Title: A quantum network of clocks

Date: Jun 17, 2014 04:00 PM

URL: http://pirsa.org/14060021

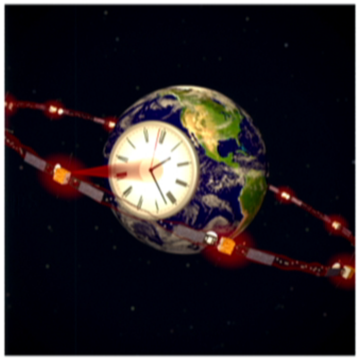
Abstract: By combining precision metrology and quantum networks, we describe a quantum, cooperative protocol for the operation of a network consisting of geographically remote optical atomic clocks. Using non-local entangled states, we demonstrate an optimal utilization of the global network resources, and show that such a network can be operated near the fundamental limit set by quantum theory yielding an ultra-precise clock signal. Besides serving as a real-time clock for the international time scale, the proposed quantum network also represents a large-scale quantum sensor that can be used to probe the fundamen- tal laws of physics, including relativity and connections between space-time and quantum physics. Prospects for realization of such networks will be discussed.

Quantum sensor networks

Mikhail Lukin

Physics Department, Harvard University

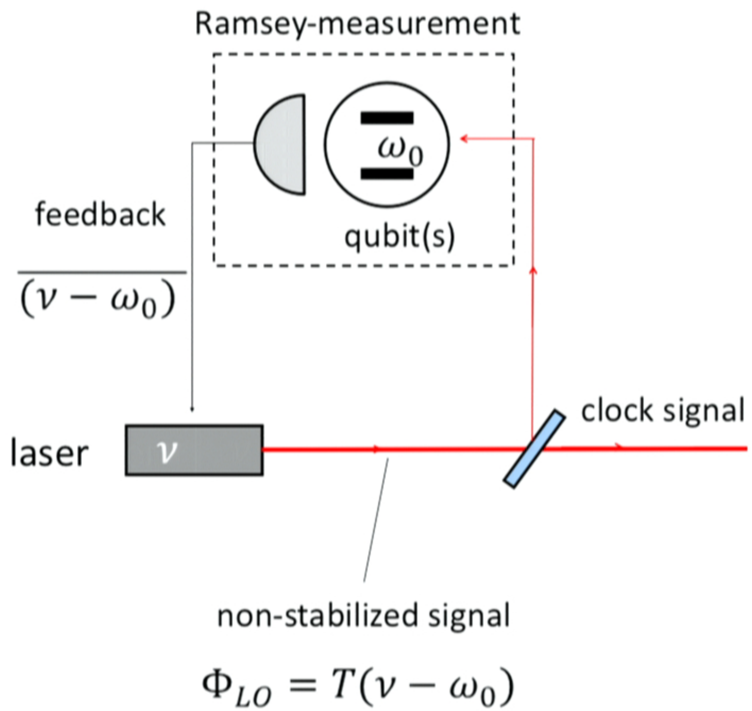
Quantum clock networks:
P. Komar, E.Kessler (Harvard)
M.Bishof (JILA), L.Jiang(Yale), A. Sorensen (NBI)
collaboration with Jun Ye's and Vladan Vuletic's groups
Ideas for dark energy detection:
collaboration with Chris Stubbs

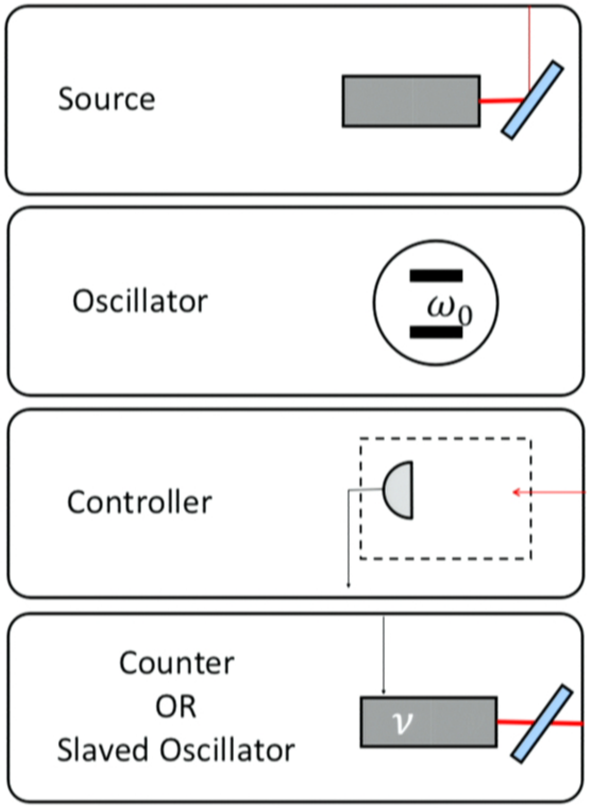


This talk

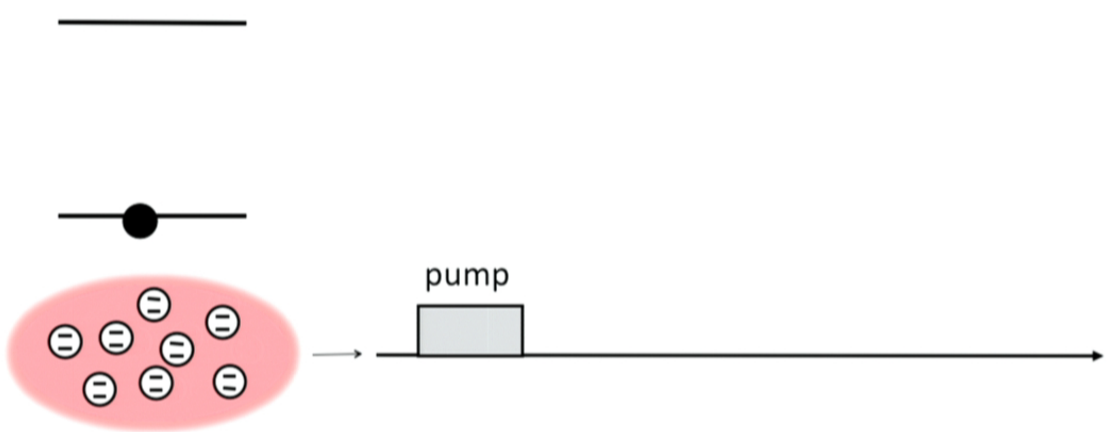
- Introduction: quantum metrology & networks
- Quantum clock networks
  - Idea & feasibility
  - Applications to non-local precision measurement?
- Quantum measurements of fast processes
  - Idea & possible application to dark matter/energy detection?

Atomic clocks





Ramsey measurement



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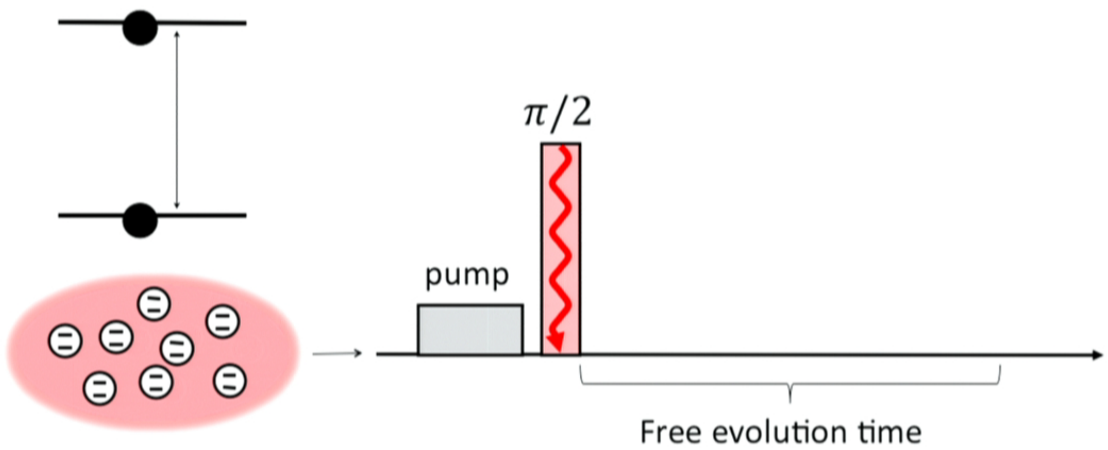

