spontaneously magnetized exciton-polariton condensates: switches and lattices

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Motivation

- Non-equilibrium system
- Solid state technology, room temperature condensation
- Fast dynamics

Spin lattices

Devices (Switches, TRNGs)

So-called "Simulators"

nature physics

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Immanuel Bloch, Jean Dalibard & Sylvain Nascimbène

Affiliations | Corresponding author

Nature Physics **8**, 267–276 (2012) | doi:10.1038/nphys2259

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nature photonics

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NATURE PHOTONICS | LETTER

日本語要約

Network of time-multiplexed optical parametric oscillators as a coherent Ising machine

Alireza Marandi, Zhe Wang, Kenta Takata, Robert L. Byer & Yoshihisa Yamamoto

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Nature Photonics **8**, 937–942 (2014) | doi:10.1038/nphoton.2014.249

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frontiers in PHYSICS

REVIEW ARTICLE
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Ising formulations of many NP problems

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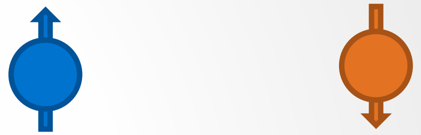
We provide Ising formulations for many NP-complete and NP-hard problems, including all of Karp's 21 NP-complete problems. This collects and extends mappings to the Ising model from partitioning, covering, and satisfiability. In each case, the required number of spins is at most cubic in the size of the problem. This work may be useful in designing adiabatic quantum optimization algorithms.

Keywords: spin glasses, complexity theory, adiabatic quantum computation, NP, algorithms

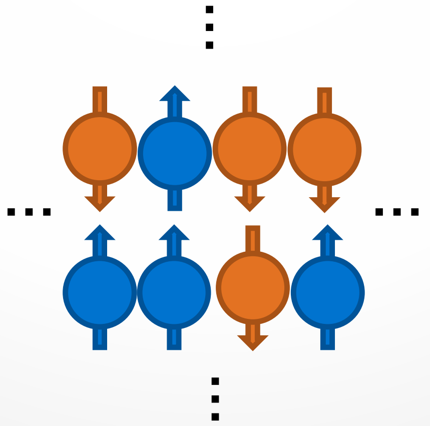
Key elements of a "simulator" or spin model

1. Binary state, which can be initialized

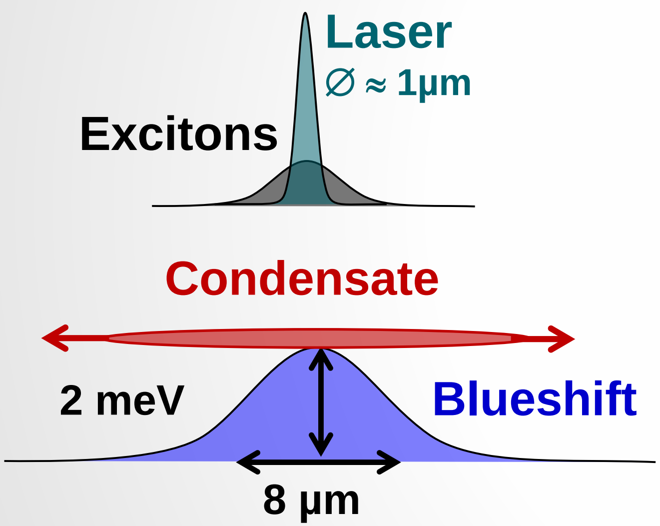


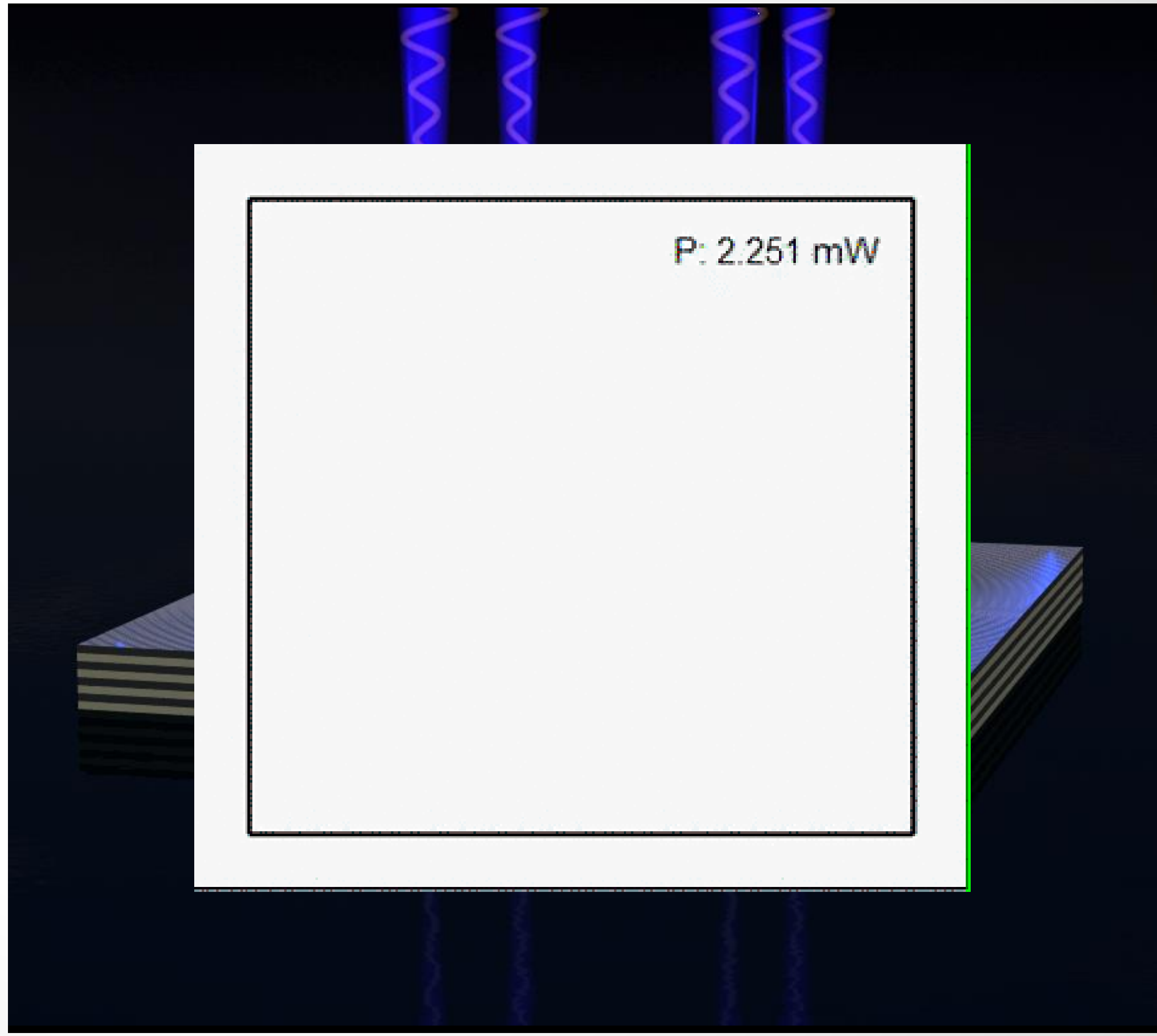
2. Tunable interactions between two

3. Scalable lattices



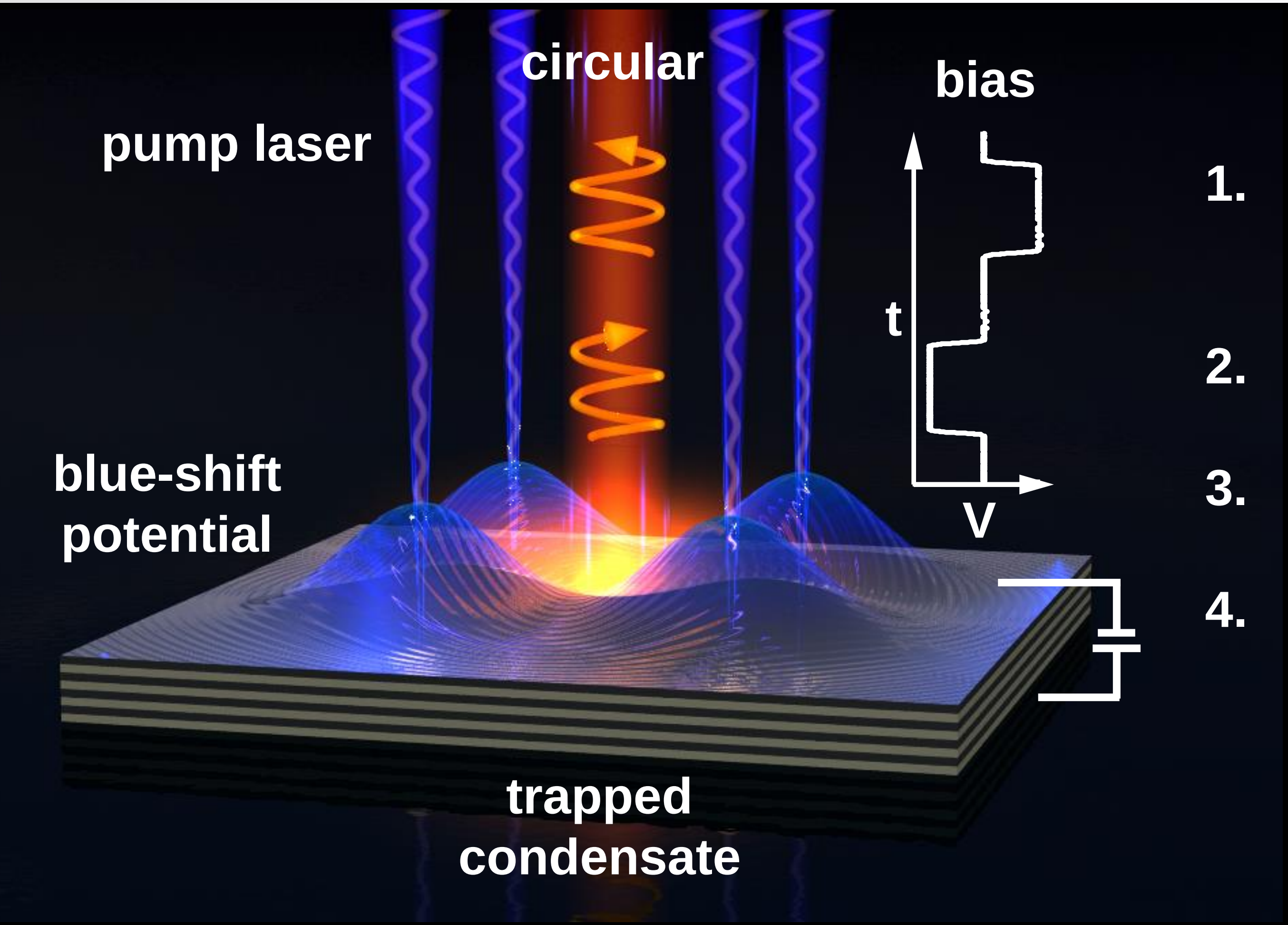
Polariton condensates in optical traps



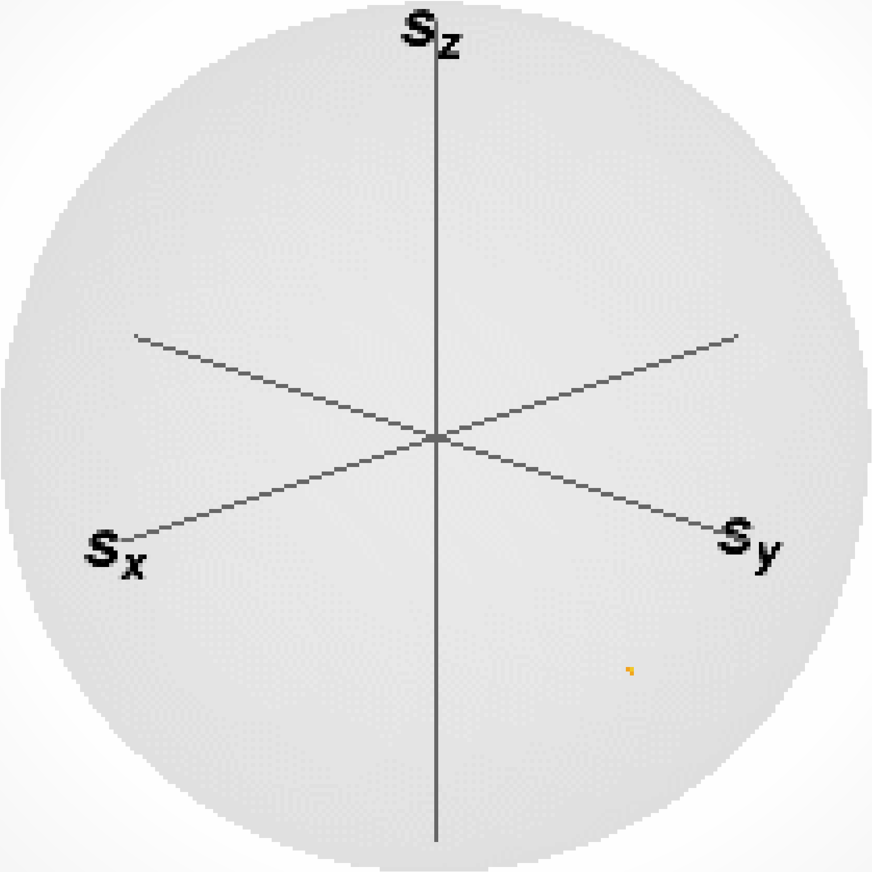


Nat. Phys. 8, 190 (2012), Nat. Comm. 3, 1243 (2012), PRL 110, 186403 (2013), PNAS 111, 8770 (2014)

