Machine Learning in Ultrafast Magnetism

New horizons for the fastest, smallest and most energy-efficient brain-inspired computing

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Acknowledgements

Radboud University

A.V. Kimel
Th. Rasing
C. Davies
K. Yamada
<u>A. Chakravarty</u>
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Max-Planck-Institut für
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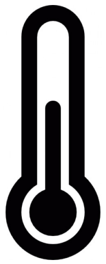
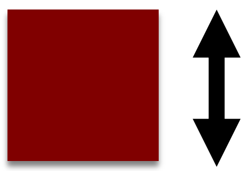
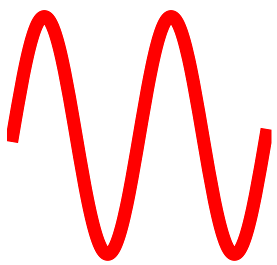
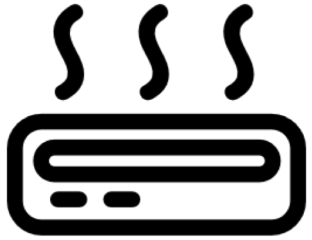
JGU

SPICE
SPIN PHENOMENA
INTERDISCIPLINARY CENTER

D. Bossini
E.V. Gomonay

NWO
Netherlands Organisation for Scientific Research

Challenges for (Brain-Inspired) Computing

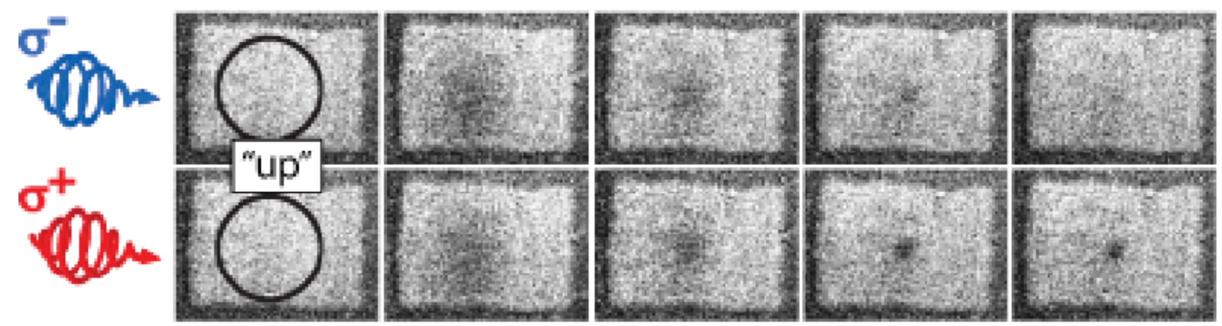
Operation conditions		T=300K P=10^5 Pa	
Dimensions (synapse, neuron)		L ~ nm	
Speed (adaptation time, oscillation period)		f ~ GHz → THz → PHz	
Energy (dissipated)		E ~ nJ → fJ → .. → zJ Landauer limit	

Potential of Ultrafast Magnetism

→ Faster than using electricity

All-optical switching of ferrimagnets as fast as 30 ps

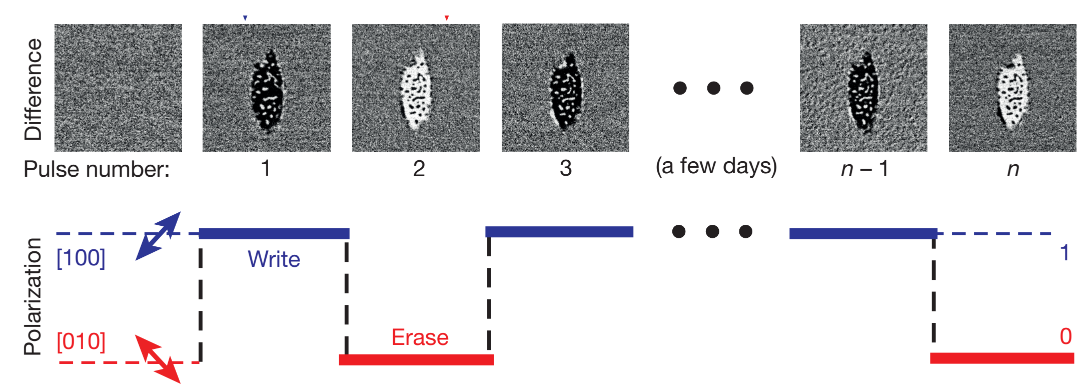
Vahaplar *et al.*, PRL 2009



→ More energy efficient

Photomagnetic recording in oxides with projected heat load down to 22 aJ/bit

Stupakiewicz *et al.*, Nature 2017



→ Possible even in technologically relevant materials

All-optical control in Co/Pt systems

Lambert *et al.*, Science 2014

First results

Experimental demonstration of artificial neural network using ultrafast optical control of Co/Pt thin films

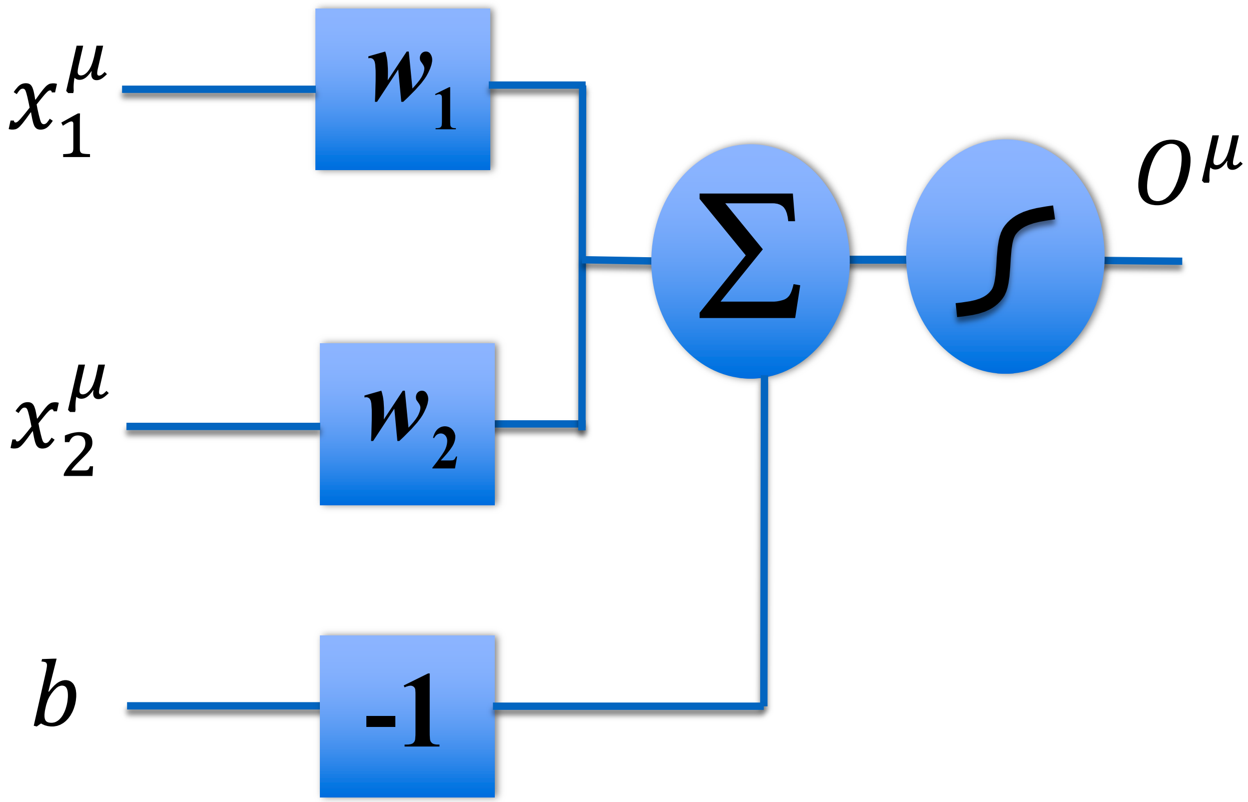
A. Chakravarty, JHM, C.S. Davies, K. Yamada, A.V. Kimel and Th. Rasing
Appl. Phys. Lett. 114, 192407 (2019)

Theoretical demonstration that artificial neural networks can simulate otherwise unsolvable nonequilibrium quantum dynamics of magnetic materials

G. Fabiani and JHM
SciPost Physics 7, 004 (2019)

Supervised learning

Perceptron model



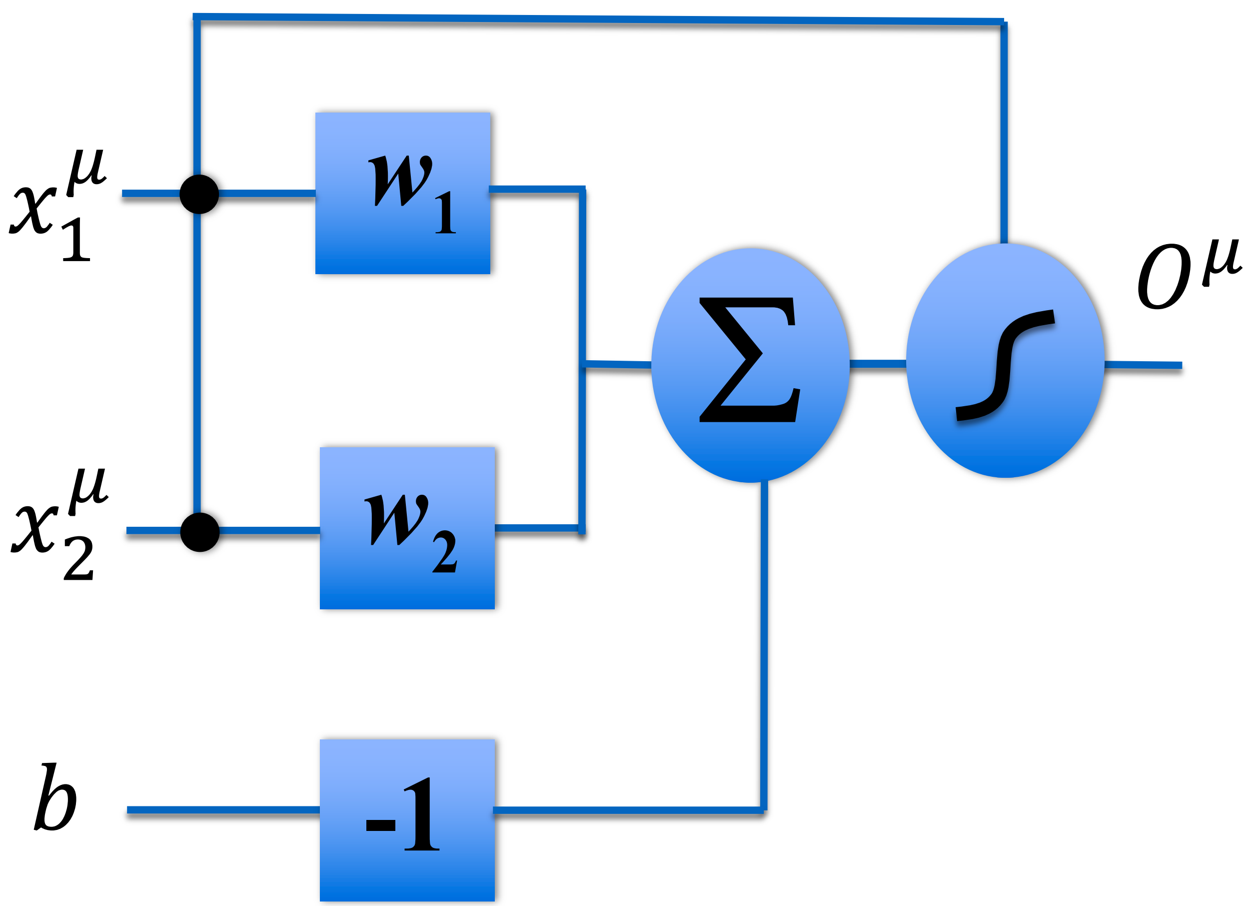
$$O^\mu = \mathrm{sign}\left(\sum_i y_i^\mu - b\right)$$

$$y_i^\mu = w_i x_i^\mu$$

Supervised learning

Perceptron model

$$E = \mathrm{sign}(O_d^\mu - O_d)$$



$$O^\mu = \mathrm{sign}\left(\sum_i y_i^\mu - b\right)$$

$$y_i^\mu = w_i x_i^\mu$$

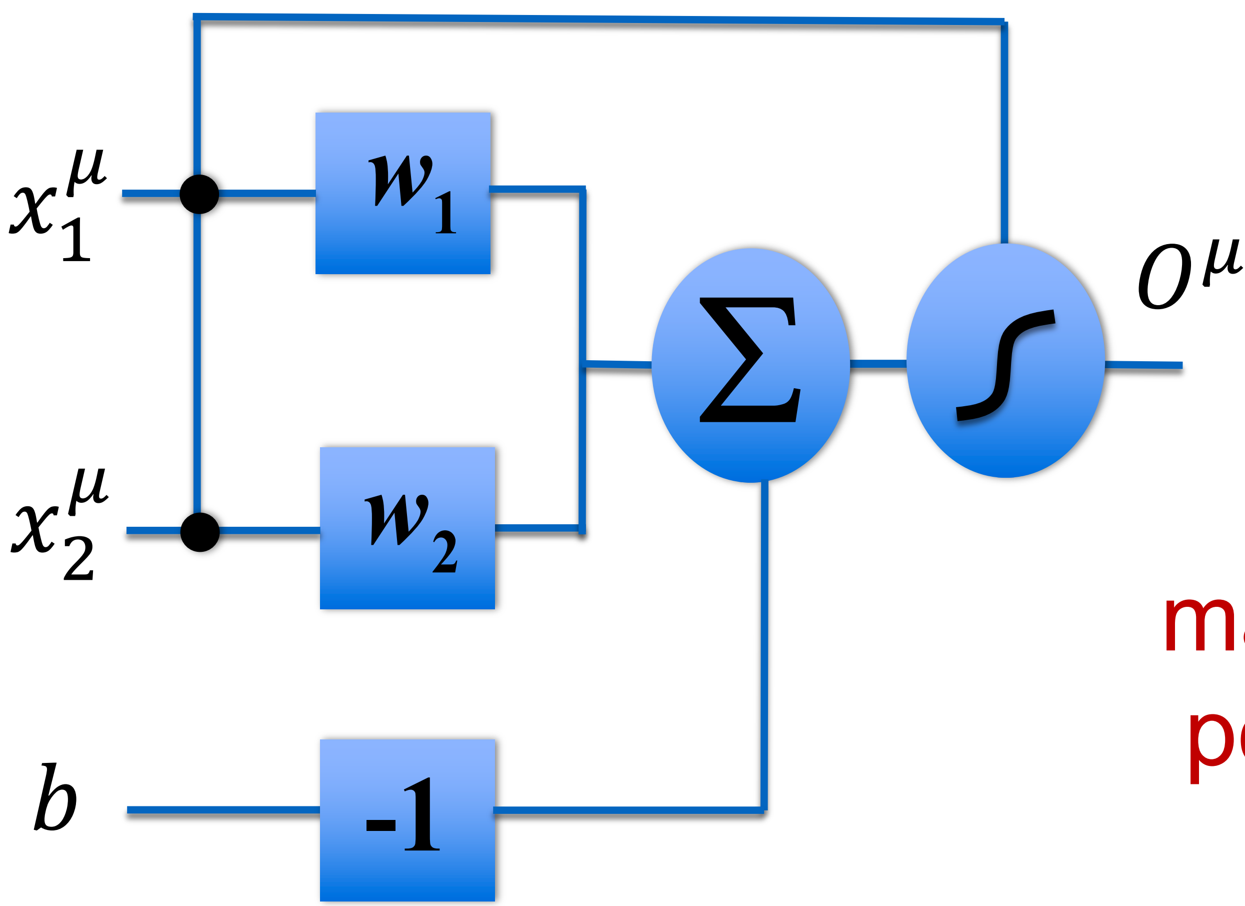
$$\Delta w_i = \eta\, E\, x_i^\mu$$

Learning requires global feedback only!

Supervised learning

Perceptron model

$$E = \mathrm{sign}(O_d^{\mu} - O_d)$$



$$O^{\mu} = \mathrm{sign}\left(\sum_i y_i^{\mu} - b\right)$$

$$\boxed{y_i^{\mu} = w_i x_i^{\mu}}$$

magneto-optical probing
polarization microscope

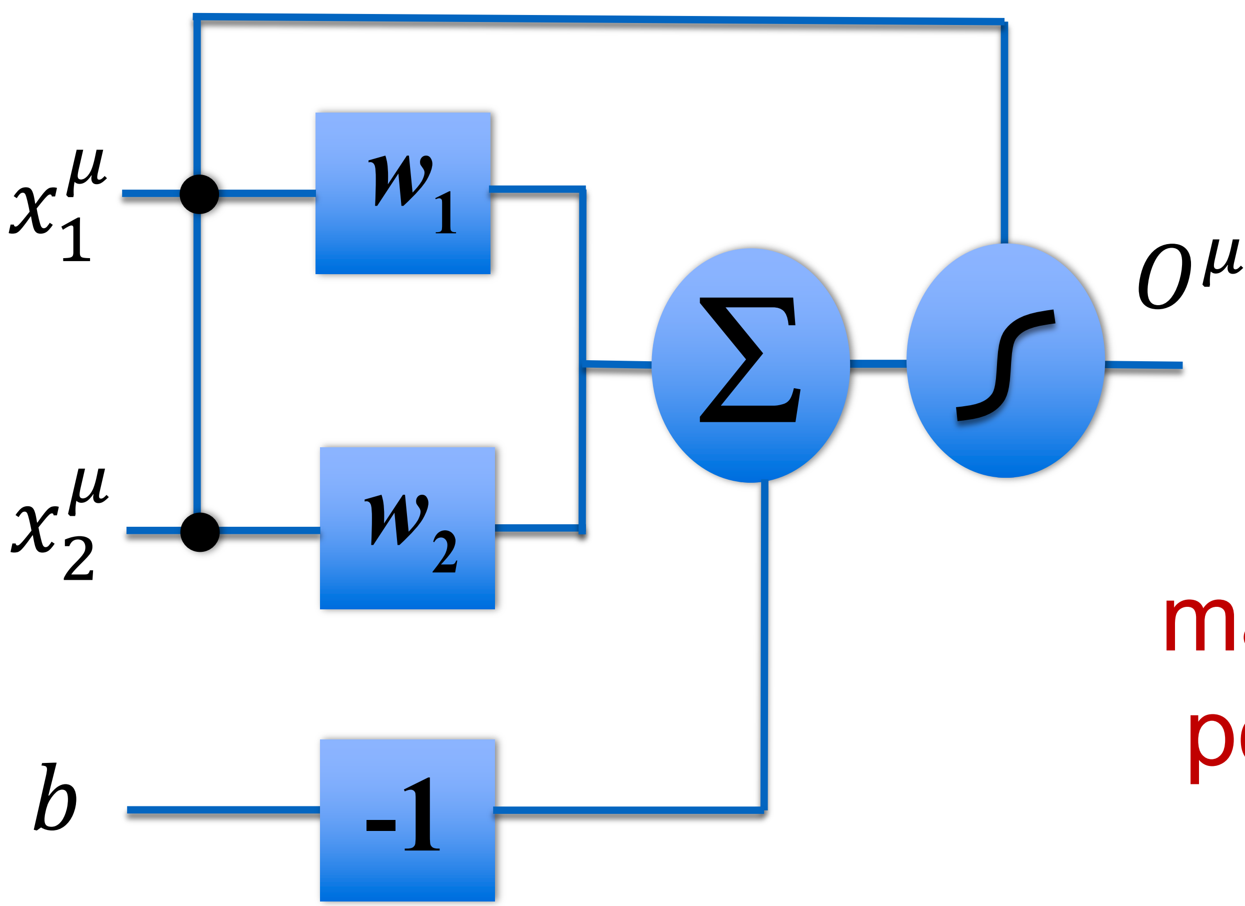
$$\Delta w_i = \eta\, E\, x_i^{\mu}$$

x_i^{μ} light/no light

Supervised learning

Perceptron model

$$E = \mathrm{sign}(O_d^\mu - O_d)$$



$$O^\mu = \mathrm{sign}\left(\sum_i y_i^\mu - b\right)$$

$$\boxed{y_i^\mu = w_i x_i^\mu}$$

magneto-optical probing
polarization microscope

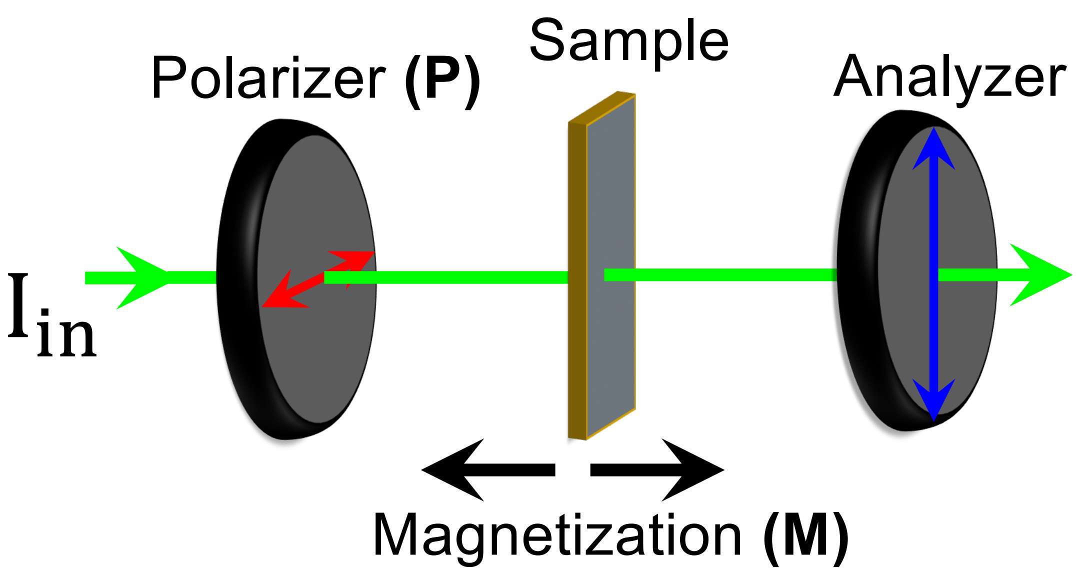
$$\Delta w_i = \boxed{\eta\ E}\, x_i^\mu$$

