Keynote: The Coming Optical Clock Paradigm Shift in Commercial Timekeeping

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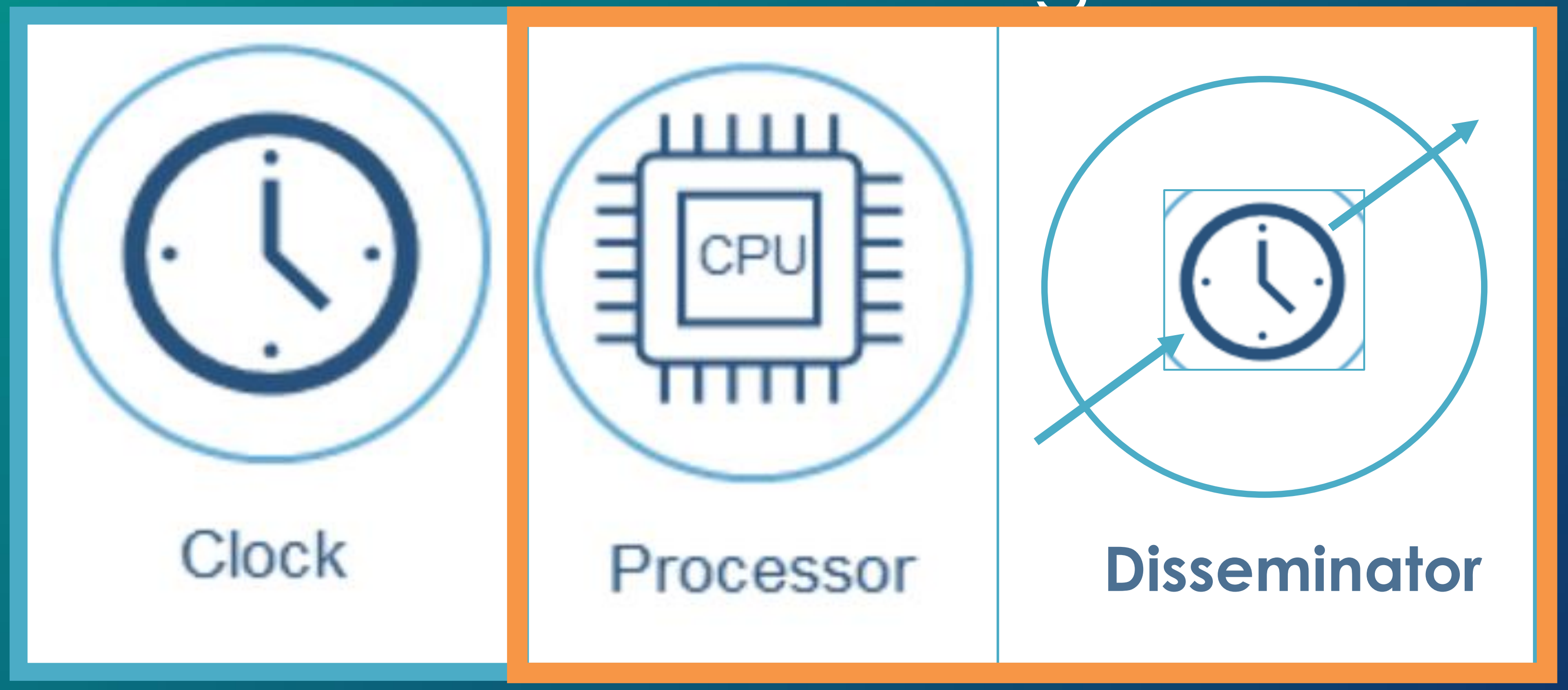
Precision timing for emerging needs

Market wants more precision for less money in smaller size

Networked Timing Unit



Functional Blocks

1. "Clock" – timing oscillator
2. Processor – counts clock oscillations, converts to use data forms
3. Disseminator – transfer and sync of distributed clocks

A lot can happen in a microsecond:

- Zero trust authentication basis
  - Avoid ransomware attacks, secure data/transfer
- Enhanced PNT capabilities (beyond-GPS)
- Avoid GPS single-point-of-failure

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References for Guidance

Resources regarding precision timing needs rollout, standards, definitions, use cases

- 2019 - High Accuracy Default Precision Time Protocol Profile - IEEE 1588-2019 (White Rabbit
- 2020 - DHS Resilient Positioning, Navigation, and Timing (PNT) Conformance Framework Version 2.0
- 2020 - Executive Order (E.O.) 13905 on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing (PNT) Services

