WSTS 2026 Conference

Low SWAP Clocks with High-Stability and Reliability Based on an Ensemble of MEMS Oscillators

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Founder / CEO - Luminous Cyber

- 2015 Graham Bell Award for Best Communications Solution (Telecom Council)
- MIT SB • Stanford MS, PhD; >12 US Patents

THE PROBLEM: Timing Is a Single Point of Failure

GNSS Vulnerability

- *Single point of failure*
- *Jamming, spoofing, denial*
- *Degraded timing → mission lost*

Alt-PNT: Resilient Overlay

- *Distributed clock infrastructure*
- *Asset-mesh timing*
- *Self-healing*

From GNSS Dependency → A New Timing Paradigm

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VARIABLES AFFECTING TIMING ACCURACY

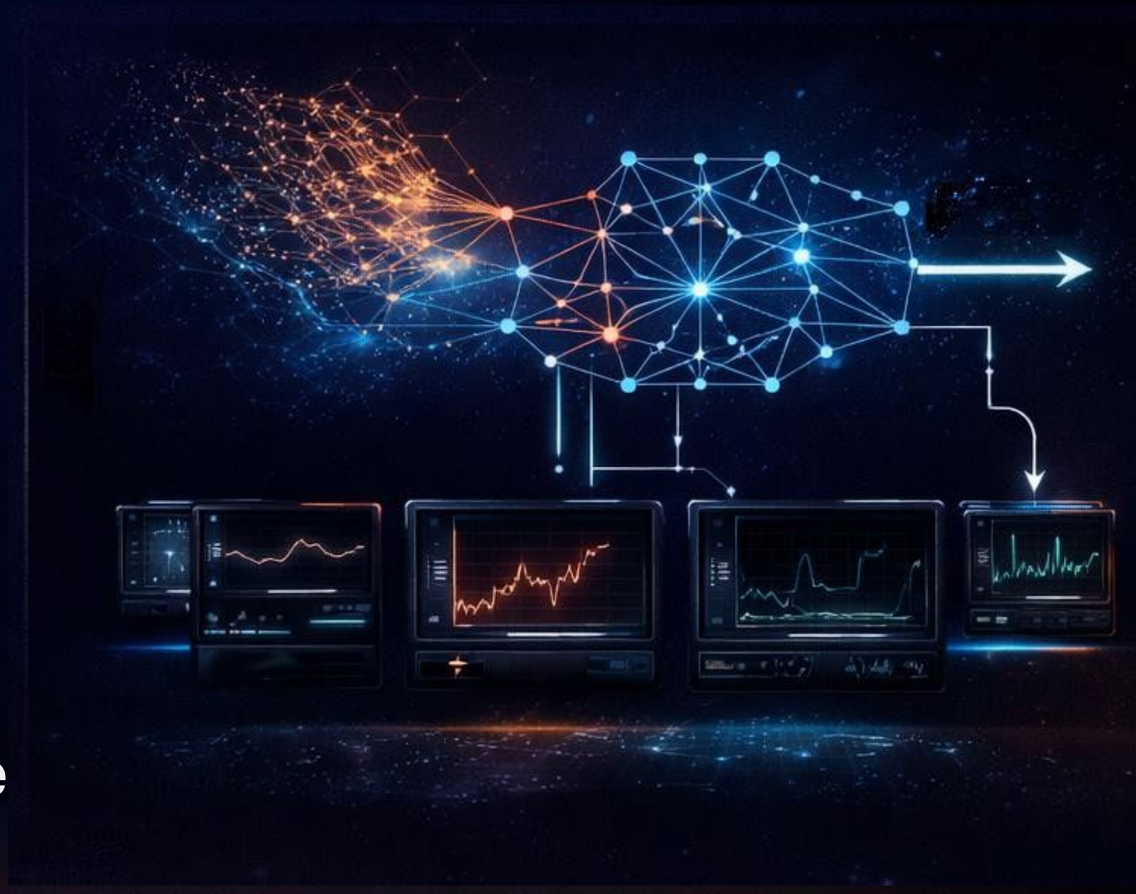
- Temperature
- Aging
- Voltage
- Linear and Gyroscopic Acceleration
- Vibration, Shock
- Air Flow
- Humidity
- Electromagnetic Interference (EMI)
- Radiation – Ionizing, Non-Ionizing
- Relativity

