Current and Future Atomic Clocks – Roadmap and Applications

David R. Scherer, Bonnie L. Schmittberger, Jonathan Hirschauer

Civil GPS Service Interface Committee (CGSIC) – Timing Subcommittee

Co-located with ION GNSS+

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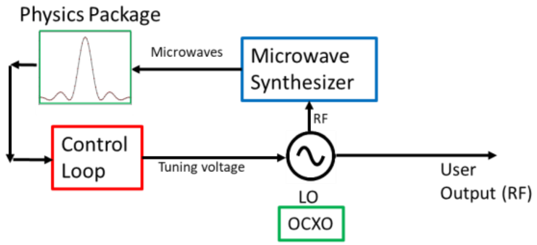
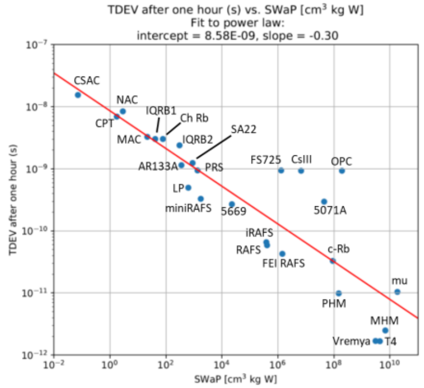
Outline – Current and Future Atomic Clocks

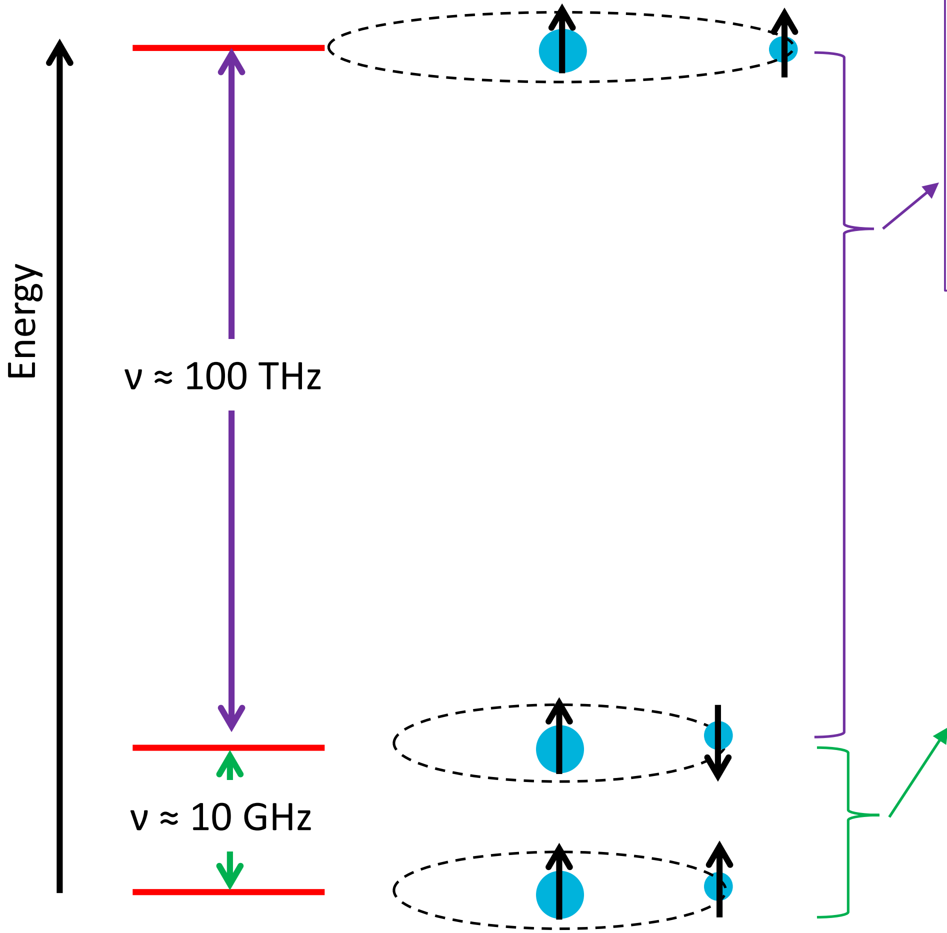


- Overview of different technologies: microwave vs. optical clocks
- Summary and comparison of current products
- Future clocks
- Applications


TDEV after one hour (s) vs. SWaP [cm³ kg W]
Fit to power law:
intercept = 8.58E-09, slope = -0.30

Microwave vs. Optical Clocks

Simplified Atomic Energy Level Diagram



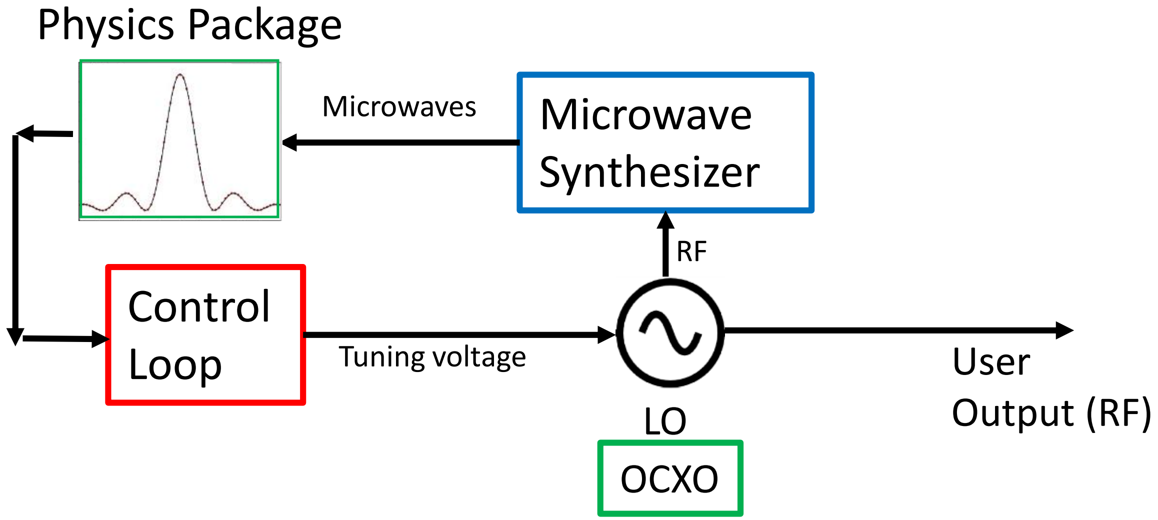
Optical Clocks

- Origin of Energy Levels: Electric dipole transition, change in orbital angular momentum of valence electron
- Excitation Source: Laser electric field
- LO: Laser
- Market Penetration: No commercial products as of 2019, basis for much of clock R&D activity

