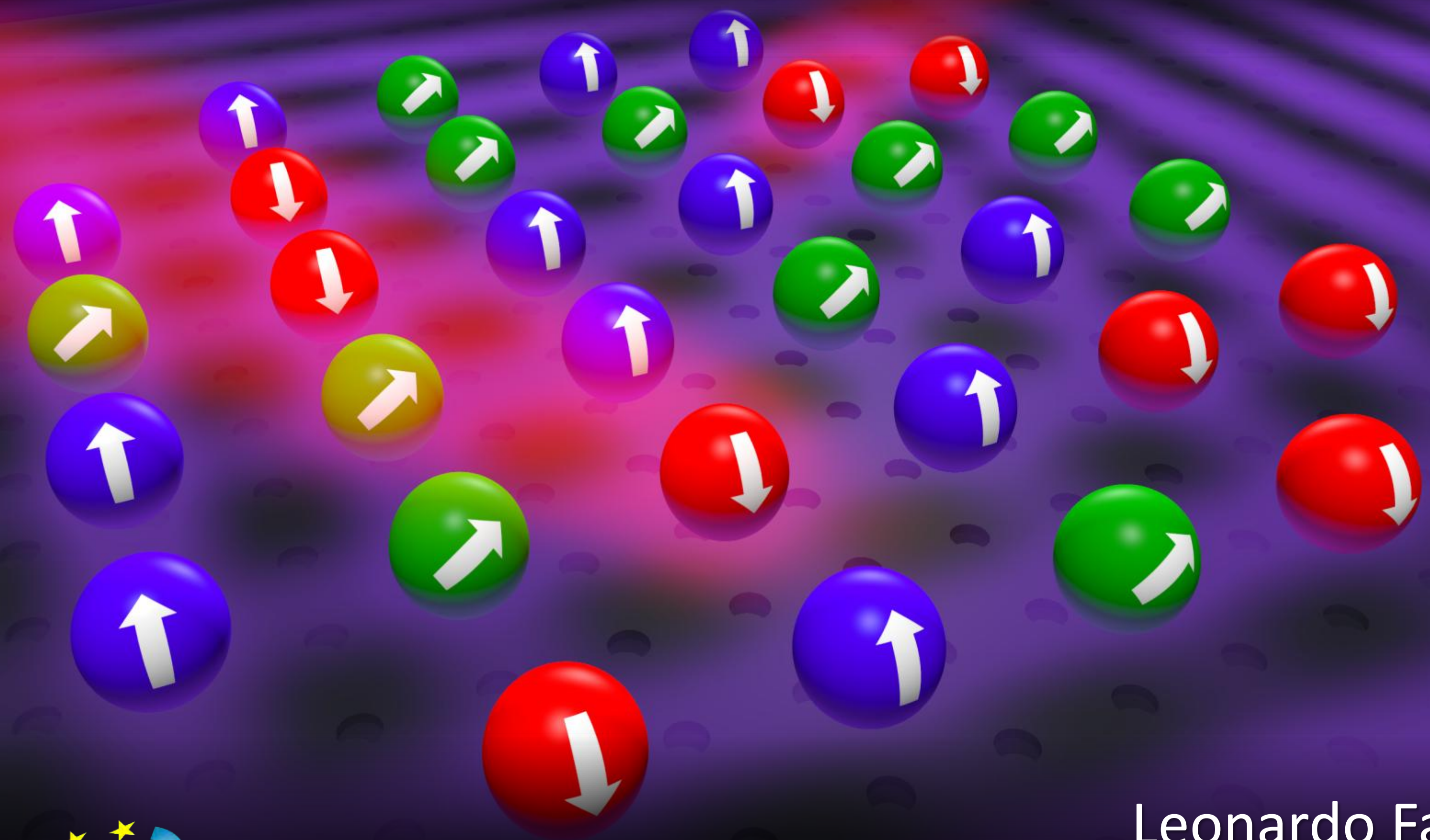
New quantum simulations with ultracold Yb fermions

Fermi legacy in low-energy physics
Accademia Nazionale dei Lincei
February 5th 2026



Leonardo Fallani

Department of Physics and Astronomy & LENS
University of Florence

Introduction

Flavour-dependent Mott localization of interacting lattice fermions

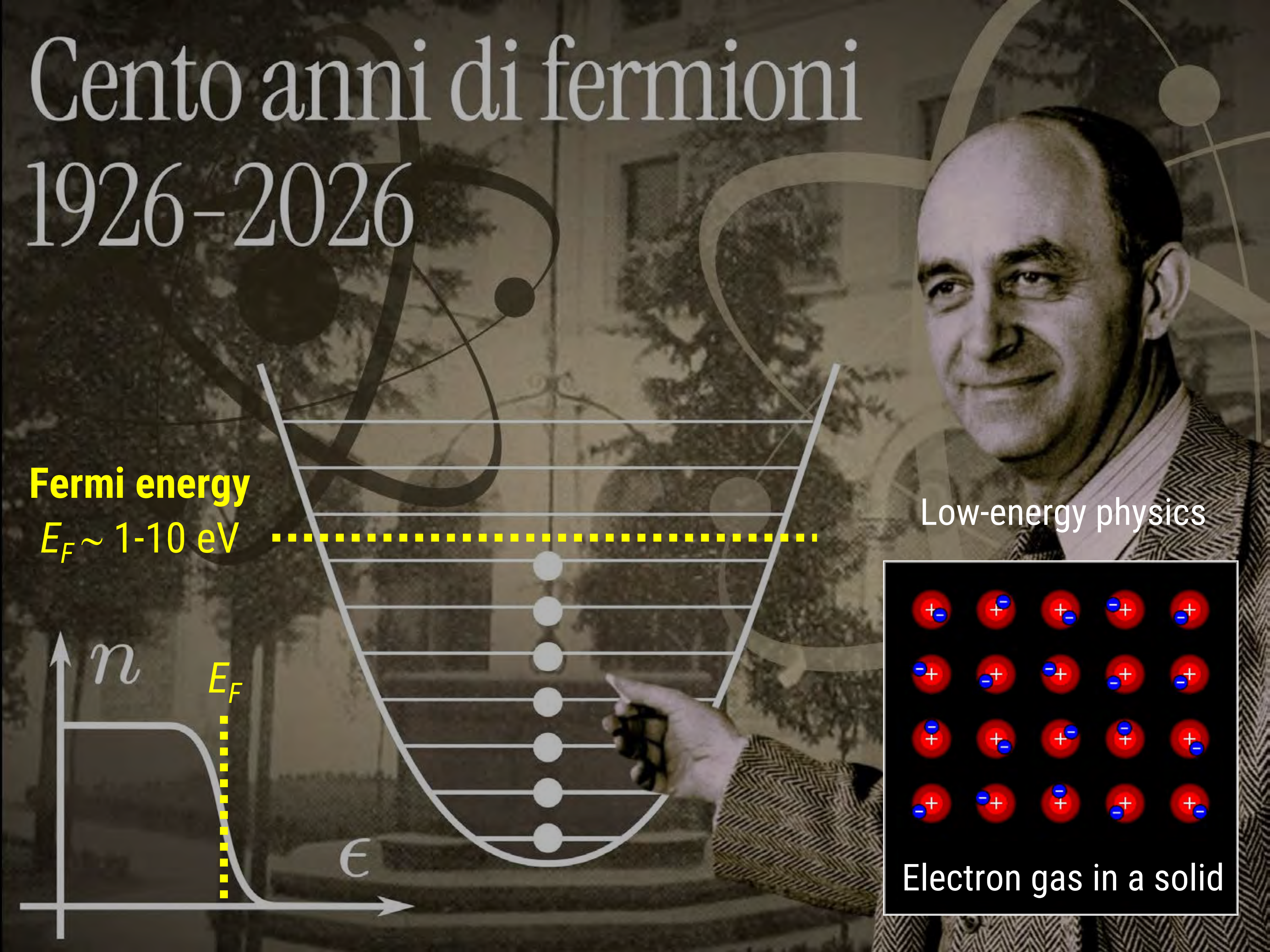
D. Tusi et al., Nature Physics **18**, 1201 (2022)

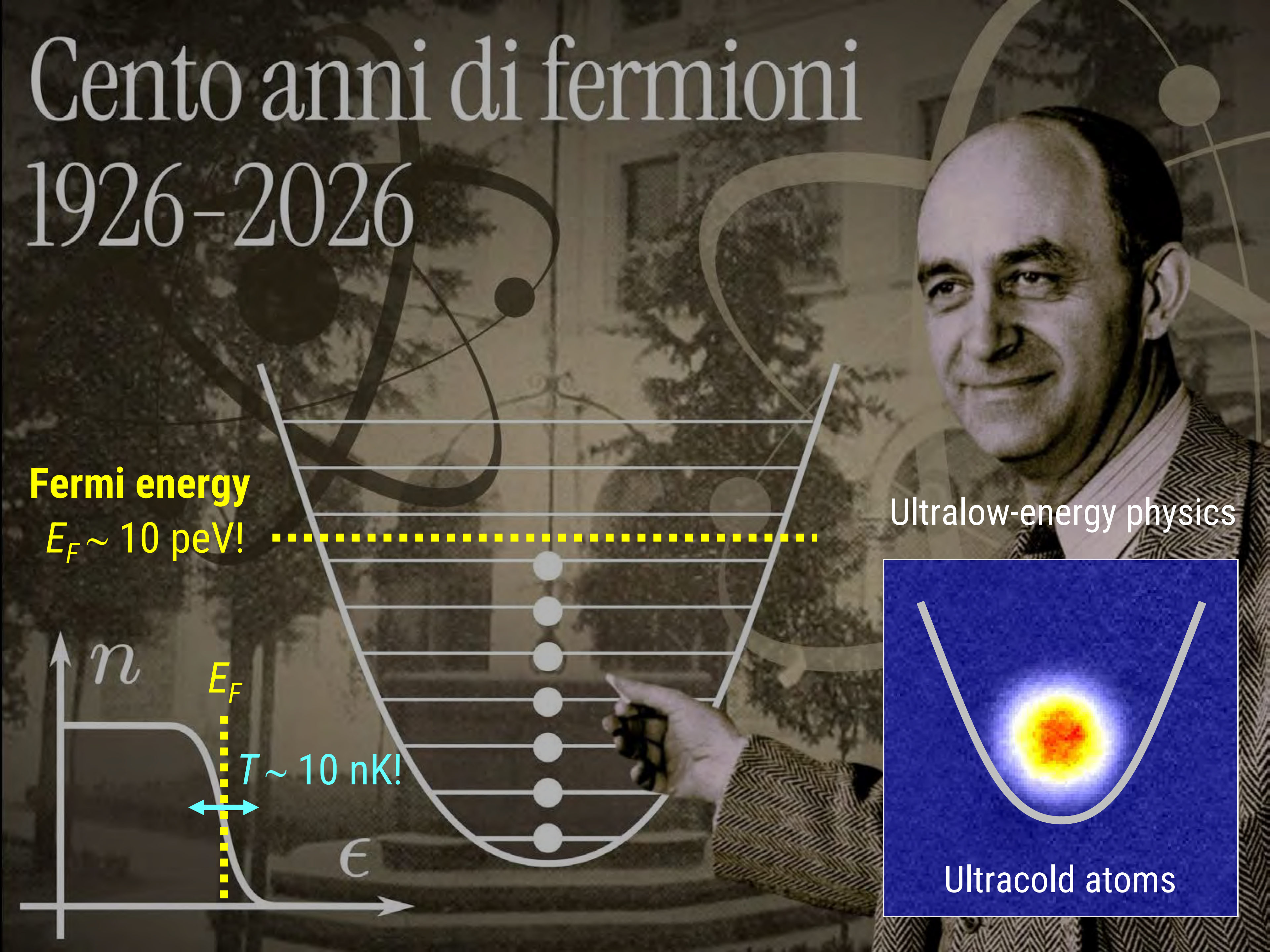
Universal Hall response in strongly interacting fermions

T.-W. Zhou et al., Science **381**, 427 (2023)
T.-W. Zhou et al., Nat. Comm. **16**, 10247 (2025)

New platforms with Rydberg atom arrays

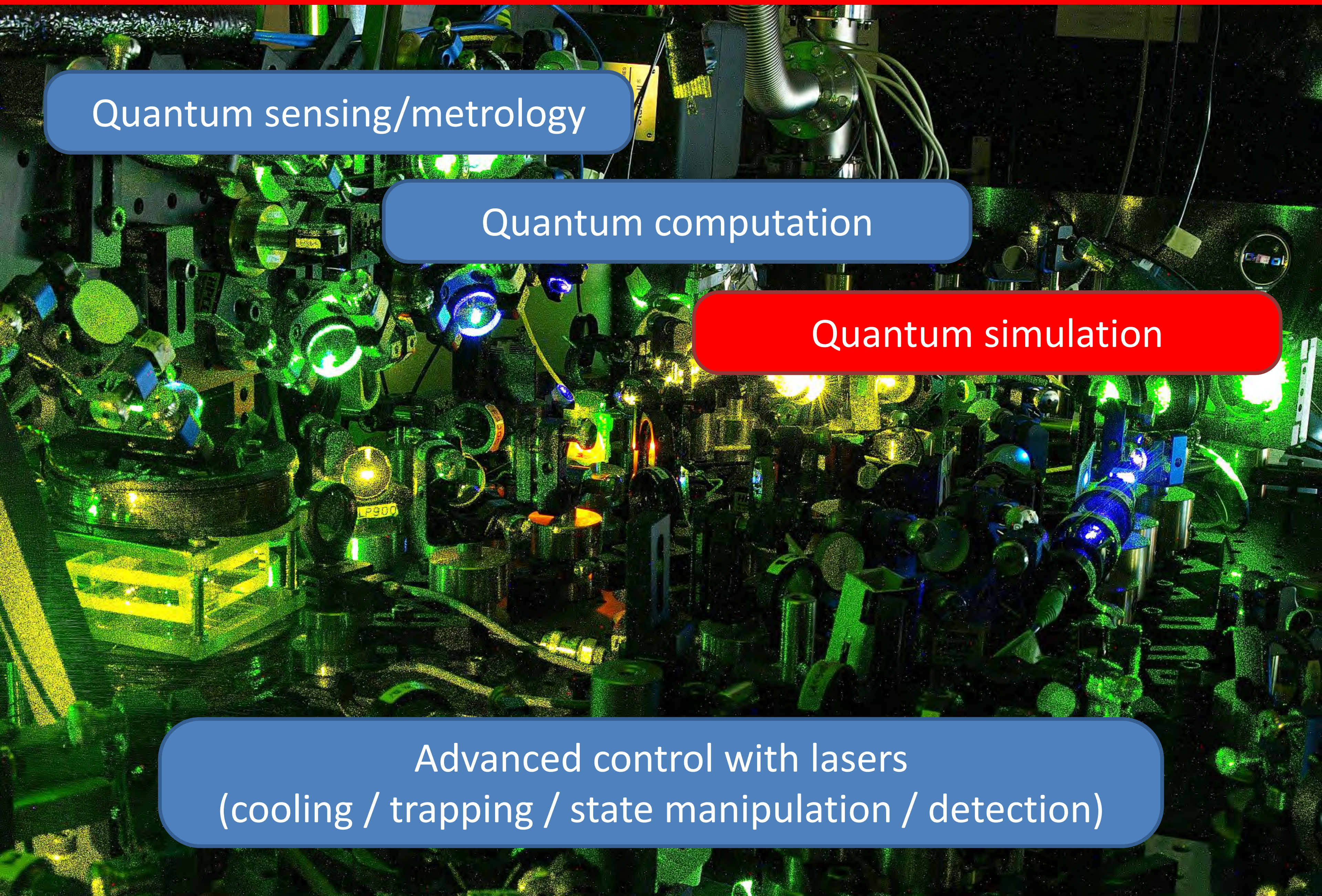

Cento anni di fermioni
1926–2026
Fermi energy
n
E_F
ϵ


Cento anni di fermioni
1926–2026
Fermi energy
$E_F \sim$ 1-10 eV
n
E_F
ϵ
Low-energy physics
Electron gas in a solid



Cento anni di fermioni
1926–2026
Fermi energy
$E_F \sim$ 10 peV!
n
E_F
$T \sim$ 10 nK!
ϵ
Ultralow-energy physics
Ultracold atoms

Ultra-low energy fermions



Quantum sensing/metrology

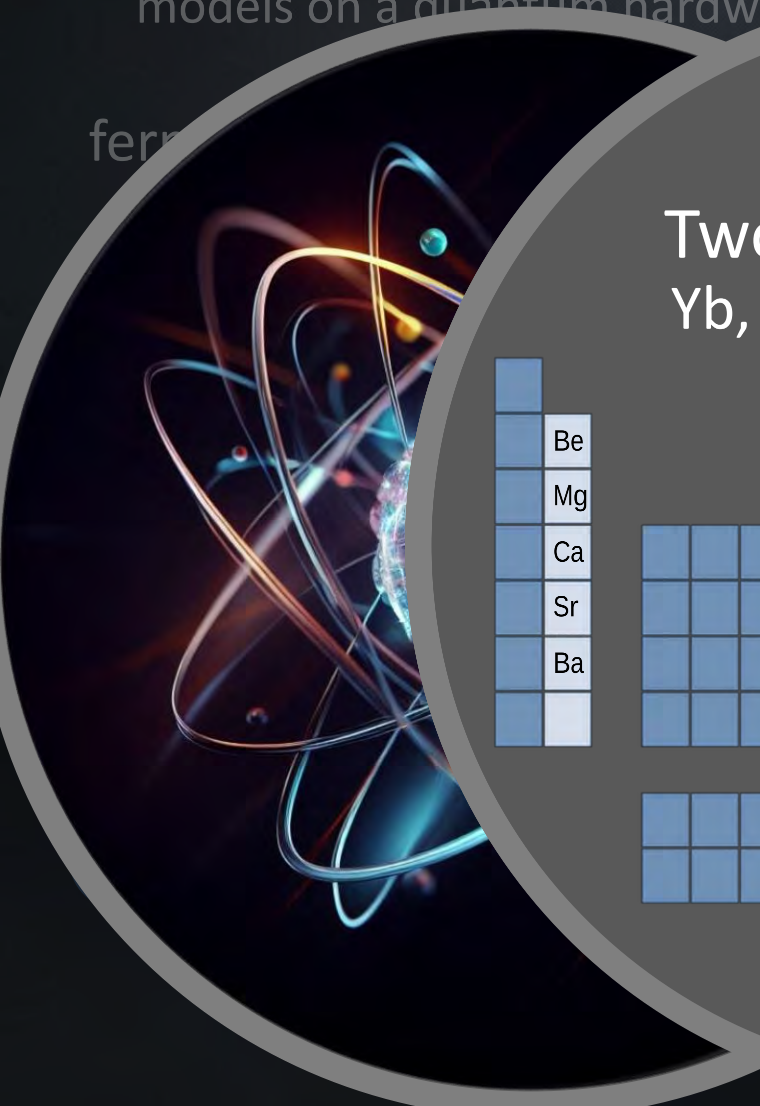
Quantum computation

Quantum simulation

Advanced control with lasers
(cooling / trapping / state manipulation / detection)

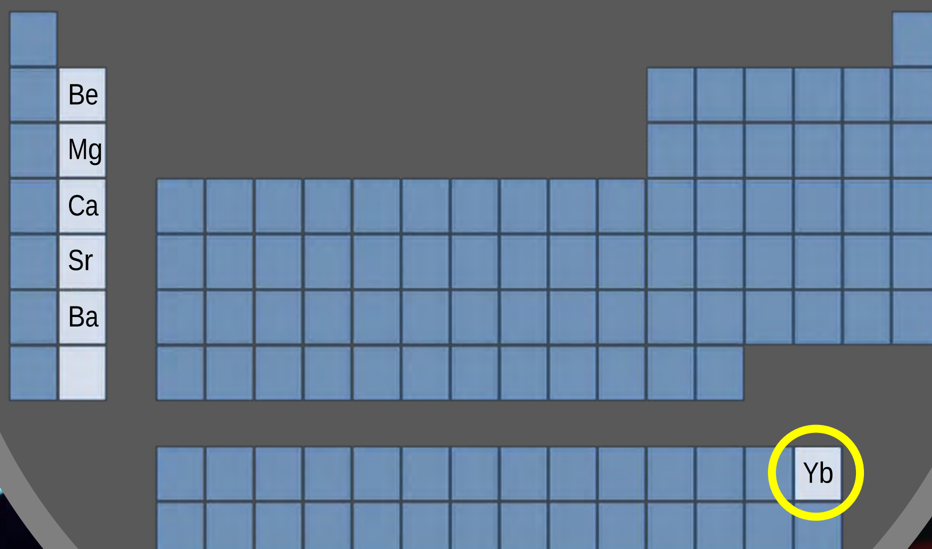
Analog Quantum simulation: build implementations of quantum models on a quantum hardware … them and measure their properties

fer… "real"!! …n solid state

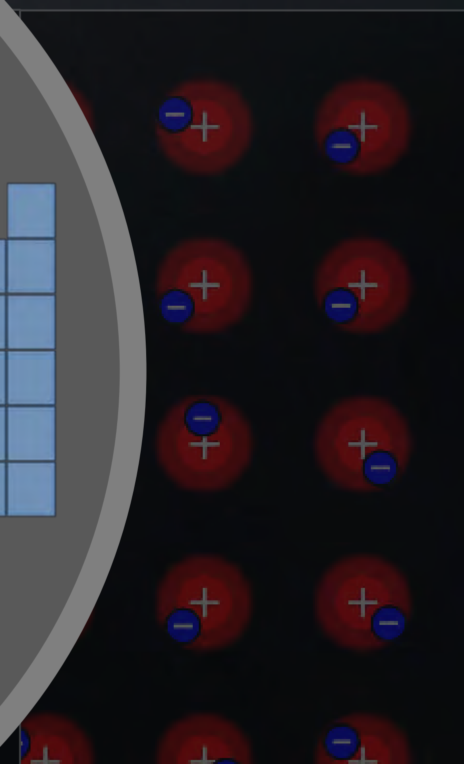


Two-electron atoms

Yb, Sr, Ca, …



Alkaline-earth-like



…eme" states of matter

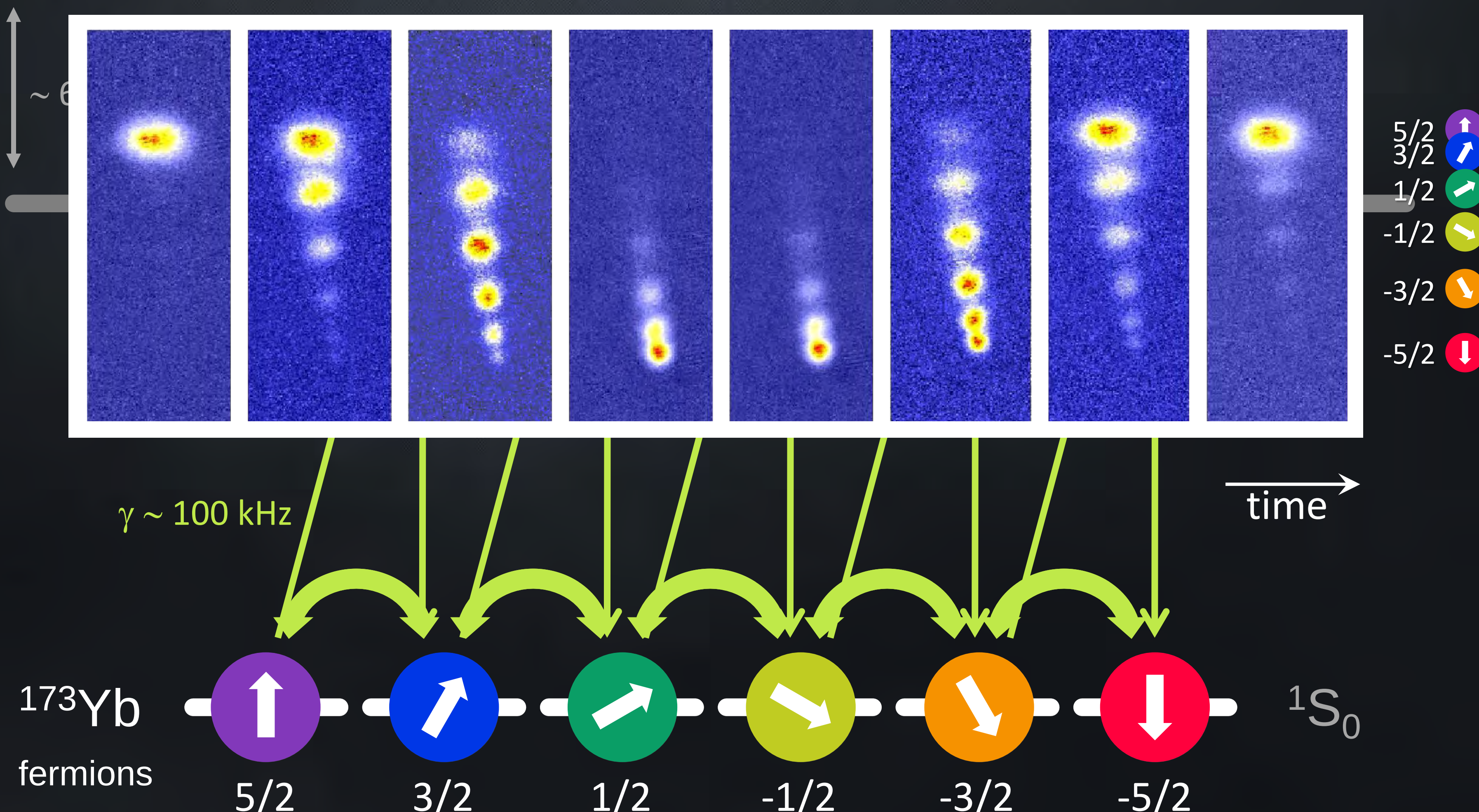
^{173}Yb fermions

Two internal degrees of freedom:
many quantum states with long coherence times:

Nuclear spin

Metastable electronic states

Coherent laser manipulation of nuclear spin state



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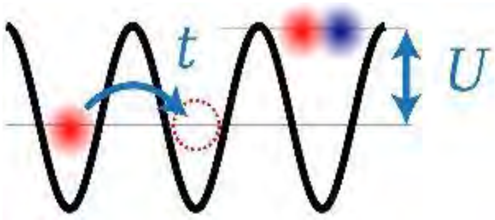
New platforms with Rydberg atom arrays

Collaboration with L. Del Re, K. Baumann, M. Capone (Trieste)

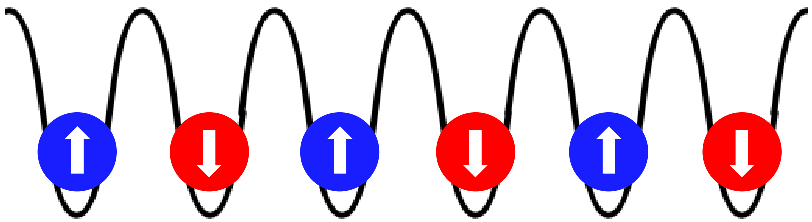
Fermi-Hubbard model

Simplest model to describe electron-electron correlations

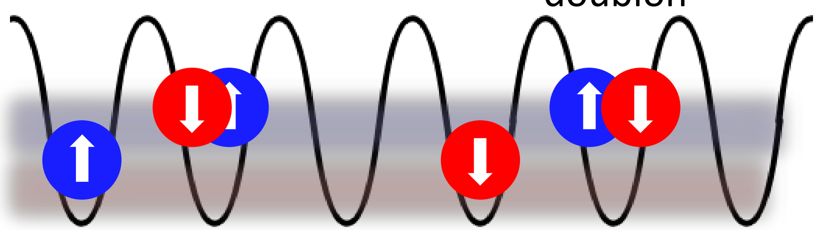
$$H = -t \sum_{\langle ij \rangle, m} \left(c^{\dagger}_{im} c_{jm} + \mathrm{h.c.} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

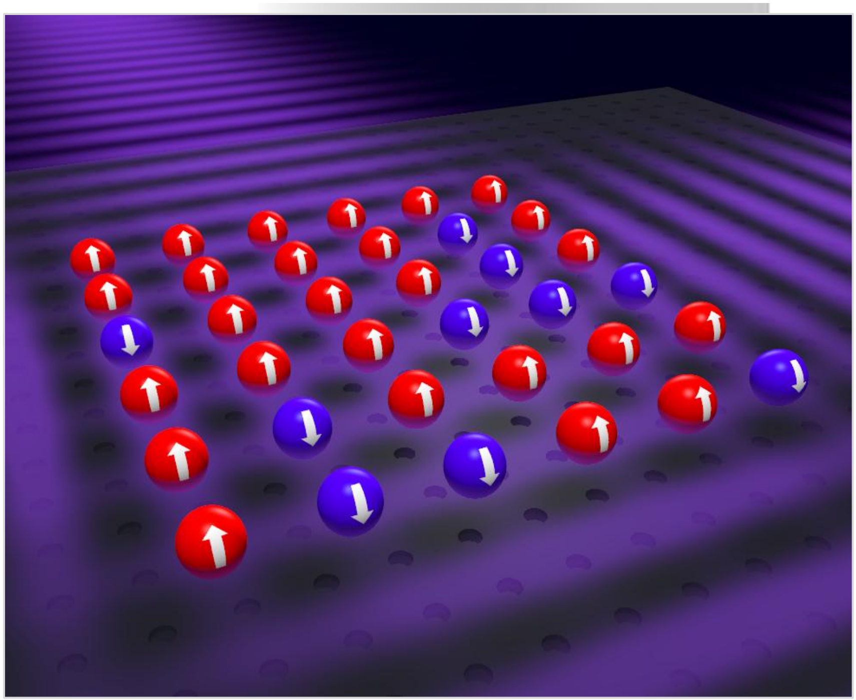


Mott insulator (U >> t) : e.g. 1 atom/site



Metal (t >> U) :

