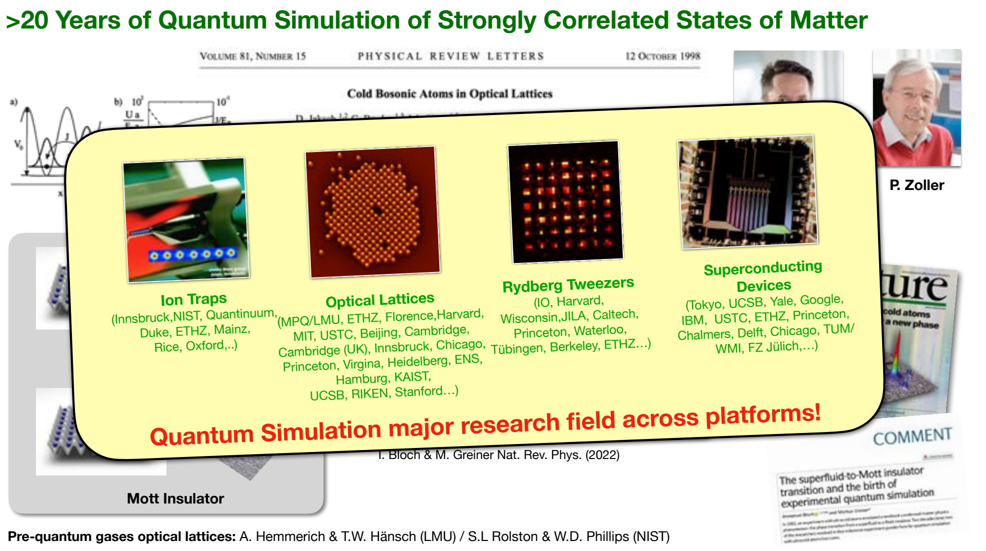
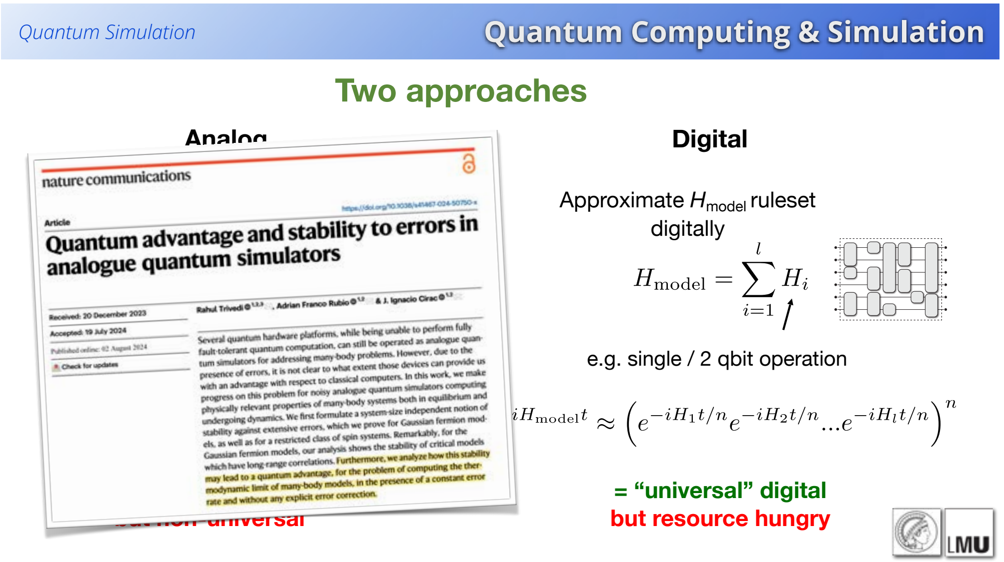
Quantum Simulation with
Ultracold Fermionic Atoms in Optical Lattices
Cento anni di fermioni
1926-2026
I.B. - 6 February 2025
Accademia dei Lincei
MCQST
Munich Quantum Valley
QUANTUM FLAGSHIP
Bundesministerium für Bildung und Forschung


Applications in Many-Body Physics
0 State Preparation/Engineering and Detection
Manipulating the Orbital Bloch Sphere
1 Strongly Correlated Electron Physics & Quantum Gates
AFM, Polarons, Pseudogap, Quantum Gates, Towards Bilayers…
2 Outlook

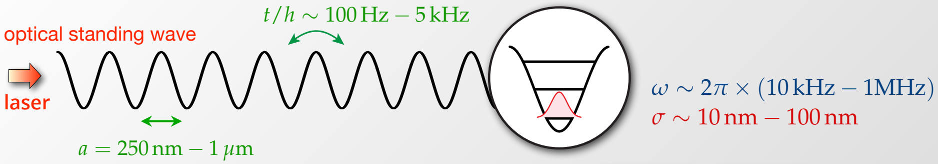



>20 Years of Quantum Simulation of Strongly Correlated States of Matter
Volume 81, Number 15 PHYSICAL REVIEW LETTERS 12 October 1998
Cold Bosonic Atoms in Optical Lattices
P. Zoller
Ion Traps
(Innsbruck,NIST, Quantinuum, Duke, ETHZ, Mainz, Rice, Oxford,..)
Optical Lattices
(MPQ/LMU, ETHZ, Florence,Harvard, MIT, USTC, Beijing, Cambridge, Cambridge (UK), Innsbruck, Chicago, Princeton, Virgina, Heidelberg, ENS, Hamburg, KAIST, UCSB, RIKEN, Stanford…)
Rydberg Tweezers
(IO, Harvard, Wisconsin,JILA, Caltech, Princeton, Waterloo, Tübingen, Berkeley, ETHZ…)
Superconducting Devices
(Tokyo, UCSB, Yale, Google, IBM, USTC, ETHZ, Princeton, Chalmers, Delft, Chicago, TUM/ WMI, FZ Jülich,…)
Quantum Simulation major research field across platforms!
Mott Insulator
I. Bloch & M. Greiner Nat. Rev. Phys. (2022)
COMMENT
The superfluid-to-Mott insulator transition and the birth of experimental quantum simulation
Pre-quantum gases optical lattices: A. Hemmerich & T.W. Hänsch (LMU) / S.L Rolston & W.D. Phillips (NIST)

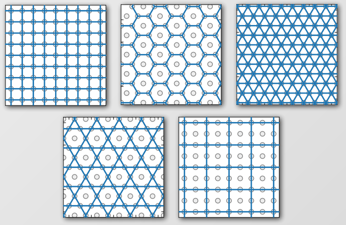
Quantum Simulation
Quantum Computing & Simulation
Two approaches
Analog
nature communications
Article
Quantum advantage and stability to errors in analogue quantum simulators
Received: 20 December 2023
Accepted: 19 July 2024
Rahul Trivedi, Adrian Franco Rubio & J. Ignacio Cirac
Digital
Approximate $H_{\text{model}}$ ruleset digitally
$H_{\text{model}} = \sum_{i=1}^{l} H_i$
e.g. single / 2 qbit operation
$e^{-iH_{\text{model}}t} \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_l t/n}\right)^n$
= “universal” digital
but resource hungry
LMU

## Primer on Optical Lattices




**Fourier synthesize aribtrary lattices:**

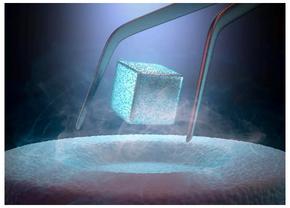
- Square
- Hexagonal/Triangular/Brick Wall
- Kagomé
- Superlattices
- Spin dependent lattices
- *Flux Lattices*



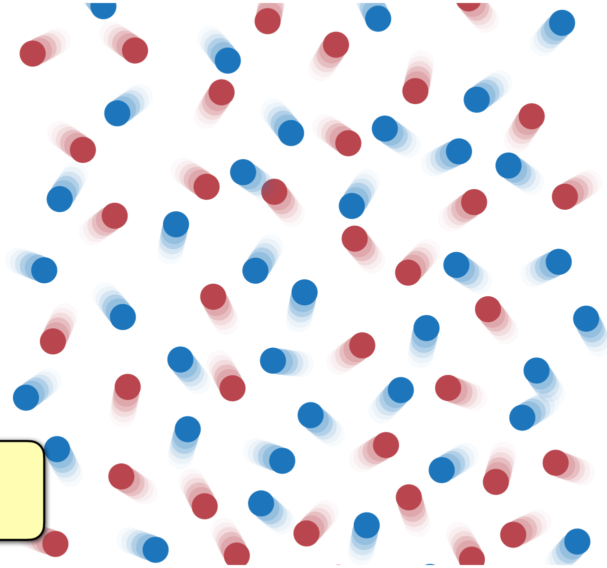
Full **dynamical** control over **lattice depth, geometry, dimensionality!**

