Atomic Clocks and Primary Frequency Sources

WSTS 2021 TUTORIAL SESSION

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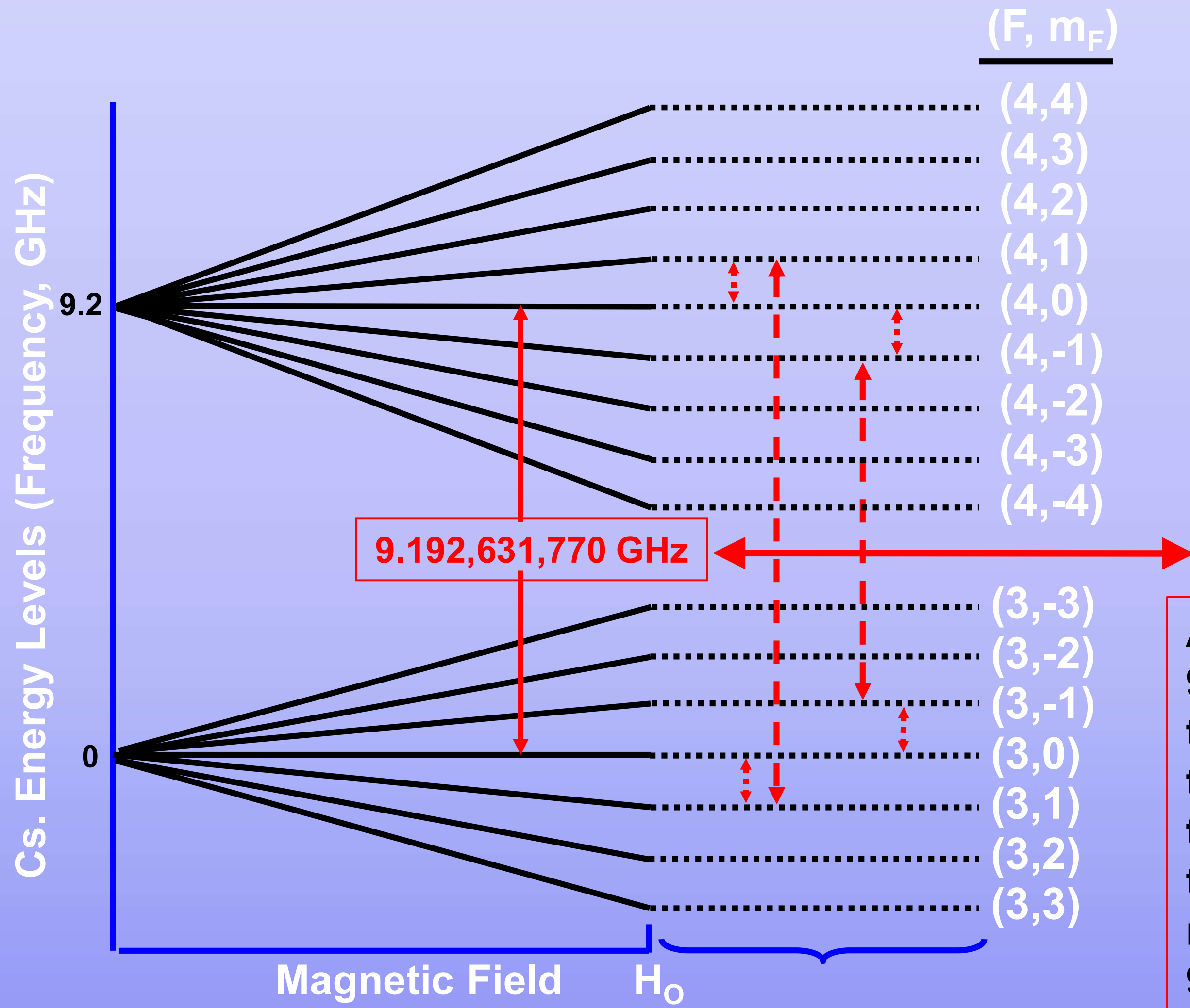
Atomic Frequency Standards: Produce Frequency Locked to an Atomic Transition



$\Delta E = h\nu$

Definition of the second is the definition of frequency accuracy: agreement with the Cs clock transition

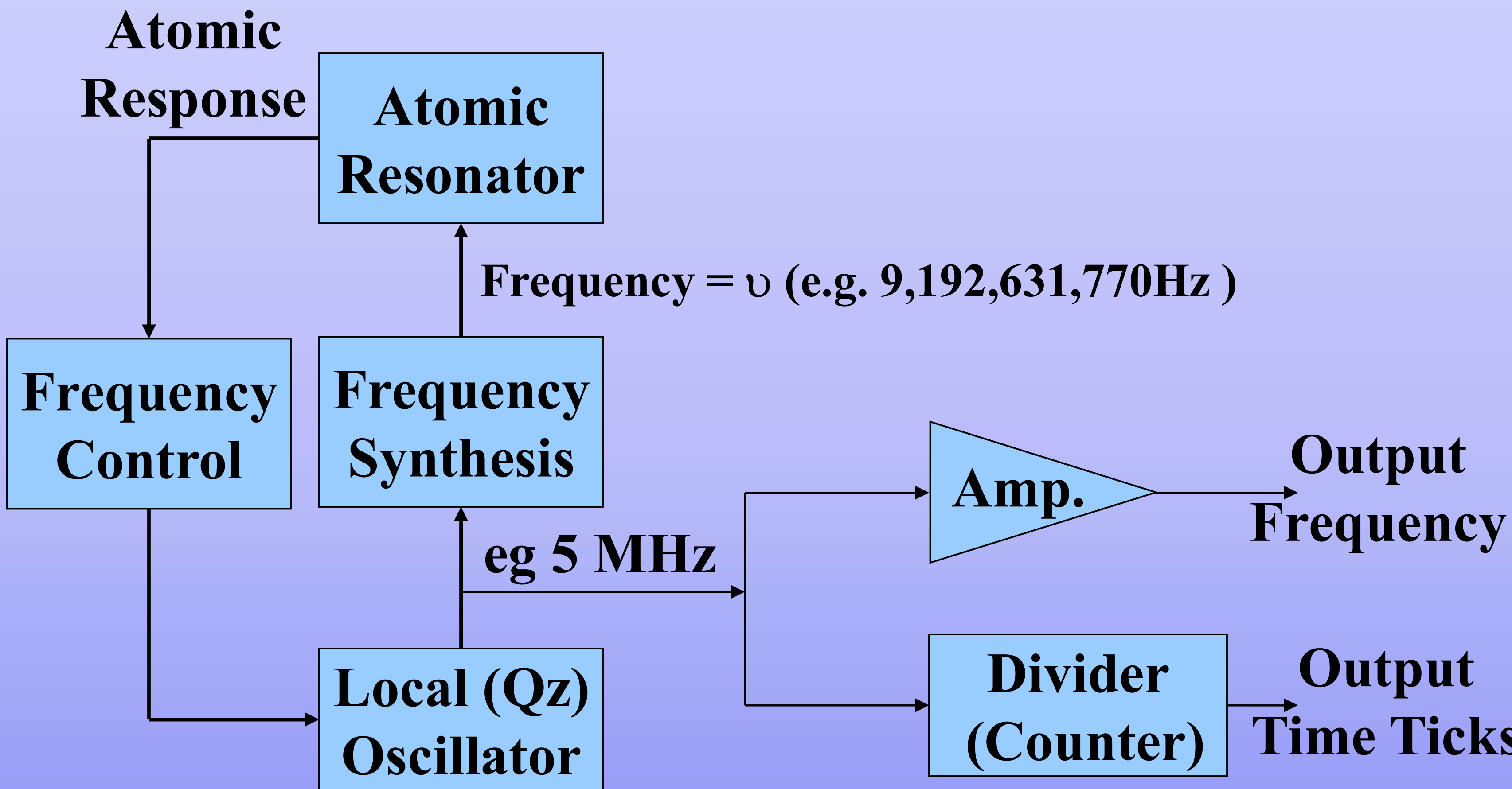
Absorption of photon at 9,192,631,770Hz results in transition from state (3,0) to state (4,0)
transition from state (3,0) to state (4,0) results in radiation of photon at 9,192,631,770Hz

