Towards scalable circuit model quantum computing with neutral atom qubits

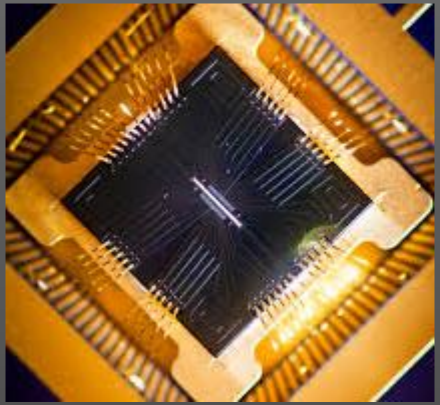
M. Saffman

Challenges of Quantum Computing

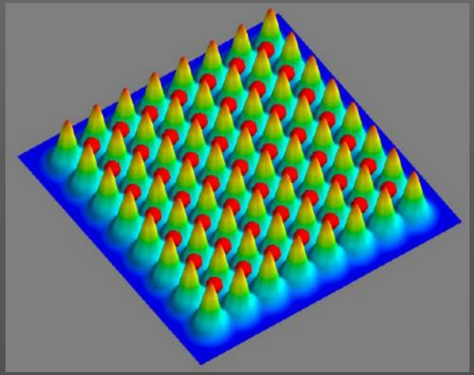
- Qubit isolation from the environment to preserve quantum states
- High fidelity quantum logic gates
- Qubit measurement without Xtalk
- Quantum error correction costs
  X10 to X1000 qubit overhead

