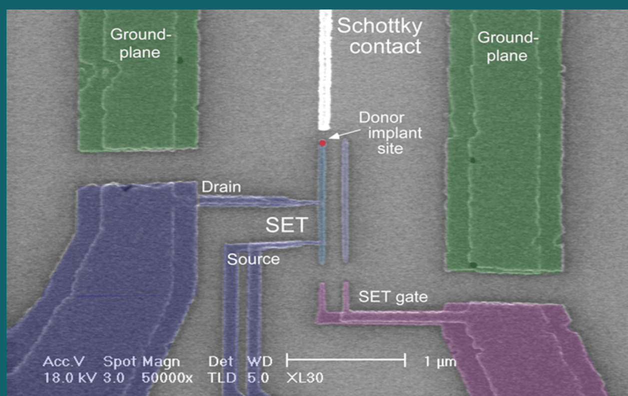
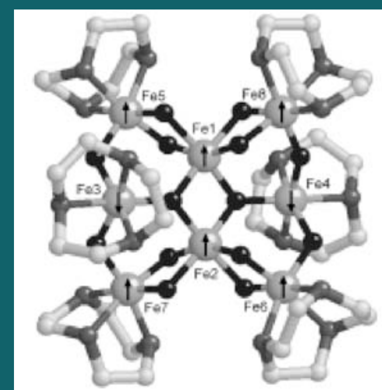
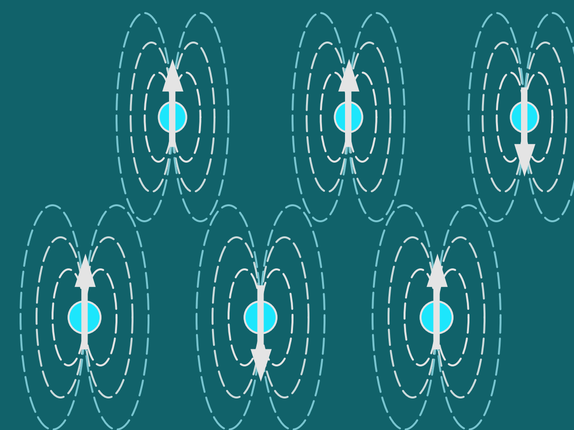
Architectures and decoherence of electron spin qubits

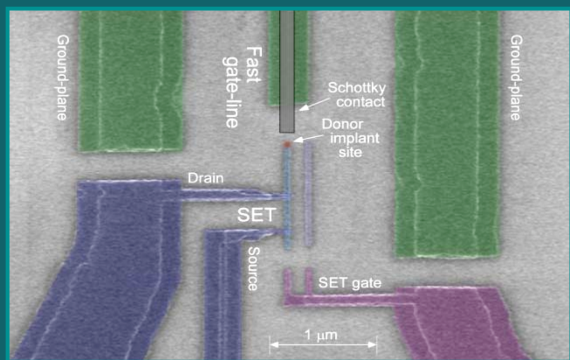




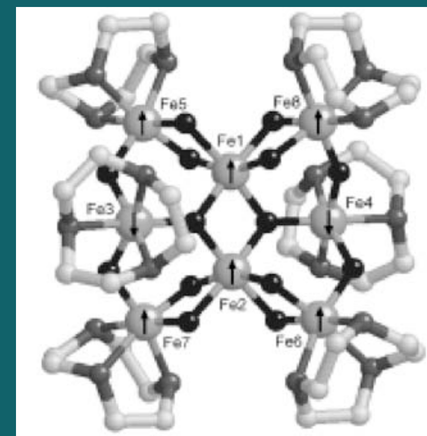


Andrea Morello

Fabricated vs synthesized



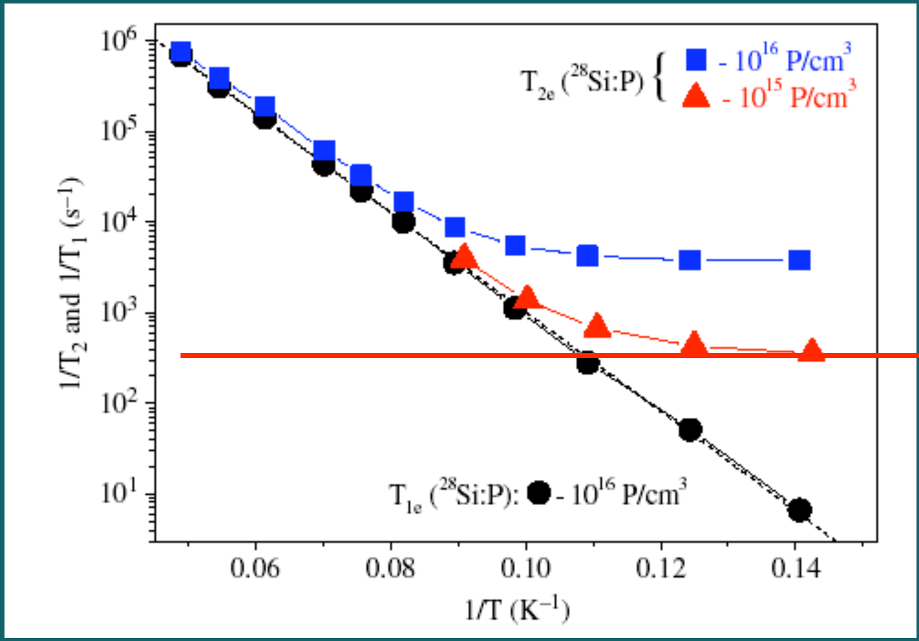
- scalable
- long coherence
- flexible design
- single-spin measurement
- variability
- environment?
- expensive fabrication



- scalability not solved
- strong decoherence
- many variants
- fragile out of the bulk
- strictly identical units
- precisely known environment
- for free

Why phosphorus in silicon?

short term perspective: **long coherence times!**



Silicon can be isotopically purifed to eliminate nuclear spins!
⇒ **T_2 ≈ 60 ms** already at T = 7 K

Residual decoherence in bulk due to dipole-dipole interactions

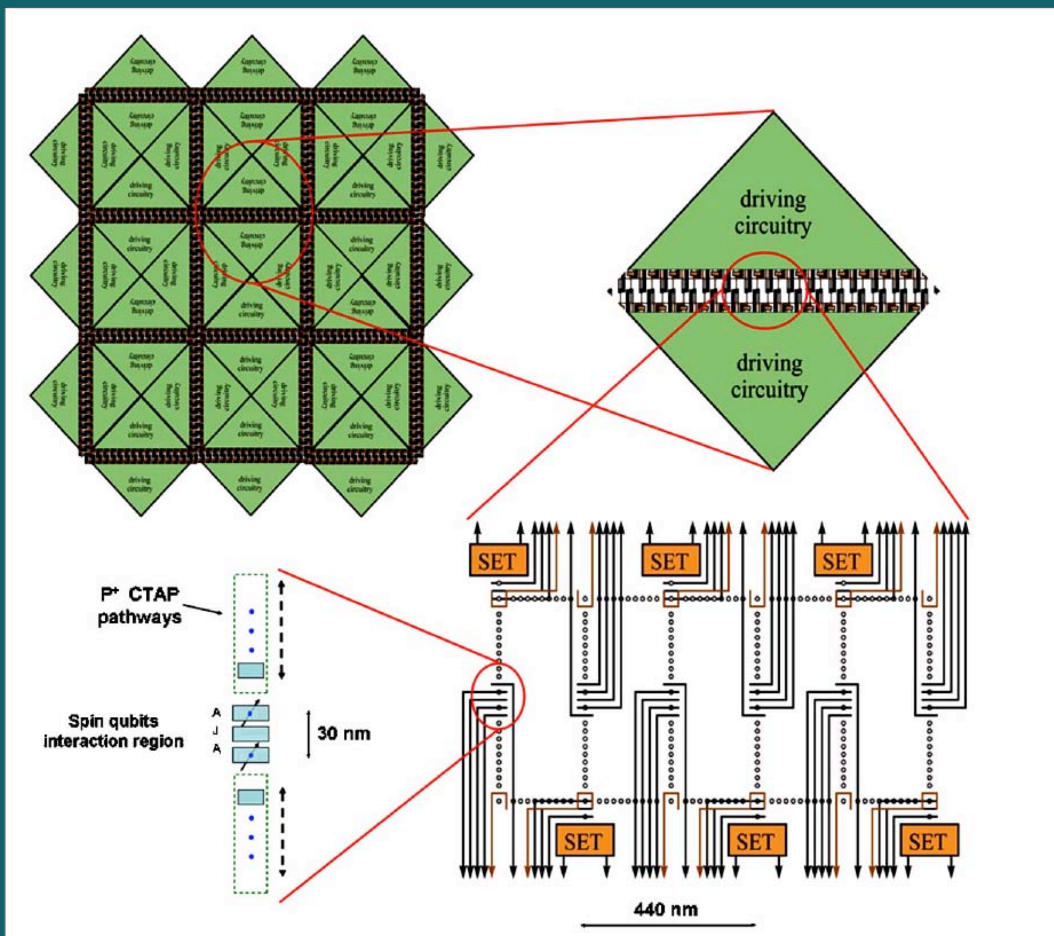
What is the ultimate low-T decoherence rate for a single spin?

Also, very long **T_1: ≈ 1 hour** at T = 1.2 K

Tyryshkin et al., PRB 68, 193207 (2003)
Feher & Gere, PR 114, 1245 (1959)

Why phosphorus in silicon?

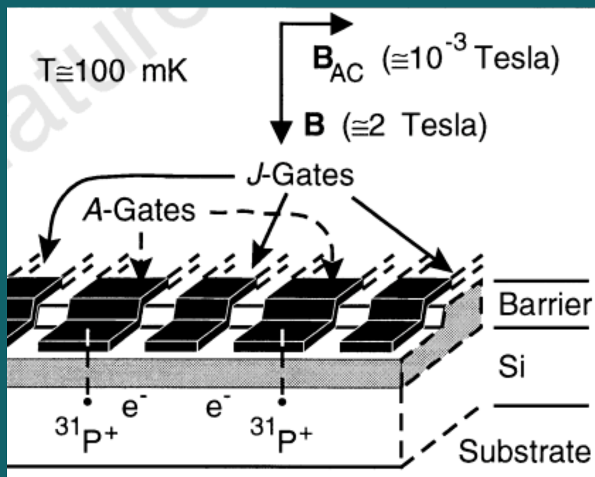
long term perspective: **scalability**
small size
huge technological interest



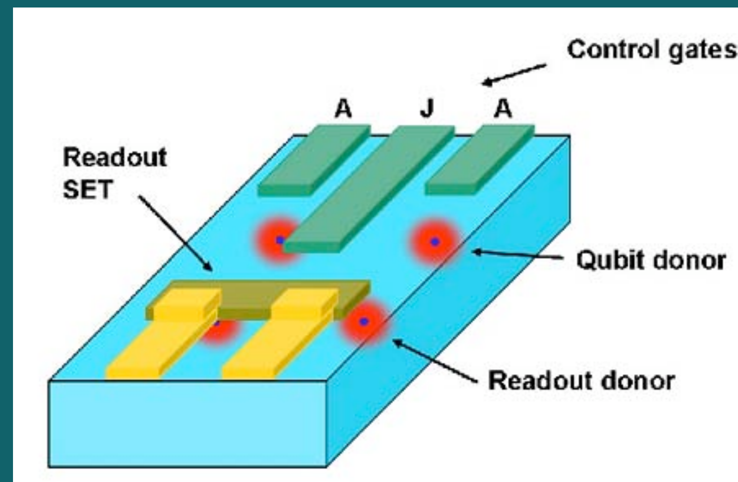
Hollenberg et al., PRB 74, 045311 (2006)

Nuclear vs Electron spin

	nuclear spin qubit	electron spin qubit



Kane, Nature 393, 133 (1998)



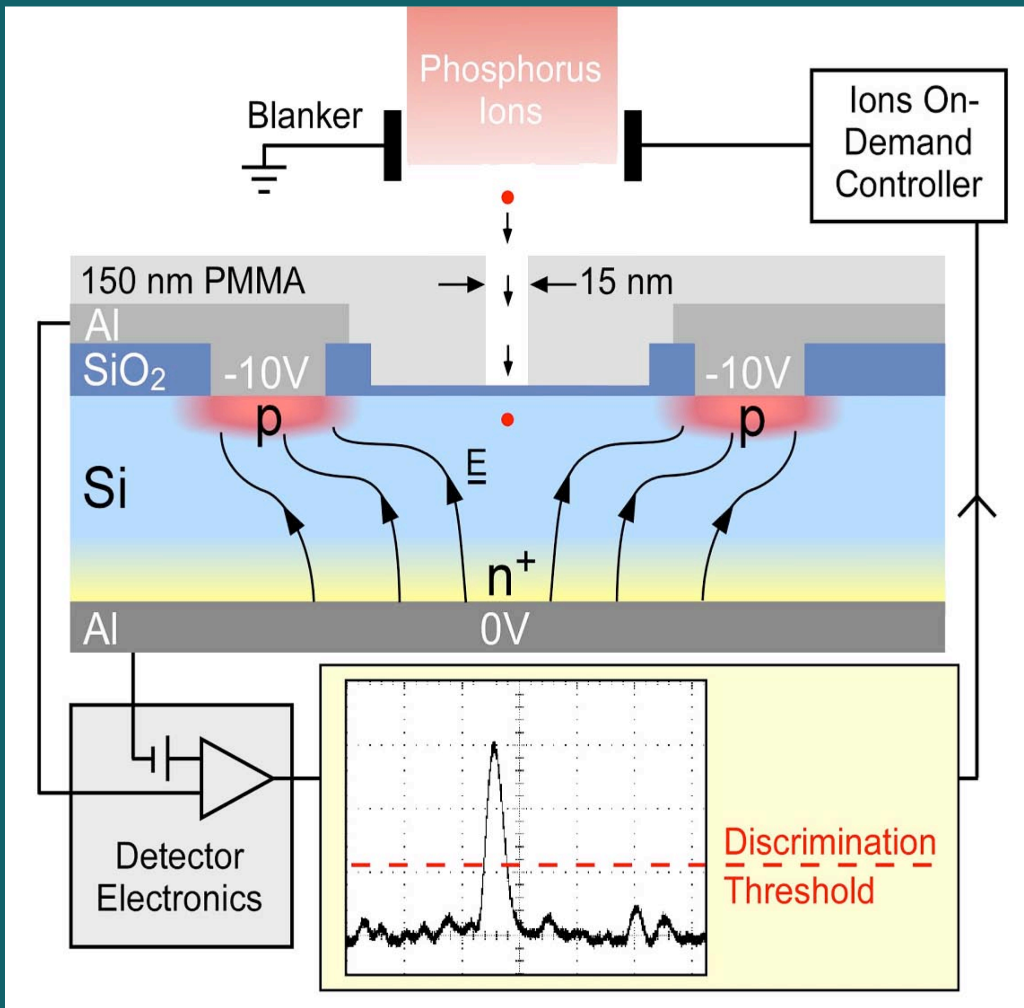
Hill et al., PRB 72, 045350 (2005)

	nuclear spin qubit	electron spin qubit
T_X	6 μs	30 ns
T_2/T_X	10^4	**2×10^6**
T_{CNOT}	16 μs	148 ns
T_2/T_{CNOT}	4×10^4	**6×10^5**

and we still don't know what the ultimate T_2 can be!