Harrison's H4 chronometer (1753)
National Maritime Museum in Greenwich

5 s / 81 days (7 M s) = 715 ppb

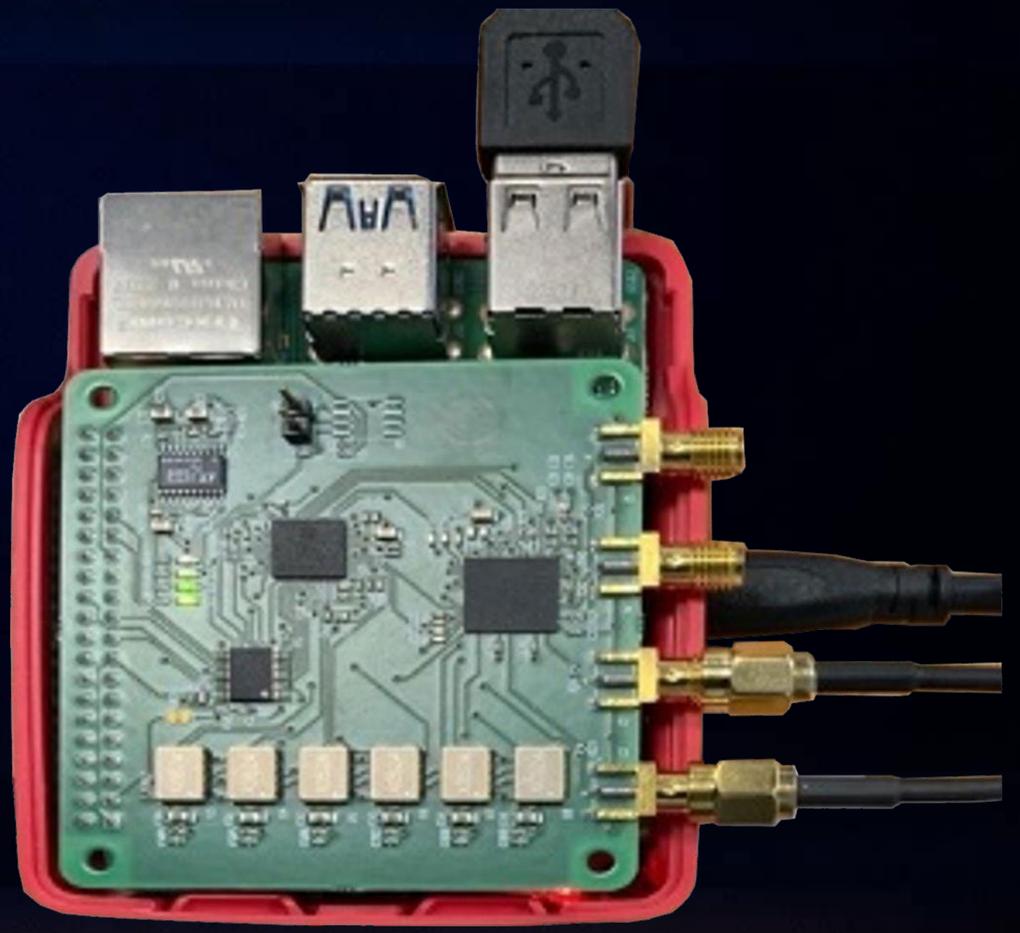
METHODOLOGY: OVERVIEW

- Ensemble alone is not sufficient
- Add:
  - AI/ML-driven sensor fusion
  - Adaptive clock steering algorithms
- Inputs:
  - Temperature
  - Aging characteristics
  - Environmental conditions
- Output:
  - Optimized time estimate in real time



