Journal Talk Presentation: Optical Atomic Clocks

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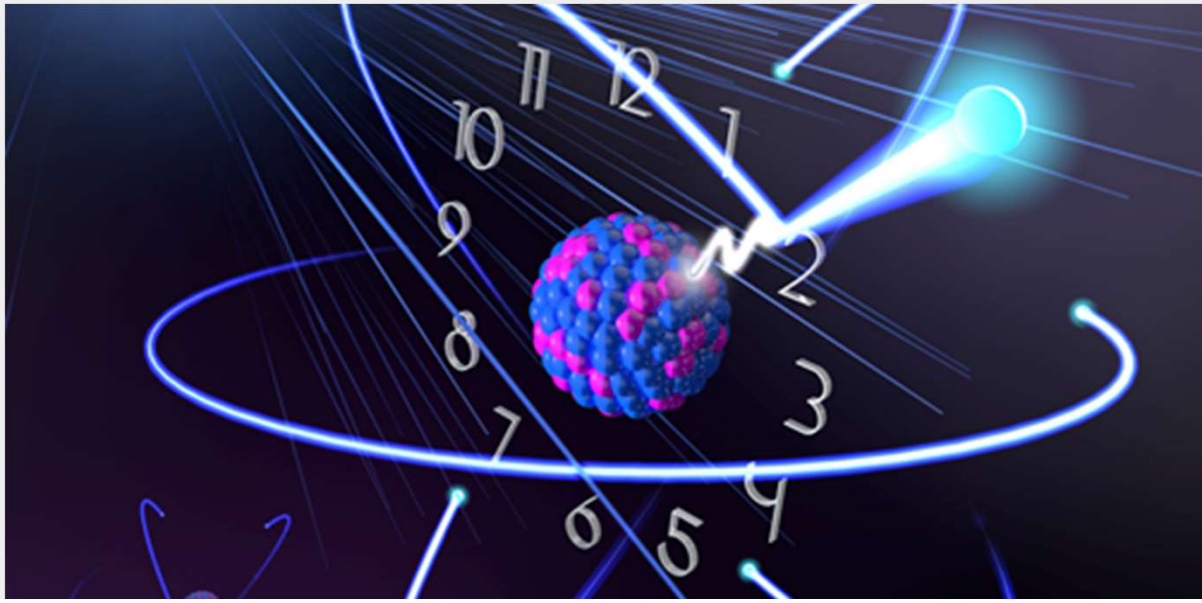
Nichol, B.C., Srinivas, R., Nadlinger, D.P. *et al.* An elementary quantum network of entangled optical atomic clocks. *Nature* 609, 689–694 (2022). https://doi.org/10.1038/s41586-022-05088-z