Leading approaches

trapped ions

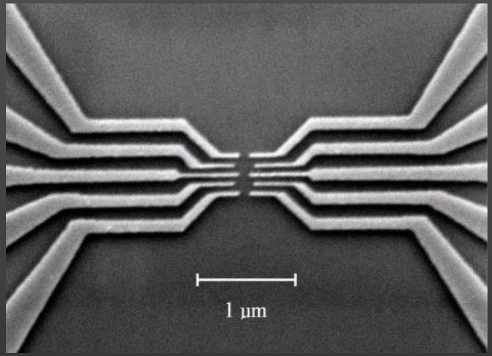


neutral atoms

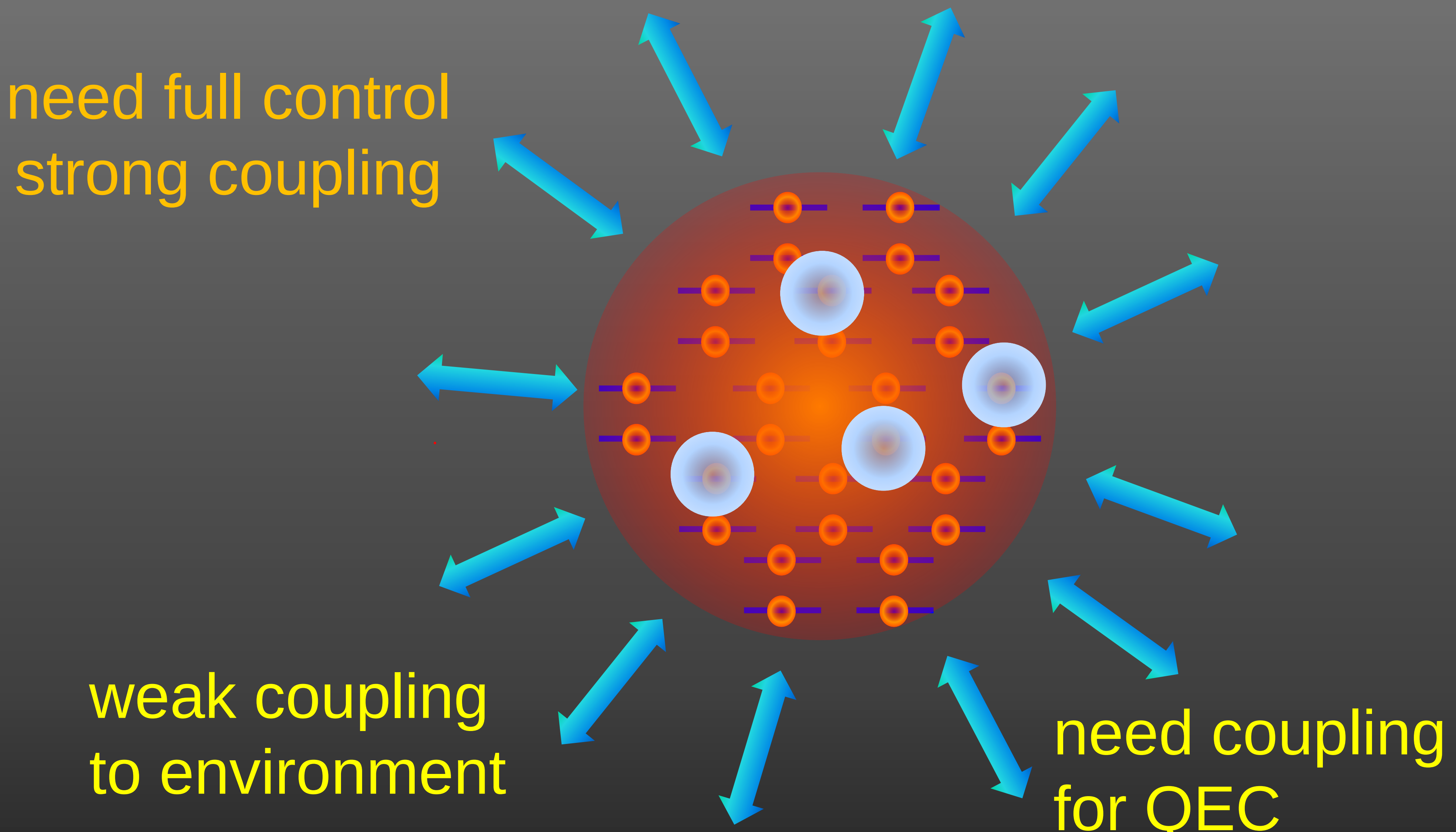


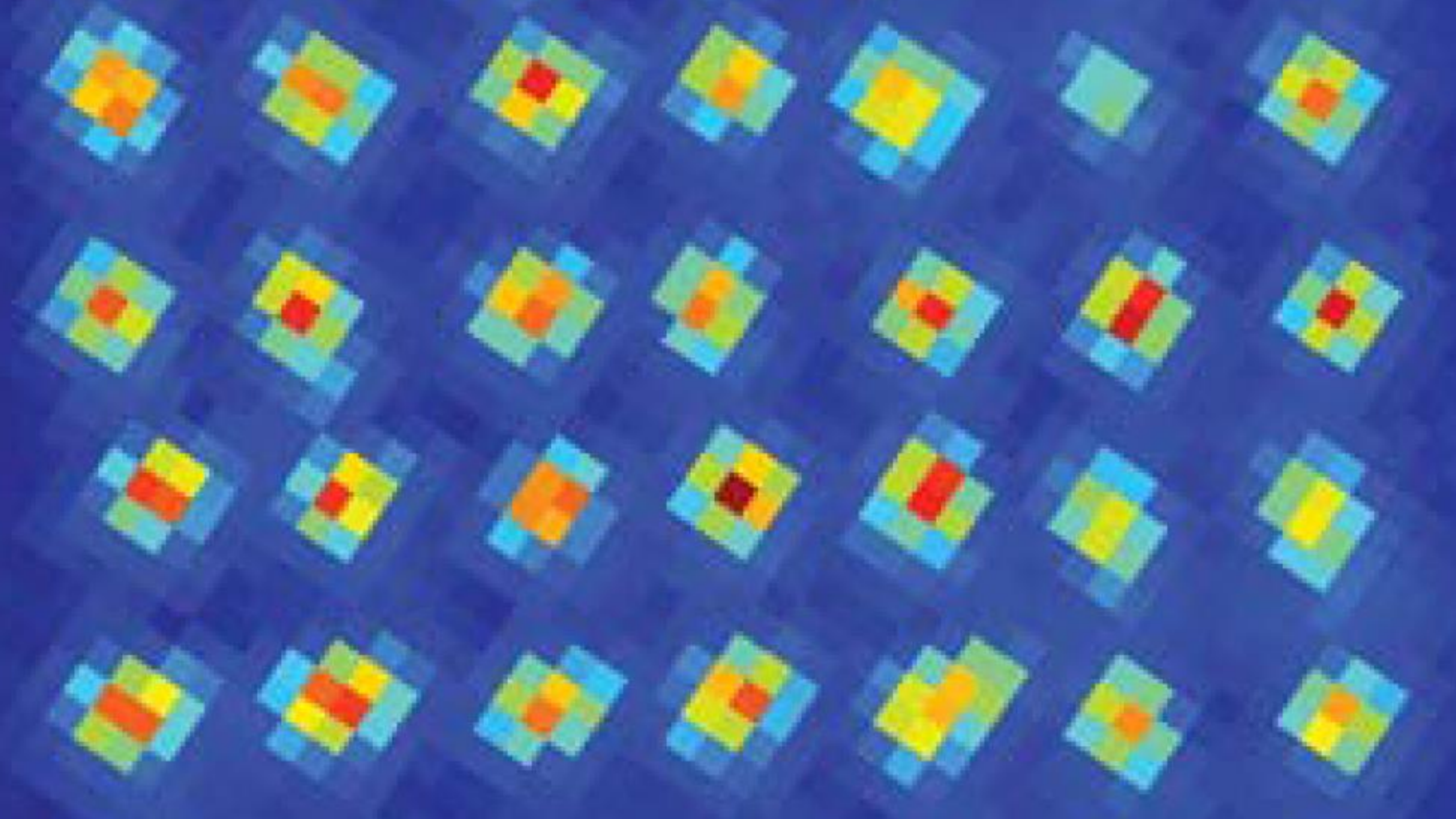
superconductors

2D quantum dots

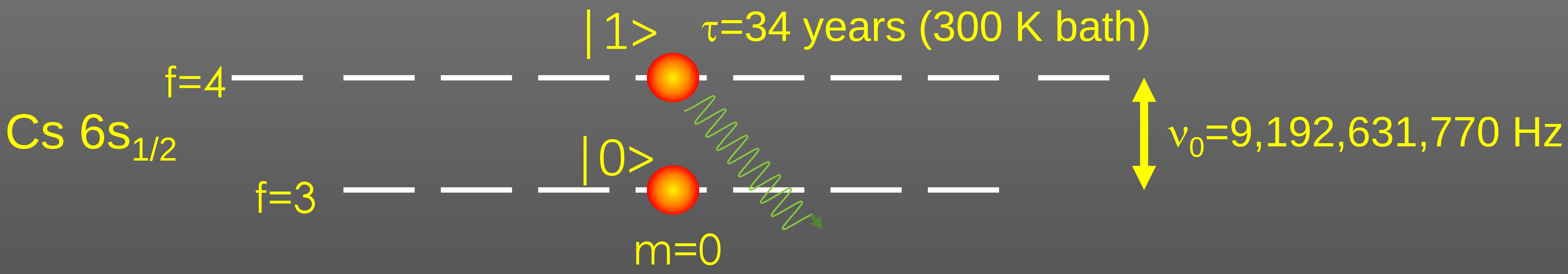


Dichotomy of Quantum Computing





Neutral atom qubits

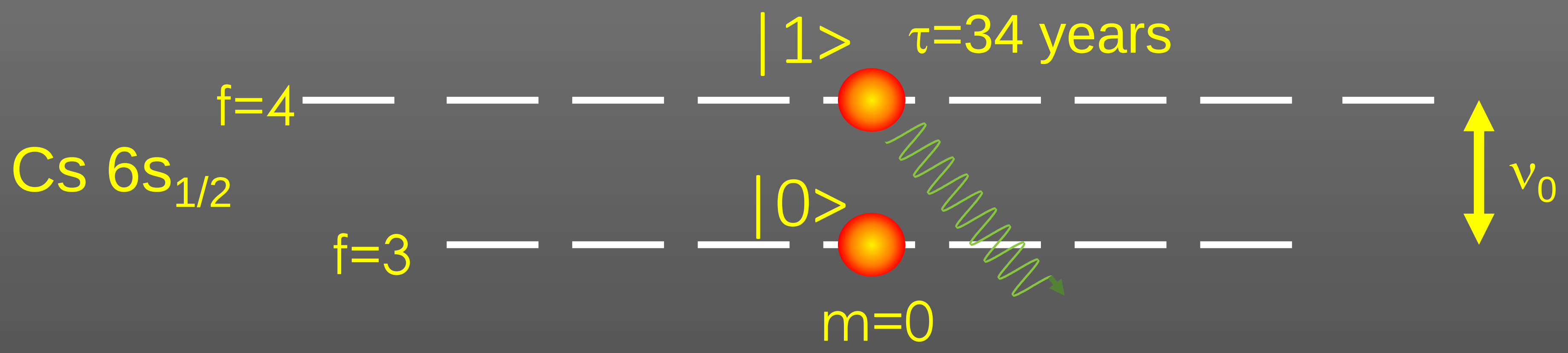


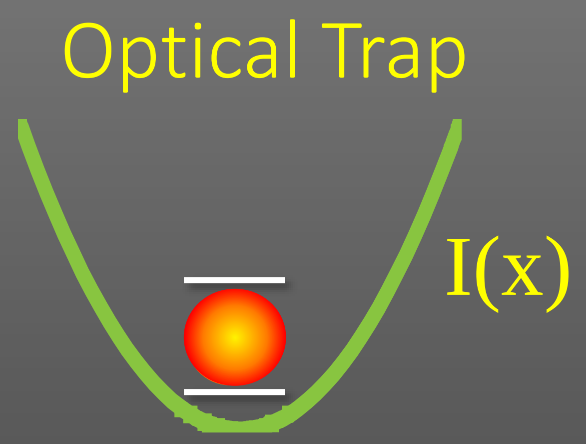
Quadratic Zeeman: $\nu = \nu_0 + 8.55 \times 10^{10}\ B_0\ \delta B$ Hz/T

$B_0 = 10^{-4}$ T, $\delta B = 10^{-8}$ T

$\Delta\nu \sim 0.1$ Hz

Neutral atom qubits





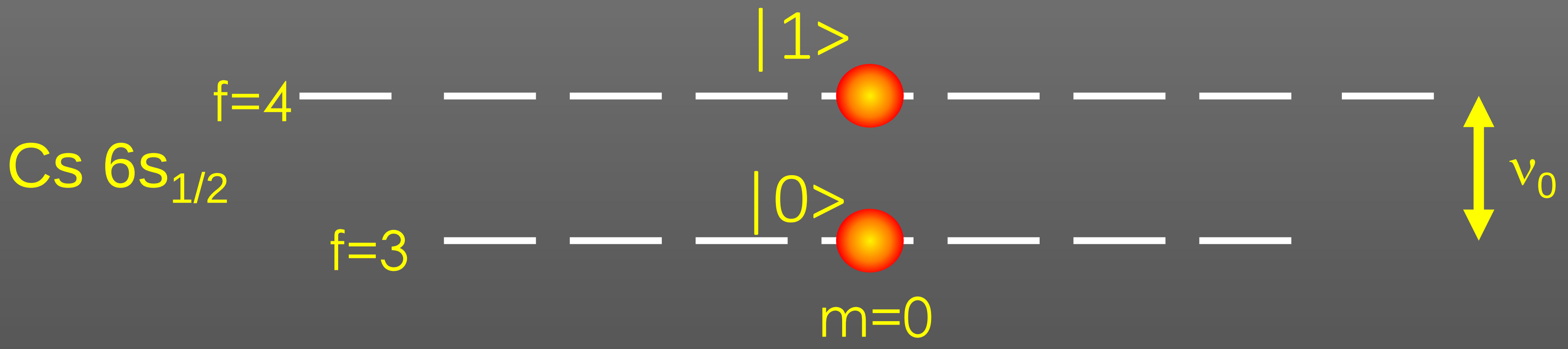
Tensor polarizability & hyperpolarizability $\delta\nu \sim \alpha\, I + \beta\, I^2$

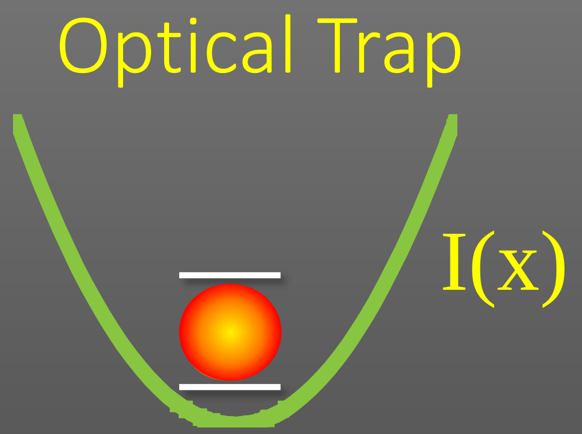
Adding sidebands to trap light can make traps doubly magic.

$$\left.\frac{\partial \nu}{\partial B}\right|_{B=B_0} = \left.\frac{\partial \nu}{\partial I}\right|_{I=I_0} = 0$$