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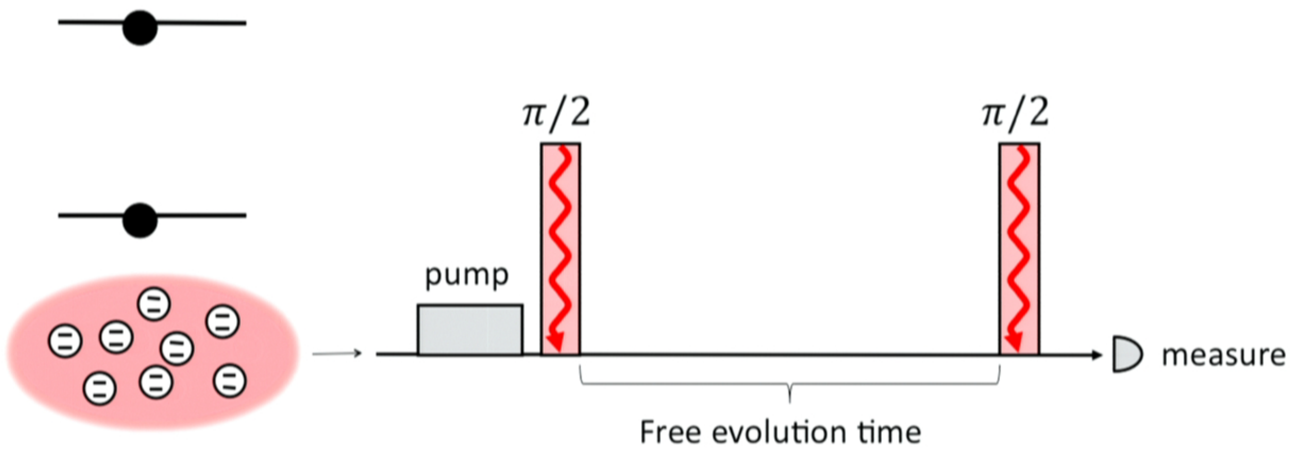

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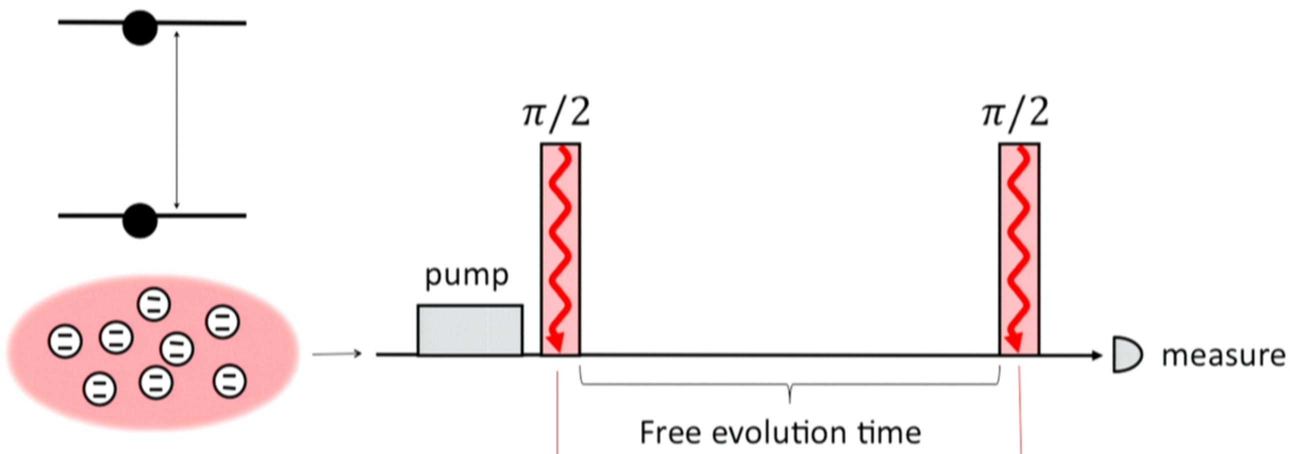
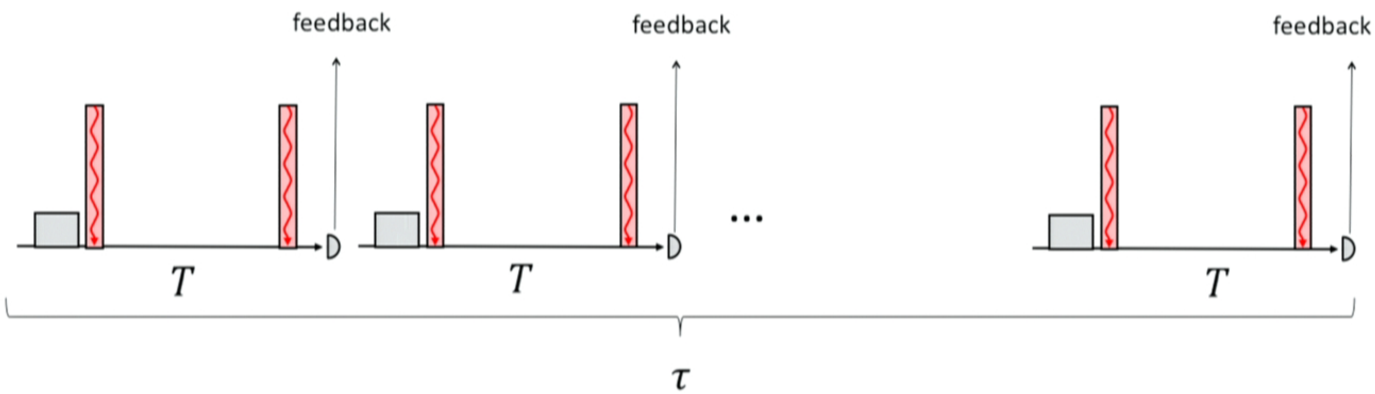


$$\Phi^{(0)}_{\text{laser}} \equiv 0 \xrightarrow{\quad T \quad} \Phi_{\text{laser}} = T(\nu - \omega_0)$$

Phase estimation uncertainty ($\Delta\Phi_{\text{laser}}$) ⟶ Frequency/time uncertainty (Allan deviation)

Long term precision



Allan deviation:

$$\sigma_y(\tau) \approx \frac{1}{\omega_0\sqrt{\tau T}}[\Delta\Phi_{\mathrm{LO}}(T)]$$

Uncertainty of estimation

Quantum limits for phase estimation

Uncorrelated state	Entangled (GHZ or cat) state
$(\vert 0\rangle + \vert 1\rangle)^N$	$\vert 0\rangle^N + \vert 1\rangle^N$
Free evolution	Free evolution
$\left(\vert 0\rangle + e^{i\nu T}\vert 1\rangle\right)^N$	$\vert 0\rangle^N + e^{iN\nu T}\vert 1\rangle^N$

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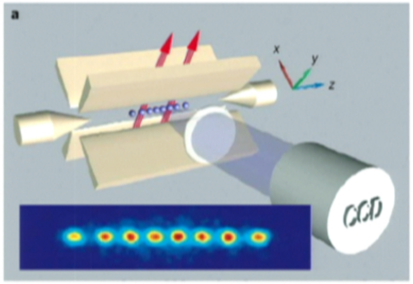
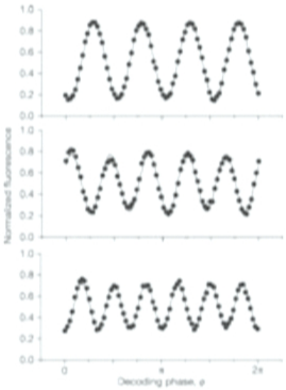
Free evolution	Free evolution
$\left(\|0\rangle + e^{i\nu T}\|1\rangle\right)^N$	$\|0\rangle^N + e^{iN\nu T}\|1\rangle^N$
$\Delta\nu \sim 1/\sqrt{N}$	$\Delta(N\nu) \sim 1$
Time uncertainty: $\sim \frac{1}{\sqrt{N}}$	Time uncertainty: $\sim \frac{1}{N}$
(Standard quantum limit)	(Heisenberg limit)

