Controlling the Quantum World with Light

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National Laser Centre

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Collaborators

UNIVERSITY OF KWAZULU-NATAL

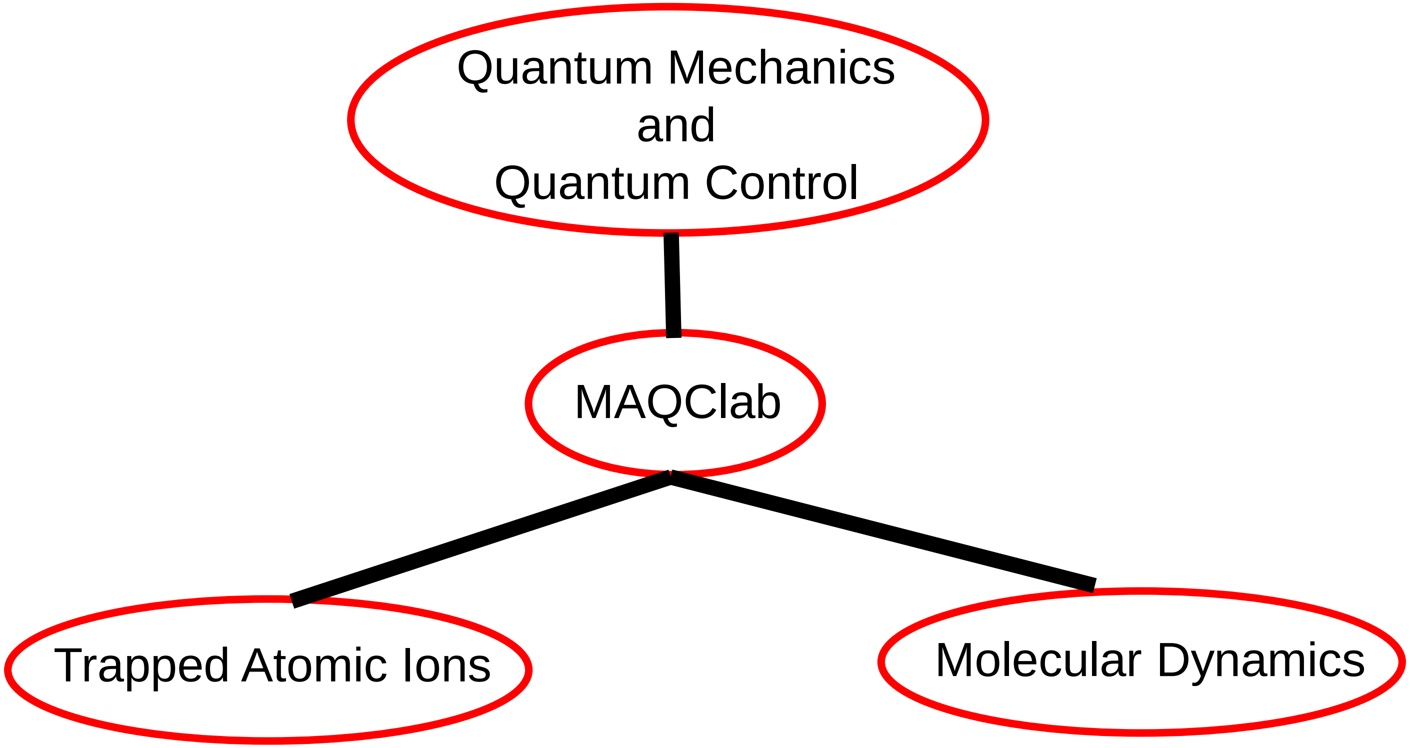
NIST

National Research Foundation (NRF)

THE UNIVERSITY OF SYDNEY

Georgia Tech

Overview



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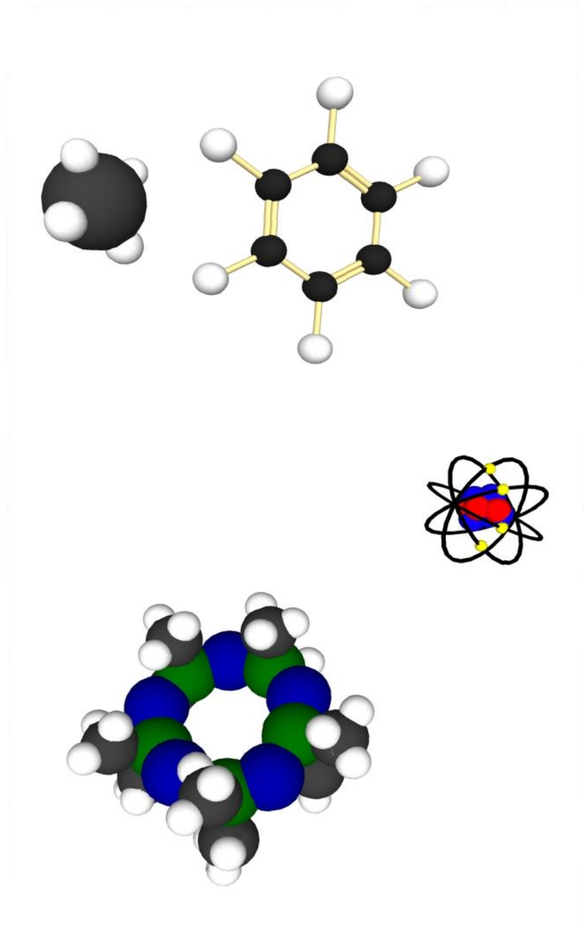
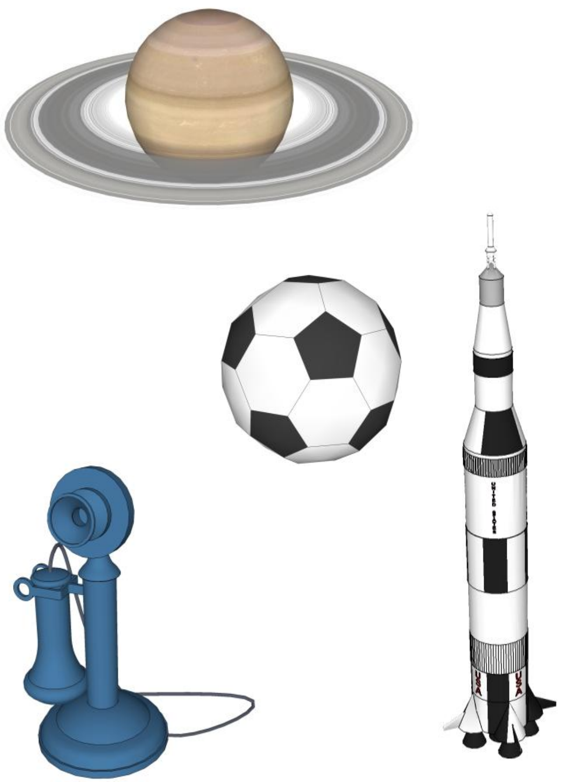
The Quantum versus the Classical World

Quantum world



Classical world



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The Quantum versus the Classical World

Quantum world

- Wave-particle duality
- Superpositions
- Heisenberg uncertainty
- Interference
- Entanglement
- Measurement outcomes statistical
- Strong measurement back-action
- Tunneling

$$\frac{\partial \psi(x,t)}{\partial t} = \hat{H}\psi(x,t)$$

Schrödinger Equation

Classical world

- Waves or particles
- Deterministic
- Trajectories
- Certainty in measurement
- No measurement back-action

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = 0$$

Euler-Lagrange Equation

Many Quantum Technologies

- Superconducting qubits
- Semiconductor charge qubits
- Quantum dots
- Photons
- Microfabricated cantilevers
- Atom interferometers
- Ultra-cold gases
- Single trapped ions
- Molecules

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MAQClab mission

Exploit phenomena which are explicitly quantum mechanical in pursuit new applications

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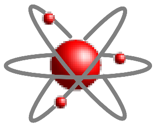
Quantum Physics Applications

Magnetic Resonance Imaging

(Superposition)

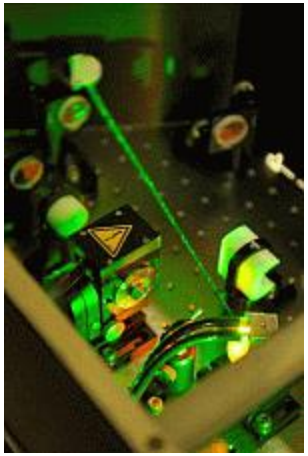
Atomic Clocks



(Superposition)

Quantum Physics

Lasers



(Bose stimulation)

Tunnel Magnetoresistance
(Tunneling)

