Title: Theory of Heavy-Hole Spin Echoes

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Abstract: Heavy-hole spin states have been proposed as a robust qubit candidate. Nevertheless, the coupling of the hole spins to nuclei in the surrounding medium likely limits hole-spin coherence and has, until very recently, been overlooked. We describe the spin decoherence of a heavy-hole in a semiconductor quantum dot, subject to spin echo pulses. We do so both analytically and numerically for an experimentally realistic number (10^4) of nuclear spins. Including the (previously neglected) nuclear Zeeman term in the Hamiltonian, we observe novel effects uniquely characterizing the decoherence mechanisms under study. In particular, we find a nontrivial dependence of the decay on the applied magnetic field, as well as novel predictions for motional narrowing and envelope modulation, which could significantly extend the hole-spin memory time in near-future experiments.

Theory of Hole Spin Echoes

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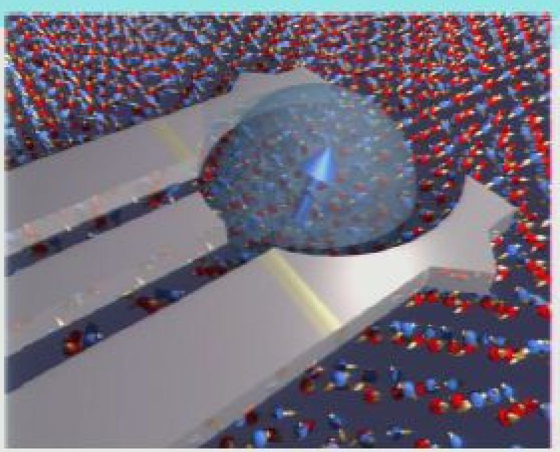
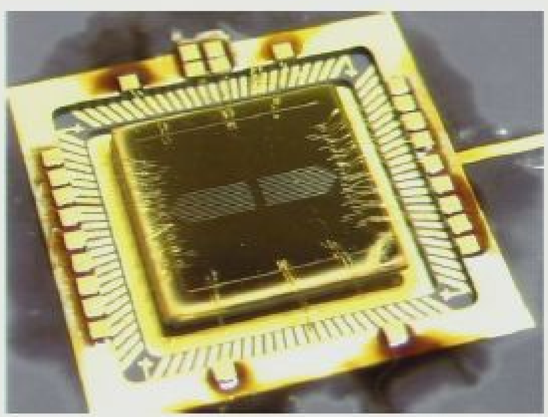
Qubit Candidates



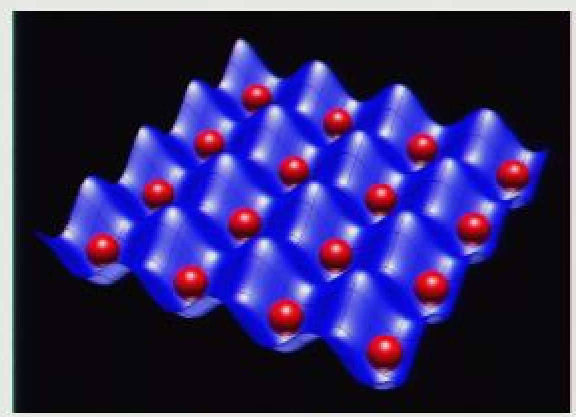
Quantum dot

Superconducting qubit



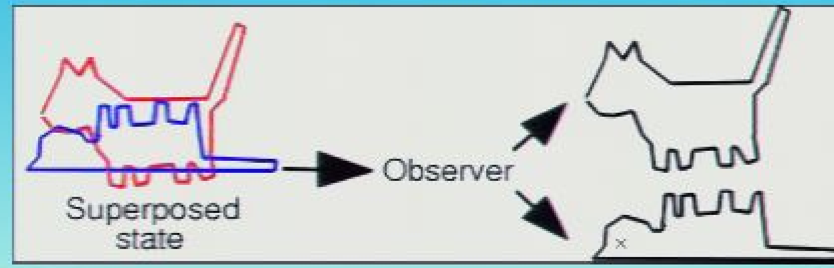
Ion trap

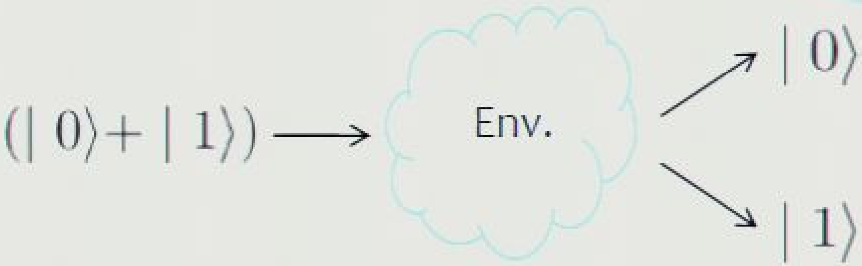
NV center in diamond



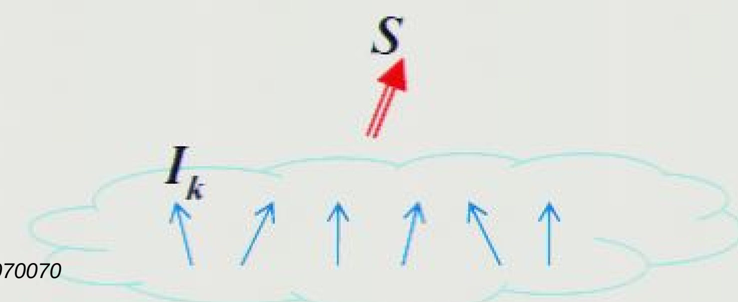
Optical lattice

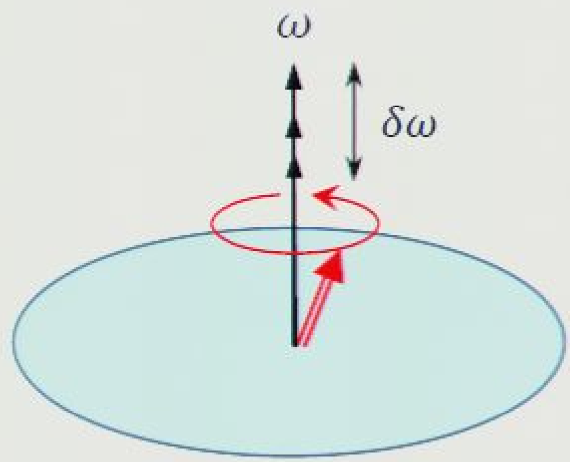
Decoherence





- Interactions with the environment cause decoherence of quantum states
- Hole spin (qubit) interacts with nuclear spins (environment)