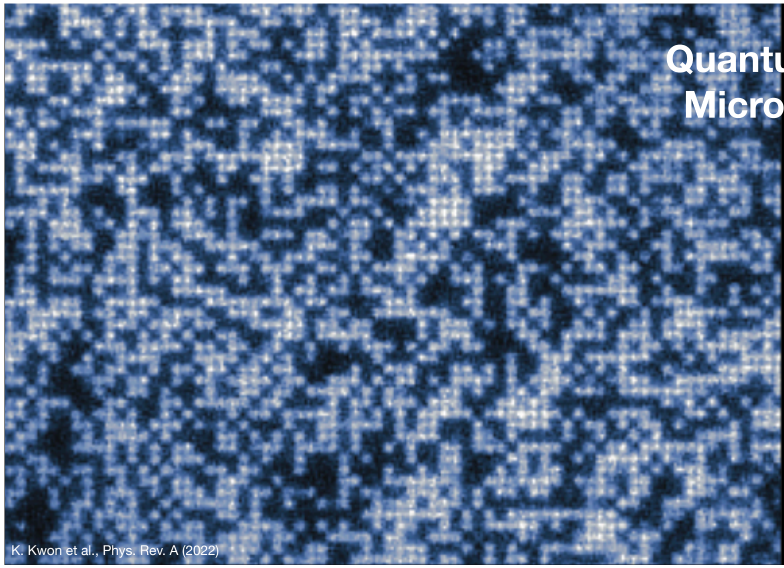
D. Wei *et al.* Phys. Rev. X **13**, 021042 (2023), recently used: M. Prichard *et al.* Nature **629**, 323 (2024) (Princeton)
related: D. Greif *et al.* Nature **535** 217 (2014), M. Xu *et al.* Nature **620**, 971 (2023)

LMU



**The dance of electrons inside a material!**





# Quantum Gas Microscopy

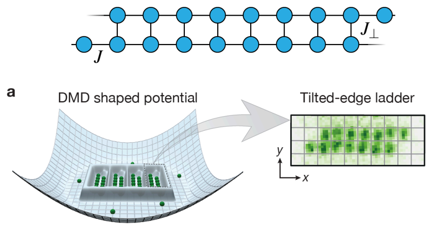
K. Kwon et al., Phys. Rev. A (2022)

W. Bakr et al., Science (2010)
J. Sherson et al., Nature (2010)



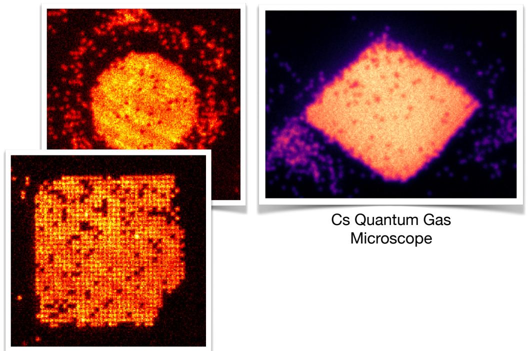
## Flexible Geometries and Large Sizes

**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%)



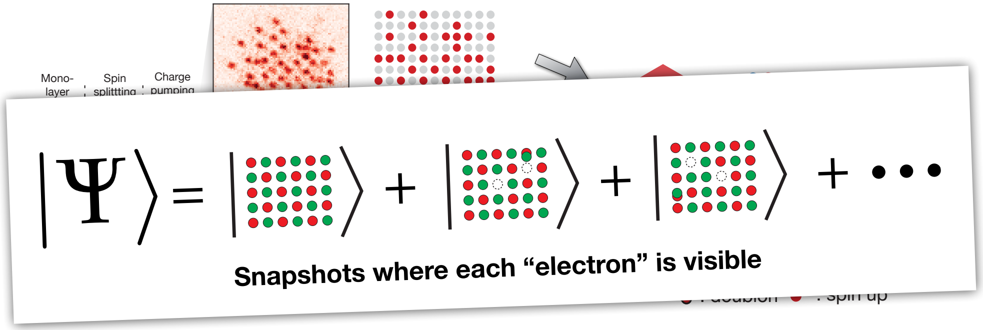
Cs Quantum Gas Microscope

Rb Quantum Gas Microscope

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

## Full Spin & Density Resolved Detection

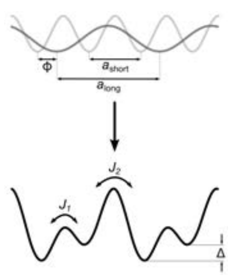



**Density and spin readout:** M. Boll et al. Science **353**, 1257 (2016), J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020),
**see also:** Harvard (Greiner), Princeton (Bakr) Phys. Rev. Lett. **129**, 123201 (2022), MIT (Zwierlein) Science **381**, 82 (2023)

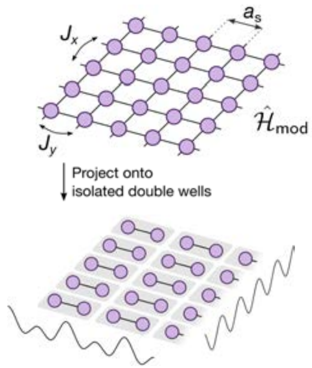


## Programmable Orbital Rotations using Superlattices

**Optical superlattices**




**Measurement scheme**

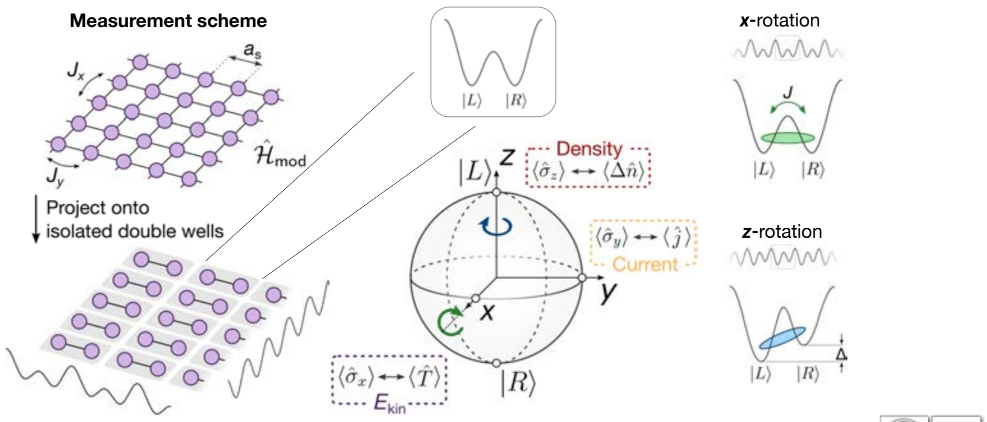



A. Impertro *et al.*
Phys. Rev. Lett. **133**, 063401 (2024)
see also SC qubits:
B. Du, R. Suresh, S. López, J. Cadiente, R. Ma,
Phys. Rev. Lett. **133**, 060601 (2024).

**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).

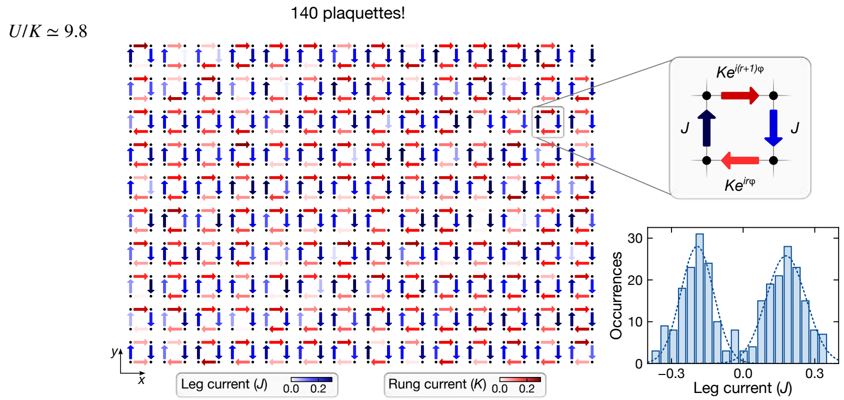


## Programmable Orbital Rotations using Superlattices





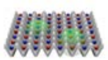

## Ground State Interacting Flux Plaquette




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

# Applications in Many-Body Physics

0 State Preparation/Engineering and Detection
Manipulating the Orbital Bloch Sphere



**1 Strongly Correlated Electron Physics & Quantum Gates**
AFM, Polarons, Pseudogap, Quantum Gates…

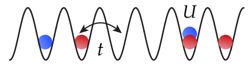
2 Probing Many-Body Quantum Dynamics using Subsystem Loschmidt Echos

3 Outlook

*Fermi Hubbard*

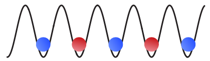
# Fermi Hubbard Model (FHM)

**Fermi-Hubbard Model**



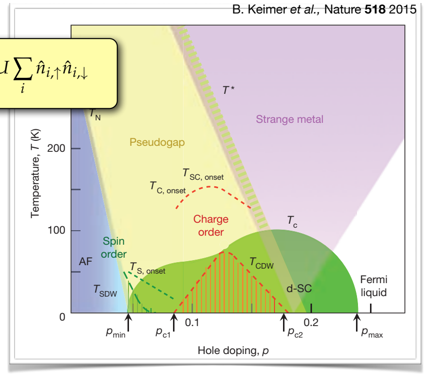

$$\hat{H} = -t \sum_{\langle i,j\rangle,\sigma} \hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + U\sum_i \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

**AFM Heisenberg Model**
Half filling & strong interaction



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

B. Keimer *et al.*, Nature **518** 2015




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

***hole delocalization*** ⟷ ***magnetic order***

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)

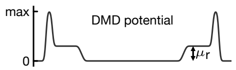
Esslinger, T. Fermi-Hubbard Physics with Atoms in an Optical Lattice. *Annu. Rev. Cond. Mat. Phys.* **1**, 129–152 (2010).

