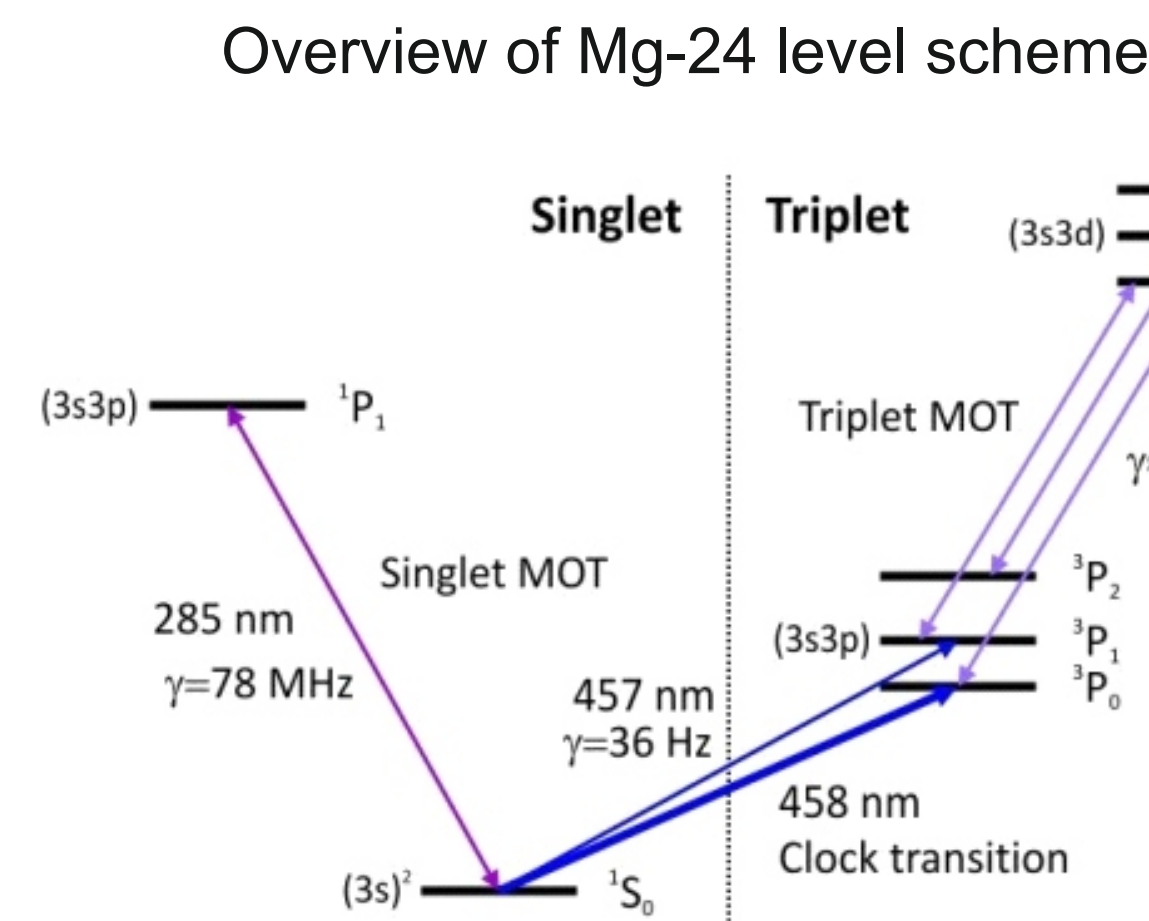


A candidate for a future frequency standard

Optical clocks based on cold neutral atoms have already exceeded the best microwave clocks in accuracy and stability.

Magnesium is a promising candidate for a future optical frequency standard due to its **low sensitivity to black body radiation**, which currently limits modern optical clocks.

Magnesium has two valence electrons which results in a singlet and triplet manifold of its electronic states. The intercombination lines between these manifolds offer a very **narrow linewidth** and, hence can be employed for the implementation of an optical clock.