Experimental progress

Entanglement in few (3-10) ion clocks
Dave Wineland, Rainer Blatt





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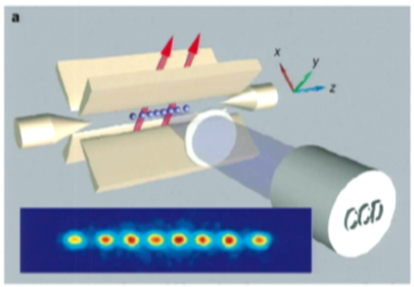
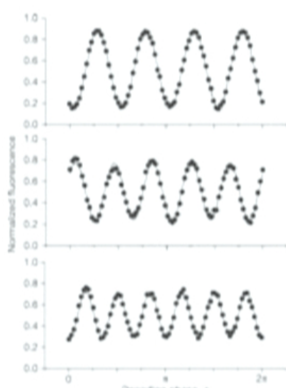
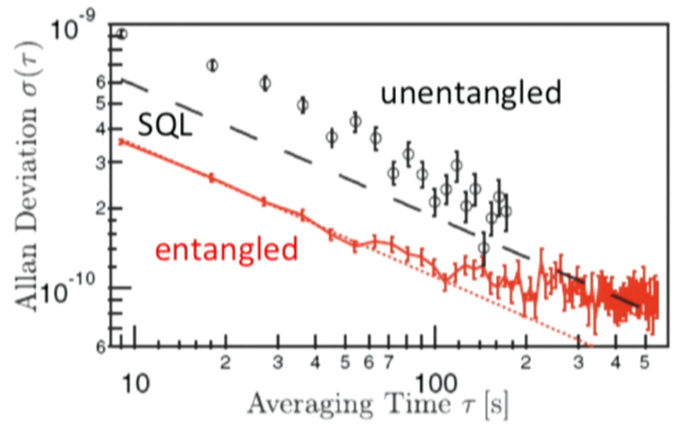
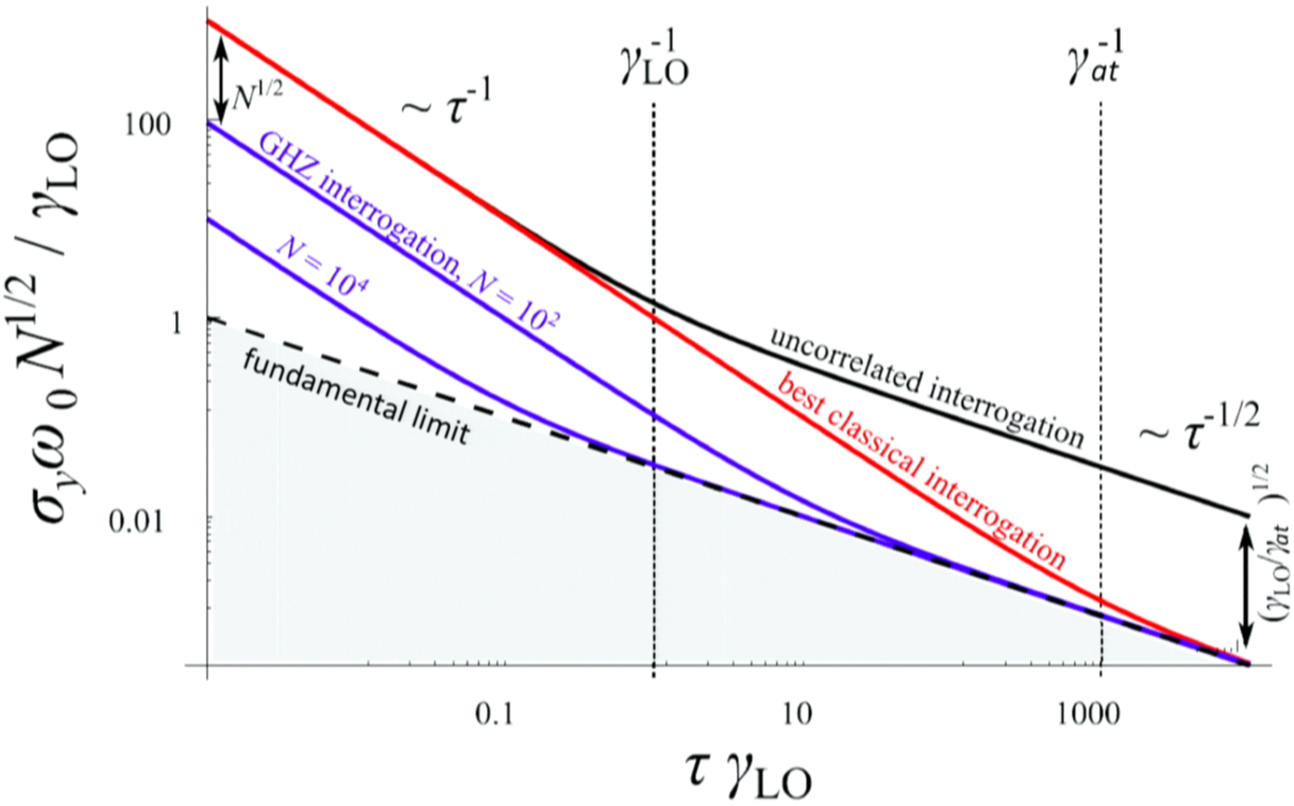




Entanglement in MW atomic clocks
(“spin squeezed” states)
Vladan Vuletic (MIT), Eugene Polzik (NBI)



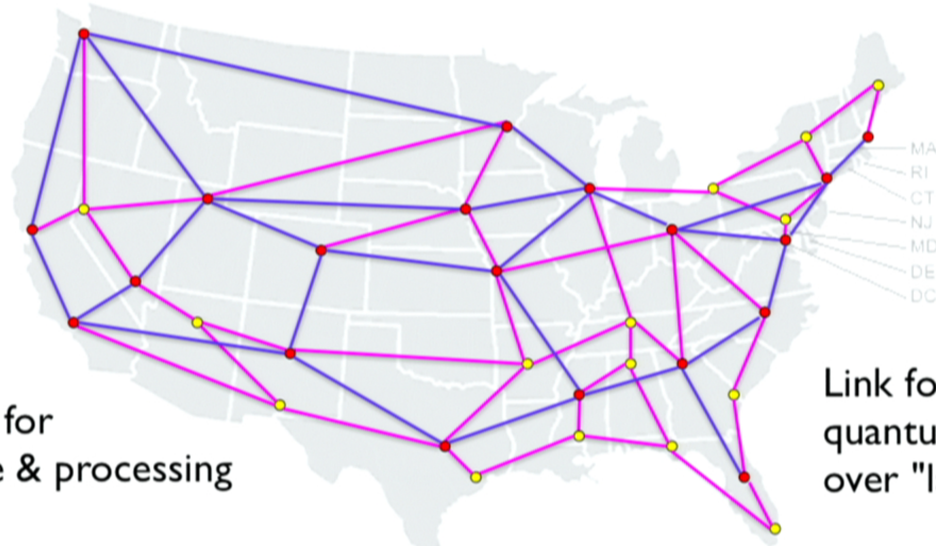
Heisenberg limit for atomic clocks



Quantum networks

✓Realization of quantum networks ...

.. is essential for long-distance quantum communication



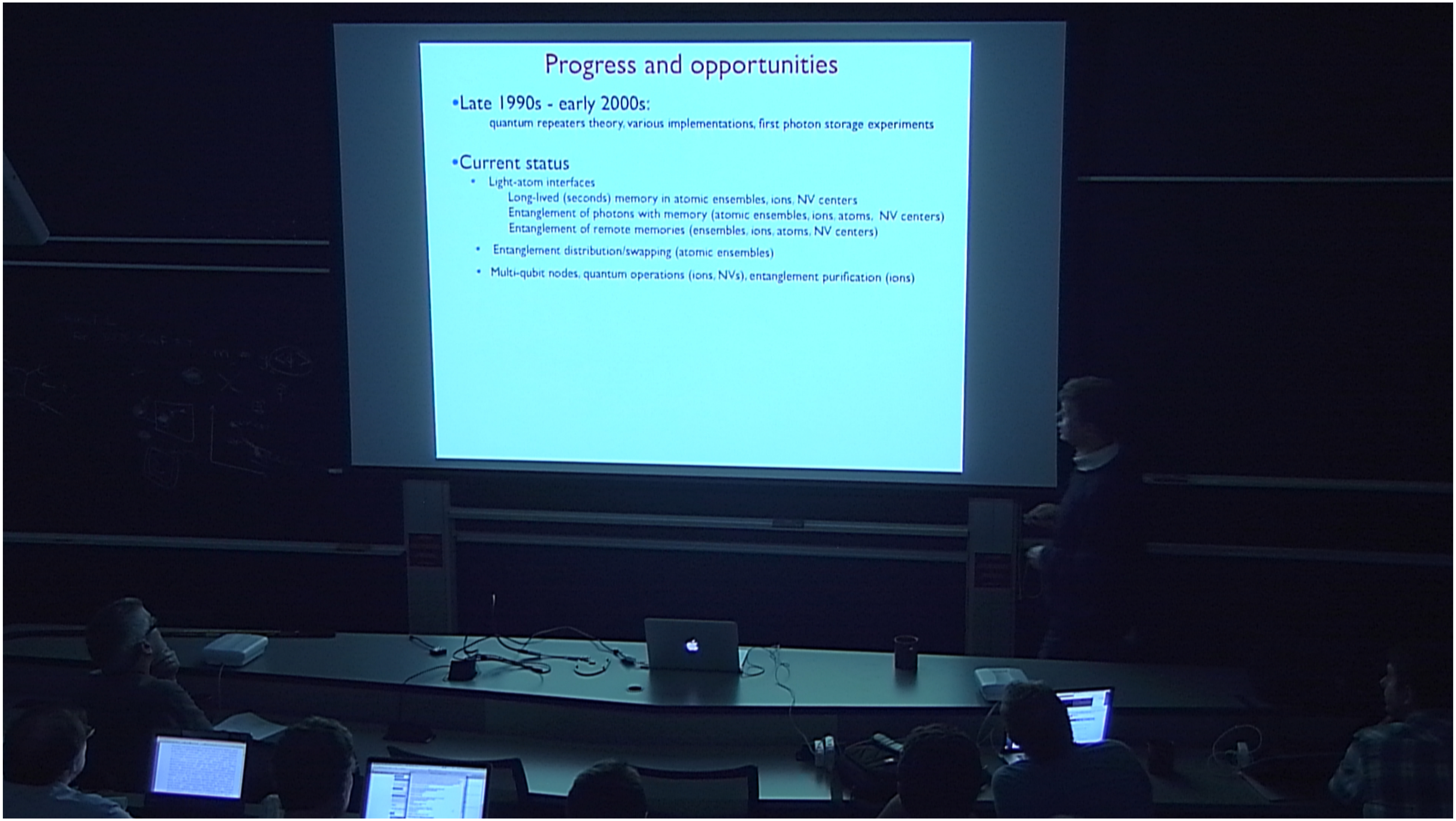
Nodes for storage & processing

Link for transmission of quantum states over "large" distances

Progress and opportunities

- Late 1990s - early 2000s:

  quantum repeaters theory, various implementations, first photon storage experiments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•Current status
• Light-atom interfaces
Long-lived (seconds) memory in atomic ensembles, ions, NV centers
Entanglement of photons with memory (atomic ensembles, ions, atoms, NV centers)
Entanglement of remote memories (ensembles, ions, atoms, NV centers)
• Entanglement distribution/swapping (atomic ensembles)
• Multi-qubit nodes, quantum operations (ions, NVs), entanglement purification (ions)

