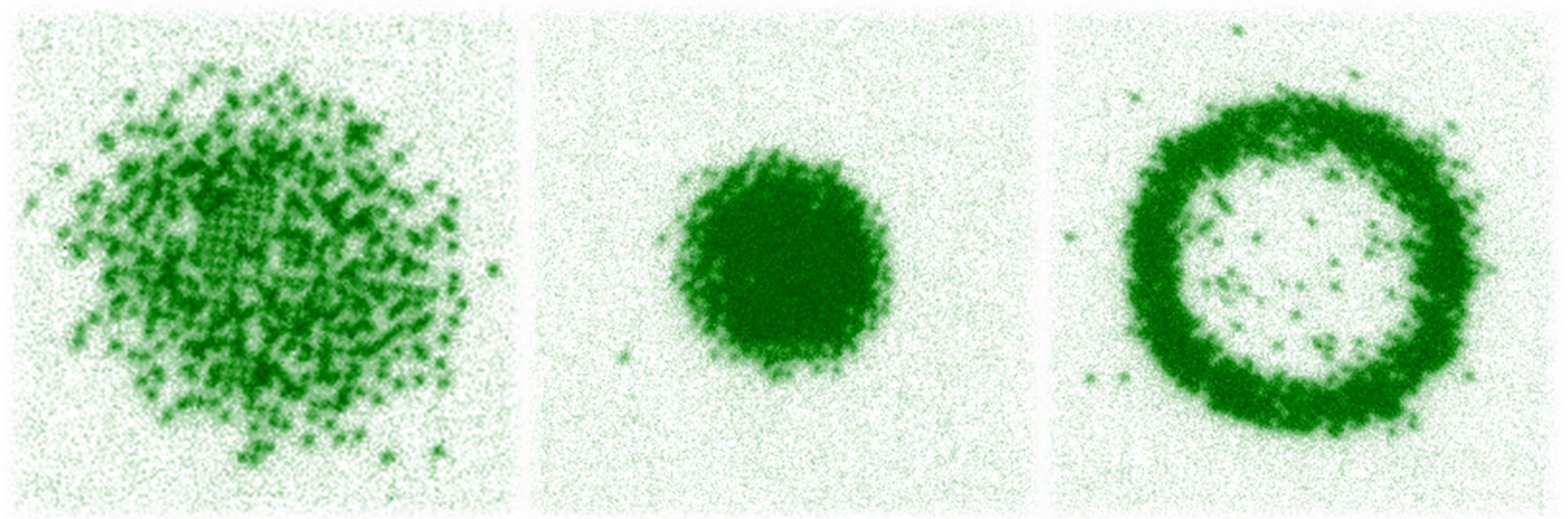


Probing dynamical properties of Fermi-Hubbard systems with a quantum gas microscope

Peter Brown
Bakr Lab

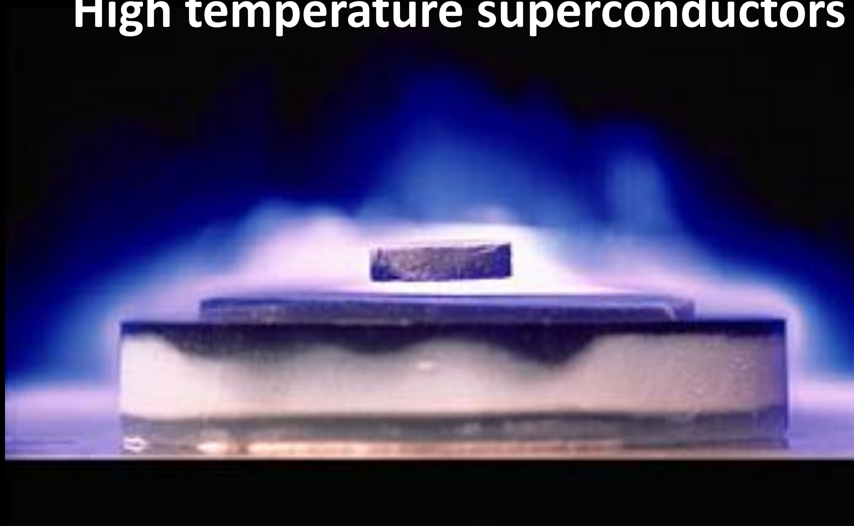
Solvay workshop, February 19th 2019

PRINCETON UNIVERSITY

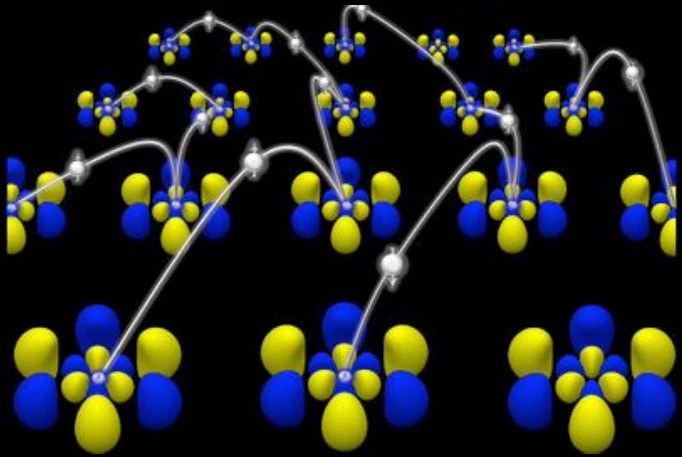
Outline

1. Studying strongly-interacting quantum matter with ultracold atoms
2. The Fermi-Hubbard Model
3. Measuring diffusion and conductivity in the repulsive Hubbard model
4. Measuring spectral functions and the pseudogap in the attractive Hubbard model

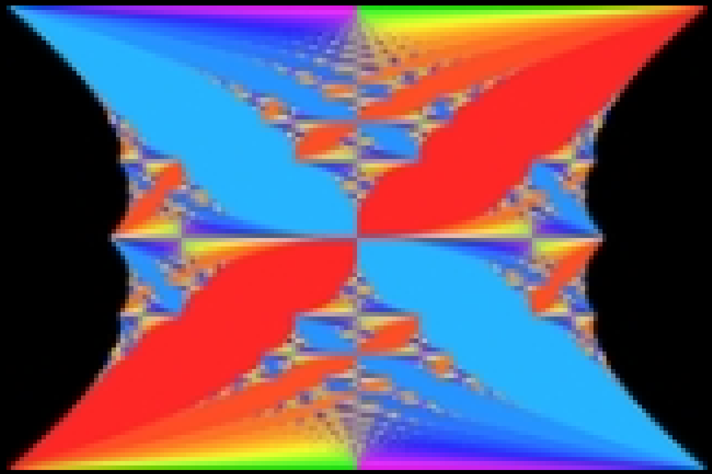
High temperature superconductors



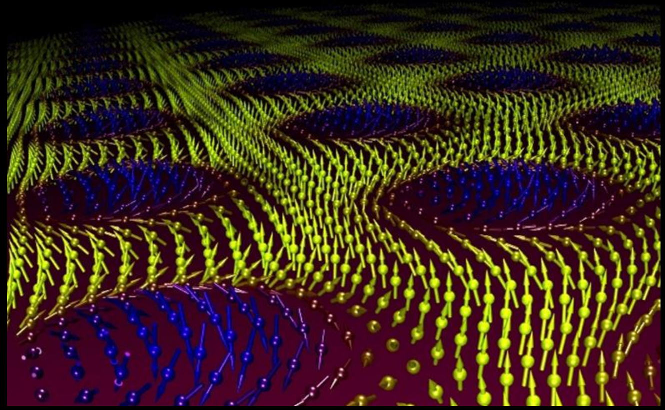
Heavy fermion metals



Strongly correlated quantum matter

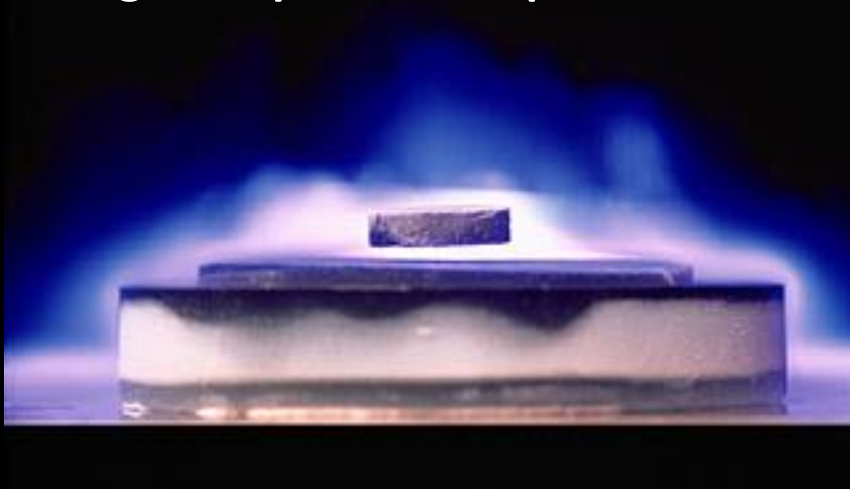


Topological phases

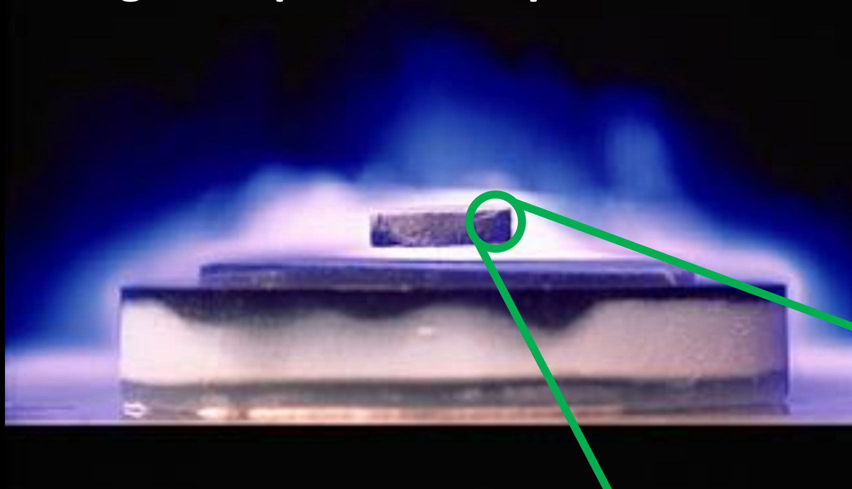


Spintronic materials

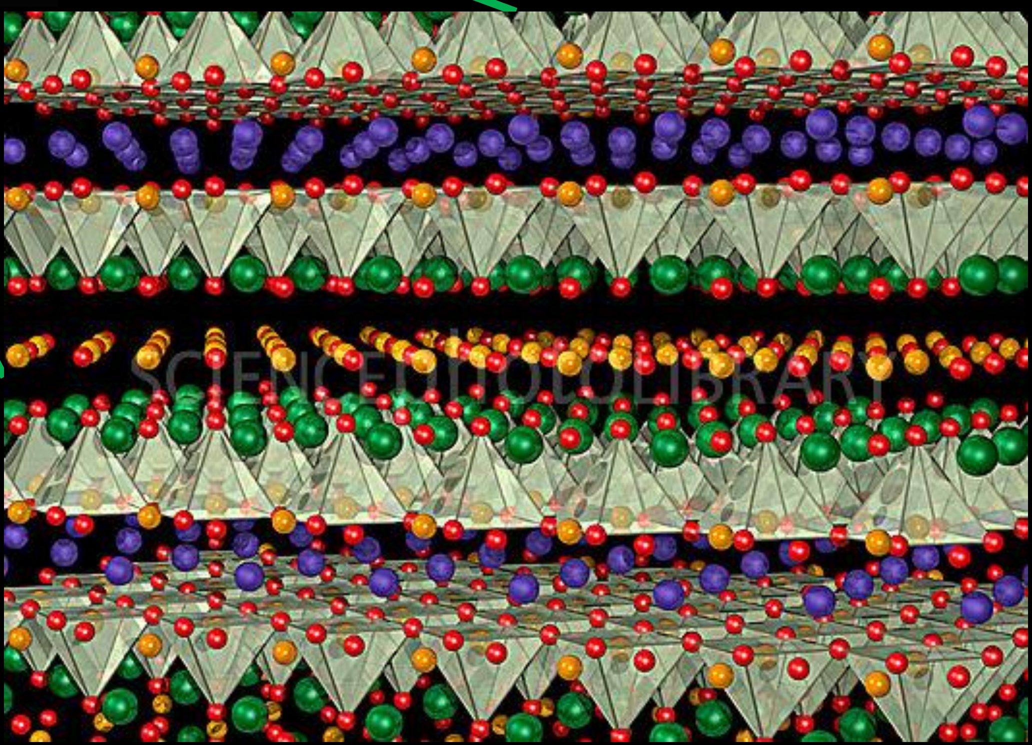
High temperature superconductors



High temperature superconductors



Yttrium Barium Copper Oxide



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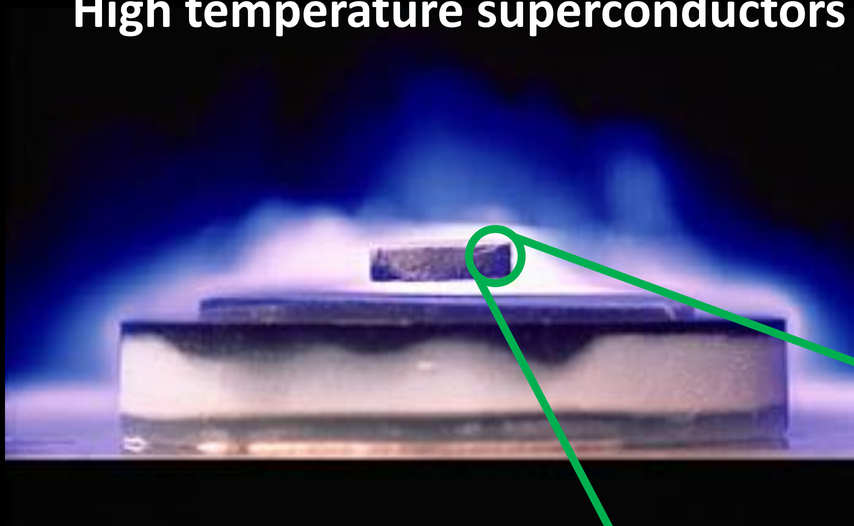

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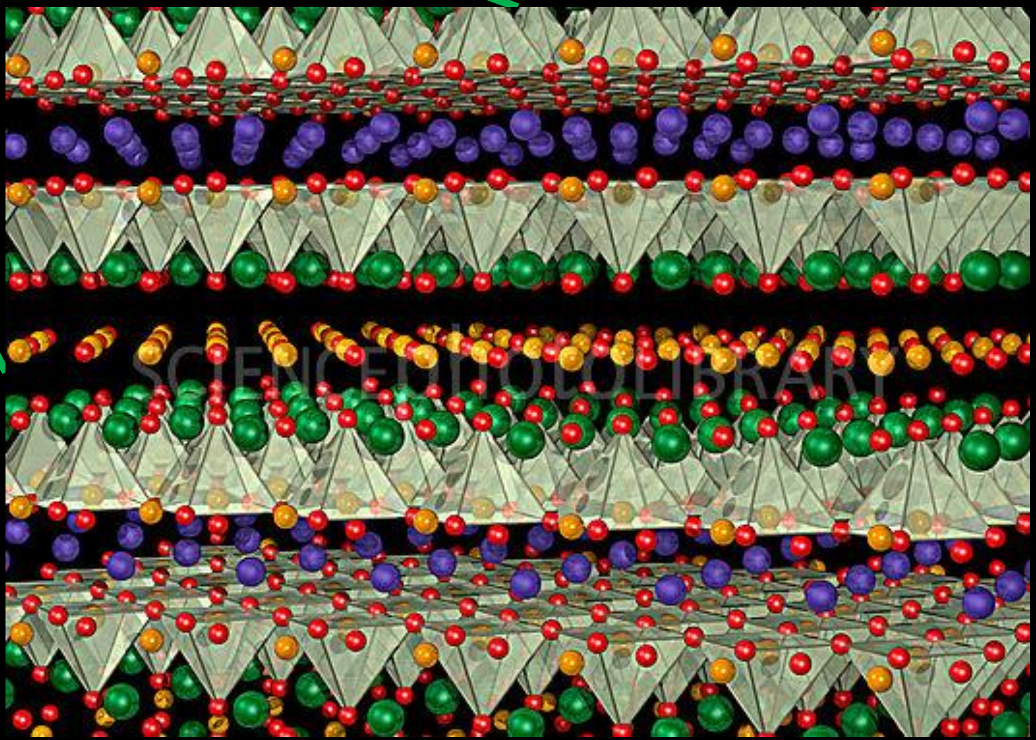
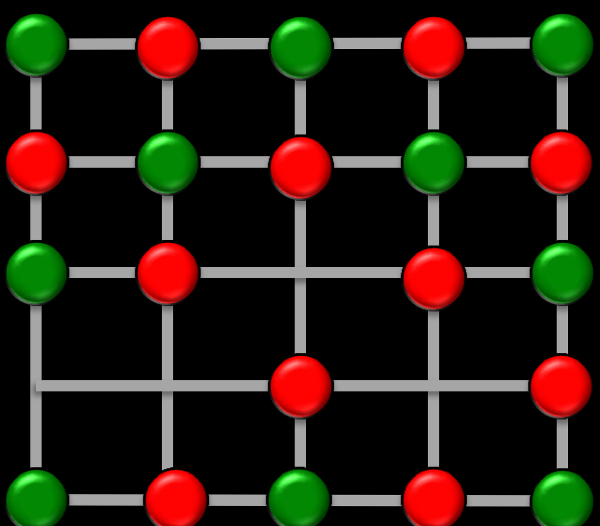
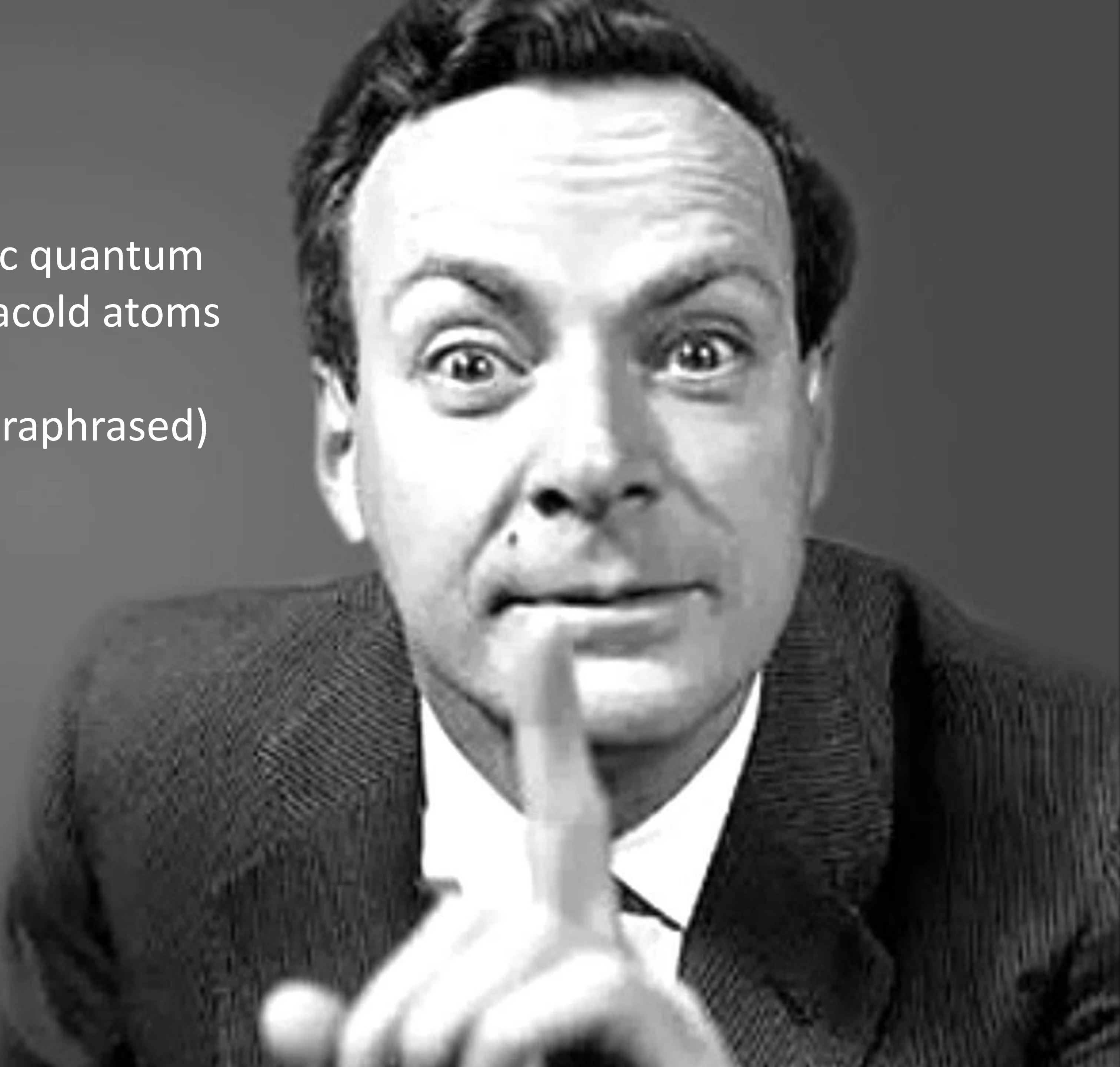


