Elements for scalable quantum information science with trapped ions

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Bundesministerium für Bildung und Forschung

Deutsche Forschungsgemeinschaft DFG

iQIT

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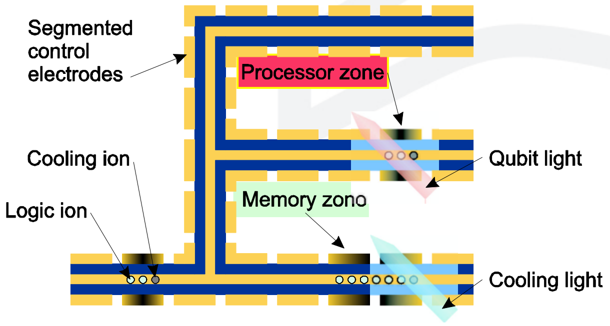
Trapped Atomic Ions in QIS

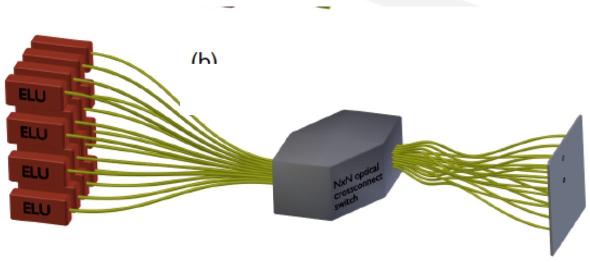
- High Fidelity Preparation, Quantum Gates, Read-out
- Programmable Small-Scale Quantum Computer
- Quantum Simulations using Spins and Phonons

Perspective:

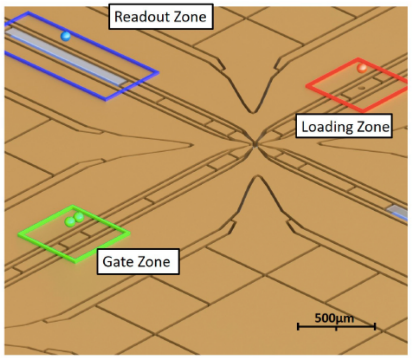
- Integrated Micro-Structured 2-D Trap Arrays
- Scalable Quantum Computer



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)

ANOMALOUS HEATING

SHUTTLING OF IONS

MAGIC: QUANTUM TOOLBOX

UNIVERSITÄT SIEGEN

ANOMOULOS HEATING

Ivan Boldin, Alexander Kraft

Anomalous Heating

- Heating of harmonic motion of trapped ion:
  A major source of decoherence

$$\Gamma_{\mathrm{h}} \simeq \frac{e^2}{4 m_{\mathrm{I}} \hbar \omega_{\mathrm{t}}} S_E(\omega_{\mathrm{t}}).$$

$$S_E(\omega) = 2 \int_{-\infty}^{\infty} \mathrm{d}\tau \langle \delta E_{\mathrm{t}}(\tau) \delta E_{\mathrm{t}}(0) \rangle \mathrm{e}^{-\mathrm{i}\omega\tau}$$

- Micro-structuring advantageous for scaling up
- Important open question: dependence on ion-surface distance

M. Brownnutt, M. Kumph, P. Rabl, R. Blatt, Rev. Mod. Phys. **87** (2015)

Anomalous Heating

- Sources for δE_t:
  - Blackbody Radiation
  - Direct EM Interference
  - EM Pickup
  - Johnson Noise
  - Technical Noise
  - Space Charge
  - Patch Potentials …

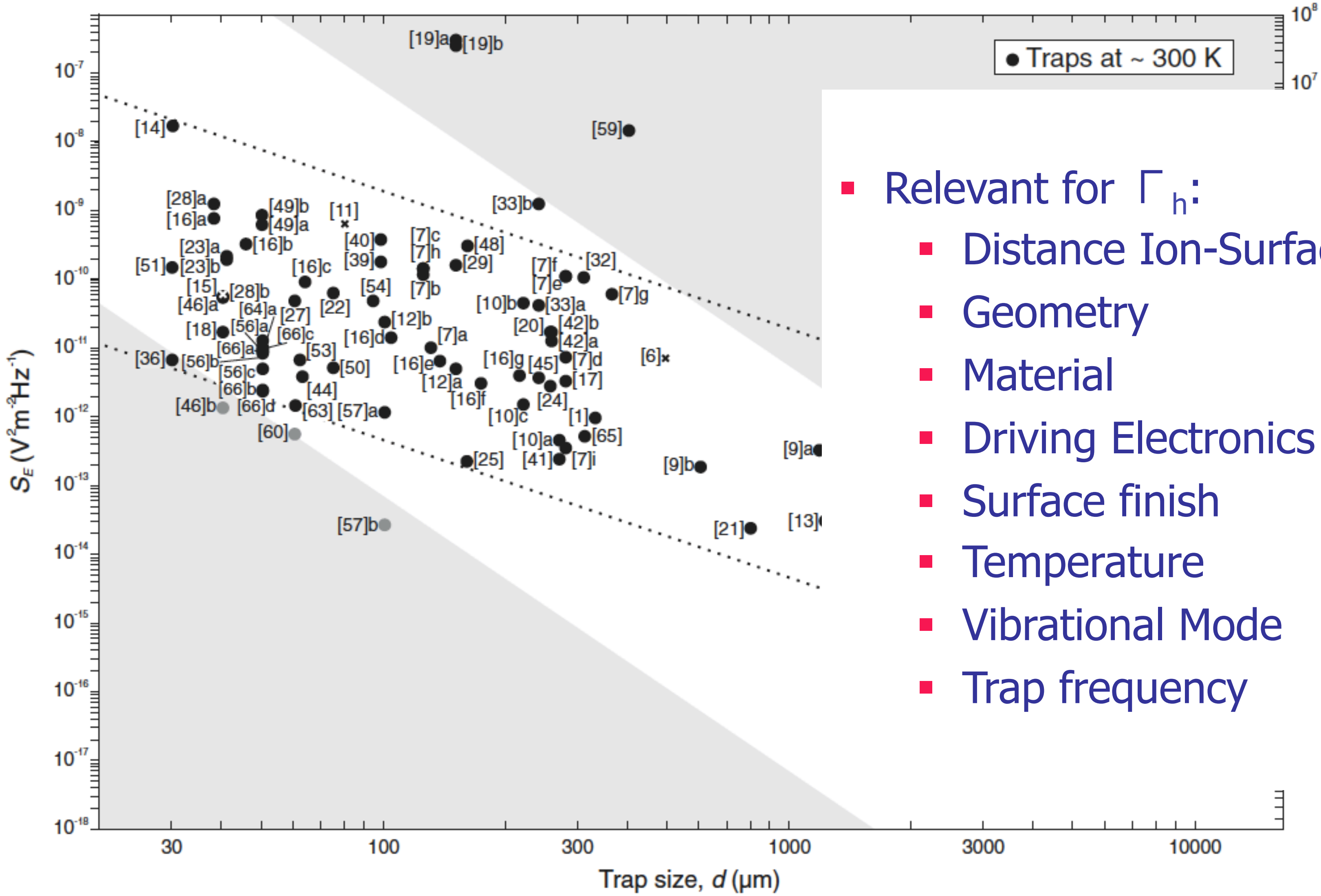
Anomalous Heating

$$\boxed{S_E \propto \omega^{-\alpha} d^{-\beta} T^{\gamma}}$$

- Sources for δE_t:
  - Blackbody Radiation
  - Direct EM Interference $\beta = 0$
  - EM Pickup $\beta = 2$
  - Johnson Noise $\beta = 2$
  - Technical Noise $\beta = 2$
  - Space Charge $\beta = 4$
  - Patch Potentials … $\beta = 4$

M. Brownnutt, M. Kumph, P. Rabl, R. Blatt, Rev. Mod. Phys. **87** (2015)

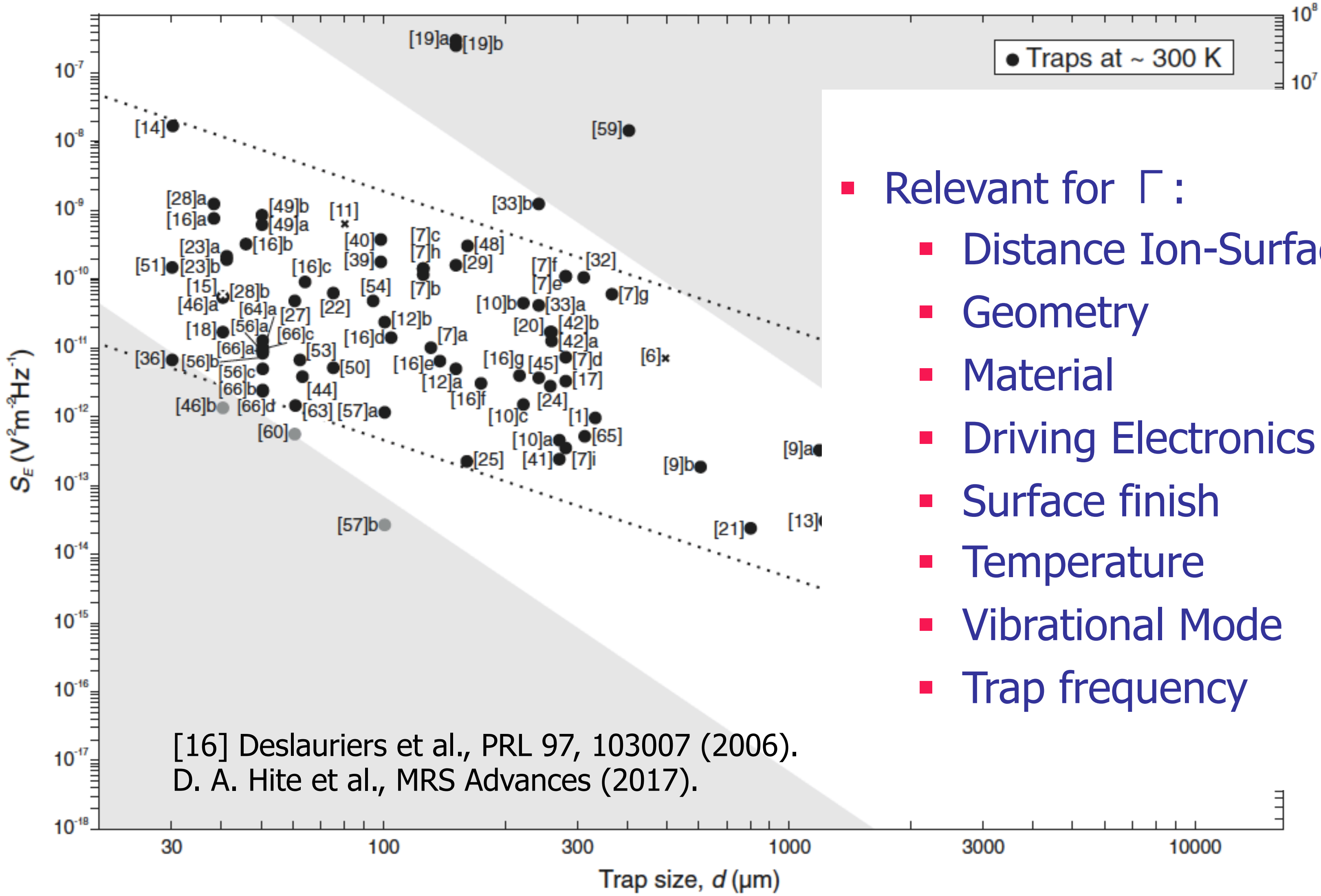
Anomalous Heating



- Relevant for Γ_h:
  - Distance Ion-Surface
  - Geometry
  - Material
  - Driving Electronics
  - Surface finish
  - Temperature
  - Vibrational Mode
  - Trap frequency

