**Interruption-free optical frequency reference**

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**Black Forest clock vs. Atomic clock**

*Clock = Oscillator + Counter*

**Uncertainty of the clock:** $\varepsilon = \frac{\Delta \nu}{\nu}$

- **Black Forest clock:** $\varepsilon \sim 10^{-5}$
- **Atomic clock:** $\varepsilon \sim 10^{-18}$

**frequency comb**

1 s

100 000 000 000 000

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**Tübingen – Tokyo clock project**

**Project timeline**

- Cooperation with Hidetoshi Katori since 2014
- First compact vacuum system with Strontium shipped to Tokyo in 2015: operation of a magneto-optical trap with the lasers at RIKEN
- Building a lasersystem for cooling Strontium in Tübingen since 2016
- Magneto-optical trap (MOT) of Strontium in Tübingen 2017
- Baden-Württemberg Stiftung project with a new concept for lattice clocks starts in 2017

**Traditional operation of a Strontium lattice clock:**

- Two (+1) cooling steps:
  - 461 nm (mK), 50 G/cm
  - 689 nm broadened, 10-15 G/cm
  - 689 nm narrow, 5 G/cm
- Clock measurement
- Dropping atoms

**New concepts within our project:**

**Strontium core-shell magneto-optical trap:**

Simultaneous two-stage cooling
- Cooling steps are separated in space instead of separation in time
- Core-shell laser beams
  - 461nm, 32MHz / 2923nm, 100-kHz
- Structured magnetic quadrupole-field

**Continuous frequency reference and continuous clock:**

- Continuous extraction of ~20mK cold atoms from the MOT with a moving optical lattice as conveyor belt
- Continuous spectroscopy of the clock transition

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**State-of-the-art atomic clocks**

**Cs-fountain clocks:**
- Current definition of SI second
- Measures MW transition
- Uncertainty: $10^{-16}$

**Ion clocks:**
- Sr⁺, Yb⁺, Al⁺,…
- Continuous measurements on a single ion
- Electromagnetic trapping
- Uncertainty: $10^{-18}$ (PTB, NIST / JILA)

**AtOMIC lattice clocks:**
- Sr, Yb, Hg, Cd
- Cycle-based operation
- $N \sim 10^5$ neutral atoms in an optical lattice
- Uncertainty: $10^{-18}$ (Tokyo, NIST)

**Stability of the clock is limited by:**

- Number of particles (projection noise)
- Useful measurement time
- Dicke effect: aliasing high-frequency technical noise to low-frequency domain

**Stabilizing the clock with: $\sigma_{\text{acc}} \propto \frac{t_m + t_p}{\sqrt{N \cdot T_{\text{tot}}}}$**