Hubbard model

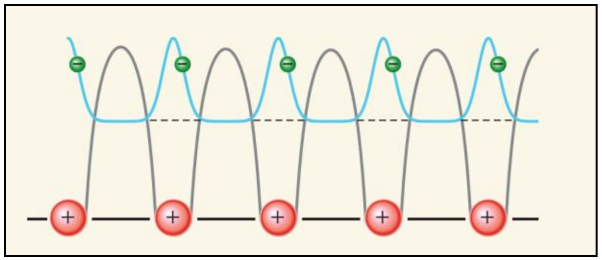


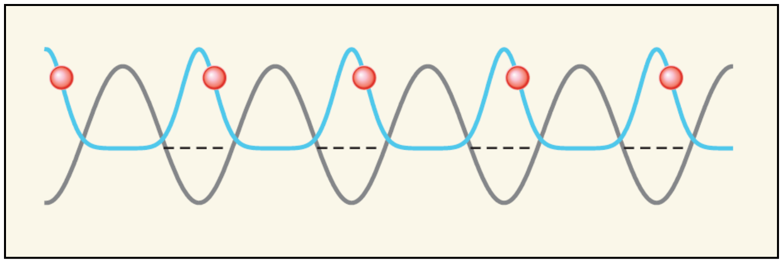
Use a synthetic quantum
system of ultracold atoms

- Feynman (paraphrased)



Interacting systems of ultracold atoms – enlarged model for condensed matter physics

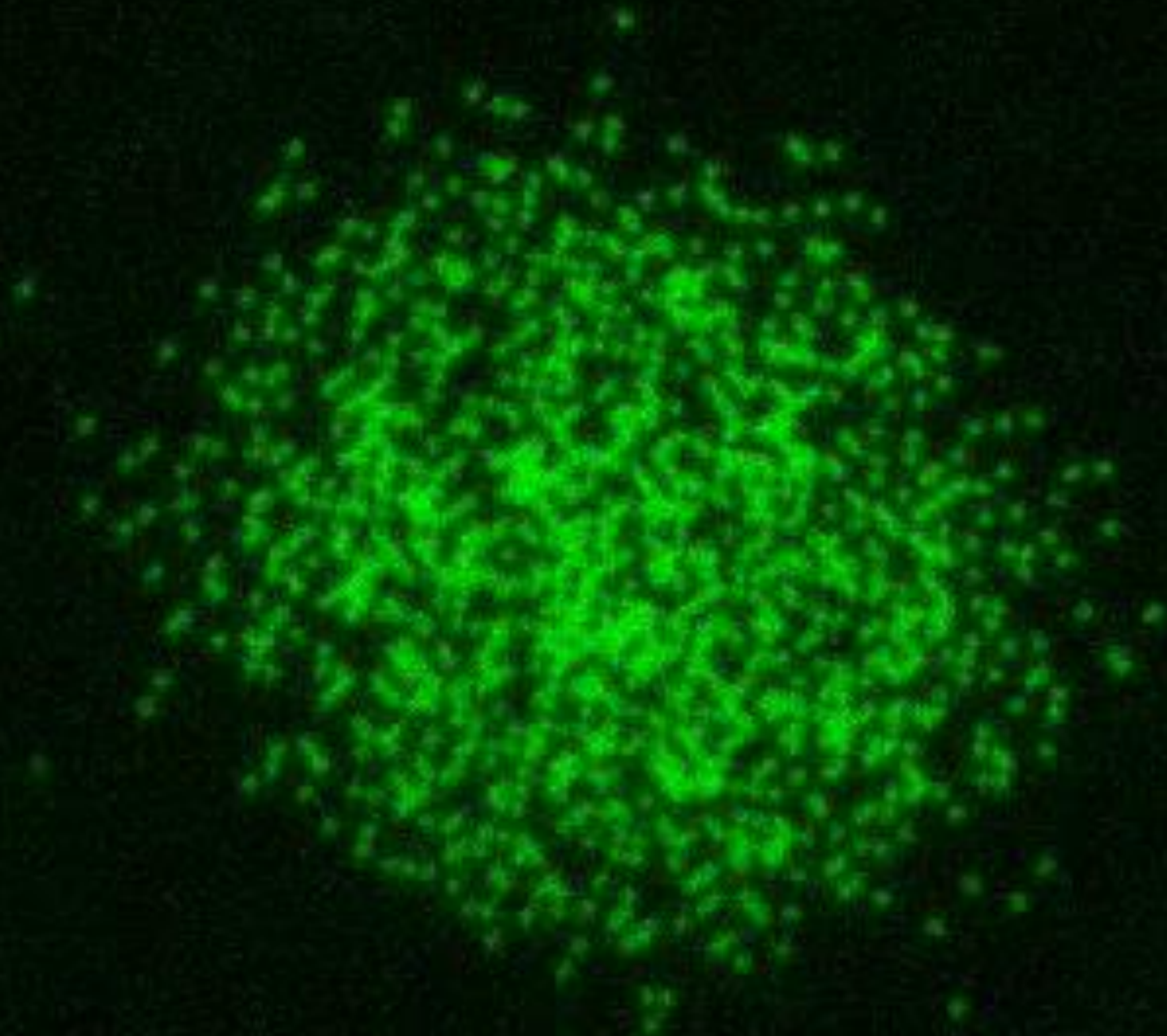




Why ultracold atoms?

- Understood from first principles
- Complete control of microscopic parameters
- Clean systems, no impurities
- Dynamics on observable timescales
- Large interparticle spacing makes optical imaging/manipulation possible

Microscopy of ultracold atoms in optical lattices



Similar fermion microscopes at: Harvard, MIT, MPQ, Toronto, Strathclyde

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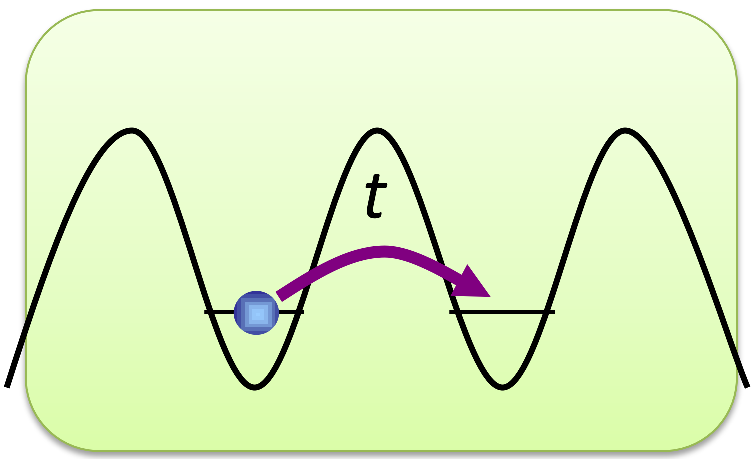
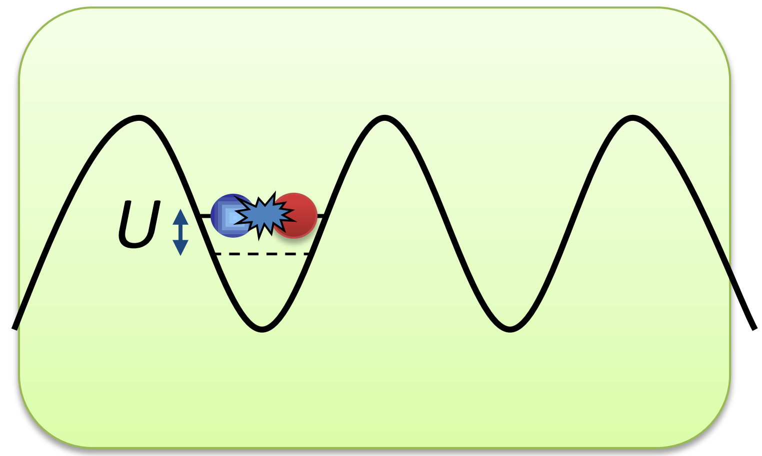
The Fermi-Hubbard model

$$\mathcal{H} = -t \sum_{\langle i,j \rangle,\sigma} \left(c^\dagger_{i\sigma} c_{j\sigma} + \text{ h.c.} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Hopping (kinetic energy)

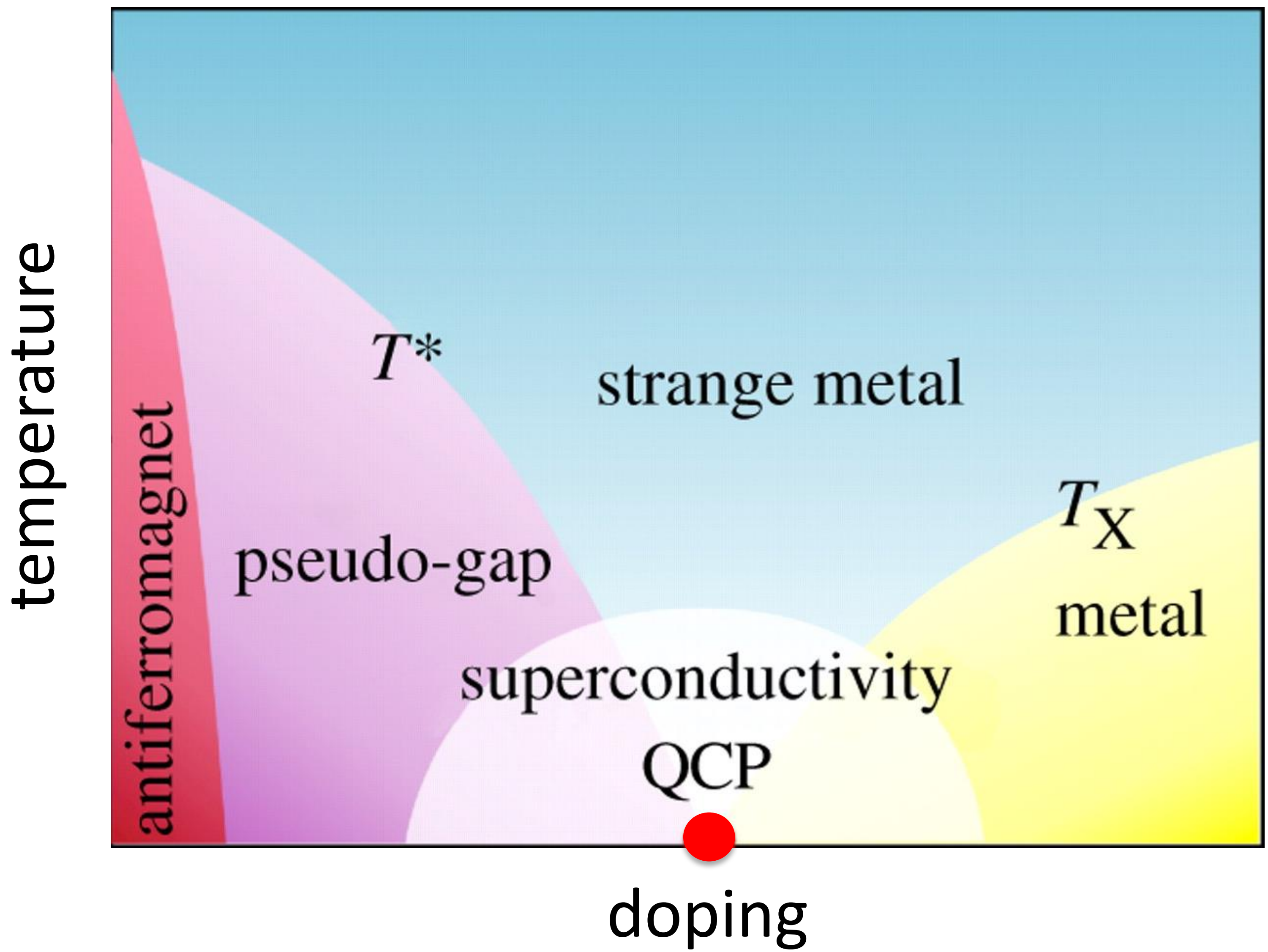
On-site interaction



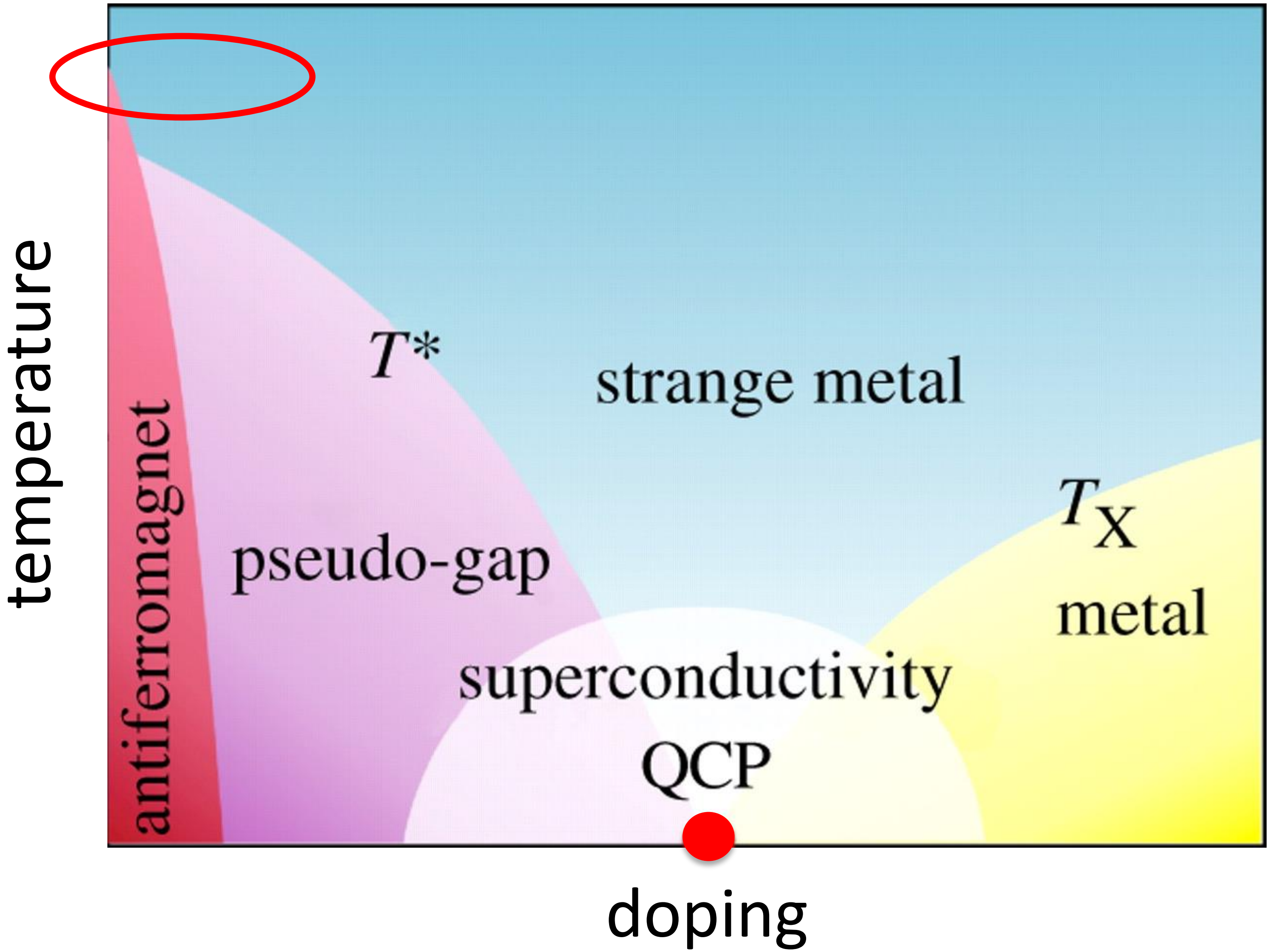


How much of the phenomenology of the cuprates does the Hubbard model reproduce?

