# Atomic Clocks as Primary Frequency Sources

## WSTS 2023

## Online Tutorial Session

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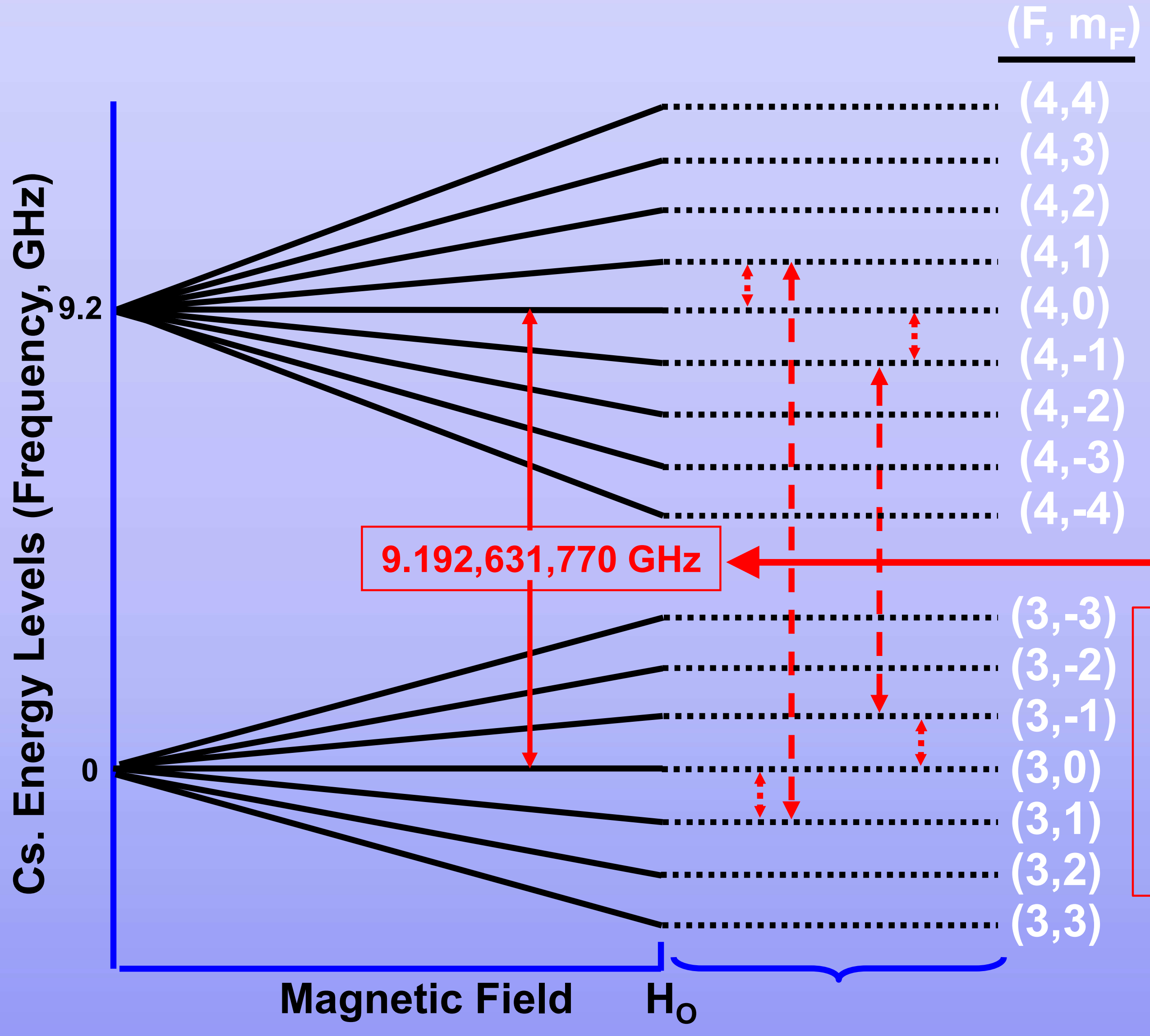
# Three Things to Understand Atomic Clocks

1. Atoms are in discrete energy levels
    a. The change in energy are quanta
    b. Magnetic fields break the levels into the hyperfine structure
2. Energy is proportional to frequency
    a. Einstein discovered the relation: $\Delta E = h\nu$
    b. A change in energy levels, $\Delta E$, is proportional to the frequency $\nu$
3. A clock is a frequency device
    a. A system whose states repeat, e.g. the day
    b. Time is a count of states of frequency, e.g. the calendar