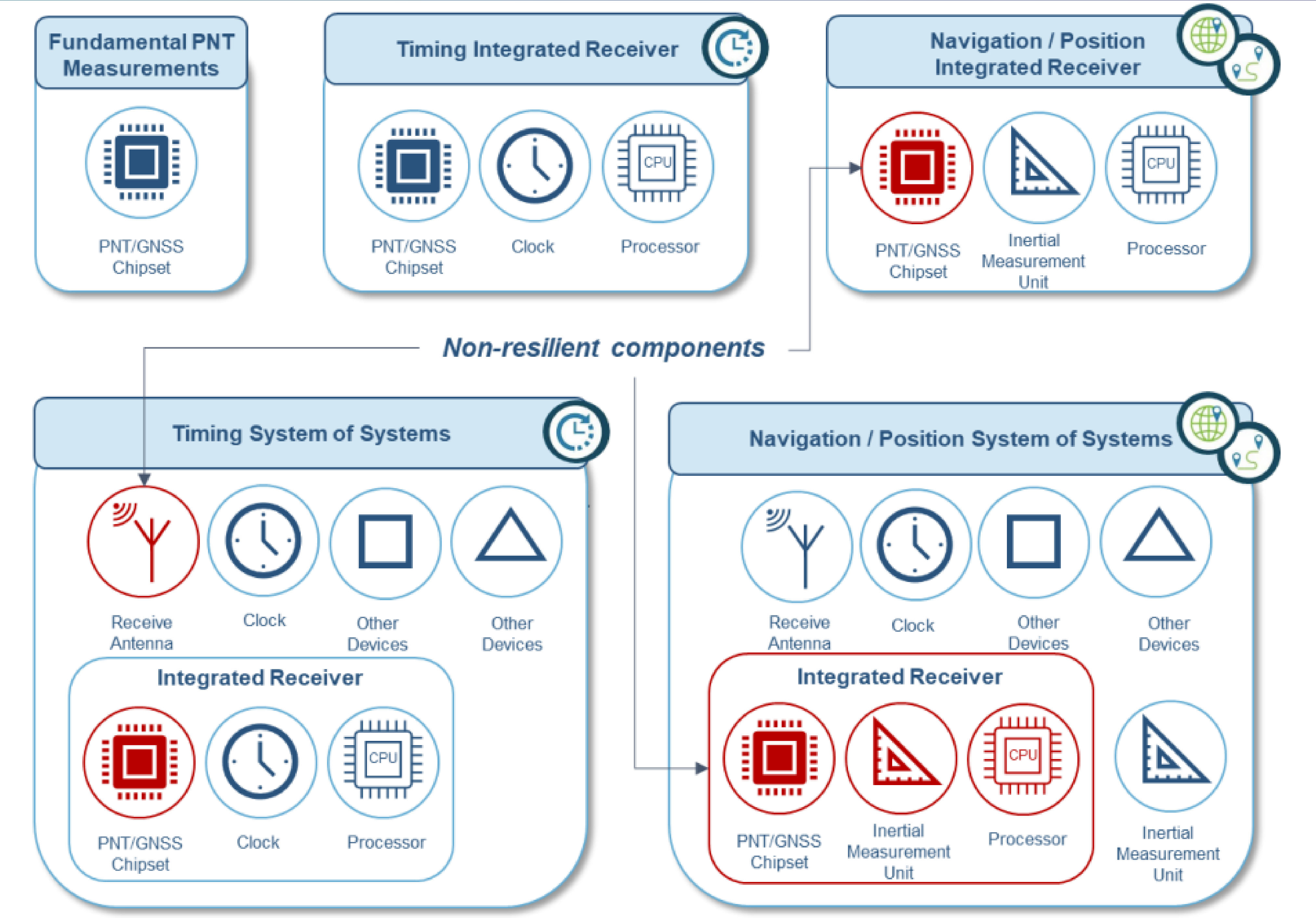
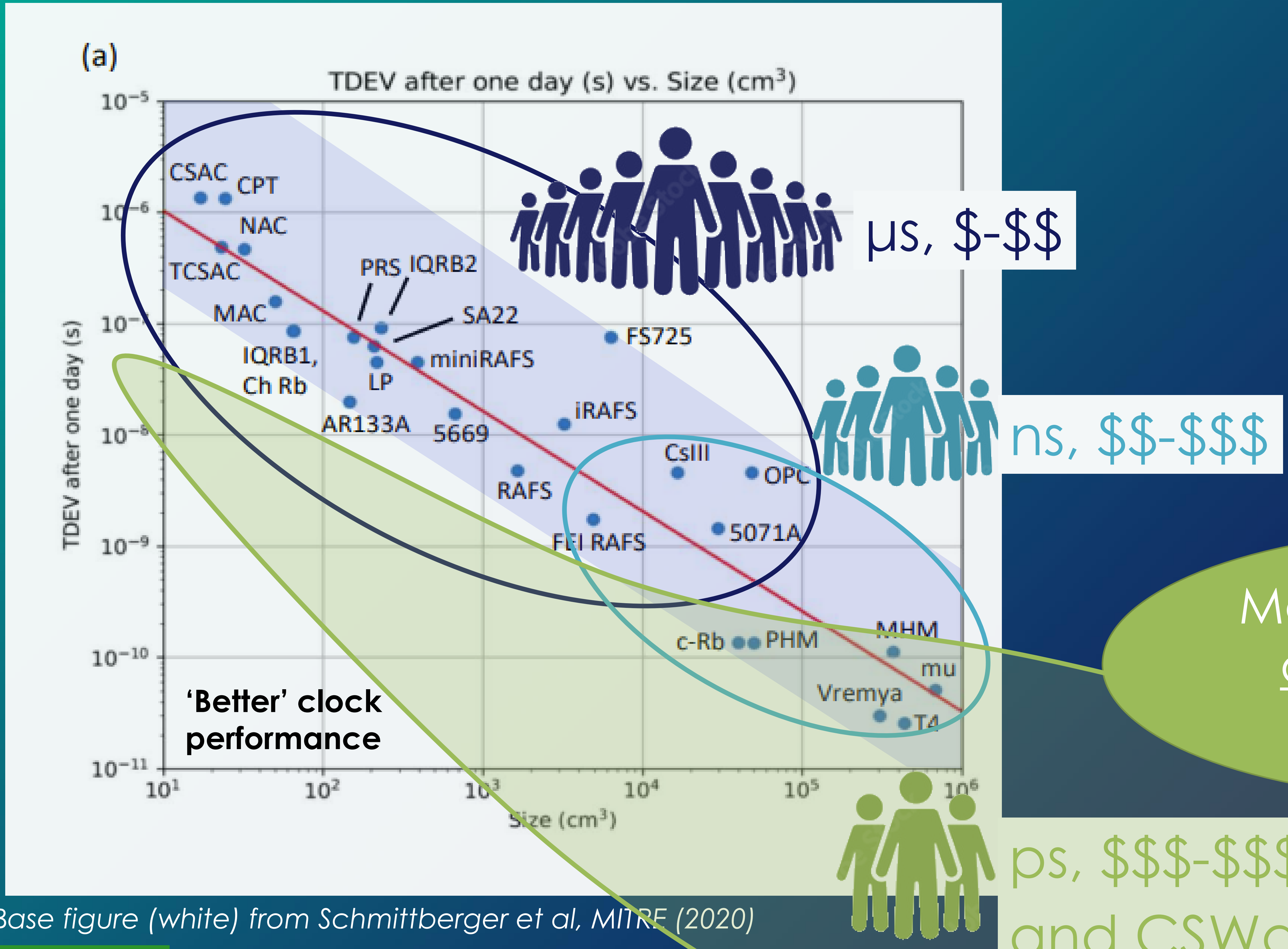


Figure 1. Examples of PNT UE boundaries across (1) Fundamental PNT measurements, (2) integrated receivers, and (3) system of systems.

DHS Resilient Positioning, Navigation, and Timing (PNT) Conformance Framework

"Buy"-able Atomic Clocks of Today

Microwave Clock Paradigm: Mature, well-optimized commercial clocks (blue area).



Base figure (white) from Schmittberger et al, MITRE (2020)

ps, $$$-$$$$
and CSWaP reduction

Many of these are <u>optical</u> atomic 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

