Optical Pumping of Electron Spins in Quantum Dot Ensembles

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Institut für Computing

TRR 160

Dortmund/St. Petersburg

technische universität
dortmund

Transregio 160 Dortmund/St Petersburg: Coherent manipulation of interacting spin excitations in tailored semiconductors

TU Dortmund

Ioffe Institute, St. Petersburg

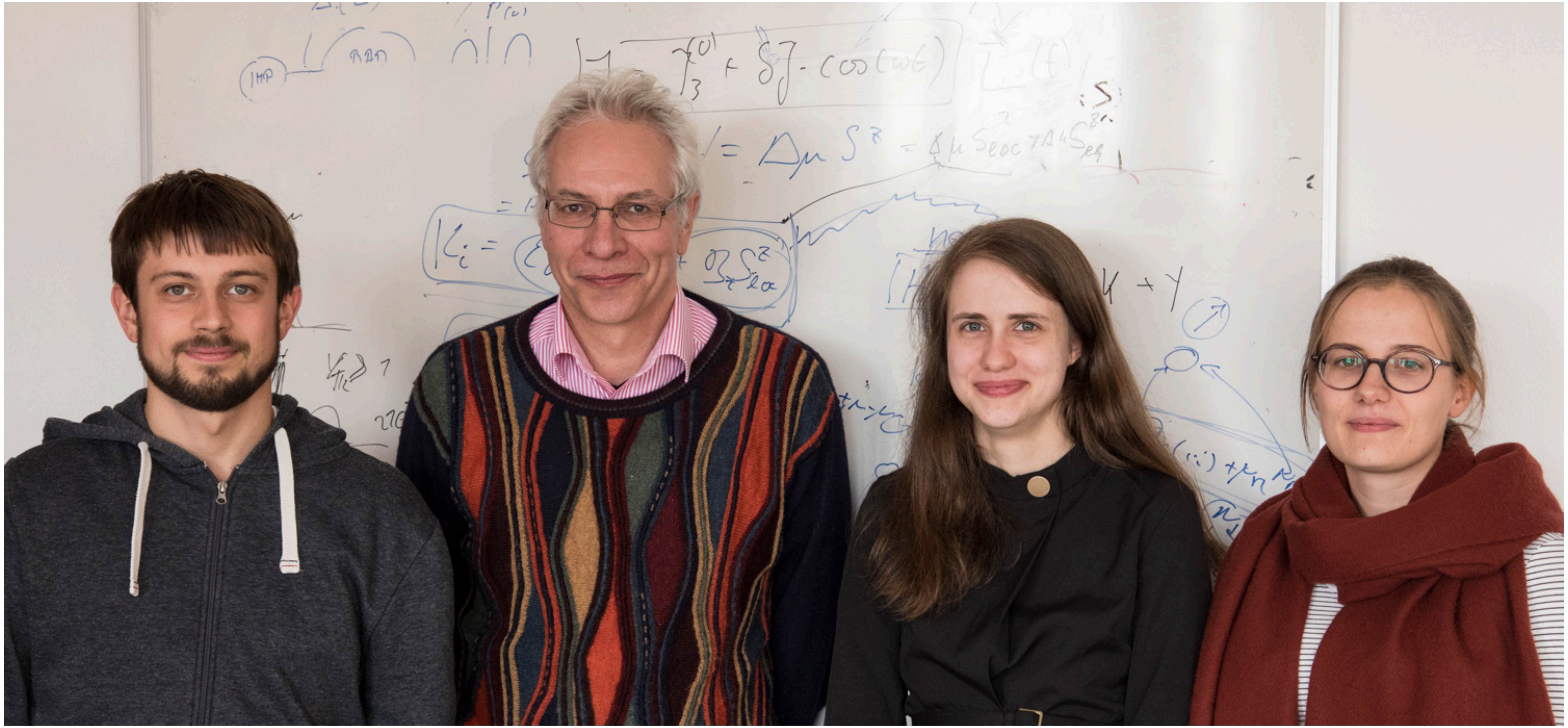
St. Petersburg State University

TRR 160

technische universität
dortmund

Frithjof B. Anders

Collaborators



Andreas Fischer

Dr. Natalie Jäschke

Iris Kleinjohann

Motivation

MENU

nature

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

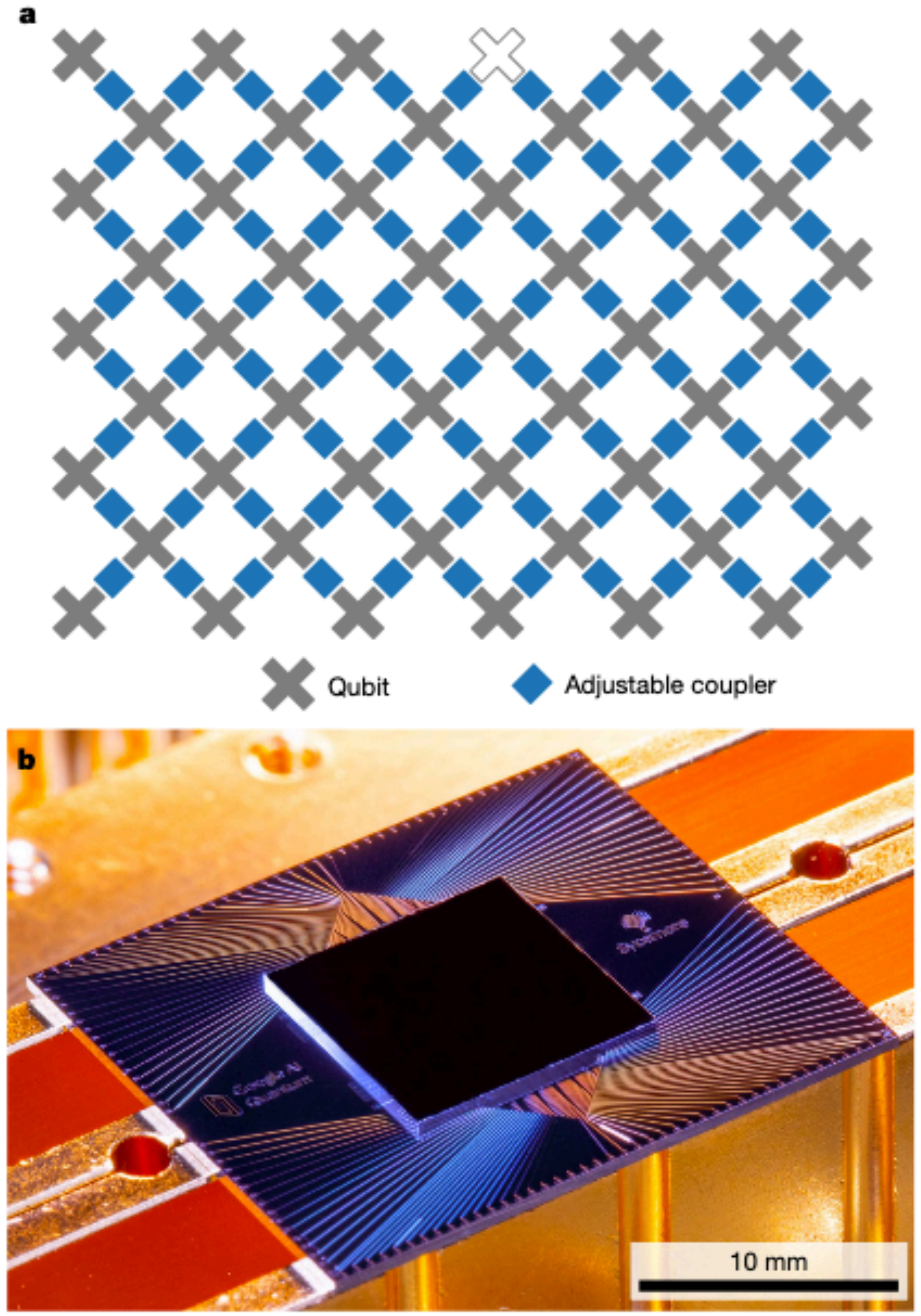


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

We verify that the quantum processor is working properly using a method called cross-entropy benchmarking [11,12,14], which compares how often each bitstring is observed experimentally with its corresponding ideal probability computed via simulation on a classical computer.

Motivation

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Quantencomputer

Ein Quantum Überlegenheit?

Google verkündet die "Quantum Supremacy": Sein Sycamore-Chip soll dramatisch viel schneller rechnen als jeder Supercomputer bislang. IBM-Forscher zweifeln am Durchbruch.

Von **Eike Kühl**

23. Oktober 2019, 16:06 Uhr / Aktualisiert am 23. Oktober 2019, 16:10 Uhr / 102 Kommentare

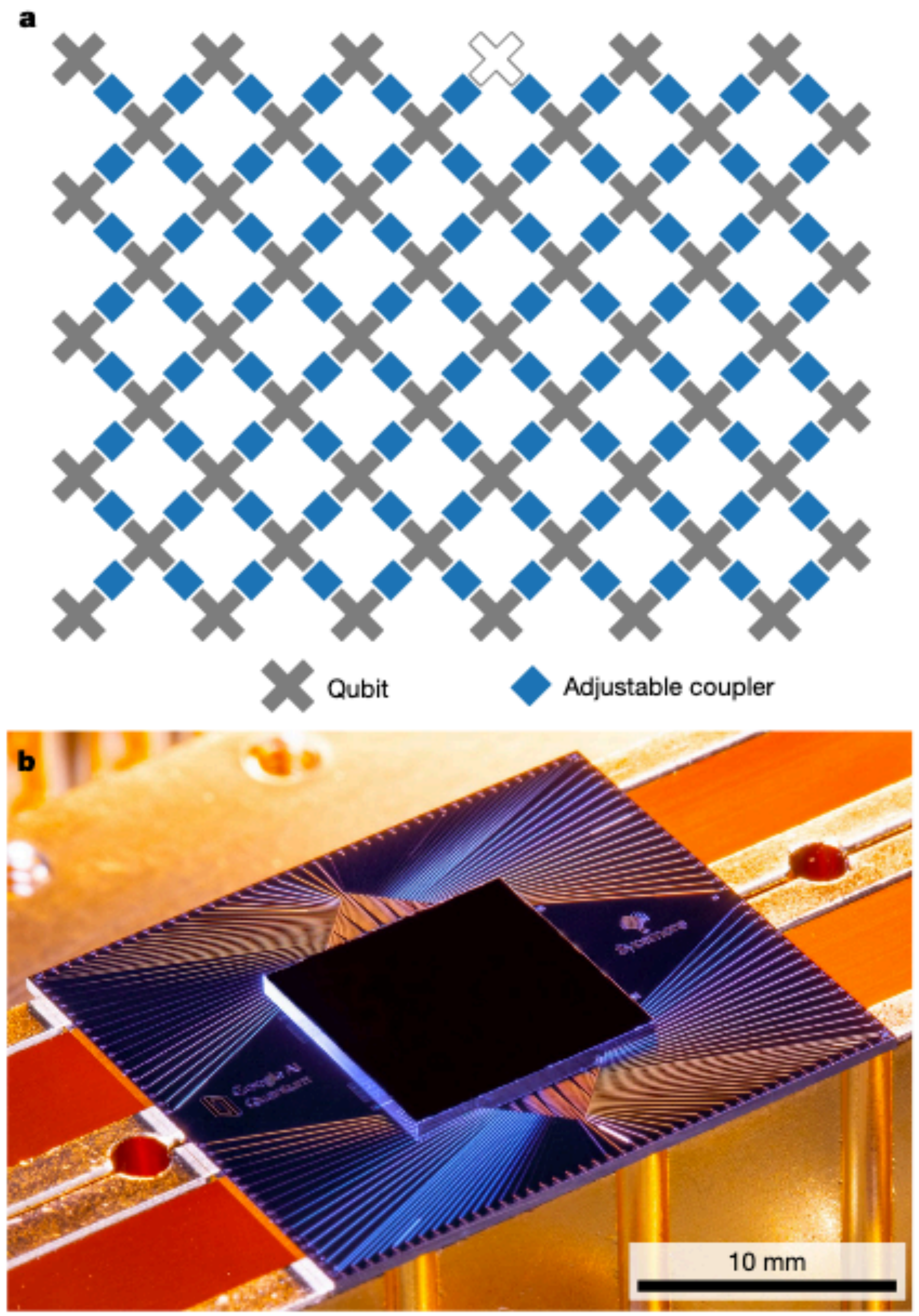
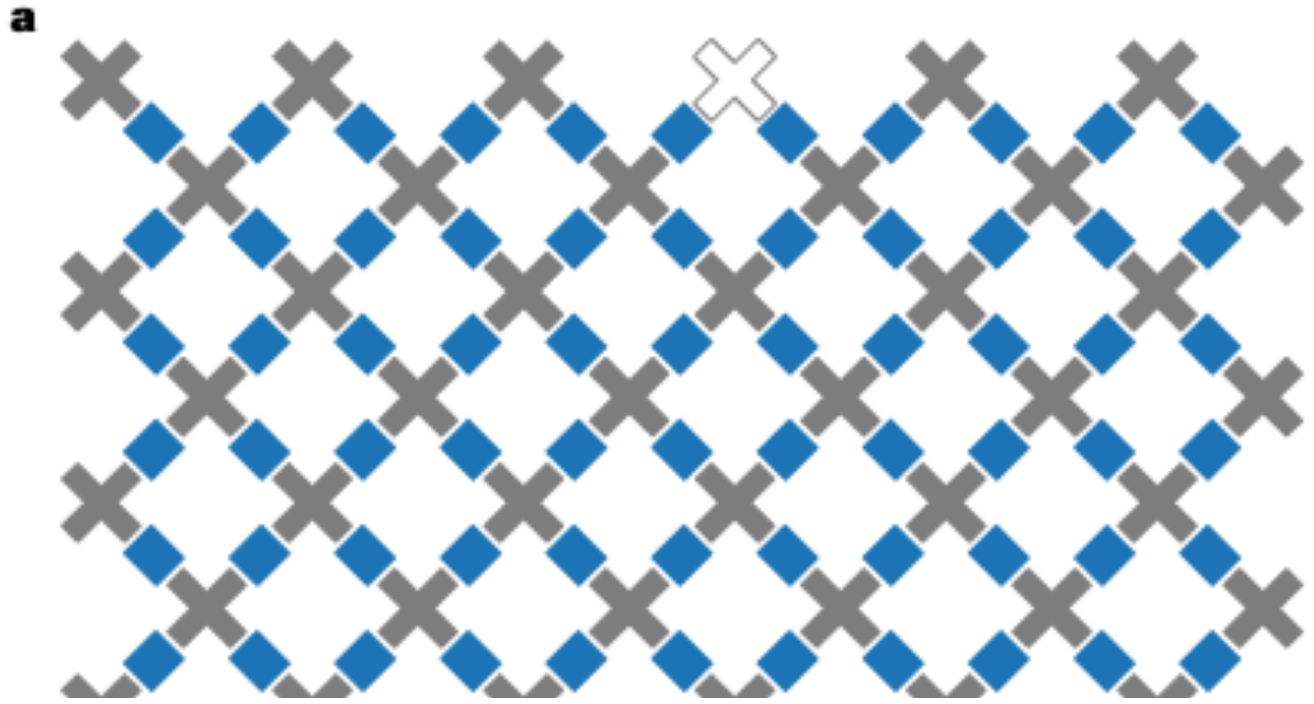


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Motivation

- works only at very low temperature (superconducting qubits)
- only nearest neighbor coupling of qubit
- IBM Q: results depend on the daily calibration
- quantum mechanical simulations on classical computers are still needed



nature COMMUNICATIONS

Feb 11.2020

ARTICLE

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Coherent spin control of s-, p-, d- and f-electrons in a silicon quantum dot

R.C.C. Leon[1*], C.H. Yang[1], J.C.C. Hwang[1,6], J. Camirand Lemyre[2], T. Tanttu[1], W. Huang[1], K.W. Chan[1], K.Y. Tan[3], F.E. Hudson[1], K.M. Itoh[4], A. Morello[1], A. Laucht[1], M. Pioro-Ladrière[2,5], A. Saraiva[1*] & A.S. Dzurak[1*]

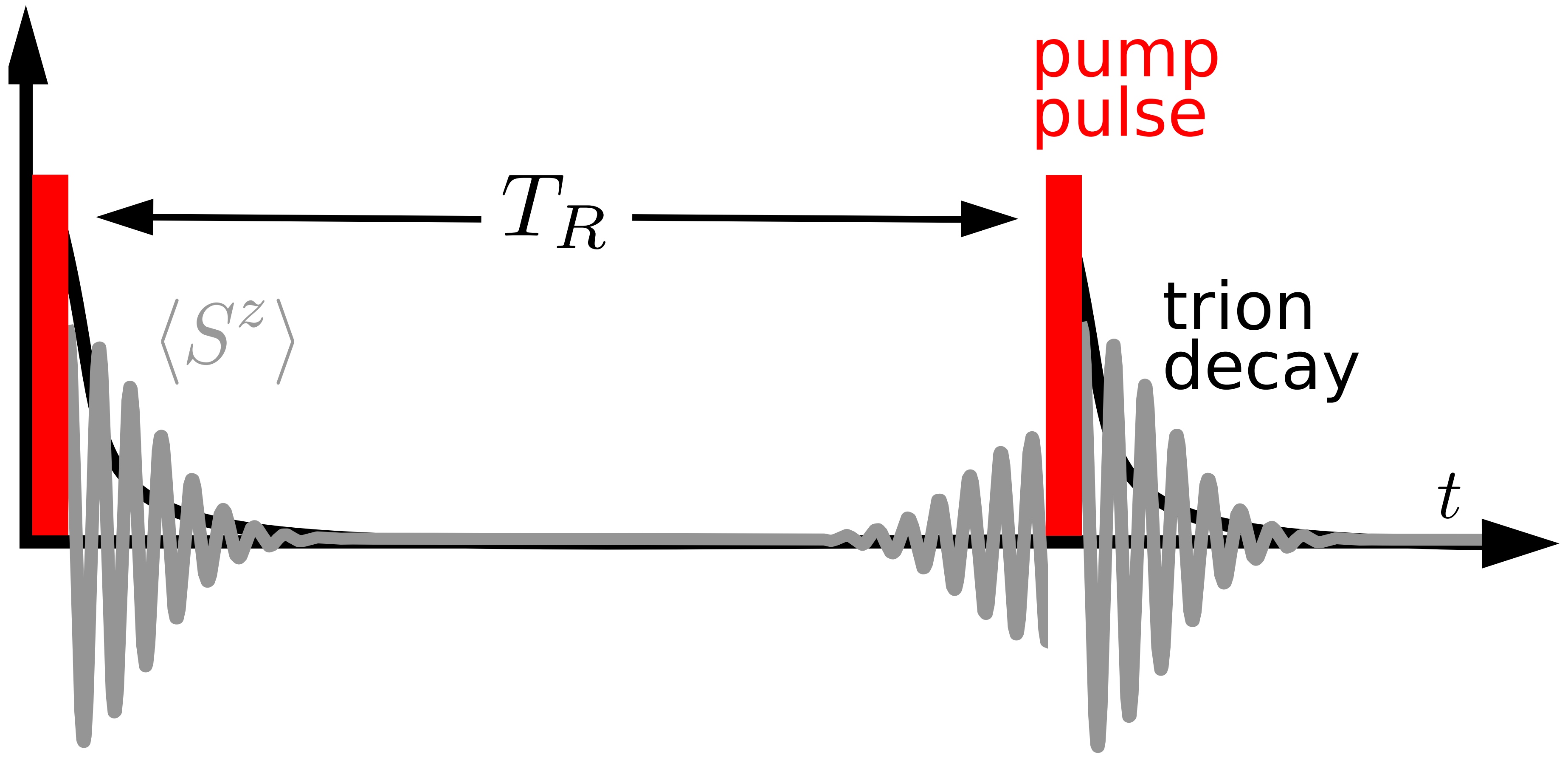
Motivation

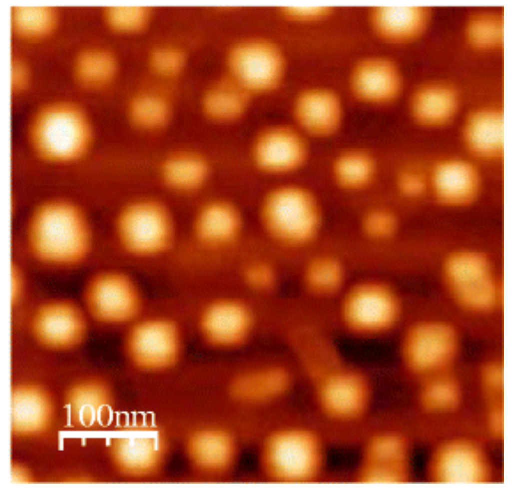
TRR 160: Coherent manipulation of interacting spin excitations in tailored semiconductors