https://physics.aps.org/articles/v13/152



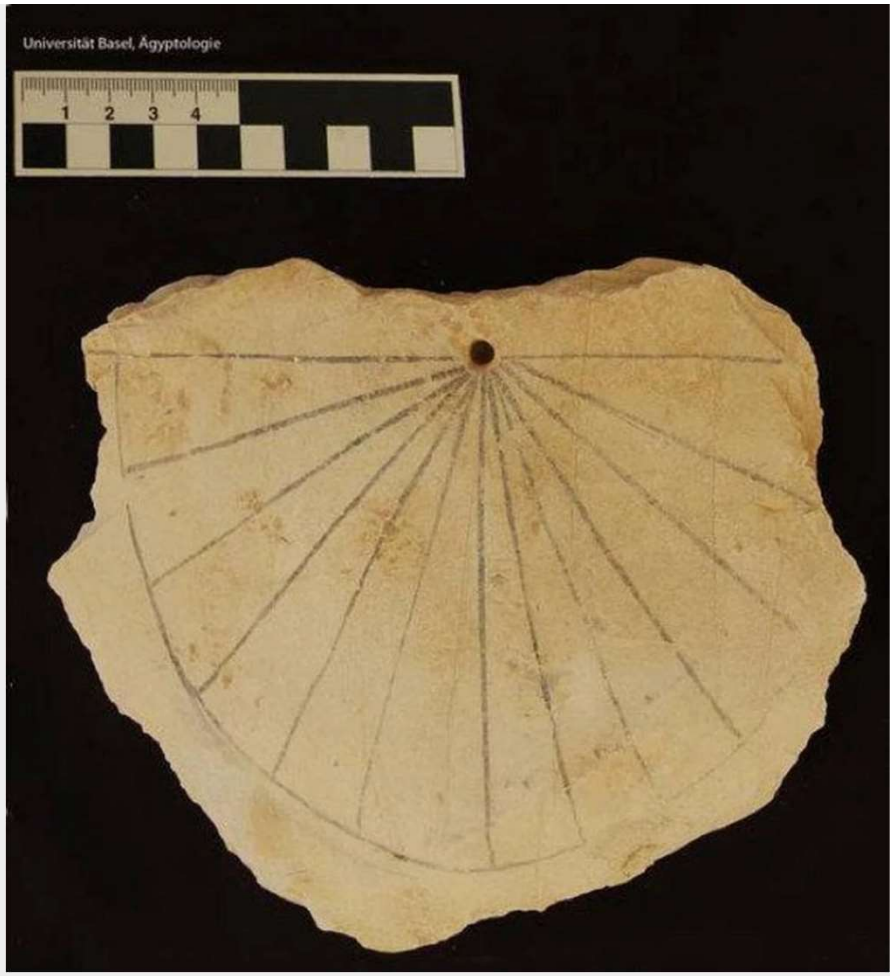
Different Timepieces Throughout History

520: China

996: Europe

1500s: Ancient Egypt

1868: Switzerland



https://www.nbcnews.com/news/all/egyptian-sundial-kept-time-13th-century-b-c-flna1c8979354

History; Goal of Paper; Experimental Setup; Results and Conclusions; Citation Evaluation; Evolution of the Field; Unexplored Problems/Key Points

Using Atomic Vibrations to Help Tell Time

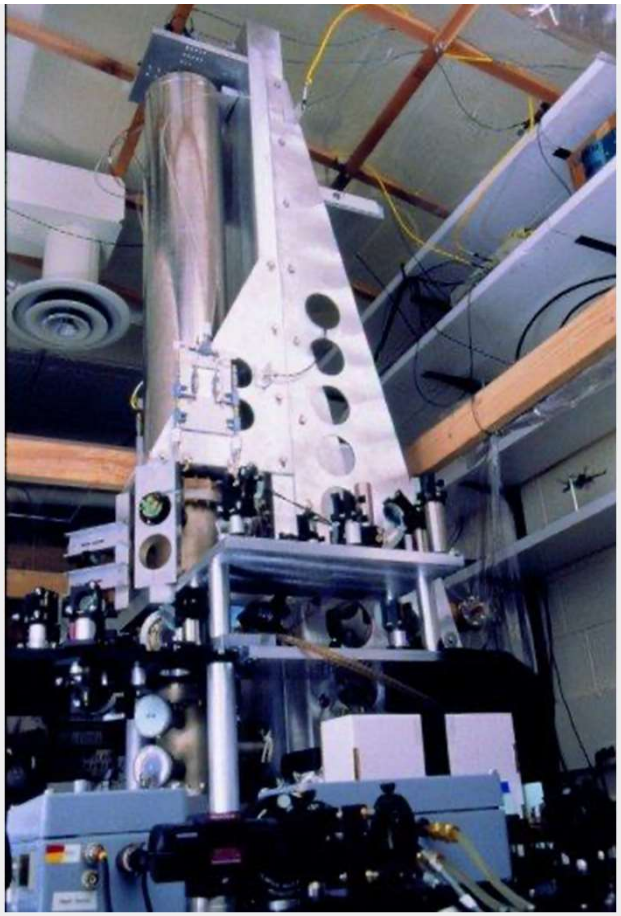
1949: First Atomic Clock

1955: First Cesium Clock

1968: Defining a Second

1999: NIST-F1

In recent years and varying atomic clocks…



https://www.nist.gov/pml/time-and-frequency-division/time-services/brief-history-atomic-clocks-nist

Previous Work Comparison

- Entanglement for the purposes of enhanced detection has been done for 20+ years.
  - Meyer, V. et al. Experimental demonstration of entanglement-enhanced rotation angle estimation using trapped ions. *Phys. Rev. Lett.* 86, 5870–5873 (2001).

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- First **macroscopic** entanglement of clocks.
  - Entanglement in general is what gives advantage to quantum systems to perform certain tasks better than classical systems (e.g. quantum computing).

Slide 6

1 Use animations to break up this slide, bring in each bullet point in separately.
Keshav Kapoor, 11/17/2022

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- First **macroscopic** entanglement of clocks.
  - Entanglement in general is what gives advantage to quantum systems to perform certain tasks better than classical systems (e.g. quantum computing).
  - Entanglement also has great applications in metrology (e.g. perturbations to the GHZ state, W state, etc).

