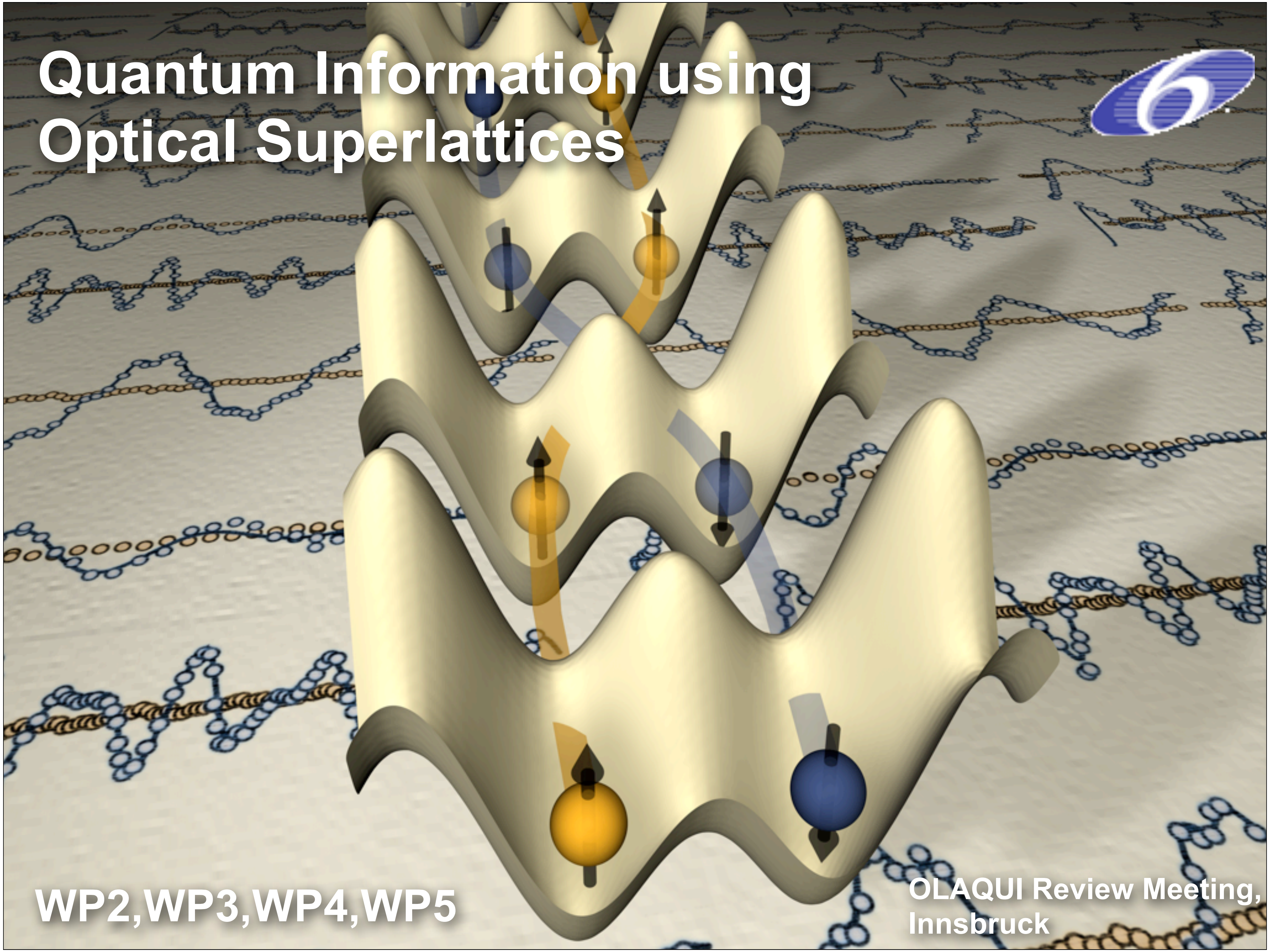
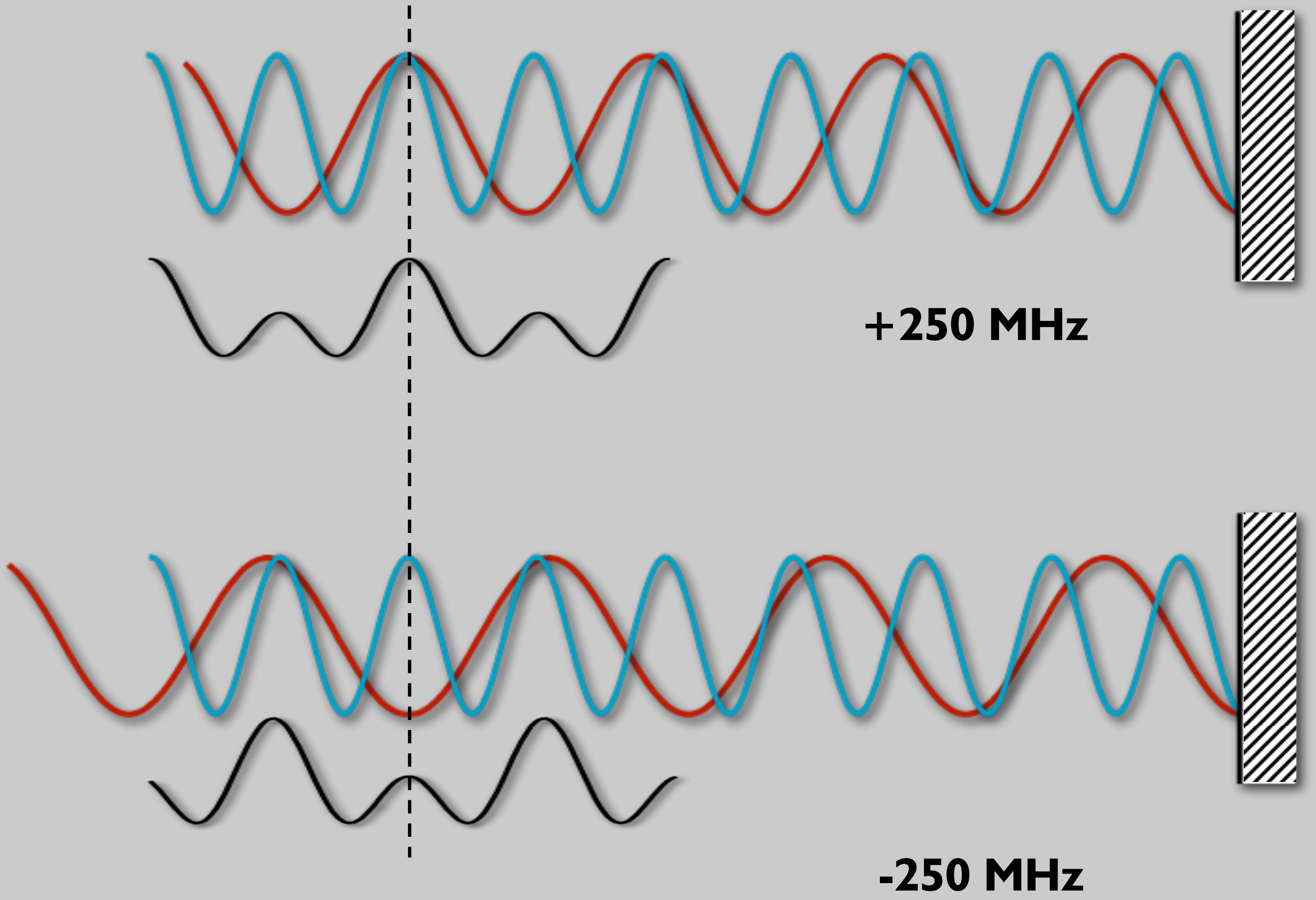

Quantum Information using
Optical Superlattices
WP2,WP3,WP4,WP5
OLAQUI Review Meeting,
Innsbruck

MAINZ Contributions

- **WP2 Addressing, manipulating and measuring on single sites**
  D5 Addressing single sites in optical lattices, M2.2
- **WP3 Two-qubit gates and compatible stable qubits**
  D6 Assessment of experimental feasibility for existing qubit encodings and quantum gate schemes, M3.2, M3.5
  D7 Novel two-qubit gate schemes, M3.7
- **WP4 Generation and characterization of multi-particle entangled states**
  D8 Experimental generation of multi-particle entanglement in optical lattices, M4.1, M4.2, M4.3, M4.7
  D9 Measures and measurement procedures for multi-particle entanglement, M4.1
- **WP5 Strategies for minimizing decoherence**
  D11 Experimental realization of optical lattices with minimized decoherence M5.1, M5.3, M5.4, M5.5, M5.6