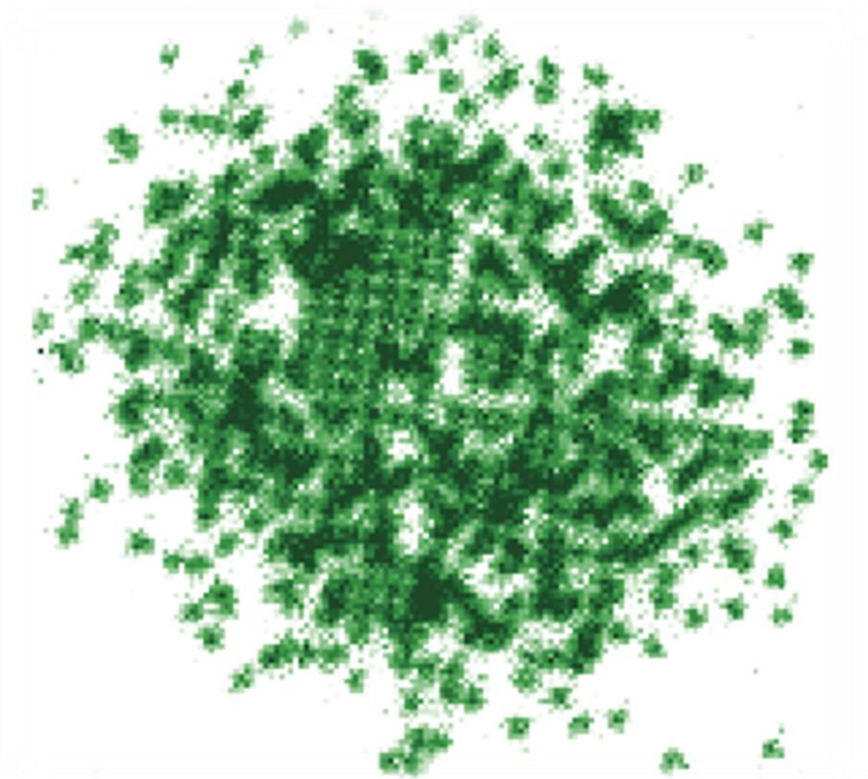
Cuprate phase diagram

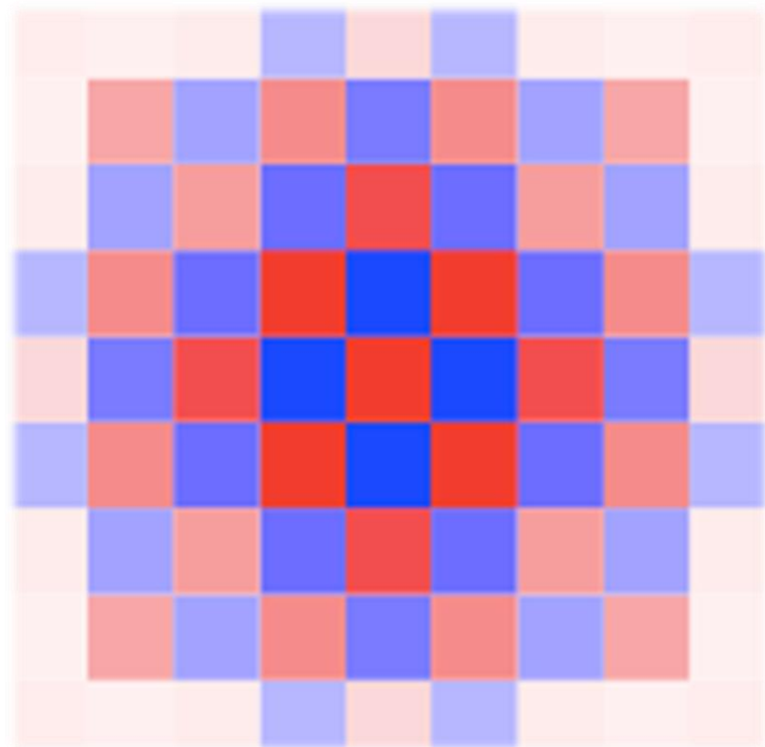


Cuprate phase diagram



Antiferromagnetic spin correlations

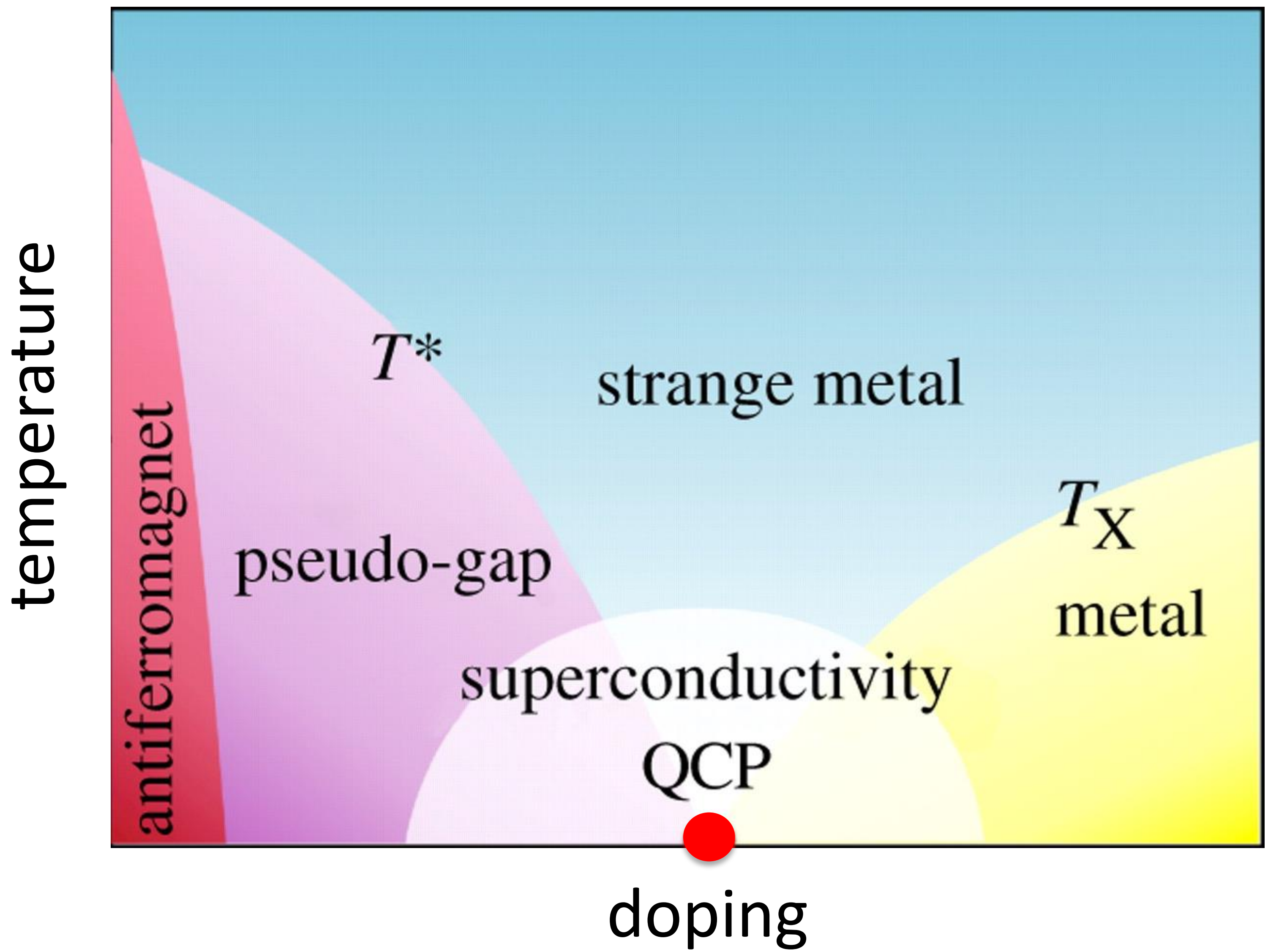




Detection of AFMs with microscopes:
Parsons … Greiner, Science 353, 1253 (2016)
Boll ... Bloch, Gross, Science 353, 1257 (2016)
Cheuk … Zwierlein, Science 353, 1260 (2016)

Previous work without microscopes:
Grief … Esslinger, Science 340, 1307 (2013)
Hart … Hulet, Nature 519, 211 (2015)
Drewes … Köhl, PRL 118, 170401 (2017)

Cuprate phase diagram



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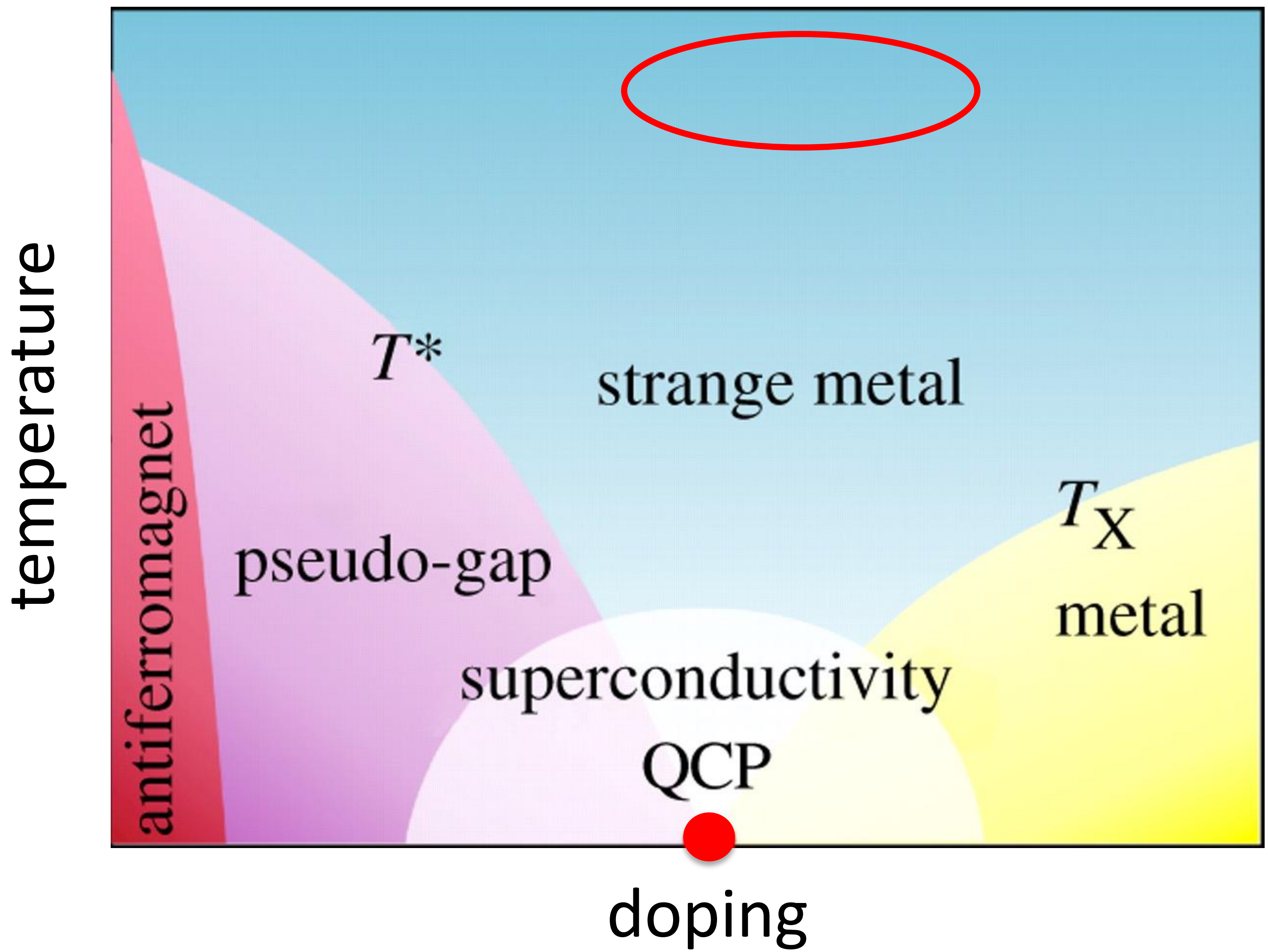
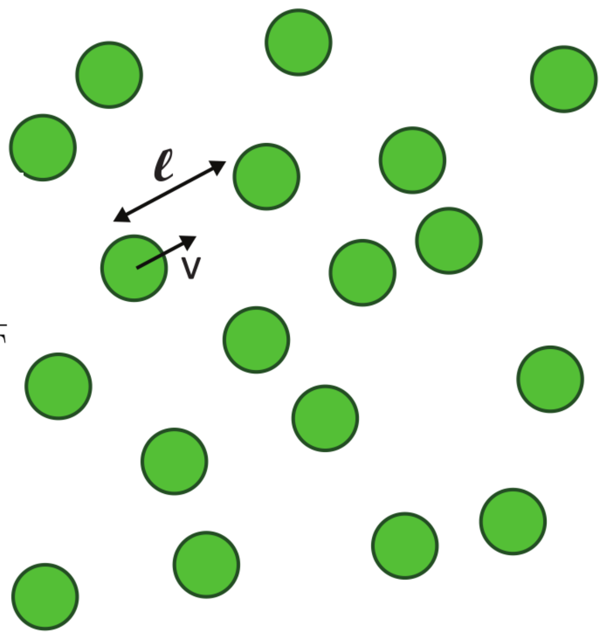


Conventional (weakly interacting)

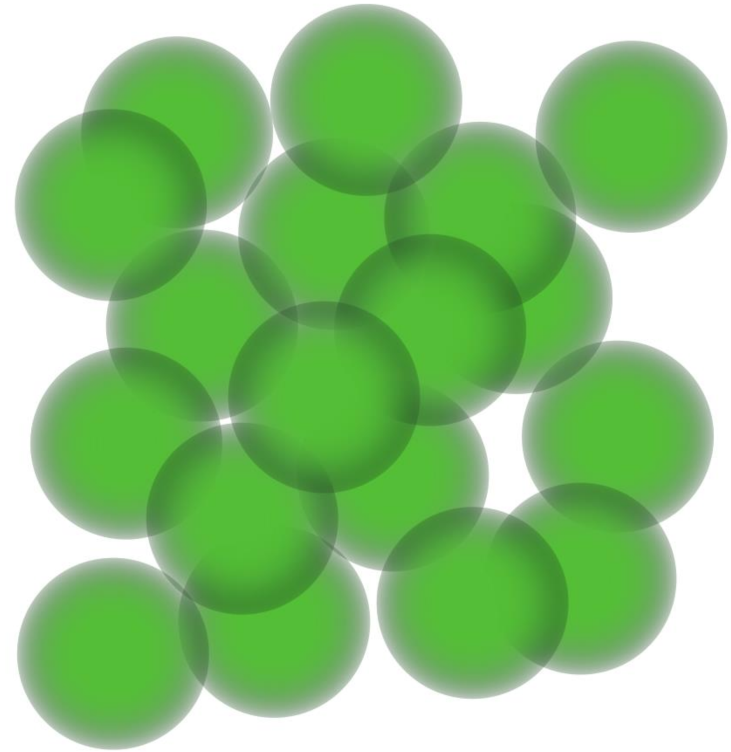
$$\Gamma = \frac{\langle v \rangle}{l}$$

$$\frac{1}{\rho} = \frac{ne^2}{m^*\Gamma}$$



- Charge, spin, energy transported by quasiparticles
- Mean free path must be larger than lattice spacing. Mott-Ioffe-Regel (MIR) limit
- $\rho \sim T^2$, Fermi-liquid

Unconventional (strongly correlated)



- Strong enough interactions destroy quasiparticles
- Momentum relaxation rate no longer gives resistivity
- "Bad metals" violate MIR limit and commonly show $\rho \sim T$

Previous Work

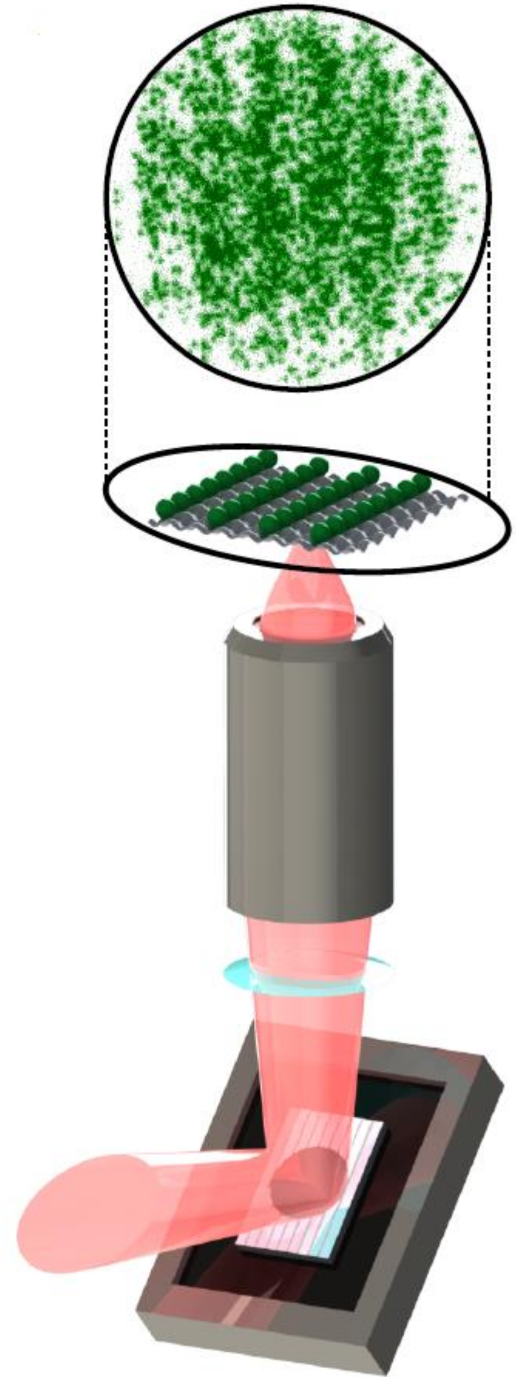
Mass transport experiments with Fermions

Mesoscopic systems:

Brantut *et al.* Science **337**, 1069 (2012) (ETH Zurich)
…
Lebrat *et al.* PRX **8**, 011053 (2018) (ETH Zurich)
Valtolina *et al.* Science **350**, 1505 (2015) (Florence)

Bulk systems:

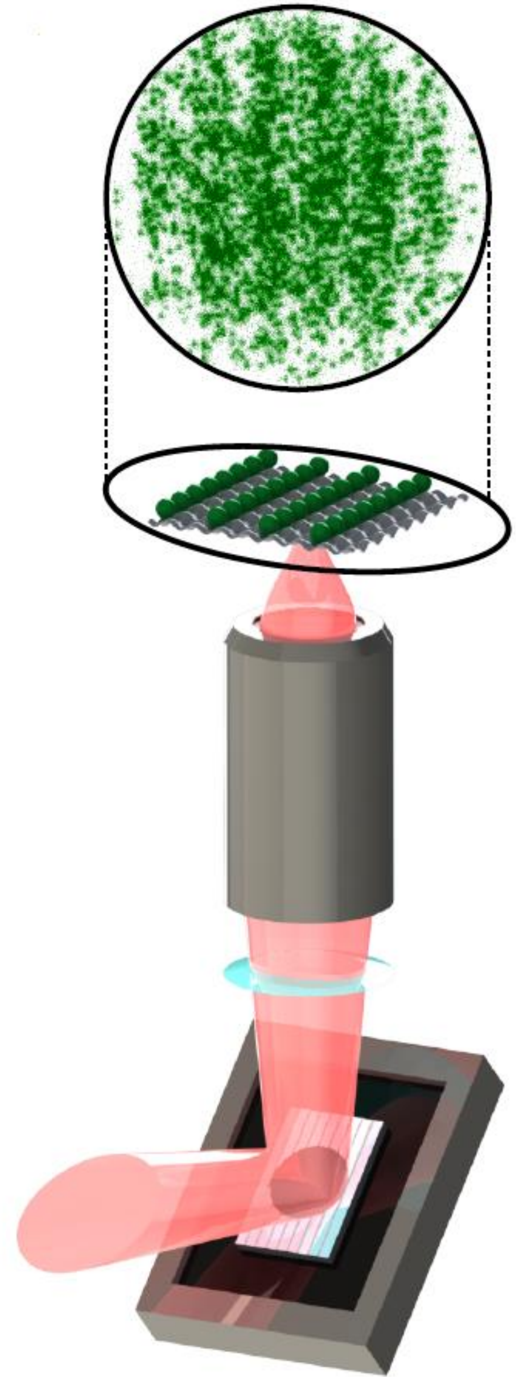
Ott *et al.* PRL **92**, 160601 (2004) (Florence)
Strohmaier *et al.* PRL **99**, 220601 (2007) (ETH Zurich)
Schnedier *et al.* Nat. Phys **8**, 213 (2012) (Munich)
Xu *et al.* arXiv:1606.06669 (2016) (UIUC)
Anderson *et al.* arXiv:1712.09965 (2017) (Toronto)



Measurement Protocol

- Load atoms in combined optical lattice + repulsive potential with sinusoidal modulation
- Turn off modulation, take fluorescence images at different times
- Macroscopic (ρ) transport connected to microscopic (D) through Nernst-Einstein relation:

$$^{1}/_{\rho} = \left(\frac{\partial n}{\partial \mu}\right)\Big|_{T} D$$



Brown *et. al.,* Science **363**, 379 (2019)
Spin transport: Nichols … Zwierlein, Science **363**, 383 (2019)

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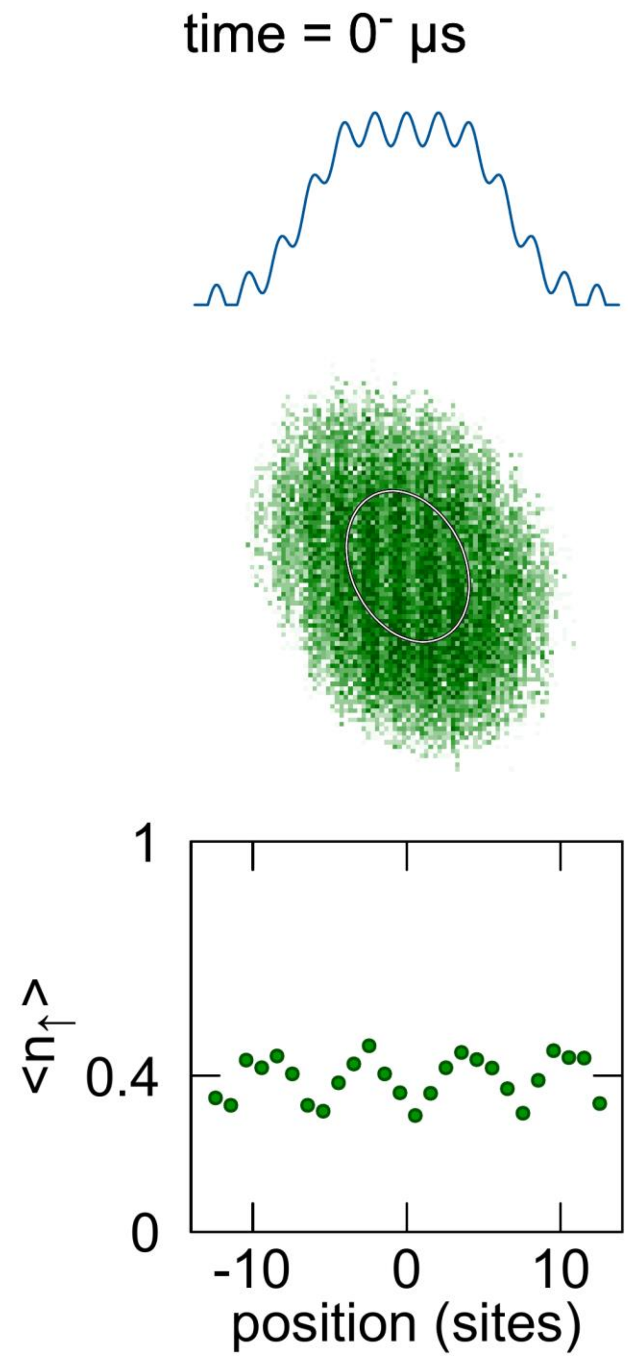

