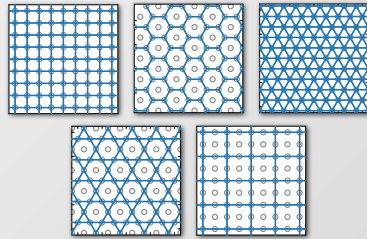




Fourier synthesize arbitrary lattices:

- Square
- Hexagonal/Triangular/Brick Wall
- Kagomé
- Superlattices
- Spin dependent lattices
- Flux Lattices
- ...



Full dynamical control over lattice depth, geometry, dimensionality!



Hubbard Regime Tweezer Arrays

Zoe Z. Yan, ..., W. Bakr, Phys. Rev. Lett. 129, 123201 (2022)

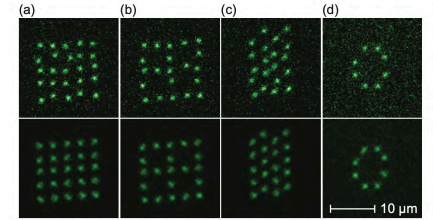
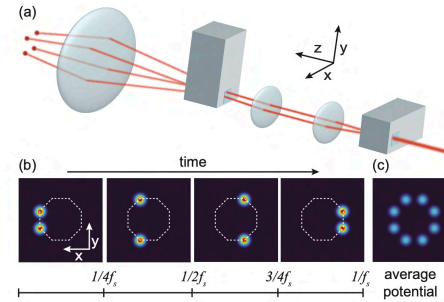
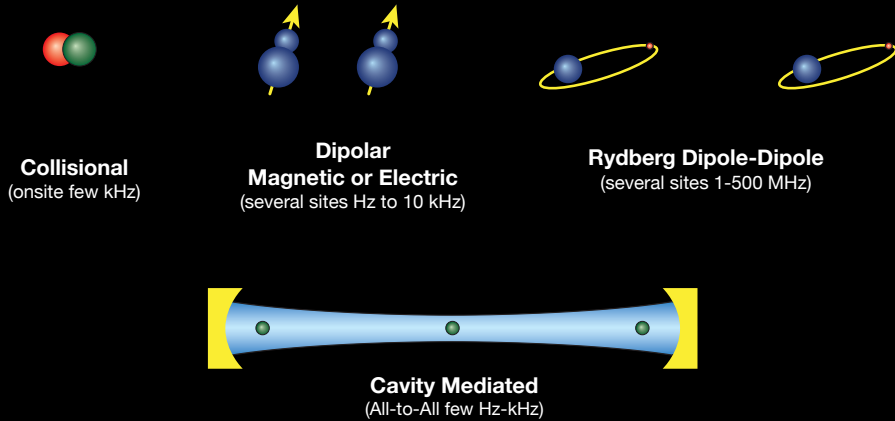


FIG. 2. Examples of band insulators of different geometries, showing (1) a square lattice, (2) a triangular lattice, (3) a kagome lattice, and (4) a brickwork lattice. The top row shows the ground state, and the bottom row shows the first excited state. The atomization rates are 93%, 92%, 91%, 89%, 88%, 87%, 86%, 85%, 84%, 83%, 82%, 81%, 80%, 79%, 78%, 77%, 76%, 75%, 74%, 73%, 72%, 71%, 70%, 69%, 68%, 67%, 66%, 65%, 64%, 63%, 62%, 61%, 60%, 59%, 58%, 57%, 56%, 55%, 54%, 53%, 52%, 51%, 50%, 49%, 48%, 47%, 46%, 45%, 44%, 43%, 42%, 41%, 40%, 39%, 38%, 37%, 36%, 35%, 34%, 33%, 32%, 31%, 30%, 29%, 28%, 27%, 26%, 25%, 24%, 23%, 22%, 21%, 20%, 19%, 18%, 17%, 16%, 15%, 14%, 13%, 12%, 11%, 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, 1%, 0%.

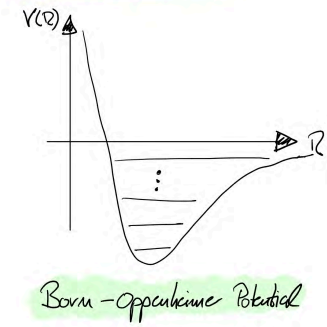
- ▶ Flexible Geometry
- ▶ Dynamical
- ▶ Homogeneity
- ▶ Larger Spacing

Interaction Control



Collisional Interactions

Interaction Potential



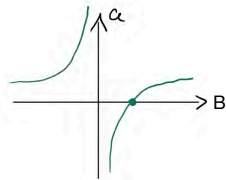
$$\frac{4\pi\hbar^2 a S(r)}{m}$$

$a \hat{=}$ scattering length

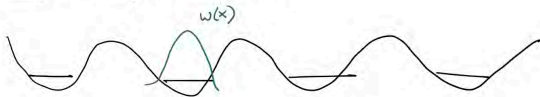
Resonance potential

Feshbach Resonances

$$\alpha(B) = a_{bg} \left(1 + \frac{\Delta}{B - B_0} \right)$$



Lattice (or tightly focused laser)



$$U = \frac{4\pi\hbar^2 a(B)}{m} \int |\psi(x)|^4 dx$$

Interacting Bosons & Fermions on a Lattice

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_{\tau} \epsilon_{\tau} \hat{n}_{\tau} + \frac{1}{2} U \sum_{\tau} \hat{n}_{\tau} (\hat{n}_{\tau} - 1)$$

Bose-Hubbard

$$\hat{H} = -J \sum_{\langle i,j \rangle, \sigma} \hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + U \sum_i \hat{n}_{i,\downarrow} \hat{n}_{i,\uparrow} + V_i \sum_{i,\sigma} i^2 \hat{n}_{i,\sigma}$$

Fermi-Hubbard

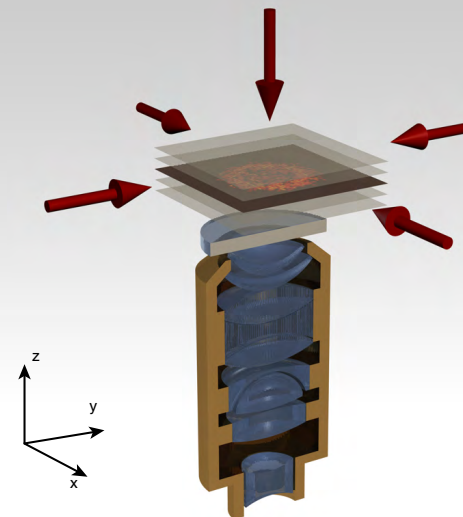
to the Heisenberg spin-1/2 model (half filling, strong interactions)

$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

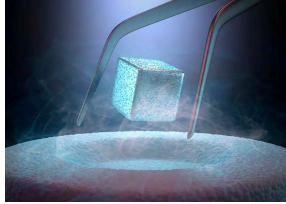
$$J = \frac{4t^2}{U}$$

(Or more generally XXZ Hamiltonian)

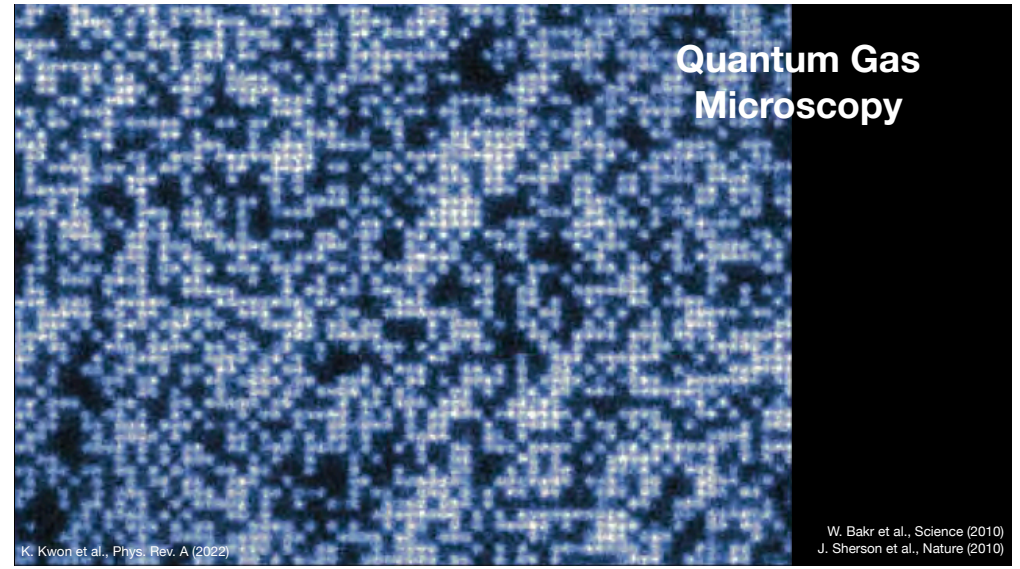
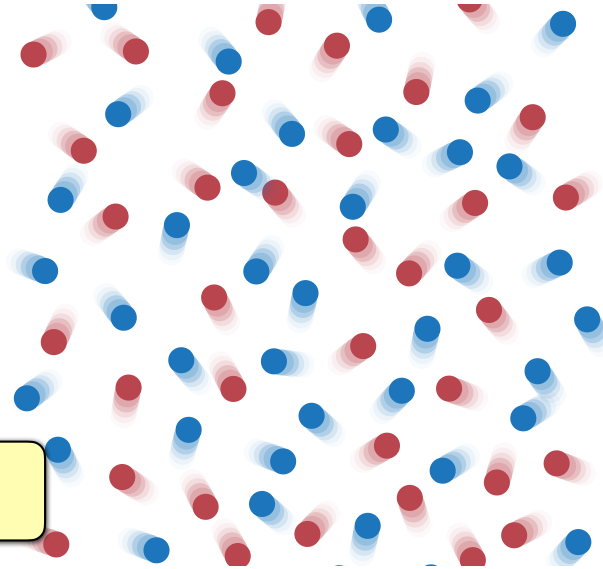
Quantum Gas Microscopy



Quantum Gas Microscopy



The dance of electrons inside a material!



Quantum gas microscopes

BOSONS			FERMIONS				MOLECULES	

Flexible Geometries and Large Sizes

Potential Shaping

Quantum Ladders with flexible edge geometries
(SPT Spin-1 Haldane Phase)

Fully tuneable coupling strengths +dimensionality +flux +frustration

Large Homogeneous 2D Systems

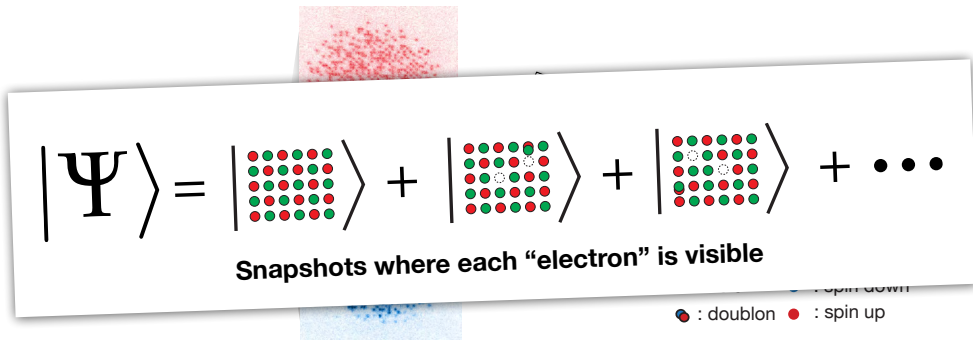
(2000-5000 atoms, filling 95-98%)

Rb Quantum Gas Microscope

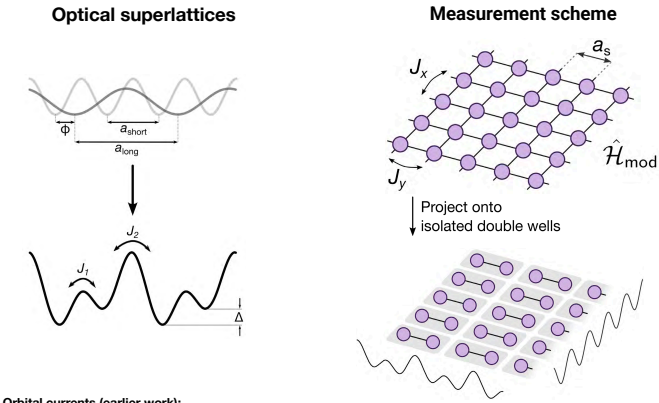
Cs Quantum Gas Microscope

Cs experiment in collaboration with M. Aidelsburger

P. Sompet et al. Nature **606**, 484 (2022)
 Tweezer SPT: Léséluc et al. Science **365**, 6455 (2019)
 see also: C. Chiu et al. Phys. Rev. Lett. **120**, 243201 (2018)
 Idea: J.-S. Bernier et al. Phys. Rev. A **79**, 061601 (2009)
 T.-L. Ho & Q. Zhou arXiv:0911.5506