Microwave Clocks

- Origin of Energy Levels: Hyperfine Structure, coupling between nuclear spin and total angular momentum of valence electron
- Excitation Source: Microwave magnetic field
- LO: Quartz oscillator (10 MHz), frequency multiplier up to 10 GHz
- Market Penetration: Basis for all commercial atomic clocks on market today, and many future clocks

Architecture: Microwave Clocks



Physics Package

Microwaves

Microwave Synthesizer

RF

Control Loop

Tuning voltage

LO

OCXO

User Output (RF)

Clock Stability

- Allan Deviation (ADEV): $\sigma_y(\tau = 1\ s) = \frac{1}{Q \cdot (SNR)_{1\ Hz}}$
- $Q = \frac{f_0}{\Delta f}$ = line quality factor
- SNR = Signal-to-Noise Ratio

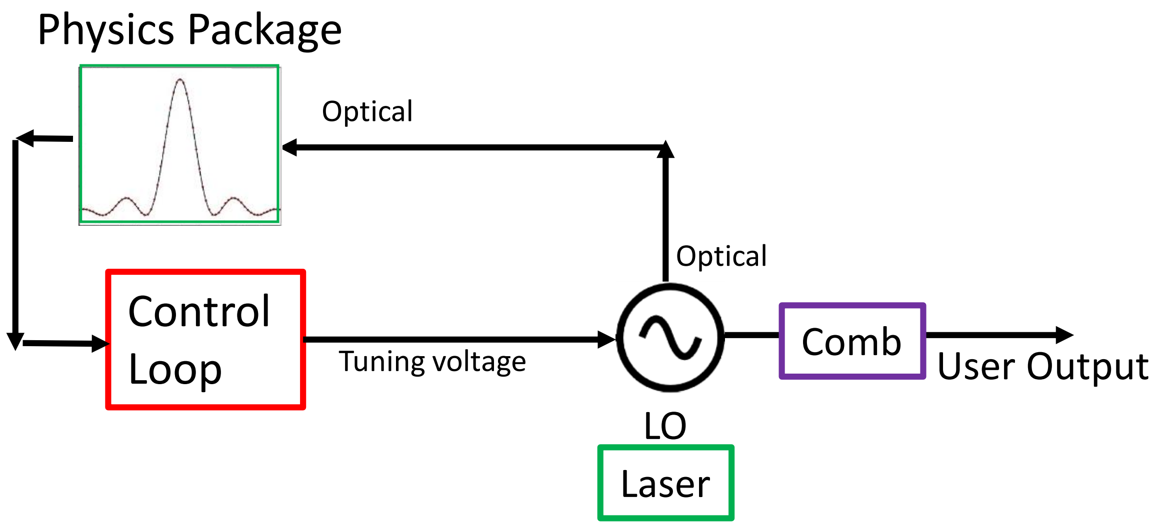
Microwave Clock Architecture

- LO: Quartz oscillator (OCXO)
- LO practical limit: $\sigma_y(\tau) \approx 1 \cdot 10^{-13}$at 1 second
- Microwave synthesizer: RF → Microwave conversion
- User output: LO output at RF

Current Products include:

- CSAC
- Rb clocks
- Cesium Beam Tube
- H maser

Architecture: Optical Clocks



Optical Clocks Compared to Microwave Clocks

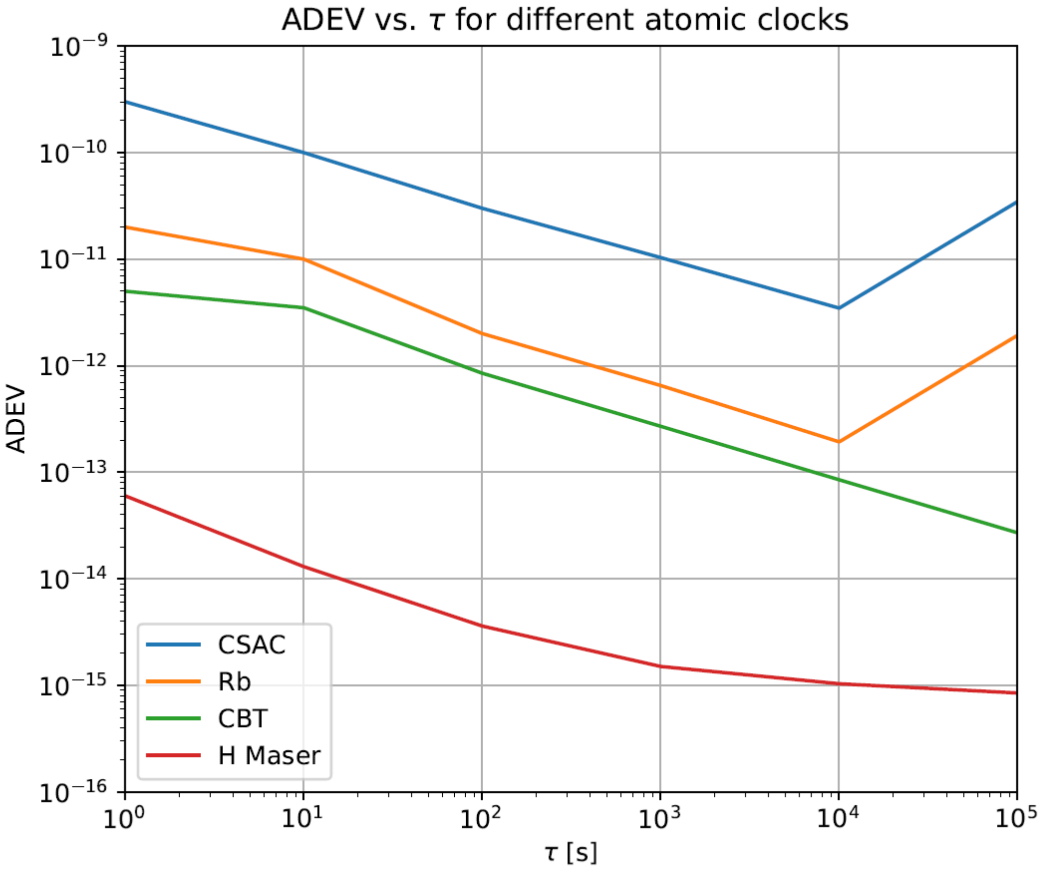
- Q is 10,000 times larger
- Short-term stability is 1,000 times better
- Uncertainty is 100 times better
- Environmental susceptibility is smaller

