Quantum control of spin correlations in ultracold lattice gases

P. Hauke
(IQOQI)

P.Hauke, R.J.S., M.W.Mitchell & M.Lewenstein,
PRA 87, 021601 (2013).

M.Lewenstein

M.W.Mitchell

ICFO Institut de Ciències Fotòniques

MAgroup Mitchell

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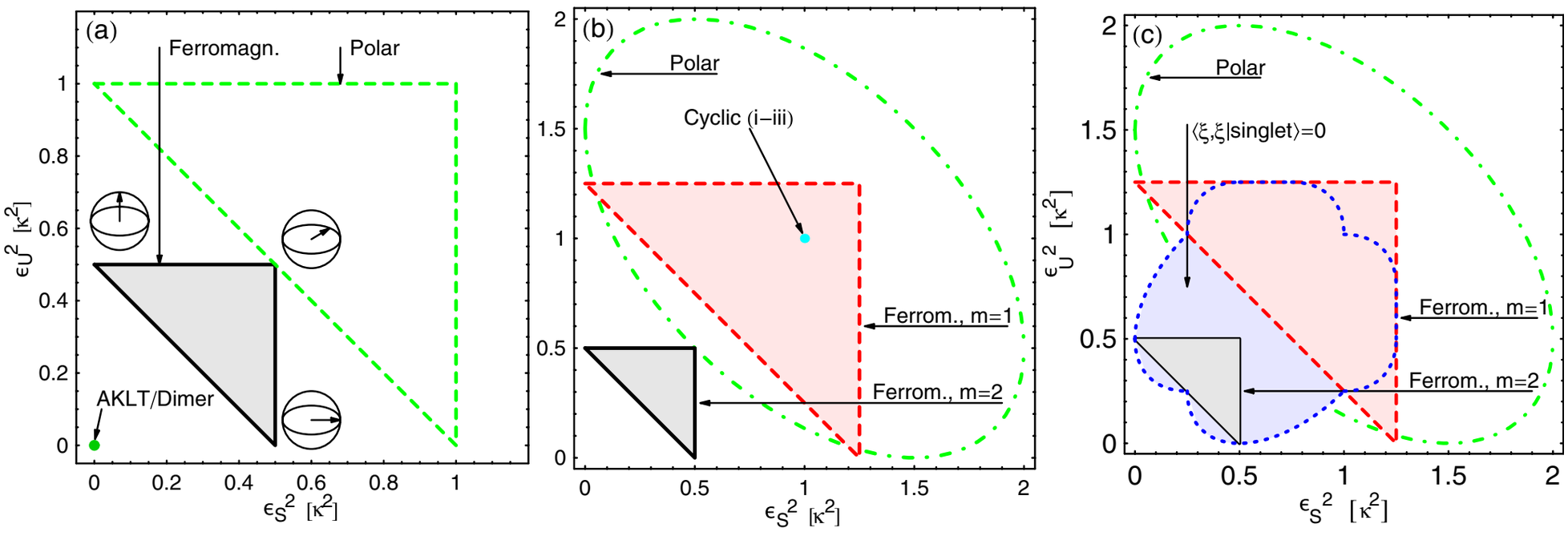
Quantum Polarization Spectroscopy

PRL **98,** 100404 (2007) PHYSICAL REVIEW LETTERS week ending 9 MARCH 2007

Quantum Polarization Spectroscopy of Ultracold Spinor Gases

K. Eckert,[1] Ł. Zawitkowski,[2] A. Sanpera,[3] M. Lewenstein,[4] and E. S. Polzik[5,6]

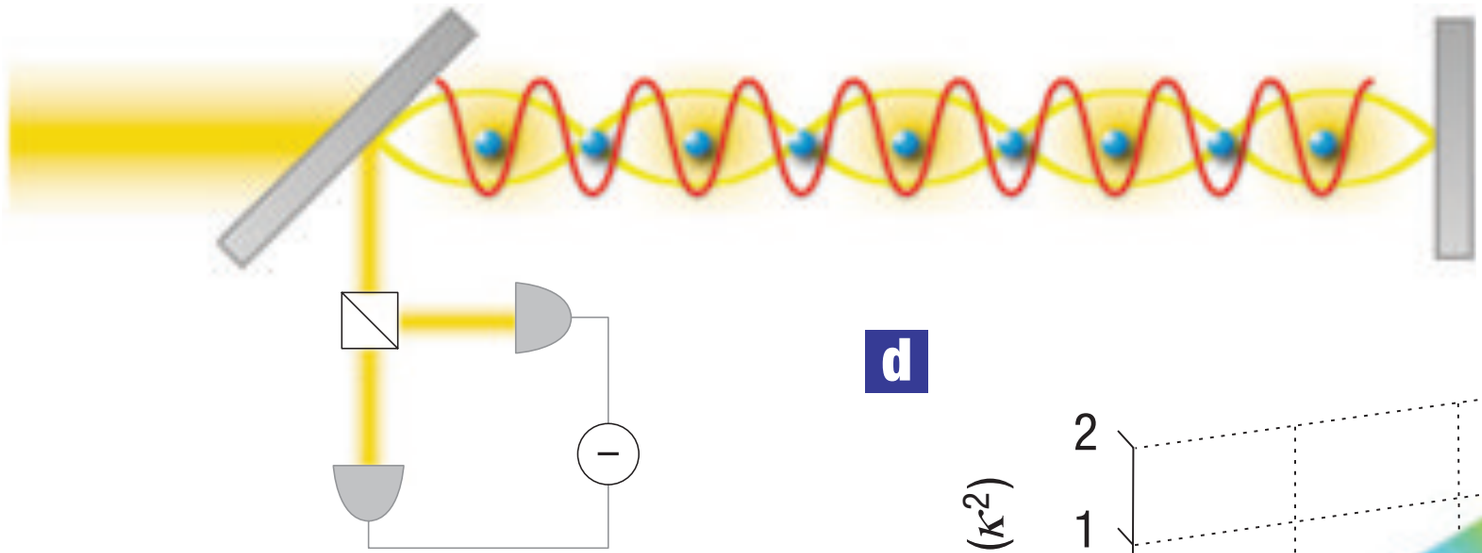


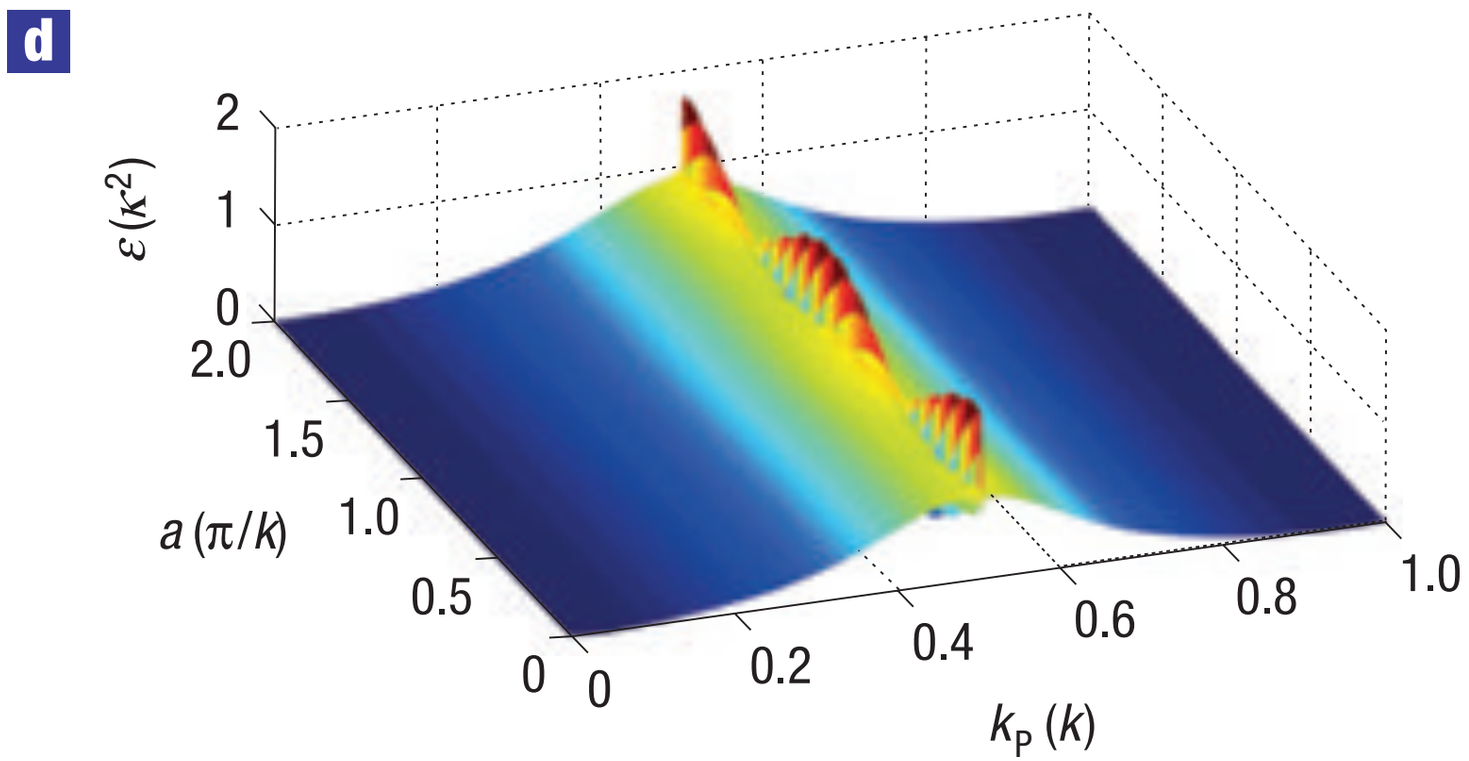
Eckert, PRL 98, 100404 (2007)

Quantum Polarization Spectroscopy

Quantum non-demolition detection of strongly correlated systems

KAI ECKERT[1], ORIOL ROMERO-ISART[1], MIRTA RODRIGUEZ[2], MACIEJ LEWENSTEIN[2,3], EUGENE S. POLZIK[4] AND ANNA SANPERA[1,3]*

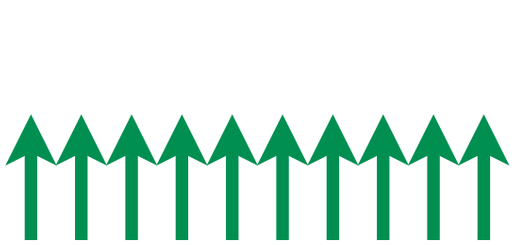


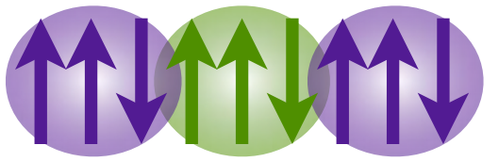


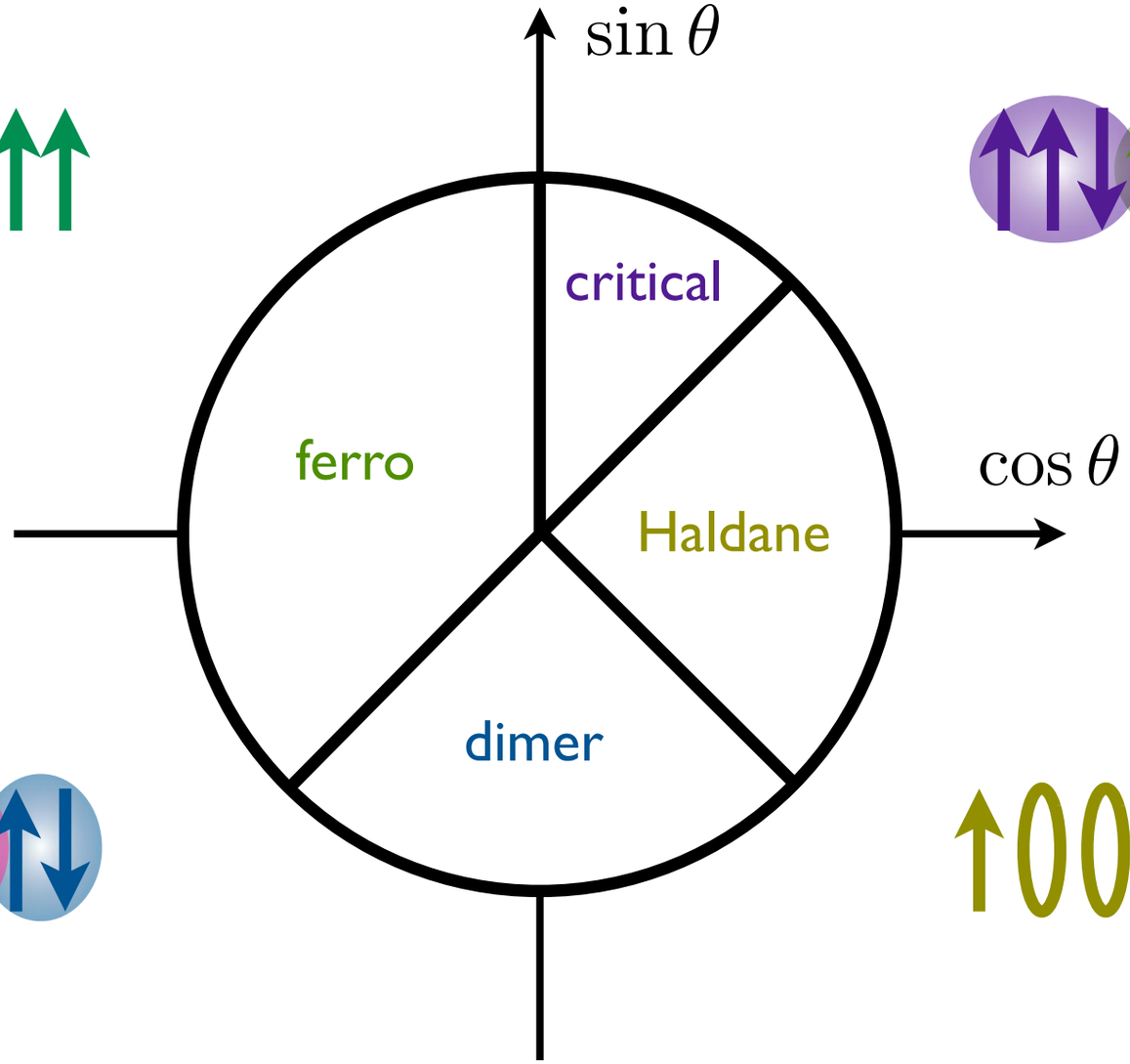
Eckert, Nat. Phys. 4, 50 (2008)

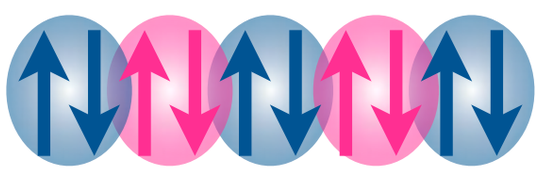
Example: 1D chain of spin-1 atoms described by the bilinear-biquadratic Hamiltonian

$$H = \sum_i \cos\theta \mathbf{S}_i \cdot \mathbf{S}_{i+1} + \sin\theta \left(\mathbf{S}_i \cdot \mathbf{S}_{i+1}\right)^2$$









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De Chiara, PRA 83, 021604 (2011)