M. Brownnutt, M. Kumph, P. Rabl, R. Blatt, Rev. Mod. Phys. **87** (2015)

Anomalous Heating



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  - Distance Ion-Surface
  - Geometry
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  - Driving Electronics
  - Surface finish
  - Temperature
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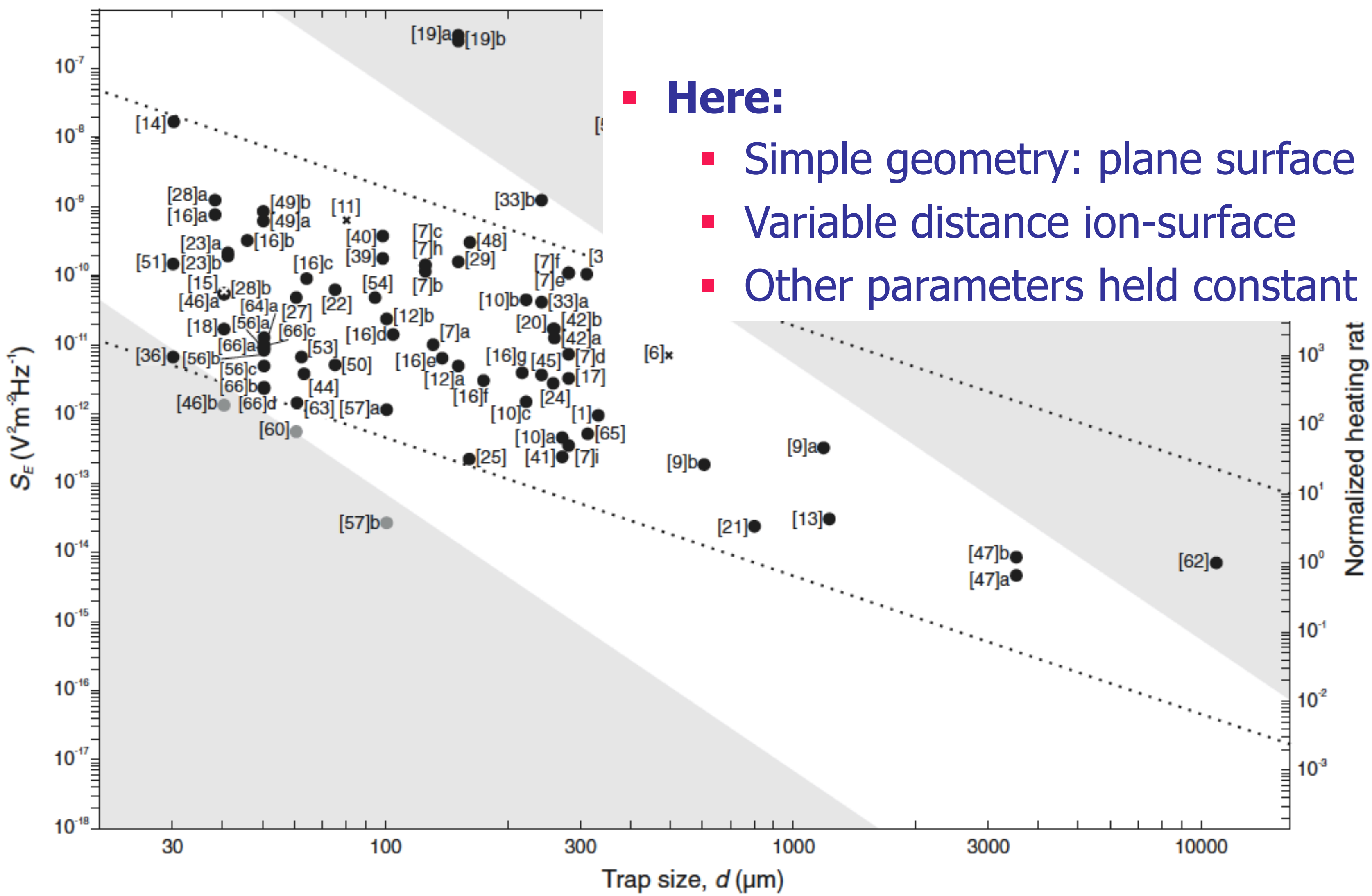
[16] Deslauriers et al., PRL 97, 103007 (2006).
D. A. Hite et al., MRS Advances (2017).

M. Brownnutt, M. Kumph, P. Rabl, R. Blatt, Rev. Mod. Phys. **87** (2015)

Anomalous Heating

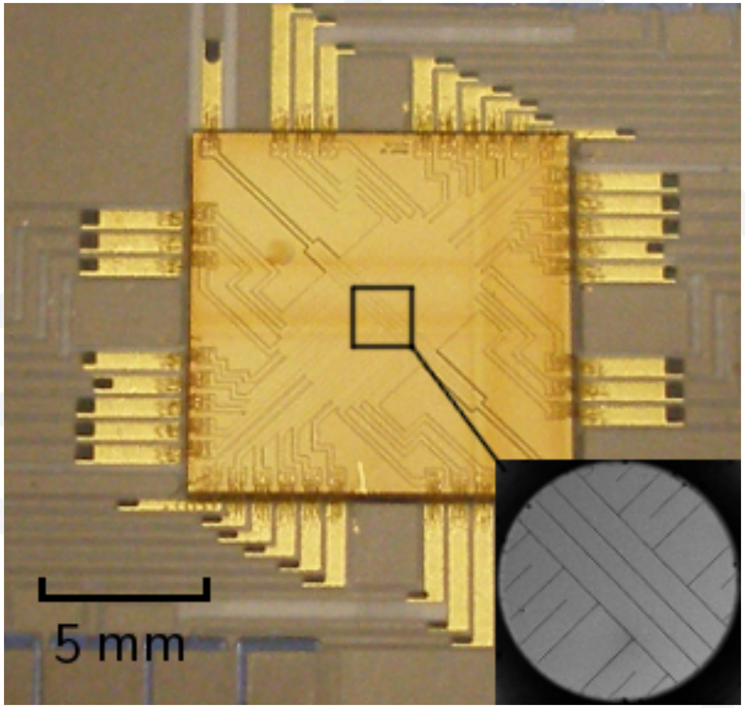


- **Here:**
  - Simple geometry: plane surface
  - Variable distance ion-surface
  - Other parameters held constant

M. Brownnutt, M. Kumph, P. Rabl, R. Blatt, Rev. Mod. Phys. **87** (2015)

Planar ion trap

- 5-electrode trap
- Central electrode 150 μm
- $^{172}Yb^{+}$



Appl. Phys. B **114** (2014).

Planar ion trap

- 5-electrode trap
- Central electrode 150 µm
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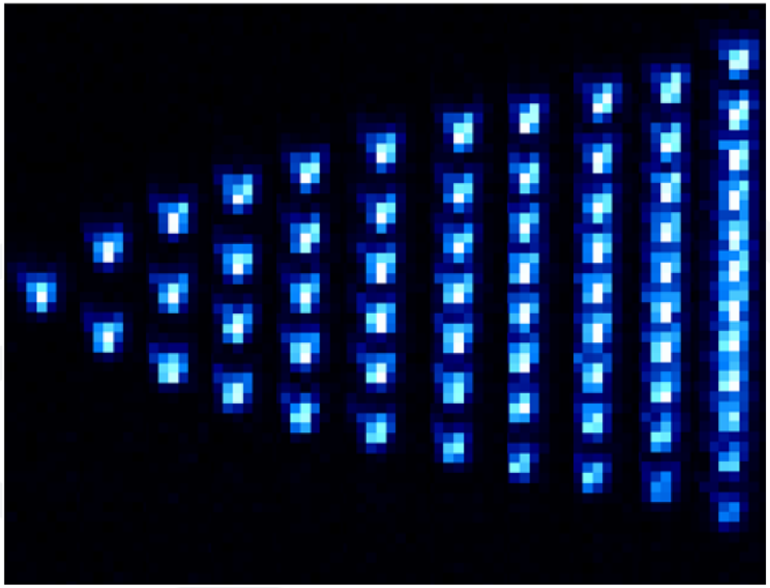
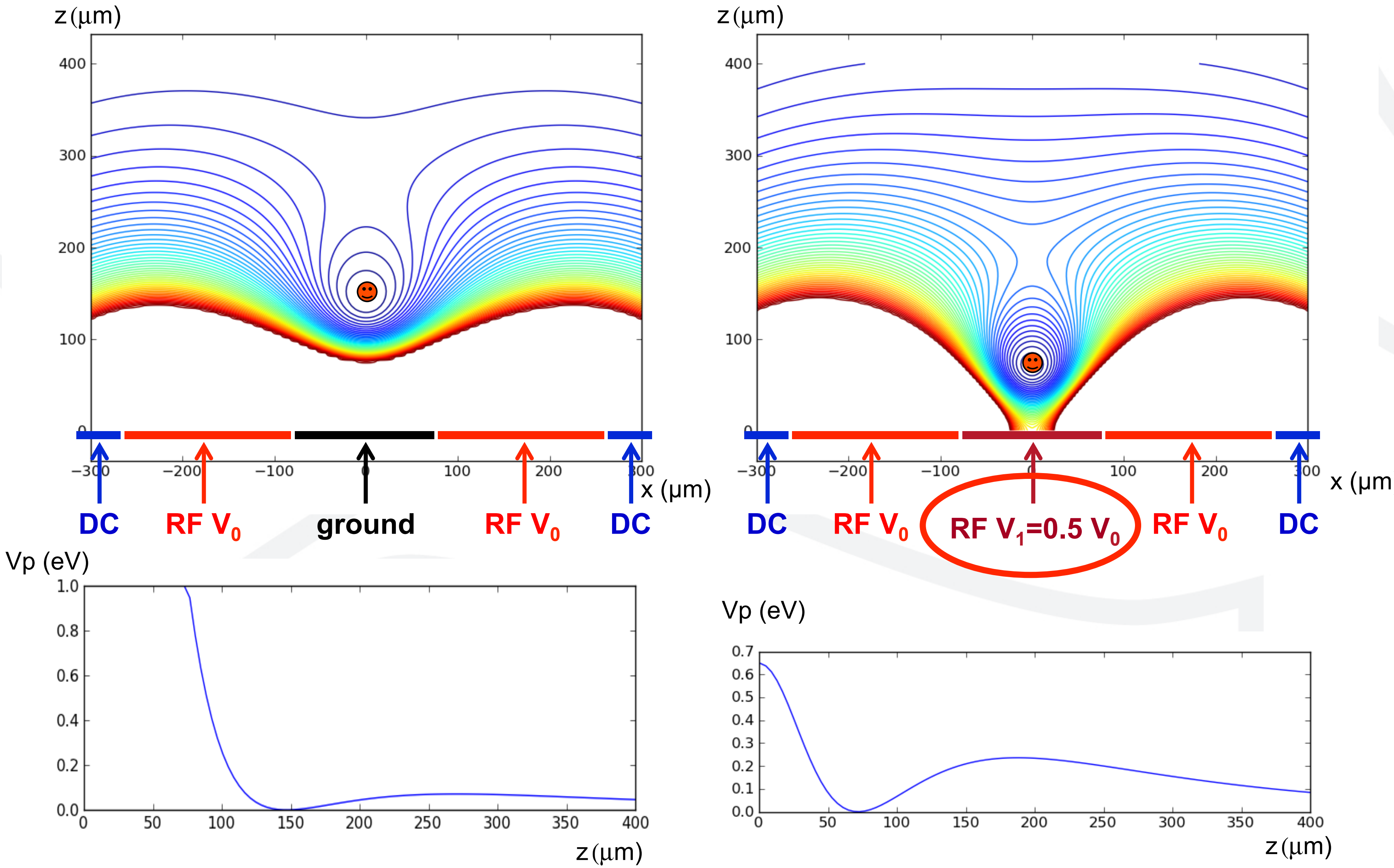


Appl. Phys. B **114** (2014).

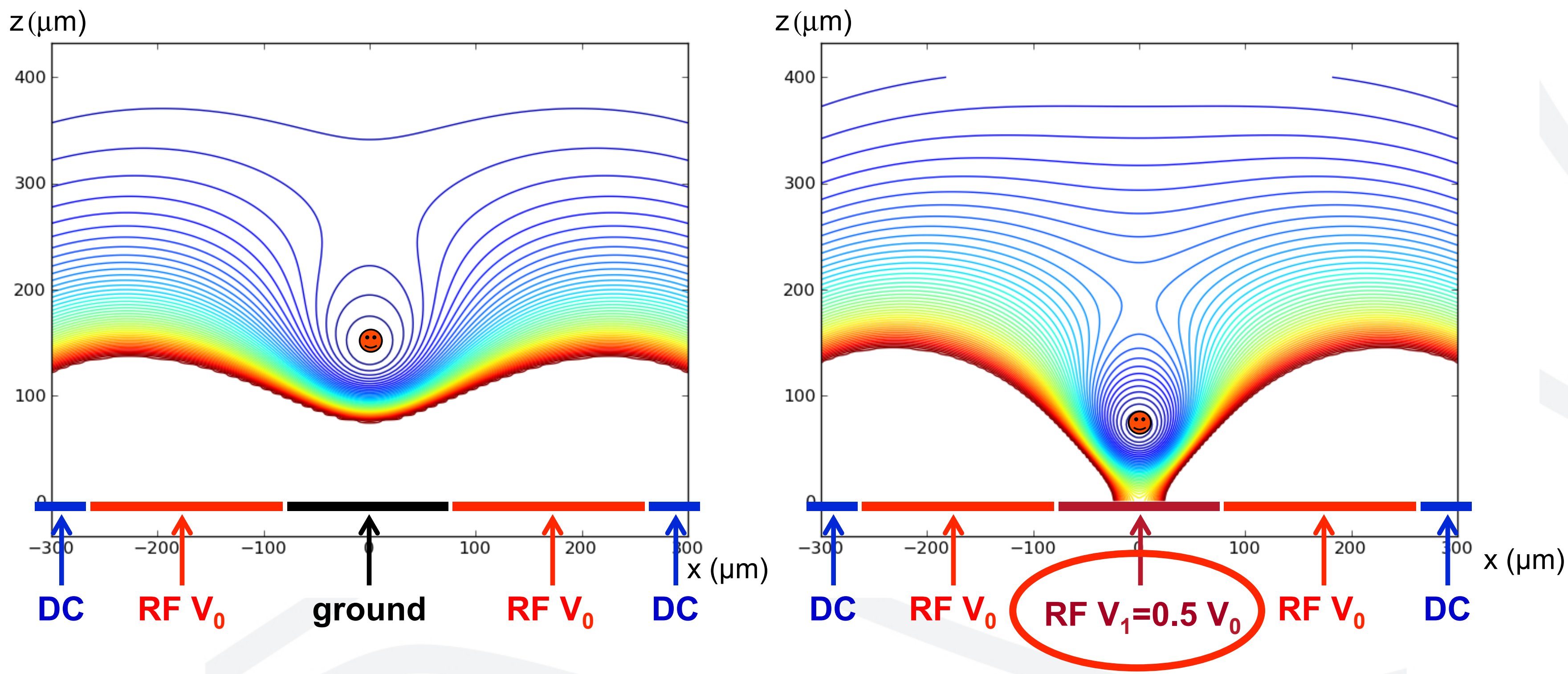
Vertical shuttling



Also: Cetina, et al. Phys. Rev. A **76**, 041401 (2007)