Basic Passive Atomic Clock

1. Obtain atoms to measure
2. Depopulate one hyperfine level
3. Radiate the state-selected sample with frequency ν
4. Measure how many atoms change state
5. Correct ν to maximize measured atoms in changed state

Block Diagram of Atomic Clock

Passive Standard

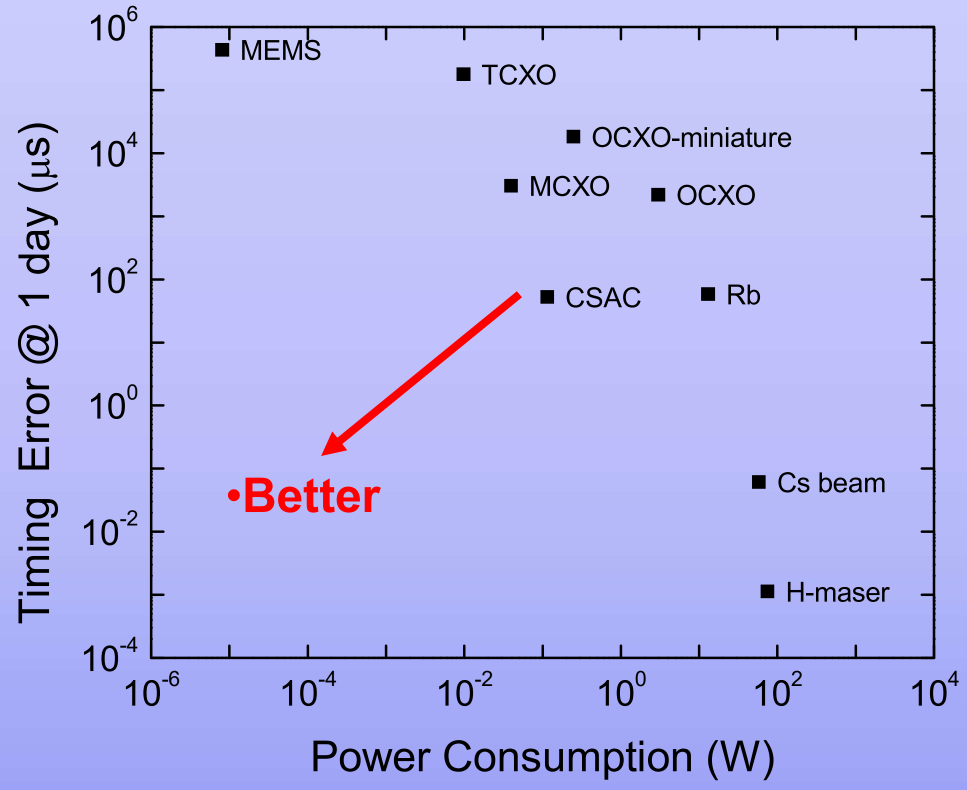


Types of Commercial Atomic Clocks

- Cesium thermal beam standard
  - Best long-term frequency stability
- Rubidium cell standard
  - Small size, low cost
- Hydrogen maser
  - Best stability at 1 to 10 days (short-term stability)
  - Expensive several $100K
- Chip Scale Atomic Clock (CSAC)
  - Very small size, low power
- Note that new clocks are under development!

Chip Scale Atomic Clock (CSAC)

- Cs or Rb miniature cell standard – not a Cs beam tube!
- Coherent Population Trapping (CPT)
- Very small size and low power consumption, but better performance than a quartz oscillator



Timing Error @ 1 day (µs)
Power Consumption (W)
MEMS
TCXO
OCXO-miniature
MCXO
OCXO
CSAC
Rb
Cs beam
H-maser
•Better

Oscillator Comparison

Technology	Intrinsic Accuracy	Stability (1s)	Stability (floor)	Aging (/day) initial to ultimate	Applications
Cheap Quartz, TCXO	10^{-6}	$\sim 10^{-11}$	$\sim 10^{-11}$	10^{-7} to 10^{-8}	Wristwatch, computer, cell phone, household clock/appliance,…
Hi-quality Quartz, OCXO	10^{-8}	$\sim 10^{-12}$	$\sim 10^{-12}$	10^{-9} to 10^{-11}	Network sync, test equipment, radar, comms, nav,…
Rb Oscillator	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	Wireless comms infrastructure, lab equipment, GPS, …
Cesium Beam	$\sim 10^{-13}$	$\sim 10^{-11}$	$\sim 10^{-14}$	nil	Timekeeping, Navigation, GPS, Science, Wireline comms infrastructure,…
Hydrogen Maser	$\sim 10^{-11}$	$\sim 10^{-13}$	$\sim 10^{-15}$	10^{-15} to 10^{-16}	Timekeeping, Radio astronomy, Science,…

Oscillator Comparison (continued)

Technology	Size	Weight	Power	World Market	Cost
Cheap Quartz, TCXO	≈ 1 cm^3	≈ 10 g	≈ 10 mW	≈ 10^9s/year	≈ $1s
Hi-quality Quartz, OCXO	≈ 50 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $100s
Rb Oscillator	≈ 200 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $1000s
Cesium Beam	≈ 30,000 cm^3	≈ 20 kg	≈ 50 W	≈ 100s/year	≈ $10Ks
Hydrogen Maser	≈ 1 m^3	≈ 200 kg	≈ 100 W	≈ 10s/year	≈ $100Ks

Holding a Microsecond after Loss of Sync (circa 2019)

	Temperature Compensated Crystal Oscillator (TCXO)	**Oven Controlled Crystal Oscillator (OCXO)**	**Chip Scale Atomic Clock (CSAC)**	**Rb Oscillator** (5E-12/mo. aging)	**Cs Beam-Tube Oscillator**
Range of times to hold a microsecond	10 minutes – 1 hour	1 – 24 hours	3-15 hours	8 hours – 3 days	10-300 days
Cost Range	$5-20	$50-250	$1.5K-3K	$500-1500	$20K - $50K

Conclusions: Atomic Standards

- Rubidium, cesium, and hydrogen atomic frequency standards share a common theme: the stabilization of an electronic (quartz) oscillator with respect to an atomic resonance.

- Although the use of atoms brings with it new quantum mechanical problems, the resulting long-term stability is unmatched by traditional classical oscillators.

