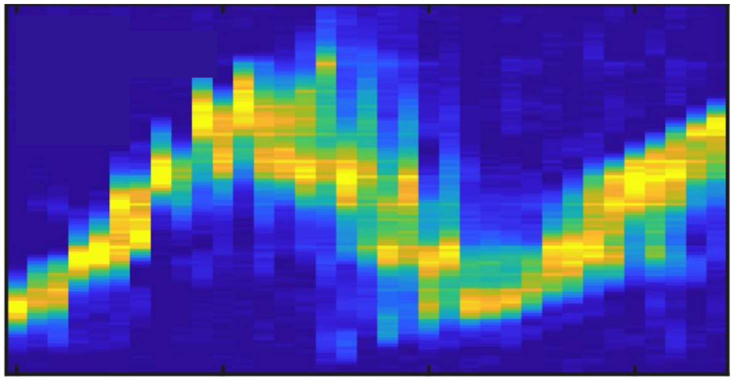
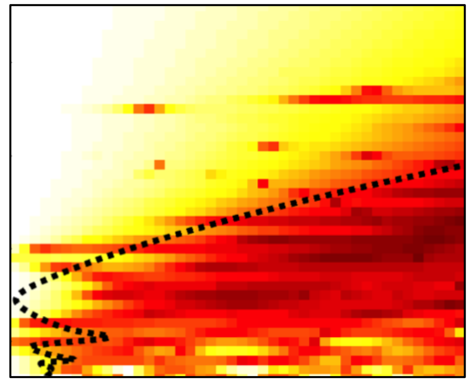
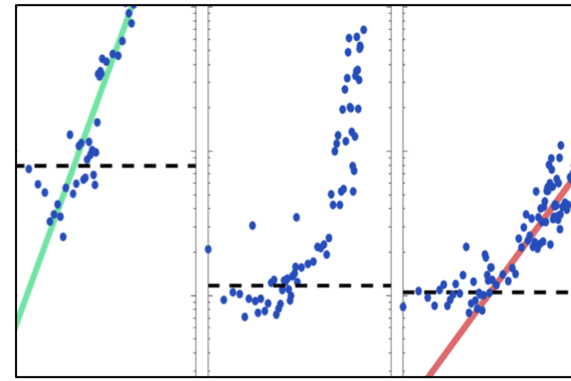
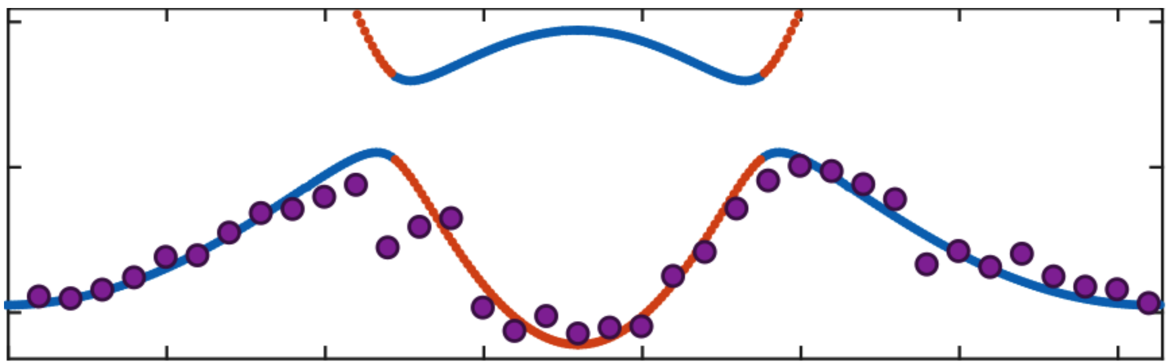
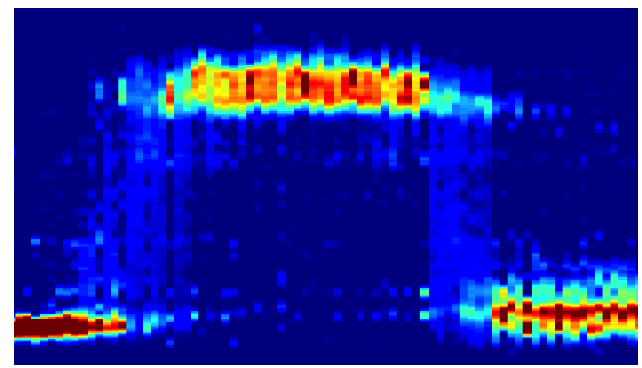
Floquet band engineering and prethermalization in driven optical lattices

David Weld
UC Santa Barbara

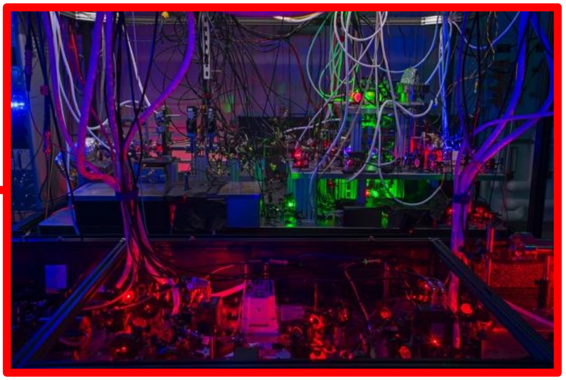
October 10, 2018
CUA Seminar

Outline

- Introduction
  - Experimental approach
- Driven optical lattices
  - Position-space Bloch oscillations
  - Floquet band engineering & transport
  - Prethermalization & the periodic Gibbs ensemble
- Other current projects

Outline

- Introduction
    - **Experimental approach**

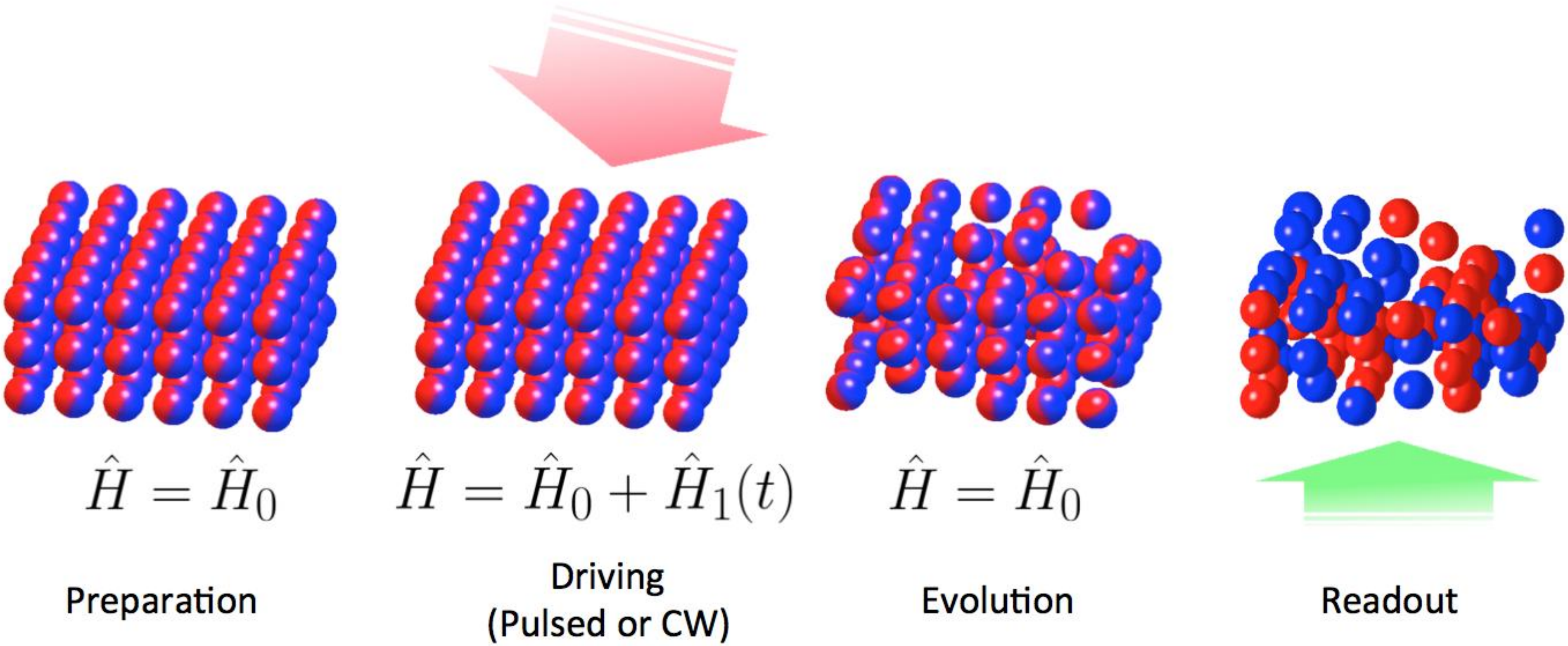


- Driven optical lattices
    - Position-space Bloch oscillations
    - Floquet band engineering & transport
    - Prethermalization & the periodic Gibbs ensemble

- Other current projects

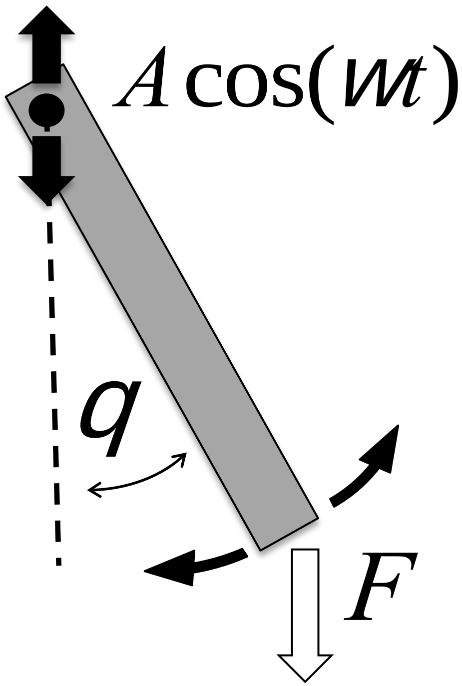
Driven Systems

The basic question: what happens when you shake stuff?



Driven Systems: Classical Example

Pendulum with vibrating pivot:

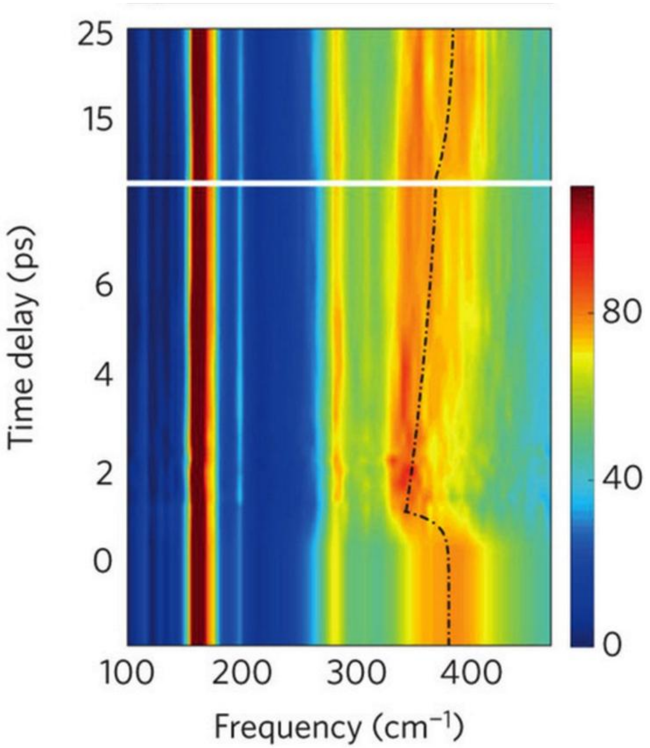


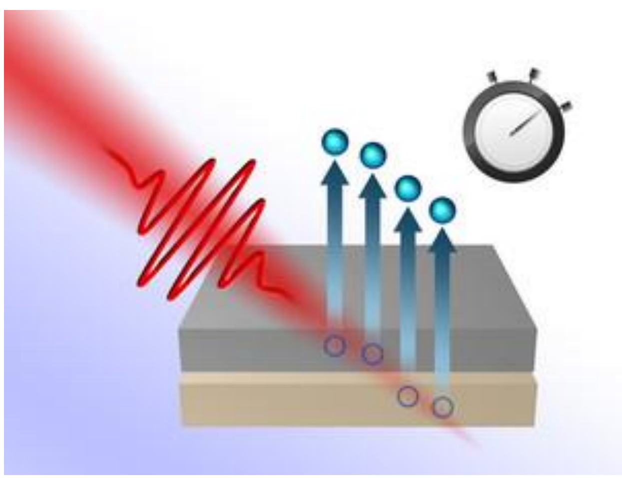
$$\ddot{q}+[d+e\cos(t)]\sin q=0$$

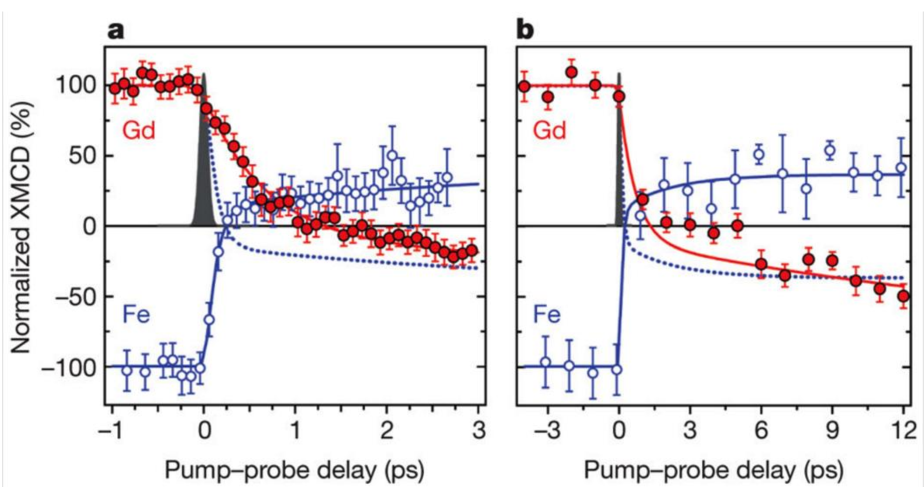
https://www.youtube.com/watch?v=rwGAzy0noU0

Driven Systems: Quantum Example

- Atoms and solids in pulsed-laser fields
- Nontrivial dynamical behavior (tunnel ionization, HHG)
- Emergent states of matter





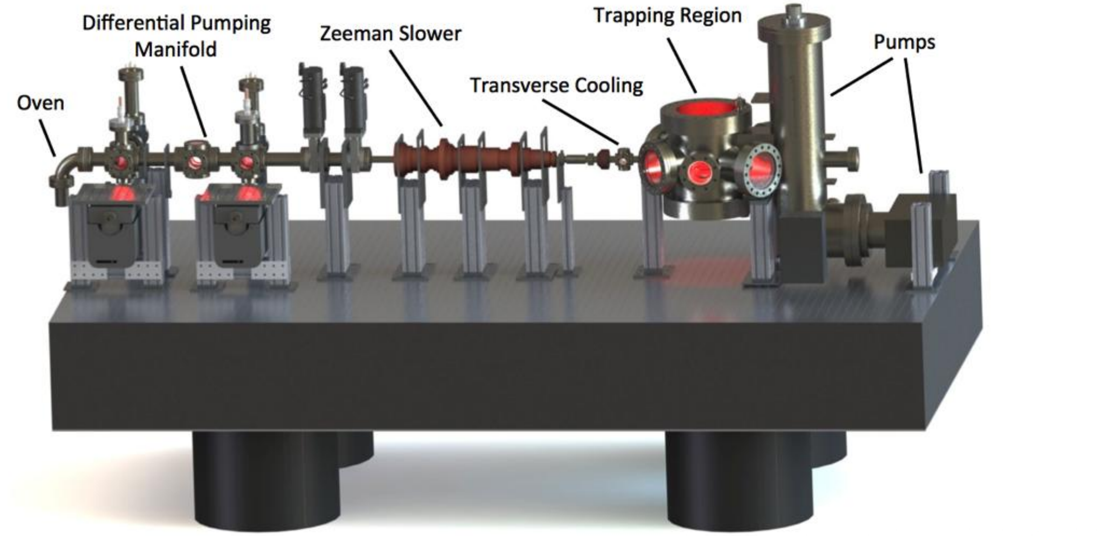


Images: Nijmegen, Hamburg, Zurich

UCSB Experiments

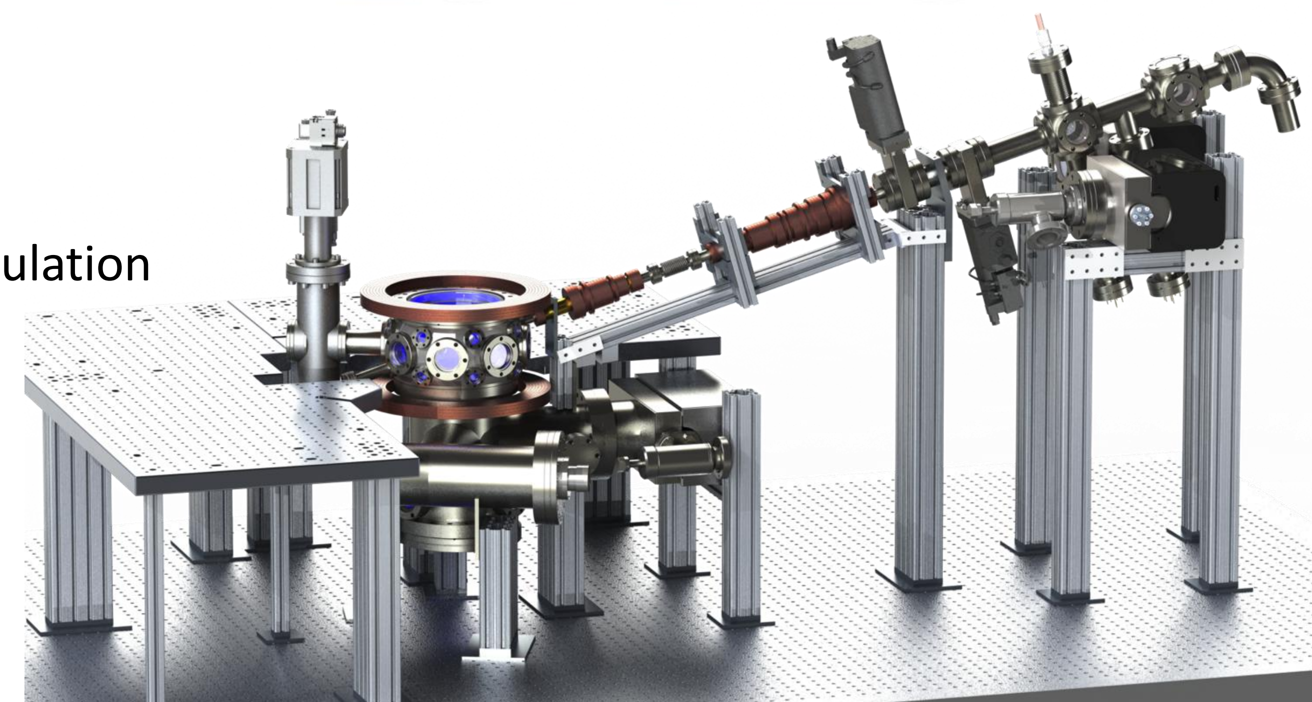
Lithium

- Floquet phases
- Quantum quasicrystals
- Bloch oscillations
- New cooling techniques



