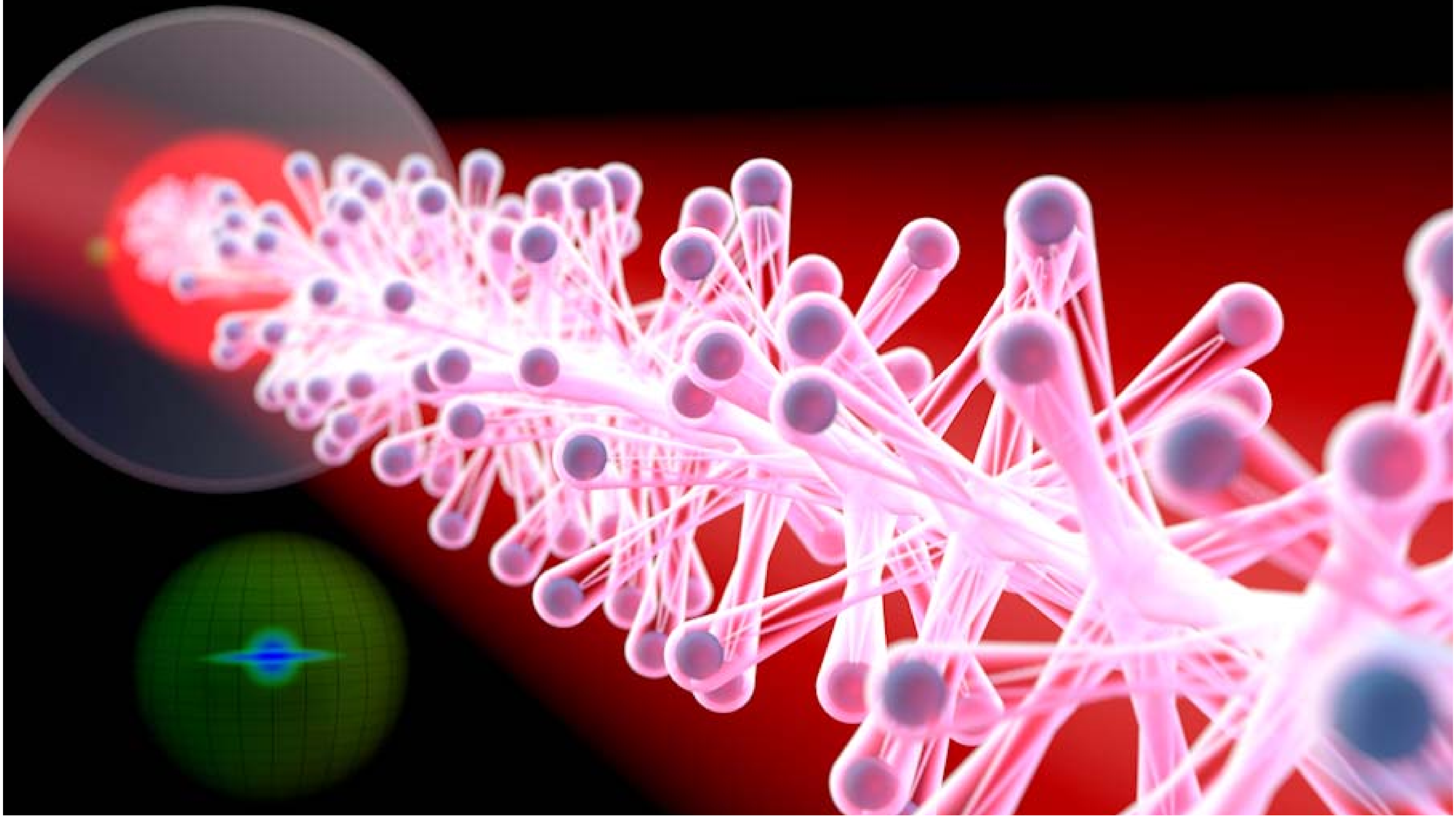
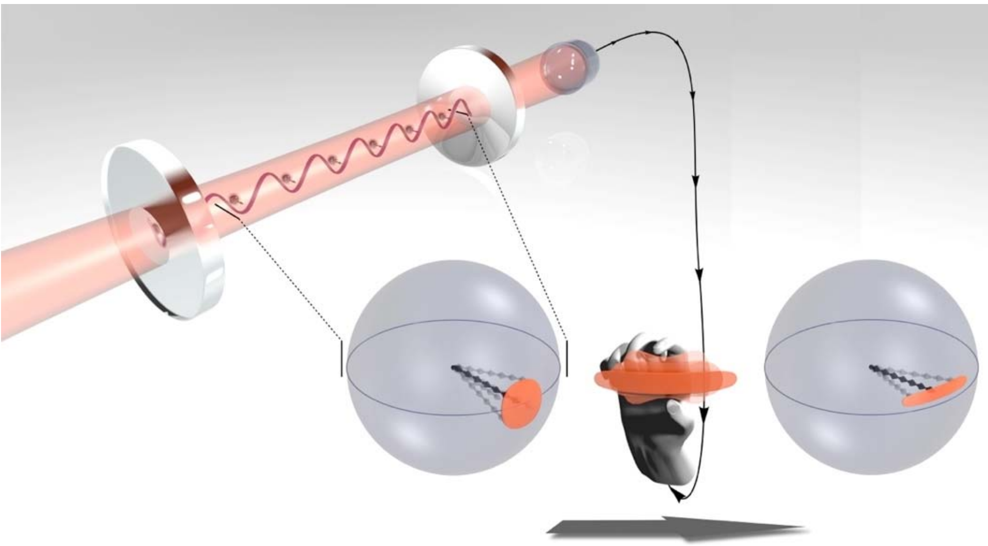
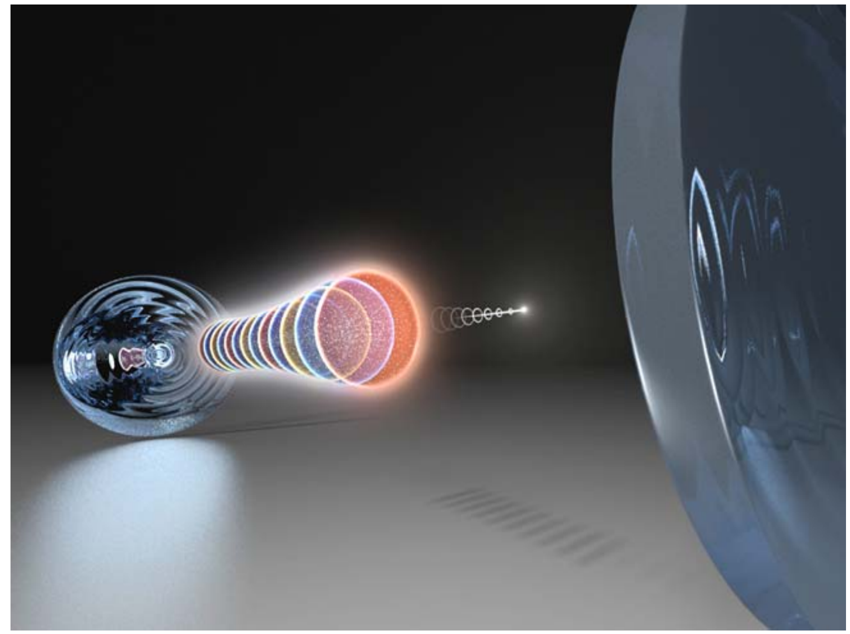
Quantum many-body states for precision measurement

James K. Thompson, NIST, JILA & Dept. of Physics at Univ. of Colorado



Precision Measurements: Things you can do with **many quantum objects**, that you can't do with **one**



