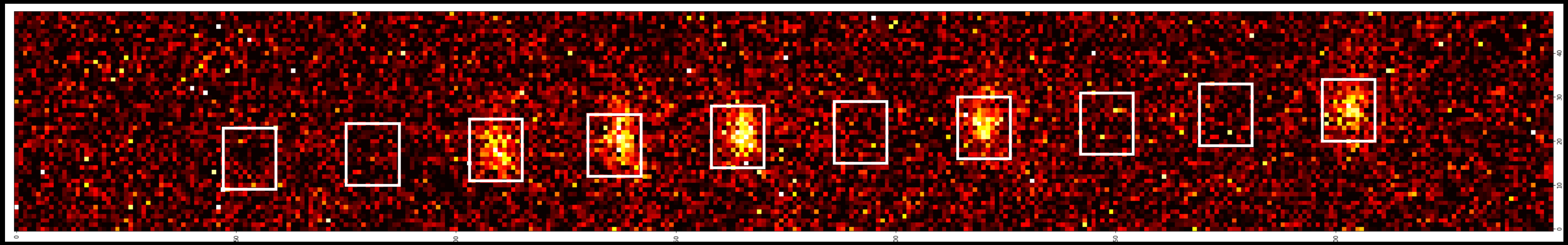
Approaches to quantum information processing with cold atoms



Dan Stamper-Kurn
Department of Physics,
Challenge Institute for Quantum Computation, UC Berkeley
Materials Sciences Division, Lawrence Berkeley National Labs

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THE NEW YORKER

DEPT. OF TECHNOLOGY JANUARY 24, 2022 ISSUE

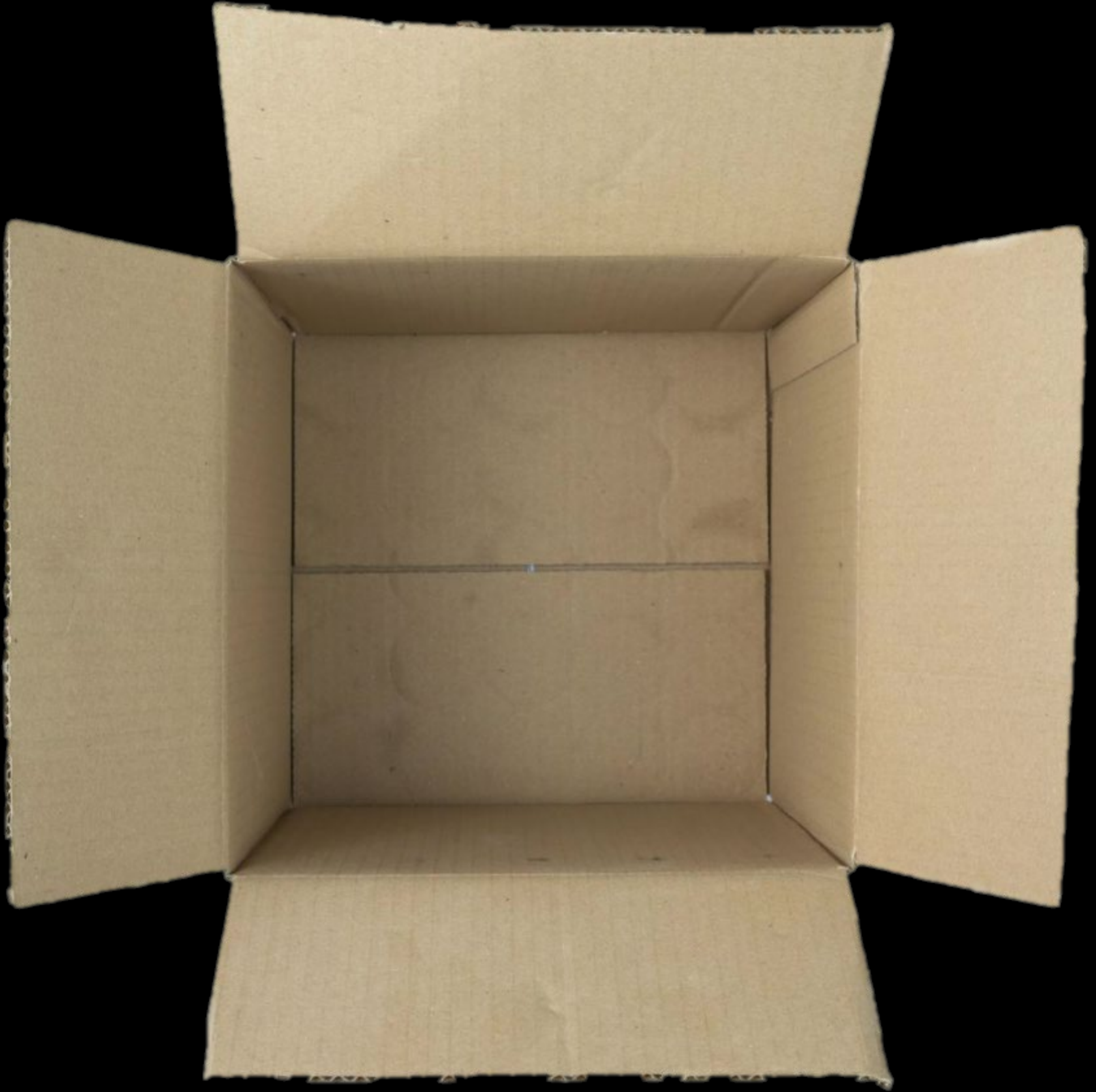
THE RISE OF A.I. FIGHTER PILOTS

Artificial intelligence is being taught to fly warplanes. Can the technology be trusted?

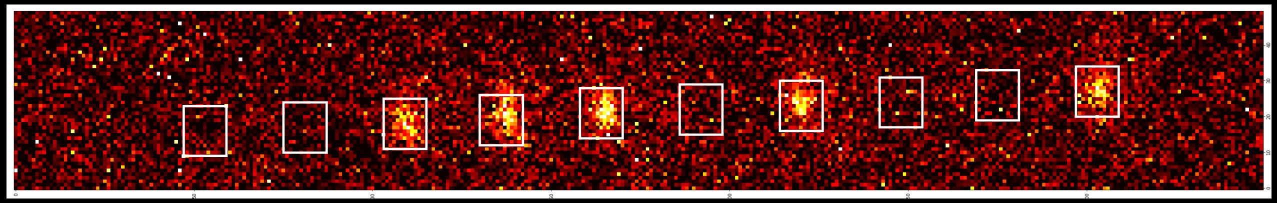
By Sue Halpern
January 17, 2022

- long reach of numerical mathematics algorithms
- trust is gained in teaspoons and lost in buckets
- gotta build a quantum computer!


Qtech



off
resonant
laser light



E6 lab

$\sim 10^{23}$ exactly identical, $\sim \infty$'ly long-lived quantum objects (qubits) inside!

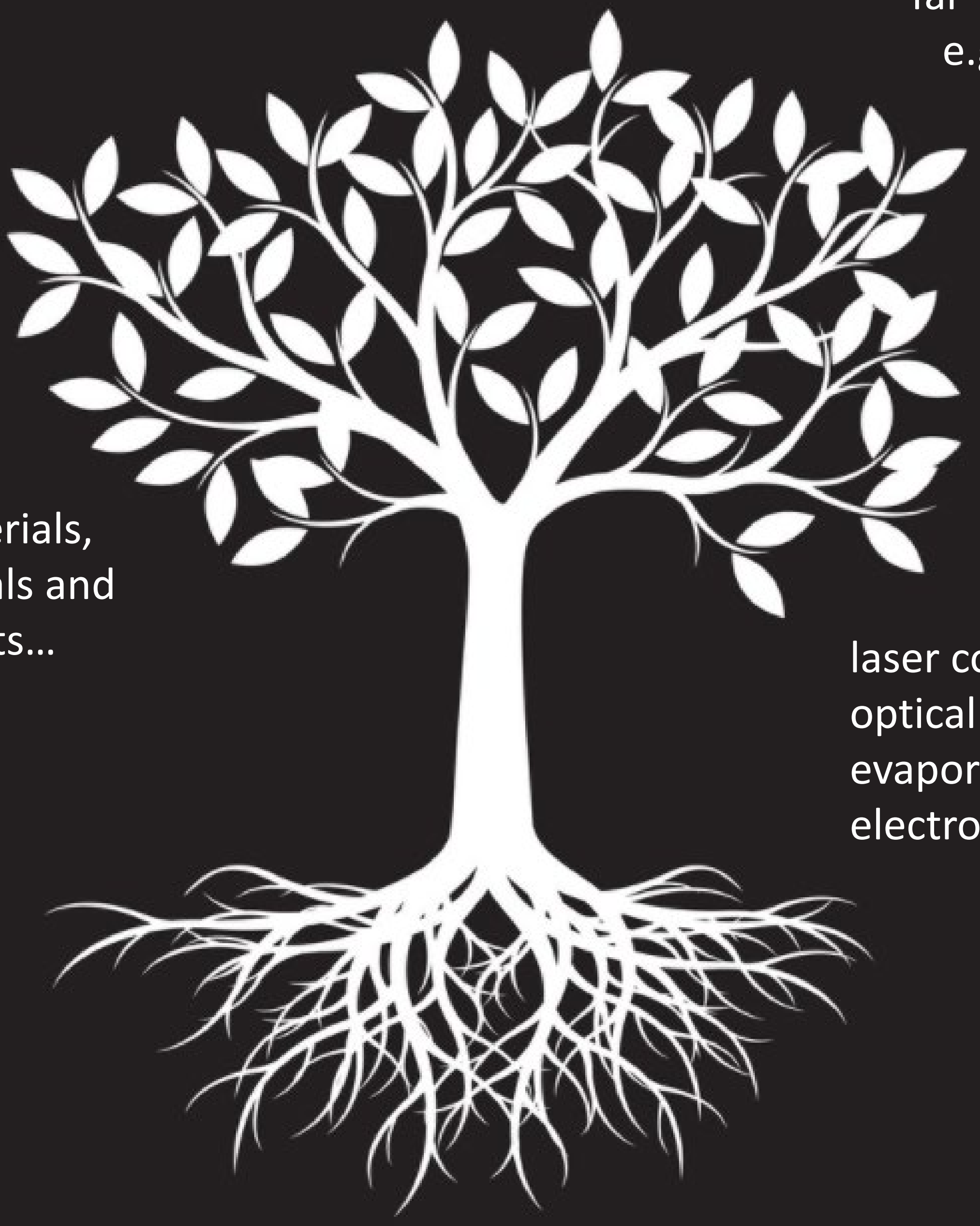
Ultracold neutral atomic gases

precise few-body physics,
e.g. Feshbach resonances,
Efimov states, ultracold
molecular reactions…

far-from-equilibrium quantum systems,
e.g. quantum quenches, many-body
localization, Floquet systems…

ultracold atom sensors,
e.g. optical atomic clocks, atom
interferometers,
magnetometers…

quantum information processing,
e.g. cluster states, Rydberg gates,
single atom/photon gates…



ultracold atom materials,
e.g. superfluids, metals and
insulators, magnets…

laser cooling, magnetic trapping,
optical trapping, optical lattices,
evaporative cooling, cavity quantum
electrodynamics…

atomic/molecular spectroscopy, Rabi
methods, Ramsey method of
separated oscillatory fields, optical
pumping, masers and lasers, dressed
states, Rydberg states …

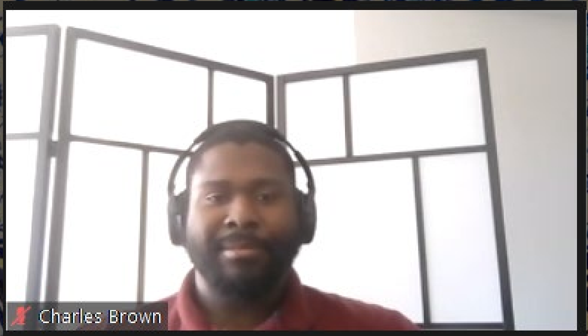
and more underway:
transition-metal atoms, ultracold
molecules, buffer-gas cooling,
electron/ion beam methods,
photonic nanostructres and
metamaterials…

Outline

- Quantum simulation
  - Touching on band structure (E5/9)
- Quantum sensing
  - Microscopy of mesoscopic thermodynamics (E3)
- Quantum computing
  - Rydberg tweezer arrays
  - Fast, selective detection of a tweezed atom (E6)

holonomy of singular points in band structure

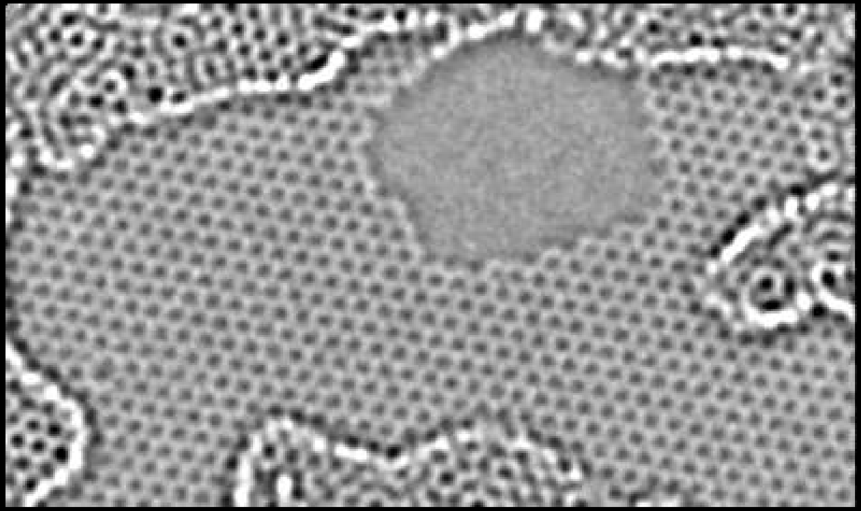
E5/9: Optical lattices



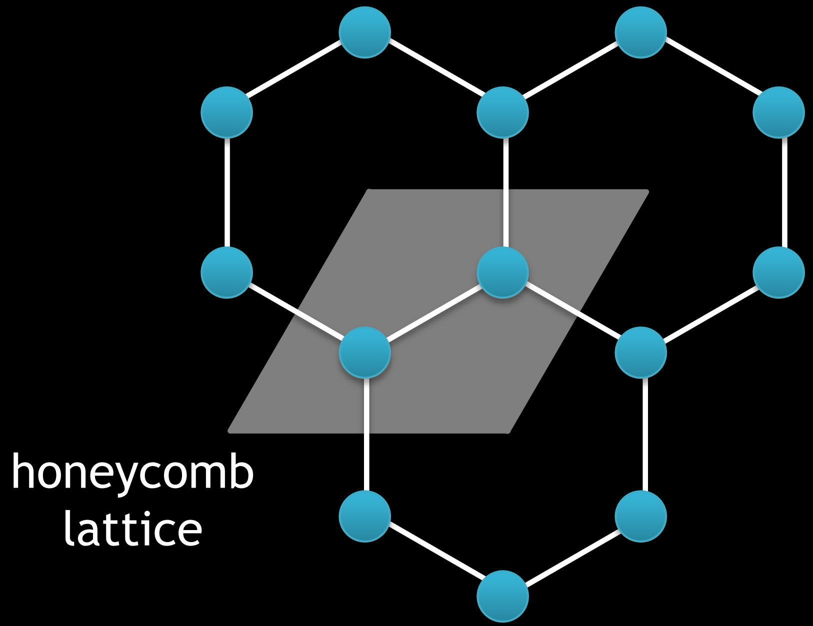
NSF, ARO MURI

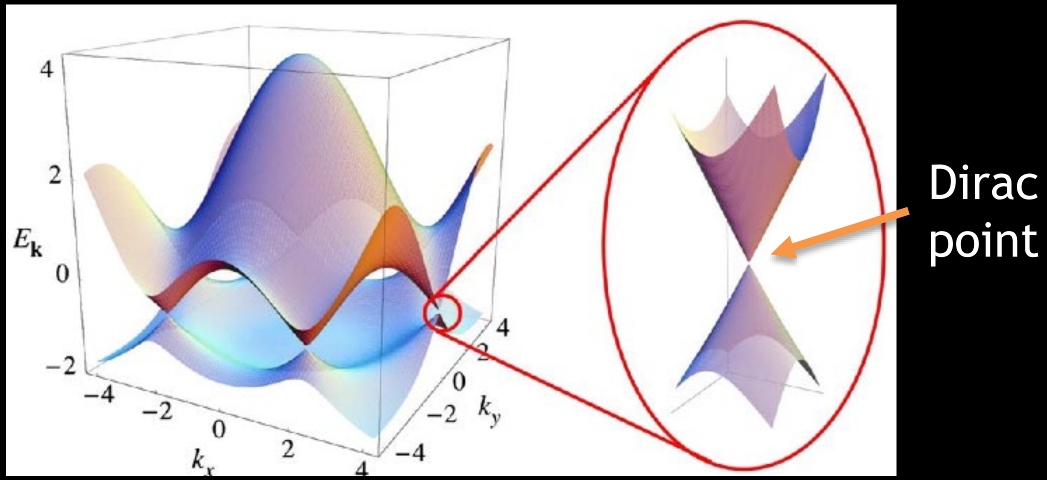
Material properties determined by band touching points