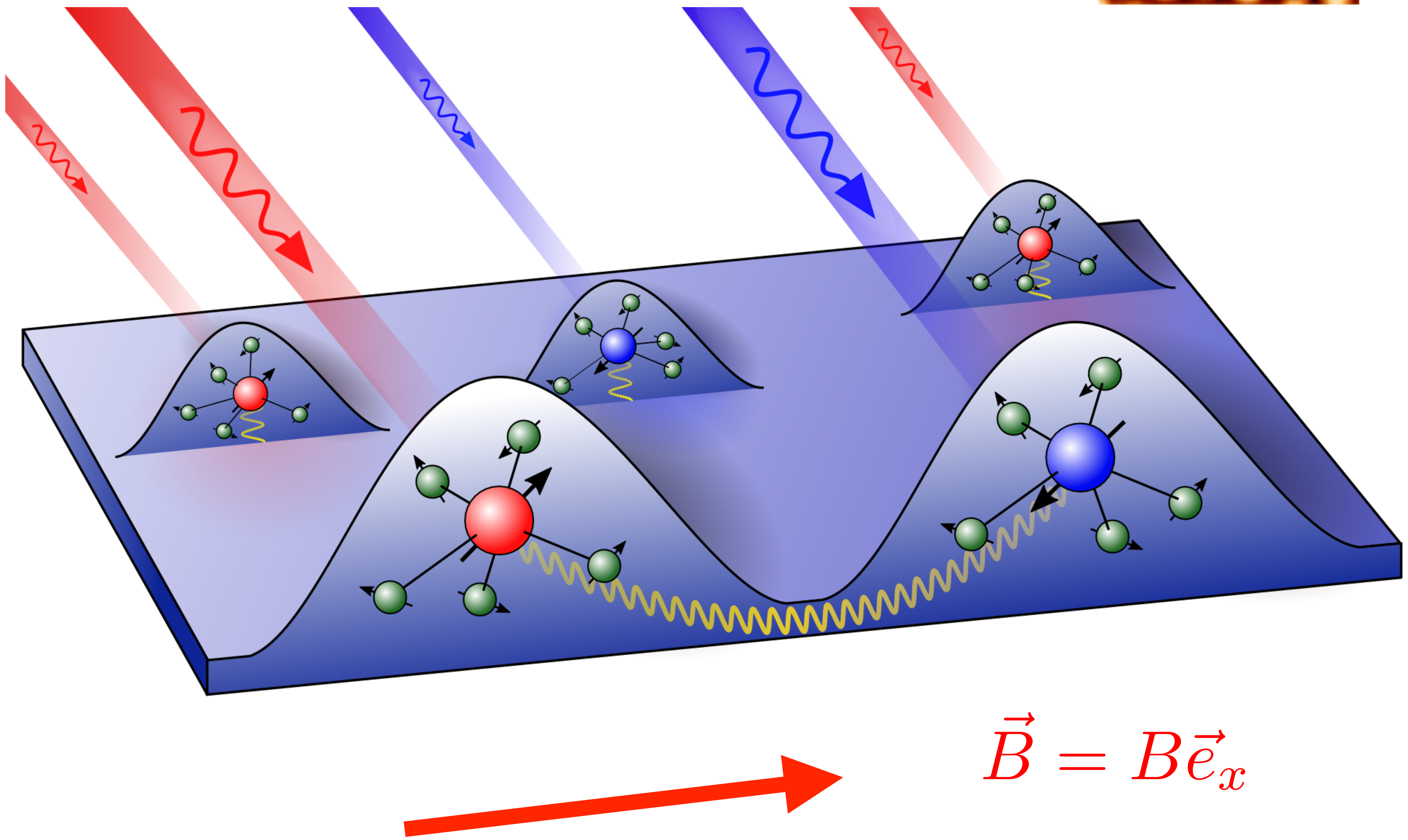
- application of spin excitation for future technology
- exploitation of spin coherence: reducing power consumption of charge driven electronics
- potential embedding in traditional semiconductor structures
- manipulation with light: opto-spintronic integration

Optical pumping of electron spins in Quantum dot ensemble

1. Periodic pumping of quantum dot ensembles





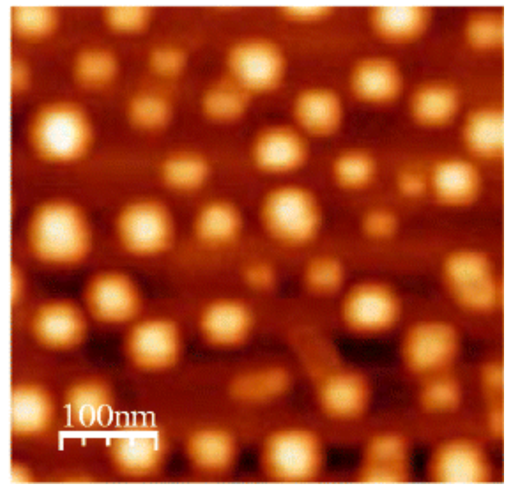


$\vec{B} = B\vec{e}_x$

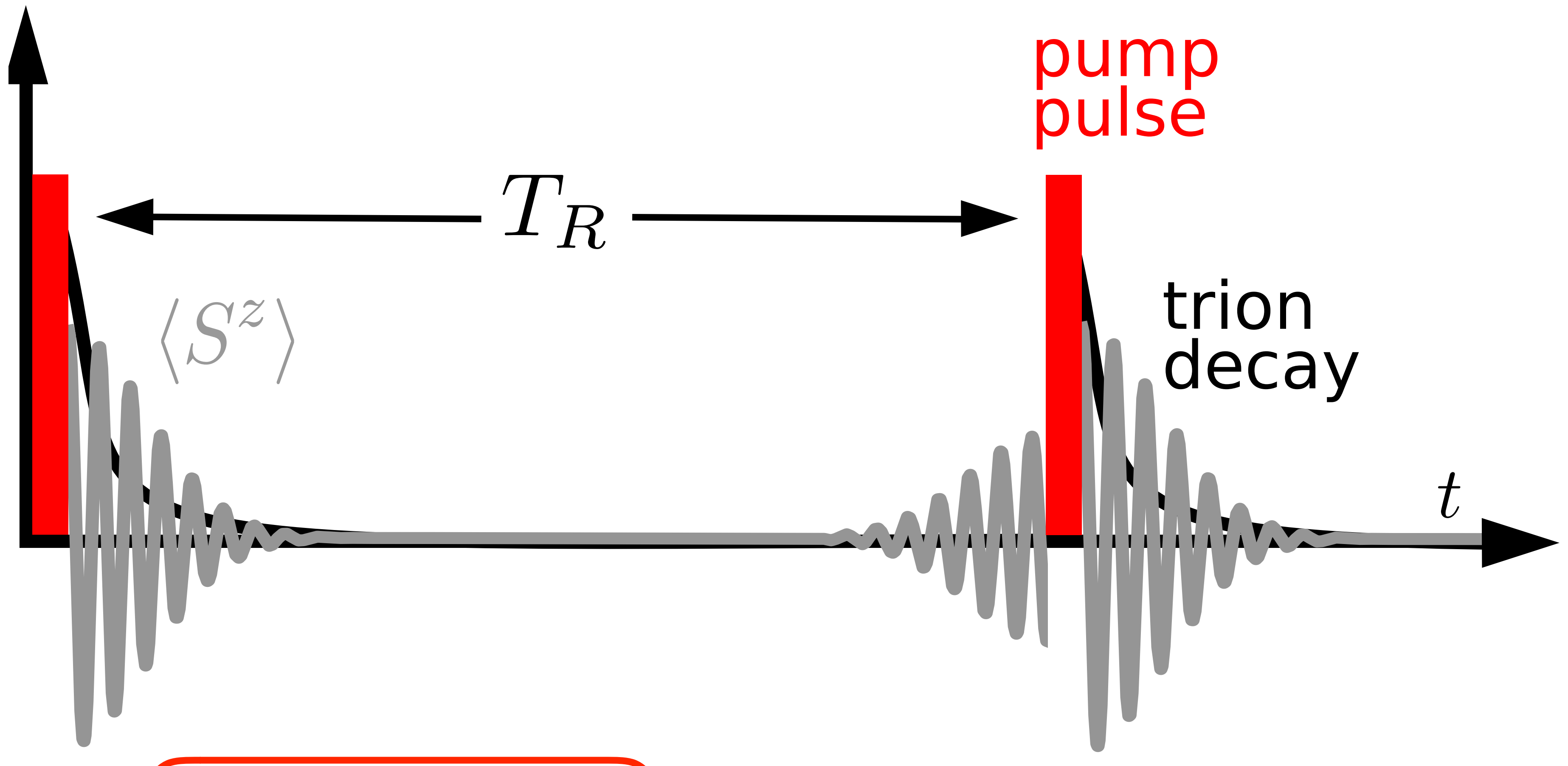
2. Multi-color pumping: addressing different QDs

3. higher-order spin noise: information on the coupling to the environment

Optical pumping of electron spins in Quantum dot ensemble



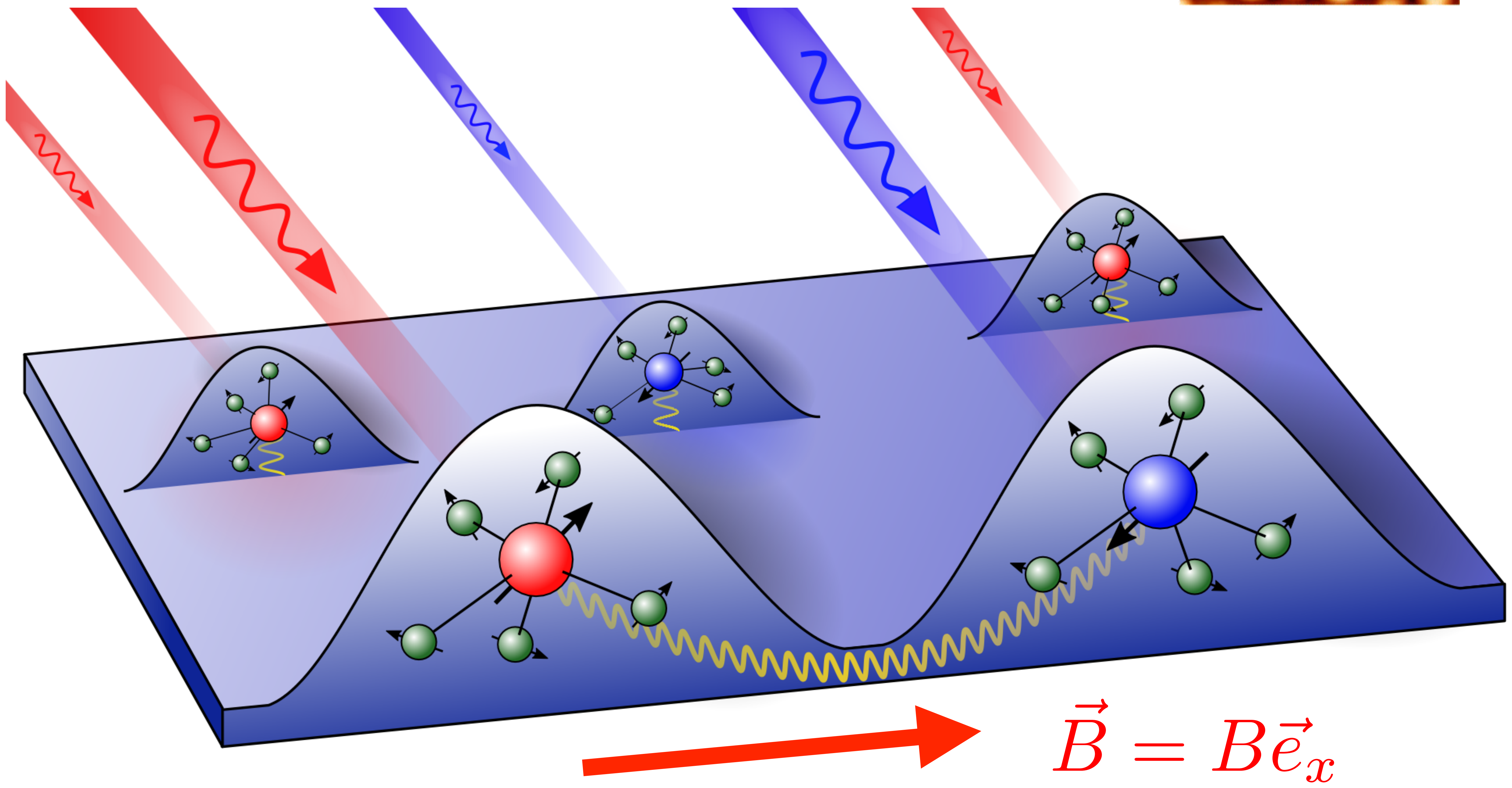
I. Periodic pumping of quantum dot ensembles



$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{S}(t) = \left(\vec{B}_{\mathrm{N}} + \vec{B}_{\mathrm{ext}}\right) \times \vec{S}(t) + \gamma P_{\mathrm{T}_\mu}(0)\vec{\mathrm{e}}_z e^{-2\gamma t}$$

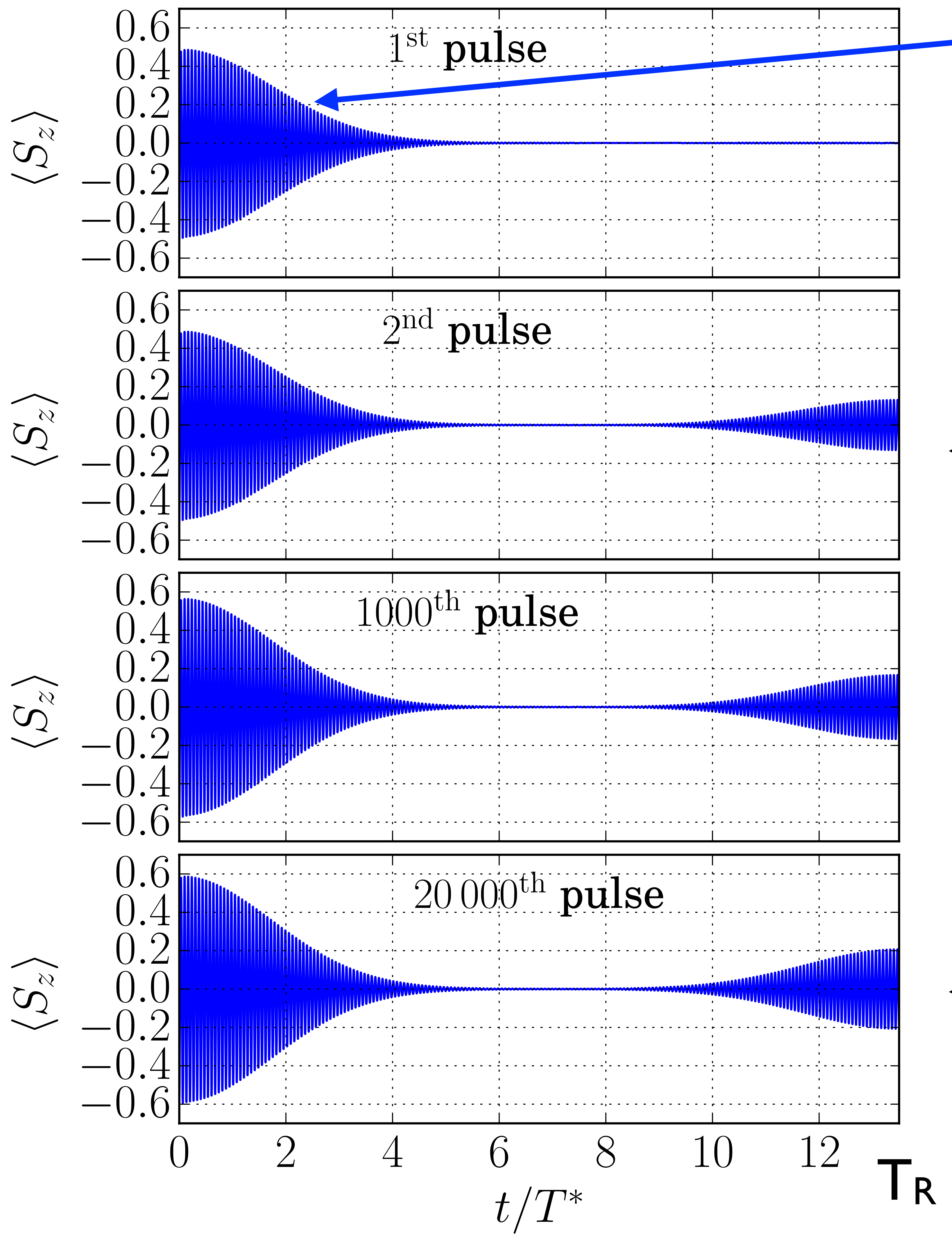
nuclear spins

trion decay: S_z



- Larmor precession around an effective magnetic field: coherence
- coupling to nuclear spins: decoherence
- challenge: combine light-matter interaction and electron-nuclear spin dynamics