How to make a Superlattice II



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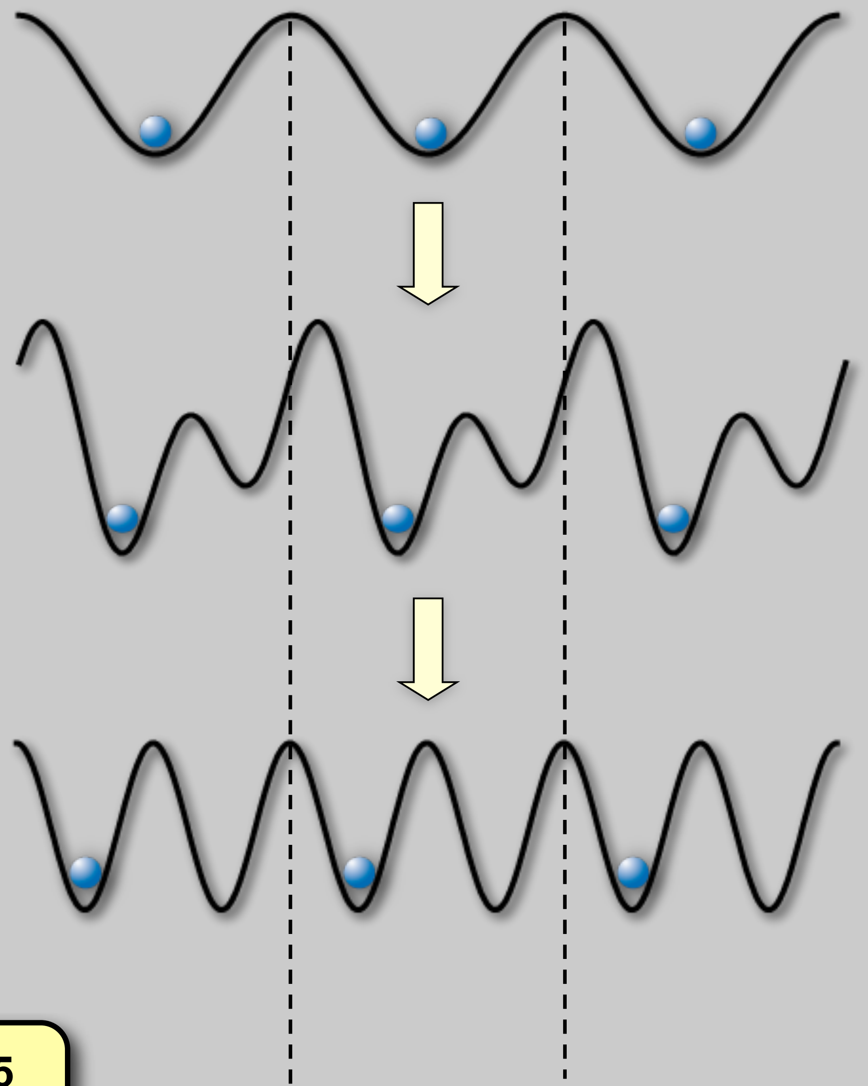
Patterned loading of the short lattice



Mott State in long lattice

Increase short lattice

Switch off long lattice

WP2 D5

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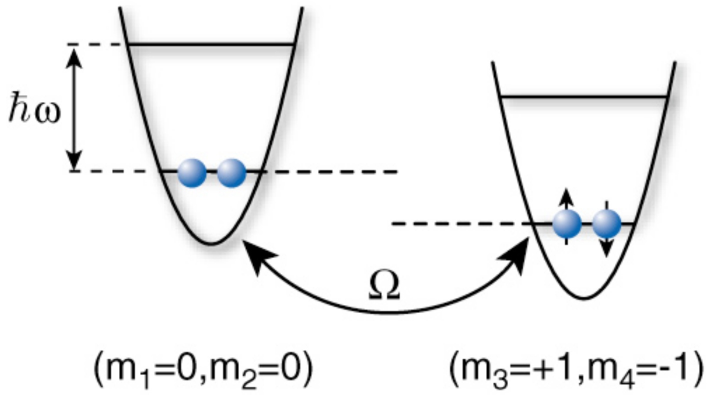
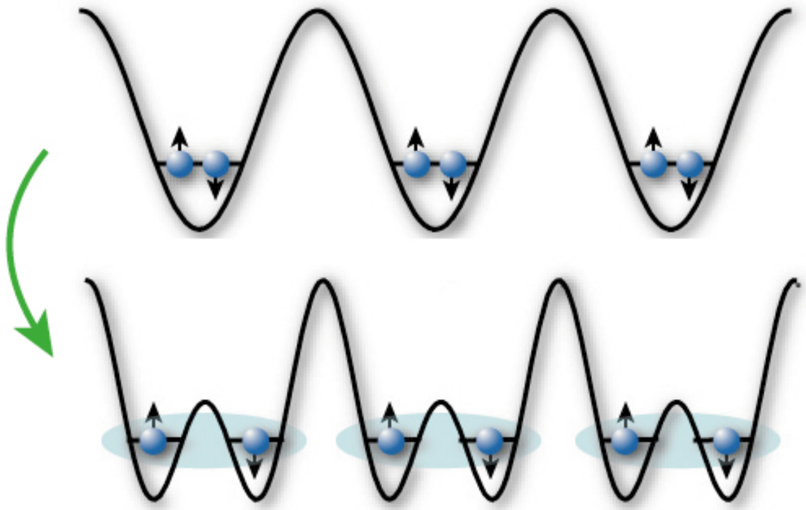
Robust multi-particle entanglement via spin changing collisions



A. Widera et al.,
Phys. Rev. Lett., 95,190405, (2005)



$$\left(|\uparrow,\downarrow\rangle+|\downarrow,\uparrow\rangle\right)\otimes|0,0\rangle$$

Spin Triplet

$$|\uparrow\rangle_L|\downarrow\rangle_R+|\downarrow\rangle_L|\uparrow\rangle_R$$

Entangled Bell state

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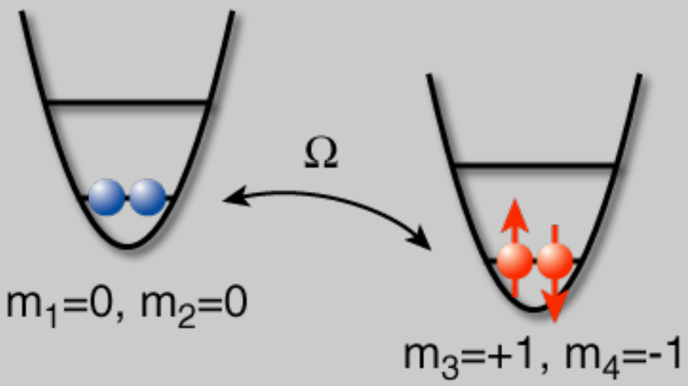
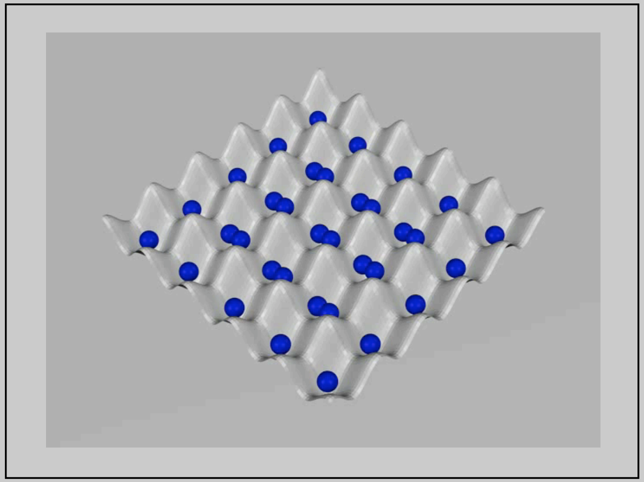
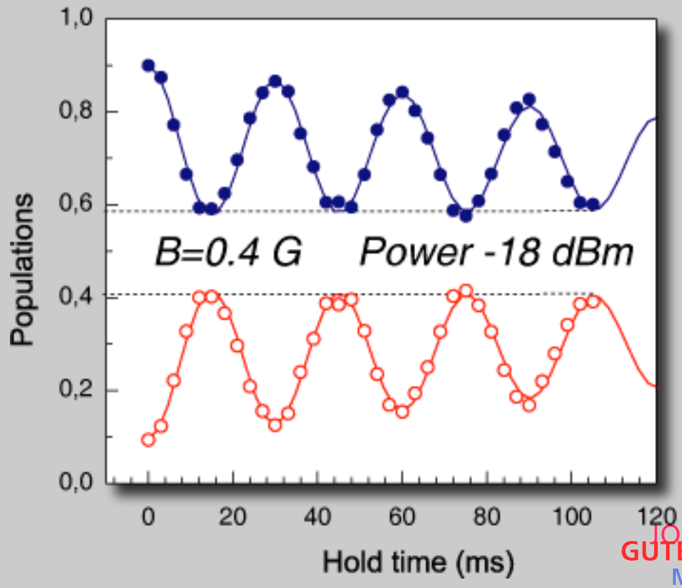
Spin Changing Collisions in an Optical Lattice





Collisionally induced
„Rabi-Type“ Oscillations

$$|0,0\rangle \leftrightarrow \left(|\uparrow,\downarrow\rangle + |\downarrow,\uparrow\rangle\right)/\sqrt{2}$$



