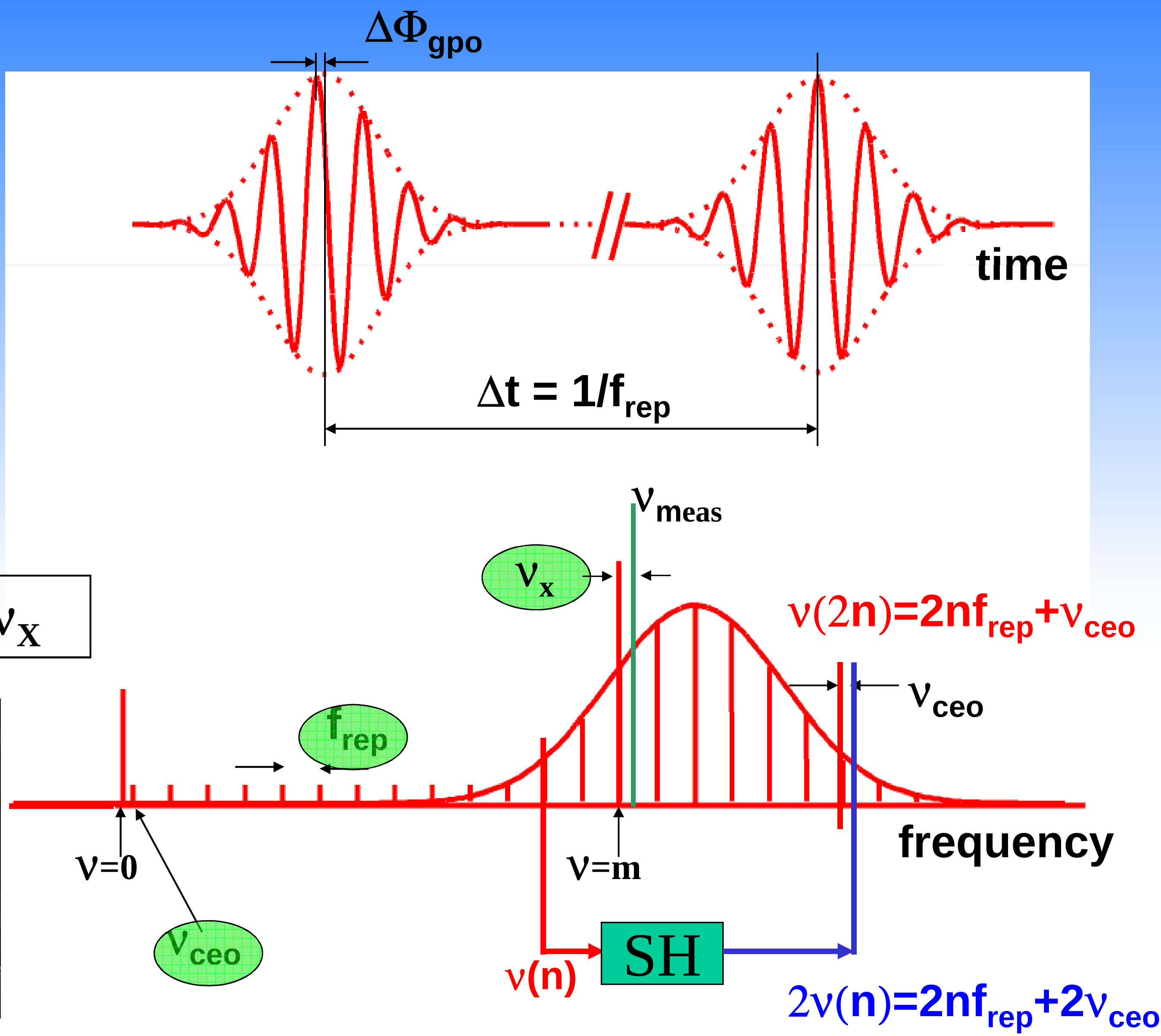
100 -1000 MHz

A Frequency Comb Generator as Clock Work

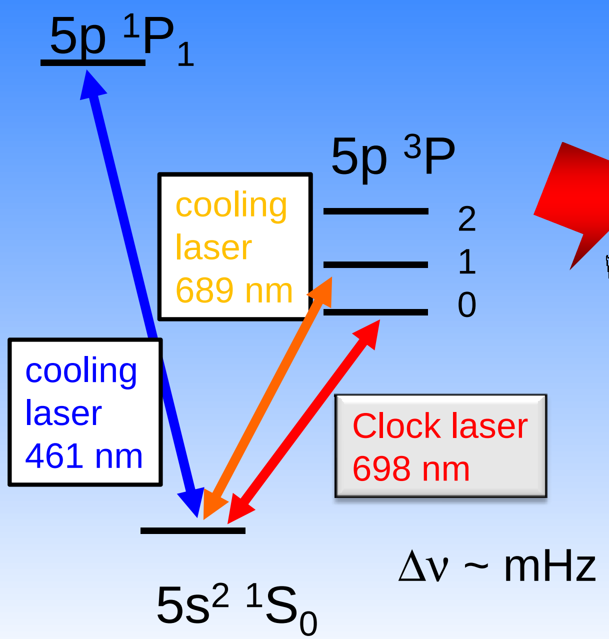
Time domain:

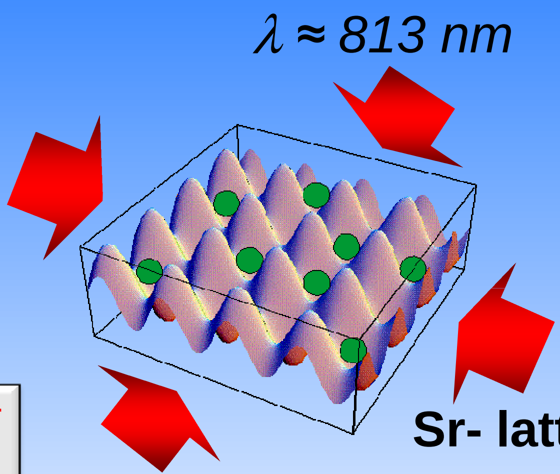
Frequency domain:

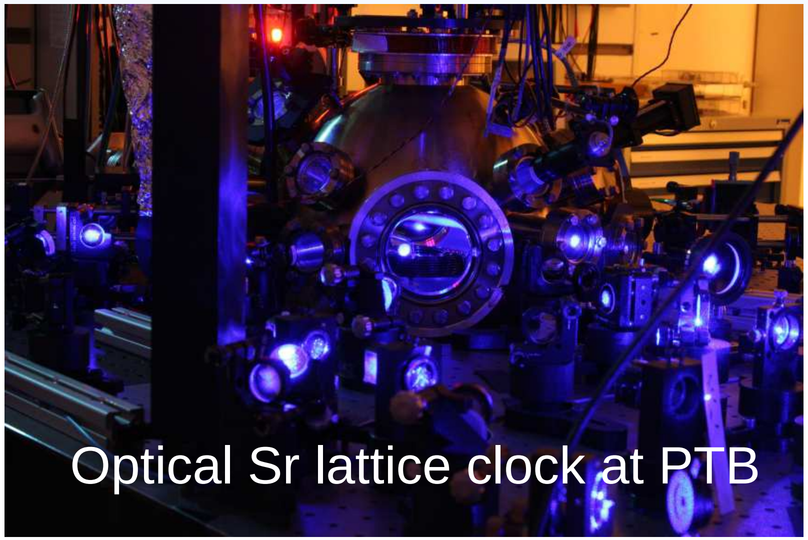
$$\nu_{meas} = \nu_{ceo} + m\, f_{rep} + \nu_X$$



Status of Sr lattice clocks






Optical Sr lattice clock at PTB

- ≈ 10 Sr-lattice clocks are operational or under construction

Sr- lattice clock @ JILA (Boulder, CO)

- rel. instability: 3.1×10^{-16} /Hz ^{½}
- estimated rel. standard uncertainty: 6.4×10^{-18}
- agreement between two independent clocks 5.4×10^{-17}