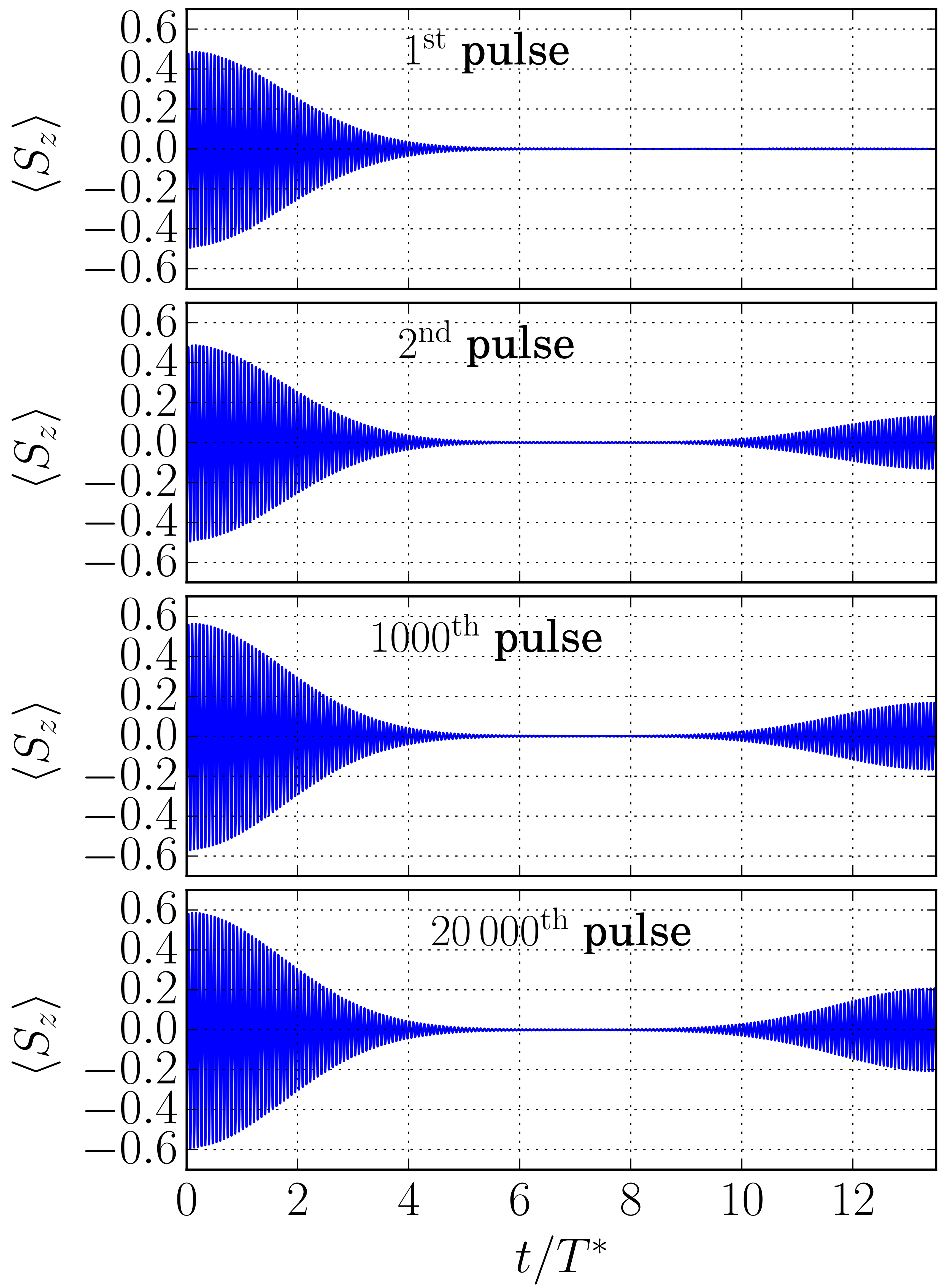
Revival of the spin polarization



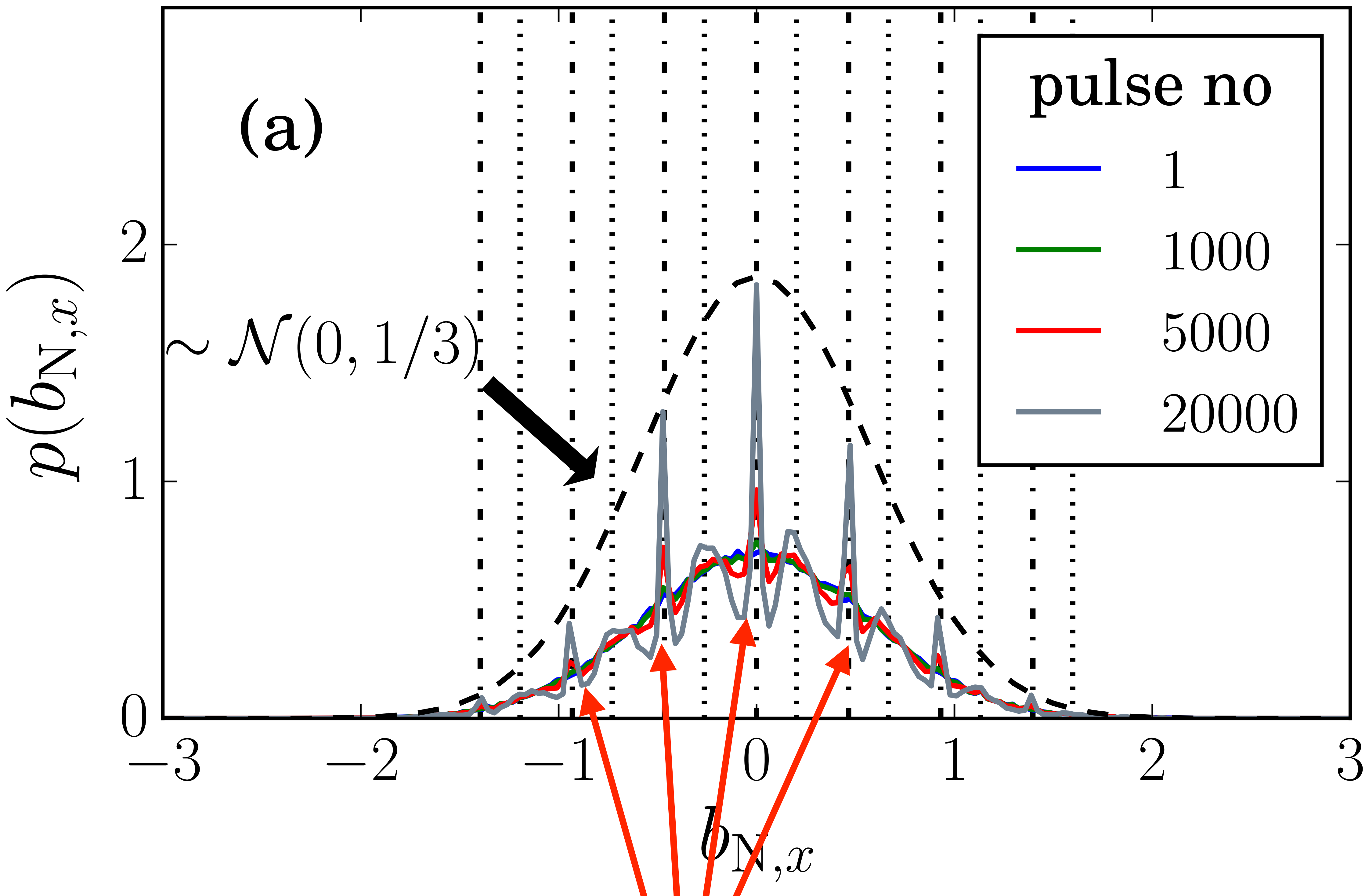
Electron spin synchronization

Nuclear spin bath synchronization

Revival of the spin polarization



Nuclear magnetic field B_N distribution



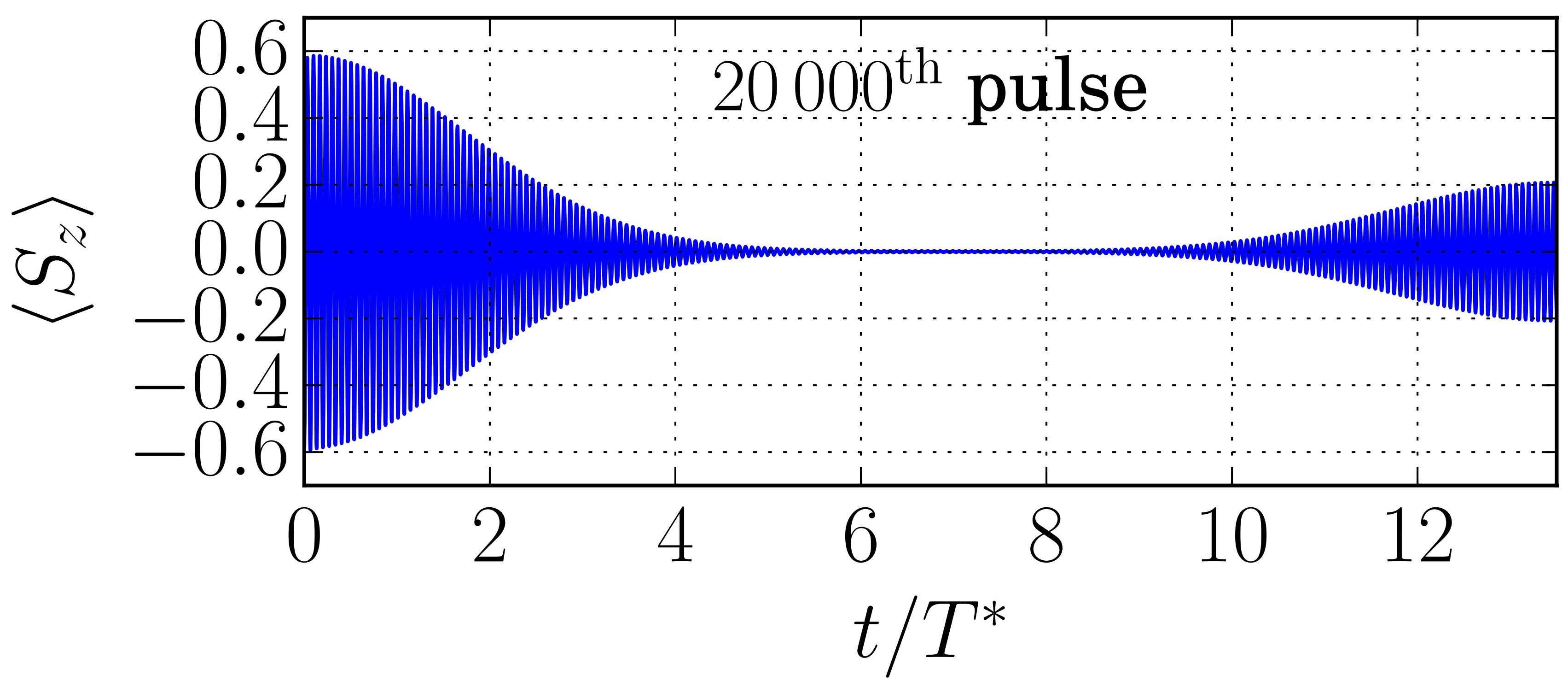
resonance conditions $\omega_L T_R = 2\pi n$