A. Widera et al., PRL 95, 190405 (2005)
Spinor dynamics without lattices:
Hamburg, GeorgiaTech, Berkley

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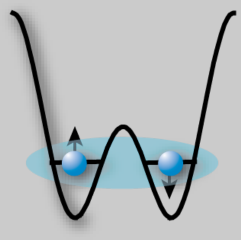
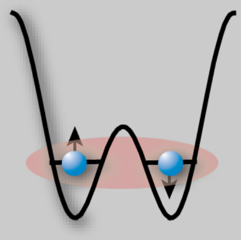
Magnetic Gradient Fields Induce Singlet-Triplet Oscillations



$$|\uparrow\rangle_L|\downarrow\rangle_R+|\downarrow\rangle_L|\uparrow\rangle_R$$



$$|\uparrow\rangle_L|\downarrow\rangle_R-|\downarrow\rangle_L|\uparrow\rangle_R$$

$$|\uparrow\rangle_L|\downarrow\rangle_R+e^{2i\phi(t)}|\downarrow\rangle_L|\uparrow\rangle_R$$

$$\phi(t)=\mu_B B' d_{DW}$$

WP3 D6,7

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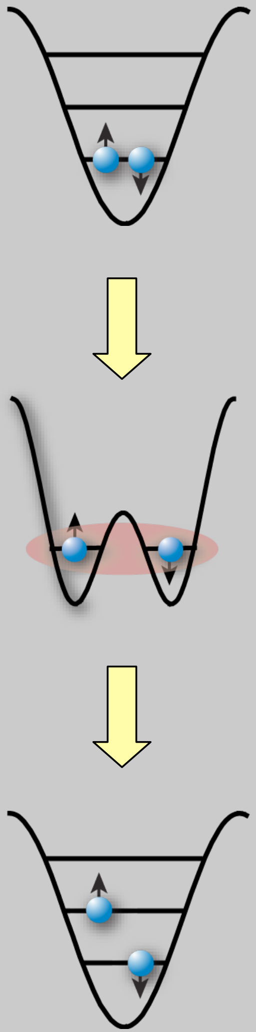
How can we detect the Bell pairs? (2)



$$\left(|\uparrow,\downarrow\rangle+|\downarrow,\uparrow\rangle\right)\otimes|0,0\rangle$$

Split

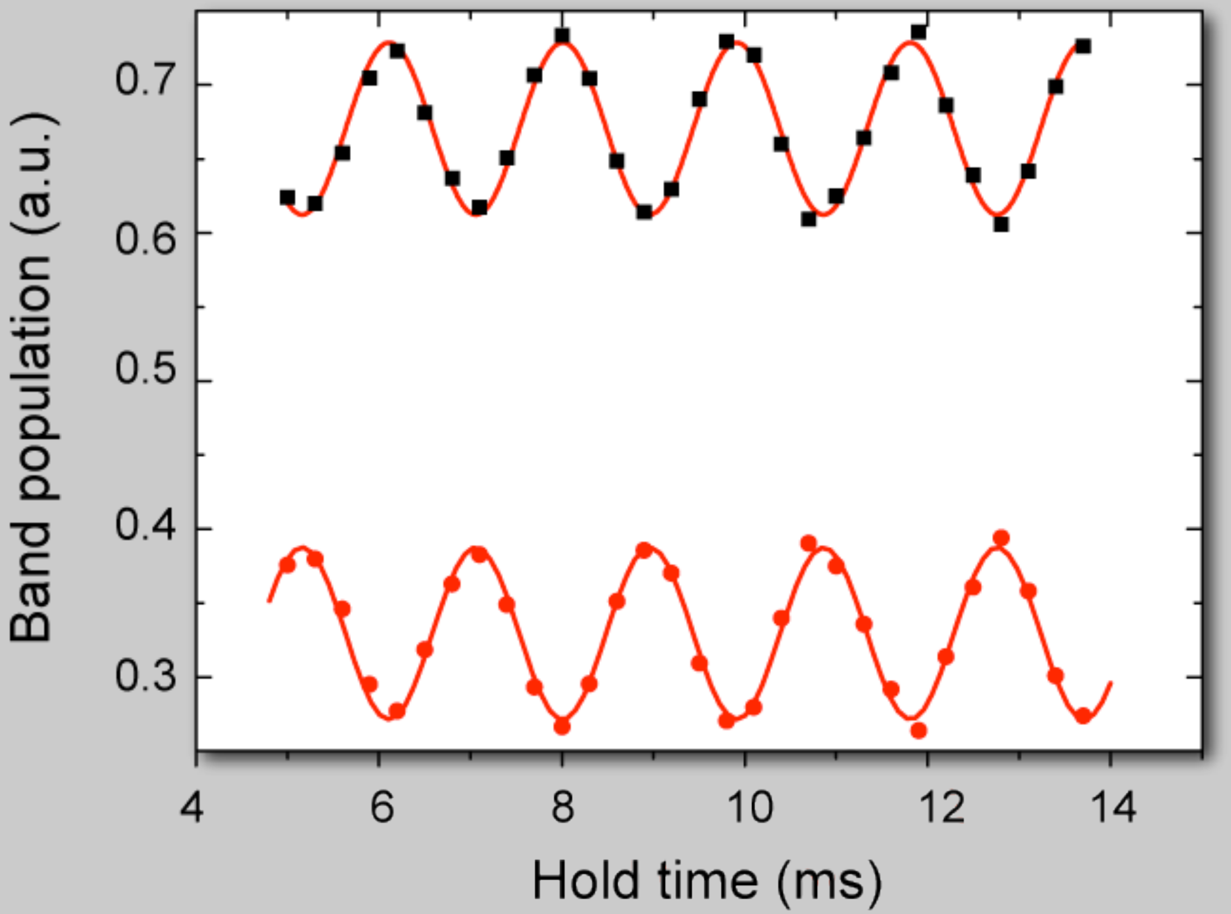
When uniting bosonic spin singlet states, one particle has to occupy the excited band!

Unite

$$\left(|\uparrow,\downarrow\rangle+|\downarrow,\uparrow\rangle\right)\otimes\left(|0,1\rangle+|1,0\rangle\right)$$

Singlet-Triplet Spin Oscillations

S. Trotzky (in preparation)



See ion trap exps: C.F. Roos et al., PRL **92**, 220402 (2004),
C. Langer et al., PRL **95**, 060502 (2005)

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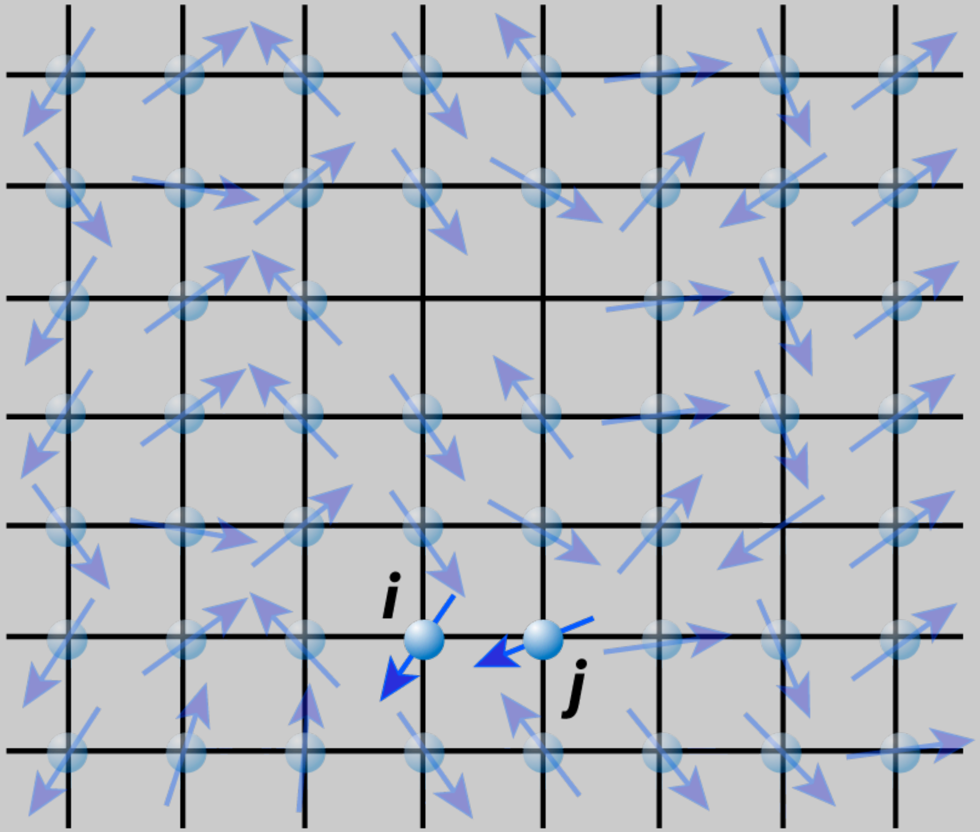
Quantum Spin Systems in Optical Lattices

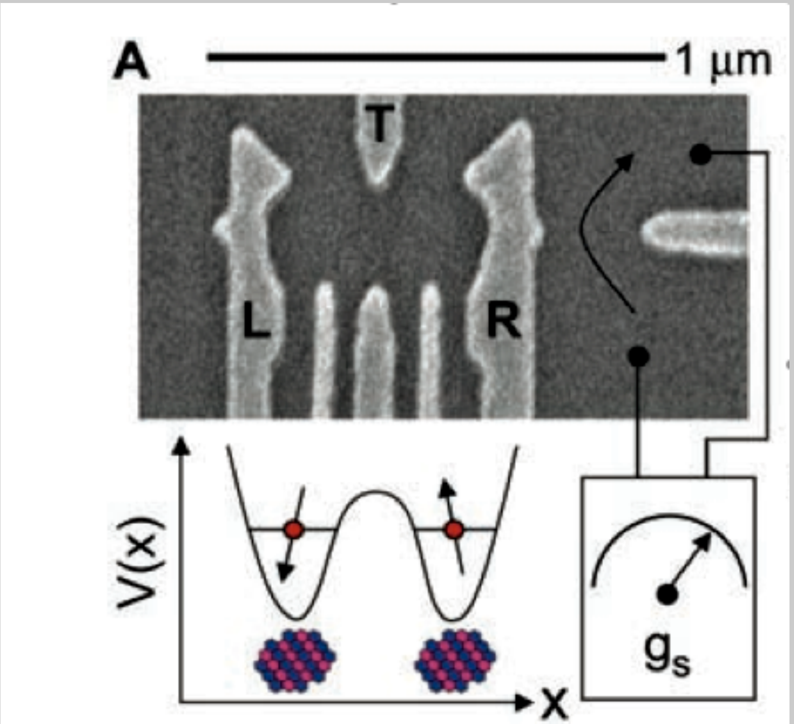


In strongly correlated electron system spin-spin interactions exist.

