# Probe of Band Structure Singularities with a Lattice-Trapped Quantum Gas

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**Experiment**
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**Theory**
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The National Academies of SCIENCES ENGINEERING MEDICINE

# Quantum Simulation

mimicking quantum systems for the purpose of understanding their states, phases, and dynamics

$$\hat{H}(\boldsymbol{r}) = \sum_{i} \hat{T}(\boldsymbol{r}_i) + \sum_{i} \hat{V}(\boldsymbol{r}_i) + \sum_{i \neq j} \hat{I}(\boldsymbol{r}_{i,}\boldsymbol{r}_j)$$

## Digital Simulation

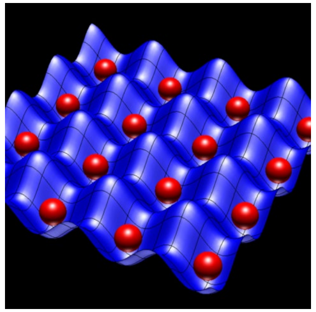
Requires quantum computer device

⋮

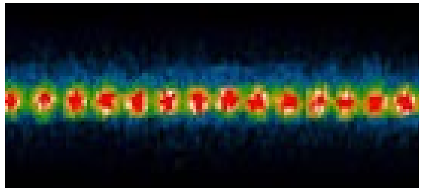
1. Initialize a state
2. Perform quantum algorithm (implement series of gates or transformations on qubits)
3. Perform measurement to get result

## Analog Simulation

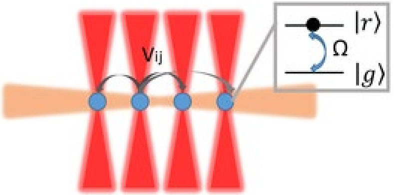
Cold atoms in lattices



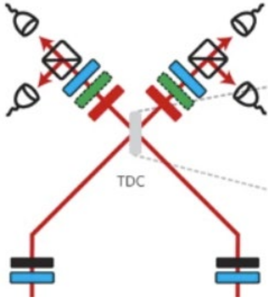
Trapped Ion Chains



Rydberg tweezers



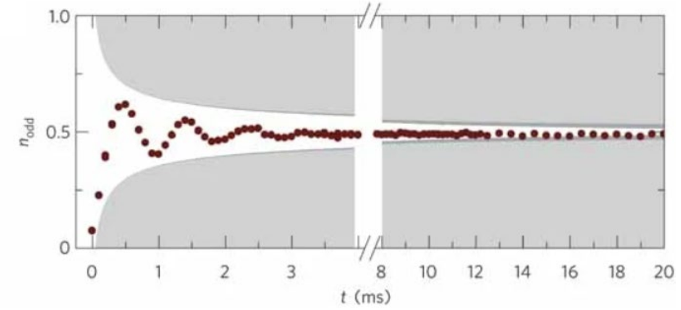
Photonics



# Problem-types that quantum simulators have addressed

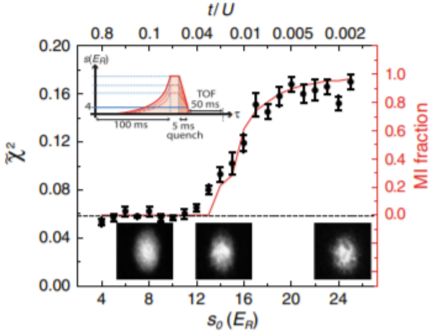
## time-dependent

### equilibration and thermalization



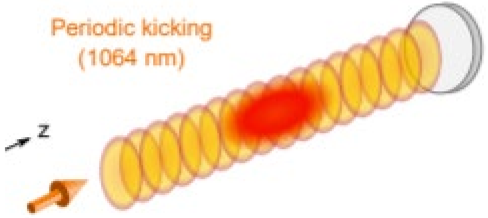
Groups
**Bloch**
**Köhl**
**Bakr**
**Greiner**
**Zweirlein**
⋮

### dynamical phase transitions, (slow) quenches



Groups
**DeMarco**
**Schneider**
**Monroe**
⋮

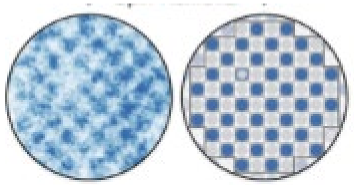
### kicked (Floquet) systems



Groups
**Weld**
**Esslinger**
**Bloch**
**Spielman**
**Aidelsburger**
**Chin**
⋮

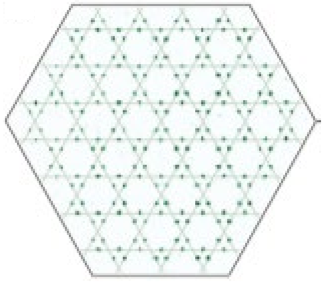
## ground states

### quantum magnetism



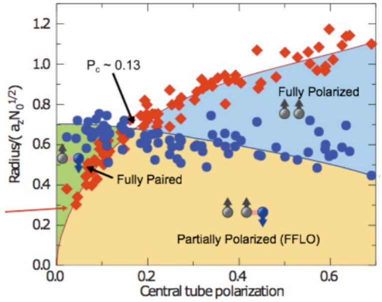
Groups
**Bloch**
**Bakr**
**Browaeys**
**Schauss**
⋮

### quantum spin liquid



Groups
**Lukin**
**Vuletic**
**Greiner**
**Stamper-Kurn**
⋮

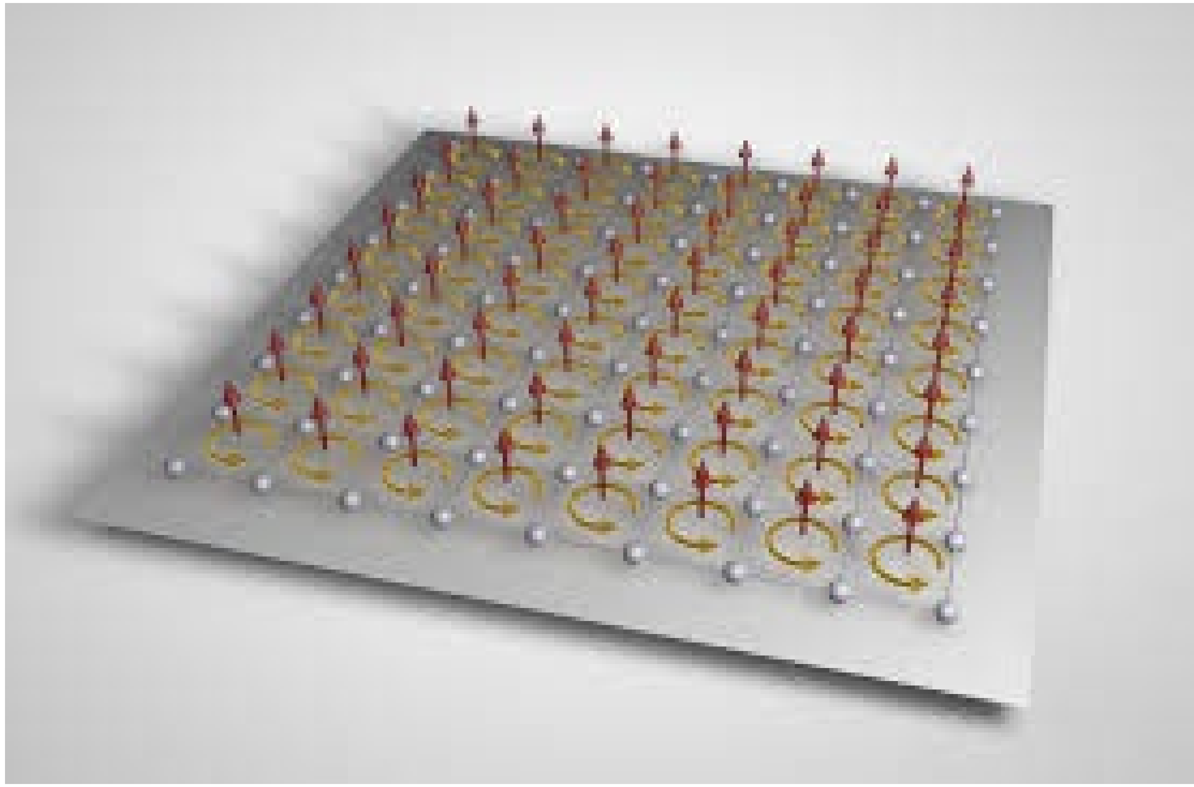
### superconductivity



Groups
**Hulet**
⋮

# Quantum simulation is not just for condensed matter

Quantum simulation experiments may provide insight on problems in particle physics



Monika Aidelsburger Thesis 2015

HEP tells us that gauge fields are ubiquitous in nature

- Photons: electromagnetism
- Gluons: strong force
- W and Z particles: weak force

How to achieve artificial gauge fields in a lattice

- Lattice shaking
- Laser-assisted tunneling (**Spielman Group**)

Time-dependent artificial gauge fields → dynamical

↑

EXCITING!

