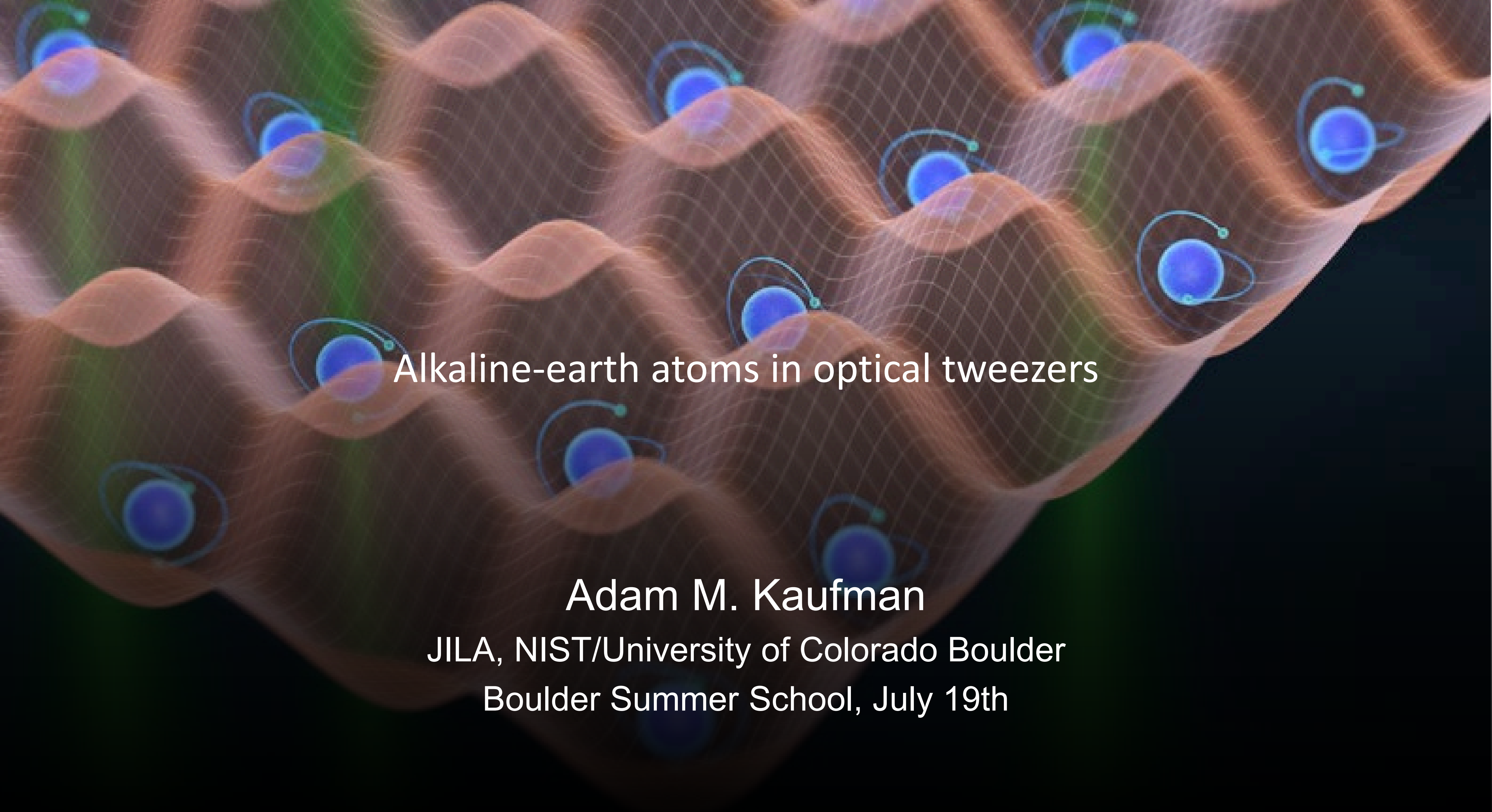


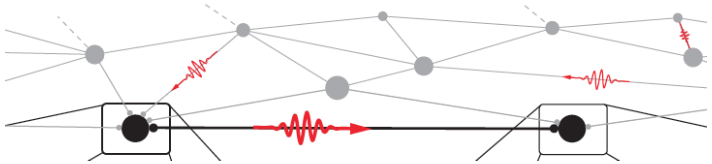
Alkaline-earth atoms in optical tweezers

Adam M. Kaufman

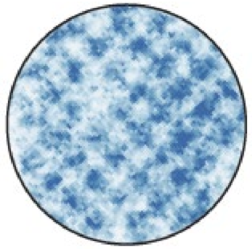
JILA, NIST/University of Colorado Boulder

Boulder Summer School, July 19th

Quantum science = “Quantum state engineering”

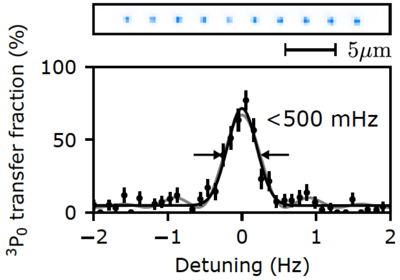


Communication



Simulation

Computing



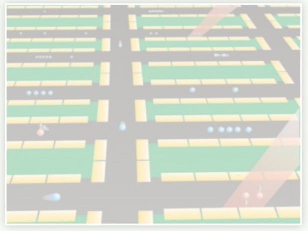
Metrology

Ritter...Rempe, Nature (2012); Britton...Bollinger, Nature (2012)
Mazurenko...Greiner, Nature (2017); Harrow and Montanaro, Nature (2017)

Quantum Science Wish List:

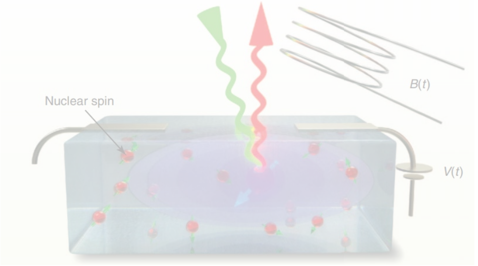
- ☑ Multiple identical quantum objects, qubits
- ☑ Long-lived quantum coherence
- ☑ Single particle control/detection
- ☑ Strong controllable interactions

Ions



Monroe and Kim, Science (2013)

Solid-state defects

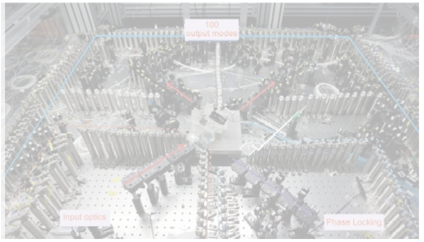


Awschalom…Petta, Science (2013)

Ultracold atoms

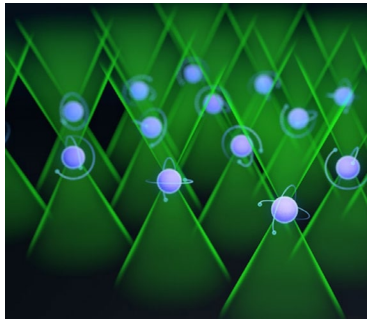
Mazurenko….Greiner, Nature (2017)

Photons

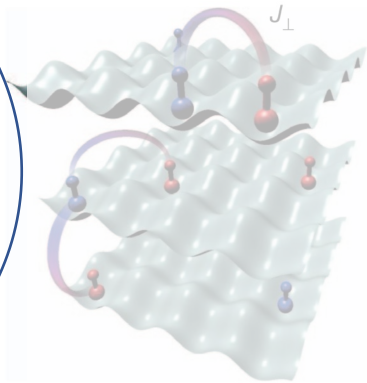


Zhong…Pan, Nature (2020)

Atoms in tweezer arrays

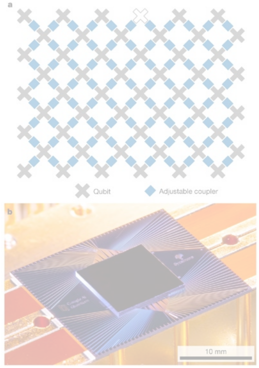


Molecules



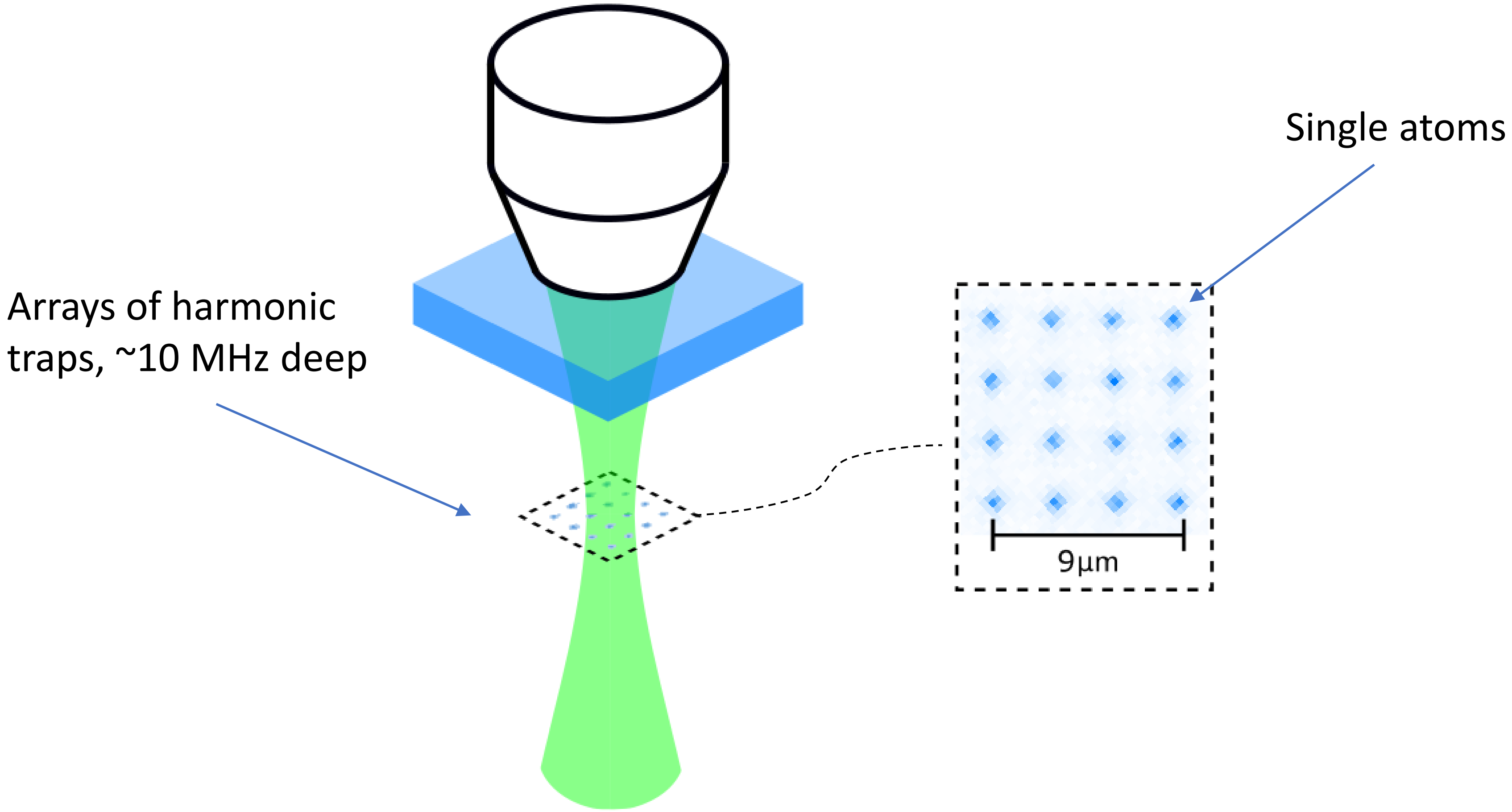
Yan…Ye, Nature (2013)

Superconducting circuits



Arute…Martinis, Nature (2019)

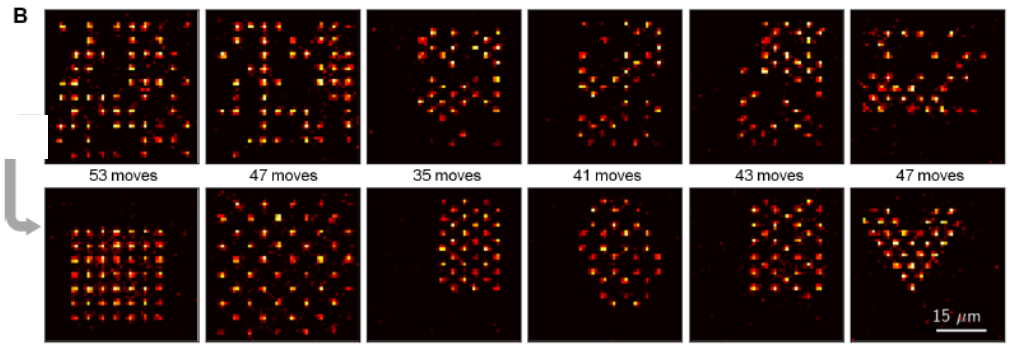
Optical tweezer arrays of neutral atoms



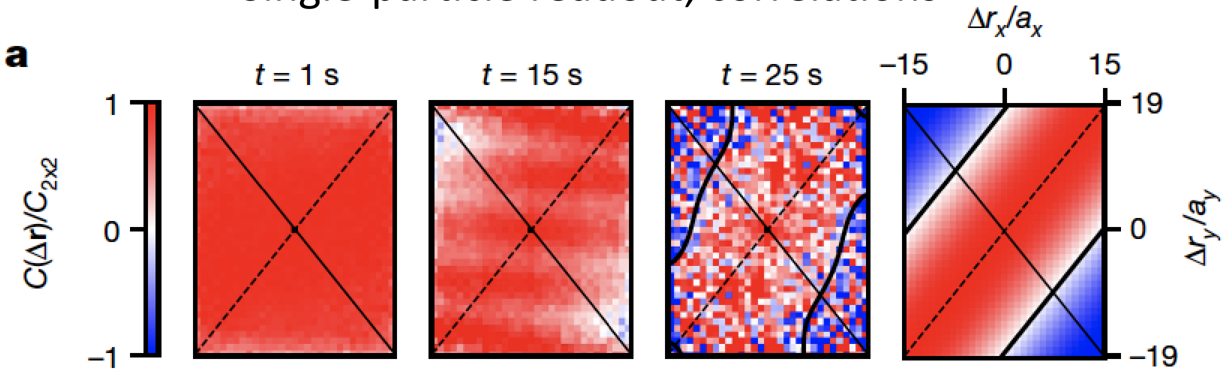
Pioneering work: Grangier group, 2000s

Optical tweezer array capabilities

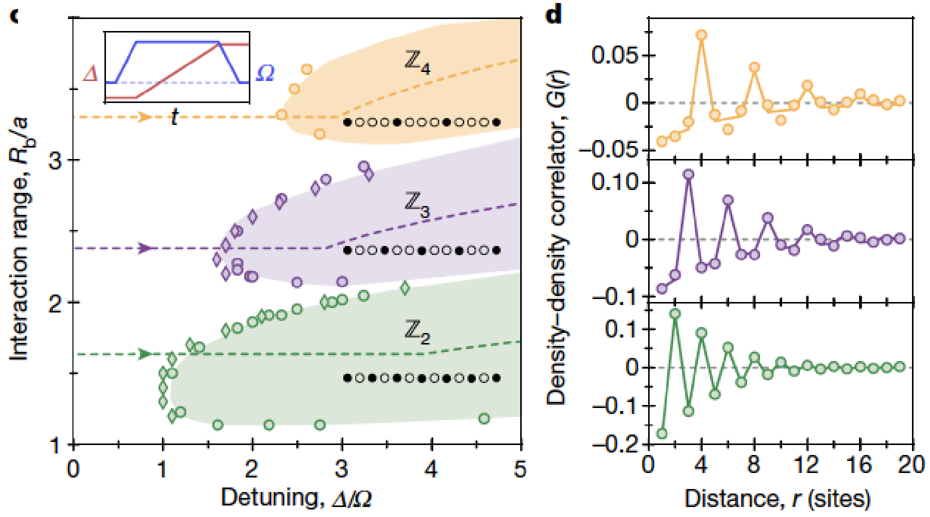
Scalable, tunable



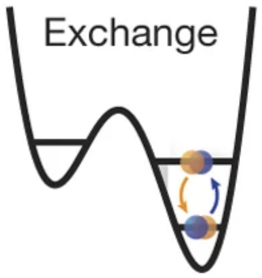
Single-particle readout, correlations

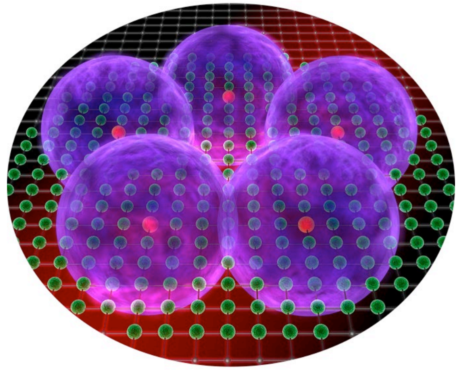


High duty cycle → precision



Controllable interactions: Rydberg, collisional, molecules

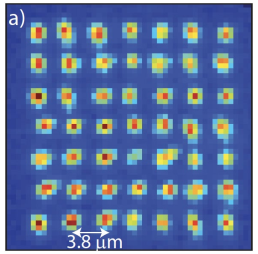




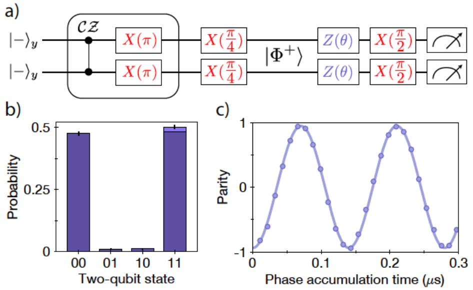
Endres…Lukin, Science (2016); Barredo…Browaeys, Science (2016); Young…Ye, Kaufman, Nature (2020); Keesling…Lukin, Nature (2019); MPI image credit

Applications

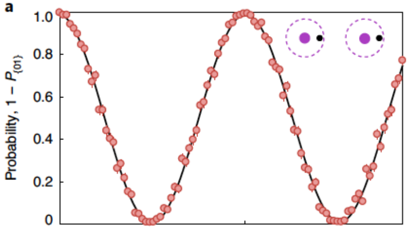
Quantum information processing



Saffman



Lukin

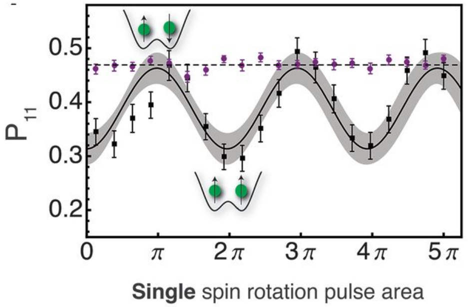


Endres

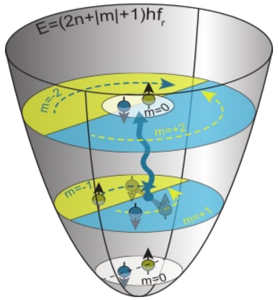
State-of-the-art for global gates:

- Single-qubit gates: 0.9983(14) [1]
- Bell-state fidelities:
  - Rydberg qubits: 0.991(4) [2]
  - Hyperfine qubits: 0.974(3), 1D [3]; 0.89, 2D [4]

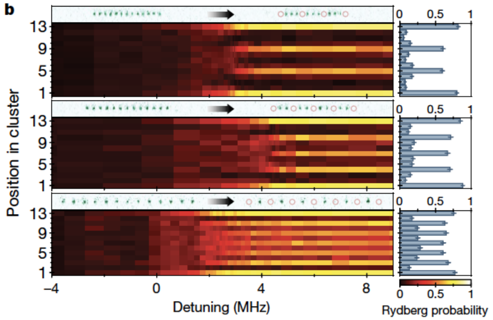
Few - to - Many-body physics



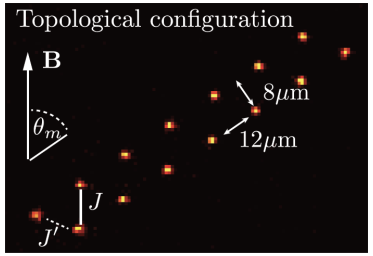
Regal



Jochim



Lukin



Browaeys

Studies of:

- Few-body Hubbard
- Transverse Ising model, gs/dynamics
- Kibble-Zurek physics
- Critical phenomena
- Topological phenomena
- Cat state generation
- …

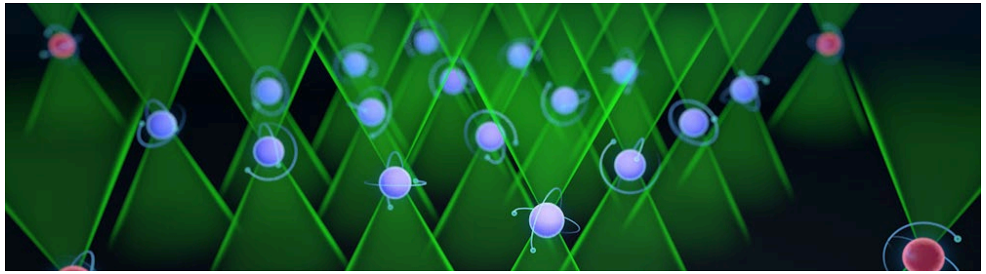
QI: [1] Xia…Saffman, PRL (2015); [2] Madjarov…Endres, Nat. Phys (2020); [3] Levine…Lukin, PRL (2019); [4] Graham…Saffman, PRL (2019)
Few/Many body: Kaufman…Regal, Science (2014); Bayha…Jochim, Nature (2020); Bernien…Lukin, Nature (2017), Léséleuc…Browaeys, Science (2019)

Expanding to more complex particles

Molecules

Doyle, Ni, Cheuk

Alkaline-earth atoms



JILA, Caltech, Princeton

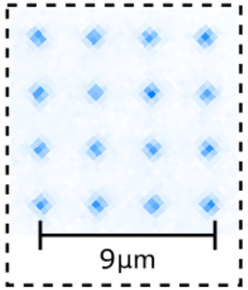
Manuel Endres

Jeff Thompson

Ben Bloom, Atom Computing

Outline

Why Alkaline-earths?



A tweezer clock

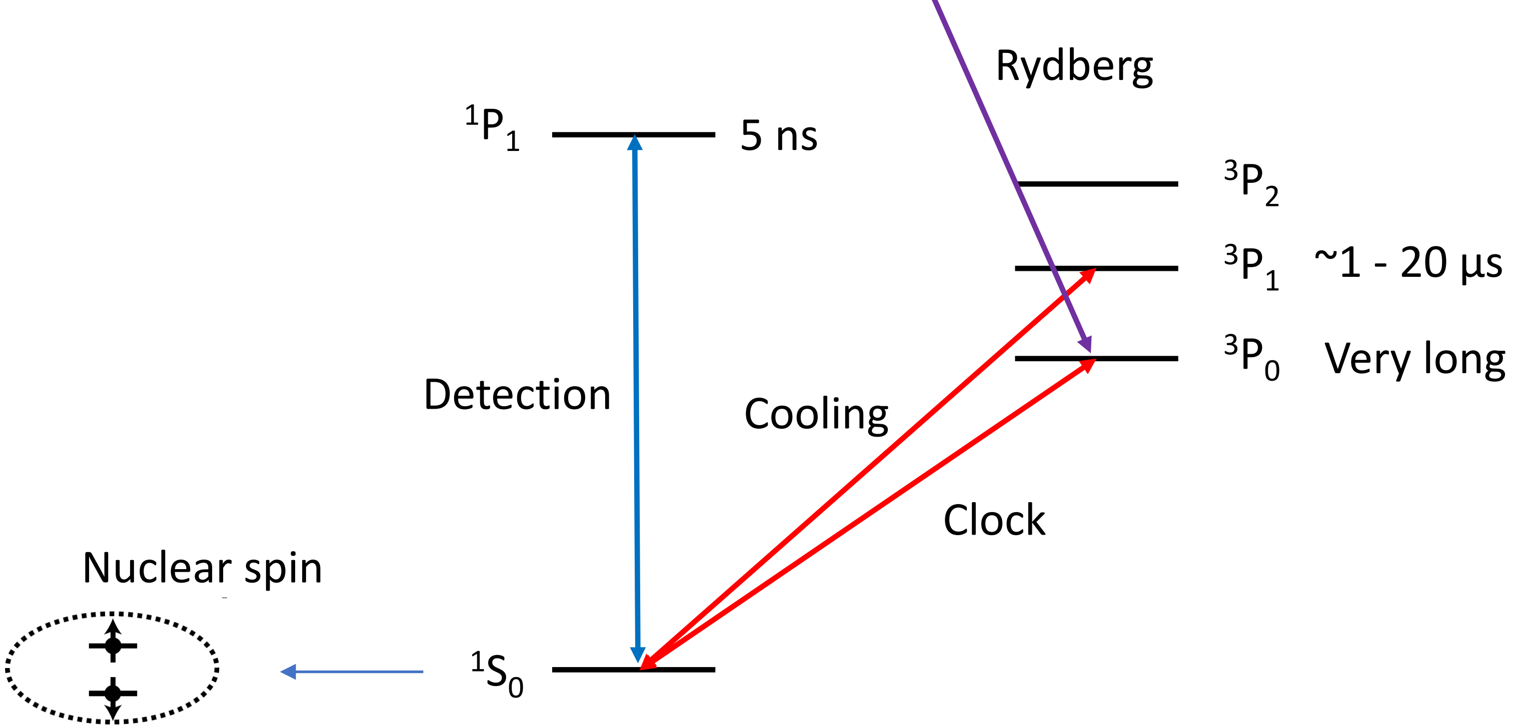
A Bell state on a neutral-atom clock transition

Tweezing single atoms into a Hubbard-regime lattice

Why alkaline-earths?

