Emerging Clock Technologies

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WSTS
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What to Expect

- A short history of the physics and technology of atomic clocks
- Discuss some recent, major advances in atomic physics
  and the impact on atomic clocks
- From the research lab and into the market place…what to expect
  in the future

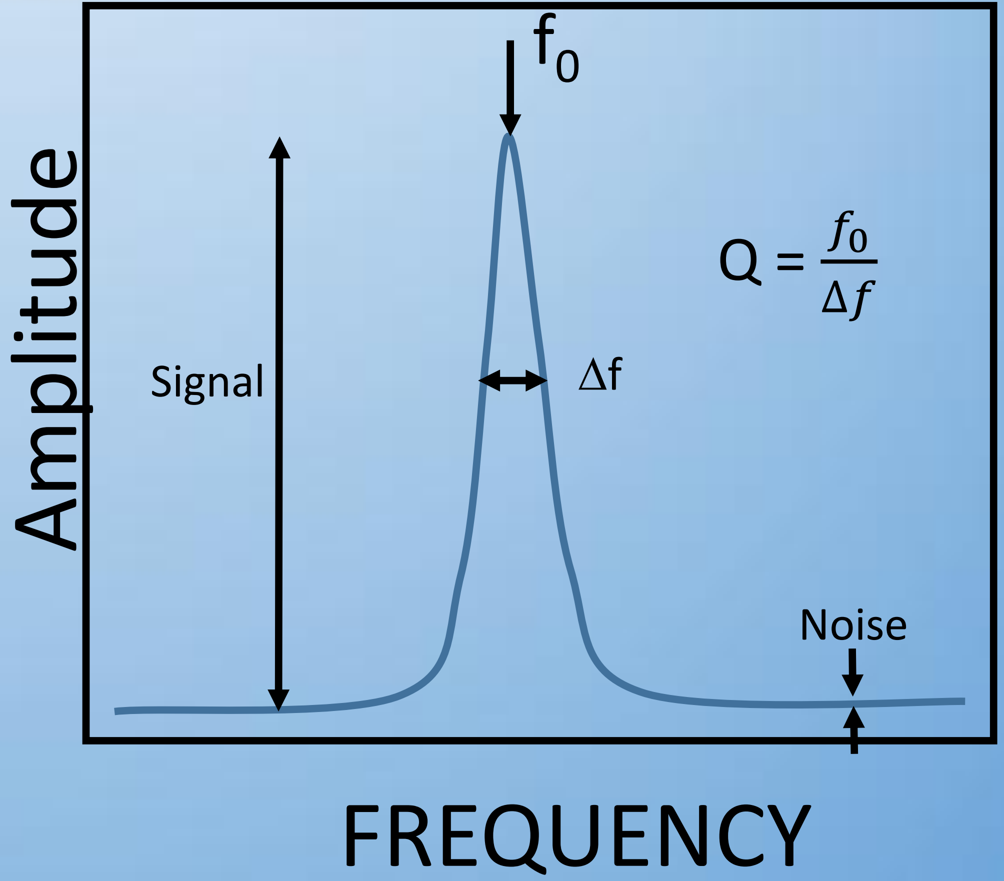
Ideal Atomic Clock

Atoms in free space and unperturbed by the environment

(Perfect Vacuum, Absolute Zero, no Electric and Magnetic fields)

Perfect Observation (Infinite S/N Ratio) of an Atomic transition

$$\sigma_y(\tau) \cong \frac{1}{Q\ (S/N)\sqrt{\tau}}$$



"Practical" Ideal Atomic Clock

$Q = 10^{10}$ (Microwave Transition in Cesium)

$S/N = 10^4$ at 1 sec (Really Good)

$$\sigma_y(\tau) \cong \frac{10^{-14}}{\sqrt{\tau}}$$

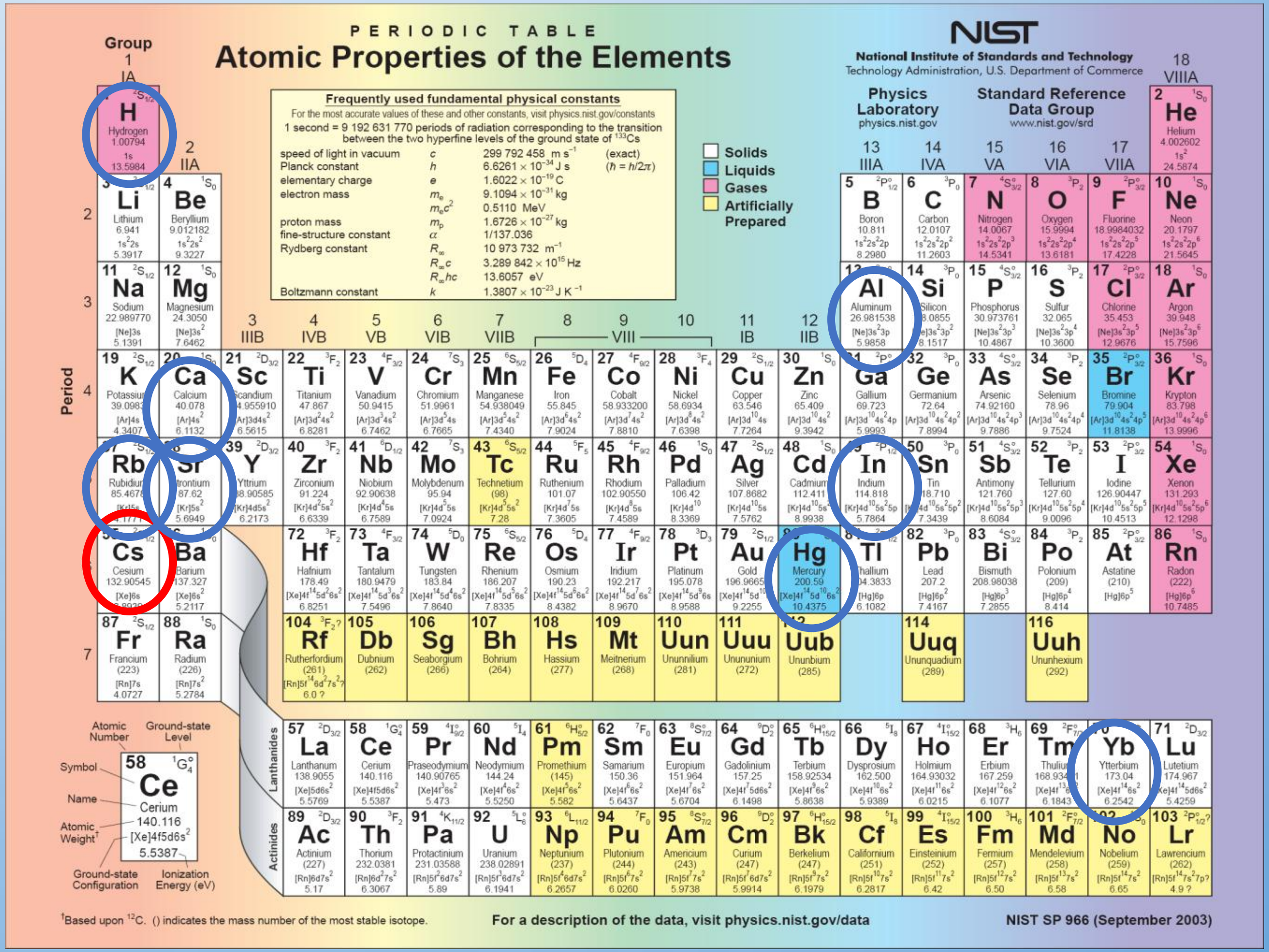
Real Atomic Clocks

- Atoms are hot, move at high speeds, undergo collisions
- Atoms can be difficult to control and measure
- The theoretical models are challenging
- Systematic biases can lead to instability
- Need a local oscillator (LO) to support the clock

Atoms used in Atomic Clocks

Each atomic species blends with various technologies to make unique types of clocks