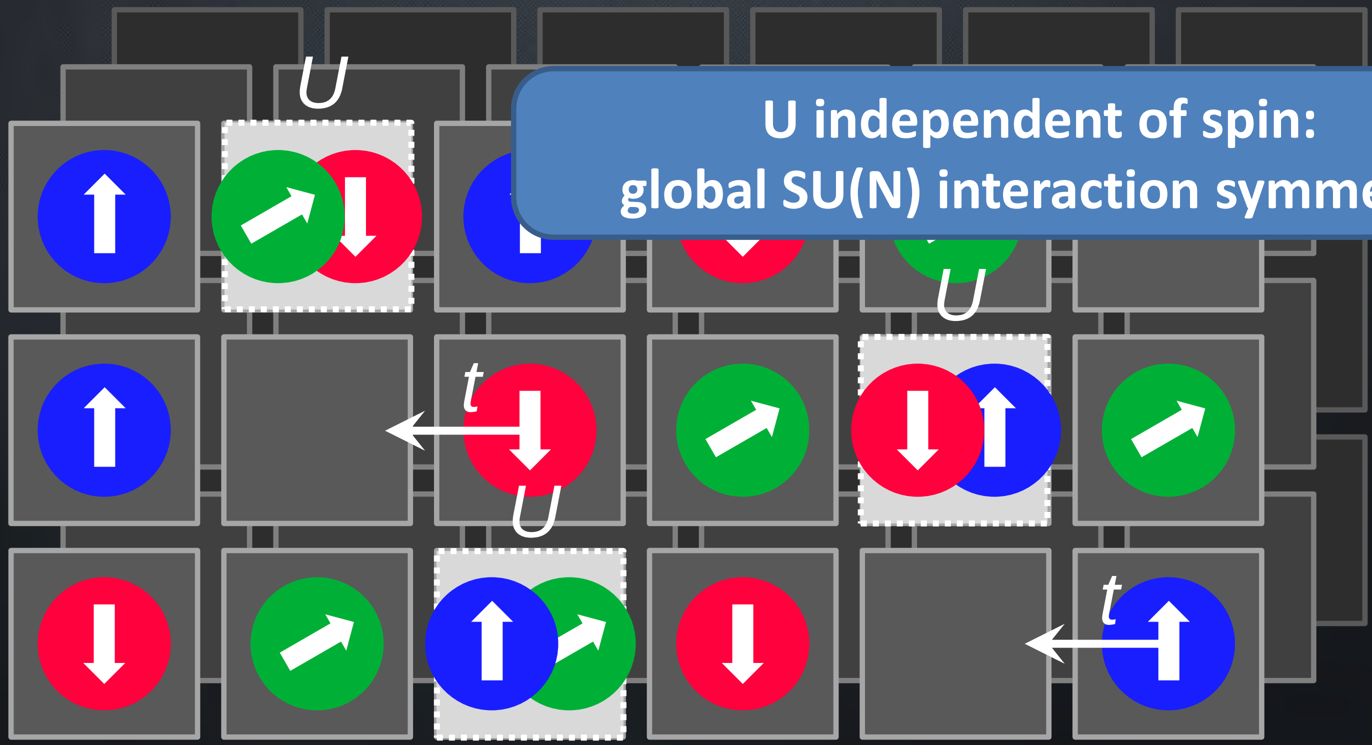




Experiments by many groups: ETH, MPQ, Harvard, Rice, MIT… and many others

SU(3) Fermi-Hubbard

SU(3) Fermi-Hubbard model (repulsive interactions U>0) in a 3D optical lattice



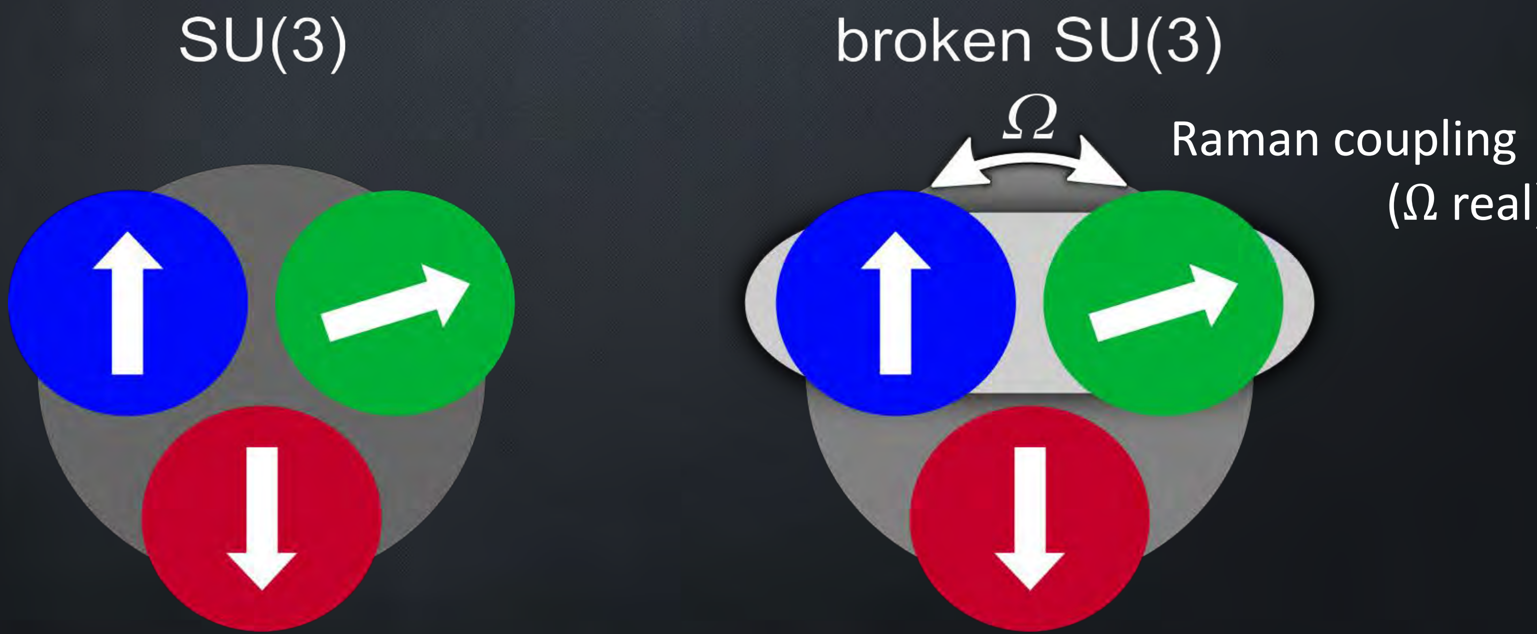
U independent of spin: global SU(N) interaction symmetry

$$H = -t \sum_{\langle ij \rangle, m} \left(c^{\dagger}_{im} c_{jm} + \mathrm{h.c.} \right) + U \sum_{i,m,m'} n_{im} n_{im'}$$

SU(3) symmetric

Breaking SU(3) symmetry

Add an extra term to the Hamiltonian coupling 2 out of the 3 states

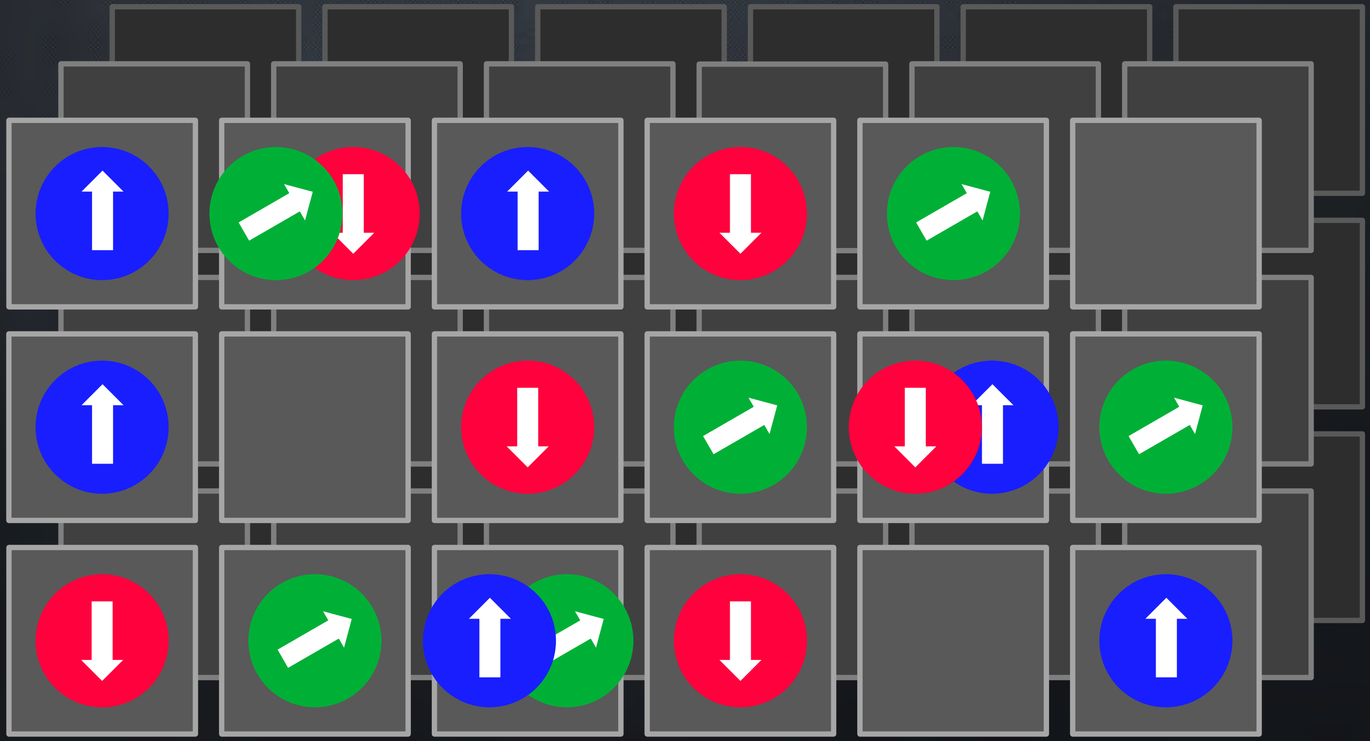


$$H = -t \sum_{\langle ij \rangle, m} \left(c^\dagger_{im} c_{jm} + \text{h. c.} \right) + U \sum_{i,m,m'} n_{im} n_{im'} + \frac{\Omega}{2} \sum_i \left(c^\dagger_{i1} c_{i2} + \text{h.c.} \right)$$

SU(3) symmetric — SU(3) breaking

Double occupancies

Characterization of the "Mottness" / "metallicity" of the many-body state by measurement of **doubly-occupied sites** with state-selective photoassociation

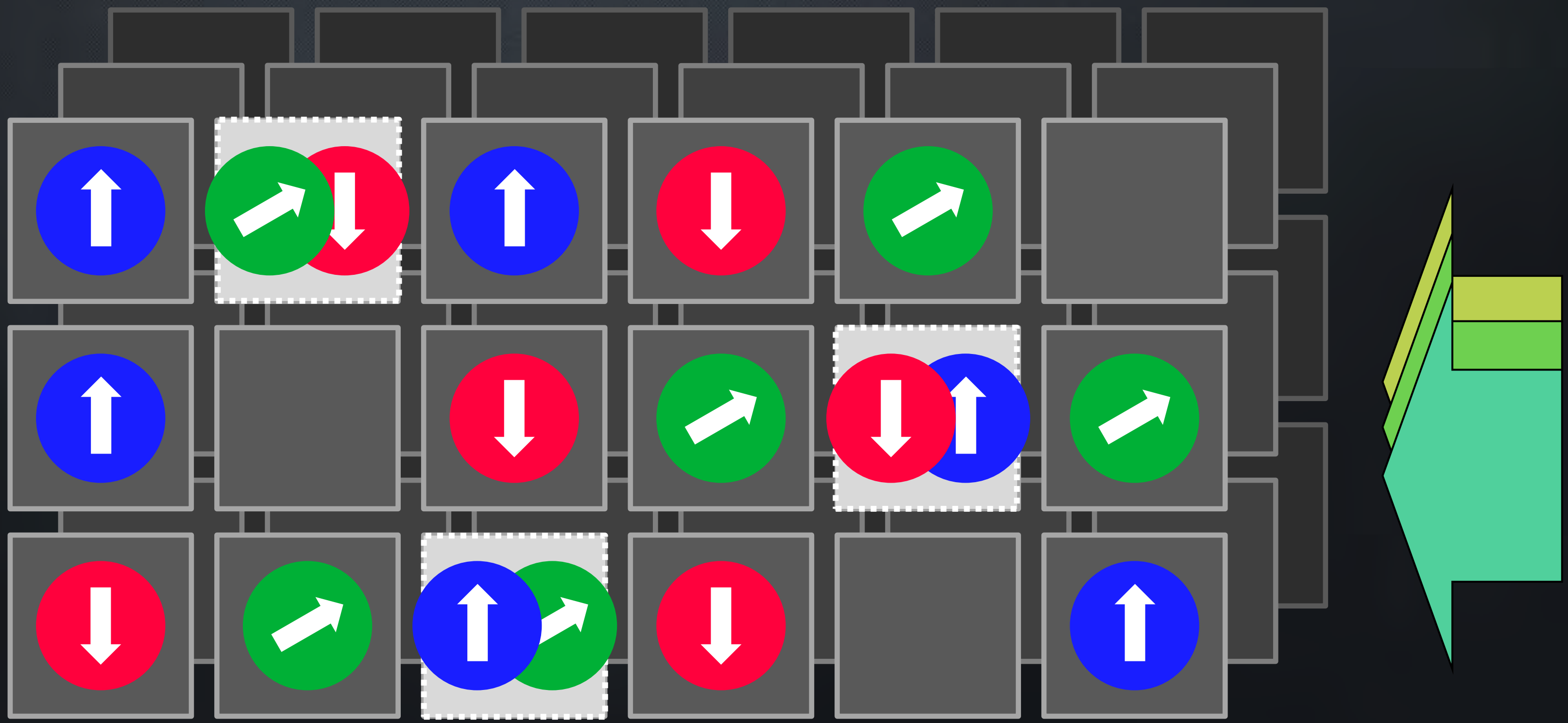


Same number of particles per fermionic flavour ($T/T_F \approx 0.25$)

Early ETH experimental work: *R. Jordens et al., Nature 455, 204 (2008)*

Double occupancies

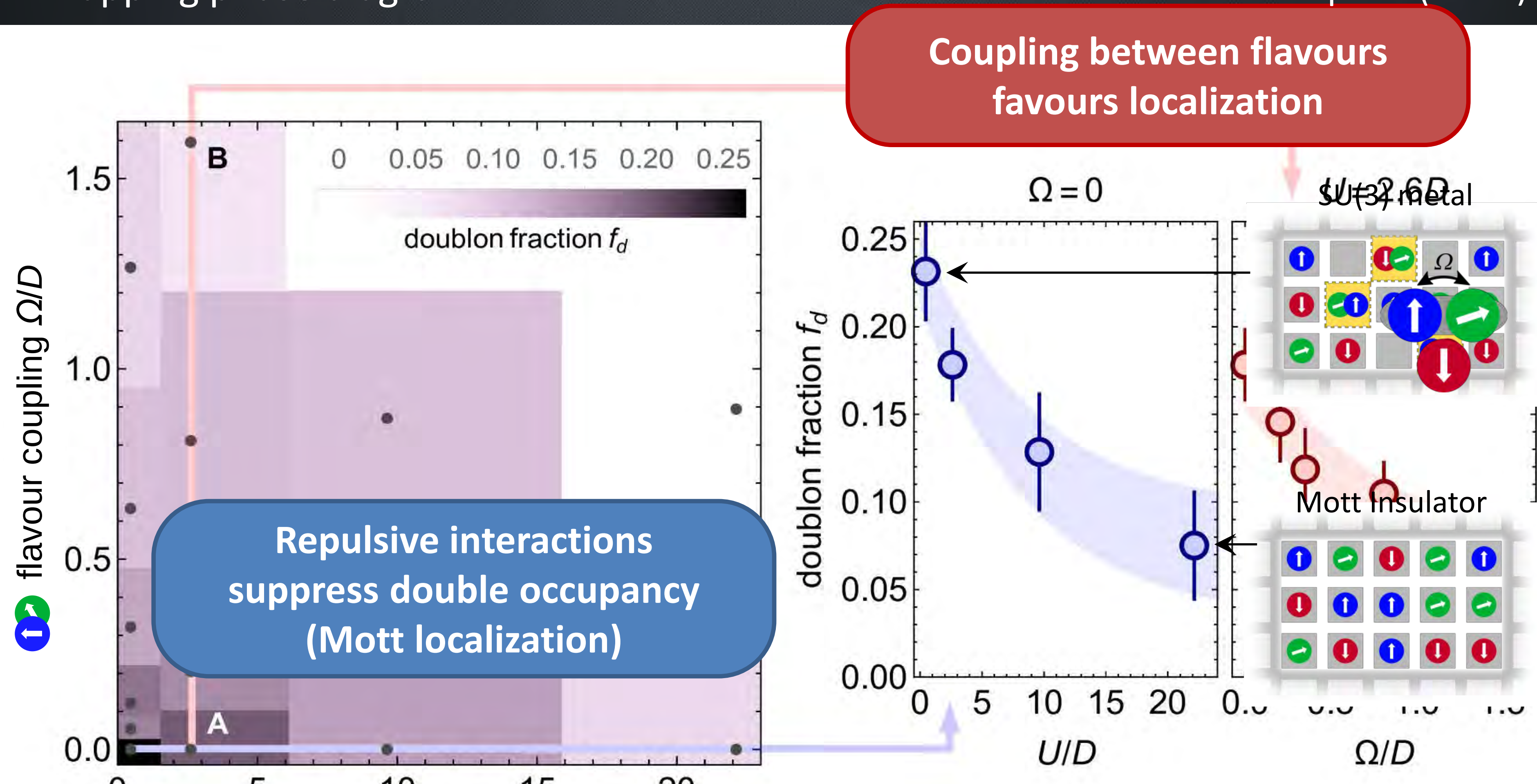
Characterization of the “Mottness” / “metallicity” of the many-body state by measurement of **doubly-occupied sites** with state-selective photoassociation



Metal to insulator

Mapping phase diagram:

with M. Capone (SISSA)

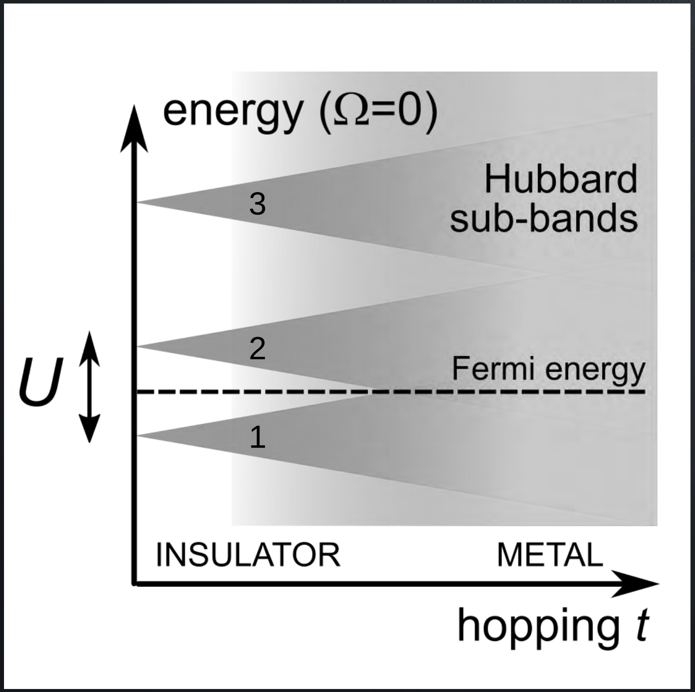


S. Taie et al., Nature Physics, 8, 825 (2012)
C. Hofrichter et al., PRX **6**, 021030 (2016)

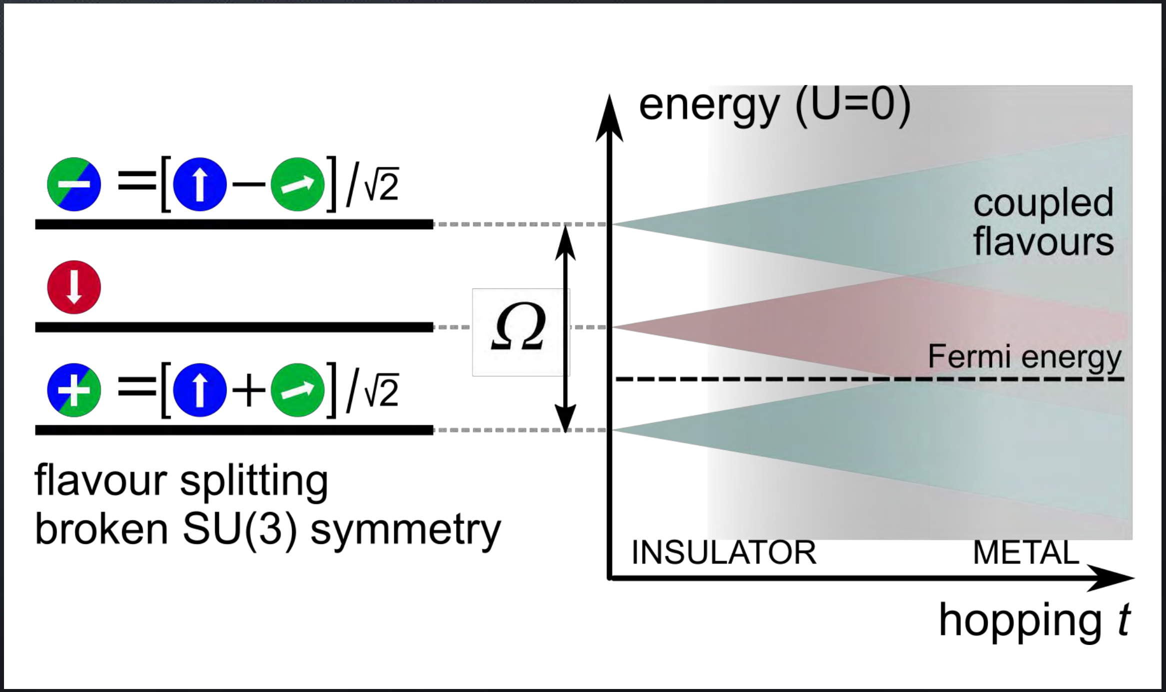
D. Tusi et al., *Nature Physics* 18, 1201 (2022)

Localization mechanisms

Localization **by repulsion:**

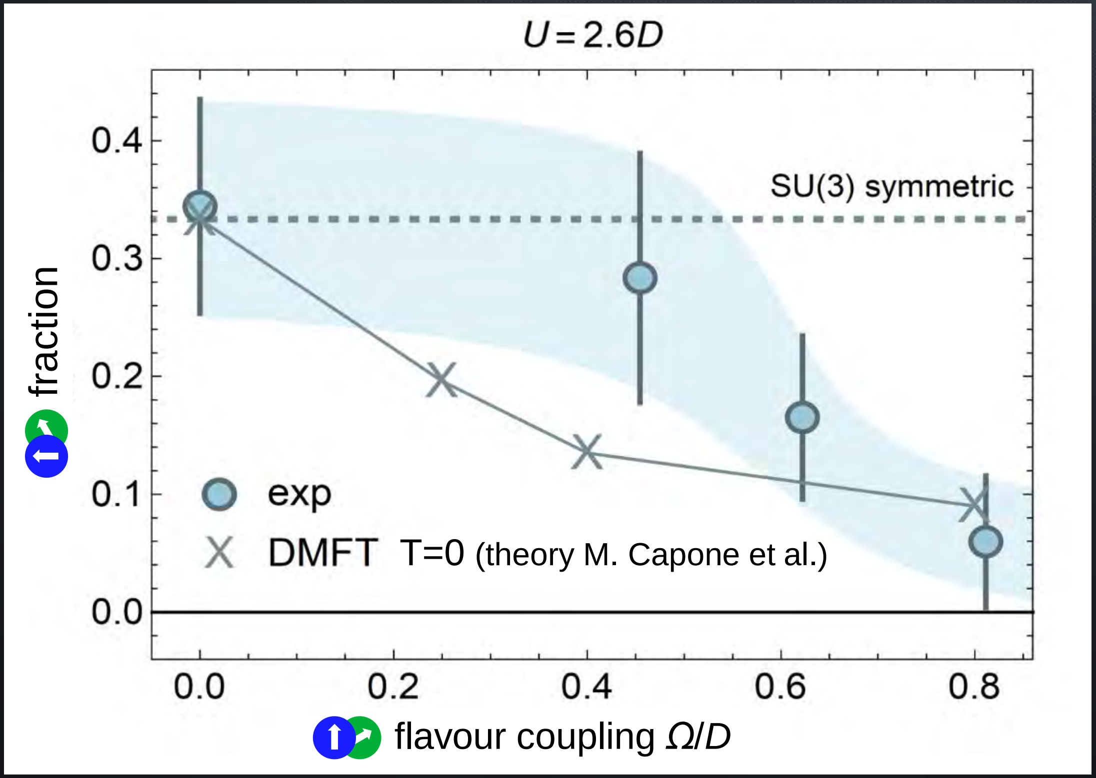


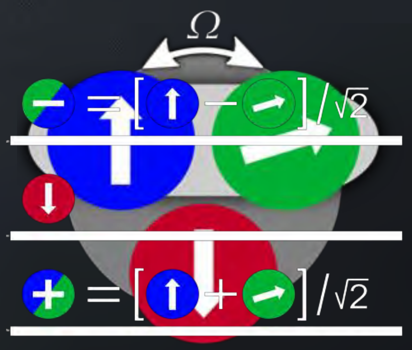
Localization **by degeneracy lifting**:



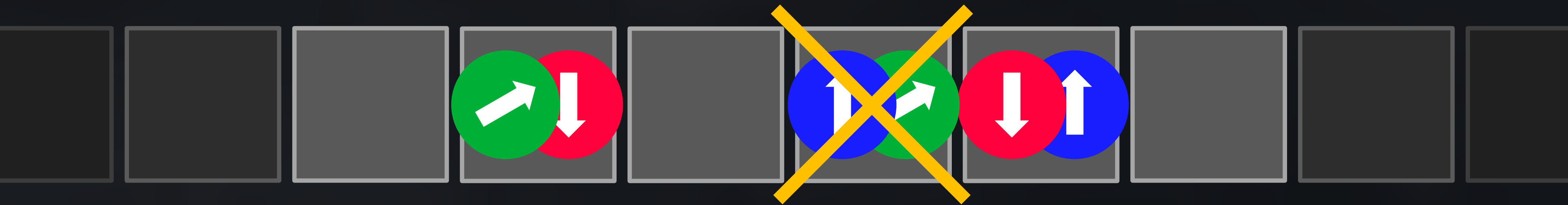
State-selective correlations

Fraction of doublons in Raman-coupled flavours:





Evidence for flavour-selective correlations

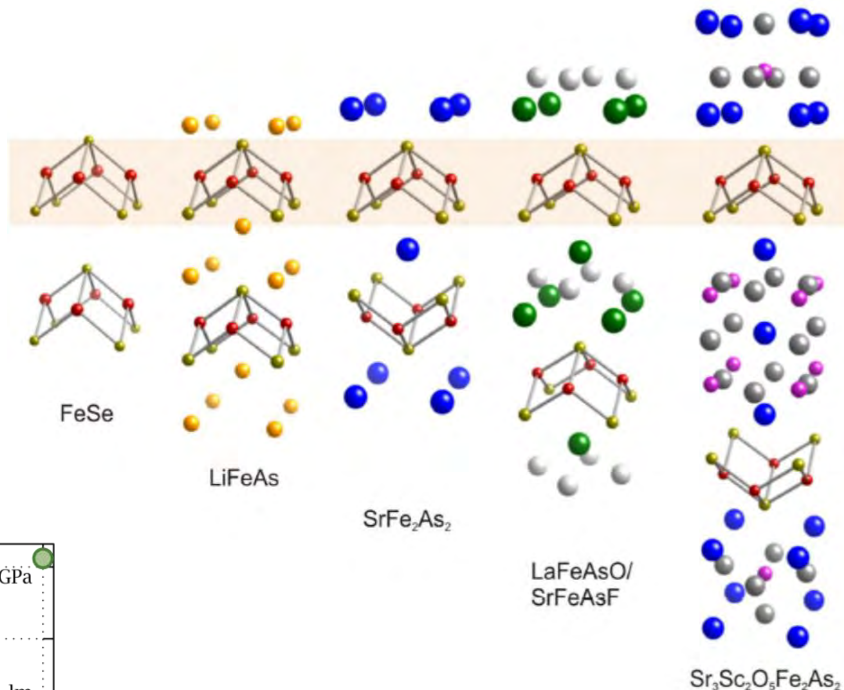


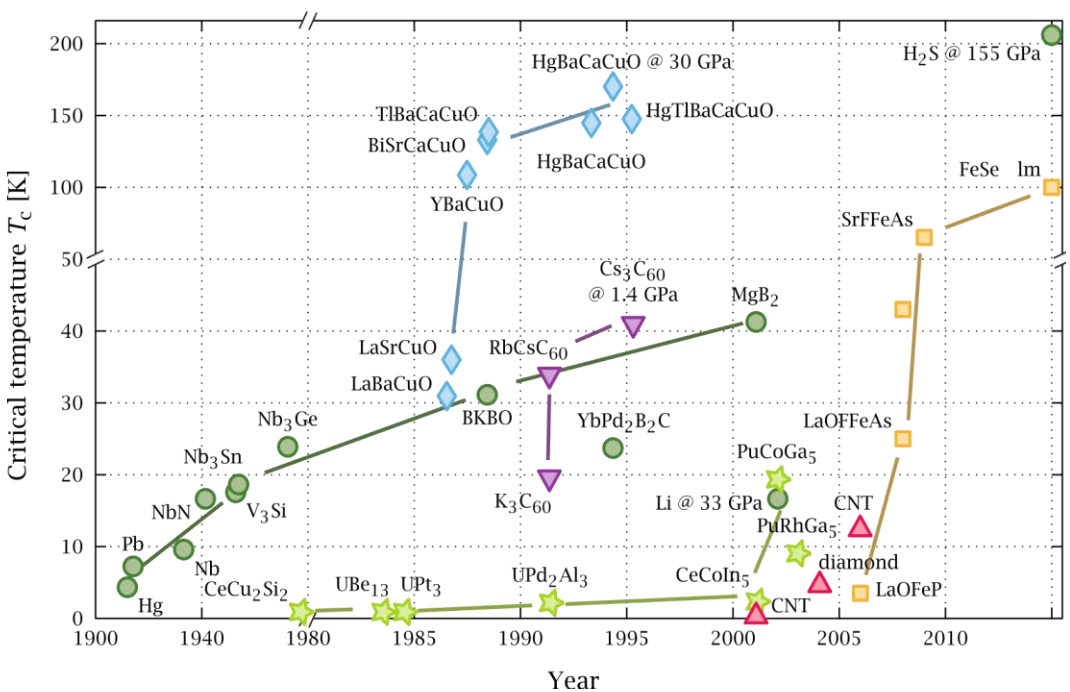
Iron-based superconductors

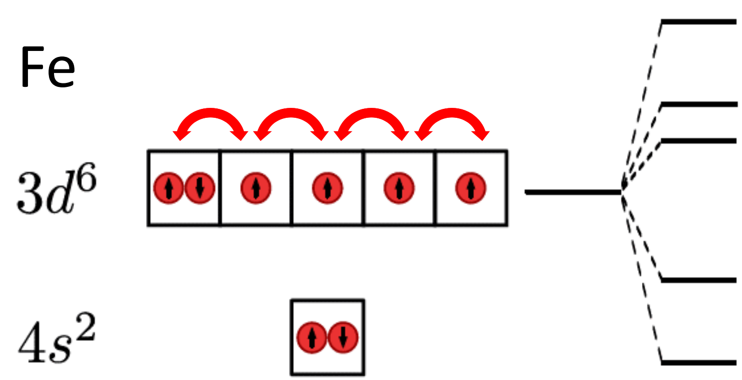
A "new" class of high-Tc superconductors

Layered structure as cuprates
Square lattices of Fe (with As, Se, …)