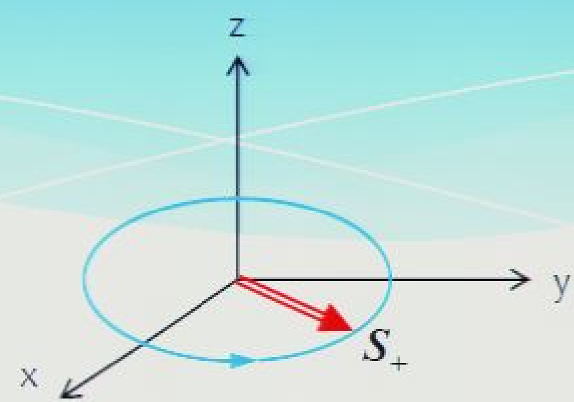


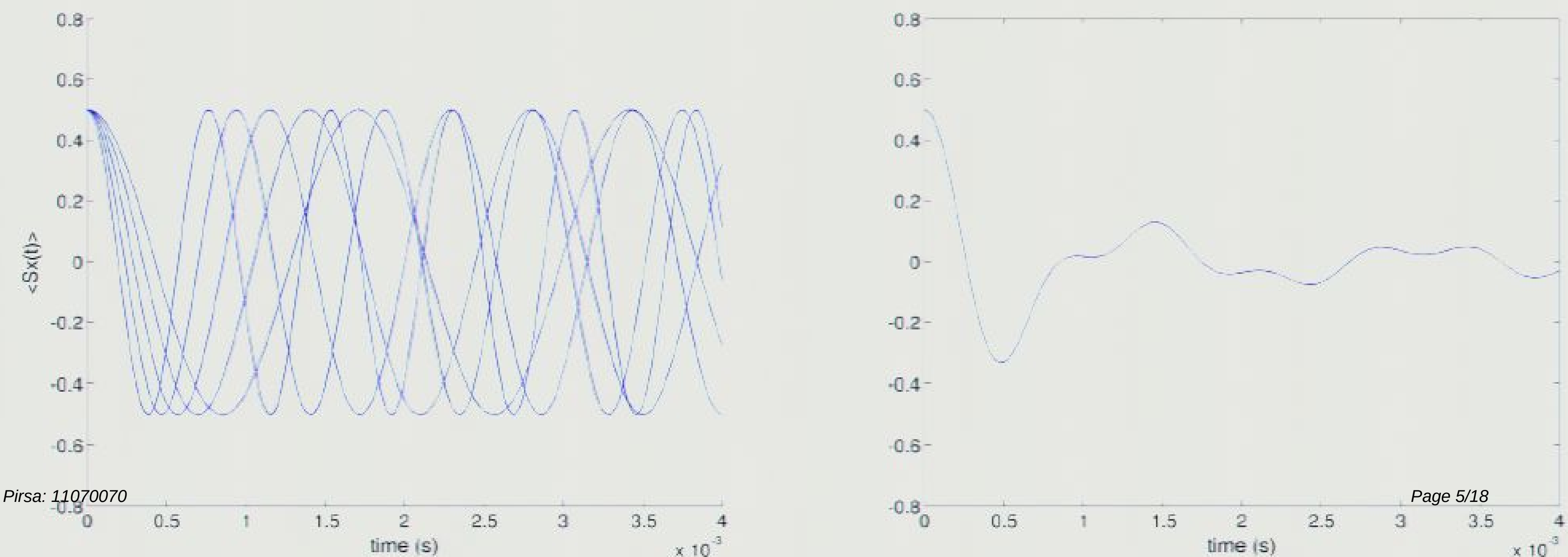


- Precession due to coupling $\sim \sum_k I_k^z S^z = h^z S^z$
- $\delta\omega$ due to random orientations of nuclear spins

