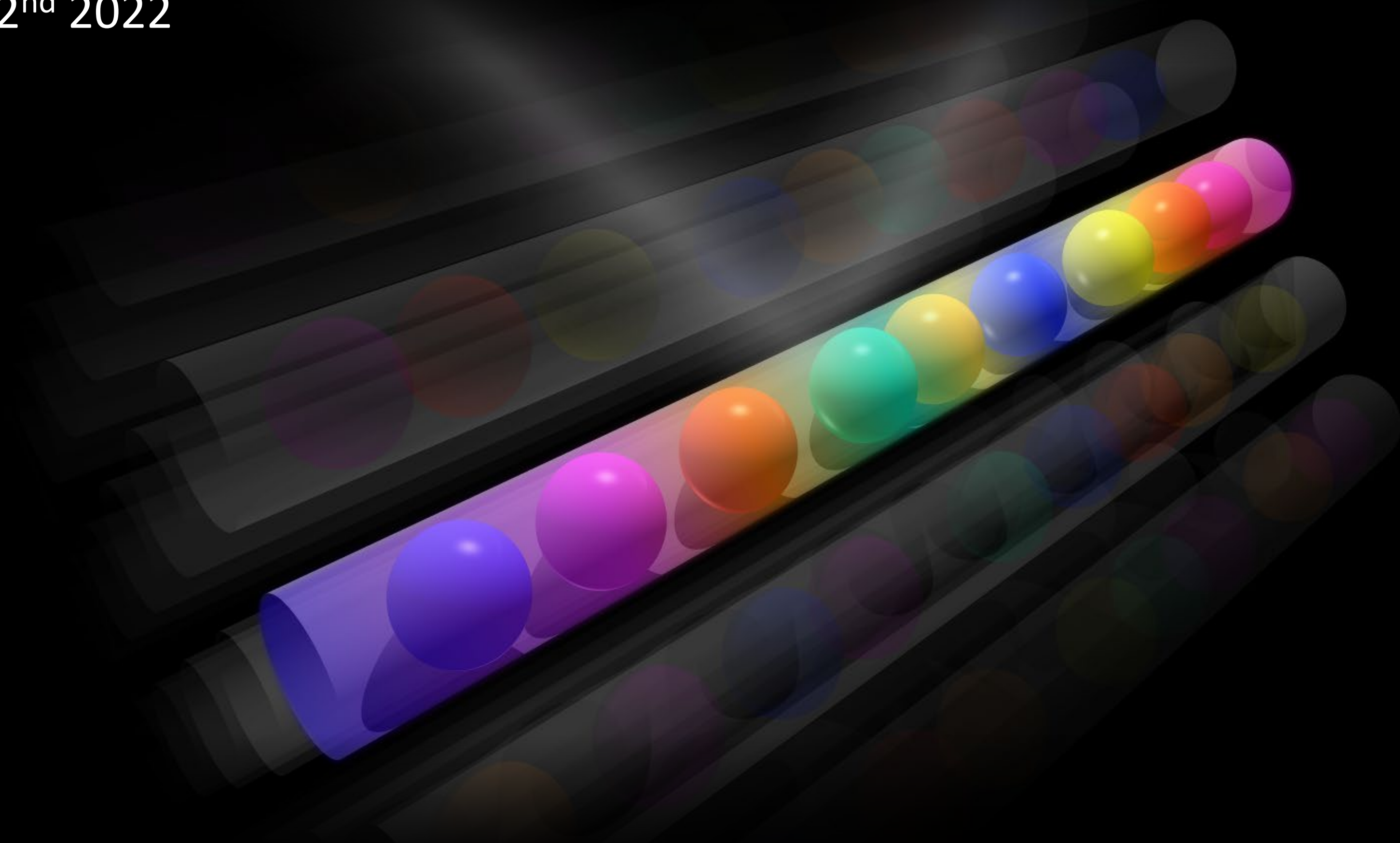
Multicomponent spin mixtures of two-electron fermions

Enrico Fermi School on Quantum Mixtures
Varenna, July 22nd 2022



Leonardo Fallani

Dept. Physics and Astronomy – University of Florence
LENS European Laboratory for Nonlinear Spectroscopy

Lecture 1

- Introduction to multicomponent quantum gases
- Interactions in two-electron fermions and SU(N) physics
- Experimental techniques
- **EXP**: SU(N) physics in low dimensions
- **EXP**: SU(N) Fermi-Hubbard and breaking SU(N) physics

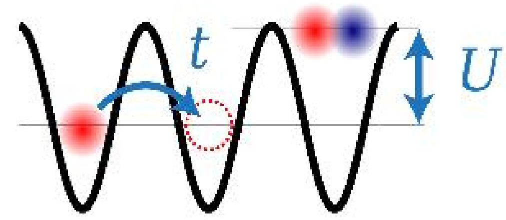
Lecture 2

- Multicomponent systems with coherent coupling
- Synthetic dimensions and artificial magnetic fields
- **EXP**: Chiral edge currents in synthetic ladders
- **EXP**: Synthetic Hall effect

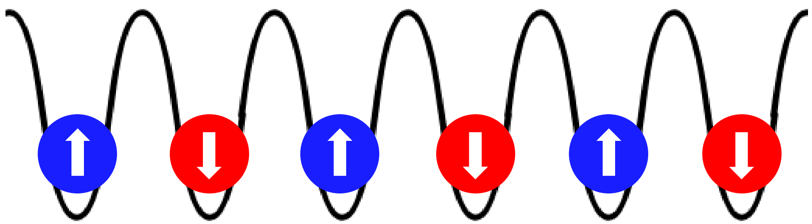
Fermi-Hubbard model

Simplest model to describe electron-electron correlations

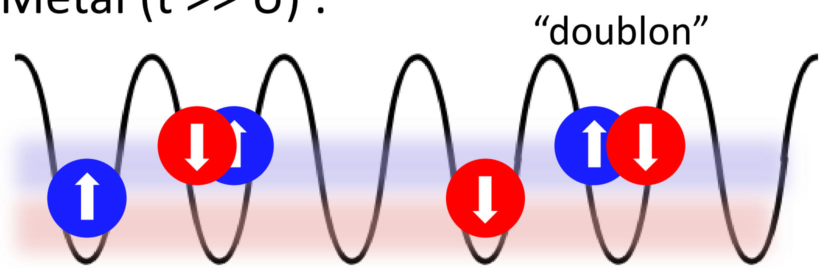
$$H = -t \sum_{\langle ij \rangle, m} \left(c^{\dagger}_{im} c_{jm} + c^{\dagger}_{jm} c_{im} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

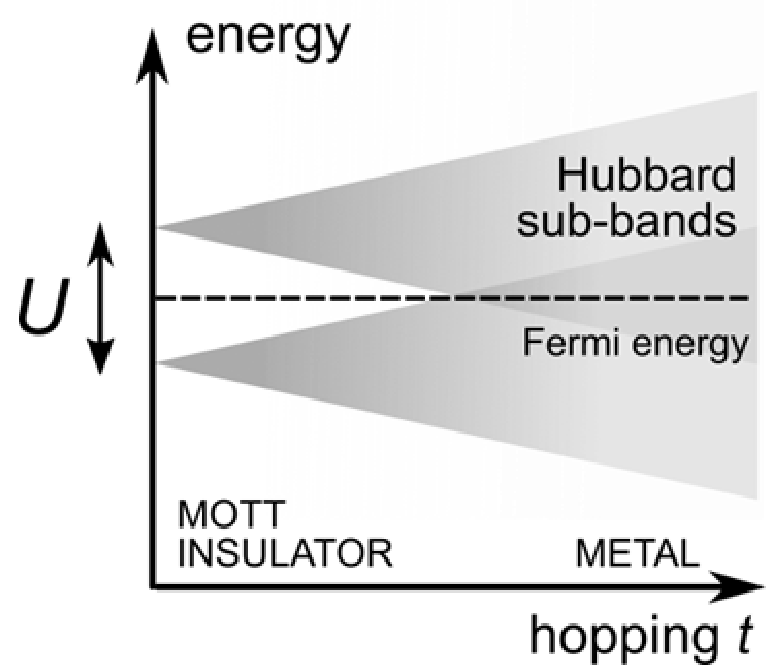


Mott insulator (U >> t) : e.g. 1 atom/site



Metal (t >> U) :

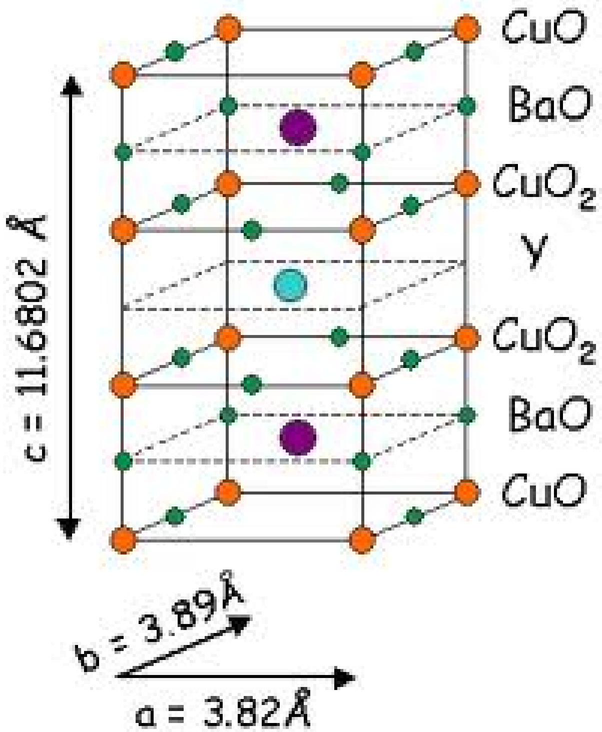


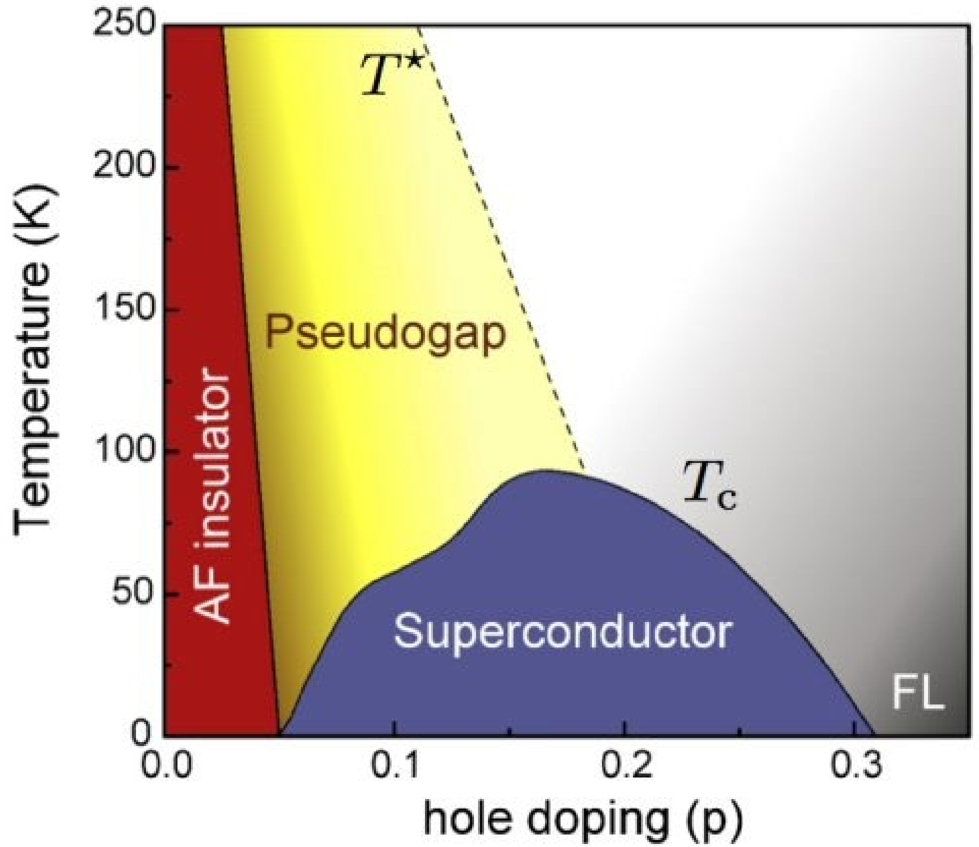


Experiments by many groups: ETH, MPQ, Harvard, Rice, MIT, Princeton, Bonn…

Simplest model to describe electron-electron correlations

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





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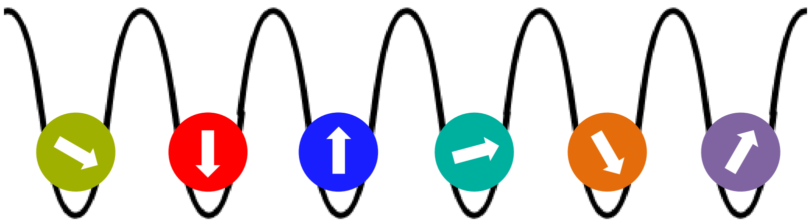
SU(N) Fermi-Hubbard model



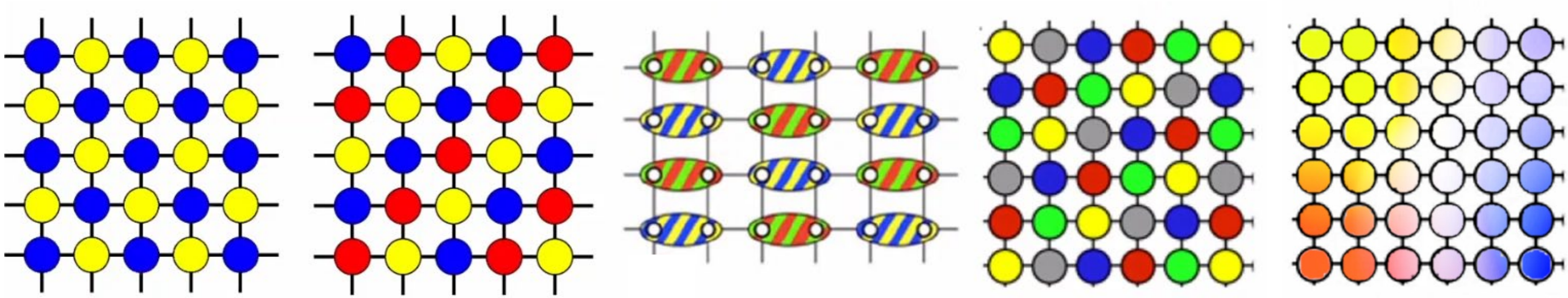
Richer physics for SU(N) Fermi-Hubbard!

