

Emerging Clock Technologies

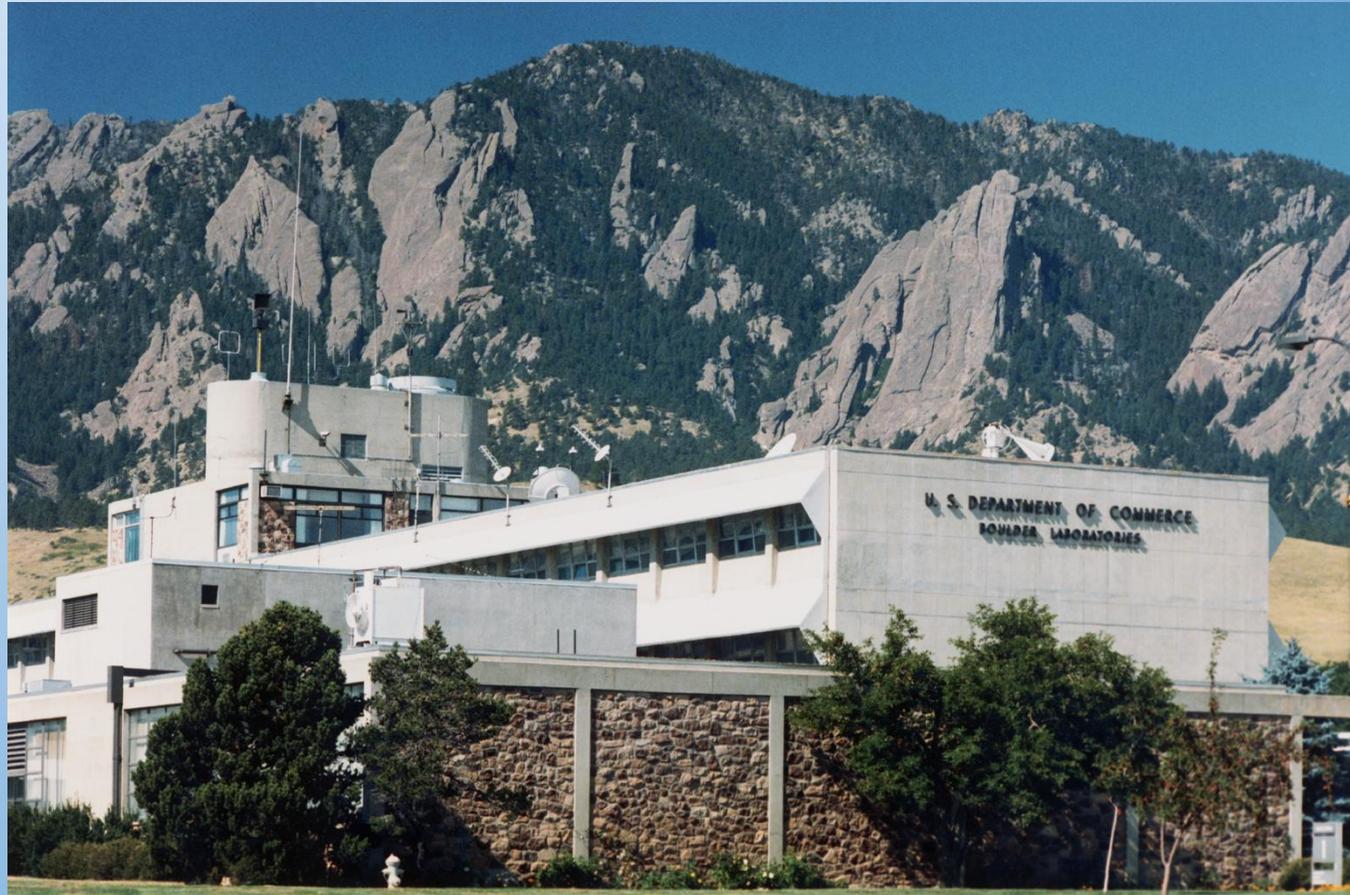
Tom Heavner

Time and Frequency Division

NIST

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

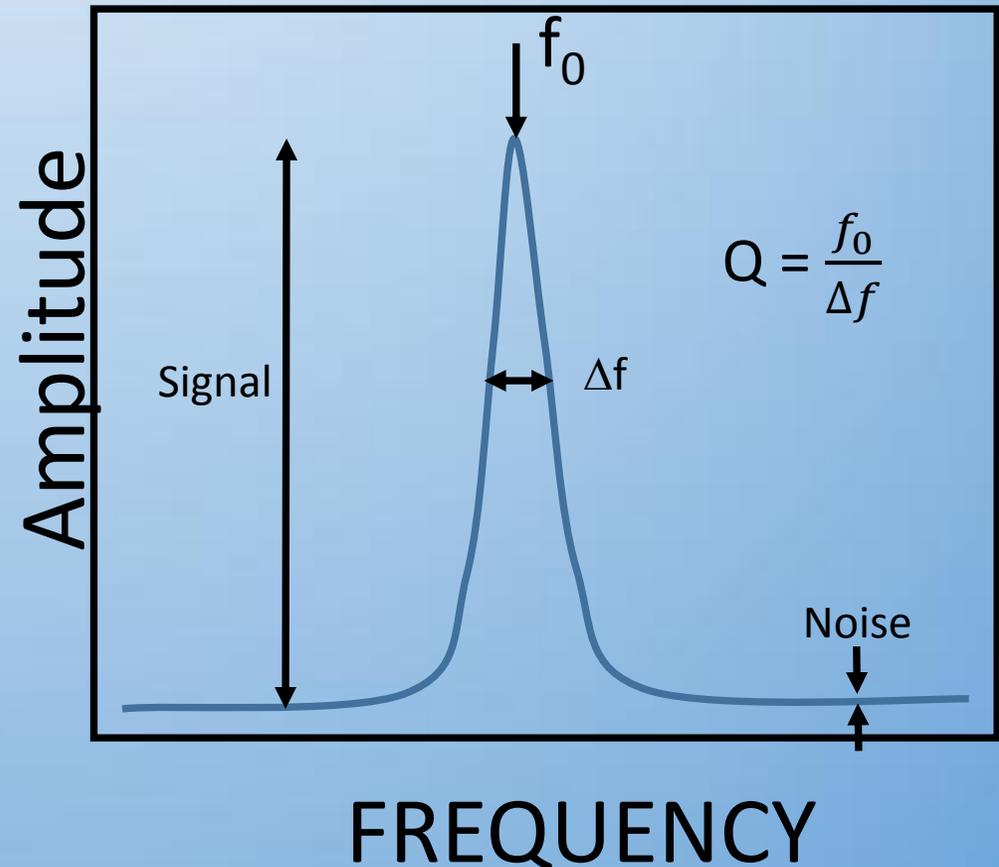
$$\sigma_y(\tau) \cong \frac{1}{Q (S/N) \sqrt{\tau}}$$

“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



PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s ⁻¹ (exact)
Planck constant	h	6.626 070 15 × 10 ⁻³⁴ J s
elementary charge	e	1.602 176 634 × 10 ⁻¹⁹ C
electron mass	m_e	9.109 383 56 × 10 ⁻³¹ kg
proton mass	m_p	1.672 621 63 × 10 ⁻²⁷ kg
fine-structure constant	α	1/137.035 999 084
Rydberg constant	R_∞	10 973 731.568 162 854 m ⁻¹
$R_\infty c$		3.289 842 × 10 ¹⁵ Hz
$R_\infty hc$		13.605 698 065 846 56 eV
Boltzmann constant	k	1.380 658 529 × 10 ⁻²³ J K ⁻¹

