Judith Olson, PhD
- ColdQuanta atomic clocks division lead, senior physicist

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Making Quantum Matter.

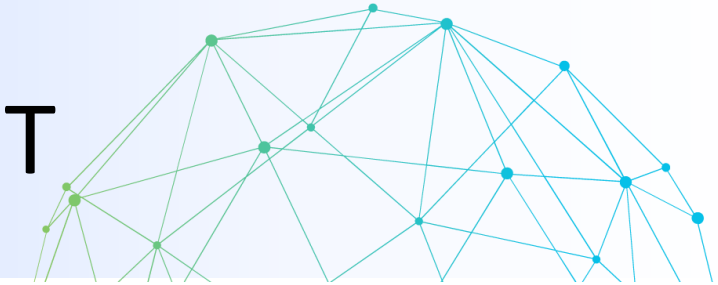
Quantum-enabled PNT technologies for the future

- A focus on next-generation, deployable atomic clocks -

November 16, 2022

27th Annual National Space-Based PNT Advisory Board

Quantum Technologies for Space PNT



- You already use quantum tech!
  - **Atomic clocks***
- You'll be using more quantum tech in the future too!
  - Quantum sensors
    - Radio frequency (RF) receivers*
    - Inertial navigation*
  - Quantum computing* and emulation*
  - Optical communications receivers and emitters

*ColdQuanta has dedicated research and product groups for each of these areas!

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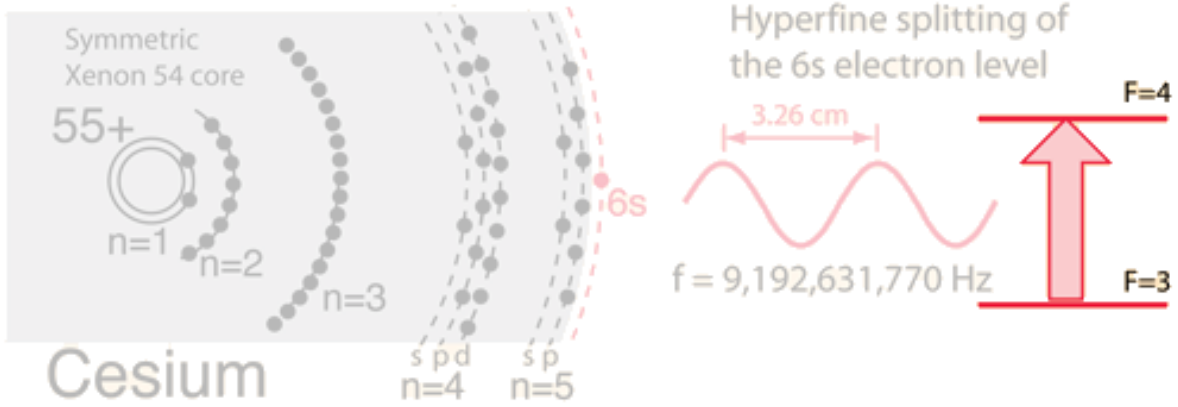
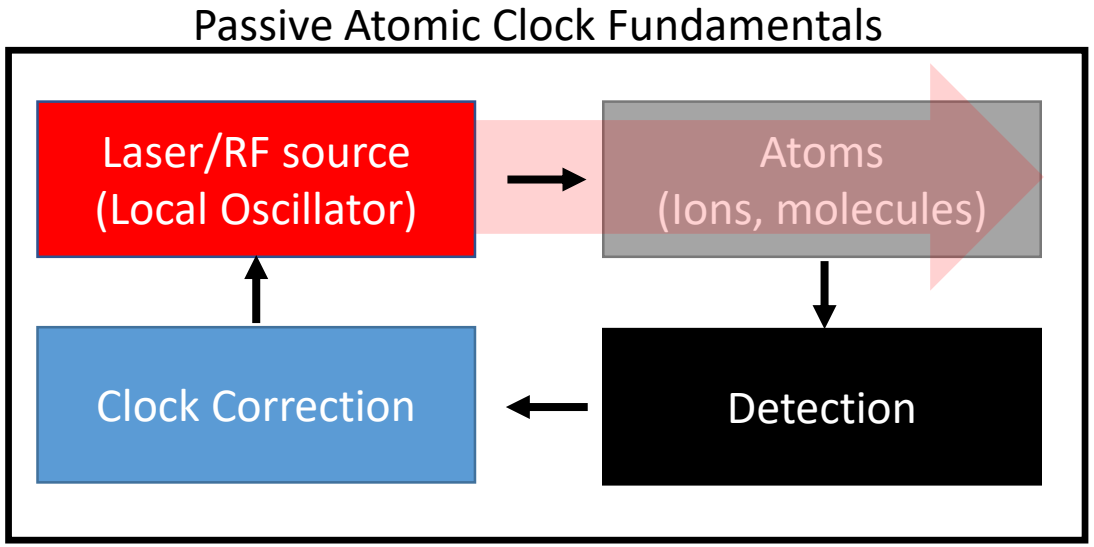
Quantum clocks