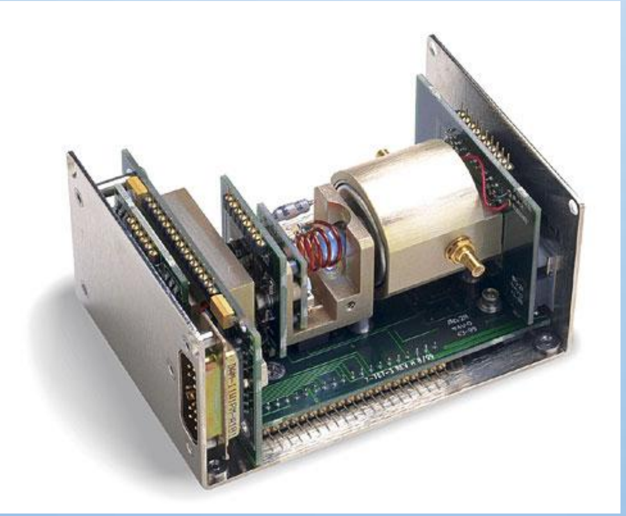
Cesium



Alkali Atoms and 50+ Years of Atomic Clocks

<u>Hydrogen Maser</u>
Large Storage Bulb and Cavity
Sophisticated Electronics
Magnets

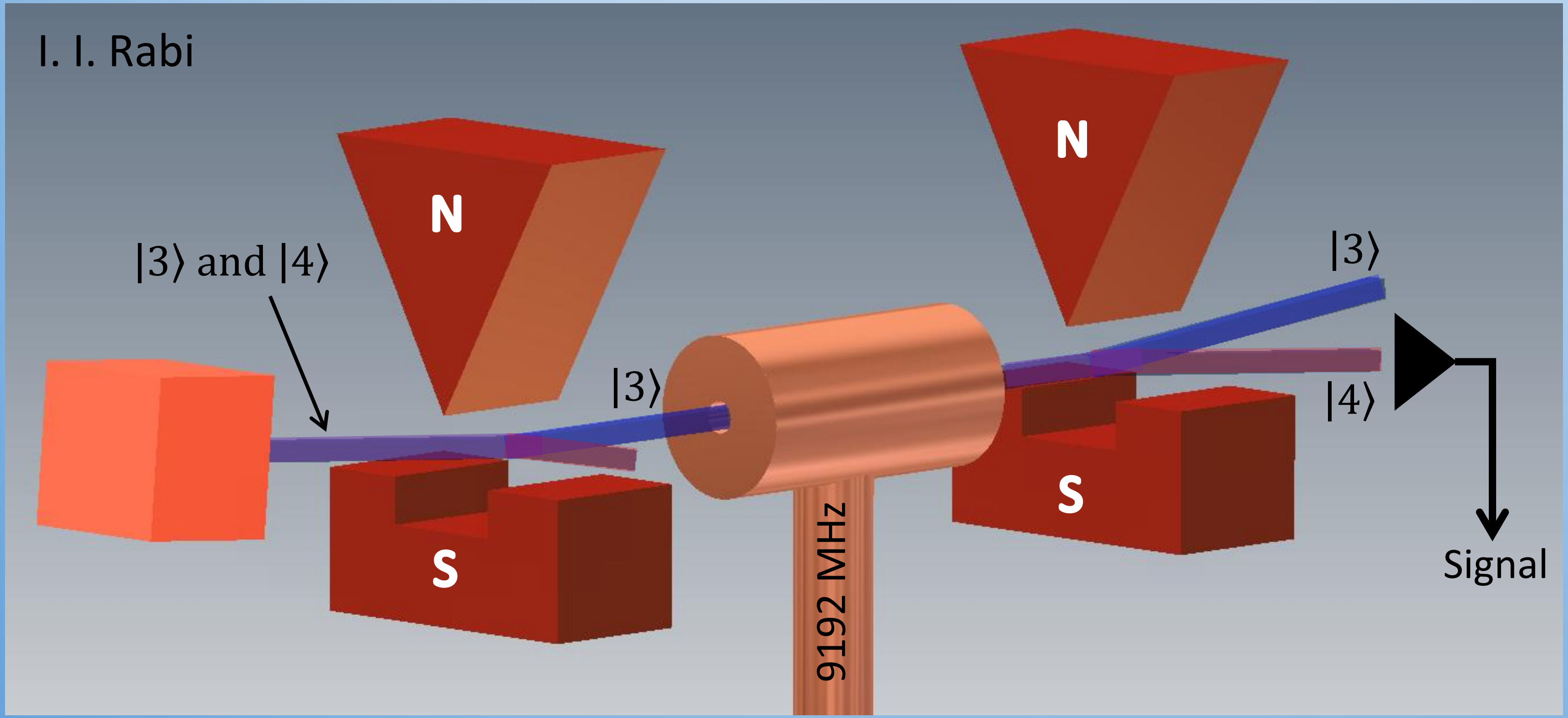
<u>Rubidium Cells</u>
Lamp
Rb Isotope allows for Optical Pumping
Small Package