Solids
 Liquids
 Gases
 Artificially Prepared

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VII	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA	
1	H Hydrogen 1.00784 1s																	He Helium 4.002602 1s ²
2	Li Lithium 6.941 1s ² 2s ¹	Be Beryllium 9.012182 1s ² 2s ²											B Boron 10.811 1s ² 2s ² 2p ¹	C Carbon 12.0107 1s ² 2s ² 2p ²	N Nitrogen 14.0067 1s ² 2s ² 2p ³	O Oxygen 15.9994 1s ² 2s ² 2p ⁴	F Fluorine 18.9984032 1s ² 2s ² 2p ⁵	Ne Neon 20.1797 1s ² 2s ² 2p ⁶
3	Na Sodium 22.989770 [Ne]3s ¹	Mg Magnesium 24.3050 [Ne]3s ²											Al Aluminum 26.981538 [Ne]3s ² 3p ¹	Si Silicon 28.0855 [Ne]3s ² 3p ²	P Phosphorus 30.973761 [Ne]3s ² 3p ³	S Sulfur 32.065 [Ne]3s ² 3p ⁴	Cl Chlorine 35.453 [Ne]3s ² 3p ⁵	Ar Argon 39.948 [Ne]3s ² 3p ⁶
4	K Potassium 39.0983 [Ar]4s ¹	Ca Calcium 40.078 [Ar]4s ²	Sc Scandium 44.955910 [Ar]3d ¹ 4s ²	Ti Titanium 47.88 [Ar]3d ² 4s ²	V Vanadium 50.9415 [Ar]3d ³ 4s ²	Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	Fe Iron 55.845 [Ar]3d ⁶ 4s ²	Co Cobalt 58.933200 [Ar]3d ⁷ 4s ²	Ni Nickel 58.6934 [Ar]3d ⁸ 4s ²	Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ²	Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ²	As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³	Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴	Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶
5	Rb Rubidium 85.4678 [Kr]5s ¹	Sr Strontium 87.62 [Kr]5s ²	Y Yttrium 88.90585 [Kr]4d ¹ 5s ²	Zr Zirconium 91.224 [Kr]4d ² 5s ²	Nb Niobium 92.90638 [Kr]4d ⁴ 5s ¹	Mo Molybdenum 95.94 [Kr]4d ⁵ 5s ¹	Tc Technetium (98) [Kr]4d ⁵ 5s ²	Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹	Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹	Pd Palladium 106.42 [Kr]4d ¹⁰	Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹	Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s ²	In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p ¹	Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ²	Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³	Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴	I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵	Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶
6	Cs Cesium 132.90545 [Xe]6s ¹	Ba Barium 137.327 [Xe]6s ²		Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	Ta Tantalum 180.9473 [Xe]4f ¹⁴ 5d ³ 6s ²	W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²	Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	Ir Iridium 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s ²	Pt Platinum 195.078 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	Au Gold 196.9665 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	Tl Thallium 204.3833 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	Pb Lead 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	Bi Bismuth 208.98038 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	Po Polonium (209) [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	At Astatine (210) [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	Rn Radon (222) [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶
7	Fr Francium (223) [Rn]7s ¹	Ra Radium (226) [Rn]7s ²		Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ²	Db Dubnium (262) [Rn]5f ¹⁴ 6d ³ 7s ²	Sg Seaborgium (266) [Rn]5f ¹⁴ 6d ⁴ 7s ²	Bh Bohrium (264) [Rn]5f ¹⁴ 6d ⁵ 7s ²	Hs Hassium (277) [Rn]5f ¹⁴ 6d ⁶ 7s ²	Mt Meitnerium (268) [Rn]5f ¹⁴ 6d ⁷ 7s ²	Uun Ununium (281) [Rn]5f ¹⁴ 6d ⁸ 7s ²	Uuu Ununium (272) [Rn]5f ¹⁴ 6d ⁹ 7s ²	Uub Ununium (285) [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	Uuq Ununquadium (289) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	Uuh Ununhexium (292) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²				
			Lanthanides	57 La Lanthanum 138.9055 [Xe]5d ¹ 6s ²	58 Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ²	59 Pr Praseodymium 140.90765 [Xe]4f ³ 6s ²	60 Nd Neodymium 144.24 [Xe]4f ⁴ 6s ²	61 Pm Promethium (145) [Xe]4f ⁵ 6s ²	62 Sm Samarium 150.36 [Xe]4f ⁶ 6s ²	63 Eu Europium 151.964 [Xe]4f ⁷ 6s ²	64 Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ²	65 Tb Terbium 158.92534 [Xe]4f ⁹ 6s ²	66 Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ²	67 Ho Holmium 164.93032 [Xe]4f ¹¹ 6s ²	68 Er Erbium 167.259 [Xe]4f ¹² 6s ²	69 Tm Thulium 168.93401 [Xe]4f ¹³ 6s ²	70 Yb Ytterbium 173.04 [Xe]4f ¹⁴ 6s ²	71 Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ²
			Actinides	89 Ac Actinium 227.0381 [Rn]6d ¹ 7s ²	90 Th Thorium 232.0381 [Rn]6d ² 7s ²	91 Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ²	92 U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ²	93 Np Neptunium 237 [Rn]5f ⁴ 6d ¹ 7s ²	94 Pu Plutonium 244 [Rn]5f ⁶ 7s ²	95 Am Americium 243 [Rn]5f ⁷ 7s ²	96 Cm Curium 247 [Rn]5f ⁸ 7s ²	97 Bk Berkelium 247 [Rn]5f ⁹ 7s ²	98 Cf Californium 251 [Rn]5f ¹⁰ 7s ²	99 Es Einsteinium 252 [Rn]5f ¹¹ 7s ²	100 Fm Fermium 257 [Rn]5f ¹² 7s ²	101 Md Mendelevium 258 [Rn]5f ¹³ 7s ²	102 No Nobelium 259 [Rn]5f ¹⁴ 7s ²	103 Lr Lawrencium 262 [Rn]5f ¹⁴ 7p ¹

58 Ce
Cerium
140.116
[Xe]4f¹5d¹6s²
5.5387 eV

Ground-state Ionization Energy (eV)