Multiple orbitals involved in conduction
Hund's coupling between orbitals







Multi-orbital Hubbard models

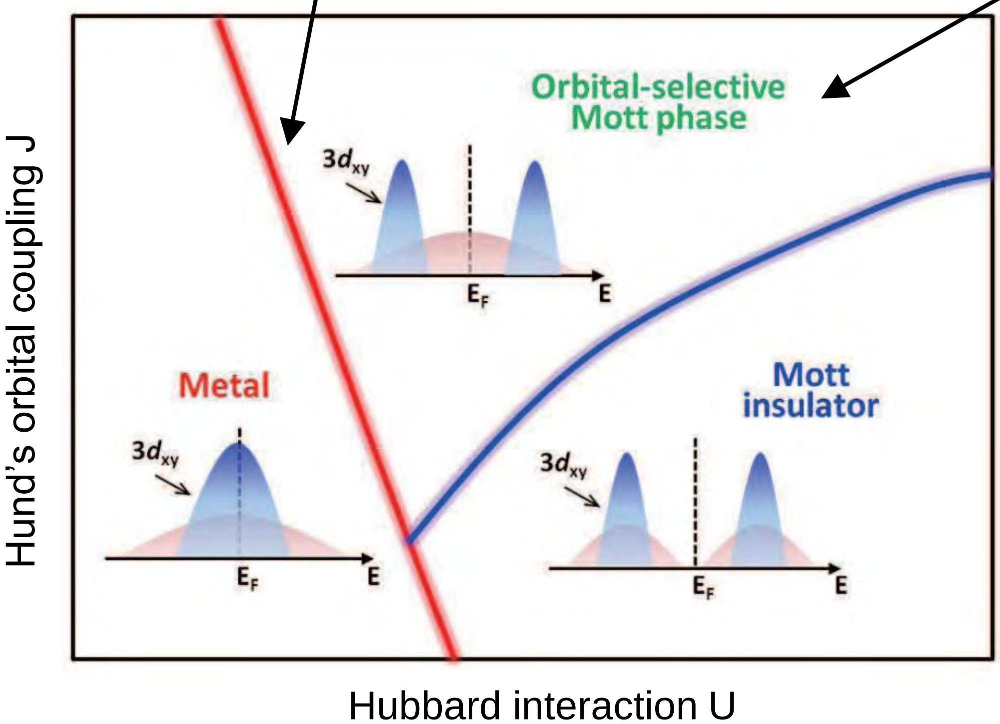
Orbital coupling shrinks metallic phase by degeneracy lifting

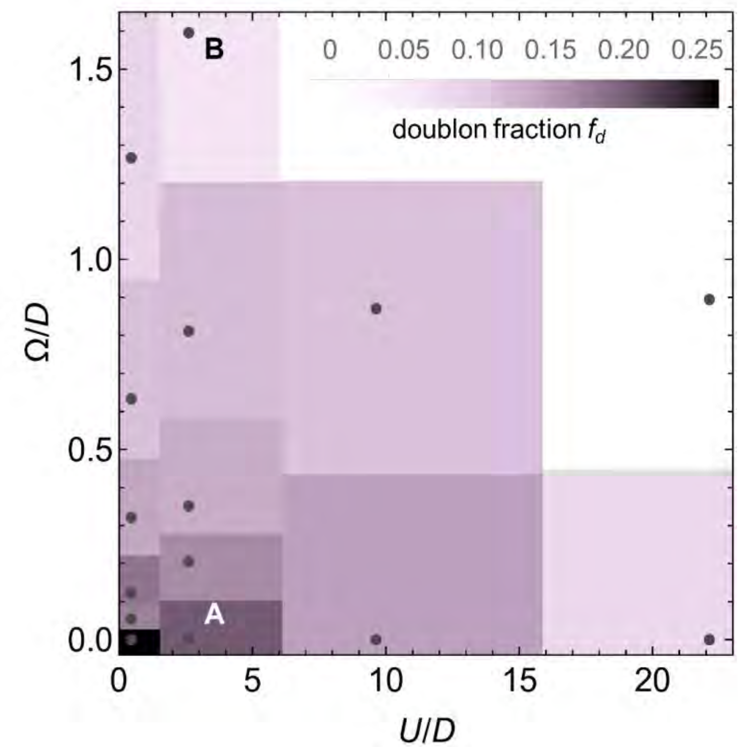
...h coherent coupling between orbitals

$$\ldots \sum_{i,m} n_{im\uparrow} n_{im\downarrow} + \left(U' \ldots \right.$$

$$- J \sum_{i,m>m'} [2\mathbf{S}_{im} \cdot \mathbf{S}_{im'} + (d^\dagger_{im\uparrow} d^\dagger_{im\downarrow} d_{im'\uparrow} d_{im'\downarrow} + \mathrm{H.c.})].$$

Mott localization only in some orbitals





Take-home messages pt.1

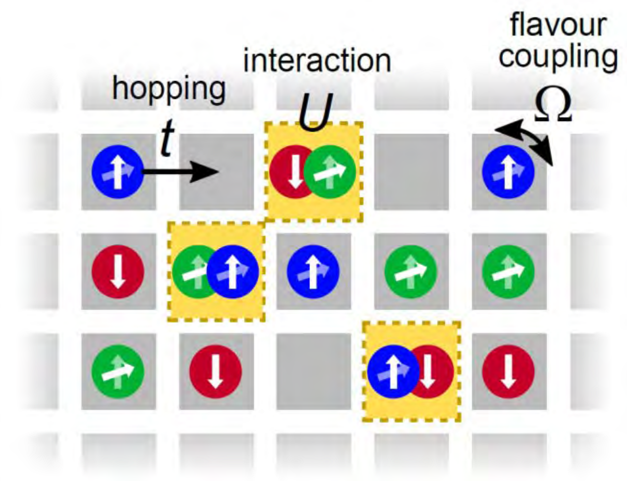
Multicomponent Fermi-Hubbard models

D. Tusi et al., Nat. Phys. 18, 1201 (2022)

SU(N) symmetry and its controlled breaking

Flavour-selective Mott localization

Connections with complex materials (and beyond?)



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T.-W. Zhou et al., Nat. Comm. **16**, 10247 (2025)

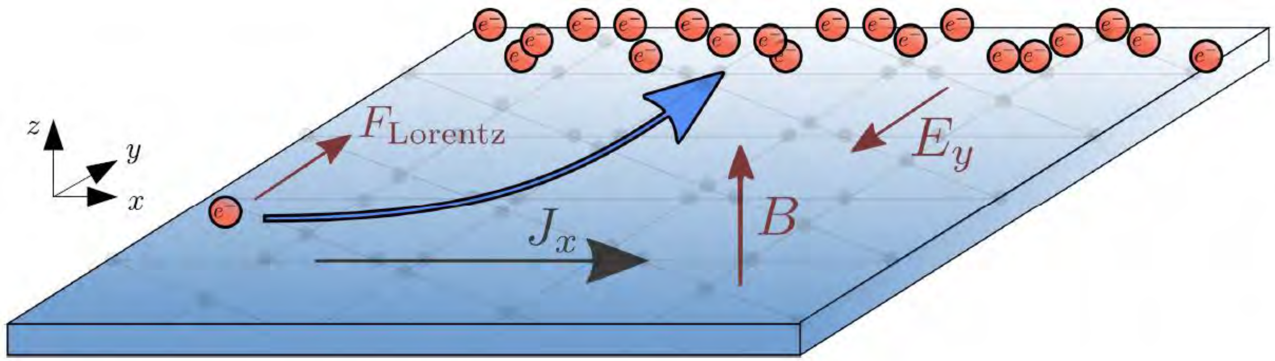
New platforms with Rydberg atom arrays

Collaboration with C. Repellin, S. Greschner, T. Giamarchi, M. Filippone

Hall effect

Classical picture of the Hall effect

Longitudinal current + magnetic field
Lorentz force + buildup of transverse voltage



Well understood for noninteracting electrons in the continuum

small B / classical: $R_H = \frac{E_y}{B \cdot J_x} = \frac{-1}{nq}$ magnetometers, characterization of materials, …

large B / quantum: $R_H B = \frac{h}{e^2} \frac{1}{\nu} \quad \nu \in \mathbf{Z}$ quantization, metrology (resistance standards), …

Quantum Hall effect

Quantization of the Hall resistance in a 2D electron gas

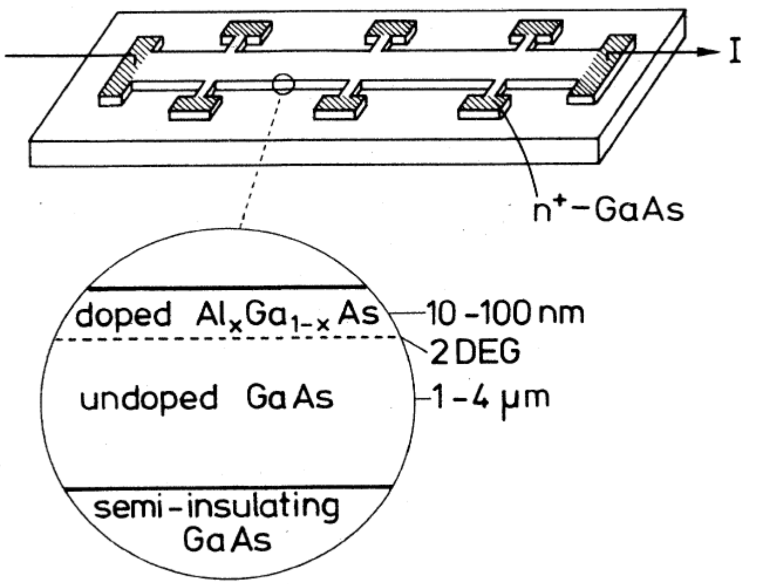


FIG. 3. Typical shape and cross section of a GaAs-$Al_xGa_{1-x}As$ heterostructure used for Hall-effect measurements.

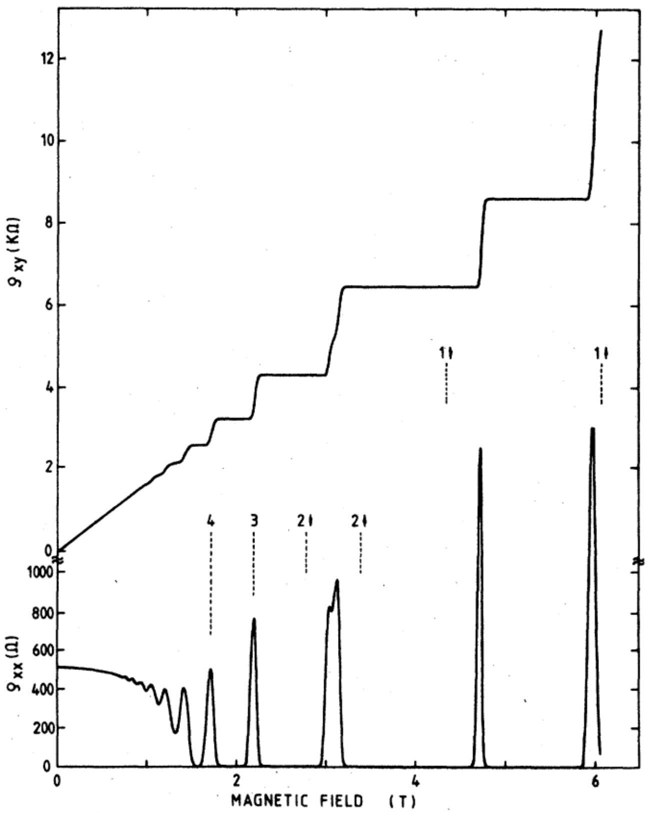


FIG. 14. Experimental curves for the Hall resistance $R_H = \rho_{xy}$ and the resistivity $\rho_{xx} \sim R_x$ of a heterostructure as a function of the magnetic field at a fixed carrier density corresponding to a gate voltage $V_g = 0$ V. The temperature is about 8 mK.

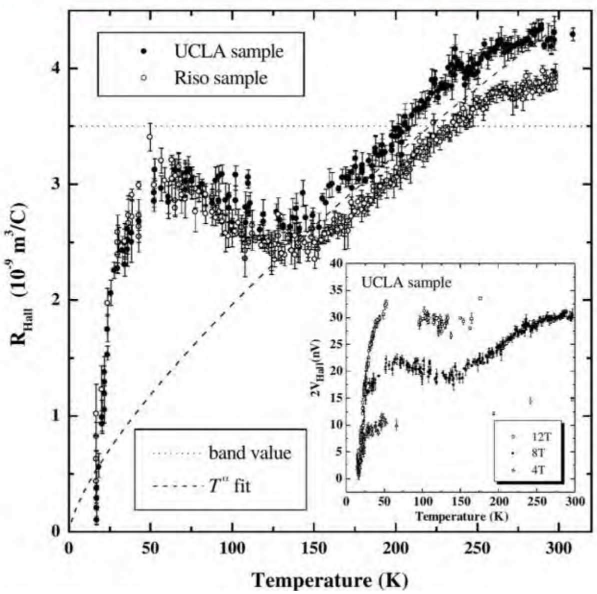
large B / quantum: $R_H B = \frac{h}{e^2}\frac{1}{\nu} \quad \nu \in \boldsymbol{Z}$

quantization, metrology (resistance standards), …

Hall effect

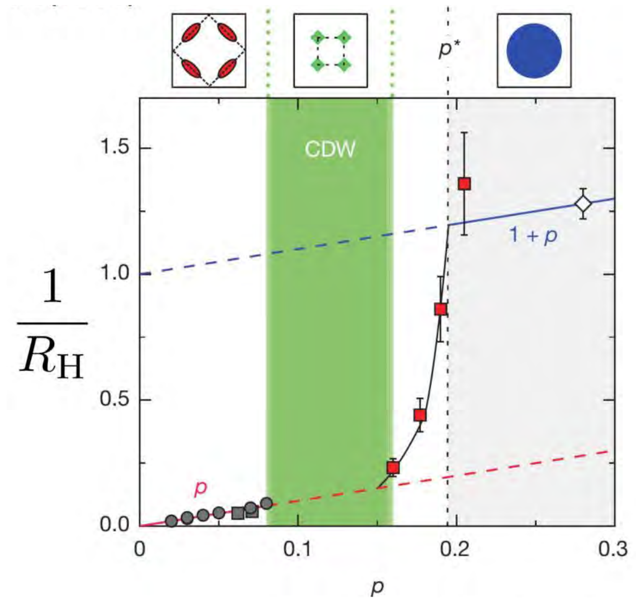
Organic quasi-1D systems

J. Moser et al., PRL ***84****, 2674 (2000)*



High-Tc superconductors (cuprates)

S. Badoux et al., Nature ***531****, 210 (2016)*



Serious challenges for low-dimensional and strongly correlated materials

small B / classical: $R_H = \frac{E_y}{B\cdot J_x} = \frac{-1}{nq}$

temperature dependence, change of sign, …

large B / quantum: $R_H B = \frac{h}{e^2}\frac{1}{\nu} \quad \nu \in Z$

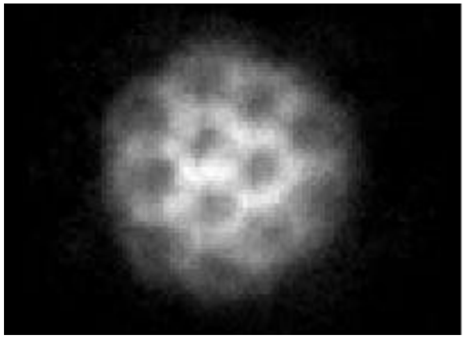
fractional quantum Hall

fractional statistics, …

J. Dalibard et al., Rev. Mod. Phys. 83, 1523 (2011)
N. Goldman et al., Rep. Prog. Phys. 77, 126401 (2014)

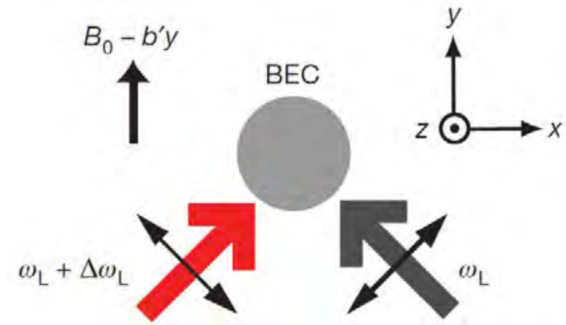
Synthetic magnetic fields

Rotating quantum gases



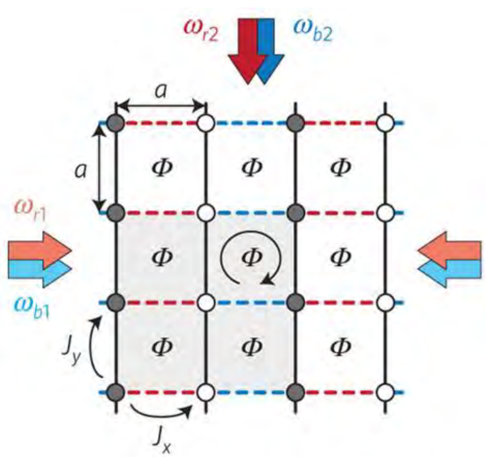
K. W. Madison et al., PRL (2000)

Raman-dressed states



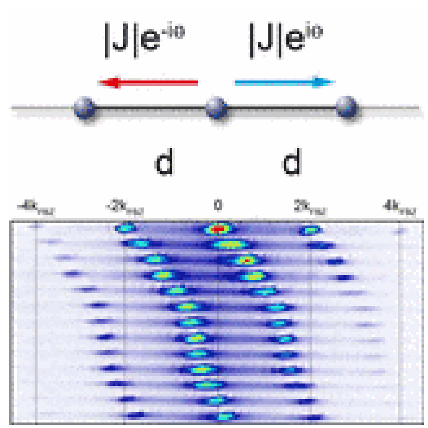
Y.-J. Lin et al., Nature (2009)

Laser-assisted tunneling



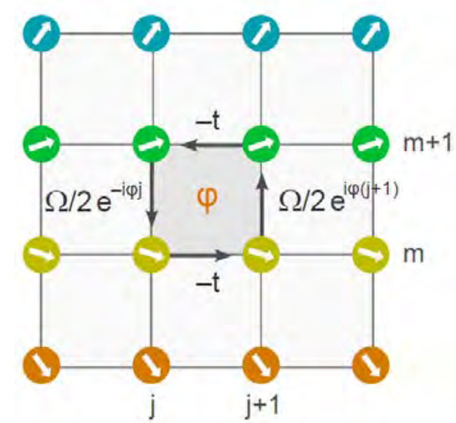
M. Aidelsburger et al., PRL (2011)

Lattice shaking



J. Struck et al., PRL (2012)

Synthetic dimensions



M. Mancini et al., Science (2015)
B. K. Stuhl et al., Science (2015)

Raman transitions coupling coherently different nuclear spin states

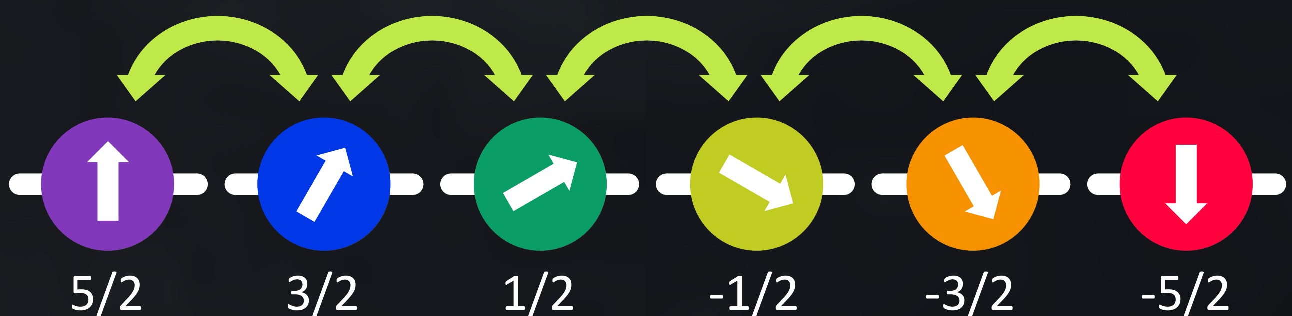
O. Boada et al., PRL 108, 133001 (2012)

Synthetic dimensions

Equivalent to quantum tunneling in a tight-binding lattice

$$H = -t \sum_j \left(c_j^\dagger c_{j+1} + h.c. \right)$$

$$H = -\Omega \sum_m \left(c_m^\dagger c_{m+1} + h.c. \right)$$



A synthetic flux ladder

$$E_1 = E_0 e^{i\mathbf{k}\cdot\boldsymbol{r}}$$
$$E_2 = E_0 e^{i\mathbf{k'}\cdot\boldsymbol{r}}$$

two-photon Rabi frequency:

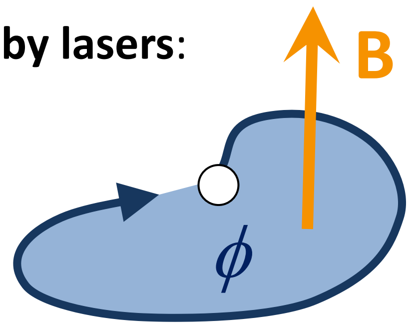
$$\Omega(\mathbf{r}) = \frac{\Omega_2^*(\mathbf{r})\Omega_1(\mathbf{r})}{2\Delta}$$
$$= |\Omega| e^{i\,(\mathbf{k}-\mathbf{k'})\cdot\boldsymbol{r}} = |\Omega$$

$$\Omega_j = |\Omega| e^{i\varphi j}$$

Aharonov-Bohm phase imprinted by lasers:

$$\psi \rightarrow e^{i\phi}\psi$$

$$\phi = 2\pi \frac{\Phi(\mathbf{B})}{\Phi_0}$$



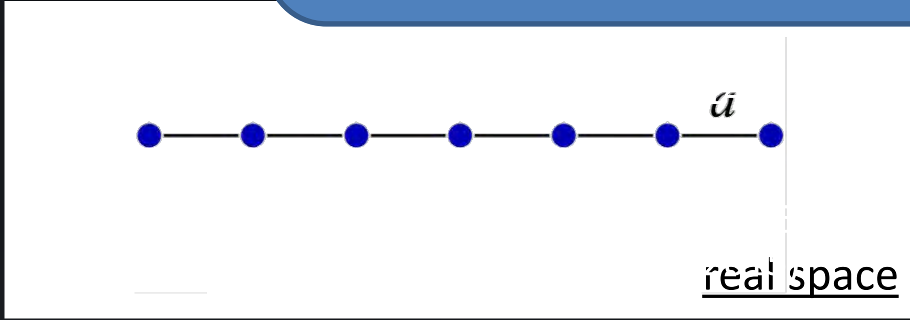
D. Jaksch & P. Zoller, NJP **5**, 56 (2003)

Reviews on gauge fields for ultracold atoms:

J. Dalibard et al., Rev. Mod. Phys. **83**, 1523 (2011)

N. Goldman et al., Rep. Prog. Phys. **77**, 126401 (2014)

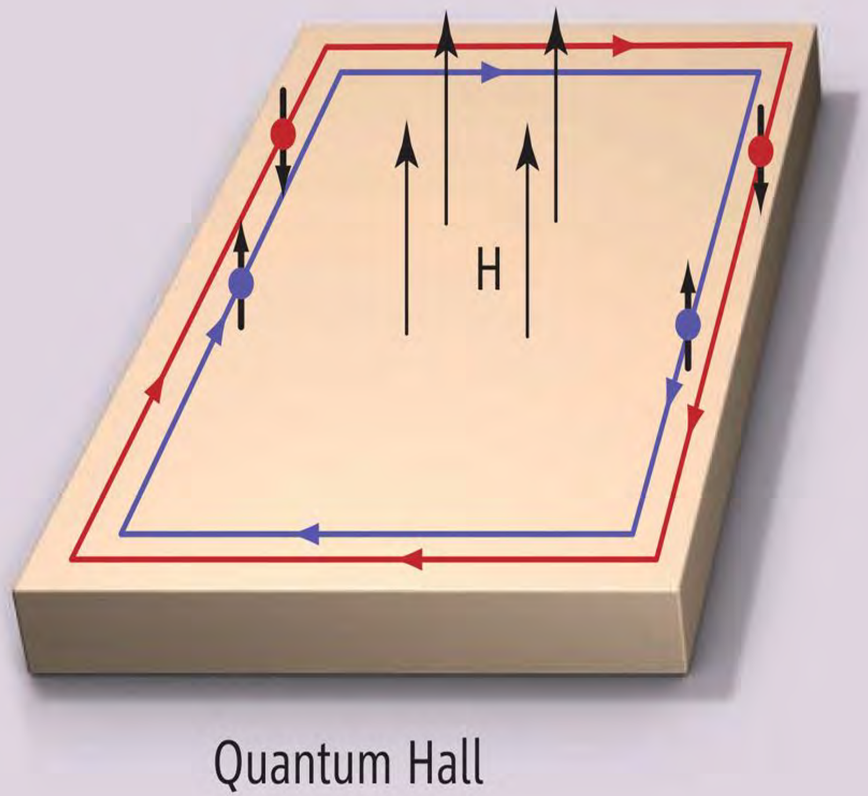
A synthetic magnetic field for effectively charged particles (up to 10^4 T!)



Observing chiral edge states

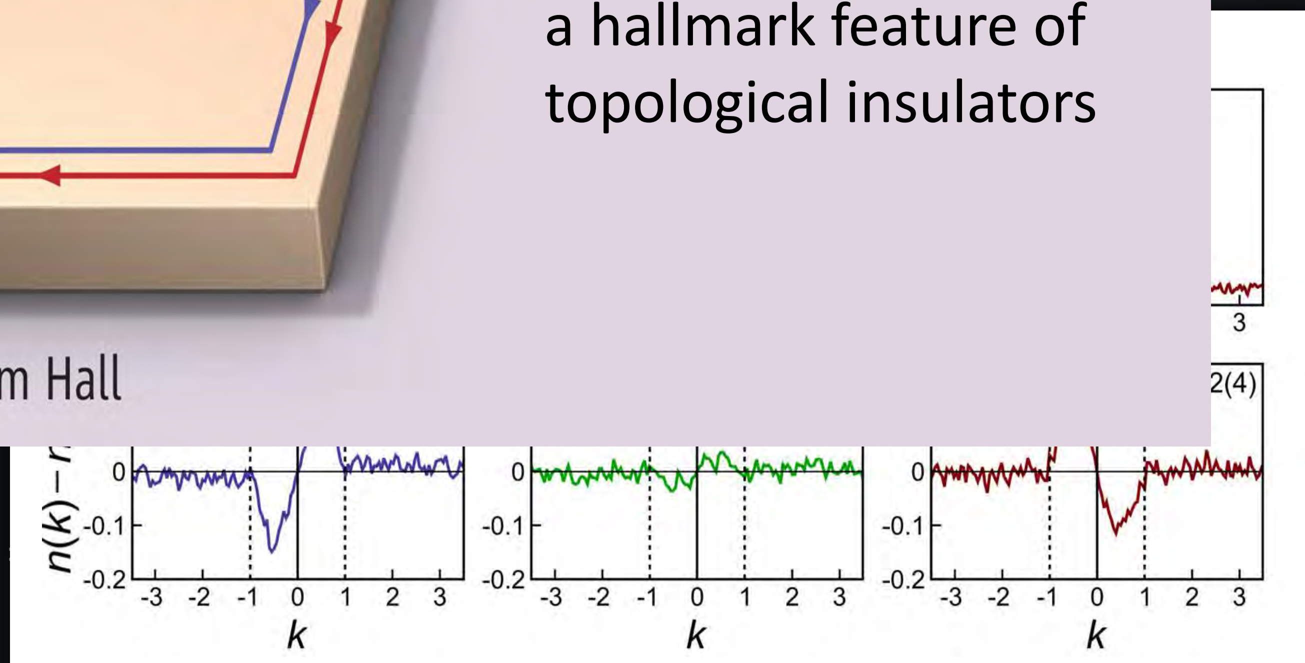
*M. Mancini et al., Science **349**, 1510 (2015)*