Strontium

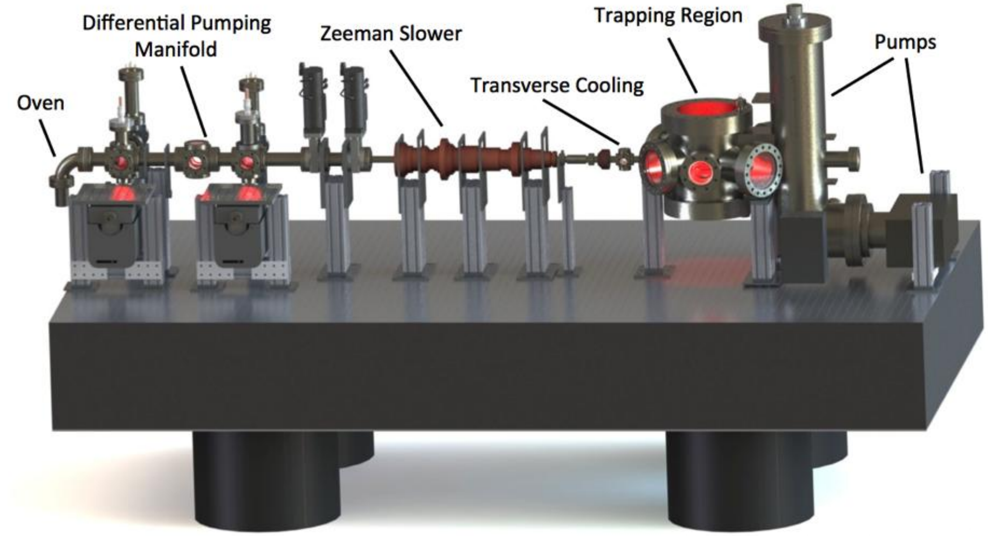
- Strong-field quantum simulation
- Quantum sensing
- Topological pumping
- Single-site resolution
- Anyons



UCSB Experiments

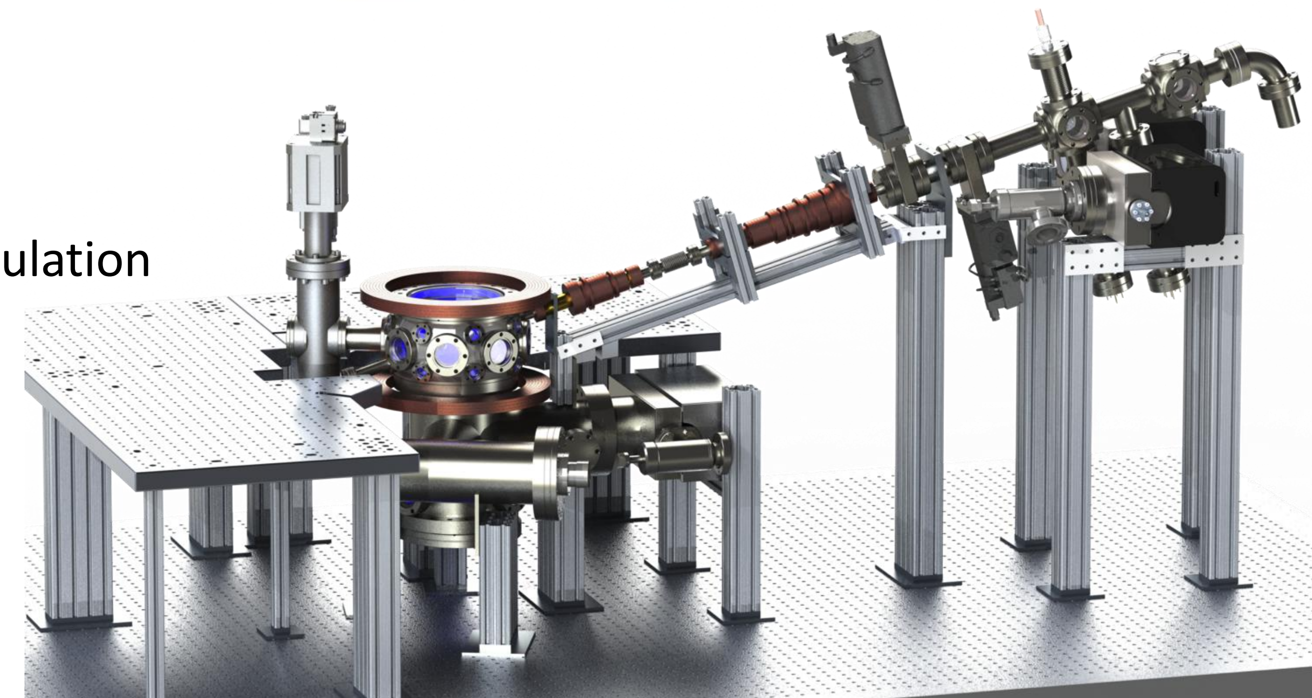
Lithium

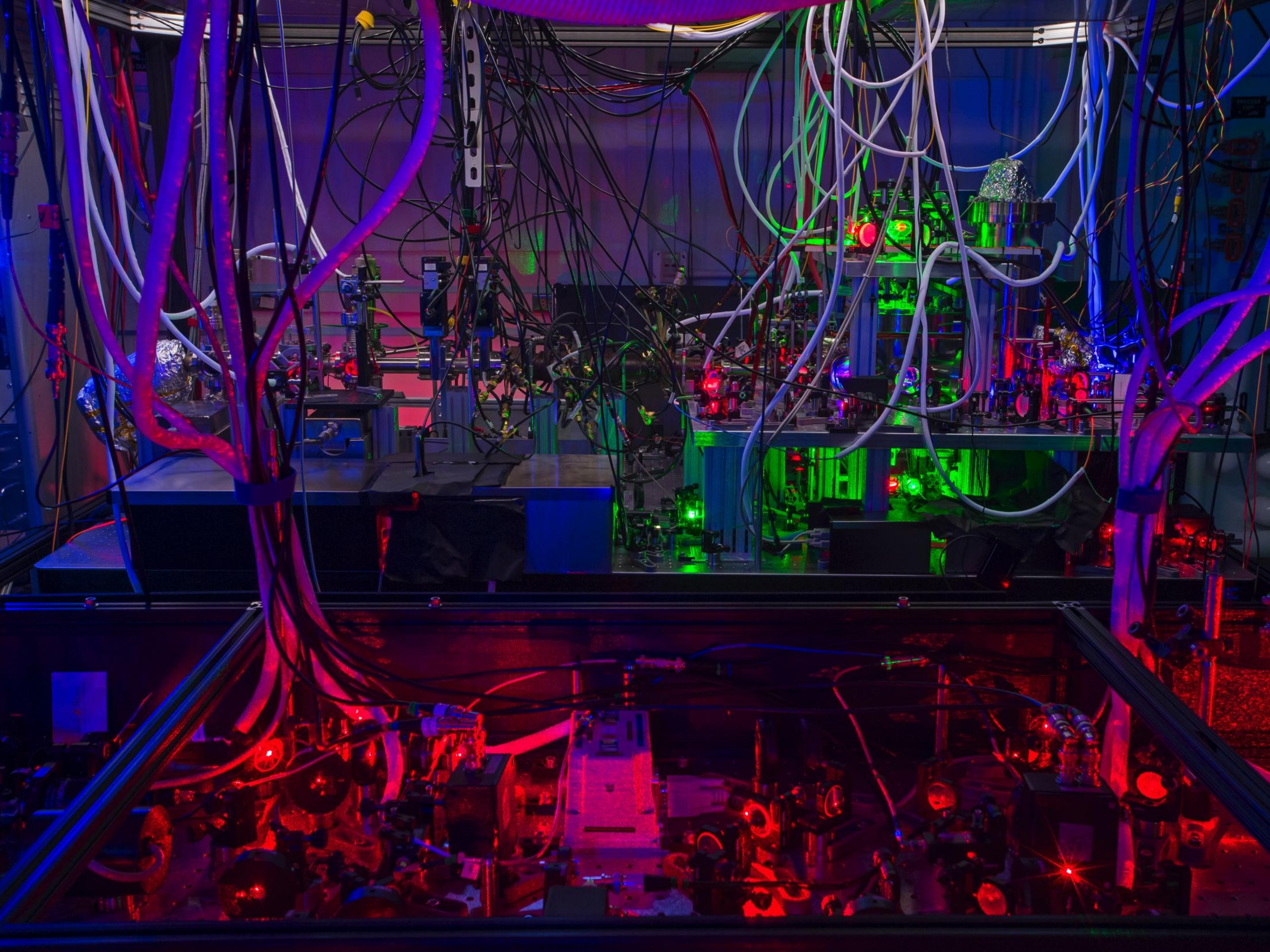
- **Floquet phases**
- Quantum quasicrystals
- **Bloch oscillations**
- New cooling techniques



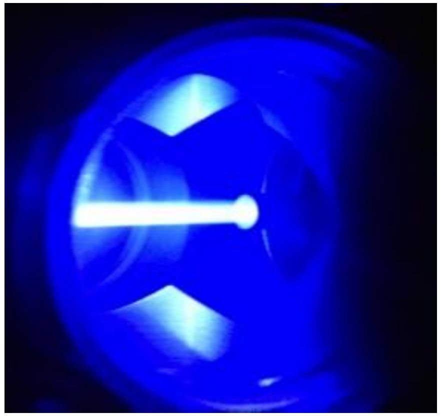
Strontium

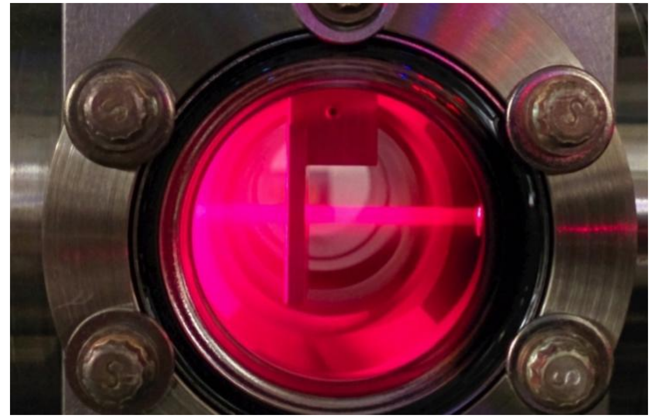
- Strong-field quantum simulation
- Quantum sensing
- Topological pumping
- Single-site resolution
- Anyons

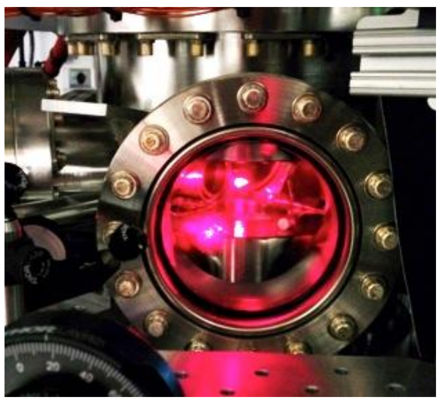


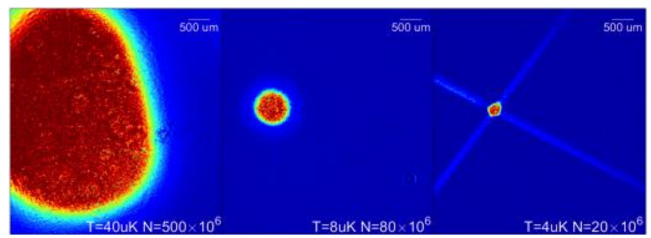


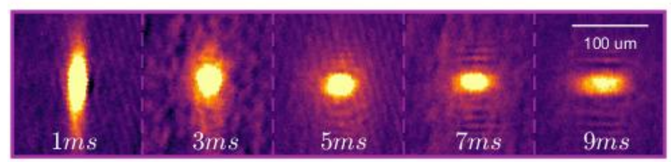
Hot and Cold Atoms

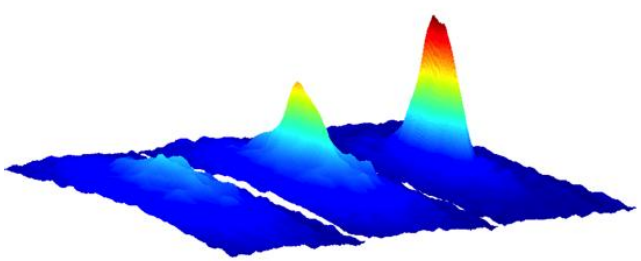


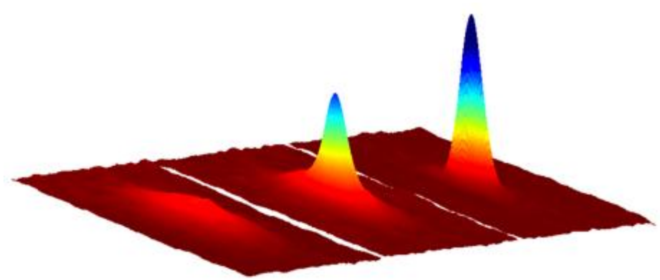












Outline

- Introduction
  - Experimental approach

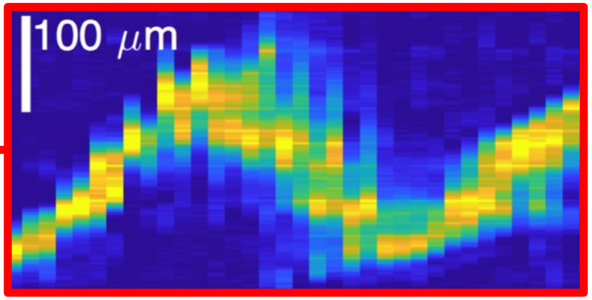
- Driven optical lattices
  - Position-space Bloch oscillations
  - Floquet band engineering & transport
  - Prethermalization & the periodic Gibbs ensemble

- Other current projects

Outline

- Introduction
  - Experimental approach

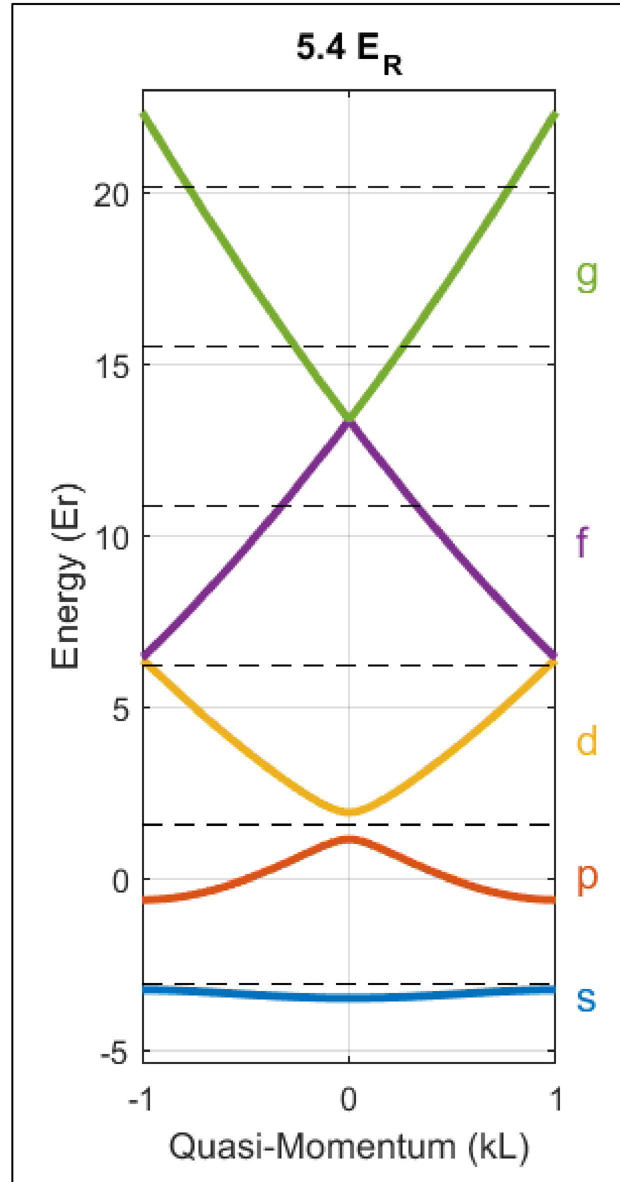
- Driven optical lattices
  - **Position-space Bloch oscillations**
  - Floquet band engineering & transport
  - Prethermalization & the periodic Gibbs ensemble



