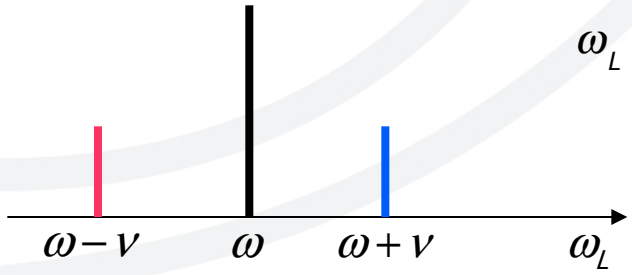
MAGIC IN THE LAB

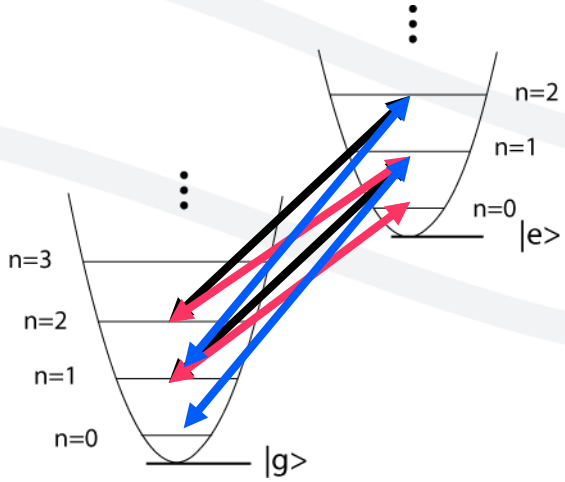
Trapped Atom-RF Interaction: MAGIC

$\omega_L = \omega$, "Carrier"

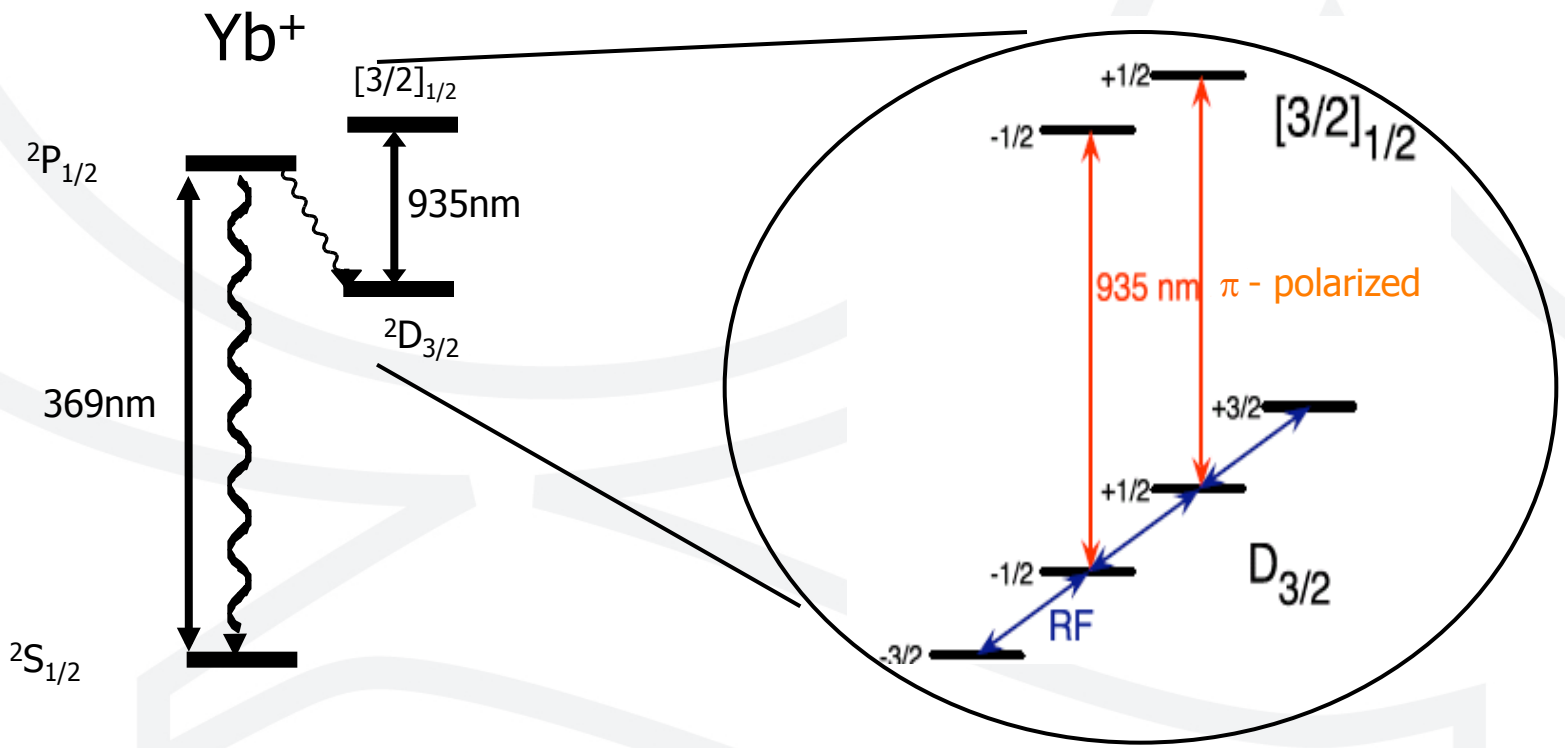
$\omega_L = \omega - \nu$, "red sideband"

$\omega_L = \omega + \nu$, "blue sideband"





MAGIC – Experiment

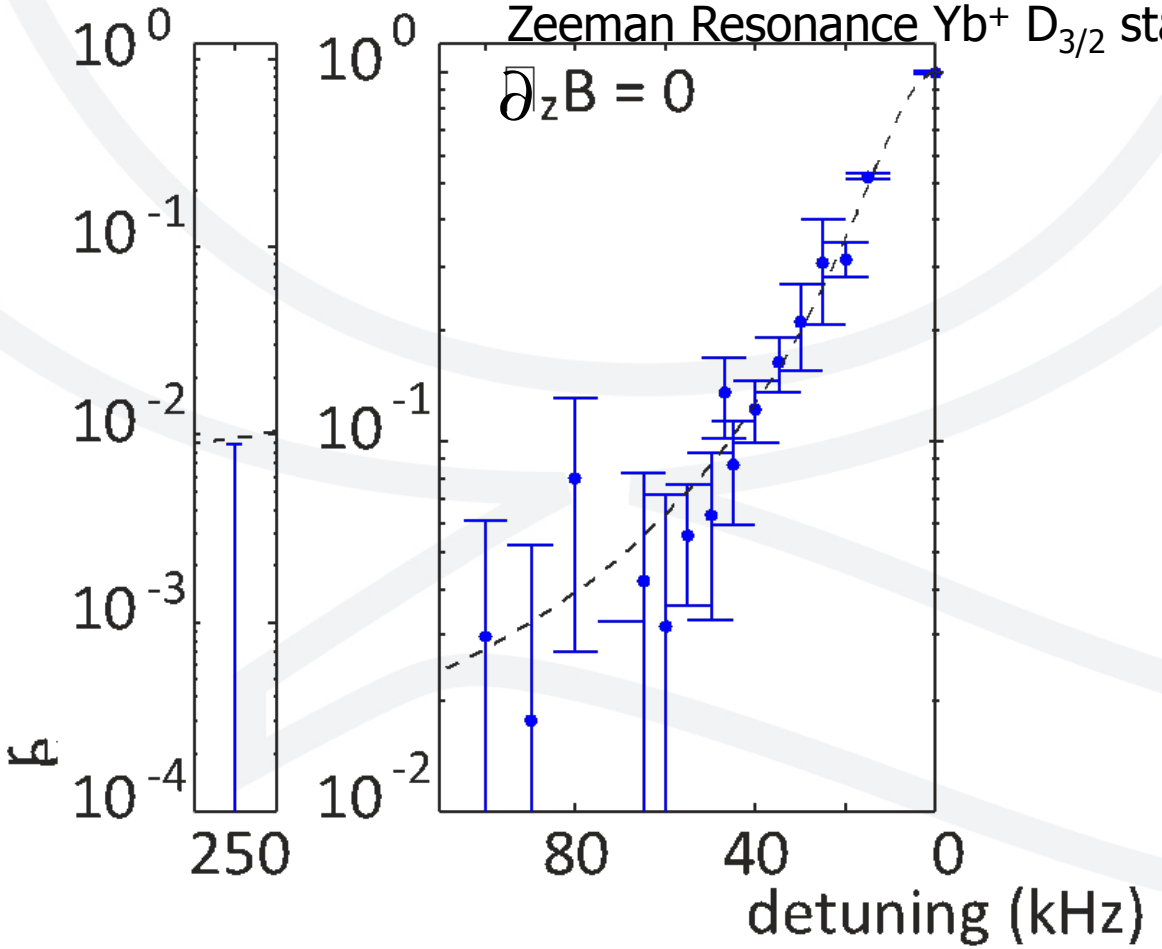


RF-optical double resonance spectroscopy

PRL **102** (2009)

MAGIC – Experiment

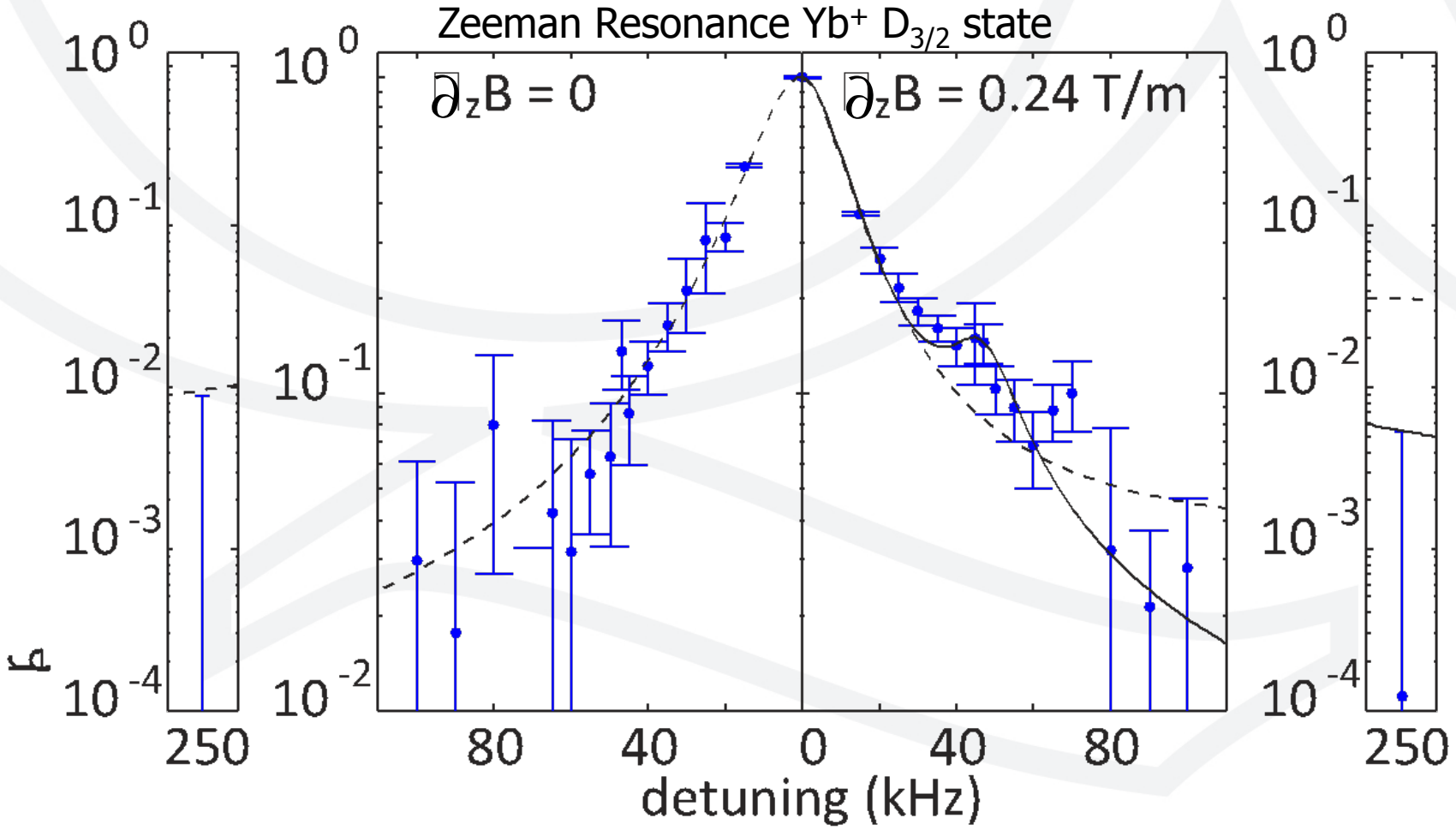
Spin-Motion coupling using RF radiation



PRL **102** (2009)

MAGIC – Experiment

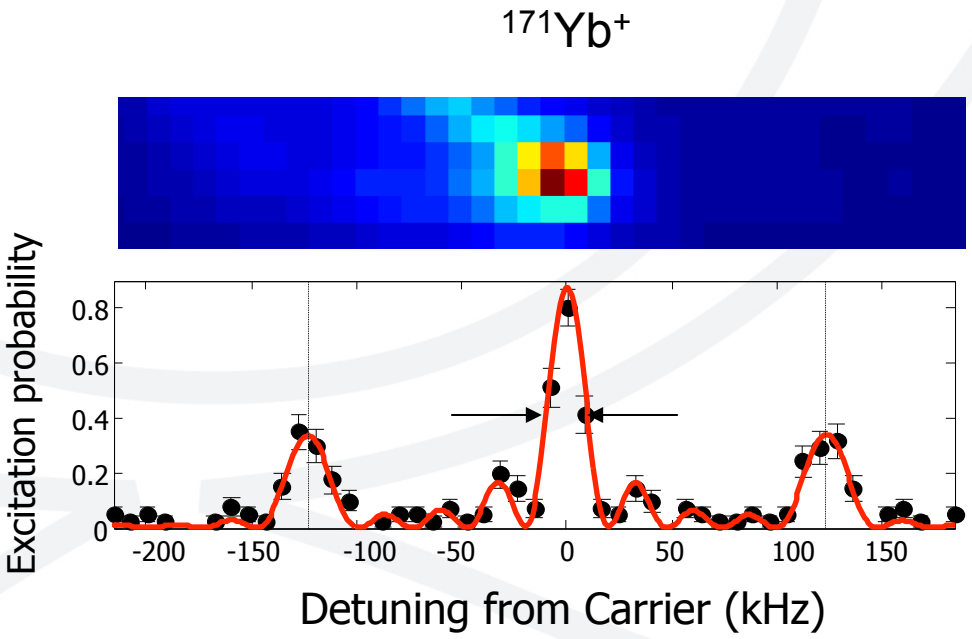
Spin-Motion coupling using RF radiation



PRL **102** (2009)

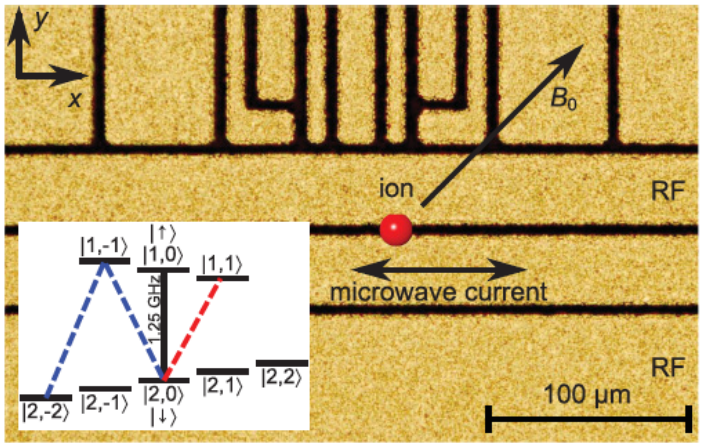
MAGIC – Experiment

Spin-Motion coupling using RF radiation



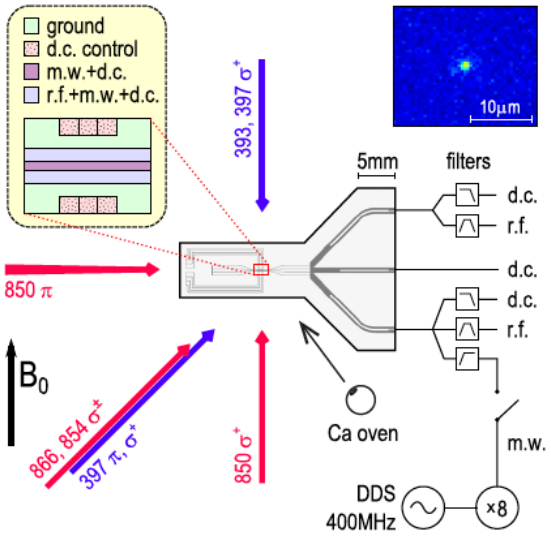
Single Qubit Gates Using **RF-waves**

Gate error O(10^{-5})



K. R. Brown *et al.*, PRA **84** (2011)

Gate error O(10^{-6})



T. P. Harty *et al.*, PRL **113** (2014)

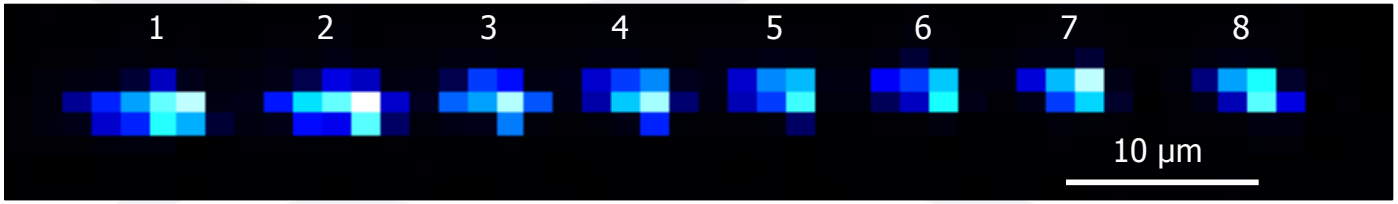
- RF (MW) for all coherent operations
- Individual Addressing

- Spin-Spin Coupling:
  - Adjust Magnitude
  - Simultaneous
  - On and Off
  - Change Sign