Optical Clock Architecture

- LO: Laser
- Optical frequency downconverter (comb): link between optical and RF domain
- User output: LO output (laser) or downconverted to microwave/RF domain

Current Atomic Clock Products - Comparison

Stability (Allan Deviation) vs. averaging time



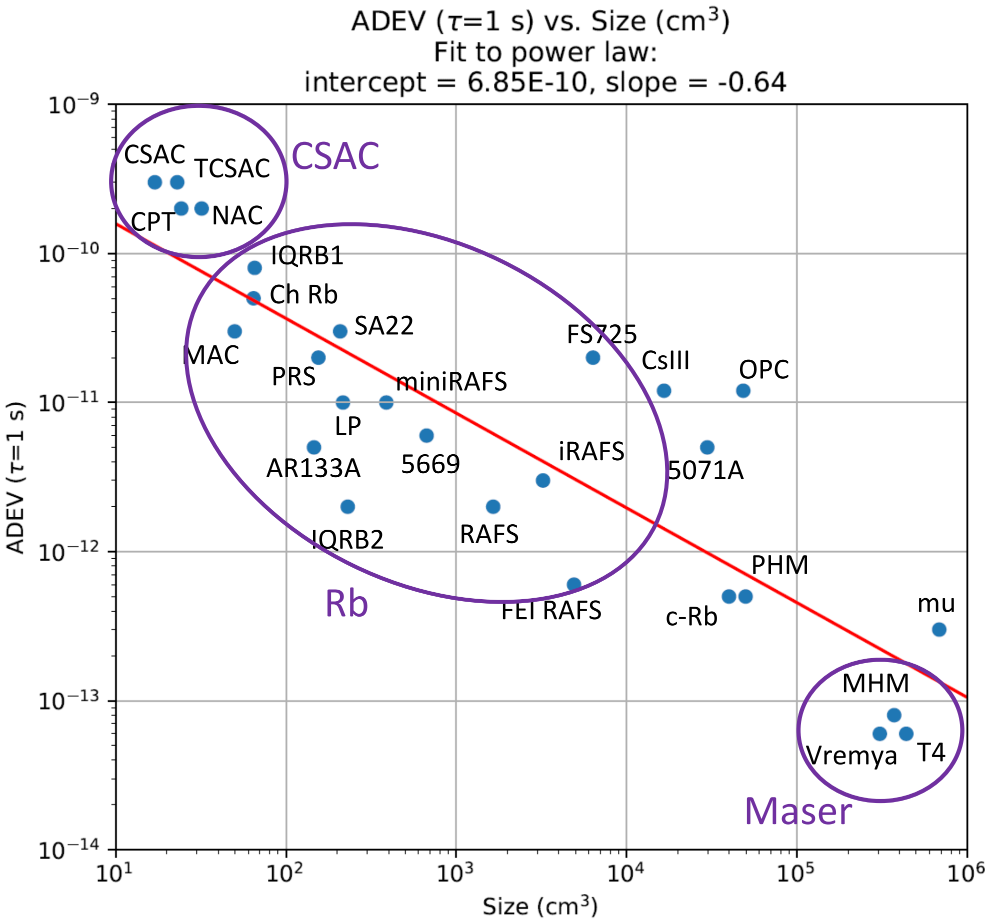
Comparison charts

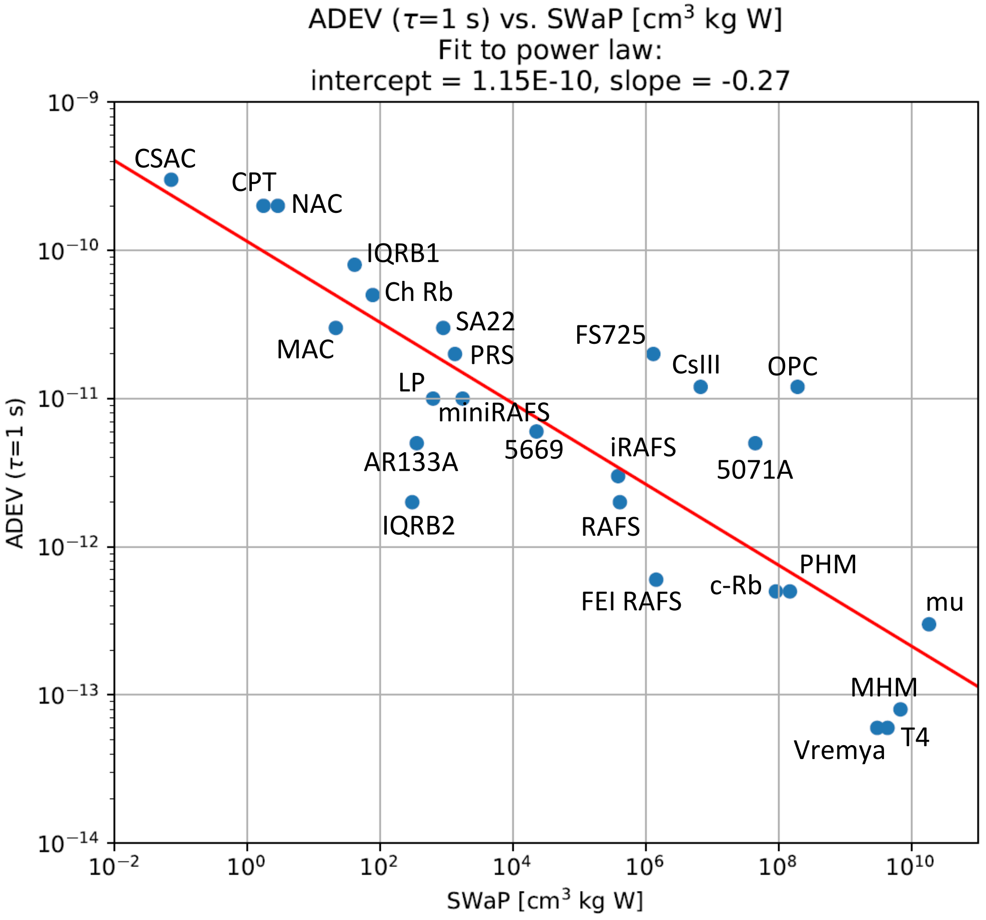
ADEV(1 s)
ADEV(100 s)
L(10 Hz)
Drift
Retrace
Accuracy
Tempco
TDEV(1 hr)
TDEV(1 day)