¹Based upon ¹²C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

Alkali Atoms and 50+ Years of Atomic Clocks

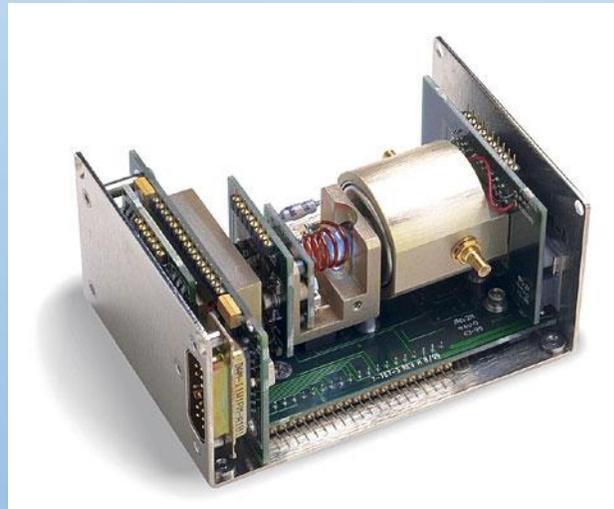
Hydrogen Maser

Large Storage Bulb and Cavity
Sophisticated Electronics
Magnets



Rubidium Cells

Lamp
Rb Isotope allows for Optical Pumping
Small Package



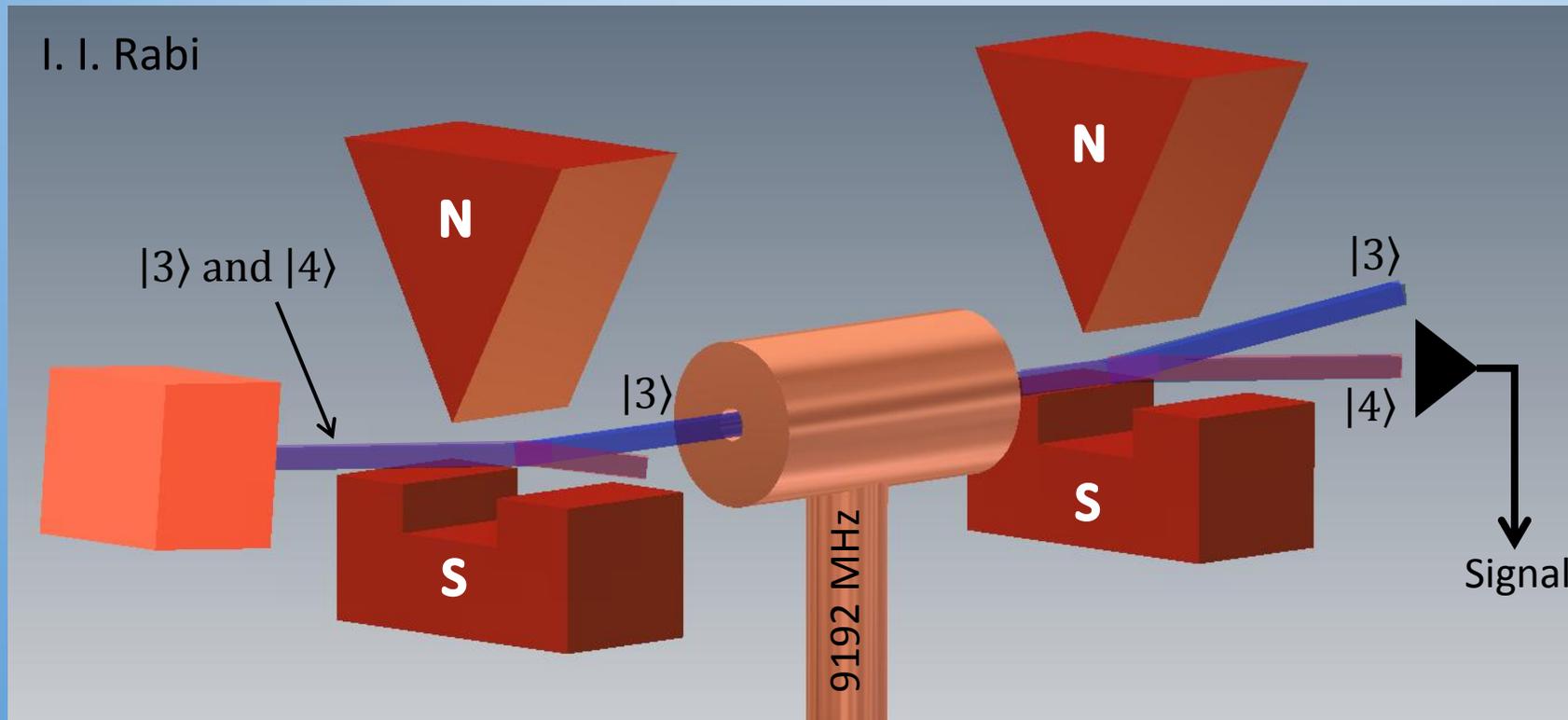
Cesium Beams

Ramsey Technique/Beam Tube
Magnets



Closer Look at Cesium Beam Clocks

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



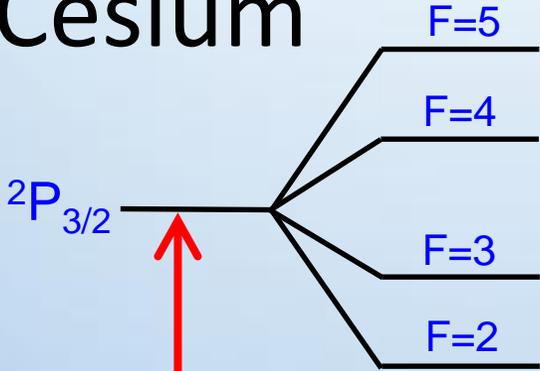
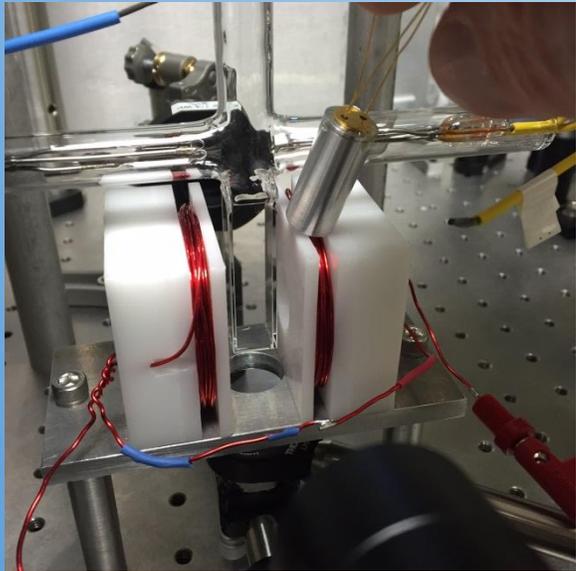
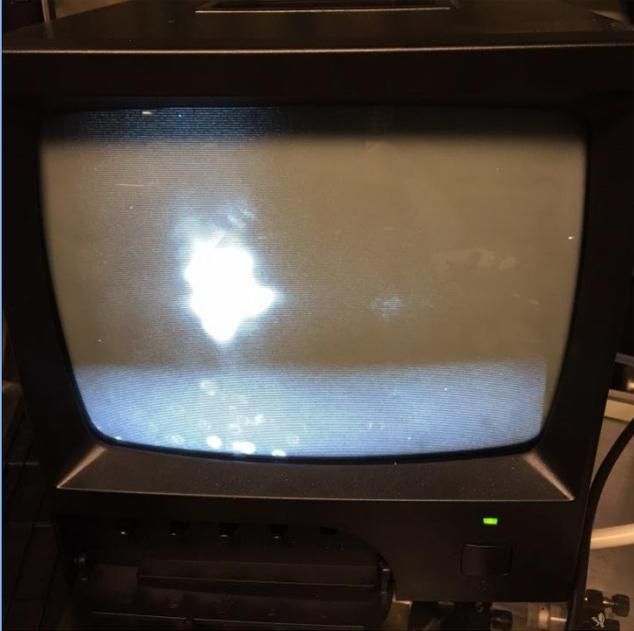
A Revolution in Clocks: Laser Cooling

- 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 ($T \sim 1 \mu\text{Kelvin}$)

