Infleqtion

Optical Atomic Clocks for Enhanced Timing Performance

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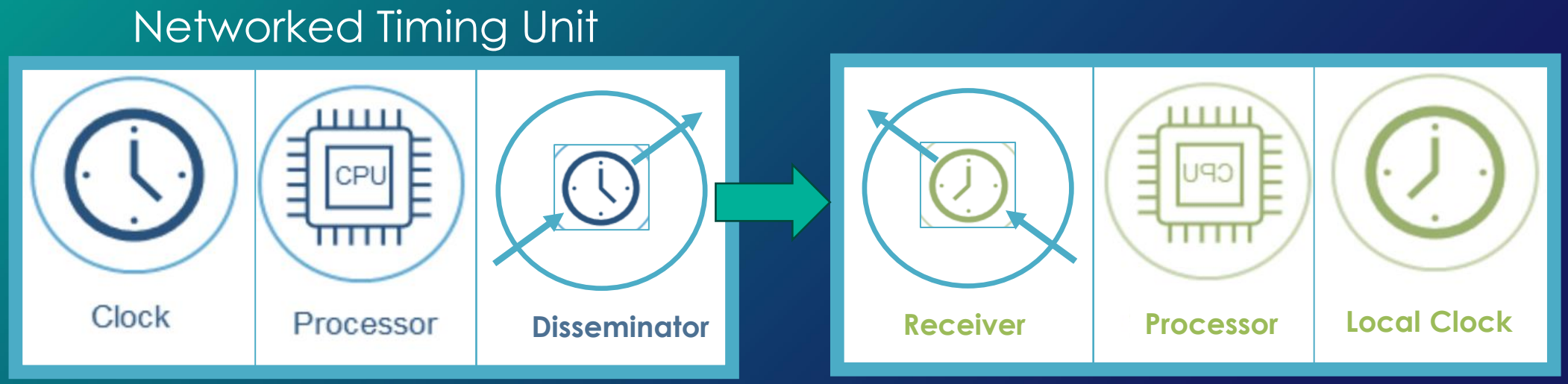
Atomic Clocks Portfolio Tech Lead

63rd Meeting of the Civil GPS Service Interface Committee
, Timing Subcommittee, Denver, CO, September 11, 2023

