Quantum optics with nanophotonic systems

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Experiments:

Atom nanotrap J.Thompson, T.Tiecke, A.Akimov, A.Zibrov, N. de Leon,
CUA collaboration with Vladan Vuletic's group (MIT)

Diamond sensors P.Maurer, G. Kuscko, A.Sushkov, I.Lovchinsky, M.Kubo, N.J.Noh, P.Lo
collaboration with Hongkun Park (Harvard Chem)

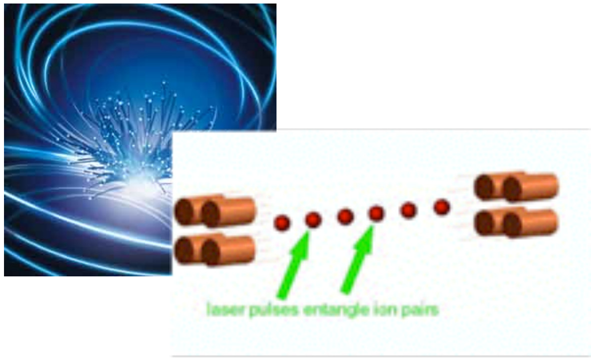
Theory:

D.Chang (ICFO), M.Hafezi (JQI),N.Yao, J. Feist, M.Gullans, E.Demler, P.Zoller (Innsbruck)

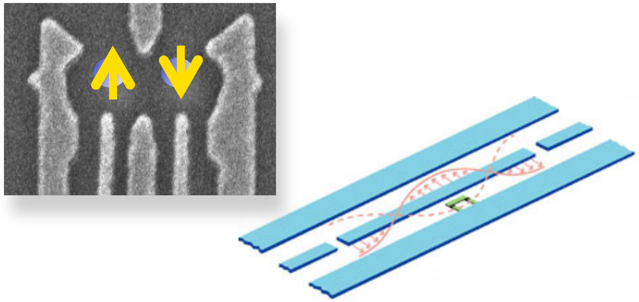
Hybrid quantum systems

- AMO systems: excellent isolation, control techniques

But: interact weakly, challenging to integrate



- Solid-state systems: strong interactions
  potential for integration



But: live in complex solid-state environment, hard to control

Hybrid approach:
aims to combine useful features of dissimilar systems

Integrating atoms with nanoscale solid-state systems: key idea

- Direct strong coupling with tightly localized photons, phonons:
  new approaches to quantum optics and quantum information
- Control, measurements at sub-micron scales:
  new possibilities for sensing, metrology at nanoscales

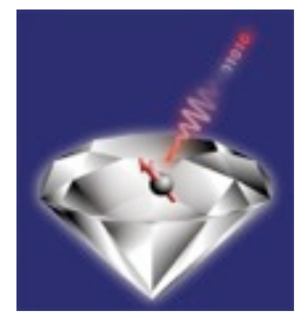
Efforts spanning physics, physics, chemistry, nano-science, biology

Today's talk: two examples

✓ Nanophotonic interface for ultracold atoms

- Isolating single atoms near nanoscale solid-state objects
- Coupling atoms with photonic crystal cavities

✓ Quantum control of solid-state atom-like systems



- Applications for nanoscale sensing in living cells

✓ Outlook: new directions

Today's talk: two examples

✓ Nanophotonic interface for ultracold atoms

- Isolating single atoms near nanoscale solid-state objects
- Coupling atoms with photonic crystal cavities

✓ Quantum control of solid-state atom-like systems

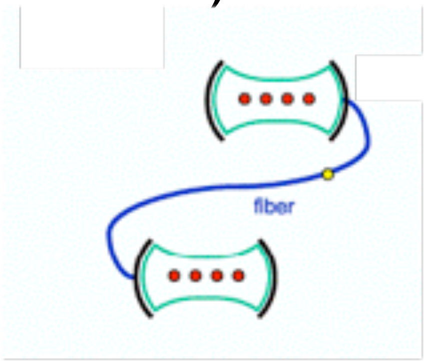
- Applications for nanoscale sensing in living cells

✓ Outlook: new directions

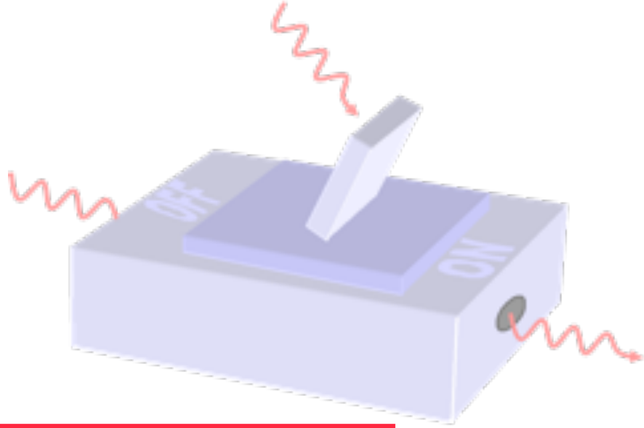
Motivation: single atom-single photon interface

✓ Long-standing goal of optical physics

- Fundamental importance: ultimate control of light quanta
- Many applications, e.g. in quantum (and classical) information



- Examples:
  - ✓Non-local qubit coupling
  - ✓Single photon nonlinear optics

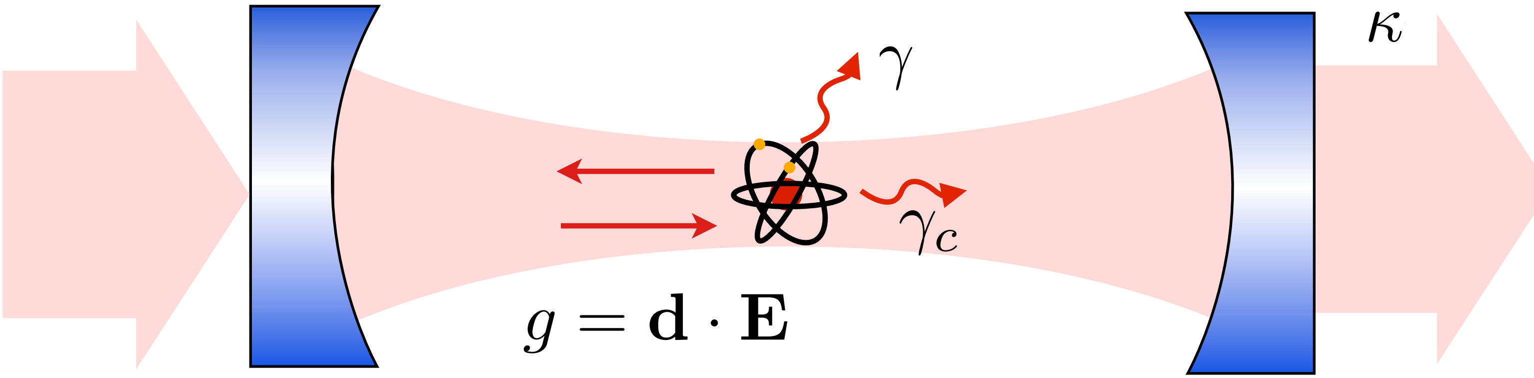


✓Challenge:

- Photons interact weakly with single atoms
- Photons are easily lost

Single optical photons are not under control

Physics of single atom-photon interface



$$g = \mathbf{d} \cdot \mathbf{E}$$

$$E \sim \frac{1}{\sqrt{V}}$$

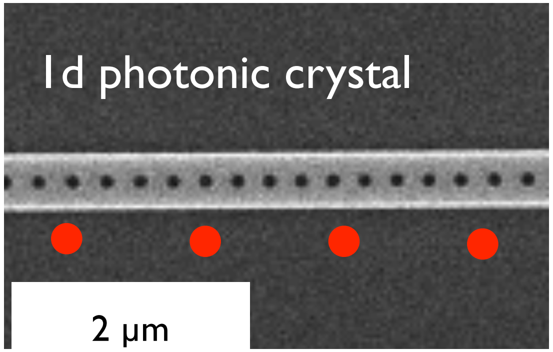
- Figure of merit: cooperativity (C) ratio of cavity to free space emission $C = \frac{\gamma_c}{\gamma} = \frac{g^2}{\kappa\gamma} \sim \frac{Q}{V}$

- Purcell regime: interaction with cavity dominates $C \gg 1$

- Idea: use sub-wavelength light localization with $V < \lambda^3$

Approach

- Sub-wavelength light localization in photonic crystals with V < λ^3
- Integrate coherent, cold atoms with subwavelength devices



Key challenge: need to confine, trap, manipulate cold atoms in the near field of nanophotonic systems

Prior work:
moving atoms near microtoroids (Kimble)
atoms near nanofiber, C ~ few % (Hakuta, Rauschenbeutel, Kimble)
quantum dots in PC (Yamamoto, Imamoglu, Vuckovic)