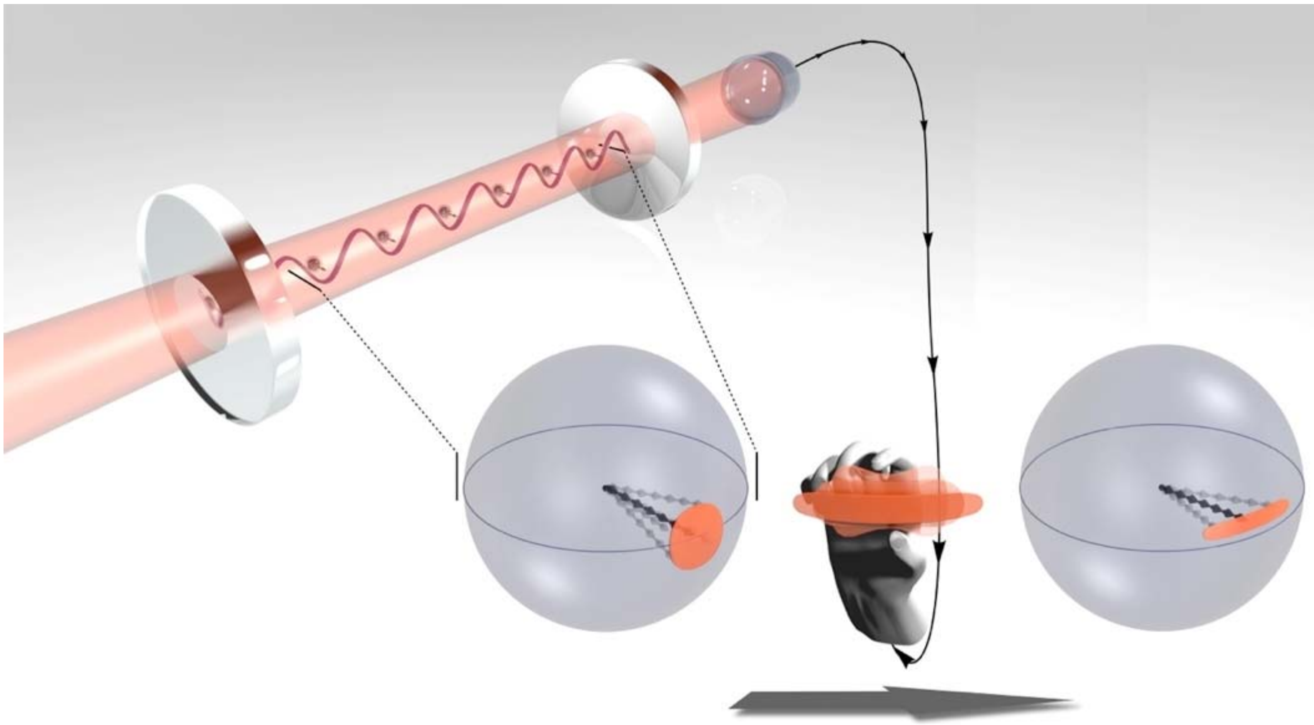


Spin squeezed states

Steady-state superradiant lasers

Reducing Quantum Noise

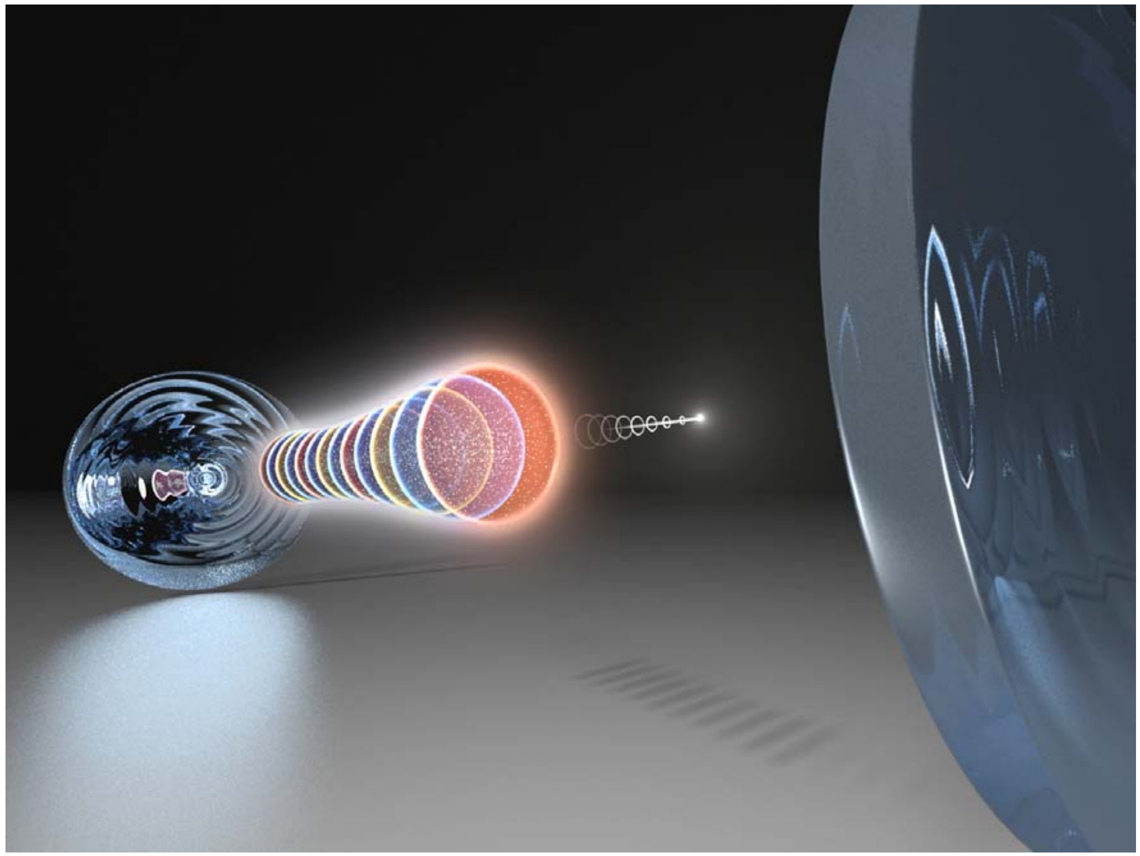
Atoms cancel each other's noise



World record entanglement for quantum sensors

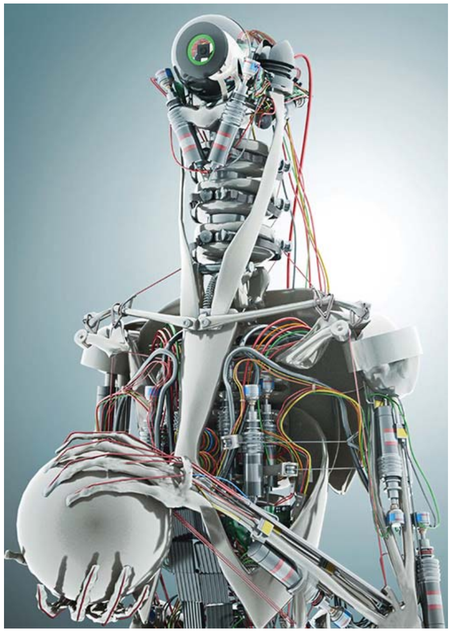
Making Sharper Optical Rulers

Hide laser information in collective state of atoms

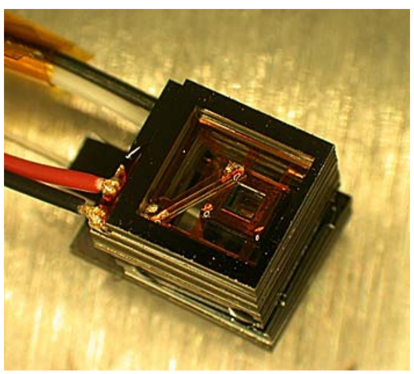


100x reduction in laser linewidth
for frequency, length, and gravity metrology

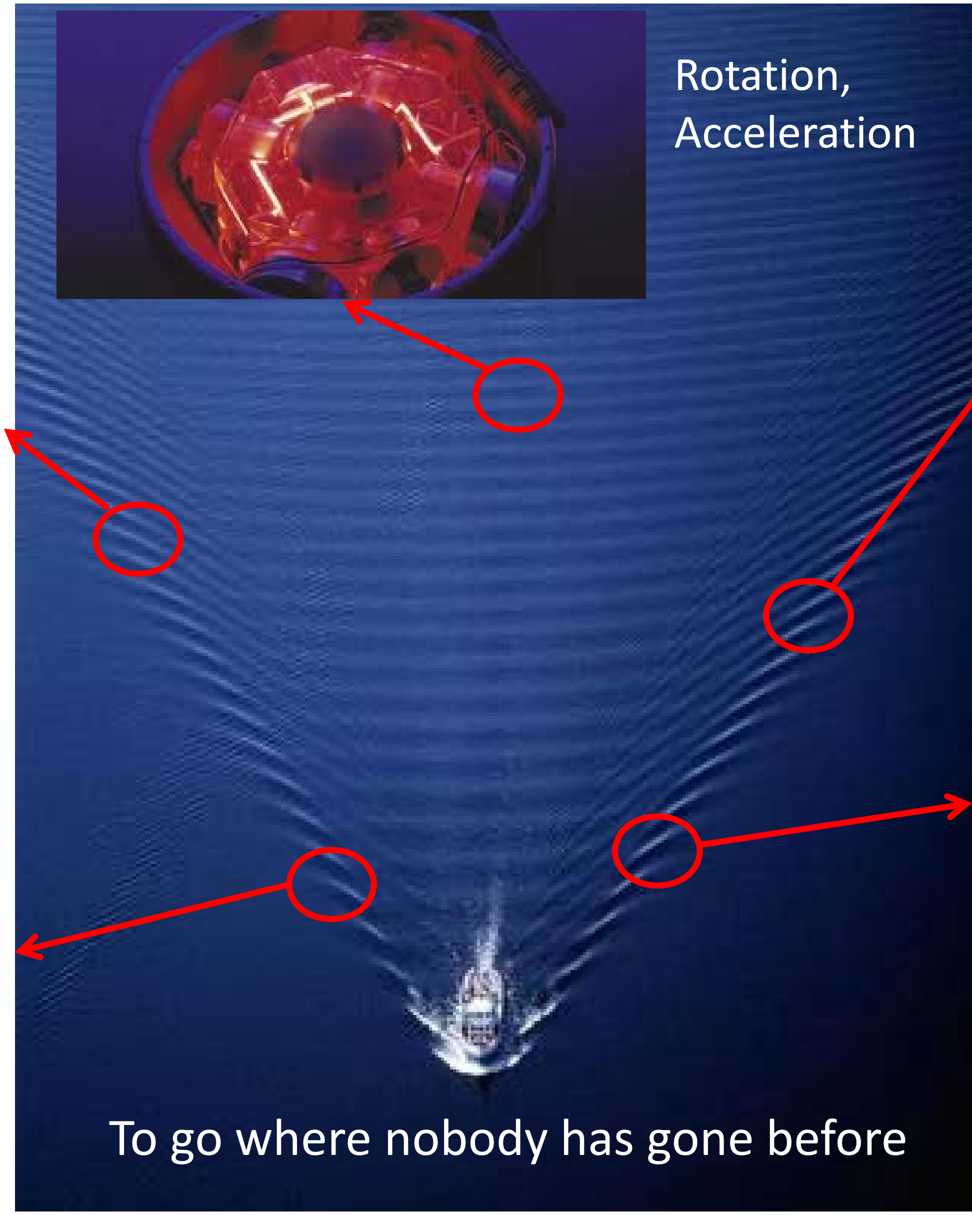
Both Impact Wide Array of Measurements

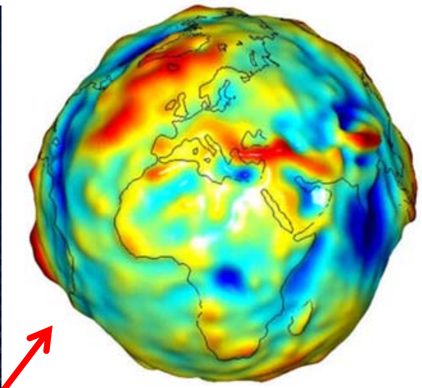


Force, pressure, temp.

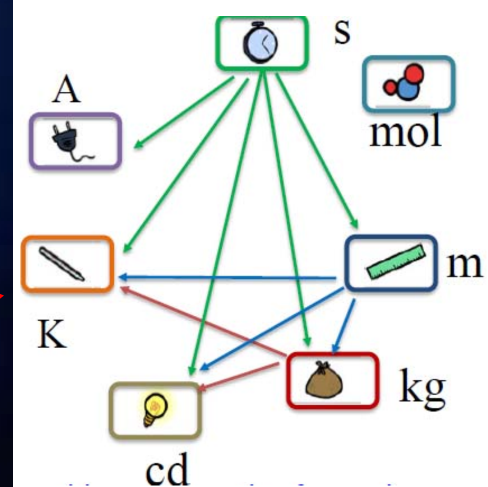


Magnetic &
electric field





Gravity field

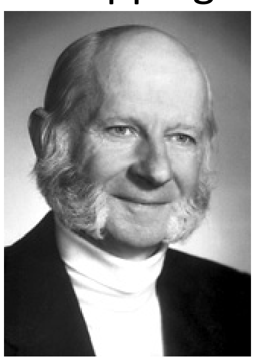


Realization
& distribution
of SI Base Units

A Lineage of Quantum Control Freaks

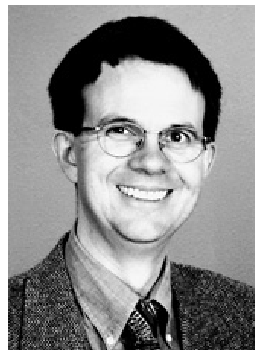
1989
Control of Internal Atomic States

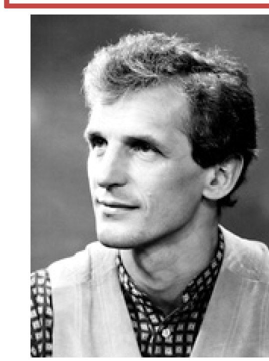
Single Ion/Electron Trapping



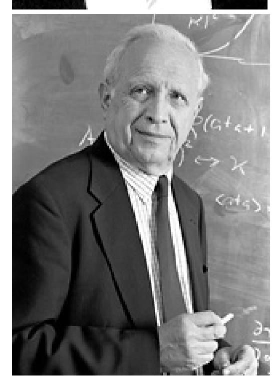
1997
Laser Cooling & Trapping

2001
Bose Einstein Condensation

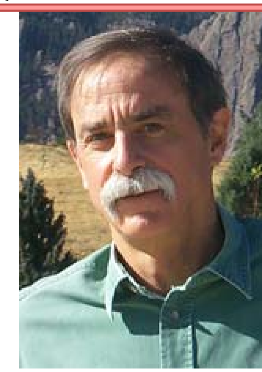




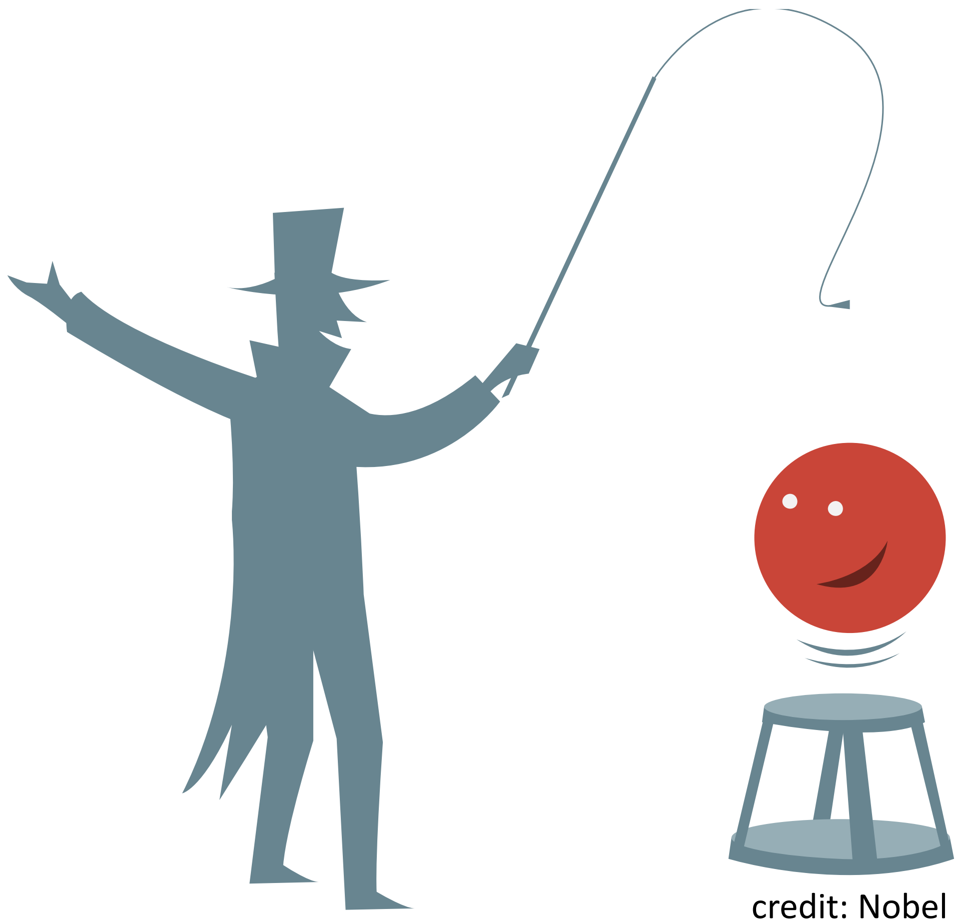
2005
Coherent Optical Control



2012
Single-System Quantum Control



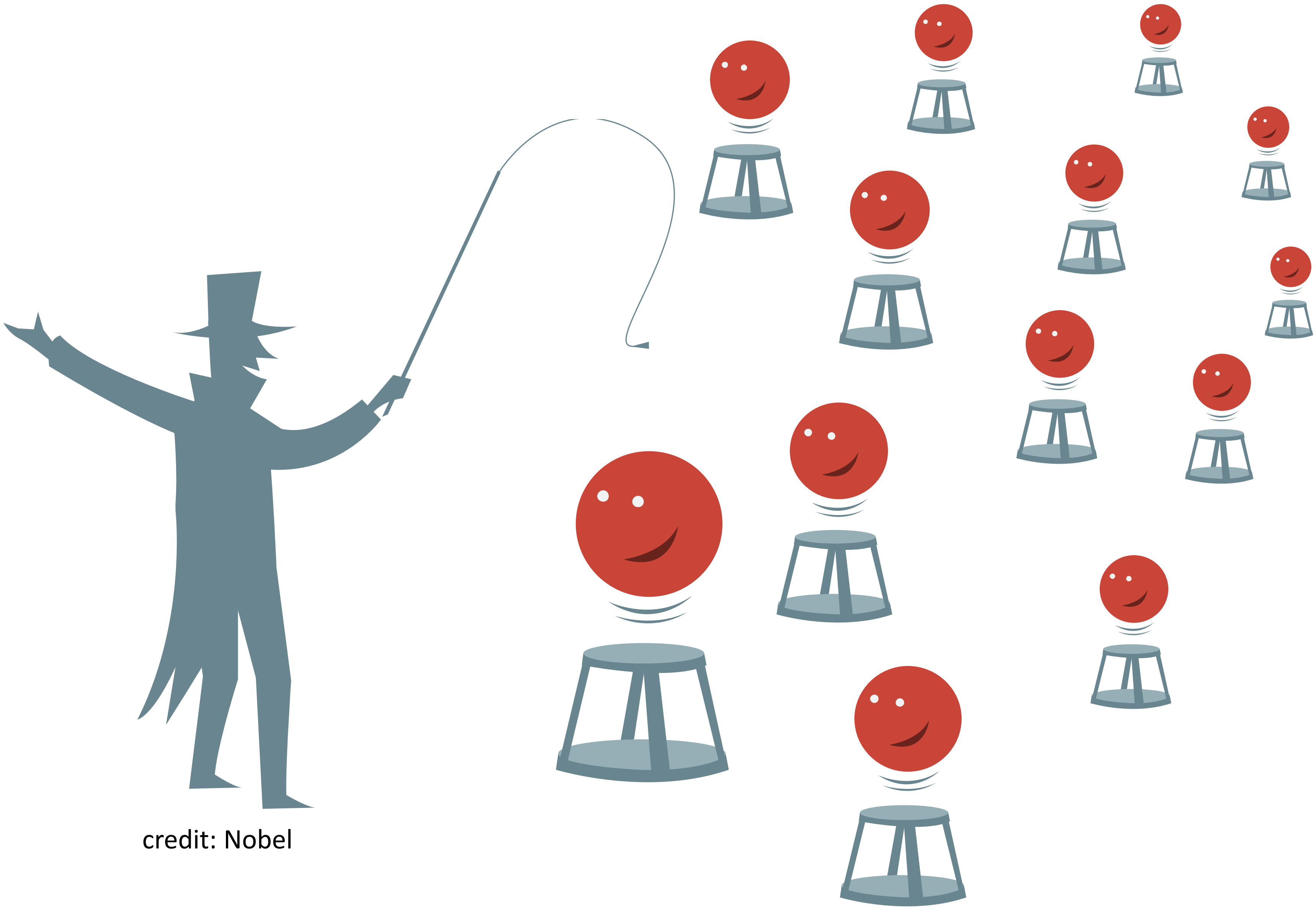
Nearly Complete Control of Single Atoms



credit: Nobel

What's next!?