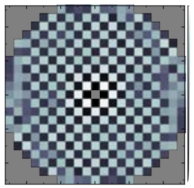
*Potential Shaping*

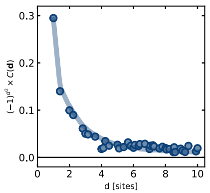
# 2D Spin Correlations

$$\frac{\langle \hat{S}^z_i \hat{S}^z_j\rangle - \langle \hat{S}^z_i\rangle\langle \hat{S}^z_j\rangle}{\sigma(\hat{S}^z_j)\sigma(\hat{S}^z_i)}$$

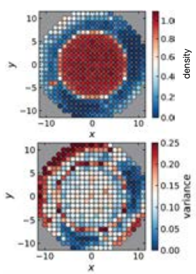
**Idea:**
T.-L. Ho, Q. Zhou, arXiv:0911.5506
J.S. Bernier *et al.* Phys. Rev. A (2009)
**related:** B. Yang *et al.* Science (2020)






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



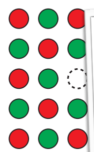

$T/t \sim 0.25$ $\quad T/J \sim 0.4$
$U/t = 6.5$ $\quad t/J \simeq 1.6$

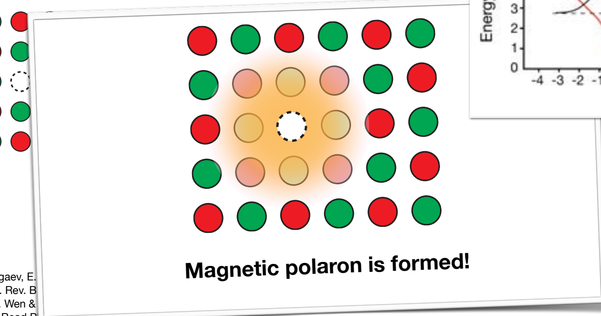
**low Temp: *T/t*=0.1:** M. Xu, …M. Greiner, Nature **642**, 909 (2025)
**See also: Harvard:** Parsons et al., Science (2016), Mazurenko et al. Nature (2017),
**MIT:** Cheuk et al., Science (2016), **Princeton:** Brown et al., Science (2017),
**Bonn:** Drewes et al., PRL (2017), **Rice:** A. Hart et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

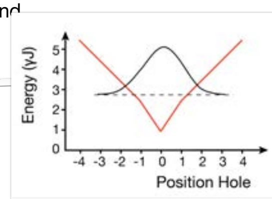
*Polarons*

# Polaron Formation in 2D

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






…ole leaves frustrated bonds
…ind - CONFINEMENT!
… and Holon form "Parton"

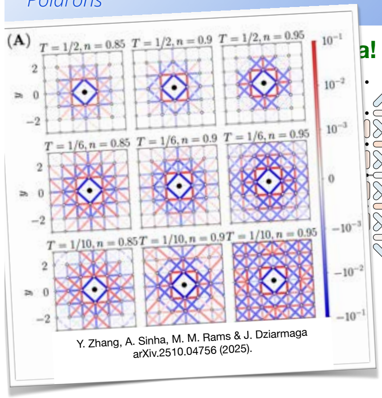
Bulaevskii, L. N., Nagaev, E. …
S. A. Trugman, Phys. Rev. B …
J. R. Schrieffer, X. G. Wen & …
C. Kane, P. Lee & N. Read P…
B. D. Simons and J. M. F. Gunn, Phys. Rev. B **41**, 7019 (1990)
P. Lee *et al.*, Rev. Mod. Phys. **78** (2006)
K. K. Nielsen, M. A. Bastarrachea-Magnani, T. Pohl, & G. M. Bruun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

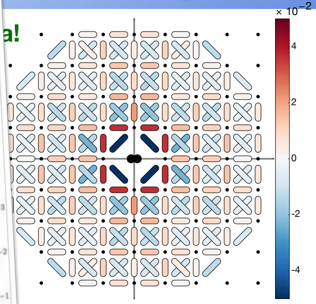
…D. Simons Phys. Rev. B **42**, 4370 (1990)
…dt *et al.*, PRX **8**, 011046 (2018)

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

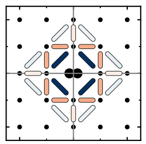



J. Koepsell *et al.* Nature **572**, 358 (2019)
J. Koepsell *et al.* Science **374**, 82 (2021)

$$\langle \hat{n}^h_{\mathbf{r}} \hat{S}^z_{\mathbf{r+i}} \hat{S}^z_{\mathbf{r+j}} \rangle^c$$

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

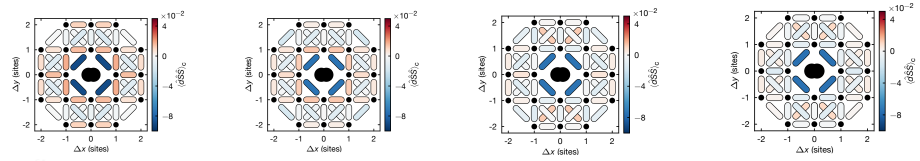


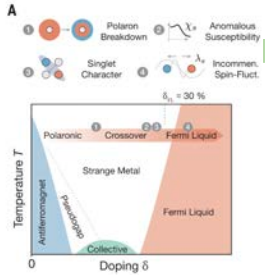
QMC Numerics
Z. Wang & Lode Pollet
**Quantitative Match!**

**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

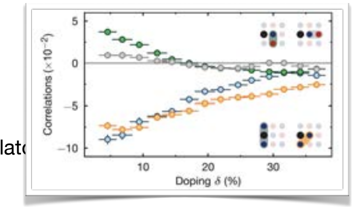





Doping → 20%

$$\langle \hat{n}^h_{\mathbf{r}} \hat{S}^z_{\mathbf{r+i}} \hat{S}^z_{\mathbf{r+j}} \rangle^c$$

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




**Exp. Data**

**Earlier results, see:** J. Koepsell *et al.* Science **374**, 82 (2021)
**Equivalent on attractive side:** T. Hartke *et al.* Science **381**, 82 (2023)

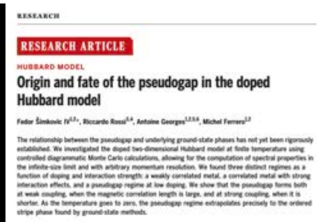
# The Pseudogap

(x10000 papers)

High-temperature superconductivity
**Mind the pseudogap**
Chandra Varma

**The pseudogap metal and FL* (a "topological" Fermi liquid)**

**The pseudogap: friend or foe of high $T_c$?**
M. R. Norman, D. Pines & C. Kallin

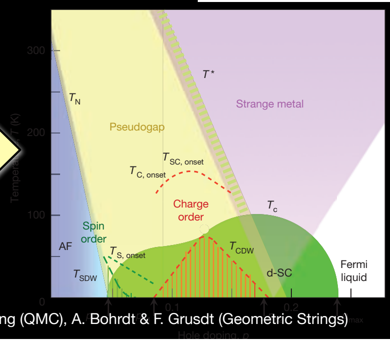



dQMC
$$\int \mathcal{D}\phi e^{-S(\phi)} = \sum \det(1 + \cdots)$$

METTS

Strings

**Theoretical methods**




**Collaboration with:** A. Georges & A. Wietek (METTS), L. Pollet & Z. Wang (QMC), A. Bohrdt & F. Grusdt (Geometric Strings)

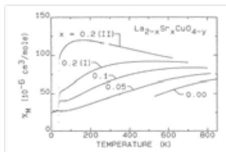
*Fermi Hubbard*

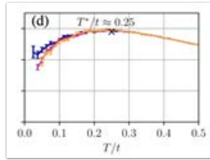
## Pseudogap Phenomenology

**1) Decrease of magnetic susceptibility with *T***

H. Alloul, T. Ohno, & P.Y. Mendels Phys. Rev. Lett. **63**, 1700 (1989)
D.C. Johnston *Phys. Rev. Lett.* **62**, 957 (1989)

**Original detection**

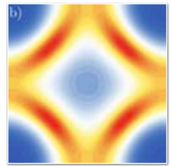



A. Wietek *et al.*, Phys. Rev. X **11**, 031007 (2021)

**2) Partial suppression of density of states /**
**low-energy excitations in selective regions of the Brillouin zone**

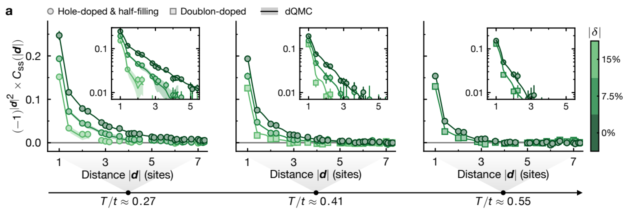
**Violation of Luttinger Theorem!**



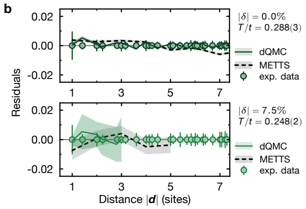
R. Rossi et al. EPL **132**, 11001 (2020)
**see also:** F. Šimkovic,..., A. Georges, M. Ferrero
Science **385** (2024).