Thanks for your attention!

Extra slides follow

Clock Stability

Clock (in)stability is given by:

$$\sigma \approx \frac{\delta f}{f} \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

Atomic Line Q **Signal to Noise**

Clock stability can be improved by:

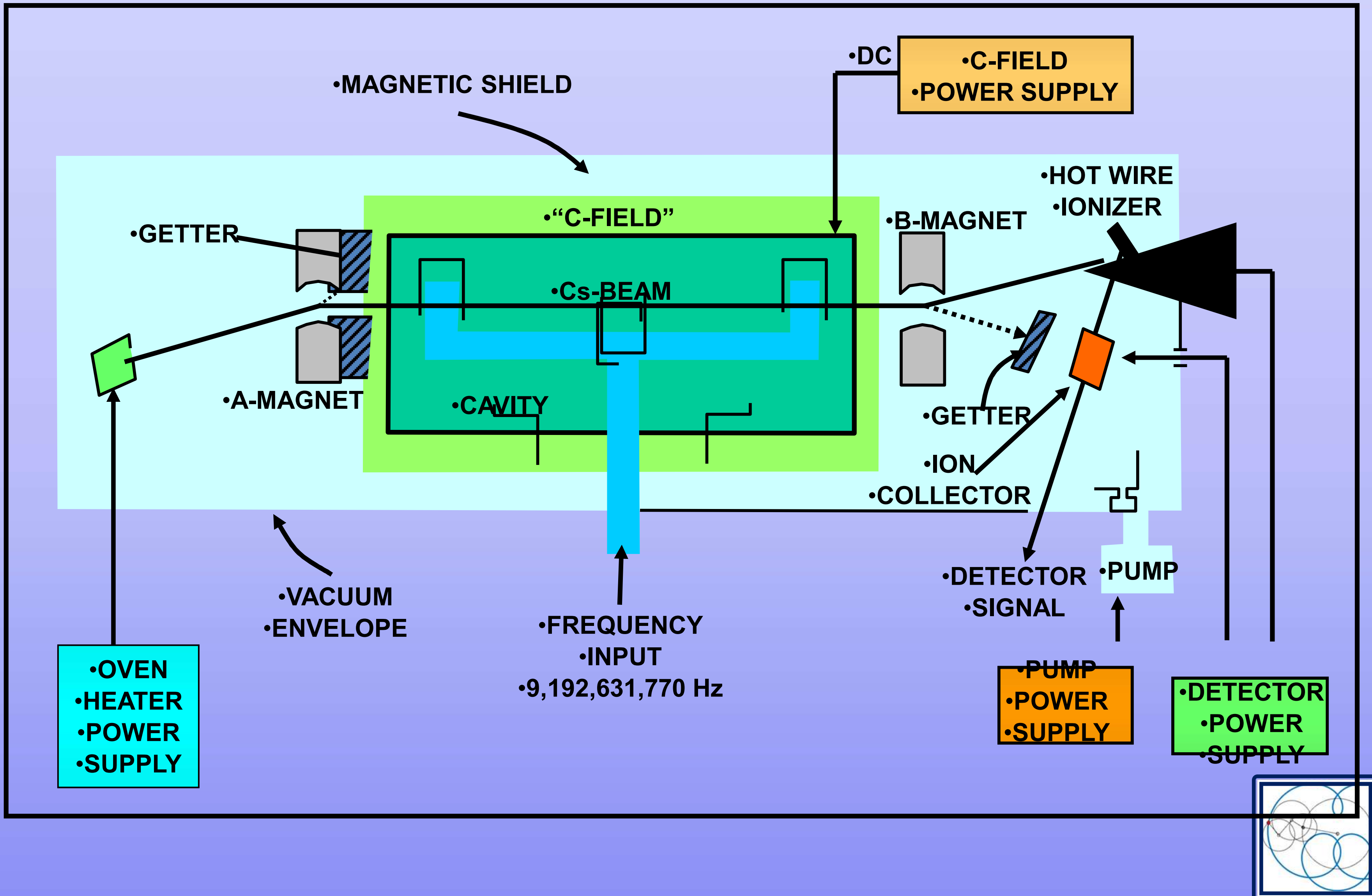
Increase Ramsey (observation) times (decrease $\Delta\omega = 1/T_{Ramsey}$)

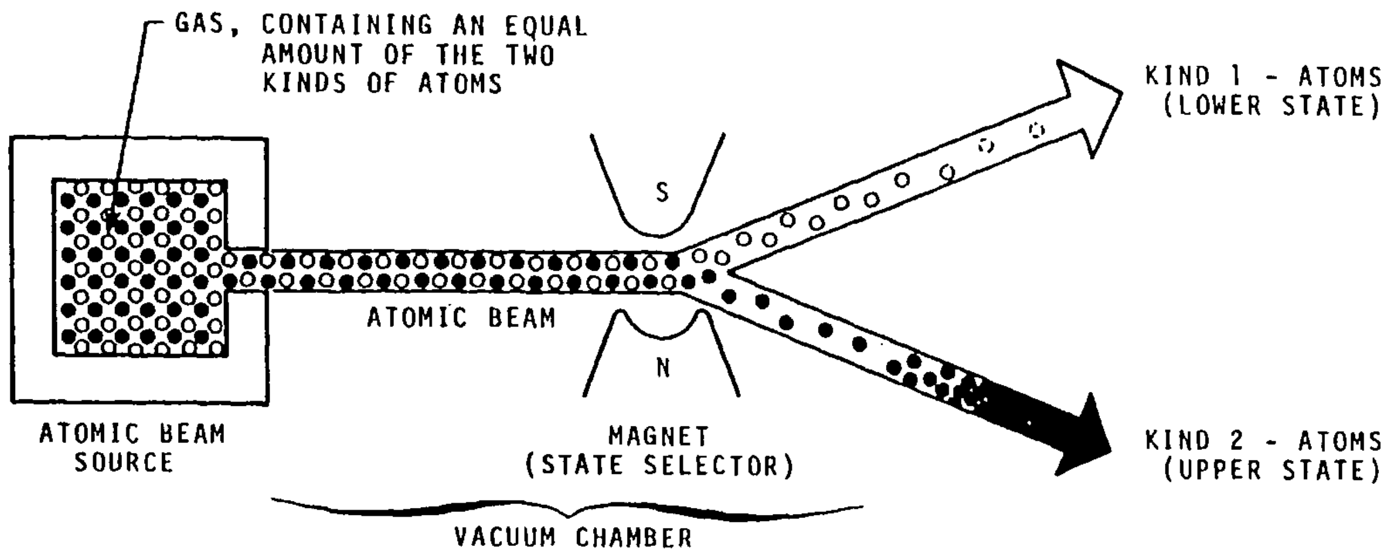
Improve the S/N (more atoms!)