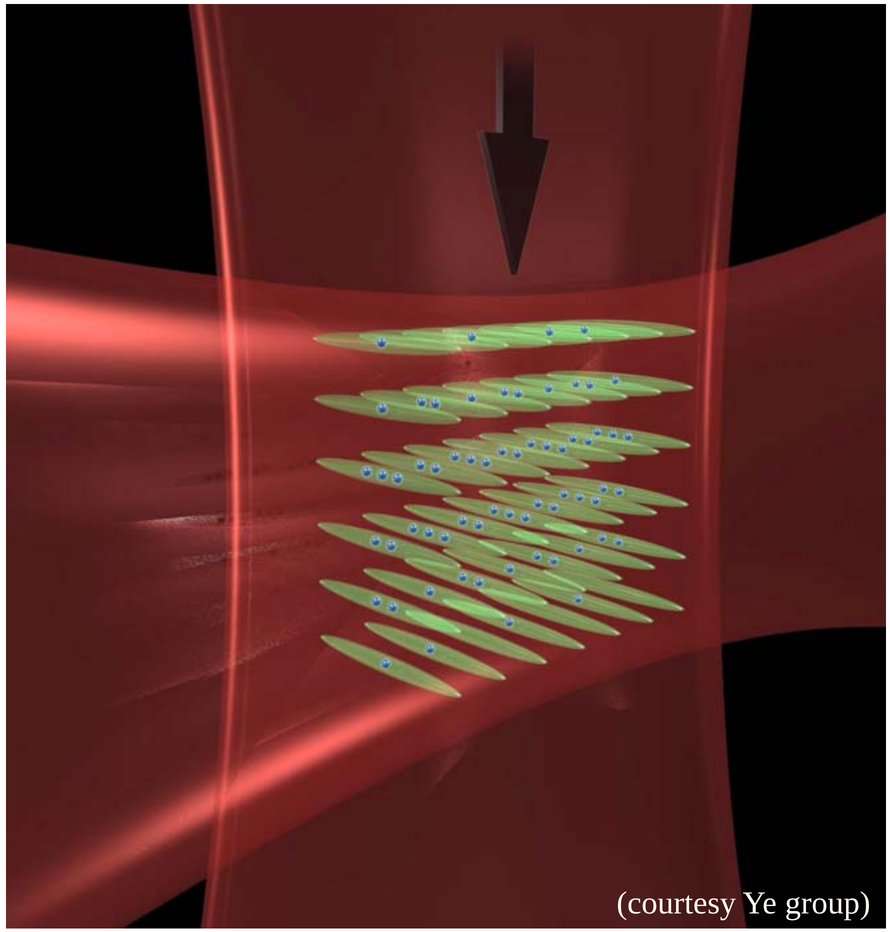
Parallel Control of Independent Atoms



credit: Nobel

Ultra-Precise

Atomic Clocks



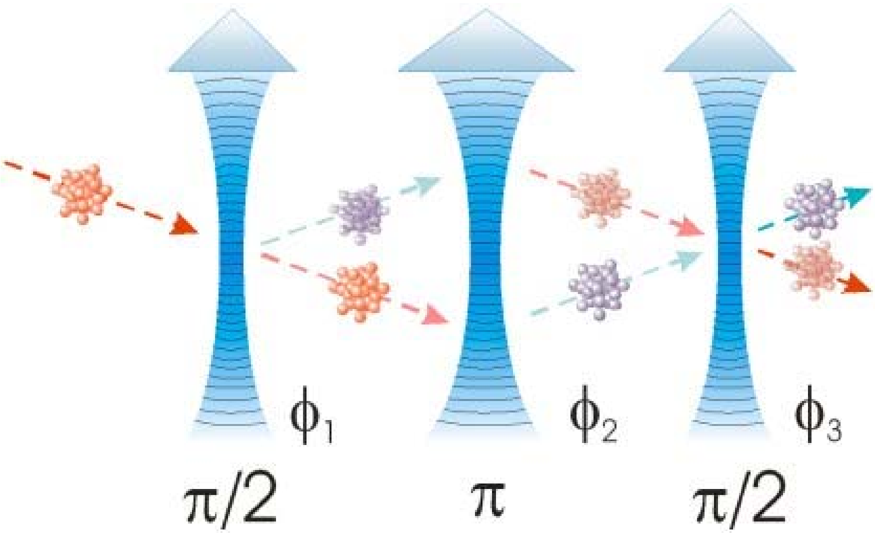
(courtesy Ye group)

0.000 000 000 000 000 003

World's most precise absolute measurement of any kind

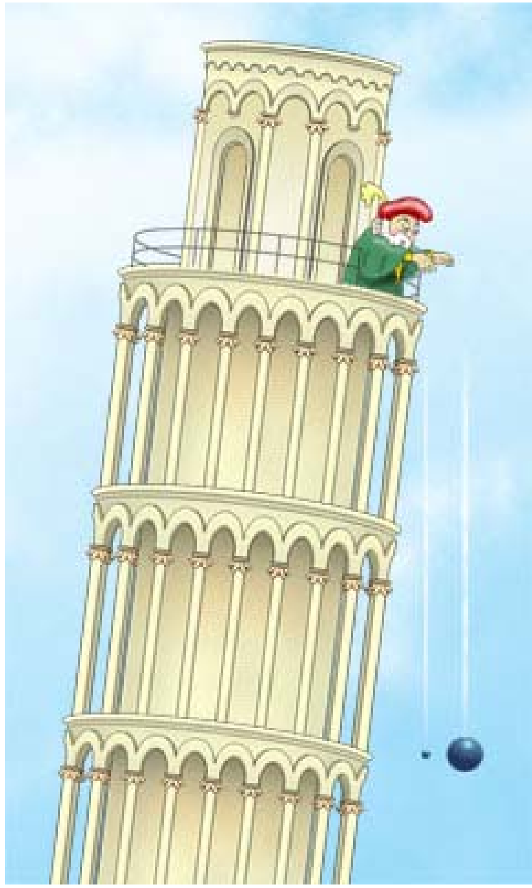
Matterwave Interferometers

Use pulses of light to spatially split the atomic wave function



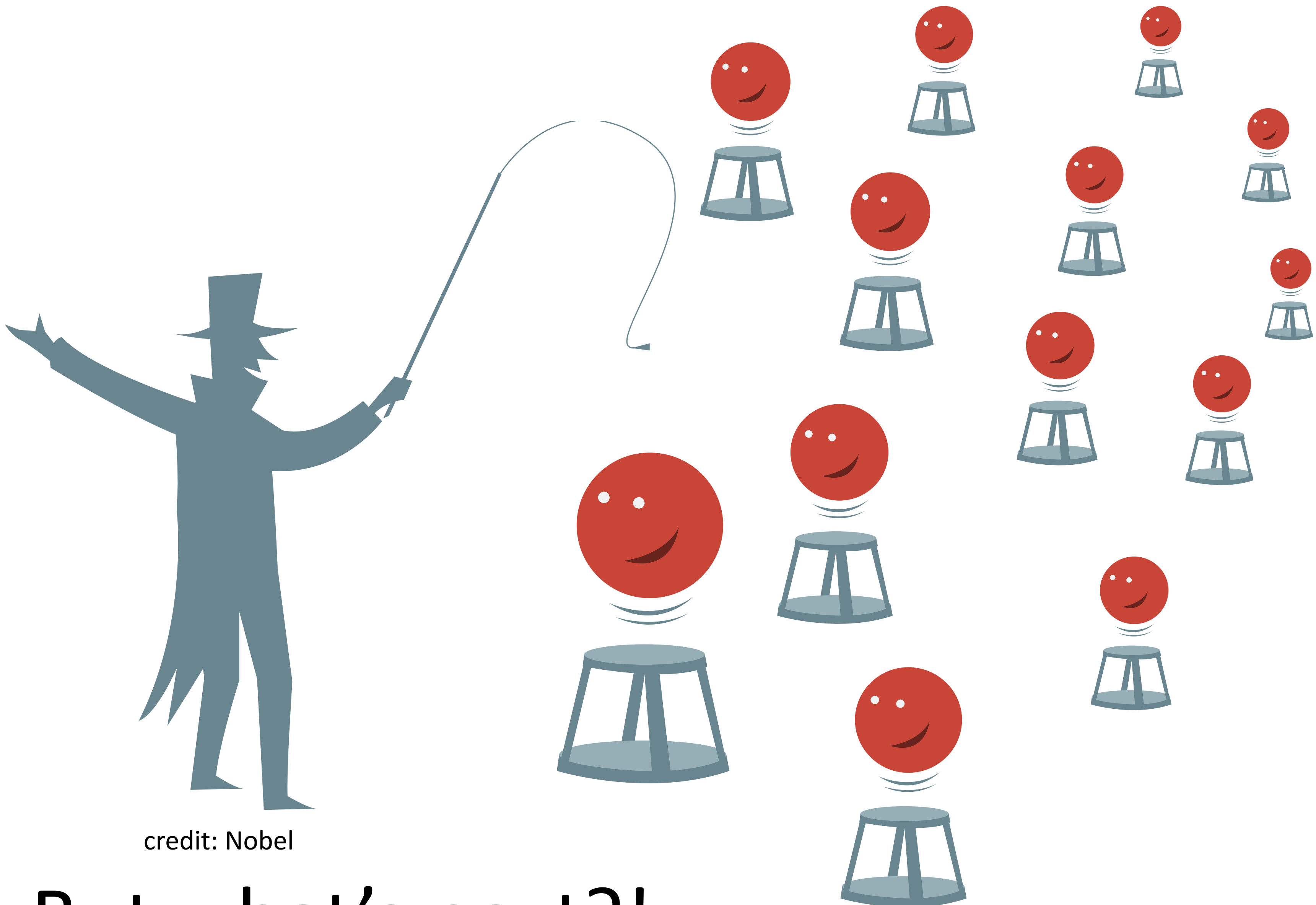
Credit: A. Peters group

Einstein's equivalence principle
Determine gravitational constant G
Detect gravity waves



GPS free navigation
Gyroscopes
Accelerometers
Gravimetry
Fundamental constants of nature
Tests of QED
Test atomic charge neutrality