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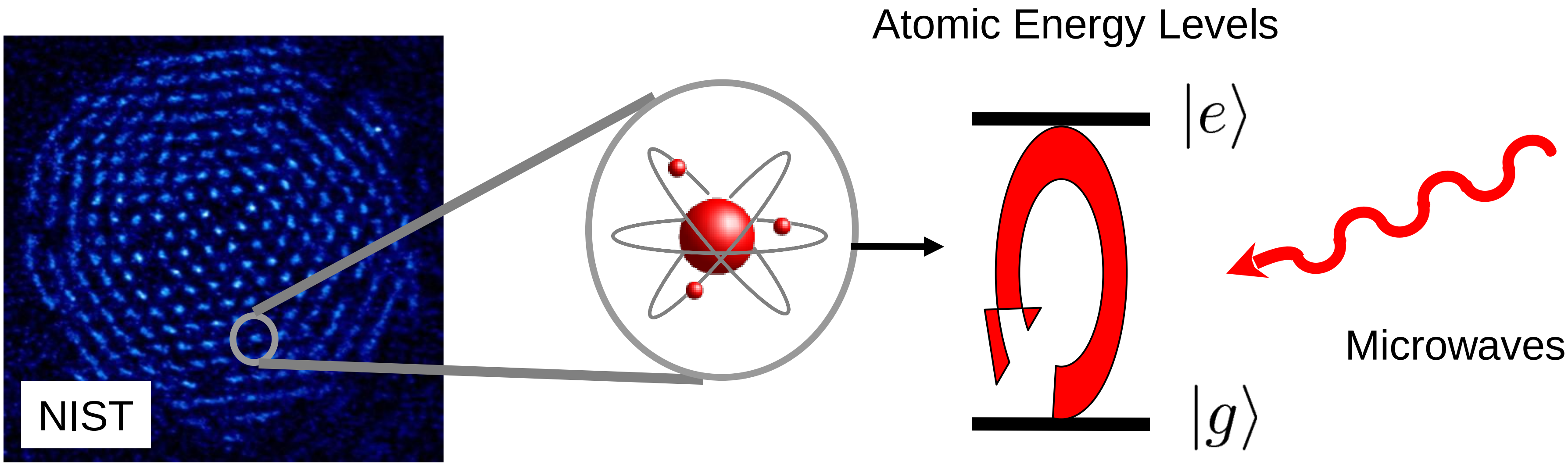
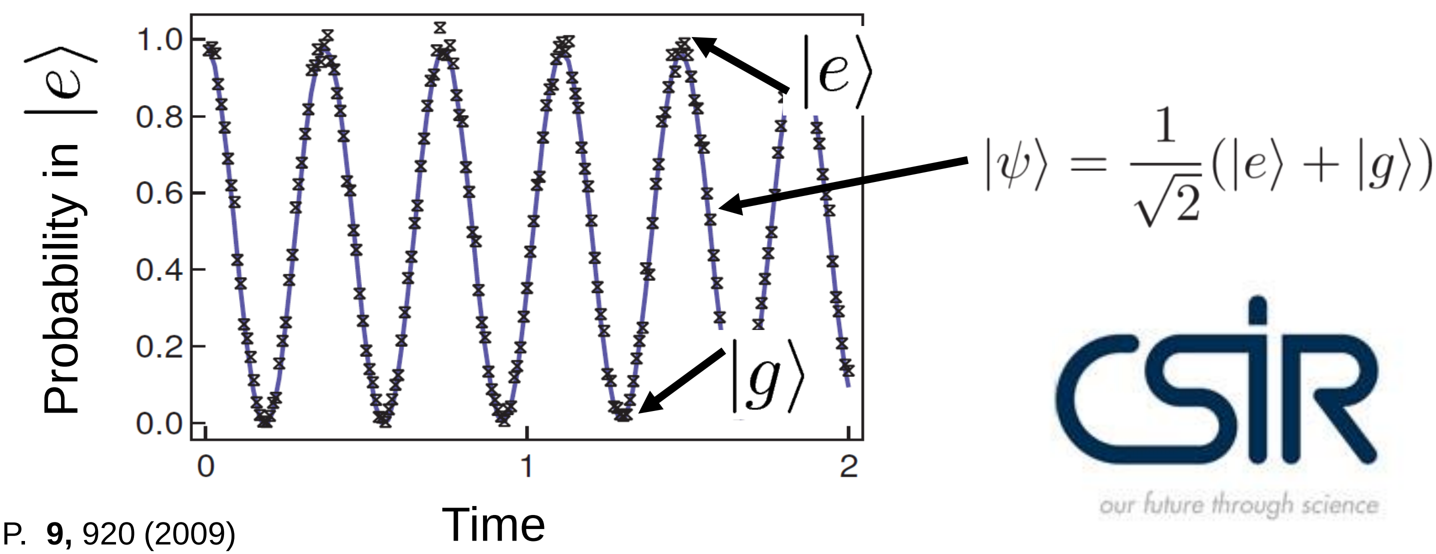
Quantum Control – a simple example

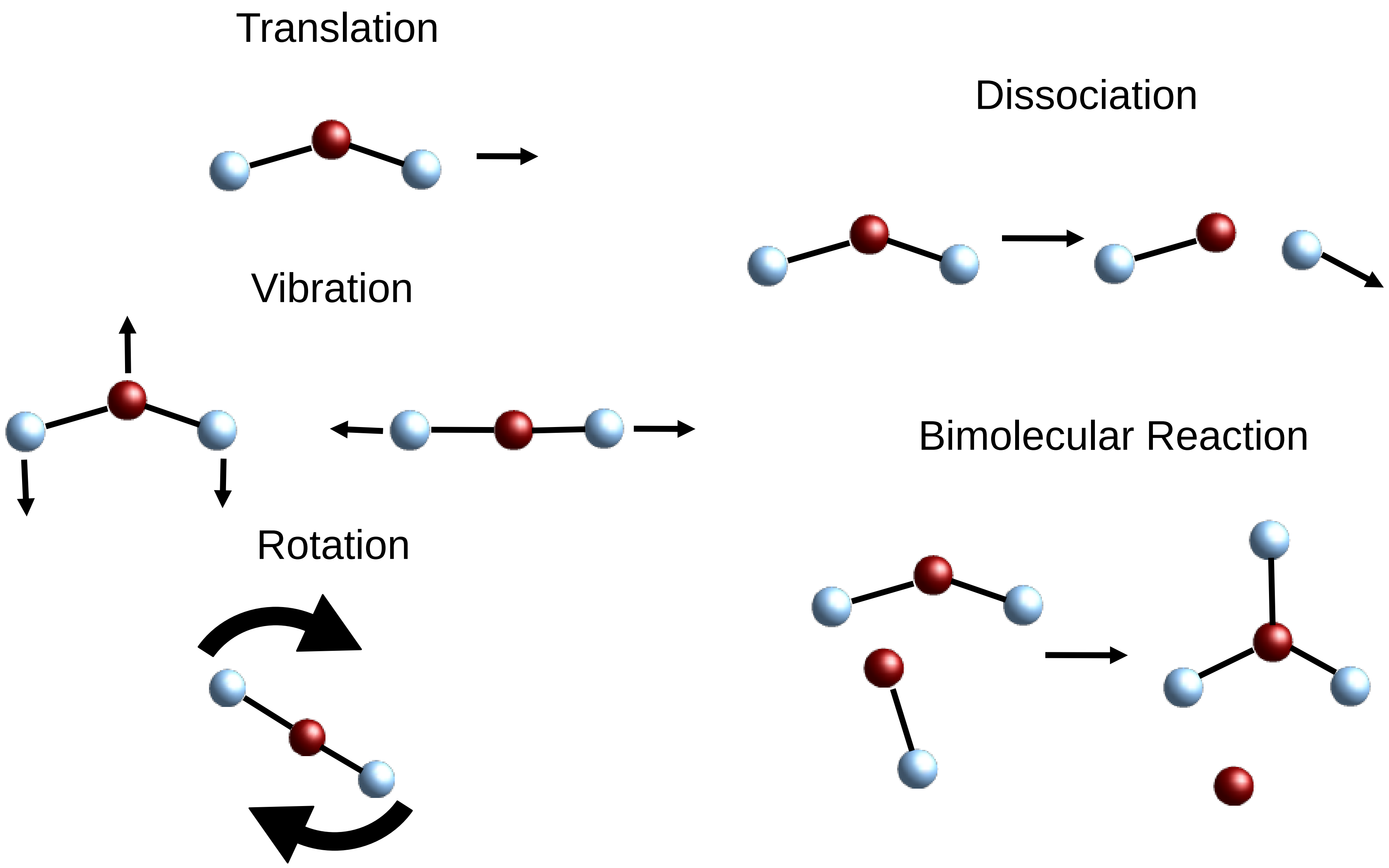


Rabi Oscillations

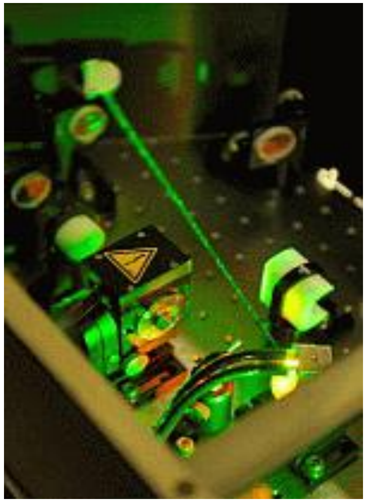


QUANTUM INF. & COMP. **9,** 920 (2009)