<u>Cesium Beams</u>
Ramsey Technique/Beam Tube
Magnets

Closer Look at Cesium Beam Clocks

- Magnets
- Vacuum System (Ion Pumps and Getters)
- Low-Noise Microwave Sources

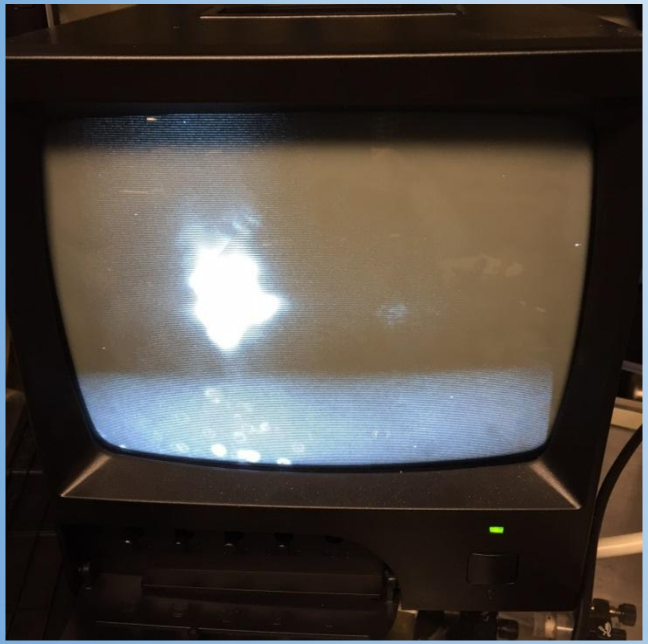


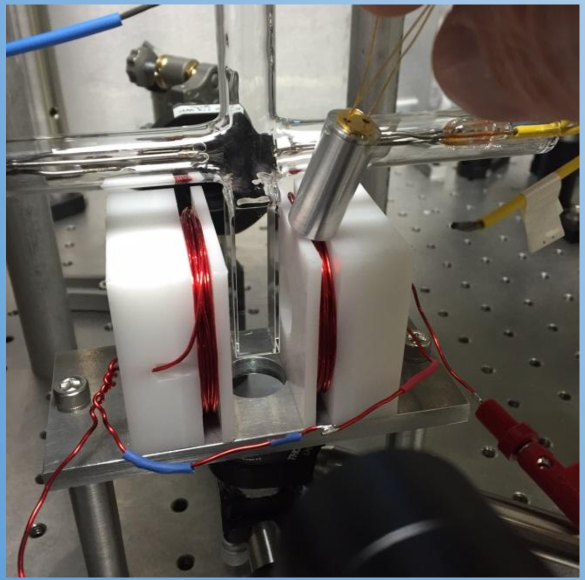
A Revolution in Clocks: Laser Cooling

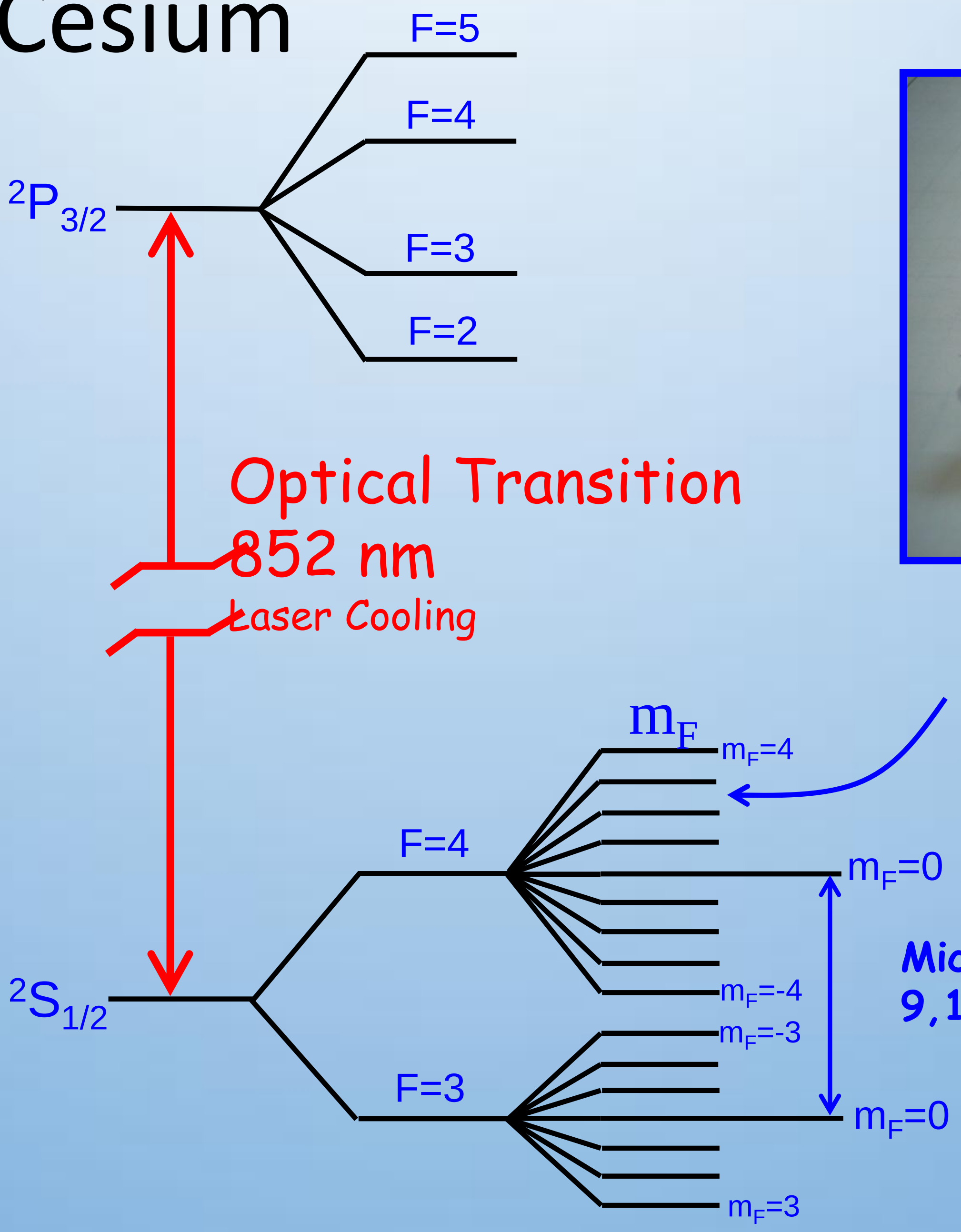
- Narrow Linewidth Laser Sources (100 KHz)
- Stabilized in Frequency
- Accessible to researchers (Low cost Laser Diodes in the IR)
- Fundamental Physics of atom/light interactions
- Optical Molasses in Cesium (T ~ 1 μKelvin)