$$-J_{ex}\vec{S}_i \cdot \vec{S}_j$$

WP3,4,6

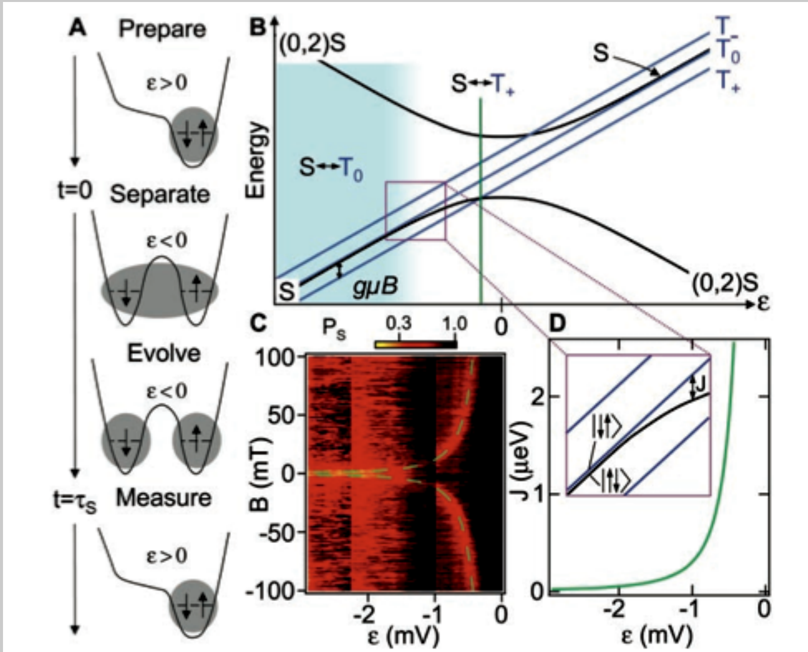
Superexchange Coupling in Quantum Dots



Local control of spin states & interactions between spin states.

J.R. Petta et al., Science **309**, 2180 (2005)

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots



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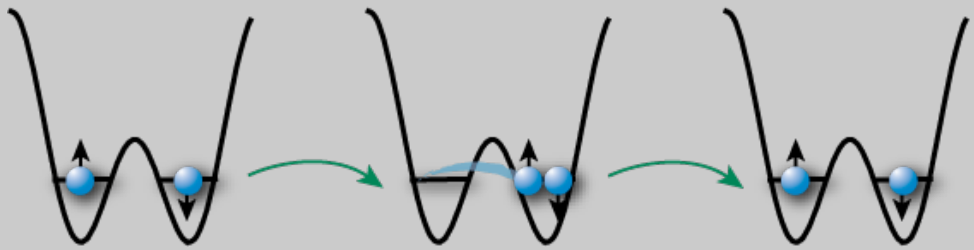
Quantum Magnetism

Second order hopping processes form the basis of superexchange interactions! (see e.g. A. Auerbach, Interacting Electrons and Quantum Magnetism)



$$J \qquad \frac{1}{U} \qquad J$$

$$-J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger\hat{a}_j + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1)$$

$$H = -J_{ex}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

$$J_{ex} \propto \frac{J^2}{U}$$

Ultracold atoms allow tuning of Spin-Hamiltonians

$$H = \sum_{\langle i,j\rangle}\left[\lambda_{\mu z}\hat{\sigma}_i^z\hat{\sigma}_j^z \pm \lambda_{\mu\perp}\left(\hat{\sigma}_i^x\hat{\sigma}_j^x + \hat{\sigma}_i^y\hat{\sigma}_j^y\right)\right]$$

$$\lambda_{\mu z} = \frac{t_{\mu\uparrow}^2 + t_{\mu\downarrow}^2}{2U_{\uparrow\downarrow}} - \frac{t_{\mu\uparrow}^2}{U_\uparrow} - \frac{t_{\mu\downarrow}^2}{U_\downarrow}$$

$$\lambda_{\mu\perp} = \frac{t_{\mu\uparrow}t_{\mu\downarrow}}{U_{\uparrow\downarrow}}$$

L.M. Duan et al., PRL **91**, 090402 (2003),
E. Altman et al., NJP **5**, 113 (2003), A.B. Kuklov et al. PRL **90**, 100401 (2003)

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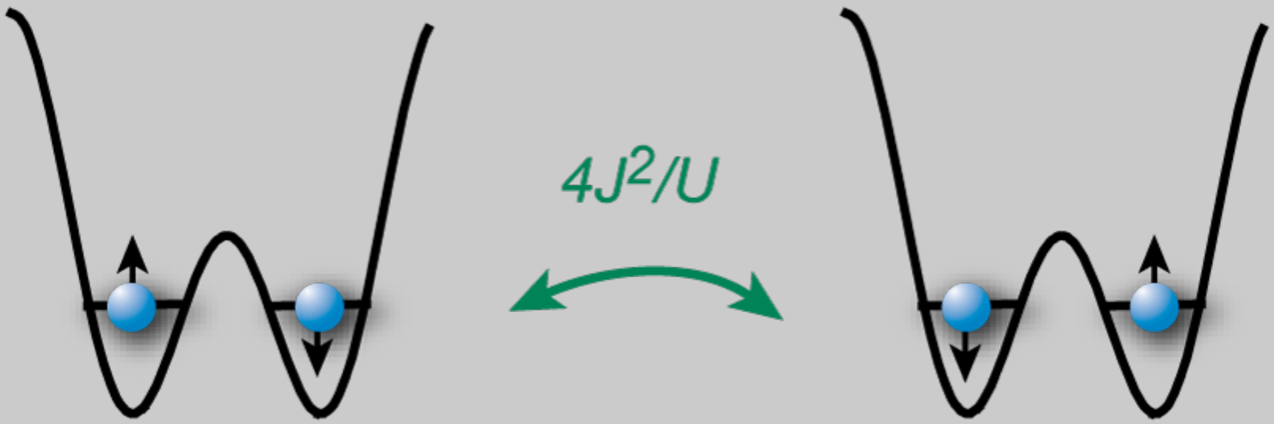
Superexchange induced flopping



$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$
$$= -\frac{J_{ex}}{2}\left(\hat{S}_i^+\hat{S}_j^- + \hat{S}_i^-\hat{S}_j^+\right) - J_{ex}\hat{S}_i^z\hat{S}_j^z$$

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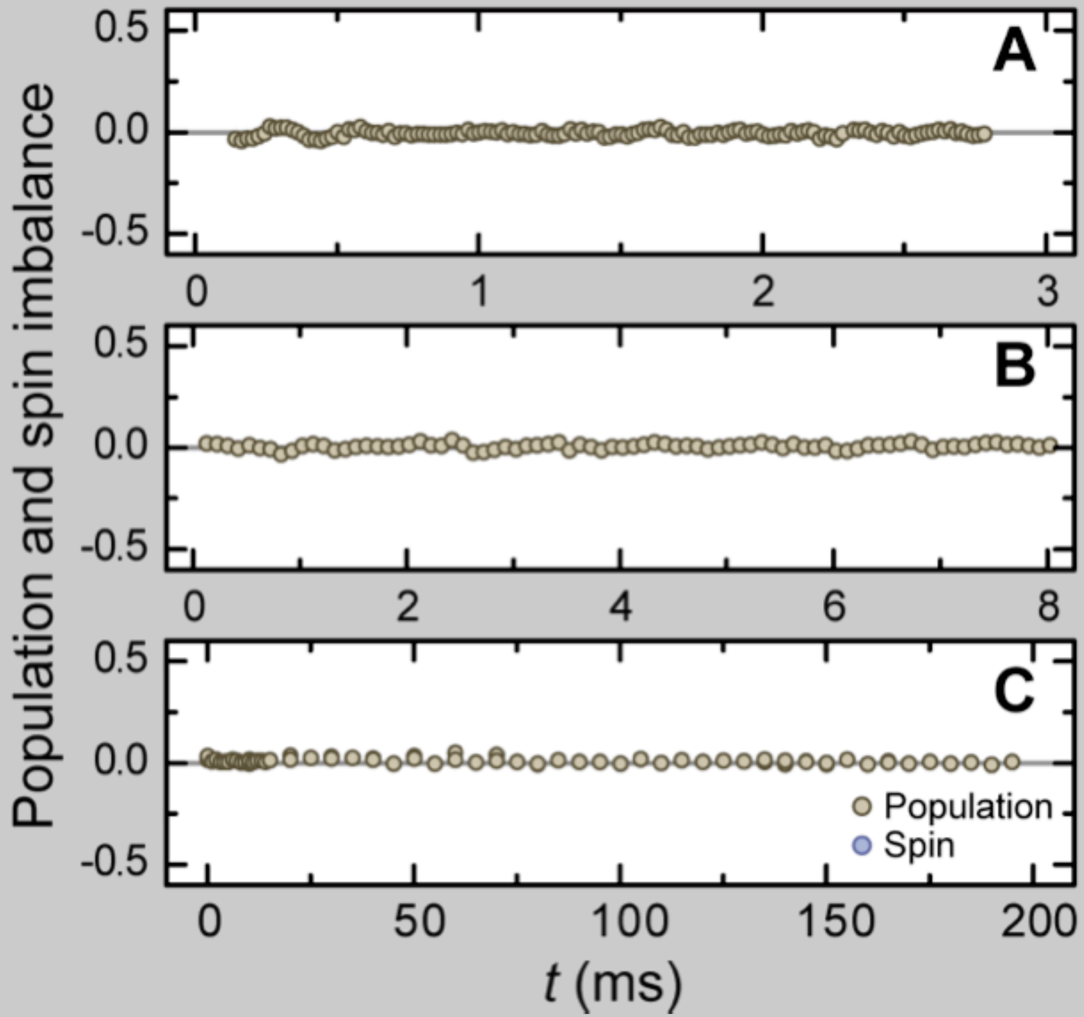
Superexchange induced flopping