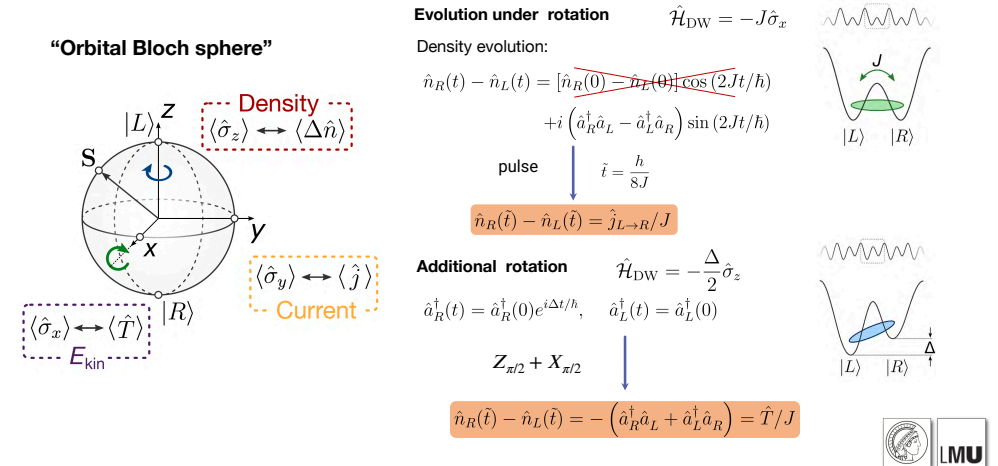
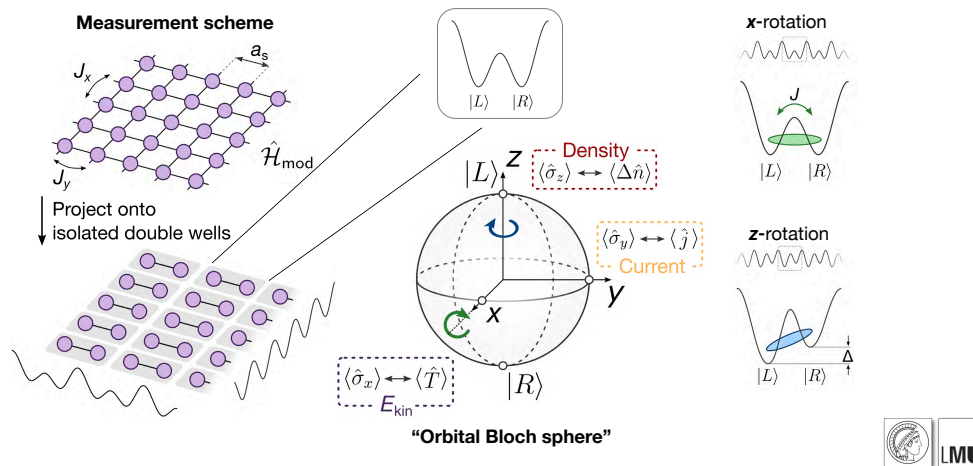


Density and spin readout: M. Boll et al. Science **353**, 1257 (2016), J. Koepsell et al. Phys. Rev. Lett. **125**, 010403 (2020), see also: Harvard (Greiner), Princeton (Bakr) Phys. Rev. Lett. **129**, 123201 (2022), MIT (Zwierlein) Science **381**, 82 (2023)

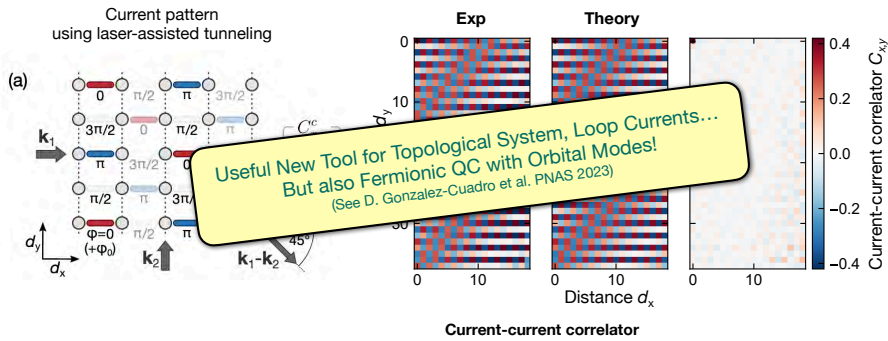


Orbital currents (earlier work):
M. Atala, ... & I. Bloch, Nat. Phys. **10**, 588 (2014).
A. M. Kaufman, ... & M. Greiner, Science **353**, 794 (2016).
Spin currents: C. Schweizer, M. Lohse, R. Citro, I. Bloch Phys. Rev. Lett. **117**, 170405 (2016)
Fermions: T. Chalopin, ... I. Bloch, T. Hilker Phys. Rev. Lett. **134**, 053402 (2025).

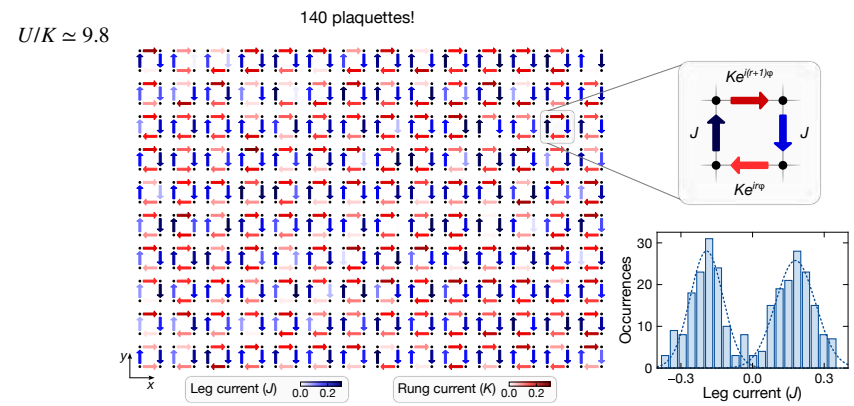
A. Impertro et al. Phys. Rev. Lett. **133**, 063401 (2024) see also SC qubits: B. Du, R. Suresh, S. López, J. Cadiente, R. Ma, Phys. Rev. Lett. **133**, 060601 (2024).



Single-shot read-out → measure correlations!



A. Impertro, et al. Phys. Rev. Lett. 133, 063401 (2024)



A. Impertro, S. Huh, S. Karch, J. F. Wienand, I. Bloch, M. Aidelsburger, Nature Physics (2025)

Quantum Dimer Models & Spin Liquids

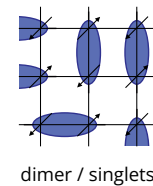


S. Karch et al. (arXiv:2604.24744)

Quantum dimer models

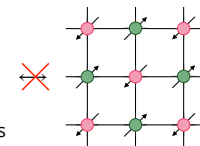
historically: study high- T_c superconductors

→ local constraint on nearest-neighbors



Novel many-body phenomena:

- Topological order
- Emergent gauge fields
- Fractionalized excitations
- Exotic critical points



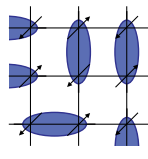
Quantum spin models

Reviews:

- Moessner & Raman, arXiv:0809.3051
- Savary & Balents, Rep. Prog. Phys. 80 (2016)
- Zhou et al., Rev. Mod. Phys. 89 (2017),...

Quantum dimer models

historically: study high- T_c superconductors → local constraint on nearest-neighbors



dimer / singlets

Novel many-body phenomena:

- Topological order
- Emergent gauge fields
- Fractionalized excitations
- Exotic critical points

Gauss's law:

hard constraint on sites of the lattice!
→ **restricts Hilbert space**



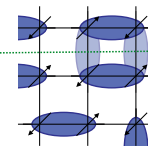
Reviews:

Moessner & Raman, arXiv:0809.3051
Savary & Balents, Rep. Prog. Phys. 80 (2016)
Zhou et al., Rev. Mod. Phys. 89 (2017),...

Quantum dimer models

historically: study high- T_c superconductors → local constraint on nearest-neighbors

winding number



dimer / singlets

Novel many-body phenomena:

- Topological order
- Emergent gauge fields
- Fractionalized excitations
- Exotic critical points

Gauss's law:

hard constraint on sites of the lattice!
→ **restricts Hilbert space**



Required ingredients:

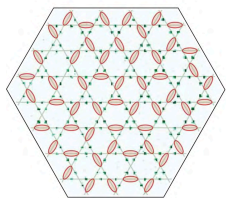
- non-trivial local constraints
- local quantum dynamics

Challenge for synthetic & real materials!

Reviews:

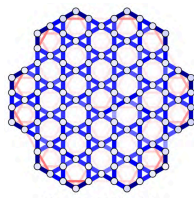
Moessner & Raman, arXiv:0809.3051
Savary & Balents, Rep. Prog. Phys. 80 (2016)
Zhou et al., Rev. Mod. Phys. 89 (2017),...

Quantum Spin Liquid Candidate



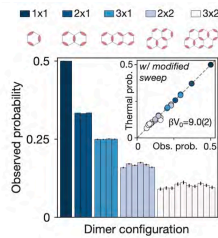
Semeghini, ..., Lukin
Science **374**, 1242 (2021)

Dirac Spin Liquid Candidate

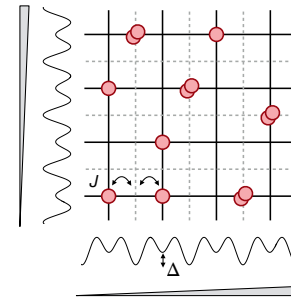


Bornet, ..., Browaeys,
arXiv:2602.14323

U(1) Spin Liquid Lakes



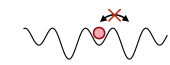
Geim, ..., Lukin,
arXiv:2602.18555



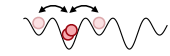
2D superlattice Bose-Hubbard model:

$$\hat{H} = -J_i \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \text{h.c.}) + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1) + \frac{\Delta_i}{2} \sum_i (-1)^i \hat{n}_i$$

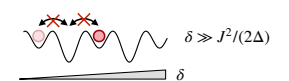
• Single-particle tunneling suppressed by $\Delta \gg J$



• Resonant correlated tunneling for $\Delta = U/2$



→ add linear tilt to protect local U(1) symmetry



String breaking: González-Cuadra, et al. (Quera) Nature **642**, 321–326 (2025); Cochran, et al. (Google) Nature **642**, 315–320 (2025)
Disorder-free localization: Google Quantum AI arXiv:2410.06557; **Qudit circuit with trapped ions:** Meth, ..., Ringbauer Nat. Phys. **21**, 570–576 (2025)

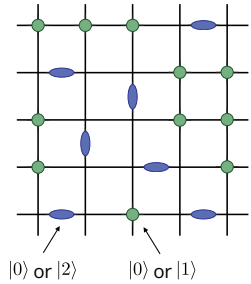
see also: J. J. Osborne et al., Commun. Phys. **8**, 273 (2025)
Halimeh et al., PRX Quantum (2021); Lang et al., PRB (2022)

1D: B. Yang et al. Nature **587**, 392–396 (2020); Z.-Y. Zhou et al., Science **377**, 311 (2022);
H.-Y. Wang et al., PRL **131**, 050401 (2023); W.-Y. Zhang et al., Nat. Phys. **21**, 155 (2025)

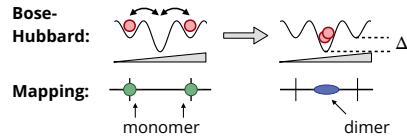
Monomer Dimer Model with Ultracold Atoms

Effective Hamiltonian

$$\hat{H}_{\text{eff}} = \sum_V \tau_i (|+\bullet+\rangle\langle-\bullet-\rangle + \text{h.c.}) - m_i |+\bullet+\rangle\langle+\bullet+|$$



- Resonant correlated tunneling for $\Delta = U/2$



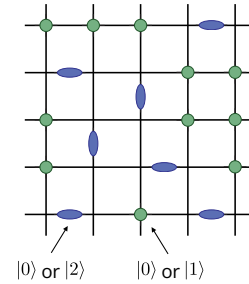
- Mass m is detuning from resonance

see also: J. J. Osborne et al., Commun. Phys. 8, 273 (2025); Halimeh et al., PRX Quantum (2021); Lang et al., PRB (2022)

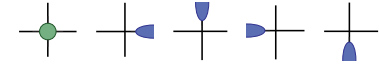
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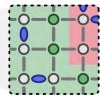
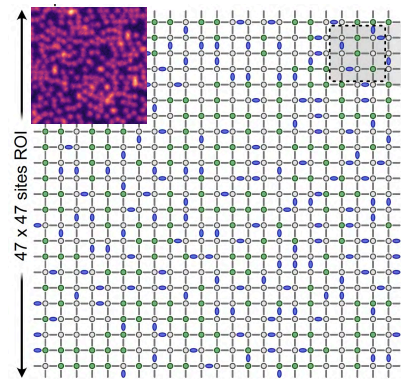
Gauss's law:



Each vertex is either occupied by monomer or connected to one dimer

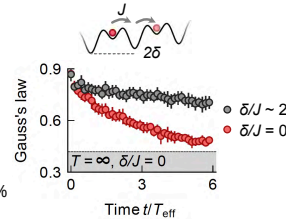
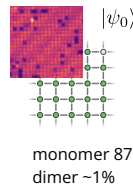
see also: J. J. Osborne et al., Commun. Phys. 8, 273 (2025); Halimeh et al., PRX Quantum (2021); Lang et al., PRB (2022)

Gauss Law Conservation

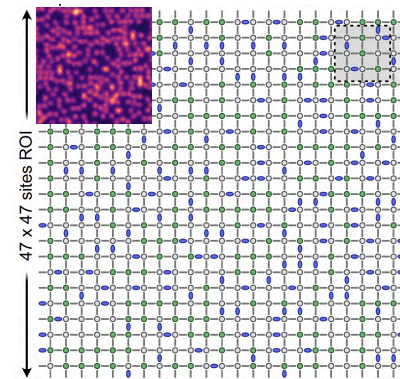


Gauss's law after quench to resonance:

Initial state: $|\psi_0\rangle$

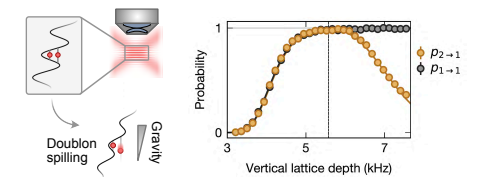


Gauss Law Conservation



Gauss's law after quench to resonance:

Overcoming the parity-projection challenge

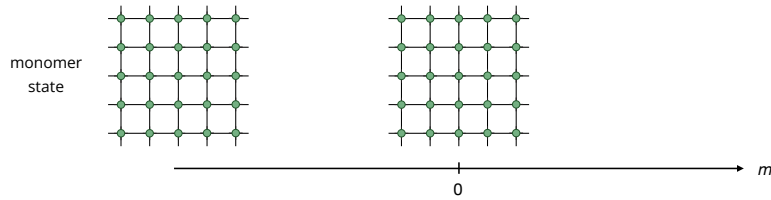


$$\mathcal{F}_{1 \rightarrow 1} = 99(1)\%; \mathcal{F}_{2 \rightarrow 1} = 98(1)\%$$

Generating U(1) Spin-Liquid Lakes

Idea: Connect the *monomer initial state* to the subspace of *dimer coverings*

$$\hat{H}_{\text{eff}} = \sum_V \tau_i (|+\bullet+\rangle\langle\blacklozenge-\blacklozenge| + \text{h.c.}) - m_i |+\bullet+\rangle\langle+\bullet+|$$



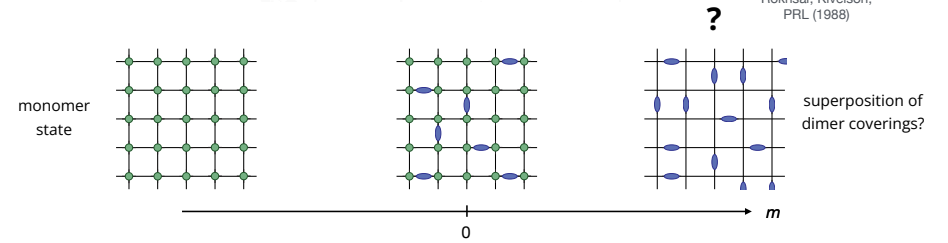
Generating U(1) Spin-Liquid Lakes

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$$\hat{H}_{\text{eff}} = \sum_V \tau_i (|+\bullet+\rangle\langle\blacklozenge-\blacklozenge| + \text{h.c.}) - m_i |+\bullet+\rangle\langle+\bullet+|$$

$$|\Psi_{\text{RK}}\rangle = \sum_i |d_i\rangle$$

Rokhsar, Kivelson, PRL (1988)

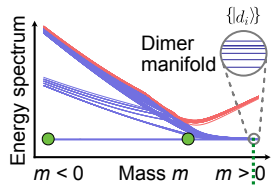


Sahay, Vishwanath, Verresen, arXiv:2211.01381
Gjonbalaj, Sahay, Yelin, arXiv:2502.03518

→ non-equilibrium preparation of spin-liquid lakes!

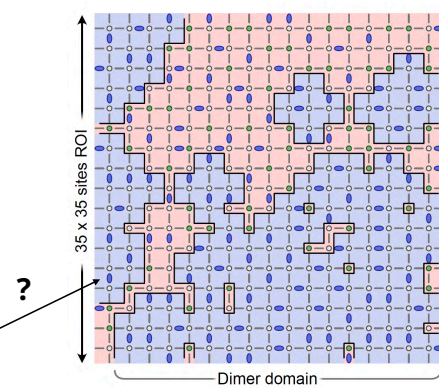
Semi-adiabatic Preparation on Spin-Liquid Lakes

Expectation: Optimal ramp rate generates U(1) spin-liquid lakes:



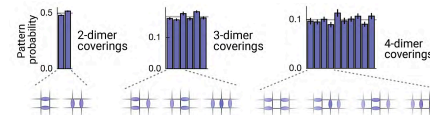
$$|\Psi_{\text{RK}}\rangle = | \text{dimer covering 1} \rangle + | \text{dimer covering 2} \rangle + | \text{dimer covering 3} \rangle + \dots$$

Rokhsar, Kivelson, PRL (1988)

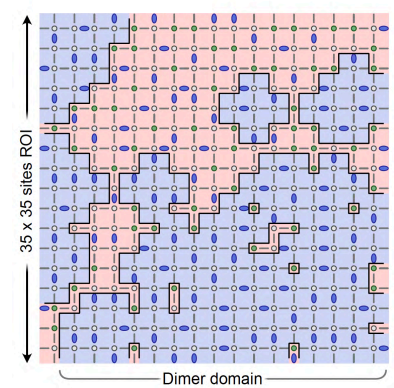
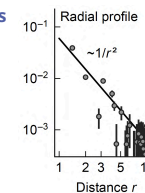
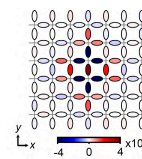


Semi-adiabatic Preparation on Spin-Liquid Lakes

Amplitudes of dimer coverings

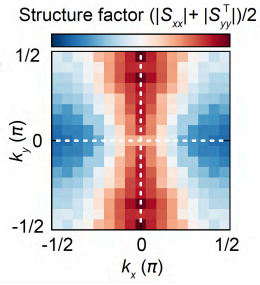
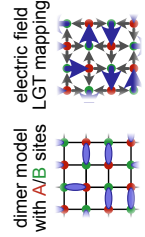


Dimer-dimer correlations



Equivalence to U(1) LGT:

$$\nabla \cdot \hat{\mathbf{E}}(\mathbf{r}) = 0$$

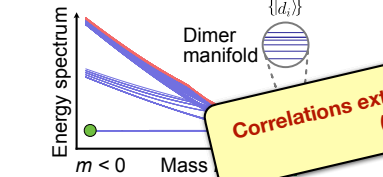


Observation of pinch-point correlations!
→ emergent U(1) gauge field

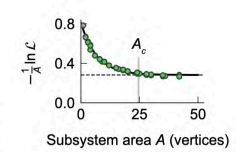
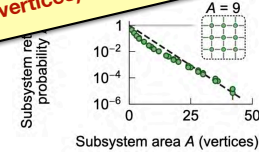
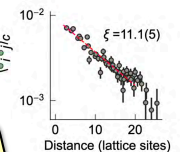
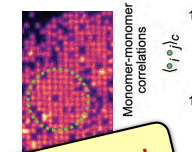
$$S_{\alpha\beta}(\mathbf{k}) = \sum_{\mathbf{d}; |\mathbf{d}| < r_{\max}} e^{i\mathbf{k} \cdot \mathbf{d}} [\langle E_{\alpha}(\mathbf{r}) E_{\beta}(\mathbf{r}') \rangle - \langle E_{\alpha}(\mathbf{r}) \rangle \langle E_{\beta}(\mathbf{r}') \rangle]$$

What about the relative phases?

Idea: Use ramp back to learn something about the phase



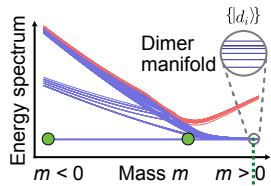
Correlations extend over 100 lattice sites! (25 vertices)



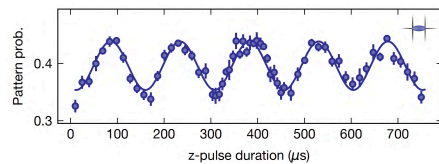
$$|\Psi_{RK}\rangle = |\text{dimer pattern 1}\rangle + |\text{dimer pattern 2}\rangle + |\text{dimer pattern 3}\rangle + |\text{dimer pattern 4}\rangle + \dots$$

Rokhsar, Kivelson, PRL (1988)

Idea: Use ramp back to learn something about the phase



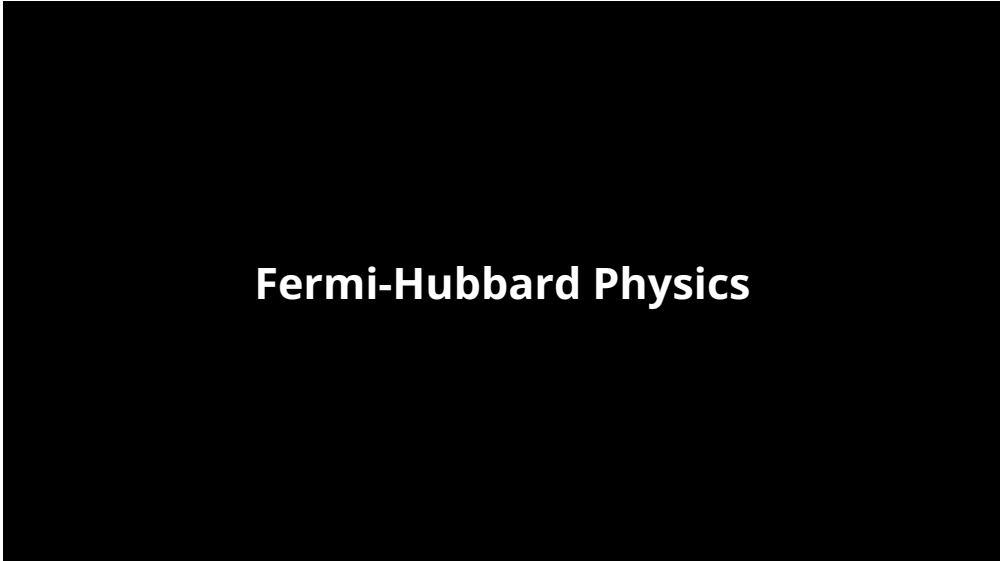
Imprint phase on vertical dimers after forward ramp



Many-body coherence!

$$|\Psi_{RK}\rangle = |\text{dimer pattern 1}\rangle + |\text{dimer pattern 2}\rangle + |\text{dimer pattern 3}\rangle + |\text{dimer pattern 4}\rangle + \dots$$

Rokhsar, Kivelson, PRL (1988)



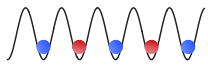
Fermi-Hubbard Model



$$\hat{H} = -t \sum_{\langle i,j \rangle, \sigma} \hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

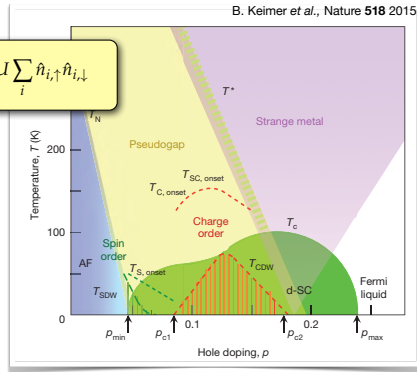
AFM Heisenberg Model

Half filling & strong interaction



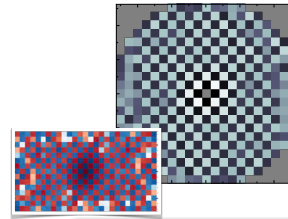
$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \quad J = \frac{4t^2}{U}$$

Away from half filling: **t-J model**
competition between



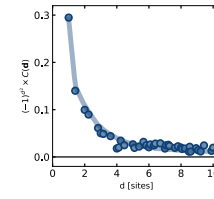
A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017), L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)

$$\frac{\langle \hat{S}_i^z \hat{S}_j^z \rangle - \langle \hat{S}_i^z \rangle \langle \hat{S}_j^z \rangle}{\sigma(\hat{S}_j^z) \sigma(\hat{S}_i^z)}$$

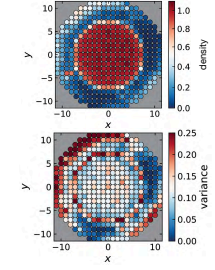
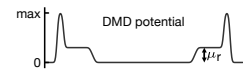


$$T/t \sim 0.1 - 0.25$$

$$U/t = 6.5 - 8 \quad t/J \approx 1.6$$



Theory QMC
Z. Wang, L. Pollet (LMU)



low Temp: $T/t=0.1$: M. Xu, ... M. Greiner, Nature 642, 909 (2025)
See also: Harvard: Parsons et al., Science (2016), Mazurenko et al. Nature (2017), MIT: Cheuk et al., Science (2016), Princeton: Brown et al., Science (2017), Bonn: Drewes et al., PRL (2017), Rice: A. Hart et al. Nature (2015).

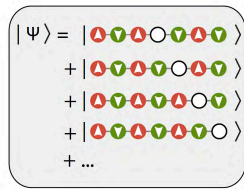
1D Hidden Order in the Ground State



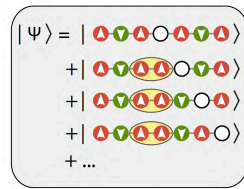
Charge & Spin Order around Hole

Minimize Energy → Two Conditions

- ▶ Holes want to delocalise
- ▶ Spins want to align antiferromagnetically



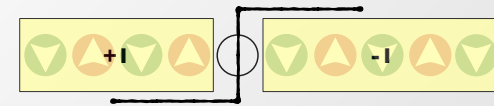
Ground State



Excited State



Microscopic Origin of SC — Separation

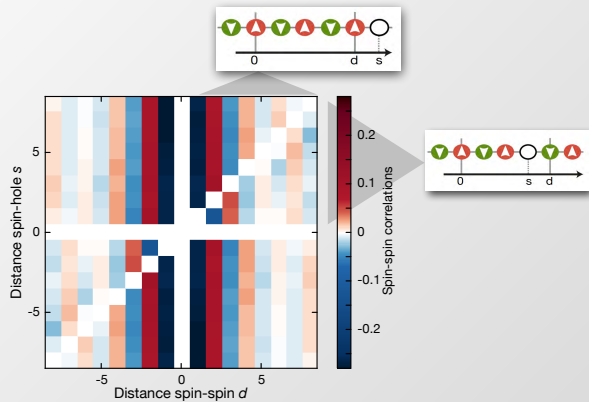


Hole introduce domain wall
“parity” kinks in AFM background!

Hole = Non local topological excitations!