B. J. Bloom et al, *Nature* 506, 71 - 75 (2014)

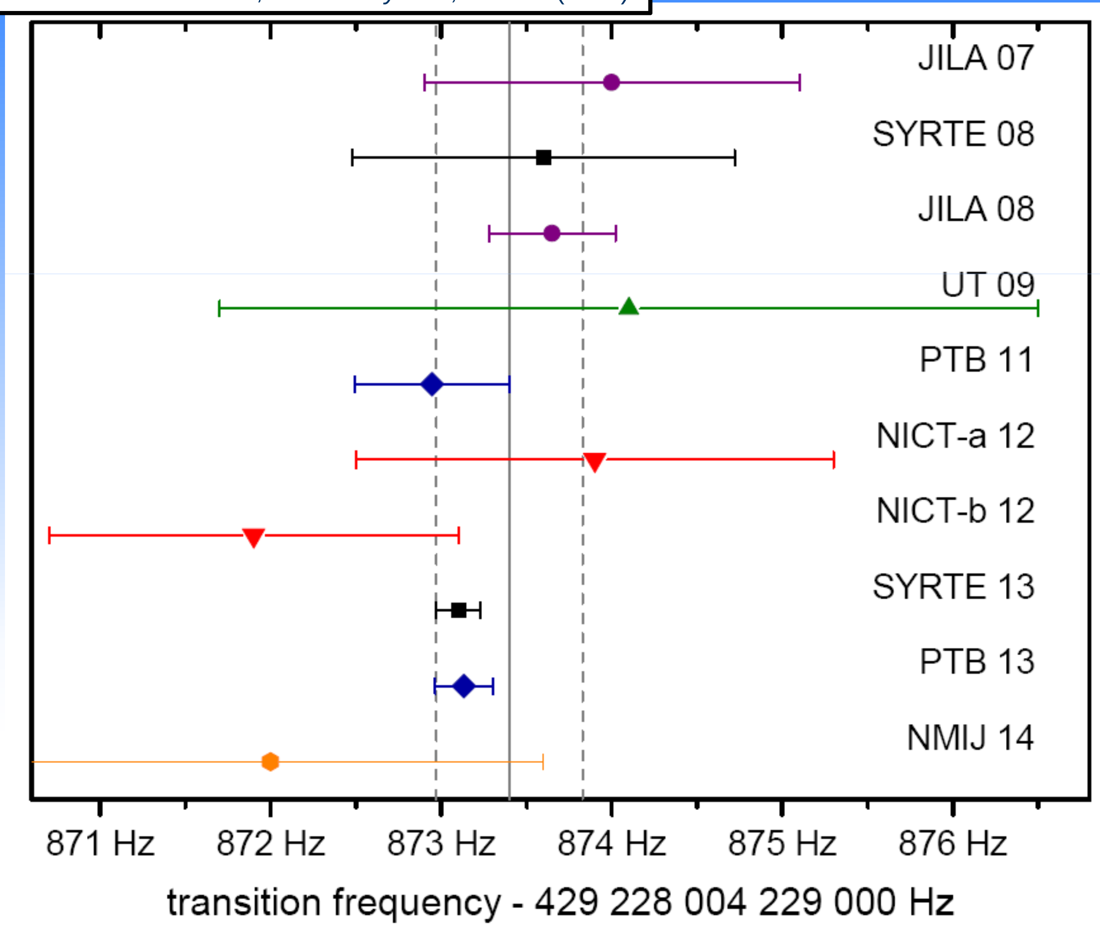
cryogenic Sr- lattice clock @ Riken (Tokyo)

- Agreement: $(1.1 \pm 1.6) \times 10^{-18}$.

I. Ushijima et al : preprint (2014) *arxiv.org/pdf/1405.4071*

Frequency measurement: Sr wrt. Cs

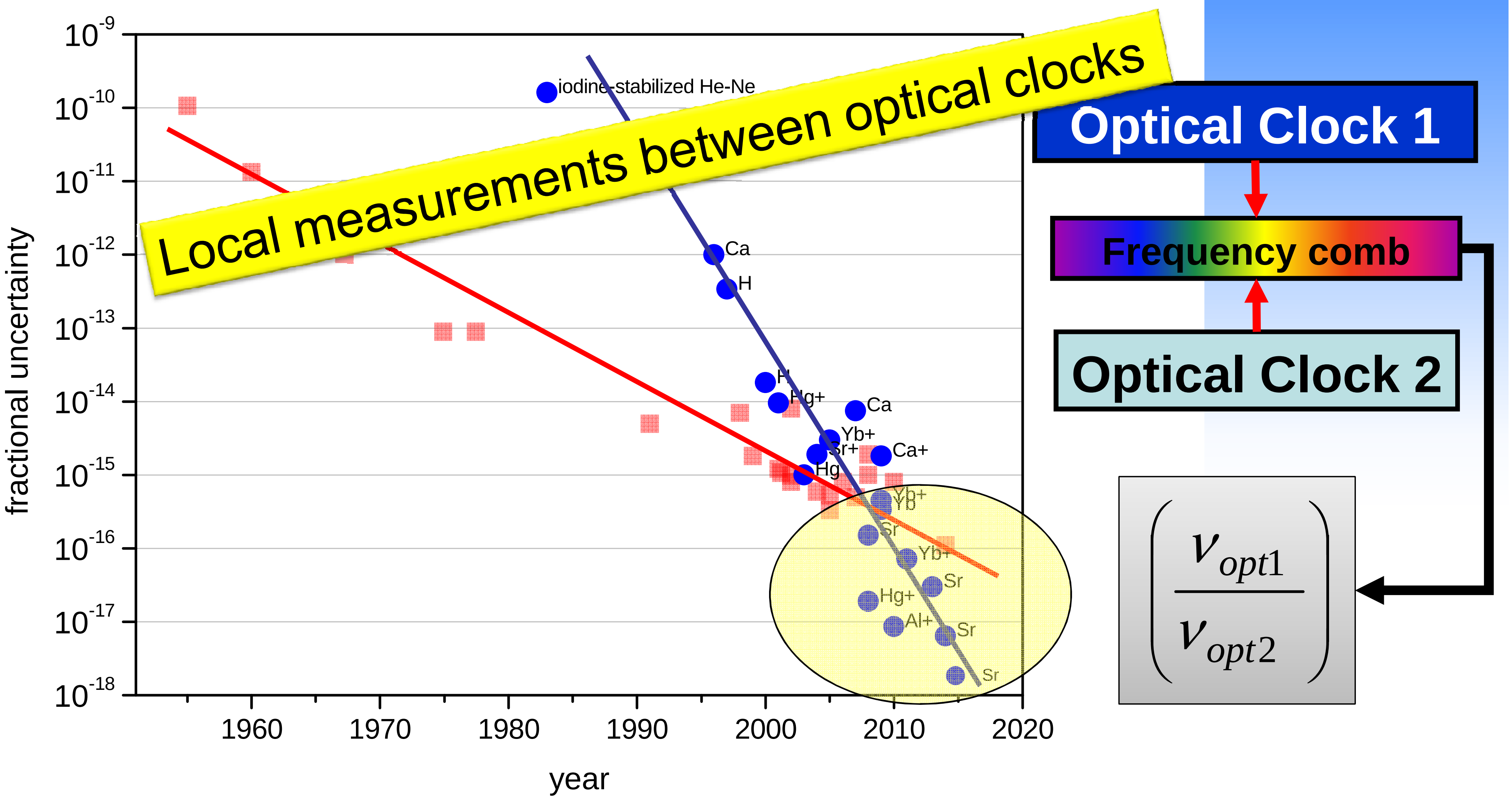
Source: S. Falke et al., *New J. Phys.* **16**, 073023 (2014)



JILA07:	Boyd et al, *Phys. Rev. Lett* **98,** 083002 (2007)
Syrte 08:	Baillard et al., *Eur. Phys. J. D* **48**, 11 (2008)
JILA08:	Campbell et al., *Metrologia* **45**, 539 (2008)
UT09:	Hong et al., *Opt. Lett.* **34**, 692 (2009)
PTB11	Falke et al., *Metrologia* **48**, 399 (2011)
NICT a,b 12	Yamaguchi et al., *Appl. Phys. Exp.* **5**, 022701 (2012)
SYRTE 13	Le Targat et al., *Nature Com.* **4**, 2109 (2013)
PTB13	Falke et al., *New J. Phys.* **16**, 073023 (2014)
NMIJ14	Akamatsu et al., *Appl. Phys. Exp.* **7**, 012401 (2014)

- good agreement of frequency measurements
- uncertianty liminted by uncertainty of Cs clocks

Direct measurement of optical frequency ratios



Direct measurement of optical frequency ratios

Reference	Absorber	Value	Relative uncertainty
Ushijima et al (2014)	$f_{Sr(1)}/f_{Sr(2)}$	1.0	1.6×10^{-18}
Bloom et al (2013)	$f_{Sr(1)}/f_{Sr(2)}$	1.0	5.3×10^{-17}
Chou et al (2010)	$f_{Al+(1)}/f_{Al+(2)}$	1.0	2.5×10^{-17}
Rosenband et al (2008)	f_{Hg+}/f_{Al+}	1/1.052871833148990438(55)	5.3×10^{-17}

$$\frac{f_{Yb^+(E3)}}{f_{Sr}}$$

1st measurement (Dec 2012, spring 2013)
estimated rel. uncertainty ~ 7×10^{-17}

2nd measurement (Oktober 2014 / in progress)

$$\left(\frac{\nu_{opt1}}{\nu_{opt2}}\right)$$

Remote frequency comparison using an OPTICAL CARRIER

local comparison at location A	**Transfer A to B**	local comparison at location B

$$\frac{\nu_{1,2}(A)}{\nu_{1,2}(B)} = const\ !$$

Optical Clock 1

Frequency comb

Transfer laser ν_1

fiber

Optical Clock 2

Frequency comb

Transfer laser ν_2

Requires stabilization of the frequency fluctuations of the link.
Details will be given in the next talk.