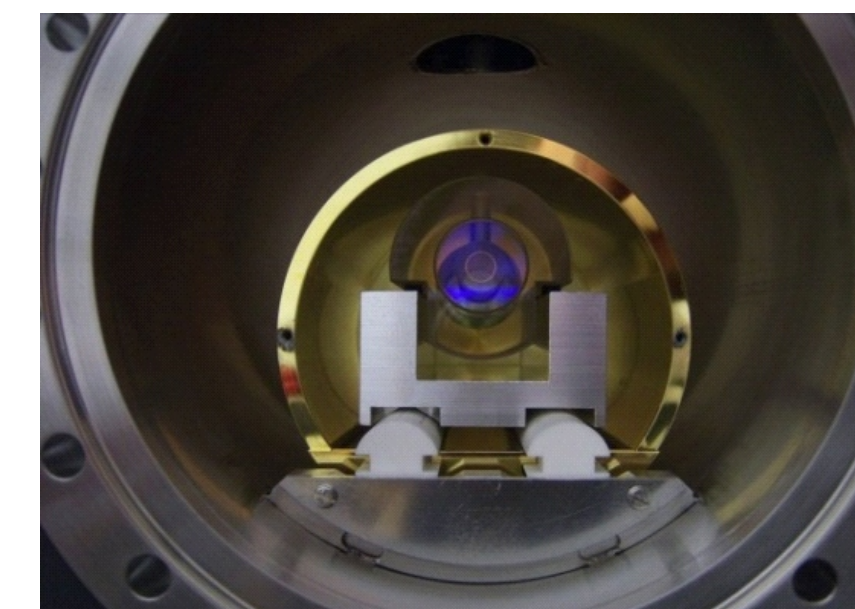
Comparison to other clock species

Element	Strontium	Ytterbium	Mercury	Magnesium
Frequency	429 THz	518 THz	1129 THz	655 THz
Magic wavelength	813 nm (measured)	759 nm (measured)	363 nm (measured)	460 – 470 nm (predicted)
Fractional Blackbody Shift	$-5.5 \cdot 10^{-16}$	$-2.6 \cdot 10^{-16}$	$-1.6 \cdot 10^{-16}$	$-3.9 \cdot 10^{-16}$

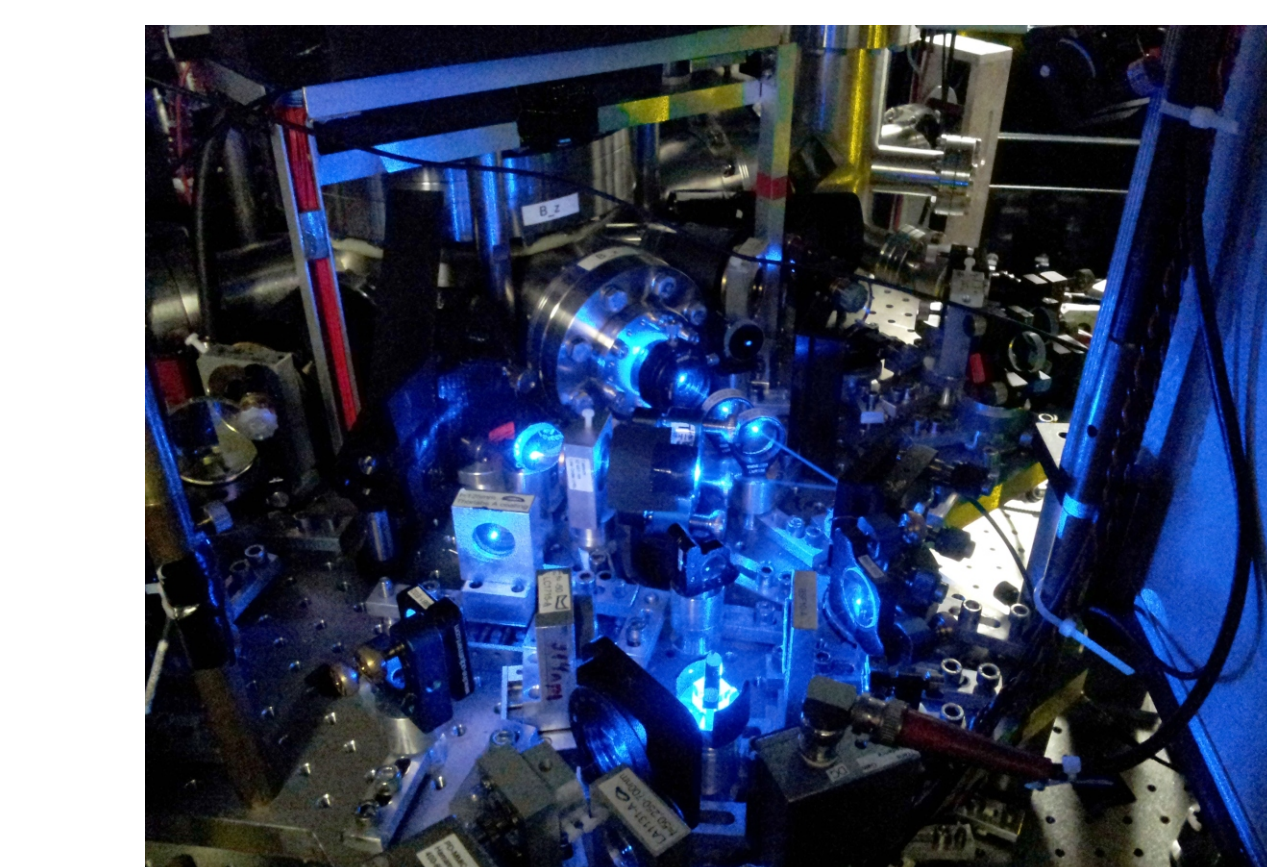
First order Doppler shifts are limiting the uncertainty of the current magnesium frequency standard with free falling atoms to 7×10^{-14} . A possibility to overcome this limitation is given by a strong spatial confinement of the atoms in the Lamb-Dicke regime. This can be realised in **optical lattices**.