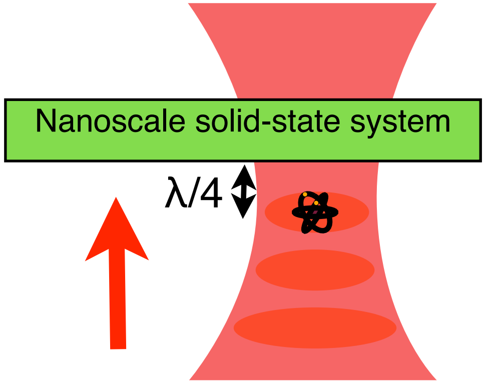
Dipole traps using near-field of nano-photonic systems

Idea:

use the interference formed by the tweezer light & reflection from subwavelength system to confine the cold atom at near-field distances from the surface

Method is general

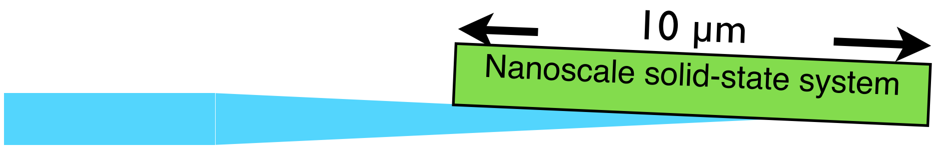
can trap near any object with sufficient reflection

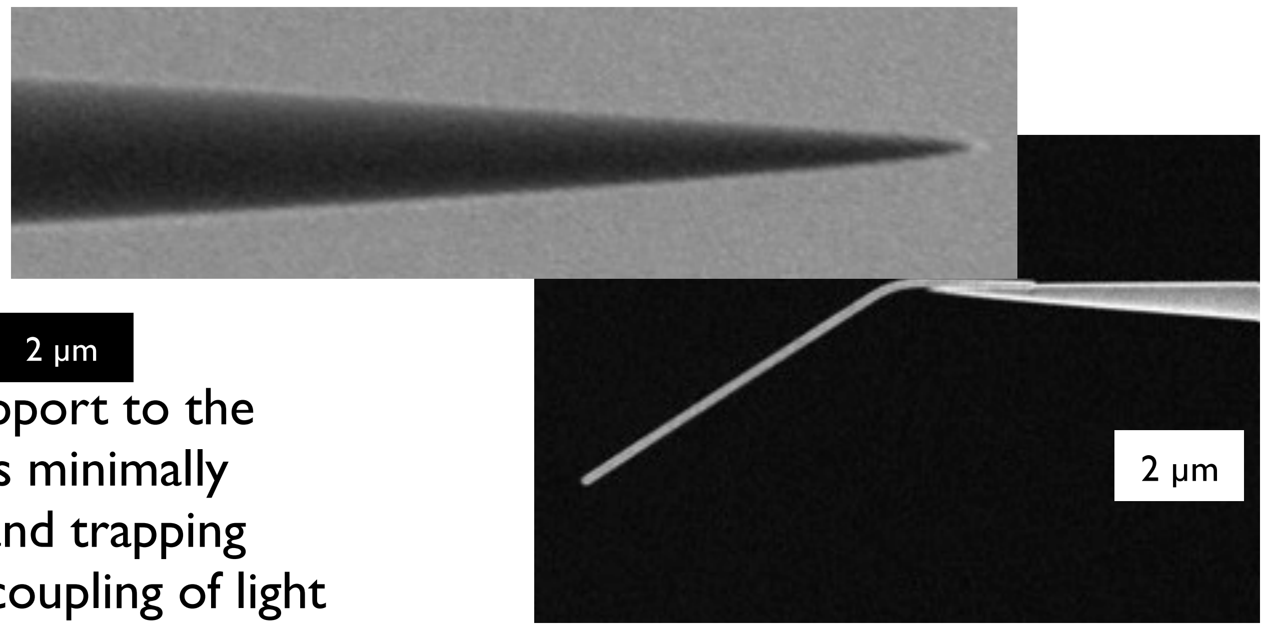


CUA collaboration with V. Vuletic

Theory idea: D. Chang et al, Phys.Rev.Lett., 103, 123004 (2009) collab. with Zoller group
Related work on atom transport: D.Meschede, ensembles near tapered fiber: A.Rauschenbeutel, J. Kimble

Tapered optical fiber: “breadboard” for nanophotonics



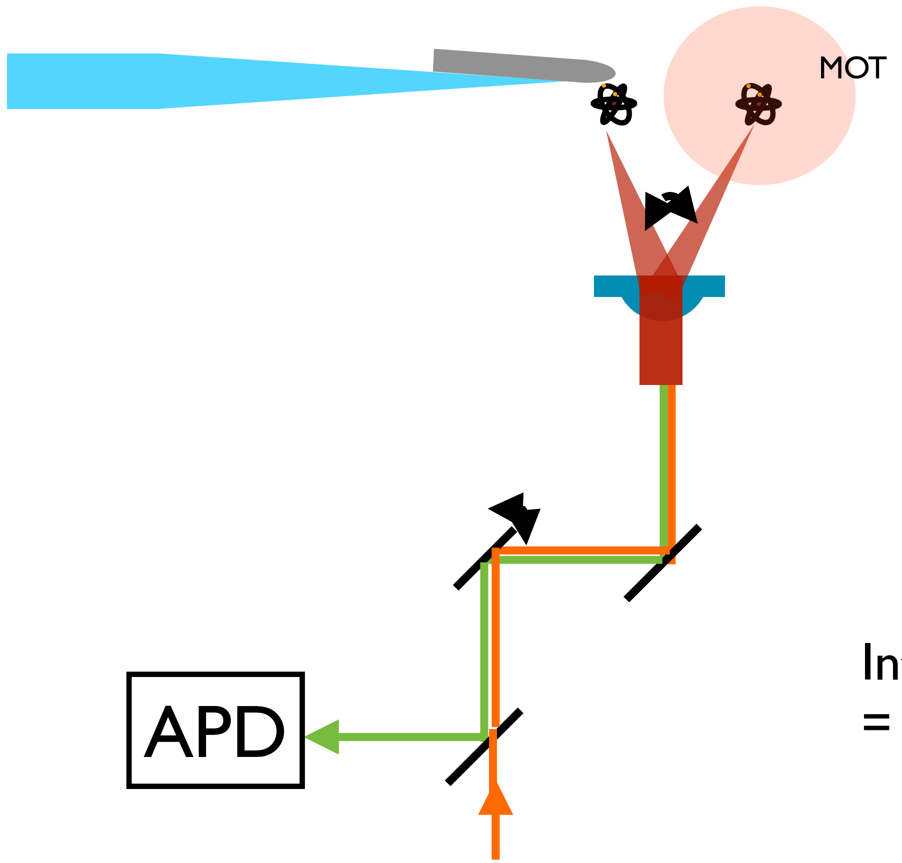


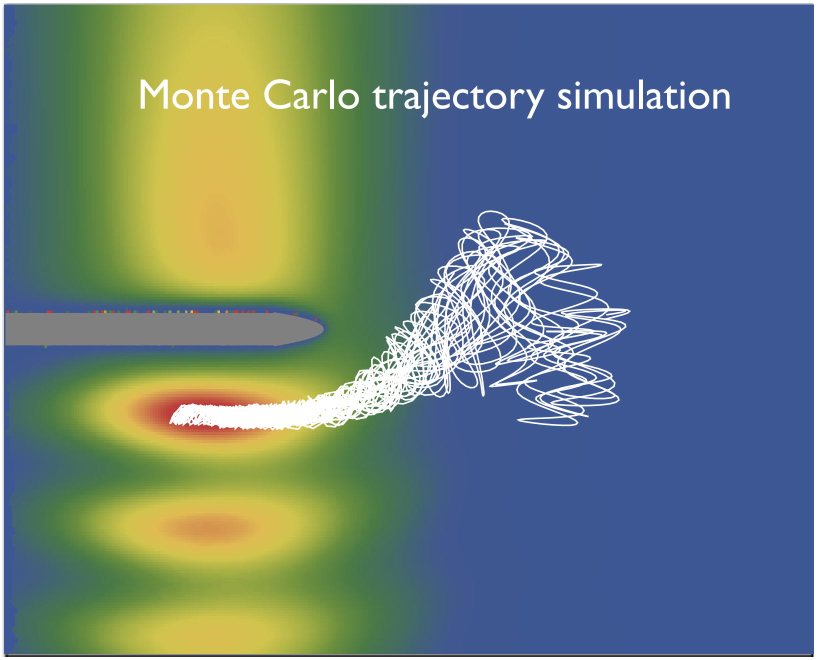
Optical fiber

- provides mechanical support to the nano-sized system, that is minimally perturbative to cooling and trapping
- allows for in- and out-coupling of light with high efficiencies (10-60%)

Assembly is done by using the fiber to “sweep” devices off of a substrate.