INTELLIGENT CLOCK ENSEMBLE (ICE)

- N=6 Semiconductor MEMS
- Small size, weight and power
- Excellent resilience to Vibration, Shake, Shock



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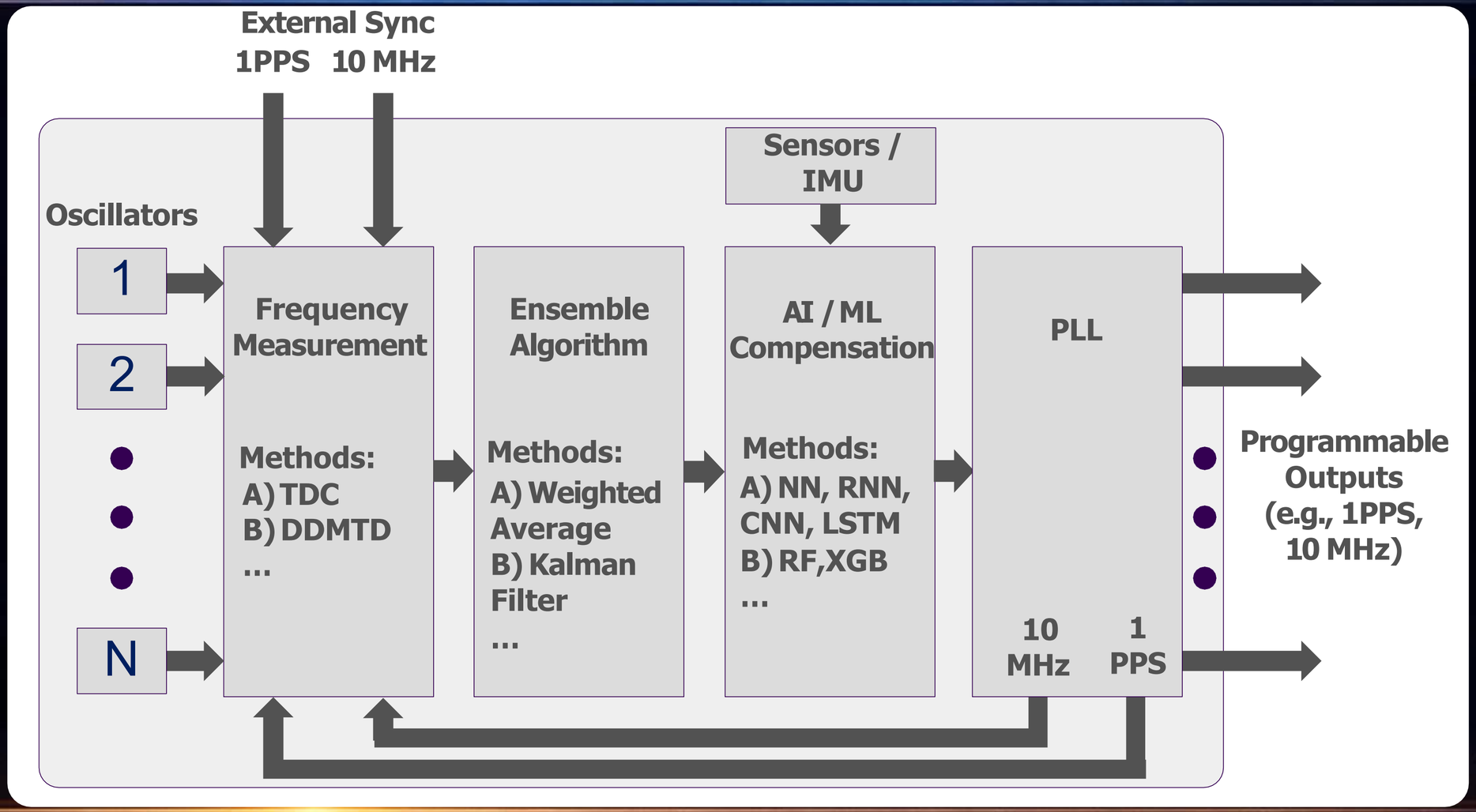
ICE PROCESS DIAGRAM