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  Active interdisciplinary efforts addressing this challenge:
  can be one of the first applications of small quantum processors

Integrating cold atoms with nano-photonic systems

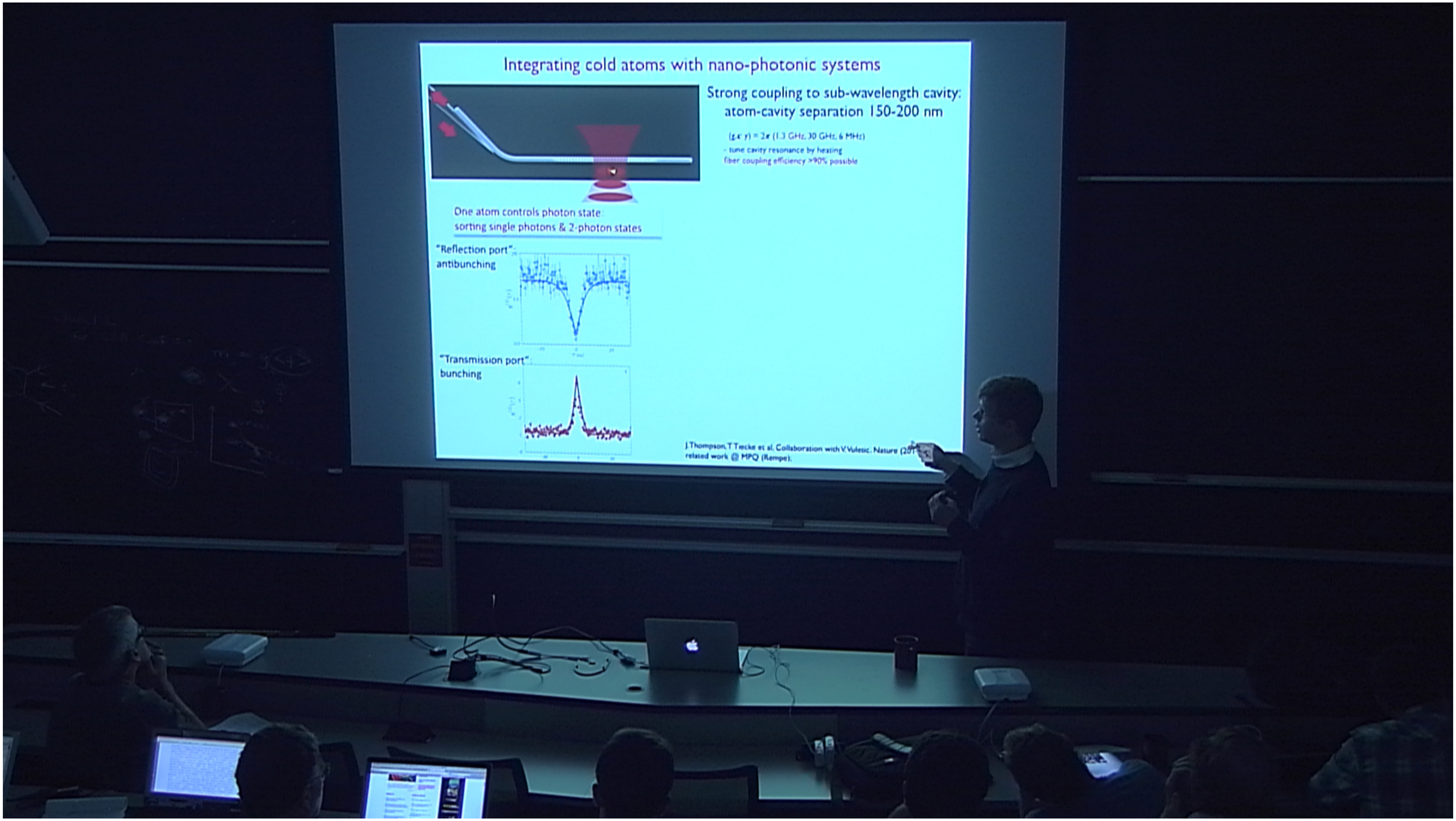
Strong coupling to sub-wavelength cavity: atom-cavity separation 150-200 nm

$(g, \kappa, \gamma) = 2\pi$ (1.3 GHz, 30 GHz, 6 MHz)

- tune cavity resonance by heating

fiber coupling efficiency >90% possible

J. Thompson, T Tiecke et al, Collaboration with V. Vuletic, Nature (2014)
related work @ MPQ (Rempe);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One atom controls photon state:
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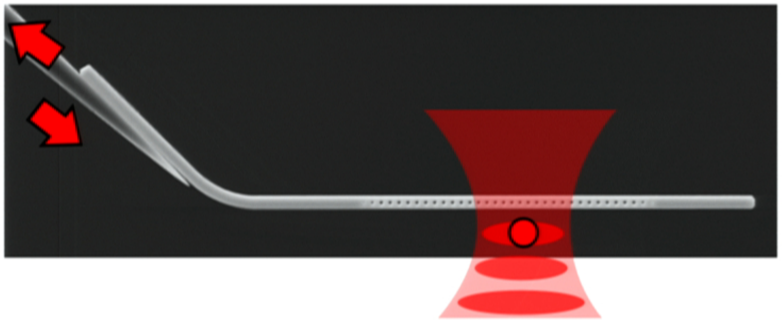

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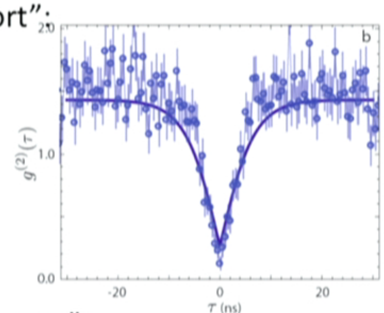
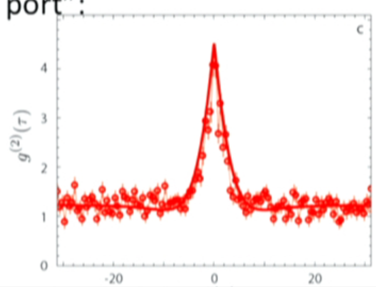
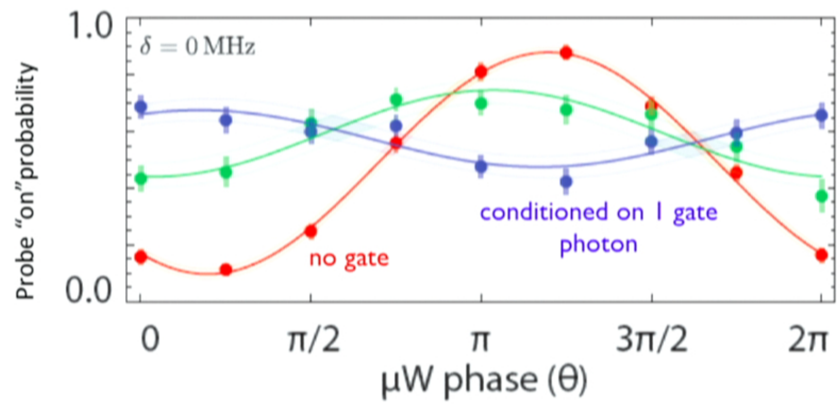


"Transmission port": bunching



One photon controls the phase of the atom



Fundamental blocks of quantum network
Tool for short distance force measurements?