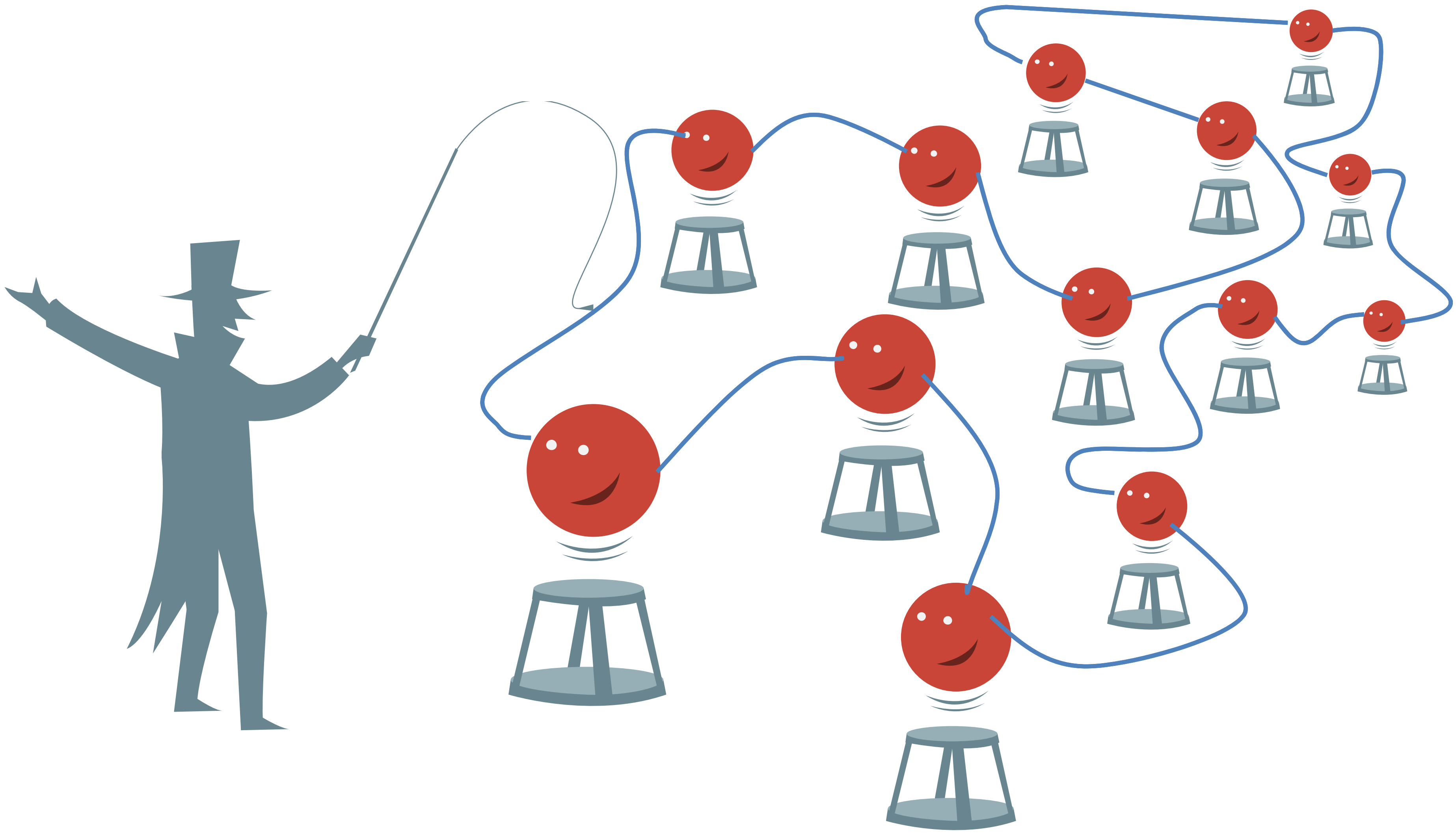
Parallel Control of Independent Atoms



credit: Nobel

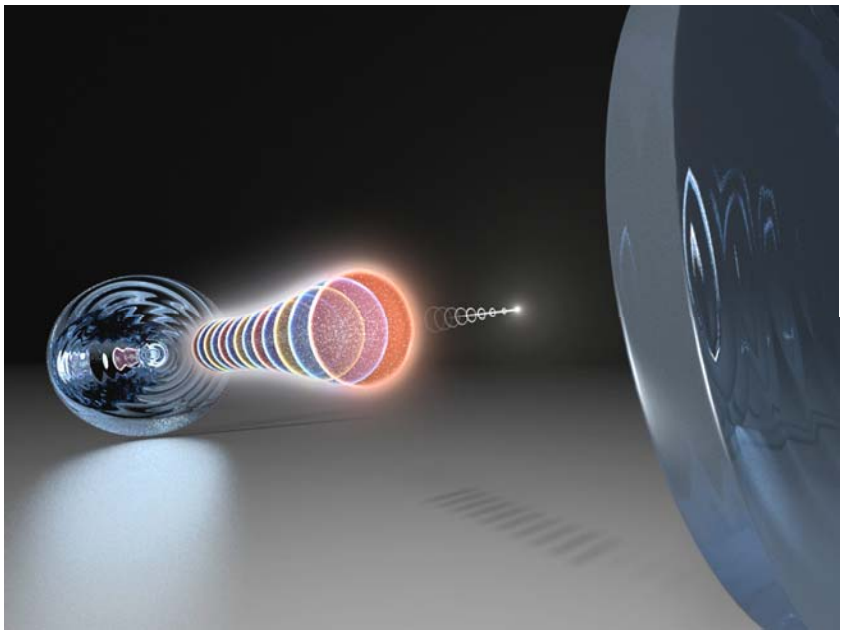
But what's next?!

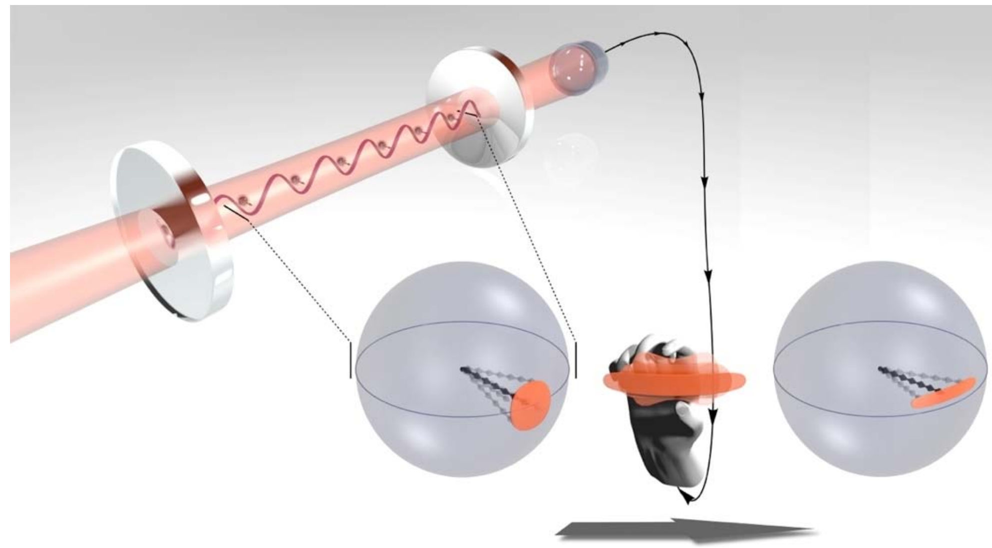
Vision for New Frontier of Precision Measurements



Can we move beyond the single atom paradigm?

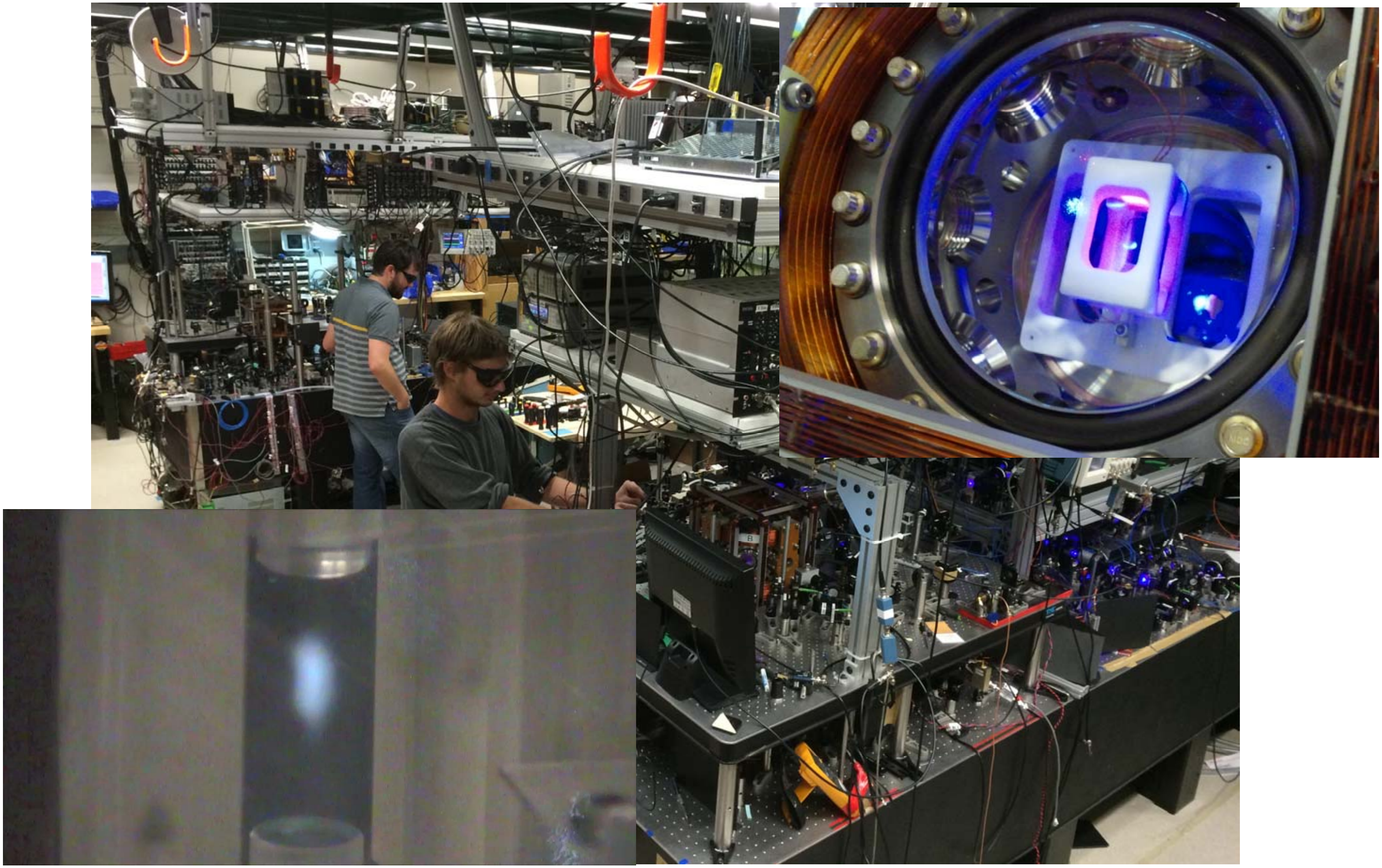
Precision Measurements: Things you can do with **many quantum objects**, that you can't do with **one**





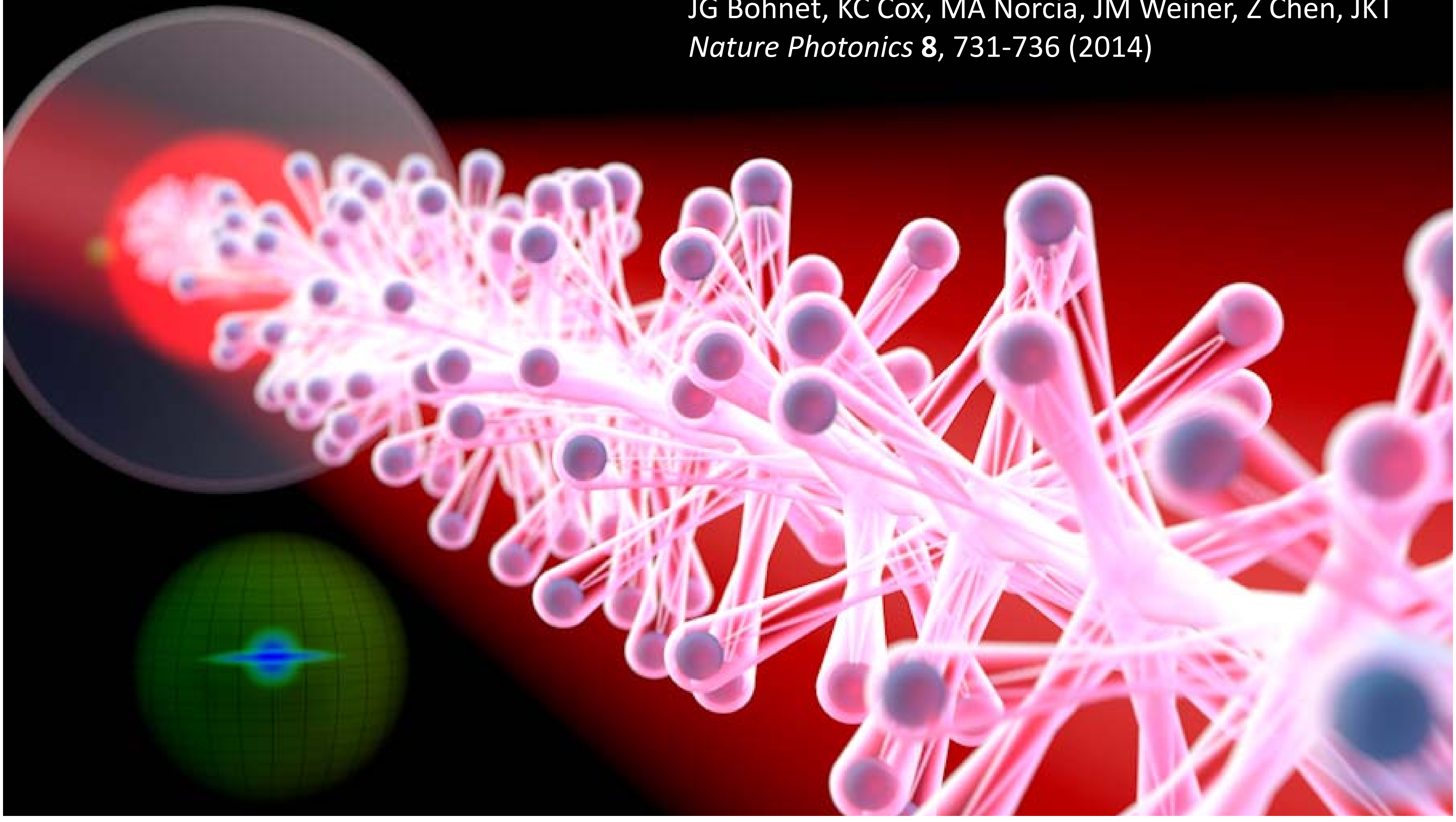
- Core NIST mission
- Critical advances in measurement science

Two Complex Experimental Systems: Rb, Sr

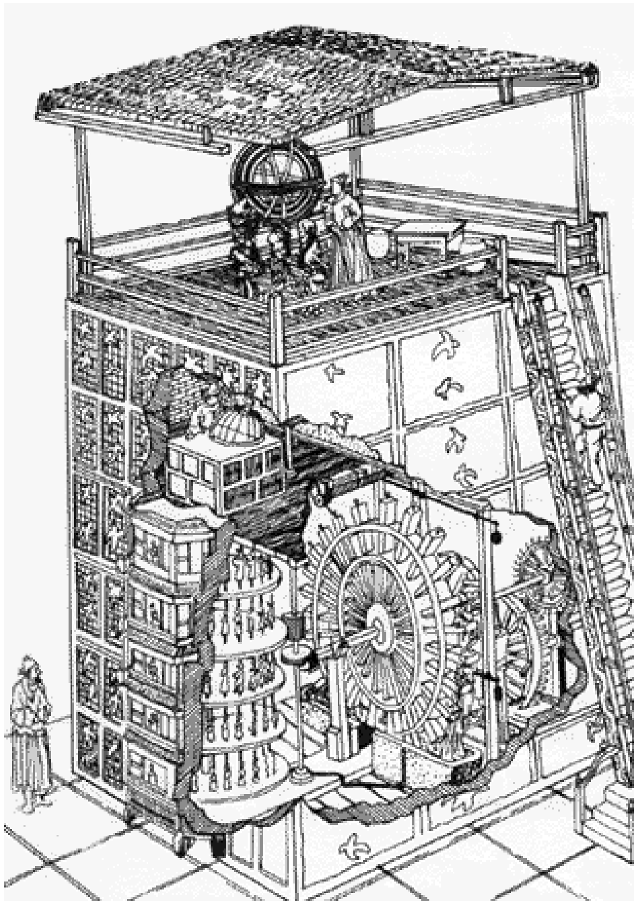


Canceling Quantum Fuzziness with Entanglement

JG Bohnet, KC Cox, MA Norcia, JM Weiner, Z Chen, JKT
Nature Photonics **8**, 731-736 (2014)