NIST-Laboratory ECDL circa 1990-2000s

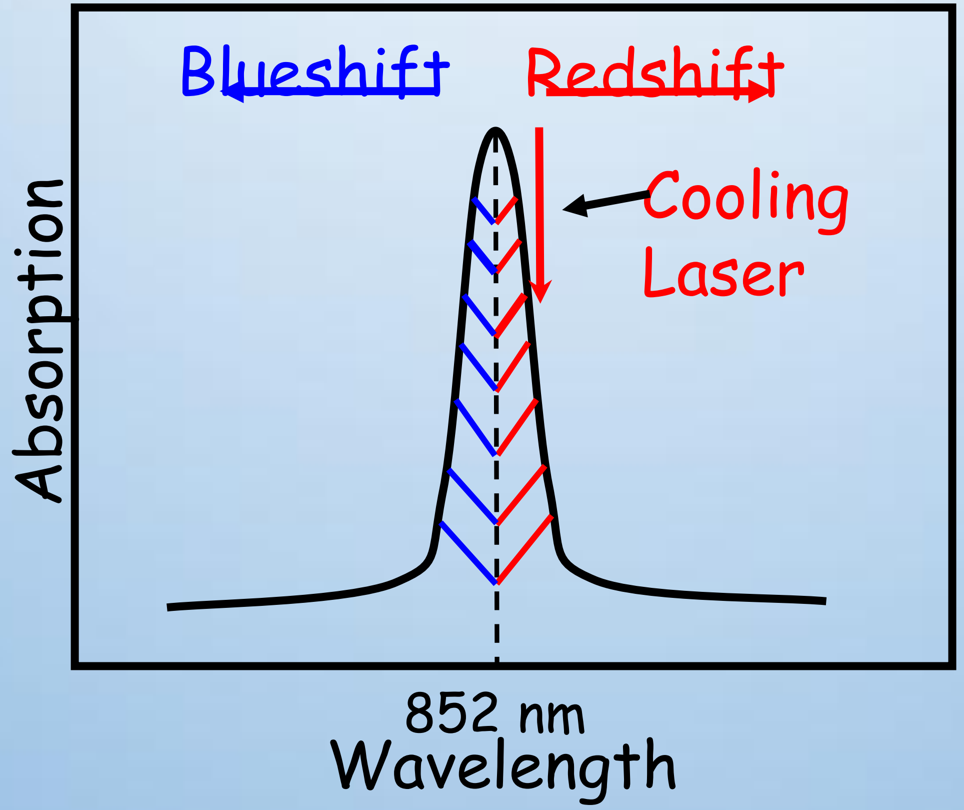
Laser Cooling in Cesium





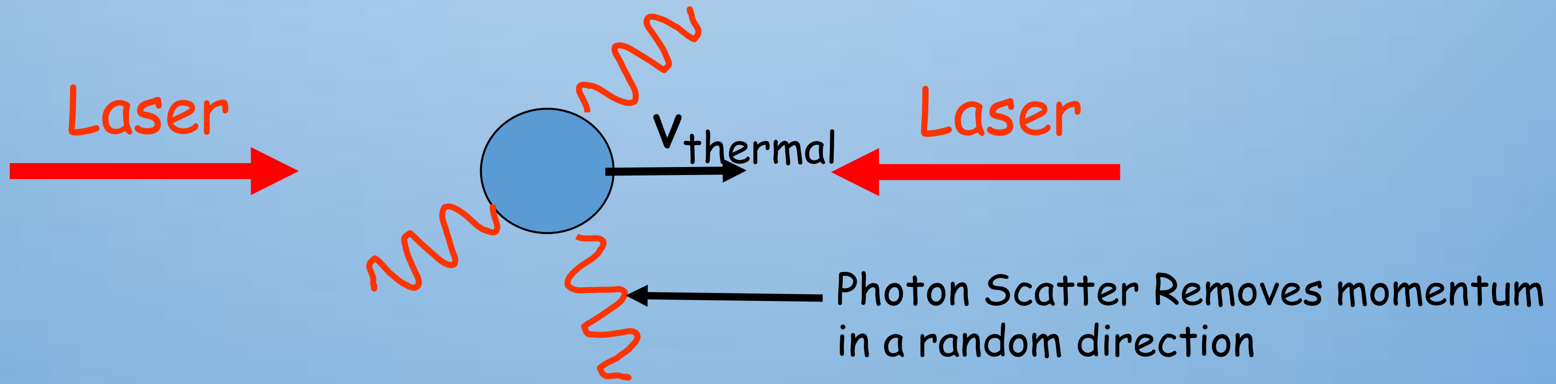


Laser Cooling Details

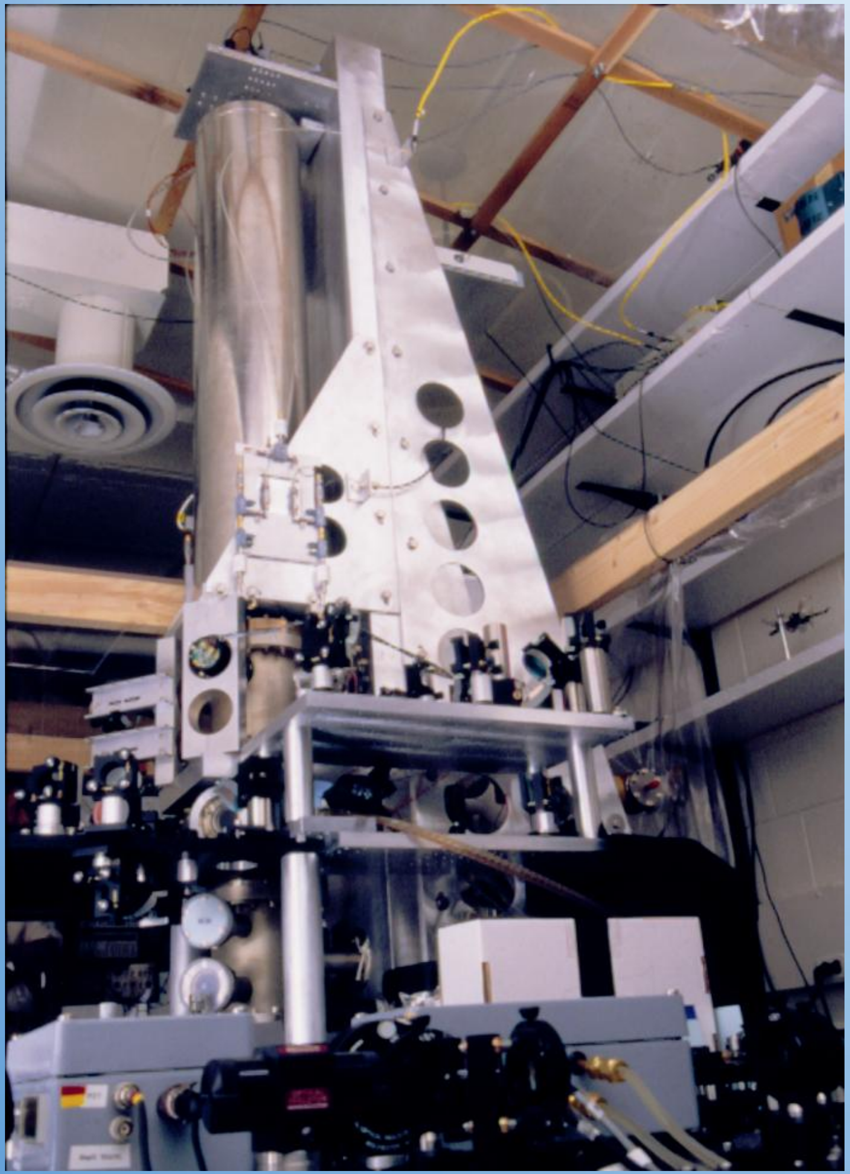


Laser Frequency is tuned slightly below the atomic resonance:
$\nu_{laser} = \nu_{atom} - \delta$

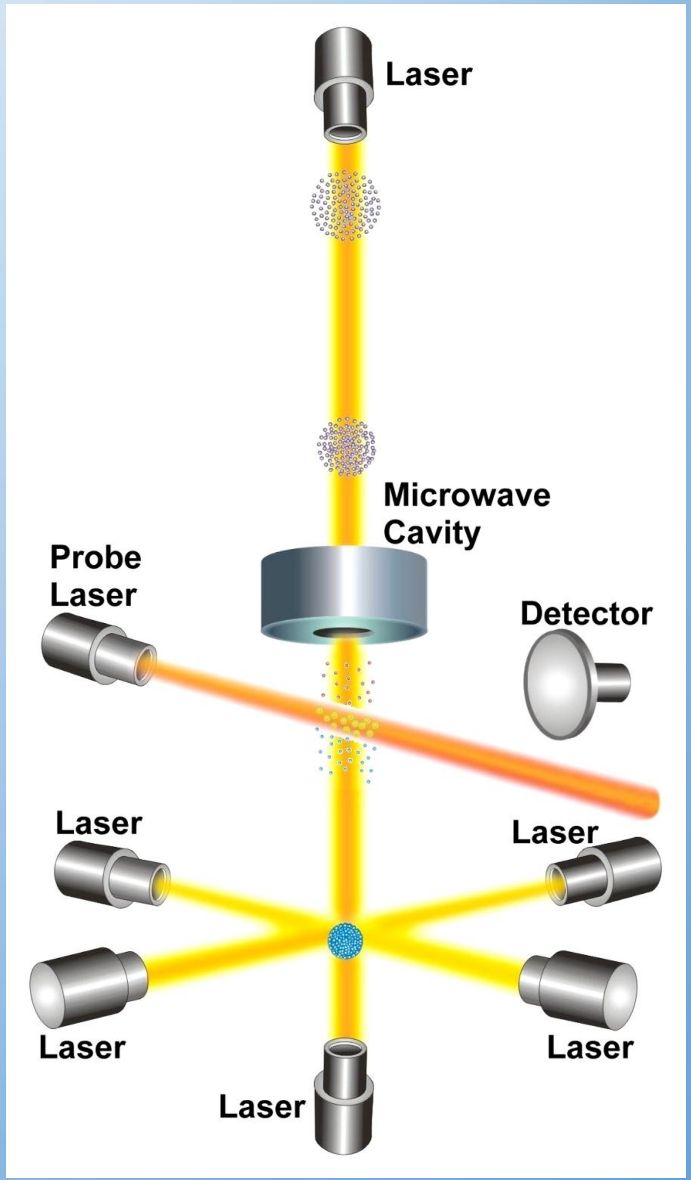
Optical Molasses
T ~ 1 μKelvin



NIST-F1 : Laser Cooled Cs Fountain

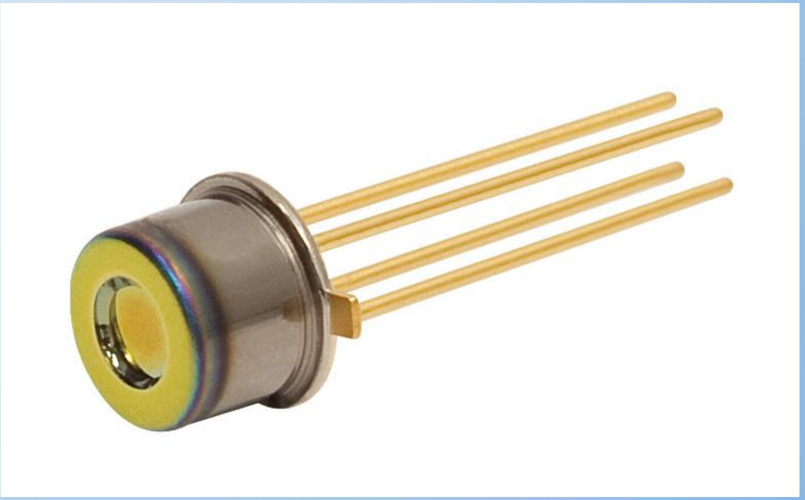


- SI Second
- $\sigma_y(\tau) \sim 10^{-13}\tau^{-1/2}$
- Accuracy ~ 10^{-16}
- Cold Atoms
- Very Large
- $$$$$