- Other current projects

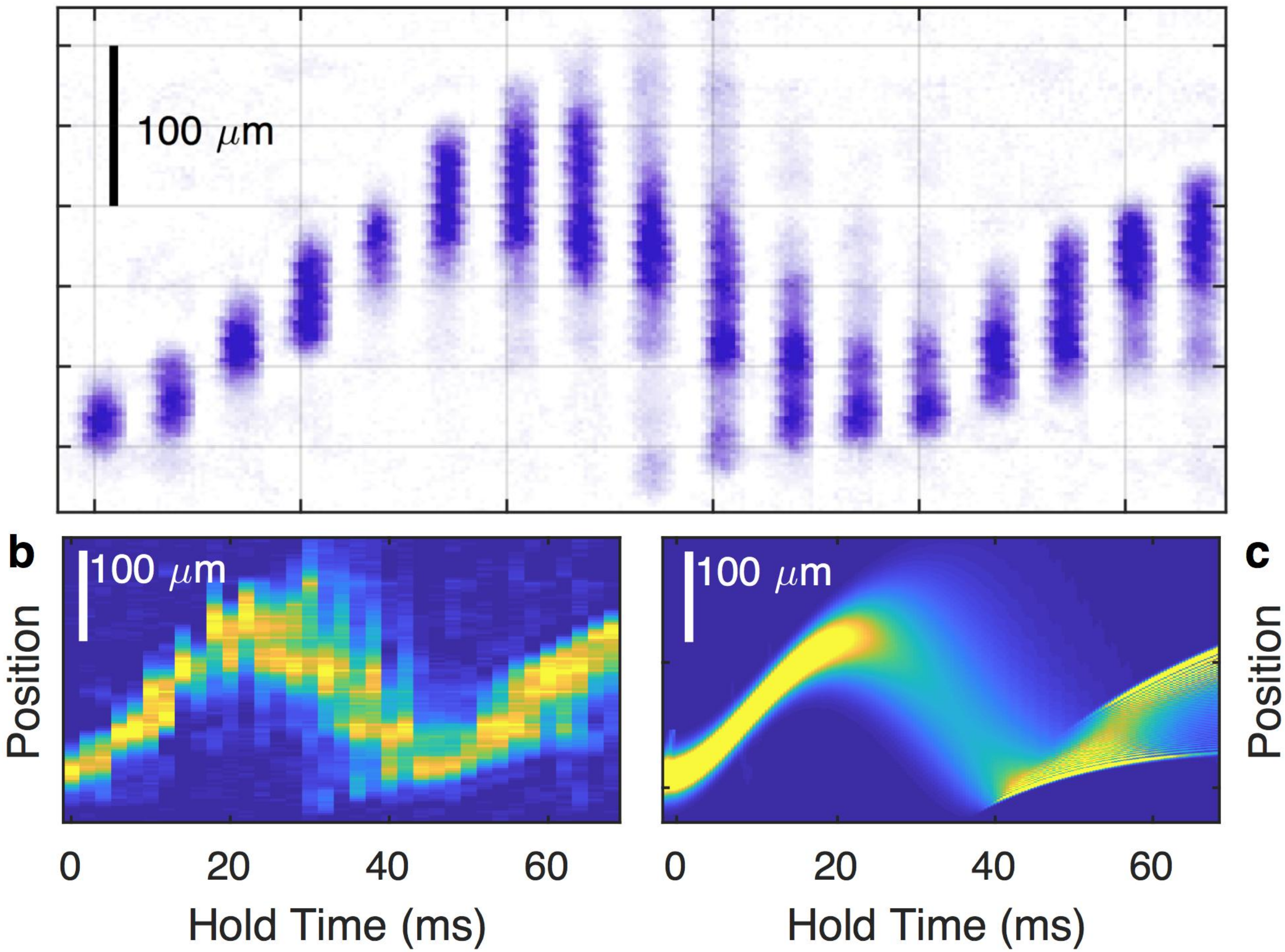
Position-Space Bloch Oscillations

- In a periodic system, static force produces oscillatory response (Bloch, Zener 1929)
- Momentum evolves through edge of BZ
- Cold atoms an excellent platform for studying such Bloch oscillations (way easier than in solids)
- Typically probed in momentum space; position-space dynamics initially predicted by Zener too small to be observed



Position-Space Bloch Oscillations

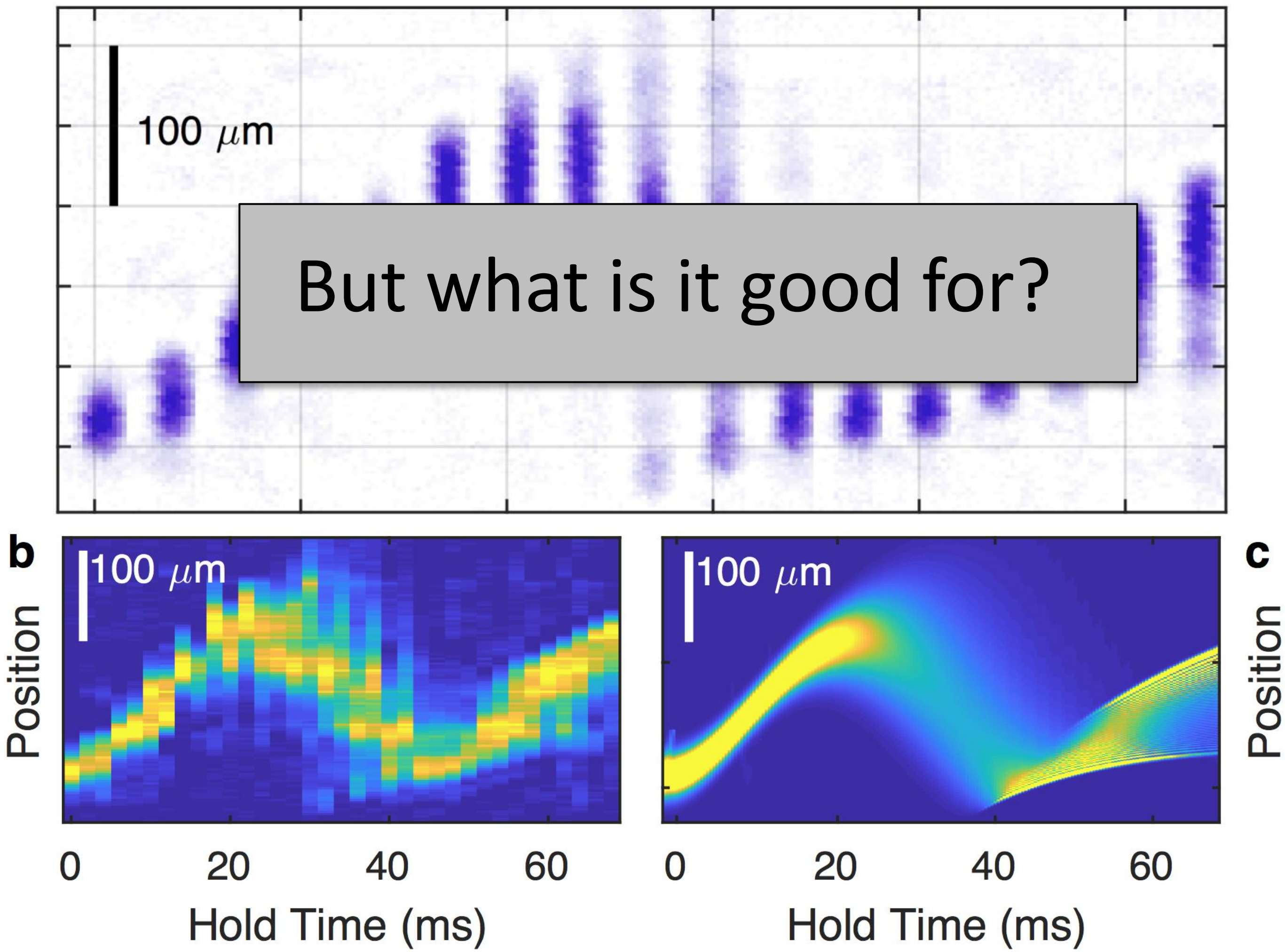
- Li (light, non-interacting) in lattice enables PSBO observation



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

Position-Space Bloch Oscillations

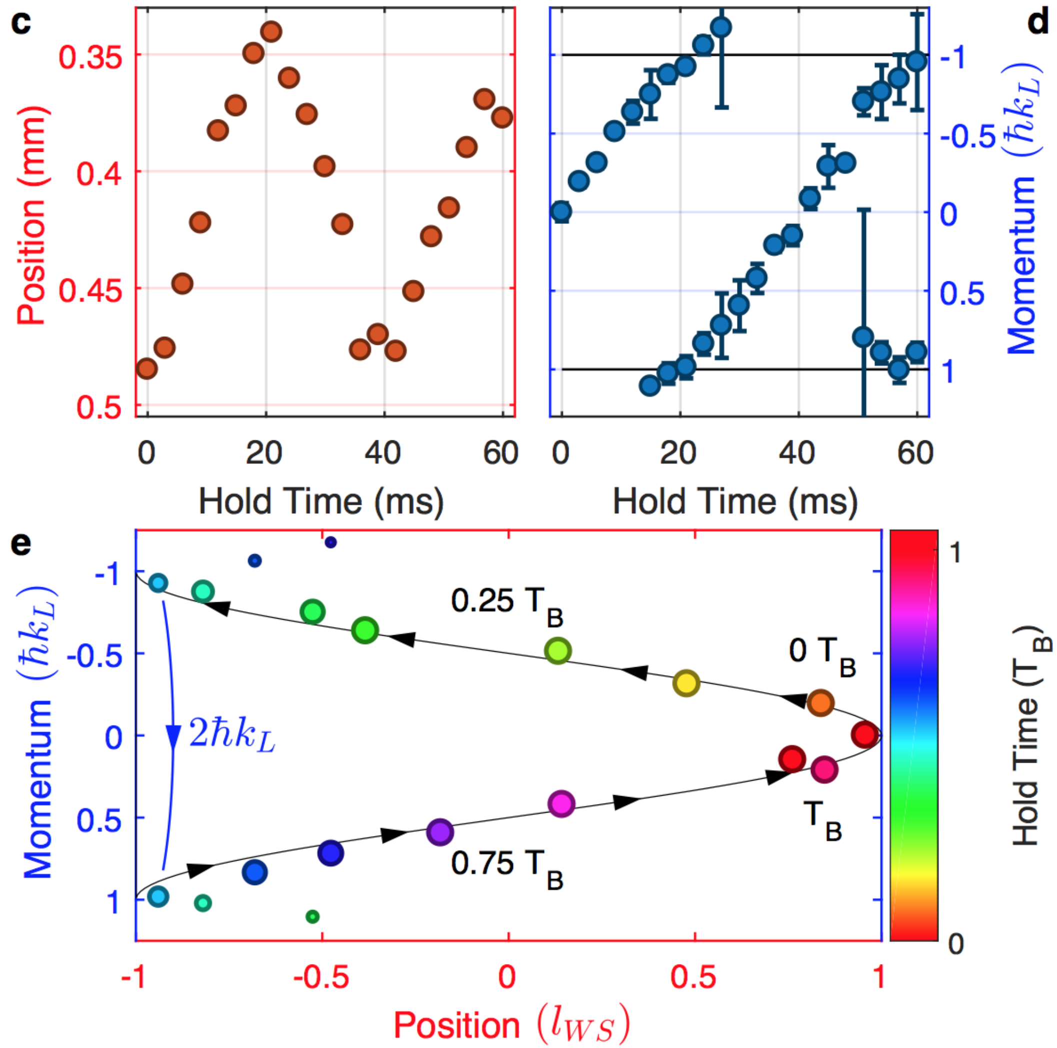
- Li (light, non-interacting) in lattice enables PSBO observation



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

Position-Space Bloch Oscillations

- Use 1: directly map phase-space evolution during a Bloch oscillation



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

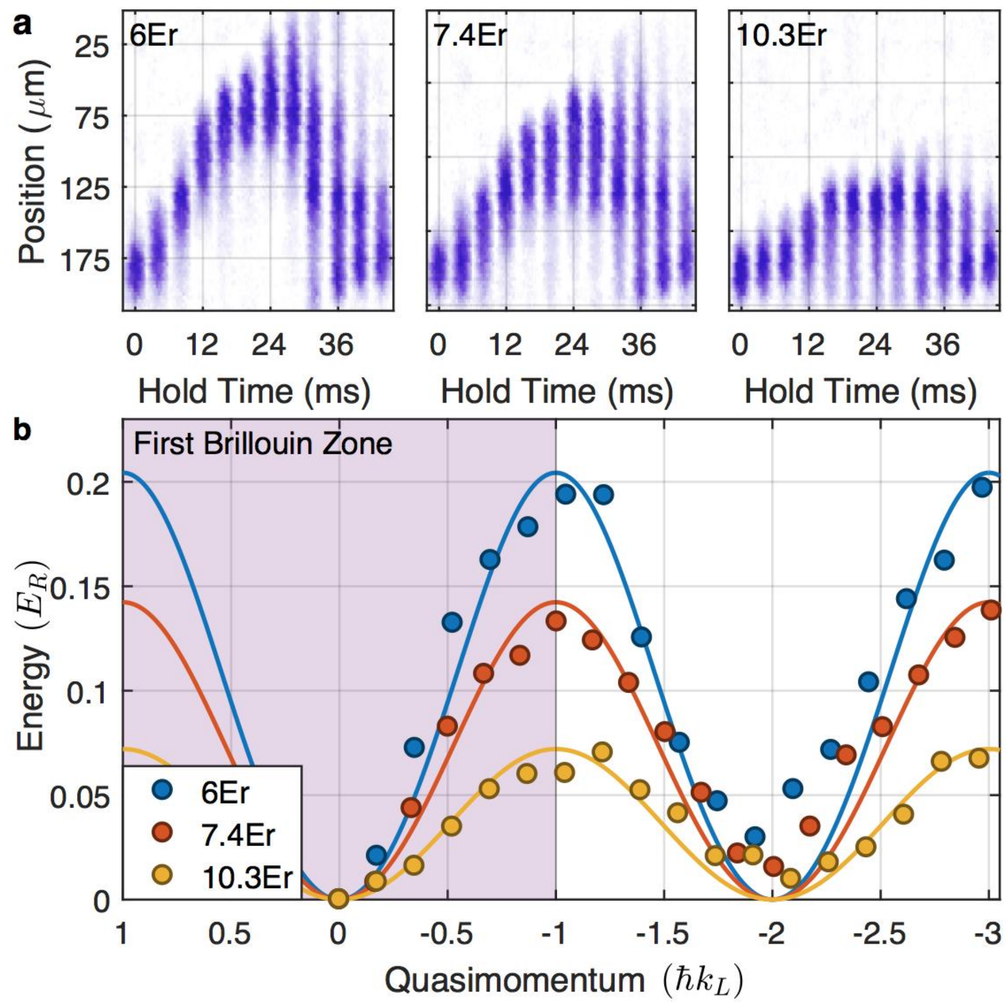
Position-Space Bloch Oscillations

- Use 2: direct imaging of band structure

- x(t) maps directly to E(k):

$$E = \frac{hf_B}{d}x, \qquad k = \frac{k_L}{2T_B}t$$

- ARPES-like measurement



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

Position-Space Bloch Oscillations

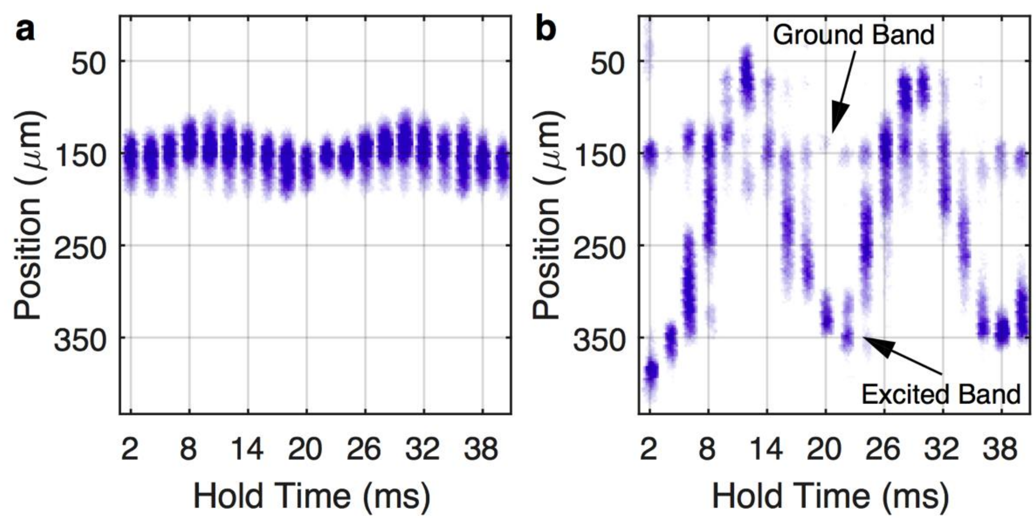
- Use 2: direct imaging of band structure

- x(t) maps directly to E(k):

$$E = \frac{hf_B}{d}x, \qquad k = \frac{k_L}{2T_B}t$$

- ARPES-like measurement

- Works in excited bands too…



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

Position-Space Bloch Oscillations

- Use 2: direct imaging of band structure

- x(t) maps directly to E(k):

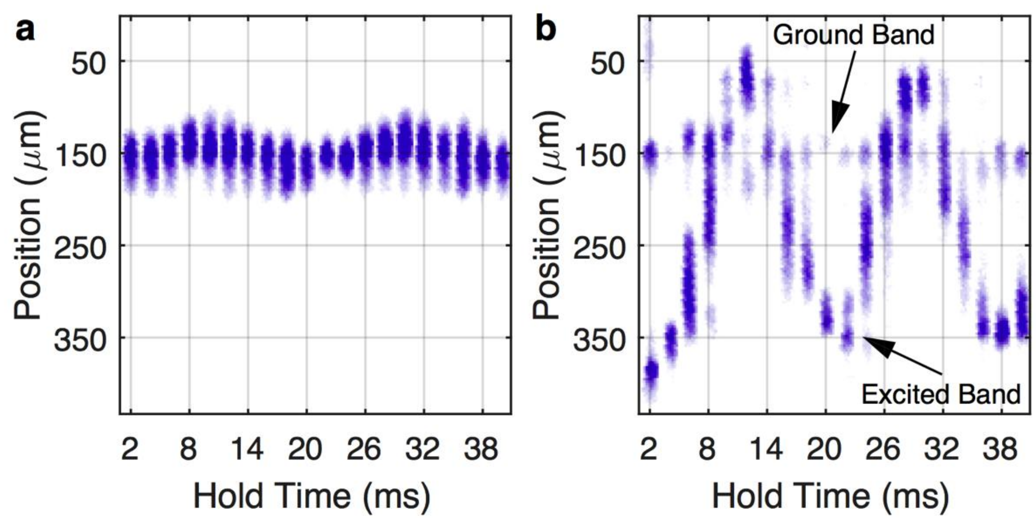
$E = \frac{hf_B}{\cdots}$ … k_L

→Position-space Bloch oscillations are visible and useful.