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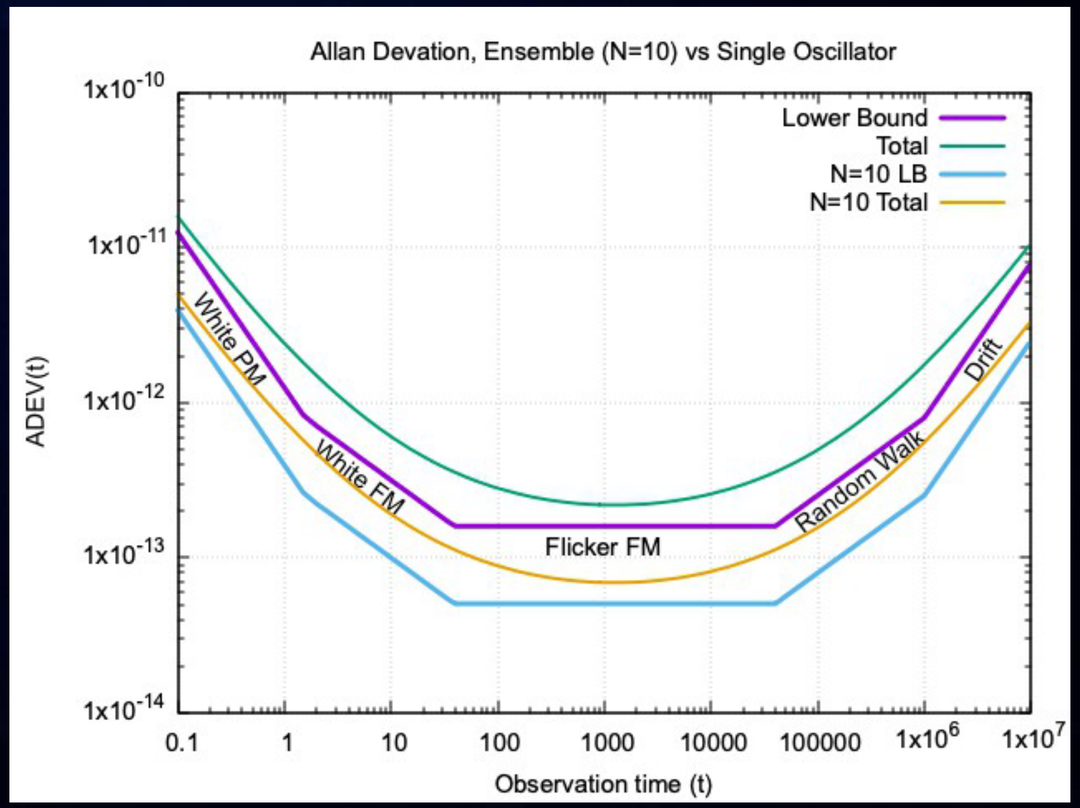
METHODOLOGY: COMPENSATION STRATEGY

- Real-time adaptation via:
  - Temperature-aware modeling
  - Aging compensation
  - Cross-oscillator weighting
- AI/ML learns:
  - Individual oscillator behavior
  - Ensemble-level behavior
  - Environmental response patterns
- Result: **stability maintained under extreme dynamics**