Brown *et. al.,* Science **363**, 379 (2019)

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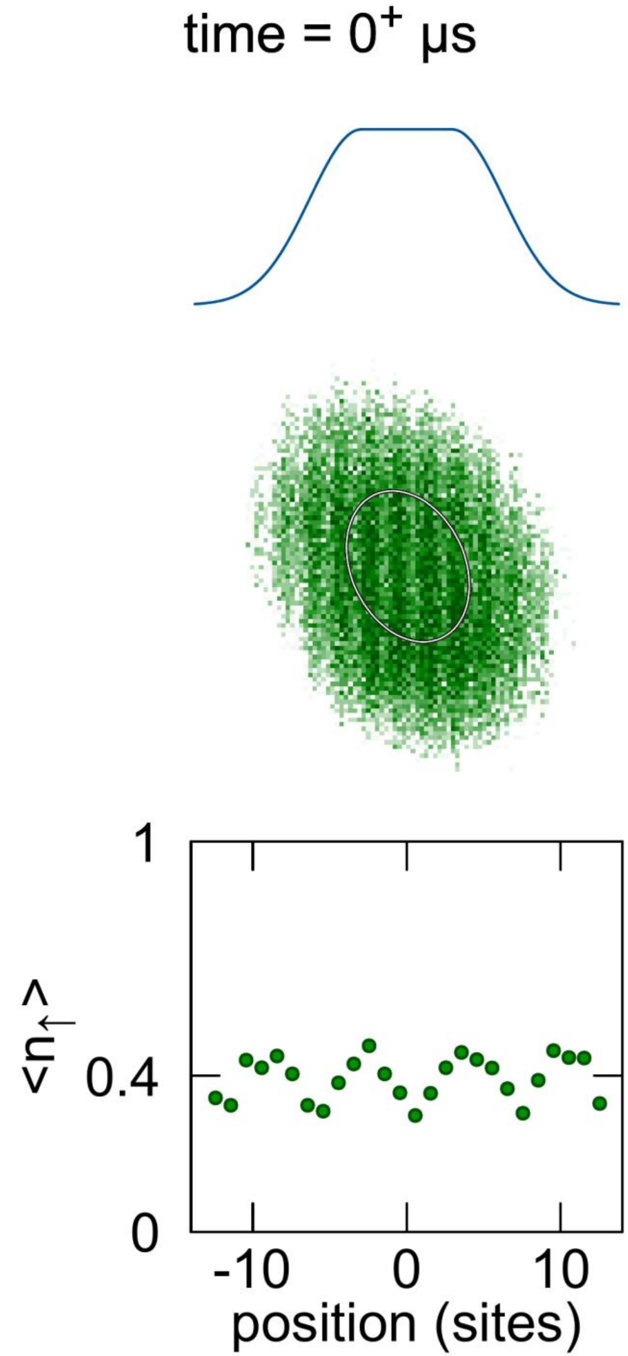

Brown *et. al.,* Science **363**, 379 (2019)

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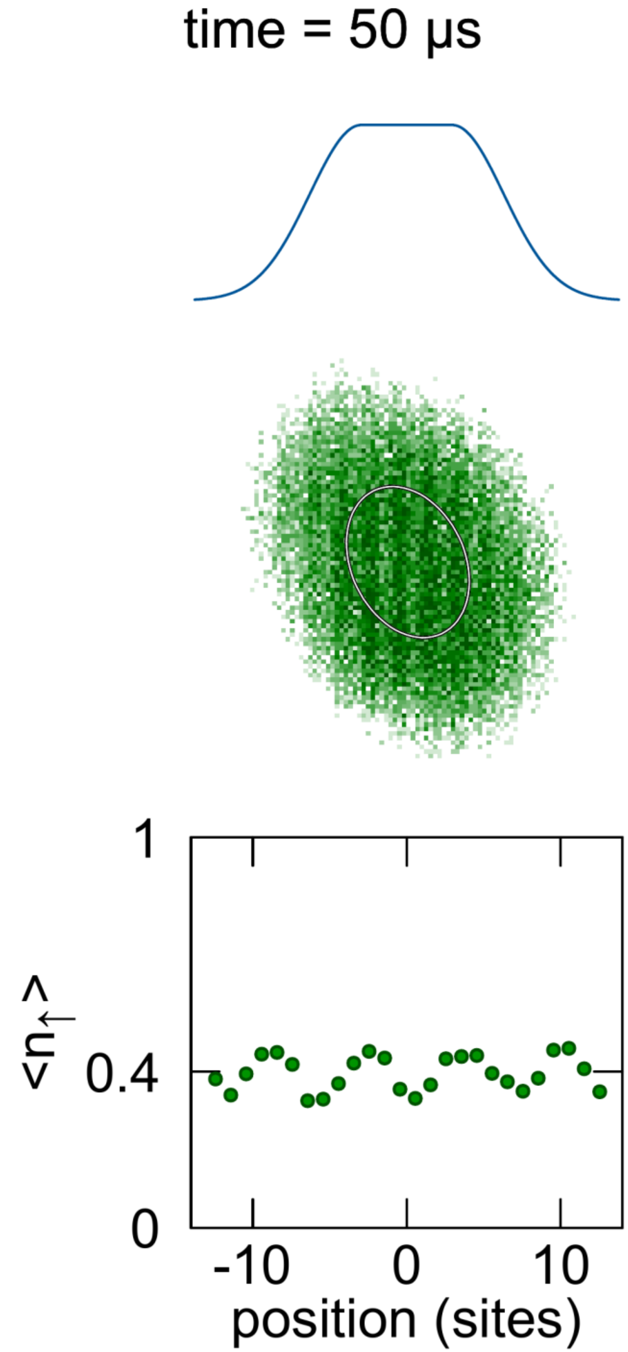

Brown *et. al.,* Science **363**, 379 (2019)

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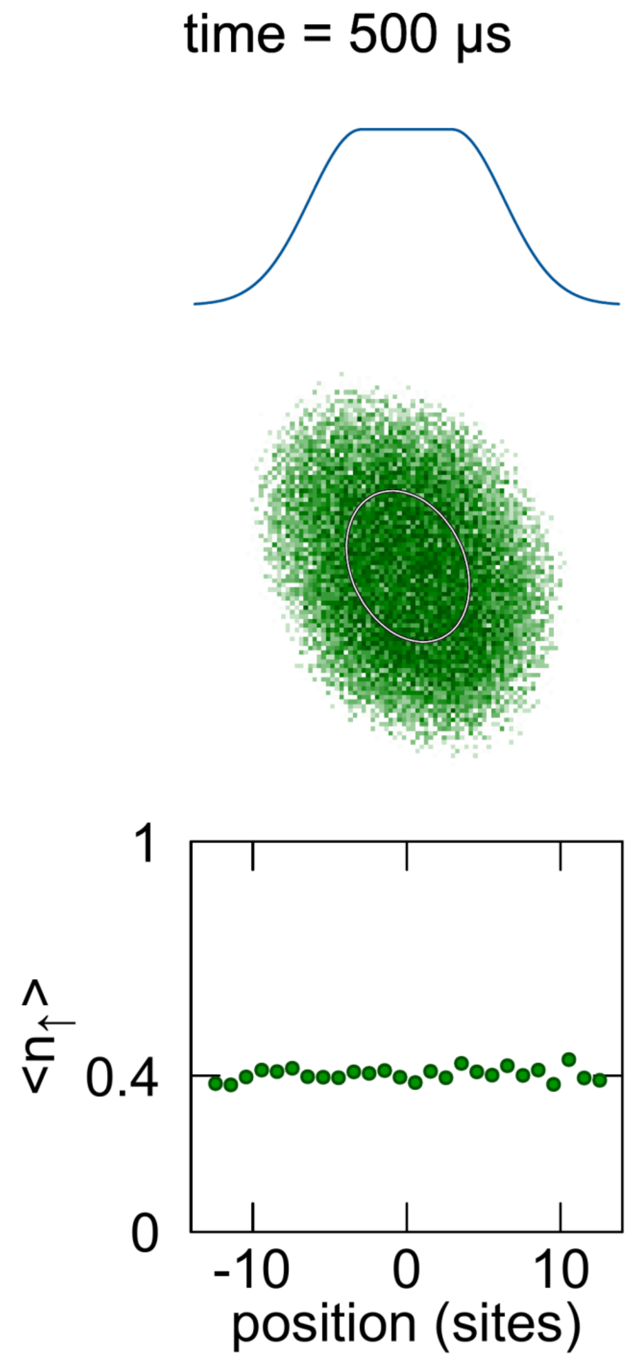
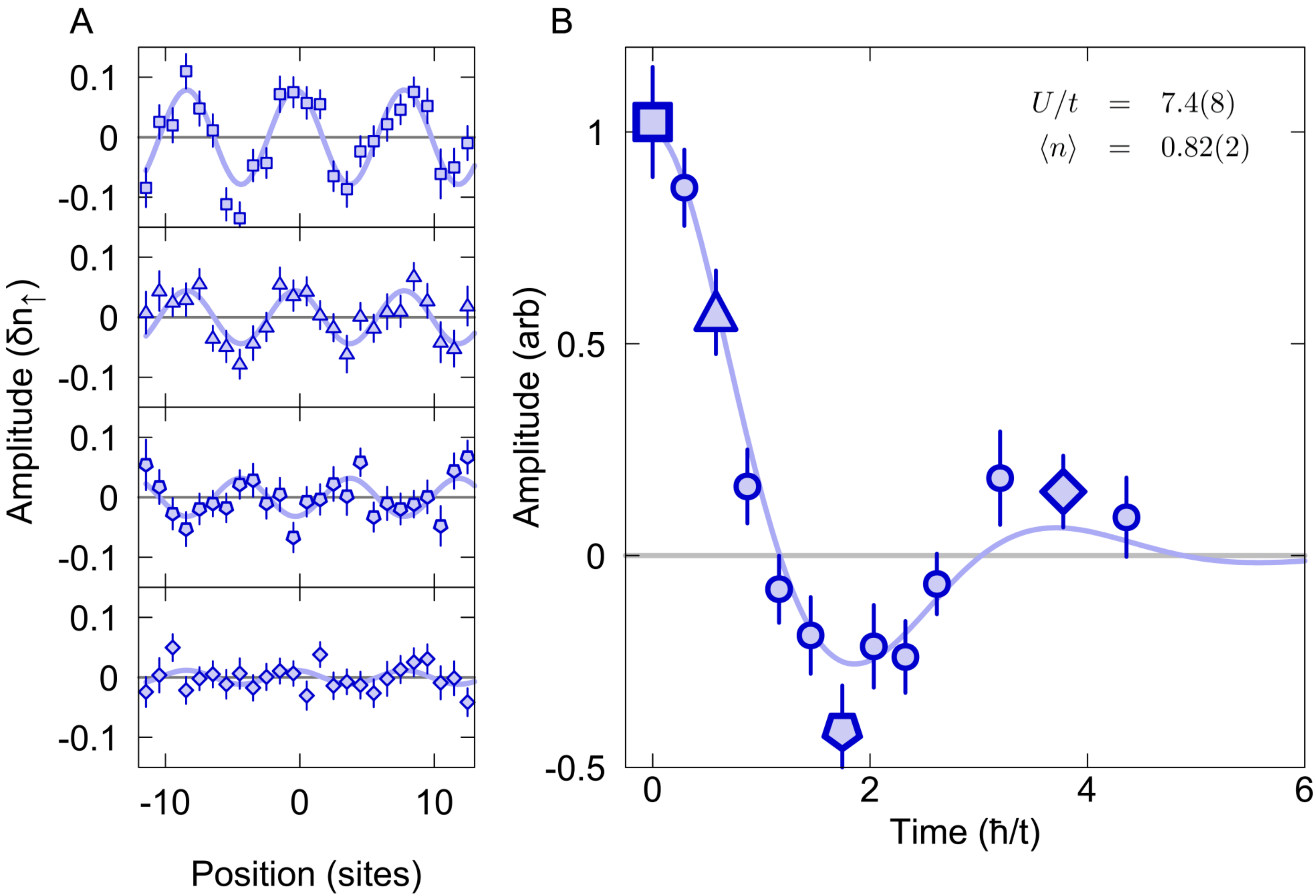


Brown *et. al.,* Science **363**, 379 (2019)

Decaying density modulation



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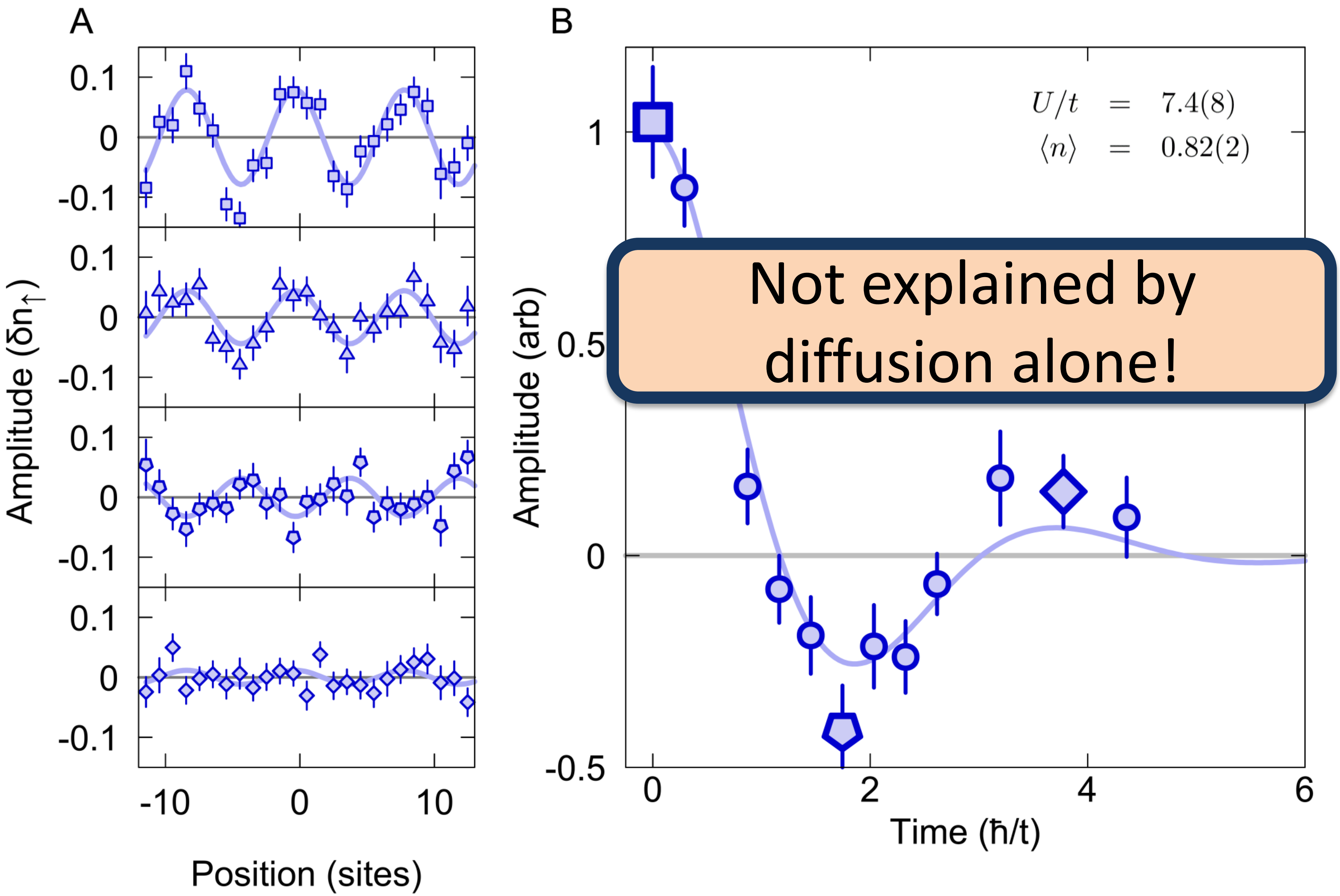

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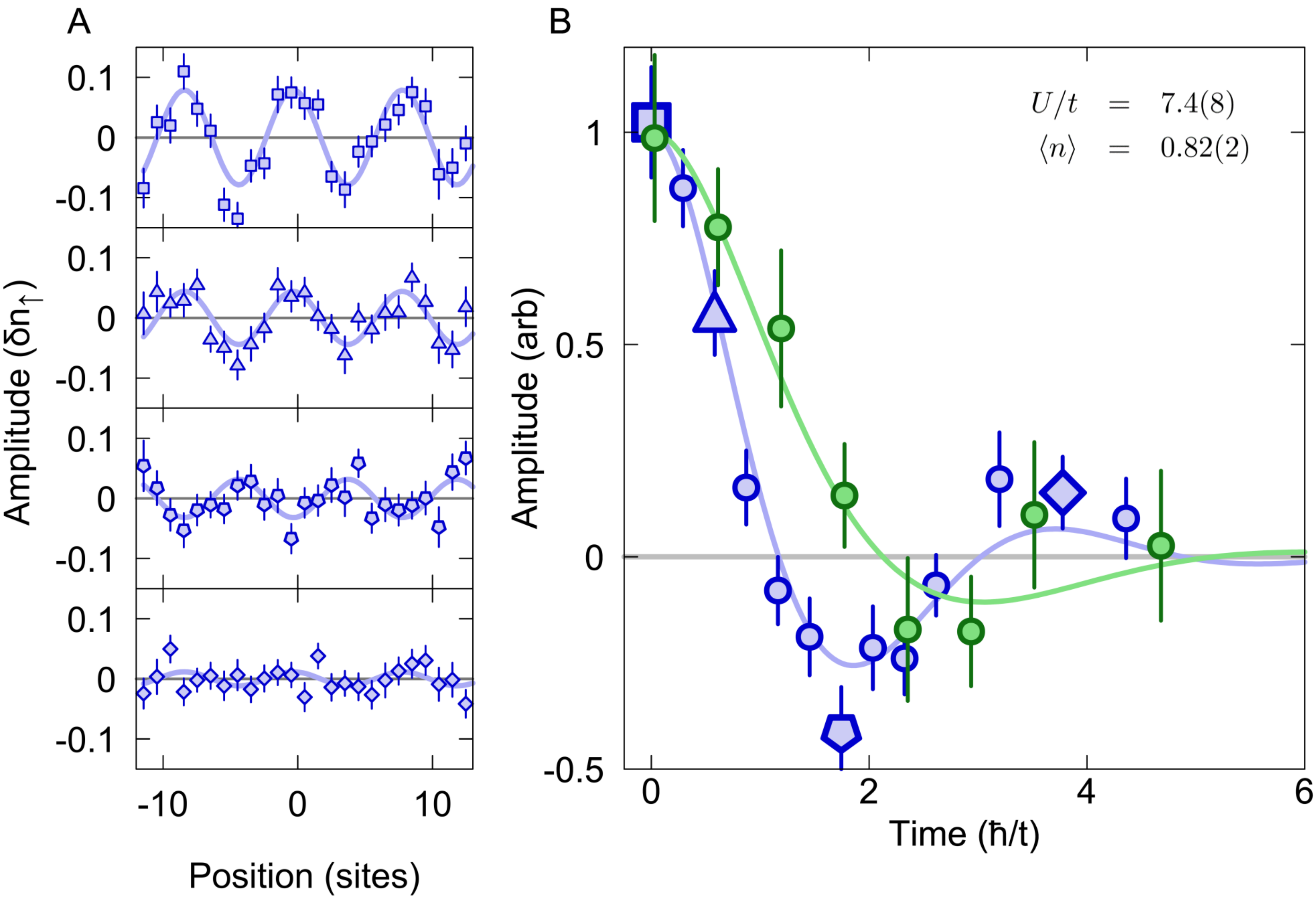