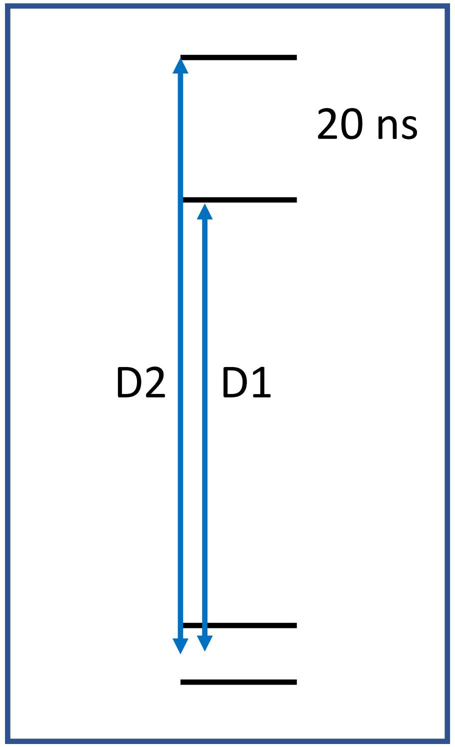
e.g. Strontium, Calcium, Magnesium, Ytterbium (“AEA-like”)

2e$^-$



e.g. Rubidium, Potassium, Caesium, Lithium

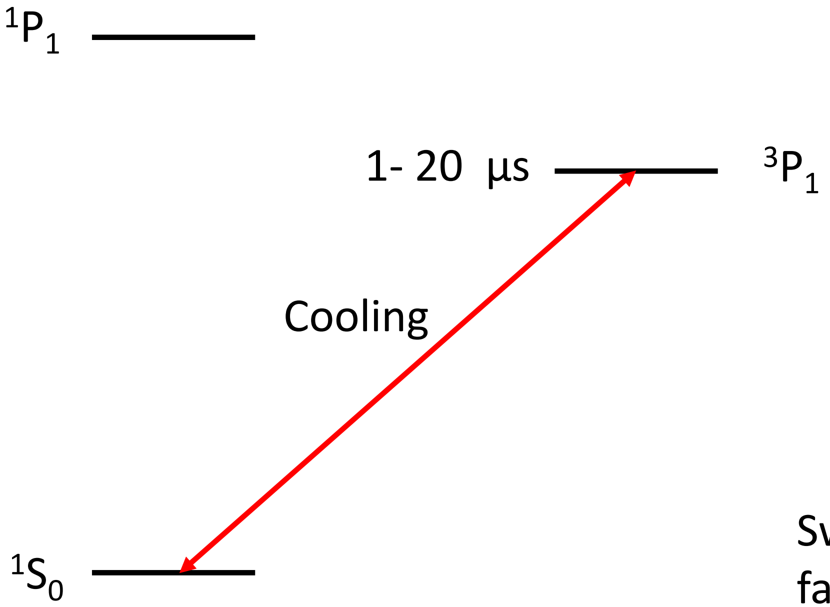
1e$^-$, “☹”

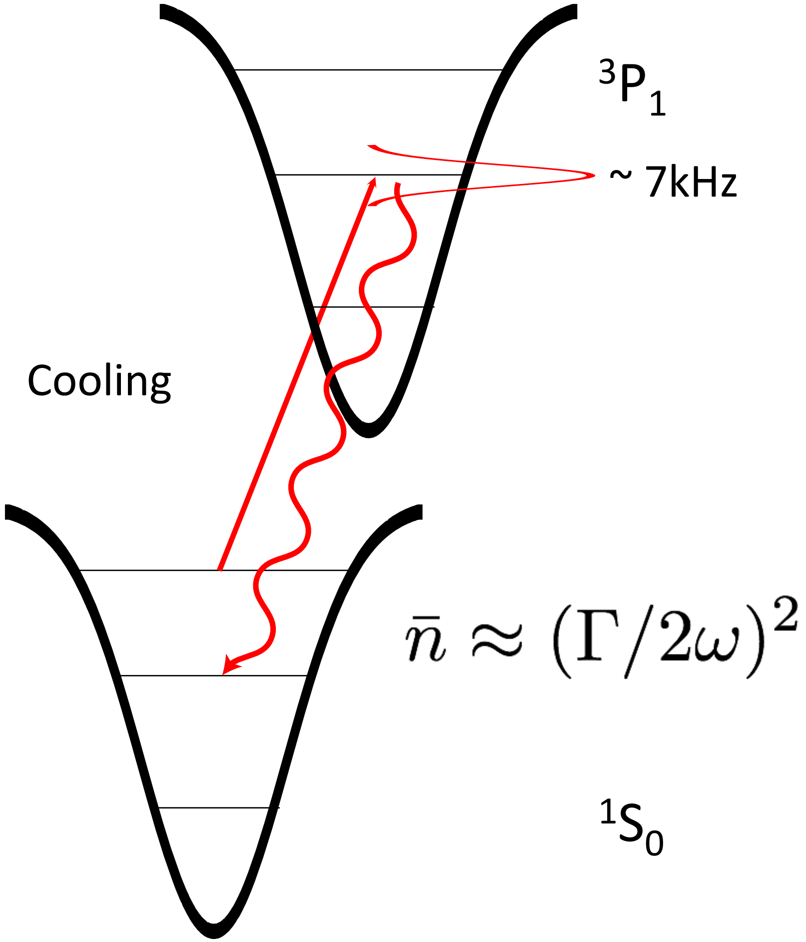


Yamamoto…Takahashi, NPJ (2016); Hermele…Gurarie, PRB (2011)
Takeuchi…Kozuma, PRA (2010); Cappellini…Fallani, PRL (2014);

Cooling, detection

$2e^-$





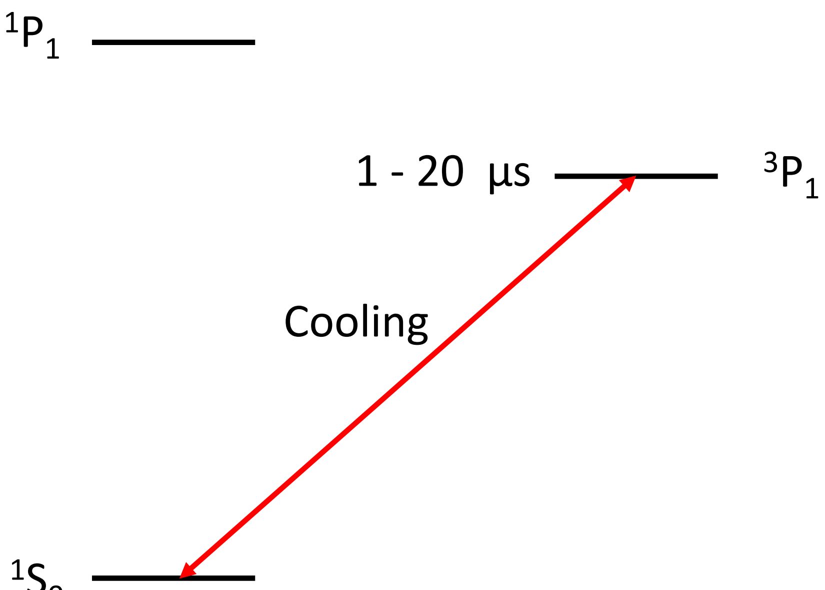
Sweet spot: narrow enough to get cold, broad enough to cool fast. And very simple.

Norcia…Kaufman, PRX (2018)
Cooper…Endres, PRX (2018)

Resolved sideband cooling in ions: Diedric…Wineland, PRL (1989)
Raman-sideband cooling in neutrals: Kerman..Chu, PRL (1998); Han…Weiss, PRL (2000)

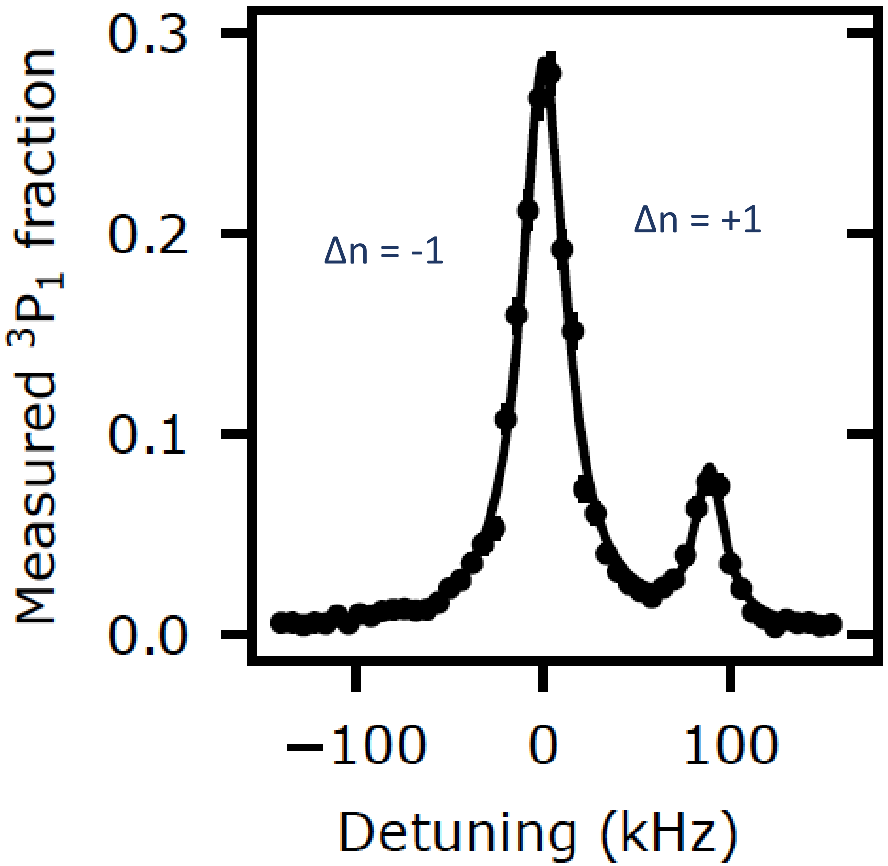
Cooling

2e⁻



Norcia…Kaufman, PRX (2018)
Cooper…Endres, PRX (2018)
Saskin…Thompson, PRL (2019)

>90% ground state, 10 ms

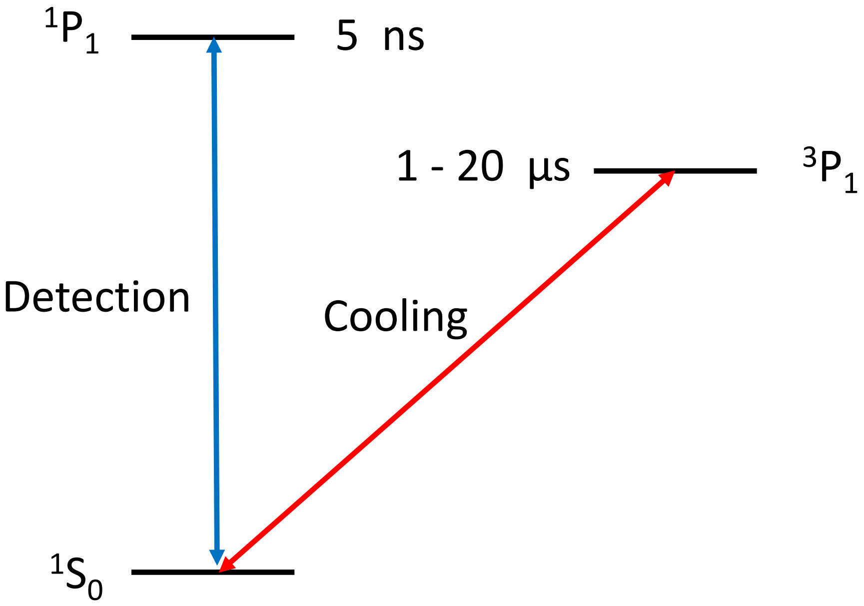


Other methods: Sisyphus cooling, Doppler cooling

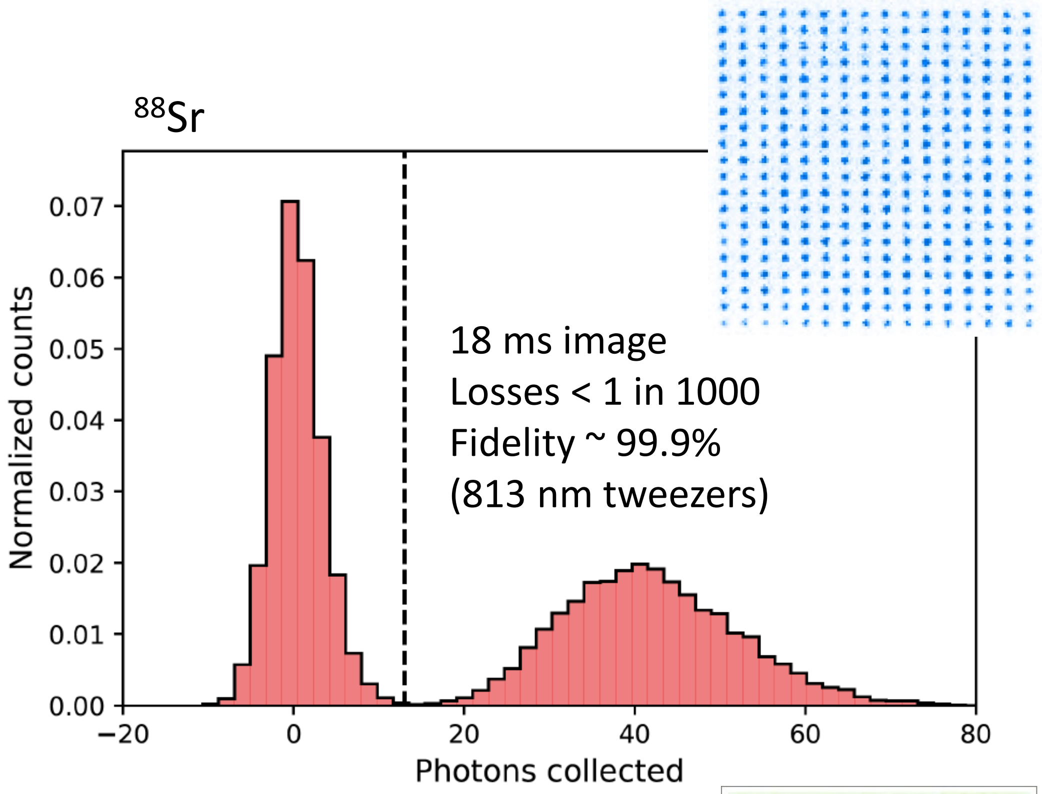
Resolved sideband cooling in ions: Diedric…Wineland, PRL (1989)
Raman-sideband cooling in neutrals: Kerman..Chu, PRL (1998); Han…Weiss, PRL (2000)

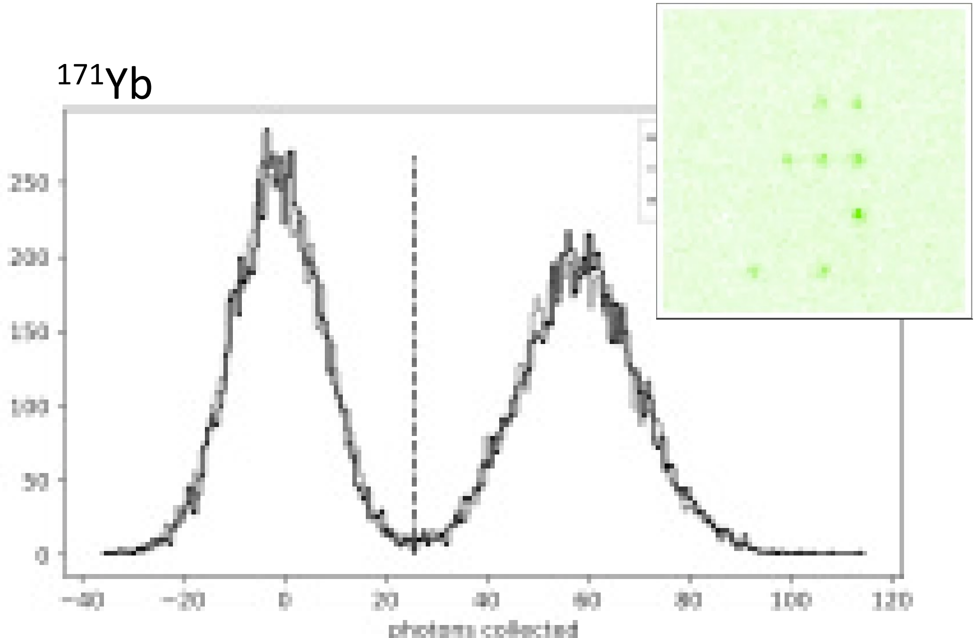
Detection

2e⁻



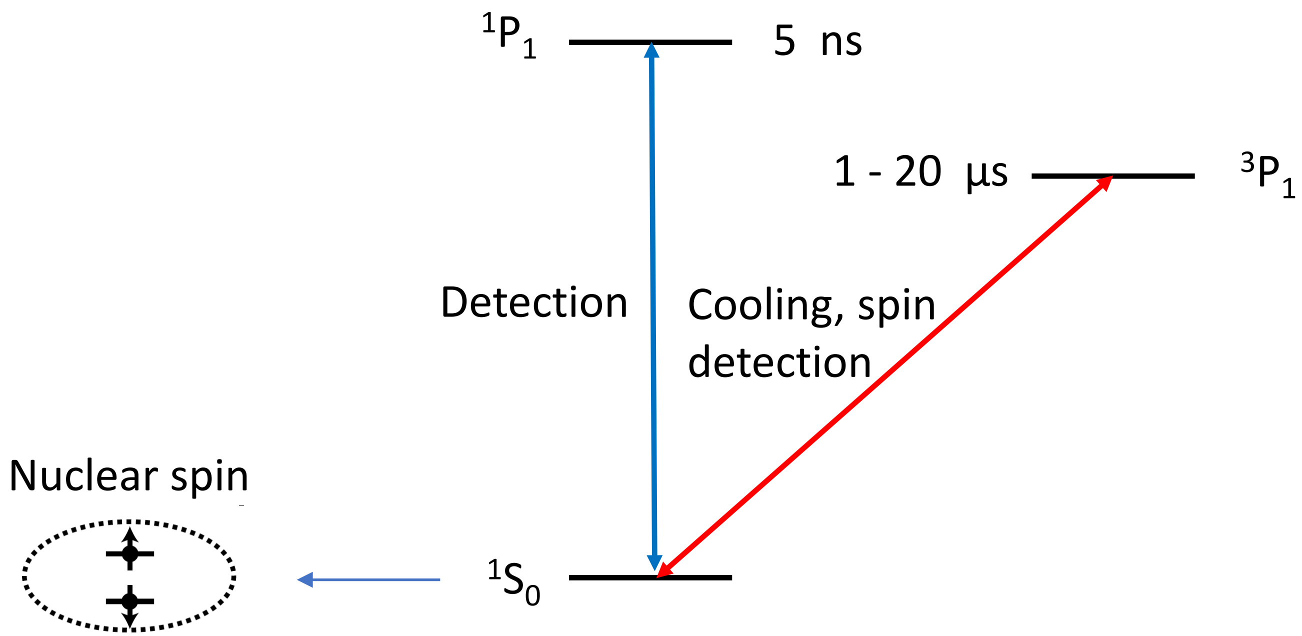
Covey…Endres, PRL (2019)
Norcia…Kaufman, Science (2019)
Saskin…Thompson, PRL (2019)





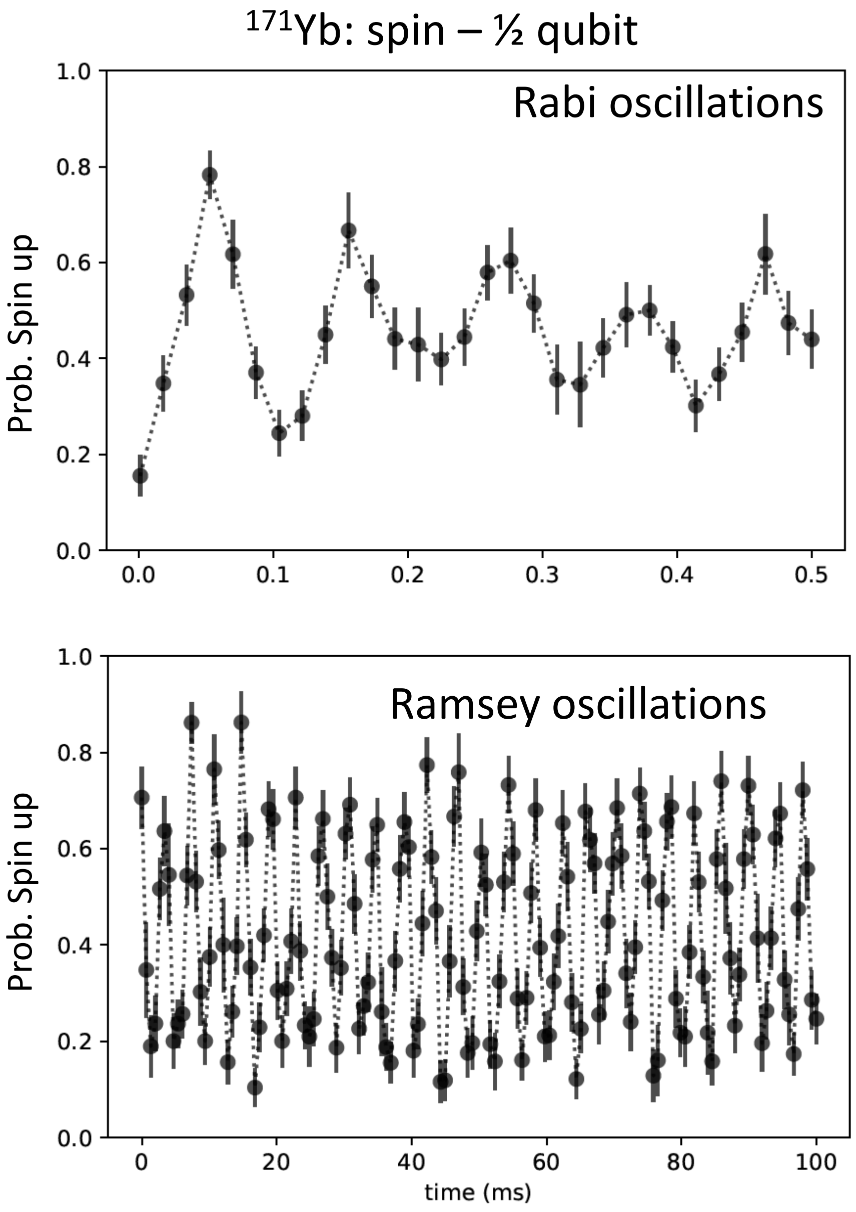
Qubit possibilities

$2e^-$



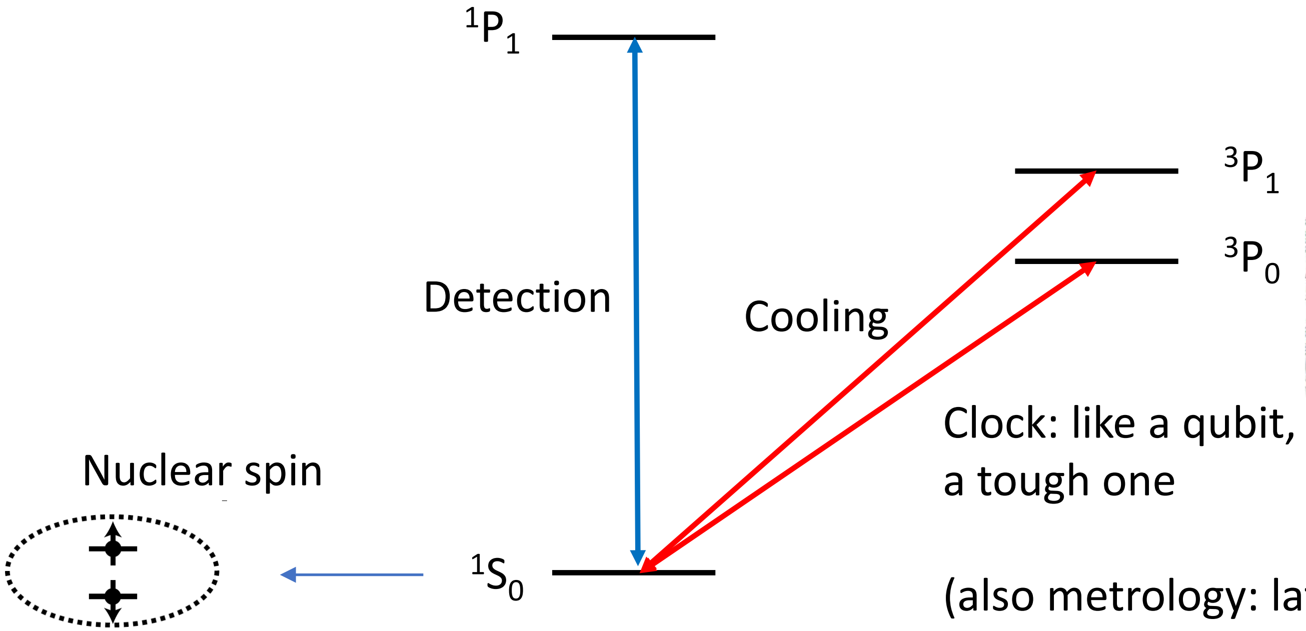
Ytterbium:1/2 , 5/2; Strontium: 9/2

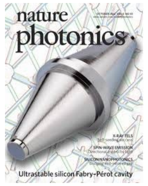
(Very.) Prelimary data



Qubit possibilities

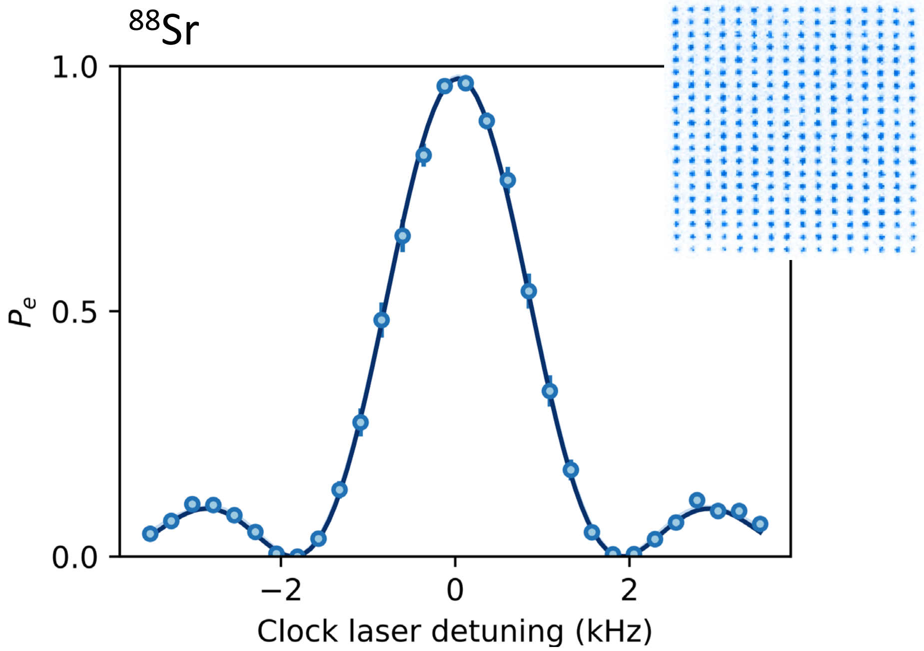
2e-

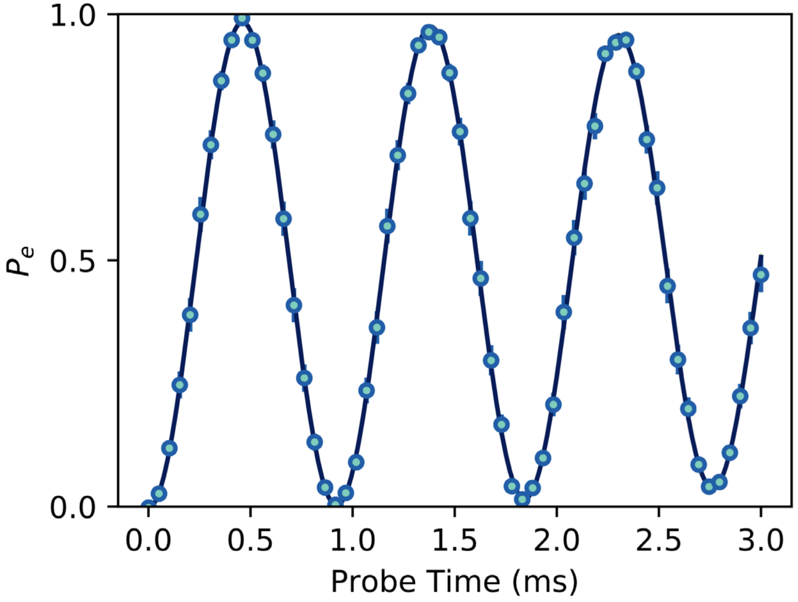




Clock: like a qubit, but a tough one

(also metrology: later)

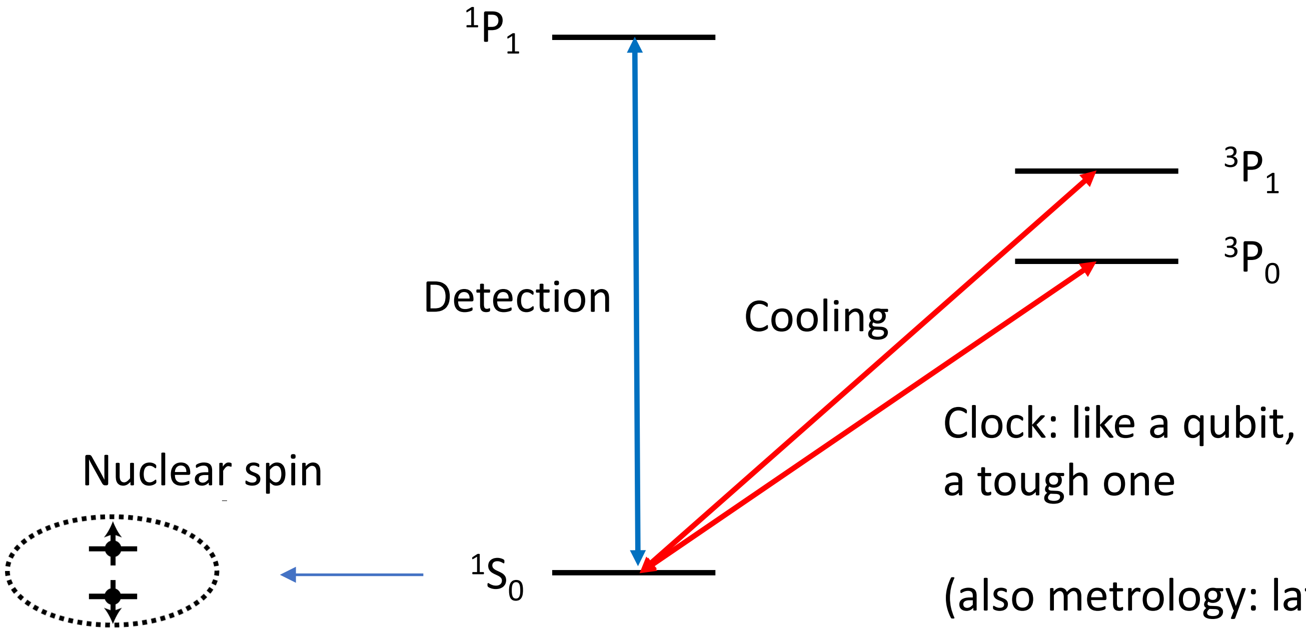




99.1(4)% contrast

Nuclear + clock → spin-orbital exchange gates

2e⁻

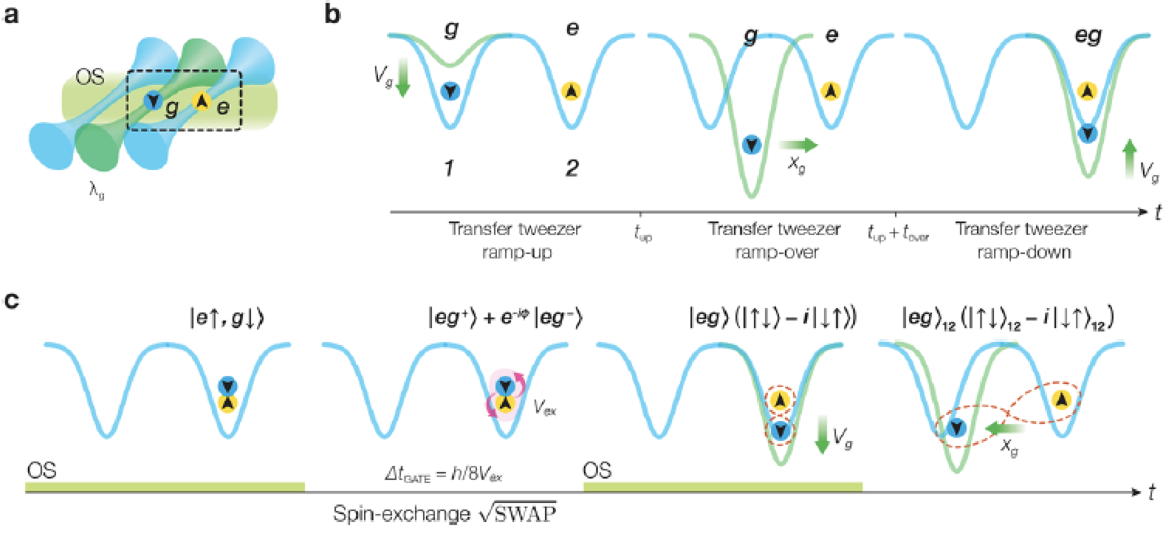


Clock: like a qubit, but a tough one

(also metrology: later)