arXiv:1708.03147

Vertical shuttling

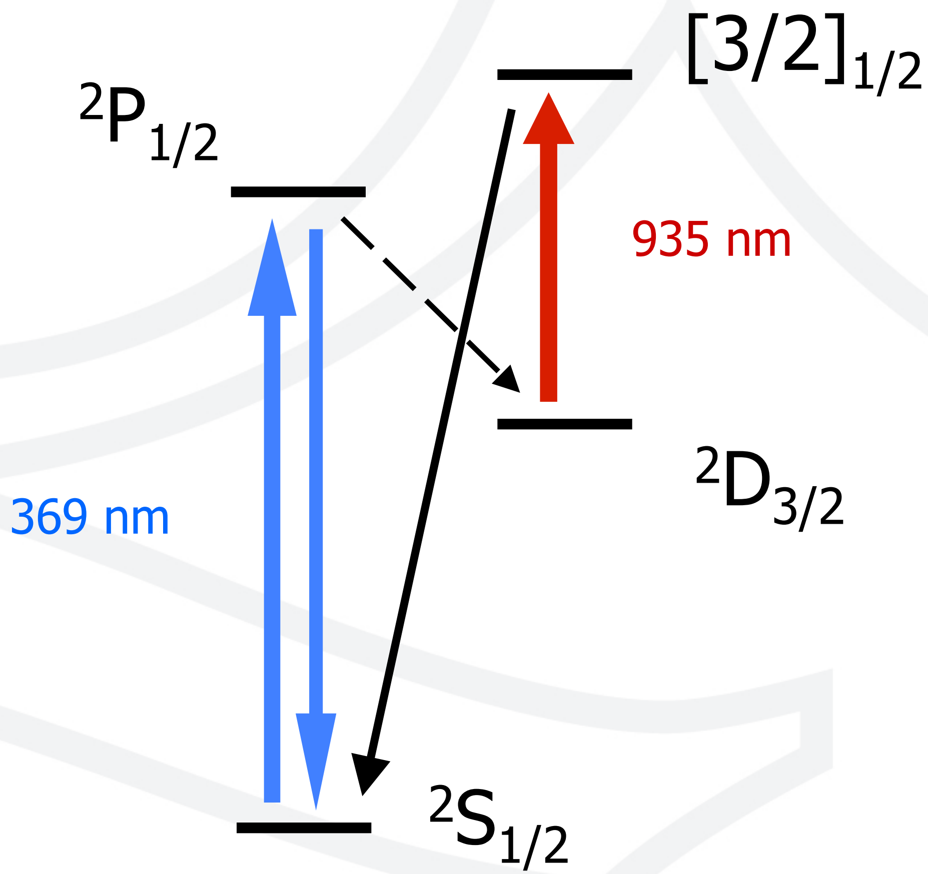


- Trapping height: 61 – 154 μm

arXiv:1708.03147

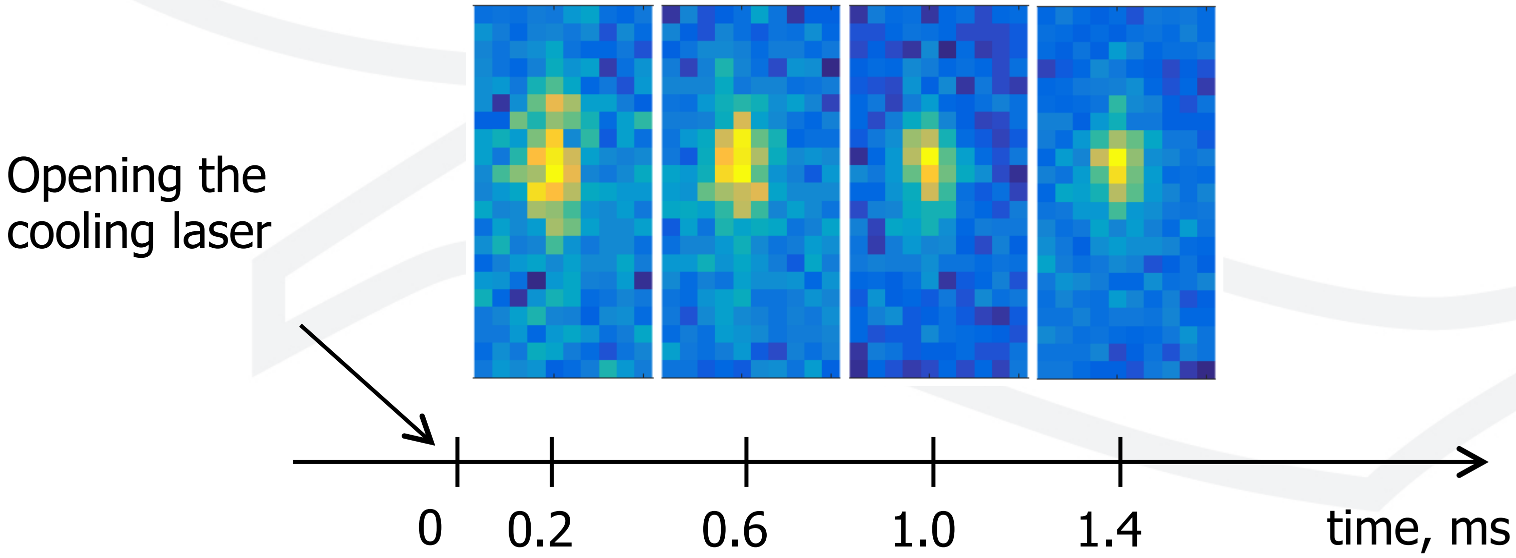
Cooling and detection

- $^{172}Yb^{+}$



Measuring the vibrational energy

- Cooling laser off: ion heats up
- Cooling laser on: record ion images
- Oscillation amplitude -> Vibrational energy



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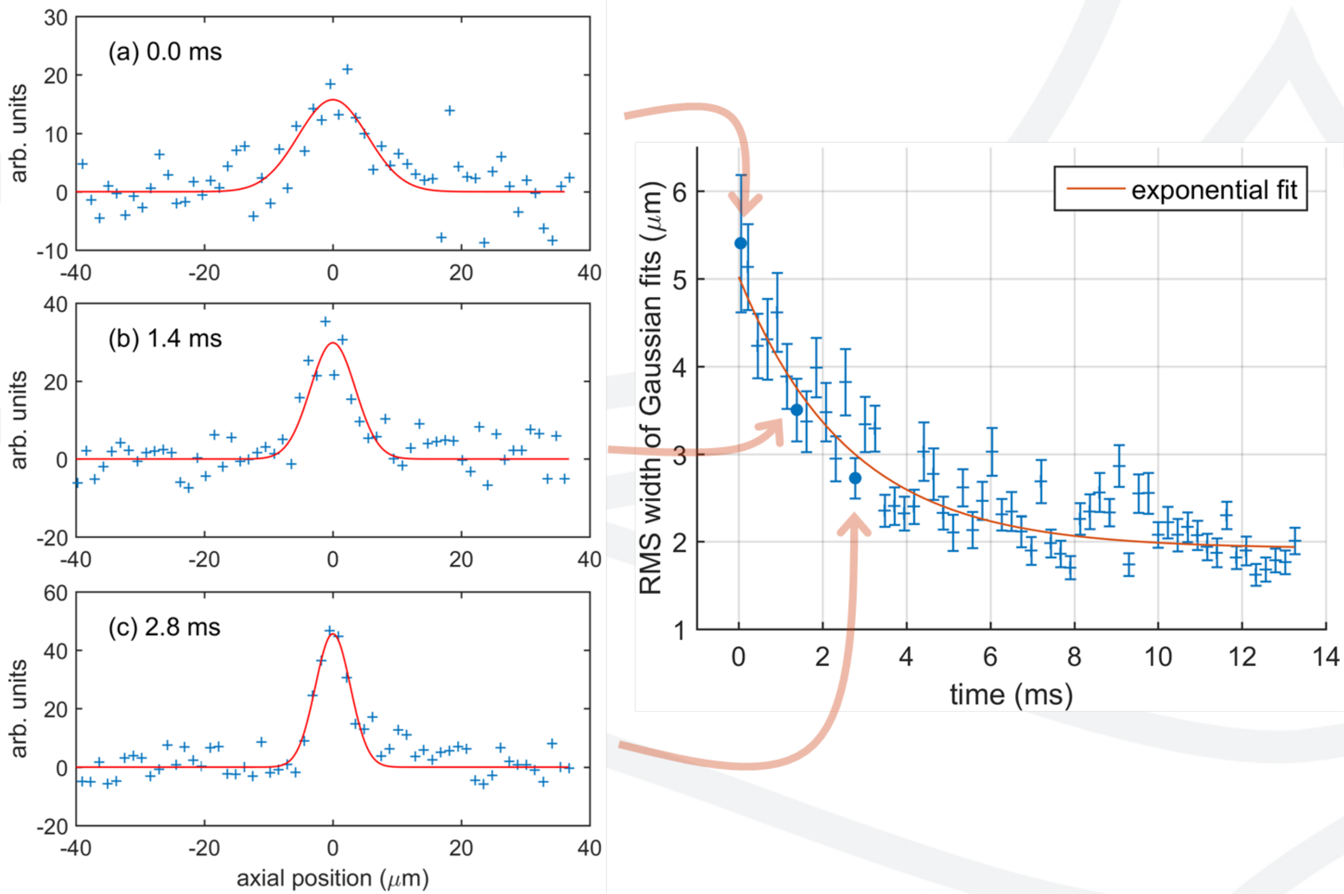
Measuring the vibrational energy

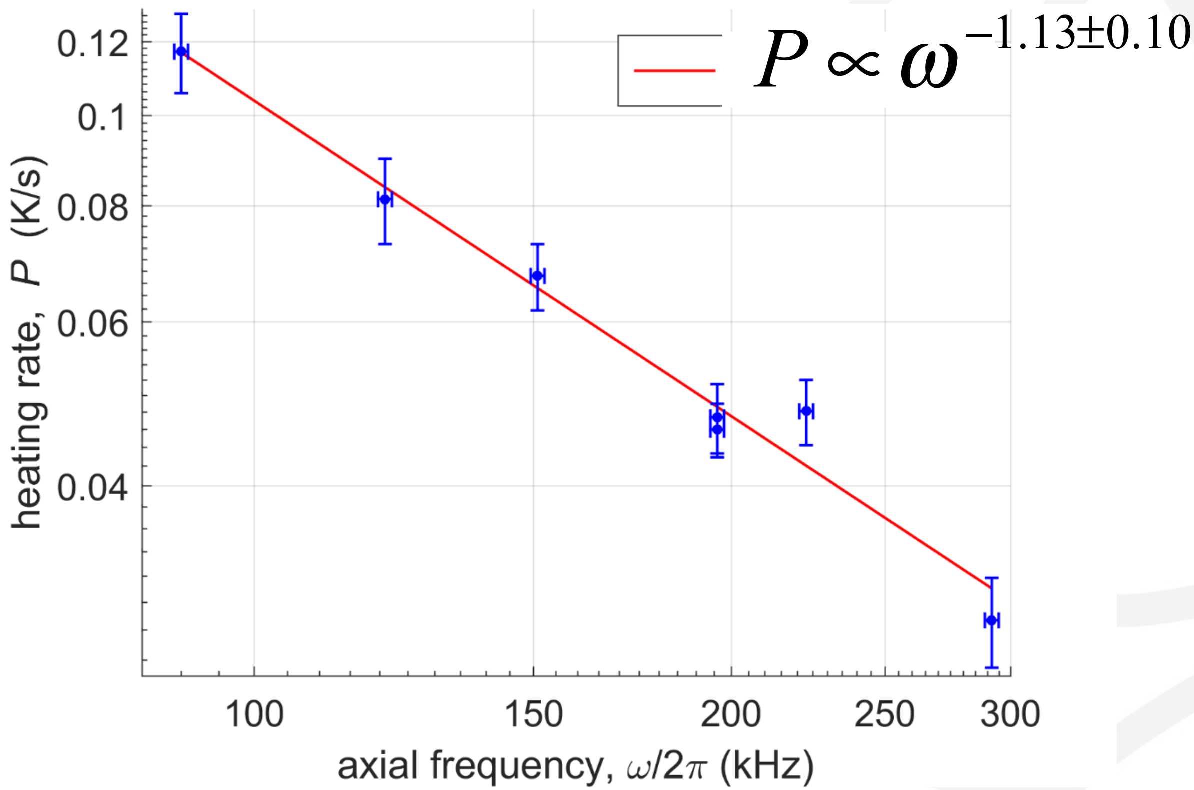


Average vibrational energy from $\sigma^2 = E / m\omega^2$

Also: S. Knünz et al., PRA **85**, 023427 (2012)