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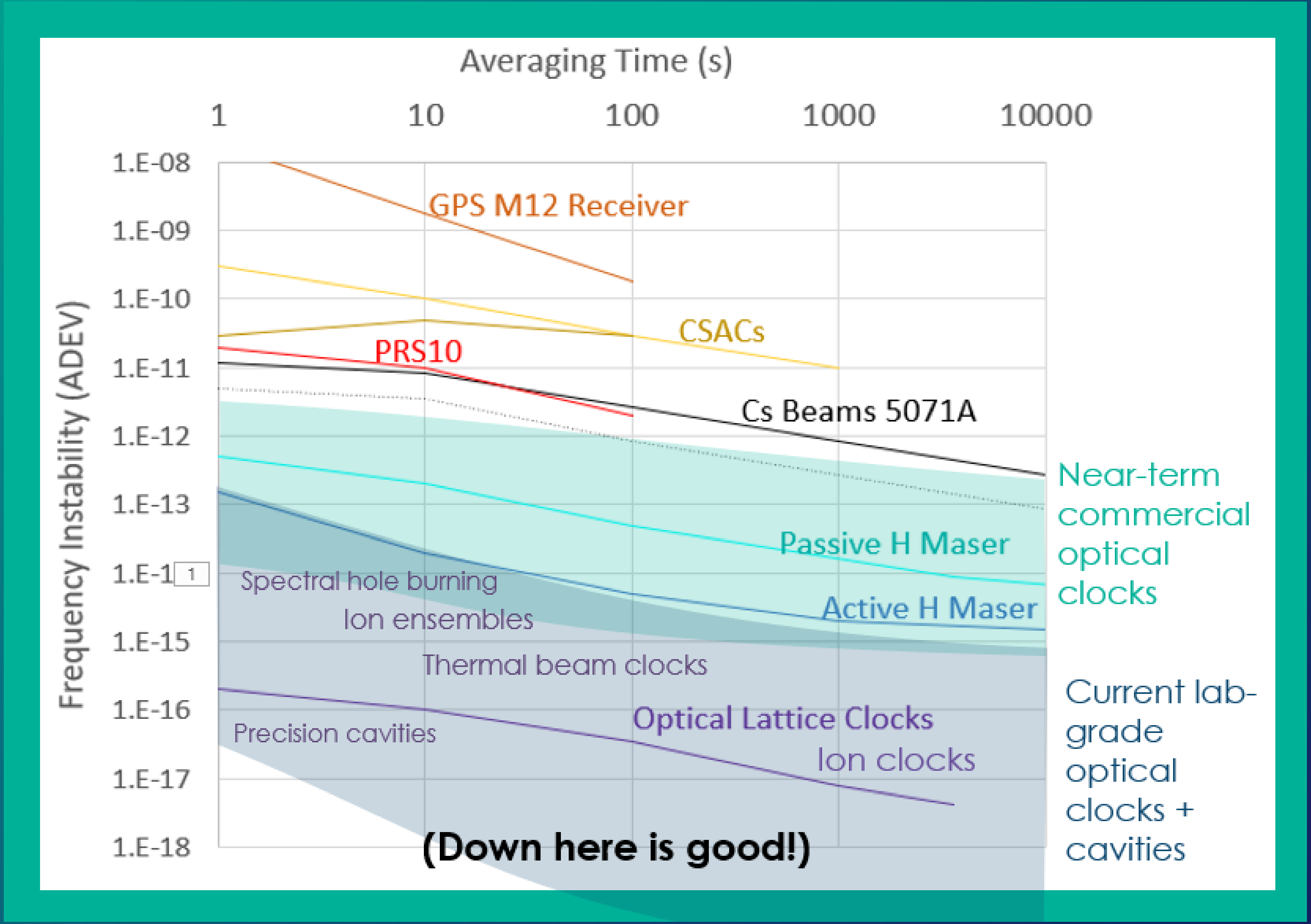
Optical clocks are fundamentally better timekeepers

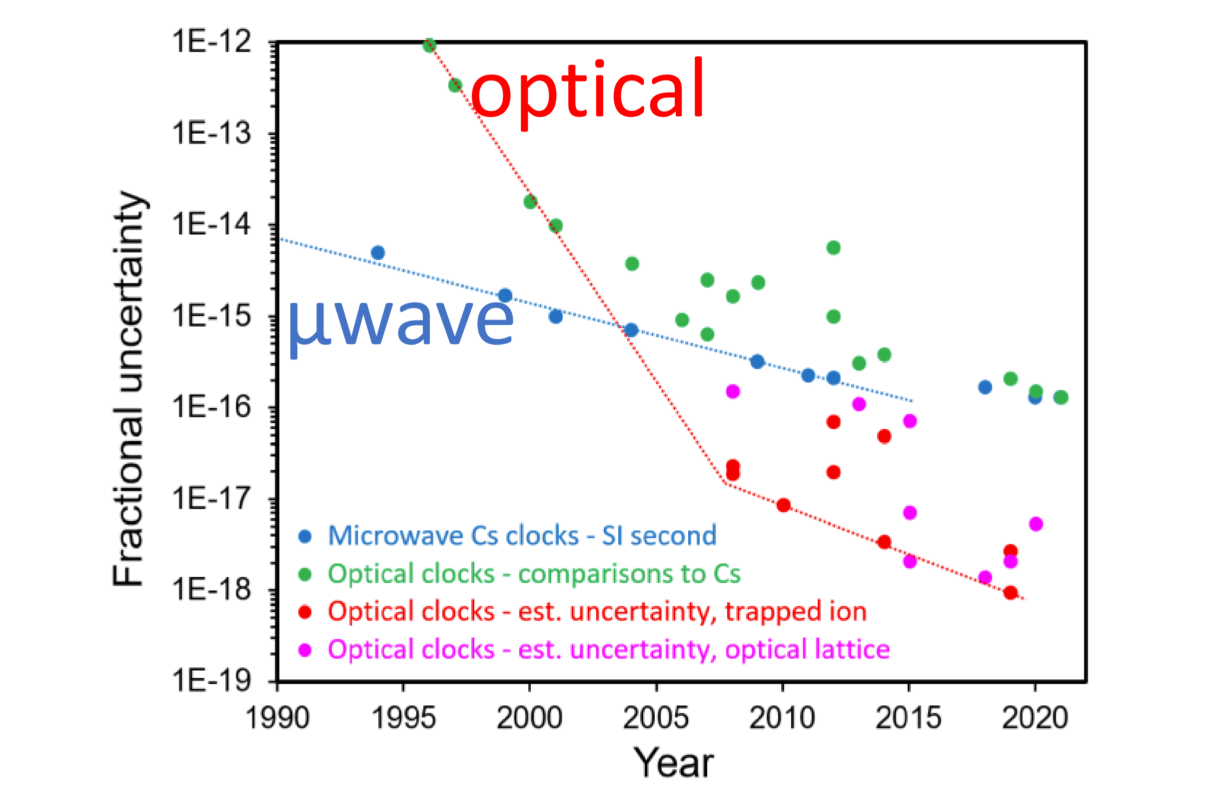
(We'd go 'nuclear' if we could)



Timing performance

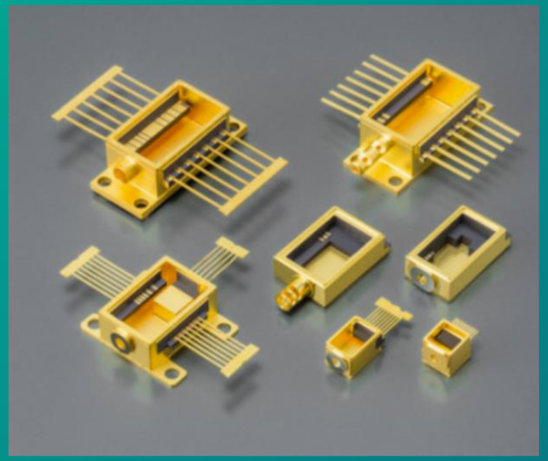
$$\propto \frac{Resonance\ Linewidth}{Resonance\ Frequency} \times \sqrt{\frac{1}{SNR}}$$

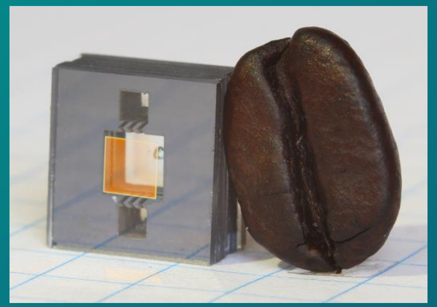
Same 'clock' but at optical frequencies performs ~10,000 times better than RF!