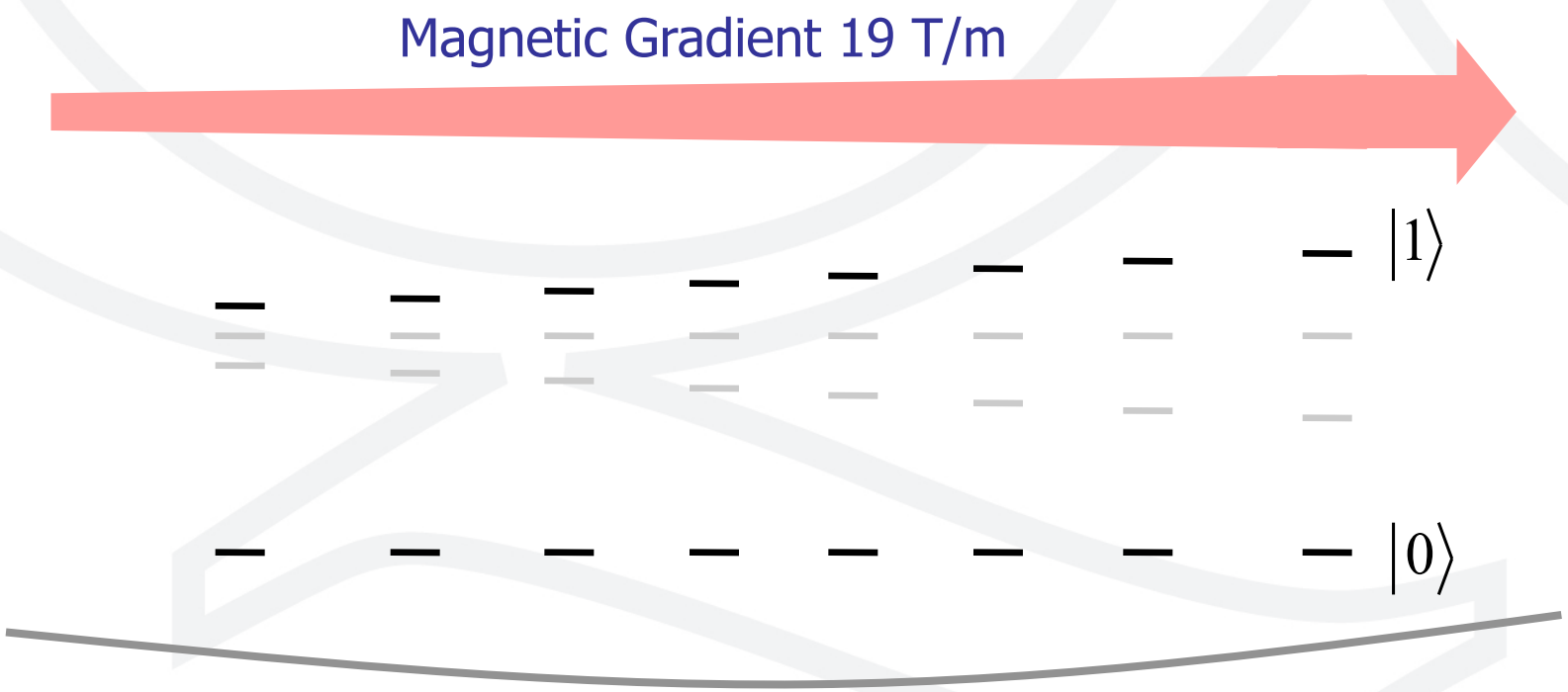
MAGIC QUANTUM TOOLBOX

Addressing a Quantum Byte

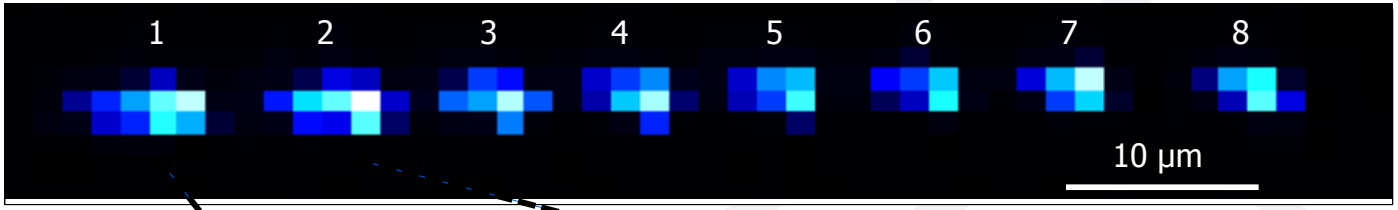
Magnetic Gradient 19 T/m

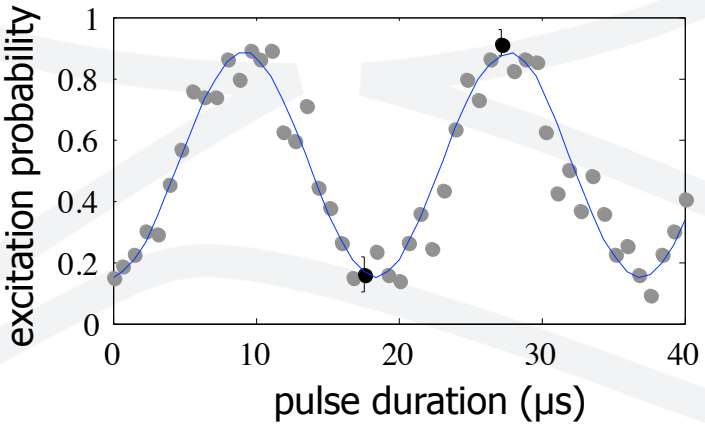


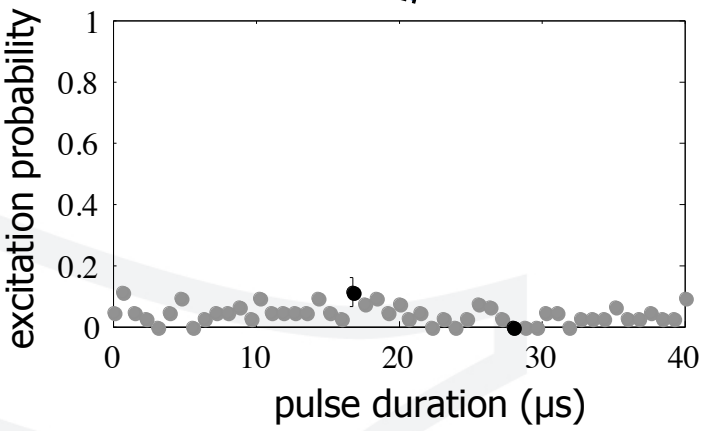
Addressing a Quantum Byte



Addressing a Quantum Byte



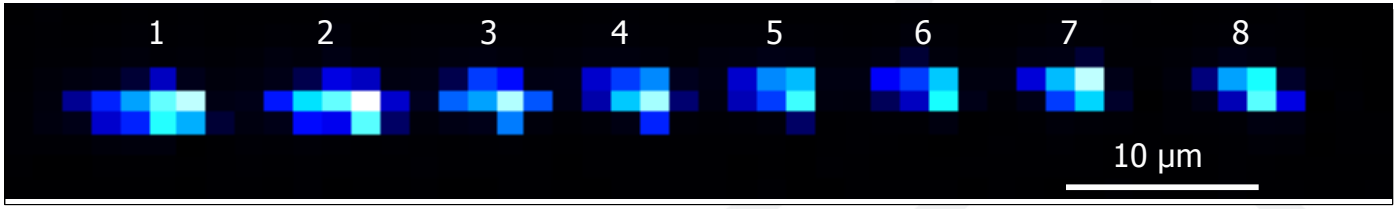




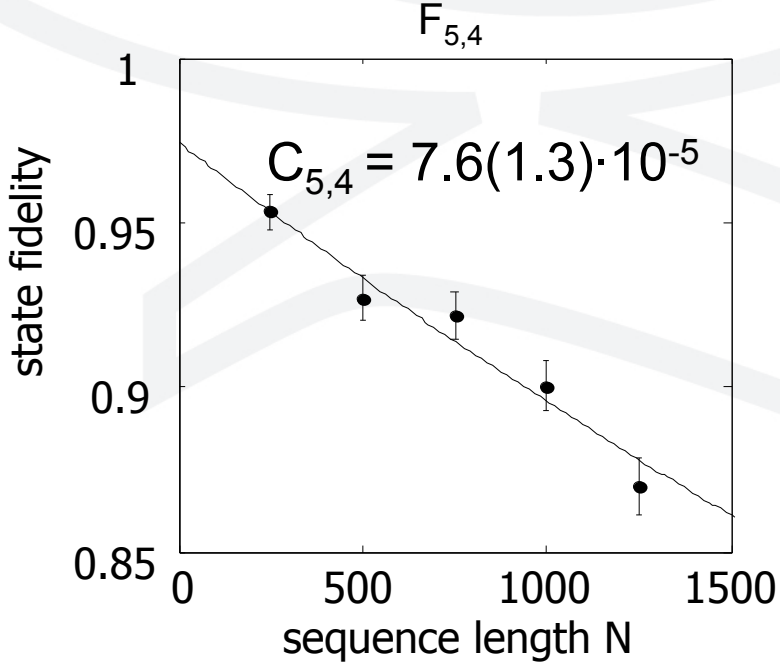
Nat. Commun. **5** (2014)

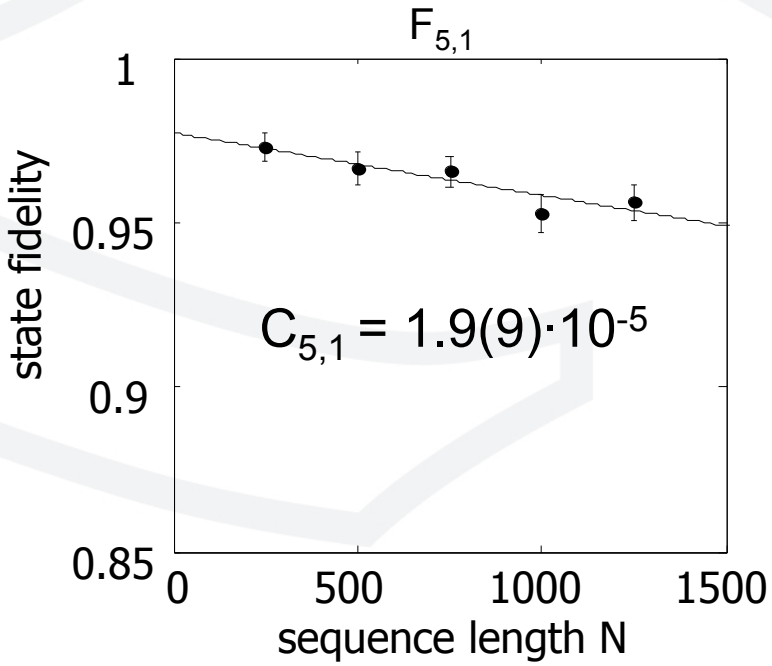
Addressing a Quantum Byte

Benchmarking



Example:

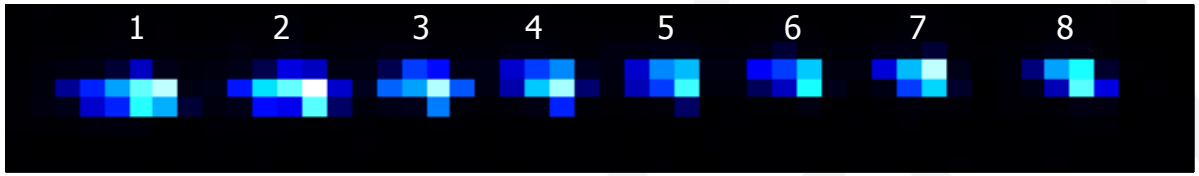




Nat. Commun. **5** (2014)

Addressing a Quantum Byte

Measured cross-talk matrix for interacting ions



$C_{i,j}$ (10^{-5})

addressed qubits (rows); observed qubits (columns)

-	**3.0(9)**	1.9(8)	2.2(9)	2.3(9)	1.0(8)	0.7(	
3.8(1.4)	-	**4.1(1.1)**	2.3(9)	2.3(1.1)	1.6(		0.9(9)
2.1(1.0)	**3.7(1.2)**	-	**4.5(1.2)**	1.(		0.8(7)	1.1(6)
0.9(9)	1.7(6)	**2.7(1.1)**		)	0.8(7)	0.6(6)	0.6(6)
1.9(9)	1.6(9)	2.		-	**3.1(1.0)**	1.8(9)	0.5(5)
1.5(5)		)	1.0(8)	**5.5(1.4)**	-	**3.6(1.3)**	0.8(8)
	)	1.5(7)	1.2(8)	1.2(8)	**2.9(1.1)**	-	**2.6(8)**
0.(	1.1(5)	0.6(6)	0.8(8)	2.5(9)	1.1(8)	**3.4(1.2)**	-

Below Error Correction Threshold

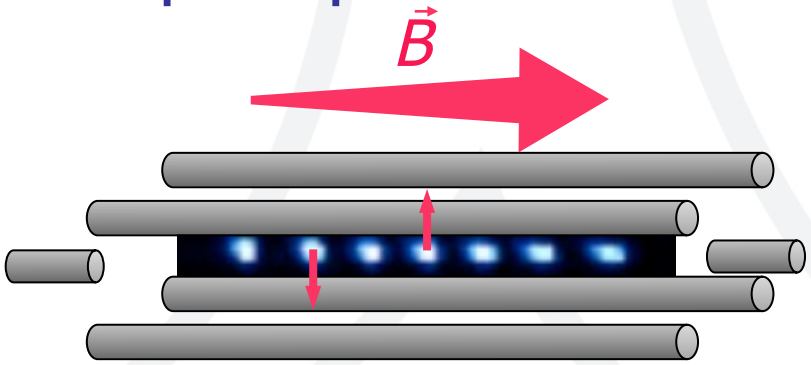
Nat. Commun. **5** (2014)

- RF (MW) for all coherent operations
- Individual Addressing

- Spin-Spin Coupling:
  - Adjust Magnitude
  - Simultaneous
  - On and Off
  - Change Sign

MAGIC QUANTUM TOOLBOX

MAGIC: Spin-Spin Interaction

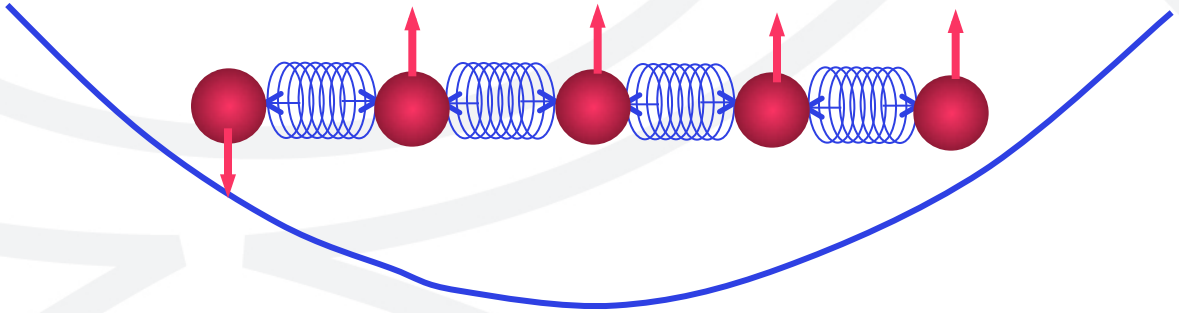


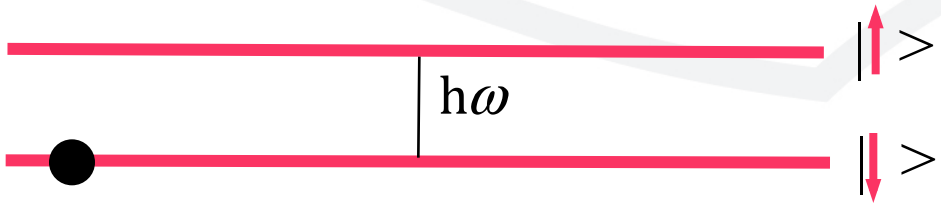
1. Individual Addressing

2. Spin-Spin Coupling

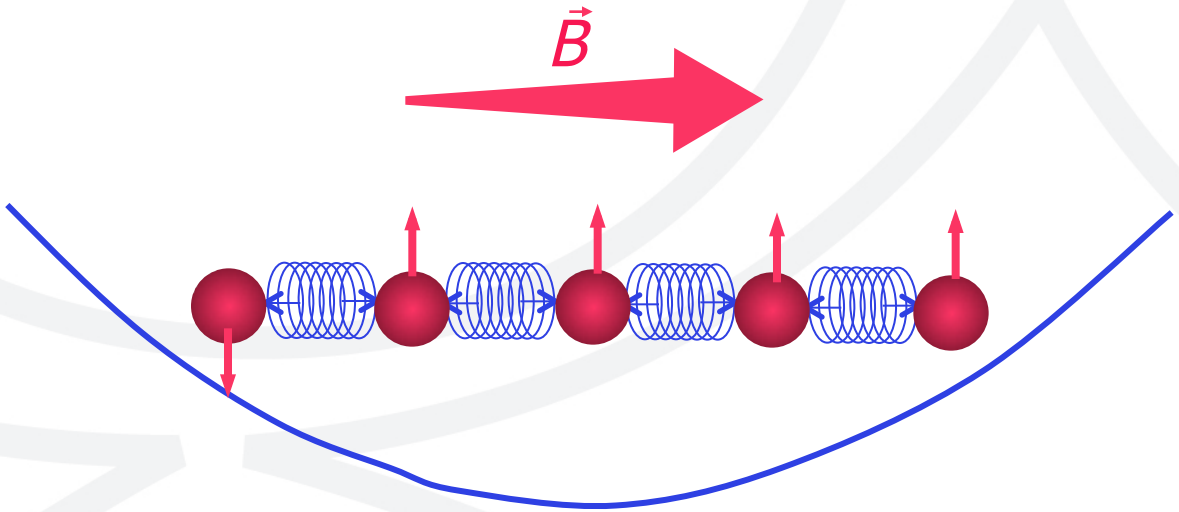
$$-\frac{\hbar}{2}\sum_{i<j}^{N}\sigma_{z,i}\sigma_{z,j}J_{ij}$$

