Electronic and nuclear spins in driven quantum dots:

Paradigm for non-equilibrium states with induced coherence

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Collaborators

(present)

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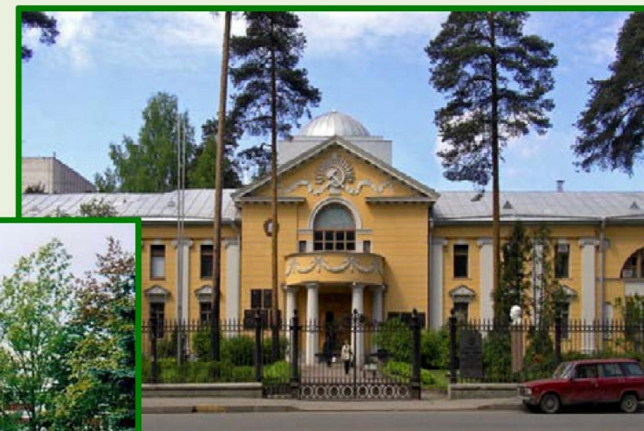
- Philipp Scherer
- Mohsen Yarmohammadi

International Collaborative Research Center TRR 160

Coherent manipulation of interacting spin excitations in tailored semiconductors

TU Dortmund

St. Petersburg State Universi.

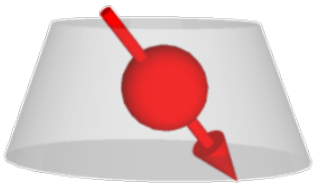


Ioffe Institute

Quantum Dots

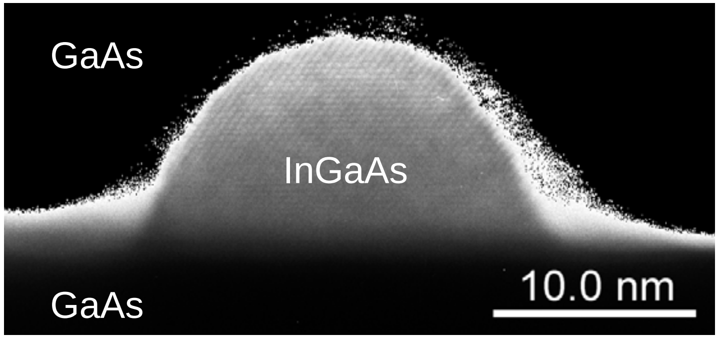
Spin in a quantum dot

- Two-level system: Quantum bit
- Long coherence time (μs)