x_i^μ light/no light

η number of pump pulses
E right/left circular polarization

Magneto-optical synapses

Multiplication realized by polarization microscope

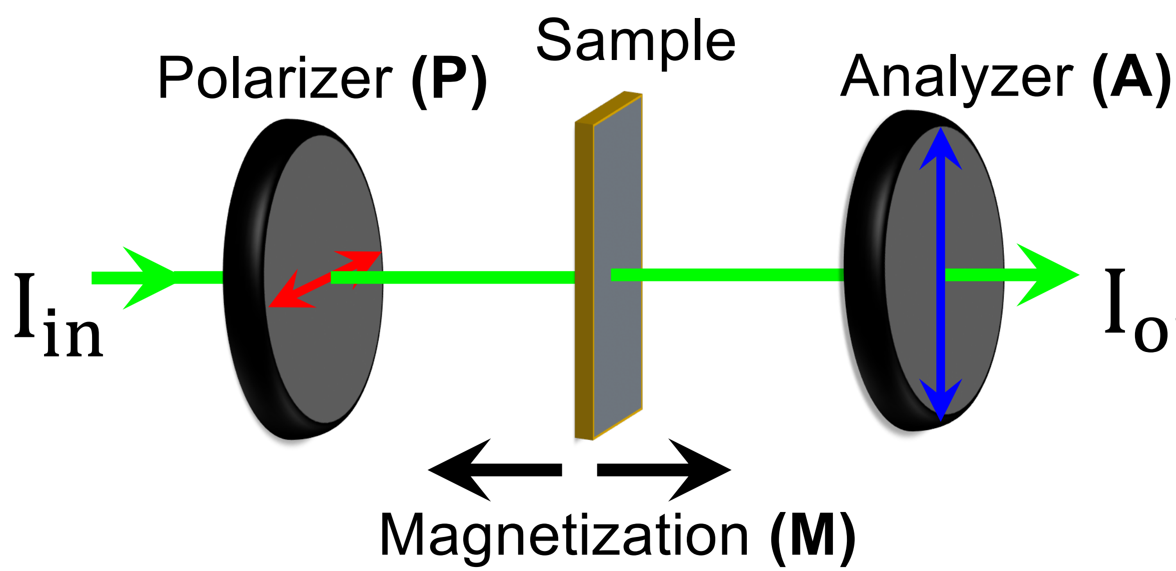


$$I_{out} = K M I_{in}$$

$$KM = w_i$$

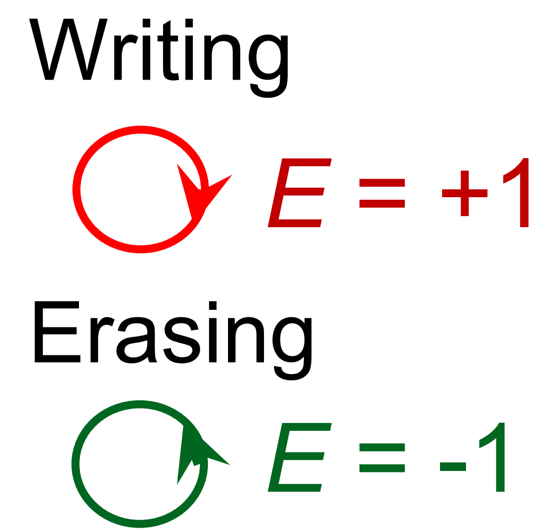
Magneto-optical synapses

Multiplication realized by polarization microscope

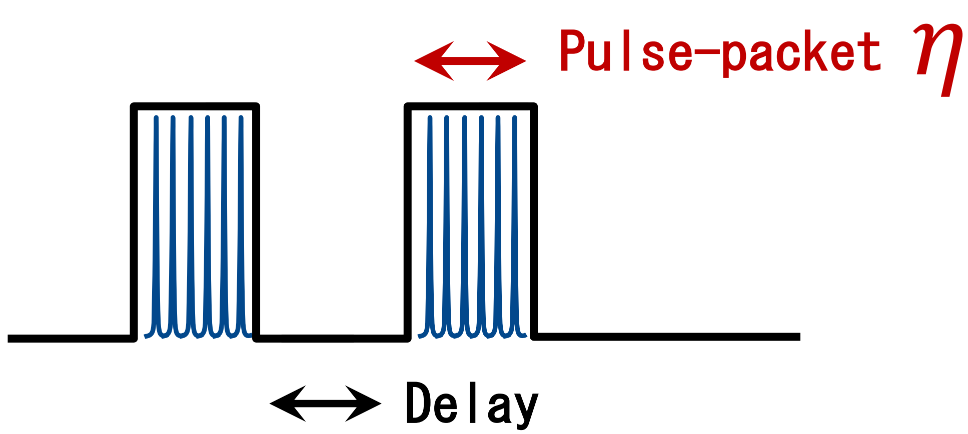


$$I_{out} = KMI_{in}$$

$$KM = w_i$$



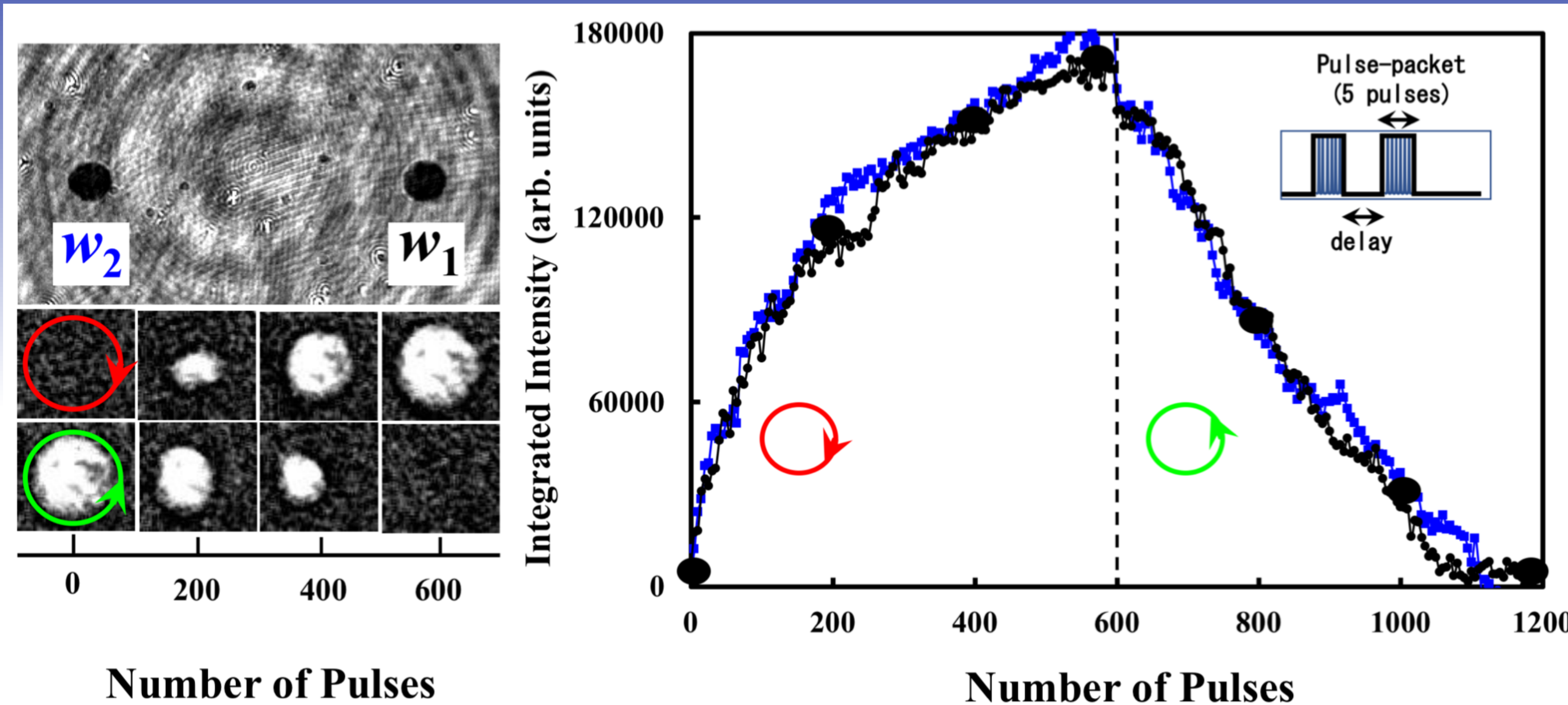
Gradual changes of *M* needed: Co/Pt thin fims



Fullerton, Magnin, Aeschlimann et al., Science 2014

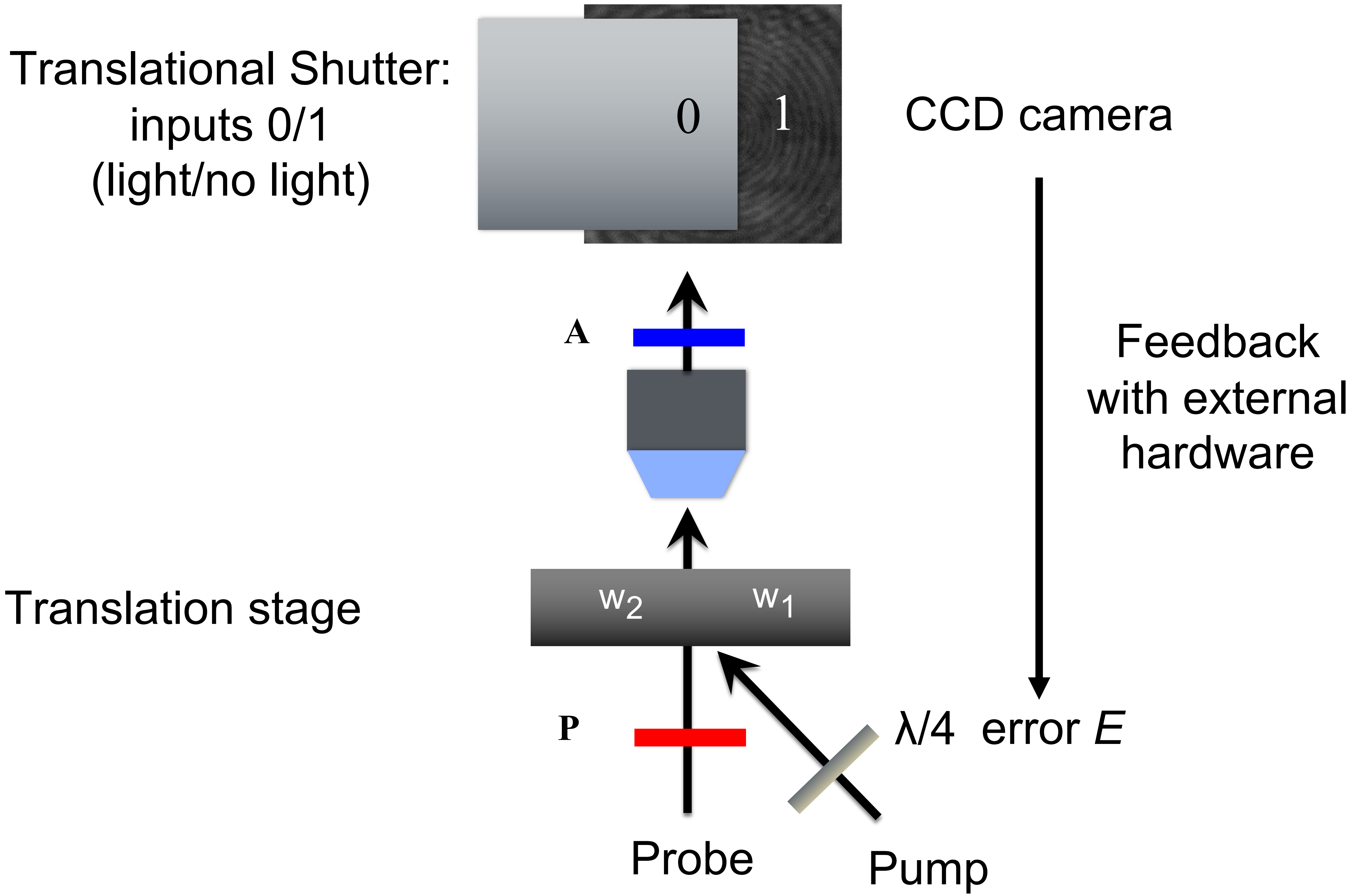
R. Medapalli et al, Phys. Rev.B 96, 224421 (2017)