The higher clock speed achievable with electrons compensates for the shorter coherence

Fabrication: top down



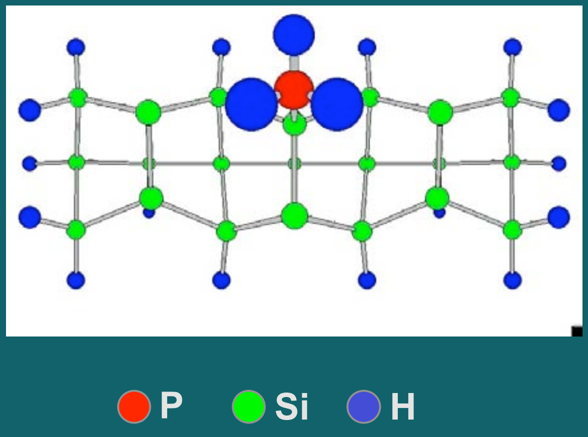
Controlled and counted implantation of single phosphorus ions

straggle sphere diameter ~ 30 nm

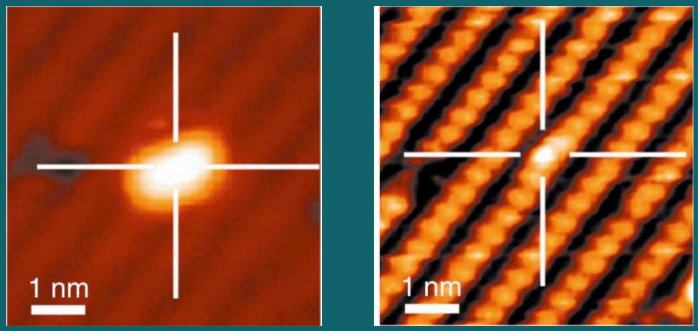
Jamieson et al., APL 86, 202101 (2005)

Fabrication: bottom up

Controlled incorporation of P from PH_3

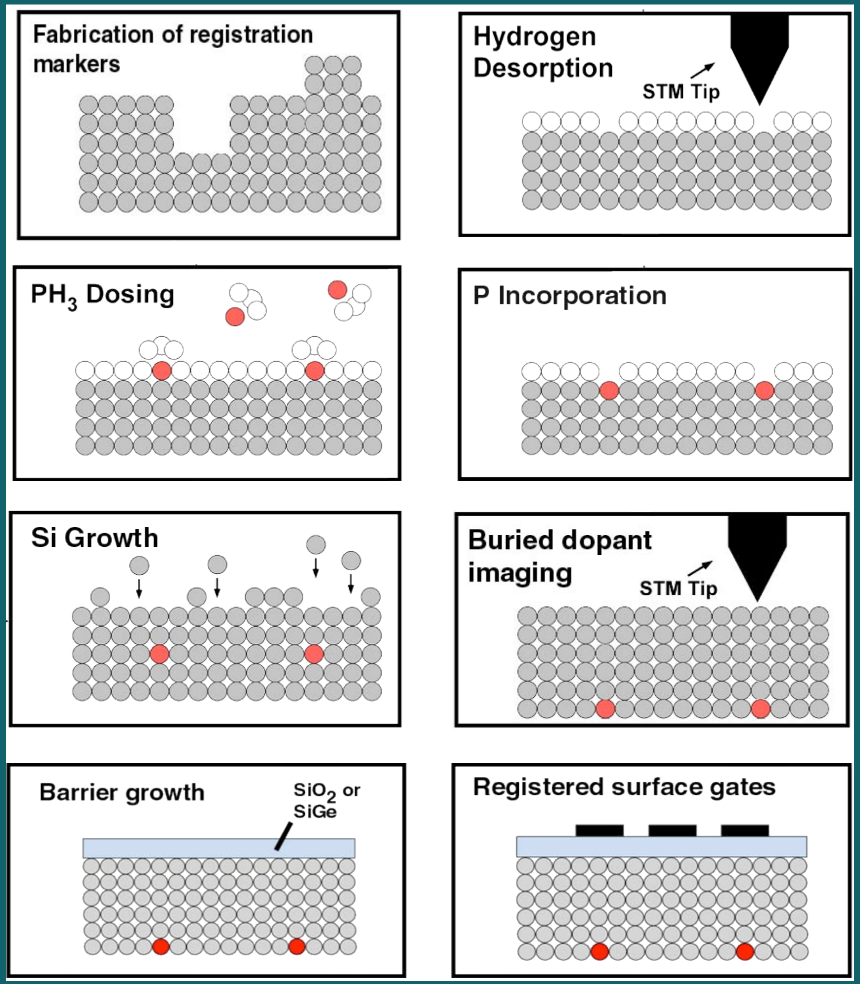


Single P Atom Incorporation



Wilson et al., PRL 93, 226102 (2004)
O'Brien et al., PRB 64, 161401 (2001)
Schofield et al., PRL 91, 136104 (2003)

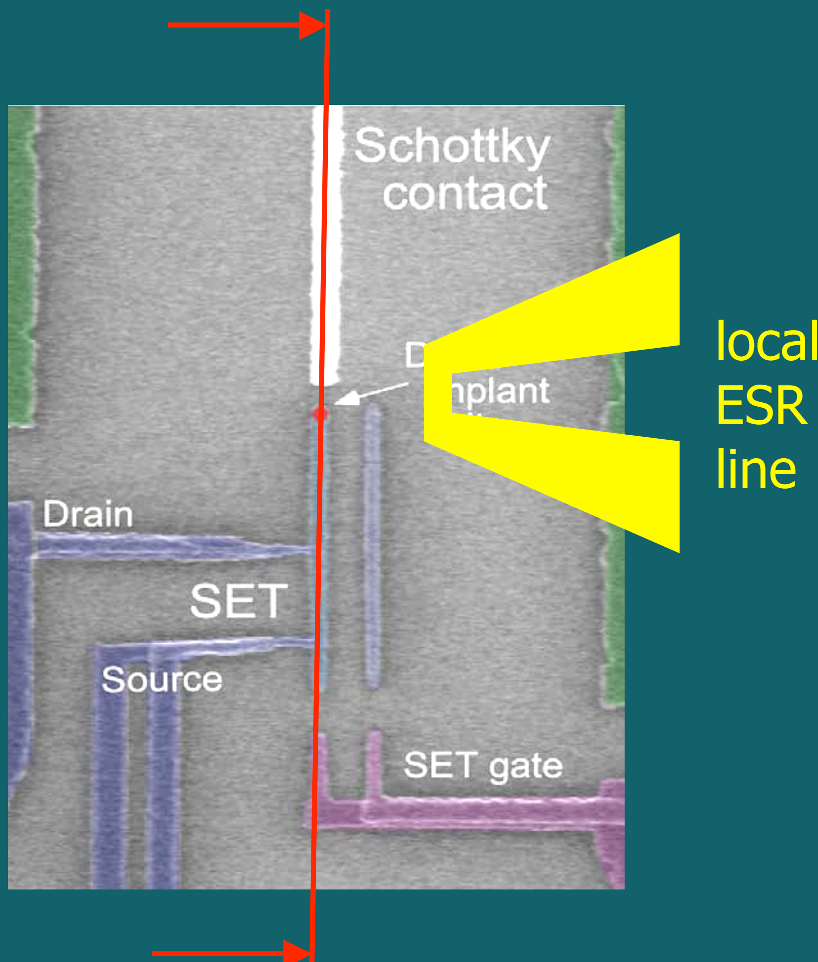
Device Fabrication

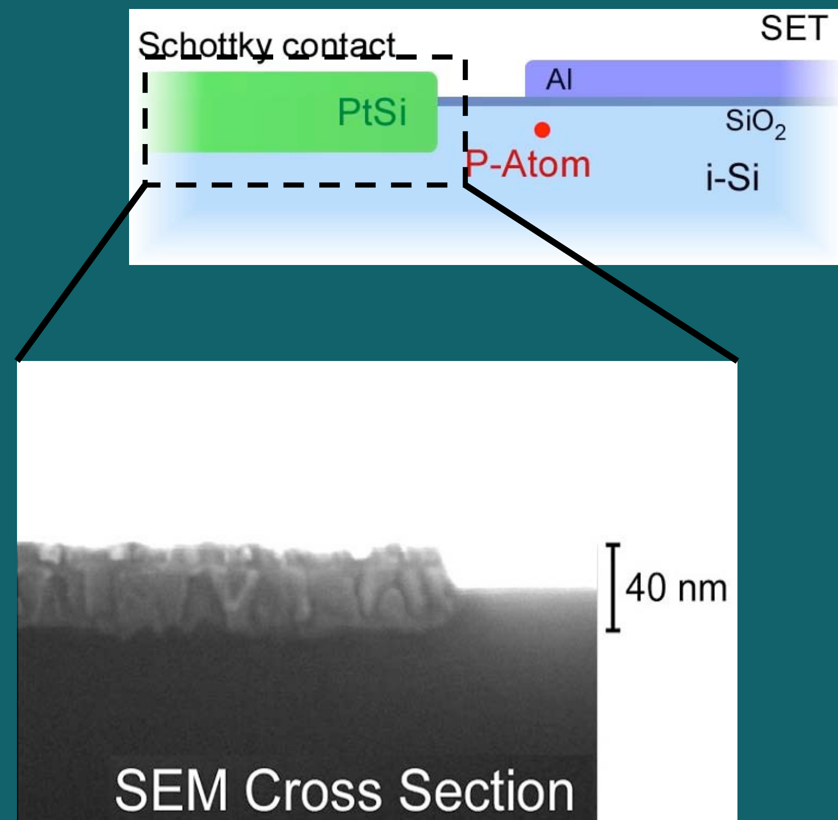


Rueß et al., Nano Letters 4, 1969 (2004)