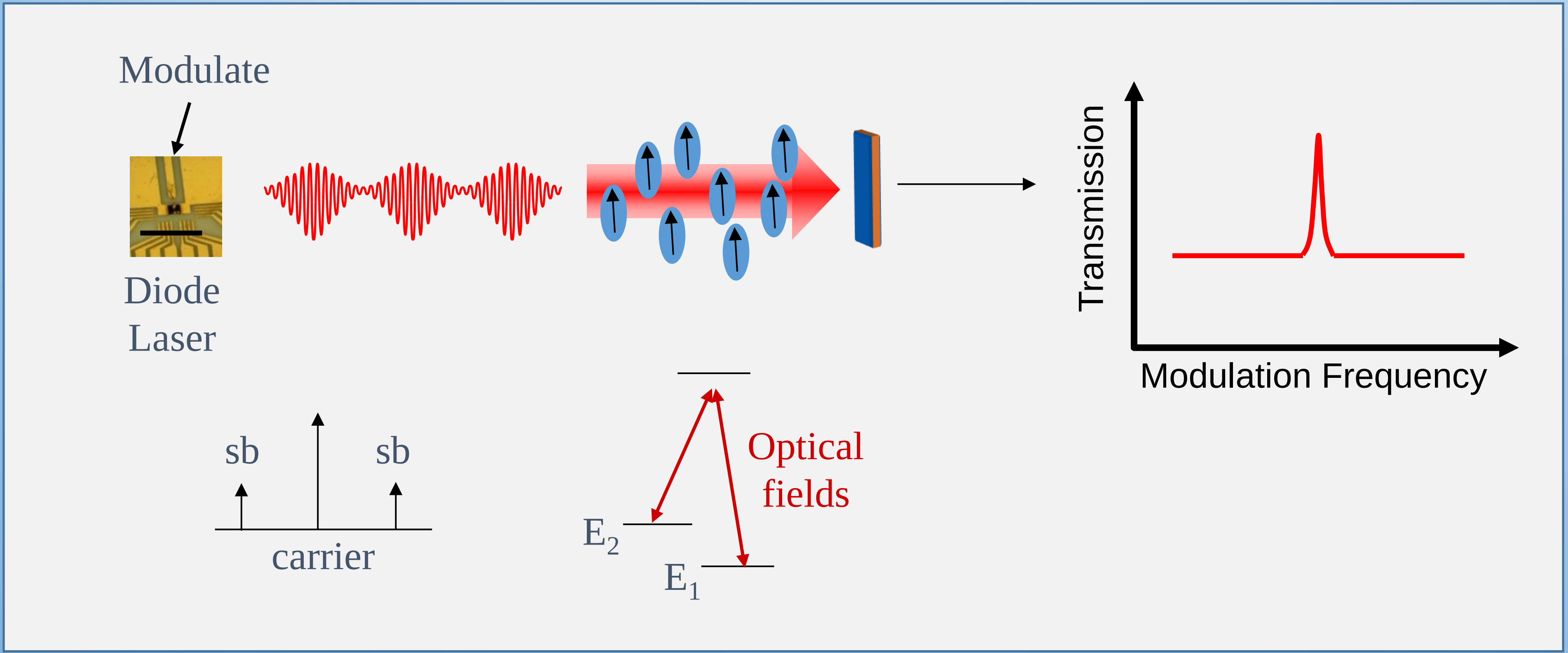


Going Small with VCSEL Laser Diodes

- Modulate at GHz Range
- Low Power (1 mW)
- Linewidth 50 MHz
- Cannot Laser-Cool Atoms
- But…Perfect for CPT

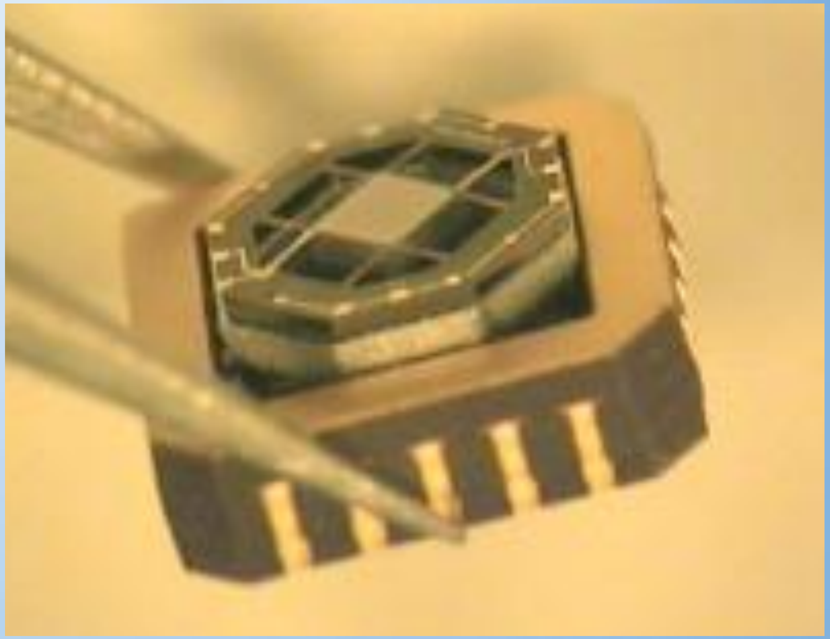


All-Optical (CPT) Excitation



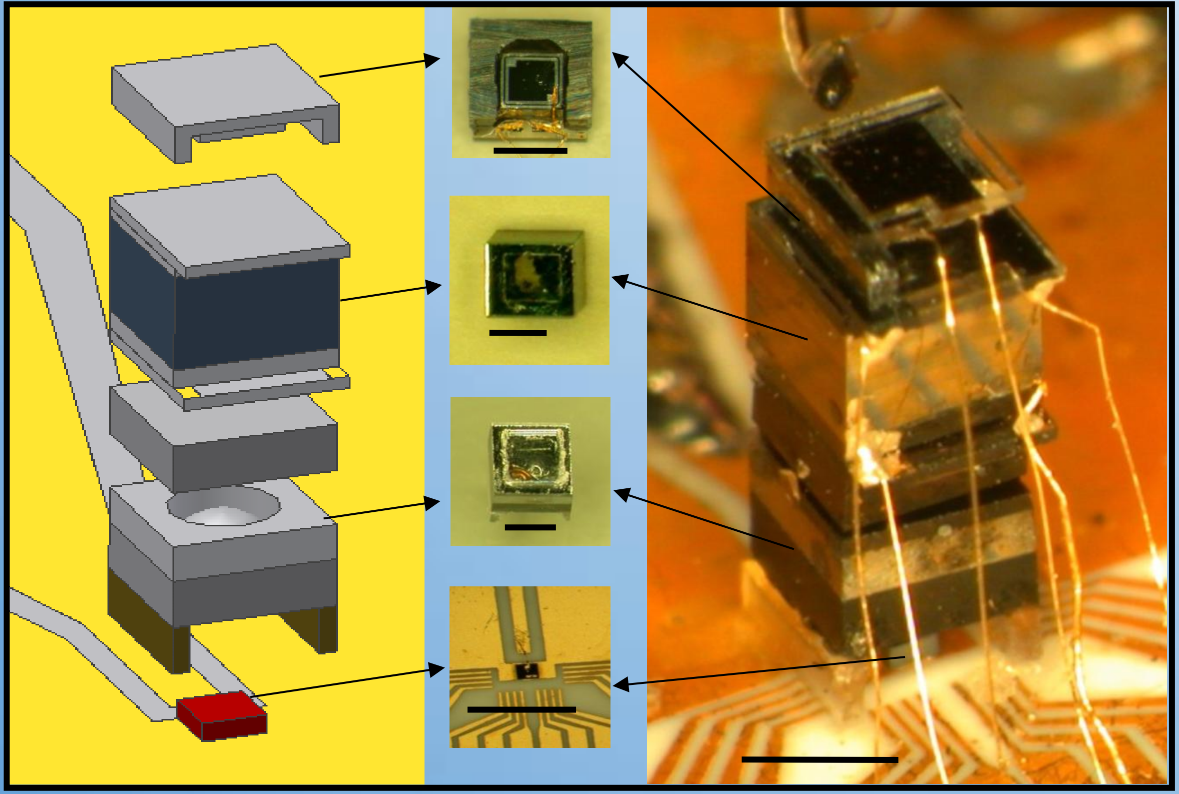
- Absorption of light drops when modulation frequency equals half of the hyperfine splitting
- Advantage: ***no microwave cavity required***