$J/U = 1.25$
$V_{short} = 6\ E_r$

$J/U = 0.26$
$V_{short} = 11\ E_r$

$J/U = 0.05$
$V_{short} = 17\ E_r$

S. Trotzky et al. (*Science* in press)

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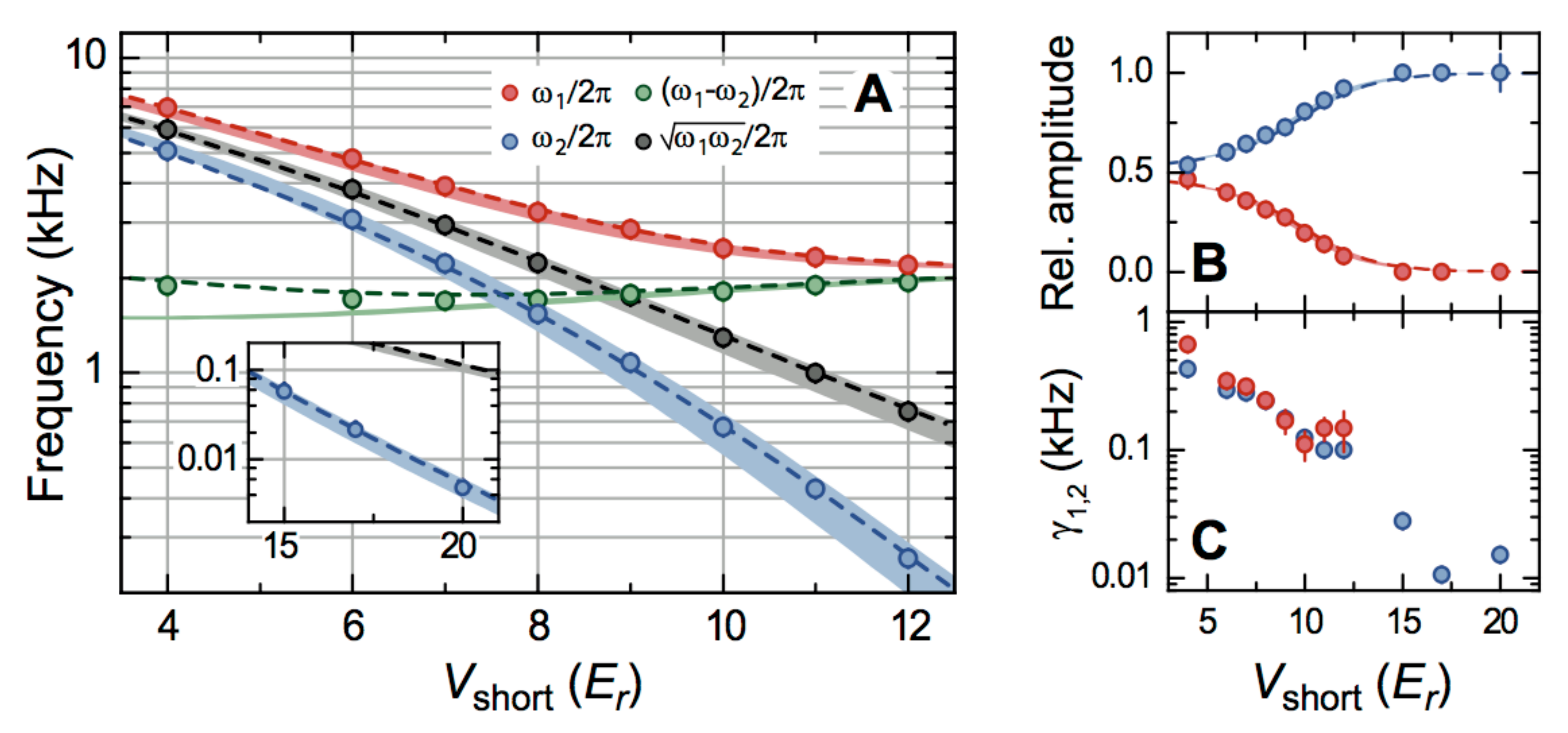
Measured Frequencies



$$U' = U + 3U_{LR} \qquad J'_{\mathrm{ex}} = 2J'^2/U - U_{\mathrm{LR}}$$

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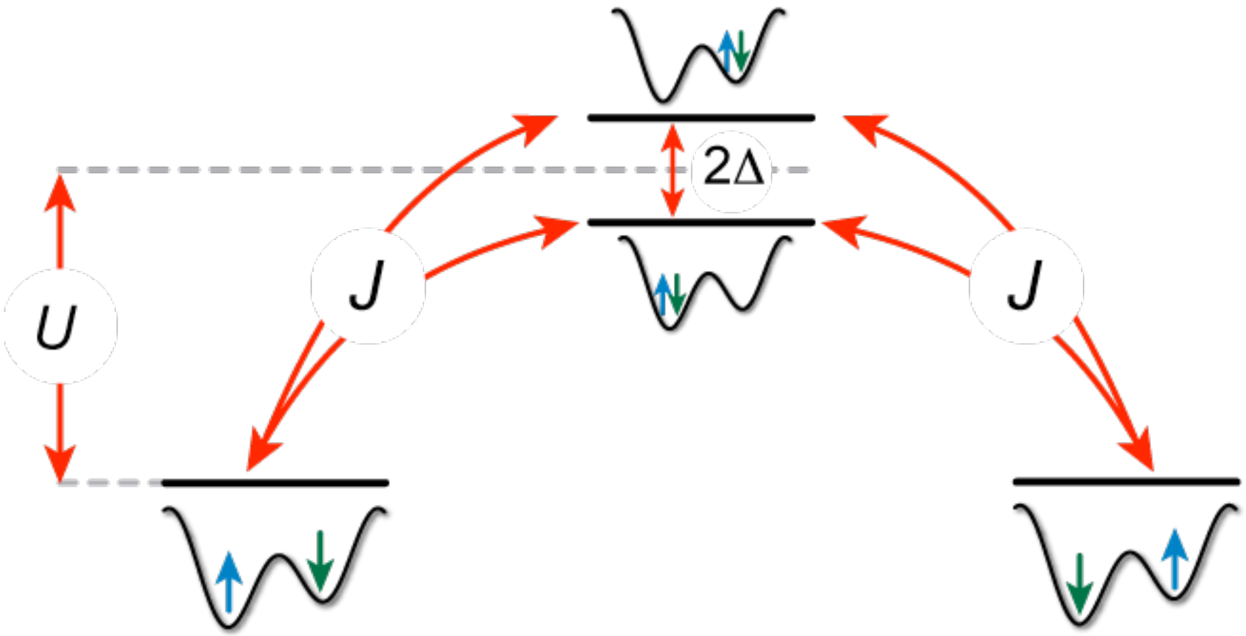
Controlling Superexchange Interactions