- You already use quantum tech! (atomic clocks)
- Many quantum systems rely on *quantized energy levels* of atoms and molecules





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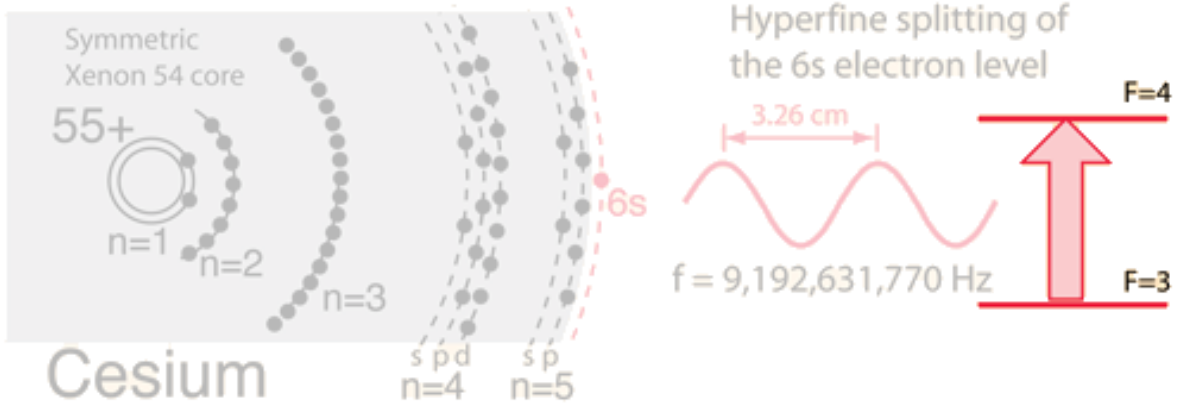
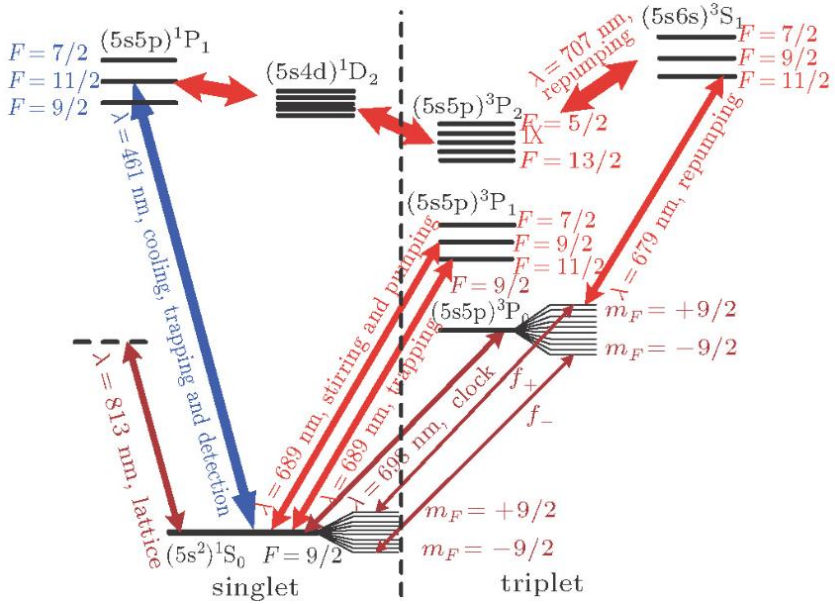
Atomic clocks have come a long way!

