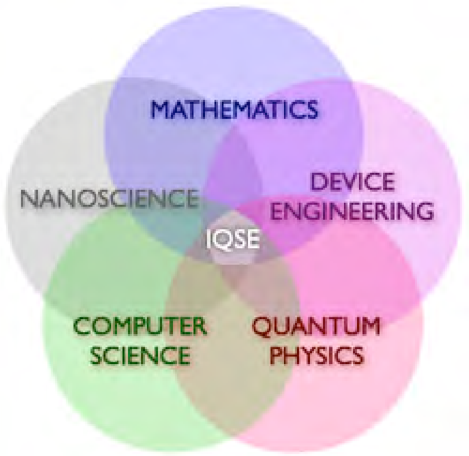
Quantum Science and Engineering



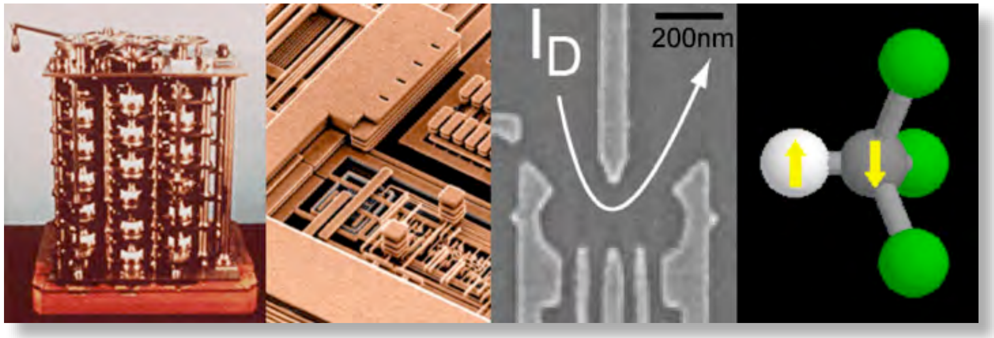
- Combines research areas on the interface of
    - atomic physics & quantum optics
    - quantum condensed matter physics
    - nanoscience
    - engineering
    - information theory

- Unifying themes:
    - Search for ways for controlled manipulation of quantum mechanical phenomena

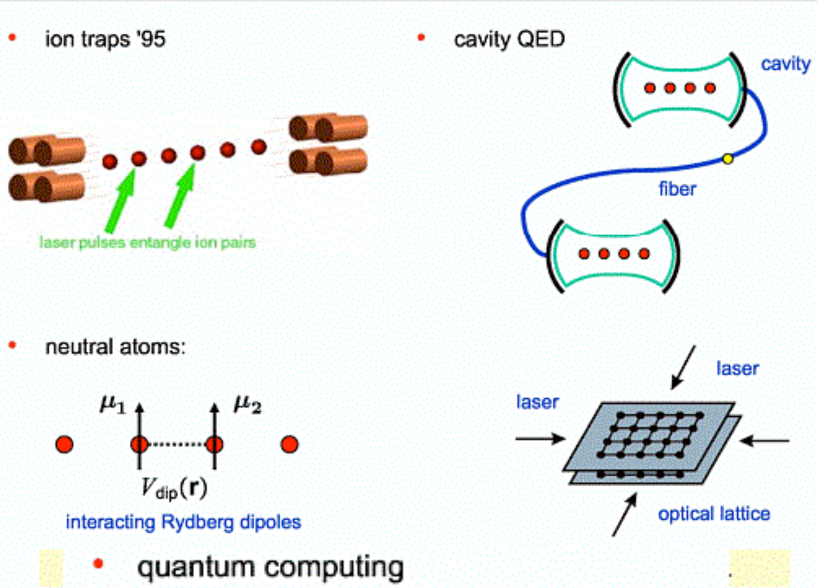
- Scientific and engineering questions
    - Fundamental physics of complex quantum systems: to what extend can they be manipulated and how?
    - Are there potential applications involving controlled quantum systems?