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

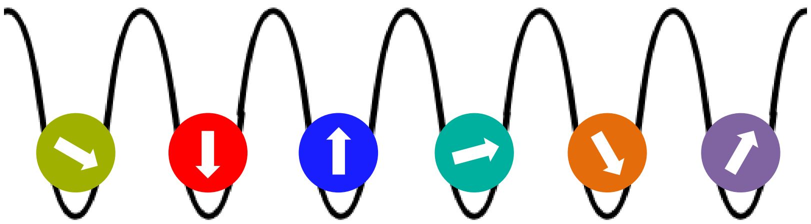
A wealth of magnetic phases is expected (antiferromagnets, dimerized, spin liquids…)



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



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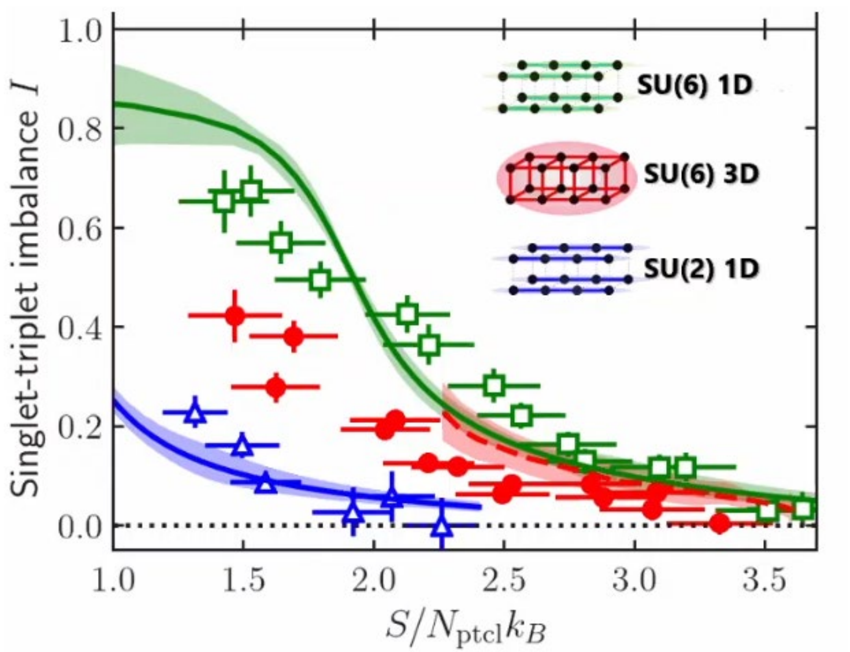
$$H \sim \frac{4t^2}{U} \sum_{\langle ij \rangle, m, n} S_{mni} S_{nmj}$$

SU(N) Heisenberg model @ low T

First experimental observation of SU(N) antiferromagnetism (Kyoto, Takahashi)

H. Ozawa et al., PRL **121**, 225303 (2018)
S. Taie et al., arXiv:2010.07730 (2020)



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Flavour-dependent localization of lattice fermions
D. Tusi et al., arXiv:2104.13338 (in press)

Lecture 2

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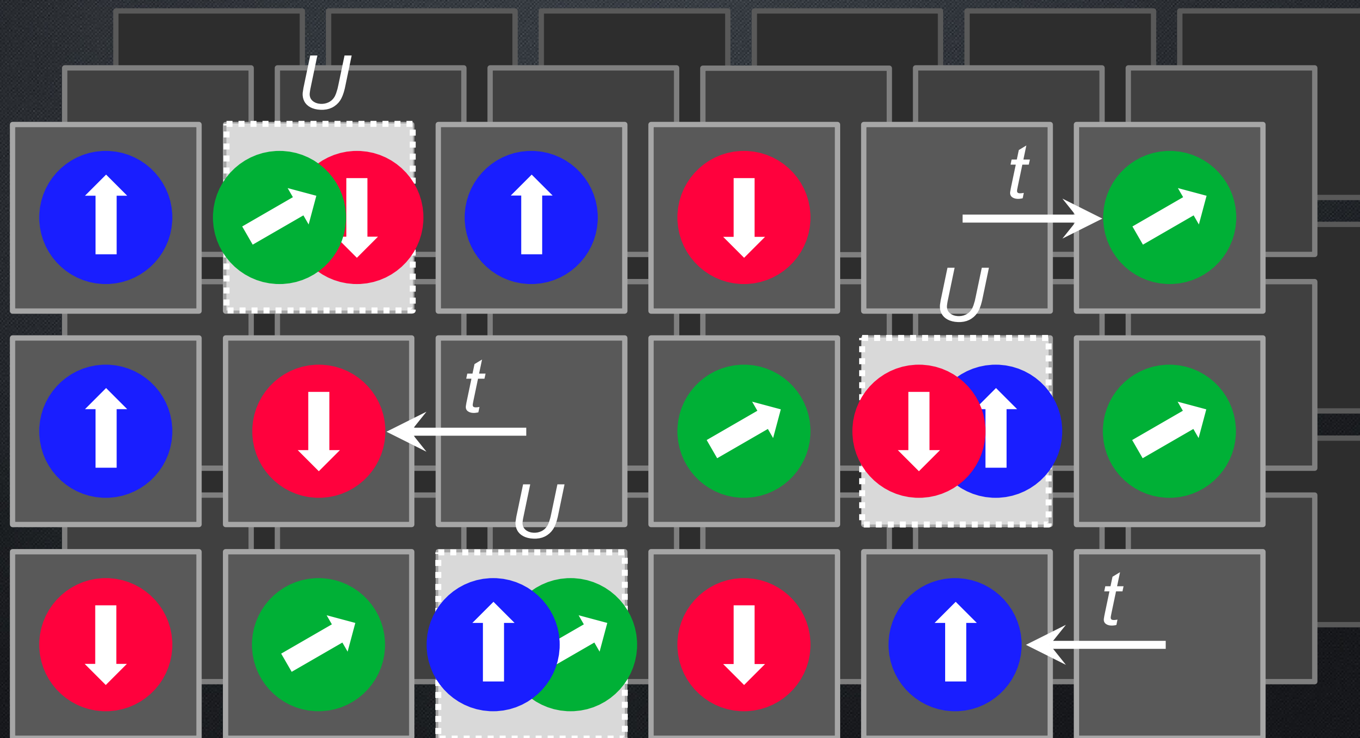
D. Tusi et al., arXiv:2104.13338 (2021)

SU(N) Fermi-Hubbard

SU(3) fermions in a 3D optical lattice



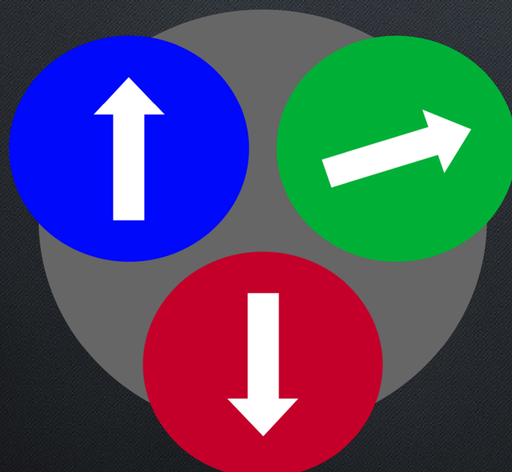
$$H = \underbrace{-t \sum_{\langle ij \rangle m} \left(c_{im}^{\dagger} c_{jm}\right) + U \sum_{imm'} \left(n_{im} n_{im'}\right)}_{\text{SU(3) symmetric}}$$

D. Tusi et al., arXiv:2104.13338 (2021)

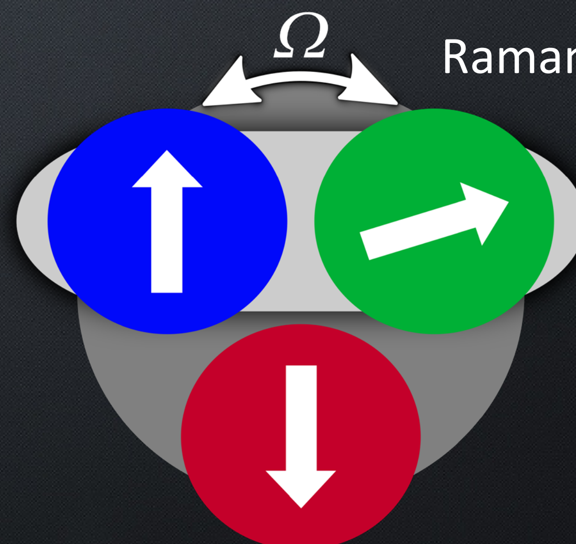
Breaking SU(N) symmetry

Add an extra term to the Hamiltonian **explicitly** breaking SU(N) symmetry

SU(3)



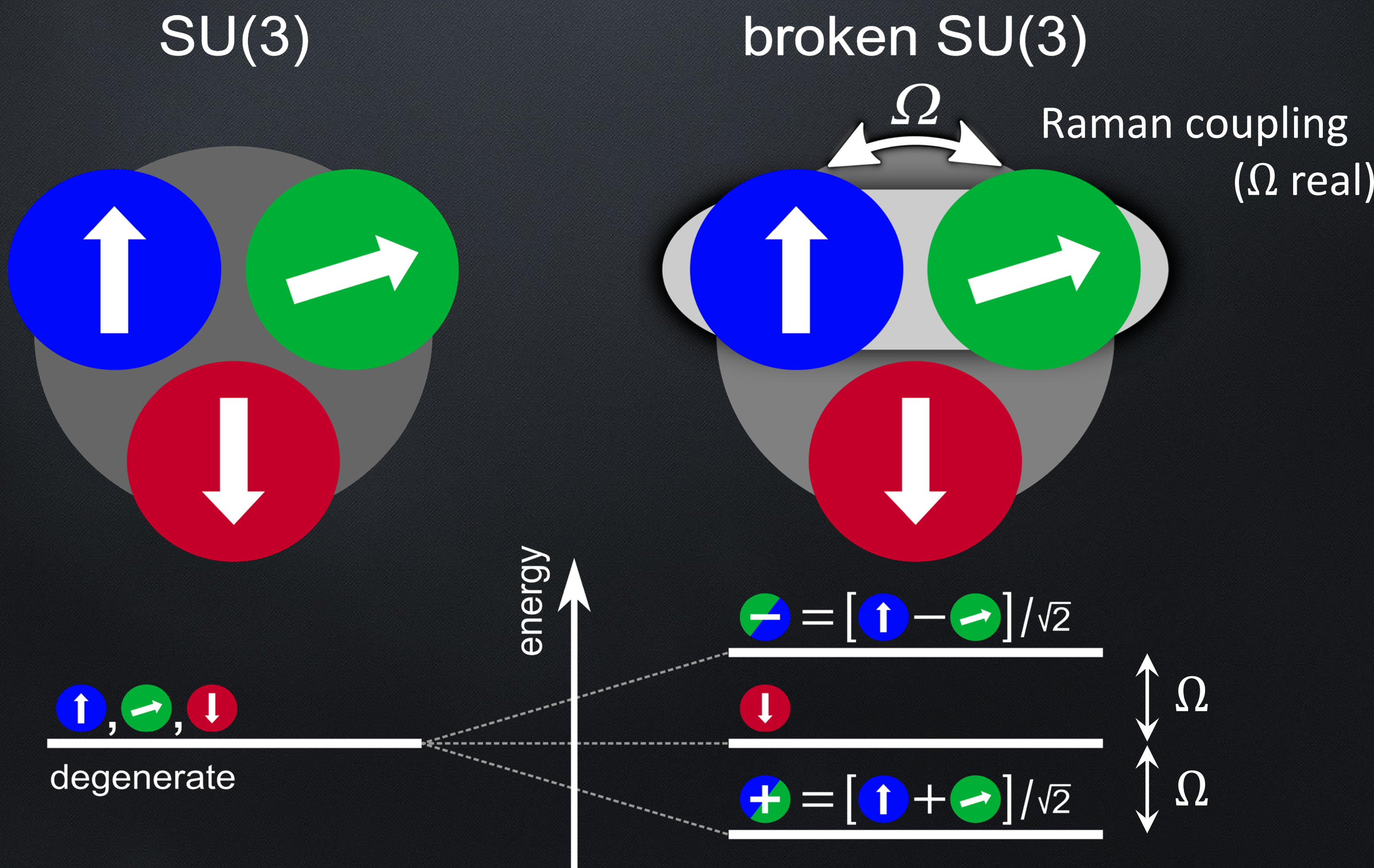
broken SU(3)



$$H = \underbrace{-t \sum_{\langle ij \rangle m} \left(c^\dagger_{im} c_{jm}\right) + U \sum_{imm'} \left(n_{im} n_{im'}\right)}_{\text{SU(3) symmetric}} \underbrace{+\Omega \sum_i \left(c^\dagger_{i1} c_{i2}\right)}_{\text{SU(3) breaking}}$$