$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$

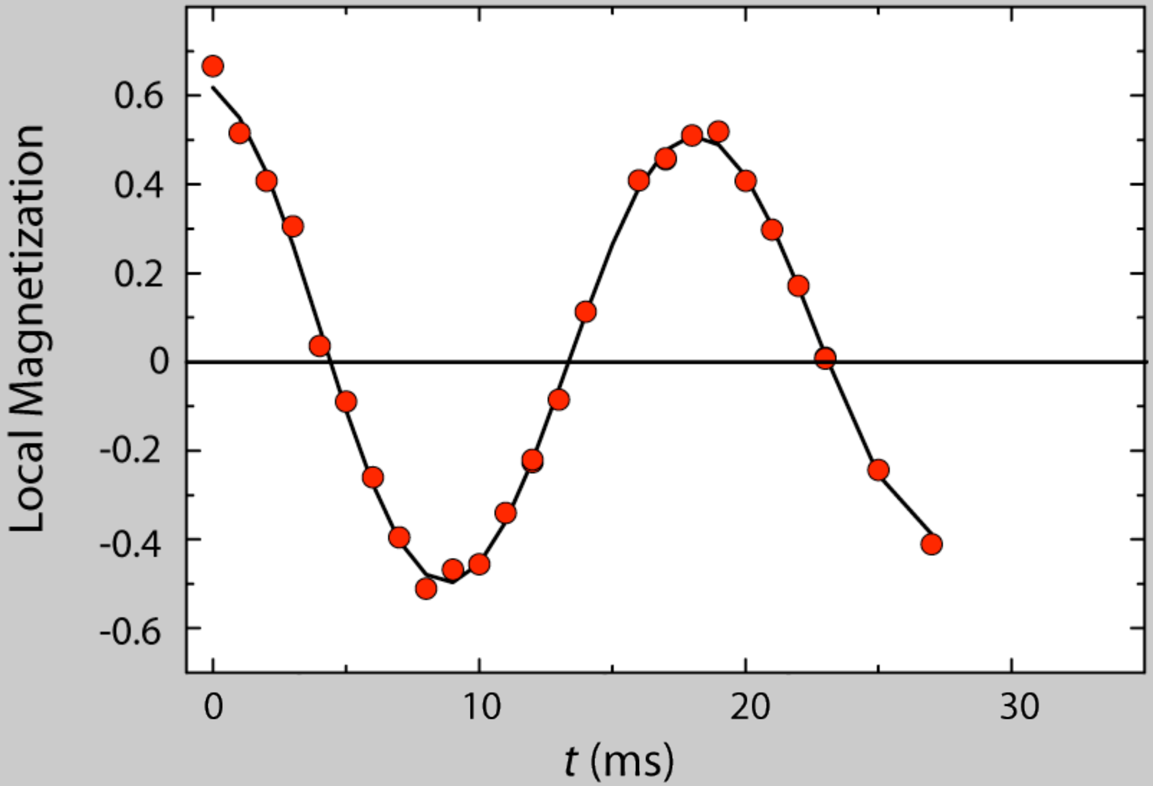


$$J_{ex} \propto \frac{J^2}{U+\Delta} + \frac{J^2}{U-\Delta}$$

Controlling Superexchange Interactions

Time evolution under action of ferromagnetic superexchange

$$H_{eff} = -J_{ex}\vec{S}_i \cdot \vec{S}_j$$



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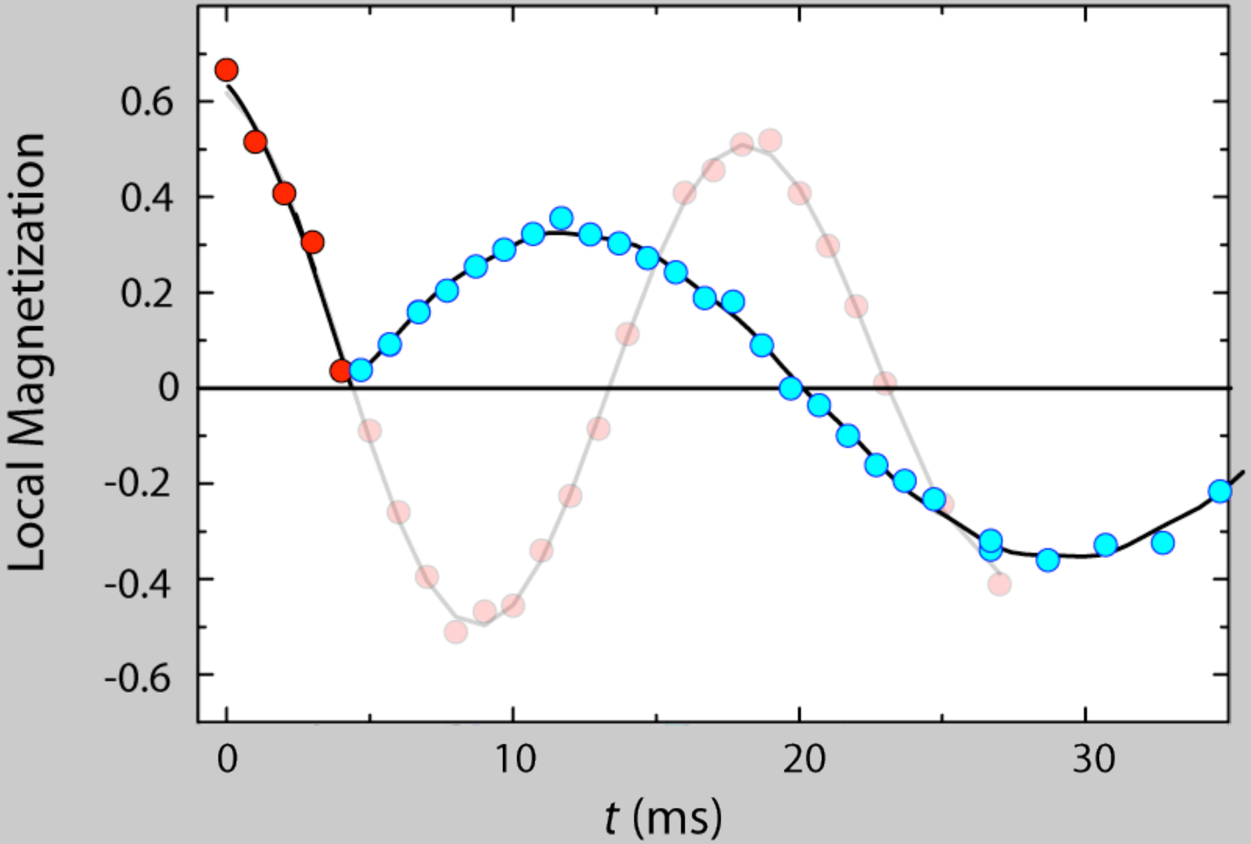
Controlling Superexchange Interactions

From ferromagnetic to antiferromagnetic superexchange interactions

$$H_{eff} = -J_{ex}\mathbf{S}_i \cdot \mathbf{S}_j \quad \Rightarrow \quad H_{eff} = +J'_{ex}\mathbf{S}_i \cdot \mathbf{S}_j$$



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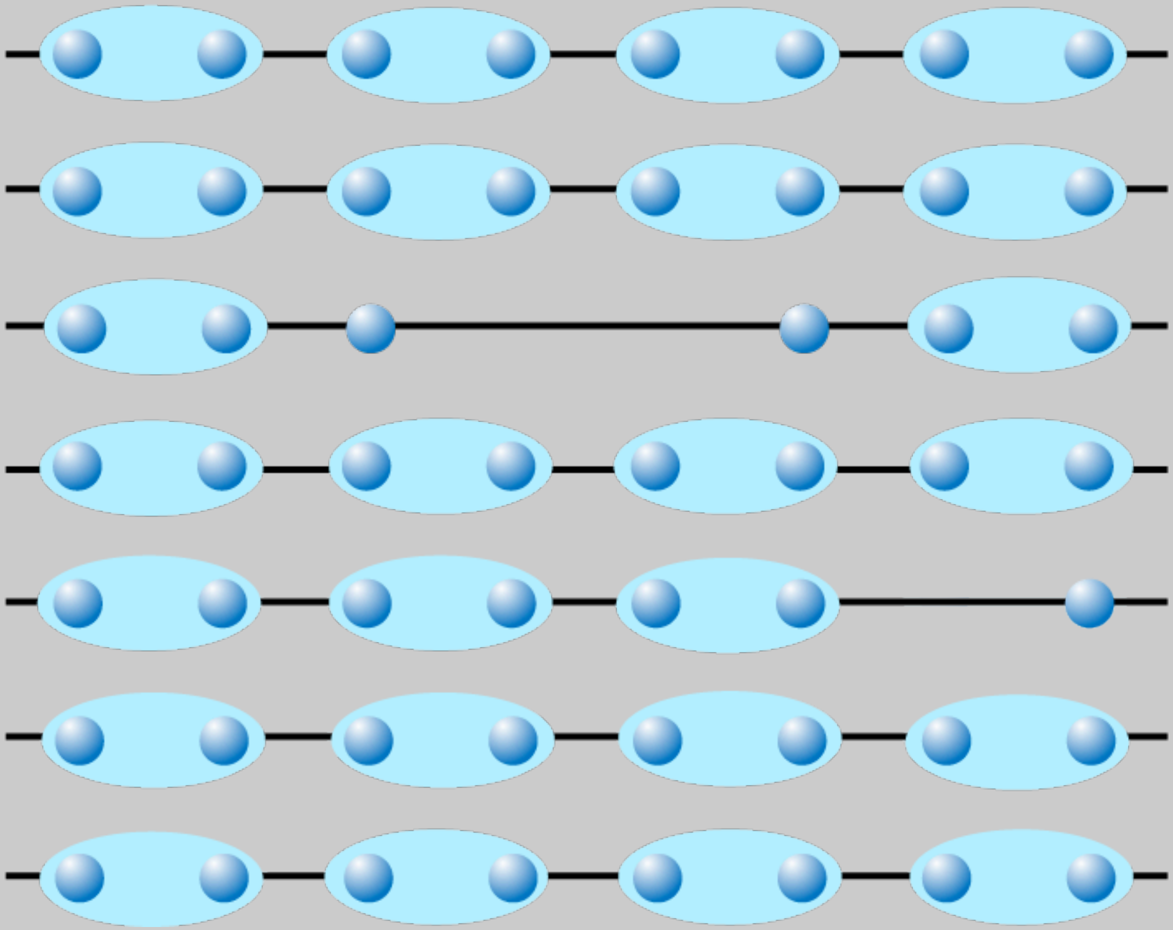
Arrays of Entangled Bell Pairs