vs.

Size
Weight
Power
SWaP

ADEV Comparison of Current Atomic Clocks


ADEV (τ=1 s) vs. Size (cm^3)
Fit to power law:
intercept = 6.85E-10, slope = -0.64


ADEV (τ=1 s) vs. SWaP [cm^3 kg W]
Fit to power law:
intercept = 1.15E-10, slope = -0.27

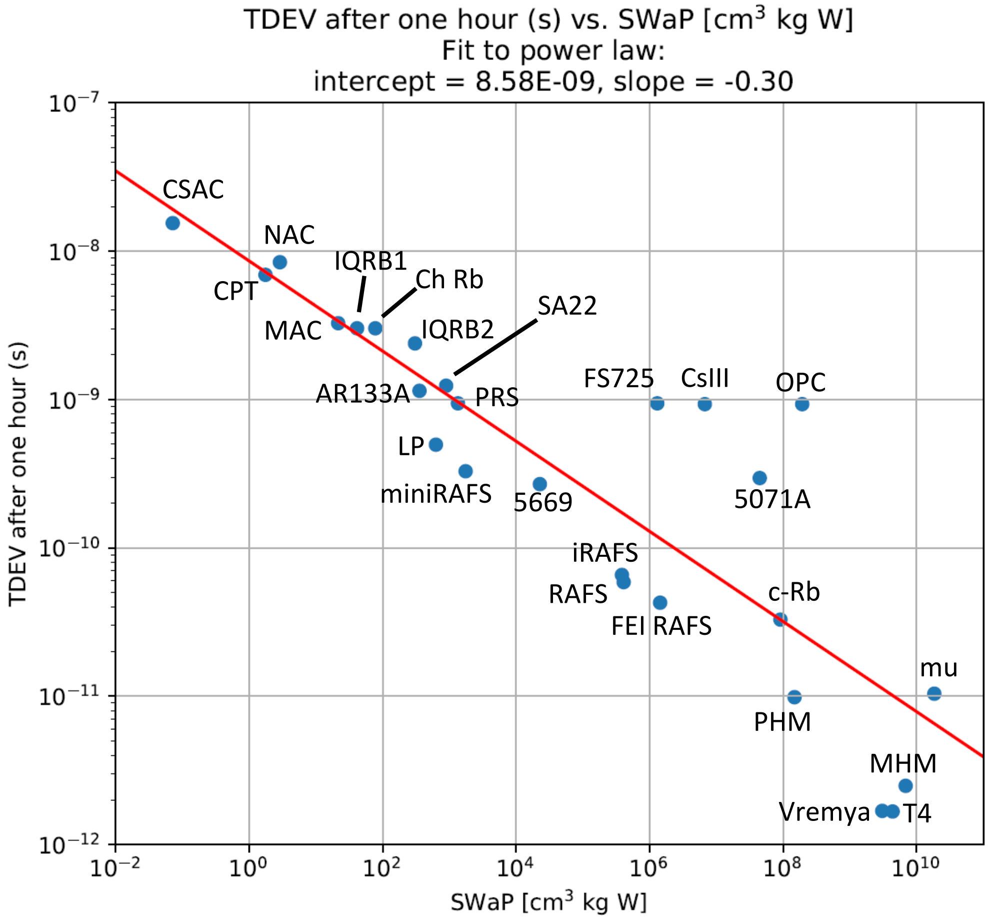
Legend

CSAC = Microsemi SA.45s CSAC
TCSAC = Teledyne CSAC (preliminary)
CPT = Chengdu Spaceon CPT
NAC = Accubeat Rb NAC1
IQRB1 = IQD IQRB-1
Ch Rb = Chengdu Spaceon XHTF1031
MAC = Microsemi SA.35m
SA22 = Microsemi SA.22c
PRS = SRS PRS10
LP = Spectratime low profile Rb
AR133A = Accubeat AR133A Rb
miniRAFS = Spectratime miniRAFS
IQRB2 = IQD IQRB-2
5669 = FEI FE-5660 Rb
FS725 = SRS FS725
RAFS = Excelitas space RAFS
iRAFS = Spectratime iSpace RAFS
CsIII = Microsemi CBT 4310B CsIII
FEI RAFS = FEI RAFS
5071A = Microsemi 5071A CBT
OPC = Chengdu Spaceon TA1000 OPC
c-Rb = Spectradynamics cold Rb c-Rb
PHM = T4Science pHMaser 1008
mu = Muquans cold-atom MuClock (preliminary)
MHM = Microsemi MHM 2010 H Maser
Vremya = Vremya VCH-1003M H Maser
T4 = T4Science iMaser-3000 H Maser