Fast and Scalable Quantum Information Processing with Two-Electron Atoms in Optical Tweezer Arrays

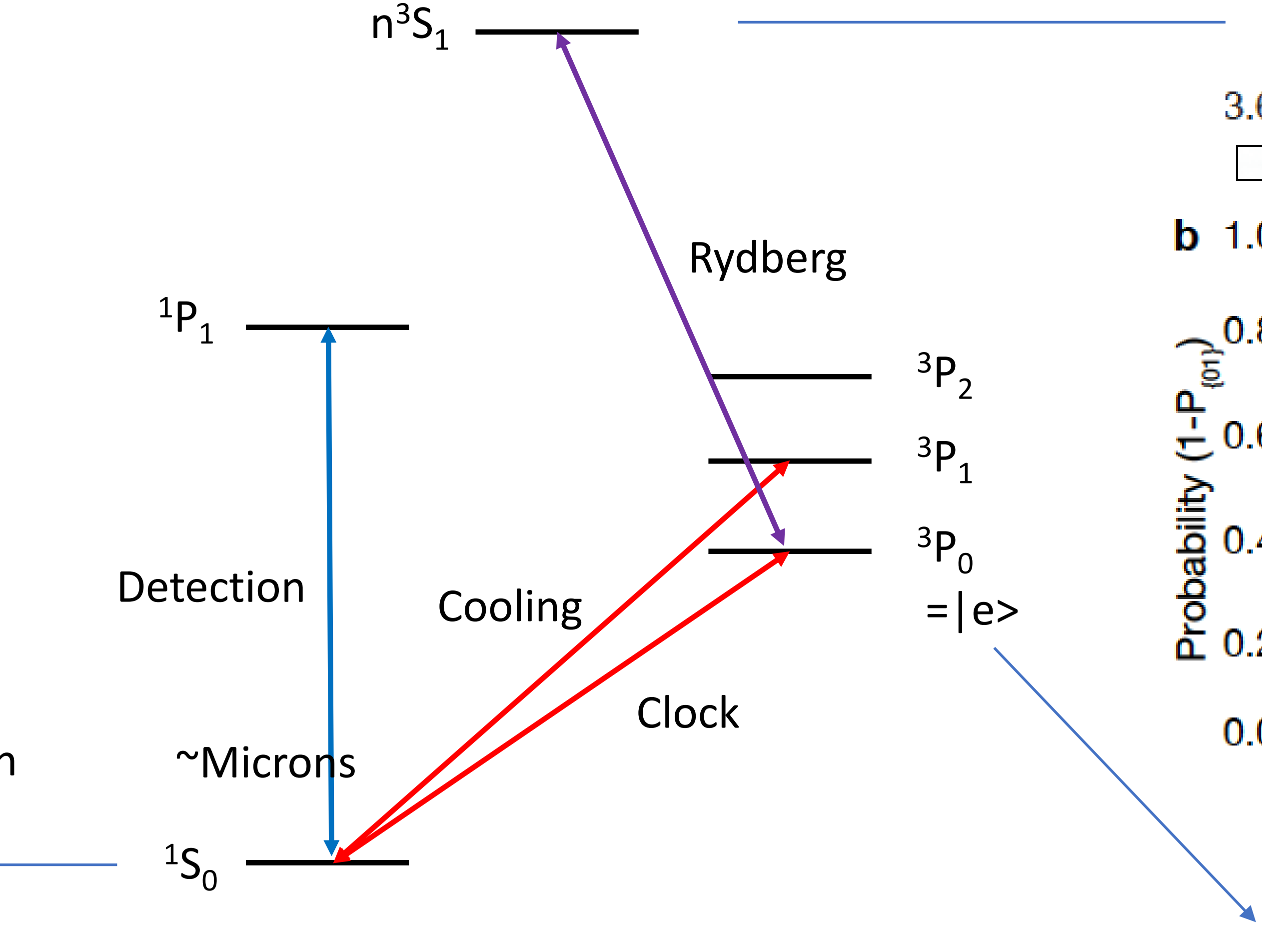
Guido Pagano, Francesco Scazza, and Michael Foss-Feig*



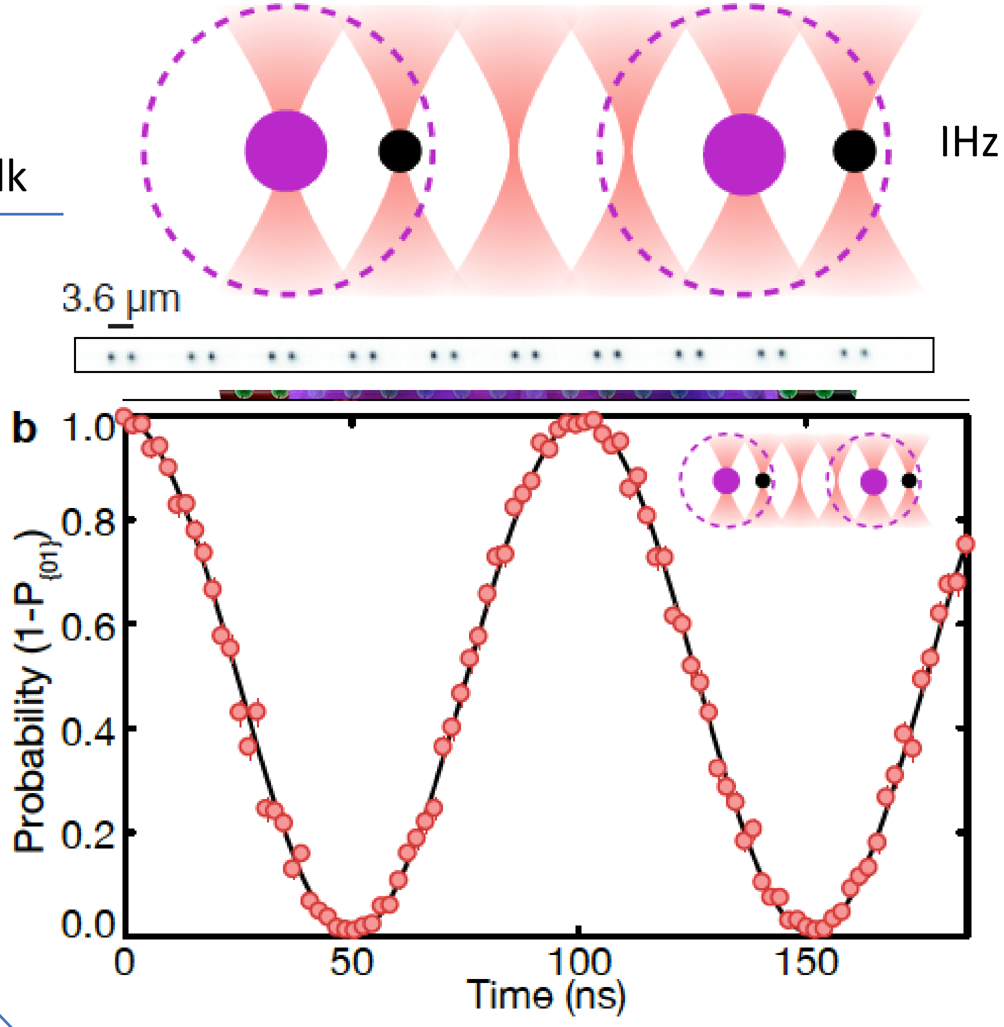
See also: Kaufman…Regal, Nature (2015) for exchange gates in tweezers w/ alkalis

Rydberg Interactions

2e$^-$



Madjarov...Endres, Nature Physics (2020)

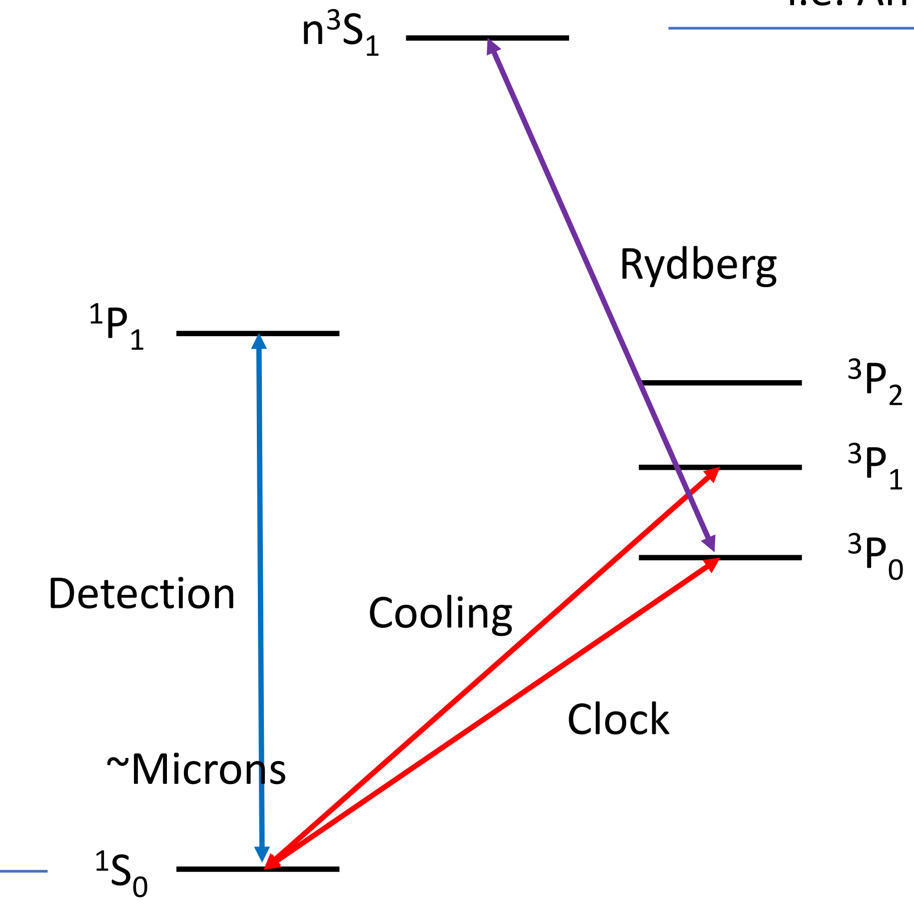


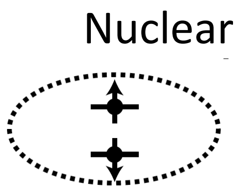
$|\Psi\rangle = \frac{1}{\sqrt{2}}(|e,r\rangle + |r,e\rangle)$

Bell state fidelity: 0.991(4)

Rydberg Interactions

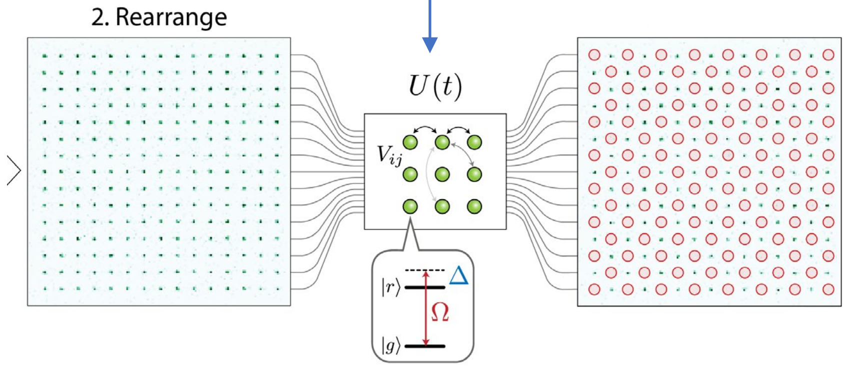
2e-

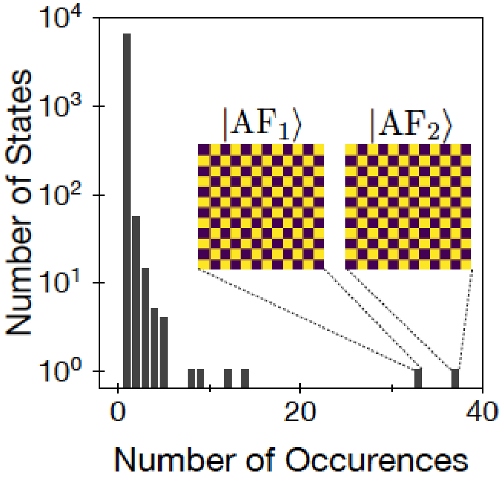


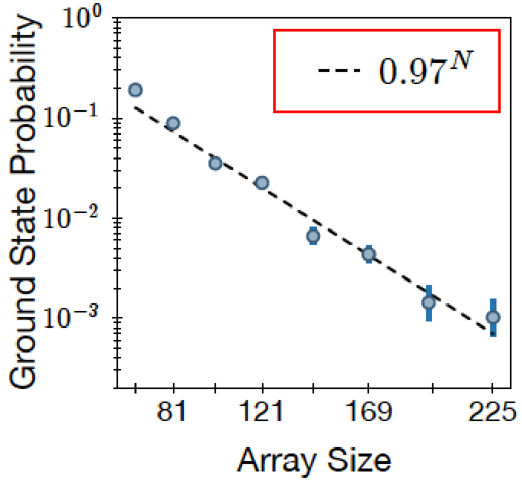


i.e. Antoine's talk

Adiabatic sweep across Ising phase transition

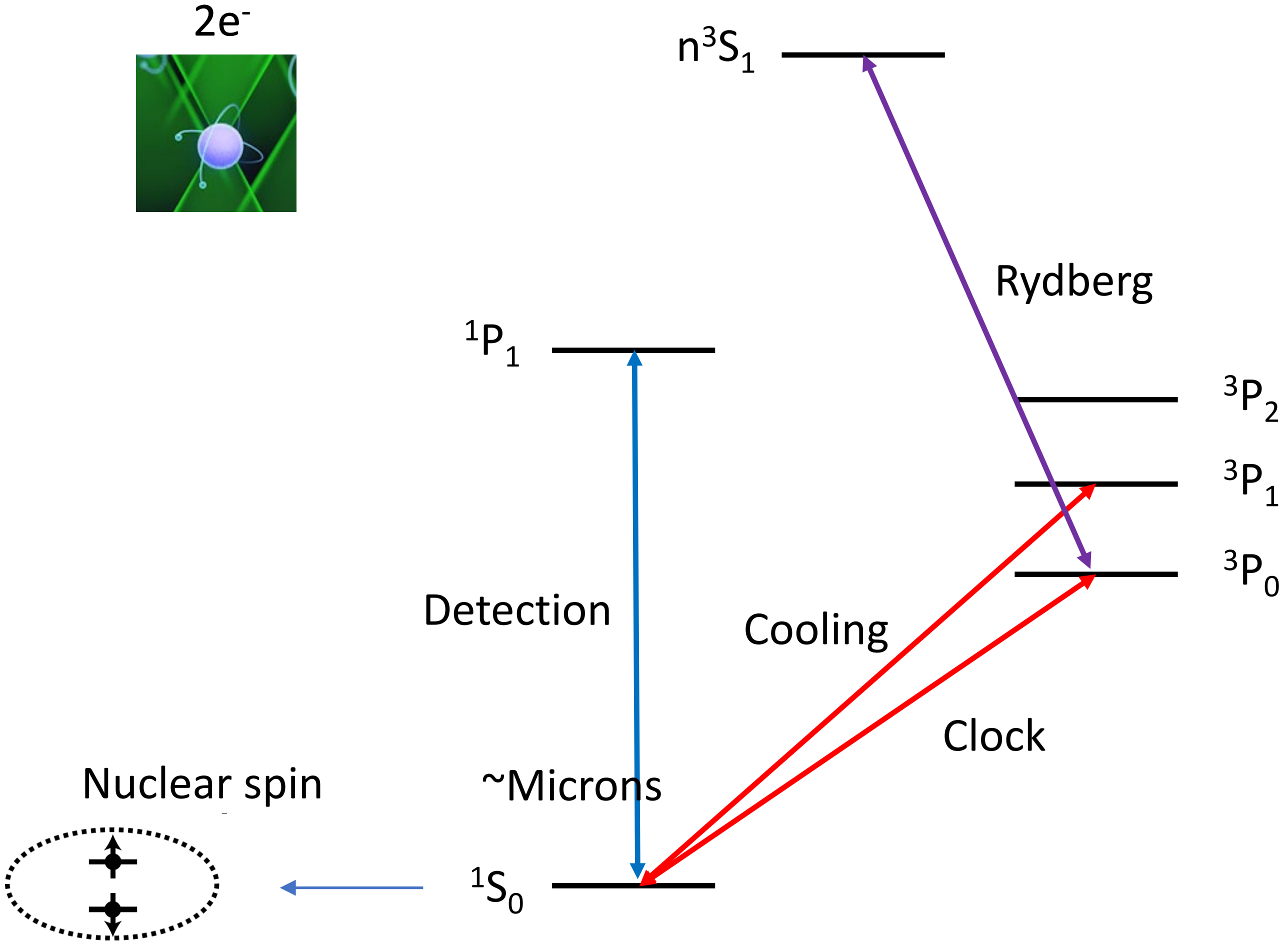




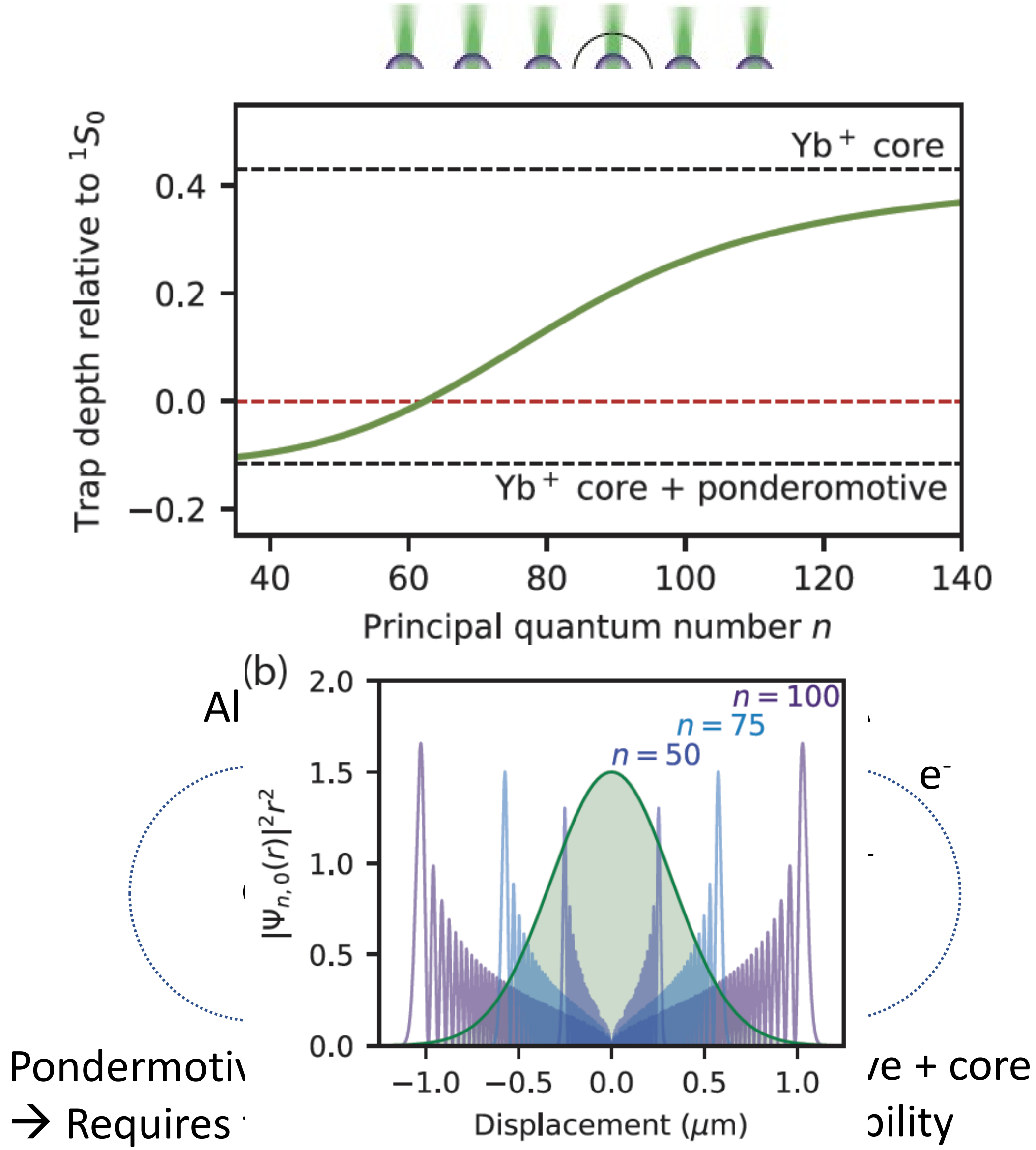


Alkali, ^{87}Rb: **Ebadi…Lukin, Nature (2021)**
Also: Scholl…Browaeys, Nature (2021)

Rydberg Interactions



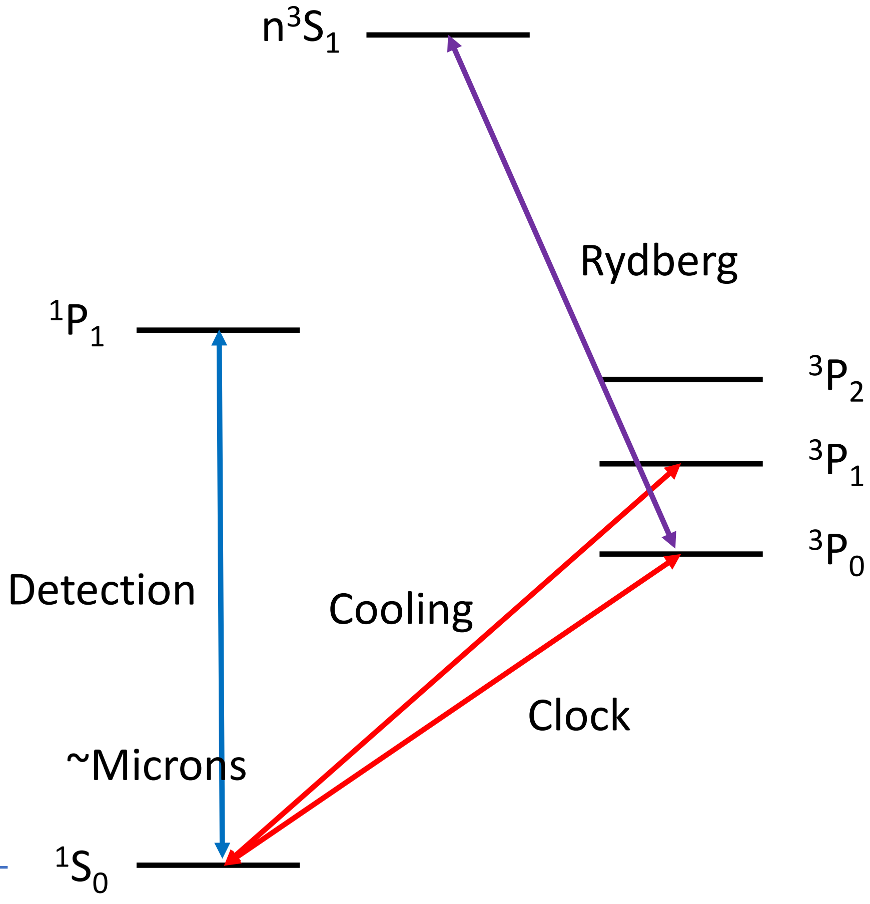
Wilson…Thompson, arXiv (2019)



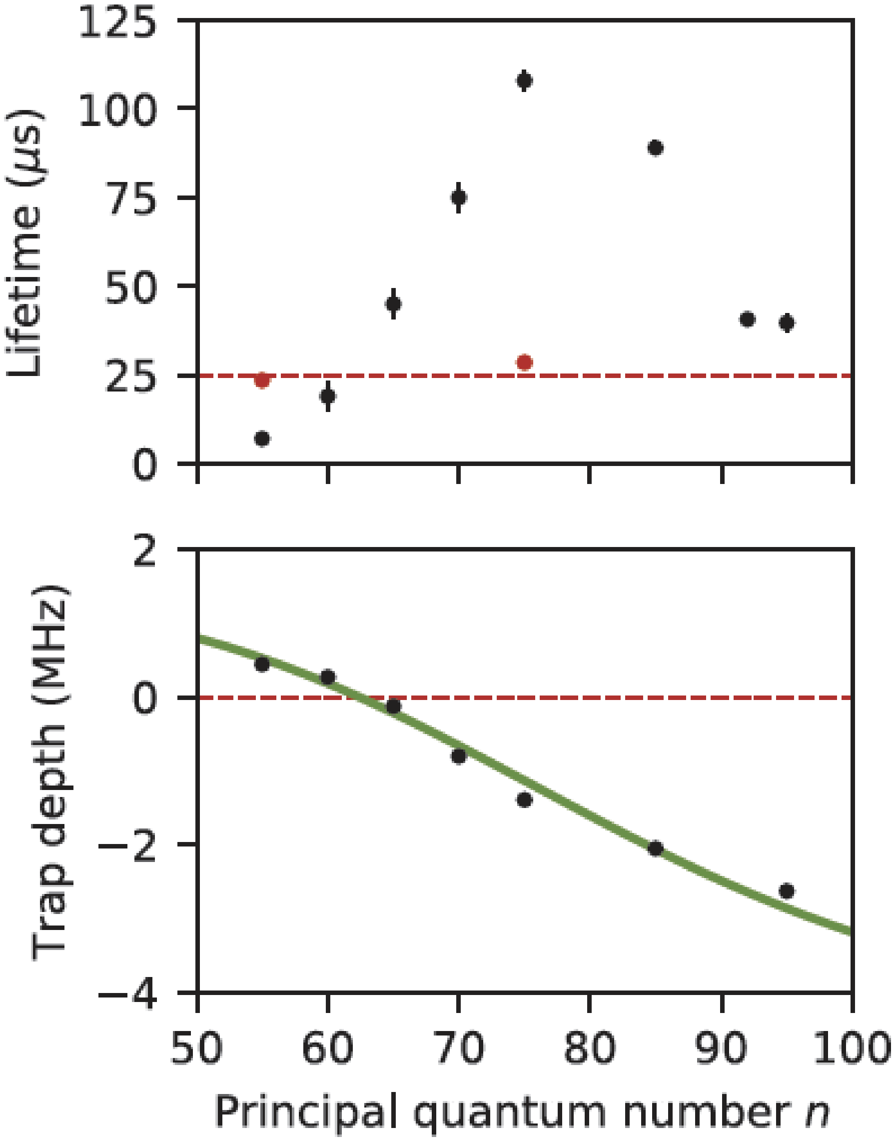
Theory proposals: Derivianko, Pohl groups

