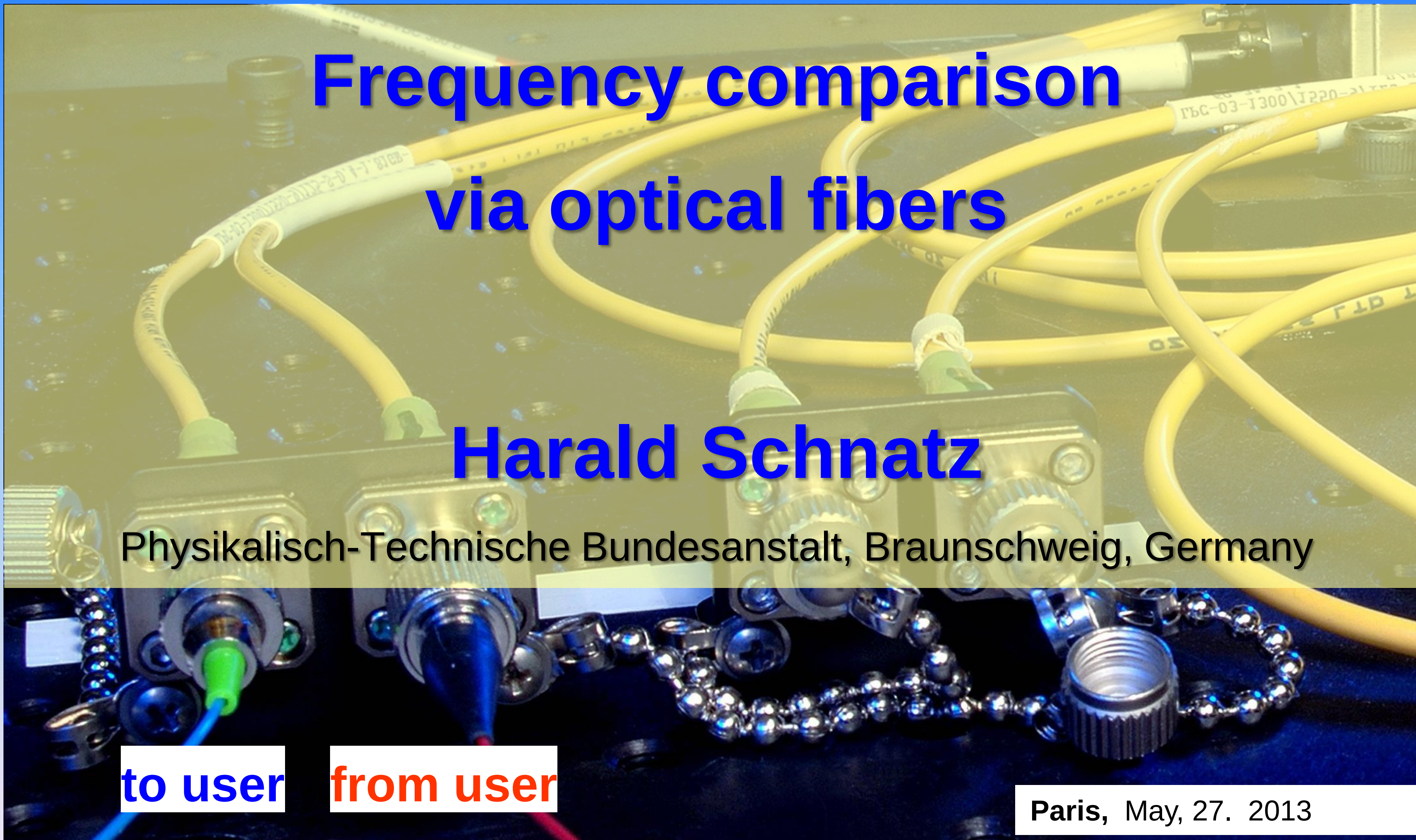
Frequency comparison via optical fibers

Harald Schnatz

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany



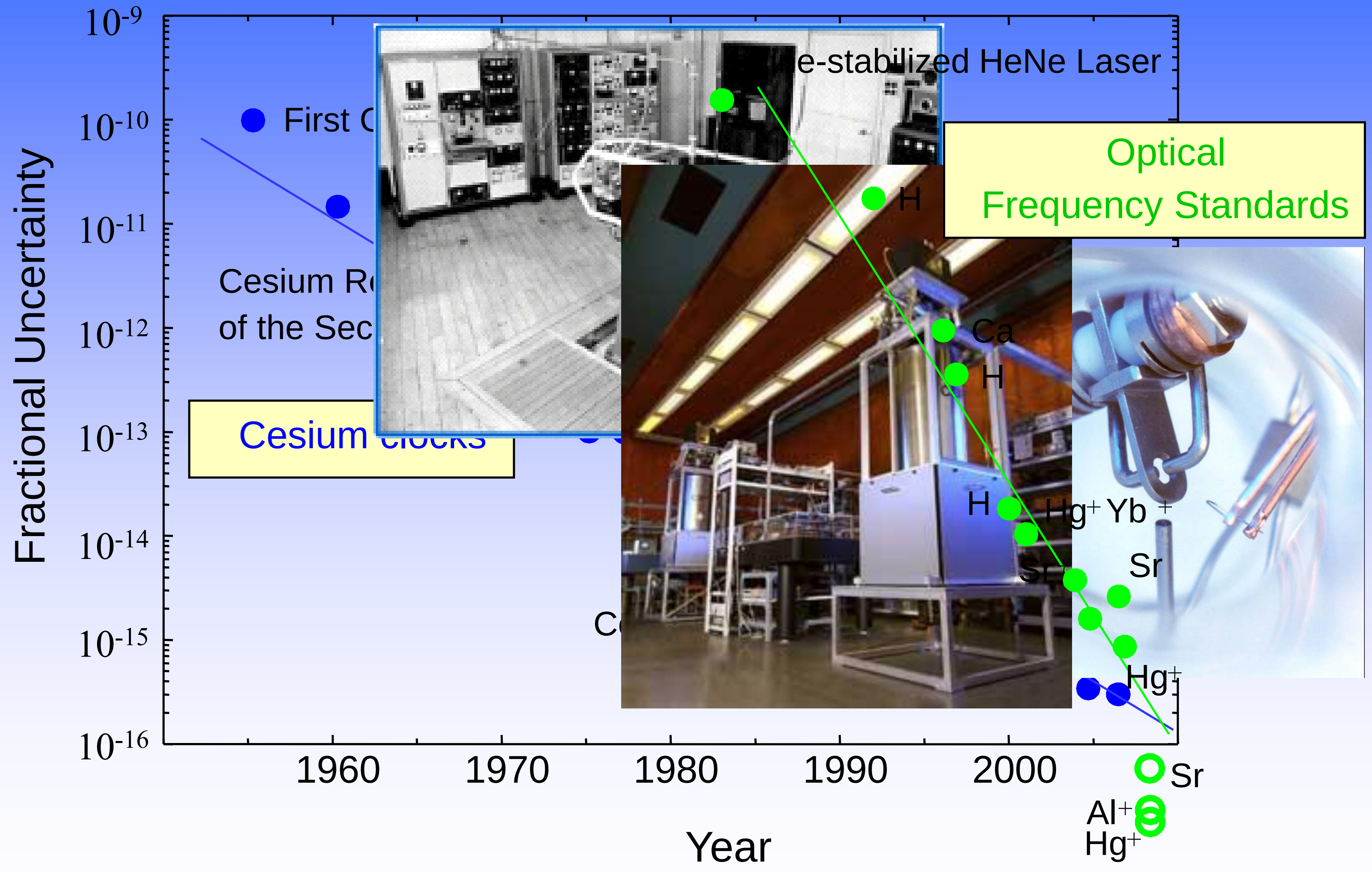
Paris, May, 27. 2013

Frequency comparison via optical fibers

PTB

- **Motivation**
- **Optical fiber links in a nutshell**
- **Frequency comparisons of optical clocks**
- **A future European network?**
- **Summary**

Uncertainty of optical and Cs clocks

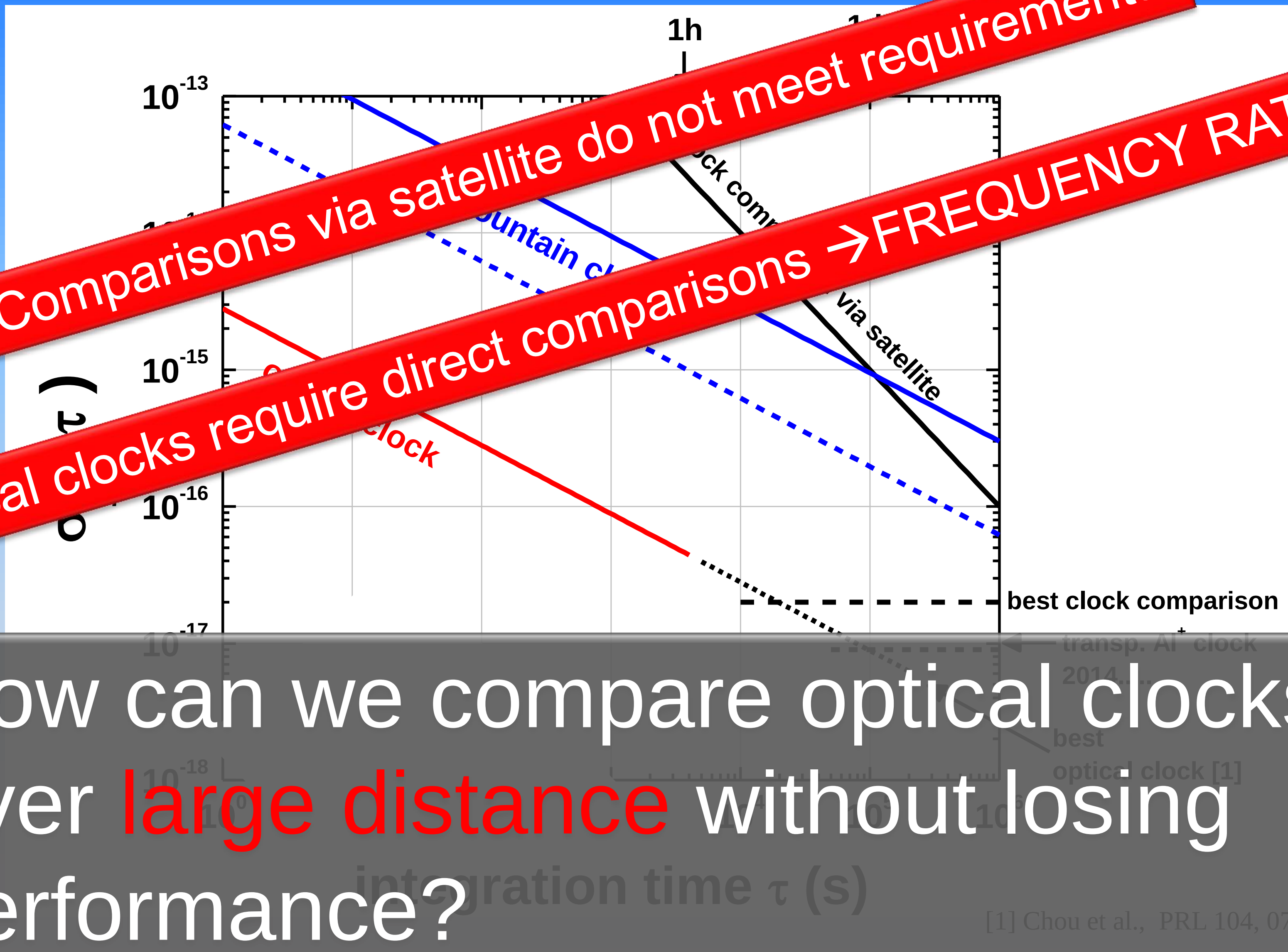


Why use (better) clocks?