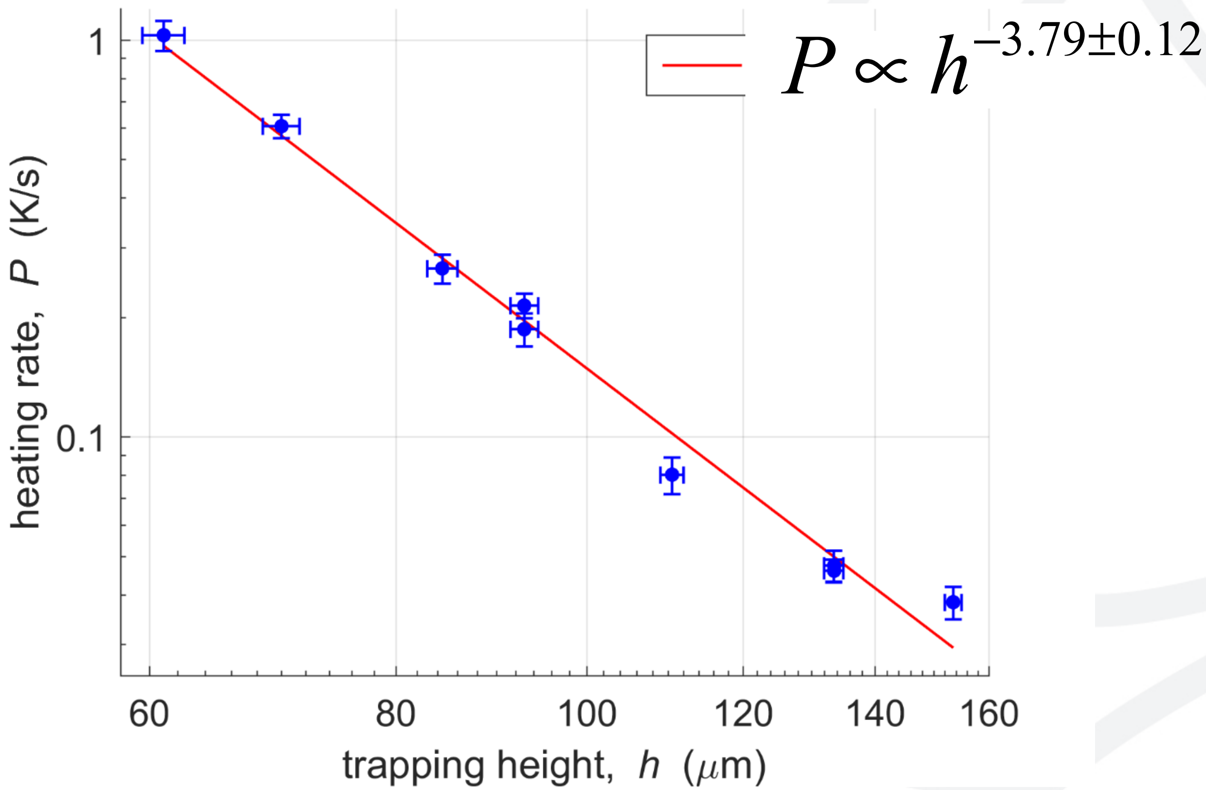
arXiv:1708.03147

Heating rate: trapping frequency dependence



arXiv:1708.03147

Heating rate: trapping height dependence



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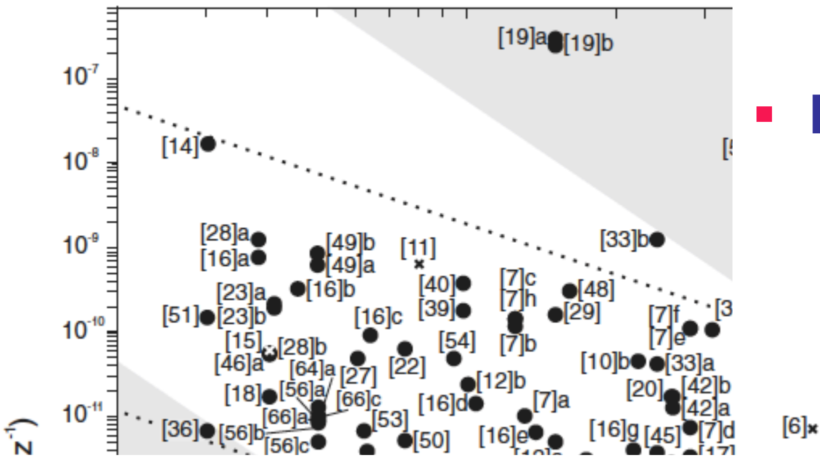
Anomalous Heating



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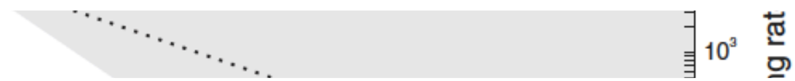

- **Conclusion:**
  - **Power law** of heating rate vs. trapping height dependence
  - Exponent α **= -3.79±0.12**
  - Close to often cited, though never before directly measured, $\alpha = -4$
  - Measured frequency and trapping height dependencies in agreement with
    - Model of small fluctuating patch potentials
    - Model of thin dielectric layer covering the electrodes

arXiv:1708.03147

SHUTTLING OF IONS

Peter Kaufmann, Timm F. Gloger Delia Kaufmann, Michael Johanning

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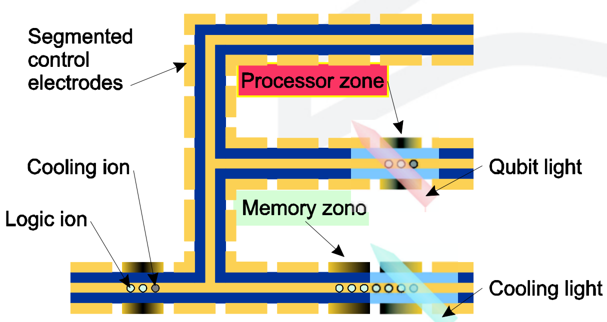

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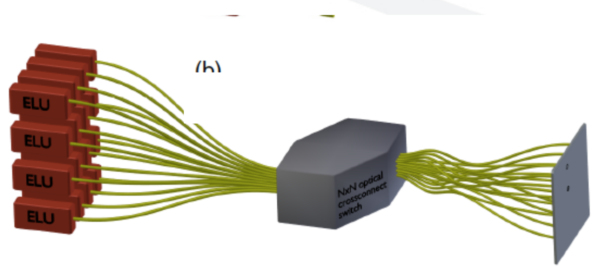

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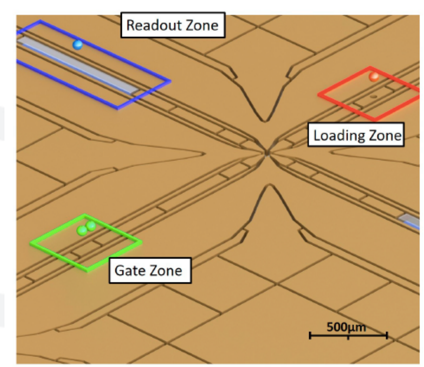
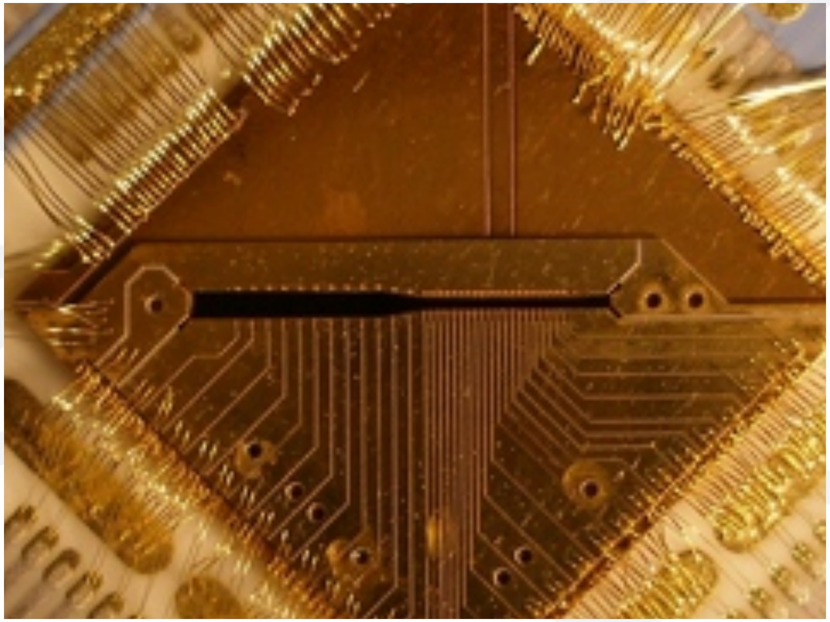


B. Lekitsch et al.,
Science Advances **3** (2017)

QI after shuttling of ions

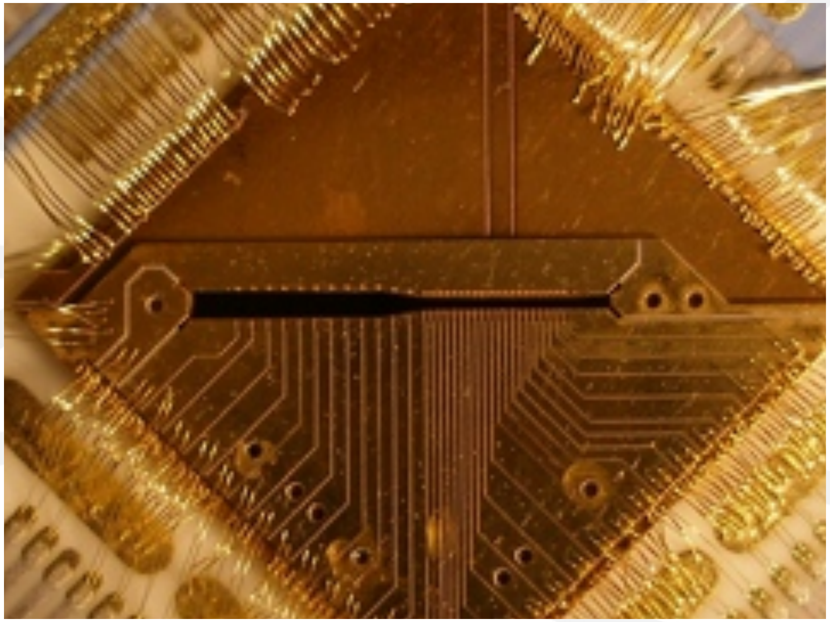
- Microstructurd linear Paul trap, three layer structure



Appl. Phys. B **107** (2012)
Also: Schulz et al., NJP **10**, 045007 (2008)

QI after shuttling of ions

- Microstructurd linear Paul trap, three layer structure
- Move ion by 280 µm in 12.8 µs with update rate 12.5 MHz

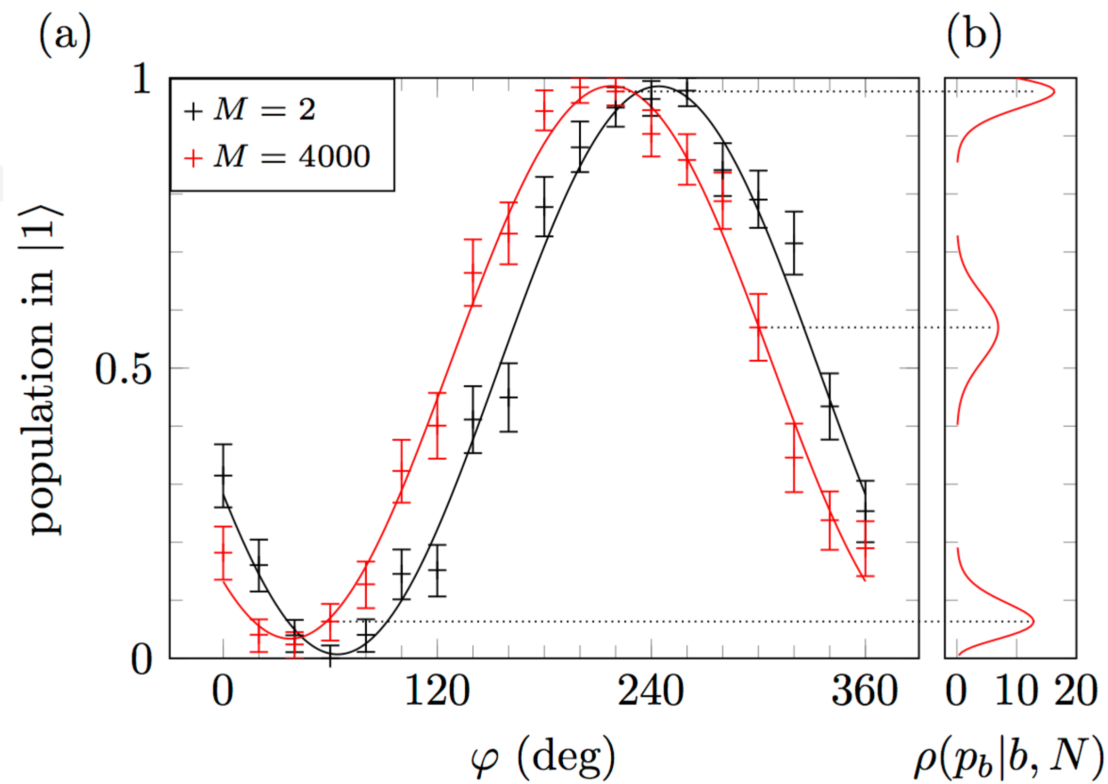


arXiv:1704.02141

QI after shuttling of ions

- 4000 shuttling events reduce Ramsey contrast by 3%
- Fidelity per shuttling ***F* = 0.999994(+6/-7)**