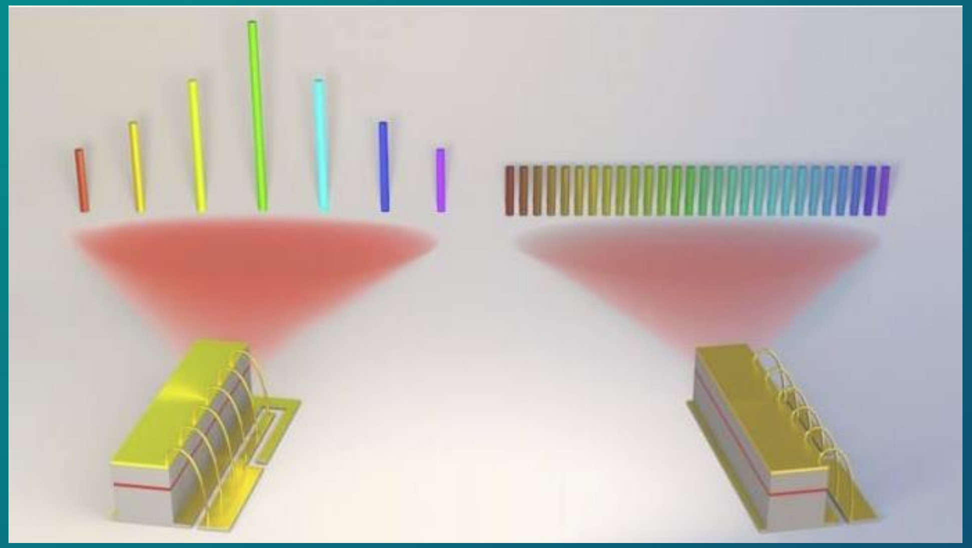


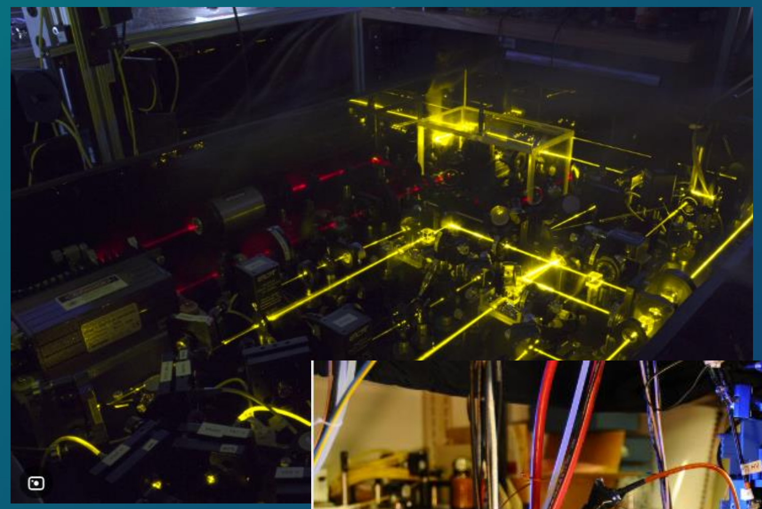
(Plot from NASA Cold Atoms in Space Workshop 2022 publication)