Increase the frequency of the clock transition (e.g. optical)

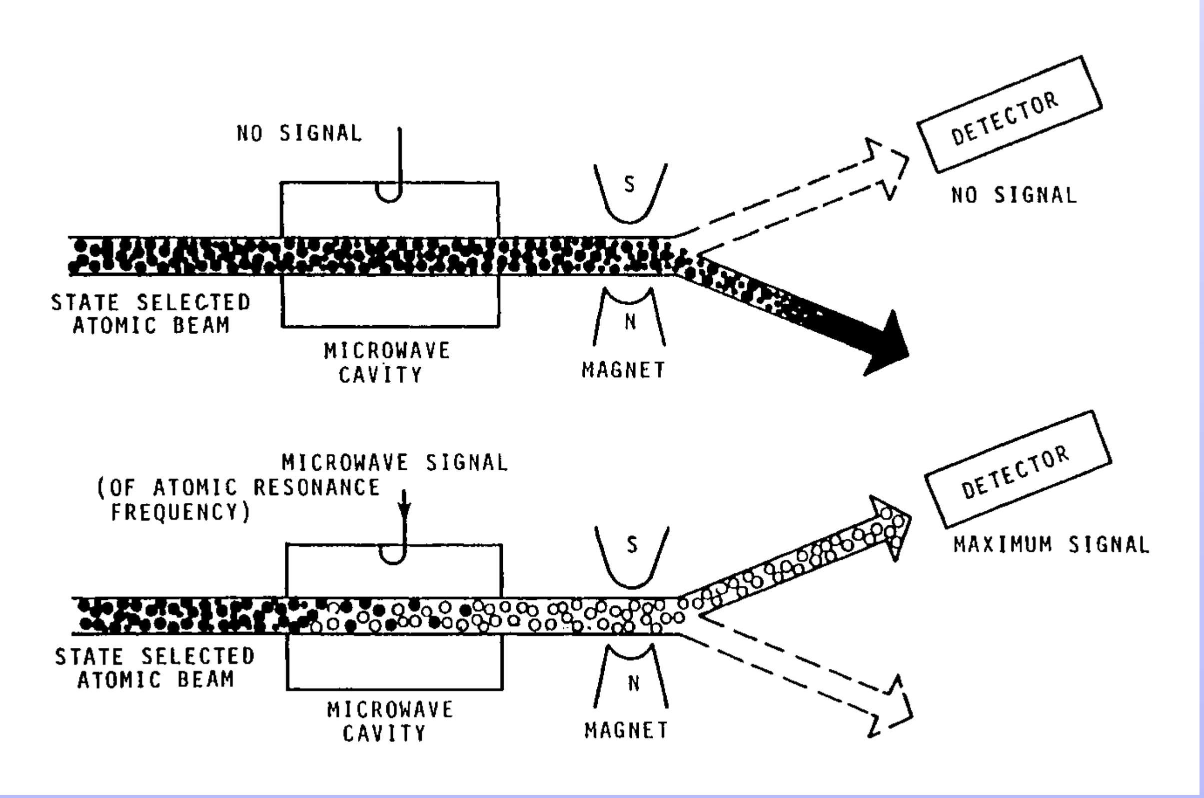
Classical Cesium Standard with Magnetic State Selection

Note there is a newer design with Optical Pumping and Detection of states





- Atoms come from an oven in a beam
-
- A magnet is used to deflect the atoms in different
- hyper-fine states



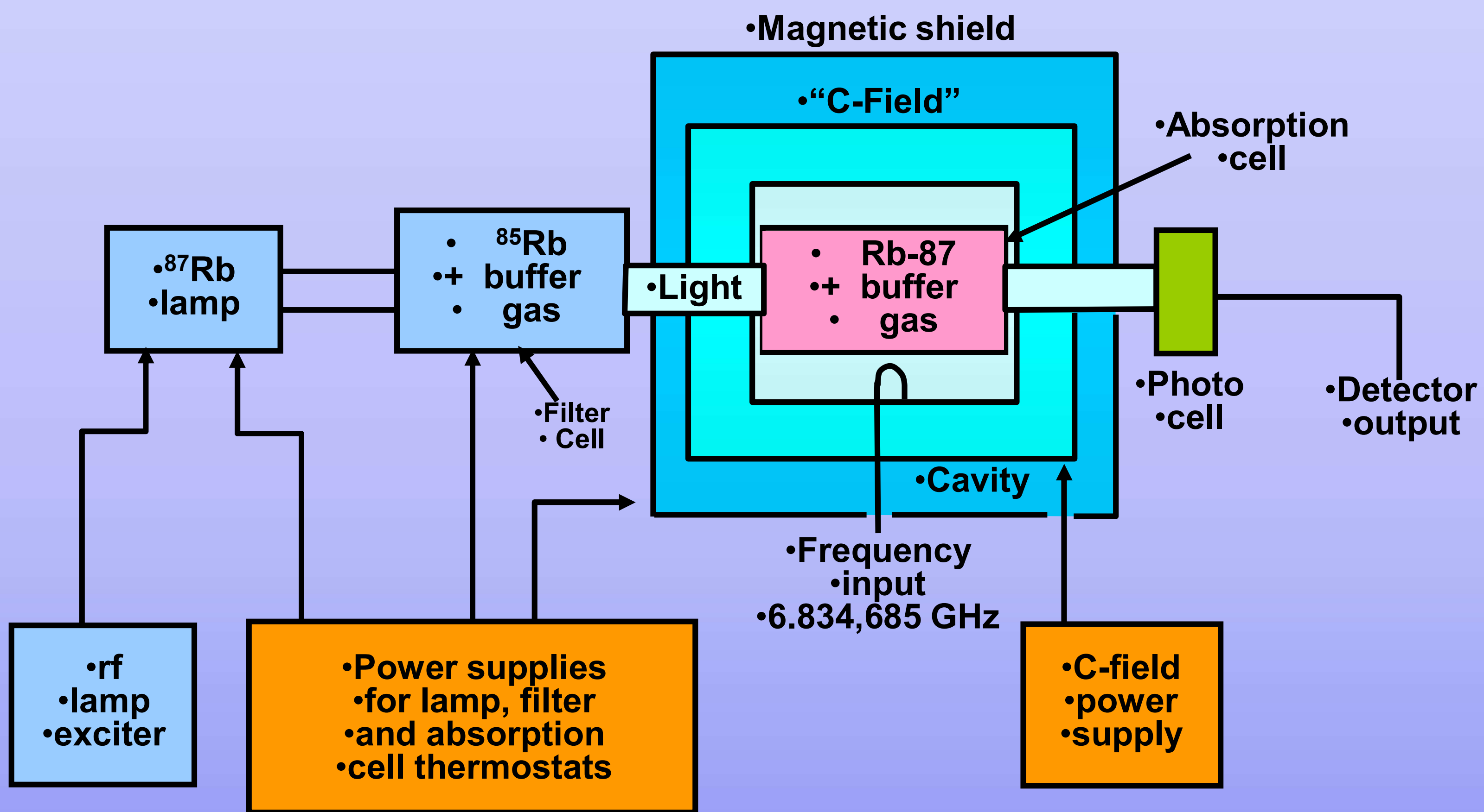
- **Atoms pass through a Ramsey cavity in a magnetic field to be exposed to microwaves at frequency ν = 9.193 GHz**
- **A second magnet selects atoms which have made the transition**
- **The number of detected atoms is used to tune the frequency**

Rubidium Standard

- Two major differences from a cesium standard
    1. Cell standard (doesn’t use up rubidium)
    2. Optically pumped (no state selection magnets)