- *F* above quantum error correction threshold



arXiv:1704.02141

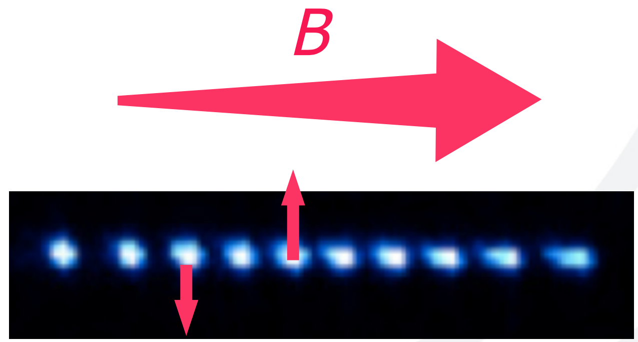
- Individual Addressing
- Processor Qubit or Memory Qubit
- Simultaneous Conditional Dynamics

MAGIC QUANTUM TOOLBOX

Ch. Piltz, Th. Sriarunothai, G. Giri

S. Ivanov, S. Wölk

Magnetic Gradient Induced Coupling: MAGIC



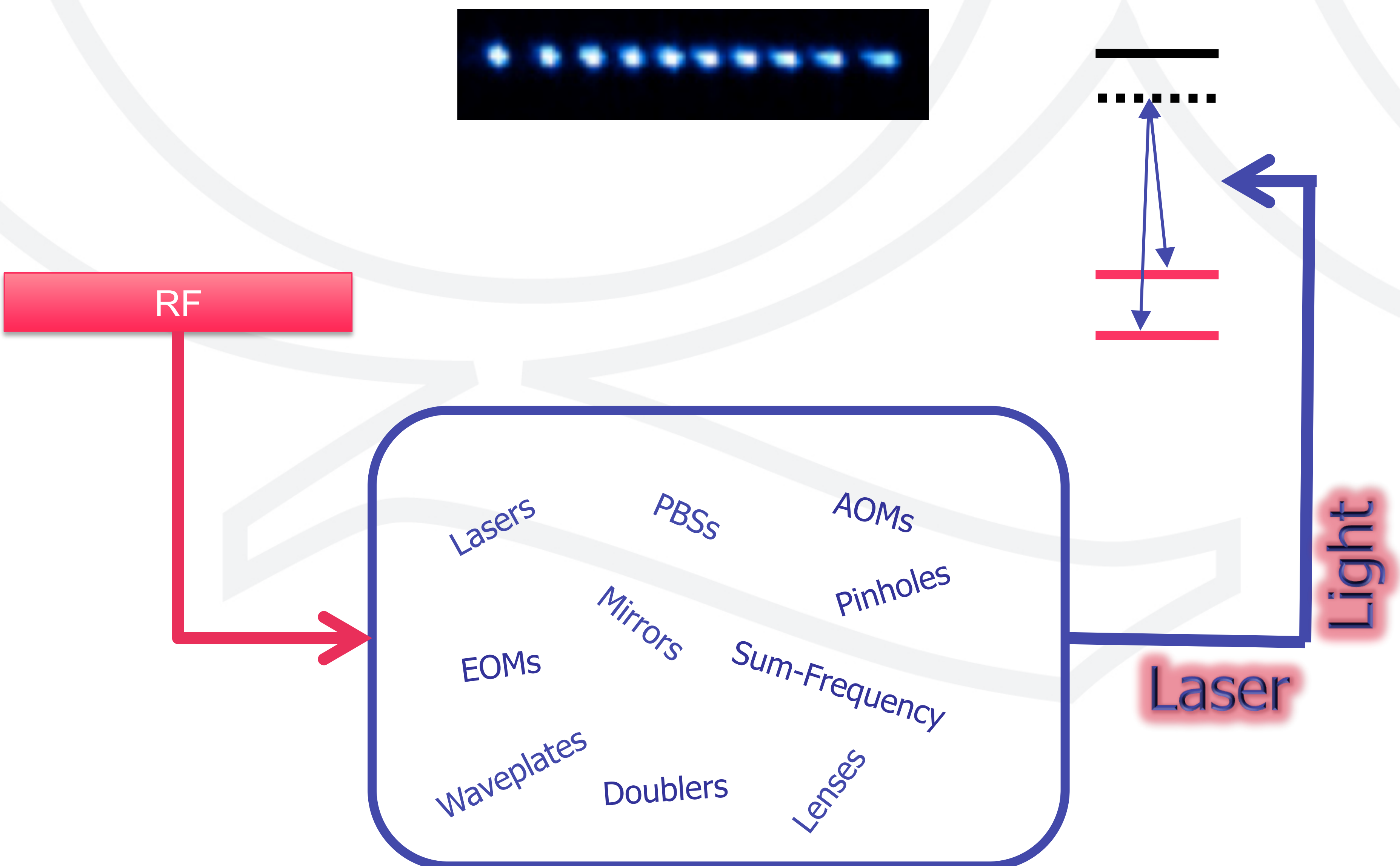
1. Individual Addressing

2. Spin-Spin Coupling

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

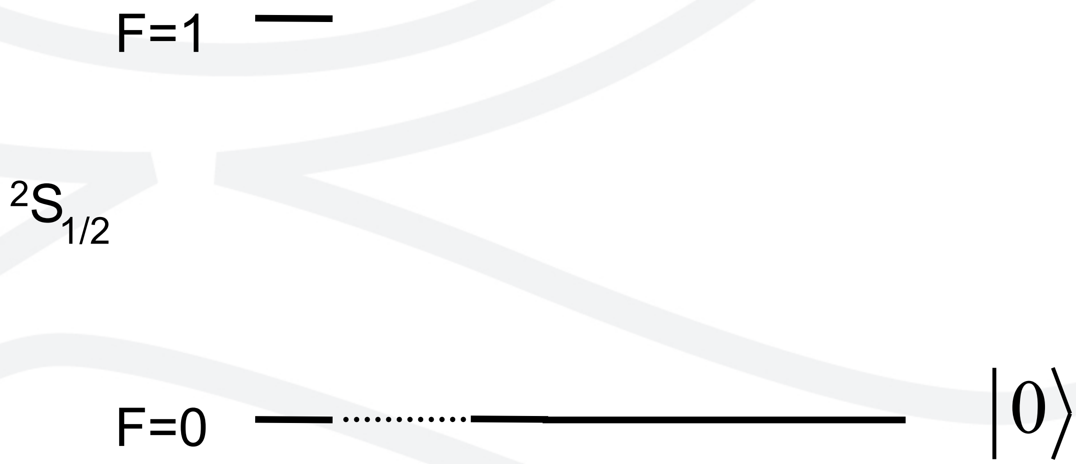
PRL **87** (2001)
In "*Laser Physics at the Limit*", Springer, 2002 = quant-ph/0111158.
Adv. At. Mol. Opt. Phys. **49** (2003) = quant-ph/0305129

Coupling and Addressing Trapped Ions



Coupling and Addressing Trapped Ions

$^{171}Yb^{+}$ Hyperfine Qubit



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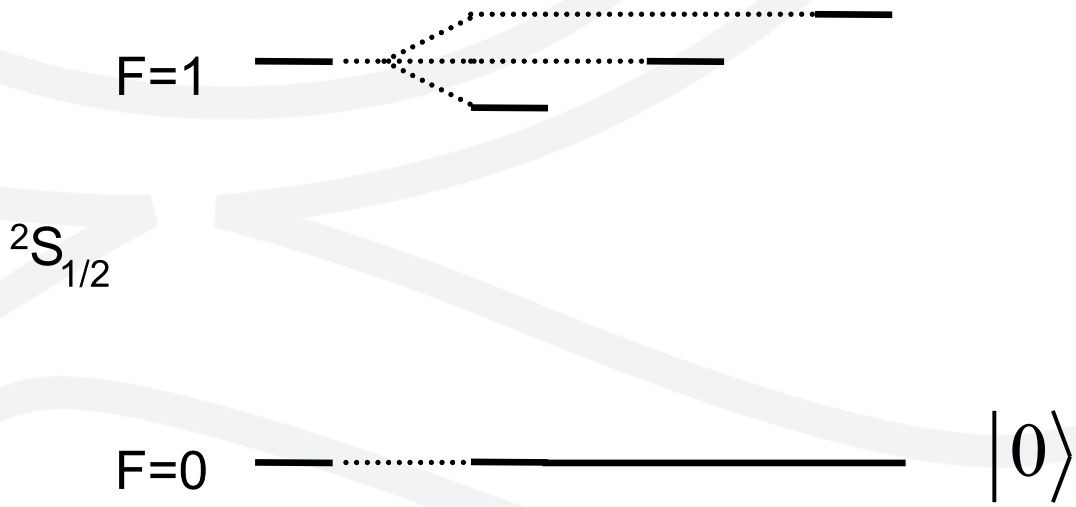
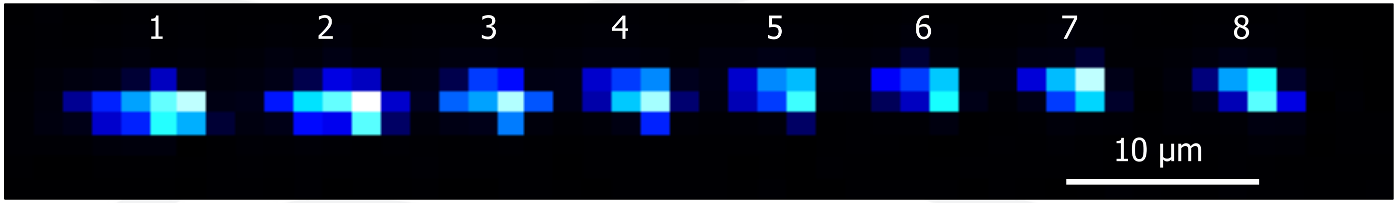
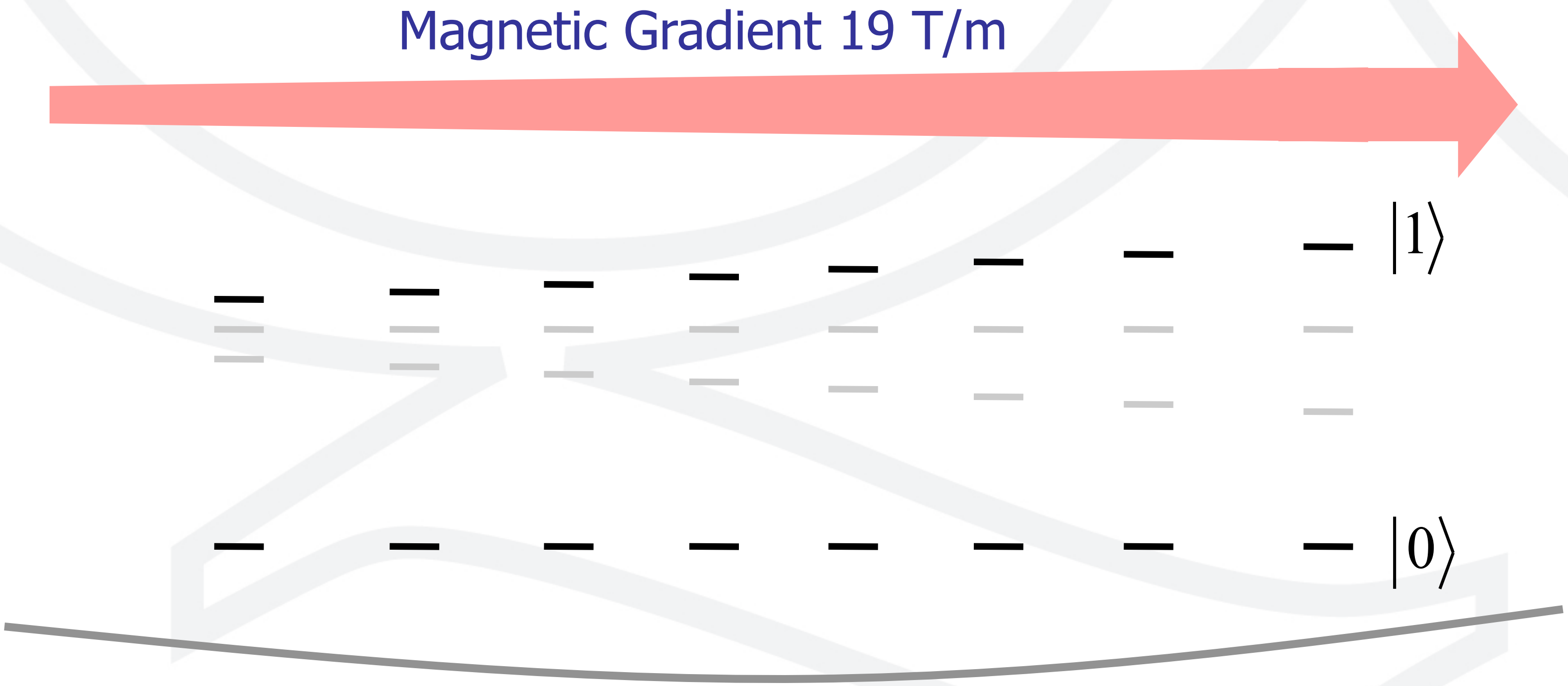