Dirac and Weyl semi-metals
(graphene + others, TaAs and others)



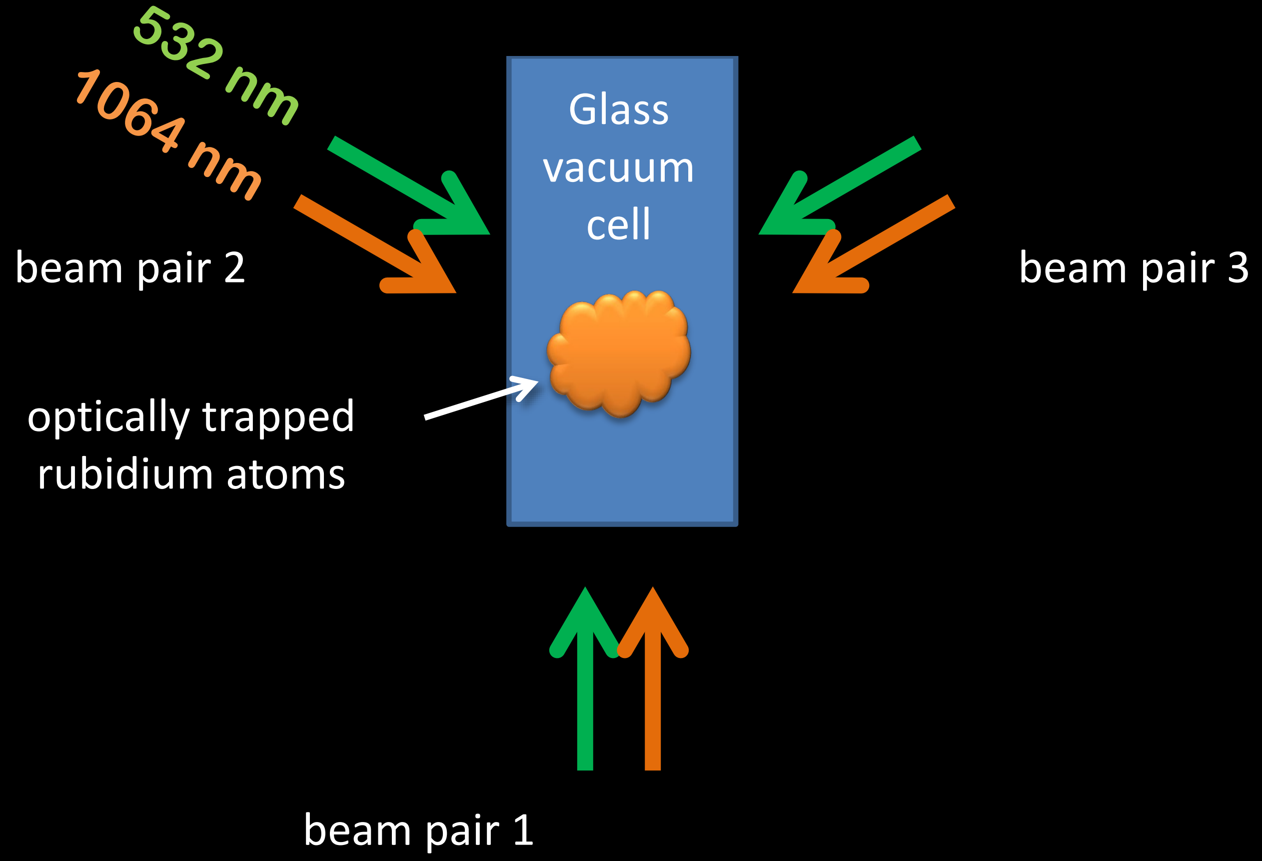
TEM image, Berkeley/LBNL





Castro Neto et al, Rev. Mod. Phys. **81**, 109 (2009)

Bichromatic lattice



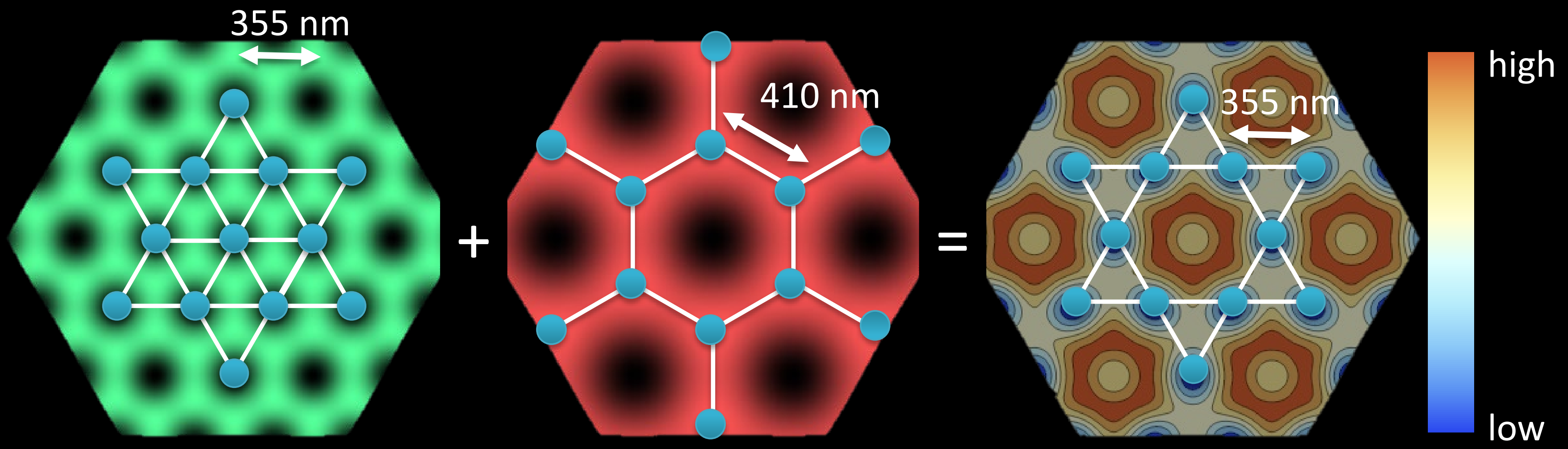
"Ultracold atoms in a tunable optical kagome lattice," Gyu-Boong Jo, et al., PRL **108**, 045305 (2012)

Triangular lattice with tunable geometry

short wavelength
λ = 532 nm
polarization in plane

long wavelength
λ = 1064 nm
polarization in plane

combined
optical potential



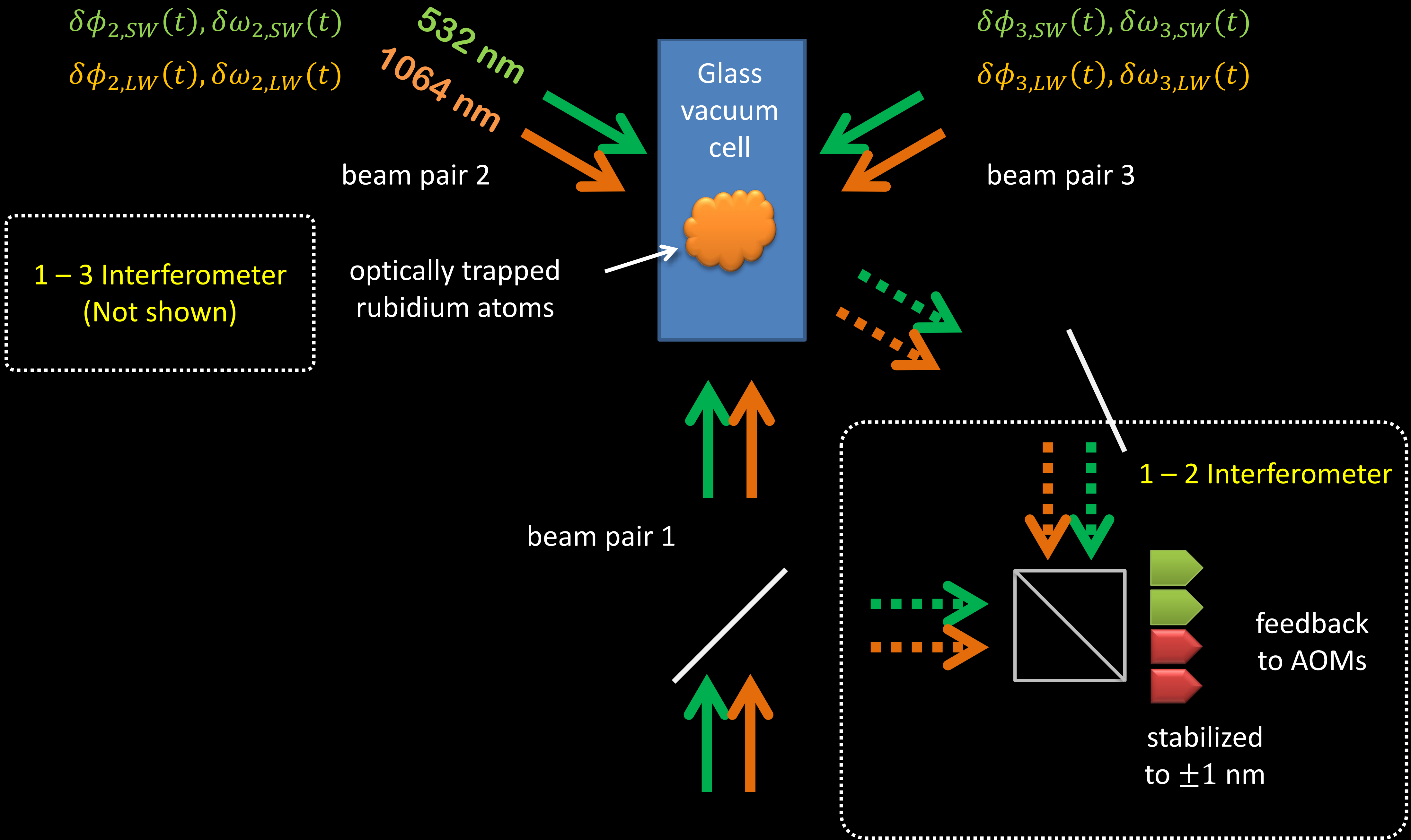
primitive triangular lattice

honeycomb lattice

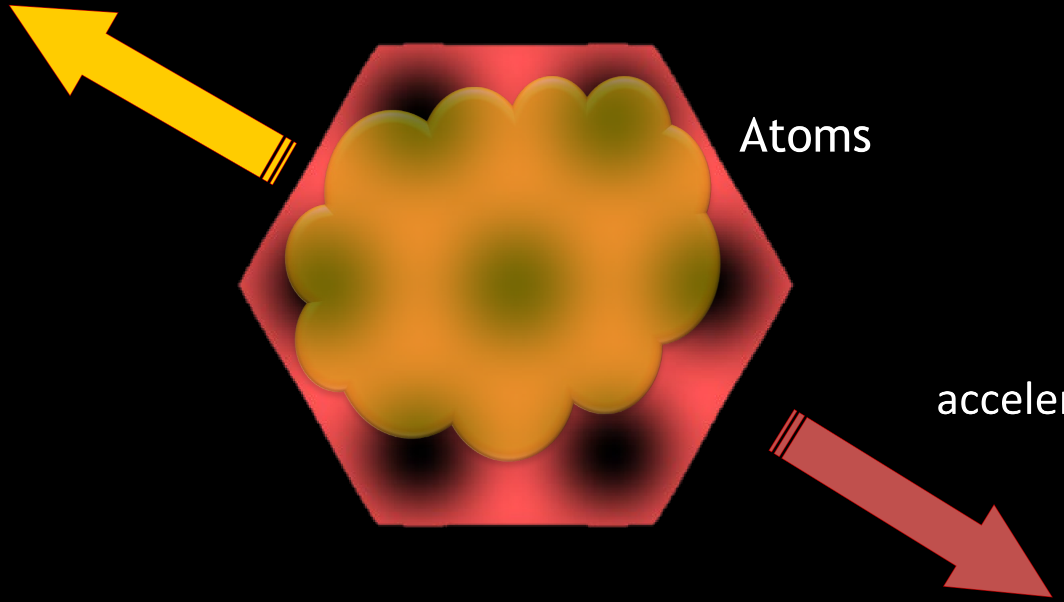
kagome lattice

"Ultracold atoms in a tunable optical kagome lattice,"
PRL **108**, 045305 (2012)

Bichromatic lattice

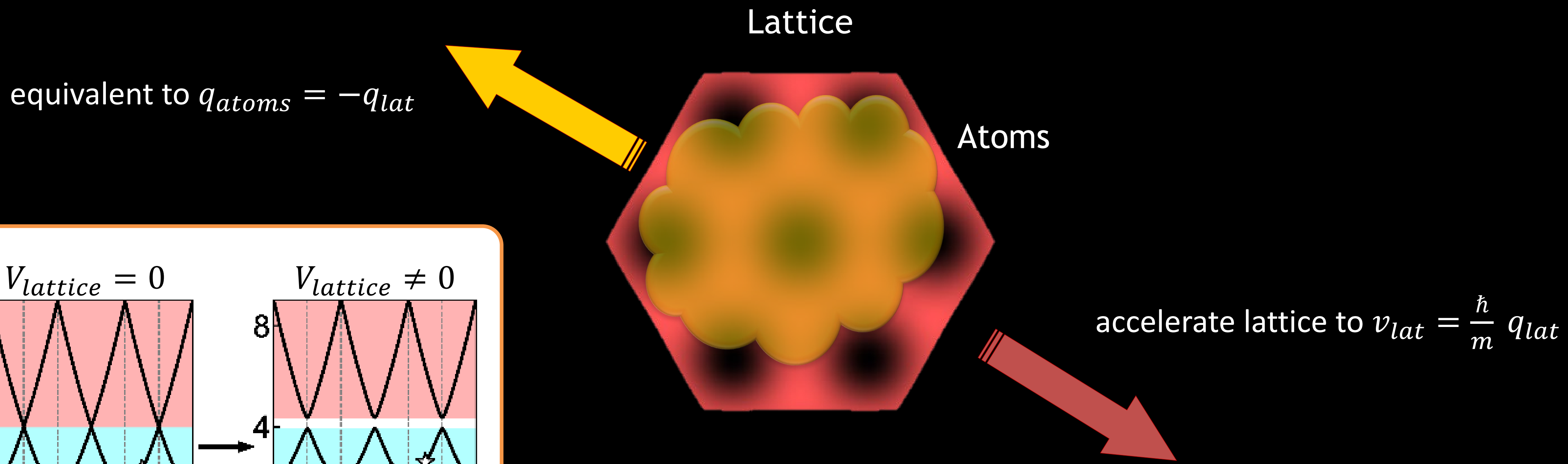


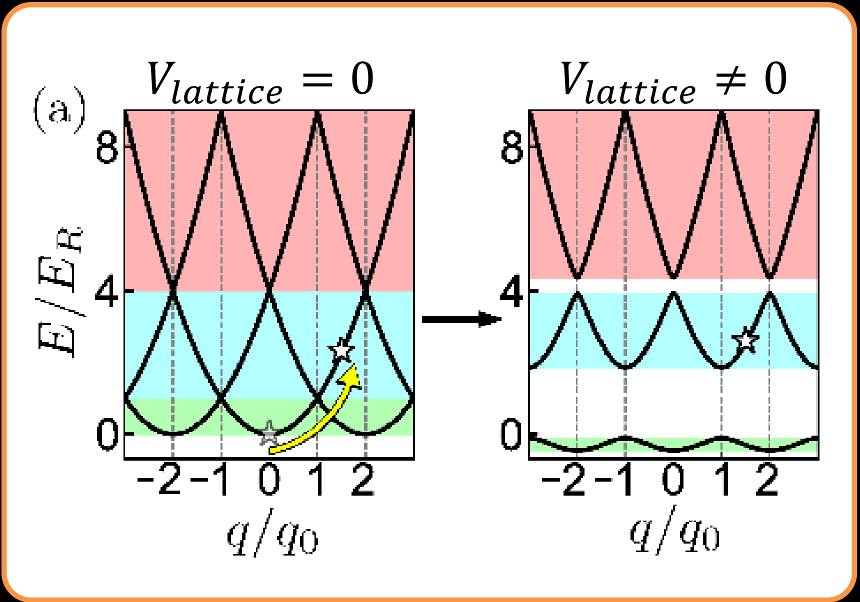
Navigating within band structure



- Turn up & then accelerate lattice: prepares atoms in ground state & then drives to $q \neq 0$