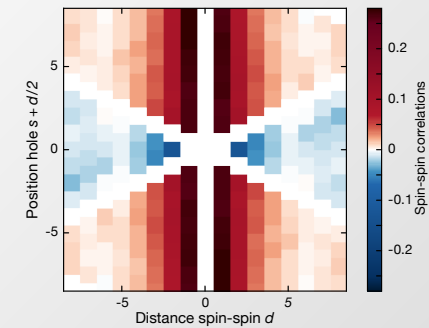
AFM around Holes



$$C_{s,h}(s,d) = \langle \hat{S}_z(i) \hat{h}_{i+s} \hat{S}_z(i+d) \rangle$$



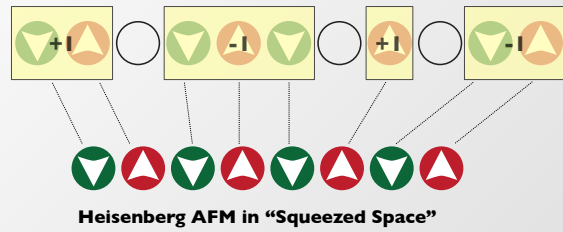
AFM around Holes



$$C_{s,h}(s,d) = (-1)^d \langle \hat{S}_z(i) \hat{h}_{i+s} \hat{S}_z(i+d) \rangle$$



Hidden (Topological) Order in the 1D Hubbard Chain



$$\Psi(x_1, \dots, x_N) = \Psi_{SF}(x_1, \dots, x_N) \Psi_{Heis}(y_1, \dots, y_M)$$

String Correlator

$$O_{top} = \langle \hat{S}_z^z(0) (-1)^{\sum_{j=1}^{d-1} 1 - \hat{n}_j} \hat{S}_z^z(d) \rangle$$

F.Woynarovich J. Phys. C (1982)
M. Ogata & H. Shiba Phys. Rev. B (1990)

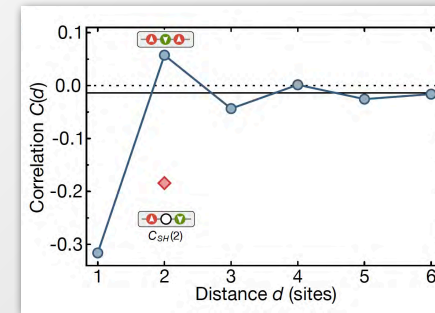
H.V. Kruis, I.P. McCulloch, Z. Nussinov & J. Zaanen EPL (2004)
H.V. Kruis, I.P. McCulloch, Z. Nussinov & J. Zaanen Phys. Rev. B (1990)



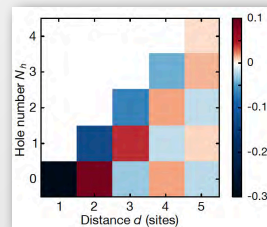
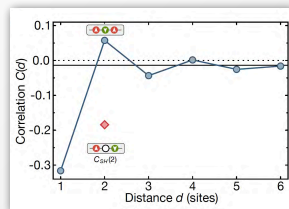
AFM order around a Single Hole



$$C_{s,h}(d=2) = \langle \hat{S}_z^z(i) \hat{S}_z^z(i+2) | \hat{h}_{i+1} \rangle$$



AFM order around more holes



Spins around holes behave much as if they were direct neighbors!



Order Parameters

Typical Order Parameter in Landau Paradigm of Phase Transition

$$\lim_{|x-y| \rightarrow \infty} \langle \hat{A}(x) \hat{A}(y) \rangle = c$$

Order Parameter:

Examples:

General classification scheme for all phases of matter ???

Order Parameter Characterized by Ground State Correlations
Local ordering!



String Order in 1D Systems

E.g. in 1D gapped systems where $\langle \hat{A}(x)\hat{A}(y) \rangle$ decays exponentially with distance

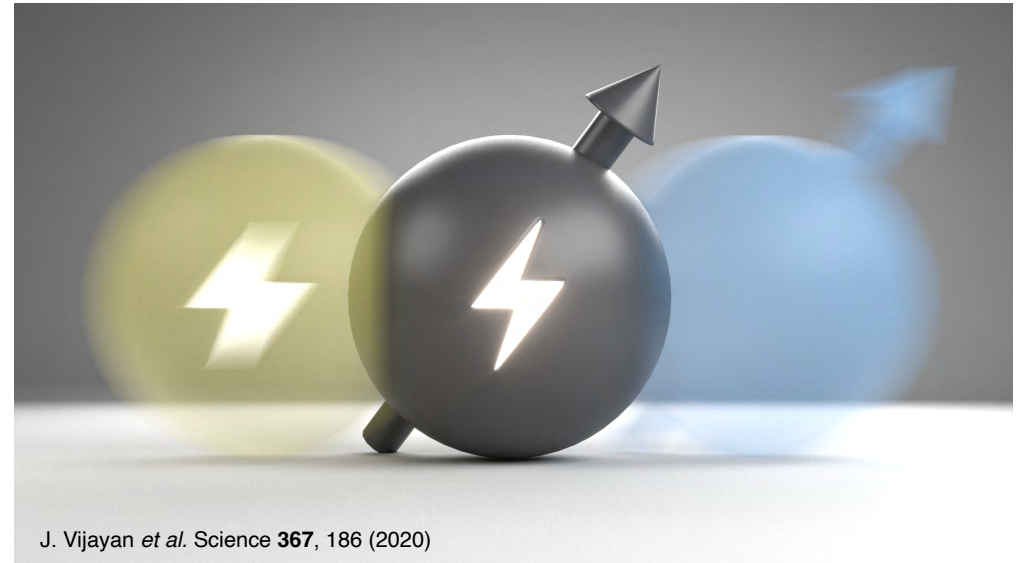
However, they can show hidden non-local order:

$$\lim_{|x-y| \rightarrow \infty} \langle \hat{A}(x) \left(\prod_{z \in S(x,y)} \hat{B}(z) \right) \hat{A}(y) \rangle = c$$

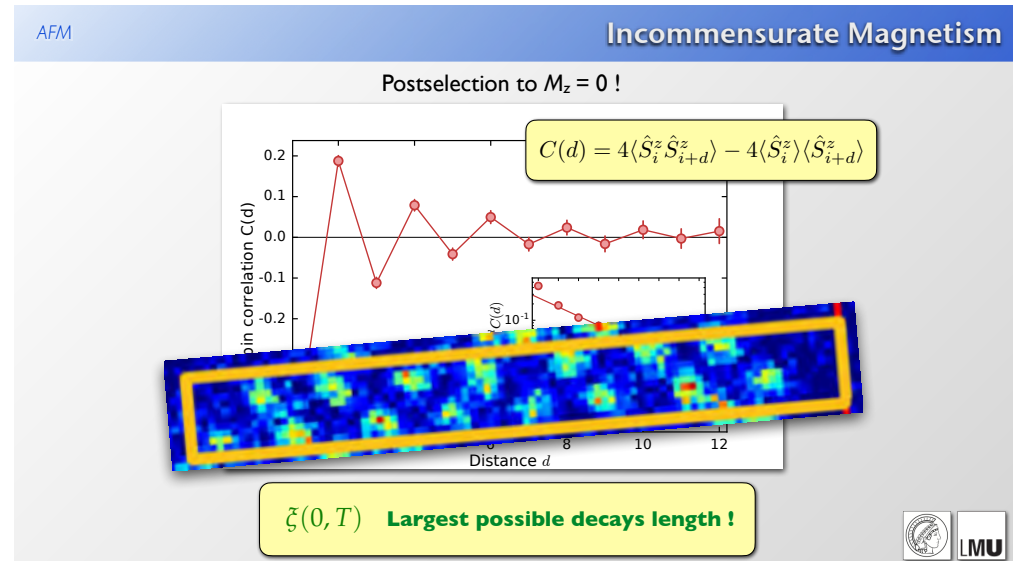
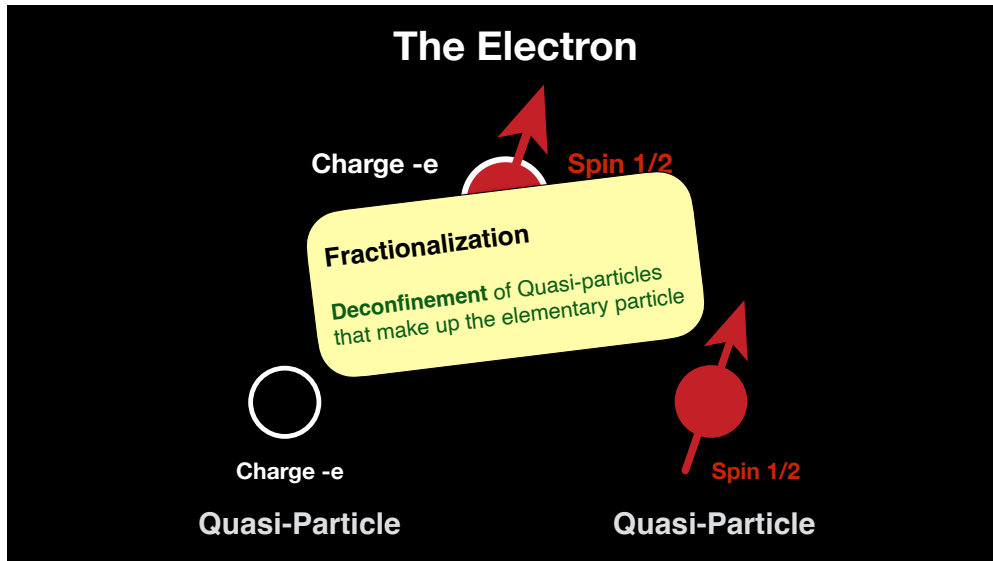
We say the order is **hidden**, because a “global view” of the underlying state is required. (**Topological Order**: X.-G. Wen)

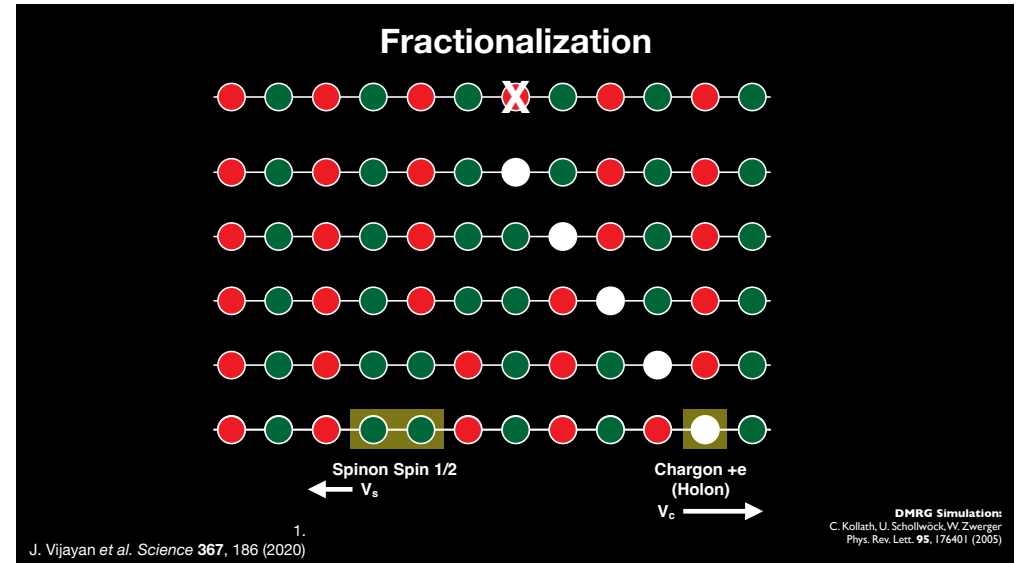
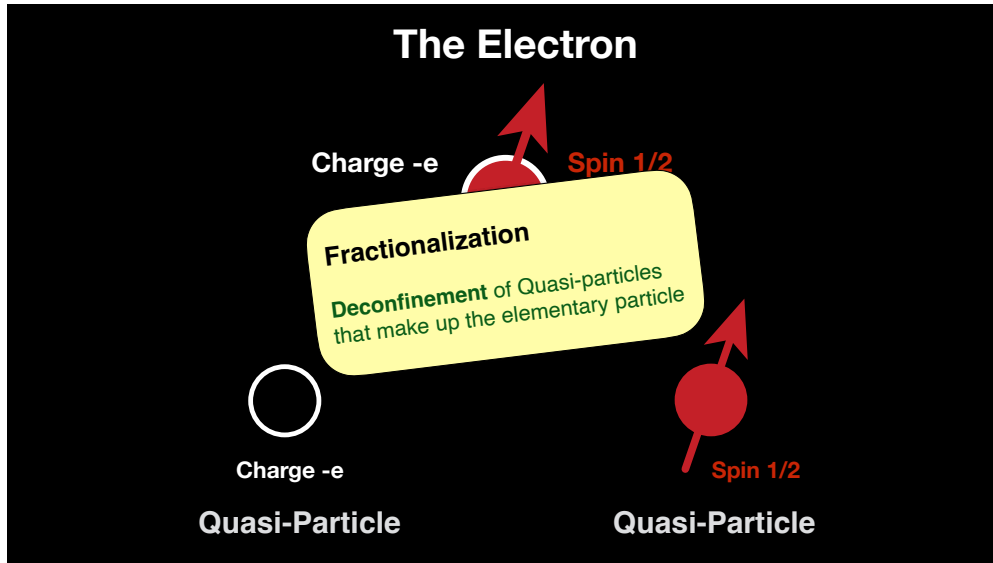
Allows us to characterize state only via its ground state correlations!