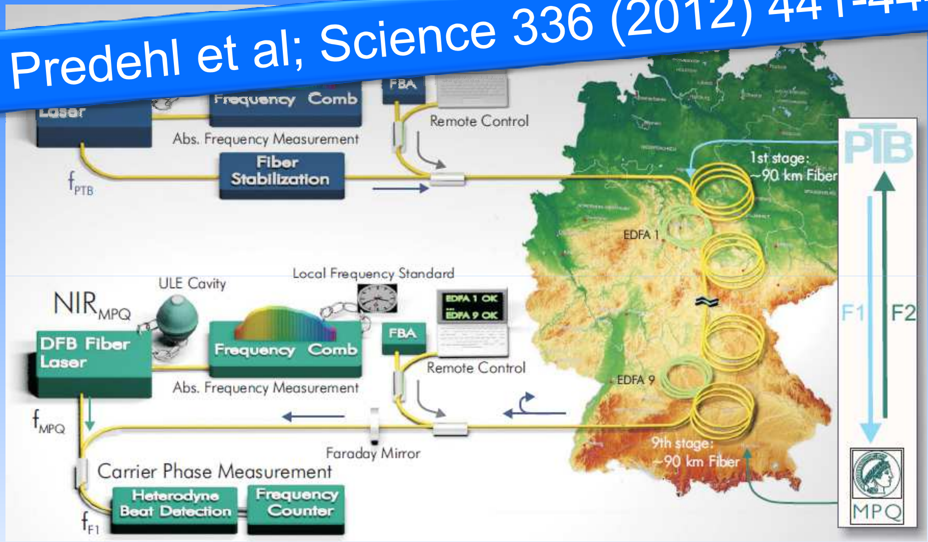
$$\left(\frac{\nu_{opt1}}{\nu_1}\right)_A \qquad \nu_1(A)/\nu_2(B) \qquad \left(\frac{\nu_2}{\nu_{opt2}}\right)_B$$

Example of a fiber link

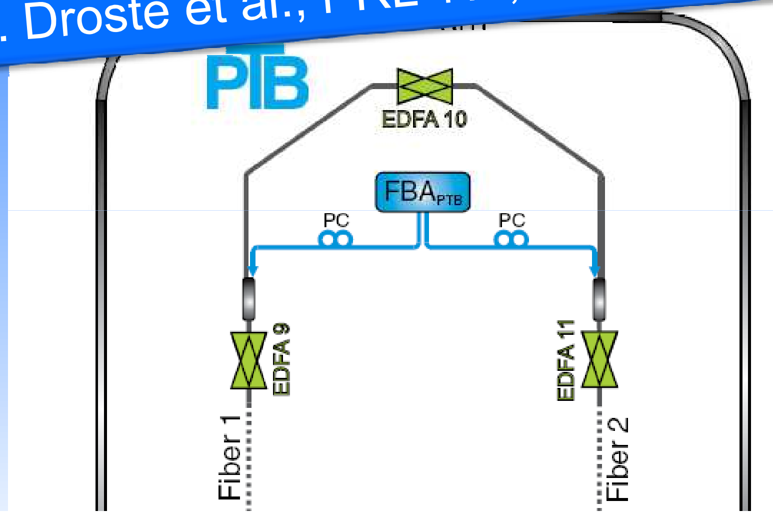
- 2 *dark* fibers (ITU-T G.652)
- Typical distance between shelters about 80 km → -20 dB
- Total fiber length 920 km
- Total one way loss >200 dB
- Access to the link at 9 station
- Operated fully bi-directional

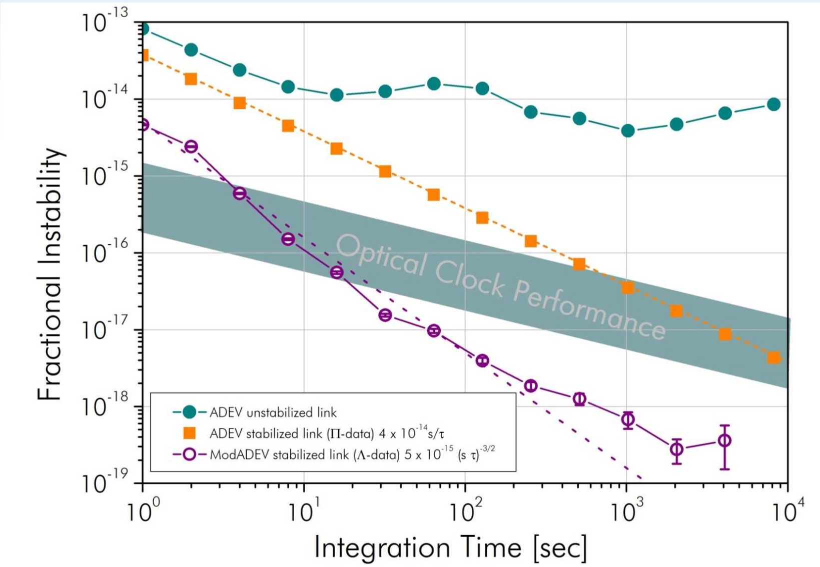
A link using a dedicated (dark) fiber

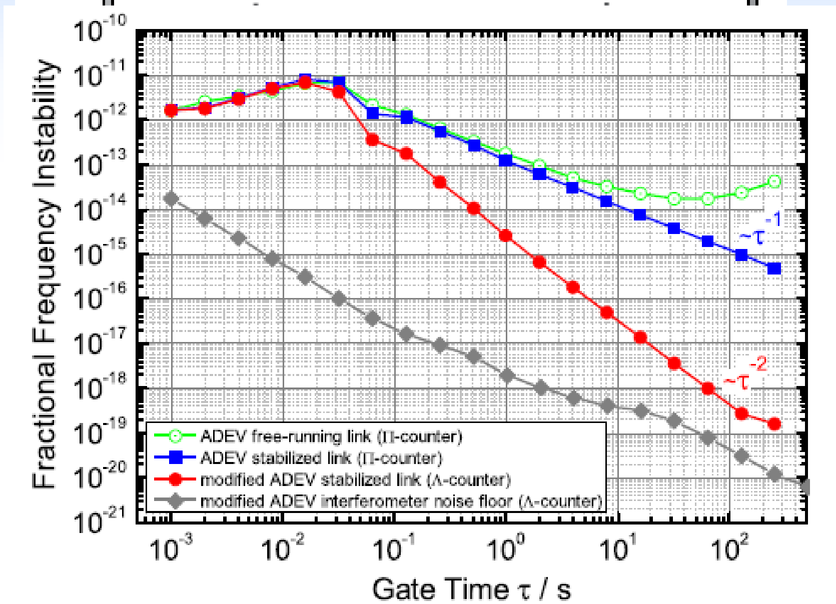
K. Predehl et al; Science 336 (2012) 441-444



S. Droste et al.; PRL 111,110801 (2013)







A link using a dedicated (dark) fiber

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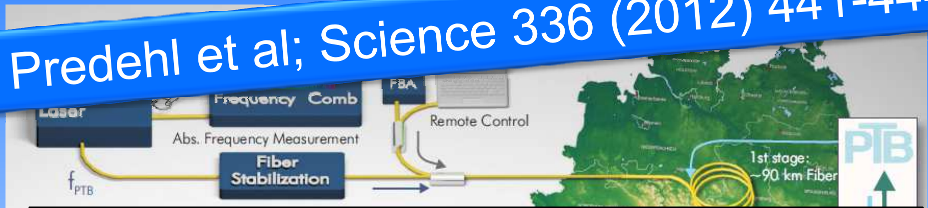
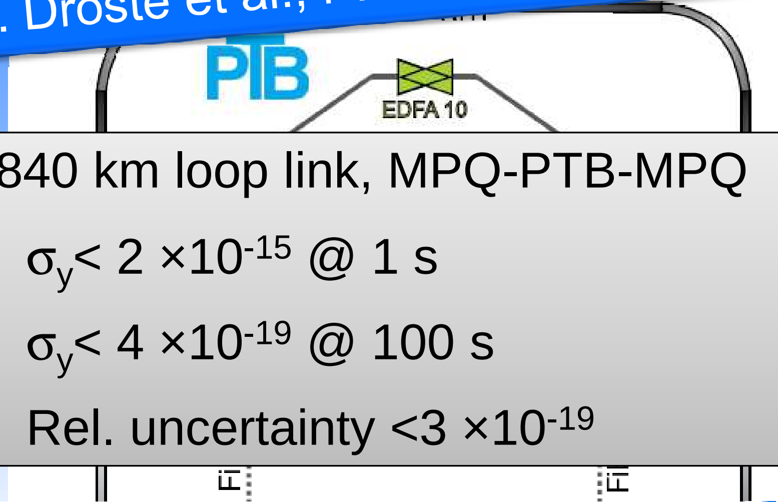