Toward an improved network timing unit

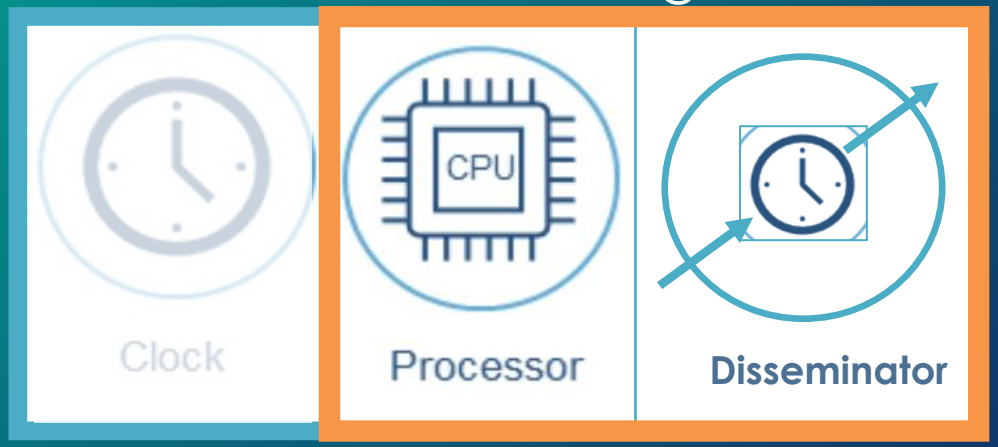
Need more than just a clock…



Toward an improved network timing unit

Network systems are rapidly enabling better timing at all levels

Networked Timing Unit



Light travels ~ 1 foot in 1 ns

Intra-clock use

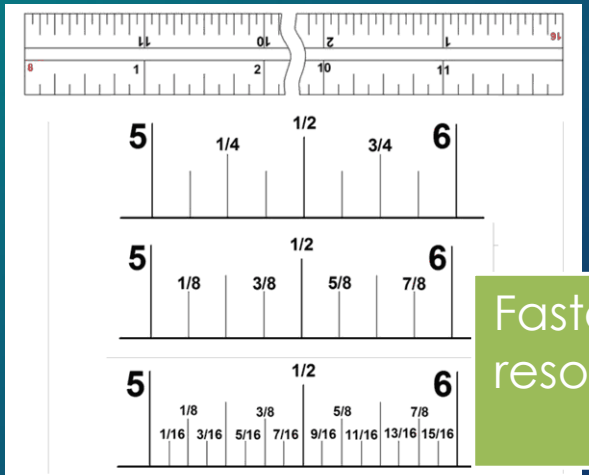
- Sub-ns time tagging
- "Last centimeters" problem
  - PCIe PTM 0 – getting time off the NIC

Inter-clock use

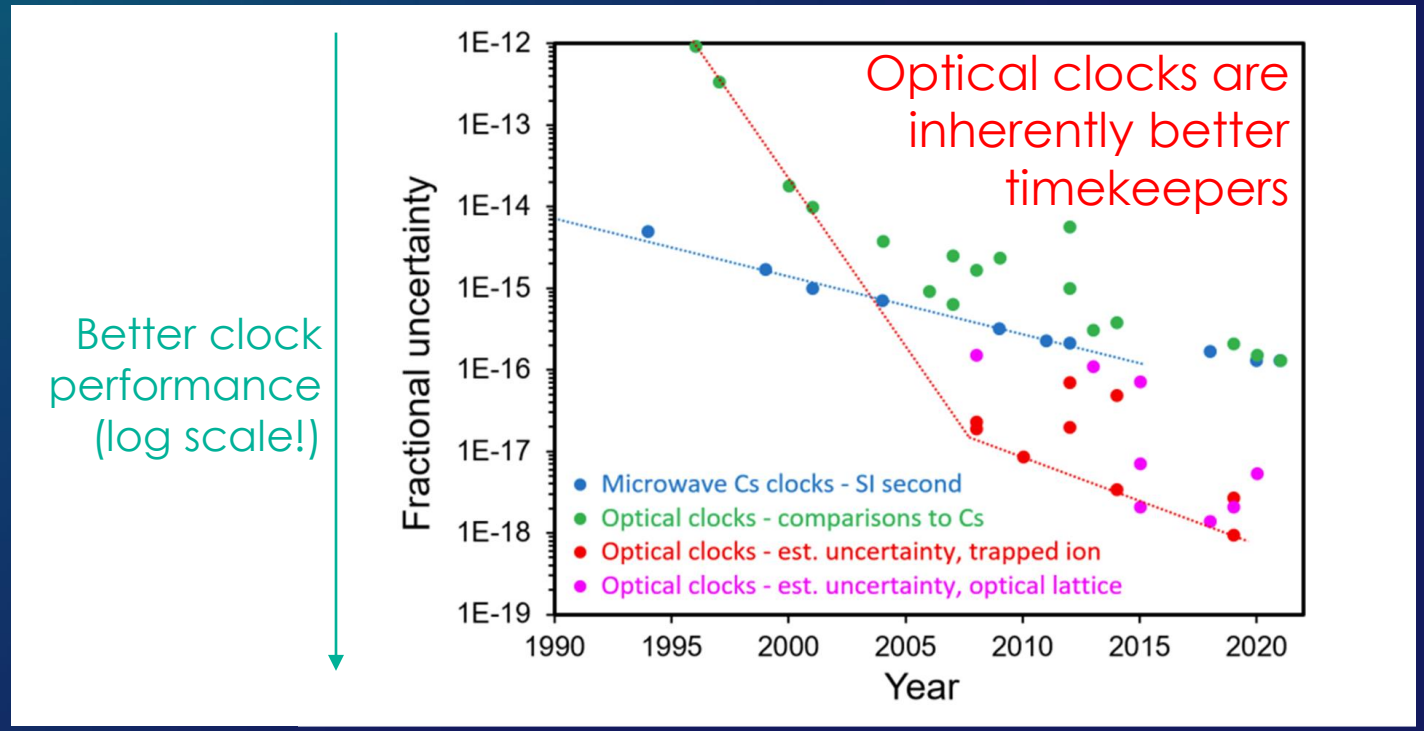
- White Rabbit (WR)
  - Sub-ns timing over ethernet developed at CERN
  - For 10 Gigabit Ethernet
- Entanglement
  - Haldar et al, Phys Rev A (2023)
- Optical frequency comb
  - NIST Newbury group
- Wireless 2Way Interferometry (WiWi)
  - NICT Shiga group