Scientific rationale

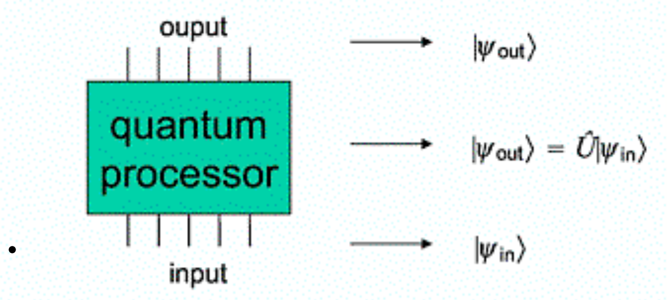
✓Miniaturization Reaches
its Limit

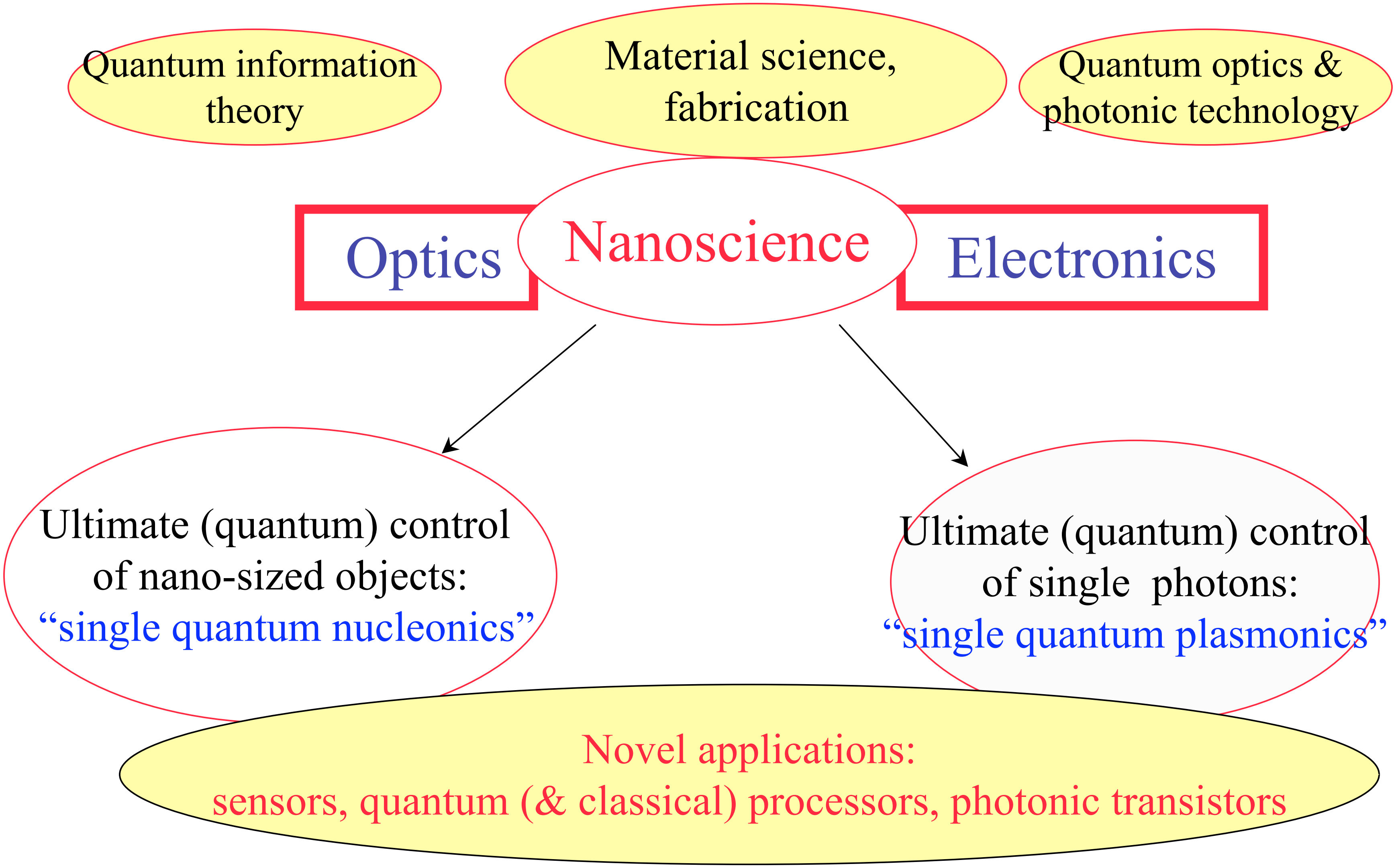


✓Advances in control of
single quantum systems



✓Quantum information science:
communication, computing,
simulations…





Quantum information theory

Material science, fabrication

Quantum optics & photonic technology

Optics

Nanoscience

Electronics

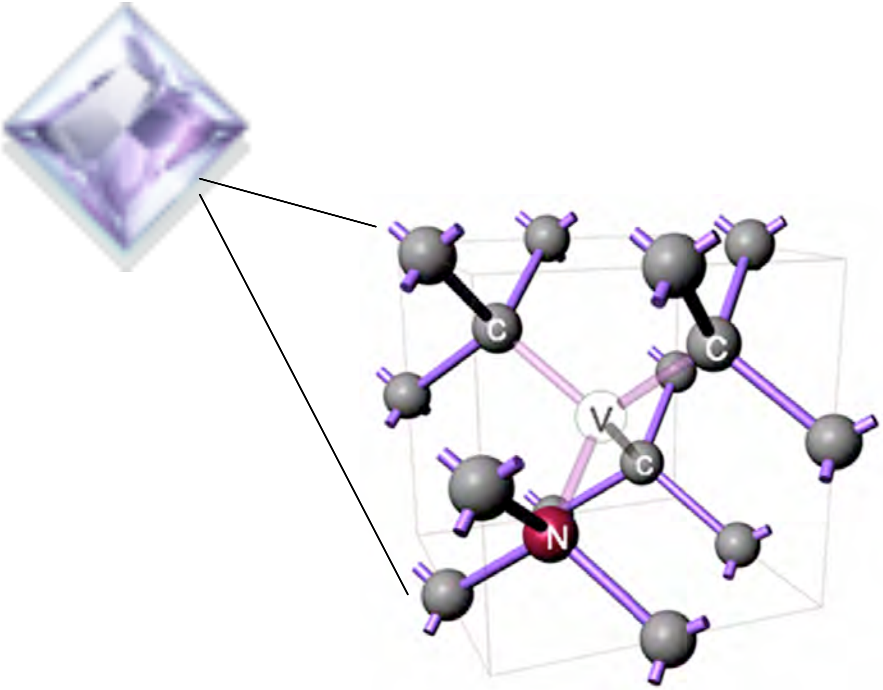
Ultimate (quantum) control of nano-sized objects: “single quantum nucleonics”