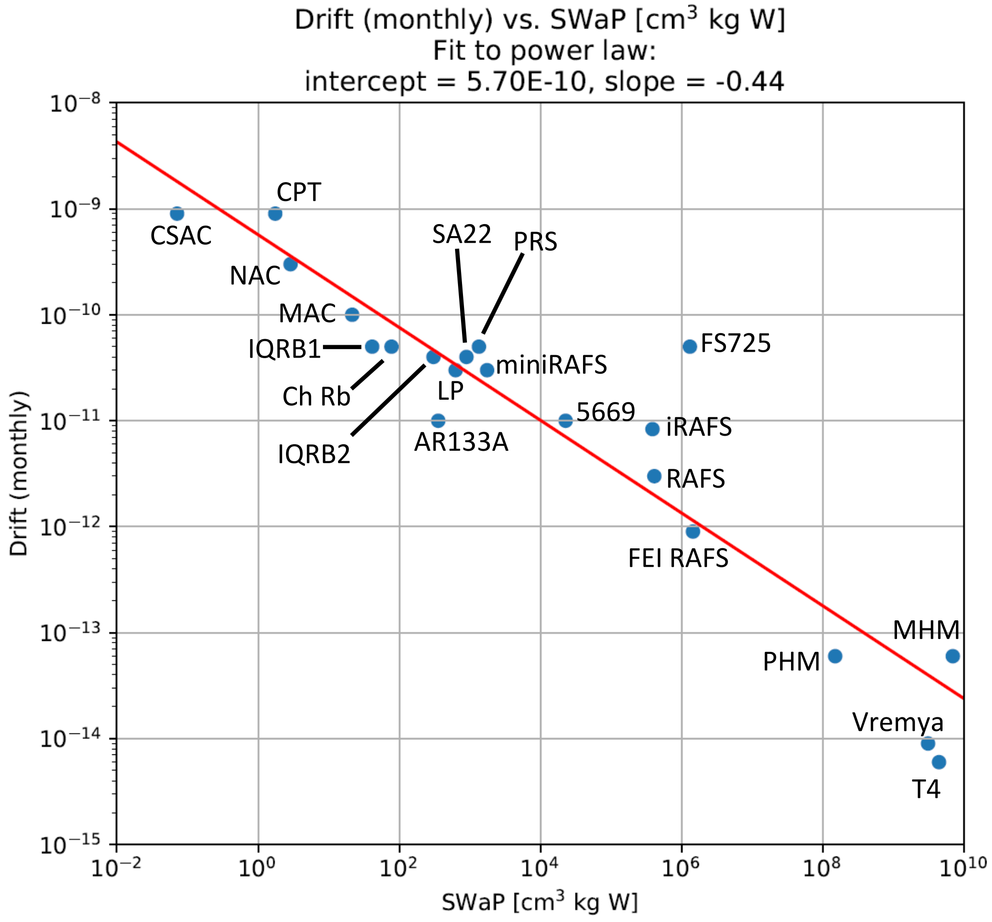
$$\sigma_y(1) = 6.85 \times 10^{-10} + (size\ in\ cm^3)^{-0.64}$$

Includes microwave clocks only

TDEV, Drift Comparison of Current Atomic Clocks



TDEV after one hour (s) vs. SWaP [cm^3 kg W]
Fit to power law:
intercept = 8.58E-09, slope = -0.30



Drift (monthly) vs. SWaP [cm^3 kg W]
Fit to power law:
intercept = 5.70E-10, slope = -0.44

Legend

CSAC = Microsemi SA.45s CSAC
TCSAC = Teledyne CSAC (preliminary)
CPT = Chengdu Spaceon CPT
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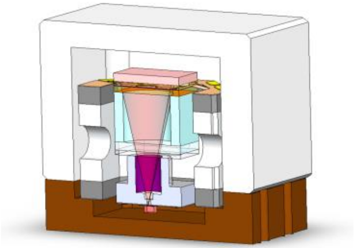
Includes microwave clocks only

Future Clocks: Reduced Environmental Sensitivity

Physics Package – current clocks

Gas cell clocks:
Hot Rb/Cs atoms
in glass cell



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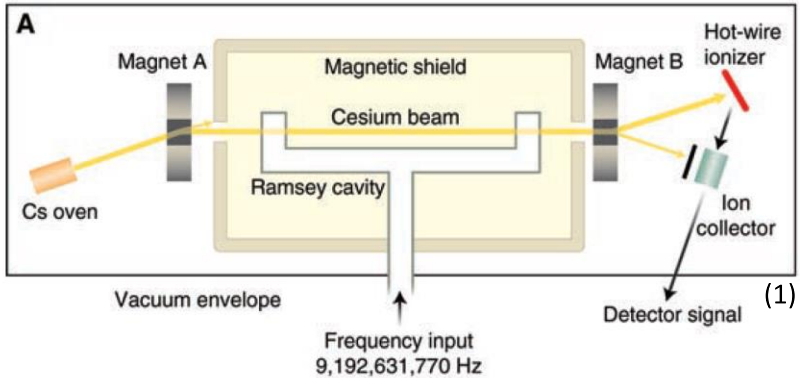
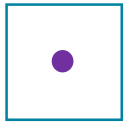
Cesium Beam Tube: Hot Cs atoms emerging from oven

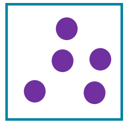


(1)

Physics Package – future clocks (trapped, cold atoms)



A single trapped, cold atom in vacuum



Ensemble of trapped, cold atoms in vacuum

Reduced coupling to environment can come from:

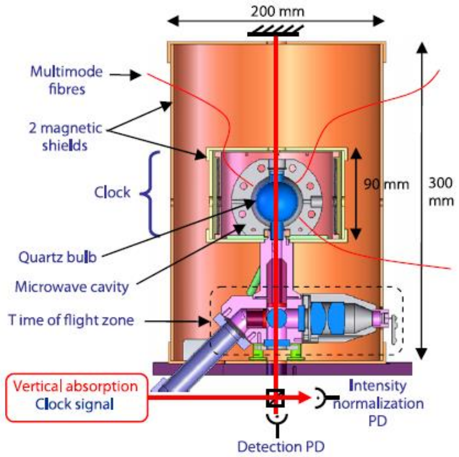
- Atom trapping (laser cooling)
- Optical transitions