Continously variable weights

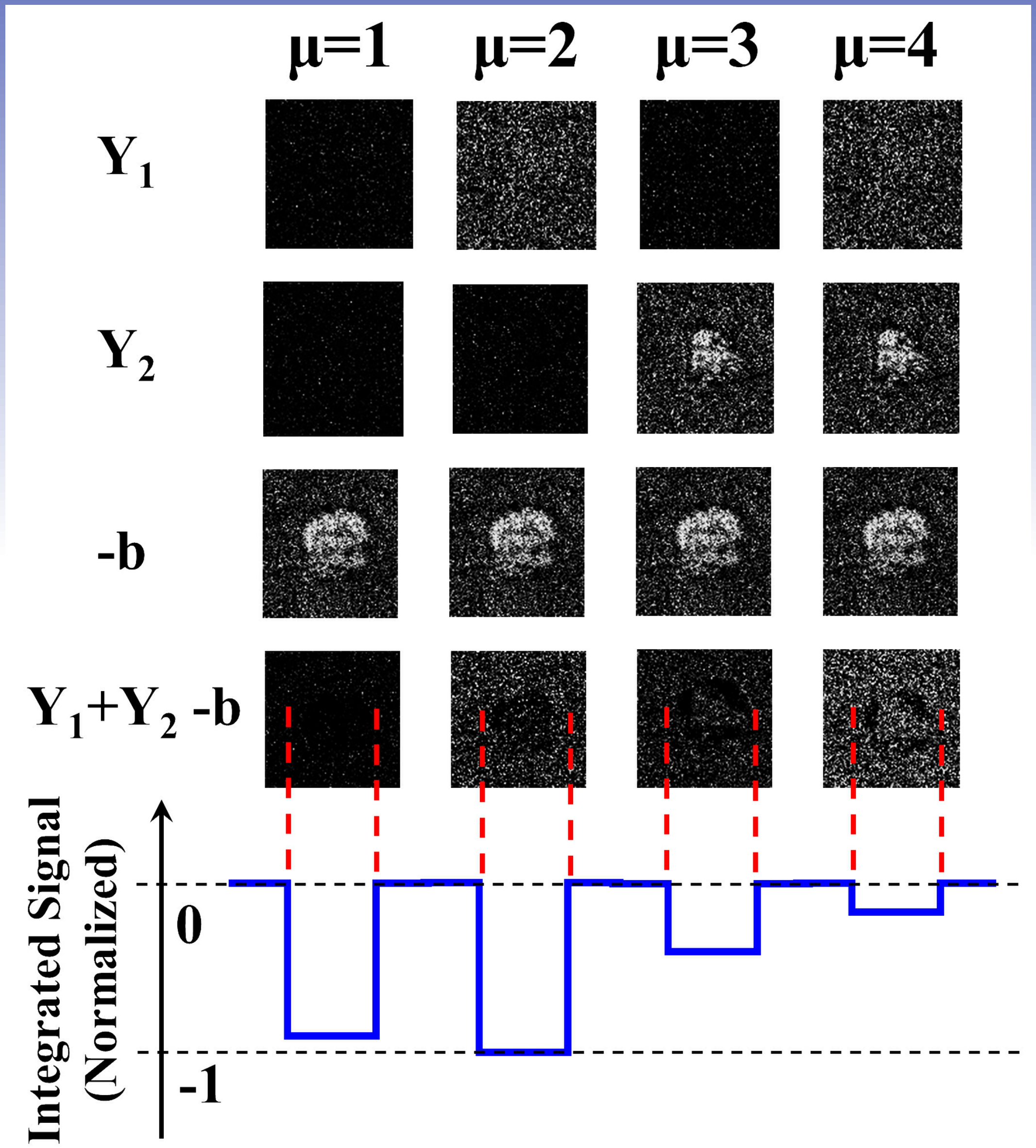


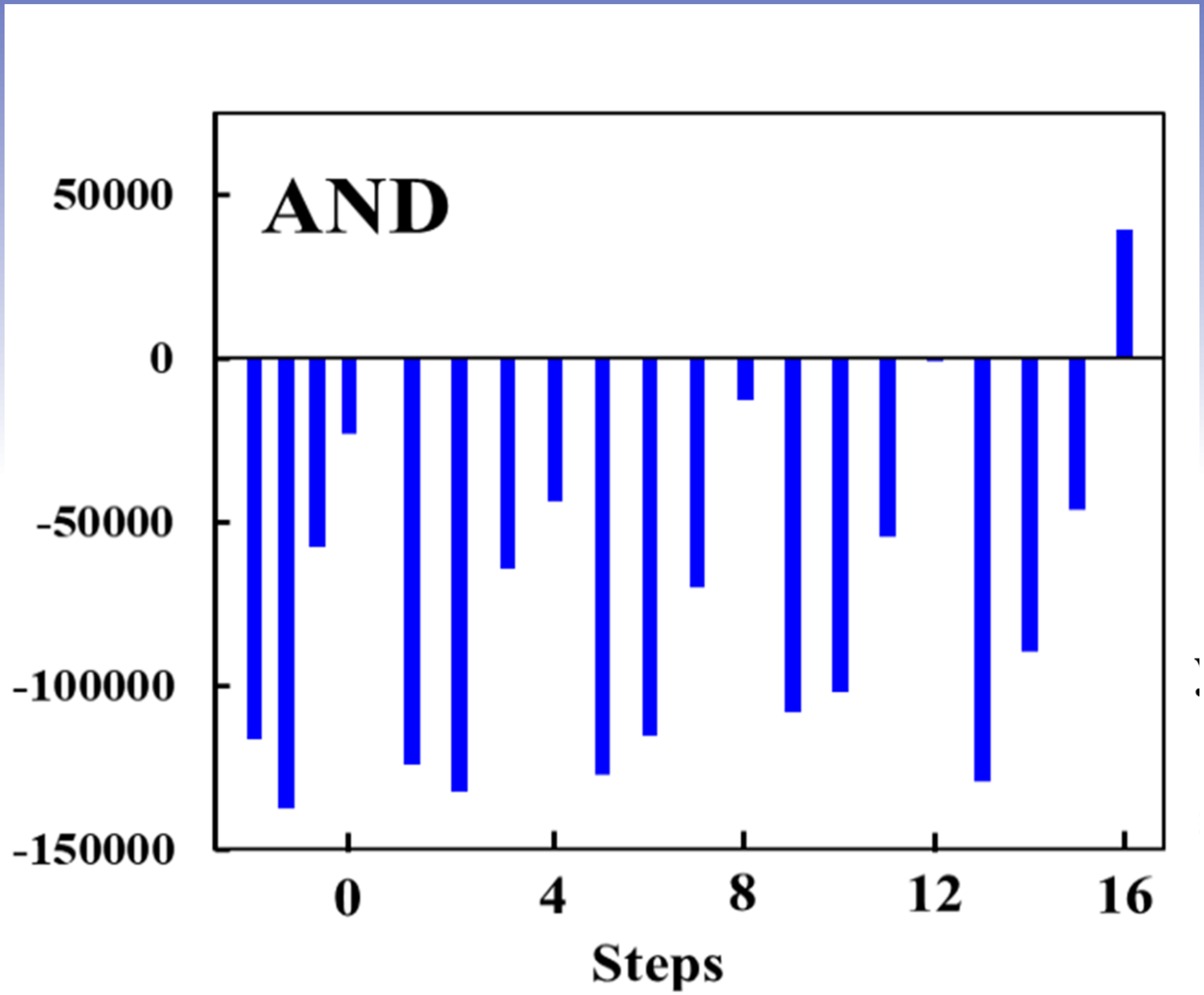
Reproducible adaptation of weights with
circularly polarized laser pulses
pulse width 4 ps, 5 pulses/packet fluence 1.3mJ/cm^2

Artificial neural network

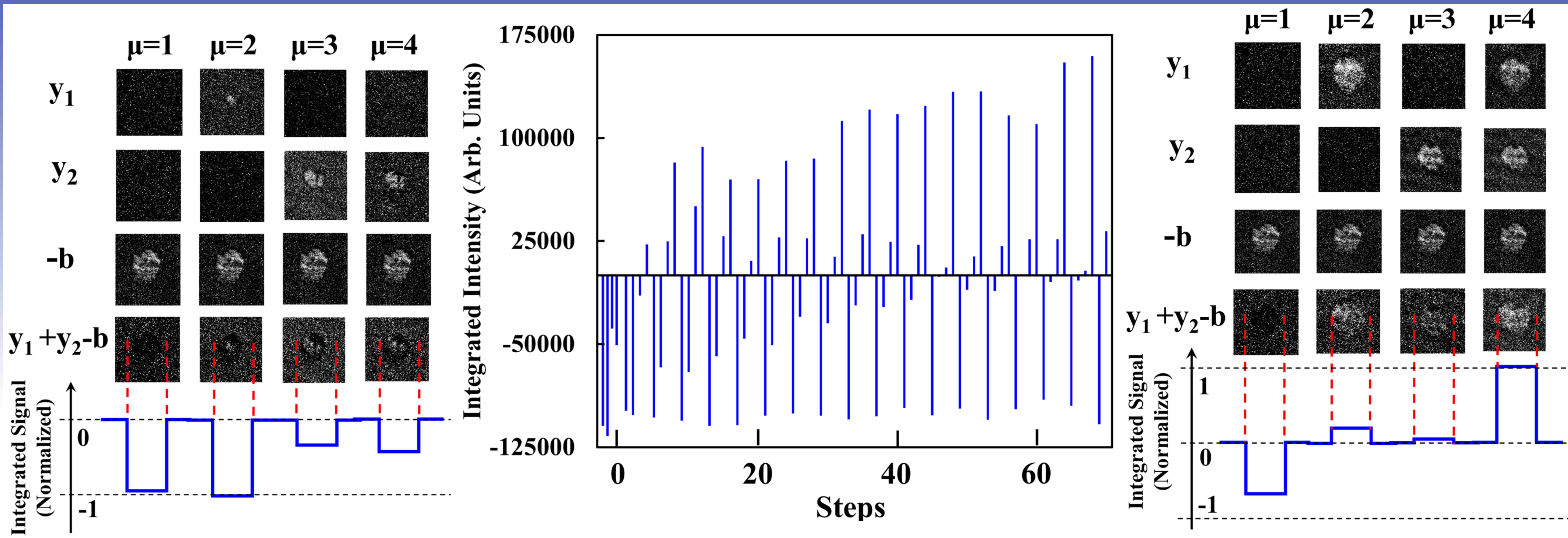


AND function





OR function


μ=1
μ=2
μ=3
μ=4
y_1
y_2
-b
y_1+y_2-b
Integrated Signal (Normalized)
0
-1
175000
100000
25000
-50000
-125000
Integrated Intensity (Arb. Units)
0
20
40
60
Steps
1

Opto-magnetic neural network

✓ Realization of opto-magnetic synapses using ultrashort laser pulses on Co/Pt films

✓ Supervised learning with opto-magnetic synapes

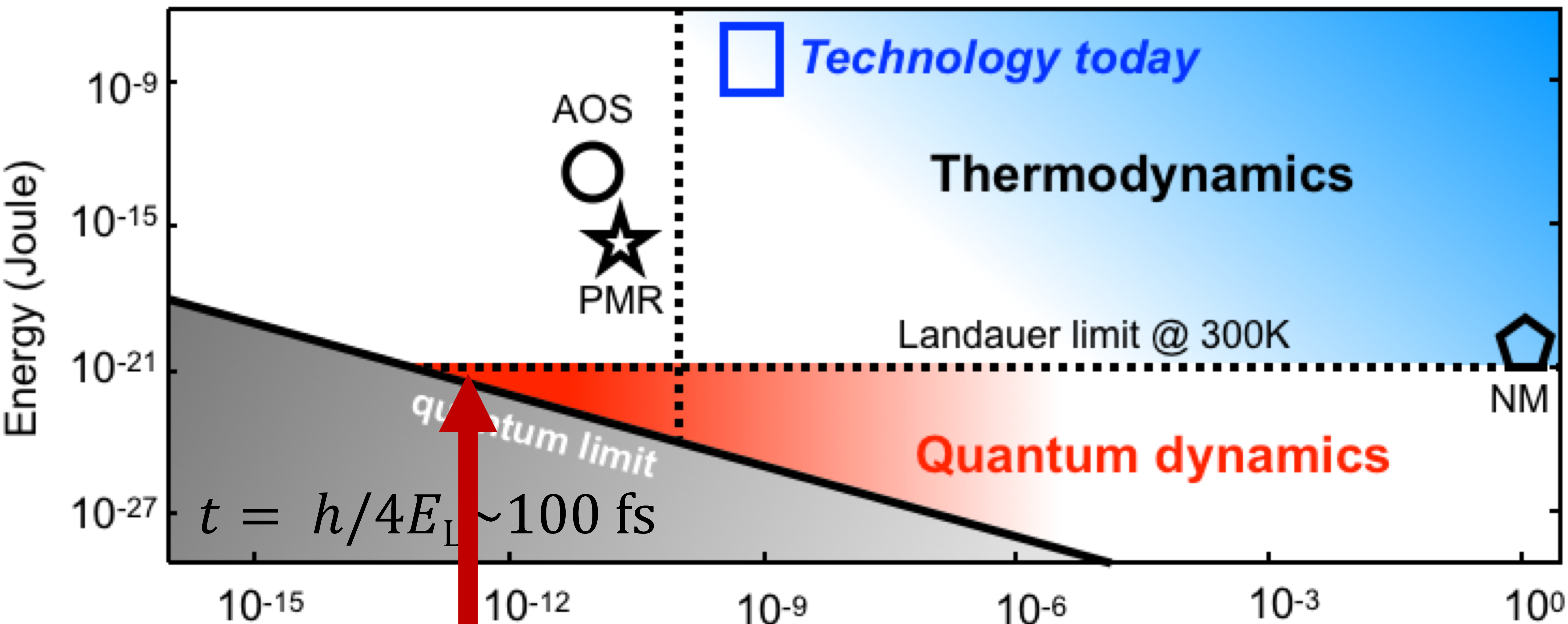
✓ Optimization with global feedback only
→ No external storage needed

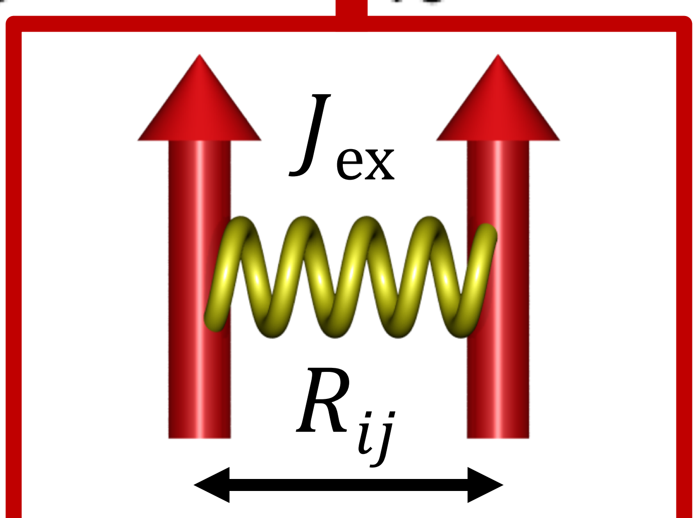
✓ Energy absorbed: 65 pJ/synapse/step (1.125 μm)
→ Extrapolates to 20 fJ/synapse/step (20 nm)

Appl. Phys. Lett. 114, 192407 (2019)

Next steps: more/smaller, implement backpropagation

Physical limits of computing





$E_L = k_B T \ln 2 = 3$ zJ = 20 meV

$E_{ex} = J_{ex} \vec{S}_1 \vec{S}_2 \sim 20$ meV

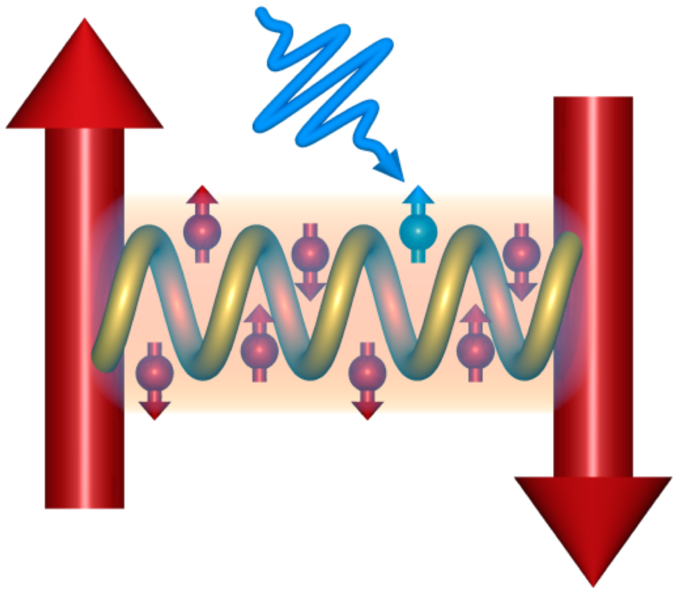
interaction range $R_{ij} \sim$ nm

AOS: Stanci
PMR: A. Stu
NM: J. Hong

Topical Review

Manipulating magnetism by ultrafast control of the exchange interaction

J H Mentink 2017 *J. Phys.: Condens. Matter* **29** 453001

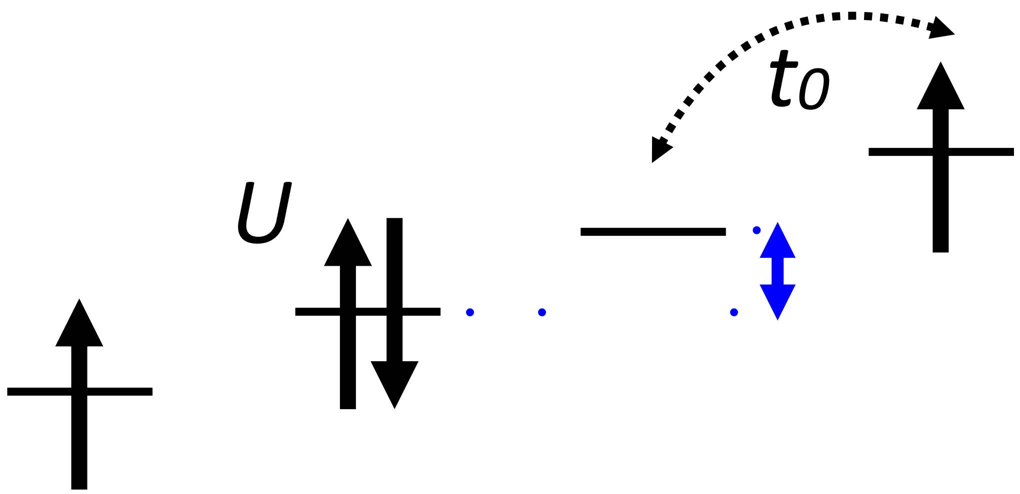


Control Jex in Mott-Hubbard systems
- Photo-doping
- *Non-resonant driving*

Manipulation of magnetism
- Excitation of spin precession
- Ultrafast cooling`
- Effective time-reversal
- *Time-resolved two-magnon dynamics*

Single-band Hubbard model

$$\hat{H} = \underbrace{-t_0 \sum_{\langle ij\rangle\sigma} e^{-\mathrm{i}[\Phi_i(t)-\Phi_j(t)]}\hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma}}_{H_{\mathrm{kin}}(t)} + \underbrace{U\sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}}_{V}$$



$$\mathcal{E} = \frac{eaE_0}{\hbar\omega}$$

$$E_0(t) = E_0\cos(\omega t) \qquad \Phi_i(t) - \Phi_j(t) = -\mathcal{E}(\hat{e}\cdot\hat{r}_{ij})\sin(\omega t)$$

Effective low-energy Hamiltonian

$$H = H_{\mathrm{kin}}(t) + V$$

Hilbert space $\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_1$

Low-energy High-energy V has only

Projectors $\mathcal{P}_0$ $\mathcal{P}_1 = 1 - \mathcal{P}_0$ $\mathcal{P}_1 V \mathcal{P}_1 = V_{11}$

Construct S(t) such that no mixing takes place at each time

$$\tilde{H} = e^{\mathrm{i}S(t)} \left(H - \mathrm{i}\partial_t\right) e^{-\mathrm{i}S(t)}$$

$$S(t) = S^{(1)}(t) + S^{(2)}(t) + \ldots$$

$$H_{\mathrm{kin}}(t) + [\mathrm{i}S^{(1)}(t), V] - \partial_t S^{(1)}(t) = 0$$

Bukov et al., *PRL* **116**, 125301 (2016)
Canovi et al., *PRE* **93** 012130 (2016)
Eckstein et al., arXiv:1703.03269 (2017)

Light-perturbation to J_{ex}

$$\tilde{H}^{(2)} = e^{\mathrm{i}\hat{S}^{(1)}(t)} \left(\hat{H} - \mathrm{i}\partial_t\right) e^{-\mathrm{i}\hat{S}^{(1)}(t)} \xrightarrow[\text{Time-averaging}]{} H_0 + \delta H$$

Half-filling (one electron per site)

$$H_0 = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j, \quad J = 2t_0^2/U$$