Navigating within band structure

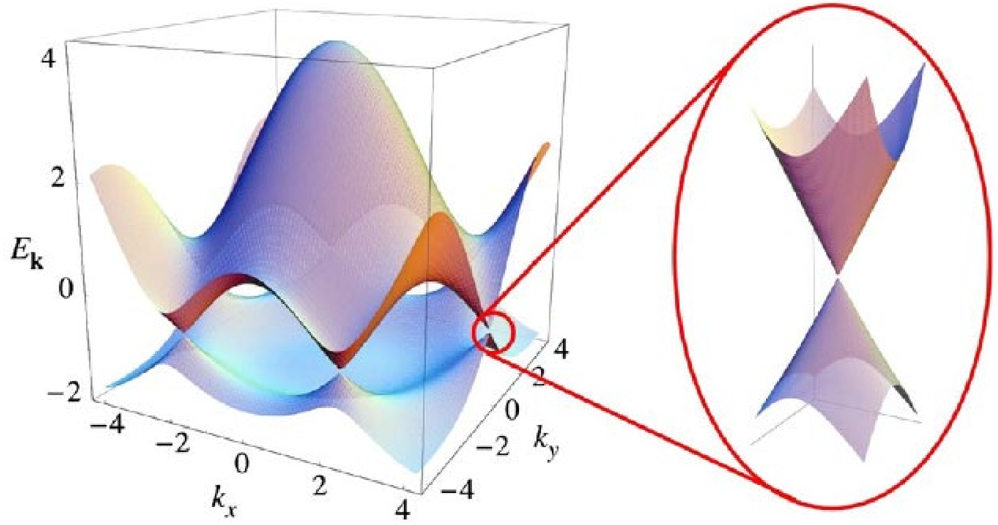


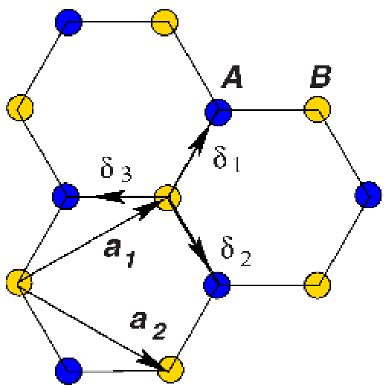


- Turn up & then accelerate lattice: prepares atoms in ground state & then drives to $q \neq 0$
- Accelerate & then turn up lattice: prepares atoms in higher band and $q \neq 0$

"Interaction-enhanced group velocity of bosons in the flat band of an optical kagome lattice," PRL **125**, 133001 (2020)

Geometry at a linear band touching point



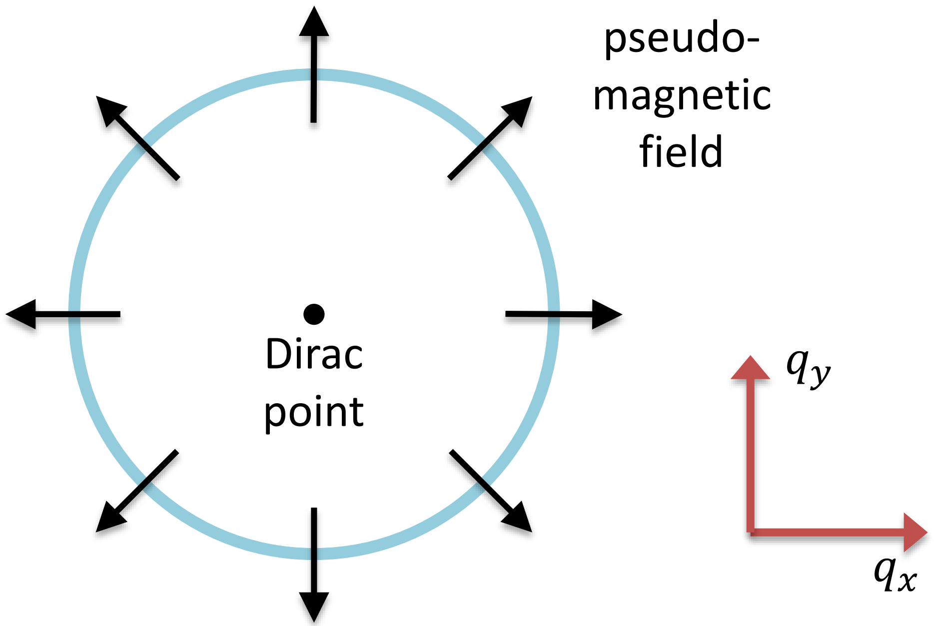


pseudospin:

$$|A\rangle = |\uparrow\rangle$$

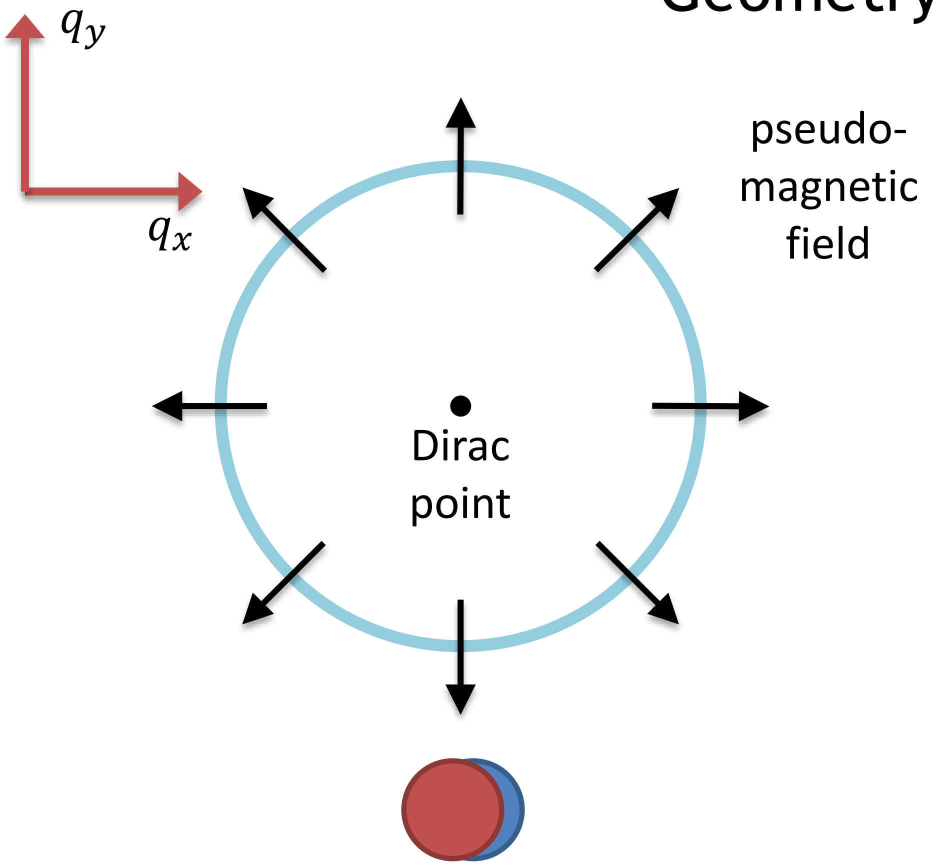
$$|B\rangle = \xi\,|\downarrow\rangle$$

$$H = v\,\boldsymbol{\sigma}\cdot(\boldsymbol{q} - \boldsymbol{q_D})$$



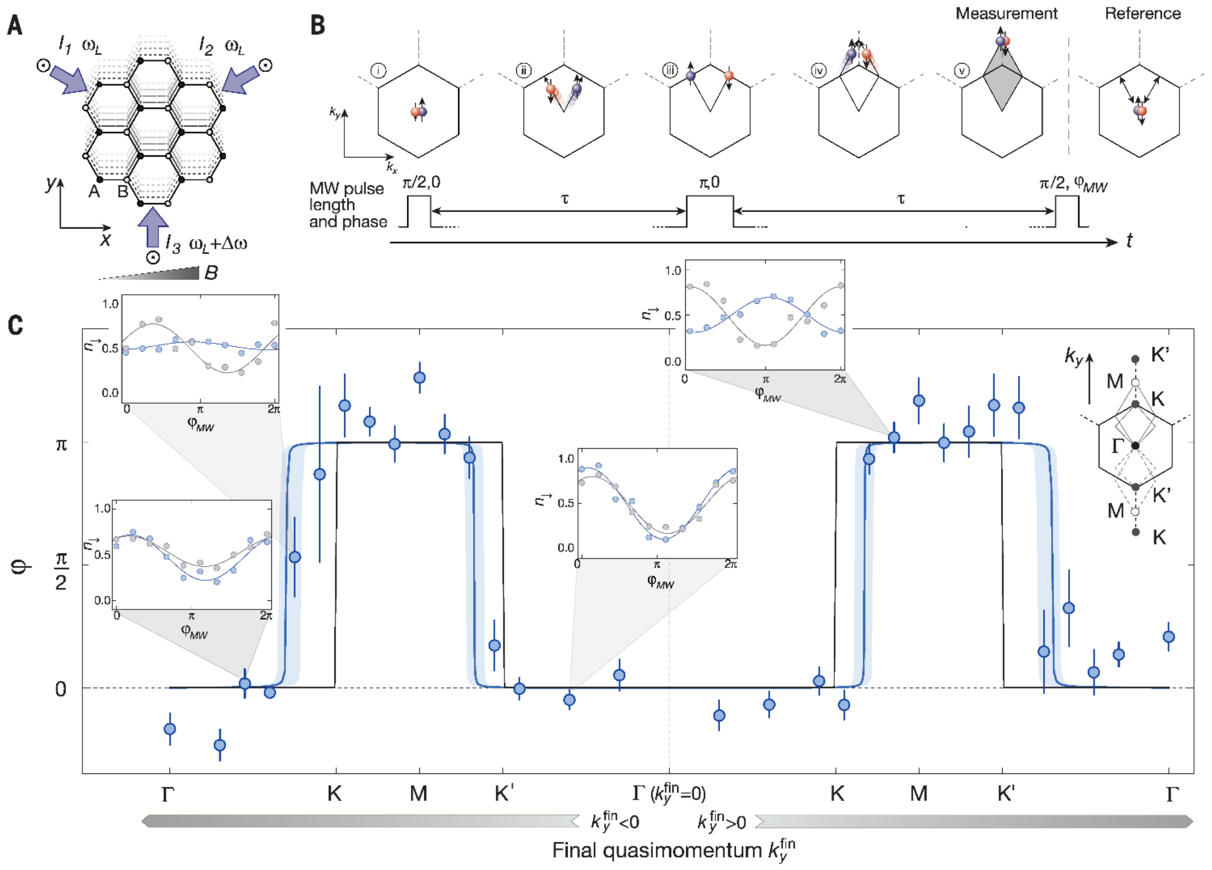
Castro Neto et al, Rev. Mod. Phys. **81**, 109 (2009)

Geometry at a linear band touching point

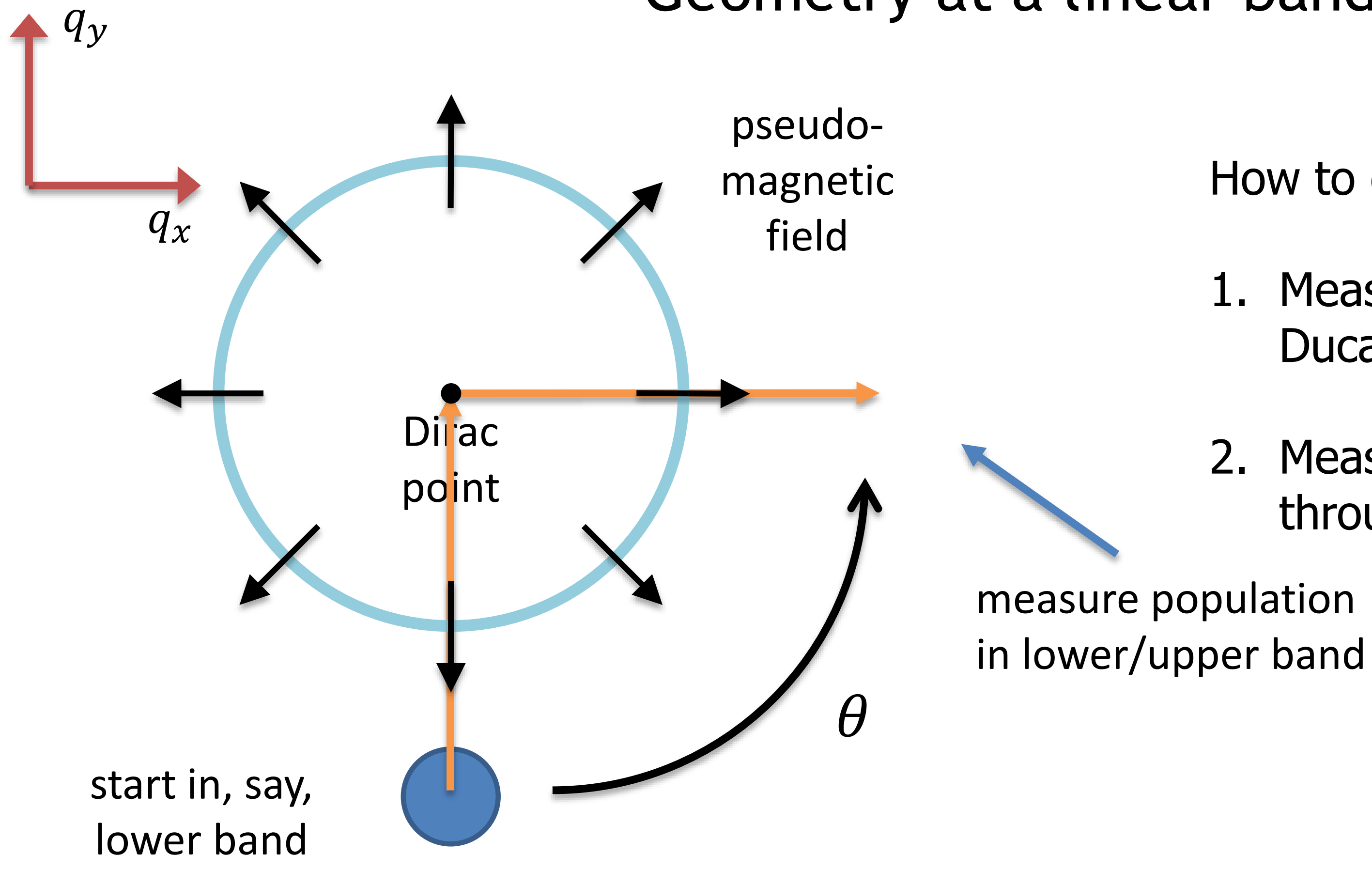


How to characterize the singularity at the Dirac point?

1. Measure Berry phase going around Dirac point
   Duca et al (Bloch group), Science 347, 288 (2015)



Geometry at a linear band touching point



How to characterize the singularity at the Dirac point?