Outline



1. Spontaneous spin-bifurcation
2. Spin alignment
3. Lattices
4. Electrical spin-switching



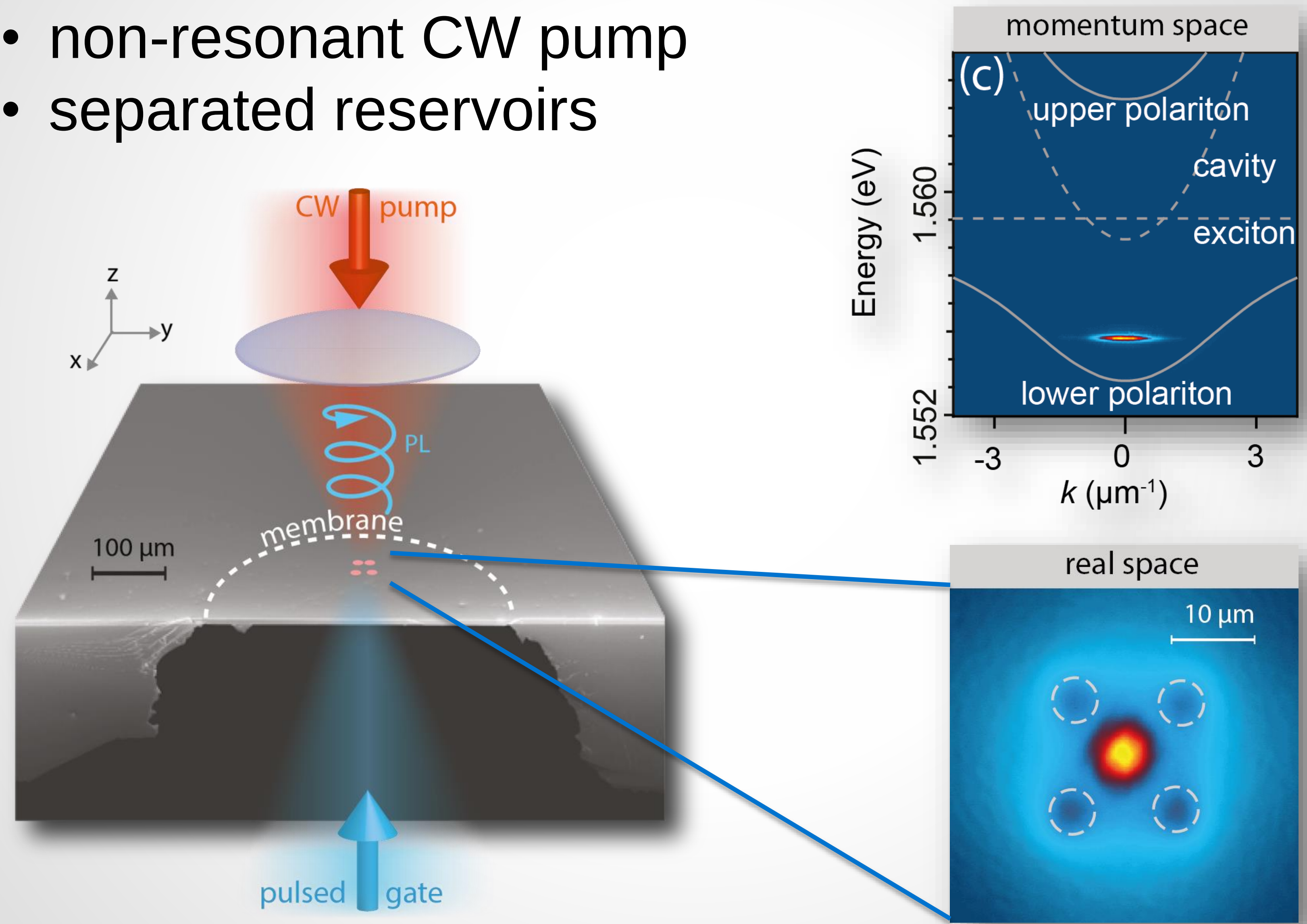
Part 1

Spin Bifurcation

PRX (2015)

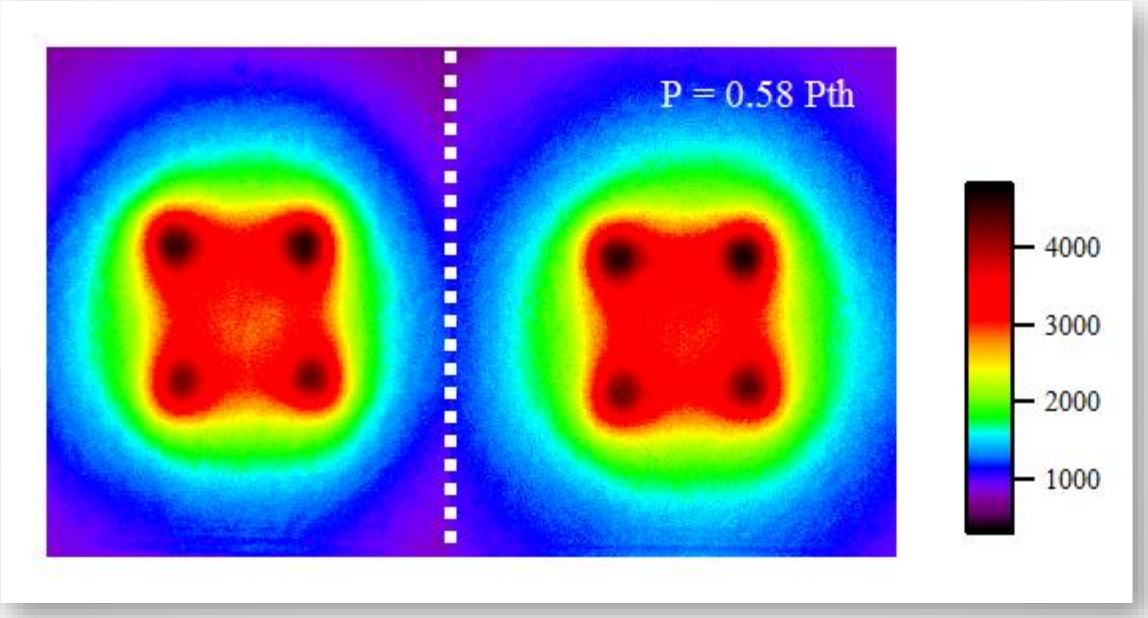
Membrane microcavity

- non-resonant CW pump
- separated reservoirs



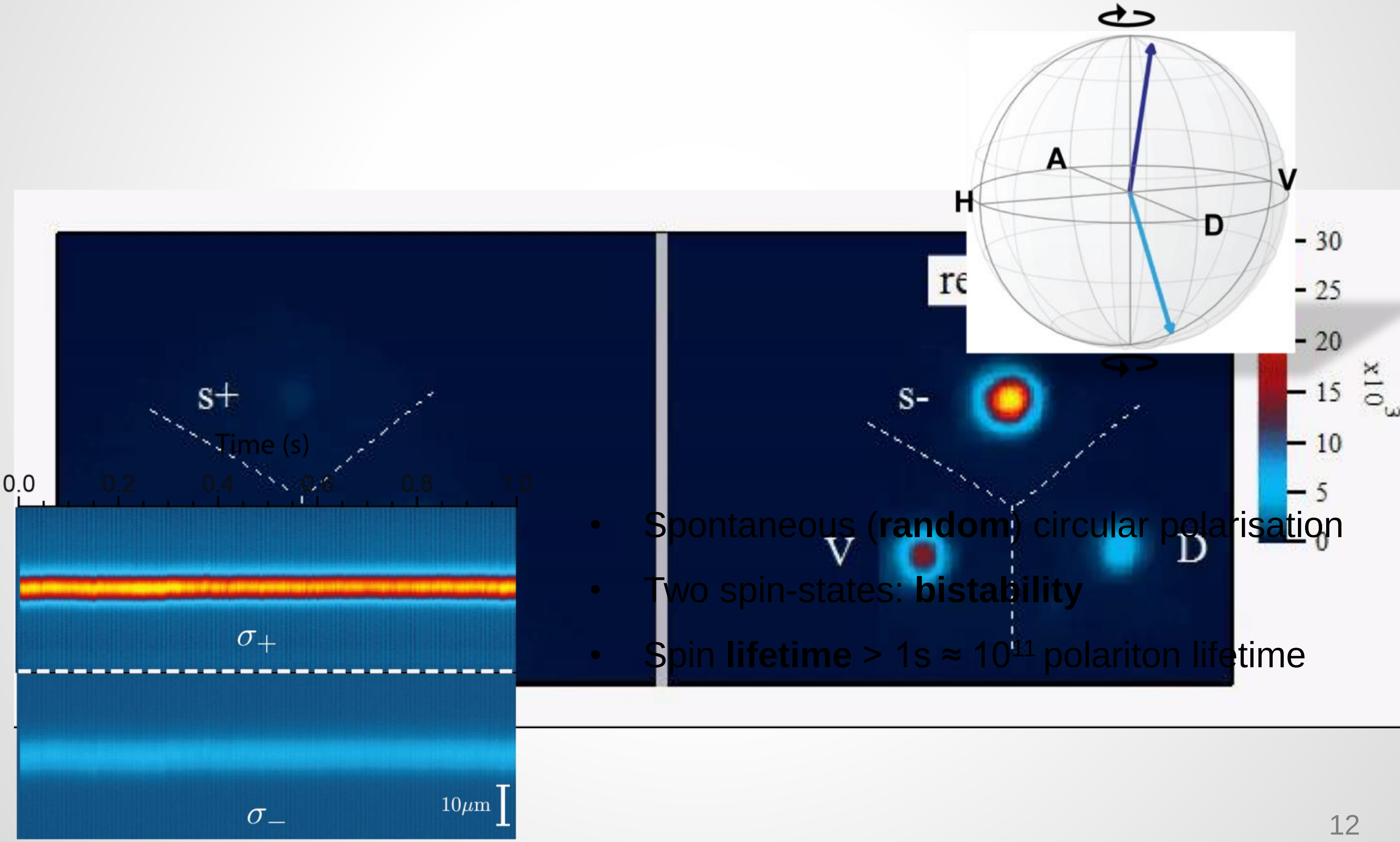
Circular polarisation with linearly polarised pump

σ_- σ_+



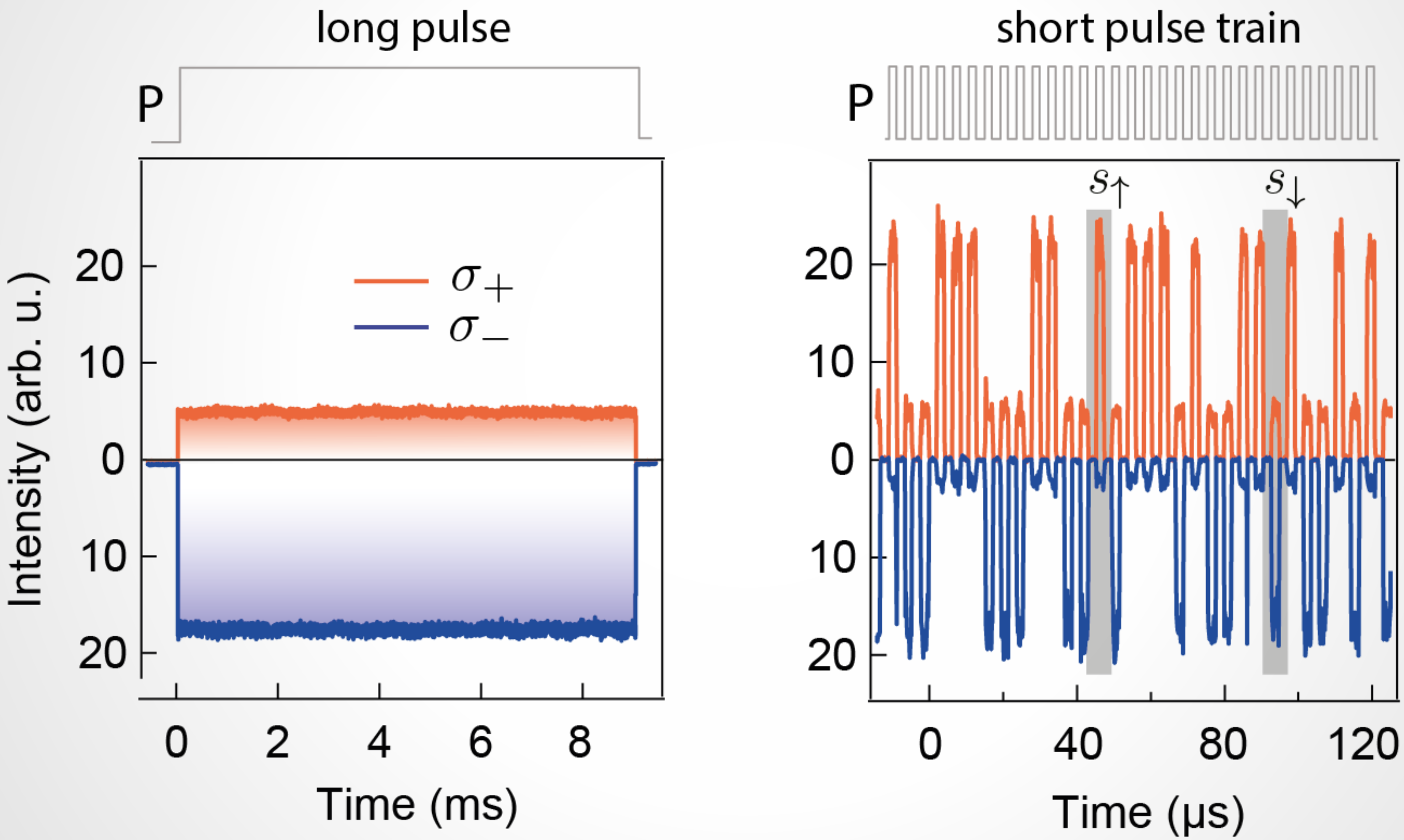
unusual: previous works reported linear polarisation