Spin qubit devices

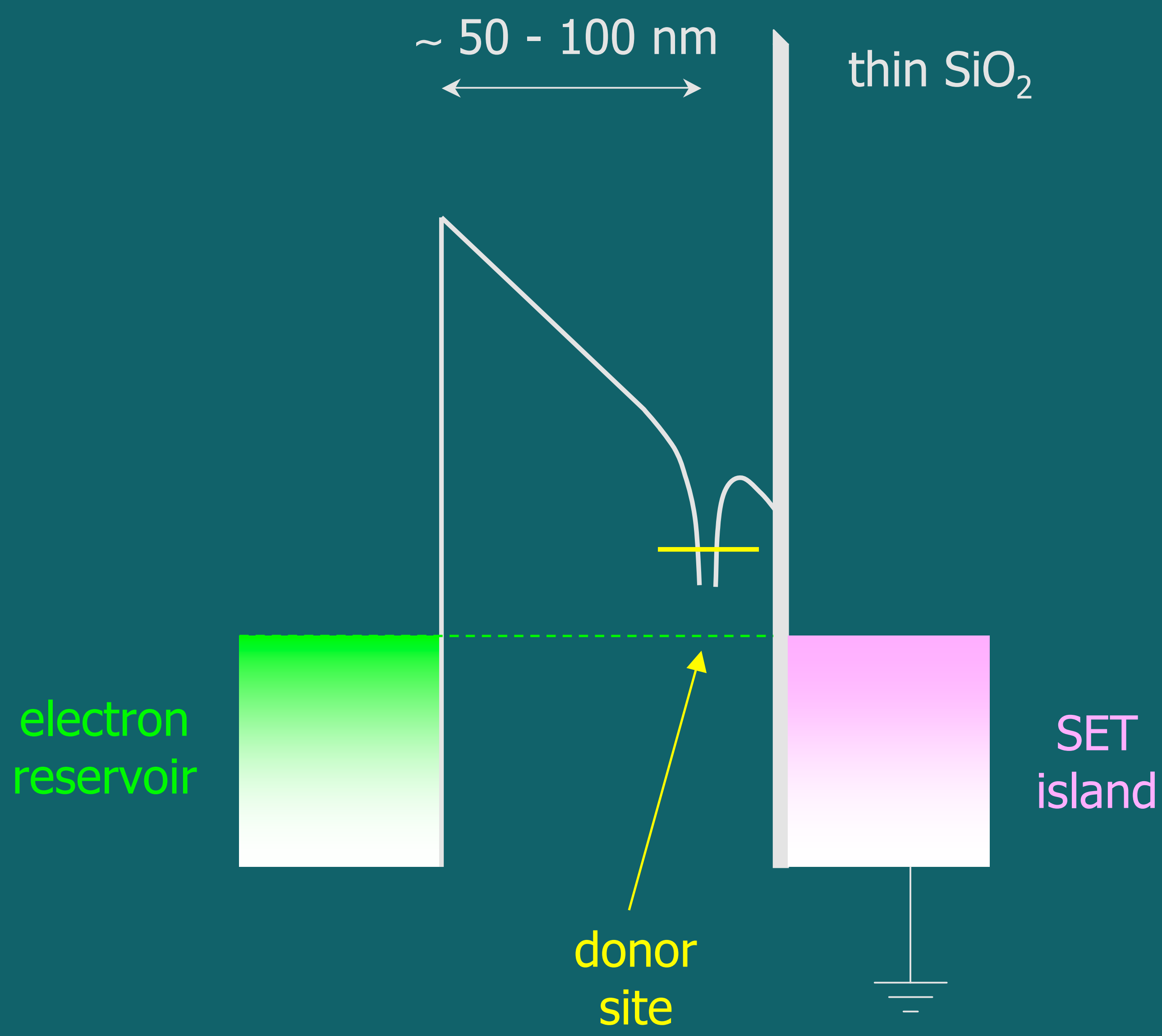
P donor next to Schottky electron reservoir for initialization