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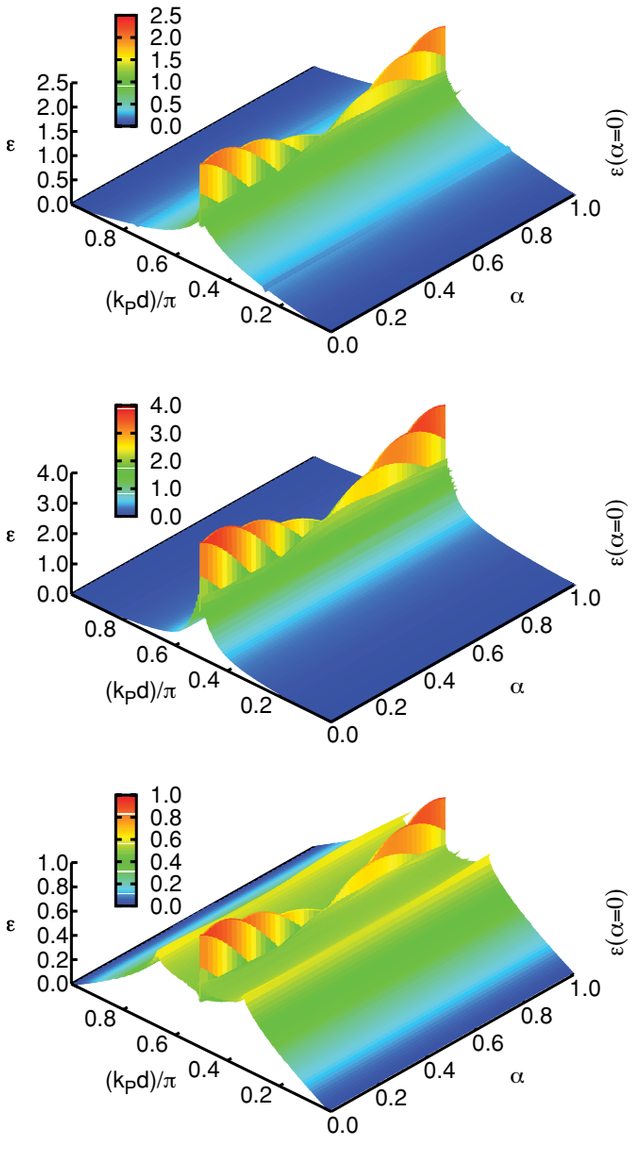
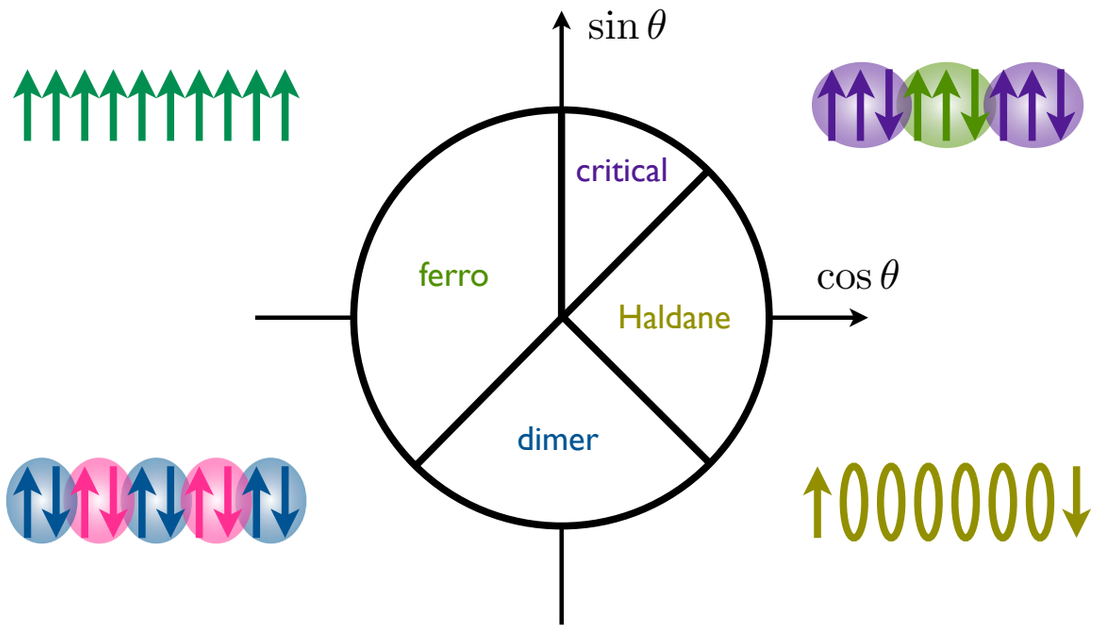
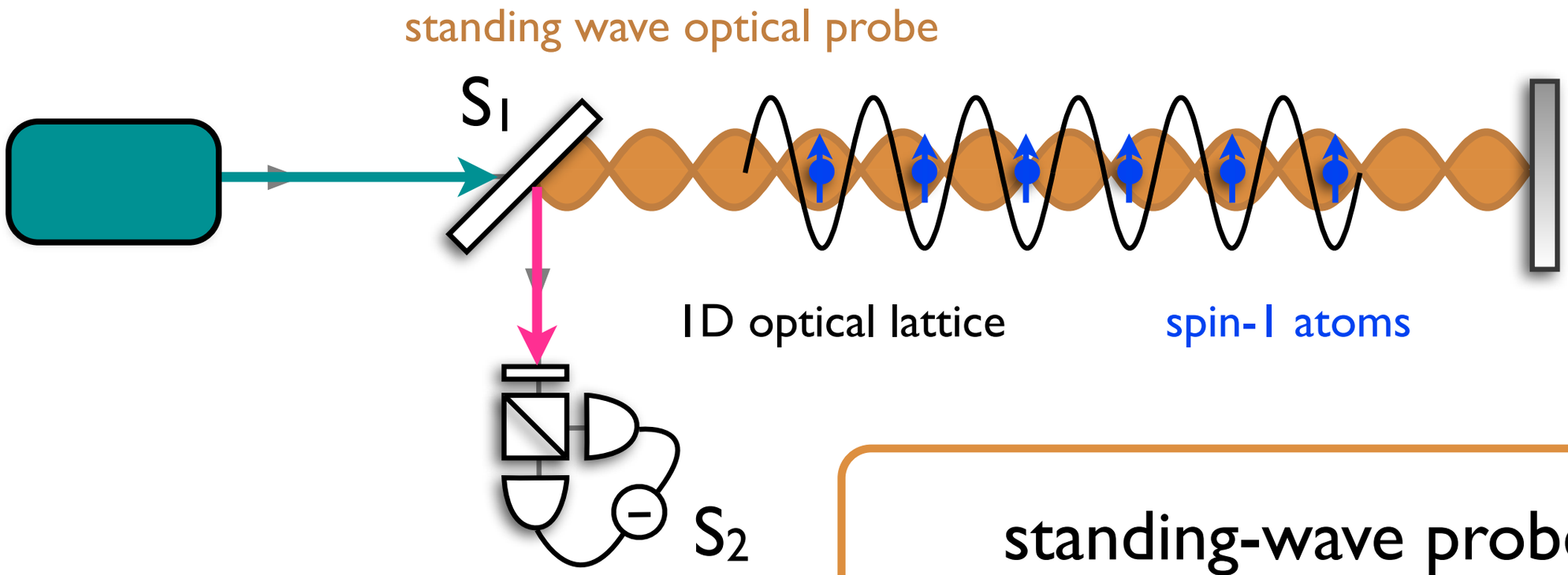




De Chiara, PRA 83, 021604 (2011)

Quantum Polarization Spectroscopy



standing-wave probe

$$c_i(k_p) = (1 + \cos(2k_p r_i))/2$$

atom-light interaction

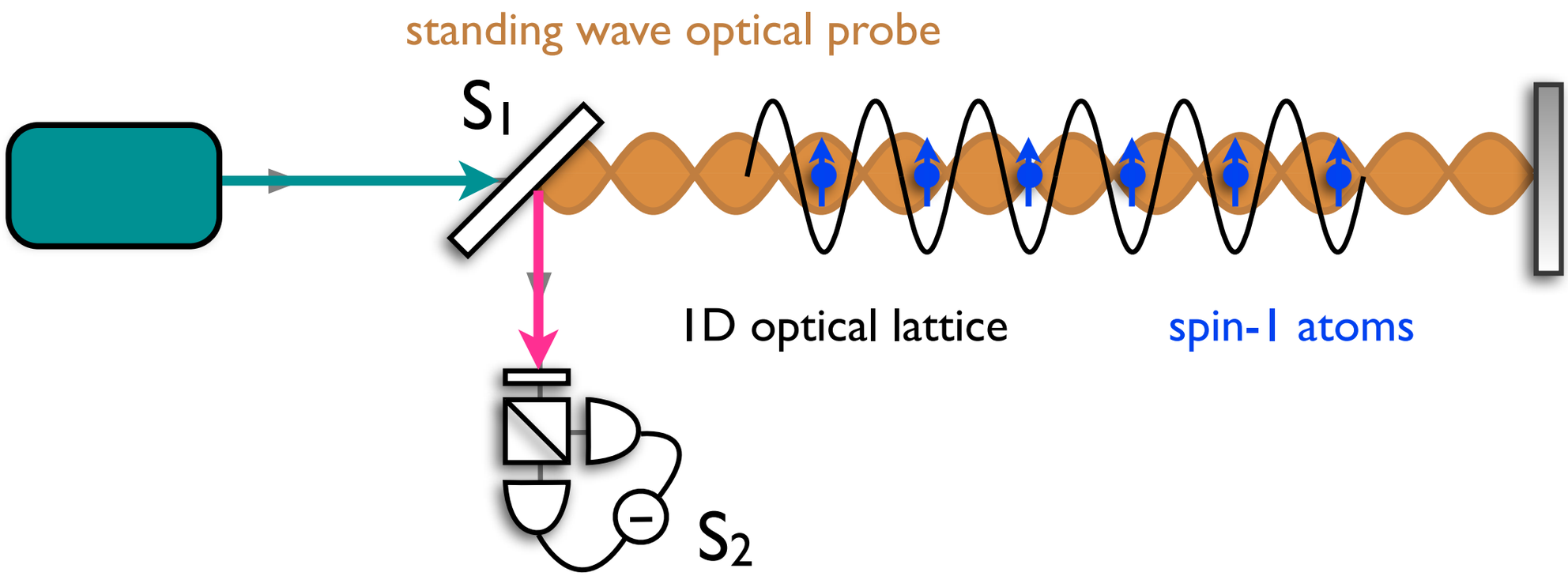
$$H_p = \Omega_p \sum_i c_i(k_p) J_{z,i} S_3$$

measurement

$$S_2^{(\mathrm{out})} = S_2^{(\mathrm{in})} + \kappa_p \sum_i c_i(k_p) J_{z,i}$$

$$J_{\alpha,i} \equiv \sum_{n=1}^{n_\mathrm{a}} j_{\alpha,i}^{(n)} \qquad \Omega_p \equiv \frac{\sigma(\Delta)}{A}$$

Quantum Polarization Spectroscopy



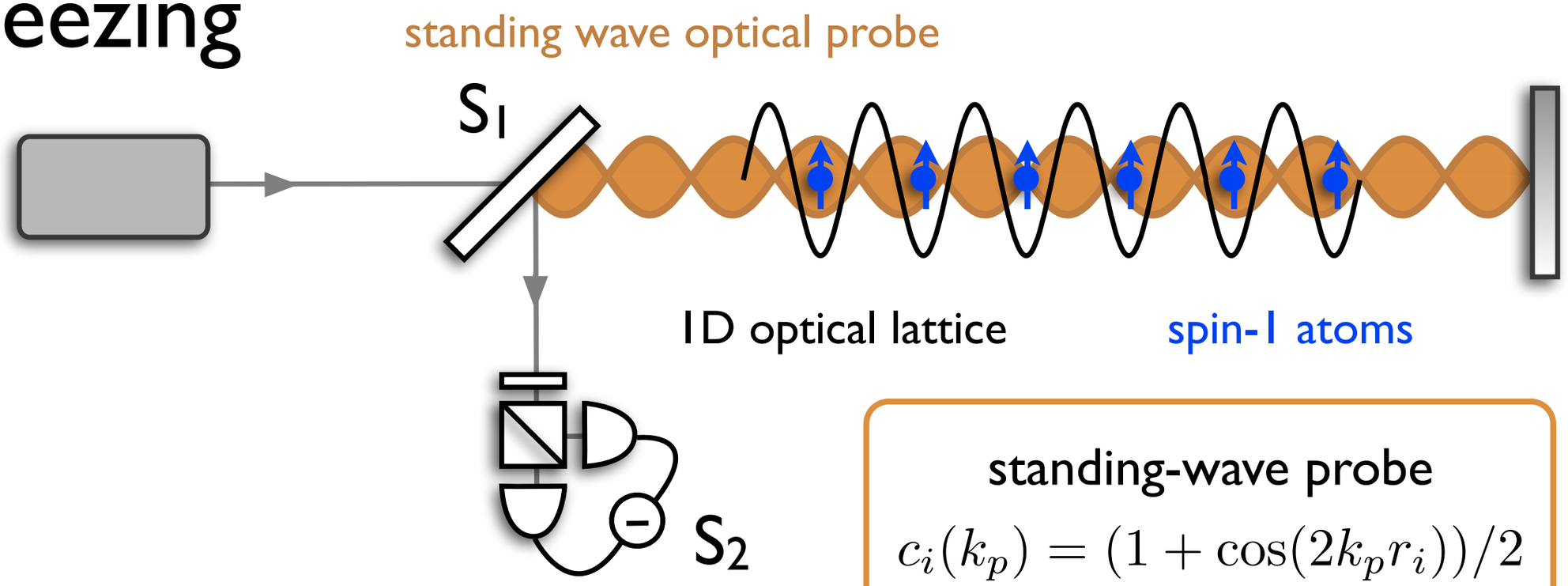
detected variance

$$\Delta^2 S_2^{(\mathrm{out})} = \Delta^2 S_2^{(\mathrm{in})} + \kappa_p^2 \sum_{i,j} c_i(k_p) c_j(k_p) G_{ij}$$

spin correlation function

$$G_{ij} \equiv \langle J_z(r_i) J_z(r_j) \rangle - \langle J_z(r_i) \rangle \langle J_z(r_j) \rangle$$