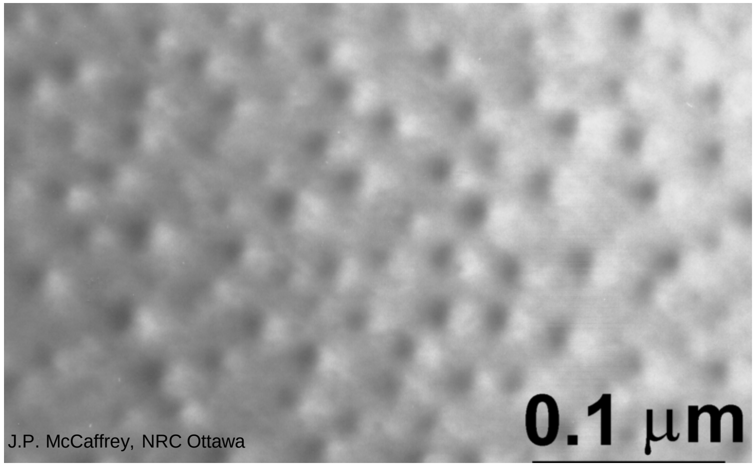


$$\alpha|\uparrow\rangle+\beta|\downarrow\rangle$$

Single quantum dot



Inhomogeneous ensemble

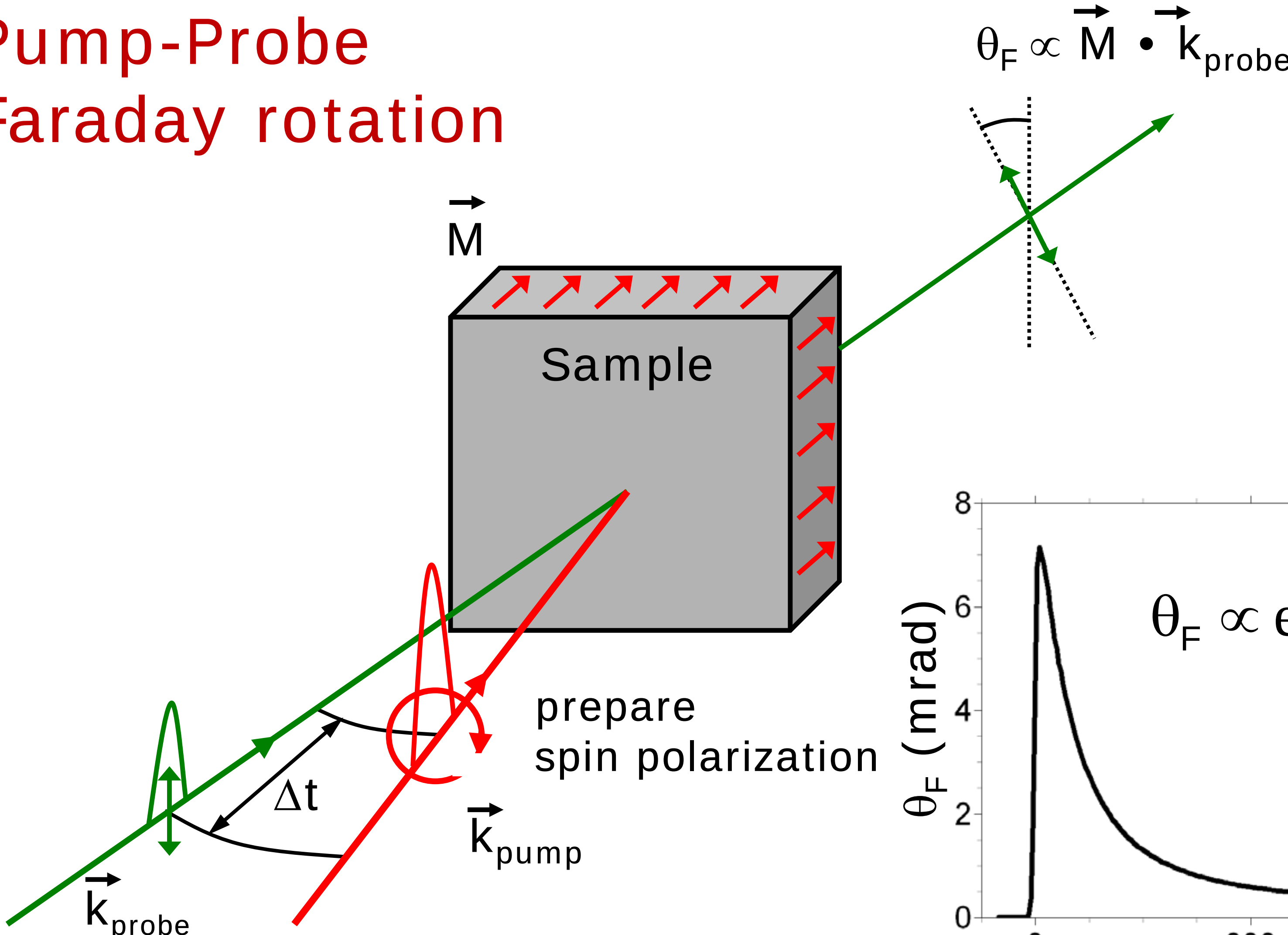


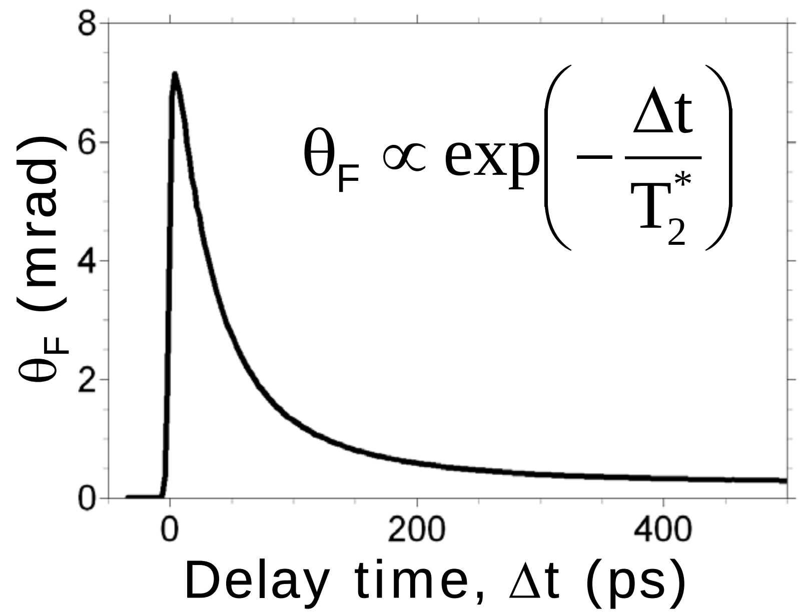
Decoherence due to nuclear spins

(Greilich et al., Science`06)

Experimental Motivation: Laser Pulses

Pump-Probe
Faraday rotation





(Greilich et al., Science`06,..., PRB'13)