Breaking SU(N) symmetry

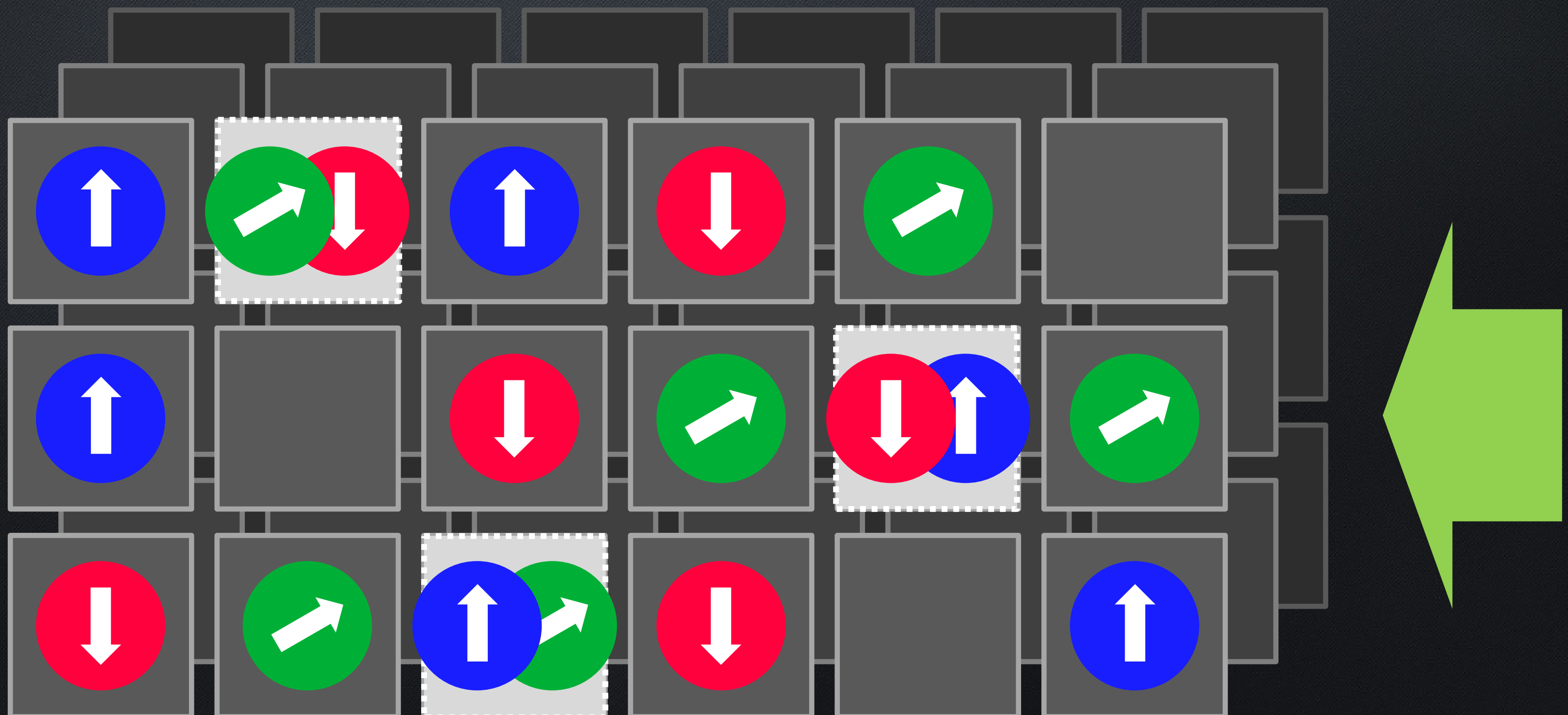
Add an extra term to the Hamiltonian **explicitly** breaking SU(N) symmetry



Double occupancies

Adiabatic preparation of ground state in a 3D lattice

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

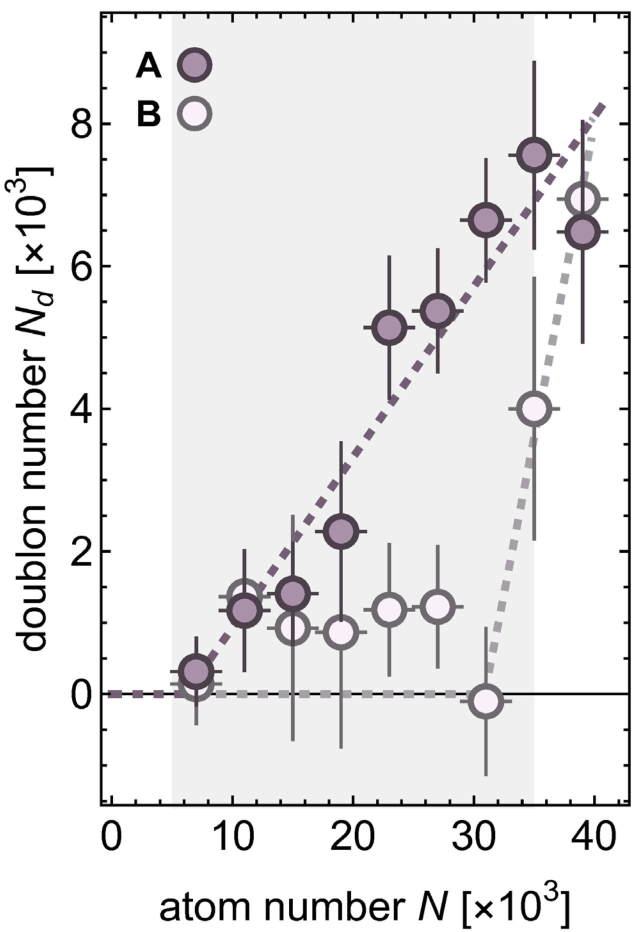


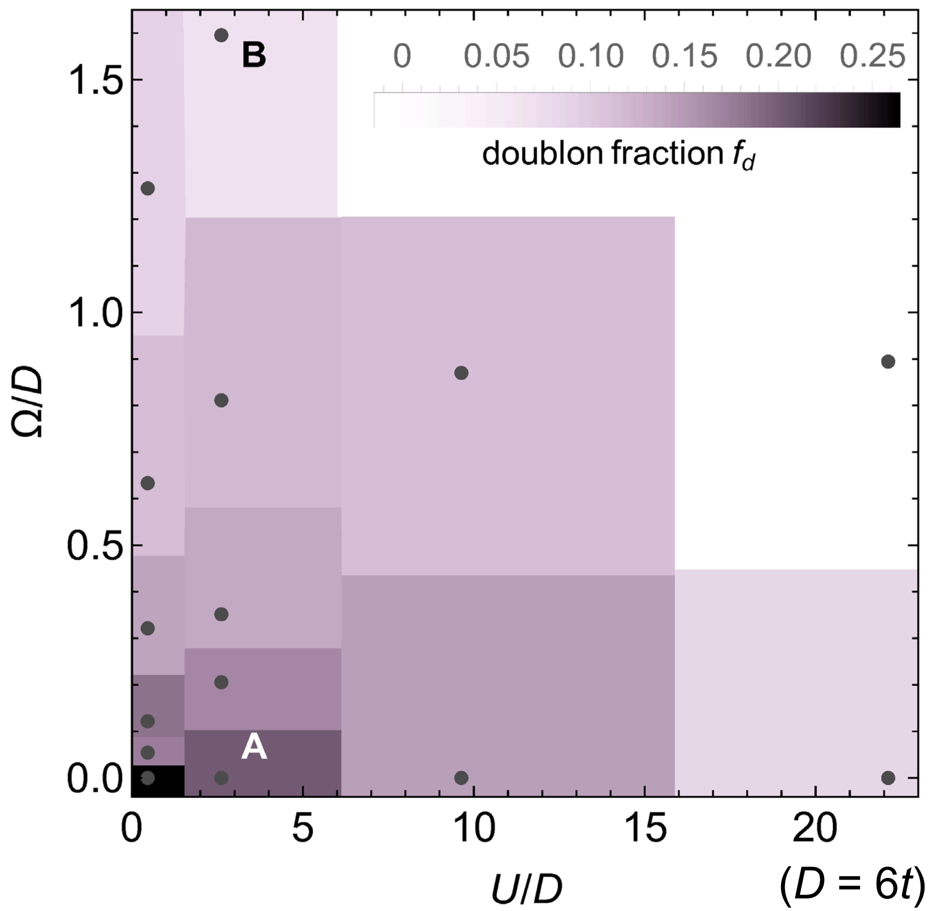
Measurement of doubly-occupied sites with photoassociation spectroscopy

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

Metal to insulator

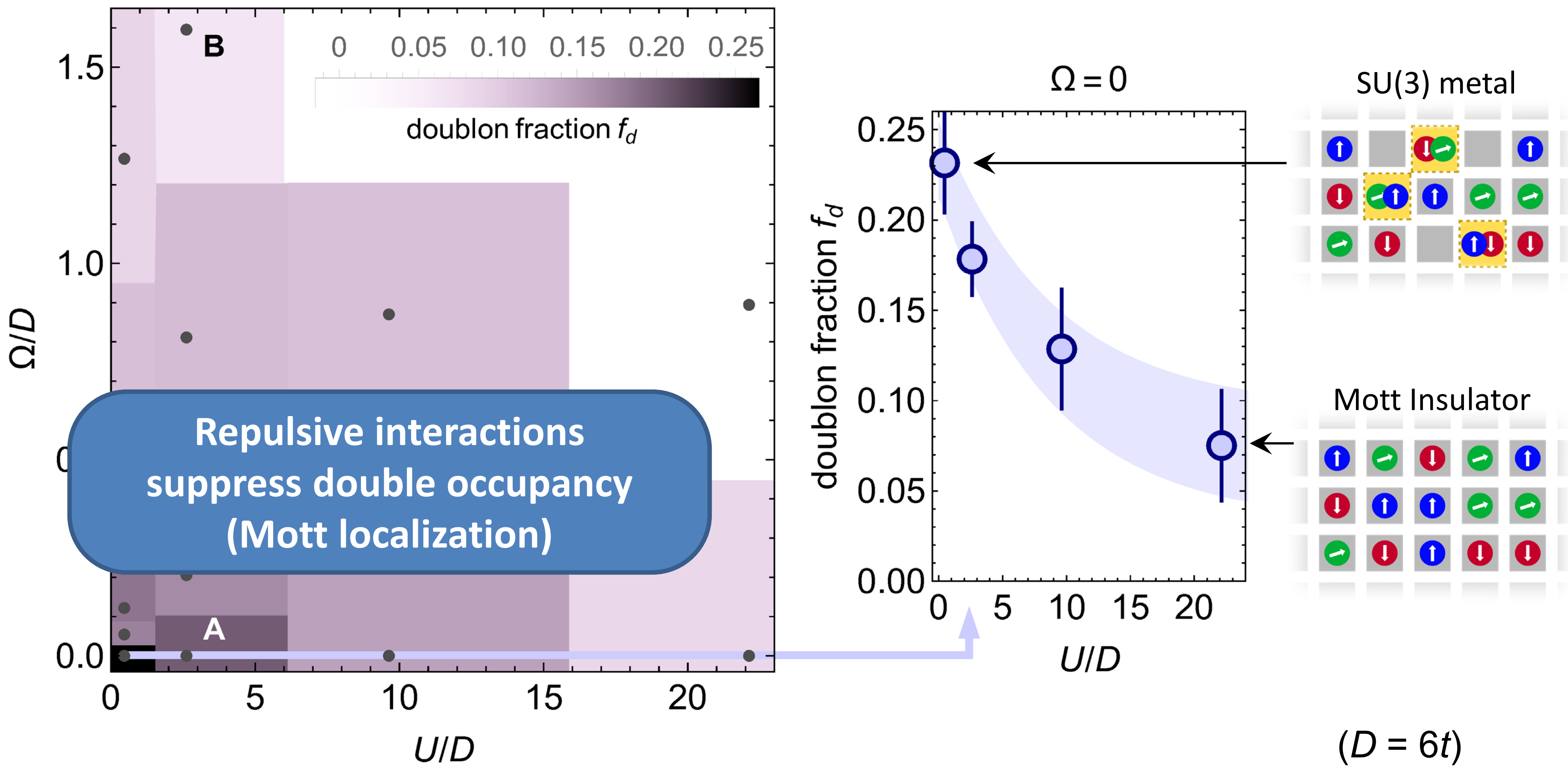
Measurement of doubly occupied sites:





Metal to insulator

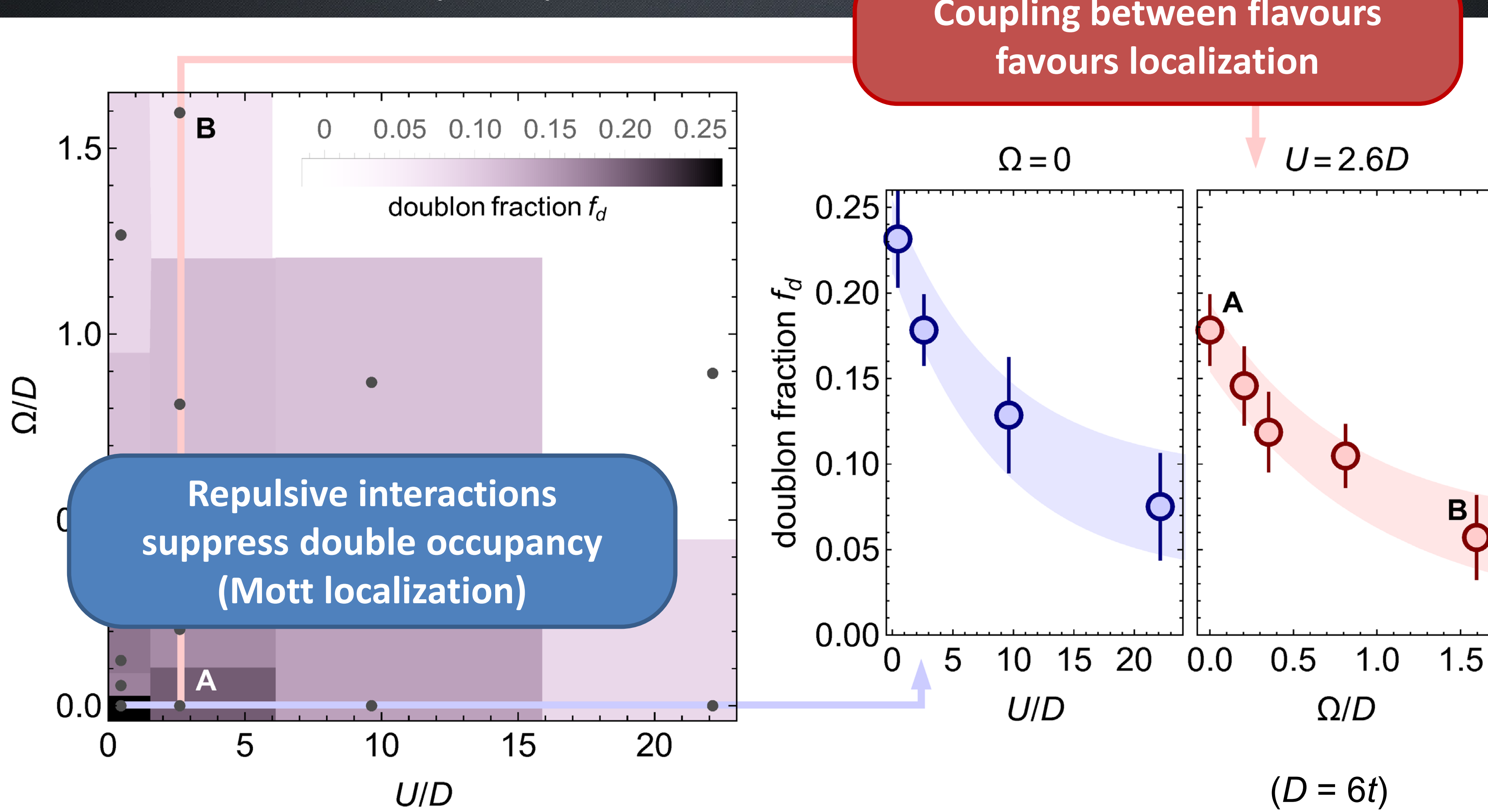
Measurement of doubly occupied sites:



(D = 6t)

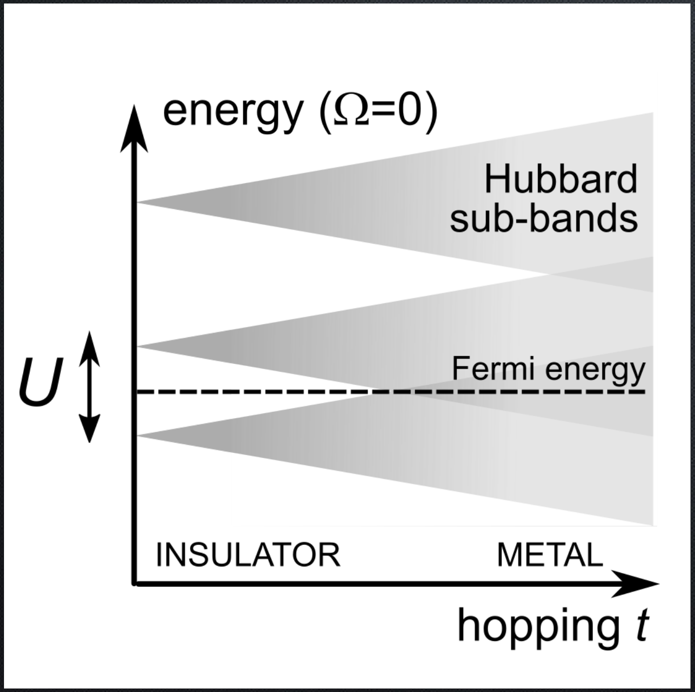
Metal to insulator

Measurement of doubly occupied sites:

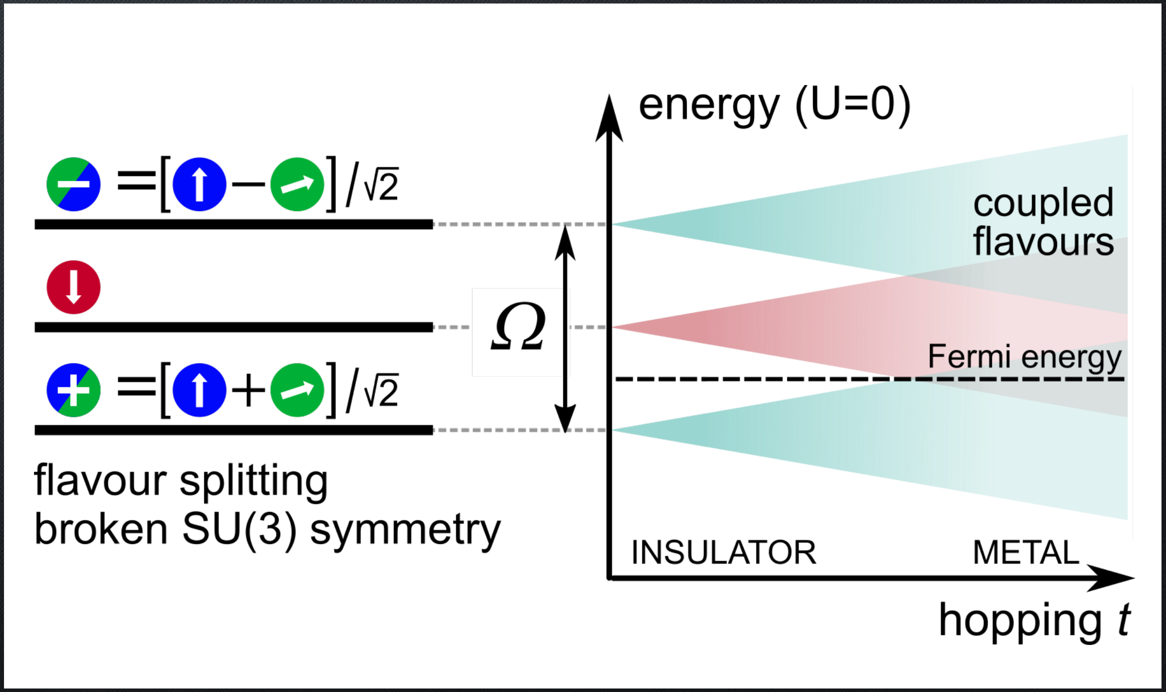


Localization mechanisms

Localization **by repulsion:**

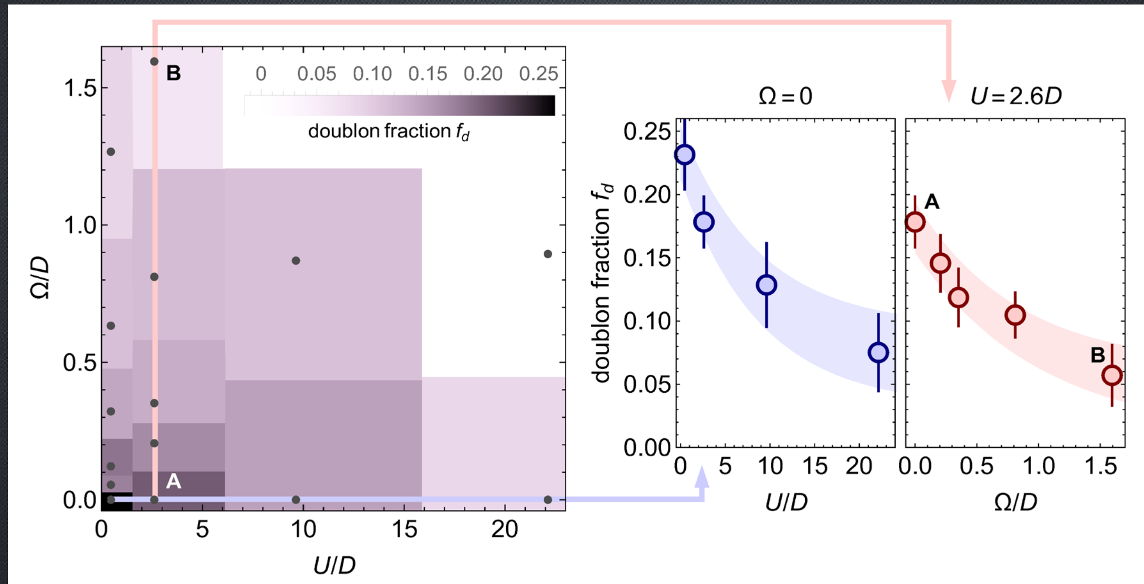


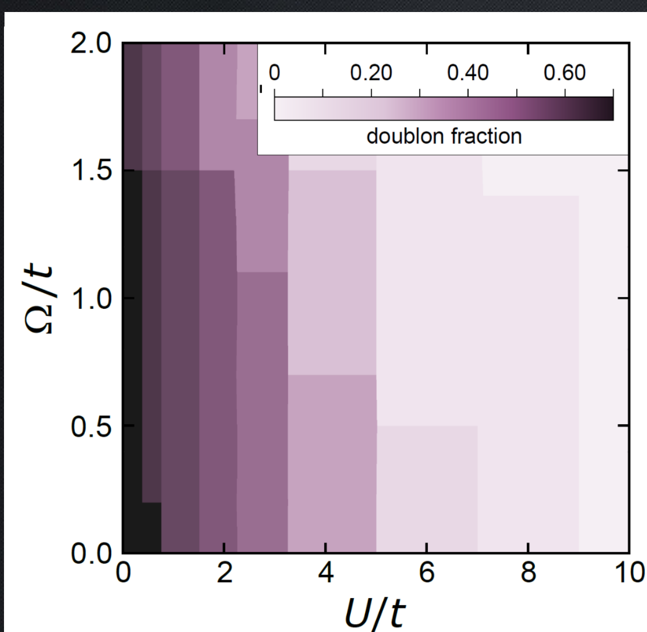
Localization **by degeneracy lifting**:



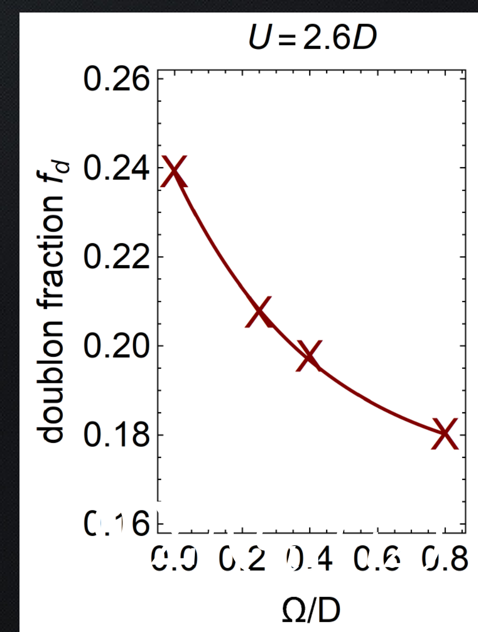
D. Tusi et al., arXiv:2104.13338 (2021)

Experiment/theory comparison





1D DMRG (T=0)
(R. Barfknecht)



DMFT (T=0) + LDA (trap)
(K. Baumann, L. Del Re, M. Capone)

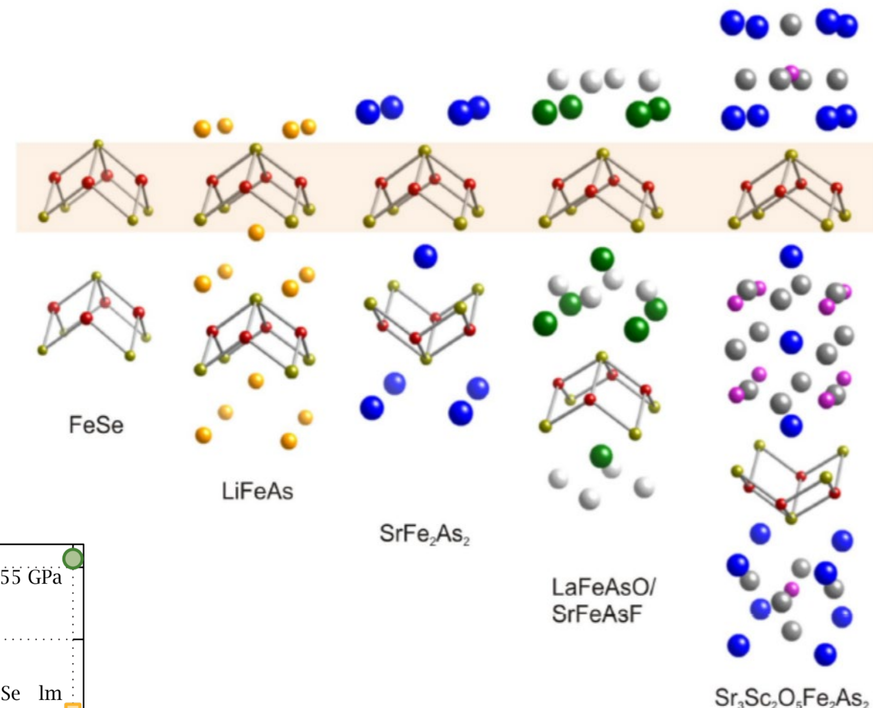
*Chubukov & Hirschfeld, Phys. Today **68**, 46 (2015)*