M. den Nijs, K. Rommelse, Phys. Rev. B 40, 4709 (1989).
 E. Kim, G. Fa'ath, J. So'lyom, D. Scalapino, Phys. Rev. B 62, 14965 (2000)
 E. G. Dalla Torre, E. Berg, E. Altman, Phys. Rev. Lett. 97, 260401 (2006)
 F. Anuso, A. Rosch, Phys. Rev. B 75, 144420 (2007)
 E. Berg, I. E. Dalla Torre, T. Giamarchi, E. Altman, Phys. Rev. B 77, 245119 (2008)

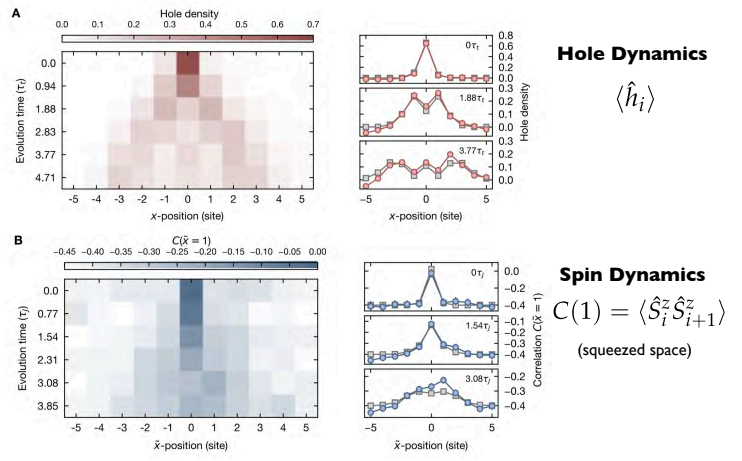


J. Vijayan *et al.* Science 367, 186 (2020)

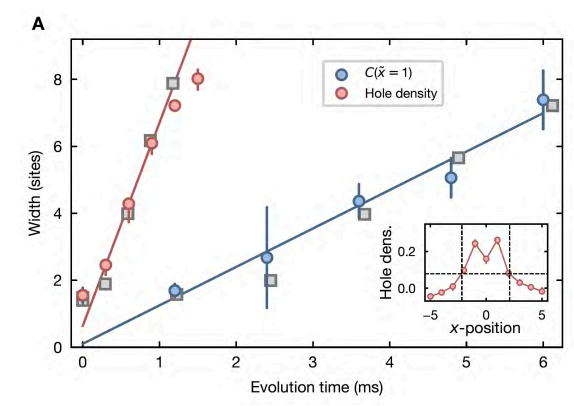




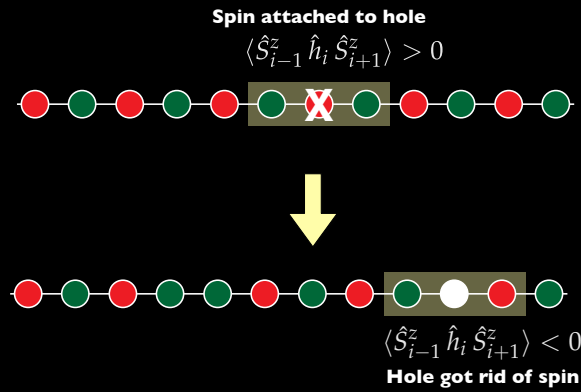
FHM Dynamics Dynamical Spin Charge Separation



FHM Dynamics Spin & Charge Velocities

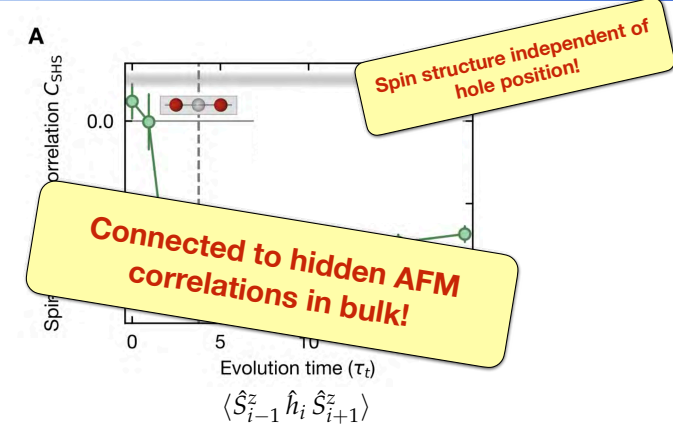


Fractionalization - Hole Shedding Spinon



SC Separation

Spin-Hole-Spin Correlations



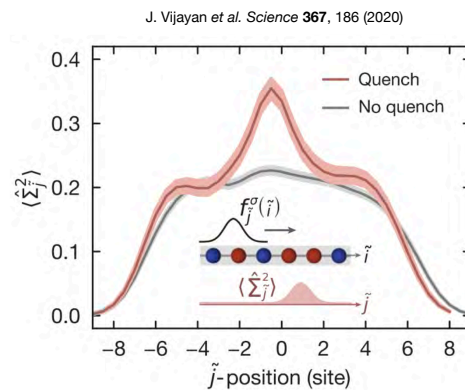
SC Separation

Detection of the Spin-1/2 Spinon

$$\hat{\Sigma}_j^2 = \left(\sum_i \hat{S}_i^z f_j^\sigma(i) \right)^2$$

$$\langle \hat{\Sigma}_j^2 \rangle - \langle \hat{\Sigma}_j^2 \rangle_{BG} = 1/4$$

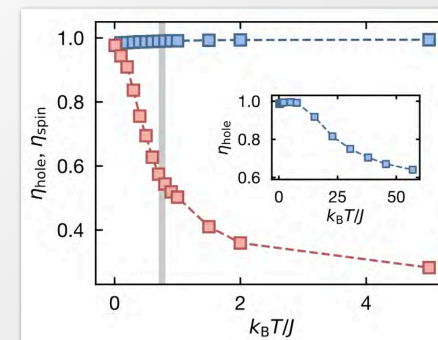
Probe Magnetization Fluctuations in Region σ



See also: Kivelson, S. & Schrieffer, J. R.
 Fractional charge, a sharp quantum observable.
Physical Review B **25**, 6447–6451 (1982).

SC Separation

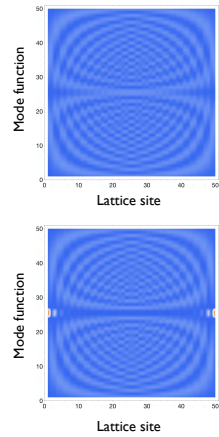
Fractionalization at Finite Temperatures



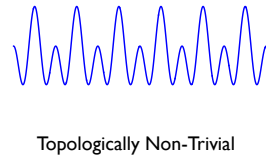
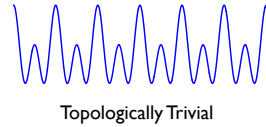
Holon created with unit efficiency
 Spinon created with 50-60% efficiency



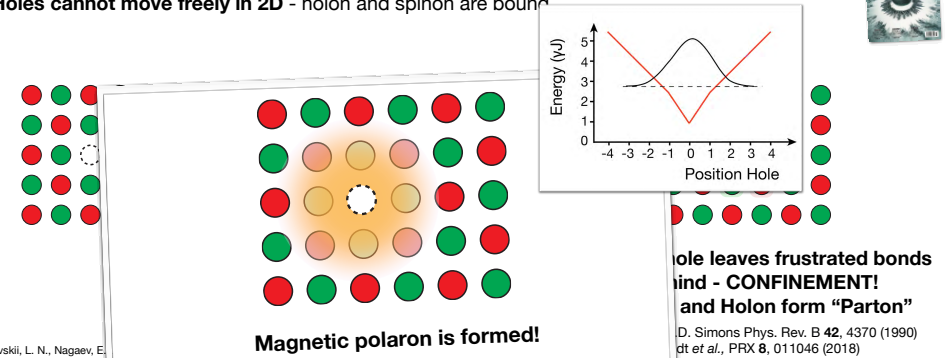
Probability Density of Eigenstates



Lattice Topology



Holes cannot move freely in 2D - holon and spinon are bound

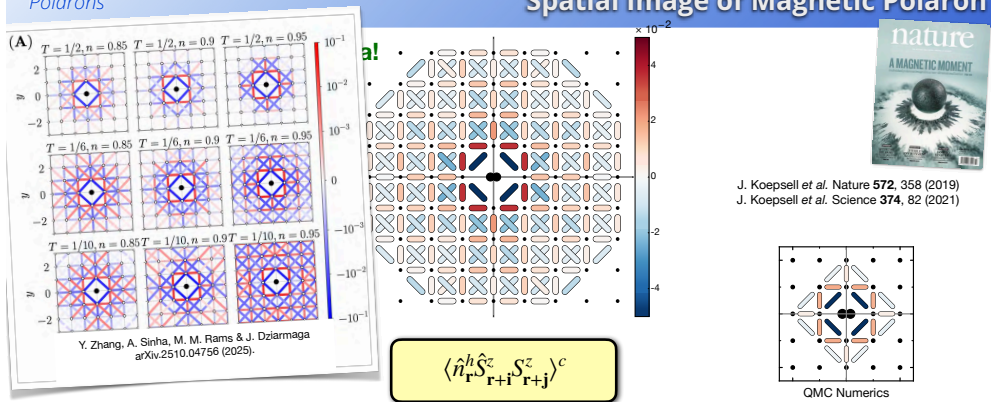


Bulaevskii, L. N., Nagaev, E. S. A. Trugman, Phys. Rev. B **41**, 7019 (1990)
J. R. Schrieffer, X. G. Wen & C. Kane, P. Lee & N. Read P. B. D. Simons and J. M. F. Gunn, Phys. Rev. B **41**, 7019 (1990)
P. Lee et al., Rev. Mod. Phys. **78** (2006)
K. K. Nielsen, M. A. Bastarrachea-Magnani, T. Pohl, & G. M. Bruun Phys. Rev. B **104**, 155136 (2021)

J. Koepsell et al. Nature **572**, 358 (2019) & J. Koepsell et al. Science **374**, 82 (2021)
See also recent results on frustrated systems: Princeton & Harvard related: imprints of string patterns Ch. Chiu et al. Nature (2019) attractive U: T. Hartke et al. Science **381**, 82 (2023)

Polarons

Spatial Image of Magnetic Polaron

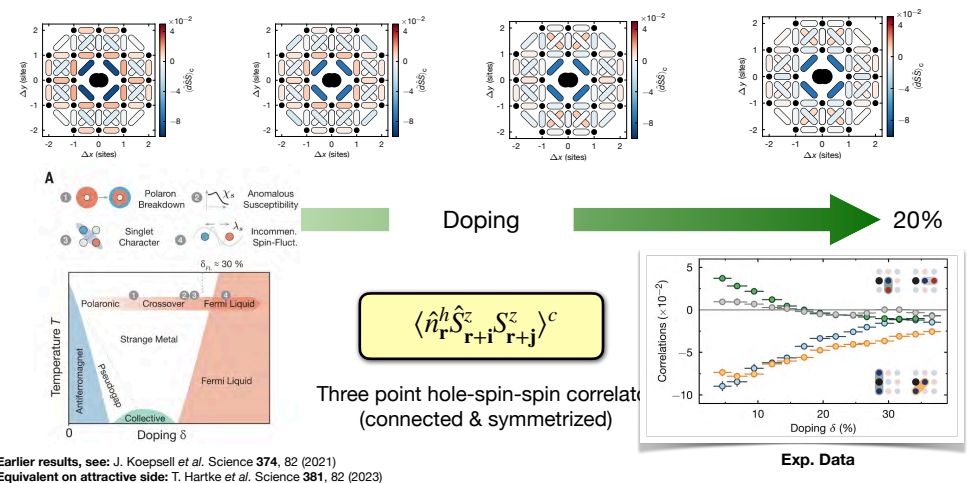


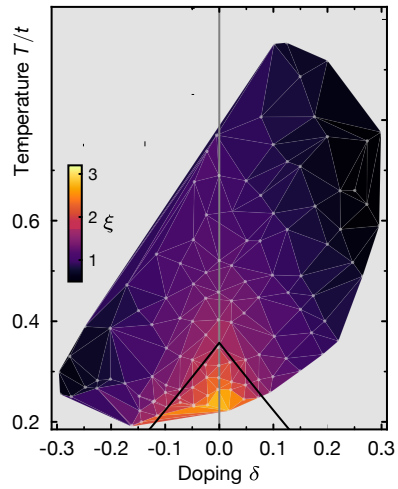
Three point hole-spin-spin correlator
(connected & symmetrized)

Kinetic Induced Polarons on Triangular Lattice:
M. Greiner Nature **629**, 317 (2024) (Harvard)
W. Bakr Nature **629**, 323 (2024) (Princeton)

Spinon-Holon

Birth and Death of Polaron in 2D





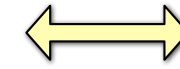
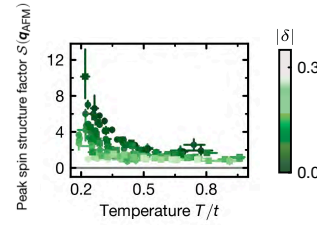
Staggered Magnetization

$$\hat{m}_S = \frac{1}{N} \sum_i (-1)^{i_x+i_y} \hat{S}_i^z$$

>35000 shots
varying T , doping δ
 $U/t \sim 6.5$

Doped FHM

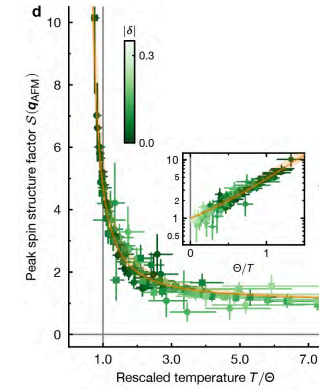
Magnetic Correlation Length



$$\Theta(\delta)$$

Replot with
doping dependent
energy scale

$$\Theta(\delta) \approx \Theta^{(0)} + \Theta^{(1)} |\delta| + \dots$$



Collapse under
Rescaling!