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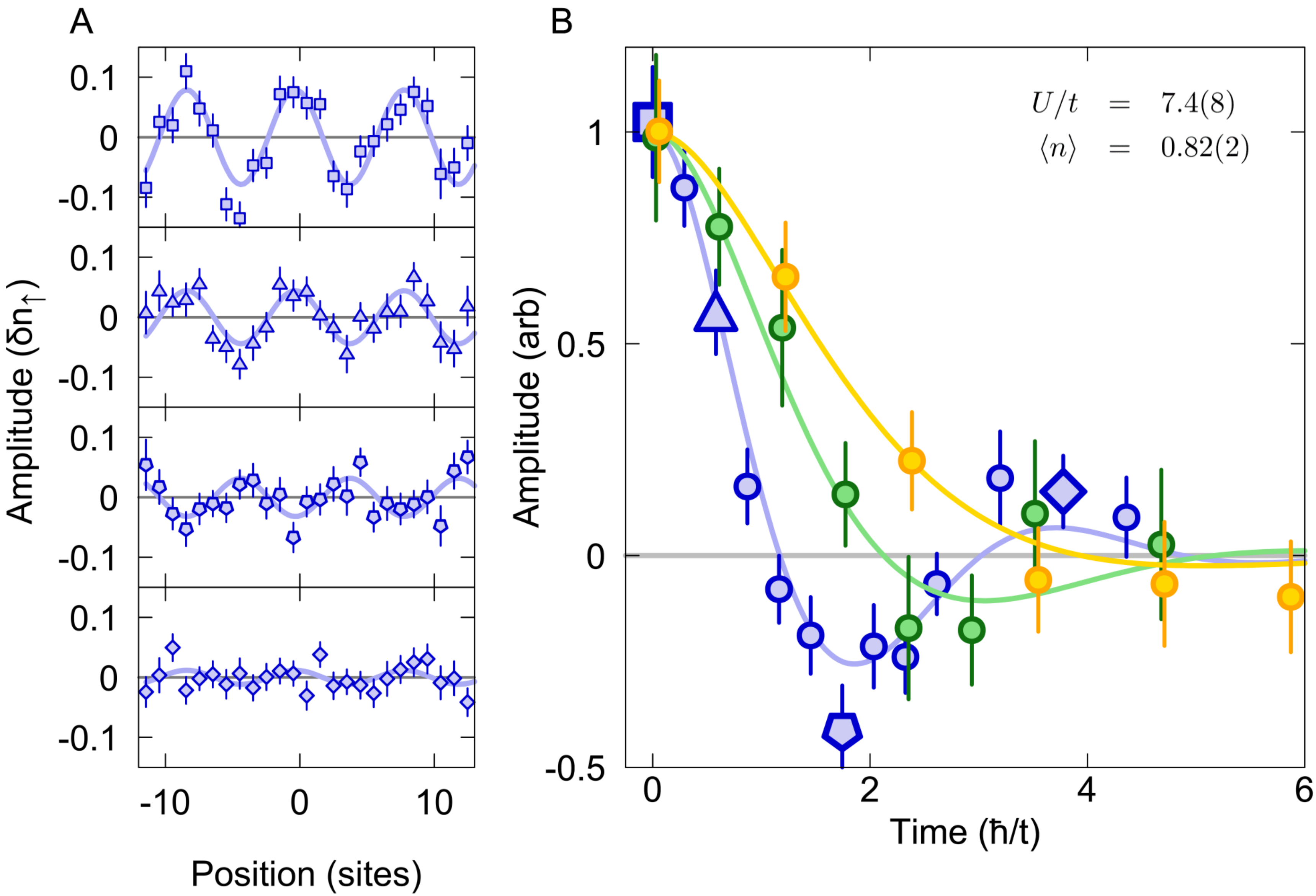

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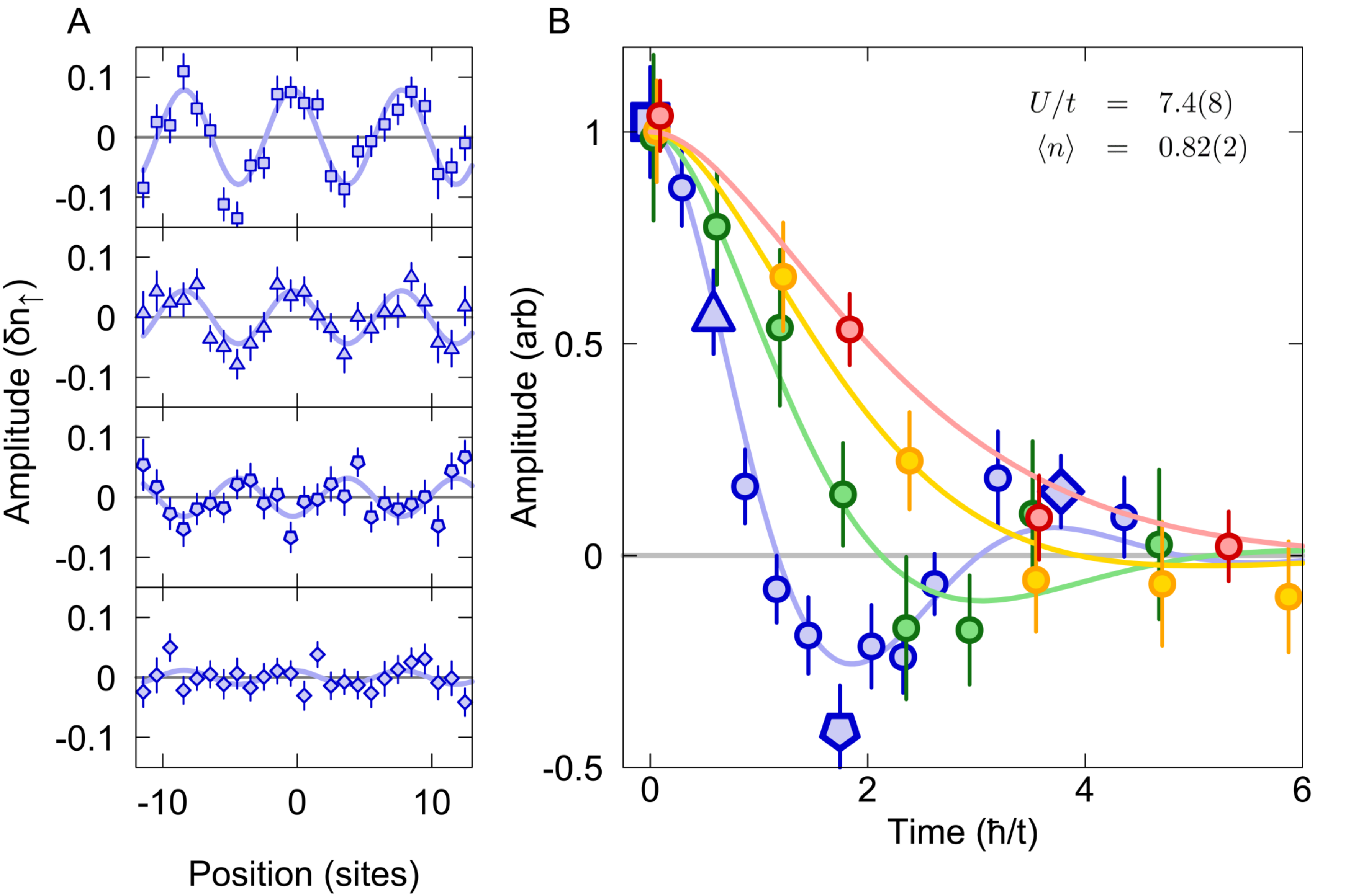


Hydrodynamic Model

- Diffusion (Fick's Law) neglects finite time to establish current.
- D, diffusion constant
- Γ, current relaxation. rate.
- Crossover from diffusive mode to sound mode.

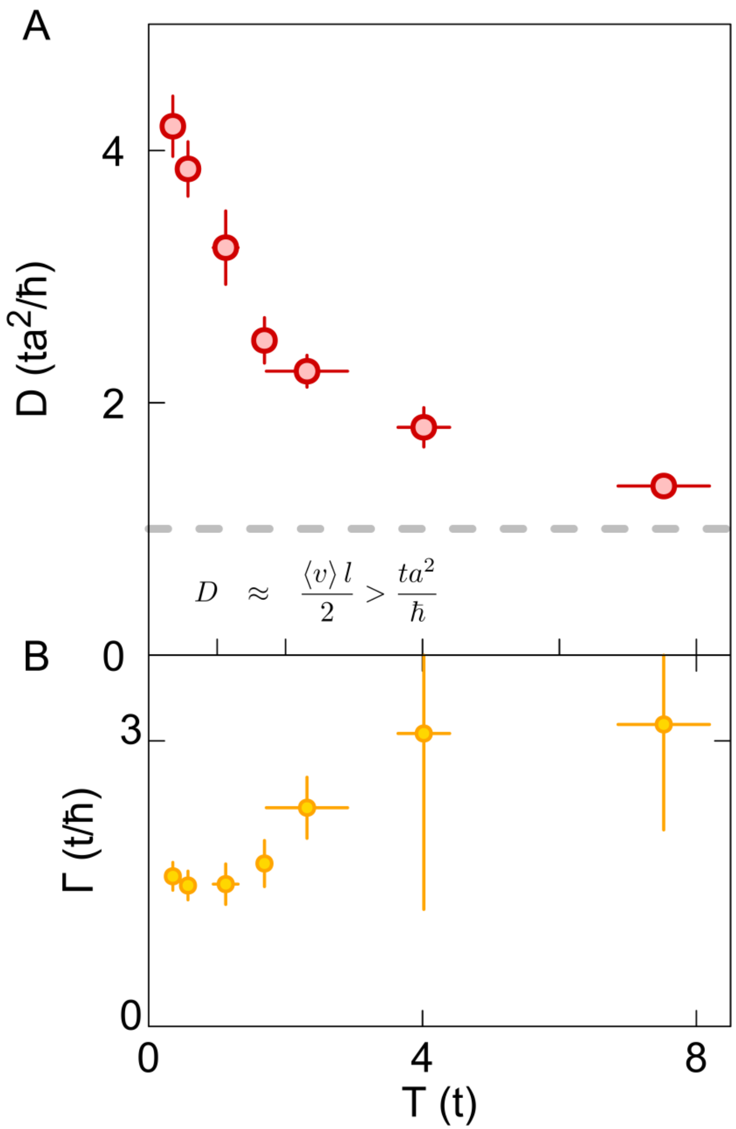
$$\overbrace{\partial_t n(\mathbf{r},t) \quad = \quad -\nabla\cdot\mathbf{J}(\mathbf{r},t)}^{\text{“charge” conservation}}$$

$$\partial_t \mathbf{J}(\mathbf{r},t) \quad = \quad -\Gamma\,(\underbrace{D\nabla n(\mathbf{r},t)+\mathbf{J}(\mathbf{r},t)}_{\text{Fick's Law}})$$

$$\boxed{\partial_t^2 n + \Gamma\partial_t n + \Gamma D k^2 n = 0}$$

Hydrodynamic Parameters

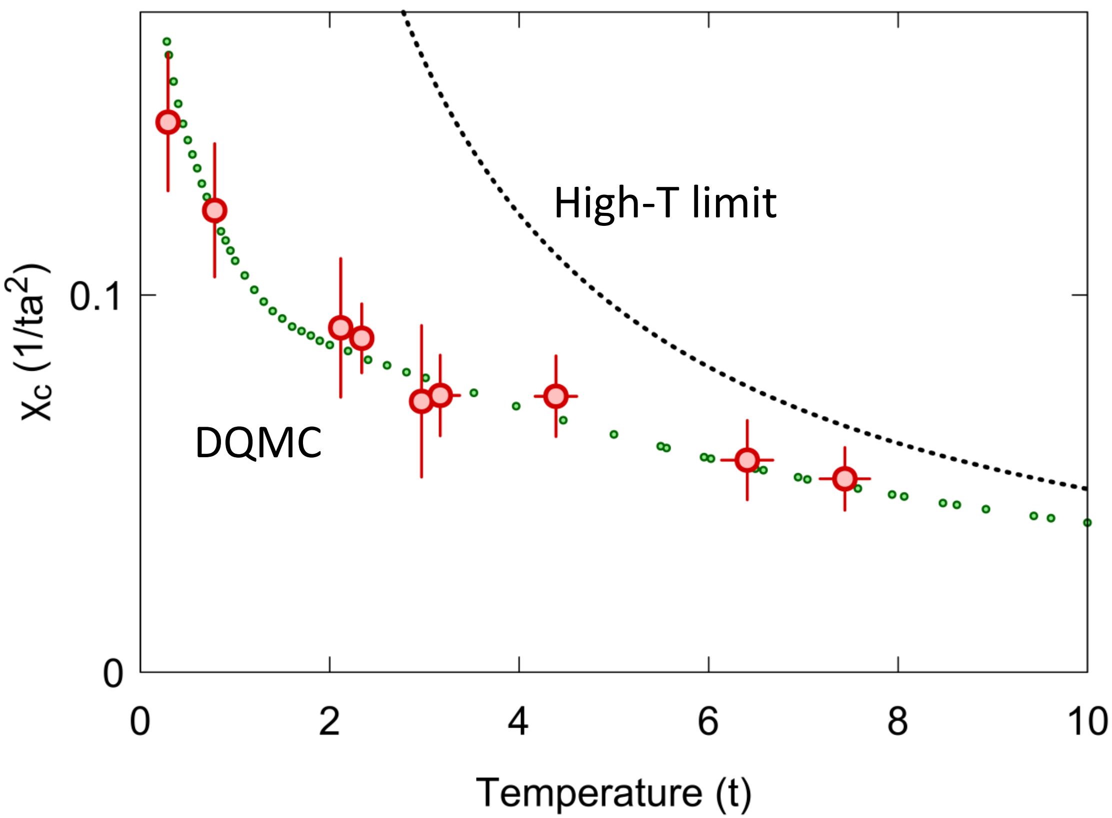
- *Simultaneous* fit of all wavelength data for each temperature
- Low temperature, Pauli blocking closes scattering channels
- D does not violate MIR derived bound.
- Model less sensitive to Γ in overdamped limit.



Compressibility

- Images of both spin states versus chemical potential
- Temperature dependent in this range
- In high temperature limit of single band model:

$$\chi = n(1 - {}^{n}/_{2})/T$$

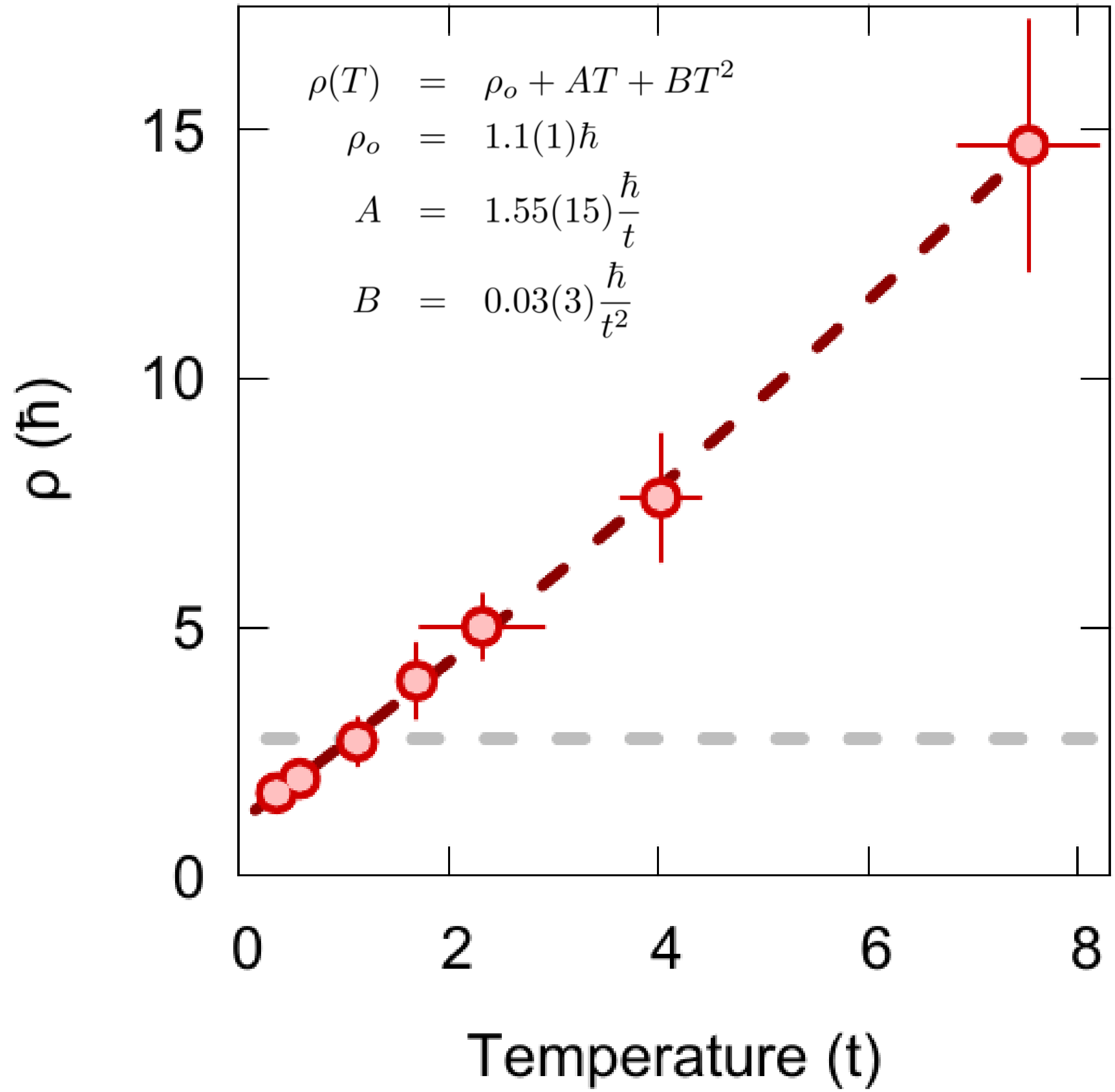


Resistivity Versus Temperature

- Resistivity from Nernst-Einstein $^1/_\rho = \left(\frac{\partial n}{\partial \mu}\right) D$
- Linear over this temperature range
- Exceeds resistivity bound inferred from MIR limit ("bad metal")

$$\rho_{\max} \approx \sqrt{\frac{2\pi}{n}}\hbar$$

Brown *et. al.,* Science **363**, 379 (2019)