A. Carr & MS, PRL 117, 150801 (2016)

Neutral atom qubits



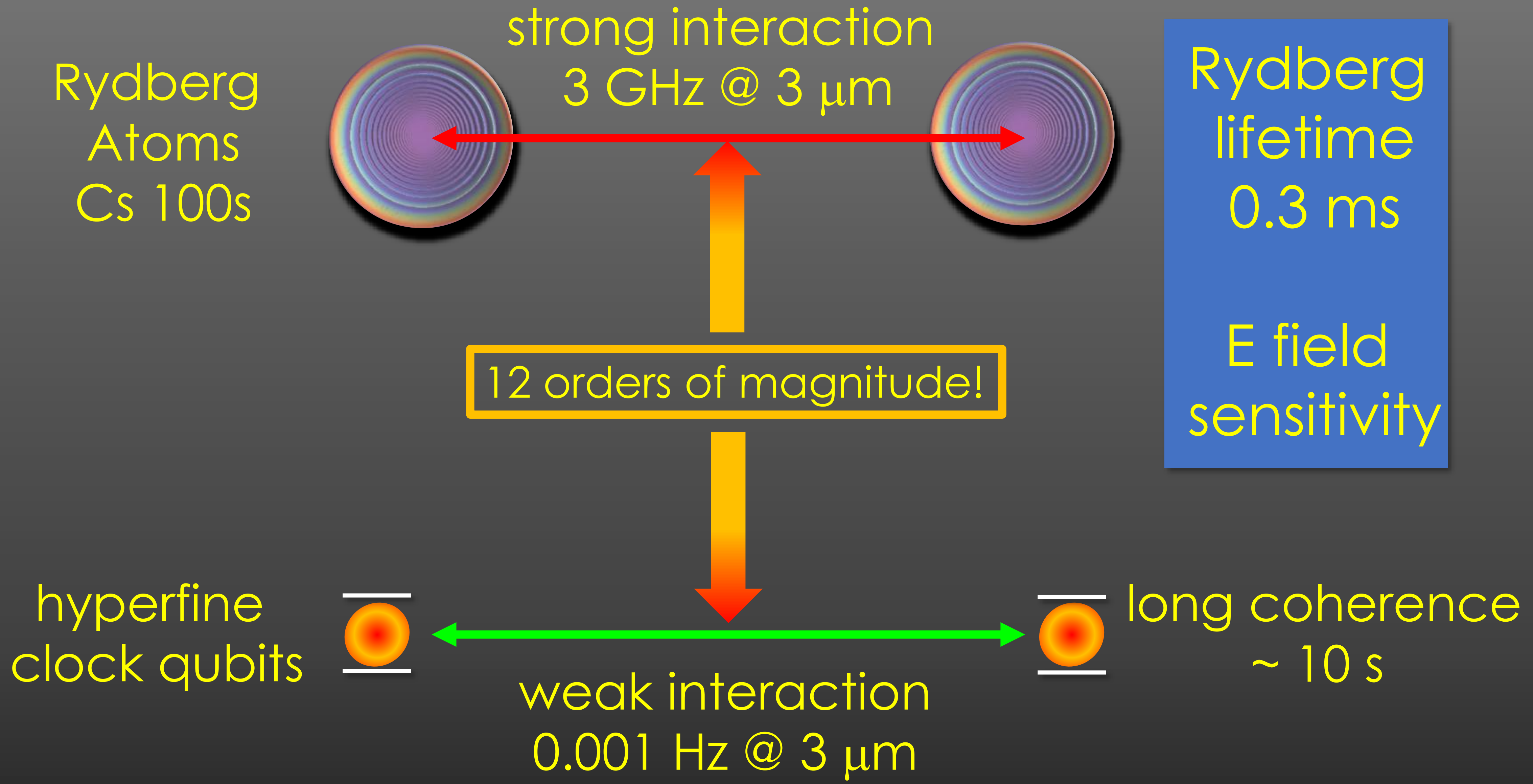


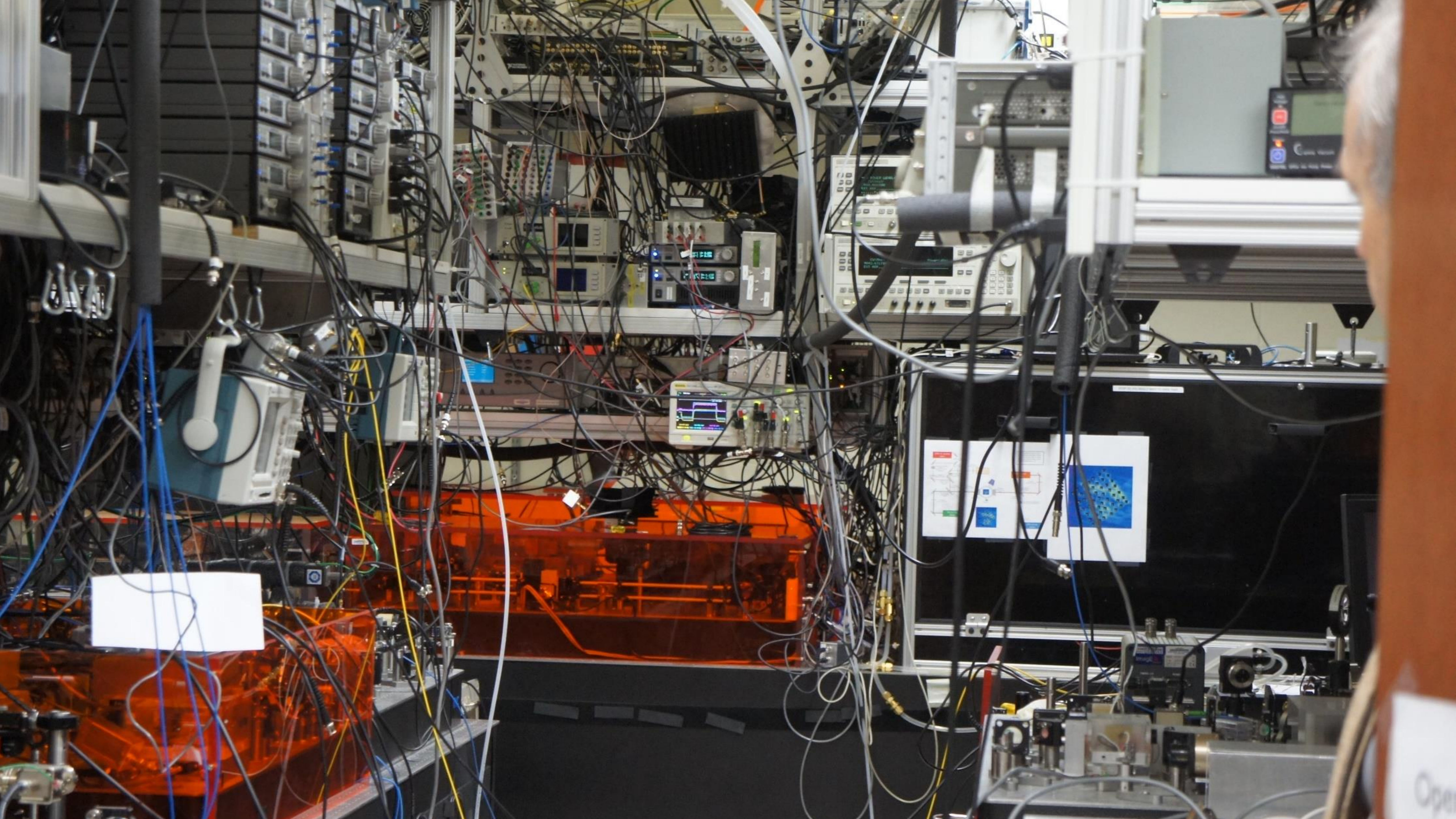
Coherence times as high as 10 sec. have been measured in optically trapped qubit arrays.

(Dave Weiss, PSU)

Decoherence rate ~ 0.1 s^{-1}

Neutral atom approach





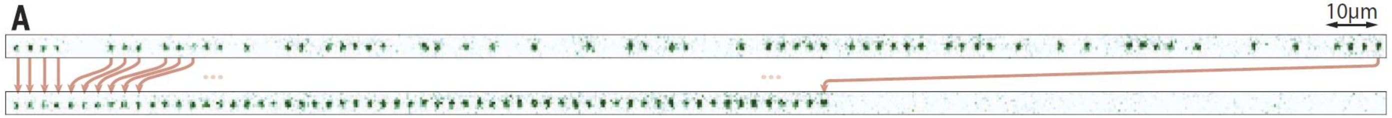
Atomic qubits in optical lattices & Rydberg interactions

1D

New Mexico, Wuhan

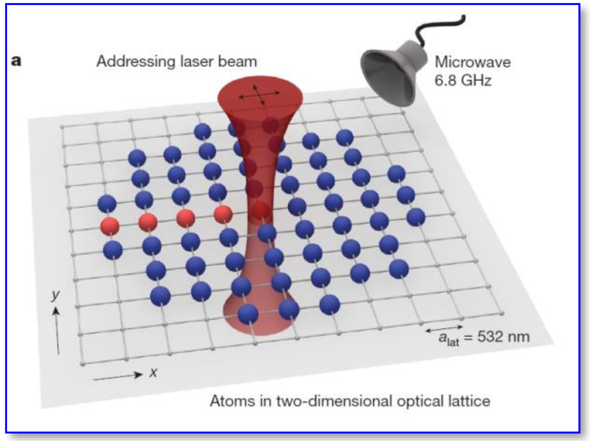
2 sites

Harvard 100 sites, atom rearrangement



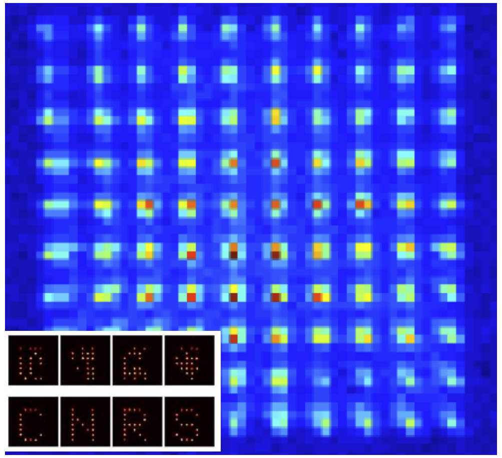
2D

~100 sites, 2D array, red detuned



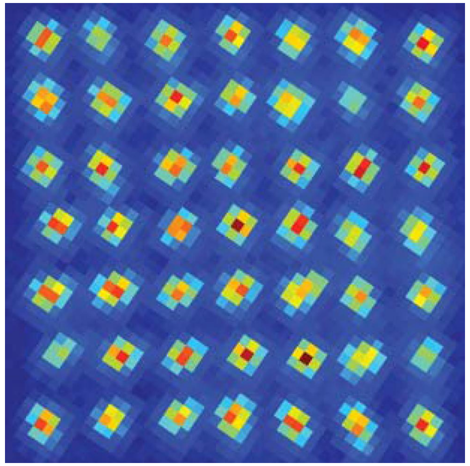
Max Planck, Garching

100 sites, 2D array, red detuned



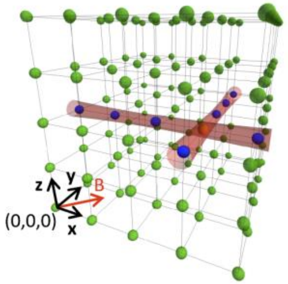
Institut d'Optique

49 sites, 2D array, blue detuned



Wisconsin

3D

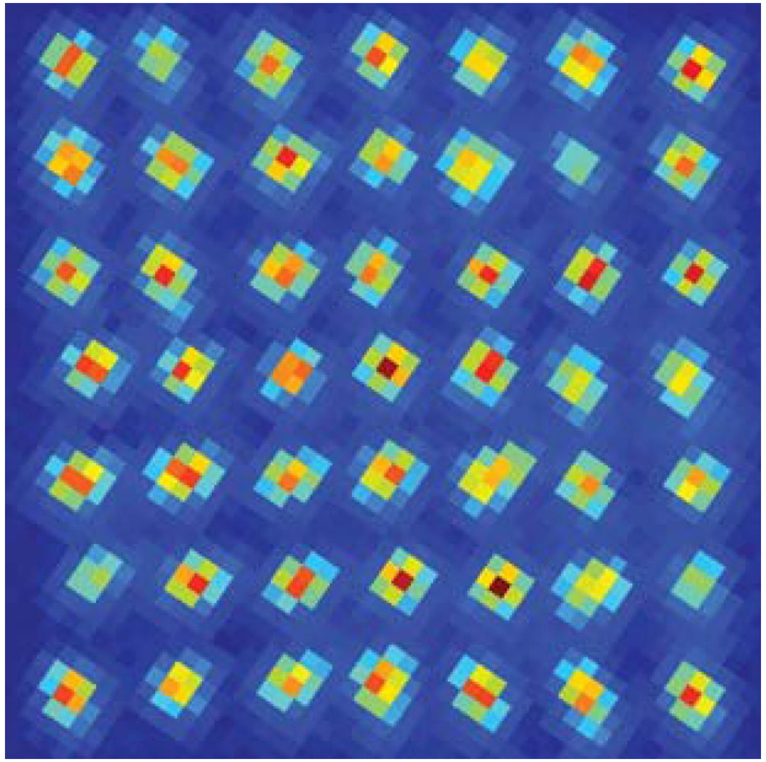


125 sites, blue detuned

PSU – not yet Rydberg

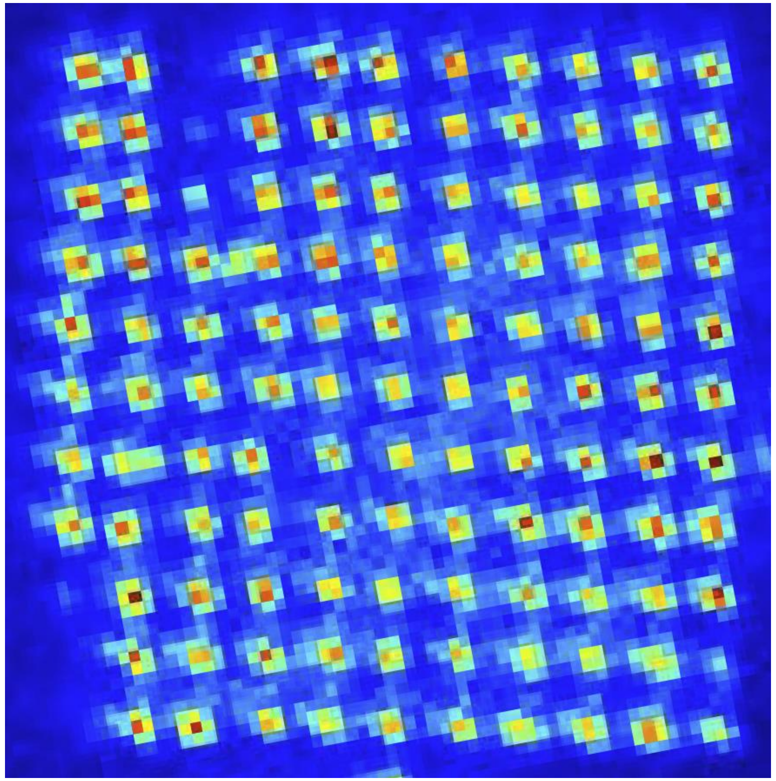
Lattice design

2D array of 3D optical traps



PRA **88**, 013420 (2013)