Addressing a Quantum Byte

Magnetic Gradient 19 T/m

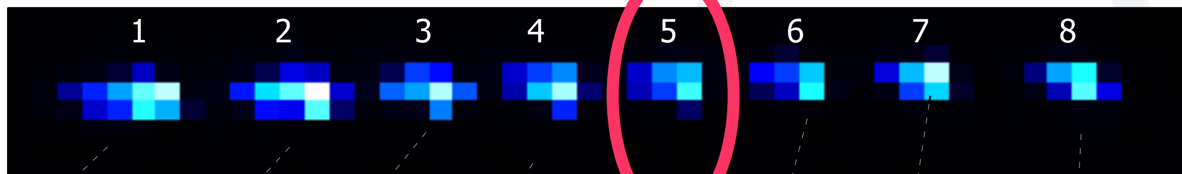


Addressing a Quantum Byte



Addressing a Quantum Byte

Cross-talk matrix

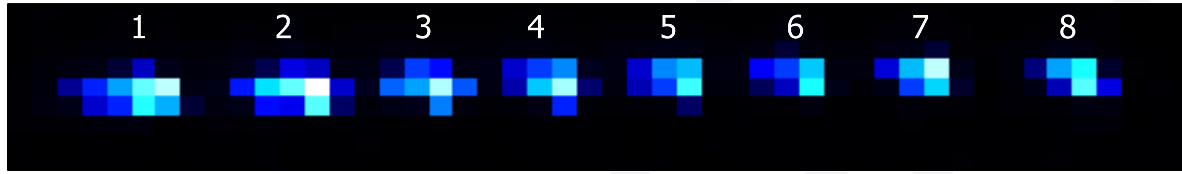


$C_{i,j}$ (10^{-5})

1.9(9)	1.6(9)	3.1(1.0)	**7.6(1.3)**	-	**3.1(1.0)**	1.8(9)	0.5(5)

Addressing a Quantum Byte

Measured cross-talk matrix of 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)	[illegible]	[illegible]
3.8(1.4)	-	**4.1(1.1)**	2.3(9)	2.3(1.1)	[illegible]	[illegible]	[illegible]
2.1(1.0)	**3.7(1.2)**	-	**4.5(1.2)**	[illegible]	[illegible]	[illegible]	1.1(6)
0.9(9)	1.7(6)	**2.7(1.1)**	[illegible]	[illegible]	[illegible]	0.6(6)	0.6(6)
1.9(9)	1.6(9)	[illegible]	[illegible]	-	**3.1(1.0)**	1.8(9)	0.5(5)
1.5(5)	[illegible]	[illegible]	1.0(8)	**5.5(1.4)**	-	**3.6(1.3)**	0.8(8)
[illegible]	[illegible]	1.5(7)	1.2(8)	1.2(8)	**2.9(1.1)**	-	**2.6(8)**
[illegible]	1.1(5)	0.6(6)	0.8(8)	2.5(9)	1.1(8)	**3.4(1.2)**	-

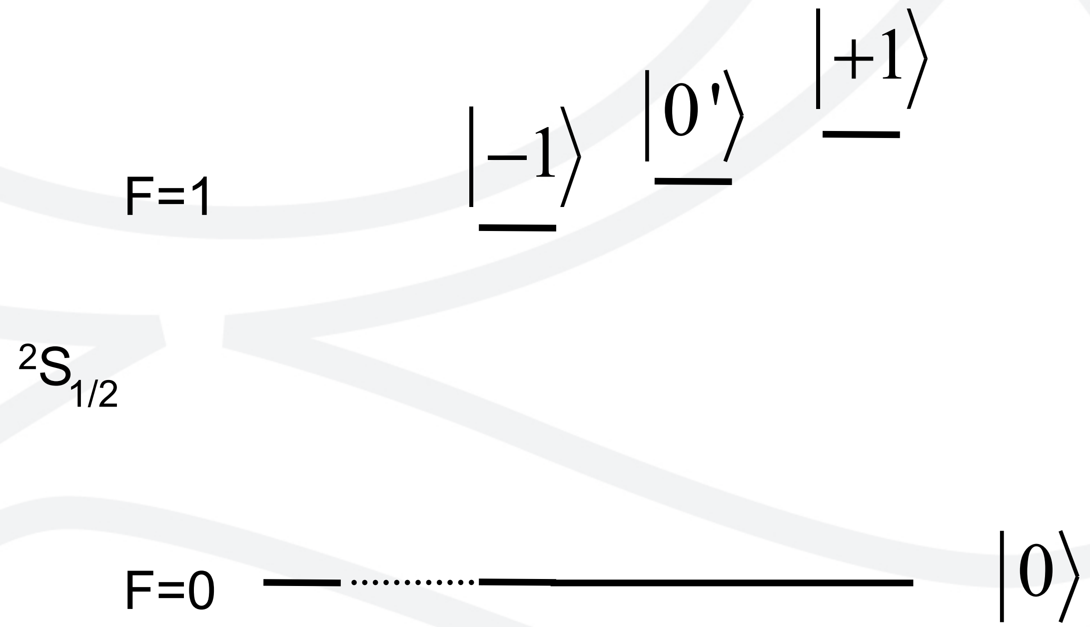
Below Error Correction Threshold

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

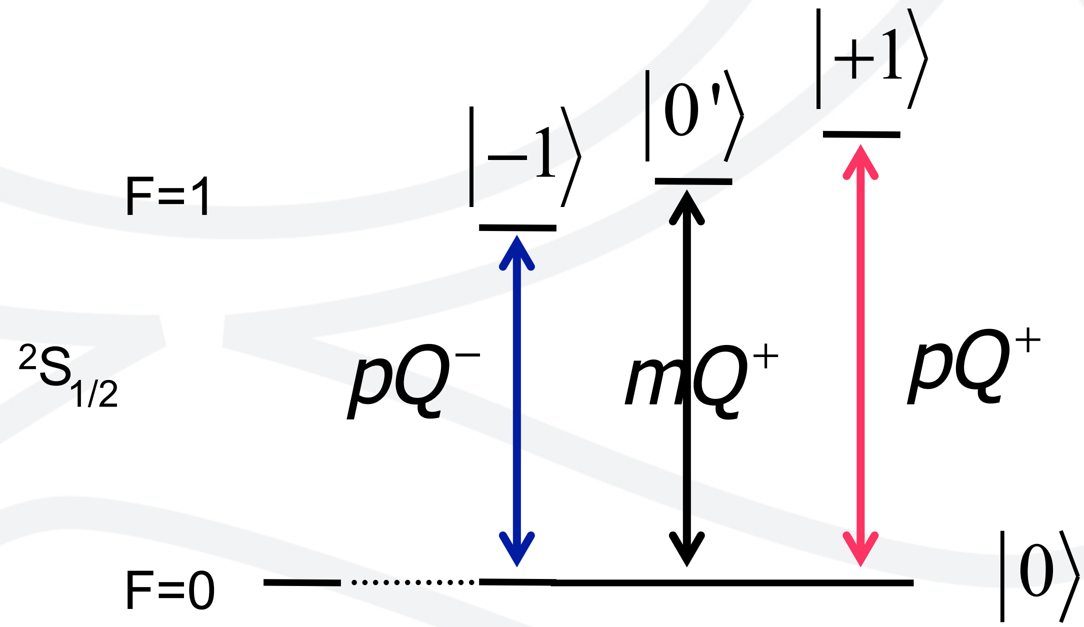
- Individual Addressing
- Processor Qubit or Memory Qubit
- Simultaneous Conditional Dynamics