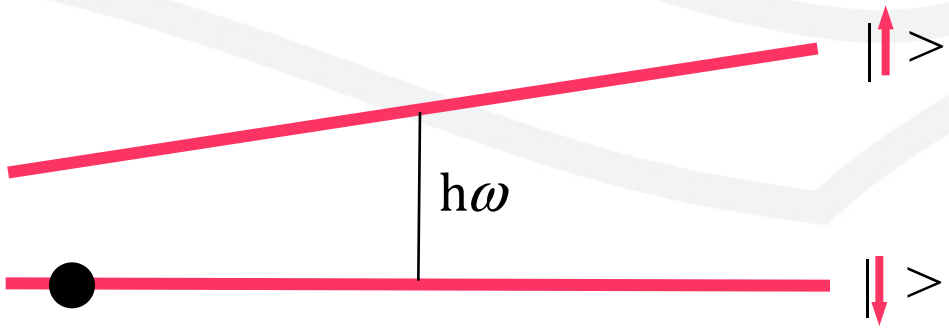
MAGIC: Spin-Spin Interaction



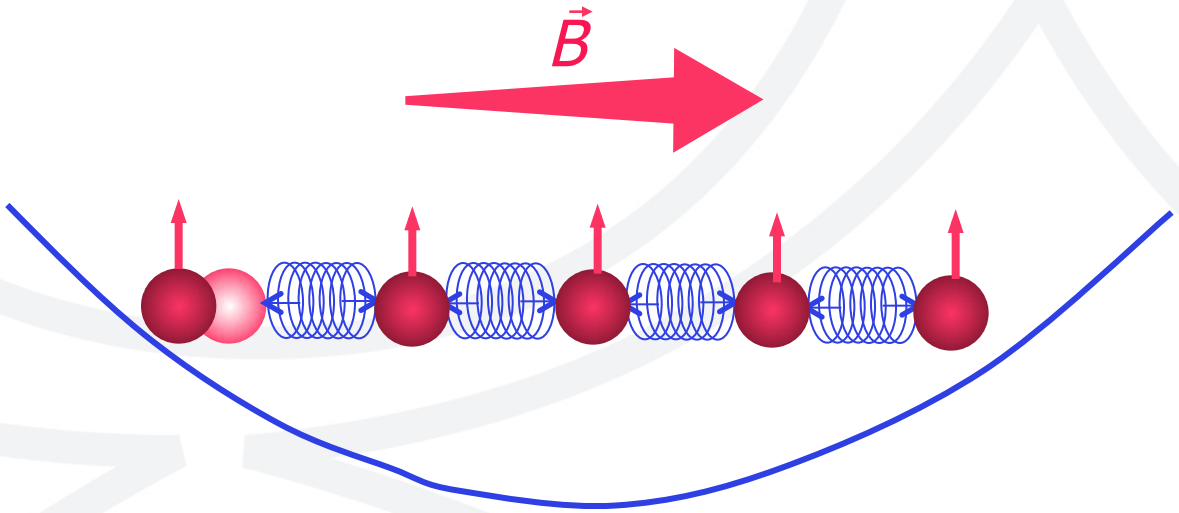


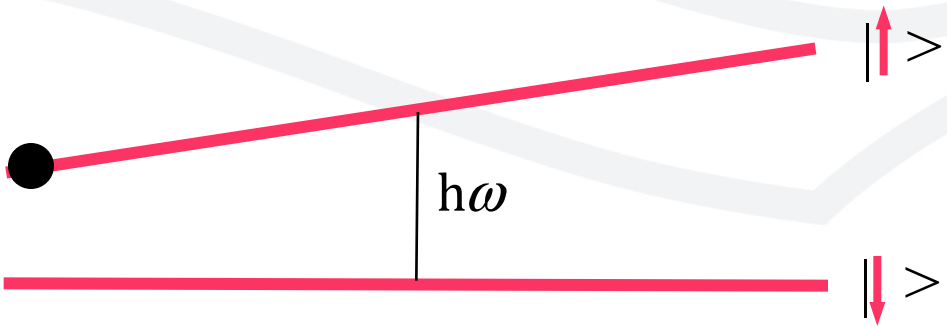
MAGIC: Spin-Spin Interaction





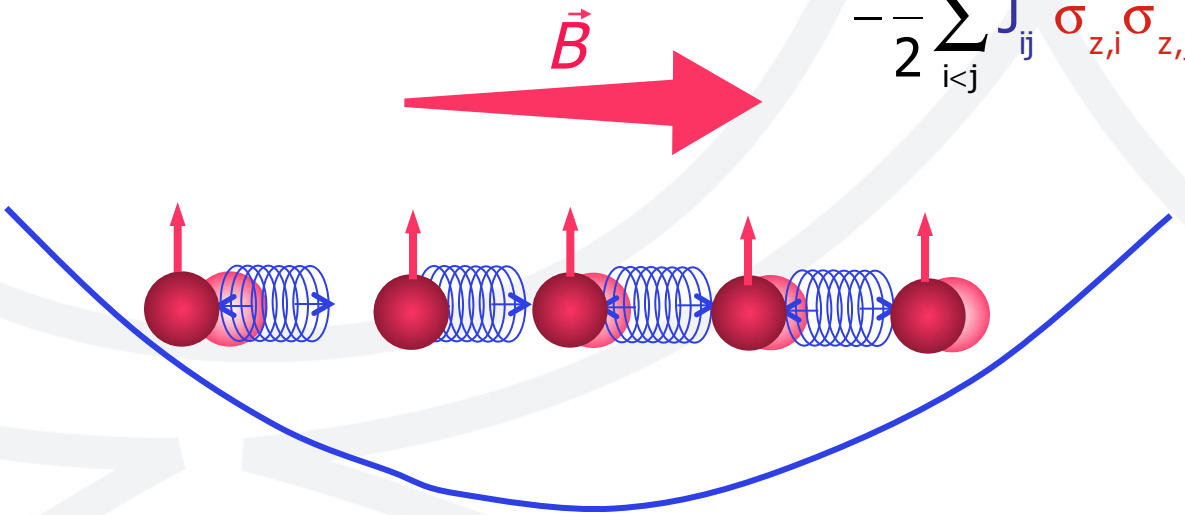
MAGIC: Spin-Spin Interaction

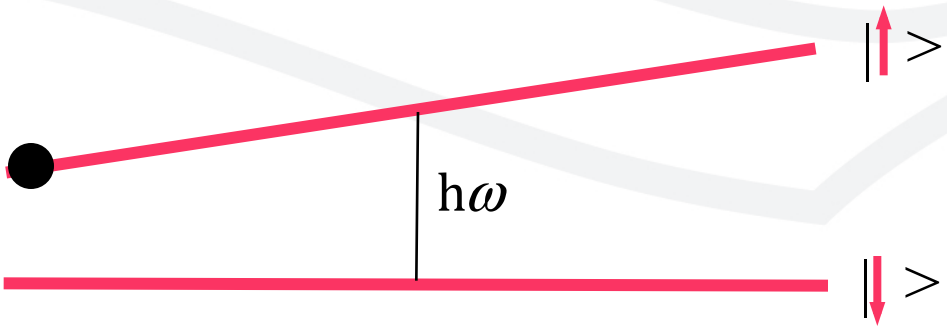




MAGIC: Spin-Spin Interaction

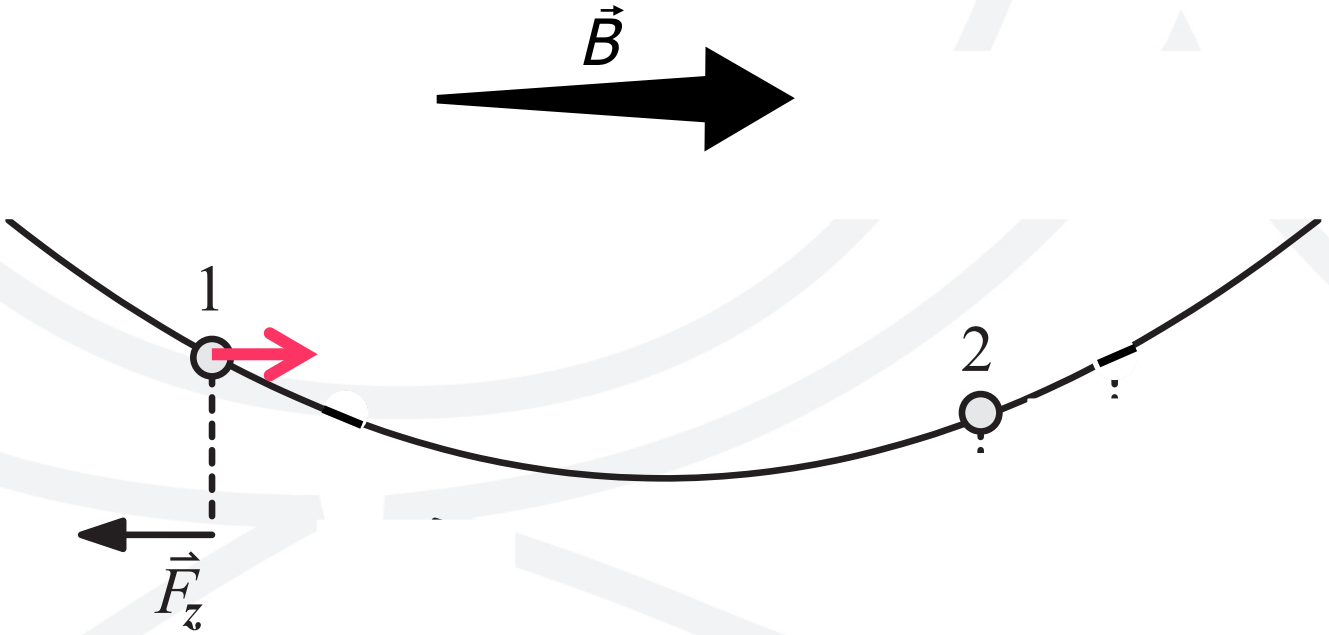
$$-\frac{\hbar}{2}\sum_{i<j}^{N} J_{ij}\,\sigma_{z,i}\sigma_{z,j}$$



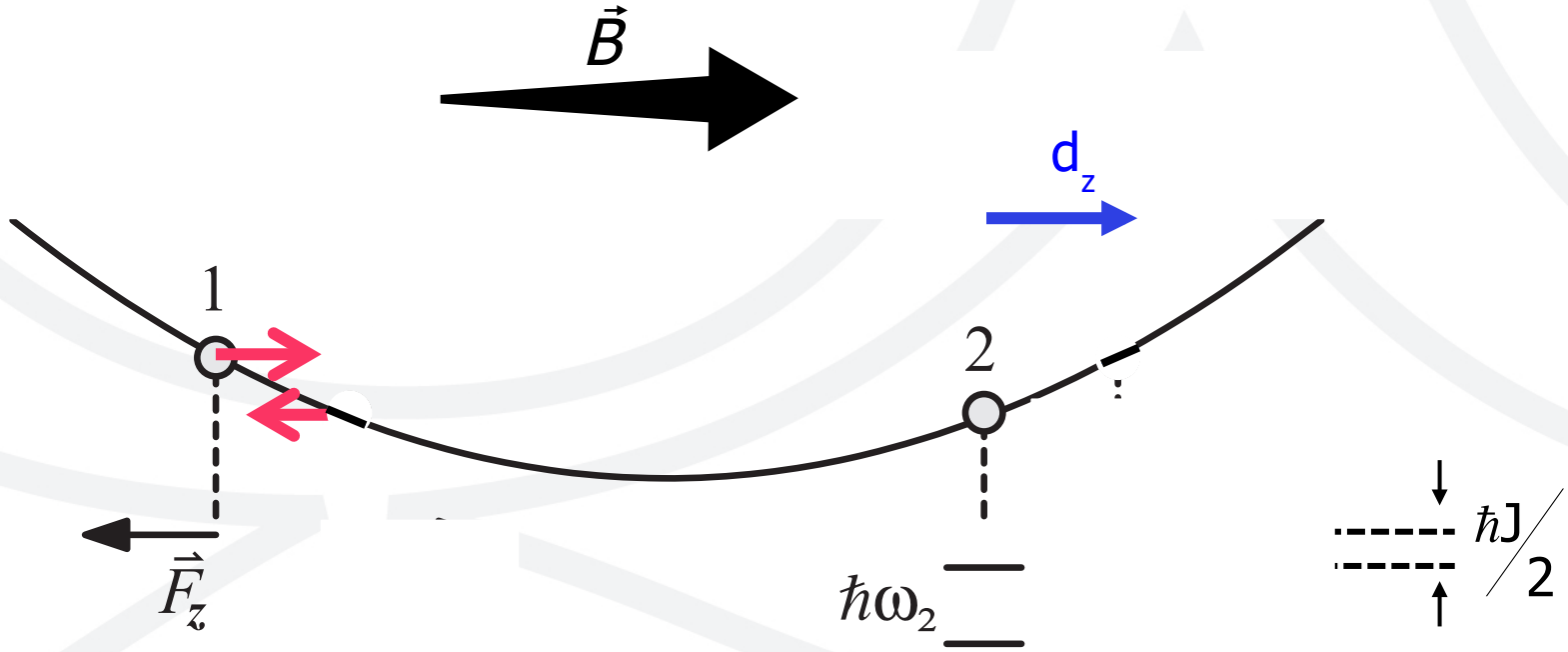


In *Laser Physics at the Limit,* Springer, 2002, p. 261; also: quant-ph/0111158
Adv. At. Mol. Opt. Phys.**49**, 295 (2003); also: quant-ph/0305129

MAGIC Example: Two Ions



MAGIC Example: Two Ions

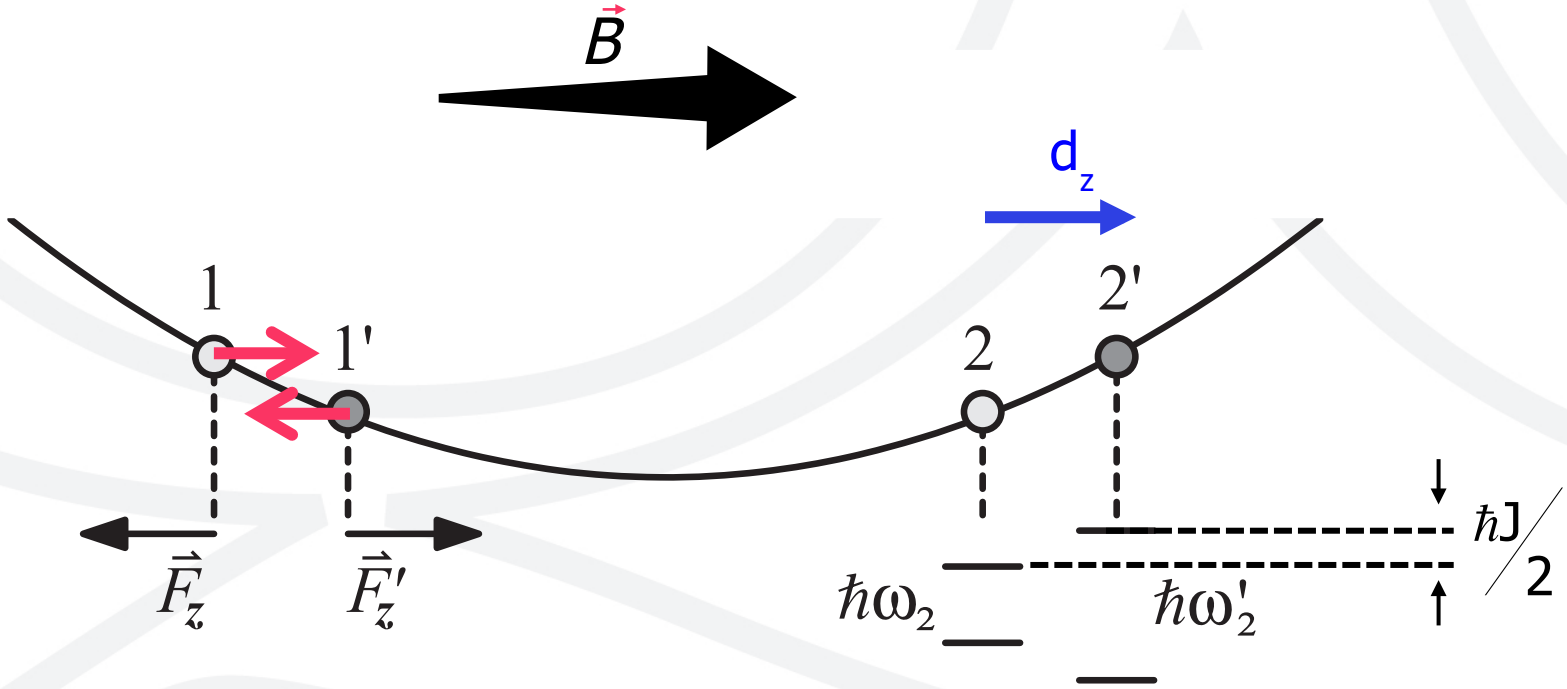


$$\text{Spin flip} \Rightarrow d_z = \mp F_z / (m\nu^2)$$

$$\hbar J_{12} = -F_z d_z = -F_z^2 / (m\nu^2) \propto (\partial_z B / \nu)^2.$$

J. Phys. B **42,** 154009 (2009)

MAGIC Example: Two Ions



$$\hbar J_{12} \propto (\partial_z B / \nu)^2$$

J. Phys. B **42,** 154009 (2009)

MAGIC: Outline of Math (1d)

Interaction

$$H_I = -\frac{\hbar}{2}\sum_{n=1}^{N}\omega_n\sigma_z^{(n)} - \frac{\hbar}{2}\sum_{n=1}^{N}\partial_z\omega_n q_n\sigma_z^{(n)}$$

$$= \quad \ldots \quad - F_0\sum_{n=1}^{N} q_n\sigma_z^{(n)}$$

Potential (external + Coulomb)

$$V^{harm} = \sum_{n=1}^{N} A_{i,j} q_i q_j$$

$\Rightarrow$ N uncoupled normal modes

Unitary transformation

$$\Rightarrow \quad \tilde{H} = -\frac{\hbar}{2}\sum_{n=1}^{N}\omega_n\sigma_z^{(n)} + \hbar\sum_{n=1}^{N}\nu_n a_n^\dagger a_n - \frac{\hbar}{2}\sum_{\substack{i,j=1\\ i<j}}^{N} J_{ij}\,\sigma_z^{(i)}\sigma_z^{(j)},$$

with

$$J_{ij} \equiv \sum_{n=1}^{N}\nu_n\varepsilon_{in}\varepsilon_{jn},$$

and

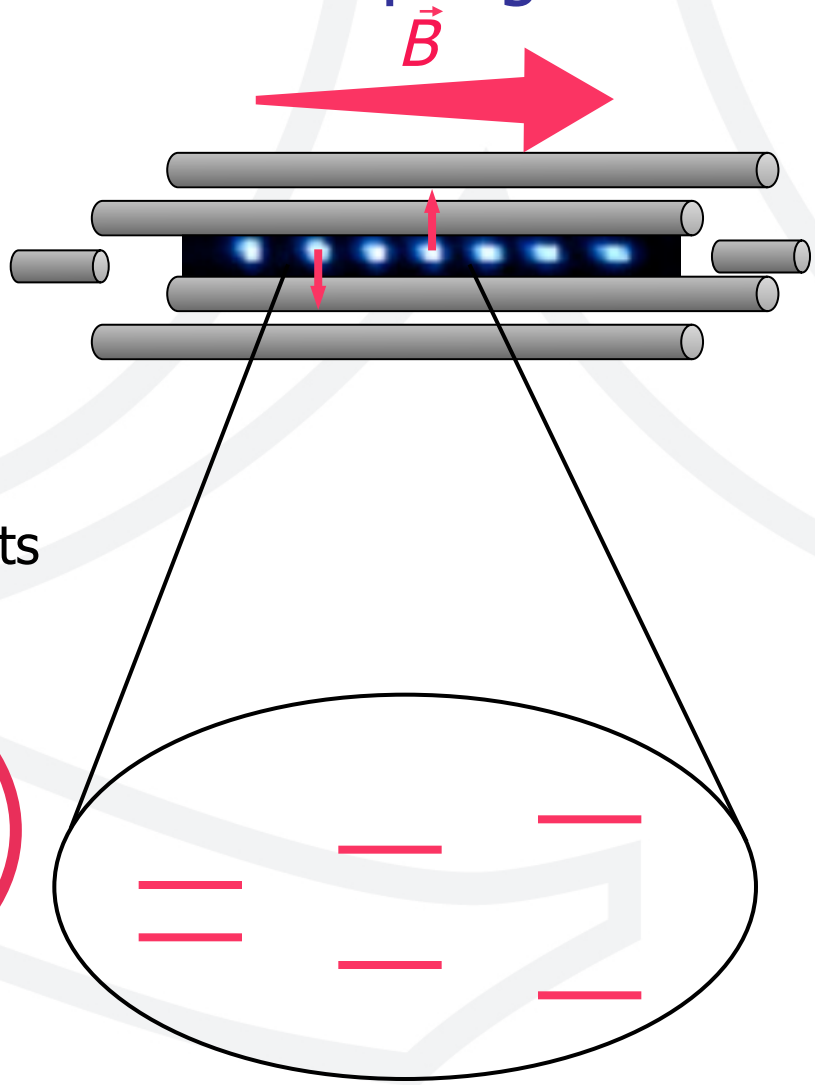
$$\varepsilon_{in} \equiv \frac{\Delta z_n\partial_z\omega_i}{\nu_n}S_{in}$$

