INSTITUTE OF SCIENTIFIC INSTRUMENTS
The Czech Academy of Sciences

Quantum Metrology

mostly of time and length

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Quantum revolution

We are on the brink of **second wave** of quantum revolution

1st wave of quantum revolution – semiconductors and microelectronics, as we know:

tranzistor, laser, optical fibers, integrated circuits, GPS ...

Its fathers are great physicists of the 20th century, Planck, Einstein, Heisenberg, Bohr and others, they laid the basis of quantum physics and wave-particle dualism

Technologies of he 1st wave operate with statistical description of the behavior of many quantum particles

European Flagship programme

2nd wave quantum revolution – present vision of quantum technologies

quantum networks, communication, computing, measurement ...

The basis are two key principles:

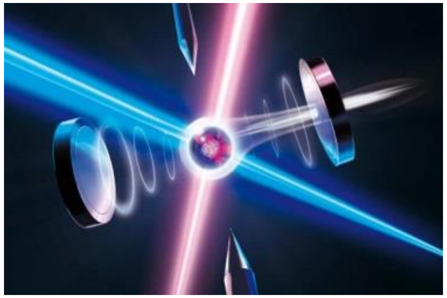
- **superposition –** objects may be in several states at once
- **entanglement –** objects may be interlinked without physical

interaction on the level of discrete quantum objects

European initiative of Quantum technologies

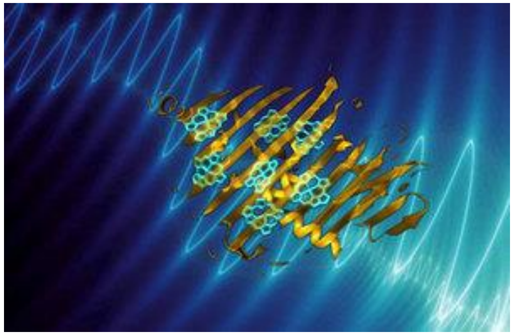
Initiative joins 6 topics ...

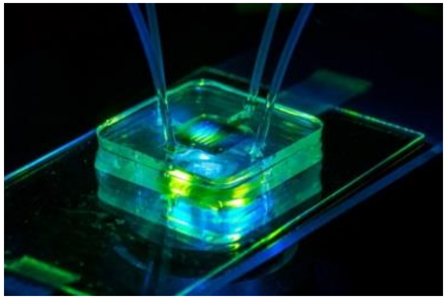
... and this is ours



Quantum metrology
(ion clock)

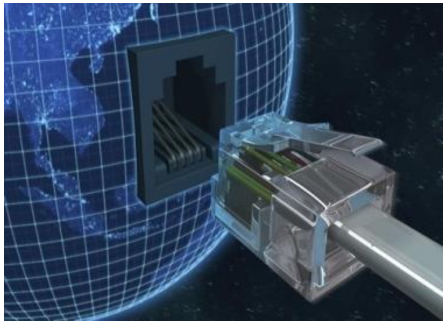
Quantum simulators





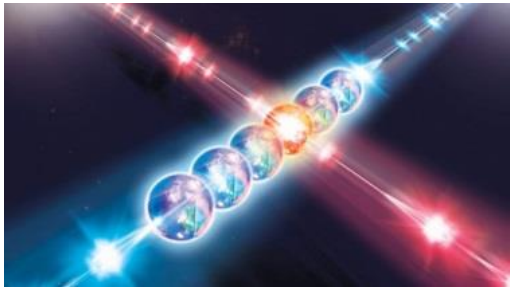
Quantum sensors

Quantum cryptography



Quantum communications

Quantum computing



Metrology

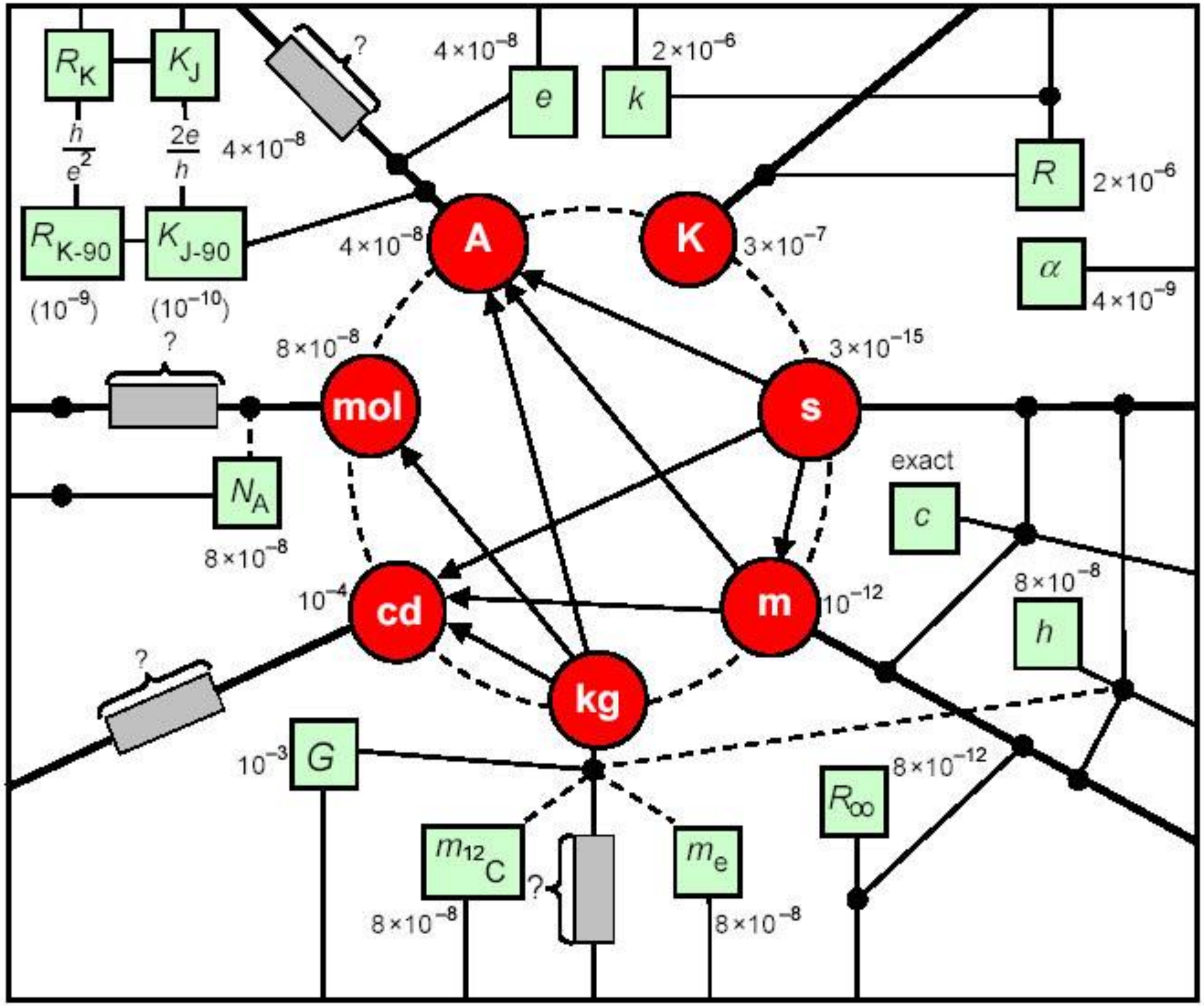


Diagram shows links between 7 fundamental quantities of **SI** system:

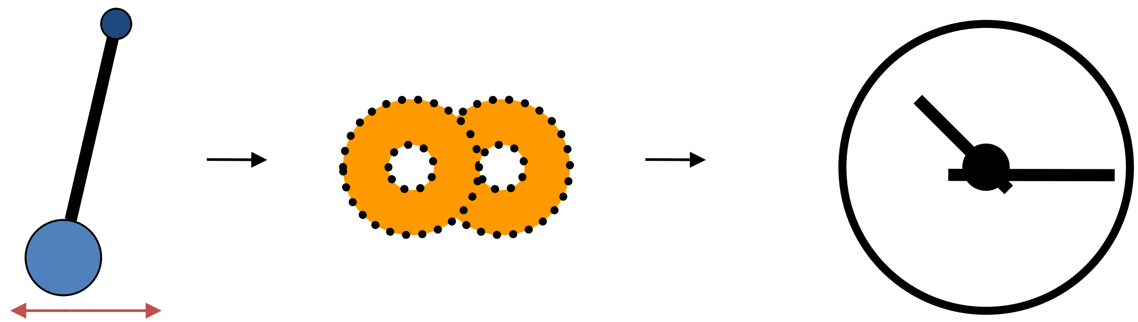
➔ It is clearly visible dependence of the unit of length on the unit of time.