Rydberg Interactions

2e-

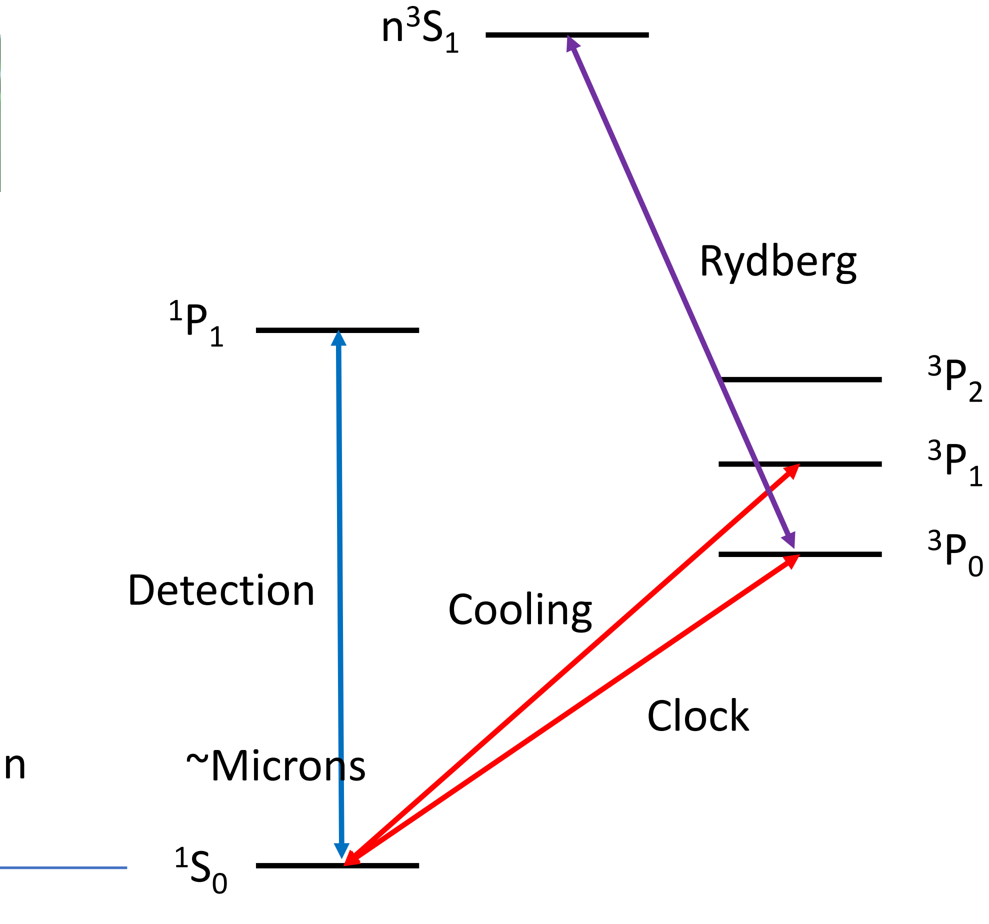


Wilson…Thompson, arXiv (2019)

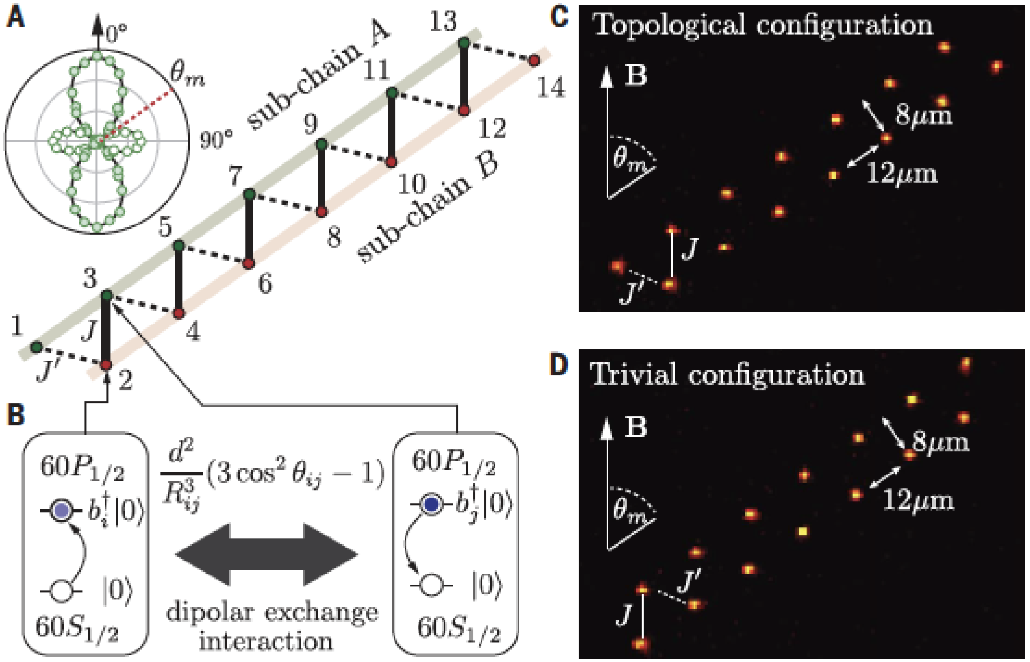


Rydberg Interactions

$2e^-$



Léséleuc…Browaeys, Science (2019)



Interacting qubits encoded both in Rydberg states

Bosonic SSH model

→ Length of quantum simulation = how long atoms stick around → extra electron helpful.

→ Also: quantum computing gate depth, errors

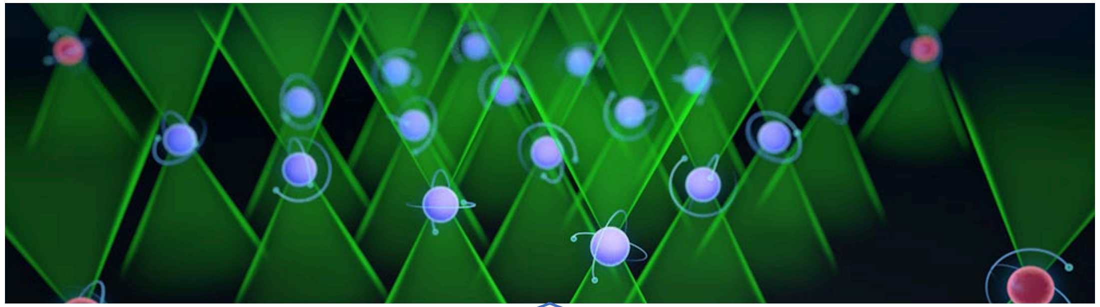
Alkaline-earths in tweezers

Most important? The intersection of all of these things.

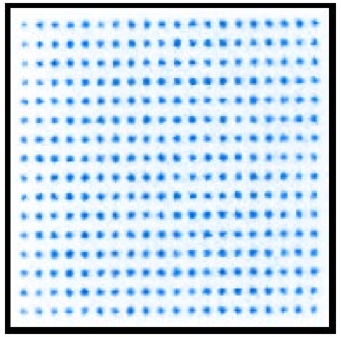
Tl;dw:

- New cooling methods
- New detection methods
- New qubit possibilities
- Rydberg: high fidelity demonstrated, trapping means longer simulations/sequences
- Long lived optical transition → optical frequency metrology, new spin detection schemes for neutrals (shelving)

Quantum science in alkaline-earth atom arrays

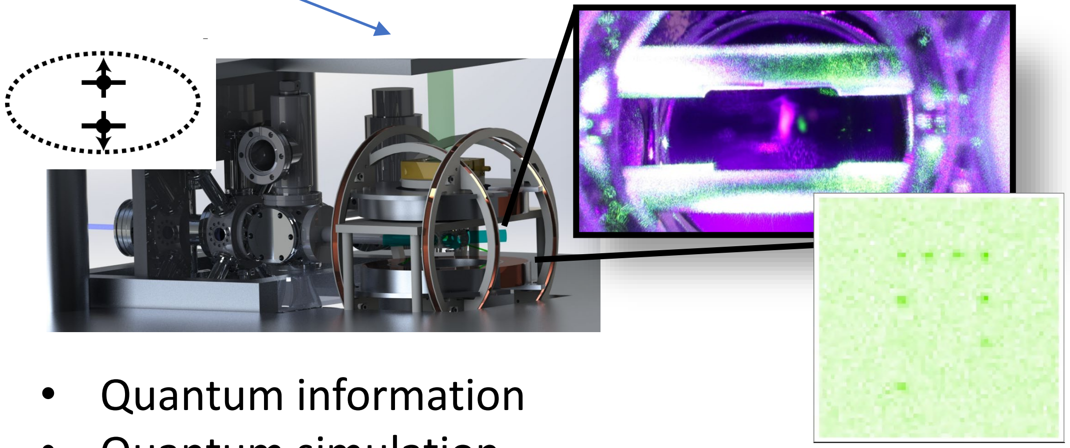


Strontium



- Metrology
- Quantum metrology
- New approaches to Hubbard physics

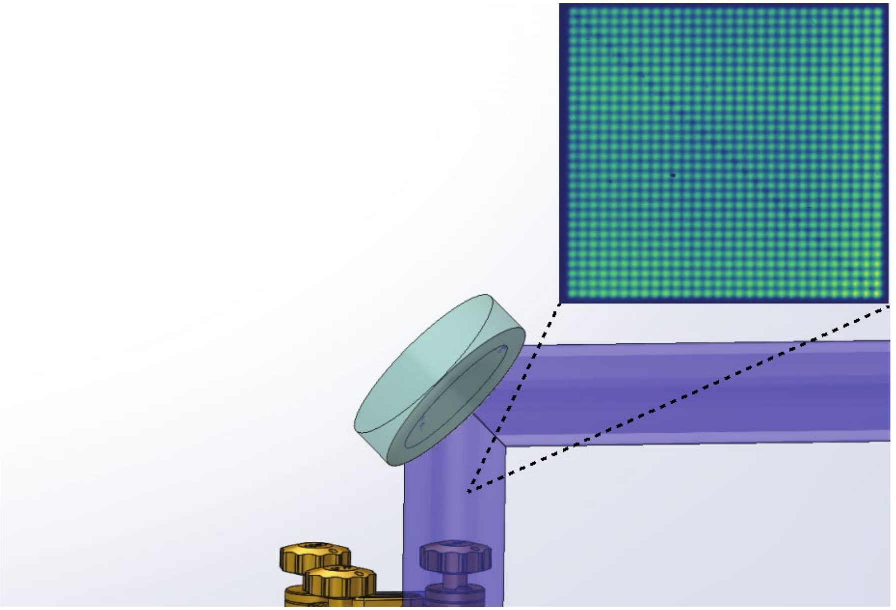
Ytterbium



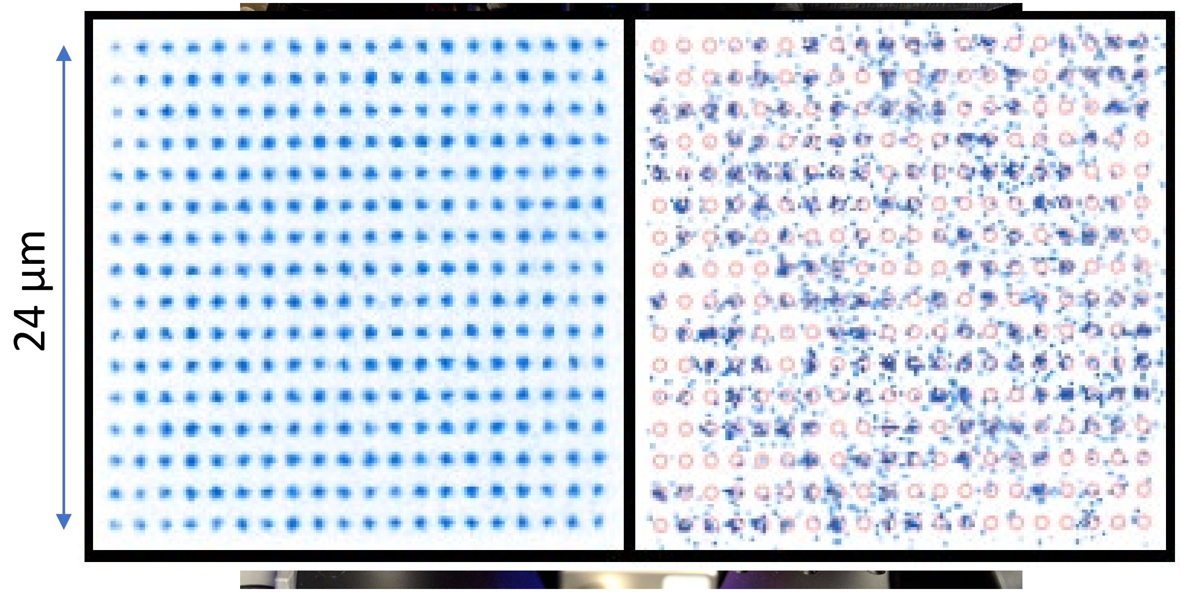
- Quantum information
- Quantum simulation
- Quantum metrology

Ingredients for trapping of single Sr atoms

Microscope + UHV chamber



Cold atom cloud (dual stage MOT)

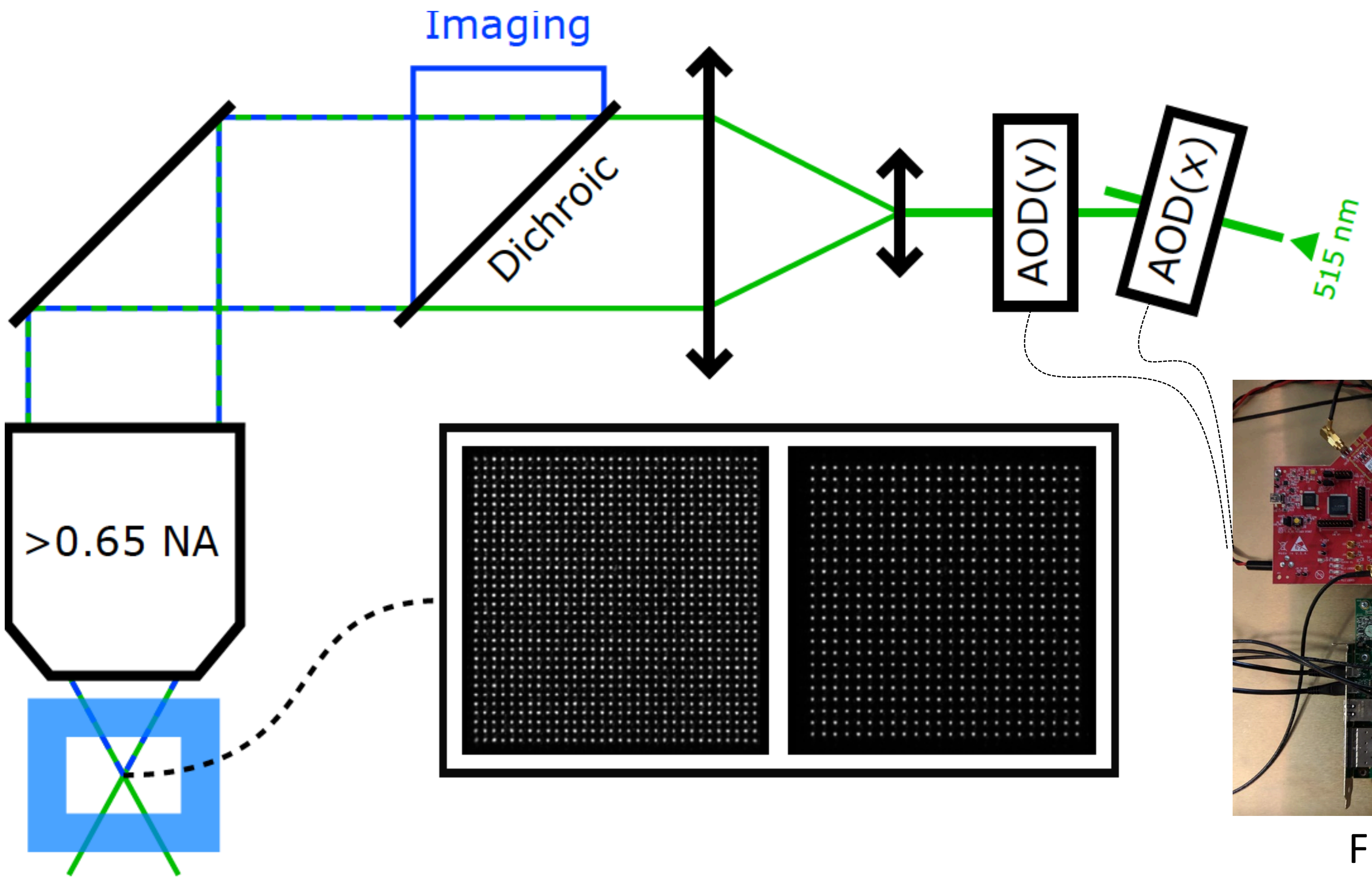


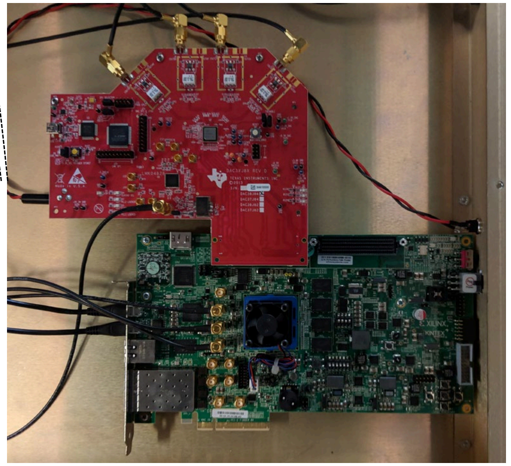
Avg. image

Single image

Norcia…Kaufman, PRX (2018)

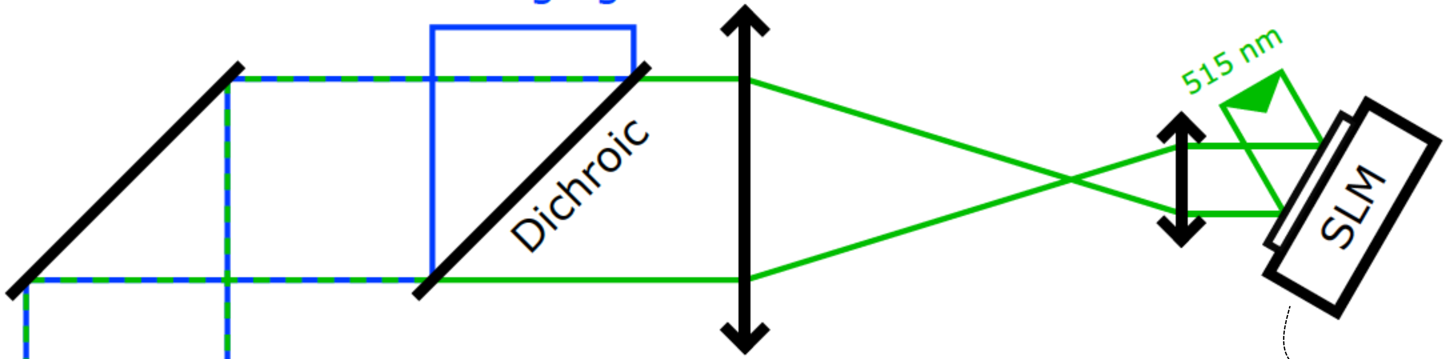
Tweezer optics

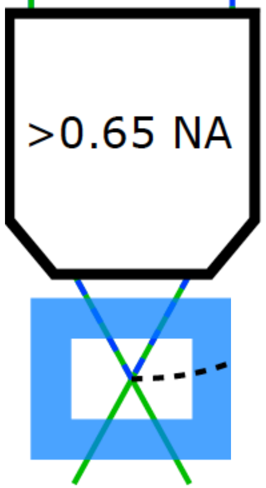




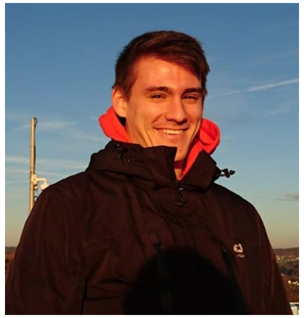
FPGA –based
RF control

Tweezer optics





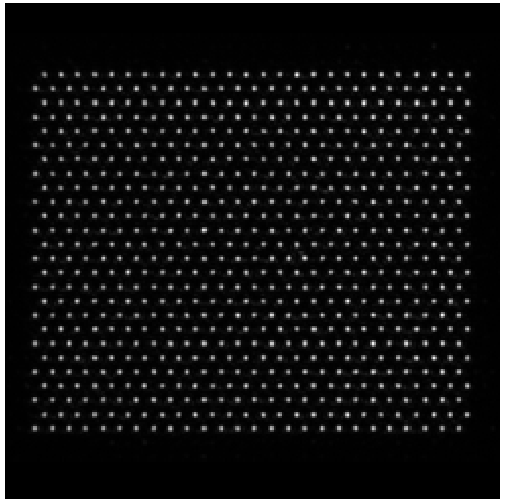
Felix Ronchen (Bonn)

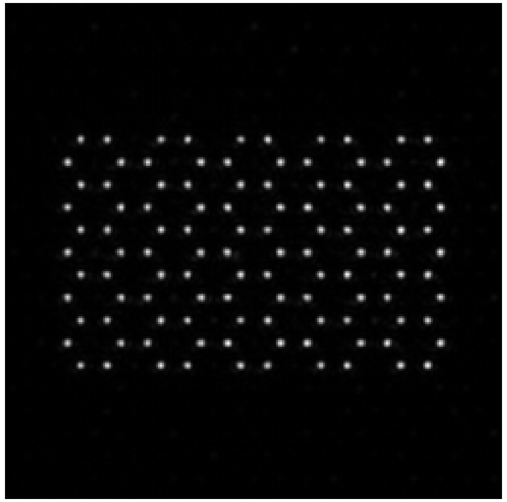


Spatial light modulator

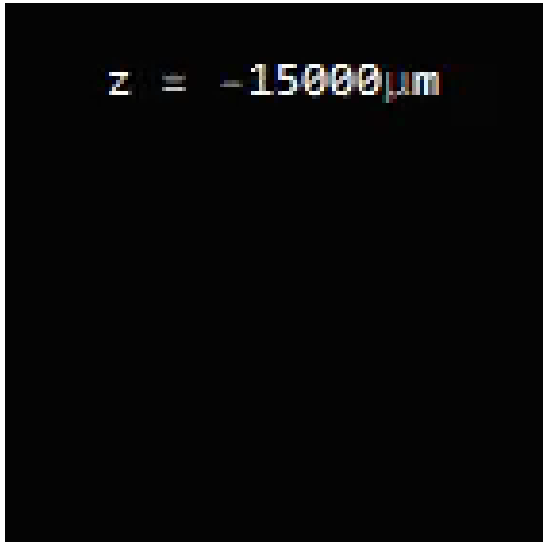
Tweezers: optical engineering → atomic engineering

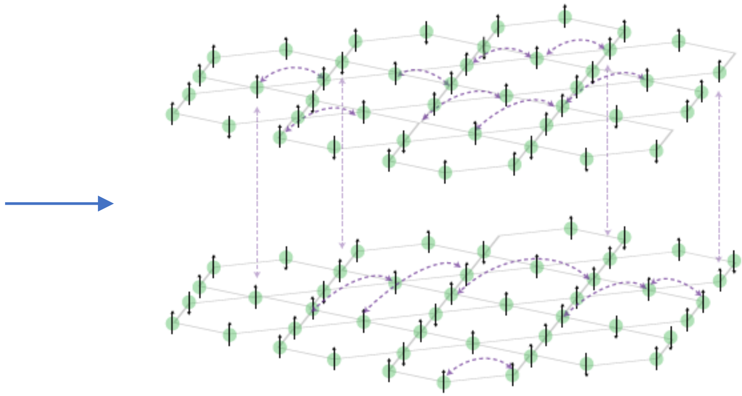
Two-dimensional





Three-dimensional



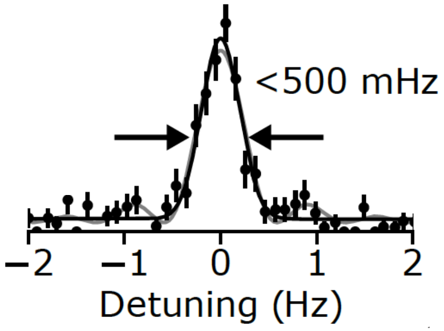


Pioneering work: Paris, Browaey's group

Outline

Why alkaline-earths?

A tweezer clock



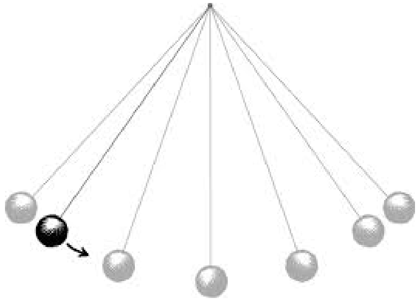
A Bell state on a neutral-atom clock transition

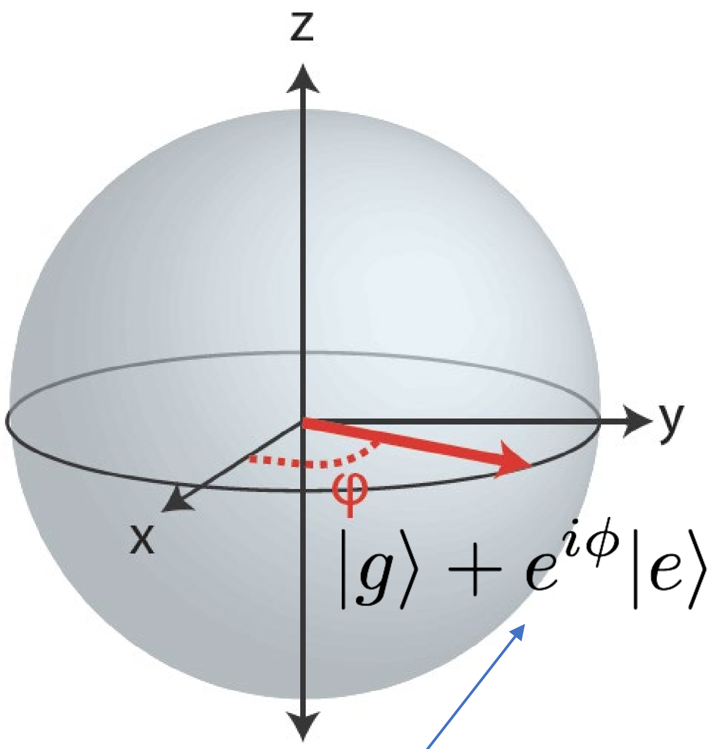
Tweezing single atoms into a Hubbard-regime lattice

Why make a tweezer clock?

Atomic clocks

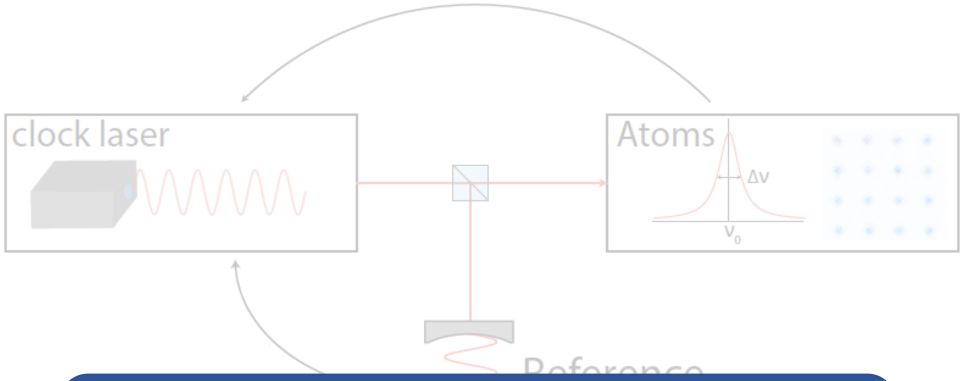
Clock





Lifetime of the superposition upper bounds the quality factor of the oscillator!