PTB

- Clocks are ideal sensors to measure tiny effects with high precision.
- This mostly requires a frequency comparison between two clocks.

Clock comparison

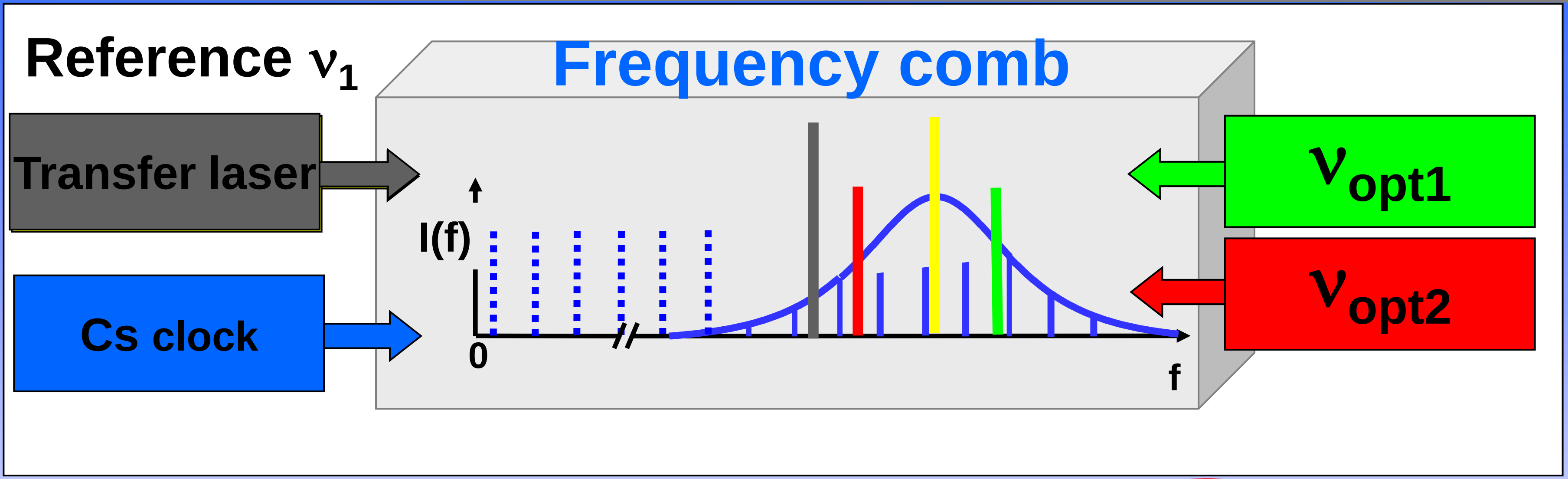


Comparisons via satellite do not meet requirements

Optical clocks require direct comparisons →FREQUENCY RATIO

How can we compare optical clocks over large distance without losing performance?

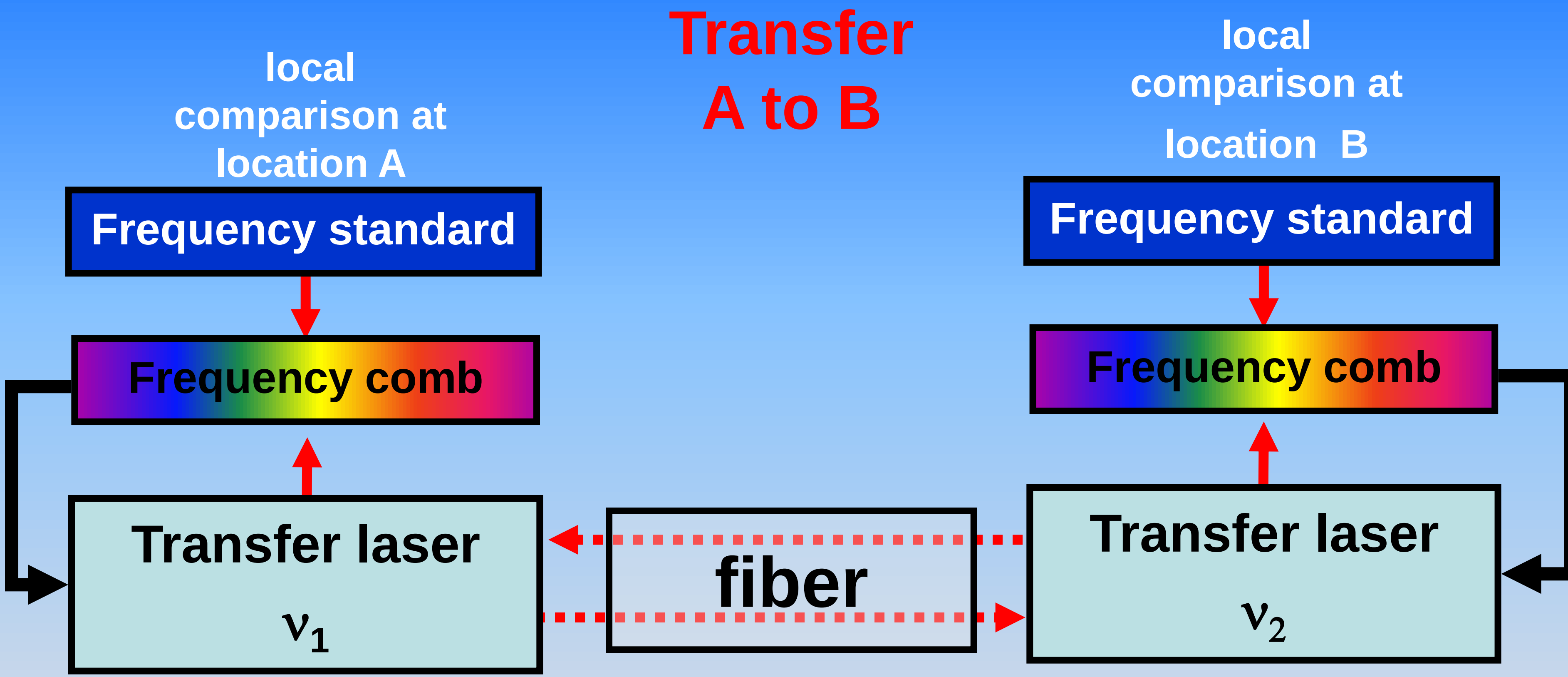
Local comparison of frequency standards



$$\frac{\nu_{opt1}(A)}{\nu_{opt2}(A)} = \left(\frac{\nu_{opt1}}{\nu_1}\right)_A \cdot \left(\frac{\nu_1}{\nu_{opt2}}\right)_A$$

local comparison versus common reference ν_1

TRANSFER of an OPTICAL CARRIER from location A to B



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

Technical requirements for optical link

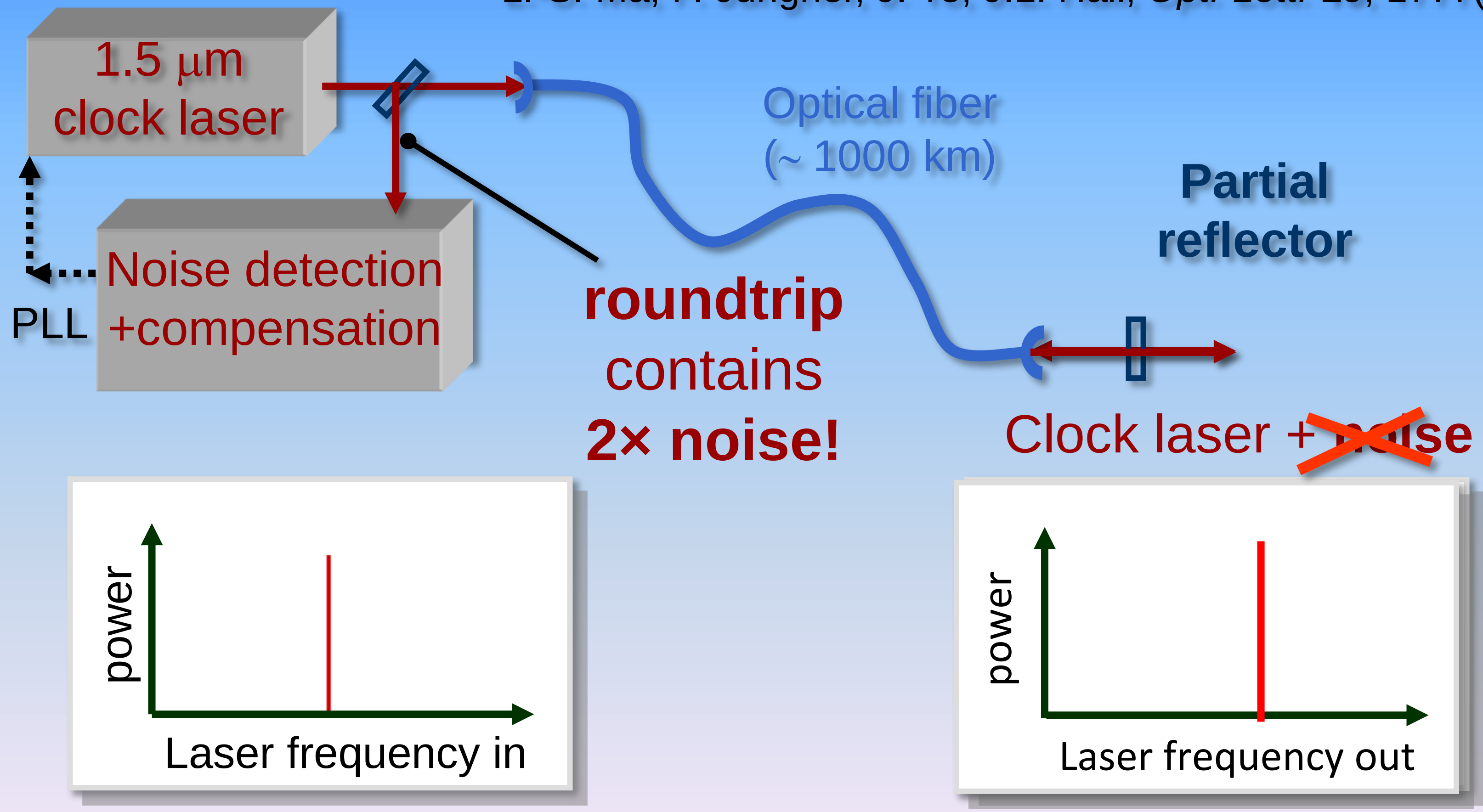
PTB

- Signal attenuation →
  select low loss fiber: 0.2 dB/km
  in-line bi-directional amplifiers: EDFA
- Stimulated Brillouin Scattering SBS →
  keep input power below threshold: 5 mW
- Coherence of transmitted frequency →
  use highly stable cw laser
- High isolation against environmental noise (thermal, acoustic, seismic, etc.) →
  use fiber buried under ground
- Optical path length changes ΔL →
  compensate ΔL by Δf using AO frequency shifter