J.Thompson, T.Tiecke et al, Collaboration with V. Vuletic, Nature (2014)
related work @ MPQ (Rempe);

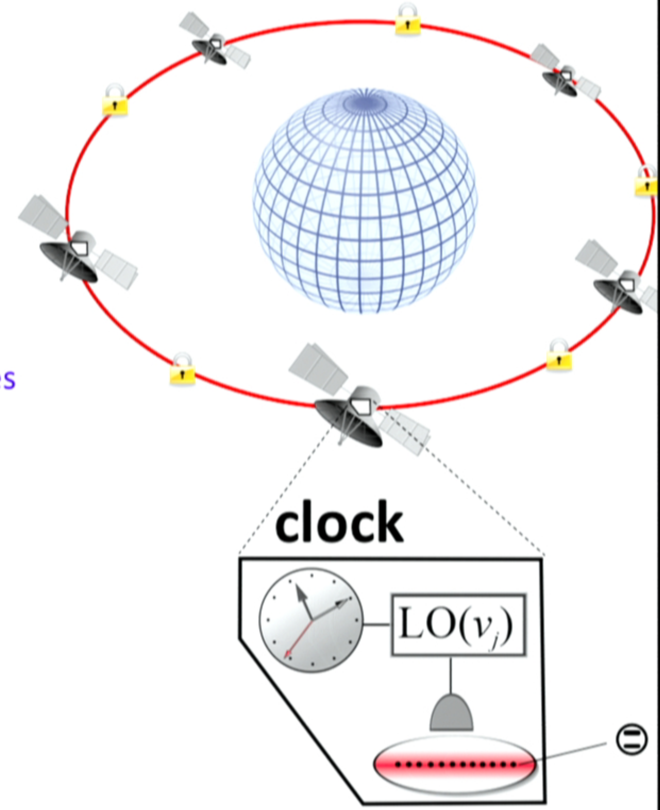
Quantum network of clocks: the idea

Approach:

Entangle atoms in multiple clocks

$$|00\ldots0\rangle + e^{i\underbrace{\sum N_j(\nu_j-\omega_{at})T}_{\Phi}}|11\ldots1\rangle$$

can be done via quantum network/repeater techniques



P. Komar, E. Kessler et al (2014)
collaboration with Jun Ye, Vladan Vuletic

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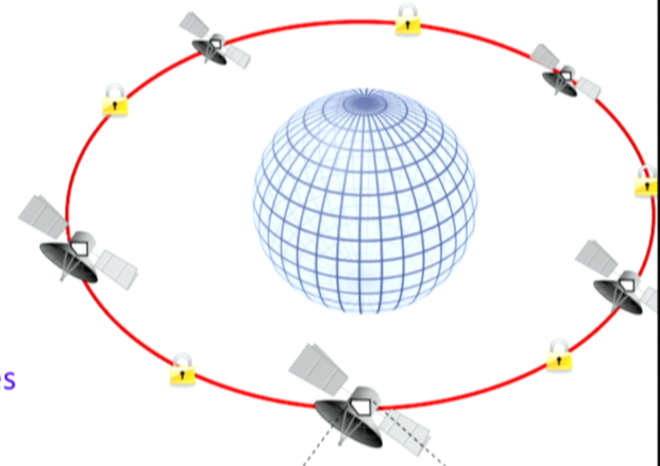

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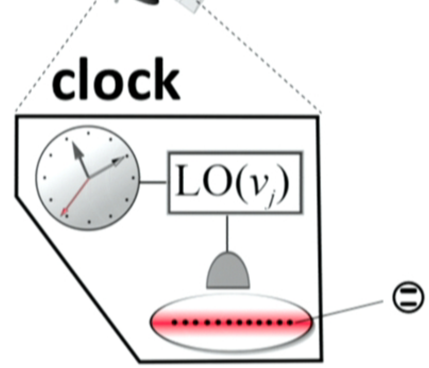
Goals:

- Maximize clock stability, use all resources optimally
- Secure, quantum-protected network
- Strongly incentivizes collaboration between different nations



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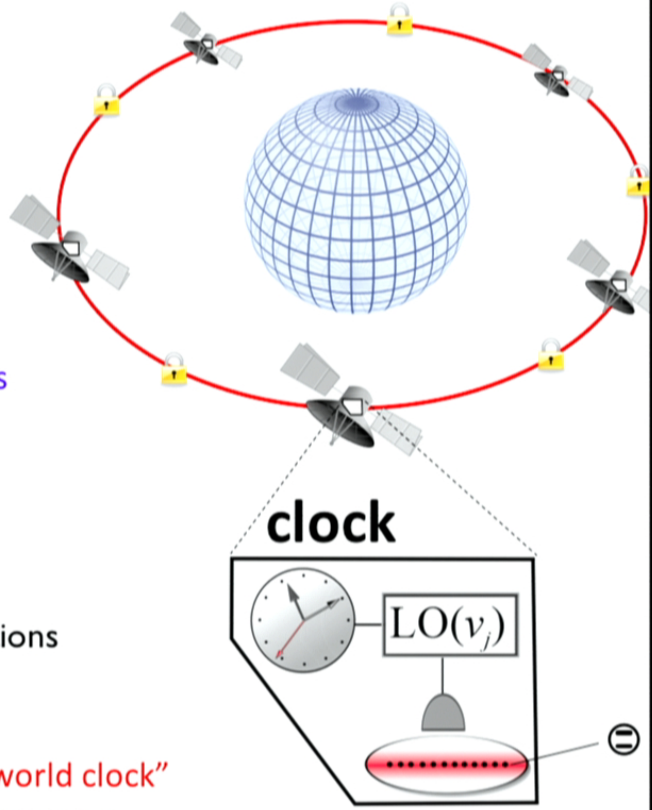

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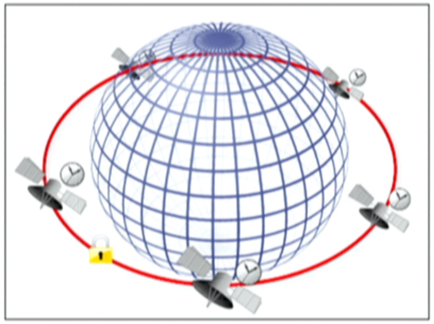
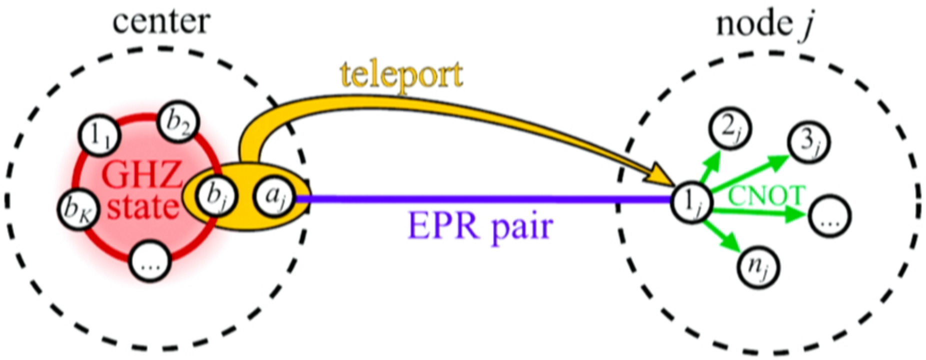
An approach to create an ultimate "world clock"
with unsurpassed stability and accuracy:
time as a universal resource

P. Komar, E. Kessler et al (2014)
collaboration with Jun Ye, Vladan Vuletic

Entangled States of Remote Clocks

Idea:
quantum communication for remote entanglement
+ teleportation





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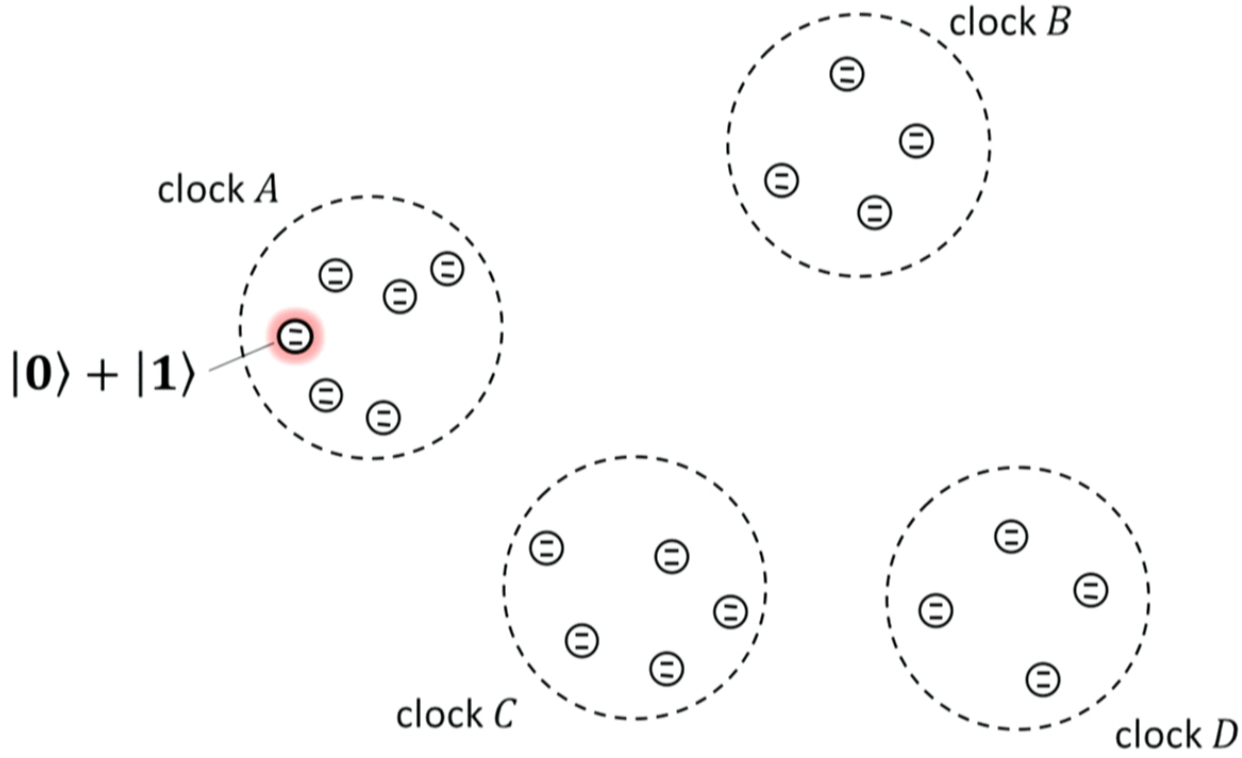