Why optical clocks weren't ready

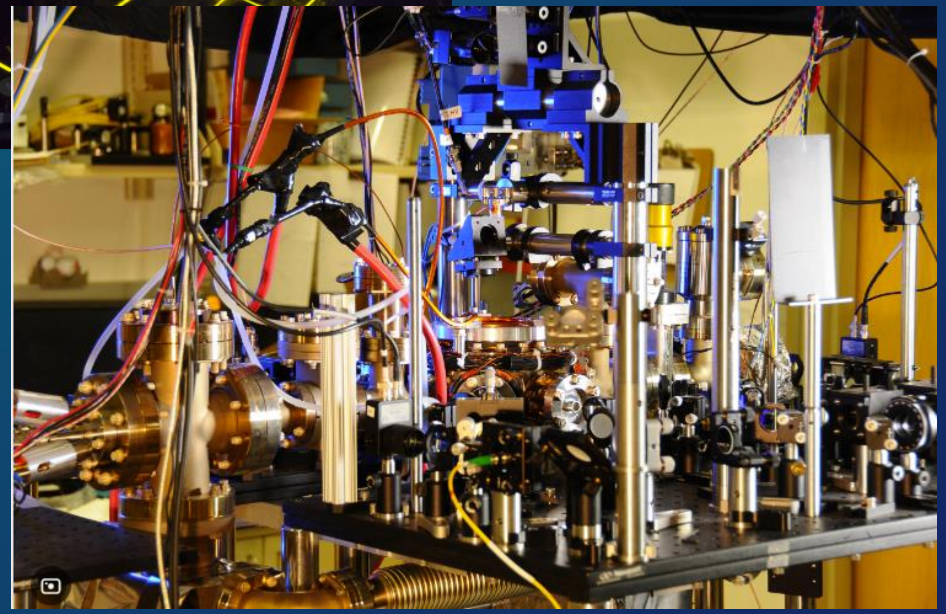


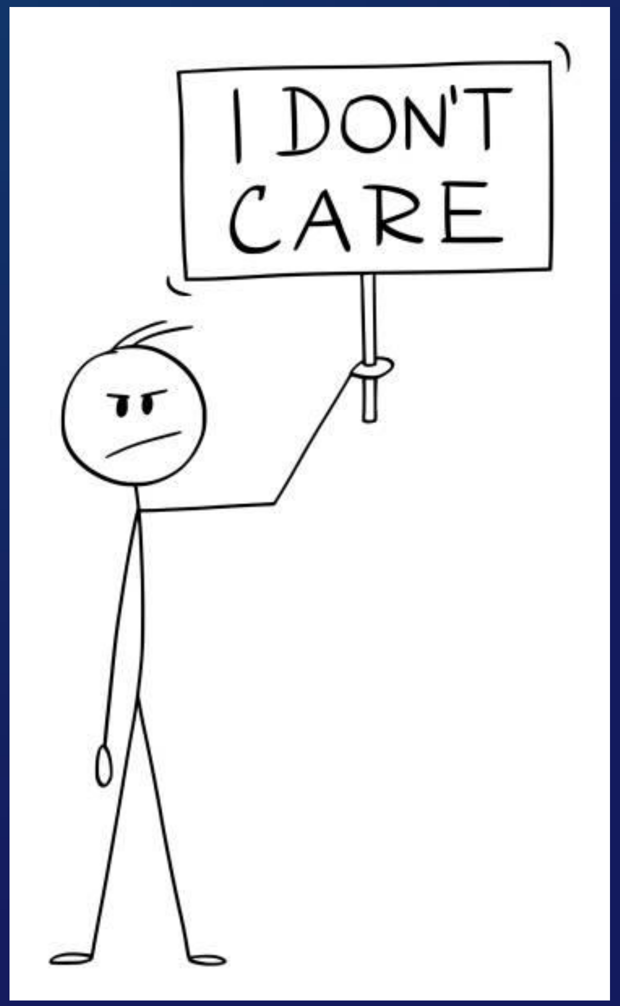






NIST Yb Lattice Clock





1. Technology was too immature (TRL + MRL)
   - Lasers
   - Optical freq. combs
   - Vacuum technology
   - Engineering gap

2. They couldn't leave the lab
   - Multi-bench rooms
   - Environmental Ruggedization
   - Extremely power-intensive
   - Complex, took teams to run

3. Poor market
   - Low value proposition
   - Unreliable supply chains
   - Invisible need

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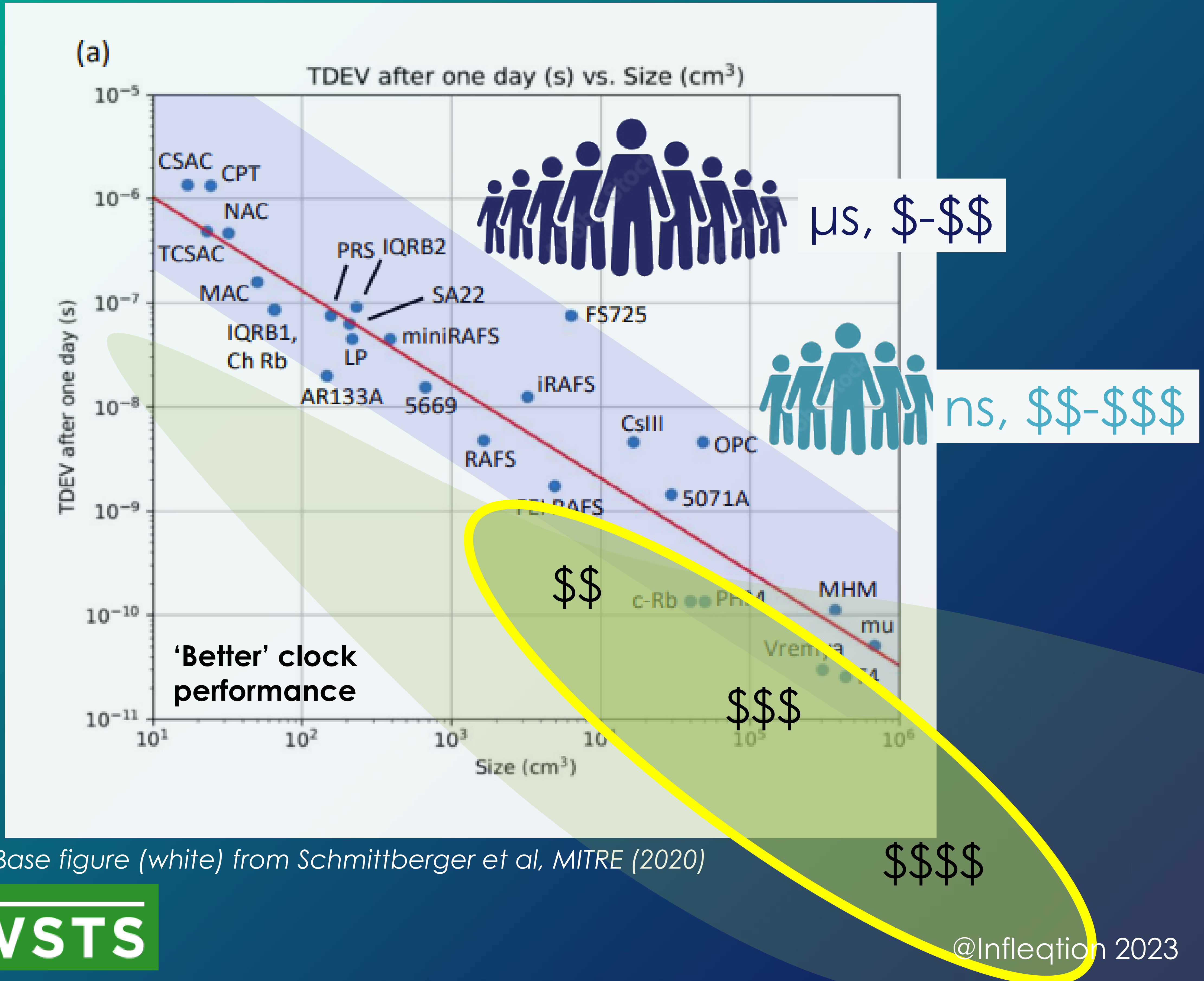
Initial optical clock products

Products available in 3 years or less



Base figure (white) from Schmittberger et al, MITRE (2020)

- Early 'stepping stone' products
- Improvements:
  - CSWaP-reduced ps timing and low phase noise
  - Extended µs, ns holdover
  - Potential ruggedization over existing COTS
- Uses:
  - Data centers
  - Network security (ZTA)
  - GPS resiliency – holdover, disturbance
  - Critical infrastructure monitoring
  - Test equipment, grandmaster
  - Grandmasters