Fiber Noise Cancelation

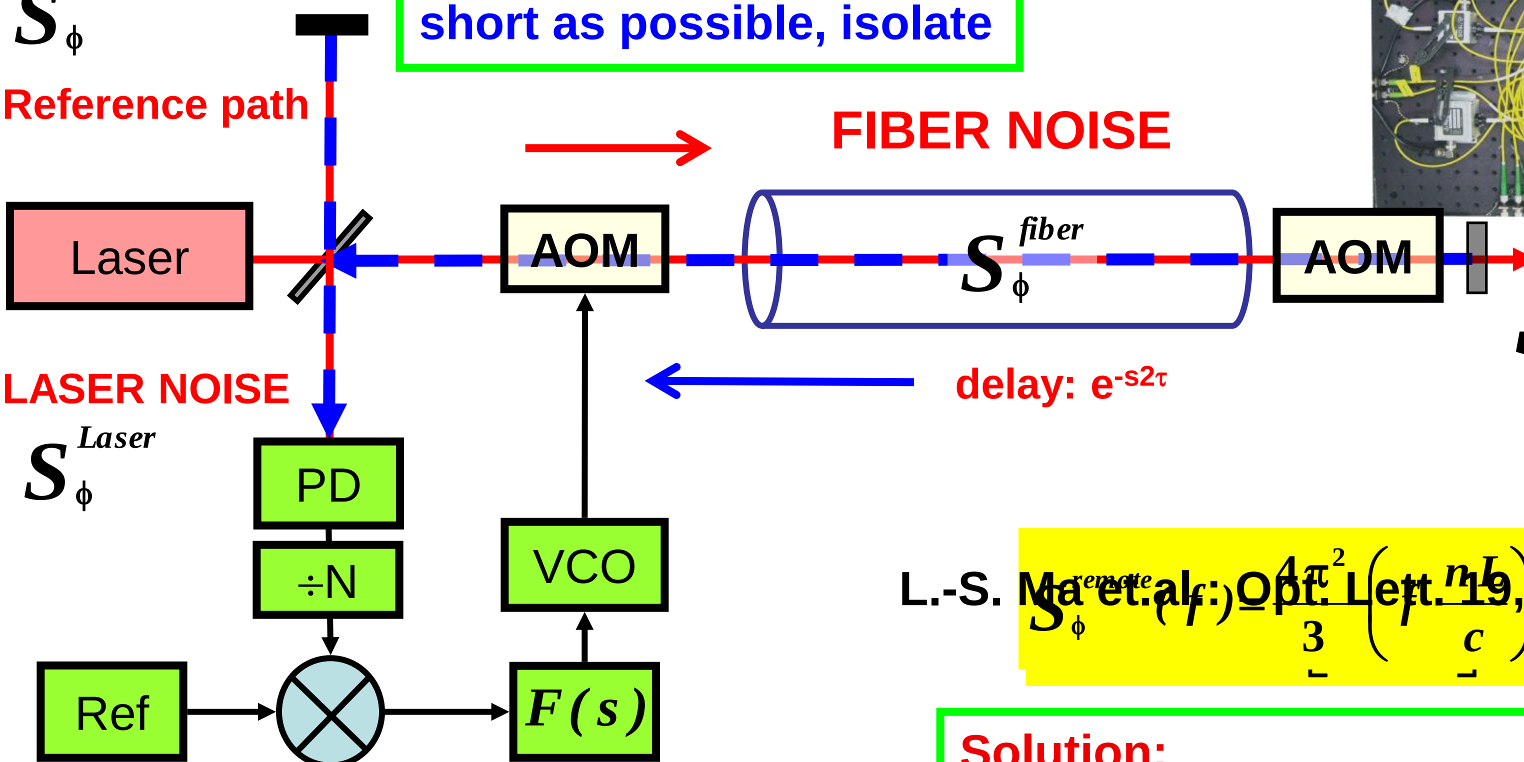
Compensation of frequency fluctuations due to length fluctuations:*

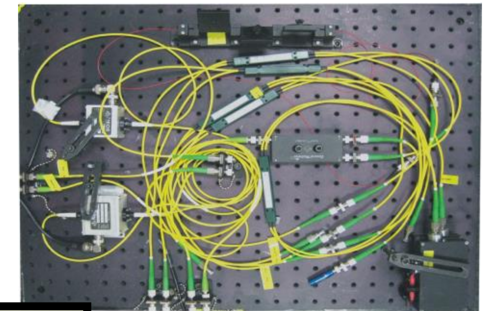
*L.-S. Ma, P. Jungner, J. Ye, J.L. Hall, *Opt. Lett.* **19**, 1777(1994)



Fiber Noise Cancelation

Solution:
short as possible, isolate





$$S_\phi^{remote}(f) = \frac{4\pi^2}{3}\left(f\frac{nL}{c}\right)^2 S_\phi^{fiber}(f)$$

L.-S. Ma et al.: Opt. Lett. 19, 1777, 1994

Solution:
Avoid “noisy” links / divide total link

Solution:
Stabilize laser, so that the coherence length > twice the length of fiber

[1] Williams *et al.*, JOSA B25,1284 (2008)

Noise Cancelation Limit

PTB

Limited by:

1. Laser noise
2. Out of loop fiber
3. Delay unsuppressed fiber noise

$$S_\Phi^{remote}(f) = \frac{4\pi^2}{3} \cdot \left[f \cdot \frac{nL}{c} \right]^2 \cdot S_\Phi^{fiber}(f)$$

P. A. Williams et al., *J Opt. Soc. Am. B* ***25*** , 1284 (2008)

Assuming:

$$S_\Phi^{fiber}(f, L) \propto L \quad \Rightarrow$$

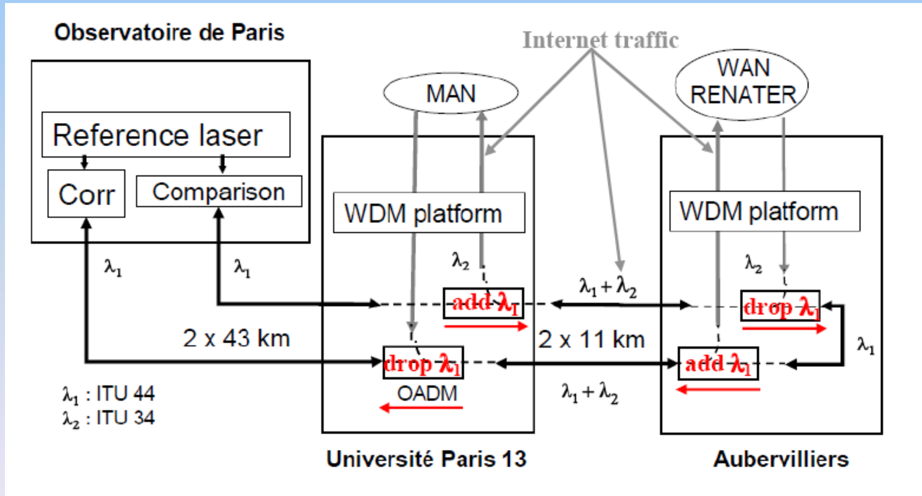
$$S_\Phi^{remote}(f, L) \propto L^3$$

$$ADEV(D,\tau) \approx 2 \cdot \times 10^{-14} \times \sqrt{\left(D / 480\,km \right)^3 \cdot 1/\tau}$$

Frequency dissemination: two approaches

- Network with Data transmission
- **parallel to data traffic**
- requires:
- Access to the same “dark channel” in two fibers of the same bundle
- Bi-directional in-line amplifiers
- Additional channel for remote control

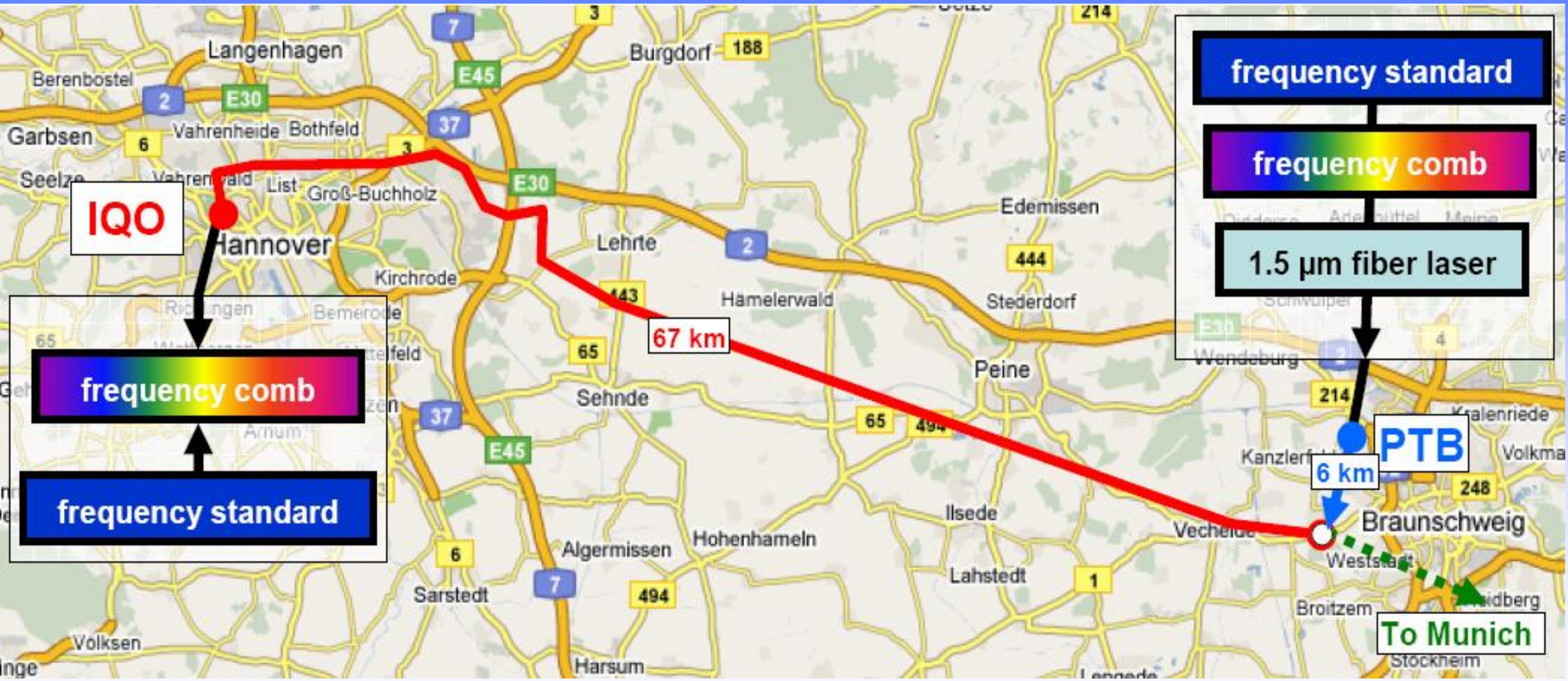
- “Dark Fiber”
- **Single user**
- requires :
- Access to the same “dark channel” in two fibers of the same bundle
- Bi-directional in-line amplifiers
- remote control (same fiber 1.3µm)