We have recently demonstrated the successful trapping of 10^4 magnesium atoms in an optical lattice near the predicted magic wavelength. At the magic wavelength the differential AC Stark shift vanishes. The lattice is generated within a build-up cavity in order to fulfill the power requirements.

The **clock laser** used for the magnesium frequency standard is a grating stabilised diode-lasers at **916 nm** locked to a high finesse cavity.

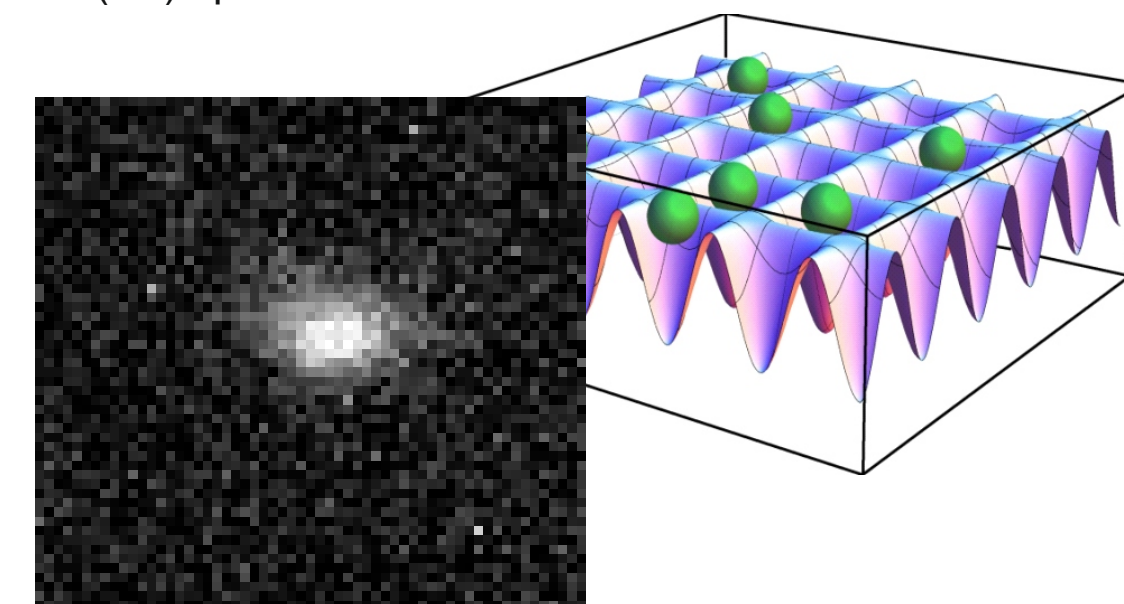


Mounting of the high finesse resonator of the clock laser.



Implemented enhancement cavity of the lattice laser around the vacuum chamber.