Experimental Motivation: Laser Pulses

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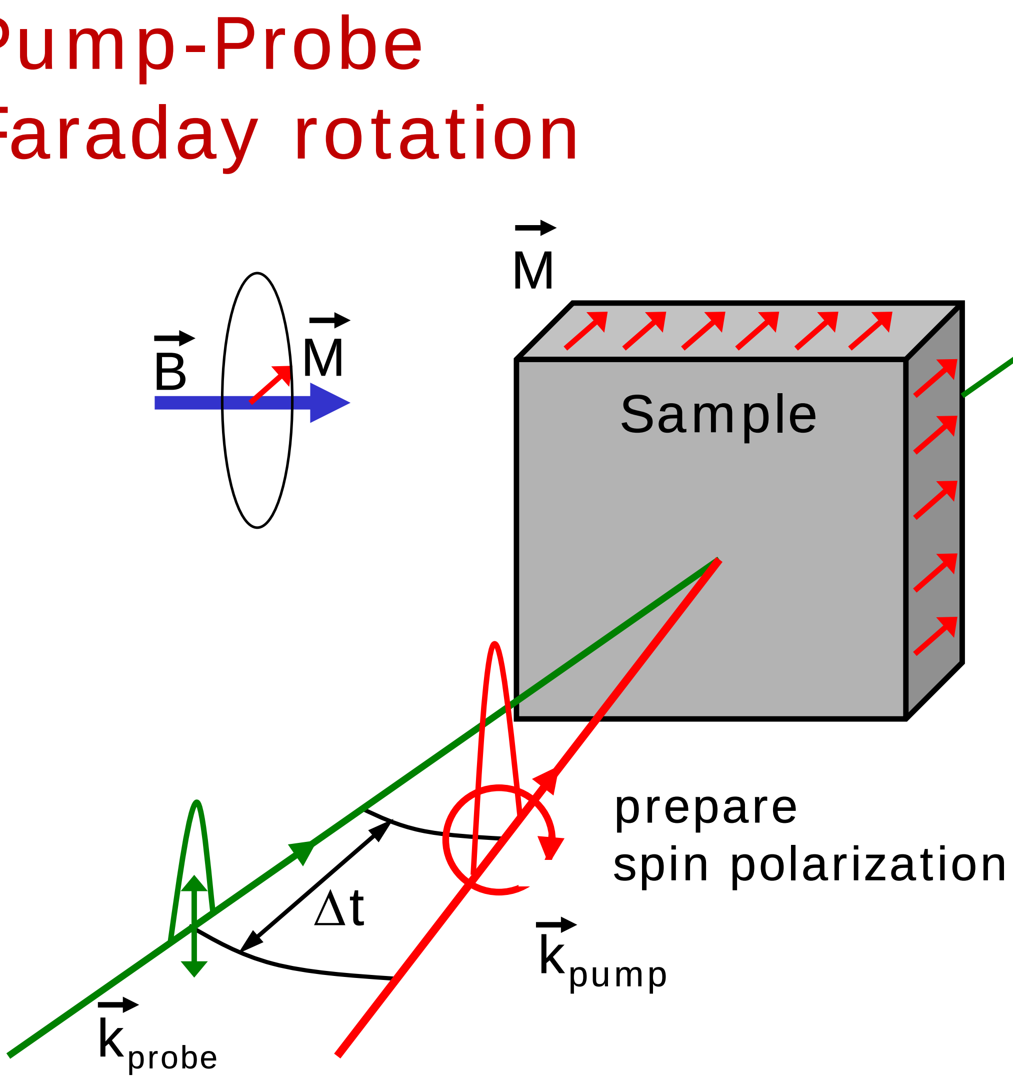
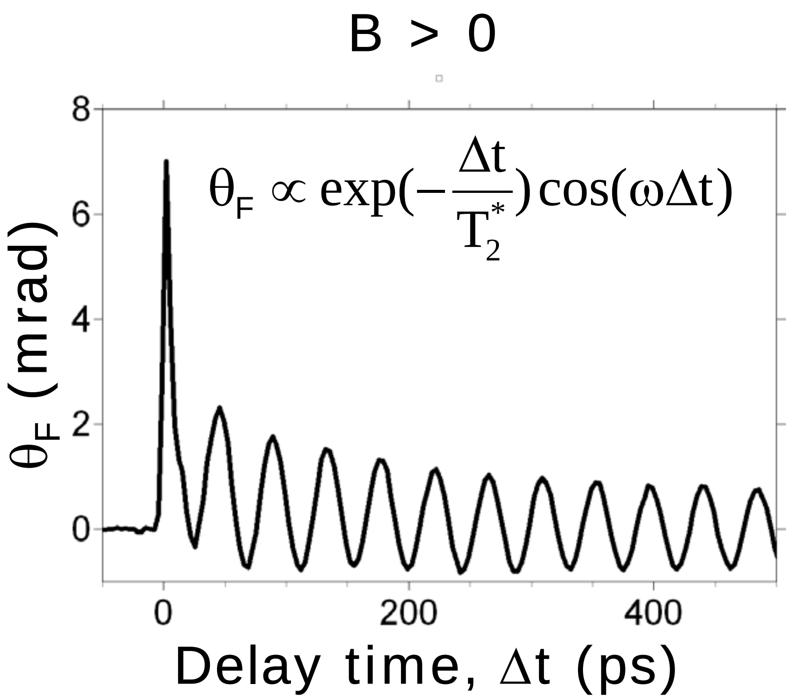