MAGIC QUANTUM TOOLBOX

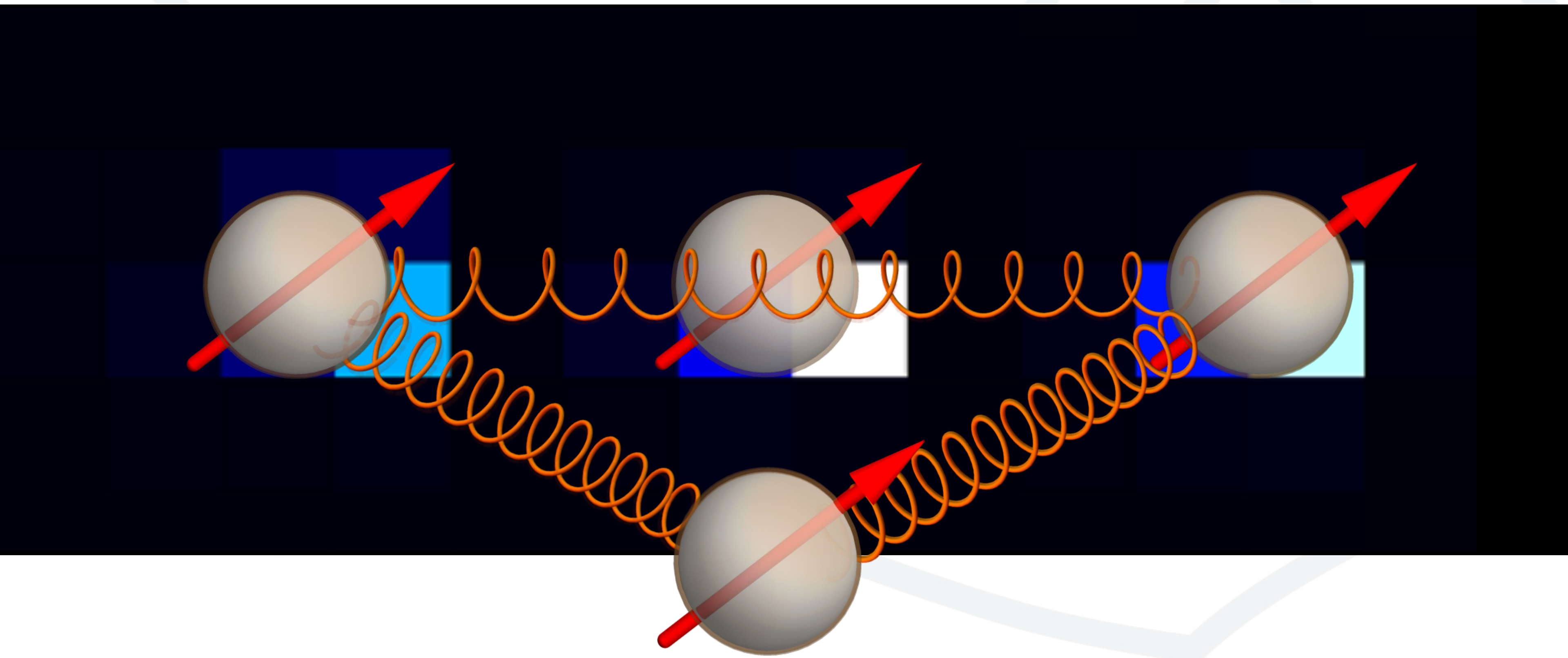
Processor Qubits and Memory Qubit



Processor Qubits and Memory Qubit

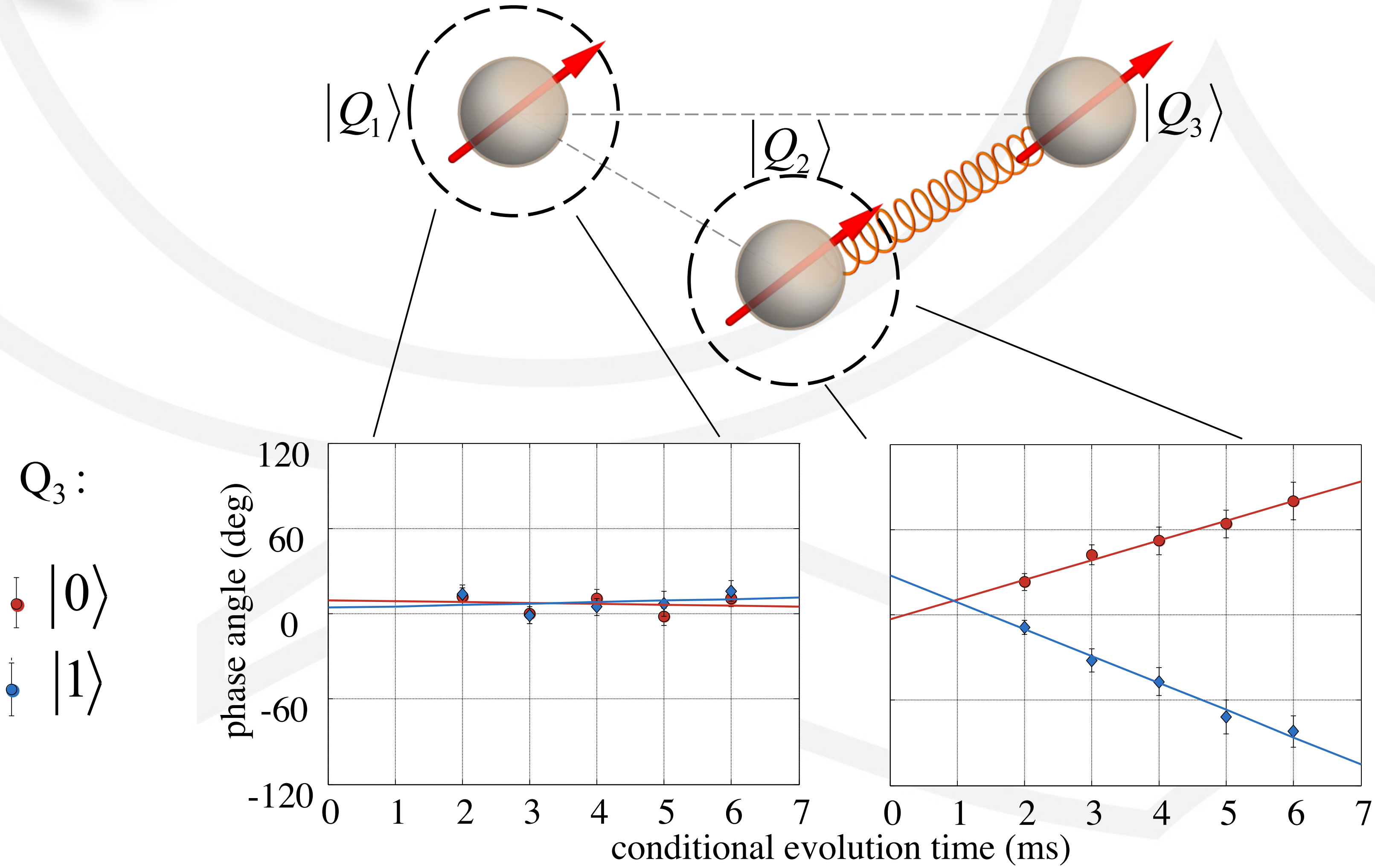


MAGIC: Spin-Spin Interaction



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

Memory: Qubit 1. Phase Gate: Qubits 2,3

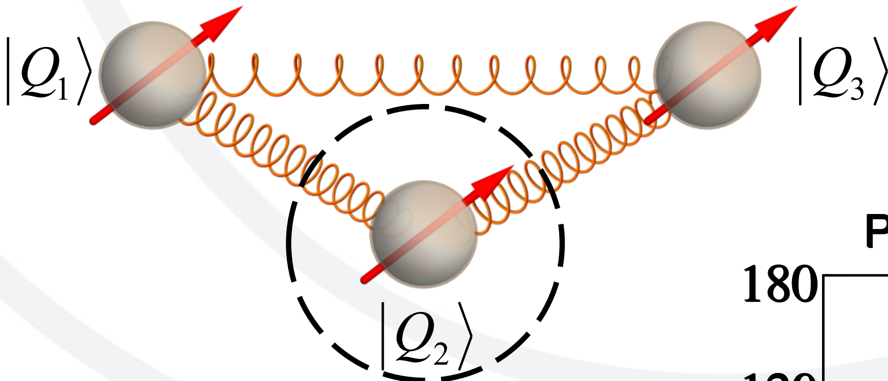


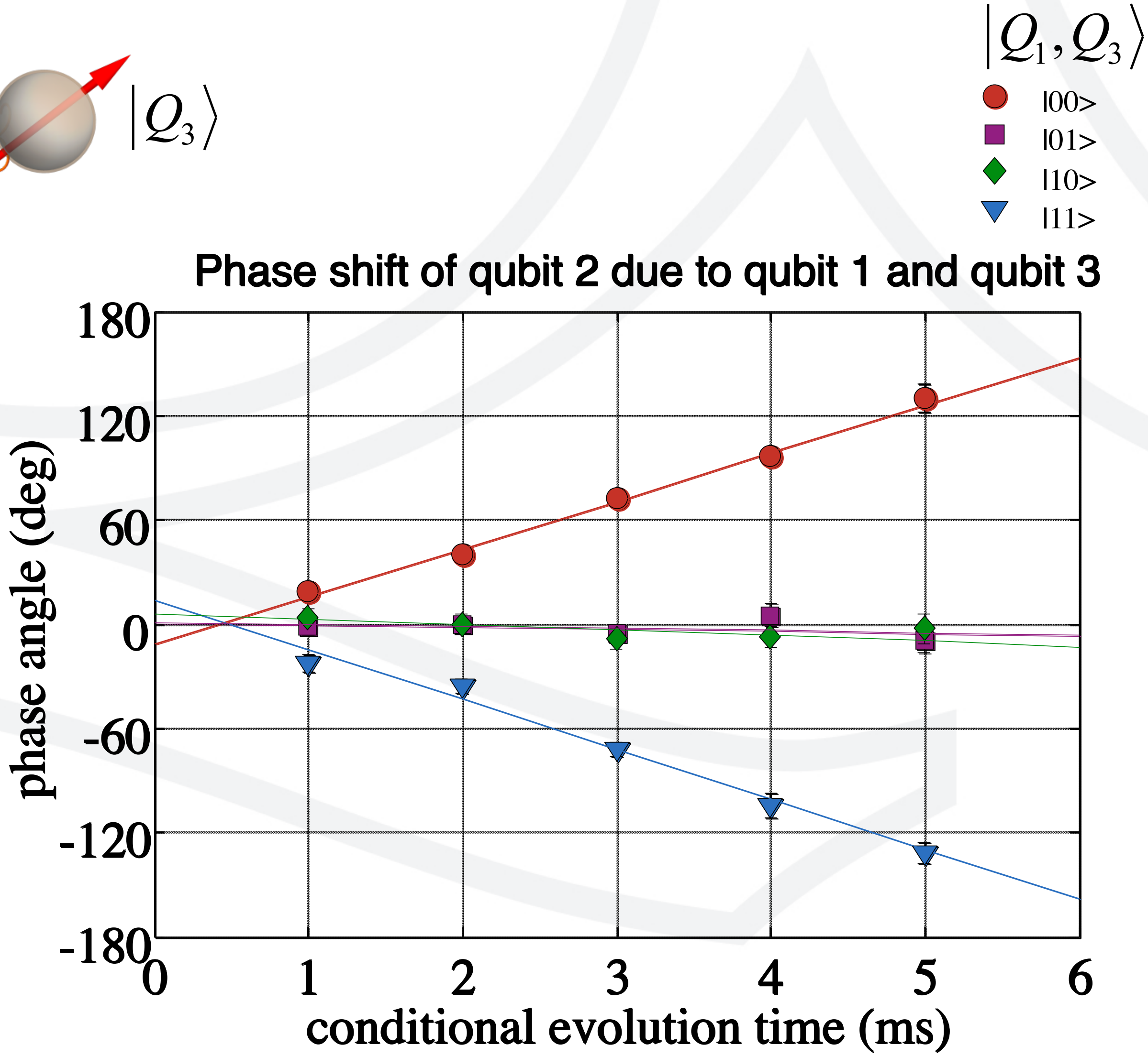
Science Advances **2** (2016)

- Individual Addressing
- Processor Qubit or Memory Qubit
- Simultaneous Conditional Dynamics

MAGIC QUANTUM TOOLBOX

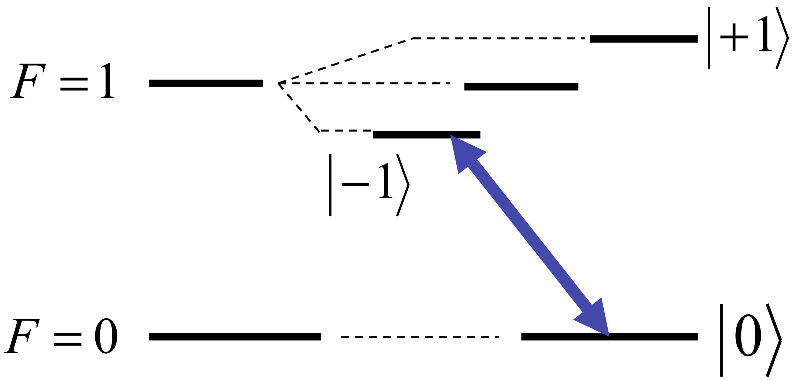
Simultaneous Coupling

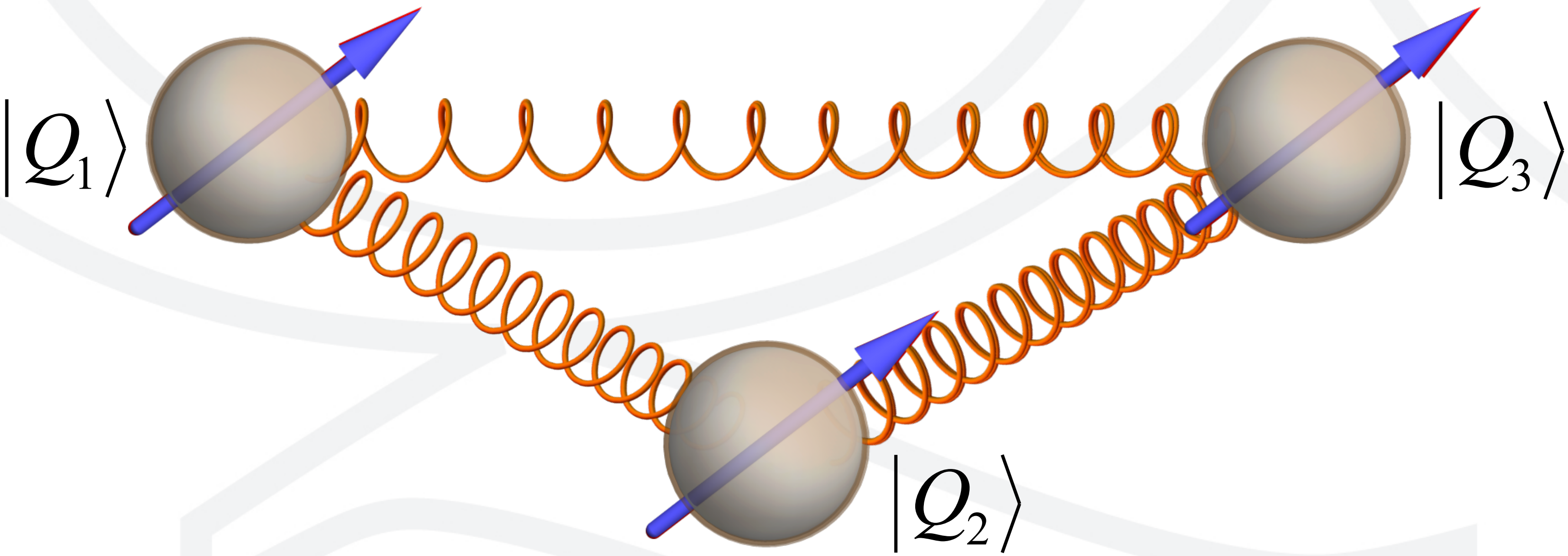




Science Advances **2** (2016)

Sign of Coupling

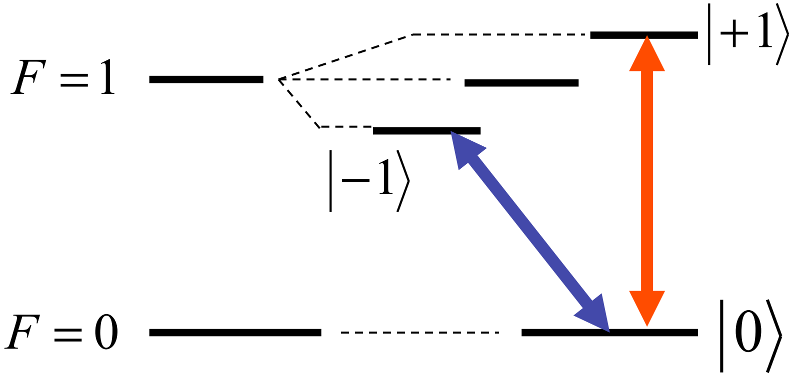


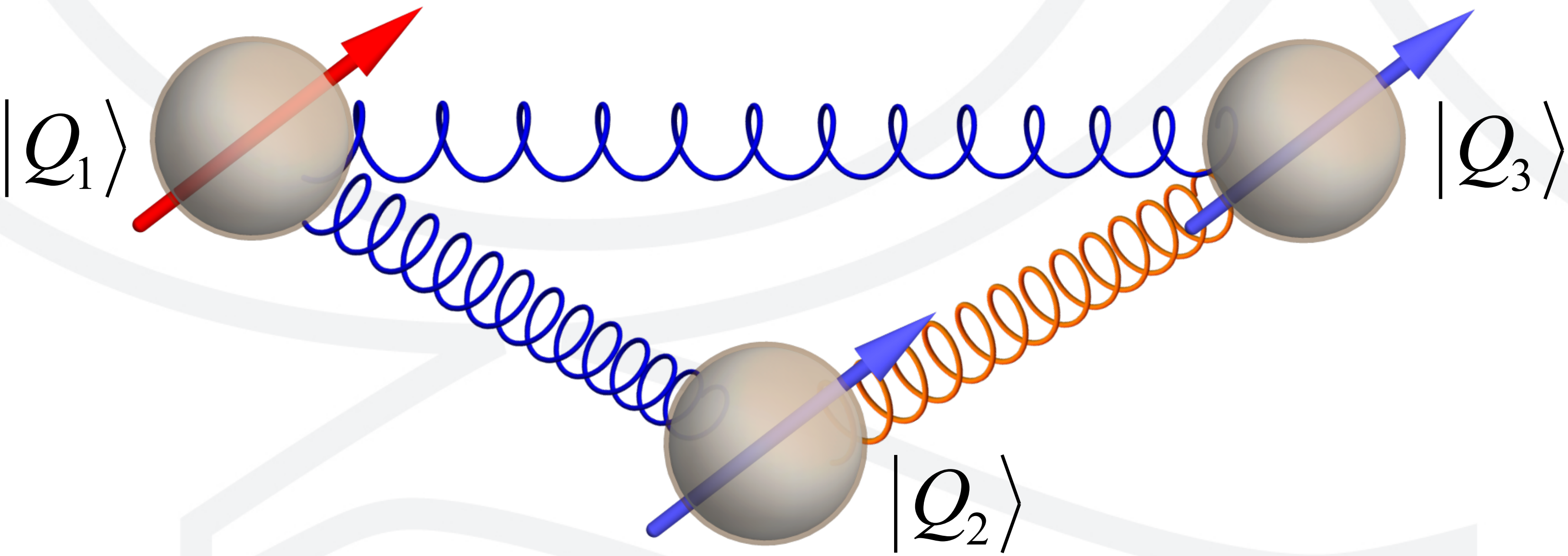


$$\frac{J_{ij}}{2\pi} = \begin{bmatrix} & 34(7) & 27(7) \\ 34(7) & & 39(7) \\ 27(7) & 39(7) & \end{bmatrix} \mathrm{Hz}$$

