



TECHNISCHE
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WIEN



QME Vienna
Thorium Nuclear Clock



AQUnet: An Austrian Quantum Fiber Network

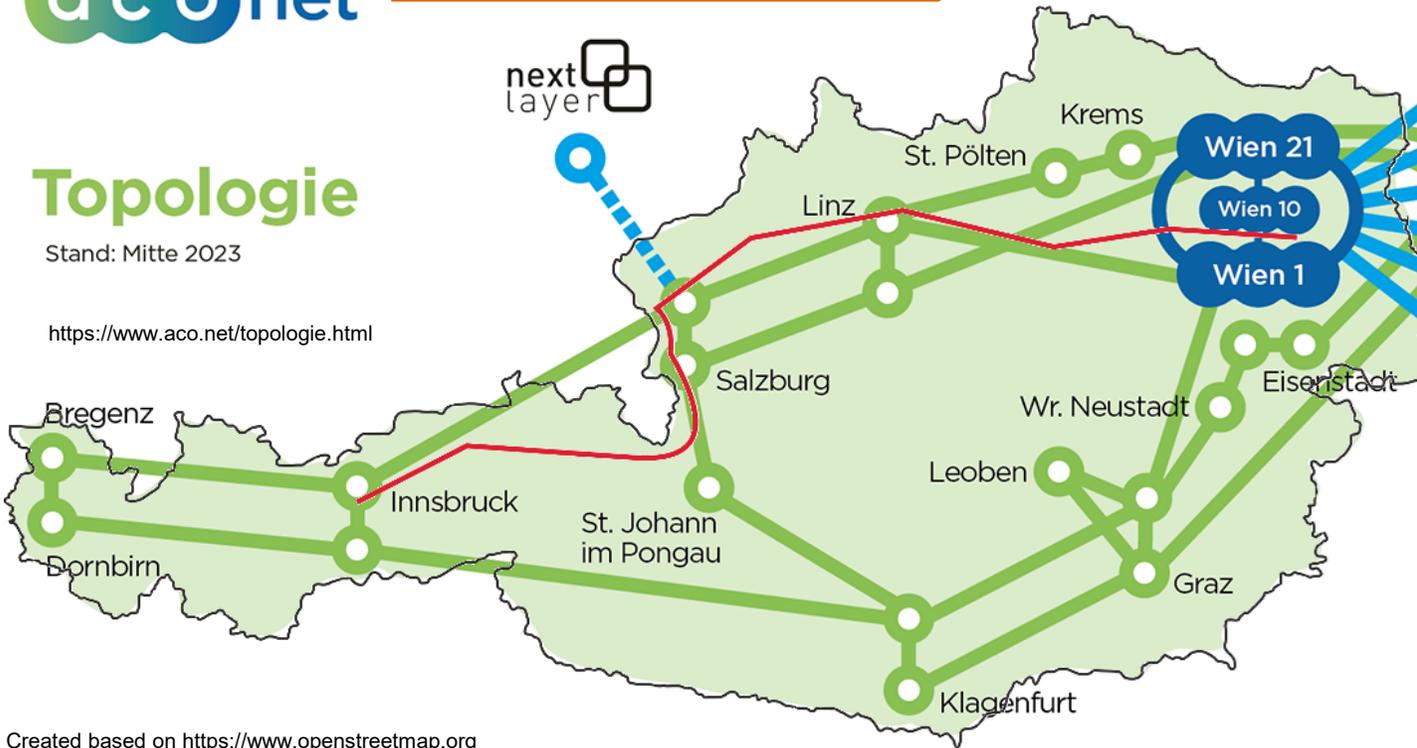
Benedikt Gerstenecker, TU Wien - Atominstitut
Assemblée Générale REFIMEVE, 01.12.2025



Topologie

Stand: Mitte 2023

<https://www.aco.net/topologie.html>



Created based on <https://www.openstreetmap.org>



- FFG-funded R&D infrastructure
- Non-economic use
- 05/2021 - 04/2026
- € 2.4 million
- Partners:
 - ACOnet (NREN, lead)*
 - BEV (NMI)*
 - Technische Universität Wien*
 - Universität Innsbruck*
 - Universität Wien*

Users





Austrian Fiber Link

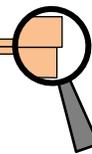
 Regeneration laser station

 Bi-directional amplifier



Created based on <https://www.openstreetmap.org>

- Fiber pair for uplink plus downlink:
2x ~700 km
- Mostly dark fibers:
> 99%
- Cascaded approach based on the model of REFIMEVE:
5 RLS units
7 Bi-directional amplifiers



Regeneration laser stations:
RLS from Exail

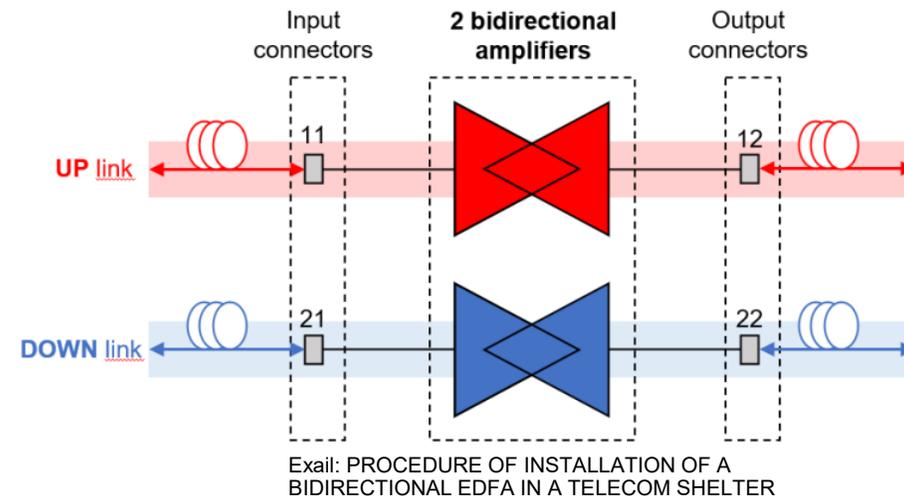


<https://www.exail.com/product/regeneration-laser-station>

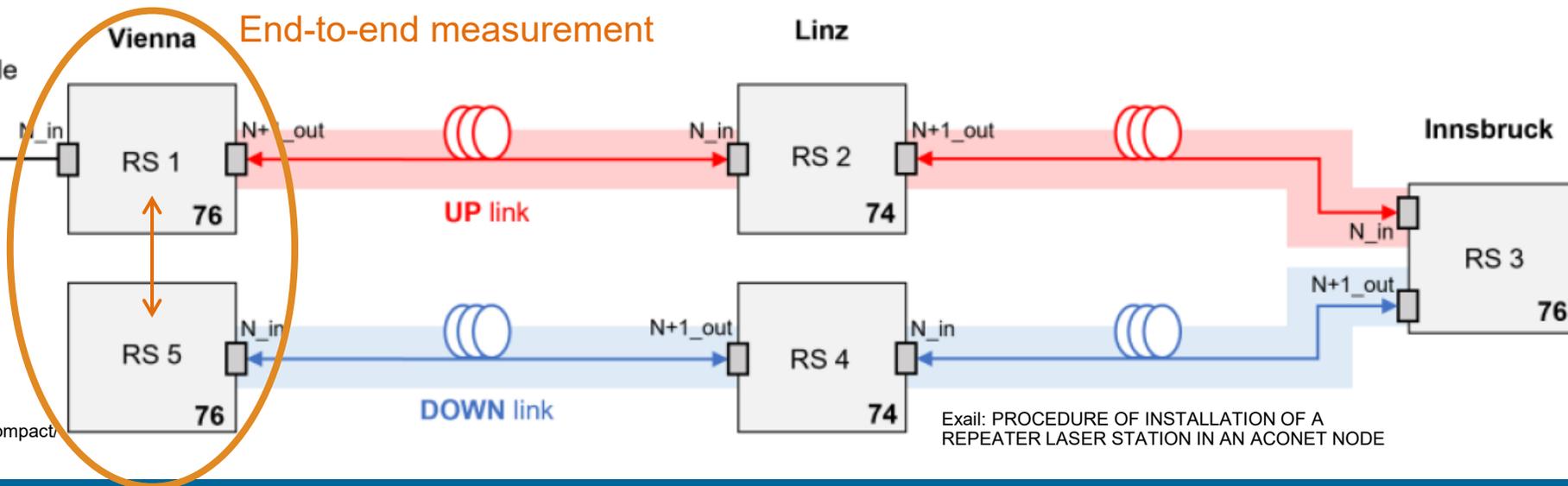
Bi-directional amplifiers:
CEFA-BD from Keopsys/Lumibird



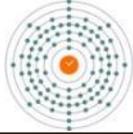
<https://www.keopsys.com/portfolio/bi-directional-fiber-amplifier/>



Ultra-stable laser
Optical flywheel

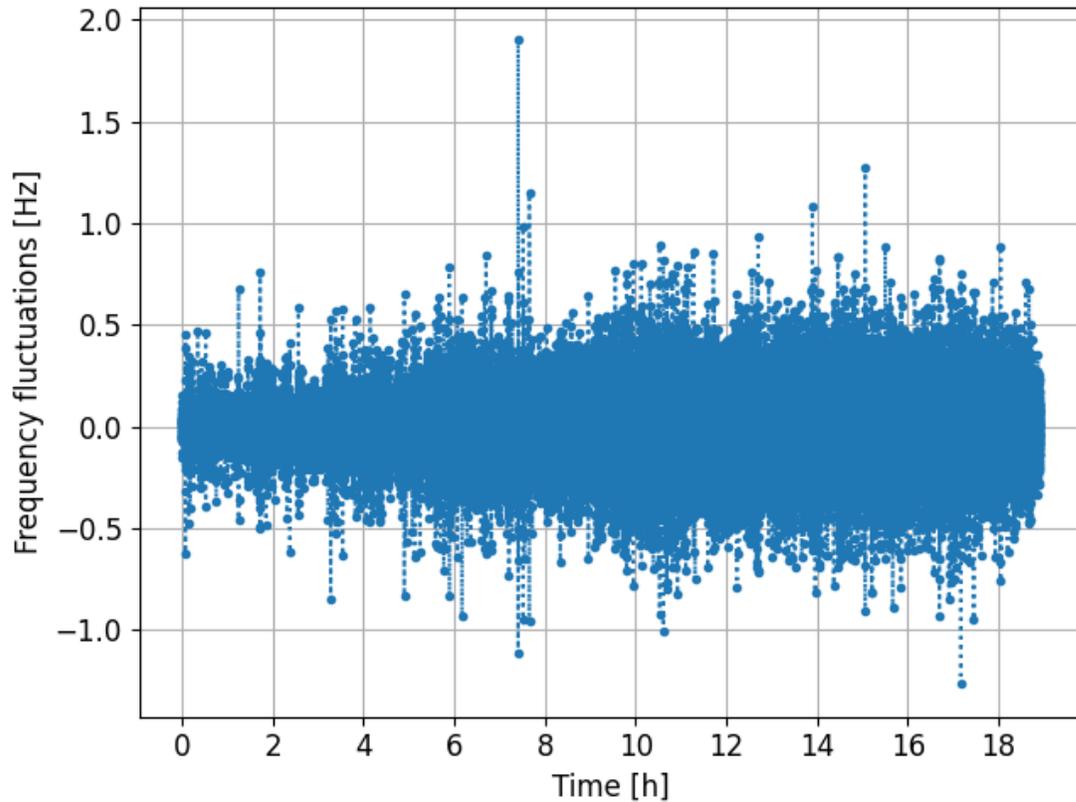


<https://www.menlosystems.com/products/ultrastable-lasers/ors-compact>



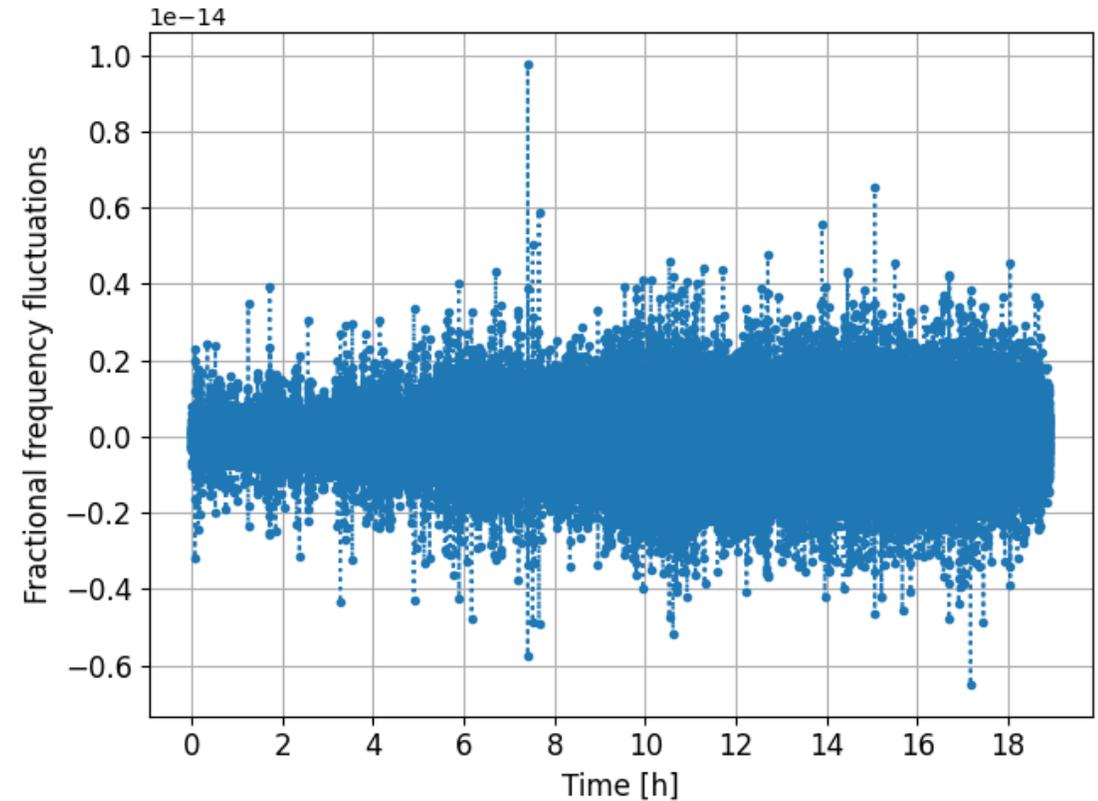
Local end-to-end two-way measurement

⇒ Frequency half difference:



Frequency counting

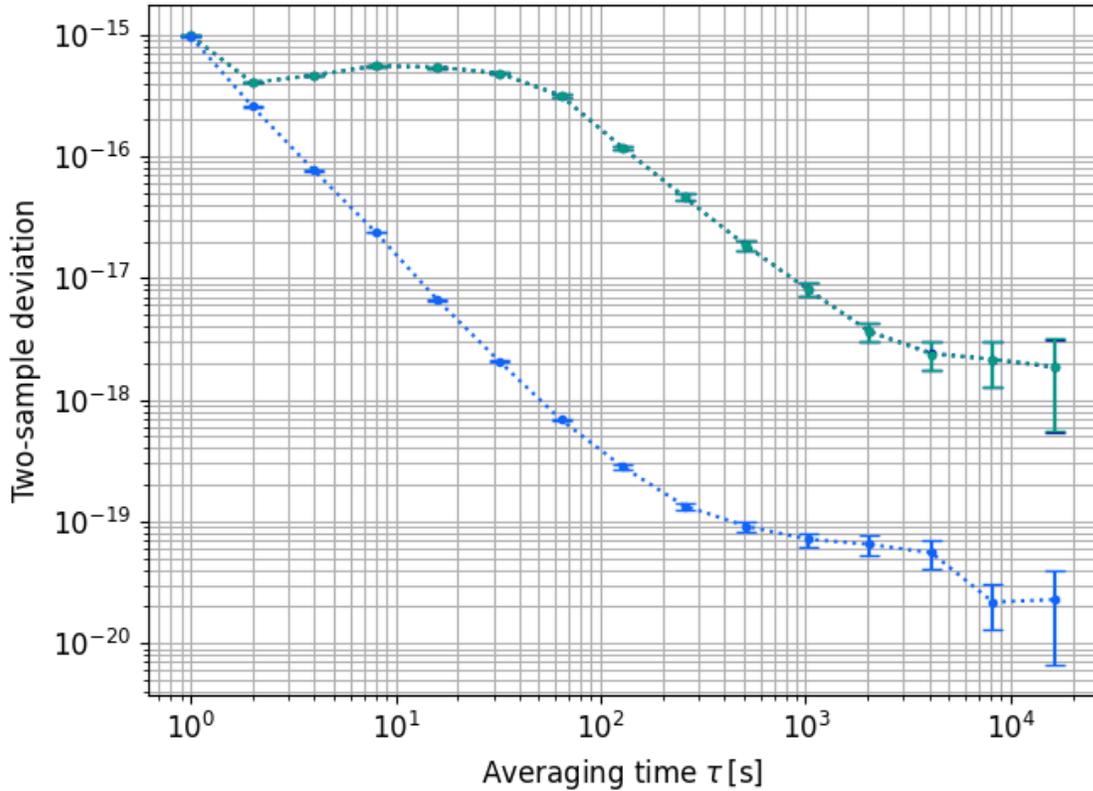
- K+K FXE
- **Phase averaging (Λ mode)**
- Gate time: 1 second (internal resolution 1 kHz)





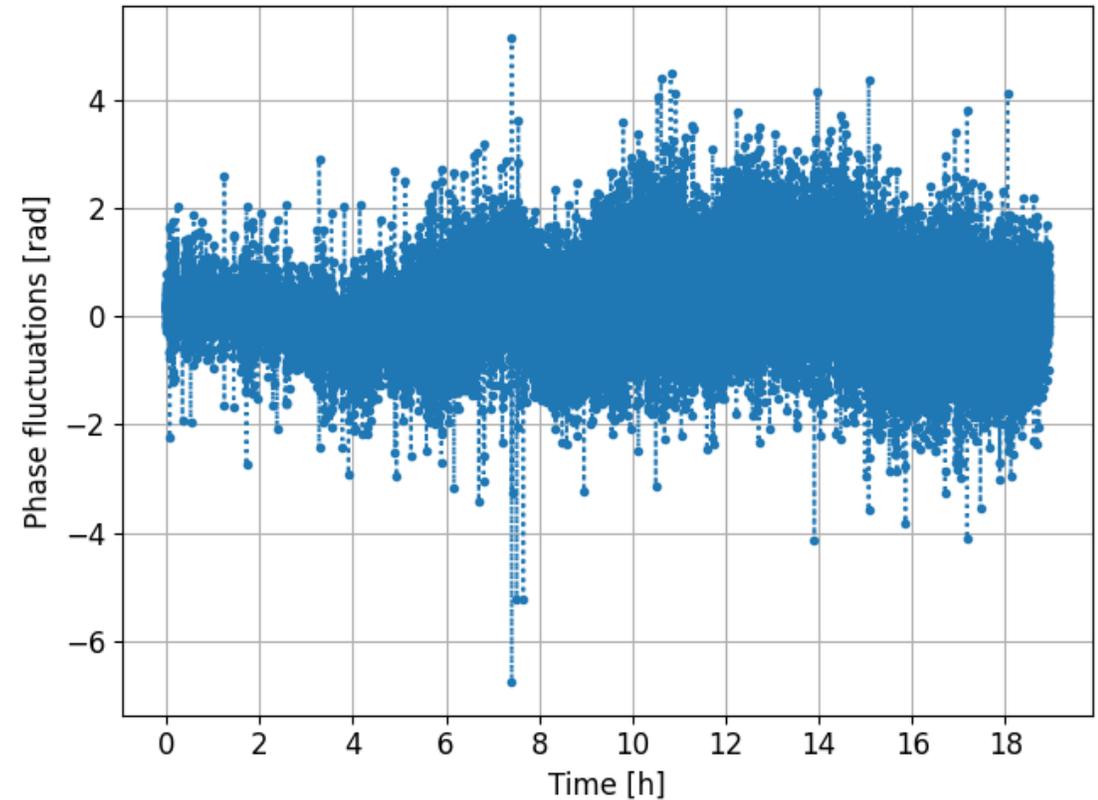
Fractional frequency (in)stability \Rightarrow Modified Allan deviation

Fractional frequency stability: MDEV from data decimation



- 25/10/05 21:05 - 25/10/06 15:59 (ch1)
- 25/10/05 21:05 - 25/10/06 15:59 (ch2)
- 25/10/05 21:05 - 25/10/06 15:59

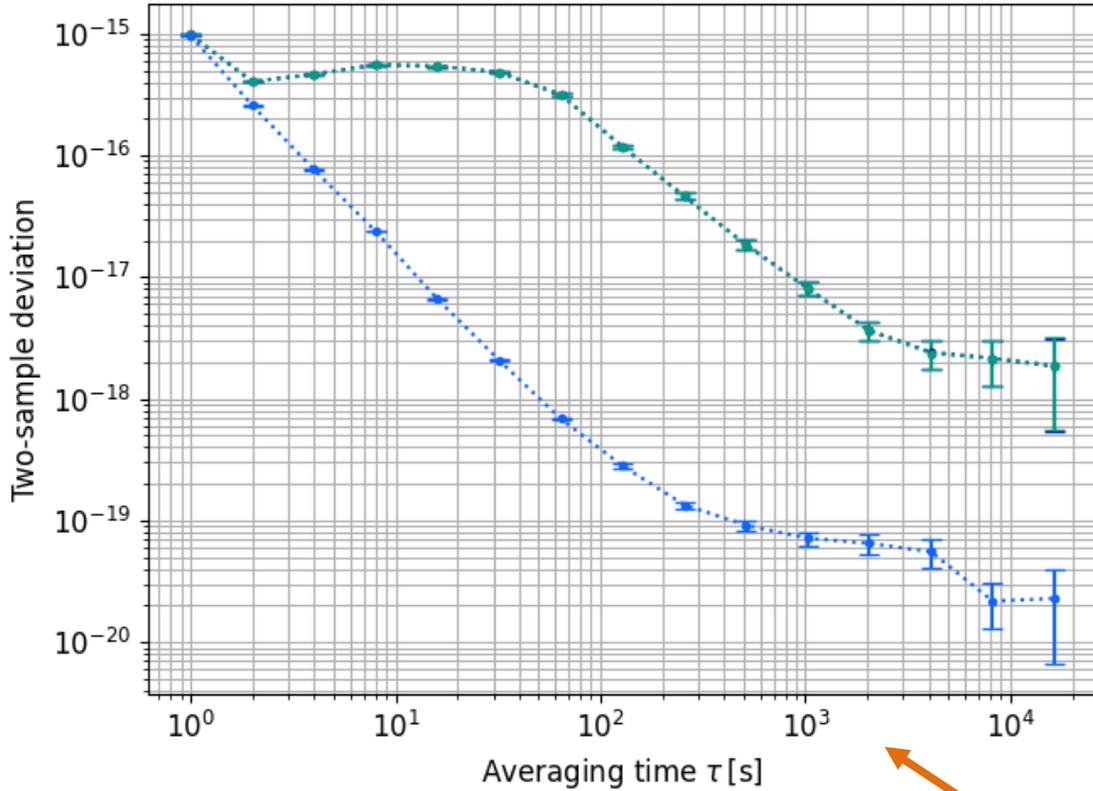
Continuous dataset \Rightarrow 100% uptime of >18 hours!





Different approaches to data processing!

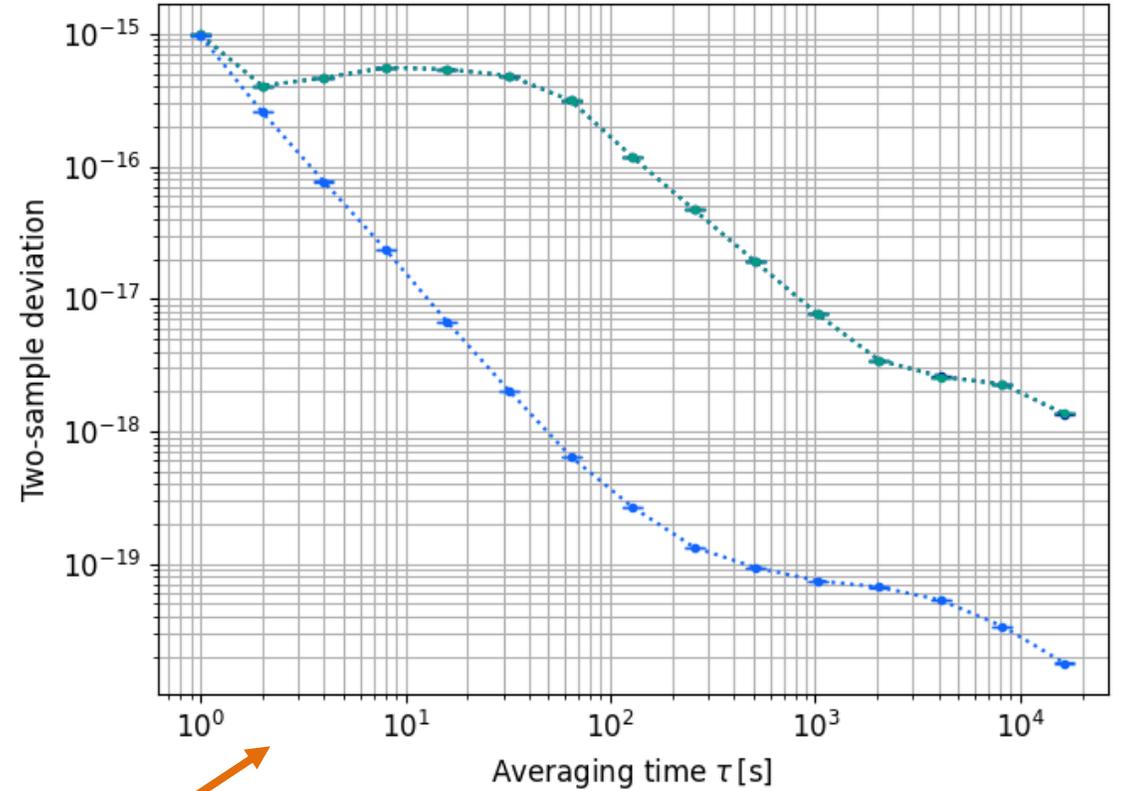
Fractional frequency stability: MDEV from data decimation



Weighted averaging for each value of τ

Identical dataset!

Fractional frequency stability: Plain MDEV calculation

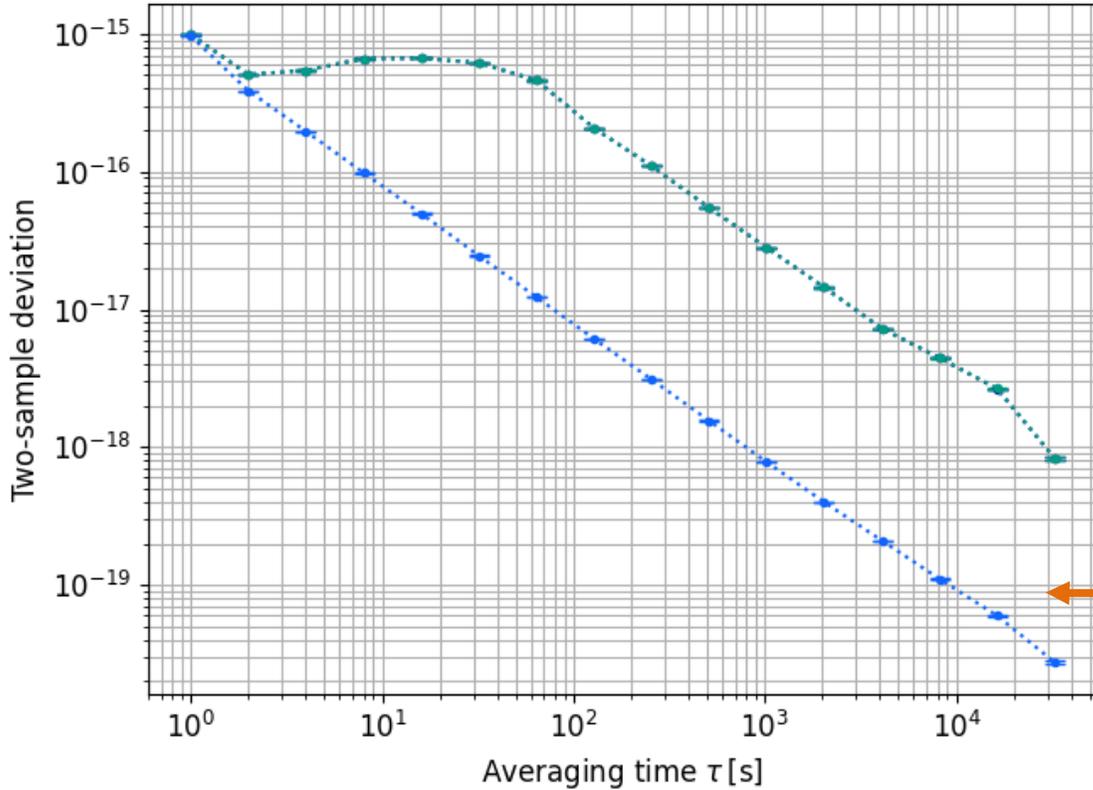


MDEV formula (*allantools*)



