Hybrid approaches to quantum information science

Challenge of simultaneous isolation and control of many-body system

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But: do not interact, hard to store

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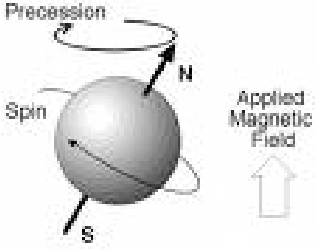

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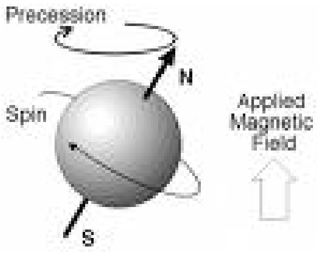

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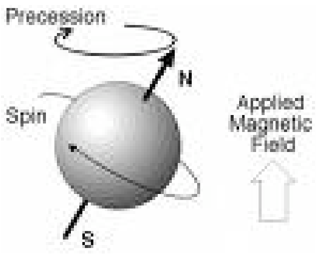

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- Isolated ions and atoms:
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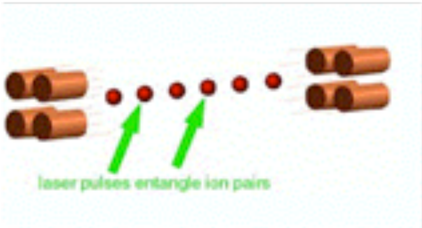

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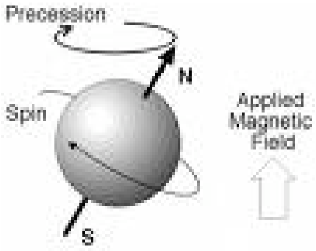

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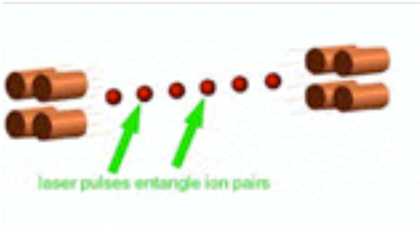

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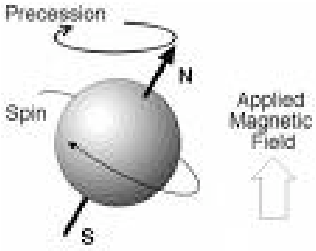

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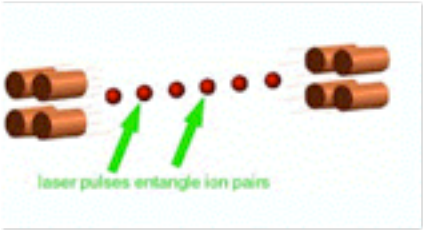

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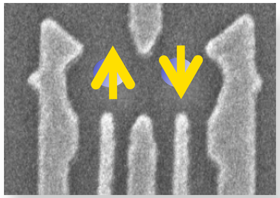
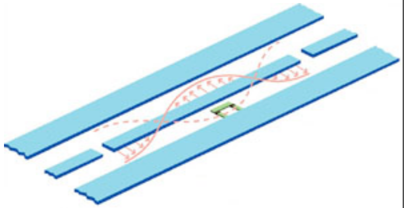
- Charged solid-state systems: stability, integration, strong interactions





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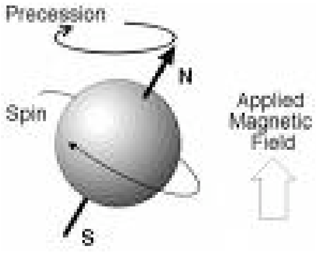

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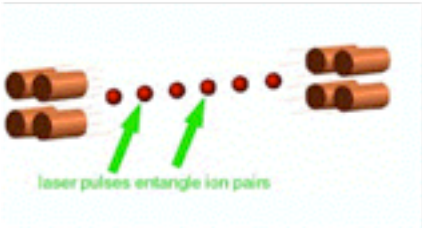

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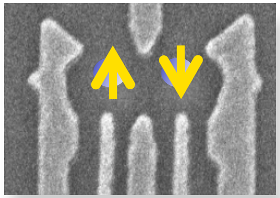

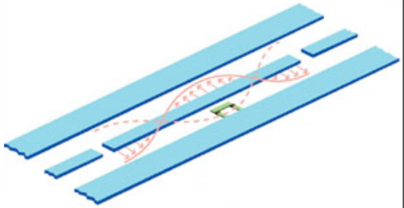

But: live in complex solid-state environment, hard to control

Hybrid approaches to quantum information

aim: address key challenges in QIS

- Hybrid tools to explore new qubits
- Hybrid architectures: combining useful features of different systems
- Outlook: new applications of hybrid systems
- Outlook: integrating hybrid experimental technologies

Hybrid tools for exploring new qubits

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one example

Example: control of single electron & nuclear spins using Nitrogen-Vacancy impurities in diamond

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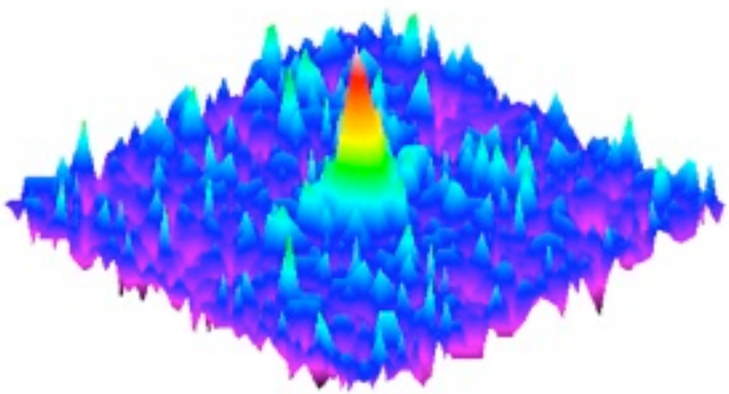

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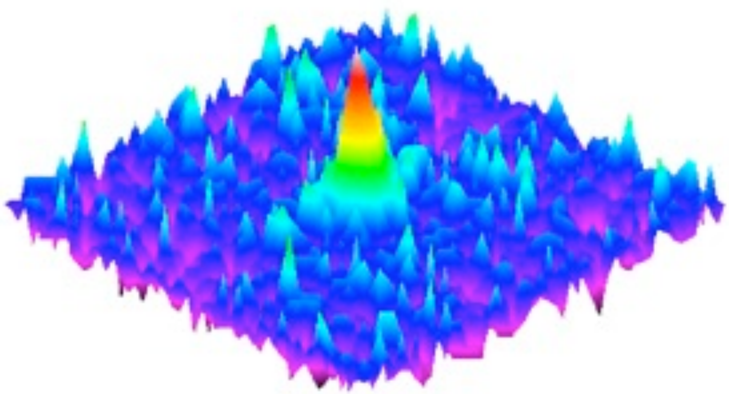

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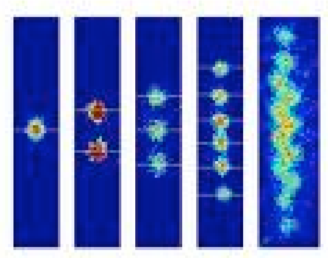

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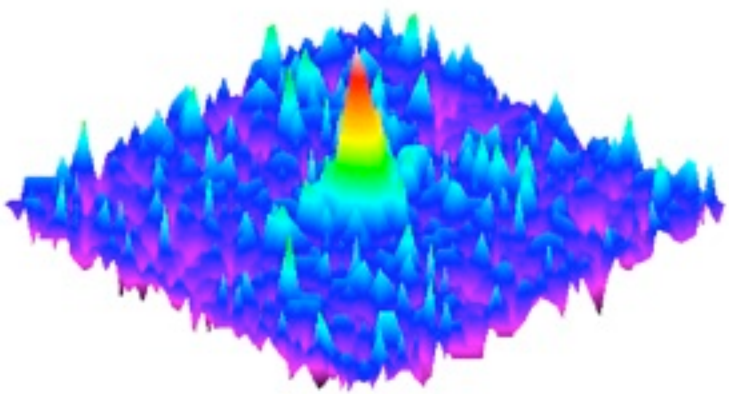

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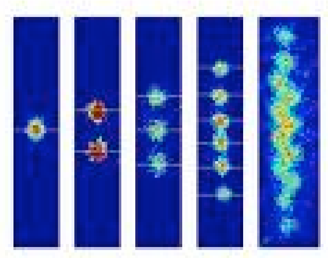
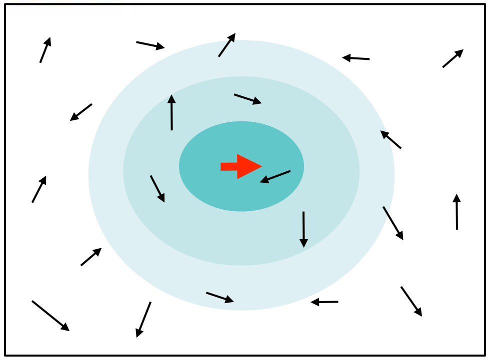


- Understanding physics of mesoscopic (spin) environment



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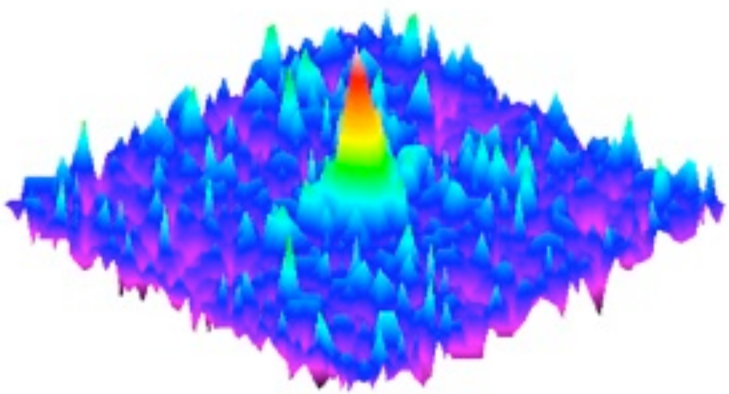

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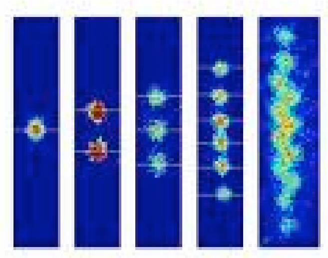

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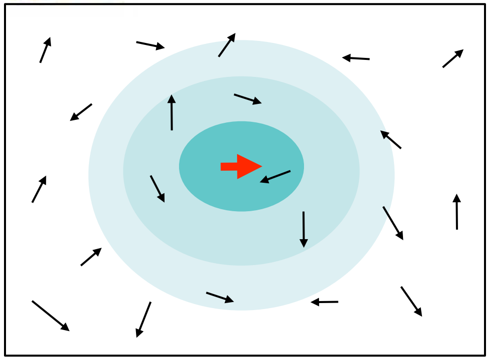
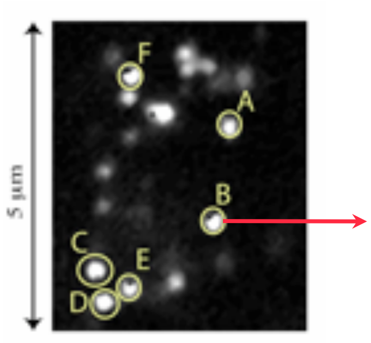


- Advances in material science

Control of single electron spin

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



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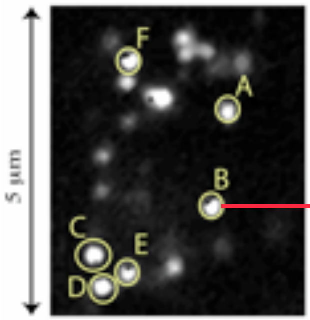

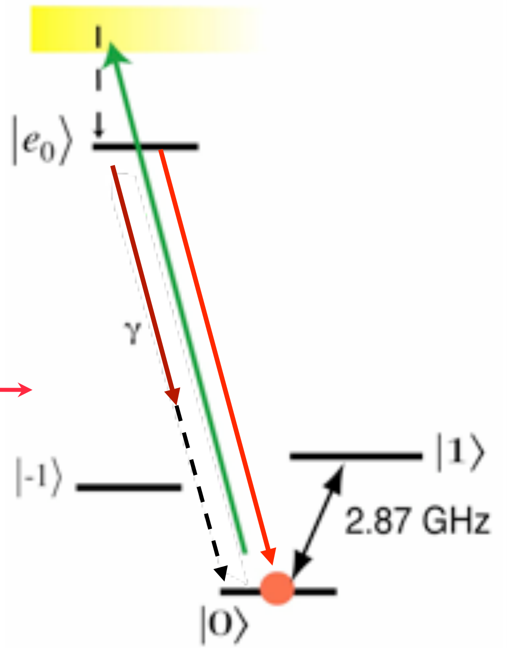

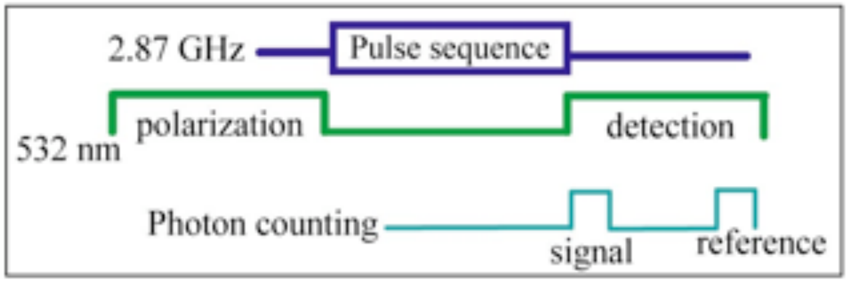

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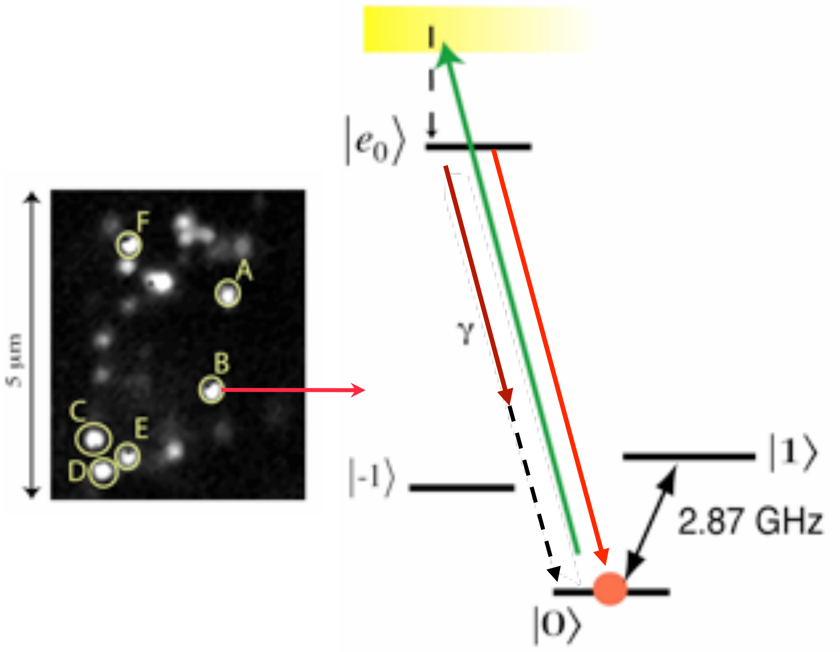

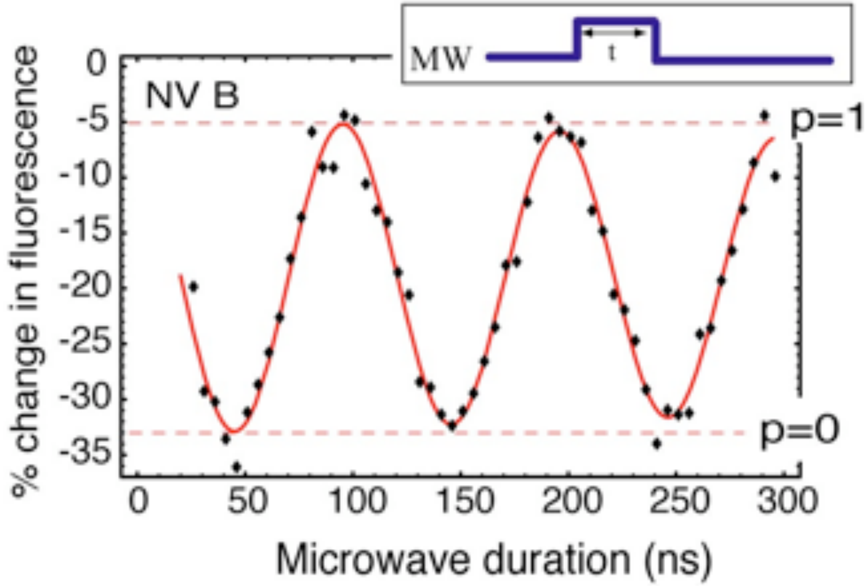

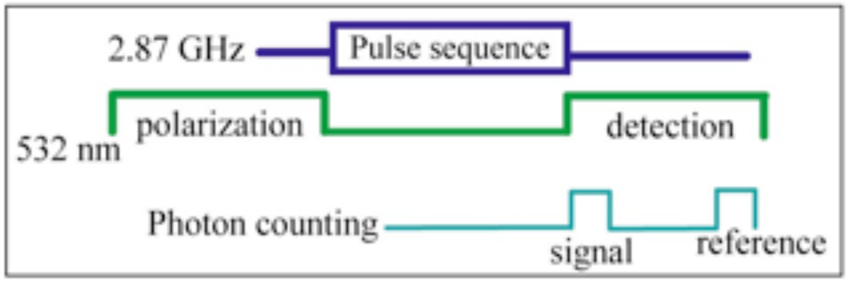

✓Pioneering work
F.Jelezko, J.Wrachtrup (Stuttgart)
D.Awschlom (UCSB)