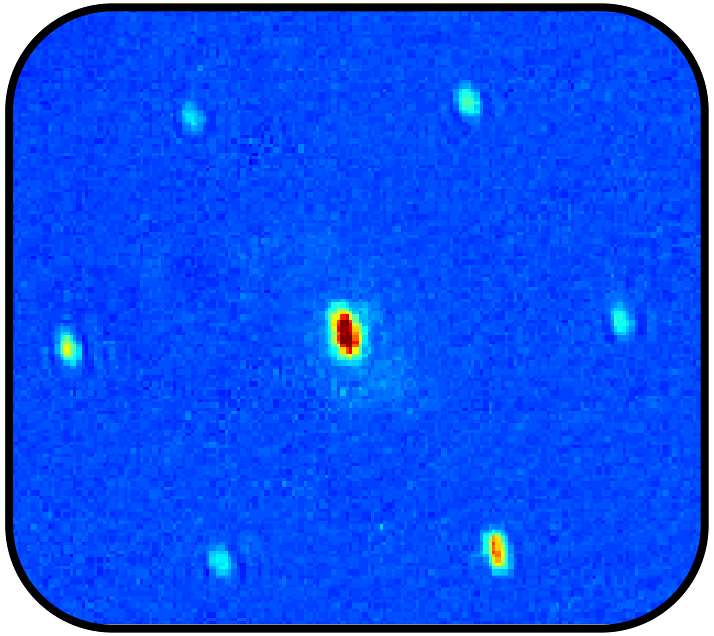
# Why do we want to simulate solid-state systems?

Many exciting questions on exotic superconductivity and magnetism, quantum Hall effects, topological matter…

An ultracold quantum simulator offers several **advantages**

- **Controllable defects**
- **Long-lived quantum coherence**
- **The ability to prepare many identical copies**
- **The ability to study out-of-equilibrium physics**

optical honeycomb lattice



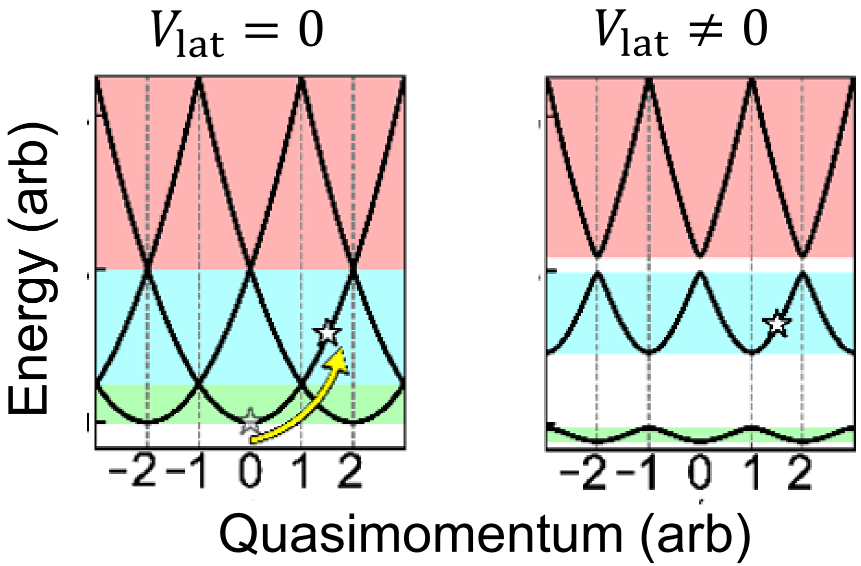
diffraction image

**We can provide great insight into the behavior of solid materials with crystalline lattice structure**

# Crystalline Lattice

A periodic set of points that has some set of symmetries

1-D lattice band structure



# Energy Bands of Particles in a Lattice

A solid’s band structure describes the allowable energy levels for electrons in a crystal lattice

**Band structure explains material properties**

Electrical Resistivity

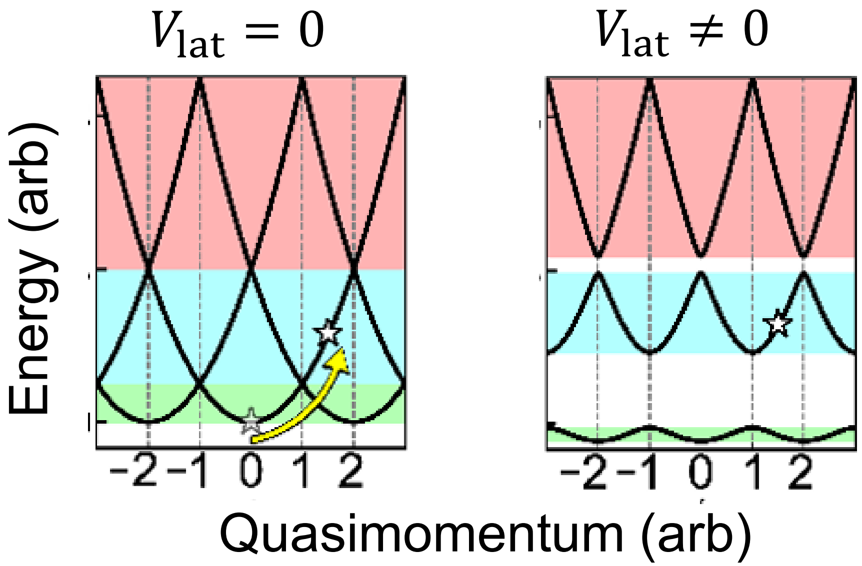
Optical Absorption

⋮

Bloch wavefunctions

$$\psi_n(q) = u_n(\vec{r})e^{i\vec{q}\cdot\vec{r}}$$

$$u_n(\vec{r}) = u_n(\vec{r}+\vec{R})$$



# Energy Bands of Particles in a Lattice

A solid's band structure describes the allowable energy levels for electrons in a crystal lattice