Spontaneous parity breaking



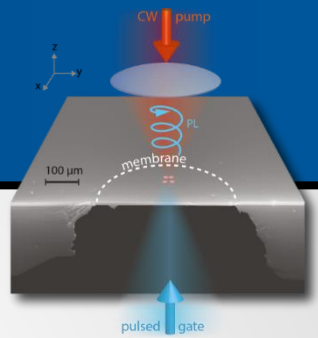
- Spontaneous (**random**) circular polarisation
- Two spin-states: **bistability**
- Spin **lifetime** > 1s ≈ 10^{11} polariton lifetime

Stochastic behaviour

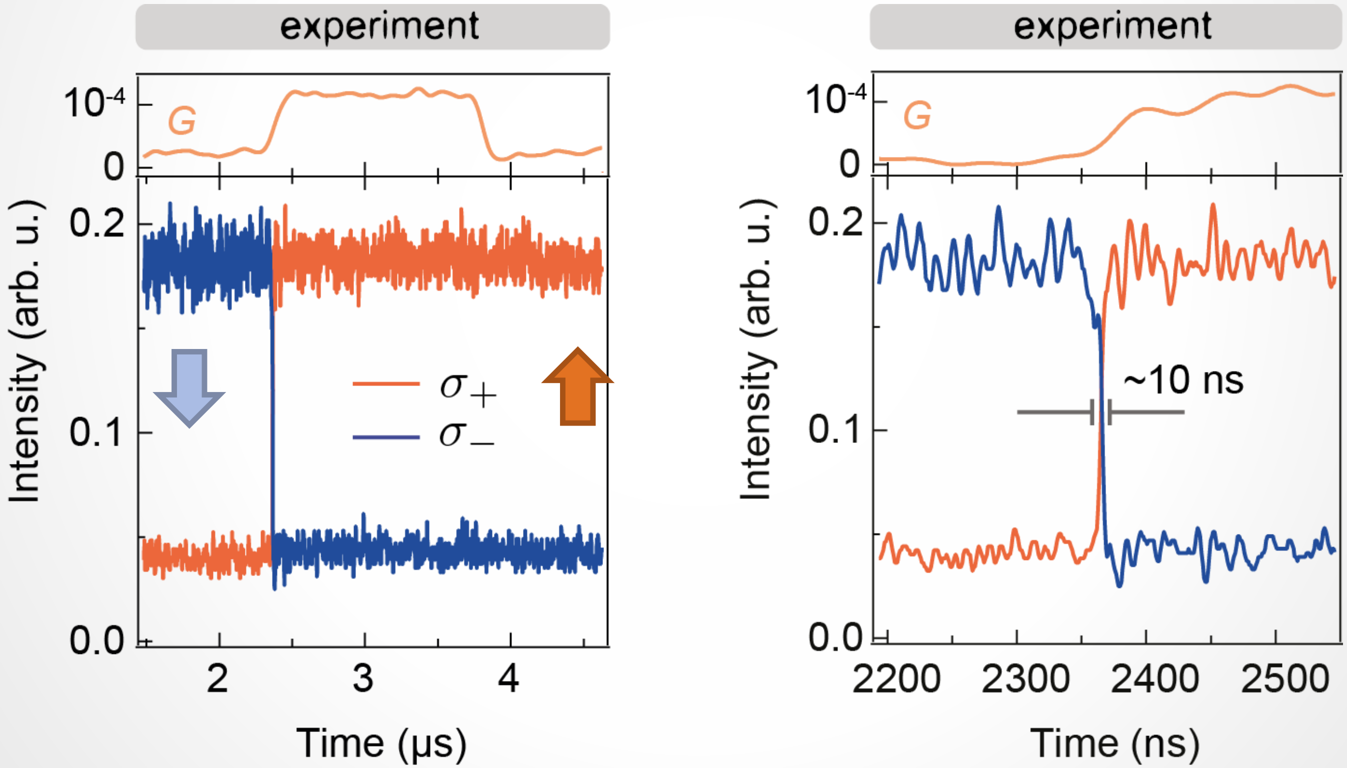


PRX 5, 031002 (2015)

Spin Switching (experiment)



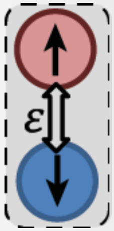
- linear pump: random
- weak σ_+ gate: 10^{-2} N, resonant



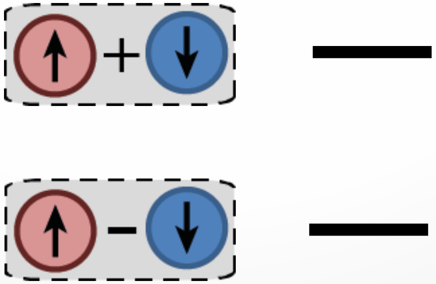
- switching energy ~ 1 fJ
- switches with ~10 polaritons

Key requirements of spin bifurcation

- Nonlinearity $$\frac{d\psi}{dt} = a\psi + \alpha|\psi|^2\psi$$
- Linear polarization energy splitting (coupling between spins)



- Lifetime difference between linear polarization modes



Spontaneous spin bifurcation – theory

$$\Psi = \begin{bmatrix} \psi_+ \\ \psi_- \end{bmatrix}$$

linear polarisation

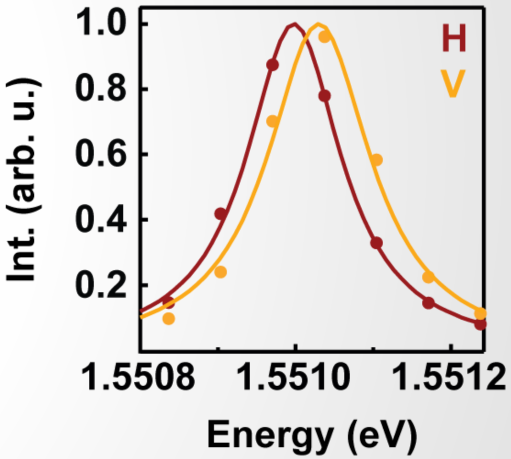
decay rate splitting + energy splitting

pump & decay

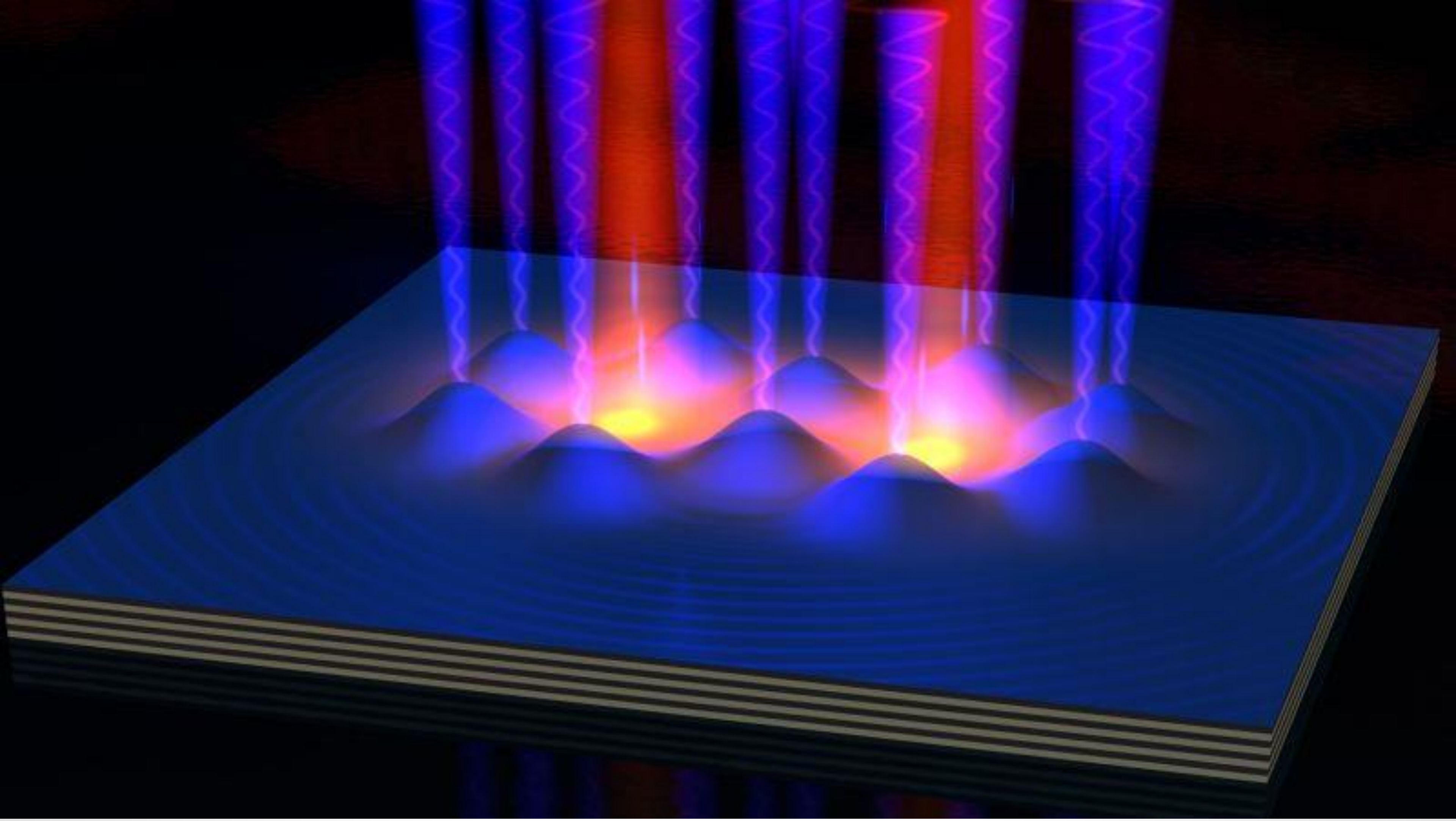
$$i\frac{d\Psi}{dt} = -\frac{i}{2}g(S)\,\Psi - \frac{i}{2}(\gamma - i\varepsilon)\sigma_x\Psi$$