•Near single shot readout at low T

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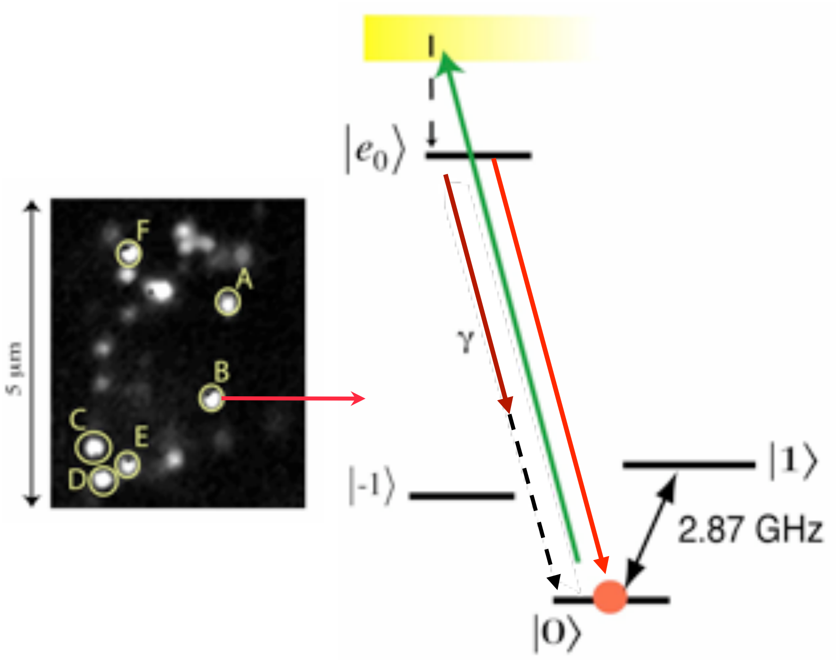

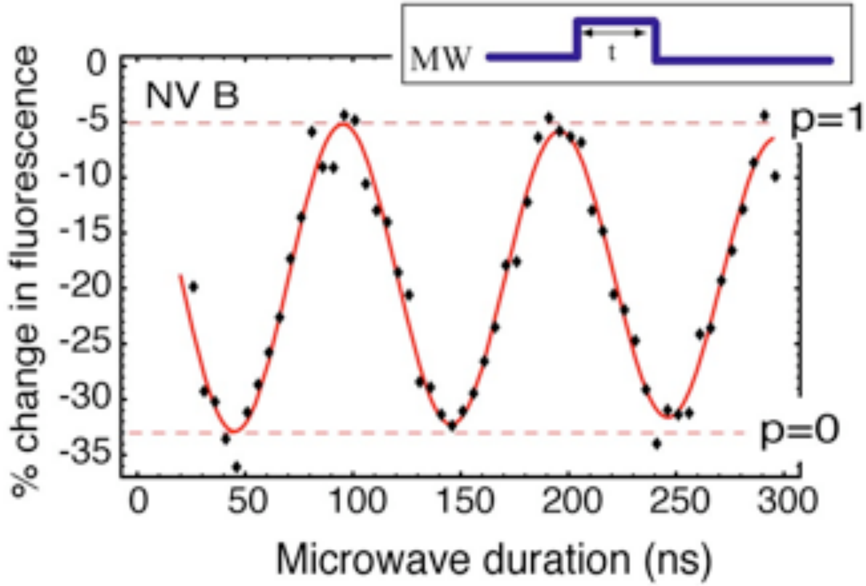

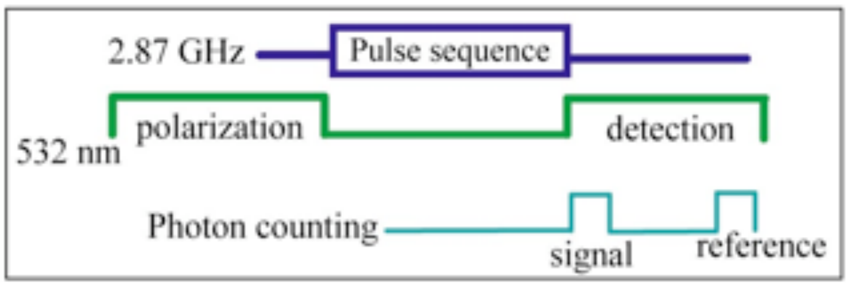

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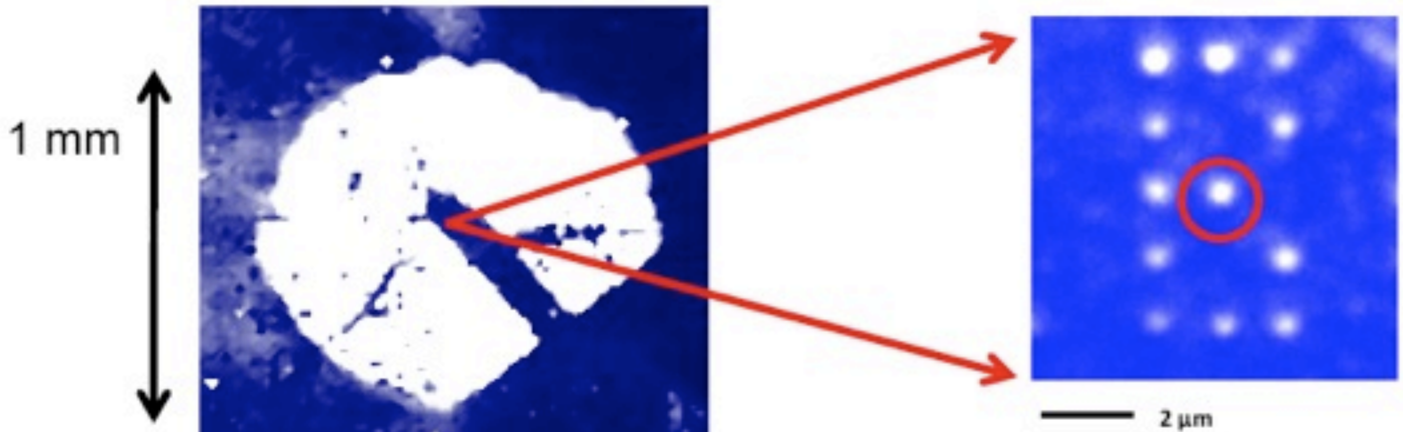
- Near single shot readout at low T

✓Electron precession decay time (average over many runs): $T_2^* \sim 1\mu s$

✓Electron decoherence time (spin echo): T2 ~ 1 ms

Ion implantation: isotopic engineering of single spins

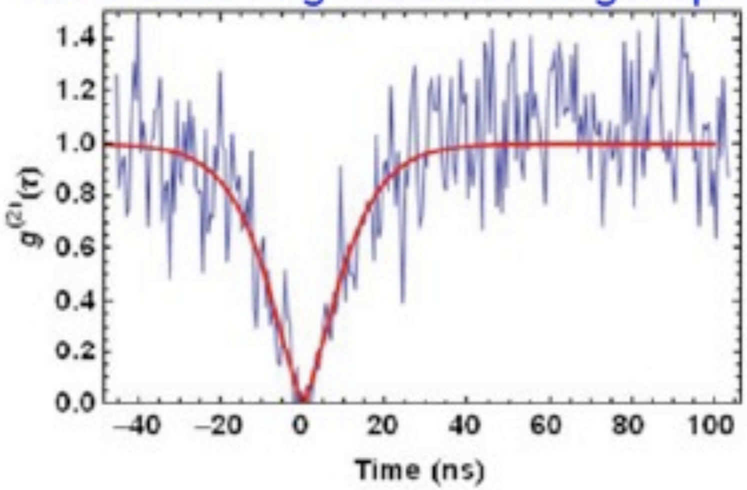
Spatially resolved photoluminescence map



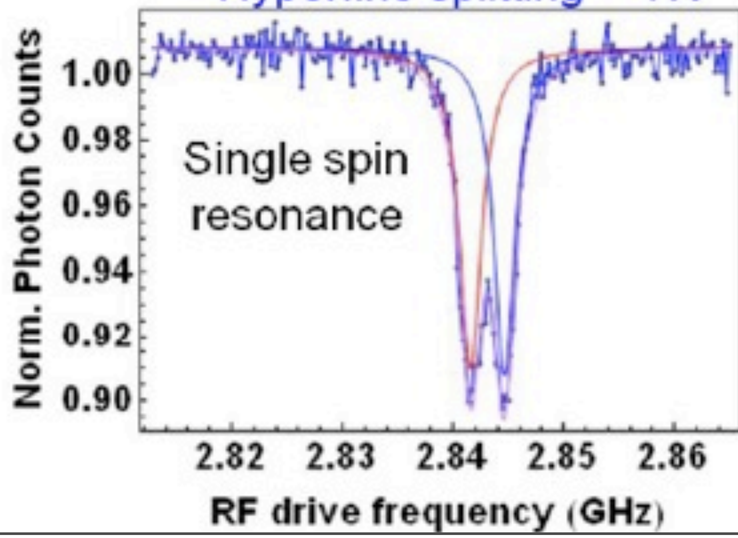
D.Awschlom (UCSB)
S.Prawer (Melbourne)

(G.F. Fuchs et al., 2009)

Anti-bunching indicates single spin



Hyperfine splitting -^{15}NV



Picture of single electron environment

- Obtained through detailed spectroscopy of individual NV centers

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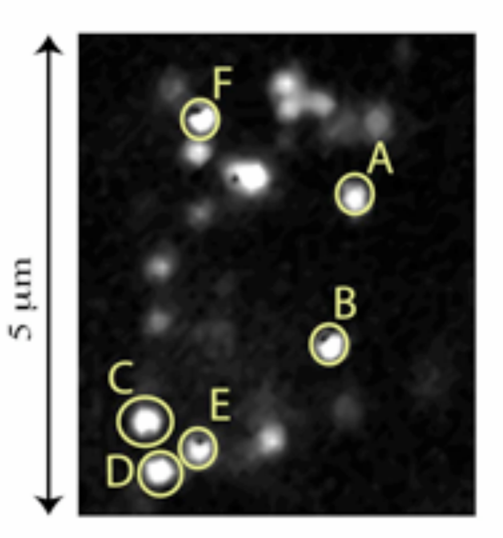

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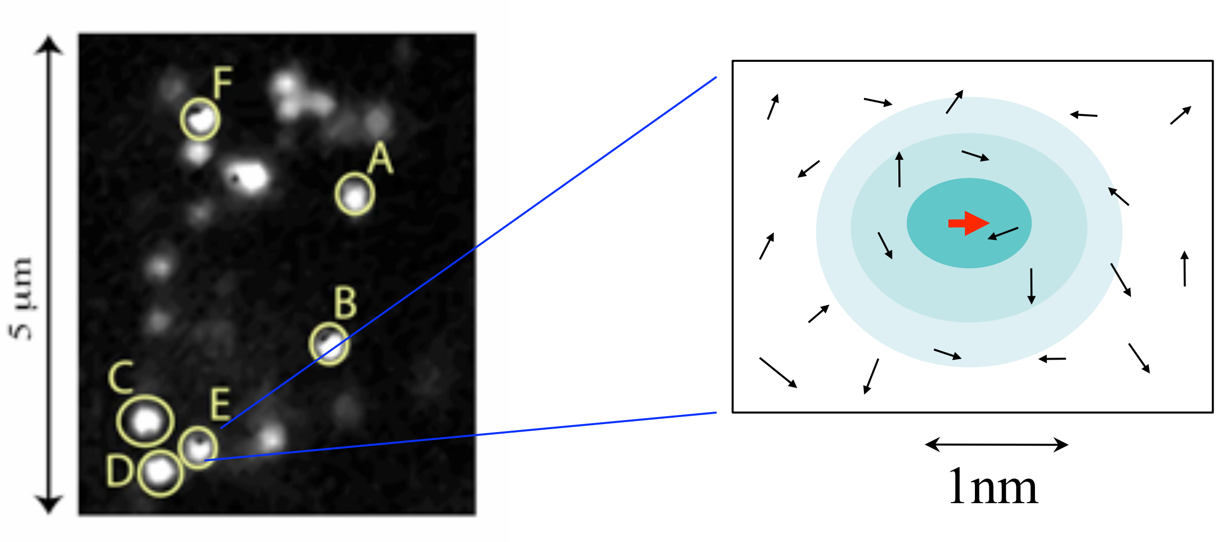

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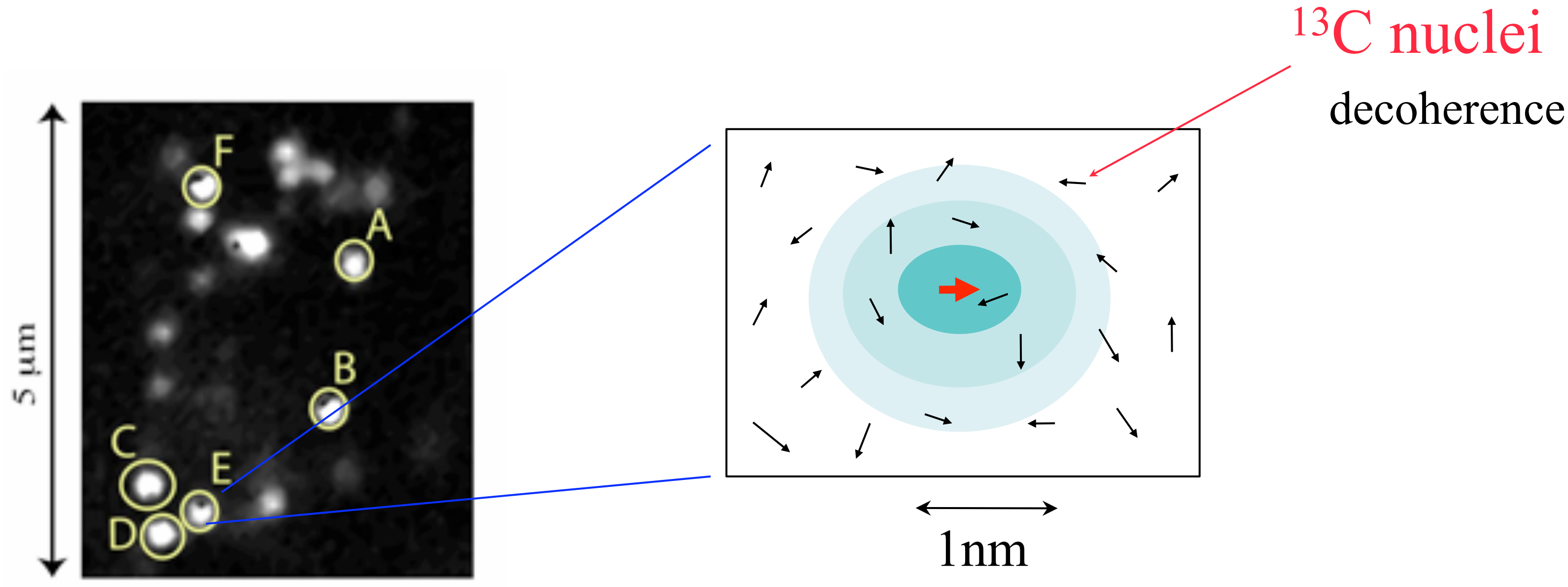

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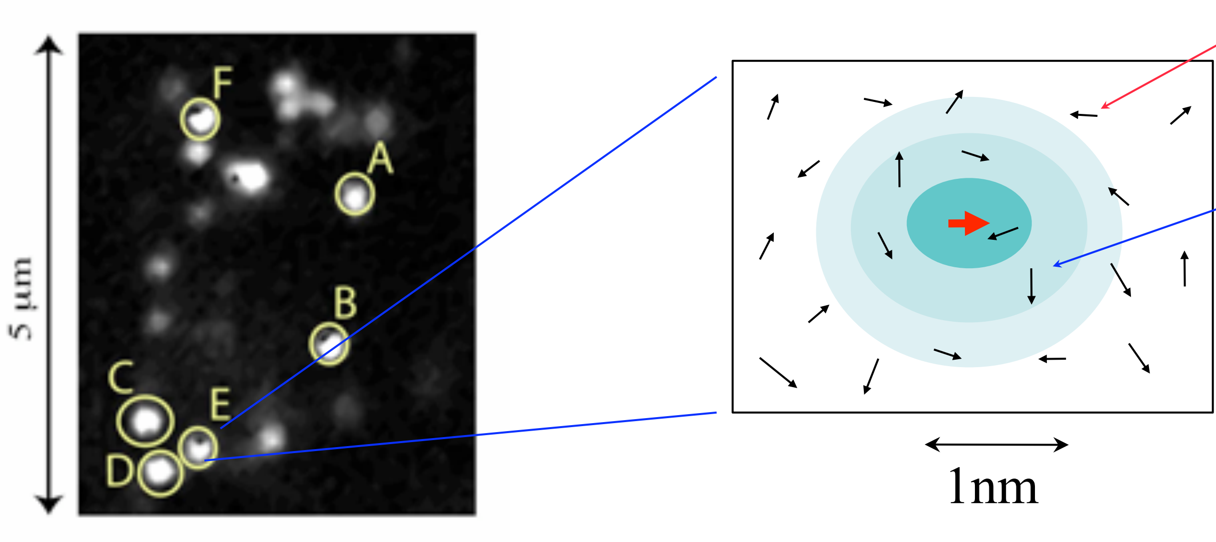

^{13}C nuclei

decoherence

Proximal nuclei are different:

strong hyperfine, can be isolated

L.Childress et al, Science (2006)
R. Hanson et al, Science (2008)

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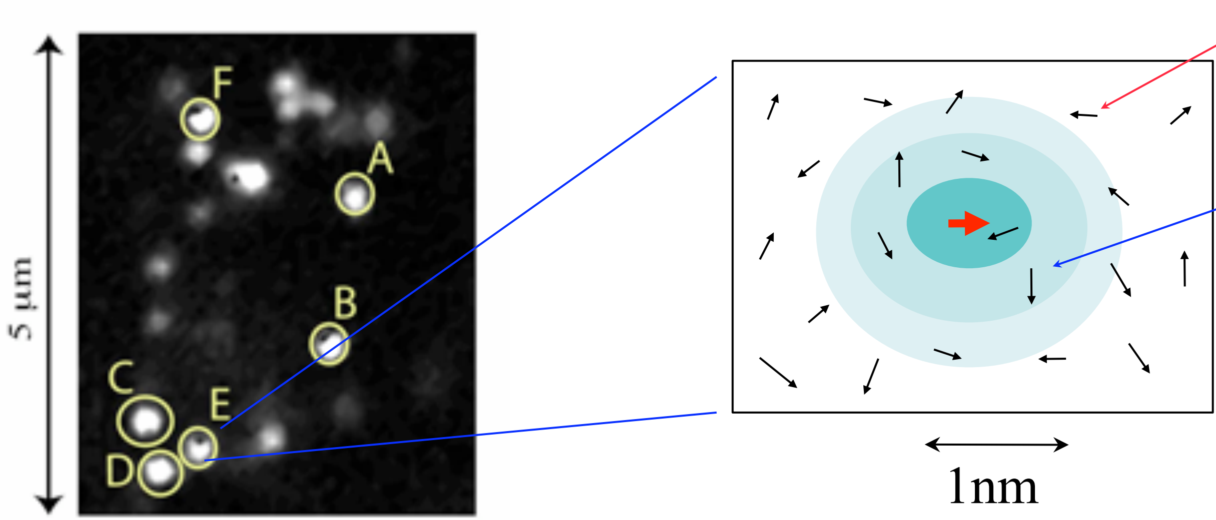