Molecular Dynamics

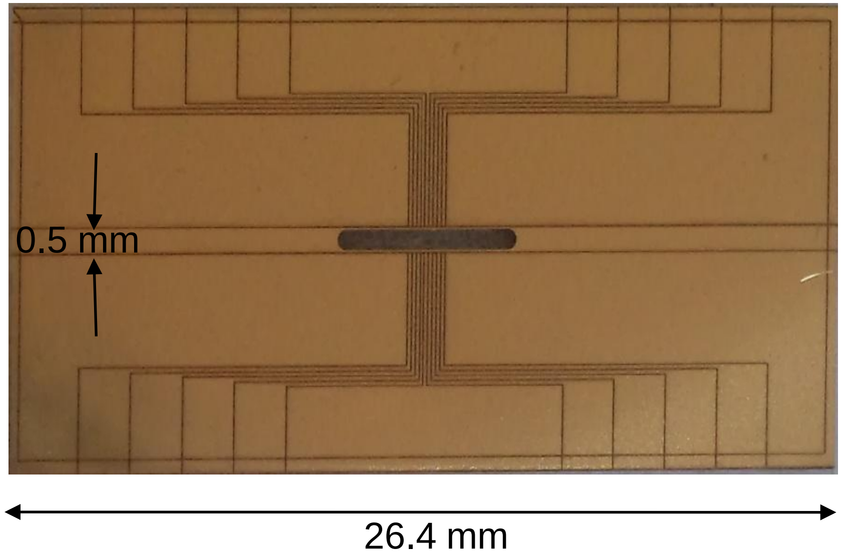


MAQClab Capabilities



Trapped Atomic Ions

- Narrowband continuous wave lasers
- Programmable microwave sources



Molecules

- Femtosecond pulsed lasers
- Pulse shaping instrumentation
- Pump-probe techniques

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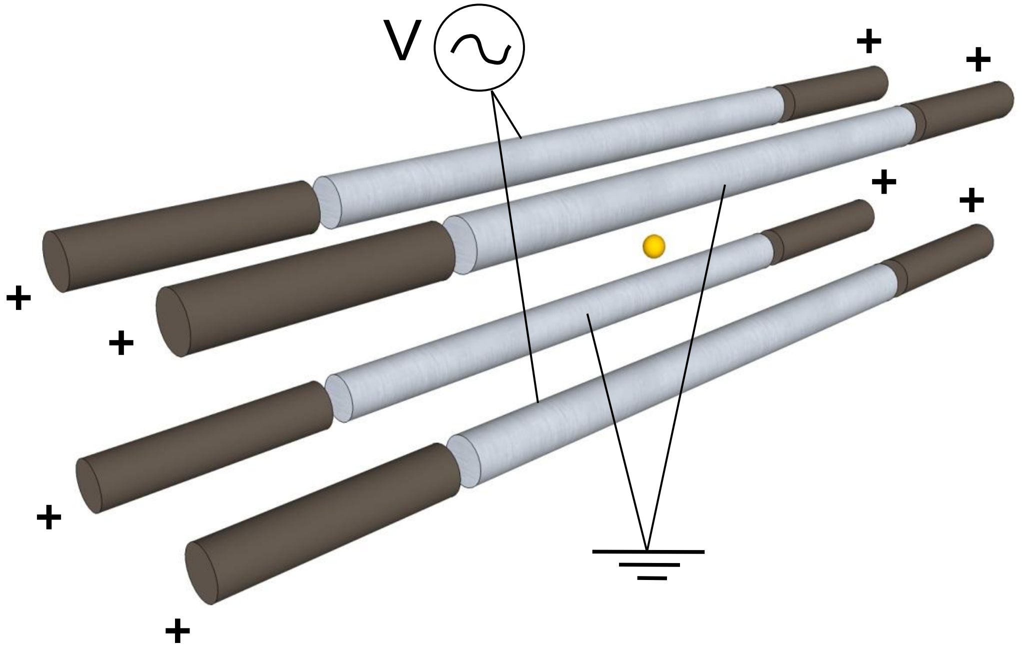
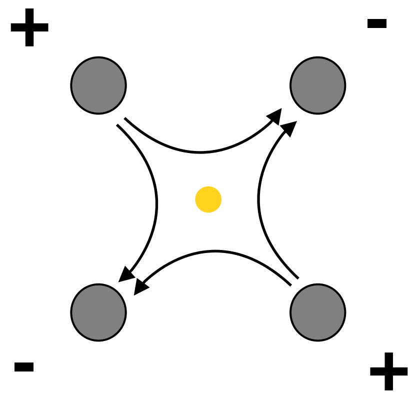
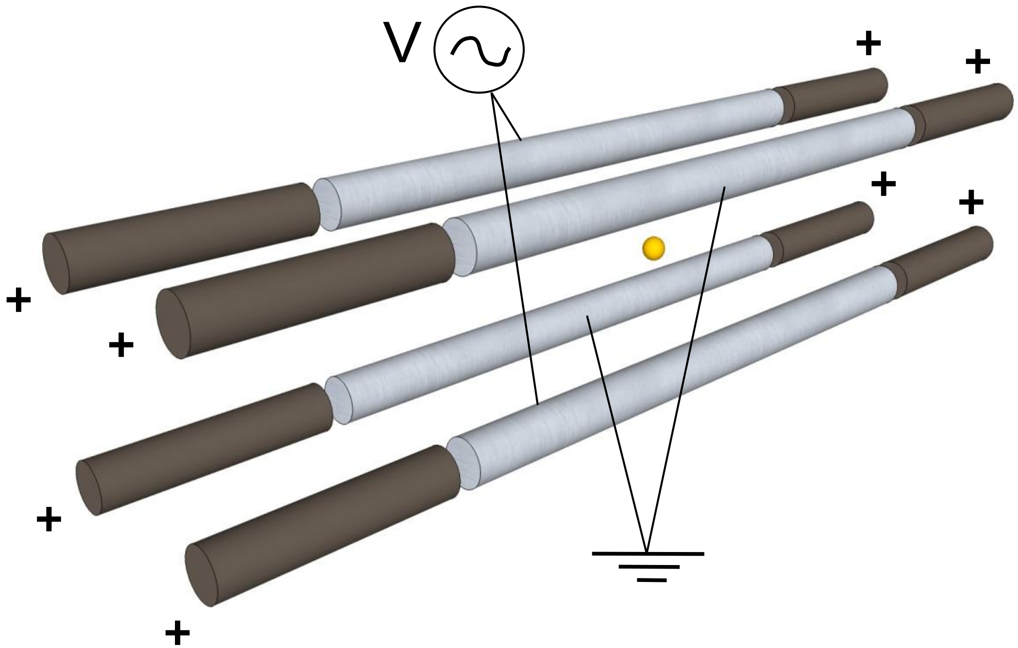
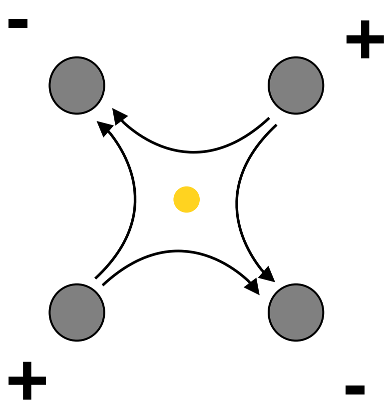
Trapping basics – Linear Paul Traps