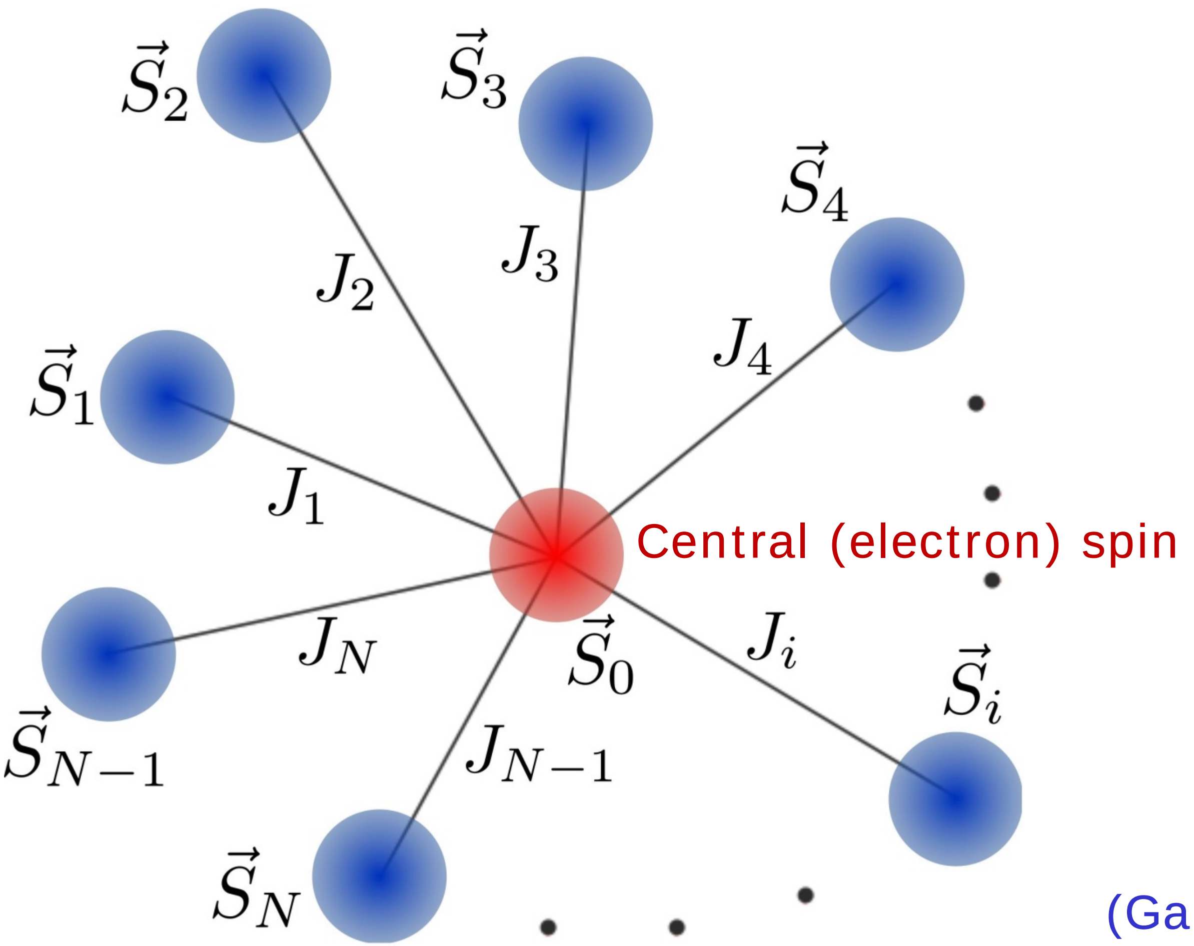


(Greilich et al., Science`06,..., PRB'13)

Model

Central spin model

Bath (nuclear) spins



$$H = \vec{S}_0 \sum_{i=1}^{N} J_i \vec{S}_i$$
$$= \vec{S}_0 \cdot \vec{A},$$

Overhauser field

$$\vec{A} = \sum_{i=1}^{N} J_i \vec{S}_i$$

Couplings resulting from contact hyperfine interaction

$$J_i \propto |\psi(r_i)|^2$$

(Gaudin, Jphys (France) 1976)

Challenges for Simulations

- pulse: trion excitation: 1.5 ps
  trion decay: 0.4 ns
- inverse rms of Overhauser field: 1ns
- repetition time of pulses: 13.2 ns
- pulsing duration: 1-100 s
- number N_{eff} of effectively coupled bath spins: 10^4-10^6

How to bridge these **vast** orders of magnitude ?

- method development: DMRG, Chebyshev polyn., (semi-)classical simulations, Bethe ansatz Mazur‘s inequality, equations of motion, ...

Simulation I

- Classical eqs. of motion: many differential equations

$$\partial_t \vec{S}_0 = (\vec{A}(t) + \vec{h}) \times \vec{S}_0$$

$$\partial_t \vec{S}_i = (J_i \vec{S}_0(t) + z\vec{h}) \times \vec{S}_i$$

- Average over Gaussian distributed initial vectors

- Pulse means:

$$\vec{S}_0 \to \begin{pmatrix} X \\ Y \\ 1/2 \end{pmatrix}$$

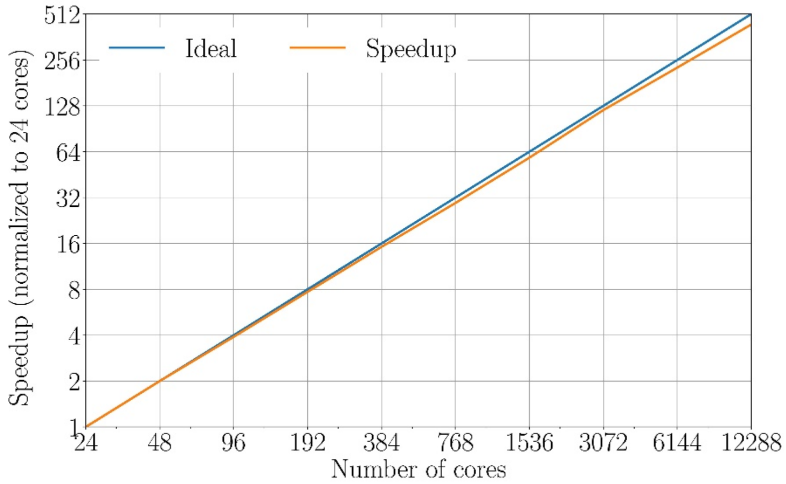
X and *Y* are chosen randomly from Gaussian distribution

mimicking Heisenberg's uncertainty.