+ geometry/topology of state space

**Band structure explains material properties**

Electrical Resistivity

Optical Absorption

+

Quantum Hall Effects

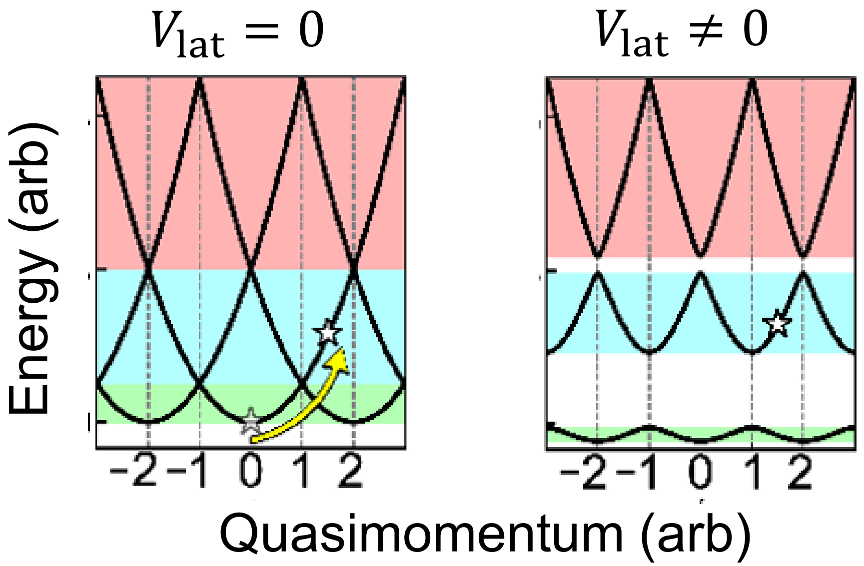
Orbital Magnetism

Topological Insulators

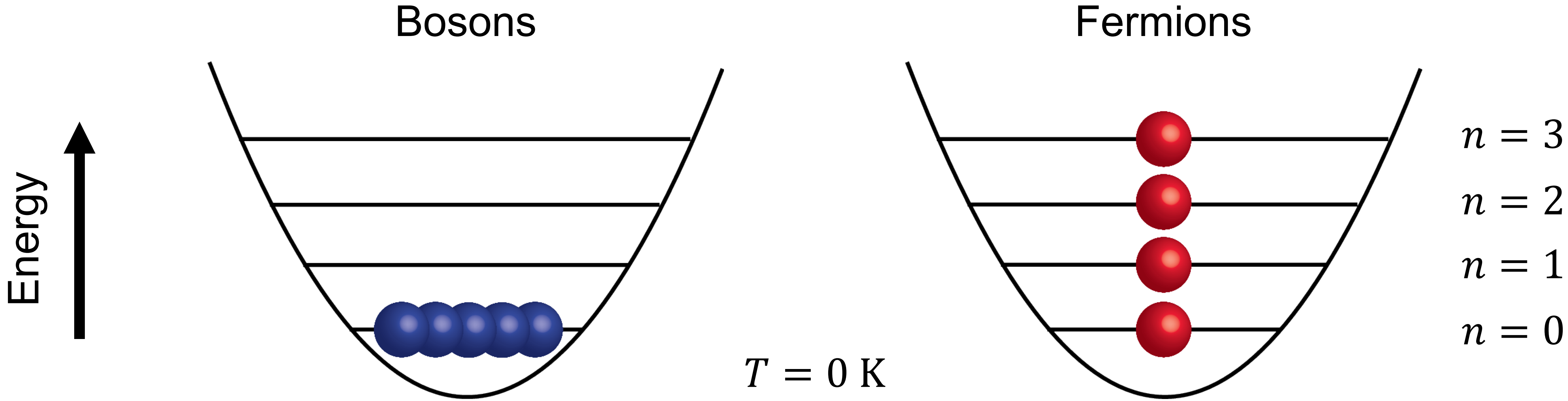
⋮

Bloch wavefunctions: $\psi_n(q) = u_n(\vec{r})e^{i\vec{q}\cdot\vec{r}}$

Berry Connection: $A_{mn}(q) = \langle \psi_m(q) | \nabla_q | \psi_n(q) \rangle$



# Bosons VS. Fermions



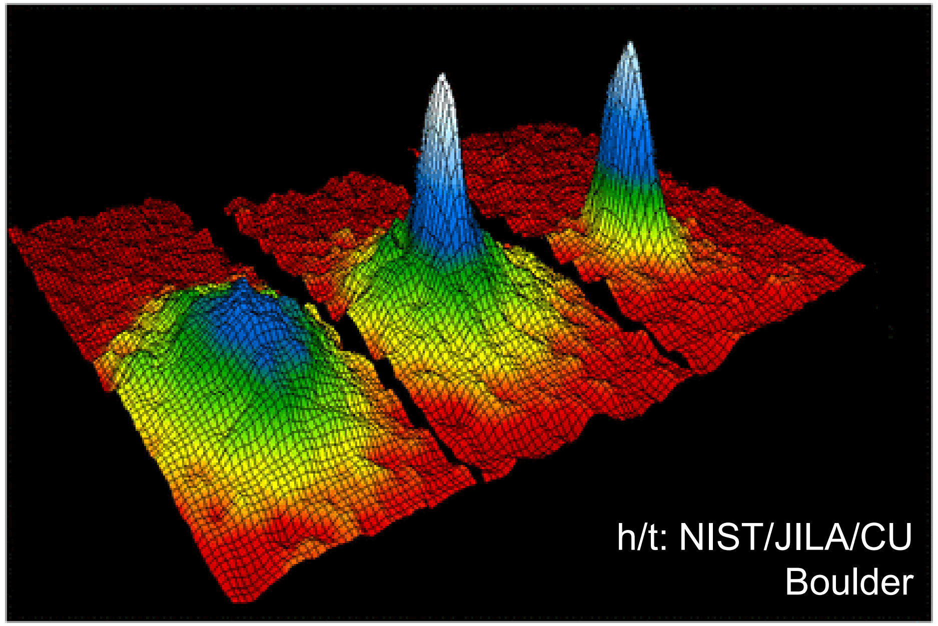
We use the bosonic isotope $^{87}$Rb to make a Bose-Einstein Condensate

# An exotic state of matter: Bose-Einstein condensate

The de Broglie wavelength describes the wavelike behavior of matter:

$$\lambda_{\mathrm{dB}} = \left(\frac{2\pi\hbar^2}{mk_{\mathrm{B}}T}\right)^{1/2}$$

When temperature is low enough: $\lambda_{\mathrm{dB}}^3 > \frac{V}{N}$


h/t: NIST/JILA/CU Boulder

## Schrödinger Equation

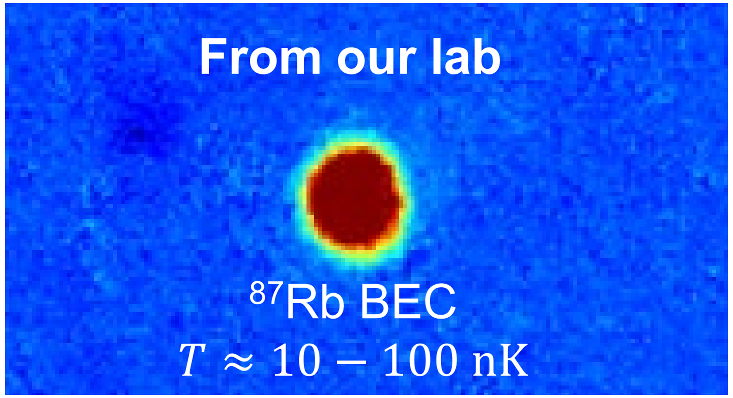
## Gross-Pitaevskii Equation

$$\left(\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \boldsymbol{r}^2} + V(\boldsymbol{r})\right)\psi(\boldsymbol{r}) \qquad = E\psi(\boldsymbol{r})$$