- Quantum understanding unlocked new ‘quantum tools’ for atomic clocks to improve → **optical atomic clocks**
  - Advanced lasers and electro-optics
  - Optical frequency combs





(Sr Lattice Clock Transition Diagram)

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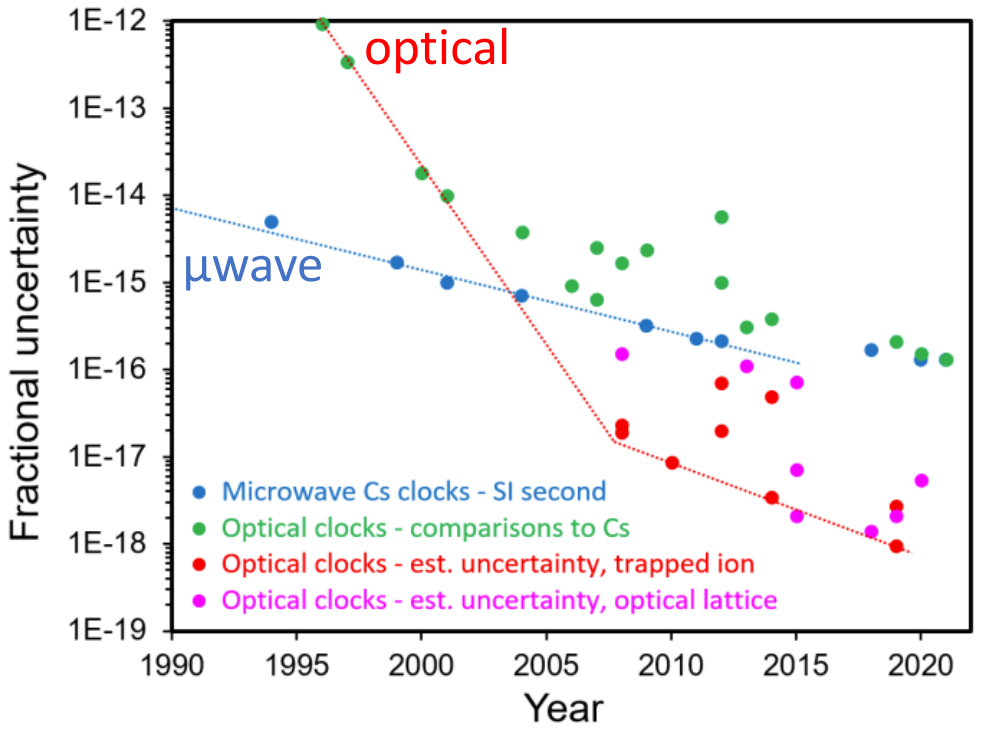
Why clocks are going optical

- Optical clocks are the future of timekeeping



(Plot from NASA Cold Atoms in Space Workshop 2022 publication)

$$Timing\ uncertainty = \sigma_y \propto \frac{\delta f}{f}$$

Optical atomic clocks have inherent advantages over microwave clocks:

- ~10,000 x immediate improvement from optical frequencies
- Multiple narrow (<= 1 Hz) optical transitions in a variety of atomic species
- Smaller physics packages possible w/o RF resonators or free-fall regions

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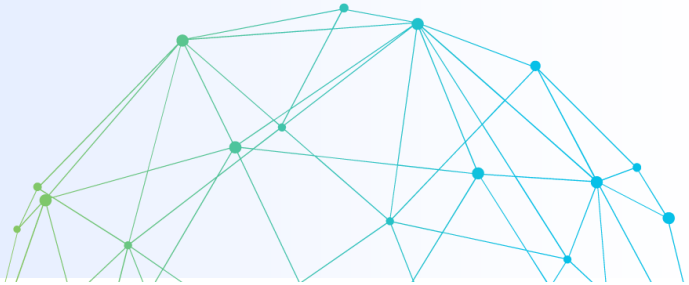
Commercial vs future clocks