Next: What if we drive the lattice directly?

- ARPES-…

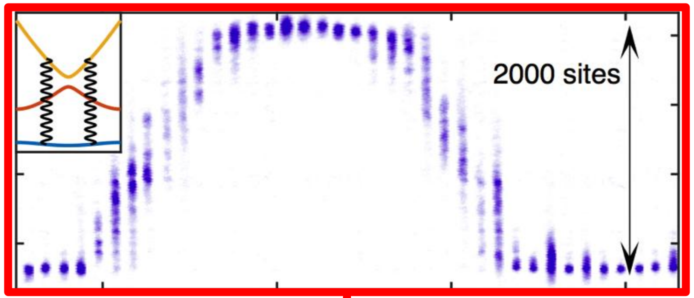
- Works in excited bands too…



Z. Geiger *et al*, *Phys. Rev. Lett.* **120**, 213201 (2018)

Outline

- Introduction
  - Experimental approach
- Driven optical lattices
  - Position-space Bloch oscillations
  - **Floquet band engineering & transport**
  - Prethermalization & the periodic Gibbs ensemble
- Other current projects



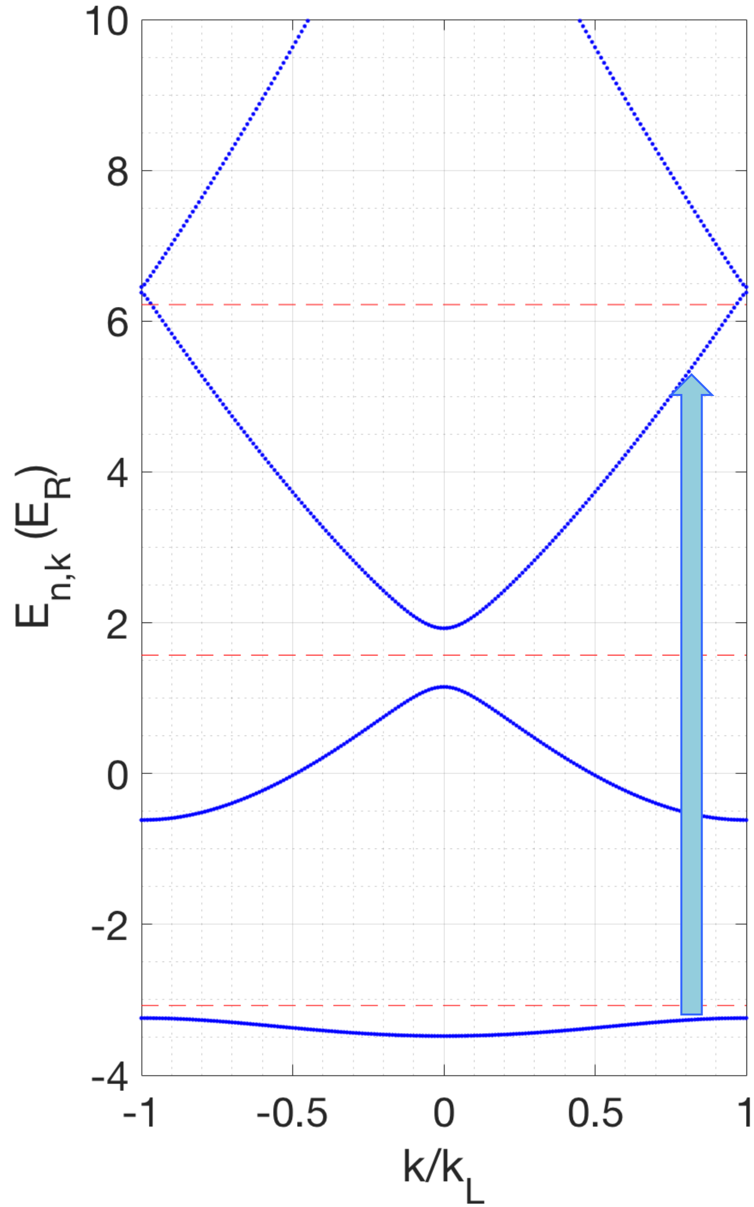
Floquet-Bloch Oscillations

- Adding external driving:

  - Apply constant AM drive resonant with s-d transition at finite k

  - Allow atoms to Bloch oscillate

  - What happens?



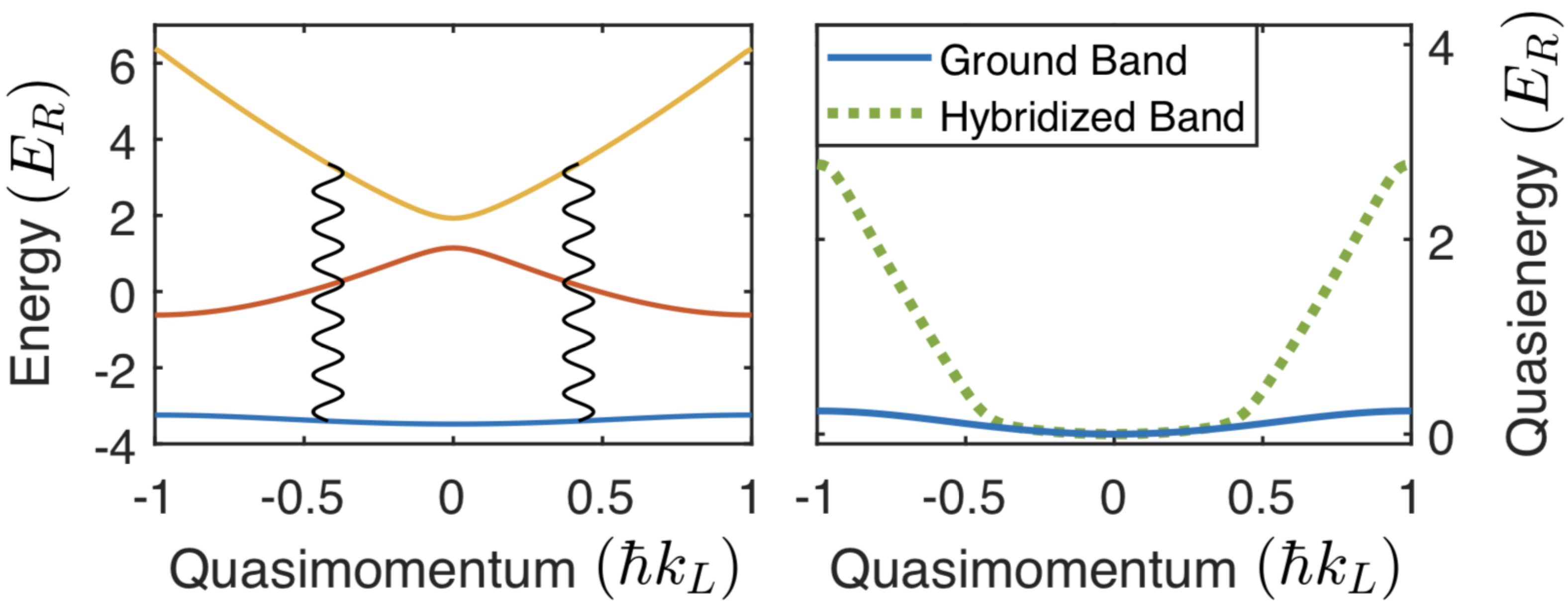
Floquet-Bloch Oscillations

- Adding external driving:

  - Apply constant AM drive resonant with s-d transition at finite k

  - Allow atoms to Bloch oscillate

  - What happens?



Floquet-Bloch Oscillations

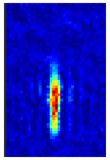
- Putting these techniques together:

  - Apply constant AM drive resonant with s-d transition at finite k

  - Allow atoms to Bloch oscillate

  - What happens?

Drive Off



Floquet-Bloch Oscillations

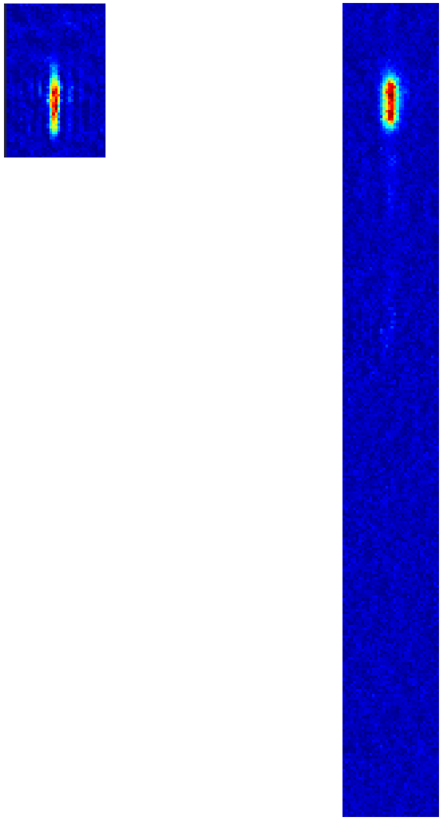
- Putting these techniques together:

  - Apply constant AM drive resonant with s-d transition at finite k

  - Allow atoms to Bloch oscillate

  - What happens?

Drive Off Drive On



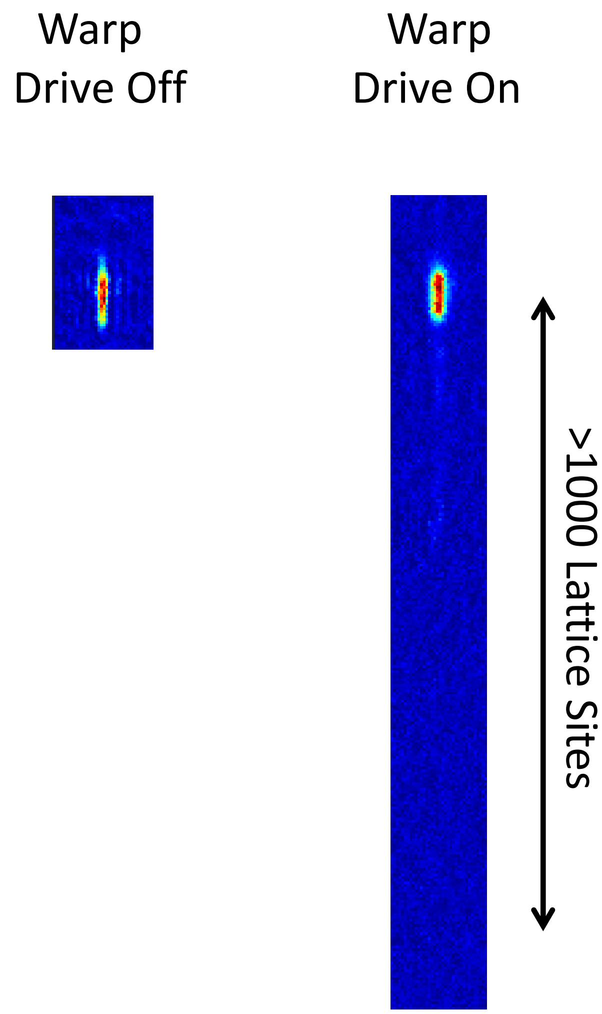
Floquet-Bloch Oscillations

- Putting these techniques together:

  - Apply constant AM drive resonant with s-d transition at finite k

  - Allow atoms to Bloch oscillate

  - What happens?