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- Current efforts:

reducing ^{13}C concentration

controlling & using proximal nuclear spins:

realization of few qubit registers

Improving coherence via materials engineering

✓New development: ultra-pure CVD grown diamond enriched ^{12}C isotope

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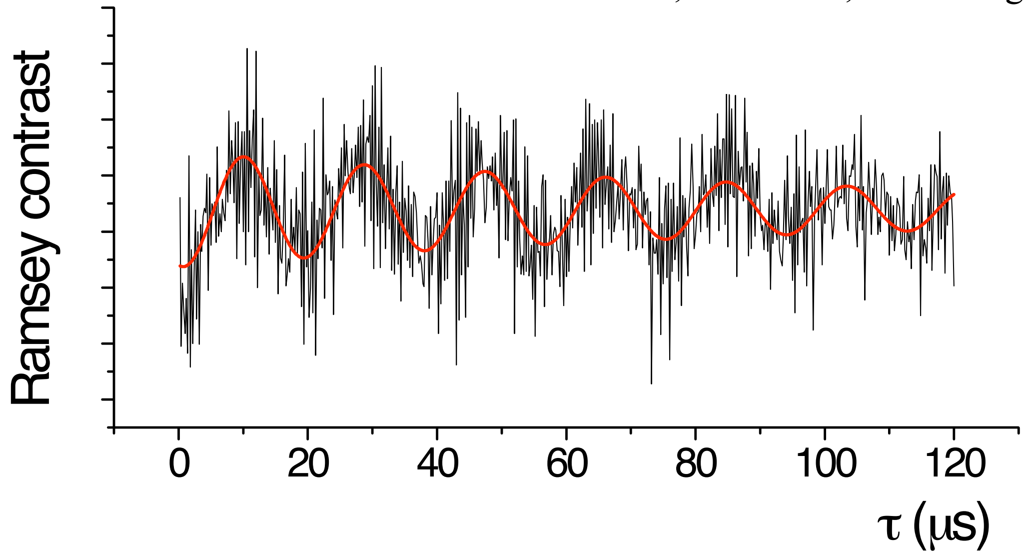
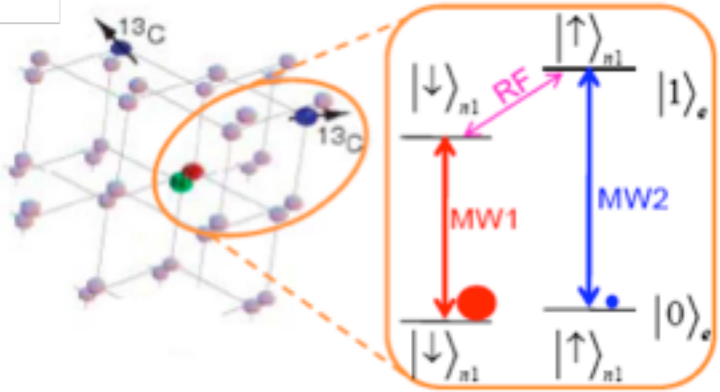
✓First results: ultra-long coherence in Ramsey measurements

D.Twitchen, Element 6, data Stuttgart group, Nature Materials (2009)



✓$T_2^* > 100$ microseconds, exceptional coherence!

Controlling nuclear spins in electron environment: recent work



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- Polarization (sub μK cooling), control, readout of single nuclei
- Long lived (~1s) quantum memory in single nuclei at room T
- Controlled few-spin systems, entanglement of 3 spins

Experiments: Gurudev Dutt et al, Science (2007), Jiang et al PRL (2008), Neumann et al (Stuttgart), Science (2008)
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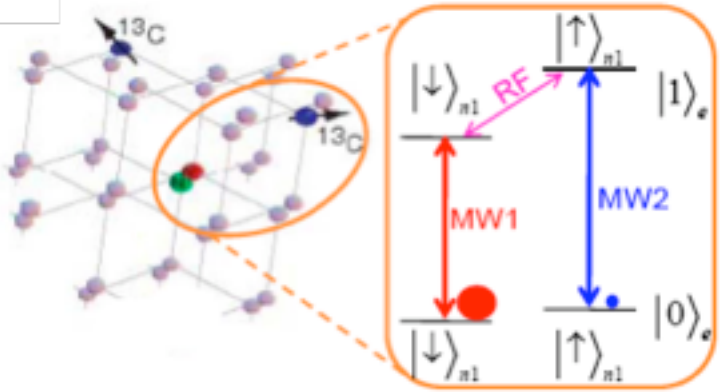

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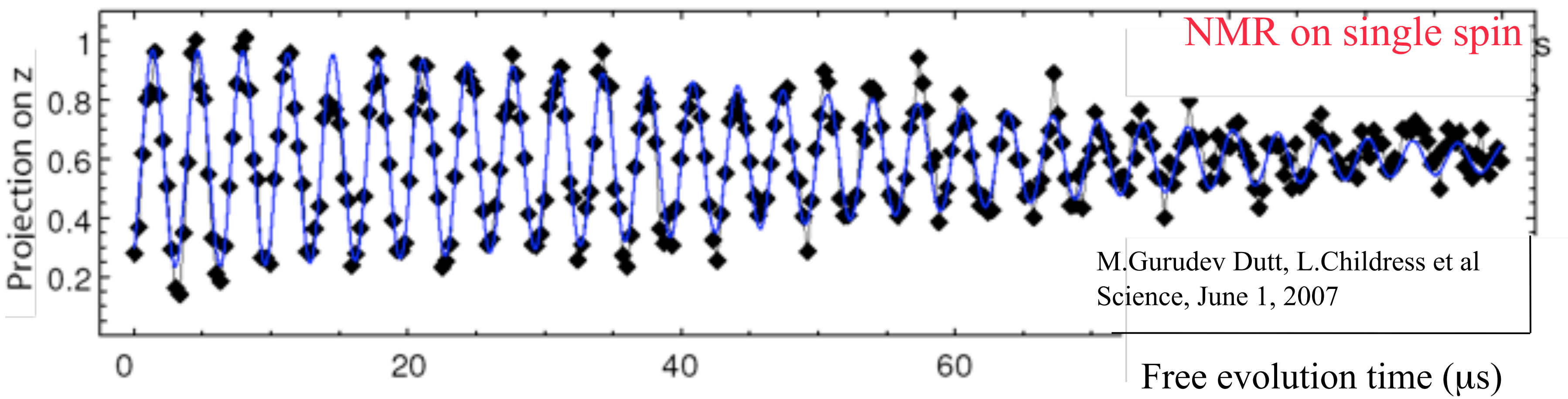
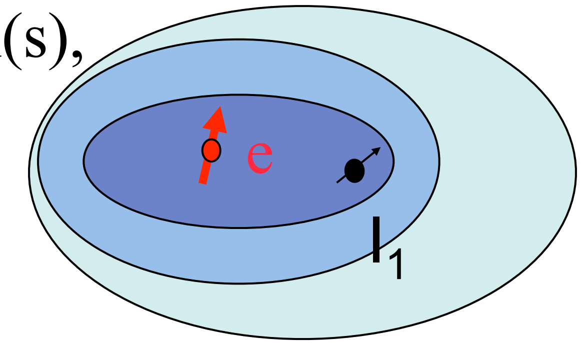


Application: repetitive readout of electronic spin using proximal nuclear spins

✓Idea: map electronic spin to nearby nuclear spin(s), repetitively measure nuclear spin



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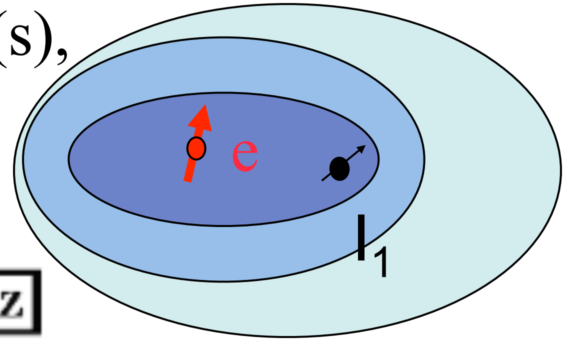

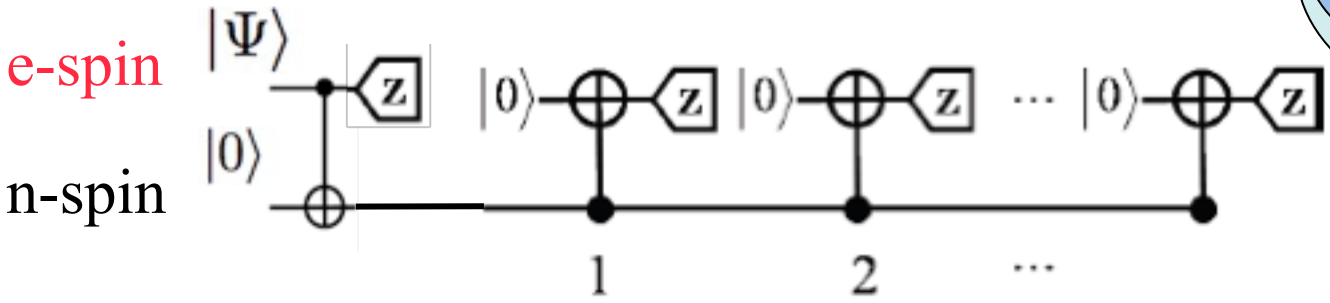

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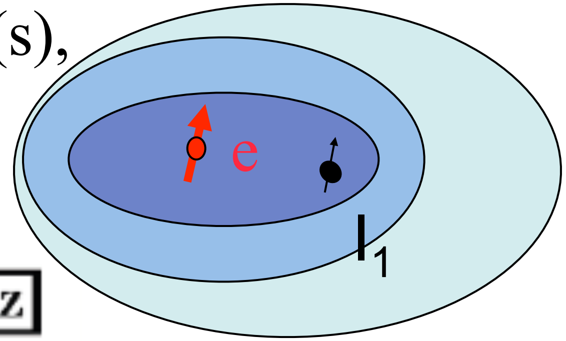

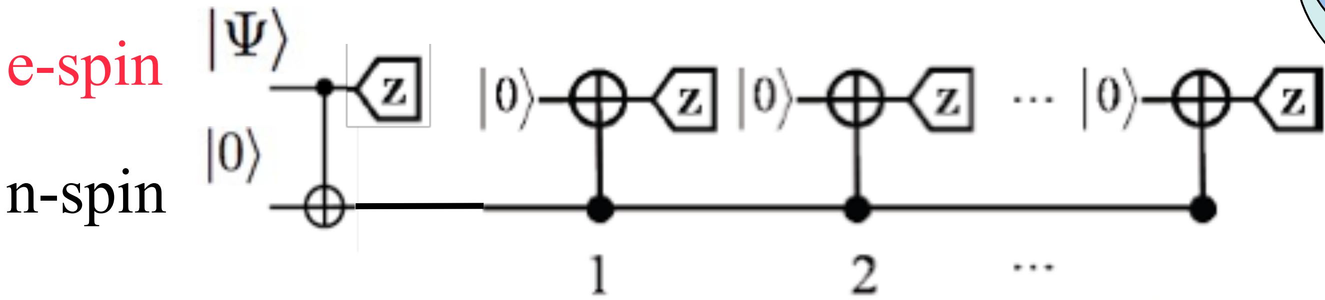

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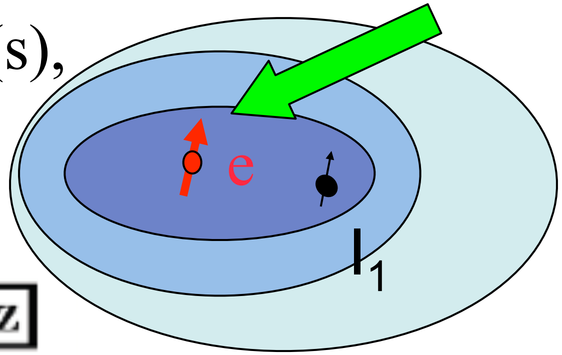

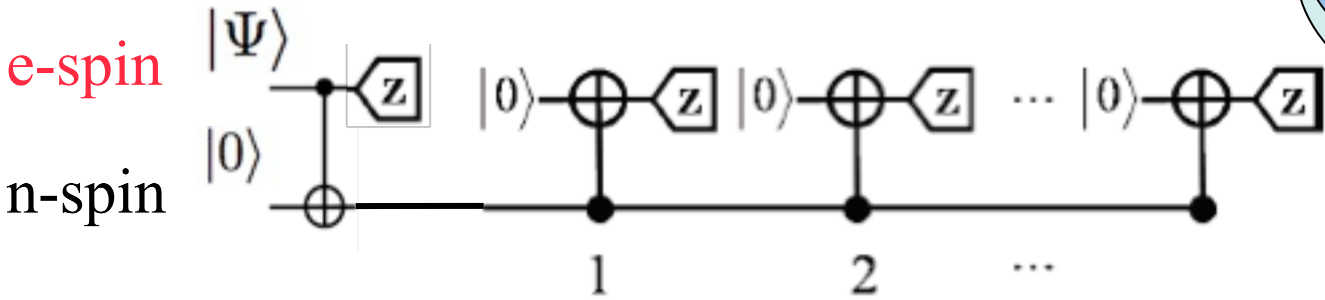

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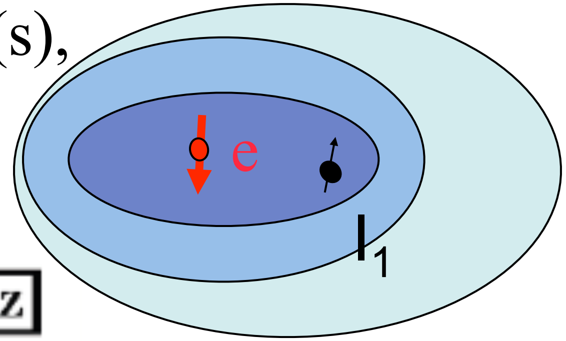

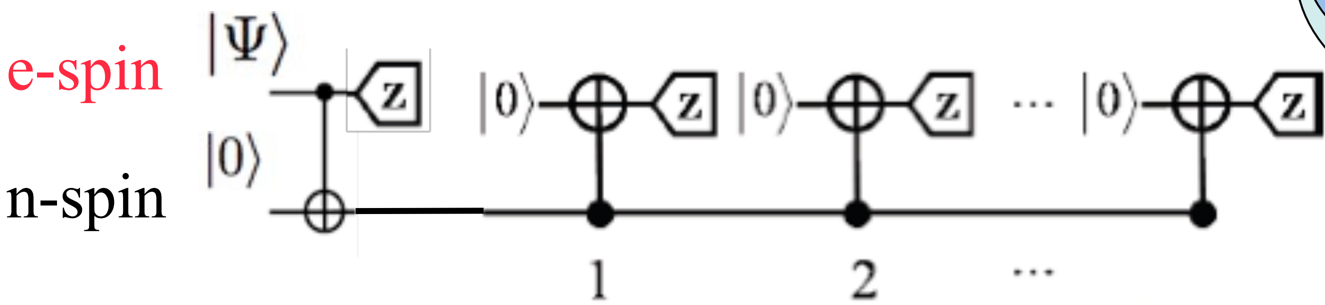

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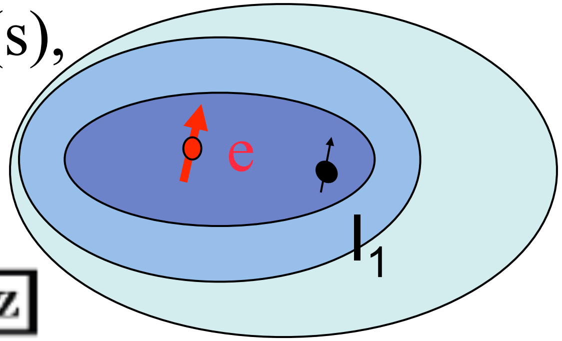

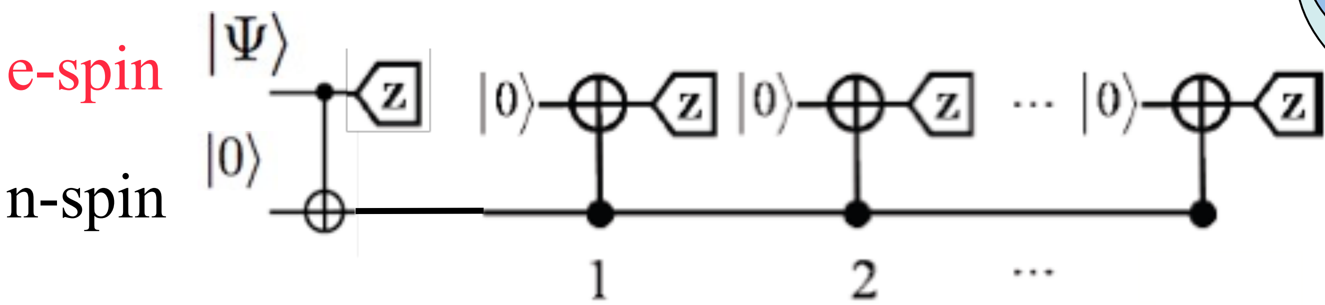

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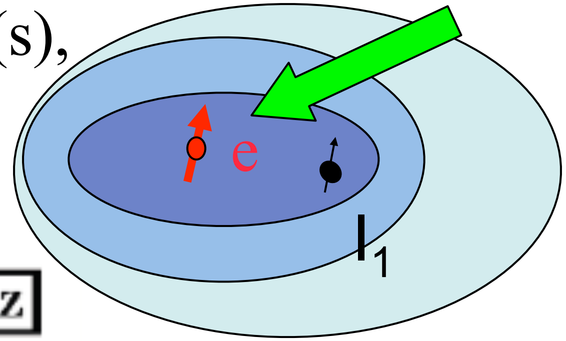
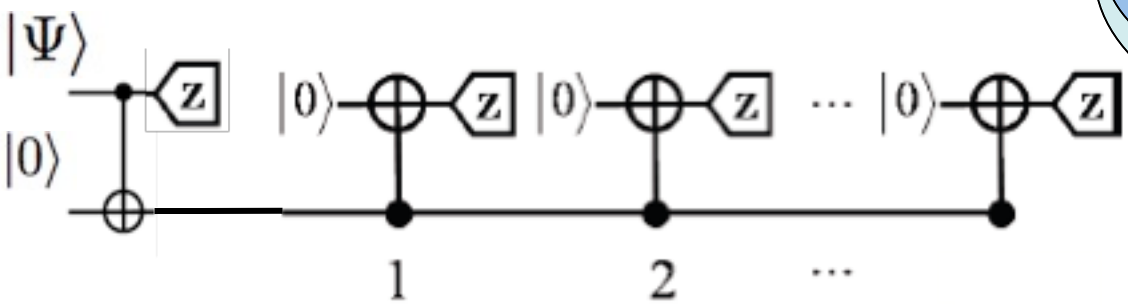