Slide 7

2 Use animations to break up this slide, bring in each bullet point in separately.
Keshav Kapoor, 11/17/2022

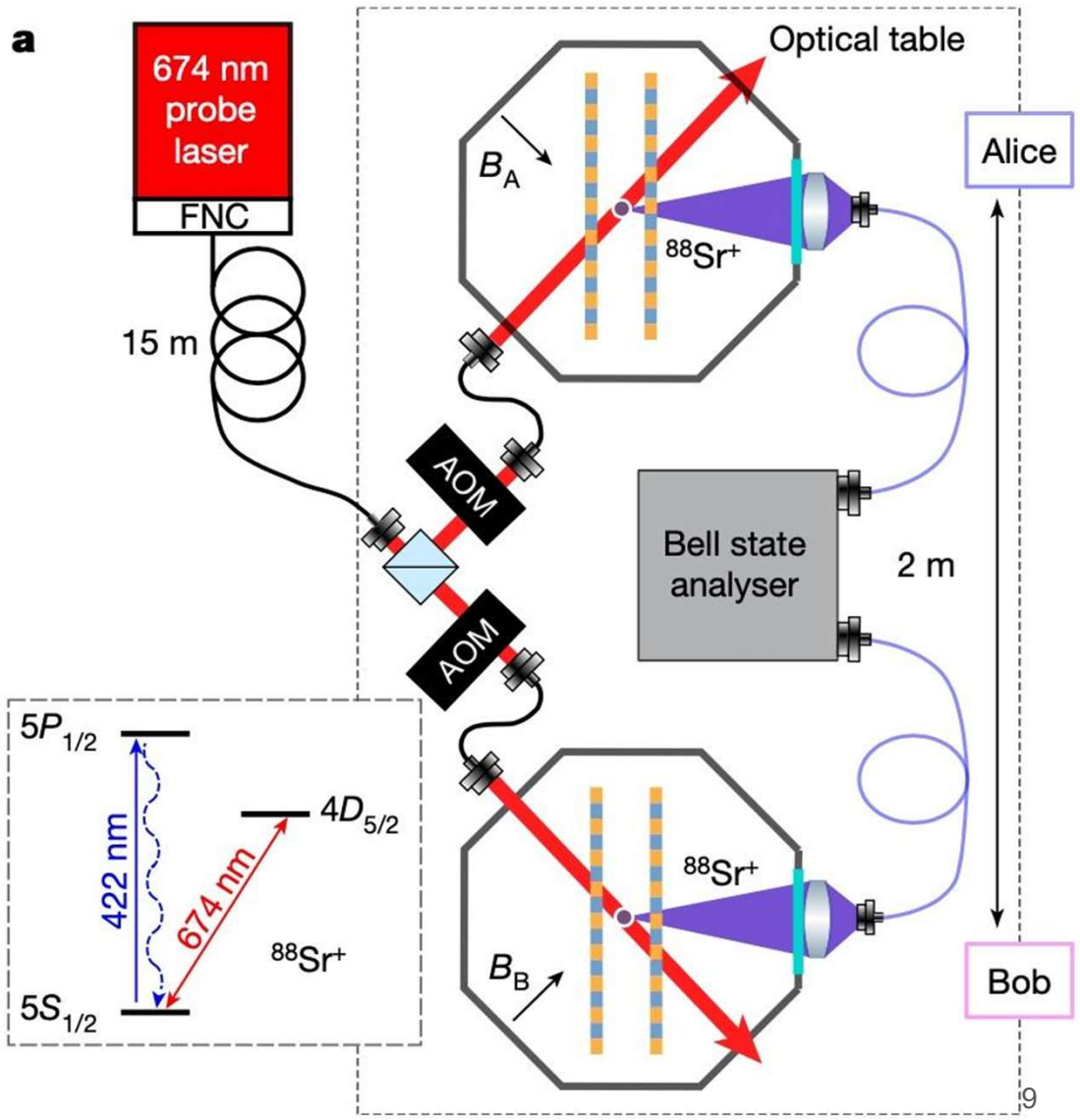
The Goal of the Paper is to Improve the Optical Clocks