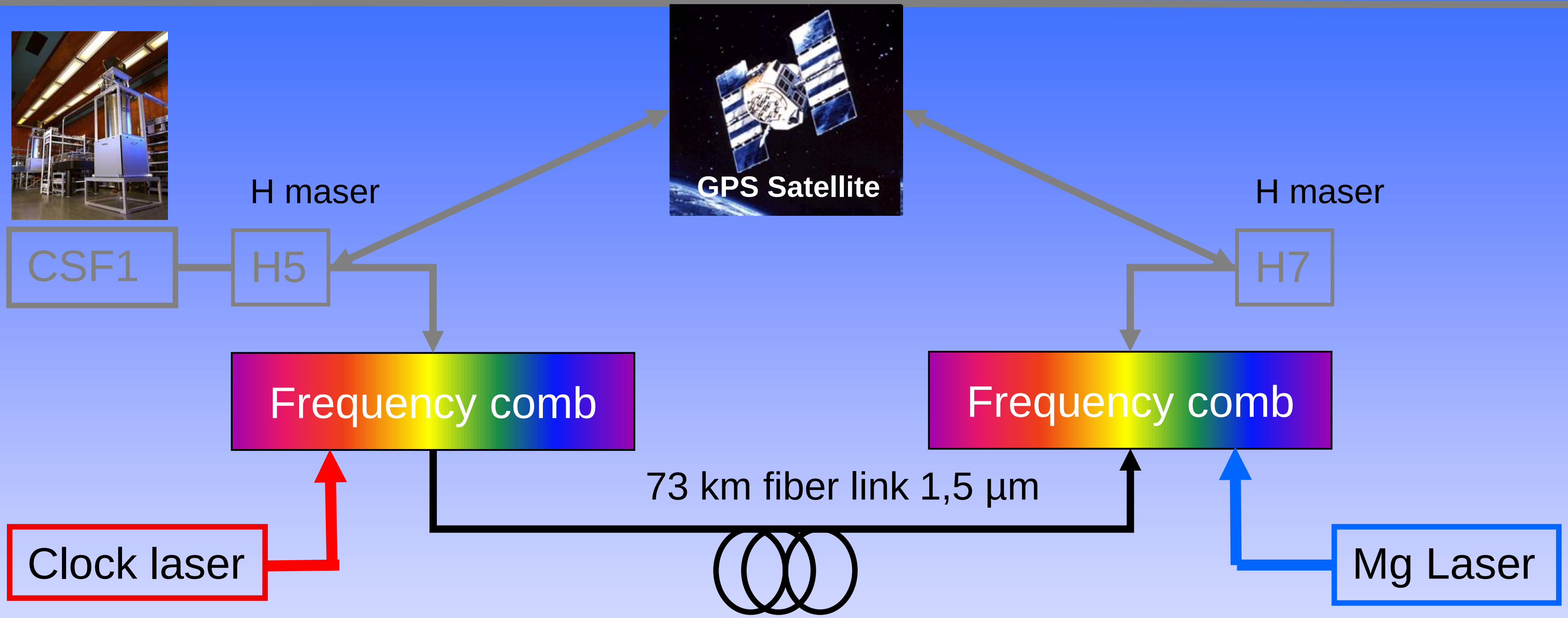
Kéfélian, et al. Opt. Lett 34, 1573, (2009)

A. Pape etal., OPTICS EXPRESS 18, 21477 (2010)

Evaluation of a Mg frequency standard



Clock laser comparison



Absolute frequency →

$$\frac{\nu_{Mg}}{\nu_{CSF1}} = \left(\frac{\nu_{Mg}}{\nu_{H7}}\cdot\frac{\nu_{H7}}{\nu_{NIR}}\right)_{IQO}\cdot\left(\frac{\nu^{IQO}_{NIR}}{\nu^{PTB}_{NIR}}\right)\cdot\left(\frac{\nu_{NIR}}{\nu_{H5}}\cdot\frac{\nu_{H5}}{\nu_{CSF1}}\right)_{PTB}$$

Stability →

$$\frac{\nu_{Mg}(t)}{\nu_{CL}(t)} = \left(\frac{\nu_{Mg}(t)}{\nu_{NIR}(t)}\right)_{IQO}\cdot\left(\frac{\nu^{IQO}_{NIR}(t)}{\nu^{PTB}_{NIR}(t)}\right)\cdot\left(\frac{\nu_{NIR}(t)}{\nu_{CL}(t)}\right)_{PTB}$$