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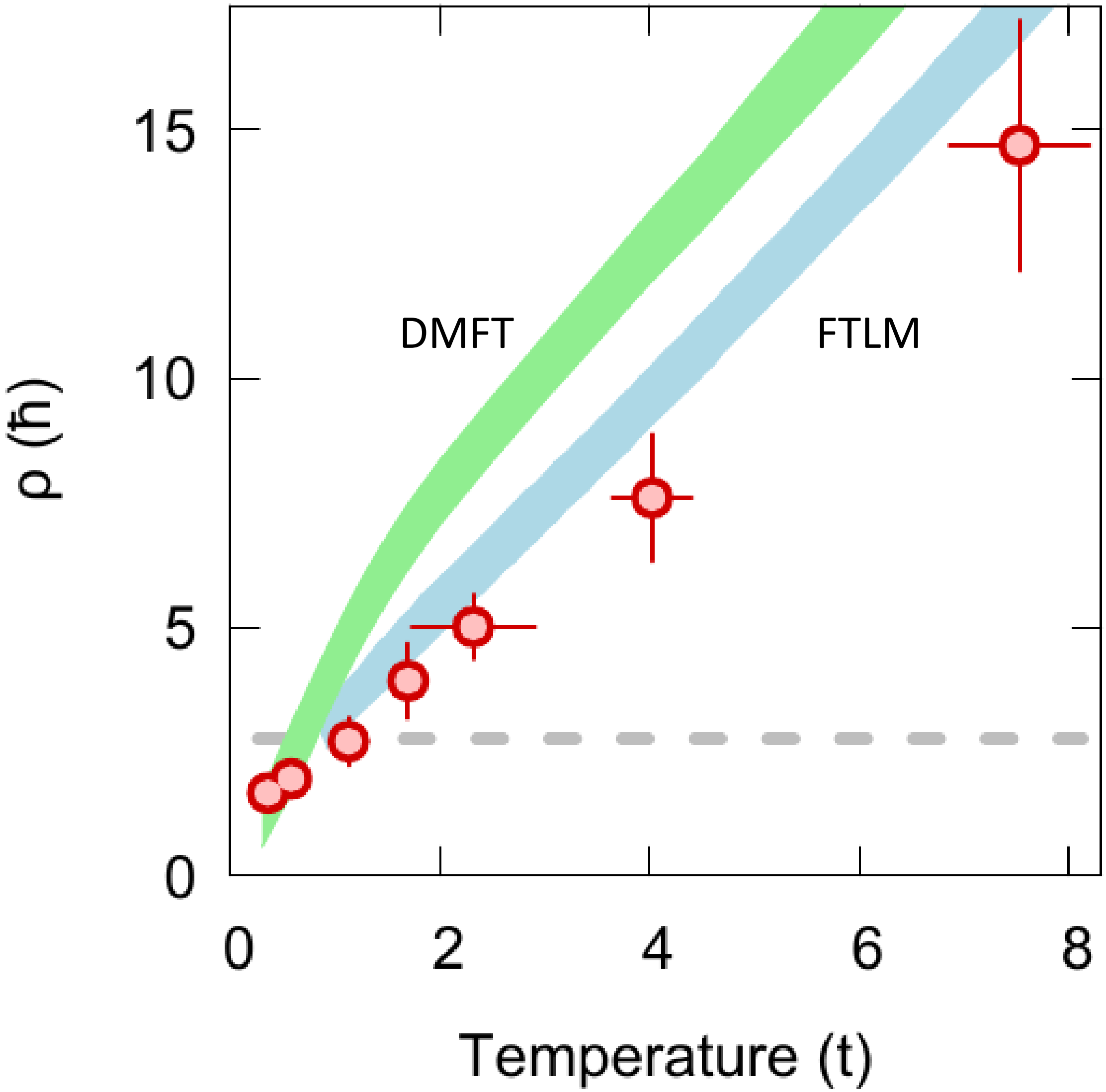

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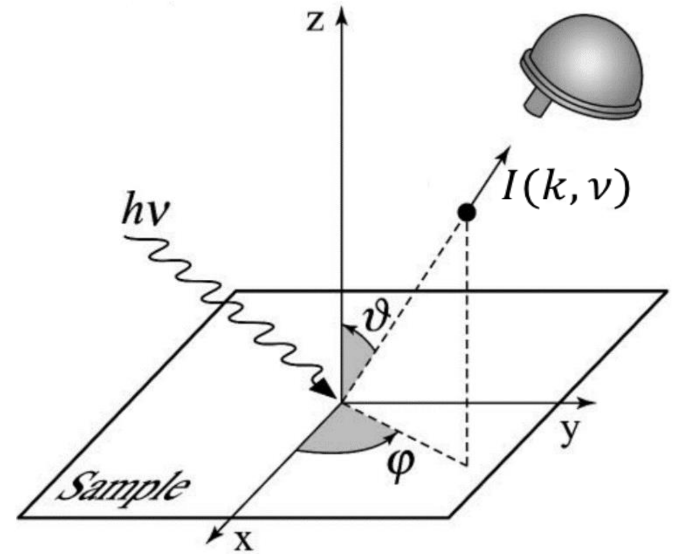
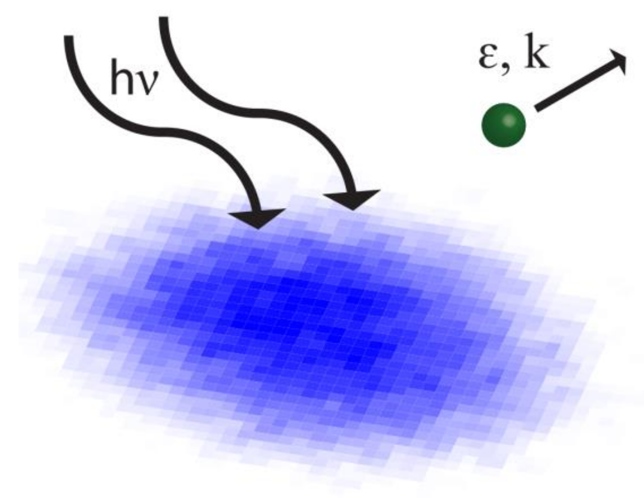
Photoemission spectroscopy

- Using a photon, excite a particle from an interacting system
- Measure the energy and momentum of the ejected particle
- *single-particle* excitations of a many-body system



Rev. Mod. Phys. **75**, 473 (2003)



What does ARPES measure?

- How does an excitation propagate in a many-body system?

$$G^R(k,t) = -i\theta(t)\left\langle \underbrace{c_k(t)c_k^\dagger(0)}_{\text{Remove hole (injection)}} + \overbrace{c_k^\dagger(0)c_k(t)}^{\text{Remove particle (emission)}} \right\rangle$$

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- How does an excitation propagate in a many-body system?
- Momentum resolved density of states

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$$A(k,\omega) = \underbrace{-\frac{1}{\pi}\mathrm{Im}\{G^R(k,\omega)\}}_{\text{Emission + injection}}$$

What does ARPES measure?

- How does an excitation propagate in a many-body system?
- Momentum resolved density of states
- ARPES particle current gives access to *emission*

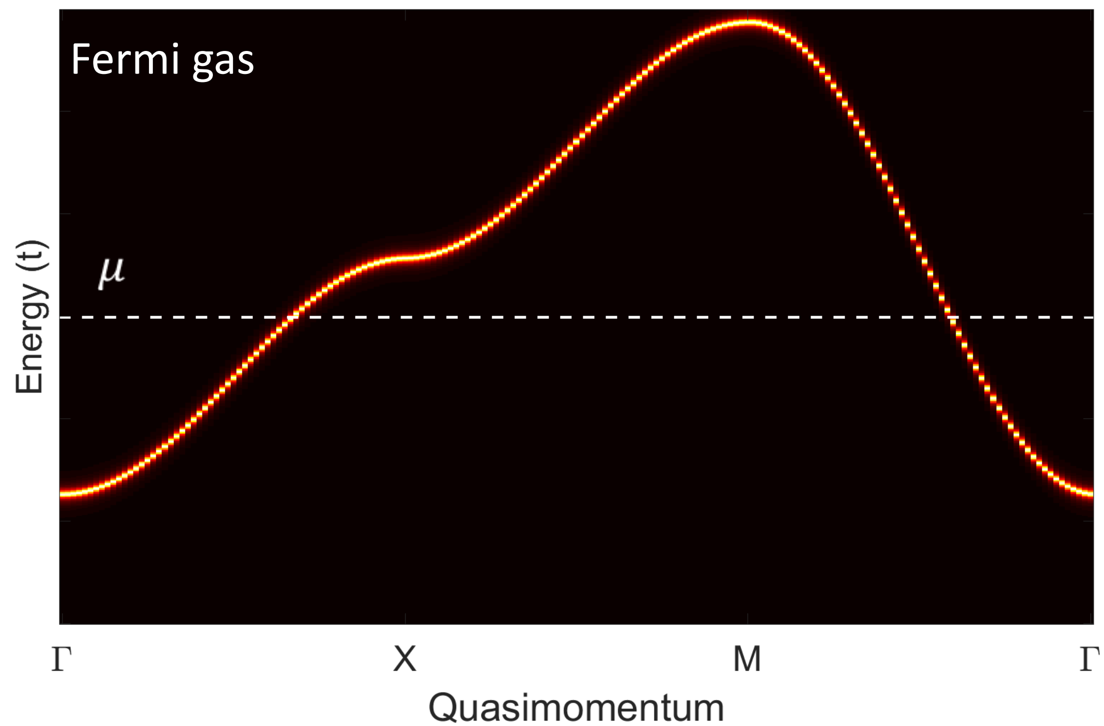
$$G^R(k,t) = -i\theta(t)\left\langle \underbrace{c_k(t)c_k^\dagger(0)}_{\text{Remove hole (injection)}} + \overbrace{c_k^\dagger(0)c_k(t)}^{\text{Remove particle (emission)}} \right\rangle$$

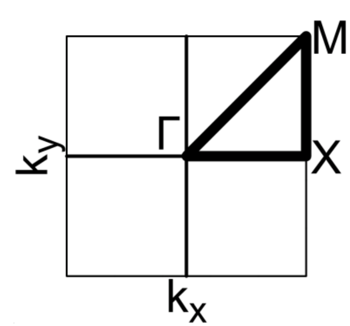
$$A(k,\omega) = \underbrace{-\frac{1}{\pi}\mathrm{Im}\{G^R(k,\omega)\}}_{\text{Emission + injection}}$$

$$A^-(k,\omega) = \underbrace{A(k,\omega)f(\omega)}_{\text{Emission only}}$$

The BCS limit

- Fermi gas, excitations have definite momentum and energy
- BCS, pairing appears as a gap
- Dispersion exhibits "backbending"





$$A(k,\omega) = \delta(\xi_k - \omega)$$

$$|\mathrm{FG}\rangle = \prod_{k<k_f} c_k^\dagger |0\rangle$$

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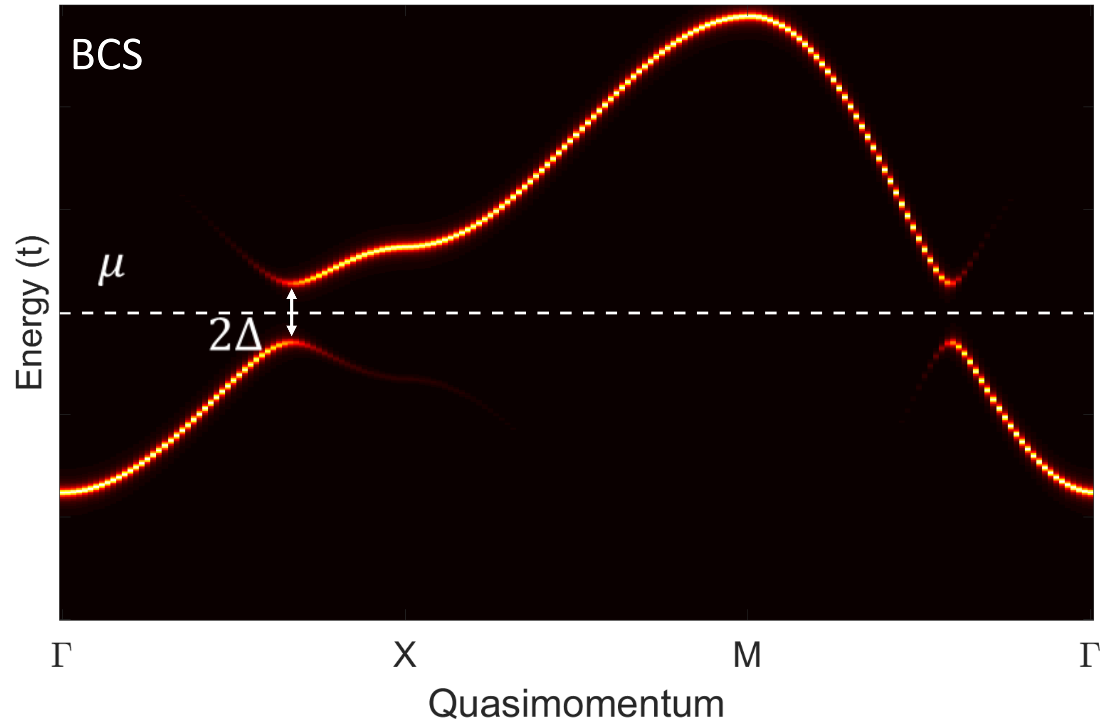


$$A(k,\omega) \quad = \quad \left|v_k^2\right| \delta(E_k+\omega) + \left|u_k^2\right| \delta(E_k-\omega)$$

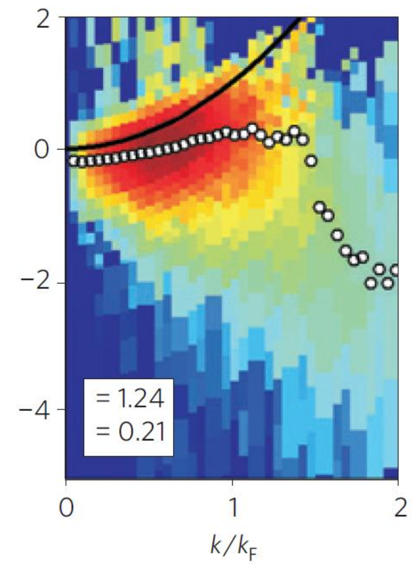
$$|\mathrm{BCS}\rangle \quad = \quad \prod_k \left(u_k + v_k c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger\right)|0\rangle$$

Pseudogaps

- Depression in the spectral function at the Fermi energy.
- Cold atom experiments: backbending in dispersion above T_c.
- Observed in High-T_c superconductors and unitary Fermi gas
- HTSC, PG origin controversial: precursor to SC or indicative of a competing order.

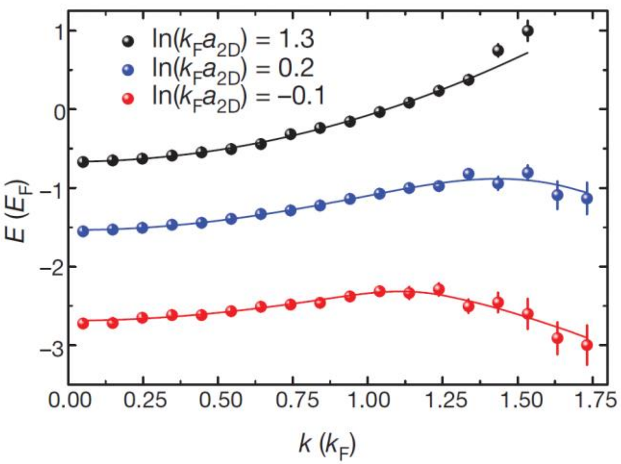
Pseudogap reviews:
Low Temp. Phys. **41**, 319 (2015)
Rep. Prog. Phys. **80**, 104401 (2017)

3D Fermi Gas



Stewart … Jin, Nature 454, 744 (2008)
Gaebler … Jin, Nature Phys. **6**, 569 (2010)

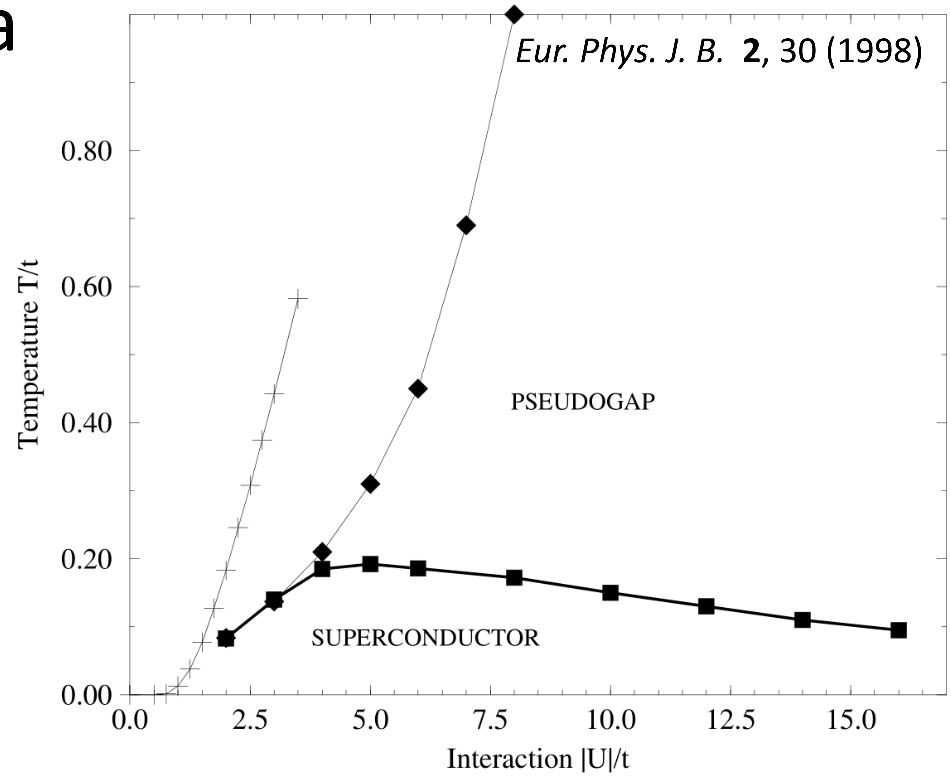
2D Fermi Gas

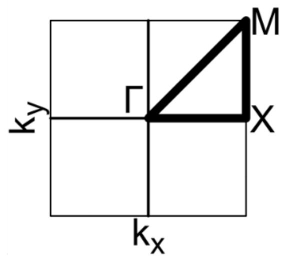


Feld … Kohl, Nature **480**, 75-78 (2011)

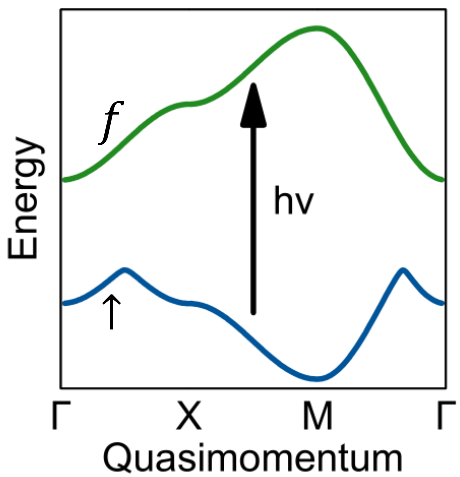
Pseudogap in the attractive Hubbard model

- Accessible model: on a lattice and no DQMC sign problem.
- BEC-BCS crossover with interaction strength.
- Temperatures near state-of-the-art for experiment



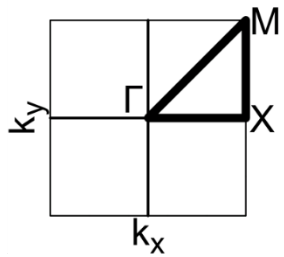


ARPES with a QGM



$$\mathcal{H} = \underbrace{\mathcal{H}_o}_{\text{Hubbard system}} - \Omega \sum_k \left(\underbrace{c^\dagger_{kf} c_{k\uparrow} + c^\dagger_{k\uparrow} c_{kf}}_{\text{rf probe}} \right)$$

- Radiofrequency photon transfers to non-interacting state but preserves momentum