Ultimate (quantum) control of single photons: “single quantum plasmonics”

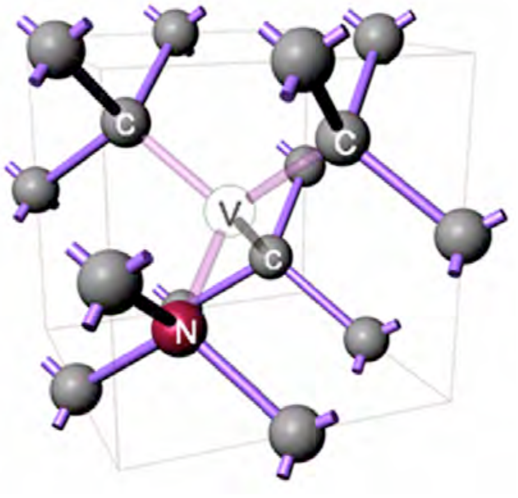
Novel applications:
sensors, quantum (& classical) processors, photonic transistors

Controlling single nuclear spins: is it possible?

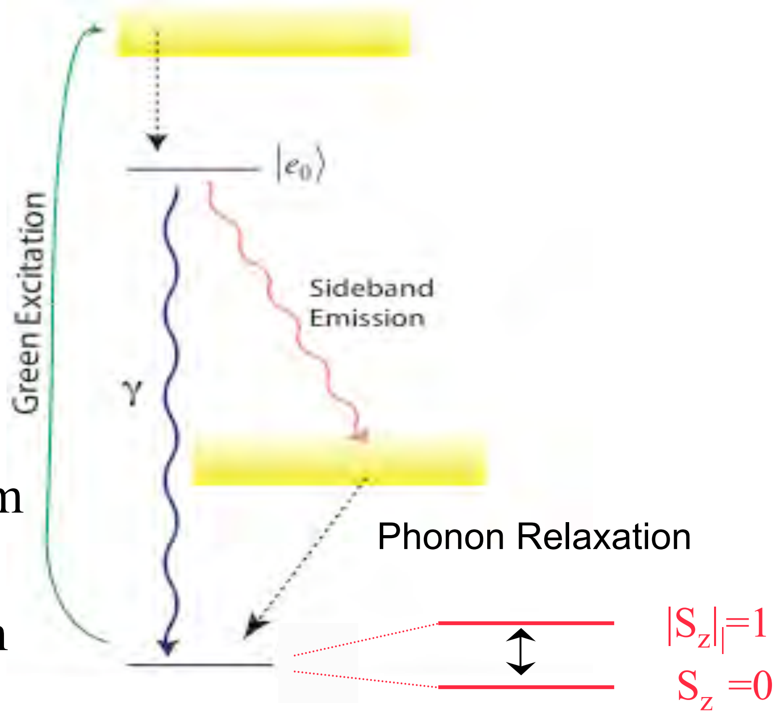
“Diamond Age” in our Lab



System: NV color center in high-purity diamond



"Nature's own trapped molecular ion"



Optical properties

- Sharp zero-phonon emission line @ 637 nm
  + phonon sidebands 650-730 nm
- Can be excited either by 637 nm or 532 nm