**Recent review:** M. Qin et al. Annu. Rev. Condens. Matter Phys. **13**, 275 (2022)

## Magnetic Correlations under Doping

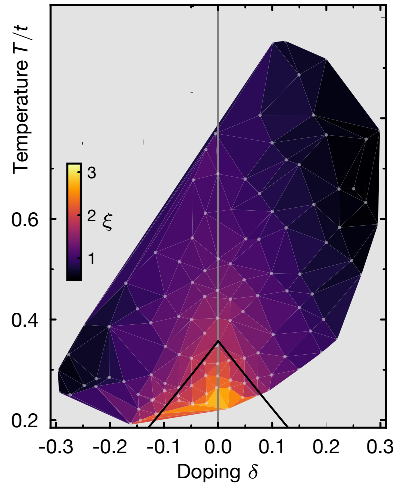



**Magnetic Correlations vs T and doping $\delta$**




**Comparison to Theory**
(dQMC, METTS)

T. Chalopin et al. PNAS **123**, e2525539123 (2026)




**Staggered Magnetization**

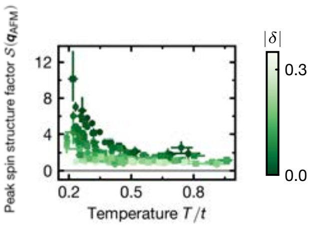
$$\hat{m}_S = \frac{1}{N}\sum_i (-1)^{i_x+i_y}\hat{S}_i^z$$

>35000 shots
varying $T$, doping $\delta$

$U/t \sim 6.5$



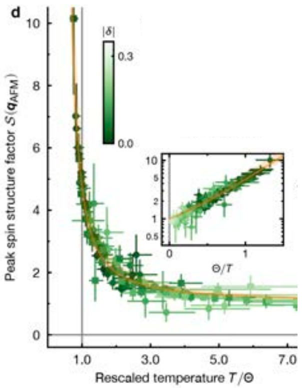
## Magnetic Correlation Length




$\Theta(\delta)$

Replot with
doping dependent
energy scale

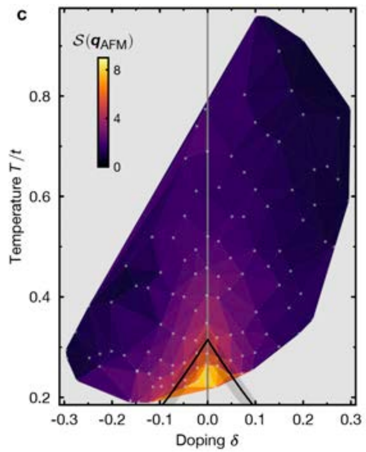
$\Theta(\delta) \approx \Theta^{(0)} + \Theta^{(1)}|\delta| + \ldots$




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)

## Pseudogap Temperature Dependence

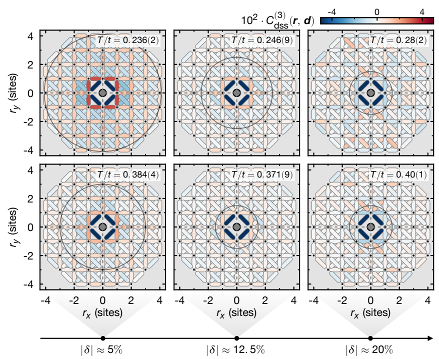



$$T^* \sim \Theta(\delta) \sim T\log\xi$$

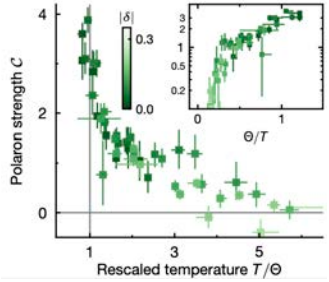
$$\Theta(\delta) \approx \Theta^{(0)} + \Theta^{(1)}|\delta| + \Theta^{(2)}|\delta|^2 + \ldots$$

LMU

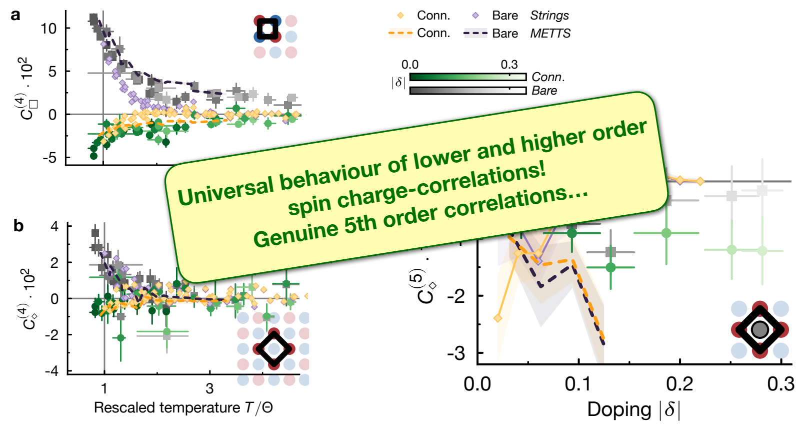
## Charge-Spin-Spin Correlations




$$C^{(3)}_{\rm dss}(\mathbf{r},\mathbf{d}) = \frac{4}{N_{\mathbf{r},\mathbf{d}}}\sum_{i\in\Omega}\frac{\langle \hat{d}_i \hat{S}^z_{i+\mathbf{r}+\mathbf{d}/2}\hat{S}^z_{i+\mathbf{r}-\mathbf{d}/2}\rangle_c}{\langle \hat{d}_i\rangle}$$



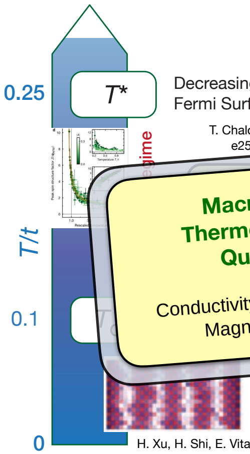

## Higher-Order Correlators




**Universal behaviour of lower and higher order spin charge-correlations!**
**Genuine 5th order correlations…**

## Square Lattice Hubbard Model - Phases (Low Doping)

*FHM*




Decreasing Spin Susceptibility & Fermi Surface Reconstruction

T. Chalopin et al. PNAS **123**, e2525539123 (2026)

**What is the physical mechanism for the Pseudogap?**

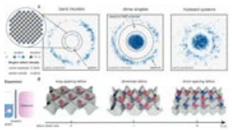
**Macroscopic Thermodynamics Quantities**

Conductivity, Compressibility, Magnetization, ….

**Microscopic Real-Space Quantities**

Hidden Order, Higher Order Correlations, Fluctuations

**Quantum Gas Microscopes**

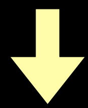


M. Xu, …M. Greiner, Nature **642**, 909 (2025)
low Temp: $T/t$=0.1

H. Xu, H. Shi, E. Vitali, M. Qin, and S. Zhang Phys. Rev. Research **4**, 013239 (2022)

H.J. Schulz *Phys. Rev. Lett.* **64**, 1445 (1990)

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

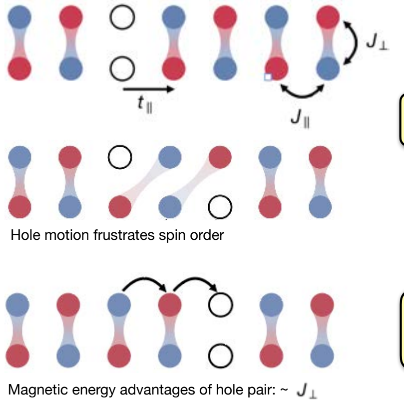


## via magnetic correlations!

## Hole - Attraction

**Do two holes in an antiferromagnet form a bound pair?**

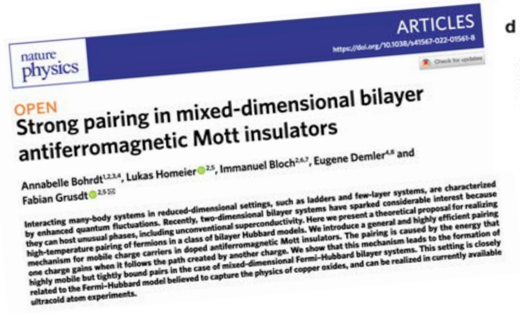
Magnetically induced hole-hole attraction




Does this lead to pairing on rungs?