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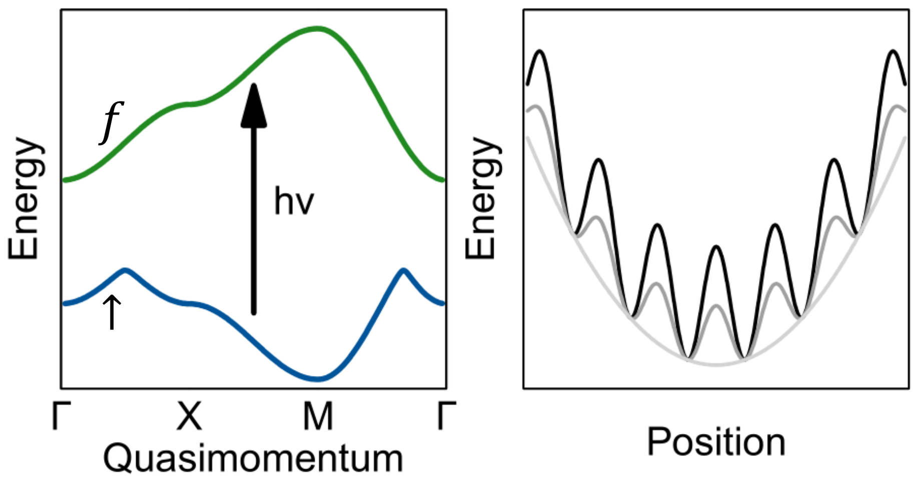
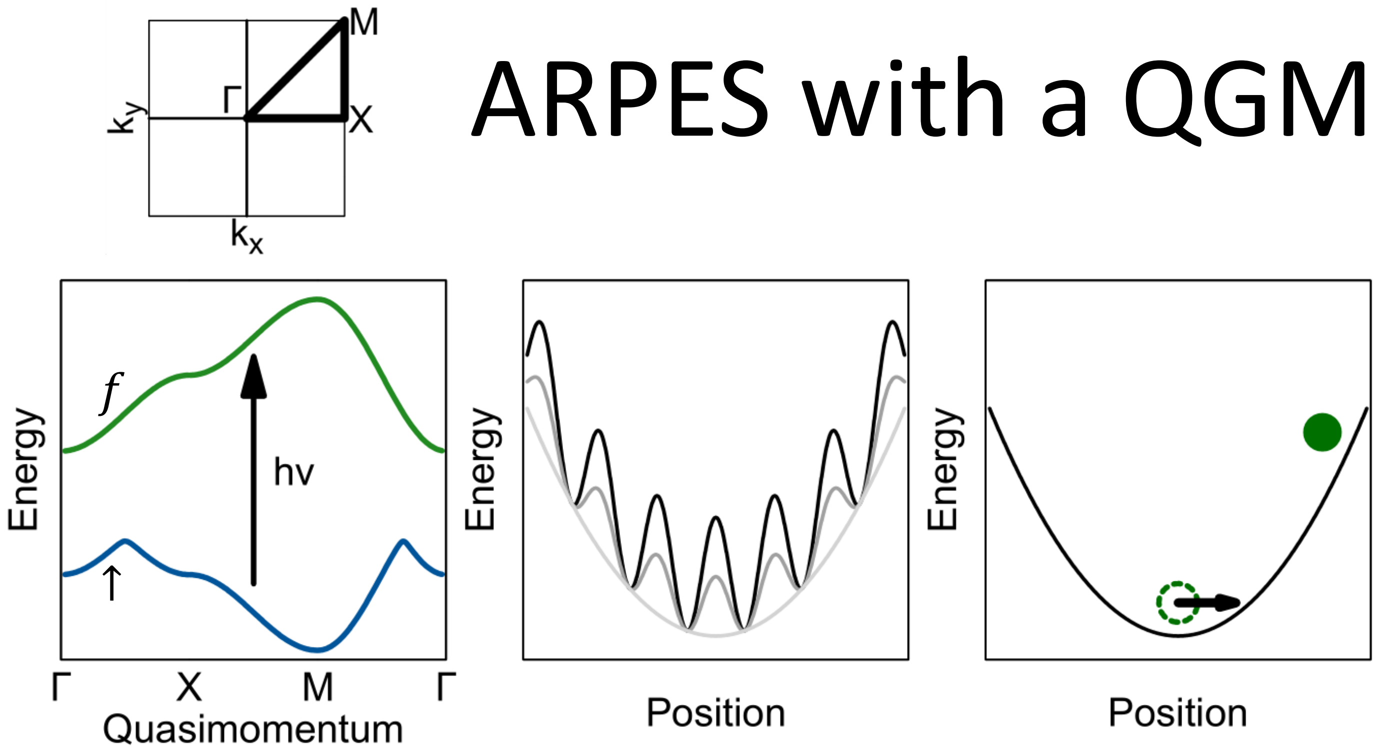


- Radiofrequency photon transfers to non-interacting state but preserves momentum
- Band mapping transforms quasimomentum to real momentum

ARPES with a QGM



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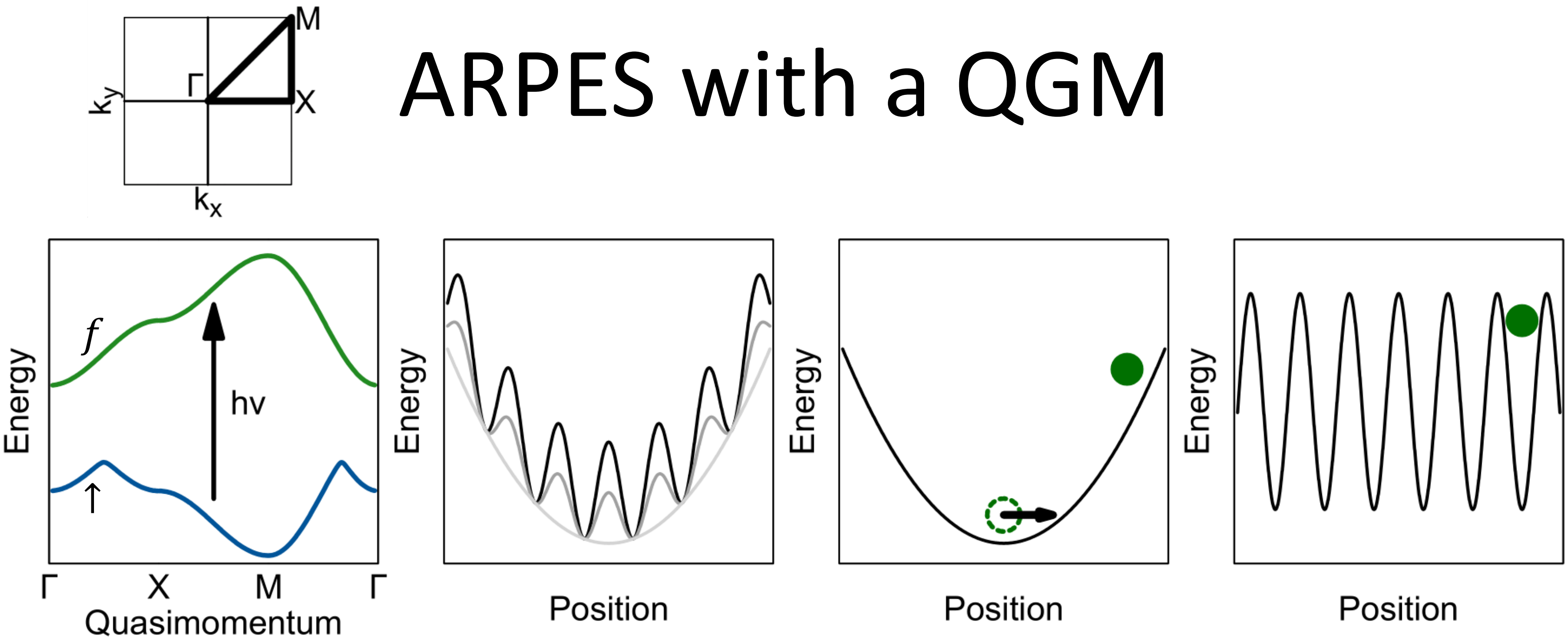
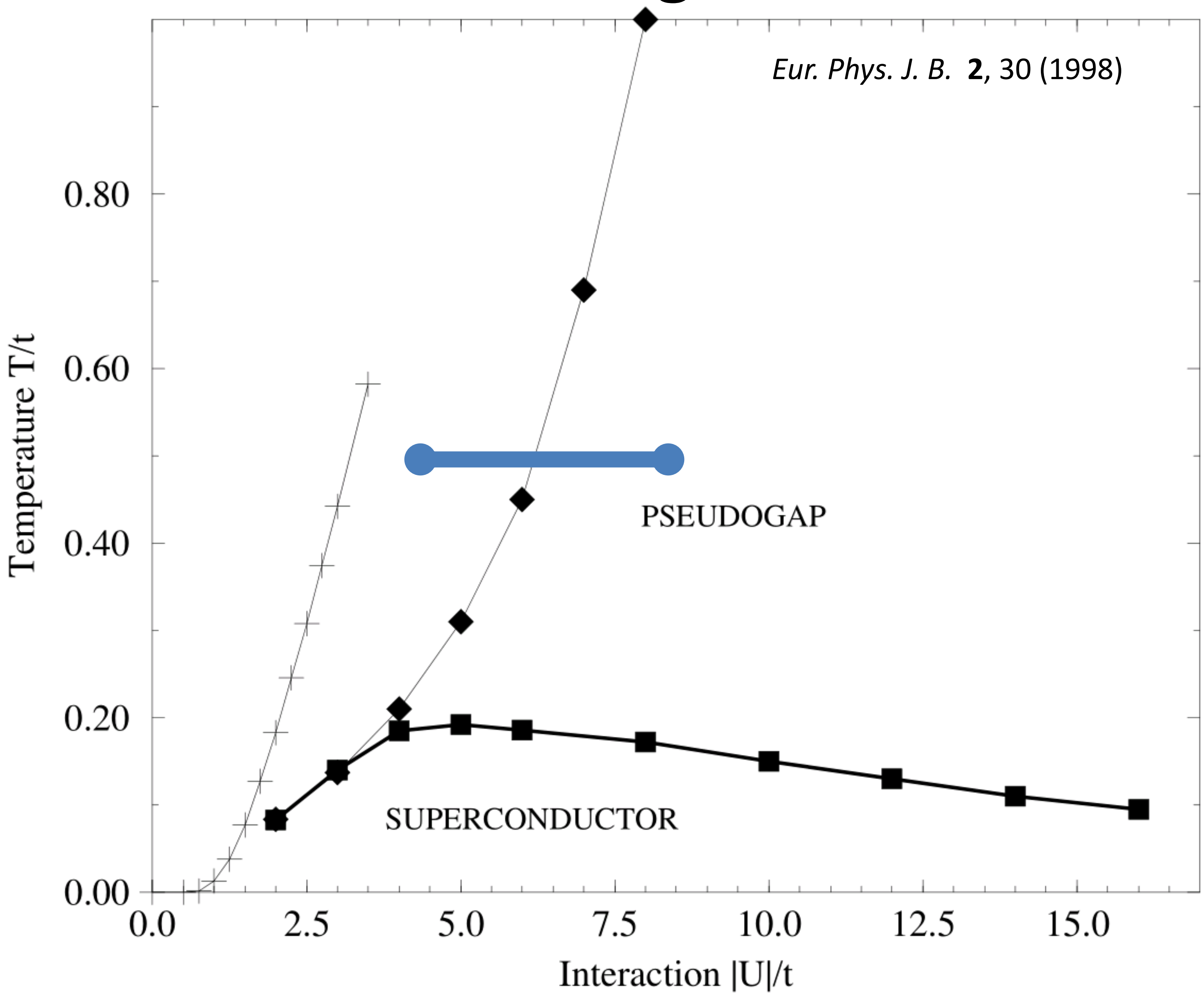


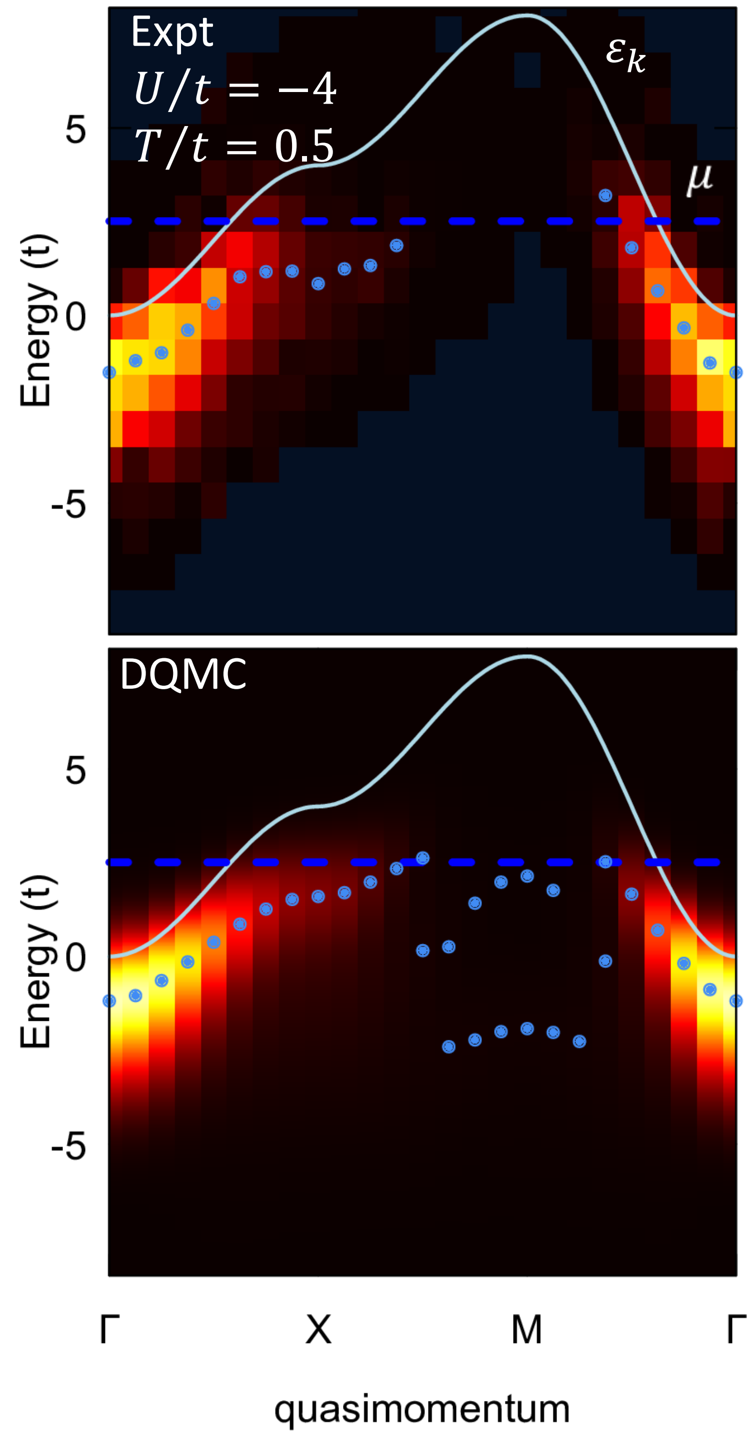
- Radiofrequency photon transfers to non-interacting state but preserves momentum
- Band mapping transforms quasimomentum to real momentum
- $T/_4$ expansion in harmonic trap maps momentum space to real space (similar to time-of-flight measurement)
- Freeze atoms in deep lattice and detect

ARPES data: increasing interaction strength



ARPES data: increasing interaction strength

- Determine $U/t, T/t$, and μ/t from fitting correlators to equilibrium DQMC
- Spectral weight shifts to lower energy ($U < 0$)
- Spectral peak shifts away from μ at stronger interaction



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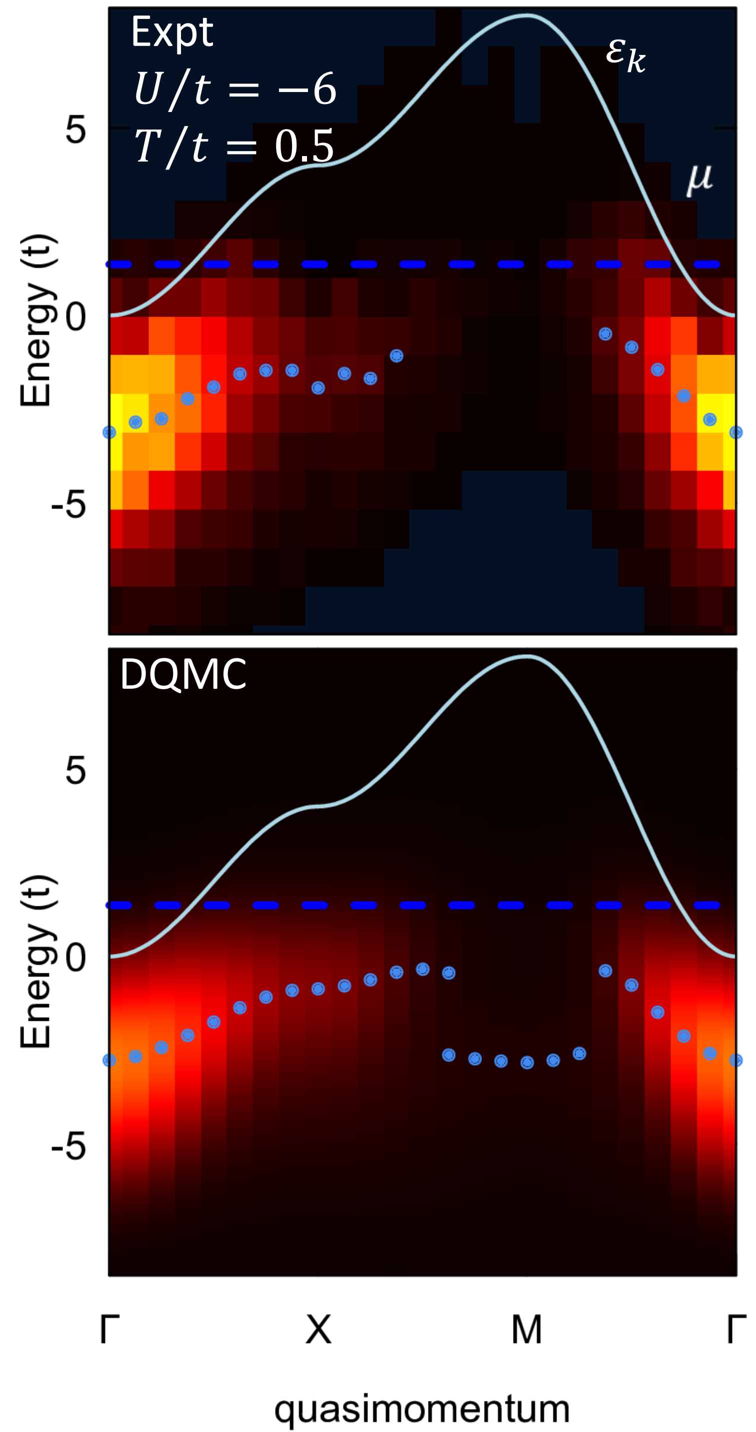

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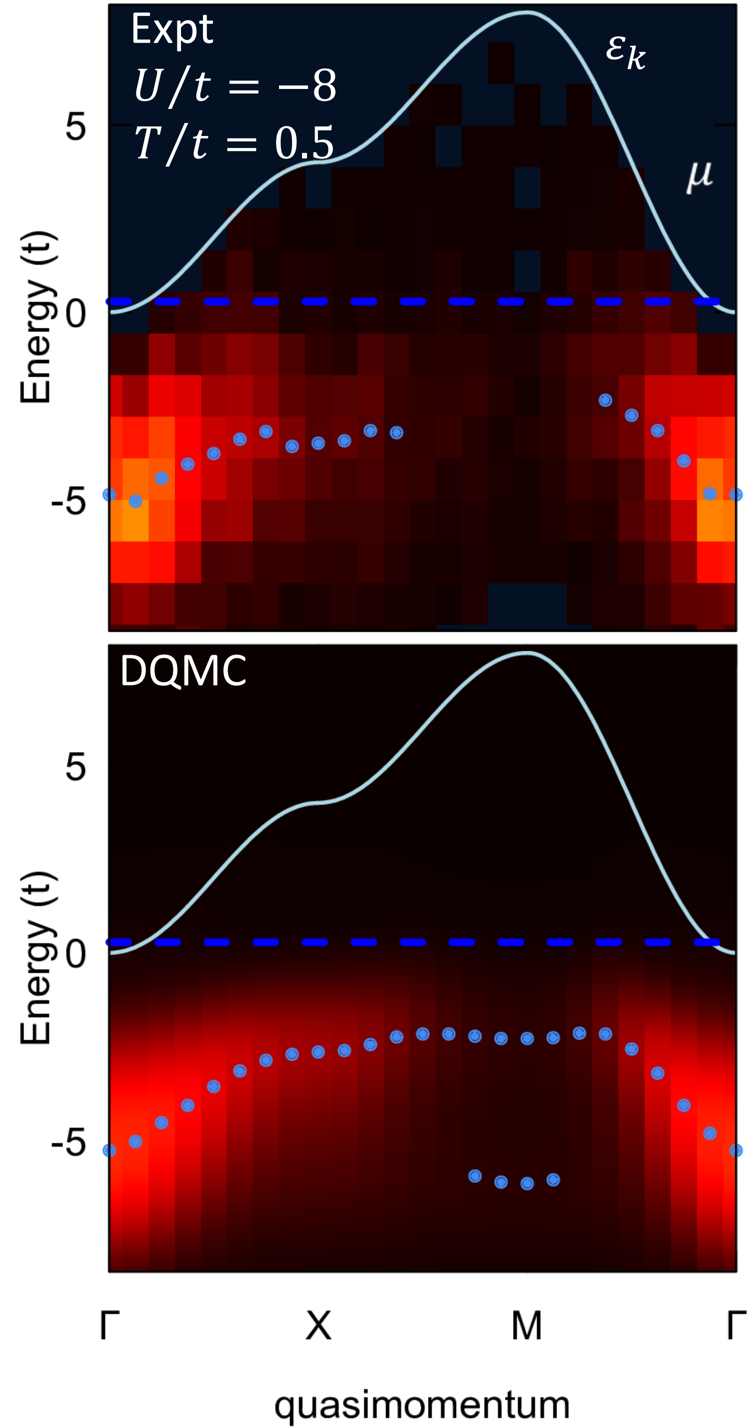