Science Advances **2** (2016)

Sign of Coupling





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

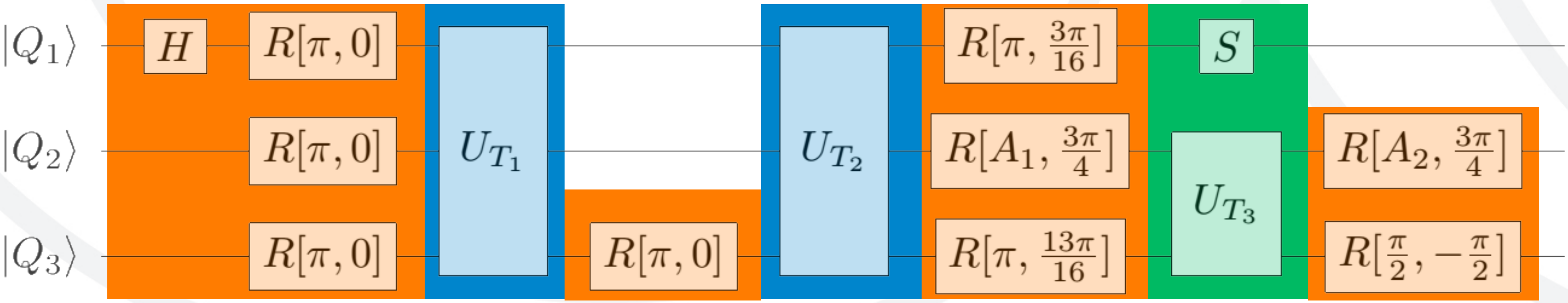
Science Advances **2** (2016)

- Individual Ad[illegible]
- Proc[illegible] [illegible]emory Qubit
- [illegible]s Conditional Dynamics

RF for all Coherent Operations

MAGIC QUANTUM TOOLBOX

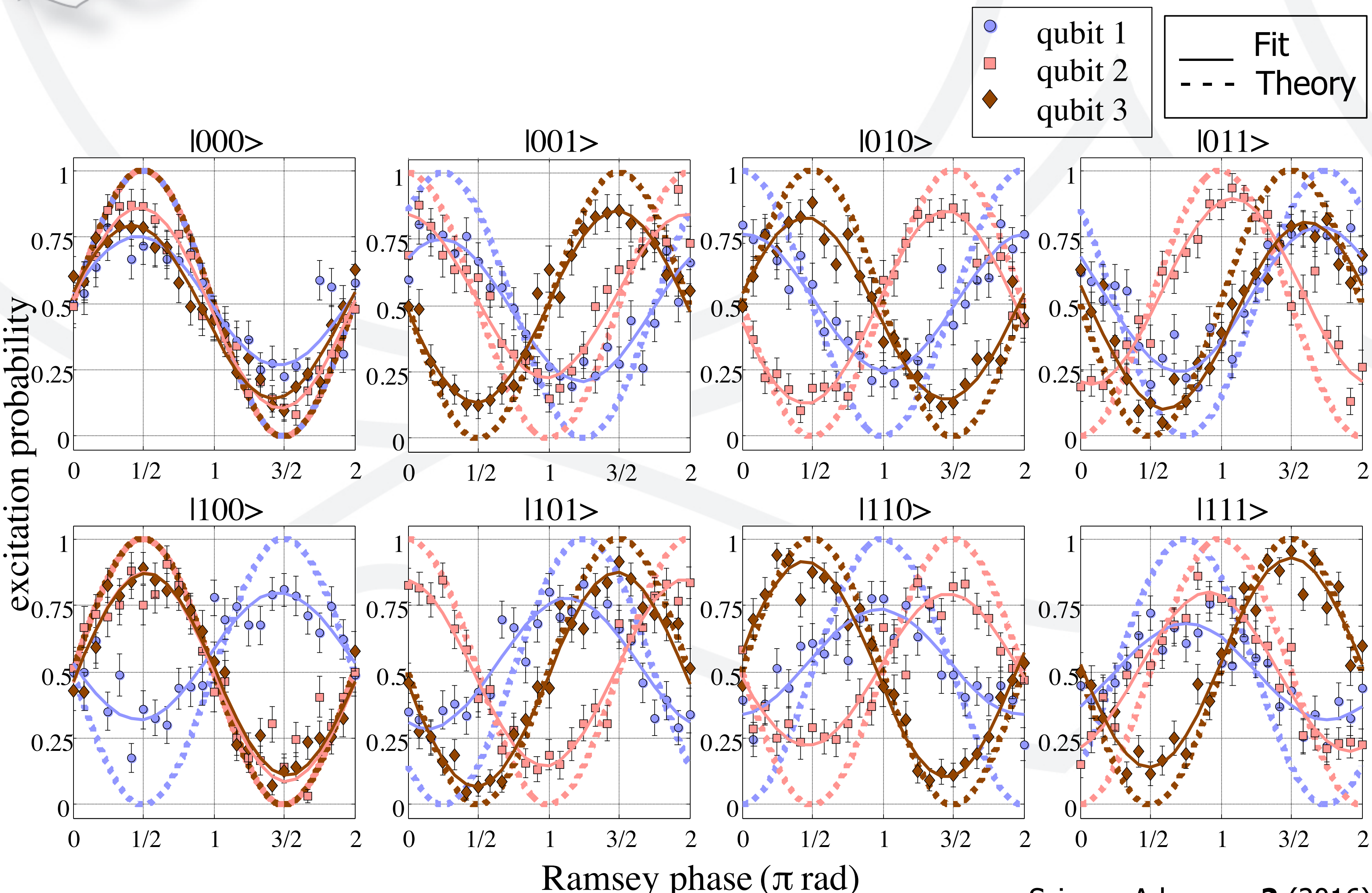
Coherent QFT Using Simultaneous Coupling



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

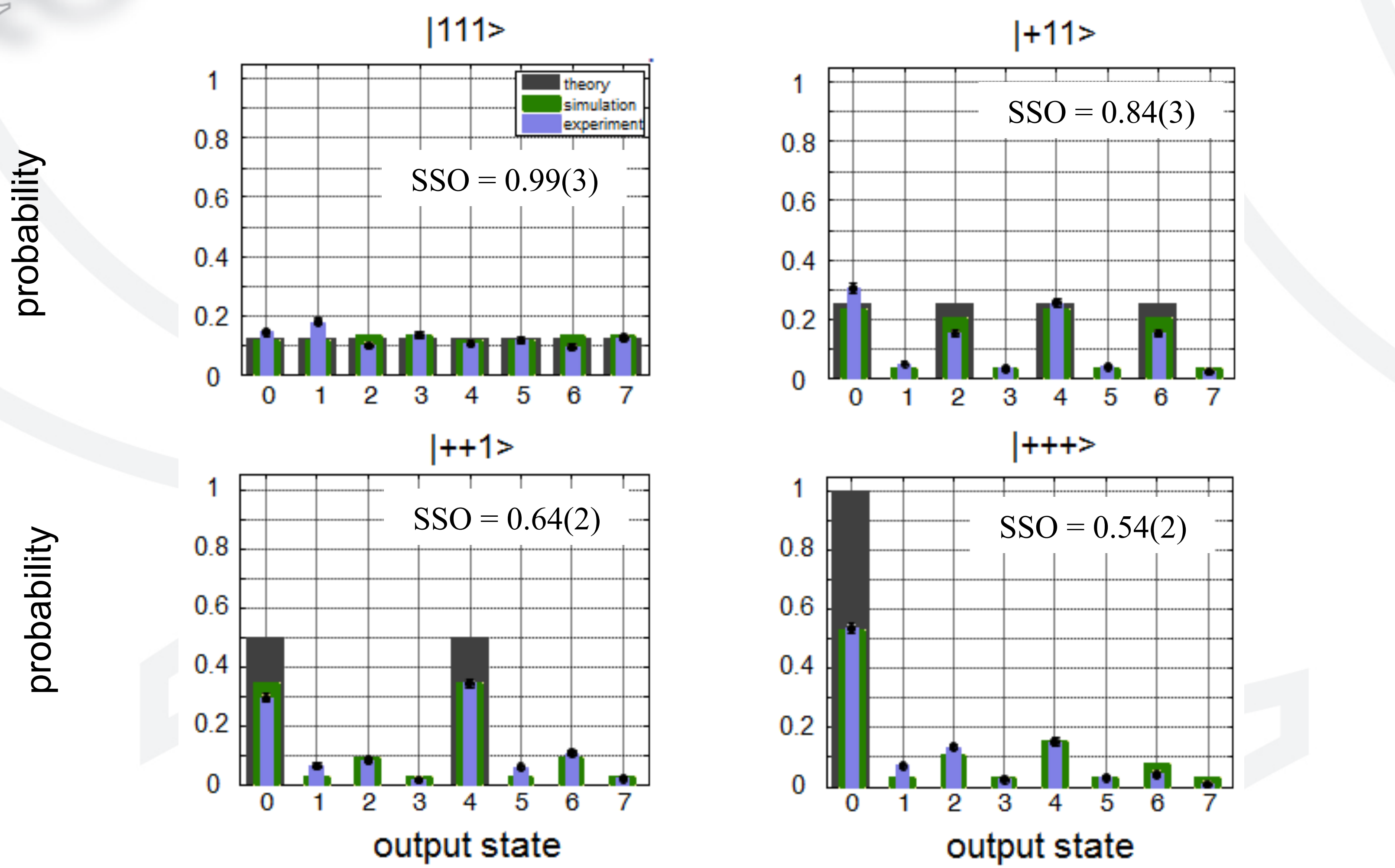
Science Advances **2** (2016)

Coherent QFT: Experiment



Science Advances **2** (2016)

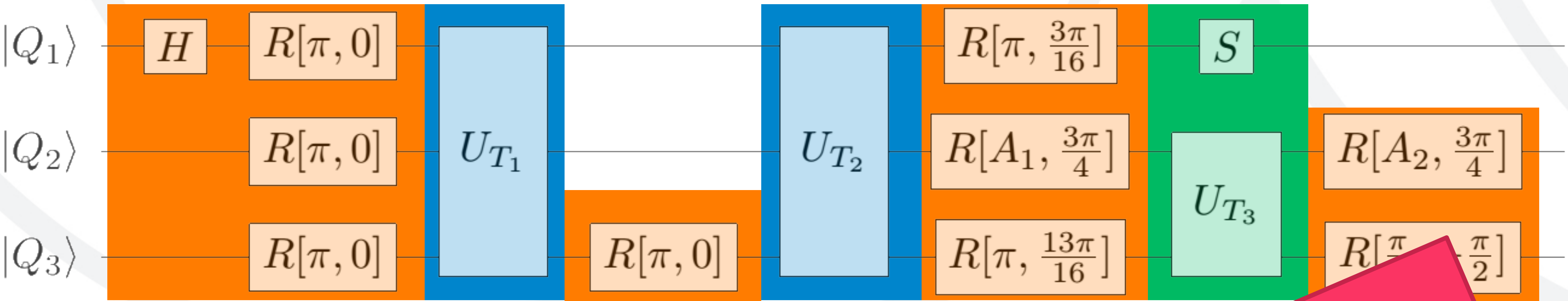
Coherent QFT: Period Finding



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

Science Advances **2** (2016)

Coherent QFT Using Simultaneous Coupling

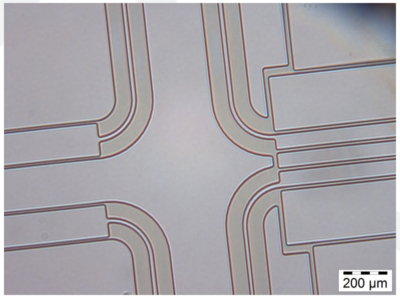


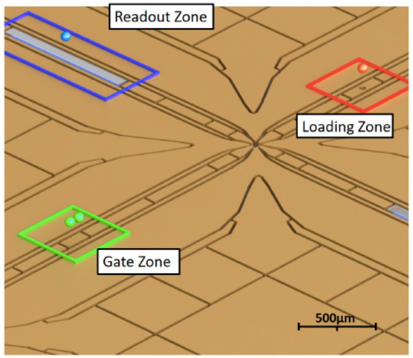
Total time 8.6 ms ≈ one CNOT gate

Science Advances **2** (2016)

MAGIC Outlook

- Stronger coupling $J \propto (\partial B)^2$
- Integrated Micro-Structured 2-D Trap Arrays
- Q-Simulations using Spins and Phonons
  e.g., D. Yang et al., PRA **94** (2016), PRA **89** (2014)
- Scalable Q-Computer





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