121 site array in progress



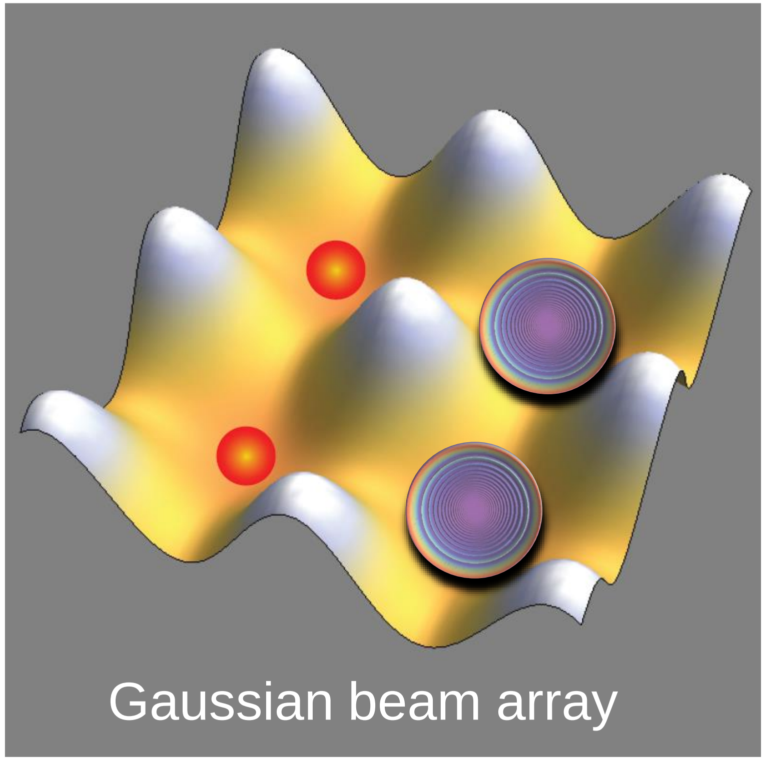
line array - twice more efficient use of optical power

insensitive to optical perturbations

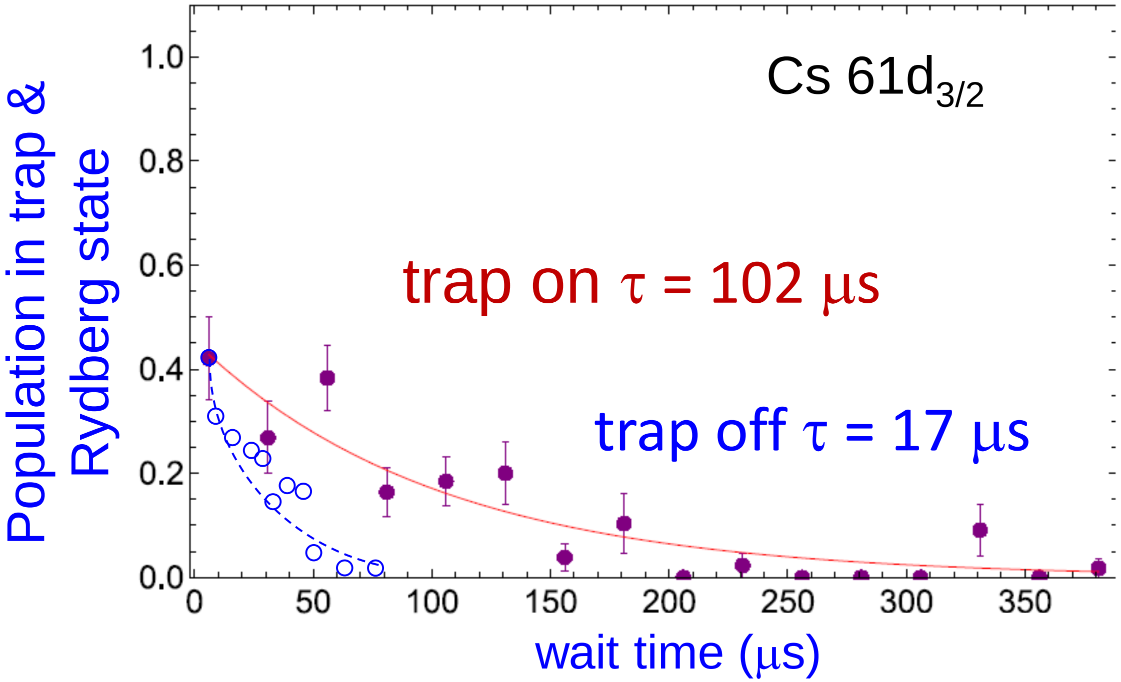
Rydberg trapping

PRA 84, 043408 (2011)

2D array of 3D traps



Blue detuned light traps ground and Rydberg states at intensity minimum.

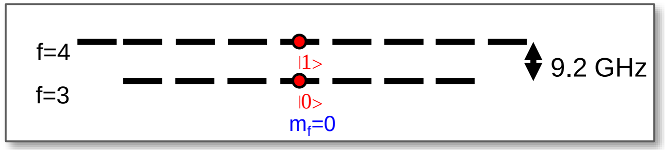


Accounting for spontaneous lifetime & blackbody repopulation this implies a mechanical trap lifetime

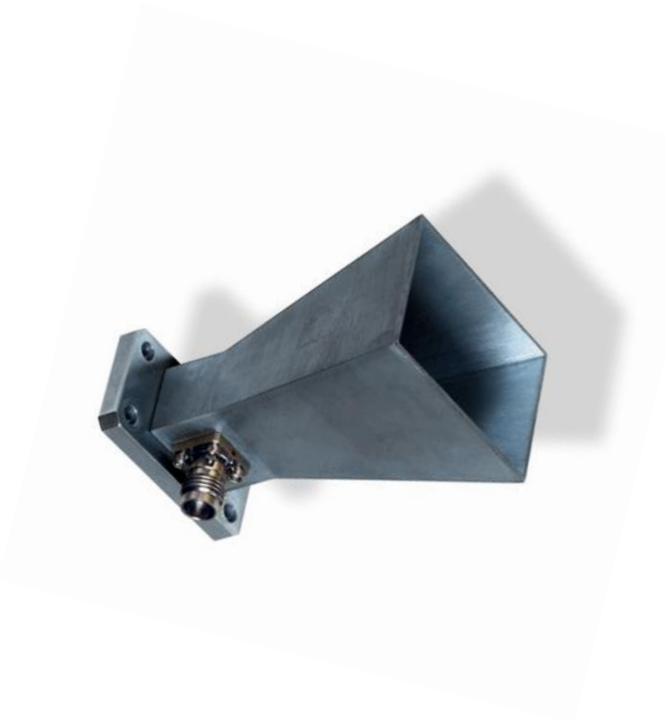
τ_{mech} =0.35 ms >> τ_{spont}

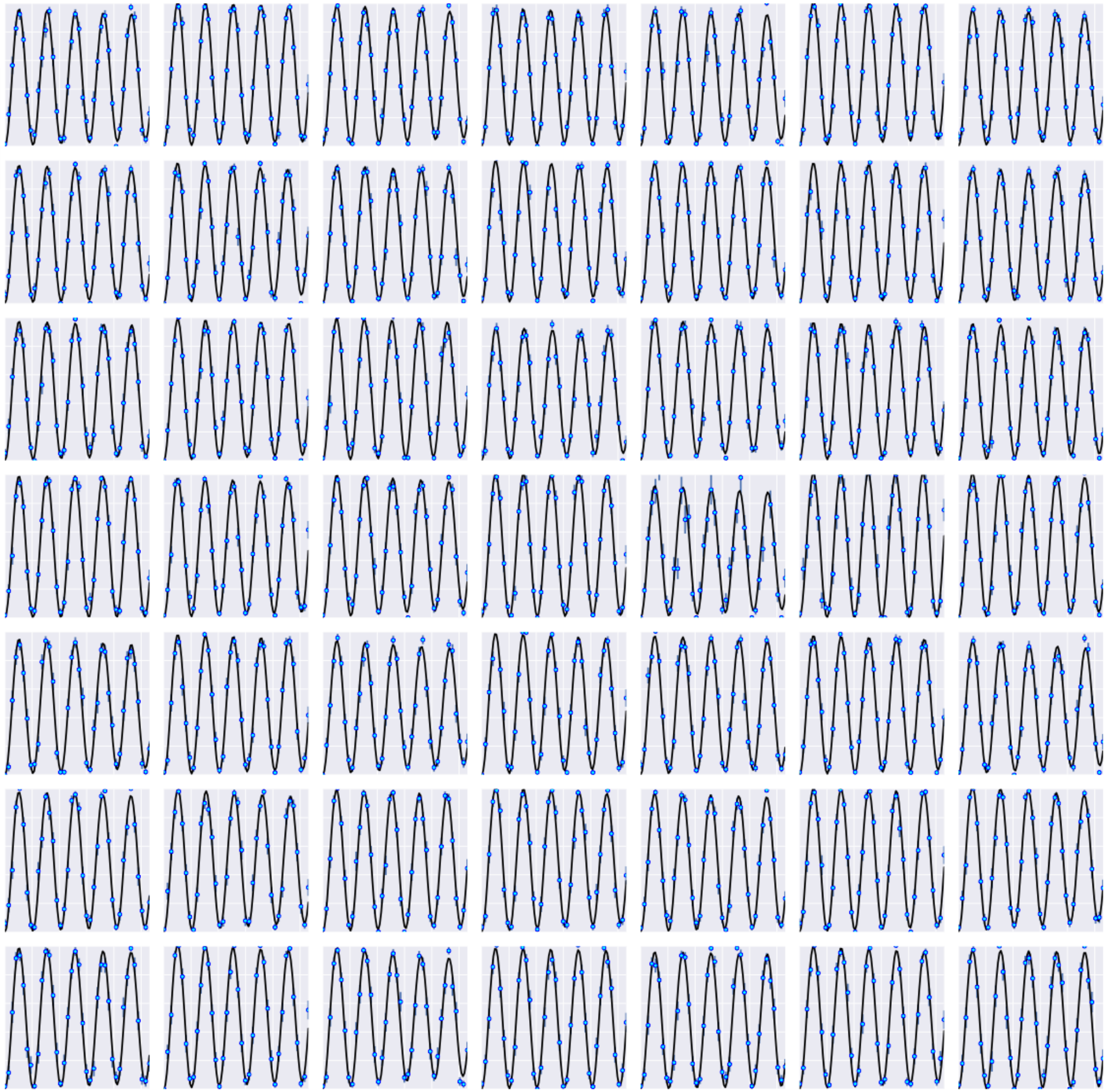
Single qubit gates - global

Cs clock state qubits



Bias field of 1.5 G





Microwaves 10 kHz Rabi frequency

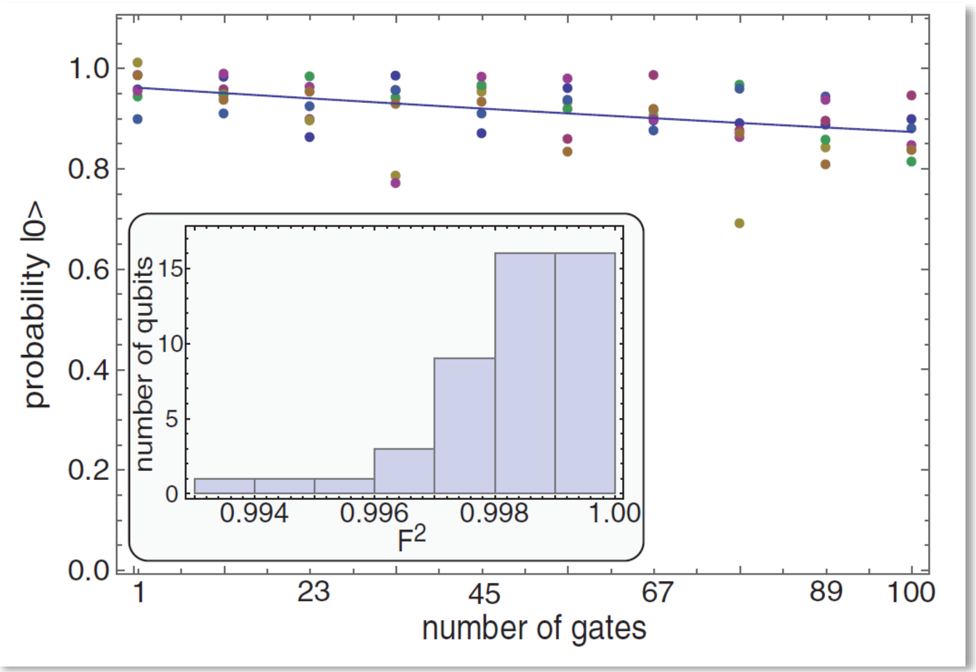
Randomized benchmarking

T.Xia, M. Lichtman et al.
PRL **114**, 100503 (2015)