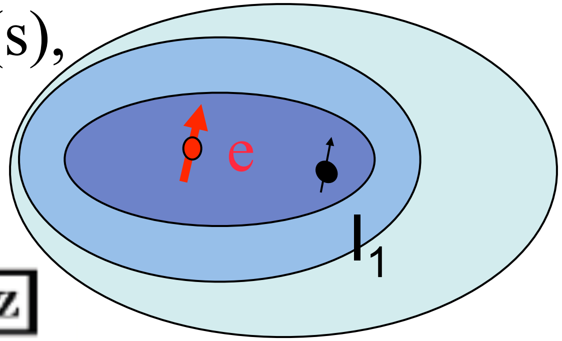
e-spin

n-spin



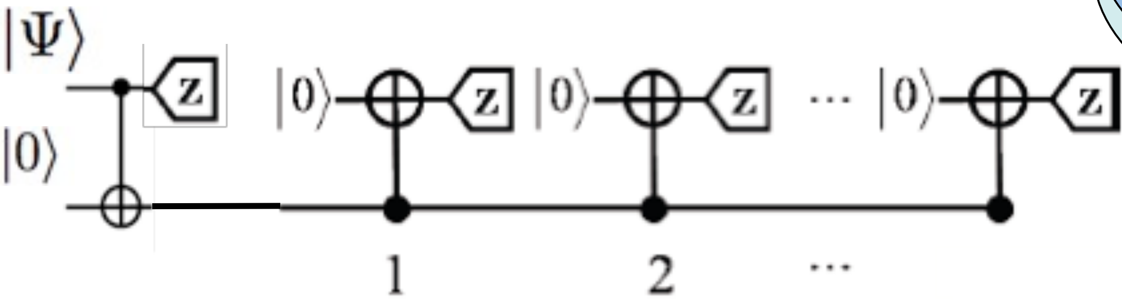
Application: repetitive readout of electronic spin using proximal nuclear spins

✓Idea: map electronic spin to nearby nuclear spin(s), repetitively measure nuclear spin



e-spin

n-spin



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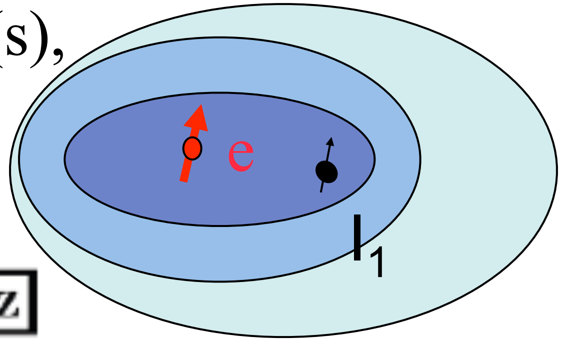

e-spin

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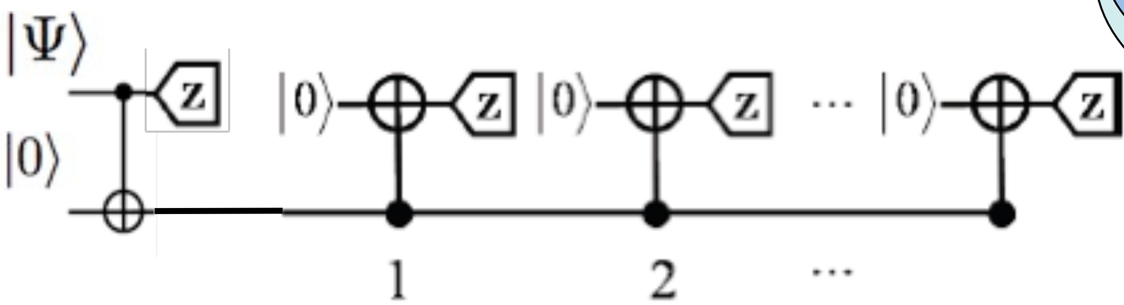
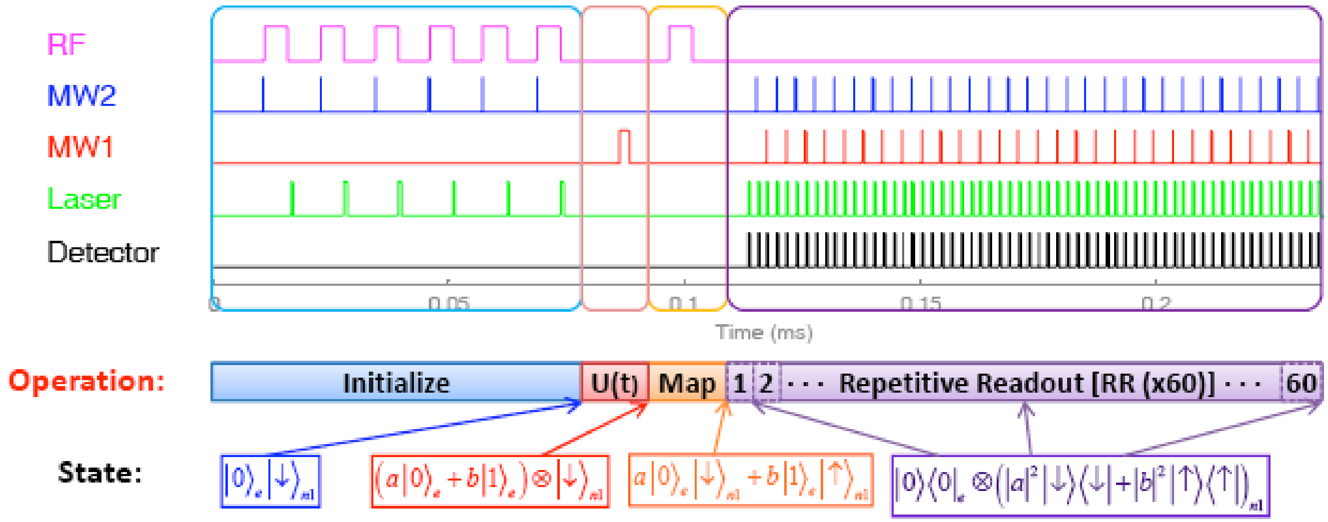


✓Pulse sequence



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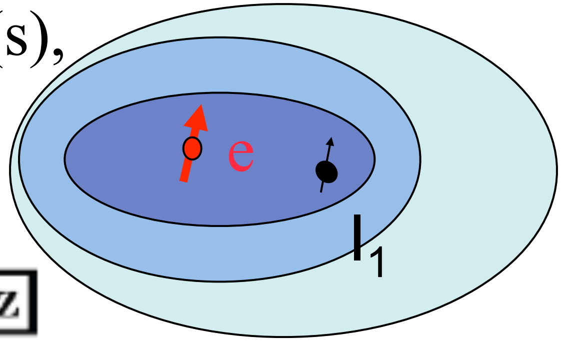

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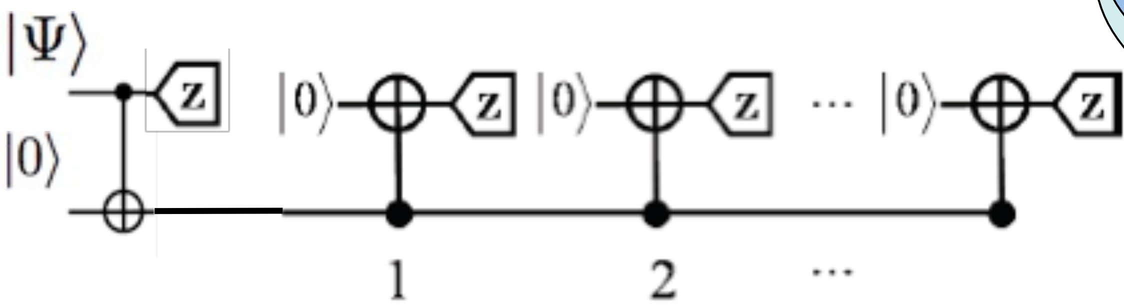

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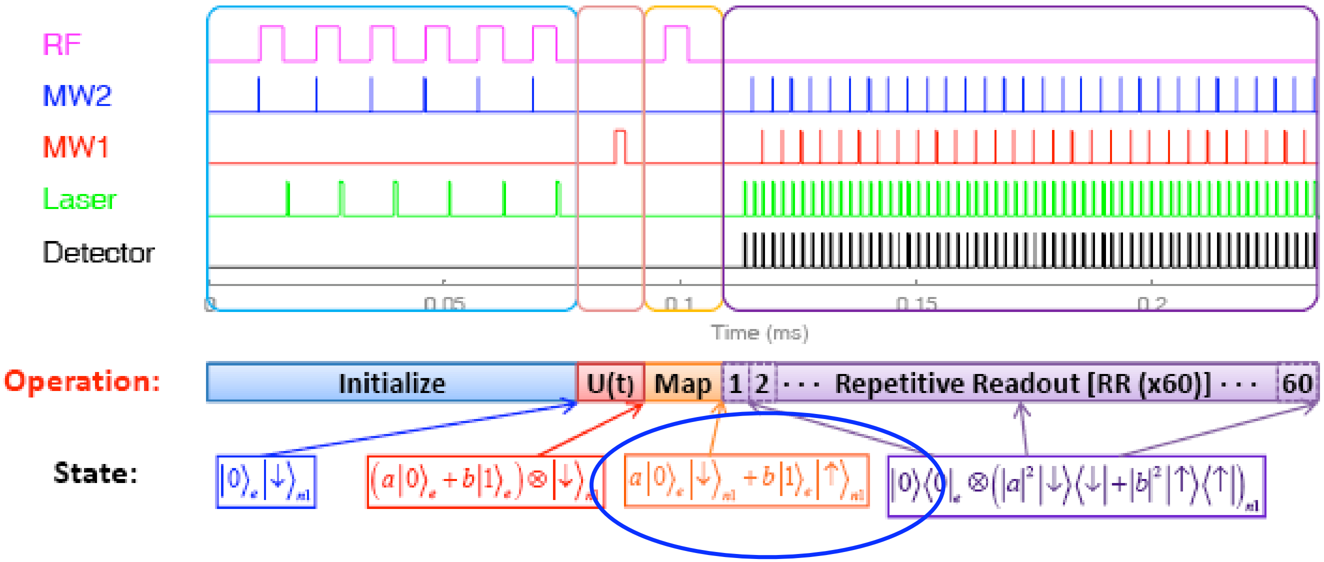

Improved readout of electron Rabi oscillations

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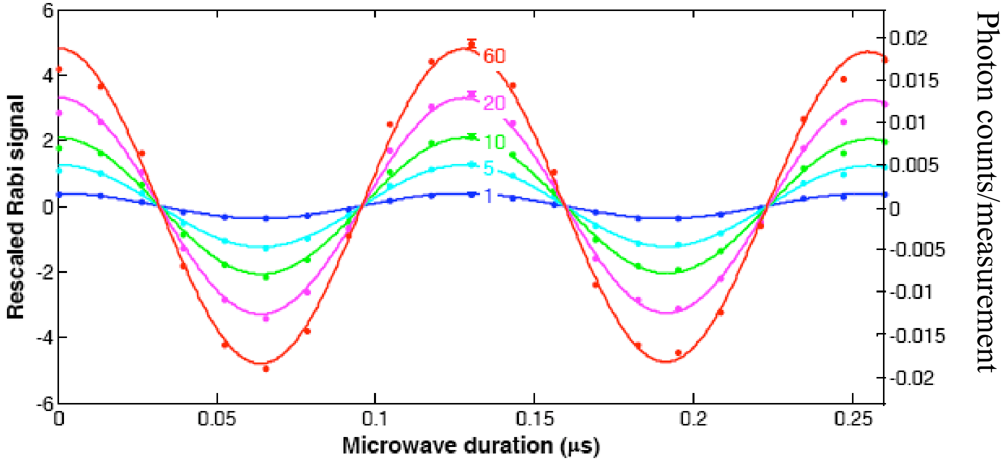
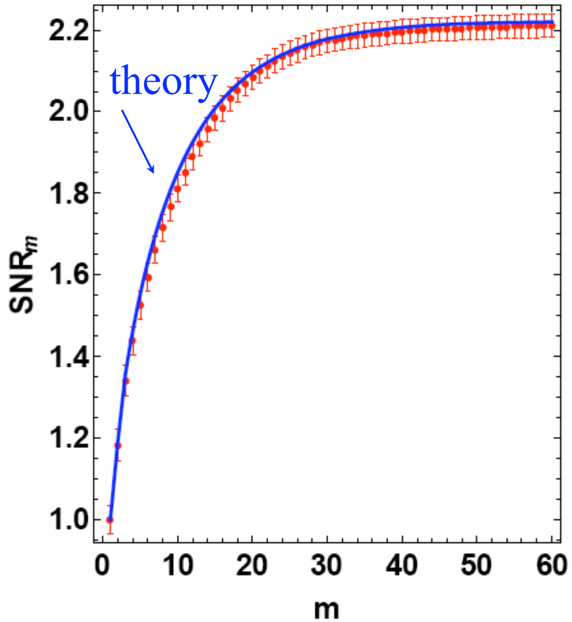


✓ Result: 10-fold improvement in contrast
> 2-fold improvement
in signal to noise of readout



L.Jiang, J. Hodges et al, (2009), similar to Al ion clock Wineland group

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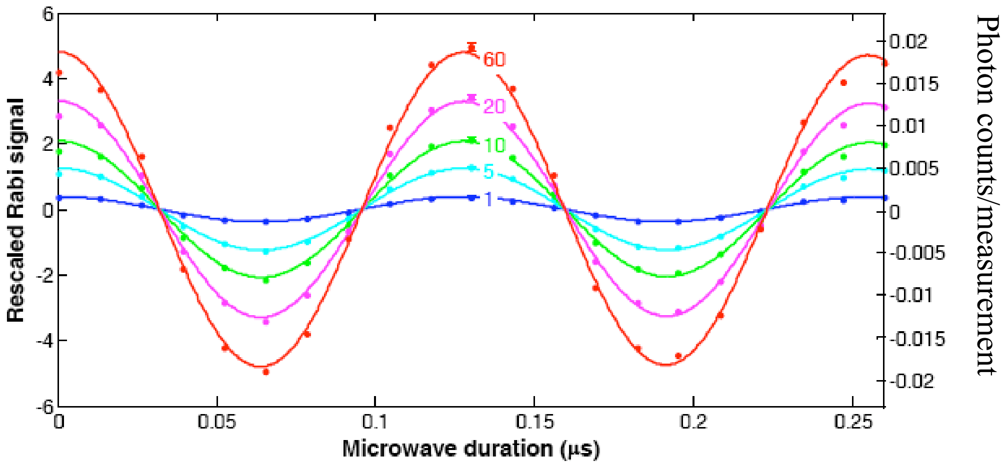

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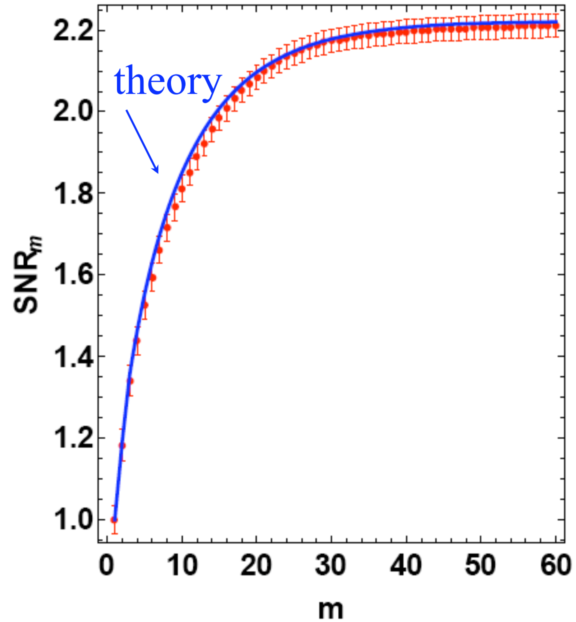
& concatenated sequence



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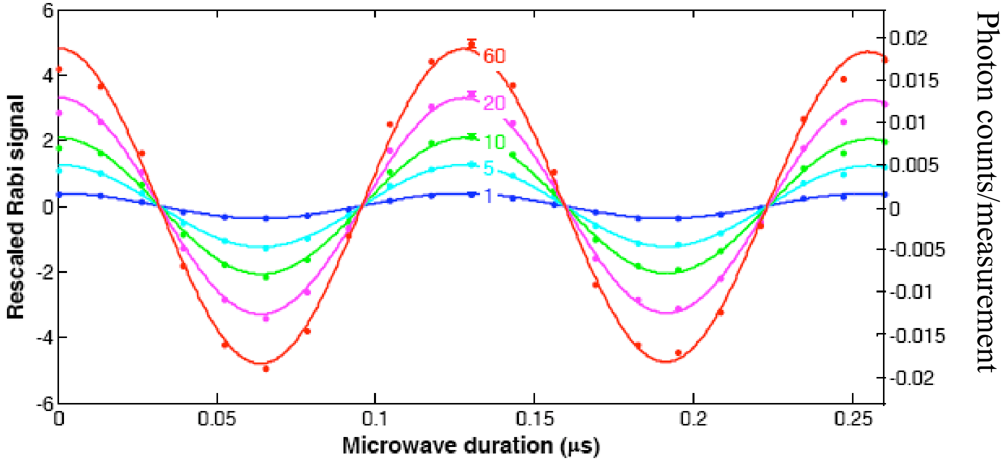

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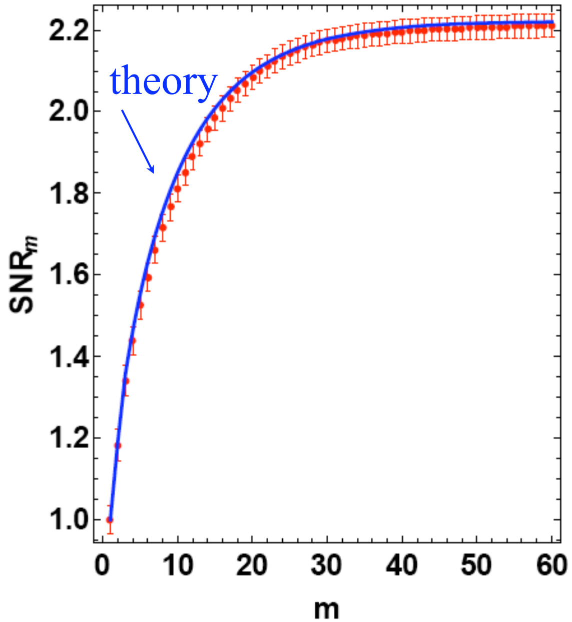


Example of useful few-qubit algorithm

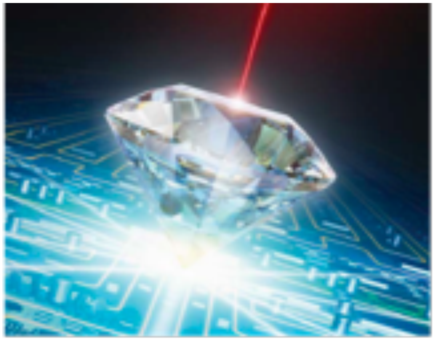
L.Jiang, J. Hodges et al, (2009), similar to Al ion clock Wineland group

Search for a “perfect” hybrid qubit

✓Remarkable efforts from experiments & material science to theory

✓Open questions:

Nitrogen-vacancy color centers in diamond
is one of 500+ impurities in diamond:
what about others?
other modern material systems: nanotubes etc?
other useful “hybrids”, e.g. topological qubits?