Optical clocks: the future of timekeeping

- Performance ∝ **fractional frequency instability**
- Optical clocks (100's THz) tick ~10,000 x faster than microwave clocks (10's GHz)
- **10,000x improvement in timing *and* environmental susceptibility** possible



Faster 'ticking' clocks allow better timing resolution and measurement, like having more ticks on a ruler

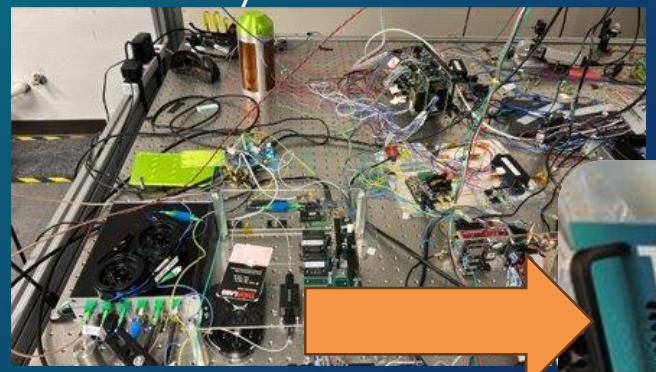


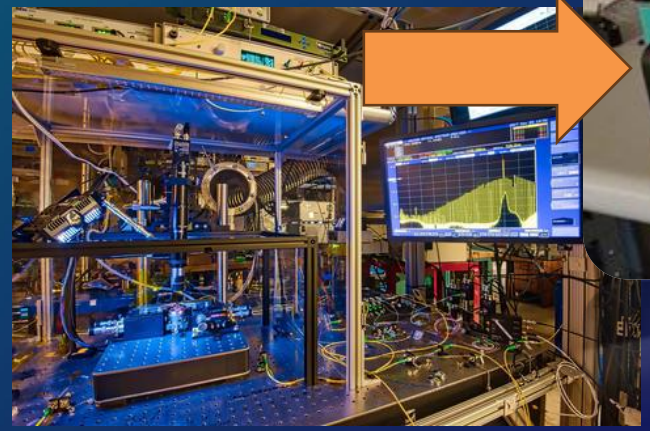
(Plot from NASA Cold Atoms in Space Workshop 2022 publication)

Optical clocks are coming to market

- Optical versus microwave clock performance and **fieldability** greatly improved
- Biggest technology barriers to commercial deployment are lowering (TRL and MRL)
- Emerging mission needs exceed current capabilities

Laboratory bench clocks





NIST comb lab

Optical clocks are leaving the lab

Readiness Level

Ultra-ruggedized

SWaP-reduced

Commercial systems

Commercial subsystems

Lab-level

Component demos

First stage
- 2 lasers (clock+comb)
- Active maser-like

Maser-like performance, but more ruggedized and affordable clocks with lower SWaP. Coming to market now.

Further SWaP-reduced and enhanced ruggedization versions to come.