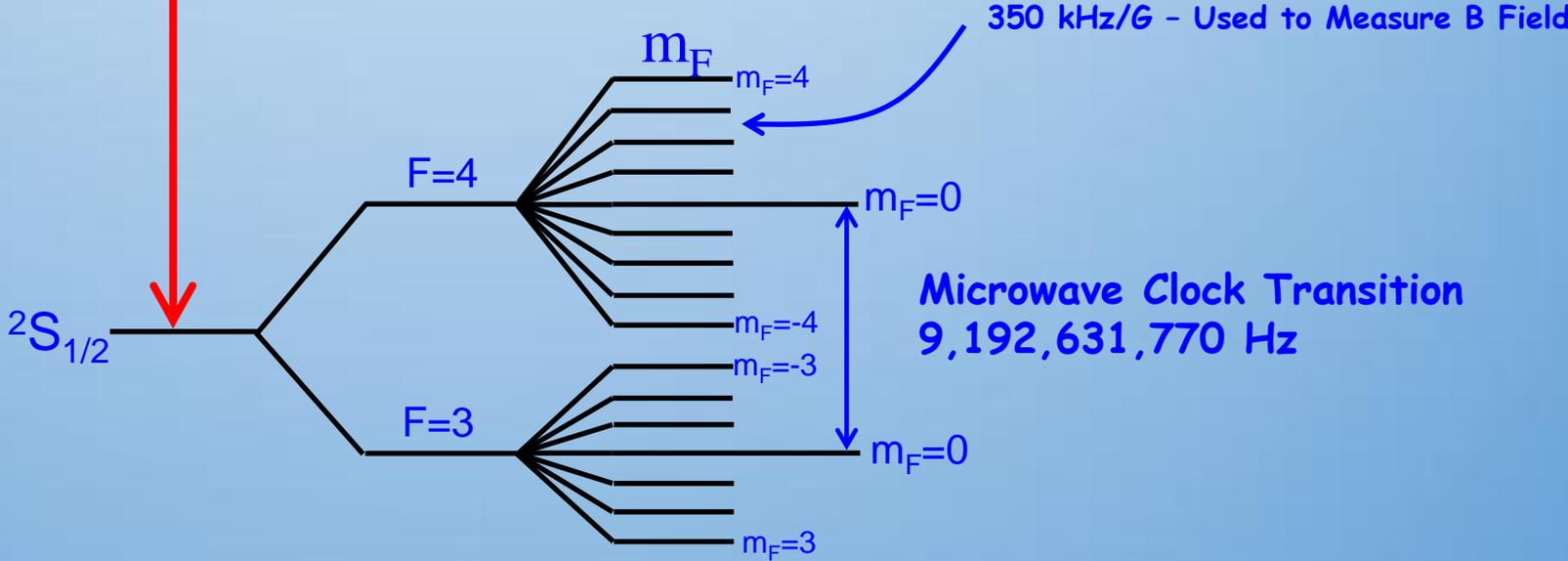


NIST-Laboratory ECDL circa 1990-2000s

Laser Cooling in Cesium

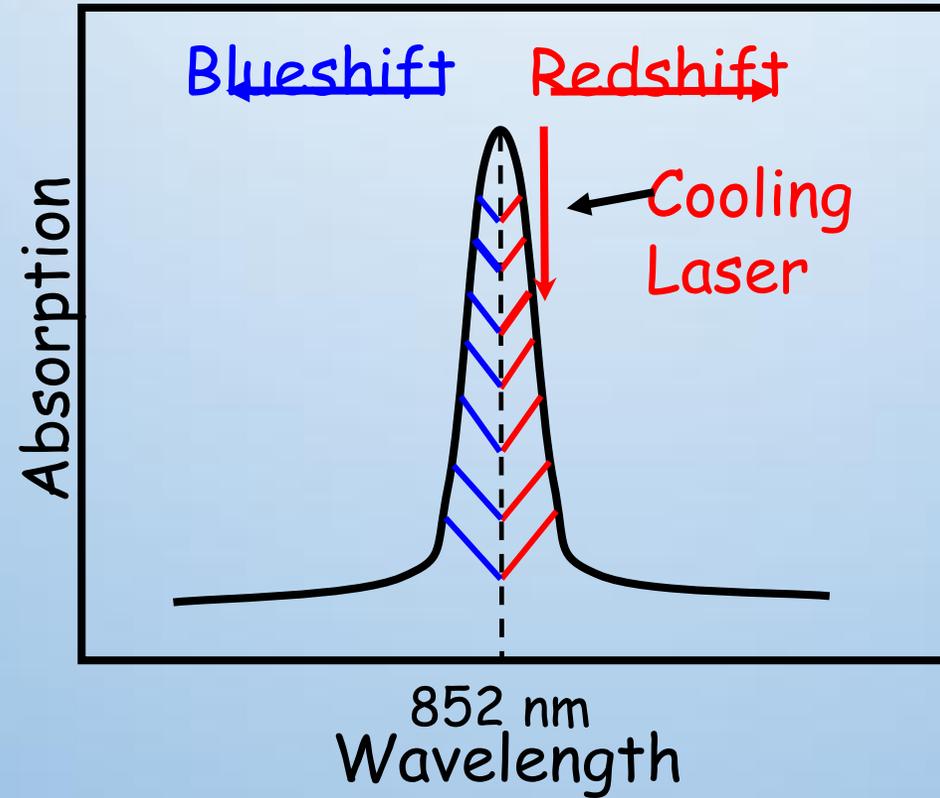


Optical Transition
852 nm
Laser Cooling

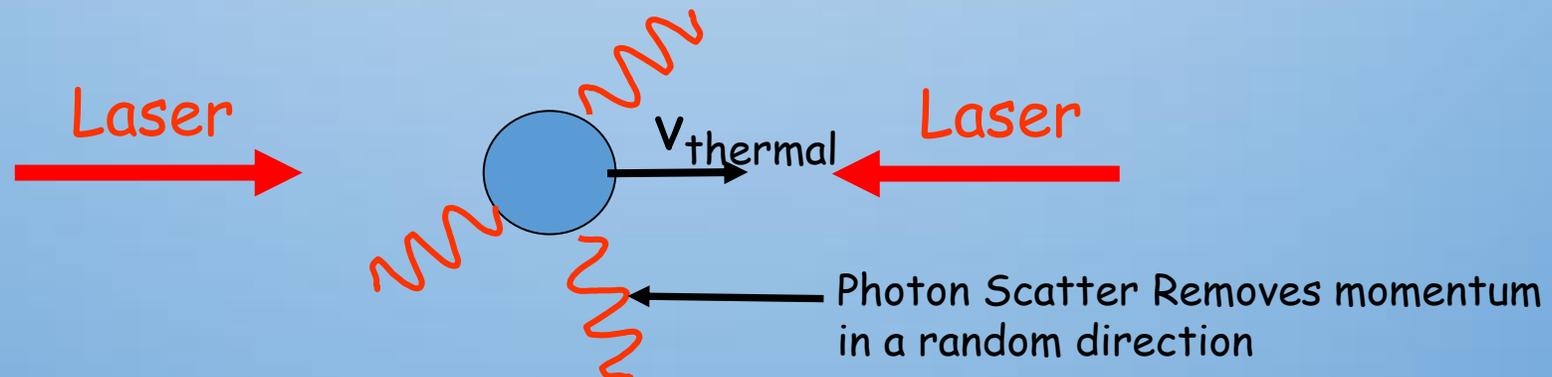


Laser Cooling Details

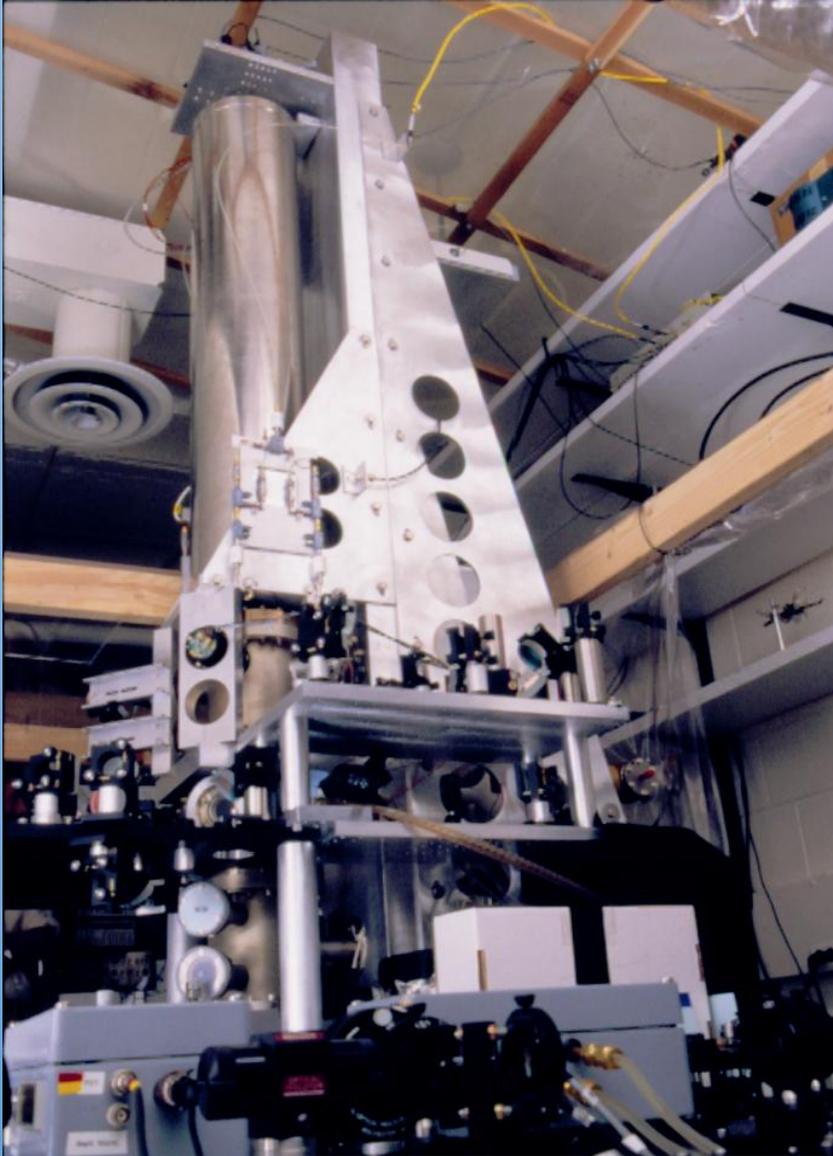
Optical
Molasses
 $T \sim 1 \mu\text{Kelvin}$