But kinetic energy disfavours rung pairs!

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

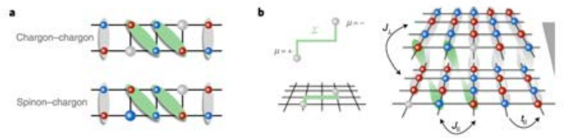

nature physics — ARTICLES
https://doi.org/10.1038/s41567-022-01561-8

OPEN

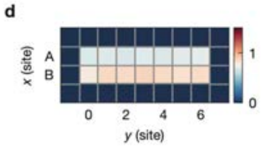
Strong pairing in mixed-dimensional bilayer antiferromagnetic Mott insulators

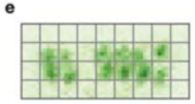
Annabelle Bohrdt, Lukas Homeier, Immanuel Bloch, Eugene Demler and Fabian Grusdt

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 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.



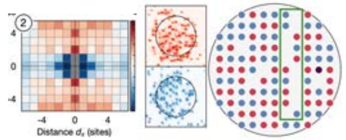

**Theory:** Bohrdt, A., Homeier, L., Bloch, I., Demler, E. & Grusdt, F. *Nat. Phys.* **18**, 651–656 (2022).



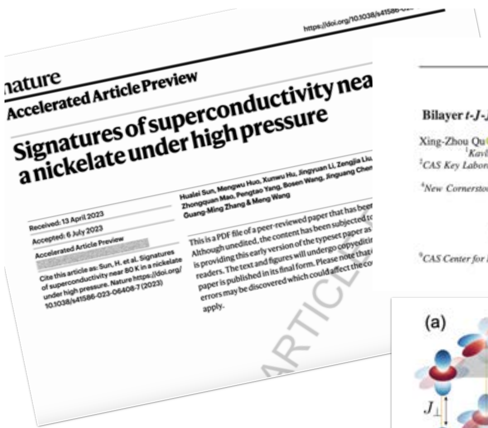

**Experiment:** S. Hirthe et al. *Nature* **613**, 463 (2023)

**Boost pairing energy x15 !!**




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

**Pairing confirmed in 2D**
**Structure formation beyond pairing!**


nature — Accelerated Article Preview

Signatures of superconductivity near 80 K in a nickelate under high pressure

Received: 13 April 2023
Accepted: 6 July 2023
Accelerated Article Preview

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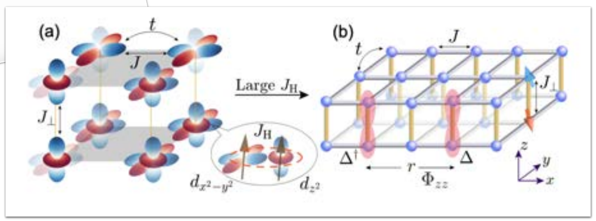
PHYSICAL REVIEW LETTERS **132,** 036502 (2024)

**Bilayer $t$-$J$-$J_\perp$ Model and Magnetically Mediated Pairing in the Pressurized Nickelate $La_3Ni_2O_7$**


Xing-Zhou Qu,[1,2,*] Dai-Wei Qu,[1,2,*] Jialin Chen,[2,3,*] Congjun Wu,[4,5,6,7] Fan Yang,[8] Wei Li,[2,3,9,†] and Gang Su[1,9,‡]
[1]Kavli Institute for Theoretical Sciences, University of Chinese Academy of Sciences, Beijing 100190, China
[2]CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
[3]Hefei National Laboratory, Hefei 230088, China
[4]New Cornerstone Science Laboratory, Department of Physics, School of Science, Westlake University, Hangzhou 310024, Zhejiang, China
[5]Institute for Theoretical Sciences, Westlake University, Hangzhou 310024, China
[6]Key Laboratory for Quantum Materials of Zhejiang Province, School of Science, Westlake University, Hangzhou 310024, Zhejiang, China
[7]Institute of Natural Sciences, Westlake Institute for Advanced Study, Hangzhou 310024, China
[8]School of Physics, Beijing Institute of Technology, Beijing 100081, China
[9]CAS Center for Excellence in Topological Quantum Computation, University of Chinese Academy of Sciences, Beijing 100190, China

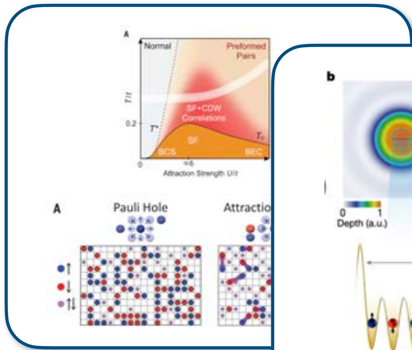

(Received 1 August 2023; accepted 19 December 2023; published 19 January 2024)



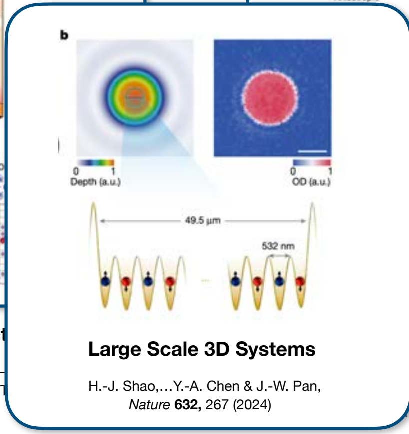

**Mixed dimensional model explains high Tc!**

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

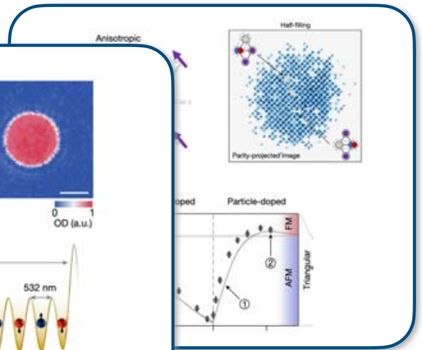
## *Quantum Gas Microscopy Fermions* — Recent Highlights




**Attractive Interact**
Hartke *et al.* *Science* **381**, 82–
M. Zwierlein group (MIT




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

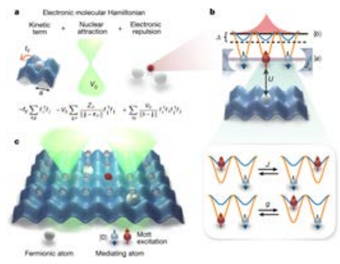



**ole Frustration**
*et al. Nature* 1–6 (2023)
38/s41586-023-06280-5.
ner group (Harvard)
so W. Bakr (Princeton)

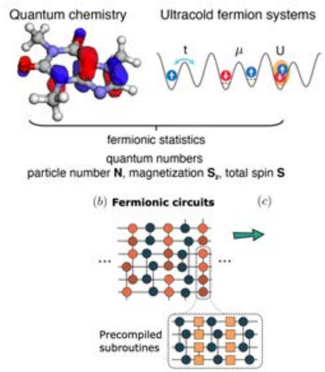
# From Analog to Digital



## Chemistry Analog or Digital using Fermions



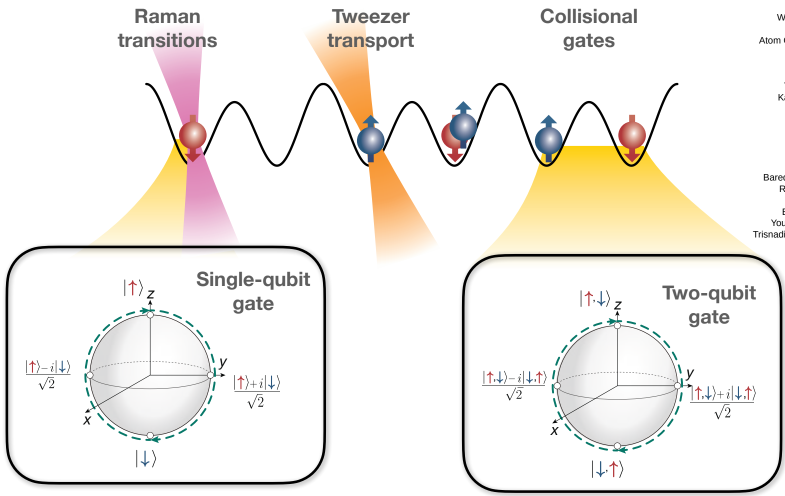
J. Argüello-Luengo, A. González-Tudela, T. Shi, P. Zoller, J. I. Cirac, Analogue quantum chemistry simulation. Nature **574**, 215 (2019)