$$+\frac{1}{2}[(\alpha_1+\alpha_2)S + (\alpha_1-\alpha_2)S_z\sigma_z]\Psi$$

polariton-polariton interactions



$$\gamma \simeq 0.1\,\varepsilon$$

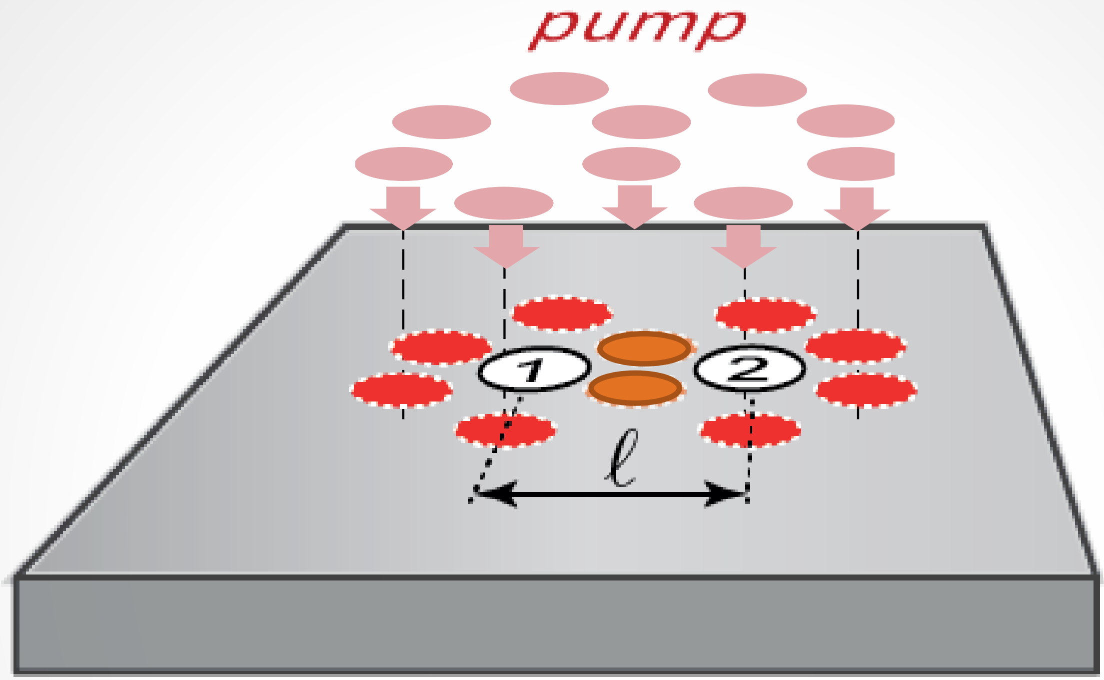


Part 3

Spin alignment

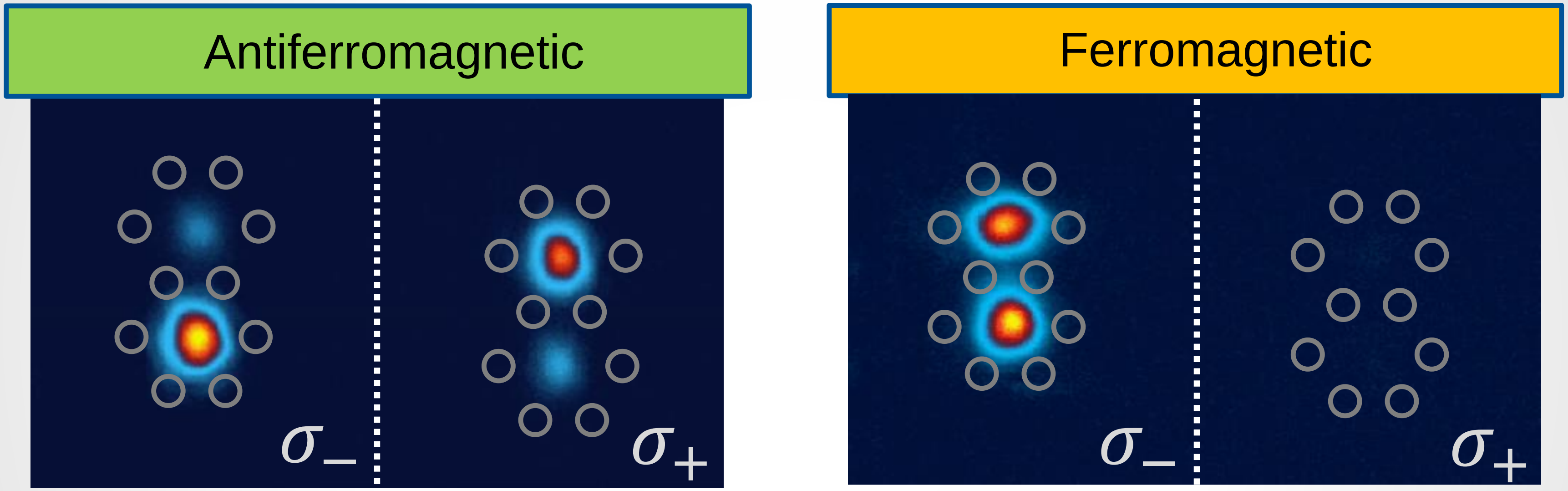
PRL (2016)

Pumping geometry



- Hexagonal **nonresonant CW pump**
- Playing parameters: **barrier** (continuous) or **separation** (discrete)

FM and AFM regimes

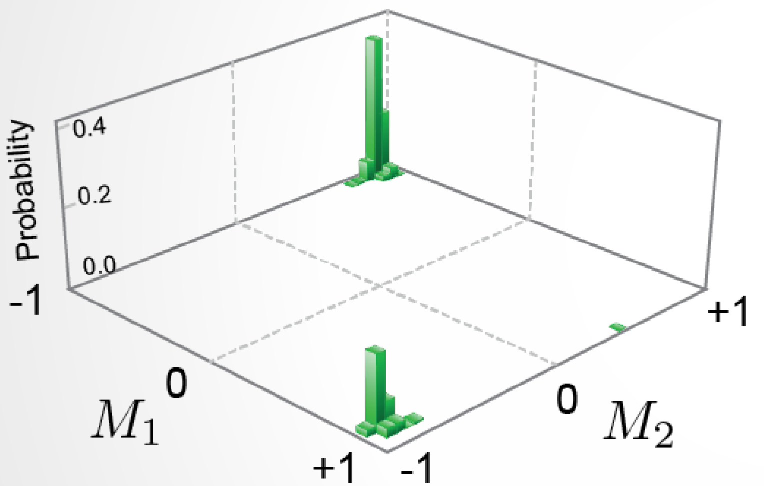


- Two distinct regimes
- sample or position independent

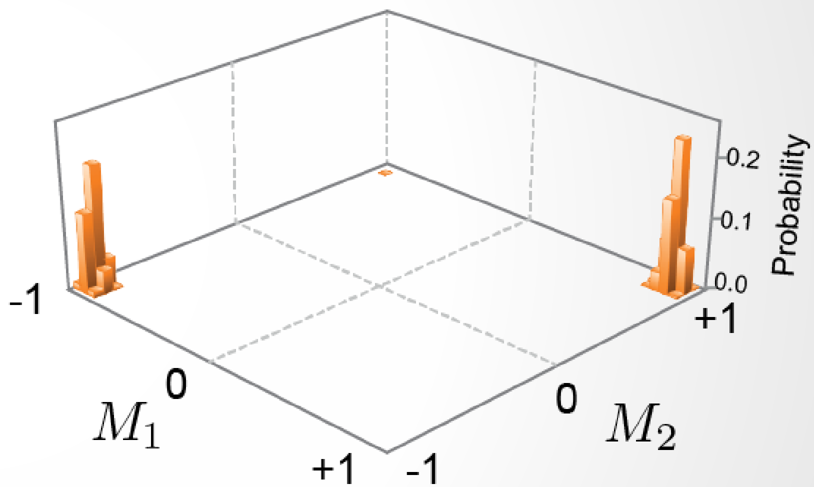
PRL 116, 106403 (2016)

Correlations

Antiferromagnetic



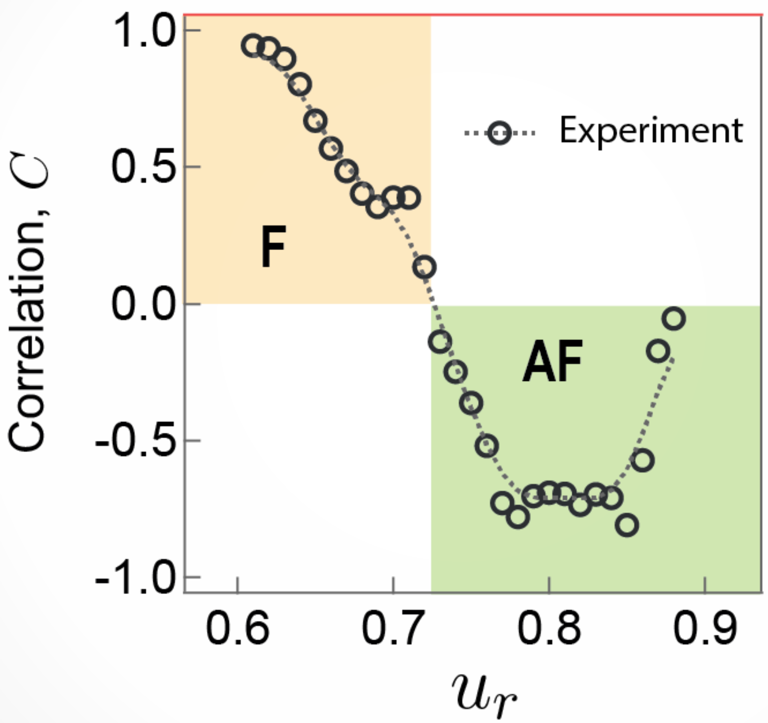
Ferromagnetic

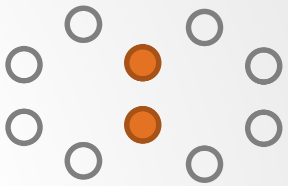


- M_n deg of circ pol of condensate n
- Only two possible states in each regime
- Very robust (>99% coupling efficiency)

PRL 116, 106403 (2016)

FM to AFM transition

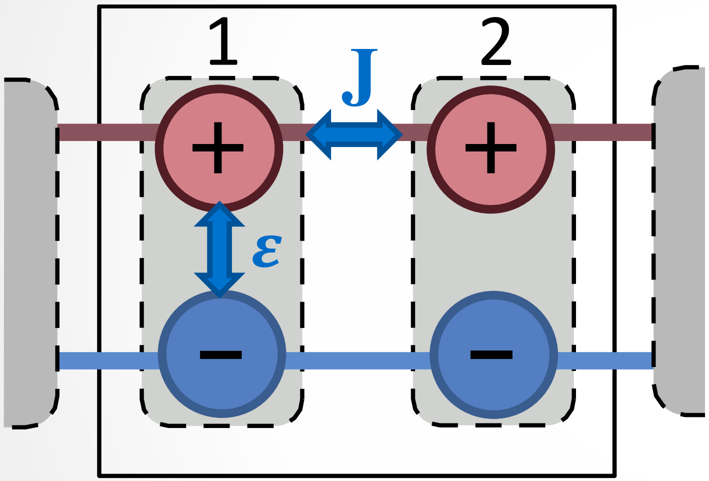


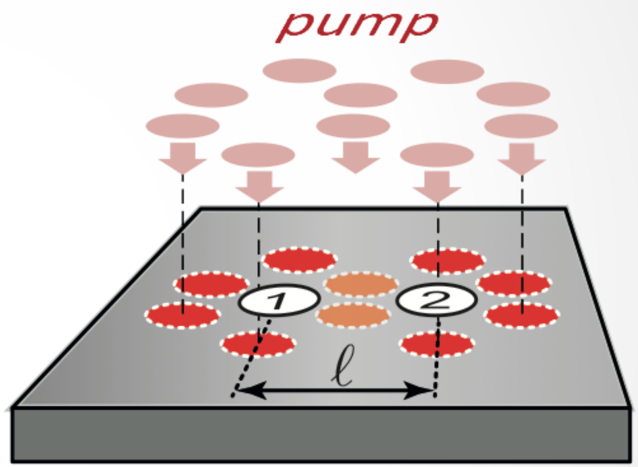


$$u_r = \frac{I_{\bullet}}{I_{\circ}}$$

Bose-Hubbard ladder

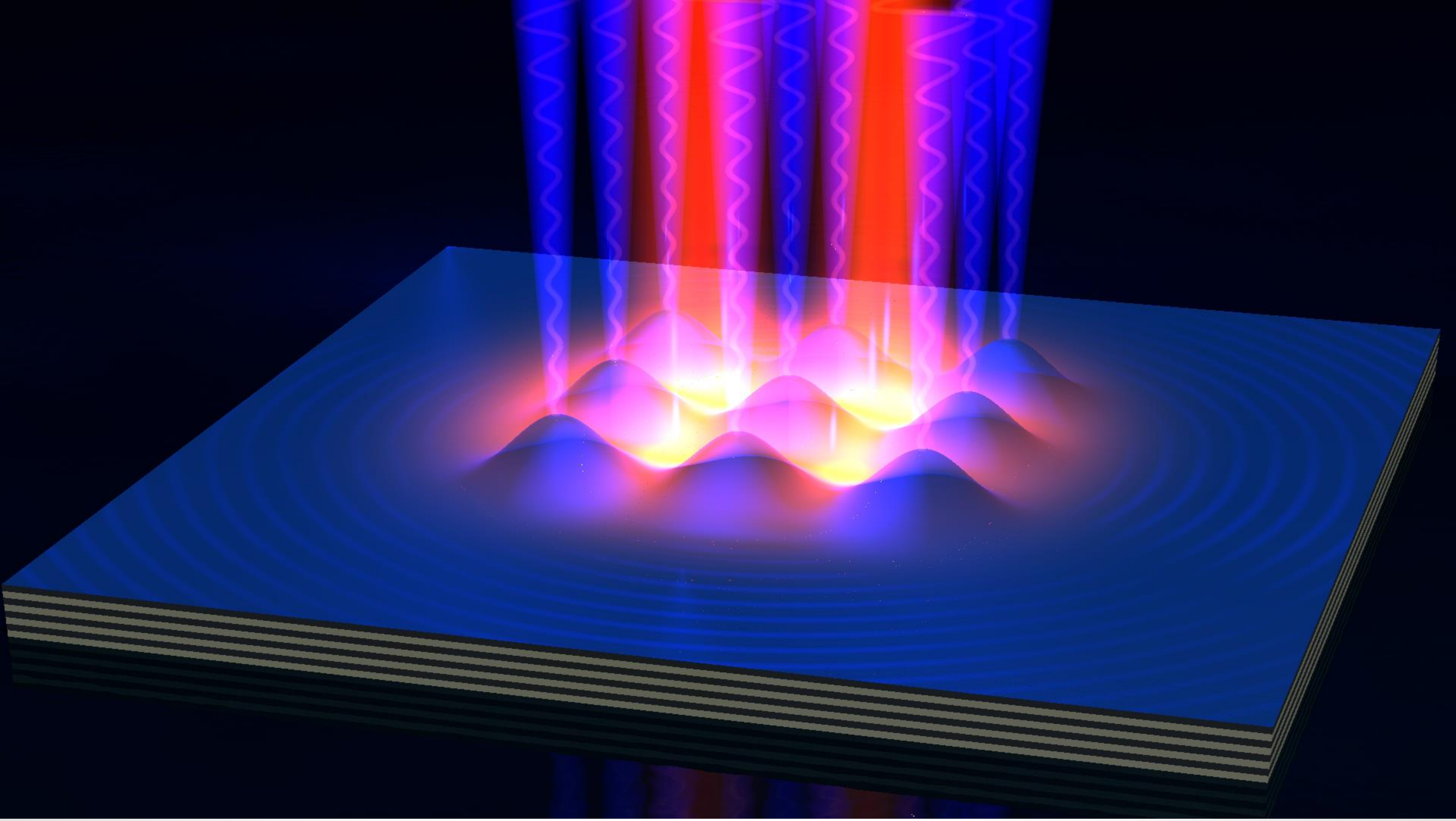
- Linear polarization splitting in **spin** space
- Josephson coupling in **real** space