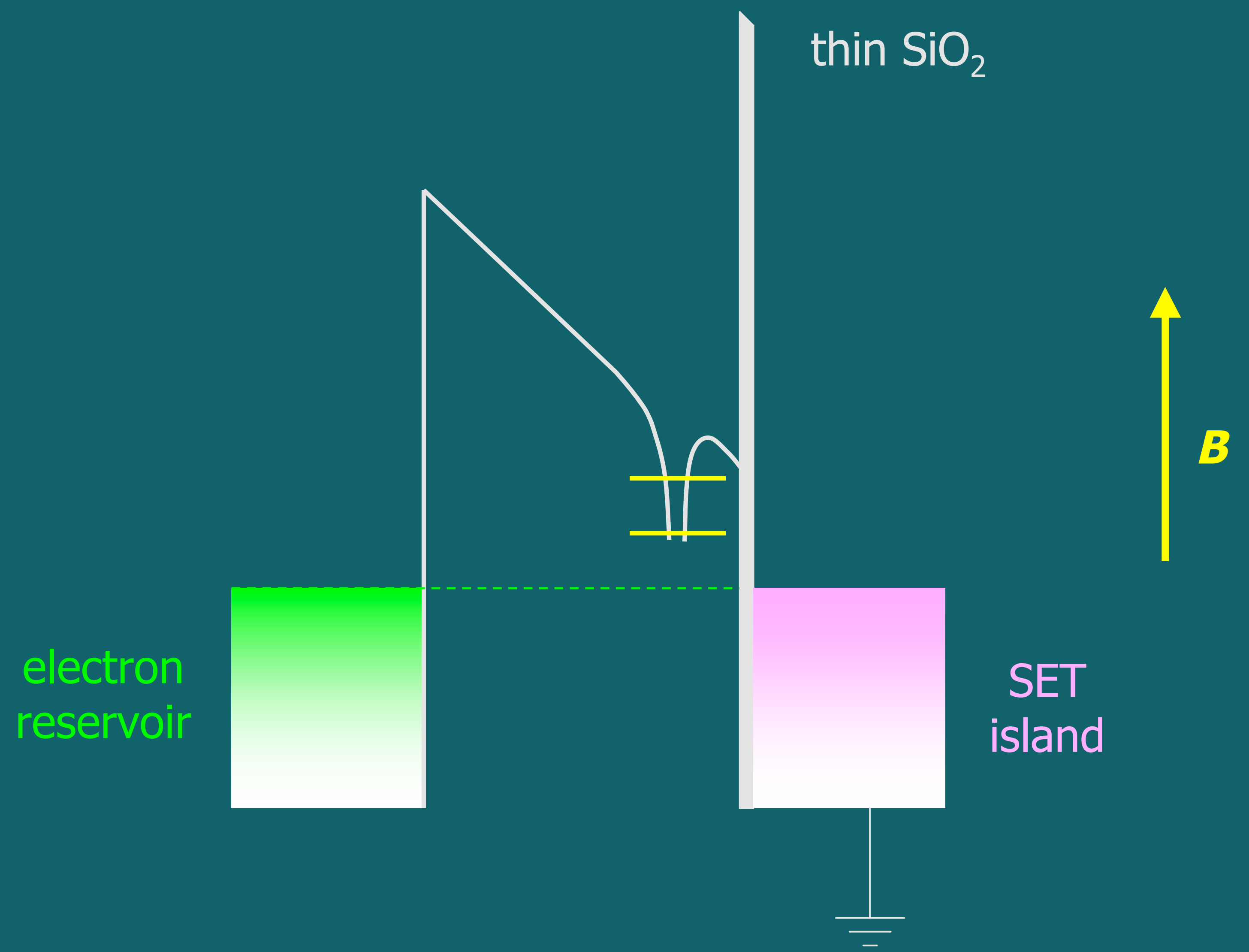


rf-SET for sensitive charge detection

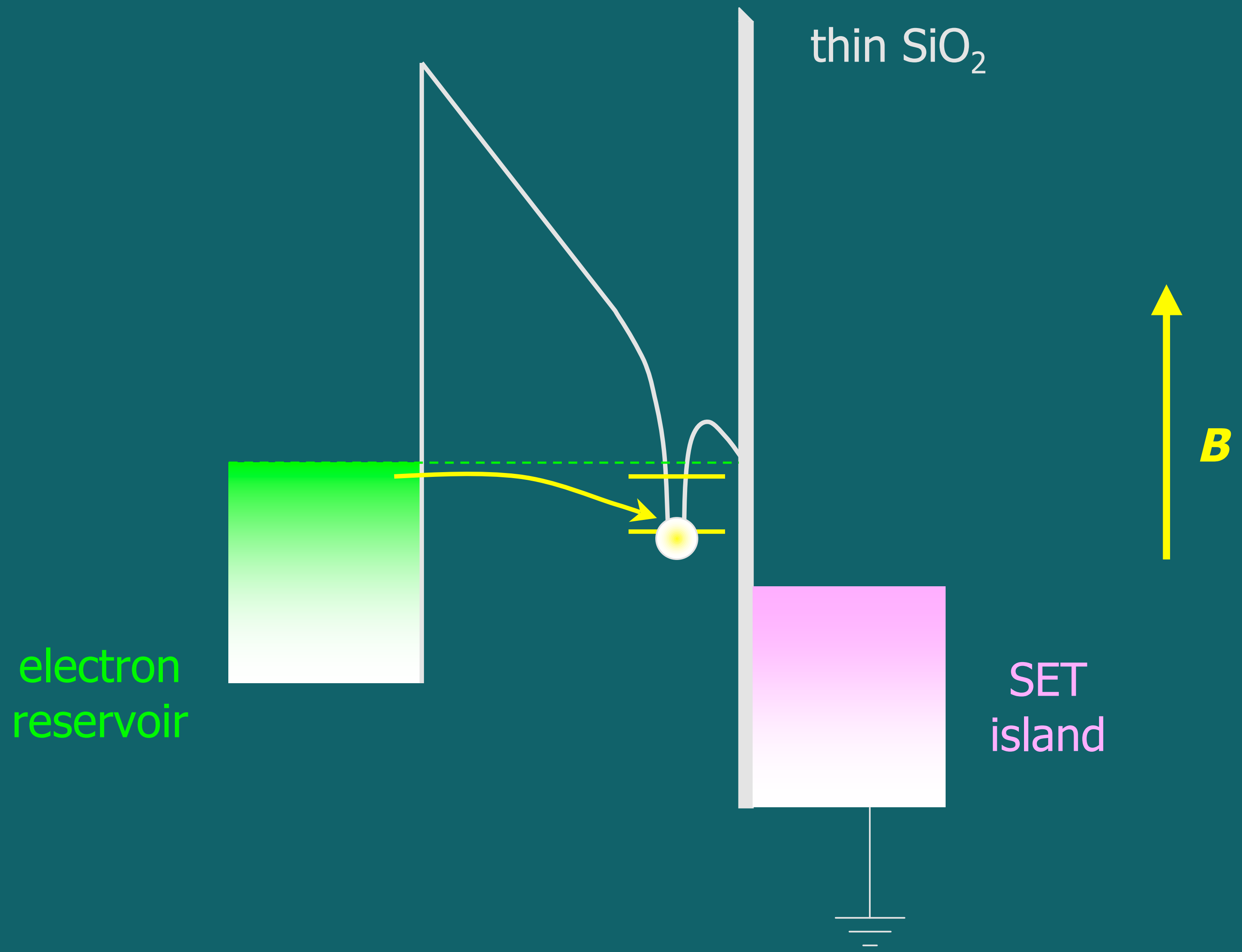
Energy landscape



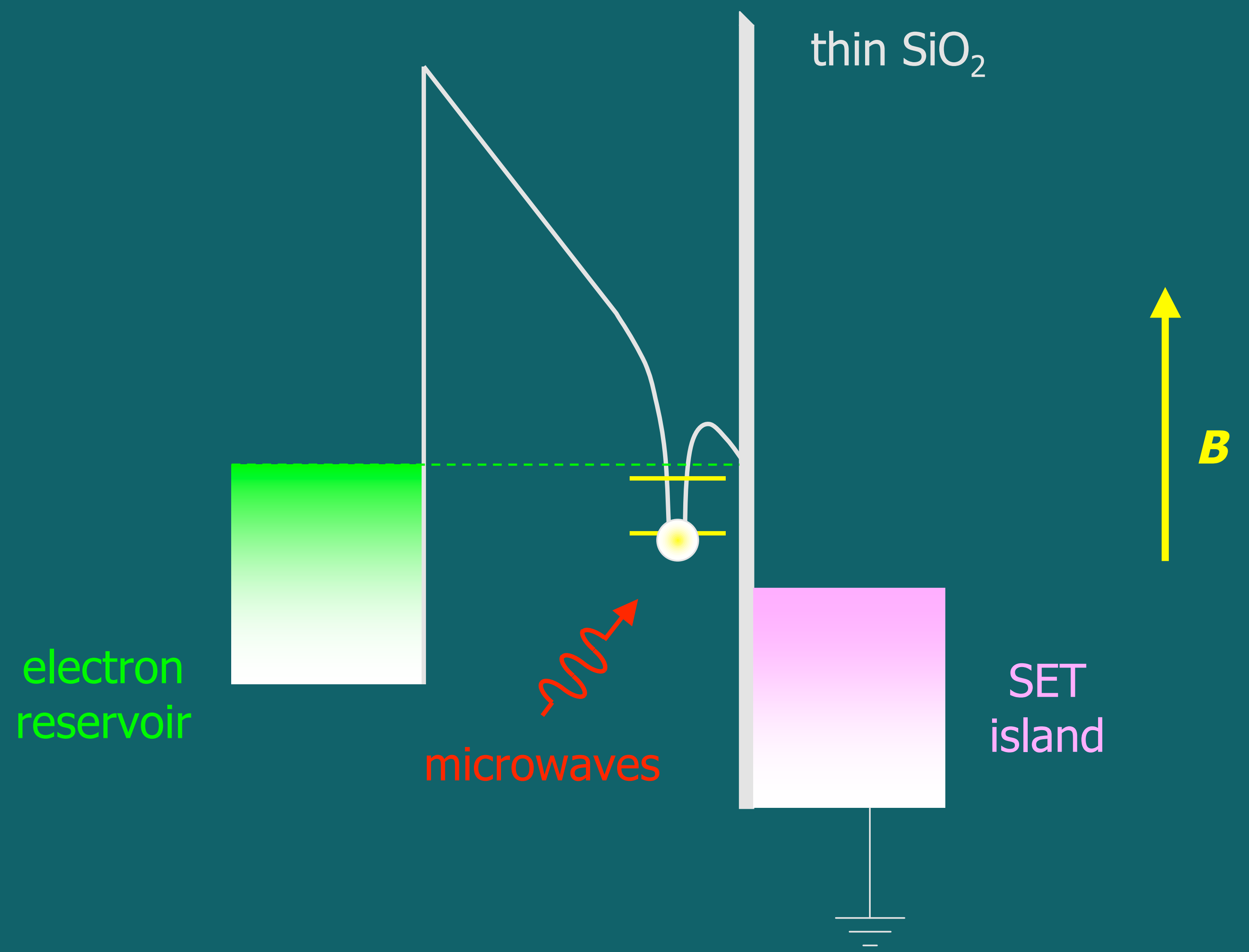
Zeeman splitting



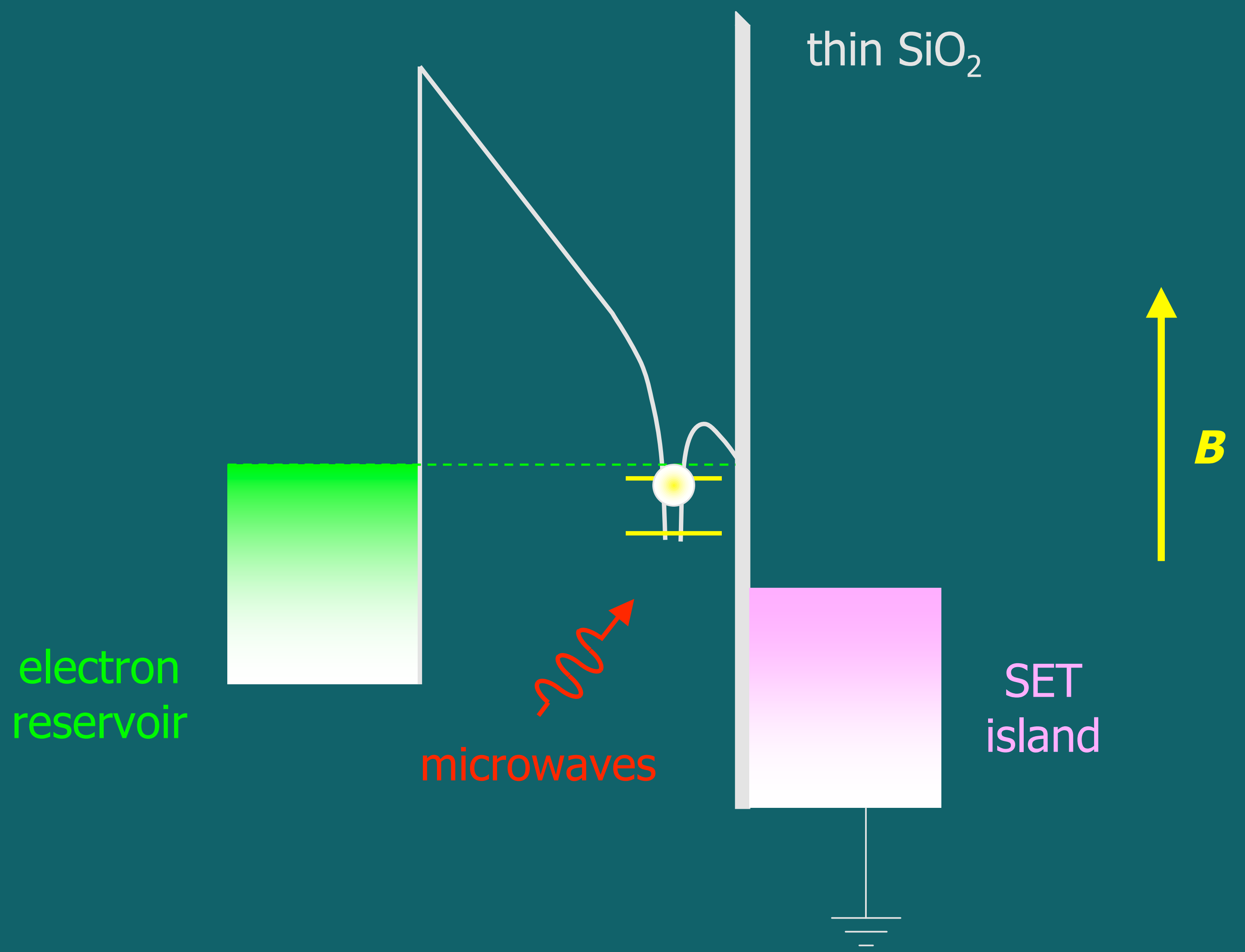
Loading the donor



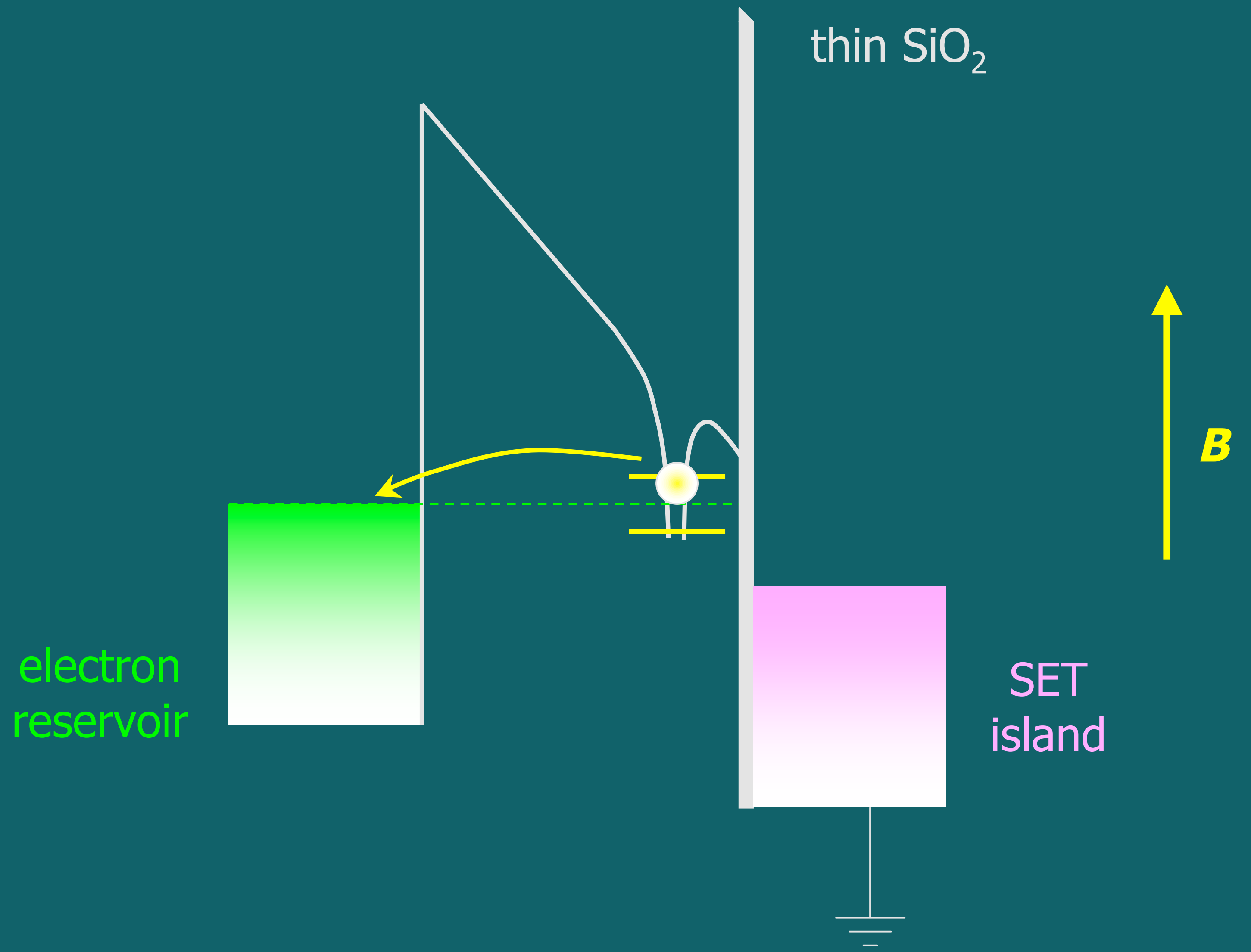
Coherent spin manipulation



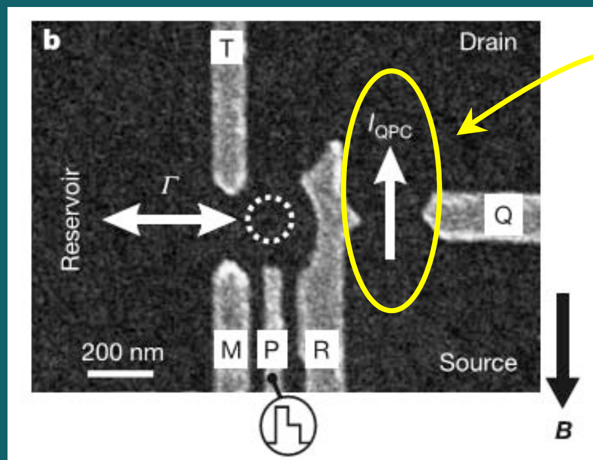
Coherent spin manipulation

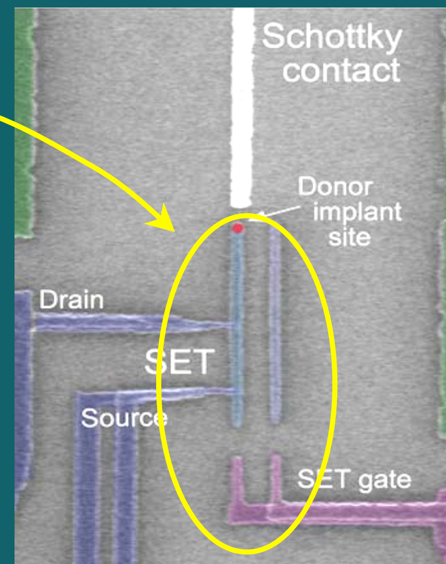


Spin readout



Comparison with quantum dot





charge detection:

quantum point contact

RF single-electron transistor

charge sensitivity ≈ 10 μe / √Hz

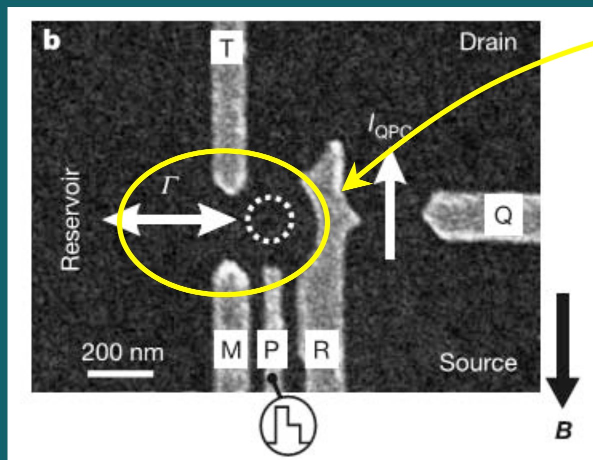
⇒ measure 0.01e in ≈ 1 μs

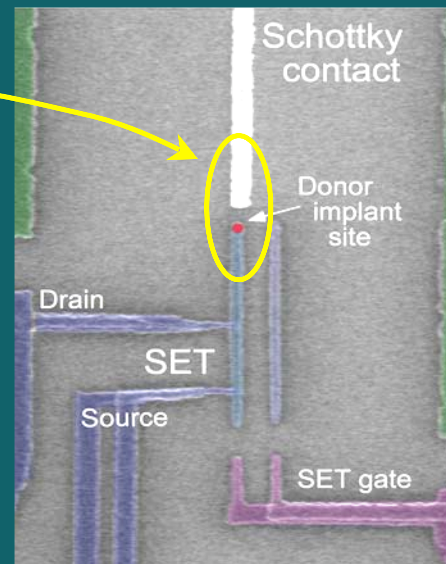
Single-shot capability

Elzerman et al., Nature <u>430</u>, 431 (2004)

Schoelkopf et al., Science <u>280</u>, 1238 (1998)

Comparison with quantum dot





Tunneling rate:

tunable by gate potentials

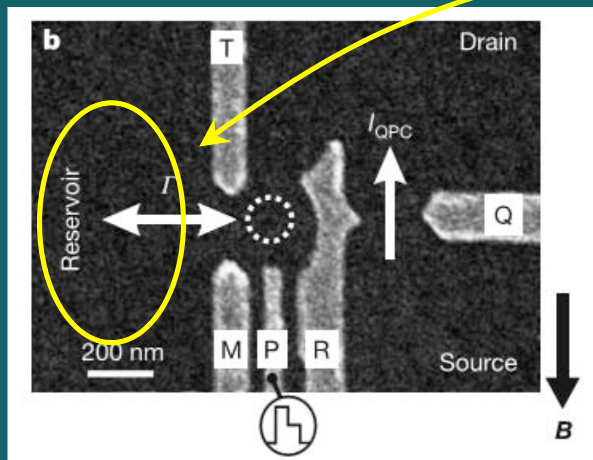
determined by donor distance

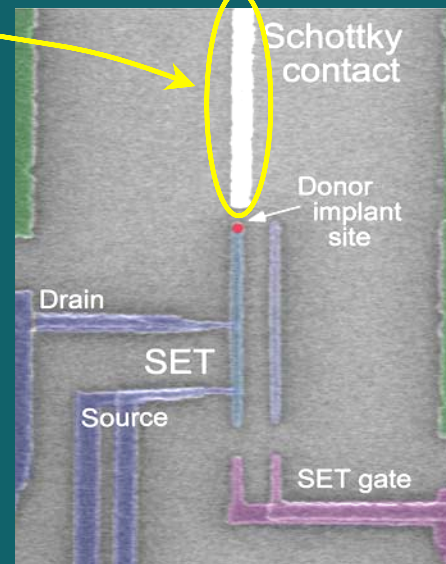
but only needs be

$1\ \mu s \ll \Gamma^{-1} \ll T_1$

Long relaxation ⇒ no problem!