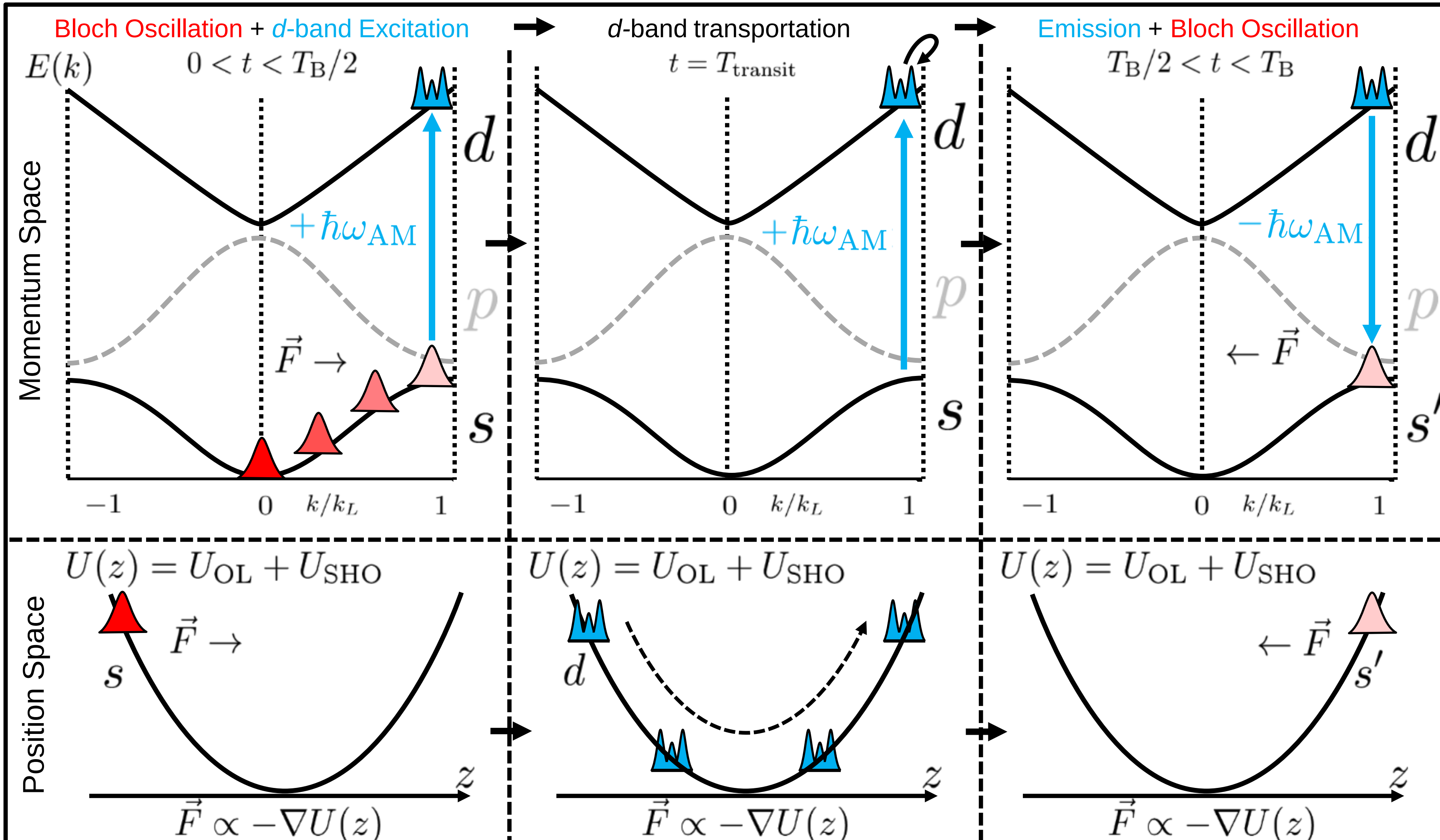


→ **Giant Floquet-Bloch oscillations**

Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

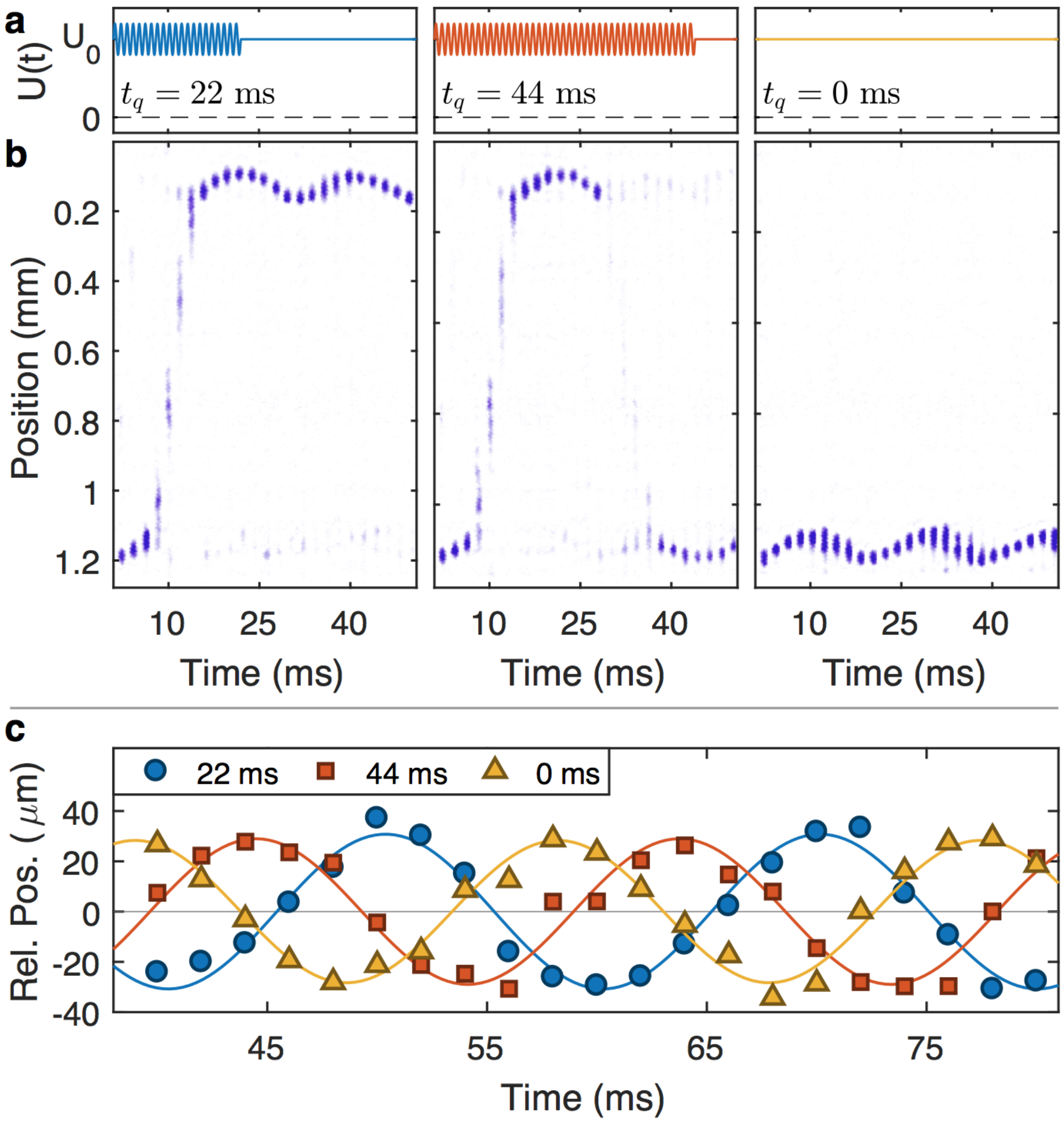
- Can think of this as evolution in a single Floquet-hybridized s/d band



Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

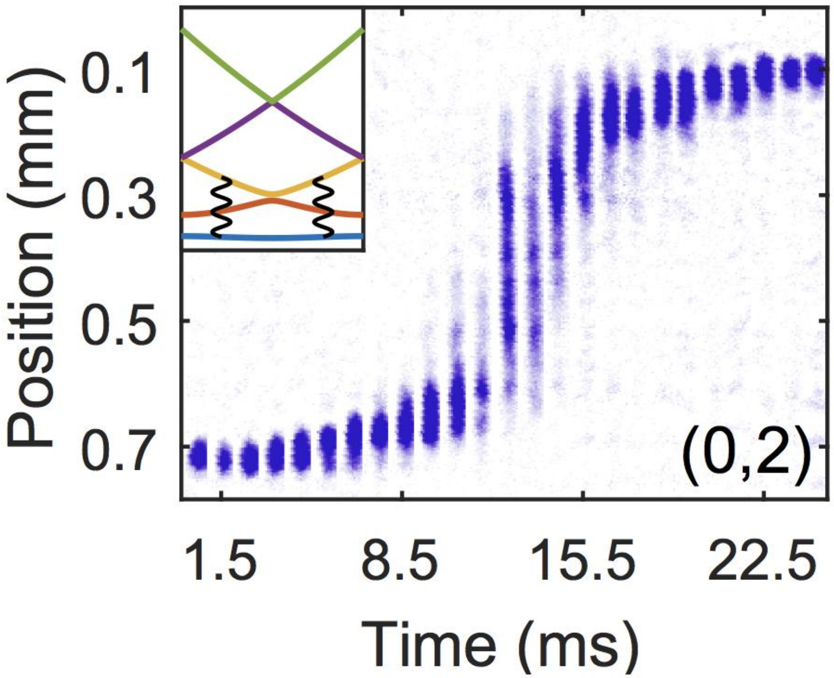
- Allows precise coherent control of long-range transport

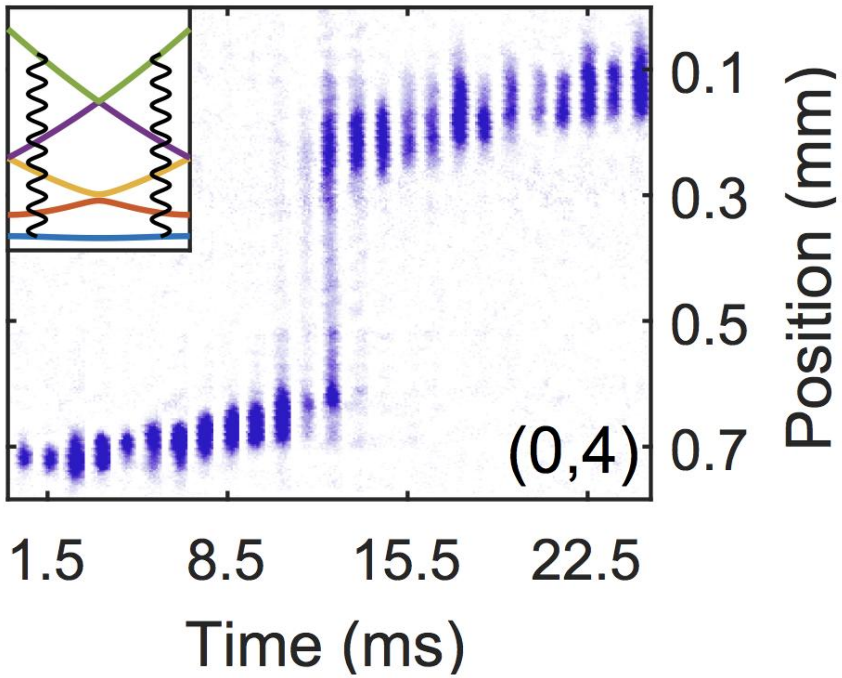


Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

- Can couple different pairs of bands at different quasimomenta

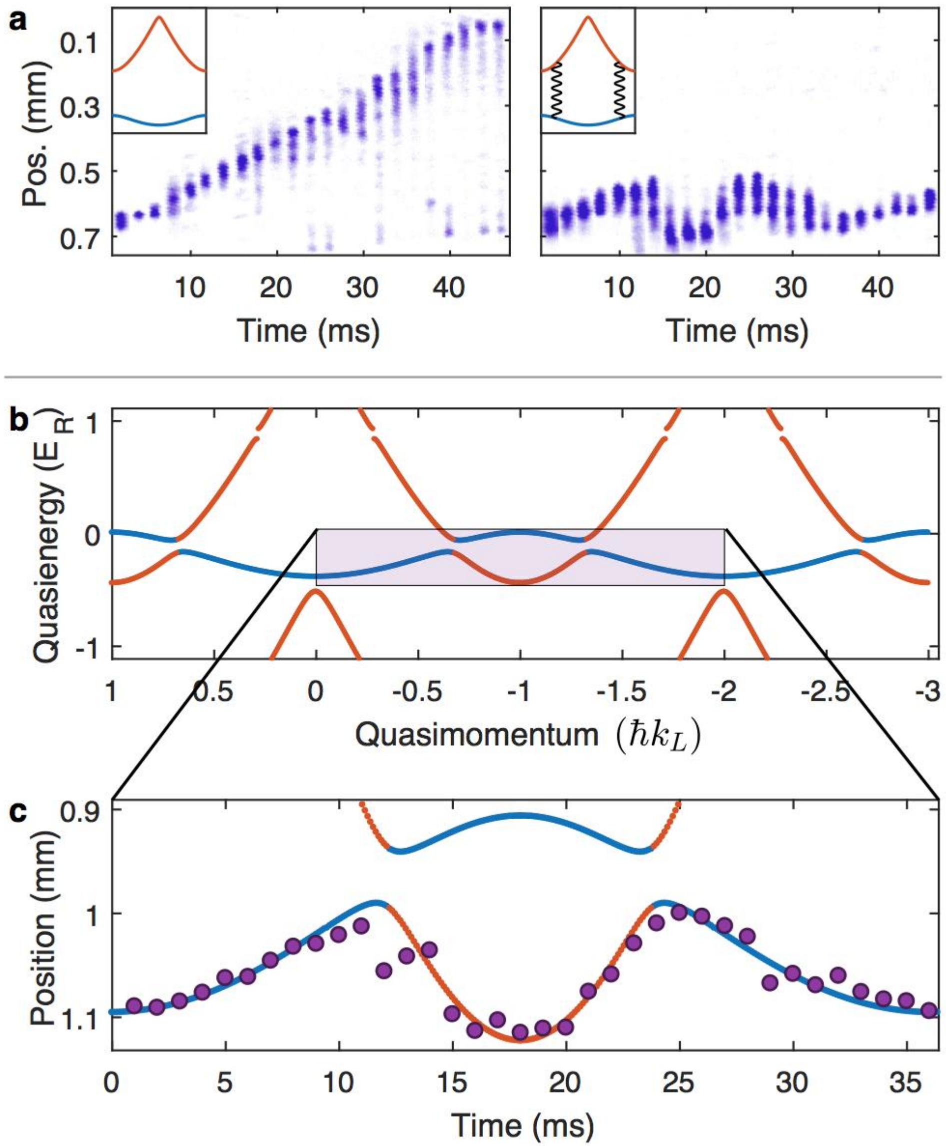




Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

- Can image dispersion of hybridized Floquet-Bloch band via PSBOs:



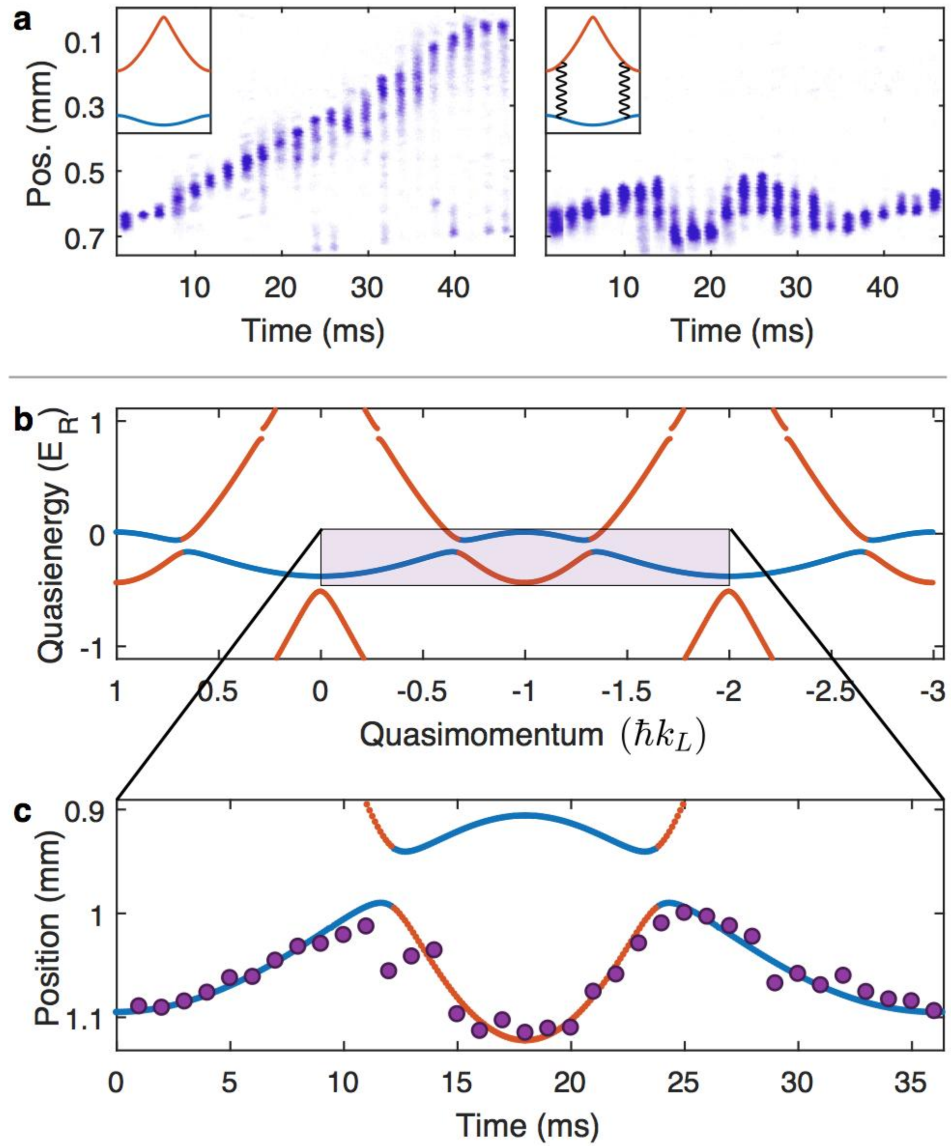
Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

- Can image dispersion of hybridized Floquet-Bloch band via PSBOs

- Flexible tool for band engineering: can sew together Frankenbands arbitrarily

- Some future possibilities:
  - Topological bands
  - Metrology
  - Multi-frequency driving



Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

Floquet-Bloch Oscillations

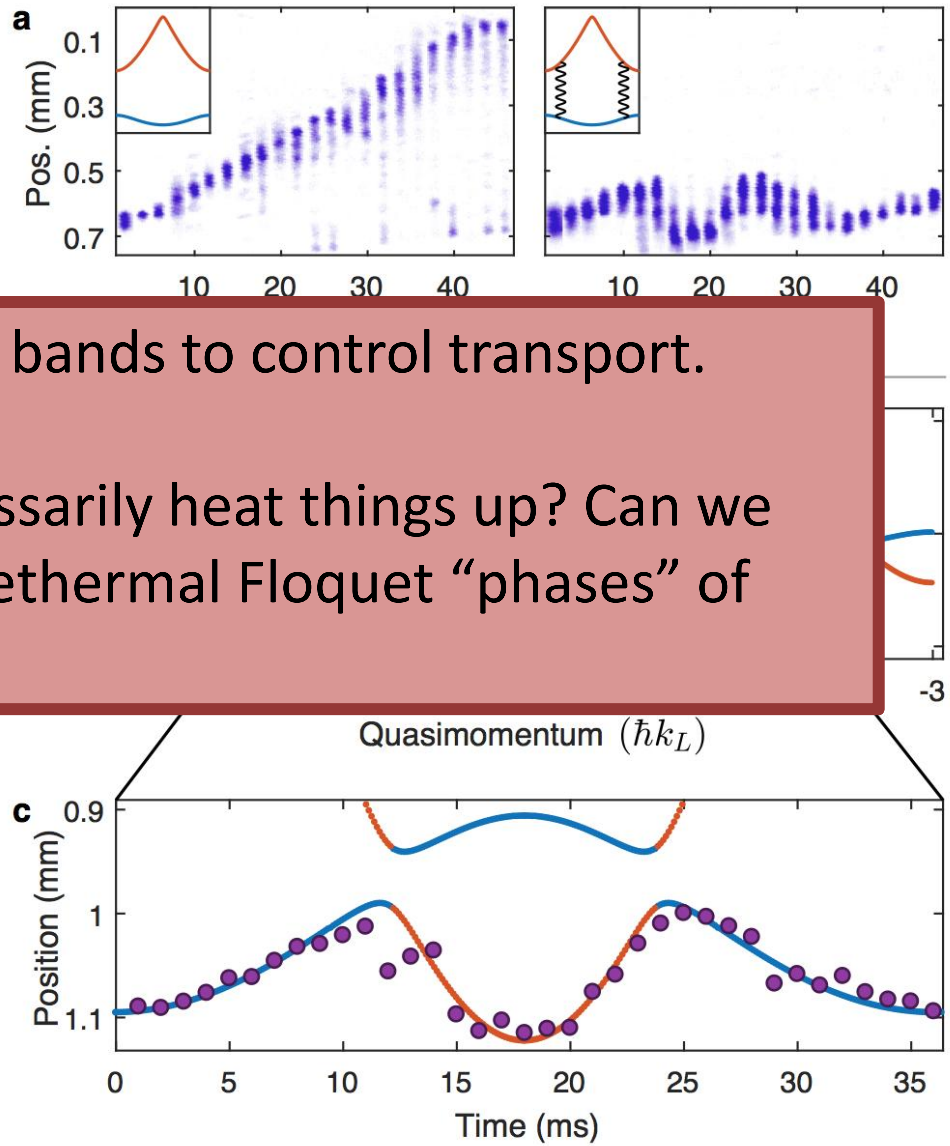
- Can image dispersion of hybridized Floquet-Bloch band via PSBOs

- Flexible tool for band engineering: can sew together Franke

- Some f
  - Top
  - Metrology
  - Multi-frequency driving

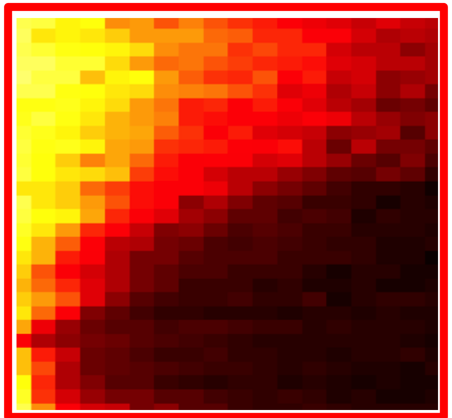
→Can engineer Floquet bands to control transport.