Assessing the frequency transfer \Rightarrow Overlapping Allan deviation

Fractional frequency stability: Plain OADEV calculation

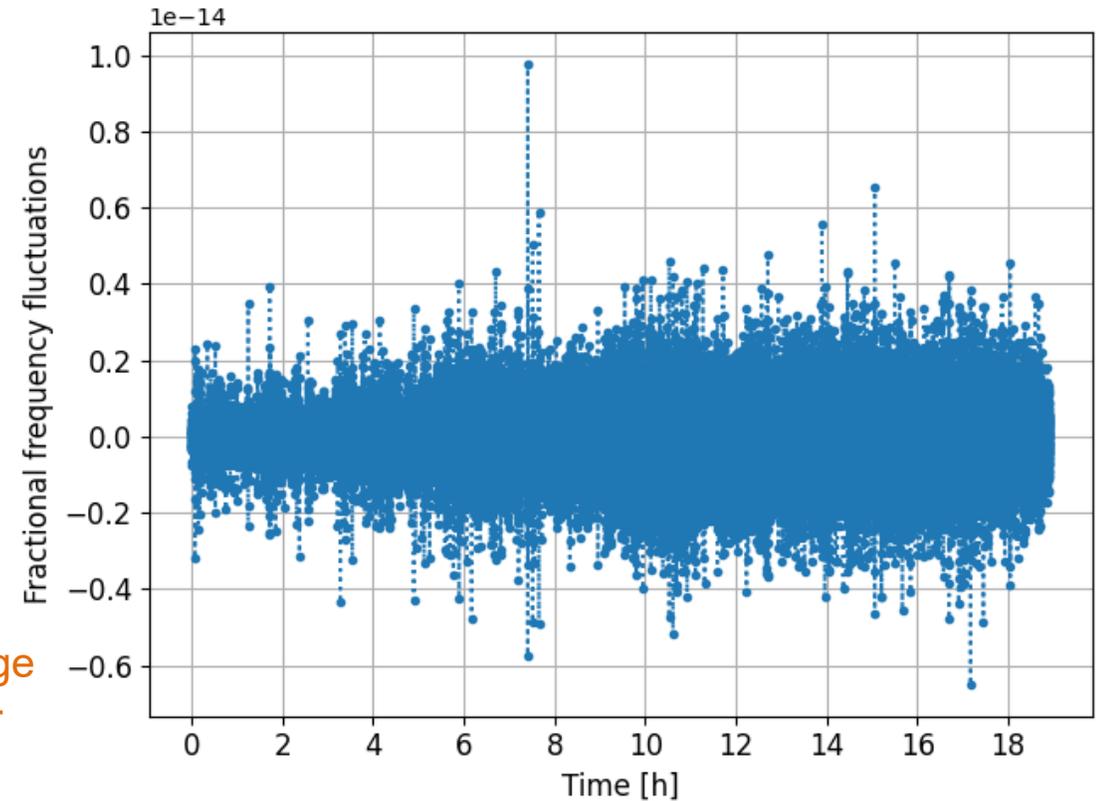


OADEV @ $\tau = 32768$ s: 2.75×10^{-20}

Should converge with frequency-averaged data!

- 25/10/05 21:05 - 25/10/06 15:59 (ch1)
- 25/10/05 21:05 - 25/10/06 15:59 (ch2)
- 25/10/05 21:05 - 25/10/06 15:59

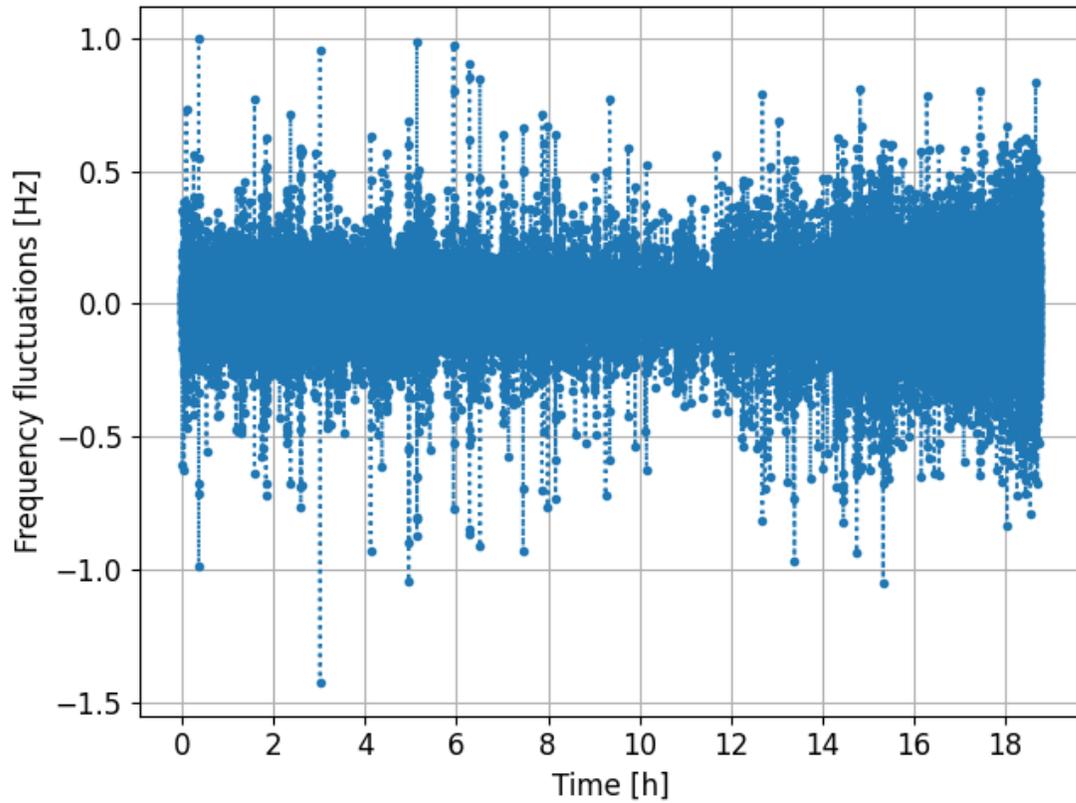
Mean of fluctuations: 2.09×10^{-20}



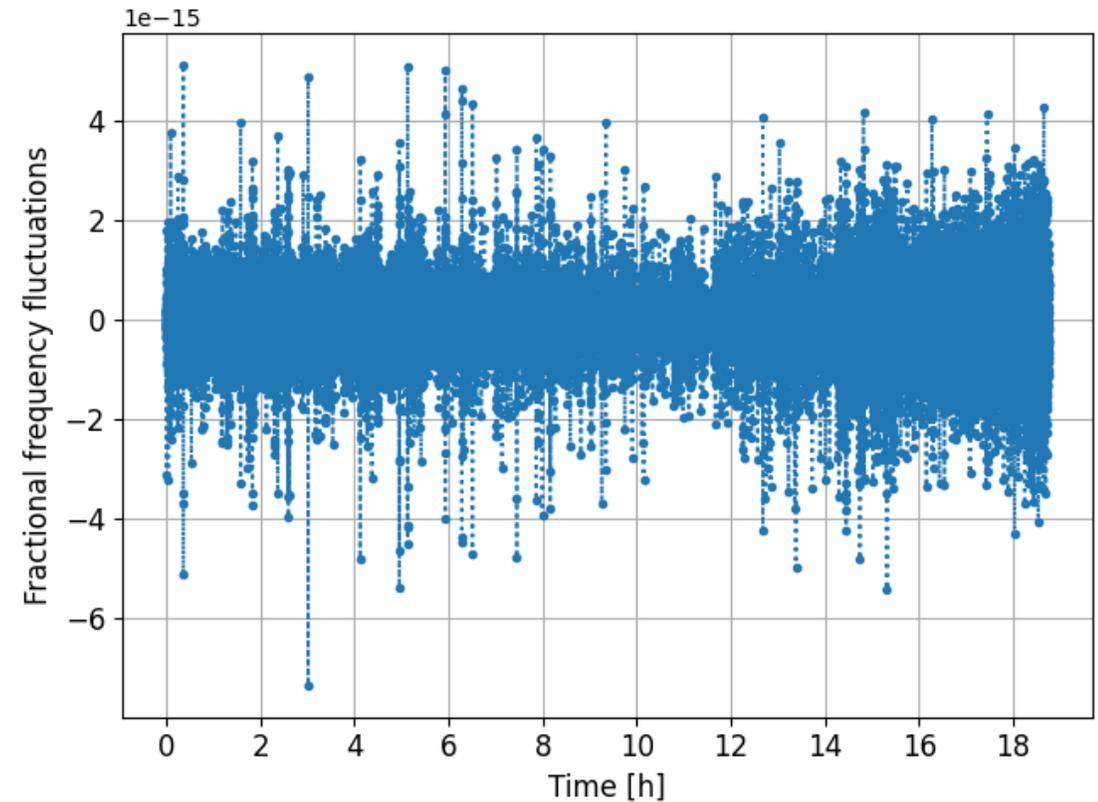


Different dataset of similar duration ...

Frequency half difference:

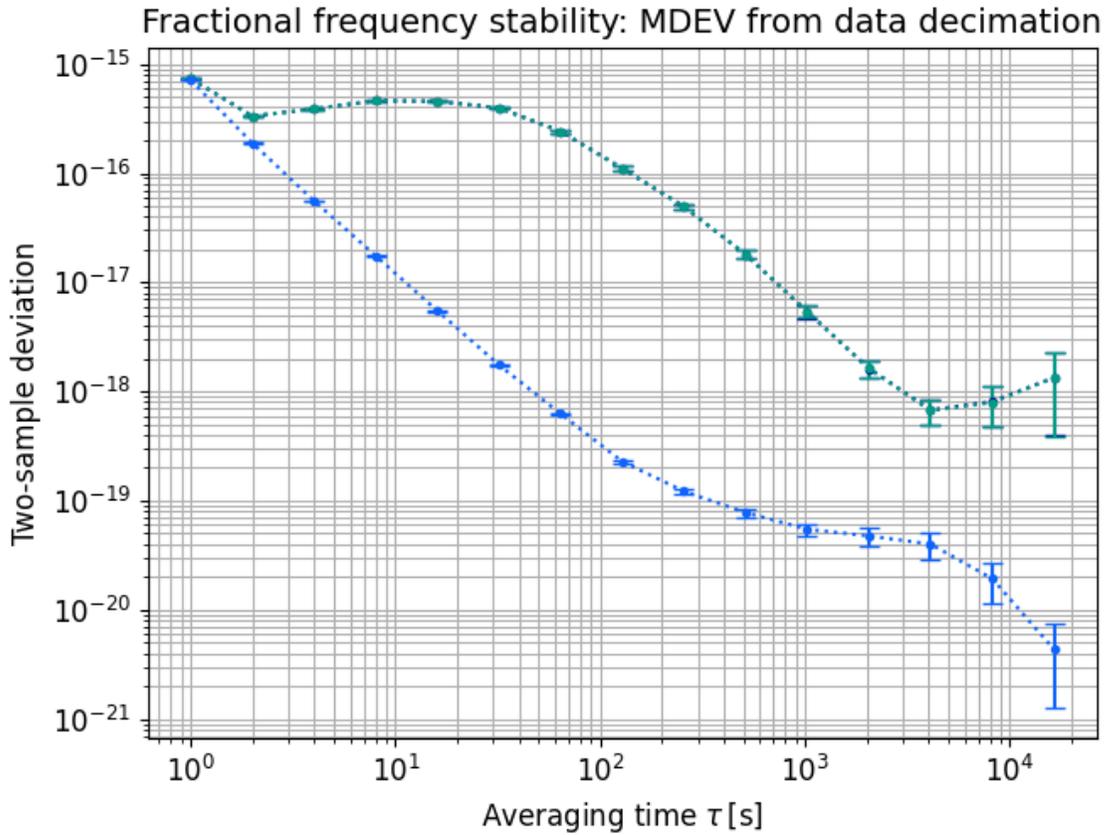


Fractional frequency fluctuations:

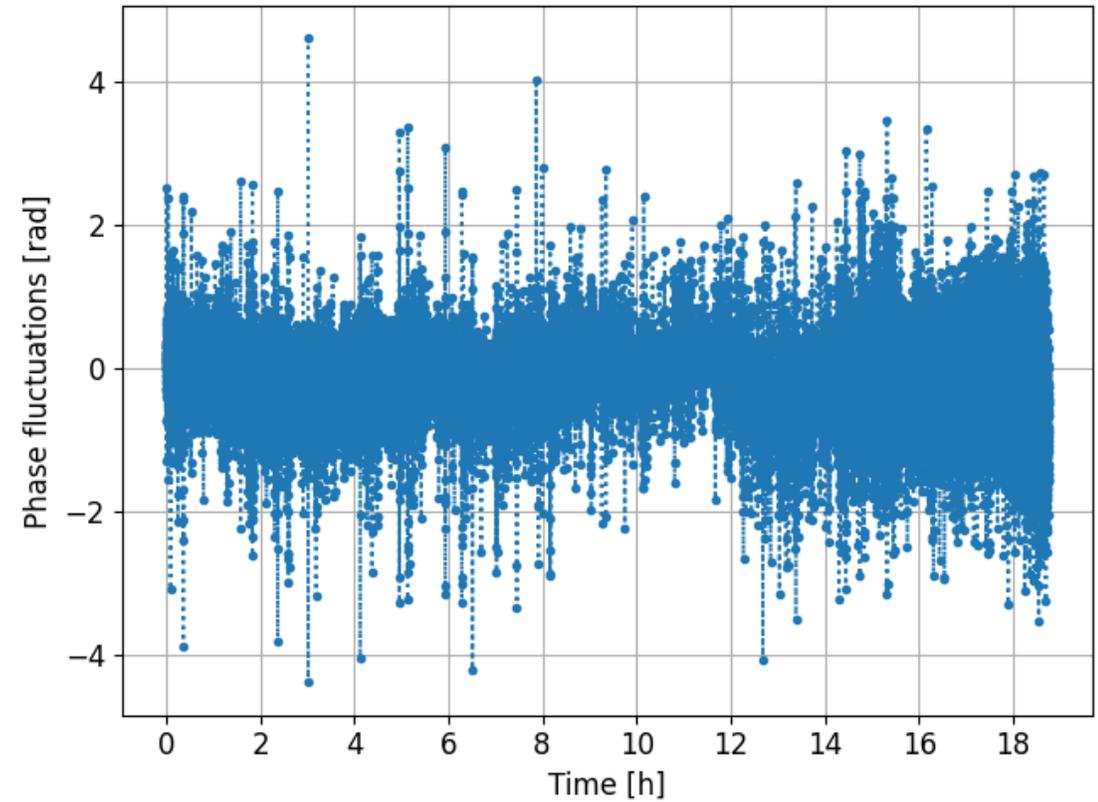


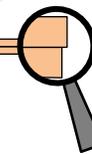


... but with better long-term stability?