(Schering,...,GSU, PRB'18)

Simulation II

- Parallelized code used:



- Single thread performance:

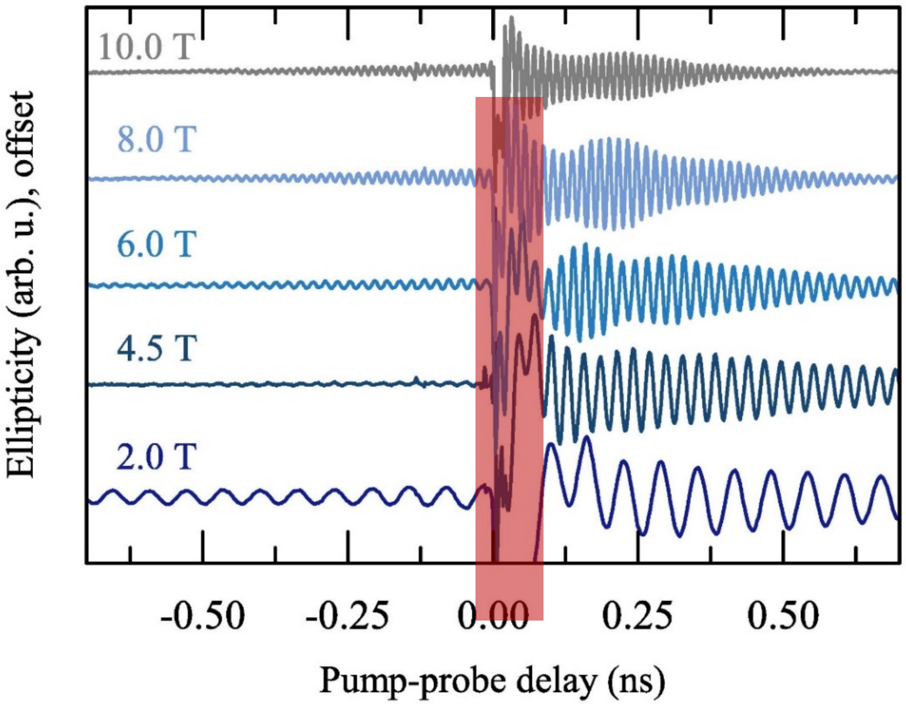
Criterion	Counted events	Derived metric
Run time	-	1,202 s
Cycles	2,990,606,954,255	2.49 GHz
Instructions	6,029,304,486,941	2.02 IPC
Branches	678,571,431,899	564.5 M/s
Brances missed	3,207,706,281	0.47% of all branches
L1-dcache-loads	1,624,791,427,721	1,352 M/s
L1-dcache-misses	30,835,374,765	1.9% of all L1 hits
LLC-loads	31,895,372	0.27 M/s
LLC-misses	1,644,291	5.2% of LLC hits

(Schering, Scherer, GSU, preprint‘19)

Experiment vs. Theory

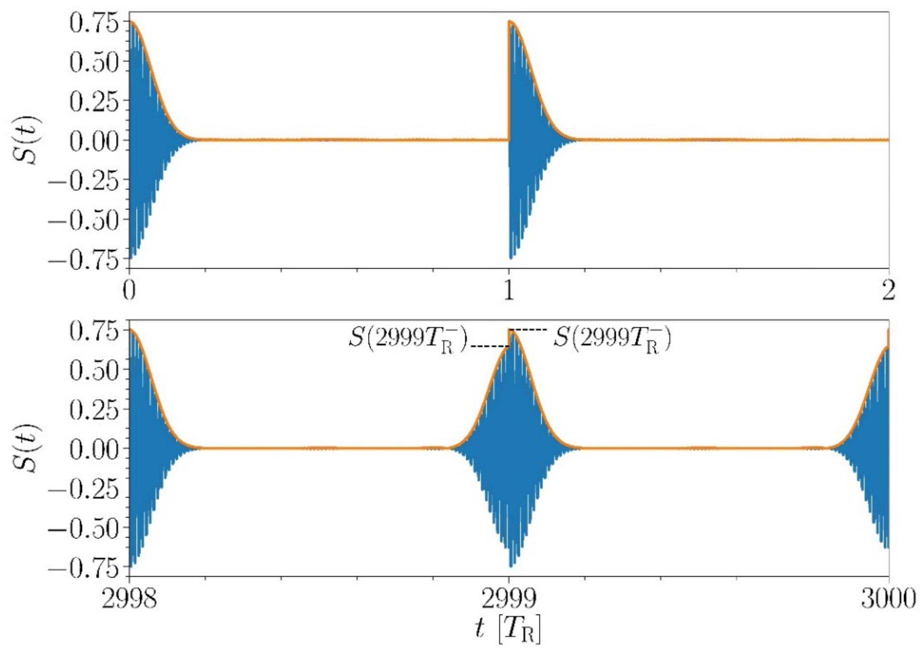
Experimental Measurement

After about 10^{10} pulses



(Kleinjohann,….,GSU,…., PRB‘18)