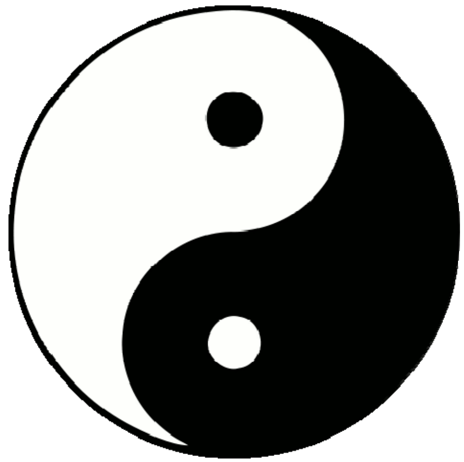
Why Use Atoms/Molecules? Accuracy



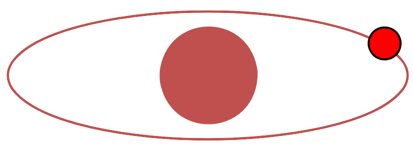
Su Sung water clock tower

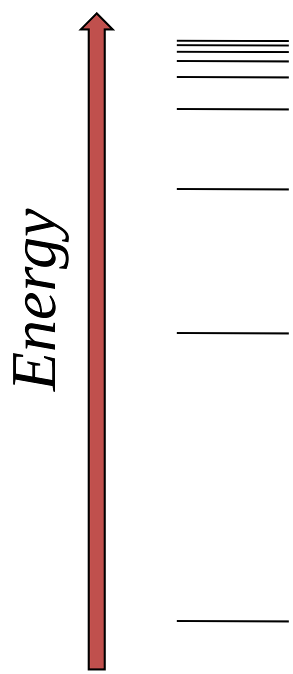
Quantum **Certainty** Principle:
all atoms are identical

Quantum Mechanics Giveth and Taketh…

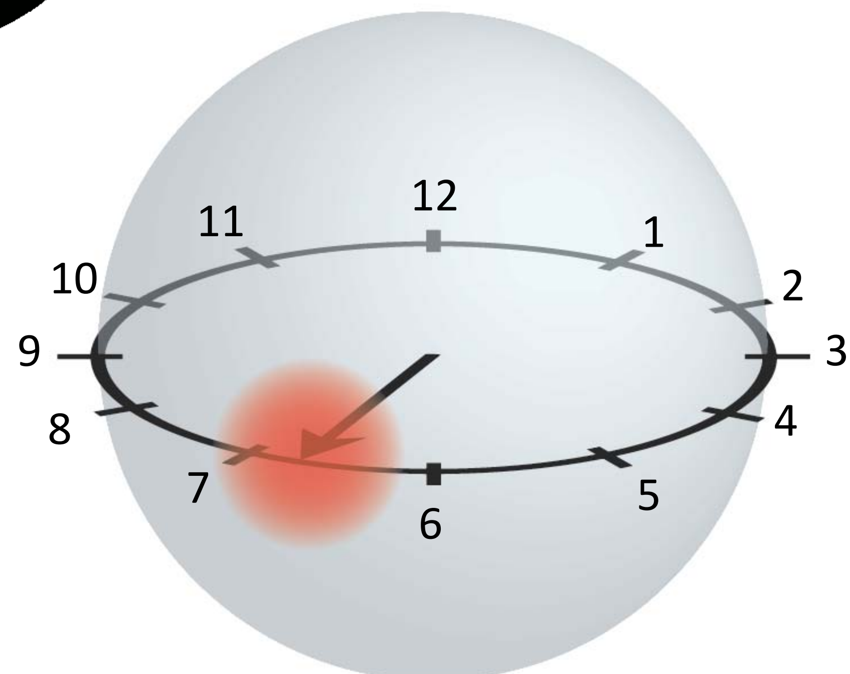


Quantum Certainty



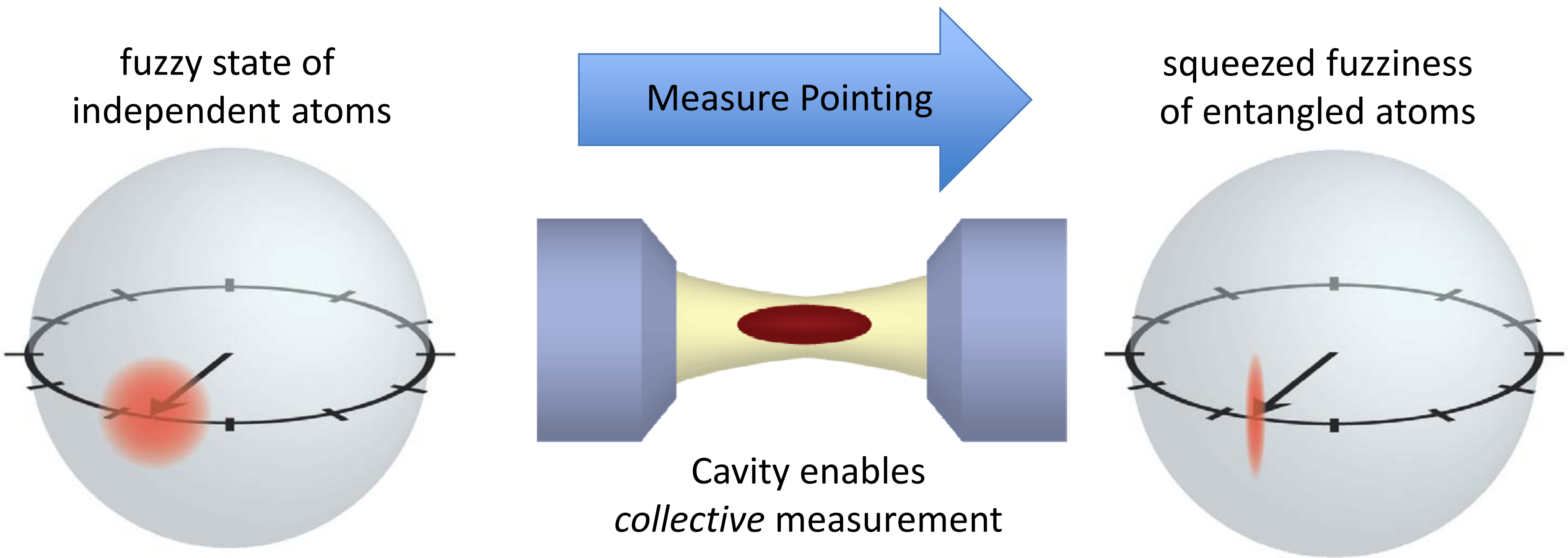


Quantum Fuzziness

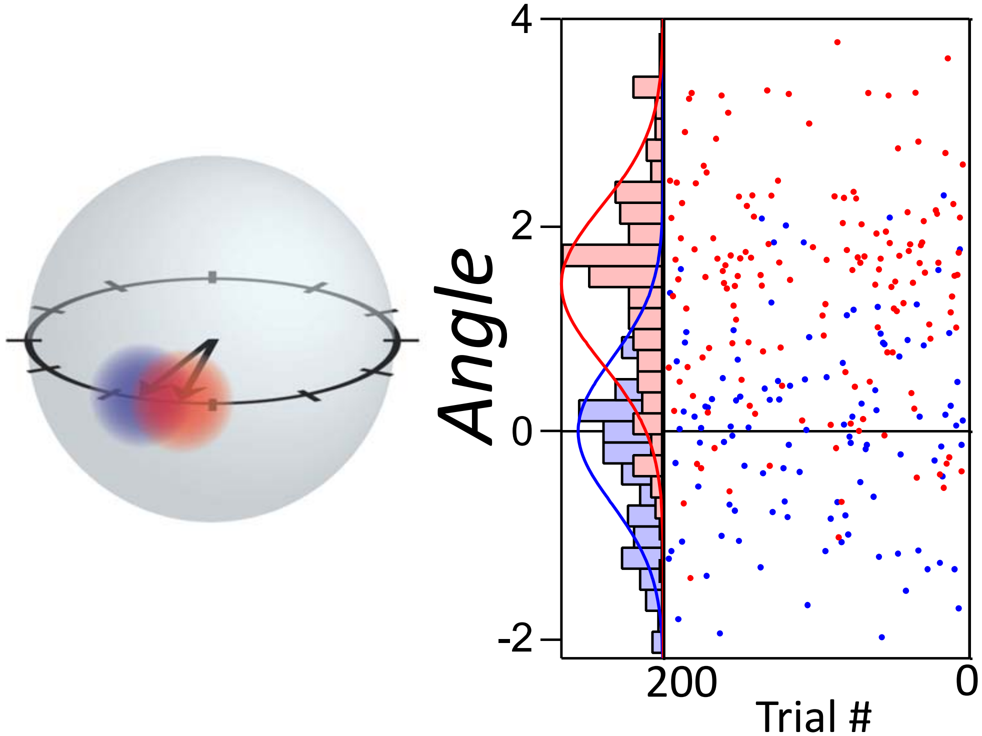


Fundamental limit for all quantum sensors

Squeezing Quantum Noise

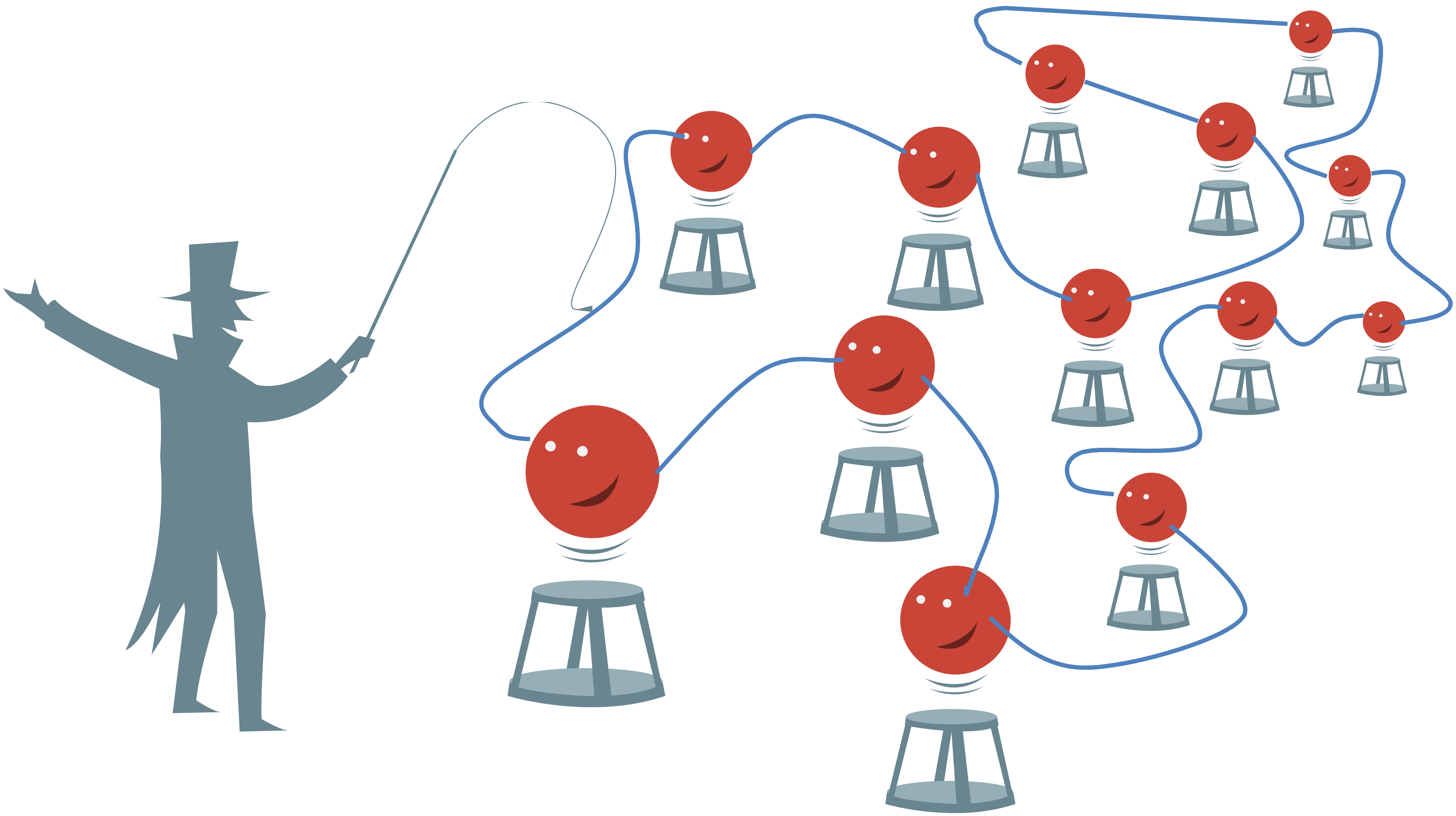


Surpassing the Standard Quantum Limit



JG Bohnet, KC Cox, MA Norcia, JM Weiner, Z Chen, JKT *Nature Photonics* **8**, 731-736 (2014)