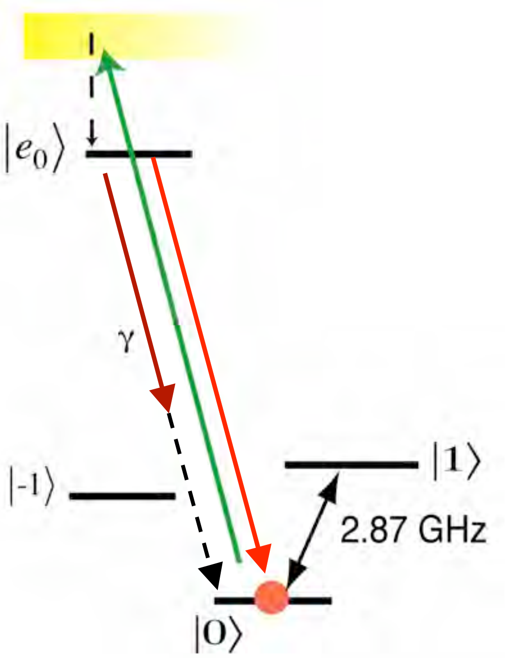
Ground state properties

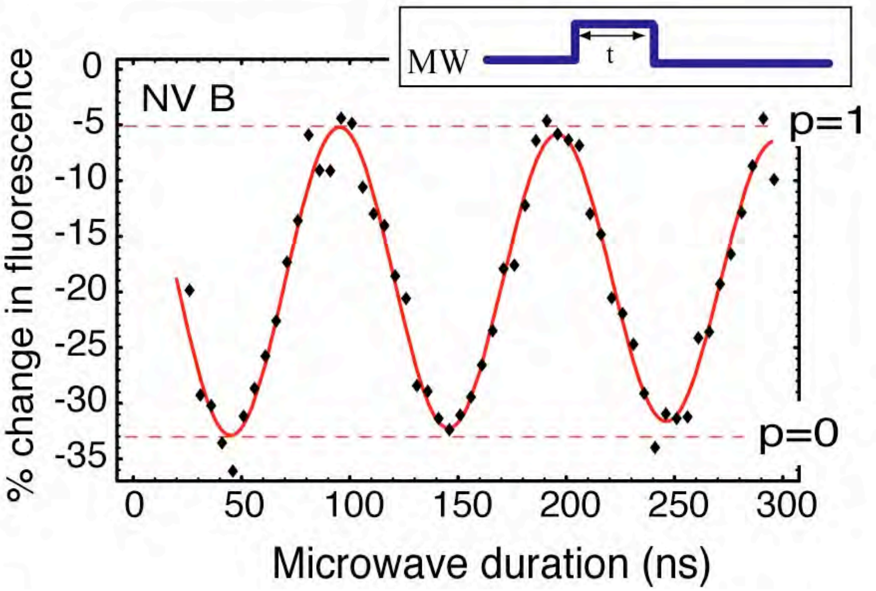
- non-zero electronic spin (S=1)
- microwave transition:
  zero-field splitting Δ=2.88 GHz

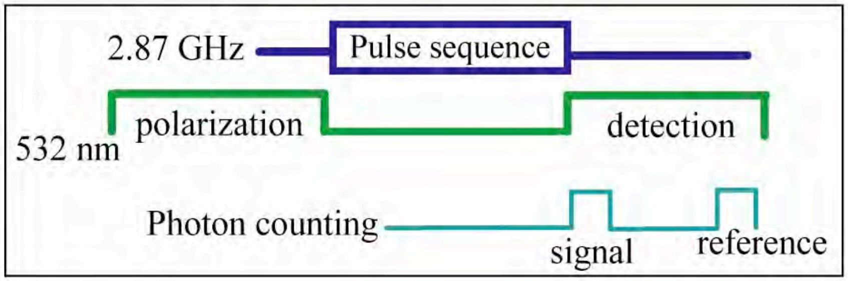
Early work:
S.Rand, N.Manson

Rabi oscillations of single electron spin

Use light to polarize, readout electron spin state at room T







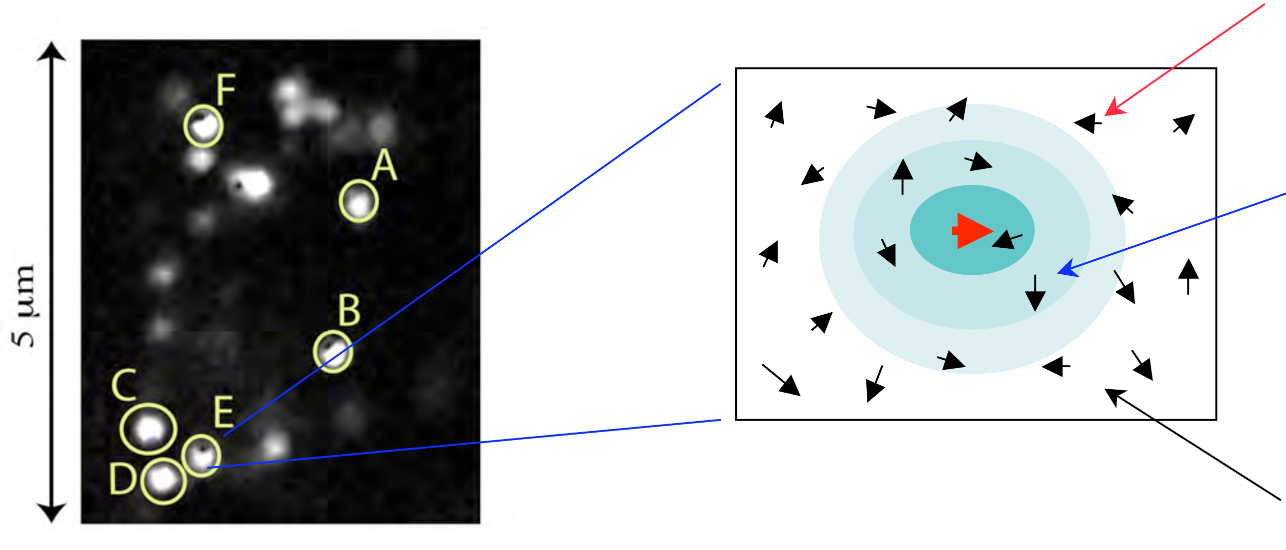
✓First experiments

F.Jelezko, J.Wrachtrup (Stuttgart)

Recent work by D.Awschlom (UCSB)

Single electron as sensitive magnetic sensor: picture of its environment

Childress et al, Science (2006)