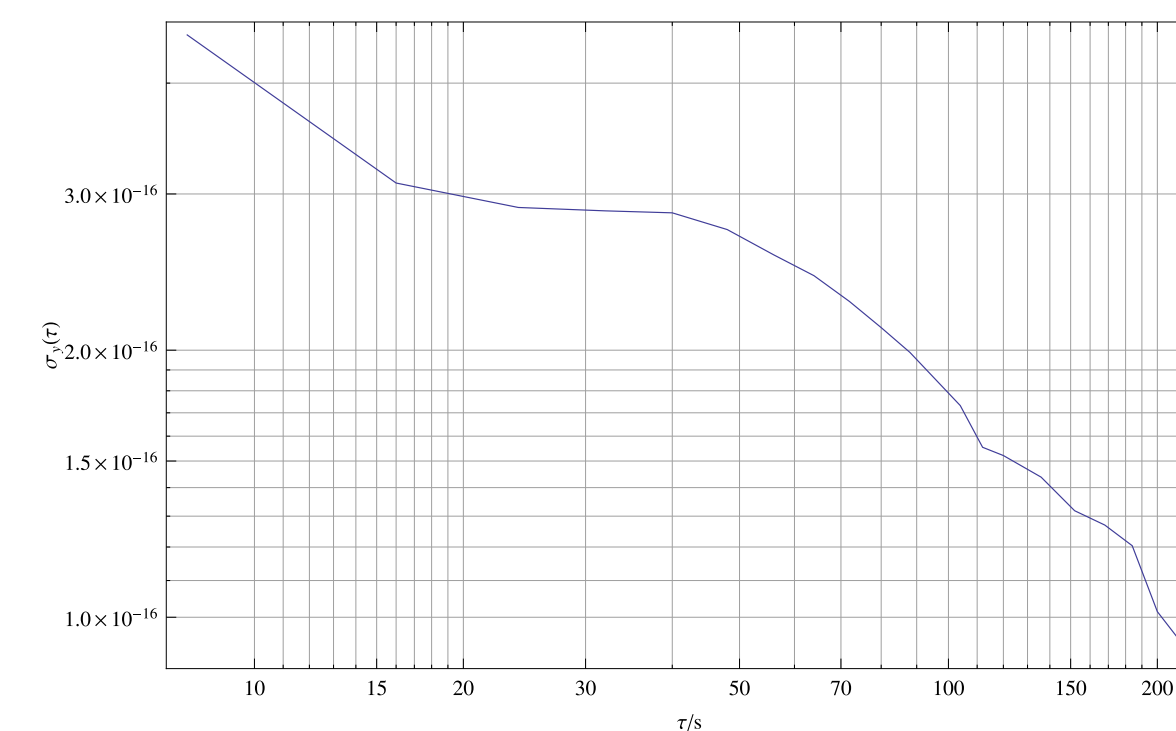
Fluorescence image of cold magnesium atoms being trapped in an (1D) optical lattice.



Remote comparison against PTB



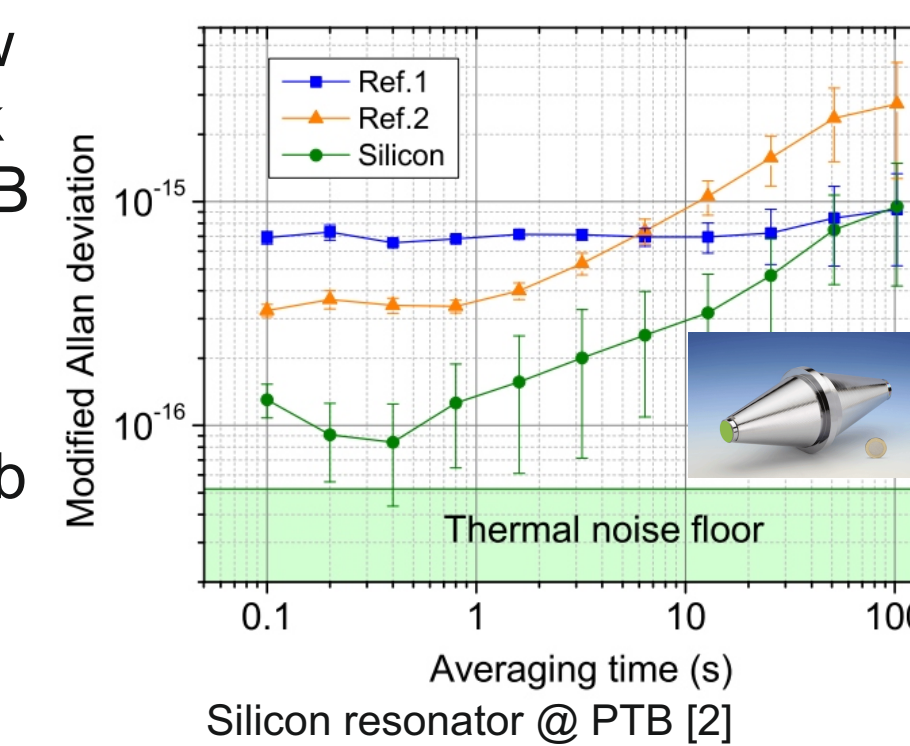
The magnesium frequency standard with free falling atoms has been compared to the calcium clock laser stabilized to the hydrogen maser H5 of the PTB via a 73 km long stabilized fiber link with an instability of 3×10^{-15} in 100 ms [1].