Hybrid architectures:

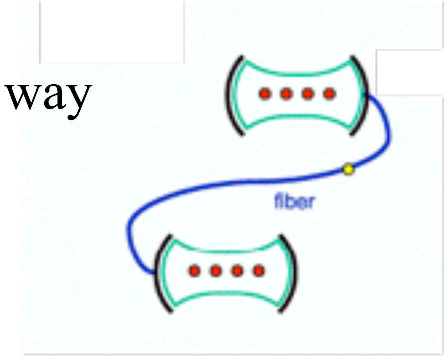
combining useful features of different qubits

Hybrid quantum architectures

Hybrid quantum architectures

✓Pioneering example: quantum optical interface

Non-local coupling of quantum bits by absorbing
or emitting a photon in a controlled way



Cirac, Zoller, Mabuchi,Kimble, PRL 78, 3221 (1997)

experiments at Caltech, MPQ

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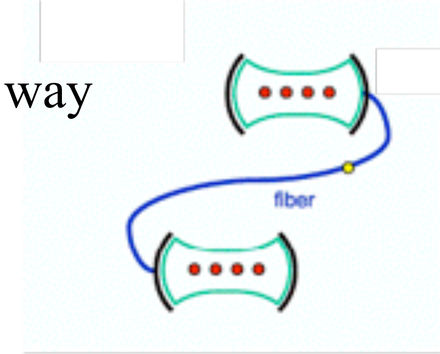

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✓Broad effort in AMO community:

single neutral atoms, ions, atomic ensembles, solid-state emitters
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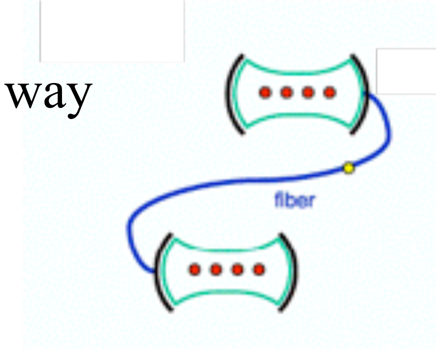

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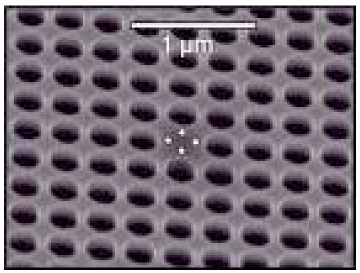
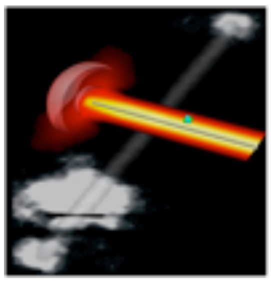
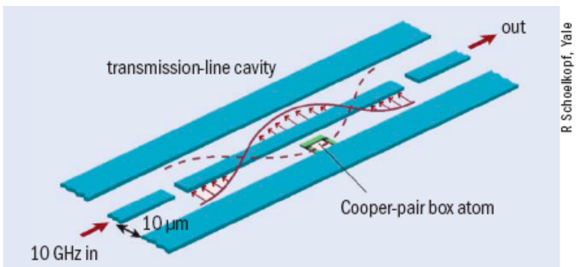
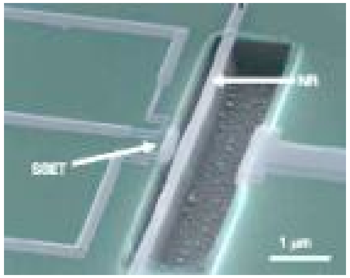
✓Remarkable new interconnects:

in optical, microwave, mechanical domains

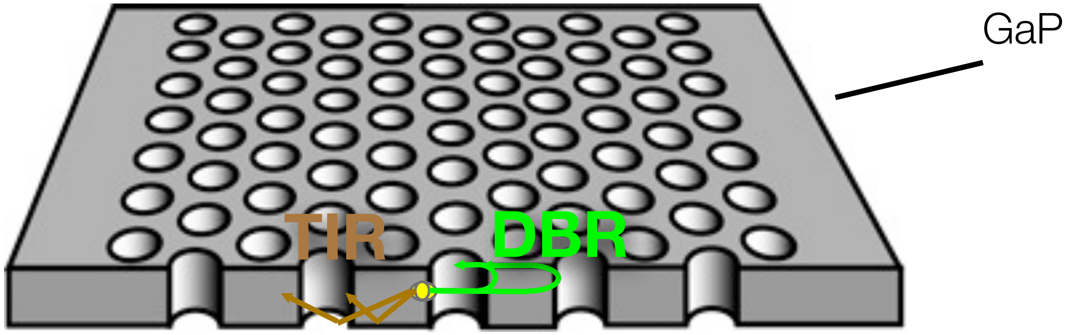








Quantum interfaces based on photonic crystal cavities



$|E|^2$

Q= τ ω

τ =decay time

V=mode volume

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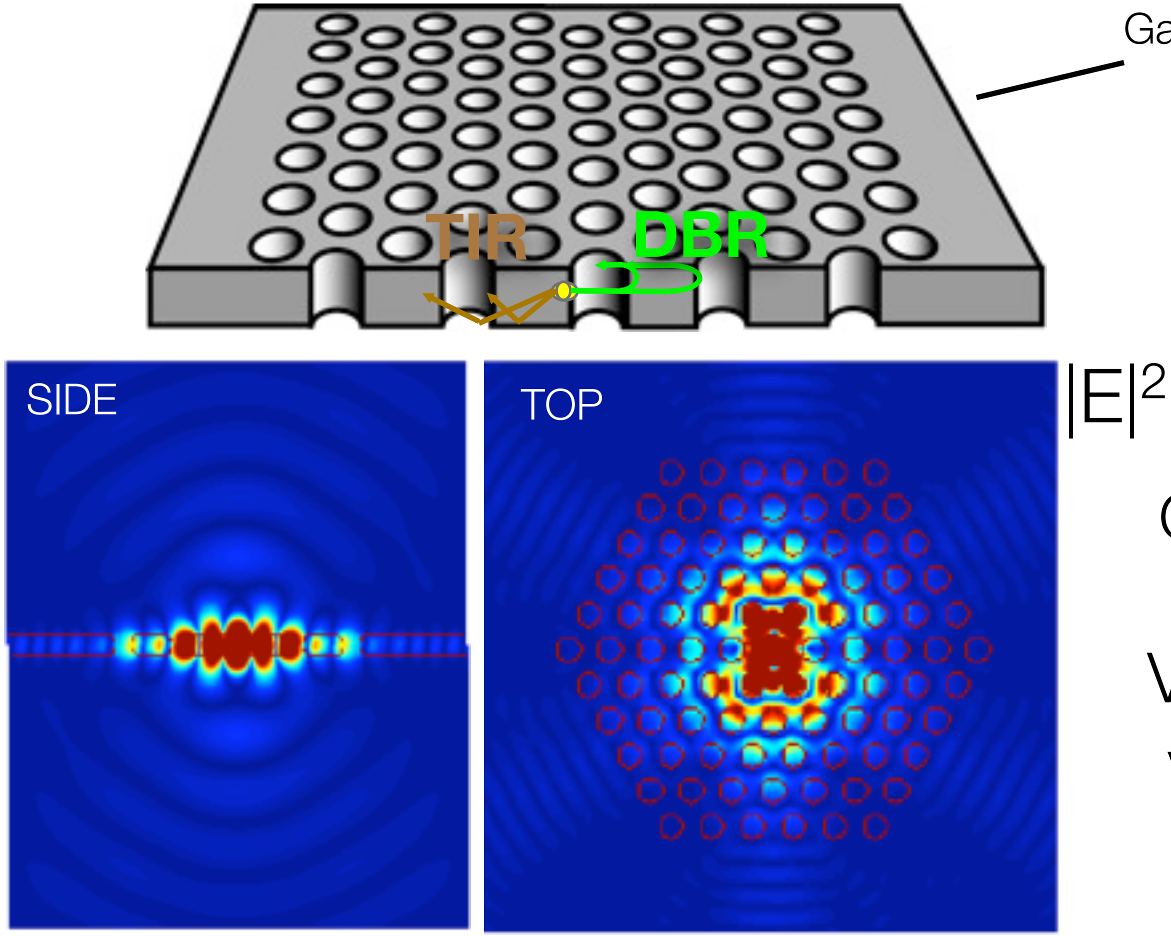

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Friday, April 24, 2009

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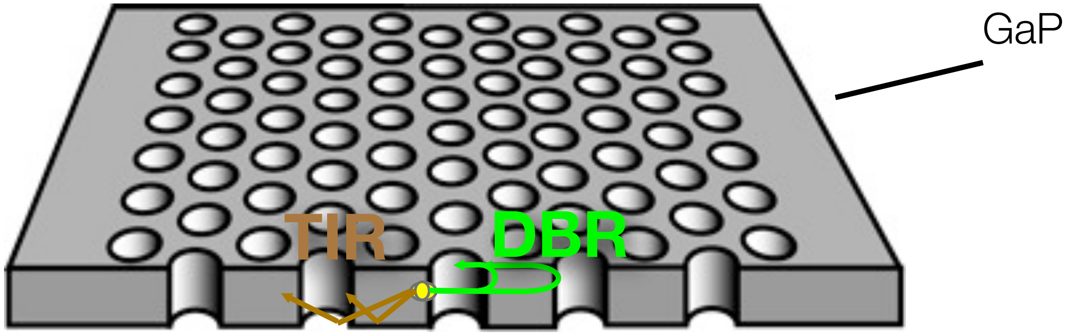

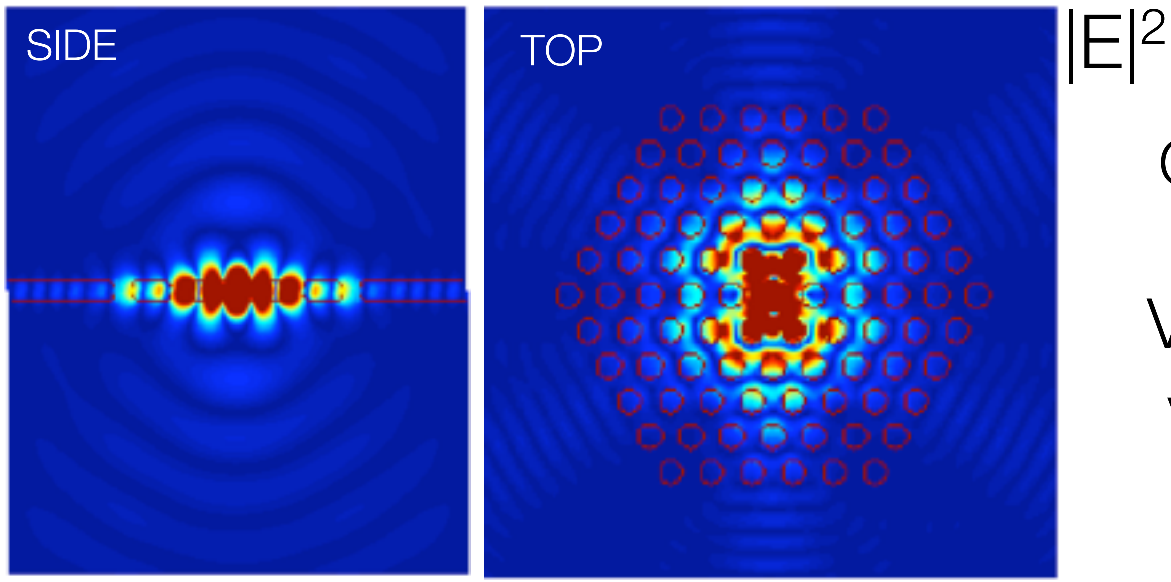

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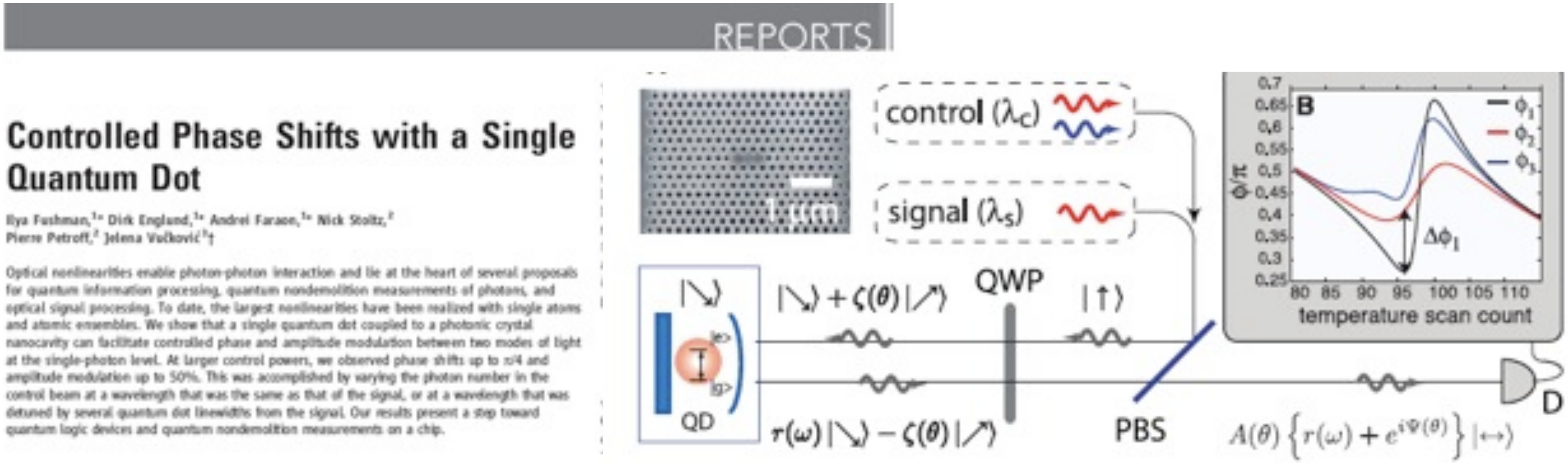
Photonic crystals can localize light into extremely small volumes $V \sim (\lambda/n)^3$ with quality factors $Q \sim 10^6$; large **Q/V**

⇒cavity QED in strong coupling regime in Si, Ga-based PCCs

Quantum interfaces based on PCs: recent advances

- Strong coupling, single photon nonlinear optics with semiconductor QDs with GaAs photonic crystal cavities

J.Vuckovic (Stanford), A.Imamoglu (ETH), J.Finley (Munich)


REPORTS

Controlled Phase Shifts with a Single Quantum Dot

Ilya Fushman,[1*] Dirk Englund,[1*] Andrei Faraon,[1*] Nick Stoltz,[2] Pierre Petroff,[2] Jelena Vučković[1]†

Optical nonlinearities enable photon-photon interaction and lie at the heart of several proposals for quantum information processing, quantum nondemolition measurements of photons, and optical signal processing. To date, the largest nonlinearities have been realized with single atoms and atomic ensembles. We show that a single quantum dot coupled to a photonic crystal nanocavity can facilitate controlled phase and amplitude modulation between two modes of light at the single-photon level. At larger control powers, we observed phase shifts up to π/4 and amplitude modulation up to 50%. This was accomplished by varying the photon number in the control beam at a wavelength that was the same as that of the signal, or at a wavelength that was detuned by several quantum dot linewidths from the signal. Our results present a step toward quantum logic devices and quantum nondemolition measurements on a chip.