$\omega_L T_R = \arctan(\omega_L/\gamma) + 2\pi n$

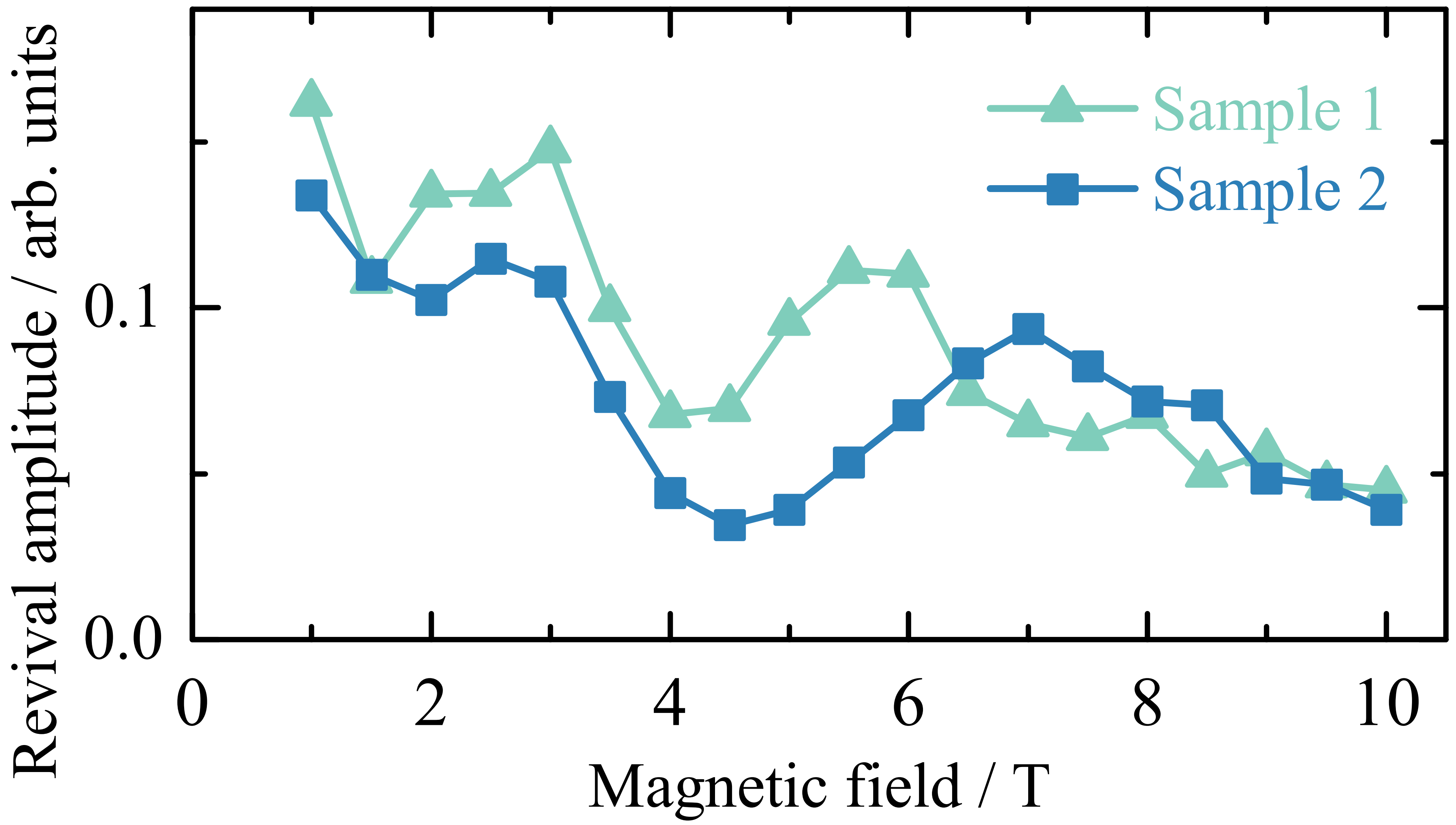
Nuclear spin bath synchronization

Jäschke, PRB 2017

Analysis of the revival amplitude



revival amplitude: magnetic field dependent

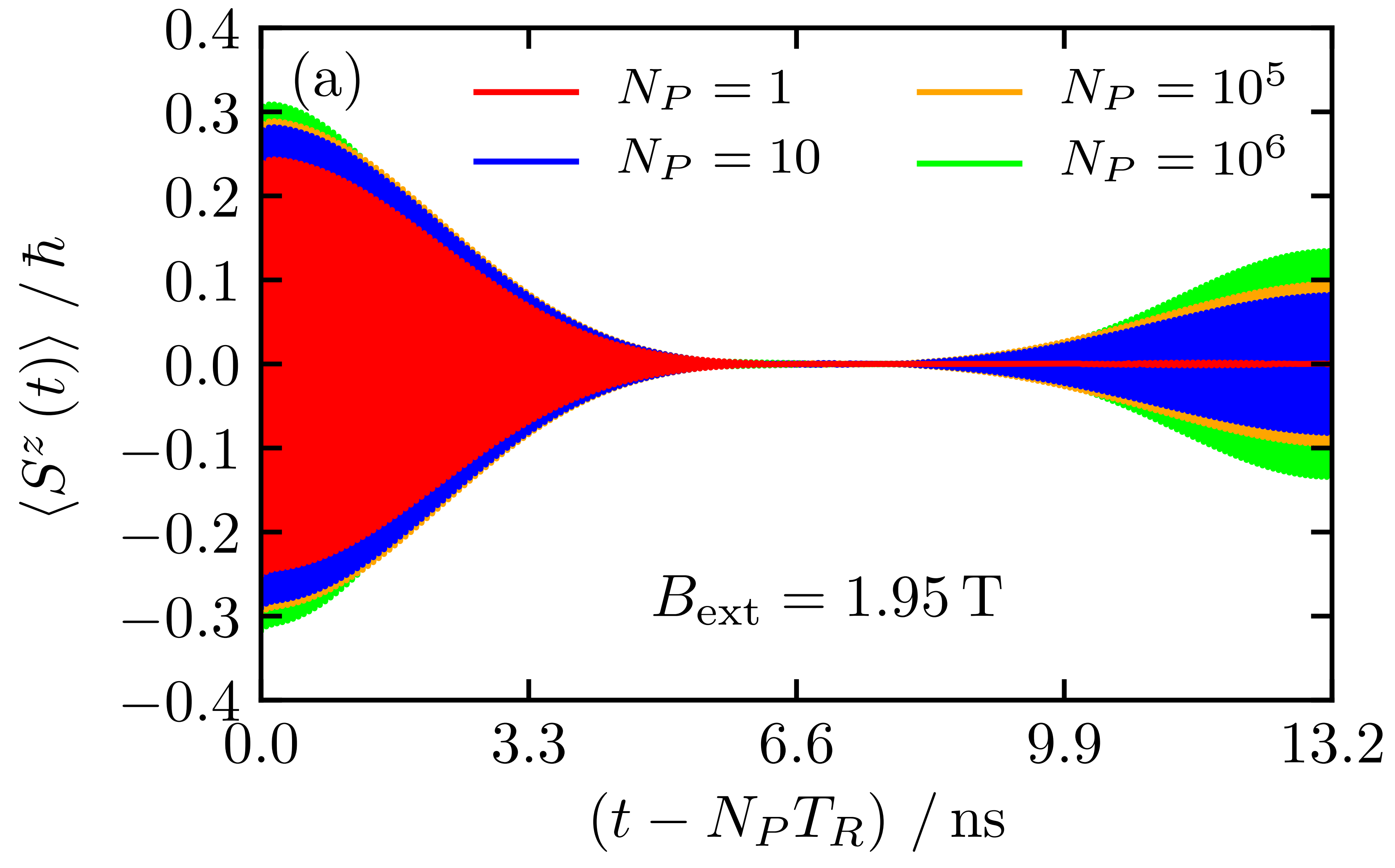


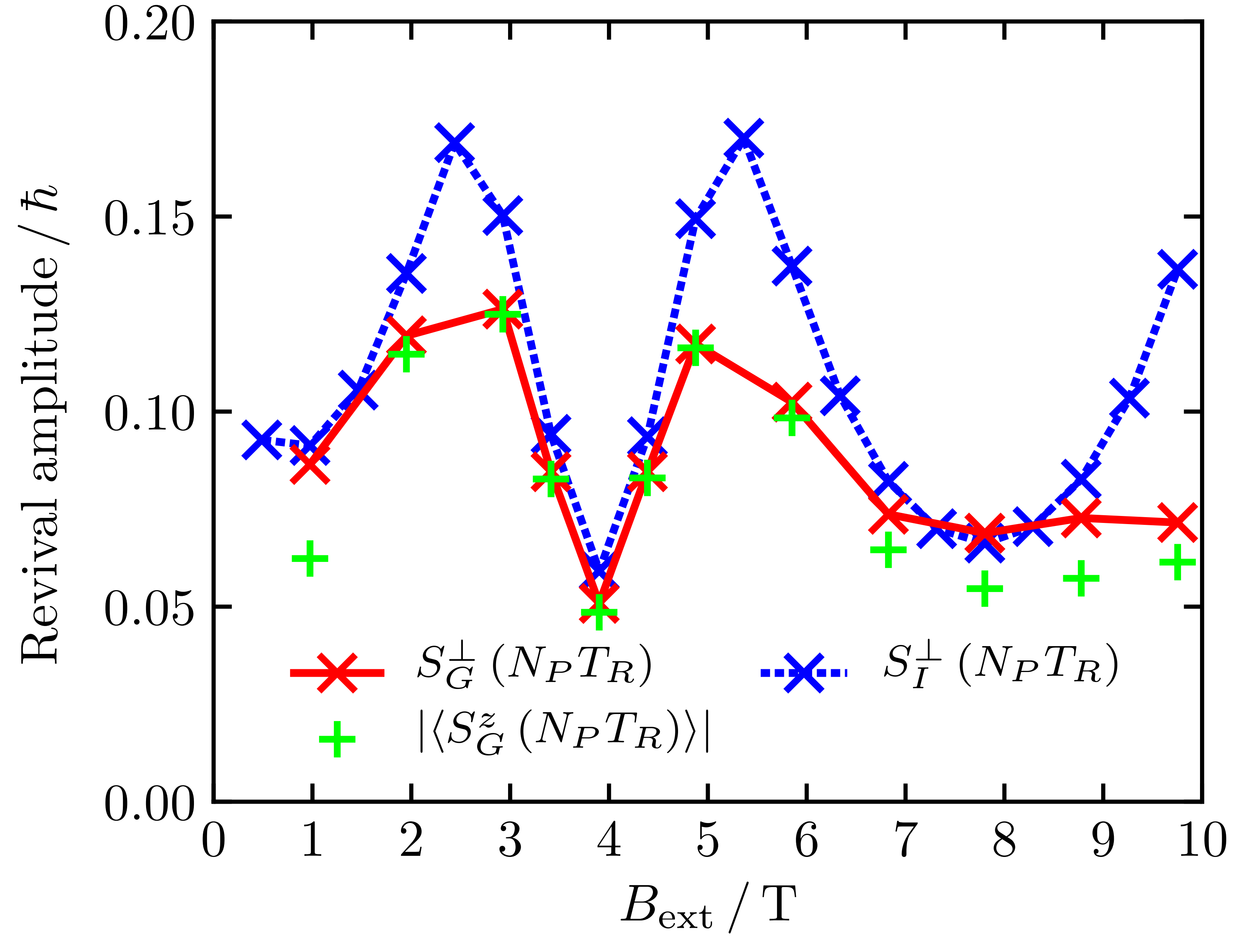
- can we understand the non-linear dependency of the revival amplitude
- what is the role of the nuclear spins?

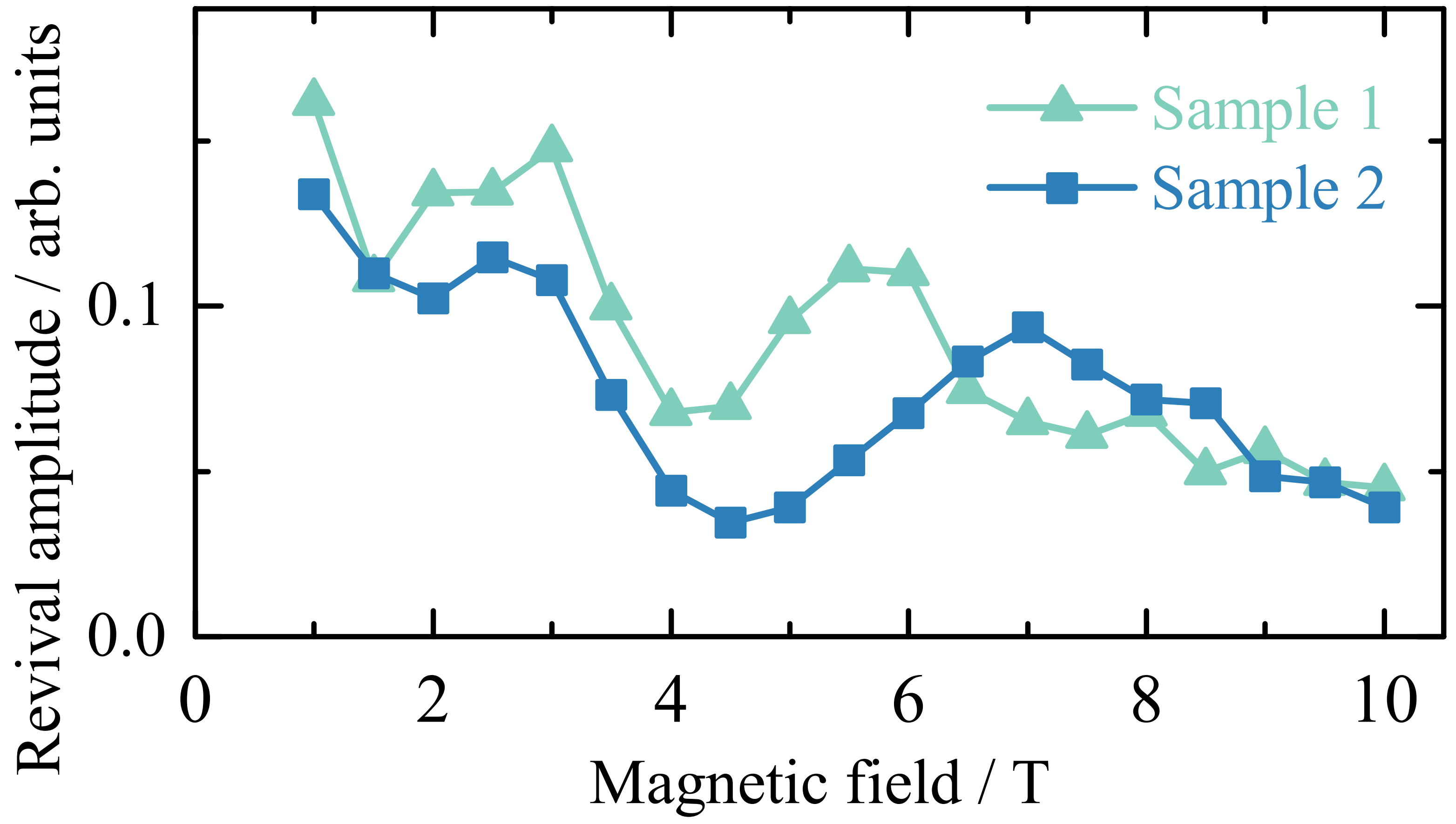
Kleinjohann et al, PRB, Oct 2018

Analysis of the revival amplitude

quantum mechanical simulation of 20mil pulses





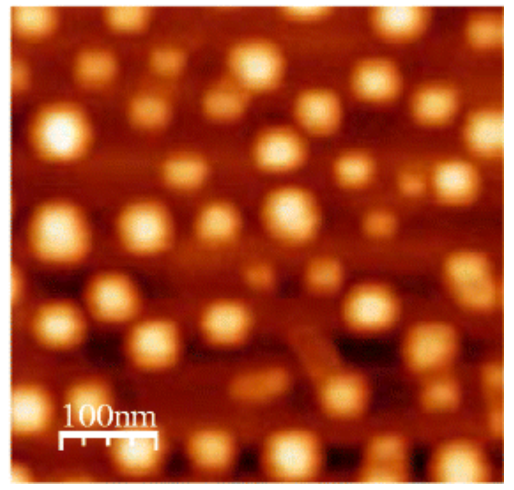


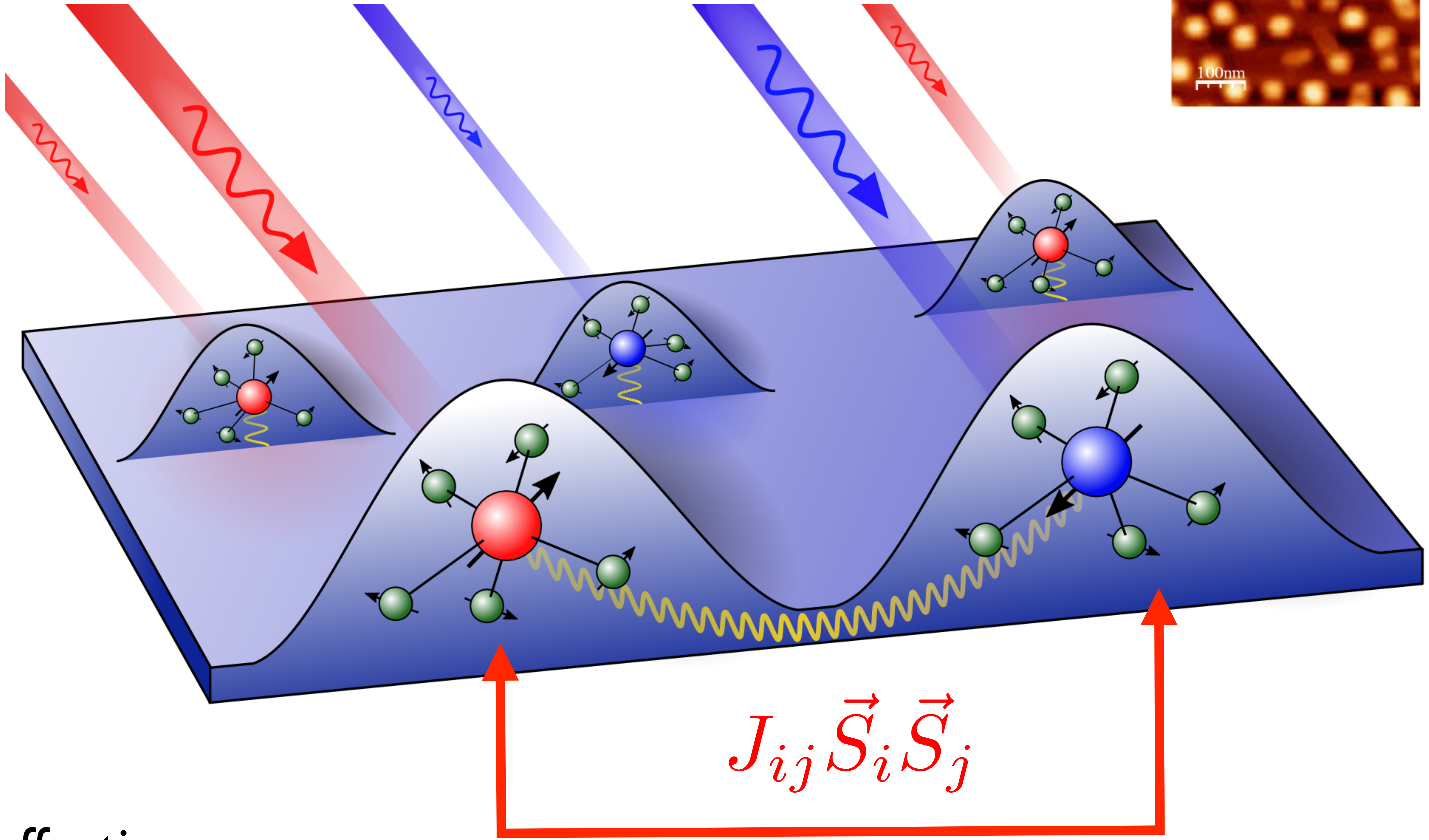
- minimum: nuclear spin resonance condition $\omega_N T_R = \pi n$
- experiment: different isotope mixtures

Kleinjohann et al, PRB, Oct 2018

Multi-color pumping: addressing different QDs

- Two color pumping of quantum dot ensembles

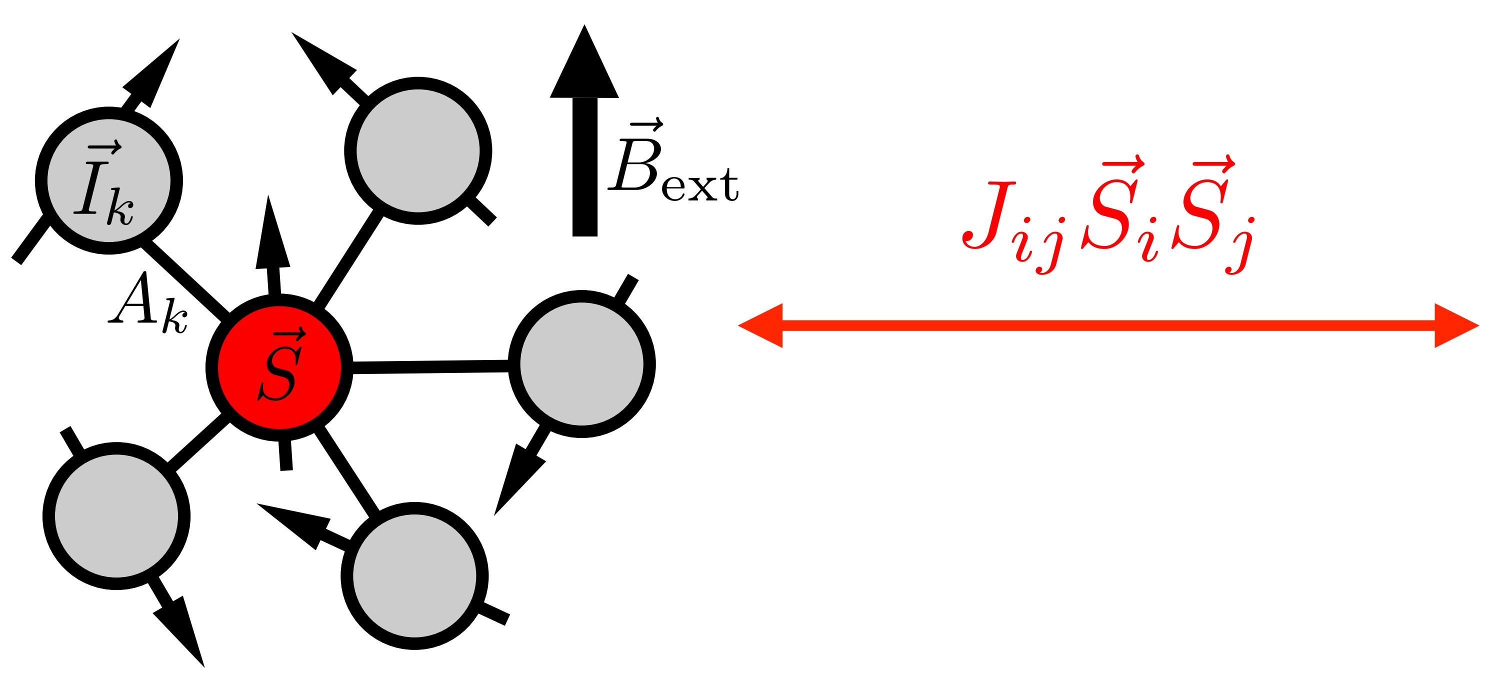


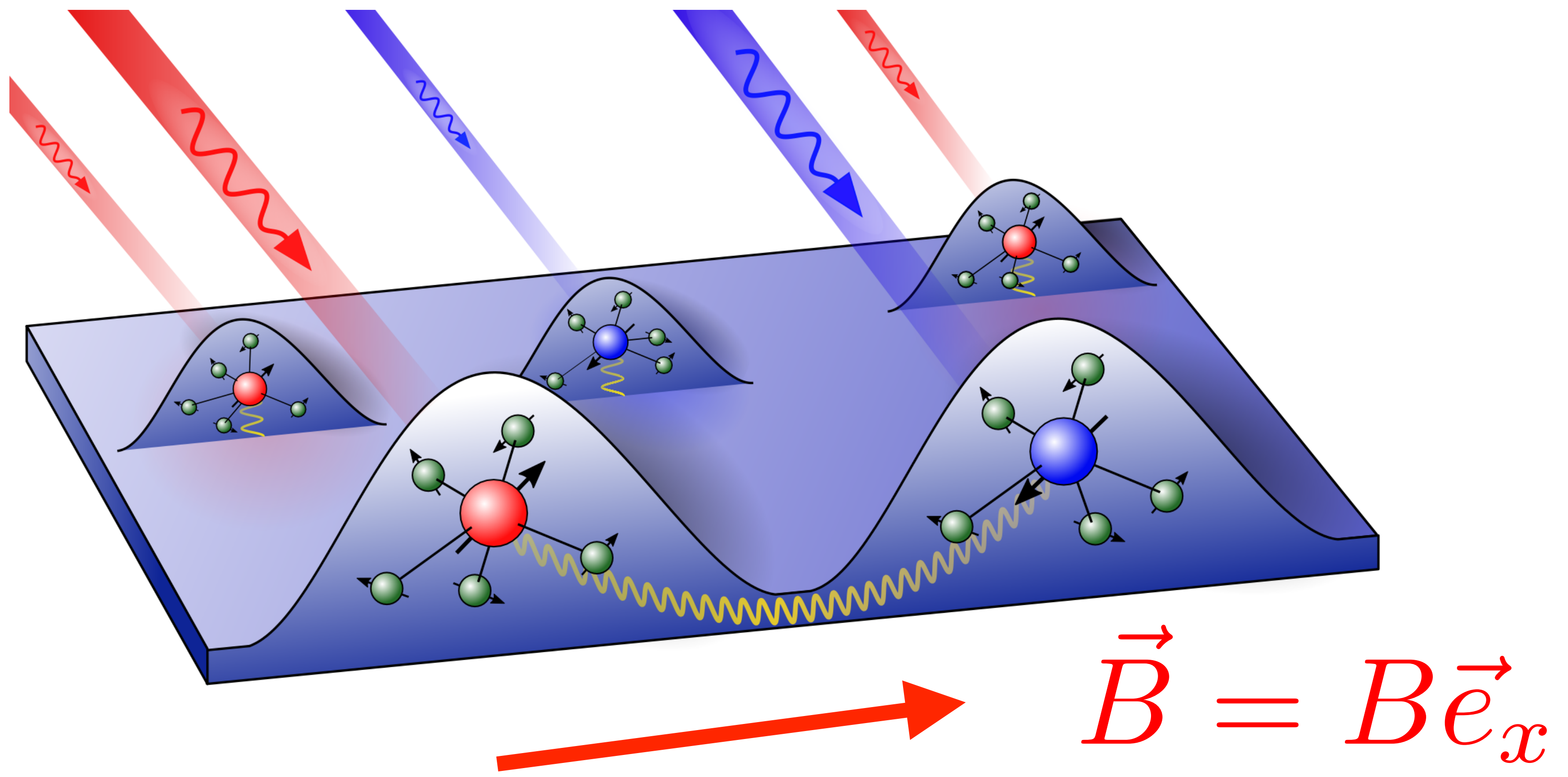


➡ experimental data is consistent with an effective Heisenberg coupling between two quantum dots