In *Laser Physics at the Limit,* Springer, 2002, p. 261. also: quant-ph/0111158

Magnetic Gradient Induced Coupling: MAGIC

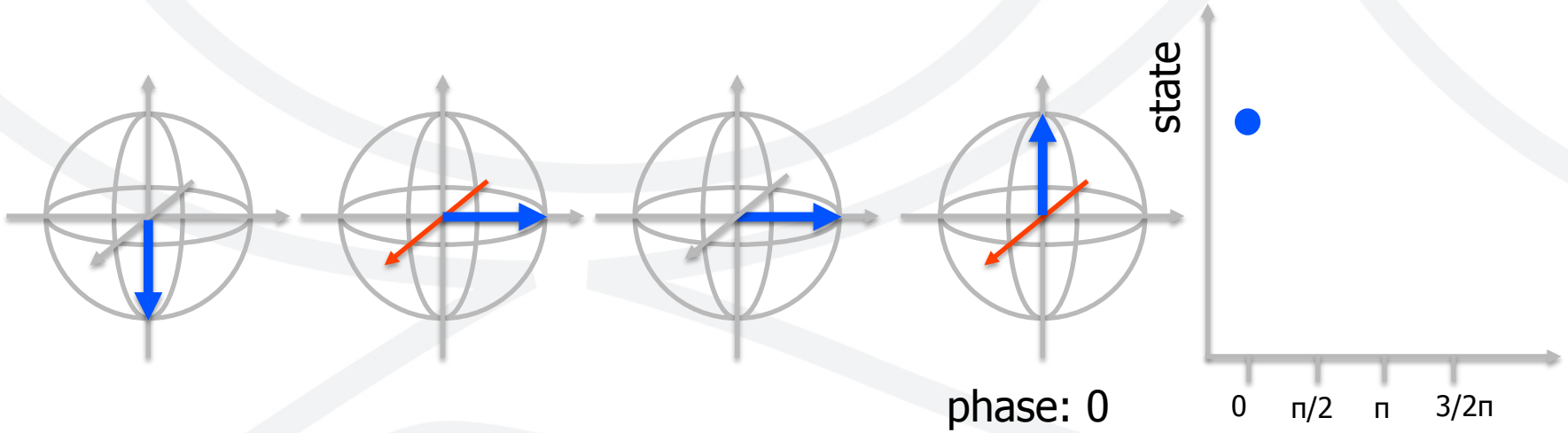
1. Qubit resonances shifted individually
2. Spin-Spin coupling between individual qubits

$$-\frac{\hbar}{2}\sum_{i<j}^{N}\sigma_{z,i}\sigma_{z,j}J_{ij}$$

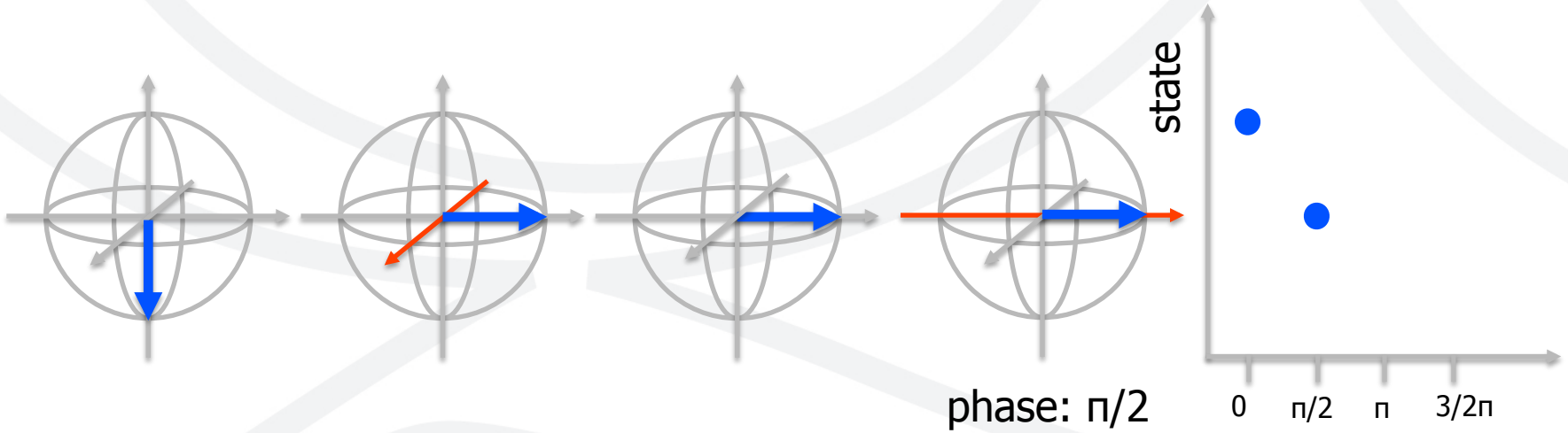


Interlude: Ramsey-type measurements

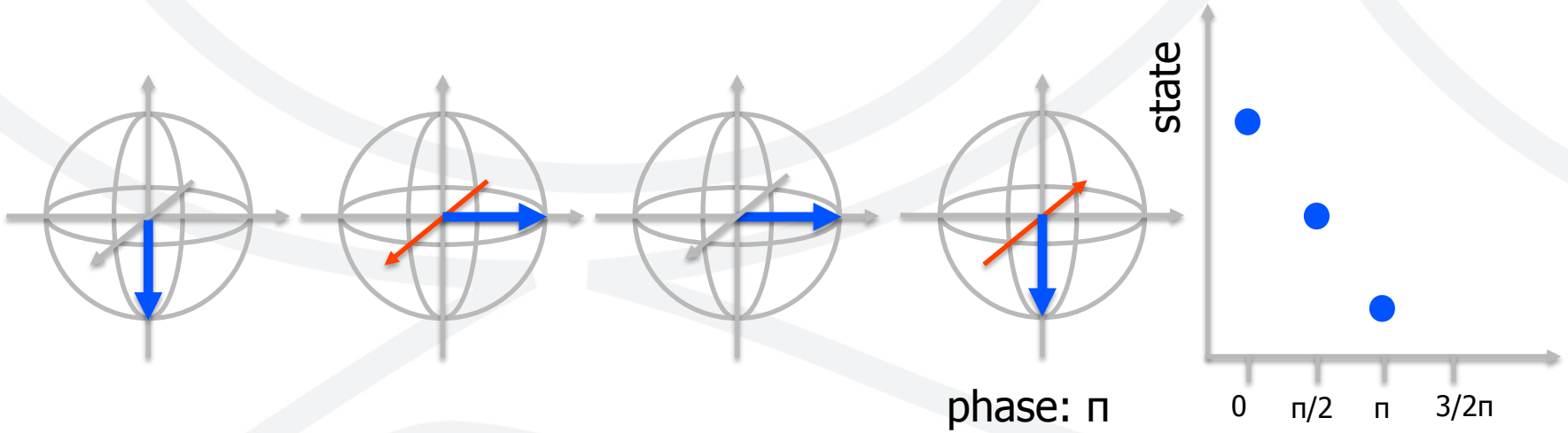
Ramsey measurement



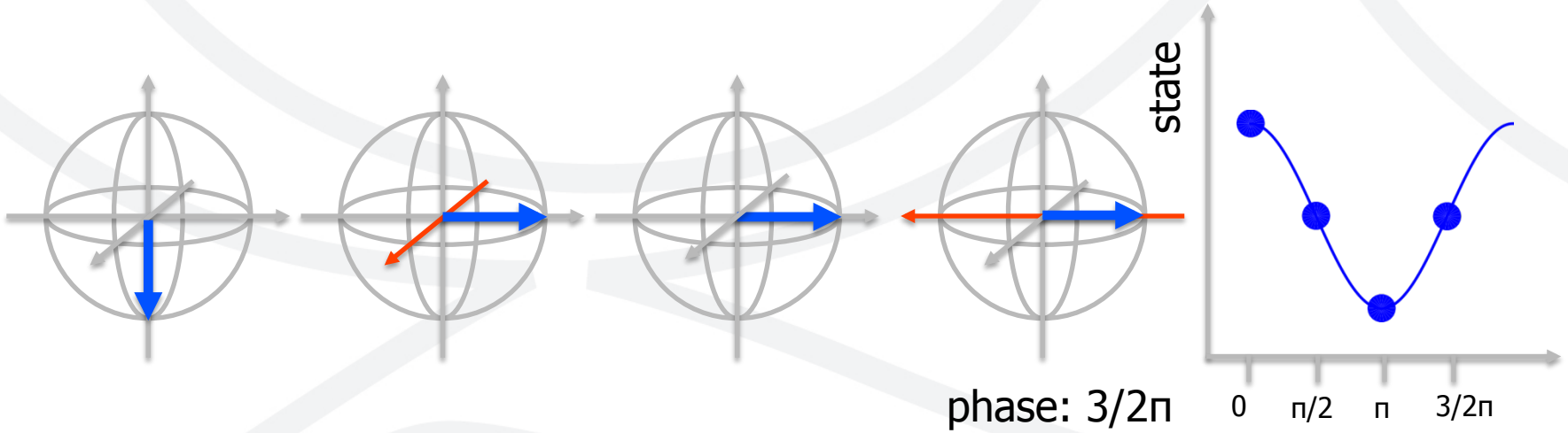
Ramsey measurement



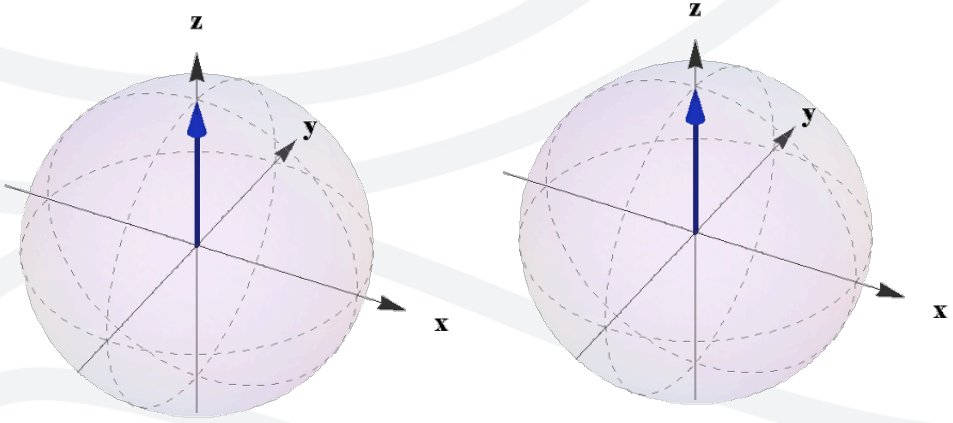
Ramsey measurement

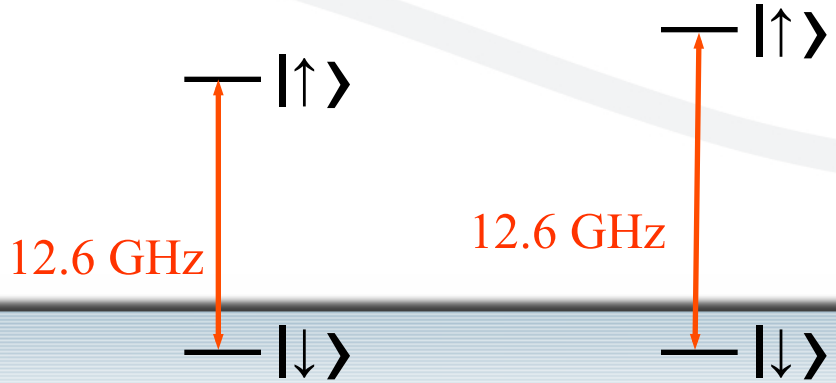


Ramsey measurement



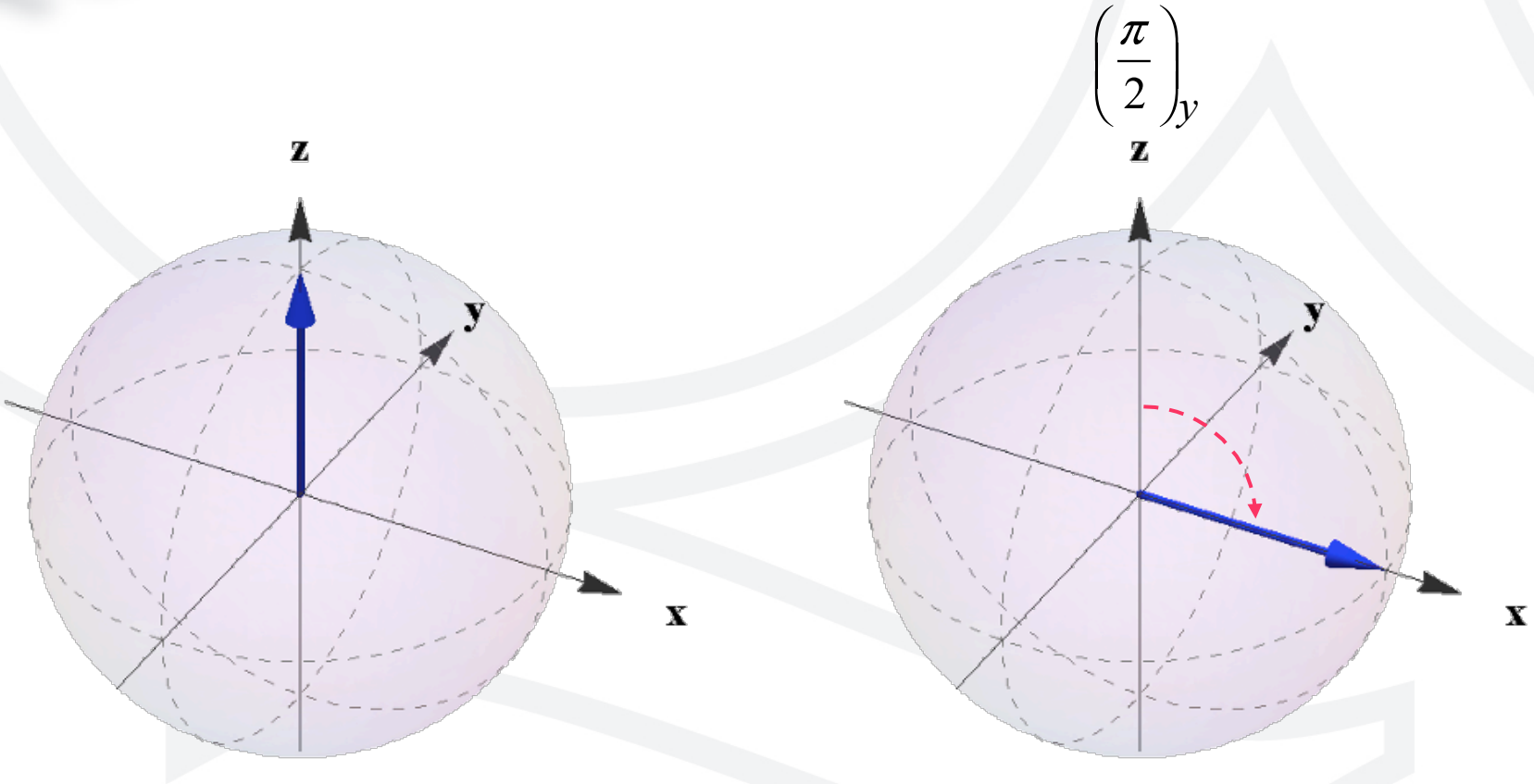
Interlude: Quantum Gates using J-coupling


z
y
x
z
y
x


|↑⟩
12.6 GHz
|↓⟩
|↑⟩
12.6 GHz
|↓⟩

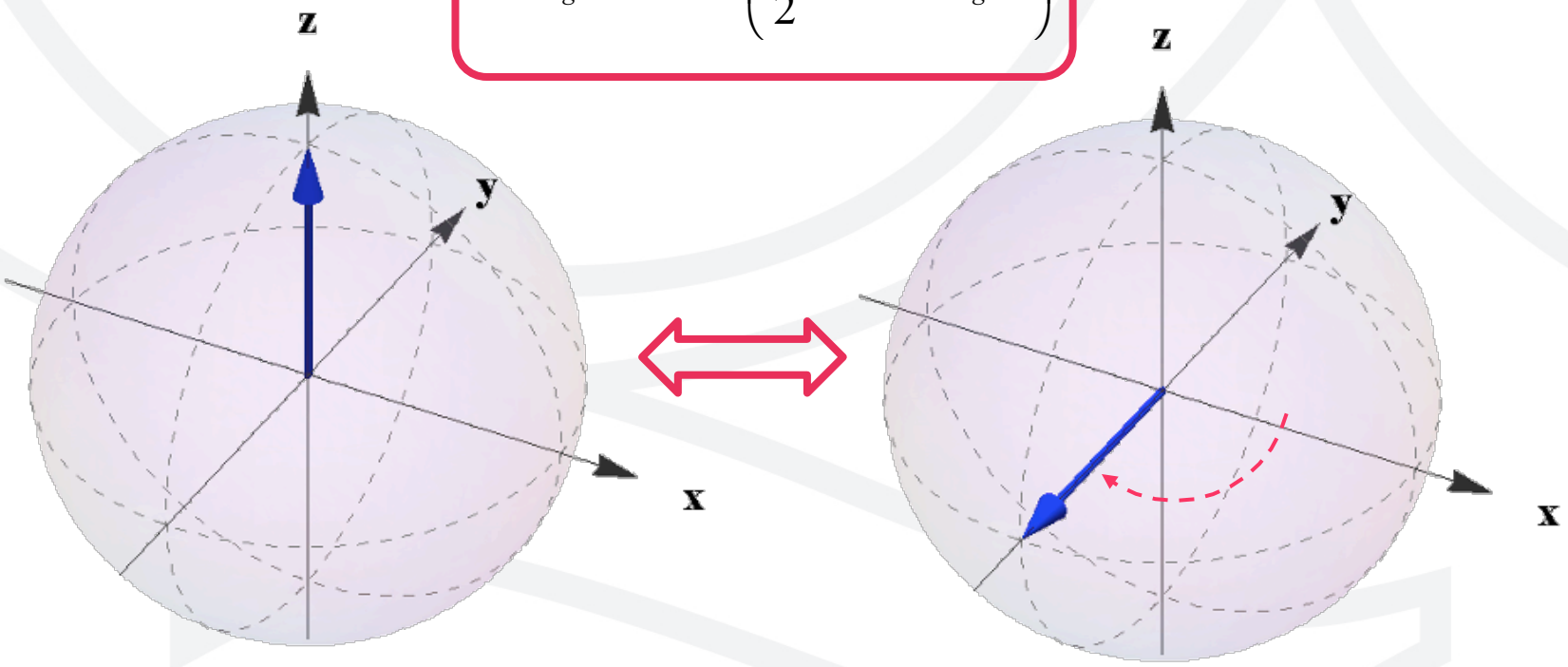
J-type coupling – CNOT Gate

Schematic



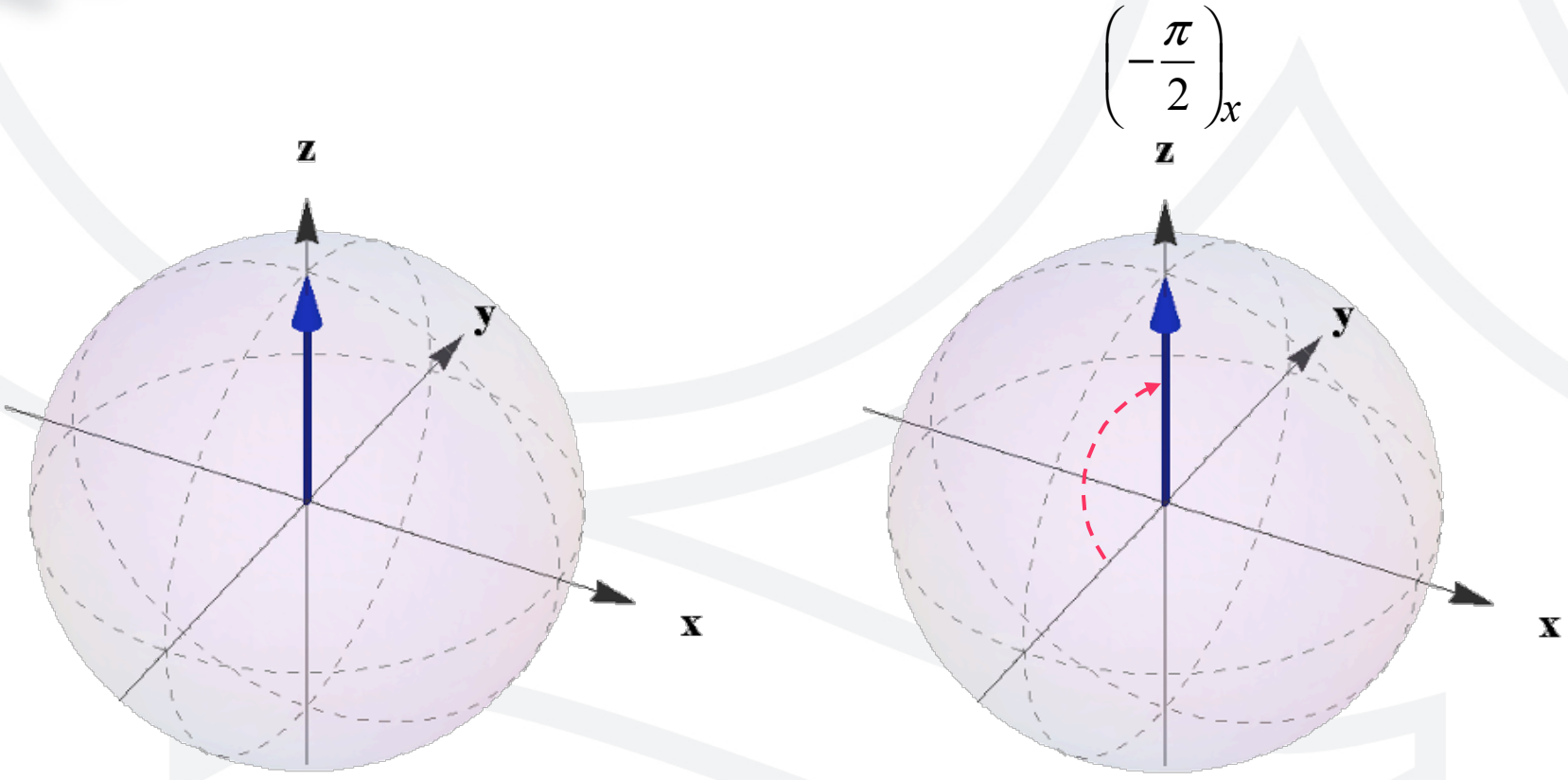
J-type coupling – CNOT Gate
Schematic

$$U(\tau_{gate}) = \exp\left(\frac{i}{2} J_{12} \sigma_1^z \sigma_2^z \tau_{gate}\right)$$