- Used where low cost and small size are important

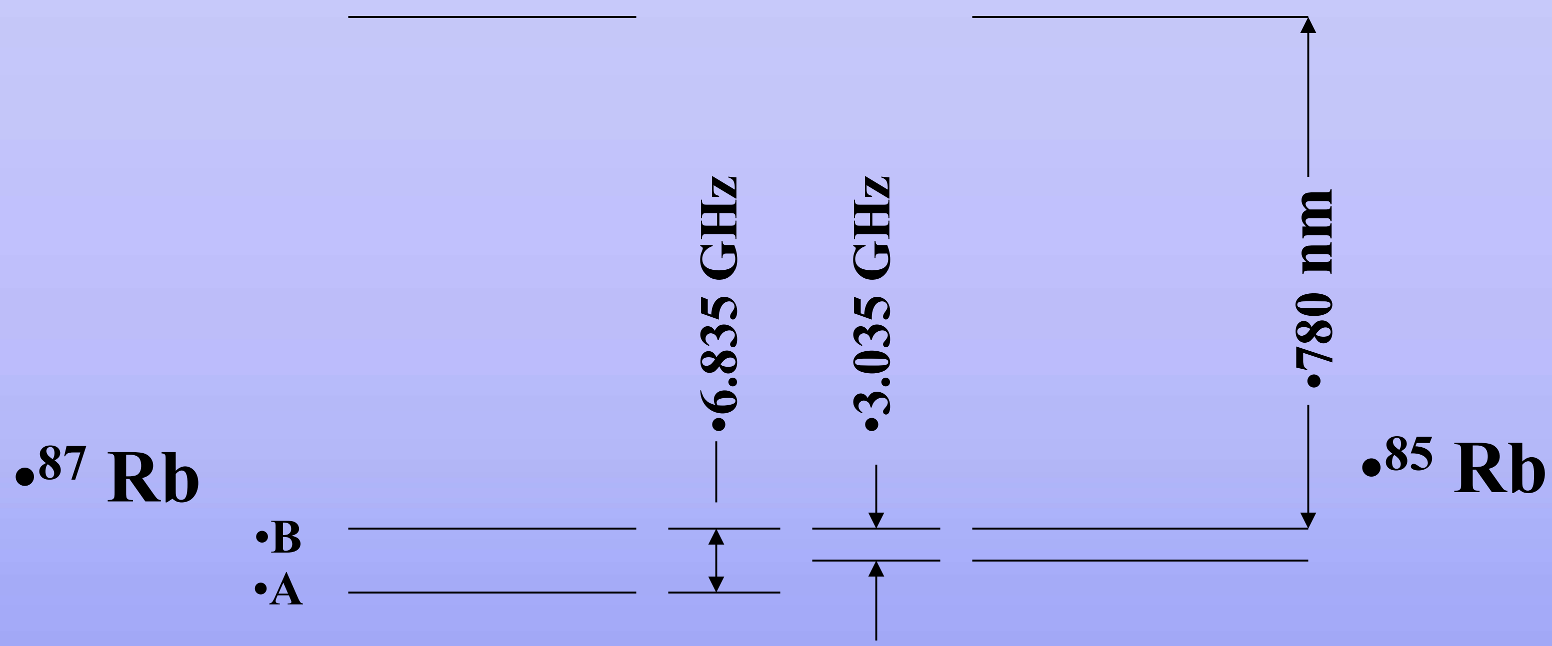
Rubidium Standard

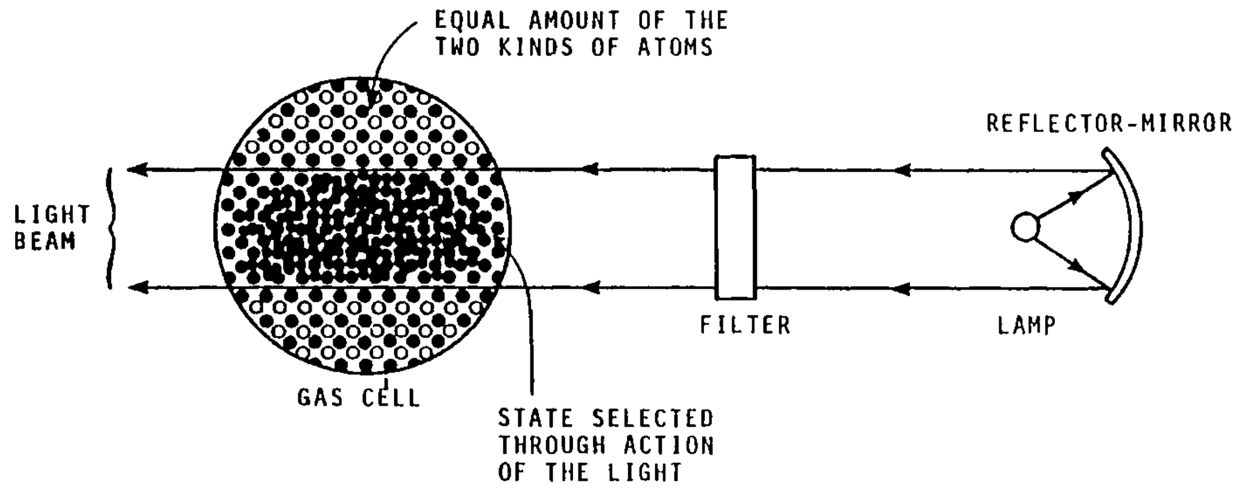


•Adapted from figure by John Vig

Optical Microwave Double Resonance

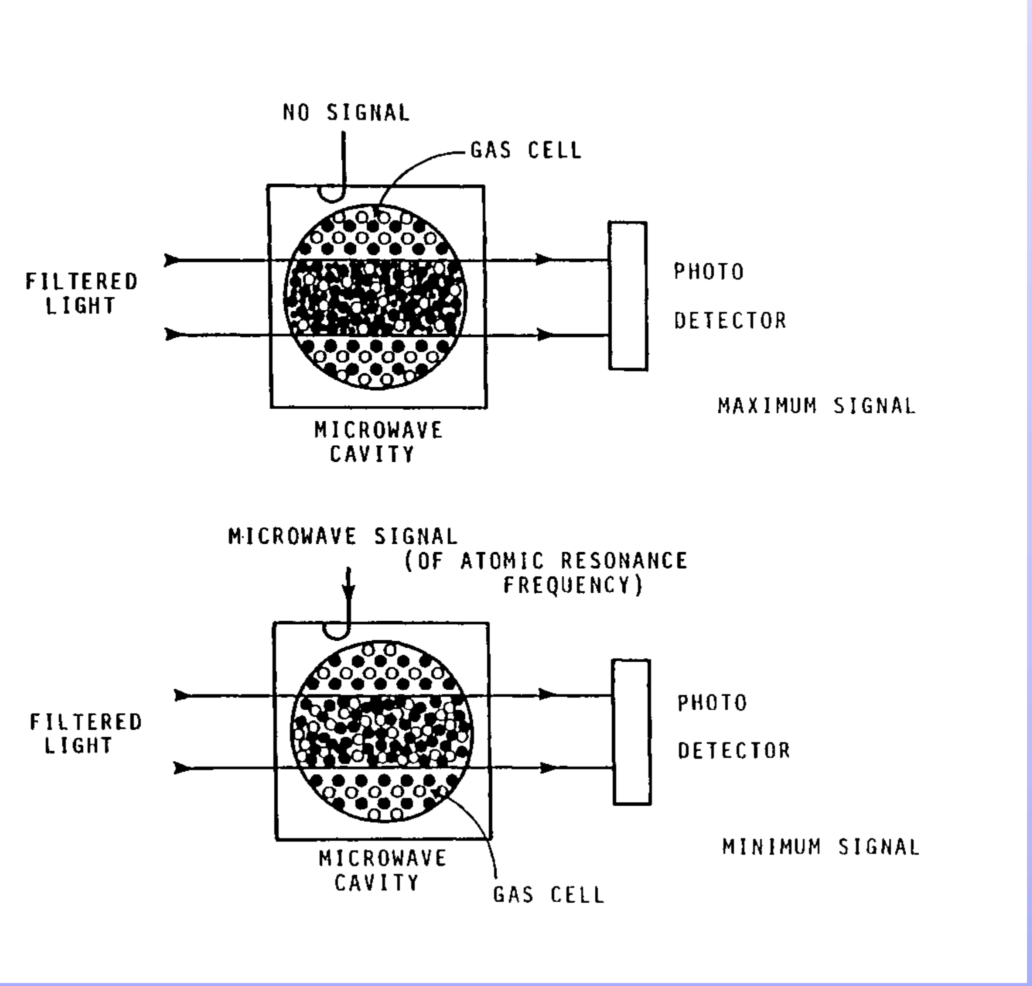
Simplified Rb energy level diagram





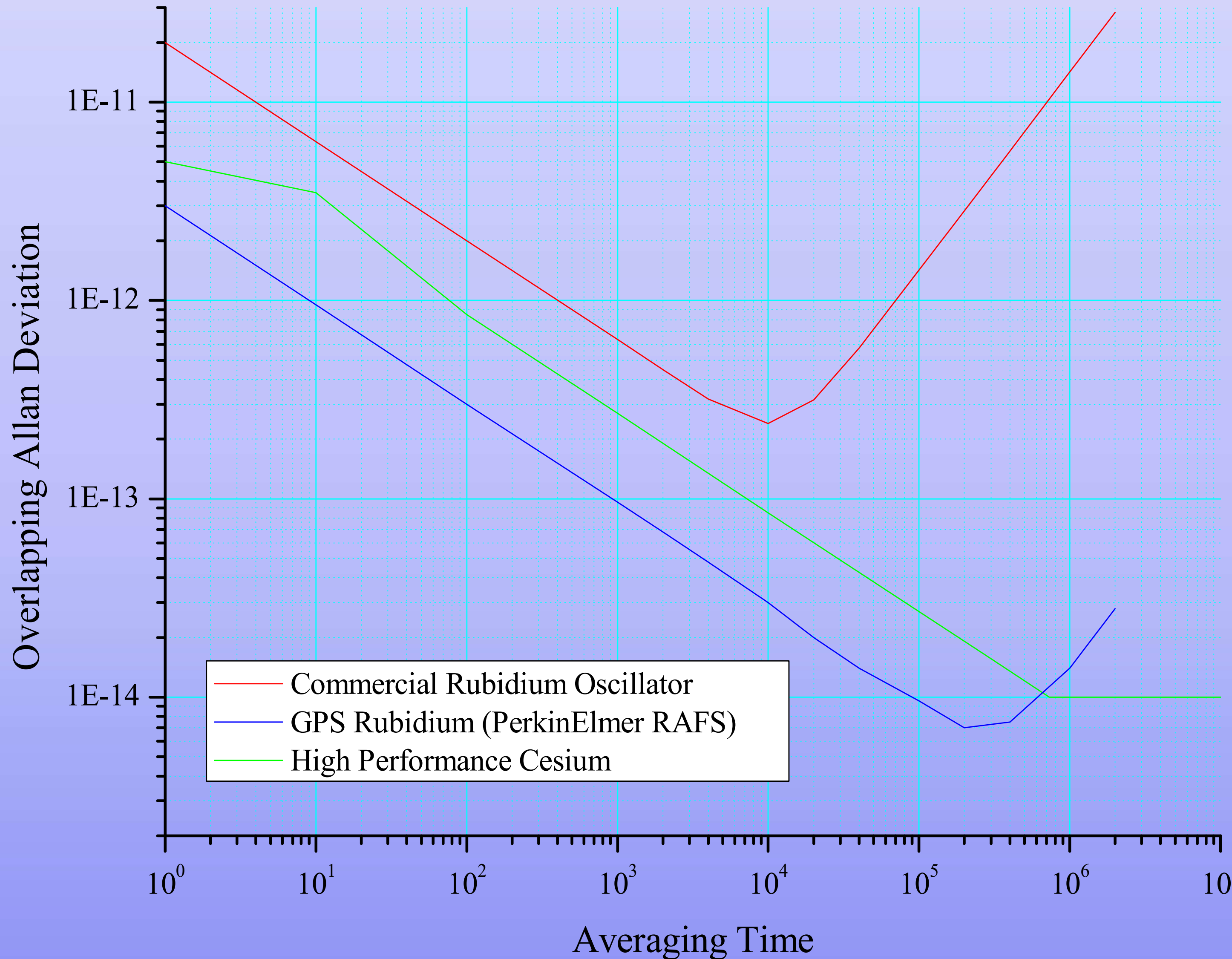
- **Optical pumping is used to deplete one hyper-fine level**

- **Light tuned to the transition frequency from "A" to the**
  - **unstable excited state puts all of the atoms in the**
    - **hyper-fine state "B"**



- Microwaves at ν = 6.835 GHz stimulate the transition from “B” to “A”
- The absorption of light is measured
- The frequency ν is tuned to minimize the light coming through the ^{87} Rb cell