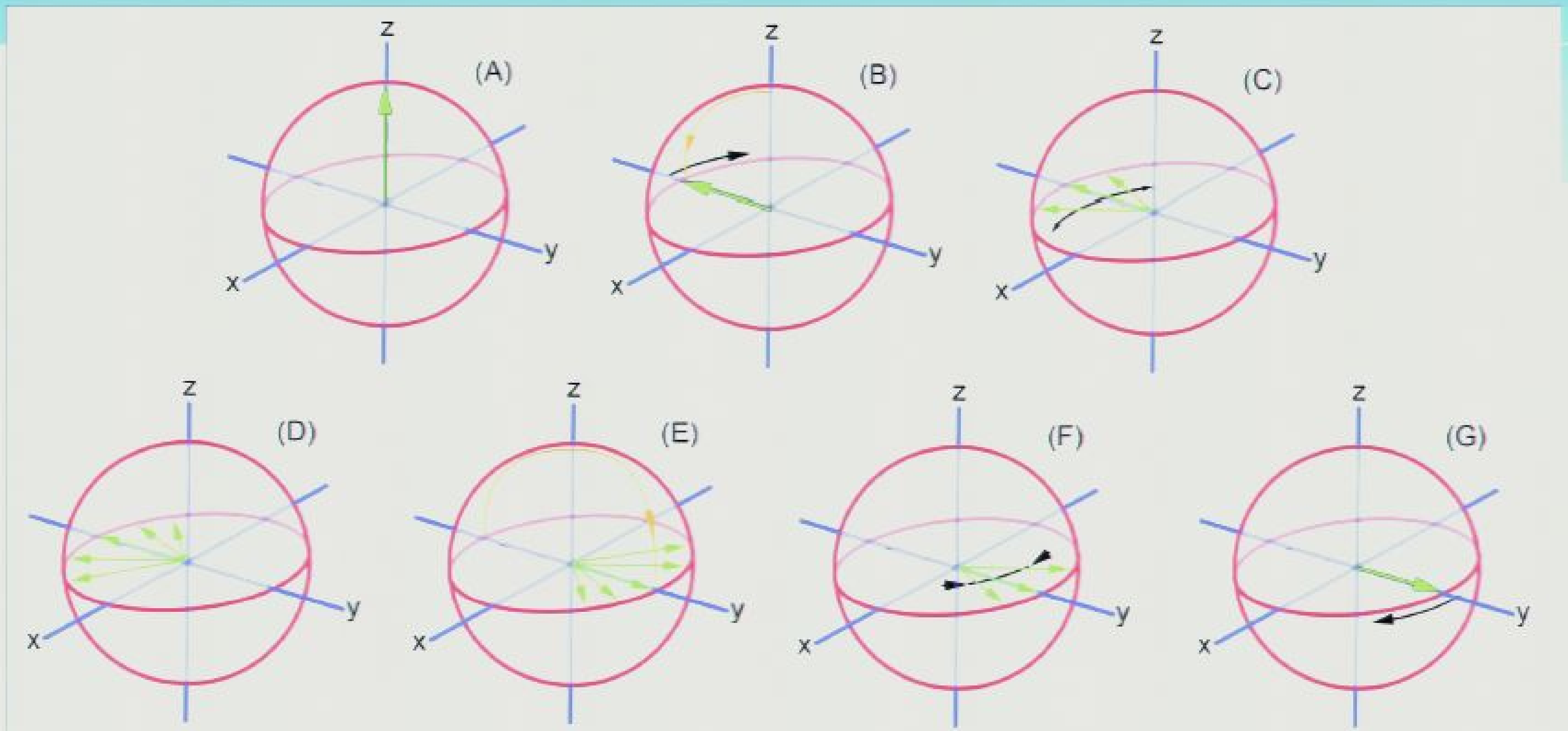
Decoherence

- Fluctuations in ω cause decoherence
- Simple example: averaging precession at 5 different frequencies





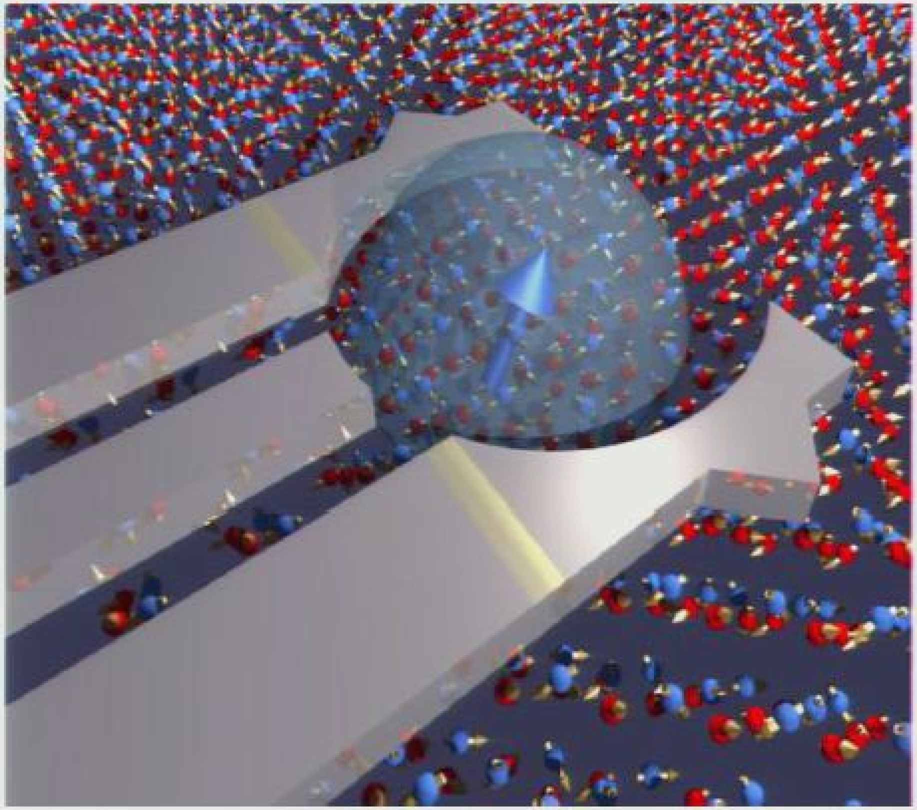
Spin Echo



Reverses decoherence due to static fluctuations in ω!

Hole spins in Quantum Dots

- Heavy-hole confined to a quasi-2D quantum dot
- Hyperfine interaction is Ising ($I_z S_z$) for holes instead of Heisenberg ($\boldsymbol{I} \cdot \boldsymbol{S}$) for electrons
- Hyperfine interaction main source of decoherence for electron spin qubit
- Possibly more coherent than electron spin