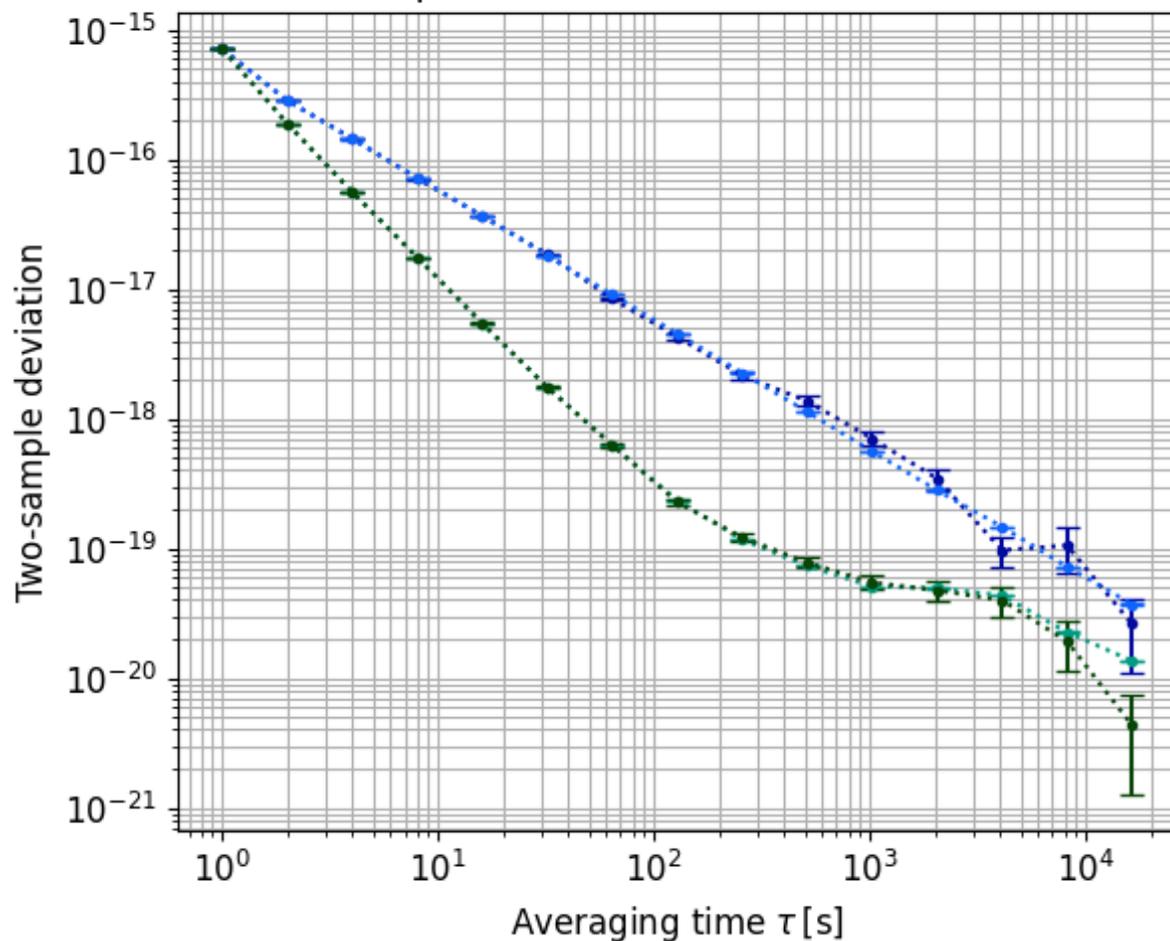
- 25/11/16 13:15 - 25/11/17 07:59 (ch1)
- 25/11/16 13:15 - 25/11/17 07:59 (ch2)
- 25/11/16 13:15 - 25/11/17 07:59





Significant difference between various approaches:

Comparison of different evaluations



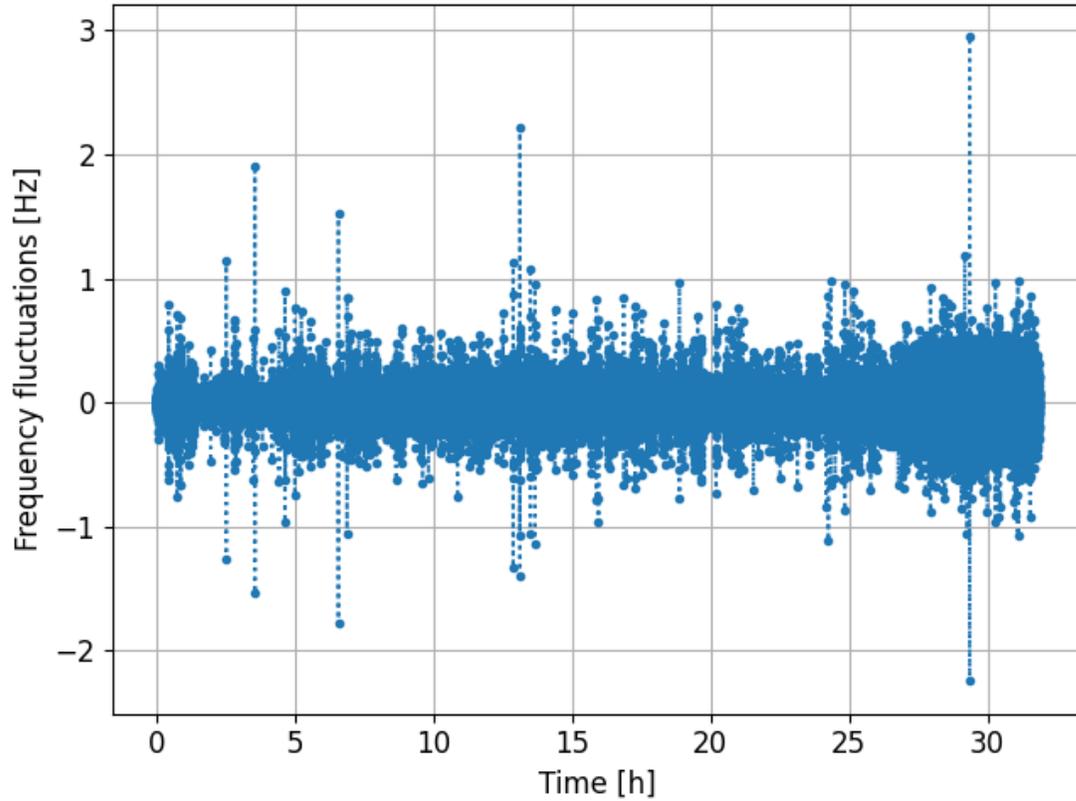
- 25/11/16 13:15 - 25/11/17 07:59 (plain ADEV)
- 25/11/16 13:15 - 25/11/17 07:59 (plain MDEV)
- 25/11/16 13:15 - 25/11/17 07:59 (plain OADEV)
- 25/11/16 13:15 - 25/11/17 07:59 (MDEV)

Identical dataset!

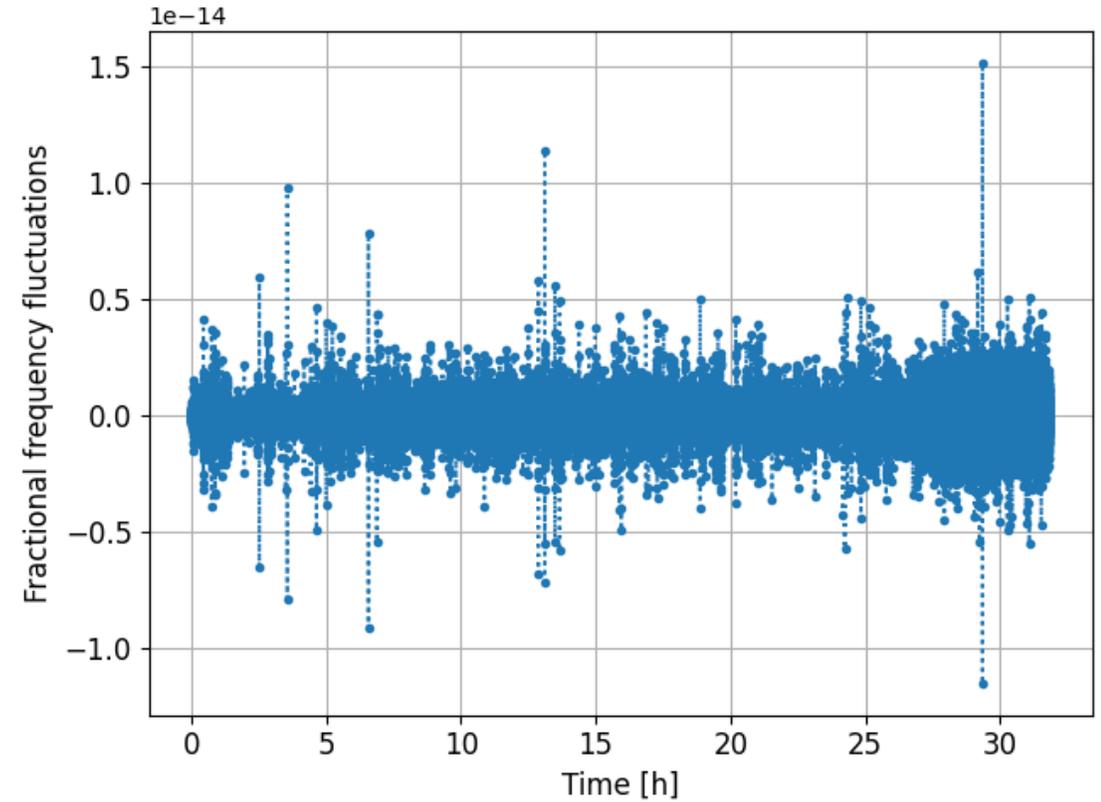


The longest period of continuous data so far!

Frequency half difference:

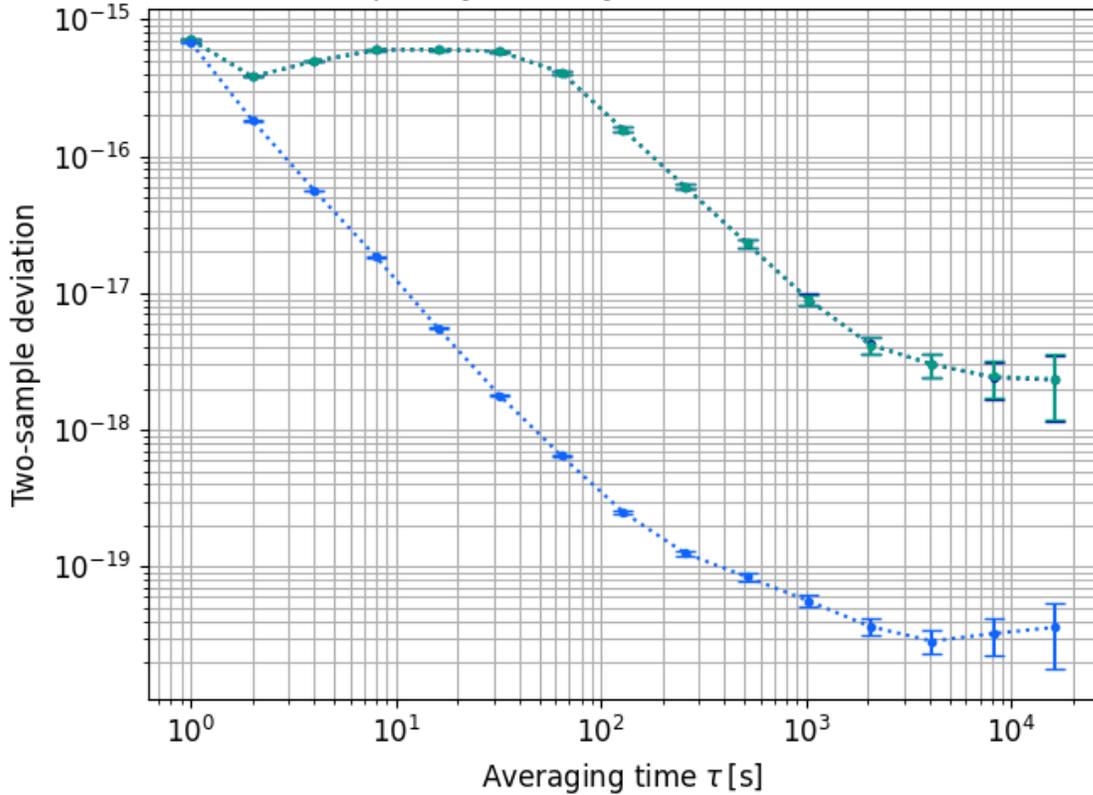


Fractional frequency fluctuations:



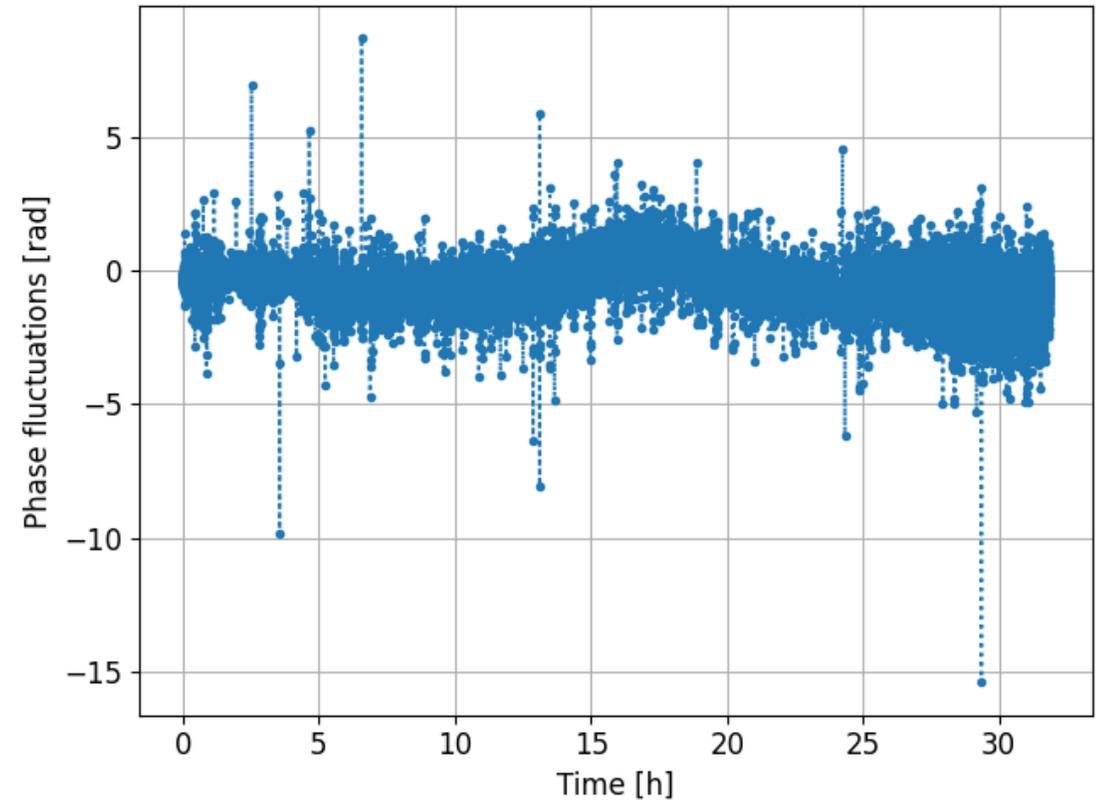


Fractional frequency stability: MDEV from data decimation



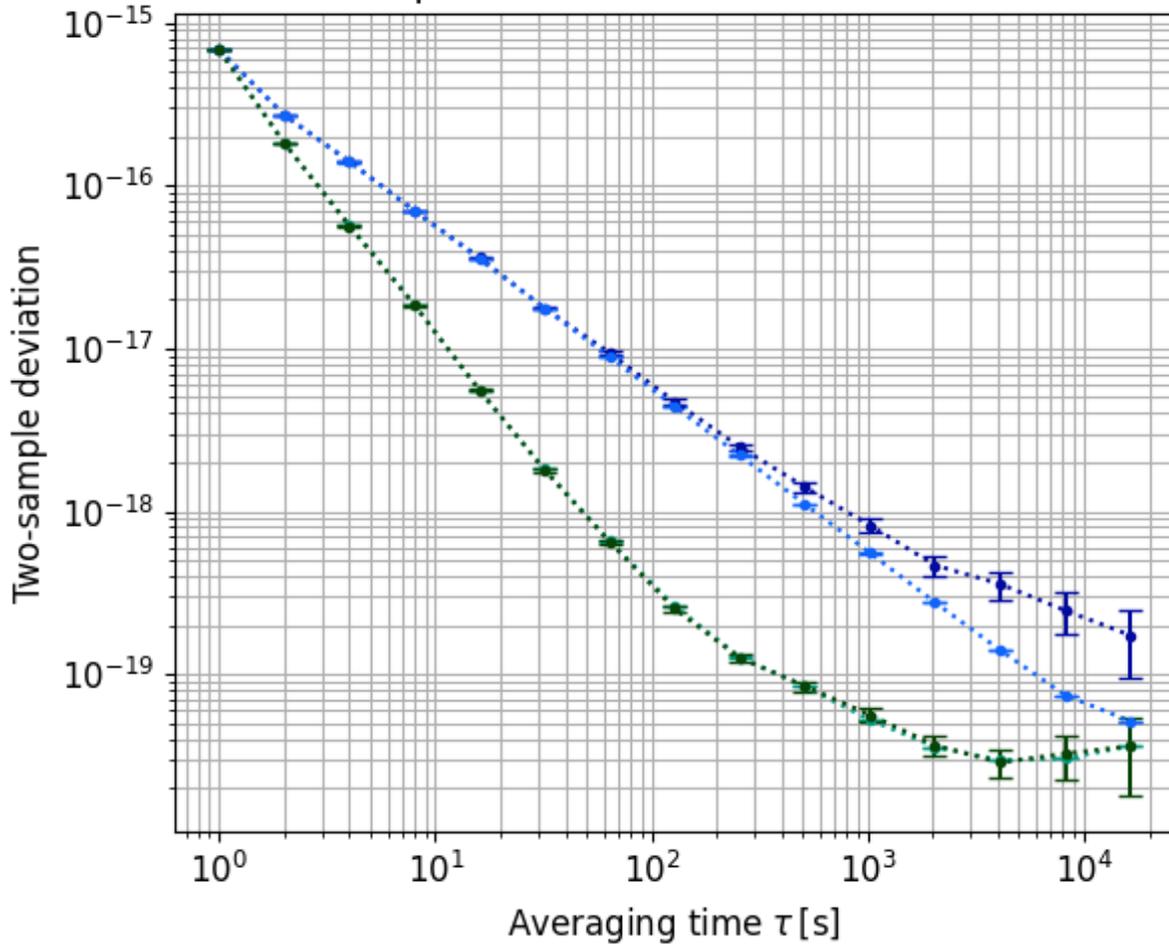
- 25/07/26 23:45 - 25/07/28 07:34 (ch1)
- 25/07/26 23:45 - 25/07/28 07:34 (ch2)
- 25/07/26 23:45 - 25/07/28 07:34

Continuous dataset \Rightarrow 100% uptime of **>31 hours!**





Comparison of different evaluations

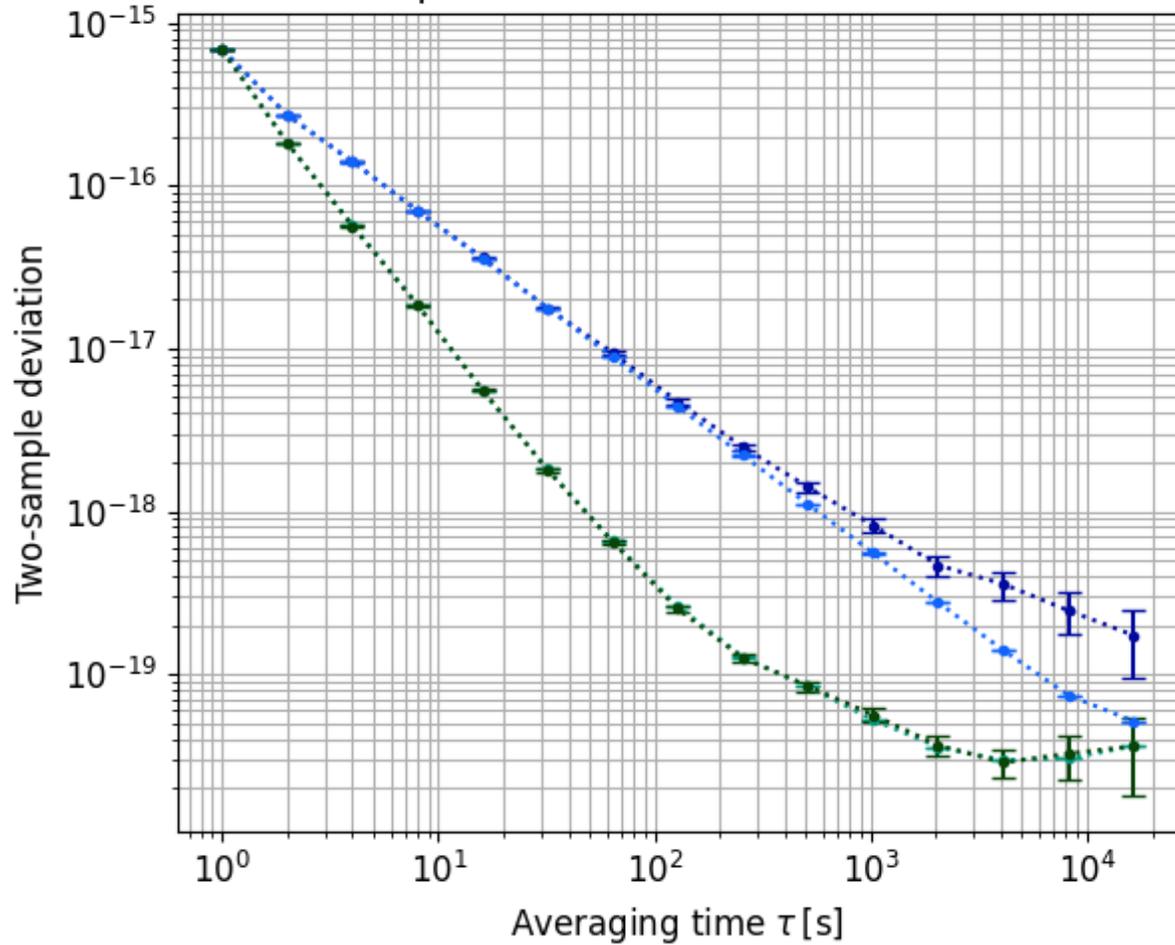


- 25/07/26 23:45 - 25/07/28 07:34 (plain ADEV)
- 25/07/26 23:45 - 25/07/28 07:34 (plain MDEV)
- 25/07/26 23:45 - 25/07/28 07:34 (plain OADEV)
- 25/07/26 23:45 - 25/07/28 07:34 (MDEV)

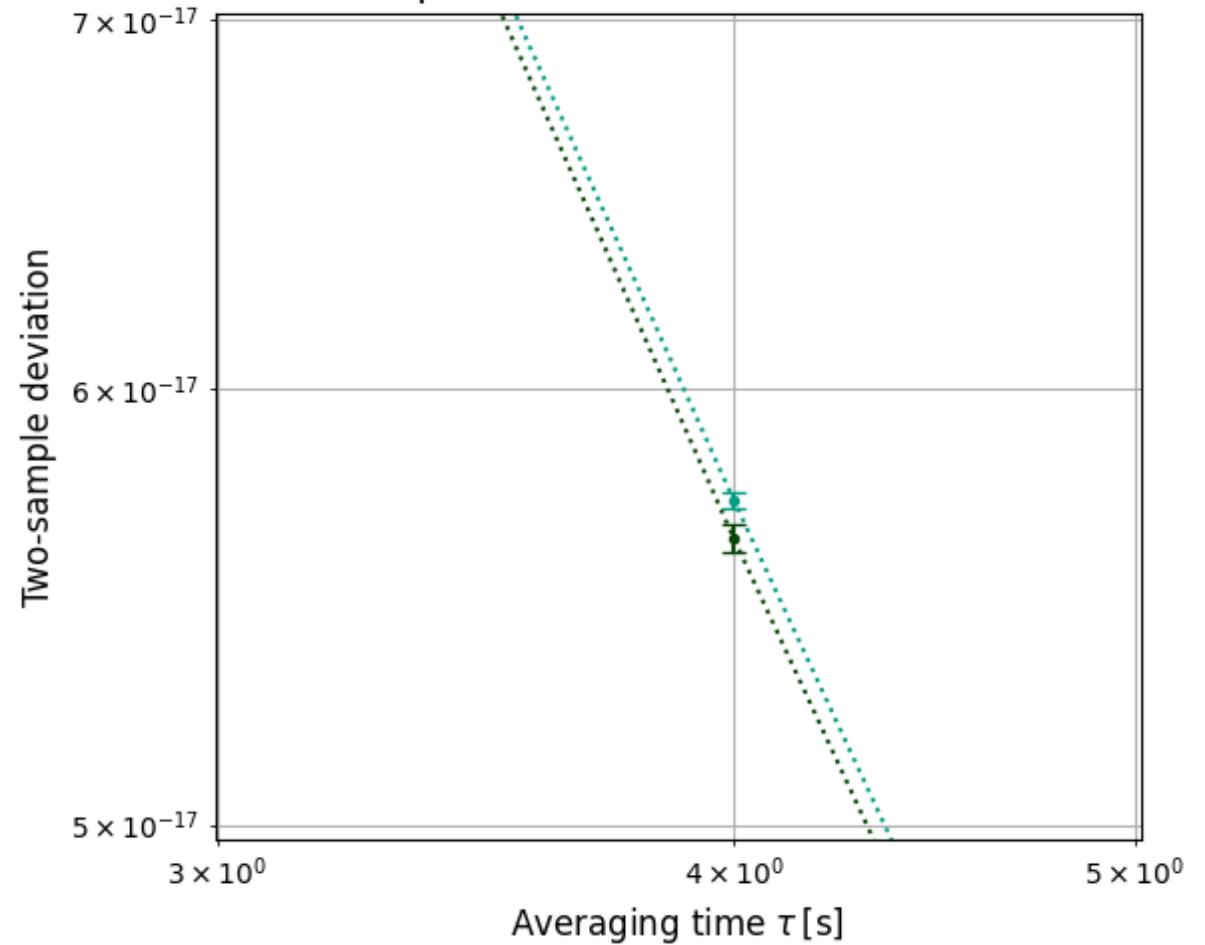
Identical dataset!