Comparison with quantum dot





Electron reservoir:

2DEG

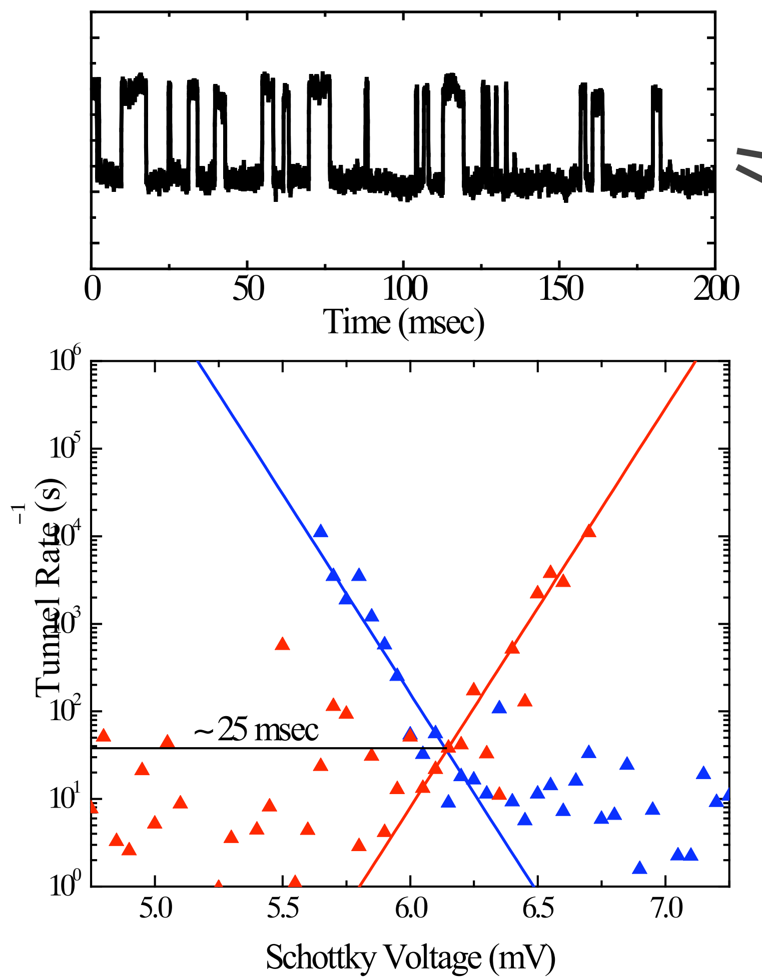
Schottky contact

lots of choices:
metallic, superconducting, ferromagnetic,

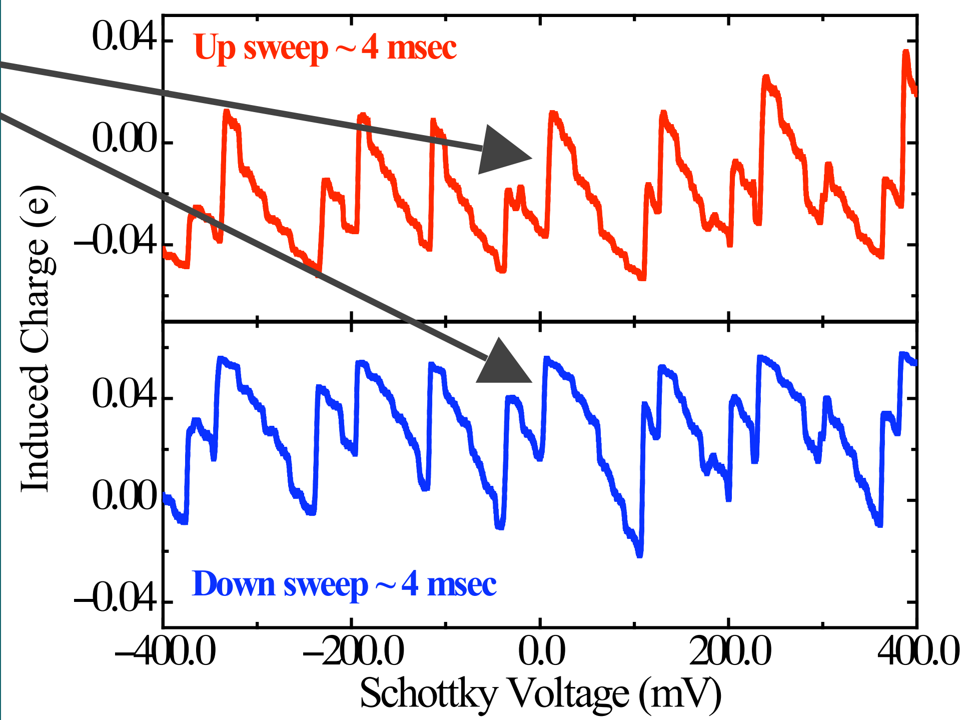
Extra “knob” to play with

Charge transfers

Counting Statistics



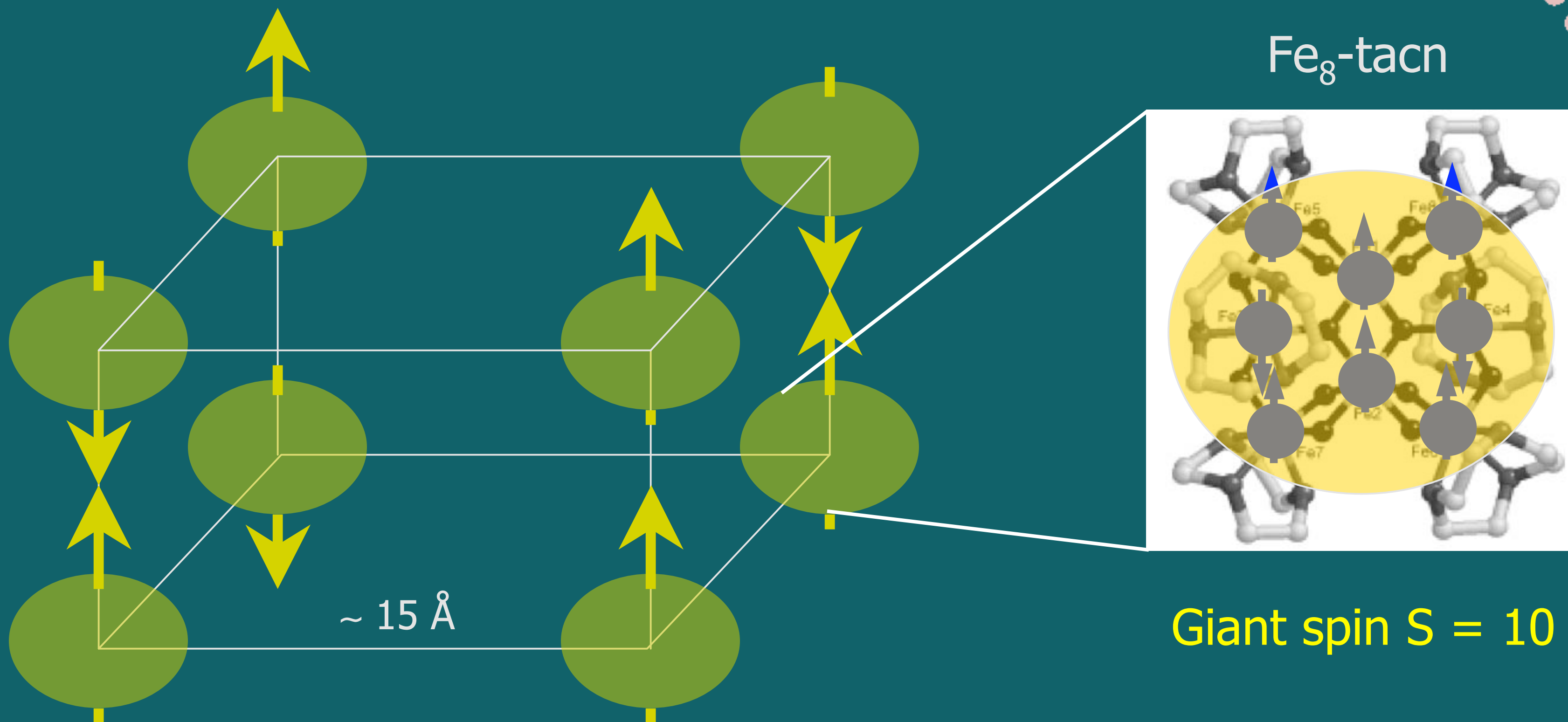
20-atom cluster, 100 nm separation



Typical tunneling rate ~ 25 msec

Brenner et al., in preparation

Single-molecule magnets

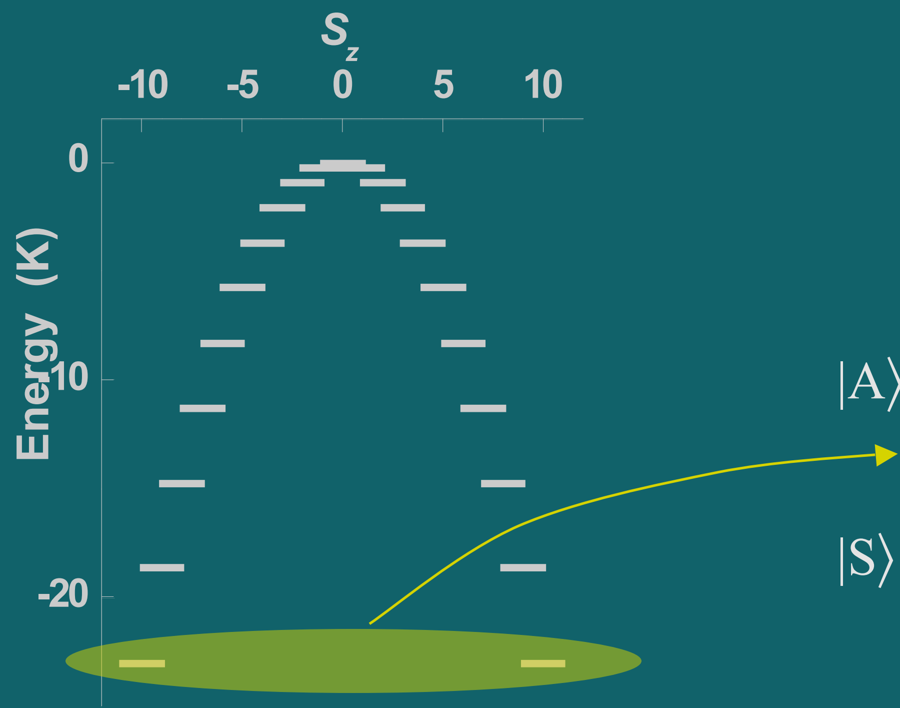


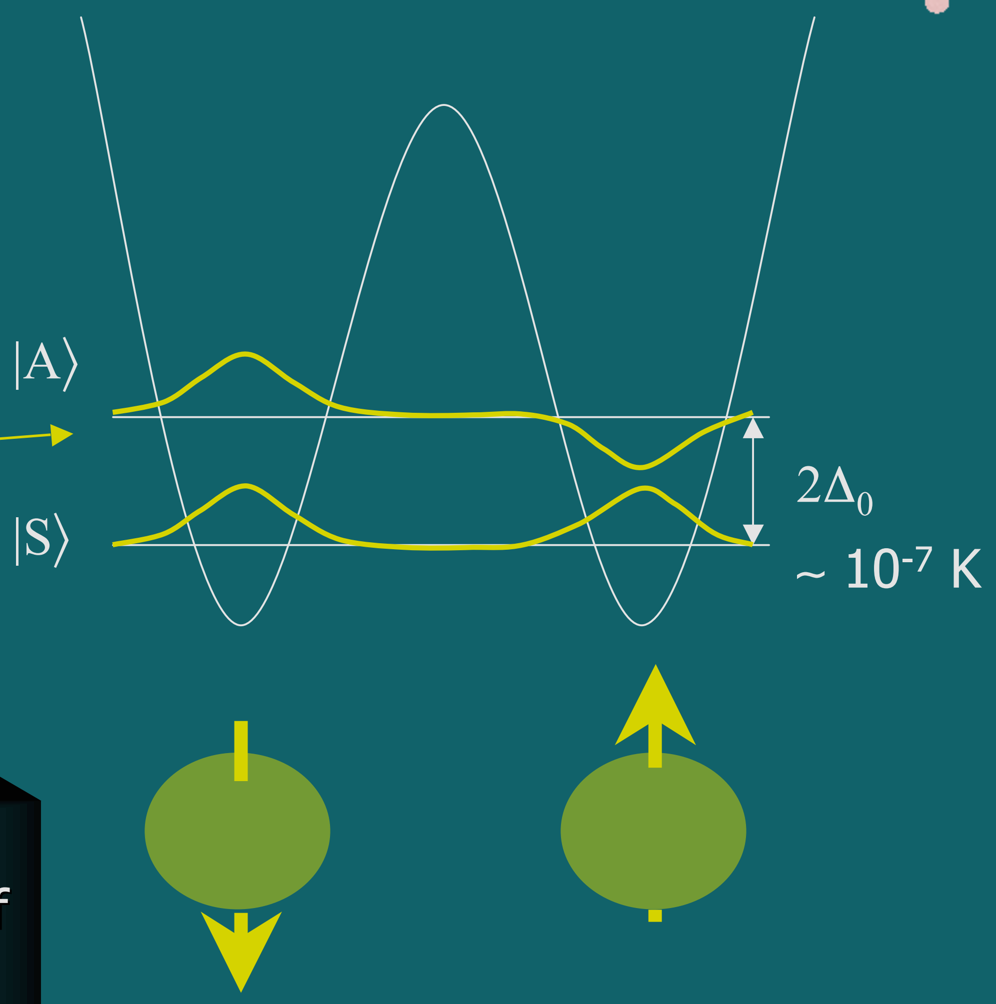
Stoichiometric chemical compounds based on macromolecules, each containing a core of magnetic ions surrounded by organic ligands, and assembled in an insulating crystalline structure