https://www.sciencephoto.com/media/222718/view/strontium-optical-clock

Experimental Setup

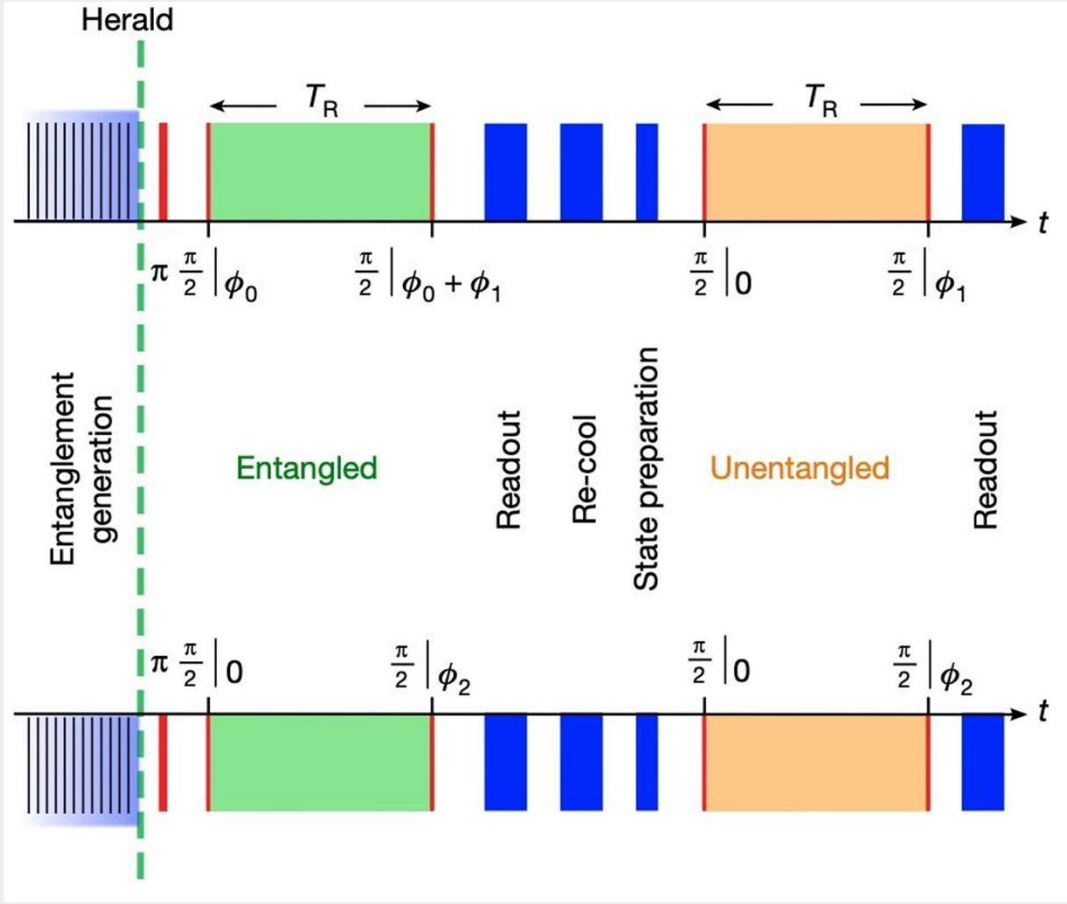
AOM- Acousto-optic Modulator

FNC- Fiber Noise Cancellation



The Experimental Process

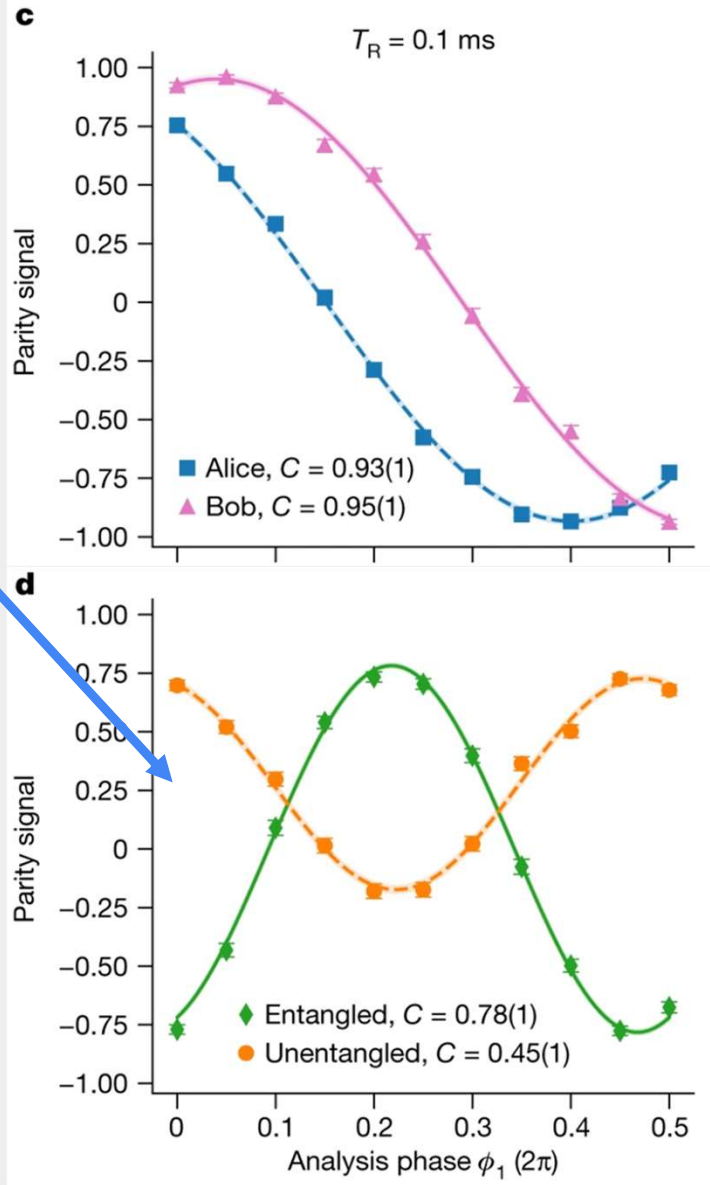
Process runs from left to right



Entanglement Doubles Parity Signal Contrast

Contrast worsens for correlated measurements:

- imperfect entangled state generation
- magnetic field noise



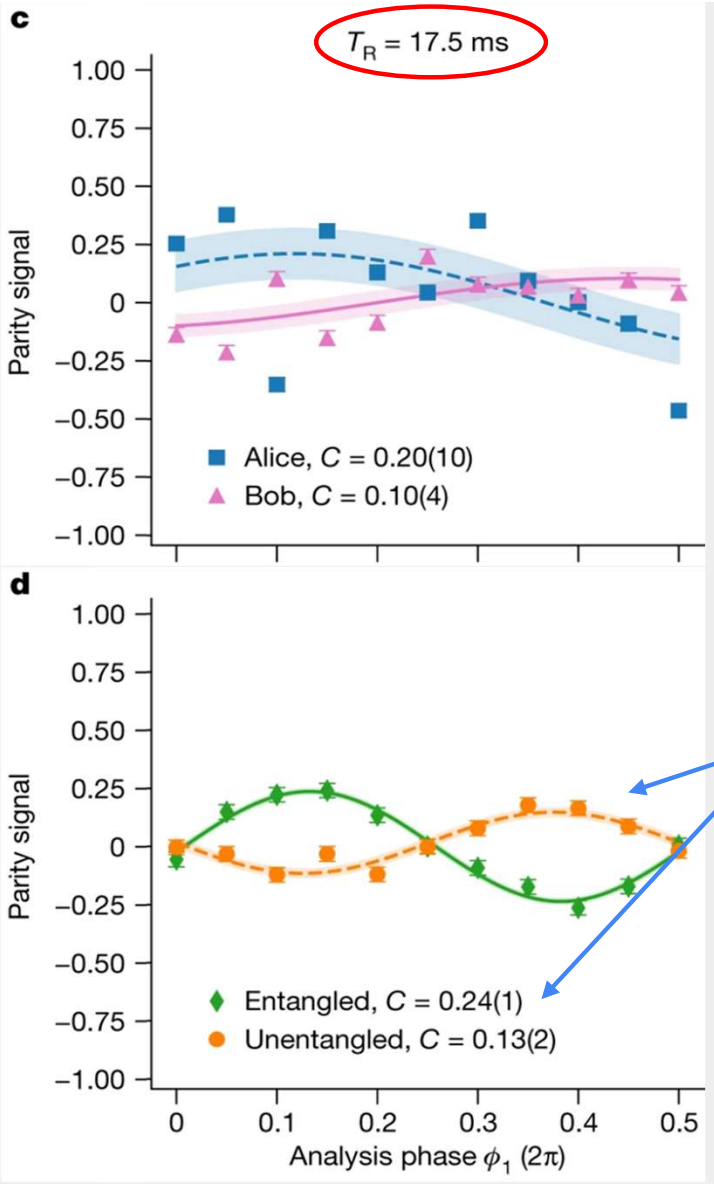
Independent single-ion measurements

Reduction in Parity Contrast

Correlated two-ion measurements

Reduced Contrast at Longer Durations

All signals reduced:
qubit decoherence from magnetic field fluctuations

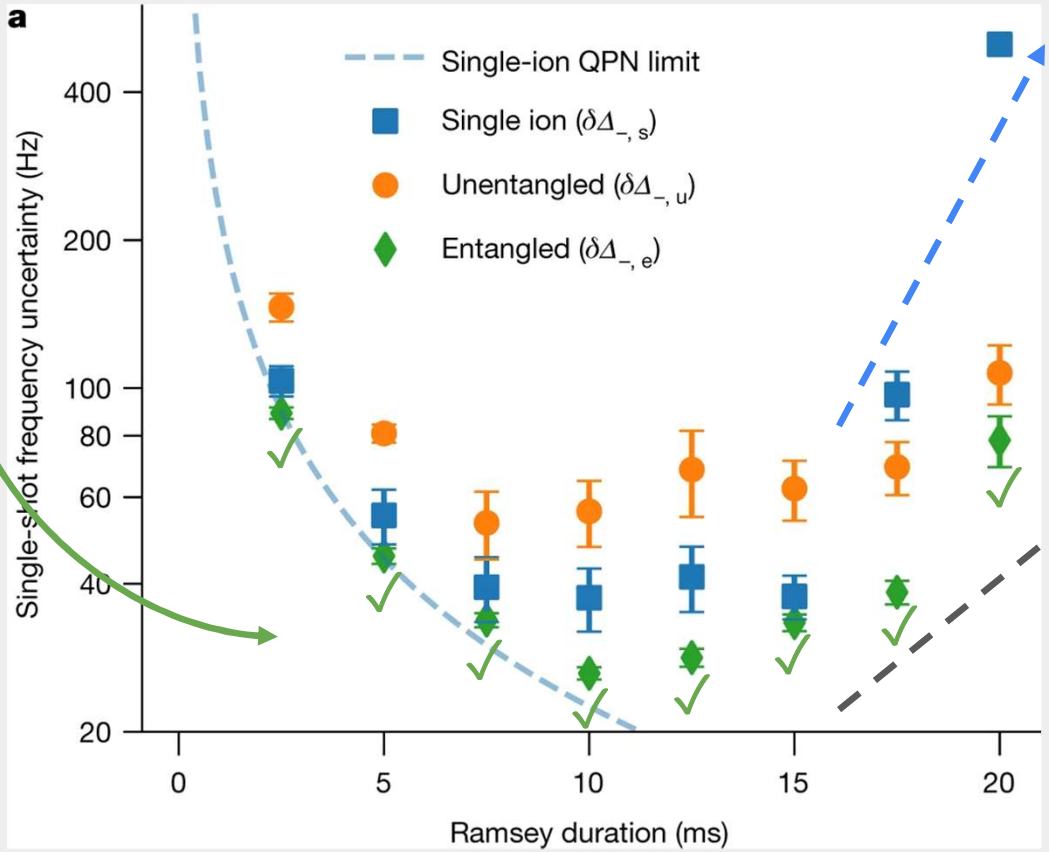


Sensitive to common mode laser phase noise

Entanglement enhancement still evident

Entangled State Yields Lowest Frequency Uncertainty

- Δ_- is frequency difference between the two clocks
- $\delta\Delta_-$ is uncertainty on Δ_-