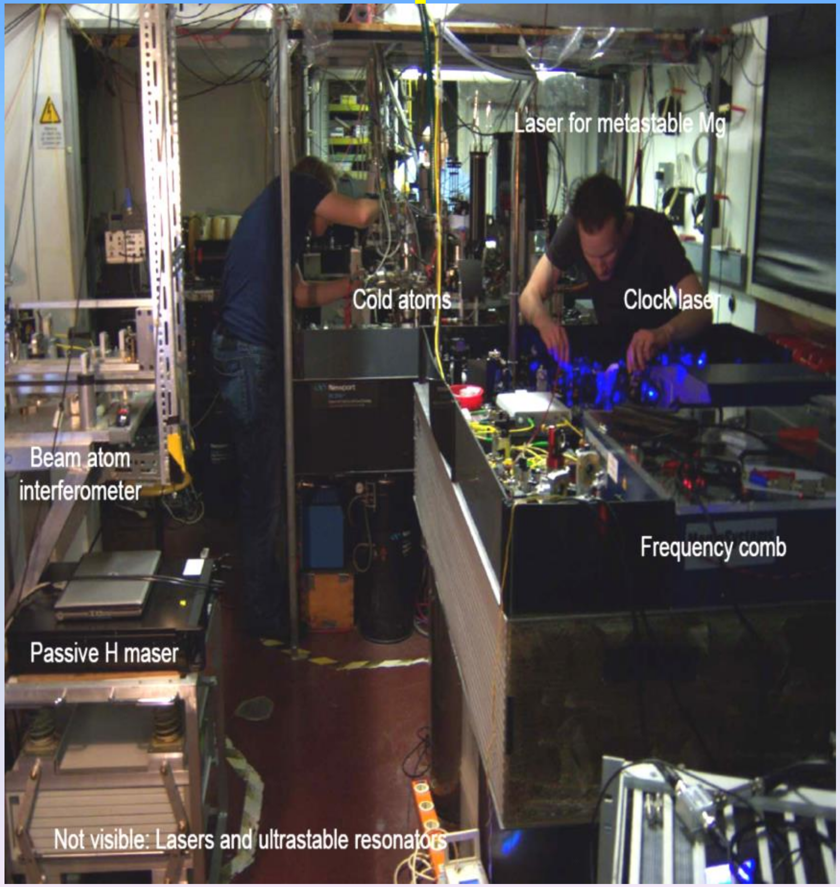
Improving an optical clock laser

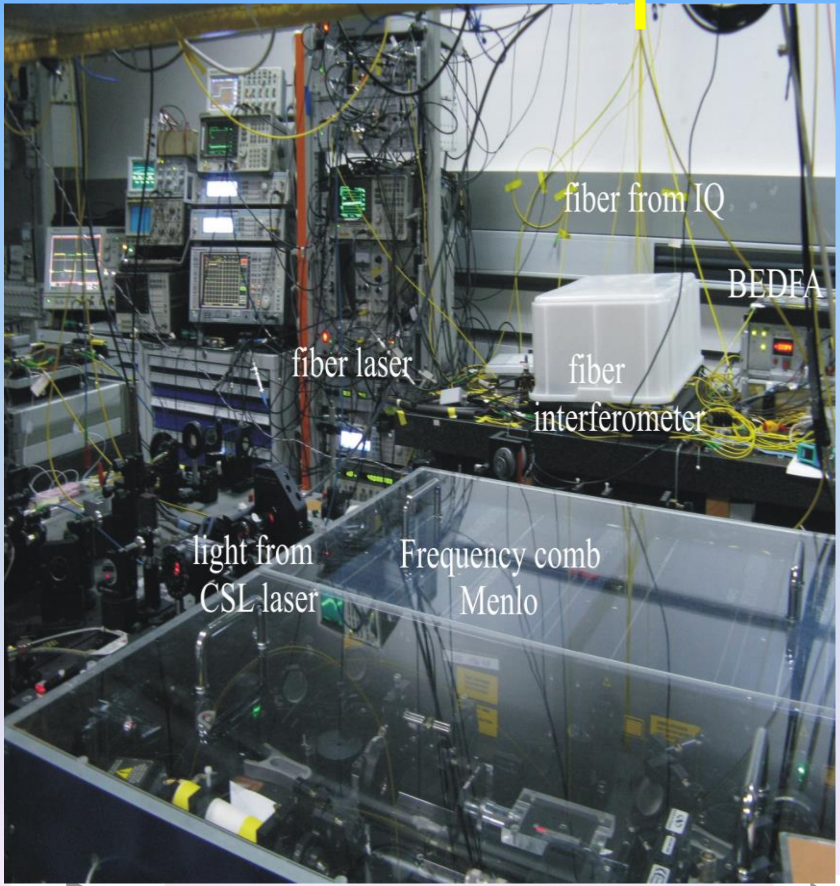
Mg-clock at IQ, LUH

PTB, Braunschweig

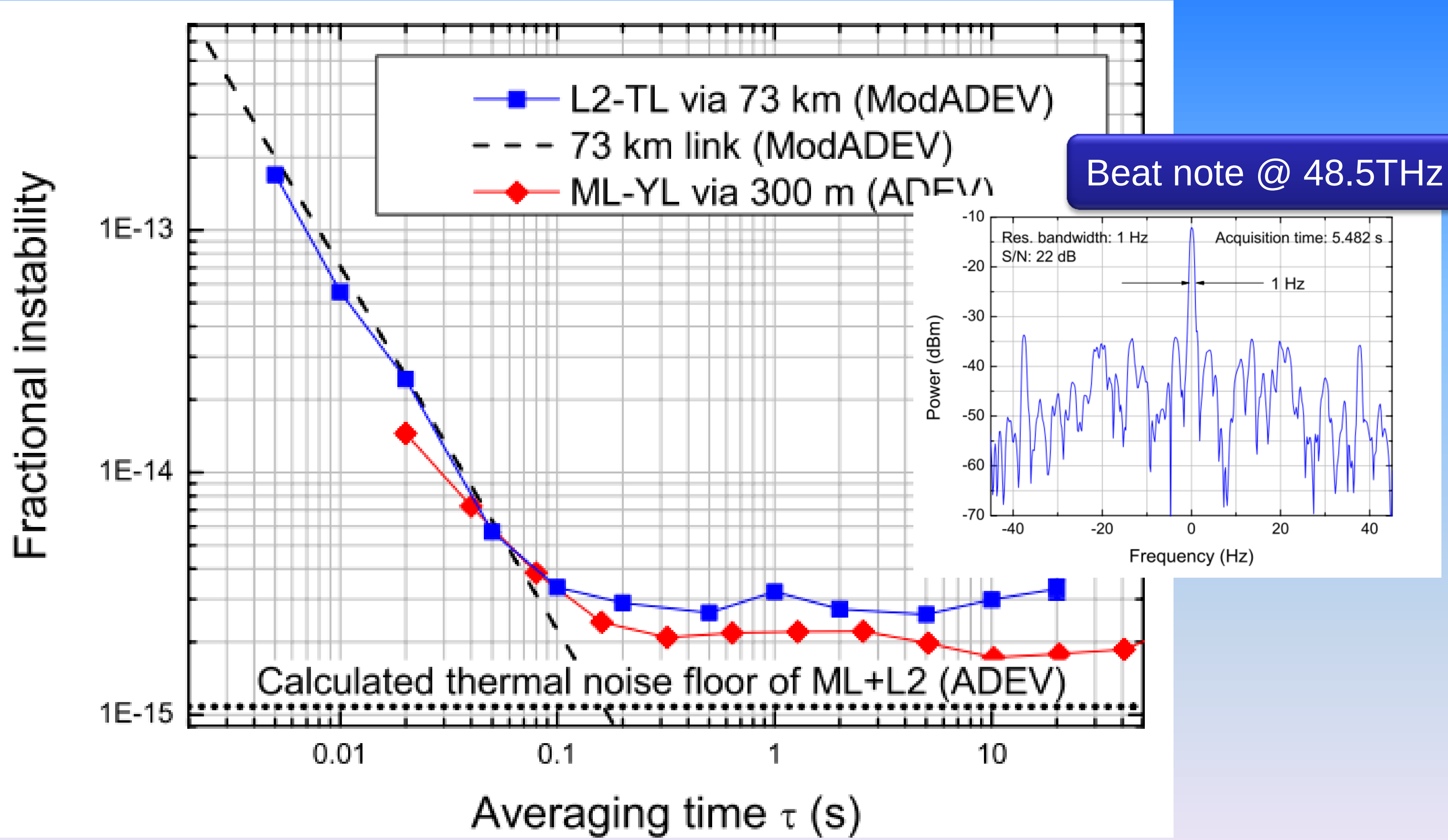
74 km

Fiber from PTB





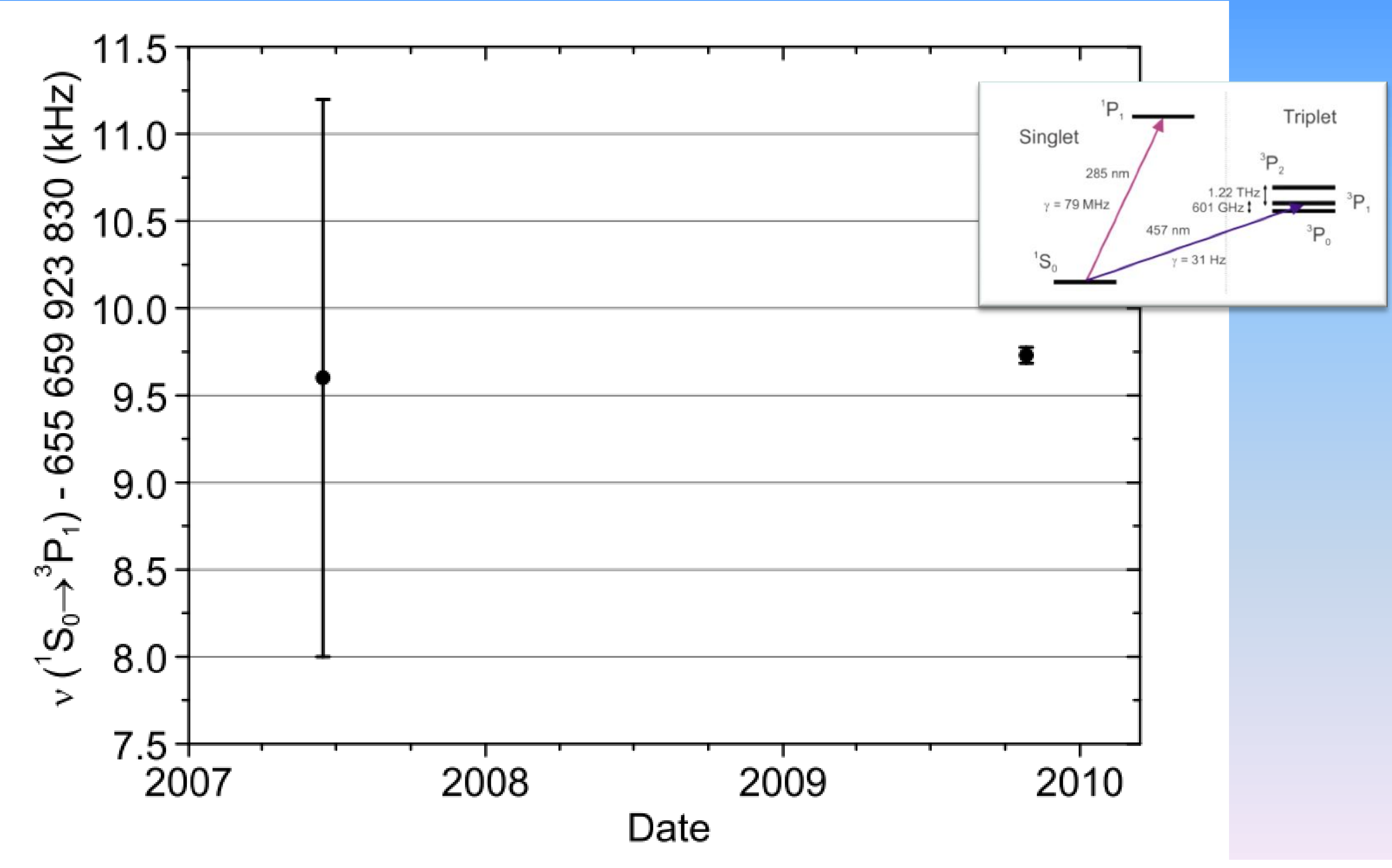
Characterization of remote clock laser



A. Pape etal., OPTICS EXPRESS 18, 21477 (2010)

$^1S_0 \rightarrow {}^3P_1$ clock transition of ^{24}Mg vs. remote CSF1

$$\nu(^{24}\mathrm{Mg} : {}^1S_0 \rightarrow {}^3P_1) = 655\,659\,923\,839\,730\ (48)\ \mathrm{Hz}.$$



J. Friebe et al., New Journal of Physics 13,125010 (2011)

Some details of the 920 km link

- 2 *dark* fibers (ITU-T G.652)

  n ~ 1.4681 at 1550 nm

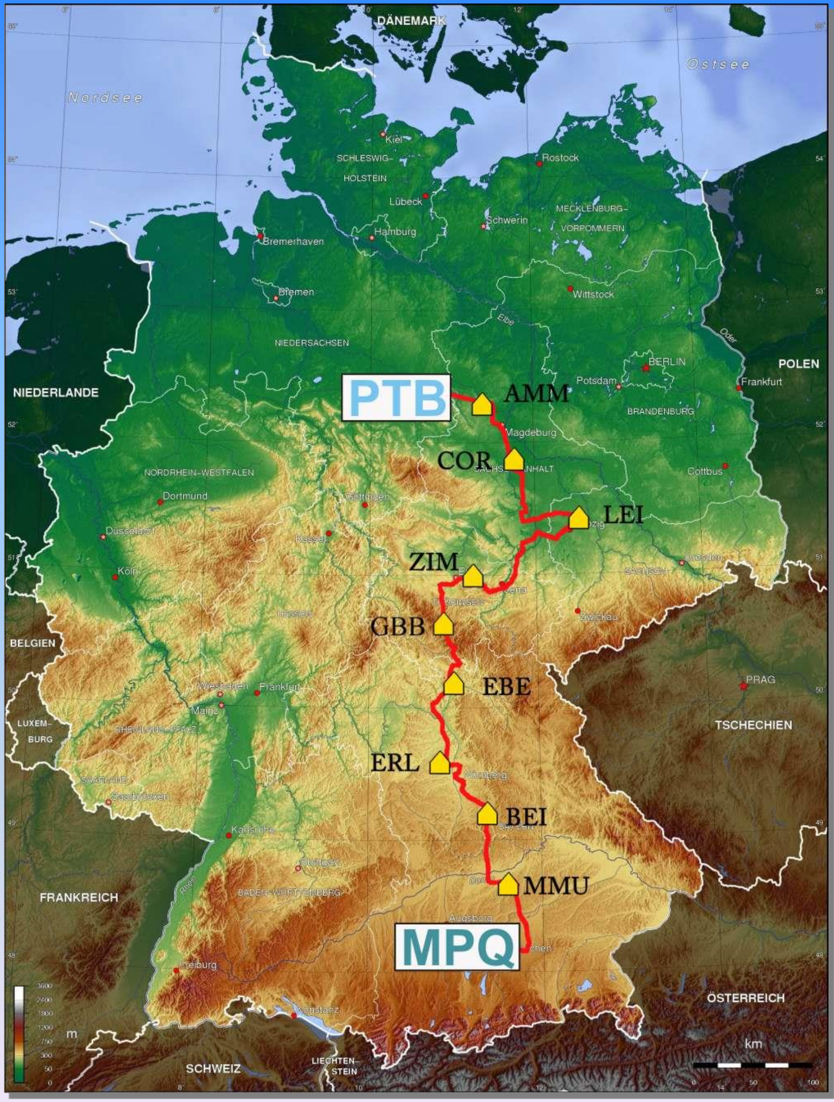
  A~ 0.23 dB/km

  CD~18 ps/(nmkm)