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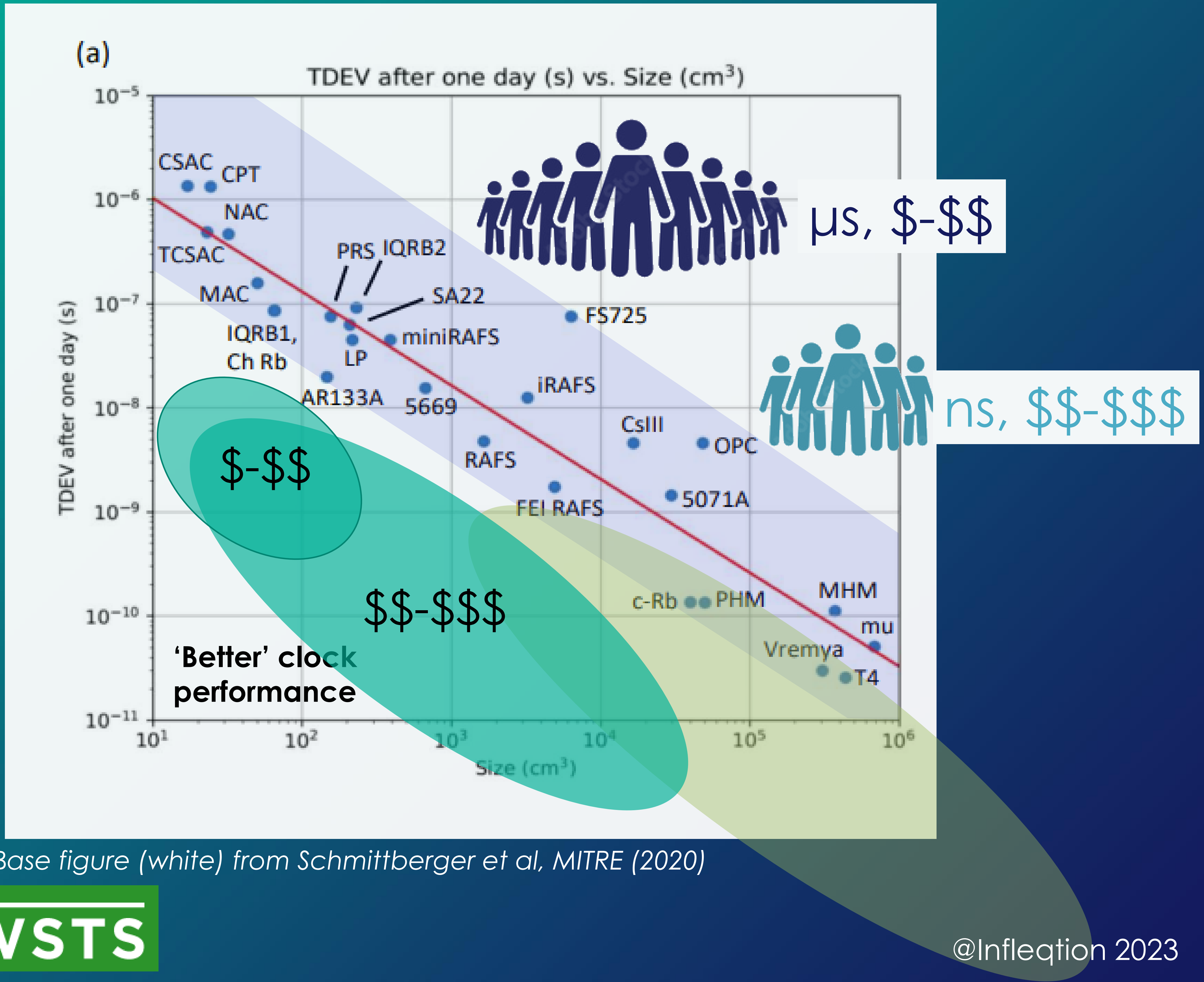
Future optical clock products

Products available in 3+ years



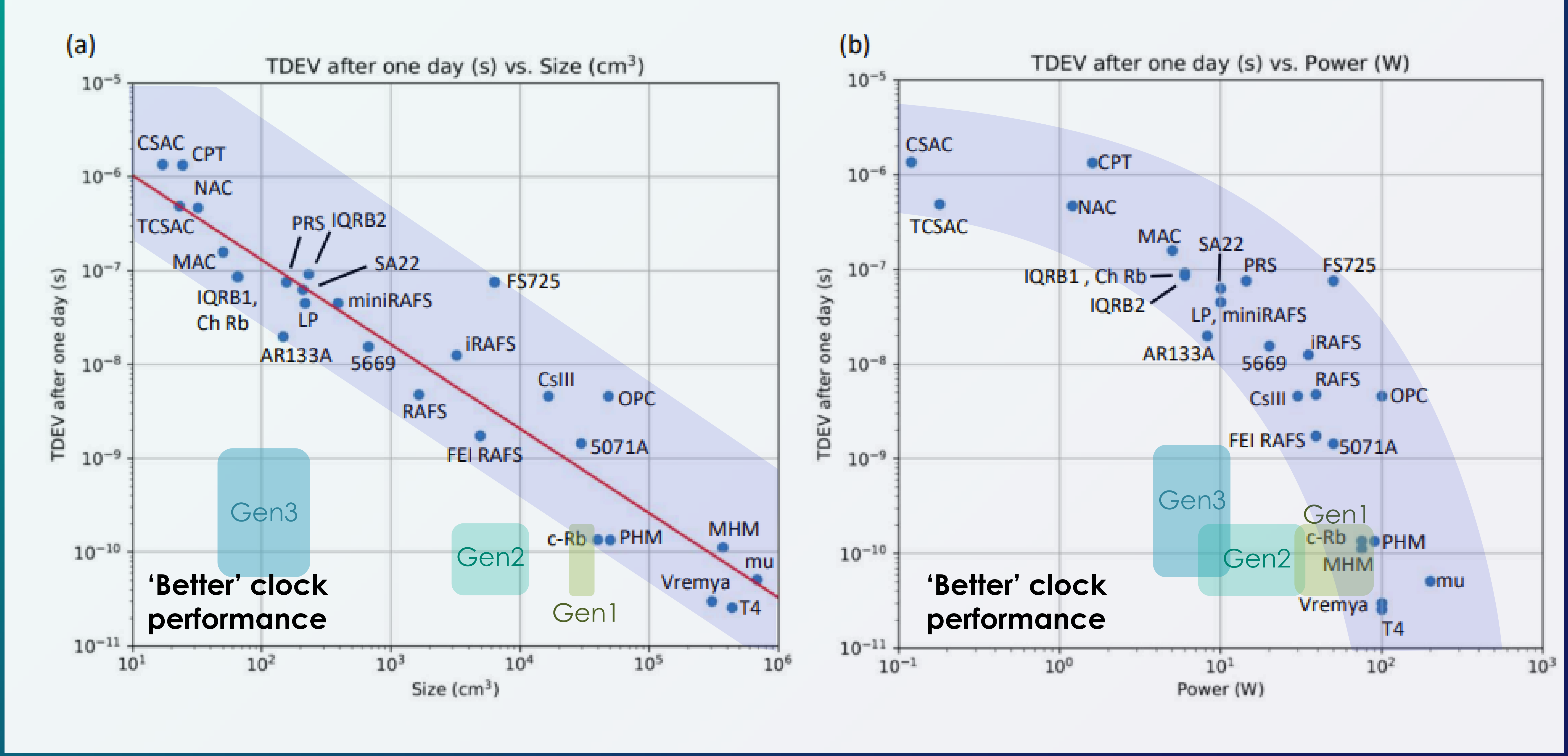
Base figure (white) from Schmittberger et al, MITRE (2020)

- Drastically reduced C-SWaP
- Vastly expanded use cases
  - On-board, sub-ns timing
  - Data security, ZTA, Cybersecurity
  - Resilient PNT – GPS alternatives
  - Optical/high frequency comms
  - 5G, 6G
  - Autonomous driving
  - UAVs, defense
  - Quantum networks/comms
  - Novel encryption/security
  - Distributed massive data networks
  - Internet of things (IoT) expansion
  - Augmented reality overlays

An example clock roadmap

Infleqtion's Clock Targets

Gen1	Gen2	Gen3
Q1 '25	3+ years out	5+ years out



Base figure (white) from Schmittberger et al, MITRE (2020)

Aiming for maser-like short-term performance, substantial holdover….