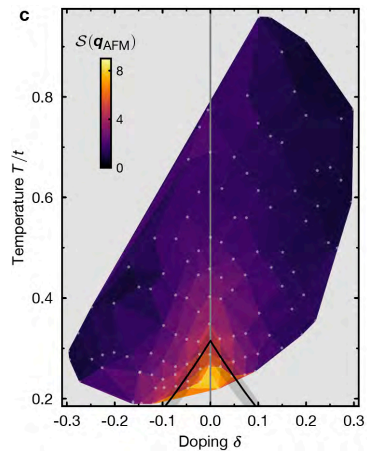
S. Chakravarty, B. Halperin & D.R. Nelson
Physical Review B **39**, 2344 (1989)
T. Schäfer et al. Phys. Rev. X **11**, 011058 (2021)

Topic

Pseudogap Temperature Dependence

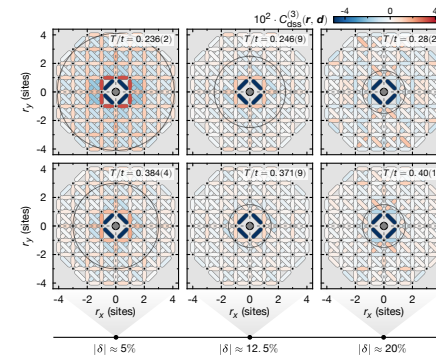
Topic

Charge-Spin-Spin Correlations

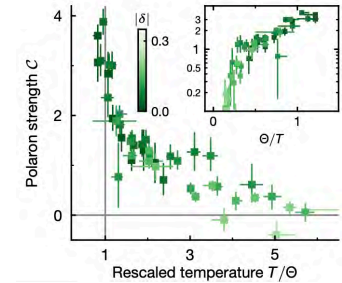


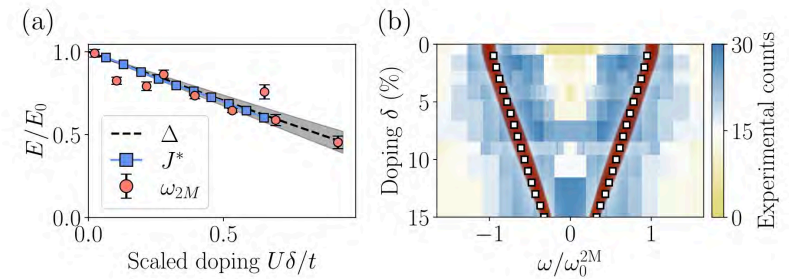
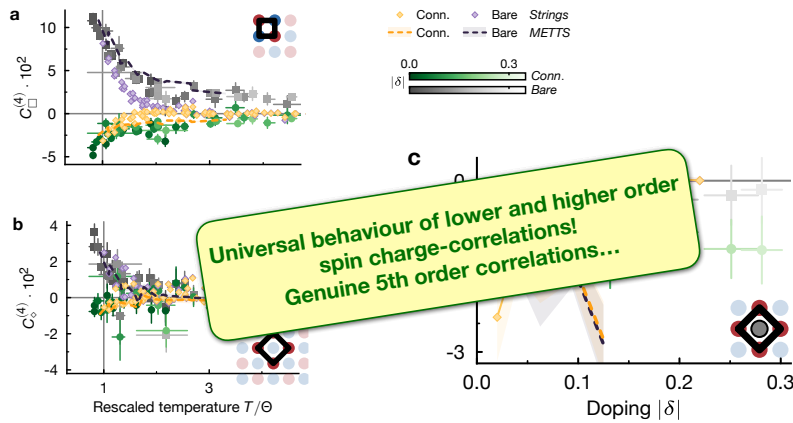
$$T^* \sim \Theta(\delta) \sim T \log \xi$$

$$\Theta(\delta) \approx \Theta^{(0)} + \Theta^{(1)} |\delta| + \Theta^{(2)} |\delta|^2 + \dots$$



$$C_{\text{dss}}^{(3)}(\mathbf{r}, \mathbf{d}) = \frac{4}{N_{\mathbf{r}, \mathbf{d}}} \sum_{\mathbf{i} \in \Omega} \langle \hat{d}_{\mathbf{i}} \hat{S}_{\mathbf{i}+\mathbf{r}+\mathbf{d}/2}^z \hat{S}_{\mathbf{i}+\mathbf{r}-\mathbf{d}/2}^z \rangle_c$$



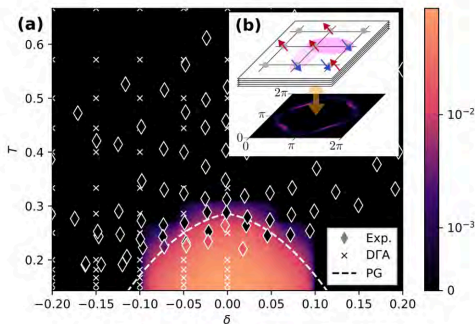


Theory: self-consistent magnon-hole coupling (Radu Andrei *et al.* E. Demler group, ETHZ) arXiv:2604.15234

Dashed line (exp):
T. Chalopin *et al.* PNAS **123**, e2525539123 (2026)
(Munich team)

Raman spectra (exp):
L. H. Kendrick, *et al.* arXiv:2509.18075 (2025)
(Harvard team)

Use snapshots to measure entanglement witness: **SSR-restricted negativity!**

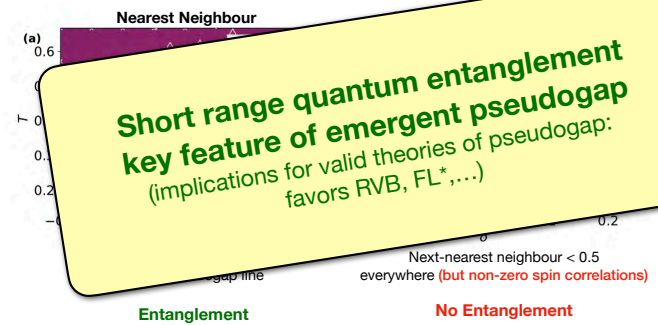


$$N_{nn} = 0.87(14) \times 10^{-2}$$

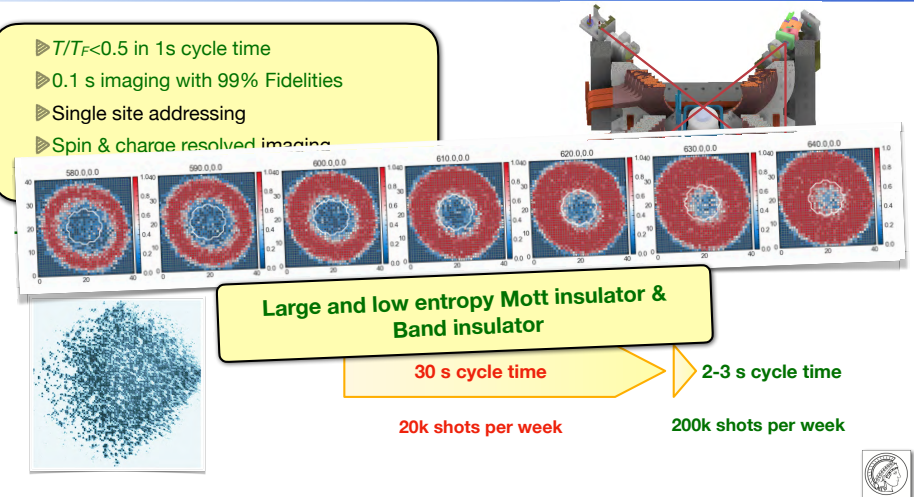
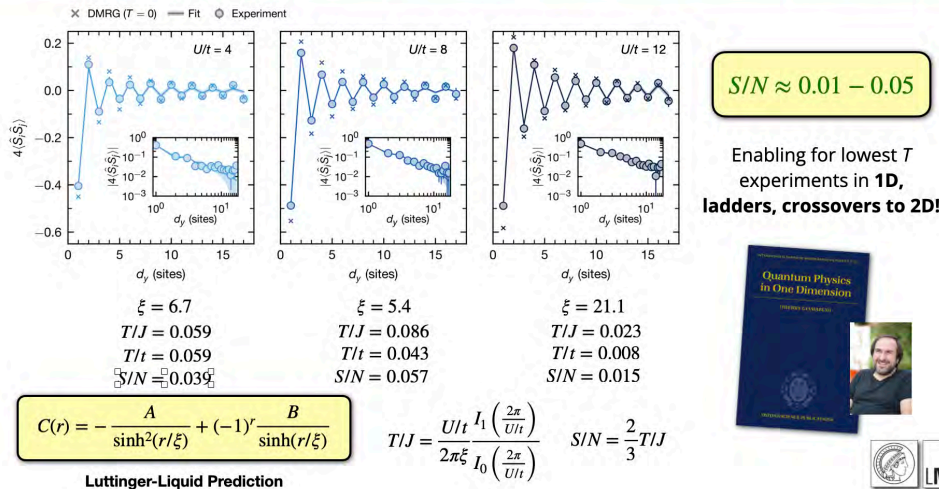
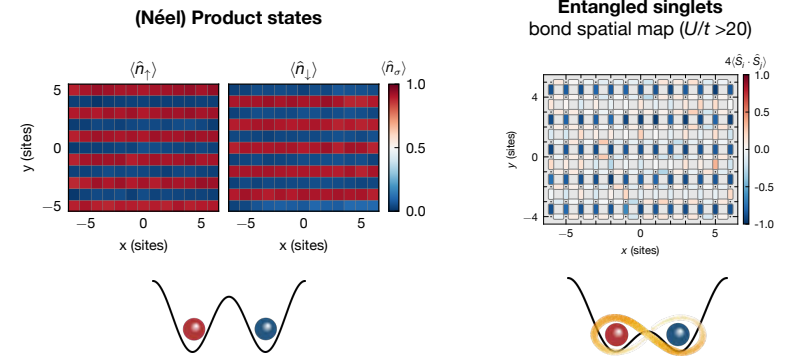
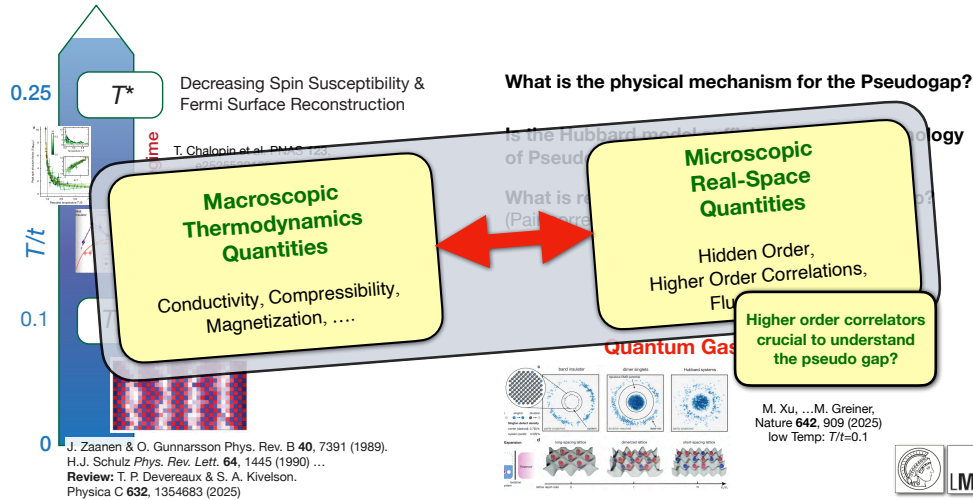
$$6\sigma > 0$$

Nearest neighbour spin entanglement (negativity)

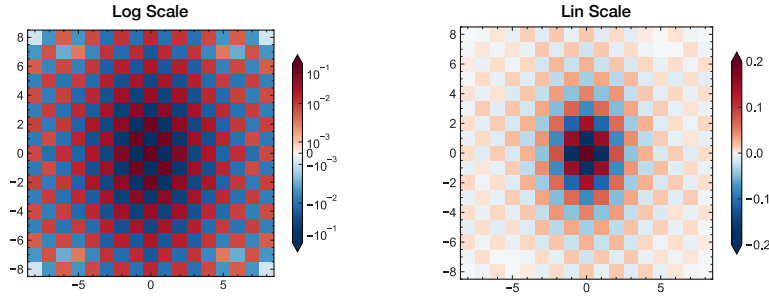
Use snapshots to measure entanglement witness: **SSR-restricted negativity!**



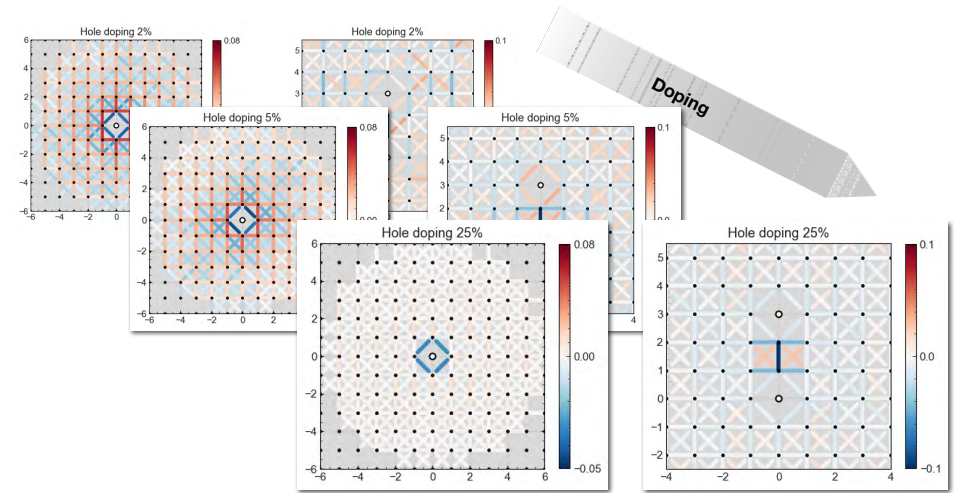
Sufficient condition (SU(2) symmetric, following Ding *et al.* 2022): $P_{\text{singlet}}/P_{\text{triplet}} > 1 \leftrightarrow N_{nn} > 0$