➔ The link is through the constant of speed of light in vacuum „c“

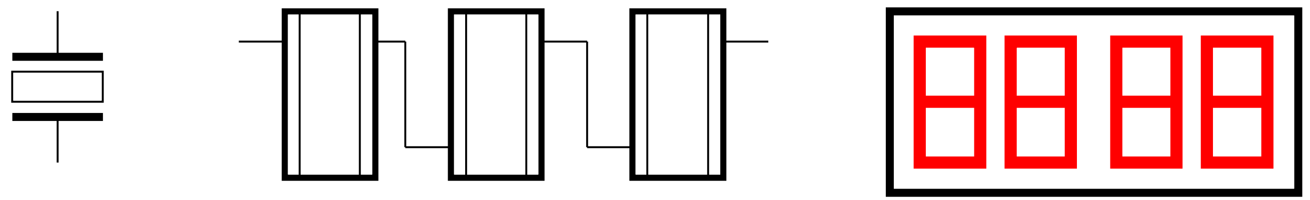
➔ Representation: time – Cesium clock (rf oscillator), length – laser (interferometer)

Clock and a meter

Mechanical clock



Electronic clock

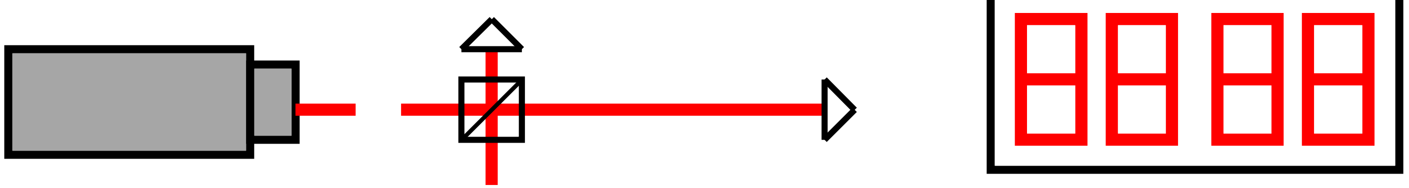


oscillator / pendulum

gear box / counter

display

Meter

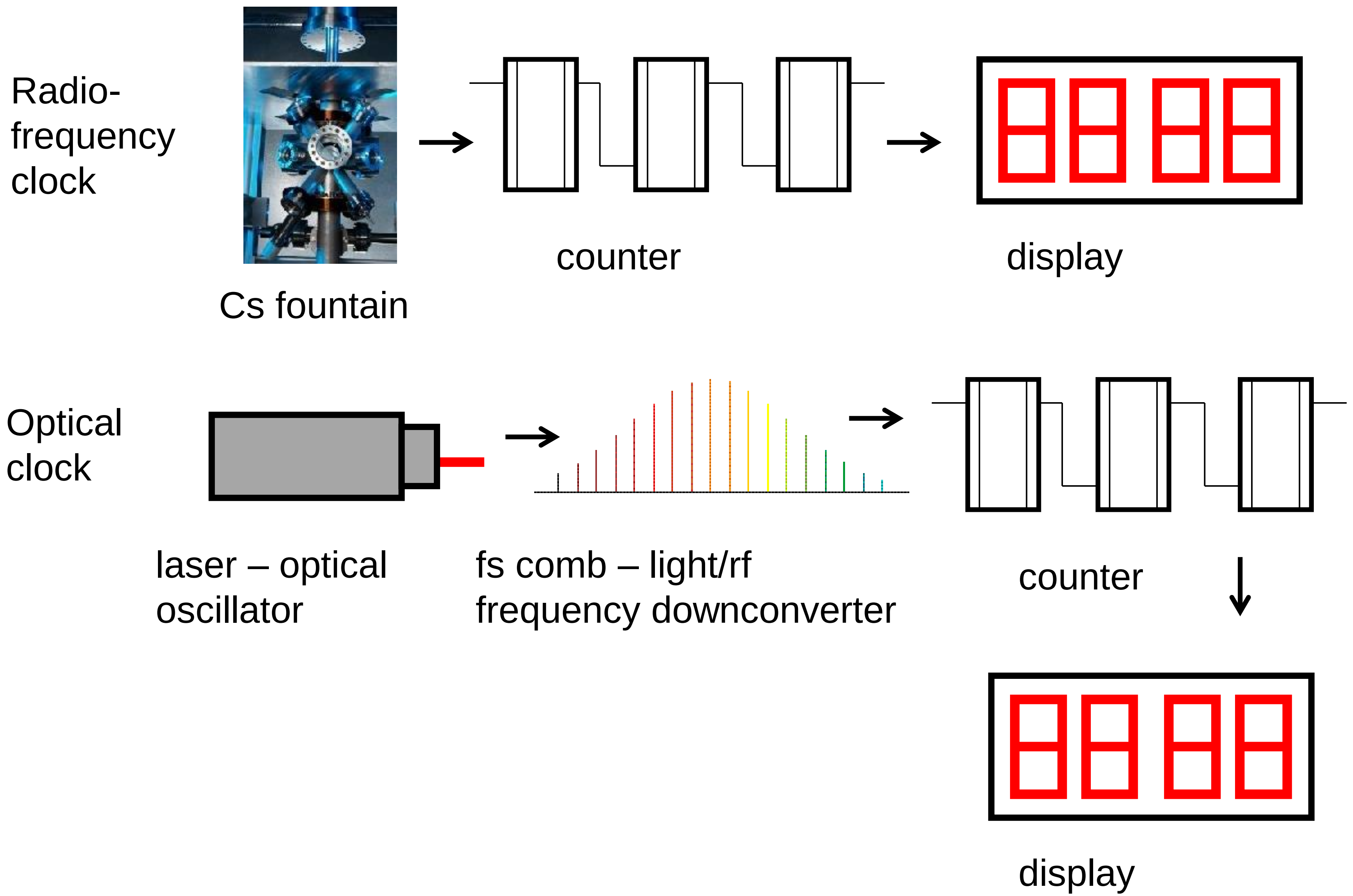


laser – optical oscillator

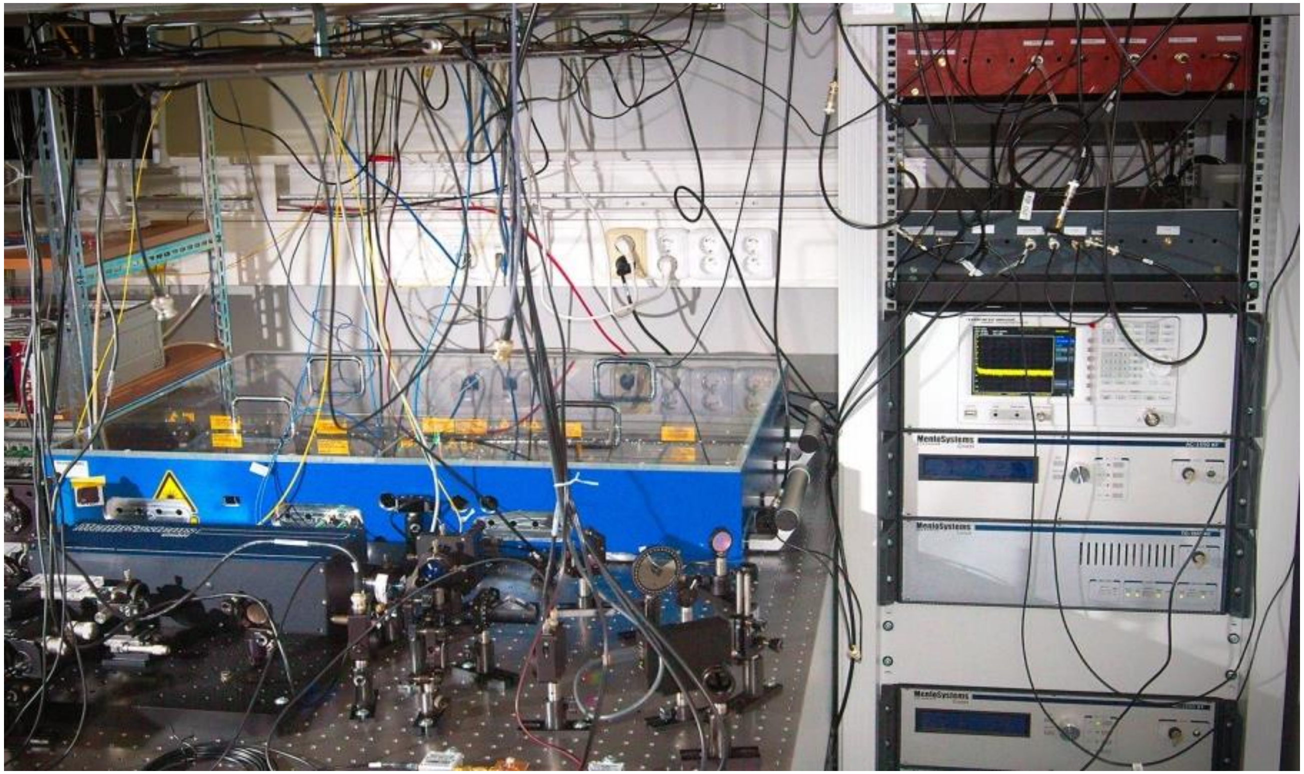
interferometer – counter of wavelengths

display

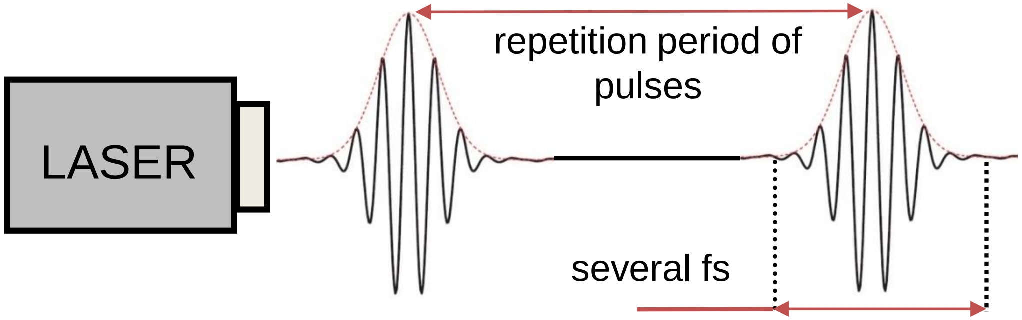