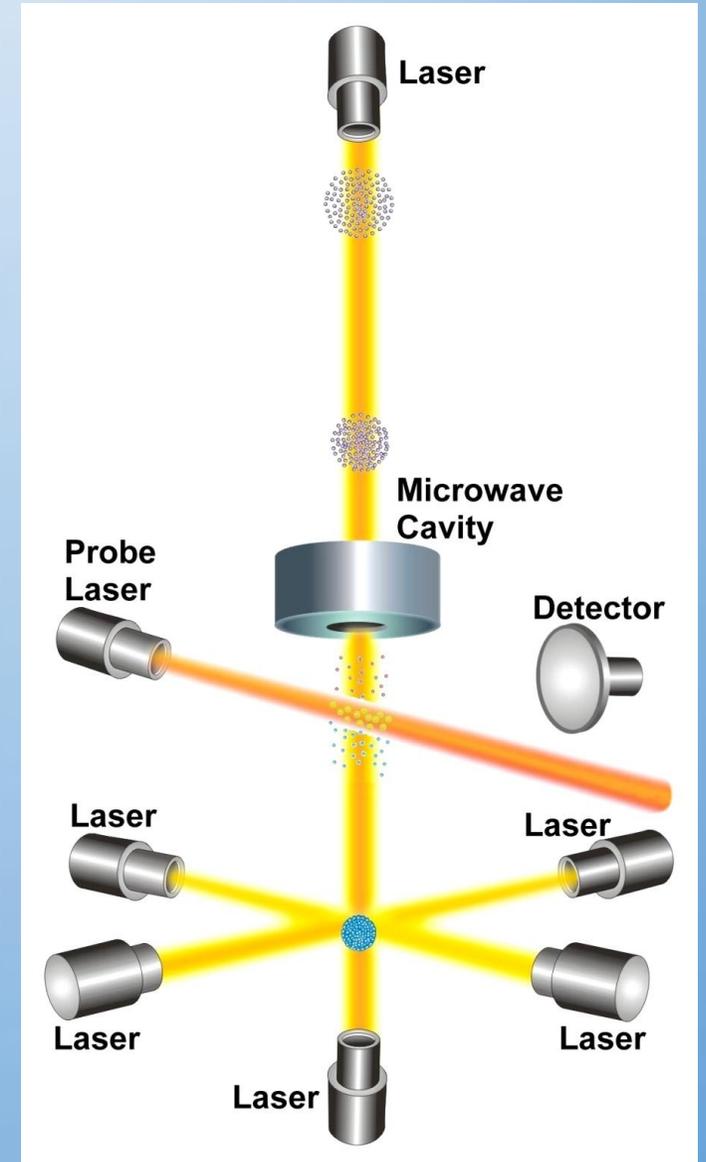
Laser Frequency is
tuned slightly below
the atomic resonance:
 $\nu_{\text{laser}} = \nu_{\text{atom}} - \delta$



NIST-F1 : Laser Cooled Cs Fountain



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

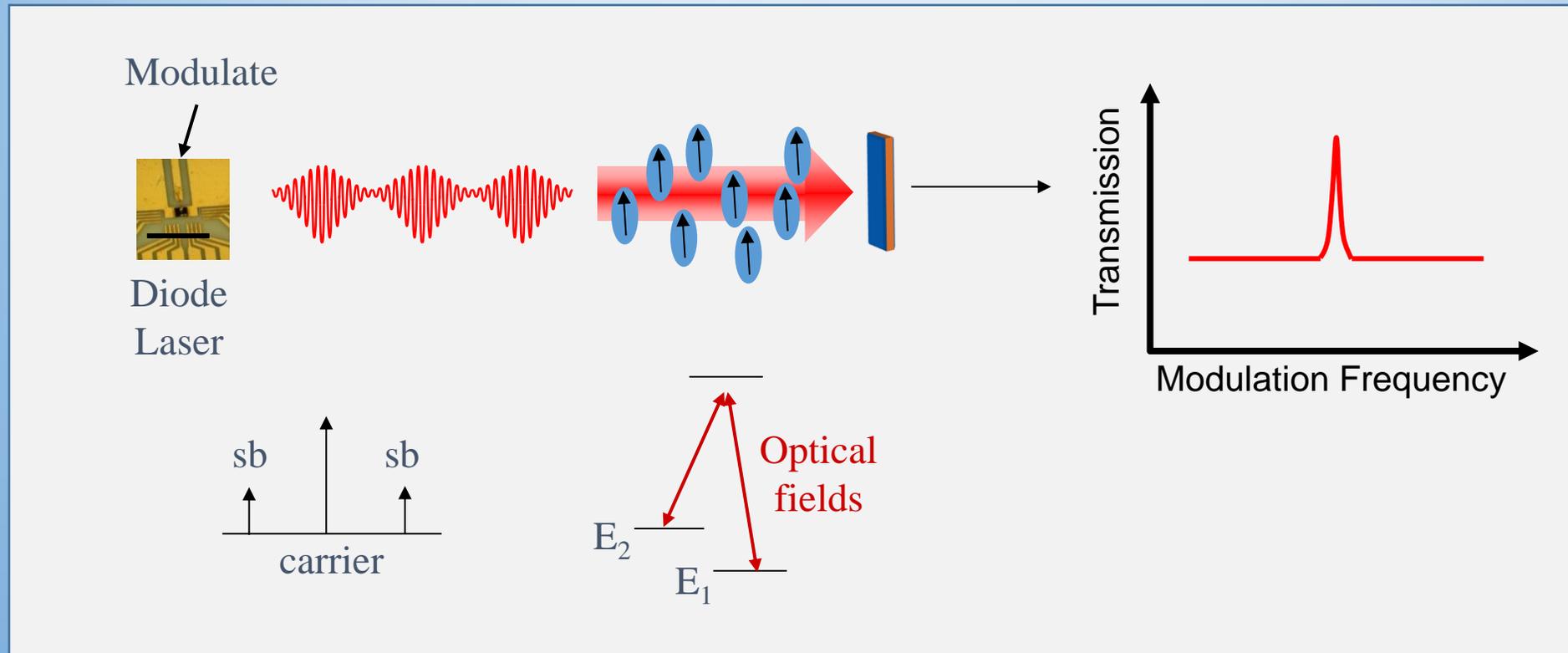


Going Small with VCSEL Laser Diodes

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



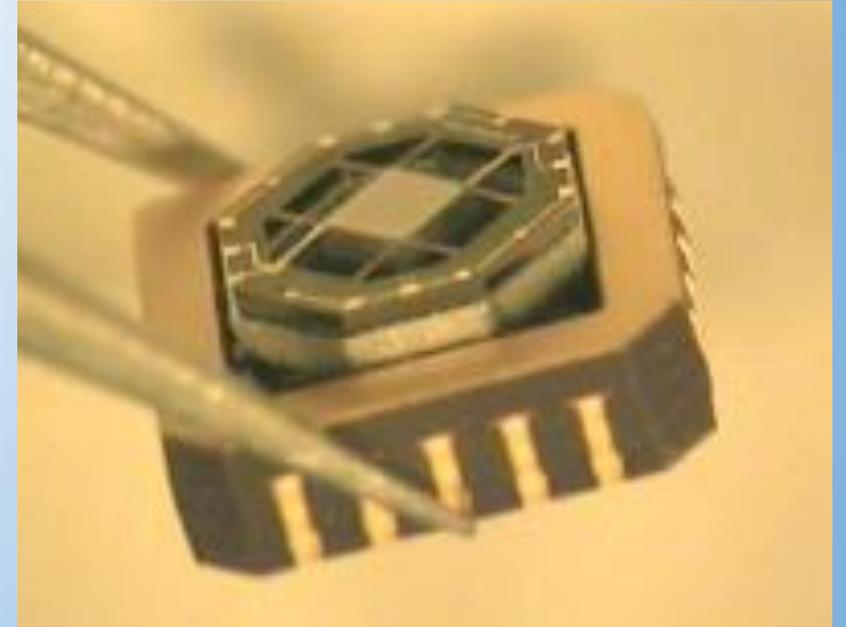
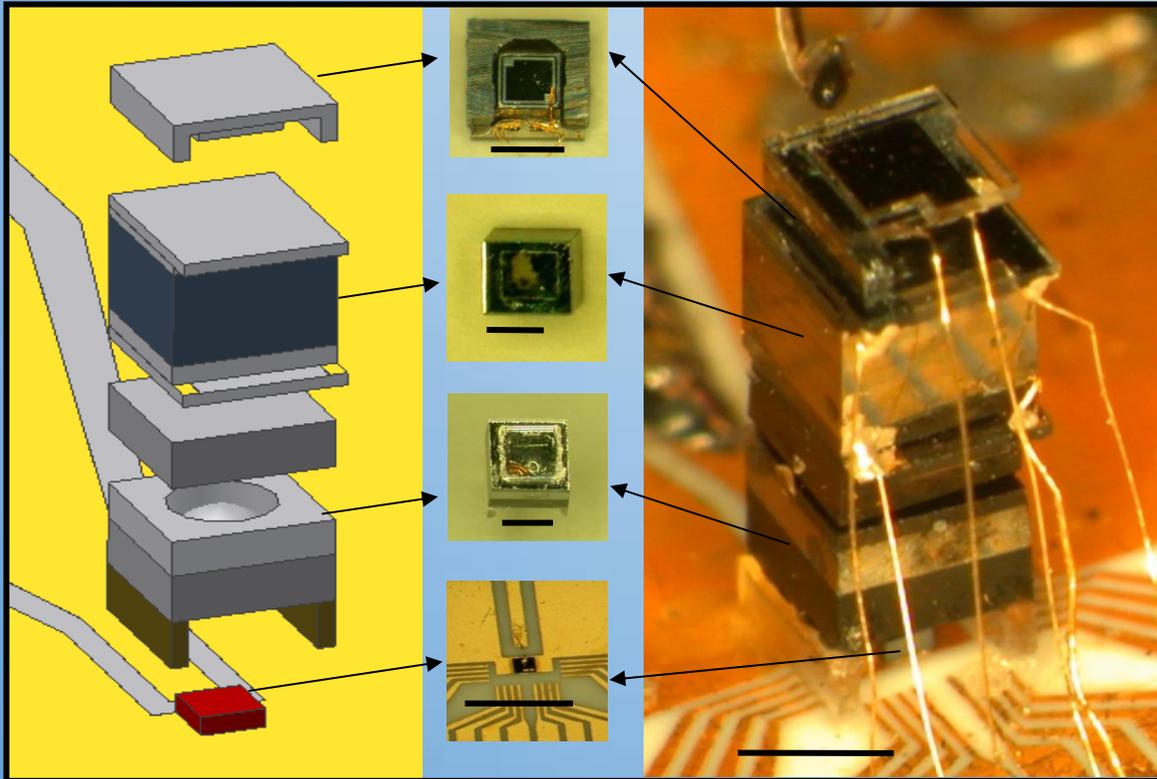
All-Optical (CPT) Excitation