Quantify gate fidelity with
random sequence of Clifford gates

Fidelity ~ 0.999
Close to threshold for
quantum error correction

$\langle F^2 \rangle_{47\ \text{sites}}$	0.9983 ± 0.0014
F^2_{min}	0.9939 ± 0.0007
F^2_{max}	0.9999 ± 0.0003



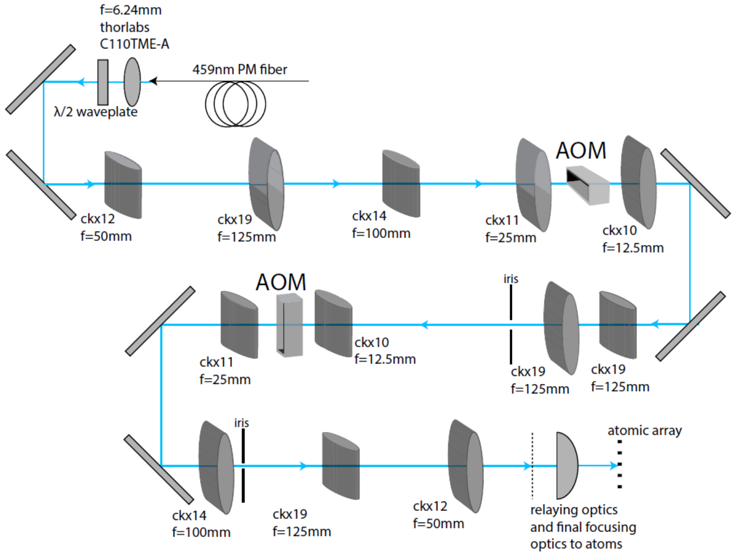
$$P_{|0\rangle} = \frac{1}{2} + \frac{1}{2}(1 - d_{\text{if}})(1 - d)^l$$

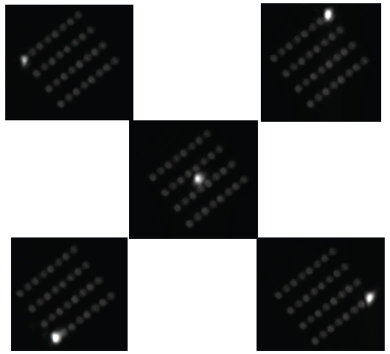
$$F(\rho, \rho') = \text{Tr}\left[\sqrt{\sqrt{\rho}\rho'\sqrt{\rho}}\right]$$

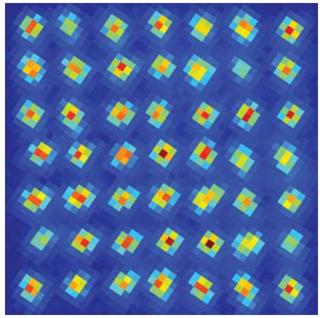
$$F^2 = 1 - \frac{d}{2}$$

Single qubit gates – site selected

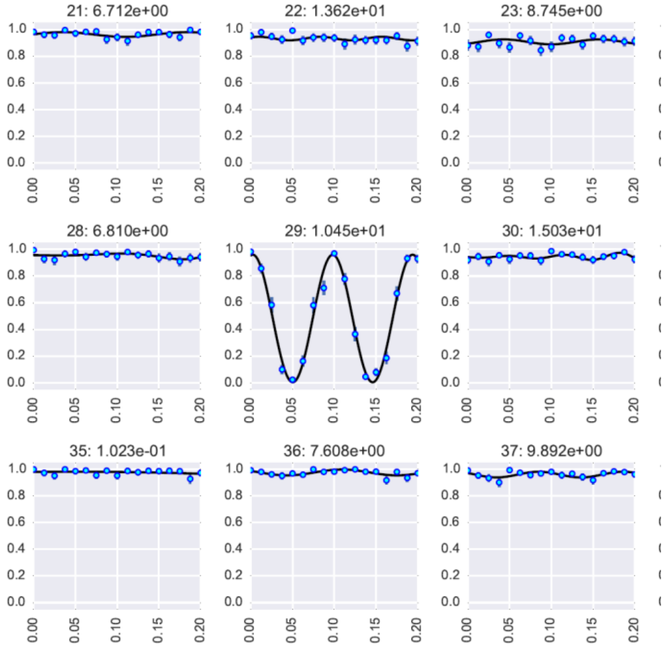
Stark shift target site with 2D acousto-optic scanner







Microwave
+ Stark shift laser



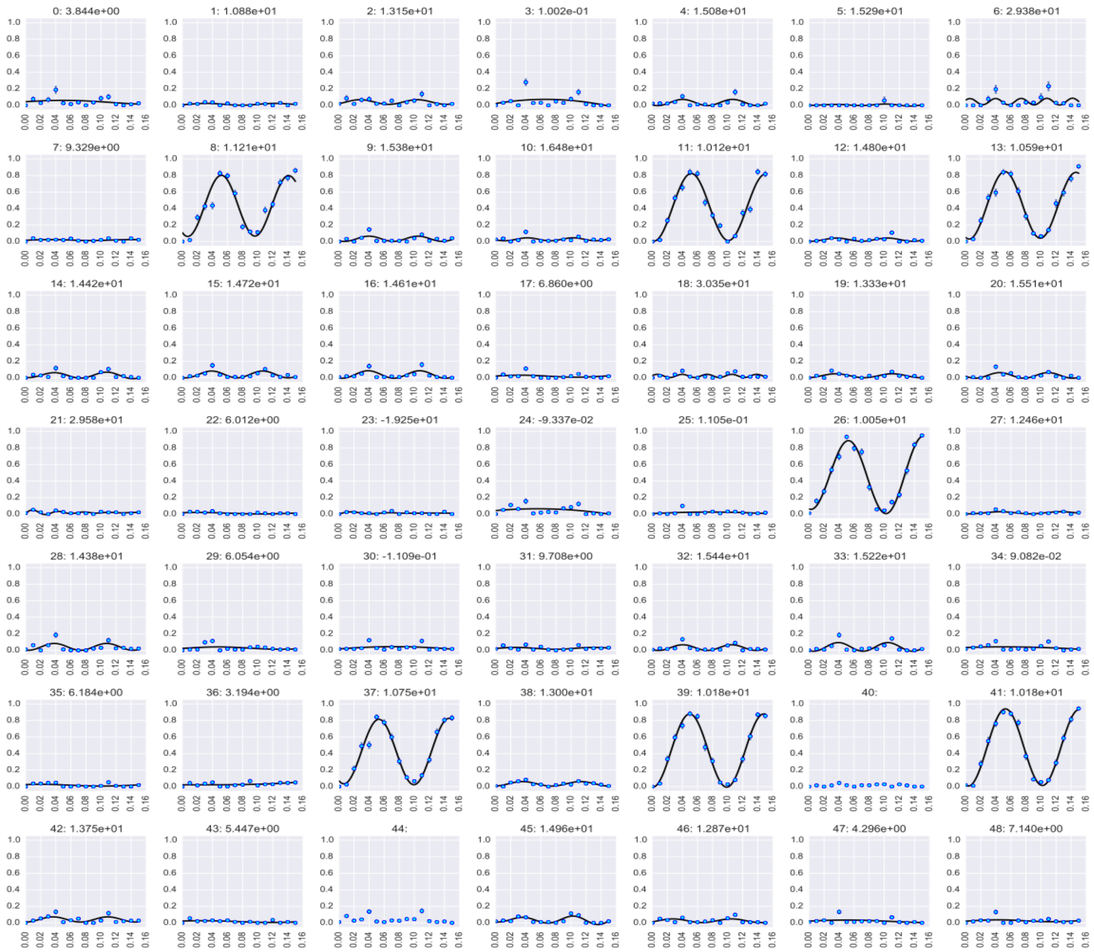
Single qubit gates – multiple sites 2D

Sequential addressing

Switching time < 1 μs

Crosstalk is accumulated in all 7 rotations ~ few %.

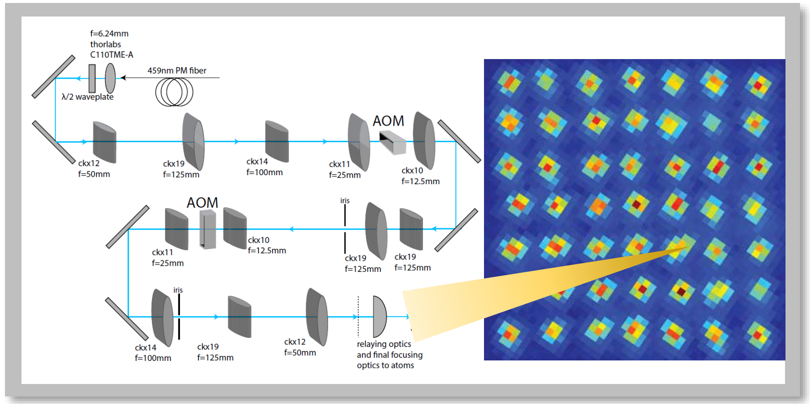
Fidelity ~ 0.99 <Xtalk> ~ 0.01



Single qubit gates – Scalability

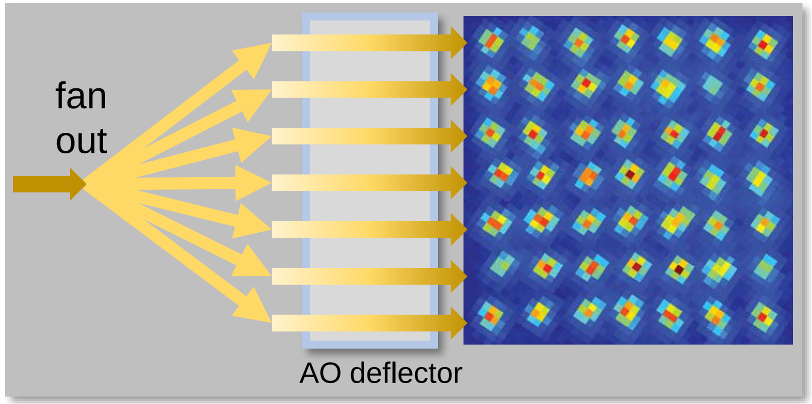
Scalable error correction requires parallel gate operations.

Crossed AOMs access one site at a time.