Spin Squeezing



standing-wave probe

$$c_i(k_p) = (1 + \cos(2k_p r_i))/2$$

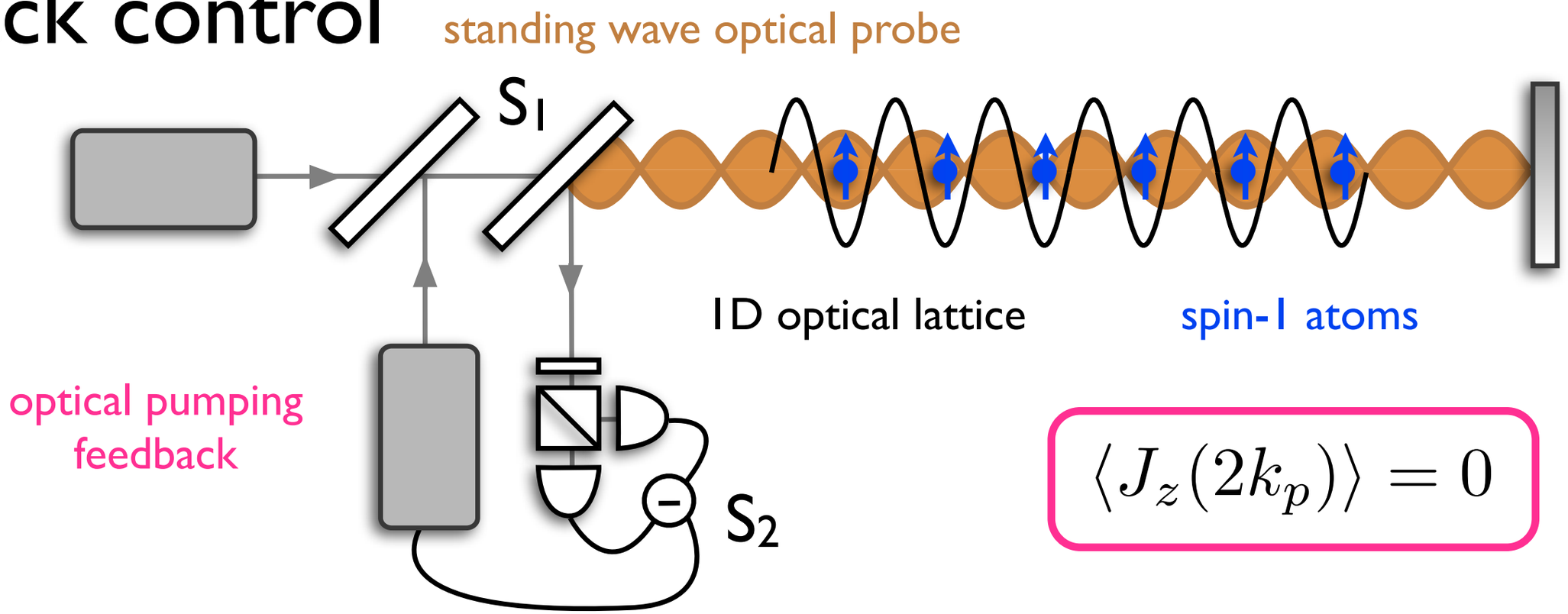
squeeze atomic spin wave

$$\Delta^2 J_z^{(\mathrm{out})}(\pm 2k_p) \simeq \frac{\Delta^2 J_z^{(\mathrm{in})}(\pm 2k_p)}{1 + \kappa_p^2}$$

Hauke, PRA 87, 021601 (2013)

$$J_\alpha(k) \equiv \frac{1}{\sqrt{n_\mathrm{s}}} \sum_i J_{\alpha,i} \exp(ikr_i)$$

Feedback control



$$\langle J_z(2k_p)\rangle = 0$$

squeeze atomic spin wave

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Hauke, PRA 87, 021601 (2013)

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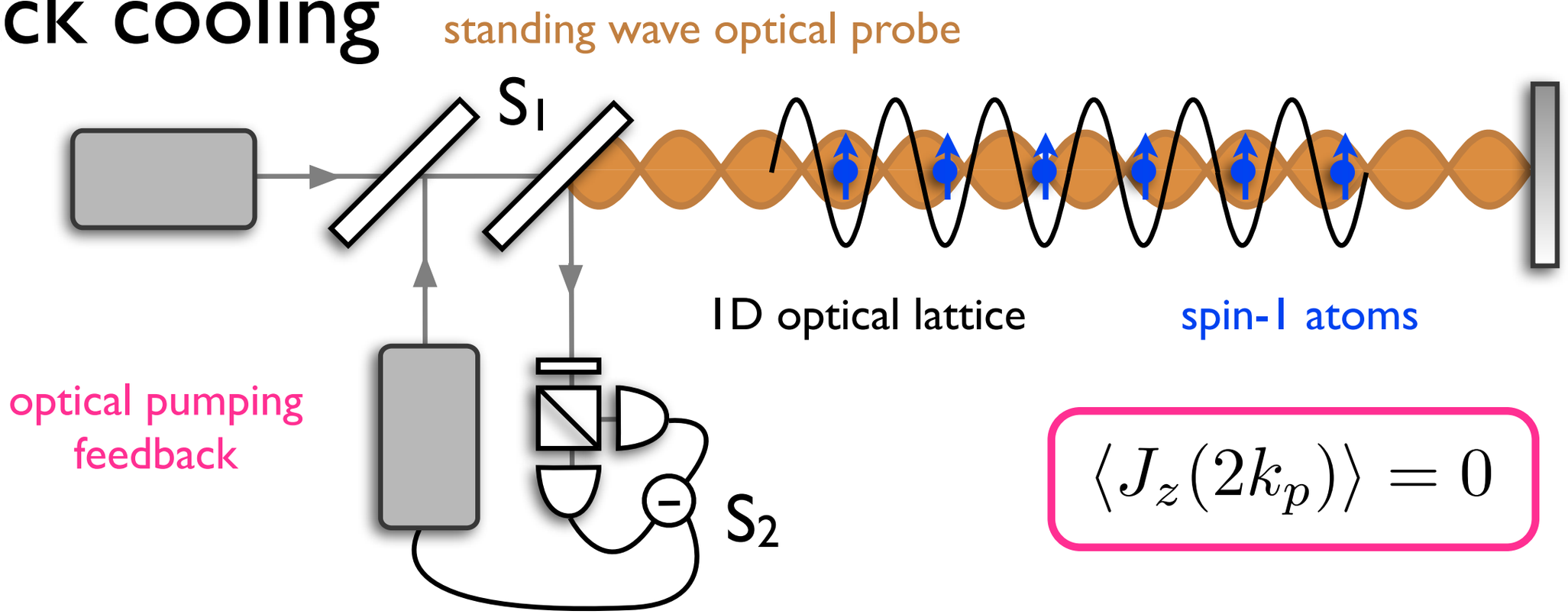
Feedback cooling



$$\langle J_z(2k_p)\rangle = 0$$

Heisenberg uncertainty relation

$$\Delta J_\alpha(k_1)\Delta J_\beta(k_2) \geq \tfrac{1}{4}|\langle J_\gamma(k_1+k_2)\rangle|$$

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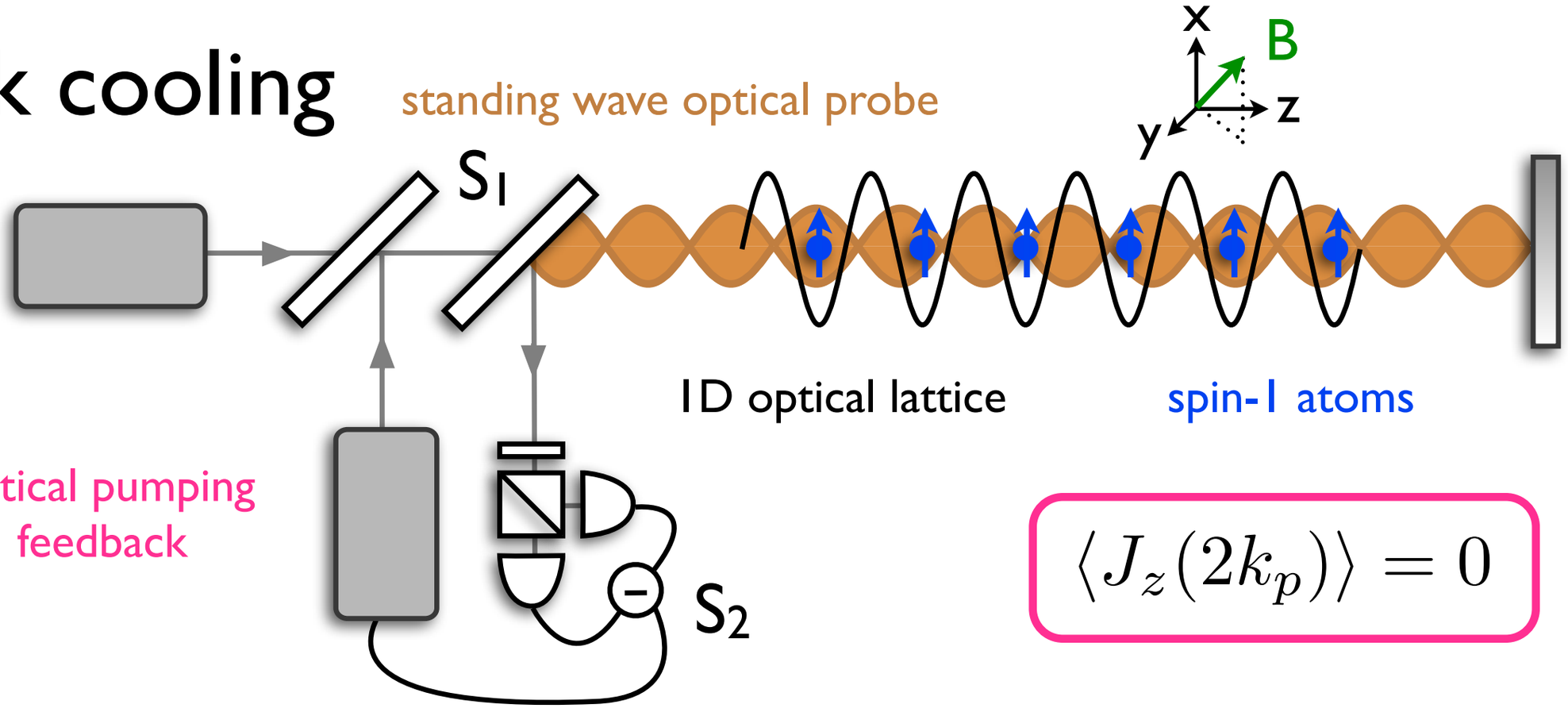
Feedback cooling



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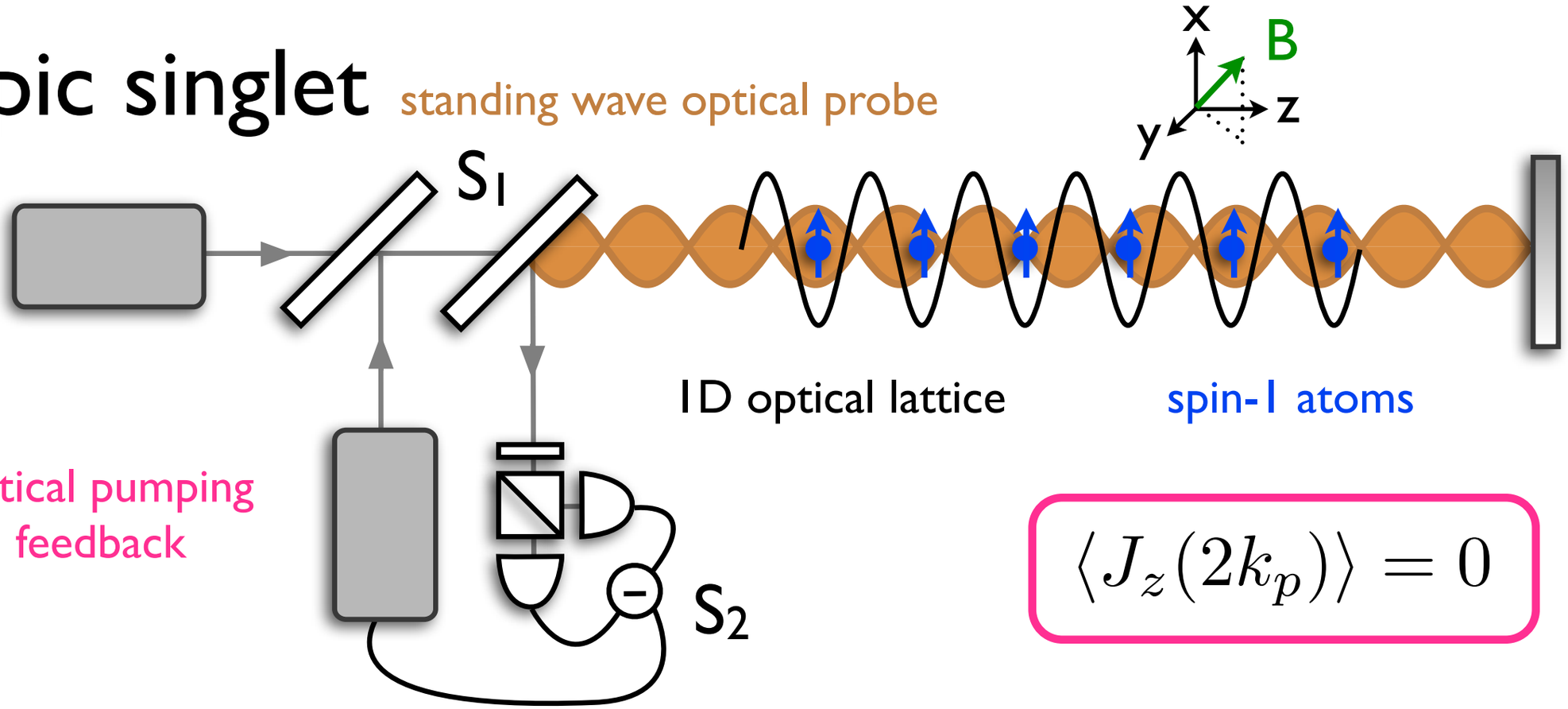
Macroscopic singlet



$$\langle J_z(2k_p)\rangle = 0$$

mascroscopic spin singlet

$$\Delta^2 J_\alpha(2k_p) \to 0 \quad \& \quad \langle J_\alpha(2k_p)\rangle = 0$$

$$|\mathbf{J}(2k_p)| \to 0$$

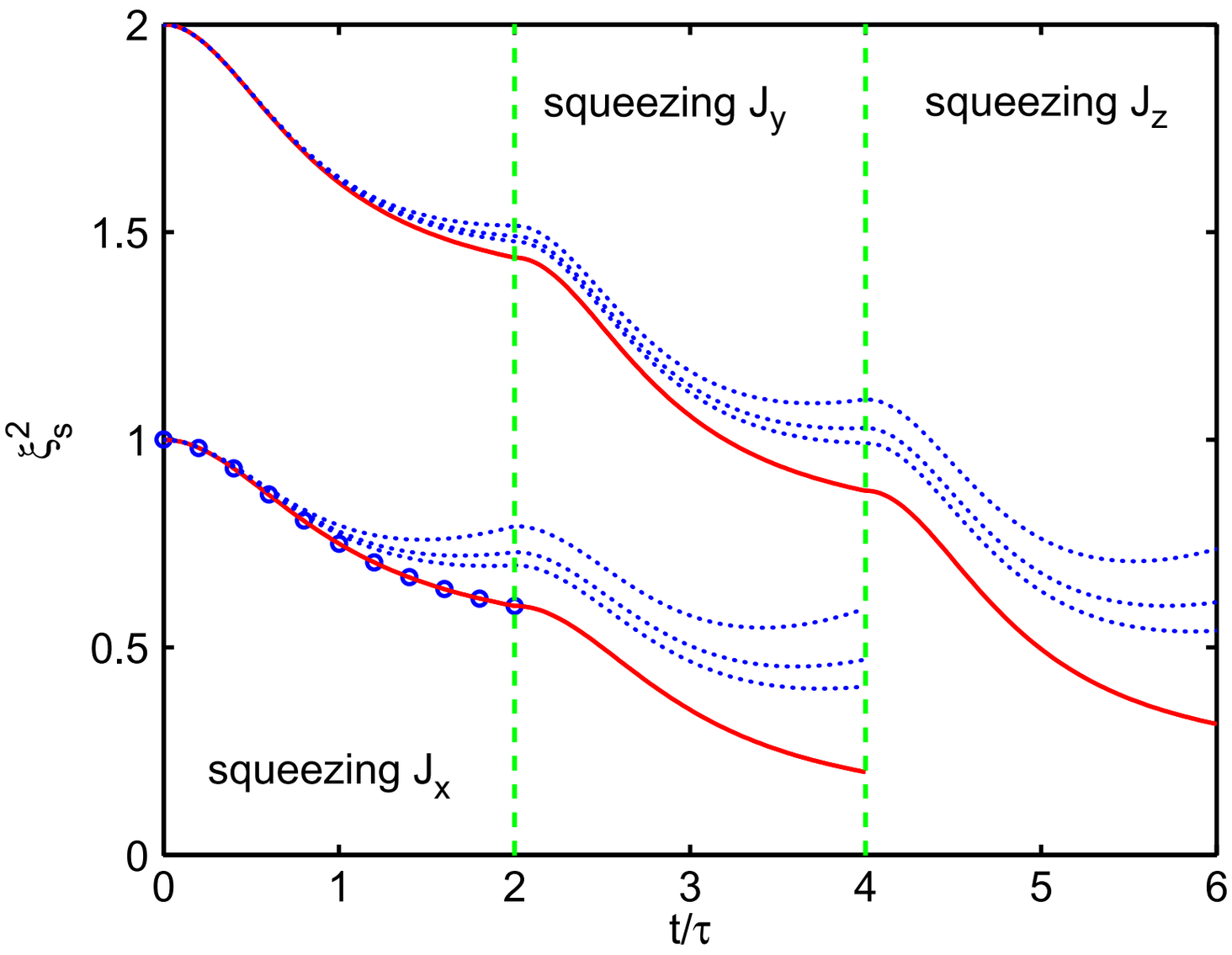
Hauke, PRA 87, 021601 (2013)