Optical and radio-frequency clocks

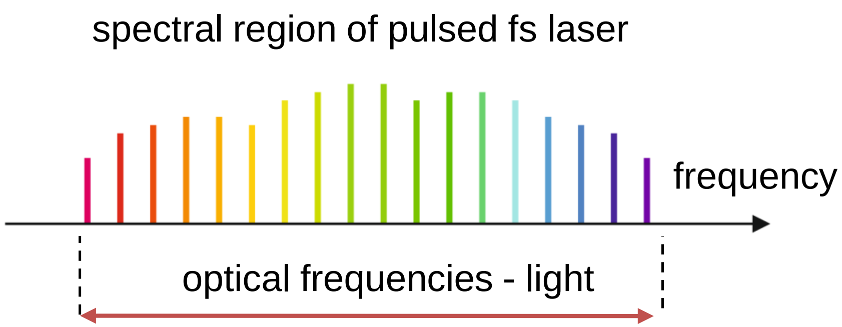


Every spectral component of the femtosecond (fs) pulsed laser (frequency) is an **integer multiple** of the repetition frequency. If the repetition frequency is derived from Cesium clock and precise on the 10^{-15} level, relative precision of every optical frequency of fs laser is the same.



fs laser works as a „transformer“ of precision





Absorption spectroscopy

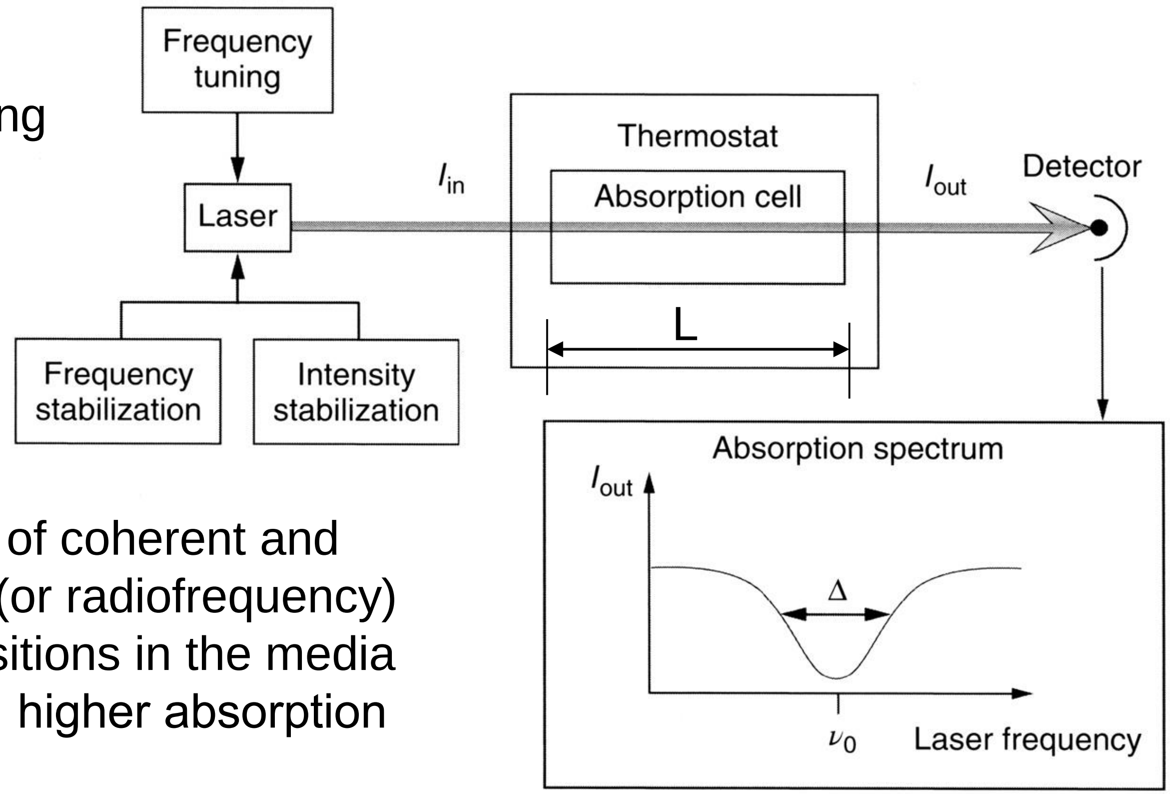
Linear absorption of light in any homogeneous media is given by the Beer law:

$$I = I_0 \, e^{-kL}$$

I ... intensity of light after passing through sample of length L

I_0 ... incident intensity

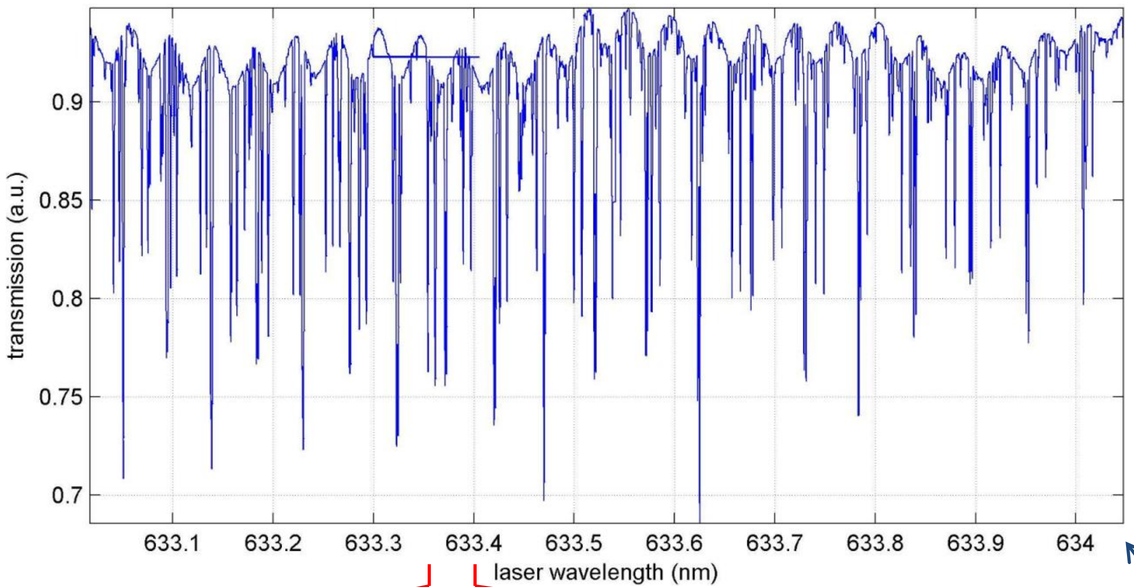
k ... absorption coefficient



Coincidence of the frequency of coherent and monochromatic incident light (or radiofrequency) with atomic or molecular transitions in the media causes absorption “lines” with higher absorption coefficients.

Absorbed photons excite atoms or molecules of media and are later emitted in random directions as spontaneous emission.

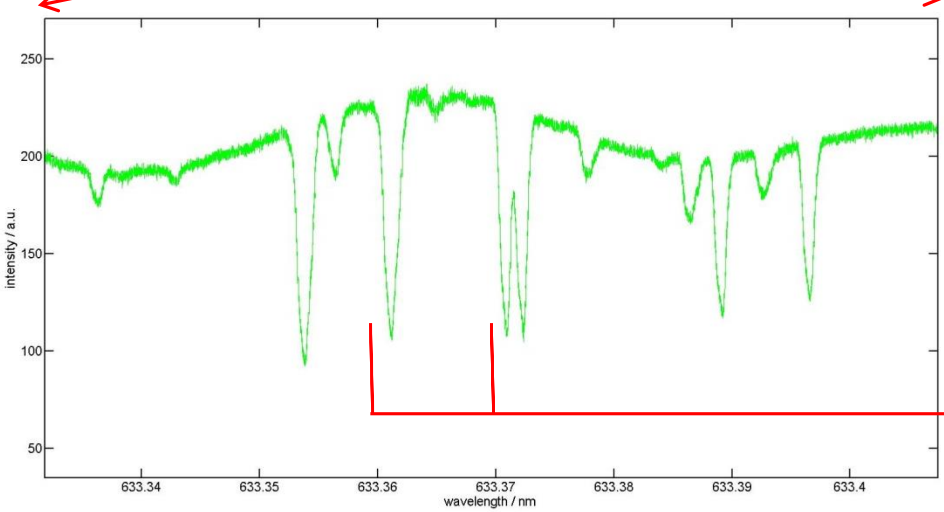
Referencing to absorption lines



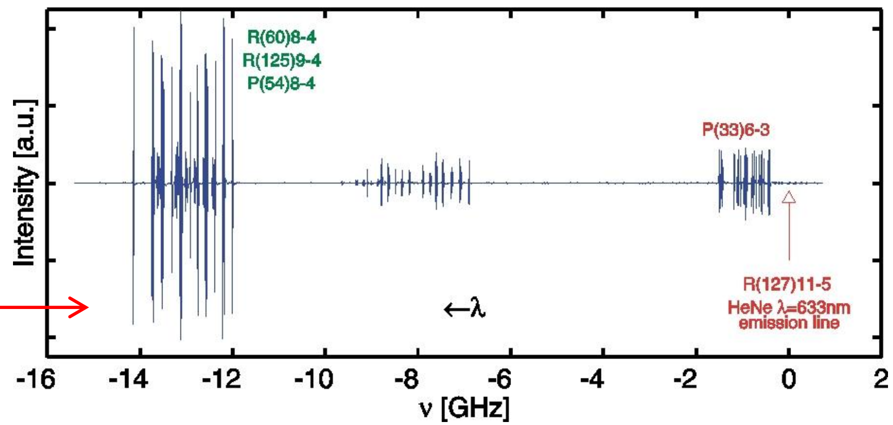
Molecular iodine offers a rich spectrum in the visible spectral range.

- Doppler broadened lines – approx. 1 GHz FWHM
- Hyperfine lines – even below 500 kHz FWHM.