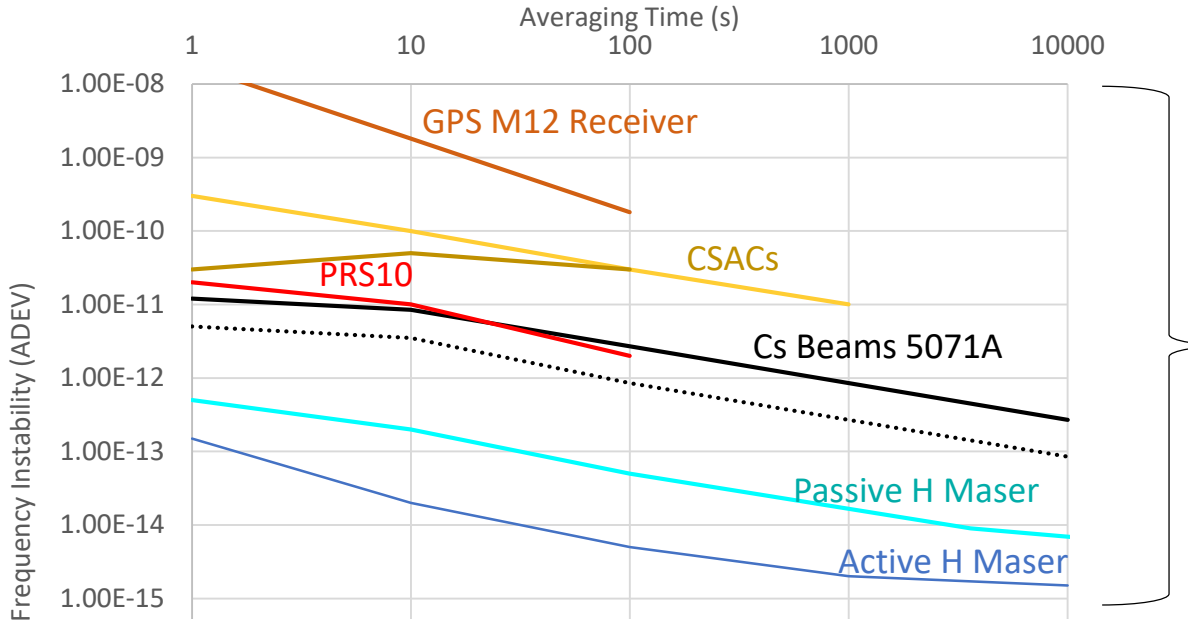


Cost, Size, Weight, and Power = C-SWaP

- Optical clocks are a game changer!

Worse timing

Better timing



Commercially Available

Better C-SWaP

Worse C-SWaP

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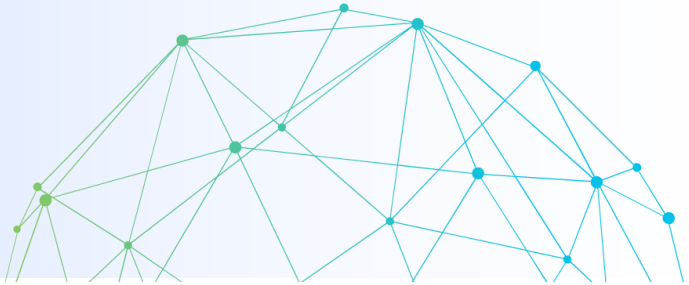
Bringing optical clocks out of the lab



- Transferring or utilizing optical clock signals is difficult
  - Free space over long distance w/ turbulent atmosphere
  - New tools are in development and moving fast!

- Environmental susceptibility
  - Atoms make good sensors -> they are sensitive
  - Some clocks are less sensitive than others
  - High-performance commercial clocks often need an environmental chamber to operate at specification