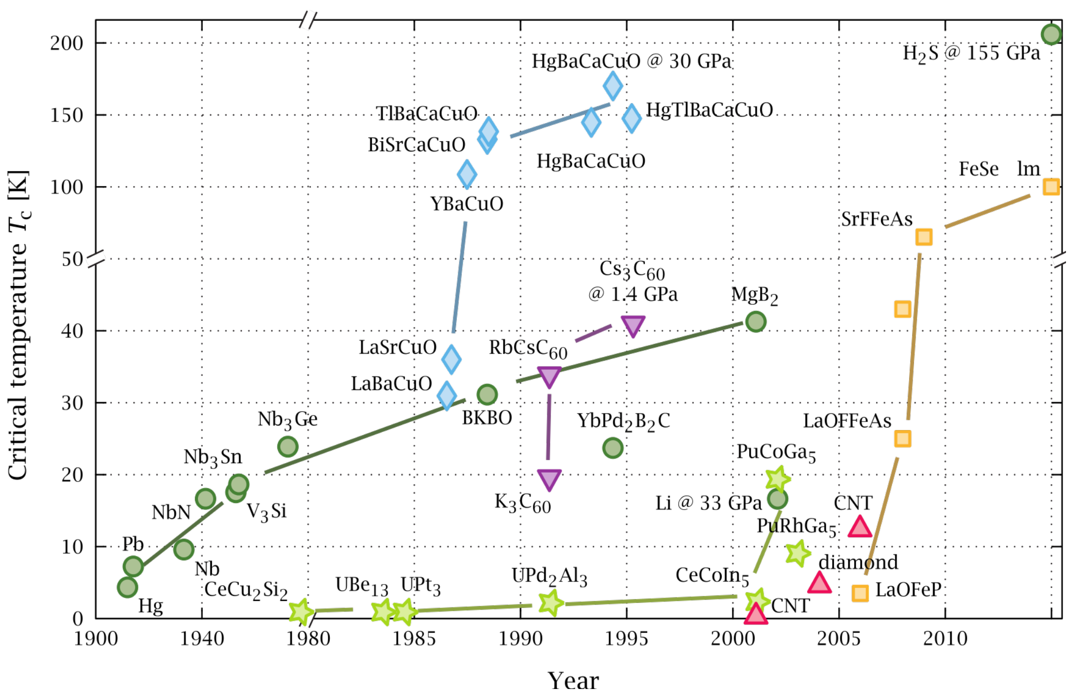
Iron-based superconductors

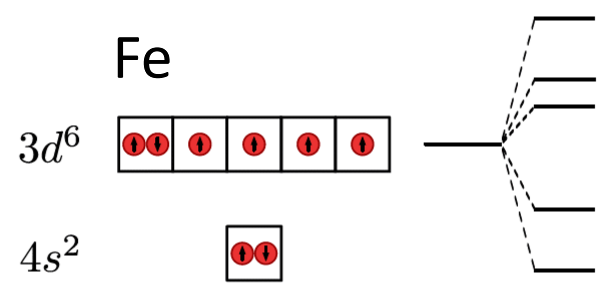
A “new“ class of high-Tc superconductors

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

Multiple orbitals involved in conduction
Hund‘s coupling between orbitals





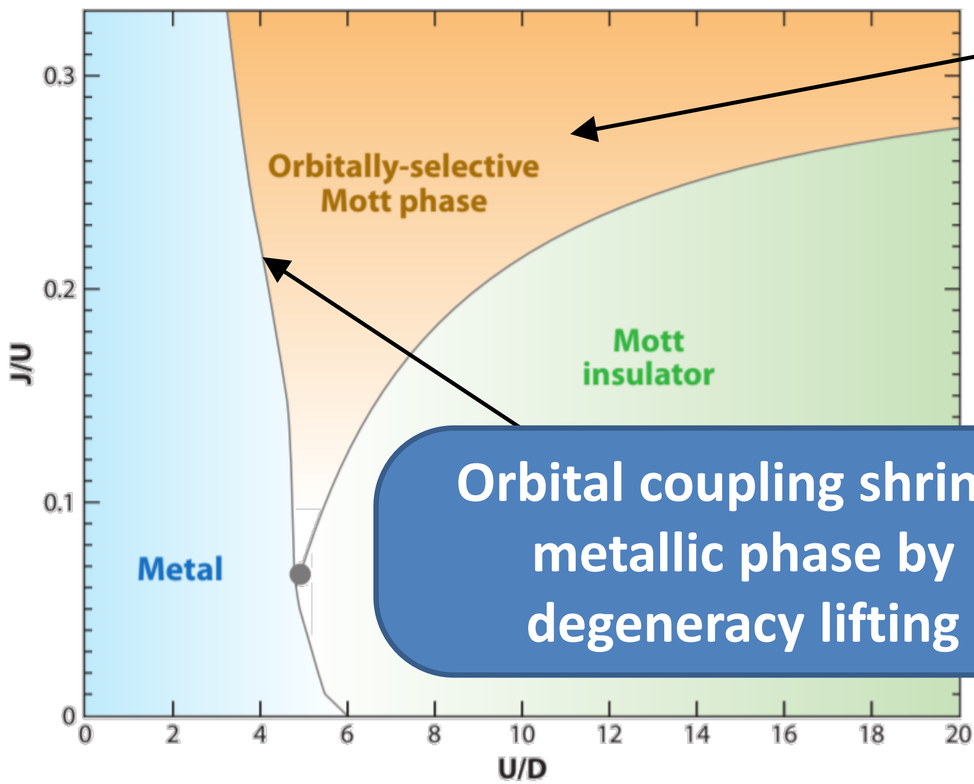


Multi-orbital Hubbard models

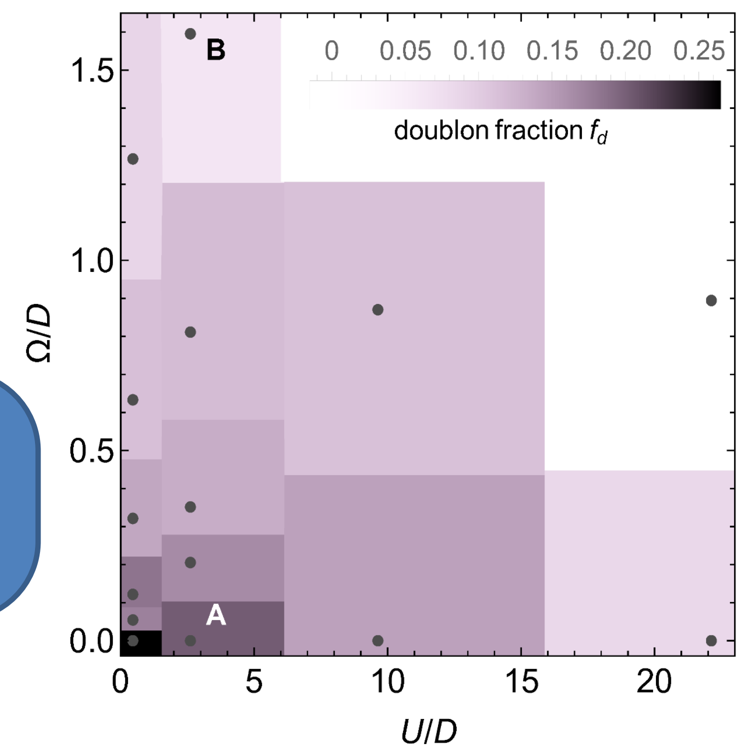
Multi-orbital Hubbard models with **coherent coupling between orbitals**

$$H = -t \sum_{\langle ij \rangle, m\sigma} (d^{\dagger}_{im\sigma} d_{jm\sigma} + \mathrm{H.c.}) + U \sum_{i,m} n_{im\uparrow} n_{im\downarrow} + \left(U' - \frac{J}{2}\right) \sum_{i,m>m'} n_{im} n_{im'} - J \sum_{i,m>m'} [2\mathbf{S}_{im} \cdot \mathbf{S}_{im'} + (d^{\dagger}_{im\uparrow} d^{\dagger}_{im\downarrow} d_{im'\uparrow} d_{im'\downarrow} + \mathrm{H.c.})].$$

Mott localization only in some orbitals



Orbital coupling shrinks metallic phase by degeneracy lifting



Multi-orbital Hubbard models

A minimal system where these effects can be observed

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

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

Lorenzo Del Re[1,2] and Massimo Capone[1,3]
[1]*International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy*
[2]*Institute for Solid State Physics, TU Wien, 1040 Vienna, Austria*
[3]*CNR-IOM Democritos, Via Bonomea 265, 34136 Trieste, Italy*

(Received 1 August 2017; published 26 December 2018)

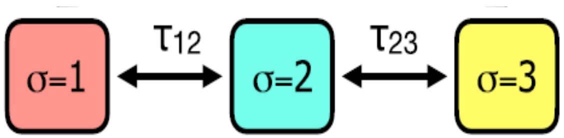
We study a three-component fermionic fluid in an optical lattice in a regime of intermediate to strong interactions allowing for optical processes connecting the different components, similar to those used to create artificial gauge fields. Using dynamical mean-field theory, we show that the combined 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.

*L. Del Re et al., PRA **98**, 063628 (2018)*

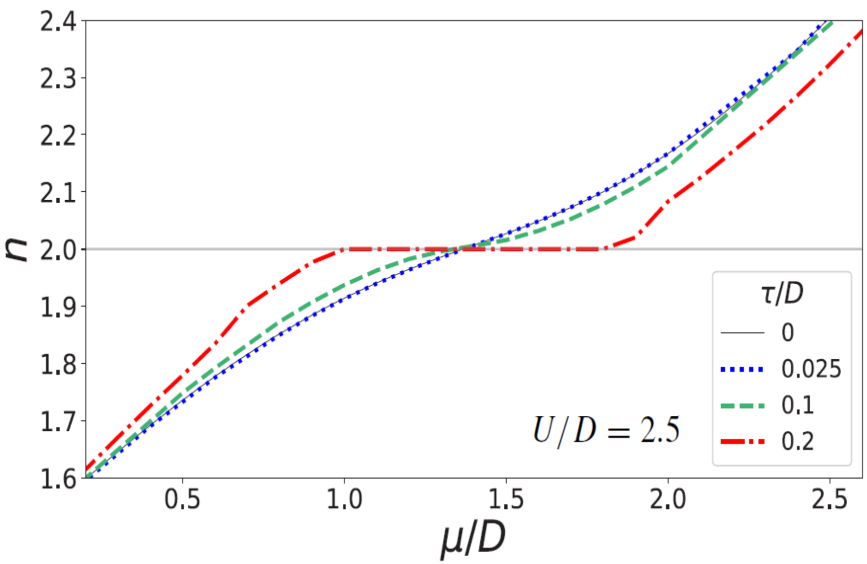
Multi-orbital Hubbard models

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

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



Coherent coupling favours localization:



State-selective properties:

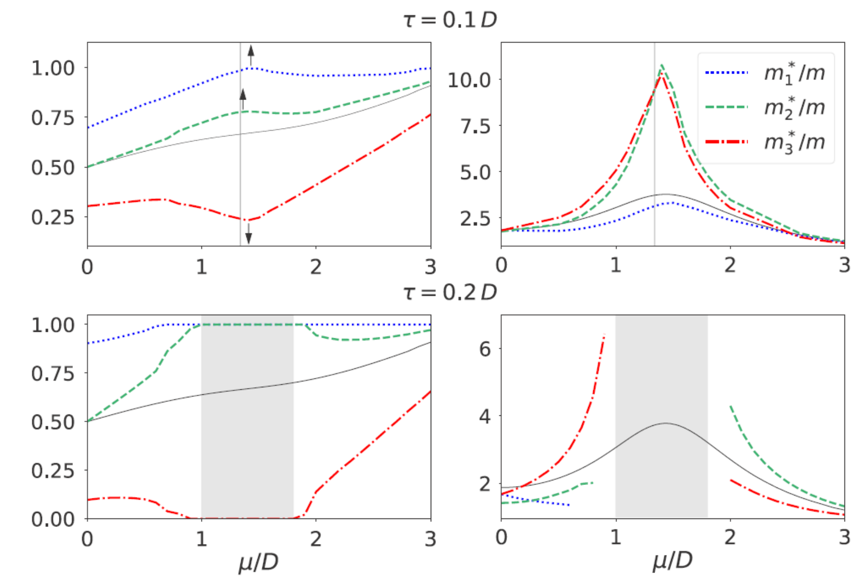


FIG. 4. Left Column: occupation numbers of the three fermionic components as functions of the chemical potential for several values of τ and $U/D = 2.5$. Right Column: effective masses of the three fermionic components as functions of the chemical potential for several values of τ and $U/D = 2.5$.