DFN Deutsches Forschungsnetz

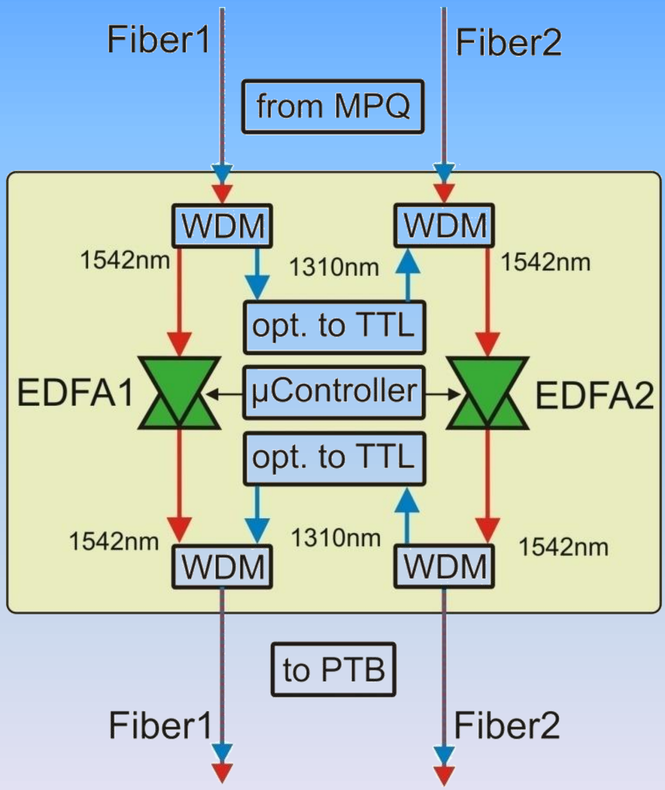
GasLINE

- Total fiber length 920 km
- Total one way loss >200 dB
- Access to the link at
  - 7 telecom containers
  - 2 computing centers



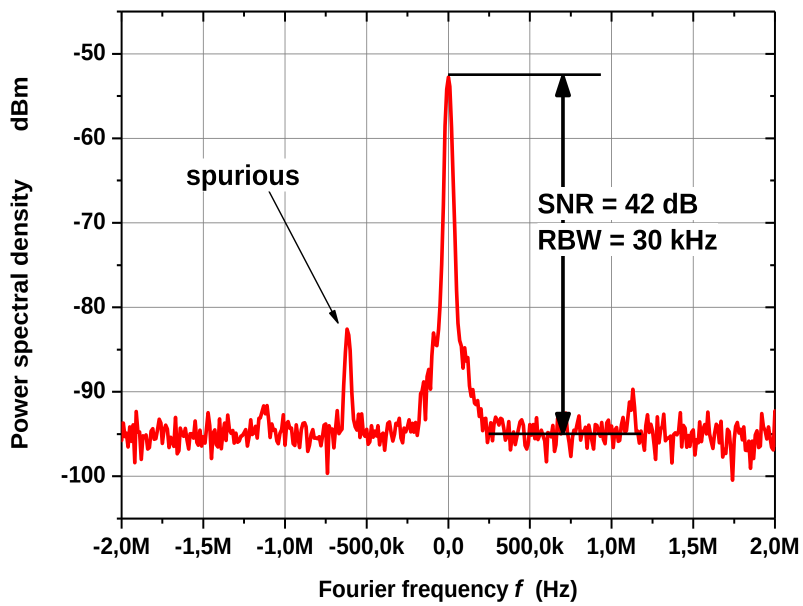
Bi-directional amplifiers - EDFA

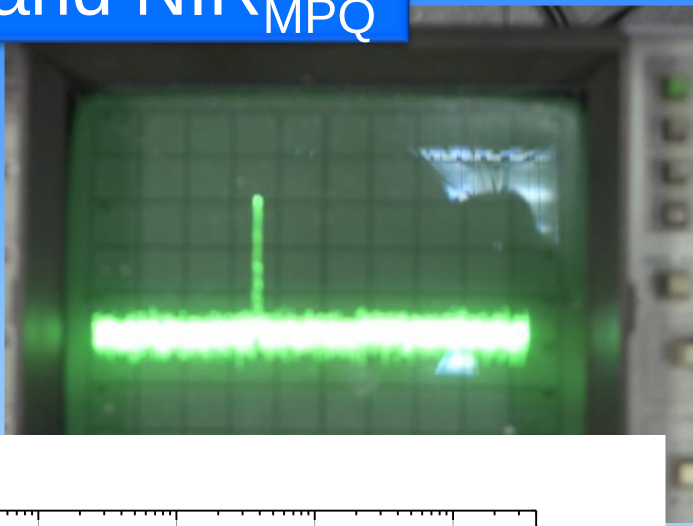
- Communicate with 16 bi-directional EDFAs along the fibre link via 1310 nm modulated signal

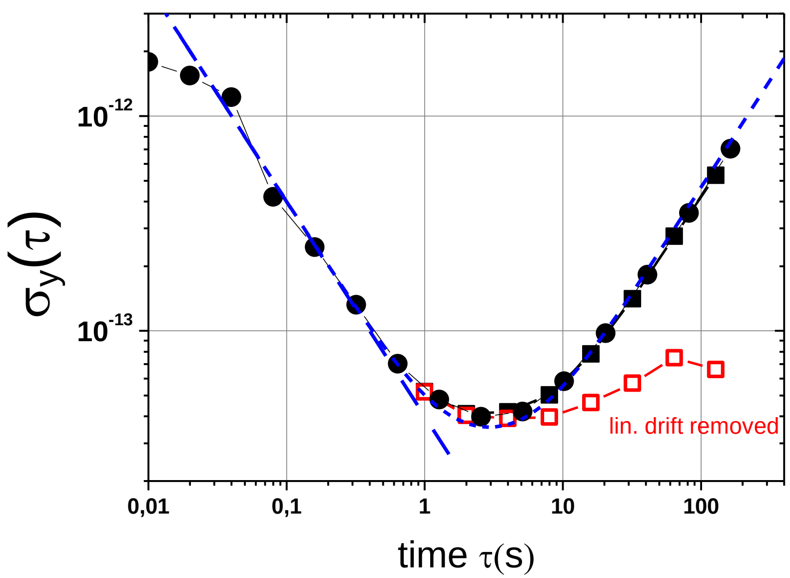


Feb. 2010: first light through 900 km

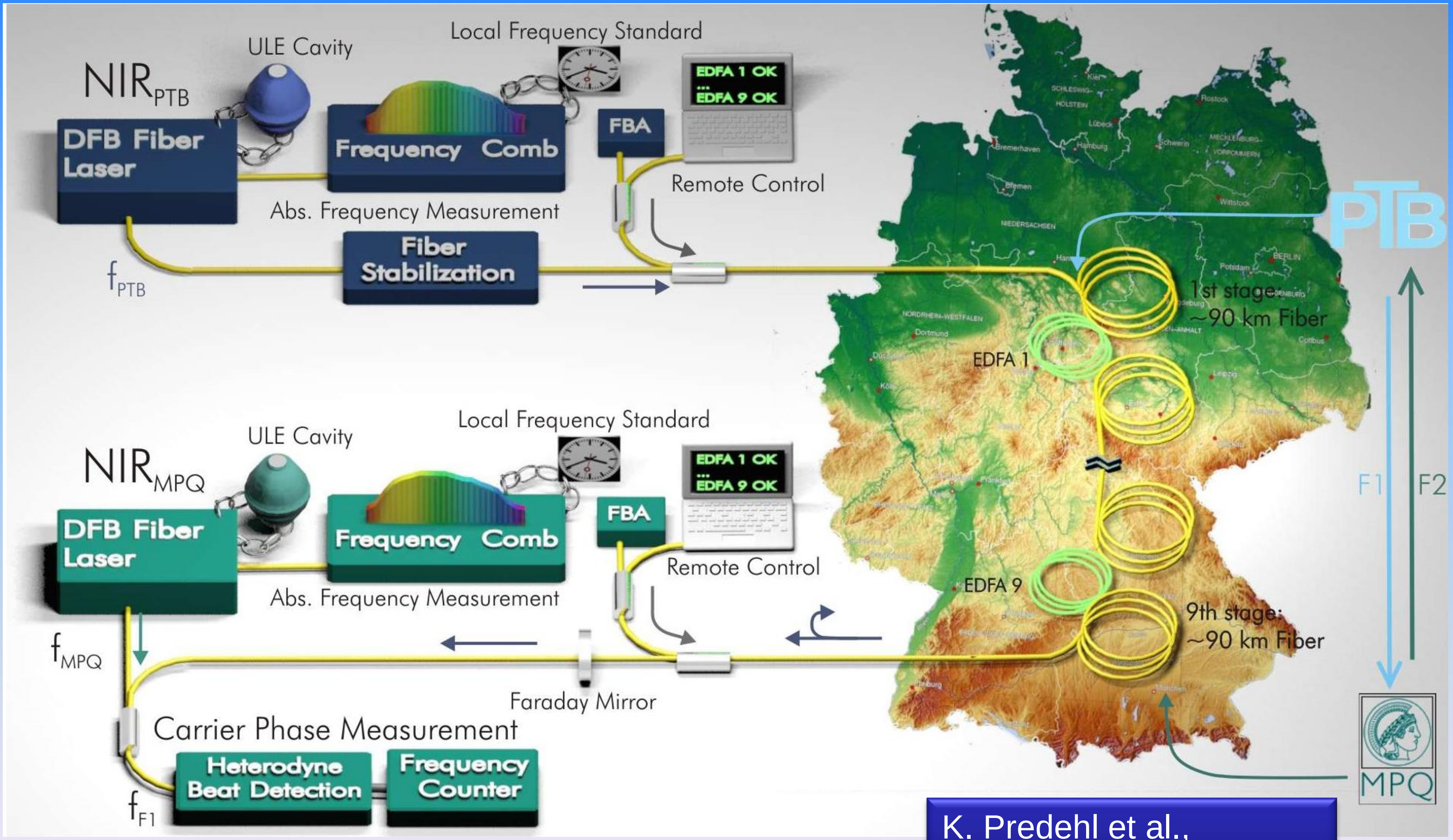
Beat note between NIR_{PTB} and NIR_{MPQ}







