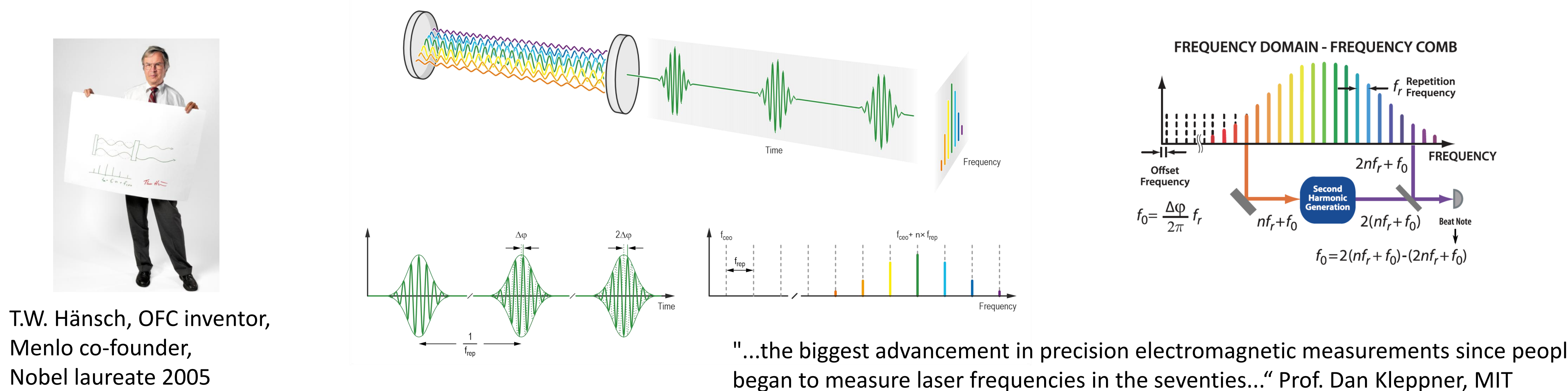


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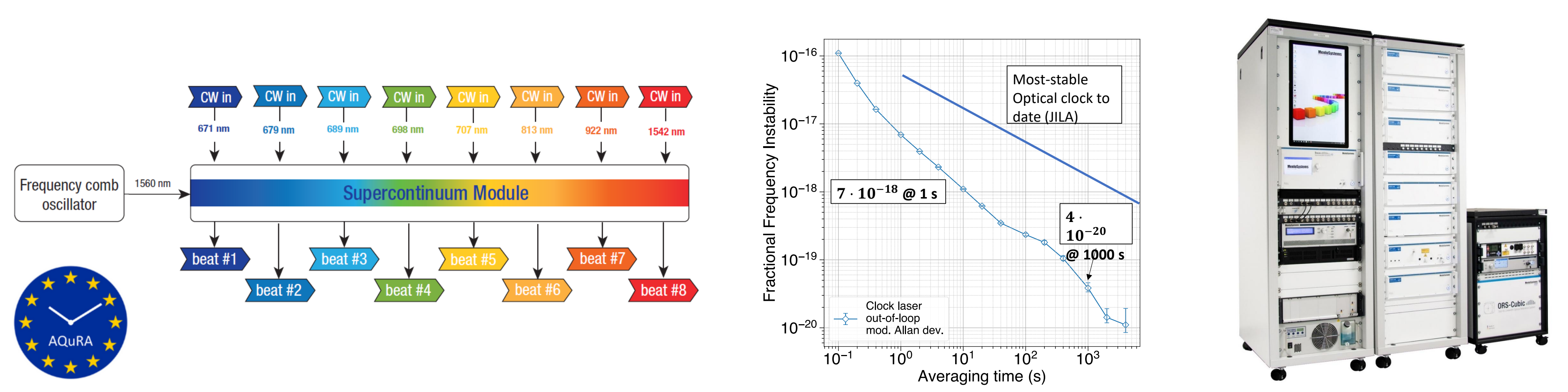
The idea behind OFCs

Optical frequency combs (OFCs) provide the gearbox between the metrological units of length being realized via stabilized CW laser radiation, and time [1,2]. The OFC metrological figures of merit have been investigated in numerous experiments in universities, research labs, and NMIs [e.g., 3]. OFCs have proven to allow for optical frequency measurements or comparisons with relative uncertainties below 1E-20 [4]. This comes along with engineering efforts rendering formerly complex opto-electronic setups into very reliable and easy-to-operate instruments which are commercially available. Consequently, OFCs are indispensable tools for applications where frequency-stabilized CW laser radiation is a central requirement, as well as for even the most advanced measurement tasks, including comparisons of the best optical clocks in laboratories worldwide [5,6], or even clock comparisons in space [7]. The OFC principle in a nutshell: The principle in some more detail: The f-2f approach for CEO stabilization:



Optical clock development

Optical clocks based on narrow transitions in atoms or ions will realize a future redefinition of the SI second. Such optical clocks, and many quantum computing schemes as well, rely on precisely prepared atoms and ions via interaction with various CW laser wavelengths for cooling, and for state preparation and manipulation. Often, the required wavelengths cover a broad range from the visible to the IR spectral region. Comparisons of different optical clocks are prerequisite for thorough understanding of systematic effects. This is simplified by stabilizing all required CW lasers on a single OFC which itself inherits its stability and spectral purity from an optical reference. OFC-OFC-comparisons prove that the OFC itself is not limiting the measurement at all. From left to right: Menlo Systems' universal supercontinuum module; OFC-OFC comparison at the Sr 698 nm wavelength; OFC including stabilized CW lasers.