Laser dephasing

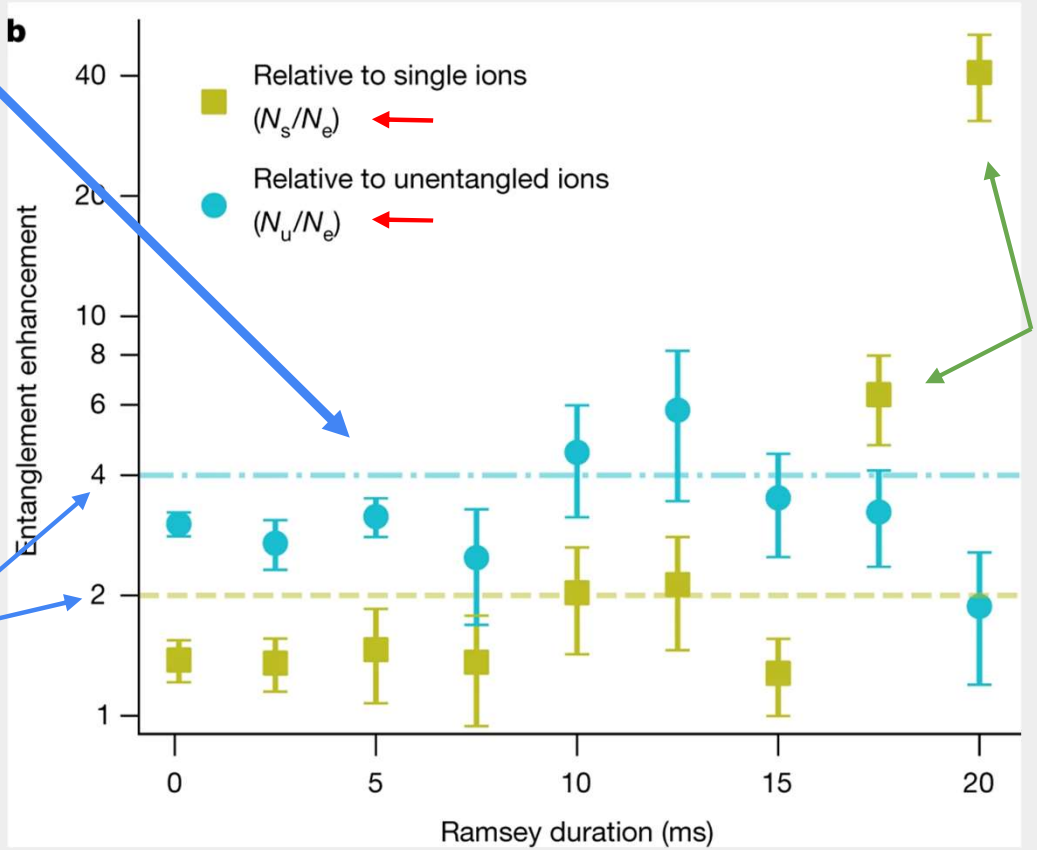
Reduction in parity contrast

Observed Enhancement Close to Theoretical Value

$N_{s|u|e}$: number of measurements required to reach a given precision

$\sigma = \delta\Delta\_ / \sqrt{N}$

Theoretical enhancement



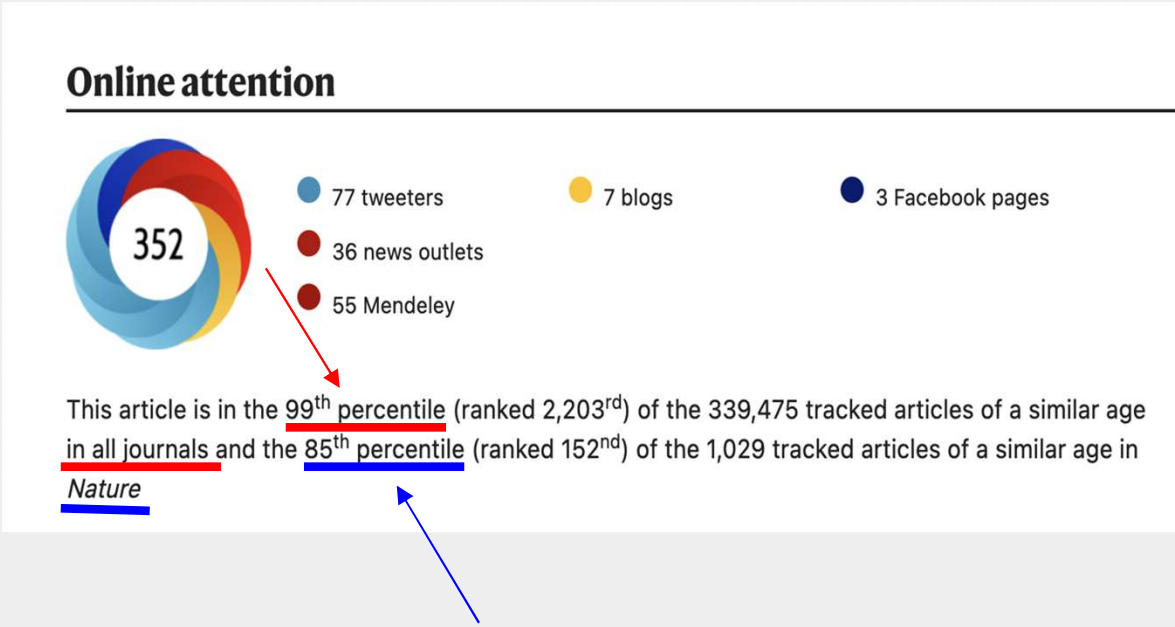
Large uncertainty for single-ions at long durations

Citation Evaluation

- Hard to make a detailed evaluation as the paper is quite young.
- 8 citations on Google Scholar
- No citation information (yet) on other major databases such as SCOPUS.