$$J > \epsilon \rightarrow FM$$

$$J < \epsilon \rightarrow AFM$$

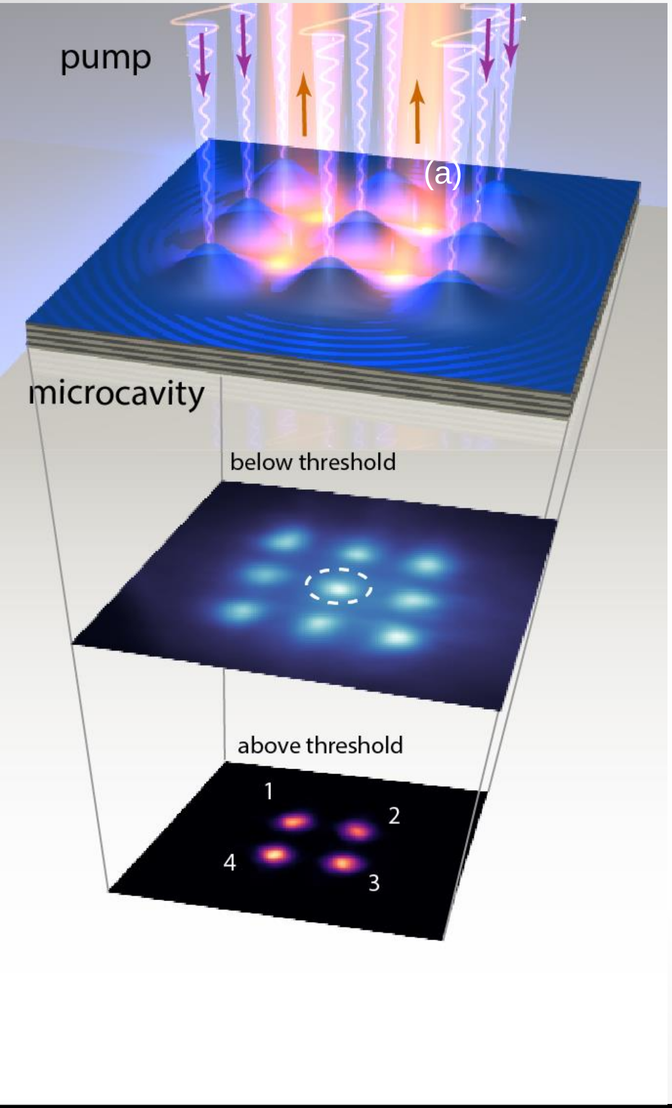


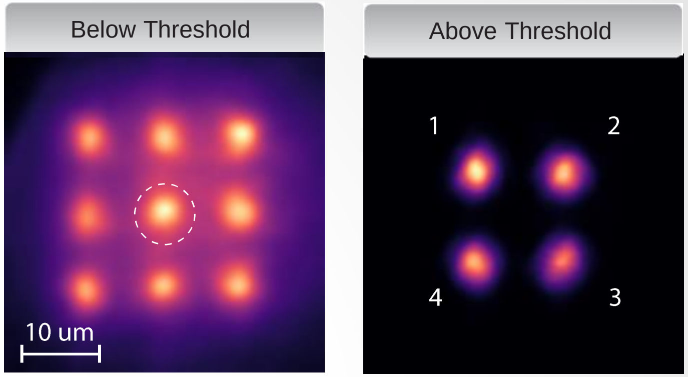
Part 3

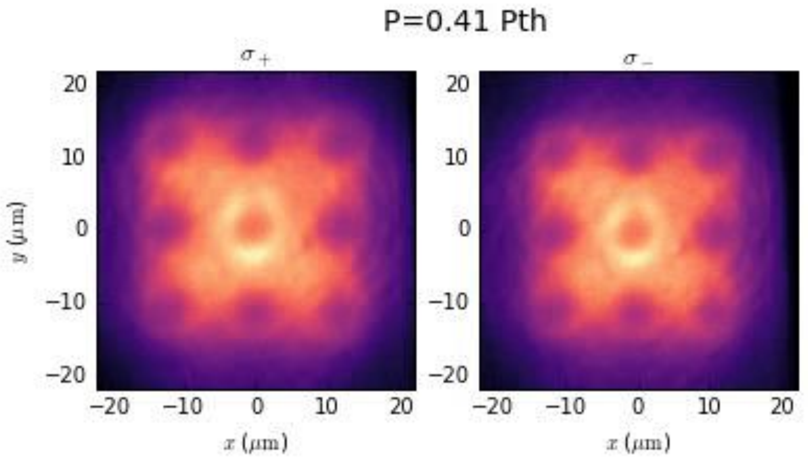
Spin chains

Under review in PRL

Spin chains



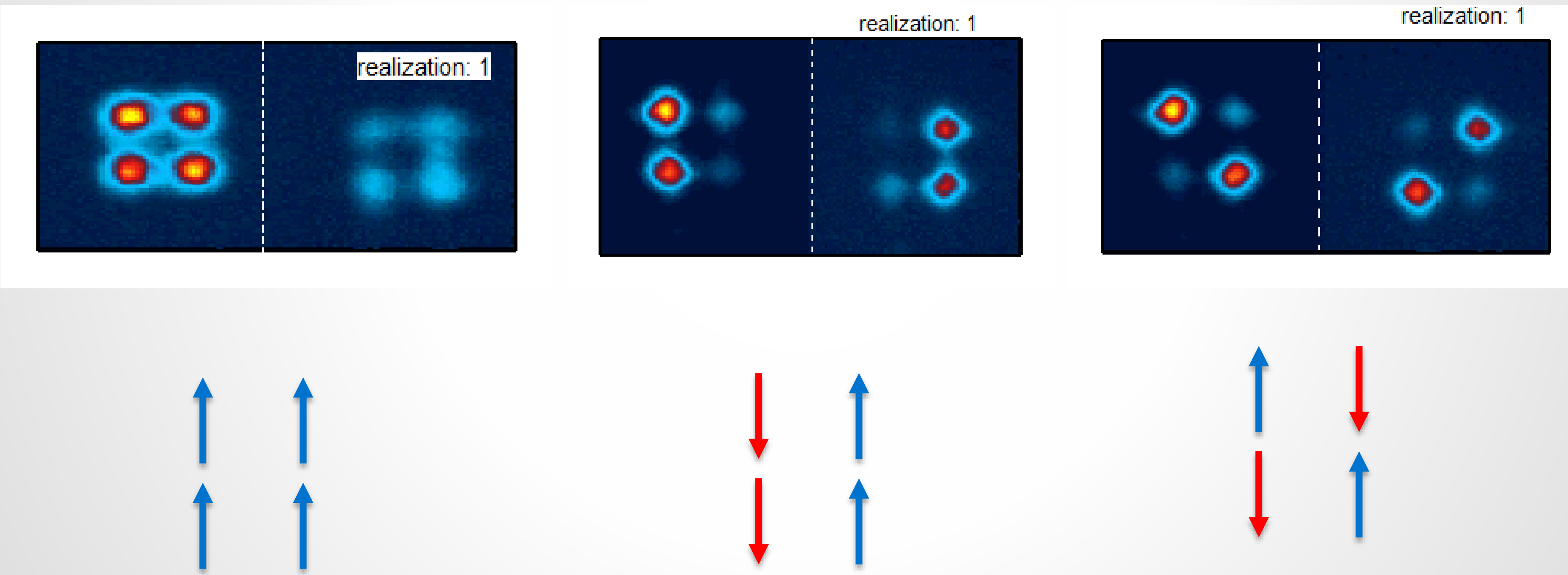




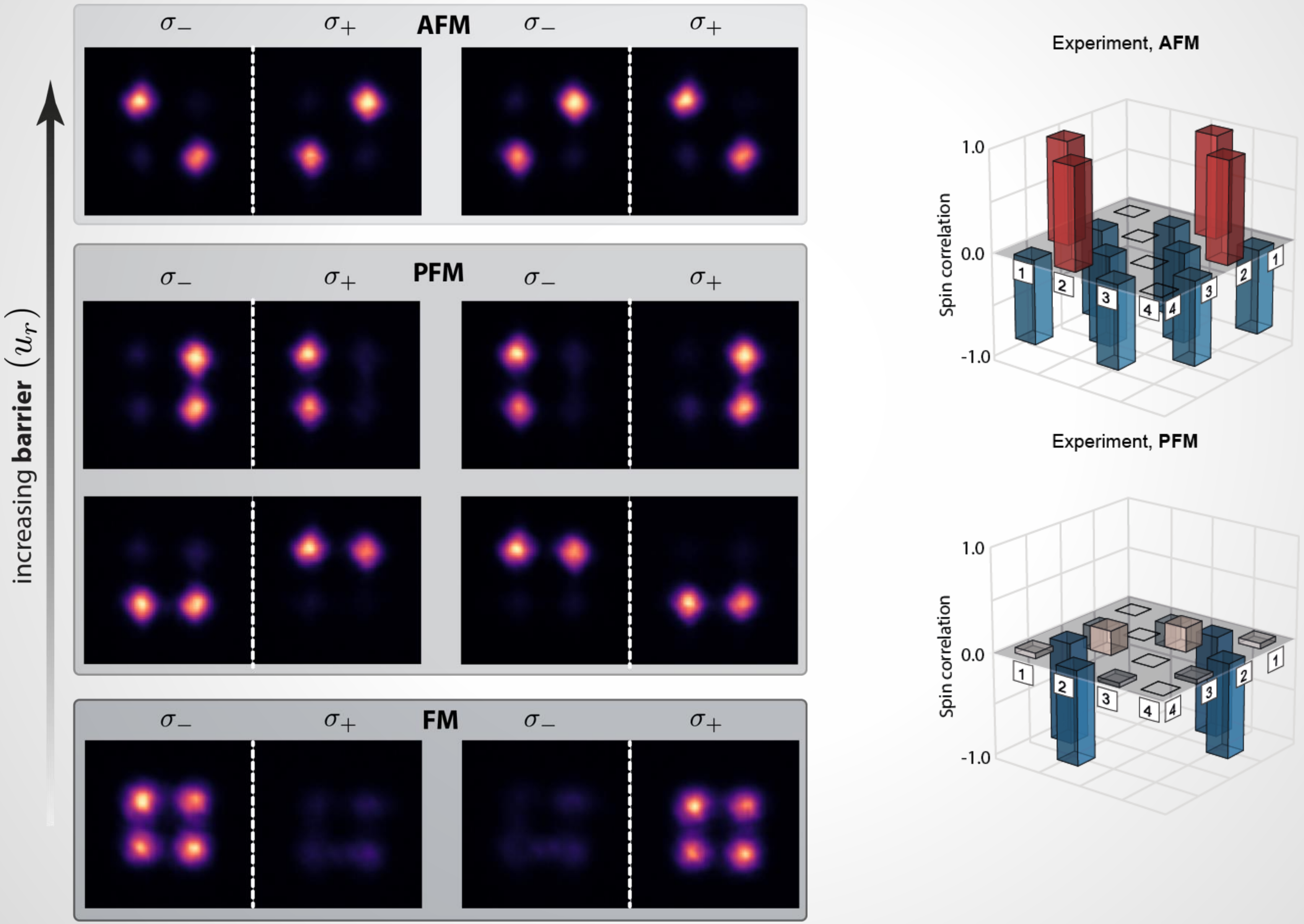
Under review in PRL

Spin chains – From FM to AFM phases

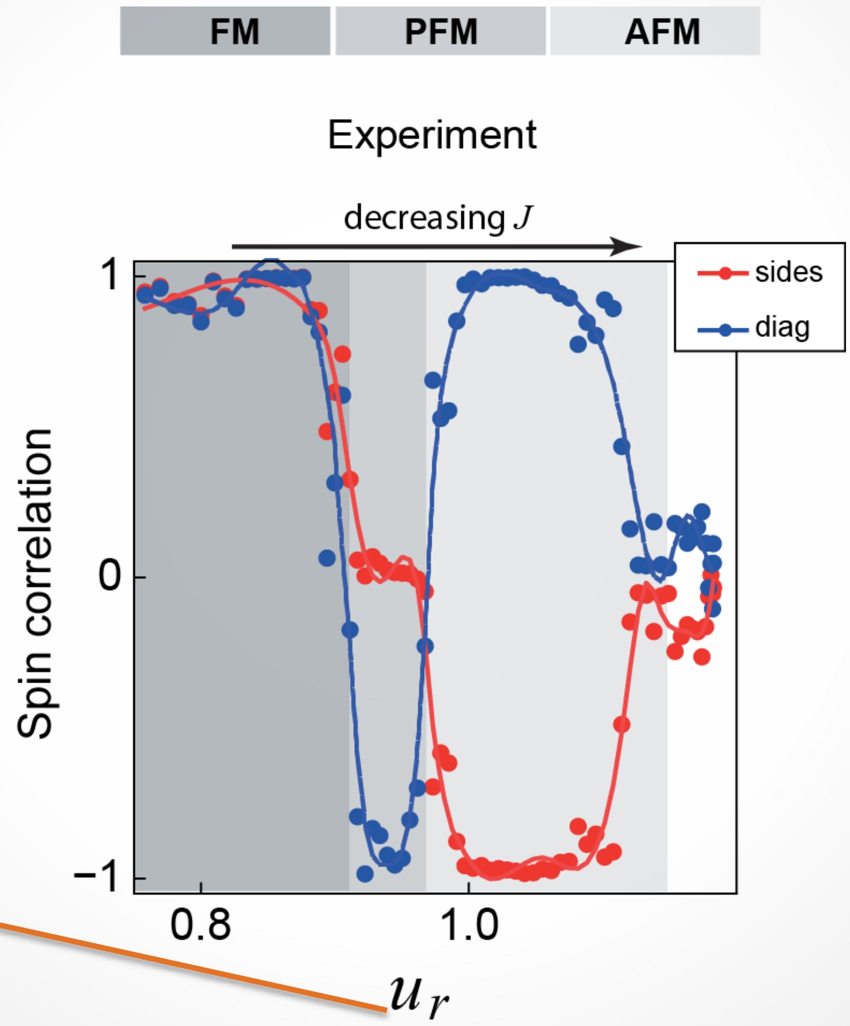
FM | Paired-spin | AFM

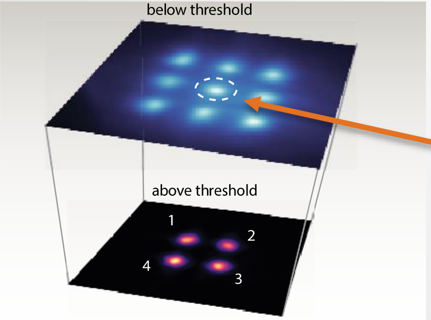


Spin chain – Possible realizations

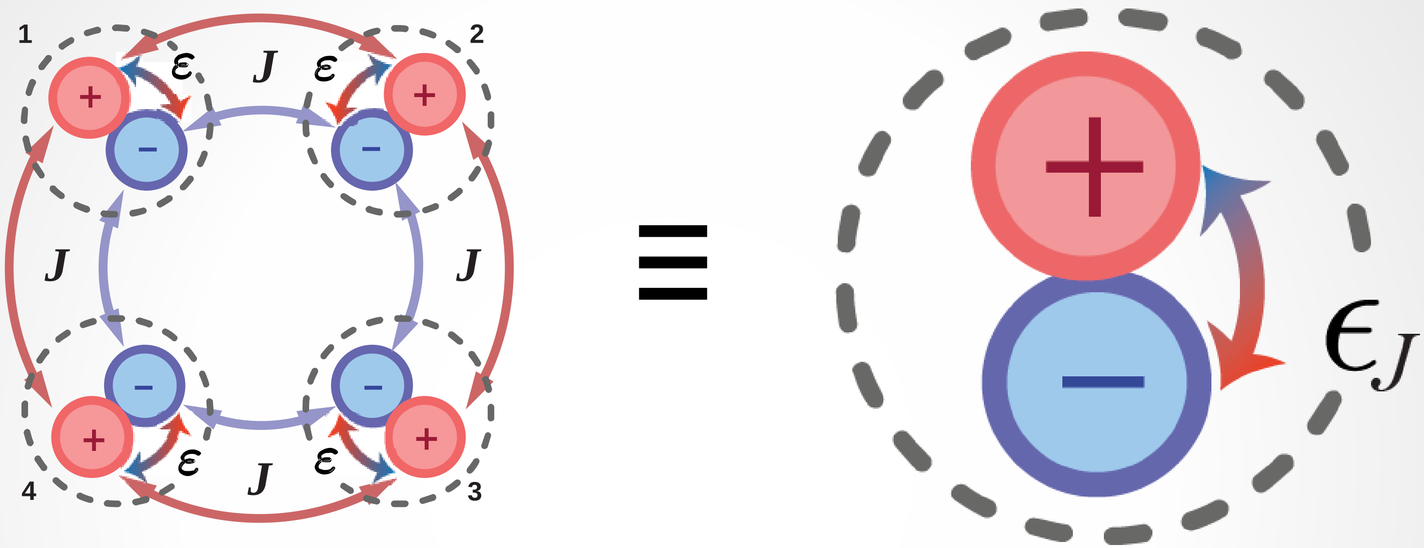