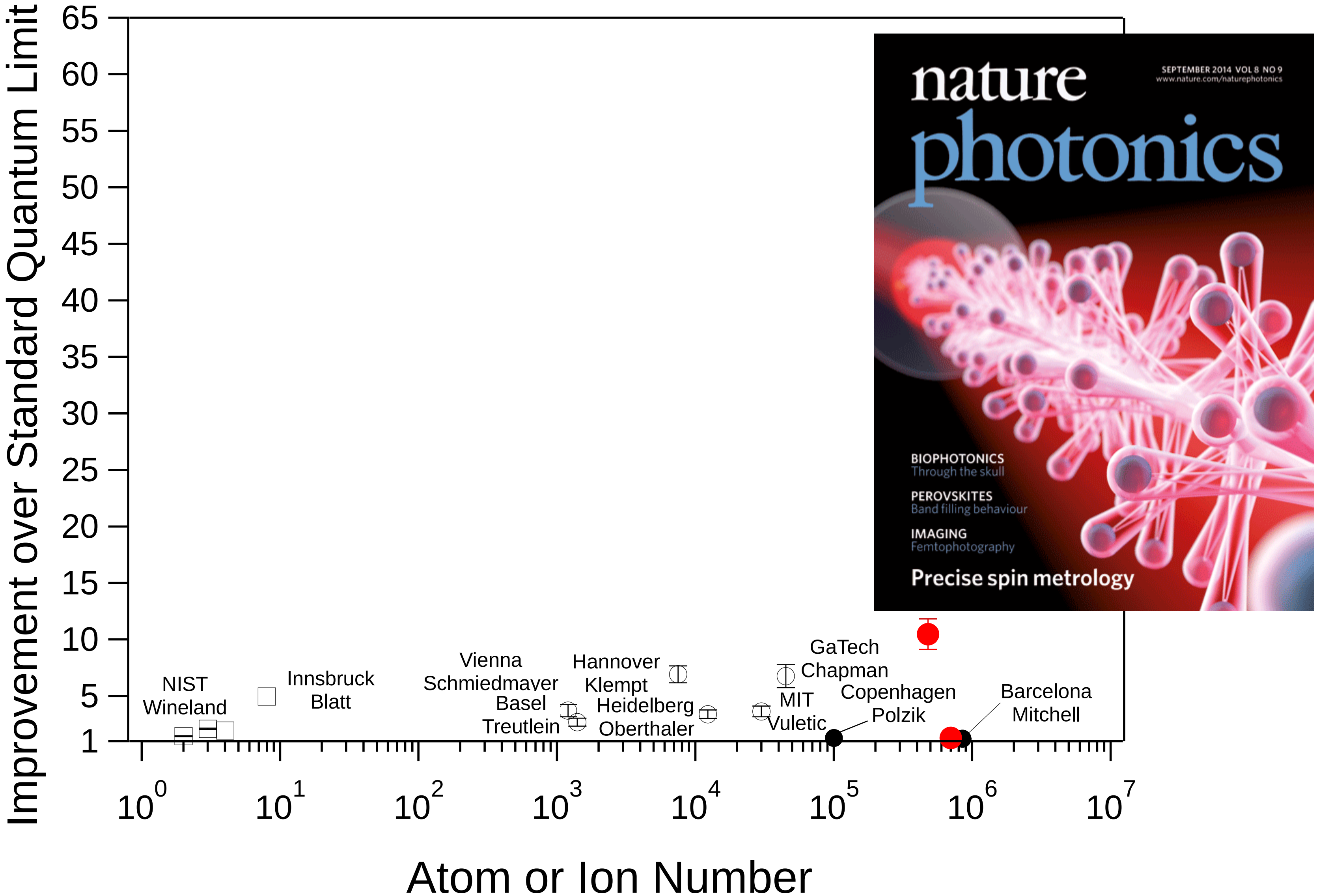
Precision Measurements: Things you can do with **many quantum objects**, that you can't do with **one**?



Entangled atoms cancel each other's quantum noise

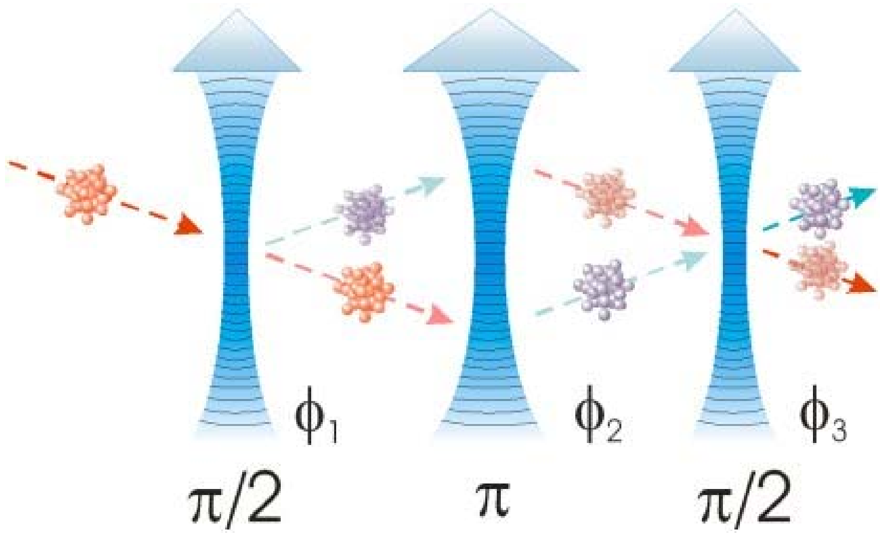
World Record Entanglement

Directly observed enhancement over SQL with no background subtractions



Technology: Matterwave Interferometers

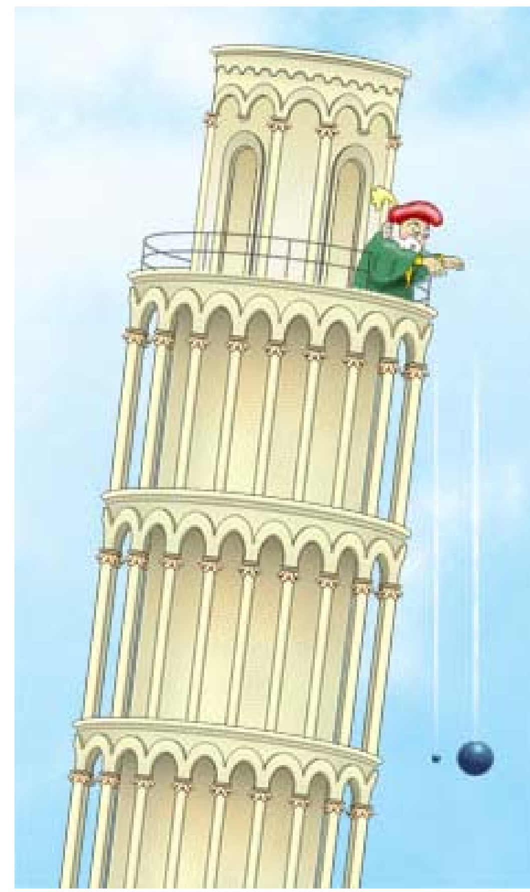
Use pulses of light to spatially
split the atomic wave function



Credit: A. Peters group

Einstein's equivalence principle
Determine gravitational constant G
Detect gravity waves?

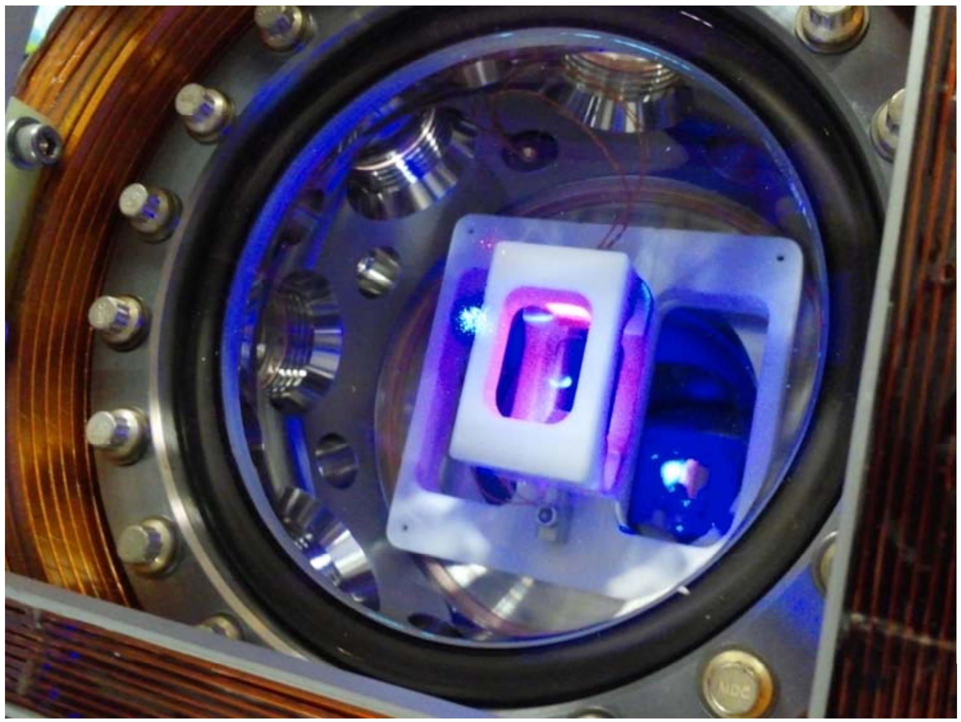
GPS free navigation
Gyroscopes
Accelerometers
Gravimetry
Fundamental constants of nature
Tests of QED
Test atomic charge neutrality



Technology: Optical Lattice Clocks

- **Extended to our strontium system**
- **Improved optical lattice clocks of Ye, Ludlow et al**

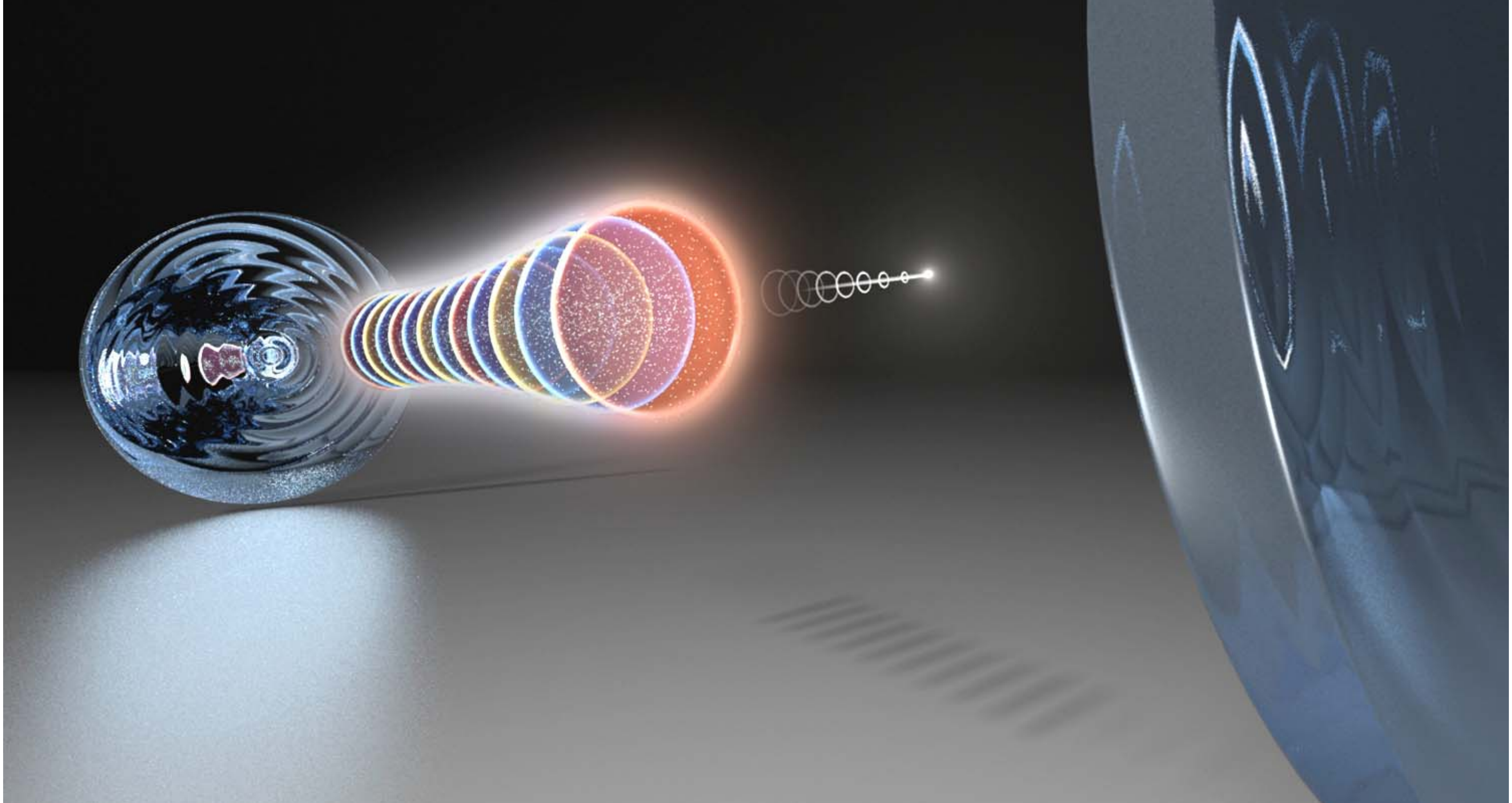
M.A. Norcia, J.K. Thompson arxiv:1506.02297 (2015)