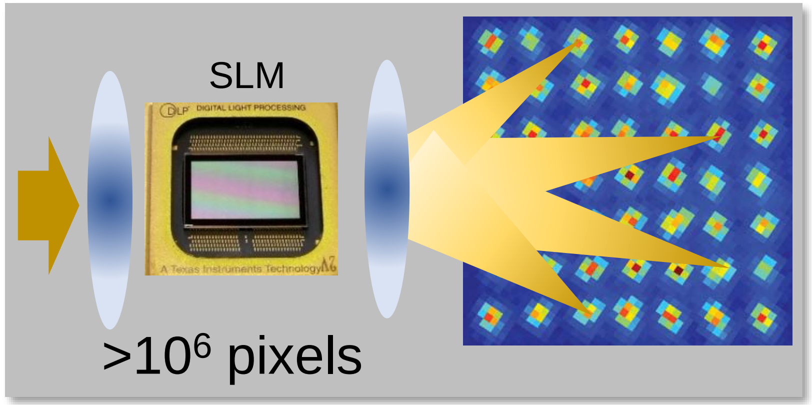
Row parallel single site gates with multichannel AO deflector.

N times optical power cost for N sites.



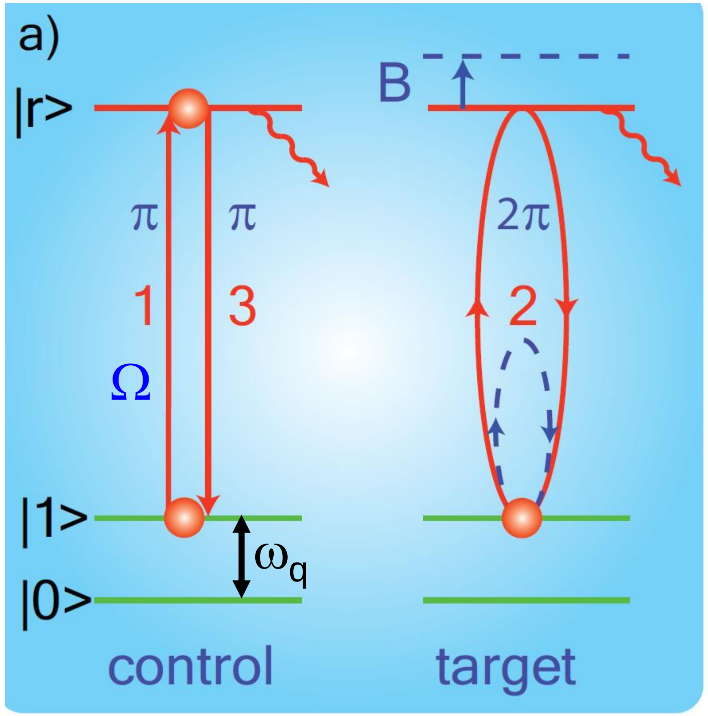
Full parallel operation with spatial light modulator

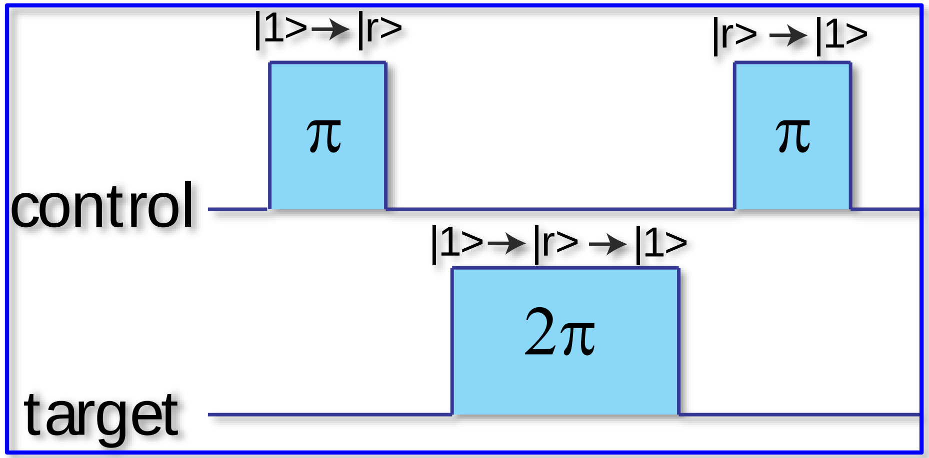
N^2 times optical power cost for N^2 array.



Rydberg blockade C_Z gate

Jaksch, et al. PRL (2000)





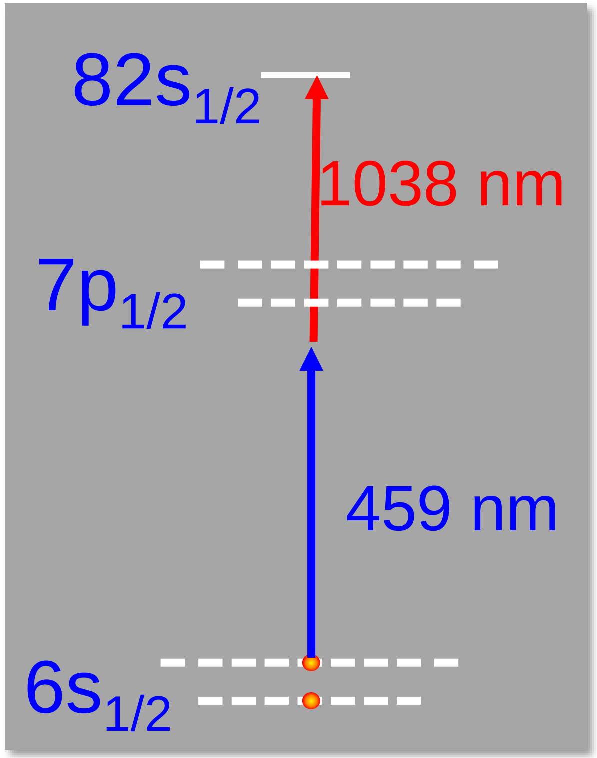
Ideal C_Z Gate

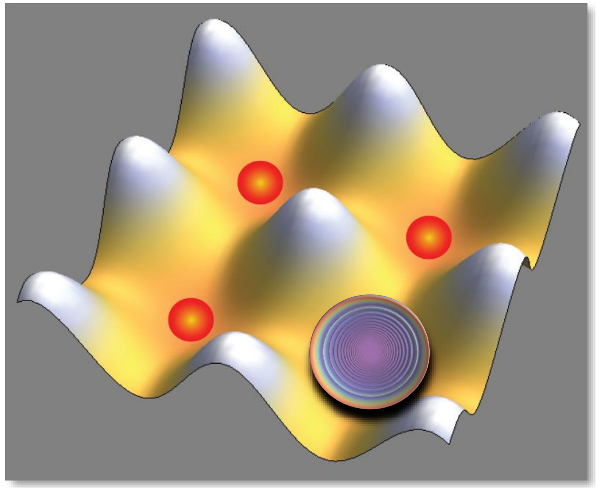
ω_q, B >> Ω >> $1/\tau_{Ryd}$

$$C_Z = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

CNOT experiment

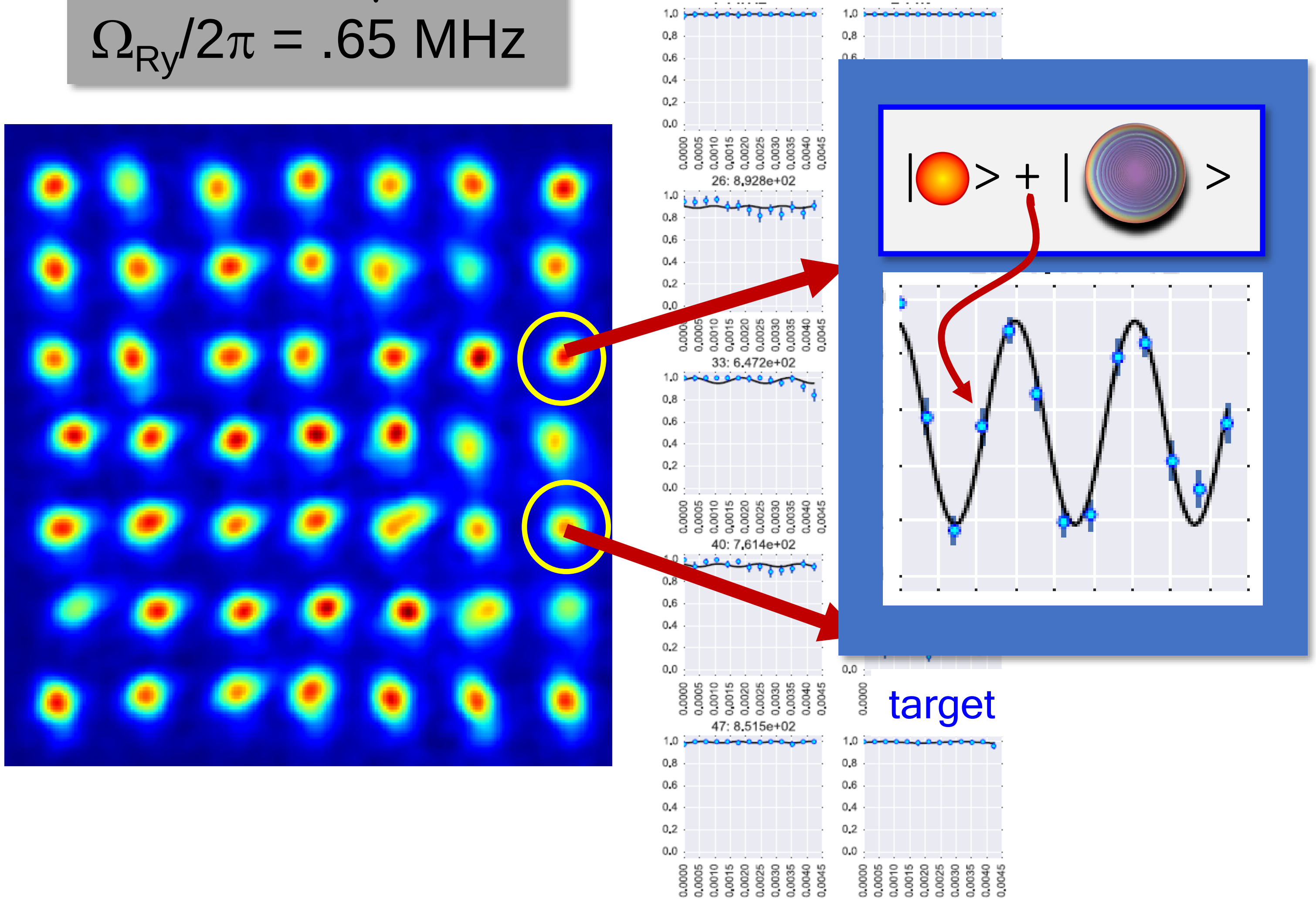
PRA **92**, 022336 (2015)