Loading near-field trap via scanning optical tweezer

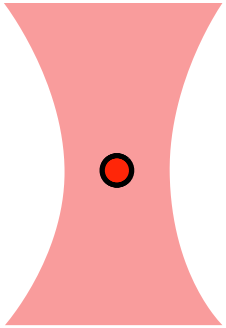


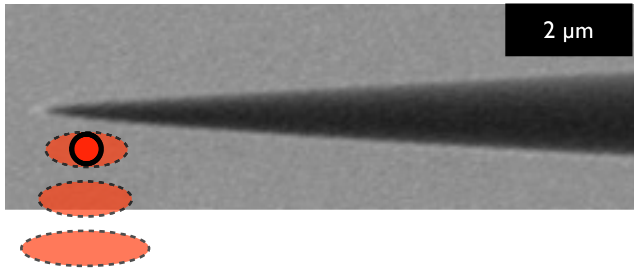


Intensity minimum < λ/4 from the surface = atom trap

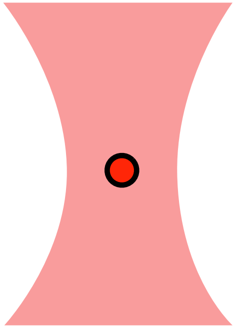
- Single atoms loaded in conventional dipole trap from the MOT using "collisional blockade" (P. Grangier et al, 2000)
- Atoms are Raman cooled to near ground state in 3D (J. Thompson et al, PRL 2013)
- Near-field traps are loaded by proper positioning the original trap

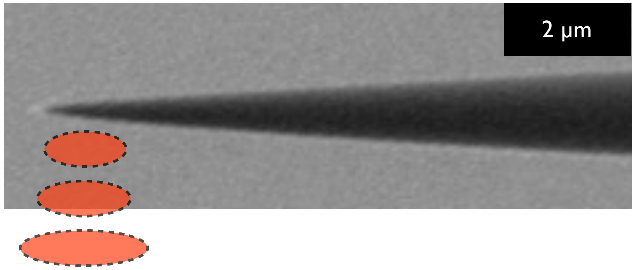
Experiment: loading different sites



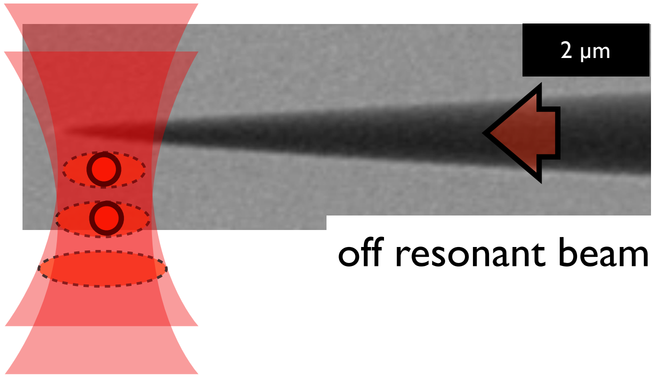


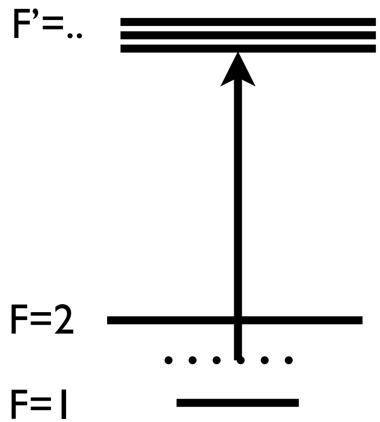
Experiment: loading different sites





Experiment: loading different sites near nano-fiber





probe AC-Stark shift of fiber mode

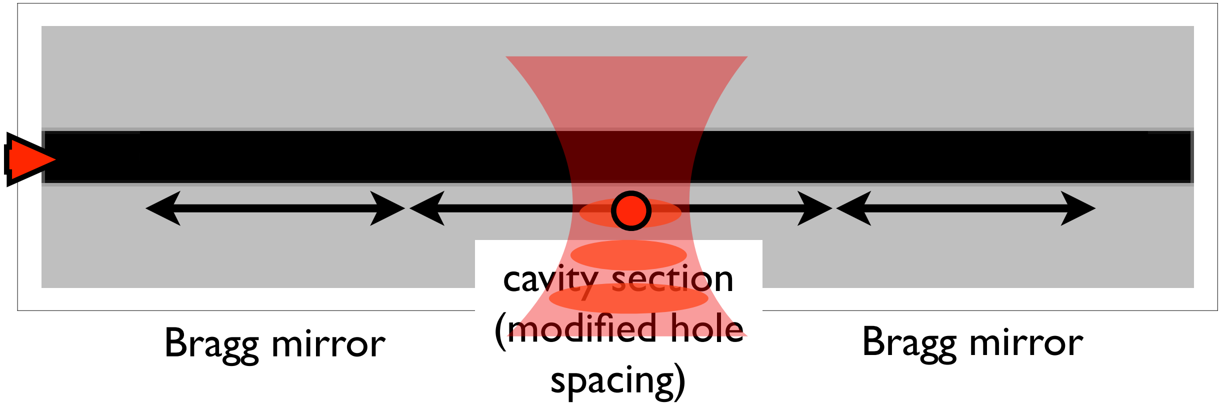
differential shift between |2,0> and |1,0> hyperfine states probed with MW π-pulse

- total loading efficiency=94(6)%
- can control distance (100-250 nm) by engineering phase shift of reflection

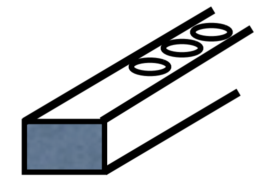
J.Thompson, T.Tiecke et al, Science (2013)

Photonic crystal cavities

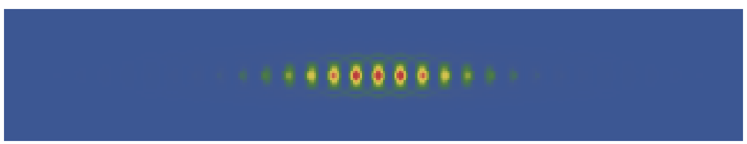
index guided in 2D



SiN waveguide

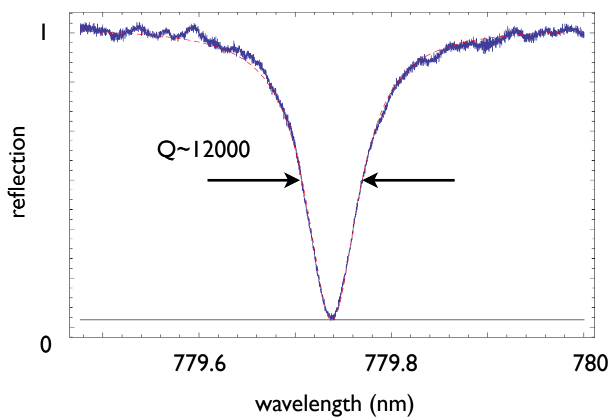


simulation of $|E|^2$



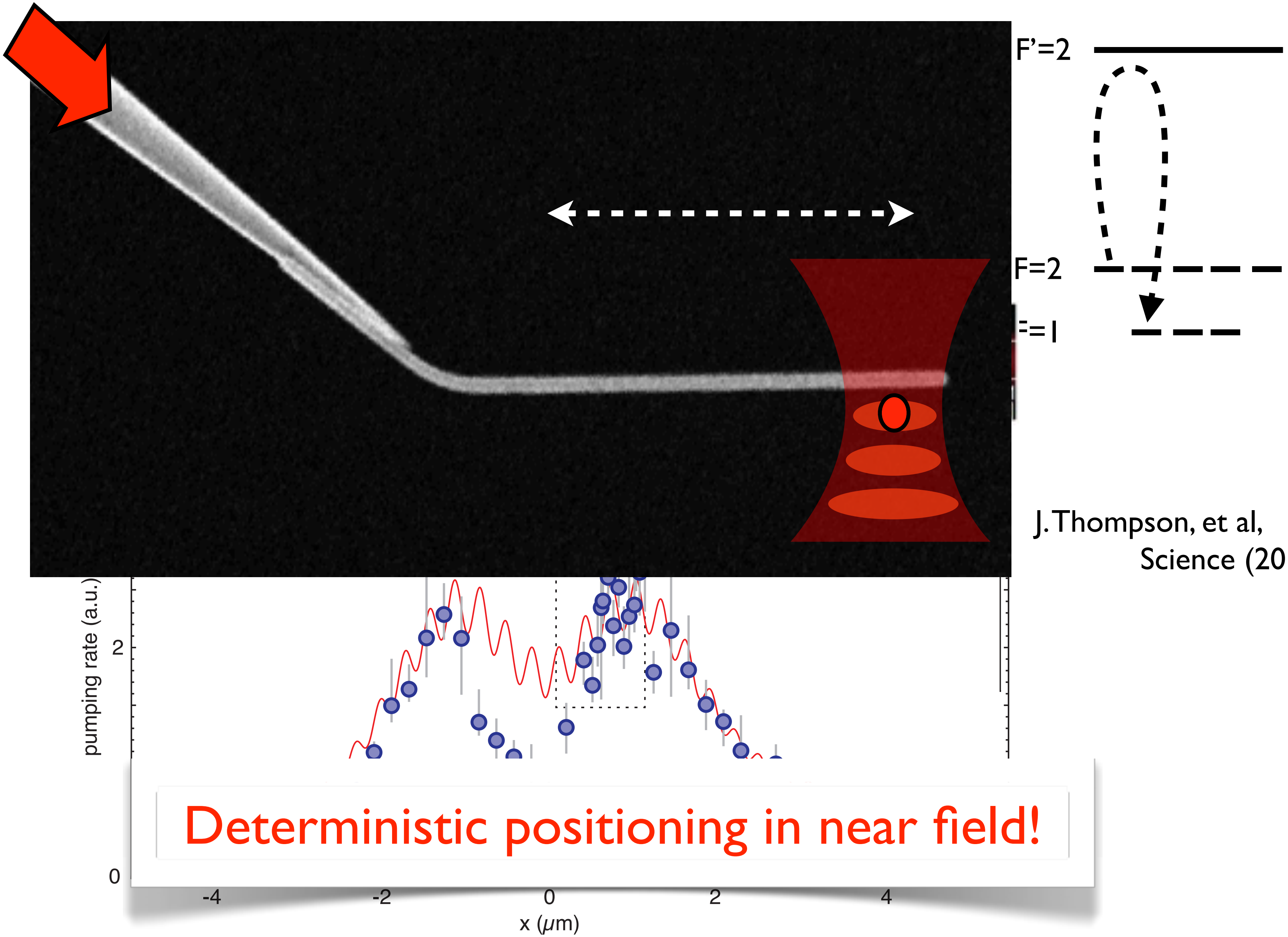
$V \sim 0.5\ \lambda^3$
$\lambda = 780$ nm