Estimated instability due to optical lattice of Mg atomic clock (left) and measured spectroscopy signal (right).

For **fast and accurate clock comparison** in the low 10^{-16} regime and even below a highly stable fiber link to other frequency standards like the Sr clock @ PTB is necessary.

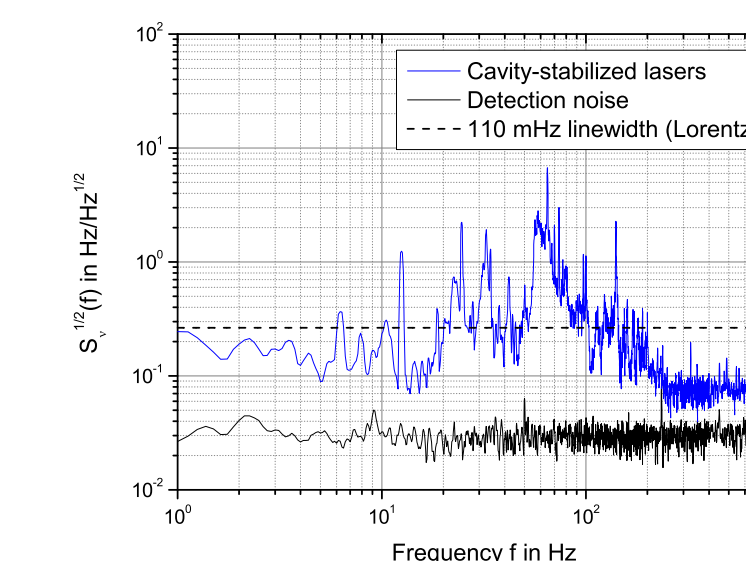
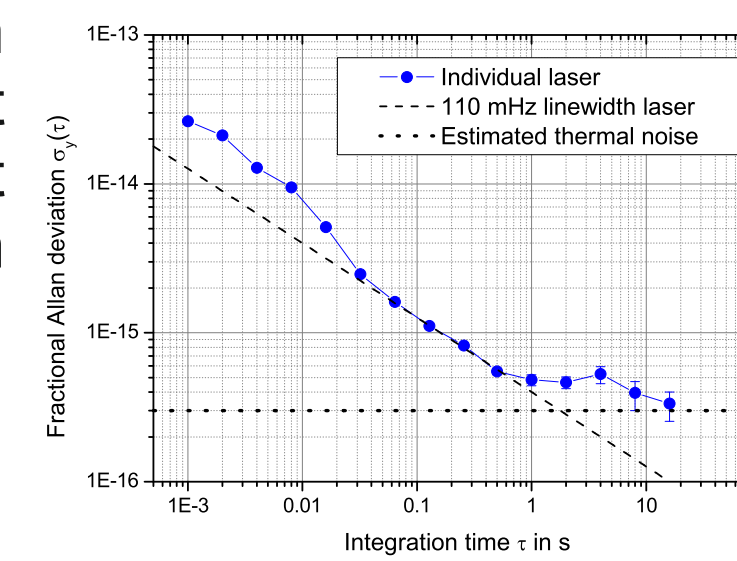
The stabilized light from IQ will be transferred to a wavelength of 1.5 μ m by means of a frequency comb and then transmitted and compared @ PTB against the silicon resonator which is stabilized to the Sr clock transition.