920 km loop link, PTB-MPQ

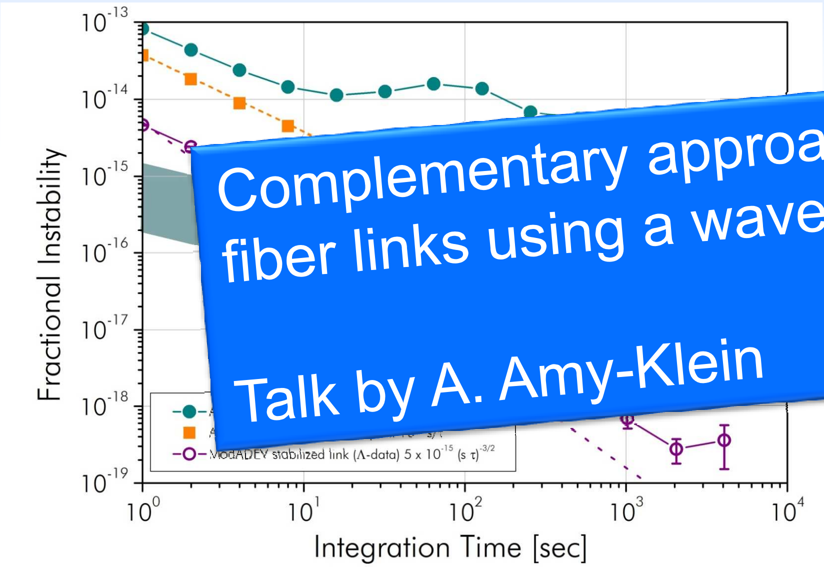
- $\sigma_y < 5 \times 10^{-15}$ @ 1 s
- $\sigma_y < 1 \times 10^{-18}$ @ 1000 s
- Rel. uncertainty <4 $\times 10^{-19}$

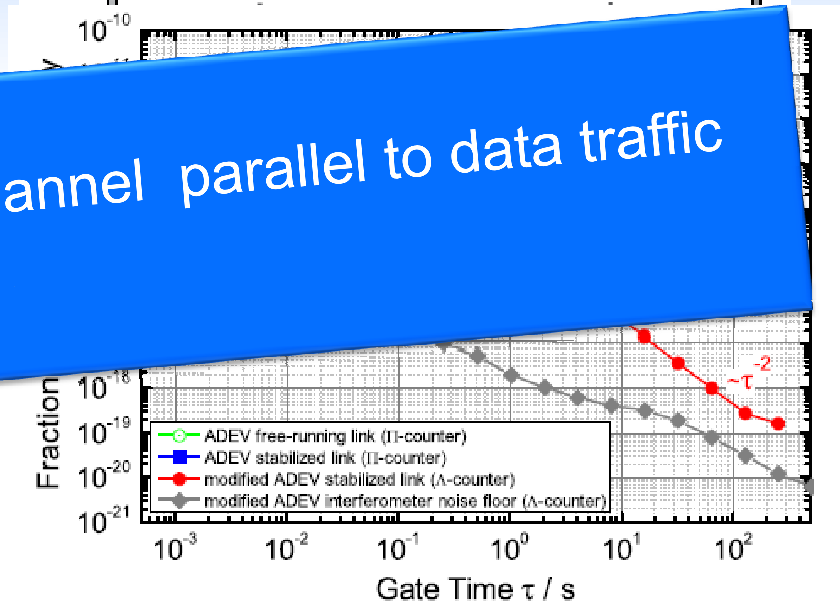
S. Droste et al.; PRL 111,110801 (2013)



1840 km loop link, MPQ-PTB-MPQ

- $\sigma_y < 2 \times 10^{-15}$ @ 1 s
- $\sigma_y < 4 \times 10^{-19}$ @ 100 s
- Rel. uncertainty <3 $\times 10^{-19}$





Complementary approach:
fiber links using a wavelength channel parallel to data traffic

Talk by A. Amy-Klein

NEAT-FT: a JRP of EMRP

JRP-Coordinator

PTB, Germany

Funded JRP-Participants

BEV,	Austria
INRiM,	Italy
MIKES,	Finland
NPL,	United Kingdom
OBSPARIS,	France
SP,	Sweden
UFE,	Czech Republic
VSL,	The Netherlands