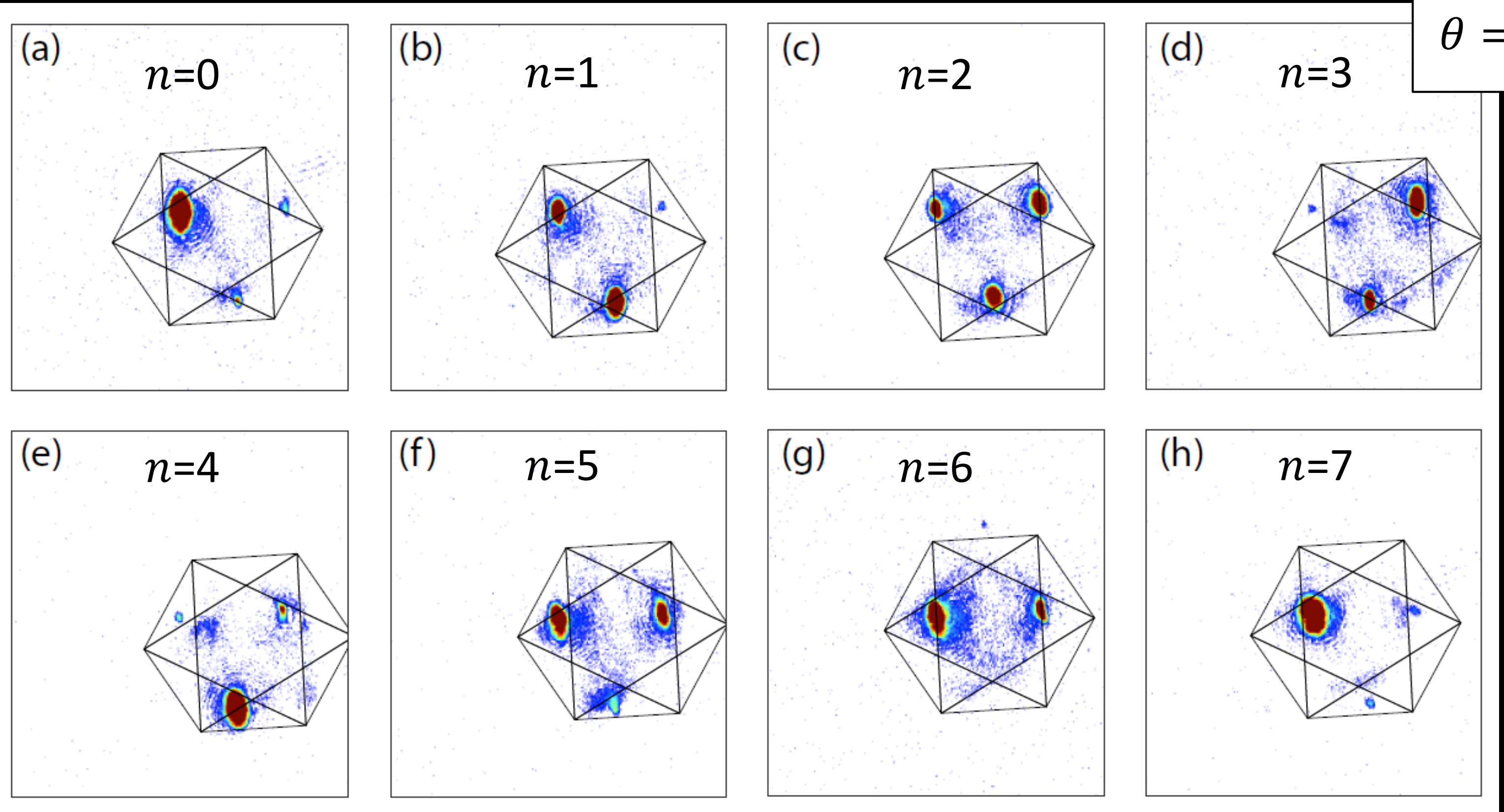
1. Measure Berry phase going around Dirac point
   Duca et al (Bloch group), Science 347, 288 (2015)

2. Measure state rotation (nonholonomy) going through Dirac point

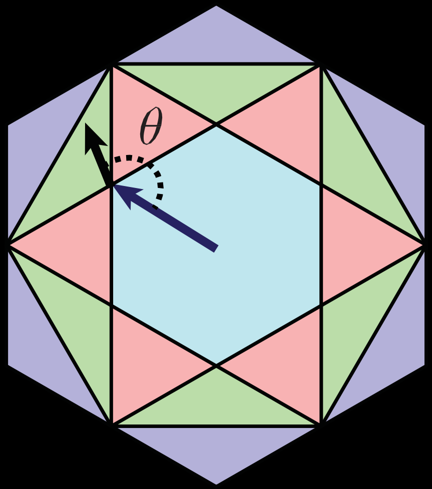
$$P_{lower} = \cos^2(\theta/2)$$

$$P_{upper} = \sin^2(\theta/2)$$

Geometry of Dirac point in honeycomb (IR only) lattice

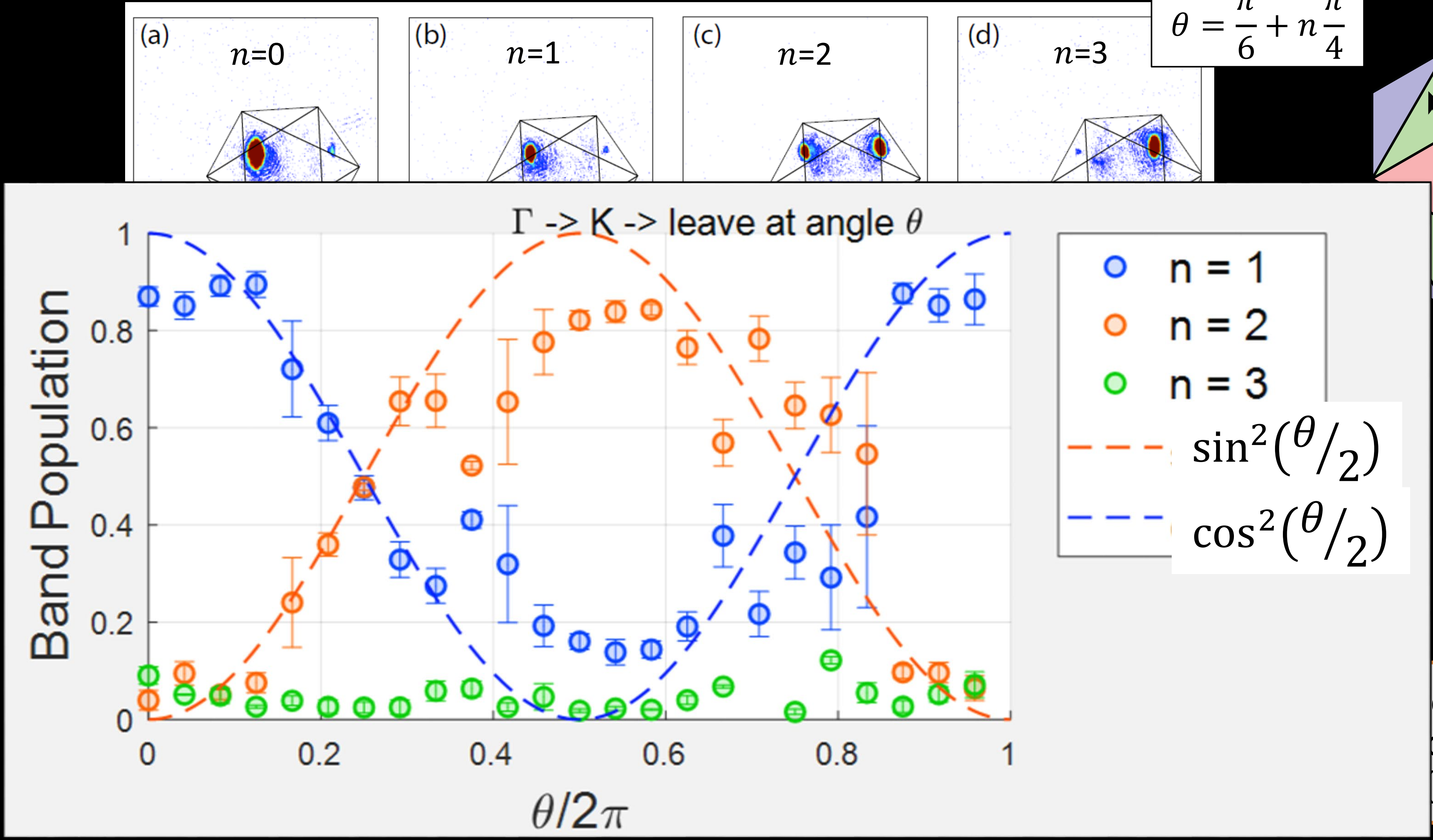


$$\theta = \frac{\pi}{6} + n\frac{\pi}{4}$$

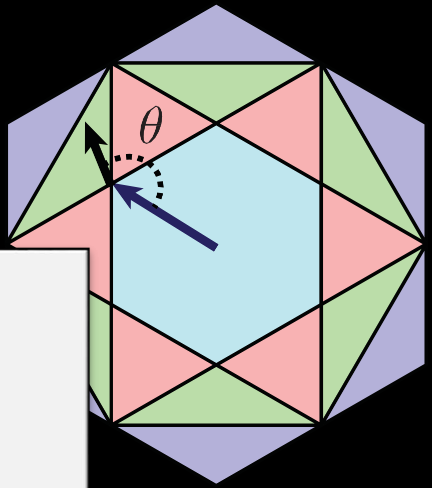


slowly ramp up honeycomb lattice → accelerate lattice to Dirac (K) point → hook a turn angle θ → slowly ramp down honeycomb lattice (band-mapping)

Geometry of Dirac point in honeycomb (IR only) lattice



$$\theta = \frac{\pi}{6} + n\frac{\pi}{4}$$



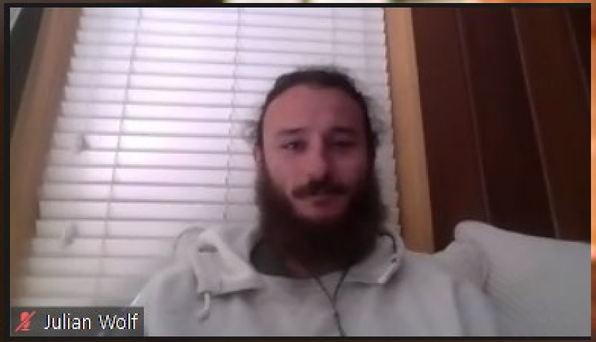
owly ramp down
oneycomb lattice
(band-mapping)

Tracking evaporative cooling of an atomic quantum gas in real time

Johannes Zeiher, Julian Wolf, Joshua A. Isaacs, Jonathan Kohler, DMSK
PRX 11, 041014 (2021)

Danny Eilbott

Joshua Isaacs

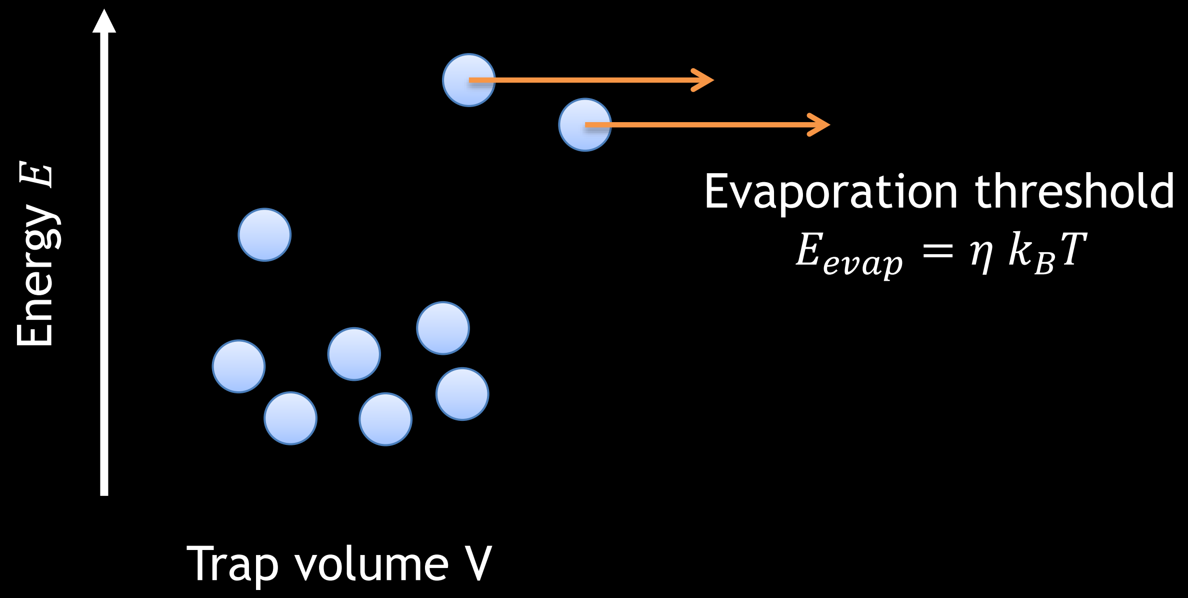


Julian Wolf

Johannes Zeiher
Jonathan Kohler

NSF CIQC, AFOSR, ARO MURI

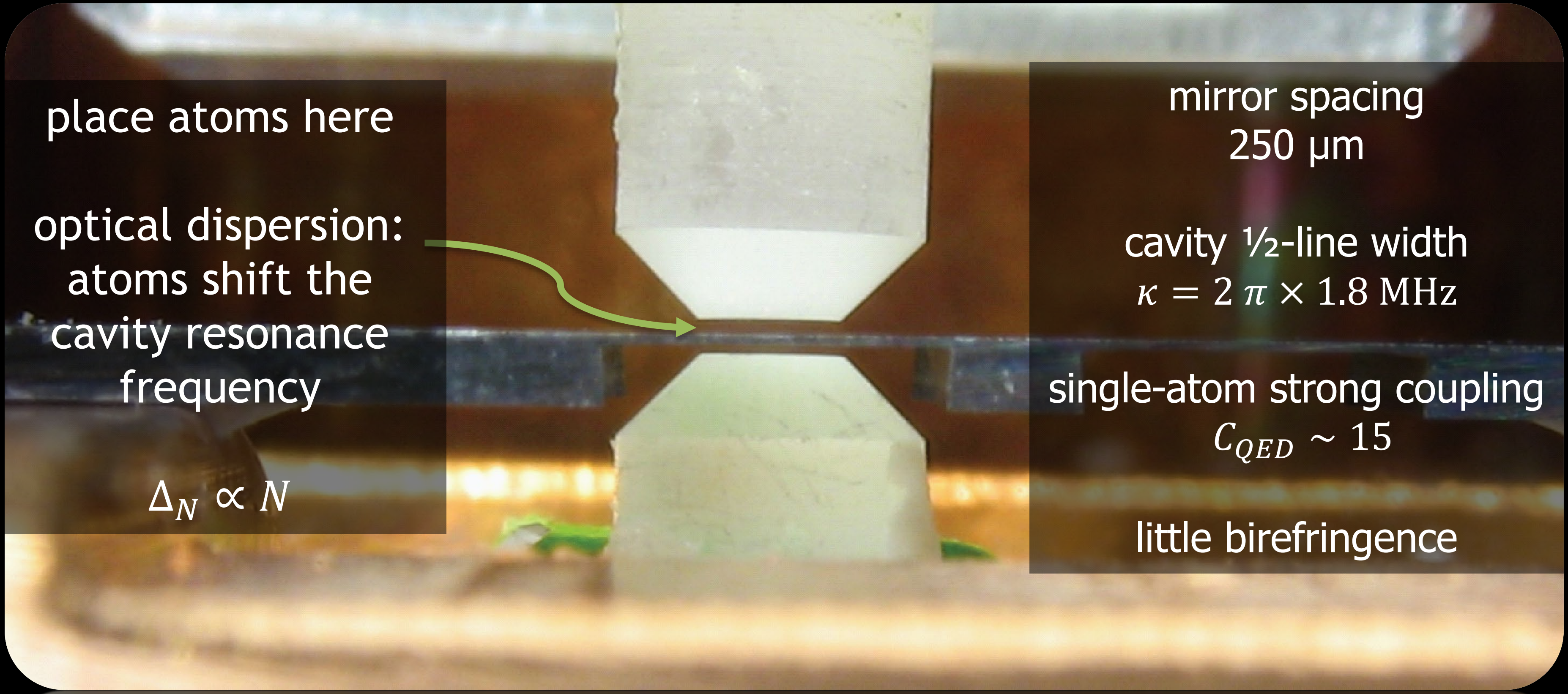
Non-equilibrium thermodynamics of evaporation



- Non-equilibrium thermodynamics describes
  - average evaporated number/rate
  - variations in evaporated number

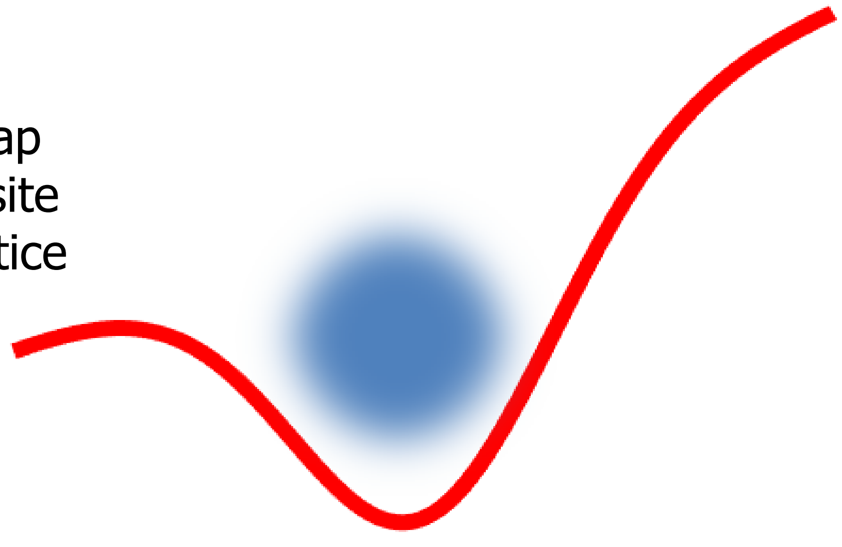
Ketterle *et al.*, Adv in At and Mol Phys **37**, 181 (1996)
Luiten *et al.*, PRA **53**, 381 (1996)
Sacket et al., PRA **55**, 3797 (1997)