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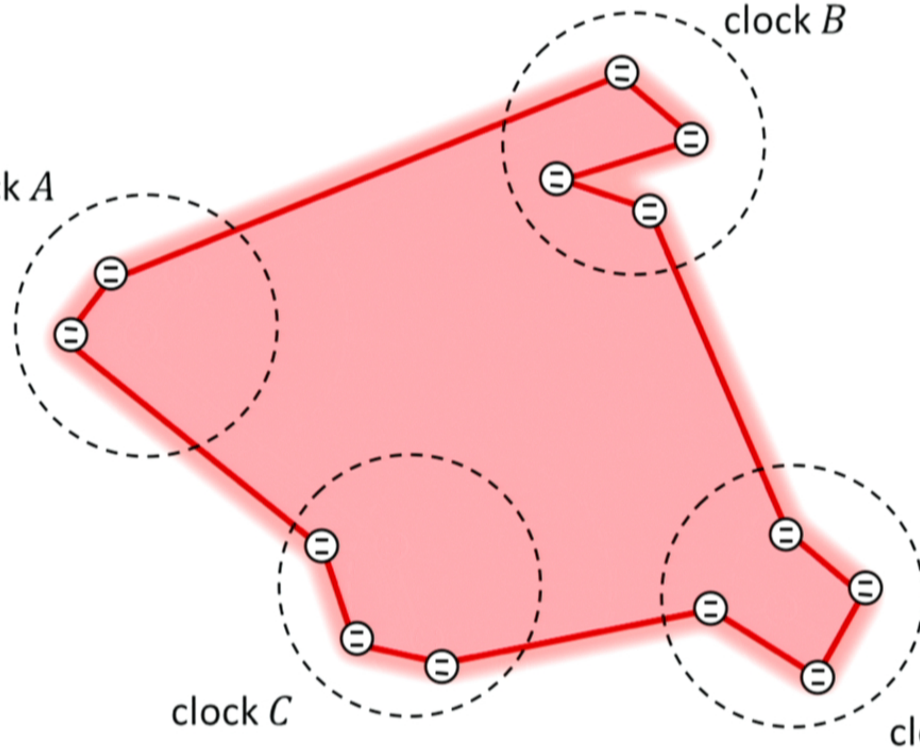
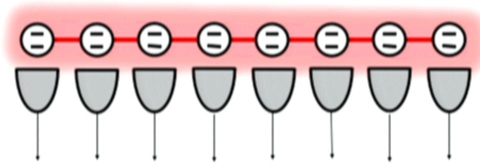


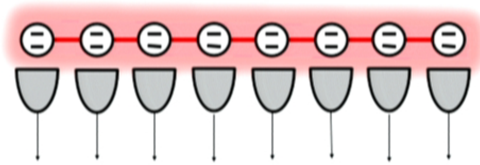
Global entangled state

Measurement



Measuring individual qubits in the $|\pm\rangle = |0\rangle \pm |1\rangle$ basis.

Measurement



Measuring individual qubits in the $|\pm\rangle = |0\rangle \pm |1\rangle$ basis.

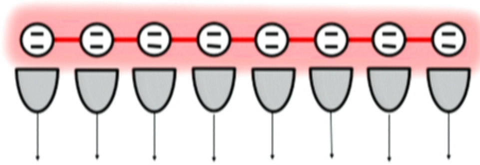
$$|00 \ldots 0\rangle + e^{i\Phi}|11 \ldots 1\rangle$$

$$= \left(1 + e^{i\Phi}\right)(\textbf{even}\text{ outcomes}) \quad + \left(1 - e^{i\Phi}\right)(\textbf{odd}\text{ outcomes})$$

$$\Rightarrow P_{\textbf{even/odd}} = \frac{1}{2}[1 \pm \cos\Phi]$$

[Bollinger, J., et al. (1996). *PRA*, *54*(6), R4649–R4652.]

Measurement



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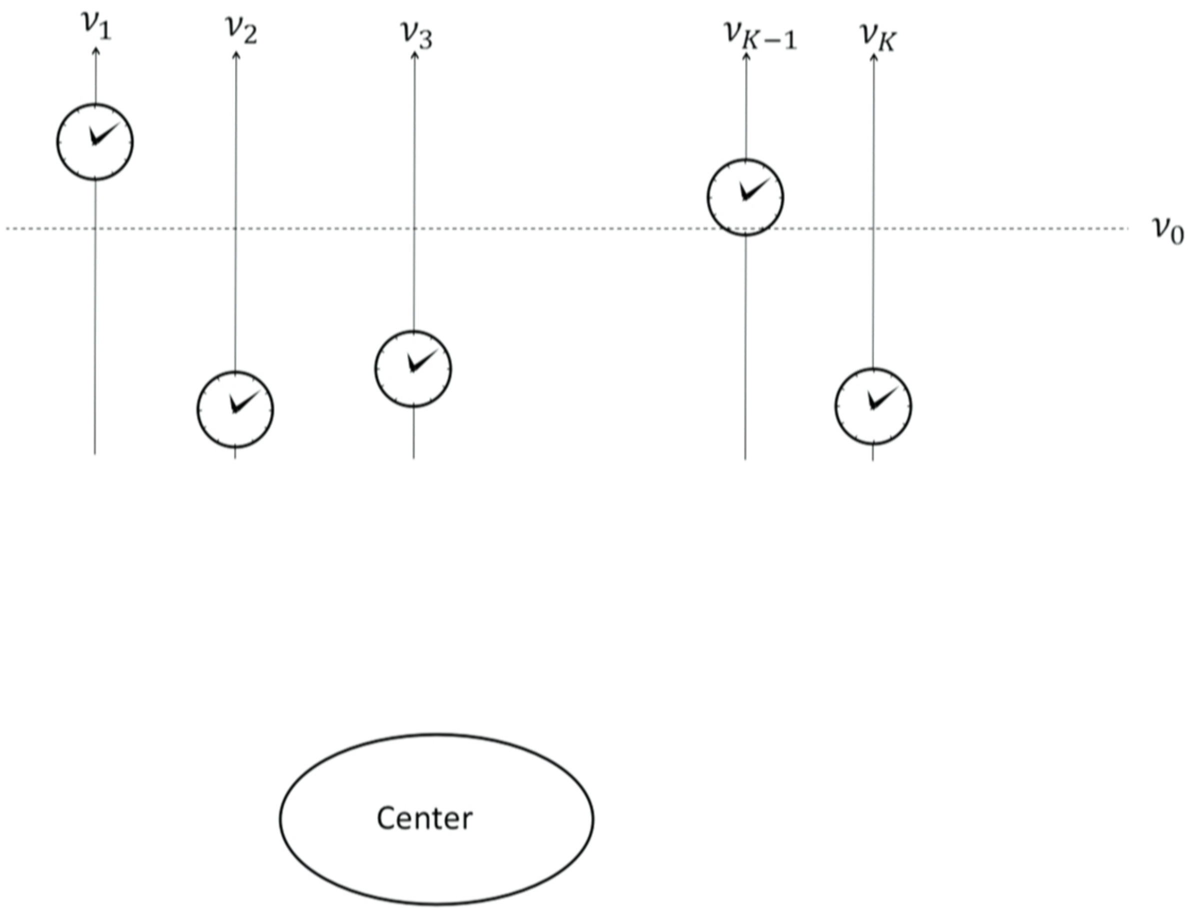
Feedback