Gatteschi et al., Science 265, 1054 (1994)

Spin Hamiltonian

$$\mathcal{H} = -DS_z^2 + E(S_x^2 - S_y^2)$$

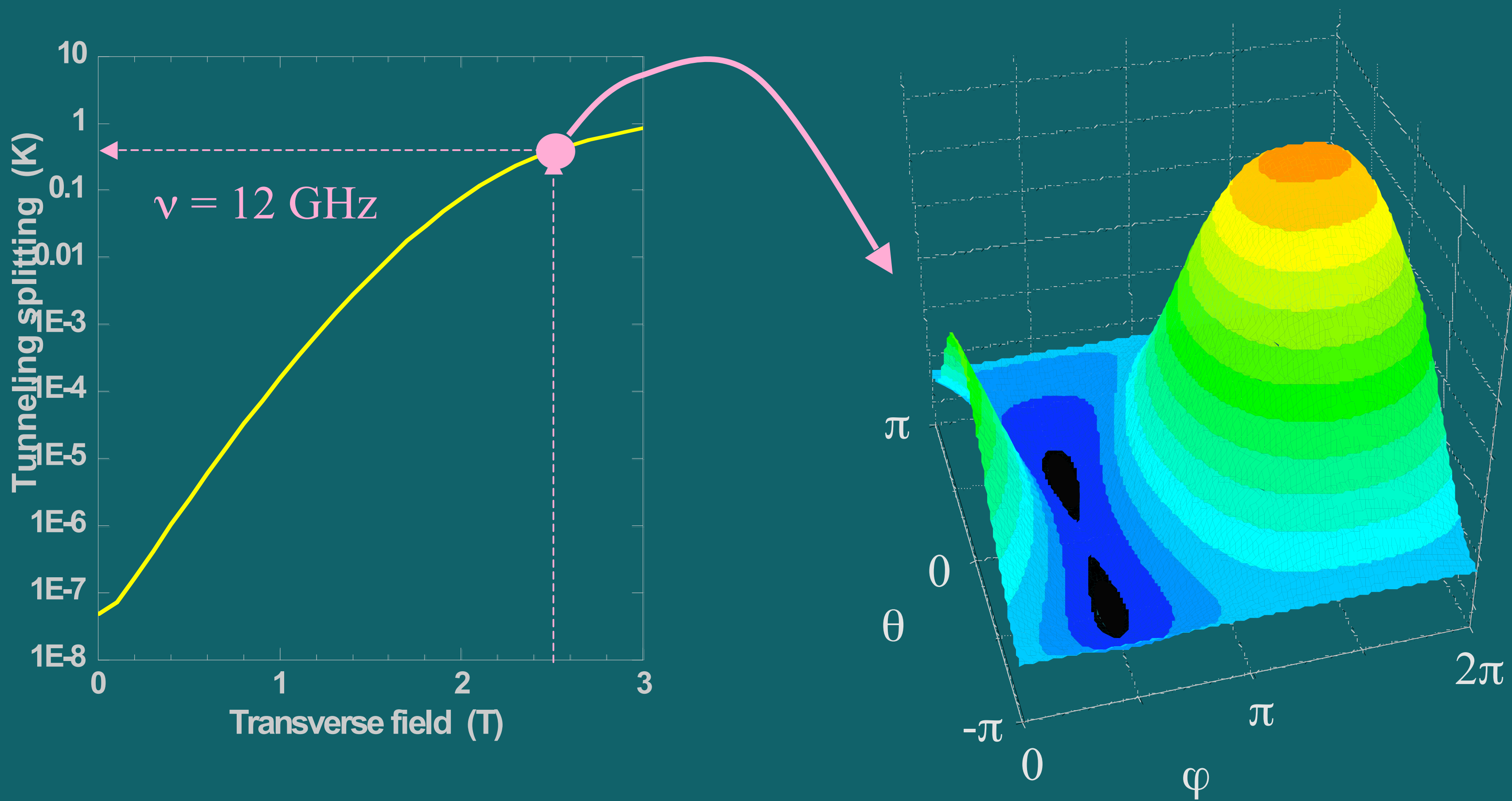




The eigenstates of the molecular spin are quantum superpositions of macroscopically different states

Tunneling splitting

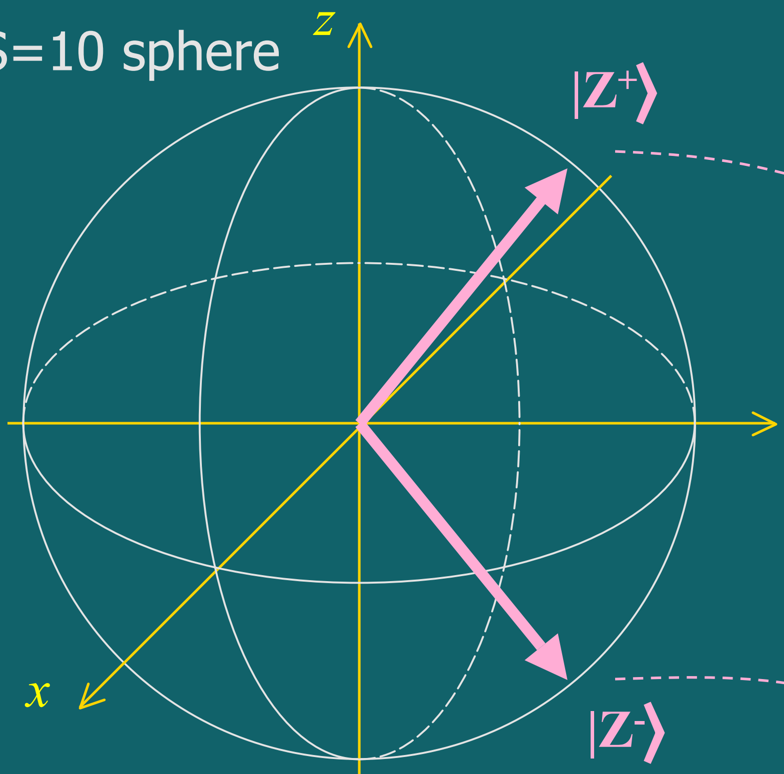
$$\mathcal{H} = - DS_z^2 + E (S_x^2 - S_y^2) - g \mu_B B_y S_y$$

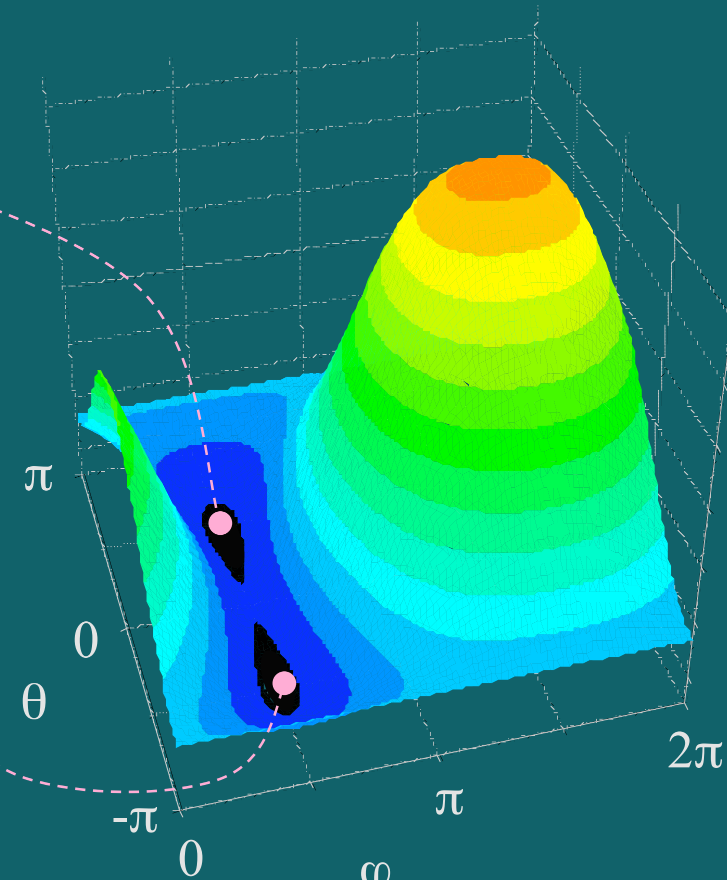


Tunneling splitting

$$\mathcal{H} = -DS_z^2 + E(S_x^2 - S_y^2) - g\mu_B B_y S_y$$

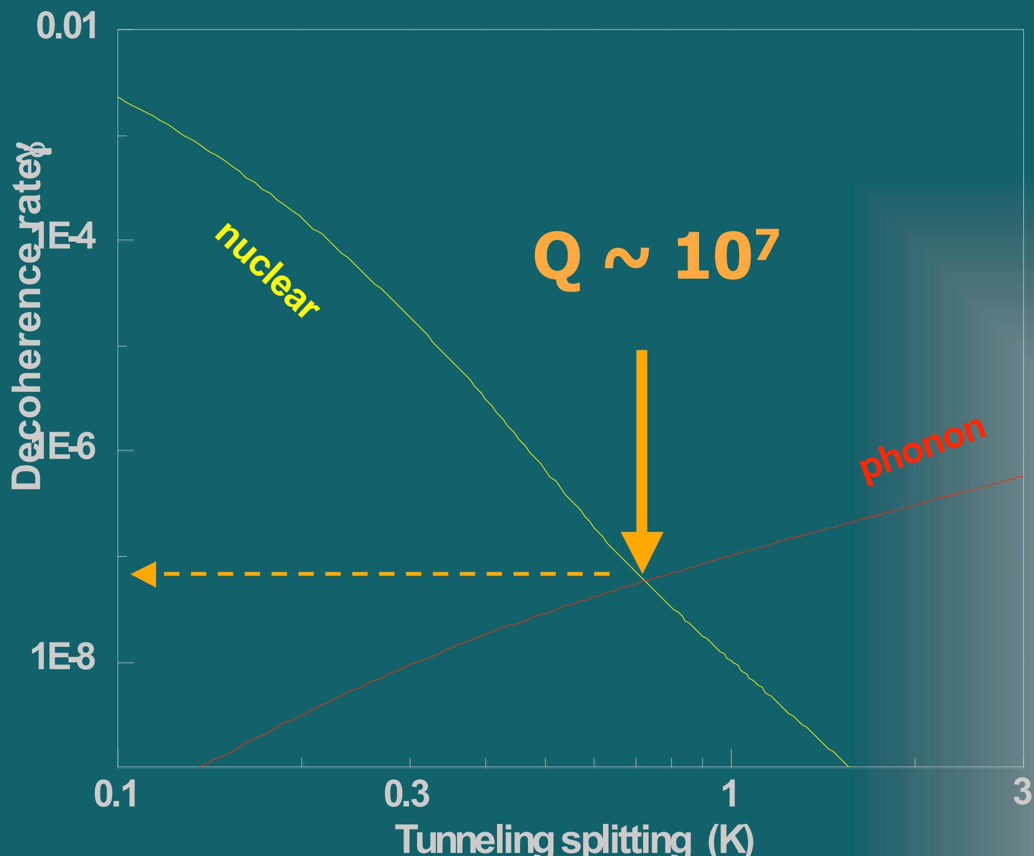
S=10 sphere





$$|Z^{\pm}\rangle = 2^{-1/2}\left(|S\rangle \pm |A\rangle\right)$$

Coherence window



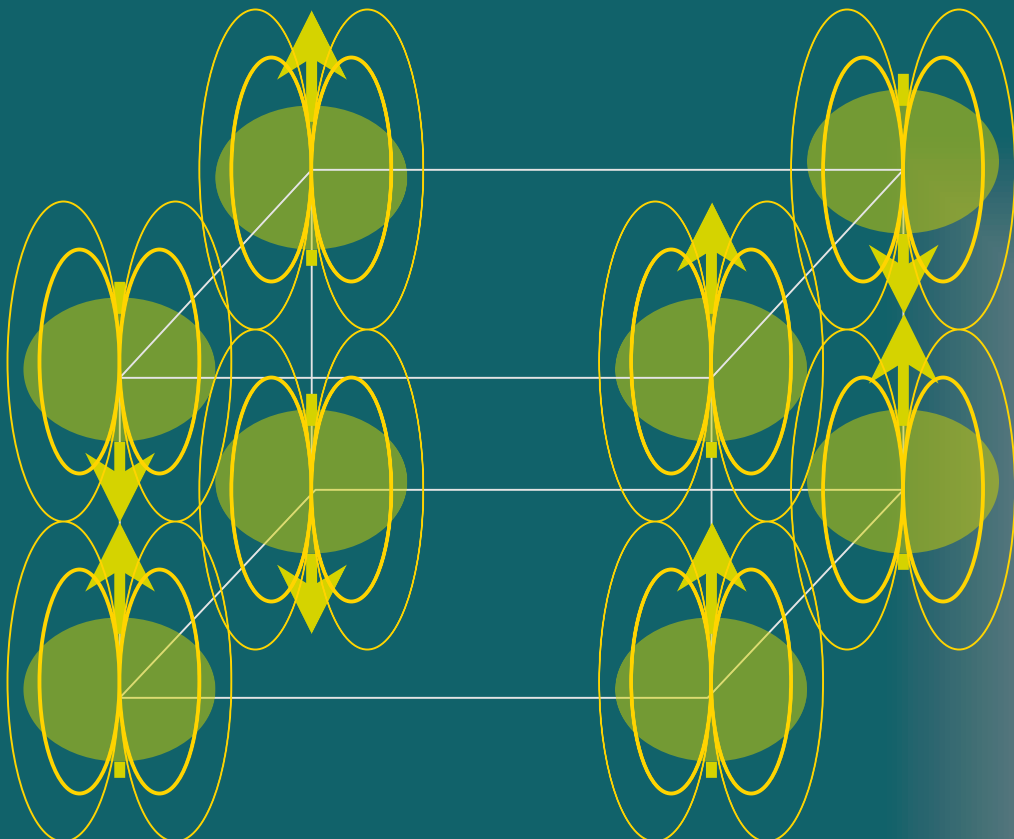
$$\gamma_\phi = \frac{\hbar}{\Delta_0 T_2}$$