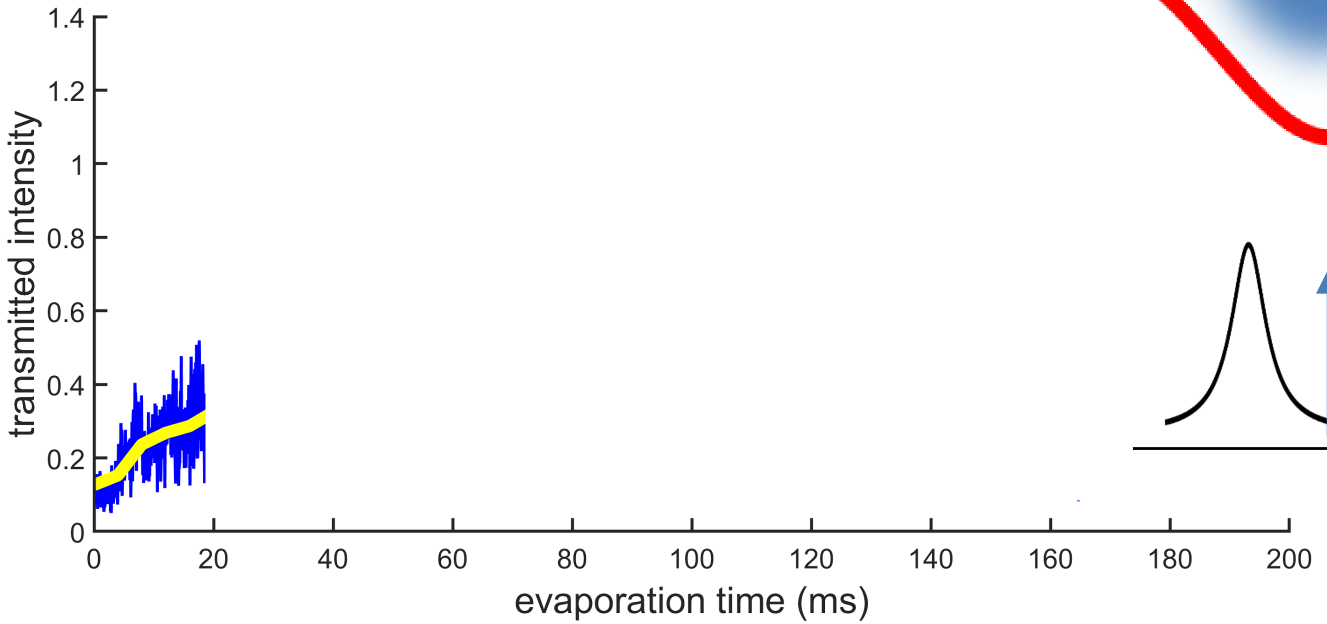
Monitoring mesoscopic thermodynamics in real time

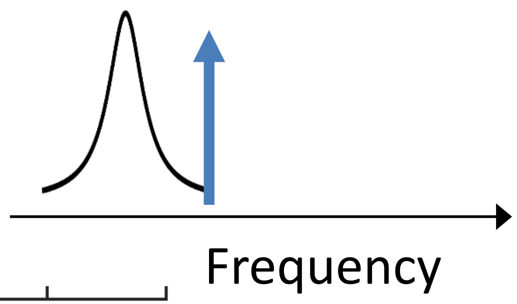


Real-time dispersive measurement of atom number during evaporation

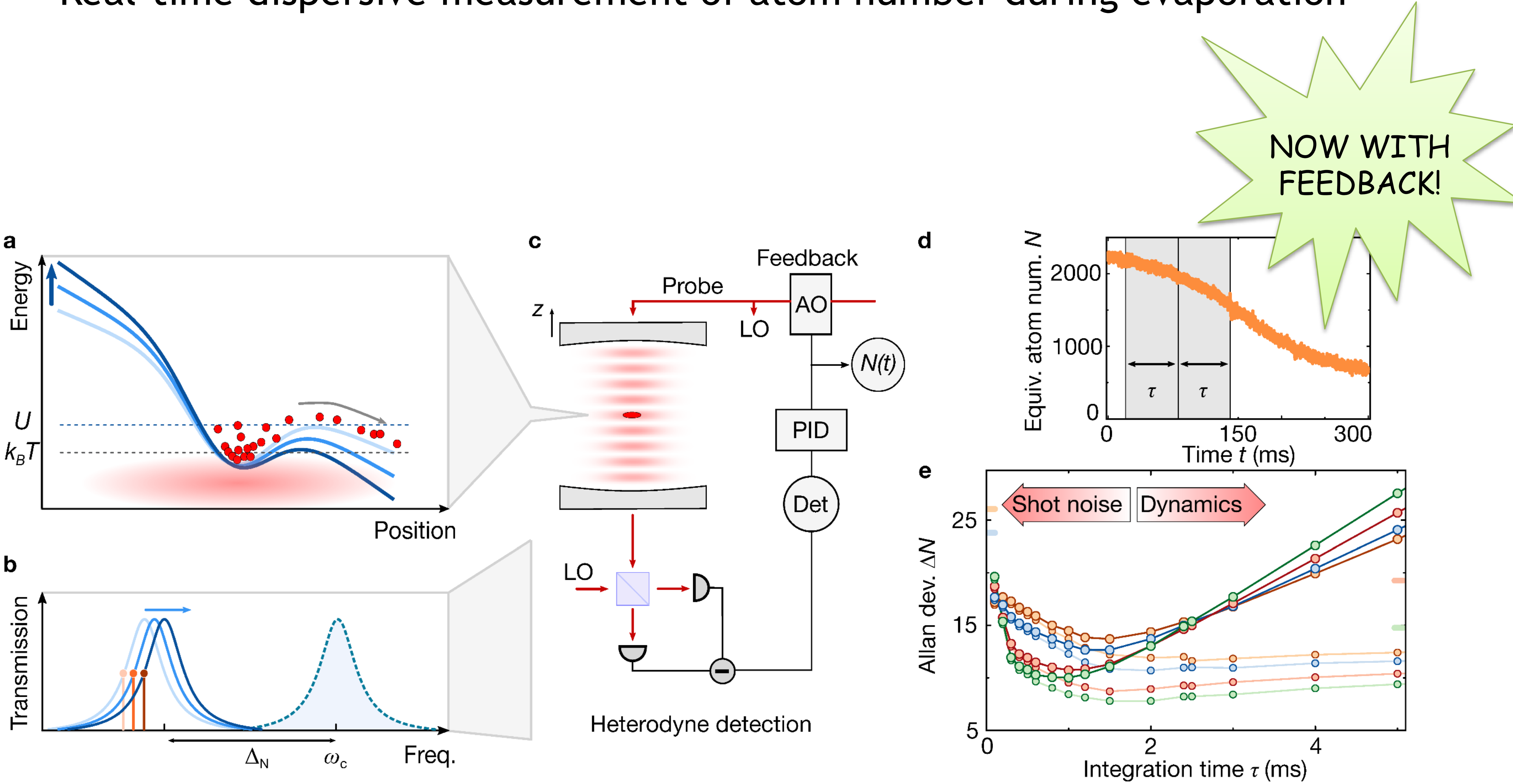
tilted optical trap
within a single site
of 1D optical lattice



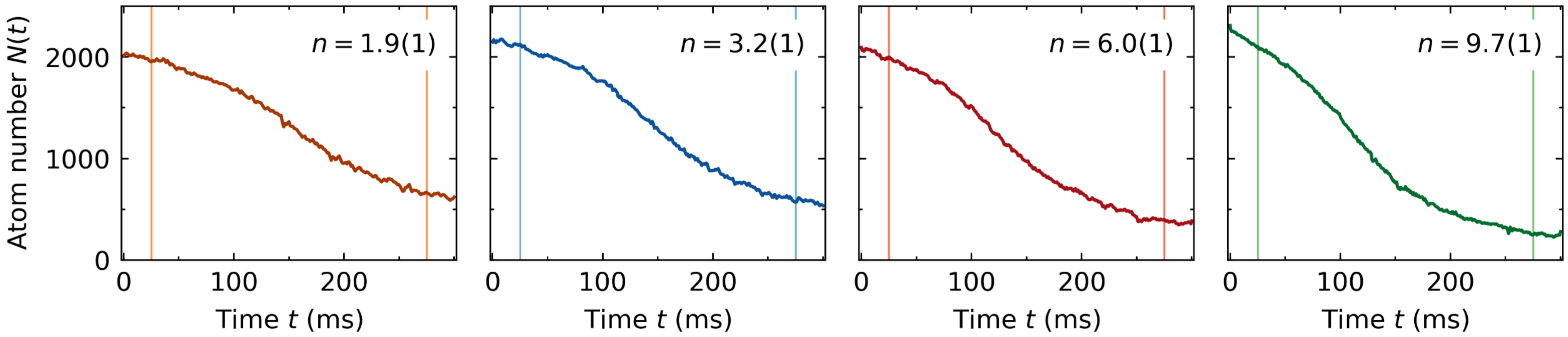




Real-time dispersive measurement of atom number during evaporation

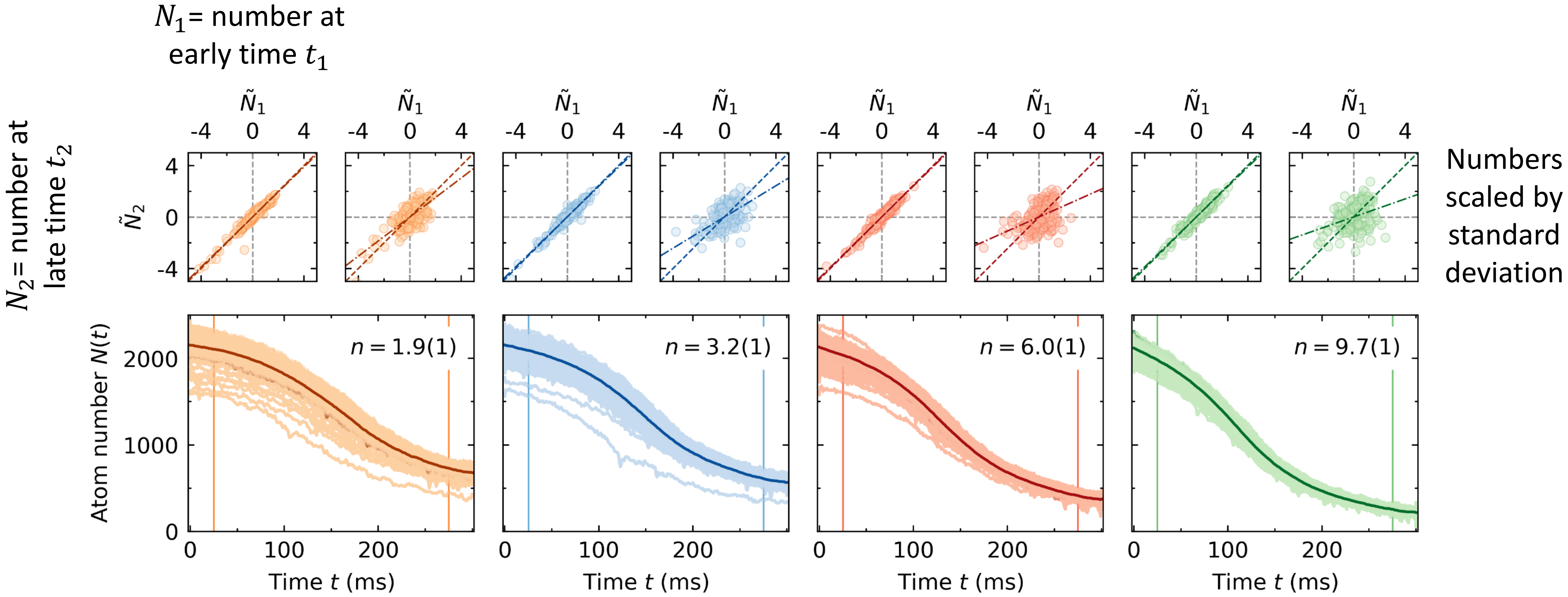


Two- (or more) time correlations from continuous measurement



Note: $\bar{n} = 1$ corresponds to 2.9 pW

Two- (or more) time correlations from continuous measurement

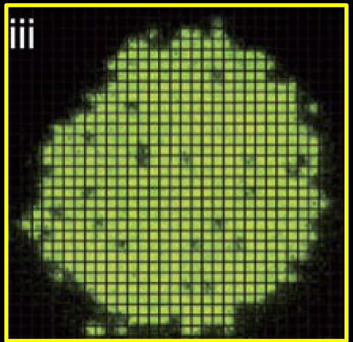


- multi-time correlation functions
- observe mesoscopic growth of fluctuations
- applications: quantum transport, non-eq. dynamics…

Note: $\bar{n} = 1$ corresponds to 2.9 pW

Neutral-atom approaches to quantum information processing

atoms in optical lattice

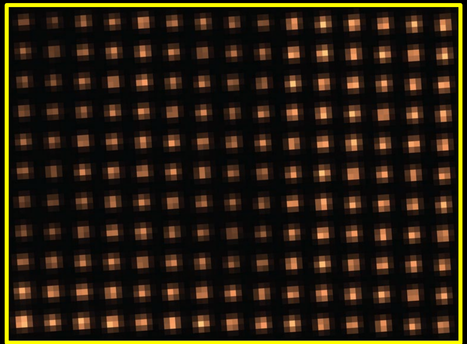


spacing $\leq \mu$m

- contact interactions
  - $\simeq$ ms, short-range
  - $\Gamma \simeq 1000$ gates

- quantum simulation of itinerant particles
- cluster states

atoms in optical tweezers

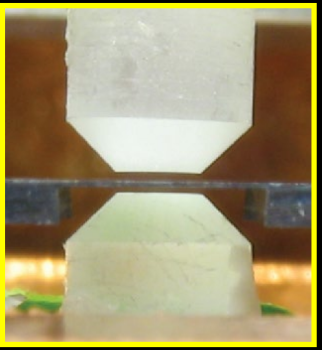


spacing few μm

- Rydberg-state mediated interactions
  - $\simeq$ sub-μs, short-range
  - $\Gamma \simeq 100$ gates