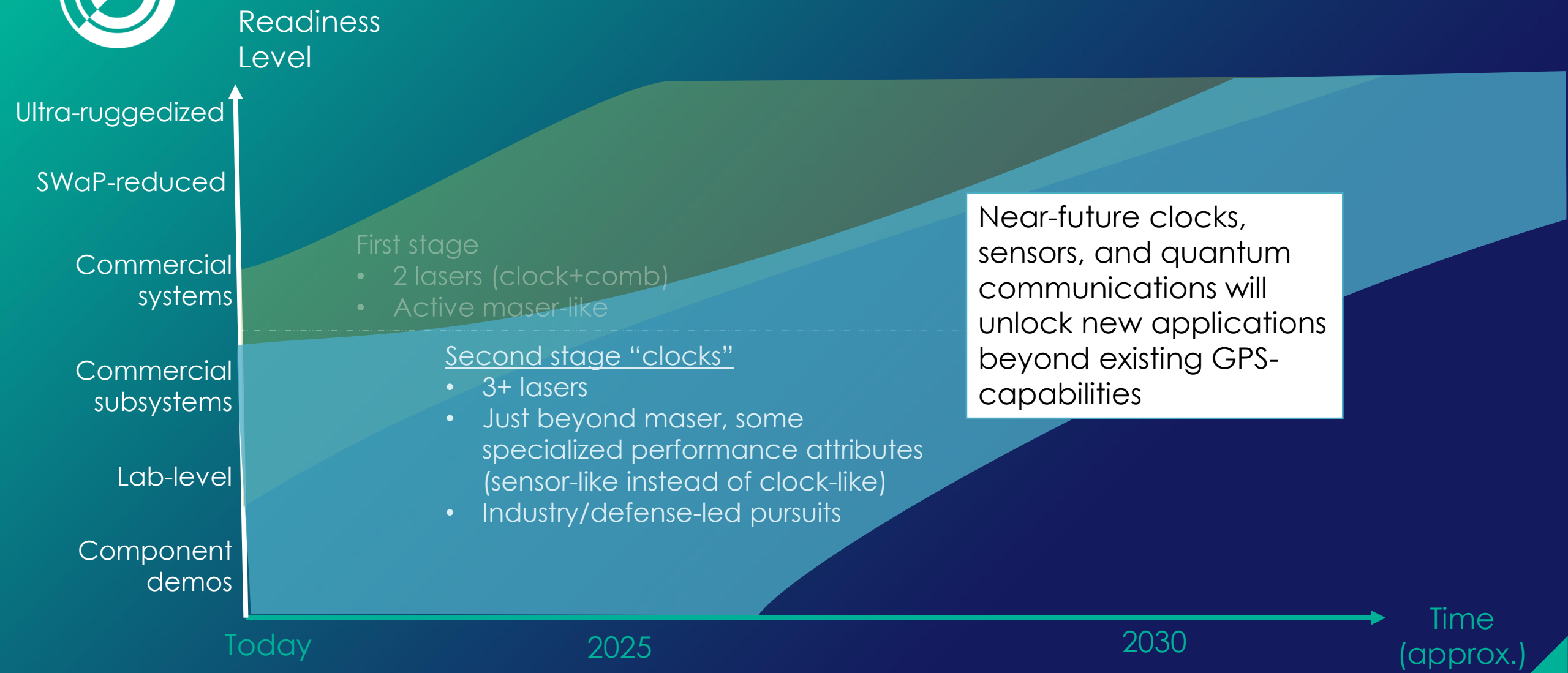
Today

2025

2030

Time (approx.)

Optical clocks are leaving the lab



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Second stage "clocks"
- 3+ lasers

Third stage clocks
- 4+ lasers
- Well beyond maser or specialized performance attributes
- Need substantial market growth to be worth commercializing

Future tech unleashes new capabilities – geodesy, gravitational corrections, optical phase references

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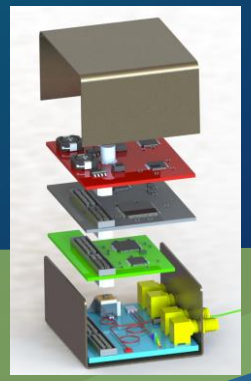
≥ 30 L