S.B. Bravyi & A. Kitaev
Annals of Physics **298**, 210–226 (2002)
D. González-Cuadra et al. PNAS **120**, e2304294120 (2023)
F. Gkritsis et al. PRX Quantum **6**, 010318 (2025),
R. Ott et al. arXiv:2412.16081



## Qubit Operations




Single Atom Addressing
Weitenberg, … Bloch, Nature **471** 319 (2011)
Xia, …, Saffman, PRL **114** 100503 (2015)
Atom Computing, Nature Communications (2022)

Collisional Gates
Anderlini, …, Porto, Nature **448** 452 (2007)
Trotzky, …., Bloch, Science **319** 295 (2008)
Kaufmann, …, Regal, Nature **527** 208 (2015)
Yang, …, Pan, Science **369** 550 (2020)
Zhang, …., Pan, arXiv 2210.02936

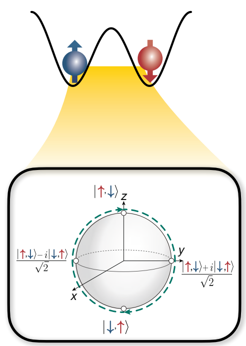
Transport of atoms
Mandel, …, Bloch, PRL **91** 010407 (2003)
Vala, … Whaley, PRA **71** 032324 (2005)
Baredo, …, Browaeys, Science **354** 1021 (2016)
Robens, …, Alberti, PRL **118** 065302 (2017), PRA **9** 034016 (2018)
Bluvstein, …, Lukin, Nature **604**, 451 (2022)
Young, …, Kaufmann, Science **377** 885 (2022)
Trisnadi, …, Chin, Rev. Sc. Instr. 93 083203 (2022)

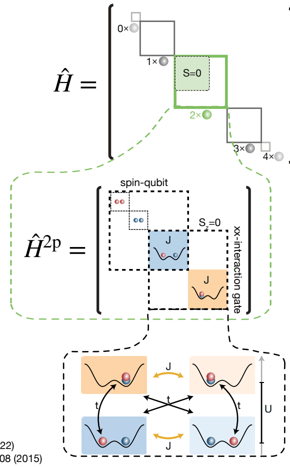
Quatum reigister
T. Hartke, … M. Zwierlein.
Nature **601**, 537 (2022)



## Collisional Gates

**Fundamental Building block:**
Double well with spin-1/2 particles



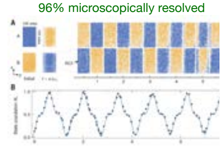



$J \approx 4t^2/U$

Demonstration Entanglement : Zhang, …, Pan, arXiv 2210.02936 (2022)
Collisional gate with tweezers: Kaufmann, …, Regal, Nature **527** 208 (2015)
Proposal Fast gate in harm. osc.: Nemirovsky, Sagi, PRR **3**, 013113 (2021)

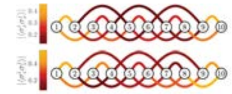
**Early experiments in tweezers:**
S. Murmann,…, Jochim, PRL **114**, 080402 (2015).
A. Bergschneider,…, Jochim, Nat. Phys. **15**, 640 (2019).

99.3(1)% Gate Fidelity on 1250 atom paris
96% microscopically resolved



B. Yang, …, J.-W. Pan, Science **369** 550 (2020)

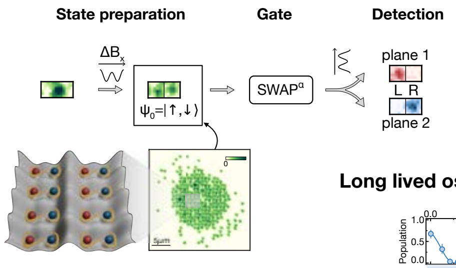
10 fully entangled qubits



Zhang, …, Pan, PRL arXiv 2210.02936

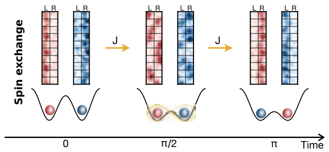
## Spin Exchange

### Experimental protocol

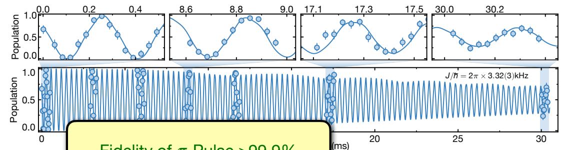



Rabi frequency: $J/\hbar = 2\pi \times 3.32(3)$ kHz
Gaussian decay of contrast: $\tau_{ex} = 33(2)$ ms

### Spin exchange




### Long lived oscillations:




Fidelity of $\pi$-Pulse >99.9%

**Limiting factors:**

- Tunneling out of double well
- Lattice inhomogeneities → local variations in Rabi frequencies

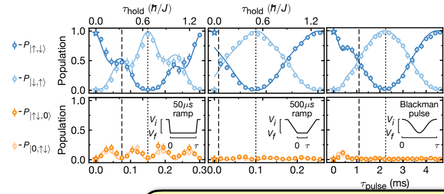


## SWAP Gate

### SWAP Gate

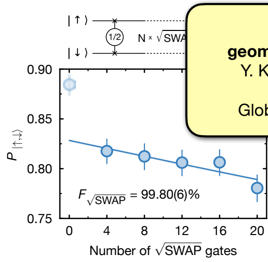
$$R_{\mathrm{SWAP}}(\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1+e^{i\alpha}}{2} & \frac{1-e^{i\alpha}}{2} \\ 0 & 0 & \frac{1-e^{i\alpha}}{2} & \frac{1+e^{i\alpha}}{2} \end{pmatrix}$$

No additional phase




### Avoid Doublon population

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



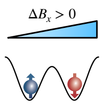

**see also:**
**geometric gate in dynamical lattices**
Y. Kiefer, ... K. Viebahn, T. Esslinger
arXiv.2507.22112.
Global detection: 99.91(7)% Fidelity

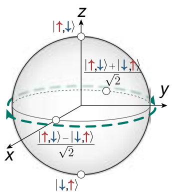


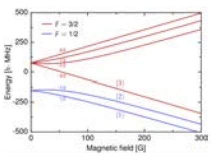
## Entangled State Coherence

### Singlet-triplet oscillations

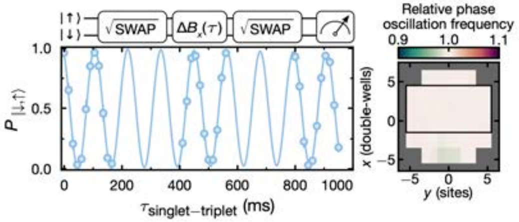
- 99% nuclear spin → Low sensitivity to field gradients
- Strong magnetic field gradient of $40$ G/cm
- Singlet-triplet oscillations at $8.72(5)$ Hz
- Coherence time $> 13(3)$ s