$$Q = \pi / \gamma_\phi$$

A chemically-synthesized spin qubit
with quality factor Q ~ 10^{-7}

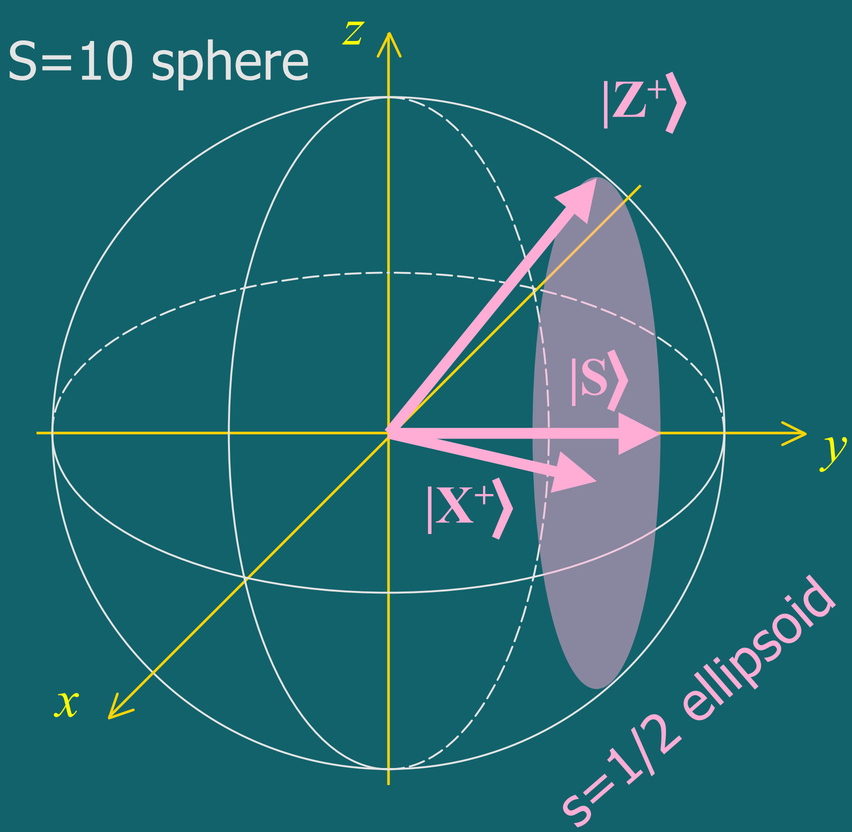
Stamp & Tupitsyn, PRB 69, 014401 (2004)

Dipole - dipole coupling



“Spin qubit network”

Qubit-qubit coupling



$|Z^{\pm}\rangle = 2^{-1/2} (|S\rangle \pm |A\rangle)$

$|X^{\pm}\rangle = 2^{-1/2} (|S\rangle \pm i|A\rangle)$

Coupled giant spins (S=10)

$(2S+1)^2 \times (2S+1)^2 = 441 \times 441$

typical coupling strength

$$U_d = \frac{\mu_0\, g^2\, \mu_B{}^2\, S^2}{4\,\pi\, V_c} \approx 0.1 \text{ K}$$

Coupled qubits (effective s=1/2)

$(2s+1)^2 \times (2s+1)^2 = 4 \times 4$

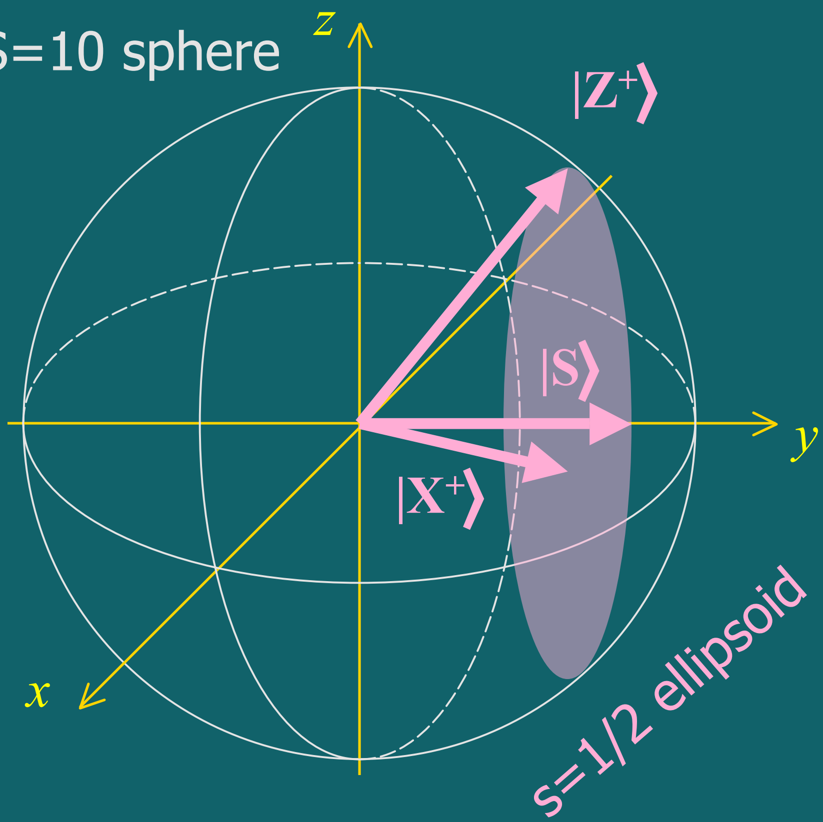
Effective g-factors

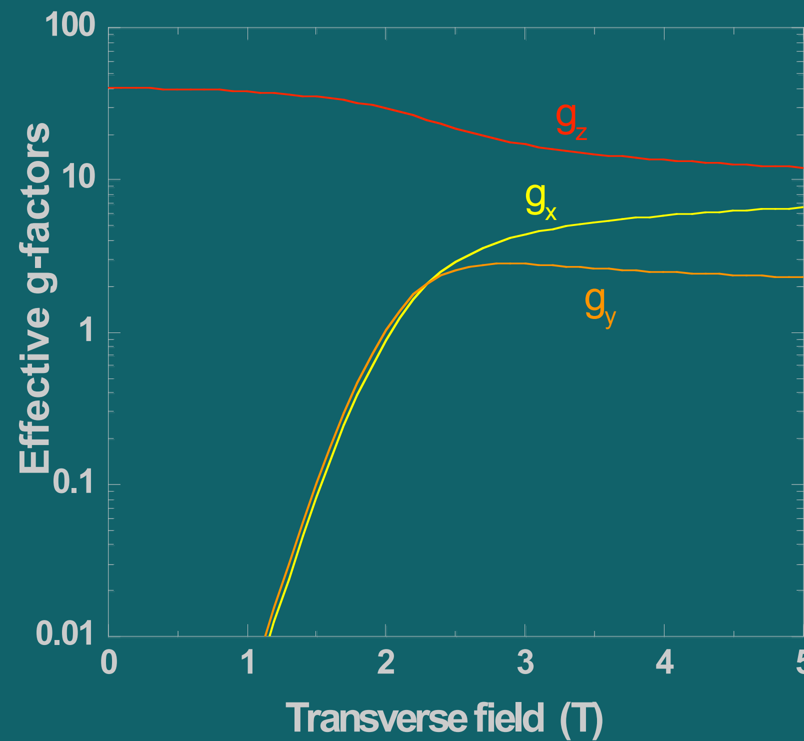
$g_x = g\, (\langle X^+|S_x|X^+\rangle - \langle X^-|S_x|X^-\rangle)$

$g_y = g\, (\langle S|S_y|S\rangle - \langle A|S_y|A\rangle)$

$g_z = g\, (\langle Z^+|S_z|Z^+\rangle - \langle Z^-|S_z|Z^-\rangle)$

Qubit-qubit coupling





$$|Z^{\pm}\rangle = 2^{-1/2}\,(\,|S\rangle \pm |A\rangle\,)$$
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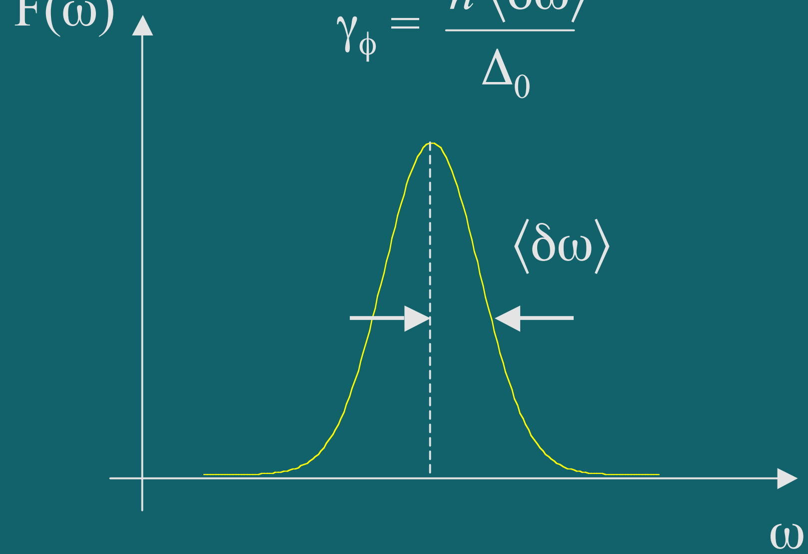
Effective g-factors

$$g_x = g\,(\,\langle X^+|S_x|X^+\rangle - \langle X^-|S_x|X^-\rangle\,)$$
$$g_y = g\,(\,\langle S|S_y|S\rangle - \langle A|S_y|A\rangle\,)$$
$$g_z = g\,(\,\langle Z^+|S_z|Z^+\rangle - \langle Z^-|S_z|Z^-\rangle\,)$$

Dipolar decoherence

Homogeneous linewidth

$$\gamma_\phi = \frac{\hbar \langle \delta\omega \rangle}{\Delta_0}$$

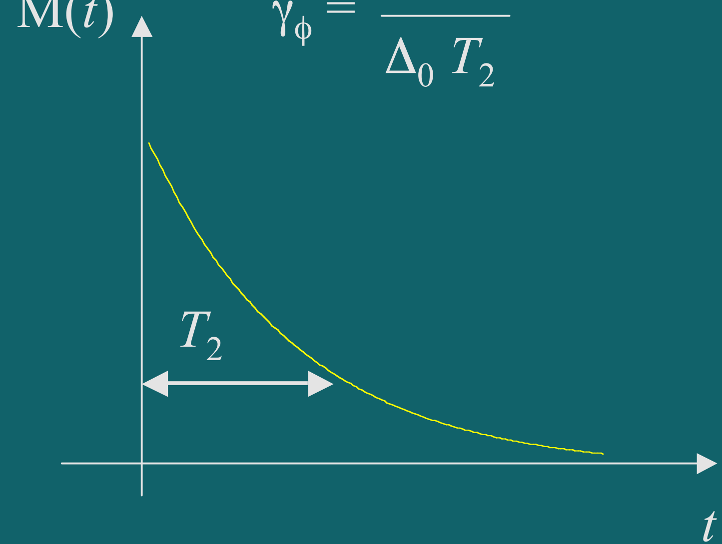


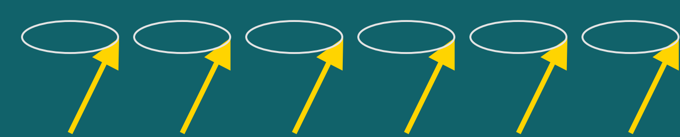
“van Vleck” method
high-*T* limit

van Vleck, PR 74, 1168 (1948)
Pincus *et al.*, PR 124, 1015 (1961)

Magnon decay

$$\gamma_\phi = \frac{\hbar}{\Delta_0 T_2}$$





Scattering of the q=0 magnon
(uniform precession)
with thermal magnons
low-*T* limit