- quantum simulation of spin models
- quantum computing

atoms in optical cavities



within cavity volume

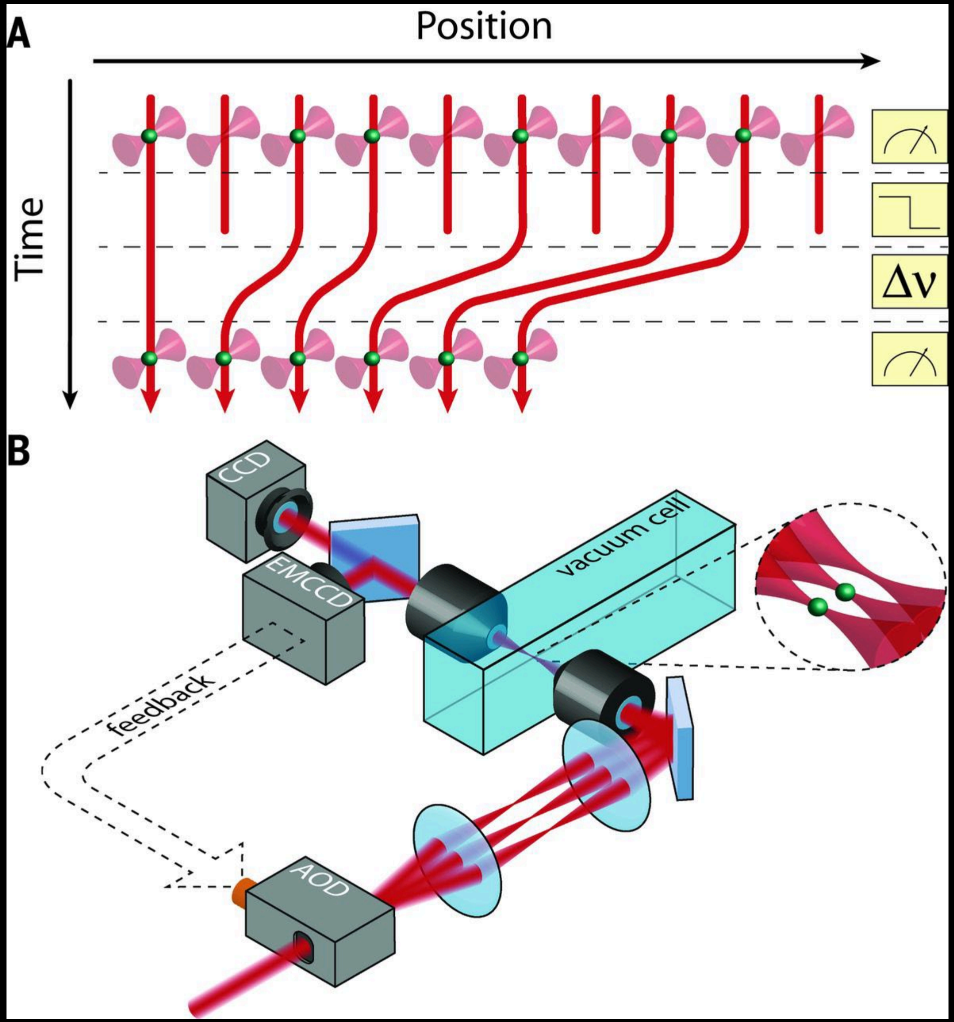
- cavity photon exchange
  - $\simeq$ sub-μs, long-range
  - $\Gamma \simeq 10$ gates

- fast high-fidelity measurement
- quantum simulation of open quantum mechanics
- quantum communication

Rydberg tweezer array quantum processor

Tweezer array experimental sequence:

1. Load tweezers



atom number reduced to 0, 1 by light-induced atom loss

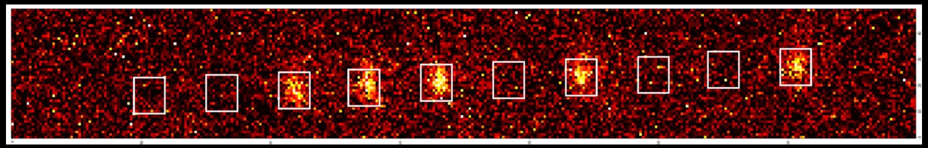
PRL 89, 023005 (2002)

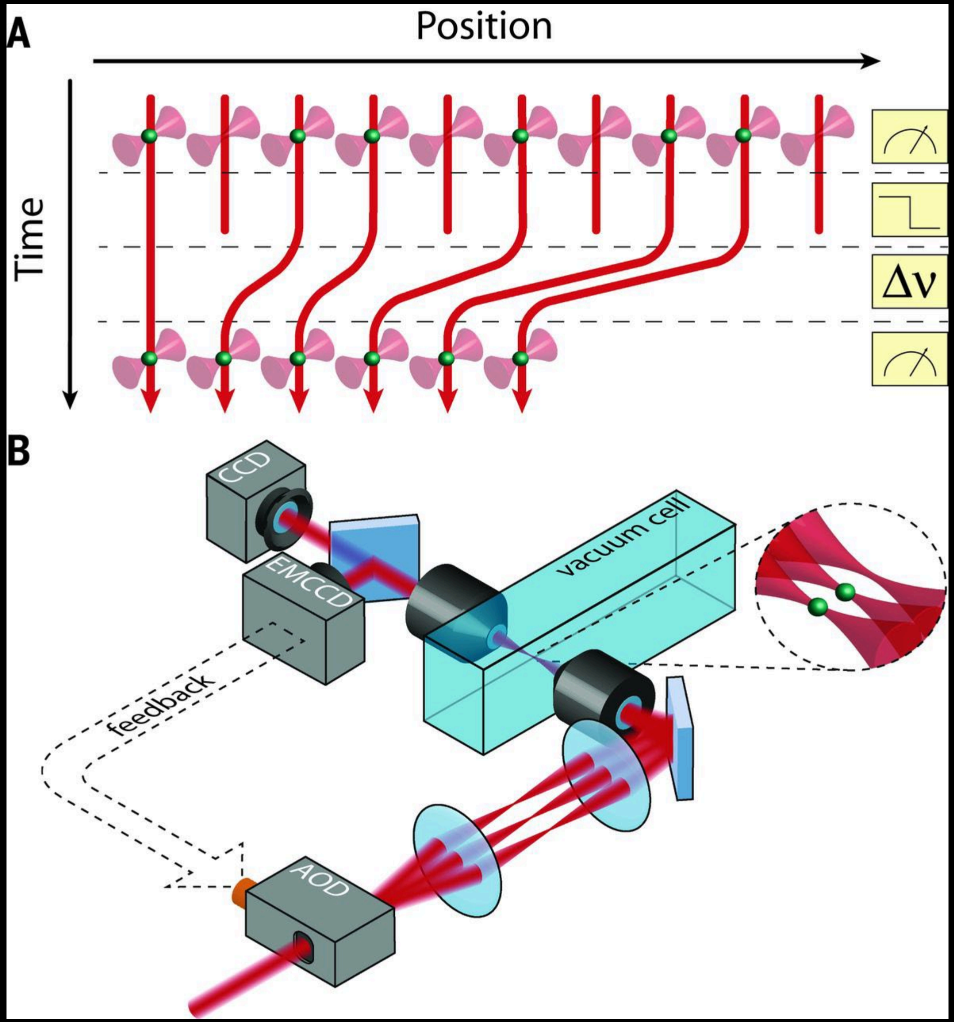
Barredo et al., Science 354, 1021 (2016)
Endres et al., Science 354, 1024 (2016)

Rydberg tweezer array quantum processor

Tweezer array experimental sequence:

1. Load tweezers
2. Image to find filled tweezers (10’s ms)





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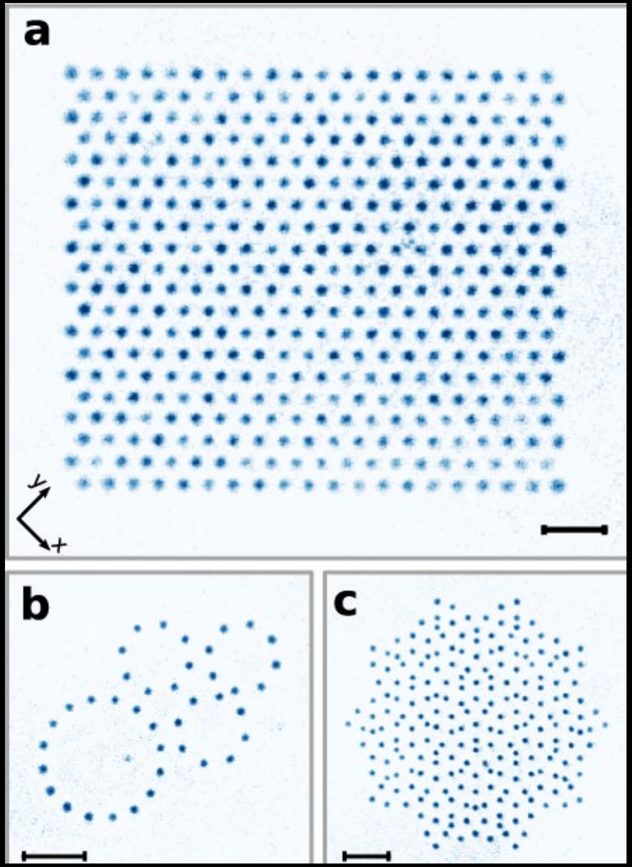
Endres et al., Science 354, 1024 (2016)

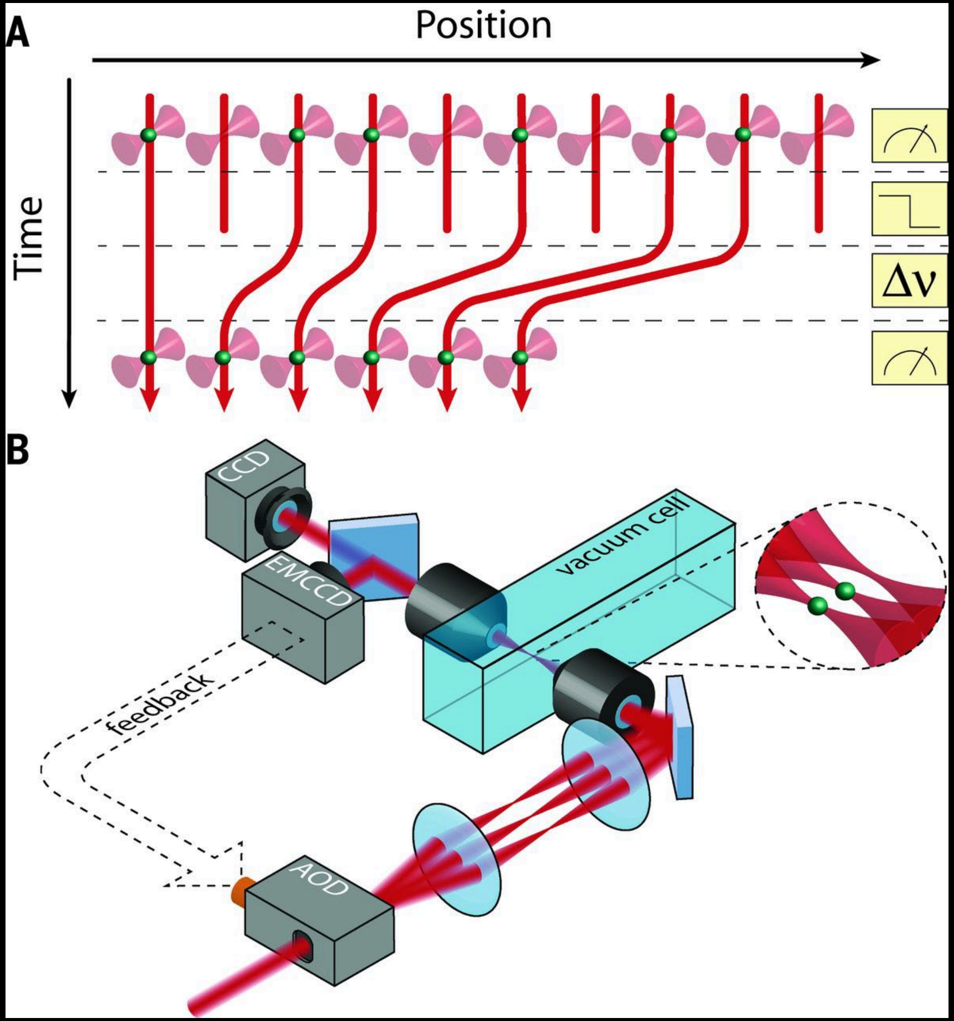
Rydberg tweezer array quantum processor

Tweezer array experimental sequence:

1. Load tweezers
2. Image to find filled tweezers (10's ms)
3. Sort



Wang et al.,
NJP QI 6, 54 (2020)



atom number reduced to 0, 1 by light-induced atom loss

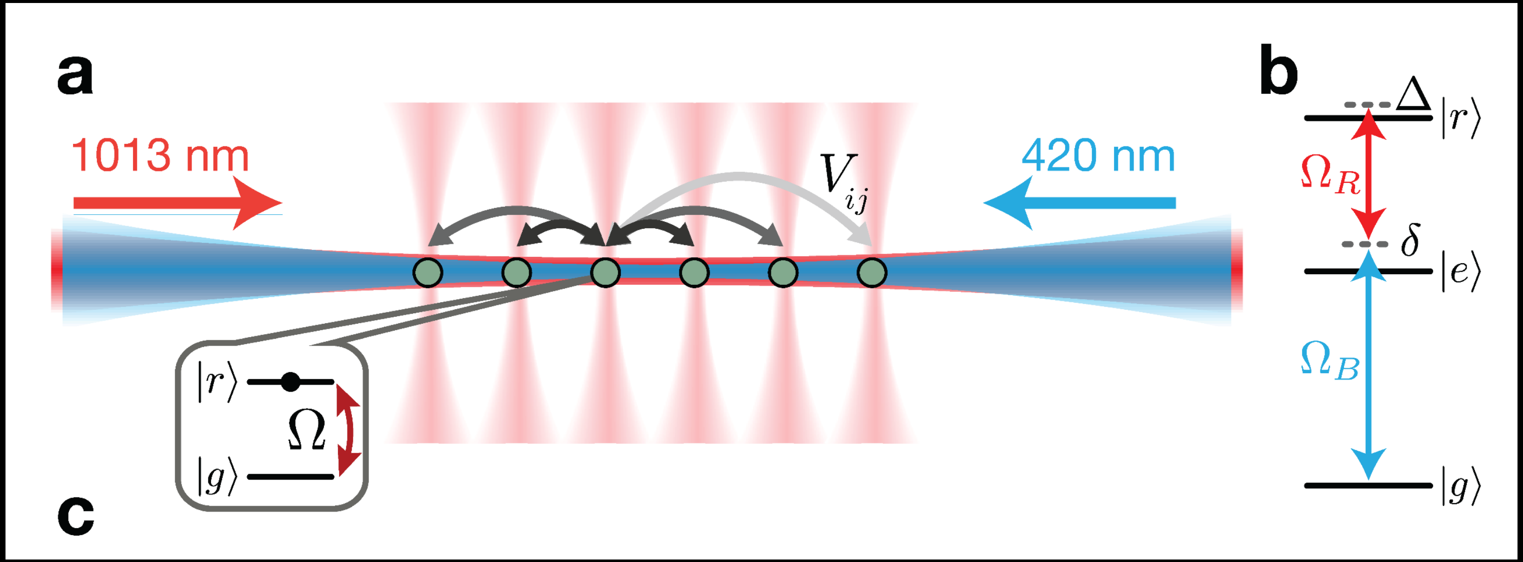
PRL 89, 023005 (2002)

Barredo et al., Science 354, 1021 (2016)
Endres et al., Science 354, 1024 (2016)

Rydberg tweezer array quantum processor

Tweezer array experimental sequence:

1. Load tweezers
2. Image to find filled tweezers (10’s ms)
3. Sort
4. Rydberg-mediated interactions

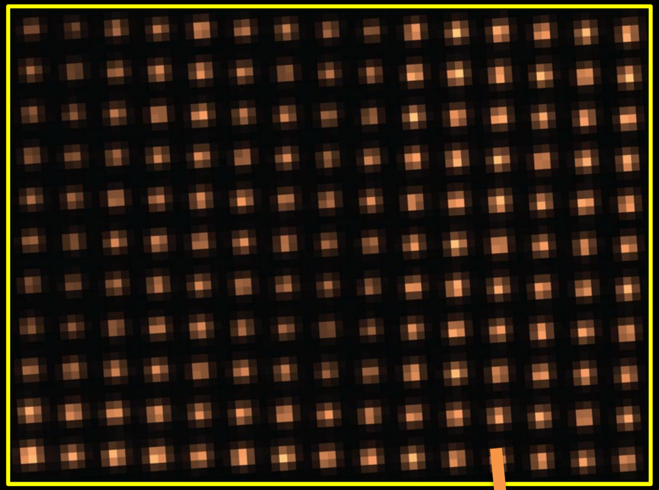


Harry Levine, PhD Thesis (2021)

Rydberg tweezer array quantum processor

Tweezer array experimental sequence:

1. Load tweezers
2. Image to find filled tweezers (10’s ms)
3. Sort
4. Rydberg-mediated interactions
5. Image again, infer state of all tweezers (10’s ms)