Simple cubic lattice, weak fields $\mathcal{E} \ll 1$

$$\delta H = \Delta J \sum_{\langle ij \rangle} (\hat{e} \cdot \hat{r}_{ij})^2 \, \mathbf{S}_i \cdot \mathbf{S}_j, \quad \Delta J = \frac{t_0^2}{2U} \frac{\omega^2 \mathcal{E}^2}{U^2 - \omega^2}$$

$$\mathcal{E} = \frac{eaE_0}{\hbar\omega}$$

Only bonds along the field perturbed

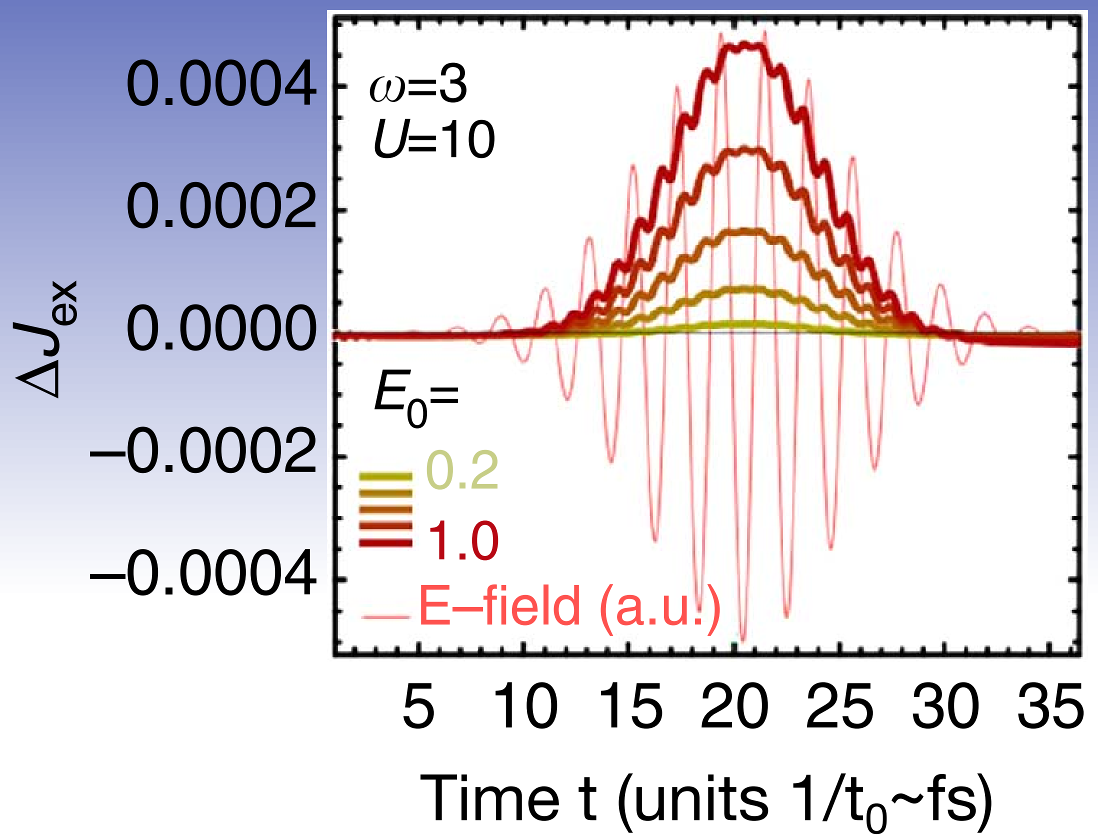
J_{ex} stronger/weaker below/above gap

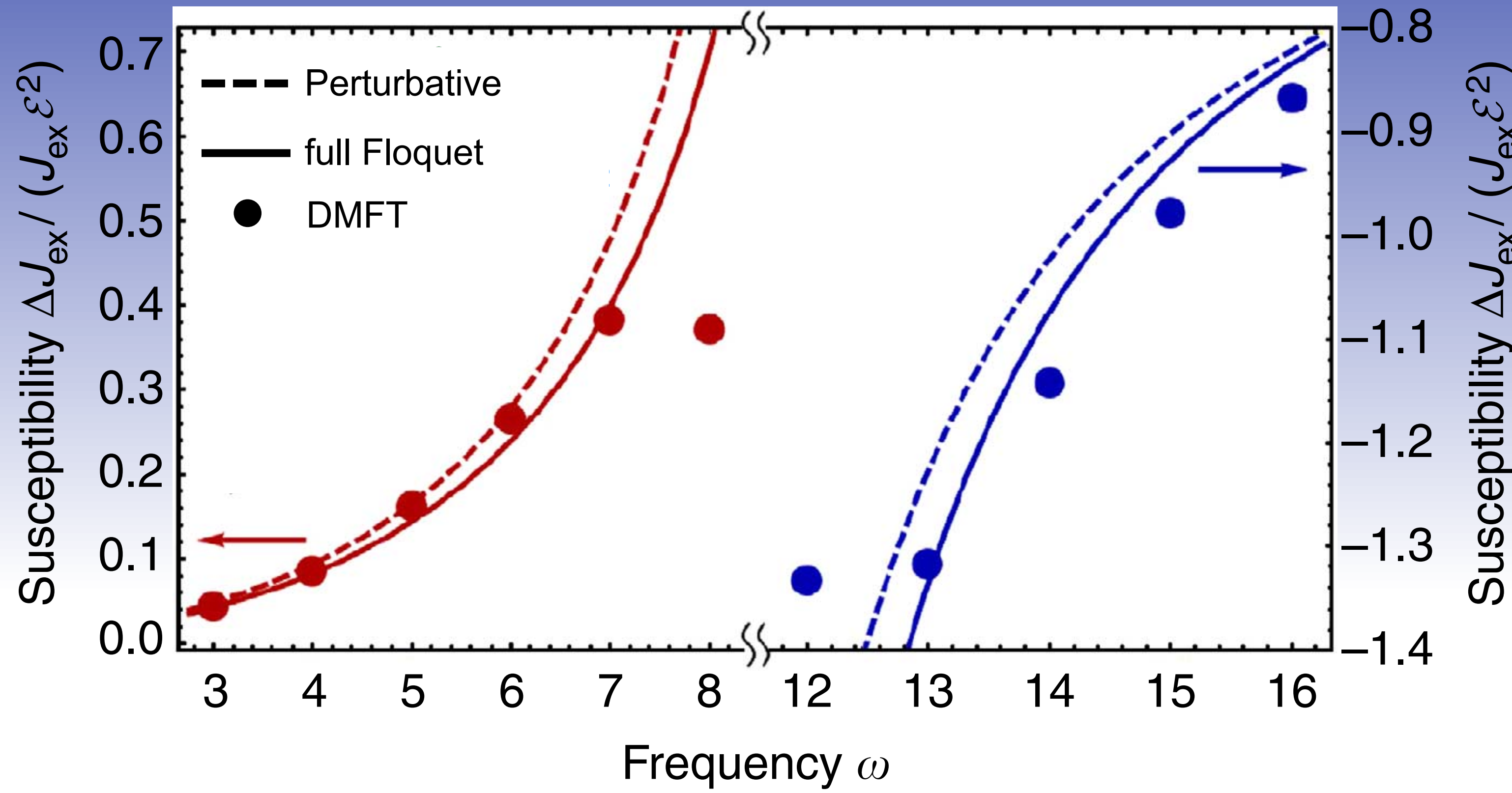
Floquet theory: Mentink et al., *Nat. Commun.* 2015

High-frequency expansion: Itin, *PRL* 2015

Time-dependent Schrieffer-Wolff: Bukov et al., *PRL* 2016

Nonequilibrium DMFT

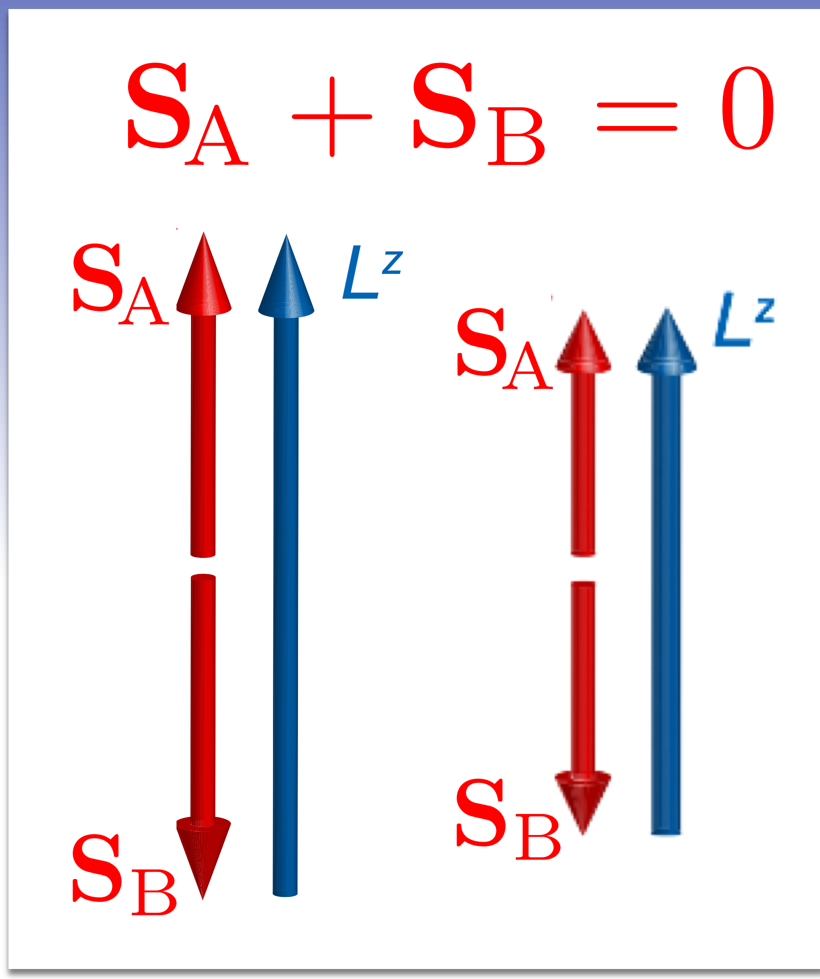




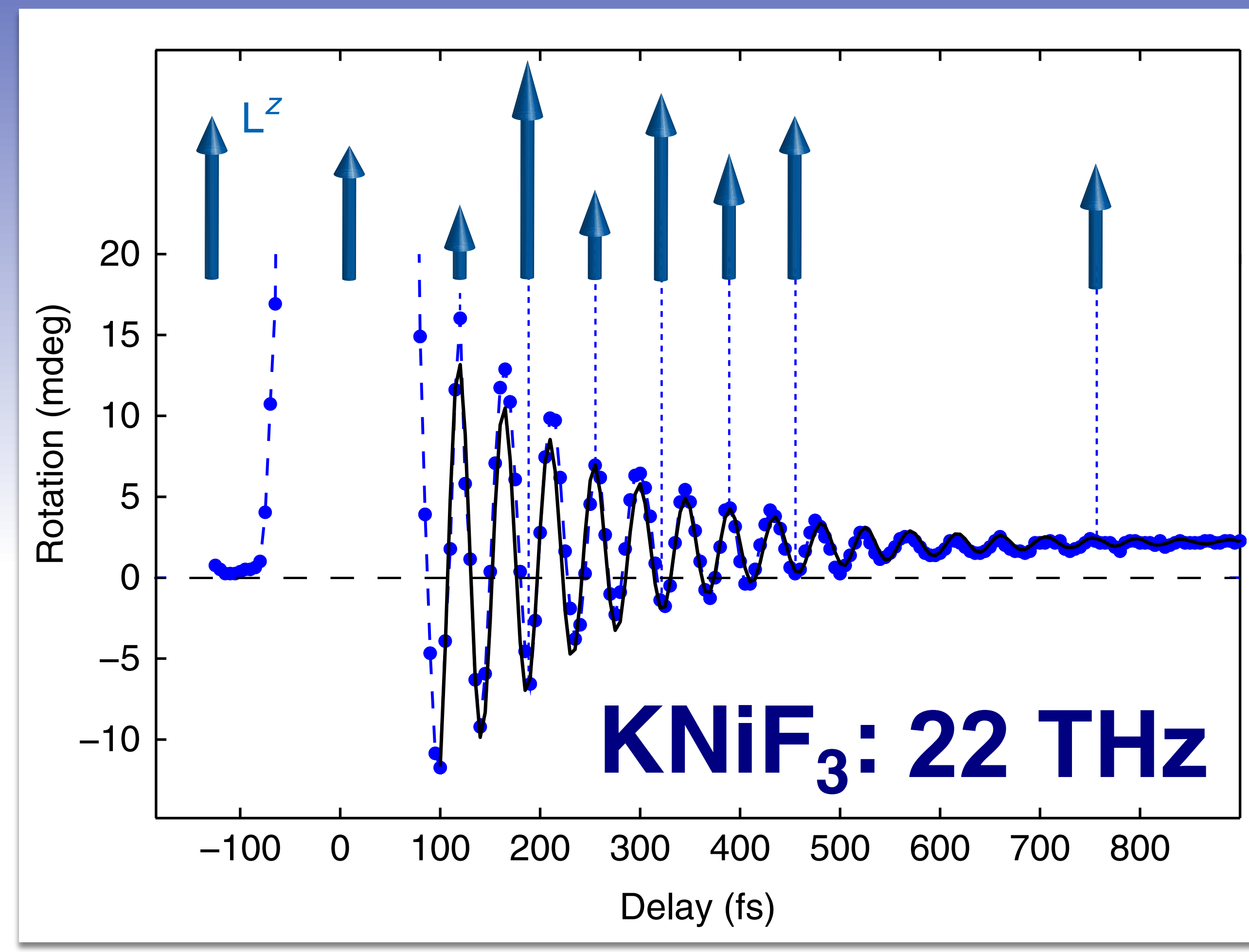
Non-equilibrium DMFT:
Aoki et al., RMP 2014

More general exchange formulas:
J.H. Mentink and M. Eckstein, PRL 2014
R.V. Mikhaylovskiy, et al. *Nat. Commun.* 2015

Quantum spin dynamics in solid state



$$\mathbf{L} = \mathbf{S}_\mathrm{A} - \mathbf{S}_\mathrm{B}$$



- **Coherent** *longitudinal* dynamics of magnetic order parameter

Zhao et al., *PRL* 2004, *PRB* 2006, D. Bossini et al. *Nat. Commun.* (2016)

Magnon-pair description

Holstein-Primakov + Bougoliubov transform

$$H_0 \sim \sum_{\mathbf{k}} \omega_{\mathbf{k}} \quad 2\hat{K}^z_{\mathbf{k}}$$

Simple cubic lattice

$$\omega_{\mathbf{k}} = zJS\sqrt{1-\gamma_{\mathbf{k}}^2} \qquad \gamma_{\mathbf{k}} = \tfrac{1}{z}\textstyle\sum_{\boldsymbol{\delta}} \exp(i\mathbf{k}\cdot\boldsymbol{\delta}) = \frac{1}{3}\sum_{i=xyz}\cos(k_i a)$$

$$\delta H \sim \sum_{\mathbf{k}} \delta\omega_{\mathbf{k}} \quad 2\hat{K}^z_{\mathbf{k}} \qquad + V_{\mathbf{k}}\left[\ \hat{K}^-_{\mathbf{k}} \ + \ \hat{K}^+_{\mathbf{k}}\ \right]$$

$$\delta\omega_{\mathbf{k}} = z\Delta JS\frac{1-\xi_{\mathbf{k}}\gamma_{\mathbf{k}}}{\sqrt{1-\gamma_{\mathbf{k}}^2}} \qquad \xi_{\mathbf{k}} = \frac{1}{z}\sum_{\boldsymbol{\delta}}(\hat{e}\cdot\hat{\boldsymbol{\delta}})^2\exp(i\mathbf{k}\cdot\boldsymbol{\delta}) = \frac{1}{3}\sum_{i=xyz}\hat{e}_i^2\cos(k_i a)$$

$$V_{\mathbf{k}} = z\Delta JS\frac{\xi_{\mathbf{k}}-\gamma_{\mathbf{k}}}{\sqrt{1-\gamma_{\mathbf{k}}^2}}$$

Magnon-pair commutators

$$\hat{K}^z_{\mathbf{k}} = (\hat{\alpha}^\dagger_{\mathbf{k}}\hat{\alpha}_{\mathbf{k}} + \hat{\beta}^\dagger_{-\mathbf{k}}\hat{\beta}_{-\mathbf{k}} + 1)/2,$$
$$\hat{K}^+_{\mathbf{k}} = \hat{\alpha}^\dagger_{\mathbf{k}}\hat{\beta}^\dagger_{-\mathbf{k}},$$
$$\hat{K}^-_{\mathbf{k}} = \hat{\alpha}_{\mathbf{k}}\hat{\beta}_{-\mathbf{k}}.$$

Bose commutator relations

$$[\alpha_{\mathbf{k}}, \alpha^\dagger_{\mathbf{k}}] = 1$$
$$[\beta_{\mathbf{k}}, \beta^\dagger_{\mathbf{k}}] = 1$$

$$[\hat{K}^z_{\mathbf{k}}, \hat{K}^\pm_{\mathbf{k}}] = \pm\hat{K}^\pm_{\mathbf{k}}, \quad [\hat{K}^-_{\mathbf{k}}, \hat{K}^+_{\mathbf{k}}] = 2\hat{K}^z_{\mathbf{k}}$$

SU(1,1), hyperbolic / Perelomov operators

Casimir invariant:

$$\hat{Q} = \frac{1}{2}\left(\hat{K}^+_{\mathbf{k}}\hat{K}^-_{\mathbf{k}} + \hat{K}^-_{\mathbf{k}}\hat{K}^+_{\mathbf{k}}\right) - \left(\hat{K}^z_{\mathbf{k}}\right)^2 = \frac{1}{4}\left(1 - \Delta^2_{\mathbf{k}}\right)$$

$$\Delta_{\mathbf{k}} = \hat{\alpha}^\dagger_{\mathbf{k}}\hat{\alpha}_{\mathbf{k}} - \hat{\beta}^\dagger_{-\mathbf{k}}\hat{\beta}_{-\mathbf{k}}$$

Only equal changes of sublattices

Free dynamics ($\Delta J=0 \rightarrow V_k=0$)

$$[\hat{K}^z_{\mathbf{k}}, \hat{K}^{\pm}_{\mathbf{k}}] = \pm\hat{K}^{\pm}_{\mathbf{k}}, \quad [\hat{K}^-_{\mathbf{k}}, \hat{K}^+_{\mathbf{k}}] = 2\hat{K}^z_{\mathbf{k}}$$

$$\hat{K}^{\pm}_{\mathbf{k}}(t) = \hat{K}^{\pm}_{\mathbf{k}} e^{\pm i 2\omega_{\mathbf{k}} t}, \quad \hat{K}^z_{\mathbf{k}}(t) = \hat{K}^z_{\mathbf{k}}$$

$$\sum_{\langle i,j\rangle} \hat{S}^z_i(t)\hat{S}^z_j(t) = -\frac{zN}{2}S(S+1) + zS\sum_{\mathbf{k}} g_{\mathbf{k}}\, 2\hat{K}^z_{\mathbf{k}} \boxed{- zS\sum_{\mathbf{k}} \gamma_{\mathbf{k}} g_{\mathbf{k}} \left[\hat{K}^+_{\mathbf{k}}(t) + \hat{K}^-_{\mathbf{k}}(t)\right]}$$

$$\frac{1}{2}\sum_{\langle i,j\rangle} \hat{S}^+_i(t)\hat{S}^-_j(t) + \hat{S}^-_i(t)\hat{S}^+_j(t) = zS\sum_{\mathbf{k}} \gamma^2_{\mathbf{k}} g_{\mathbf{k}}\, 2\hat{K}^z_{\mathbf{k}} \boxed{+ zS\sum_{\mathbf{k}} \gamma_{\mathbf{k}} g_{\mathbf{k}} \left[\hat{K}^+_{\mathbf{k}}(t) + \hat{K}^-_{\mathbf{k}}(t)\right]}$$

Ising and spin-flip terms play role of kinetic and potential energy

$$\hat{L}_z(t) = \frac{NS}{2} - \frac{1}{zS}\sum_{\langle i,j\rangle} \hat{S}^z_i(t)\hat{S}^z_j(t).$$

Longitudinal dynamics at frequencies $2\omega_{\mathbf{k}}$

Non-classical magnon dynamics

Interaction representation

$$|\Psi(t>0)\rangle = e^{\mathrm{i}\tau\sum_{\mathbf{k}}\left[\bar{V}_{\mathbf{k}}\left(\hat{K}^{+}_{\mathbf{k}}(t)+\hat{K}^{-}_{\mathbf{k}}(t)\right)+\delta\bar{\omega}_{\mathbf{k}}\hat{K}^{z}_{\mathbf{k}}(t)\right]}|\Psi_{\mathrm{G}}\rangle$$

Ground state wave function

$$|\Psi_{\mathrm{G}}\rangle = \Pi_{\mathbf{k}}|0_{\mathbf{k}}\rangle|0_{-\mathbf{k}}\rangle$$