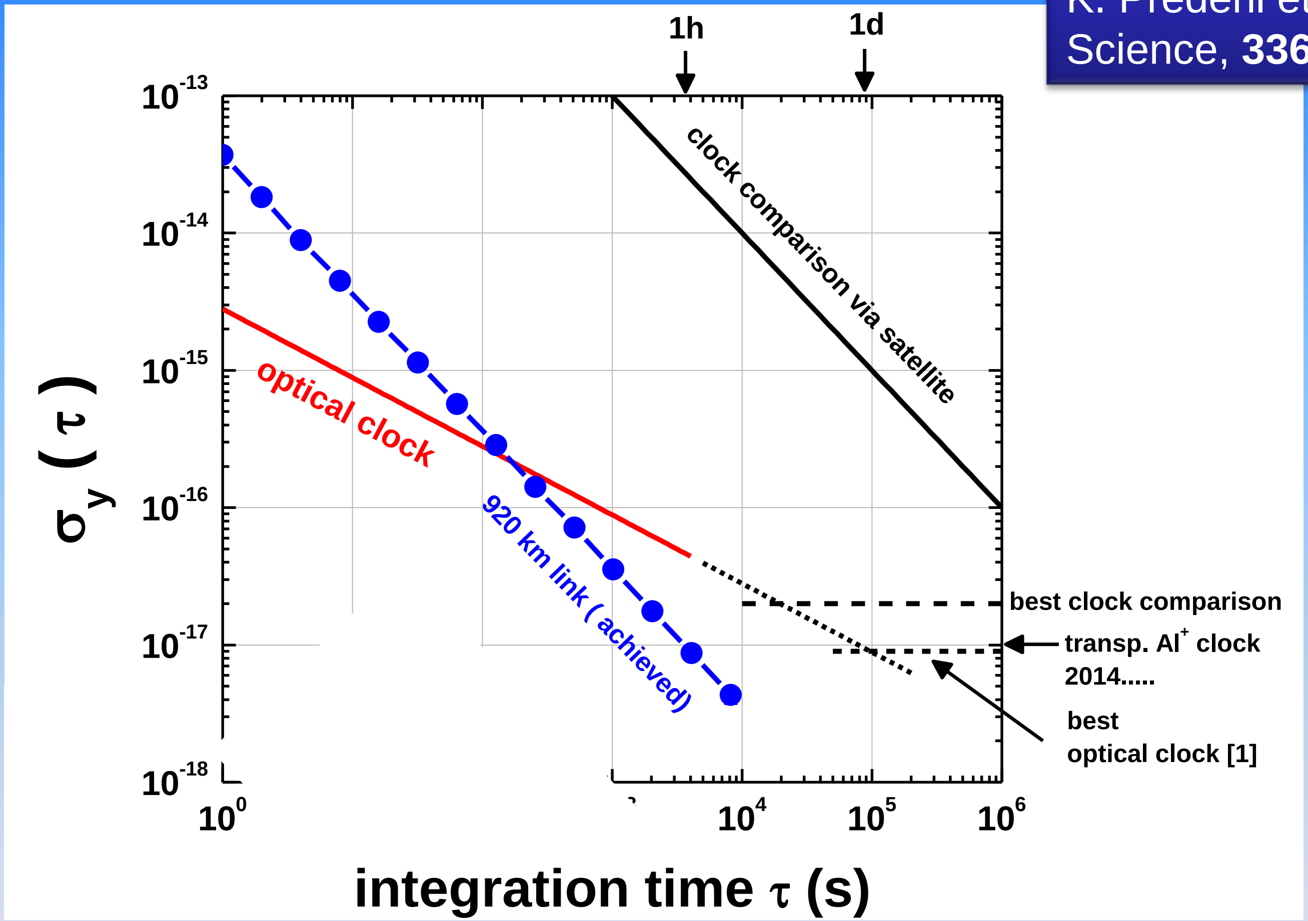
Experimental Setup



K. Predehl et al.,
Science, **336**, 441 (2012)

Link Instability & Clock Comparisons

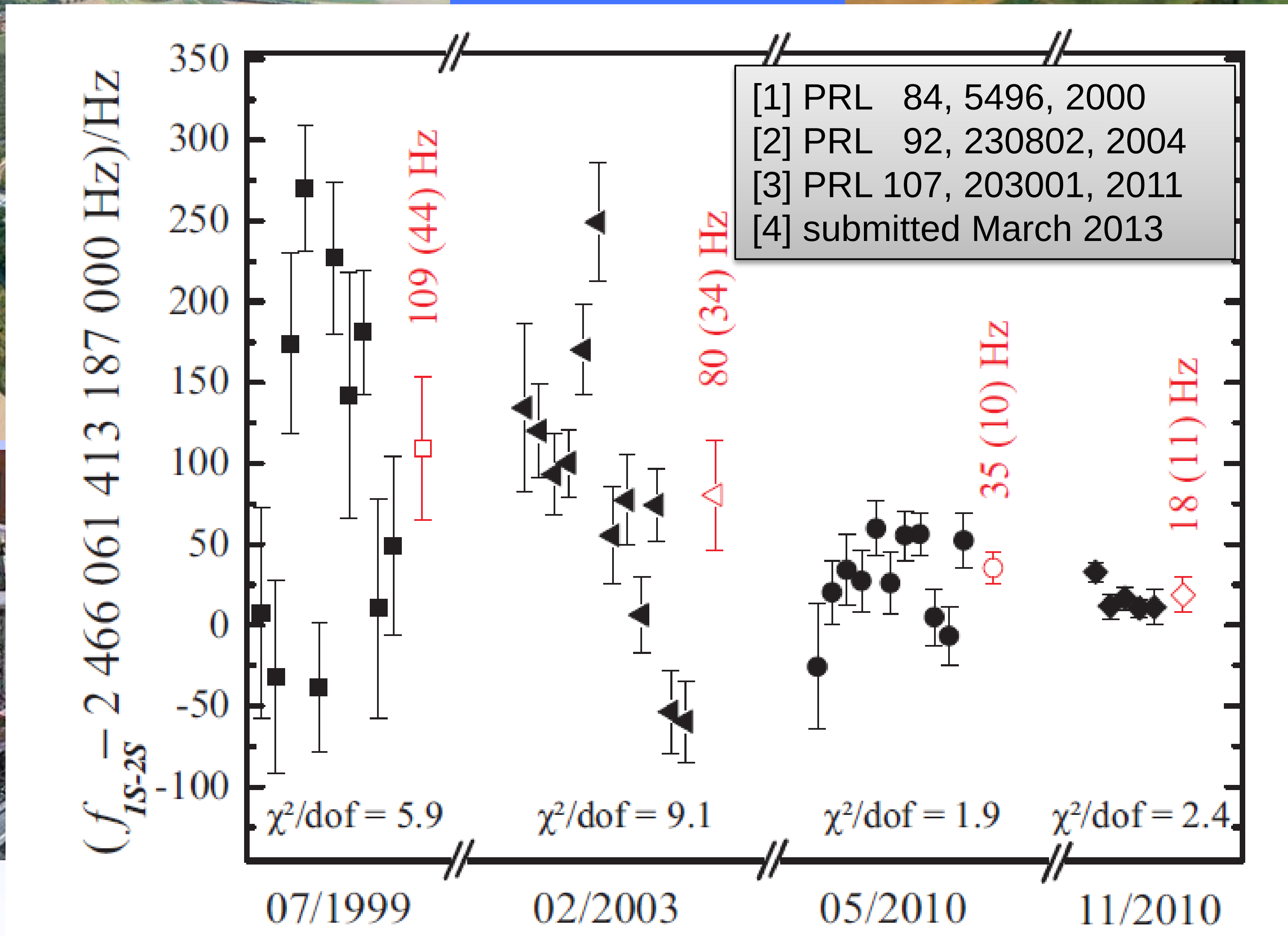
K. Predehl et al., Science, **336**, 441 (2012)

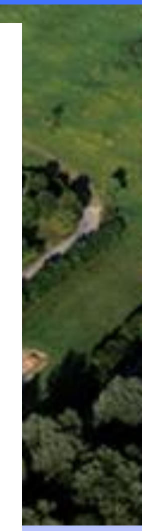


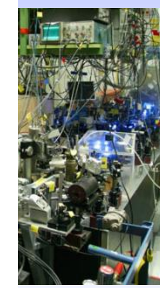
Accuracy: $(\nu_{out} - \nu_{in}) / \nu_{in} < 0.7\ (3.7)\times10^{-19}$ (<100 µHz)

[1] Chou et al., PRL 104, 070802 (2010)

1S-2S Frequency measurement





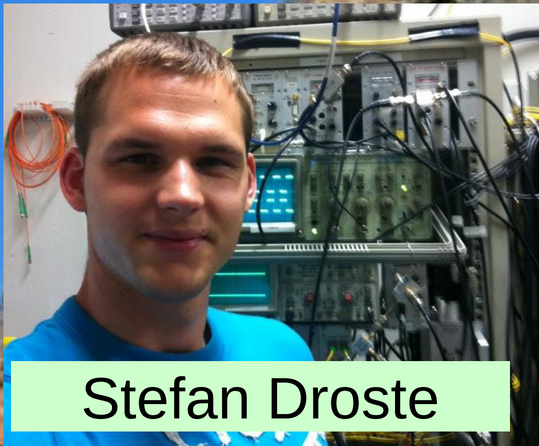


Fiber link

Sebastian Raupach

EFTF student contest

2010 2011



Stefan Droste

MPQ

Opt. frequency standards

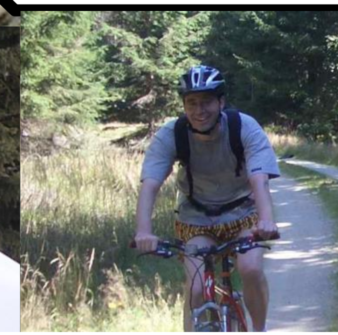
- Uwe Sterr
- Christian Lisdat
- Stefan Falke
- Thomas Legero

Opt. cavities & stable Lasers

- Thomas Legero
- Thomas Kessler
- Christian Hagemann

DFN

Deutsches Forschungsnetz



MPQ Garching

- Katharina Predehl
- Stefan Droste,
- T. W. Hänsch,
- Thomas Udem
- Ronald Holzwarth

Frequency measurement & dissemination

Burghard Lipphardt, Thomas Legero, Osama Terra, Sebastain Raupach, Gesine Grosche