Comparison of different evaluations



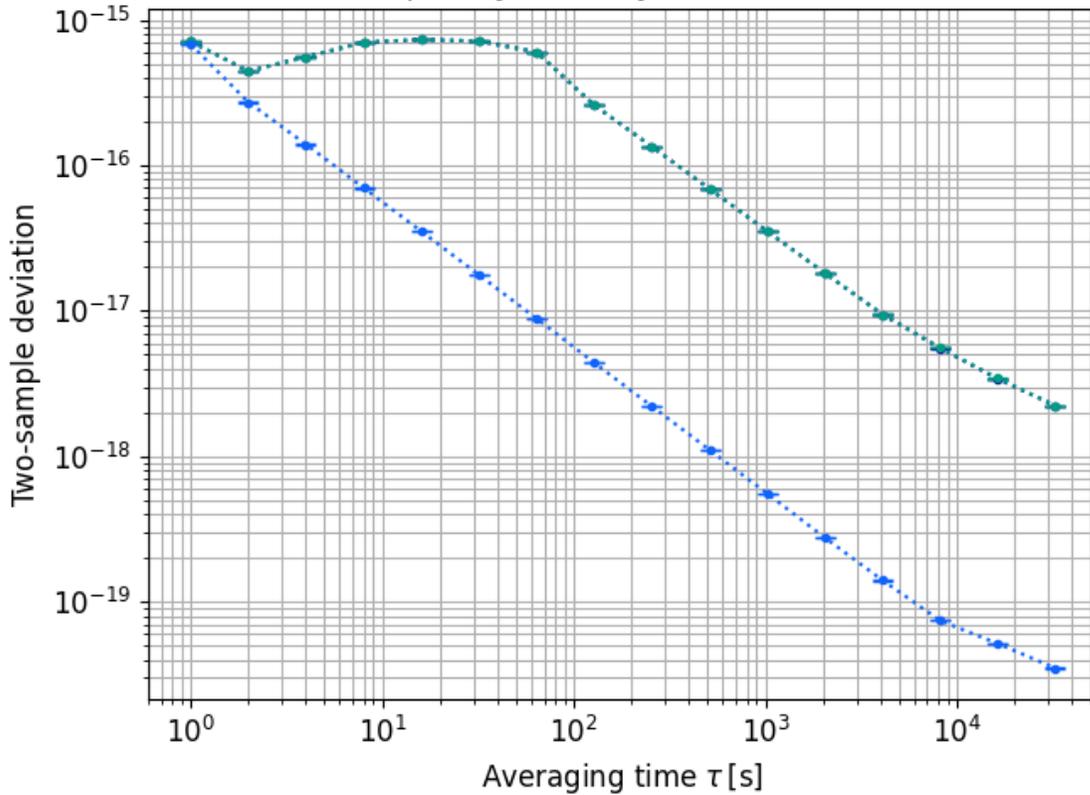
Comparison of different evaluations





Assessing the frequency transfer \Rightarrow Overlapping Allan deviation

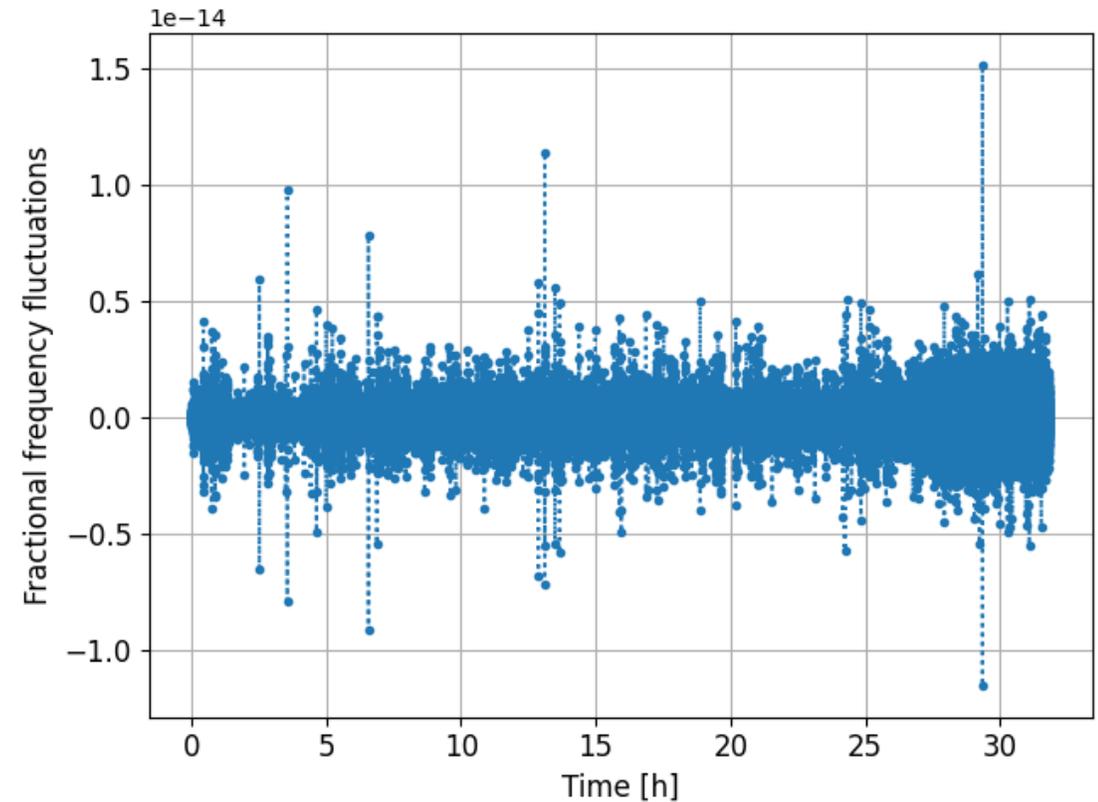
Fractional frequency stability: Plain OADEV calculation



OADEV @ $\tau = 32768$ s: 3.50×10^{-20}

- 25/07/26 23:45 - 25/07/28 07:34 (ch1)
- 25/07/26 23:45 - 25/07/28 07:34 (ch2)
- 25/07/26 23:45 - 25/07/28 07:34

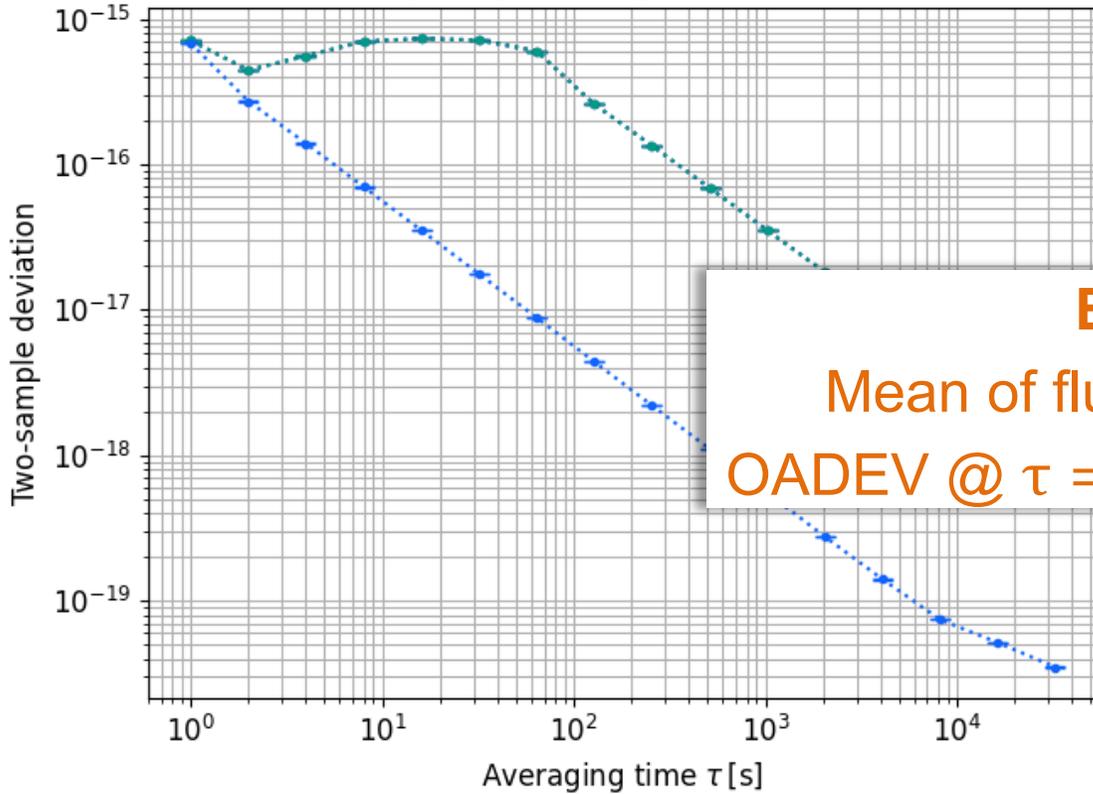
Mean of fluctuations: 3.61×10^{-20}





Assessing the frequency transfer \Rightarrow Overlapping Allan deviation

Fractional frequency stability: Plain OADEV calculation

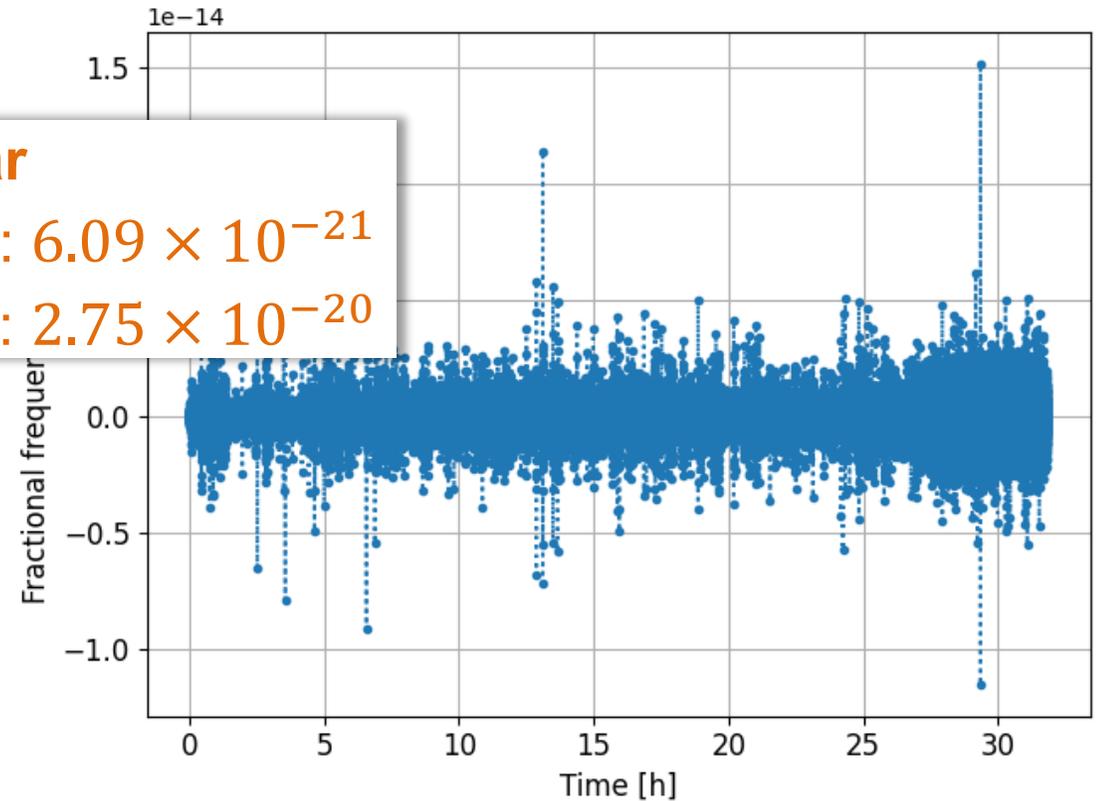


- 25/07/26 23:45 - 25/07/28 07:34 (ch1)
- 25/07/26 23:45 - 25/07/28 07:34 (ch2)
- 25/07/26 23:45 - 25/07/28 07:34

Mean of fluctuations: 3.61×10^{-20}

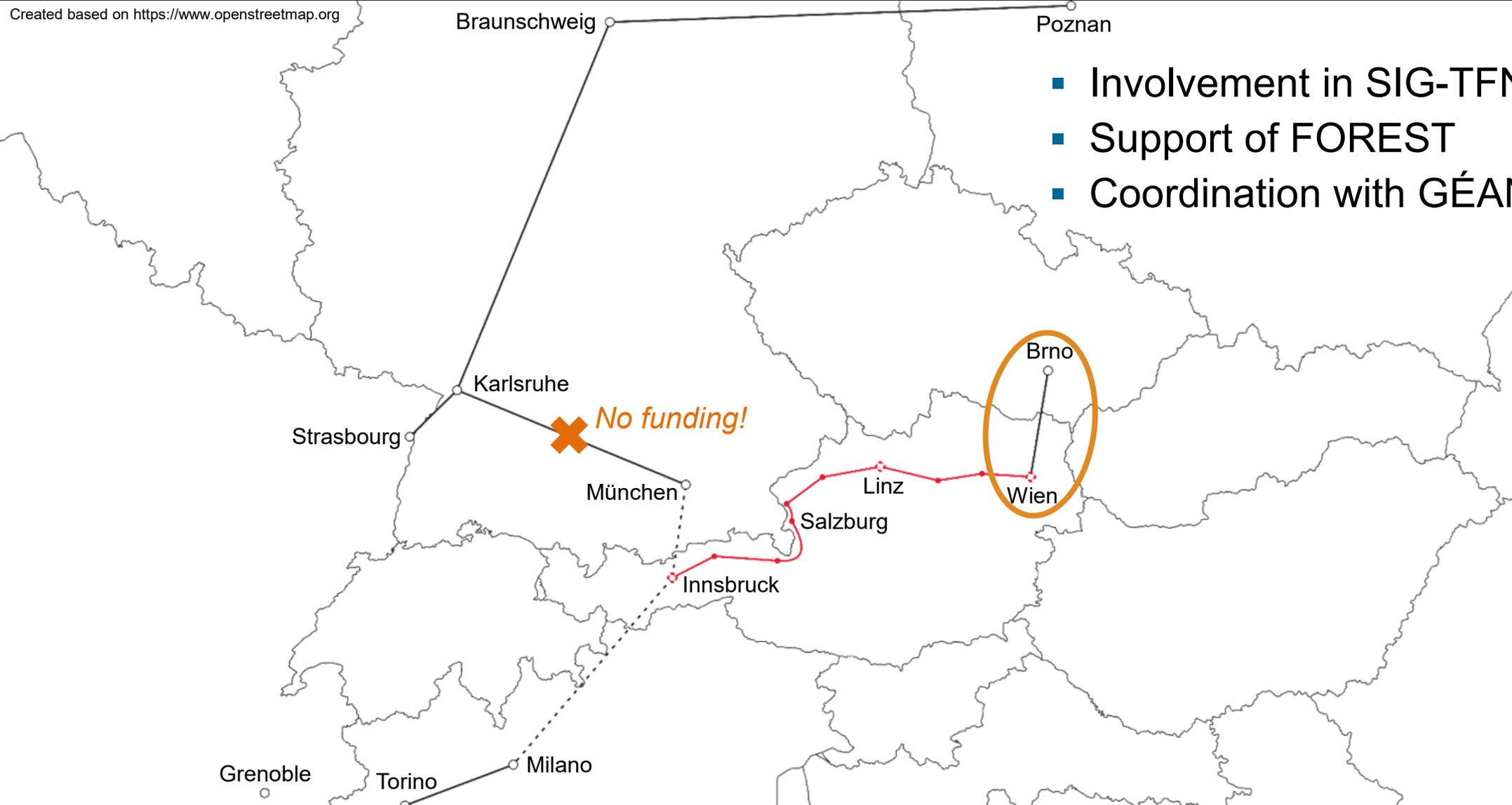
Best so far
 Mean of fluctuations: 6.09×10^{-21}
 OADEV @ $\tau = 32768$ s: 2.75×10^{-20}