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

CSAC – Chip Scale Atomic Clock

NIST Prototype

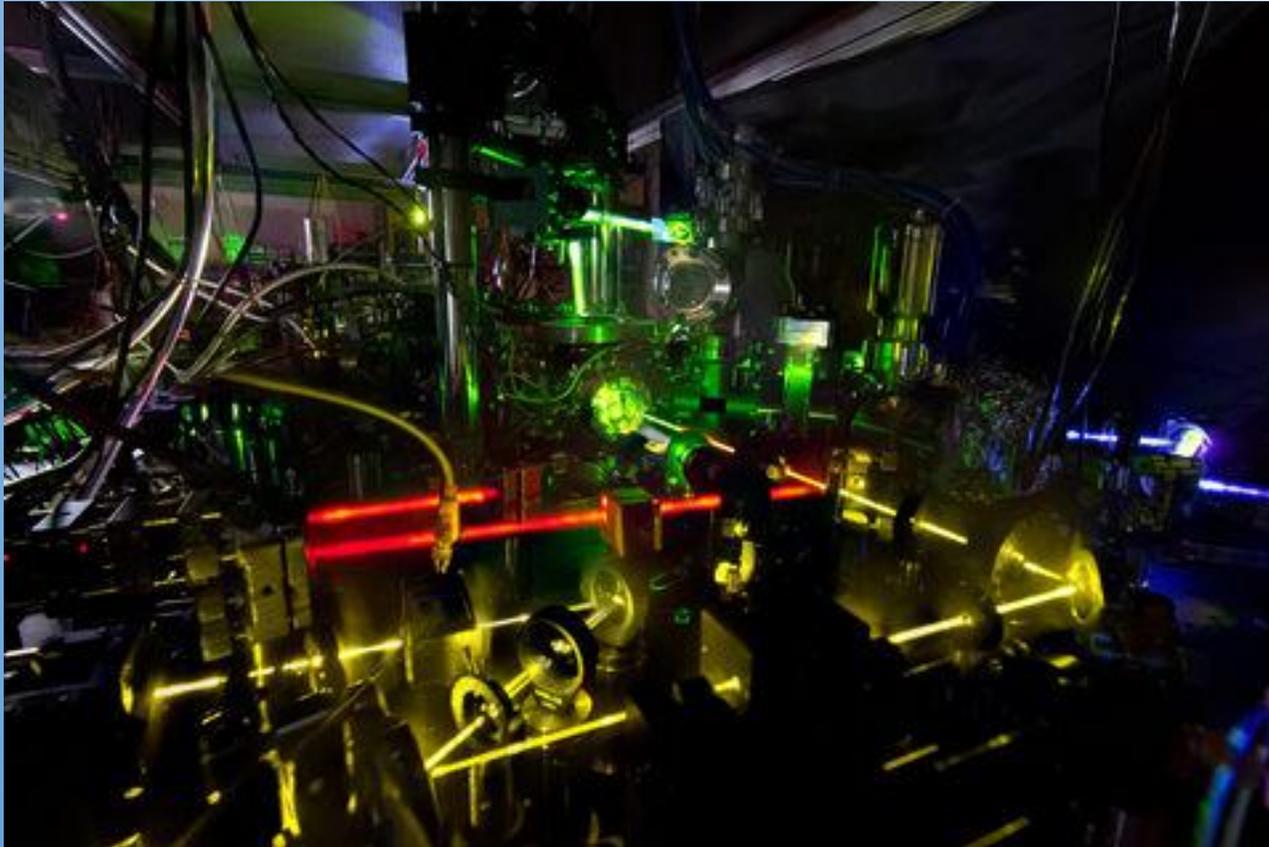


Microsemi

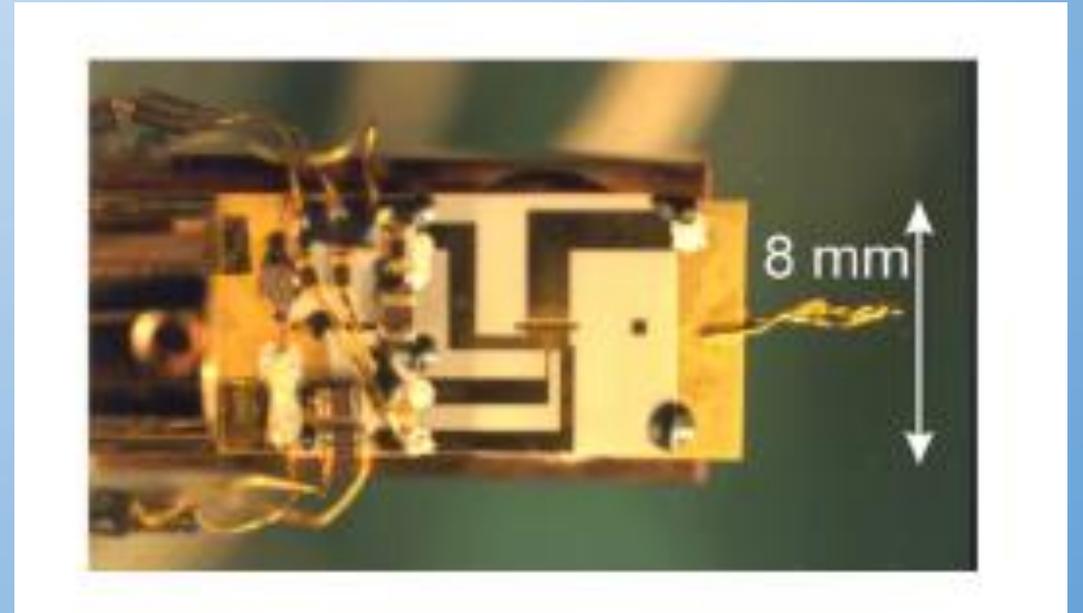


More Trapping and Cooling: Optical Clocks

Optical Lattice

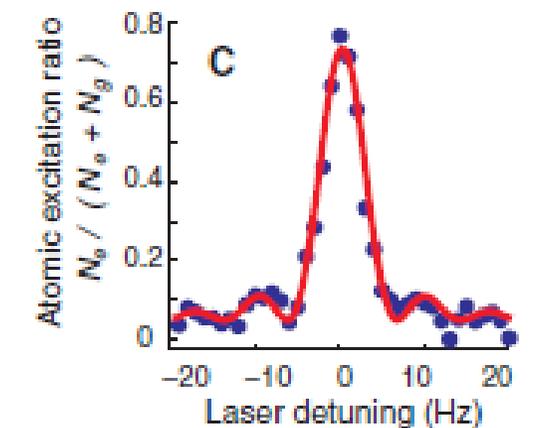