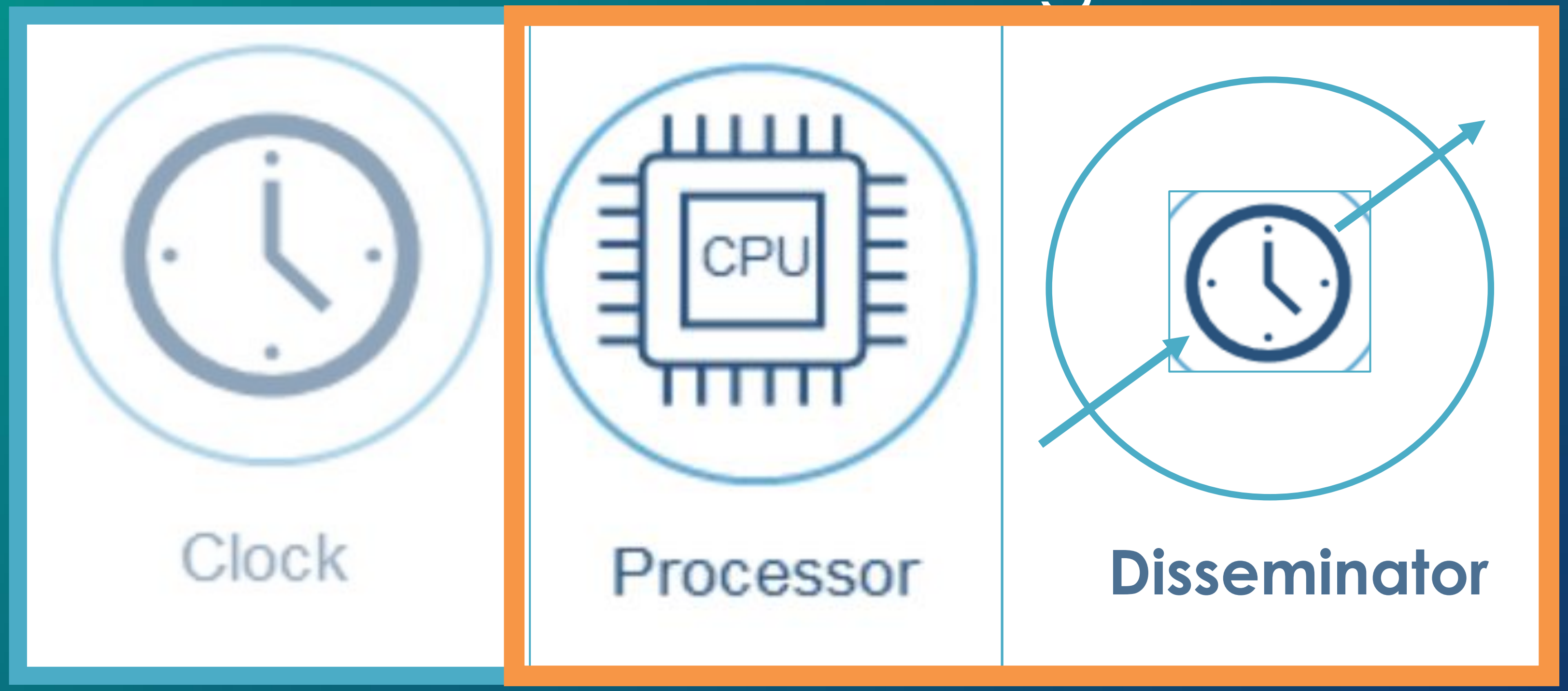
In a board-level, miniaturized device ~0.1 L …

With accessible pricing

Using ns and better timing

How to distribute and use timing near 1 ns or better

Networked Timing Unit



Light travels ~ 1 foot in 1 ns

Intra-clock use

- Sub-ns time tagging
- “Last centimeters” problem
  - PCIe PTM 0 – getting time off the NIC