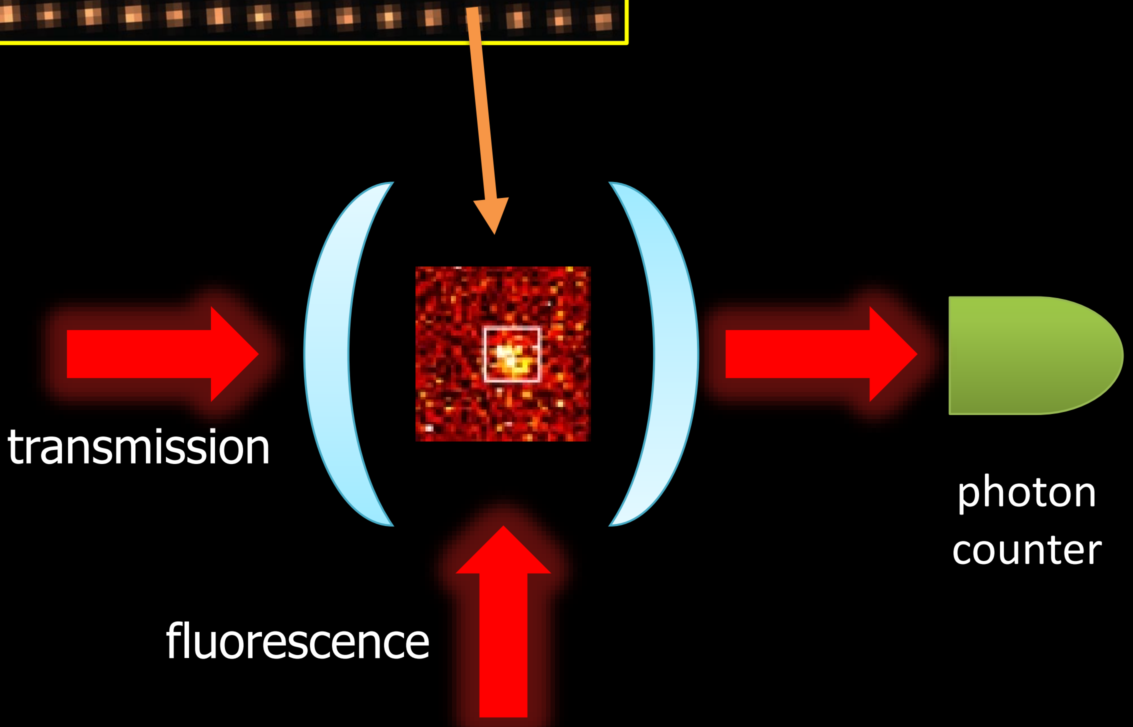


256+ atom quantum simulator

start of quantum computer

Possible improvements:

- Faster readout
  - Currently takes 10’s of ms. Limits cycle time.
- Atom(s) specific, non-global readout
  - Feedback on live quantum system, error correction.
  - Cluster state quantum computing, sensing



Cavity QED with a tweezer array (E6)

Zhenjie Yan | Emma Deist | Mary Kate Pasha | Jacquelyn Ho | Leon Lu

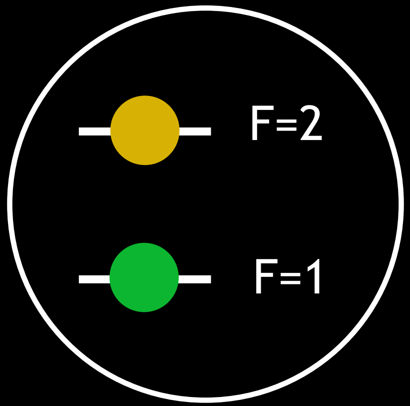
Justin Gerber

Johannes Zeiher

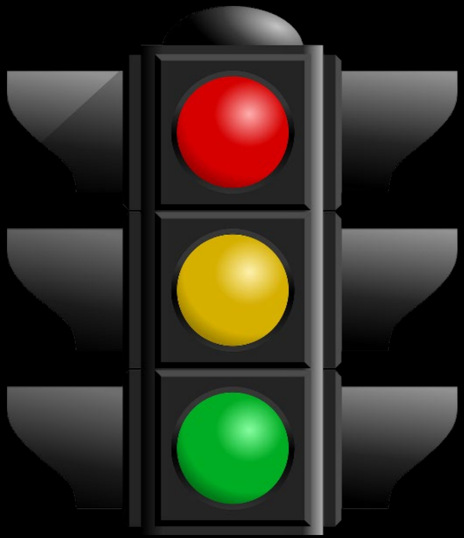
$$$ Thanks to AFOSR, ARO MURI (ReQuIEM), DARPA APHI, NSF CIQC (QLCI)

Cavity-based single-atom state detection

Goal: fast, high fidelity detection of three states



^{87}Rb hyperfine qubit

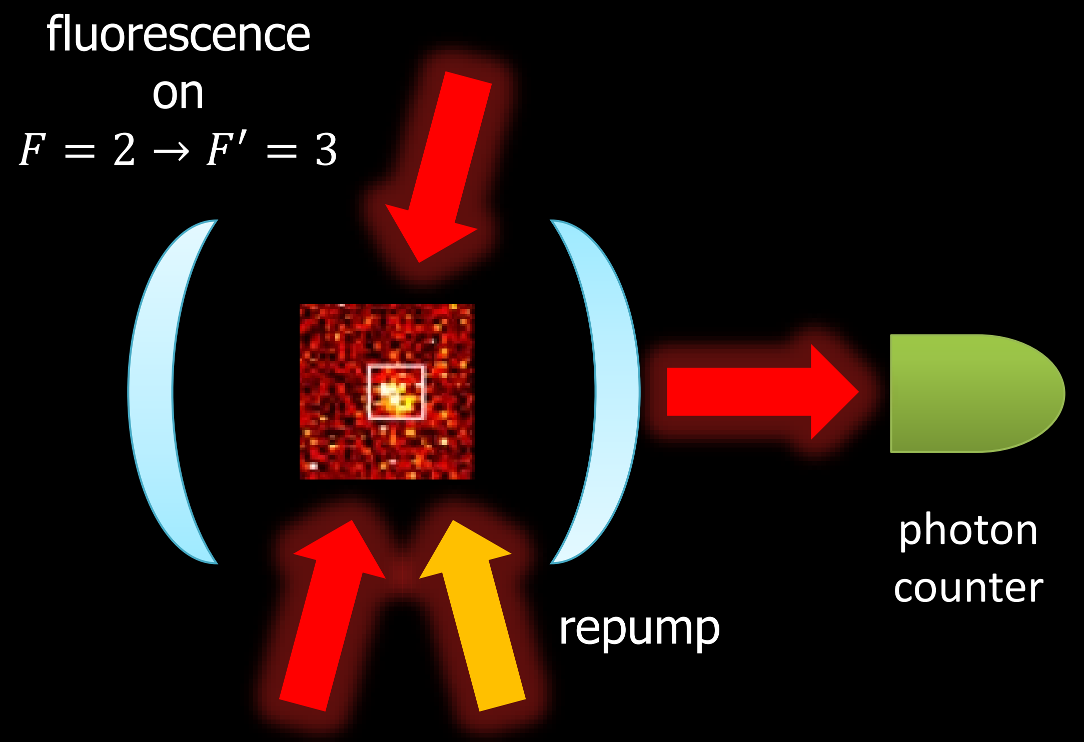


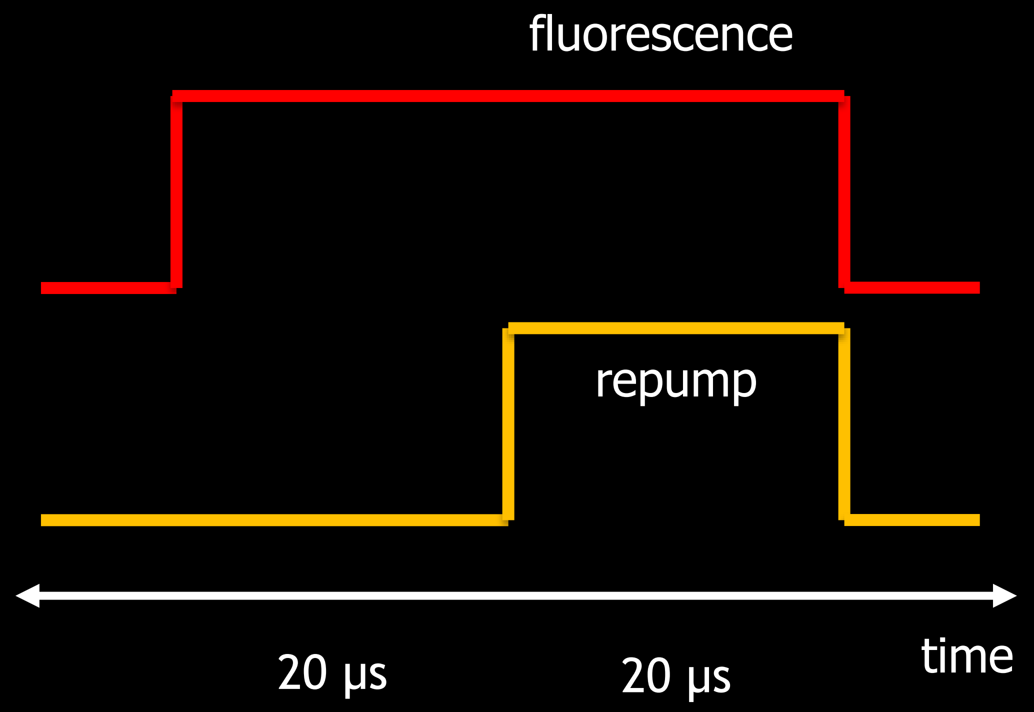
no atom

atom in $|F = 2\rangle$

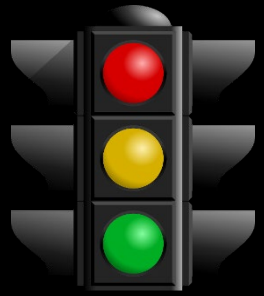
atom in $|F = 1\rangle$

Method 1: (F)luorescence – (R)epump (F)luorescence (FRF)