Kinetic Energy

Potential Energy

Interaction Energy


**From our lab**

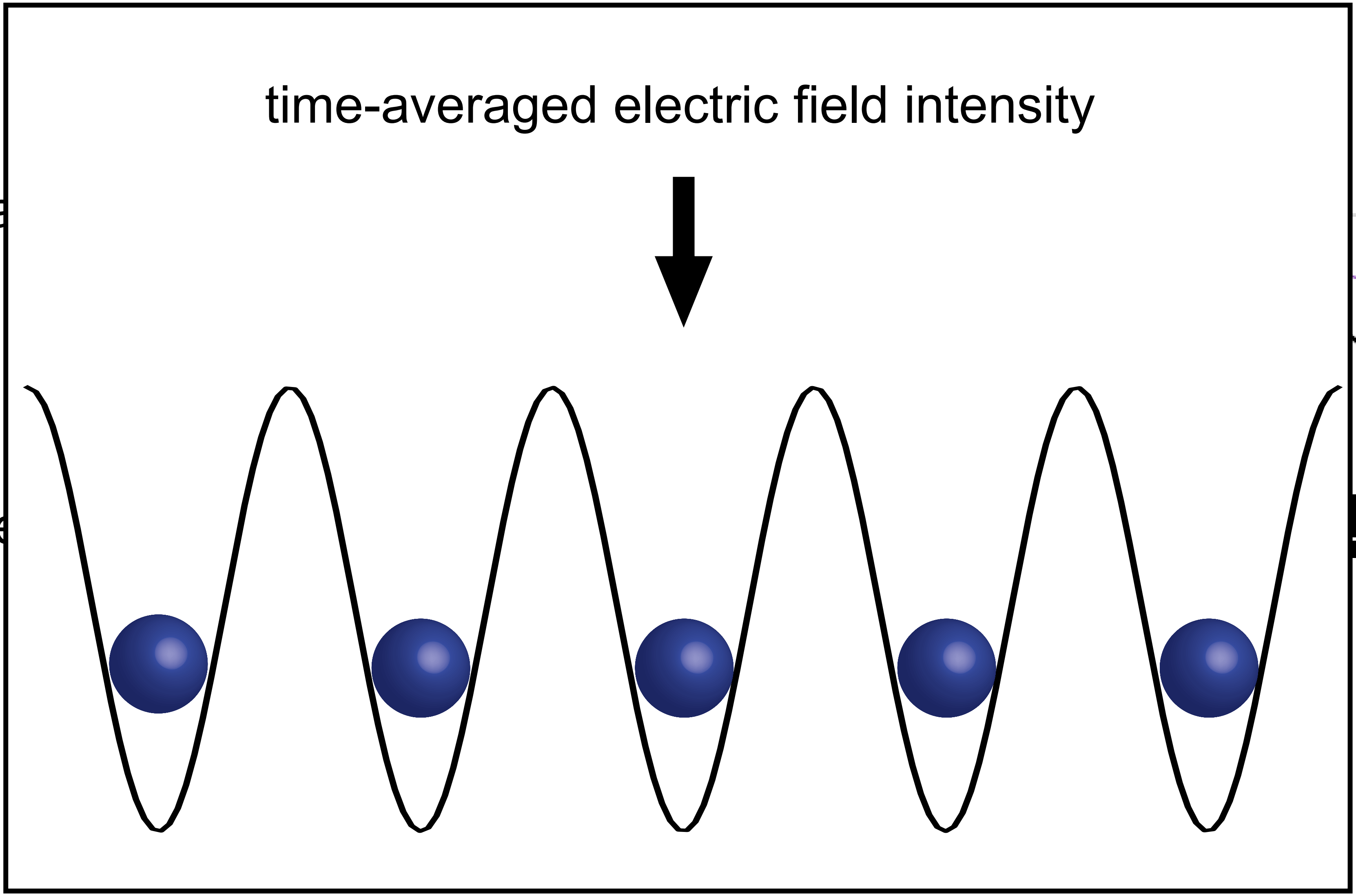
$^{87}$Rb BEC

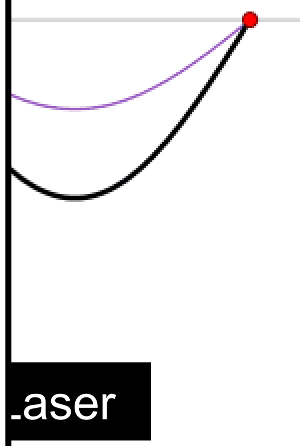
$T \approx 10 - 100\ \mathrm{nK}$

# Optical Lattice Potential – “Optical Lattice”

Mathema

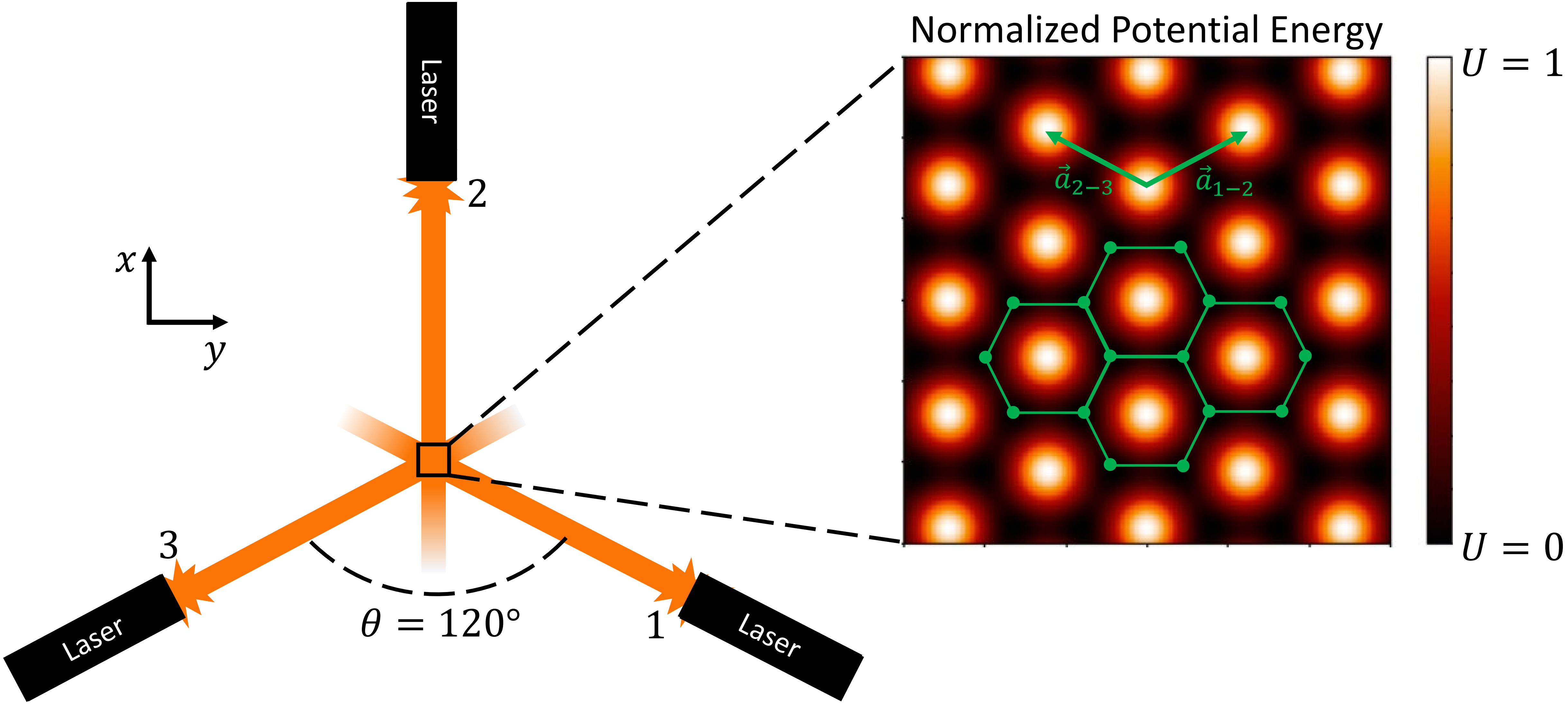
Experime





We use multiple pairs of intersecting beams to make 2D or 3D lattices

# An Optical Honeycomb Lattice

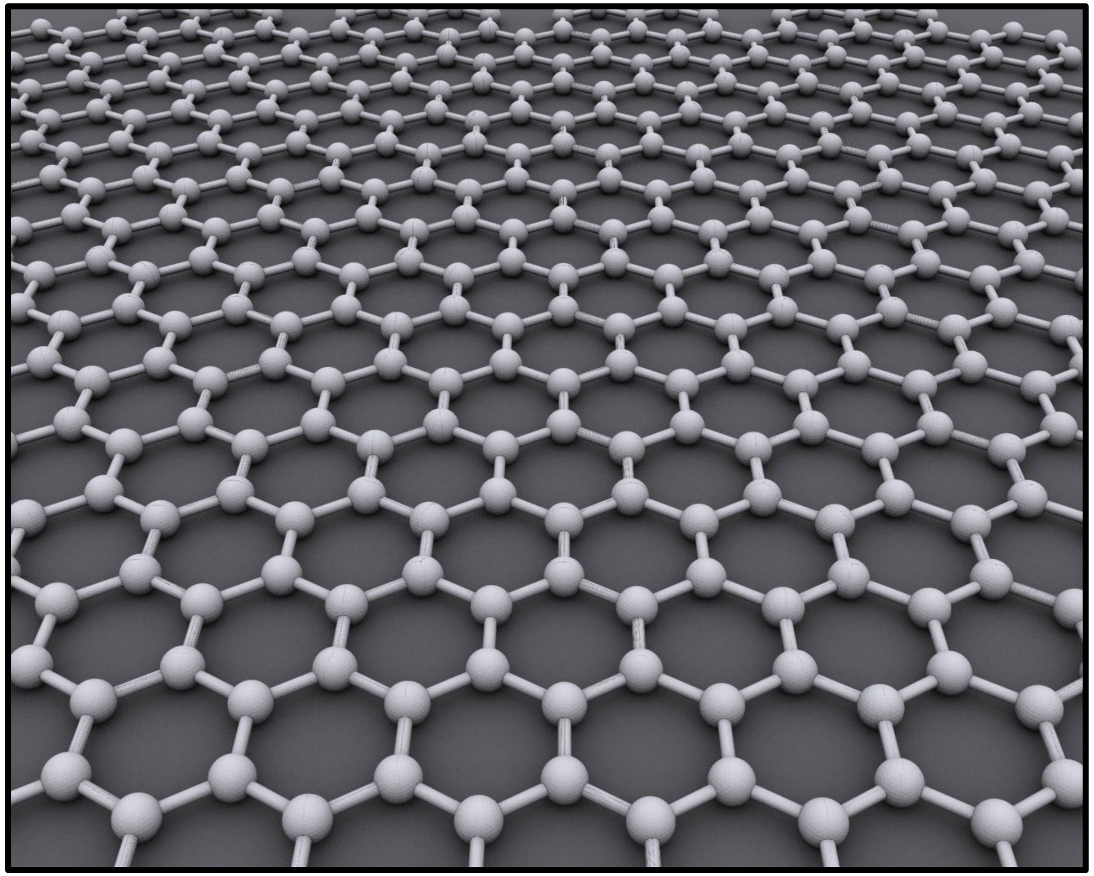


This allows us to create an **ultracold atom analog of graphene**

# Solid-State Graphene

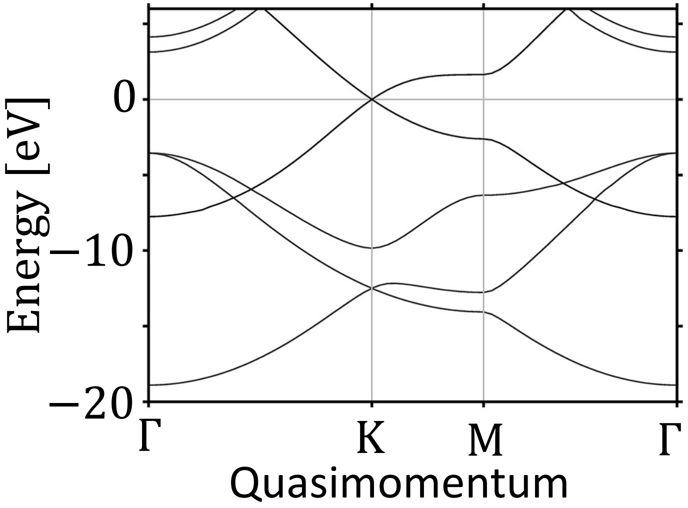
A crystal's band structure and the geometry/topology of state space determines its properties

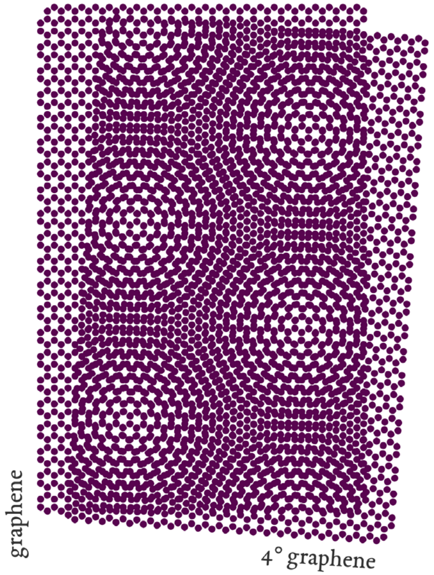
Graphene



- Andrew Geim, Konstantin Novoselov – 2010 Nobel prize
- Dirac singular points with Berry (geometric) phase
  - Klein tunneling
  - Half-integer quantum Hall effect
- Twisted bi-layer graphene and Moire patterns