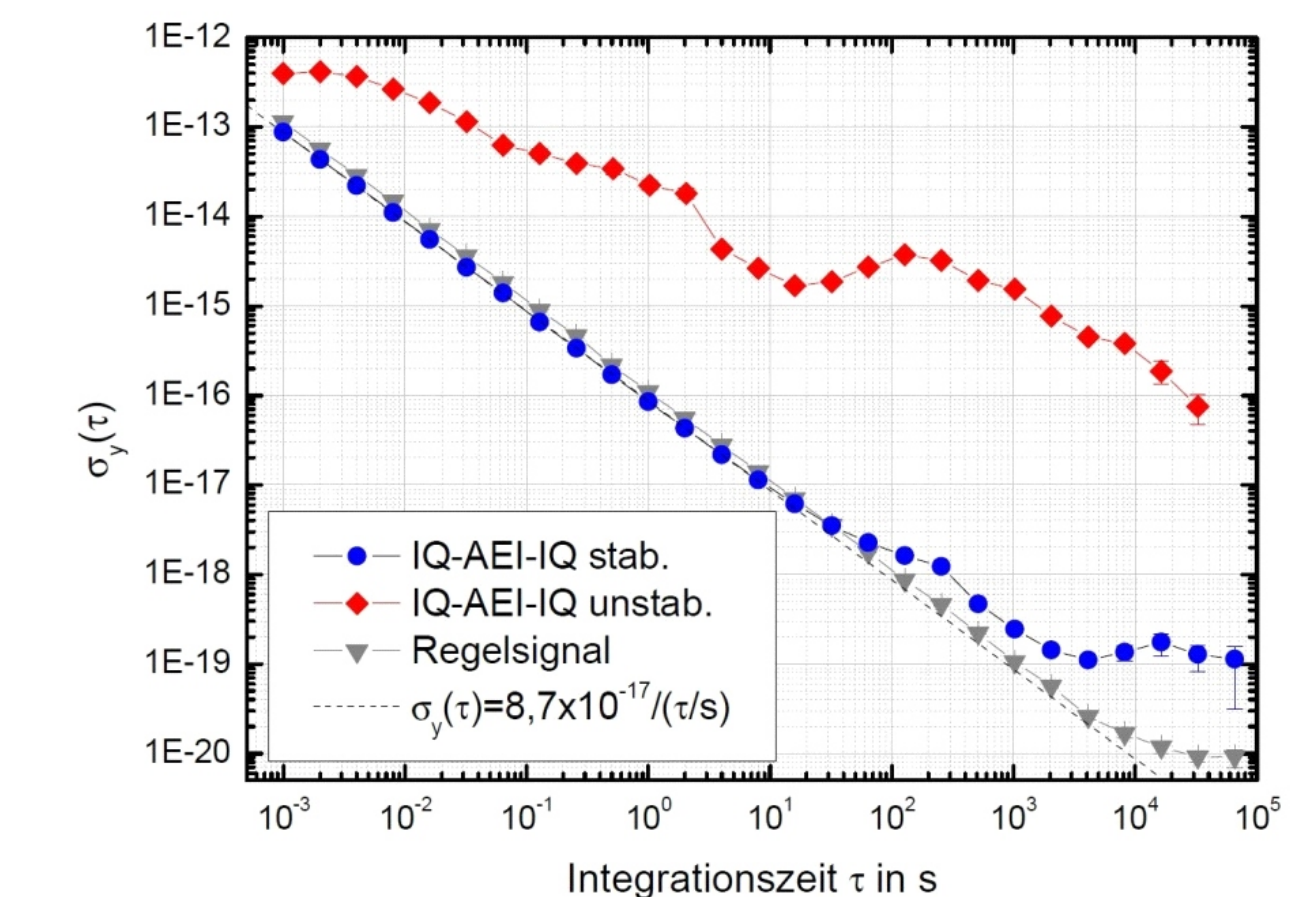
Clock laser performance

For reasons of laser characterization two independent laser systems at 916 nm have been set up such that the resonators are isolated from environmental perturbations.

An individual frequency instability of 5×10^{-16} has been achieved.