Adiabatic preparation of a fermions in a synthetic flux ladder

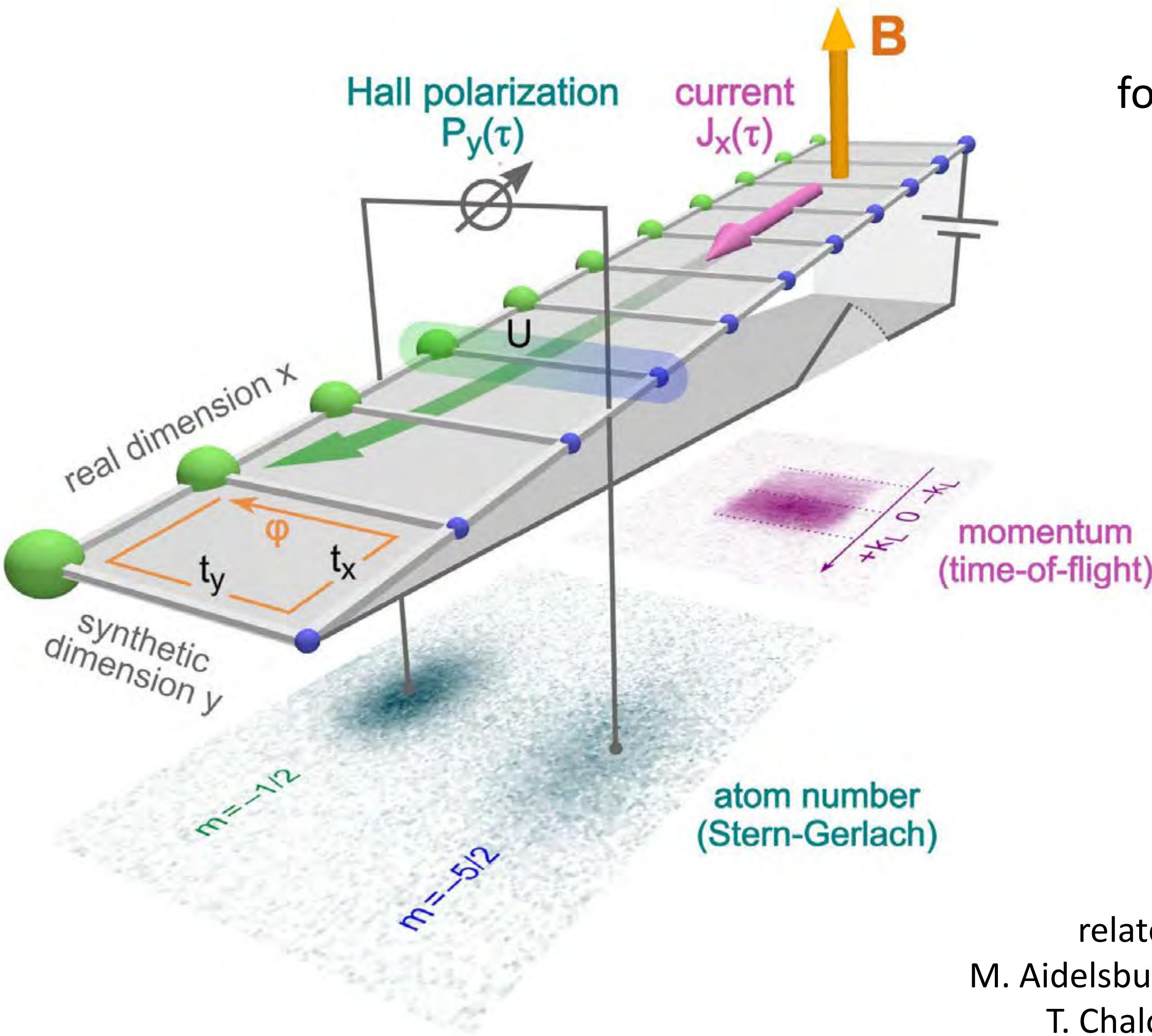


Edge states:
a hallmark feature of
topological insulators

Spin-selective detection



Measurement of Hall response



Quenched dynamics following the activation of a longitudinal field

Metallic regime: <1 atom/rung

Flux $\varphi \simeq \pi/3$

Hall imbalance

$$\Delta_H = \frac{P_y}{J_x}$$

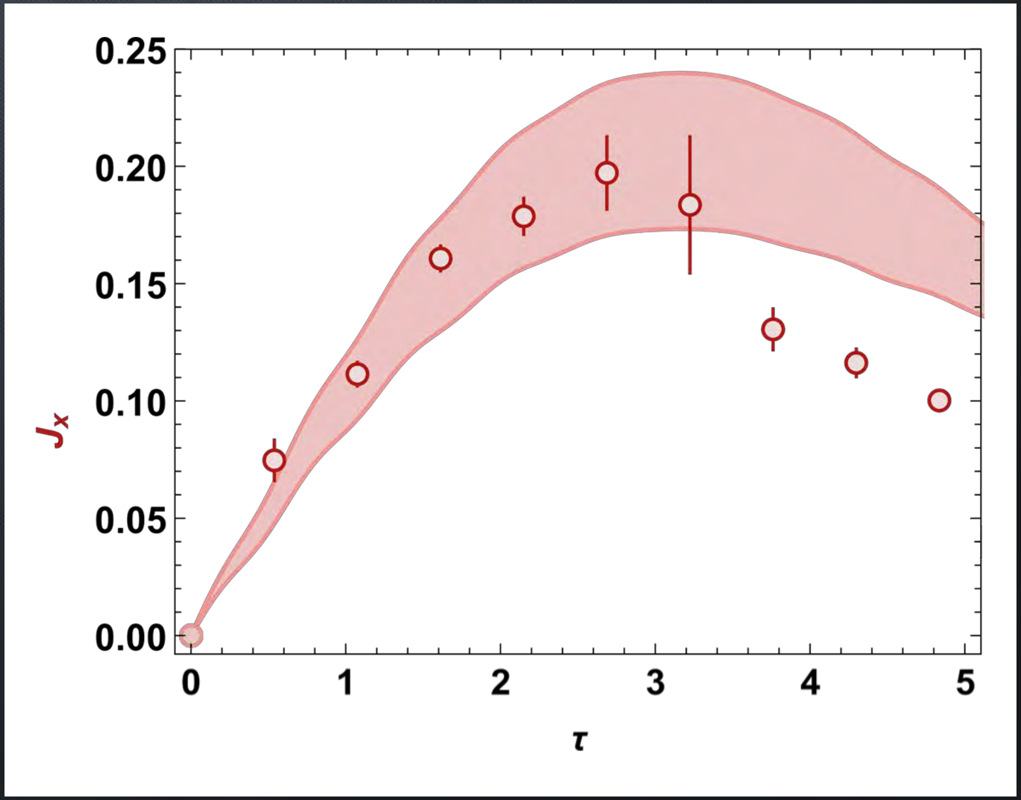
related works on Hall deflection:
M. Aidelsburger et al., Nat. Phys. (2015)
T. Chalopin et al., Nat. Phys. (2020)

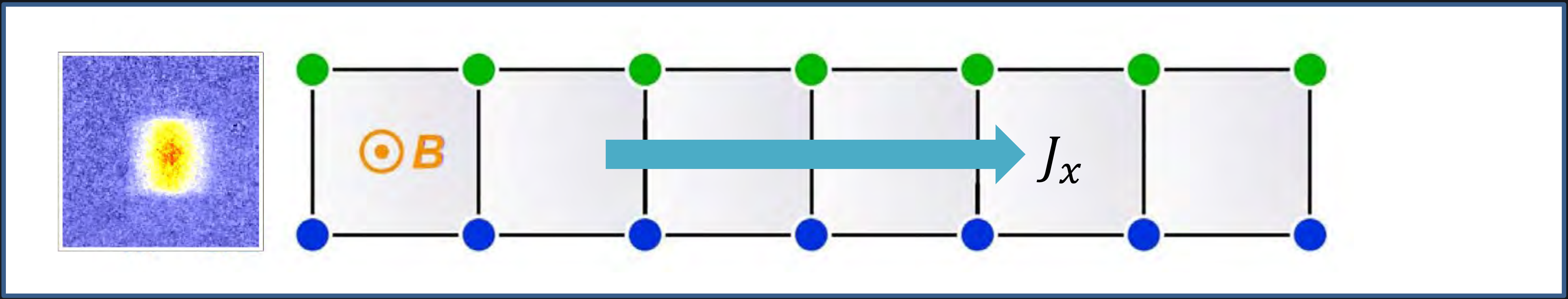
T.-W. Zhou et al., Science **381**, 427 (2023)

Hall effect in synthetic ladders

Optical gradient along x induces a longitudinal current

$$J_x = \sum_m \int \sin(k) n_m(k) dk$$





T.-W. Zhou et al., *Science* **381**, 427 (2023)

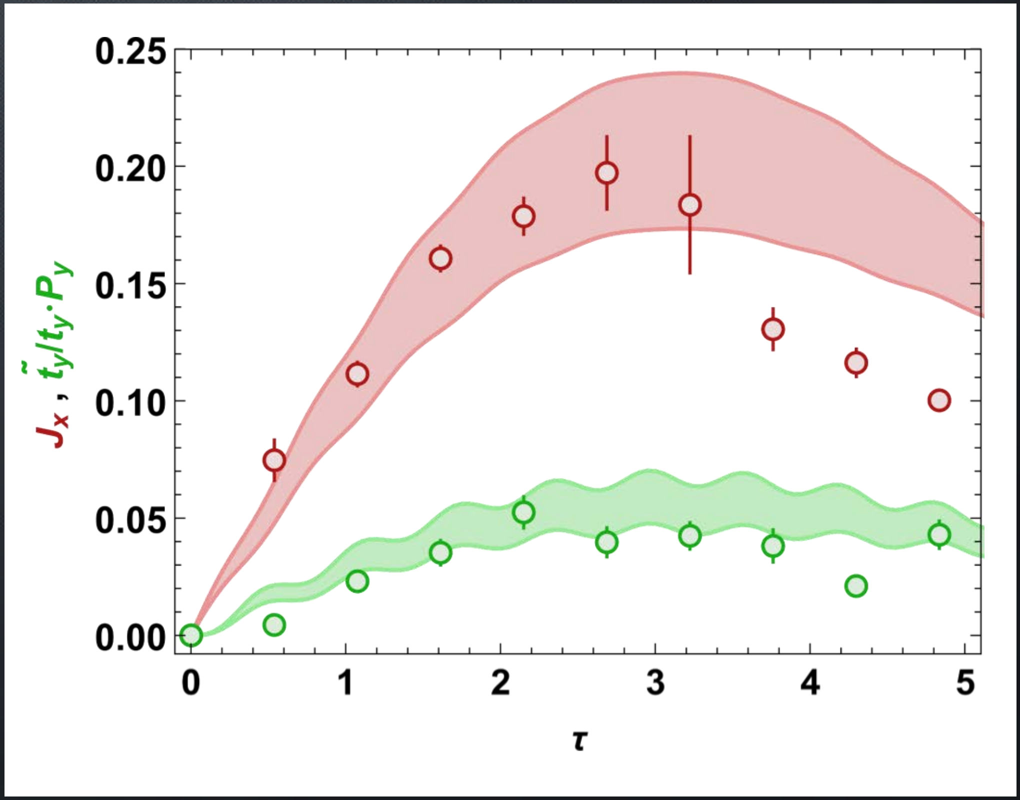
Hall effect in synthetic ladders

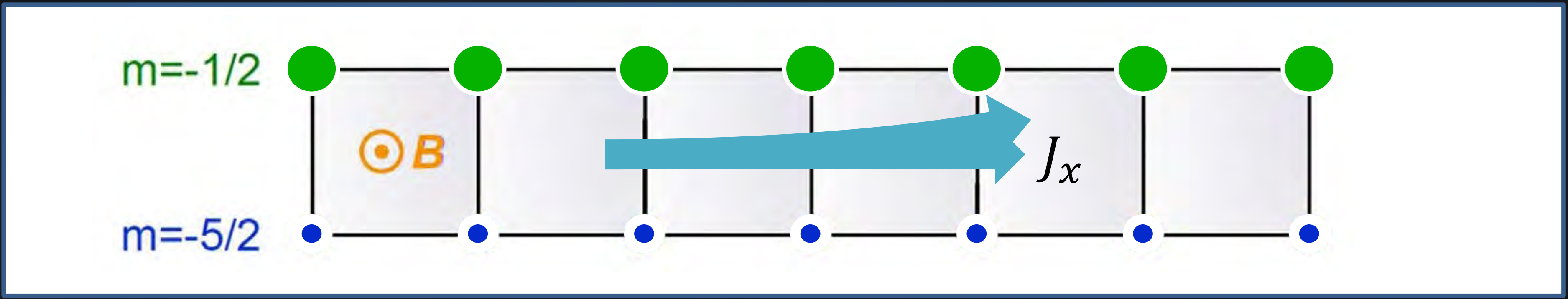
Optical gradient along x induces a longitudinal current

$$J_x = \sum_m \int \sin(k) n_m(k) dk$$

and a time-dependent polarization (Hall response)

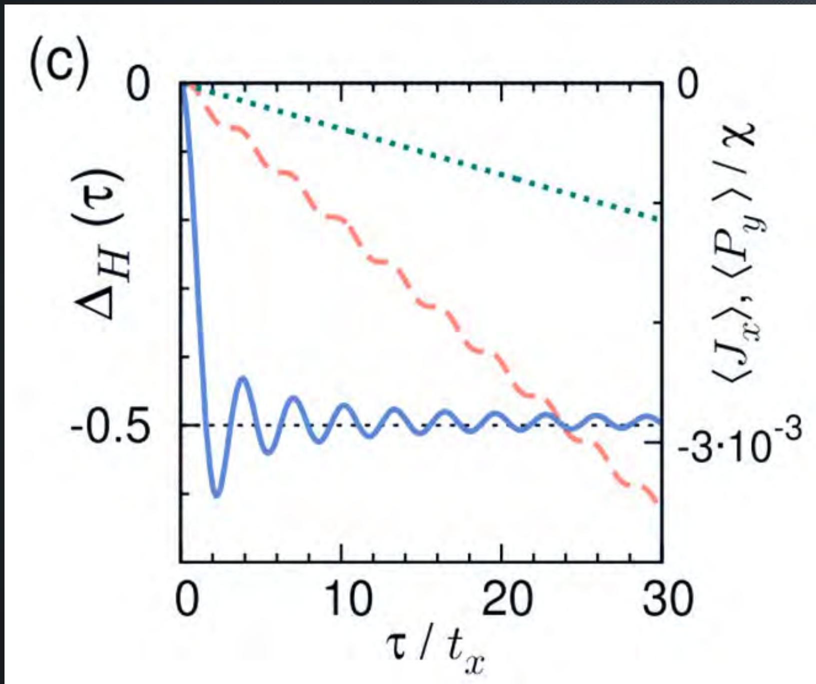
$$P_y = \sum_m (m - m_0) N_m$$

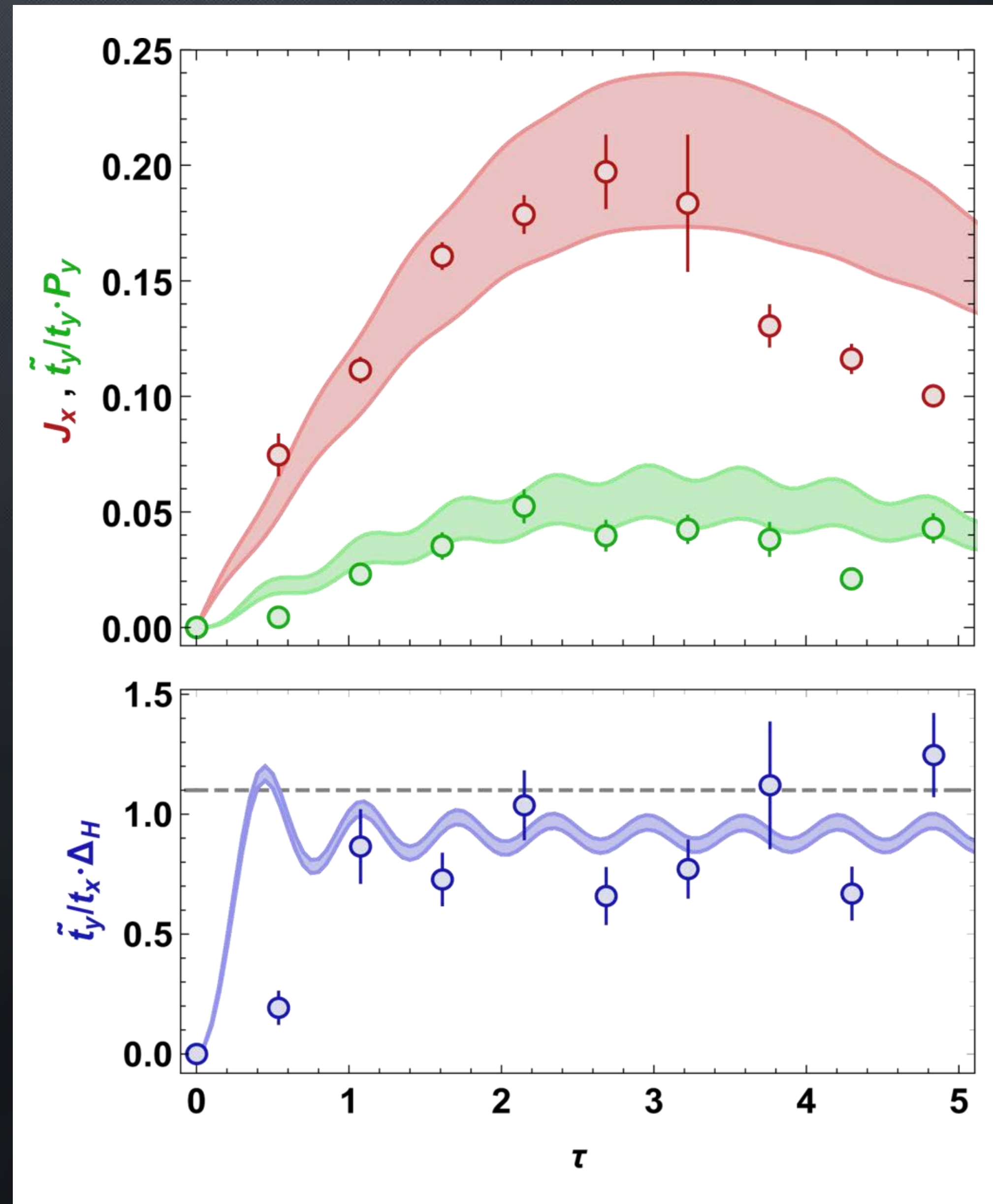




T.-W. Zhou et al., Science **381**, 427 (2023)

Hall effect in synthetic ladders



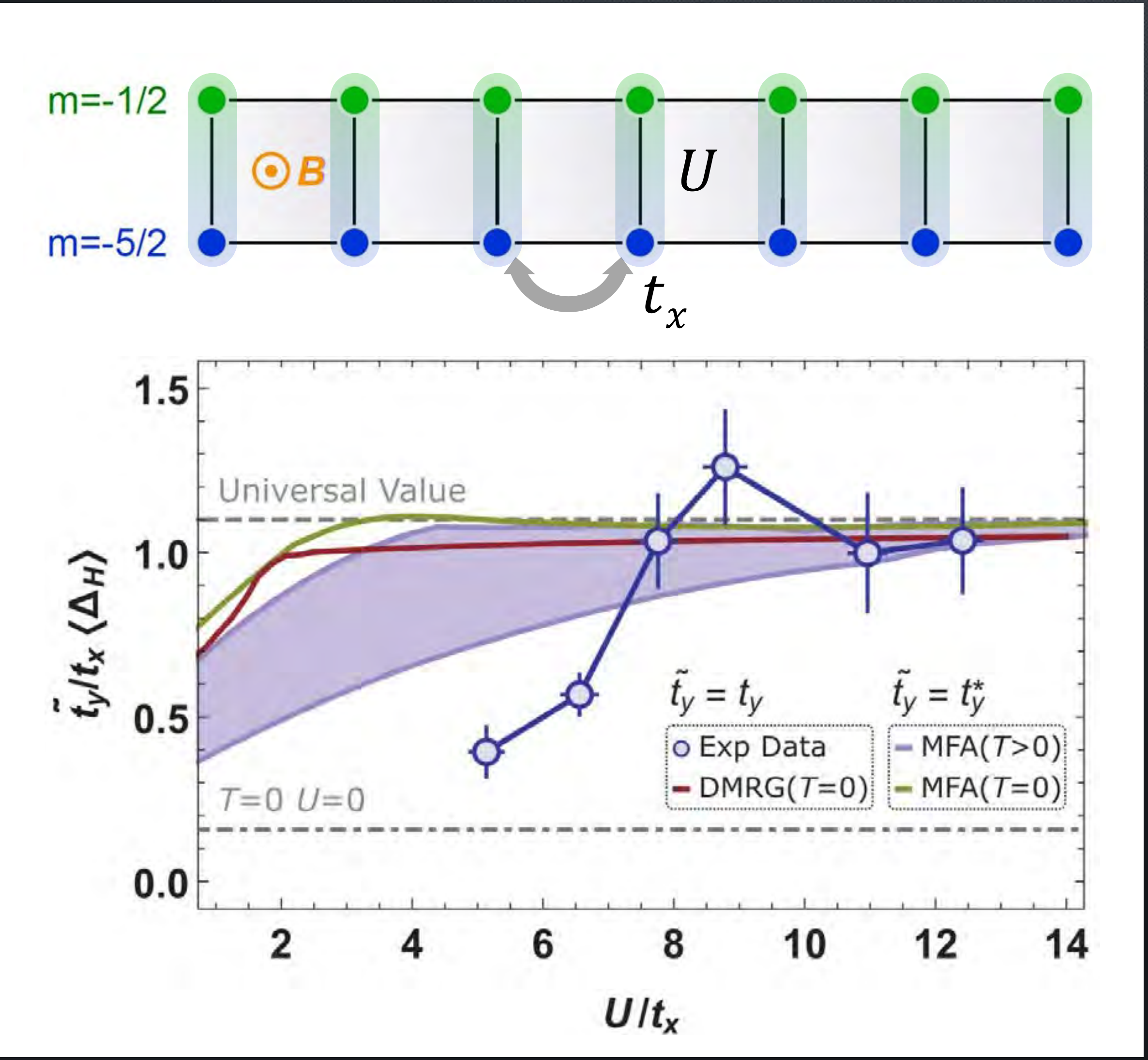


The **Hall imbalance** rapidly approaches a stationary regime

$$\Delta_H = \frac{P_y}{J_x}$$

T.-W. Zhou et al., Science ***381****, 427 (2023)*

Universal Hall response



Dependence of the Hall imbalance on the interaction strength U

Clear effect of atom-atom interactions on Hall dynamics

Increasing U stabilizes a single-band correlated metal characterized by the universal Hall imbalance

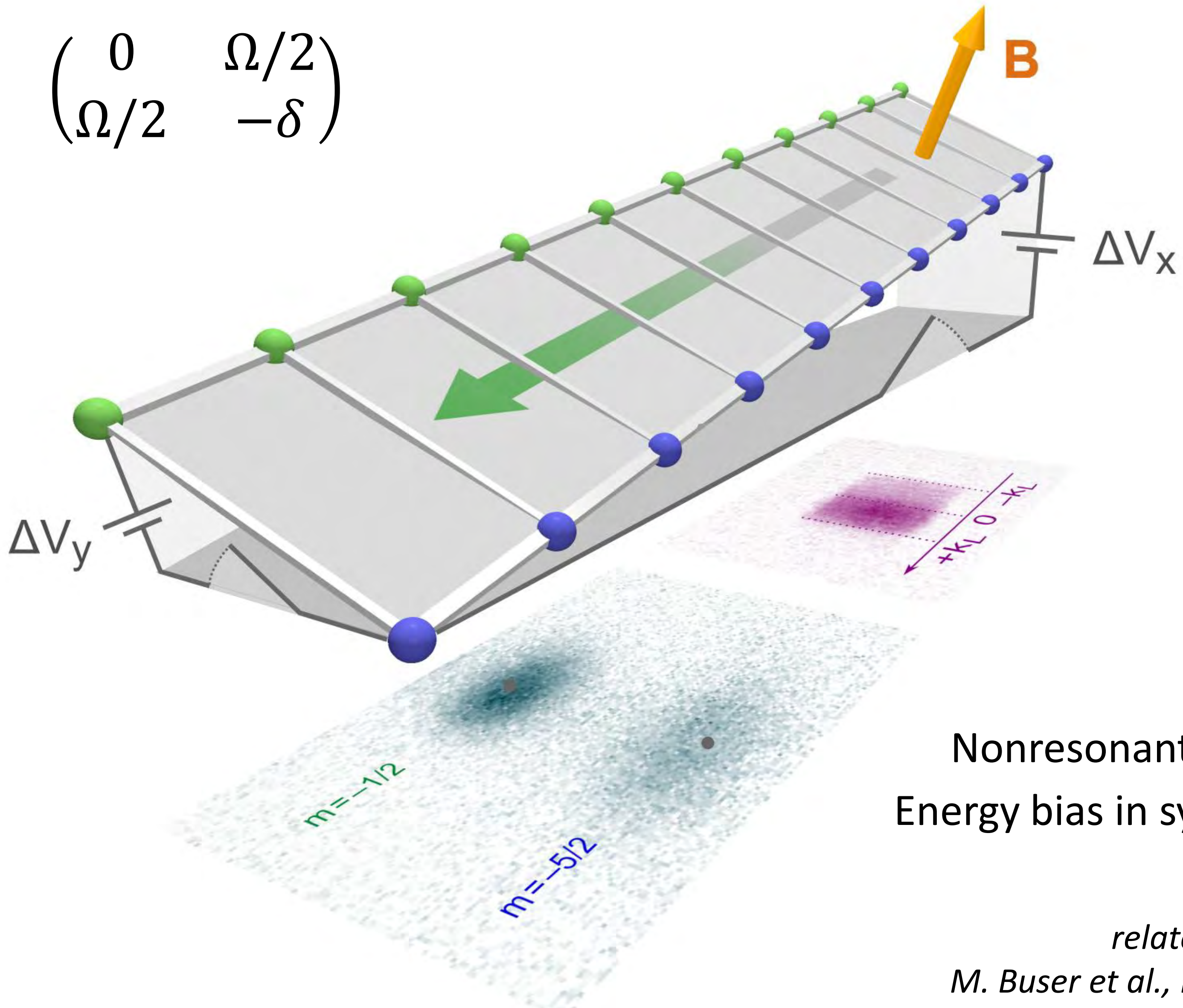
$$\Delta_H = 2\frac{t_x}{t_y}\tan\left(\frac{\varphi}{2}\right)$$

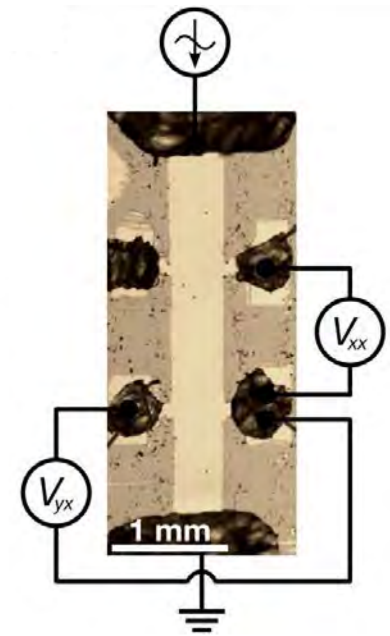
Theory: C. Repellin, S. Greschner, T. Giamarchi, M. Filippone

T.-W. Zhou et al., Nat. Comm. ***16****, 10247 (2025)*

Measurement of Hall voltage

$$\begin{pmatrix} 0 & \Omega/2 \\ \Omega/2 & -\delta \end{pmatrix}$$





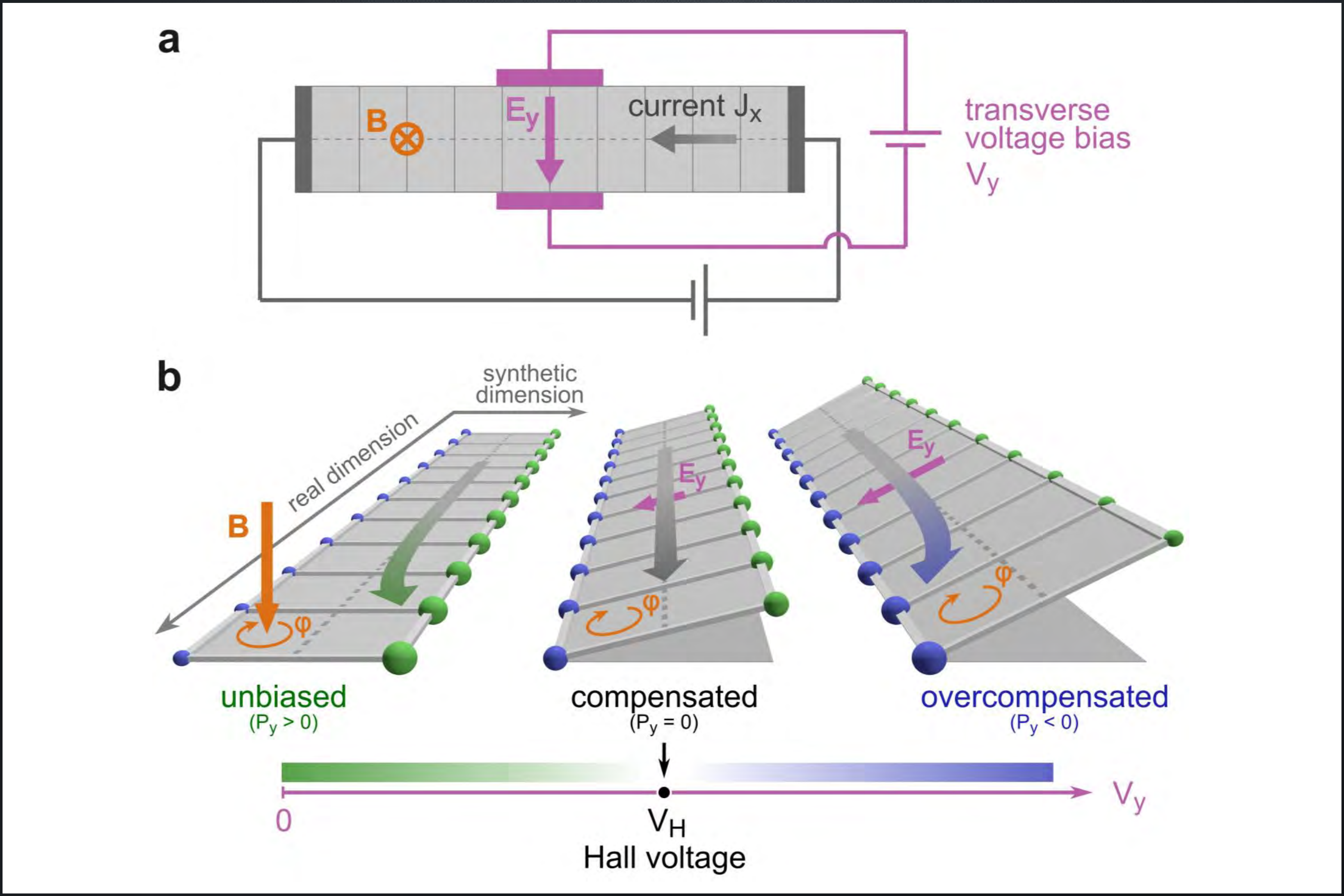
Bestwick et al., PRL 114, 187201 (2015)

Nonresonant Raman coupling =

Energy bias in synthetic dimension

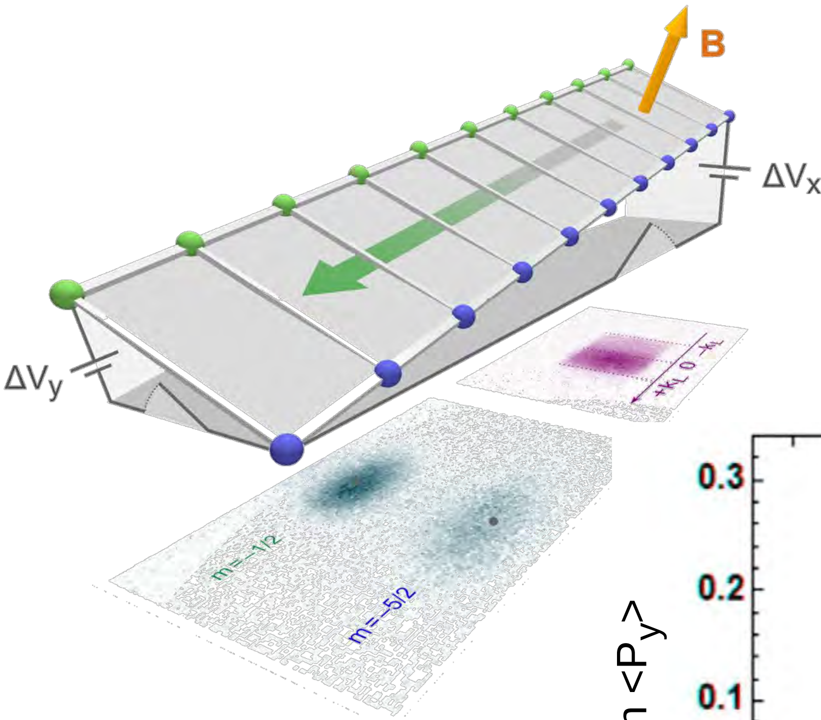
related theoretical proposal:
M. Buser et al., PRL ***126****, 030501 (2021)*