Atomic clocks

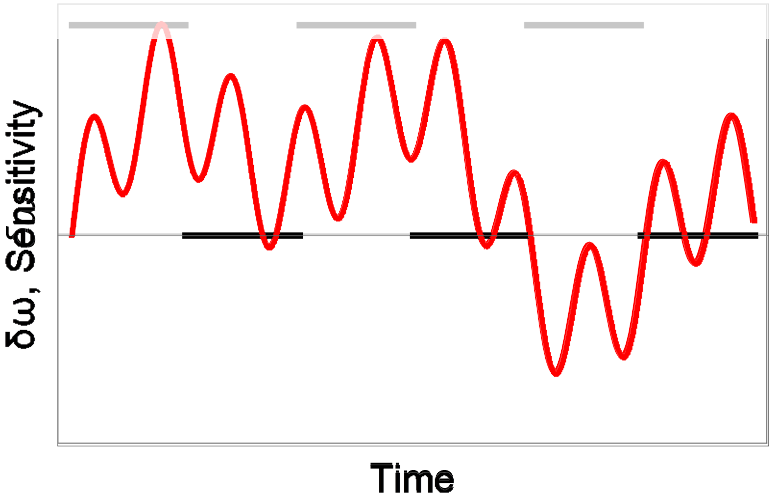


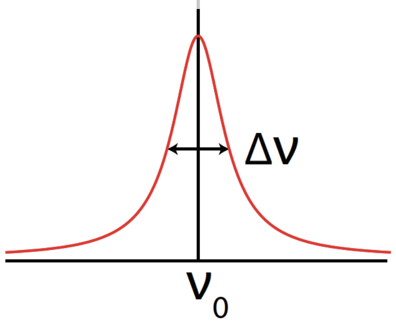
Stability

$$) \approx \frac{1}{Q\sqrt{N}}\sqrt{\frac{T_c}{\tau}}$$

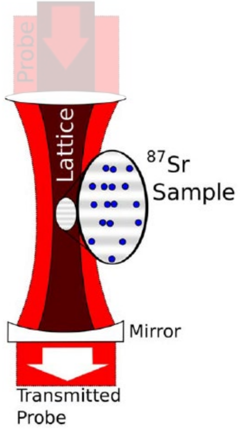
Dick Eff

Wish list: many atoms, long coherence time, high duty cycle





High Q / long coherence times



Many atoms

Ludlow…Schmidt, RMP (2015)

Leading platforms

Wish list: many atoms, long coherence time, high duty cycle

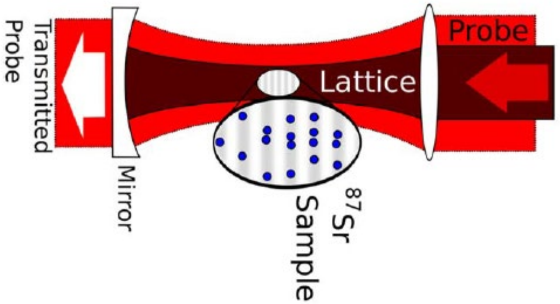
Trapped-ions

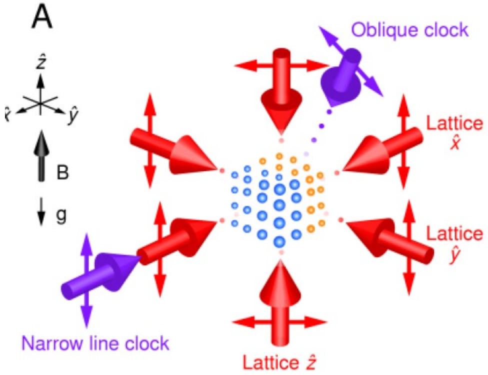
Single clock ion, high duty cycle

Challenges: mainly stability/QPN of one ion

Room here?

Optical lattice clocks (neutral atoms)





1000s of optically-trapped atoms

Challenges: interactions, tunneling, duty cycle

Ludlow…Schmidt, RMP (2015)

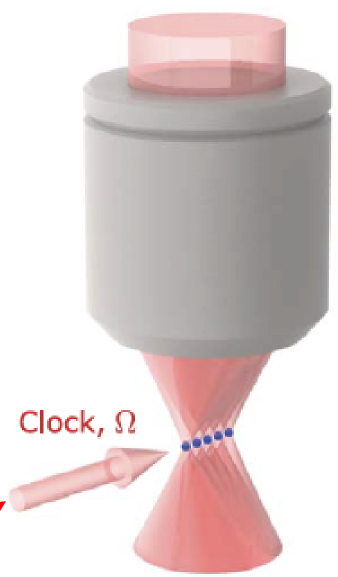
DFG lattice clocks: Campbell…Ye Science (2017); Hutson…Ye, PRL (2019)

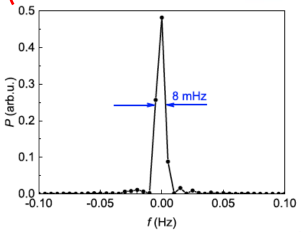
Wish list: many atoms, long coherence time, high duty cycle

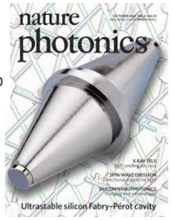
Tweezer clocks, 2019

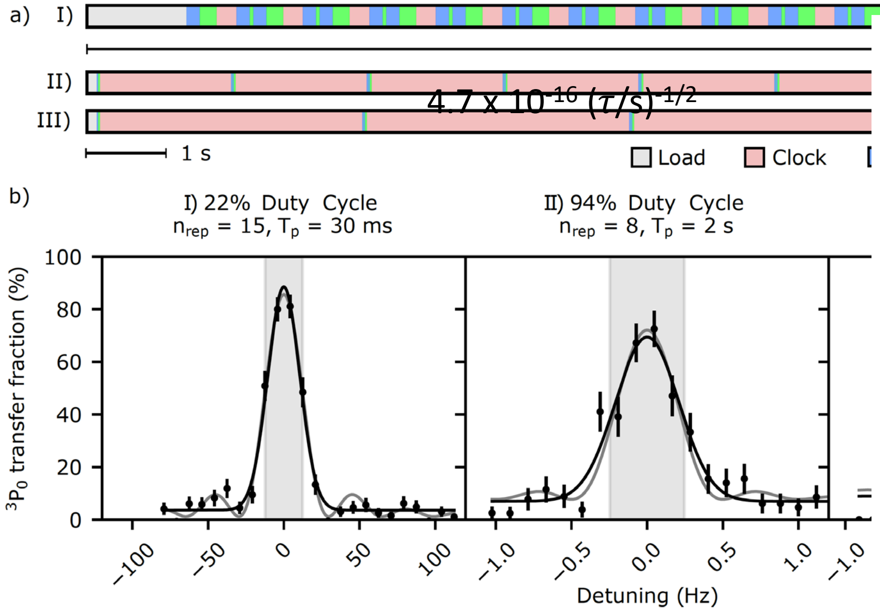
Demonstrate: 3 seconds of atom-laser coherence,

$4.7 \times 10^{-16} (\tau/s)^{-1/2}$

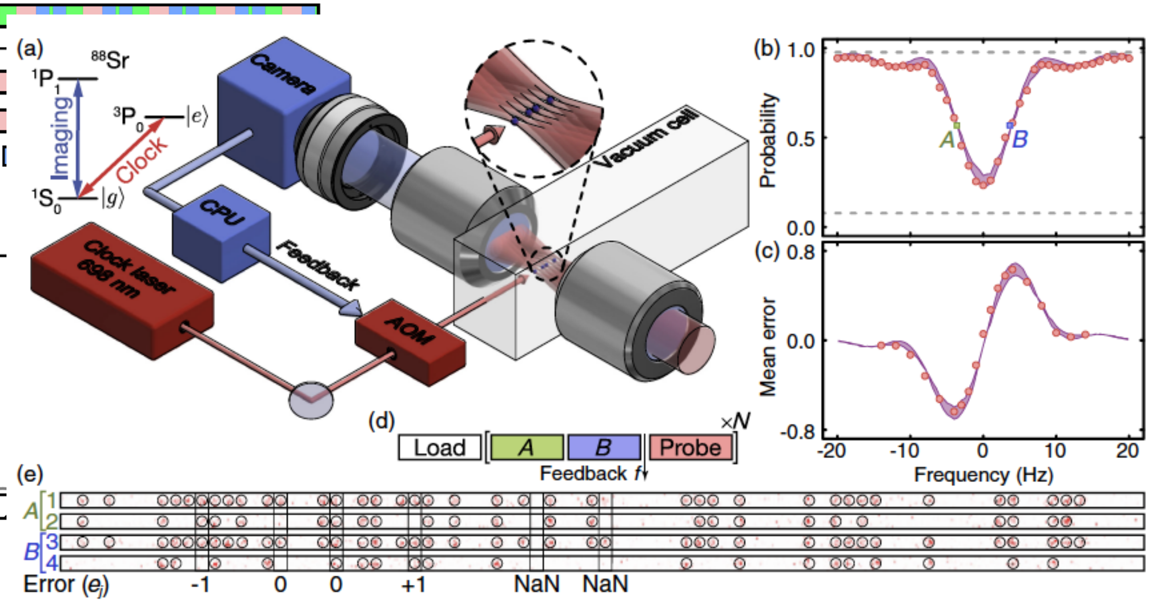








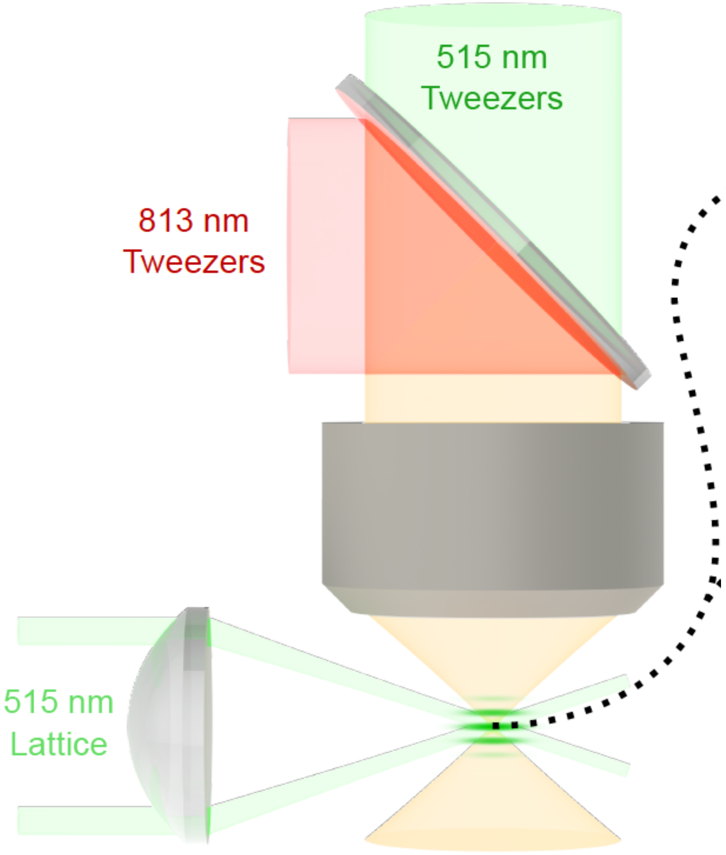
Norcia…Ye, Kaufman Science (2019)

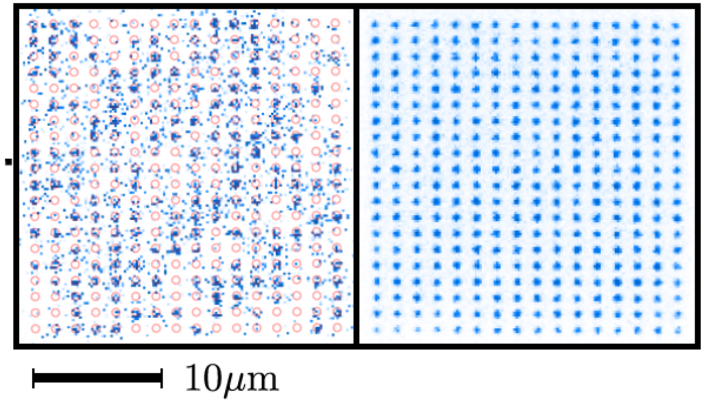


Madjarov…Williams, Endres, PRX (2019)

Question: how large a system can we scale to while maintaining coherence?

Scalable, long-lived tweezer clock systems



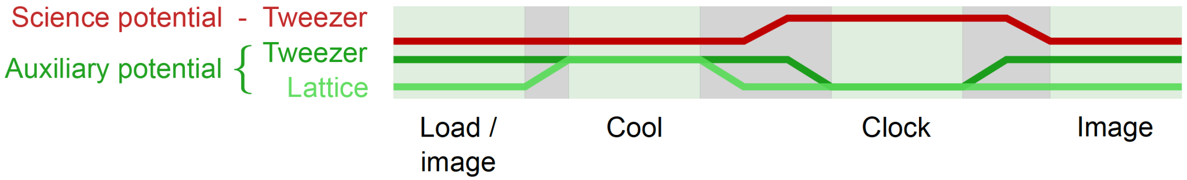


Combines:

- 320 sites, 160 atoms
- 3D Ground-state cooling: $\langle n_i \rangle < 0.2$
- 1-2 minutes of hold time
- 55(8) fundamental coherence time expectation

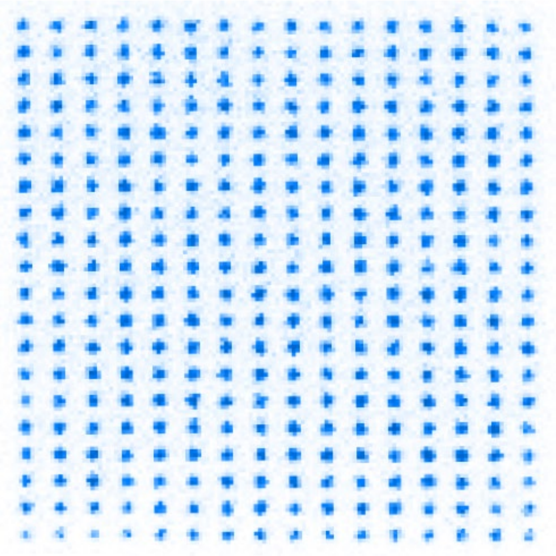
515 nm: great for loading and ground-state cooling , high polarizability

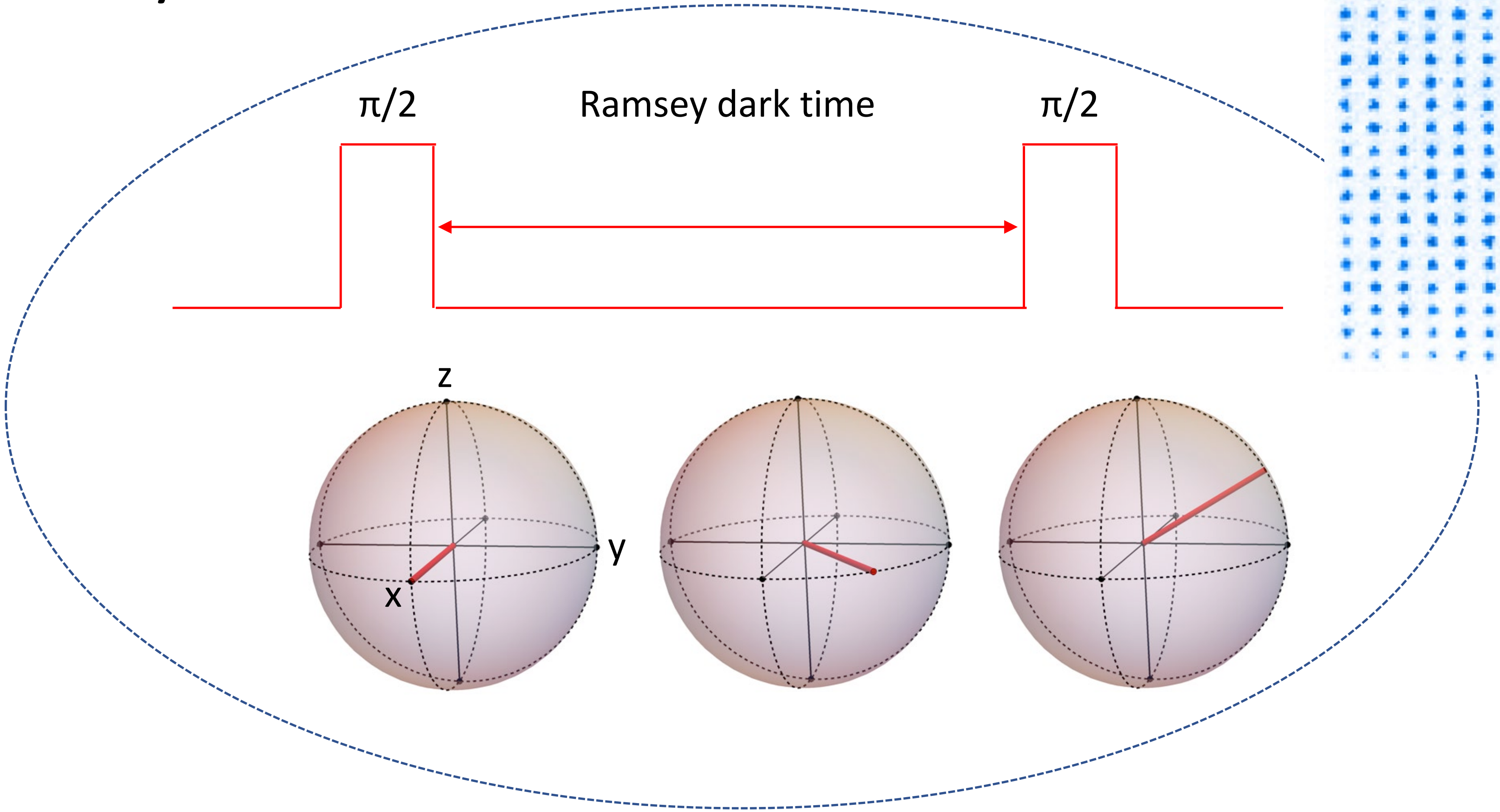
813 nm: maintains coherence of the clock transition, lots of power/trap



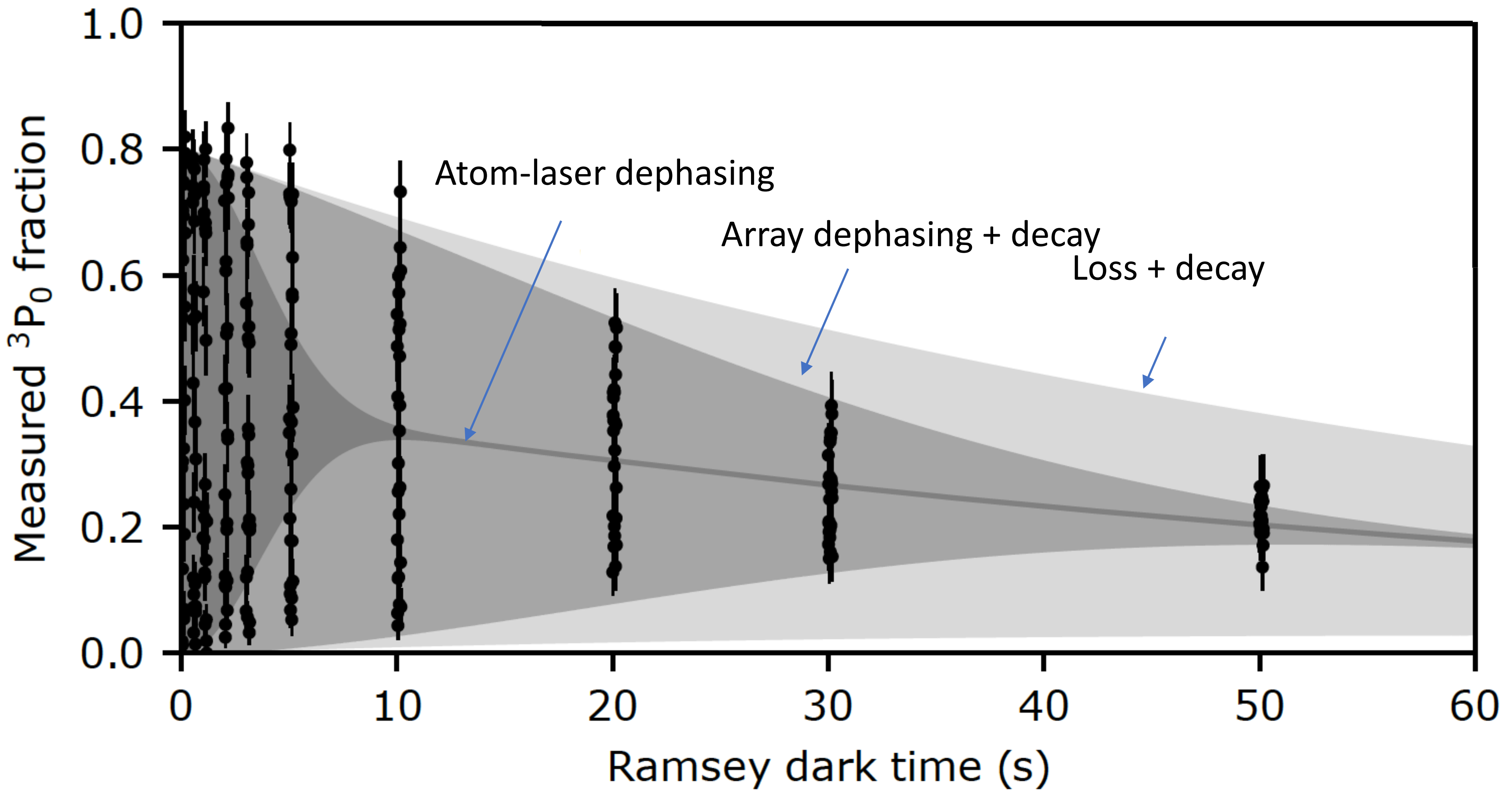
Ramsey measurements

Single run yields sufficient statistics





Ramsey measurements



Young, Eckner, Milner, Kedar, Norcia, Oelker, Schine, Ye, Kaufman, Nature (2020)

Forms of coherence

Yes **atom-laser** coherence,
Yes **atom-atom** coherence

No **atom-laser** coherence,
Yes **atom-atom** coherence

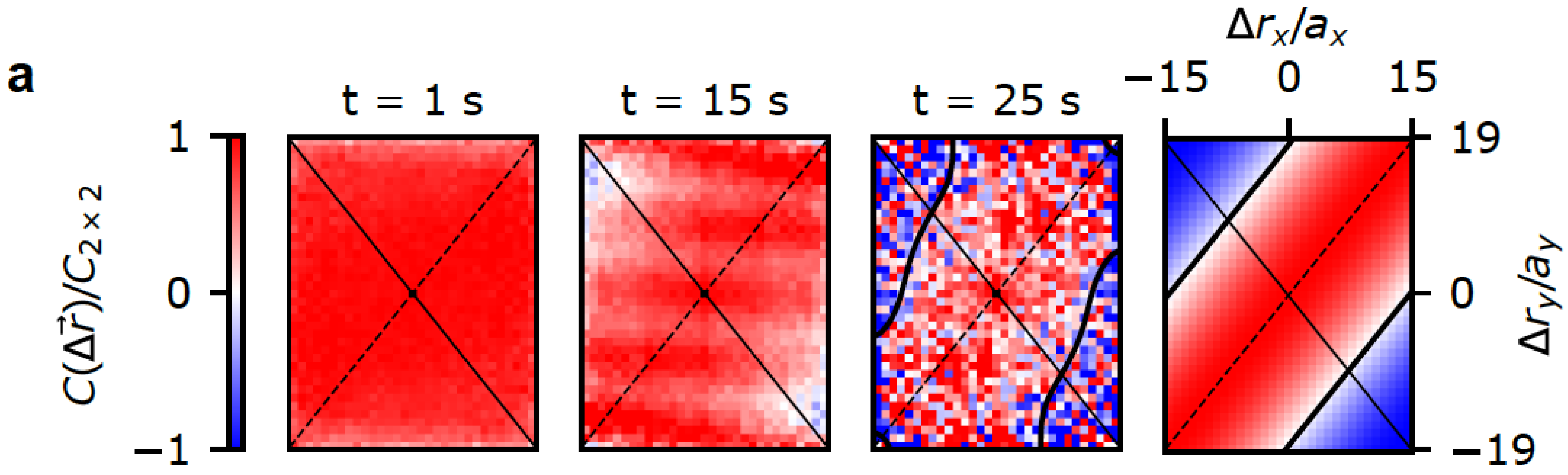
→ Bloch vectors of individual atoms correlated across the array

No **atom-laser** coherence,
No **atom-atom** coherence

Microscopic study of atomic coherence

S_z correlator after Ramsey sequence:

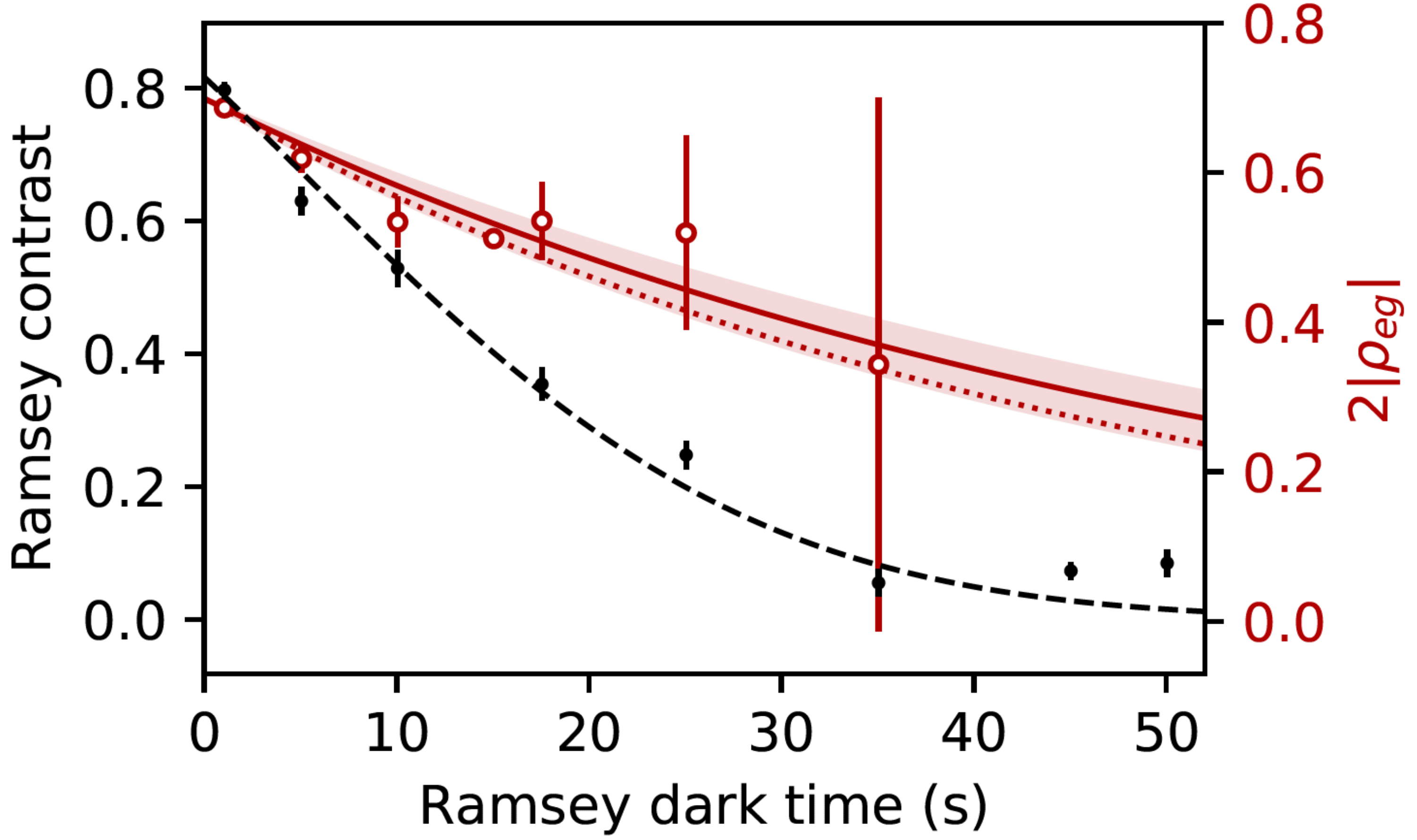
$$g_2(i,j) = 2|\rho_{eg,i}||\rho_{eg,j}|\cos(\phi_i - \phi_j)$$



Millihertz scale light shifts…
from tweezers AODs!!