# 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**

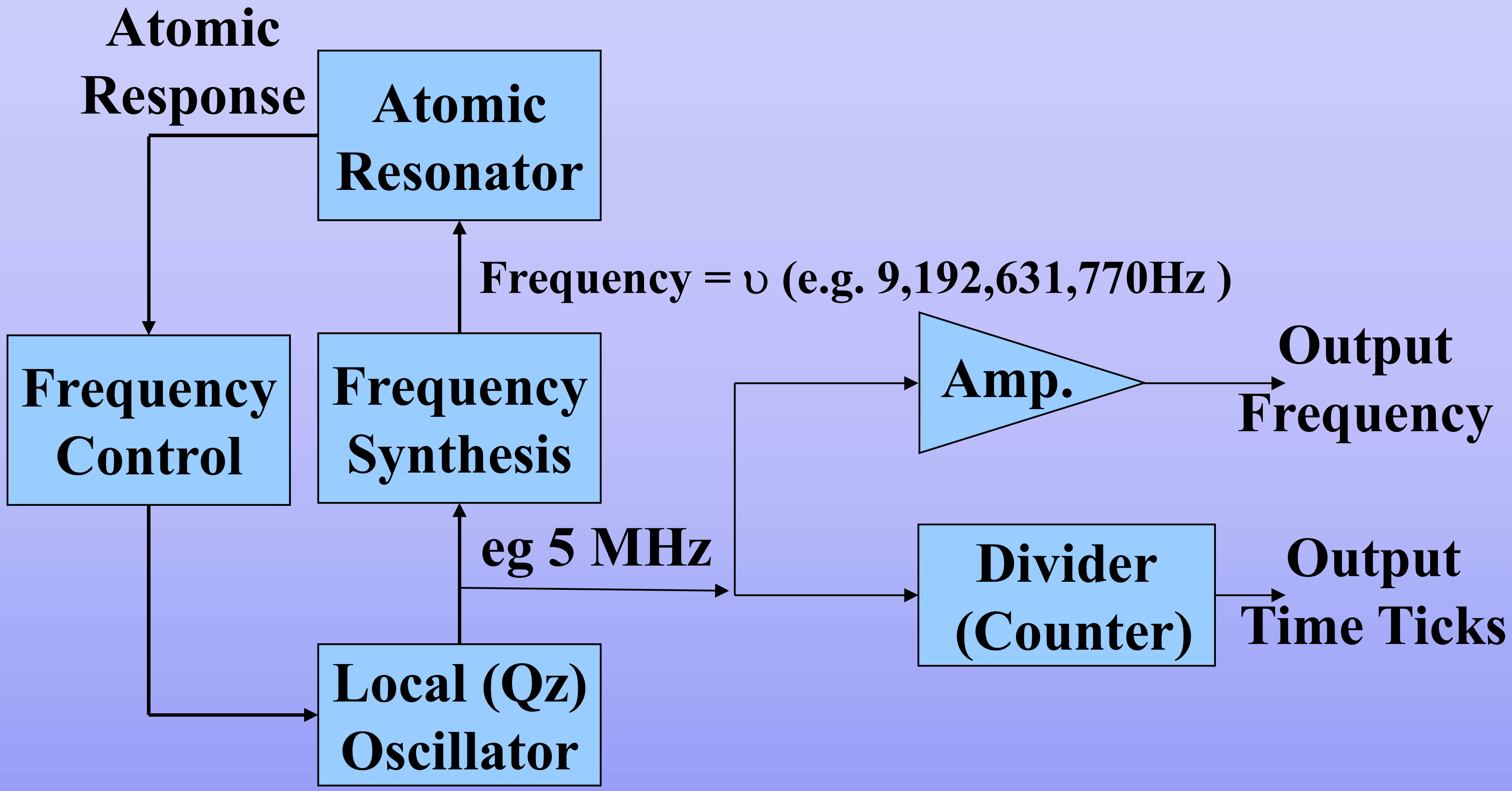
**Absorption of photon at 9,192,631,770Hz results in transition from state (3,0) to state (4,0)**
**transition from state (3,0) to state (4,0) results in radiation of photon at 9,192,631,770Hz**

# Basic Passive Atomic Clock

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

# Block Diagram of Atomic Clock

## Passive Standard



Atomic Response

Atomic Resonator

Frequency = υ (e.g. 9,192,631,770Hz )

Frequency Control

Frequency Synthesis

Amp.

Output Frequency

eg 5 MHz

Divider (Counter)