CSAC – Chip Scale Atomic Clock



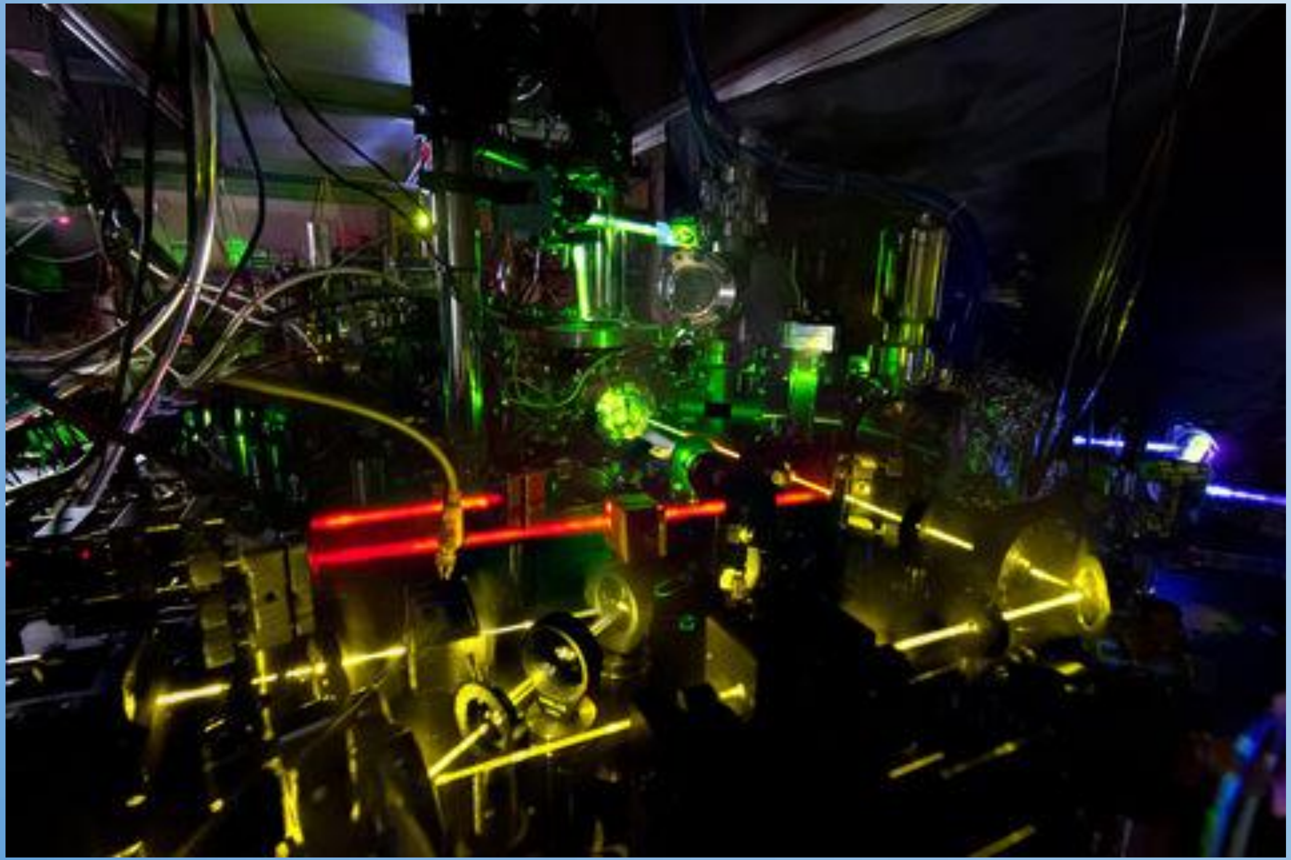
Microsemi

NIST Prototype

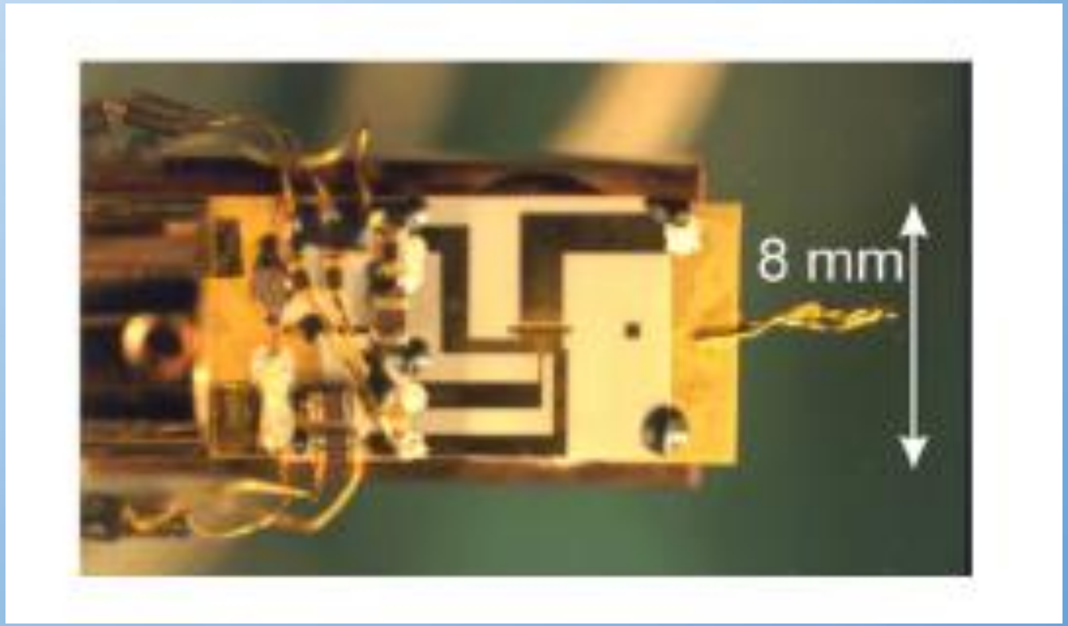


More Trapping and Cooling: Optical Clocks

Optical Lattice

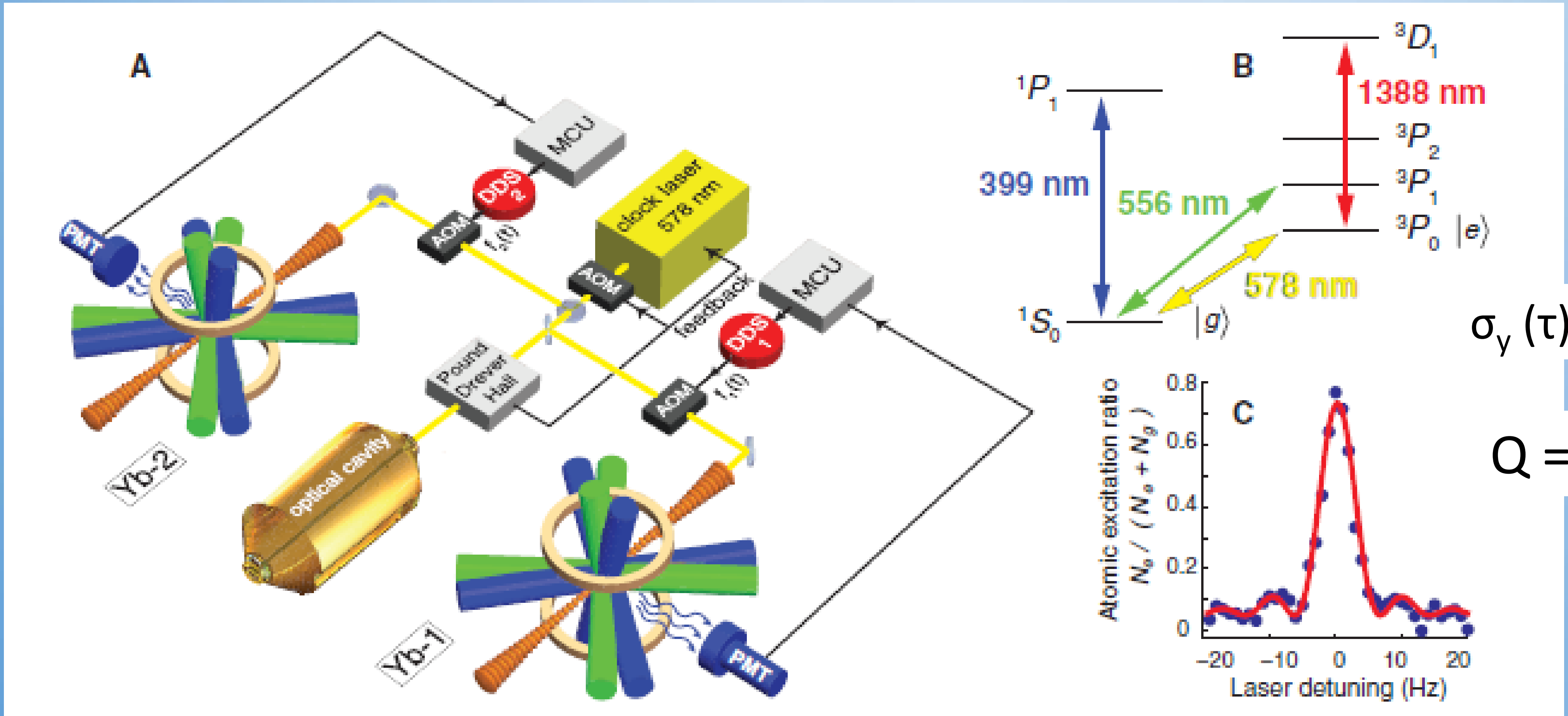