^{13}C nuclei

Proximal nuclei:
larger hyperfine,
faster precession

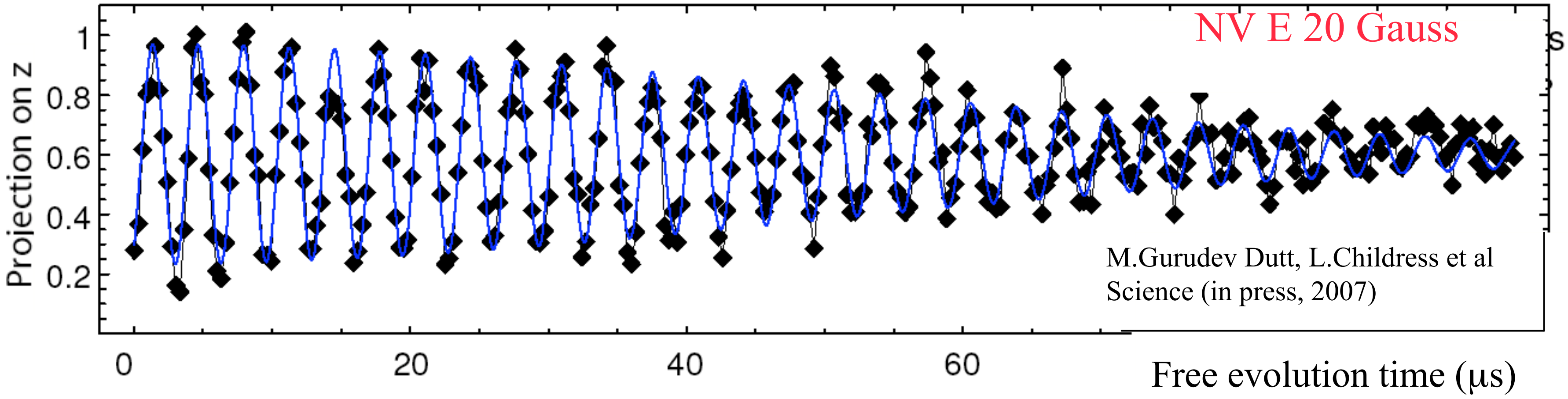
Remote nuclei:
spin bath

Environment as a resource

✓Idea: use electron spin to address proximal nuclei =
kind of NMR molecule

Early ideas: Kilin,Wrachtrup, Hemmer, MDL

Example: watching single nuclear spin precession



M.Gurudev Dutt, L.Childress et al
Science (in press, 2007)

- NMR on single, isolated nuclear spin!

Contrast ~ 70% => Nuclear spin preparation
& readout fidelity ~ 85%

- ✓ Effective nuclear temperature~ 300 nanoKelvin
- ✓ Nuclear coherence time: fraction of second
- ✓ "Quantum register": electron + several coupled nuclei

Outlook: useful quantum information systems from few coupled qubits

✓Idea: encode qubits in nuclear spins (“storage” qubits)

✓Entangle electrons (“communication” qubits)
via optical photons

✓Perform quantum gates between remote nuclei
via electron-nuclear coupling: “teleportation based gates”

✓Operations between any pairs at random locations can be performed simultaneously: purely optical scaling possible

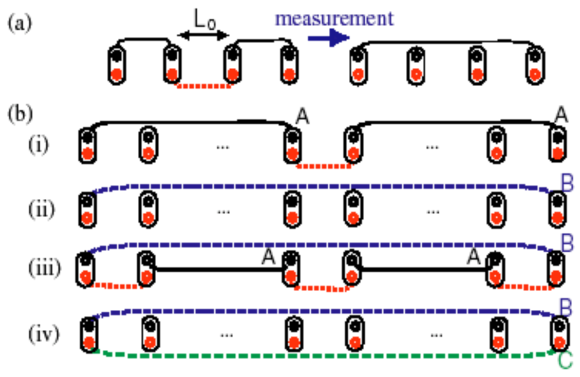
- quantum repeaters for long-distance communication

L.Childress, J.Taylor, A.Sorensen. MDL, 2004

- fault tolerant quantum computation

possibly with very high error thresholds

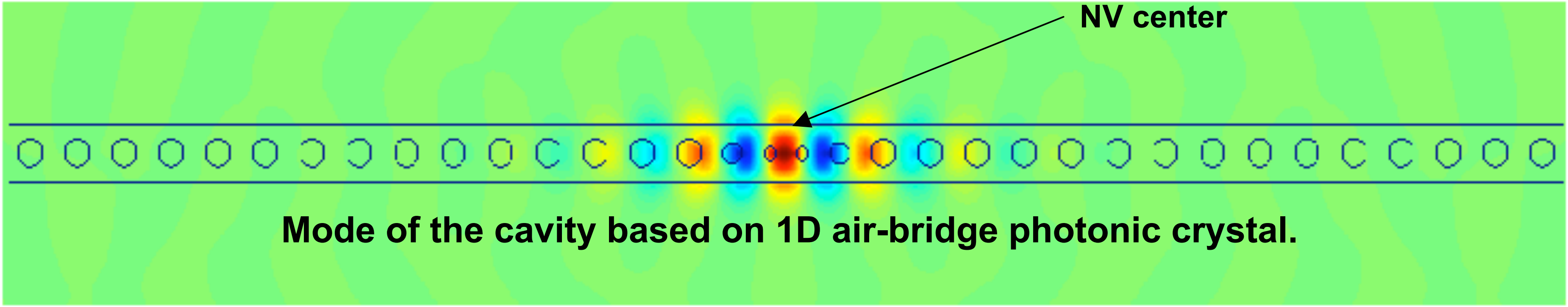
L.Jiang, J.Taylor et al, (quant-ph, 2007)