Correlation spectroscopy in ions: Olmschenk…Monroe, PRA (2007) ; Chou…Wineland, PRL (2011); Tan. .Barret, PRL (2019)

Ensemble and single-particle coherence time



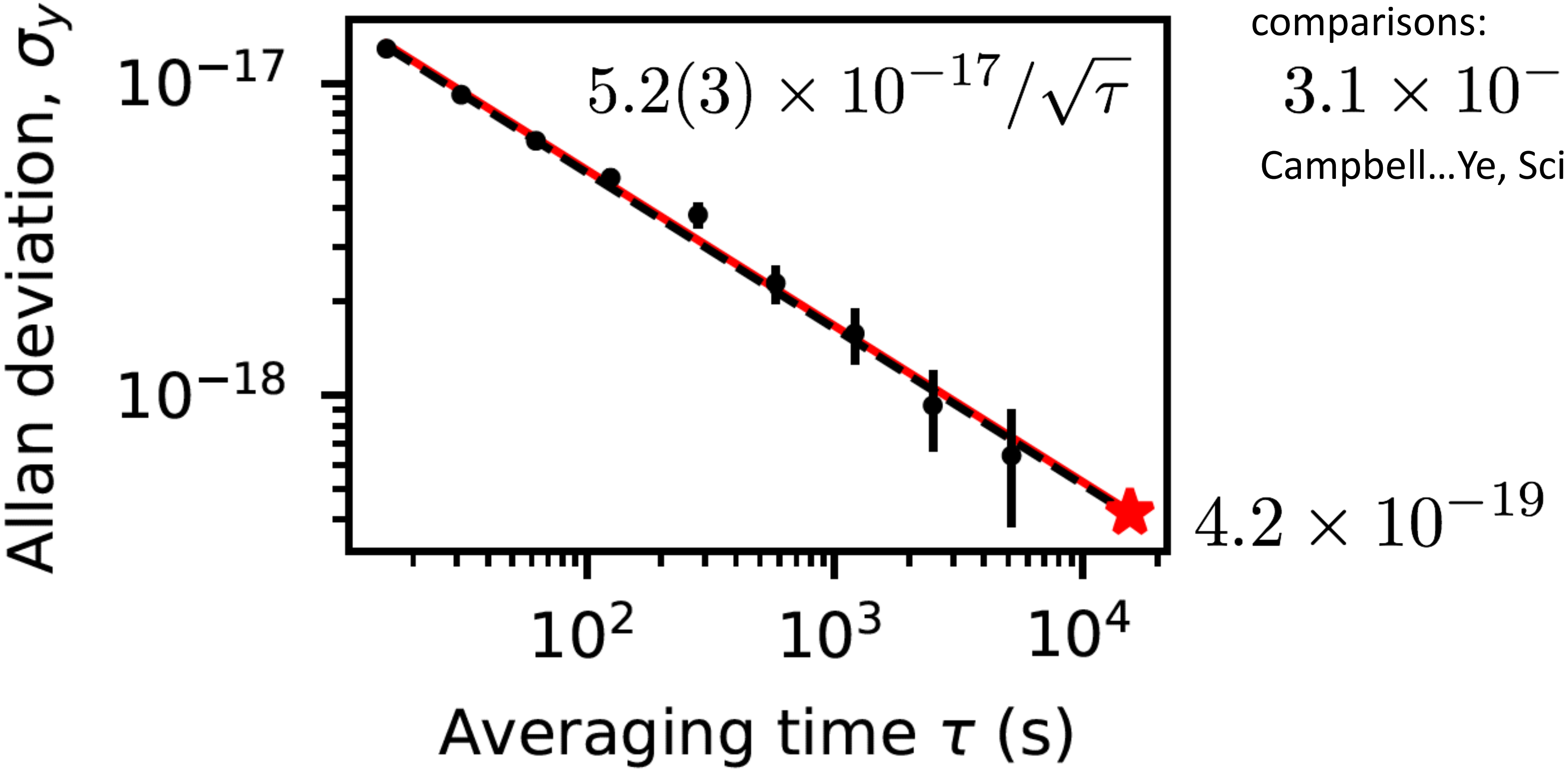
Ensemble coherence:
19.5(8) seconds
Limited by AODs → SLM

Single-particle coherence:
48(8) seconds including loss
92(9) seconds correcting loss

Quality factor: 6.5 x 10^{16}

Young, Eckner, Milner, Kedar, Norcia, Oelker, Schine, Ye, Kaufman, Nature (2020)

High stability, precision in self-comparisons



Lattice clock record for synch. comparisons:

$$3.1 \times 10^{-17}/\sqrt{\tau}$$

Campbell…Ye, Science (2017)

Young, Eckner, Milner, Kedar, Norcia, Oelker, Schine, Ye, Kaufman, Nature (2020)

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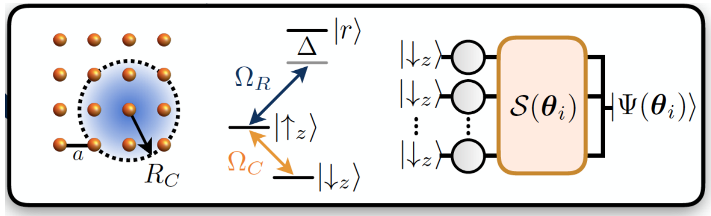
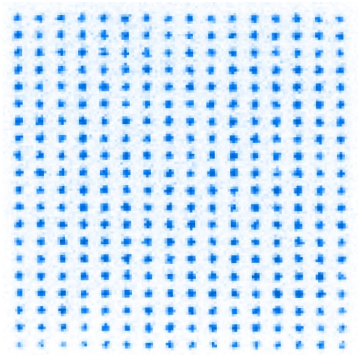
A tweezer clock

A Bell state on a neutral-atom clock transition



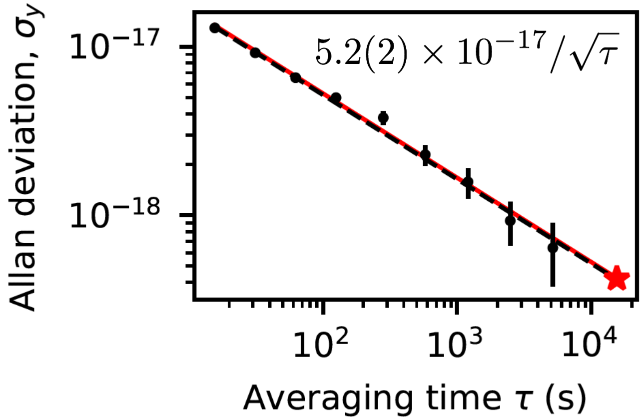
Tweezing single atoms into a Hubbard-regime lattice

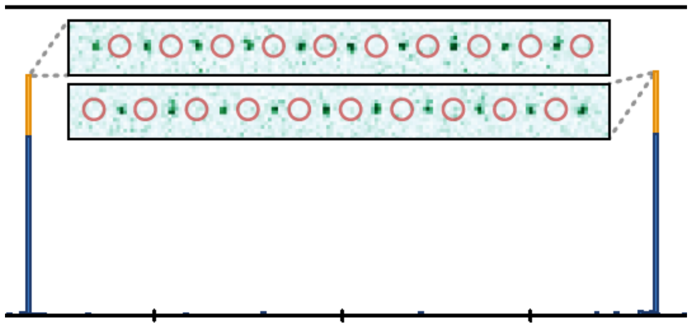
Combining a tweezer clock with entanglement



Stable, long-lived clocks

Entanglement generation w/ Rydberg interactions





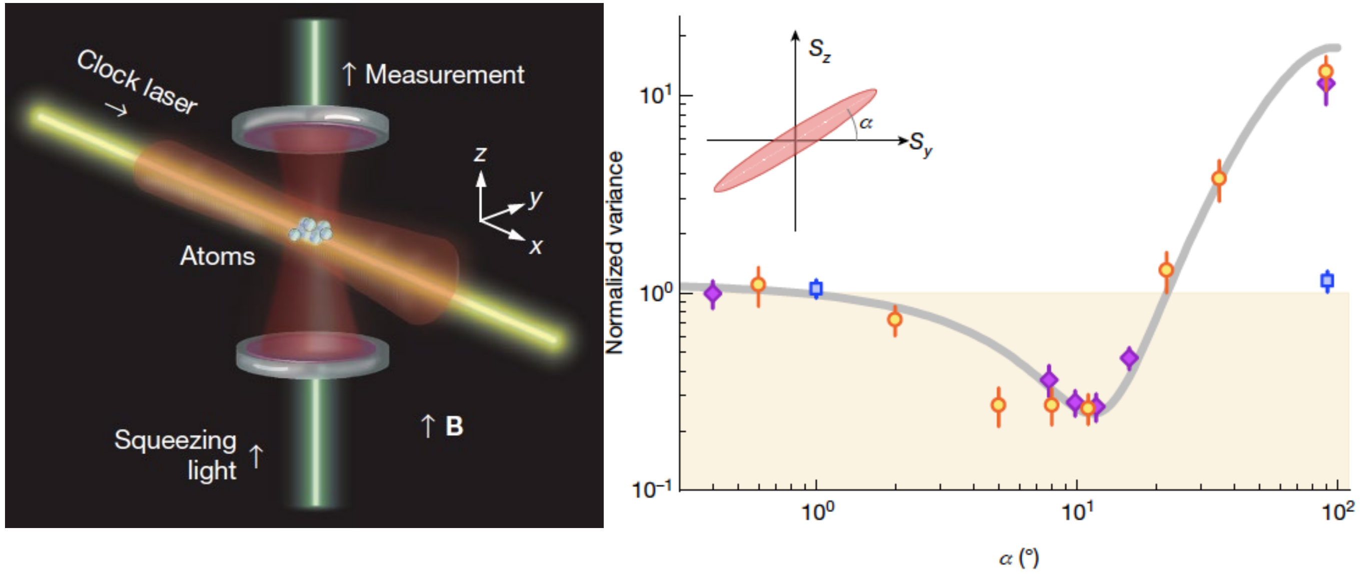
Omran…Lukin, Science (2019)

Long-lived, well-controlled entangled optical clocks

Pioneering work in ions: NIST, Ozeri Group, Blatt Group

Approaches to entanglement-enhanced clocks

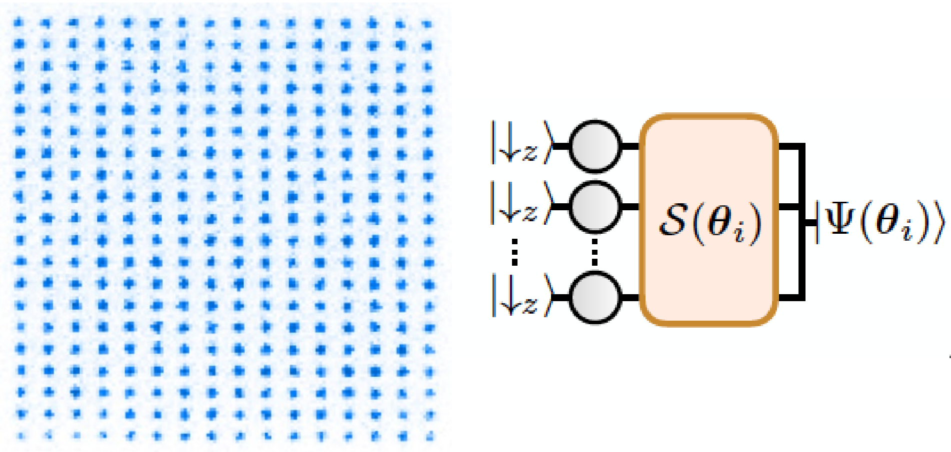
Cavity squeezing in optical-lattice clocks



Pedrozo-Peñafiel…Vuletic, Nature (2020)

Also being pursued at JILA: Thompson, Ye

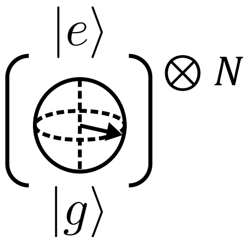
Programmable quantum sensors with tweezer clocks



Kaubruegger…Rey, Ye, Kaufman, Zoller, PRL (2019)

Entanglement-enhanced metrology

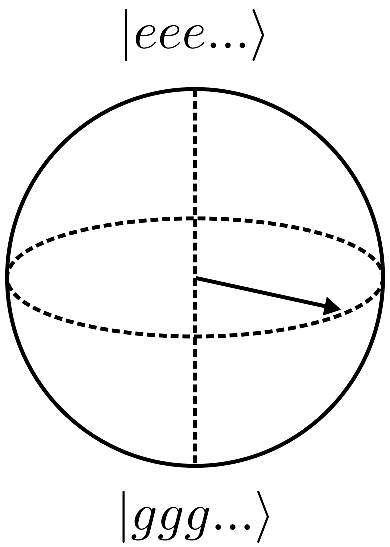
Many uncorrelated TLSs



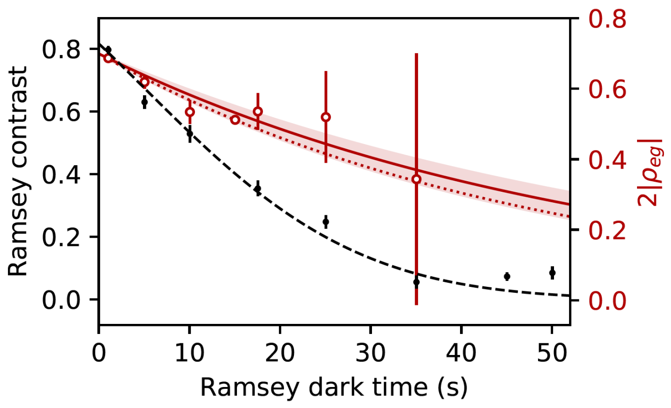
If lifetime limited, same Q, $\sqrt{N}\times$ worse QPN. If not, $N\times$ higher Q → higher bandwidth sensors

$$\sigma_{QPN} \propto \frac{1}{Q}\sqrt{\frac{T_c}{N\tau}}$$

Single TLS, $N\times$ larger energy separation, $N\times$ faster decay



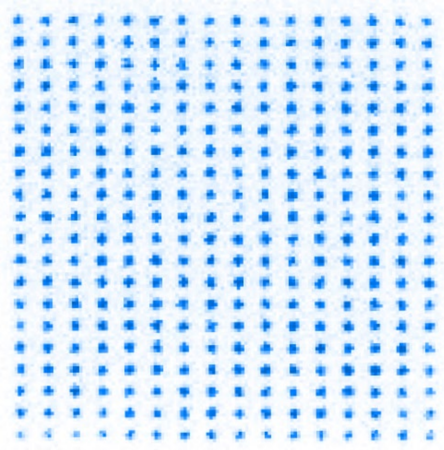
For us, $\sim$20s atomic coherence, $\gtrsim \sim 10\times$ longer than typical clock laser

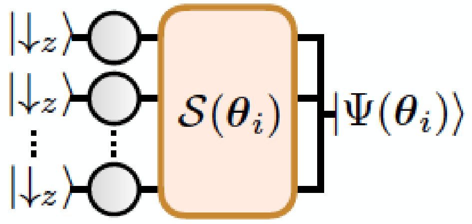


Many other subtleties:

- Dick effect phase diffusion
- Measurement basis
- Form and time of decoherence

Experiment needs

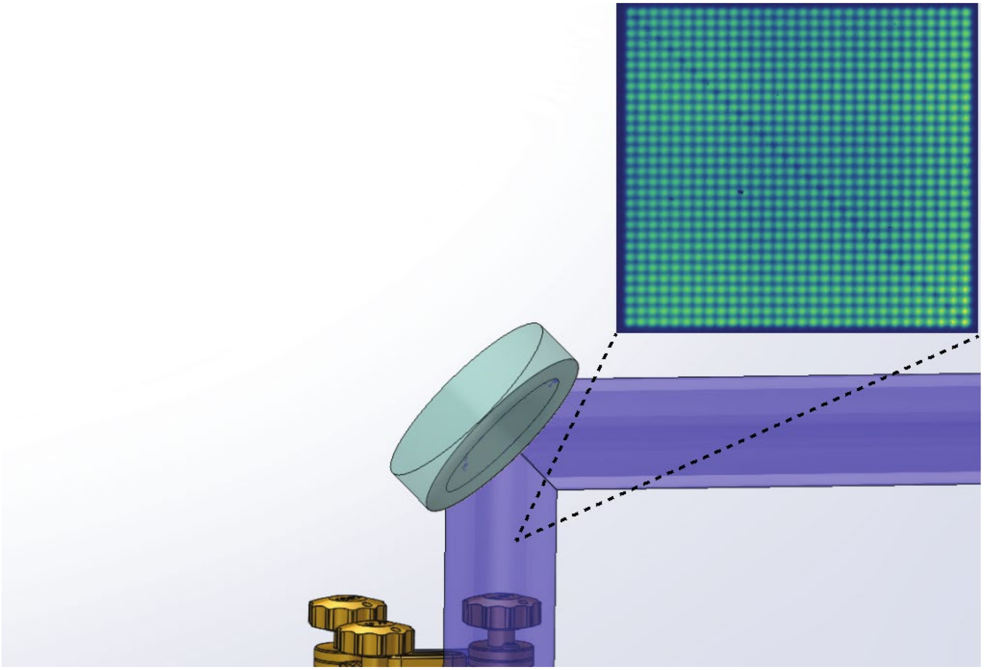


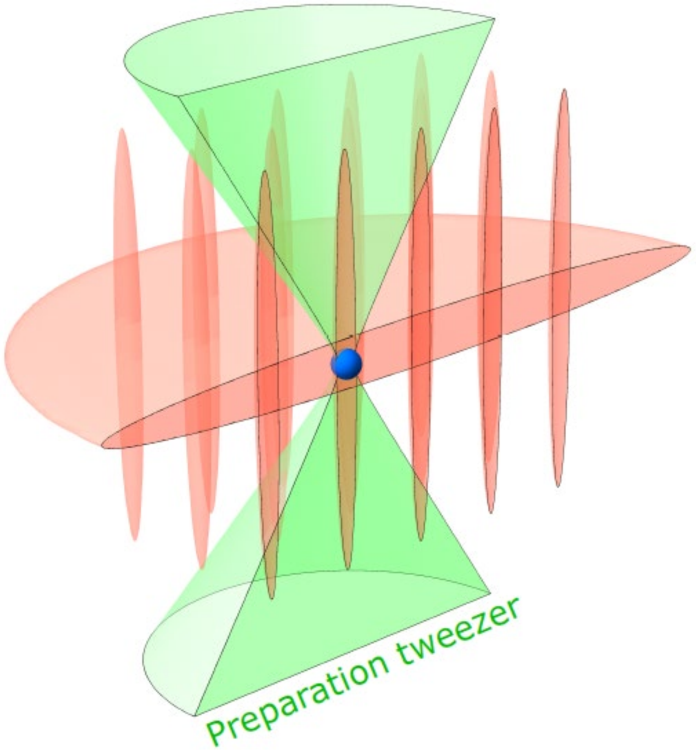


- High fidelity qubit/clock control: need many gates for large enhancements, want better detection
- Two-qubit control: coherent Rydberg excitation

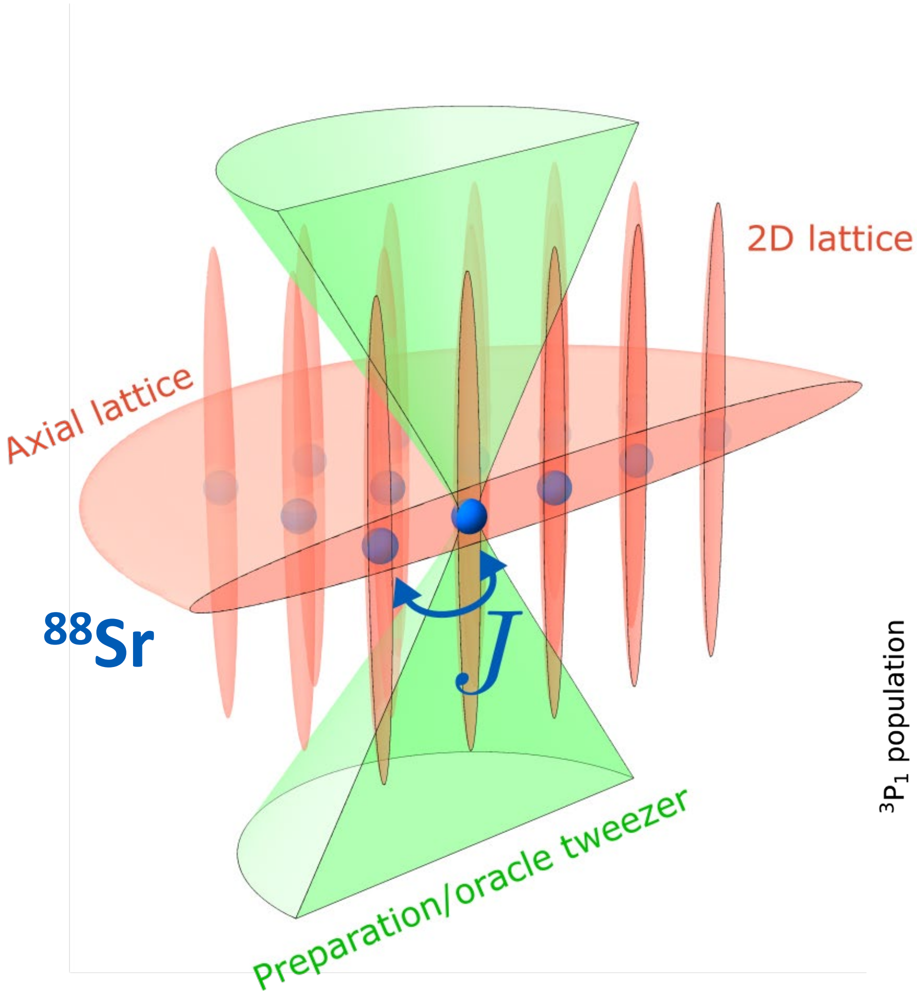
(All during COVID!)

Interfacing tweezers and lattice

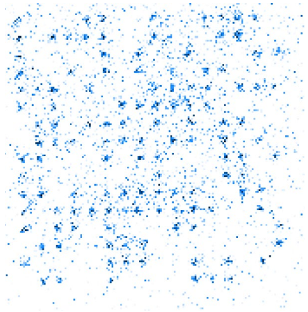




Interfacing tweezers and lattices

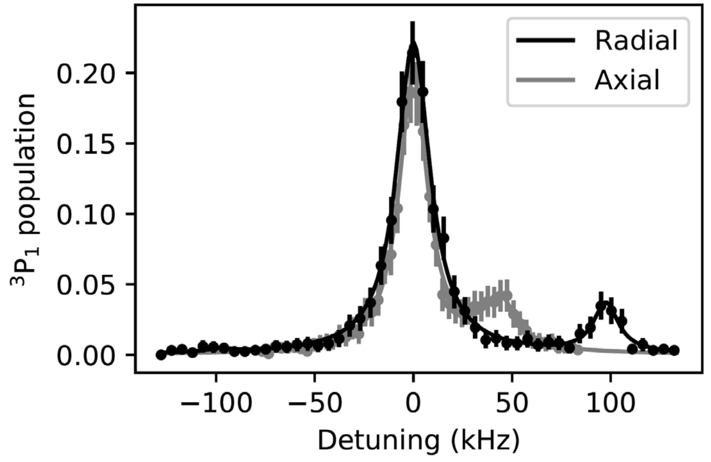


< 1% imaging loss + infidelity



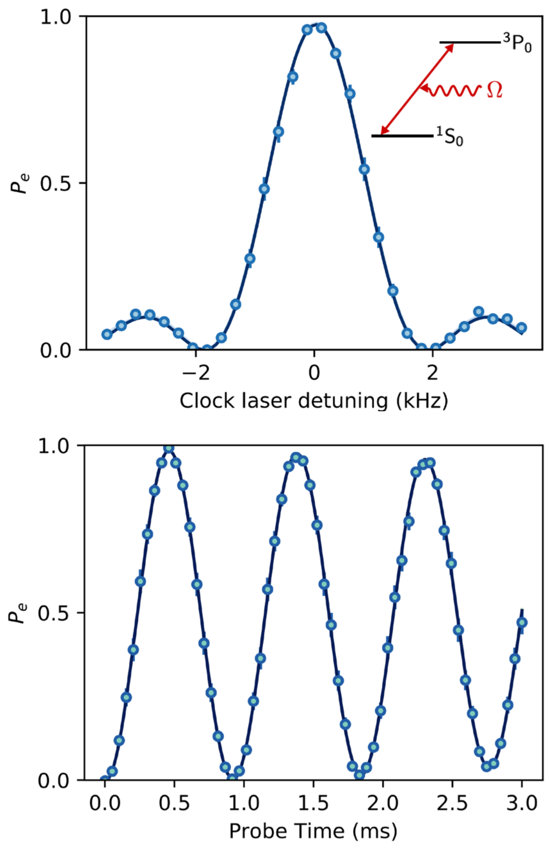
Expect to push to < 0.1% - Covey…Endres, PRL (2019); Norcia…Kaufman, Science (2019)

~90% 3D motional ground state fraction



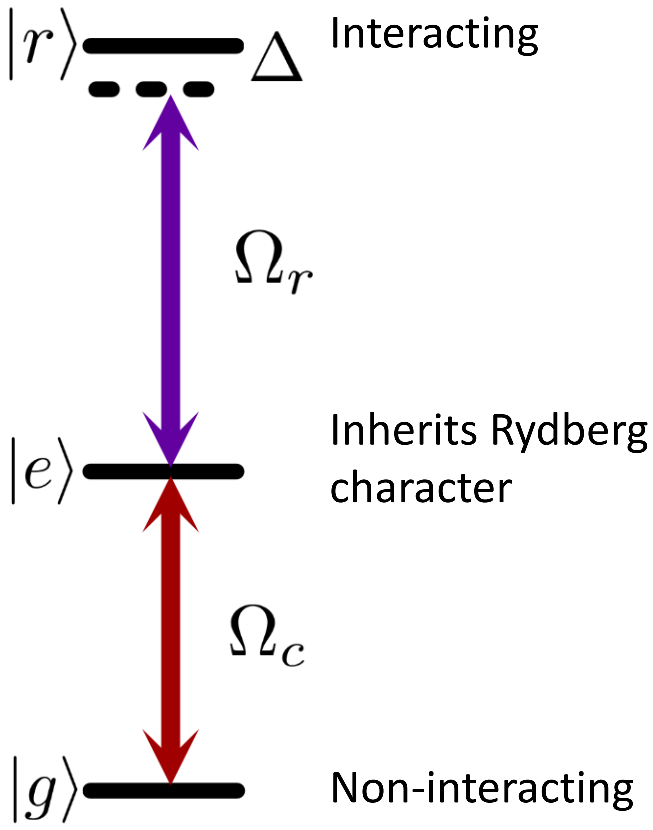
99(1)% single qubit gate fidelity (previously ~80%)

consistent with expectation of 99.5% (with SPAM correction)

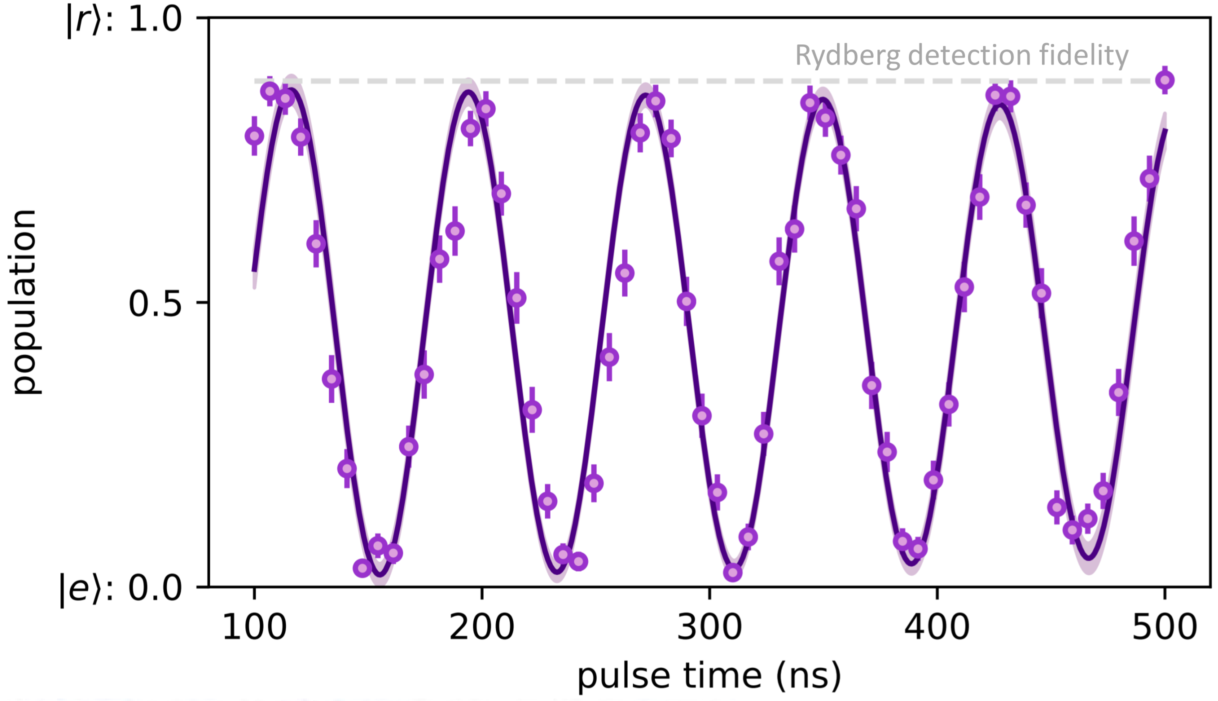


>3000 lattice sites compatible with imaging, 3D ground state cooling, and control of clock qubit