G.Tóth, NJP 12, 053007 (2010)

I. Urizar-Lanz, PRA 88, 013626 (2013)

Generation of macroscopic singlet states in atomic ensembles

Géza Tóth[1,2,3,5] **and Morgan W Mitchell**[4]



spin squeezing via QND measurement

$$\Delta^2 J_z^{(\mathrm{out})} = \frac{\Delta^2 J_z^{(\mathrm{in})}}{1+\kappa}$$

+

quantum control

$$\langle J_z(2k_p)\rangle = 0$$

=

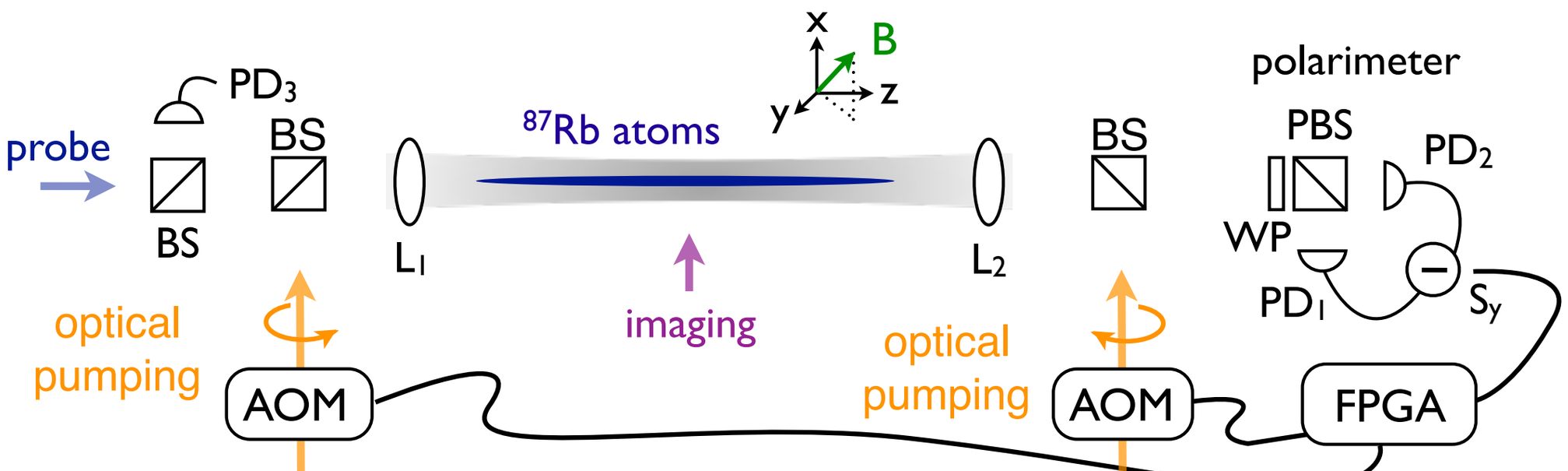
macroscopic singlet

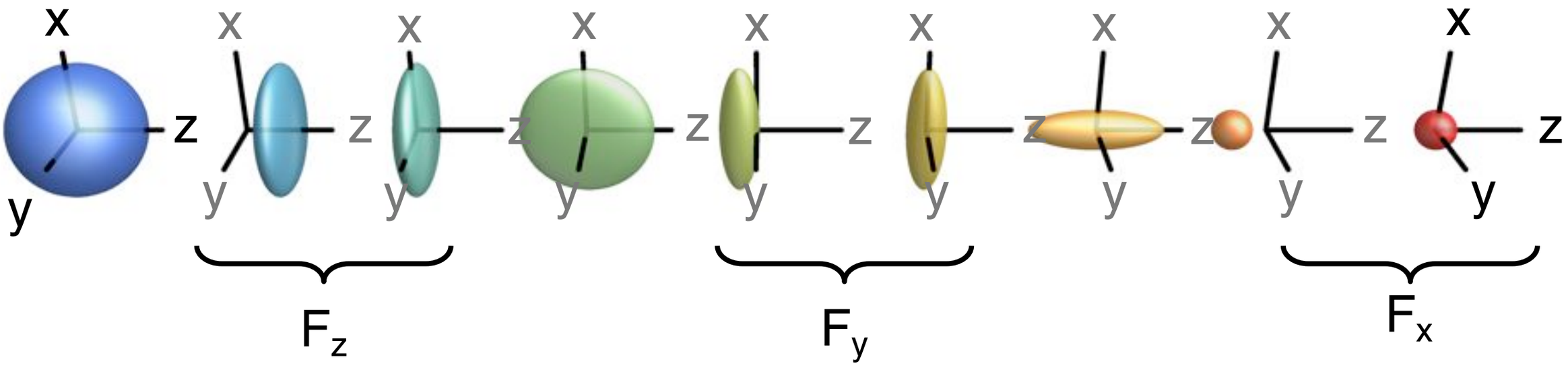
$$|\mathbf{J}| \to 0$$

G.Tóth, NJP 12, 053007 (2010)

I. Urizar-Lanz, PRA 88, 013626 (2013)

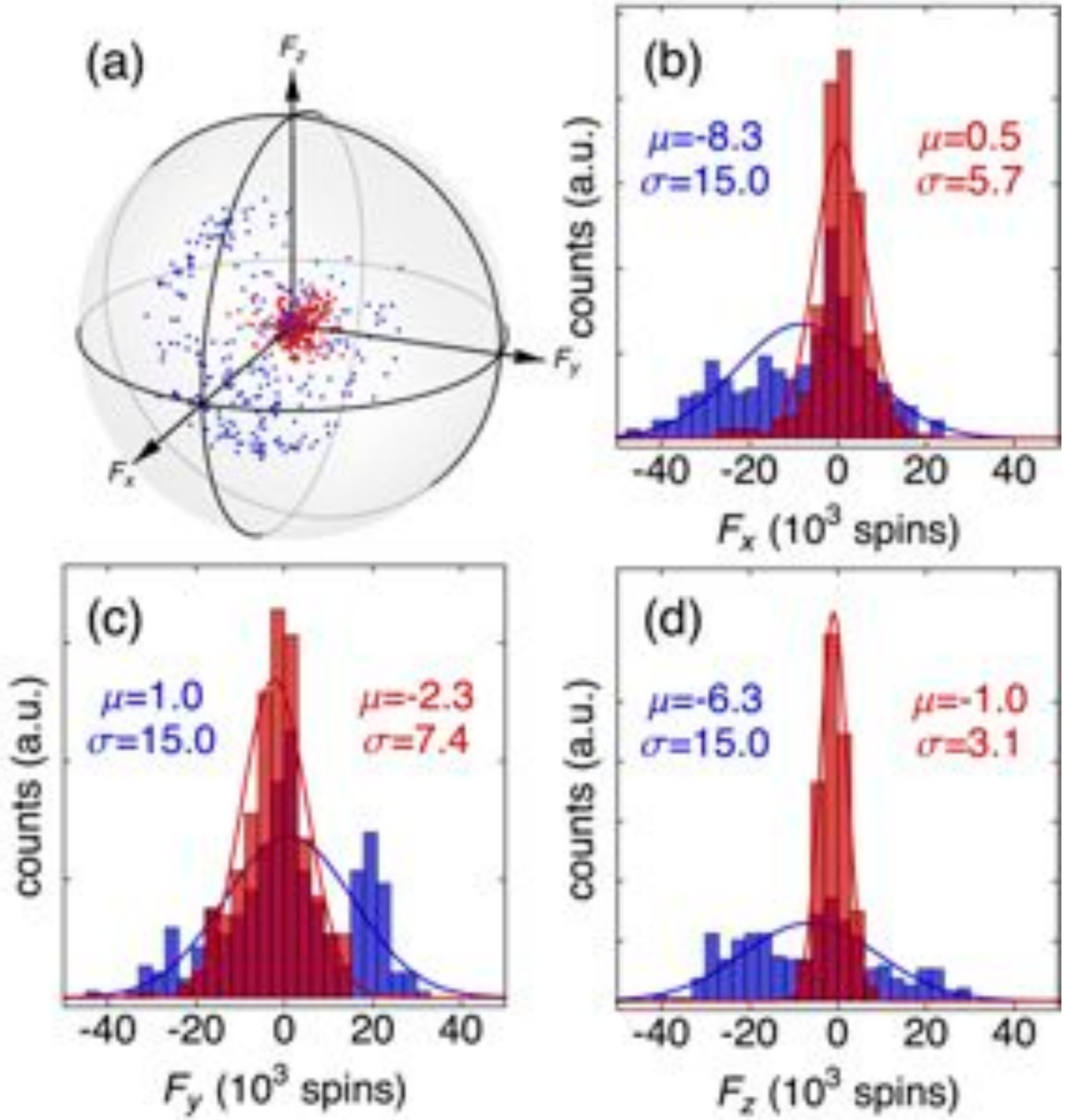
Feedback cooling of atomic spins





Behbood et al. PRL 111, 103601 (2013)

Feedback cooling of atomic spins



Behbood et al. PRL in press (2013)

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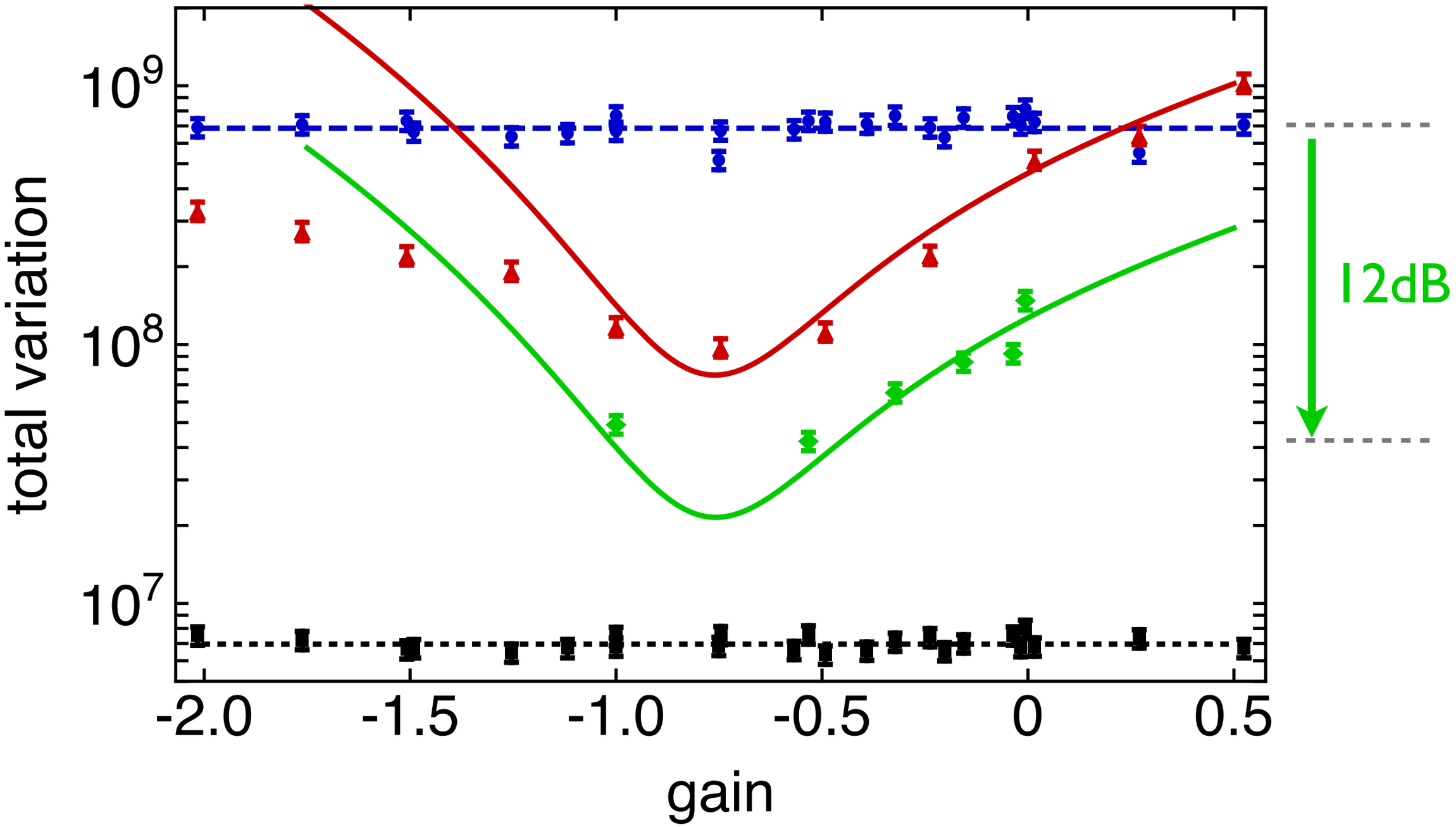