Spin chain – Phase diagram





Spin chain - Mean-field theory of spin chains



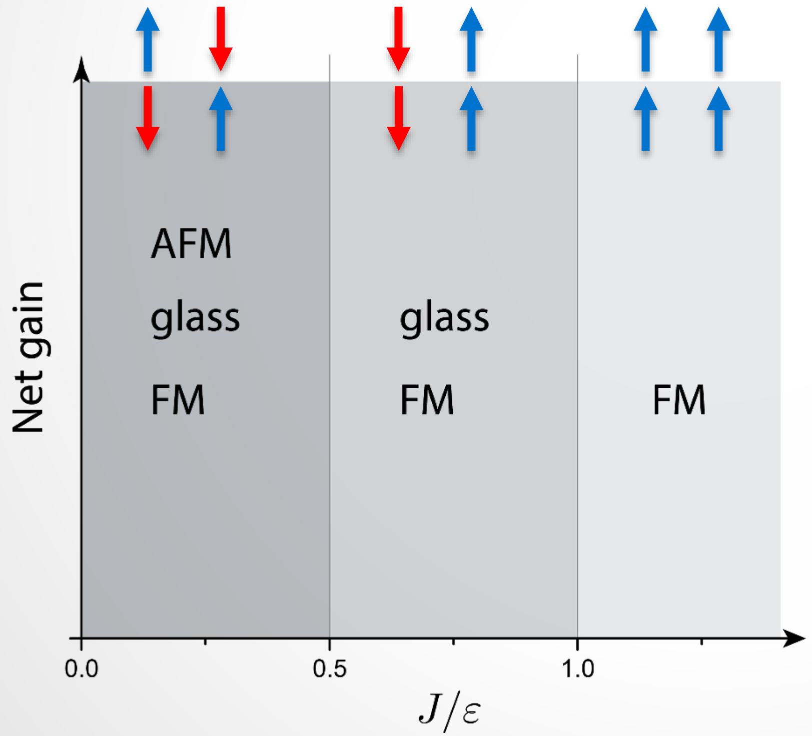
renormalized $\varepsilon_J = \varepsilon + J(a_+ e^{i\phi_+} + a_- e^{i\phi_-})$ $\quad a = \begin{cases} 0: & \text{FM} \\ 1: & \text{AFM} \end{cases}$

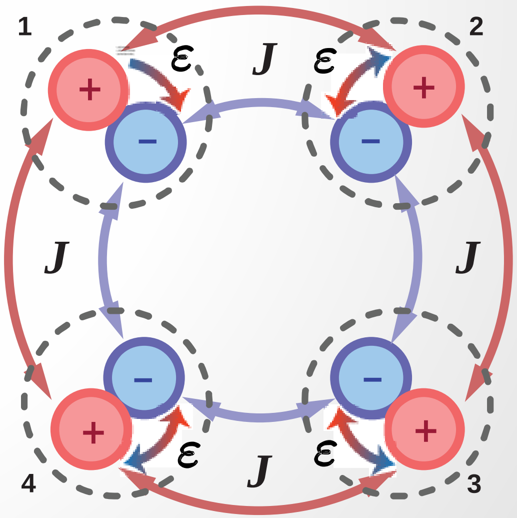
energy shift: $\omega_J = -J((1-a_+)e^{i\phi_+} + (1-a_-)\, e^{i\phi_-})$

Three key rules of spin chains

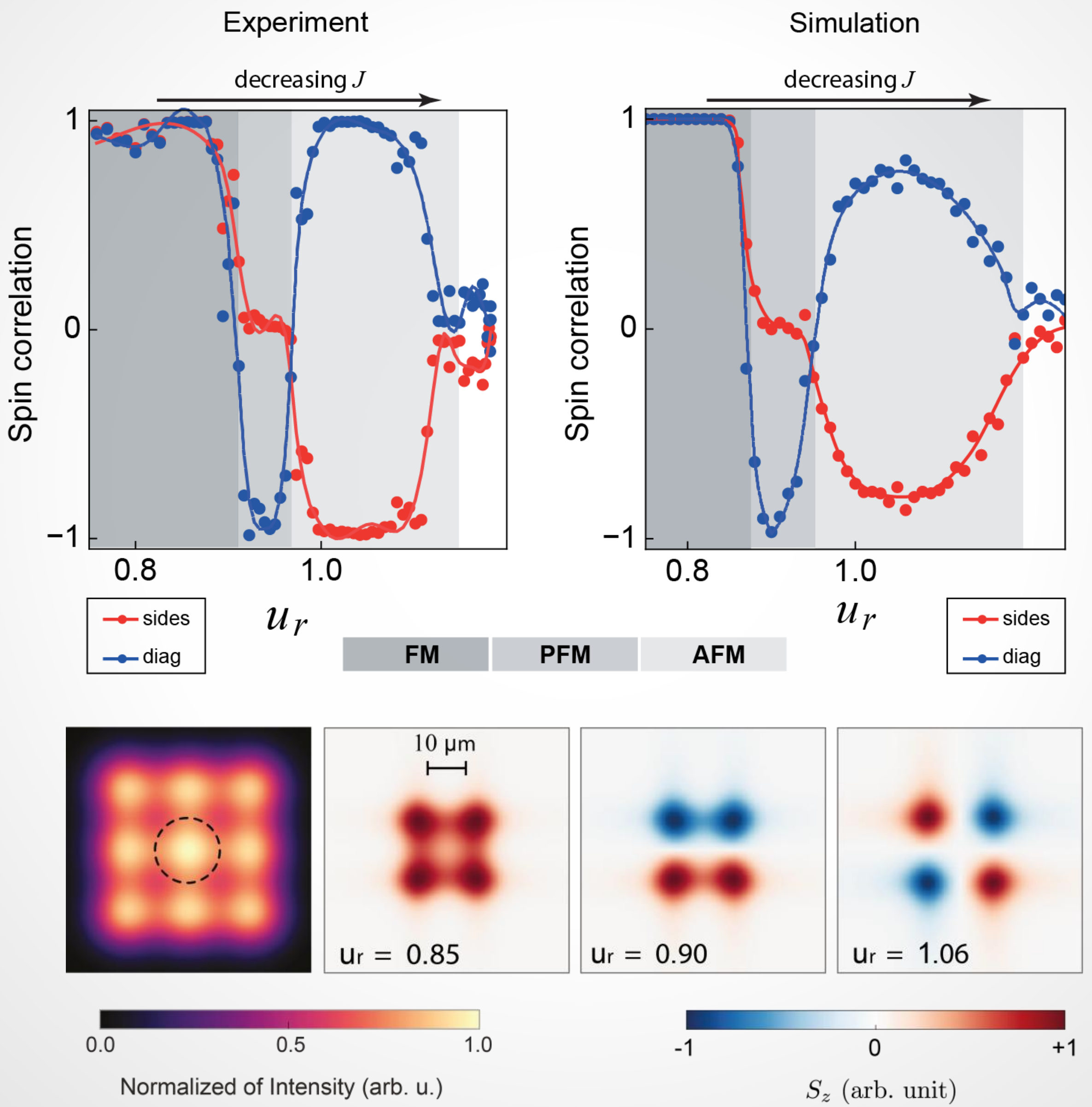
- ε_J should be real and positive
- ω_J should be the same for all condensates
- Lowest threshold states win (smallest ε_J)