M. Katsnelsen, *The Physics of Graphene*



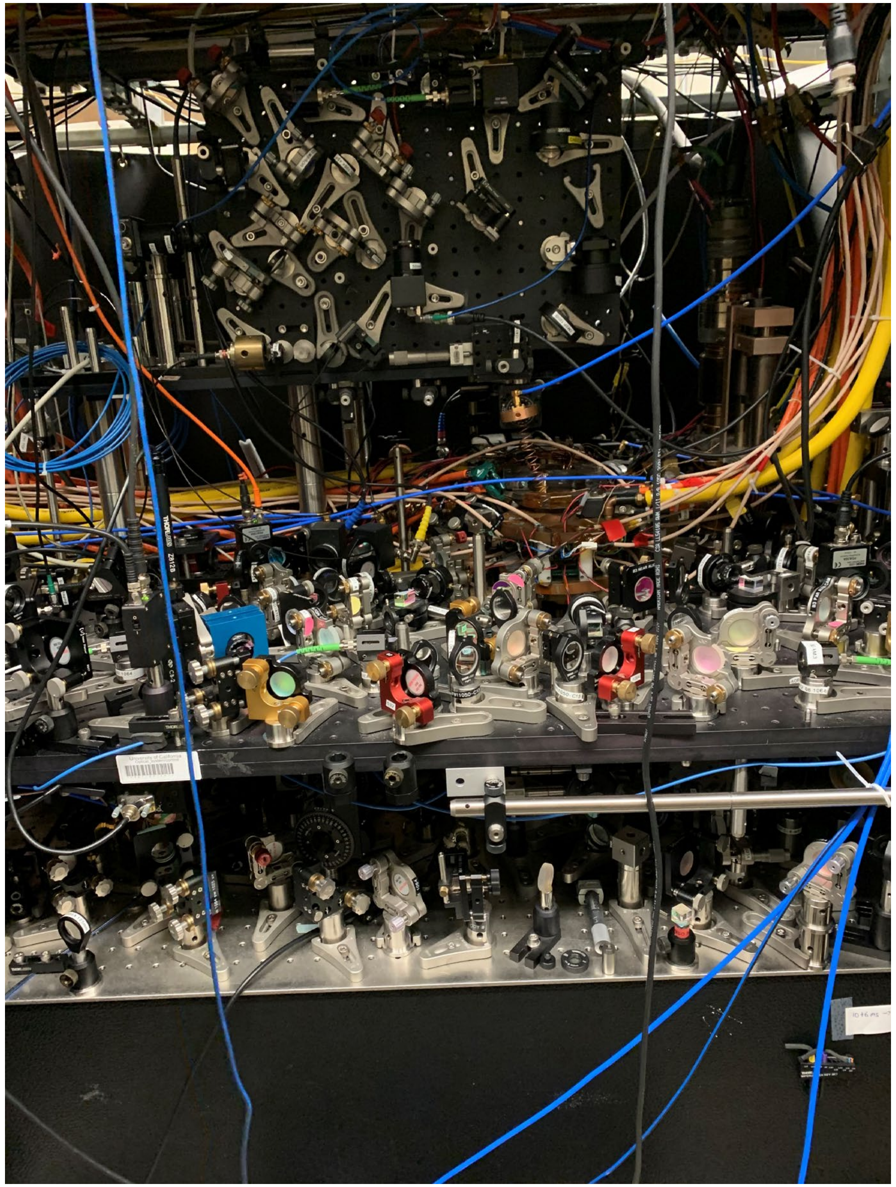


**My artificial graphene also has Dirac points with interesting topological properties**

# Experimental Setup

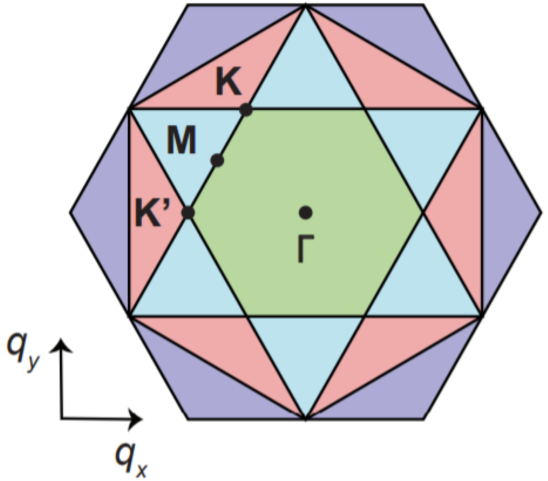
"light preparation" table

"science" table

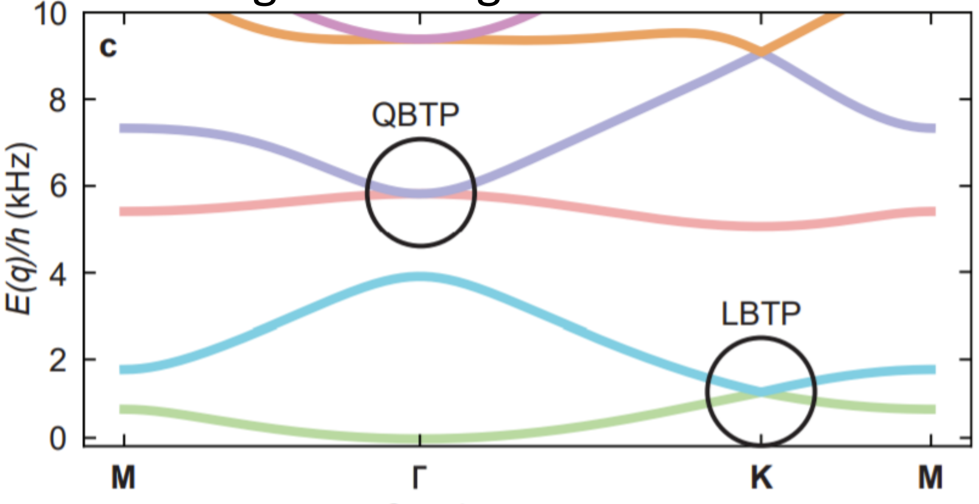


# Ultracold Atom Analog of Graphene

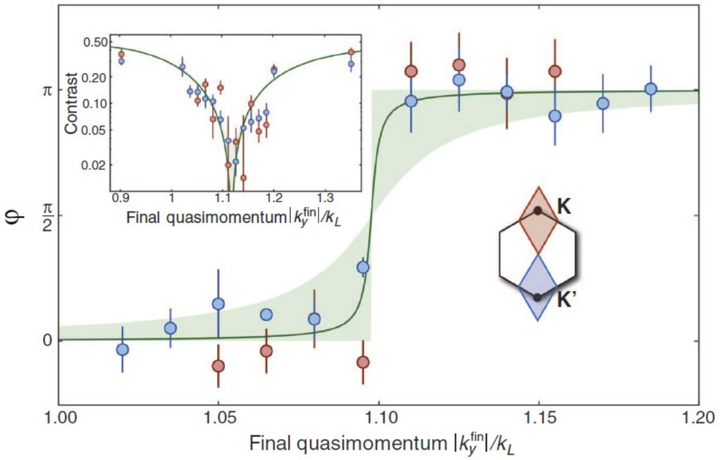
2D Brillouin zone map



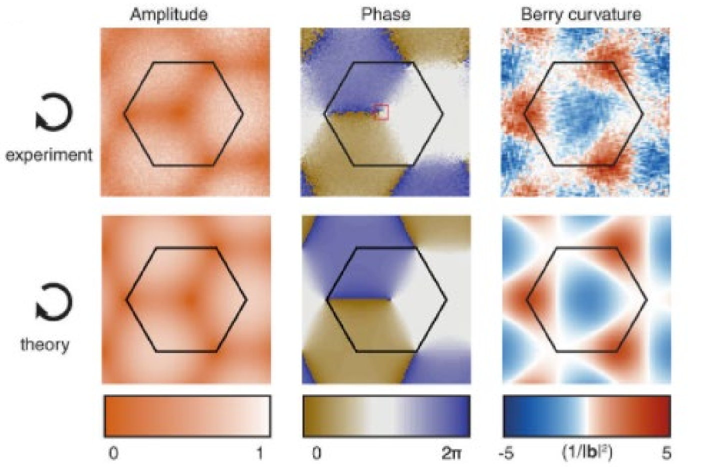
Tight-binding band structure



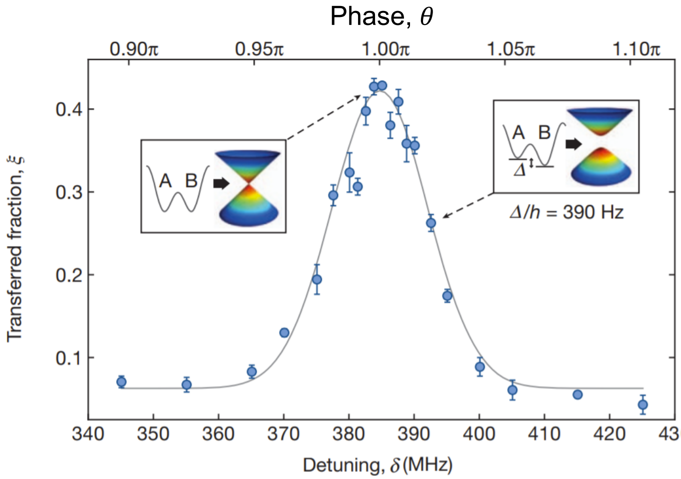
**CDB**,…, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354