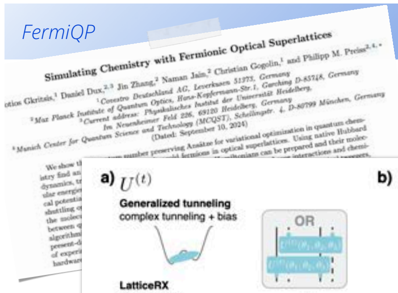




>10s coherence time

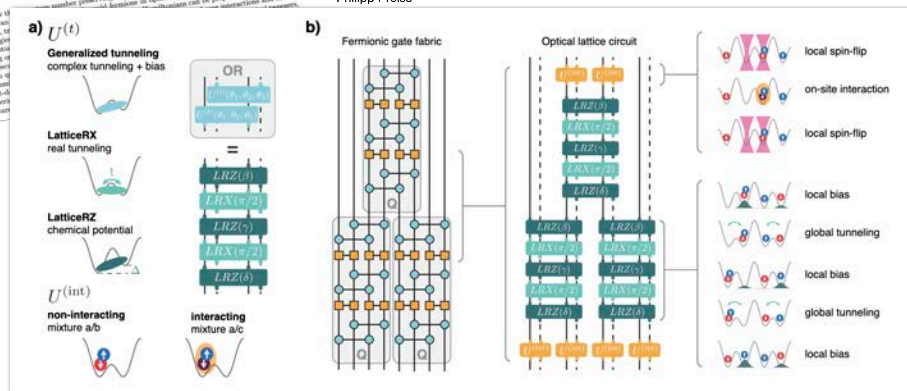




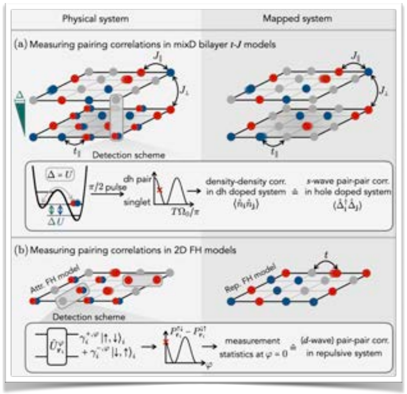

## Digital QC with Fermions



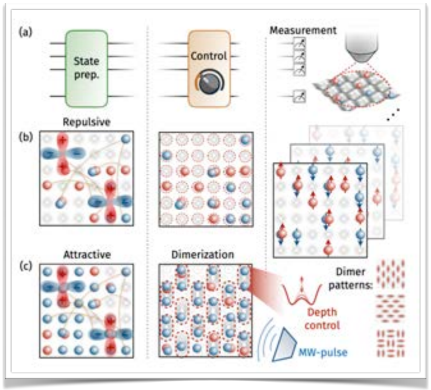

Philipp Preiss



## Fermionic Gates — New Tools to Reveal Order Parameters

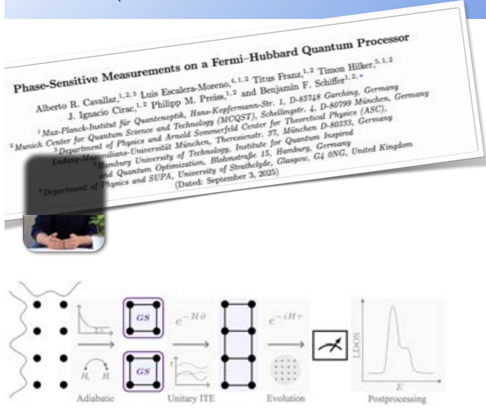



H. Schlömer, H. Lange, T. Franz, T. Chalopin, P. Bojović, S. Wang, I. Bloch, T. A. Hilker, F. Grusdt, A. Bohrdt, PRX Quantum (2024)

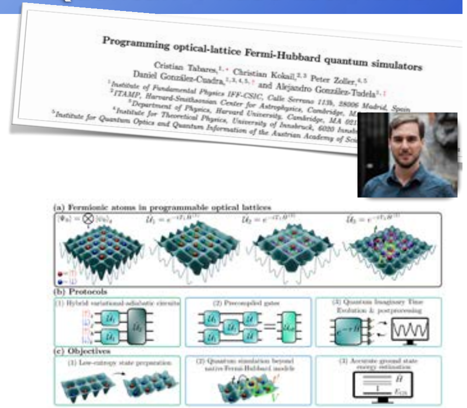



D. K. Mark, H.-Y. Hu, J. Kwan, C. Kokail, S. Choi, S. F. Yelin, PRL (2025)

## Fermionic QC — Quantum Phase Estimation




**Phase Sensitive Measurements**
(LDOS, finite T,…)

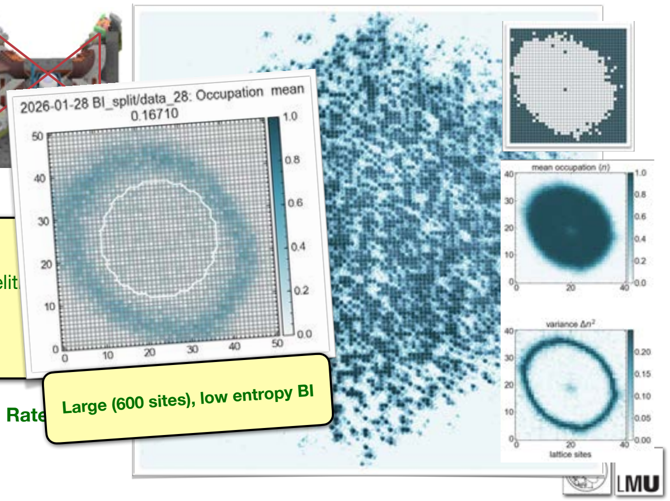



**Programmability**

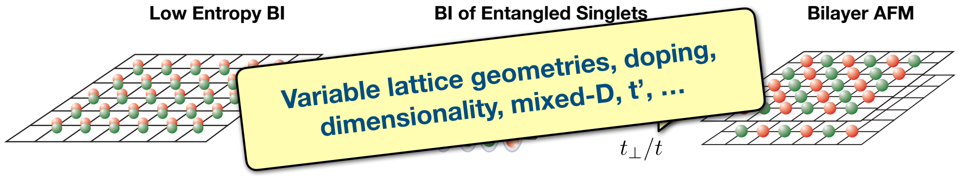
## FermiQP — Towards Fast Cycle Time Lithium QG Microscopes

- $T/T_F$<0.5 in 1s cycle time
- 0.1 s imaging with 99% Fidelit
- Single site addressing
- Superlattice & bilayer

**Sub Second - High Repetition Rate QG Microscopy**




## Bilayer — From Low Entropy BI to Doped Bilayers

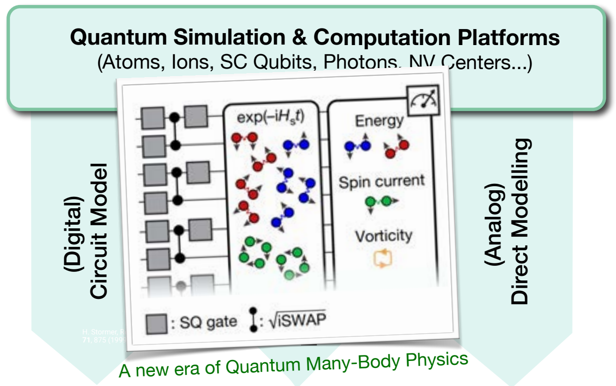




**Theory:** A. W. Sandvik & D. J. Scalapino. Phys. Rev. Lett. 72, 2777–2780 (1994)
A. W. Sandvik, A. V. Chubukov & S. Sachdev. Phys. Rev. B 51, 16483 (1995)
S. S. Kancharla & S. Okamoto Phys. Rev. B 75, 193103 (2007)
T. A. Maier & D. J. Scalapino. Phys. Rev. B 84, 180513 (2011)
…
**Exp:** M. Gall, N.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

# Where Next?

## A Joint Look Ahead...



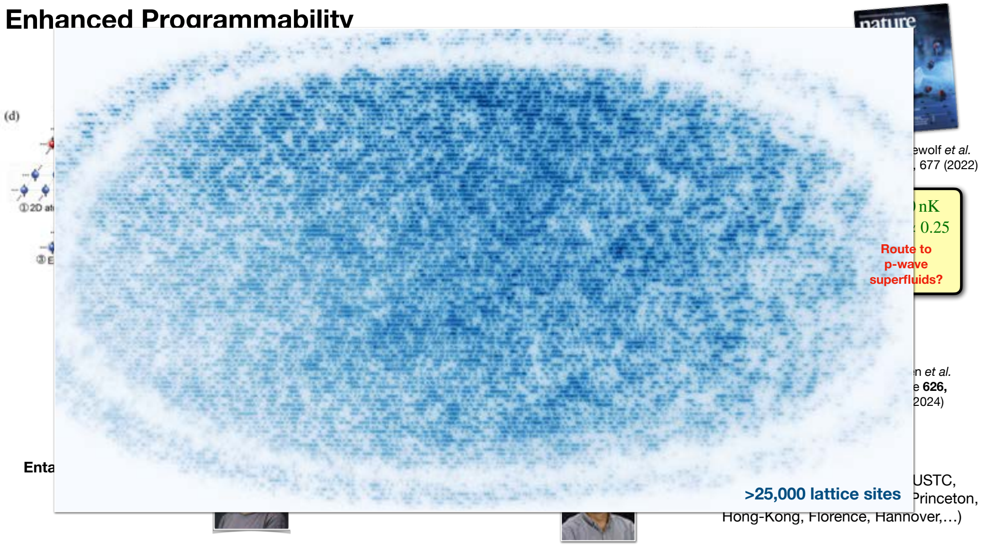


Perspective

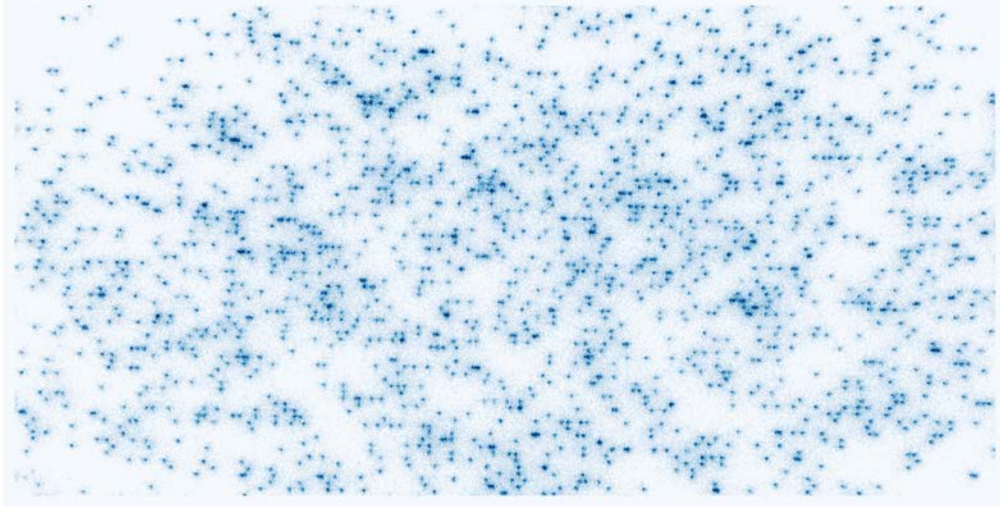
Practical quantum advantage in quantum simulation