Two-particle coherence: **entangled magnons**

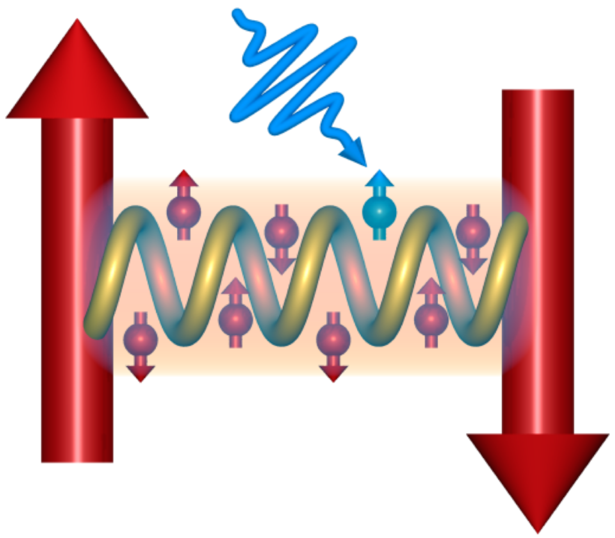
$$\Delta J \ll J$$

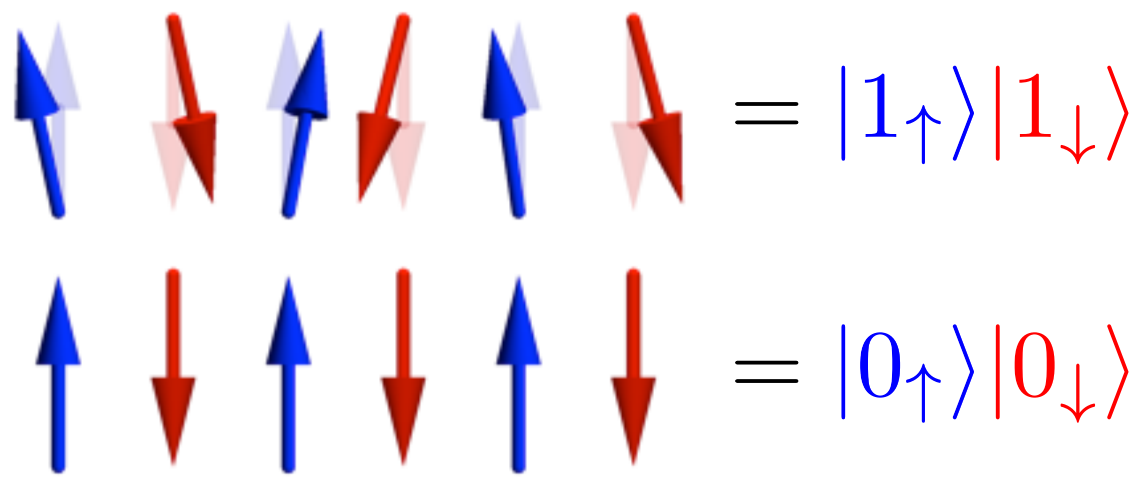
$$|\Psi_{\mathbf{k}}(t>0)\rangle \approx |0_{\mathbf{k}}\rangle|0_{-\mathbf{k}}\rangle + \mathrm{i}V_{\mathbf{k}}e^{\mathrm{i}2\omega_{\mathbf{k}}t}|1_{\mathbf{k}}\rangle|1_{-\mathbf{k}}\rangle$$

D. Bossini, E.V. Gomonay, **J.H. Mentink**, et al.,
PRB 100, 024428 (2019) Editor's suggestion

Non-classical magnon dynamics

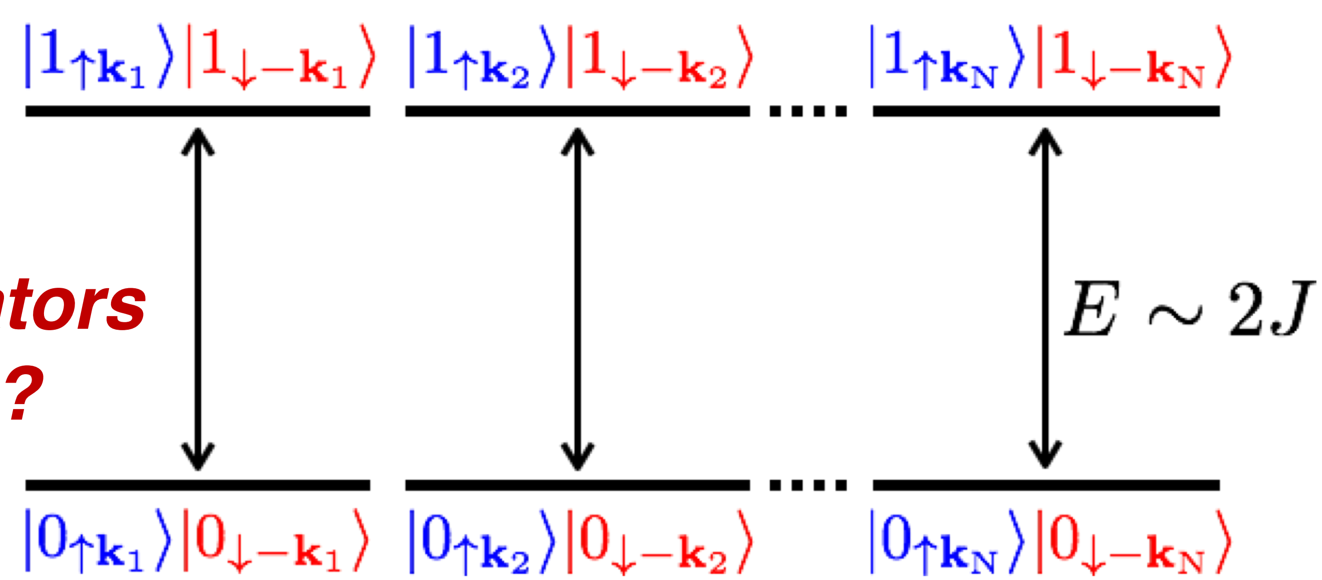
- Perturbation of Jex causes excitation of **magnon-pairs**





- Femtosecond quantum spin dynamics in antiferromagnets
- $\hbar\omega_{2M} > k_B T$: survives at $T_{ambient}$

- **Quantum oscillators for every *k***
  → *Large ensemble nano-oscillators*
  → *Non-linear? Synchronization?*



J.H. Mentink et al., Nat. Commun 2015
J.H. Mentink JPCM 2017
D. Bossini, E.V. Gomonay, **J.H. Mentink**, et al., PRB 100, 024428 (2019)

Non-classical magnon dynamics

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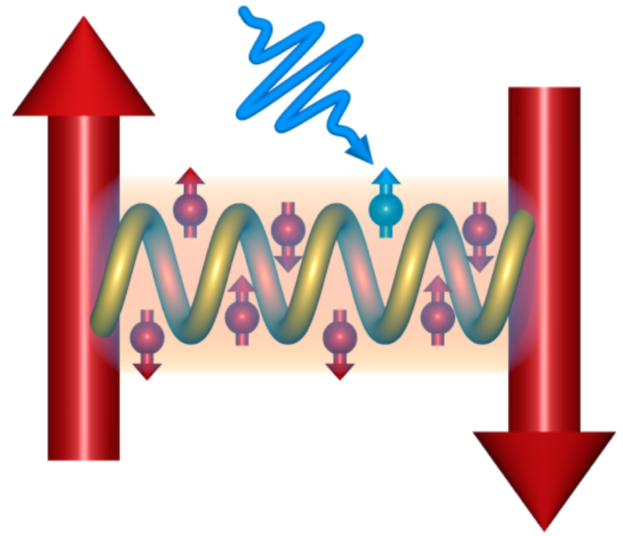
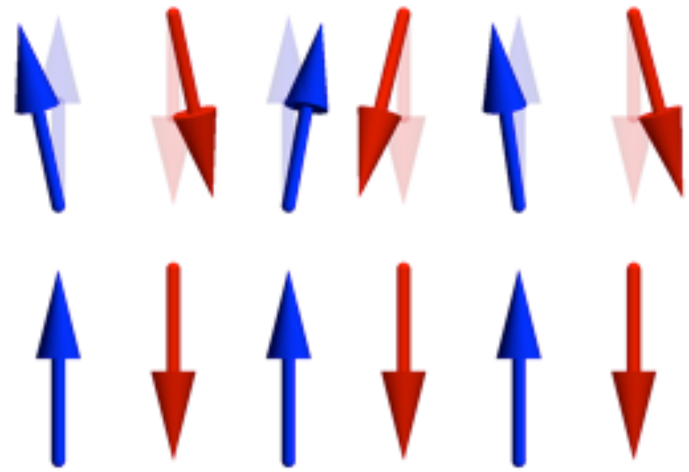




$$= |1_\uparrow\rangle|1_\downarrow\rangle$$

$$= |0_\uparrow\rangle|0_\downarrow\rangle$$

- um spin dynamics in antiferromagnets
- s at $T_{ambient}$

Nanoscale

$|1_{\uparrow \mathbf{k}_1}\rangle|1_{\downarrow -\mathbf{k}_1}\rangle$ $|1_{\uparrow \mathbf{k}_2}\rangle|1_{\downarrow -\mathbf{k}_2}\rangle$ $|1_{\uparrow \mathbf{k}_N}\rangle|1_{\downarrow -\mathbf{k}_N}\rangle$

-

$2J$

J.
J.
D.

Ultrafast Nanoscale Quantum Magnonics

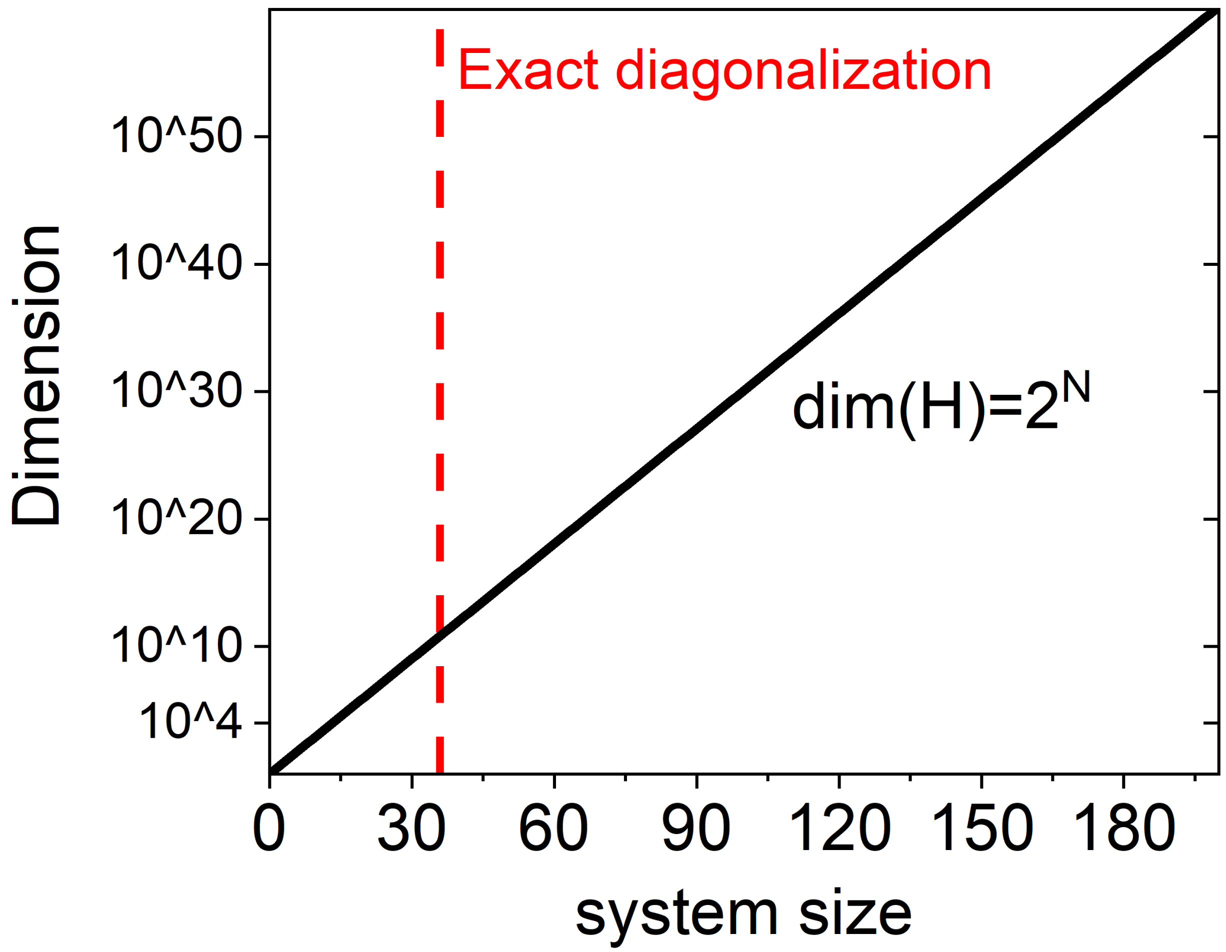
$$\langle S_i(t) S_j(t) \rangle$$

Quantum Many-Body Problem

Minimal model: 2D Heisenberg model $H_0 = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$

Challenge: non-local correlations both in space and time!

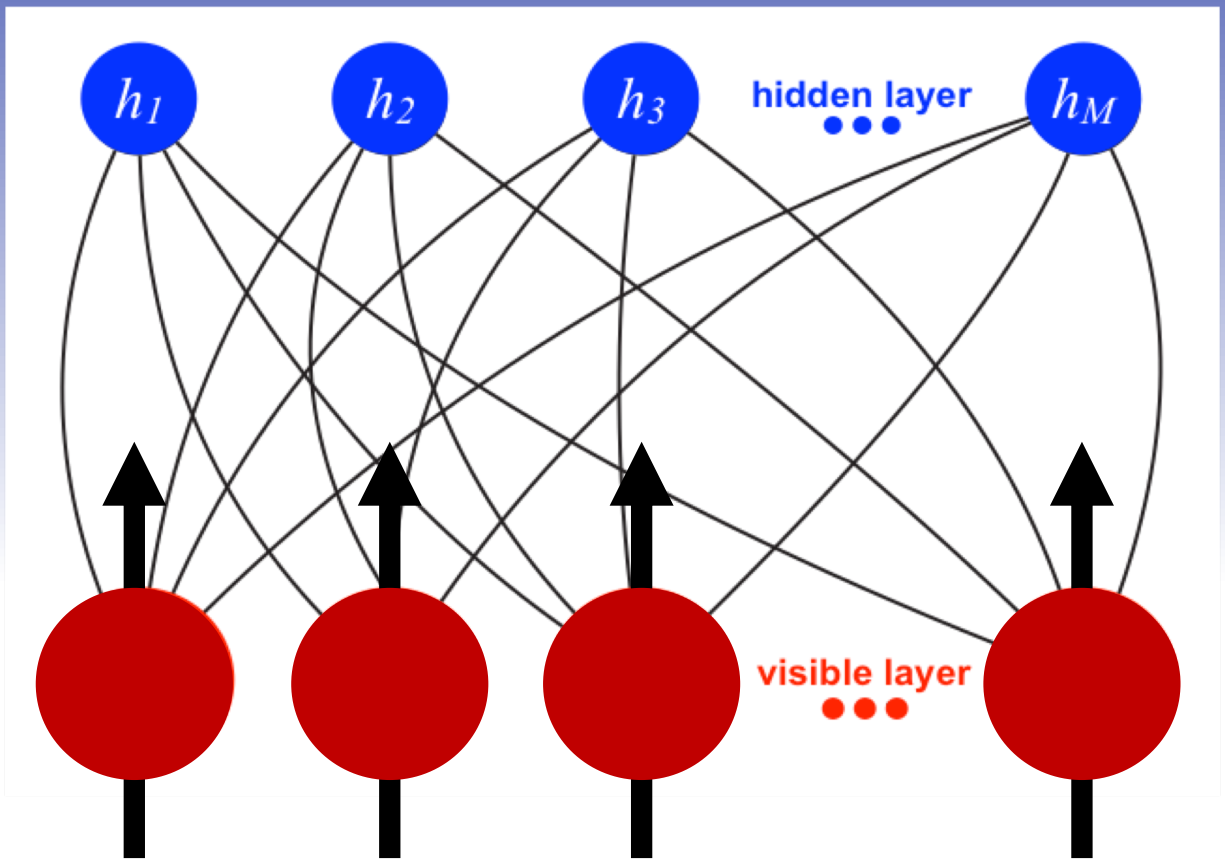
$i\partial_t \Psi(t) = \mathcal{H}(t)\Psi(t)$ impossible for large systems



Existing variational algortihms (DMRG, MPS, PEPS…) capture area-law entanglement

fail with large entanglement (**high-dimension, dynamics**)

Machine Learning in Many-Body physics



Giuseppe Carleo, Matthias Troyer.
"Solving the Quantum Many-Body Problem with Artificial Neural Networks". Science 355, 602 (2017).

Hidden neurons represent correlations: $\alpha = \dfrac{\#\ hidden\ neurons}{\#\ spins}$

PHYSICAL REVIEW X 7, 021021 (2017)

Quantum Entanglement in Neural Network States

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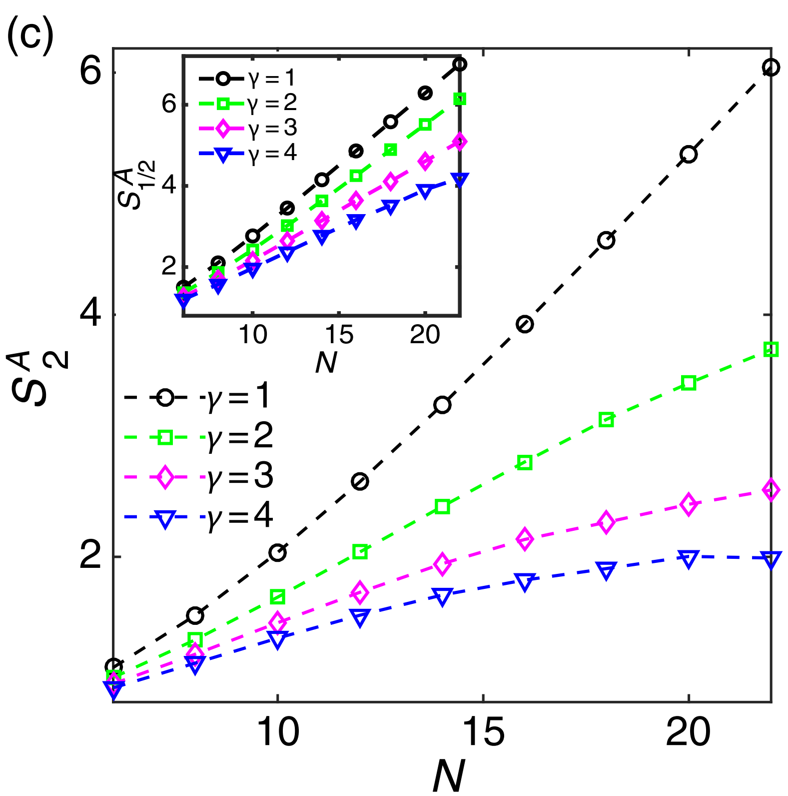
dimensions and bipartition geometry. For long-range RBM states, we show by using an *exact* construction that such states could exhibit volume-law entanglement, implying a notable capability of RBM in representing quantum states with massive entanglement. Strikingly, the neural-network representation for