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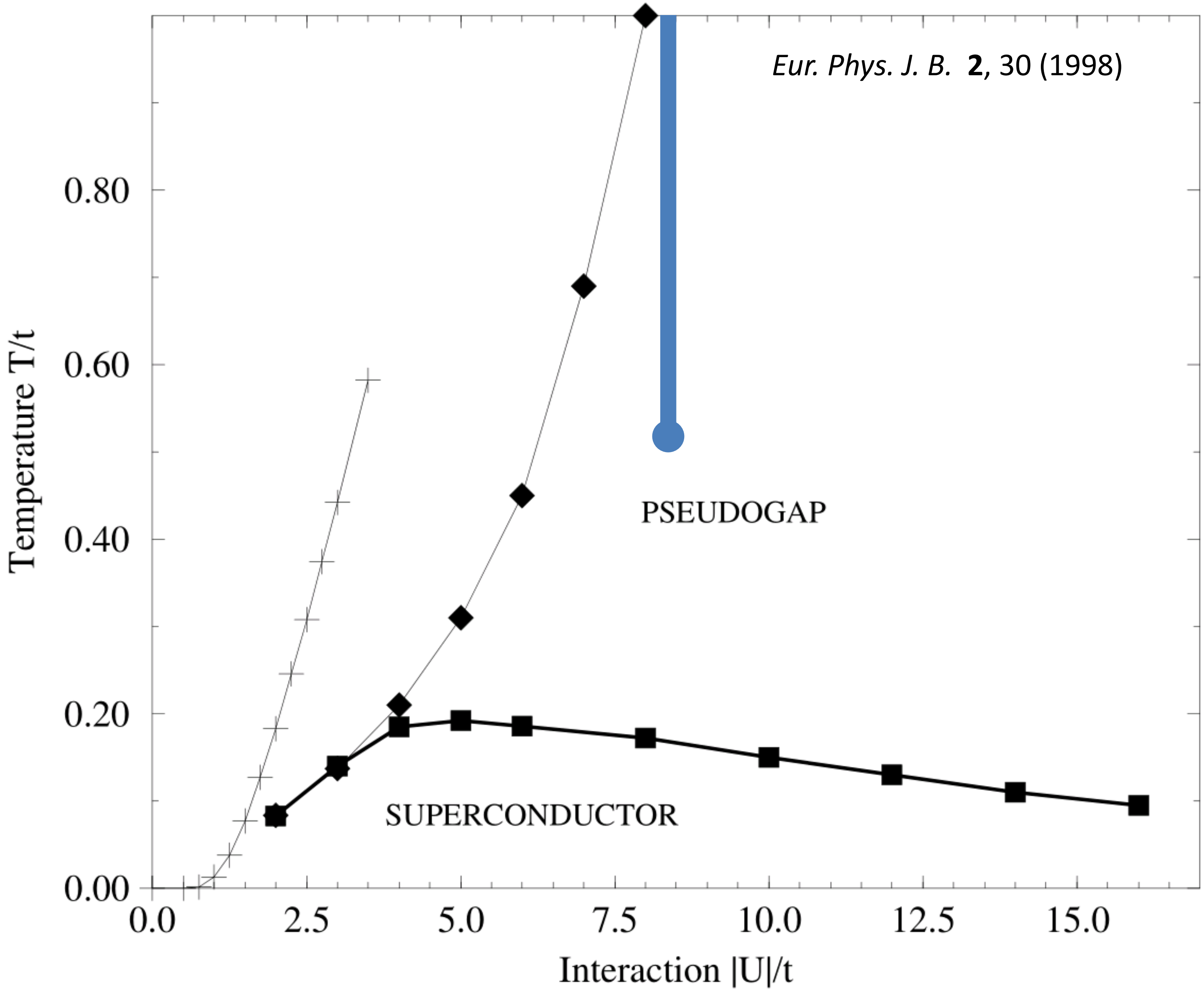
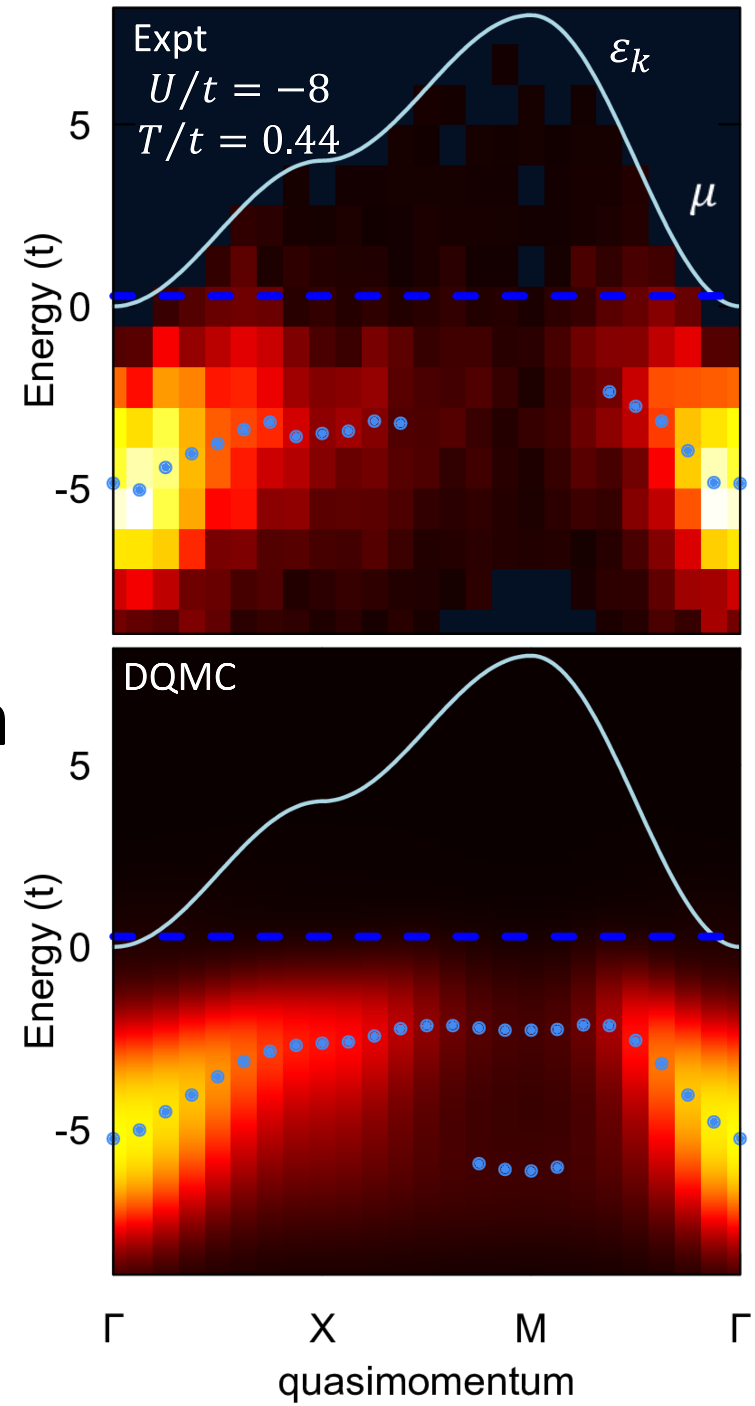


ARPES data: increasing temperature

- Determine U/t, T/t, and μ/t from fitting correlators to equilibrium DQMC
- Second branch emerges with increasing temperature
- Lower branch: doublons
- Upper branch: singles



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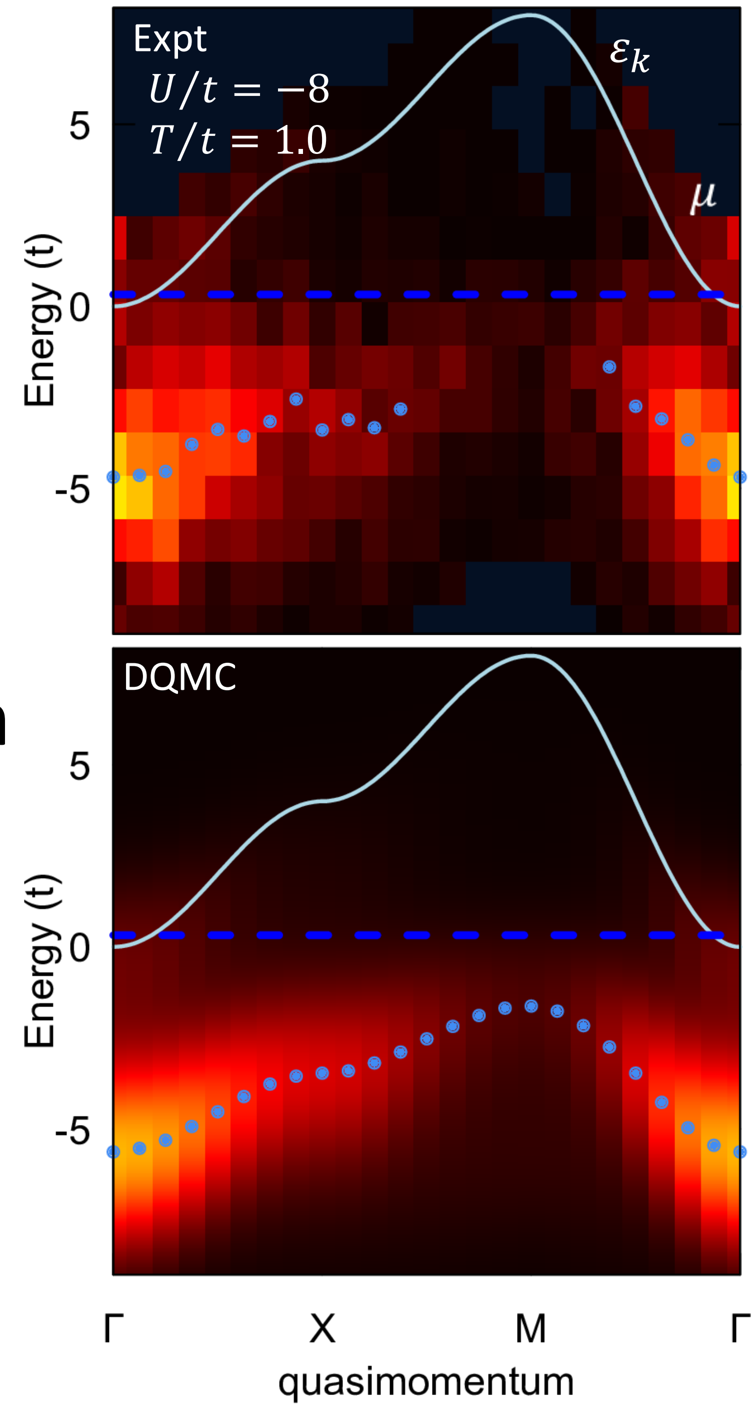

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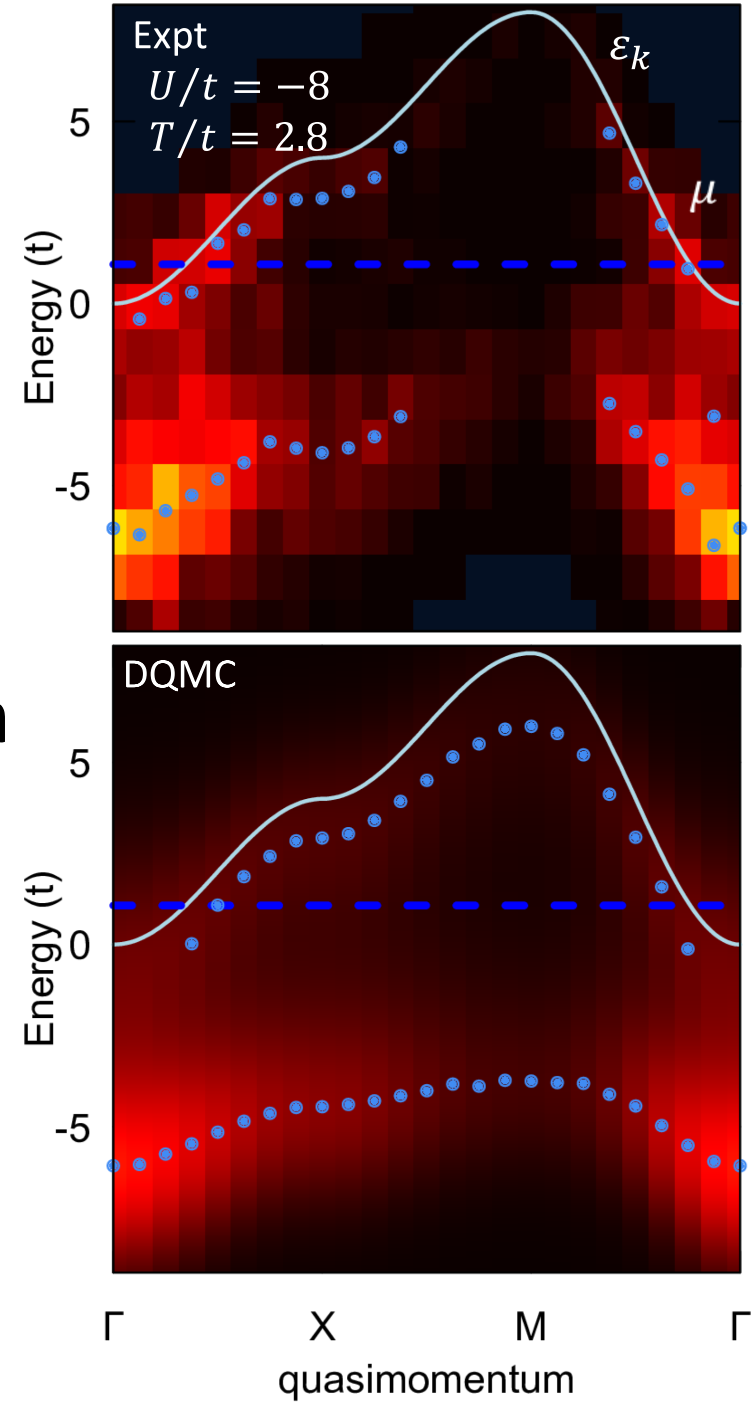

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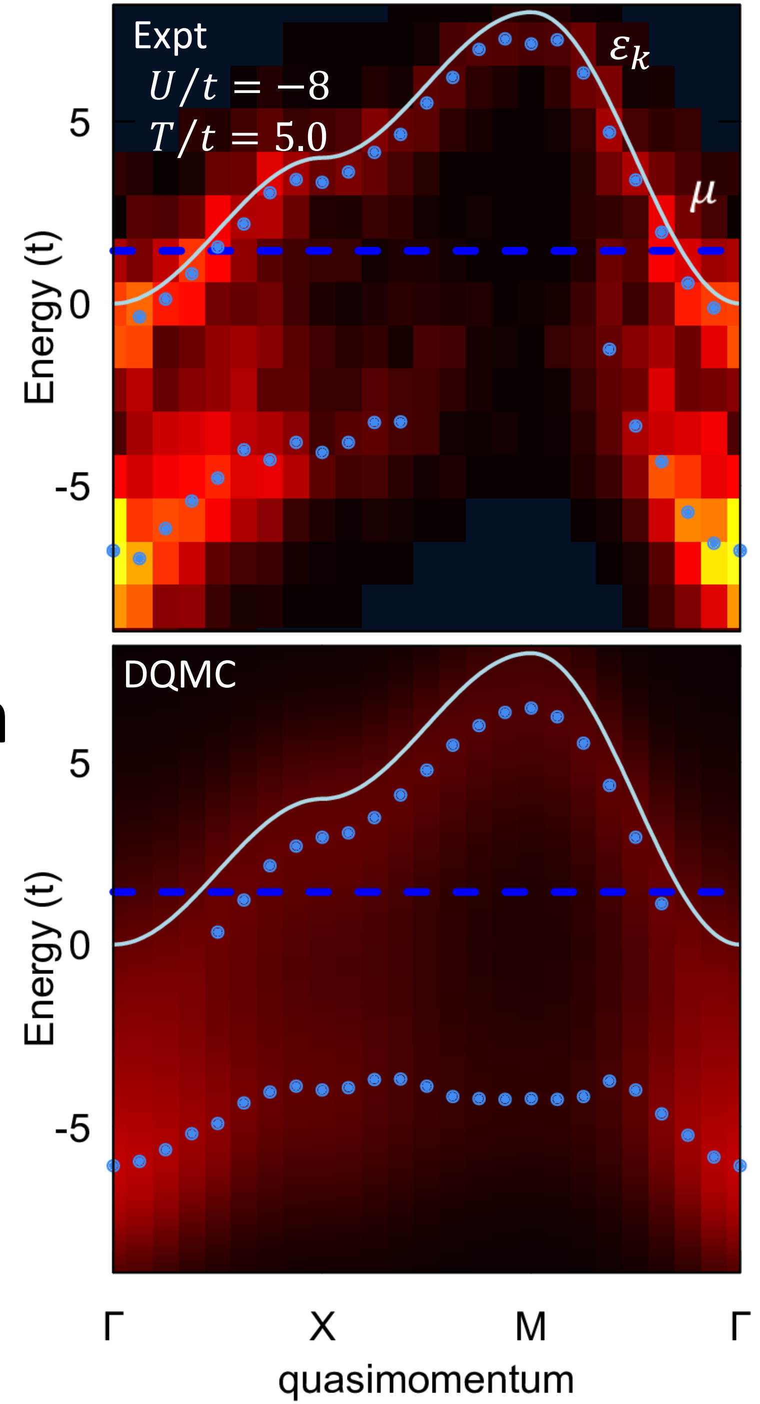
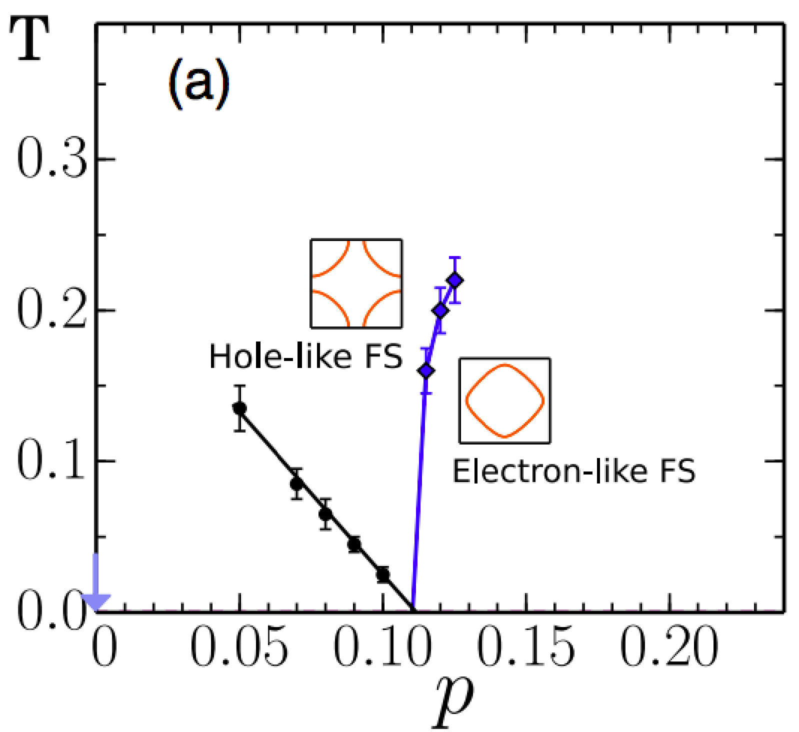


Challenges and opportunities

Pseudogap and Fermi-Surface Topology in the Two-Dimensional Hubbard Model

Wei Wu, Mathias S. Scheurer, Shubhayu Chatterjee, Subir Sachdev, Antoine Georges, and Michel Ferrero
Phys. Rev. X **8**, 021048 – Published 22 May 2018

- ARPES of repulsive model: further cooling is a key challenge.
  - ➢ Entropy redistribution.
  - ➢ Immersion in bosonic baths.
  - ➢ Floquet engineering of t-J models.
- Dynamical observables
  - More challenging for theory
  - Test approximations
  - Toolkit small compared with materials



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