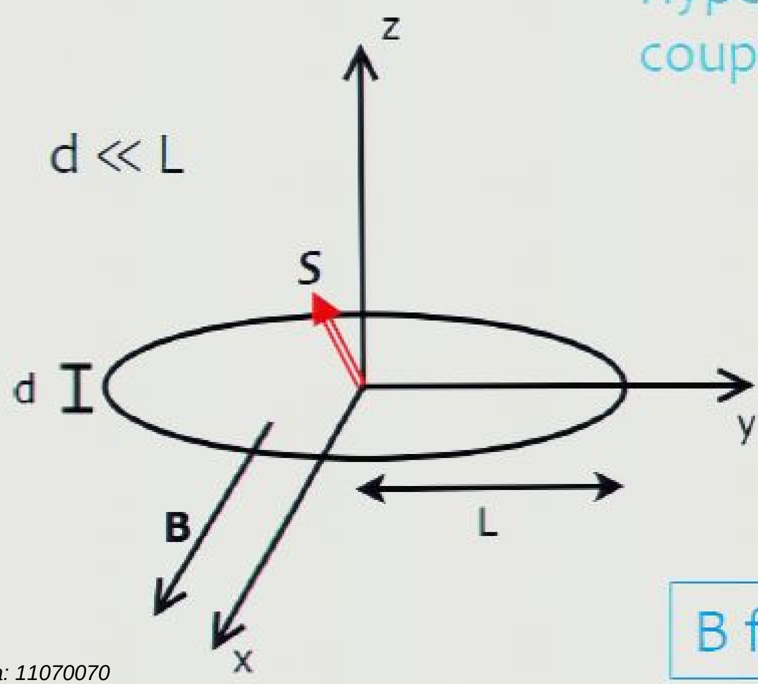
Hamiltonian

$$H = \sum_{k=1}^{N} A_k I_k^z S_z + B \sum_{k=1}^{N} \gamma_k I_k^x + \mu_B g_{\parallel} B S_x$$

Hyperfine coupling

Nuclear Zeeman

Hole Zeeman



Pancake-like (2-D) quantum dot:

* 2-level system for holes
* Ising coupling
* Hole spin in plane g-factor very small $\Rightarrow g_{\parallel} \cong 0$

$\boxed{\text{B field introduces dynamics in } I_k^z}$

Hamiltonian

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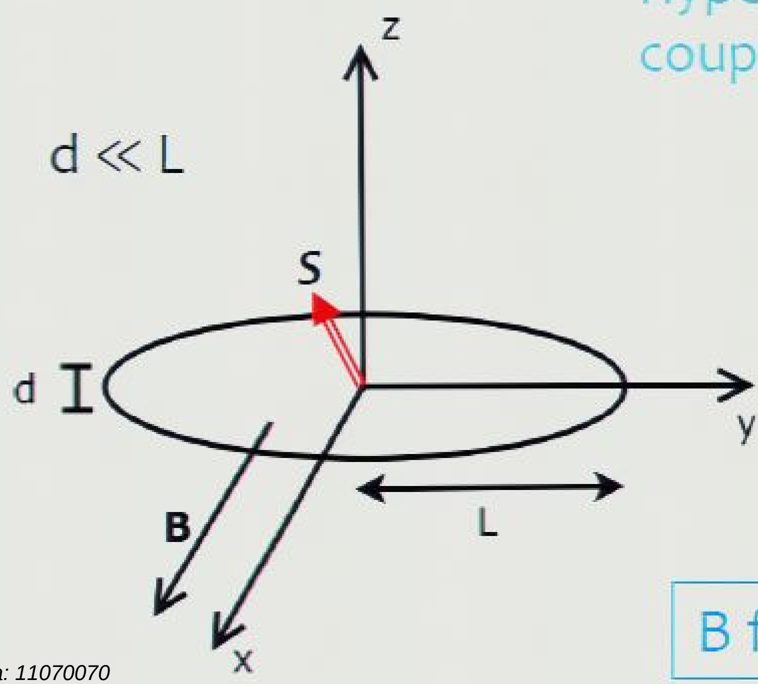

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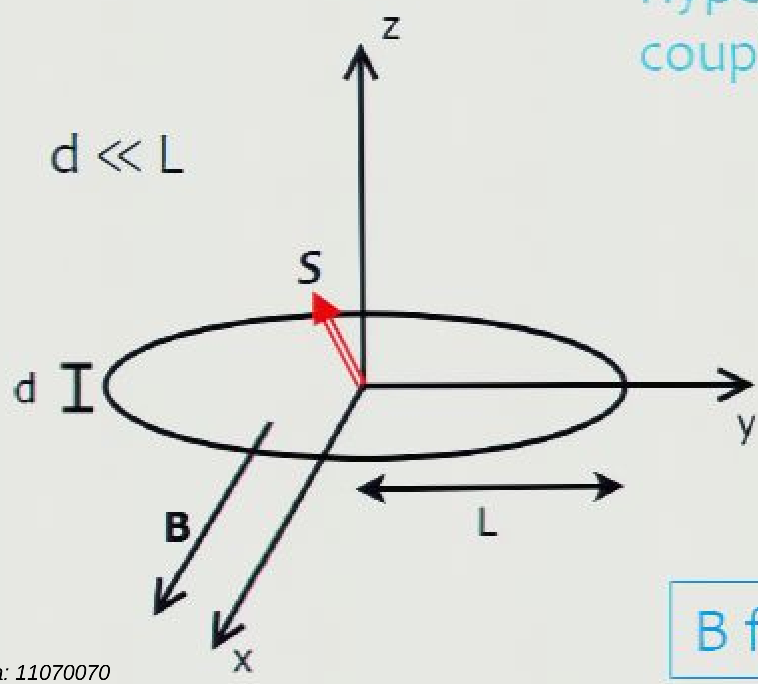

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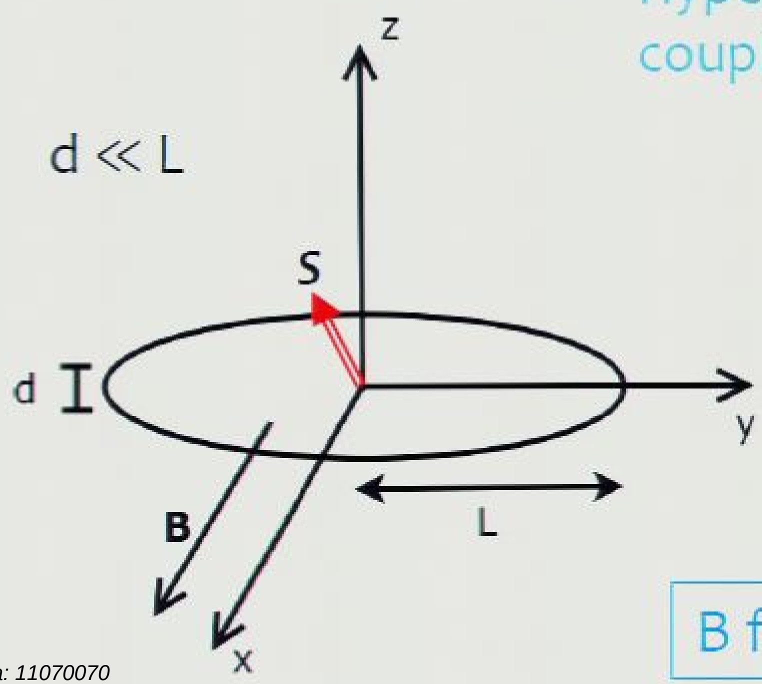