Measurement of Hall voltage

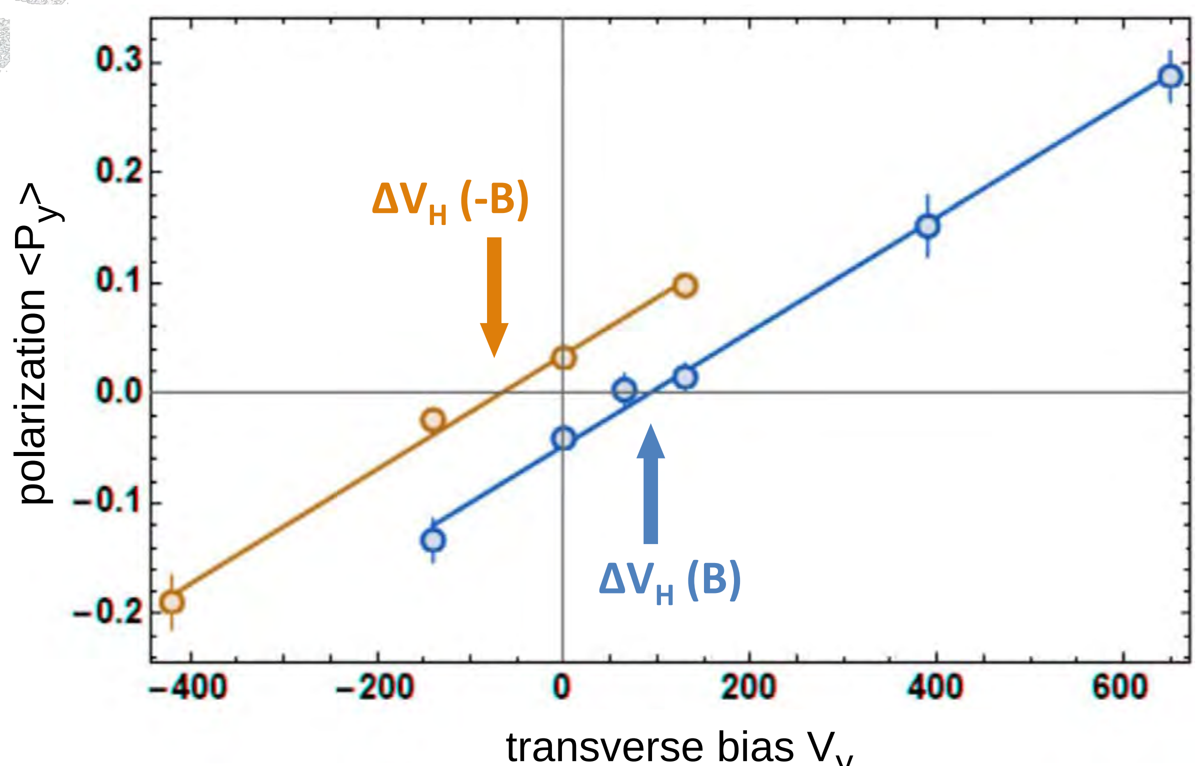


T.-W. Zhou et al., Nat. Comm. ***16****, 10247 (2025)*

Measurement of Hall voltage



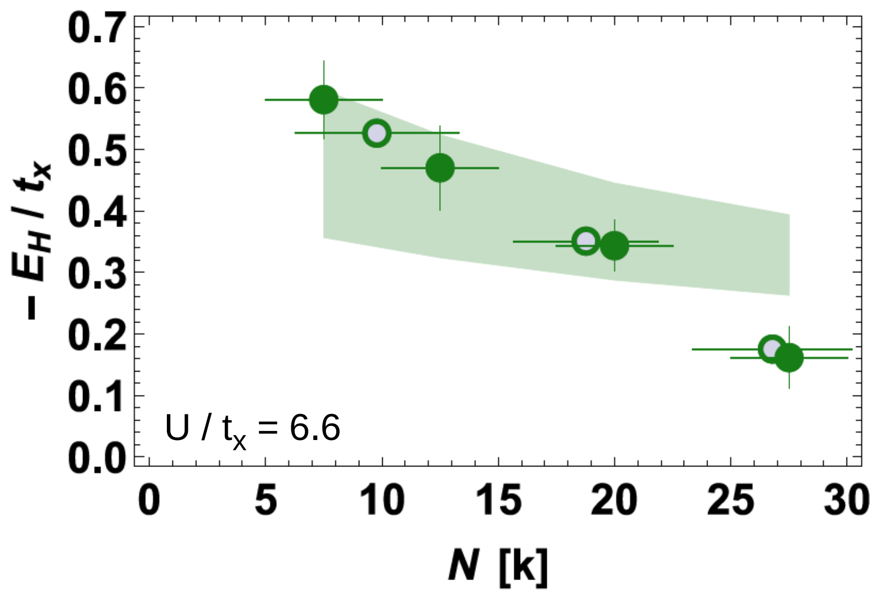
Hall voltage ΔV_H =
energy difference (detuning) along synthetic dimension that compensates for the Hall drift



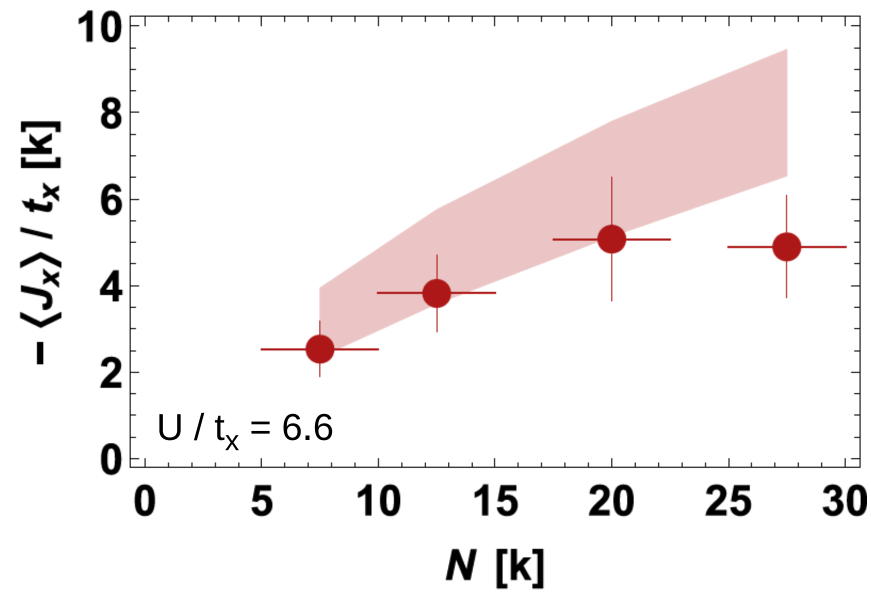
T.-W. Zhou et al., *Nat. Comm.* **16**, 10247 (2025)

Hall resistance

Hall voltage ΔV_H vs atom number



Current J_x vs atom number

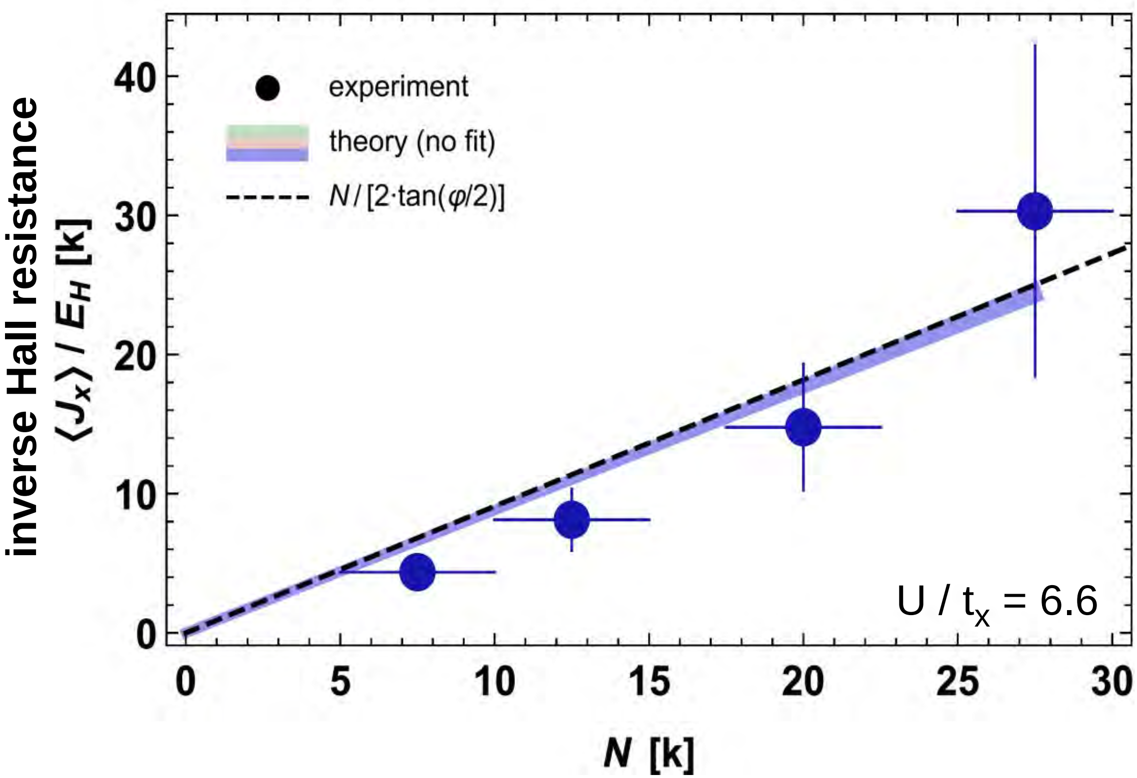


Measurement of the Hall resistance

$$R_H = \frac{\Delta V_H}{J_x}$$

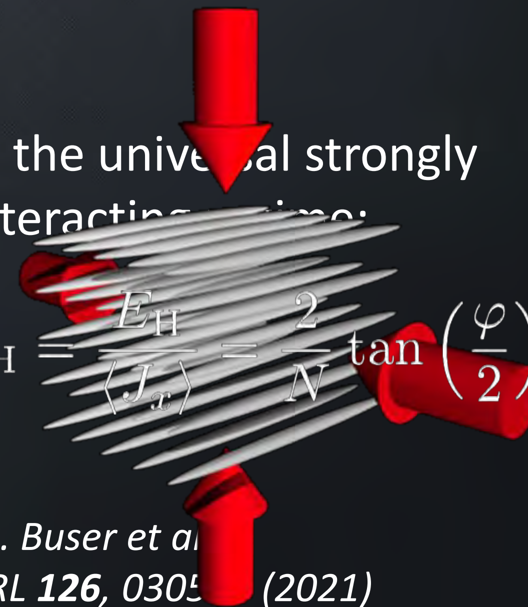
Hall resistance

Dependence of the Hall resistance on atom number



In the unive sal strongly interacting regime:

$$\rho_{\mathrm{H}} = \frac{E_{\mathrm{H}}}{\langle J_x \rangle} = \frac{2}{N} \tan\left(\frac{\varphi}{2}\right)$$



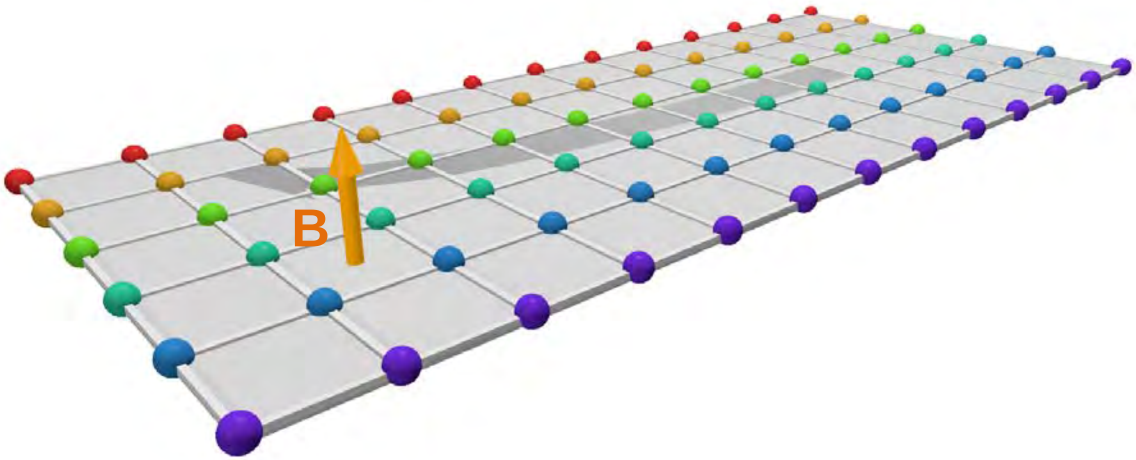
M. Buser et al
PRL ***126****, 0305 (2021)*

Experimental verification of 1/N scaling

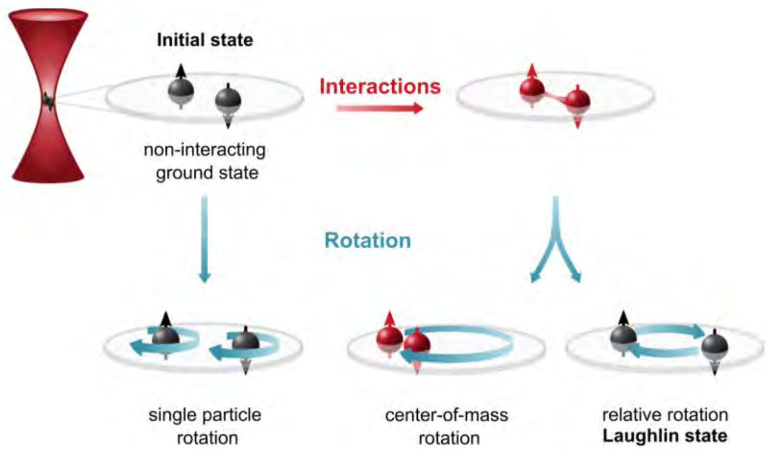
Theory: C. Repellin, T. Giamarchi, M. Filippone

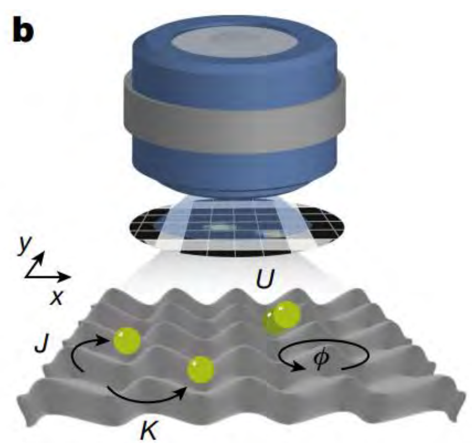
Quantum Hall

Perspective: quantized transport of interacting fermions in larger-sized synthetic ladders



Recent observations of FQH physics in few-body limit (2-particle Laughlin states)





P. Lunt et al., PRL 133, 253401 (2024)

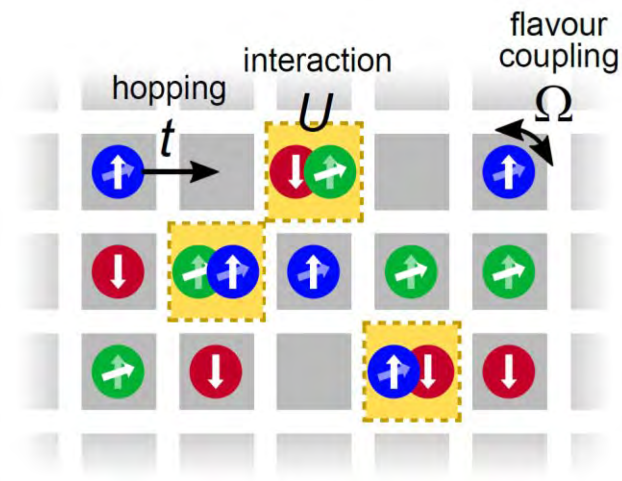
J. Léonard et al., Nature 619, 495 (2024)

Take-home messages pt.2

Multicomponent Fermi-Hubbard models

D. Tusi et al., Nat. Phys. 18, 1201 (2022)

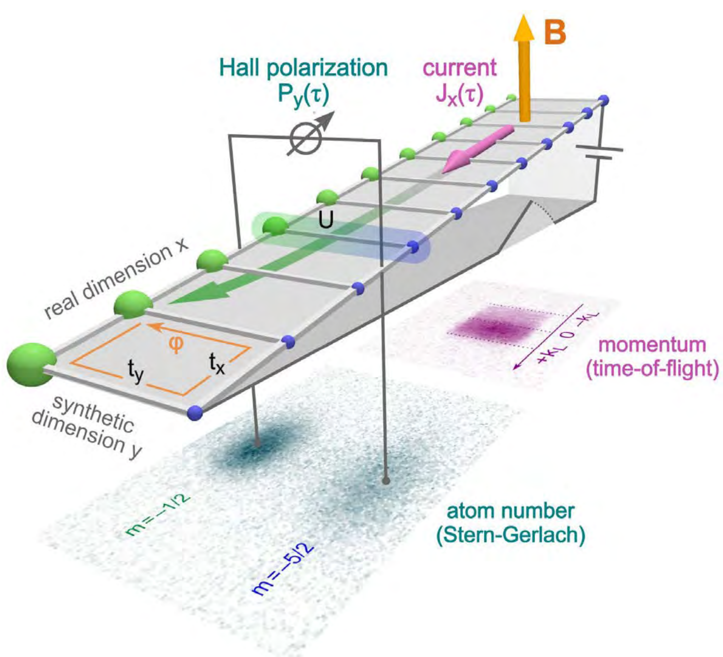
- **SU(N) symmetry and its controlled breaking**
- **Flavour-selective Mott localization**
- **Connections with complex materials** (and beyond?)



Hall response of interacting fermions

T.-W. Zhou et al., Science ***381****, 427 (2023)*
T.-W. Zhou et al., Nat. Comm. ***16****, 10247 (2025)*

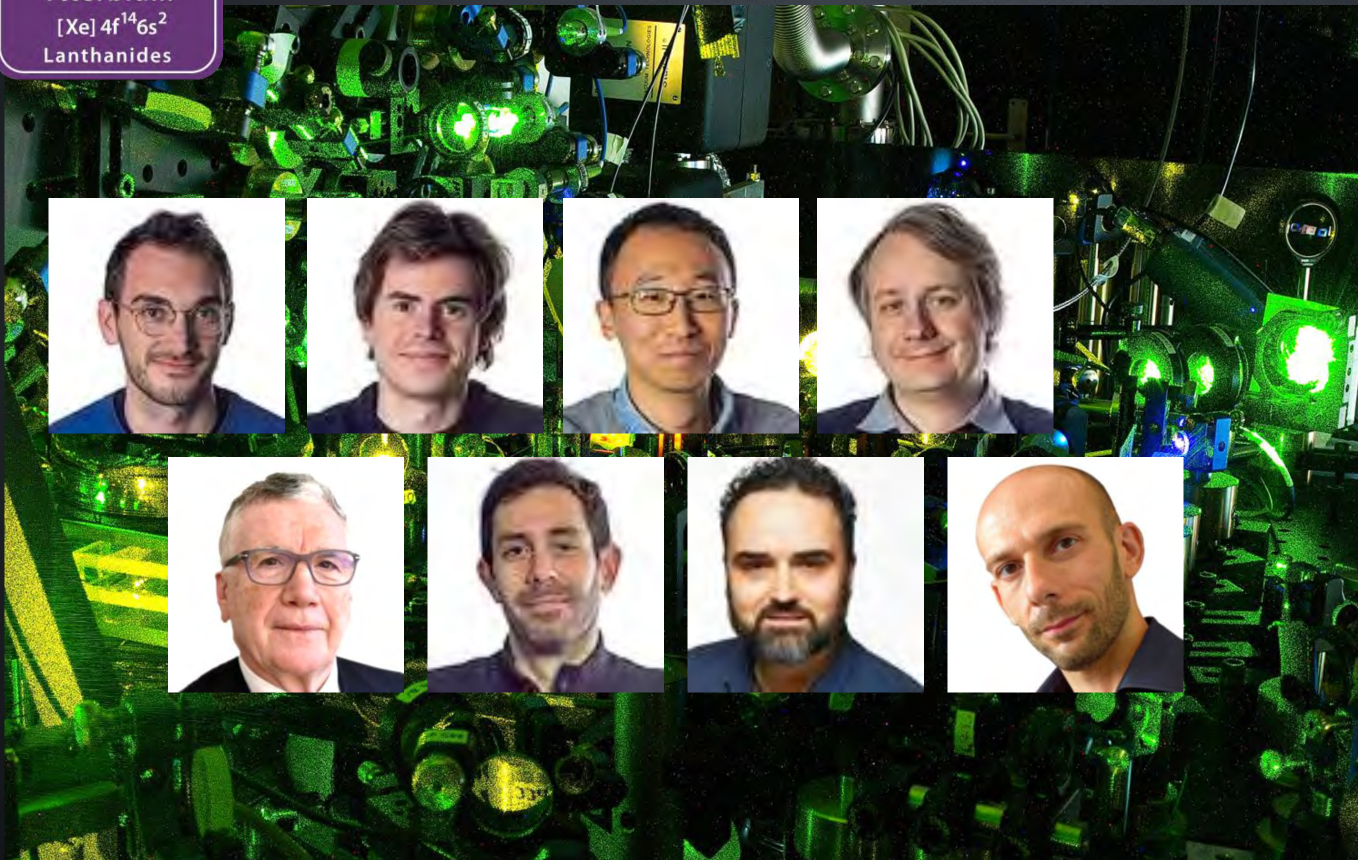
- **Synthetic dimension and synthetic B fields**
- **Observation of build-up of Hall response and universal regime at strong interactions**
- **Direct measurement of electric-like quantities**



Review: *L. F., arXiv:2308.06591 (2023)*

70 173.055
Yb
Ytterbium
[Xe] $4f^{14}6s^2$
Lanthanides

Yb1 Team



Gianmarco Masini
Thomas Beller
Tianwei Zhou
Jacopo Parravicini
Giacomo Cappellini
Massimo Inguscio
Jacopo Catani
L. F.

Former members:

Daniele Tusi
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Lorenzo Franchi
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Marco Mancini
Jorge Mellado Munoz
Guido Pagano
Florian Schafer
Pietro Lombardi
Carlo Sias

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute
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PASQuanS2
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MUR PRIN

Introduction

Flavour-dependent Mott localization of interacting lattice fermions

D. Tusi et al., Nature Physics **18**, 1201 (2022)

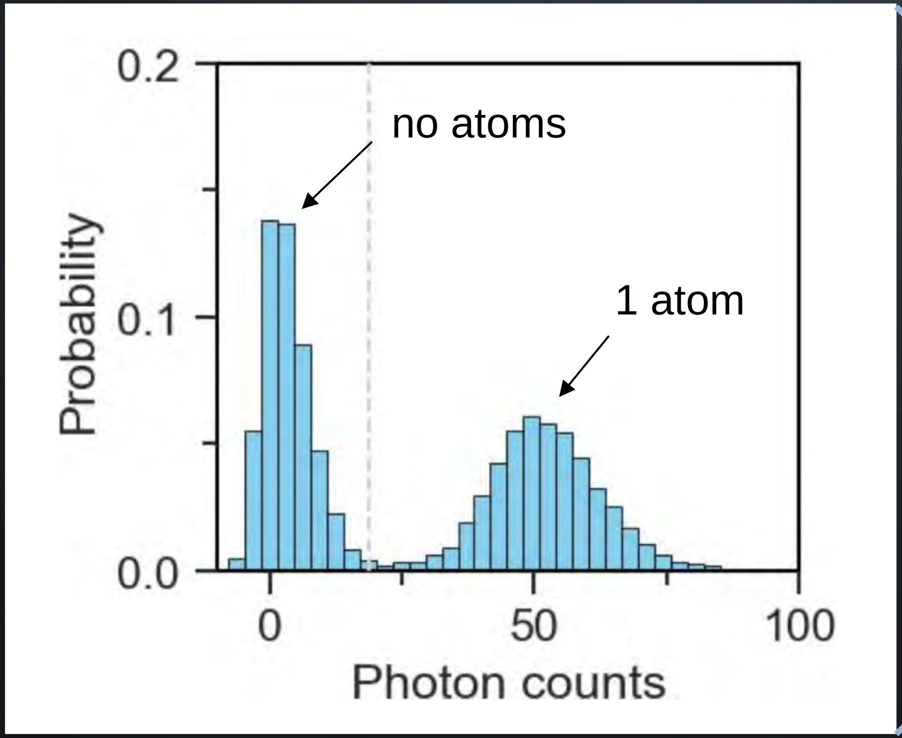
Universal Hall response in strongly interacting fermions

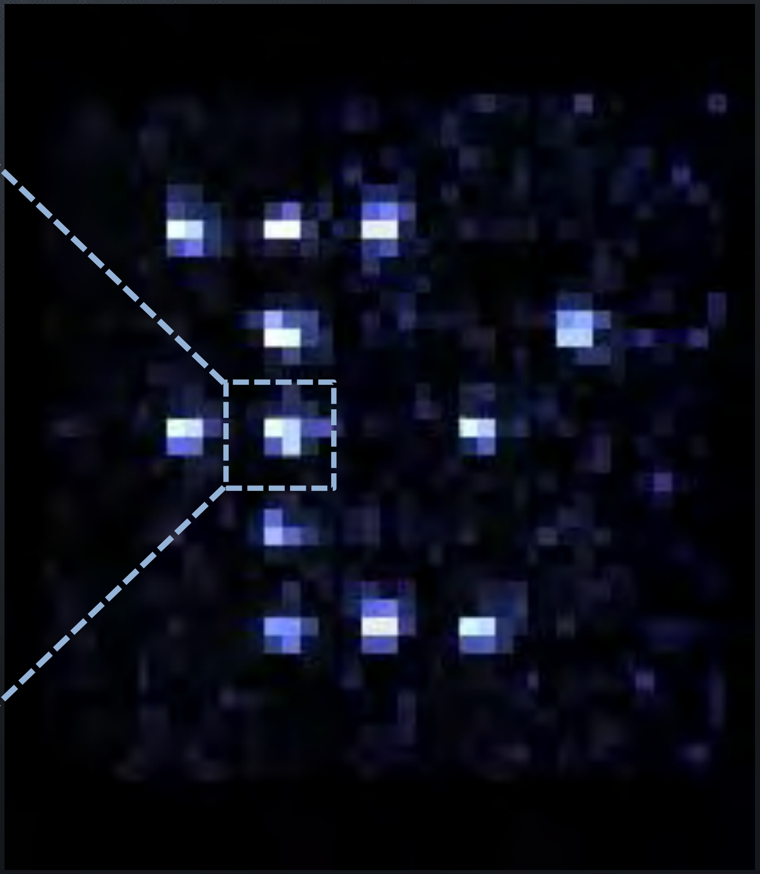
T.-W. Zhou et al., Science **381**, 427 (2023)
T.-W. Zhou et al., Nat. Comm. **16**, 10247 (2025)

New platforms with Rydberg atom arrays

Single-atom trapping in optical tweezers

Optical tweezer arrays

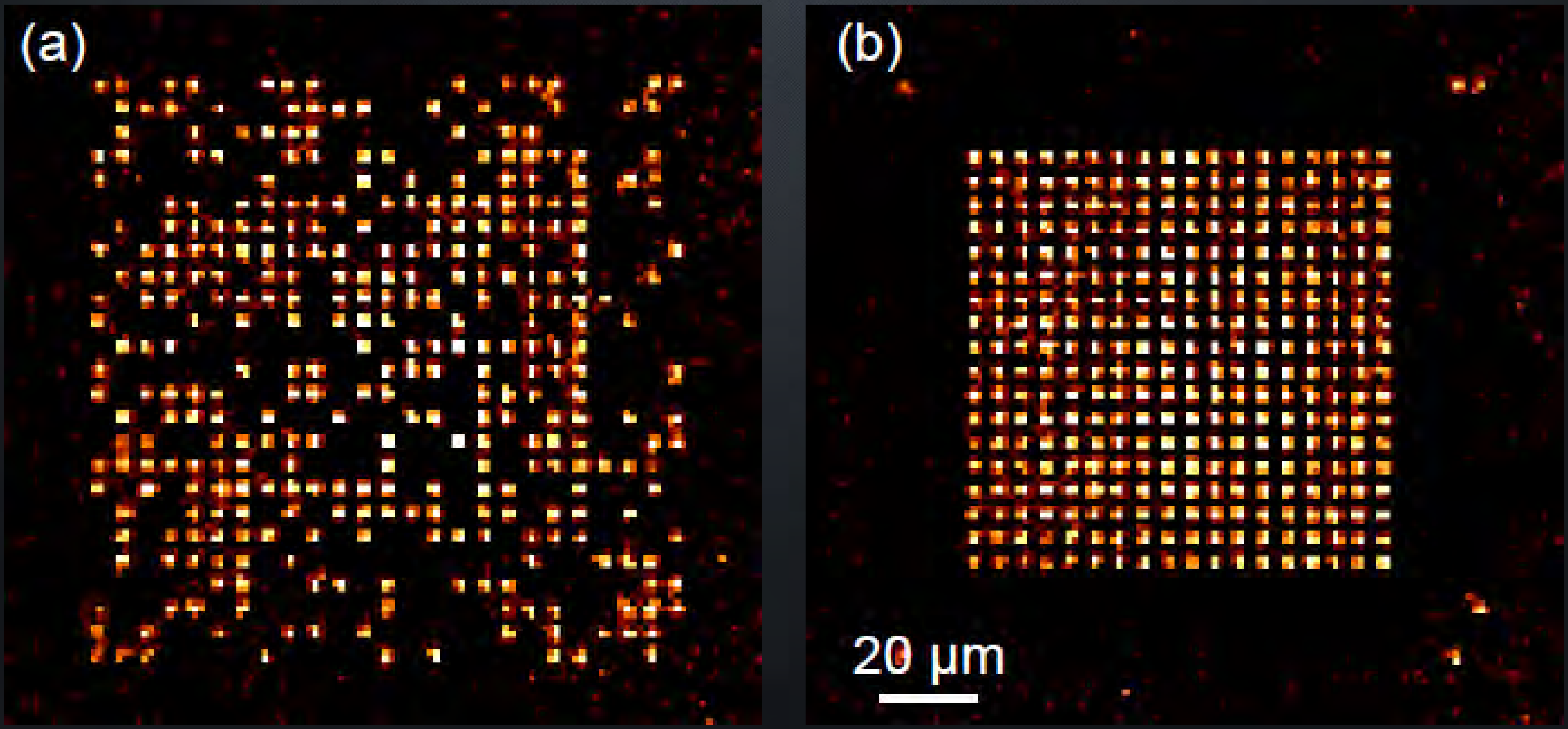




Fluorescence from single Sr atoms trapped in optical tweezer arrays

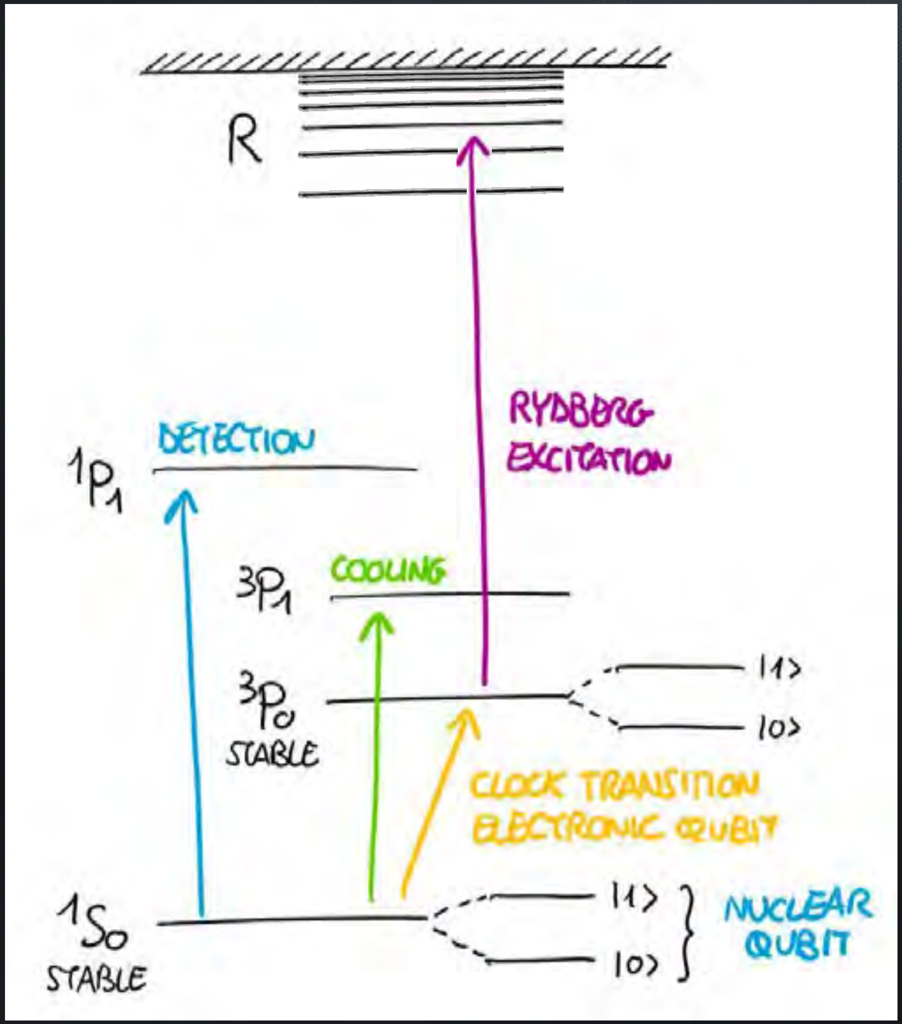
D. Barredo et al., Science 354, 1021 (2016)
K. N. Schymik, Phys. Rev. A 106, 022611 (2022)