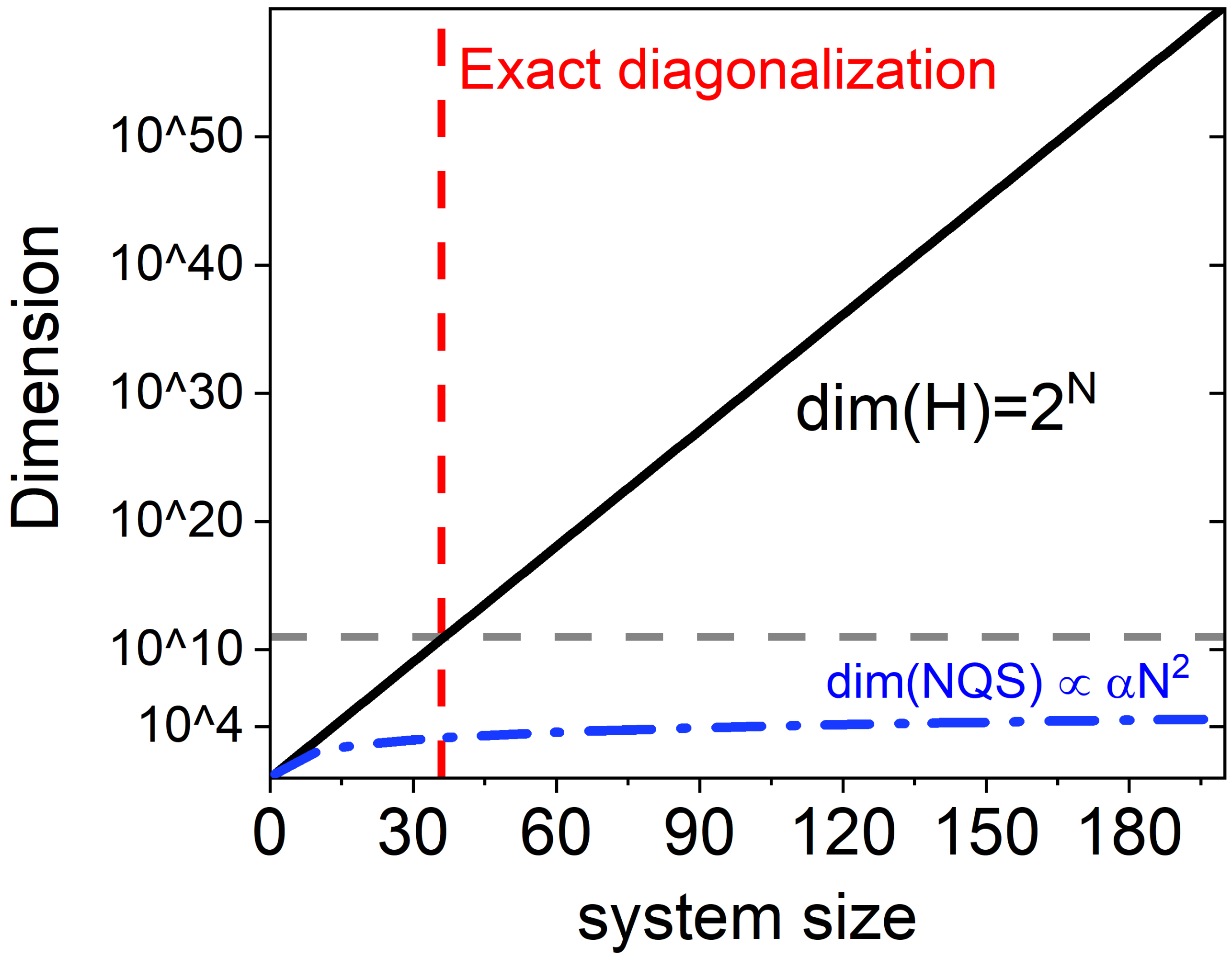


- Reduction from 2^N to αN parameters.
- Wavefunction based: no memory limitation on accessible simulation time
- Simulate dynamics of non-local correlations in systems relevant for magnetic materials

Neural Quantum States

Probability of Neural Network as variational Ansatz for wave function

$$\Psi_{\mathcal{W}}(\sigma) = P_{ANN}(\sigma) = \sum_{\{h_i\}} e^{\sum_j a_j \sigma_j^z + \sum_i b_i h_i + \sum_{ij} w_{ij} \sigma_i^z h_j}$$



Solve by optimizing network parameters $\mathcal{W} = \{a_i, b_j, w_{ij}\}$ using Monte Carlo methods

Ground state

$$\left\|\hat{\mathrm{H}}\Psi - \mathrm{E}\Psi\right\|_{\mathcal{W}}$$

Dynamics

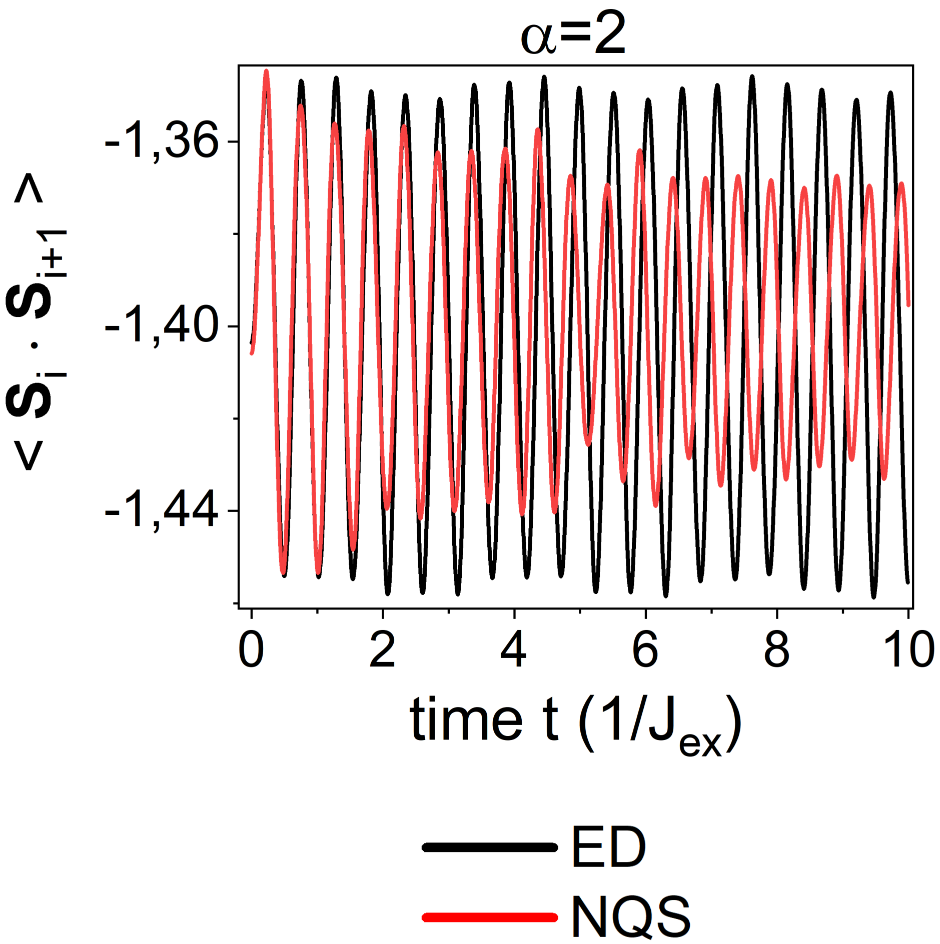
$$\|\mathrm{i}\partial_{\mathrm{t}}\Psi(\mathrm{t}) - \mathcal{H}(\mathrm{t})\Psi(\mathrm{t})\|_{\mathcal{W}}$$

ODE for network parameters

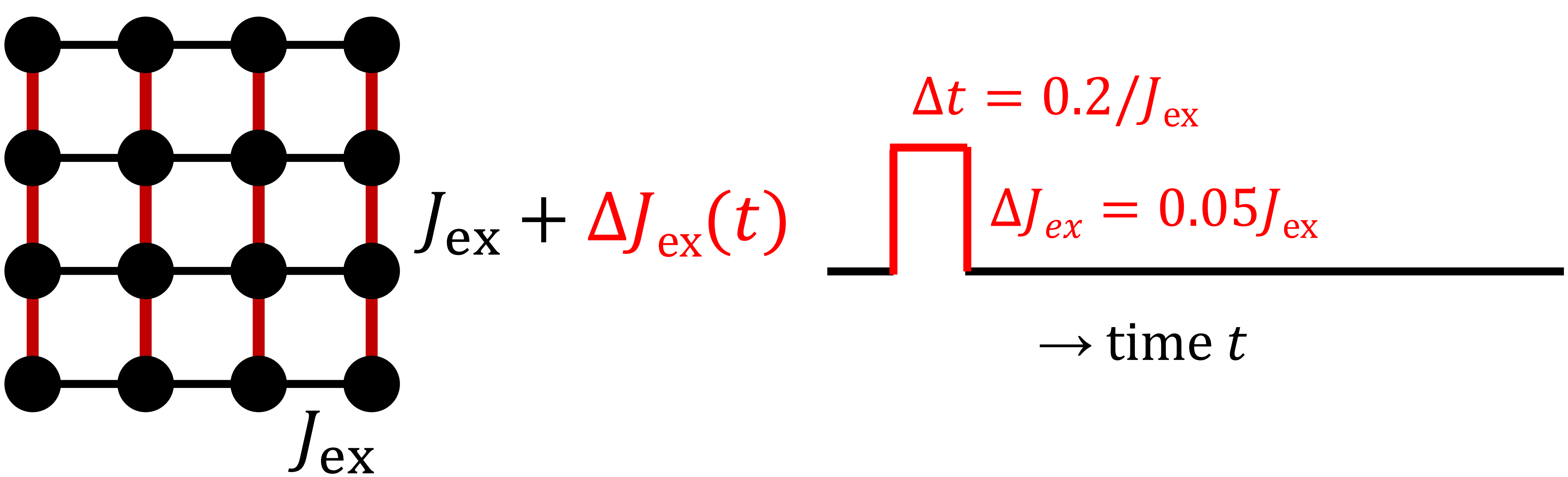
$$i\, S_{kk'}(t)\, \dot{\mathcal{W}}_{k'}(t) = \mathcal{F}(\mathcal{W}(t))$$

Here: apply NQS to study dynamics of magnon pairs

NQS vs ED (4x4)

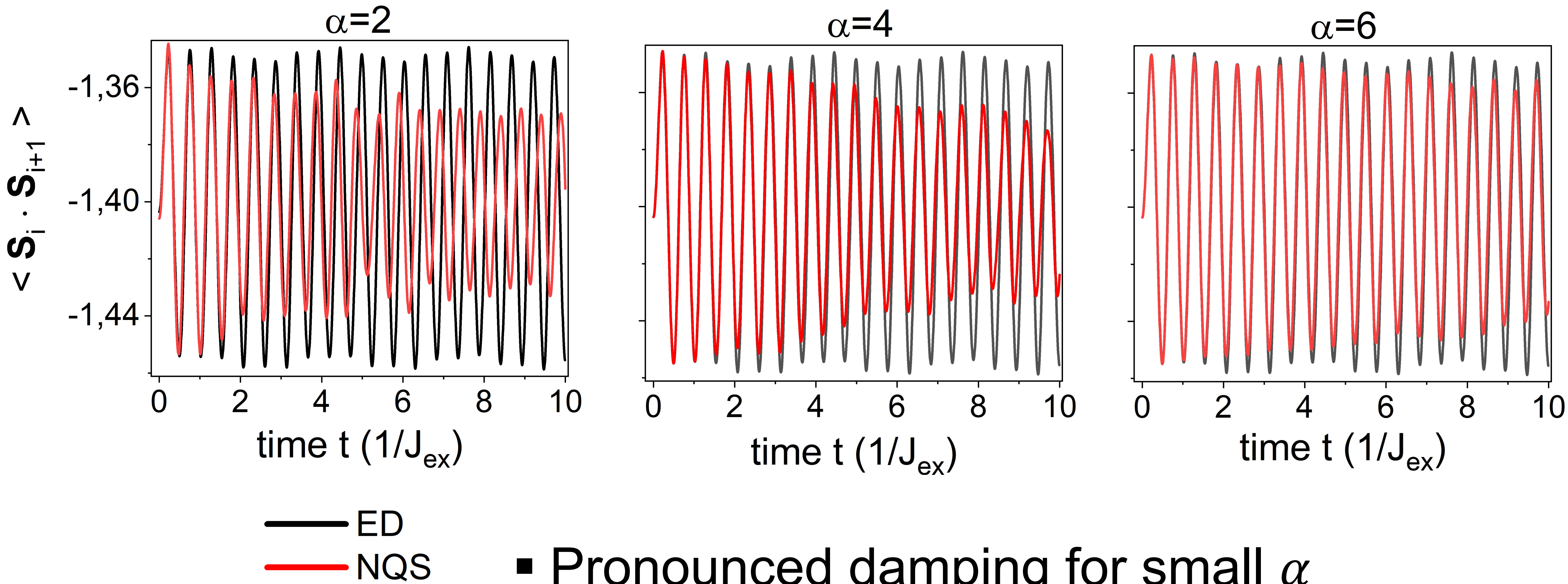


α=2
< S_i · S_i+1 >
-1,36
-1,40
-1,44
0
2
4
6
8
10
time t (1/J_ex)
ED
NQS

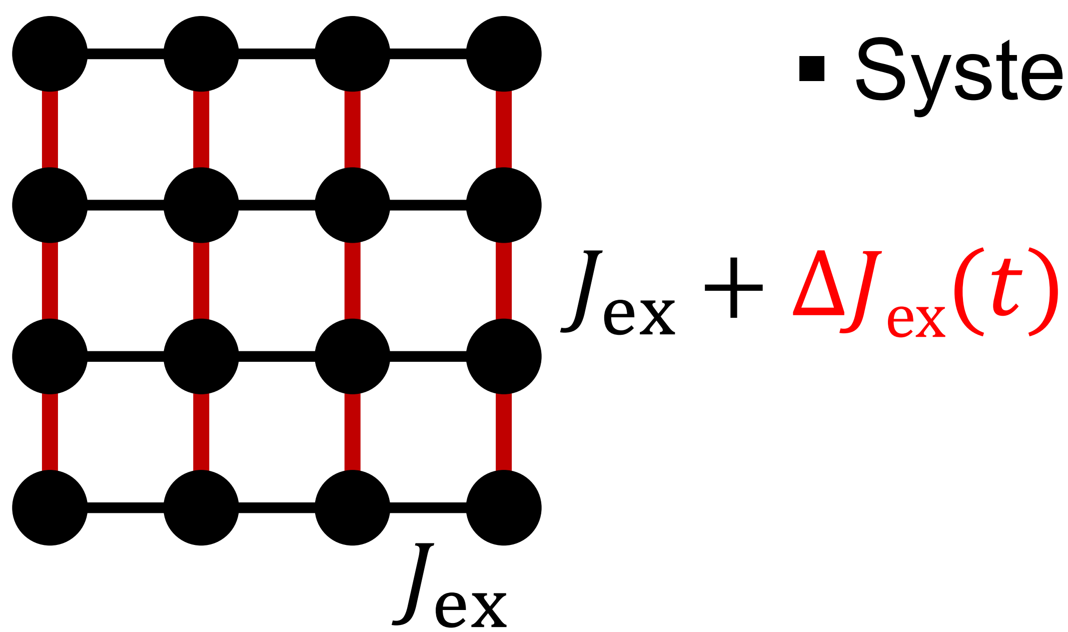


$J_{\mathrm{ex}} + \Delta J_{\mathrm{ex}}(t)$
J_{ex}
$\Delta t = 0.2/J_{\mathrm{ex}}$
$\Delta J_{ex} = 0.05J_{\mathrm{ex}}$
$\rightarrow$ time t

NQS vs ED (4x4)

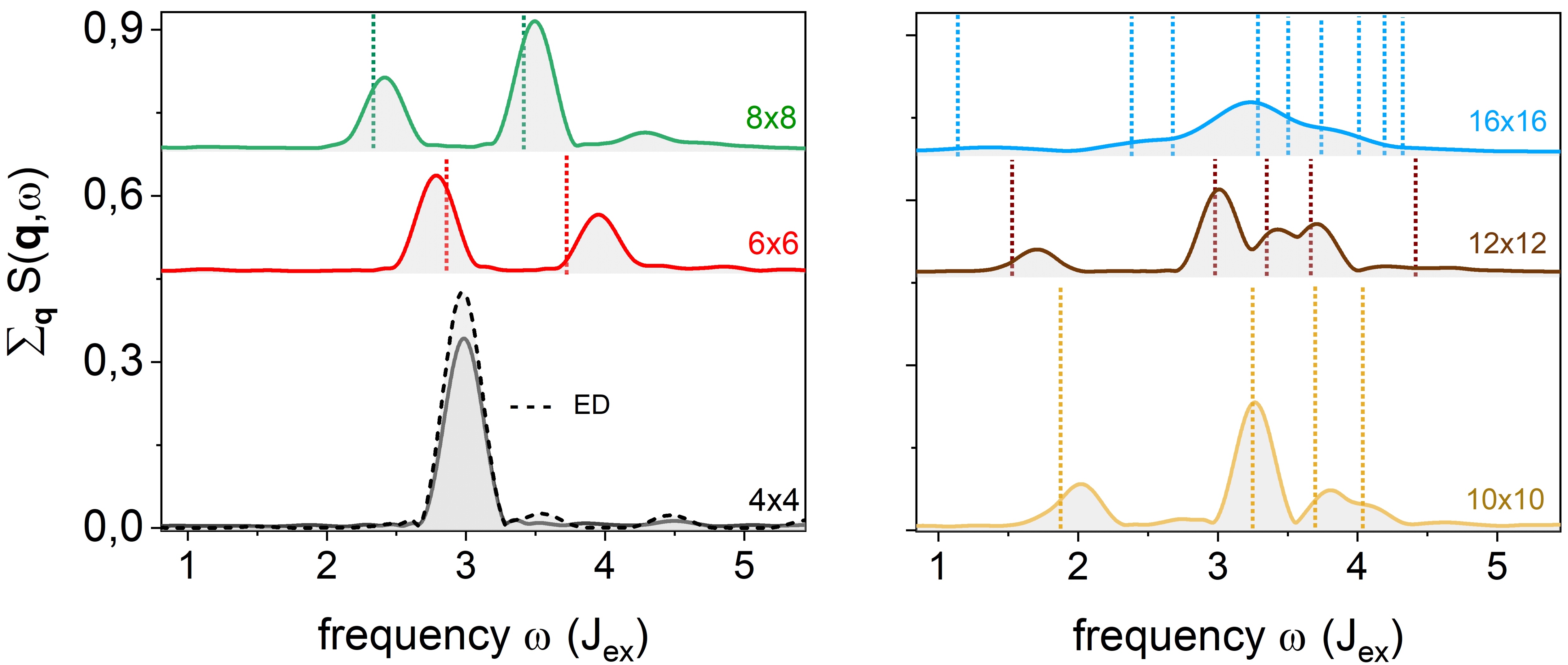


- Pronounced damping for small α
- Systematic improvement with increasing α



Comparison interacting magnon theory

$$S(\vec{q},\omega) = \int dt\, e^{i\omega t}\, S(\vec{q},t)$$



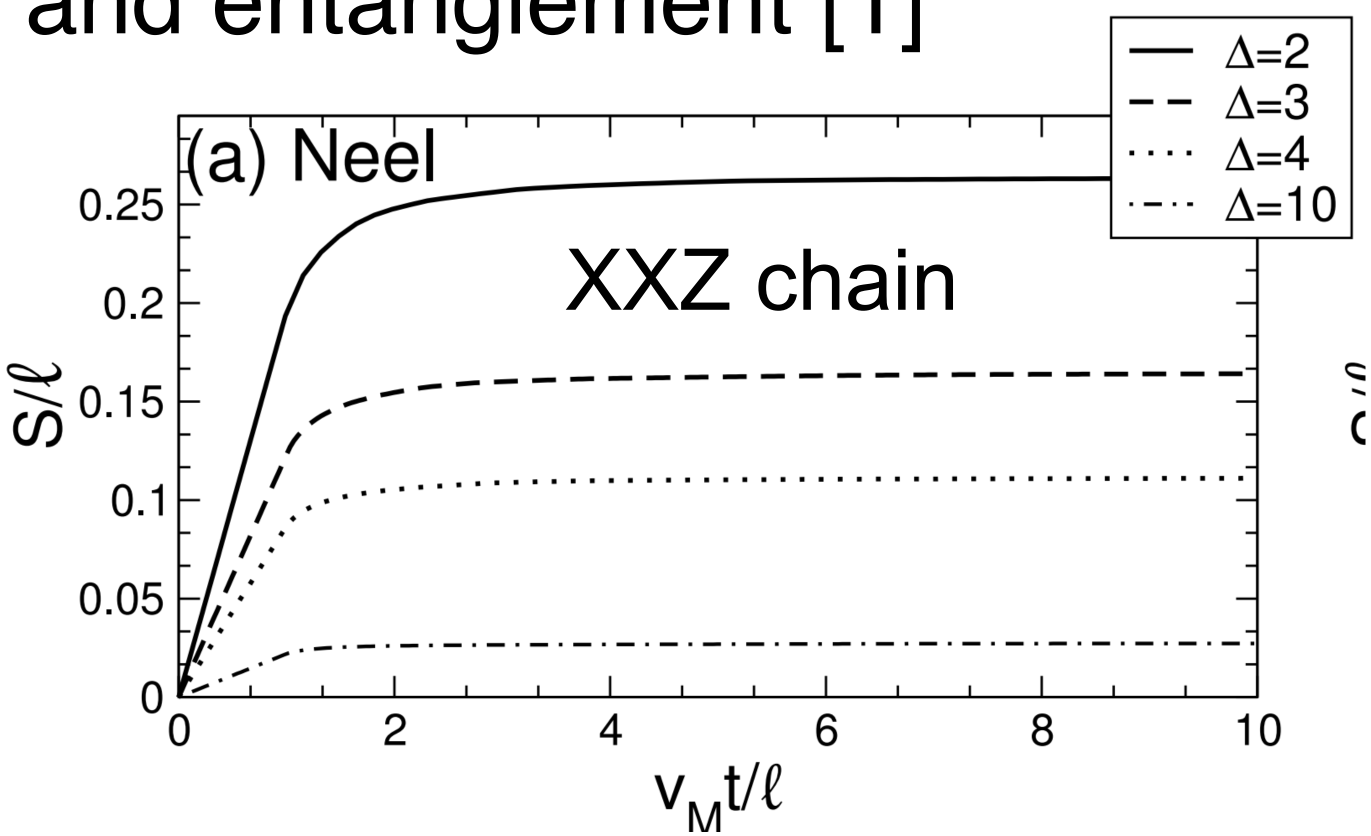
G. Fabiani, J.H. Mentink SciPost Phys. **7**, 004 (2019)
https://github.com/ultrafast-code/ULTRAFAST

RPA results from Lorenzana and Sawatsky, PRB **52**, 8576 (1995)

Entanglement and spin correlations

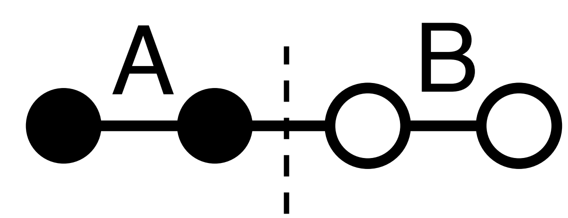
How to measure entanglement?