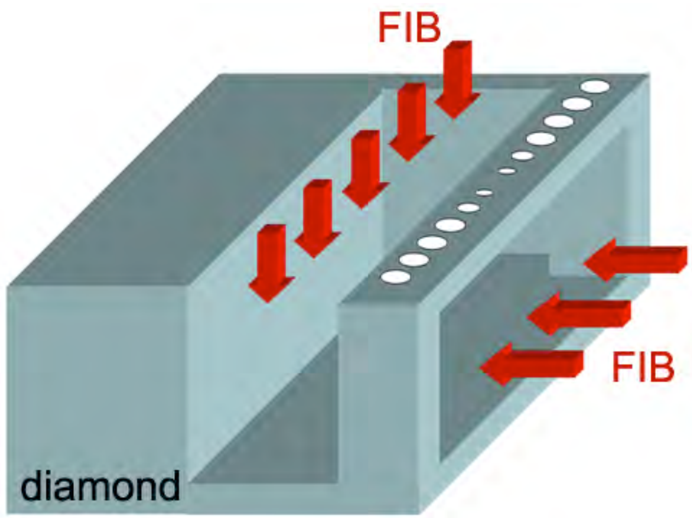
✓ Small registers with 2-5 isolated qubits can be efficiently scaled!

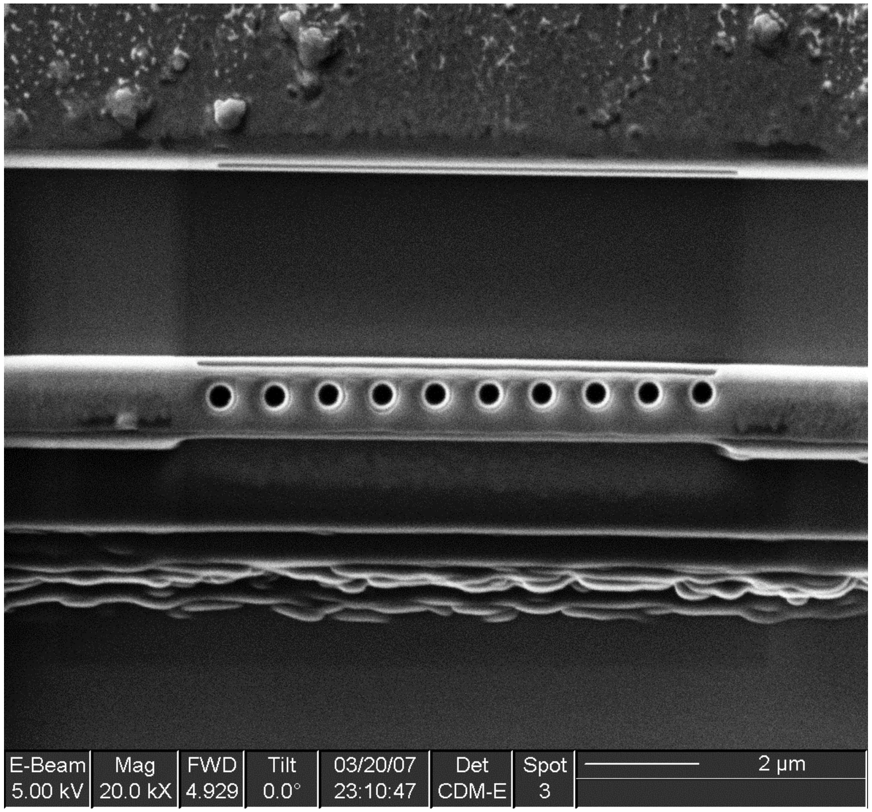
Outlook: diamond photonics

cavity QED techniques for efficient emitter-photon coupling



Mode of the cavity based on 1D air-bridge photonic crystal.