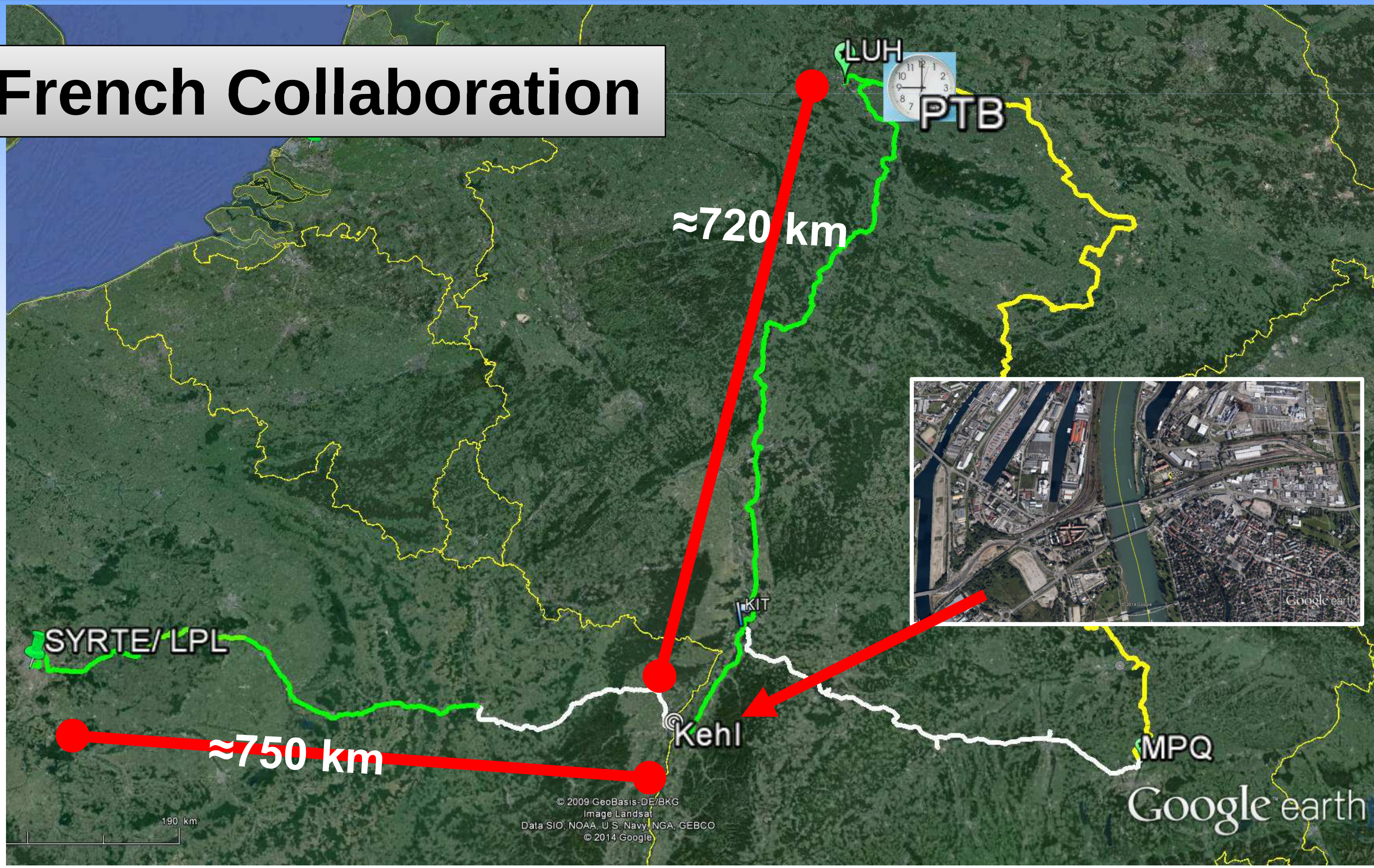
Unfunded JRP-Participants

CESNET, Czech Republic

Towards the first international frequency link

PTB, Braunschweig ← → LNE-SYRTE, Paris

A German-French Collaboration



l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

LPL
Laboratoire de physique des lasers

PTB

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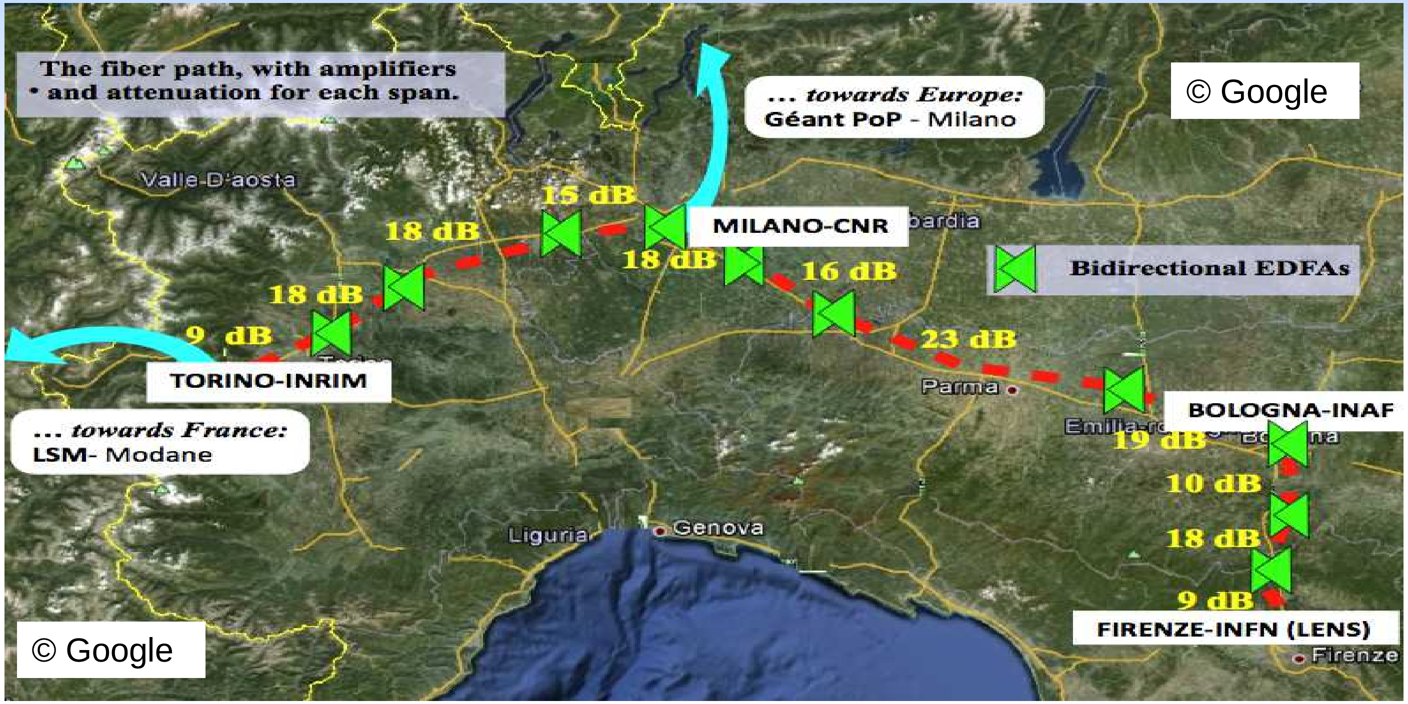
The Italian links: Modane-Torino- Firenze



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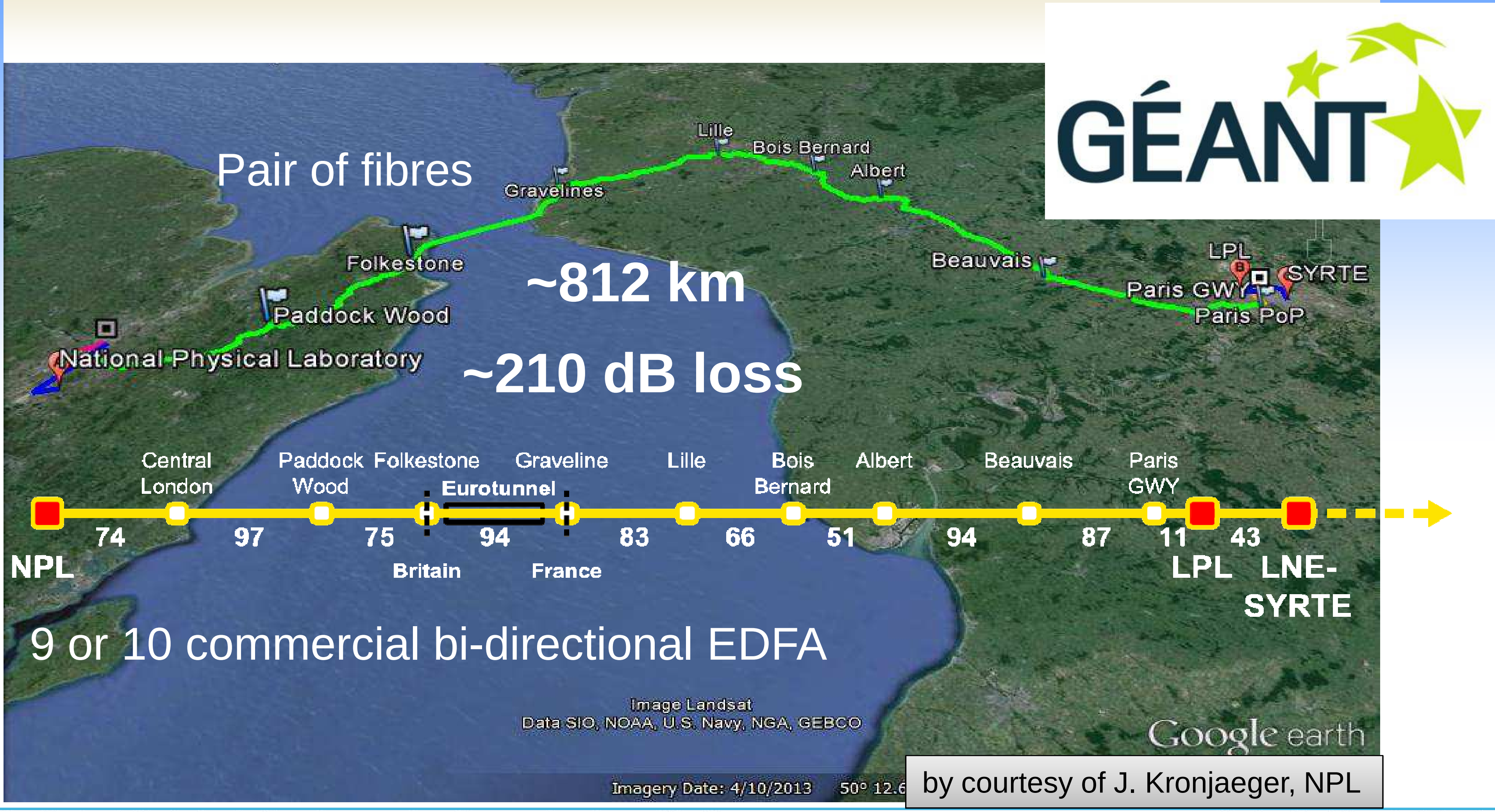
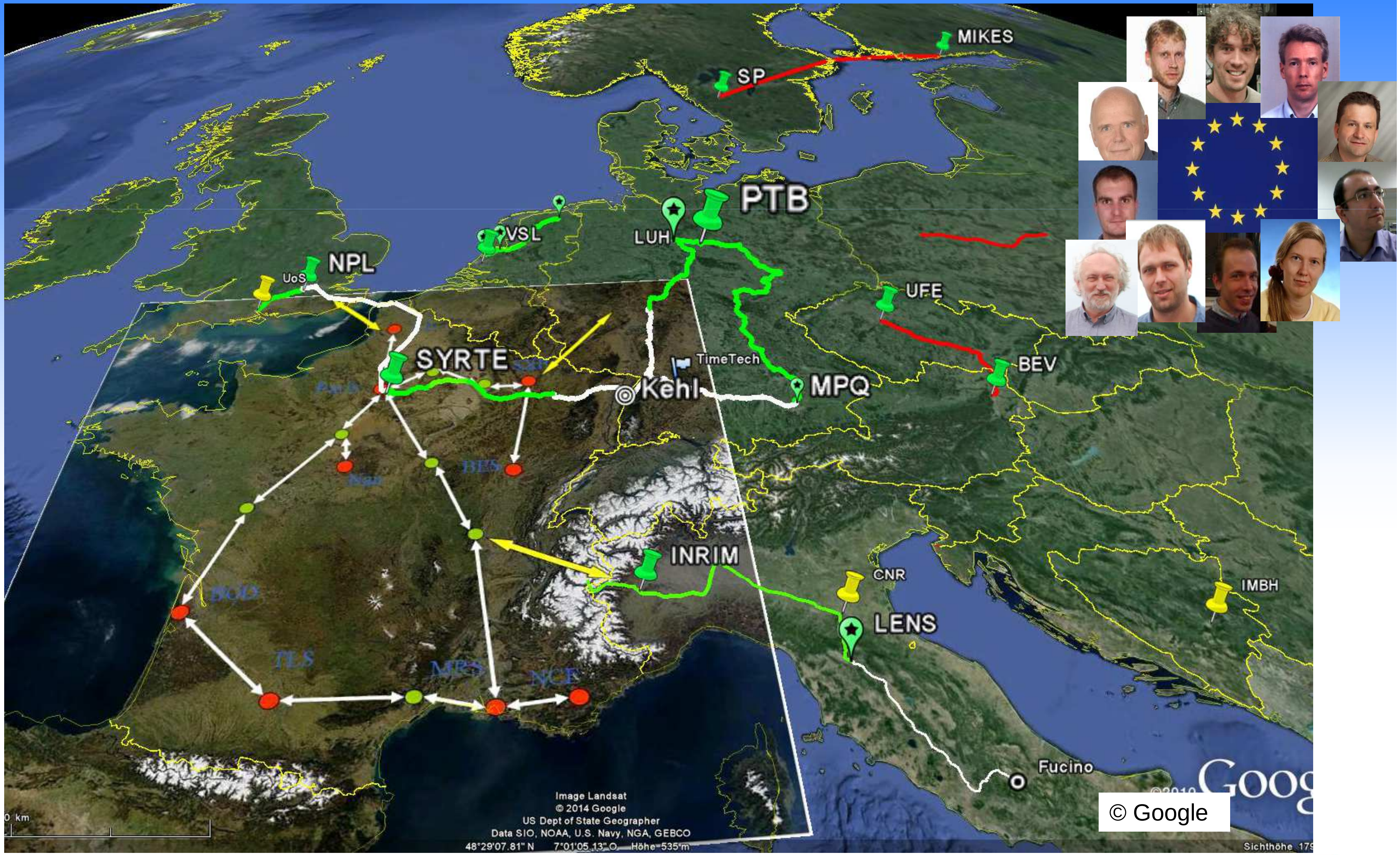
The London-Paris link