Cs Clocks

- Andreas Ba
- Stefan Weyers

Giorgio's Dream around 2006 / 07

L
S
en
To

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

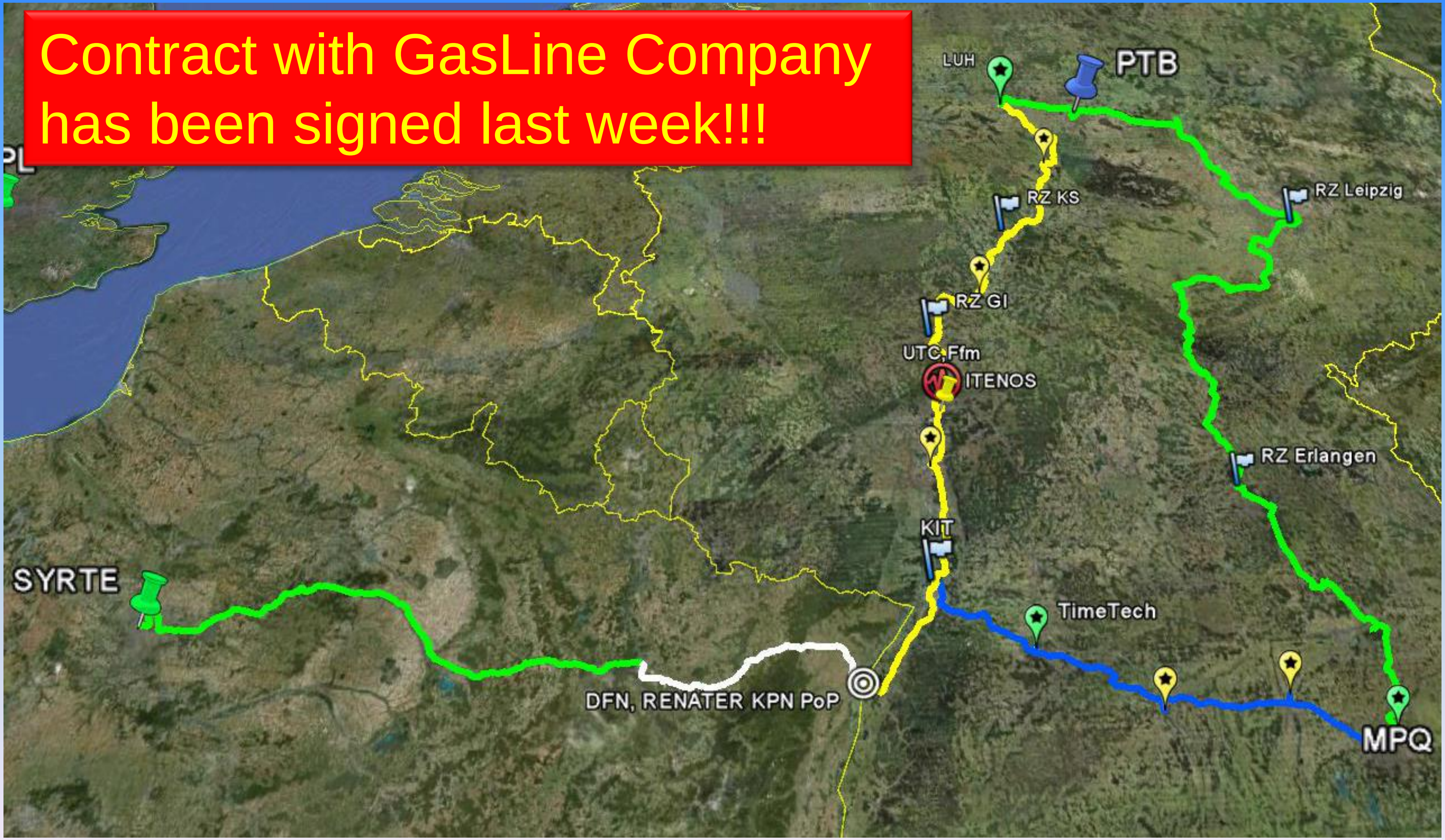
CESNET, Czech Republic

NEAT-FT Participants

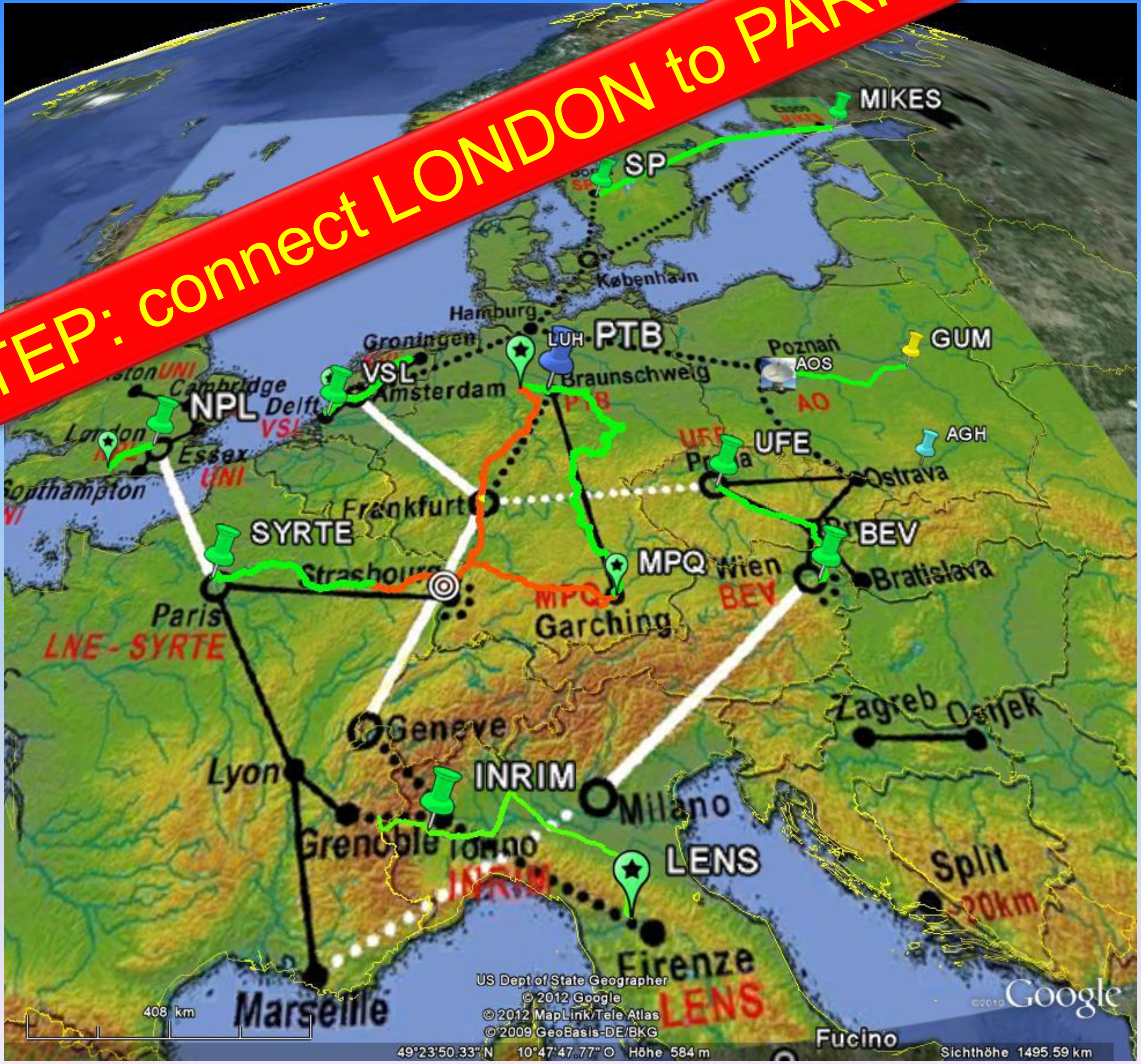
All fiber links are operated in collaboration with NRENs

Braunschweig - Paris Link via Frankfurt

Contract with GasLine Company has been signed last week!!!



Fiber links in Europe via GEANT



NEXT STEP: connect LONDON to PARIS

Comparisons between Cs clocks and recommended secondary representations

- Frequency ratio measurements at the 10^{-17} level
  - Comparisons of remote optical clocks
    - ✓ Independent systematics
    - ✓ Test of fundamental physics
- Consistency checks

Cs	X								
Al^+	X	X							
Hg^+	X	X							
Sr^+	X			X					
Yb^+(E2)	X	O		✡	X				
Yb^+(E3)	X	O		✡	✡	✡			
Yb	X								
Sr	X	O		O ✡	X	X	O	X	
Rb (MW)	X								X
Representa-tion of SI: **s**	Cs	Al^+	Hg^+	Sr^+	Yb^+ (E2)	Yb^+ (E3)	Yb	Sr	Rb (MW)

GÉANT NPL /SYRTE / PTB

PTB / QUEST

JRP ITOC 2013-16

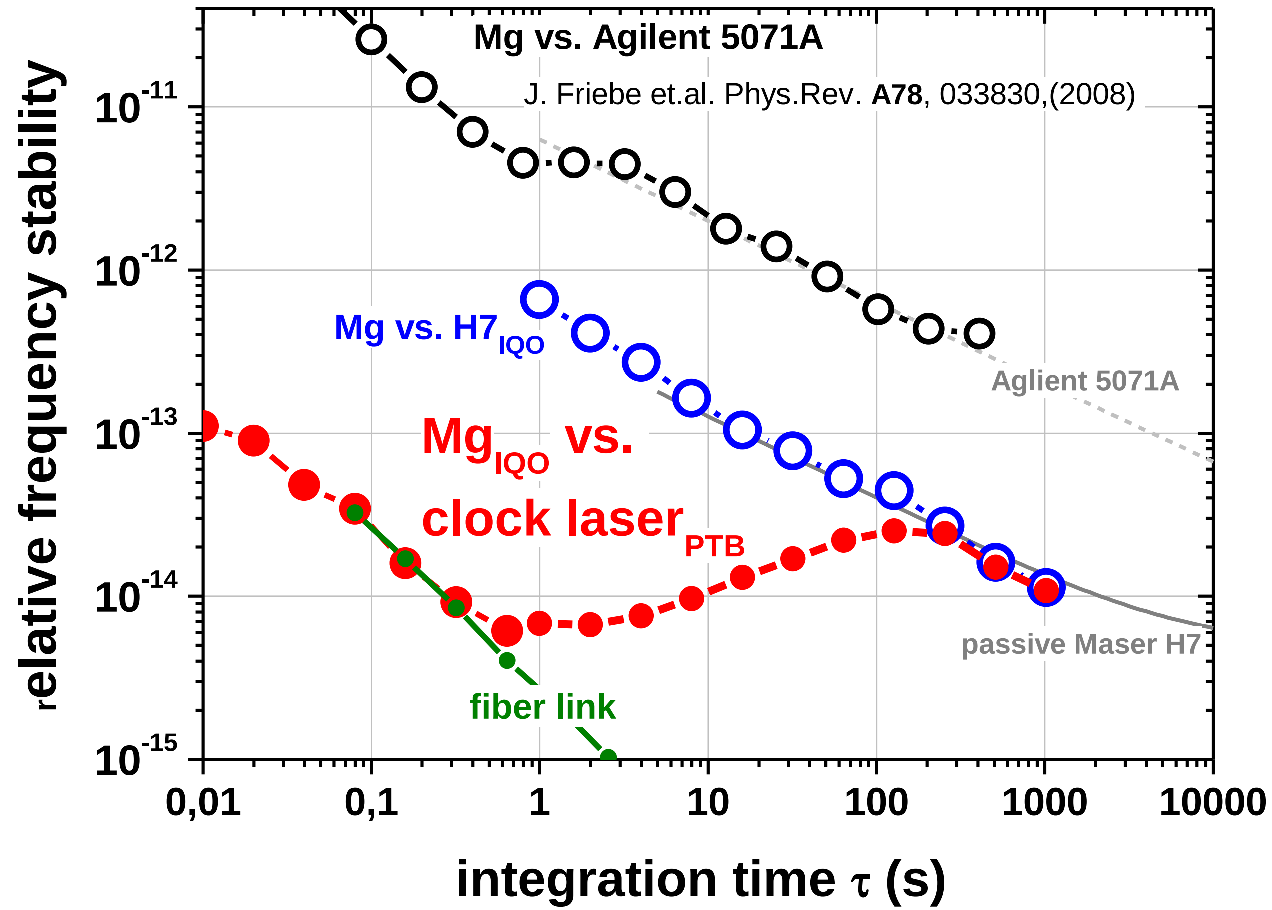
recent work at PTB

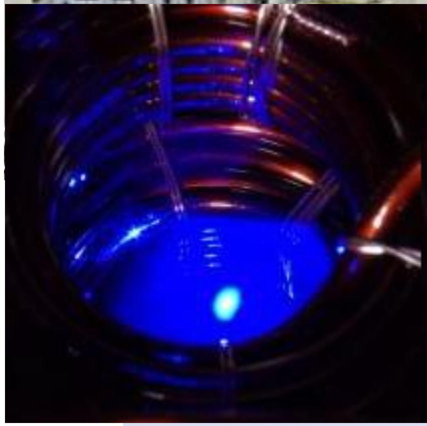
Report of the 19th meeting of the CCTF (2012)

Congratulations

Thank you for your attention !

Result: Mg Frequency standard





Installing Equipment