A. M. Rey et al., PRL 99, 140601 (2007),
B Vaucher, A Nunnenkamp and D. Jaksch, arXiv:0710:5099

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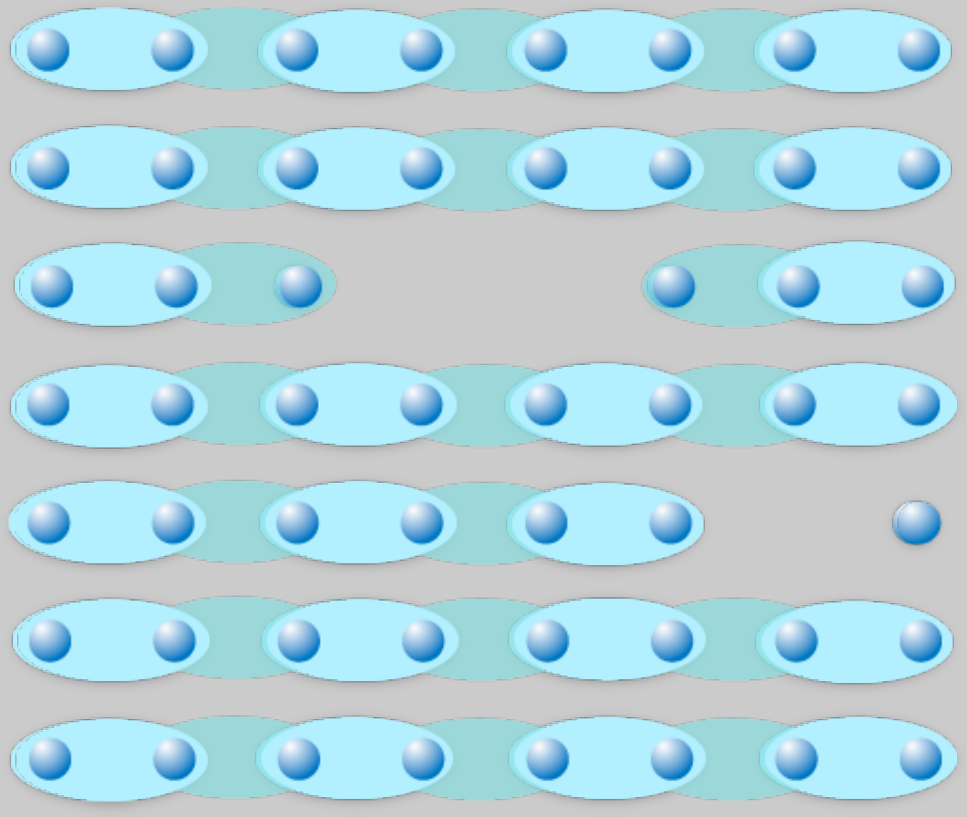
Large Entangled States - Entanglement Knitting



Pushbutton simultaneous creation of thousands of entangled Bell pairs in a single experiment.

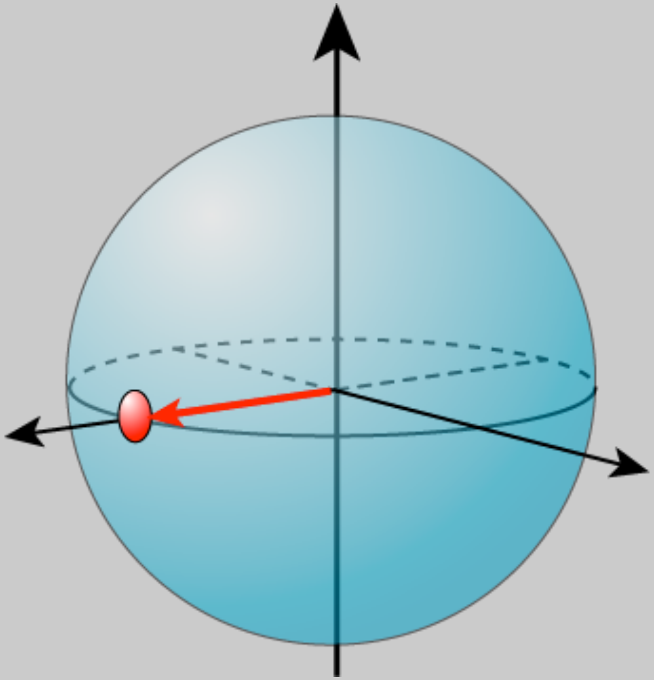
Connection of entanglement possible via e.g. superexchange interactions.

See also work of D. Jaksch et al.

Nonlinear Quantum Spin Dynamics in Bose-Einstein Condensates

WP4

From Spin Squeezing to Schrödinger Cats
- Nonlinear Quantum Spin Dynamics -



What happens if you tune interactions in larger ensembles?

$$\left(\hat{a}^{\dagger} + \hat{b}^{\dagger}\right)^{\otimes N} |0\rangle$$

$$\hat{H} = \chi \hat{S}_z^2$$

$$\chi = a_{aa} + a_{bb} - 2a_{ab}$$

A. Sørensen et al., Nature 409, 63 (2001),
L. You, PRA (2002),
A. Micheli et al. PRA 67, 013607 (2003)

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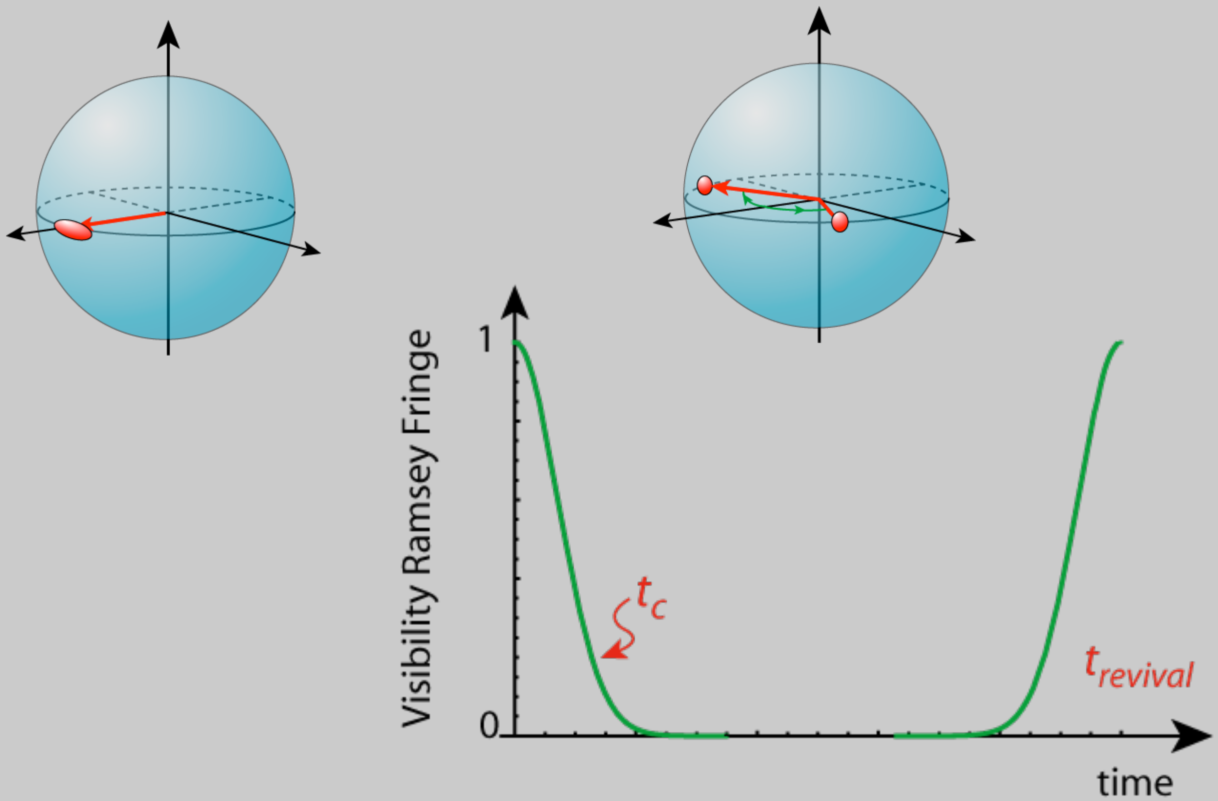
Ramsey Fringe Visibility Evolution

π/2 → **Tune interactions and wait** → π/2



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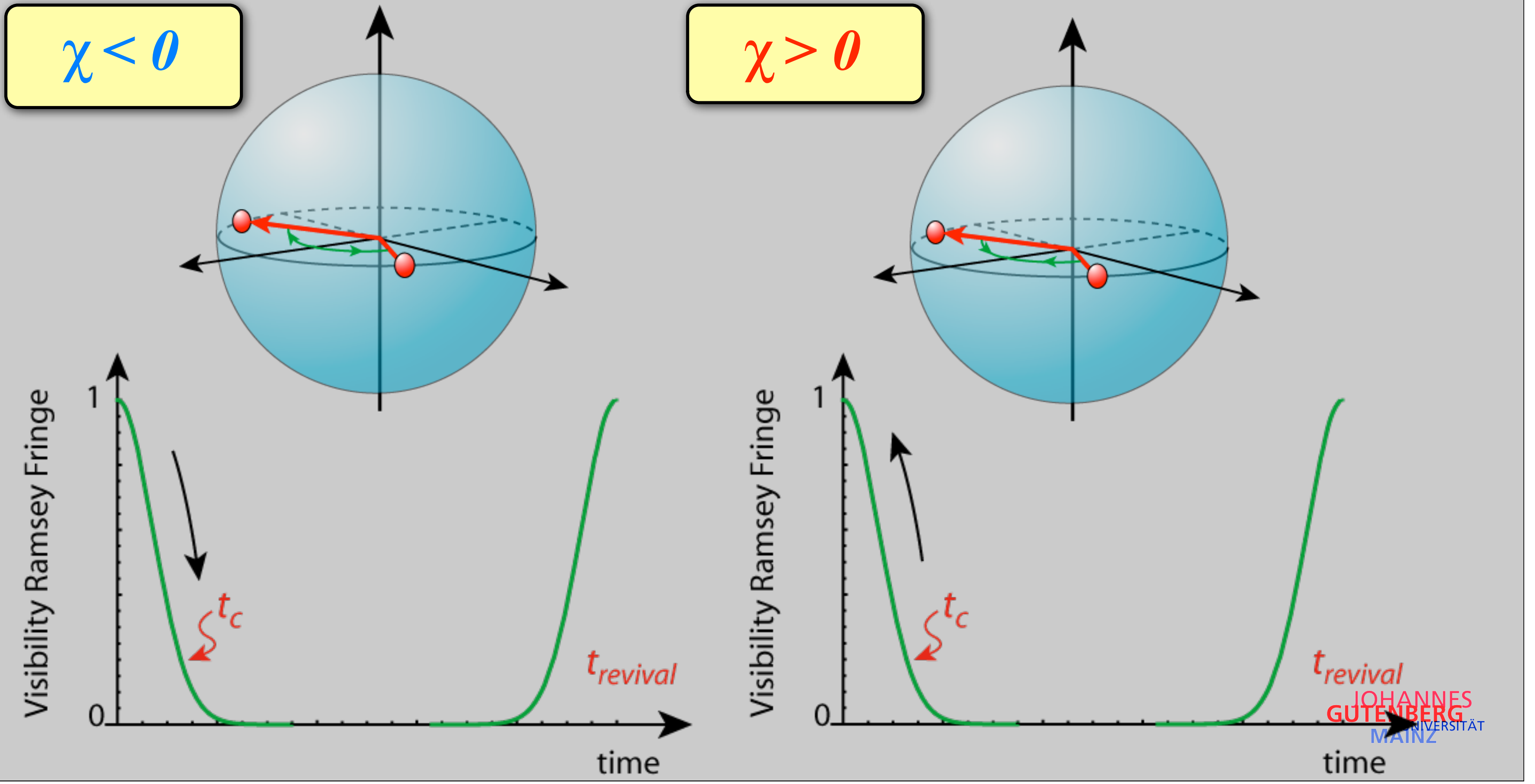
Decoherence Problems