Fibre provided by European research and education network GÉANT



by courtesy of J. Kronjaeger, NPL

Fiber links: NEAT-FT & REFIMEVE



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Take home messages: Part I

- Optical clocks are superior to the best primary Cs clocks w/r to stability and accuracy.
- It can be expected that the improvements of the optical clocks will continue at least in the next decade.
- Advanced time and frequency transfer (ATFT) methods needed to realize the full potential of such clocks have been established.
- Demonstrated instability / uncertainty of fiber links are well below that of the best clocks.
- Fiber links connecting clocks at **N**ational **M**etrology **I**nstitutes, NMI, are in progress.

“Never measure anything but frequency!”

A. Schawlow’s advice to T. Hänsch

The transition frequency of an atom realized by an atomic clock is the most stable and precisely known physical quantity.

☞ **Once characterized clocks are ideal sensors to measure tiny effects with high precision.**

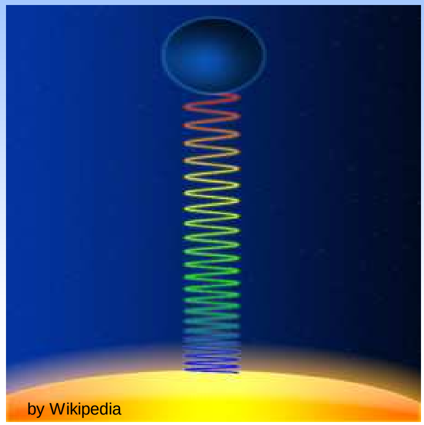
This mostly requires a frequency comparison between two clocks.

Gravitational potential	→	red shift
Grand Unification	→	are fundamental constants stable?

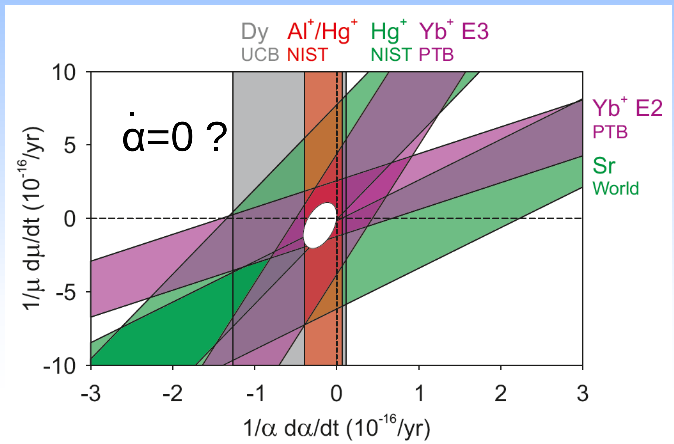
Who needs (better) clocks?

Precise tests of fundamental physics

Gravitational red shift

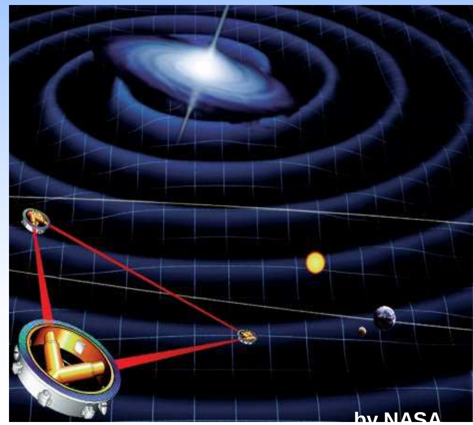


„Constancy“ of fundamental constants



N. Huntemann et al., arXiv:1407.4408

Gravitational wave detection



Tests of SRT

Fundamental constants

Tests of GRT

Redefinition of the “s”

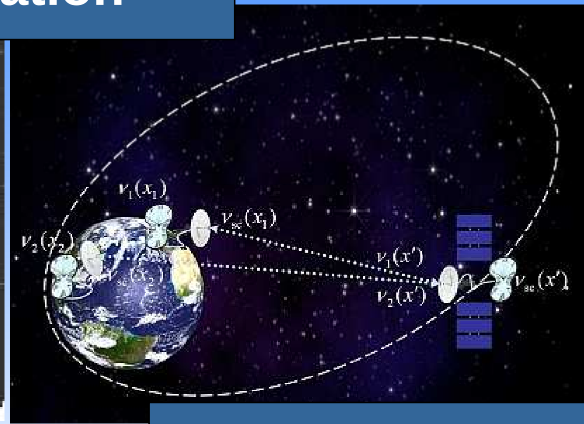
Dimensional Metrology

Who needs (better) clocks?

Astronomy

Navigation

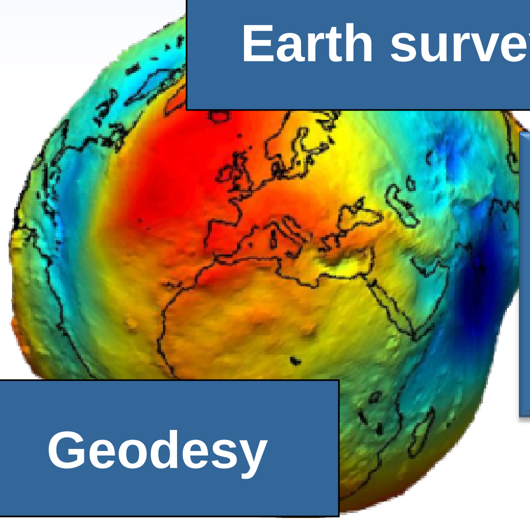
Galileo, GPS



SOC, STE-QUEST

Earth survey

Accelerators



Geodesy

seismics, natural resources , hydrological water inventory, melting of the polar ice caps

App 1: Relativistic Geodesy

1m height difference
between two clocks corresponds to a relative frequency shift of 10^{-16}

The frequency of a transportable Sr lattice clock (429 THz) at the Sphinx laboratory (3580m) at the Jungfraujoch would be upshifted by 150 Hz compared to a clock in Braunschweig (75 m).

$$\frac{f_{\mathrm{high}} - f_{\mathrm{ref}}}{f_{\mathrm{ref}}} \approx \frac{g}{c^2} \cdot \Delta h$$

Optical Clocks and Relativity,
C. W. Chou, et al, Science Vol. 329. no. 5999, pp. 1630 – 1633, (2010)

Proof of principle: Modane-Torino

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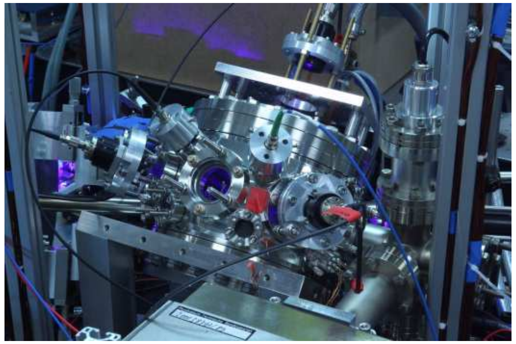
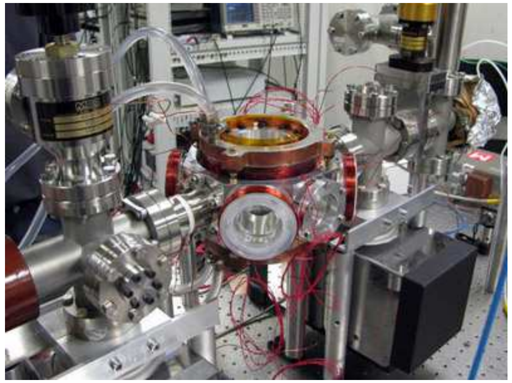
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