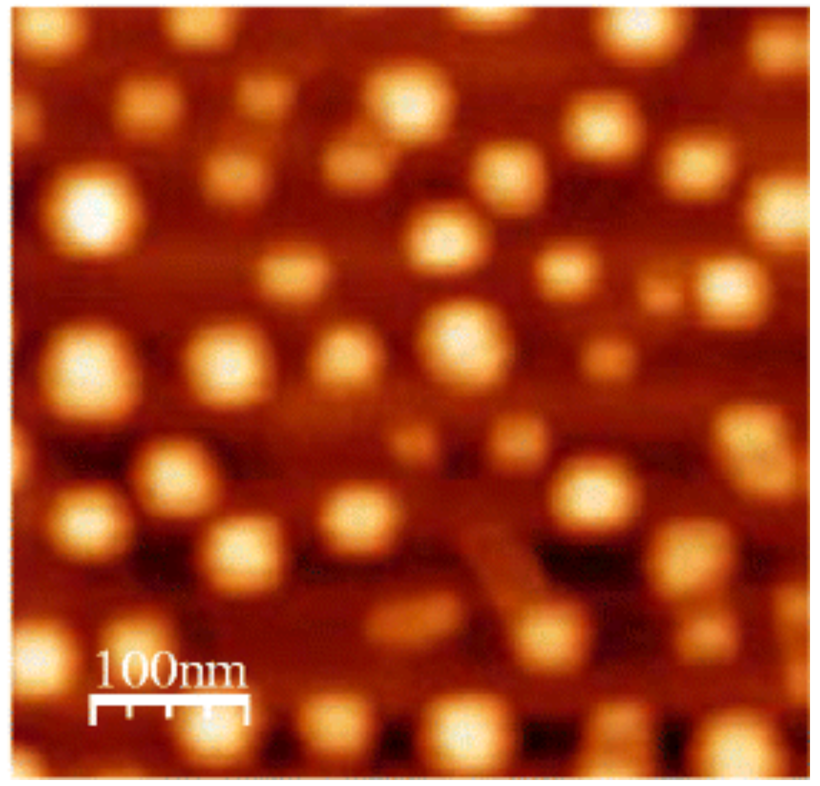
◉ RKKY via wetting layer?

Multi-color pumping: addressing different QDs





$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{S}_i(t) = \left(\vec{B}_{\mathrm{N}}^{i} + \vec{B}_{\mathrm{QDs}}^{no-pump} + \vec{B}_{\mathrm{QDs}}^{pumped} + \vec{B}_{\mathrm{ext}}\right) \times \vec{S}_i(t) + \gamma P_{\mathrm{T}\mu}^{i}(0)\vec{\mathrm{e}}_z e^{-2\gamma t}$$

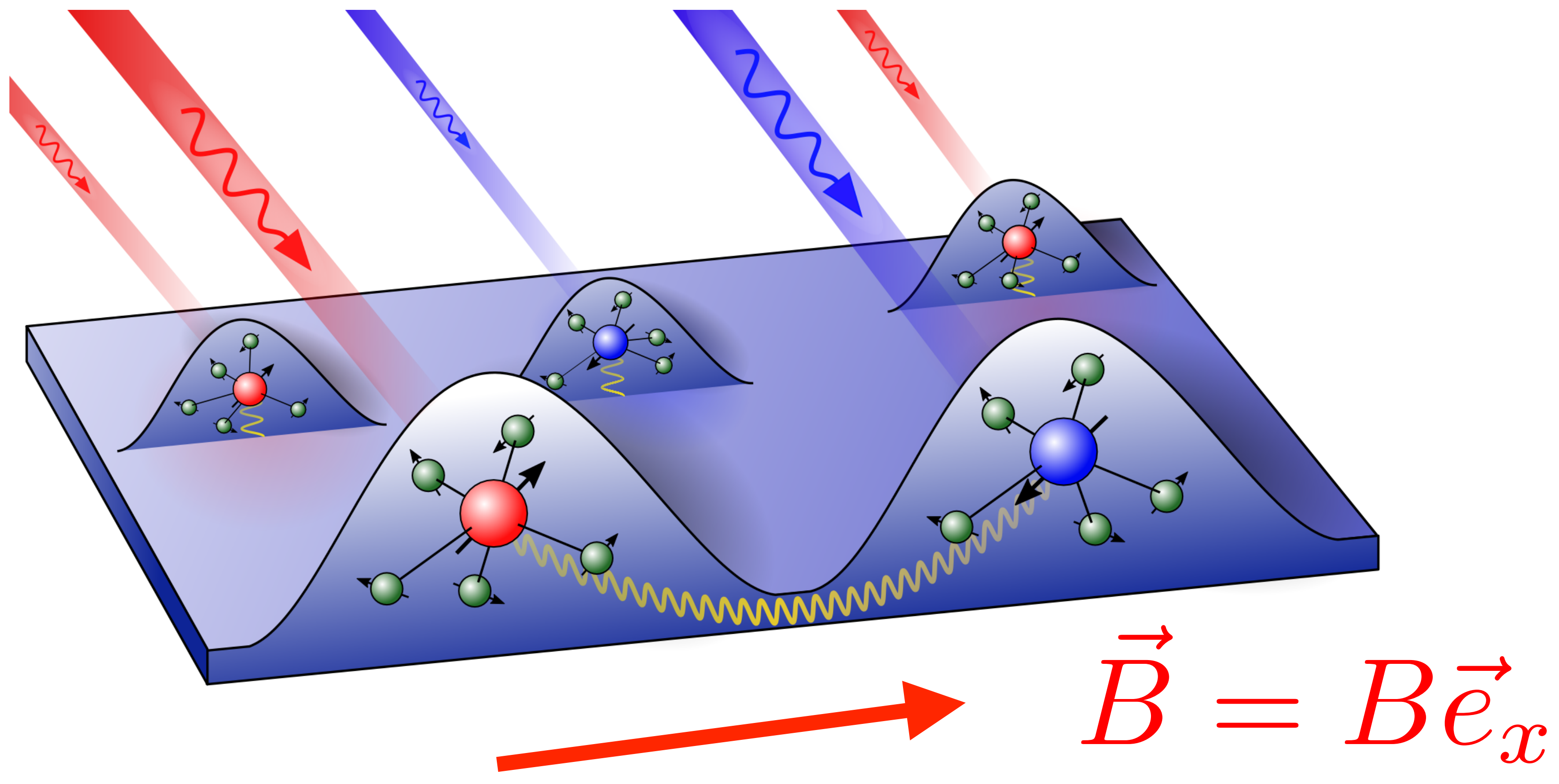


- two **random** Gaussian magnetic fields: the Overhauser field B_N and $B_{QDs}^{\text{no-pumped}}$
- coupled semiclassical differential equations plus QM light-matter interaction: massive parallelized on JURECA booster Intel Phi architecture

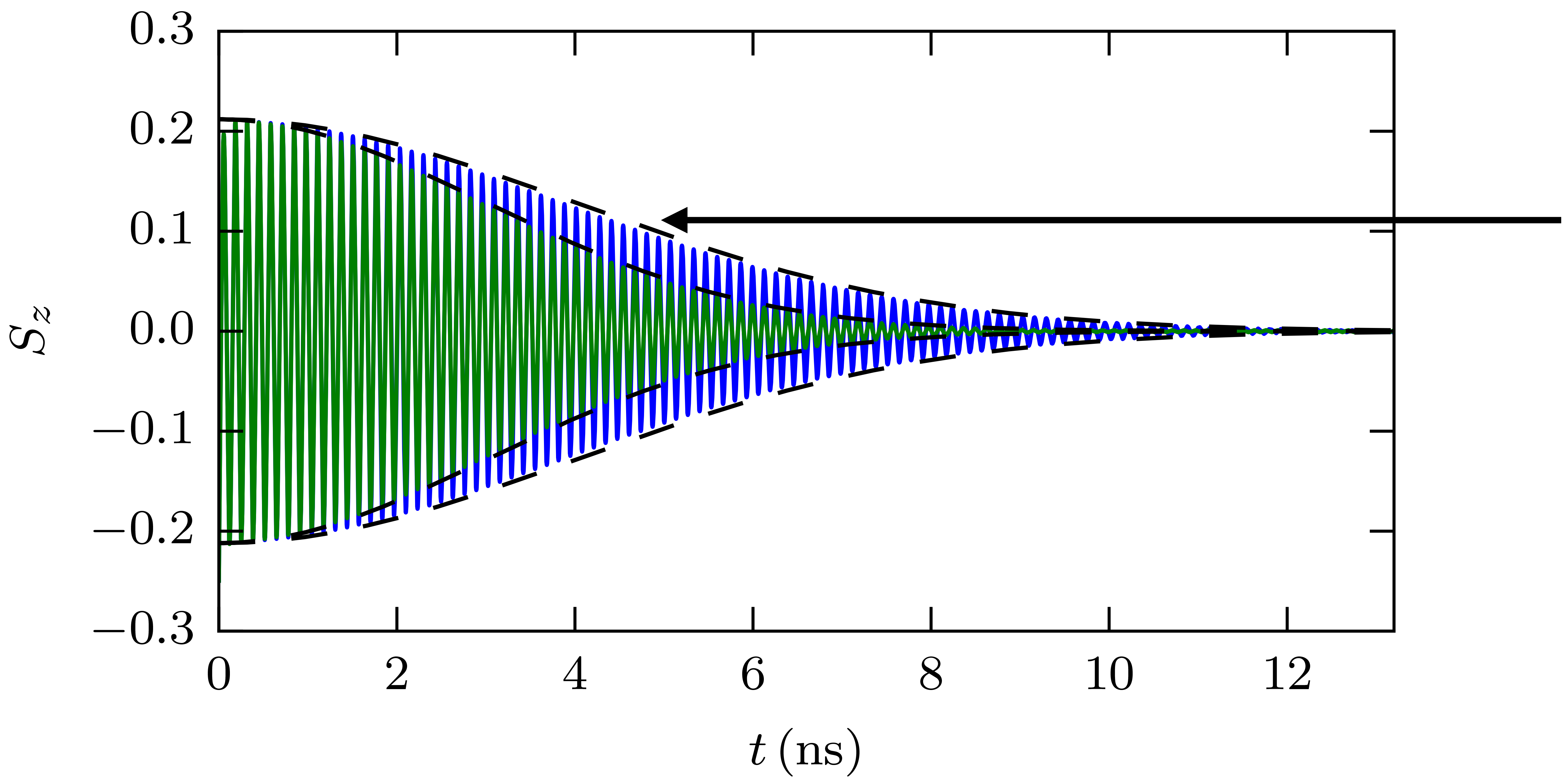
Fischer et al, PRB, Nov 2018

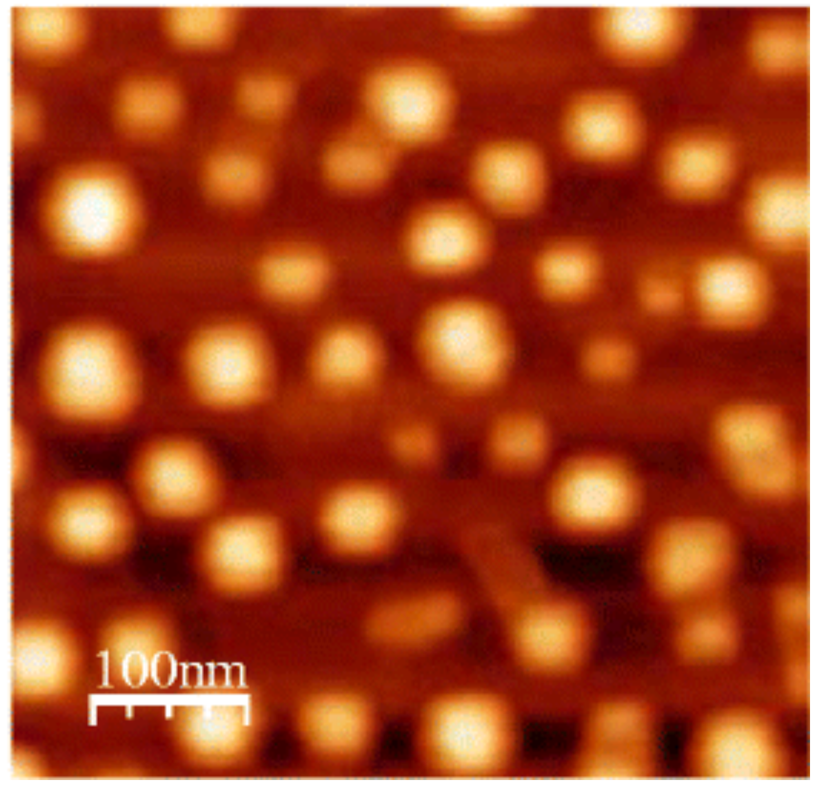
Multi-color pumping: addressing different QDs

- resonance energy depends on the random shape of the QD
  ➡ sharp laser frequency: pumping of only one sub-ensemble



- finite pulse:
  ✓ finite width ΔE
  ✓ pumping several sub-ensembles
  ✓ synchronisation vs dephasing of unpumped QDs





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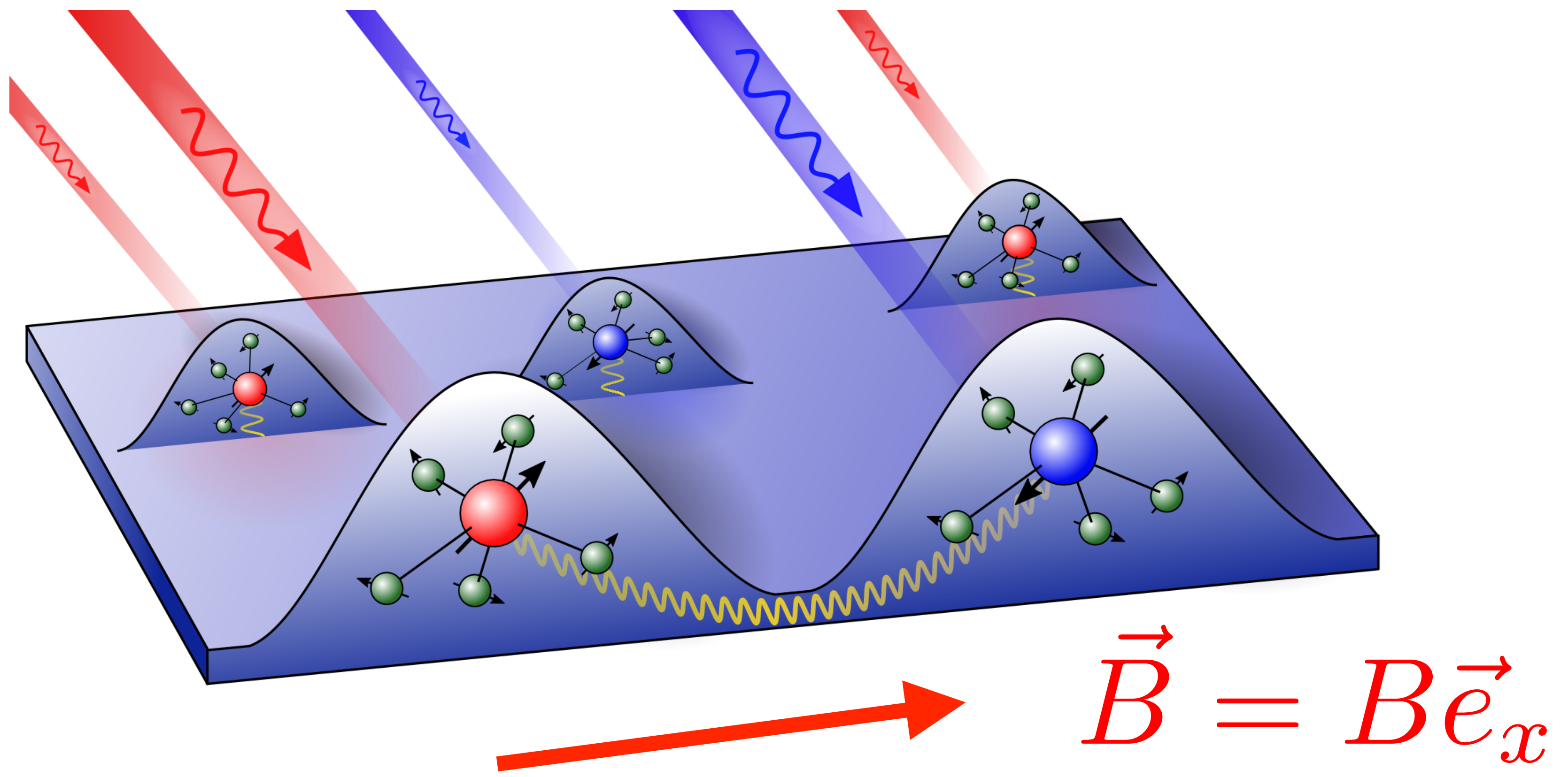