OADEV @ $\tau = 32768$ s: 3.50×10^{-20}

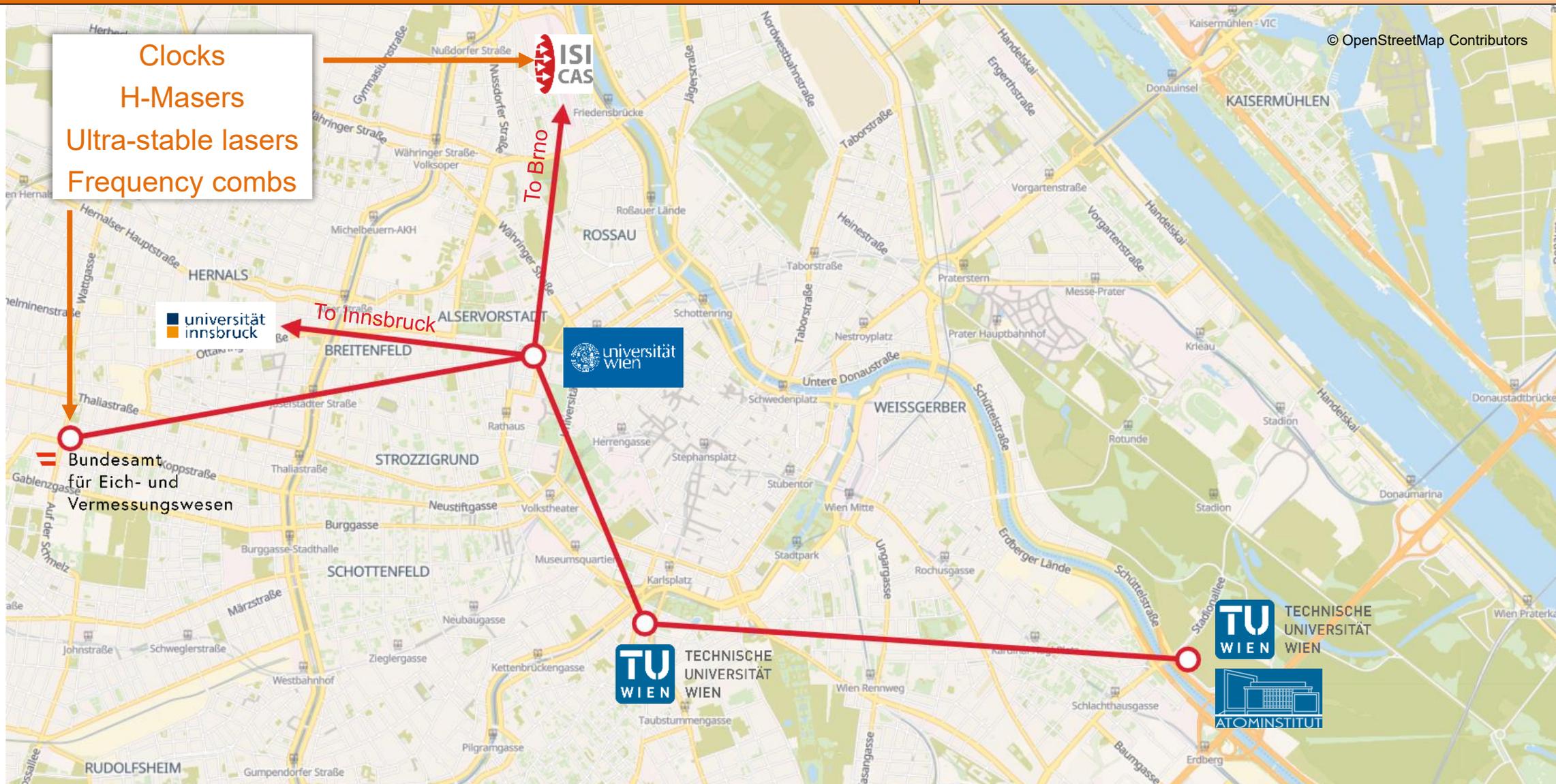




Created based on <https://www.openstreetmap.org>



- Involvement in SIG-TFN community
- Support of FOREST
- Coordination with GÉANT





cesnet

Bundesamt für Eich- und Vermessungswesen

Fibre link for optical frequency transfer between ISI and BEV

Cizek M¹, Pravdova L¹, Hrabina J¹, Lazar J¹, Pronebner T^{1*}, Aekens E², Premper J³, Havlis O⁴, Smotlacha V⁵, Altmannova L¹, Schumm T⁶, Vojtech J¹, Niessner A¹, Cip O¹

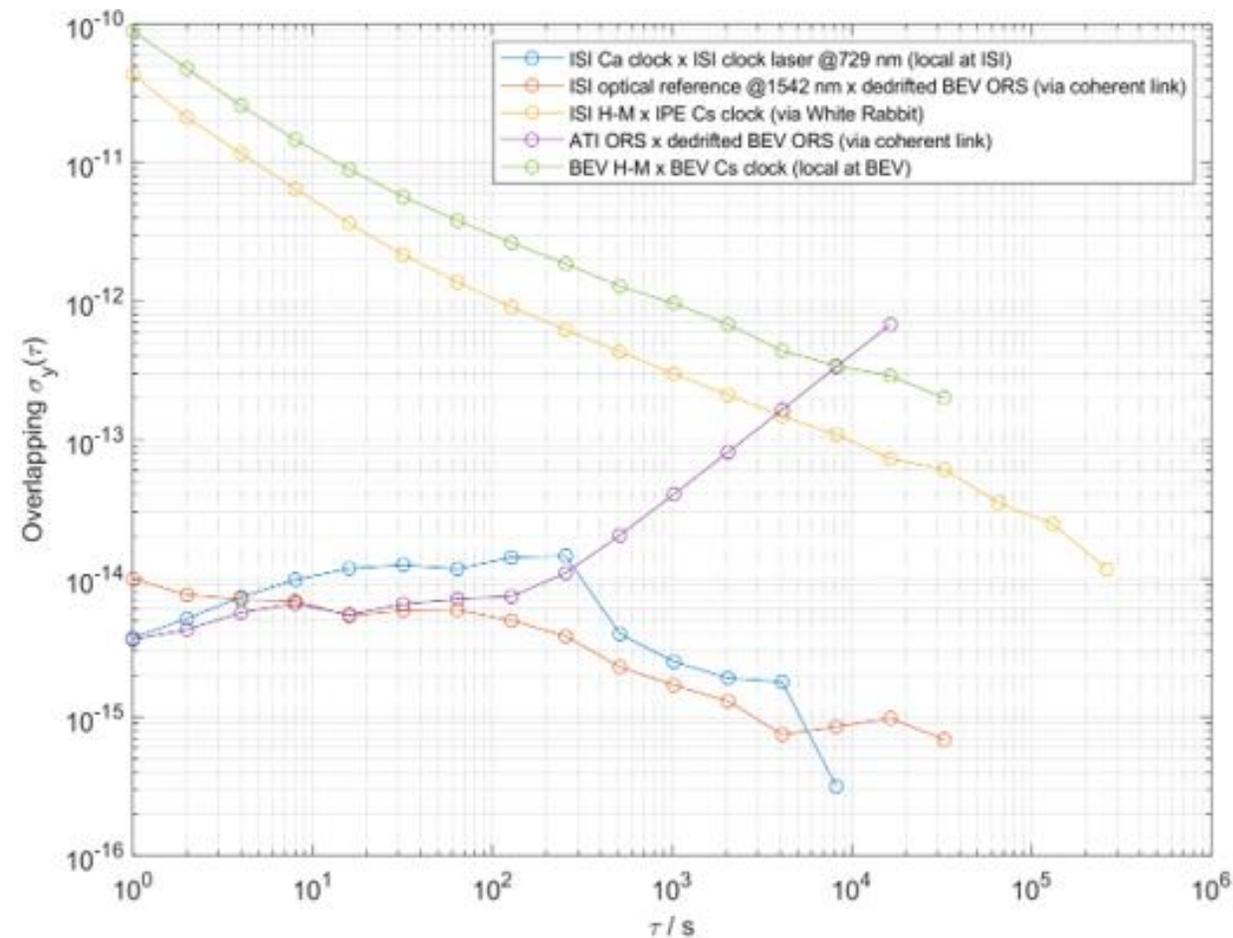
¹Institute of Scientific Instruments of the CAS, s. r. o., Brno, CZ, www.isi.cas.cz
²BEV - Federal Office of Metrology and Surveying in Vienna, AT
³CESNET, s. r. o., Prague, CZ
⁴Atominstytut, TU Wien, Vienna, AT

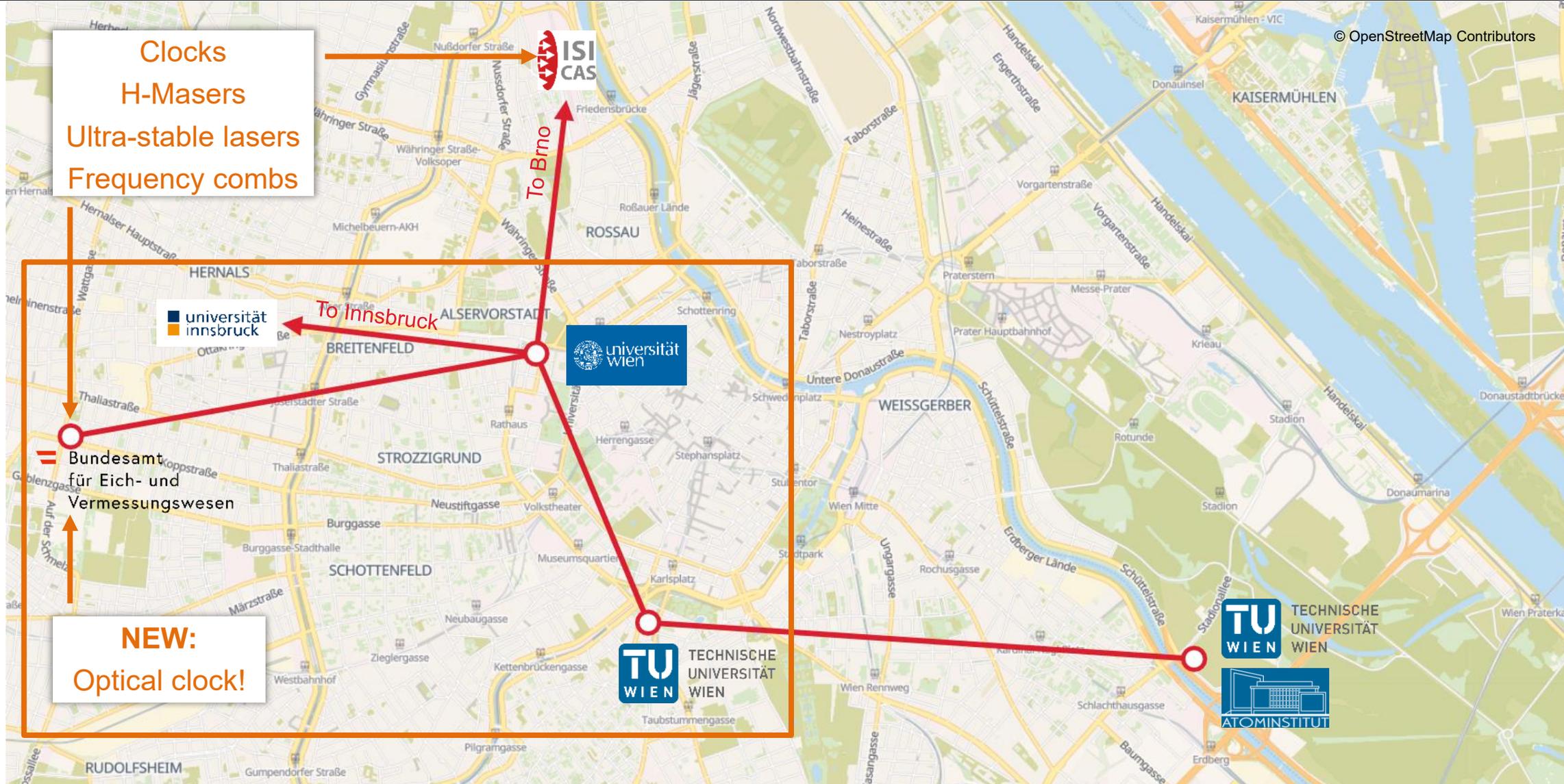
Our contribution presents the current state of operation and preliminary experiments conducted on a recently established 232 km-long Doppler compensated fibre link between the Institute of Scientific Instruments in Brno (ISI), CZ and Federal Office of Metrology and Surveying in Vienna (BEV), AT using CESNET, CZ communication infrastructure. To demonstrate the link functionality we measured phase noise power spectral density of atomic beam, role of two lasers locked to high-mass stable resonators. Using optical frequency combs at the both ends of the link, the long-term relative frequency deviation of local active hydrogen masers operating at ISI and BEV was estimated.

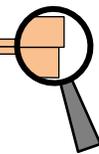
Development of electronics & optics @ ISI!



Comparison campaign:



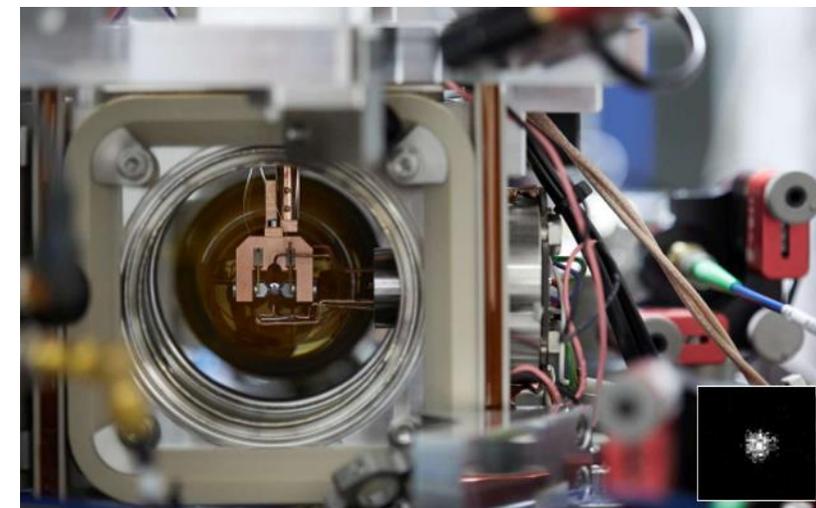




New star at BEV: “Topticlock”