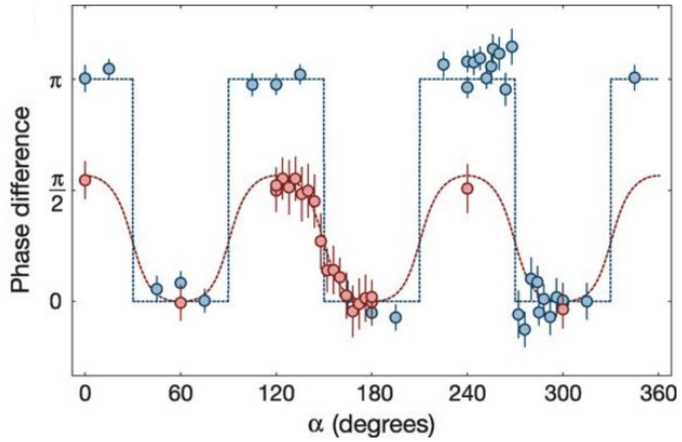
Duca et al (Schneider, Bloch), **Science** 2015



Flaschner et al (Sengstock), **Science** 2016

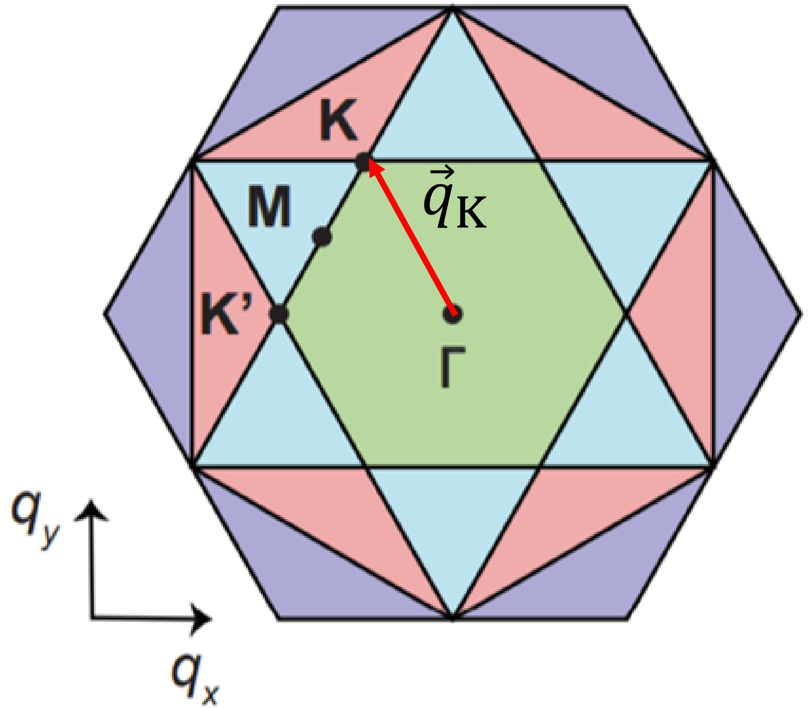


Tarruell et al (Esslinger), **Nature** 2012
Jotzu et al (Esslinger), **Nature** 2014



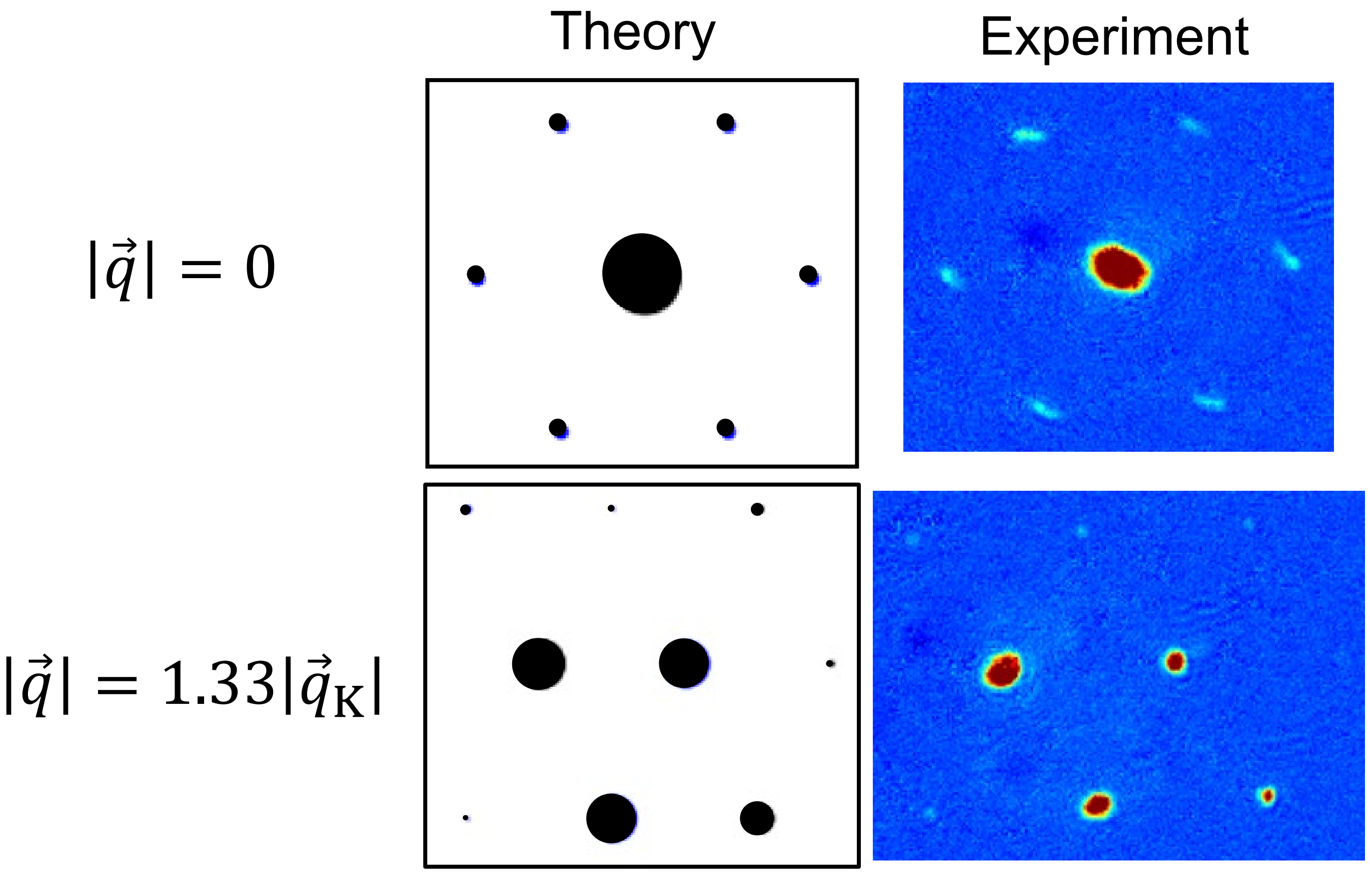
Li et al (Bloch, Schneider), **Science** 2016