Next: Does driving necessarily heat things up? Can we create metastable or prethermal Floquet "phases" of interacting matter?



Fujiwara et al, *Transport in Floquet-Bloch Bands,* arXiv:1806.07858 (2018).

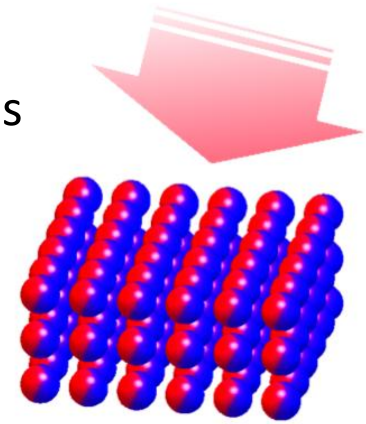
Outline



- Introduction
  - Experimental approach
- Driven optical lattices
  - Position-space Bloch oscillations
  - Floquet band engineering & transport
  - **Prethermalization & the periodic Gibbs ensemble**
- Other current projects

“Floquet Matter”

- Non-equilibrium steady states of driven interacting systems
  - Application example: condensed matter in pulsed laser fields
- Role for cold atom quantum emulation
  - Microscopically well-understood system
- Open Questions:
  - Conditions for (meta)stability? Thermalization?
  - Can drive force “phase transitions?”
  - Effect of interactions?
  - Prethermal “memory?”
  - Dynamics of quantum information?



$$\hat{H} = \hat{H}_0 + \hat{H}_1(t)$$

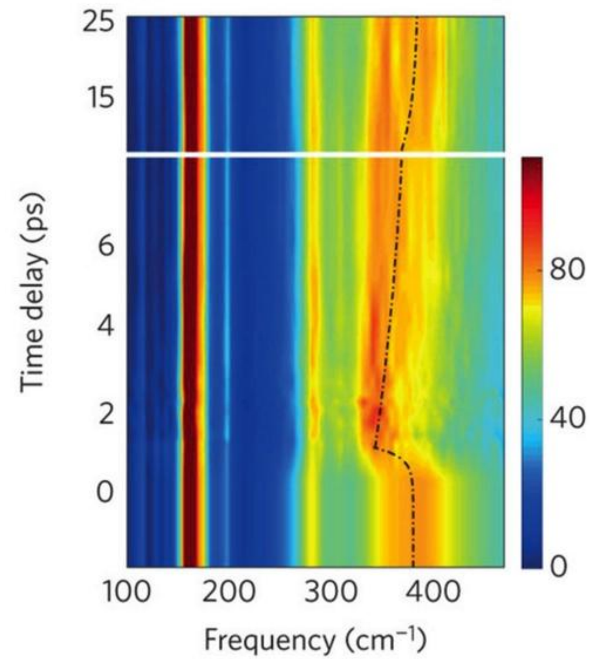
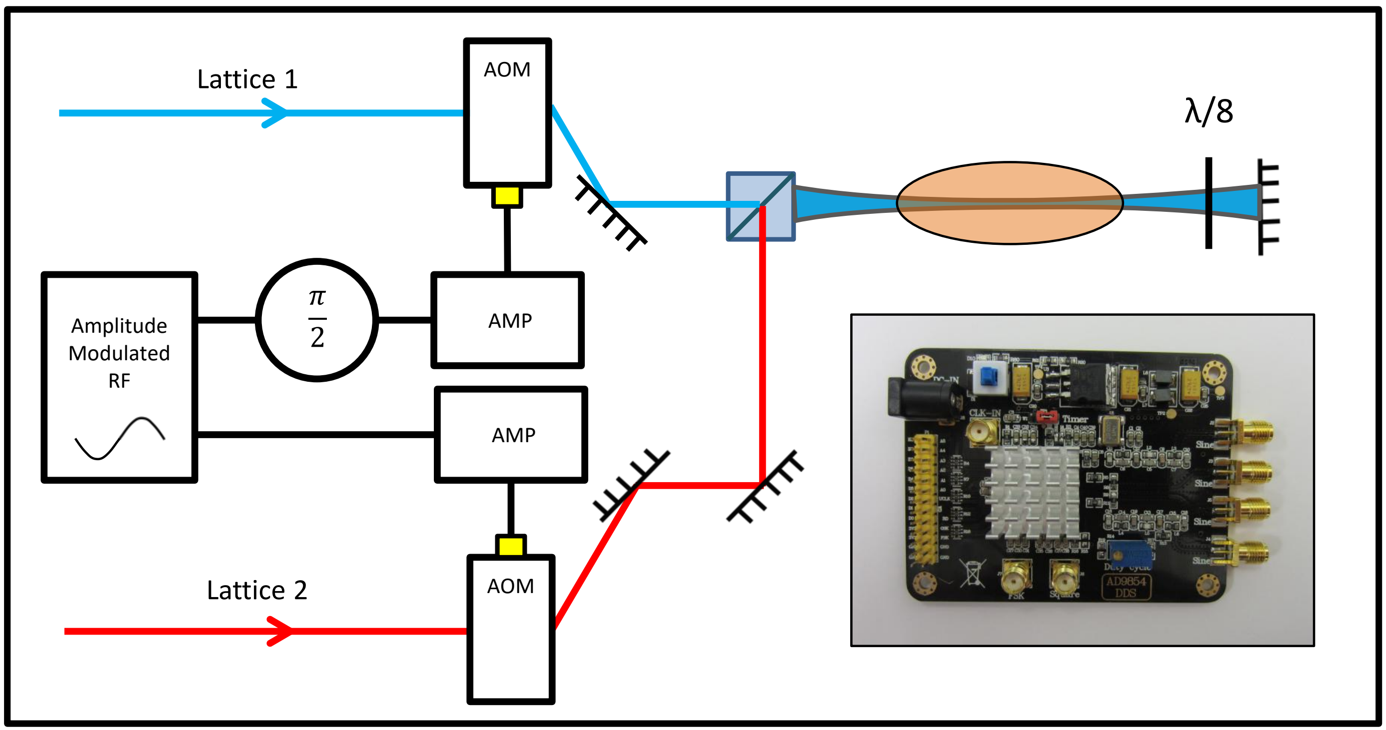


Image: Hamburg

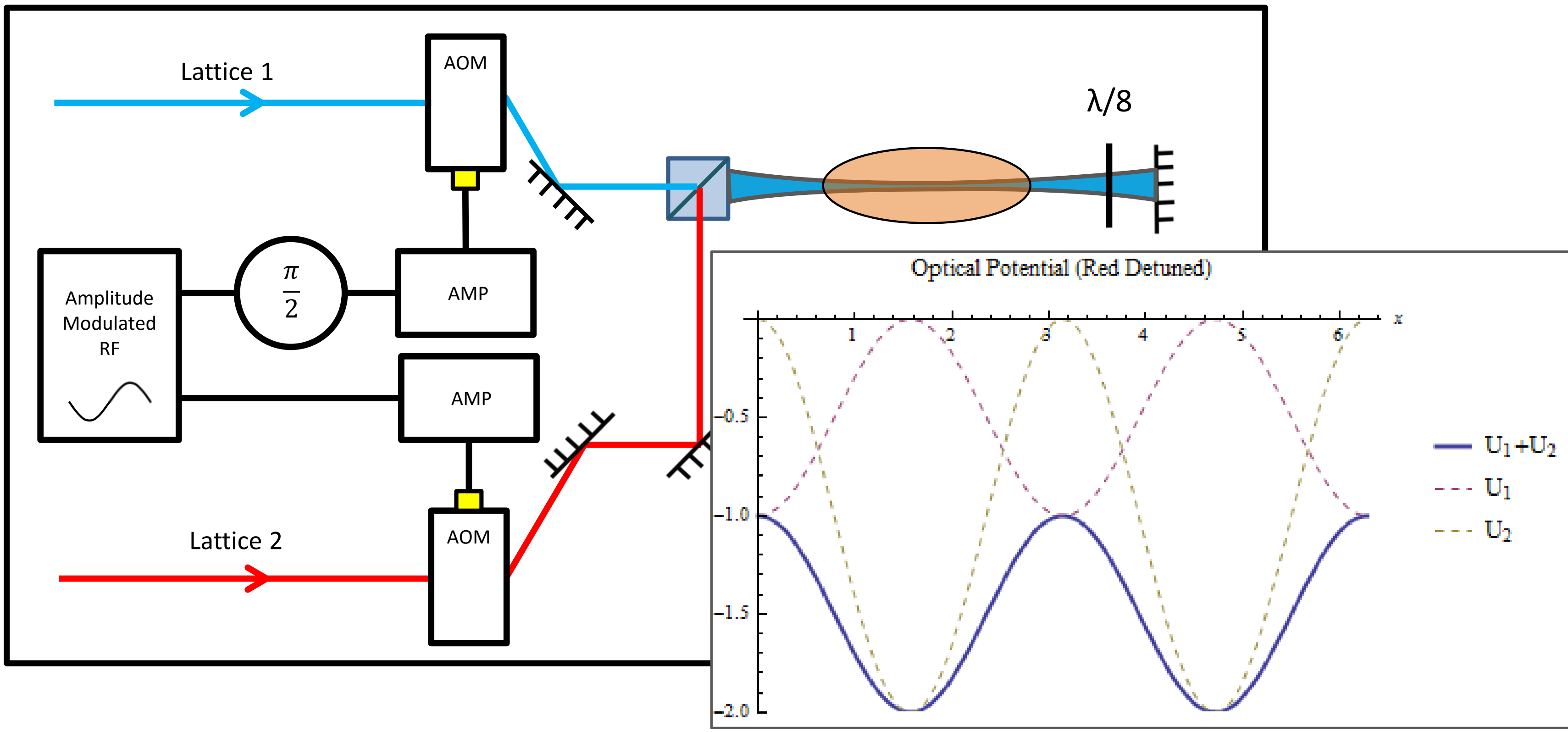
Experiment: Quantum Kapitza Lattice

- Goal: realize Kapitza physics in a many-body quantum system
- Optical lattices easily modulated, but need ~1000% modulation
- Possible with two independent phase-shifted lattices:



Experiment: Quantum Kapitza Lattice

- Goal: realize Kapitza physics in a many-body quantum system
- Optical lattices easily modulated, but need ~1000% modulation
- Possible with two independent phase-shifted lattices:



Experiment: Quantum Kapitza Lattice

- Goal: realize Kapitza physics in a many-body quantum system
- Optical lattices easily modulated, but need ~1000% modulation
- Possible with two independent phase-shifted lattices:

$$H(t) = -(\hbar^2/2m)\partial_x^2 + V_0[1 + \alpha \sin(\omega t)] \cos^2(k_L x)$$

$$\Omega = \omega/\omega_0$$

$$\omega_0 = 2\sqrt{V_0 E_R}/\hbar$$

Experiment: Quantum Kapitza Lattice

- Goal: realize Kapitza physics in a many-body quantum system
- Optical lattices easily modulated, but need ~1000% modulation
- Possible with two independent phase-shifted lattices:

$$H(t) = -(\hbar^2/2m)\partial_x^2 + V_0[1 + \alpha \sin(\omega t)] \cos^2(k_L x)$$

$$\Omega = \omega/\omega_0$$

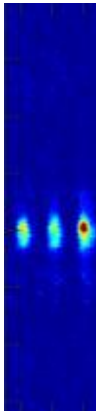
$$\omega_0 = 2\sqrt{V_0 E_R}/\hbar$$

(plus interactions)

Experiment: Ultrastrong Lattice Modulation

- Vary modulation frequency and amplitude to explore Floquet "phase diagram"
- Experimental Protocol: double quench
  - Load atoms into time-average lattice
  - Fixed A (static lattice depth)
  - Quench to driven lattice with some α (modulation depth) and Ω (frequency of drive)
  - After some drive time, quench back to static lattice and bandmap
- Results depend on α and Ω

A = 10 Er, α = 5 (-50Er → 50Er)



25 kHz
Ω = 0.22

2.5 MHz
Ω = 22.2

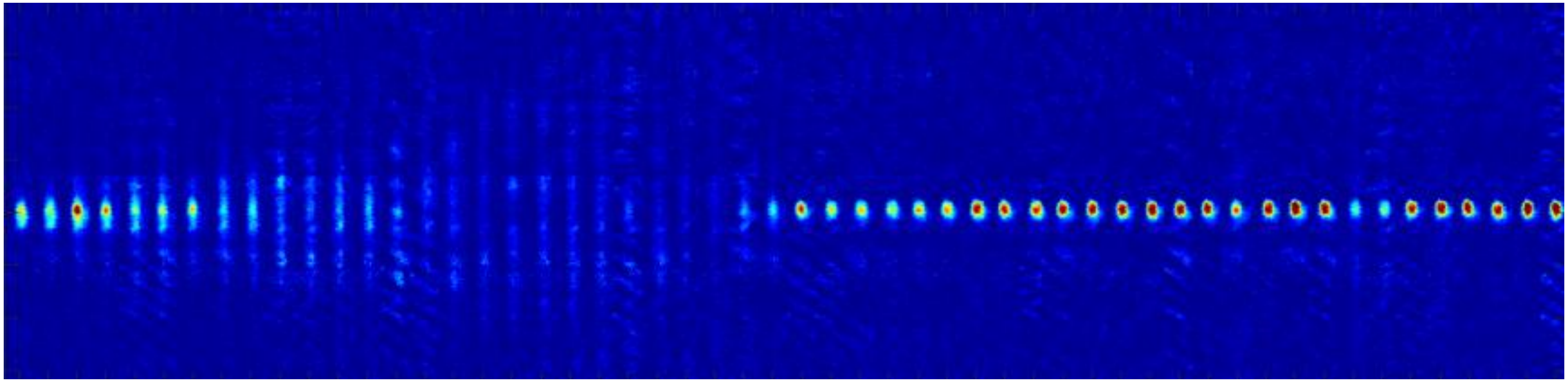
Quantifying ergodicity

- f_0 = fraction of atoms in ground band after modulation
  → Quantitative measure for characterizing non-ergodicity

$$|\psi(t)\rangle = \sum_n c_n |n(t)\rangle e^{-i\varepsilon_n t/\hbar}$$

$$\overline{f_0(t_\nu)} = \overline{|\langle\psi_0|\psi(t_\nu)\rangle|^2} = \sum_n |\langle\psi_0|n(0)\rangle|^4 \equiv \text{IPR}.$$

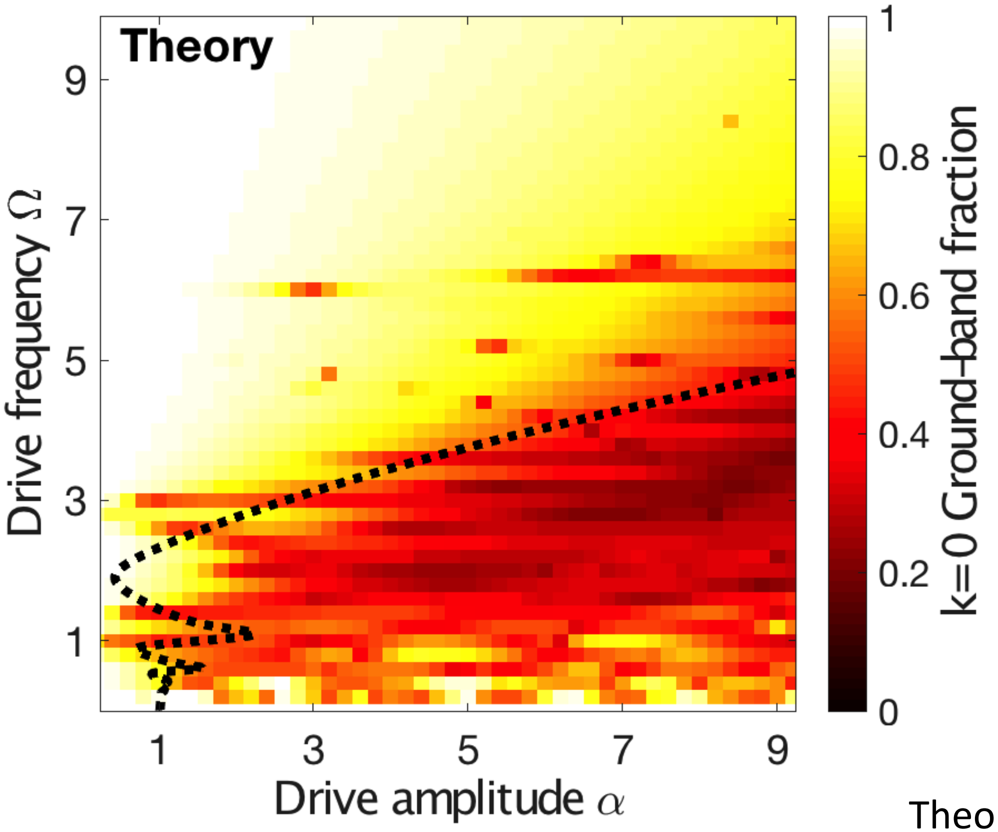
$$t_\nu = \nu T$$



Theory in collaboration w/ Eckardt & Heyl; more details here → Singh *et al,* arXiv:1809.05554 (2018).