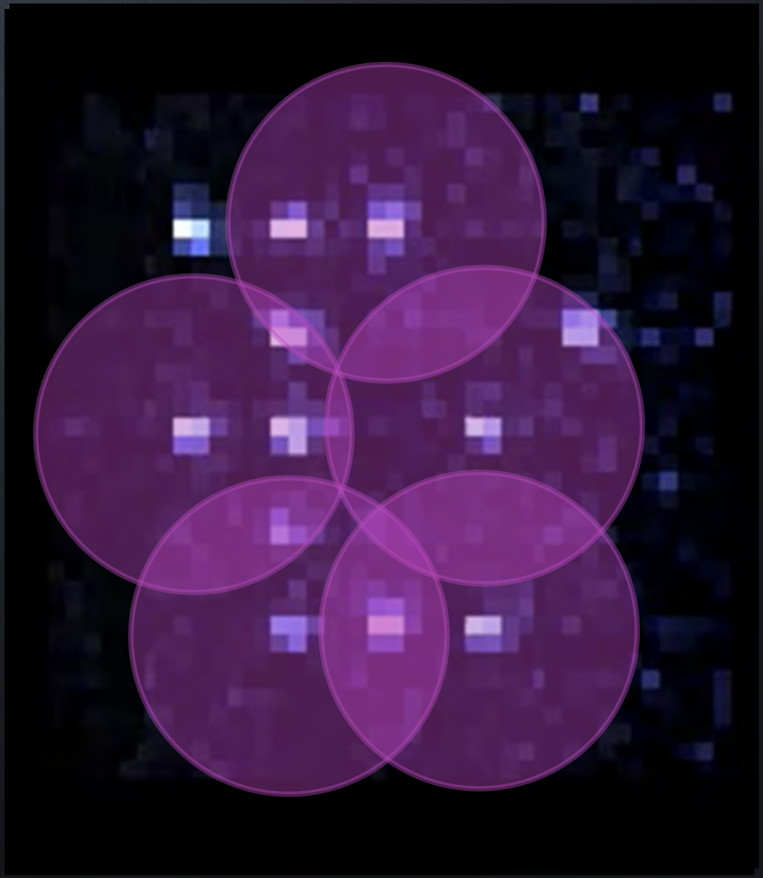
Sorting atomic arrays



Palaiseau (A. Browaeys group)

Rydberg atom arrays





Strong, controllable interactions between localized atoms

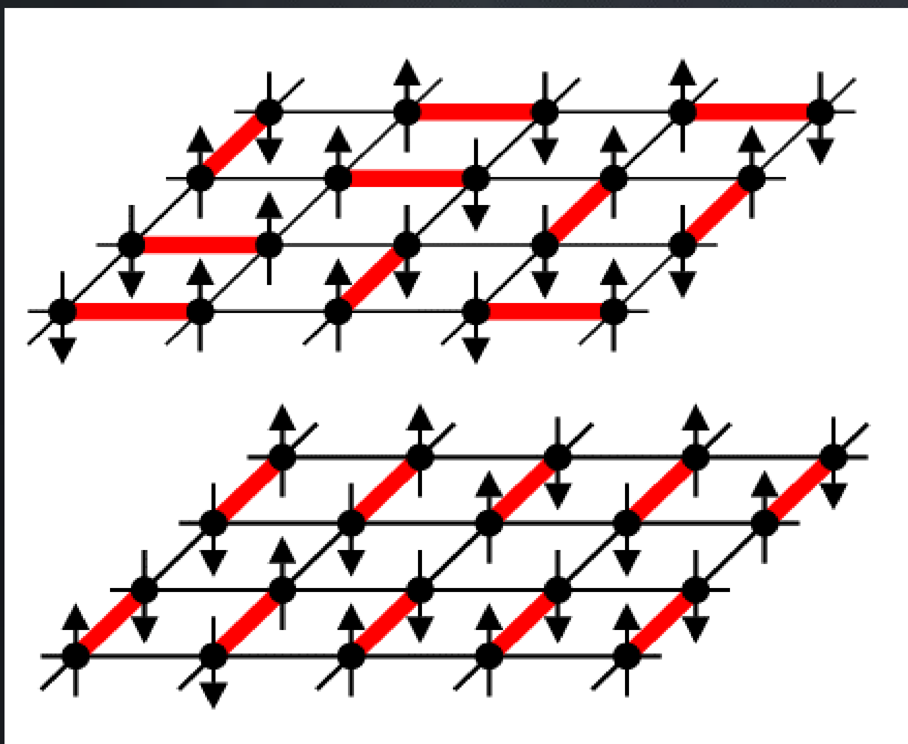
Rydberg atom arrays

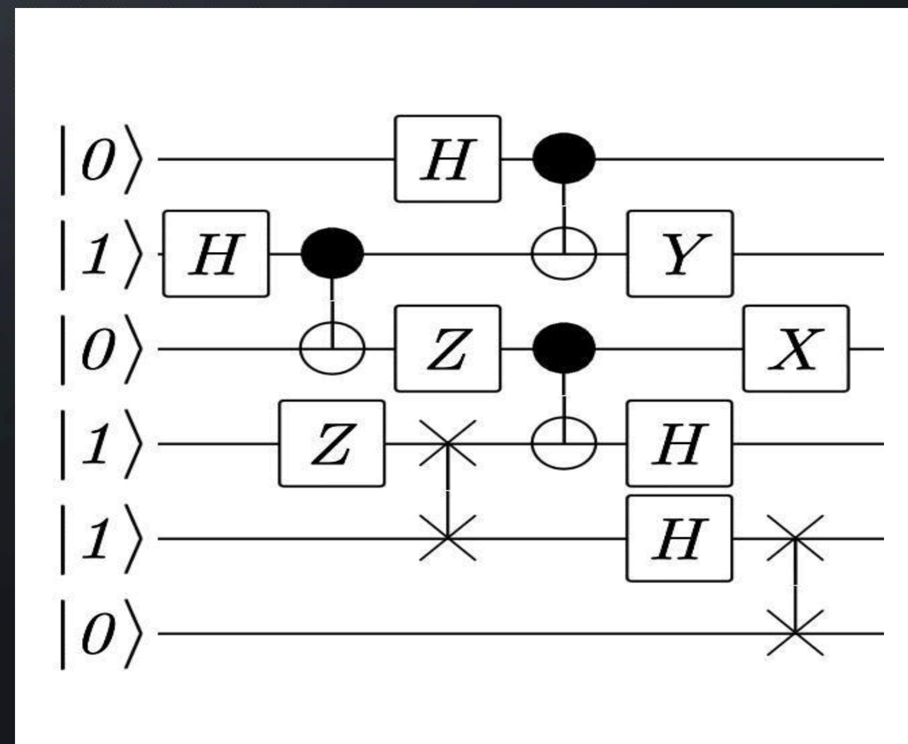
Analog quantum simulators

Engineering many-body quantum spin models (Ising, Heisenberg)

Digital quantum computers

Programmable quantum gates and circuits

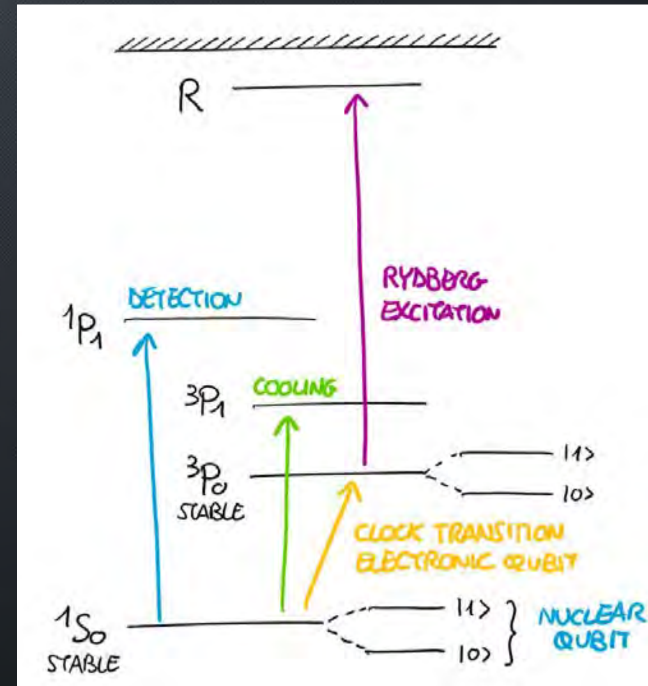




Rydberg atom arrays of two-electron atoms

Two-electron Rydberg atom arrays:

- rich electronic structure
  (narrow lines for cooling and hi-fi quantum state manipulation)
- storing information with long coherence
  (nuclear spins & metastable electronic states)
- possibility of trapping Rydberg states
  (inner-electron polarizability)



38 87.62
Sr
Strontium
[Kr] $5s^2$
Alkaline Earth Metal

Sr Rydberg Lab (UNIFI and CNR PASQUA)

- analog quantum simulation
- quantum spin models, many-body entanglement

70 173.055
Yb
Ytterbium
[Xe] $4f^{14}6s^2$
Lanthanides

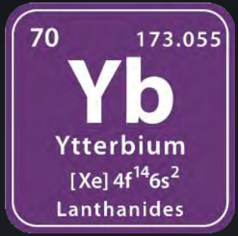
Yb Rydberg Lab (UNIFI and CNR PNRR ICSC)

- gate-based quantum computing
- testing new approaches

Rydberg atom arrays of two-electron atoms

Sr Rydberg Lab (UNIFI and CNR PASQUA)

- analog quantum simulation
- quantum spin models, many-body entanglement



Yb Rydberg Lab (UNIFI and CNR PNRR ICSC)

- gate-based quantum computing
- testing new approaches

Rydberg atom arrays of two-electron atoms

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Strontium
[Kr] $5s^2$
Alkaline Earth Metal

Andrea Fantini
Veronica Giardini
Shawn Storm
Luca Guariento
Massimo Inguscio
Jacopo Catani
Vladislav Gavryusev
L. F.

70 173.055
Yb
Ytterbium
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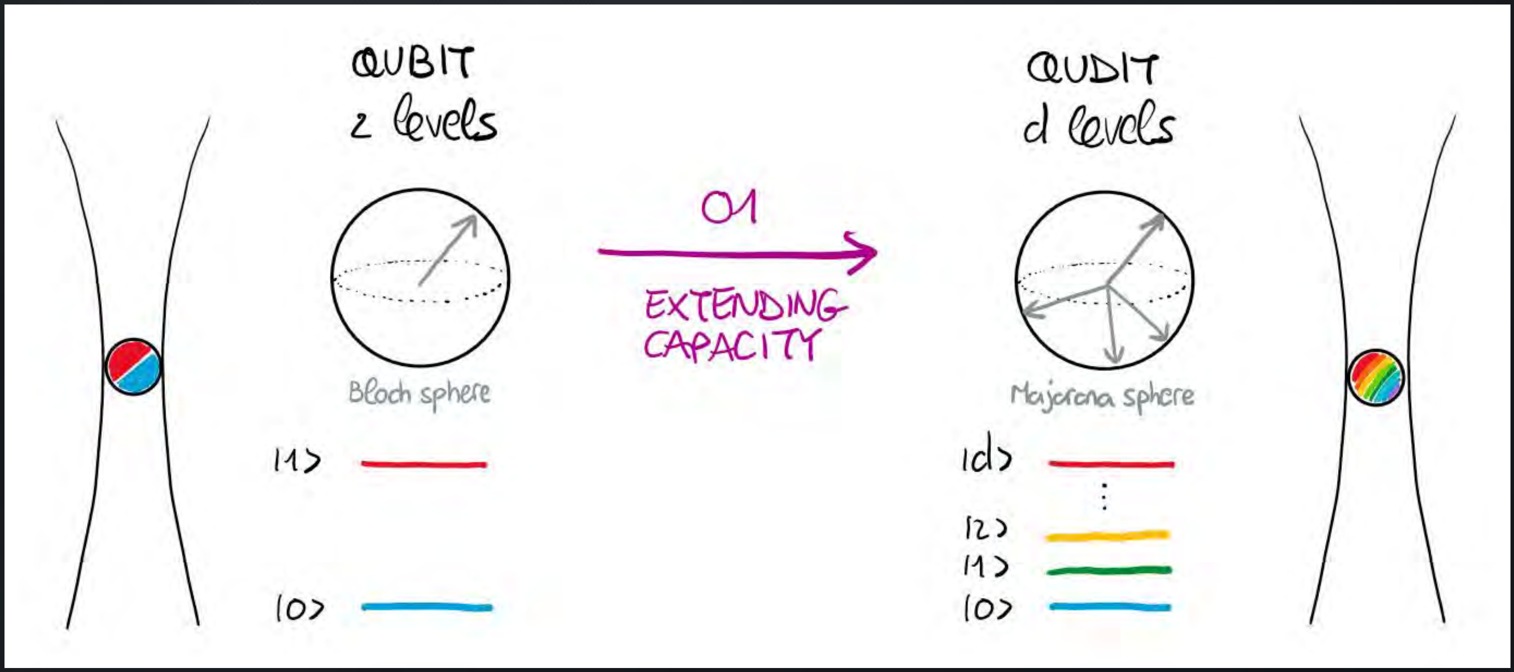
Lanthanides

Alessandro Vanni
Thomas Beller
Krishan Joshi
Louise Wolswijk
Andreas Trenkwalder
Massimo Inguscio
Giacomo Roati
Jacopo Catani
Luca Tanzi
L.F.

New directions

1) Processing quantum information with atomic qudits

- large nuclear-spin manifold (up to d=10 in 87Sr)
- engineer arbitrary rotations with Raman transitions (state-selective with intercombination transitions)
- higher information density, lower quantum circuit depth

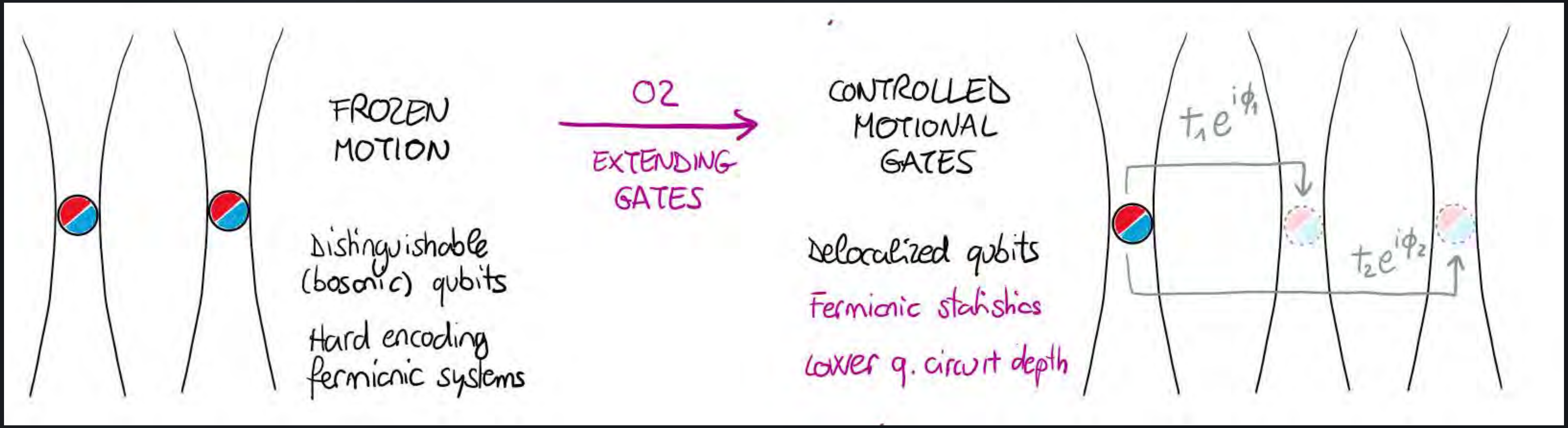


New directions

2) Engineer tunnelling gates for digital fermionic quantum simulators

- from localized to delocalized qubits
- tunnelling/shuttling gates between traps with movable tweezers
- embedding fermionic statistics at a hardware level
(no need for algorithmic overhead to embed commutation rules)

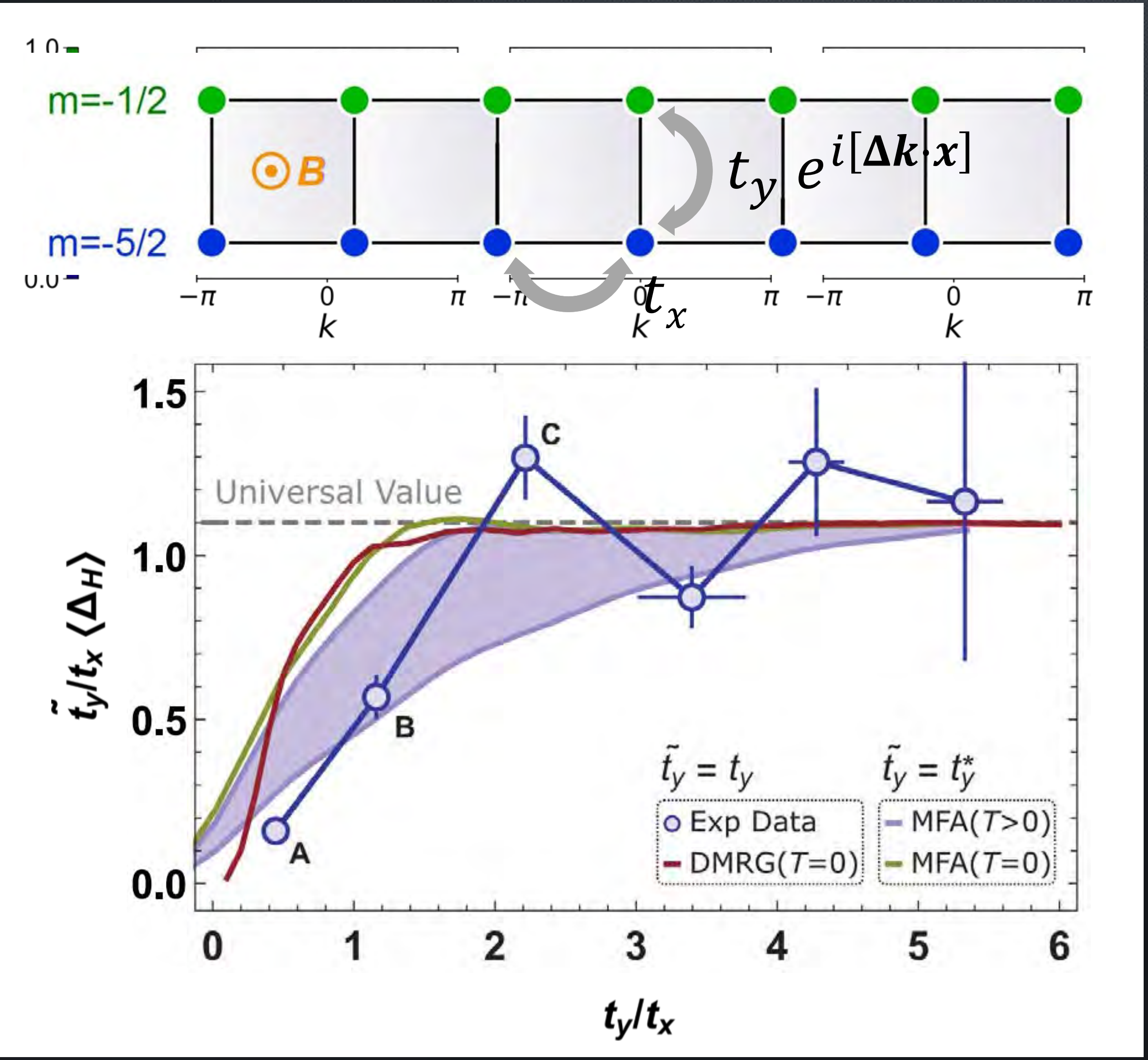
D. Gonzalez-Cuadra et al., Fermionic quantum processing with programmable neutral atom arrays, PNAS 120, e2304294120 (2023)




Thank you!
leonardo.fallani@unifi.it
FLORENTINA STUDIORUM UNIVERSITAS
Lens
European Laboratory for Non-Linear Spectroscopy

T.-W. Zhou et al., Science **381**, 427 (2023)

Universal Hall response



Dependence of the Hall imbalance on the transverse hopping t_y

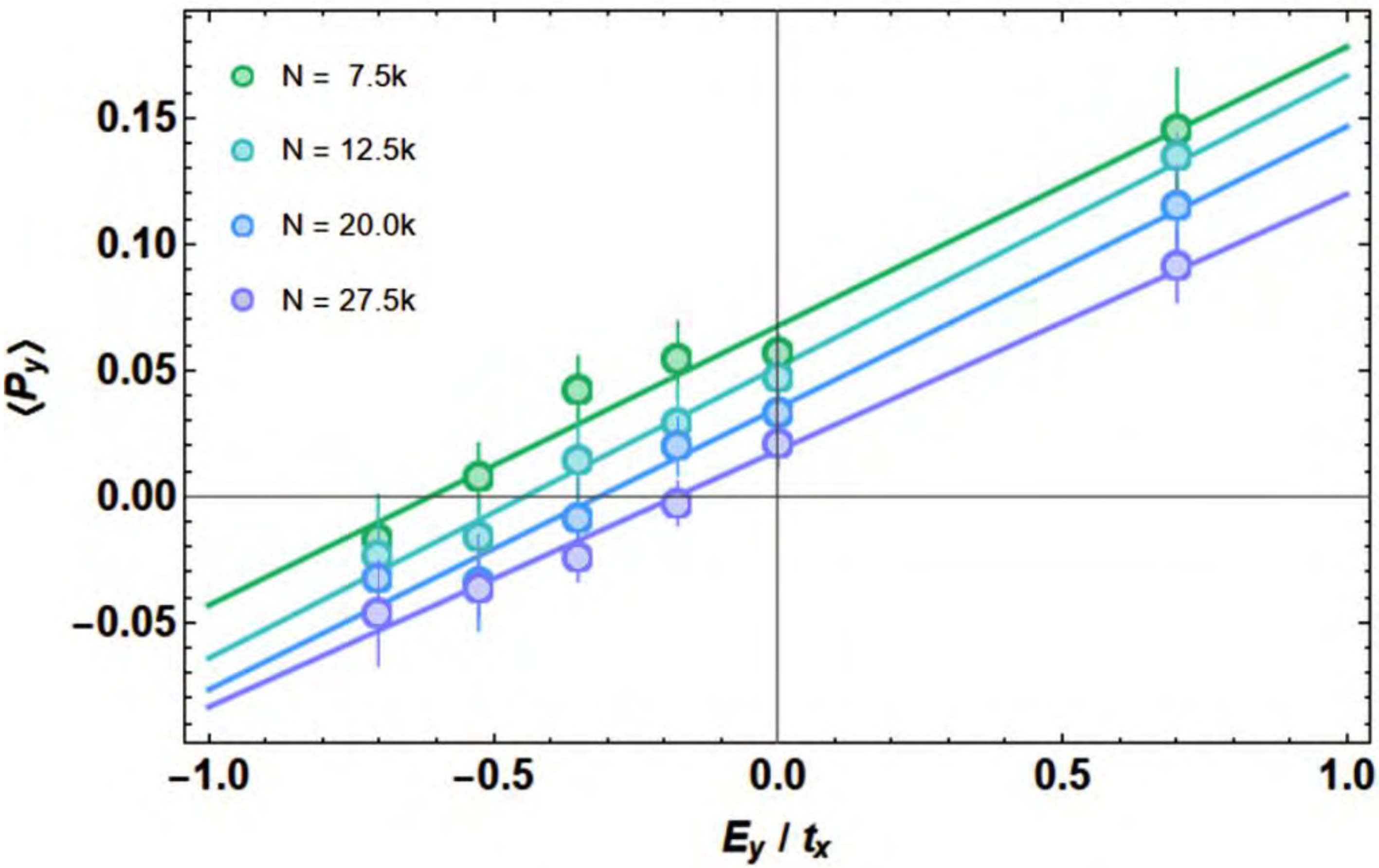
A large t_y stabilizes a single-band metal where Δ_H takes the universal value

$$\Delta_H = 2\frac{t_x}{t_y}\tan\left(\frac{\varphi}{2}\right)$$

Theory: C. Repellin, S. Greschner, T. Giamarchi, M. Filippone

Measurement of Hall voltage

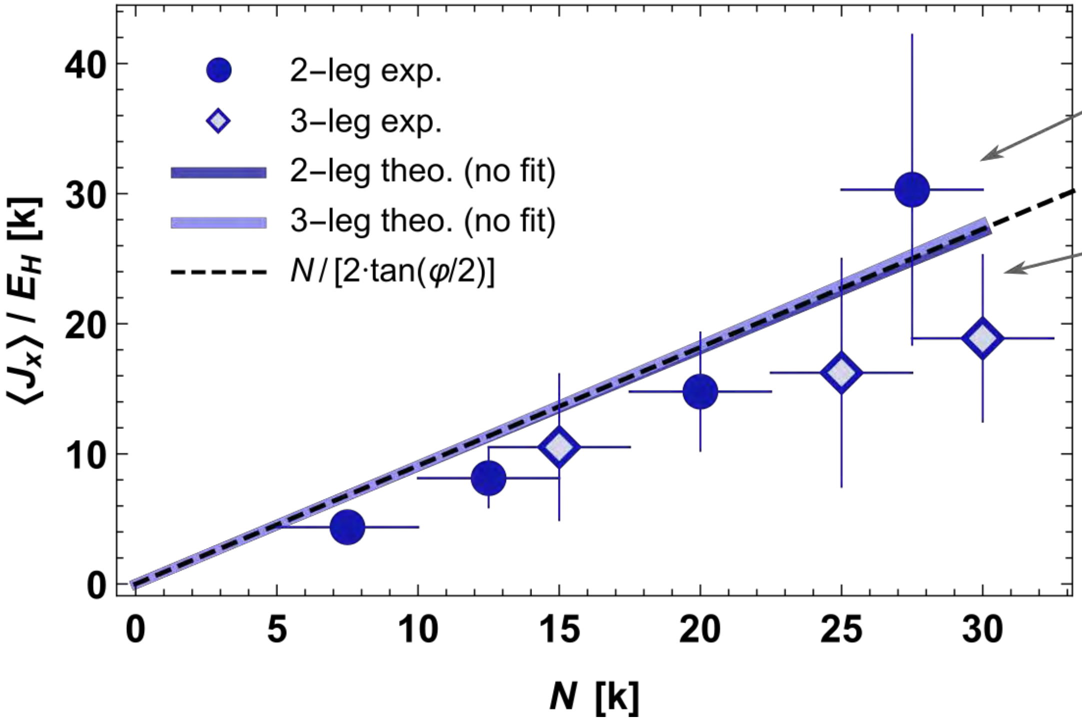
Determination of the Hall voltage ΔV_H vs atom number

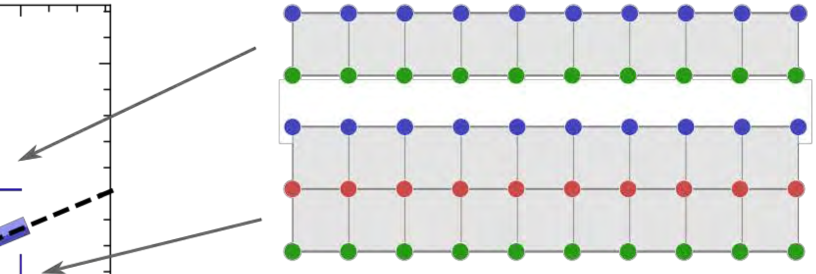


theory: $\langle P_y \rangle = \left(E_y - 2\tan\left(\frac{\varphi}{2}\right) \frac{\langle J_x \rangle}{N} \right) \mathcal{I}_M$

Hall resistance

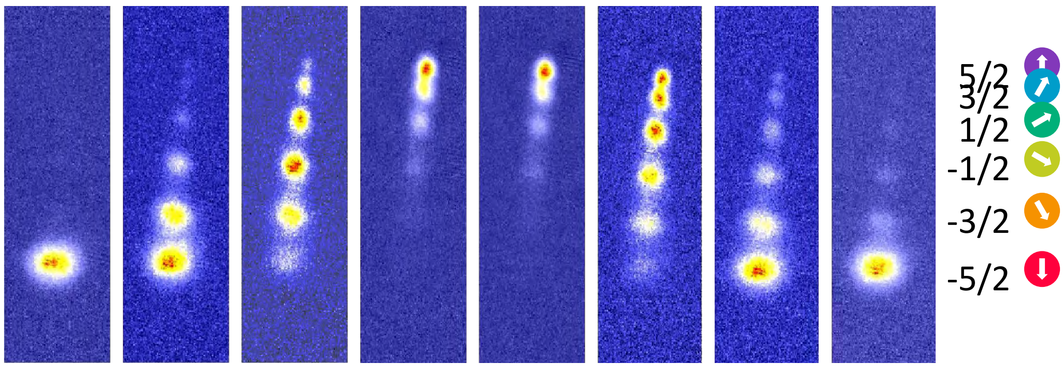
Robustness of the Hall resistance vs number of legs