Many Key Advantages of Optical Approach

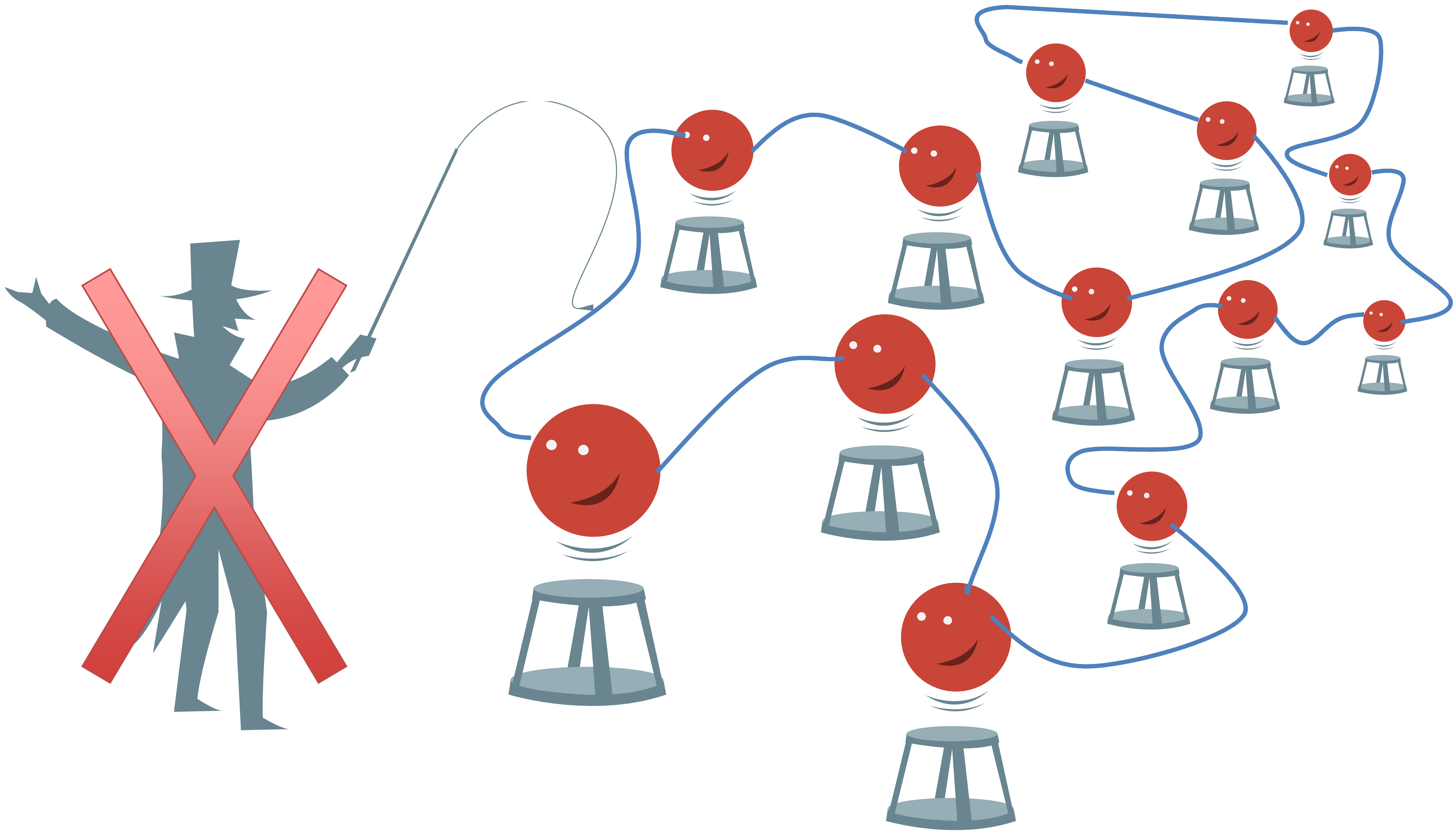
- Very fast: 40 μs
- Avoids inaccuracies
- Non-destructive for higher bandwidth

Superradiant Lasers: Ultraprecise Rulers of Time and Space



JG Bohnet, Z Chen, JM Weiner, D Meiser, MJ Holland & JKT, *Nature* 484, 78-81, April 5, 2012