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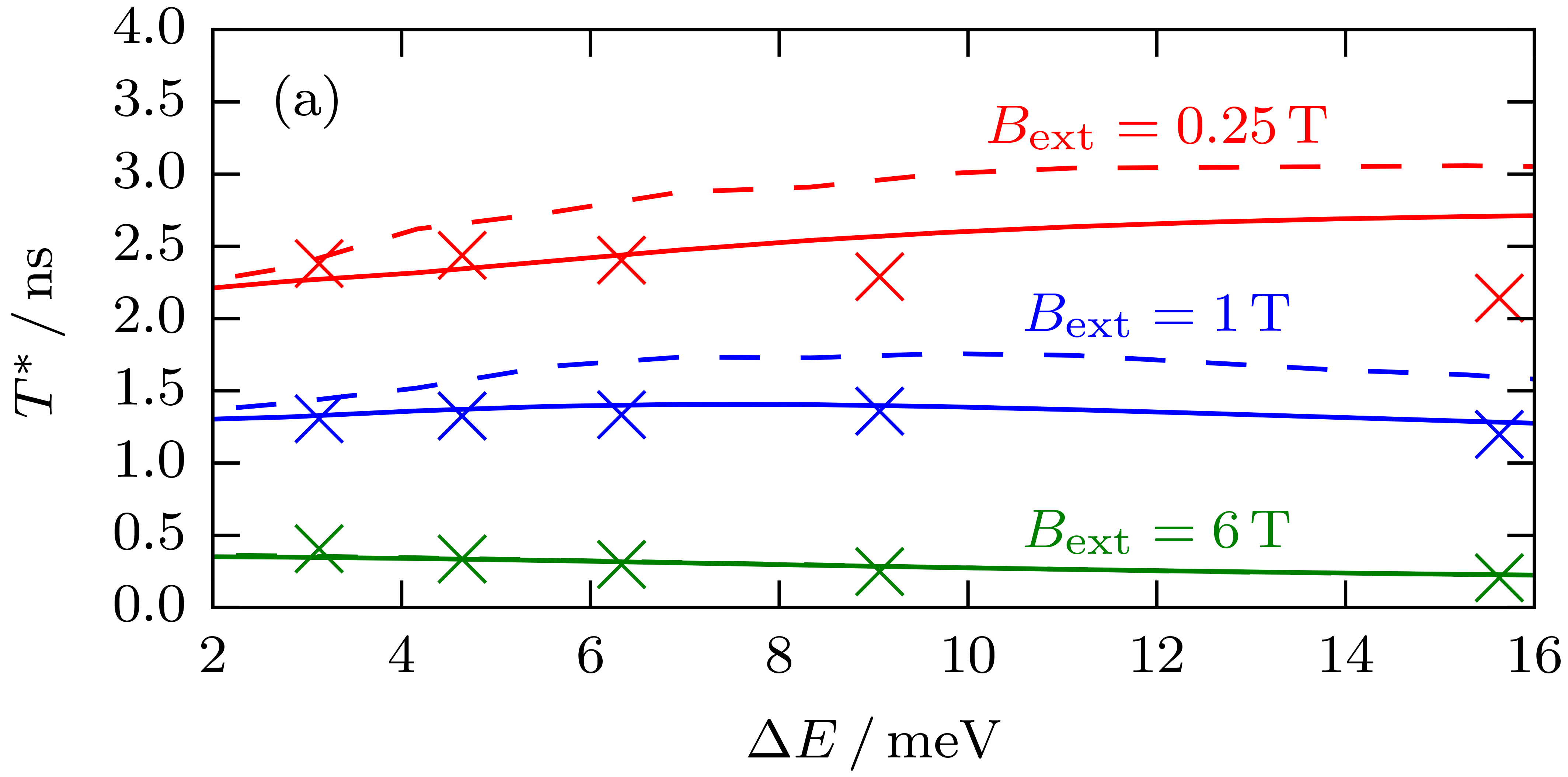
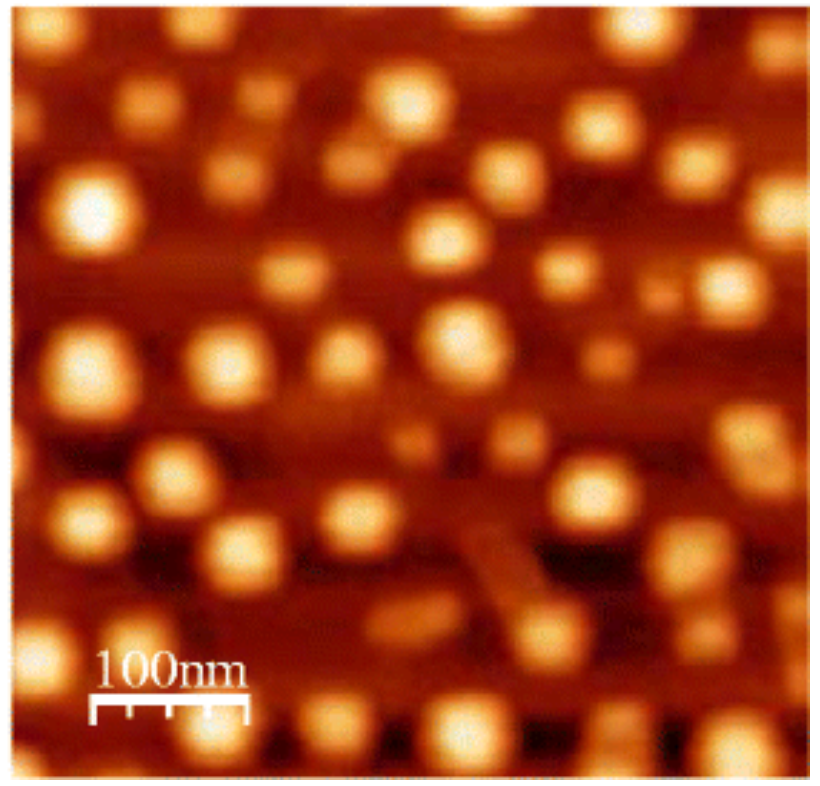


Fischer et al, PRB, Nov 2018

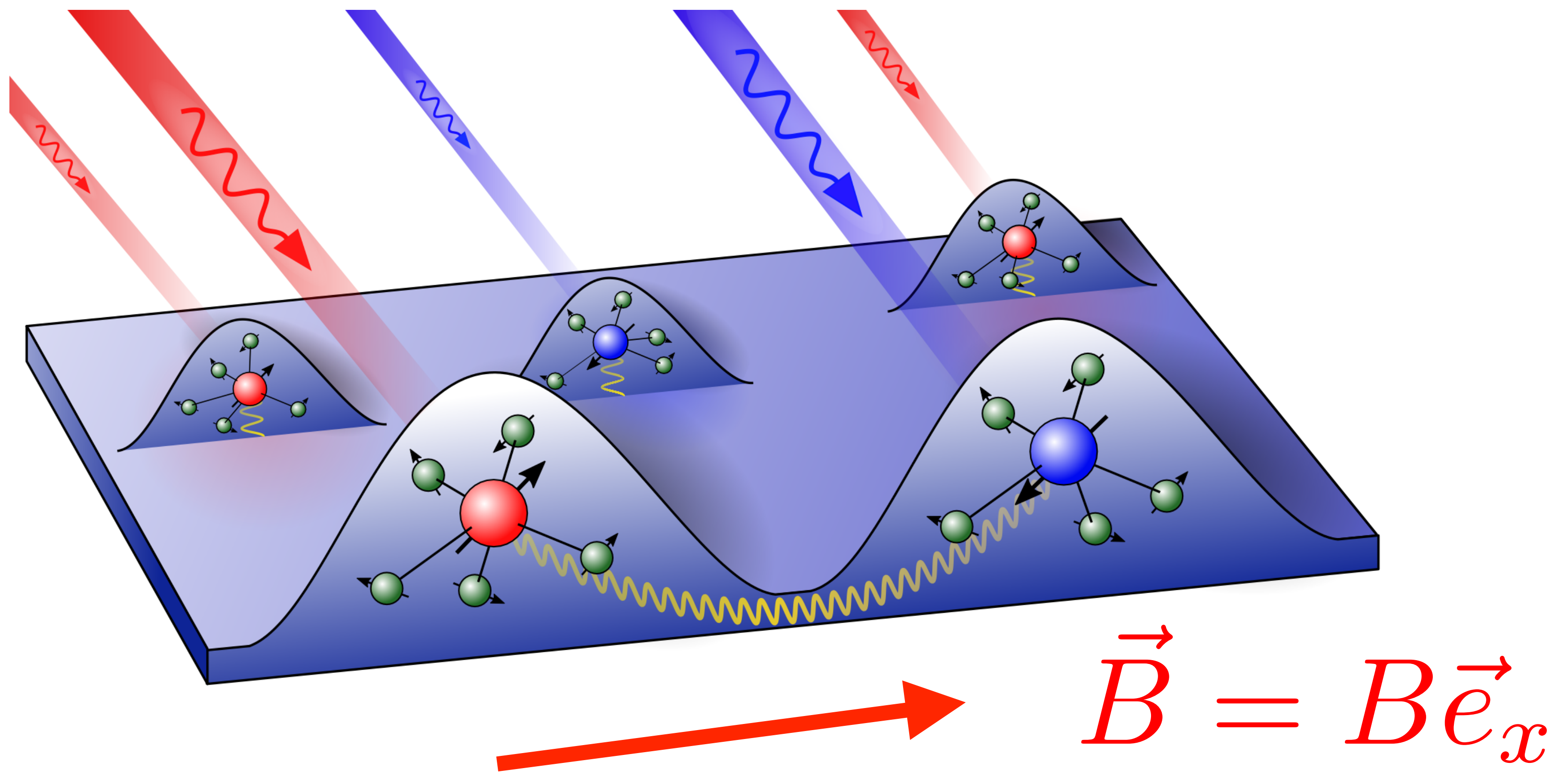


JURECA BOOSTER: Intel Phi

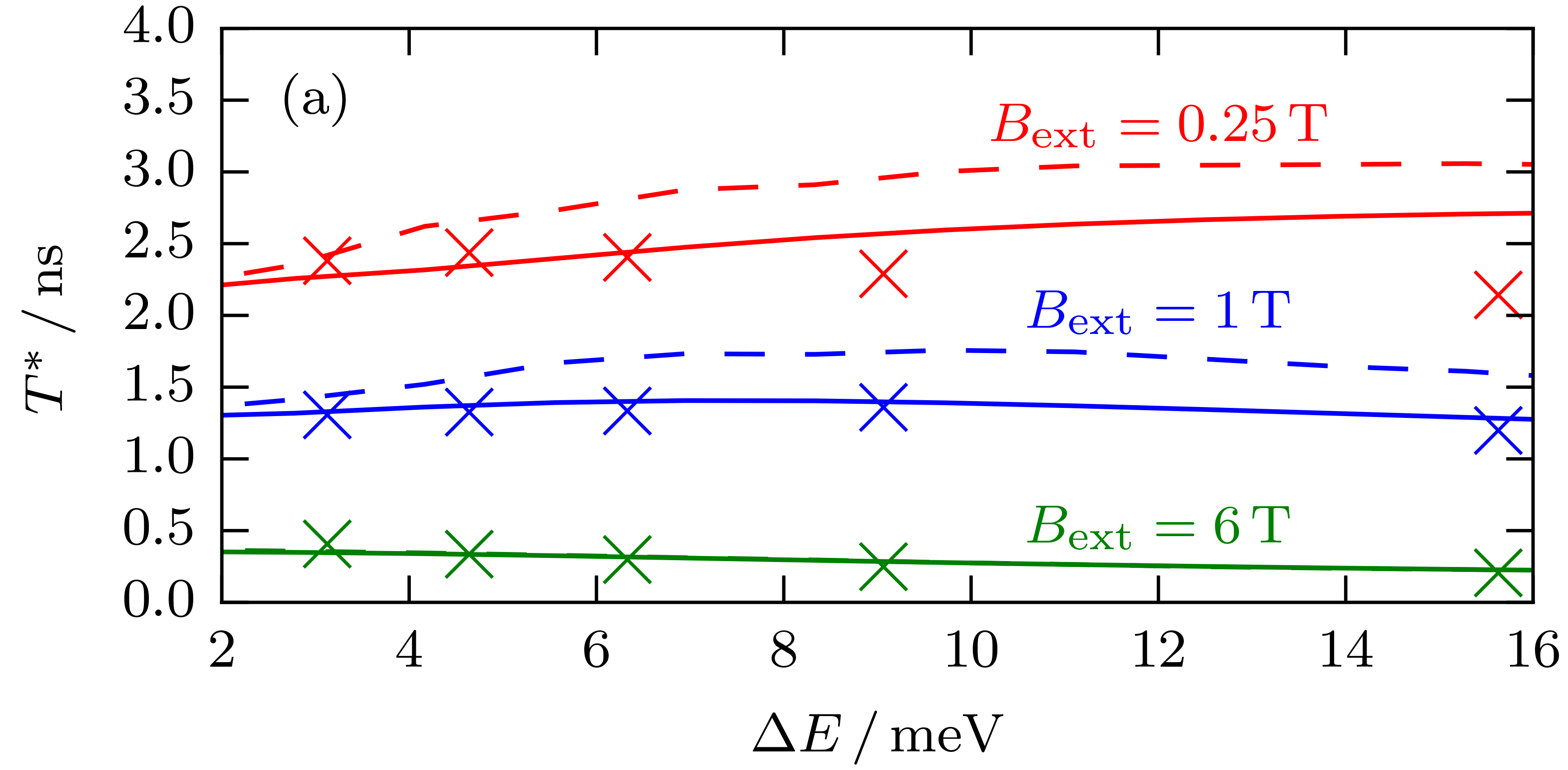
Multi-color pumping: addressing different QDs

Summary of the multi-color pumping

- surprising experimental finding: decoherence time independent of the LASER energy width ΔE
- simulation: consistent with spin-coupled QD spins

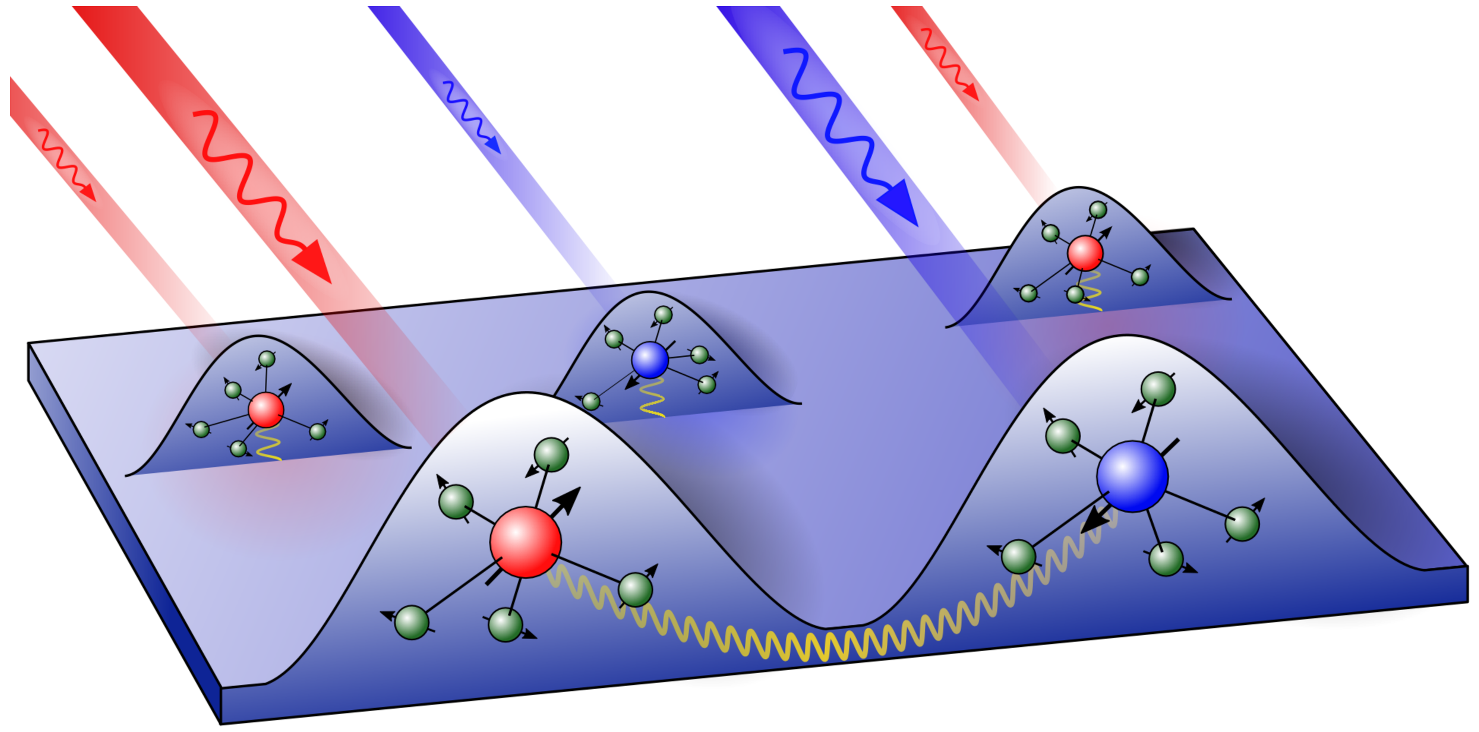


- Questions
  - origin of the coupling?
  - can we learn to manipulate this coupling?
  - coupling of different subset: qubit interactions?
  - different pulse sequences