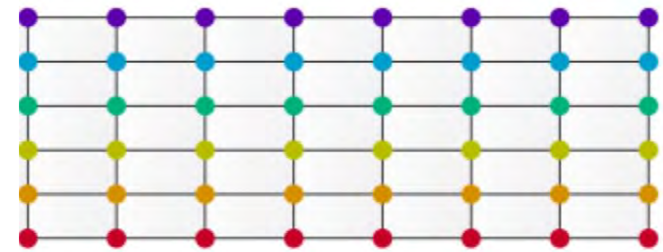


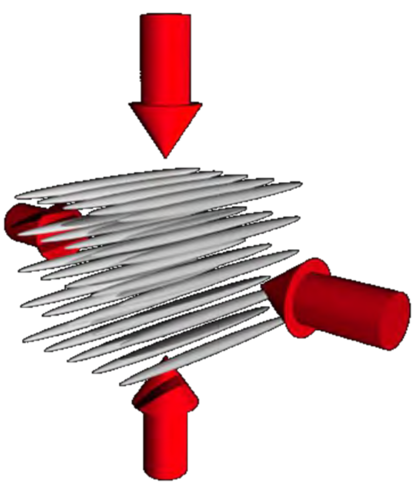


Quantized Hall response of strongly interacting fermions

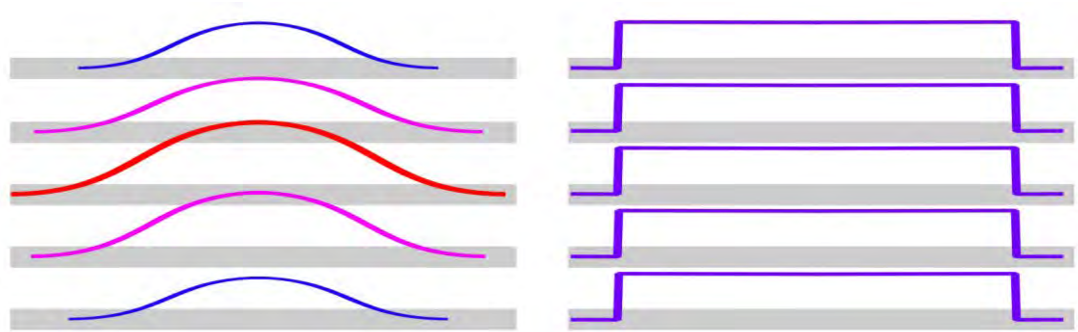
Extended synthetic dimensions





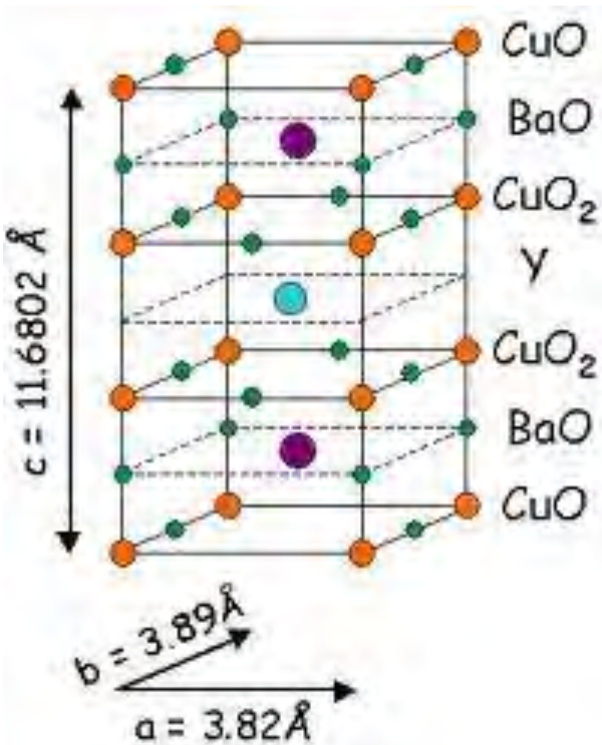


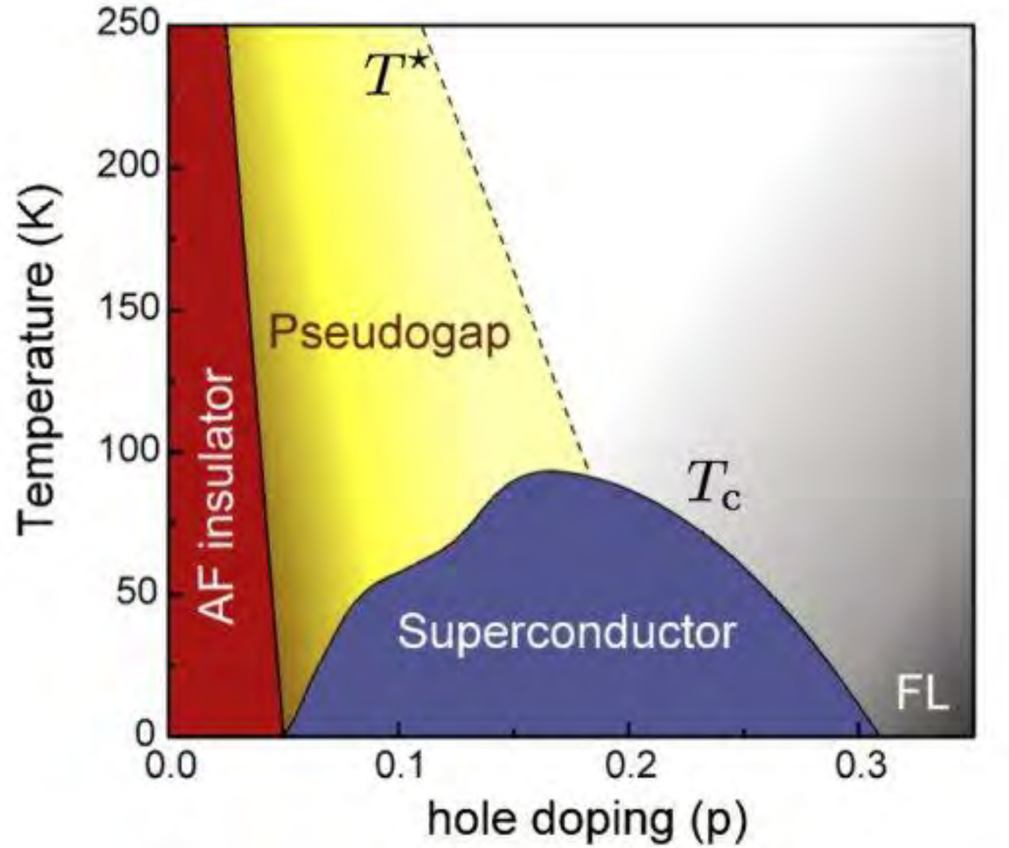
Control of density/homogeneity with tailored optical potentials



Simplest model to describe electron-electron correlations in materials

Relevant model for high-Tc superconductivity (e.g. cuprates)

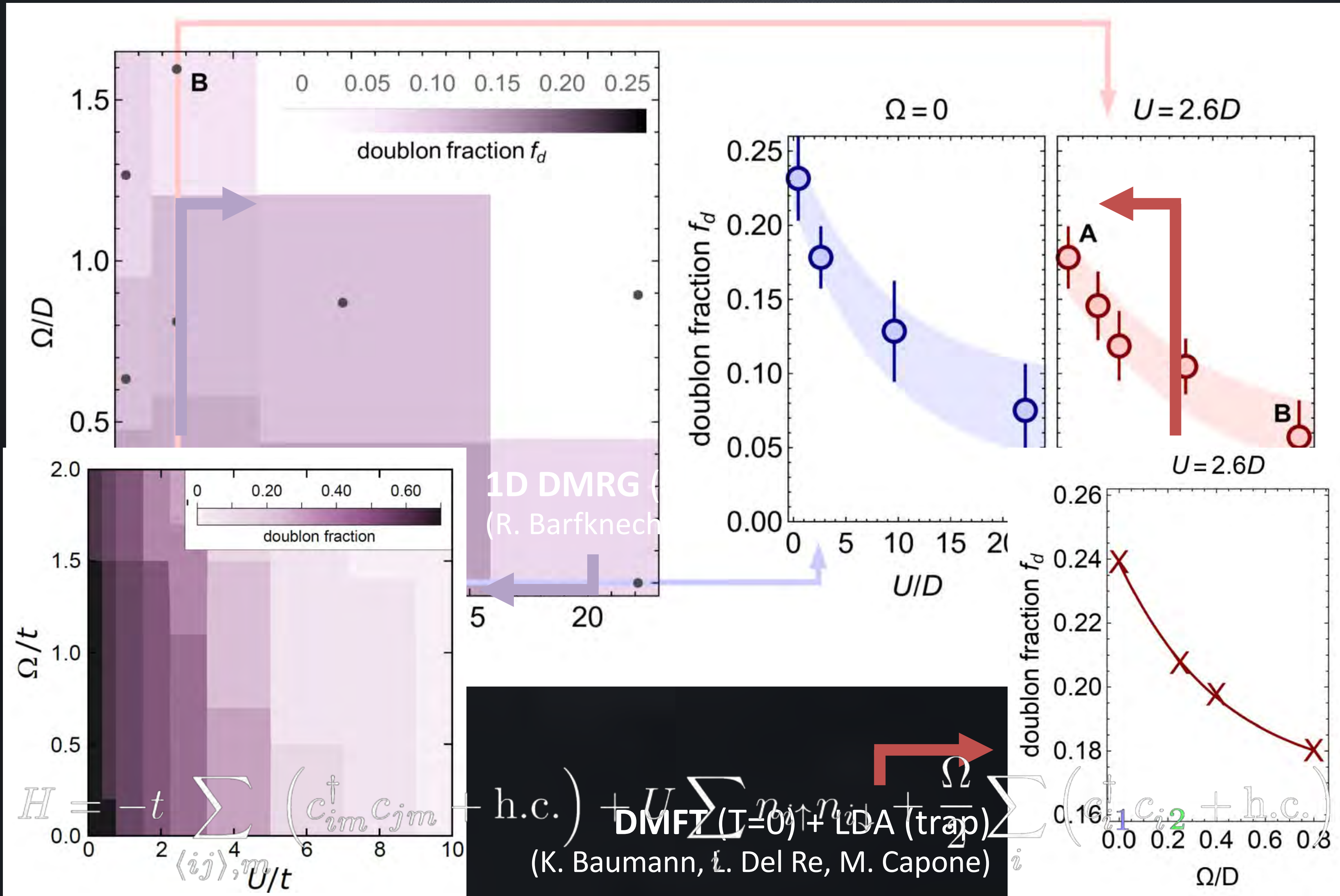




Experiments by ETH, MPQ, Harvard, Rice, MIT, Princeton, Bonn…

D. Tusi et al., Nature Physics 18, 1201 (2022)

Experiment vs theory



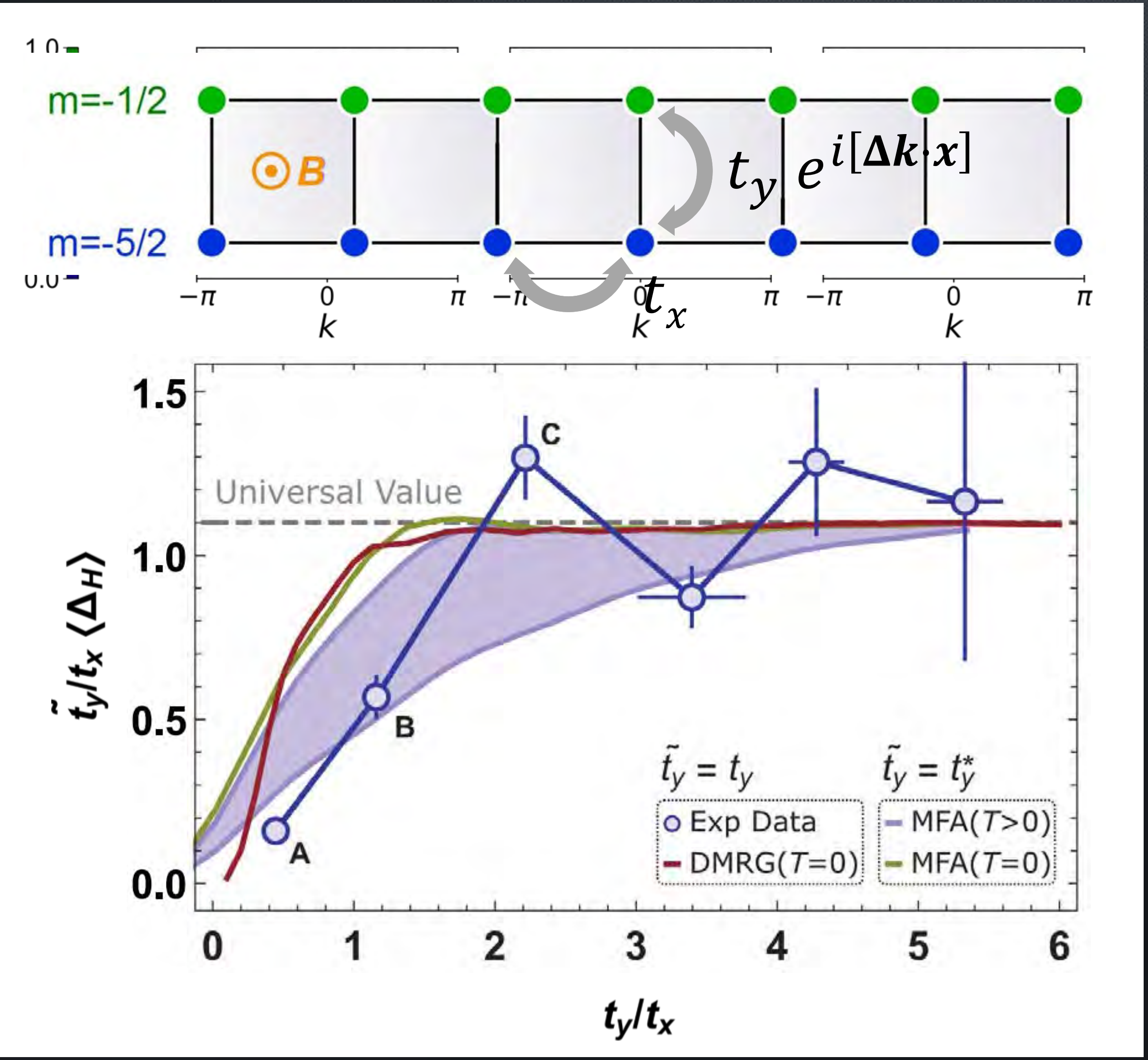
$$H = -t\sum_{\langle ij\rangle,m}\left(c^\dagger_{im}c_{jm} + \mathrm{h.c.}\right) + U\sum_i n_{i\uparrow}n_{i\downarrow} + \frac{\Omega}{2}\sum_i\left(c^\dagger_{i1}c_{i2} + \mathrm{h.c.}\right)$$

DMFT (T=0) + LDA (trap)

(K. Baumann, L. Del Re, M. Capone)

T. Zhou et al., Science ***381****, 427 (2023)*

Universal regime of Hall response



Dependence of the Hall imbalance on the transverse hopping t_y

A large t_y stabilizes a single-band metal where Δ_{H} takes the universal value

$$\Delta_H = 2\frac{t_x}{t_y}\tan\left(\frac{\varphi}{2}\right)$$

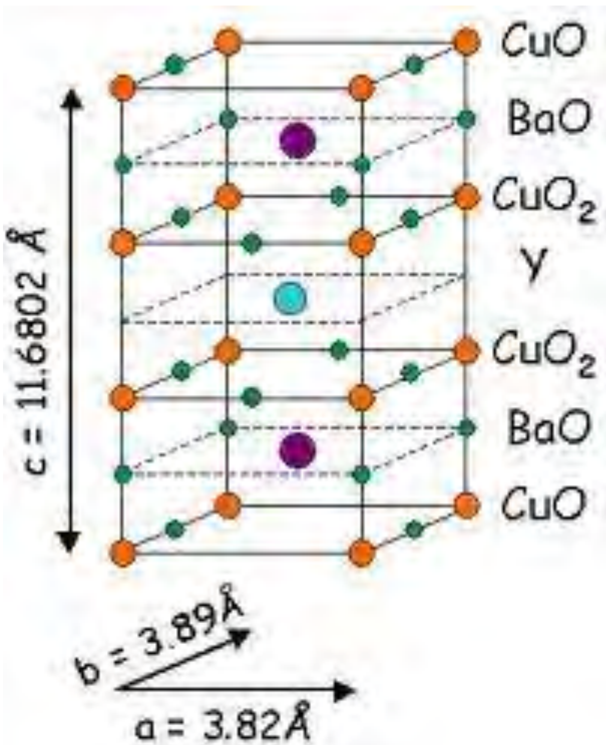
corresponding to the «classical» Hall coefficient

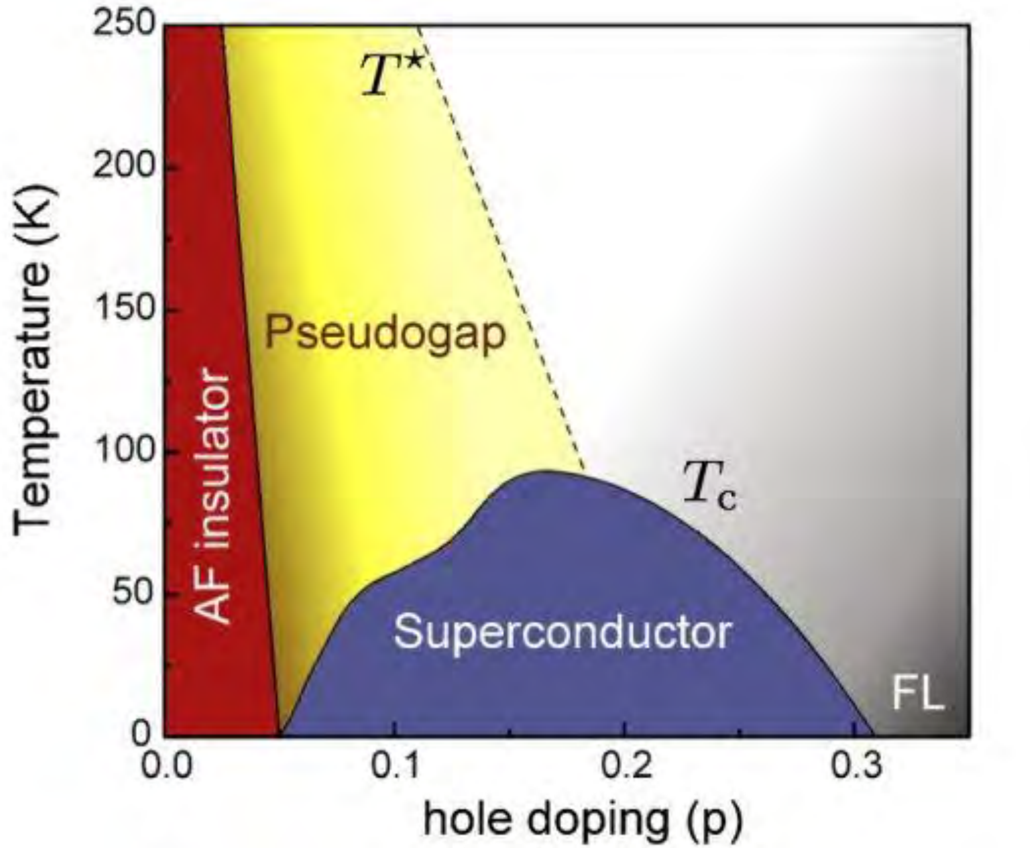
$$R_H = \frac{-1}{nq}$$

Theory: C. Repellin, S. Greschner, T. Giamarchi, M. Filippone

Simplest model to describe electron-electron correlations

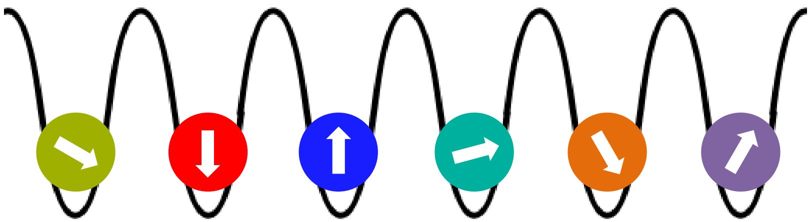
Relevant model for high-Tc superconductivity (e.g. cuprates)





Experiments by many groups: ETH, MPQ, Harvard, Rice, MIT… and many others!

SU(N) Fermi-Hubbard model



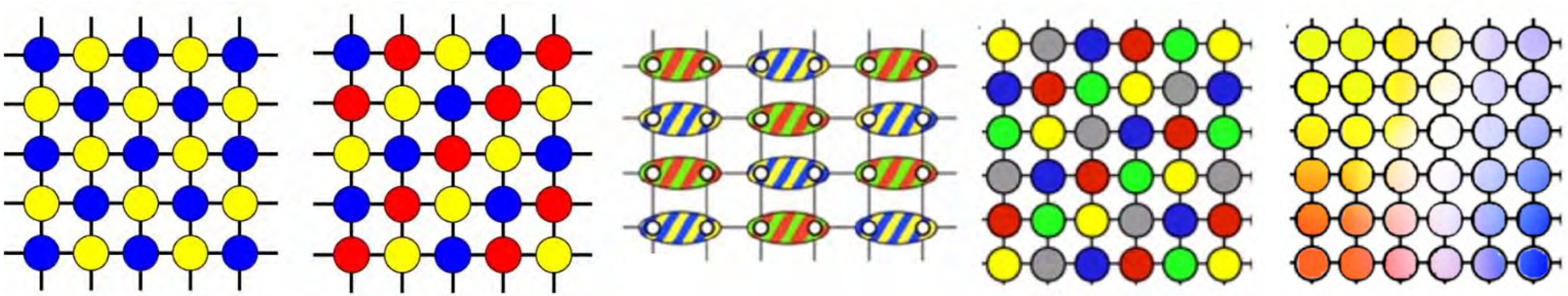
Richer physics for SU(N) Fermi-Hubbard!

Different thermodynamics,
Novel quantum phases, exotic magnetism

$$H \sim \frac{4t^2}{U} \sum_{\langle ij \rangle, m, n} S_{mni} S_{nmj}$$

SU(N) Heisenberg model @ low T

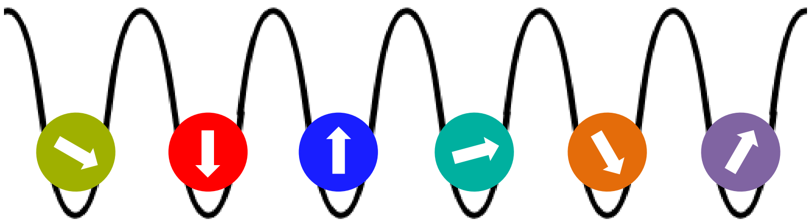
A wealth of magnetic phases is expected (antiferromagnets, dimerized, spin liquids…)



SU(2) SU(3) SU(4) SU(5) SU(>=5)

M. Hermele et al., PRL **103**, 135301 (2009)
T. A. Tóth et al., PRL **105**, 265301 (2010)
P. Corboz et al., PRL **107**, 215301 (2011)
P. Nataf & F. Mila, PRL **113**, 127204 (2014)
…and many many others

SU(N) Fermi-Hubbard model



Richer physics for SU(N) Fermi-Hubbard!

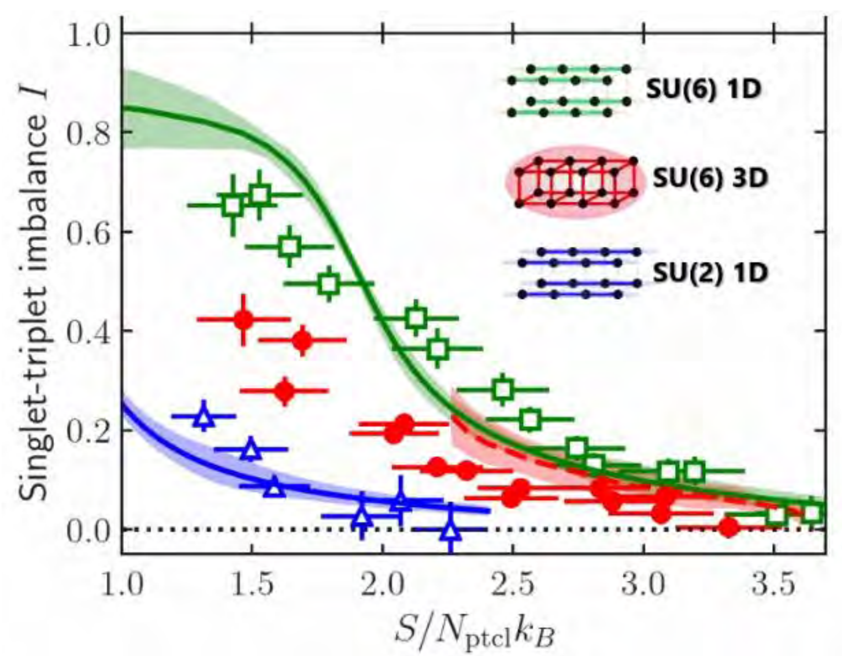
Different thermodynamics,
Novel quantum phases, exotic magnetism

$$H \sim \frac{4t^2}{U} \sum_{\langle ij \rangle, m, n} S_{mni} S_{nmj}$$

SU(N) Heisenberg model @ low T

Experimental observation of SU(N) antiferromagnetism (Kyoto, Takahashi)

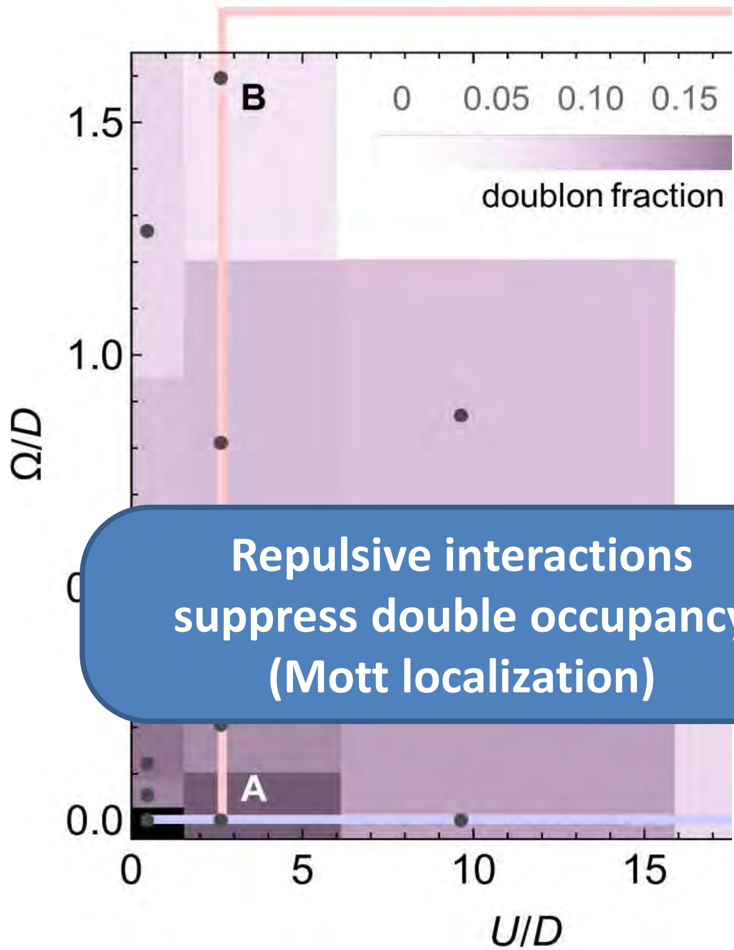
H. Ozawa et al., PRL ***121****, 225303 (2018)*
S. Taie et al., Nat. Phys. ***18****, 1356 (2022)*



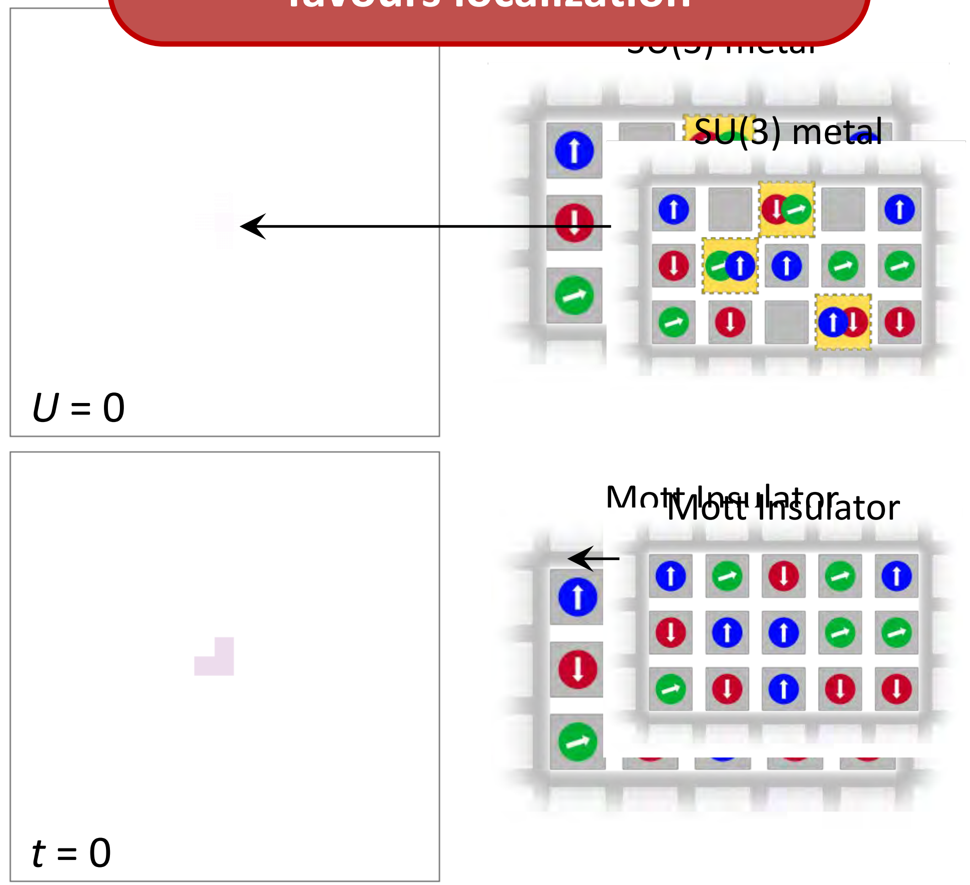
Metal to insulator

Measurement of doubly occupied sites:

Coupling between flavours favours localization



Repulsive interactions suppress double occupancy (Mott localization)