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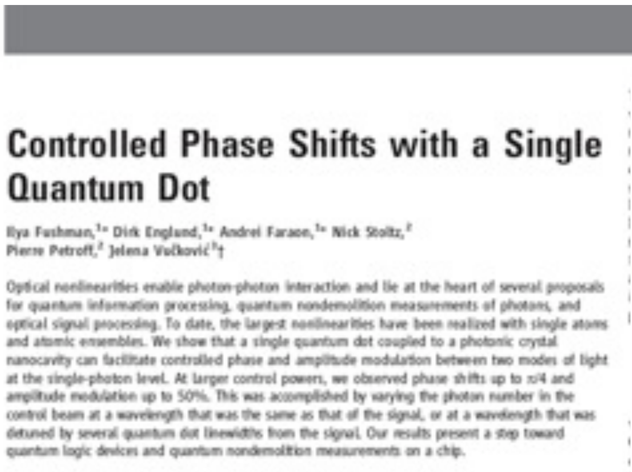

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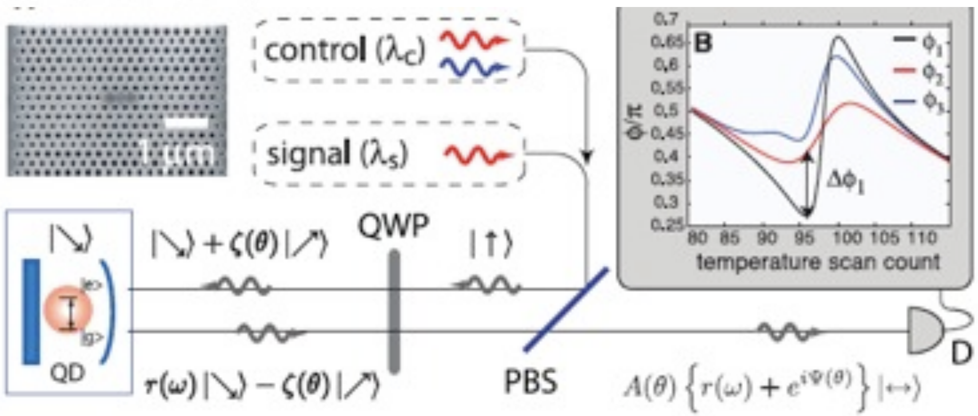
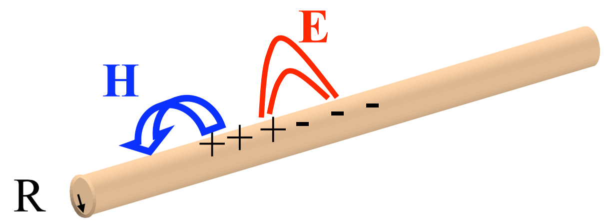


- Challenge: extend these techniques to other qubits with better coherence properties, other materials, hybrid qubit/cavity systems, e.g. diamond+GaP cavities

Extension to nanoscale using plasmonic systems

- ✓ Sub-wavelength localization and guiding electromagnetic field on conducting wires results in strong coupling of single atoms to plasmon field



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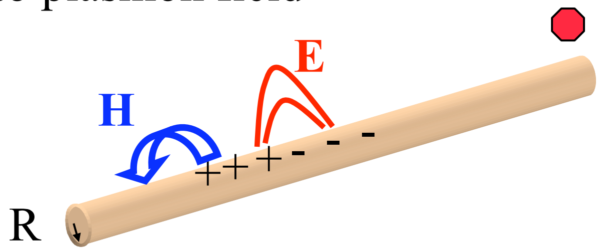
- ✓ Example: proximal atom emission guided almost completely into the wire accompanied by large enhancement



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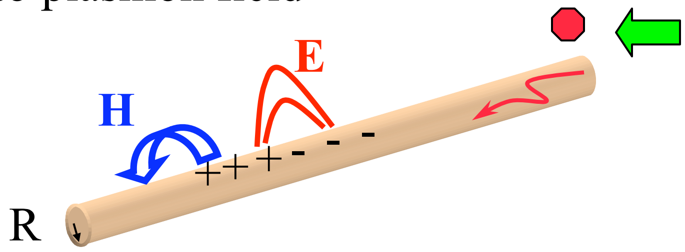

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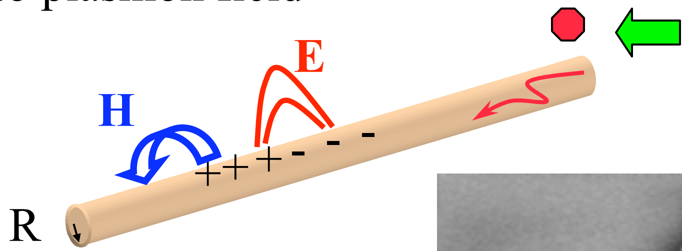

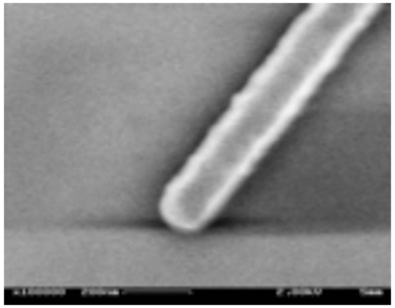

✓ Realization: atoms = single CdSe q.dots, NVs in nanocrysals efficiently coupled to silver nanowires (~100 nm)

D. Chang et al, PRL (2006), A.Akimov, et al, Nature (2007), collaboration with H.Park (Harvard-Chemistry)

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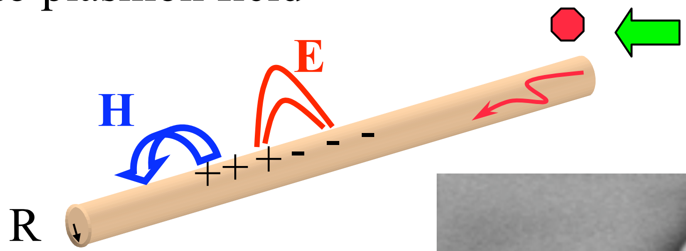

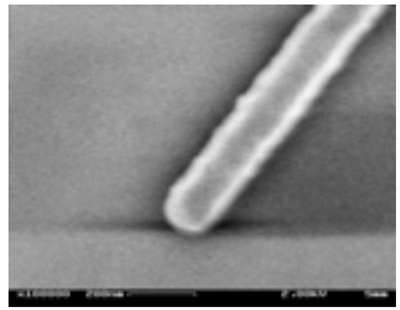

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✓Current efforts:

hybrid optoplasmonic systems to avoid losses

e.g. K.Vahala group, Nature (2009)

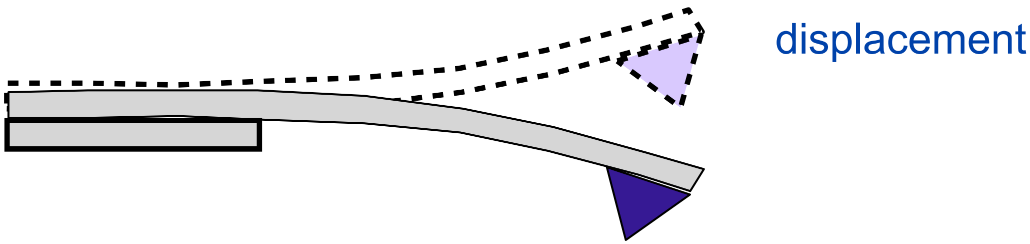
on-chip detection, nano-scale "dark"optical circuits

A.Folk, F. Koppens et al, Nature Physics, in press

application to single photon collection, switches, transistors

D.Chang et al, Nature Physics (2007)

Nano-mechanical quantum spin transducers



Quantum nanomechanics
M. Aspelmeyer, D. Bouwmeester,
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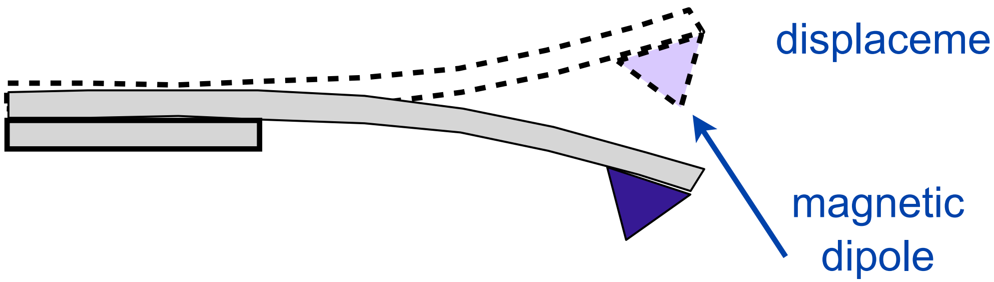

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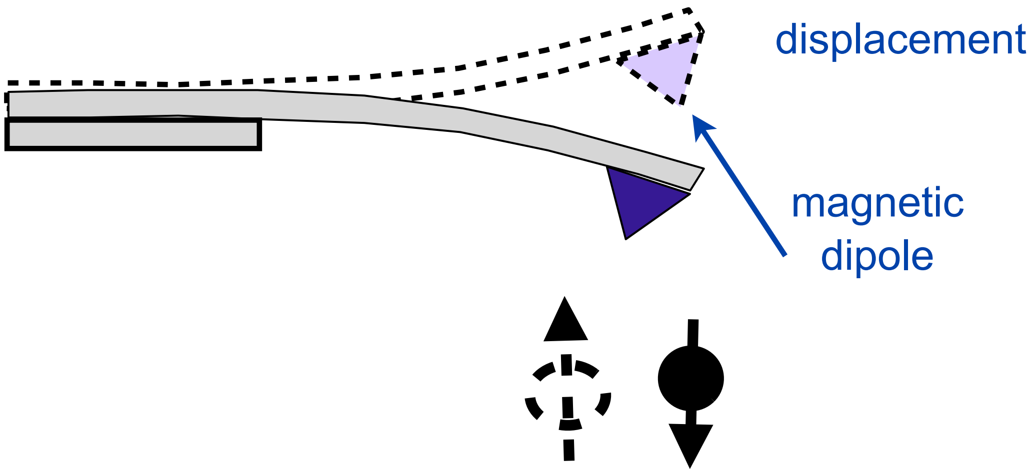

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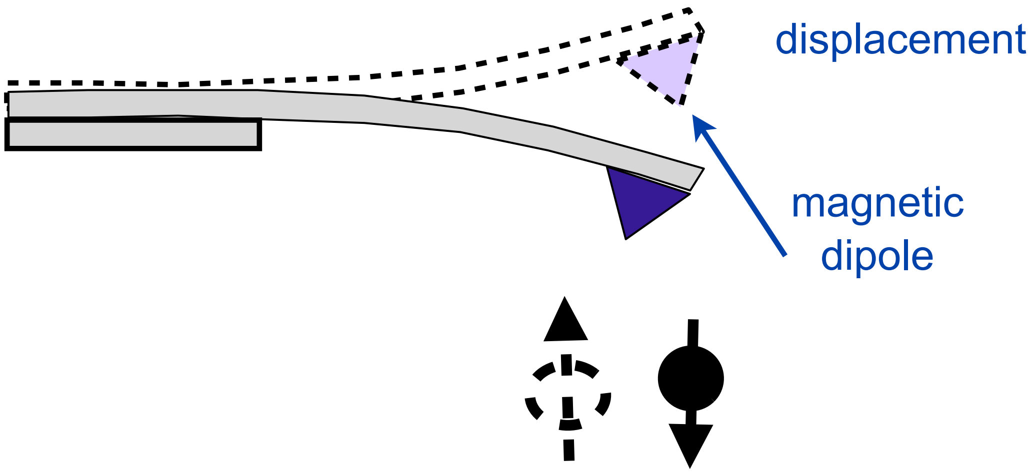

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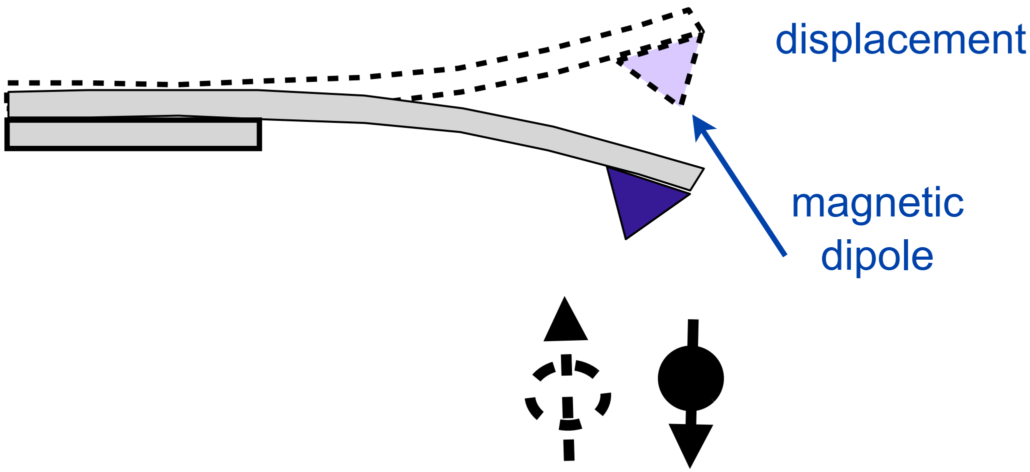

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$$H_S = H_{NV} + \hbar\omega_r a^\dagger a + \hbar\lambda(a + a^\dagger)S_z$$

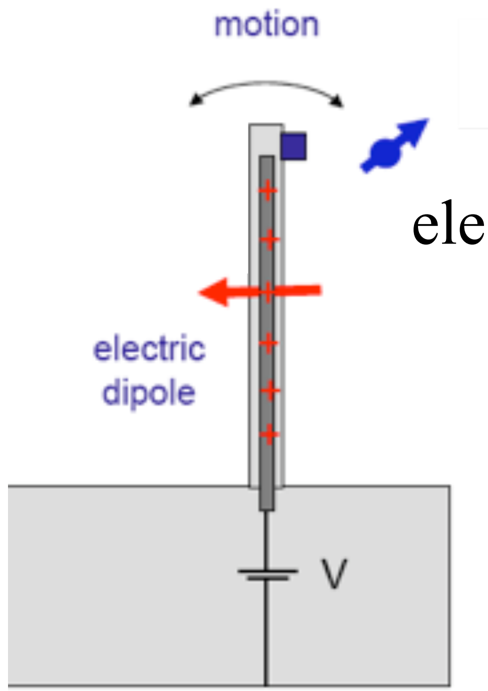
✓"Cavity QED" with mechanical motion

✓New possibilities:

cooling, quanta by quanta engineering "arbitrary" motional states, mapping spin into motion, amplifying spin signals using charged tips…

Remote spin coupling via NEMS data bus

✓Mapping spin to mechanical motion of magnetic, charged tip can be used to "amplify" spin signals



P.Rabl et al, collaboration with J.Harris, P.Zoller's groups

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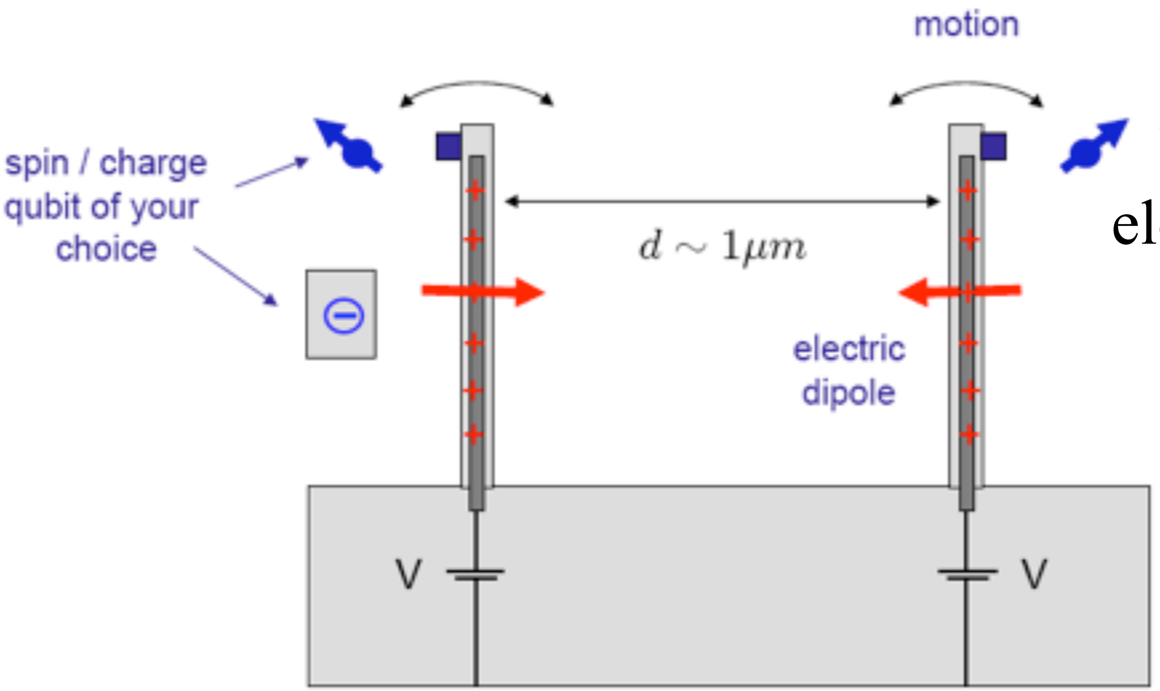

electronic spin

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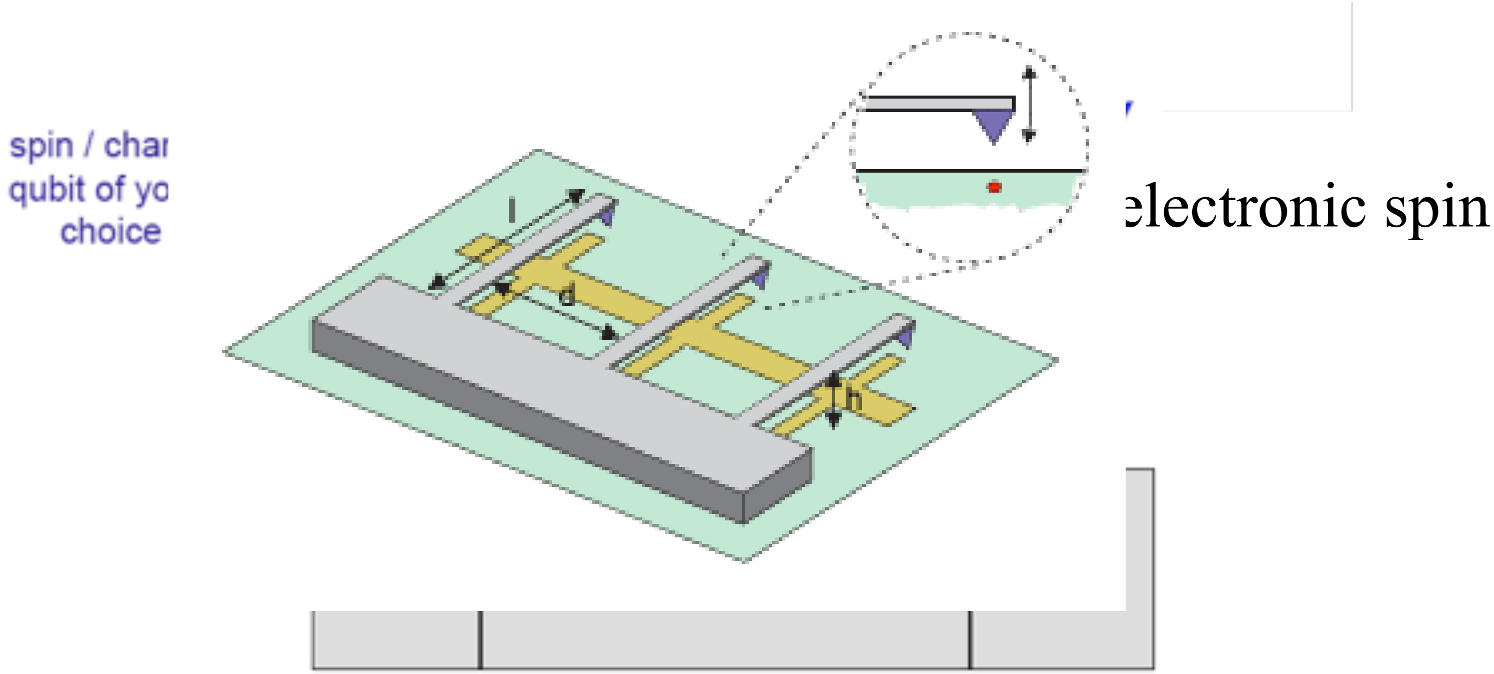