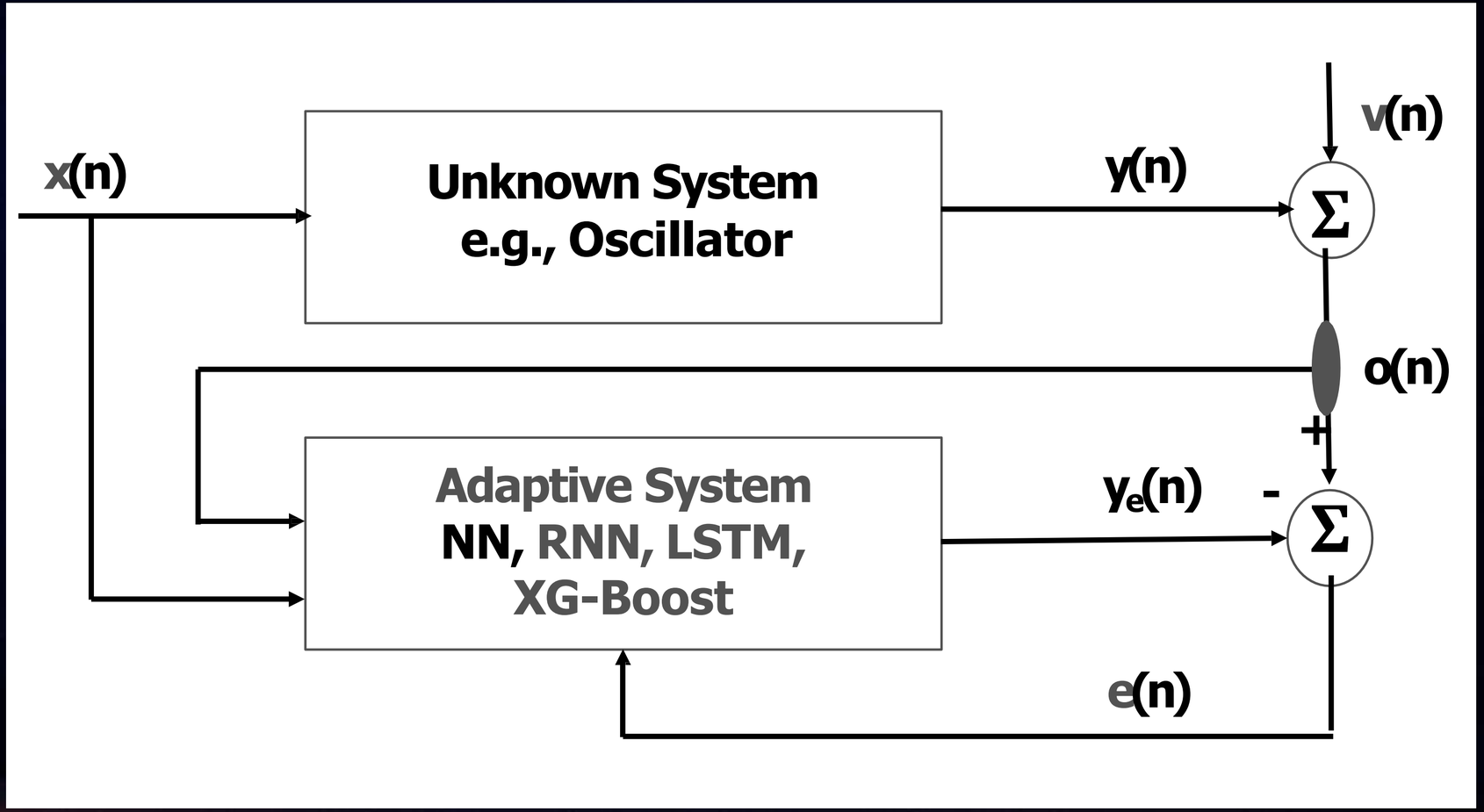
METHODOLOGY: ENSEMBLE

- Clock Ensembles
  - Allan Deviation
    - Ensemble ADEV >= ADEV/Sqrt(N)
    - Various Methods / Performance
      - Averaging versus a chosen clock
      - “AT1”, “AT2”, Kalman Filter
    - Good Oscillator => Excellent



METHODOLOGY: AI / ML IMPROVES HOLDOVER

- System ID
  - Predict System Behavior
  - Train with observed inputs/outputs
  - Minimize estimation error
  - Supervised
  - Adaptive
  - Accuracy & Stability