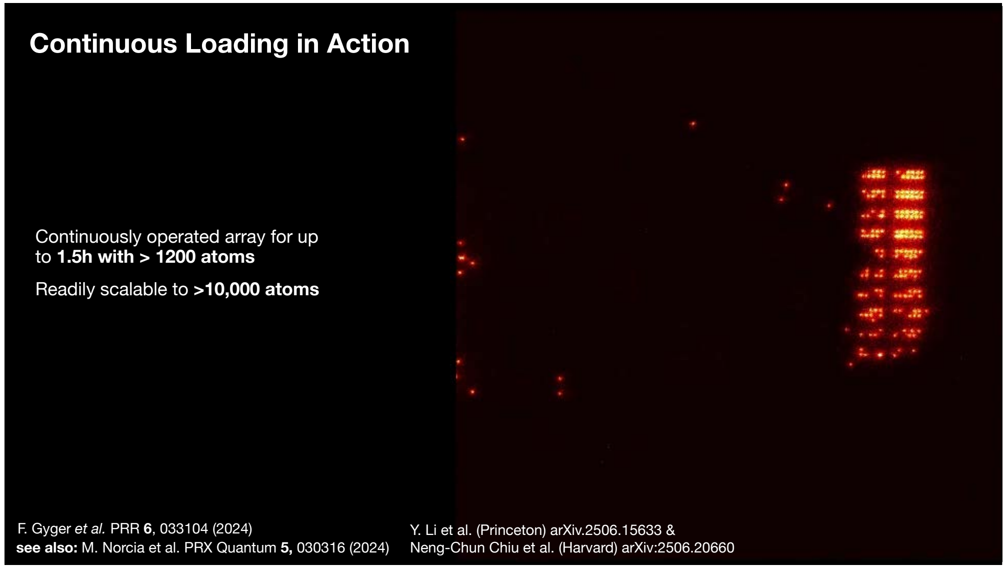
A.J. Daley, I. Bloch, C. Kokail, S. Flannigan, N. Pearson, M. Troyer, P. Zoller
Nature **607**, 667–676 (2022)

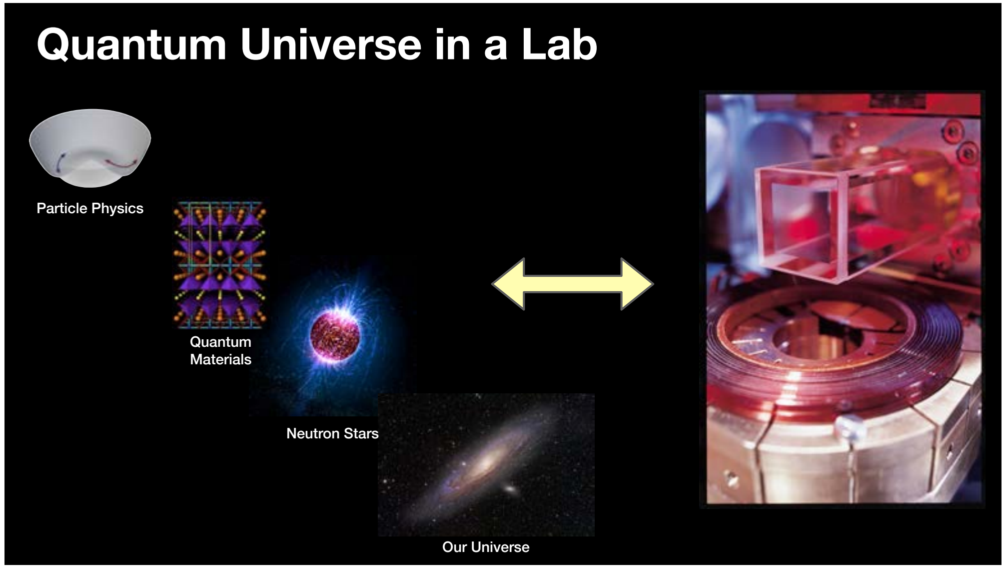
## Enhanced Programmability




## Direct Lattice Loading and Sorting




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)
see also: M. Norcia et al. PRX Quantum 5, 030316 (2024)
Y. Li et al. (Princeton) arXiv.2506.15633 &
Neng-Chun Chiu et al. (Harvard) arXiv:2506.20660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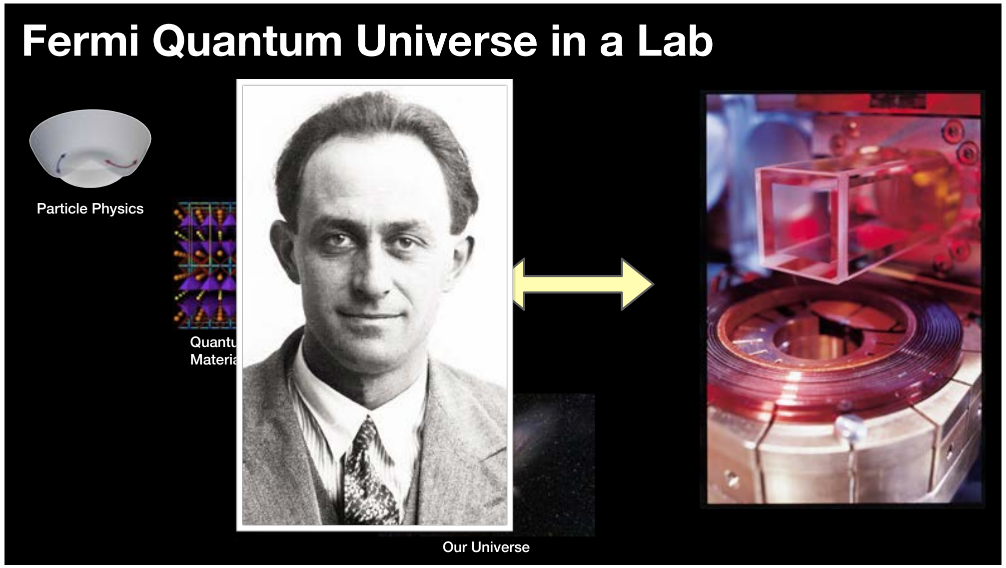
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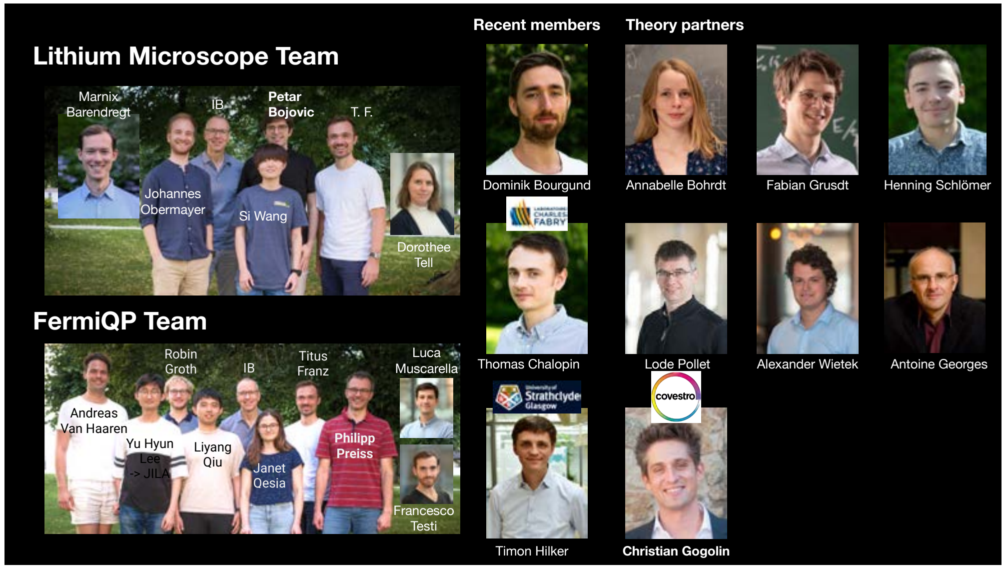
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