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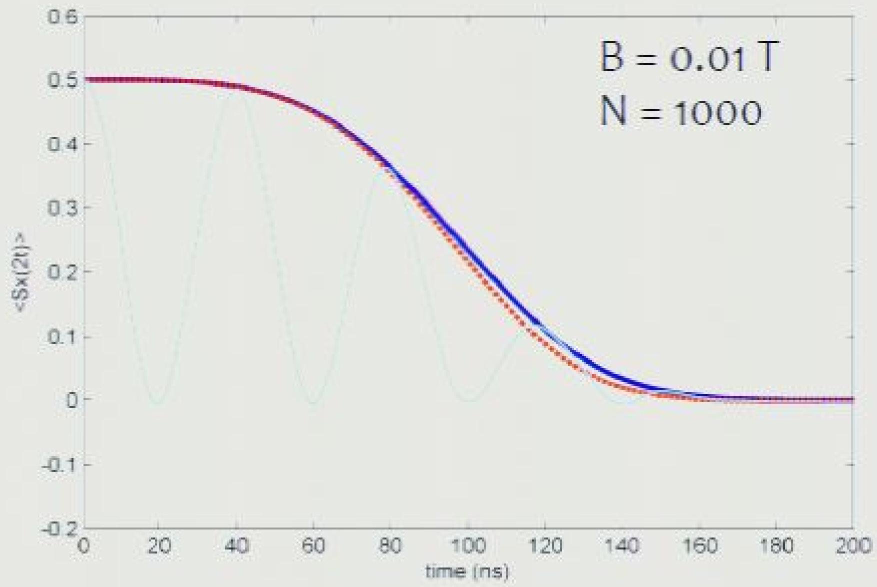
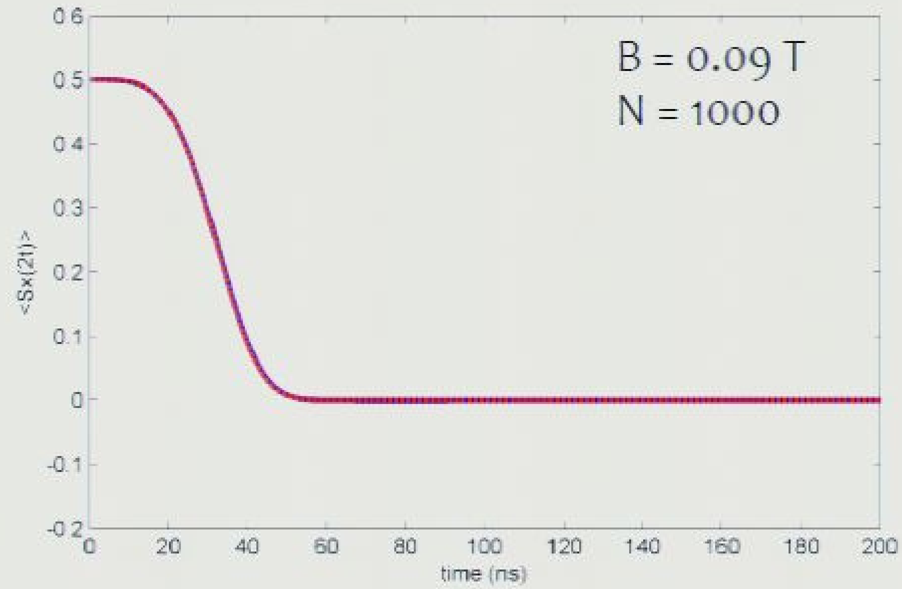
Results





- Numerical solution in solid blue line
- Short-time approximation in dotted red line: $\langle S_x(t) \rangle \cong \frac{1}{2} e^{-(t/\tau)^4}$
- Decay time $\tau \sim (N/B^2)^{1/4} \sim 1/\sqrt{B}$
- B field induces nuclear spin precession
- Dynamic fluctuations are not reversed by spin echoes, leading to decoherence

Decoherence

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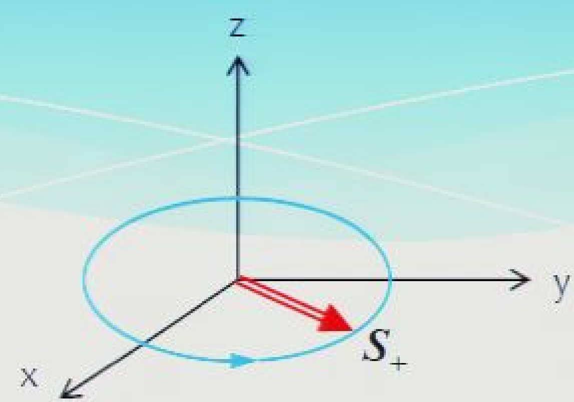