Fischer et al, PRB, Nov 2018

Higher-order spin noise in QDs

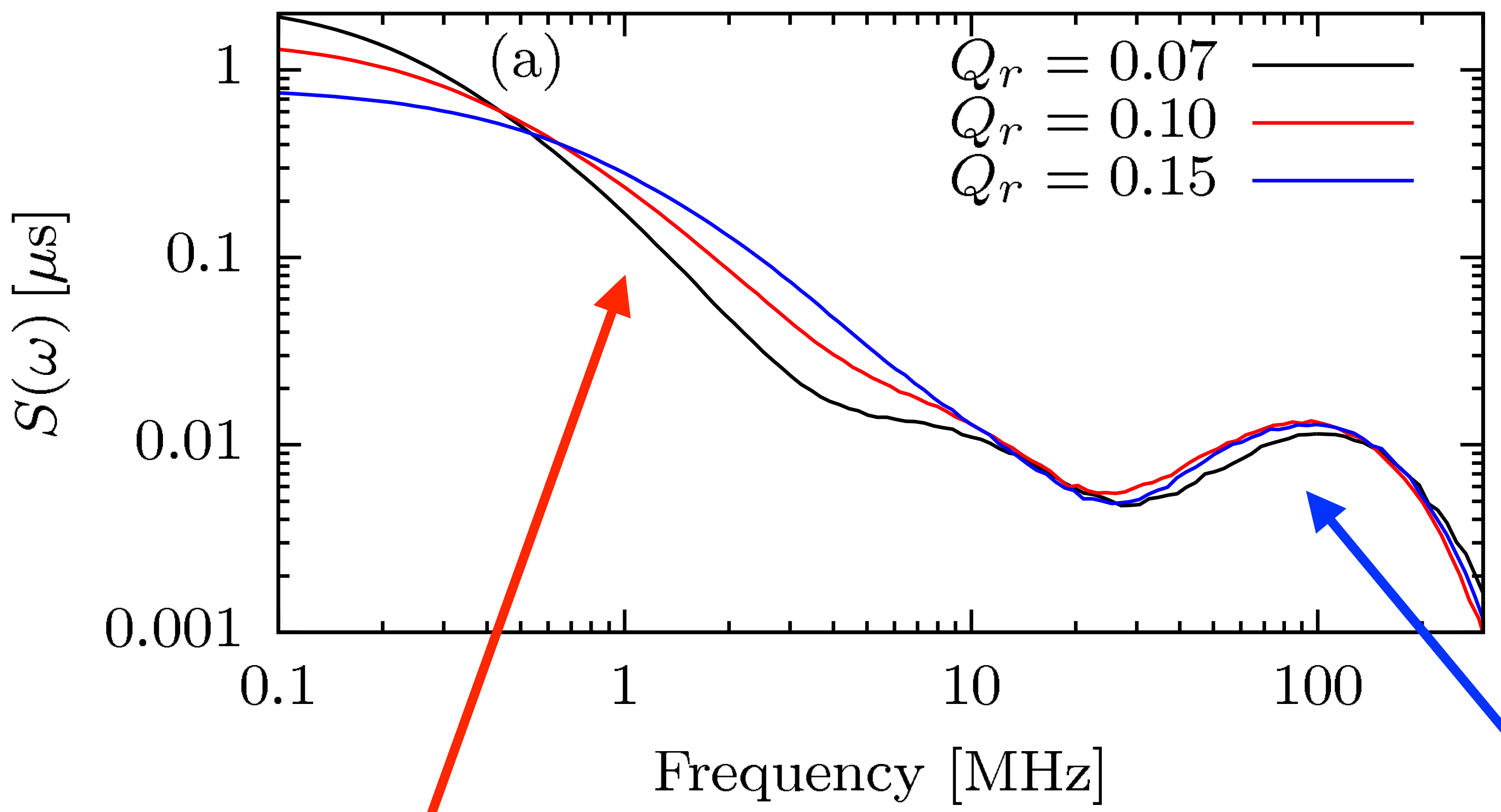


Spin noise

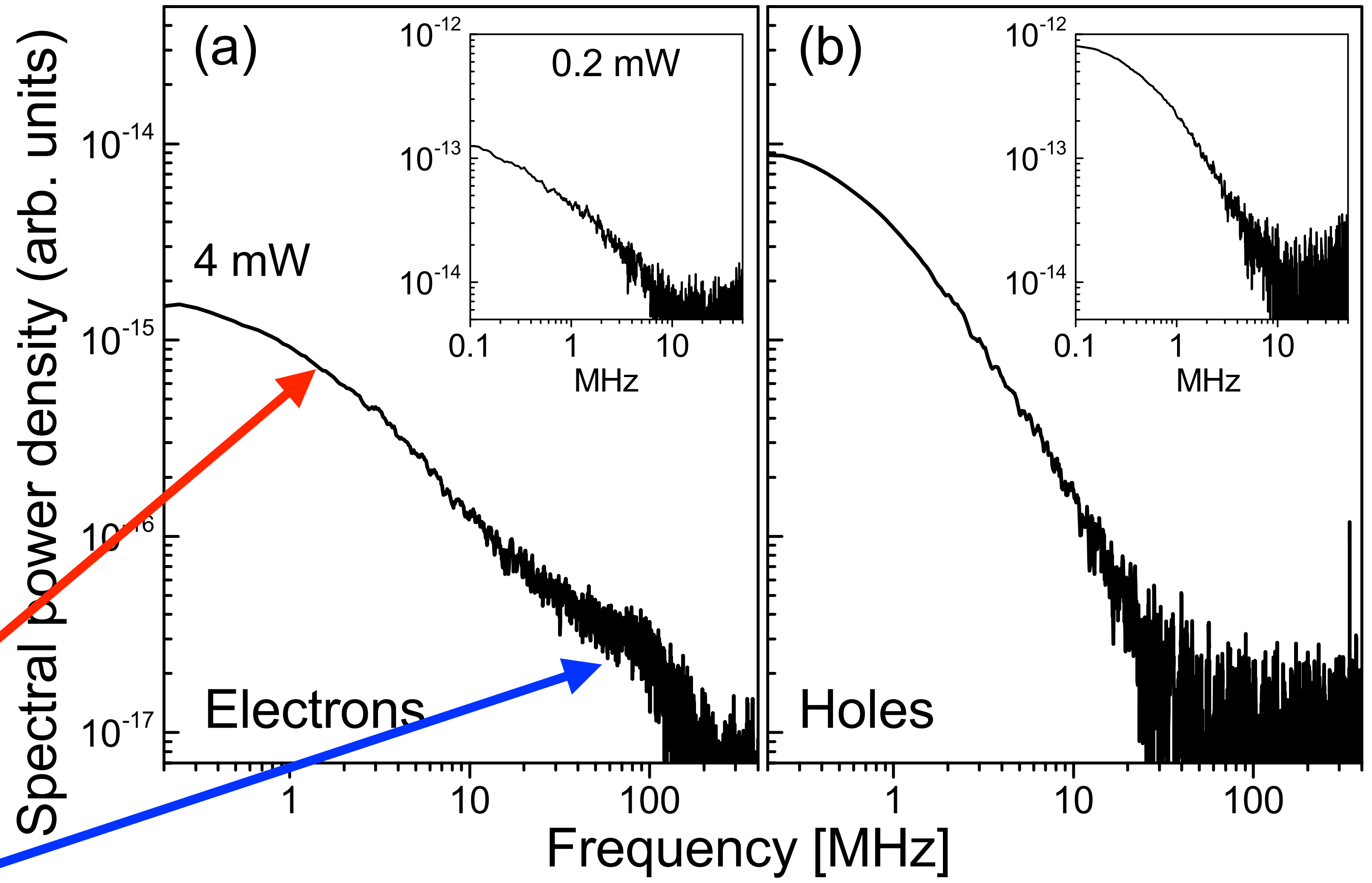
$$C_2(t) = \mathrm{Tr}\left[\rho S_z(t) S_z\right]$$

- spin noise: Fourier transformation of $C_2(t)$

$$S(\omega) = C_2(\omega) =< |S_z(\omega)|^2 >$$



theory



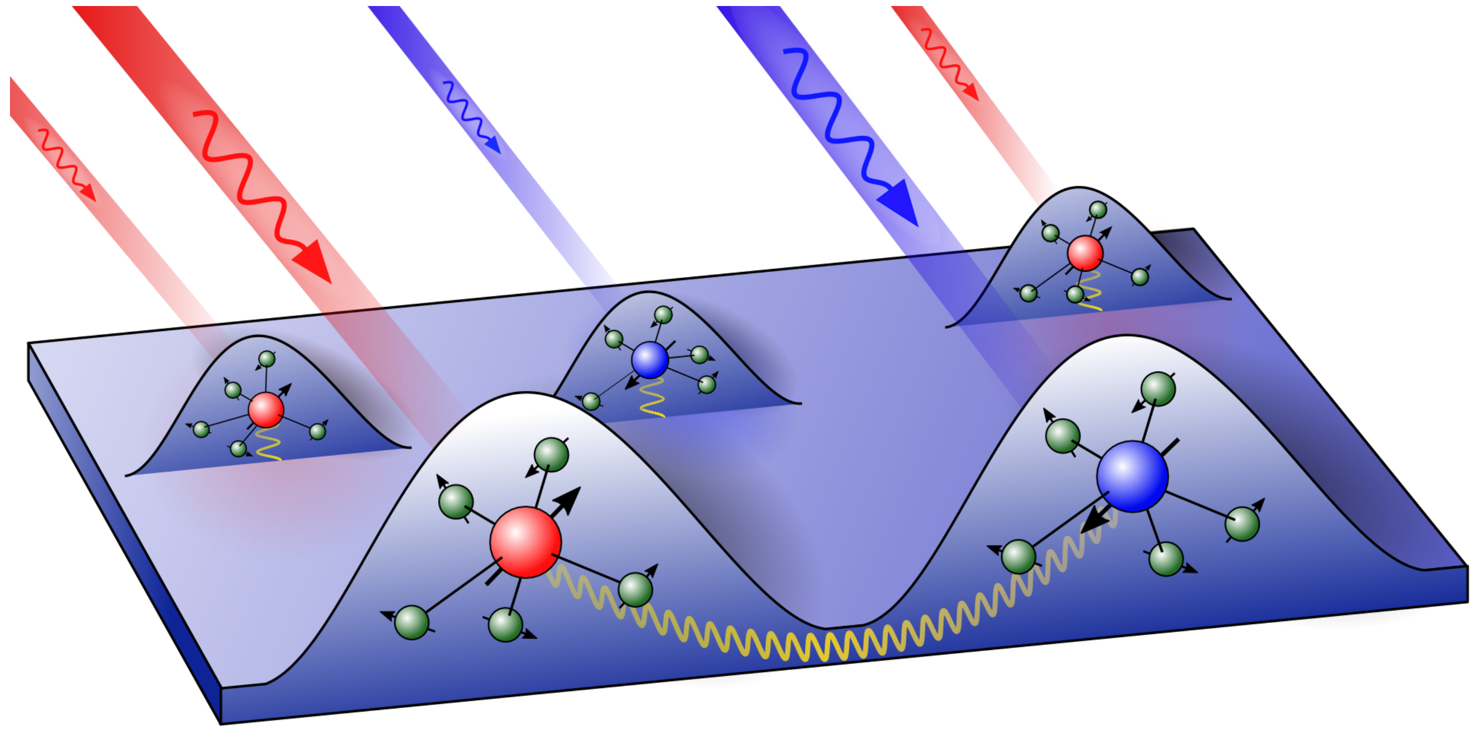
experiment

Gaussian nuclear spin fluctations

nuclear electric quadrupolar interaction

Hackmann et al, PRL, 2015

Higher-order spin noise in QDs



Spin noise

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- spin noise: Fourier transformation of $C_2(t)$

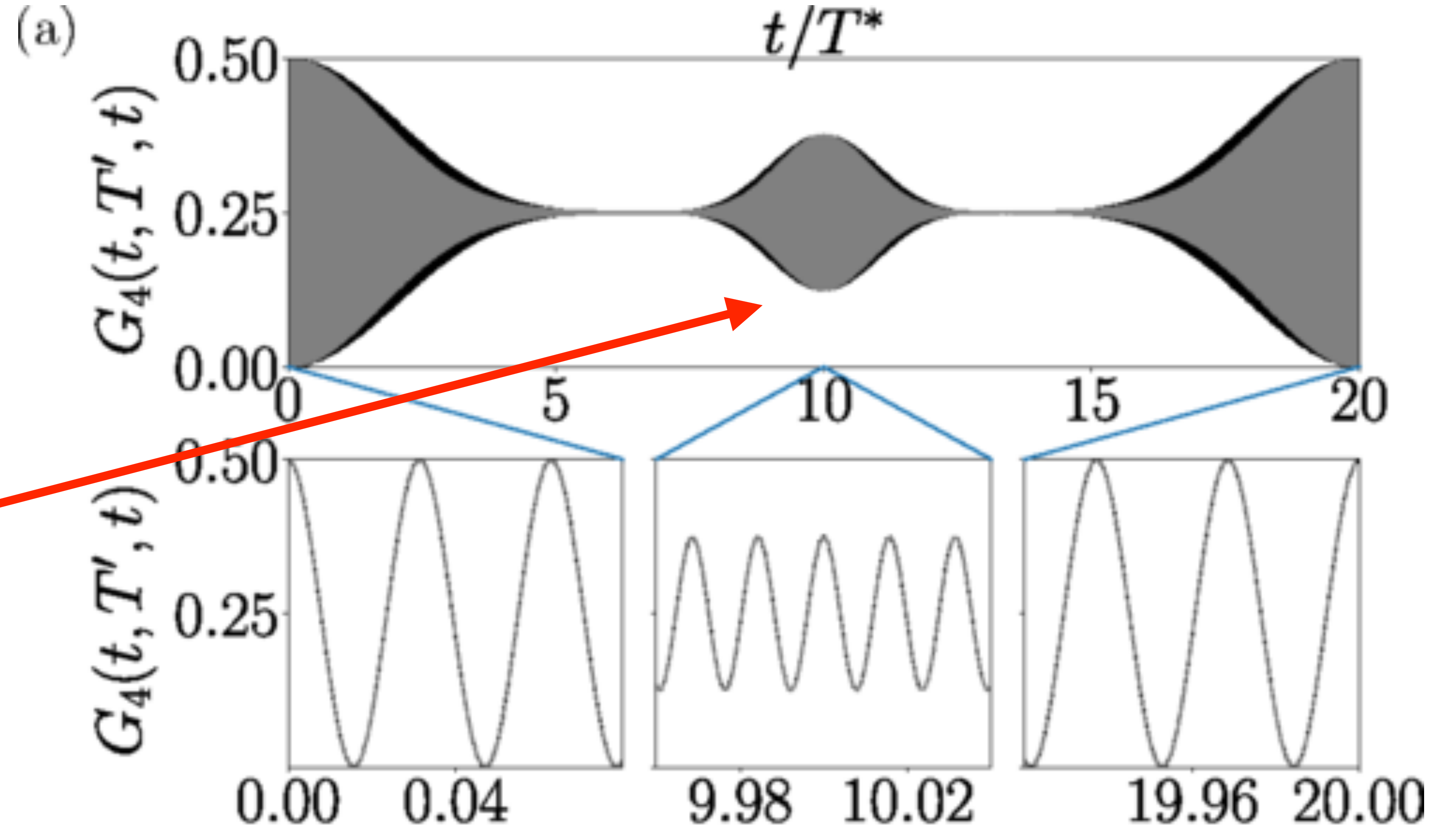
$$S(\omega) = C_2(\omega) =< |S_z(\omega)|^2 >$$