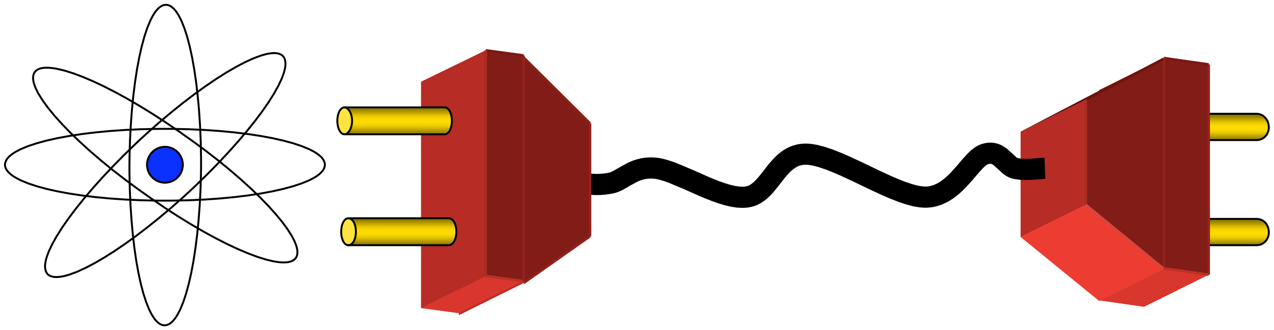


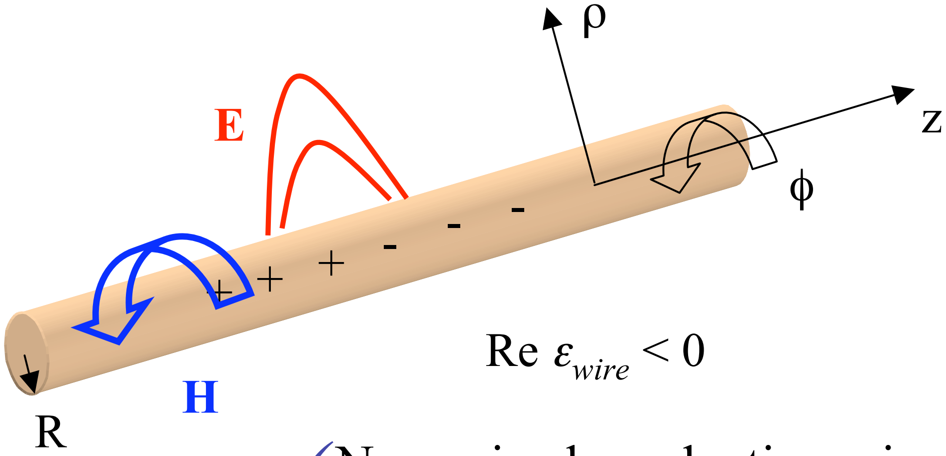


Marco Loncar

“Quantum plasmonics”:

new approach approach to atom-photon interface via sub-wavelength confinement on metallic nanowires



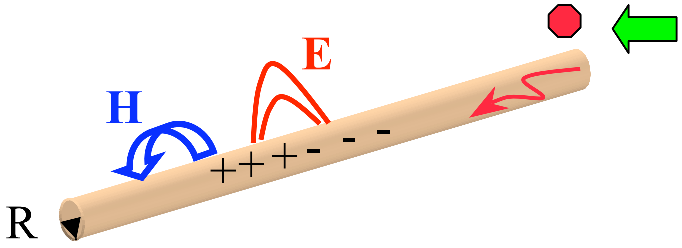


✓Nano-sized conducting wire: optical waveguide

collaboration with H.Park (Harvard-Chemistry), M.Loncar (Harvard EE), P. Hemmer (TAMU)

Strong coupling with nanowire surface plasmons

- ✓ Key idea: tight concentration of electromagnetic field on conducting wires

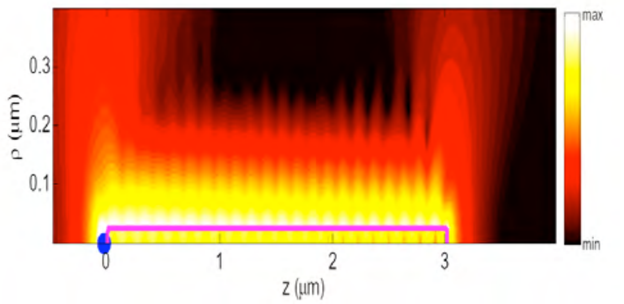


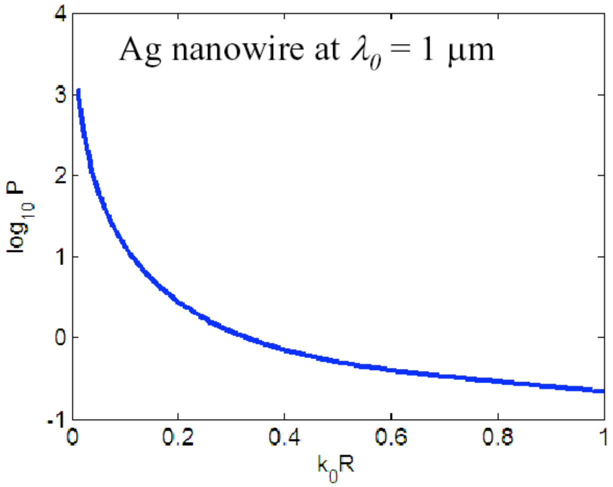
$$P = \frac{\Gamma_{plasm}}{\Gamma_0} \sim \frac{1}{(k_0 R)^3}$$

…results in strong coupling of single photon emitters to plasmon field

- ✓Atom emission guided almost completely into the wire, this emission should be completely reversible

- ✓Calculation for realistic system (includes losses)