ITOC a European Project of the EMRP



portable
Sr lattice clock
PTB

stationary
Yb lattice clock
INRIM, Torino,
Italy

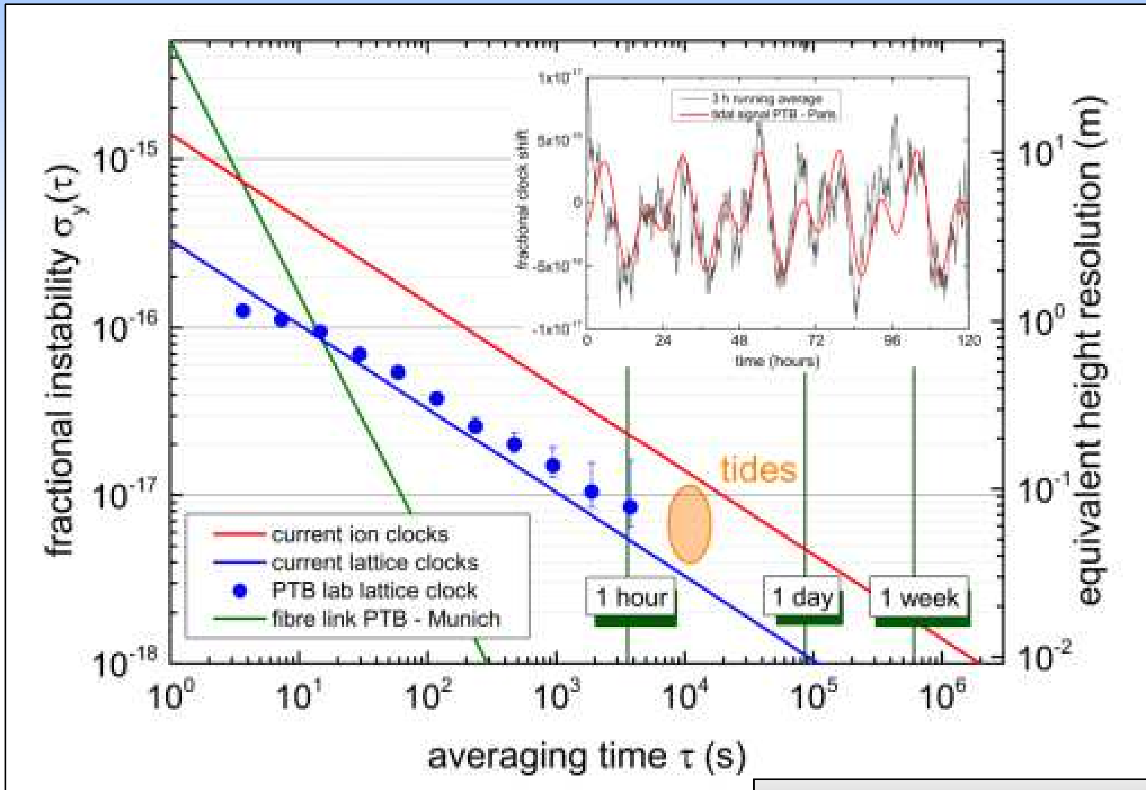


height difference 1000 m

$$\Delta\nu/\nu = 1 \times 10^{-13}$$

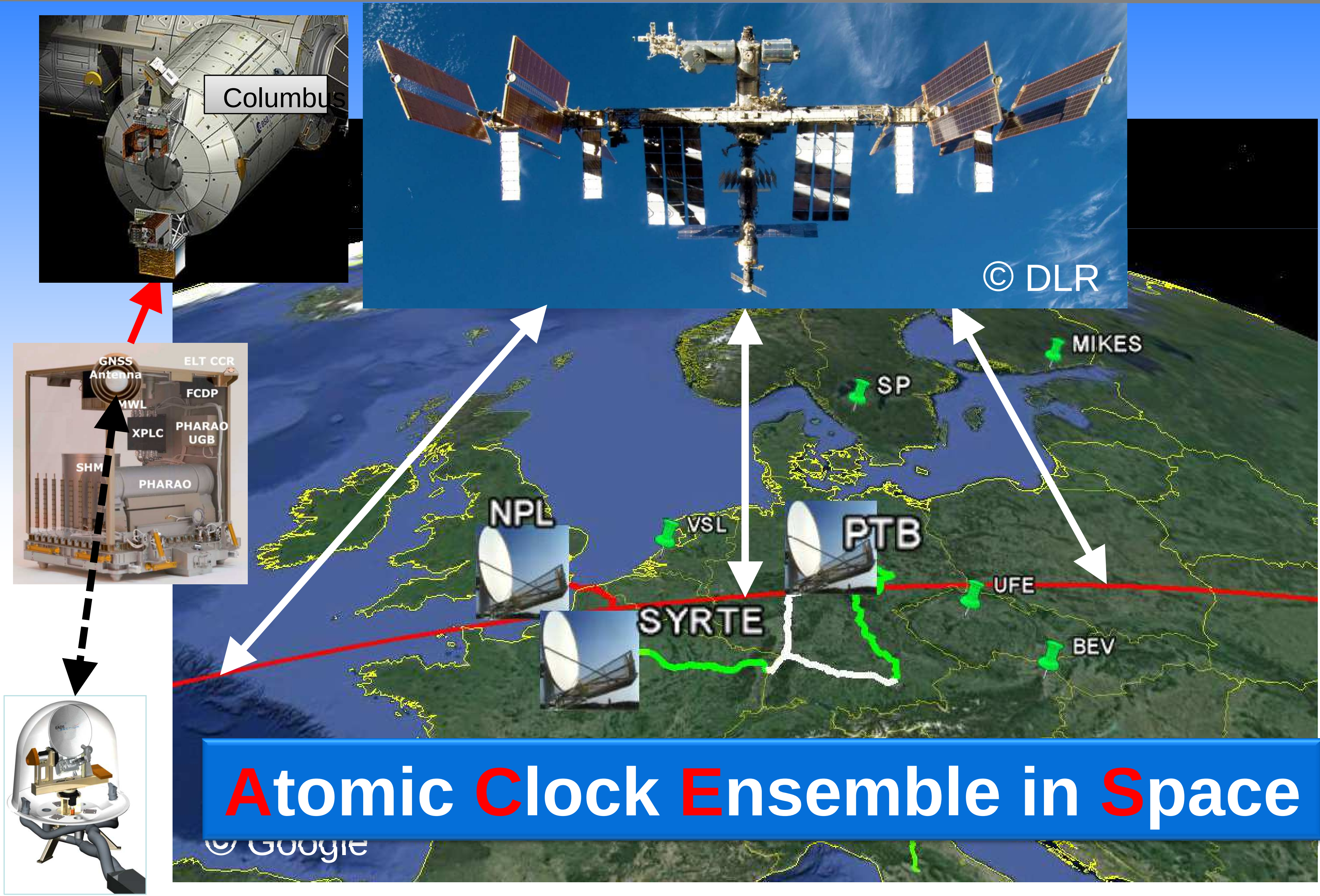
App 2: Observation of temporal variations

- Chronometric leveling with < 10 cm resolution (PTB/Paris)
- First observation of Tides
- Improvement of geodetic modeling