$$Q = \frac{\lambda_0}{\Delta\lambda}$$



- high Q cavities (up to 1M), currently Q~10,000
- thermal tuning of cavity
- cavities are radiatively damped:
  i.e. all photons can be collected

Coupling single atom to photonic crystal cavity

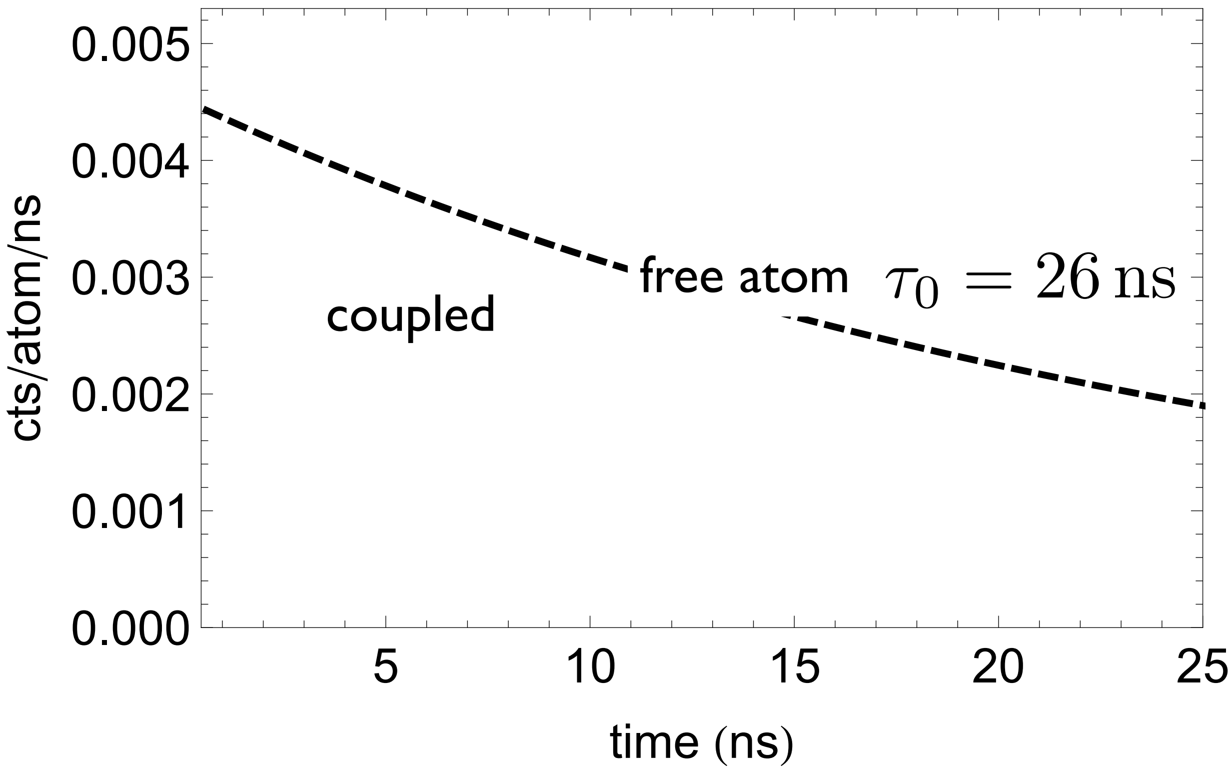


J. Thompson, et al,
Science (2013)

Deterministic positioning in near field!

Purcell effect: entering strong coupling

- excite coupled atom-cavity system with short (3ns) pulse
- monitor decay of cavity signal

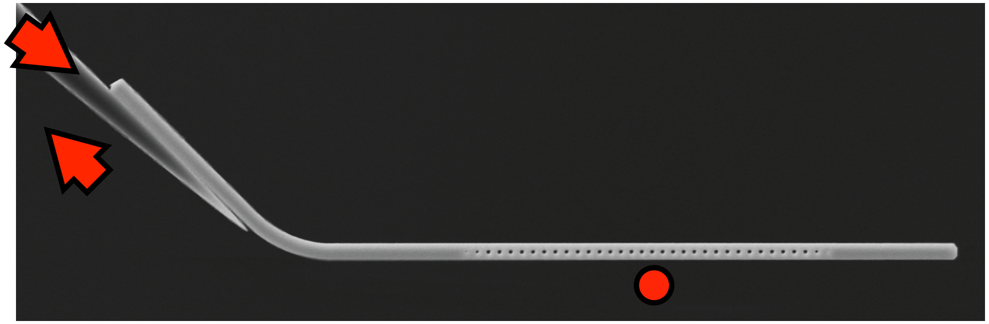


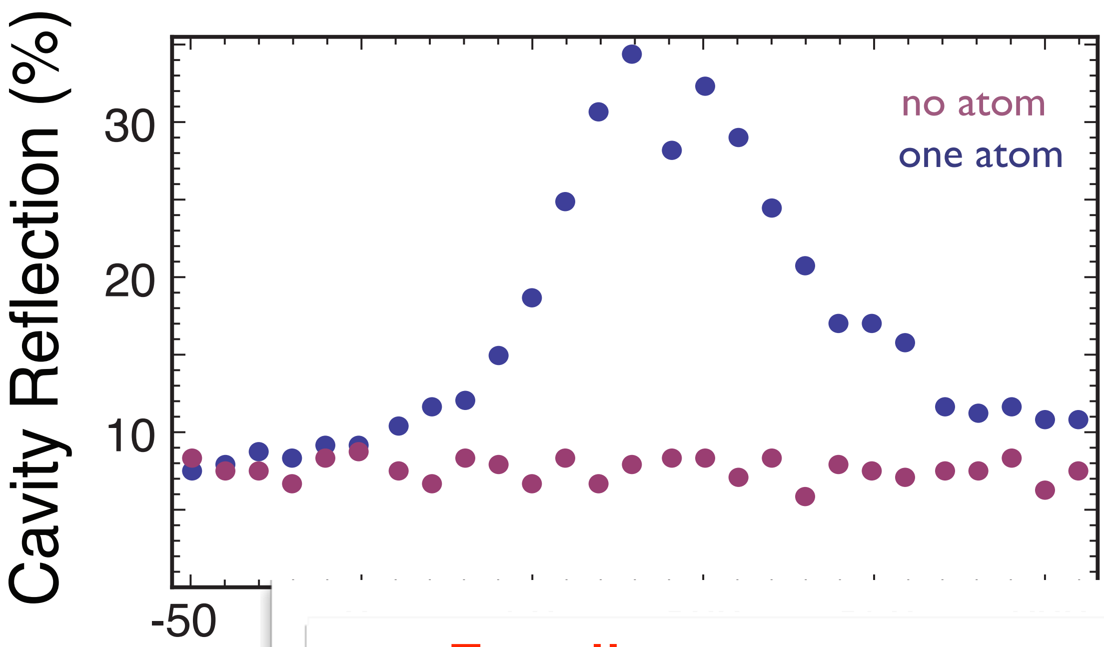
J.Thompson, T.Tiecke et al, 2013
collaboration with Vladan Vuletic

$(g, \kappa\ \gamma)$ =
2π (0.95 GHz, 30 GHz, 6 MHz)

Strong coupling!