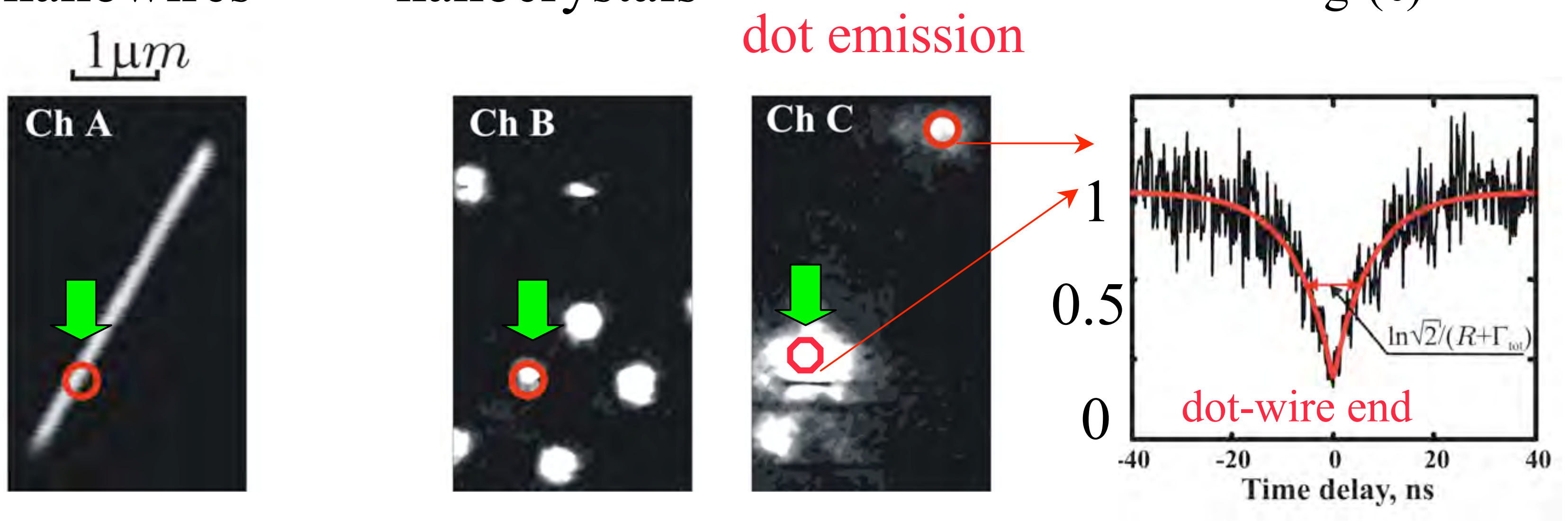
Theory: D. Chang, A.Sorensen, P.Hemmer and M.D.L. PRL (2006)

Experimental realization: nanowires light up

Chemically grown silver nanowires

CdSe quantum dot nanocrystals

Cross-correlations $g^2(\tau)$



Spontaneous emission into surface nanowire plasmons

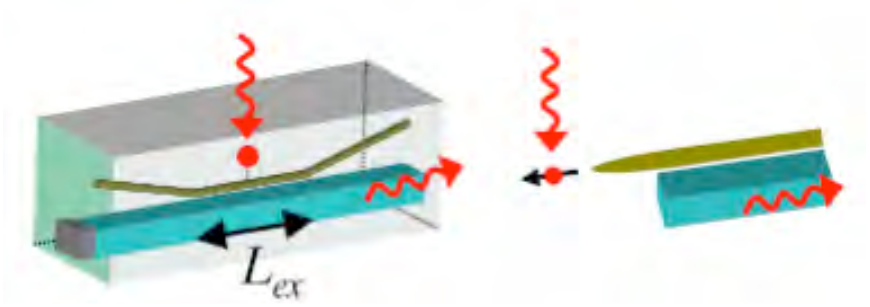
- ✓ Single quantum plasmonics: dot to single plasmon coupling
- ✓ 100 nm wires: Purcell enhancement factor P>3, efficiencies ~60%

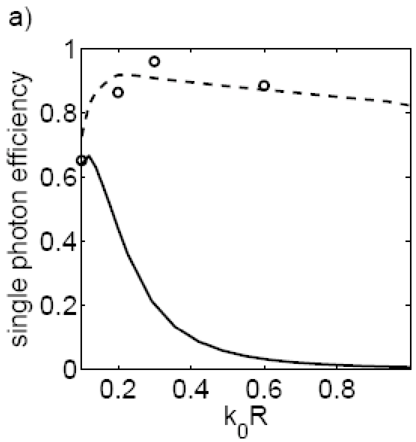
A.Akimov, et al (submitted)

Outlook: atom-photon interface using nanoscale plasmons

✓Efficient photon collection via integrated devices

- Problem: plasmons are lossy
- Approach: efficient evanescent coupling to dielectric waveguides





Theory: over 95% collection into fiber possible

✓New exciting opportunities for

single photon transistors, switching and nonlinear optics
remote spin-spin coupling
photonic quantum simulations: optical realization of Kondo model

Collaboration with H. Park, M. Loncar

Approaches for single
photon switching, transistors,
nonlinear optics

New sensors:
e.g. ultra-sensitive, high resolution
magnetometer
based on NV electron spins

New interface of nanoscience, quantum optics, NMR, photonics, materials technology and quantum information

Entanglement of remote
nuclear
spins in solid-state

NMR manipulation of
multi-qubit register
with high polarization and
single spins addressing

Systems for efficient
photon collection:
photonic crystals,
plasmons…

Quantum repeaters and novel
approaches to fault-tolerant
quantum compuation