D. Tusi et al., arXiv:2104.13338 (2021)

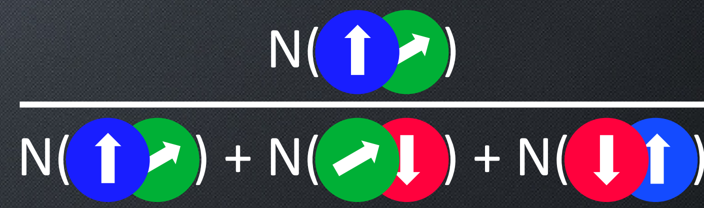
State-selective correlations

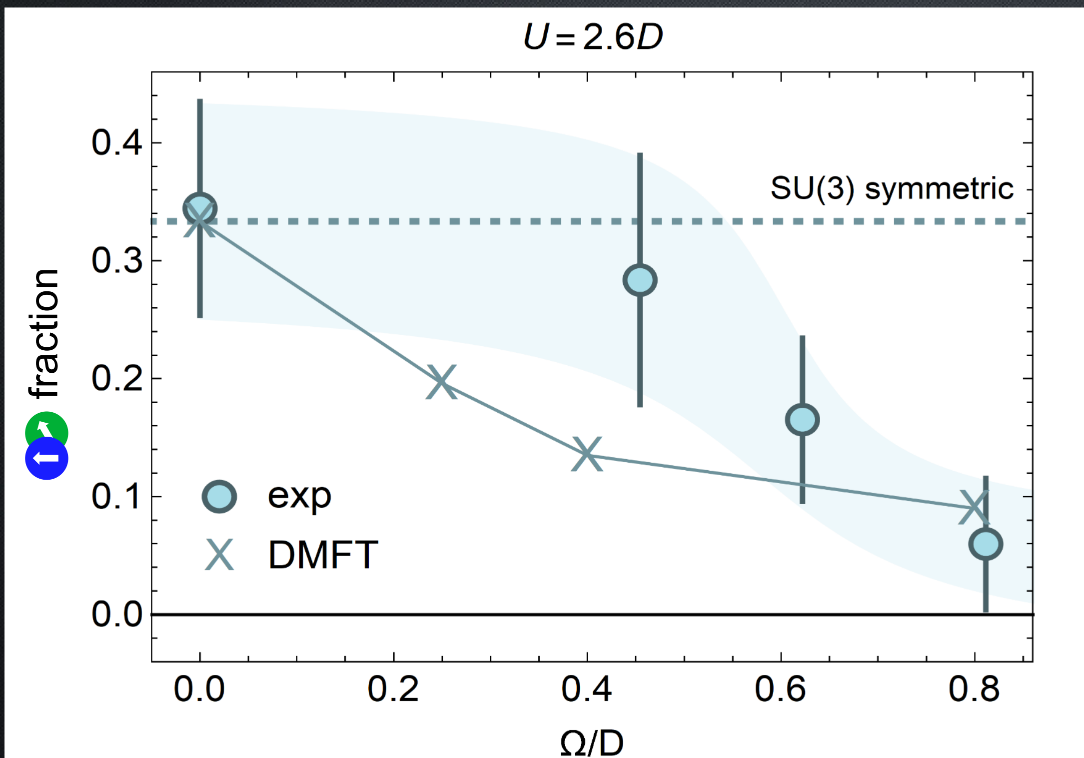
Measurement of doublon character

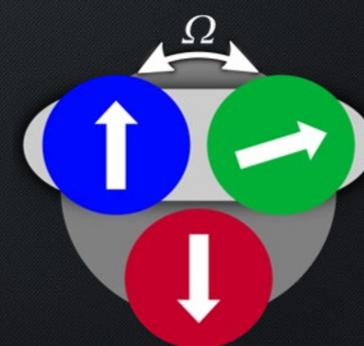
State-selective photoassociation at finite B

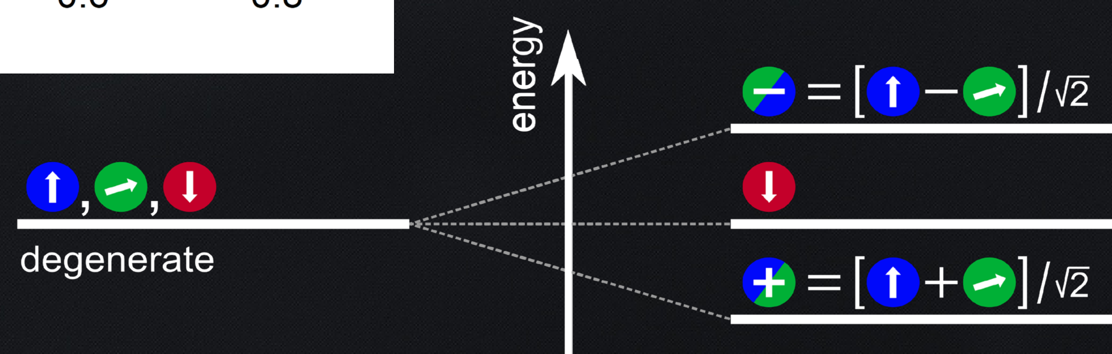
State-selective correlations

Fraction of doublons in Raman-coupled flavours:









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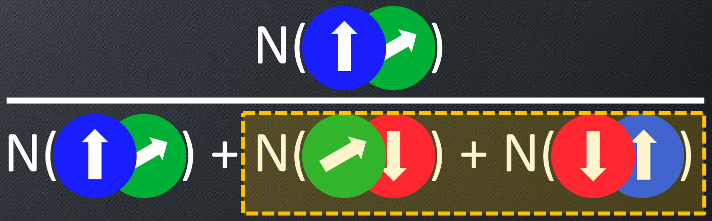
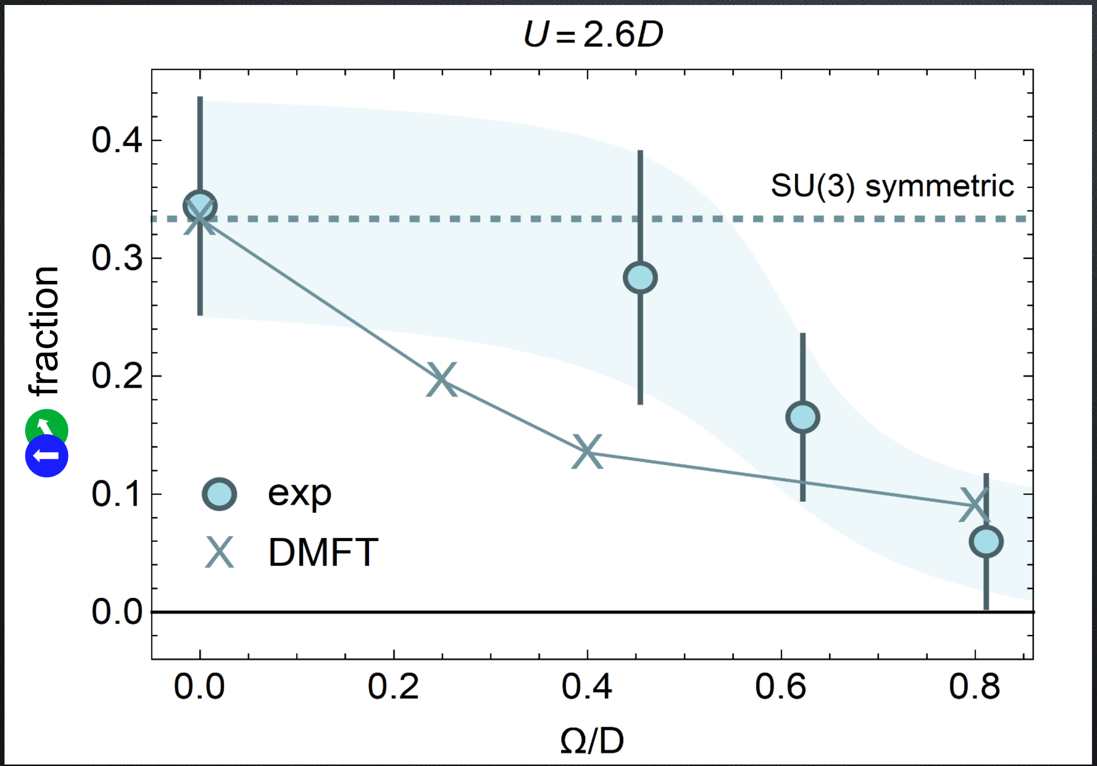
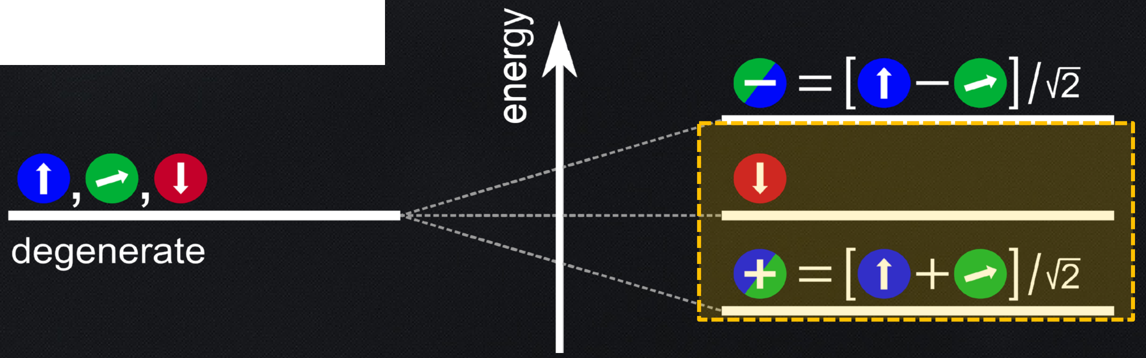
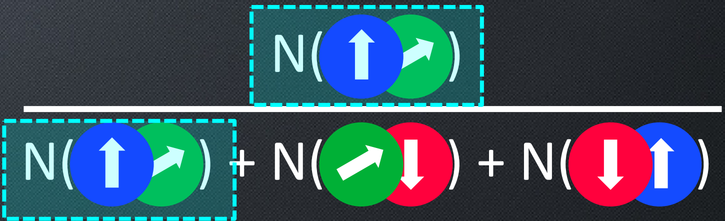




State-selective correlations triggered by polarization in rotated basis



State-selective correlations



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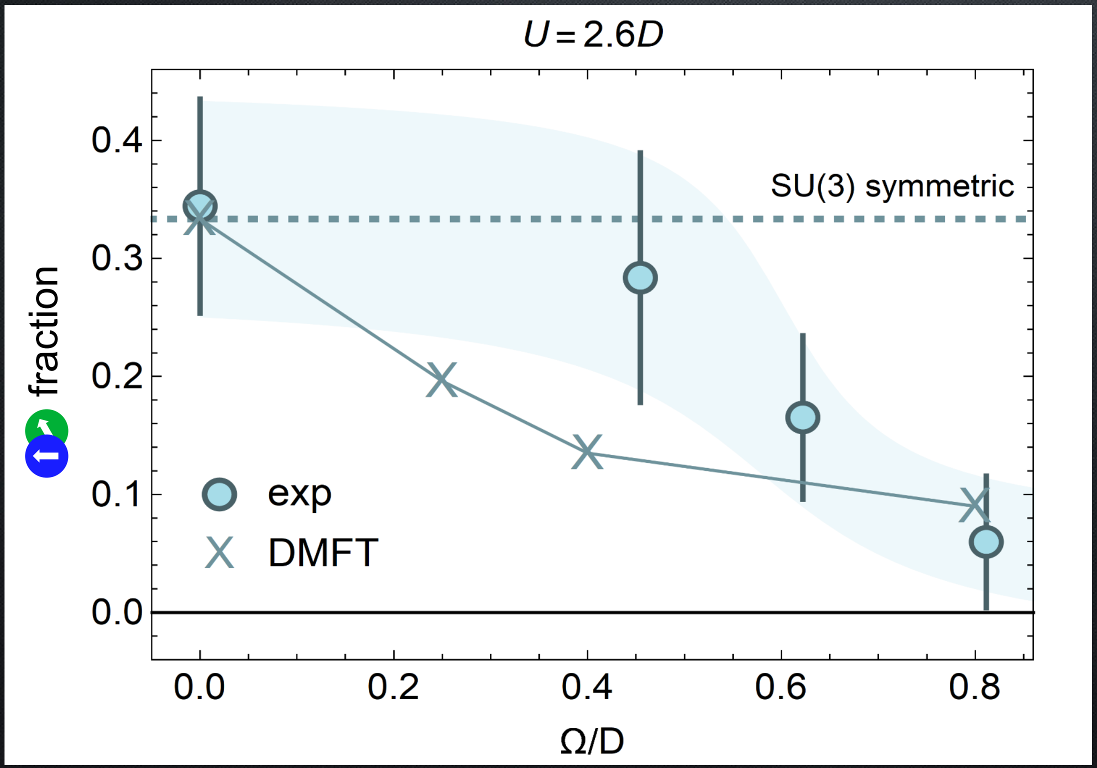

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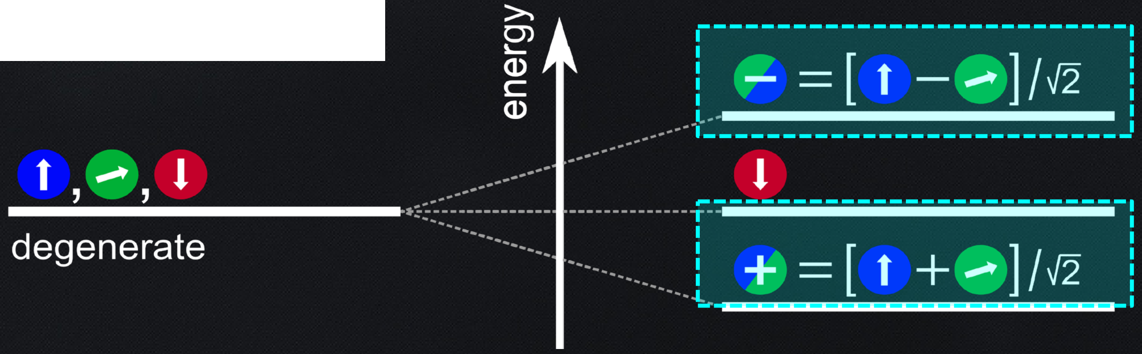