Collective Synchronization

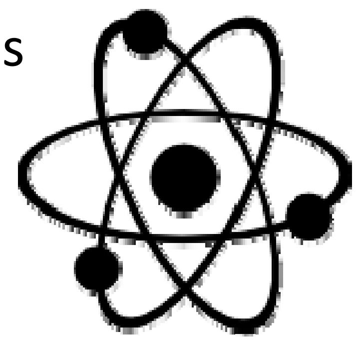


Atoms collectively store information inside laser

Laser is *the* Central Ruler of **Time** & Space

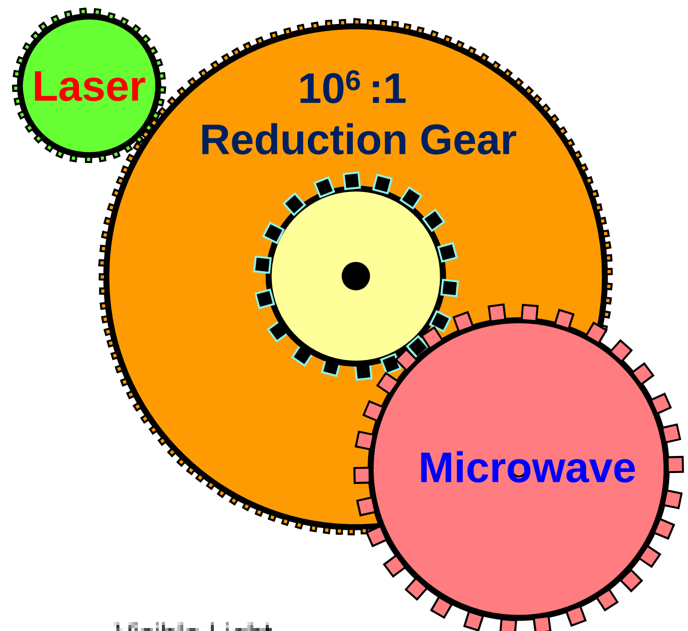
<u>Optical Atomic Clock</u>

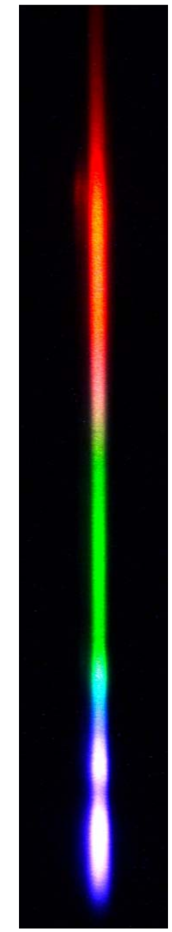
Quantum atoms

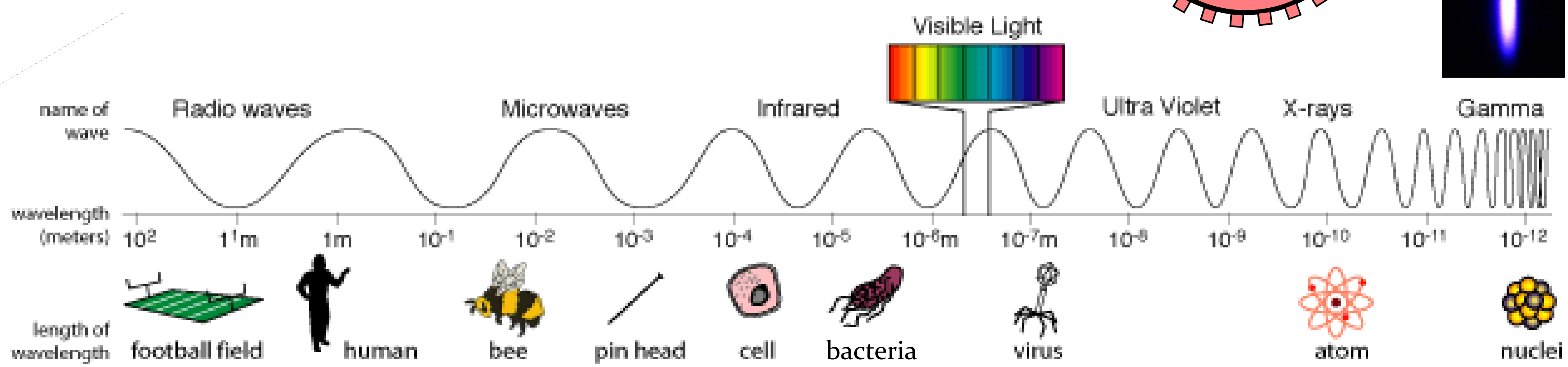


Classical probe laser

<u>Optical frequency comb</u>

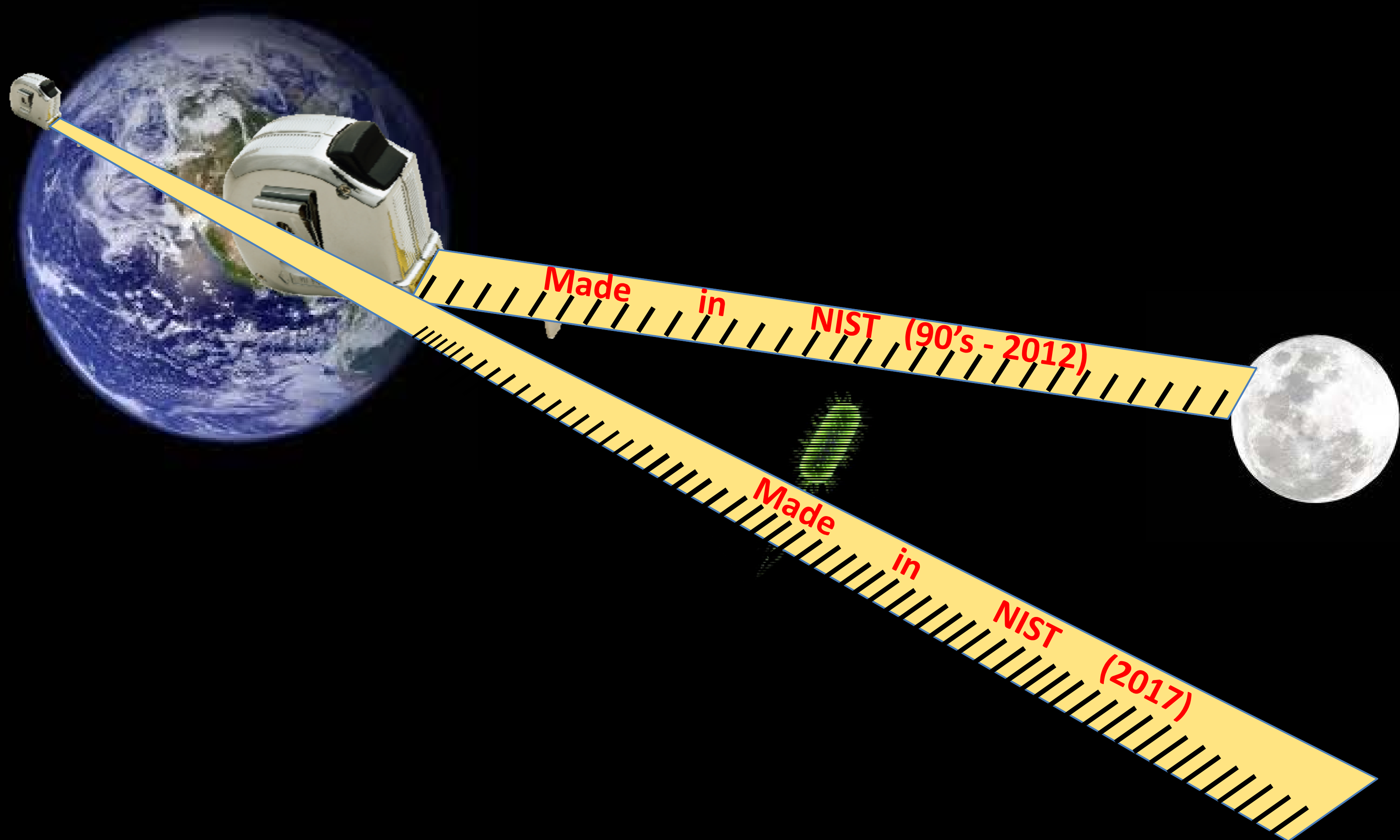






A Sharper Ruler

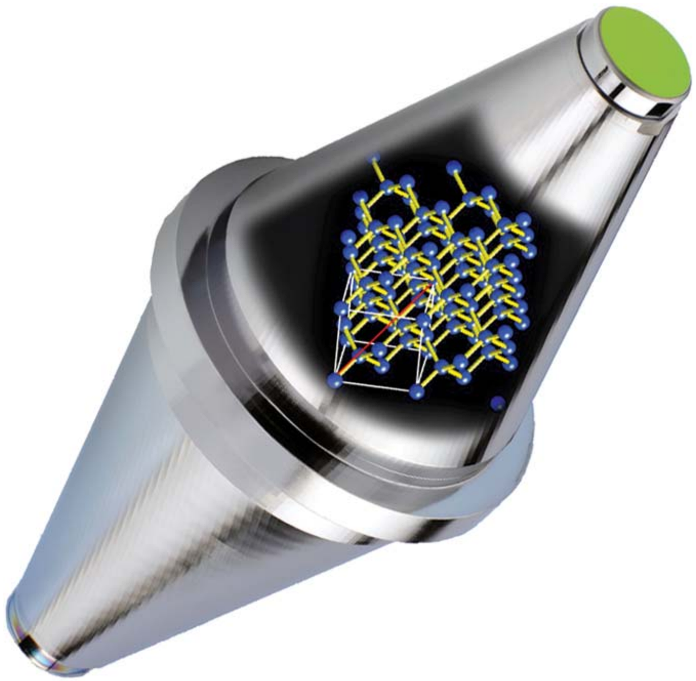
A Sharper Ruler



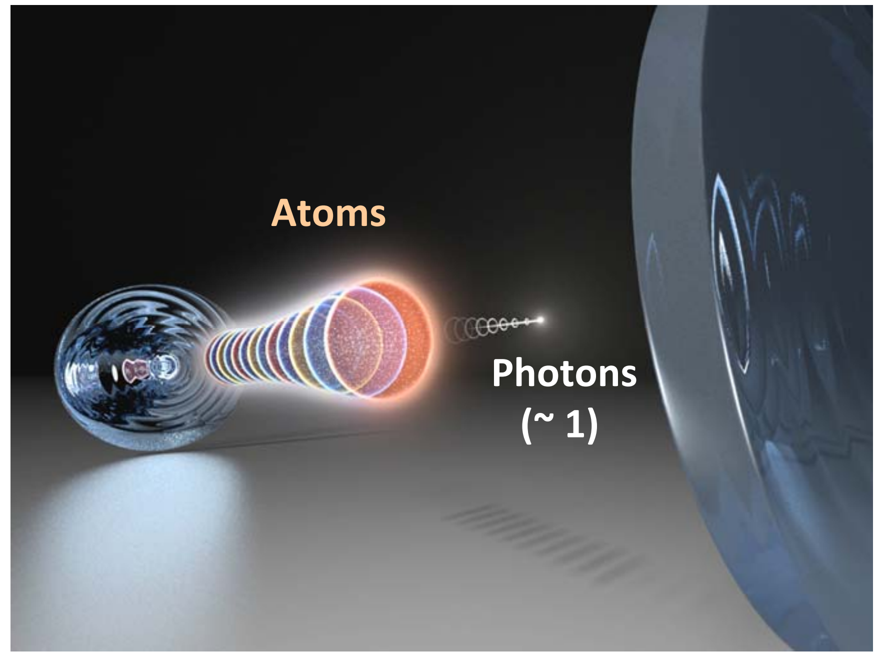
IMS: Two Innovative Paths

Thompson, Ye, Jin, Holland, Rey, Gorshkov

Ye Lab: New Optical Materials



Thompson Lab: Superradiant Laser

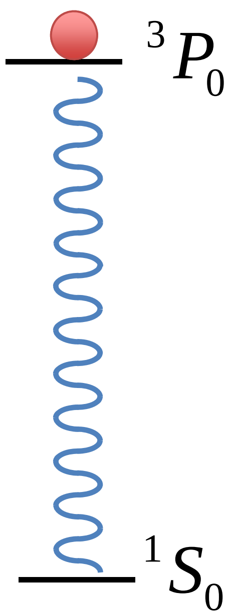


Goal: x 100 improvement
Radically different approach
Quiet laser lab not needed

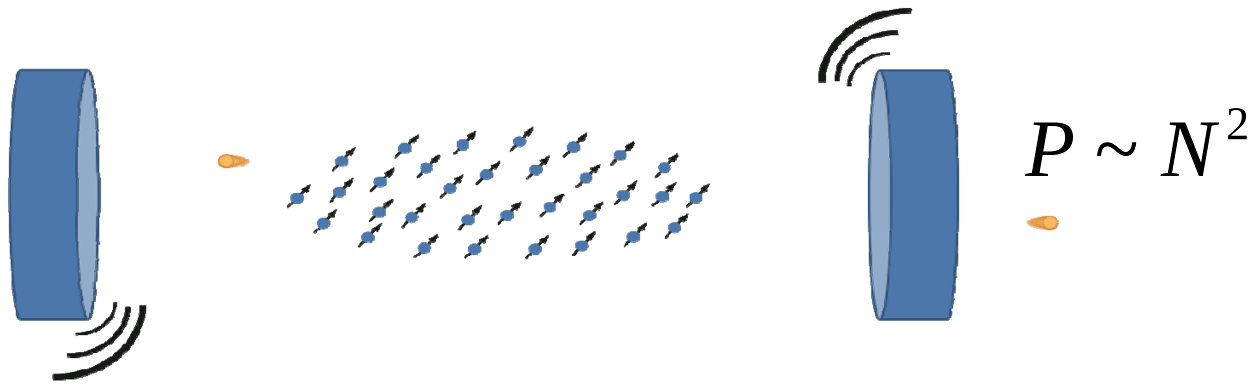
Lasing on ultranarrow atomic transitions

Meiser, Ye, Carlson, Holland, *PRL* **102**, 163601 (2009)
JG Bohnet, Z Chen, JM Weiner, D Meiser, MJ Holland & JKT, *Nature* **484**, 78-81, 2012

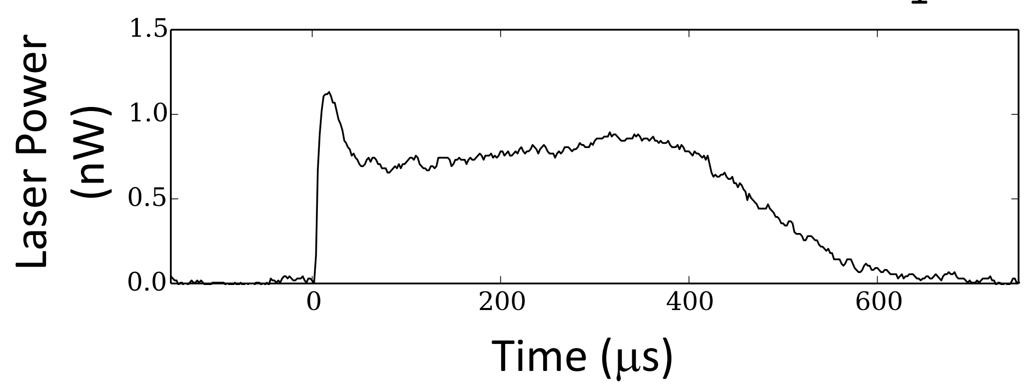
Strontium
Lifetime 150 seconds



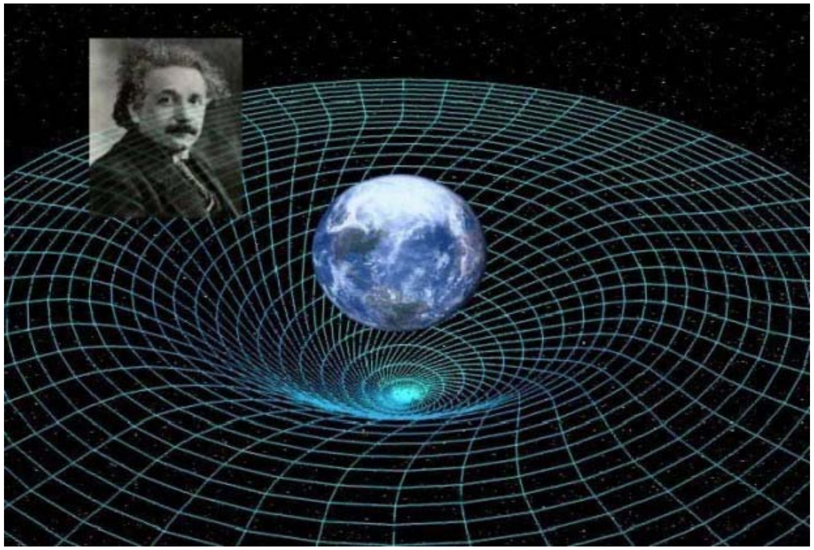
>10,000 x less sensitive to cavity noise
~1 mHz quantum linewidth, Q~ 10^{18}



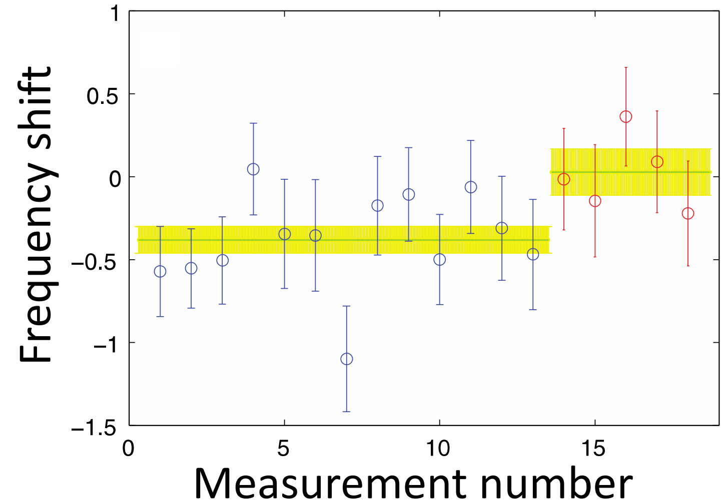
Stepping Stone: Lasing on 7.5 kHz $^3P_1$ transition



Gravity’s Impact on Time



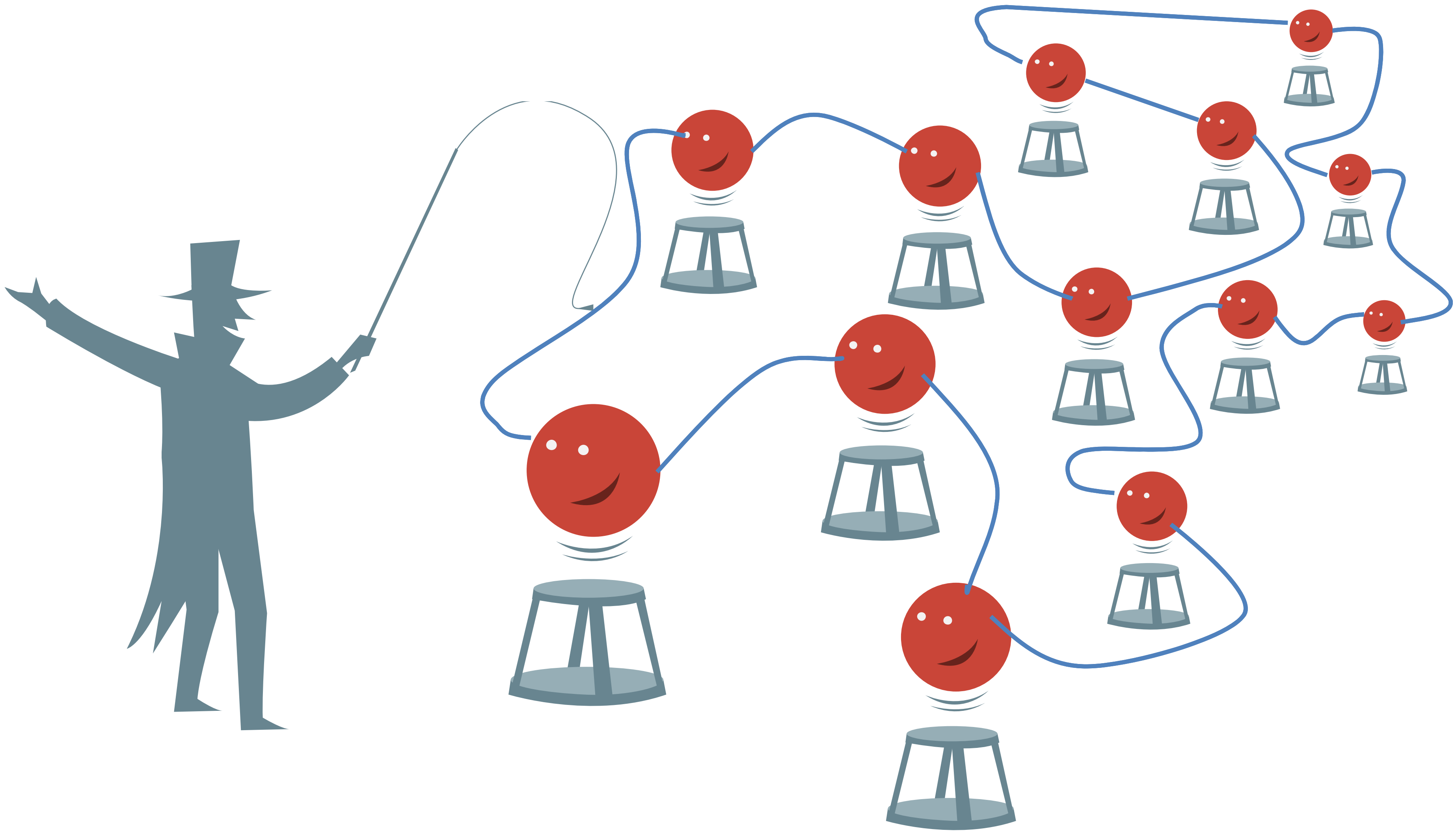
NIST Al$^+$ clock



~ 30 cm in 1 day

Proposed IMS work: ~1 cm in 1 second!

Vision for New Frontier of Precision Measurements

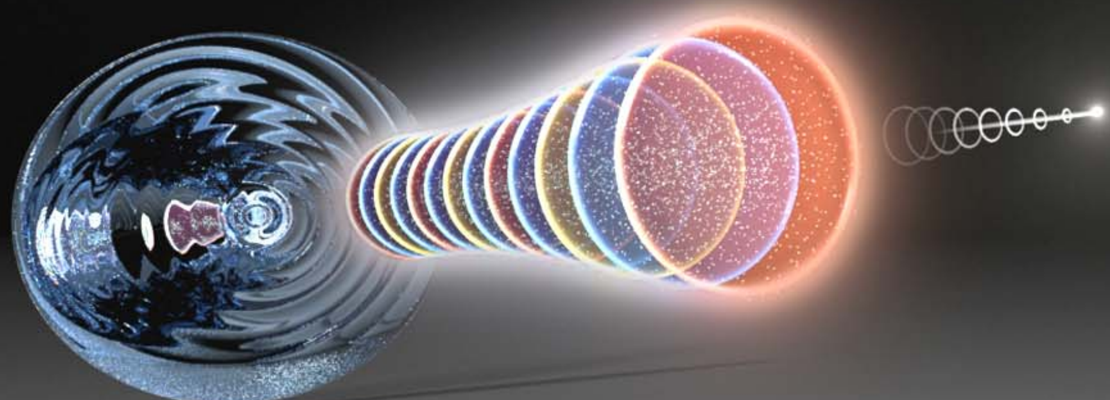


Can we move beyond the single atom paradigm?

Thanks to the Team :

Rubidium
Justin Bohnet (NRC postdoc)
Kevin Cox
Joshua Weiner
Zilong Chen (Data Storage Inst.)
Graham Greve
Jiayan Dai, Shannon Sankar

Strontium
Matthew Norcia
Karl Mayer
Matthew Winchester



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Steven Moses (JILA)
Katherine McAlpine (UW)
Elissa Picozzi (Whitman College)
Michelle Chalupnik (U. Chicago)

DARPA QUASAR, ARO, ONR, NSF PFC, NIST, NSF GRF, NDSEG, A*STAR