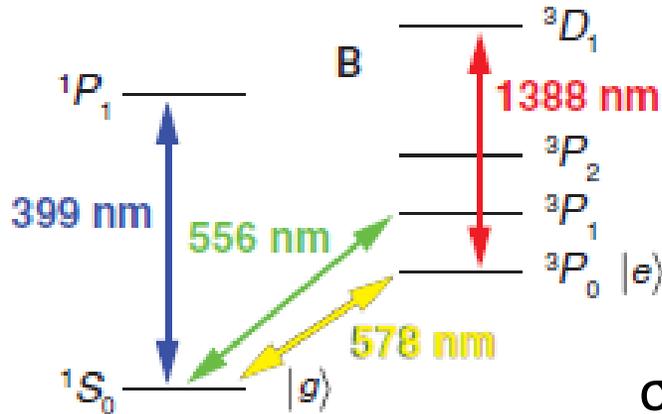
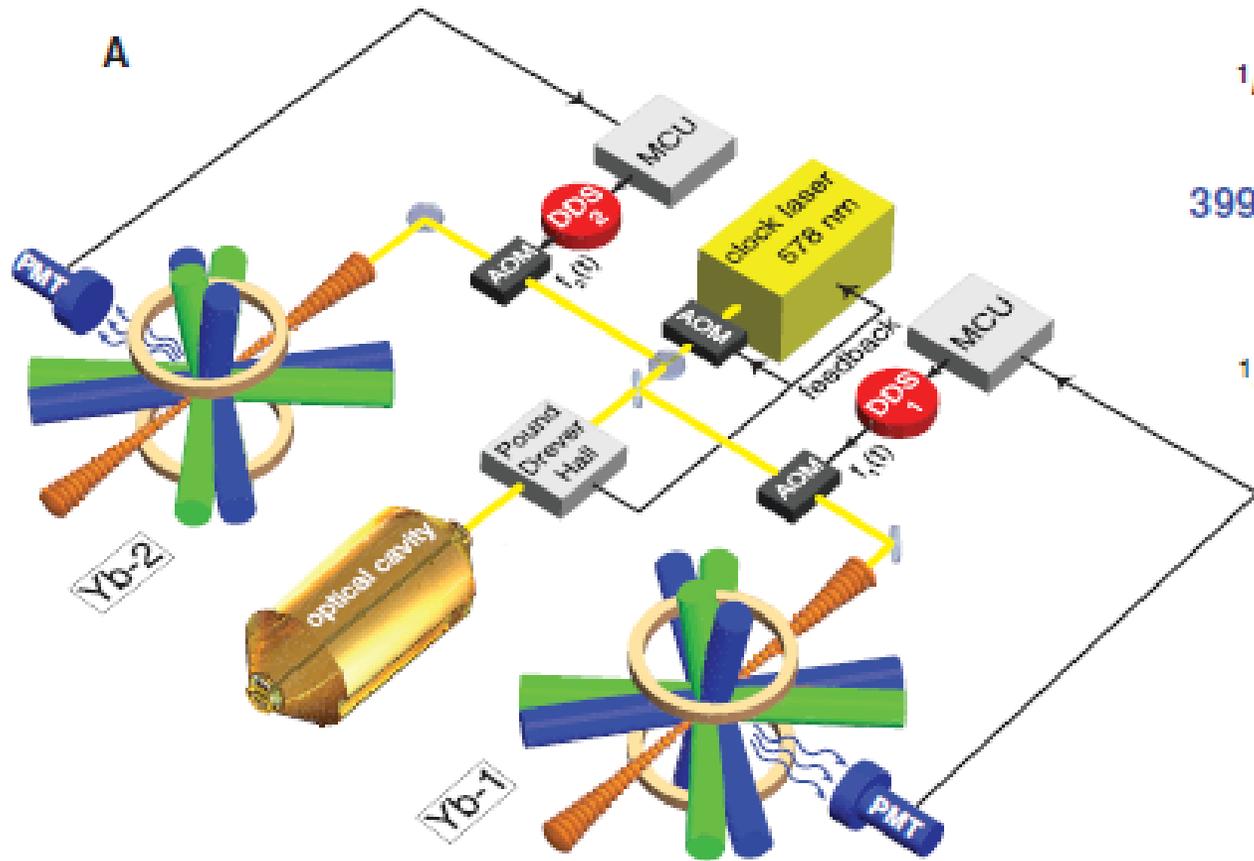


Ion Traps



Images from NIST Boulder

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



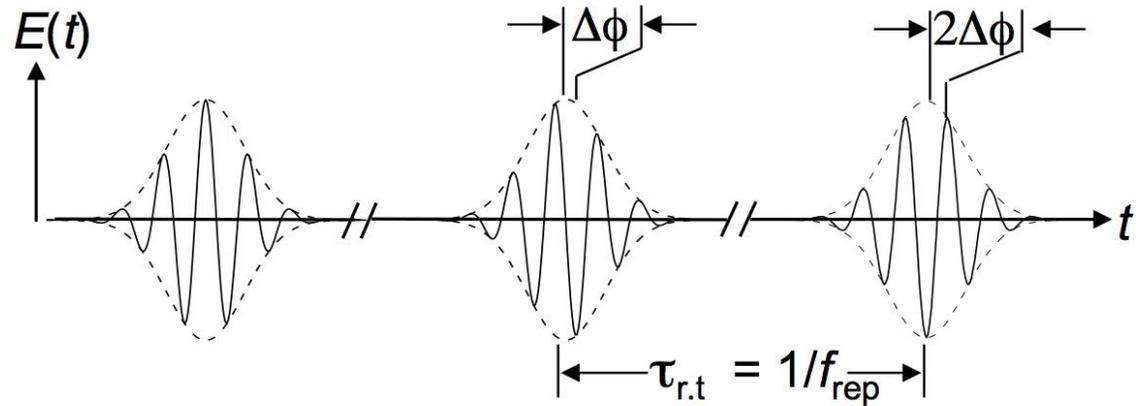
$$\sigma_y(\tau) = 6 \times 10^{-17} \tau^{-1/2}$$