Half filling (undoped)

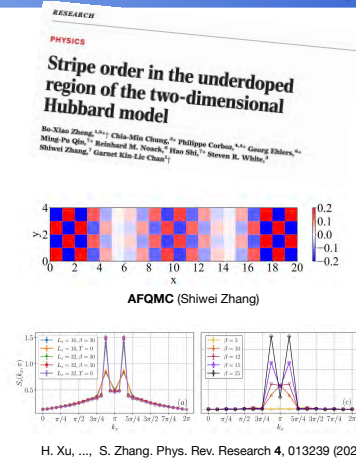


Speeding up - gives new possibilities



Key insights (Ground State Hubbard model $t'=0$)

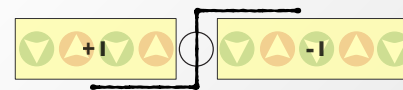
- ▶ Ground State: Filled Stripes
- ▶ Doping $\delta = 1/8$ optimal
- ▶ Stripes act like antiphase domain walls
- ▶ Spin domain wavelength $\lambda_s = 2/\delta, k_s = (\pi \pm \pi\delta, \pi)$
- ▶ Charge wavelength $\lambda_c = 1/\delta, k_c = 2\pi\delta$
- ▶ Appear below $T/t = 0.1$



B.-X. Zheng, ..., S. R. White, S. Zhang & G. K.-L. Chan. Science 358, 1155-1160 (2017)
 B. Xiao, Y.-Y. He, A. Georges & S. Zhang. Phys. Rev. X 13, 011007 (2023)

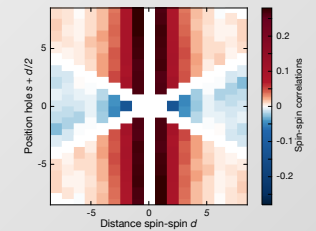
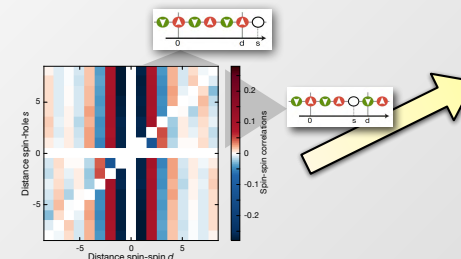
⋮

H. Xu, ..., S. Zhang. Phys. Rev. Research 4, 013239 (2022)



Hole = Non-local topological excitations!

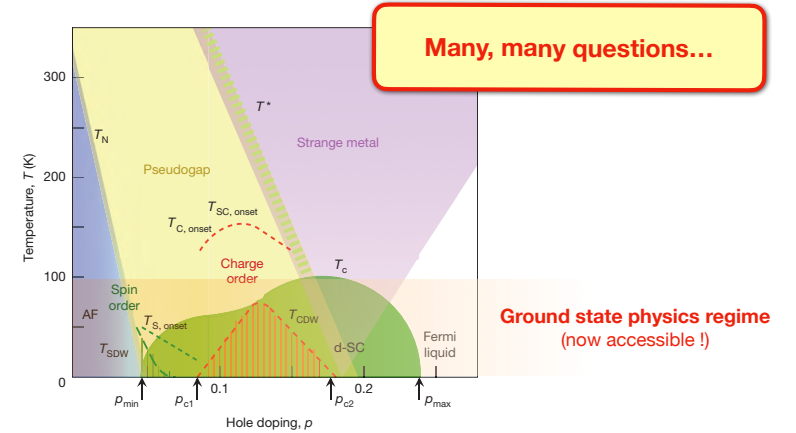
Hole introduce antiphase domain wall in AFM background!




T. A. Hilker, ..., I. B. & C. Gross. Science 357, 484 (2017)

- ▶ **Ground State: Filled Stripes** ✓
- ▶ **Doping $\delta = 1/8$ optimal** ✓ close (acquiring more statistics!)
- ▶ **Stripes act like antiphase domain walls** ✓
- ▶ **Spin domain wavelength $\lambda_s = 2/\delta, k_s = (\pi \pm \pi\delta, \pi)$** ✓
- ▶ **Charge wavelength $\lambda_c = 1/\delta, k_c = 2\pi\delta$ (tbc)**
- ▶ **Appear below $T/t = 0.1$** ✓
- ▶ Still figuring out what best pins orientation of stripes ?
- ▶ Quantum / thermal fluctuations of strips ?
- ▶ Clustering of charges along magnetic domain walls

Probing ground state physics of Fermi-Hubbard model

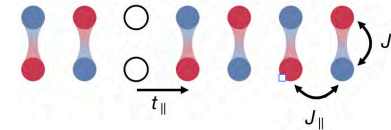


How to bind with purely repulsive interactions?
(non standard binding mechanism)

via magnetic correlations!

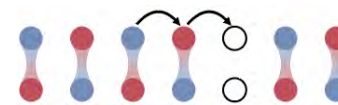
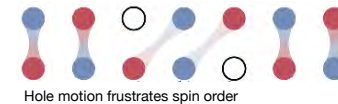
Hole - Attraction

Do two holes in an antiferromagnet form a bound pair?

Magnetically induced hole-hole attraction

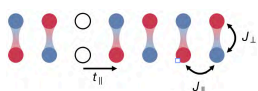


Does this lead to pairing on rungs?

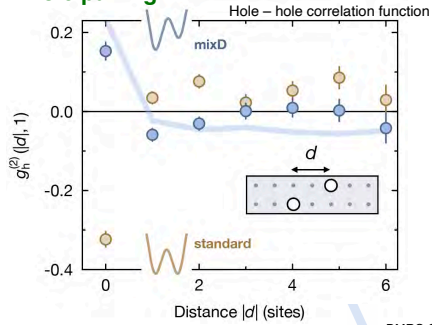


But kinetic energy disfavours rung pairs!

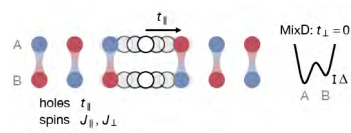
Magnetically induced hole-hole attraction



Hole pairing!



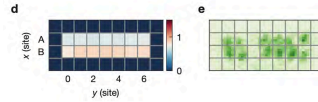
DMRG Calculation



Hole binding energy (mixD)

$$E_b = 0.82(6) J_{\perp}$$

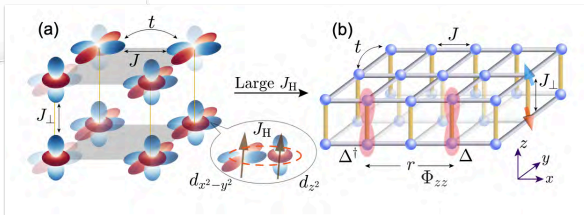
15 x higher than in ladder system!!



PHYSICAL REVIEW LETTERS 132, 036502 (2024)

Bilayer t - J - J_{\perp} Model and Magnetically Mediated Pairing in the Pressurized Nickelate $\text{La}_2\text{Ni}_2\text{O}_7$

Xing-Zhou Qu^{1,2*}, Dai-Wei Qu^{1,2*}, Jialin Chen^{3,5*}, Congjun Wu^{4,5,6,7}, Fan Yang⁸, Wei Li^{9,1}, and Gang Su^{1,8,1}
¹Key Laboratory for Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
²CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
³Hefei National Laboratory, Hefei 230088, China
⁴New Cornerstone Science Laboratory, Department of Physics, School of Science, Westlake University, 310024 Hangzhou, China
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 * (Received 1 August 2023; accepted 19 December 2023; published 19 January 2024)



Mixed dimensional model explains high T_c !

See also: Hanbit Oh and Ya-Hui Zhang
 Phys. Rev. B 108, 174511

OPEN
Strong pairing in mixed-dimensional bilayer antiferromagnetic Mott insulators
 Annabelle Bohrdt^{1,2,3,4}, Lukas Homeier^{5,6}, Immanuel Bloch^{2,6,7}, Eugene Demler^{8,9} and Fabian Grusdt^{1,2,3,4}

Interacting many-body systems in reduced-dimensional settings, such as ladders and few-layer systems, are characterized by enhanced quantum fluctuations. Recently, two-dimensional bilayer systems have sparked considerable interest because they can host unusual phases, including unconventional superconductivity. Here we present a theoretical proposal for realizing high-temperature pairing of fermions in a class of bilayer Hubbard models. We introduce a general and highly efficient pairing mechanism for mobile charge carriers in doped antiferromagnetic Mott insulators. The pairing is caused by the energy that one charge gains when it follows the paths created by another charge. We show that this mechanism leads to the formation of highly mobile but tightly bound pairs in the case of mixed-dimensional Fermi-Hubbard bilayer systems. This setting is closely related to the Fermi-Hubbard model believed to capture the physics of copper oxides, and can be realized in currently available ultracold atom experiments.

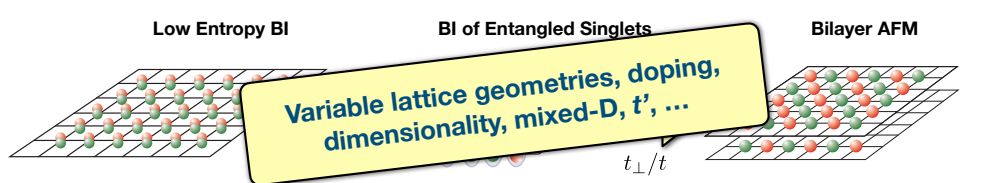
Experiment: S. Hirthe et al. *Nature* 613, 463 (2023)

Boost pairing energy x15 !!

Stripe formation in 2d systems
 D. Bourguind et al. *Nature* 637, 57–62 (2025).

Pairing confirmed in 2D
 Structure formation beyond pairing!

Theory: Bohrdt, A., Homeier, L., Bloch, I., Demler, E. & Grusdt, F. *Nat. Phys.* 18, 651–656 (2022).

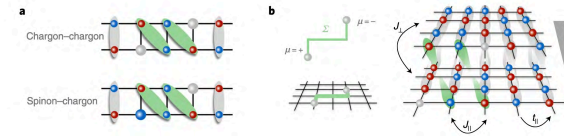


Theory: A. W. Sandvik & D. J. Scalapino. *Phys. Rev. Lett.* 72, 2777–2780 (1994)
 A. W. Sandvik, A. V. Chubukov & S. Sachdev. *Phys. Rev. B* 51, 16483 (1995)
 S. S. Kancharla & S. Okamoto. *Phys. Rev. B* 75, 193103 (2007)
 T. A. Maier & D. J. Scalapino. *Phys. Rev. B* 84, 180513 (2011)
Exp: M. Gall, N. Wurz, J. Samland, C. F. Chan & M. Köhl *Nature* 589, 40 (2021)

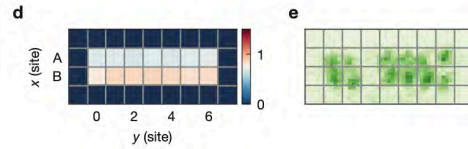
OPEN
Strong pairing in mixed-dimensional bilayer antiferromagnetic Mott insulators

Annabelle Bohrdt^{1,2,3,4}, Lukas Homeier^{1,2,5}, Immanuel Bloch^{2,6,7}, Eugene Demler^{4,8} and Fabian Grusdt^{2,9,10}

Interacting many-body systems in reduced-dimensional settings, such as ladders and few-layer systems, are characterized by enhanced quantum fluctuations. Recently, two-dimensional bilayer systems have sparked considerable interest because of their potential for realizing unconventional superconductivity. Here we present a theoretical proposal for realizing high-temperature pairing of fermions in a class of bilayer Hubbard models. We introduce a general and highly efficient pairing mechanism for mobile charge carriers in doped antiferromagnetic Mott insulators. The pairing is caused by the energy that one charge gains when it follows the path created by another charge. We show that this mechanism leads to the formation of highly mobile but tightly bound pairs in the case of mixed-dimensional Fermi-Hubbard bilayer systems. This setting is closely related to the Fermi-Hubbard model believed to capture the physics of copper oxides, and can be realized in currently available ultracold atom experiments.

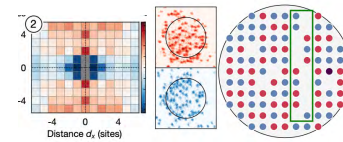


Theory: Bohrdt, A., Homeier, L., Bloch, I., Demler, E. & Grusdt, F. *Nat. Phys.* **18**, 651–656 (2022).



Experiment: S. Hirthe et al. *Nature* **613**, 463 (2023)

Boost pairing energy x15 !!



Stripe formation in 2d systems
 D. Bourguind et al. *Nature* **637**, 57 (2025).

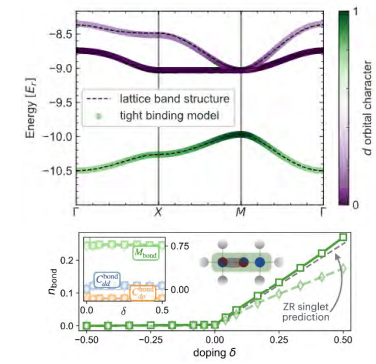
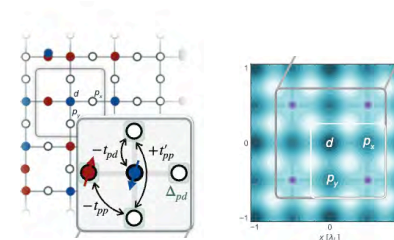
Pairing confirmed in 2D
Structure formation beyond pairing!