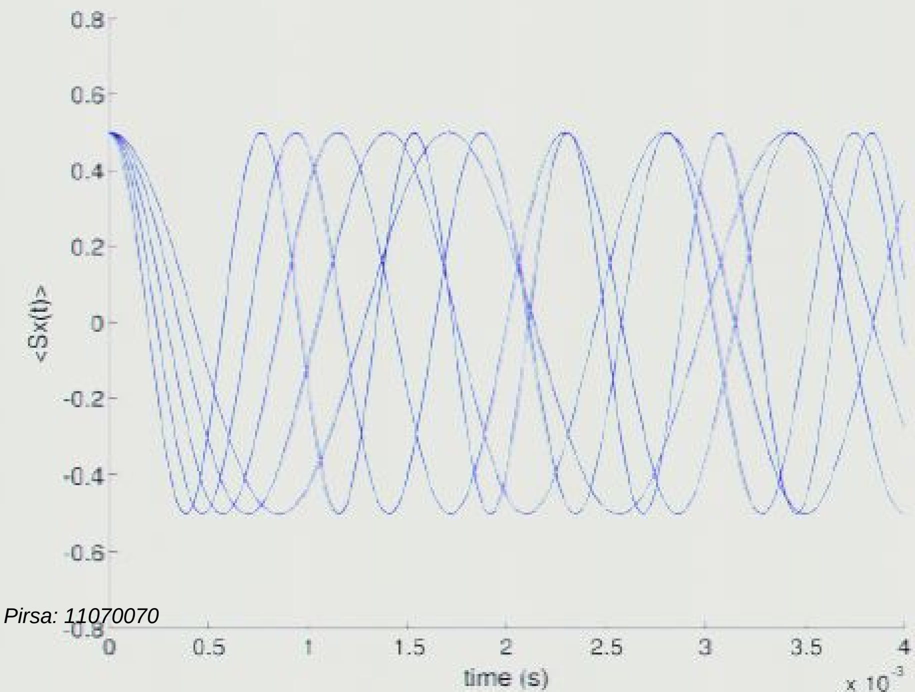

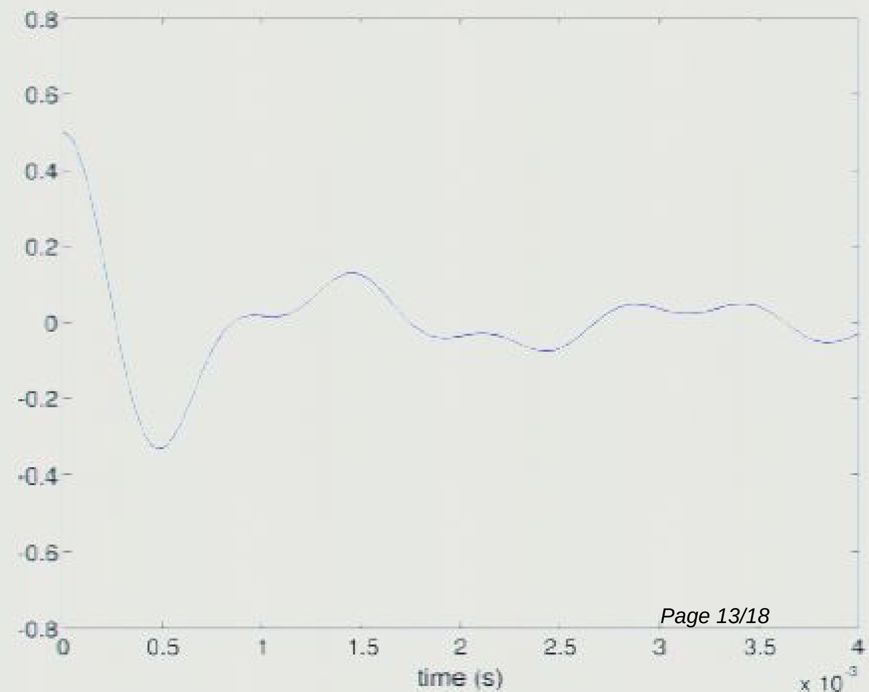

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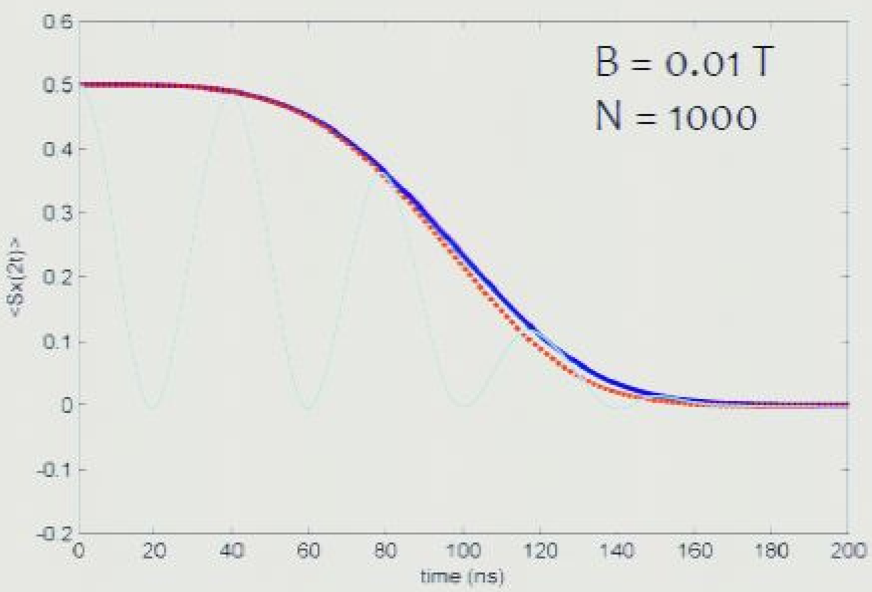