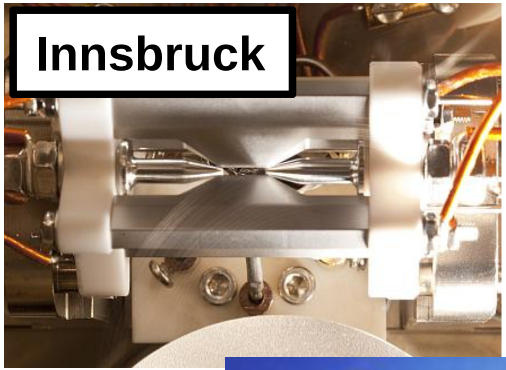


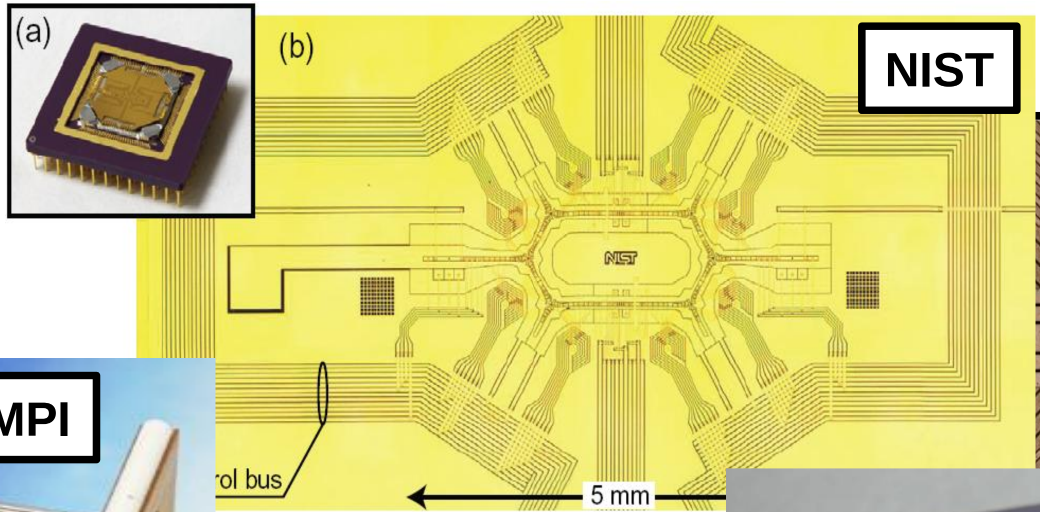
Trapping basics – Linear Paul Traps

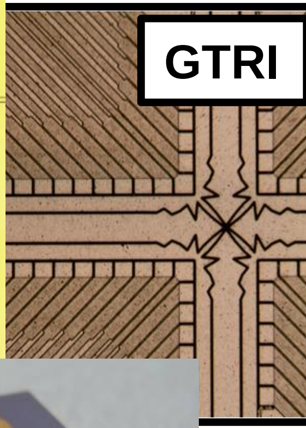


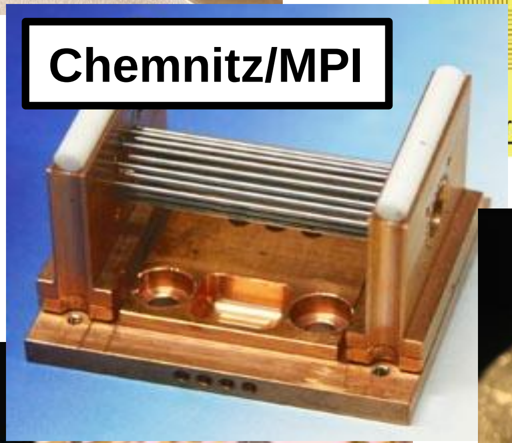


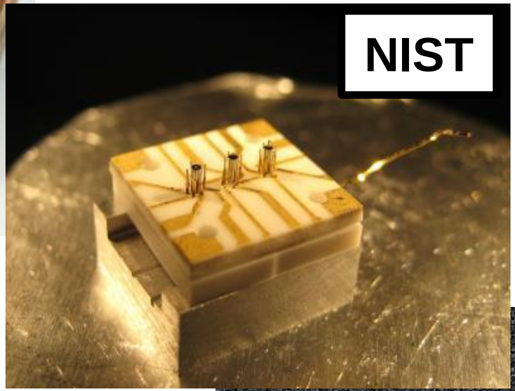
Traps

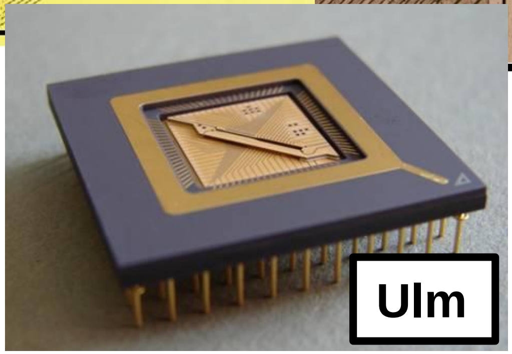

Innsbruck

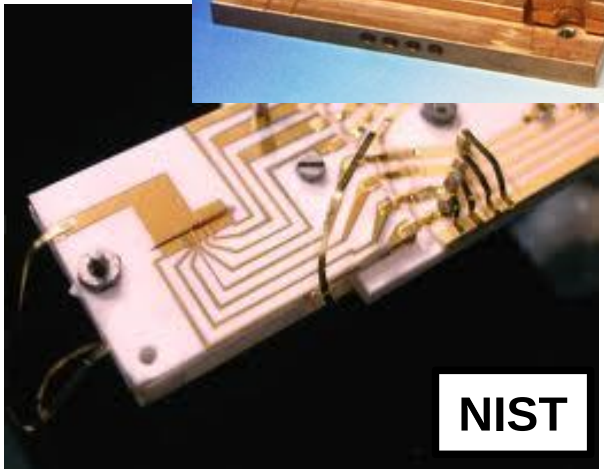

(a)
(b)
NIST
rol bus
5 mm

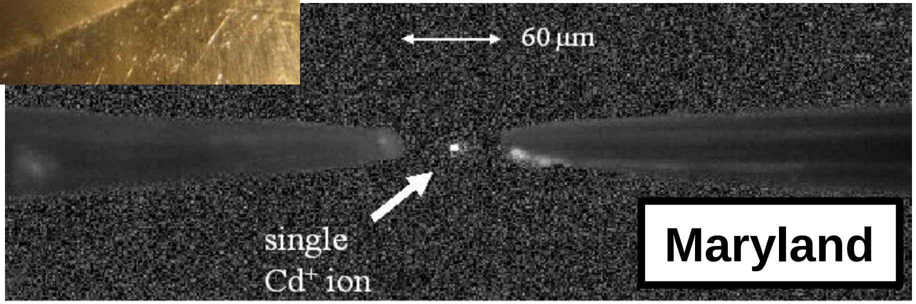

GTRI


Chemnitz/MPI

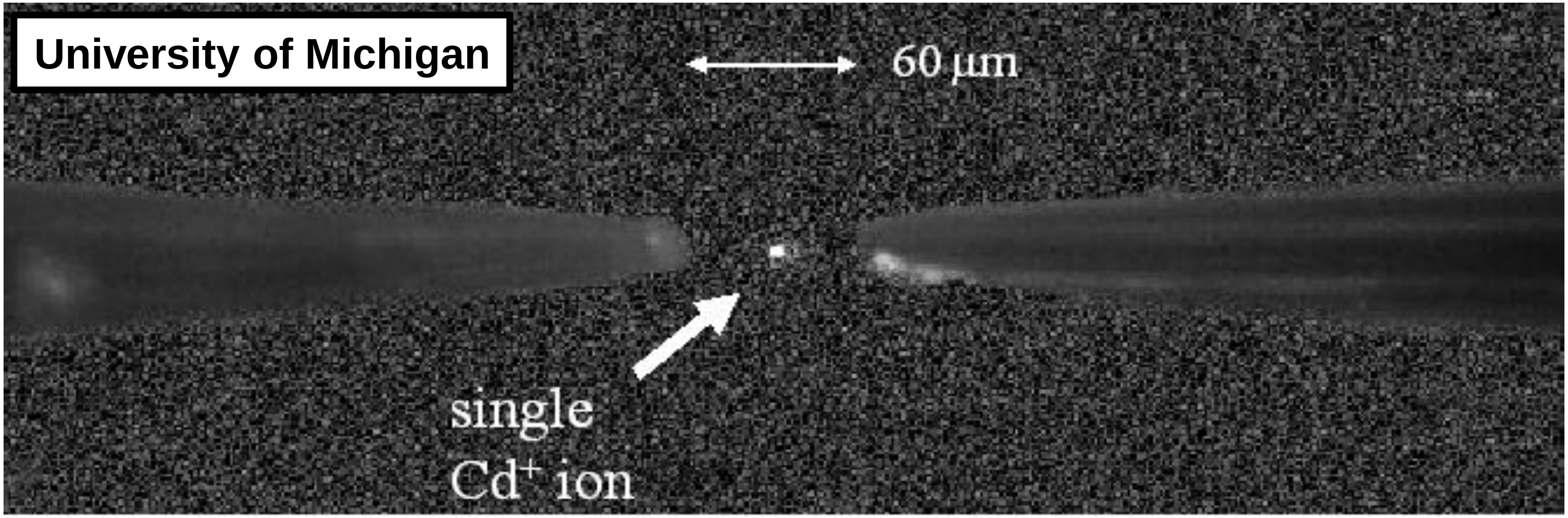

NIST


Ulm


NIST


60 μm
single
Cd+ ion
Maryland

Single Atoms!