Quantum control on the Rydberg transition



~35 oscillations, 2d homogeneity limited



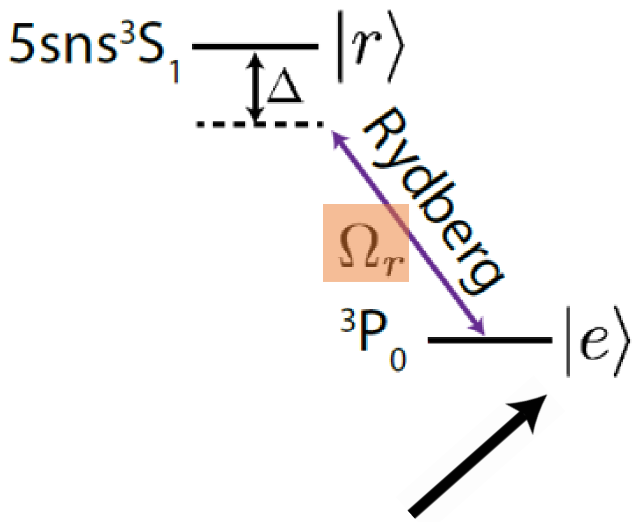
tweezer defined, lattice imaged

Rydberg Rabi frequency: $2\pi \times 12$ MHz

see also Madjarov…Endres, Nat. Phys. 2020

Rydberg-mediated clock entanglement

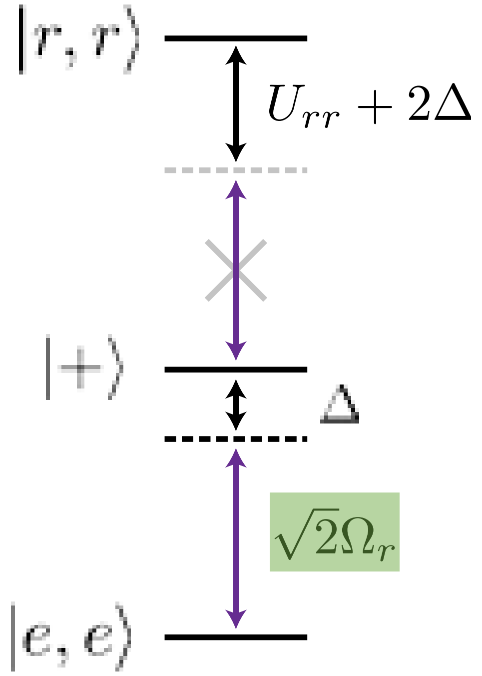
Single atom



(two particle state: $|ge\rangle, |eg\rangle$)

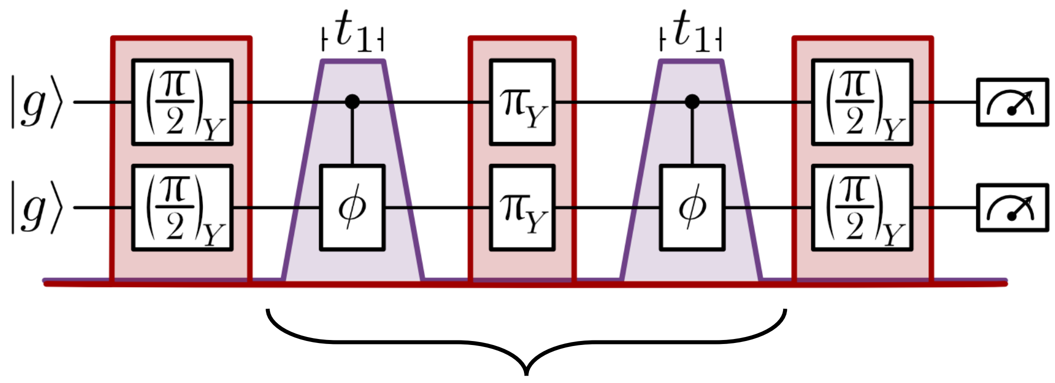
$$E_{\pm}^{(1)} = \frac{1}{2}\left(-\Delta \pm \sqrt{\Omega_r^2 + \Delta^2}\right)$$

Two atoms (r $\ll R_c = \left(\frac{C_6}{\Omega_r}\right)^{\frac{1}{6}}$)



$$E_{\pm}^{(2)} = \frac{1}{2}\left(-\Delta \pm \sqrt{2\Omega_r^2 + \Delta^2}\right)$$

Energy scale for entanglement: $\kappa = E^{(2)} - 2E^{(1)}$



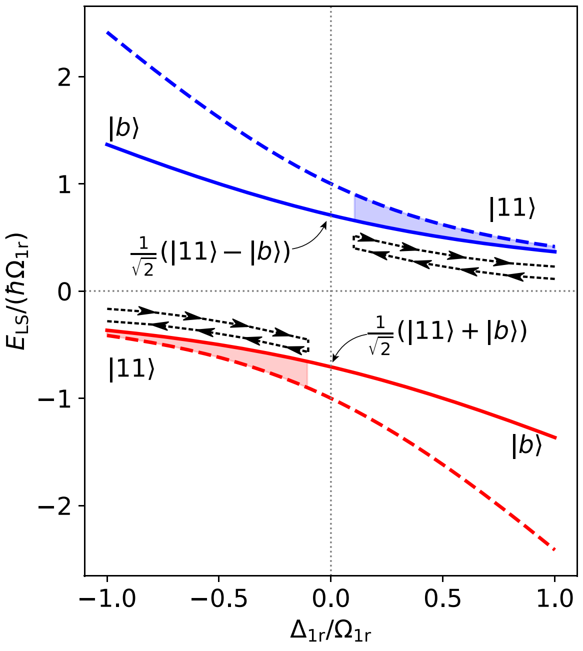
$$H_{eff} \propto \kappa S_z^2$$

Rapid adiabatic Rydberg dressing

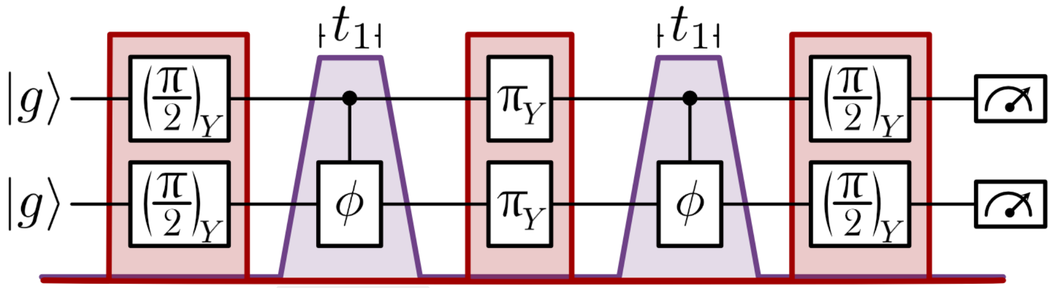
For $\Delta \gg \Omega$:

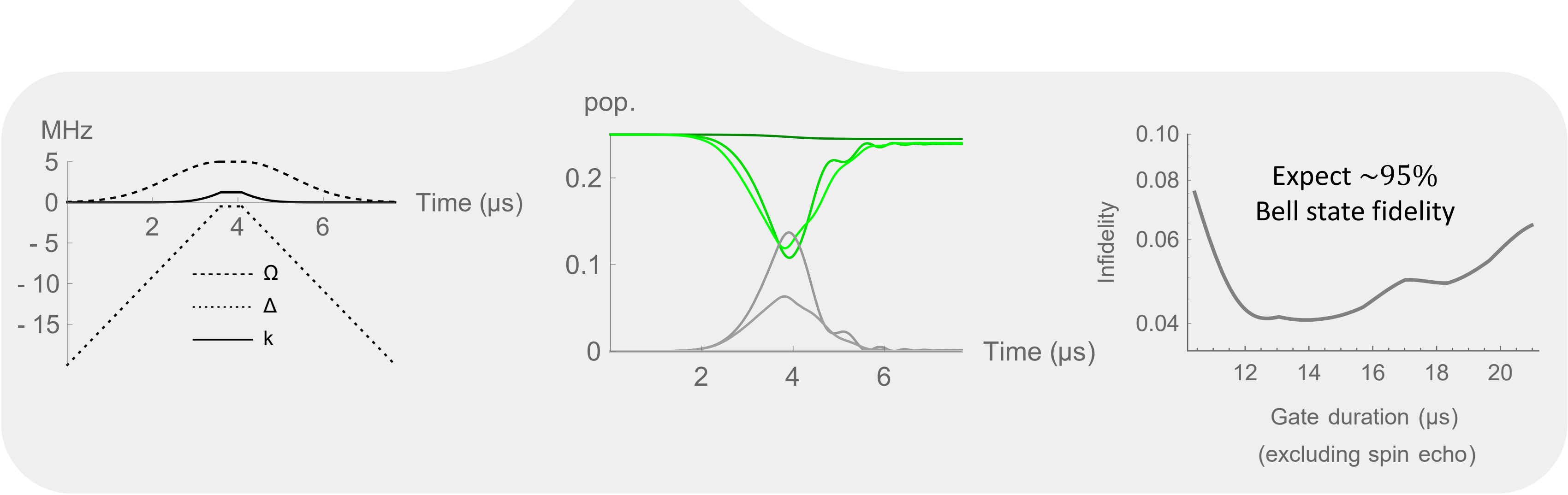
Dominant error – decay of Rydberg state $\sim \frac{\Omega^2}{\Delta^2}$

Interaction strength $\sim \frac{\Omega^4}{\Delta^3}$

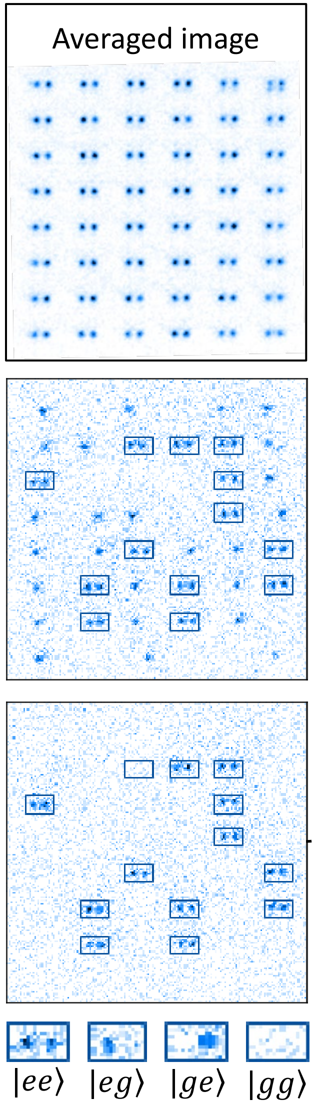


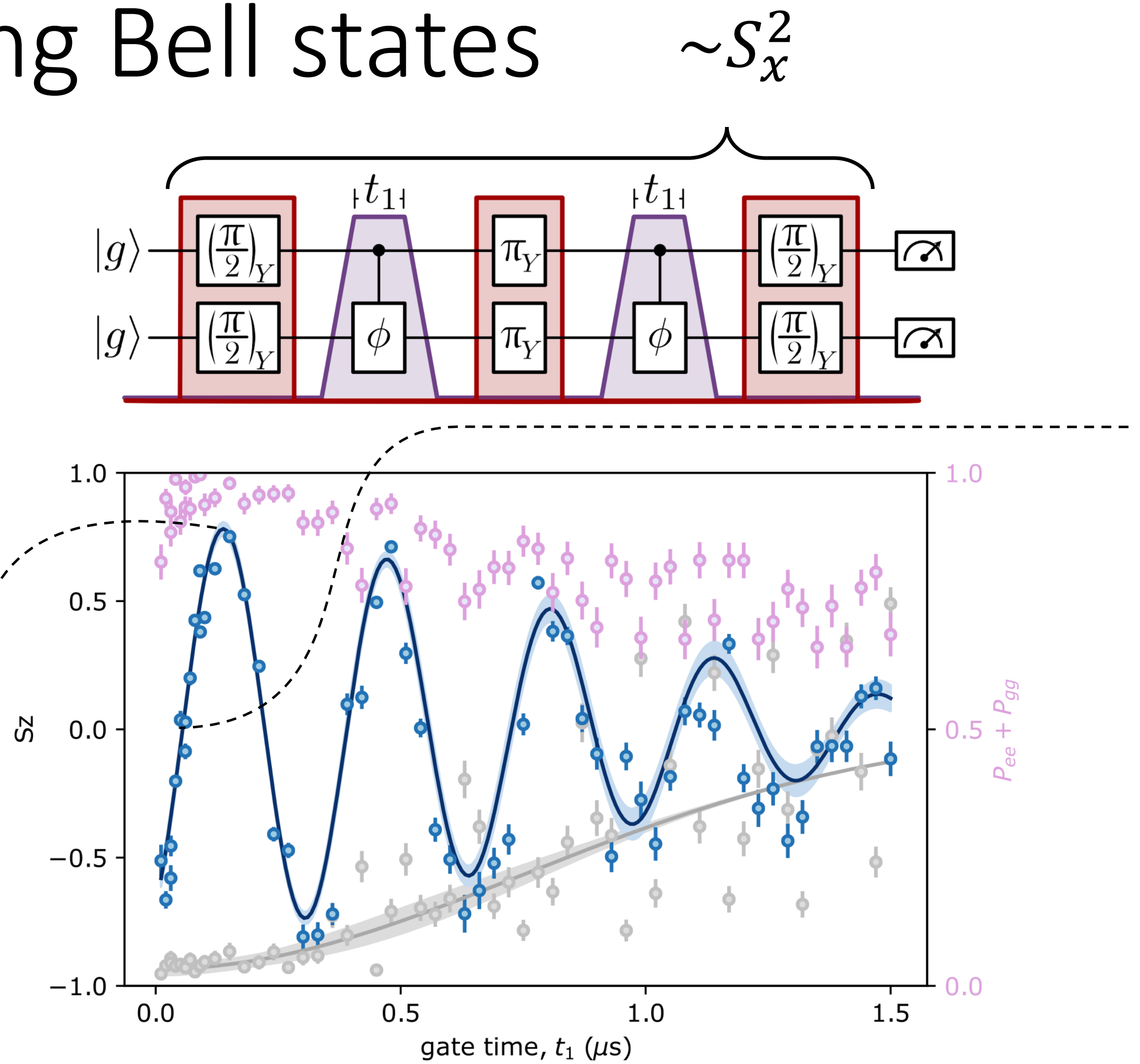
Mitra… Deutsch, PRA (2020)





Generating Bell states





$$|\psi\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + e^{i\theta}|ee\rangle)$$

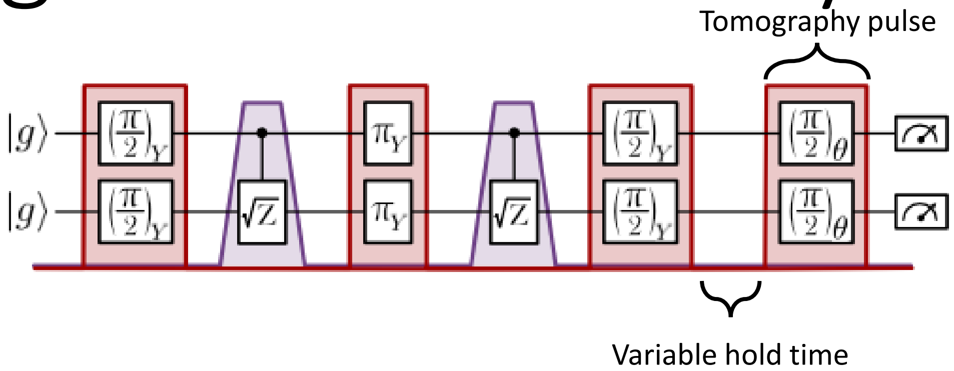
$$P_{ee} + P_{gg} \simeq 0.96$$

θ consistent/well-defined?

$$R_{\hat{n}}\left(\frac{\pi}{2}\right)$$

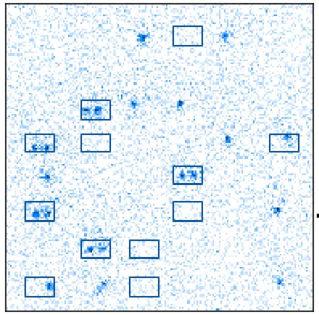
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$$

Certifying Bell state fidelity and lifetime

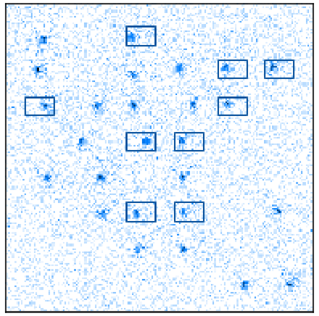


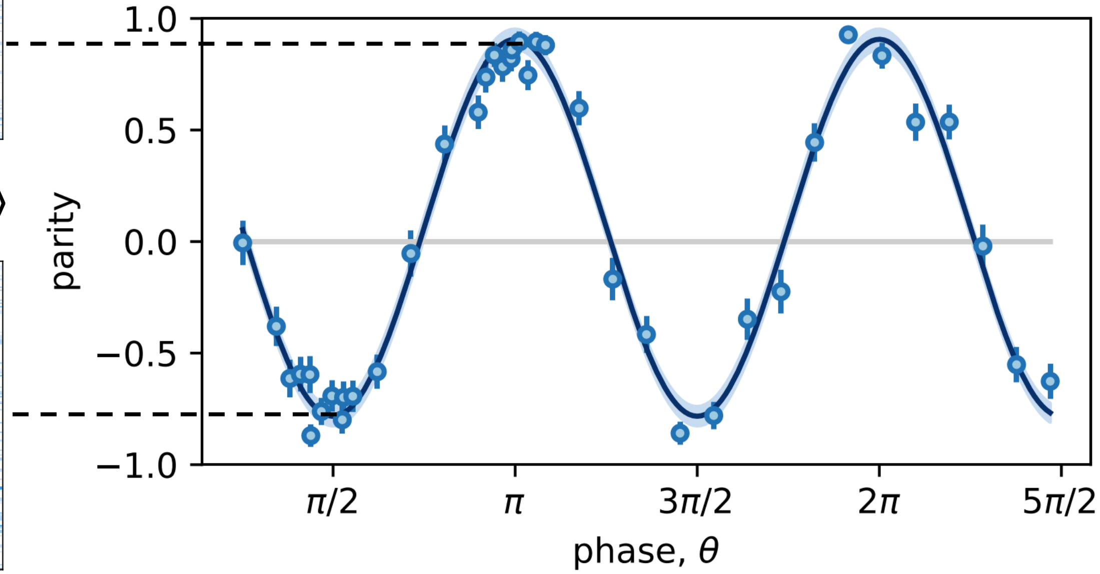
In progress: correlation spectroscopy to certify longer expected coherence time

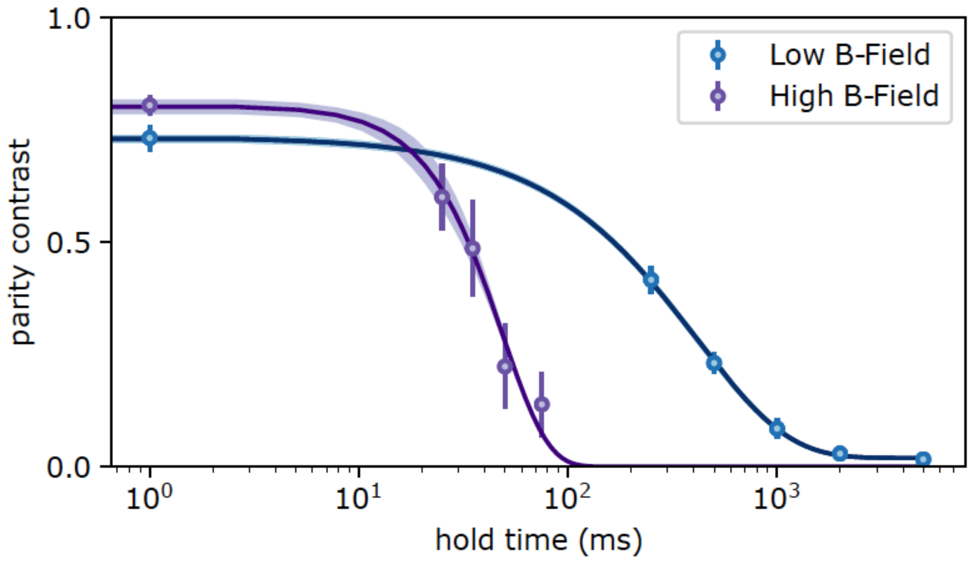
$|\psi\rangle \sim |gg\rangle + i|ee\rangle$



$|\psi\rangle \sim |eg\rangle + |ge\rangle$







Bell state fidelity with [without] SPAM correction: $F = 89(3)\%\ [86(3)\%]$

> 418(8) ms Bell-laser coherence time

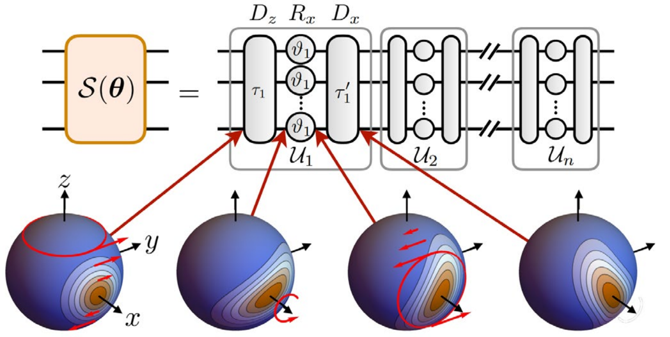
Prior results in alkalis: 97.4% in 1D arrays (Lukin), 88% in 2D arrays (Saffman)

Manuscript in preparation

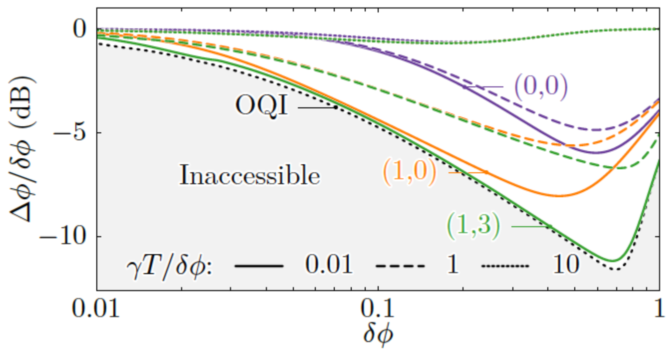
On the horizon:

Metrology with bell states

Variational optimization with σ_z^2 + Global rotations



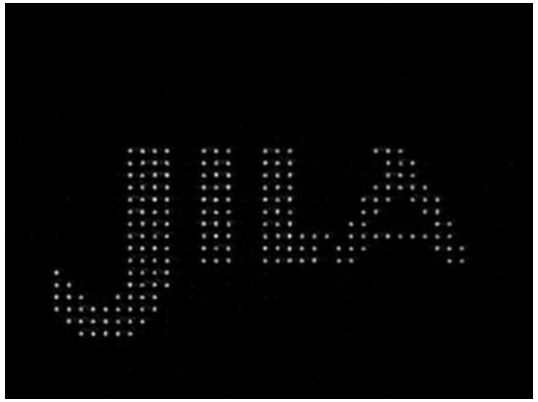
Kaubruegger… Zoller, PRL (2019)



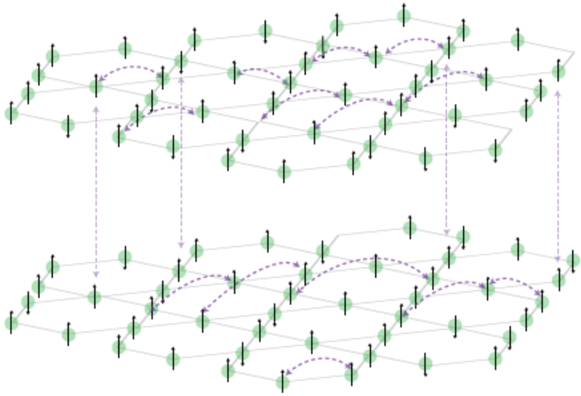
Kaubruegger…Zoller, arXiv 2102:05593 (2021)
Plot shown: 64 particles

Dynamics of Ising, transverse Ising models, in and out-of equilibrium (collaboration with Rey group)

Programmability



Controlled studies of the useful entanglement arising from many-body spin models



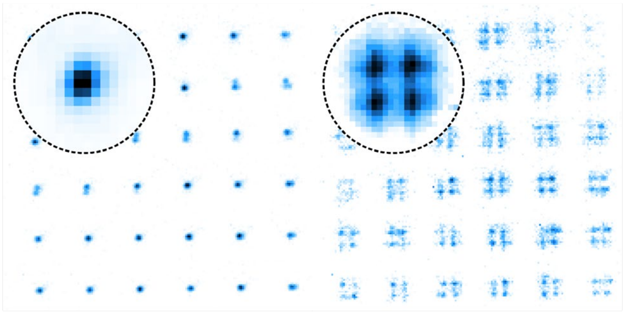
Outline

Why alkaline-earths?