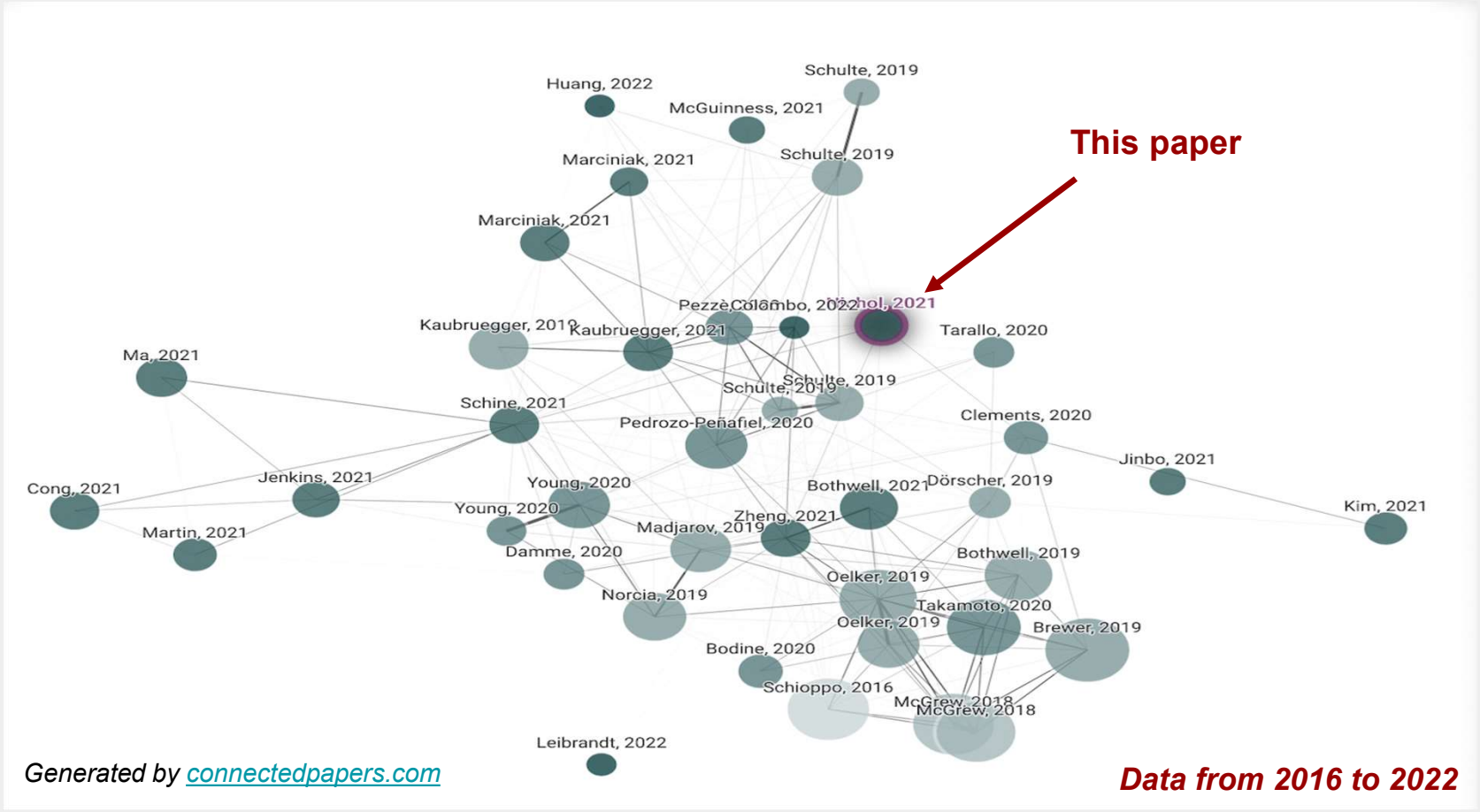
Citation Evaluation

- Considerable online attention received…
  - 99th percentile among all articles of similar age[1]
  - 85th percentile among all ***Nature*** articles of similar age[1]



1. Source to the metric employed: https://www.nature.com/articles/s41586-022-05088-z/metrics

Citation Evaluation – Map of Connected Papers



Evolution of the Field

- Results will have direct impact on multiple subfields:
  - Metrology
  - Quantum Computation
  - Cryptography
  - Fundamental Theory
  - …
- Schine et al. announced long-lived Bell states in an array of optical-clock-qubits (just published in Nature)[1] – quantum metrology

1. https://www.nature.com/articles/s41567-022-01678-w

Evolution of the Field

- Krutyanskiy et al. reported the entanglement of trapped ion qubits separated by 230 (!) meters[1]– quantum information/network theory:
  - Also mentioned the importance of this work in the context of enhanced timekeeping.

- Follow-up study in which a long-lived quantum memory is integrated into the network discussed in this paper[2]:
  - Great news… But still not good enough for practical purposes.

- Malia et al. also made progress in robust quantum communication techniques using a mode-entangled network and spin-squeezed states[3]