First Neuhauser *et al.*, Laser Spectroscopy of a Single Ion, J. Opt. Soc. Am. **70**, 660 (1980)

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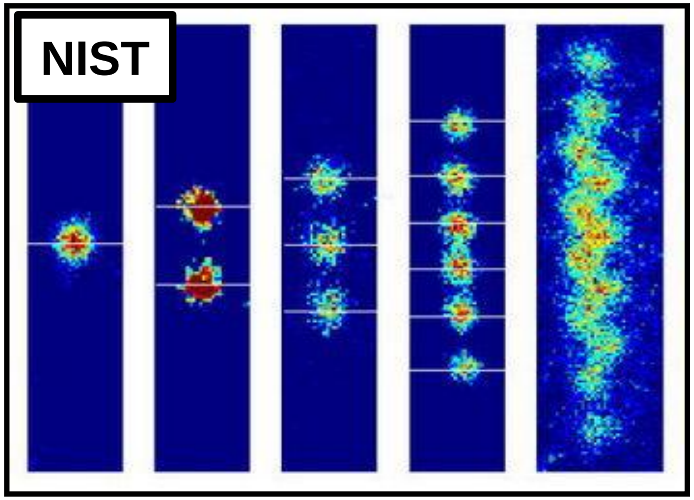
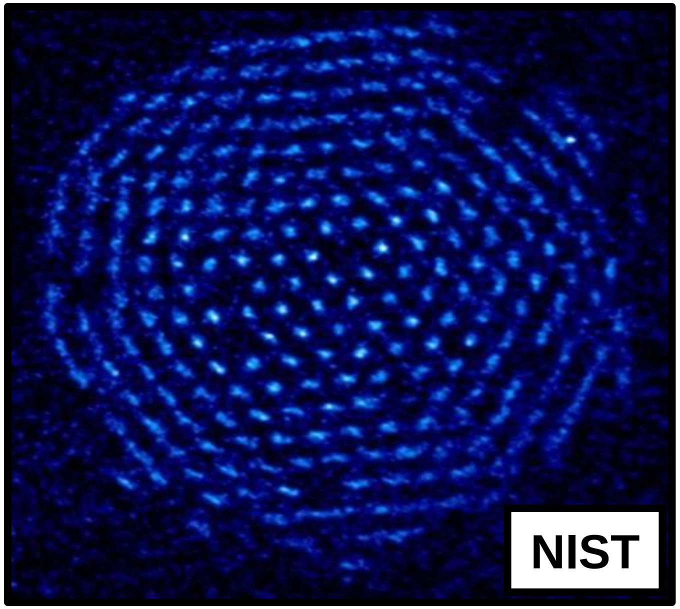
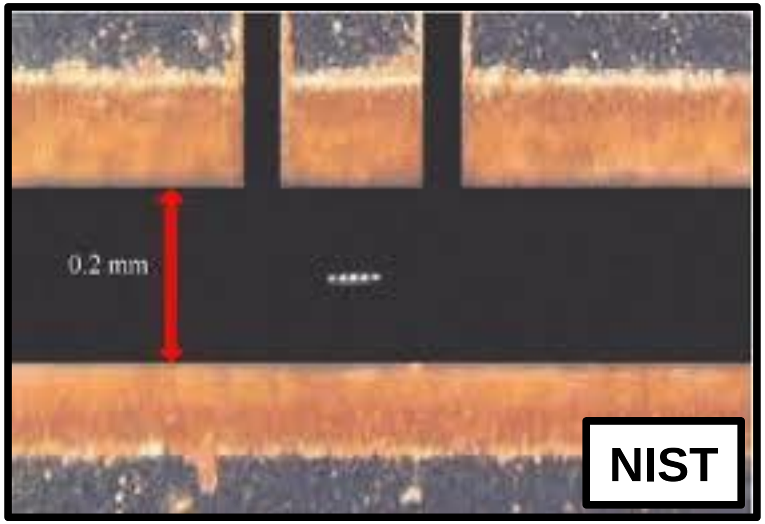
Single Atoms!







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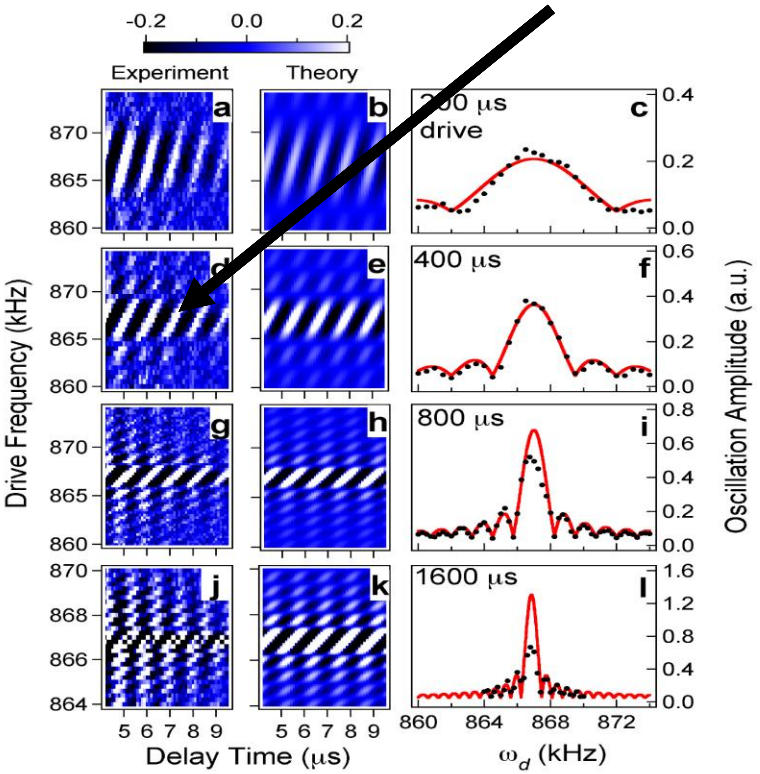
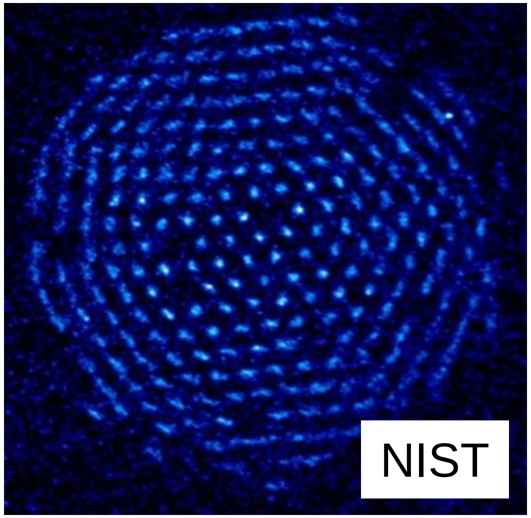
Ultra-sensitive precision measurement - Force

Oscillations in ion fluorescence due to tiny force





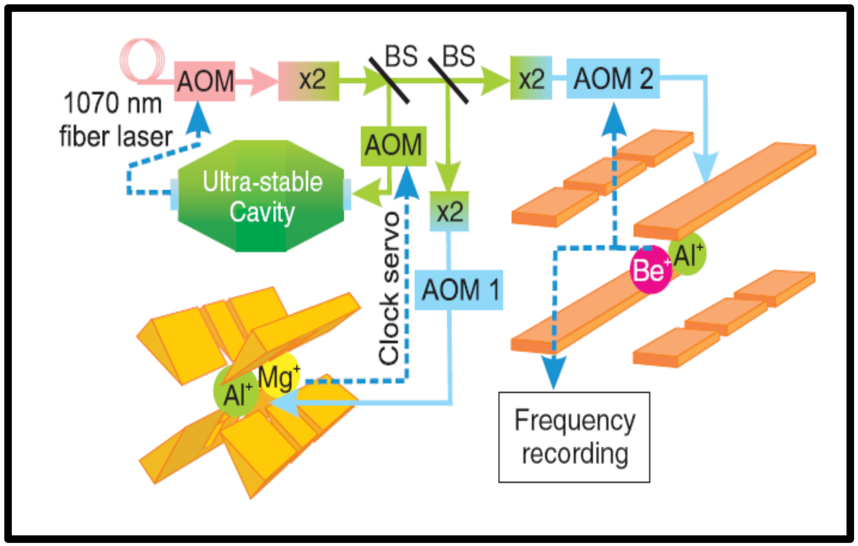
Biercuk *et al.*, Nature Nanotech **5**,646 (2010)

F_d = 174 yN   (Remember: weight due to 1kg on earth = 10 Newton)

1 yoctonewton = 1×10^{-24} Newton = 0.000000000000000000000001 Newton

Ultra-sensitive precision measurement - Time

Quantum Logic Spectroscopy Clock



- Won't lose a second in 4 billion years
- Age of the universe: 13.7 billion years

PRL **104,** 070802 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks

C. W. Chou,* D. B. Hume, J. C. J. Koelemeij,† D. J. Wineland,
Time and Frequency Division, National Institute of Standards and Technology,
(Received 23 November 2009; published 17 February

fractional frequency difference of -1.8×10^{-17}

We have constructed an optical clock with a fractional frequency inaccuracy of 8.6×10^{-18}, based on quantum logic spectroscopy of an Al^+ ion. A simultaneously trapped Mg^+ ion serves to sympathetically laser cool the Al^+ ion and detect its quantum state. The frequency of the ${}^1S_0 \leftrightarrow {}^3P_0$ clock transition is compared to that of a previously constructed Al^+ optical clock with a statistical measurement uncertainty of 7.0×10^{-18}. The two clocks exhibit a relative stability of $2.8 \times 10^{-15}\tau^{-1/2}$, and a fractional frequency difference of -1.8×10^{-17}, consistent with the accuracy limit of the older clock.