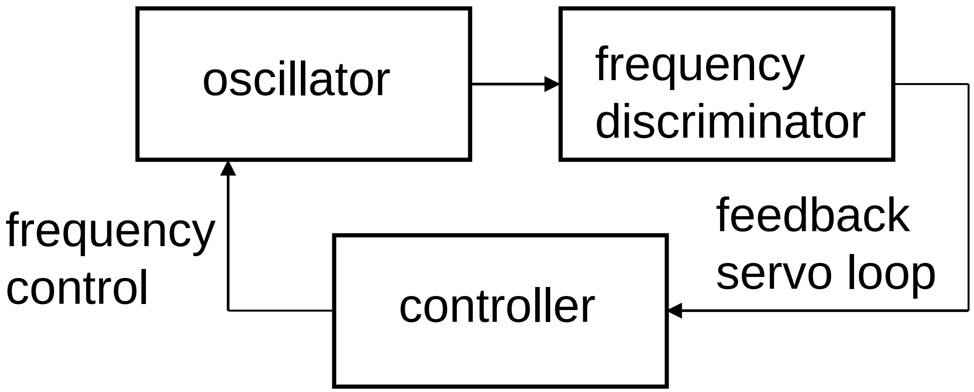
Linear (Doppler broadened) spectroscopy



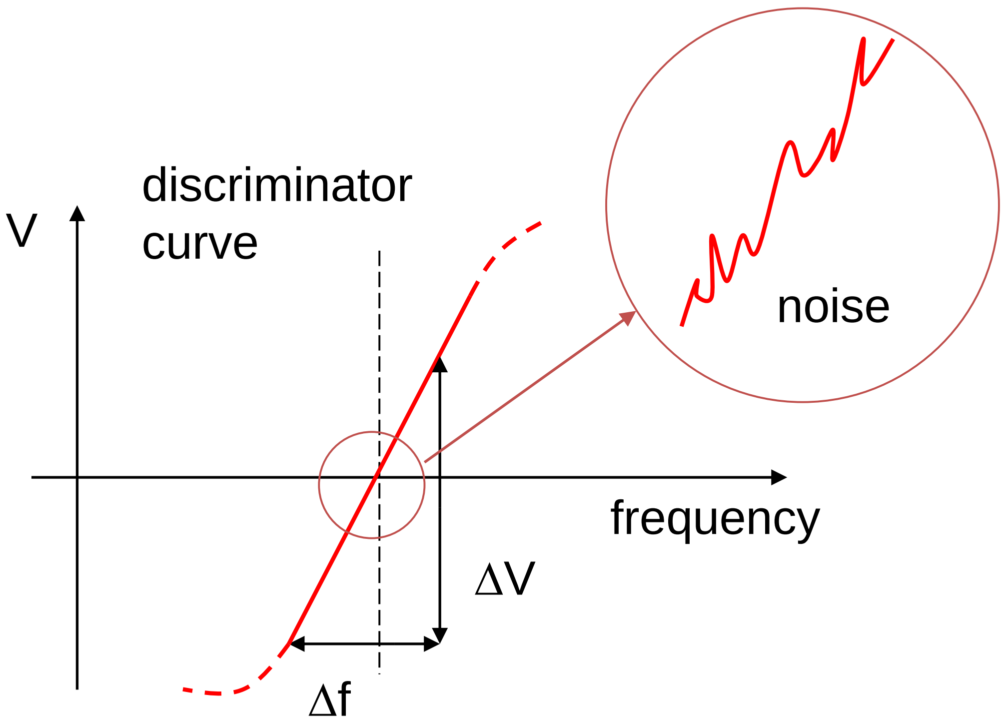
Saturated (Doppler-free) spectroscopy



Stabilization of optical frequency

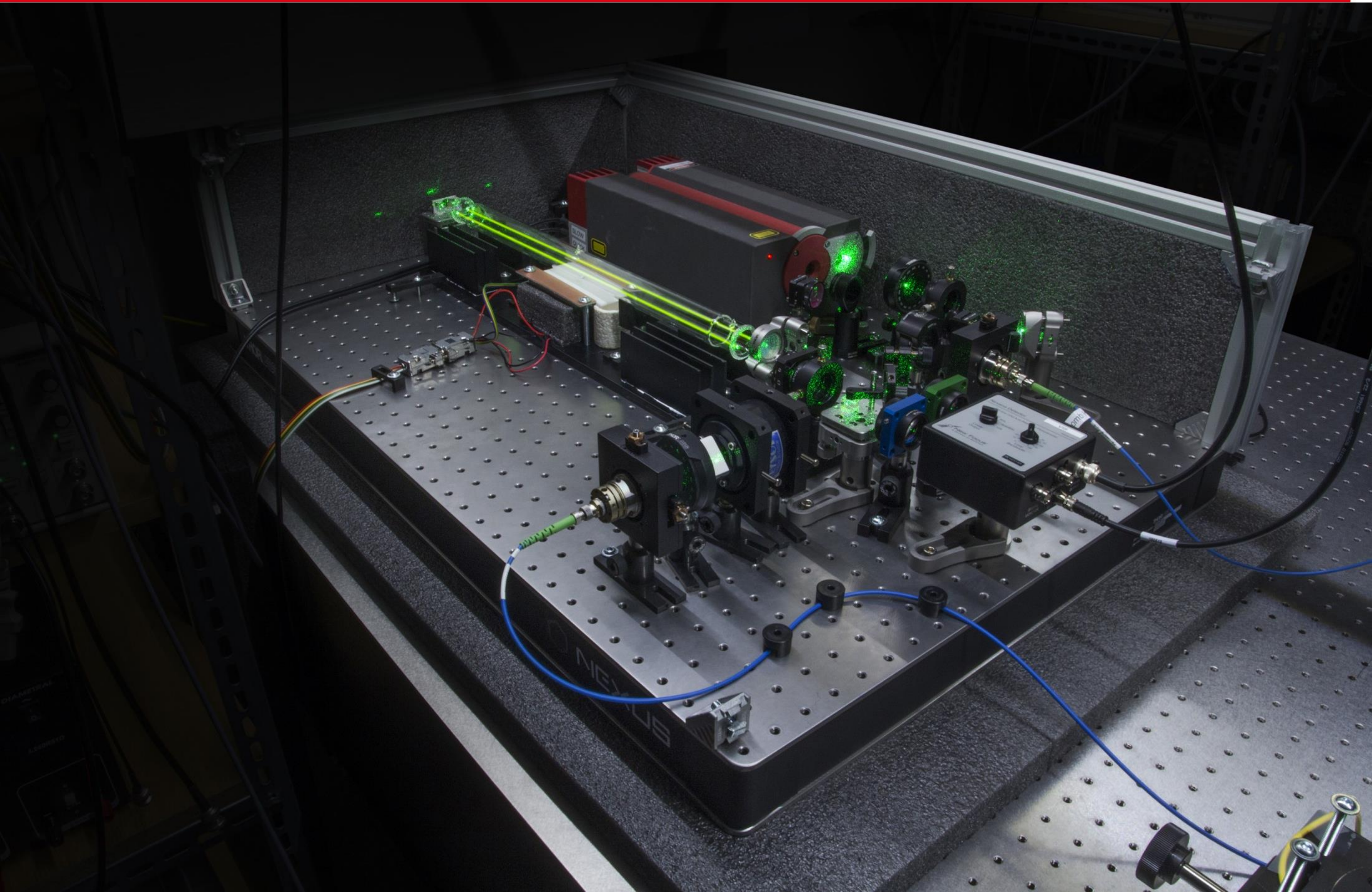


Improvement of frequency stability may be done by an active frequency control of tunable oscillator. Error signal is derived from precise and stable frequency discriminator.

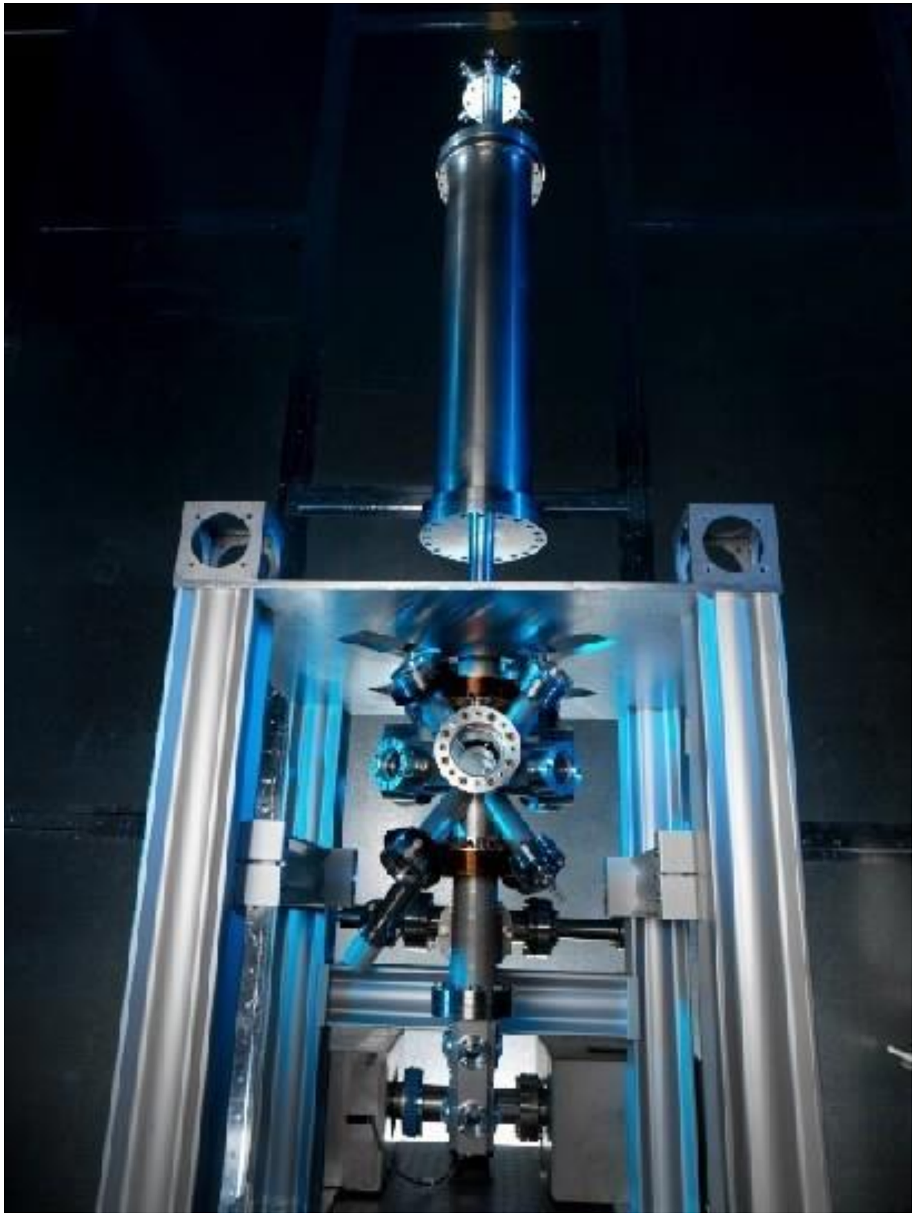


Quality of discriminator is given by “gain” of the discriminator curve, by its signal-to-noise ratio and bandwidth.