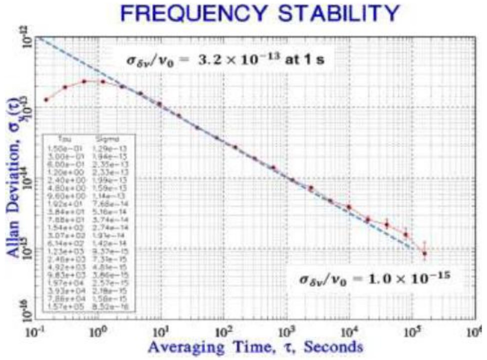
(1): S. A. Diddams, "Standards of Time and Frequency at the Outset of the 21st Century", Science, 306, 1318 (2004)

Cold-Atom Microwave Clocks – *Emerging Products*

Muquans (France) - LNE-SYRTE, HORACE, Rubiclock

- Isotropic laser cooling of Rb in spherical cavity
- Stability = $3 \times 10^{-13}/\sqrt{\tau}$, Floor = 2×10^{-15}

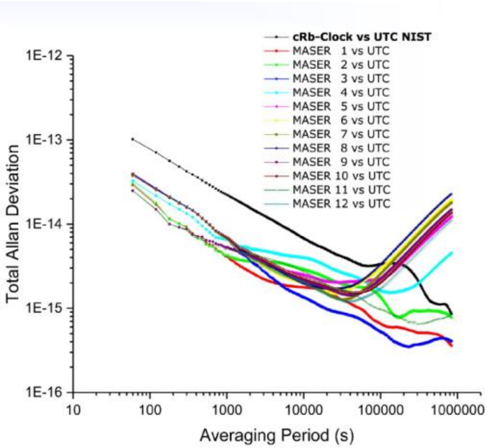


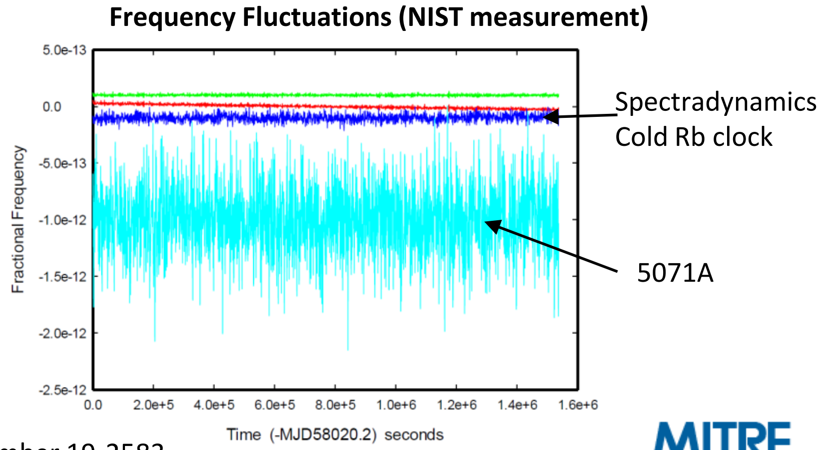


F.X. Esnault et al., "HORACE: A compact cold atom clock for Galileo", Advances in Space Research, 47 (2011)

Spectradynamics (Colorado) - NIST

- Laser cooling of Rb
- Stability = $8 \times 10^{-13}/\sqrt{\tau}$, Floor = 1×10^{-15}





F. Ascarrunz et al., "Long term frequency instability of a portable cold ^{87}Rb atomic clock", Proc. PTTI (2018)

Future Optical Clocks – *Promising Prototype*

O-RAFS (AFRL) – Optical Rubidium Atomic Frequency Standard

- Doppler-free two-photon transition in Rb
- Stability (demonstrated) = $3 \times 10^{-13}/\sqrt{\tau}$,
- Floor at 1 day (target) = 1×10^{-15}

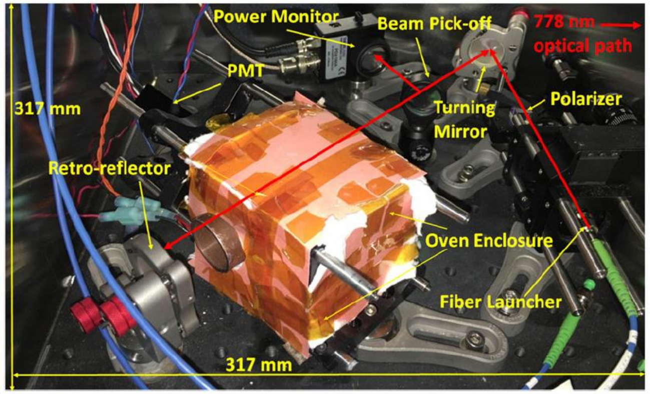
Benefits of using an optical transition

Parameter	O-RAFS (optical)	RAFS (microwave)	O-RAFS Improvement
Clock frequency	778 nm (385 THz)	6.8 GHz	56,000
Pressure shift (Helium)	$5.5 \times 10^{-9}/\text{Torr}$	$3.1 \times 10^{-4}/\text{Torr}$	56,000
Second-order Zeeman shift	$6.5 \times 10^{-11}/G^2$	$8.4 \times 10^{-8}/G^2$	1,300

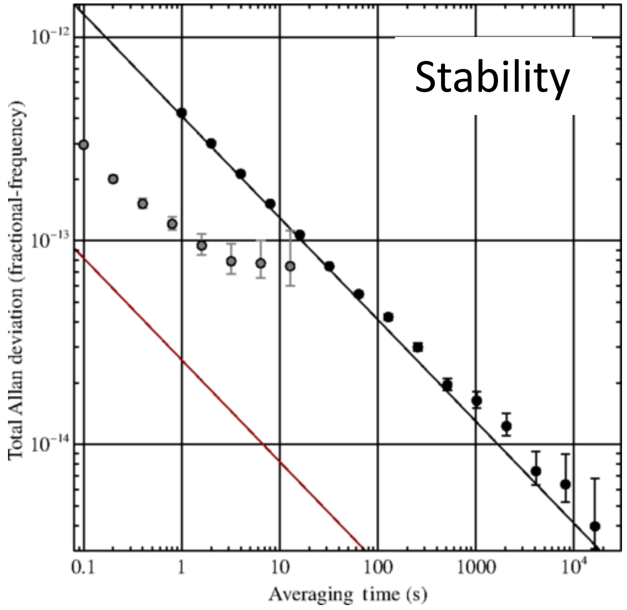
G. Phelps et al., “Compact Optical Atomic Clock with 5×10^{-13} *Instability at 1 s”, NAVIGATION, 65 (2018)*