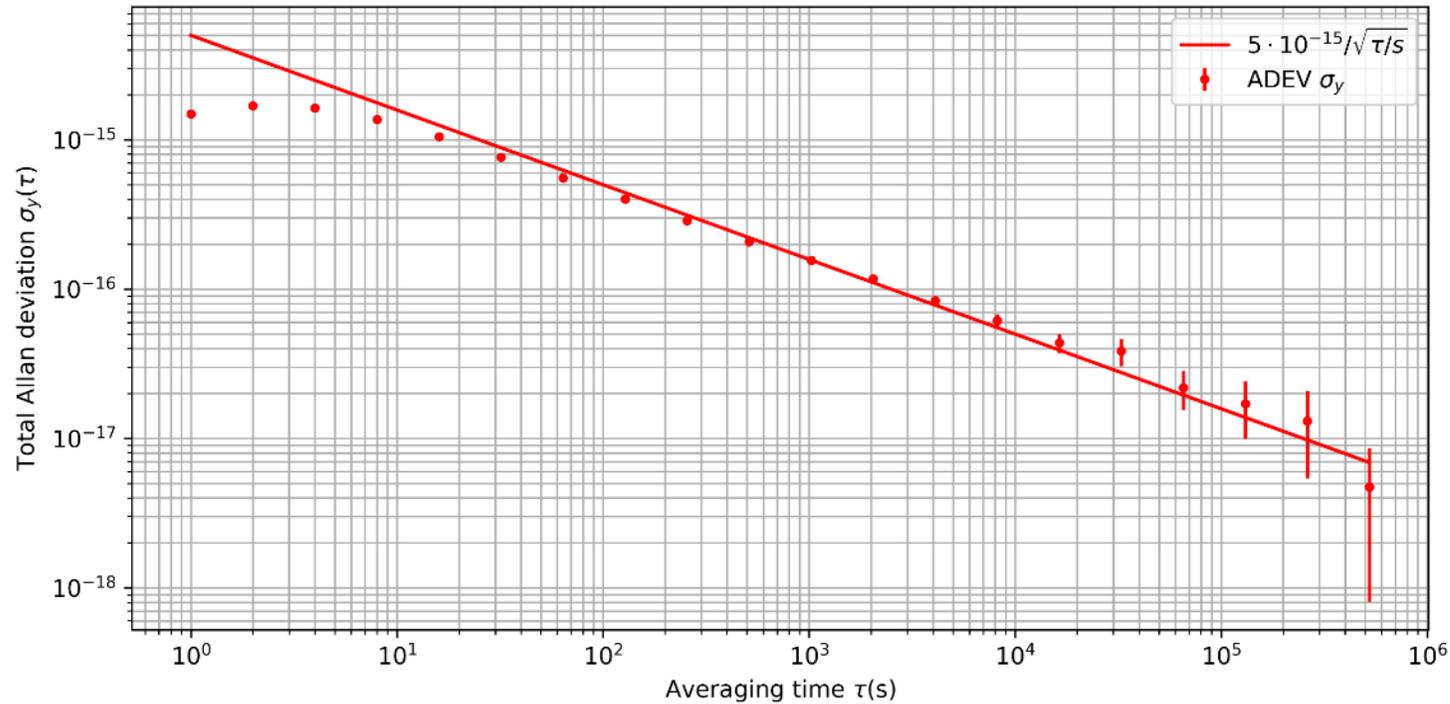
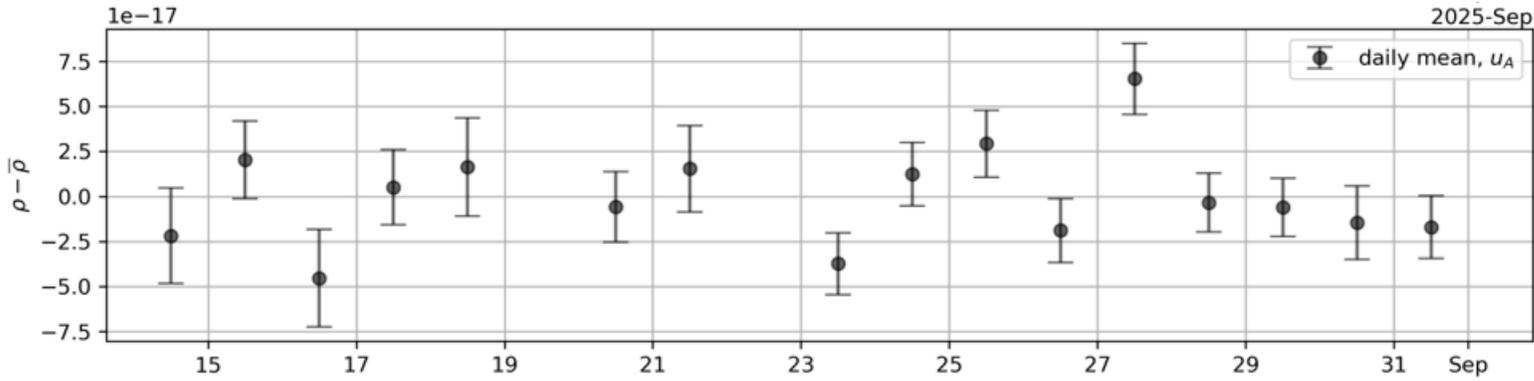


TOPTICA's OFS in the Clock Hall at PTB Braunschweig

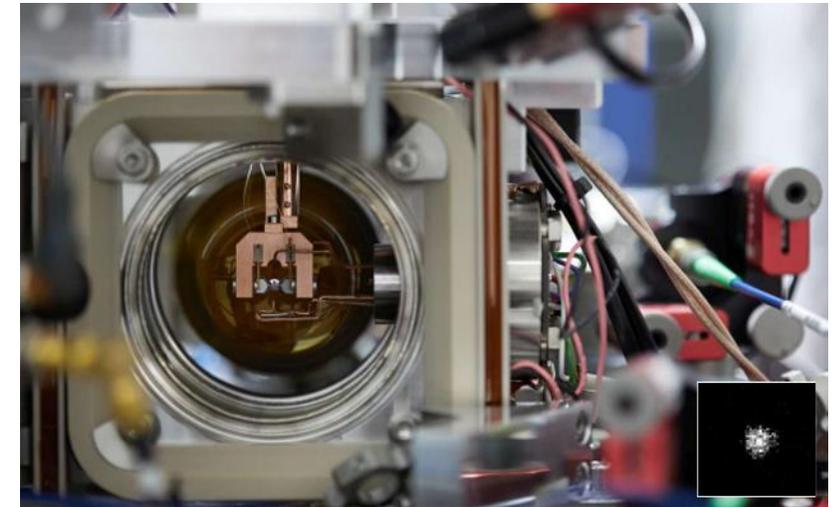


All contents from poster presentation

A. Friedenauer et al., *Commercial optical frequency standard based on a single $^{171}\text{Yb}^+$ ion*

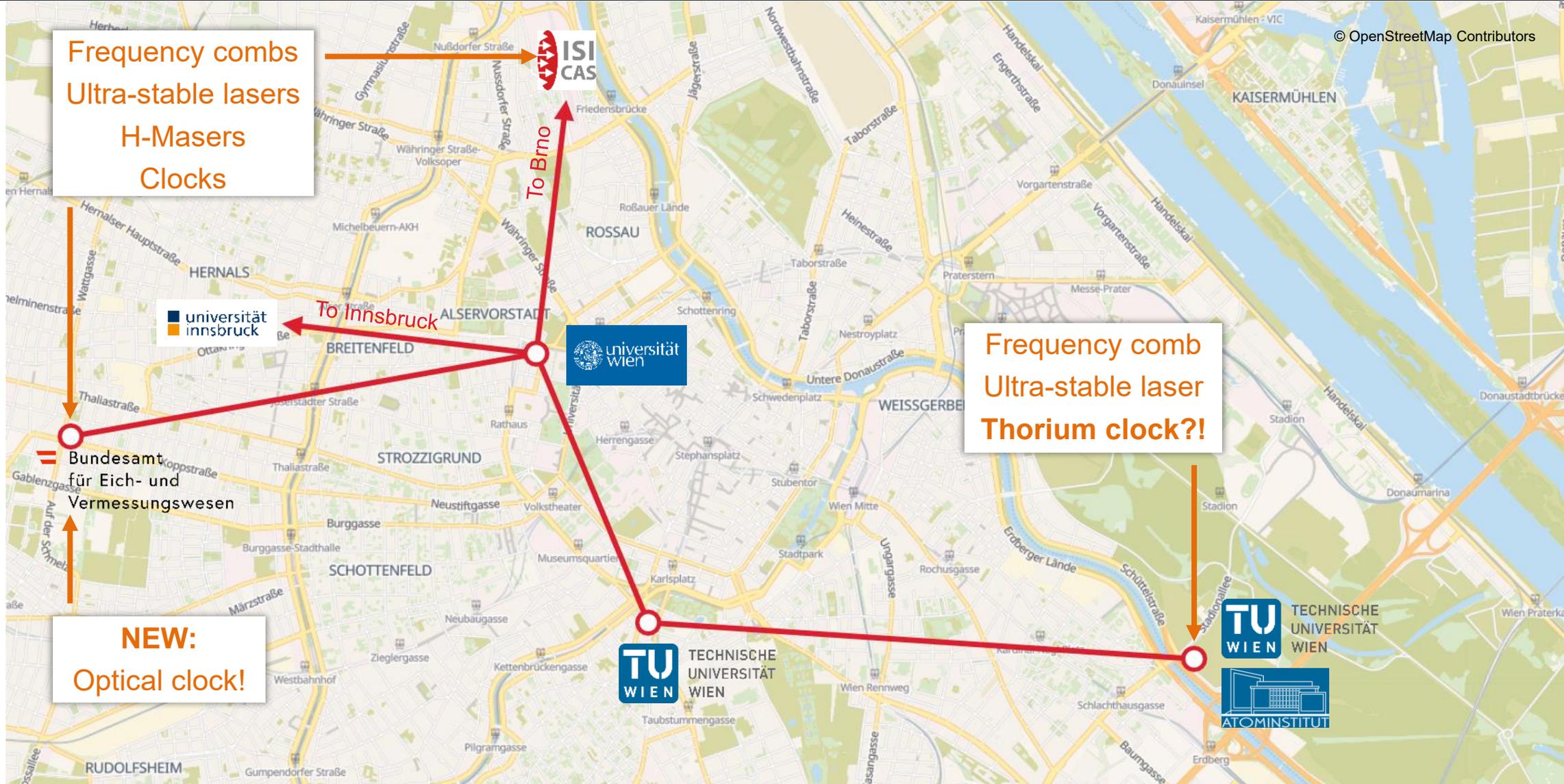


New star at BEV: “Topticlock”



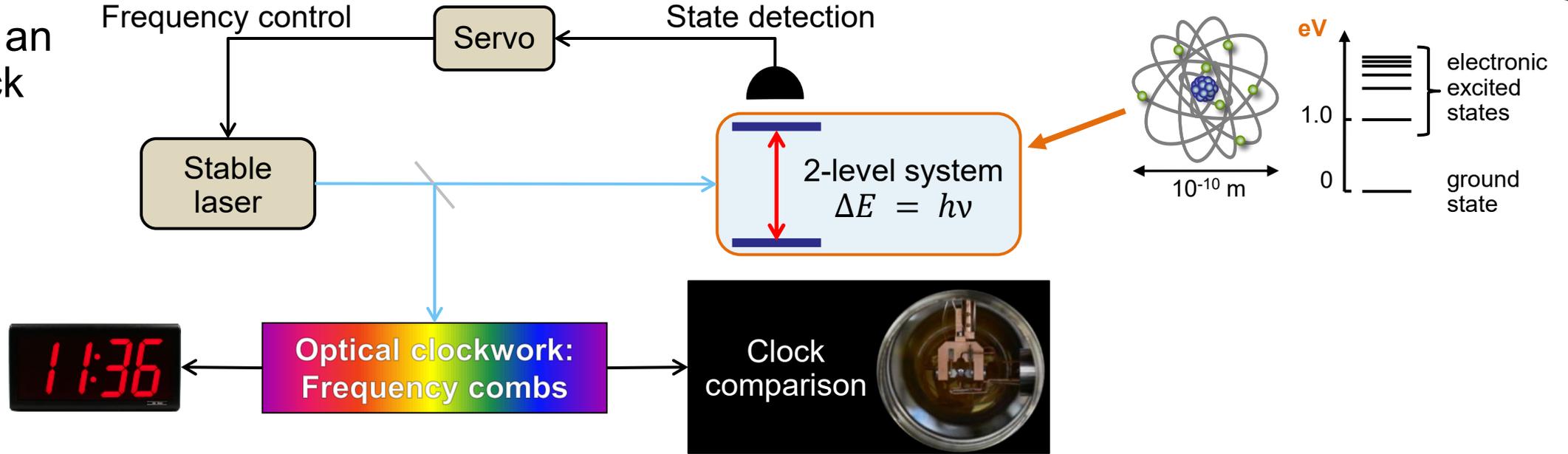
All contents from poster presentation

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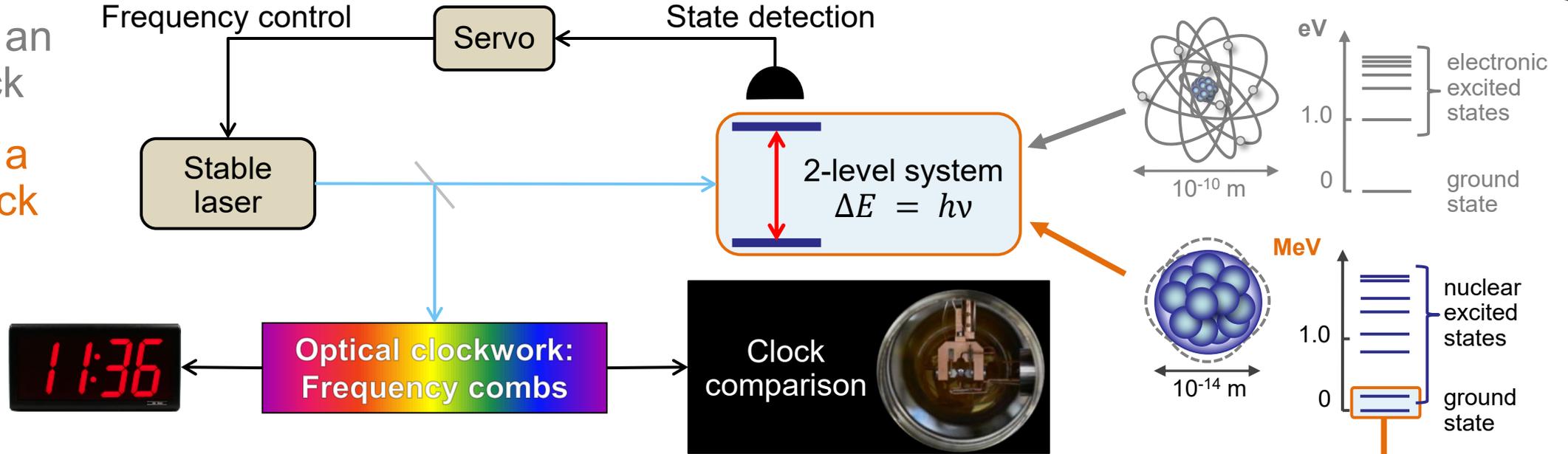
Scheme of an atomic clock





Scheme of an atomic clock

Scheme of a nuclear clock



Nuclear clock proposal: E. Peik and Chr. Tamm, *Europhys. Lett.* 61, 181-186 (2003)

The thorium-229 low-energy isomer and the nuclear clock: K. Beeks et al., *Nature Reviews Physics* 3, 238–248 (2021)

Laser Excitation of the Th-229 Nucleus: J. Tiedau et al., F. Schaden et al., *Phys. Rev. Lett.* 132, 182501 (2024)

²²⁹Th
90
7917 a
α: 4.845 MeV

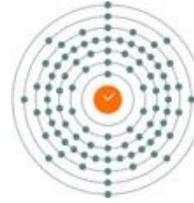
²²⁹Thorium properties:

- Lowest excitation energy of all nuclides
- Half-life (α-decay): ~7900 a
- Production: α-decay of ²³³U or β-decay of ²²⁹Ac
- Nuclear transitions: Robust against perturbations

²²⁹Th isomer
 $\Delta E \approx 8.36 \text{ eV} \approx 148.38 \text{ nm}$
~0.1 mHz natural linewidth
ground state



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QME Vienna
Thorium Nuclear Clock



Questions?

Quantum Metrology group Vienna

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