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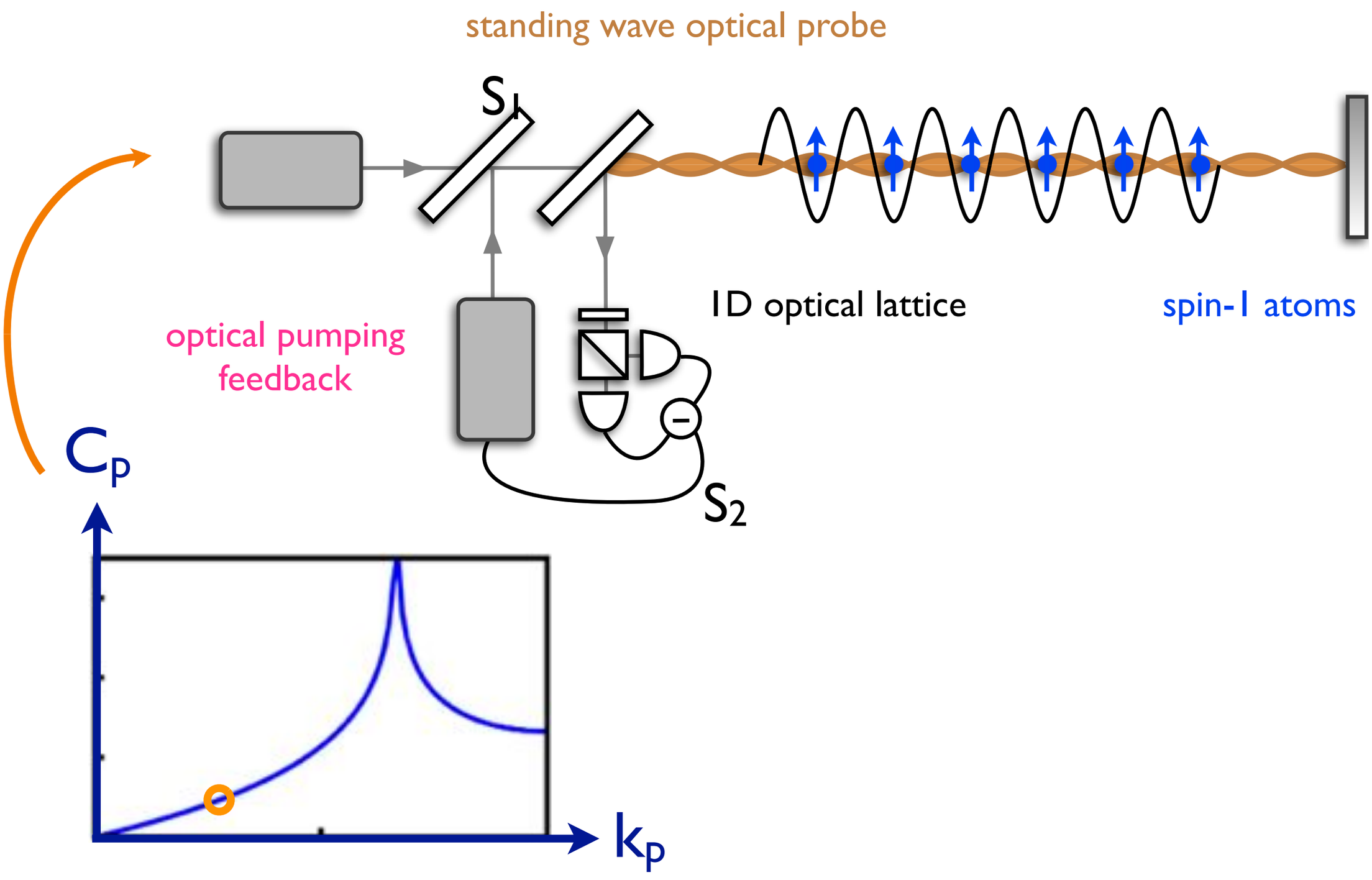
Engineering quantum spin correlations



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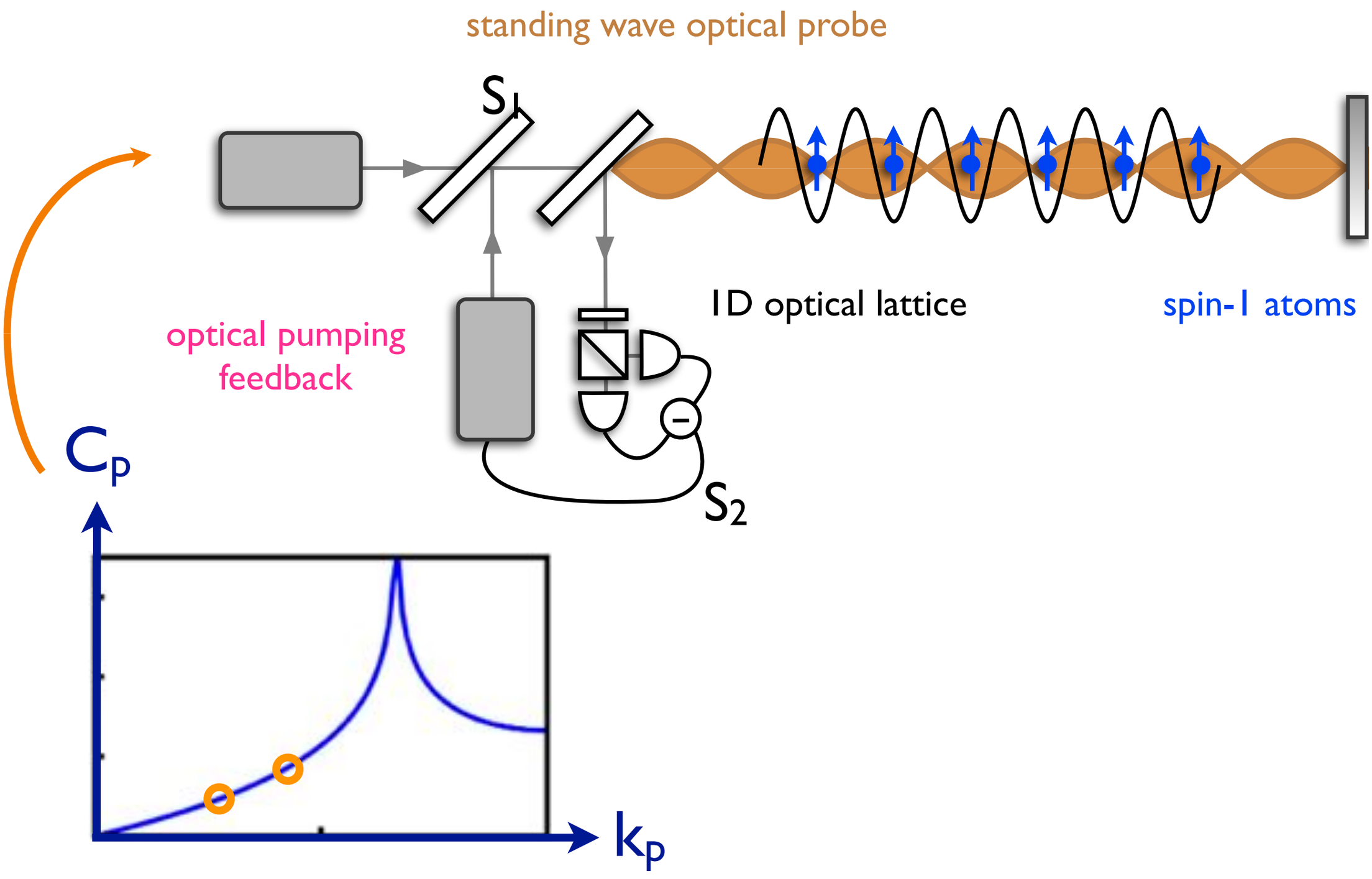
Engineering quantum spin correlations



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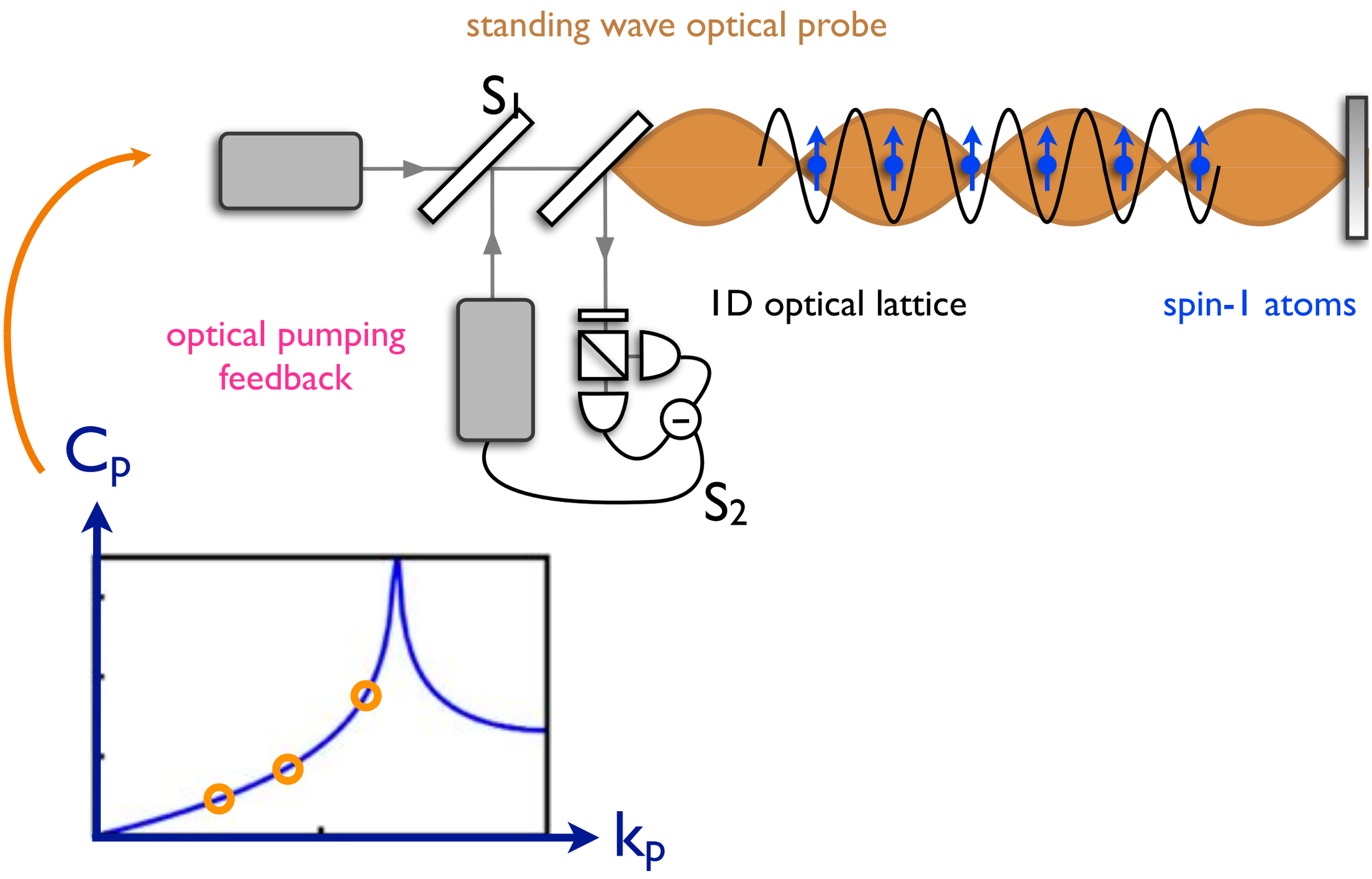

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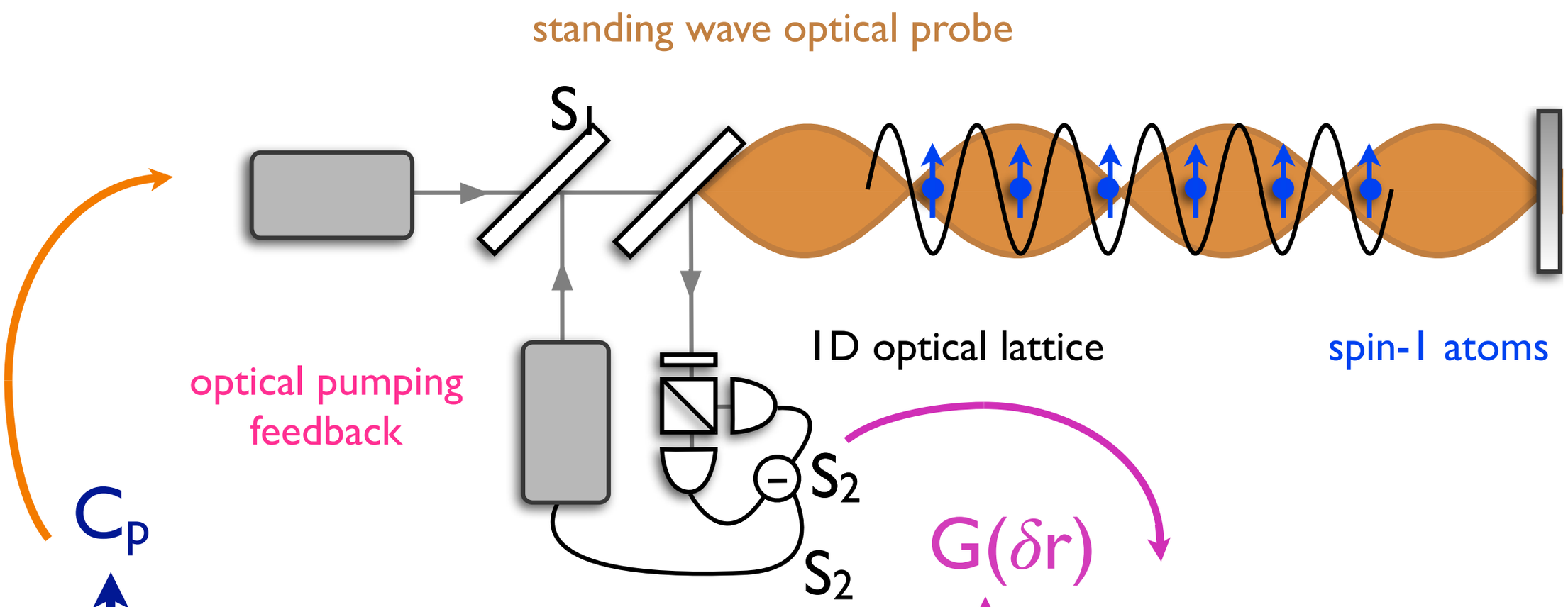
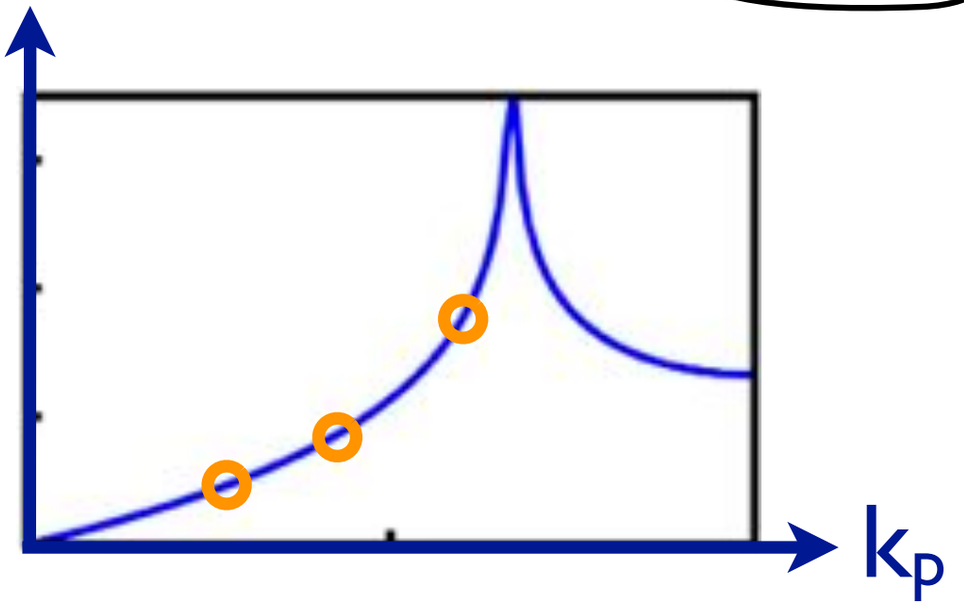
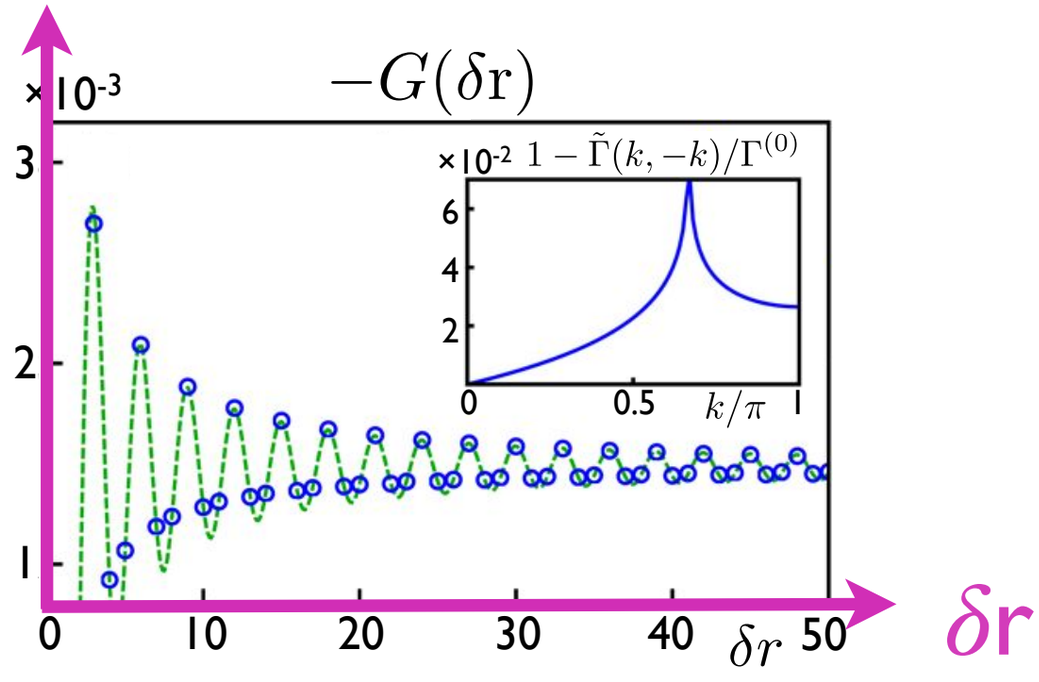
Engineering quantum spin correlations