K. Martin et al., “Compact Optical Atomic Clock Based on a Two-Photon Transition in Rubidium”, Phys. Rev. Applied 9 (2018)

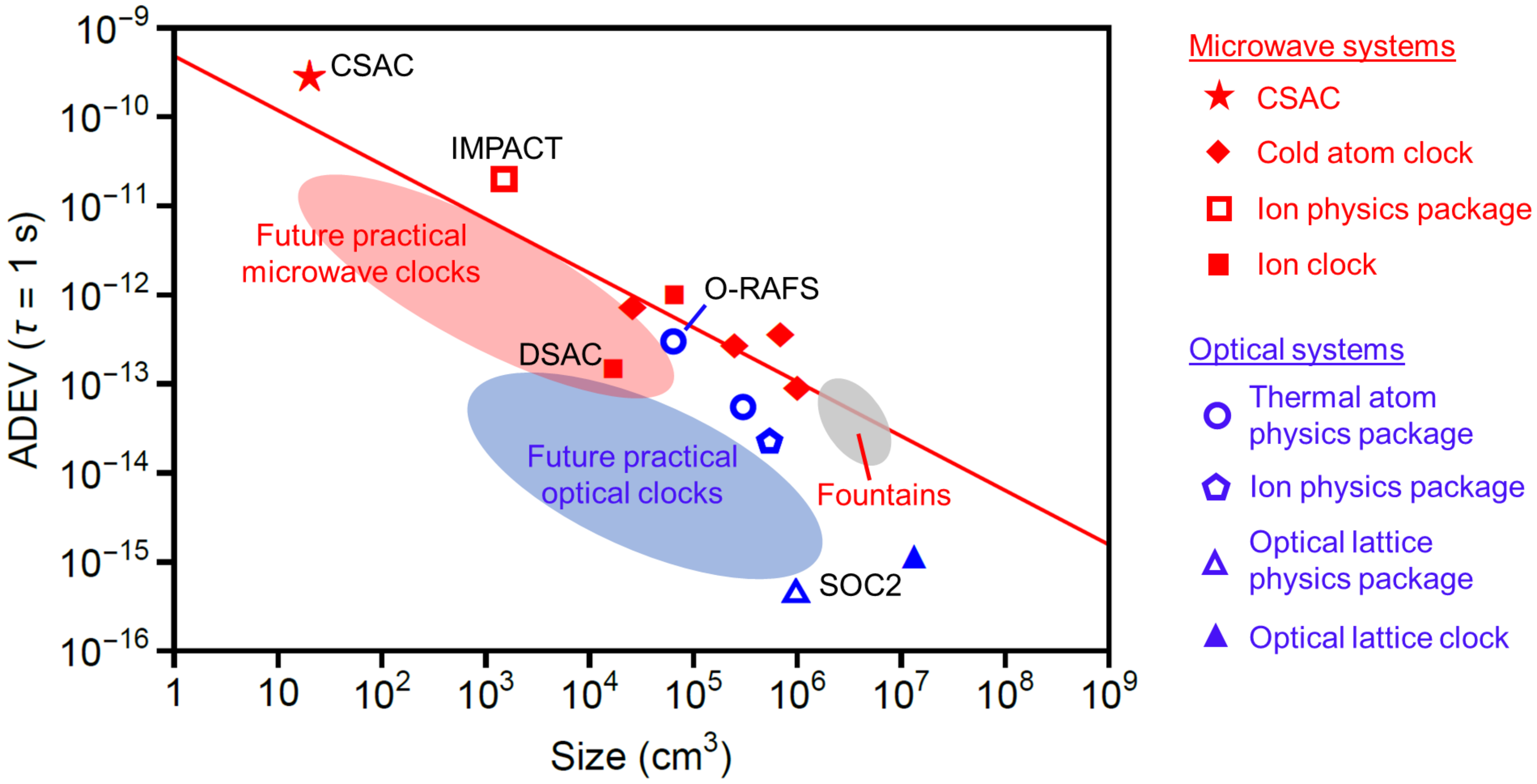
Prototype Physics Package



Stability

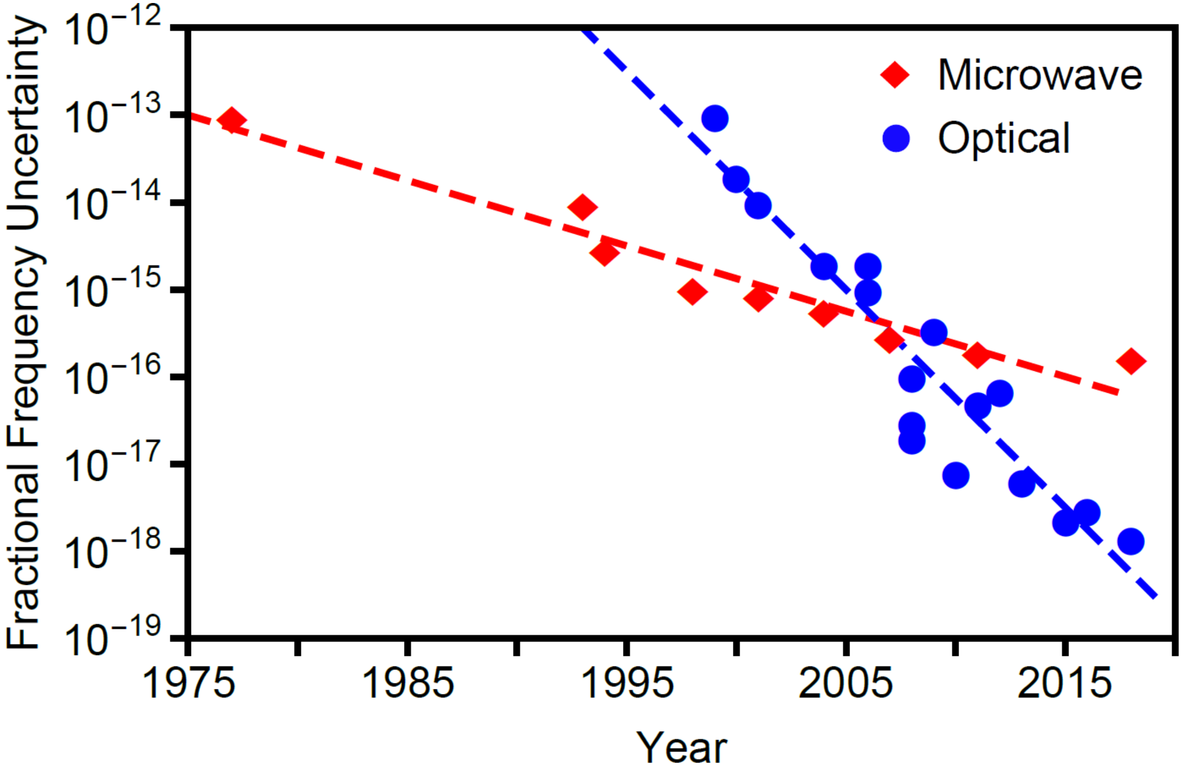


Comparison – Current vs. Future Atomic Clocks



Clock accuracy improvements (1975 – present)

Improvement in uncertainty over time

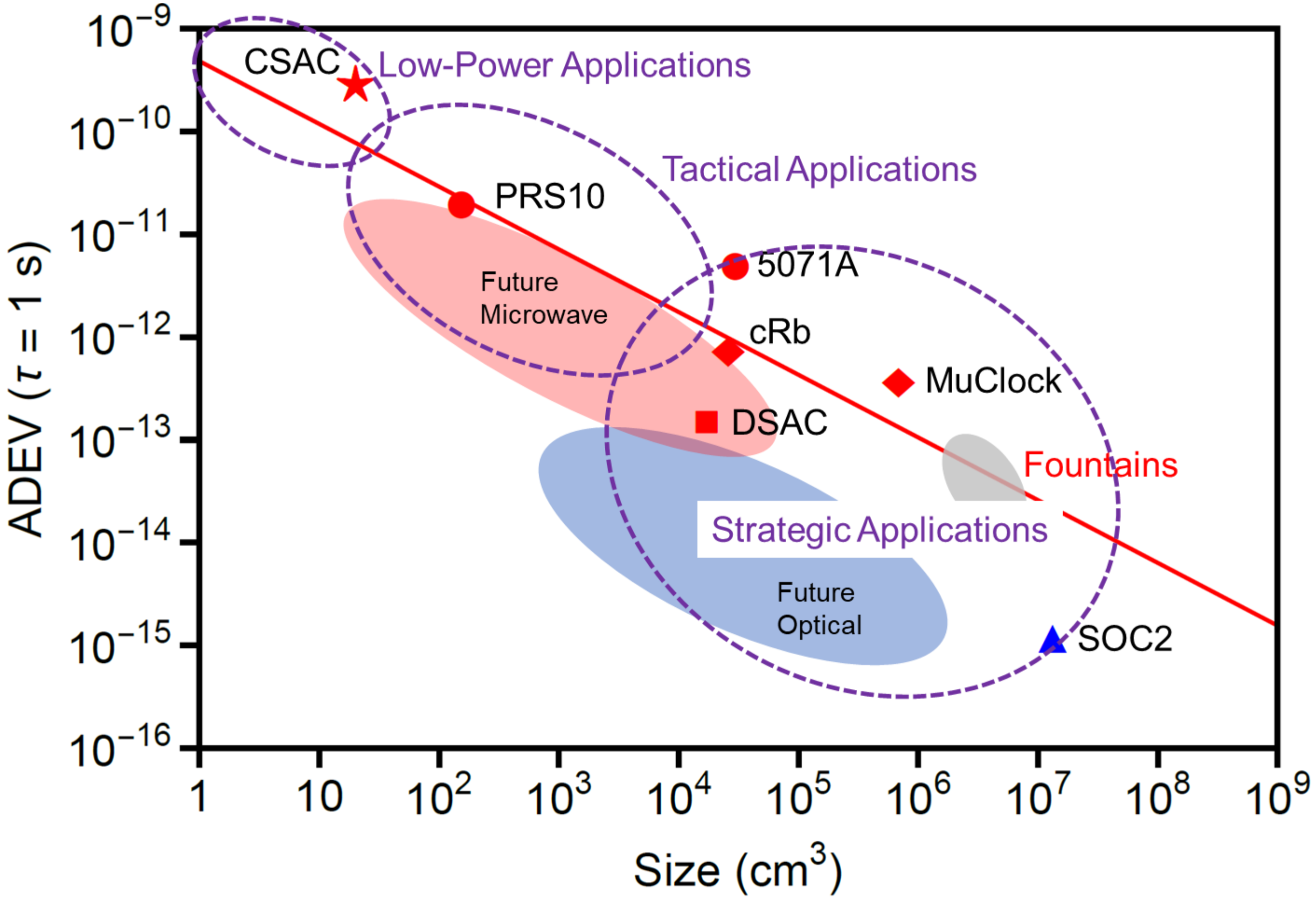


Important themes:

- Future improvements to clocks will result from ***reduced coupling to environment***
  - *Cold atoms, trapped ions, optical transitions*
- Microwave and optical clocks are on a different trajectory in terms of improvement over time
- Optical clocks may have a different scaling in terms of ADEV vs. SWaP

Adapted from M. S. Safronova et al., “Search for new physics with atoms and molecules” Rev. Mod. Phys. ***90****, 025008 (2018)*

Applications of Clocks



Three Main Application Areas:

Low-SWaP clocks for low-power applications

- Clocks = CSAC
- Applications = TTFF, GNSS augmentation, undersea exploration

Fieldable clocks for tactical applications

- Clocks = Rb clocks
- Applications = telecom, finance, military, communications

Reference clocks for strategic applications

- Clocks = Cs Beam Tube, Maser, cold atom, two-photon Rb, trapped ion, optical clocks
- Applications = Synthetic aperture radar, fundamental physics, GNSS, metrology

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