$$J_{12} \cdot \tau_{gate} = \frac{\pi}{2}$$

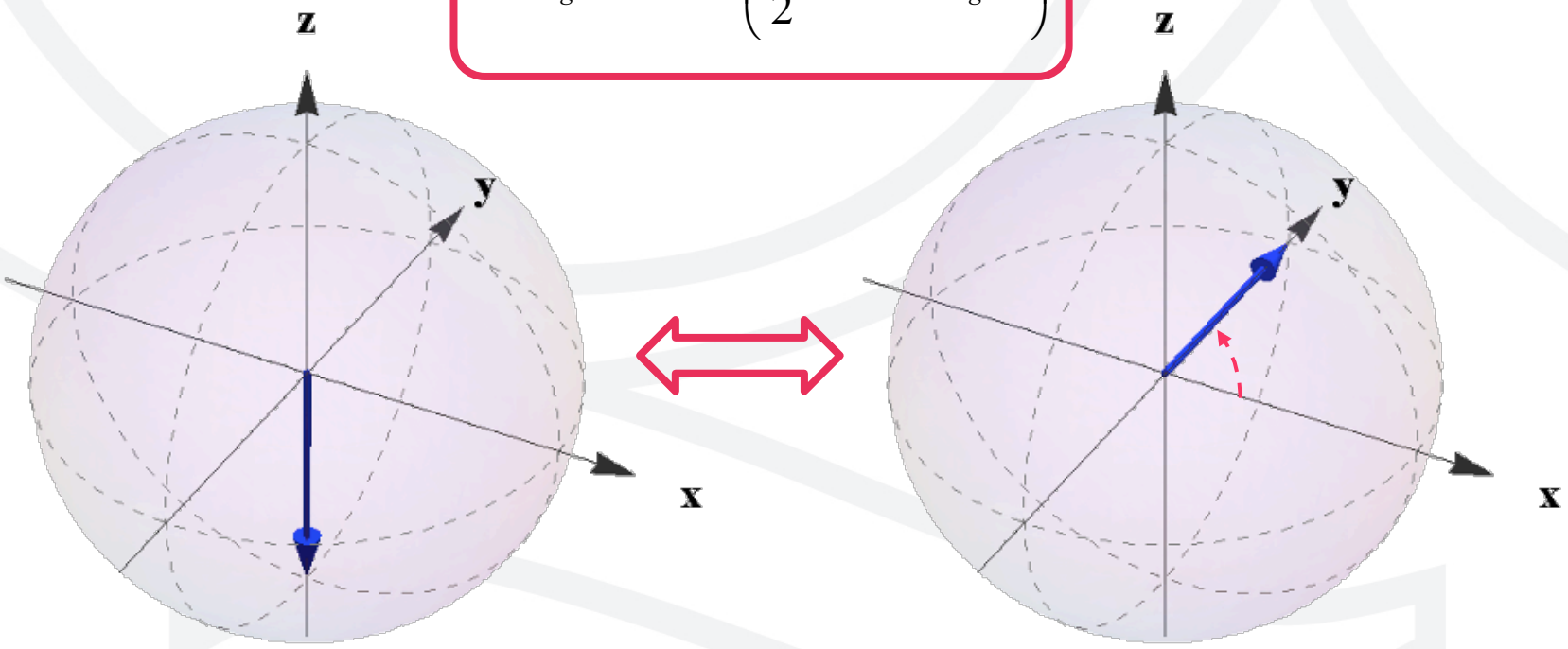
J-type coupling – CNOT Gate
Schematic



$$|\uparrow\uparrow\rangle \xrightarrow{CNOT} |\uparrow\uparrow\rangle$$

J-type coupling – CNOT Gate
Schematic

$$U(\tau_{gate}) = \exp\left(\frac{i}{2} J_{12} \sigma_1^z \sigma_2^z \tau_{gate}\right)$$



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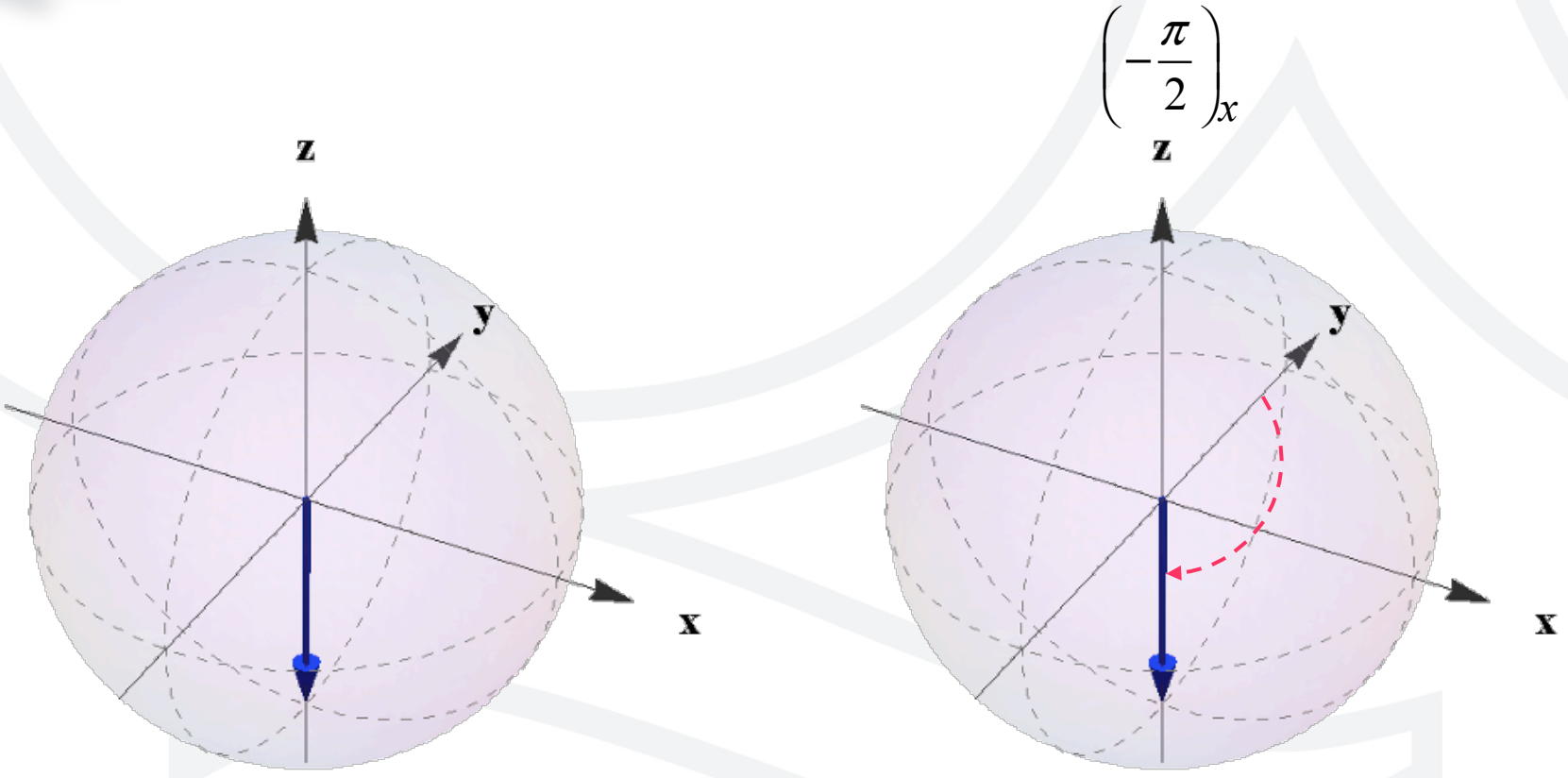
J-type coupling – CNOT Gate

Schematic



$$|\downarrow\uparrow\rangle \xrightarrow{CNOT} |\downarrow\downarrow\rangle$$

- RF (MW) for all coherent operations
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  - Adjust Magnitude
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  - On and Off
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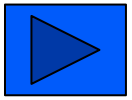
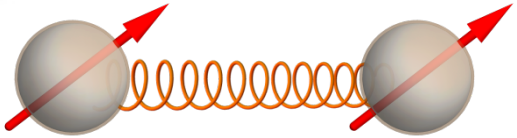
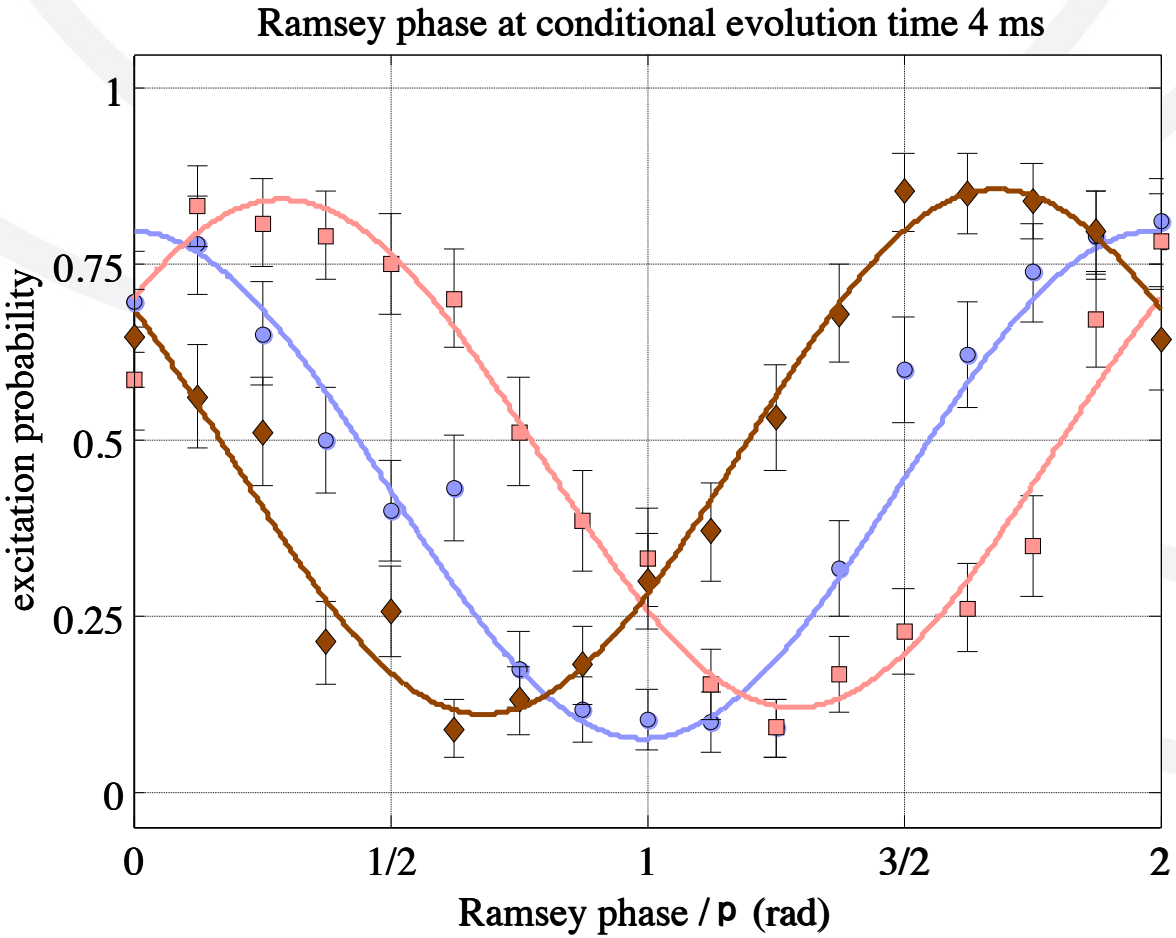
MAGIC QUANTUM TOOLBOX



Measuring MAGIC



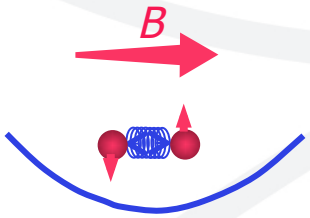


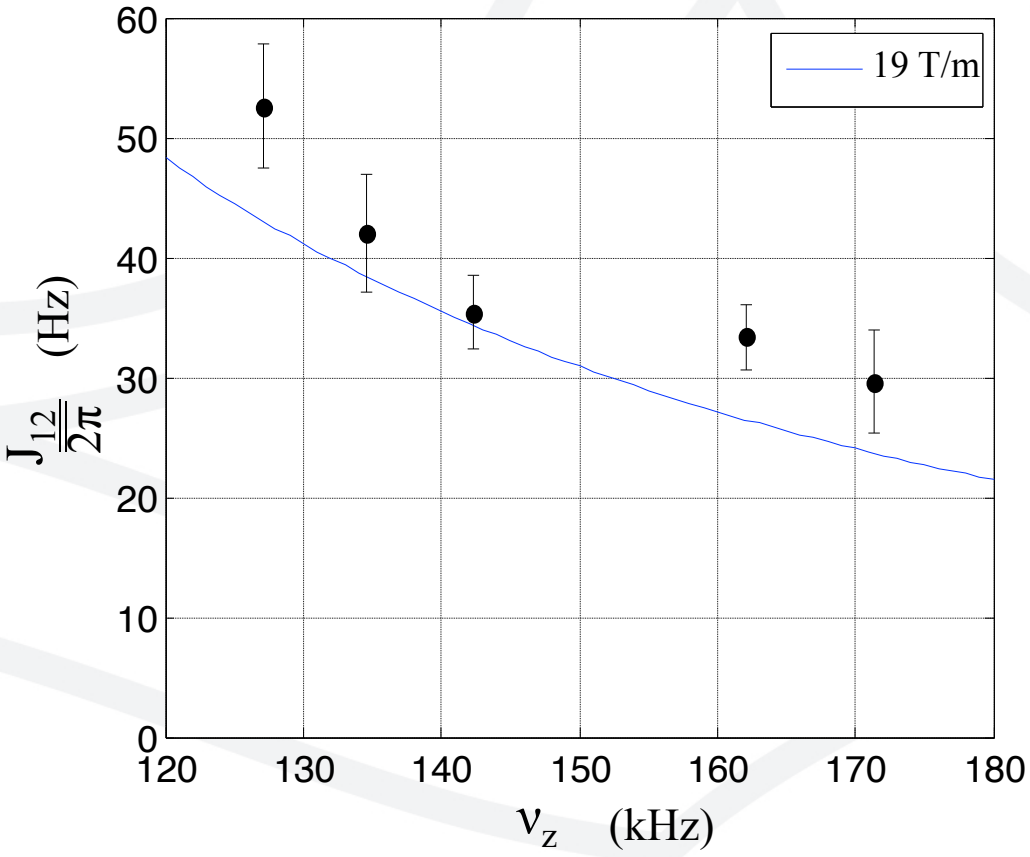
$$J_{ij} = \frac{\Delta\phi_{ij}}{2\tau}$$

PRL **108**, 220502 (2012)
Science Advances **2** (2016)

Magnitude of MAGIC
Variation of trapping potential

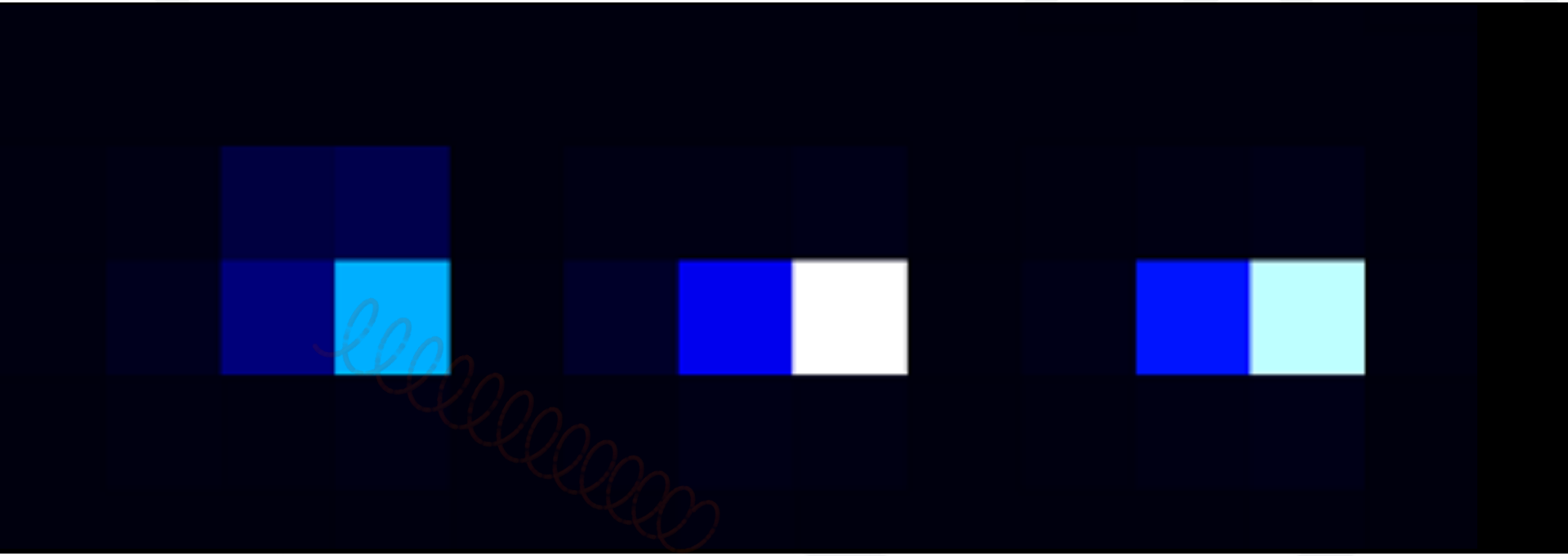
$$J \propto \left(\frac{\partial_z B}{\nu_z} \right)^2$$





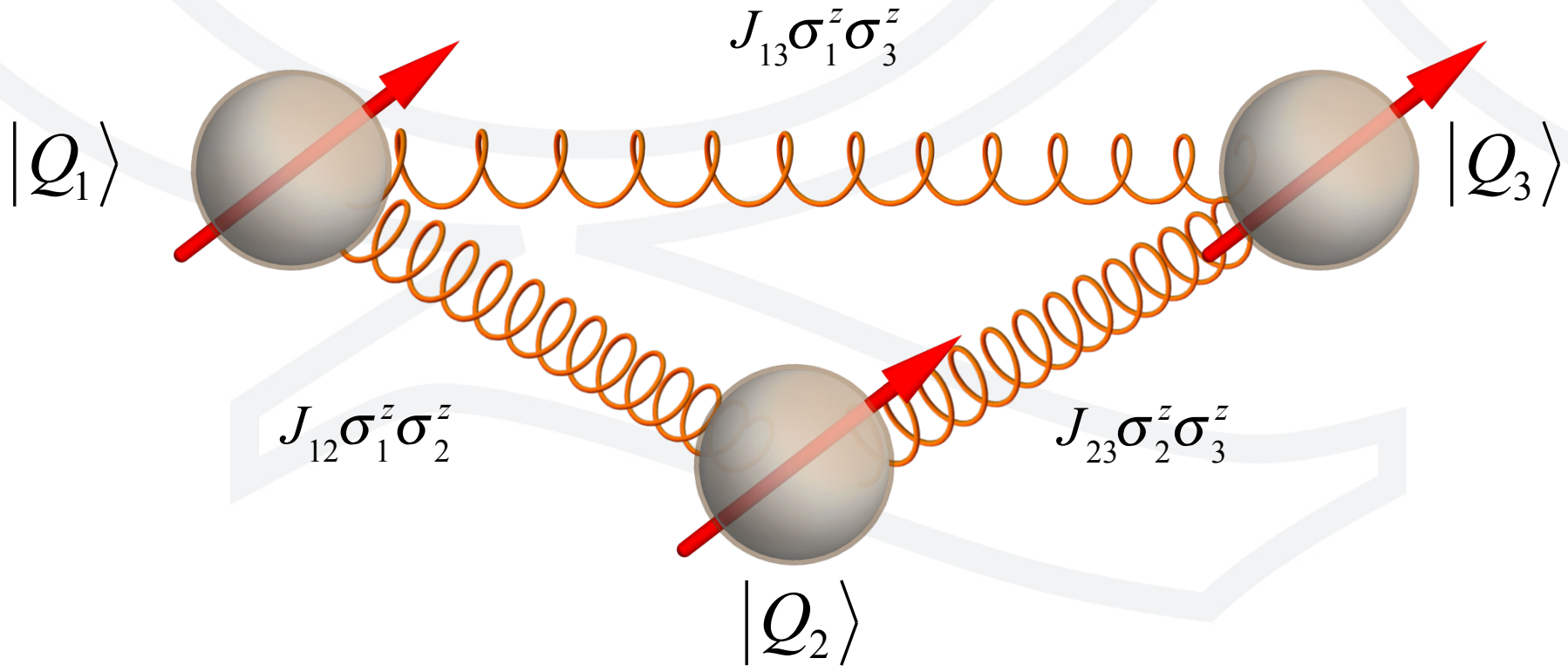
PRL **108**, 220502 (2012)