Ion Traps



Images from NIST Boulder

Optical Clocks and Sub 1 Hz Linewidth Lasers (Local Oscillator)

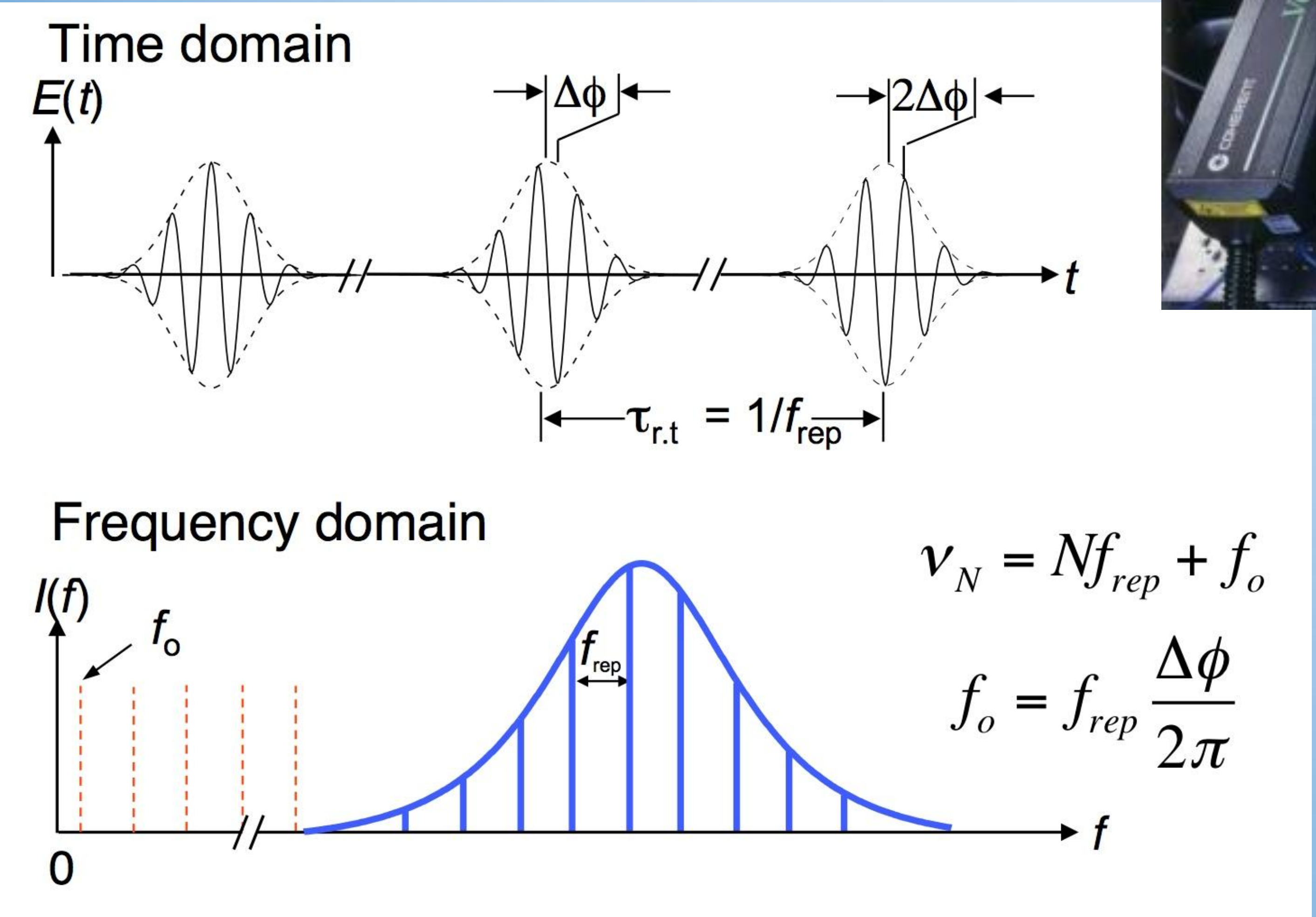


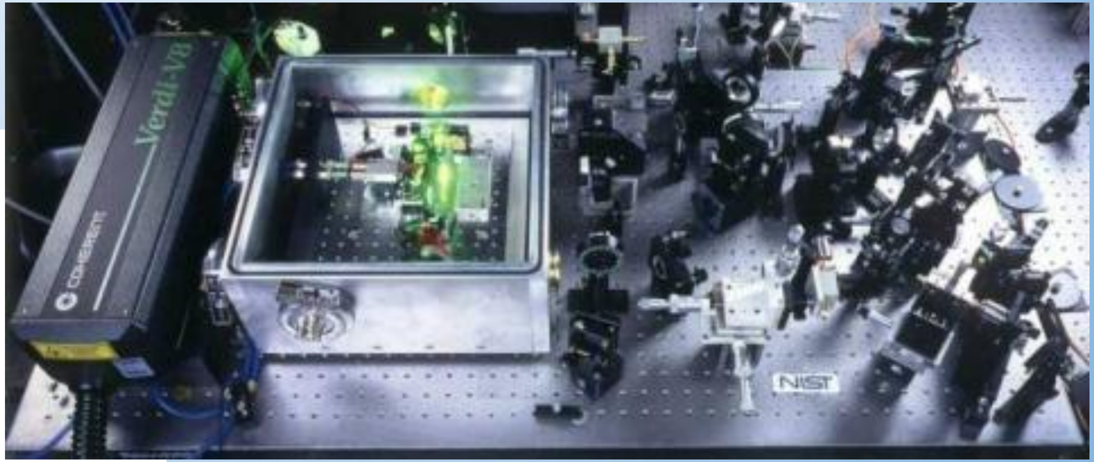
$\sigma_y(\tau) = 6 \times 10^{-17} \tau^{-1/2}$