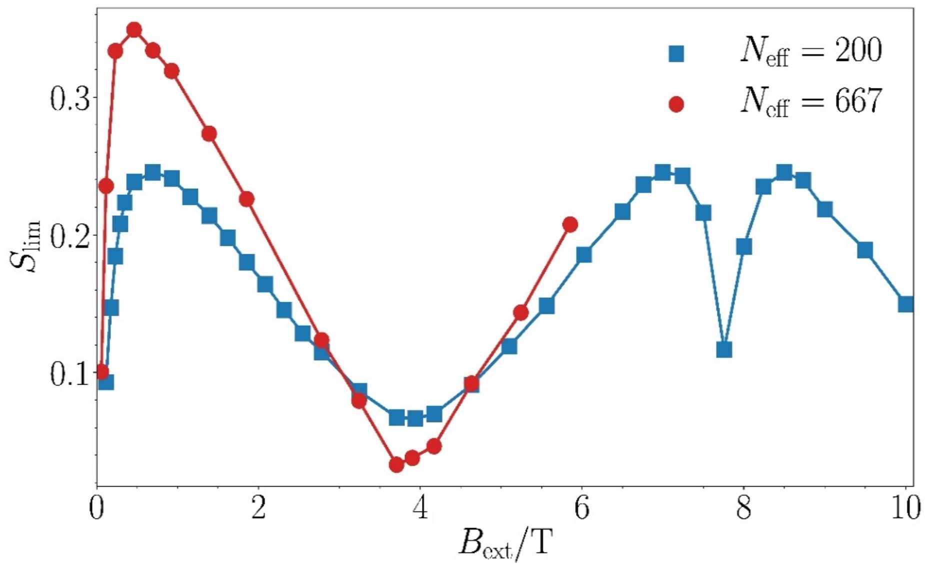
Theoretical Simulation



Schering,…,GSU, PRB‘18

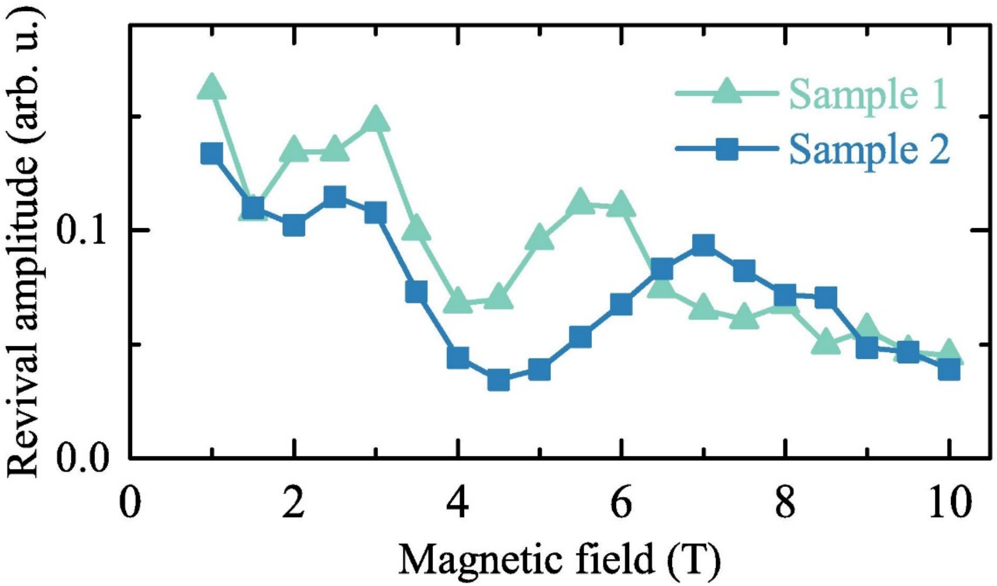
See also Petrov/Yakovlev, JETP’12
Jäschke et al. PRB‘17