1D systems: direct link between spreading of correlations and entanglement [1]



Renyi entropy (γ=2)

$$S_\gamma(\rho_A) = \frac{1}{1-\gamma}\log(\mathrm{Tr}\,\rho_A^\gamma)$$



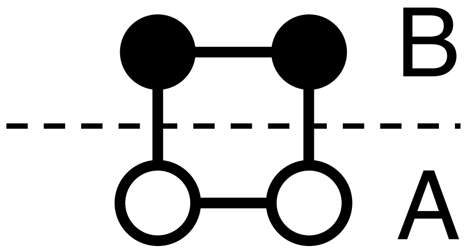
A and B not entangled:
S_A=0 (product state)

[1] V. Alba, P. Calabrese, SciPost Phys. **4**, 017 (2018)

Entanglement and spin correlations

How to measure entanglement?

2D systems: 2x2 system



Analytical result after $\Delta J_{ex}(t)$

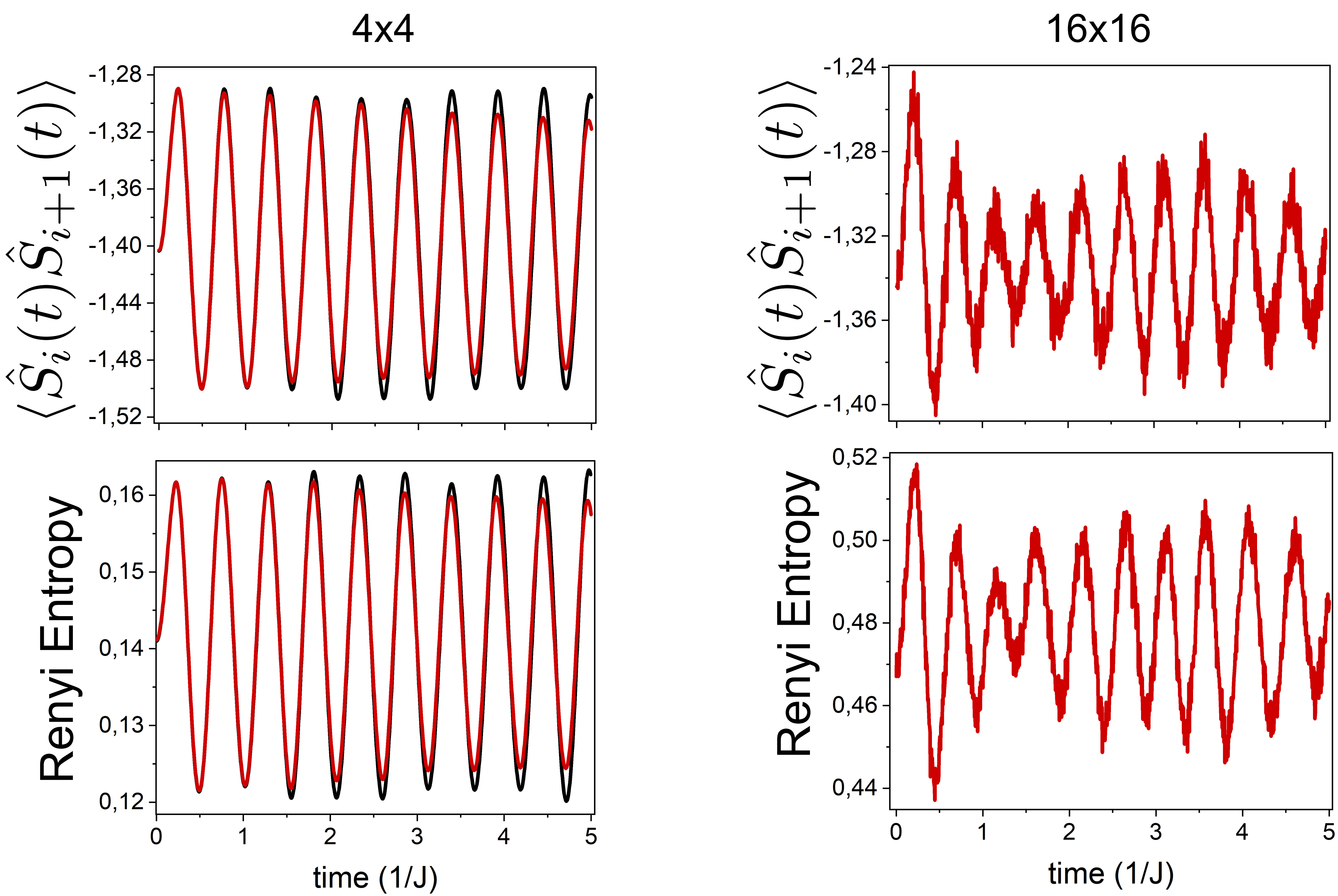
$$S_A(t) = -\log\left(\text{const} + 12\left\langle S_1^z S_2^z \right\rangle^2\right)$$

General result:

$$S_A = N_A \log(2) - \log(1 + \sum_i \sum_\alpha < S_i^\alpha >^2 + \sum_{ij\in A} \sum_{\alpha\beta} < S_i^\alpha S_j^\beta >^2 +$$
$$+ \textstyle\sum_{ijk} \sum_{\alpha\beta\gamma} < S_i^\alpha S_j^\beta S_k^\gamma >^2 + \ldots + N_A - \text{point correlators})$$

Suggests direct link between entanglement dynamics and nearest-neighbor spin correlations!

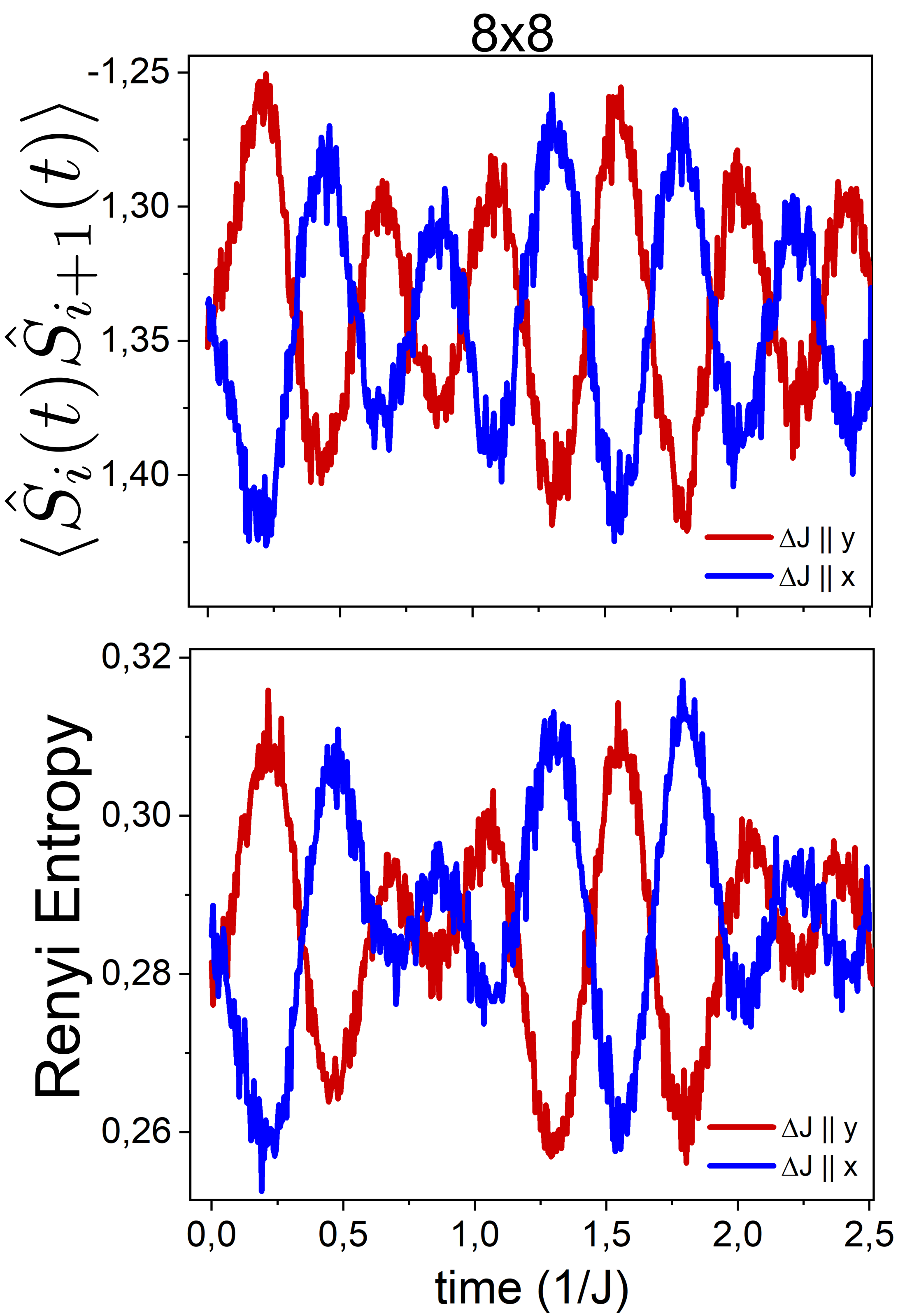
Entanglement and spin correlations

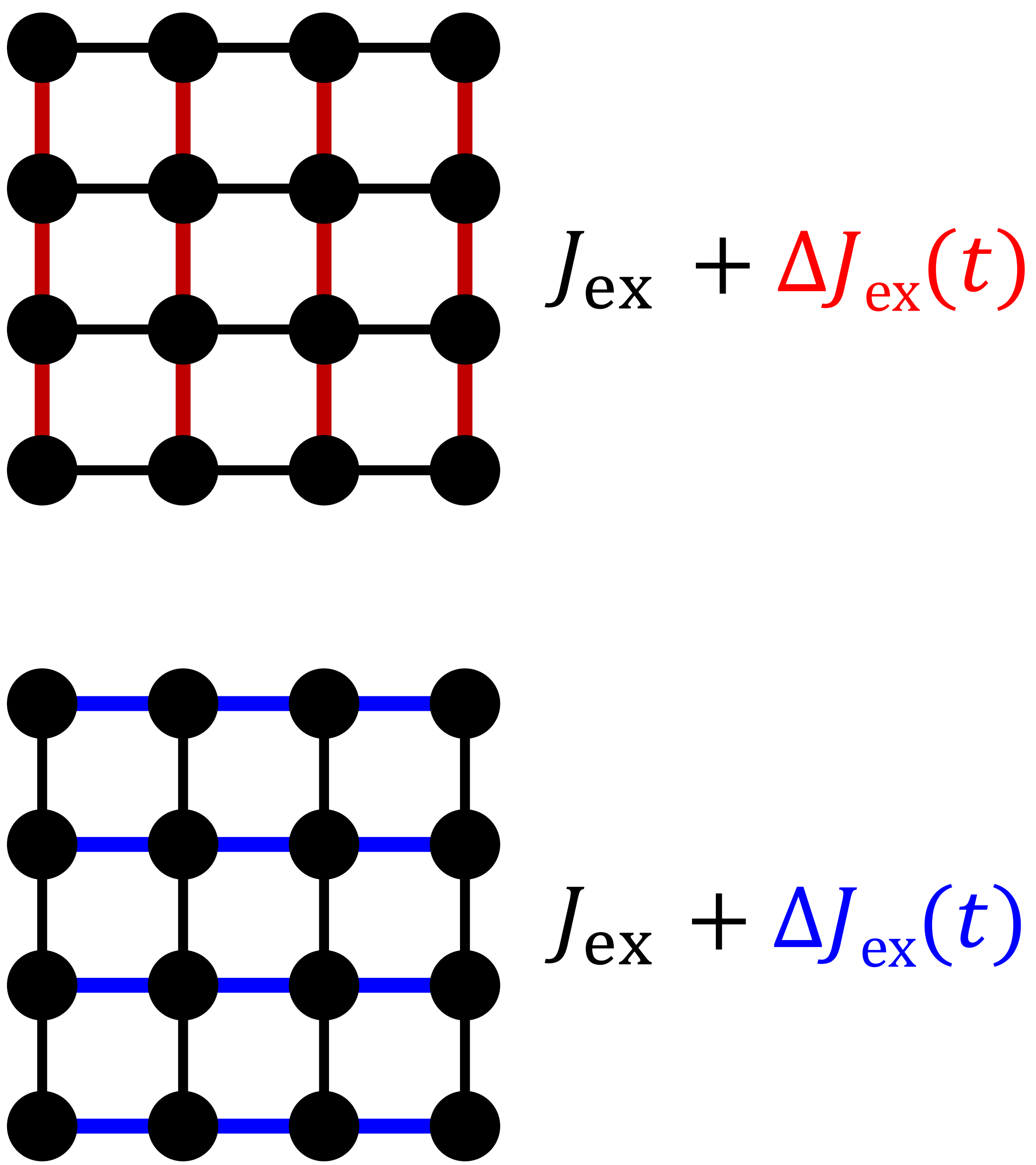


– Exact Diagonalization
– NQS wavefunction

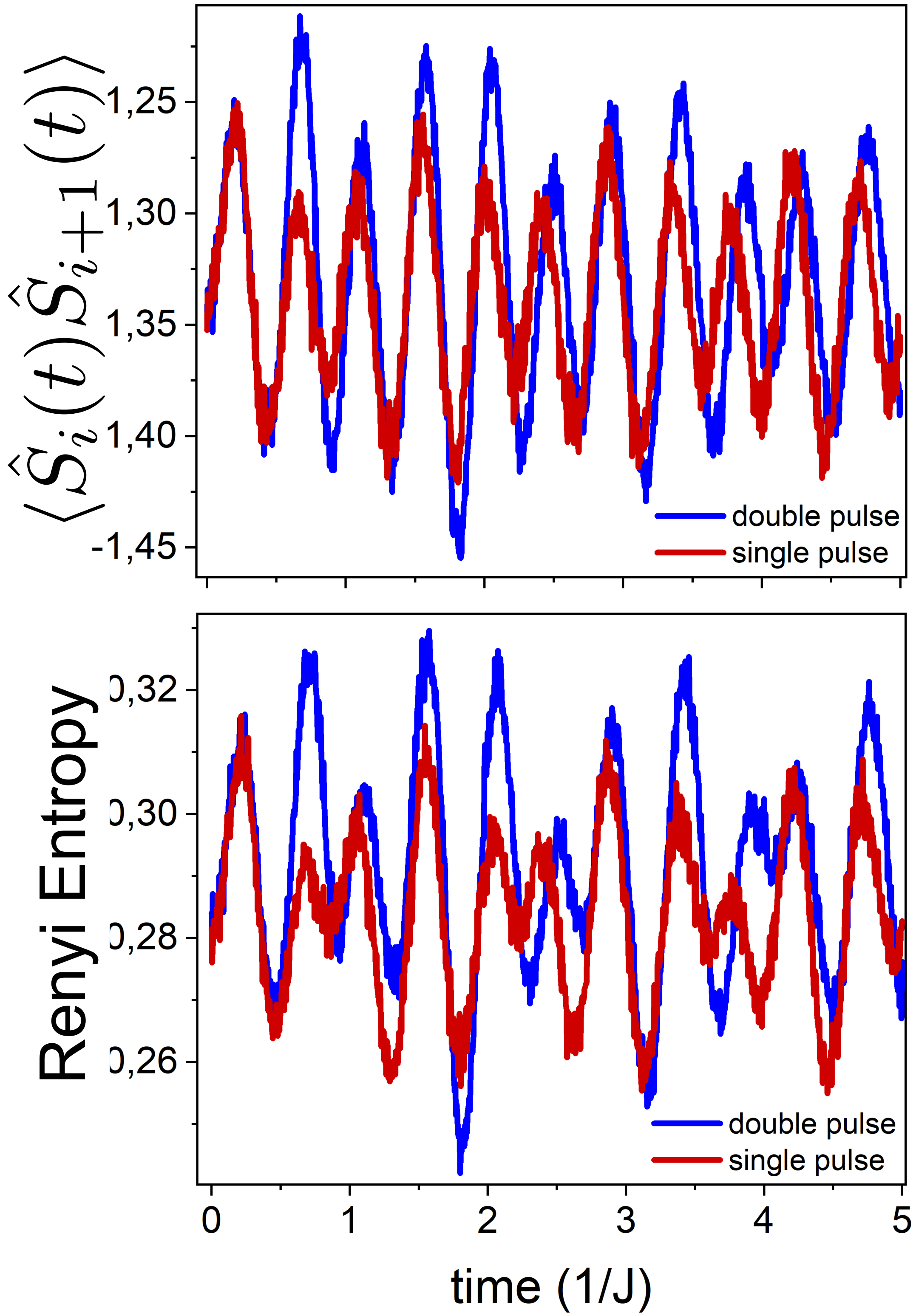
SWAP operators* on NQS wavefunctions
*Hastings et al., PRL 104 157201 (2010)