MAGIC: Spin-Spin Interaction

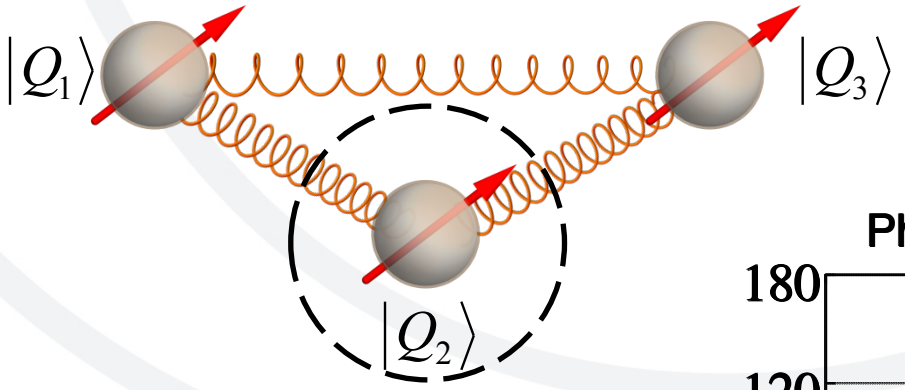


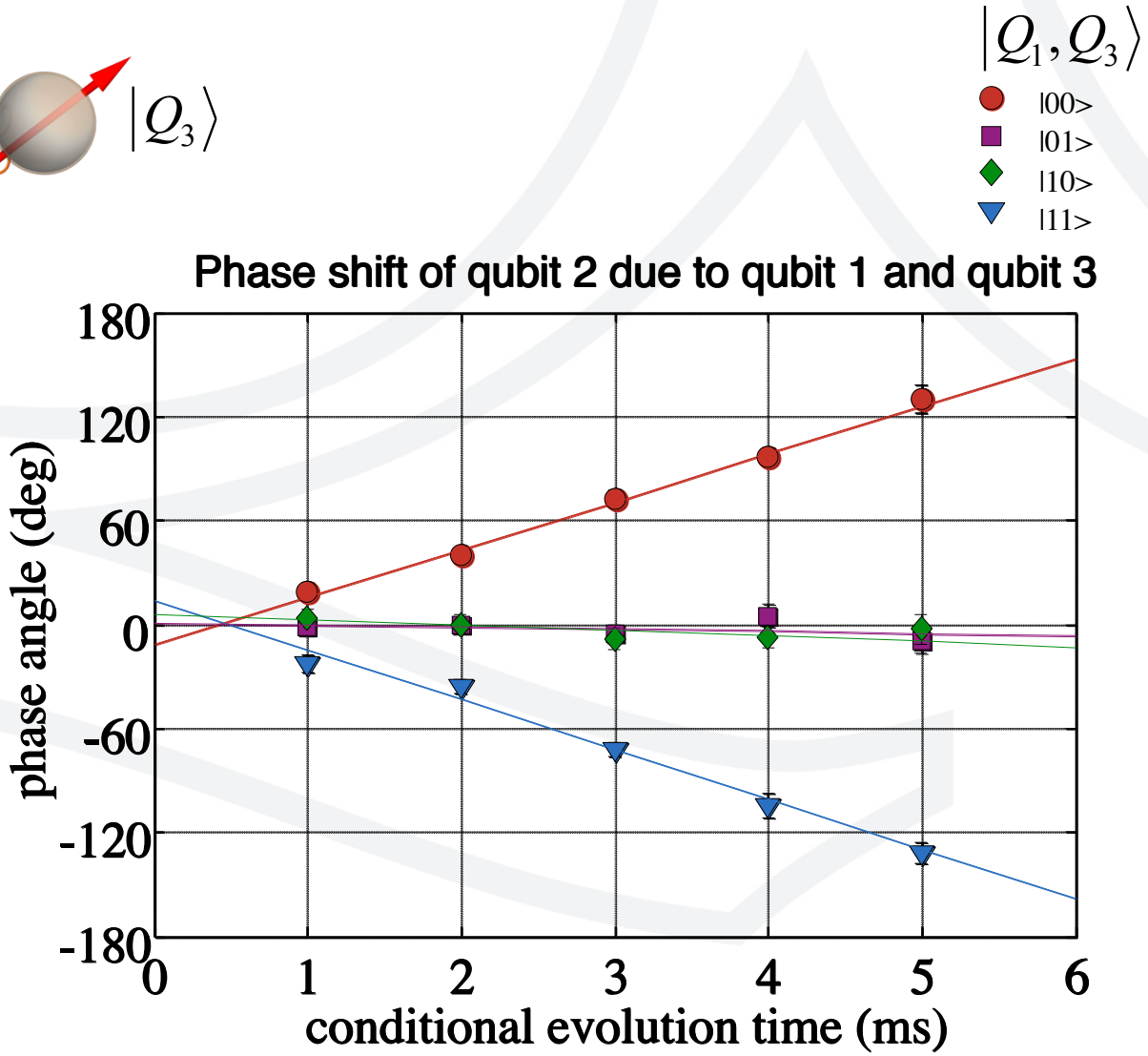
$|Q_1\rangle$ $|Q_2\rangle$ $|Q_3\rangle$

MAGIC: Spin-Spin Interaction



Simultaneous Coupling

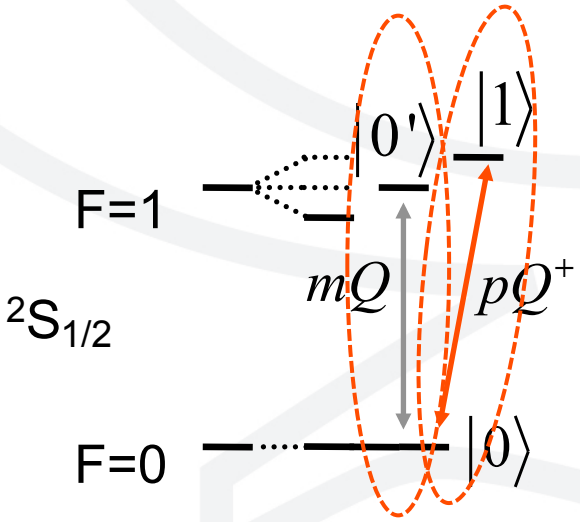


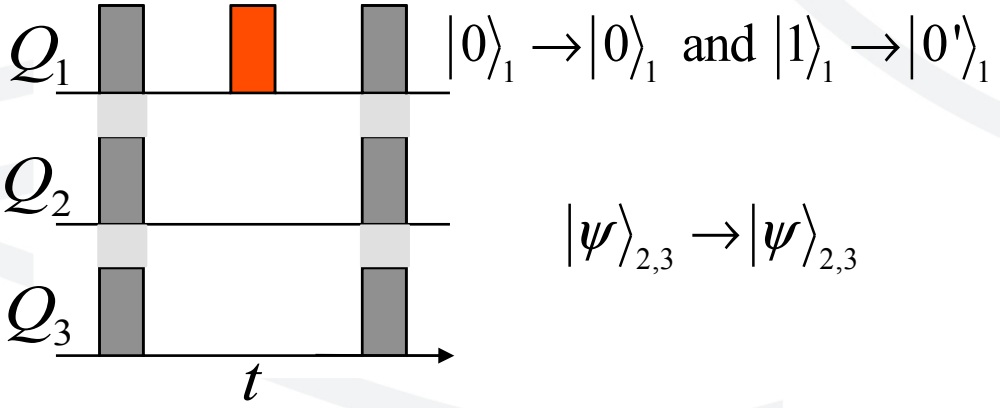


Science Advances **2** (2016)

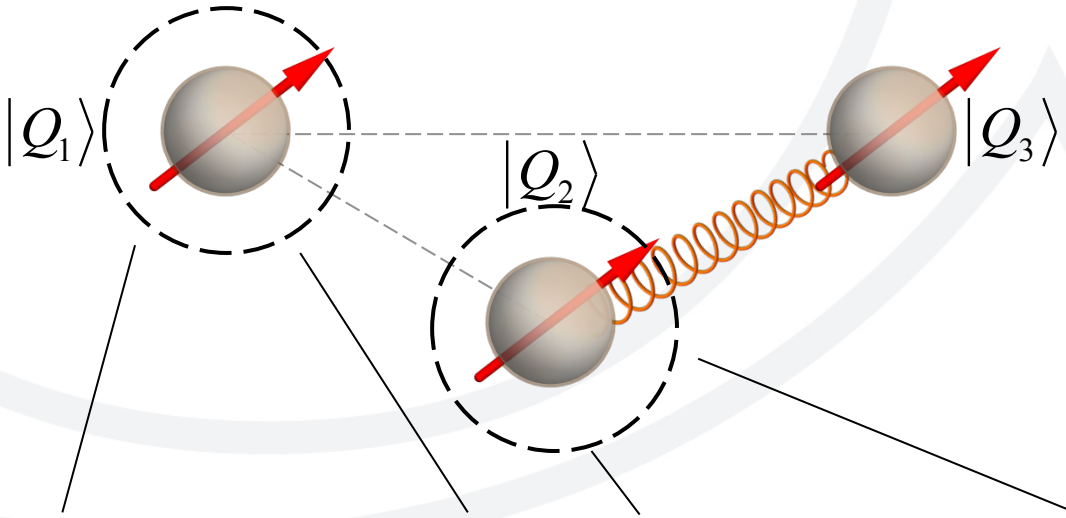
Turn coupling off

Recoding





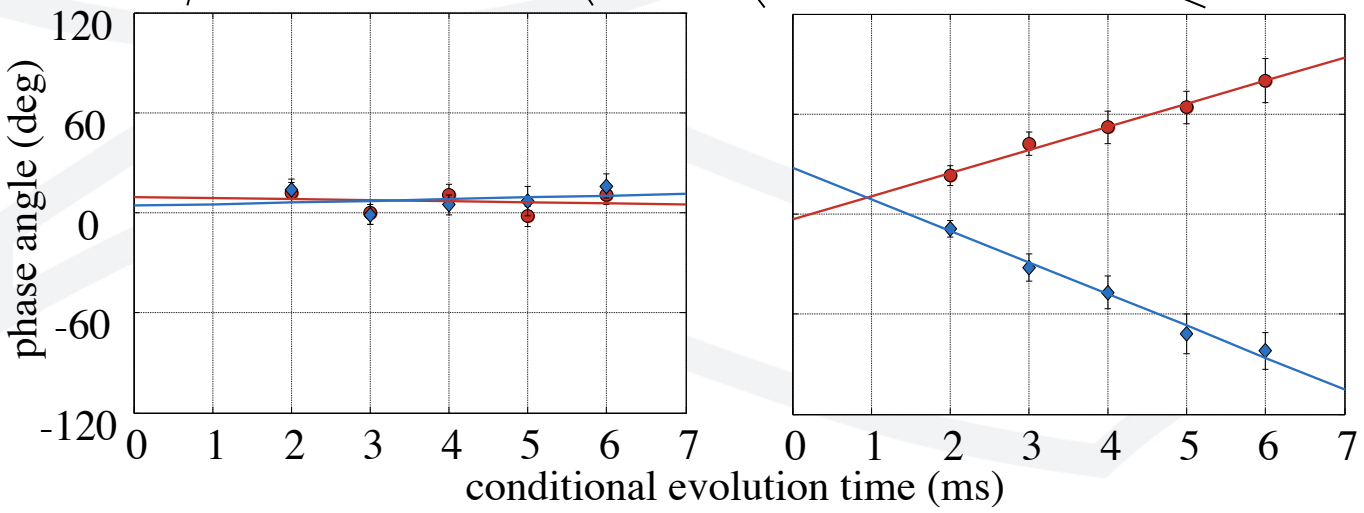
Qubit 1: Isolation by Recoding



Q_3 :

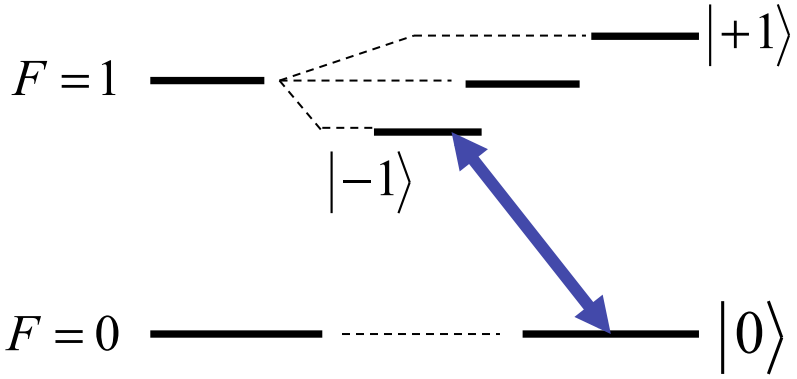
$|0\rangle$

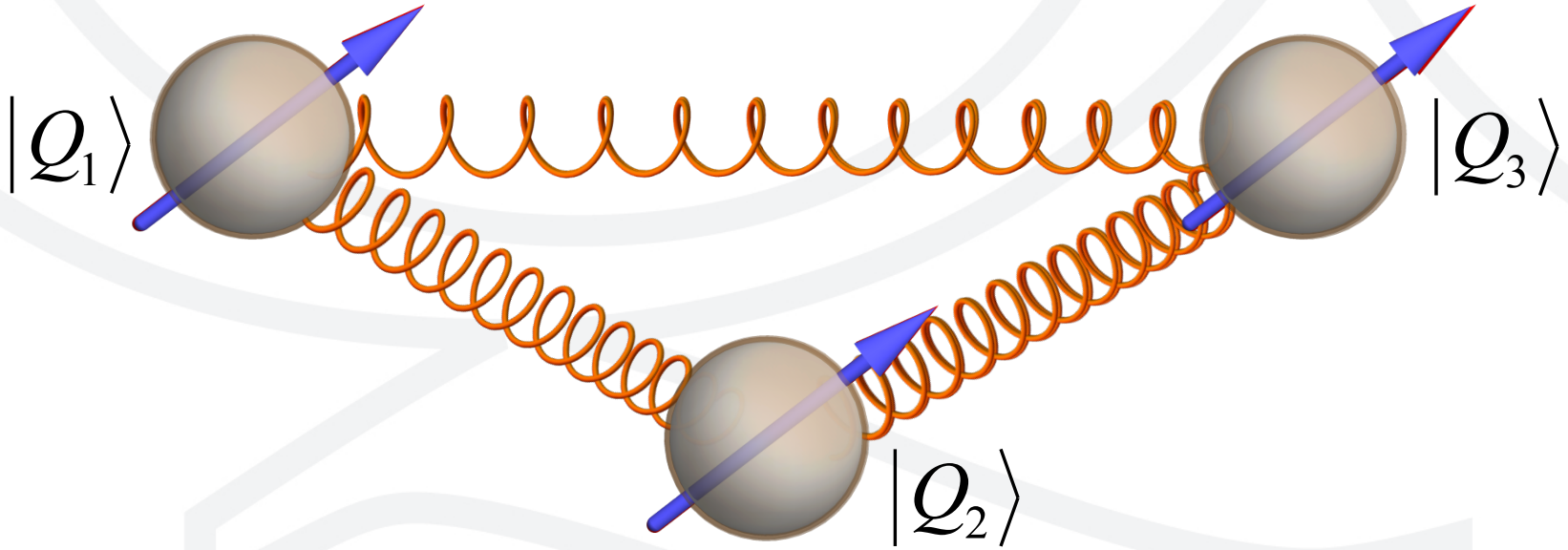
$|1\rangle$



Science Advances **2** (2016)

Sign of Coupling

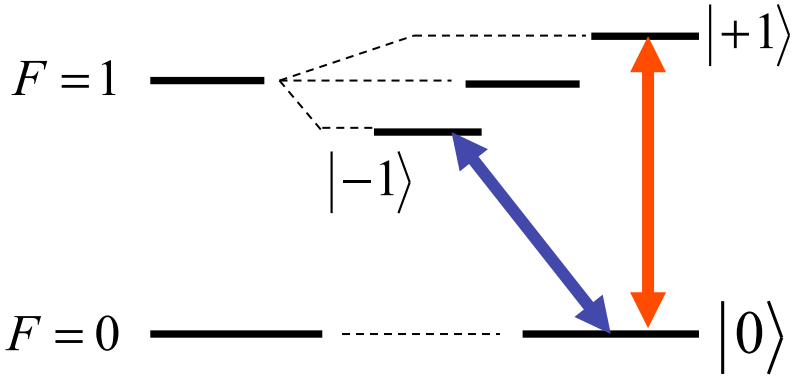


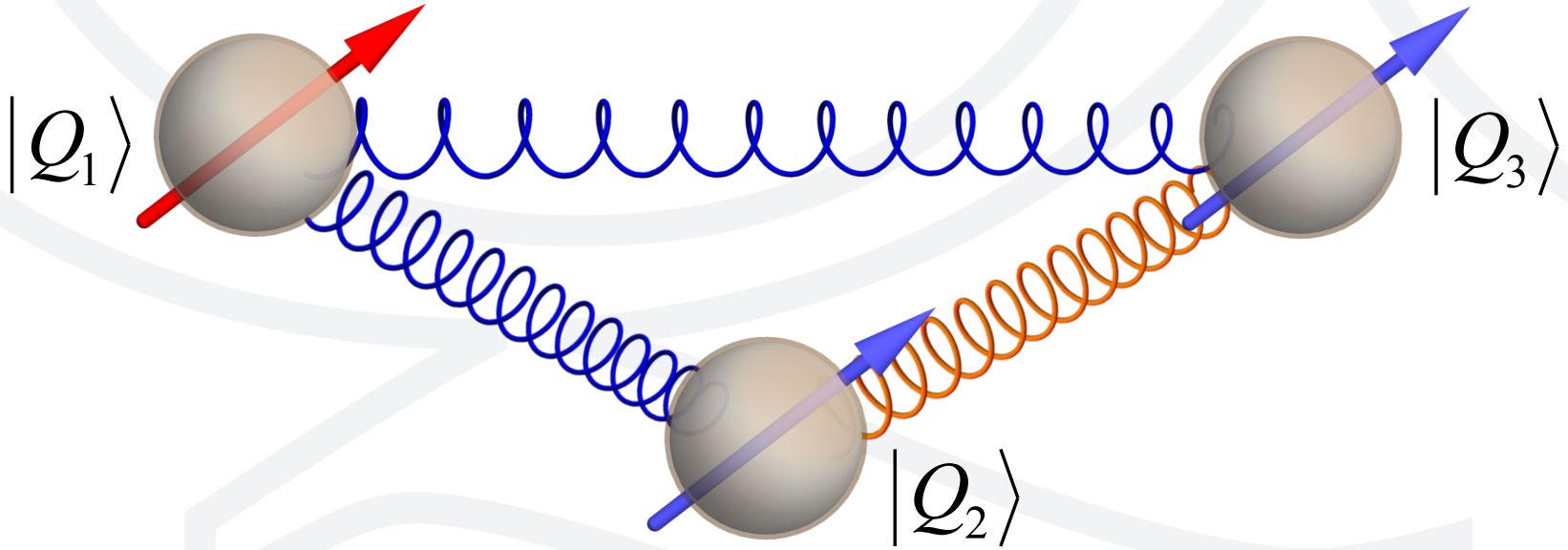


$$\frac{J_{ij}}{2\pi} = \begin{bmatrix} & 34(7) & 27(7) \\ 34(7) & & 39(7) \\ 27(7) & 39(7) & \end{bmatrix} \text{Hz}$$