✓100kHz coupling strength over 10s of μm distances

P.Rabl et al, collaboration with J.Harris, P.Zoller's groups

Remote spin coupling via NEMS data bus

✓Applications: remote coupling between spins,
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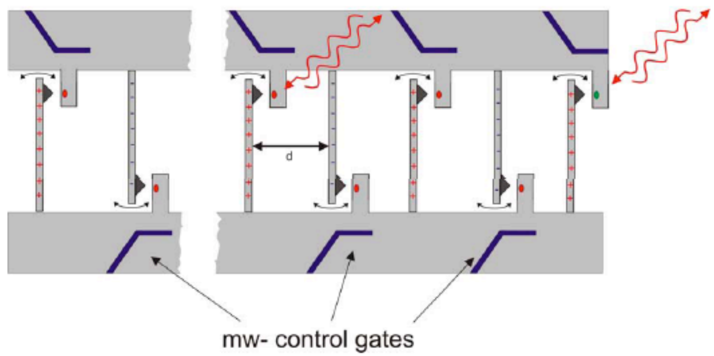

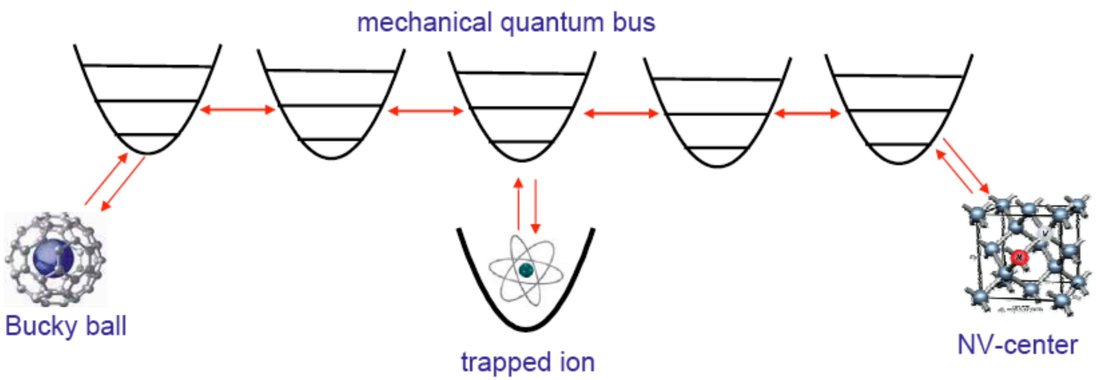

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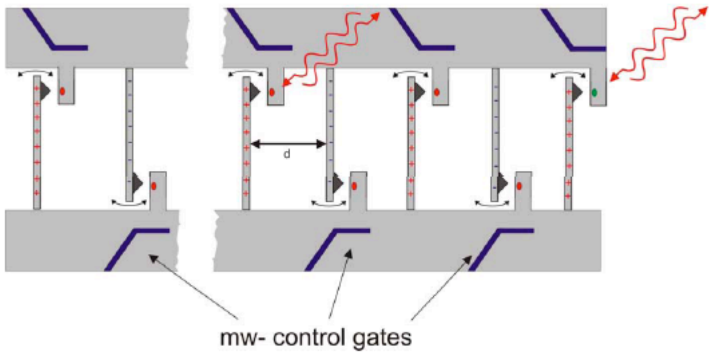
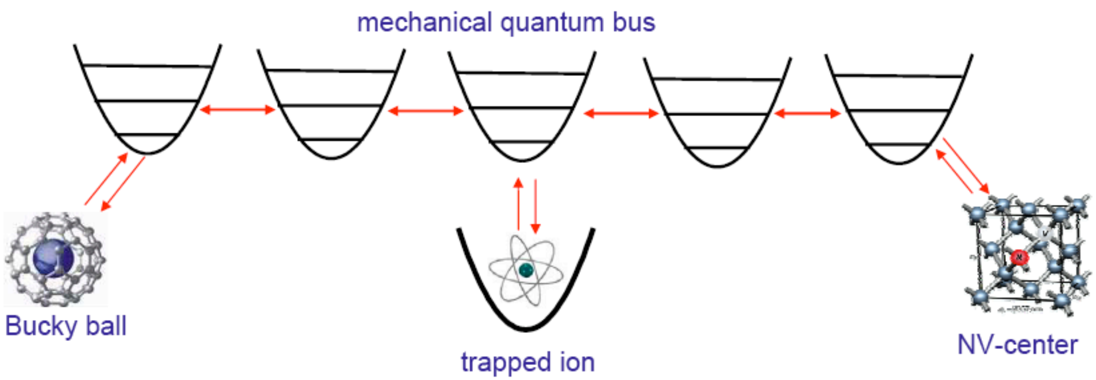




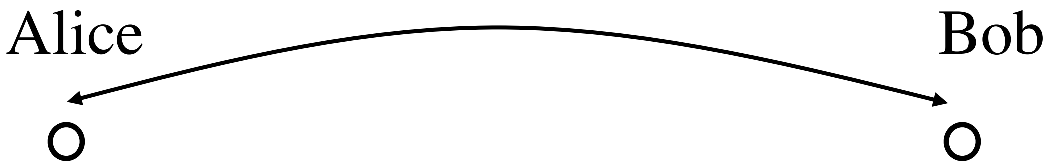
Search for "ideal" quantum bus is not over!

P.Rabl et al, collaboration with J.Harris, P.Zoller's group

Outlook: potential applications of hybrid systems

Quantum communication: long-distance challenge

✓ High quality entanglement and QKD over >1000 km channels



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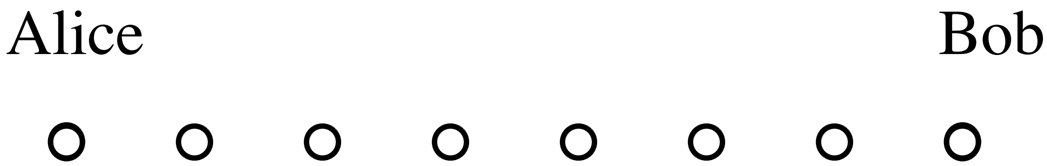

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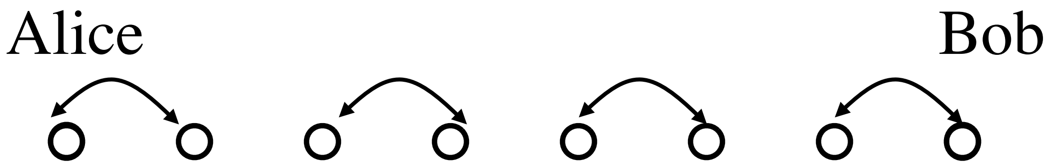

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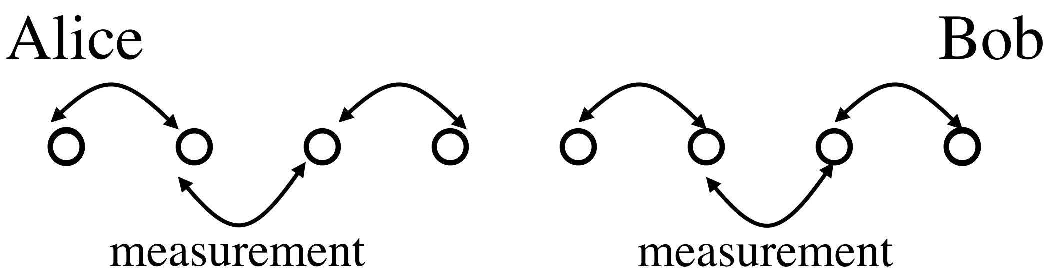

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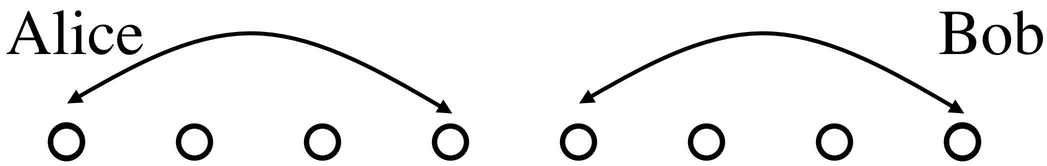

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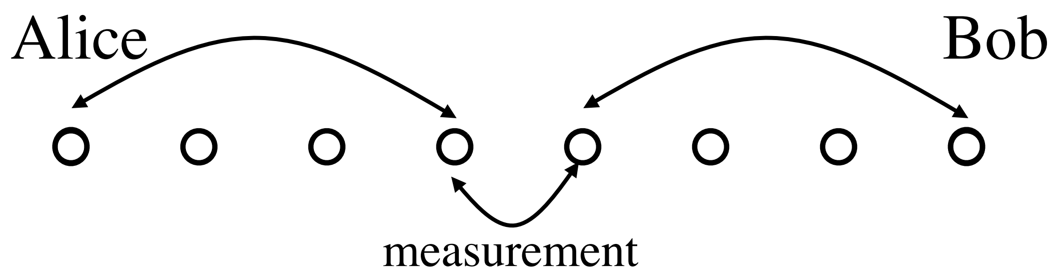

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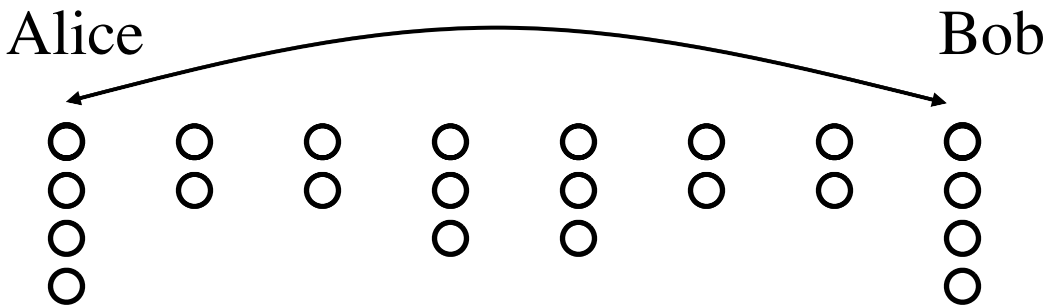

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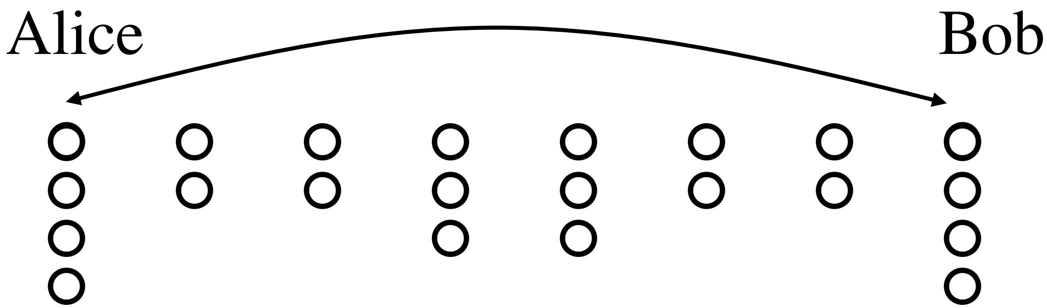

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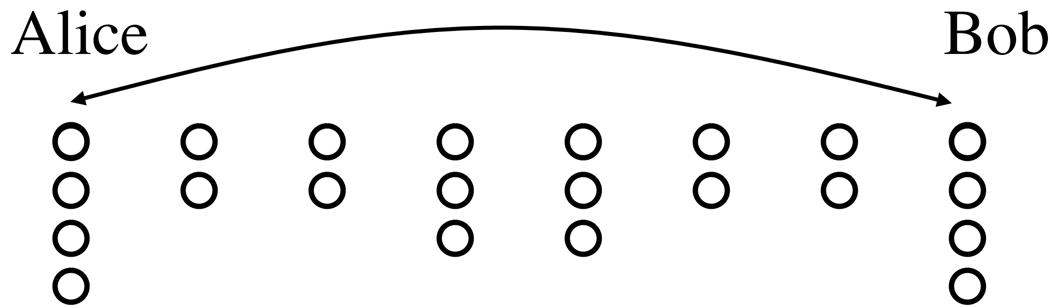

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Need new, more efficient protocols & architectures

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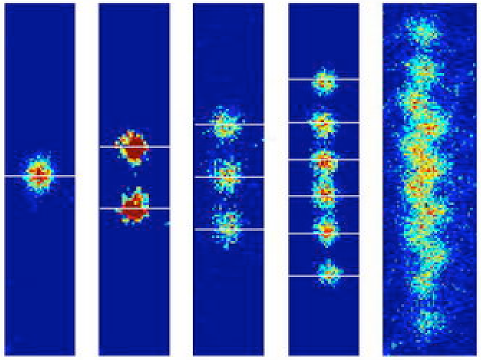
- Better clocks: one of the early motivation to study entanglement in AMO systems



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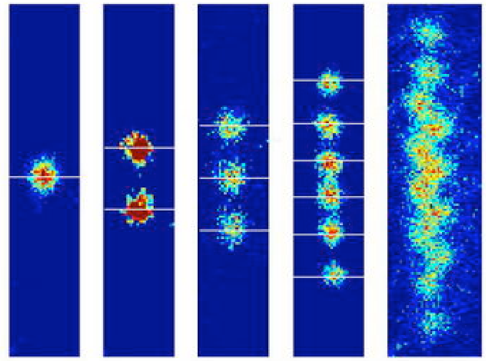

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- New avenues:
  use solid-state systems
  extend to new domains, e.g. nanometer-scale sensing

Example: application to nanoscale magnetic sensing

✓ A new sensor that makes use of single NV spin close to diamond surface to detect magnetic fields via Zeeman effect

J.Maze et al, Nature (2008),
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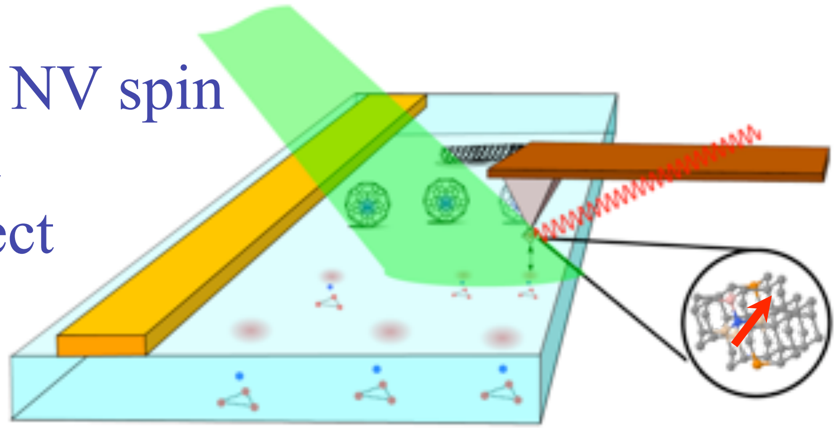

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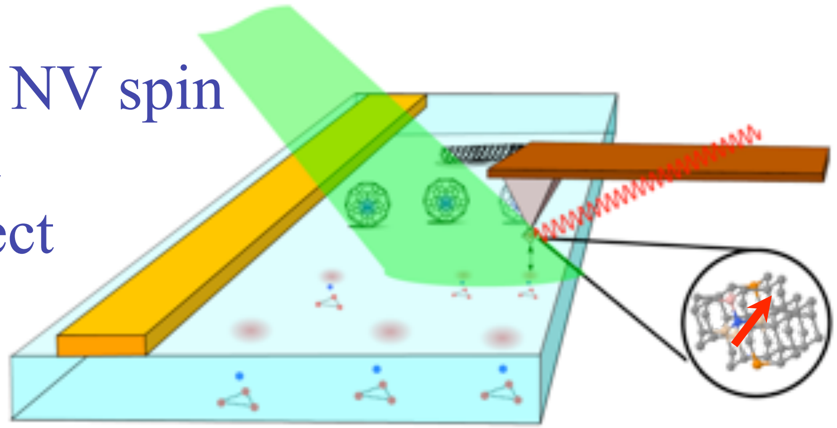

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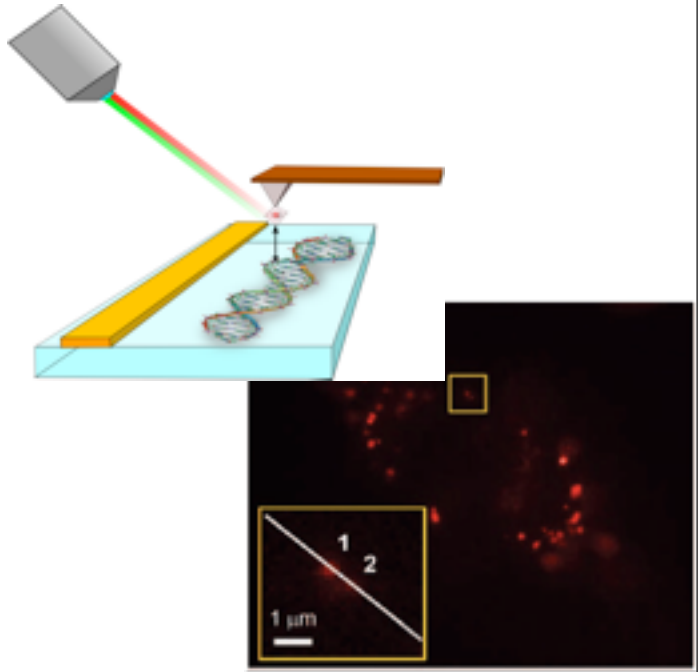