$$N_c \simeq \frac{\varepsilon}{\alpha}$$



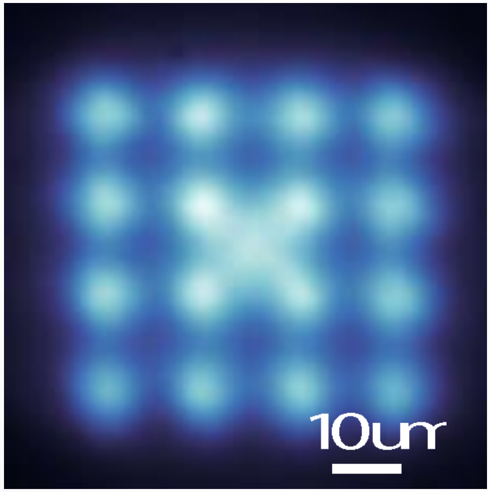


Spin chain - 2D simulations

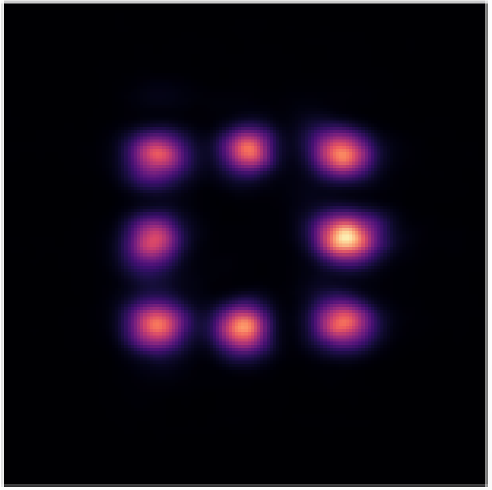


Large spin rings

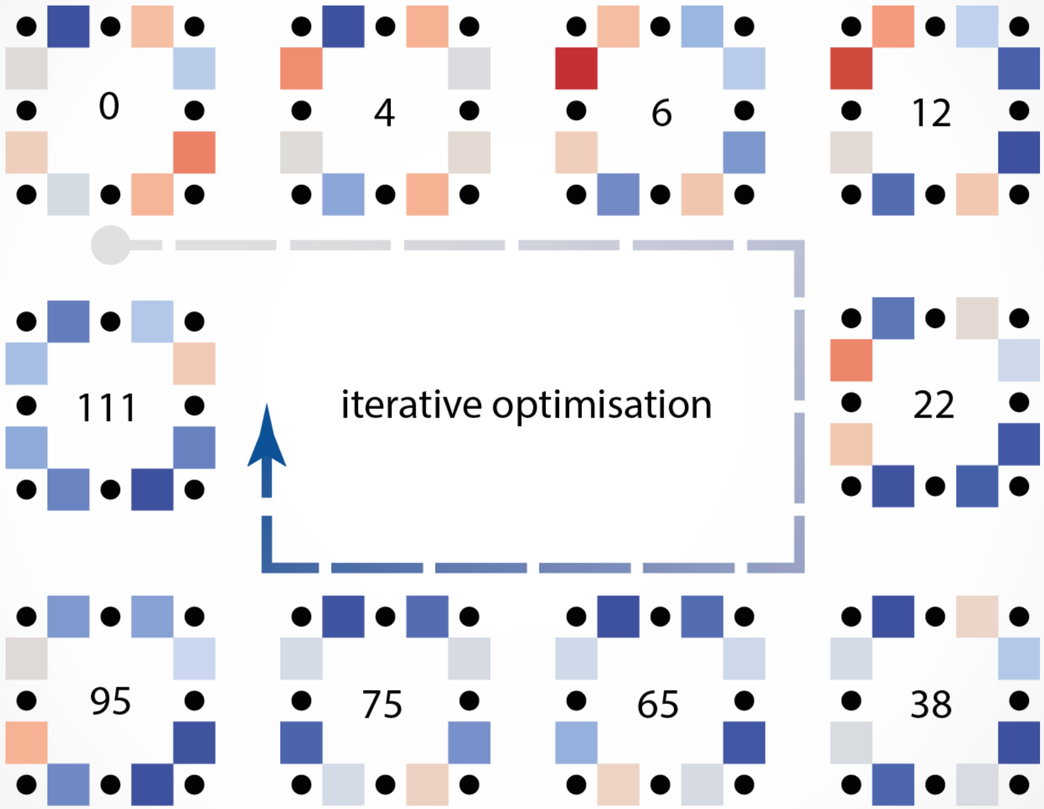
pump



condensate ring

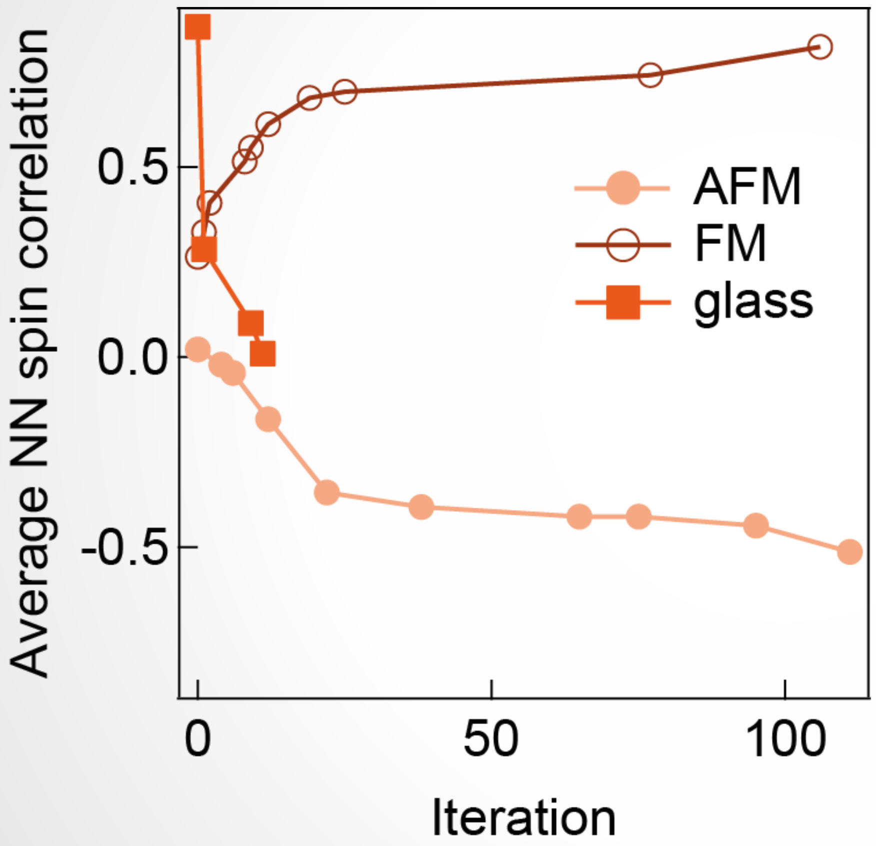


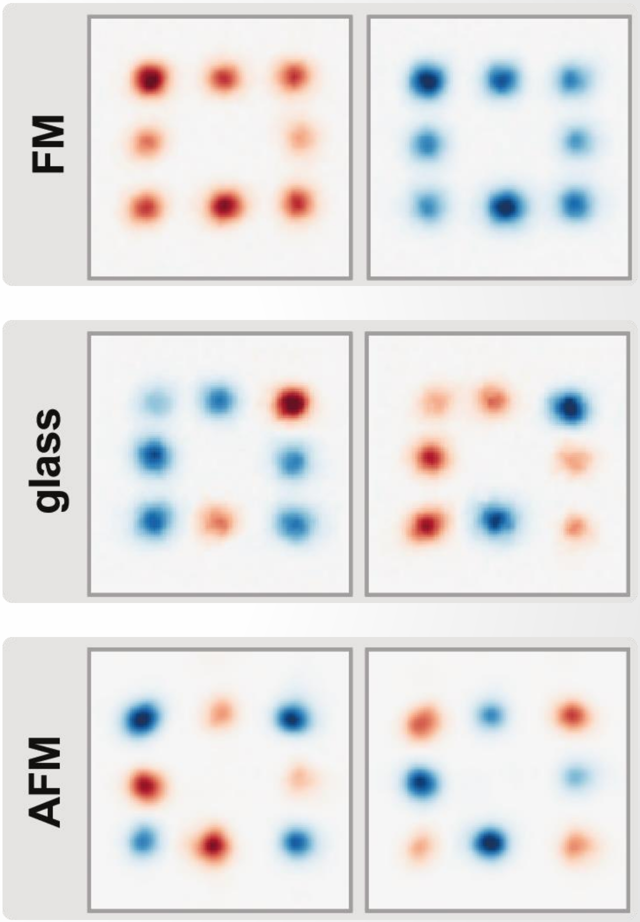
Engineering spin interactions

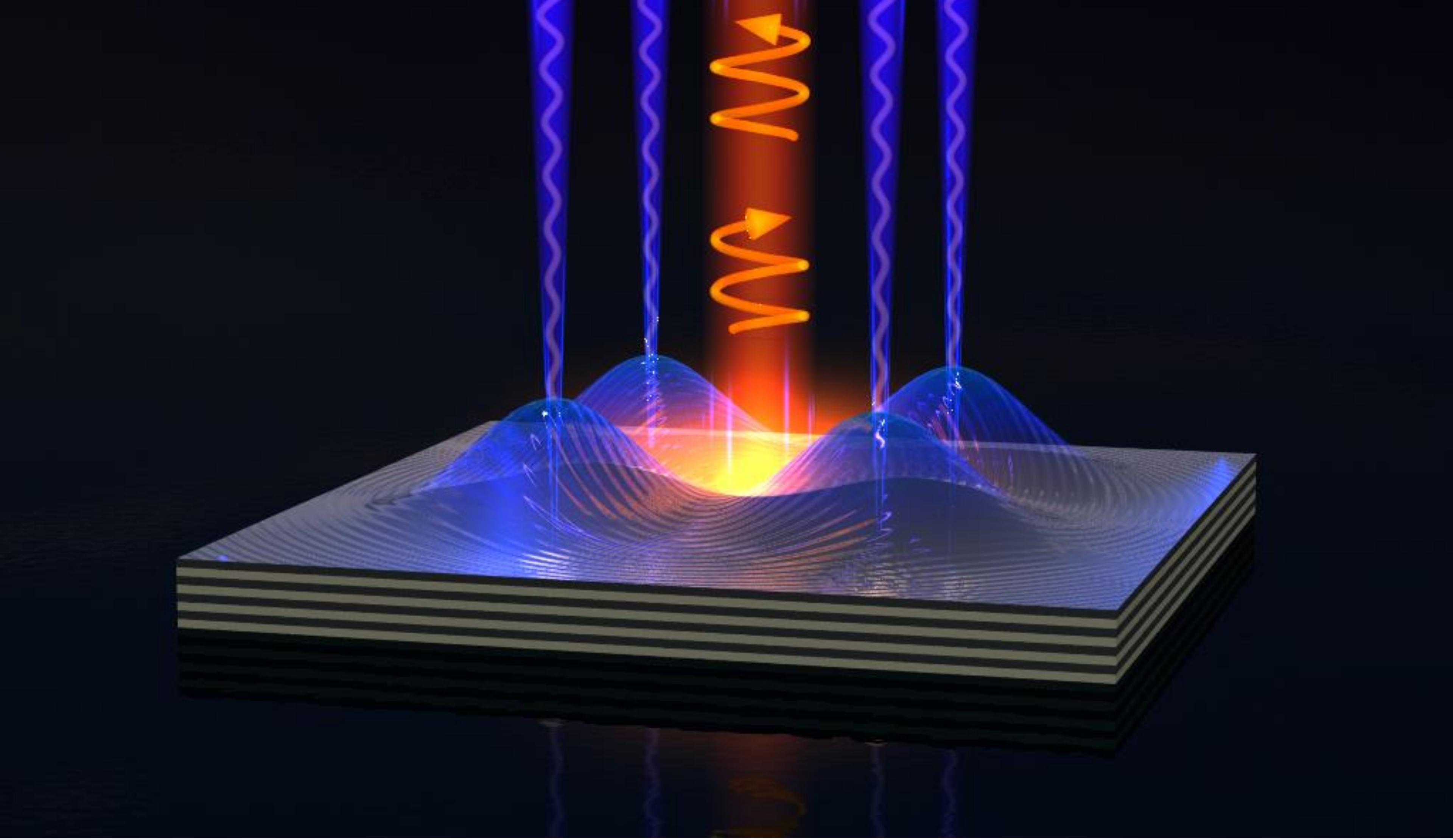


blue link: AFM coupling
red link: FM coupling

From AFM to glass to FM







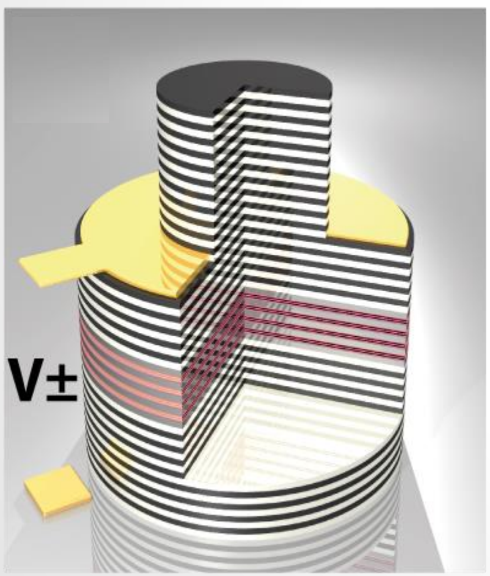
Part 4

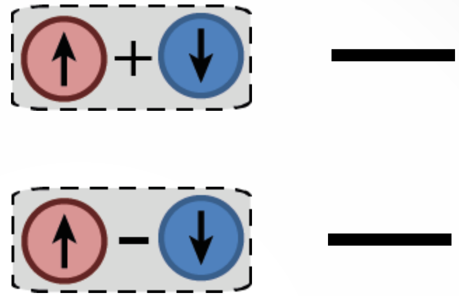
Electrical Spin Switching

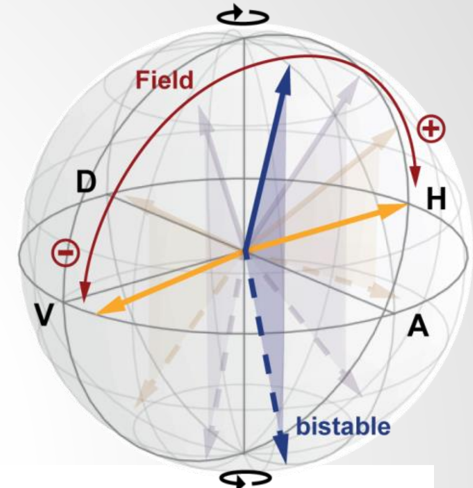
Nature Materials (2016)

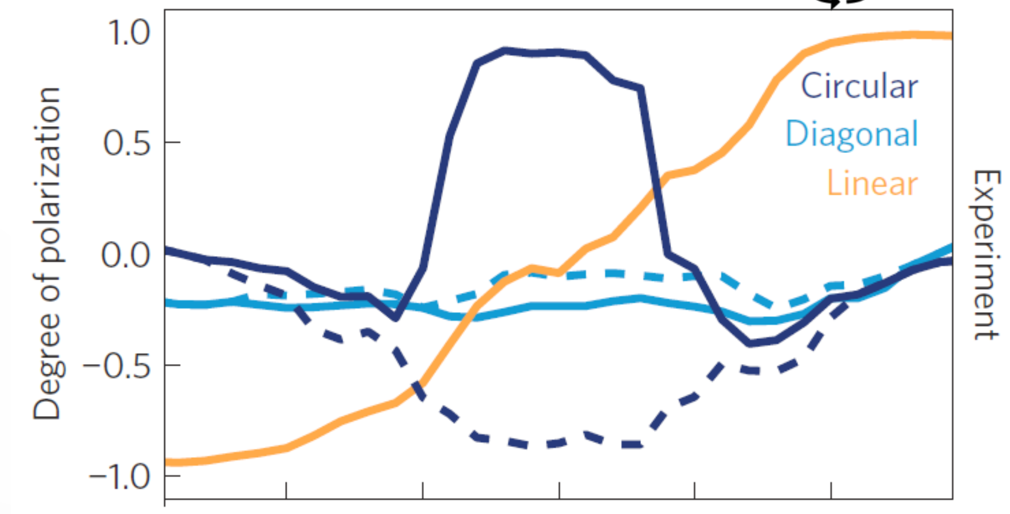
Applying electric fields

- bias tunes linear polarization energy splitting (Pockel's effect)
- linear splitting controls bifurcation threshold