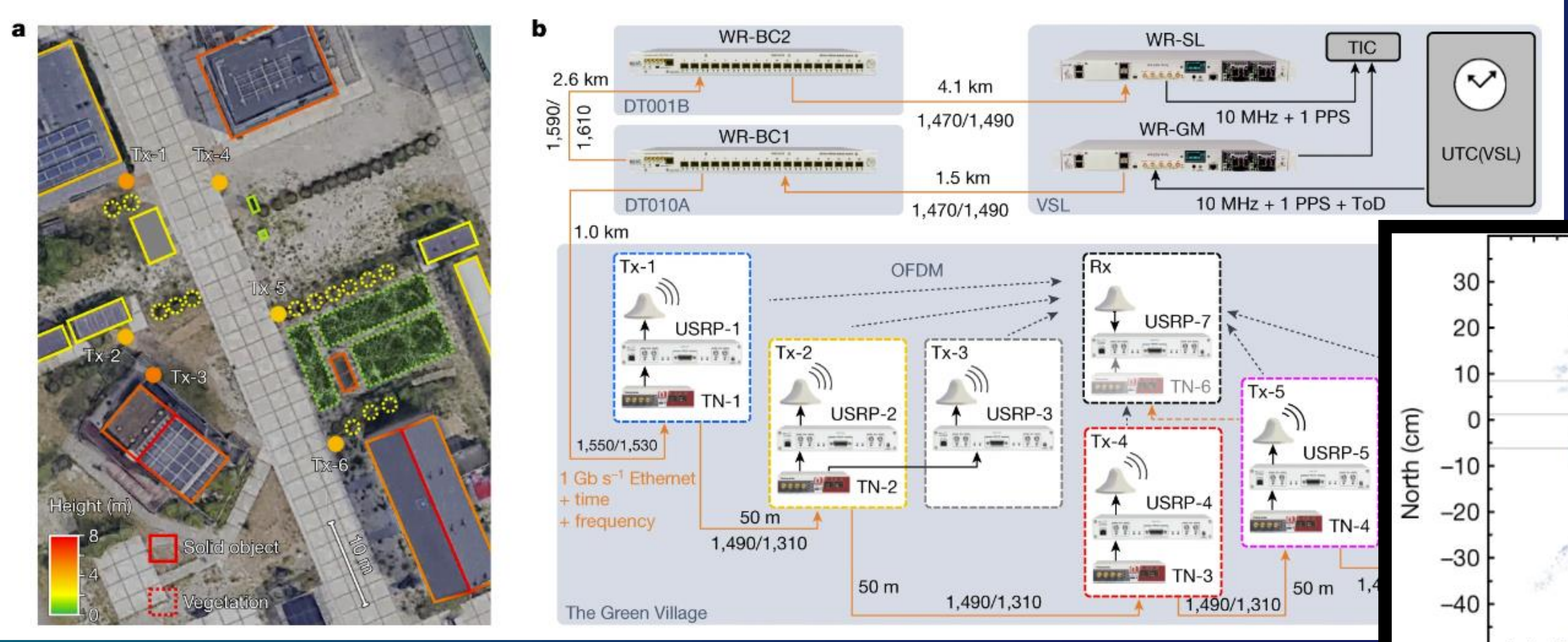
Inter-clock use

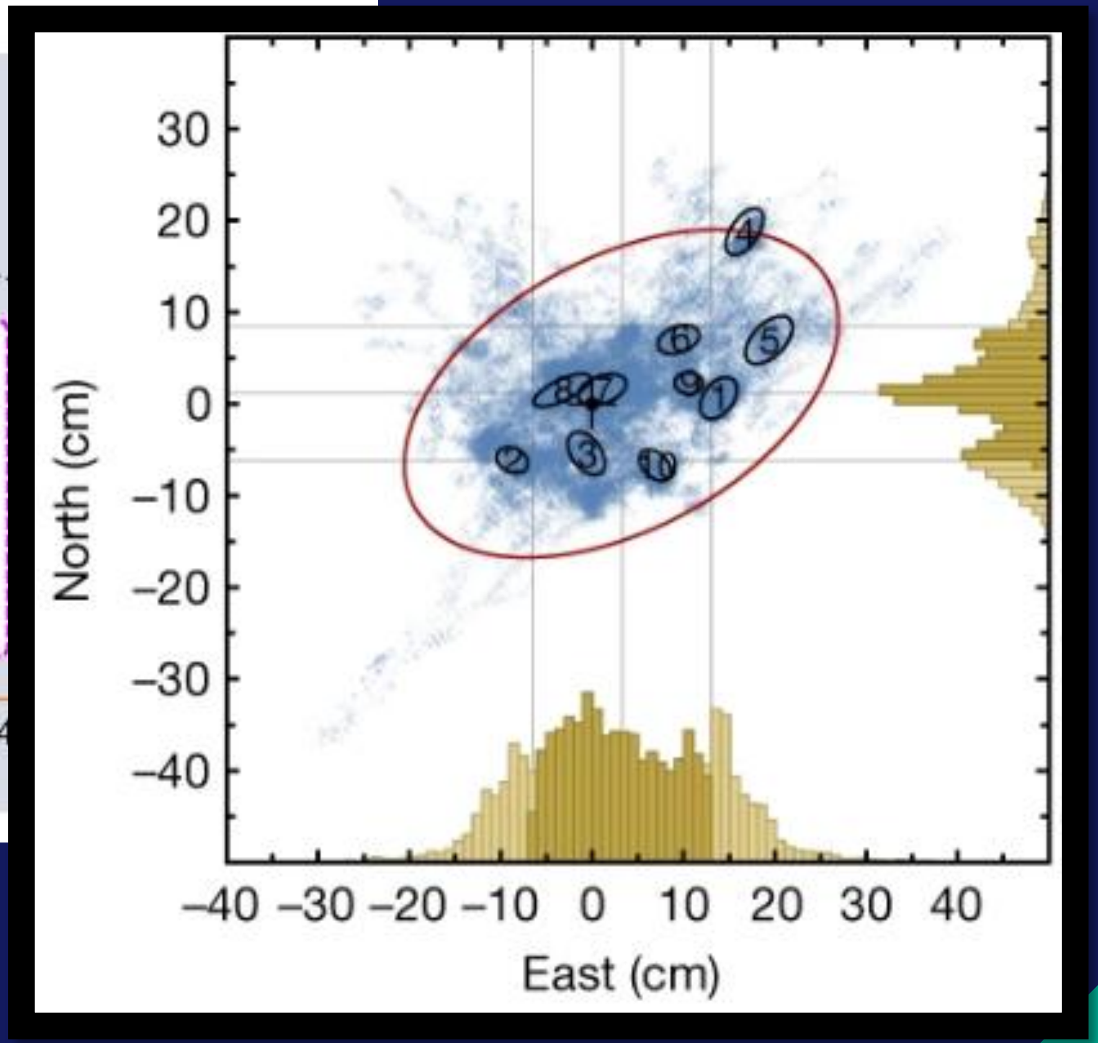
- White Rabbit (WR)
  - Sub-ns timing over ethernet developed at CERN
  - For 10 Gigabit Ethernet
- Entanglement
  - Haldar et al, Phys Rev A (2023)
- Optical frequency comb
  - NIST Newbury group
- Wireless 2Way Interferometry (WiWi)
  - NICT Shiga group

New Application Example

Decimeter positioning w/ fiber-optic ethernet and mobile networks

- *Koelemeij, J. C., Dun, H., Diouf, C. E., Dierikx, E. F., Janssen, G. J., & Tiberius, C. C. (2022). A hybrid optical–wireless network for decimetre-level terrestrial positioning. Nature, 611(7936), 473-478.*





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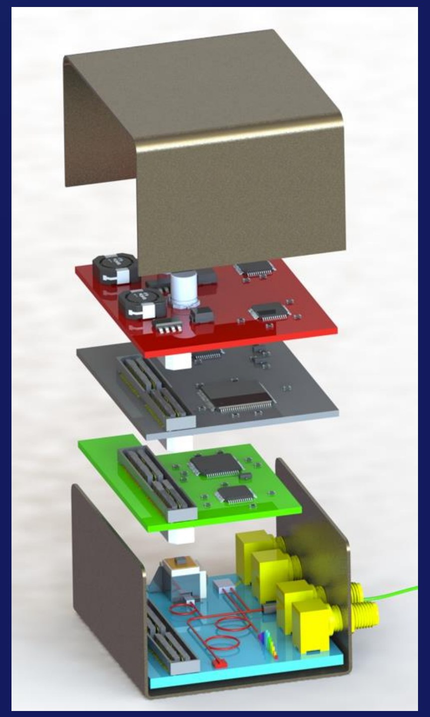
- Optical clocks productization is happening NOW
- Timekeeping and dissemination is rapidly changing

Gen0
In testing now

Gen1
~30 L, Q1 2025

Gen2
≤ 15 L, 3+ years out

Gen 3
≤ 1 L, 5+ years out



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