- message: $C_2(t)$ is well understood

Higher order spin correlations

$$C_4(t_1, t_2, t_3) =< S_z(t_1) S_z(t_2) S_z(t_3) S_z >$$

1. spin echo $\quad C_4(t_1, t_1 + t_2, t_1)$



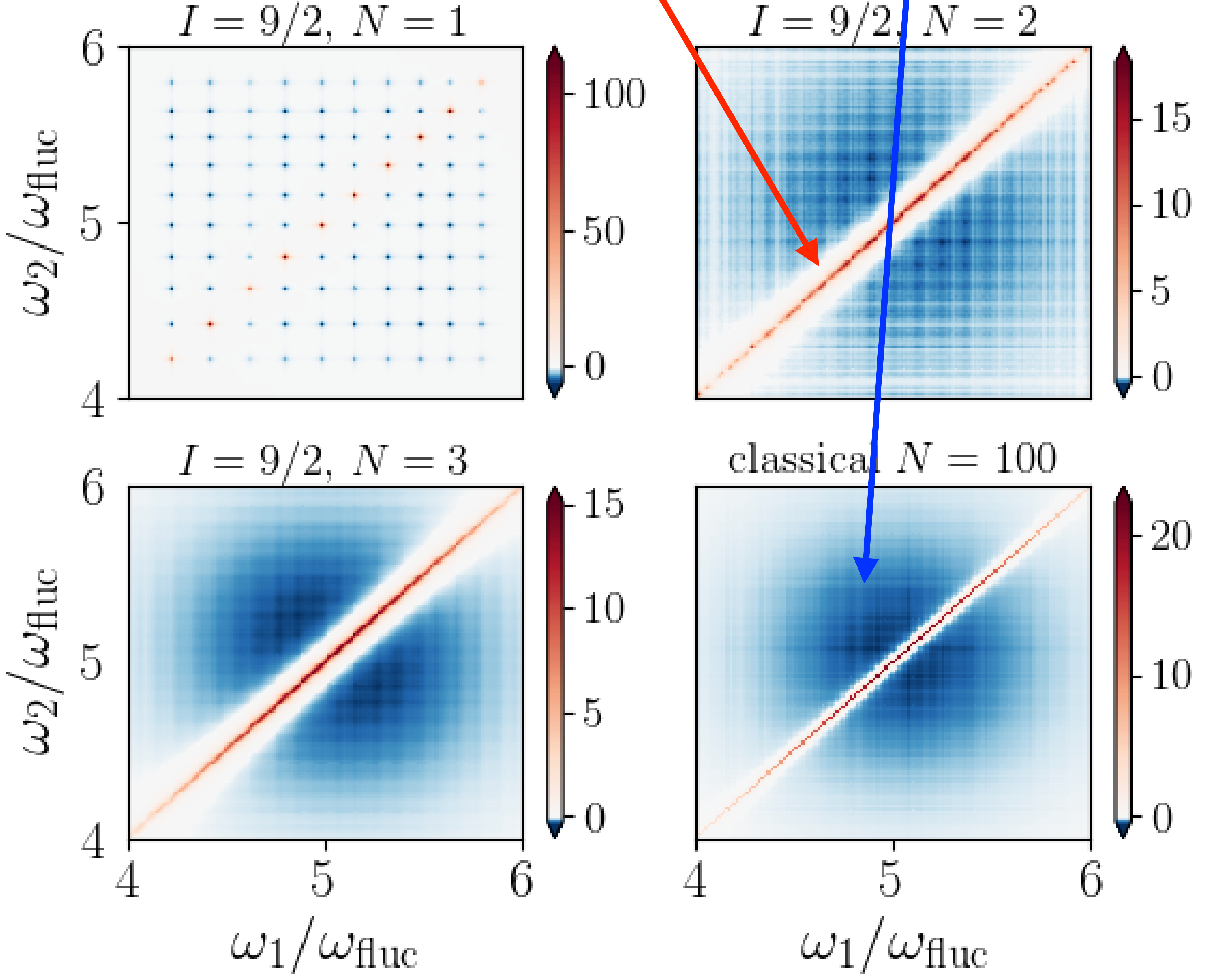
2. 4th-order spin noise

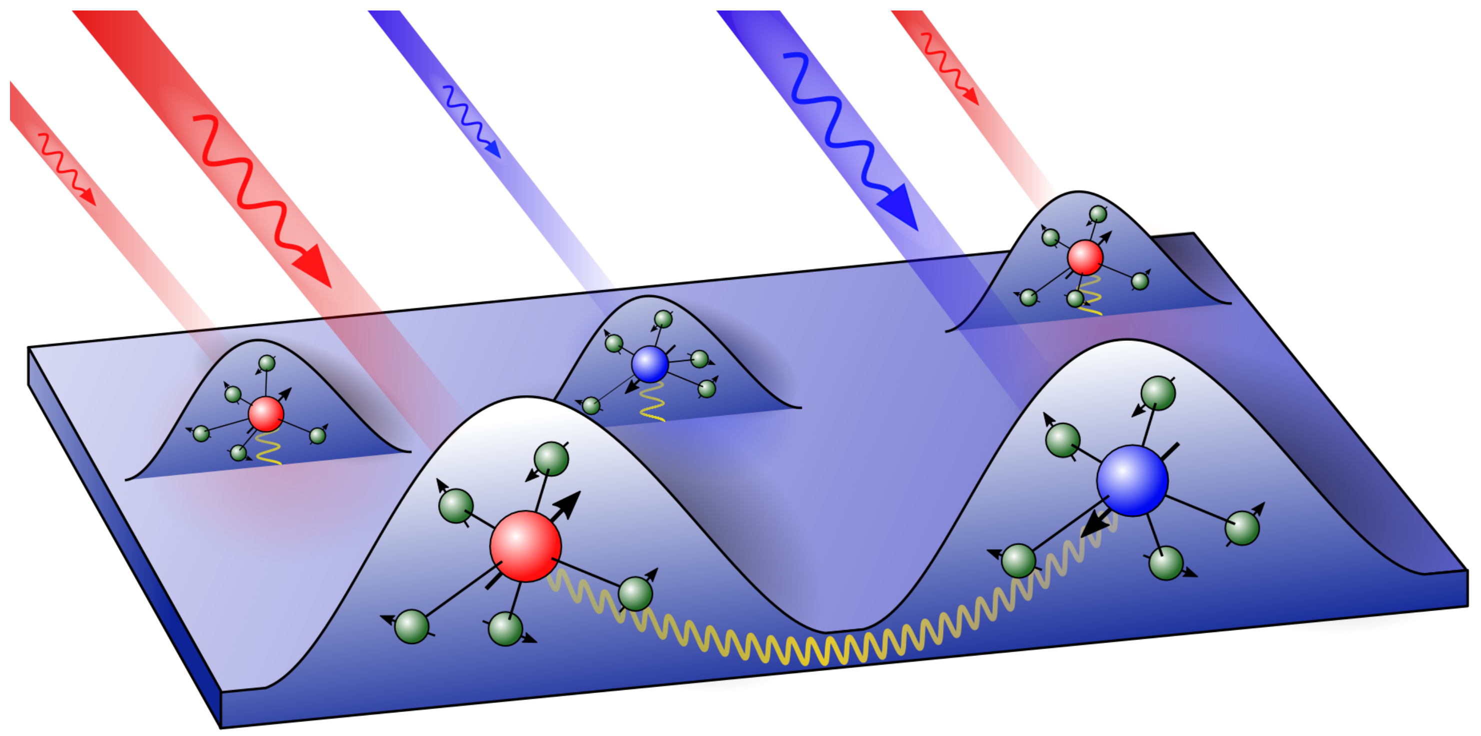
$$C_4(\omega_1, \omega_2) =< |S_z(\omega_1)|^2 |S_z(\omega_2)|^2 >= \mathrm{FT}\left[\lim_{T_m \to \infty} \frac{1}{T_m} \int_{-T_m}^{T_m} d\tau C_4(t_1 + \tau, \tau, t_2)\right]$$

Fröhling, FBA, PRB 2017

4th-order spin noise

$$S_4(\omega_1,\omega_2) = C_4(\omega_1,\omega_2) - C_2(\omega_1)C_2(\omega_2)$$

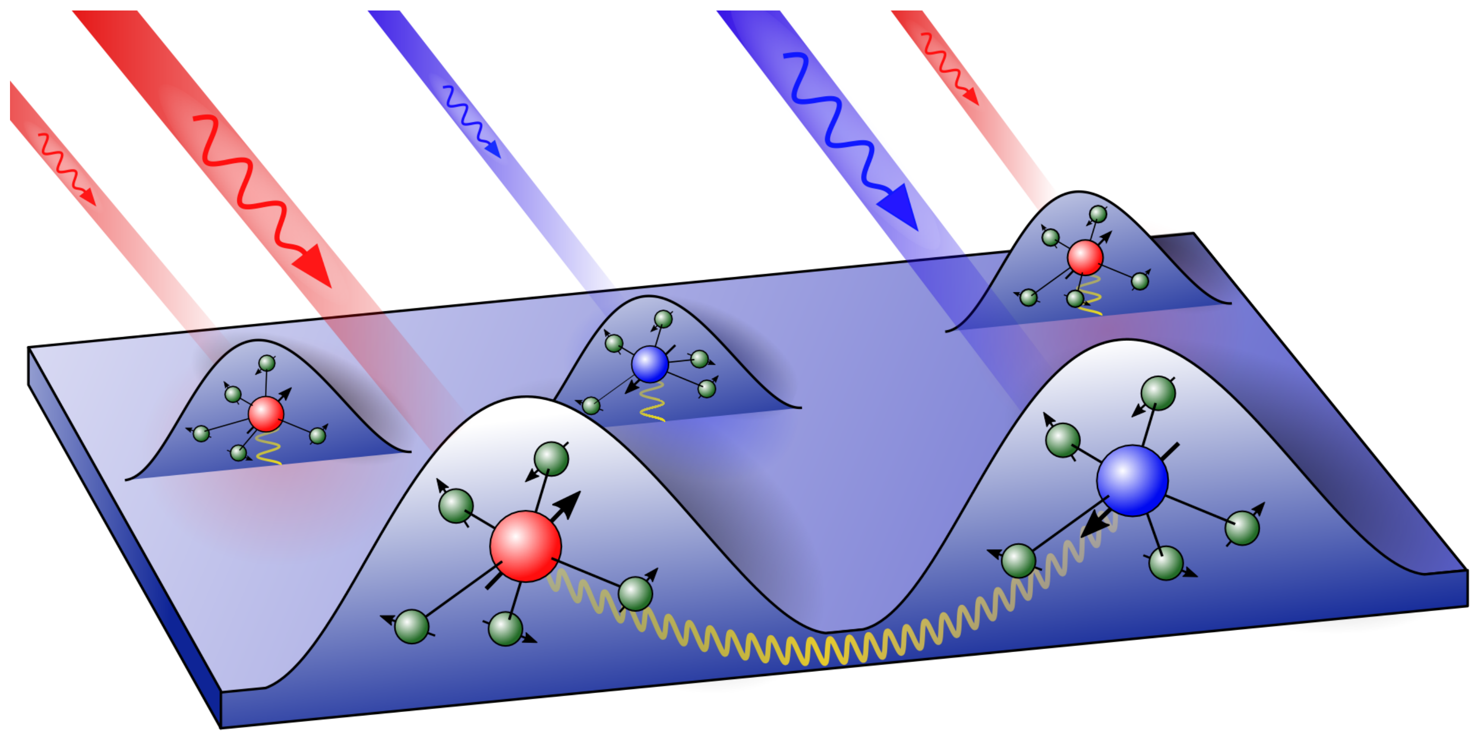




- crossover from a single spin to a classic continuum
- 4th-order: only correlation on the diagonal for a simple model
- finite magnetic field: Gaussian anti-correlations

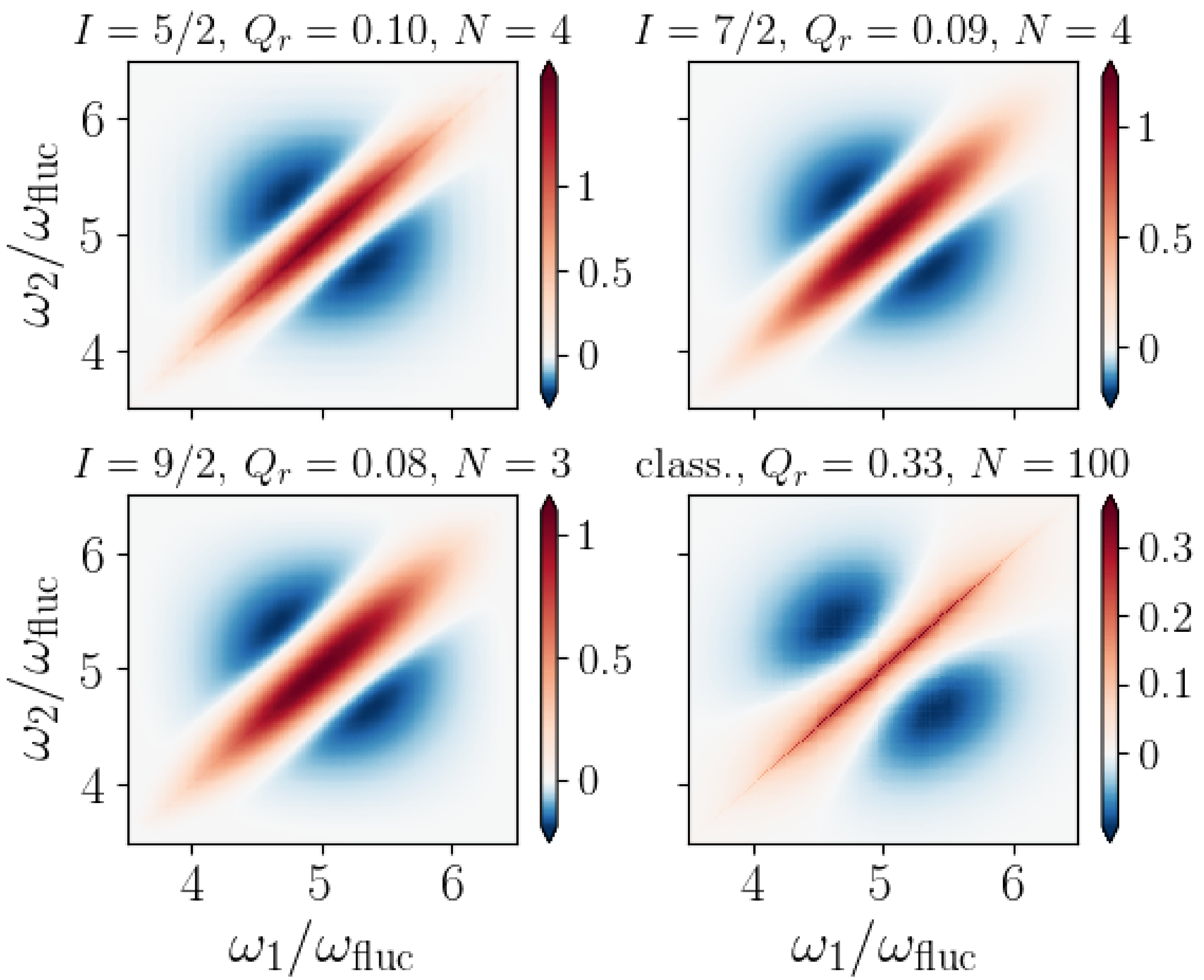
Fröhling, Jäschke, FBA, PRB 2019
JUWELS simulations

Higher-order spin noise in QDs



4th-order spin noise: include quadrupolar interactions

$$S_4(\omega_1, \omega_2) = C_4(\omega_1, \omega_2) - C_2(\omega_1)C_2(\omega_2)$$



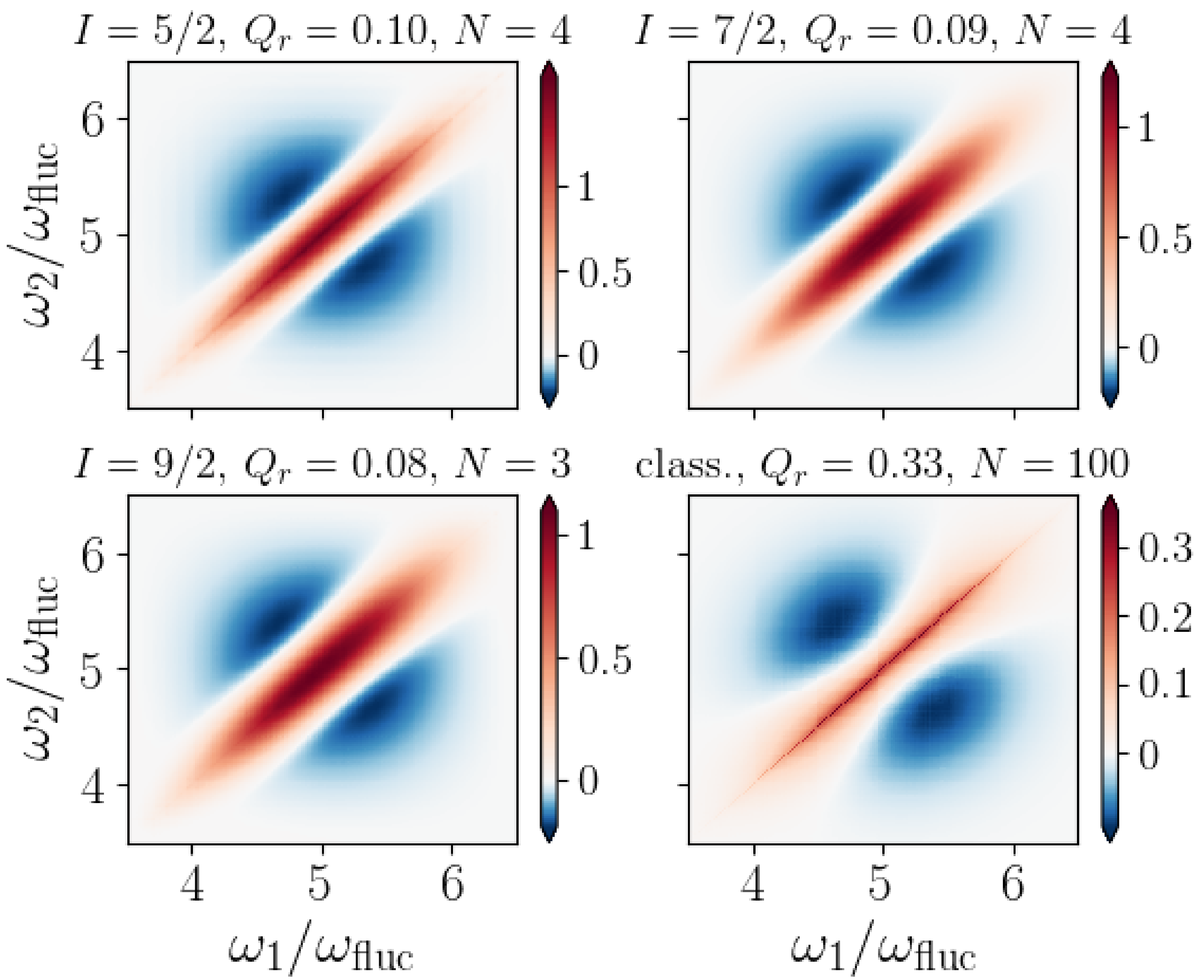
- off-diagonal noise: probe for additional interactions that causes decoherence
- modification of the Gaussian noise

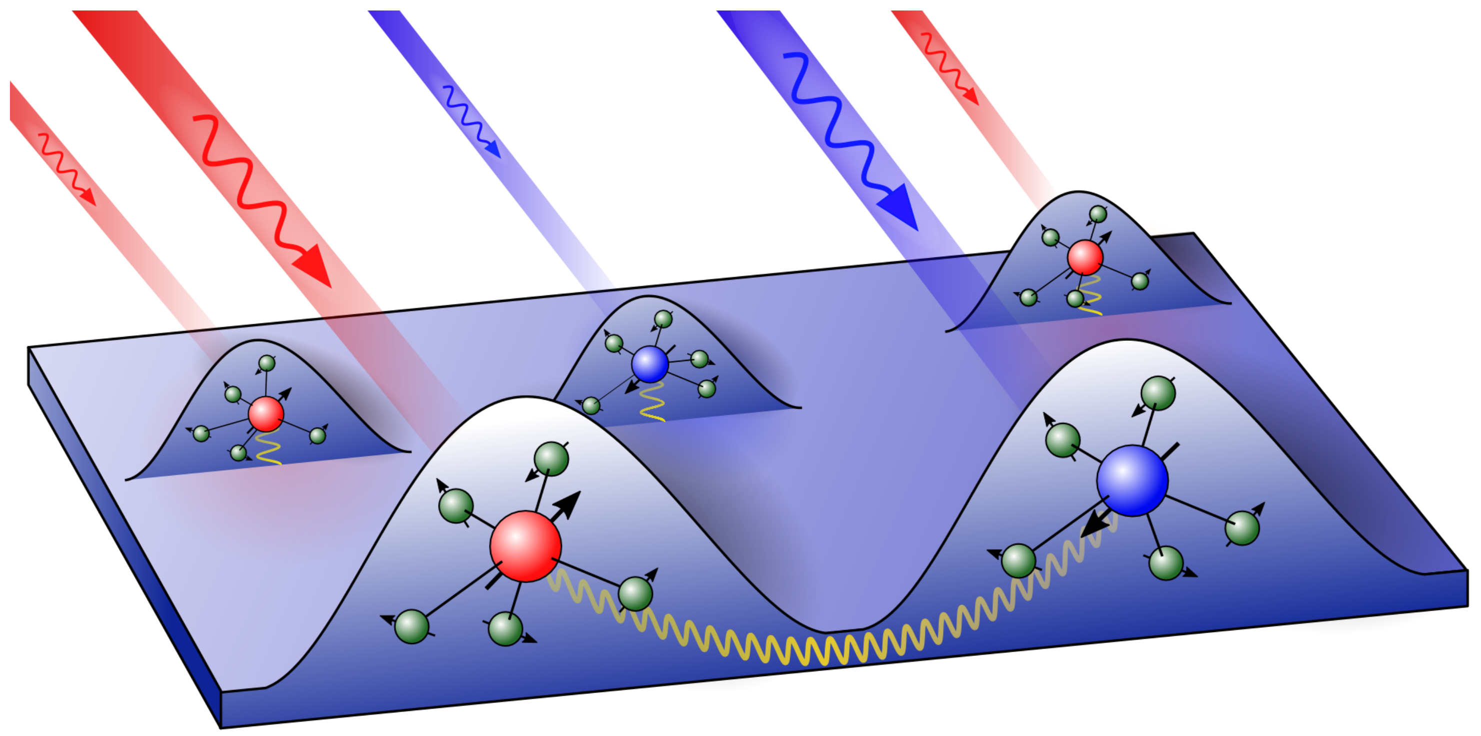
Fröhling, Jäschke, FBA, PRB 2019
JUWELS simulations

Higher-order spin noise in QDs

4th-order spin noise: include quadrupolar interactions

$$S_4(\omega_1,\omega_2) = C_4(\omega_1,\omega_2) - C_2(\omega_1)C_2(\omega_2)$$





- off-diagonal noise: probe for additional interactions that causes decoherence
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Fröhling, Jäschke, FBA, PRB 2019
JUWELS simulations

Summary

1. Numerical simulation of periodically pulsed quantum dot ensembles: understanding the synchronisation of the nuclear spin bath
2. Long-range spin interaction between quantum dots: coupling of subsystems pulsed with different laser colors
3. Proposal: higher-order spin correlation functions can reveal additional weak interactions

Thank you very much!