Spectroscopy of single atom coupled to PC



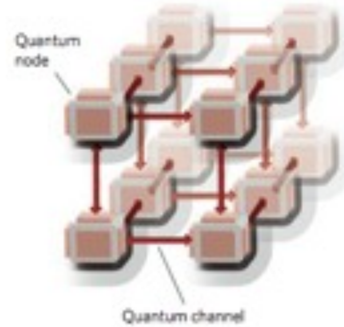


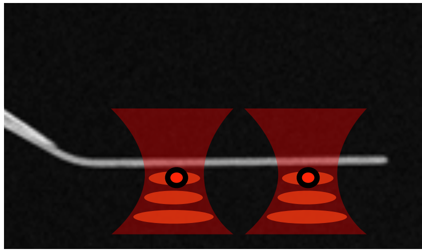
- can scatter ~500 photons/atom
- lineshape reflects steady-state distribution among Zeeman sub-levels

Excellent starting point for realizing integrated cold atom/nanophotonic systems

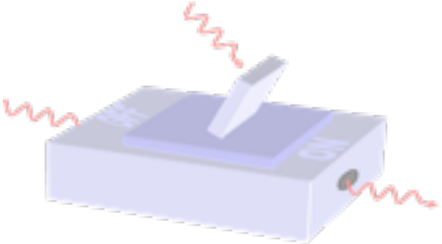
Outlook: new approaches to building quantum light and matter

•Quantum networks:
from multiple atoms on-chip to long distance

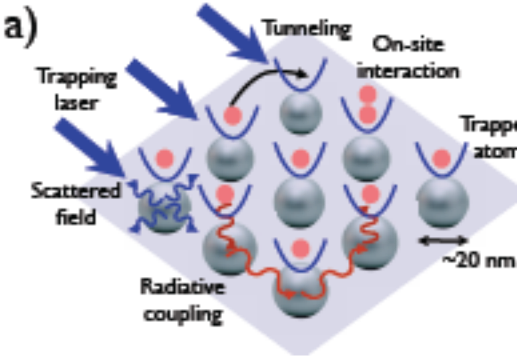




• Many-body physics with strongly interacting photons



•Single photon switches and transistors



•Sub-wavelength optical lattices for cold atoms
new regimes for many-body physics

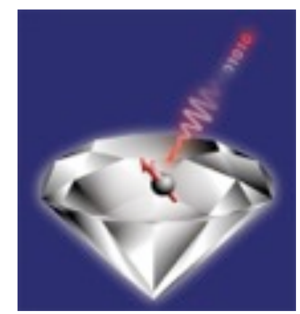
M. Gullans et al, Phys.Rev.Lett. (2013)

Today's talk

✓ Nanophotonic interface for ultracold atoms

- Trapping single isolated atoms near nanoscale objects
- Coupling atoms with photonic crystal cavities: interface between cold atoms and nanoscience

✓ Quantum control of solid-state atom-like systems



- Applications for nanoscale sensing in living cells

✓ Outlook: new directions

Atom-like systems: localized impurities in solid state

Trapped "atoms" for research and technology:

solid-state realization of isolated atomic "model systems"
key - combining nanoscale localization with excellent quantum control

New parameter regimes:

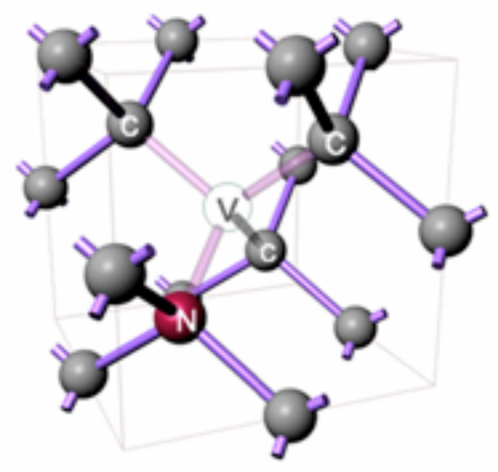
"hybrid" quantum systems
strong coupling to photons, phonons, spins

New applications:

Practical (room T) single atoms for information storage, processing
atomic sensors - measurement of tiny fields in solid-state and biological systems

Realization: nitrogen-vacancy color center

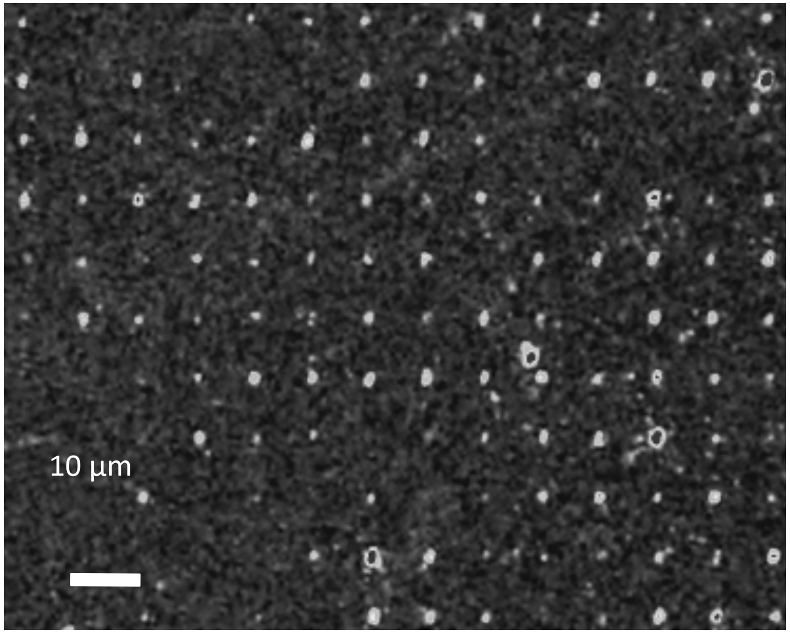
✓One of the many stable impurities in diamond



✓"Nature's own trapped ion"

✓Optical properties

- Narrow emission line @ 637 nm
- Individual isolation with laser microscopy



✓Spin properties

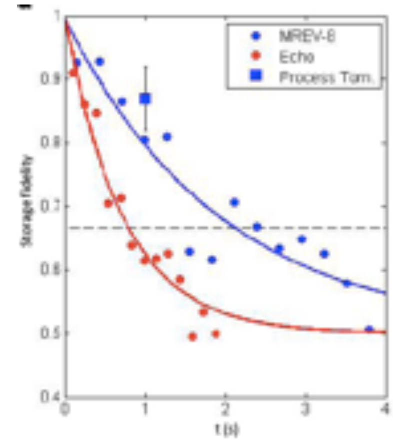
- non-zero electronic spin (S=1, $|m_s|$=0,1)
- spin rotation with microwaves

✓Can be created

by N ion implantation & annealing in CVD diamond

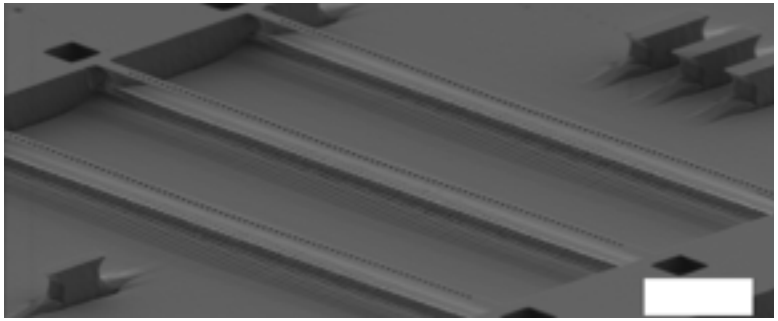
Atom-like systems:current efforts

Coupling to single nuclei: multi-second quantum memory in isotopically pure diamond



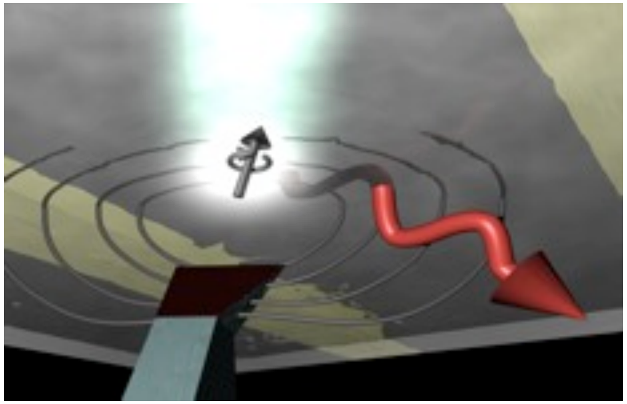
P.Maurer, G.Kucsko et al (Science, 2012), collaboration with I. Cirac group (MPQ), samples D.Twitchen (E6)

Coupling to single photons: diamond nanophotonics for quantum networks



Yiwen Chu, Nathalie de Leon, collaboration with M. Loncar, H.Park's groups

Coupling to single phonons: nano-mechanical resonators as spin transducers



S. Kolkowitz, A. Jayich et al, (Science, 2012)

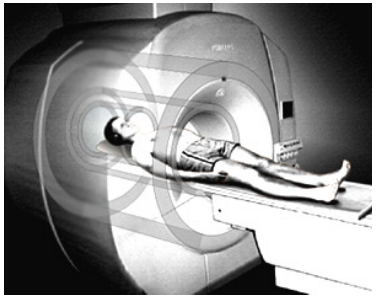
Application: nanoscale sensing with atom-like systems

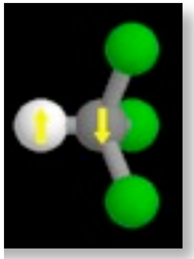
✓Idea: use single impurity spin to sense magnetic fields via Zeeman effect

Theory: J. Taylor, P.Cappellaro et al, Nature Physics (2008)