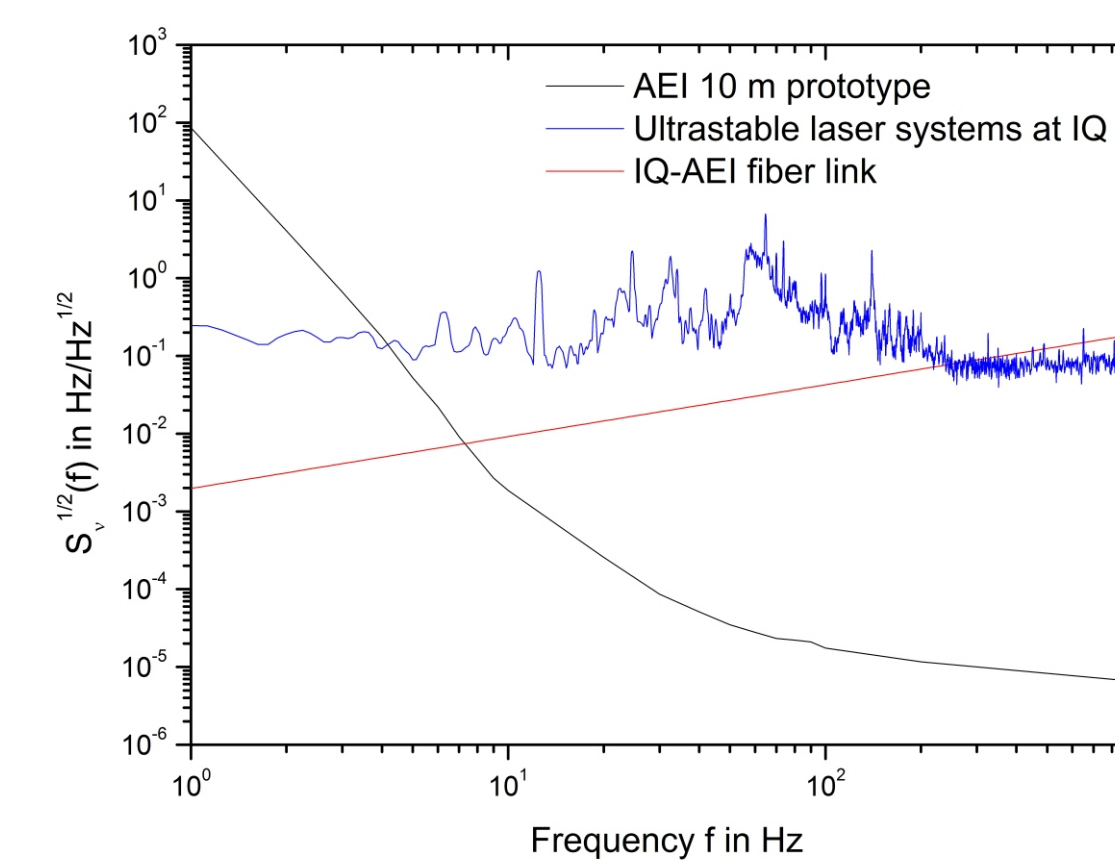


Synergies with gravitational wave detectors



Shown is the frequency transfer from IQ to the Albert Einstein Institut (AEI) Hannover with and w/o fiber stabilization. The transfer instability achieved is 9×10^{-17} (1/s).