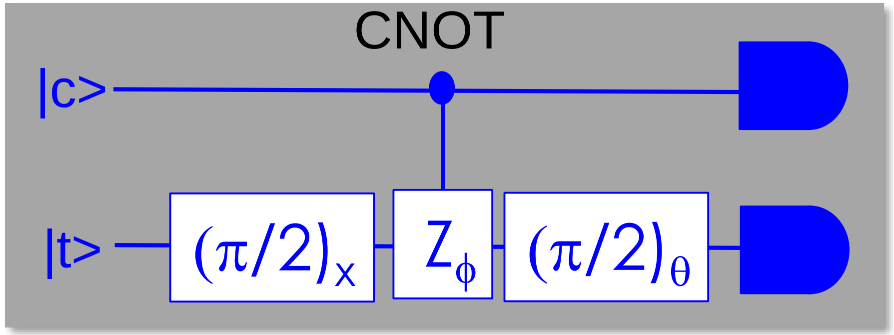
$B(R)/2\pi$ = 23 MHz
$R=2d$ = 7.6 μm
$\Omega_{Ry}/2\pi$ = .65 MHz

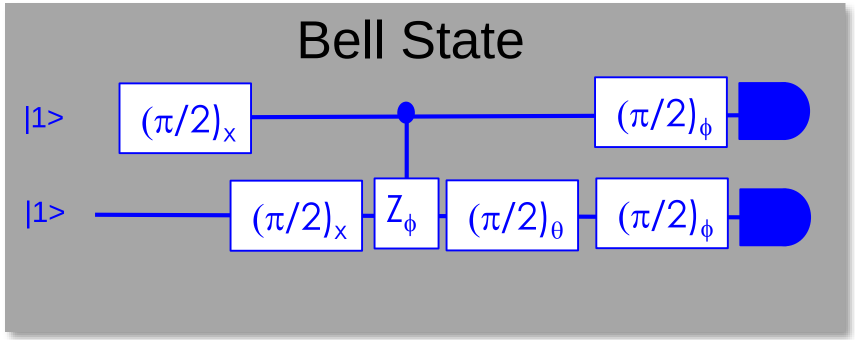
Ground-Rydberg
Rabi oscillations



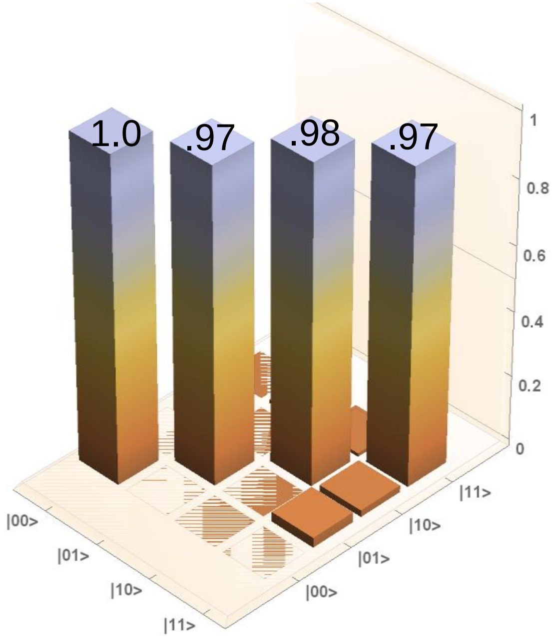
CNOT sequence & Bell states

PRA **92**, 022336 (2015)

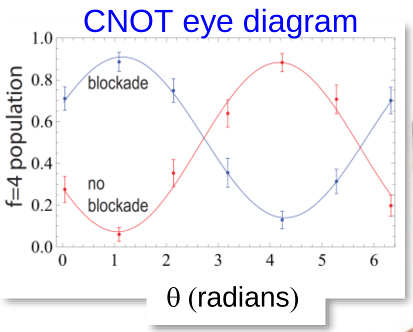


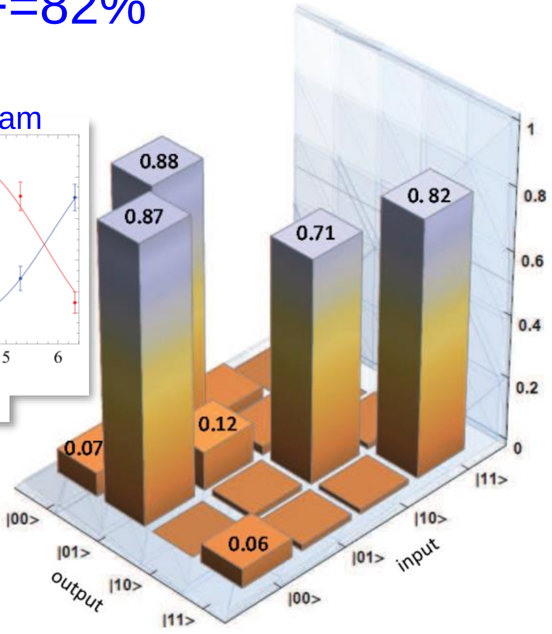


State preparation
F=98%

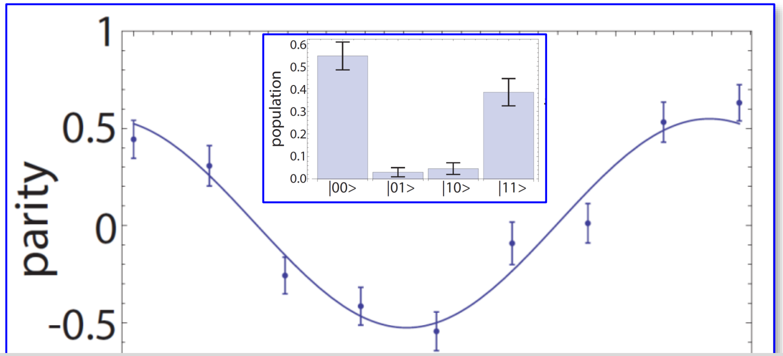


CNOT truth table
F=82%





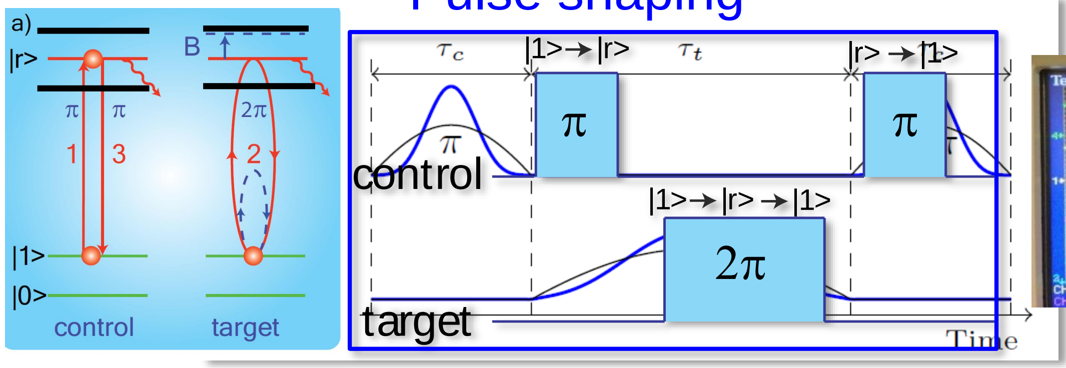
Bell state: F=0.73 +/- 0.05
F=0.79 +/- 0.05 (post selected)

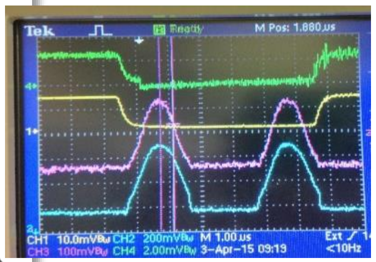


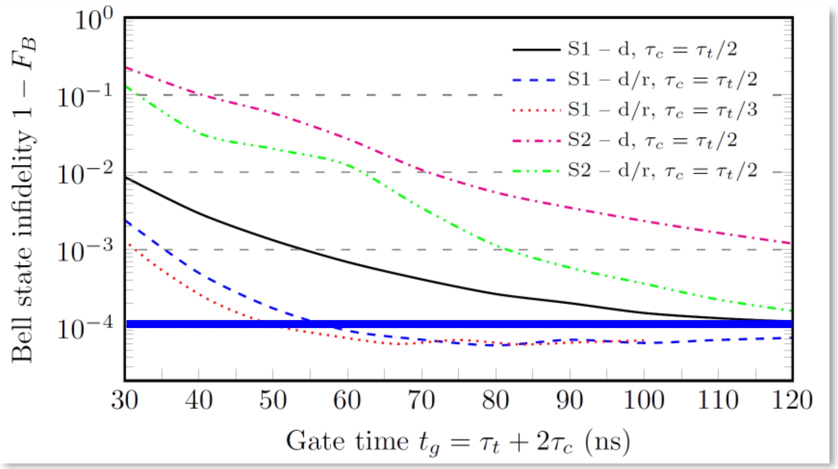
F limited by SPAM errors, atom motion (Doppler), perturbing fields, laser noise, beam position noise, physics.

Improved CNOT protocols

Pulse shaping





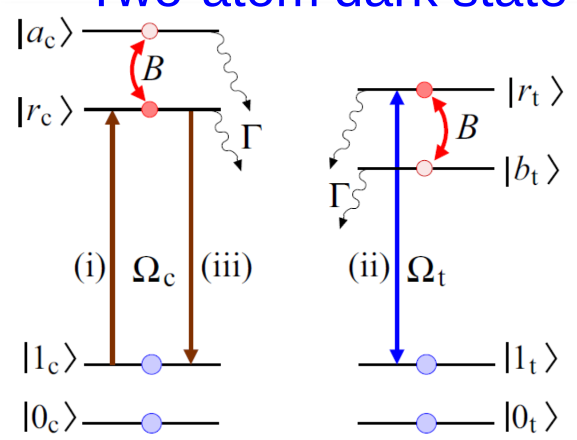


PHYSICAL REVIEW A **94**, 032306 (2016)

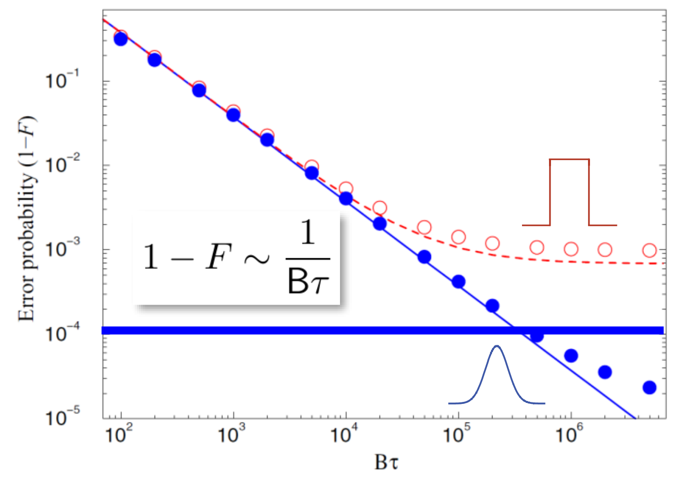
High-fidelity Rydberg-blockade entangling gate using shaped, analytic pulses

L. S. Theis,* F. Motzoi, F. K. Wilhelm M. Saffman

Two-atom dark state



$1\text{-}F<10^{-4}$



PHYSICAL REVIEW A **96**, 042306 (2017)