≤ 1 L



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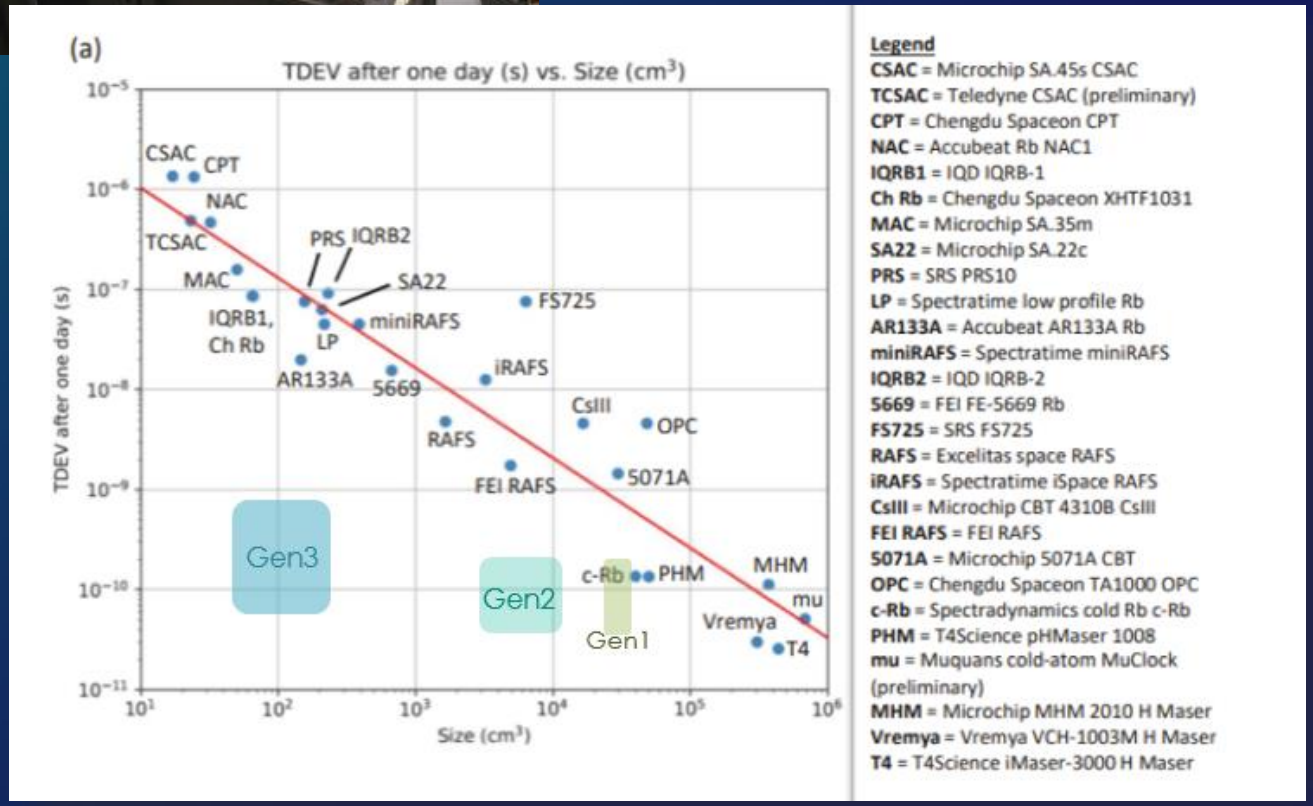
Commercial optical clocks today

- Optical clocks coming to market now, pre-production units available
- Maser-like performance with added benefits of:
  - More fieldable, ruggedized
  - Lower cost
  - Shorter lead times
  - Much smaller size
  - Better holdover/drift performance

Pre-Production

Tiqker Prime (Gen1)

Tiqker HD (Gen2)



Areas of interest for near-term clocks

Pre-Production

Early adopters and those wanting to ensure future compatibility with optical clocks

- Pilot Program underway
- Field demos

Contact for Pilot Program information:
Too Vira, Director of Product Engagement
too.vira@infleqtion.com

Tiqker Prime (Gen1)

"Office-use" version for

- Data networks
  - Meshed, distributed
- 6G infrastructure
- National timescales
- Science and research
- IoT and local networks
- **Tests and demos of new capabilities for GPS security, hyper-accurate positioning, backup networks**

Tiqker HD (Gen2)

Ruggedized version for deployed and mounted scenarios

- Intelligent surveillance and reconnaissance
- Autonomy
- Radar

New timing tools + performance

- Supplemented or alternative GPS timing systems
  - Incorporate local timing, eLoran, cellular, 4G+, and wifi information
    - Koelemeij et al in *Nature*, 2022 – Eindhoven, Netherlands
    - SuperGPS, Point One Nav, TRXSystems,OPNT, Hellen Systems, PassTime, Hoptroff, Safran, TrustPoint… there are many!

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We'd love to hear from you: judith.olson@infleqtion.com