Experiments: J.Maze et al, Nature (2008)

G. Balasubramanian et al, Nature (2008)



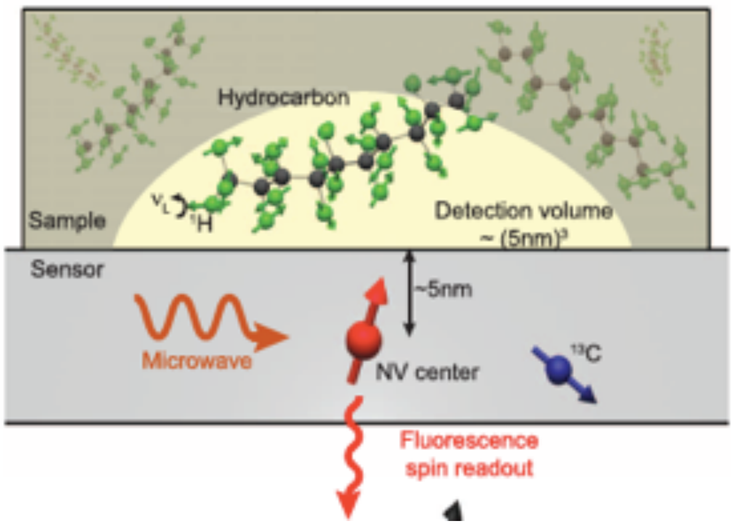


- A unique sensor: Magnetic Resonance Imaging with nanoscale spatial resolution limited by proximity

- Can also be used to sense E-fields, temperature, rotations

Nuclear Magnetic Resonance Spectroscopy on a (5-Nanometer)^3 Sample Volume

T. Staudacher,[1,2] F. Shi,[3] S. Pezzagna,[4] J. Meijer,[4] J. Du,[3] C. A. Meriles,[5] F. Reinhard,[1*] J. Wrachtrup[1]



Nanoscale Nuclear Magnetic Resonance with a Nitrogen-Vacancy Spin Sensor

H. J. Mamin,[1] M. Kim,[1,2] M. H. Sherwood,[1] C. T. Rettner,[1] K. Ohno,[3] D. D. Awschalom,[3] D. Rugar[1*]

Extension of nuclear magnetic resonance (NMR) to nanoscale samples has been a longstanding challenge because of the insensitivity of conventional detection methods. We demonstrated the use of an individual, near-surface nitrogen-vacancy (NV) center in diamond as a sensor to detect proton NMR in an organic sample located external to the diamond. Using a combination of electron spin echoes and proton spin manipulation, we showed that the NV center senses the nanotesla field fluctuations from the protons, enabling both time-domain and spectroscopic NMR measurements on the nanometer scale.

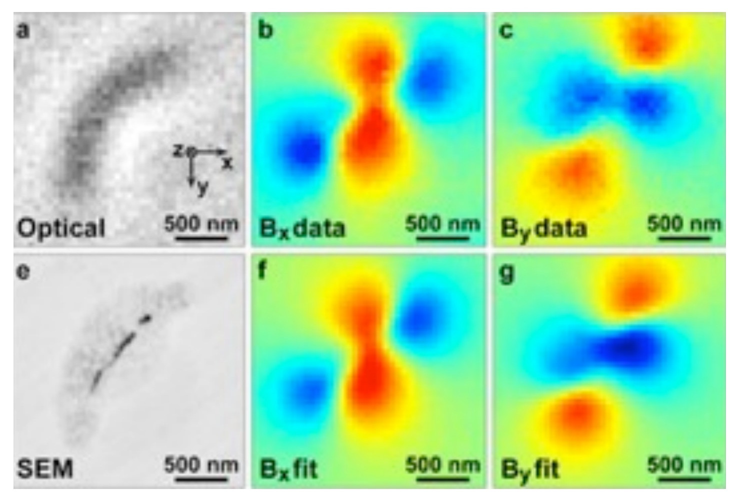
www.sciencemag.org SCIENCE VOL 339 1 FEBRUARY 2013

LETTER

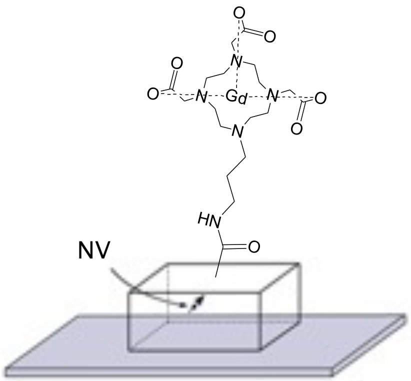
doi:10.1038/nature12072

Optical magnetic imaging of living cells

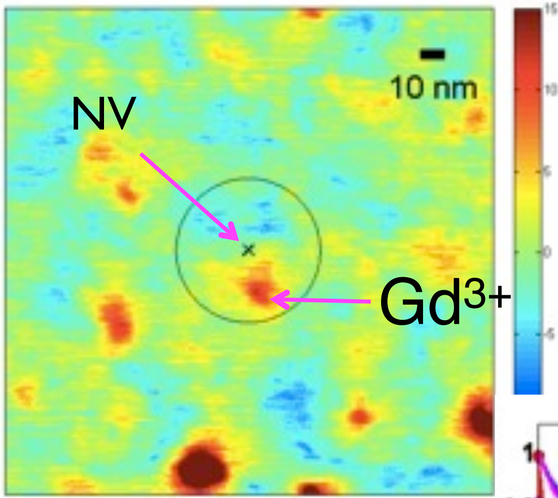
D. Le Sage[1,2*], K. Arai[3*], D. R. Glenn[1,2,4*], S. J. DeVience[5], L. M. Pham[6], L. Rahn-Lee[7], M. D. Lukin[2], A. Yacoby[2], A. Komeili[7] & R. L. Walsworth[1,2,4]



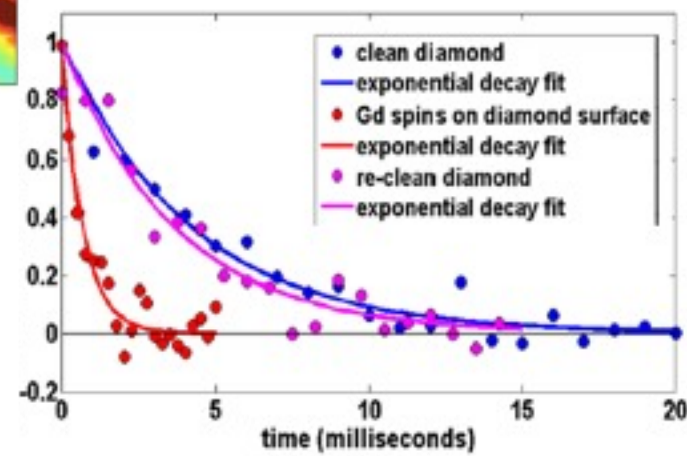
All-optical Detection of Single Radical Spin



Combined AFM & Optical Image



NV spin polarization

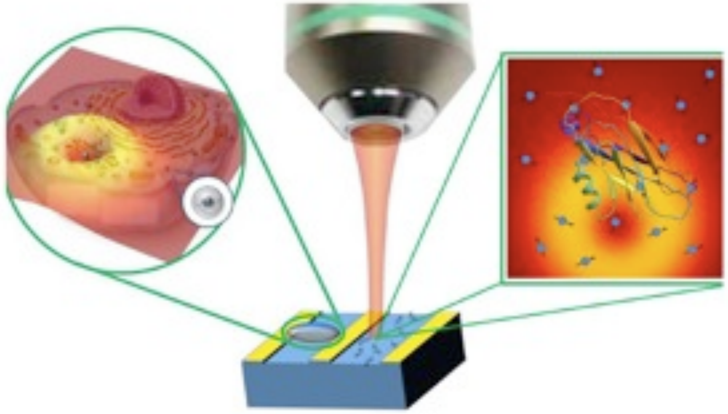


- The Gd^{3+} ion has 7 unpaired 4f electrons
- The presence of a Gd^{3+} spin accelerates population relaxation between NV ground-state sublevels.