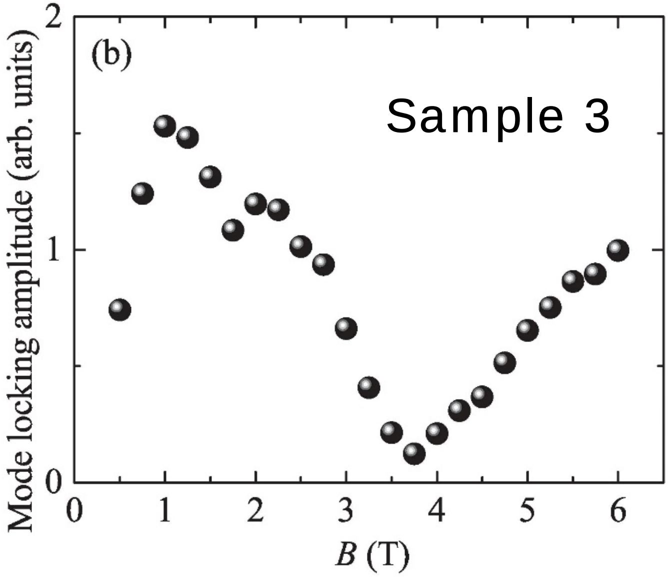
Field dependence of Revival amplitude



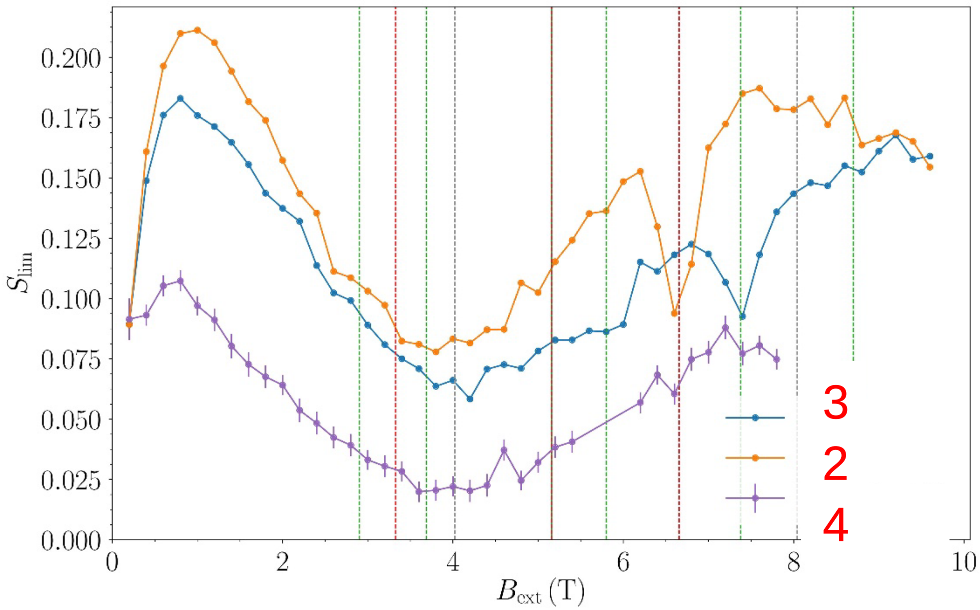
(Kleinjohann,…,GSU,…, PRB‘18; Jäschke et al., PRB’17)

To be compared with



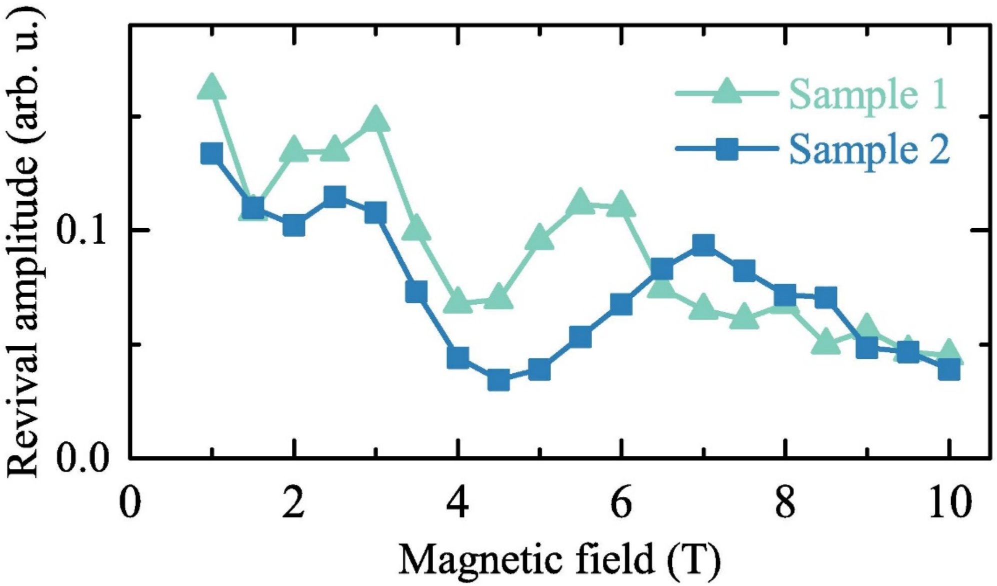


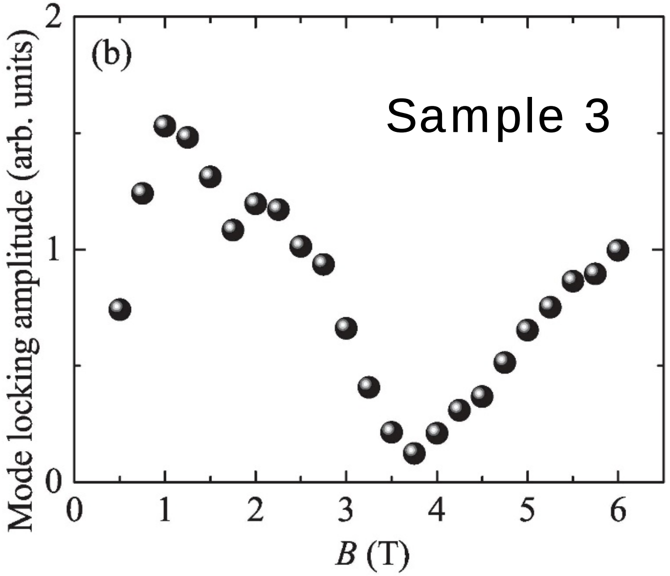
Field dependence of Revival amplitude II