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Quantum Simulation - Supercomputer performance

Fujitsu K computer, 10.51 PFLOPS (2011)

IBM Sequia, 16.32 PFLOPS (2012)

Tianhe-IA, 2.566 PFLOPS (2010)

- Performance measured in Floating Point Operations per Second (FLOPS)

~ 10's Petabytes of memory

~ 10 MWatt power consumption

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Why quantum simulation?

- Hilbert space for *N* two-level systems: $D \sim 2^N$

  N=2:

- Memory for N=10: $8*2^{10} \sim$ 8 KB (Floating point notation 8 bytes per number)

  N=20: $8*2^{20} \sim$ 8 MB

  N=30: $8*2^{30} \sim$ 8 GB

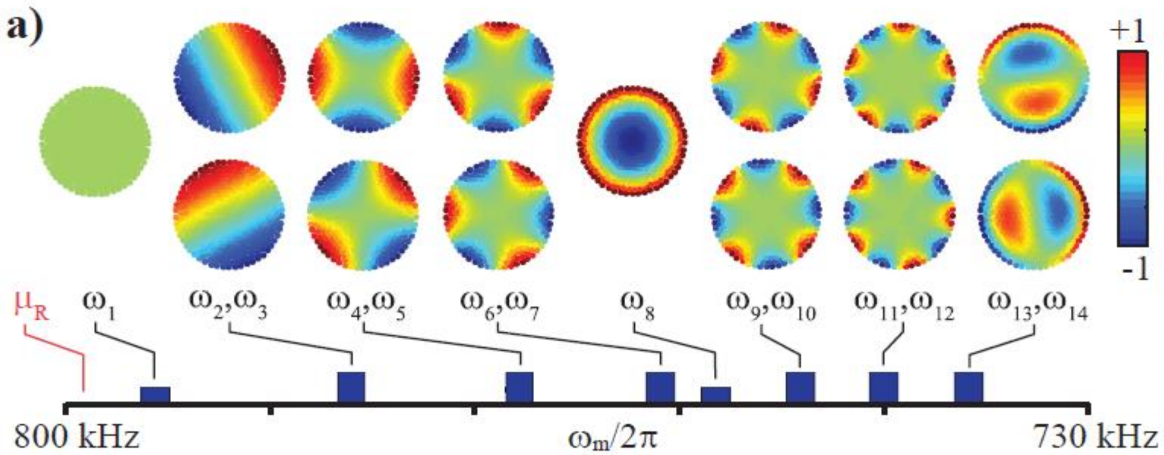
- Size of density matrix 2^{2N}

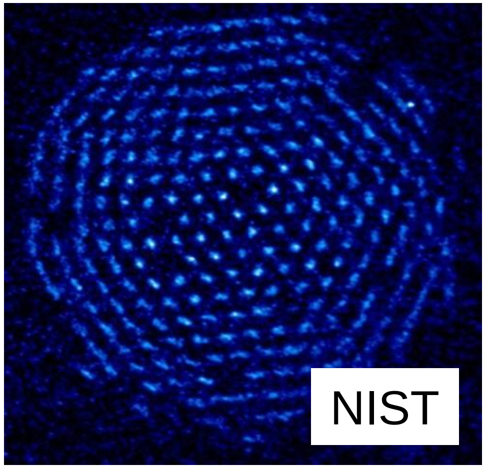
- Memory for N= 20: $8*2^{40} \sim$ 8.7 TB

  N= 25: $8*2^{50} \sim$ 9 PB

Quantum simulation of Quantum Magnetism

Modes of Motion of an Ion Pancake





Engineered two-dimensional Ising interactions in a trapped-ion quantum simulator with hundreds of spins. Nature ***484****, 489 (2012)*

350 Particles: Computationally relevant regime
(Memory required for classical computer: 2^{700} = 5×10^{10}xgoogol^2 numbers..?)

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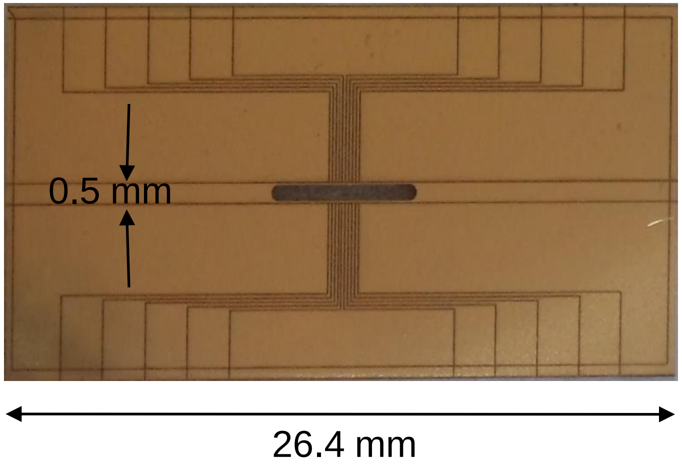
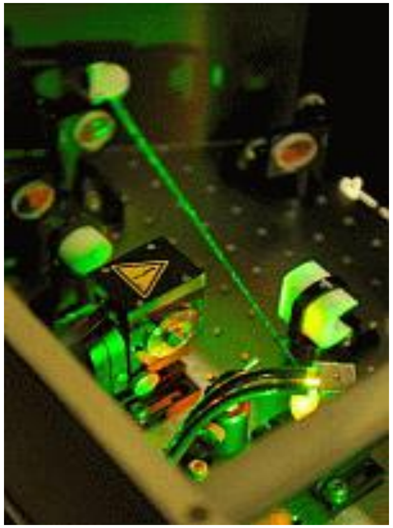
MAQClab Capabilities

<u>Trapped Atomic Ions</u>

- Narrowband continuous wave lasers
- Programmable microwave sources





<u>Molecules</u>

- Femtosecond pulsed lasers
- Pulse shaping instrumentation
- Pump-probe techniques

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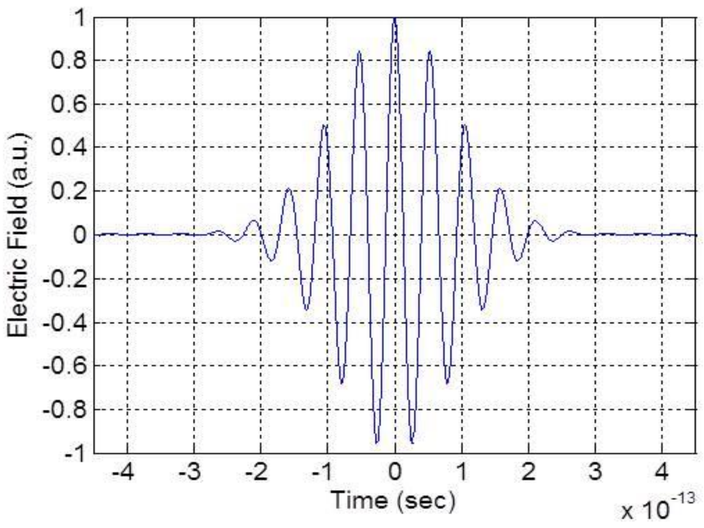
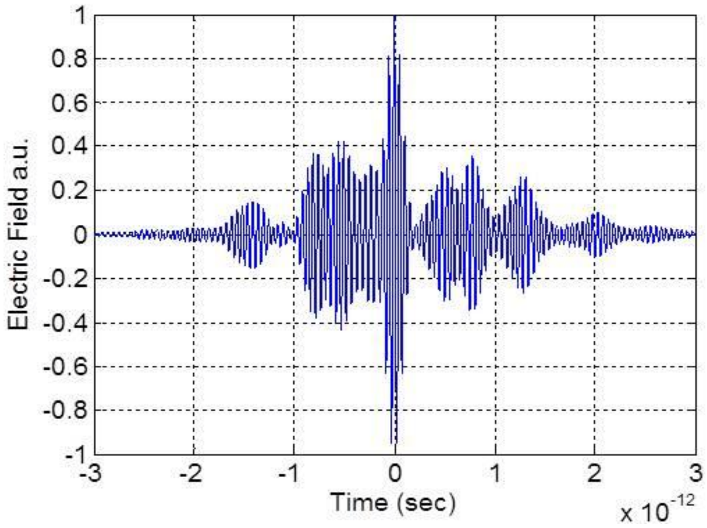
Shaped vs. Unshaped Laser Pulses