$Q = 4 \times 10^{15}$

Ludlow
NIST Boulder

The Frequency Comb-Linking The Optical and Microwave





Fortier, Diddams
NIST Boulder

Current Advanced Clock Products: Two Paths

Big, expensive

µQuans

Laser Cooled Atoms
2×10^{-13} @ 1 sec
< 4×10^{-15} @ 5000 sec

250 W
75 kg

Small, affordable

Microsemi

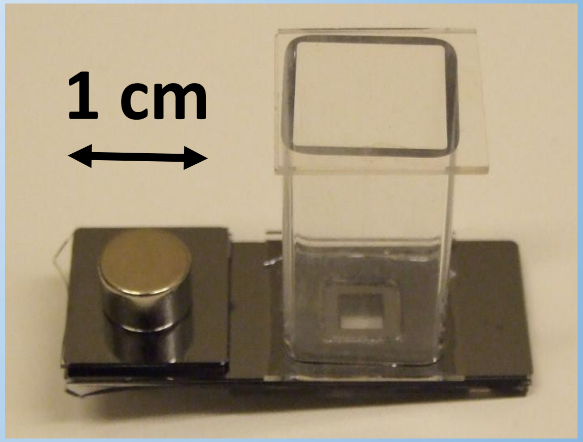
< 120 mW
<17 cm^3
< 10^{-11} @ 1000 sec
Cost: $ 10^3

Current Research and Problems

- Small, Cold Atom devices
- Small and Low Power Vacuum Pumps
- Passive Pumping
- Micro-Fabrication techniques

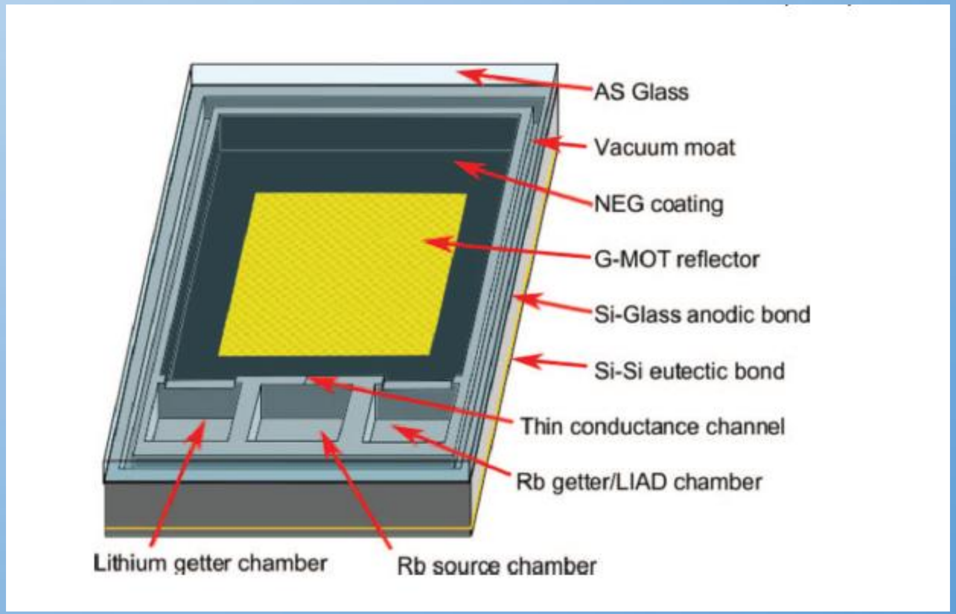
Micro Ion Pump

Dziuban
Wroclaw Univ of Tech



Prototype Miniature chip MOT
With Rb Source and Passive Pumping

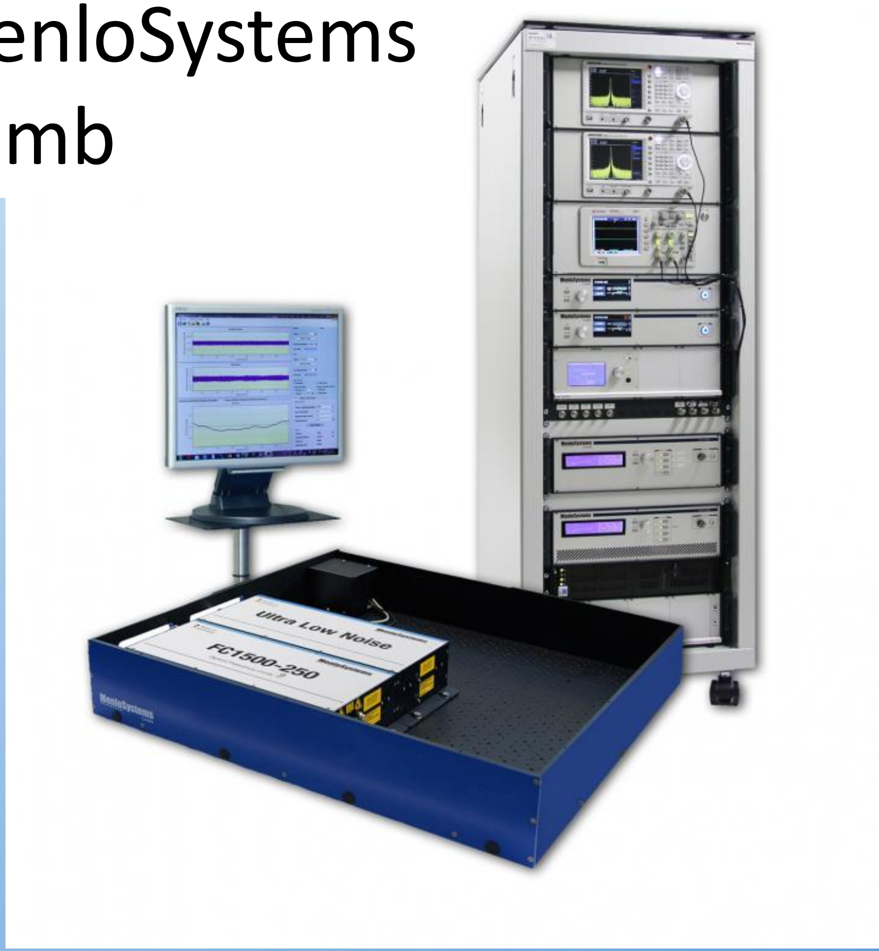
Himsworth Group
Univ of Southampton, UK



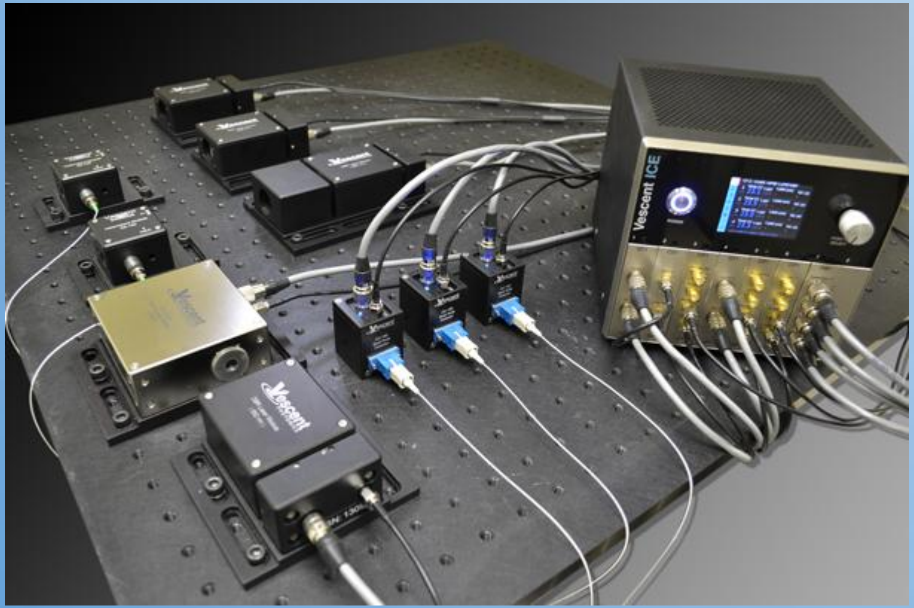
Laser Issues for Practical Atomic clocks

- Practical (affordable, small), narrow linewidth laser sources
- Micro-Combs

MenloSystems
Comb



Vescent Photonics
Laser Diode system for Laser-Cooling



End of Presentation