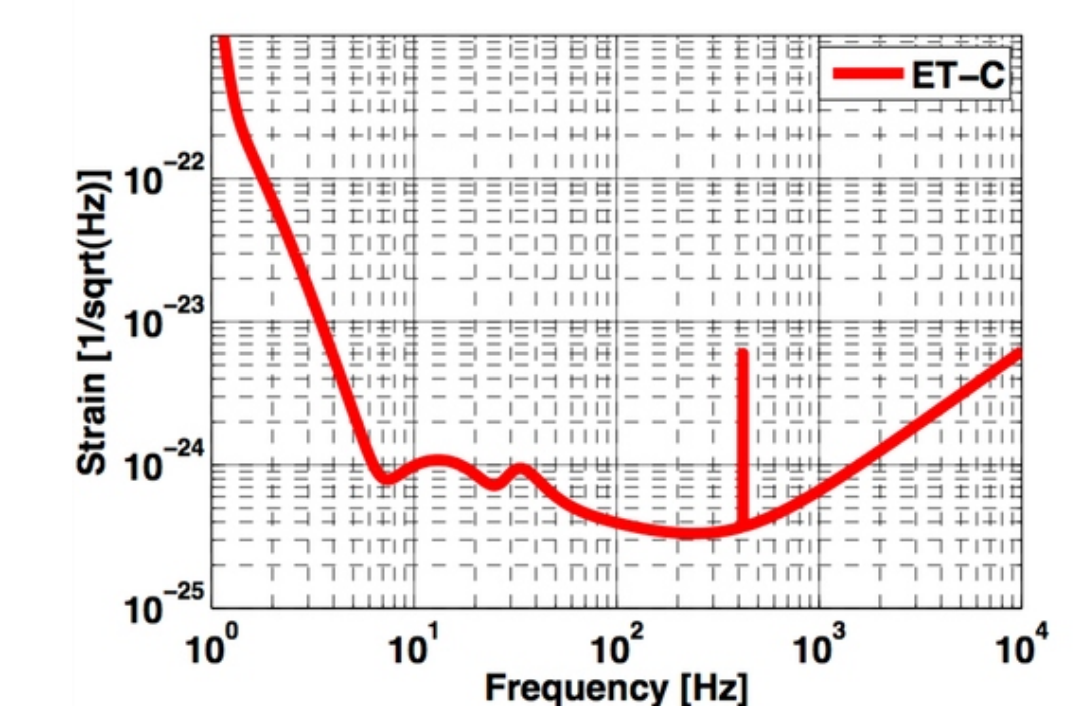
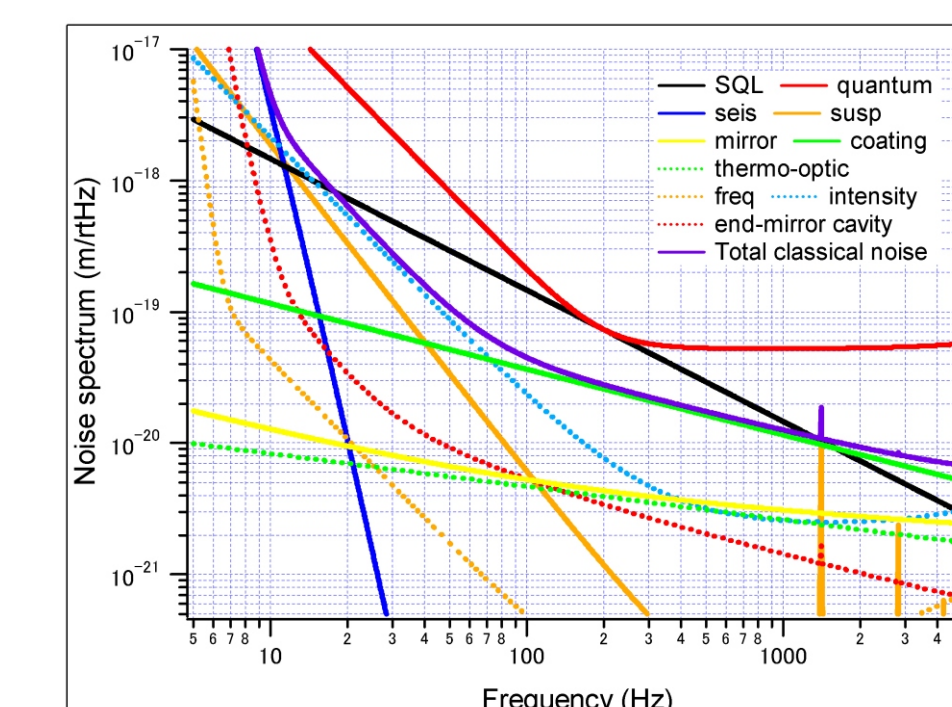
Combination of a variety of frequency standards to realize a highly stable reference frequency in a broadband frequency regime, i.e. combining gravitational wave detectors with clock laser systems and atomic references.



The overlap of instabilities of the clock laser system @ IQ and the 10 m prototype interferometer @ AEI is shown.

The systems could benefit from each other by **complementary** stabilization. Clock laser systems would improve in higher frequency regimes due to typically long interferometer arms of gravitational wave detectors compared to clock laser resonators.

Therefore more stable fiber links would further improve synergies.



Possible candidates for further clock laser improvements:
Left: Calculated sensitivity of 10 m prototype interferometer @ AEI [3]
Right: Theoretical sensitivity of planned Einstein Telescope (gravitational wave detector) [4]

References

- [1] J. Friebe et al., New J. Phys. 13, 125010 (2011)
- [2] T. Kessler et al., Nature Photonics 6, 687–692 (2012)
- [3] S. Goßler et al., Class. Quantum Grav. 27 084023 (2010)
- [4] <http://www.et-gw.eu/etsensitivities>

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Contribution to collaboration projects:

Development of highly stable interrogation, cooling and trapping lasers (SOC 2)
Cavity tests in microgravity (PRIMUS 2)
Optical atomic clocks in space (OACS)