- Detection of a single-molecule spin at room temperature using shallow NV magnetometer

A. Sushkov et al. (2013), collaboration with H. Park

Nanoscale sensing in biology

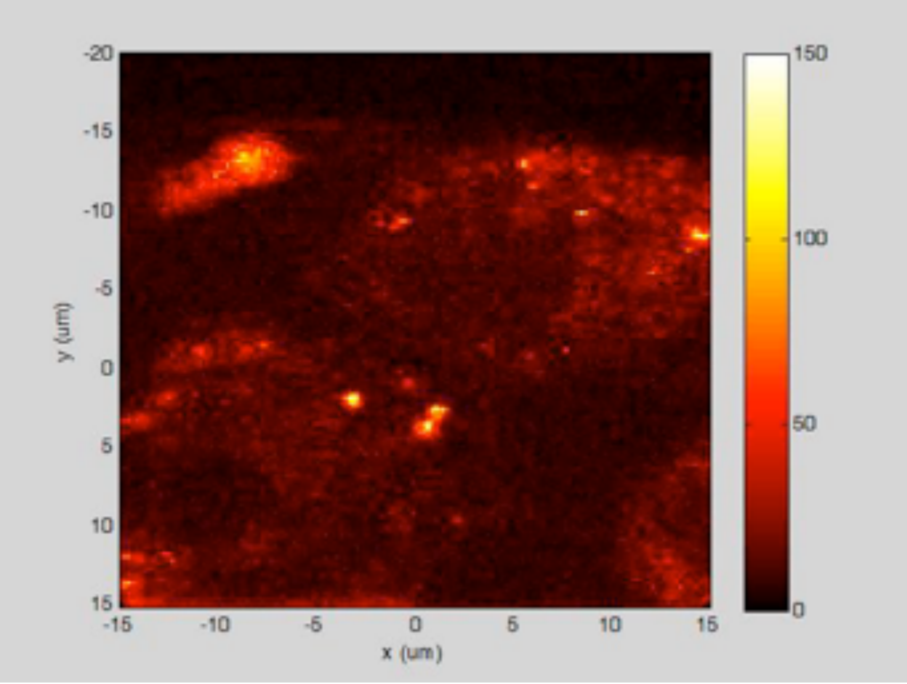


- Diamond nanocrystals inside living objects

  => new tool for nano-biology, medicine

  => B,E-fields, T sensing in living cells

  => understanding brain activity

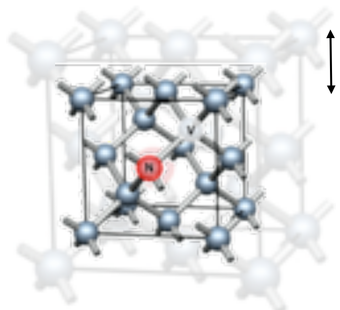


collaboration with H.Park's group (Harvard Chemistry)

Example: nanoscale temperature sensing

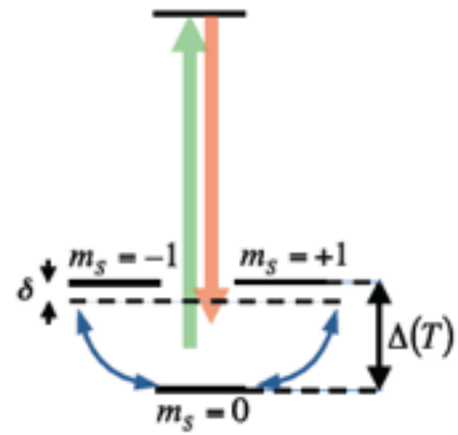
- Nitrogen vacancy spin transition depends on temperature

- Temperature ≙ stretching of orbital



→ Shift of resonance

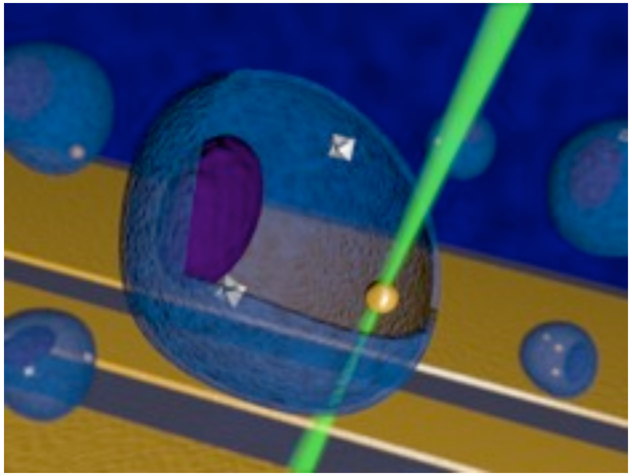
$$\frac{d\Delta}{dT} = -74.2\,\frac{kHz}{K}$$



V. M. Acosta, E. Bauch et al., PRL (2011)
Budker group

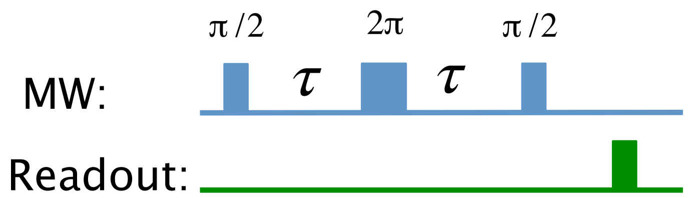
Idea

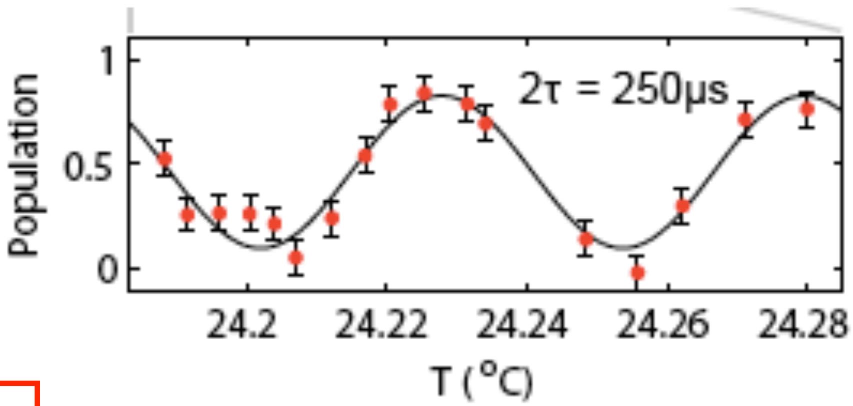
- High dynamic range thermometer (100–800 K)
- milli-Kelvin sensitivity by decoupling mag. noise
- Nanoscale detection volume & bio compatibility



Temperature via spectroscopy of spin impurity

- Benchmark: single NV sensor in bulk, (2π)-Echo



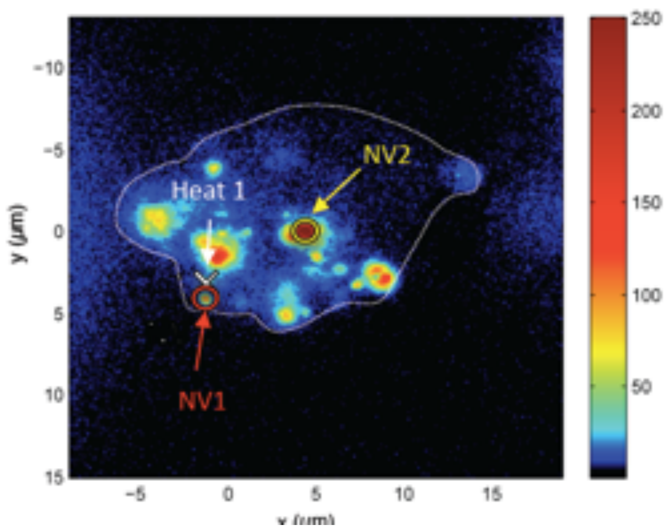


Sensitivity at T_2 = 0.25 ms: ~ 9 $mK/\sqrt{Hz}$

Temperature sensing in a cell

Temperature gradient in a human embryonic skin fibroblasts cells

- 100 nm-wide nanodiamonds & gold colloids introduced in a cell
- locally induce & control temperature within a single cell by using:
  gold nanoparticles as heat source
  NVs in nanodiamonds as temperature sensor

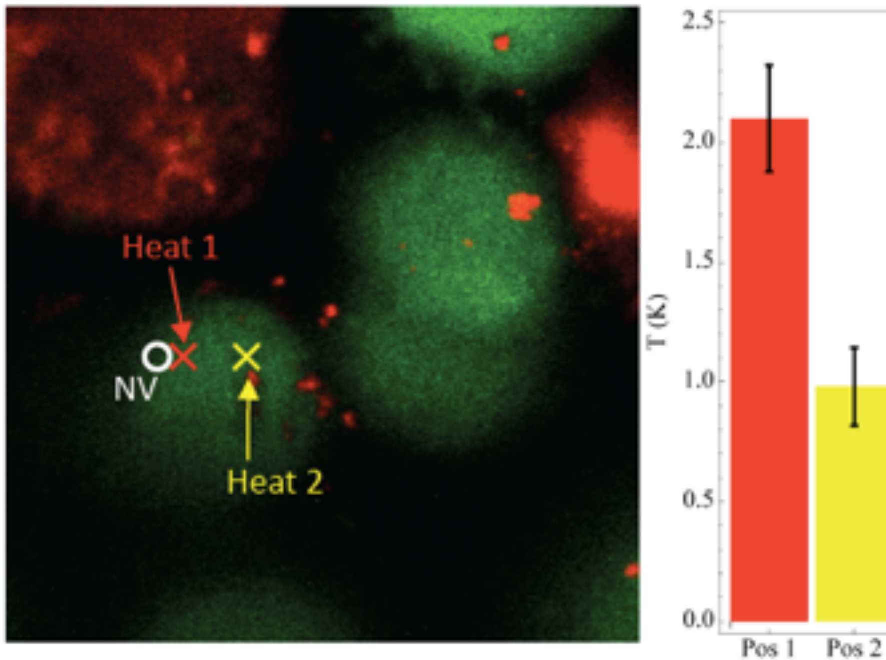


G.Kuscko, P.Maurer et al, collaboration with Park group, Nature in press (2013)