# Direct Probe of Dirac Singularity

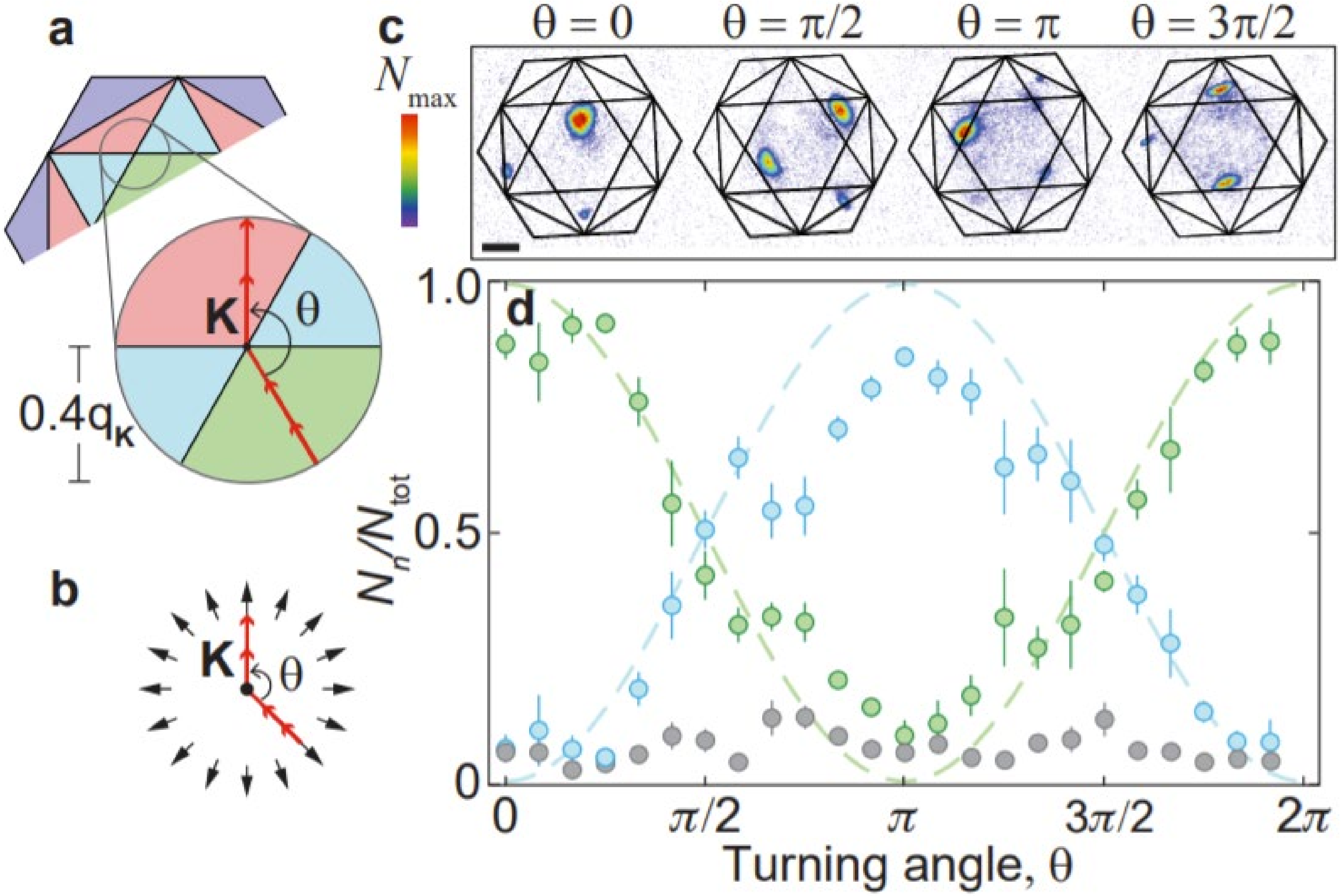


$$\vec{q} = -m\vec{v}_{\mathrm{lat}}$$

$$\vec{v}_{\mathrm{lat}} = \mathrm{f}_{1-2}\vec{a}_{1-2} + \mathrm{f}_{2-3}\vec{a}_{2-3}$$



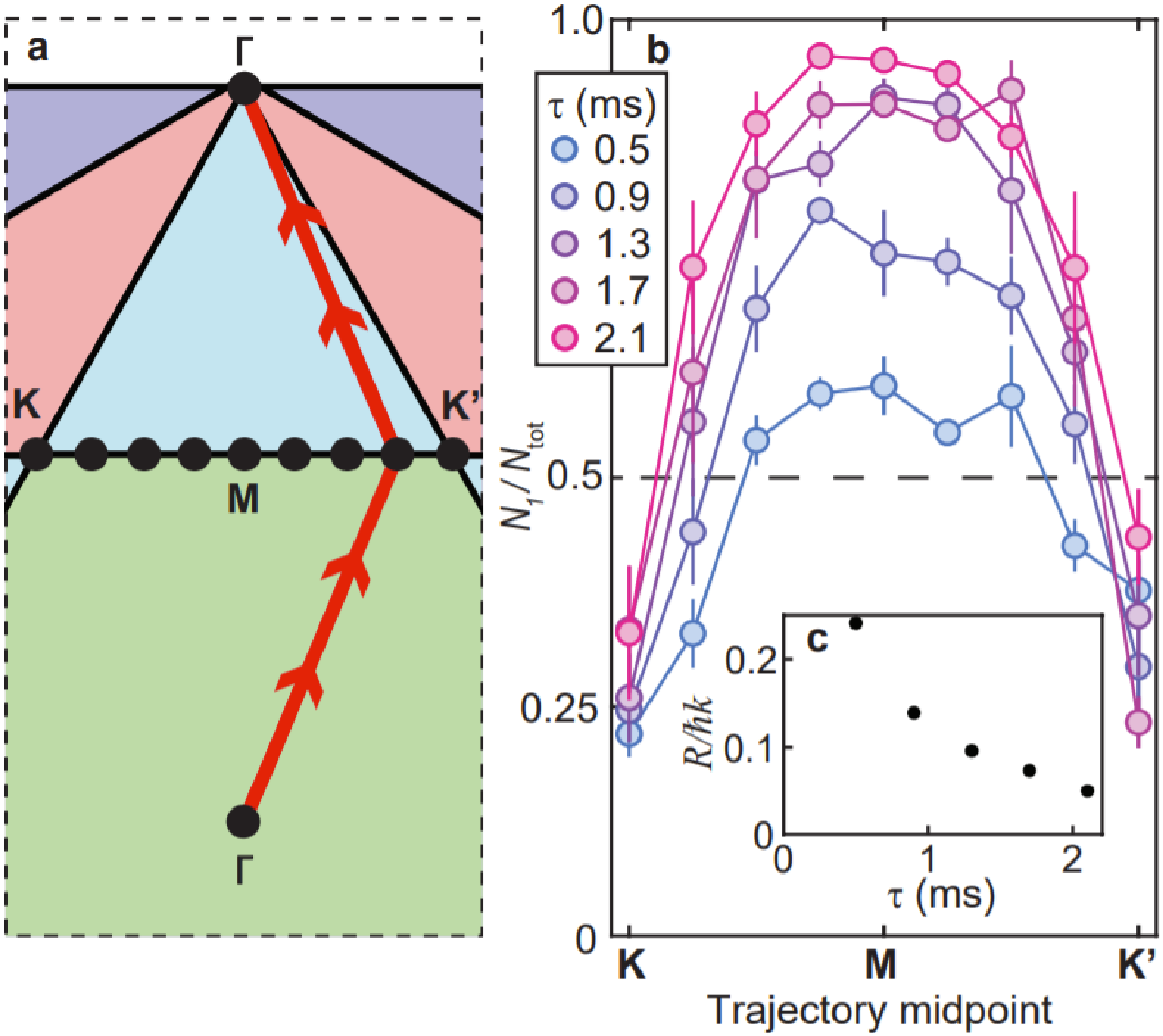
# Direct Probe of Dirac Singularity



- Two band model
  - population dynamics driven by:
    $$A_{mn}(\boldsymbol{q}) = \langle \psi_m(\boldsymbol{q}) | \nabla_{\boldsymbol{q}} | \psi_n(\boldsymbol{q}) \rangle$$
  - Measure of quantum distance:
    $$\mathrm{d}^2 = 1 - |\langle u_2(\boldsymbol{q}') | u_1(\boldsymbol{q}) \rangle|^2$$
  - Reveals the quantum metric tensor $g$ :
    $$\mathrm{d}^2(\mathbf{q}, \mathbf{q} + \mathrm{d}\mathbf{q}) = g_{\mathrm{ij}}(\mathbf{q})\mathrm{d}\mathbf{q}_{\mathrm{i}}\mathrm{d}\boldsymbol{q}_{\boldsymbol{j}}$$