Floquet Phase Diagram: Experiment

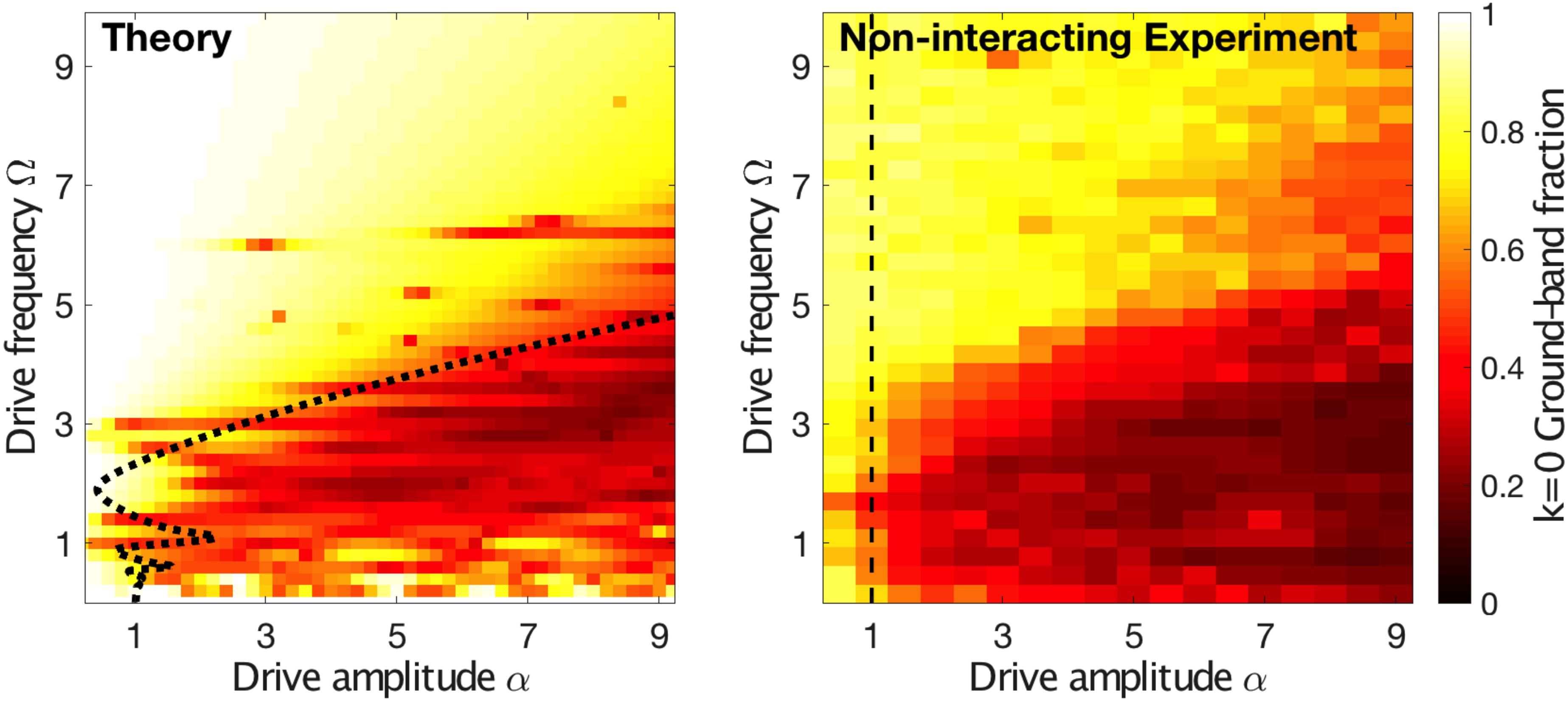
- Can map out Floquet phase diagram describing how state depends on α and Ω
- Ground band occupation an IPR quantifying Floquet localization
- Theoretical expectation based on periodic Gibbs ensemble (PGE):



Theory: André Eckardt, Markus Heyl (MPIPKS Dresden)

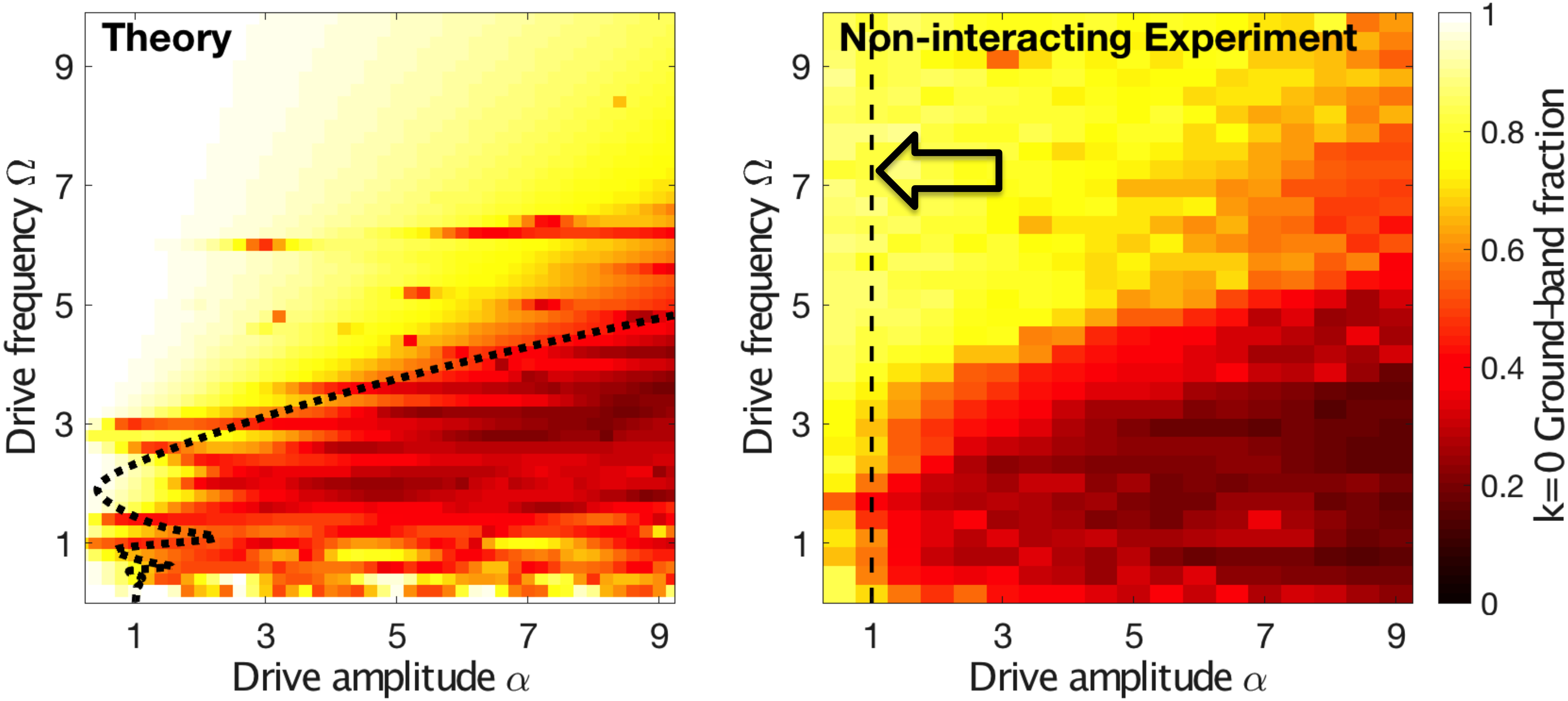
Floquet Phase Diagram: Experiment

- Can map out Floquet phase diagram describing how state depends on α and Ω
- Ground band occupation an IPR quantifying Floquet localization
- Theoretical expectation based on periodic Gibbs ensemble:



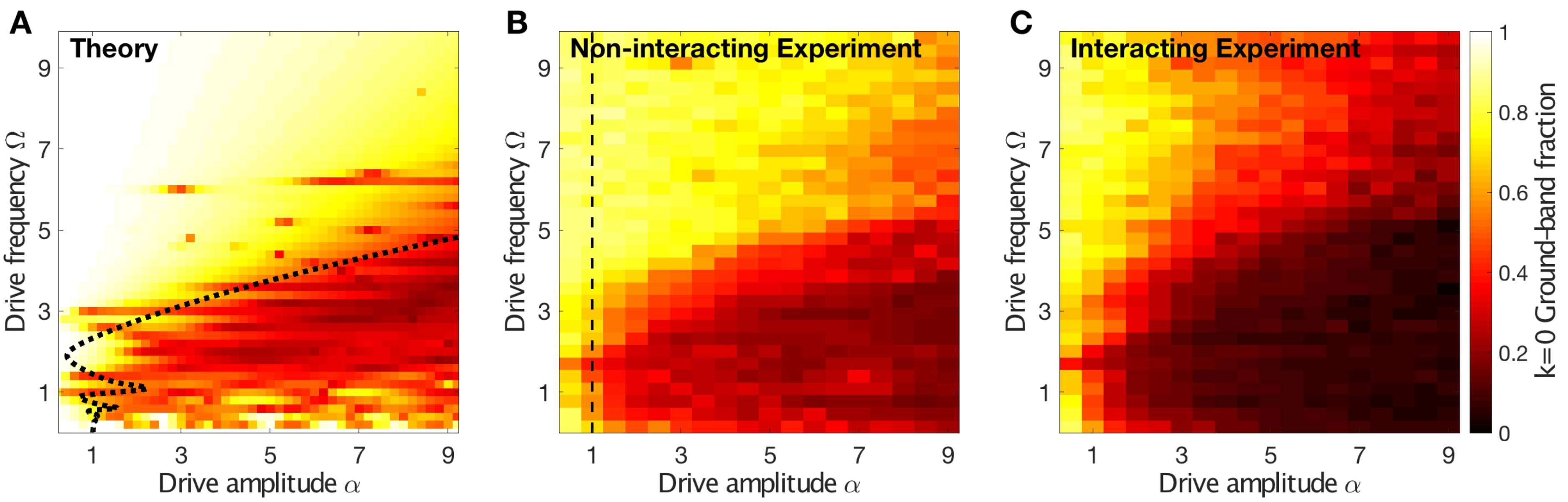
Floquet Phase Diagram: Experiment

- Can map out Floquet phase diagram describing how state depends on α and Ω
- Ground band occupation an IPR quantifying Floquet localization
- Theoretical expectation based on periodic Gibbs ensemble:



Floquet Phase Diagram: Experiment

- Can map out Floquet phase diagram describing how state depends on α and Ω
- Ground band occupation an IPR quantifying Floquet localization
- Interactions modify but do not destroy the "phase diagram"

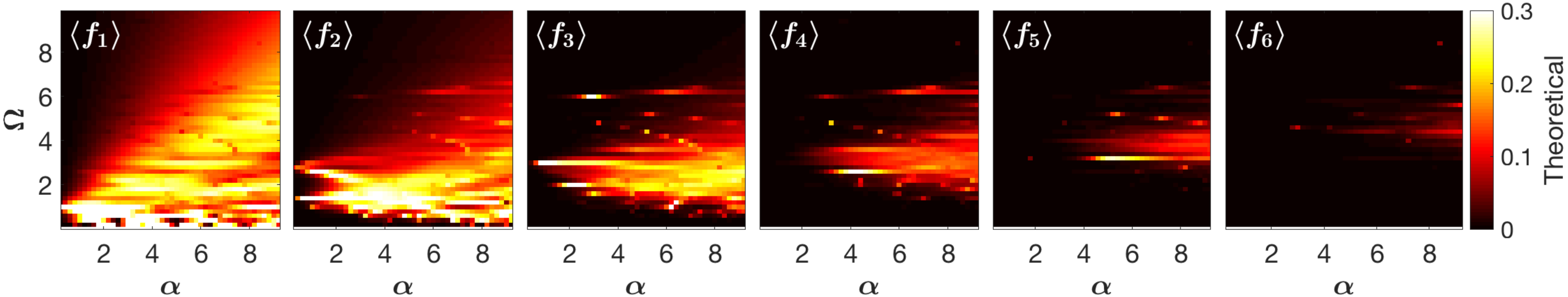


Singh *et al,* arXiv:1809.05554 (2018).

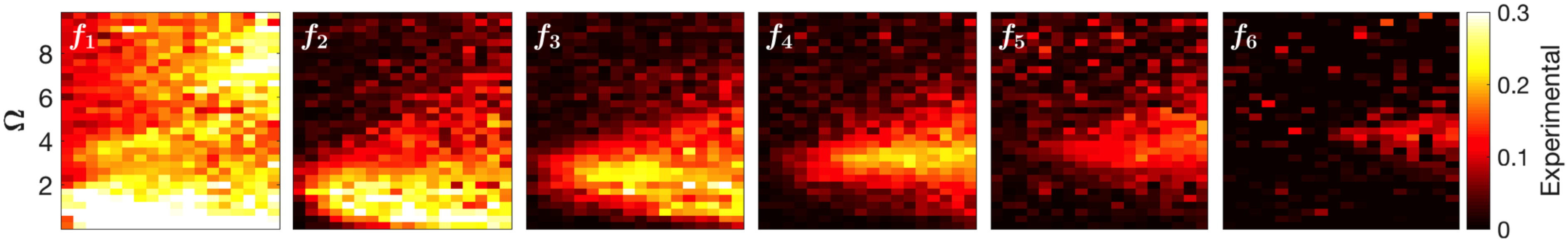
Fully characterizing a Floquet state

- All band occupations can be mapped as a function of drive parameters, both theoretically and experimentally

Theory



Experiment

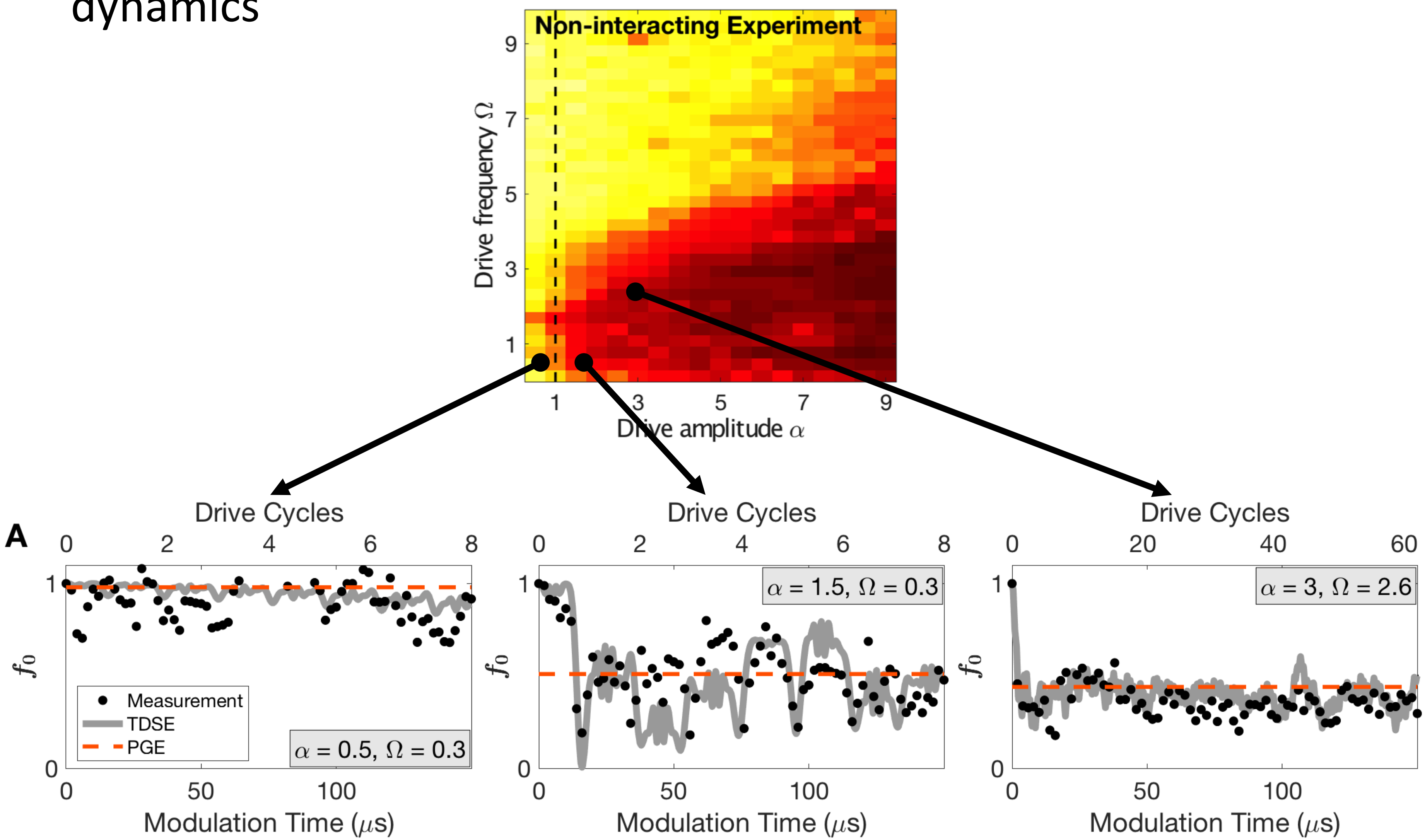


→ Complete experimental characterization of the PGE

Singh *et al,* arXiv:1809.05554 (2018).