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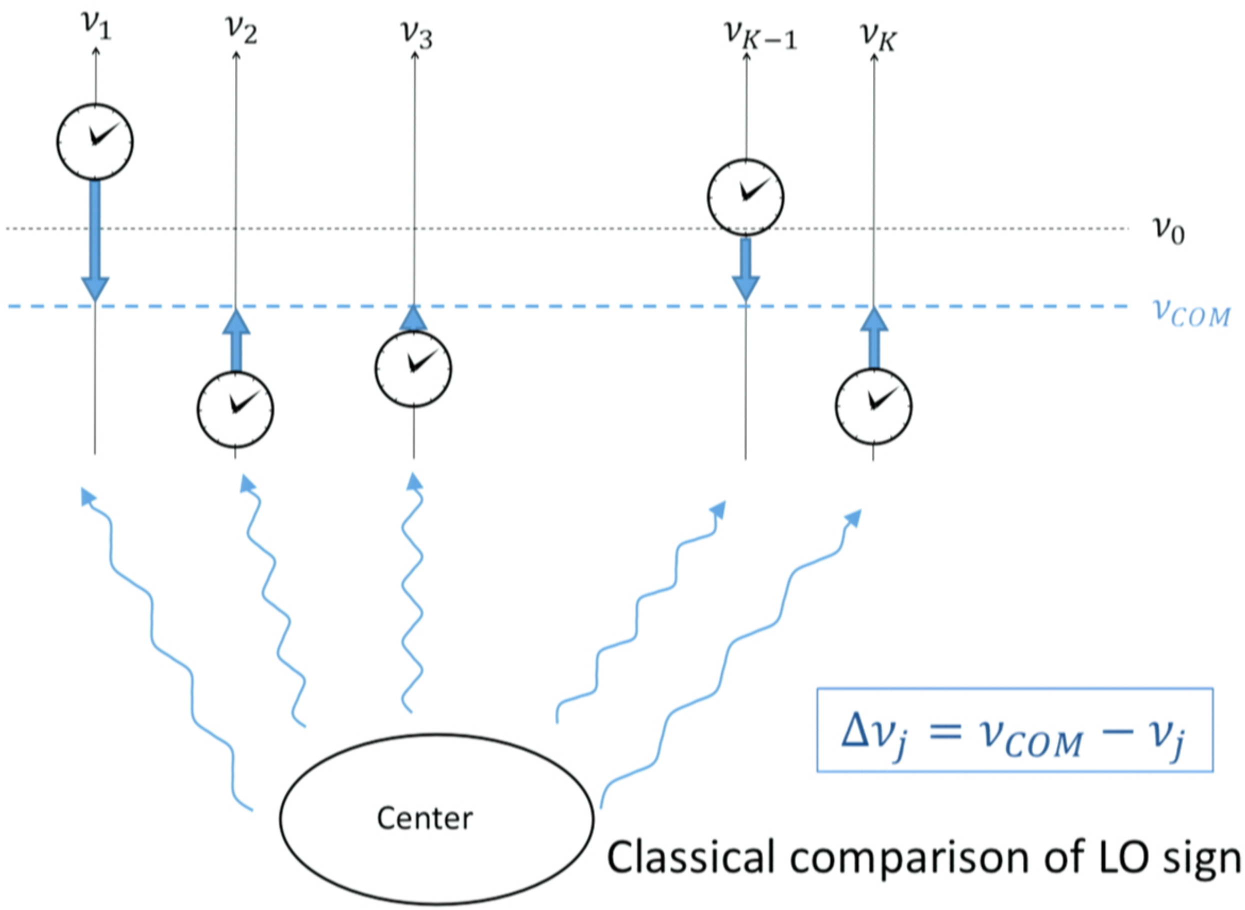


Classical comparison of LO signals

Cooperation in network

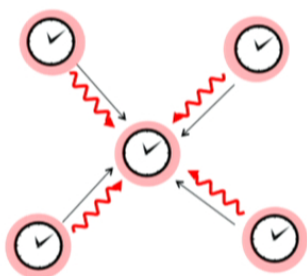
Clocks share:

Quantum cooperation

Classical cooperation

- LO signals (via fiber link)
- Measurement results (via classical communication), and
- Entanglement (via quantum channel)

Classical cooperation

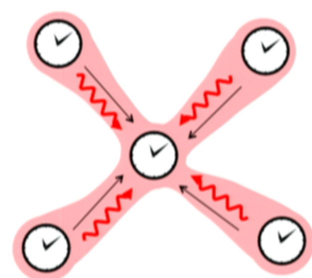


N_{clocks} # of GHZ states

↓

$$\sigma_y \propto \left(\frac{N_{total}}{N_{clocks}}\right)^{-1} N_{clocks}^{-1/2}$$

Quantum cooperation



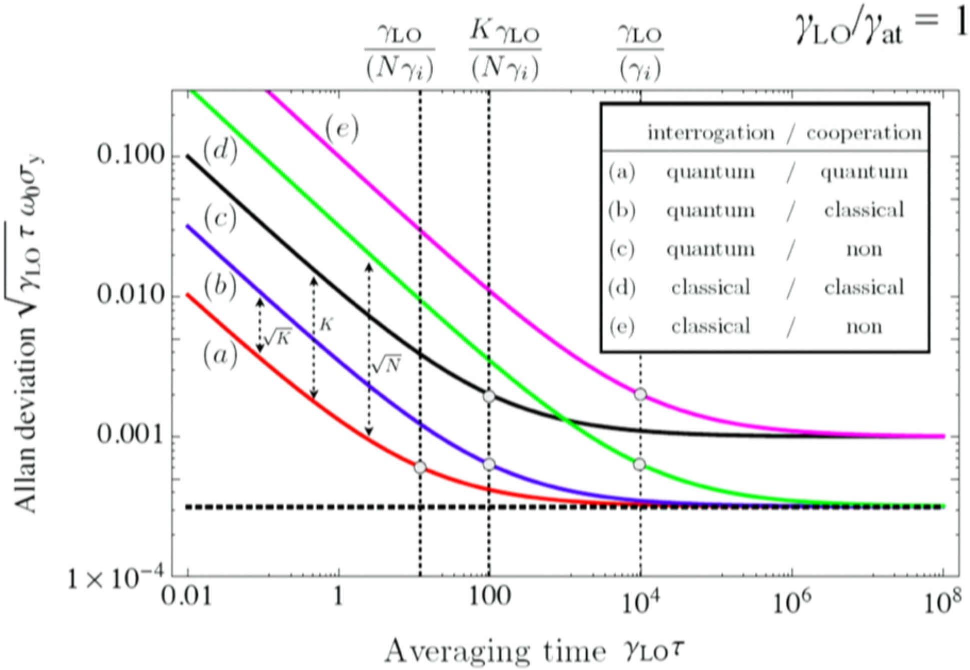
one global GHZ state

↓

$$\sigma_y \propto N_{total}^{-1}$$

Stability gain

K = 10 clocks
N = 1000 of atoms per clock
$\gamma_{LO}/\gamma_{at} = 10^4$



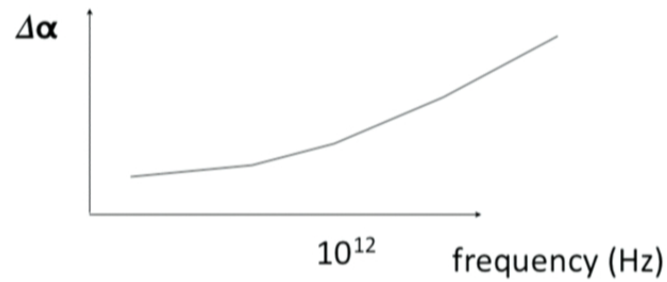
[P. Kómár, et al., *A quantum network of clocks*, arXiv:1310.6045 (2013)]

Key features

- Security: profit from global stability without loosing sovereignty
- Cooperation: only those contributing benefit
- Systematic differences between nodes can be detected with high precision

Outlook: probing fast variation of fundamental constants?

- Dark matter:
  discussion yesterday



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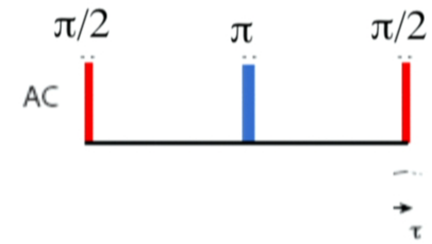
AC measurements with clocks and magnetometers

✓Idea: use "spin echo"-type techniques to "slow down" the clock
✓Echo is sensitive to AC fields:



Idea: spin-based magnetometry J.Taylor, P. Cappalaro et al, arXiv:0805.1367, Nature Physics (2008)

AC measurements with clocks and magnetometers

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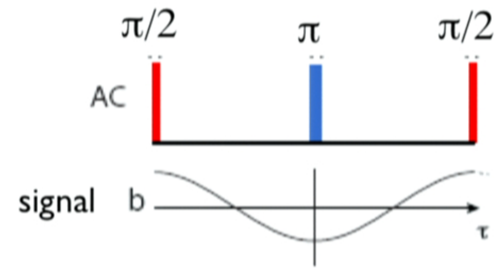
✓Echo is sensitive to AC fields:

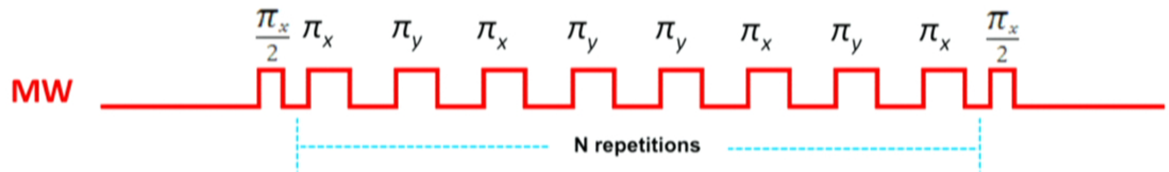
$$\delta\phi = \frac{g\mu_B}{\hbar}\left[\int_0^{\tau/2} b(t)dt - \int_{\tau/2}^{\tau} b(t)dt\right]$$