Gaussian Pulse



Shaped Pulse



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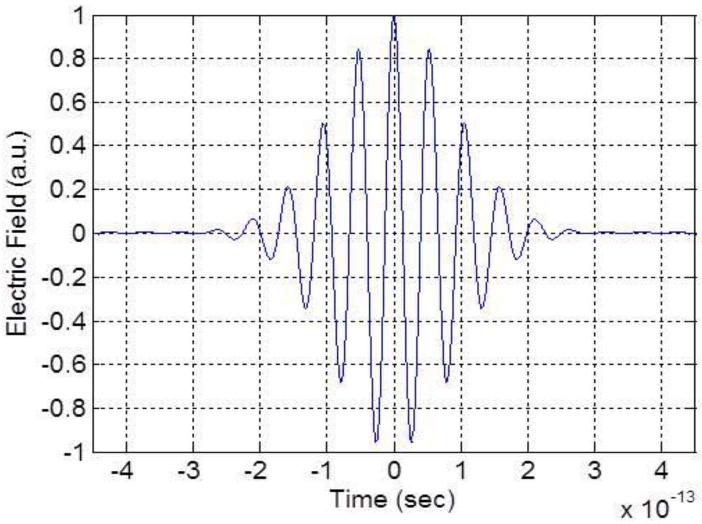
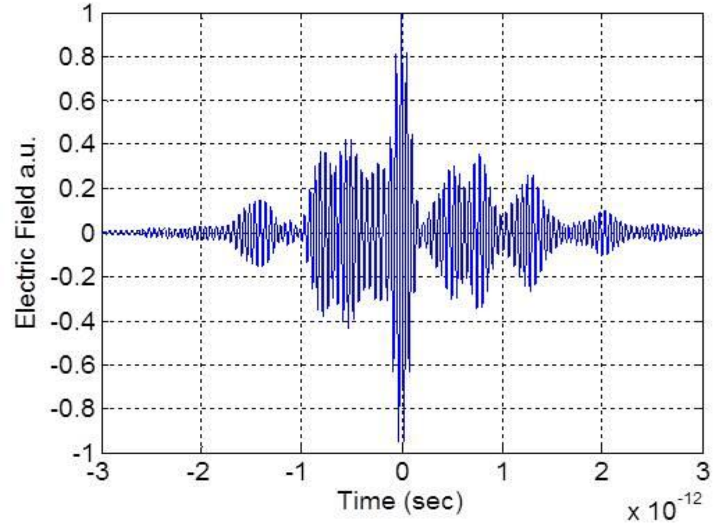
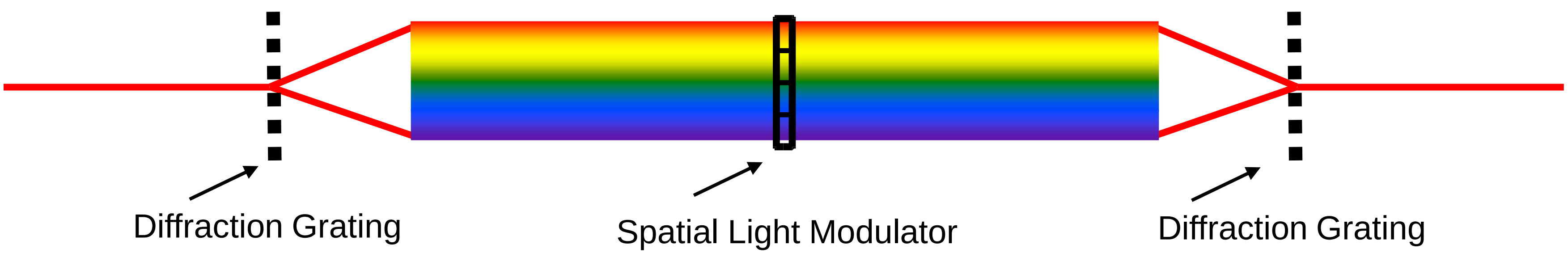
Shaping a Laser Pulse