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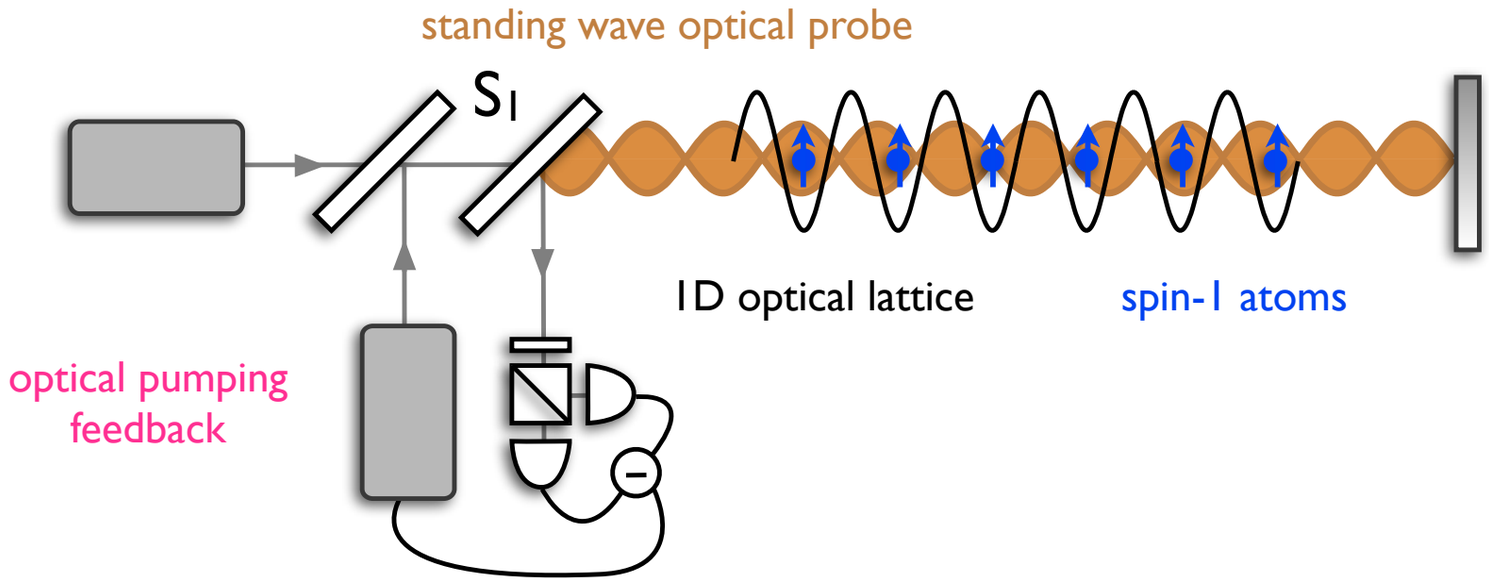
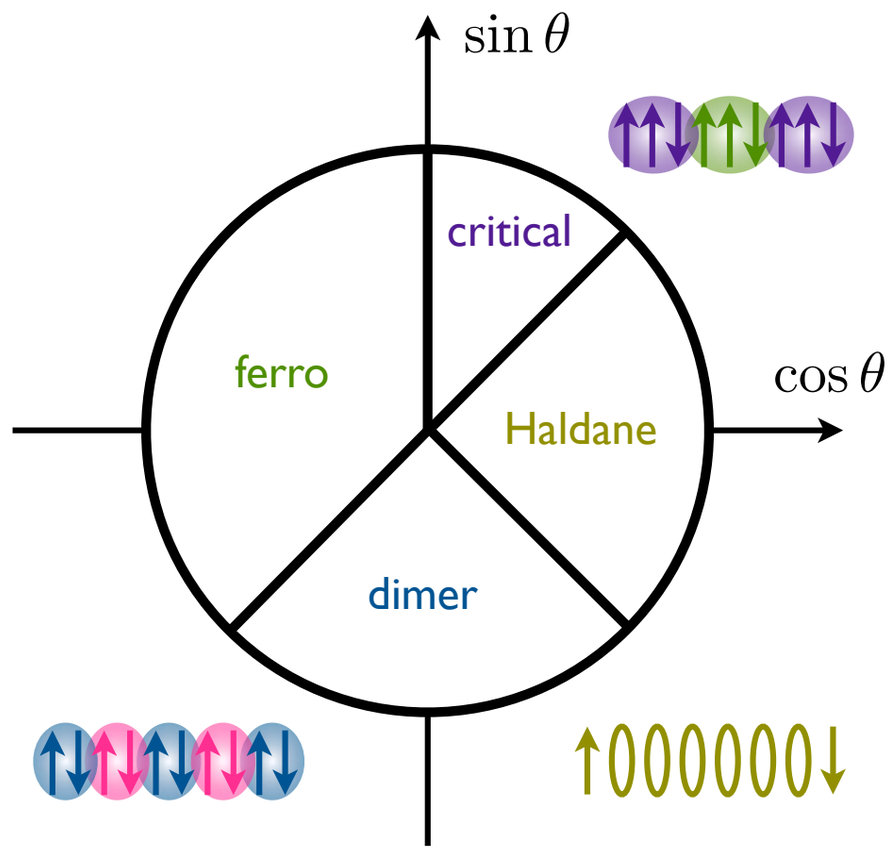
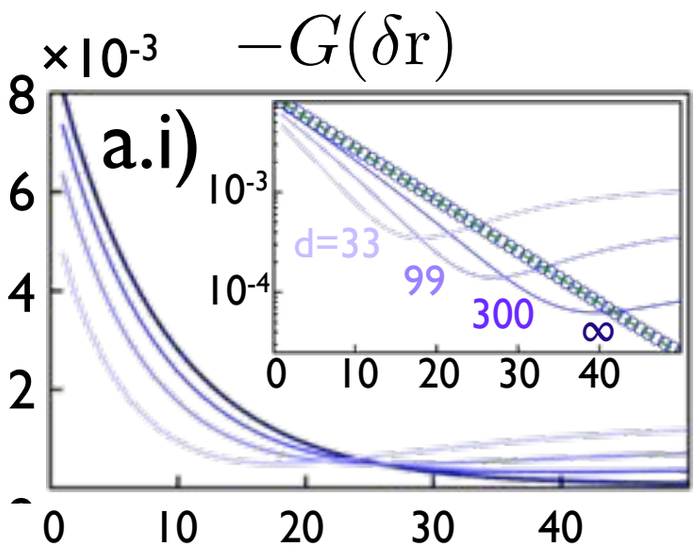
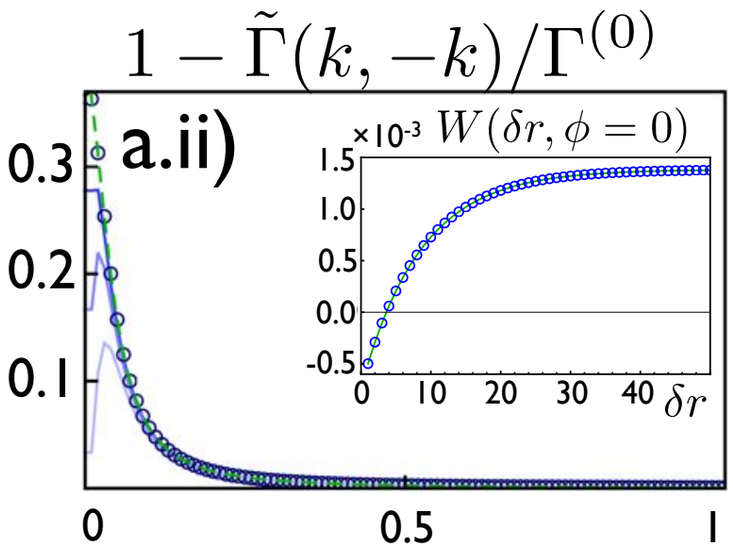
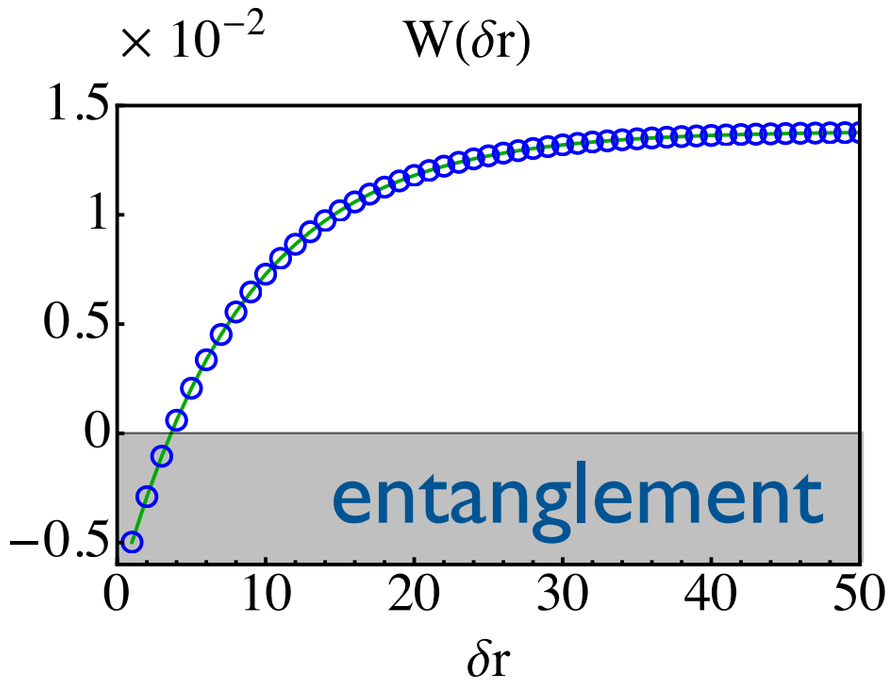