Decoherence rates

"van Vleck" method

$$\gamma_\phi = \frac{\hbar \langle \delta\omega \rangle}{\Delta_0}$$

$$\langle \delta\omega \rangle^2 \approx M_2 = \int (\omega - 2\Delta_0/\hbar)^2 f(\omega)\, d\omega$$

$$\hbar^2 \langle \omega^2 \rangle = \frac{\sum (E_n - E_m)^2 |\langle \psi_n | s_z | \psi_m \rangle|^2 (e^{-\beta E m} - e^{-\beta E n})}{\sum |\langle \psi_n | s_z | \psi_m \rangle|^2 (e^{-\beta E m} - e^{-\beta E n})}$$

Boltzmann factors
for T-dependence

$$(\gamma_\phi^{vV})^2 = [1 - \tanh^2 (\Delta_0/kT)] \sum (A_{yy}^{ij}/\Delta_0)^2$$

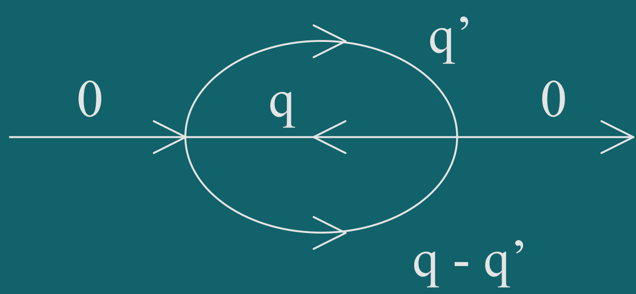
$$A_{yy}^{ij} = \frac{U_d}{(2\, g\, S)^2} [(2g_y^2 + g_z^2) R_{yy}^{ij} + (g_x^2 - g_z^2) R_{xx}^{ij}]$$

Effective g-factors
for qubit-qubit coupling

Decoherence rates

Magnon decay

4-magnon process (energy-conserving)



$$\gamma_\phi^{\,m} = \frac{2\pi}{\hbar\Delta_0} \sum_{qq'} |\Gamma_{qq'}^{(4)}|^2 \, F[n_q] \, \delta(\omega_0 + \omega_q - \omega_{q'} - \omega_{q-q'})$$

$$F[n_q] = \frac{1}{[\exp(\hbar\omega_q / kT) - 1]}$$

Bose factors for magnon populations

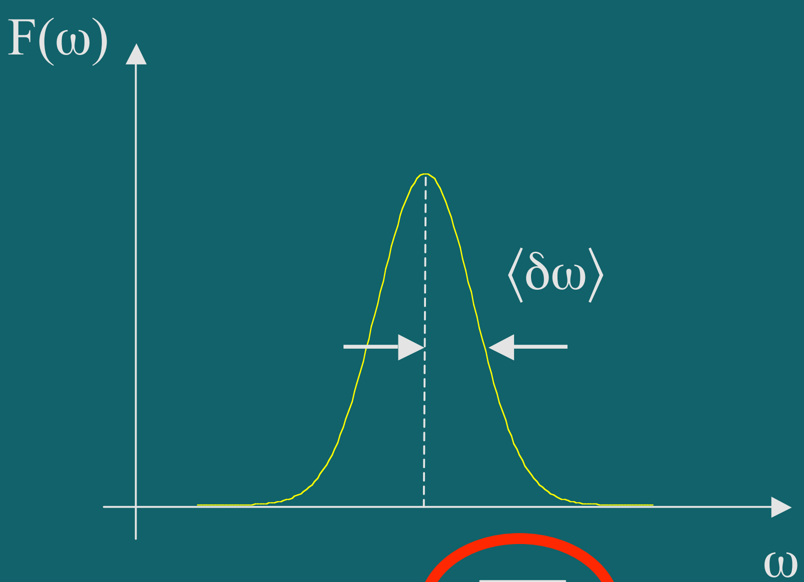
Temperature dependence

$$\gamma_\phi^{vV} \propto \sqrt{[1 - \tanh^2(\Delta_0/kT)]} \sim \exp(-\Delta_0/kT)$$

$$\gamma_\phi^{m} \propto \exp[(2\Delta_0/kT) - 1]^{-1} \sim \exp(-2\Delta_0/kT)$$

factor 2 discrepancy...

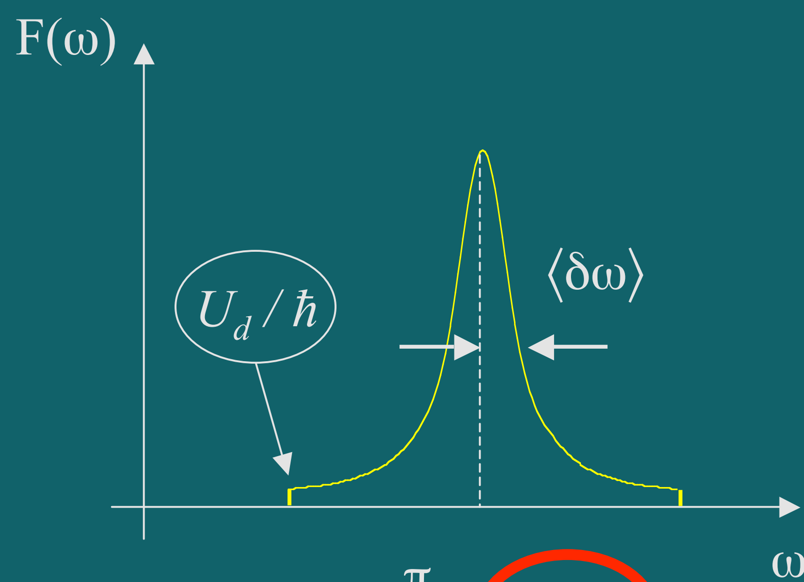
High T - Gaussian line



$$\langle\delta\omega\rangle \approx \sqrt{M_2}$$

square root

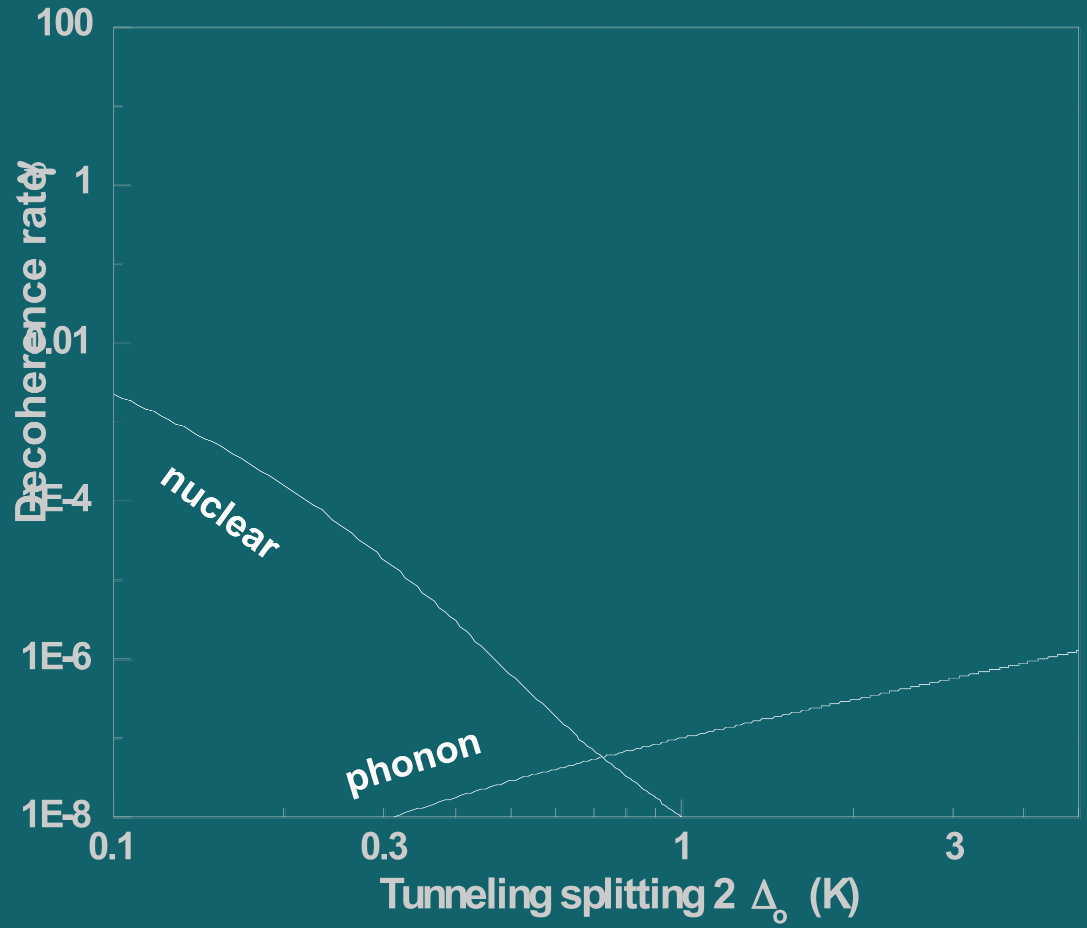
Low T - truncated Lorentzian



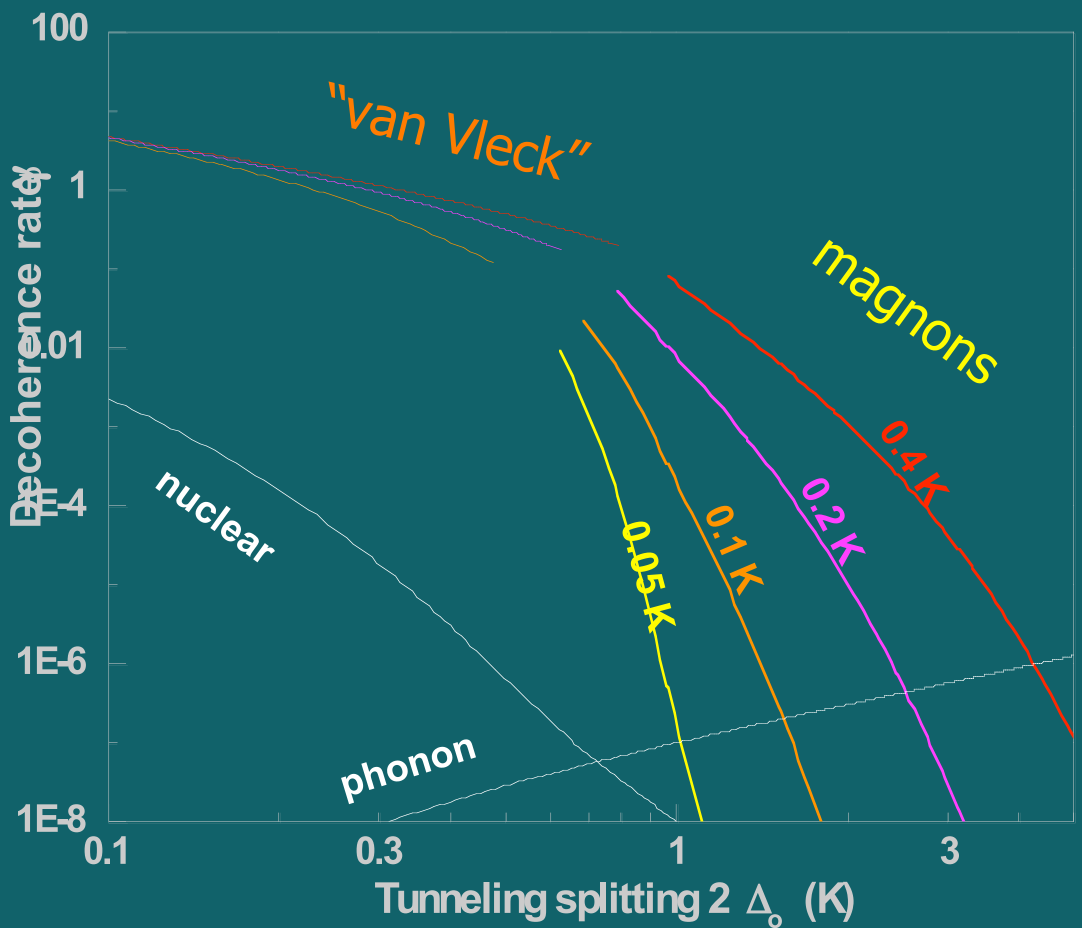
$$\langle\delta\omega\rangle \approx \frac{\pi}{2U_d/\hbar} M_2$$

NO square root

Results for Fe8



Results for Fe8



The pairwise decoherence completely dominates

Morello, Stamp & Tupitsyn, PRL 97, 207206 (2006)

Quantum information perspective

Long-range memory of quantum reservoir ⇒ correlated noise breaking the assumption for quantum error correction

Alicki et al., PRA 65, 022101 (2002)

One can still find a threshold for error correction with non-Markovian noise, provided the errors are "sparse"

Terhal & Burkard, PRA 71, 012336 (2005)

Spatial noise correlations are harmful for error-correcting codes

Klesse & Franck, PRL 95, 230503 (2005)

Some protection against correlated errors can be obtained with slightly modified error correction codes

Novais & Baranger, PRL 97, 040501 (2006)

How does this relate to the "condensed matter" perspective?

E.g.: meaning of temperature

Low-T means:

$$|\psi\rangle = |000000001000000000000000000000000000010000000000\rangle$$

but this is not the most general state that will be used during a computation!

Should one always use the high-T limit when estimating pairwise decoherence?

Summary

Electron spin qubits based on single donors in silicon are ready to go!

The long coherence times and flexibility in the design promise lots of interesting physics

We have worked out a general method to calculate pairwise decoherence in coupled spin qubit networks

May have interesting implications for quantum information theory

Acknowledgements

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Others

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