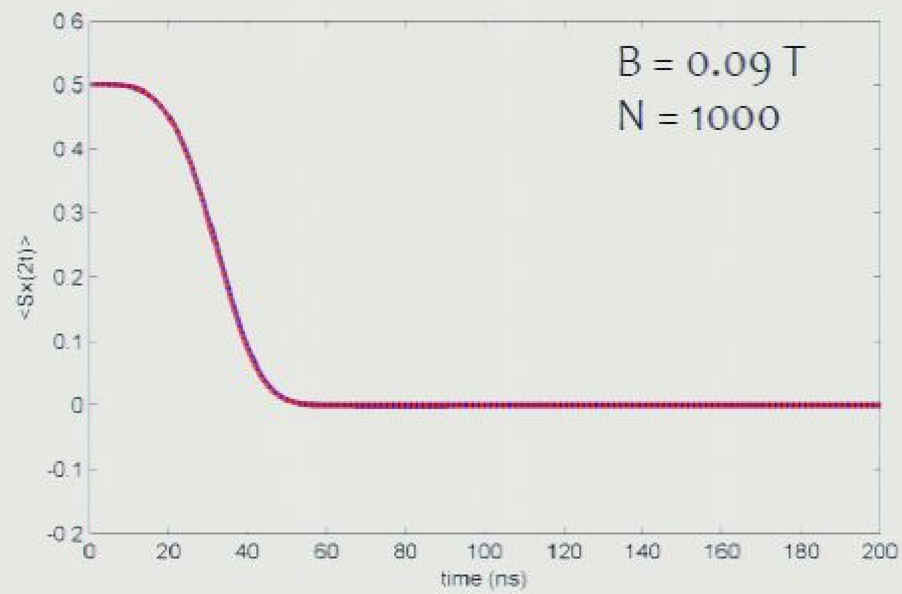

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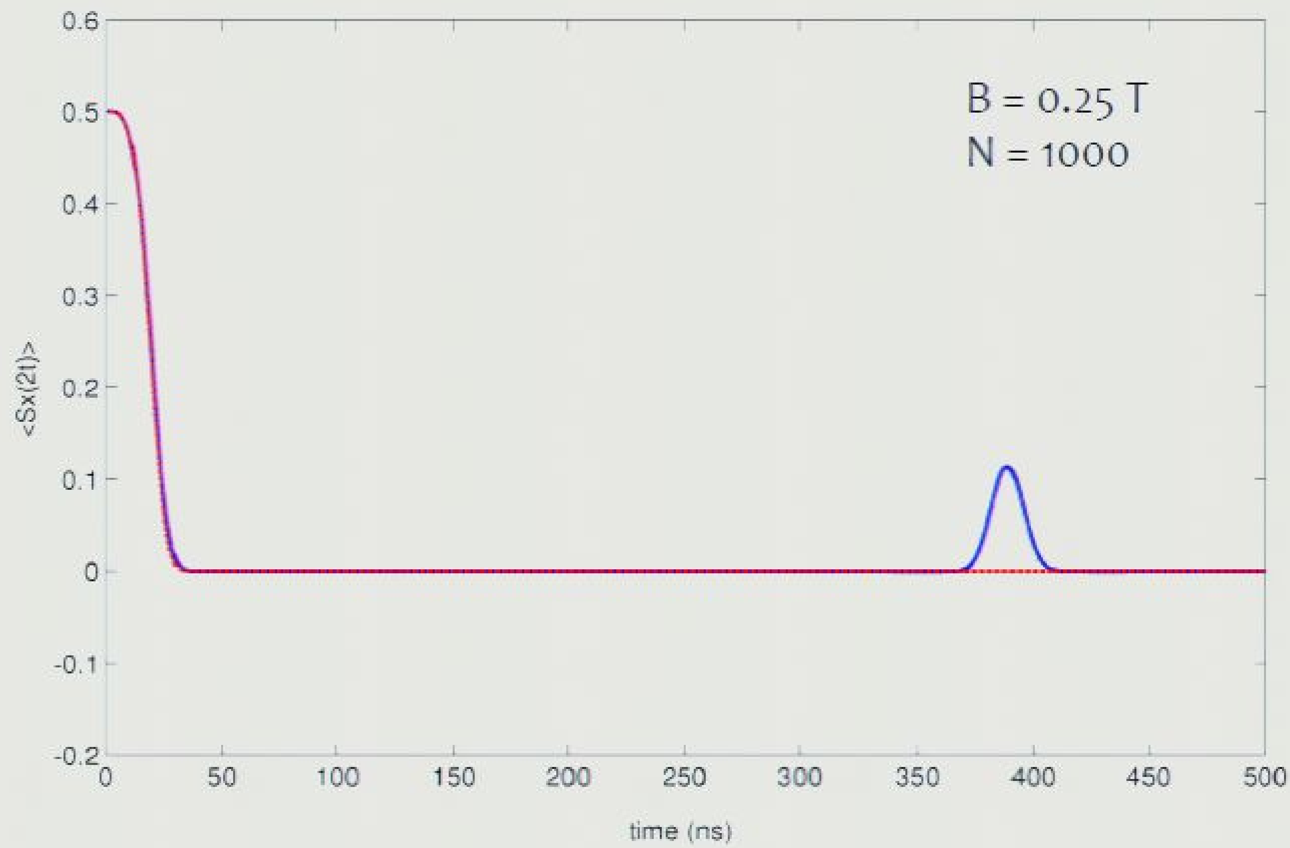
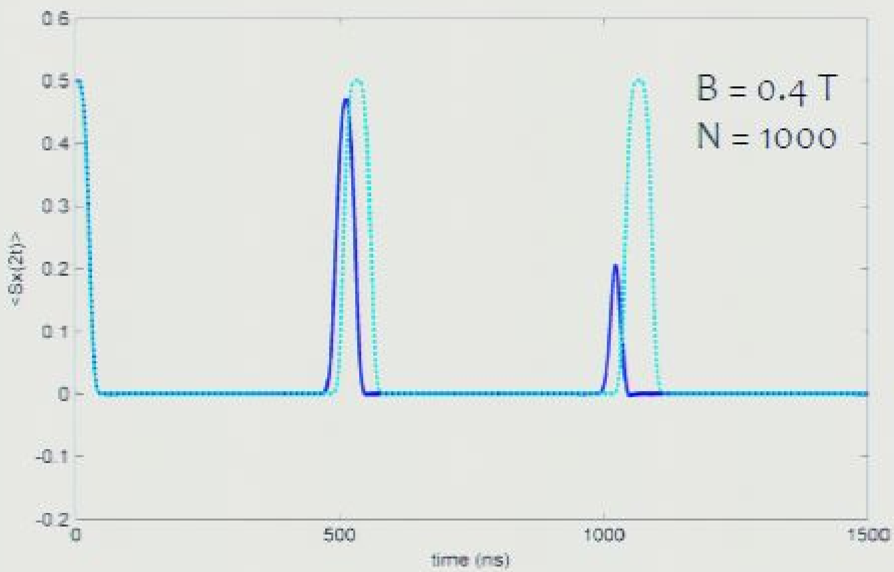
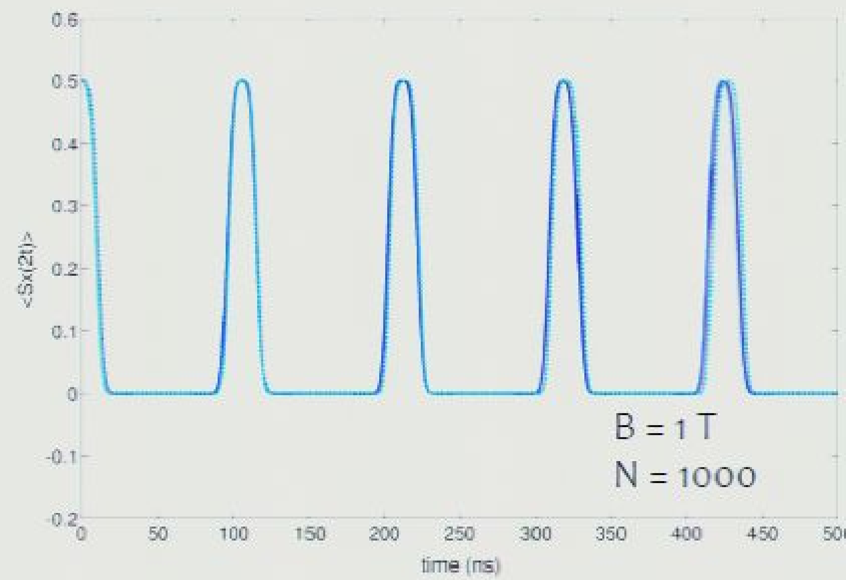
Results