**CDB**,…, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354

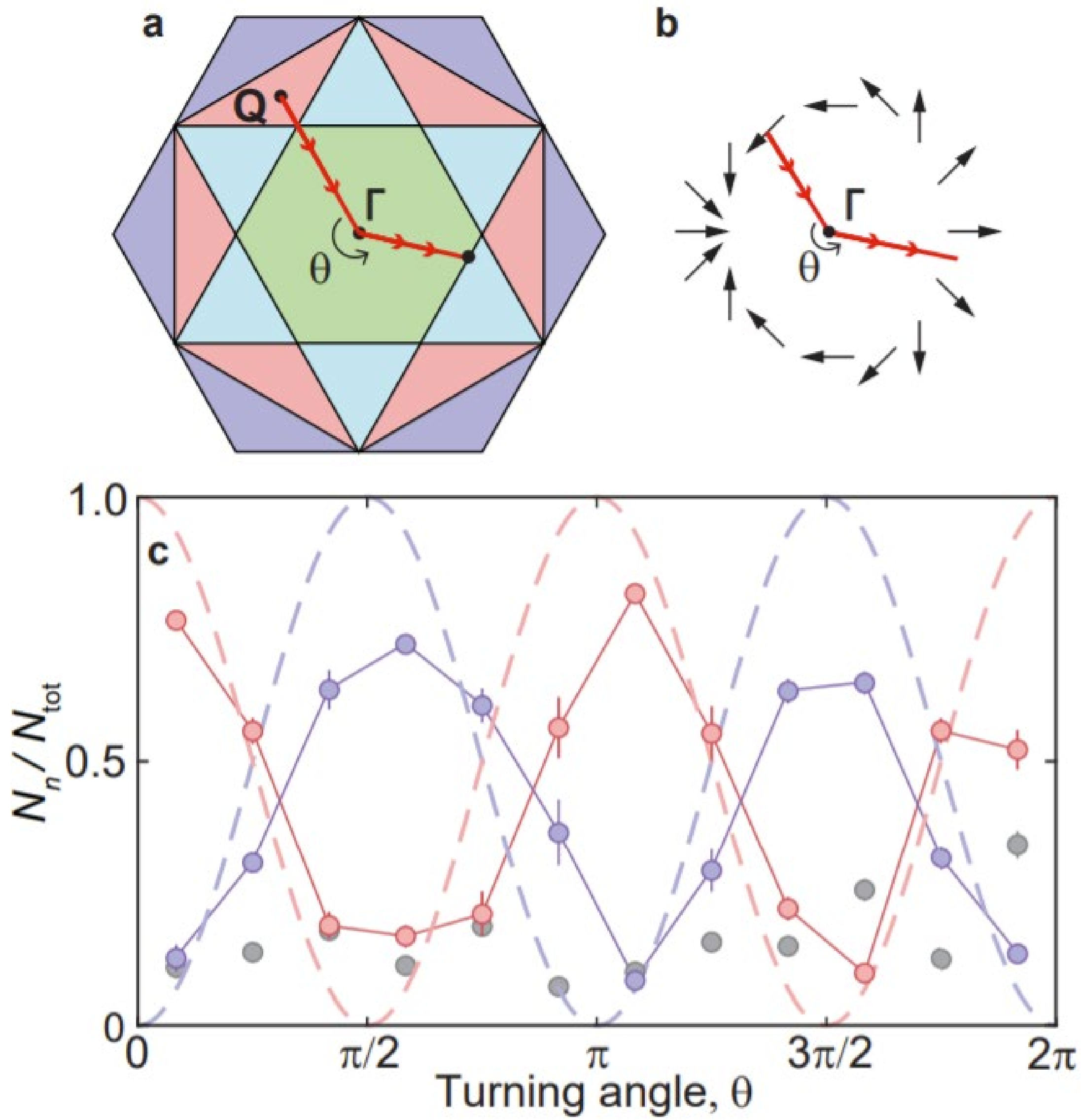
# Effective Size of Dirac Singularity

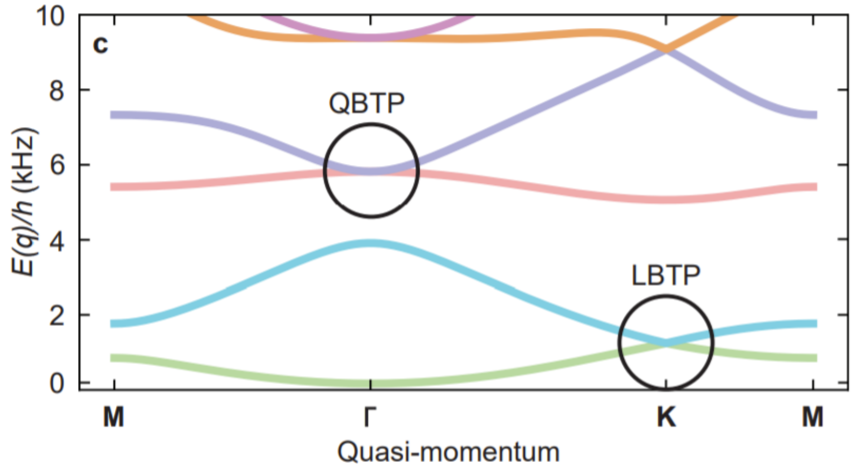


- Band population transfer is only geometry-dependent for evolution through Dirac points
- Time-dependence returns for trajectories away from the Dirac points
  - Landau-Zener physics
- Singularity size grows with shorter acceleration times
  - Effectively increased band degeneracy

**CDB**,…, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354

# Direct Probe of QBTP





- QBTP at Γ
  - Load a running lattice, then evolve to Γ
  - Interferometric measurements can't detect non-trivial topology of QBTP by encircling it
  - Quantum distance measurement is better for observing non-trivial topology of this singularity

- **2** windings around the QBTP instead of **1** around the Dirac point

**CDB**,…, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354

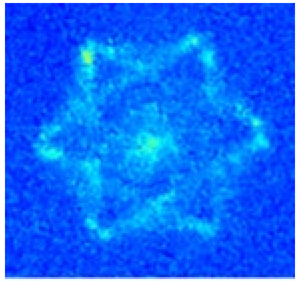
# Conclusion and Future Work

Conclusion

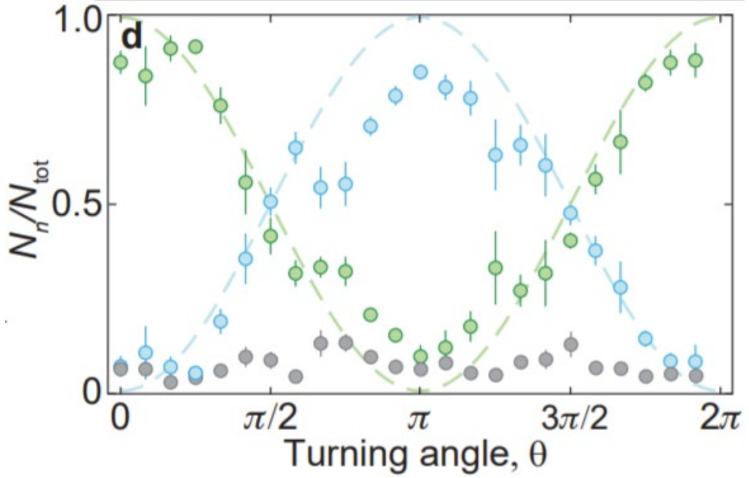
- An ultracold atom quantum simulator is a powerful tool that allows for simulation of real materials or toy Hamiltonians
- Measurements of quantum distance allow the non-trivial topology of Dirac points and QBTPs to be directly revealed
- We observe quantized winding numbers
  - **1** winding around the Dirac point
  - **2** windings around the QBTP

Future Work

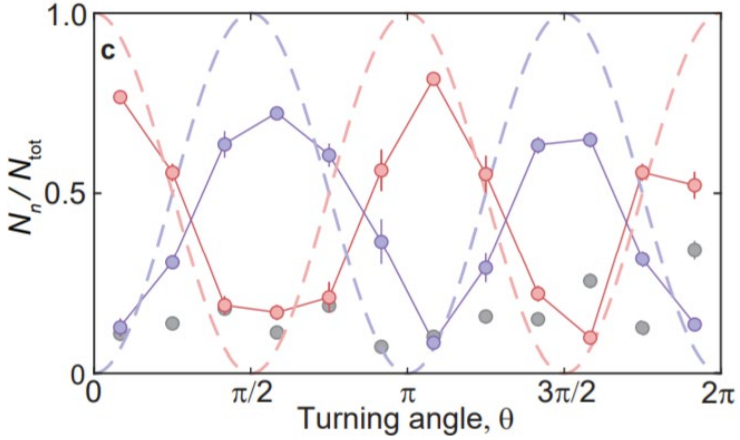
- Flat p-band in the honeycomb lattice
  - Where do bosons condense?
- What happens if atoms are held at singularity for various times?



Dirac point



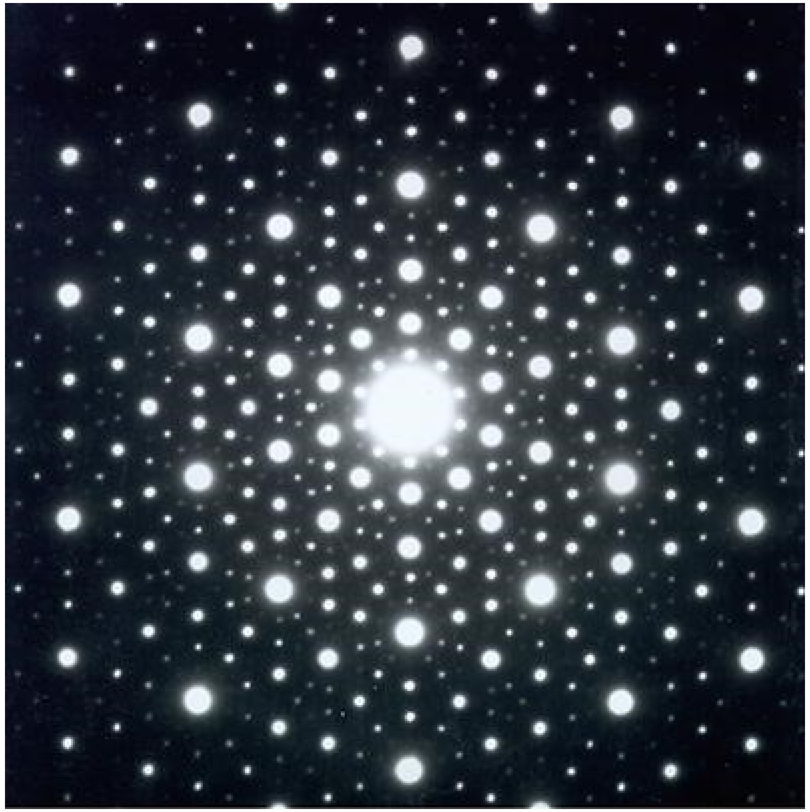
QBTP



**CDB**,…, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354

# Quantum Simulation of Quasicrystals

2X Nobel laureate Linus Pauling once said, “There is no such thing as quasicrsytals, only quasi-scientists.”



Al-Mn alloy
Shechtman et al, **PRL** 1984

- Dan Shechtman - 2011 Nobel prize in Chemistry for discovery
- Quasicrsytals are <u>aperiodic</u> but ordered, with no translation symmetry
- Superconductivity discovered in a 5-fold quasicrystal in 2018
  - Unusual superconductivity?
- What sorts of other interesting and unusual states of matter might be realizable in a quasicrystal?
  - No translation symmetry means no well defined quasimomentum or Fermi surface
- A 5-fold rotation-symmetric ultracold atom quasicrystal would be very interesting
  - Quantum physics of quasicrystals
  - Wave packet diffusion
  - Phason excitations
  - Topology in quasicrystals

# EXTRA SLIDES