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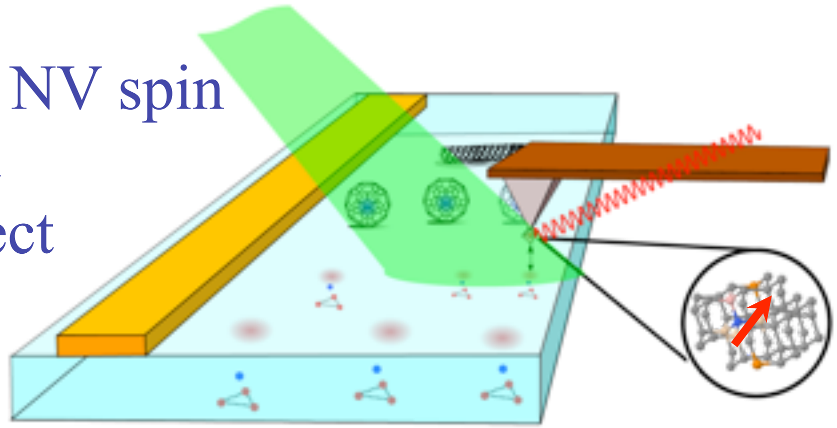

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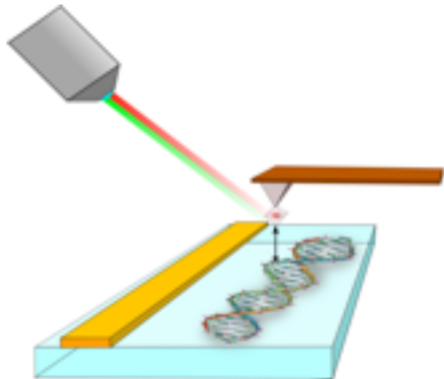
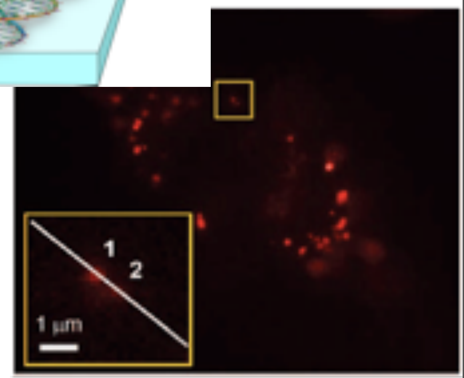


•Current efforts:
development of AFM-based scanning sensors
far-field nonlinear optical spin imaging at nanoscales
use few spin entangled states for sensing



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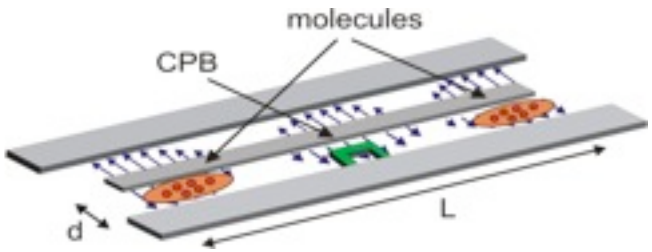

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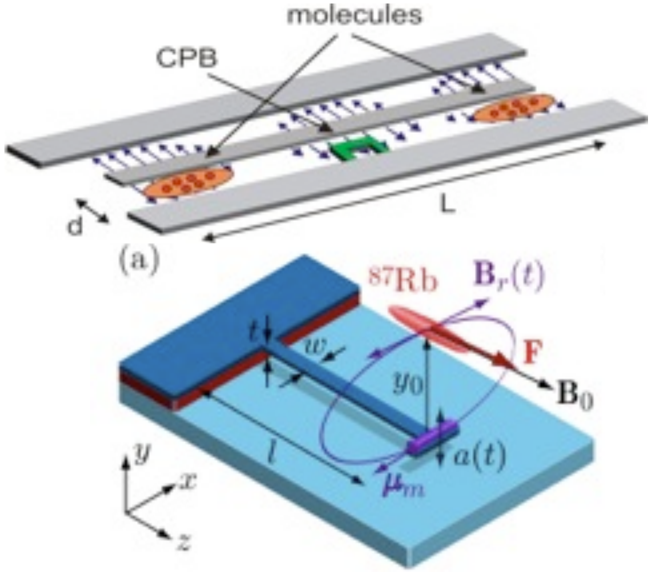
Memory, optical interface for superconducting qubtis: molecules, spins

Magnetic coupling to single atom spin



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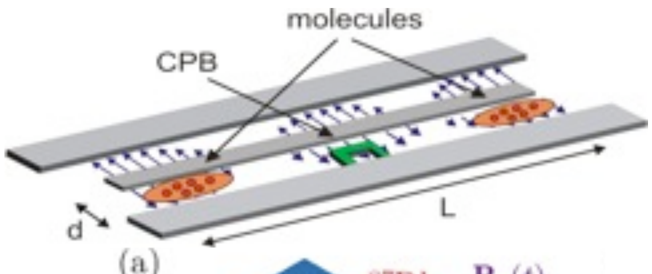

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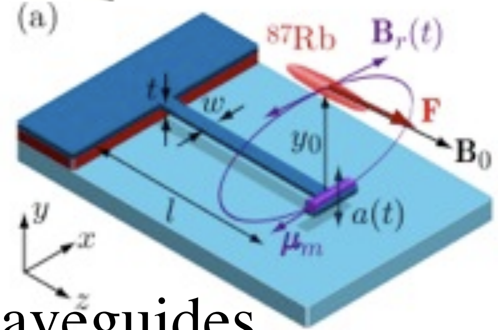

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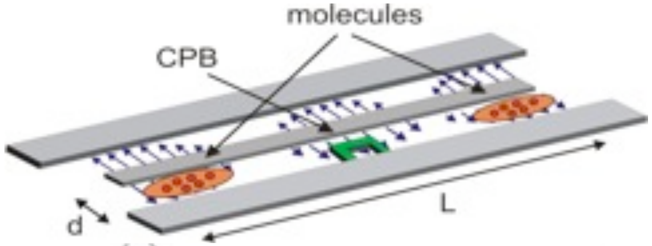

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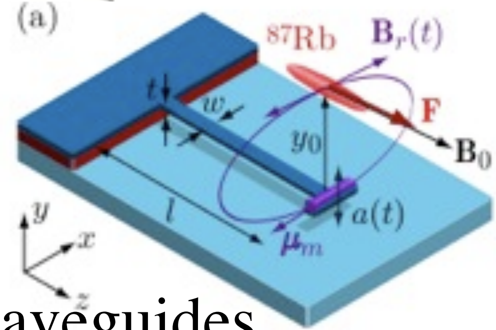

Memory, optical interface for superconducting qubtis: molecules, spins

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Optical coupling to nano-photonic cavities and waveguides

All require atom trapping within 100 nm of solid-state surface
Challenges: noise, patch potentials, van der Wal interaction ...

Toward nanoscale interface for isolated atoms

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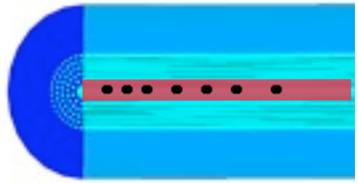

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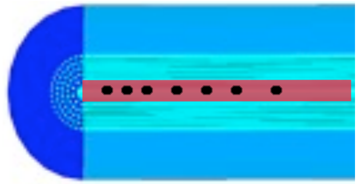

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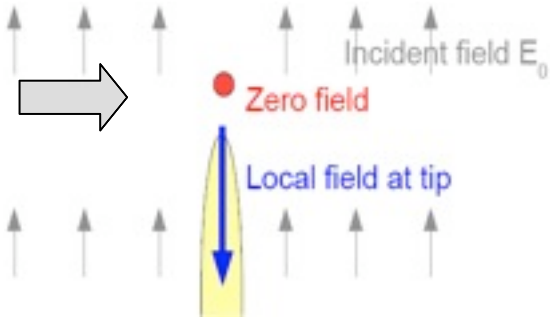

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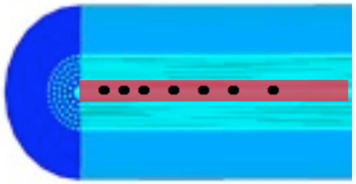

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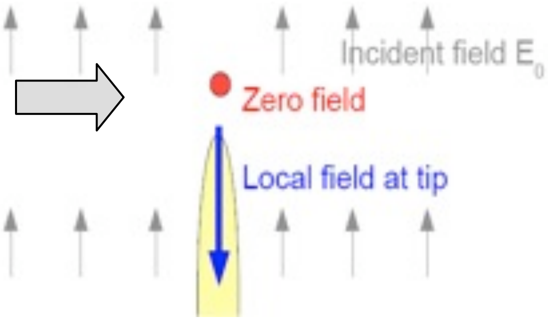

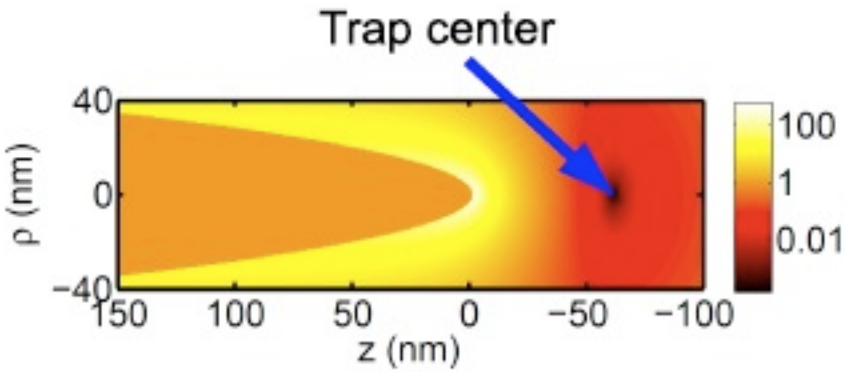

- Tight atom confinement, large energy scales, trapping frequencies > 10 MHz
- Strong blue "shield" for nanotip => can trap 50 nm from surfaces

D.Chang et al., collaboration with Peter Zoller, Vladan Vuletic, Hongkun Park

Also: plasmon tweezer work @ ICFO (Barcelona), atoms around nanotubes ideas (Hau)

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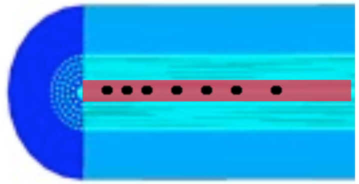

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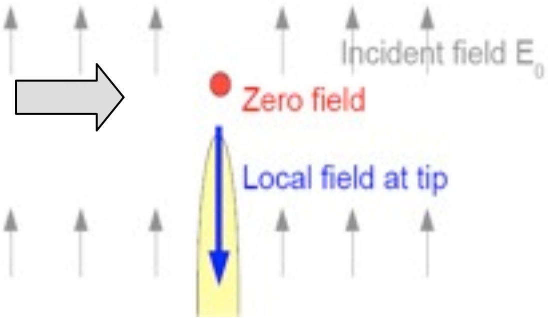

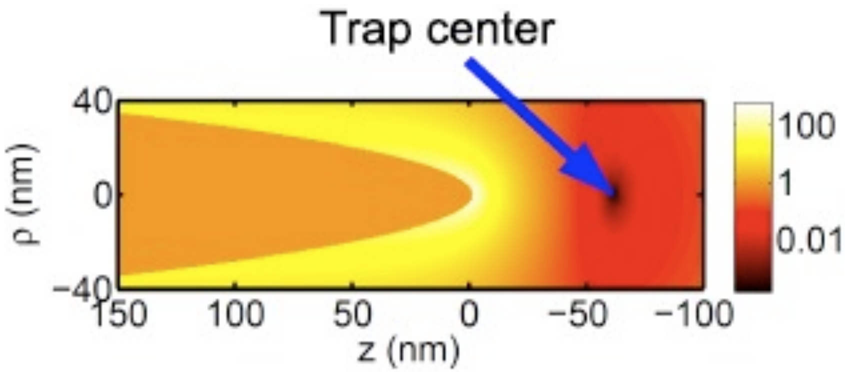

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- St

D.Char

Also: p

Such techniques will be critical for combining isolated atoms, molecules with solid-state quantum systems

New field of low-energy quantum science

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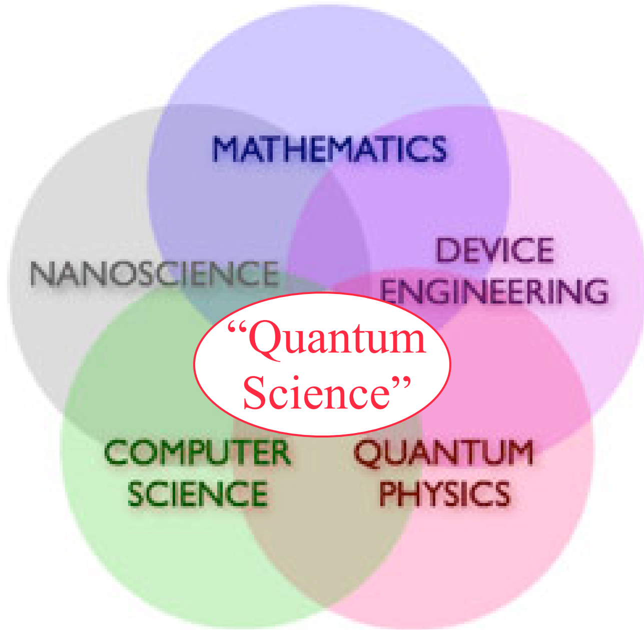

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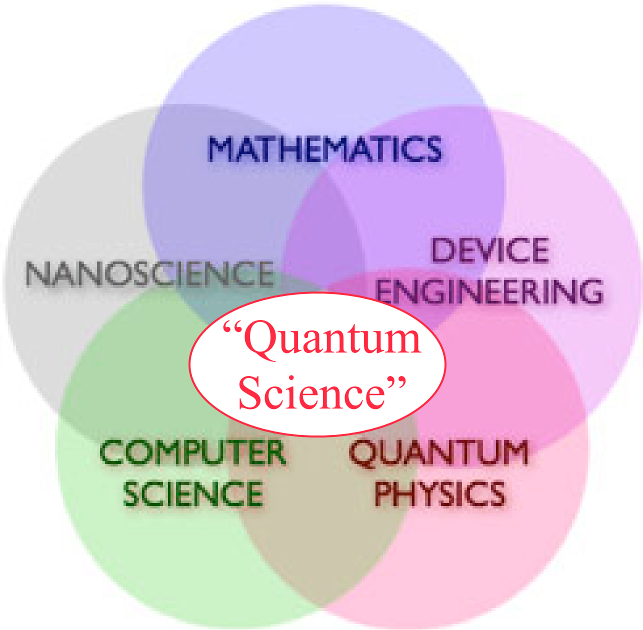

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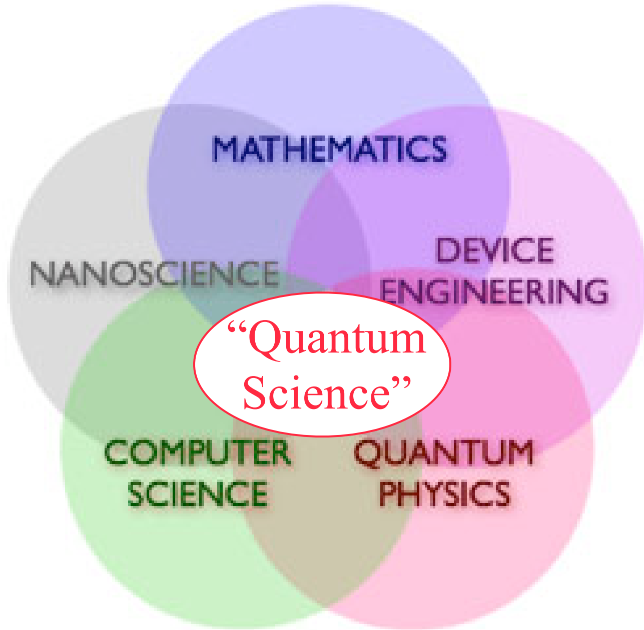

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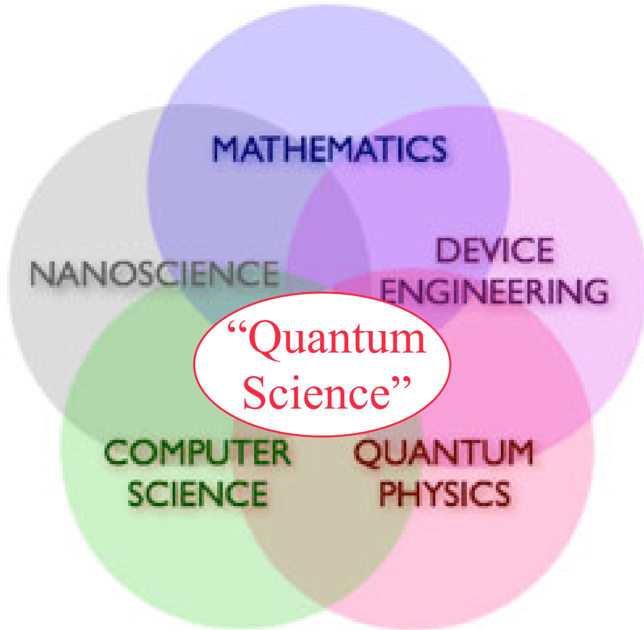

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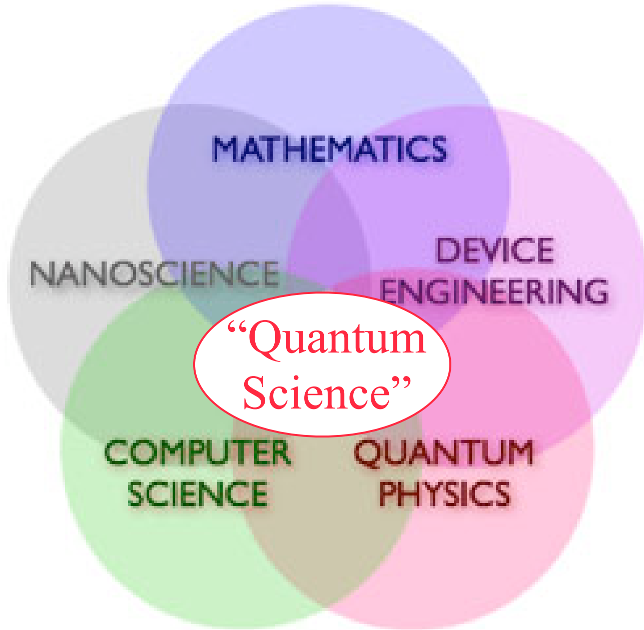

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These are long-term, "high risk" projects: stable funding is critical!