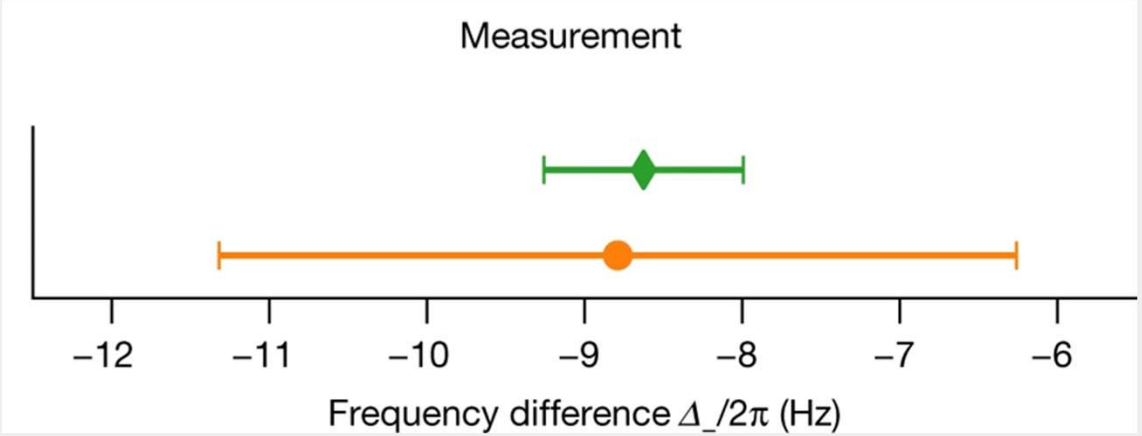
1. https://arxiv.org/pdf/2208.14907.pdf
2. https://arxiv.org/abs/2210.11447
3. https://arxiv.org/abs/2205.06382

Unexplored Problems

- This is a massive accomplishment, but there are areas which need to be explored to make it a more viable for future applications.
  - Longer distance!
  - Noise reduction through isolation of magnetic and electric fields.
  - Use a transition that is magnetic field agnostic.

Key Points

- The main point of this paper is the demonstration of macroscopically remote entanglement.
  - Map entanglement onto a long lived state after preparation through a bell state measurement of light.
  - Demonstrate the improvement in visibility performance of the entangled system vs. unentangled system.
    - 4 times lower uncertainty!



Overview

Different timepieces throughout history

Experimental setup and process

Analysis of double parity signal contrast and reduction of contrast att long durations

Entanglement state uncertainty<unentangled state uncertainty

Enhancement is close to theoretical value

Citation Evaluation

Evolution of the Field

Unexplored Problems

Key points of the Paper