by courtesy of Piet Schmidt, QUEST

App 3: Compare clocks via ACES



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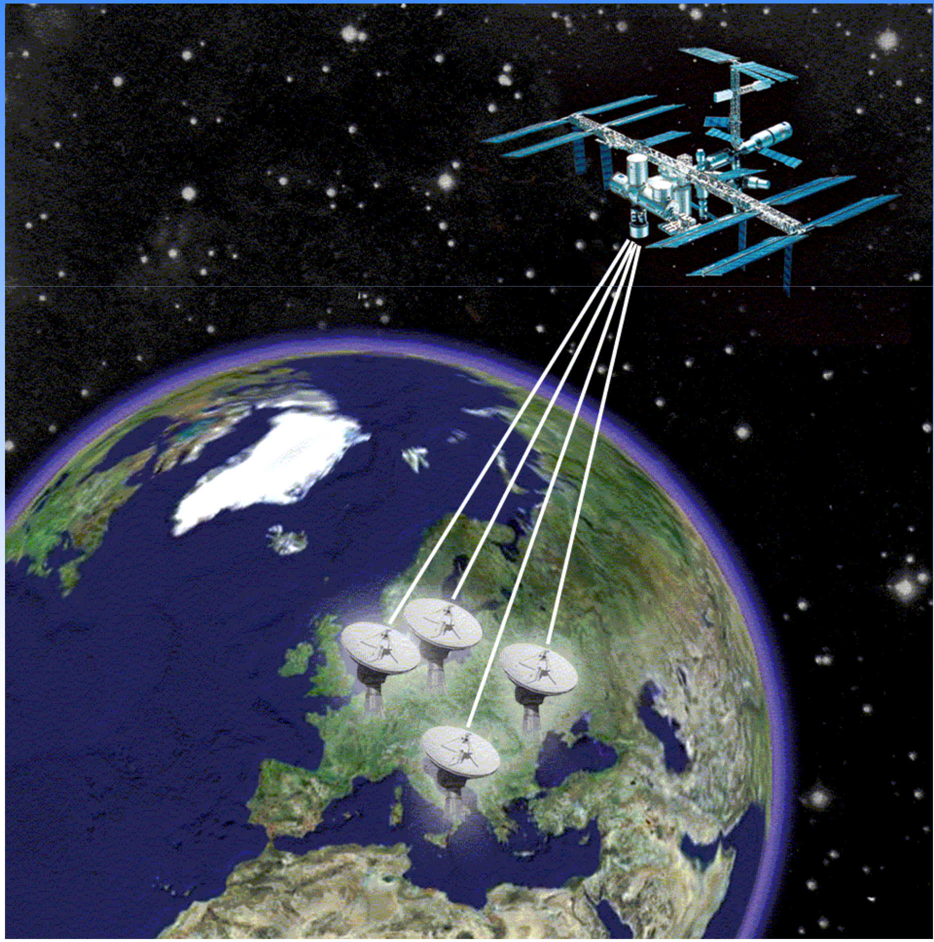
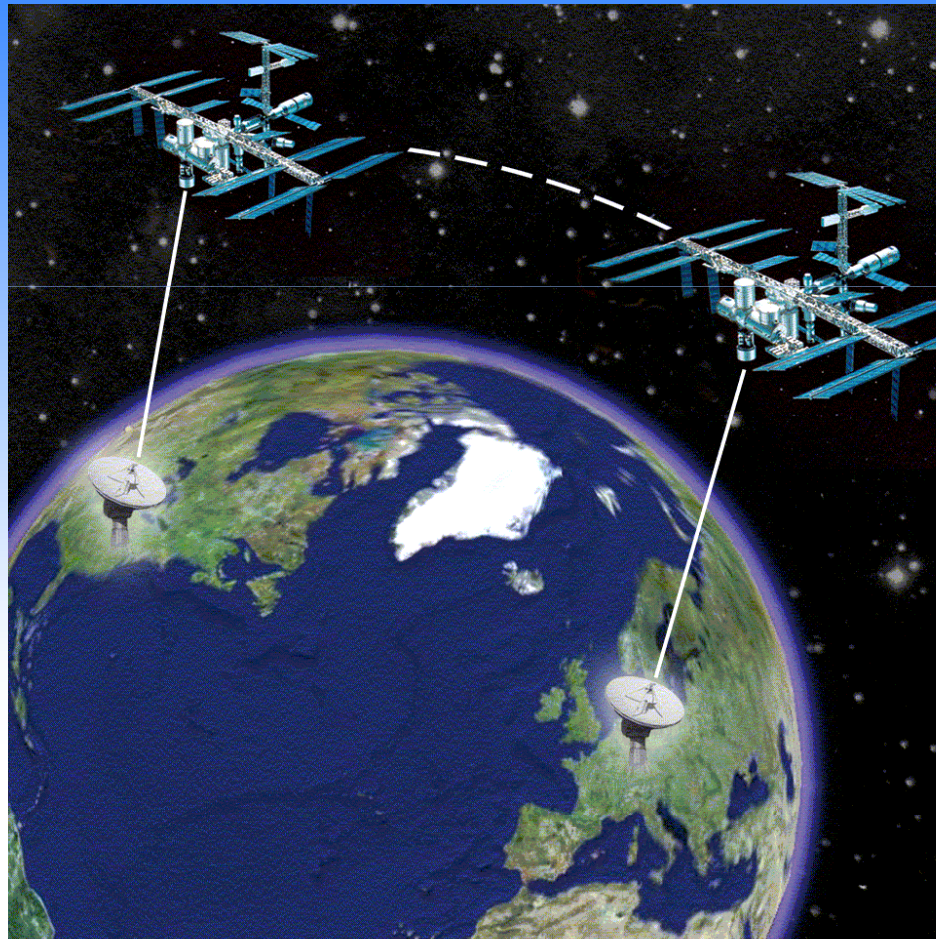
ACES MWL Time & Frequency Transfer





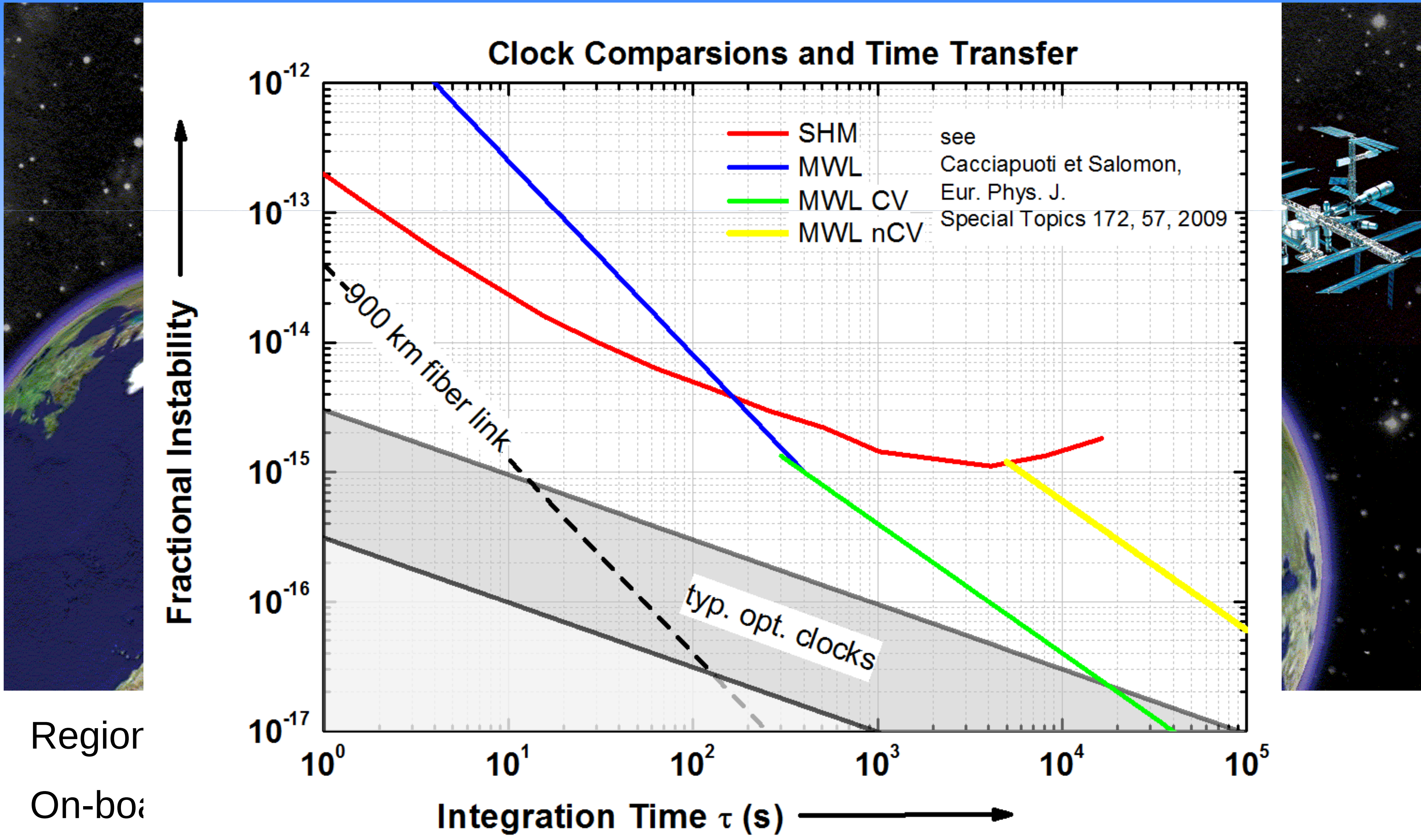
Regional: common view

On-board clock cancelled

Inter-continental

Relies on on-board clocks

ACES MWL Time & Frequency Transfer



Regior

On-boa

Take home messages: Part II

The combination of superior optical clocks and optical fiber links will allow for

- remote clock comparisons at the highest level, which will lead to a new definition of the SI second,
- measuring differences of the gravitational potential between remote sites with high spatial resolution,
- monitoring temporal variations of the gravitational differences, and
- to define the Geoid as proposed by Bjerhammar[1] in 1985.

"The relativistic geoid is the surface where precise clocks run with the same speed and the surface is nearest to mean sea level."

[1] A. Bjerhammar, On a relativistic geodesy ***Bull. Gdod. 59 (1985) pp. 207-220***

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Ekkehard Peik
Christian Sanner
Piet Schmidt
Christian Tamm
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