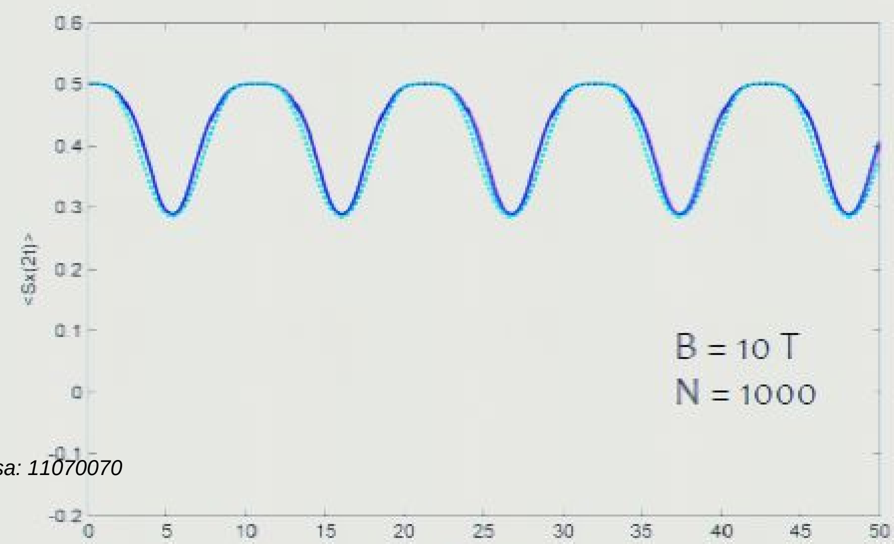
Something strange happens as we keep increasing B…



Results





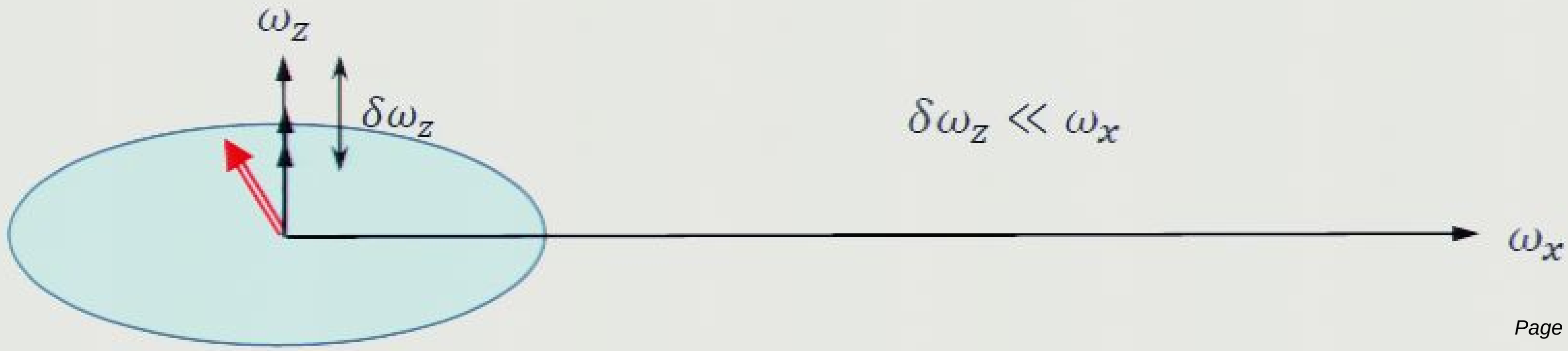


* Large B approximation in pale blue dotted line
* Approximation valid for $B > \frac{A}{\gamma N}$
* Amplitude of oscillations $\sim \frac{A}{B\sqrt{N}}$

$$A = \sum_{k=1}^{N} A_k$$

Results explained

- For $B \ll \frac{A}{\gamma N}$, raising B increases the amplitude of dynamic fluctuations $\Rightarrow$ shorter coherence time
- For $B > \frac{A}{\gamma N}$, nuclear spins precess very fast, so longitudinal fluctuations are "averaged out" (motional averaging)
- Coherence times can be extended through motional averaging



Conclusions

* Observe echo envelope modulation and motional averaging
* Include hole Zeeman term in Hamiltonian: more realistic situation but same qualitative physics
* Hole spins potentially better qubits than electron spins