Laser with frequency stabilization

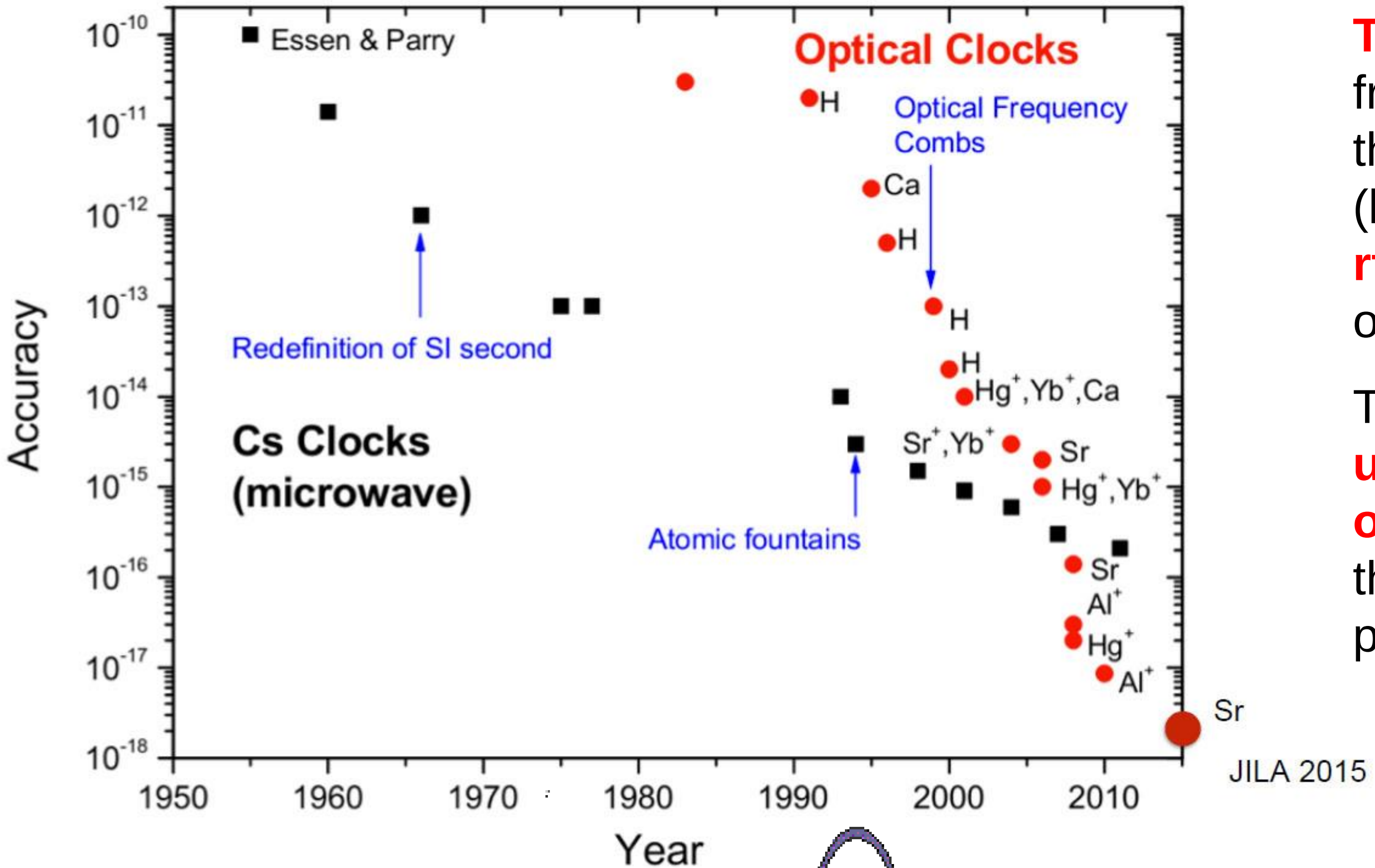


Cesium clock



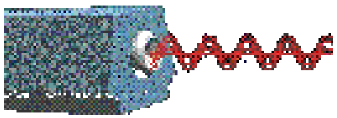
Precise time of the **Cesium clock** is now widely available it is transmitted by radio transmitters, e.g. in Europe from PTB Braunschweig in Germany as **DCF** signal, which we can receive also in Central Europe or through network of **GPS** satellites.

Radiofrequency vs. optical clock



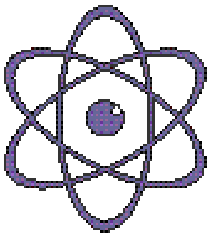
Transfer of relative frequency stability from the **optical oscillator** (laser) via fs laser into **rf spectrum** can bring optical clock into life.

This will lead to **unification of the unit of length and time** on the basis of a single precise oscillator.



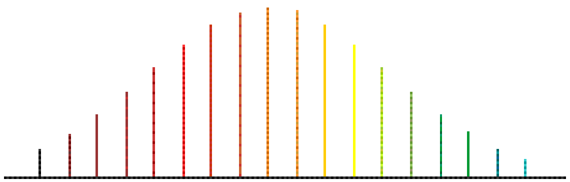
oscillator
(laser)

+



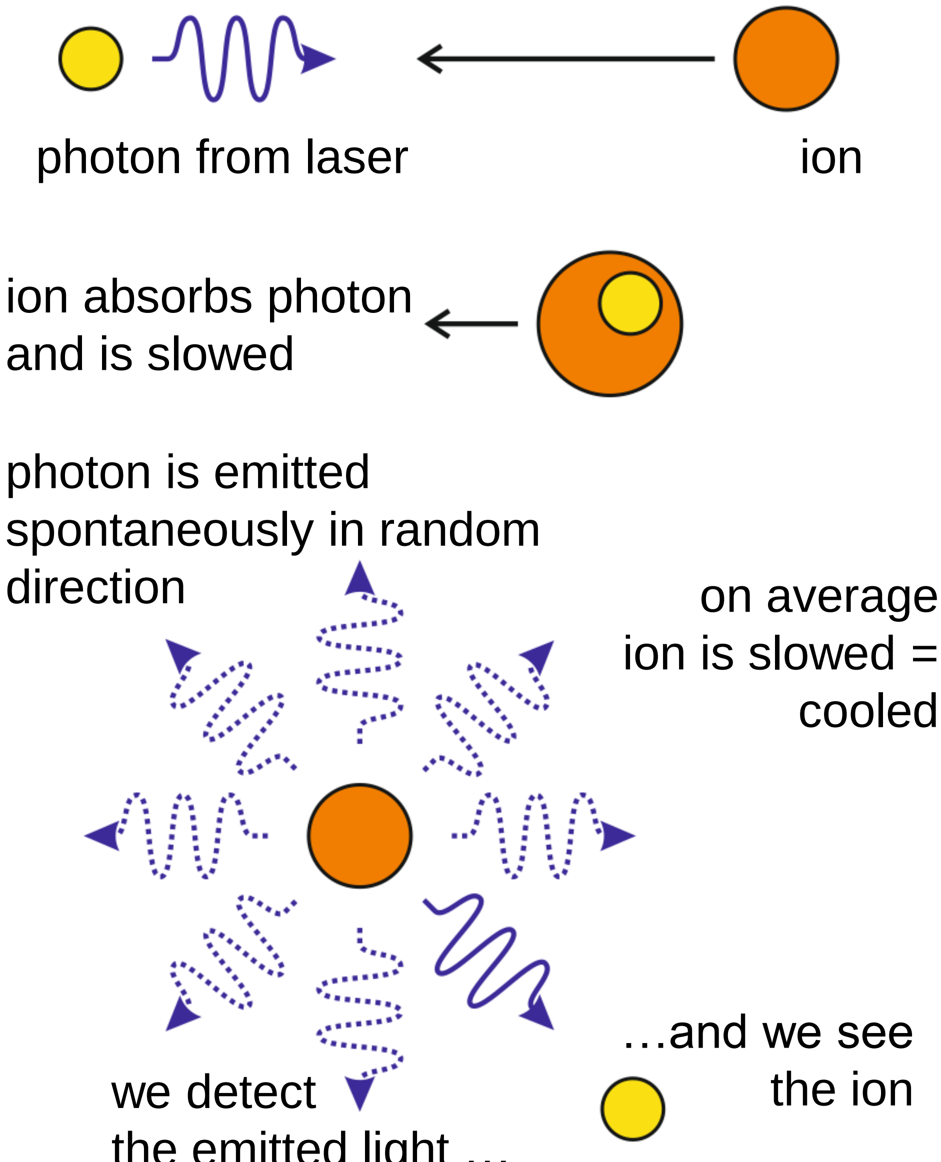
reference
(atom or ion)

+



counter
(femtosecond comb)

Laser Doppller cooled ion as a reference



Optical frequencies (hundreds of THz) gives chances to build oscillators with unprecedented relative stability.