dimer phase



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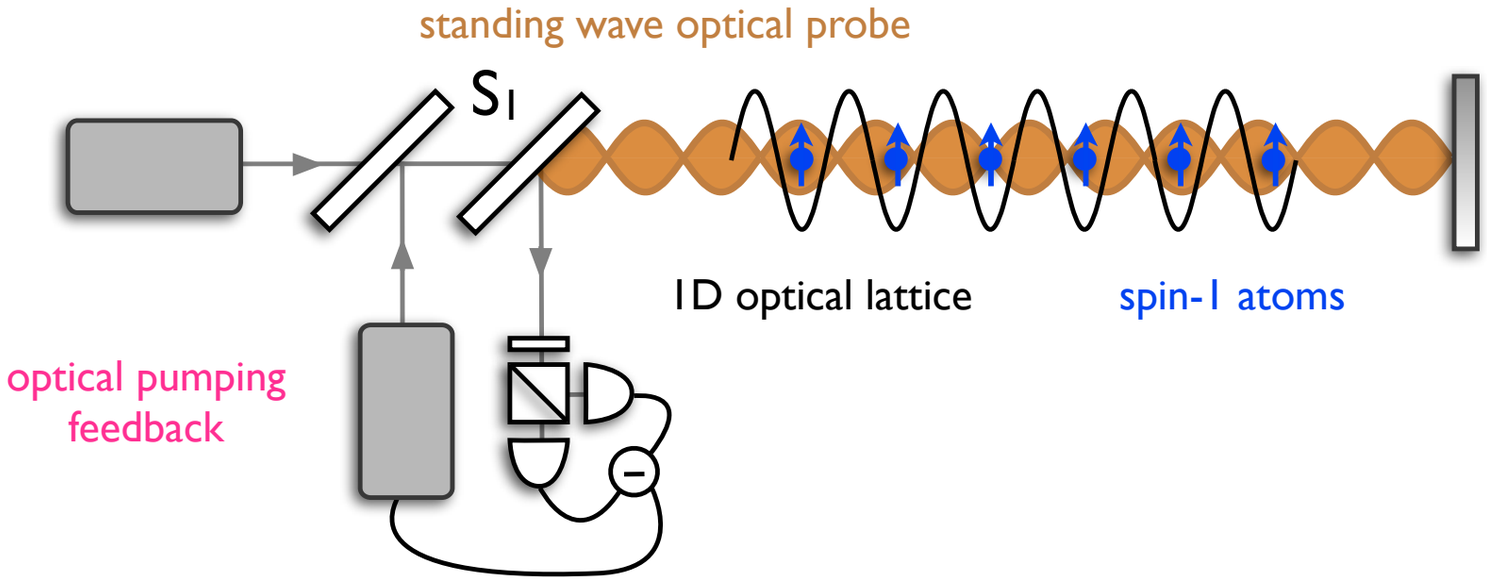
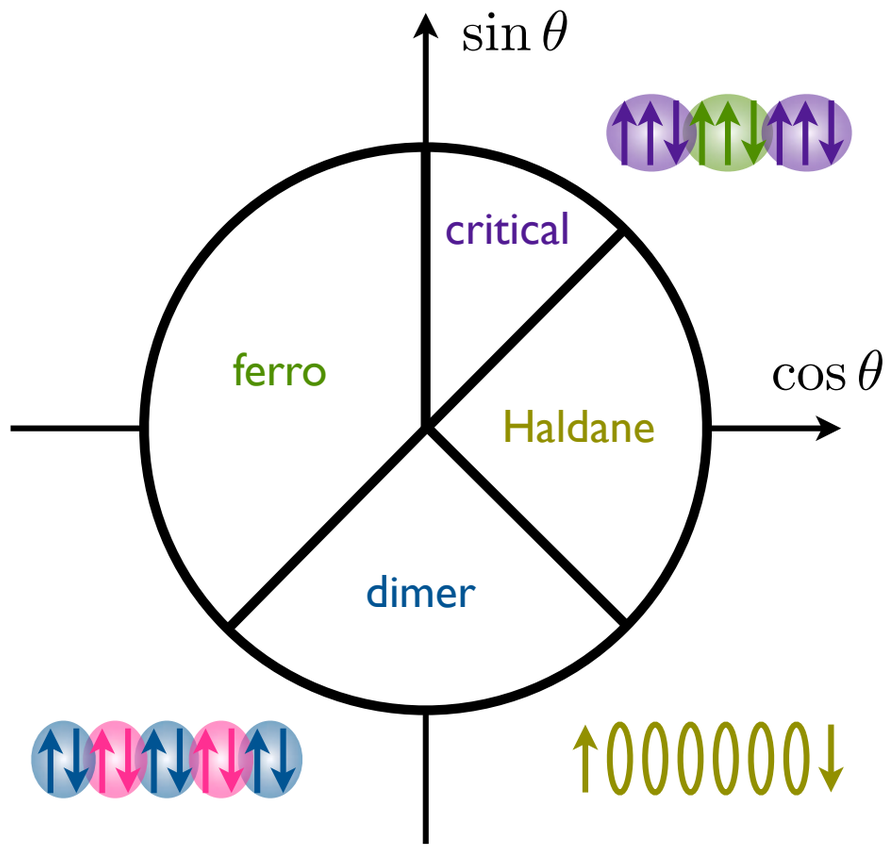
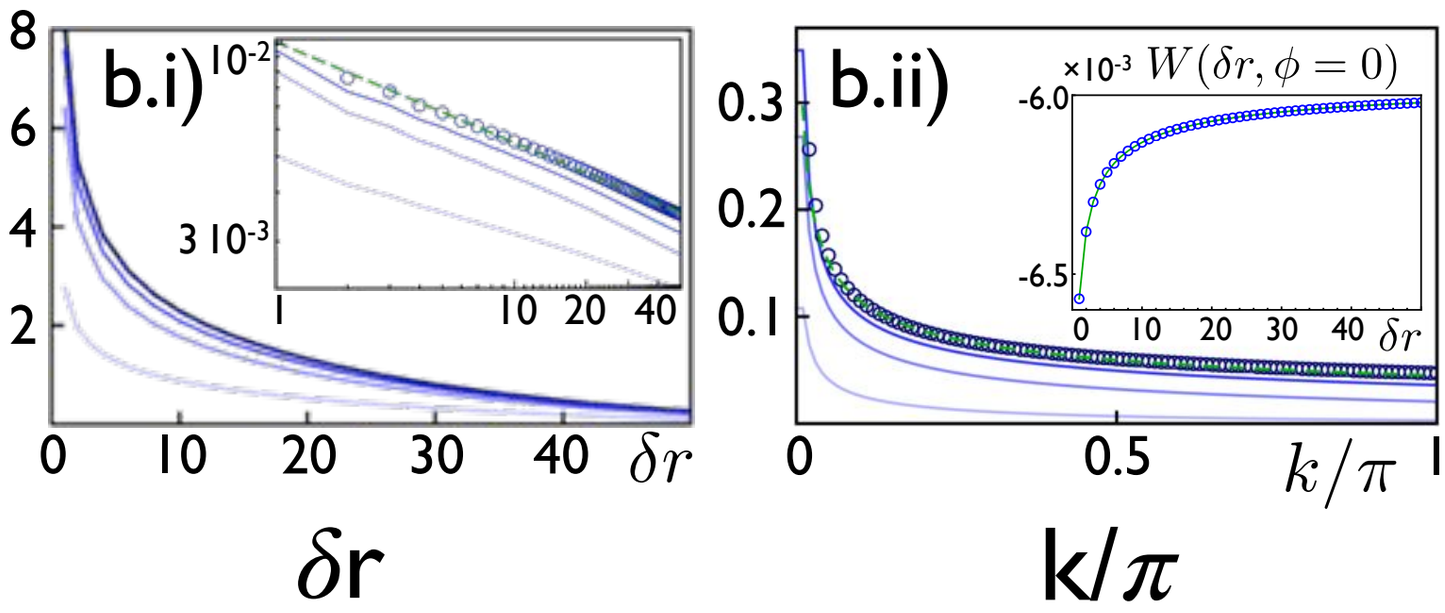
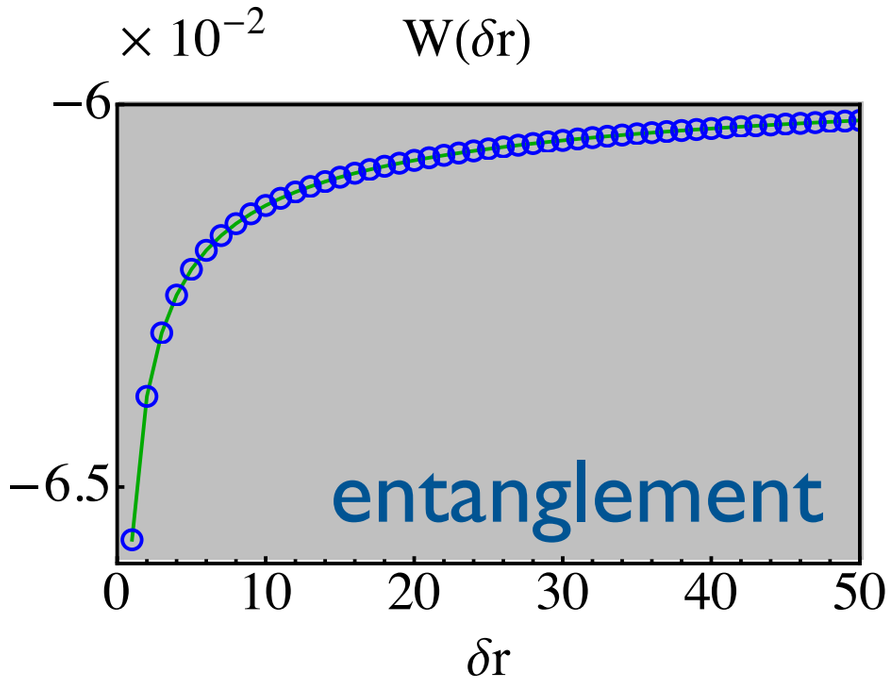




Haldane phase



δr k/π



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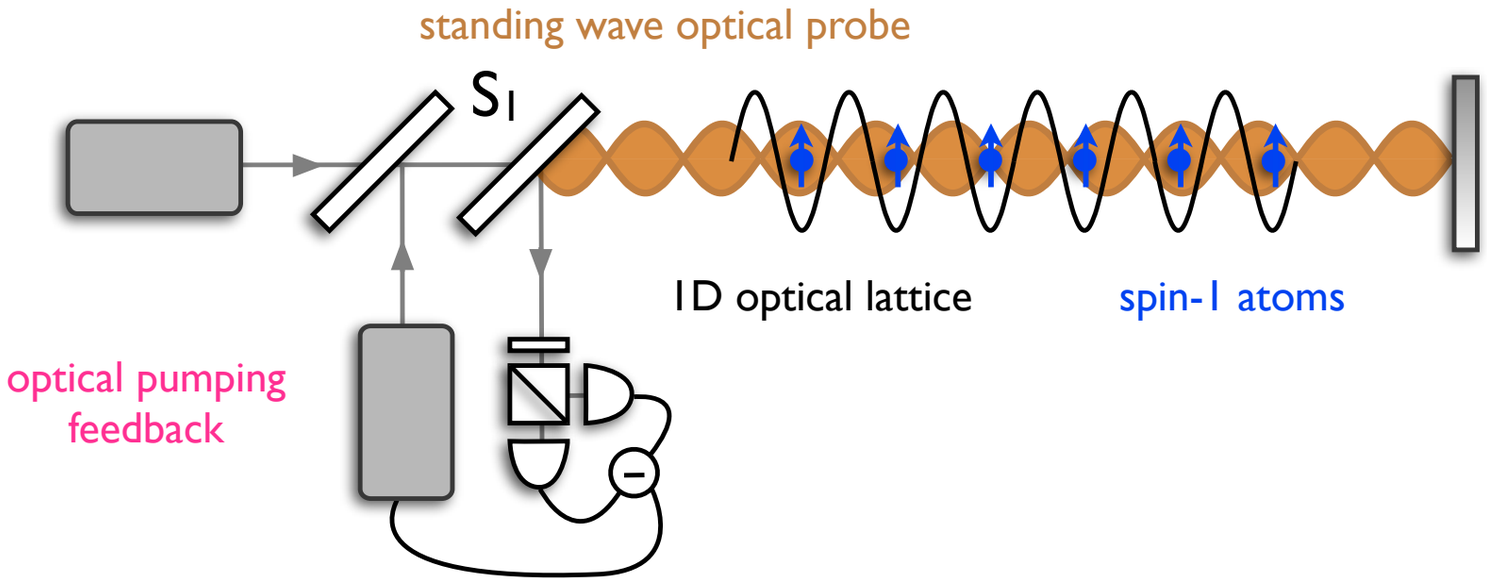