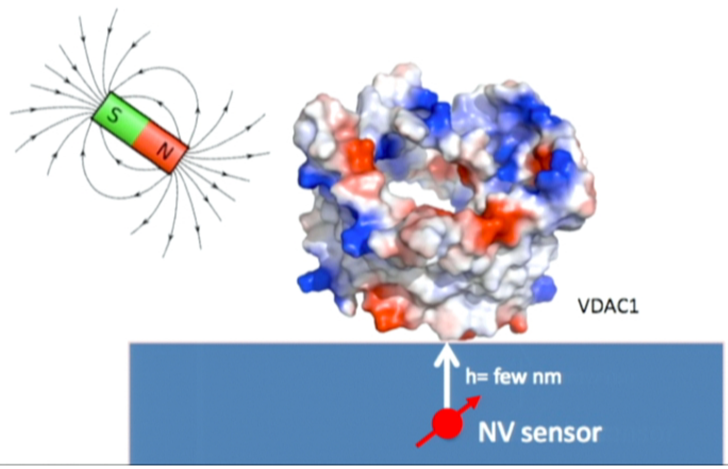


Idea: spin-based magnetometry J.Taylor, P. Cappalaro et al, arXiv:0805.1367, Nature Physics (2008)

Example application: MRI of single molecules

Idea use the long composite pulse sequence
to synch single spin magnetometer with evolution of specific nuclei

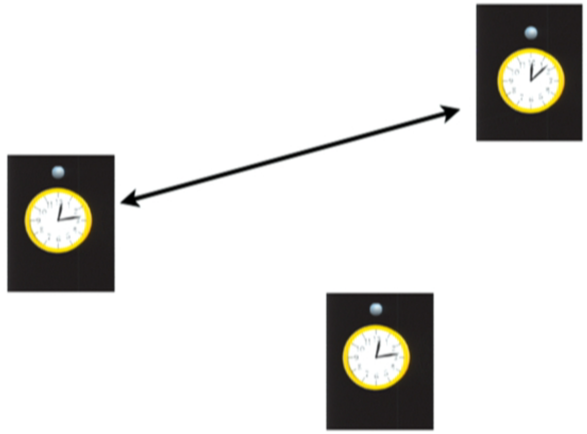




theory: Taylor et al, Nature Physics (2008)
exp: Alex Sushkov, Igor Lovchinsky

Approach to probing fast variations

- Idea: compare high-frequency noise of separated clocks



N.B. Dark-energy induced noise in JJs controversy, Beck, Mackey et al 48

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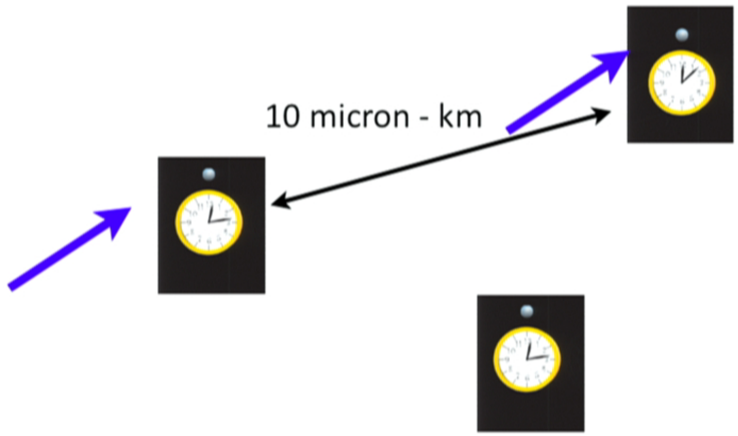
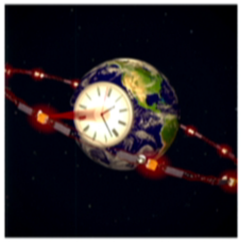


- Allows one (in principle) to probe spatial & temporal coherence of the variations

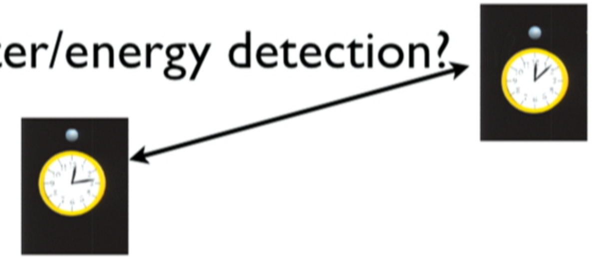
Question: can one find "interesting" bounds for signal values?

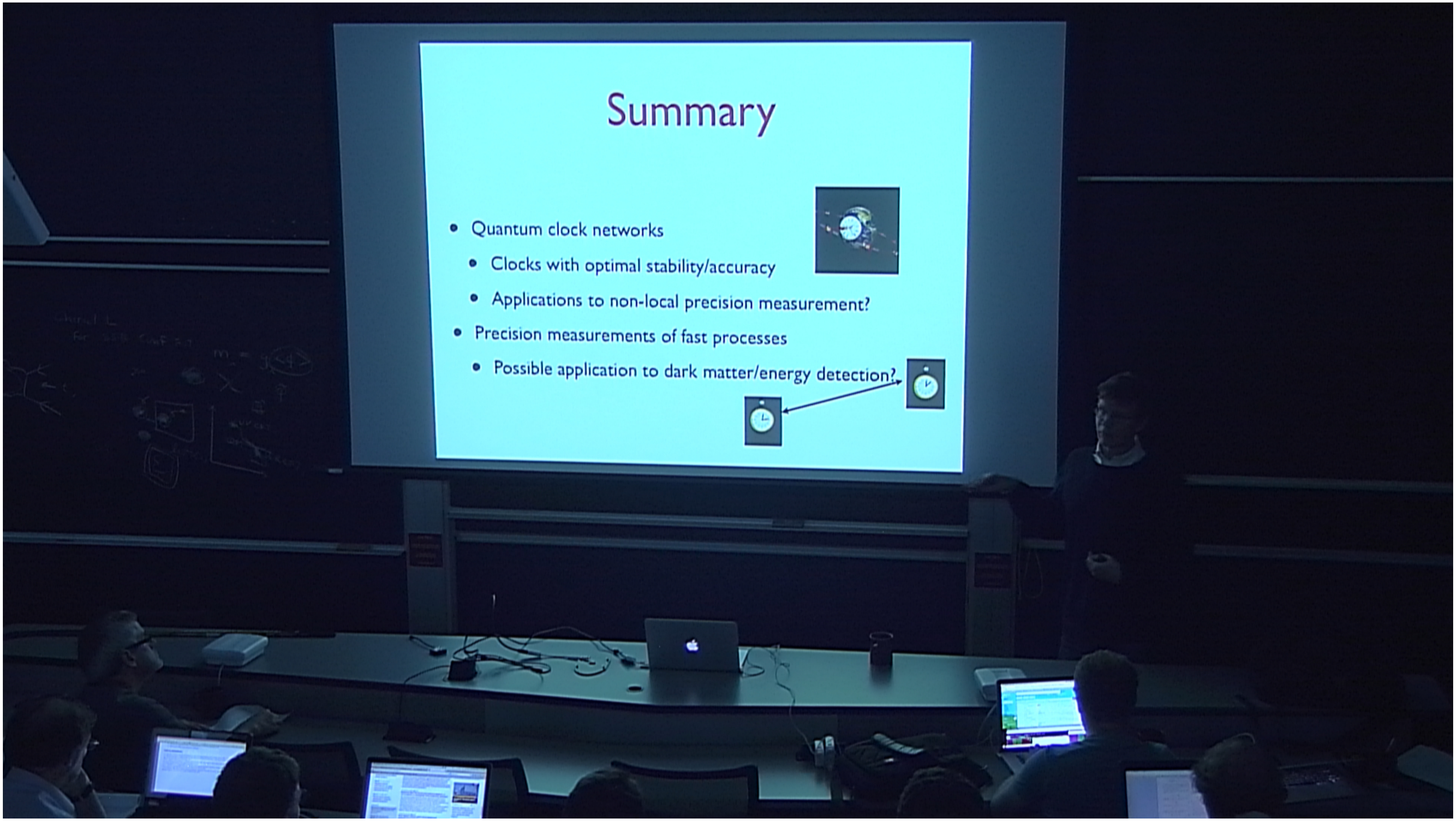
N.B. Dark-energy induced noise in JJs controversy, Beck, Mackey et al 48

Summary



- Quantum clock networks
  - Clocks with optimal stability/accuracy
  - Applications to non-local precision measurement?
- Precision measurements of fast processes
  - Possible application to dark matter/energy detection?

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