Science Advances **2** (2016)

Sign of Coupling





$$\frac{J_{ij}}{2\pi} = \begin{bmatrix} & -39(5) & -27(5) \\ -39(5) & & 34(7) \\ -27(5) & 34(7) & \end{bmatrix} \text{Hz}$$

Science Advances **2** (2016)

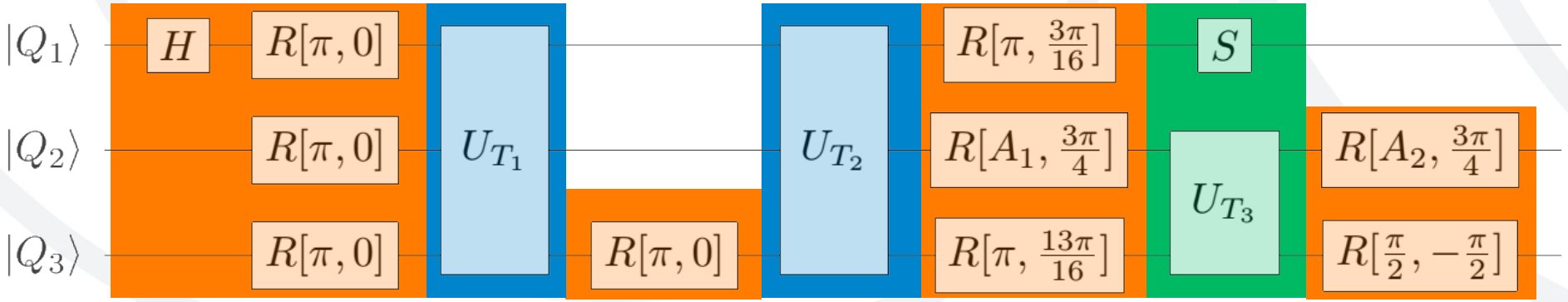
- RF (MW) for all coherent operations
- Individual Addressing

- Spin-Spin Coupling:
  - Adjust Magnitude
  - Simultaneous
  - On and Off
  - Change Sign

Microwave pulses change coupling topology ($2\pi/\Omega_{Rabi}$)

MAGIC QUANTUM TOOLBOX

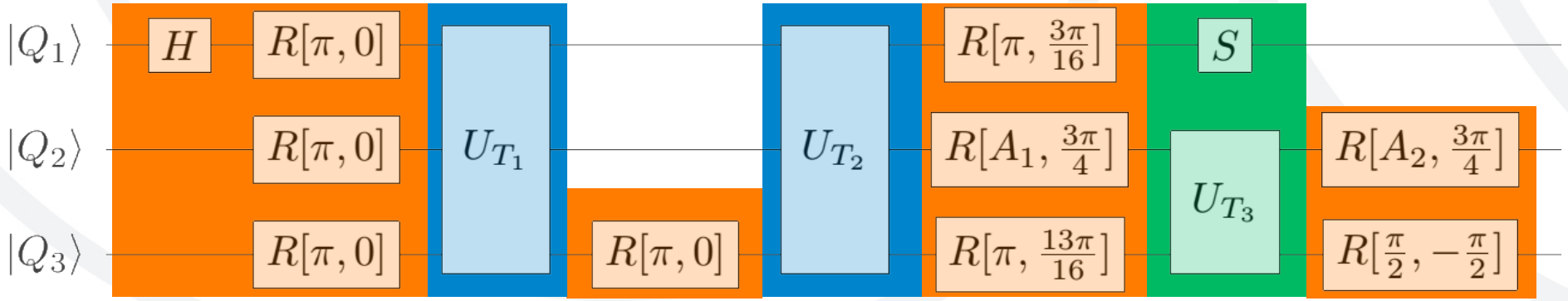
Coherent QFT Using Multiple Coupling



- single-qubit gates: rotations and Hadamard gate
- conditional dynamics: all mutual couplings
- conditional dynamics: selected coupling

Science Advances **2** (2016)

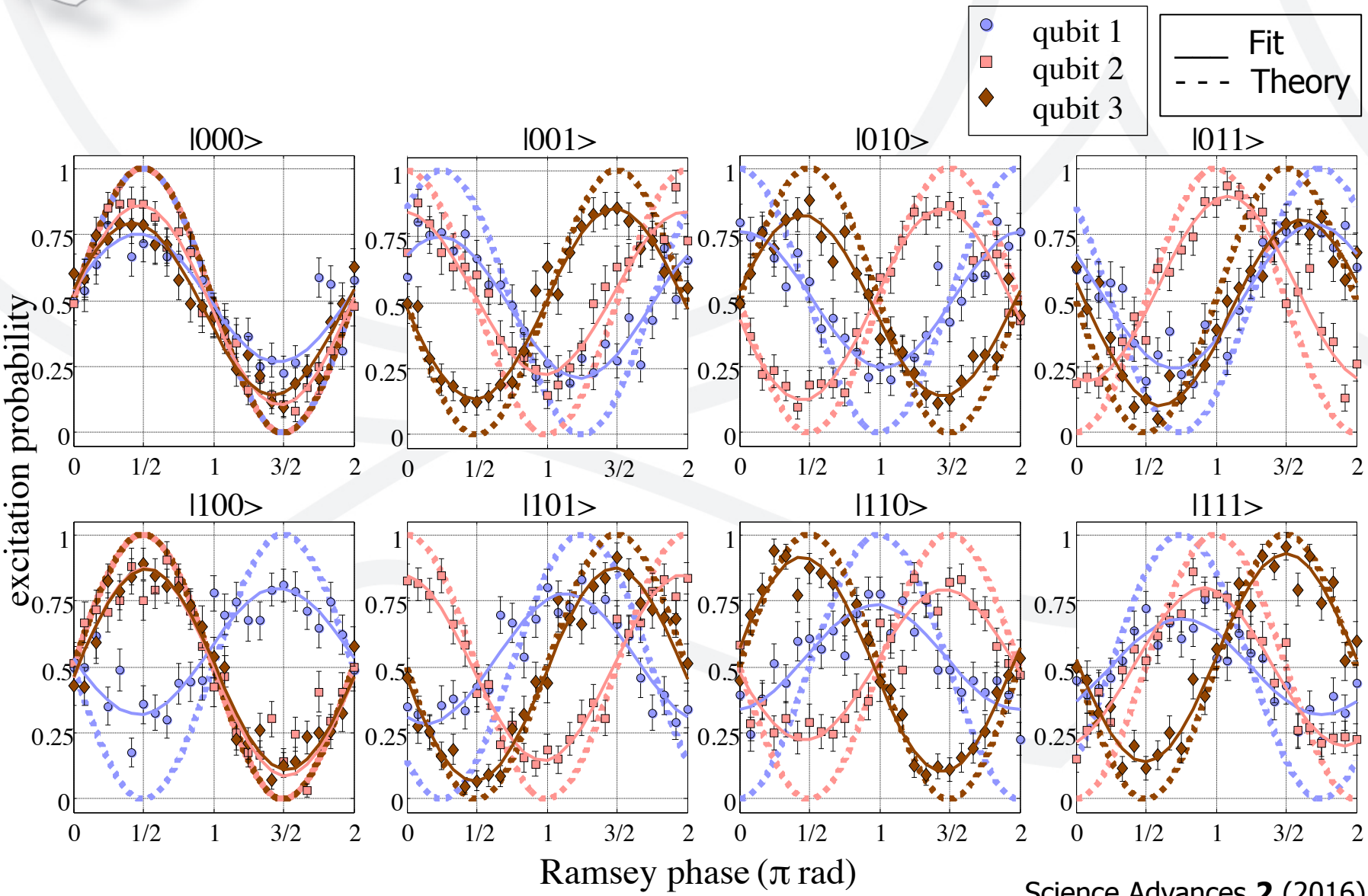
Coherent QFT Using Multiple Coupling



- Total time 8.6 ms ≈ one CNOT gate

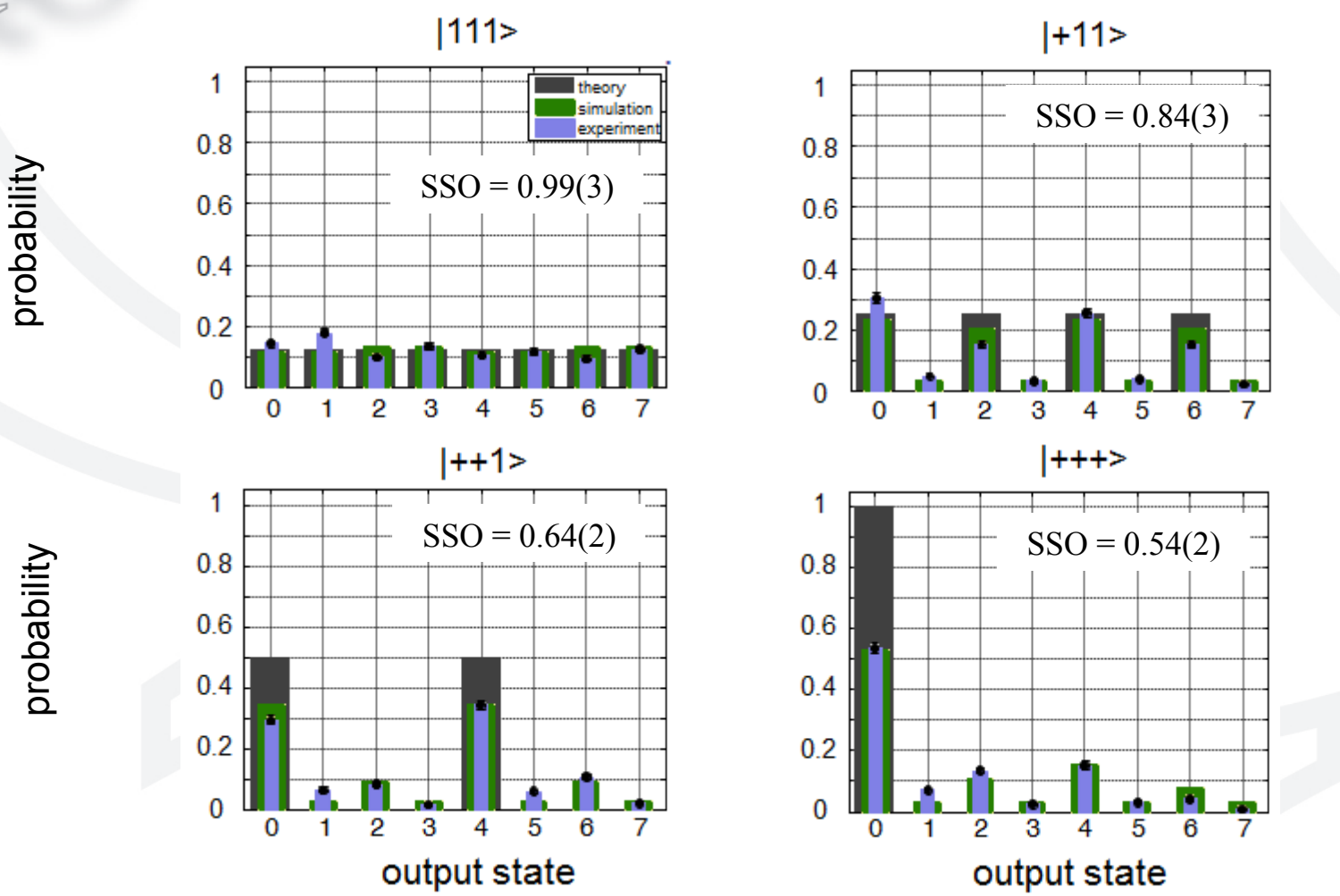
Science Advances **2** (2016)

Coherent QFT: Experiment



Science Advances **2** (2016)

Coherent QFT: Period Finding



$$S(p,q) = \left(\sum_i \sqrt{p_i q_i}\right)^2$$

Science Advances **2** (2016)

See also:

J. Chiaverini *et al., Science* **308** (2005)

P. Schindler *et al., New. J. Phys.* **15** (2013)

MAGIC using Dressed State Gates

Nature **476**, 185 (2011)

University of Sussex (W. Hensinger):

S. C. Webster et al. PRL **111** (2013)
I. Cohen et al., NJP **17** (2015)
J. Randall et al., PRA **91** (2015)

High-Fidelity 2-Qubit Gate:
S. Weidt et al., PRL **117** (2016)

Dynamic Magnetic Field Gradient

$$B(t,z) = B_0(z)\ \cos(\omega t)$$

Dynamic Gradient <-> Static Gradient:
New J. Phys. **19** (2017)

Theory and Experiments:

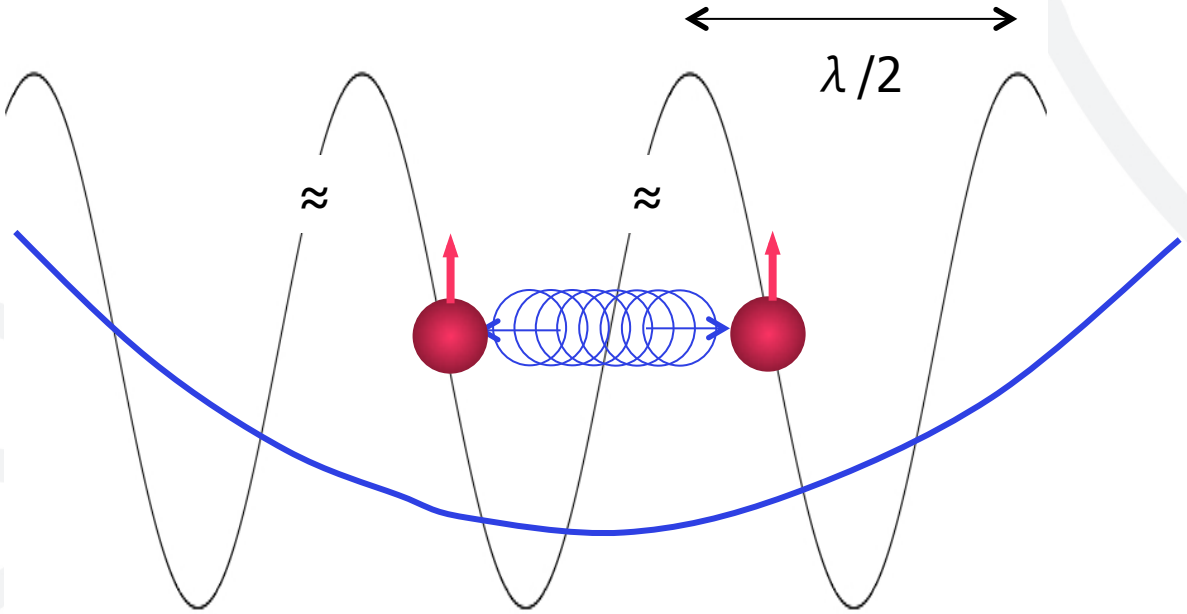
NIST, Boulder (D. Wineland):
Ospelkaus et al., PRL **101** (2008).
Ospelkaus et al., Nature **476** (2011).

University of Oxford (D. Lucas):
Aude Craik et al., Appl. Phys. B **114** (2014).

High-Fidelity 2-Qubit Gate:
Harty et al., PRL **117** (2016)

Leibniz University Hannover (Ch. Ospelkaus):
M. Carsjens et al., Appl. Phys. B **114** (2014)

Optical Dipole Force: Spin-Spin Interaction

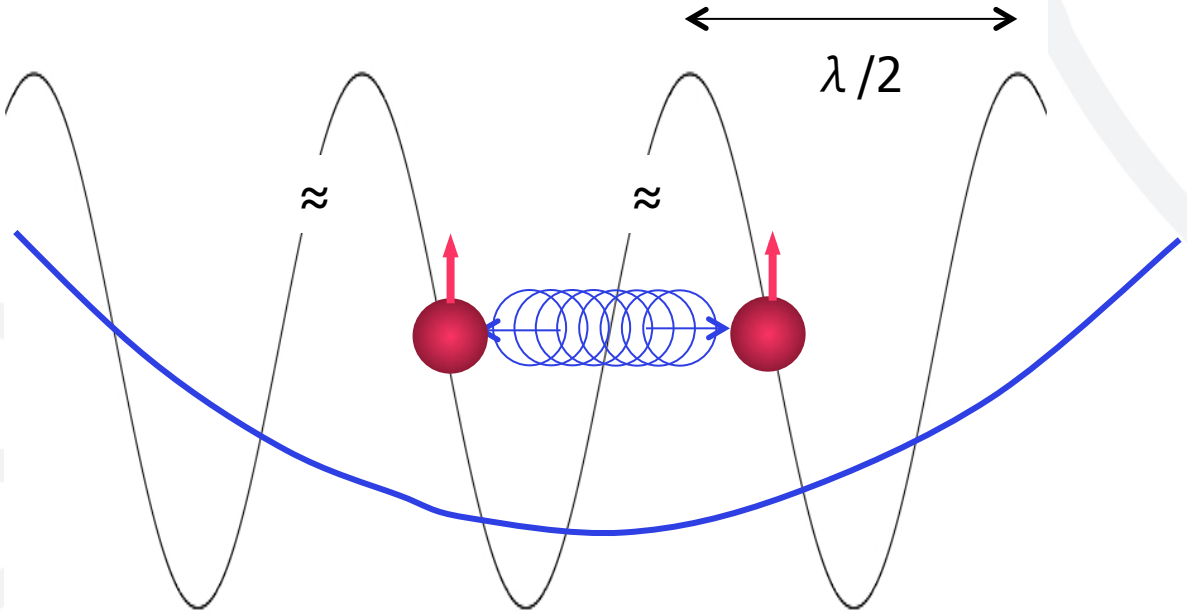


$$\text{Spin flip} \Rightarrow d_z = \mp F_z / (m\nu^2)$$

$$\hbar J_{12} = -F_z d_z = -F_z^2 / (m\nu^2)$$

D. Porras and I. Cirac PRL **92** (2004)

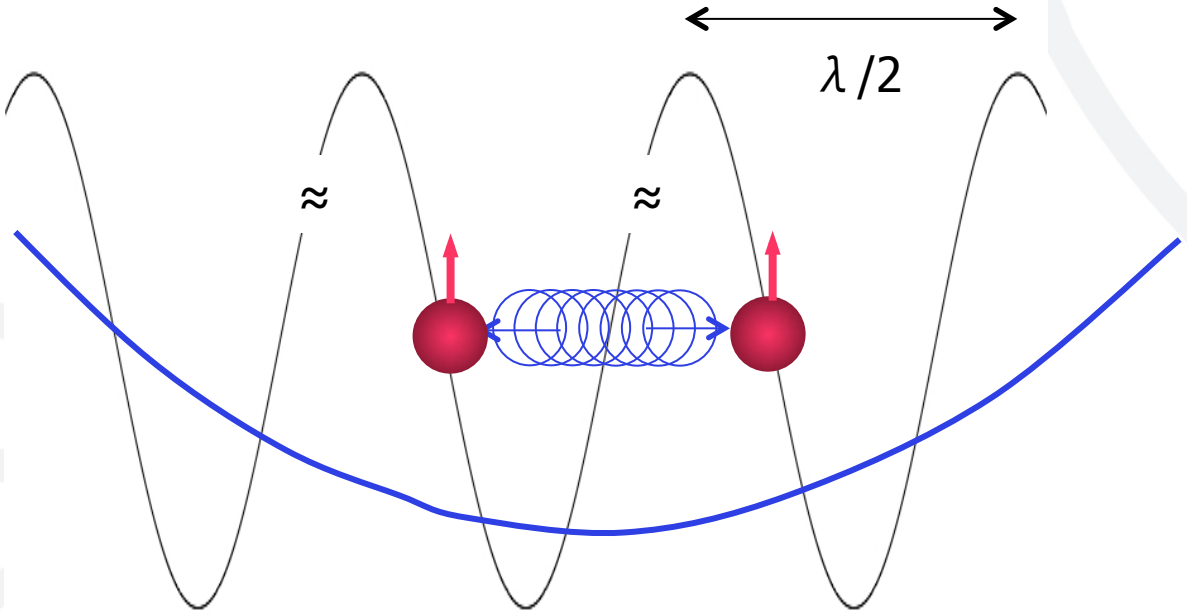
Optical Dipole Force: Spin-Spin Interaction