Cuprates

From Fermi Hubbard to Cuprates

Quantum Simulation of Three-Band Model

- ▶ High- T_c superconductivity in Cuprates
- ▶ Described by **three-band Emery model**
- ▶ Realized with polarization-tuned folded lattice



Hannah Lange, LMU

H. Lange, L. Qiu ... A. Bohrdt, arXiv 2603.11037 (2026)
see also: L. Homeier, ..., A. Kaufman, A.M. Rey (to be submitted)

Fermi Hubbard QGM

Recent Highlights

A Phase diagram showing Normal, Preformed Pairs, SF+CDW Correlations, SF, BEC, and BCS regions. **B** Experimental images of a Pauli Hole and Attraction. **C** Large Scale 3D Systems showing a 49.5 μm scale and a 532 nm scale. **D** Diagram of Multiple Frustration showing AFM and FM interactions in a triangular lattice.

Attractive Interactions
 Hartke et al. *Science* **381**, 82–85 (2023)
 M. Zwierlein group (MIT)

Large Scale 3D Systems
 H.-J. Shao, Y.-A. Chen & J.-W. Pan, *Nature* **632**, 267 (2024)

Multiple Frustration
 et al. *Nature* 1–6 (2023)
<https://doi.org/10.1038/s41586-023-06280-5>
 Researcher group (Harvard)
 also W. Bakr (Princeton)



From Analog to Digital

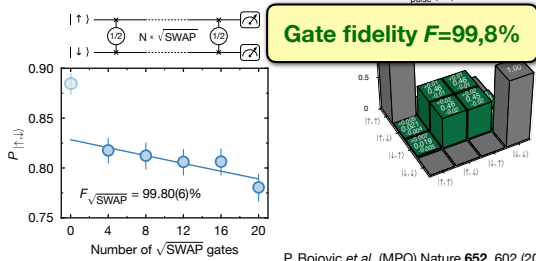
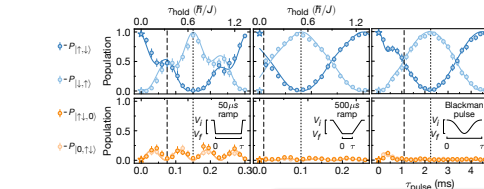
SWAP Gate

$$R_{\text{SWAP}}(\alpha) = \begin{pmatrix} \uparrow\downarrow & & & \\ \downarrow\uparrow & & & \\ & \frac{1+e^{i\alpha}}{2} & \frac{1-e^{i\alpha}}{2} & \\ & \frac{1-e^{i\alpha}}{2} & \frac{1+e^{i\alpha}}{2} & \\ & & & \uparrow\downarrow \\ & & & & \downarrow\uparrow \end{pmatrix}$$

No additional phase

Avoid Doublon population

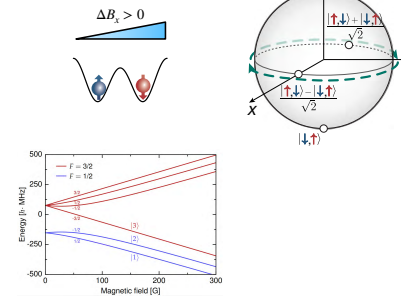
- Limit $U/t \gg 1$
 - Slow dynamics
 - Remaining error $\sim (U/t)^2$
- Magic ratio $U/t = 4/\sqrt{3}$
 - Fast dynamics
 - In theory: No gate error
 - Sensitive to timing and interaction strength
- Slow ramps
 - Intermediate time scales
 - In theory: No gate error
 - Robust to experimental imperfections



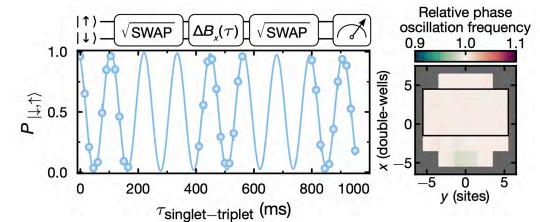
P. Bojovic et al. (MPQ) Nature 652, 602 (2026)
Y. Kiefer, et al. (ETHZ) Nature 652, 609 (2026)

Singlet-triplet oscillations

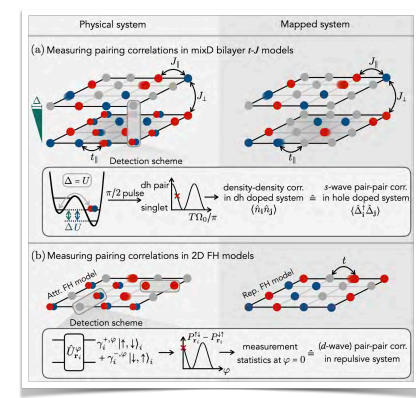
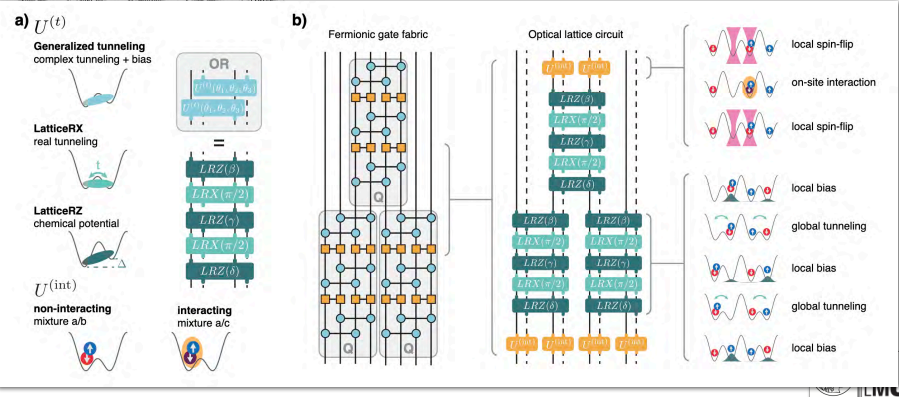
- 99% nuclear spin \rightarrow Low sensitivity to field gradients
- Strong magnetic field gradient of 40 G/cm
- Singlet-triplet oscillations at 8.72(5) Hz
- Coherence time $> 13(3)$ s



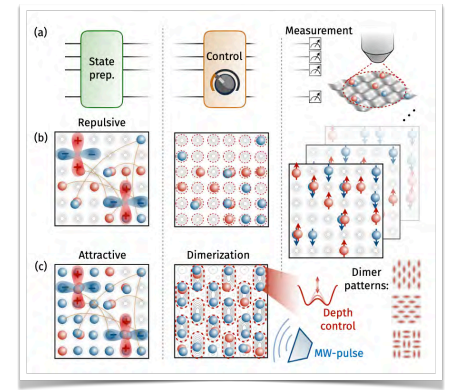
>10s coherence time



Simulating Chemistry with Fermionic Optical Superlattices
 ovin Gährtske,¹ Daniel Dax,^{2,3} Jiu Zhang,² Naman Jain,² Christian Gogolin,¹ and Philipp M. Preis^{1,*}
¹Quantum Deutschland AG, Lise-Meitner-Straße 1, 85748 Garching, Germany
²Max Planck Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
³Current address: Physikalisches Institut für Universitäre Beschleuniger, Im Neuenheimer Feld 206, 69110 Heidelberg, Germany
 *Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany (Email: philipp.ppreis@mcqst.org)



H. Schliömer, H. Lange, T. Franz, T. Chalopin, P. Bojović, S. Wang, I. Bloch, T. A. Hilker, F. Grusdt, A. Bohrdt, PRX Quantum (2024)

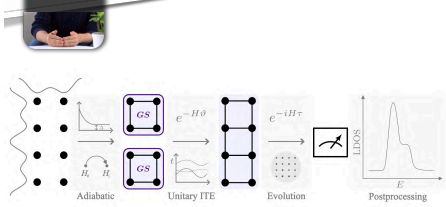


D. K. Mark, H.-Y. Hu, J. Kwan, C. Kokail, S. Choi, S. F. Yelin, PRL (2025)

Quantum Phase Estimation

Phase-Sensitive Measurements on a Fermi-Hubbard Quantum Processor

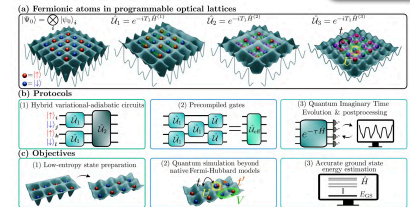
Alberto R. Cavalari,^{1,2,3} Luis Escalera-Morino,^{4,5} Tino Franz,^{1,2} Timon Hilber,^{5,1,2} J. Ignacio Cirac,^{1,2} Philipp M. Preiss,^{1,2} and Benjamin F. Schiffrin^{1,2,*}
¹Max-Planck-Institut für Quantenoptik, Hans-Koellner-Str. 1, D-85748 Garching, Germany
²Center for Quantum Science and Technology (CQST), Schellingstr. 4, D-80799 München, Germany
³Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, München D-80333, Germany
⁴Department of Physics, Harvard University, Cambridge, MA 02138, USA
⁵Department of Physics, University of Innsbruck, 6020 Innsbruck, Austria
 *Department of Physics and SUPA, University of Strathclyde, Glasgow, G4 0NG, United Kingdom
 (Date: September 3, 2020)



Phase Sensitive Measurements
(LDOS, finite T,...)

Programming optical-lattice Fermi-Hubbard quantum simulators

Cristian Tabares,^{1,*} Christian Kokil,^{2,3} Peter Zoller,^{4,5} Daniel González-Castaño,^{1,3,4,5,1} and Alejandro González-Tudela^{1,1}
¹ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
²Department of Physics, Harvard University, Cambridge, MA 02138, USA
³Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria
⁴Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences
⁵Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences
 (Date: September 3, 2020)



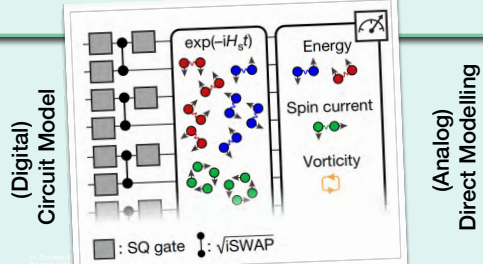
Programmability



Where Next?

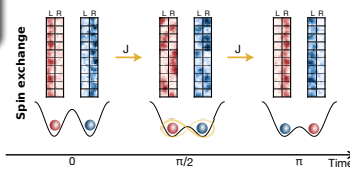
A Joint Look Ahead...

Quantum Simulation & Computation Platforms (Atoms, Ions, SC Qubits, Photons, NV Centers...)



A new era of Quantum Many-Body Physics

Spin exchange

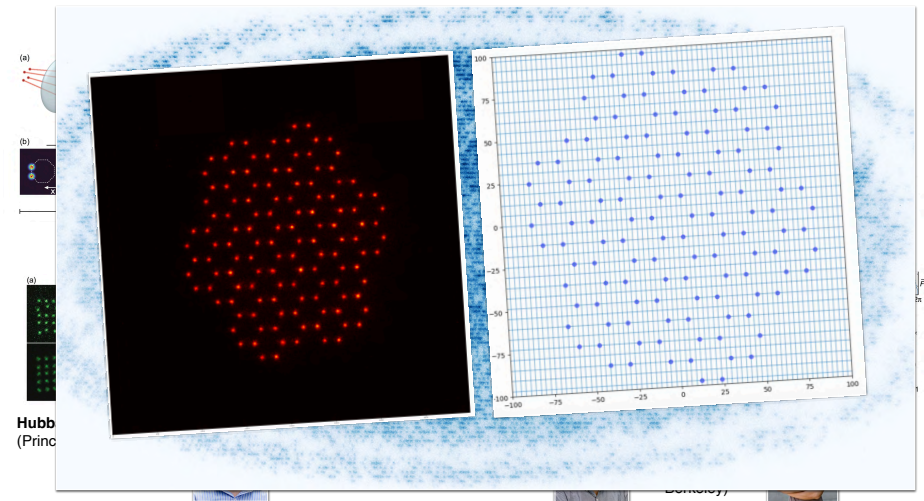


High fidelity collisional quantum gates with fermions

Gate fidelity $F=99,8\%$

P. Bojovic et al. (MPQ) Nature 652, 602 (2026)
 Y. Kiefer, et al. (ETHZ) Nature 652, 609 (2026)

Enhanced Programmability



Continuous Loading in Action

Continuously operated array for up to 1.5h with > 1200 atoms

Readily scalable to >10,000 atoms



F. Gyger *et al.* PRR 6, 033104 (2024)

Y. Li *et al.* (Princeton) arXiv:2506.15633 &

see also: M. Norcia *et al.* PRX Quantum 5, 030316 (2024)

Neng-Chun Chiu *et al.* (Harvard) arXiv:2506.20660

Platforms

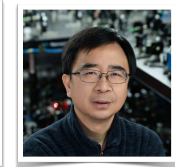
Putting Atoms into Place Superfast!



(Video slowed down)



Chao-Yang Lu

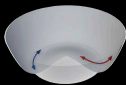


Jian-Wei Pan

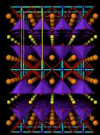


中国科学技术大学
University of Science and Technology of China

Quantum Universe in a Lab



Particle Physics



Quantum Materials



Neutron Stars



Our Universe

Fundamental Precision Tests
of Quantum Matter
using Quantum Simulations



Optical Lattices

Outlook

Opportunities

- ▶ (Precision) Many-body physics, New detection methods, Novel quantum phases, Non-equilibrium dynamics
- ▶ **Materials science, High-energy physics, Quantum chemistry, Coherent Quantum annealing, Optimization, Metrology**

Challenges

- ▶ **Programmability, scalability, reducing calibration errors**
- ▶ **Certification and verification;** demonstration of *practical* quantum advantage.
- ▶ Developing **applications relevant to industry and other fields of science**, and connections to an end-user base (e.g. spin models / optimization)
- ▶ **Entropy management** (cooling)
- ▶ **Cycle times**





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