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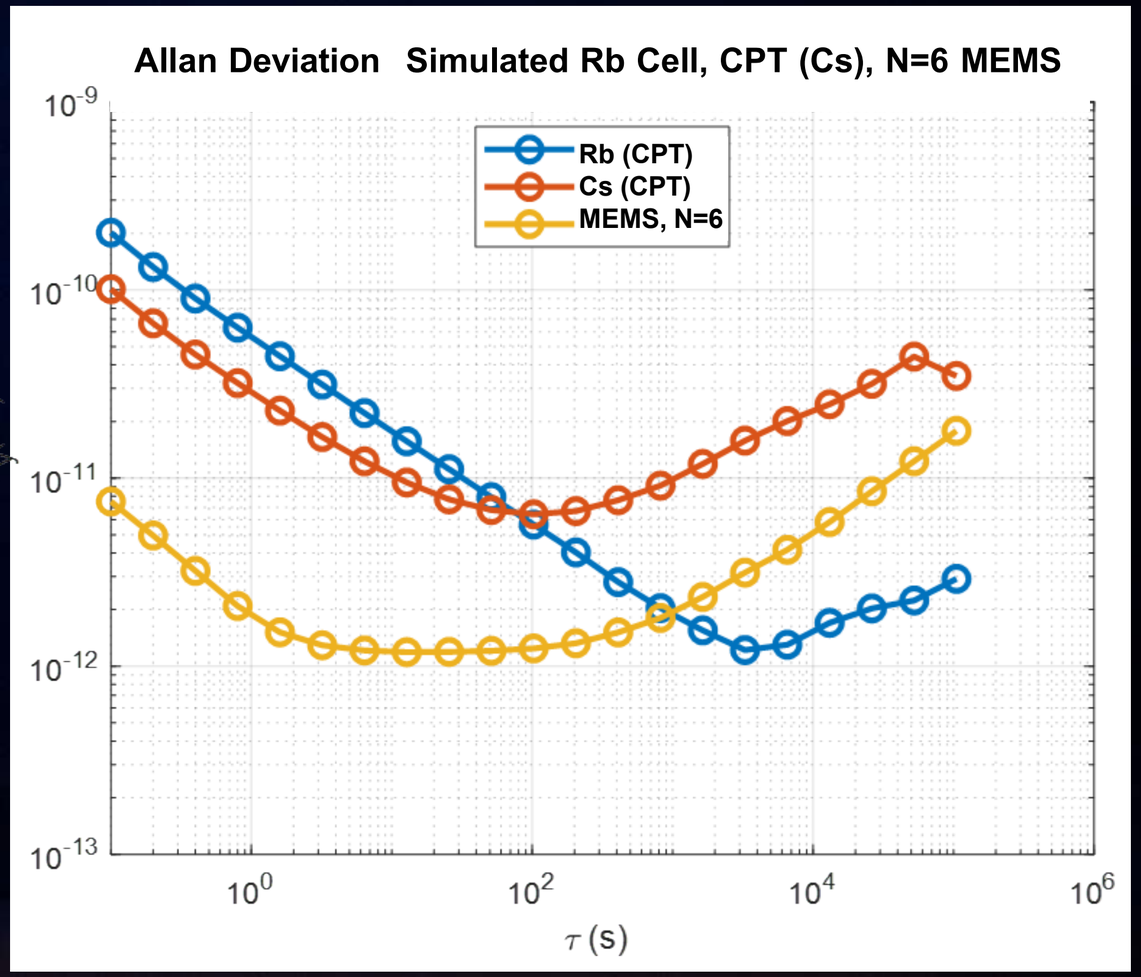
PERFORMANCE: Simulated Clock Ensemble

- Allan Deviation
  - Clock Ensemble
  - N=6 MEMS
  - Small size, excellent resilience to Vibration, Shake, Shock, Unit Failure



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CONCLUSION

- Alt-PNT adoption depends on stable timing
- Ensemble + ML clock advantages:
  - Practical (semiconductor processes)
  - Resilient (dynamic environment, anomalies)
  - Highly stable timing (enhanced holdover)
- Hierarchical mesh network of ensembles
  - Hyper-ensembles => ADEV/sqrt(L*M*N)