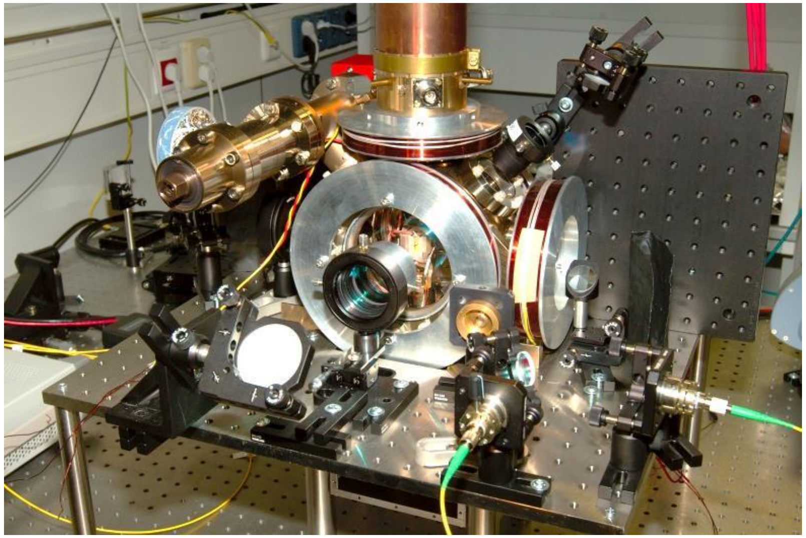
optical transitions with natural linewidths around **1 Hz or less** therefore offer potential Q-factors of order 10^{15} or higher.

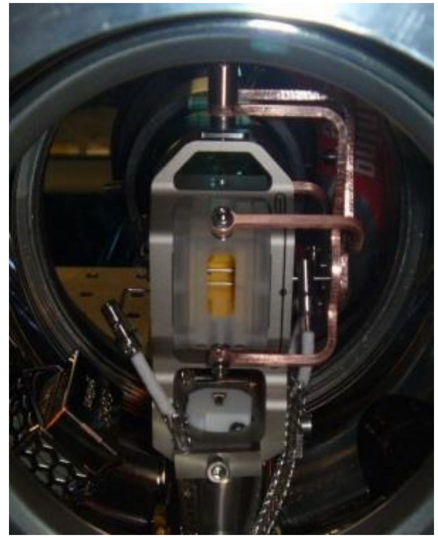
A number of different candidates for optical frequency standards are currently being investigated in various laboratories, based on forbidden transitions in **cooled trapped ions or atoms**, and over recent years there has been significant progress in both areas.

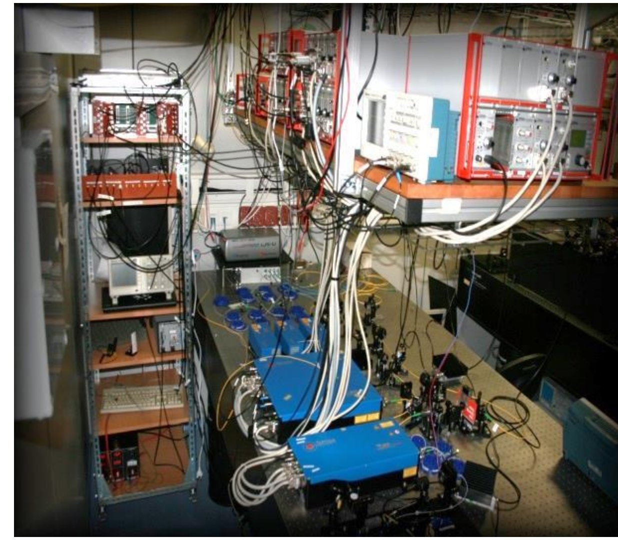
By laser cooling, the atom or ion can be confined to within a wavelength of light, ensuring that the transition is free from Doppler frequency shifts to all orders. Since there is only one ion held in the trap, in a vacuum, the transition is also free from frequency shifts caused by collisions. This results in **very narrow transitions**

ISI CAS

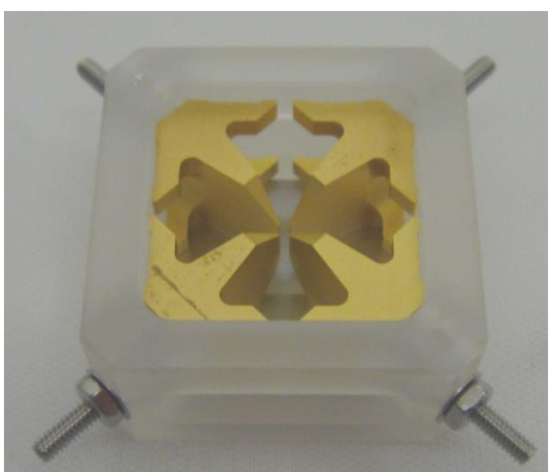
Optical clocks experimental infrastructure (ISI & UPOL)







XHV chamber
with Paul trap

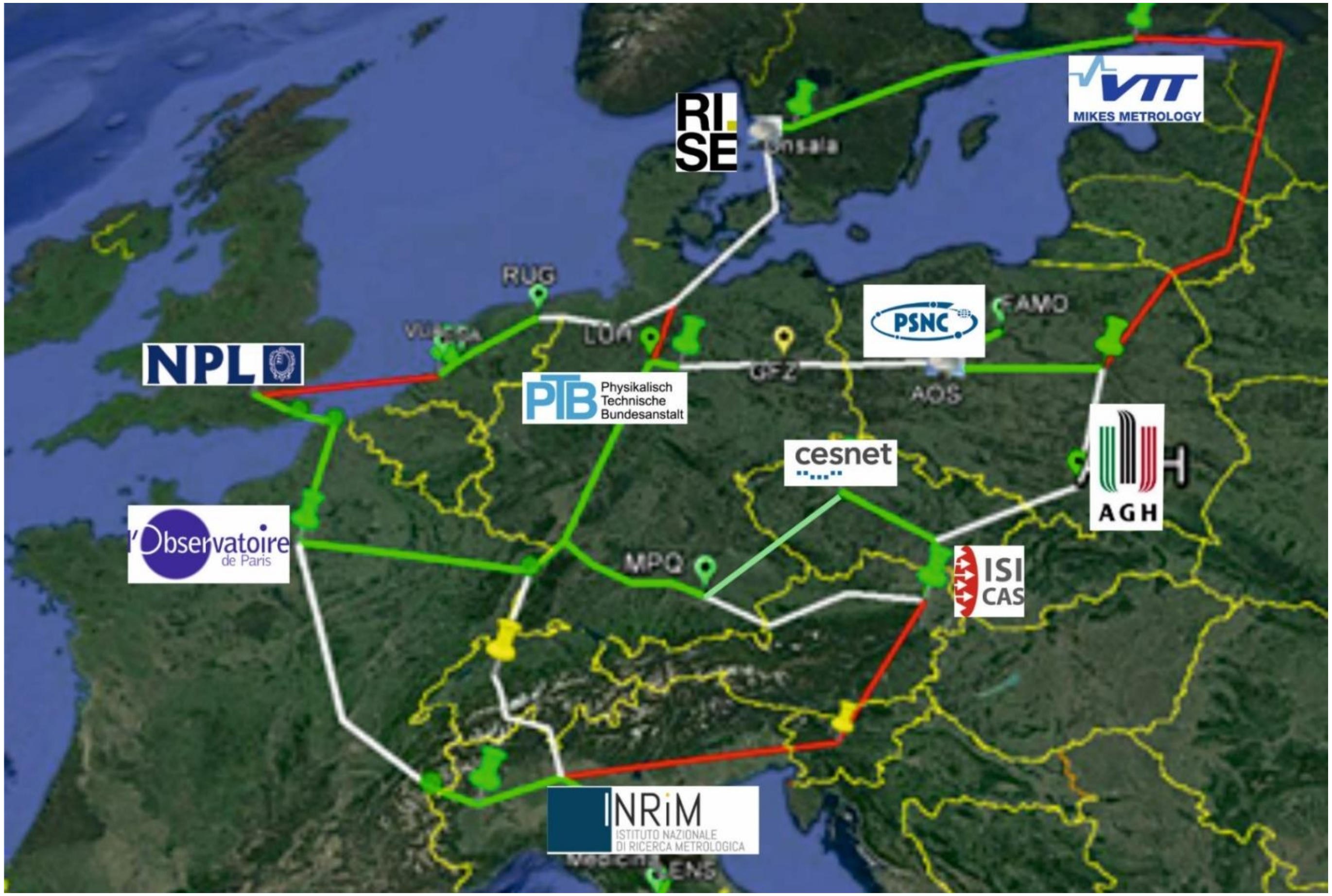


Lasers for $^{40}Ca^{+}$ ion excitations
and high finesse cavity

European TF - infrastructure

Goals of the planned EU-wide infrastructure for transfer of frequencies

- Verification and comparison of interlinked atomic clocks
- Improvement of national time scales
- Distribution of precise time and stable frequency
- Experimental operation of coherent transfer of optical frequency
- Unification of existing links into one network