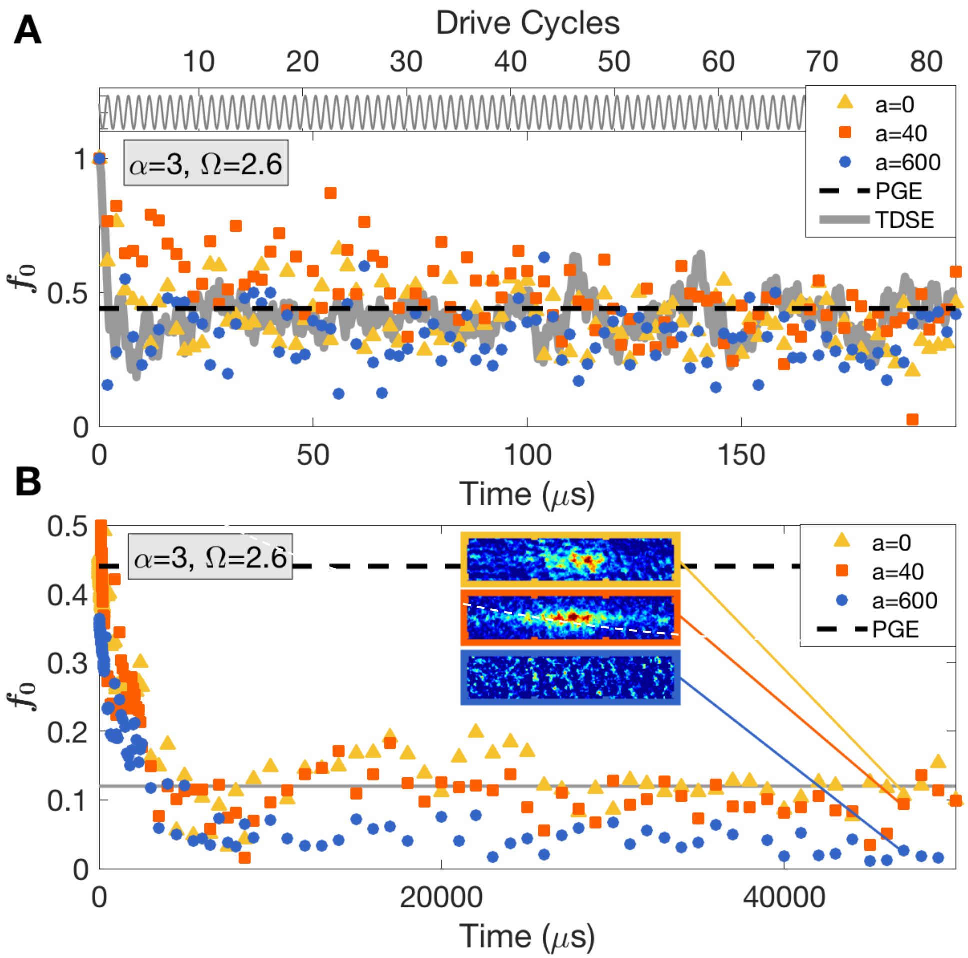
Time evolution of Floquet Phases

- At each point on the "phase diagram" one can measure the full time dynamics



Singh *et al,* arXiv:1809.05554 (2018).

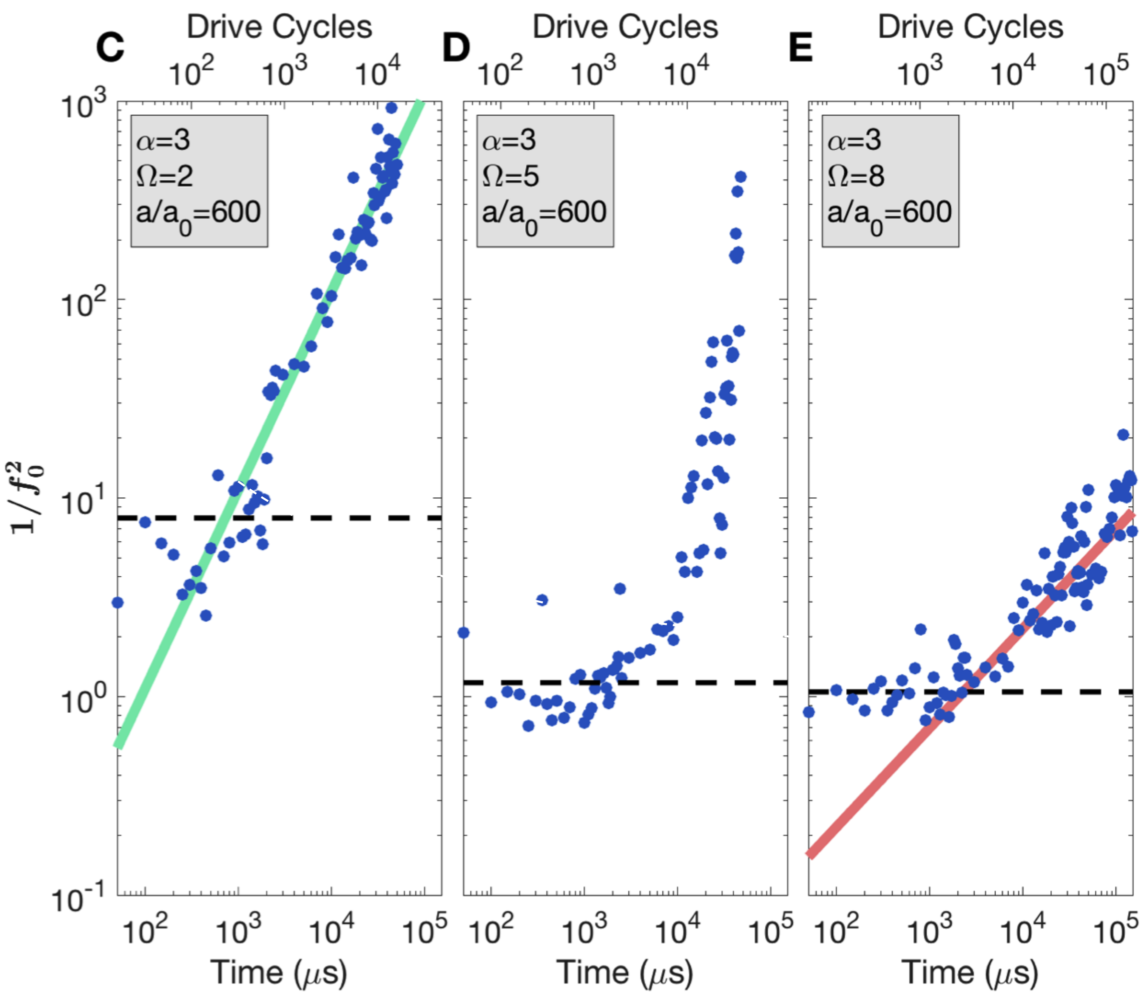
Moving beyond theory: the long-time limit



- Observation of two Floquet prethermalization plateaux
- Long-time behavior depends on drive parameters & interactions

Singh *et al,* arXiv:1809.05554 (2018).

Moving beyond theory: the long-time limit

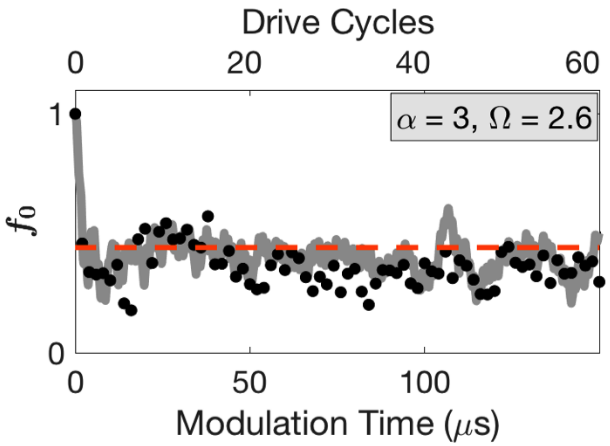


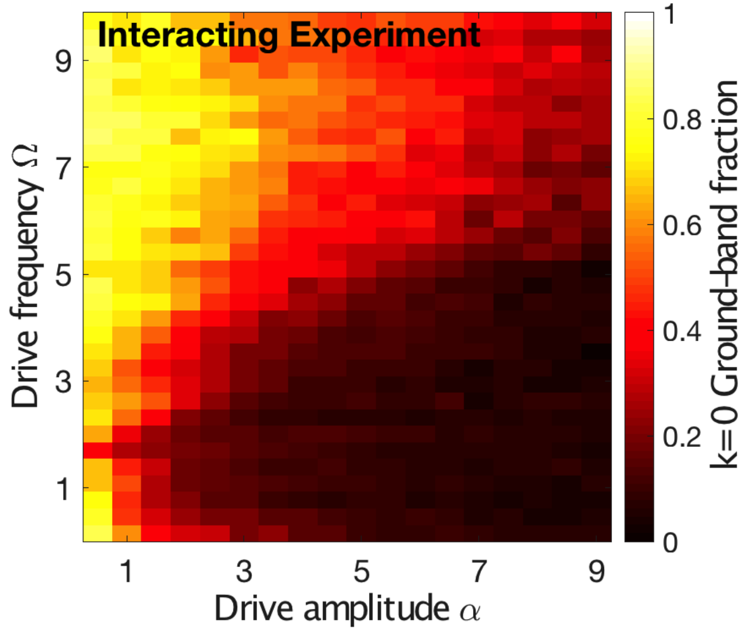
- Prethermal plateau recovered by increasing drive frequency
- High-frequency and strong interactions → sub-Joule heating

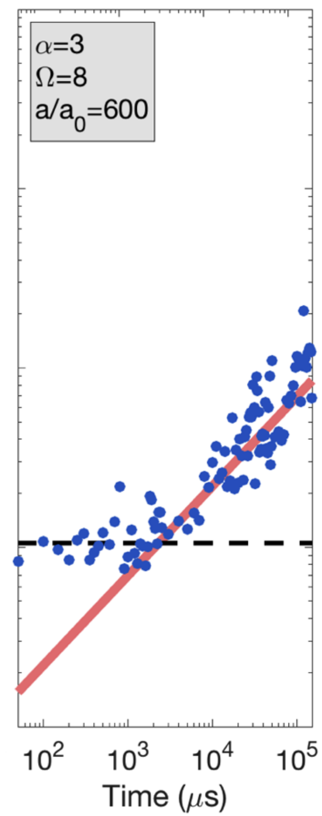
Singh *et al,* arXiv:1809.05554 (2018).

Floquet matter: Prethermalization and PGEs

- → Clean, tunable realization of Floquet matter & Floquet prethermalization
- → Can study dependence of properties of Floquet matter on drive parameters
- → Interactions introduce poorly-understood long-time dynamics (e.g. root-t heating)







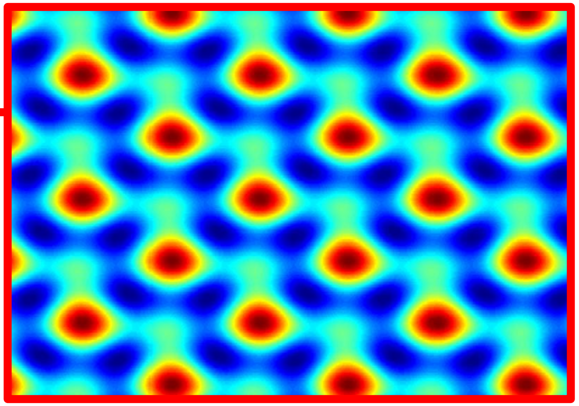
Singh *et al,* arXiv:1809.05554 (2018).

Outline

- Introduction
  - Experimental approach

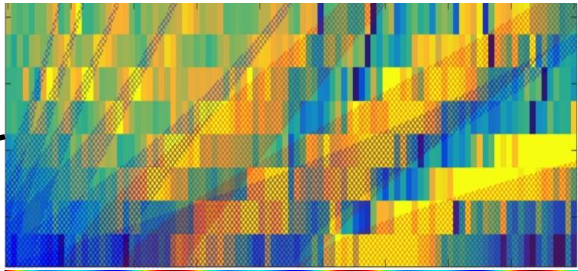
- Driven optical lattices
  - Position-space Bloch oscillations
  - Floquet band engineering & transport
  - Prethermalization & the periodic Gibbs ensemble

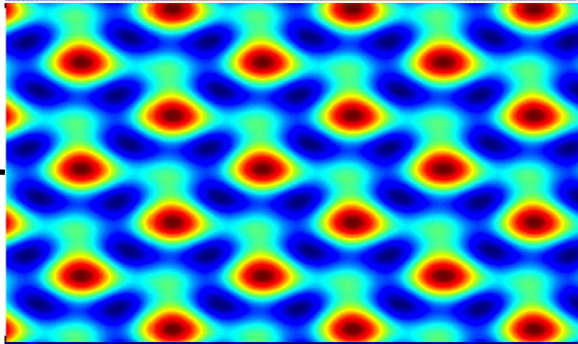
- **Other current projects**

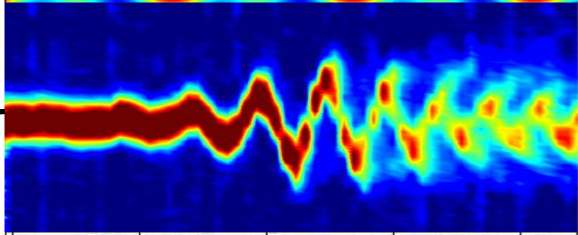


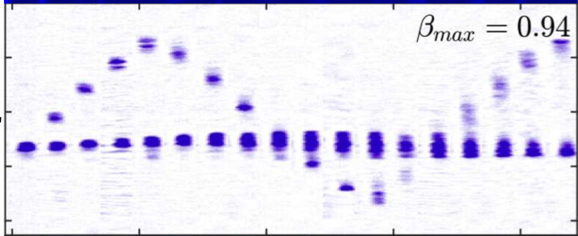
Additional Projects

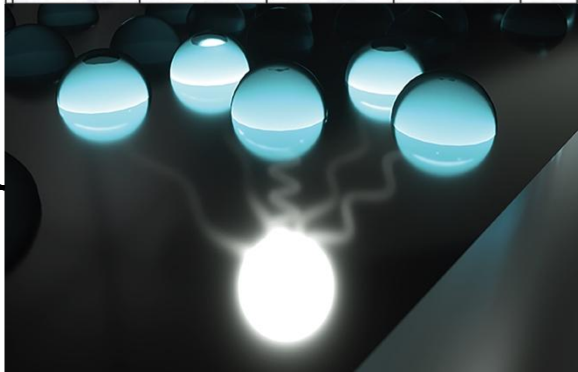
- Tunable quantum quasicrystals
- Anyon synthesis
- Topological bands
- Ultrafast quantum emulation
- Relativistic harmonic motion
- Quantum interfaces
- Targets of opportunity…











Conclusions

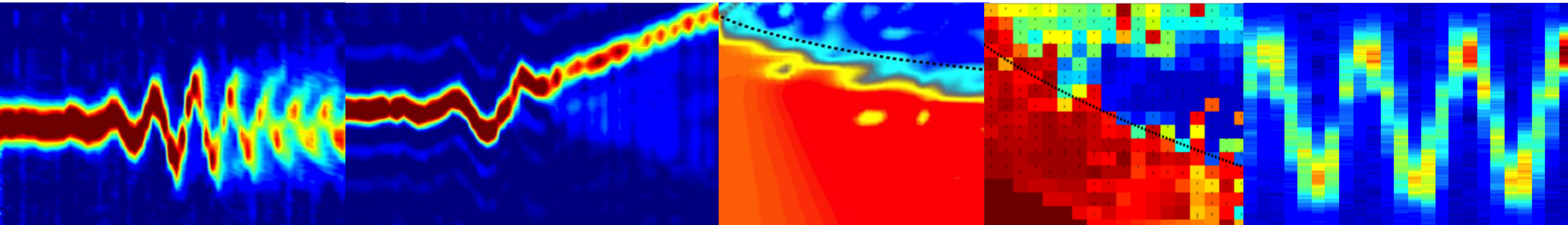
Cold atoms are a flexible tool for the study of quantum matter

→ Position-space Bloch oscillations probe band structure

→ Floquet engineering can hybridize bands & tune transport

→ Strongly modulated lattices can realize and probe nontrivial Floquet phases of matter.

→ Also: quasicrystals, anyons, topological bands, ultrafast quantum emulation, quantum interfaces



Acknowledgements

UCSB Group:
Dr. Zach Geiger
Dr. Ruwan Senaratne
Shankari Rajagopal
Kurt Fujiwara
Kevin Singh
Peter Dotti
Quinn Simmons
Roshan Sajjad
Alec Cao (UG)
Max Prichard (UG)
Toshi Shimasaki (PD)

Collaborations & Ideas:
Torsten Meier
André Eckardt
Markus Heyl
Rodislav Driben
Volodya Konotop
Tarun Grover
CAIQuE team
MURI team

California Institute for Quantum Emulation CAIQUE
Army Research Office
Department of the Navy ONR Science & Technology
NSF
Air Force Office of Scientific Research
ARC ANYON RESEARCH CENTER