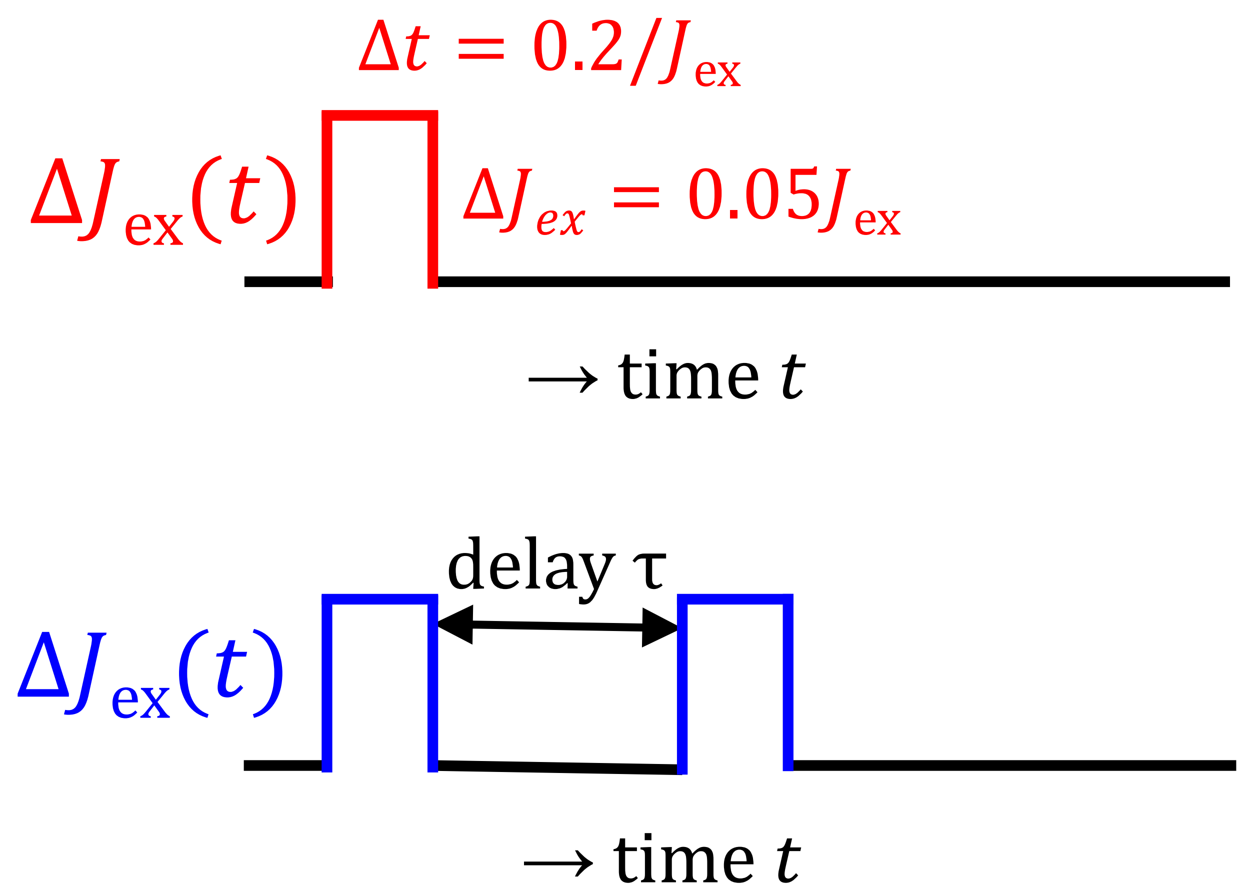
Control of the phase



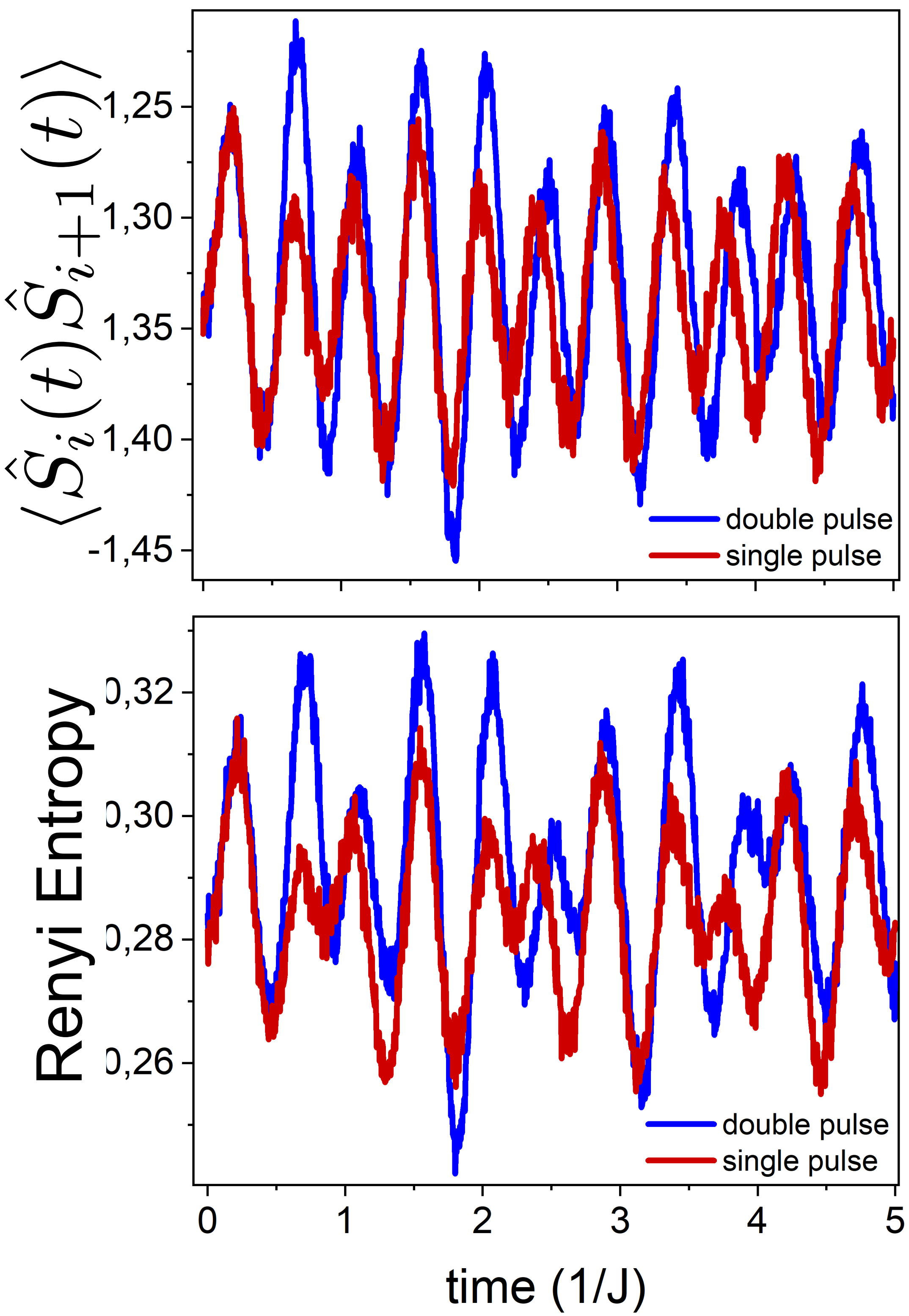


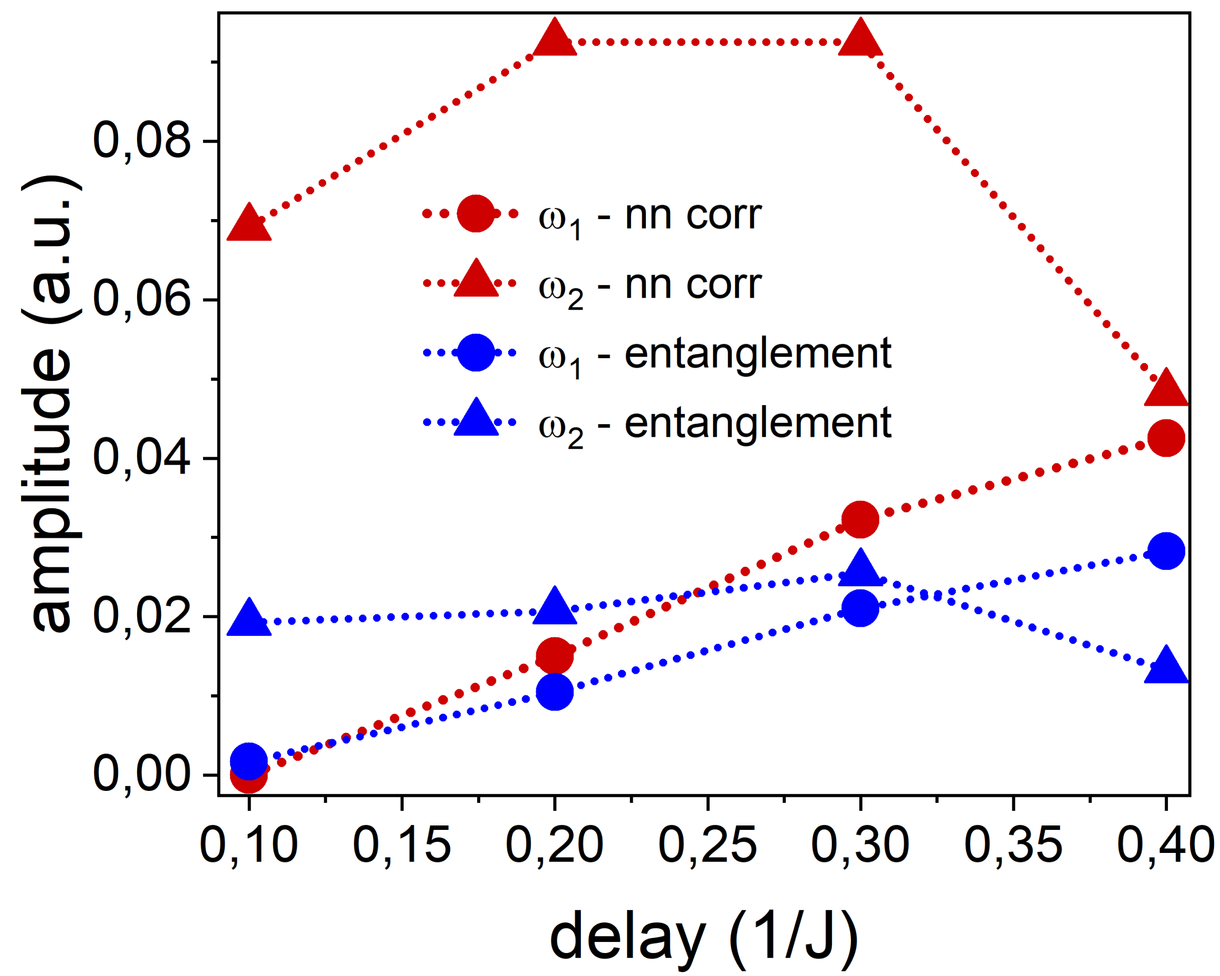
Control of the amplitude





Control of the amplitude

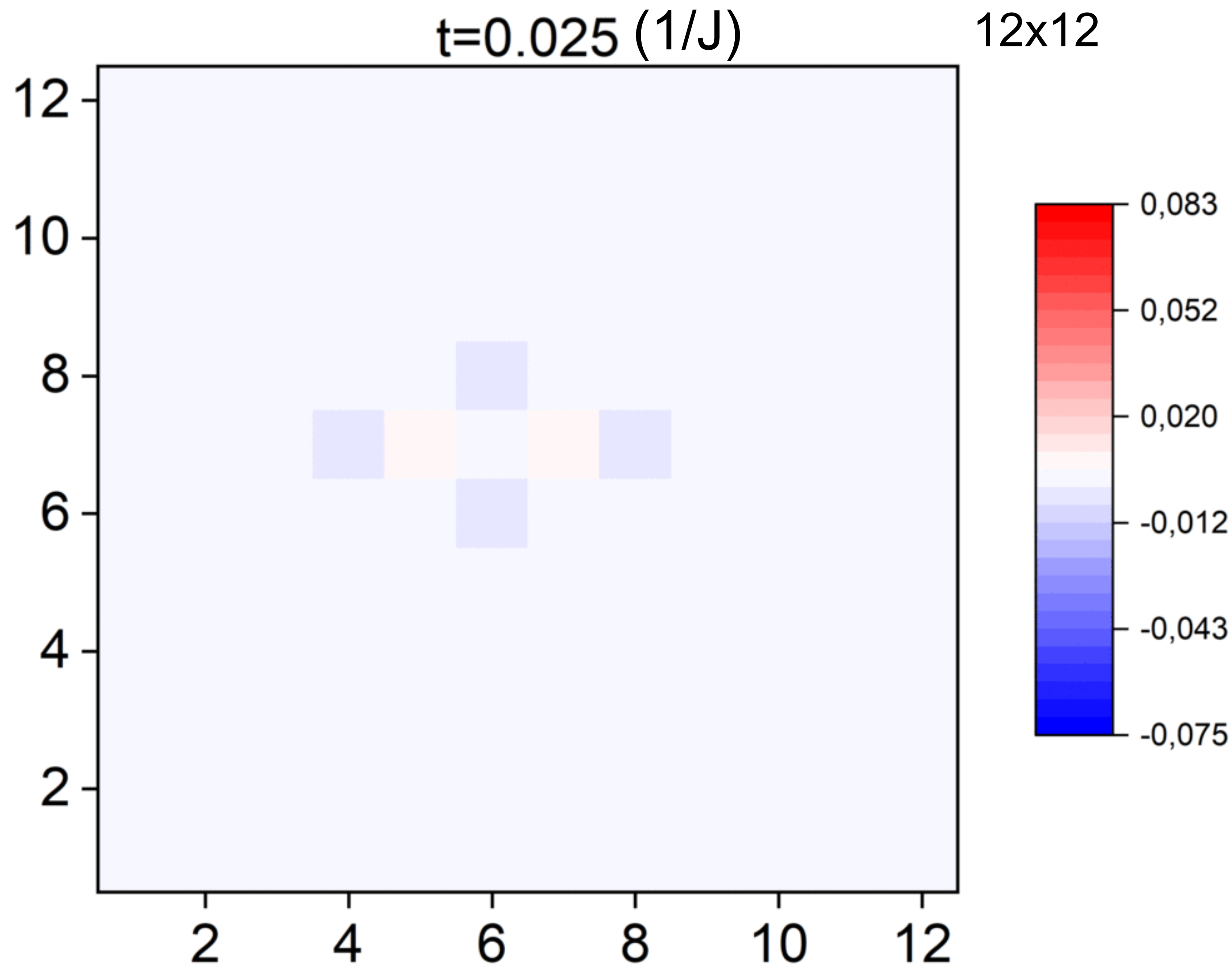




- ***Reinforces that dynamics is purely quantum***

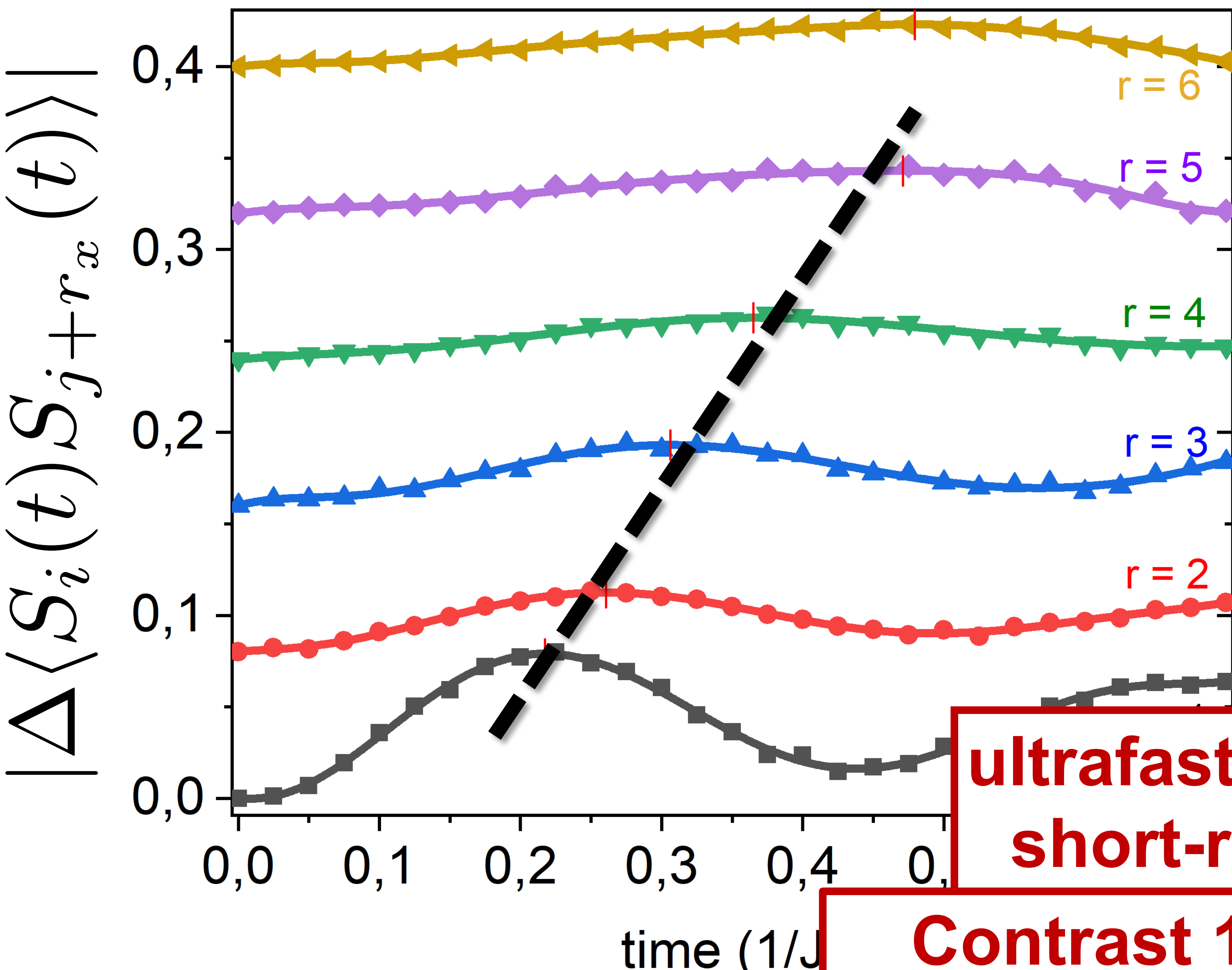
Spreading of correlations

$$\langle S_i(t)S_j(t)\rangle - \langle S_i(0)S_j(0)\rangle$$



Similar anisotropic spreading known in Bose-Hubbard systems
Carleo et al., Physical Review A 89, 031602(R) (2014)

Velocity of spreading



Estimated speed

$$v = (4.2 \pm 0.8) Ja/\hbar$$

Consistent with
***k* = 0** velocity
single magnons

$$2v_g = 3.3 Ja/\hbar$$
$$\rightarrow 10 - 100\,\mathrm{km/s}$$

ultrafast spreading even for short-range correlations!

Contrast 1D: spreading not related to entanglement growth

Conclusions

- ✓ Control of J_{ex} induces >10 THz quantum dynamics in solid state
- ✓ Neural quantum states highly efficient for studying this dynamics in the 2D AFM Heisenberg model
- ✓ Entanglement manifest in nearest-neighbor spin correlations
- ✓ Coherent control of phase and amplitude of entanglement
- ✓ Ultrafast spreading of spin correlations in real space

- *Great potential for the fastest, smallest and most energy-efficient computing!*