Temperature control in a living cell

Idea: induce a small temperature change, test if cells are alive/dead

green cells = alive
red = dead

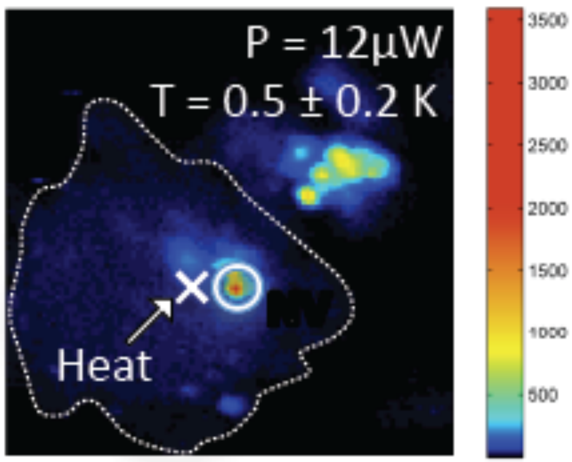


G.Kuscko, P.Maurer et al, collaboration with Park group, Nature in press (2013)

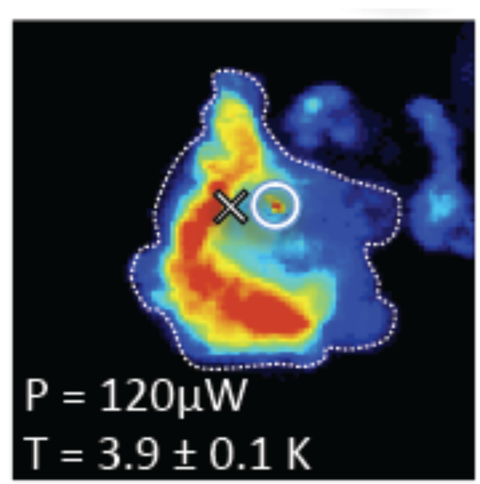
Temperature control in a living cell

Idea: induce a small temperature change, test if cells are alive/dead

Little heating - cell alive



Stronger heating - cell dead

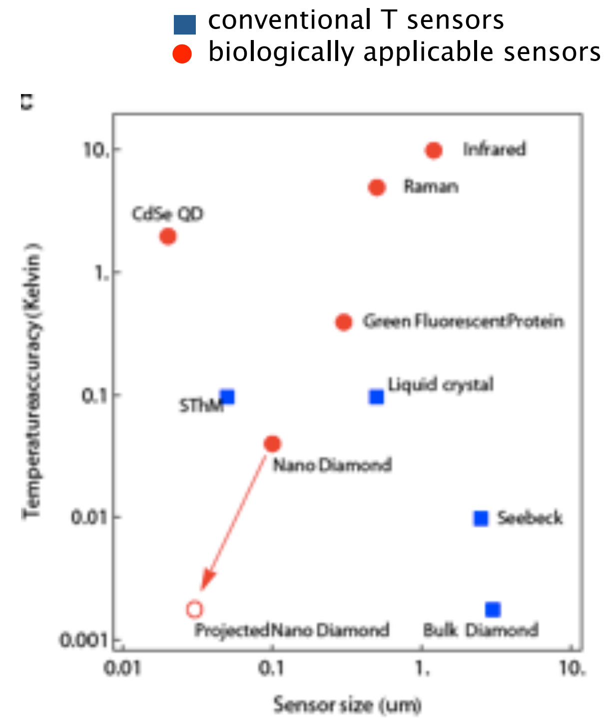


Controlling cell death with local heating

Accurate, 100 nm-scale temperature control within a living cell

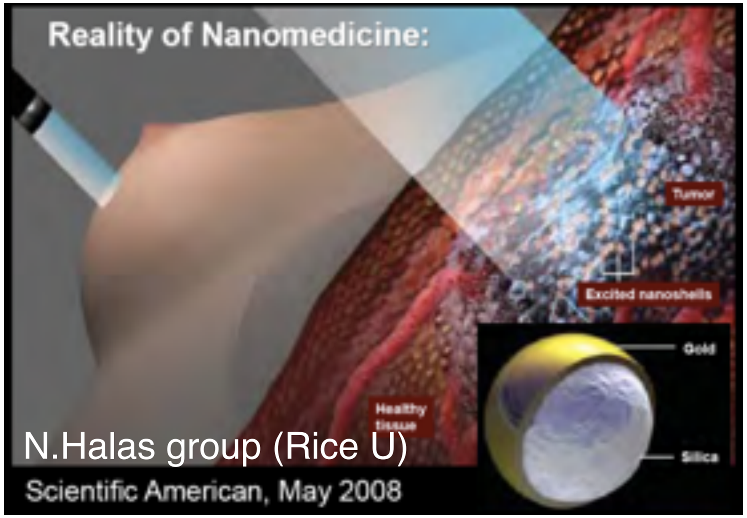
ress (2013)

Outlook



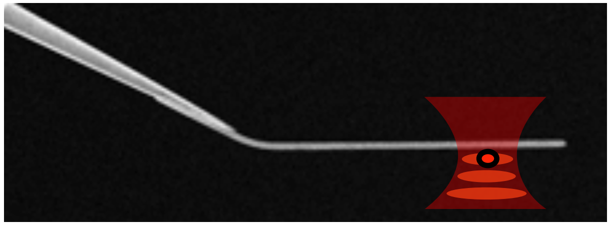
- Attractive method for in vivo biological measurements
- Optimize sensitivity vs. size
- spin squeezed states for increased sensitivity

Exciting potential applications



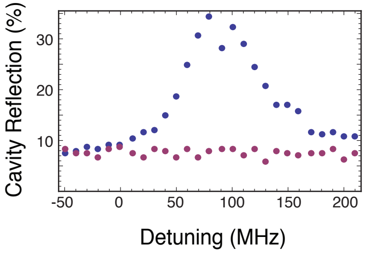
- Local control of gene expression
- Cancerous tissue detection and cure
- Control of physical and chemical processes at nanoscales

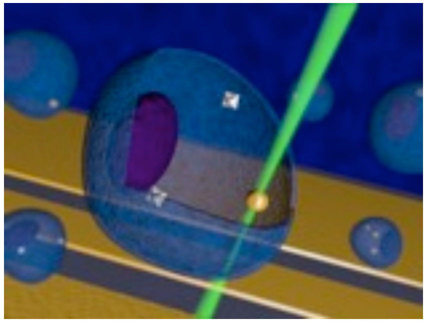
Summary



✓ Interfacing cold atoms and nanosized solid-state systems:

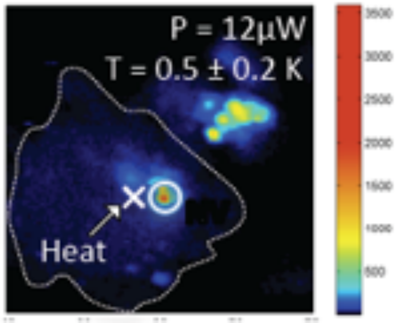
technique for trapping and control near surfaces
deterministic strong coupling to PC cavities





✓ Atom-like systems in solid state:

applications for nanoscale sensing

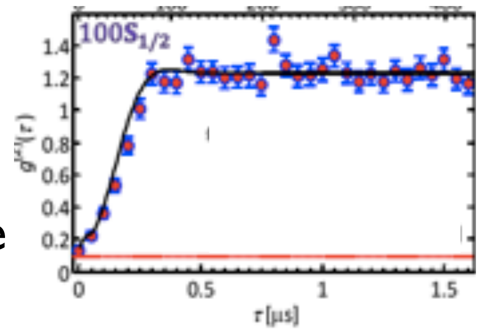


✓Outlook:

new platform for interfacing quantum optics & nanoscience

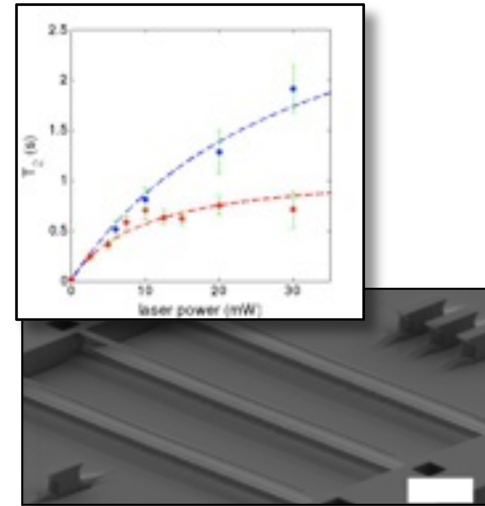
from single photon transistors and many-body physics with photons to cavity QED, nanomechanics and quantum-bio interface

Summary



✓Novel nonlinear materials via slow light
in strongly interacting matter

single photon nonlinear optics using Rydberg blockade
photon blockade, phase shifts and bound states



✓ Atom-like systems in solid state:

qubit memory on "human" timescale in room T solid
efforts towards integrated systems

✓ New science and applications

from photon transistors and many-body physics with photons to quantum nanomechanics and quantum-bio interface
first applications may be "around the corner"