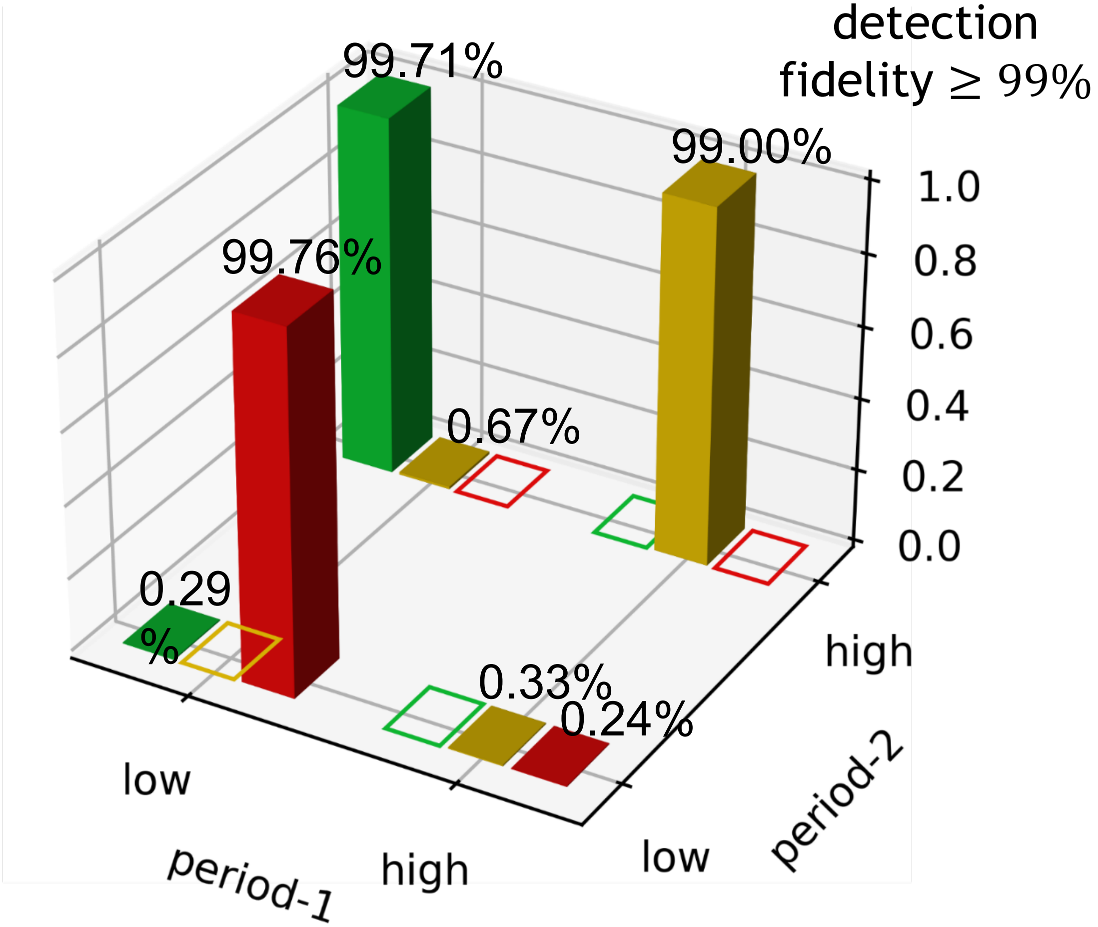
Fluorescence (FRF) detection 40 μs

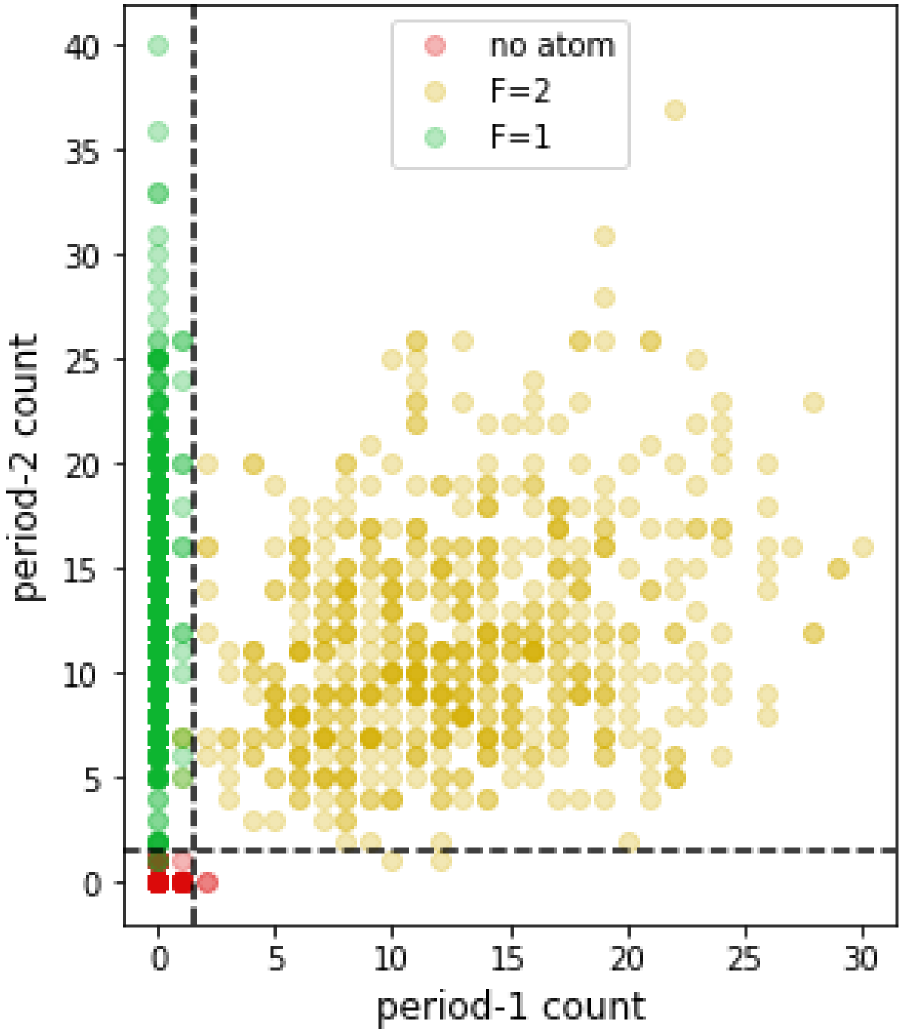


no atom

atom in $|F=2\rangle$

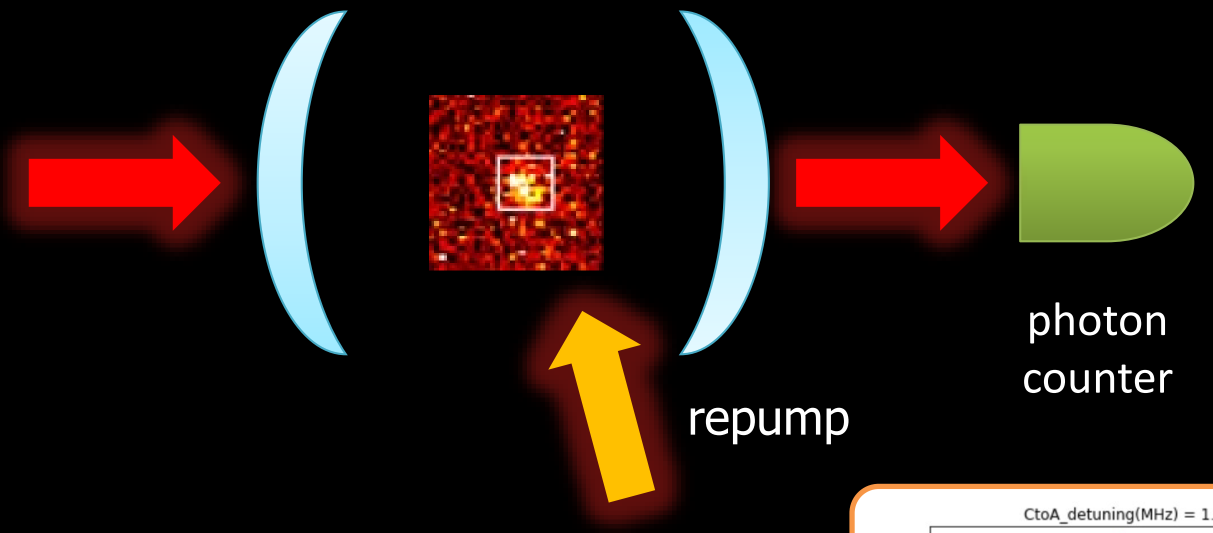
atom in $|F=1\rangle$

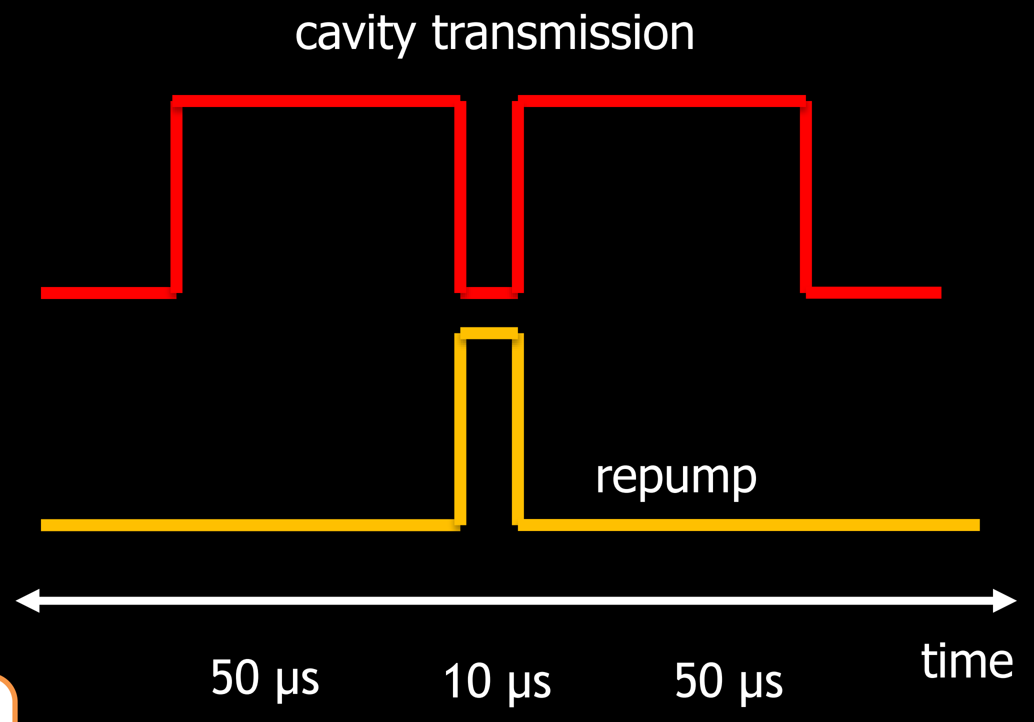


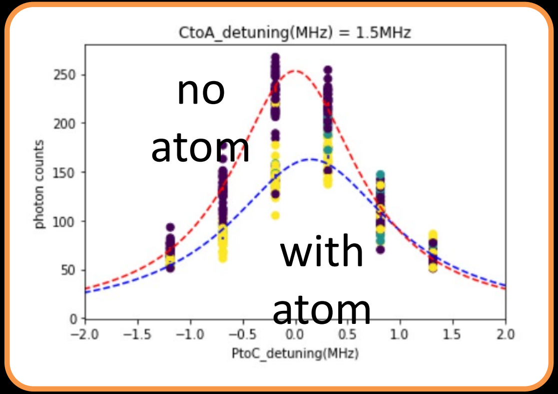


Method 2: (T)ransmission – (R)epump – (T)ransmission (TRT)

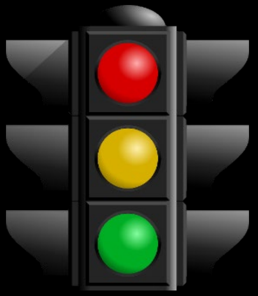
transmission
few MHz above
$F = 2 \rightarrow F' = 3$







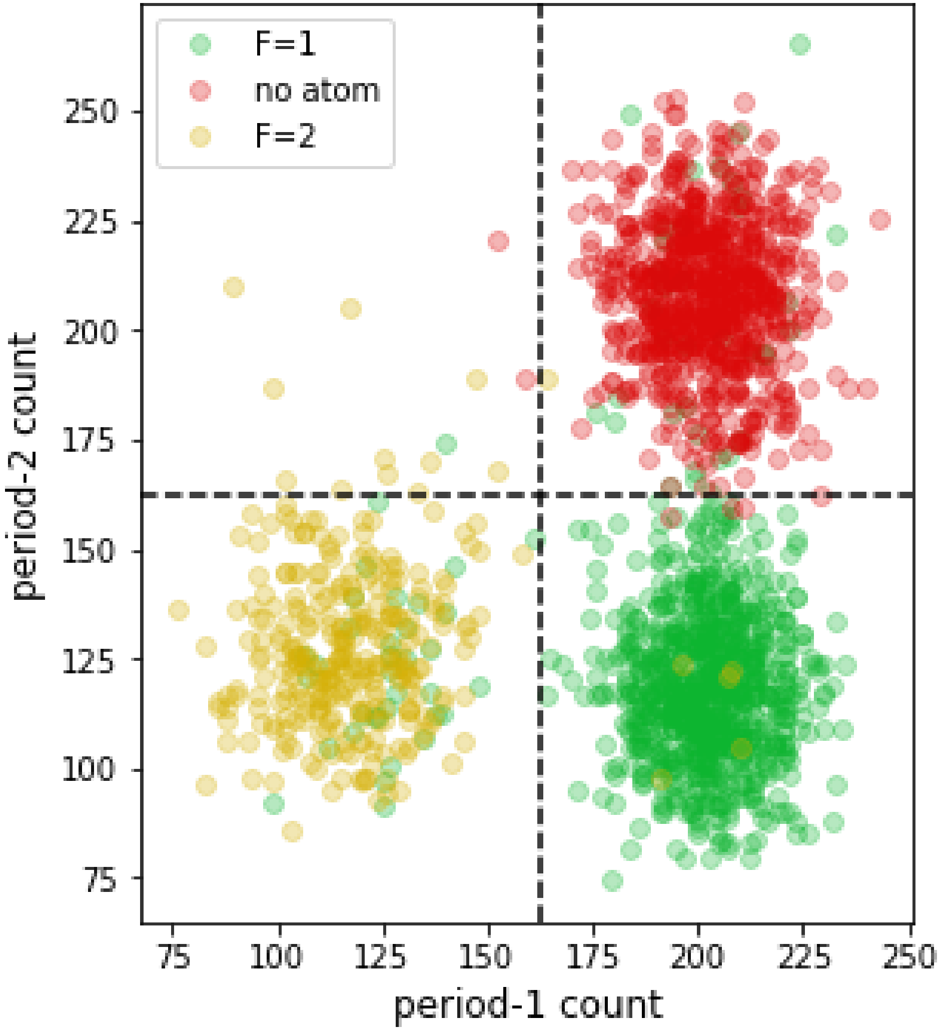
Cavity transmission (TRT) detection in 120 μs



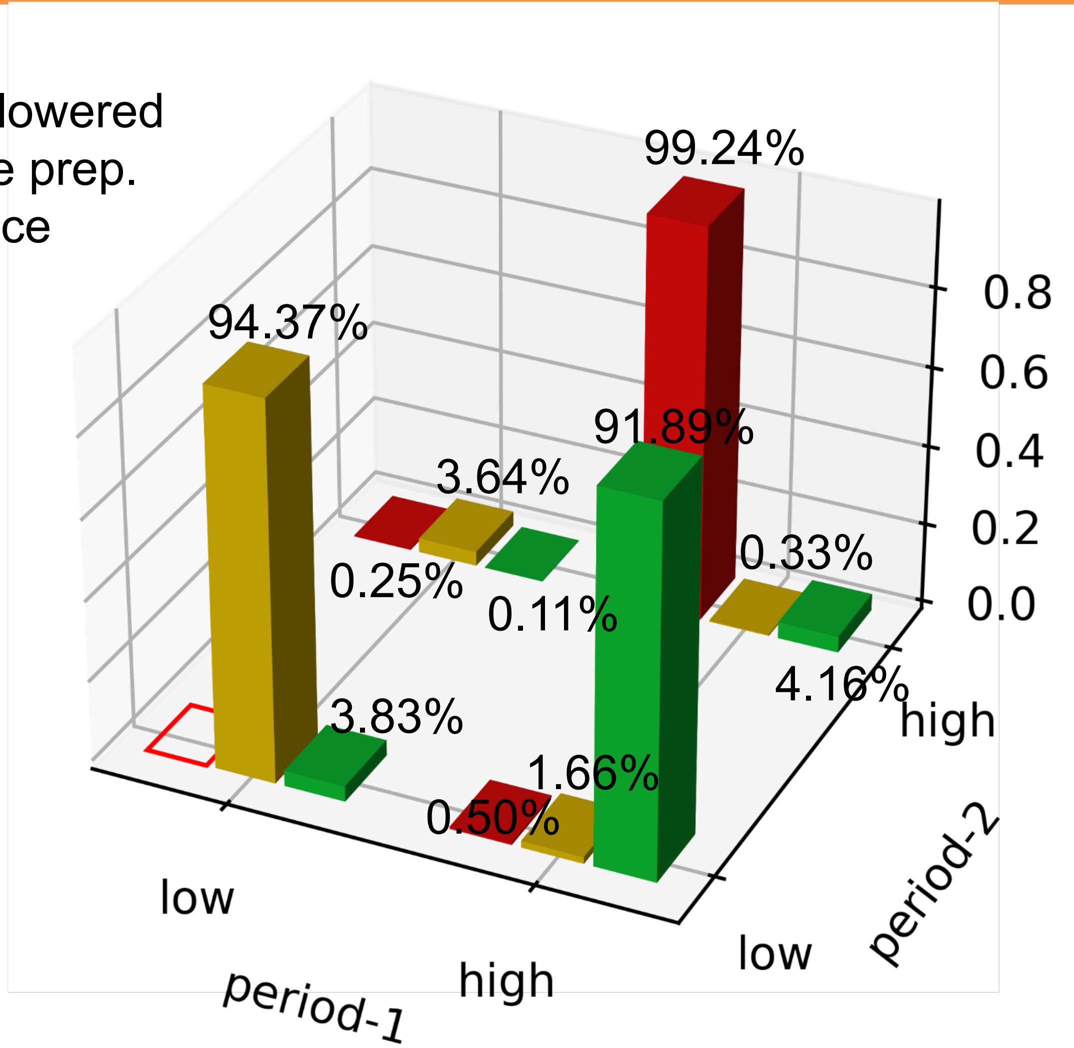
no atom

atom in $|F = 2\rangle$

atom in $|F = 1\rangle$



Fidelity likely lowered by poor state prep. fixed since



Challenge Institute for Quantum Computation (CIQC)

an NSF Quantum Leap Challenge Institute

addressing fundamental challenges
to the development of
the quantum computer

Leadership team

Dan Stamper-Kurn UC Berkeley	Hartmut Häffner UC Berkeley	Eric Hudson UCLA	Umesh Vazirani UC Berkeley	K. Birgitta Whaley UC Berkeley
Institute director	*scaling quantum systems*	*CQSE, IPAM partnership*	*quantum algorithms*	*quantum advantage*
CQCS partnership	*research coordination*	*education and workforce dev.*	*Simons partnership*	*institutional partnerships*

ciqc.berkeley.edu

Challenge Institute for Quantum Computation

Theoretical computer science (8): Scott Aaronson, Shafi Goldwasser, Aram Harrow, Urmila Mahadev, Ben Reichardt, Peter Shor, Umesh Vazirani, Thomas Vidick

Computer architecture (2): John Kubiatowicz, Jens Palsberg

Theoretical chemistry (3): Martin Head-Gordon, K. Birgitta Whaley, Nathan Wiebe

Electrical and optical engineering (3): Boubacar Kante, John Martinis, Alp Sipahigil, Ming Wu

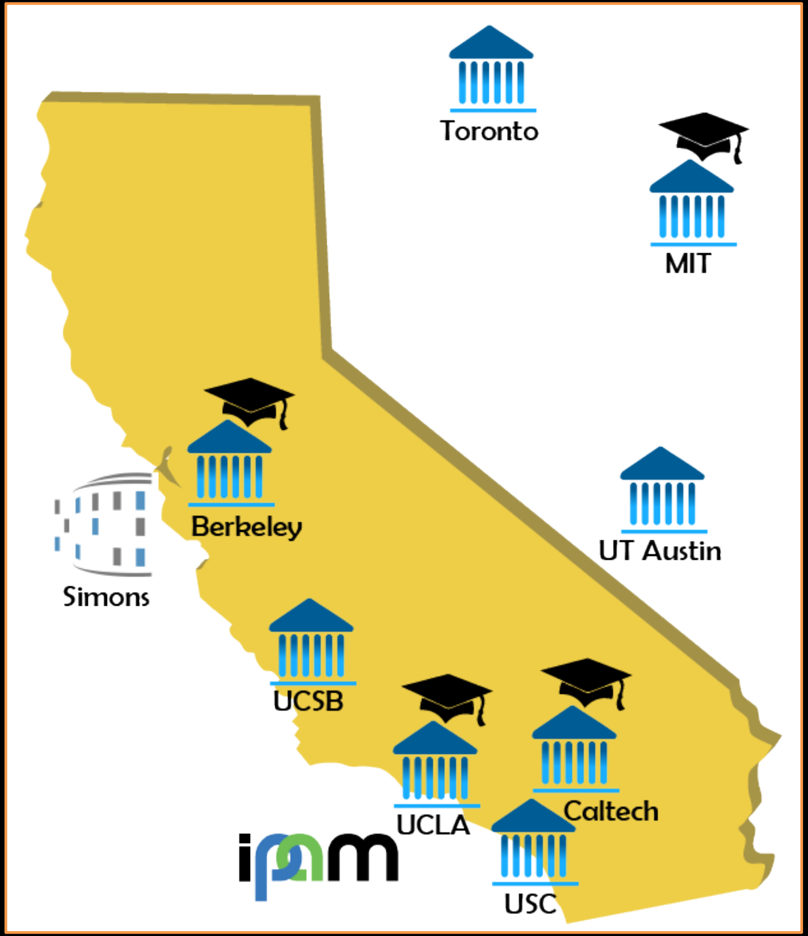
Mathematics (3): Lin Lin, Peter Shor, Thomas Vidick

Experimental quantum physics (9): Wesley Campbell, Manuel Endres, Eric Hudson, Hartmut Häffner, Ania Jayich, John Martinis, Alp Sipahigil, Dan Stamper-Kurn, David Weld, Norman Yao

Theoretical quantum physics (6): Ehud Altman, Aram Harrow, Joel Moore, K. Birgitta Whaley, Nathan Wiebe, Norman Yao

Materials science (3): Ania Jayich, John Martinis, Joel Moore

28 investigators (25 funded)
8 universities
2 institutes
>100 students, postdocs



Working groups

quantum algorithms	Optimization, linear algebra and machine learning	Aram Harrow
	Verification	Umesh Vazirani
	Digital simulation and chemistry	Brigitta Whaley
quantum advantage	Error correction, fault tolerance and noise models	Ben Reichardt
	Quantum advantage in analog quantum simulation	Ehud Altman
	NV systems for quantum advantage and many-body quantum physics	Norman Yao
scaling quantum systems	Calibration and verification of experimental hardware	Hartmut Häffner
	Hardware-aware compilation	John Kubiatowicz
	Rydberg tweezer experiments	Manuel Endres
	Ion trapping and photonics	Wes Campbell
	Neutral atom quantum information processing	David Weld
	Advanced optical systems	Boubacar Kante

YOU ARE INVITED: NSF may offer funding for seed projects that link you and QLCI center