2, 3, and 4 different species of bath spins considered

To be compared with





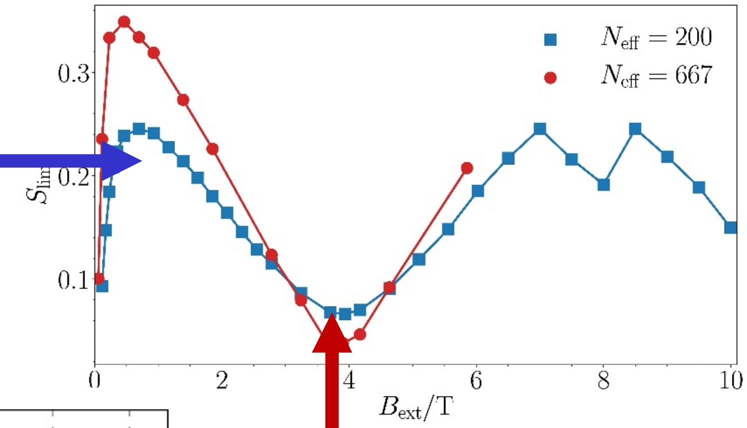
Summary

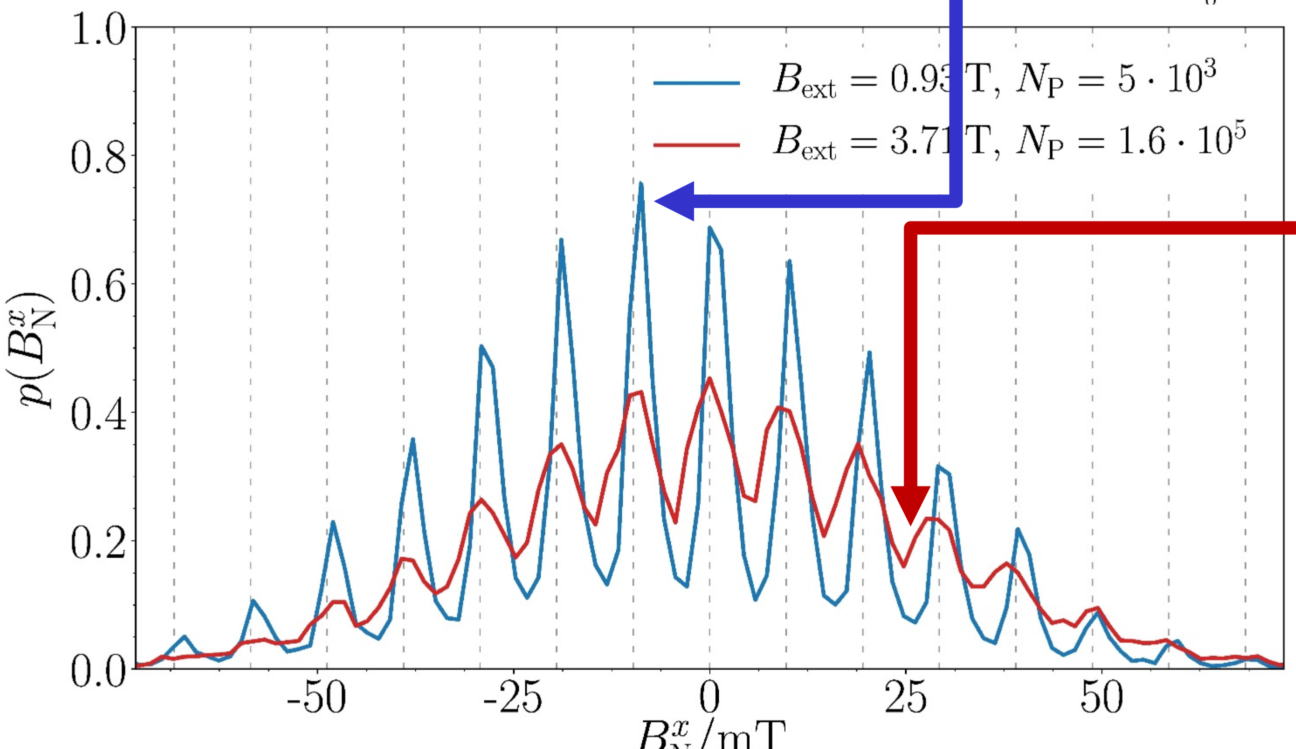
- Main features of experimental mode-locking are explained qualitatively
- Outlook: Include further experimental aspects:
  - Ensemble of quantum dots
  - several nuclear spins with different g-factors finite pulse length
- True quantumness & quantum coherence?

Field dependence of nuclear frequency focusing III

Overhauser field distribution

less nuclear focusing
at minimum





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PRB‘18)