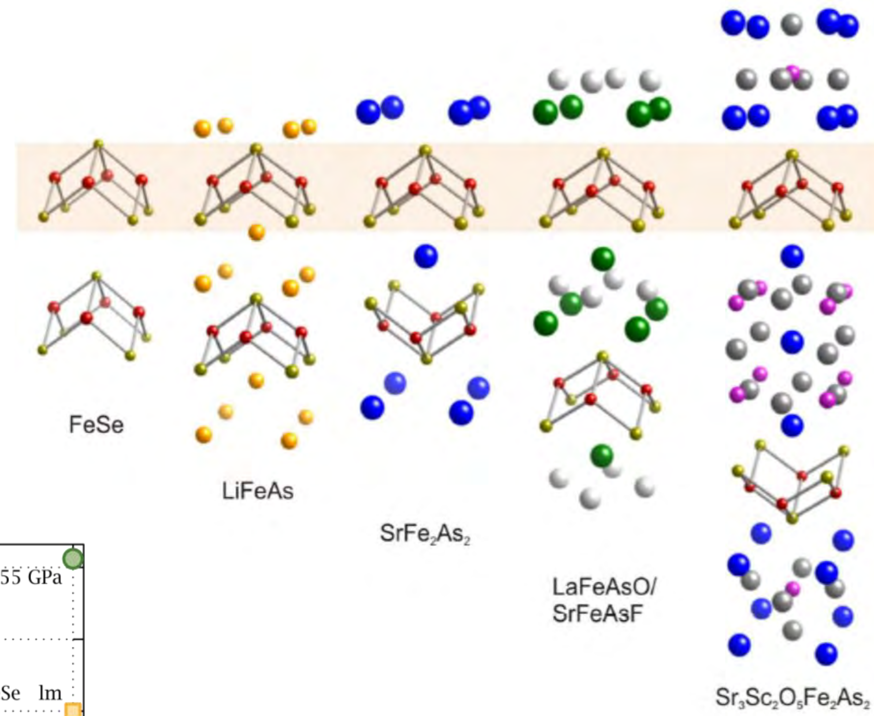
($D = 6t$)

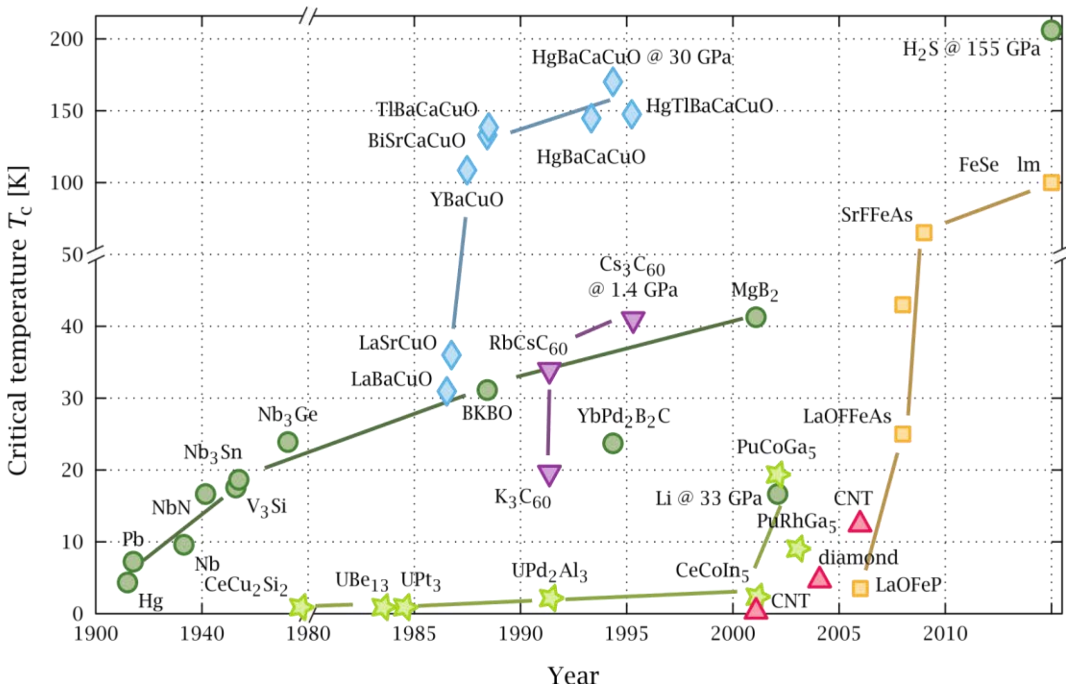
Iron-based superconductors

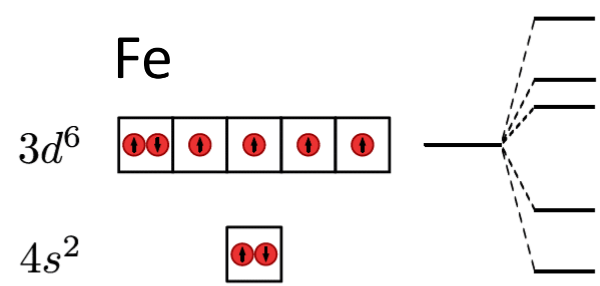
A "new" class of high-Tc superconductors

Layered structure as cuprates
Square lattices of Fe (with As, Se, ...)

Multiple orbitals involved in conduction
Hund's coupling between orbitals







Multi-orbital Hubbard models

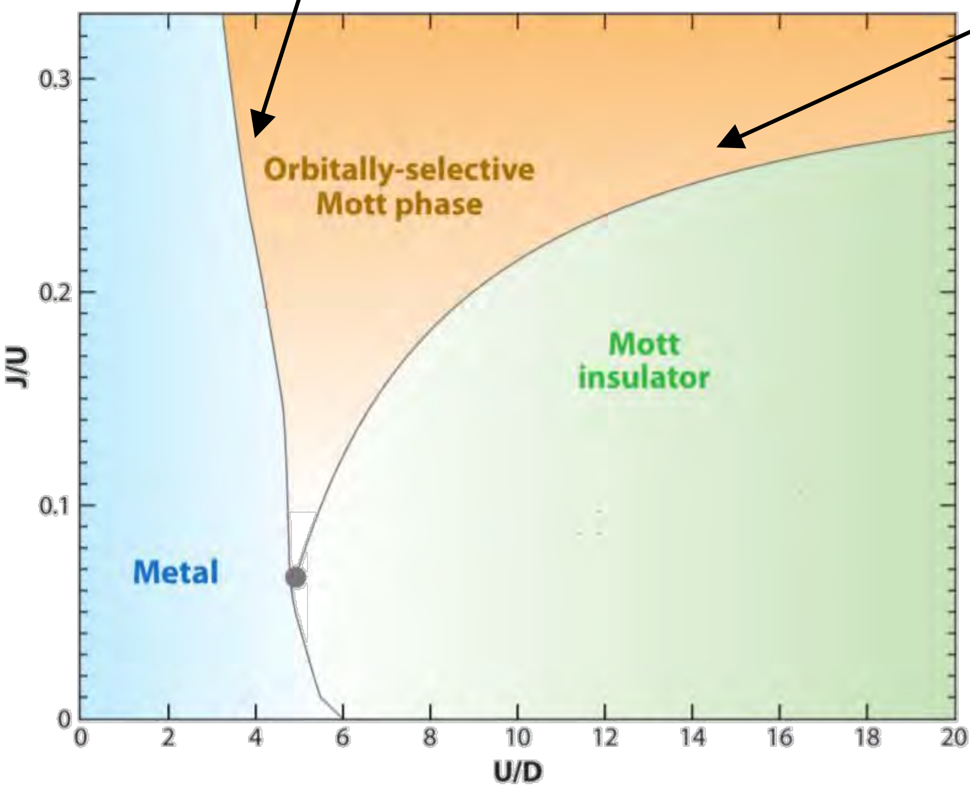
…ith **coherent coupling between orbitals**

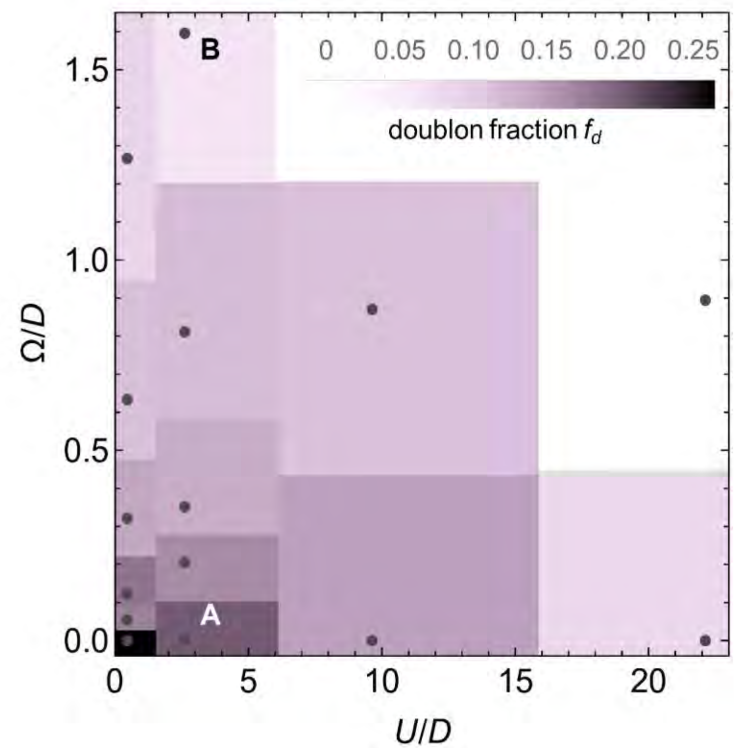
Orbital coupling shrinks metallic phase by degeneracy lifting

Mott localization only in some orbitals

$$\sum_{i,m} n_{im\uparrow} n_{im\downarrow} + \Big(U' \ldots$$

$$- J \sum_{i,m>m'} [2\mathbf{S}_{im} \cdot \mathbf{S}_{im'} + (d^\dagger_{im\uparrow} d^\dagger_{im\downarrow} d_{im'\uparrow} d_{im'\downarrow} + \mathrm{H.c.})].$$





Multi-orbital Hubbard models

How to realize a minimal system where to observe these effects?

PHYSICAL REVIEW A **98**, 063628 (2018)

Selective insulators and anomalous responses in three-component fermionic gases with broken SU(3) symmetry

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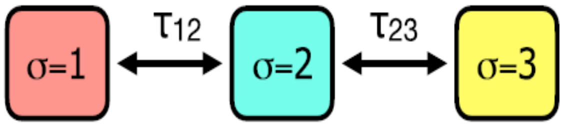
(Received 1 August 2017; published 26 December 2018)

We study a three-component fermionic fluid in an optical lattice in a regime of intermediate to strong interactions allowing for optical processes connecting the different components, similar to those used to create artificial gauge fields. Using dynamical mean-field theory, we show that the combined effect of interactions and the external field induces a variety of anomalous phases in which different components of the fermionic fluid display qualitative differences, i.e., the physics is flavor selective. Remarkably, the different components can display huge differences in the correlation effects, measured by their effective masses and nonmonotonic behavior of their occupation number as a function of the chemical potential, signaling a sort of selective instability of the overall stable quantum fluid.

Multi-orbital Hubbard models

Raman coupling in ultracold SU(N) fermions emulates coupling between orbitals

$$\hat{H} = -t \sum_{\langle \mathbf{R}\mathbf{R}' \rangle \sigma} c^{\dagger}_{\mathbf{R}\sigma} c_{\mathbf{R}'\sigma} + \sum_{\mathbf{R},\sigma\sigma'} c^{\dagger}_{\mathbf{R}\sigma} \tau_{\sigma\sigma'} c_{\mathbf{R}\sigma} + U \sum_{\mathbf{R},\sigma<\sigma'} \left(\hat{n}_{\mathbf{R}\sigma} - \frac{1}{2}\right)\left(\hat{n}_{\mathbf{R}\sigma'} - \frac{1}{2}\right) - \mu \sum_{\mathbf{R}\sigma} \hat{n}_{\mathbf{R}\sigma}$$



State-selective properties:

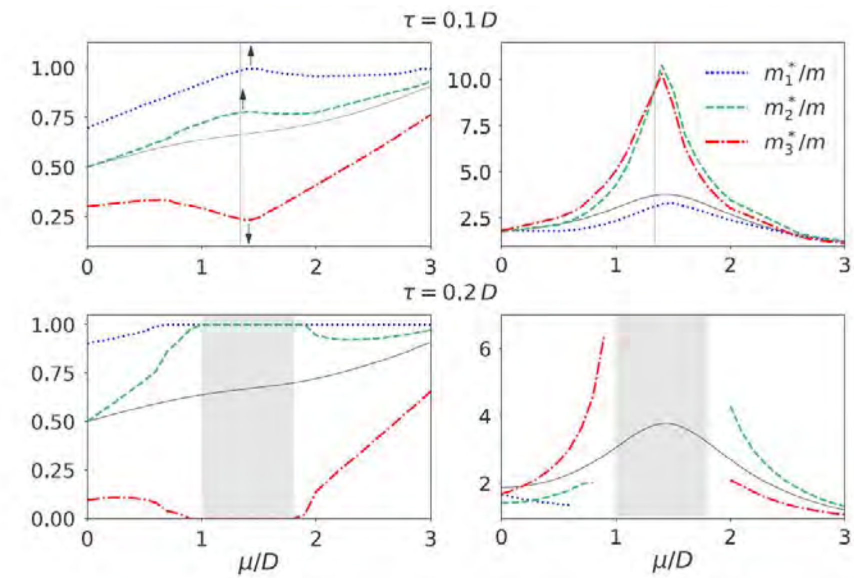
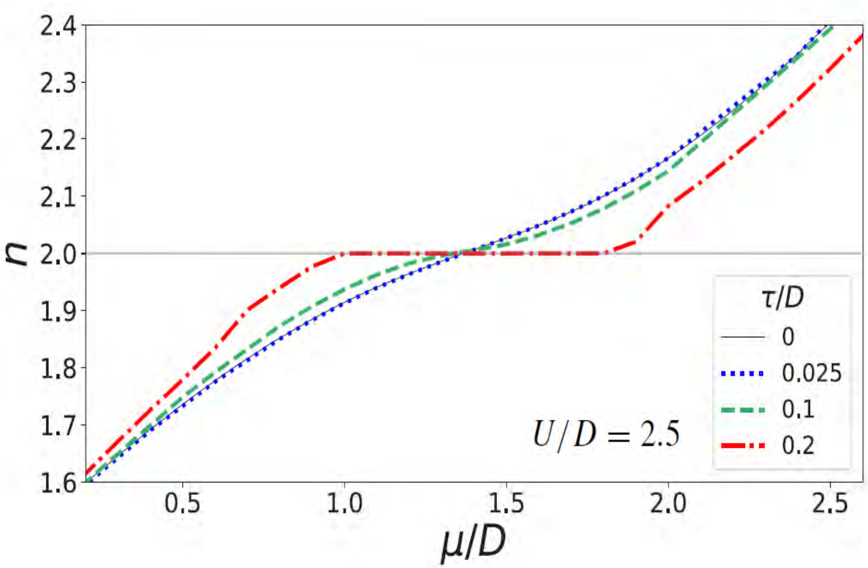


FIG. 4. Left Column: occupation numbers of the three fermionic components as functions of the chemical potential for several values of τ and $U/D = 2.5$. Right Column: effective masses of the three fermionic components as functions of the chemical potential for several values of τ and $U/D = 2.5$.

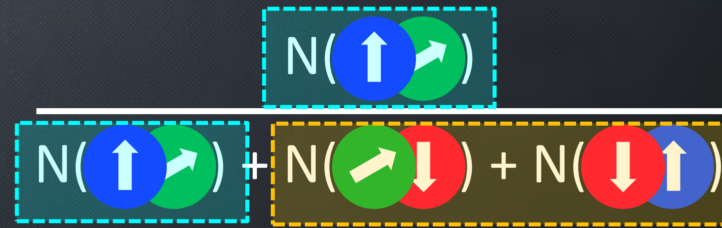
Coherent coupling favours localization:

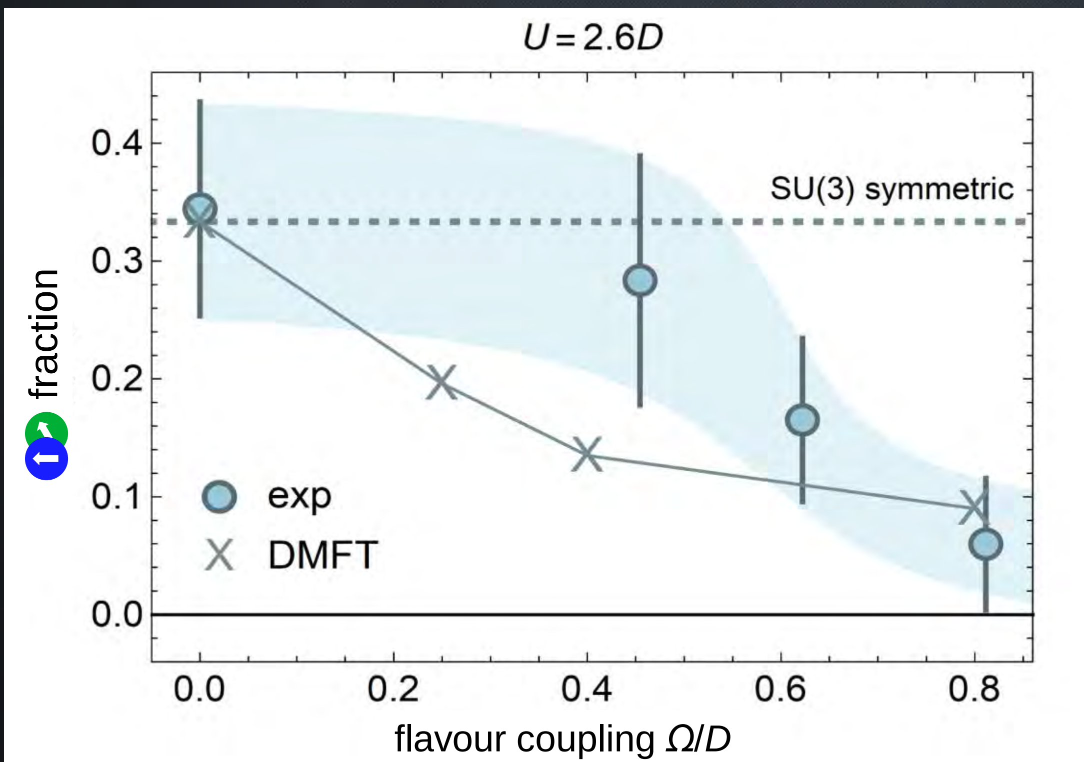


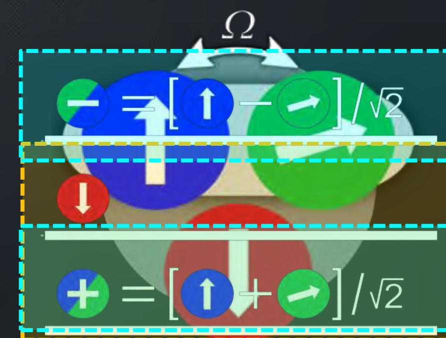
D. Tusi et al., Nat. Phys. ***18****, 1201 (2022)*

State-selective correlations

Fraction of doublons in Raman-coupled flavours:



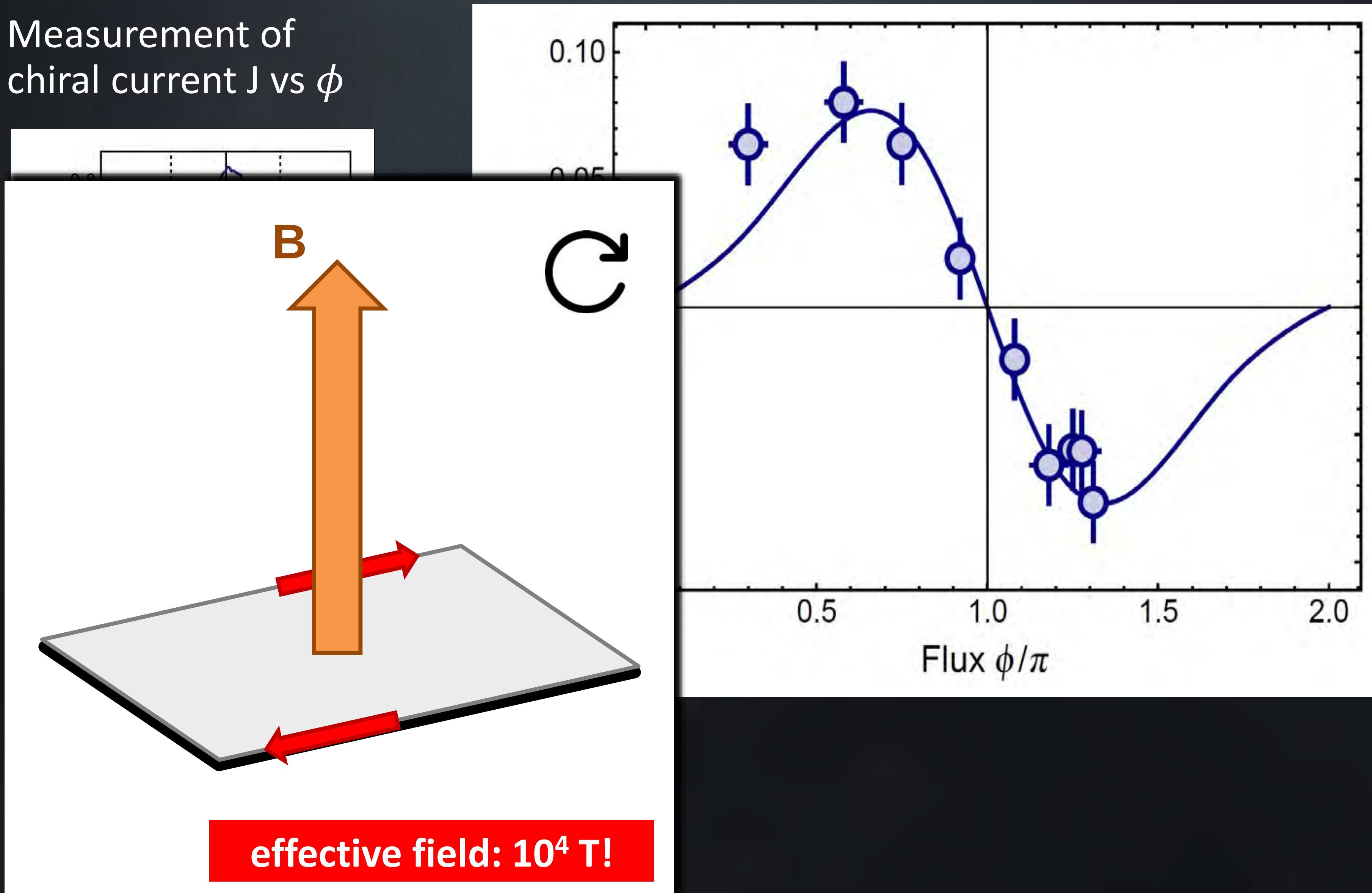




Evidence for flavour-selective correlations

Chiral currents with tunable flux

Measurement of chiral current J vs ϕ



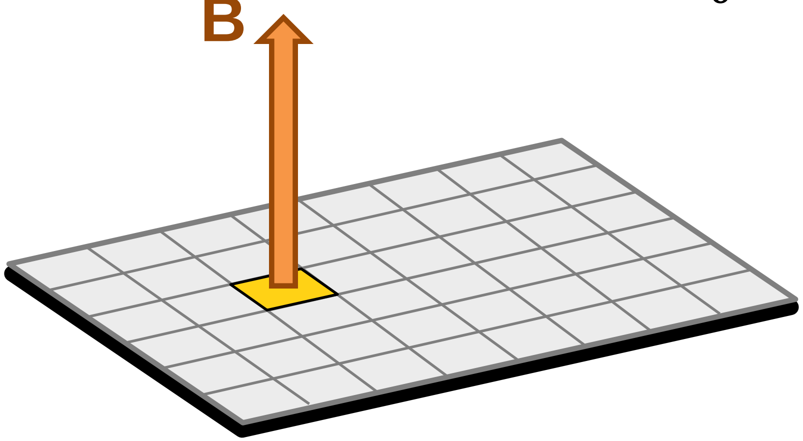
L. Livi et al., PRL **117**, 220401 (2016)

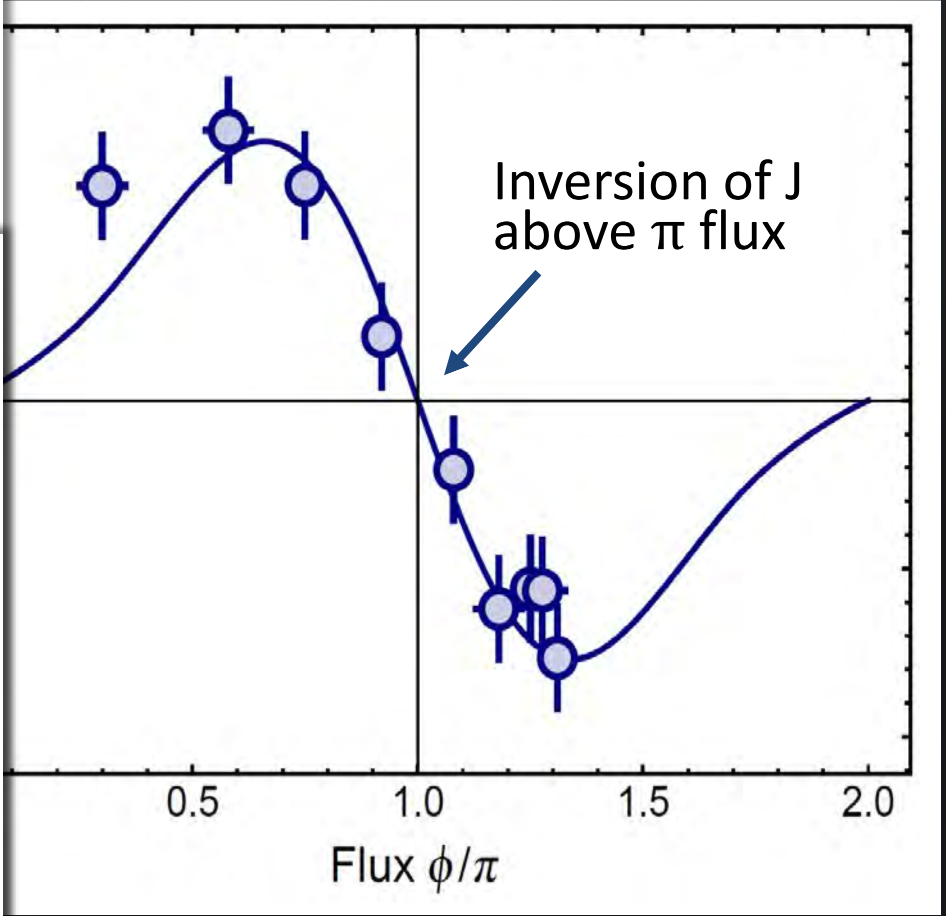
Chiral currents with tunable flux

Harper-Hofstadter model:

$$H = -t\sum_{j,m}\left(c^{\dagger}_{j,m}c_{j+1,m} + h.c.\right)$$
$$-\Omega\sum_{j,m}\left(e^{i\varphi j}c^{\dagger}_{j,m}c_{j,m+1} + h.c.\right)$$

$$\phi = 2\pi\frac{\Phi(\mathbf{B})}{\Phi_0}$$



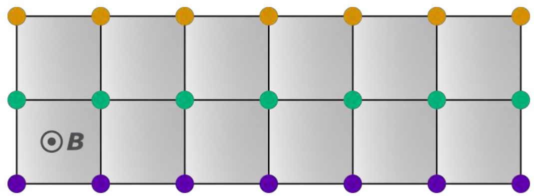


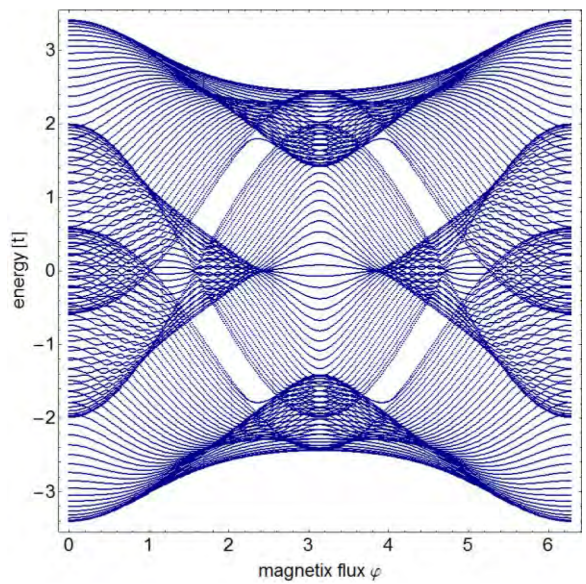
$J(\phi) = -J(-\phi)$ time-reversal

$J(\phi) = J(2\pi + \phi)$ lattice

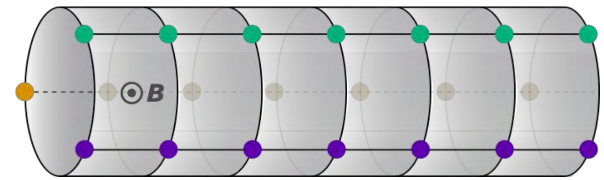
#1: Engineer

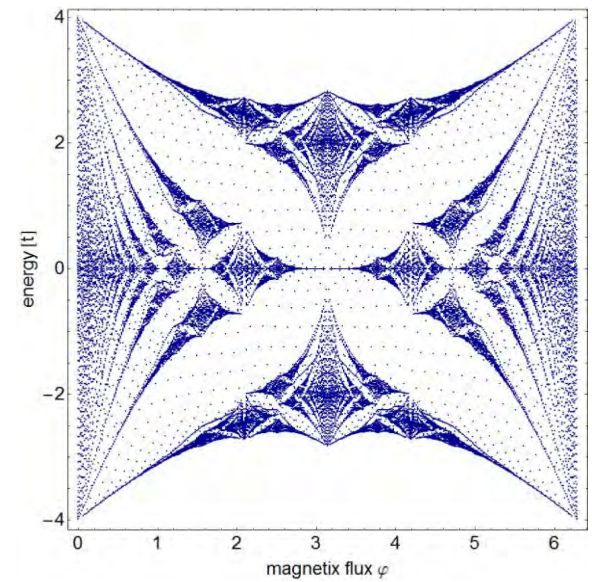
Open boundaries → edge physics





Closed boundaries → edge physics

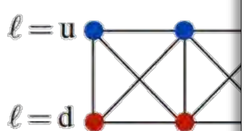


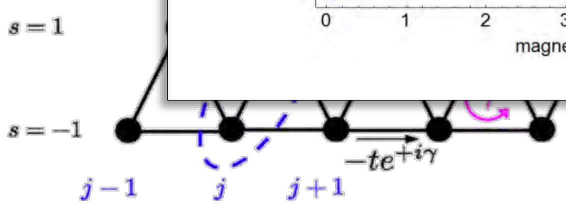


Extending t

Periodic bo

E. Boada et al.,





Multidim. structures and 4D quantum Hall effect

E. Boada et al., PRL **108**, 133001 (2012)

H. Price et al., PRL **115**, 195303 (2015)