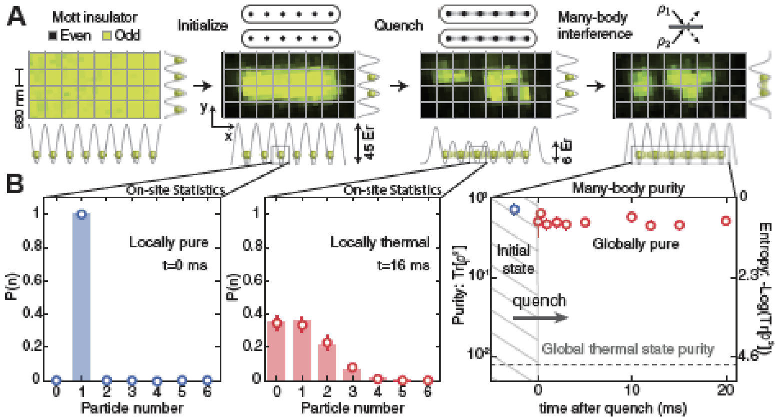
A tweezer clock

A Bell state on a neutral-atom clock transition

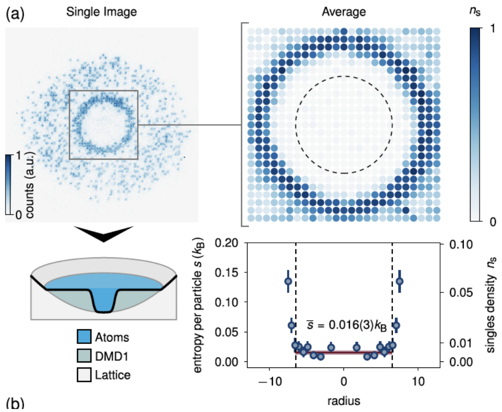
Tweezing single atoms into a Hubbard-regime lattice



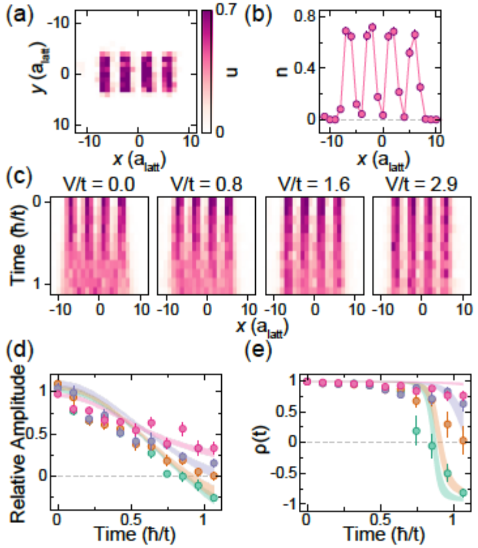
Initializing low entropy samples with QGMs is useful



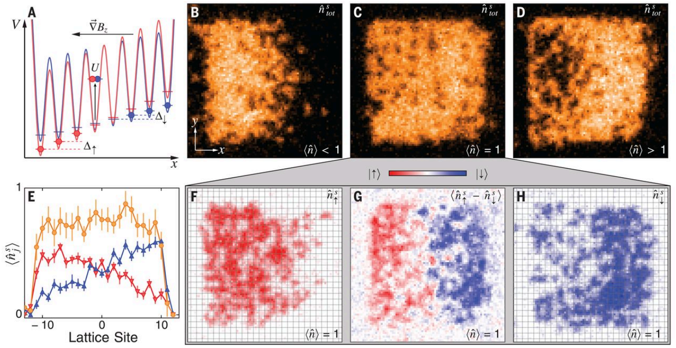
Greiner: thermalization



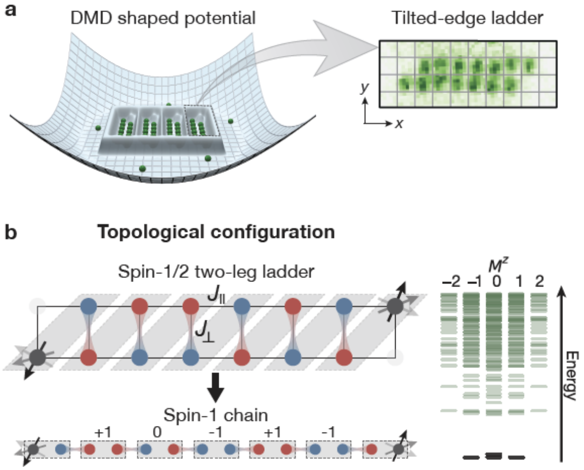
Greiner: low entropy AFM



Bakr: extended Hubbard models



Zweirlein: spin transport

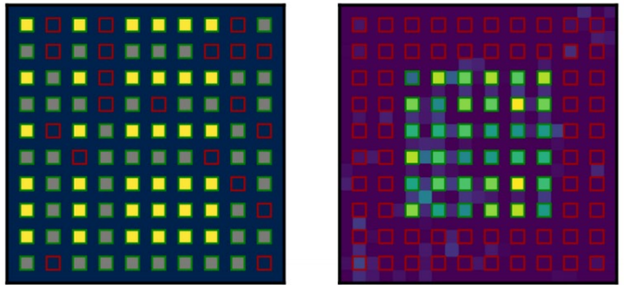


Bloch: SPT phases in FHM

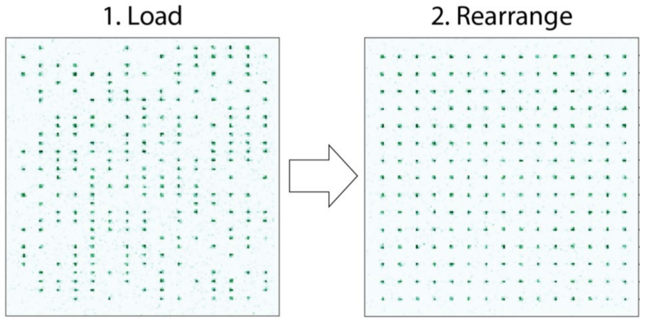
Incomplete list…

Other ways to reach unity filled arrays…

Programmable rearrangement in tweezer arrays

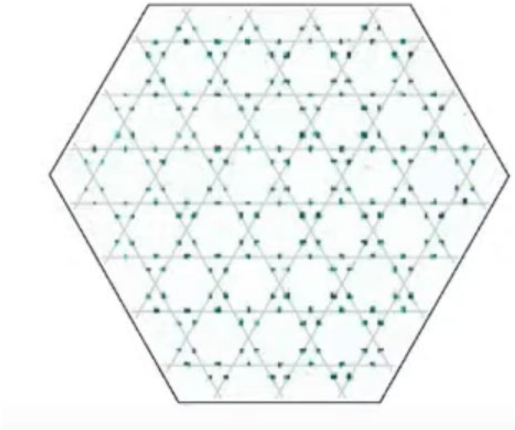


Brown… Regal, PRX (2019)



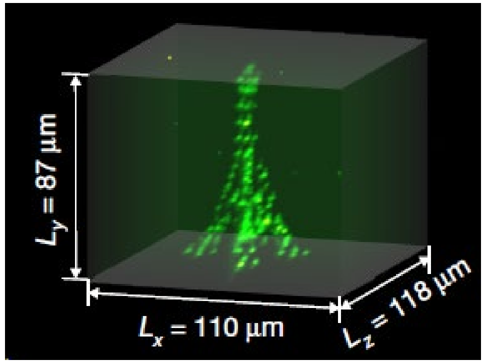
Ebadi… Lukin arXiv:2012.12281

Extends to arbitrary geometries/configurations



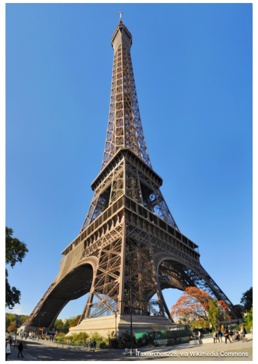
Lukin group, unpublished

$10^{30} \times$



Barredo… Browaeys Nature (2018)

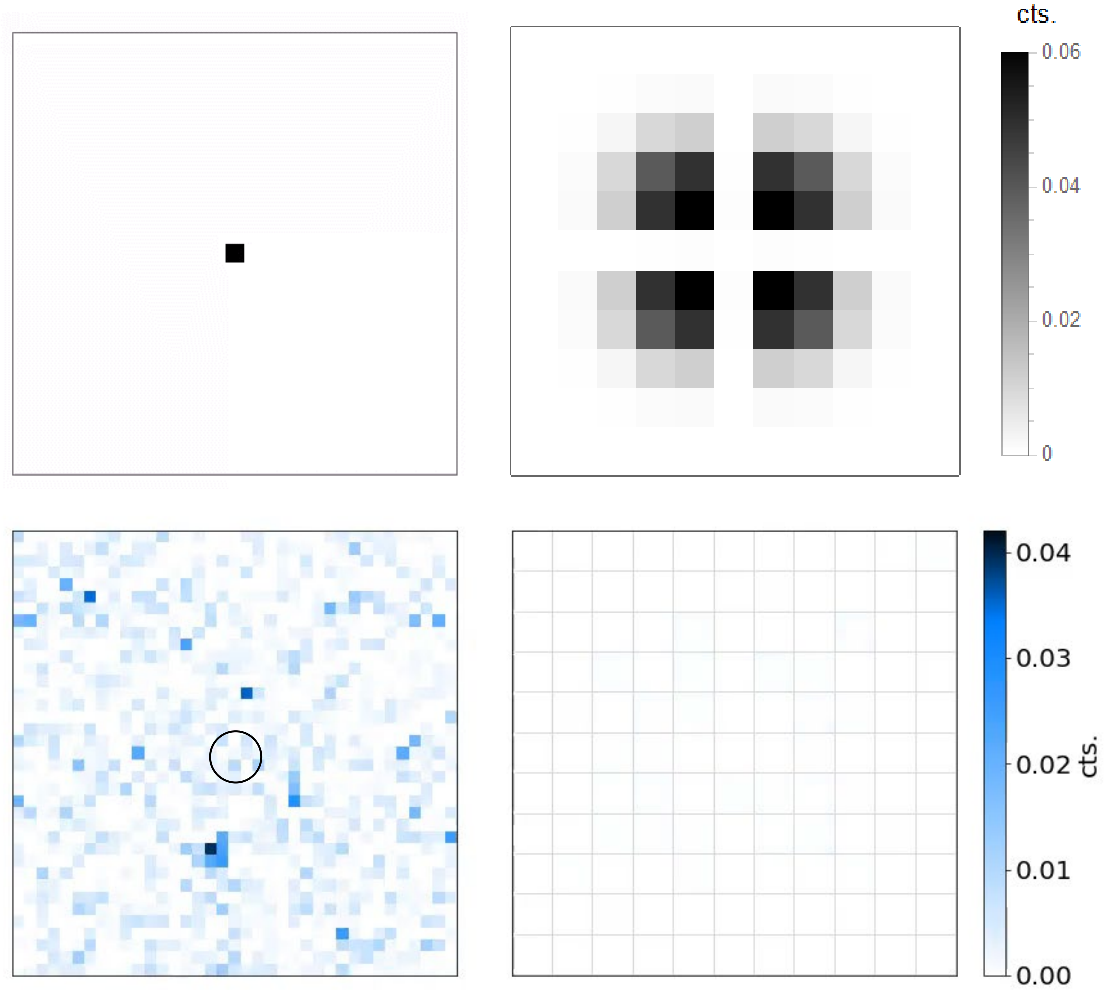
$\simeq$



..and fast

Can you combine lattice itinerance with the preparation capabilities of tweezers?

Quantum random walk



Ultracold atoms:
Karski… Meschede, Widera, Science (2009)
Preiss… Greiner, Science (2015)

Ions:
Zähringer… Blatt, Roos, PRL (2010)

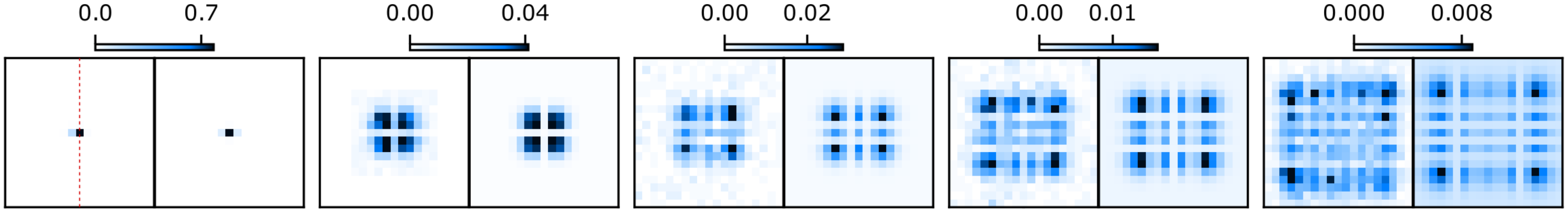
NMR:
Du… Han, PRA (2003)

Photonics:
Schreiber… Silberhorn, PRL (2010)
Tang… Jin, Sci. Adv. (2018) – 2D

Superconducting qubits:
Gong… Zhu, Pan, Science (2021) – 2D

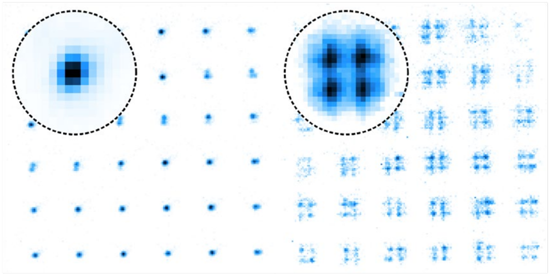
…and more

2D quantum random walk



Coherent exploration of > 200 lattice sites with ~150 Hz tunneling rate

Fast cycle time enables exploration of large systems



Search via 2D quantum random walk

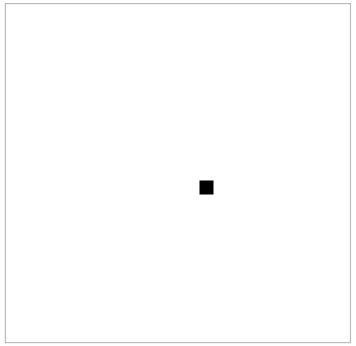
Spatial search by quantum walk – Childs and Goldstone, PRA (2004)

$H_{Oracle} = -V_l|l\rangle\langle l|$

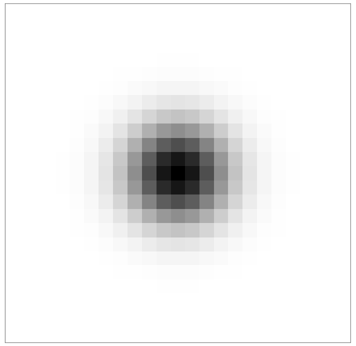
$$H_{Lat} = -J \sum_{\{i,j\ neighbors\}} |j\rangle\langle i| + \sum_i V_i|i\rangle\langle i|$$

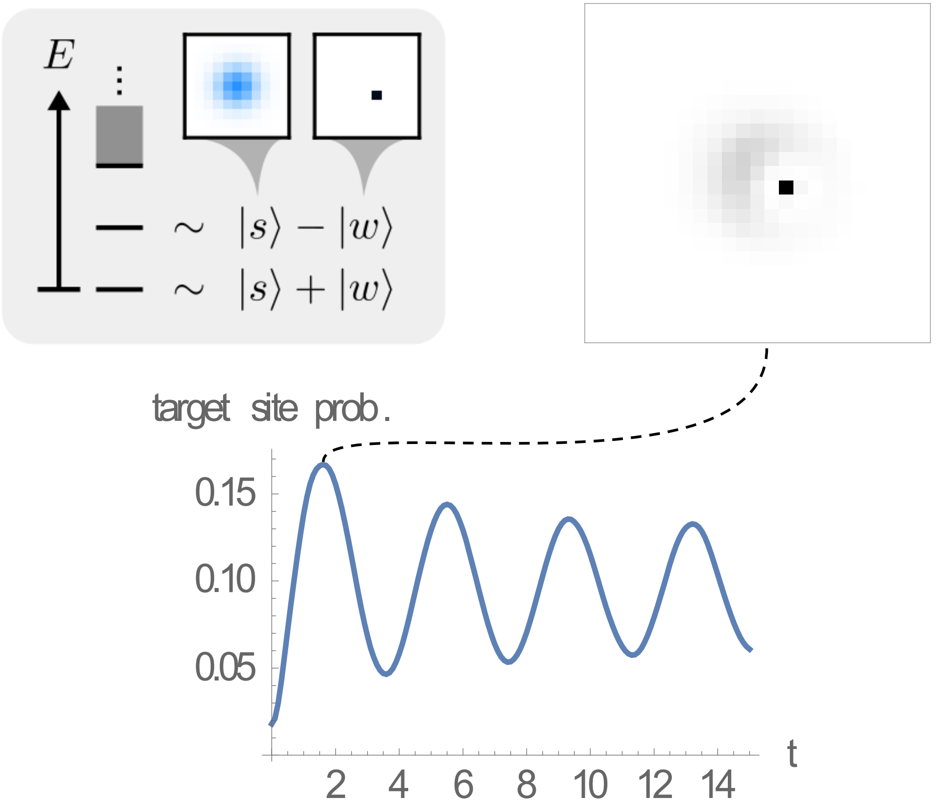
Quench from H_{Lat} to $H_{Lat} + H_{Oracle}$

Oracle ground state



Lattice ground state
(resource state)

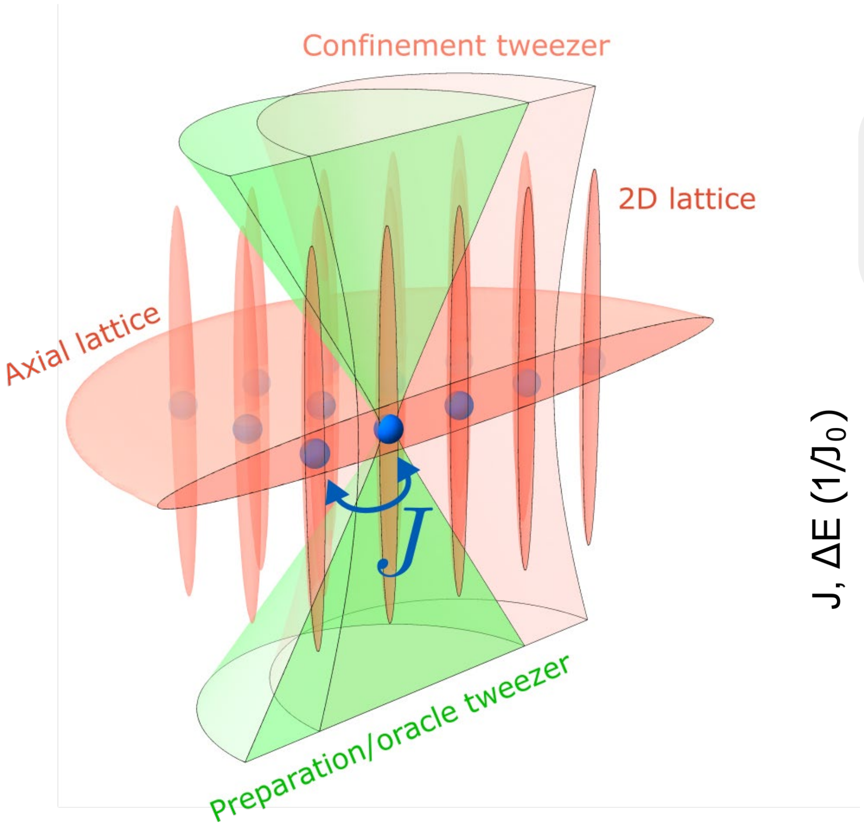


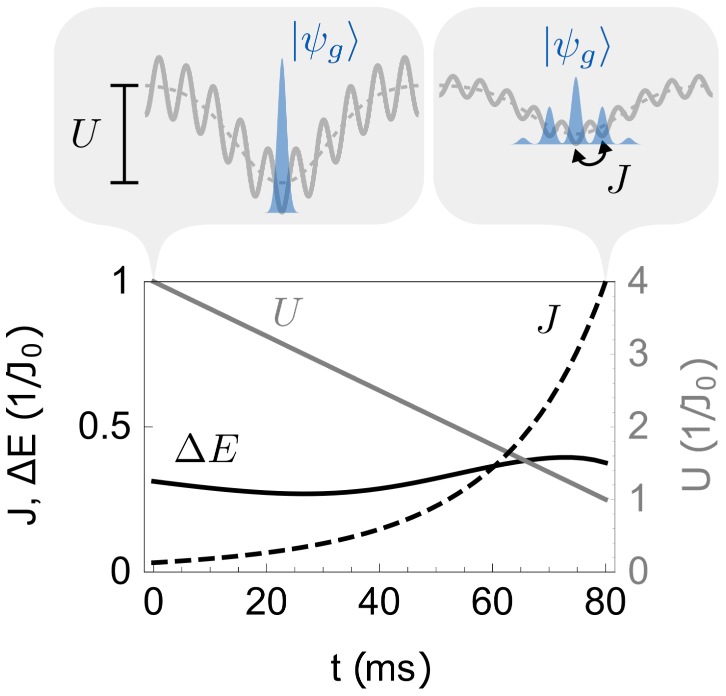


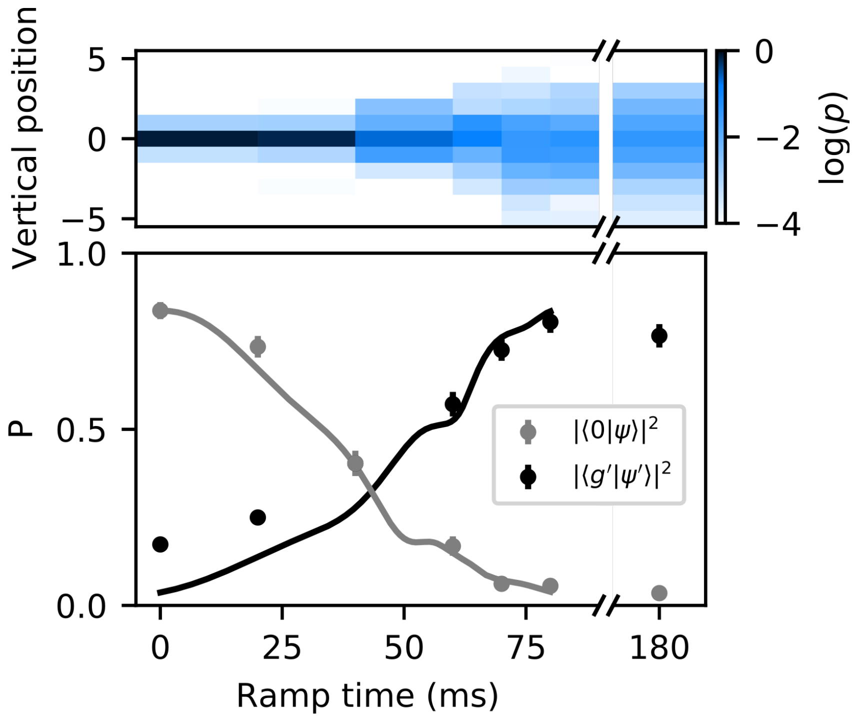
Advantage in ≥ 4 dimensions

Prospects for scaling to multiple particles, resulting in effective lattice dimension of $2 \times$(#particles)

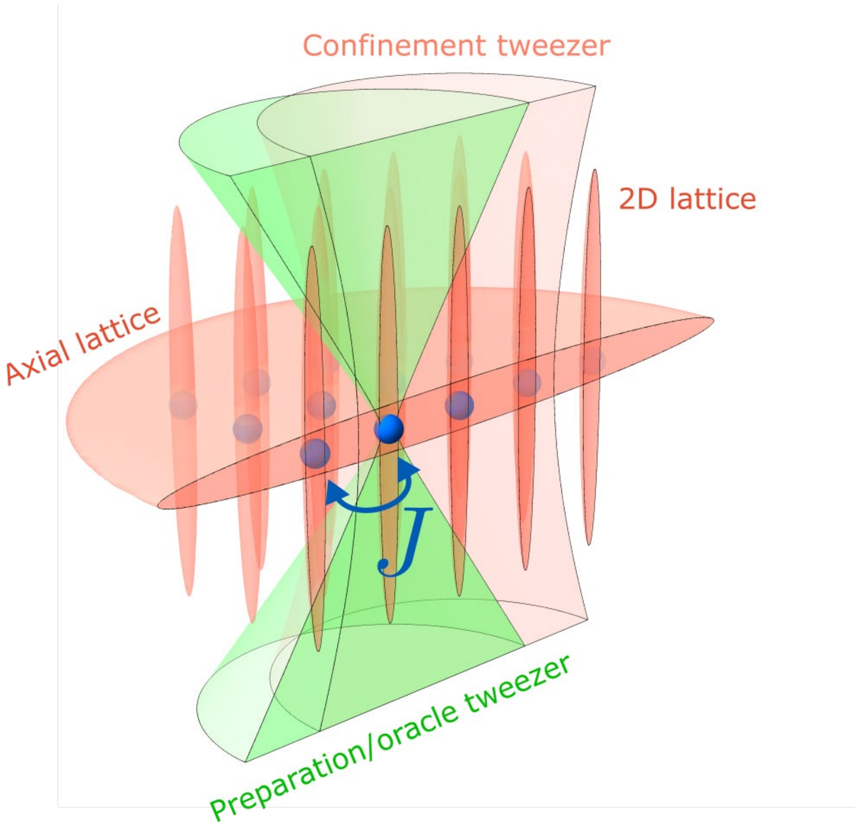
Adiabatic preparation of resource state

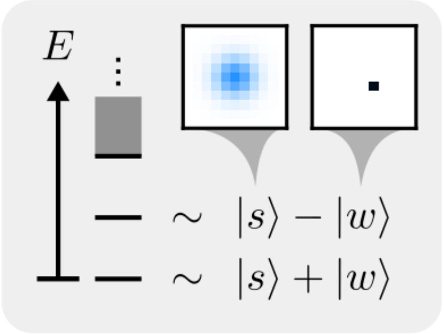


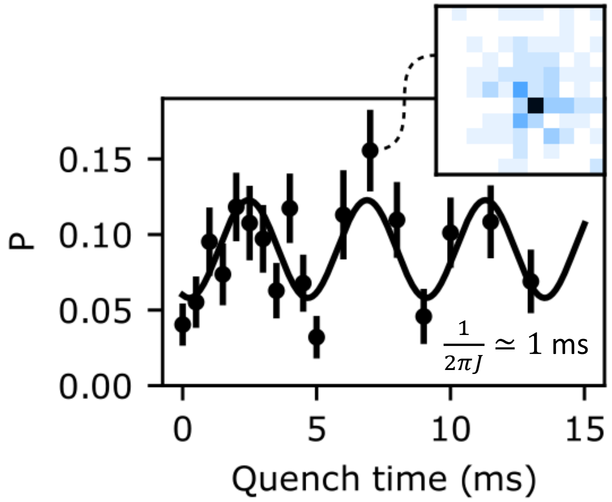


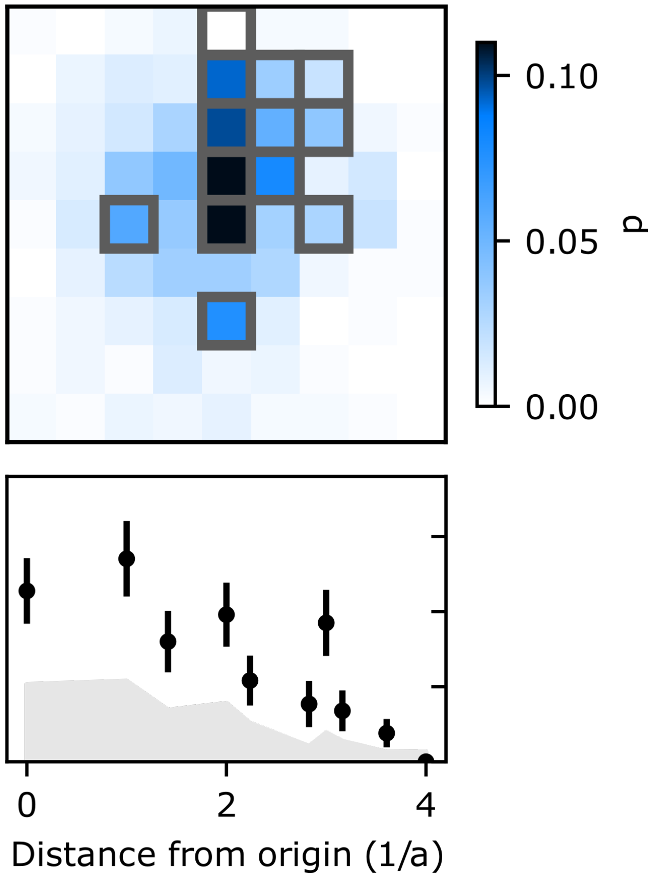


Search via 2D quantum random walk









Searching an unstructured set with 13-45 elements

Young et al., et al., *in preparation*

What is quantum about this?

A Classical Analog of Quantum Search*

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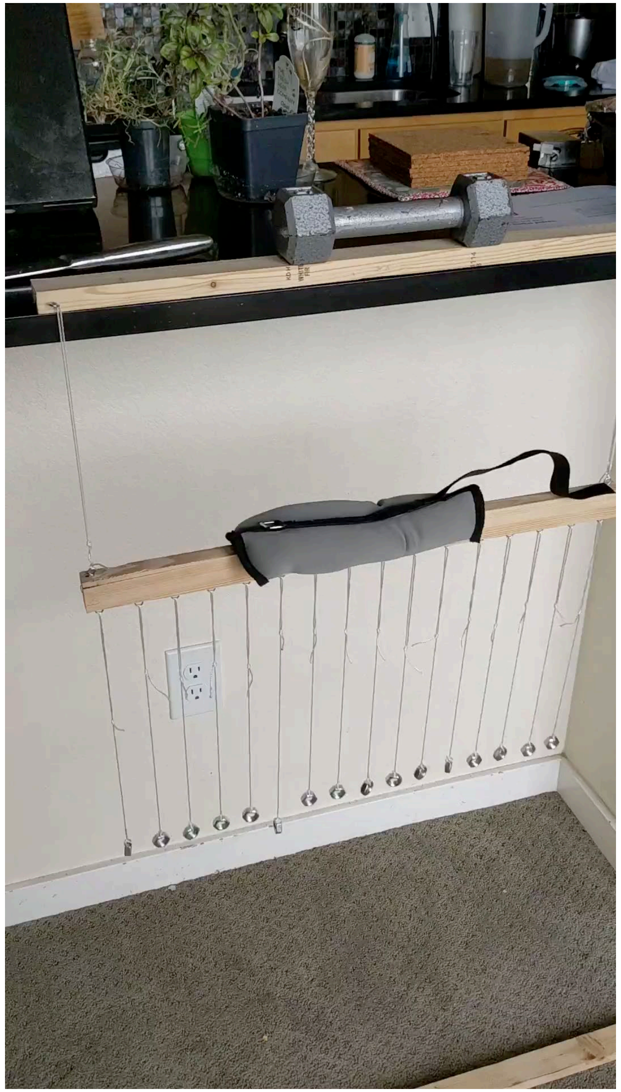
Abstract

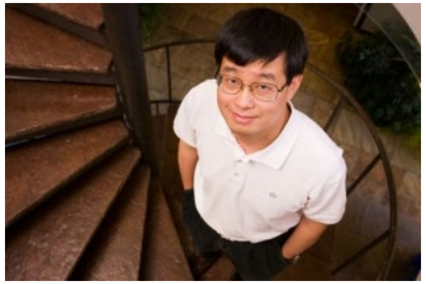
Quantum search is a quantum mechanical technique for searching N possibilities in only $\sqrt{N}$ steps. We show that the algorithm can be described as a resonance phenomenon. A similar algorithm applies in a purely classical setting when there are N oscillators, one of which is of a different resonant frequency. We could identify which one this is by measuring the oscillation frequency of each oscillator, a procedure that would take about N cycles. We show, how by coupling the oscillators together in a very simple way, it is possible to identify the different one in only $\sqrt{N}$ cycles.



Quantum enhancement: primarily in the ability to have exponential storage space with qubit number, error correction. But quantum algorithm does saturate max O(\sqrt(N)) bound.

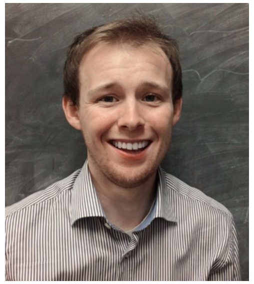
Thanks!

Ye clock laser team



Jun Ye

Eric Oelker



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