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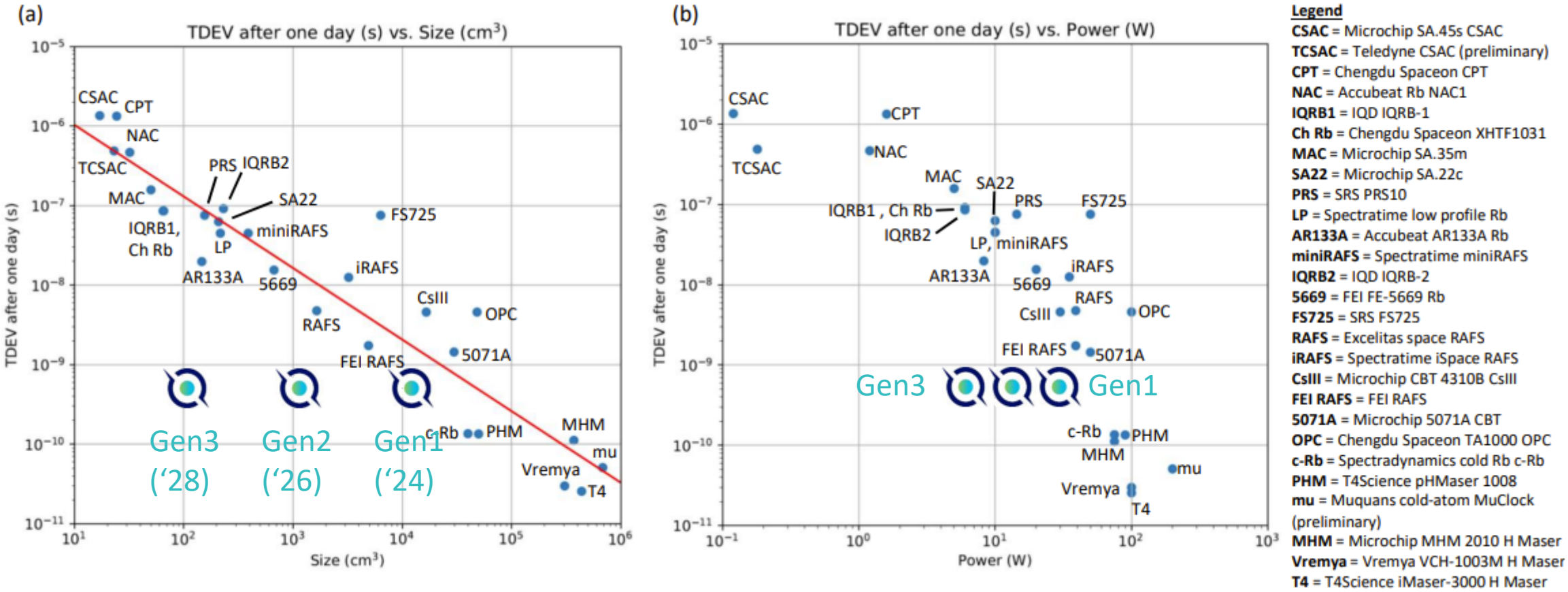
Where ColdQuanta is pushing optical clocks



Legend

CSAC = Microchip 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 = Microchip SA.35m
SA22 = Microchip SA.22c
PRS = SRS PRS10
LP = Spectratime low profile Rb
AR133A = Accubeat AR133A Rb
miniRAFS = Spectratime miniRAFS
IQRB2 = IQD IQRB-2
5669 = FEI FE-5669 Rb
FS725 = SRS FS725
RAFS = Excelitas space RAFS
iRAFS = Spectratime iSpace RAFS
CsIII = Microchip CBT 4310B CsIII
FEI RAFS = FEI RAFS
5071A = Microchip 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 = Microchip MHM 2010 H Maser
Vremya = Vremya VCH-1003M H Maser
T4 = T4Science iMaser-3000 H Maser

Plots from Schmittberger and Scherer (MITRE) 2020

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Uses for next-gen clocks like ColdQuanta's

- Ultra-low phase noise applications
  - Synthetic aperture radar
  - Optical communications
  - Encryption/security
- Ultra-long holdover applications
  - GPS-denied timing operation for days or weeks
- Ultra-stable timing frequencies
  - Beyond-GPS location accuracy
  - Geodesy
  - Gravimetry

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Quantum Opportunities for Space PNT

- RF sensing
  - Ultra-sensitive and much smaller
- Inertial measurement
  - Accelerometers, gyros,
- Quantum computing/emulation
  - Advanced material development
  - Massive logistics optimization
- Atomic clocks
  - Environmentally ruggedized, maser-like performance with extended holdover in a dramatically reduced package size.

If interested in learning more or collaborating on future work, contact:

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