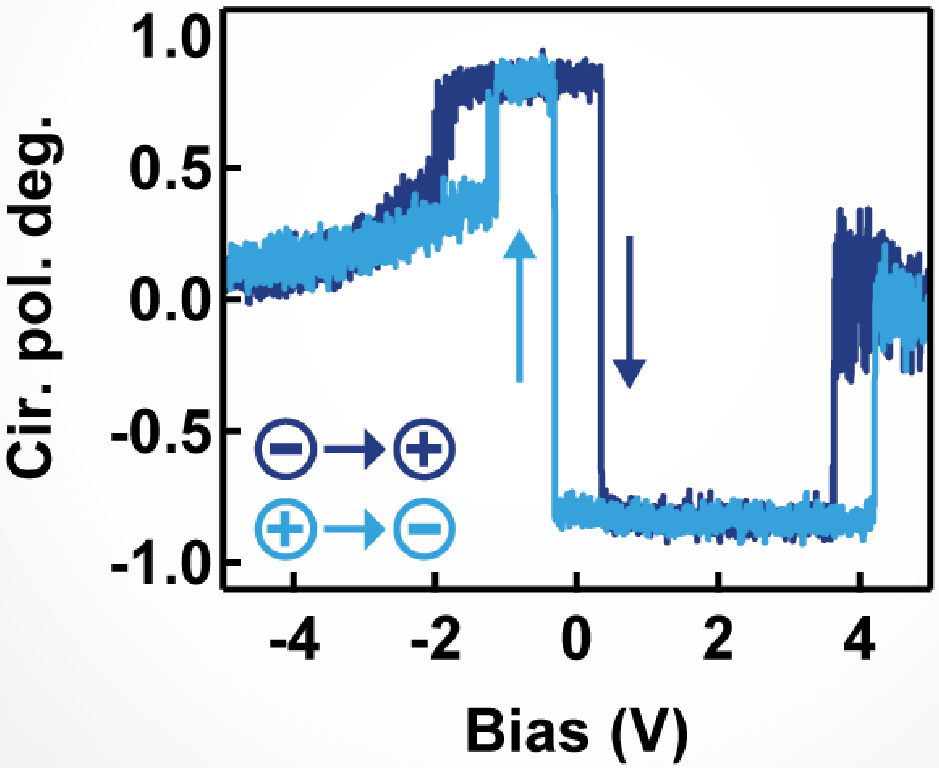






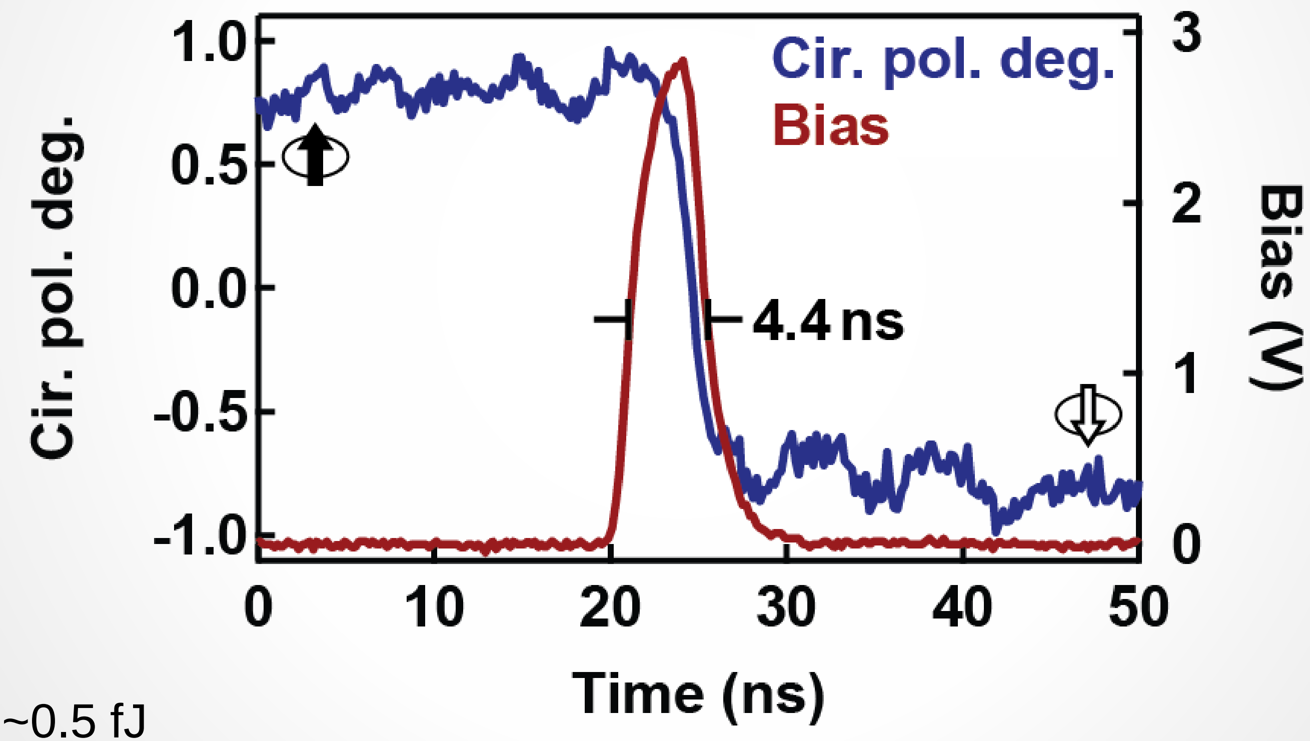
Hysteresis

Pumping imbalance



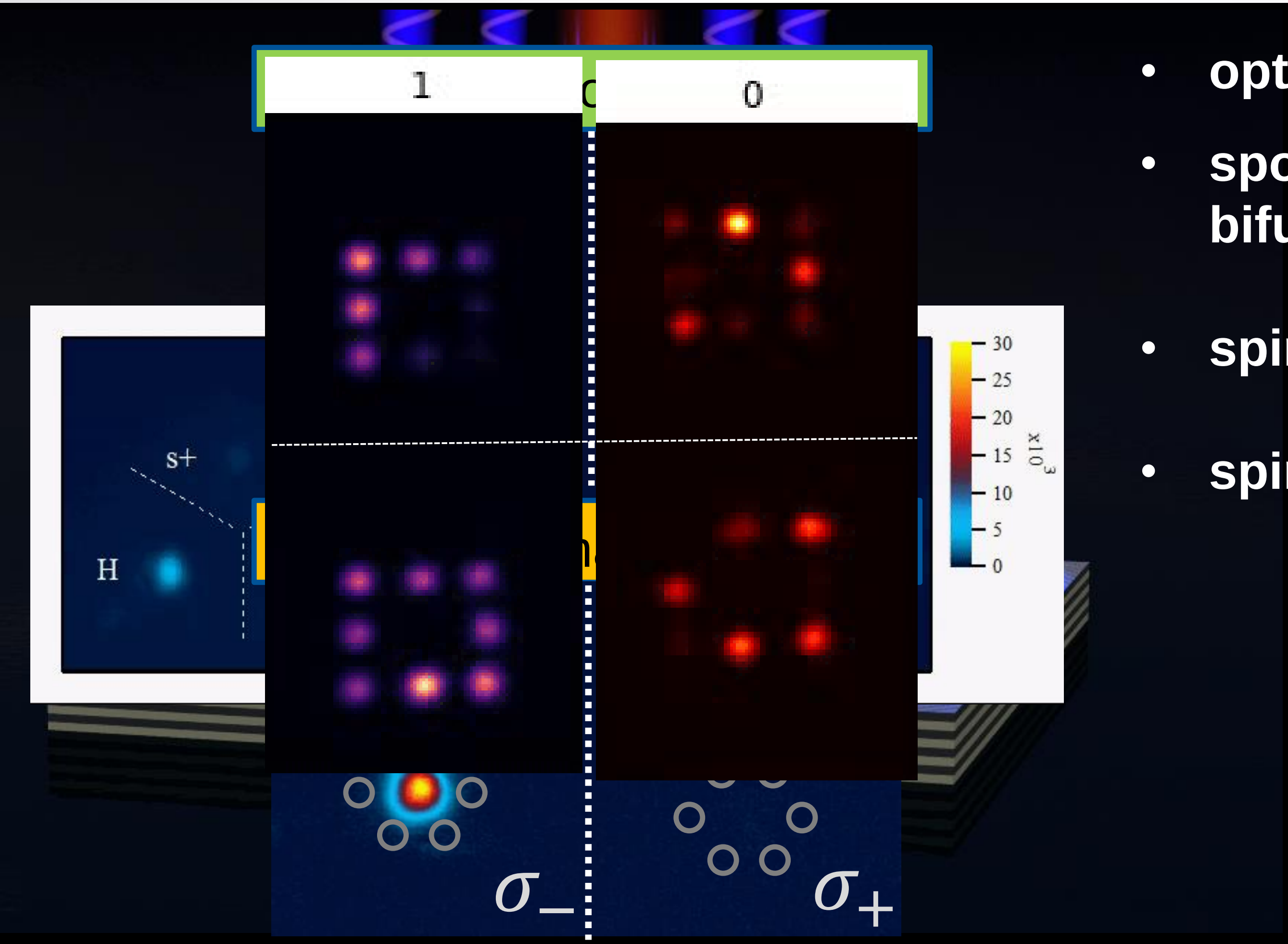
Nature Mat. (2016)

Electrical spin switching

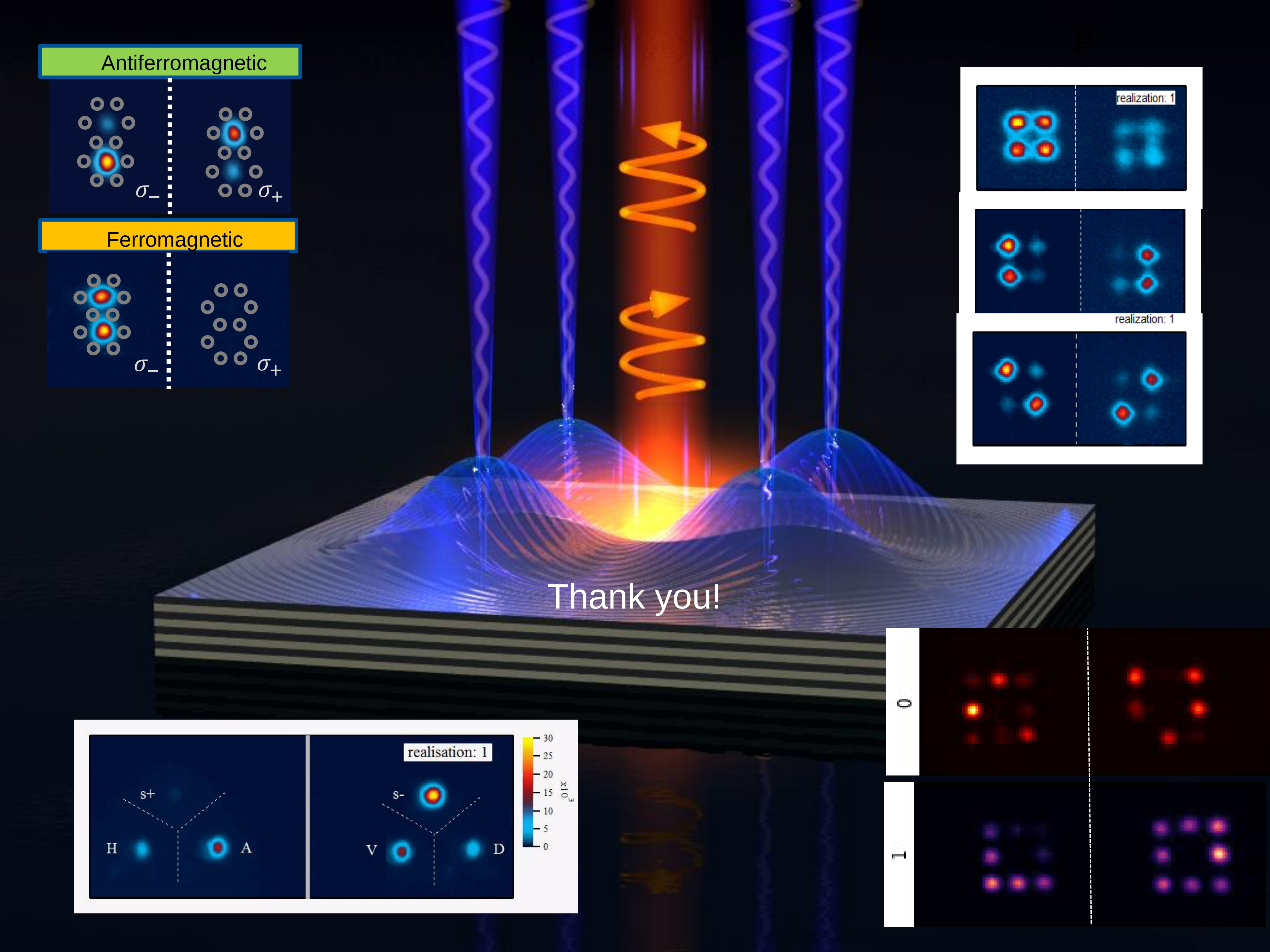


- E=~0.5 fJ
- $t_s \approx 2.5$ ns

Conclusion and outlook



- optically induced traps
- spontaneous spin-bifurcation
- spin coupling
- spin chains


Antiferromagnetic
σ−
σ+
Ferromagnetic
σ−
σ+
realization: 1
realization: 1
Thank you!
realisation: 1
s+
H
A
s-
V
D
30
25
20
15
10
5
0
x10³
0
1