Standing wave: static force

D. Porras and I. Cirac PRL **92** (2004)

Optical Dipole Force: Spin-Spin Interaction



Two waves with relative detuning ω_{Opt}:

$$F_0 \cos(\omega_{Opt} t)\, q_n \sigma_n^z$$

D. Porras and I. Cirac PRL **92** (2004)

Optical Spin-Spin Interaction

$$\vdots$$

$$\ldots - F_0 \cos\left(\omega_{Opt}\right) \sum_{n=1}^{N} q_n \sigma_n^z$$

$$\vdots$$

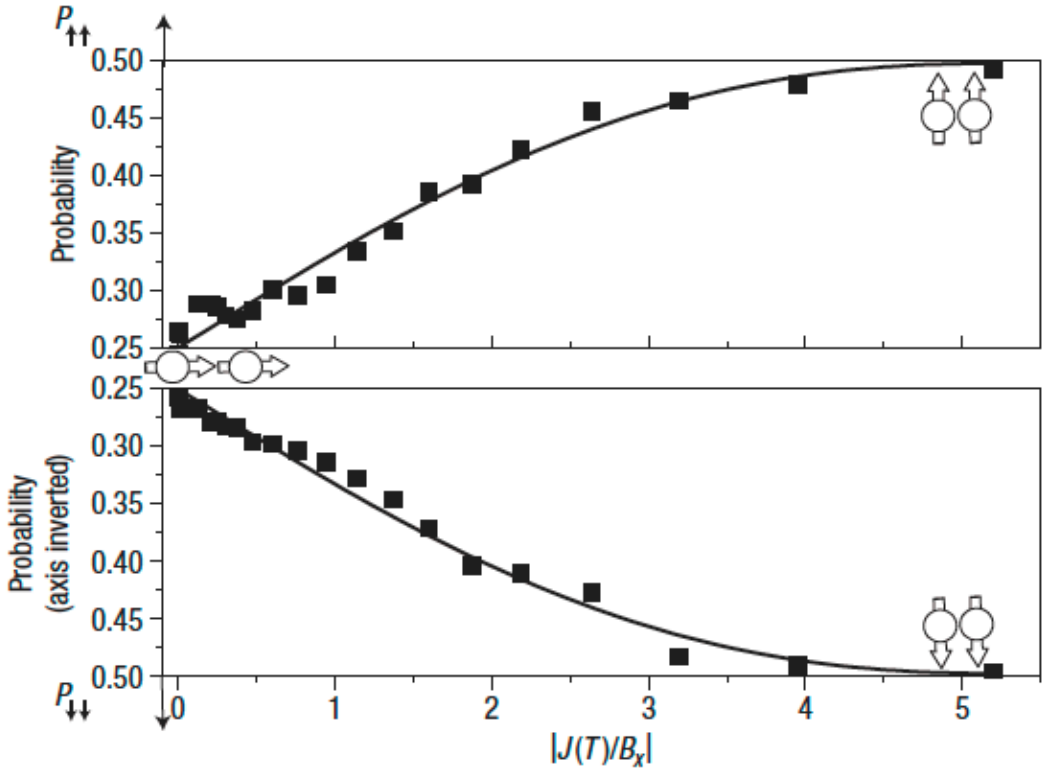
$$\Rightarrow \text{Coupling} \propto \sum_{i<j}^{N} J_{i,j} \sigma_i^z \sigma_j^z$$

$$\text{with} \quad J_{ij} \propto \sum_n \frac{S_{i,n} S_{j,n}}{\omega_{Opt}^2 - \omega_n^2}$$

$$\text{under the condition} \quad \left|\omega_{Opt} - \omega_n\right| \ll \eta_{i,n} \Omega_i$$

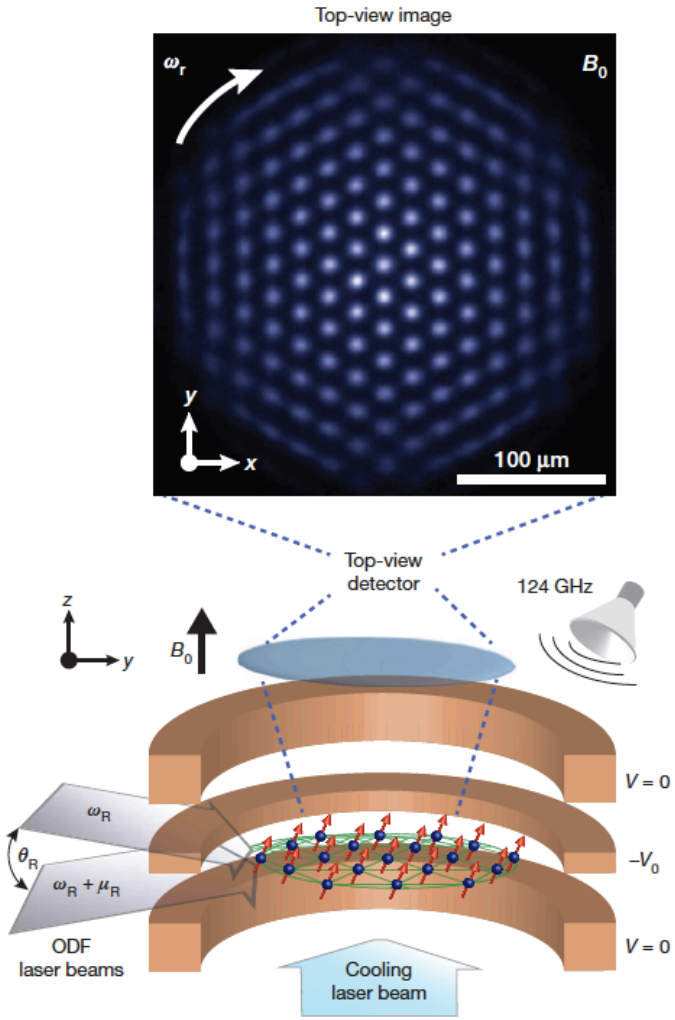
Optical Spin-Spin Interaction

$$-B_x \sum_i^N \sigma_i^x + J \sum_{i<j}^N \sigma_i^z \sigma_j^z$$



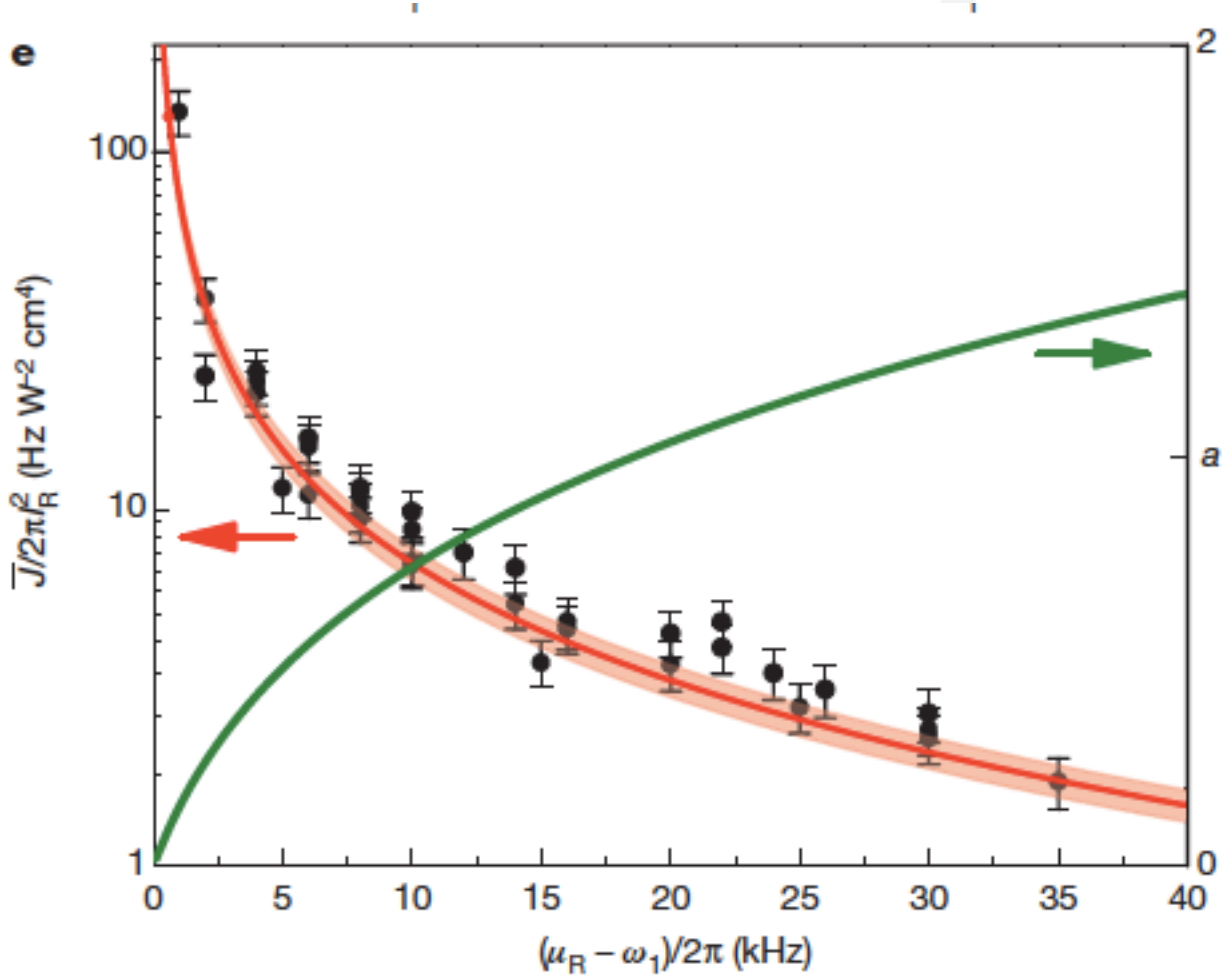
A. Friedenauer et al., Nat. Phys. **4** (2008).

Optical Spin-Spin Interaction



J. W. Britton et al., Nature **484** (2012).

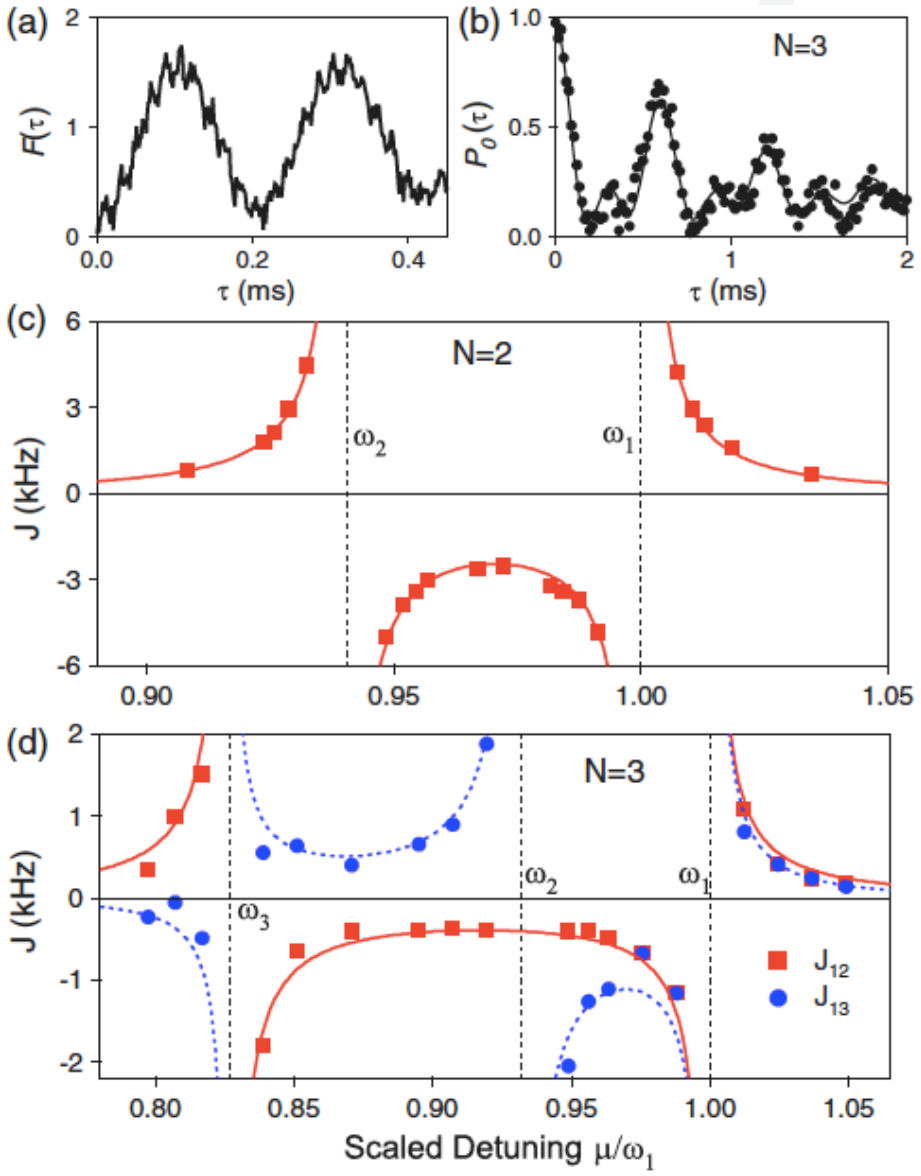
Optical Spin-Spin Interaction



J. W. Britton et al., Nature **484** (2012).

Optical Spin-Spin Interaction

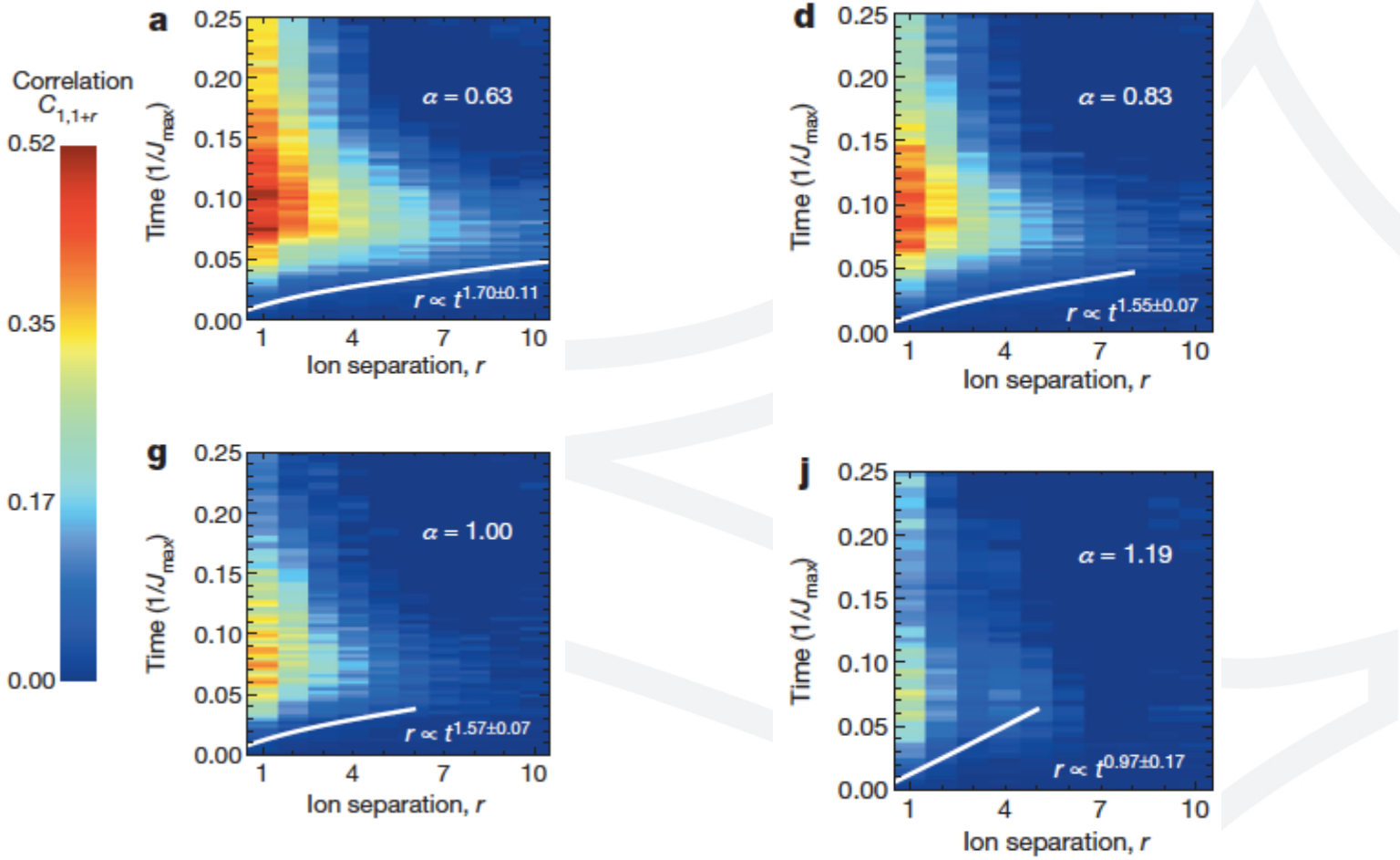
Bichromatic force
Transverse modes



K. Kim et al., PRL **103** (2009).

Optical Spin-Spin Interaction

Entanglement Propagation after Global Quench



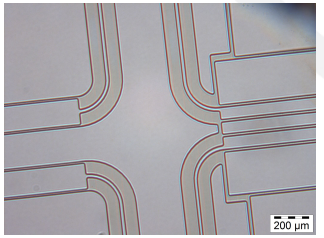
P. Richerme et al., Nature **511** (2014).

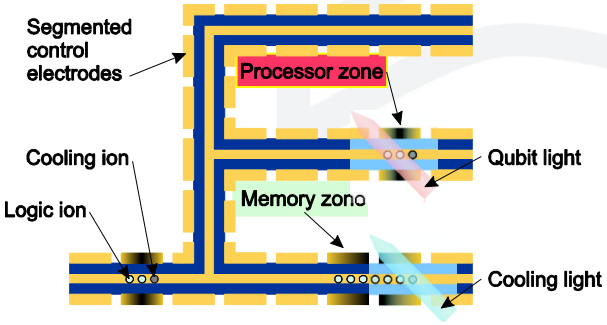
Trapped Atomic Ions in QIS

- High Fidelity Single- and Multi-Qubit Gates
- Programmable Small-Scale Quantum Computer
- Quantum Simulations using Spins and Phonons

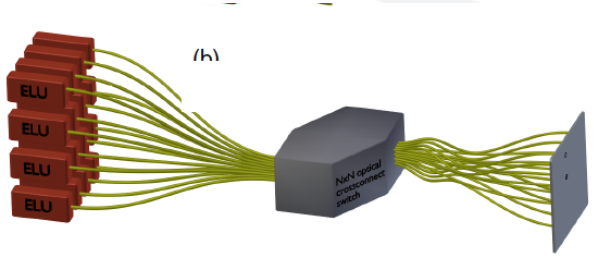
Outlook:

- Integrated Micro-Structured 2-D Trap Arrays
- Scalable Quantum Computer

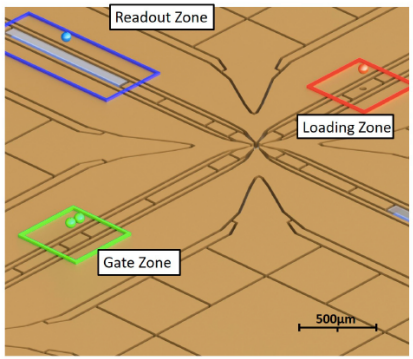




J. Chiaverini et al.,
Quant. Inf. Comput. **5**, 419 (2005).



C. Monroe et al.,
PRA **89**, 022317 (2014)



B. Lekitsch et al.,
Science Advances **3** (2017)