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

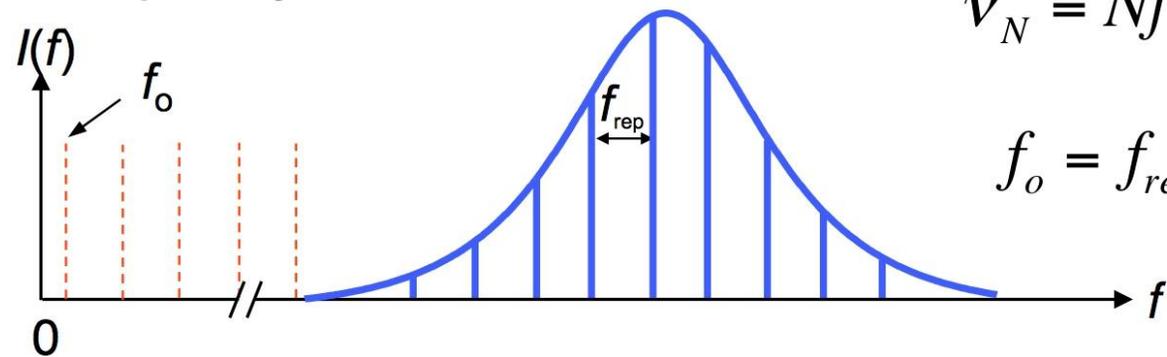
Ludlow
NIST Boulder

The Frequency Comb-Linking The Optical and Microwave

Time domain

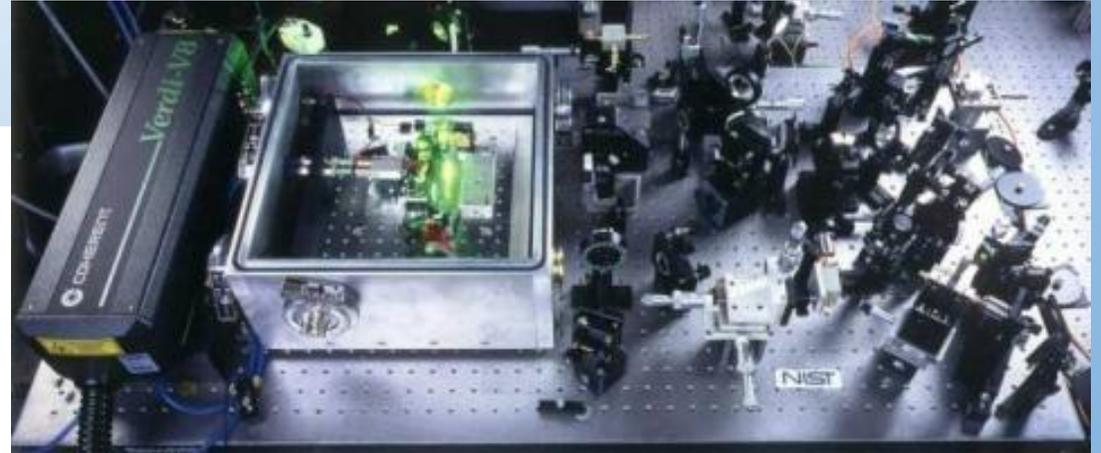


Frequency domain



$$\nu_N = Nf_{rep} + f_0$$

$$f_0 = f_{rep} \frac{\Delta\phi}{2\pi}$$



Fortier, Diddams
NIST Boulder

Current Advanced Clock Products: Two Paths

Big, expensive

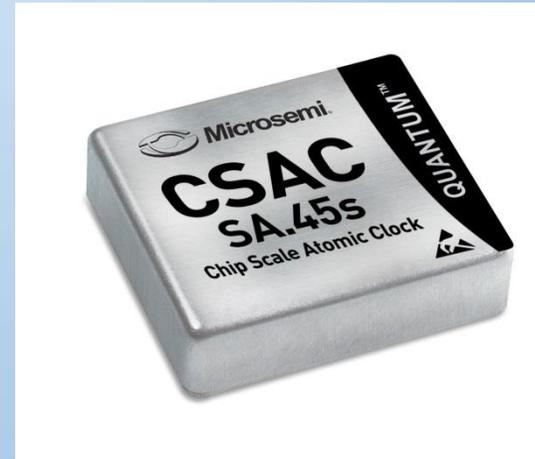


μ Quans

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

250 W
75 kg

Small, affordable



Microsemi

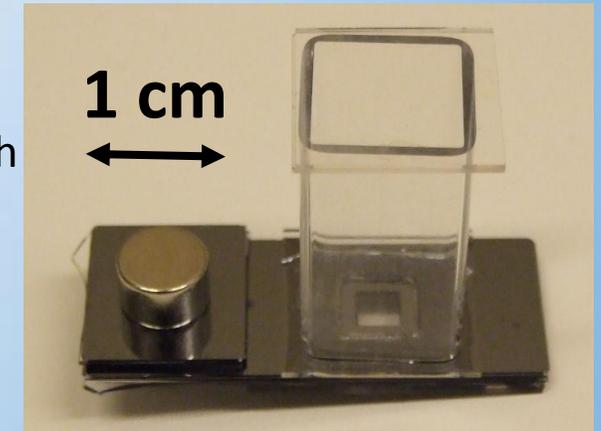
< 120 mW
 < 17 cm³
 $< 10^{-11}$ @ 1000 sec
Cost: \$ 10^3

Current Research and Problems

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

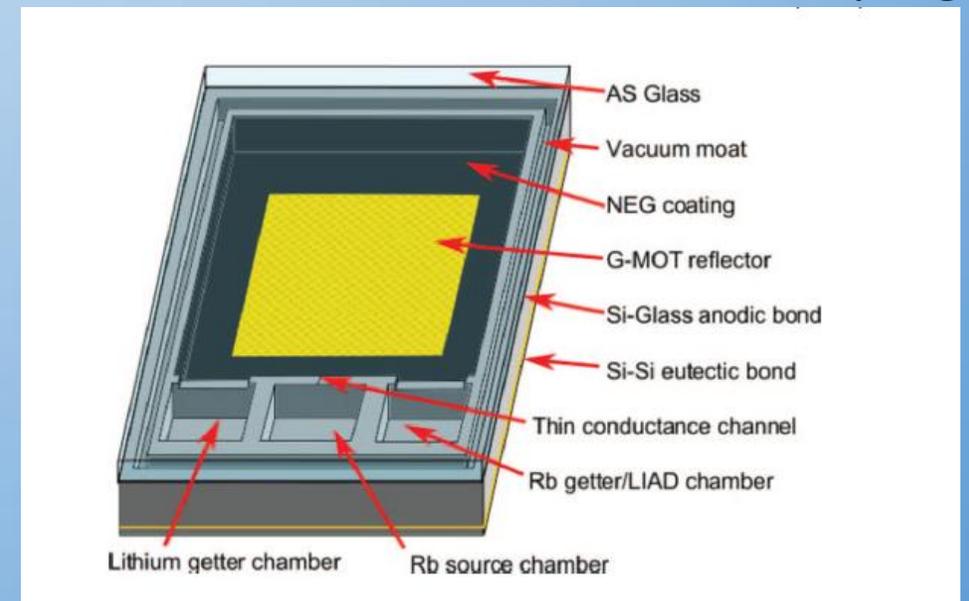
Dziuban
Wroclaw Univ of Tech

Micro Ion Pump



Prototype Miniature chip MOT With Rb Source and Passive Pumping

Himsworth Group
Univ of Southampton, UK



Laser Issues for Practical Atomic clocks

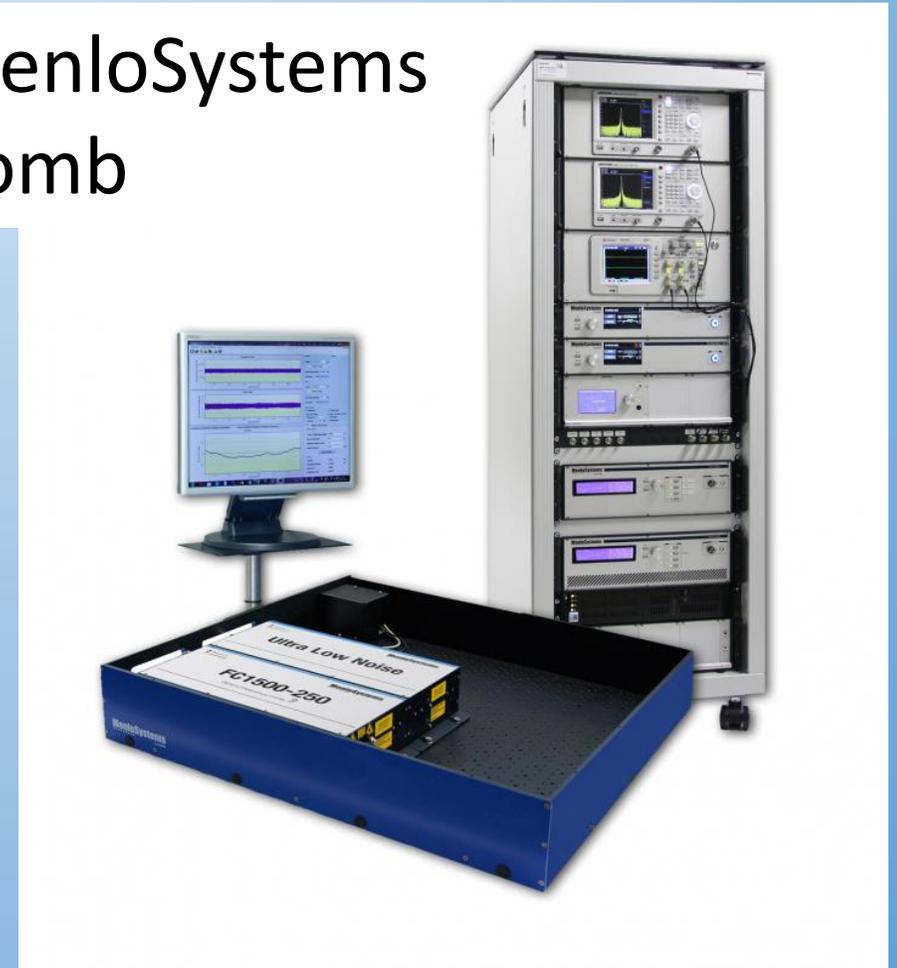
- Practical (affordable, small), narrow linewidth laser sources
- Micro-Combs

Vescent Photonics

Laser Diode system for Laser-Cooling



MenloSystems
Comb



End of Presentation