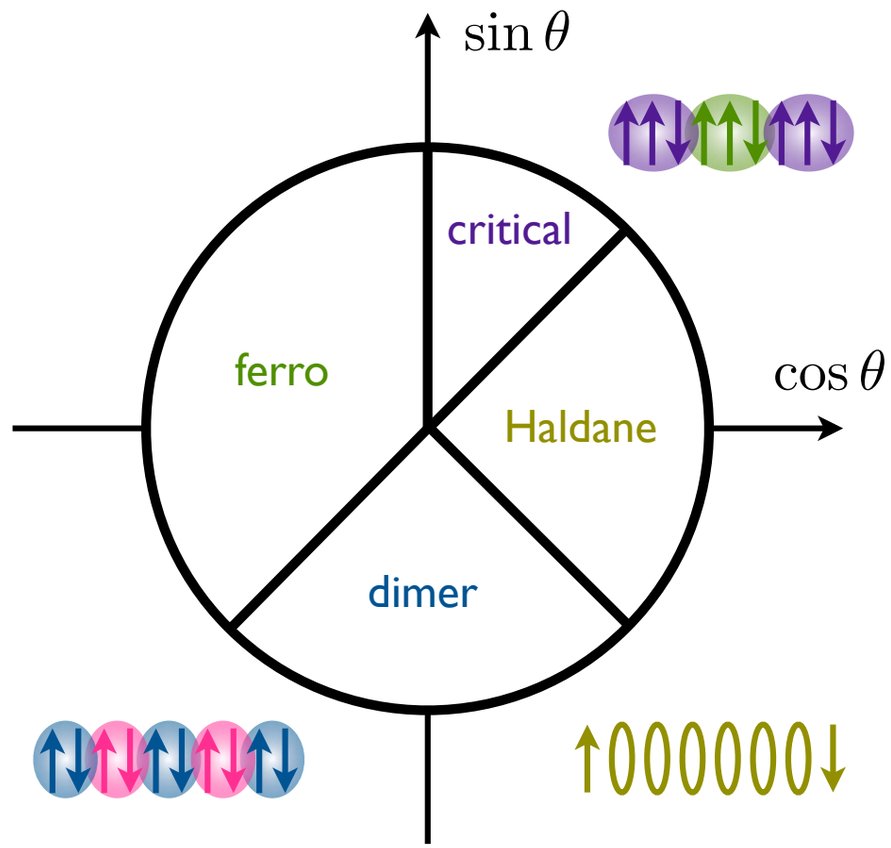

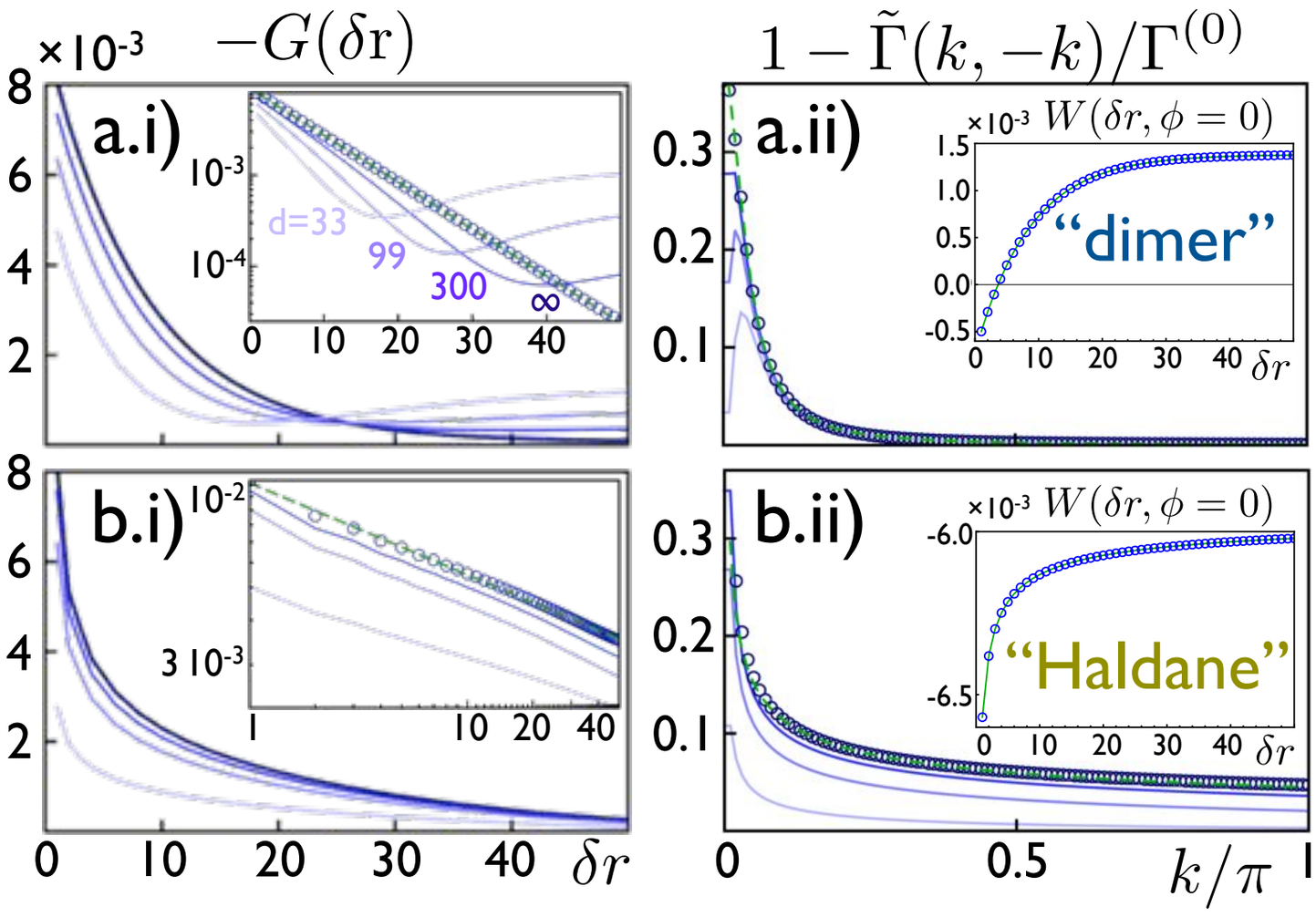

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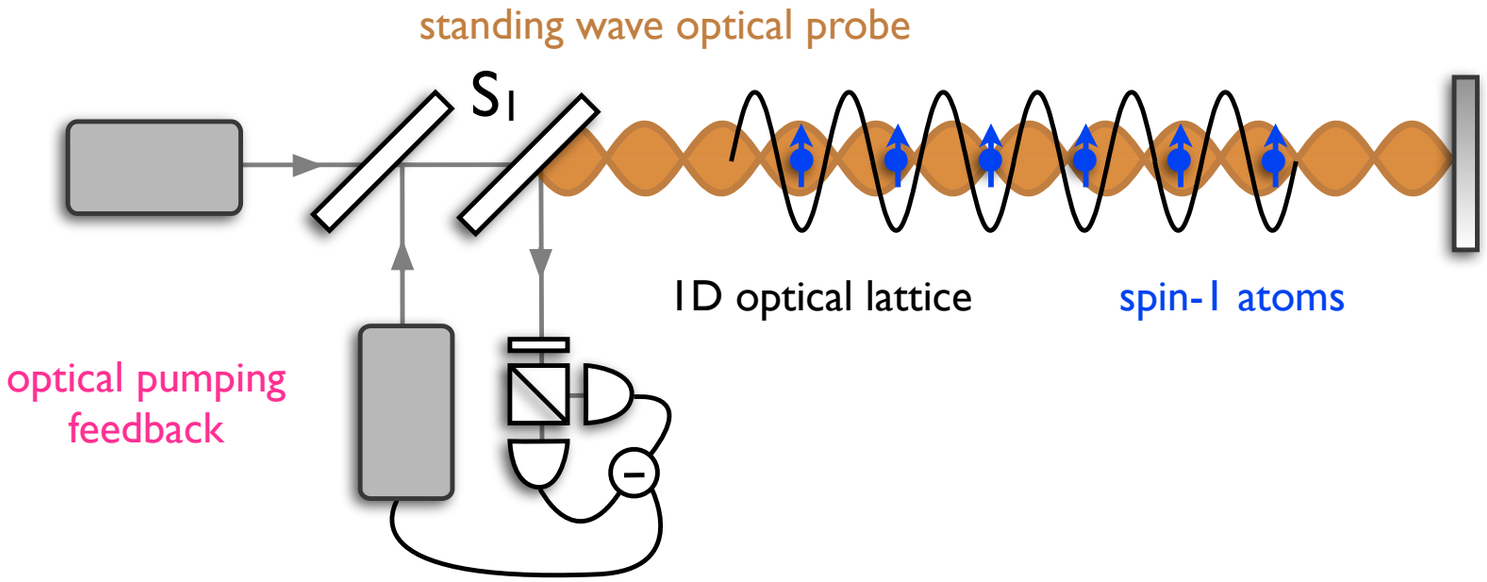
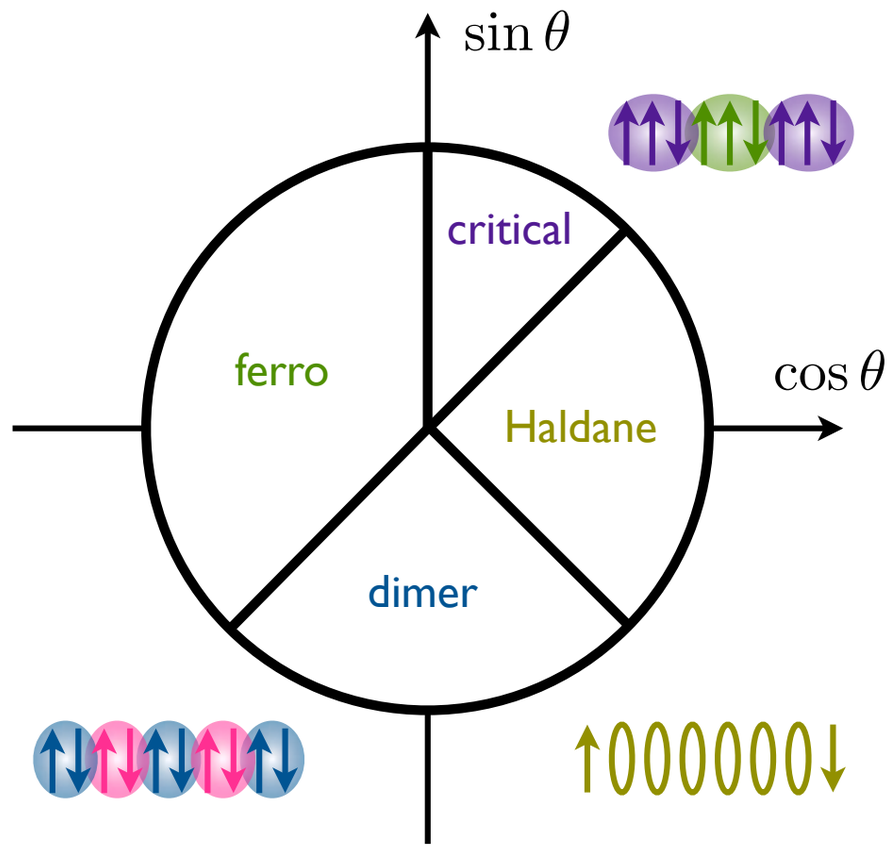
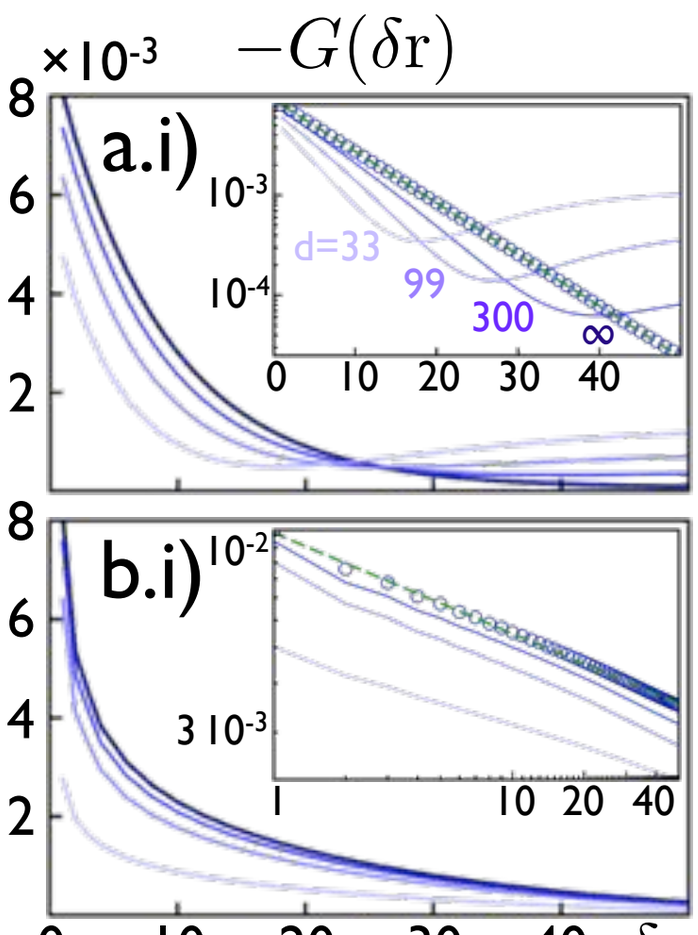
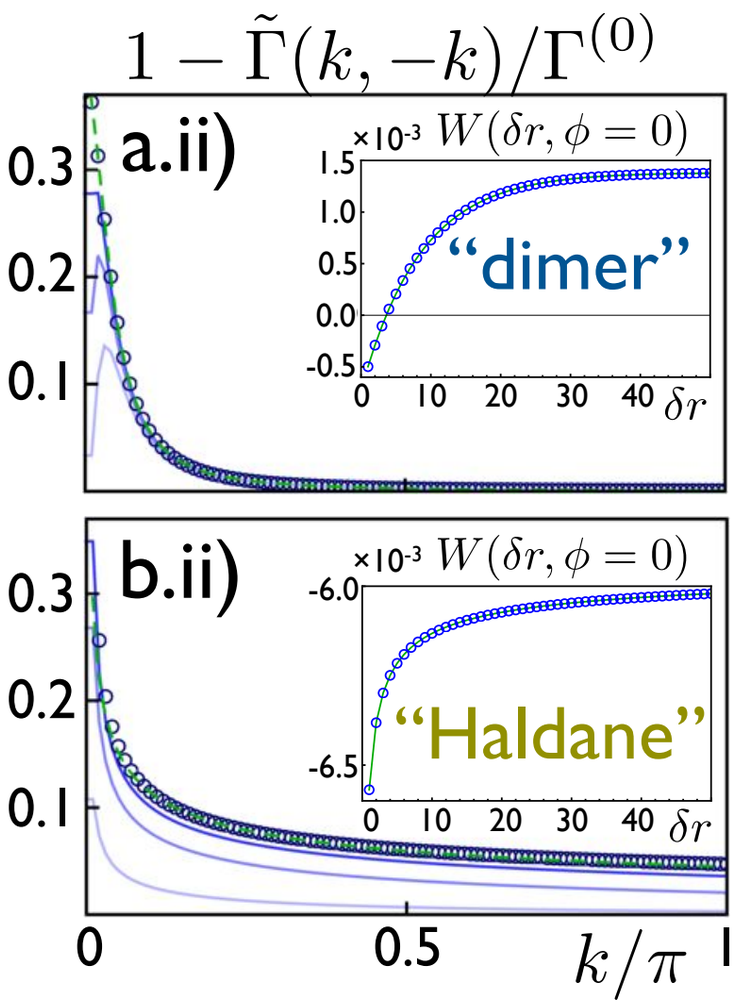
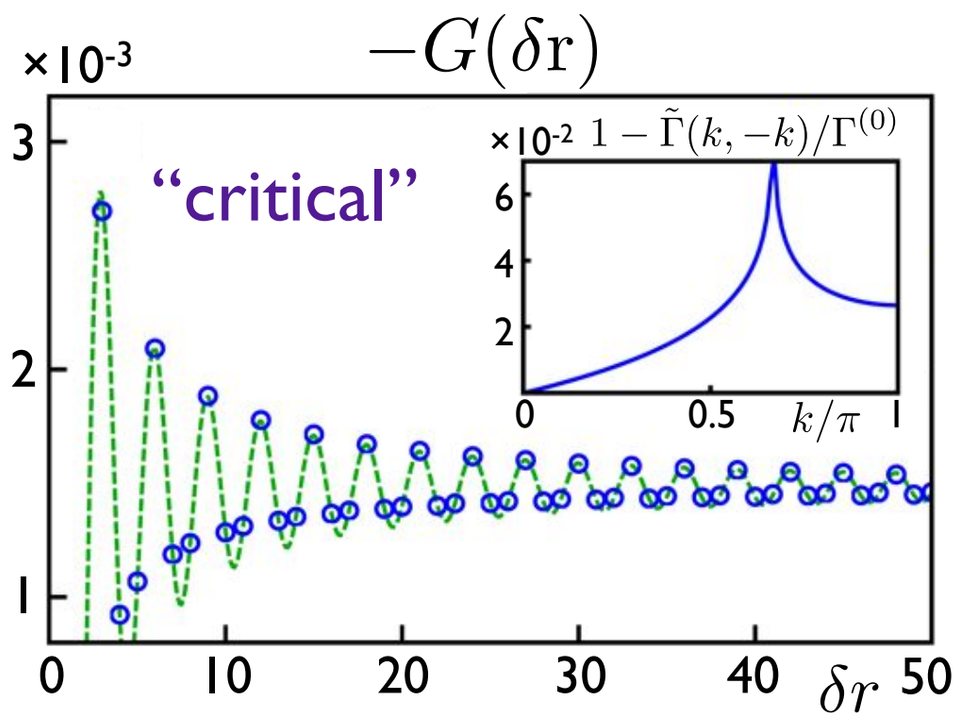




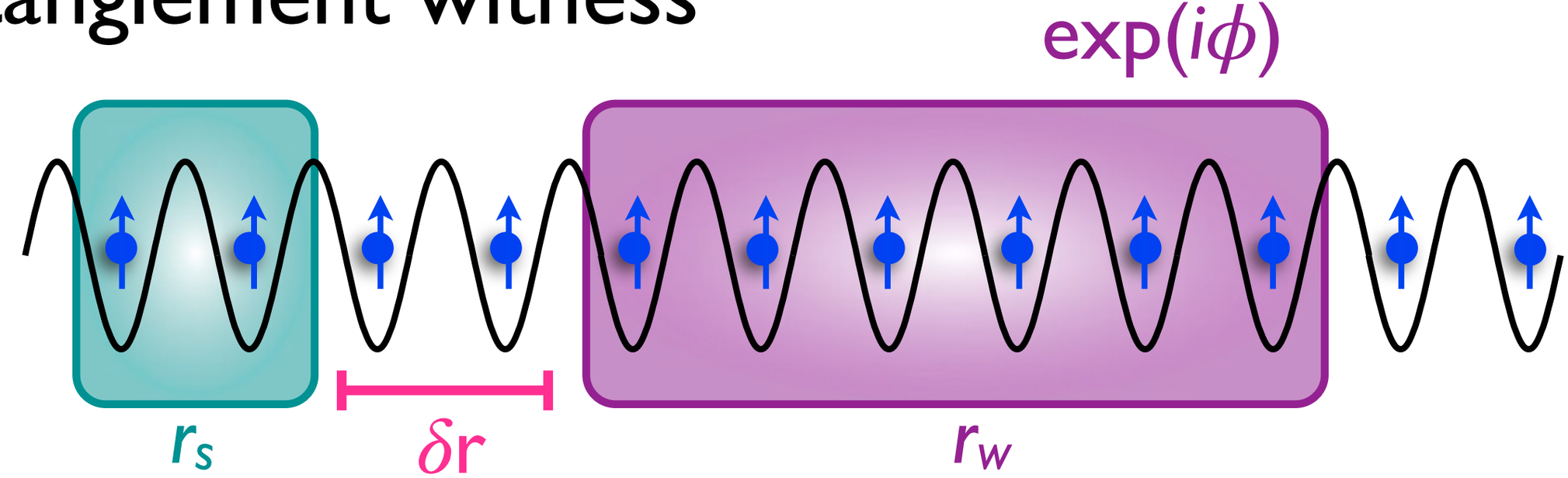






Hauke, PRA 87, 021601 (2013)

Entanglement witness



$$W \equiv \mathcal{S}/n_{\mathrm{a}} - 1 < 0$$

$$\mathcal{S} \equiv \sum_{\alpha} \mathcal{S}_{\alpha} = \sum_{\alpha} \sum_{i,j=1}^{n_{\mathrm{s}}} \langle J_{\alpha,i} J_{\alpha,j} \rangle f^*(r_i) f(r_j)$$

$$f(r_i) = \begin{cases} 1 & \text{if } r_i \in r_s, \\ \exp(i\phi) & \text{if } r_i \in r_w, \\ 0 & \text{otherwise.} \end{cases}$$

Cramer, PRL 106, 020401 (2011)

Quantum control of spin correlations in ultracold lattice gases

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PRA 87, 021601 (2013).

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