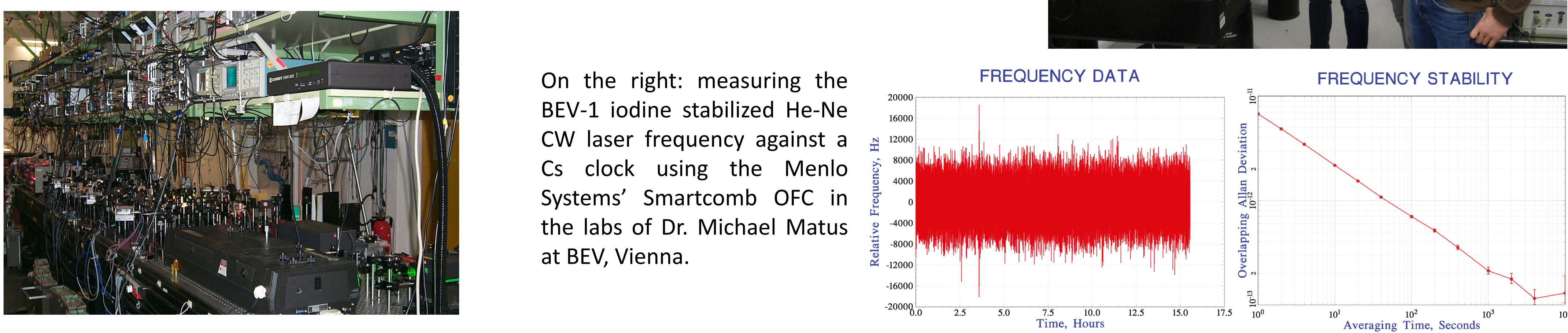


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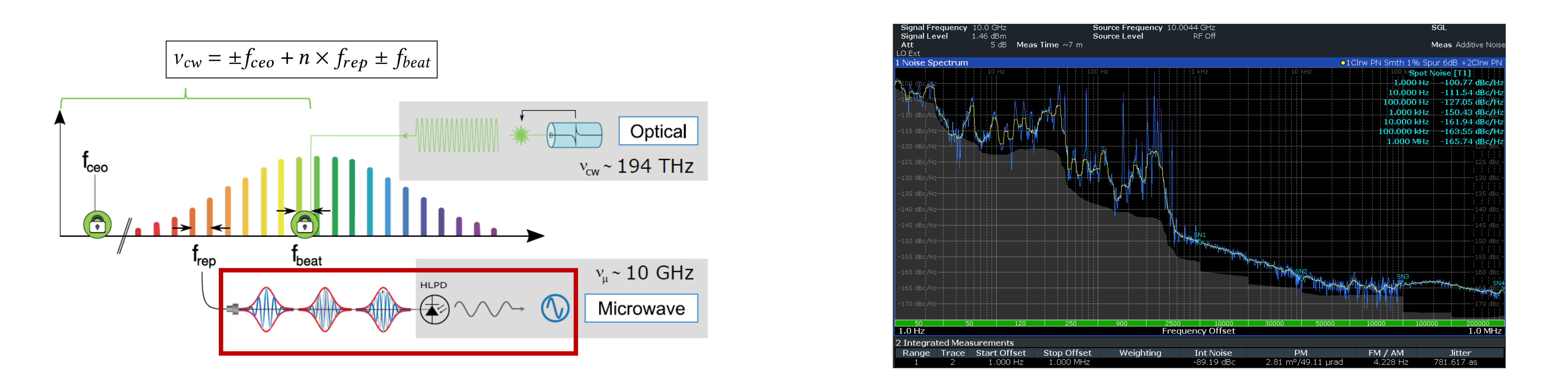
OFCs in frequency and length metrology

OFCs link frequency and length metrology. This allows to measure the realization of the definition of the meter, e.g. via iodine stabilized He-Ne lasers, with respect to the realization of the definition of the second in Cs atomic clocks. NMIs routinely perform such measurements without the need to ship their precious metrology lasers around the world. Still, so-called key comparisons as described in [8] support in maintaining consistency in this very important field of metrology. Over the course of the last three decades, the technology of optical frequency combs has matured. On the left: early OFC experiments at MPQ Garching (1999), utilizing a fs Ti:Sa laser as comb generator in a measurement of the hydrogen 1S-2S transition frequency against the 9.2 GHz frequency from a Cs atomic clock.



Photonic microwaves

Using OFCs, the spectral purity and the stability of optical references can be divided down into the RF and microwave domain. This is the classical clockwork approach for optical clocks. Done properly, this division results in a vast phase noise improvement, outperforming any other microwave source in terms of phase noise [9,10]. Applications of such photonic microwaves include optical clocks, radar, test and measurement, VLBI, and 6G mobile communication. For utmost performance, Ultra-low-noise OFCs with high-bandwidth actuators are tightly locked to ultra-stable optical references. Optical interleavers enhance the signal strength at harmonics of the fs laser pulse repetition rate. They are being detected by highly linear photodiodes operating at minimum AM- to PM-conversion. Principle of photonic microwave generation: Phase noise trace at 10 GHz:



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- Worldwide collaborators, project partners, and customers
- German, European, and international funding agencies
- **The Menlo staff, including all previous colleagues**