Gaussian Pulse

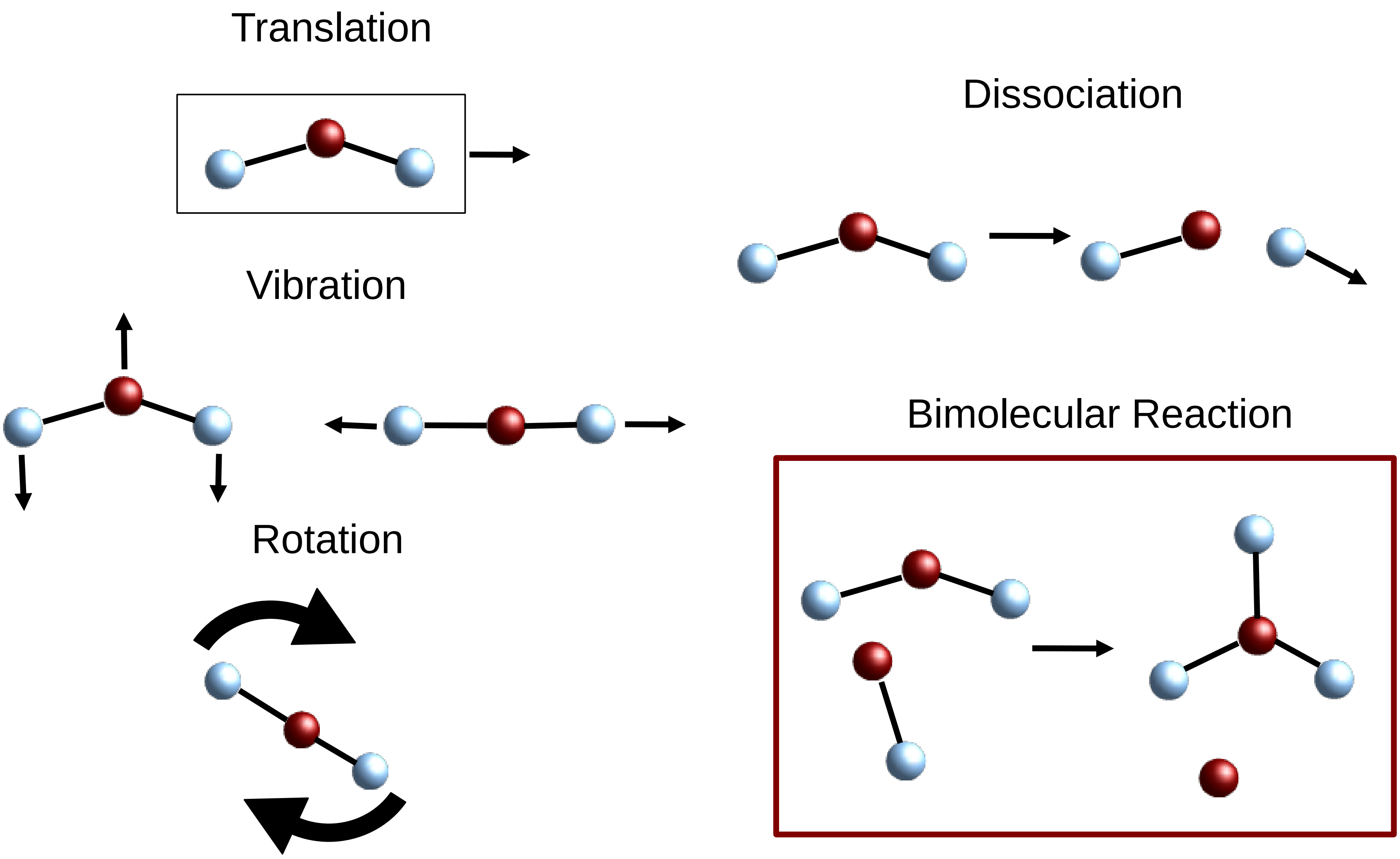


Shaped Pulse



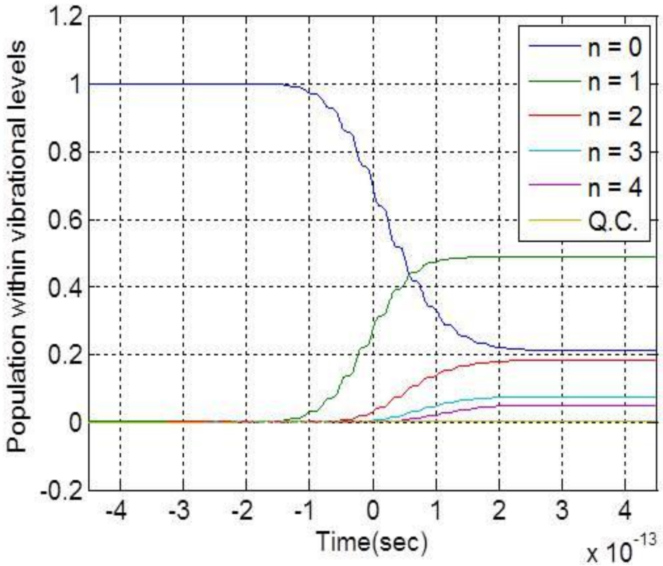


Molecular Dynamics

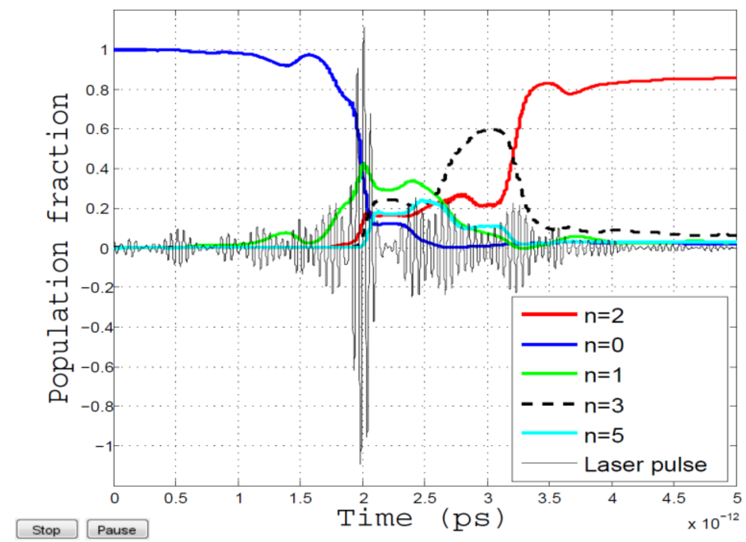


Quantum Control Simulation (Vibrational Excitation)

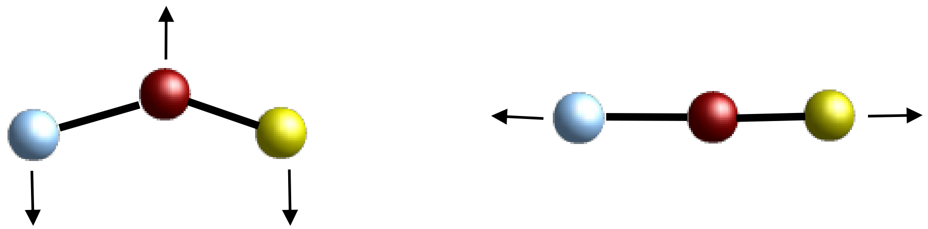
Gaussian Pulse



Shaped Pulse



“n” labels the amount of energy in a specific vibrational mode of a molecule
(Lourens Botha, Ludwig de Clercq, Ramathabathe Madigoe, Andre Smit)



E.g. modes of molecular vibrations

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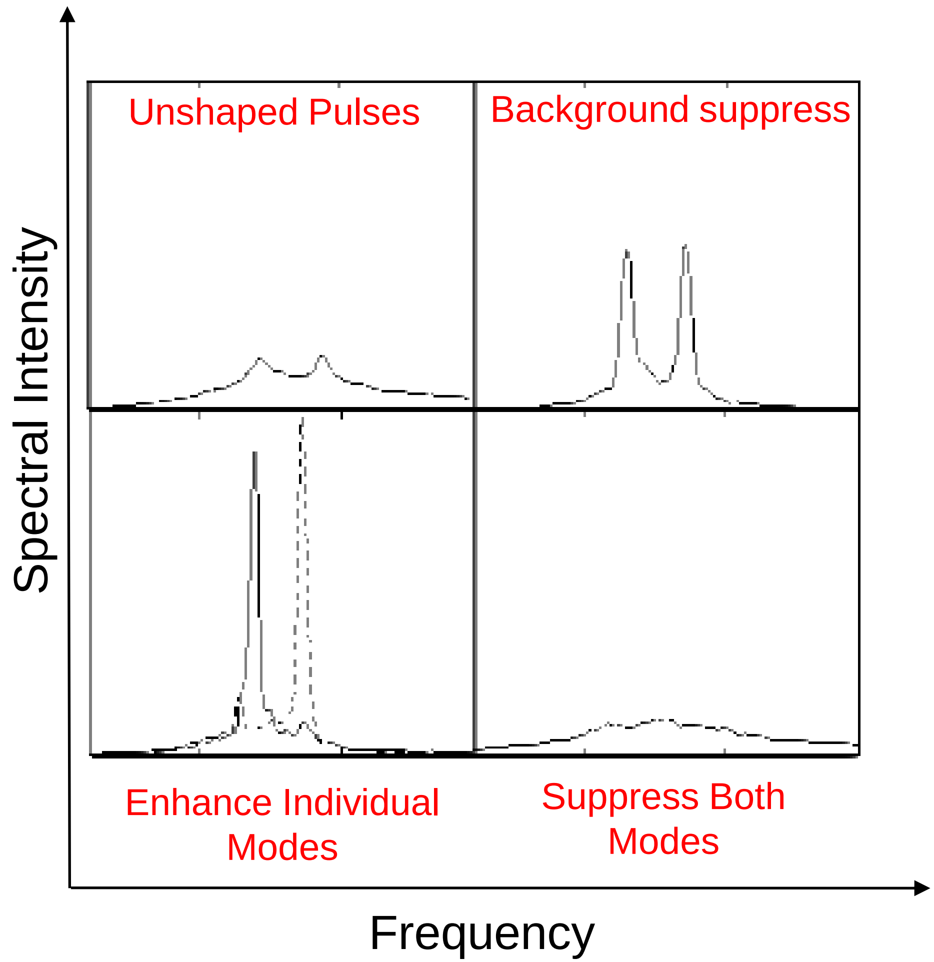
Control of Fluorescence

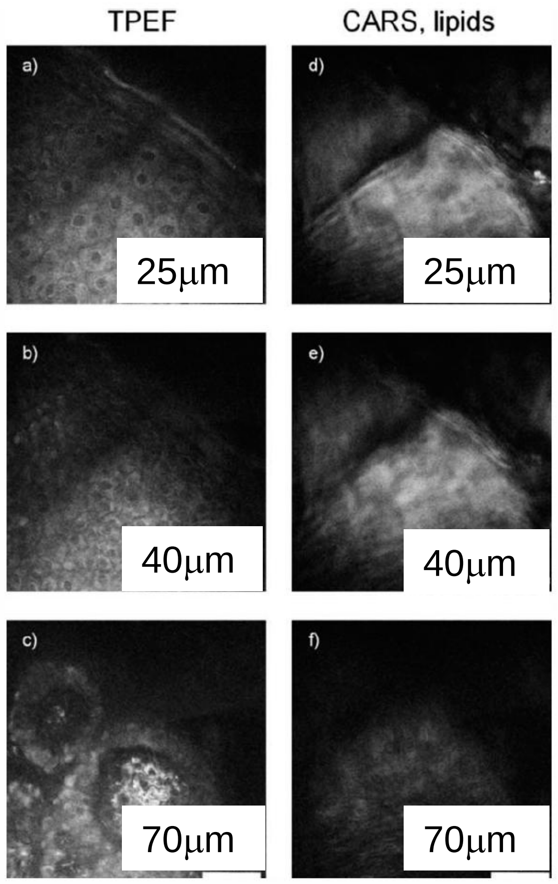
Vibrational Excitation of Methanol (CH_3OH), C-H Stretch Mode

Weinacht and Bucksbaum, Journal of Optics B **4**, S1464 (2002)



Fluorescence Detection Optimization?

In Vivo Skin Imaging



Can we use shaped laser pulses to optimize a fluorescence detection signal to enhance sensitivity of trace substance detection?

Bruenig *et al.*, Microscopy Res. &Techni. **75**, 492 (2012)

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Summary

Quantum control is an emergent technological tool with a wide range of potential applications in the field of atomic and molecular physics

Thank You

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