Precision synchronization

The use of **metrology instruments** offering extreme precision

Synchronization of computer networks:

- for higher transmission capacity
- for electronic trading with stocks and commodities

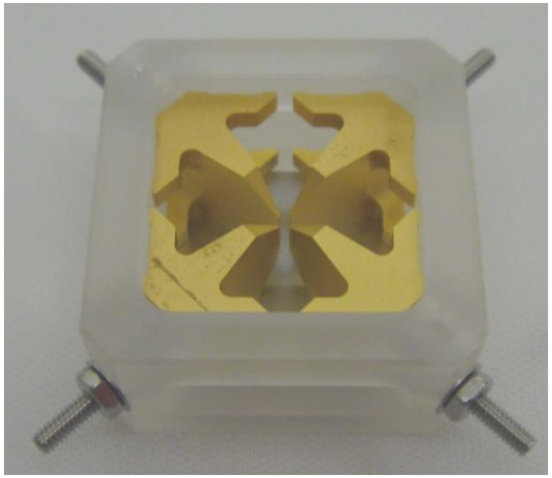
In radio-astronomy the shift from GHz band into THz needs much more precise synchronization of the antenna arrays (e.g. ALMA project ESO)

Spectroscopy and Quantum mechanics of ions

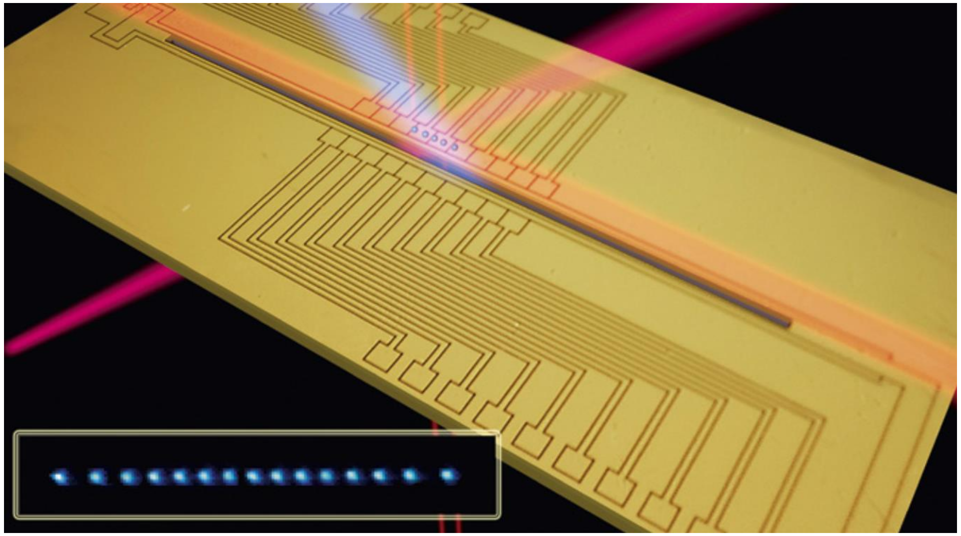
Next steps:

We plan to put together next setup with trapped and cooled **Ca^{+} and Al^{+} ions**. We intend to do spectroscopy with quantum logic and trapping in linear segmented trap. we plan experiments with **Al^{+} clock laser**.

➢ Segmented trap is a step towards **quantum computing**



Au coated Ti blades of the Paul trap

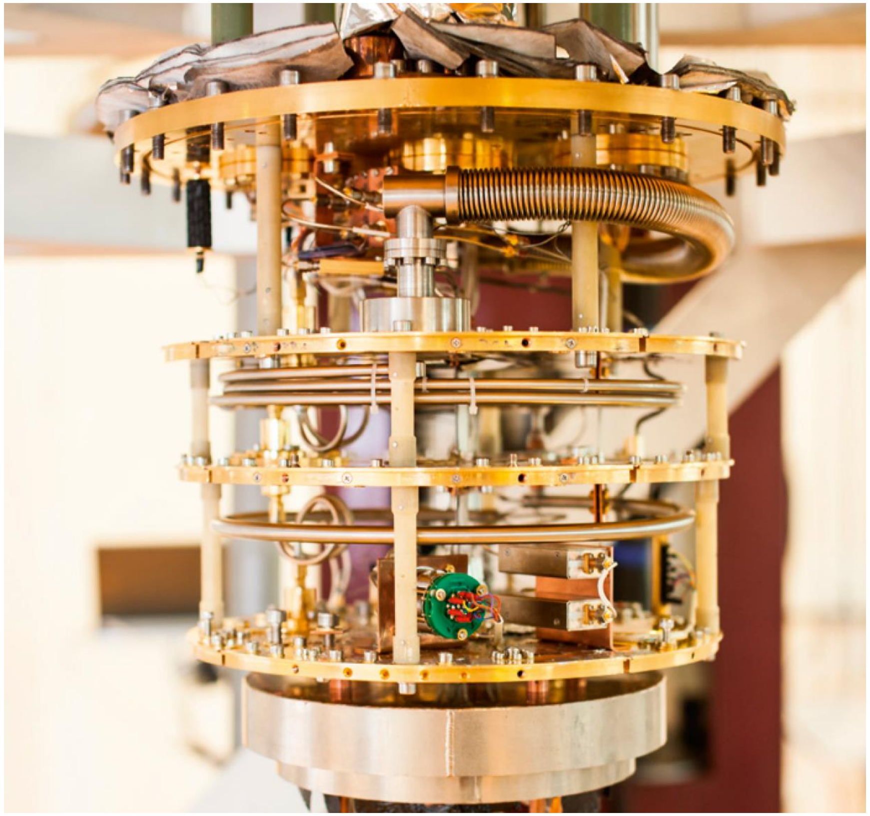


Quantum computing

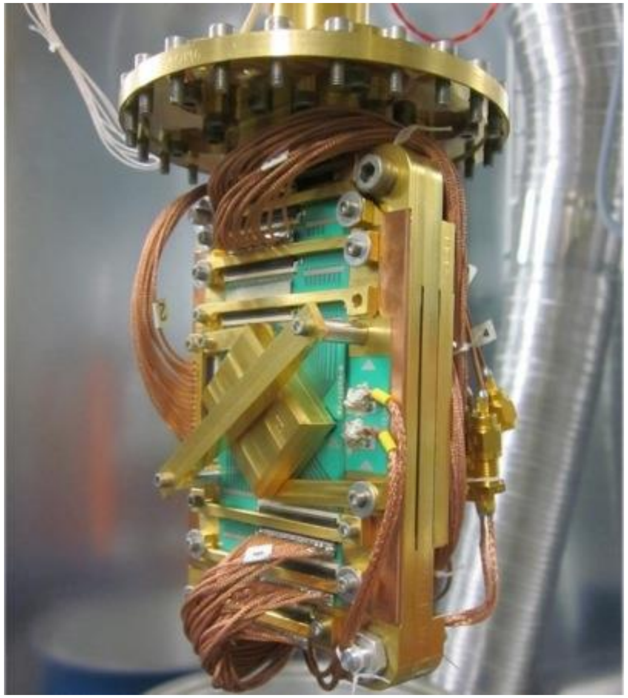
The design of a **Quantum computer** is the biggest challenge of the quantum initiative.

Q-bits are in a superposition of the 0 and 1 ans are quantum entangled.

Quantum computer is a parallel - working machine for tasks with exponentially rising complexity.



Superconductive chips with Q-bits of the infrastructure in Delft, the Netherlands



Thank you for your attention

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