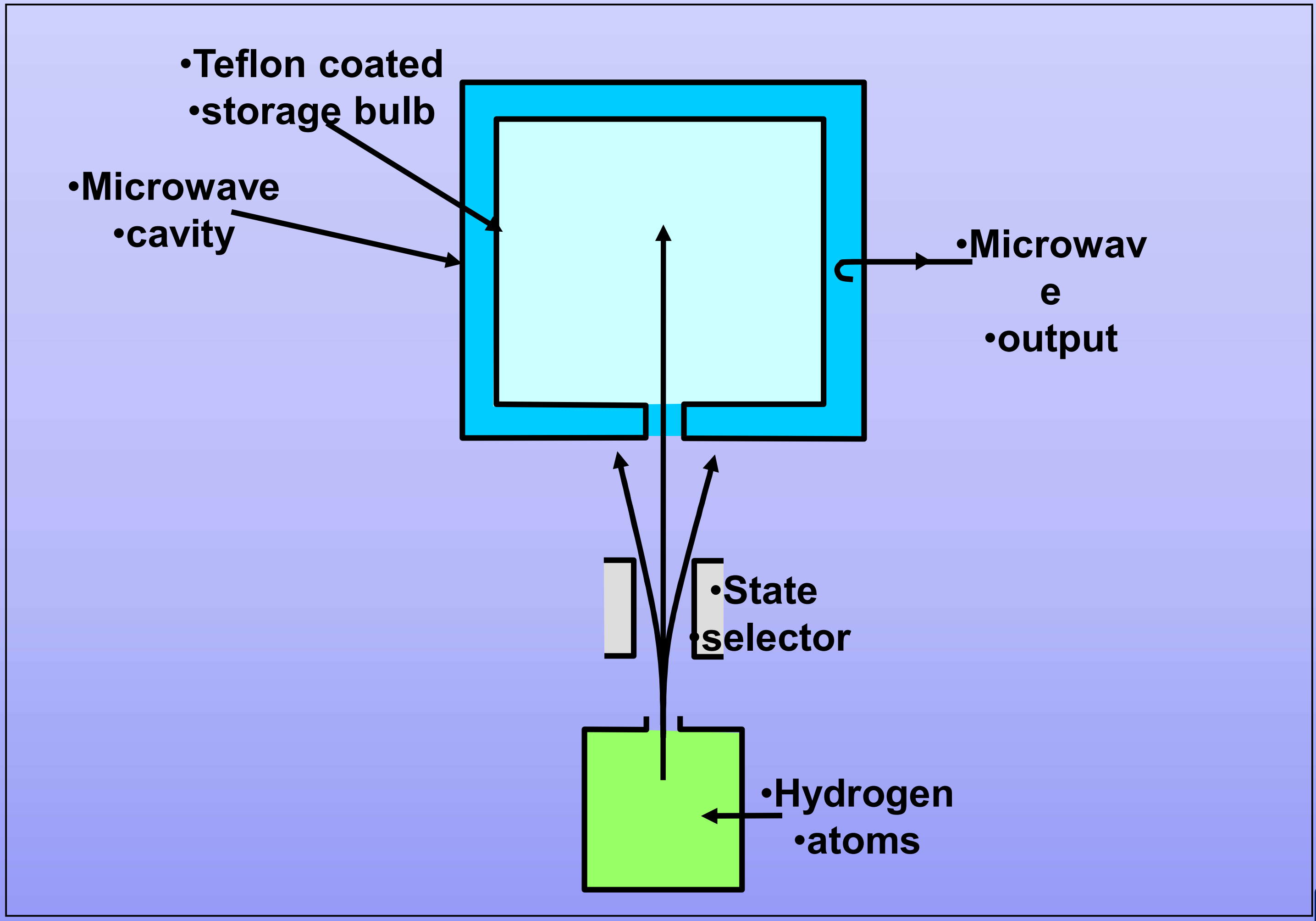
Frequency Stability of a Rubidium Standard



•**Courtesy of Robert Lutwak, Symmetricom**

Hydrogen Maser

(Active Standard)



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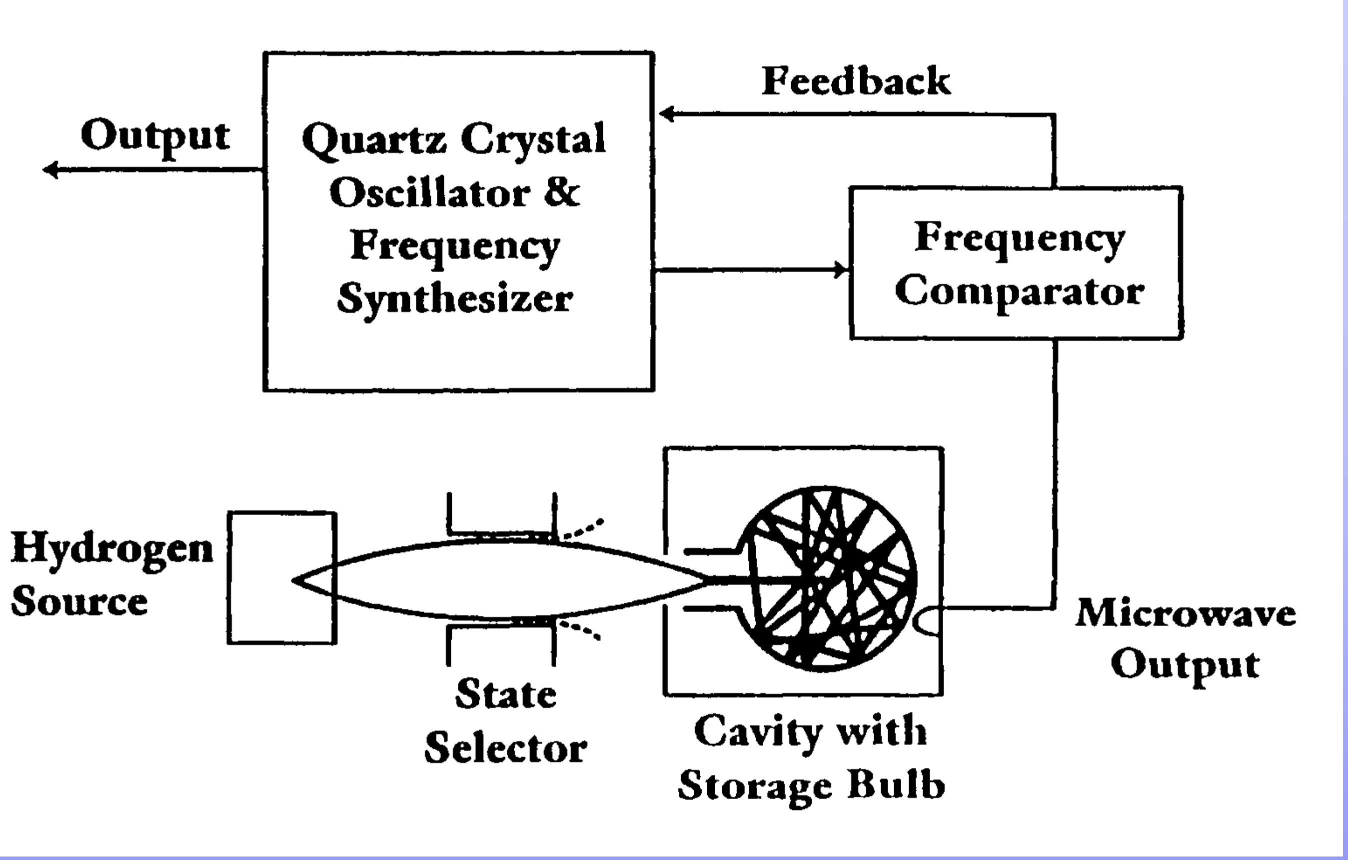
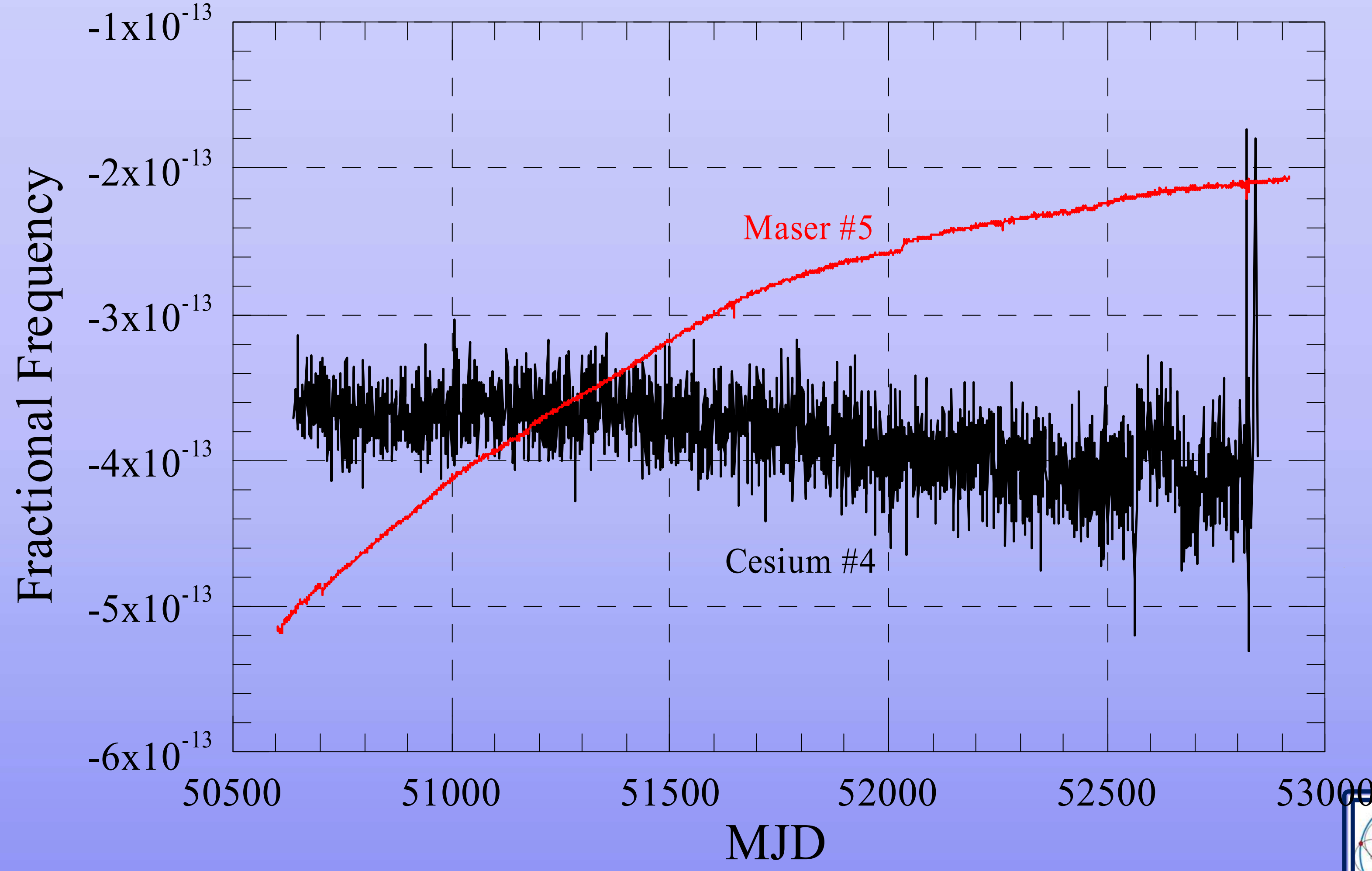
Hydrogen Maser
(Active Standard)