Output Time Ticks

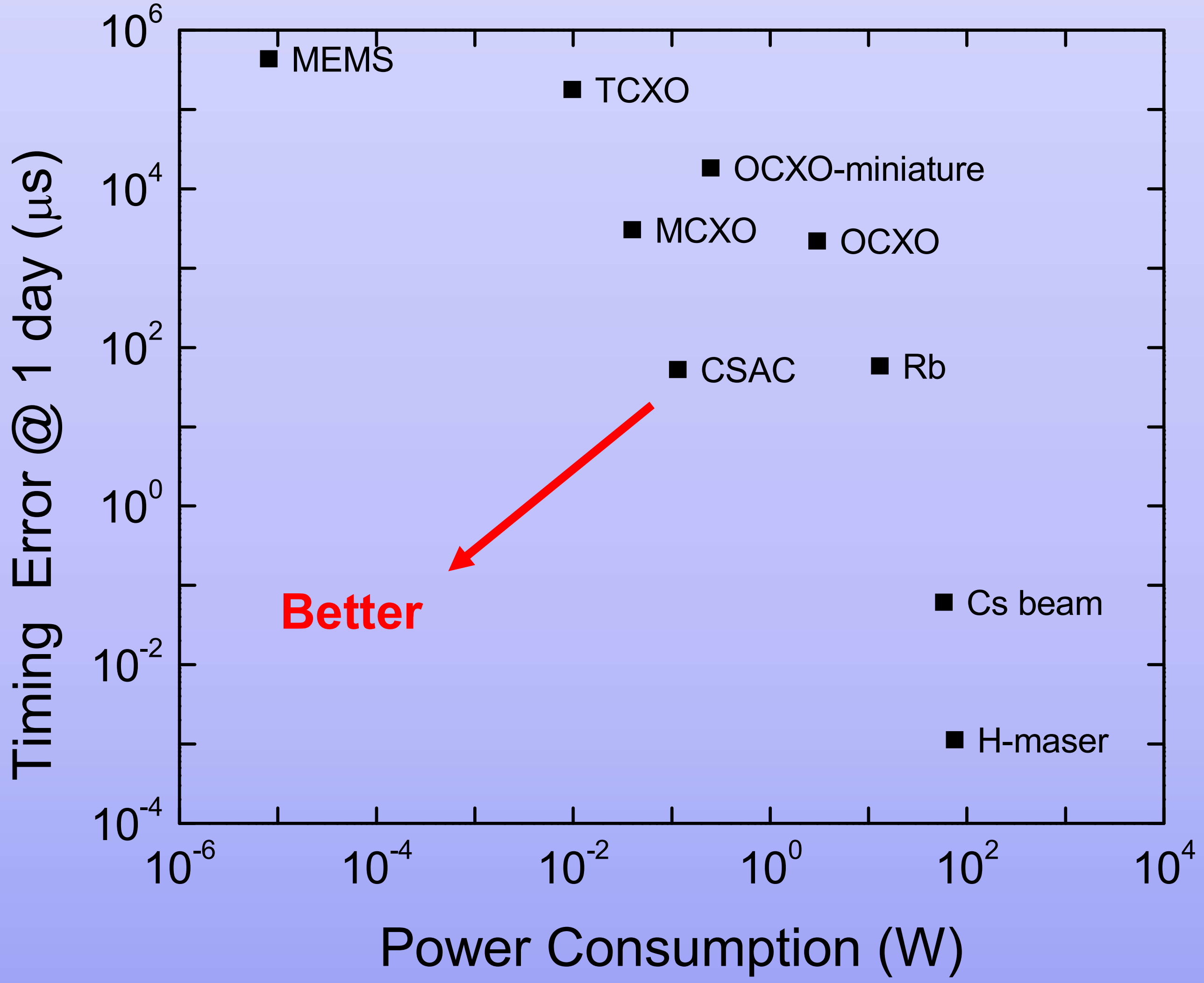
Local (Qz) Oscillator

# 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
  - Cs CSAC not to be confused with Cs beam tube
- Note that new clocks are under development!
  - E.g., using atoms cooled to micro-Kelvin
  - Using transitions whose frequency is optical
  - Come to WSTS 2023 for details

# Chip Scale Atomic Clock (CSAC)

- Cs or Rb miniature cell standard – not a Cs beam tube, nor a Rb cell!
- Uses a different way of interrogating atoms: Coherent Population Trapping (CPT)
- Very small size and weight and low power consumption
- Better performance than a quartz oscillator



MEMS
TCXO
OCXO-miniature
MCXO
OCXO
CSAC
Rb
Better
Cs beam
H-maser
$10^6$
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
Timing Error @ 1 day (μs)
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^0$
$10^2$
$10^4$
Power Consumption (W)

# Oscillator Comparison

| Technology | Intrinsic Accuracy | Stability (1s) | Stability (floor) | Aging (/day) initial to ultimate | Applications |
|---|---|---|---|---|---|
| Inexpensive 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,… |
| CSAC | $\sim 10^{-9}$ | $< 10^{-10}$ | $< 10^{-11}$ | $< 10^{-12}$ | Drones, satellites, underwater, network sync, … |
| 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 |
|---|---|---|---|---|---|
| Inexpensive Quartz, TCXO | ≈ 1 cm$^3$ | ≈ 10 g | ≈ 0.010 W | ≈ 10$^9$s/year | ≈ $30-50 |
| Hi-quality Quartz, OCXO | ≈ 50 cm$^3$ | ≈ 500 g | ≈ 10 W | ≈ 10Ks/year | ≈ $100s |
| CSAC | ≈ 17 cm$^3$ | ≈ 35 g | ≈ 0.12 W | ? | ≈ $1000s |
| Rb Oscillator | ≈ 200 cm$^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

| | **Temperature Compensated Crystal Oscillator (TCXO)** | **Oven Controlled Crystal Oscillator (OCXO)** | **Chip Scale Atomic Clock (CSAC)** | **Rb Oscillator** | **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 | $50-500 | $1.5K-3K | $500-1500 | $20K - $50K |

# Conclusions: Atomic Standards

- Classic (over decades) commercial atomic clocks are Cs. beam tubes, Rb. Cells, and H-masers, with more recently CSACs
- These 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.
- Revolutionary new atomic frequency standards are in development as commercial devices

# Thanks for your attention!