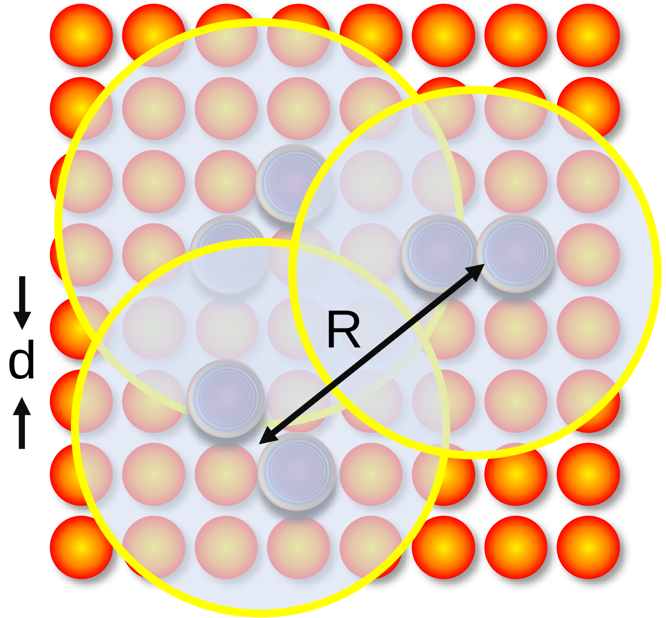
High-fidelity Rydberg quantum gate via a two-atom dark state

David Petrosyan,[1,2] Felix Motzoi,[1] Mark Saffman,[3] and Klaus Mølmer[1]

Two qubit gates – Scalability

Dense parallel operations not possible due to long range Rydberg interaction

$1/R^6$ vdW interaction



R/d > 5

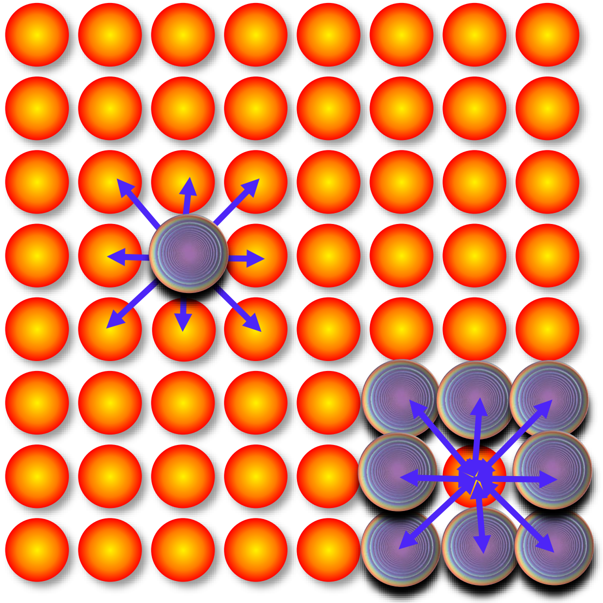
gives

Xtalk < 10^{-4}

Multi-qubit gates

Can turn a bug into a feature for multi-qubit gate operations. Native $CNOT^k$ & C_kNOT gates.

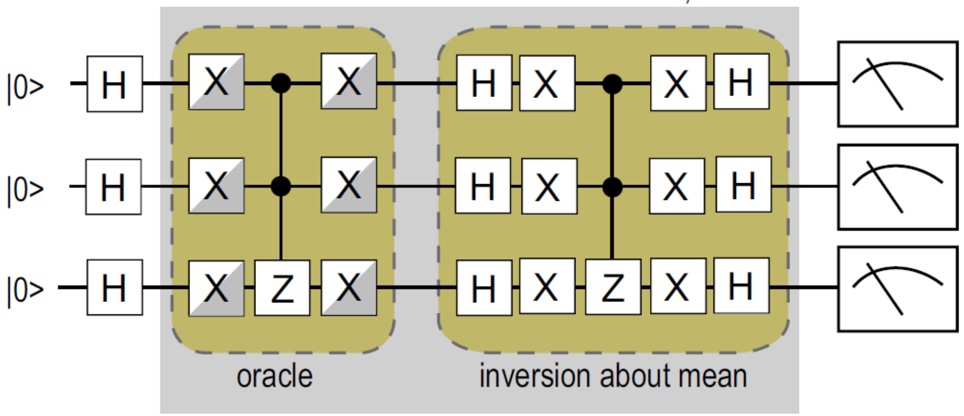
Wisconsin, Aarhus, Innsbruck….



J. Phys. B: At. Mol. Opt. Phys. **49** (2016) 094004

Grover search algorithm with Rydberg-blockaded atoms: quantum Monte Carlo simulations

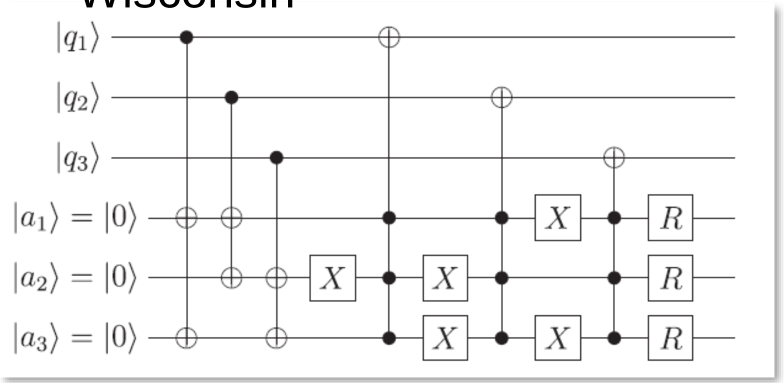
Aarhus, Wisconsin



PRL **117,** 130503 (2016)

Improved Error Thresholds for Measurement-Free Error Correction

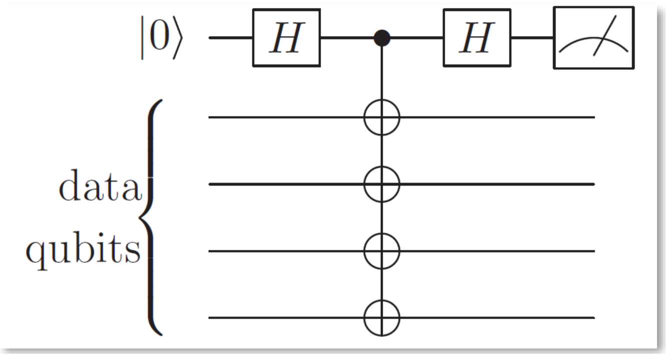
Wisconsin



PHYSICAL REVIEW A **96**, 052320 (2017)

Blueprint for fault-tolerant quantum computation with Rydberg atoms

UCL, London



Hardware outlook

Parameter	Today	Near term realism	
Number qubits	80/121	600/900	laser&optics upgrade
Fidelity qubit measurement	0.99@10 msec	>0.99@1 msec	higher NA lens
Fidelity one-qubit gate	0.99-0.999@100 μs	>0.999@200 ns	Raman laser
Fidelity two-qubit gate	0.73@3 μs	>0.99@500 ns	sideband cooling, laser noise reduction

Quantum simulator

Many proposals for cold atom quantum simulators. Erez Zohar yesterday

Rydberg versions

ARTICLES
nature physics
PUBLISHED ONLINE: 14 MARCH 2010 | DOI: 10.1038/NPHYS1614

A Rydberg quantum simulator

Hendrik Weimer[1]*, Markus Müller[2], Igor Lesanovsky[2,3], Peter Zoller[2] and Hans Peter Büchler[1]

A quantum annealing architecture with all-to-all connectivity from local interactions

Wolfgang Lechner,[1,2]* Philipp Hauke,[1,2] Peter Zoller[1,2]

Sci. Adv. 2015;1:e1500838 23 October 2015

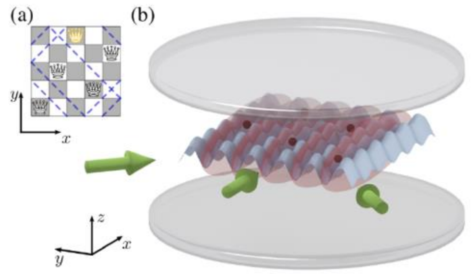
ARTICLE
Received 27 Oct 2016 | Accepted 4 May 2017 | Published 22 Jun 2017 DOI: 10.1038/ncomms15813 OPEN

A coherent quantum annealer with Rydberg atoms

A.W. Glaetzle[1,2,3,4,*], R.M.W. van Bijnen[1,2,*], P. Zoller[1,2] & W. Lechner[1,2]

arXiv:1803.00735 **A Quantum N-Queens Solver**

Valentin Torggler,[1] Philipp Aumann,[1] Helmut Ritsch,[1] and Wolfgang Lechner[1]



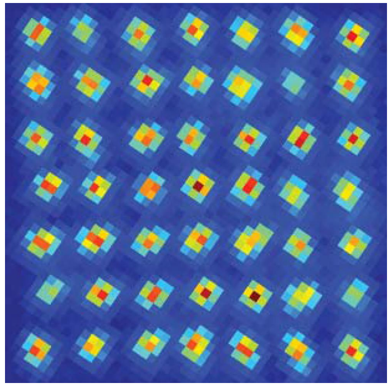
Summary

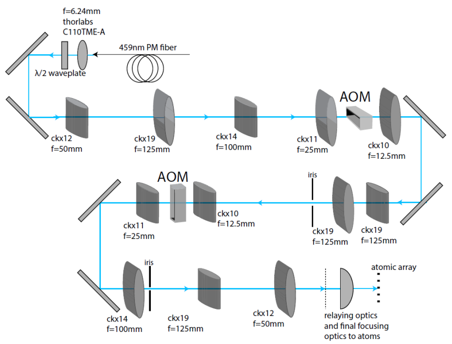
Neutral atom qubits

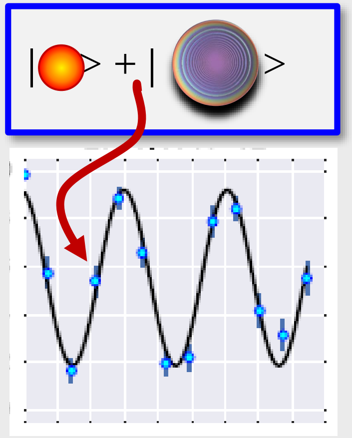
Optical wiring

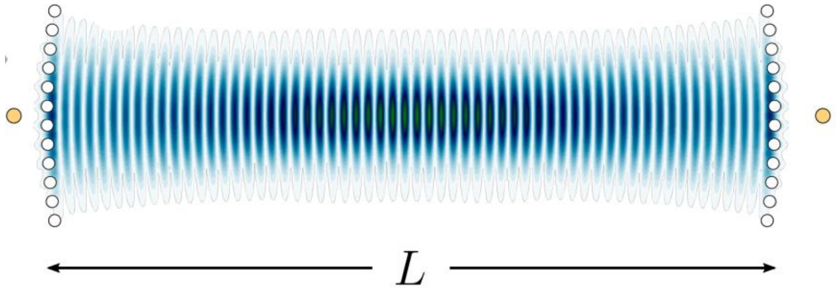
Rydberg interactions for entangling gates

Atom-photon interface for connectivity



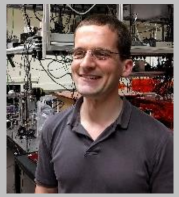







Trent Graham


Matt Ebert


Garrett Hickman


Xiaoyu Jiang


Cody Poole

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

NSF ARL
WARF Wisconsin Alumni Research Foundation