Full revival can so far not be reached due to decoherence, but time evolution can be reversed!



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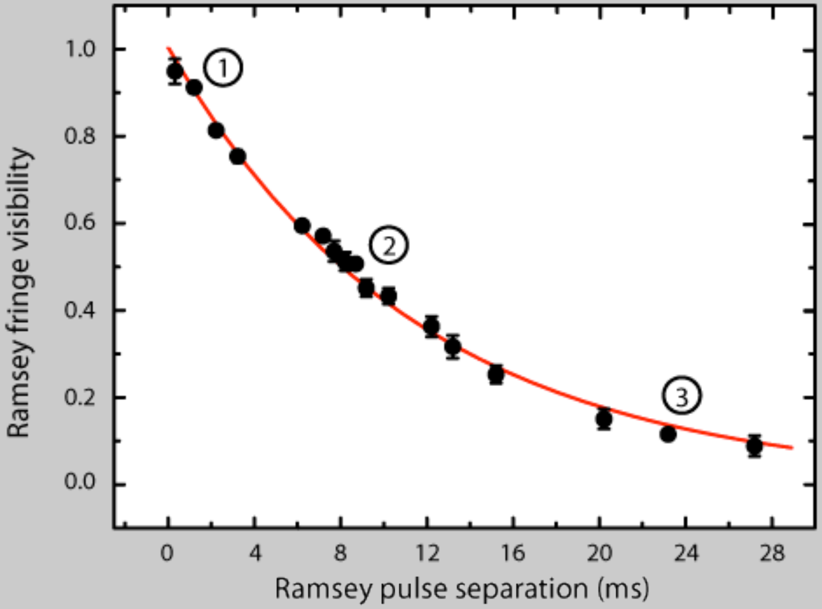
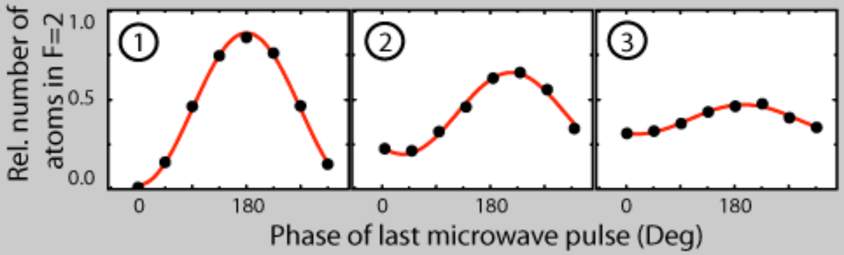
Experimental Results





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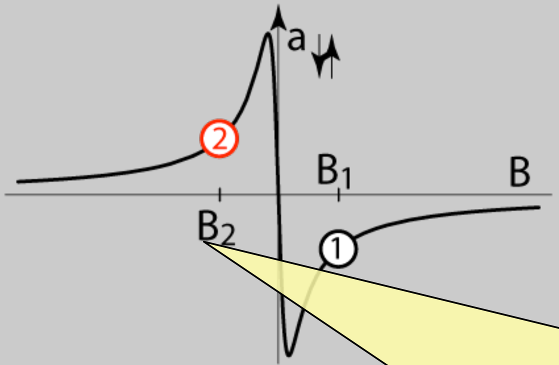
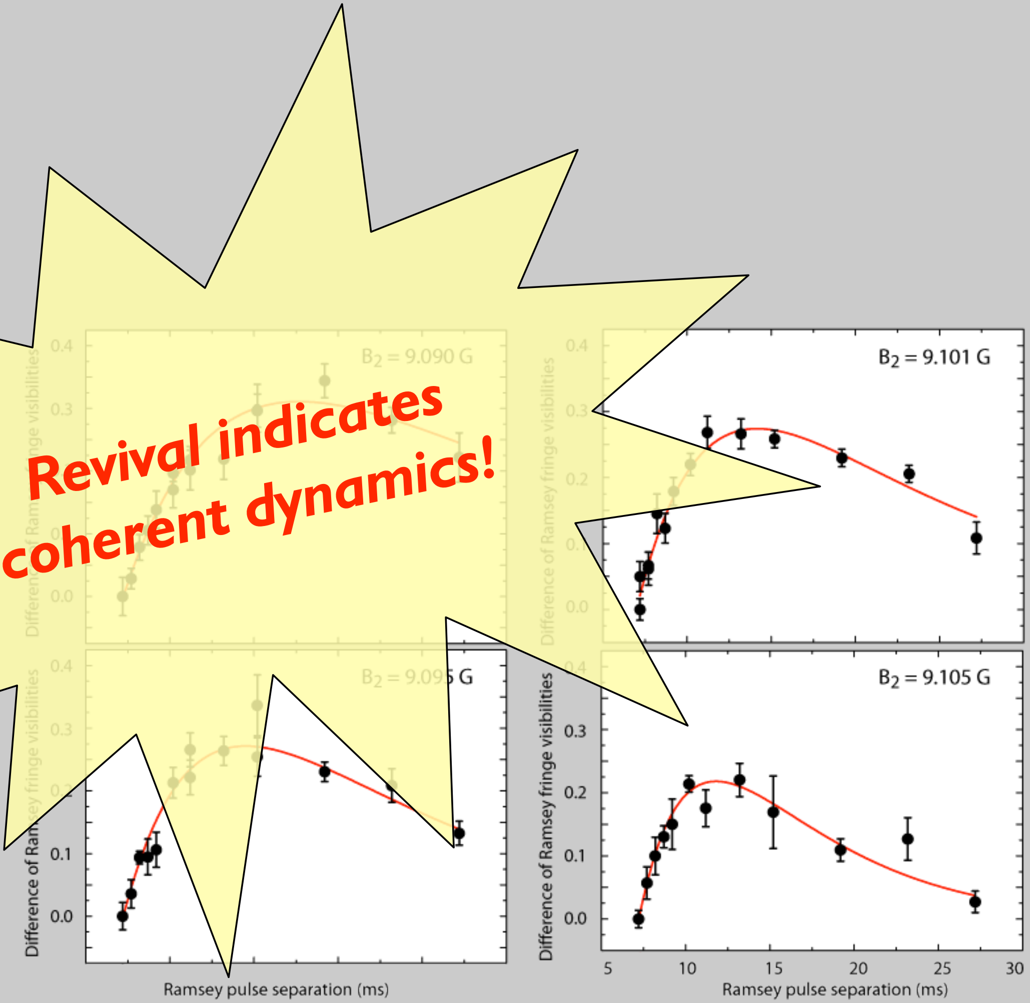
Reversing the Coherent Dynamics



B_1 fixed at 9.131 G for all four series.



A. Widera et al.
(submitted to PRL, arXiv:0709.2094)

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- **WP5 Strategies for minimizing decoherence**
  D11 Experimental realization of optical lattices with minimized decoherence M5.1, M5.3, M5.4, M5.5, M5.6

Summary & Outlook

- Creation and loading of atoms in optical superlattices
- Single Qubit State Manipulation
- Massively Parallel Creation of Bell Pairs
- Characterization of Bell Pairs
- Measurement of Coherence Time of Single Qubits and Bell Pairs
- Controllable Superexchange Spin-Spin Interaction
- Novel Multiparticle Entanglement Schemes for Generation of Robust MP Entangled Quantum States
- Multiparticle Entanglement via Spin-Squeezing in 1D Quantum Systems
- Investigation of Dynamical Effects in Mode-Squeezed 1D Luttinger Liquids

- How defect free can we create array of Bell pairs?
- Can we observe dynamical effects of quantum spin systems an compare to advancec numerical methods?
- How longlived can multiparticle states be with zero magnetization?
- Can we create/engineer **topologically ordered quantum states** and use them for topological quantum computation?