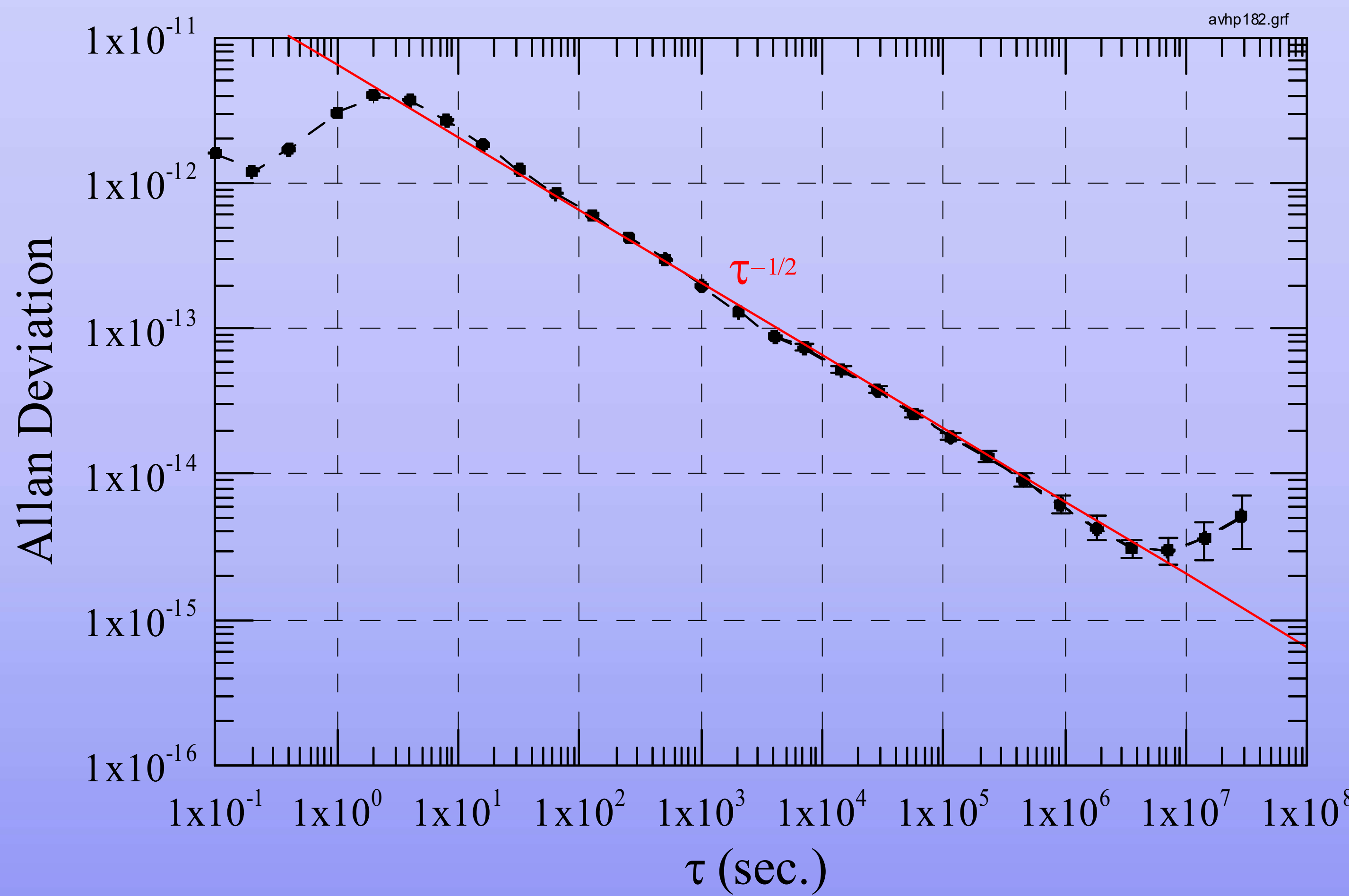


Frequency Drift of a Commercial Cesium Standard and a Hydrogen Maser



Frequency Stability of a Cesium Standard

(No frequency drift removed)



Frequency Stability of a Hydrogen Maser

(Frequency drift removed – $1x10^{-16}$/day typical)