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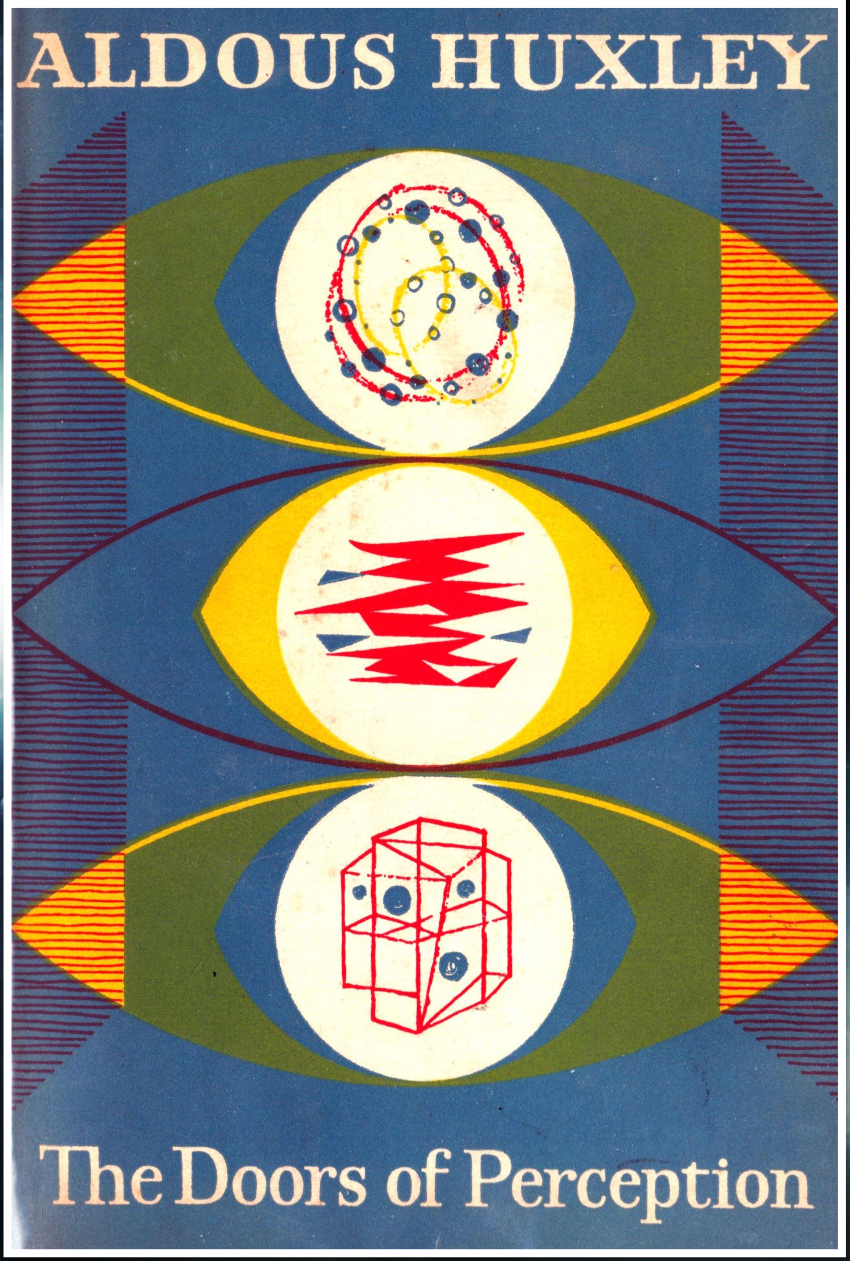
Synthetic dimensions?



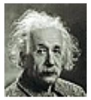
Synthetic dimensions?

CORRIERE DELLA SERA

Nella quarta dimensione

«Così l'abbiamo simulata negli atomi» Come in «Interstellar» i ricercatori italiani creano una realtà spaziotemporale extra

La scheda



● La quarta dimensione è riferita a una estensione degli oggetti ulteriore rispetto alla lunghezza, alla larghezza e alla profondità. Nella teoria della relatività di Albert Einstein *(in alto)* la quarta dimensione è il tempo

● Trent'anni fa il Premio Nobel per la fisica Richard Feynman *(sopra)* aveva immaginato che controllando le proprietà degli atomi un giorno avremmo sviluppato dei computer quantistici

di **Anna Meldolesi**

Il mondo ci appare in tre dimensioni, quattro se contiamo anche il tempo come ci ha insegnato Einstein. Ma la fisica non esclude l'esistenza di altre dimensioni, magari accartocciate su se stesse e dunque invisibili. Vi ricordate il film *Interstellar*? Matthew McConaughey è partito alla ricerca di un pianeta gemello e comunica con la figlia sulla Terra attraverso una stanza che sembra tridimensionale, ma è la proiezione di una realtà spaziotemporale extra. Questo consente all'astronauta di interagire con la ragazza in momenti diversi della sua vita e di comunicarle informazioni in codice che salveranno l'umanità.

È fantascienza certo, ma sin dagli anni 20 è stato ipotizzato che lo spazio sia costituito non da 3 ma da 4 dimensioni, nel tentativo di unificare, sotto una descrizione teorica comune, la forza gravitazionale e la forza elettromagnetica.

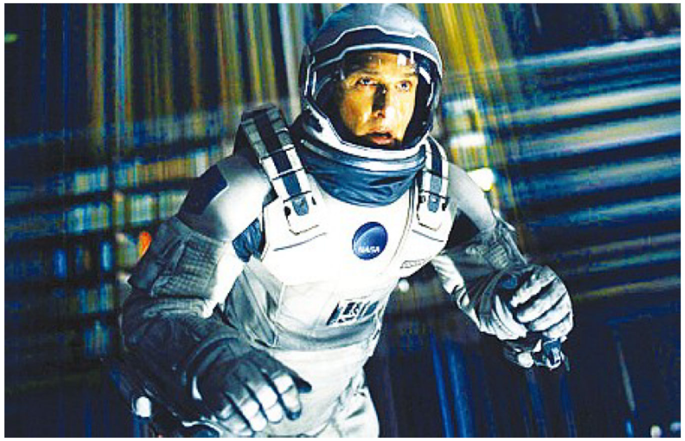
«Quasi un secolo dopo non siamo ancora in grado di affermare quante dimensioni esistano ma una novità c'è: al Laboratorio europeo di Spettroscopia nonlineare di Firenze siamo riusciti a simulare all'interno degli atomi una quarta dimensione», ci dice Massimo Inguscio, presidente dell'Istituto nazionale di ricerca metrologica.

Il team sperimentale, tutto italiano, ha costruito un nuovo bizzarro mondo quantistico, che possiamo immaginare composto da tanti mattoncini Lego colorati. Per farlo, arrivando a pubblicare il lavoro su *Science*, c'è voluta una bella dose di fantasia e una tecnologia avanzata che consente di manipolare la materia a temperature vicine allo zero assoluto. I ricercatori hanno lavorato con atomi di itterbio-173 perché hanno una proprietà particolare: si presentano in tanti possibili stati diversi. A cambiare è una caratteristica detta *spin* nucleare, ma Leonardo Fallani dell'Università di Firenze ci viene in aiuto con una similitudine. Possiamo pensare che gli atomi siano dei mattoncini che passano semplicemente da un colore all'altro. Con dei fasci laser è possibile trasformarli da viola a blu, verde, arancione, rosso. Ogni posizione sulla scala cromatica equivale a uno spostamento sulla quarta dimensione dello spazio.

Per visualizzare il fenomeno immaginiamo gli atomi disposti su una riga (1D), poi componiamo un quadrato (2D) e un cubo (3D). Con la quarta dimensione si ottiene un ipercubo di luce, costituito da una fitta trama di vertici di tanti colori. La extradimensione così rappresentata non è soltanto un esperimento del pensiero, la sua creazione in laboratorio si può considerare reale. Per dimostrarlo i ricercatori hanno verificato se gli atomi cangianti intrappolati lungo una linea si comportassero come una realtà a una o a due dimensioni.

Esiste un effetto quantistico detto Hall che si può verificare solo in 2D ma si manifesta in questo sistema di atomi allineati, facendoli curvare e rimbalzare in un campo magnetico. Quella che avrebbe dovuto essere una linea unidimensionale, dunque, ha acquisito una extra dimensione. «È l'inizio di una nuova avventura che speriamo porti alla creazione di nuovi stati della materia mai osservati prima», ci dice Inguscio. Mentre la fisica delle particelle che si fa al Cern di Ginevra lavora sulle altissime energie e rompe la materia per osservarne i costituenti fondamentali, questo approccio realizza energie bassissime e ricompone la materia, mettendo insieme gli atomi come se fossero tanti mattoni colorati.

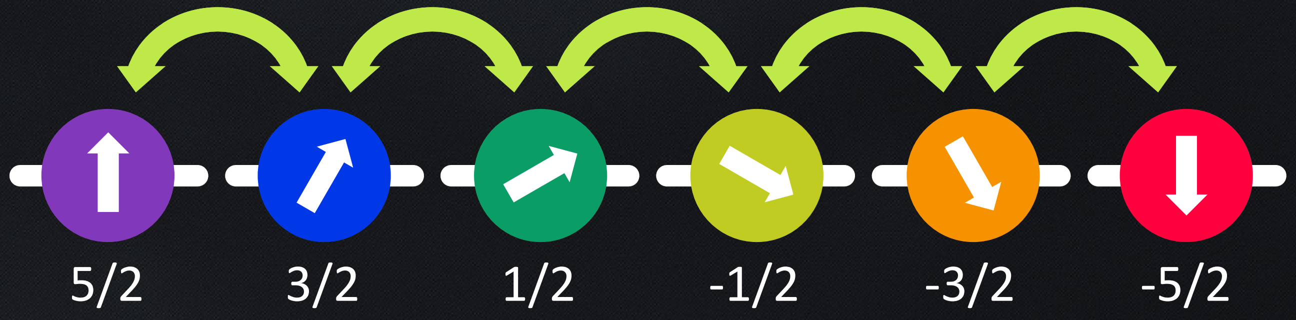
Si tratta di un'idea che sarebbe piaciuta al grande Richard Feynman. Trent'anni fa il premio Nobel per la fisica aveva immaginato che controllando le proprietà degli atomi un giorno avremmo sviluppato dei computer quantistici. «Siamo su questa strada. Stiamo imparando a sfruttare le potentissime risorse dei quanti per simulare nuove teorie, creare mondi con extra dimensioni, sviluppare tecnologie per comunicazioni ultrasicure e misurazioni ultraprecise», conclude Fallani.



Finzione e realtà Sopra Matthew McConaughey (alias Cooper) in *Interstellar*: dentro a una realtà spaziotemporale extra può comunicare con la figlia rimasta sulla Terra. Sotto i ricercatori del Laboratorio europeo di spettroscopia nonlineare di Firenze

Synthetic dimensions

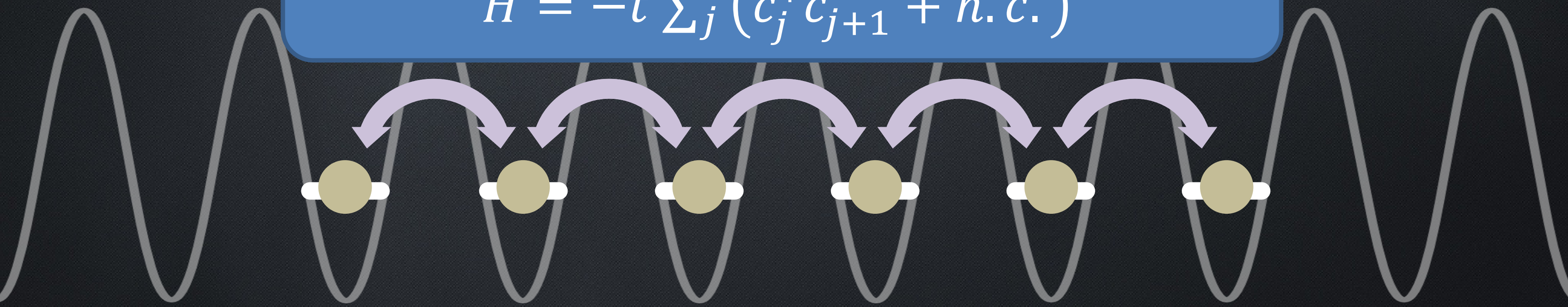
Raman transitions coupling coherently different nuclear spin states:



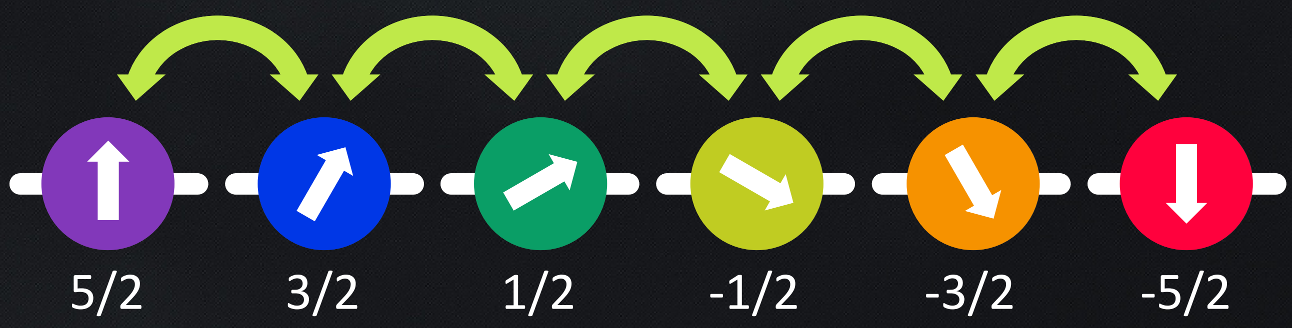
Synthetic dimensions

Analogous to coherent tunnelling coupling in a lattice:

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



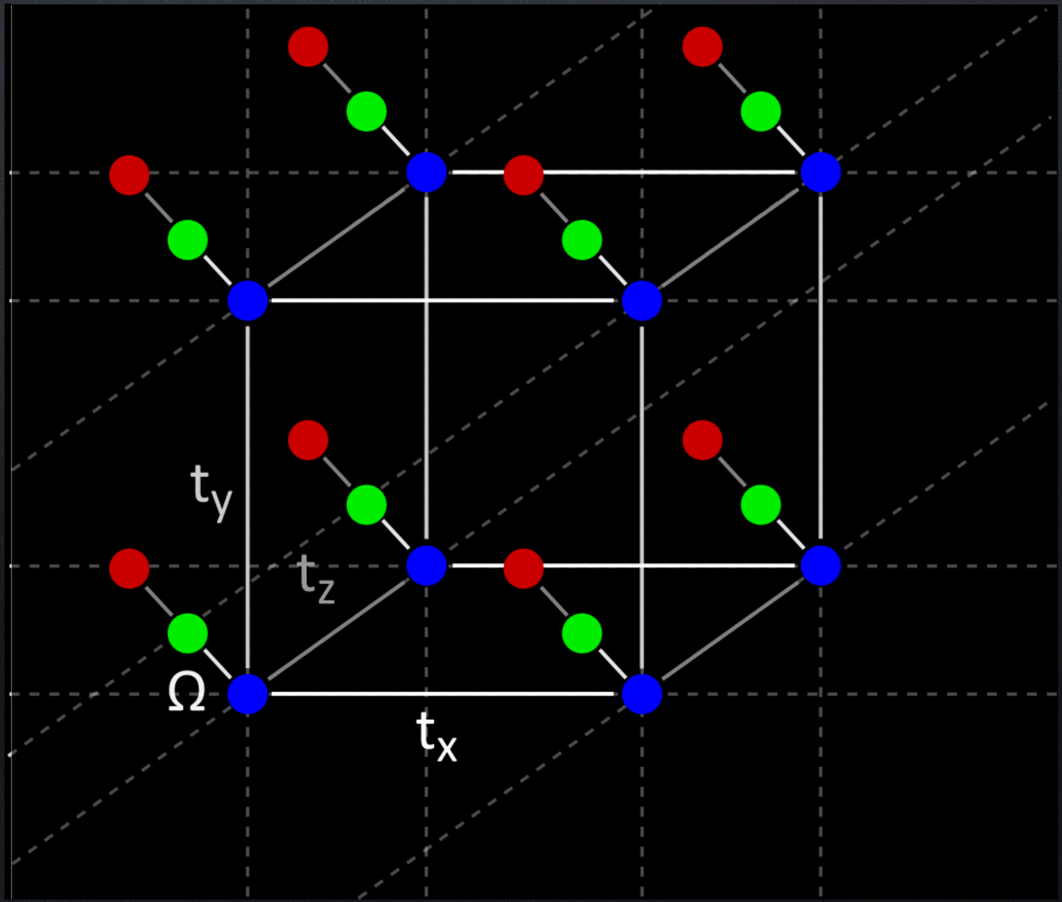
$$H = -\Omega \sum_m \left(c_m^\dagger c_{m+1} + h.c. \right)$$



Simulating an "extra dimension"

Realization of a synthetic lattice dimension

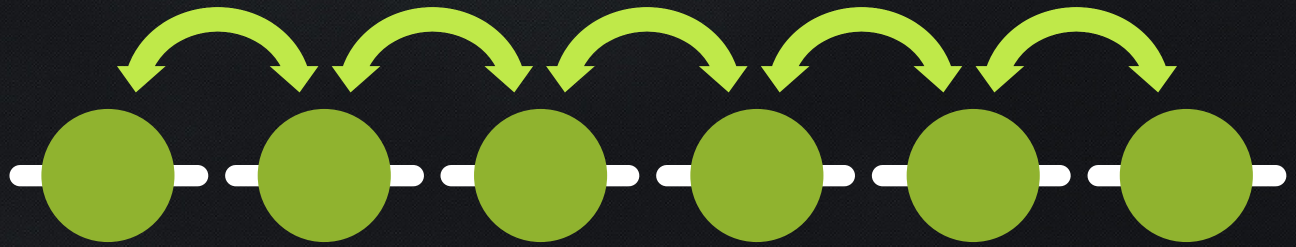
Quantum simulation of 4D models: O. Boada et al., PRL **108**, 133001 (2012)



Opening new synthetic dimensions

The idea of synthetic dimensions is quite general:
stable quantum states + coherent coupling

T. Ozawa & H. M. Price
Nature Reviews Physics ***1****, 349 (2019)*



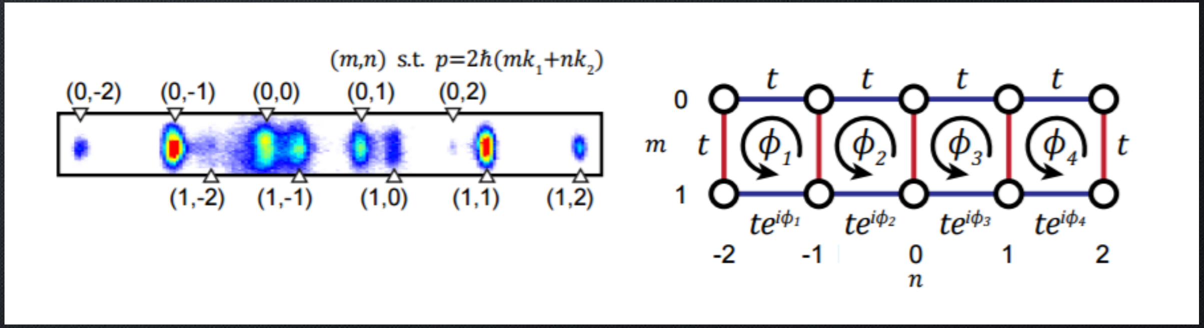
Opening new synthetic dimensions

The idea of synthetic dimensions is quite general:
stable quantum states + coherent coupling

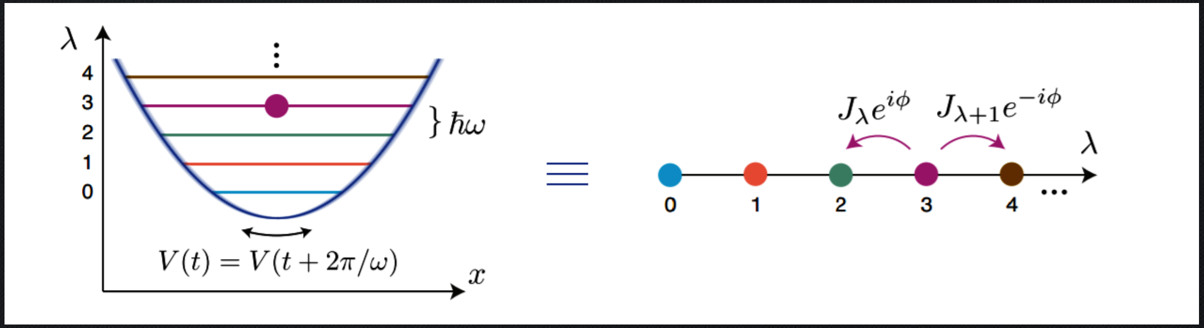
T. Ozawa & H. M. Price
Nature Reviews Physics ***1**, 349 (2019)*

Examples of recent implementations:

Momentum states *F. A. An et al., Science Advances* ***3**, e1602685 (2017)*



Trap levels *C. Oliver et al., arXiv:2112.10648*



Opening new synthetic dimensions

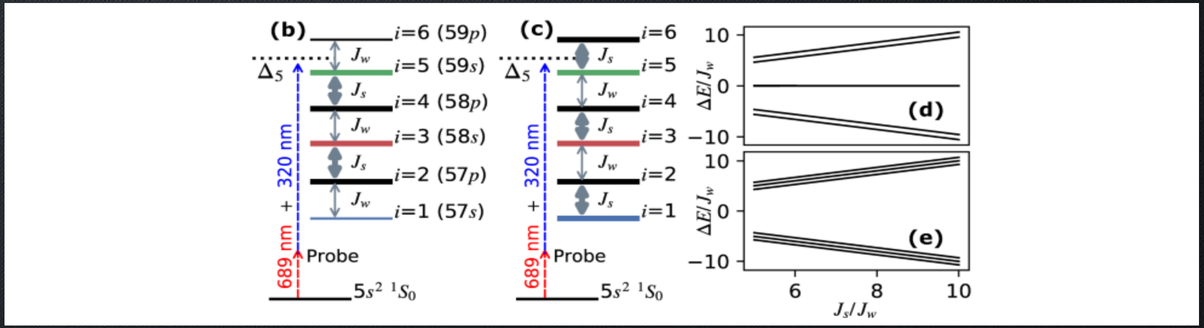
The idea of synthetic dimensions is quite general:
stable quantum states + coherent coupling

T. Ozawa & H. M. Price
Nature Reviews Physics ***1****, 349 (2019)*

Examples of recent implementations:

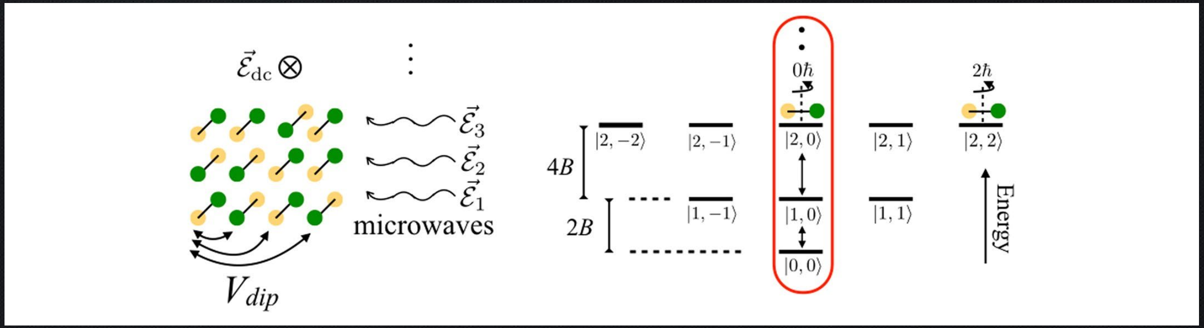
Rydberg states

S. K. Kanungo al., Nat. Comm. ***13****, 972 (2022)*



Molecular rotational states (theory)

B. Sundar et al., Sci. Rep. ***8****, 3422 (2018)*



Lecture 1

- Introduction to multicomponent quantum gases
- Interactions in two-electron fermions and SU(N) physics
- Experimental techniques
- **EXP**: SU(N) physics in low dimensions
- **EXP**: SU(N) Fermi-Hubbard and breaking SU(N) physics

Lecture 2

- Multicomponent systems with coherent coupling
- Synthetic dimensions and artificial magnetic fields
- **EXP**: Chiral edge currents in synthetic ladders
- **EXP**: Synthetic Hall effect

A quantum charged particle in a magnetic field

$$H = \frac{1}{2m}(\vec{p} - q\vec{A})^2 + V(\vec{r}) \qquad \vec{B} = \vec{\nabla} \times \vec{A}$$

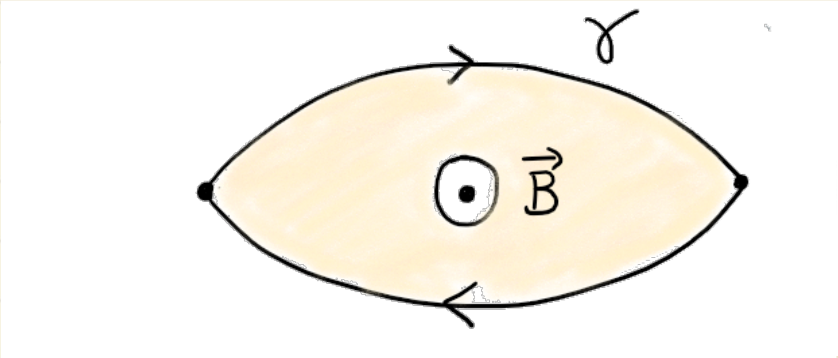
$$\downarrow$$

$$\psi(\vec{r}) = \psi_0(\vec{r})\, e^{\frac{iq}{\hbar}\int_0^{\vec{r}} \vec{A}(\vec{r}\,')\cdot d\vec{r}\,'}$$

AHARONOV-BOHM EFFECT

$$\psi_1(Q) = \psi_0(Q)\, e^{\frac{iq}{\hbar}\int_{\gamma_1} \vec{A}\cdot d\vec{r}\,'}$$

$$\psi_2(Q) = \psi_0(Q)\, e^{\frac{iq}{\hbar}\int_{\gamma_2} \vec{A}\cdot d\vec{r}\,'}$$



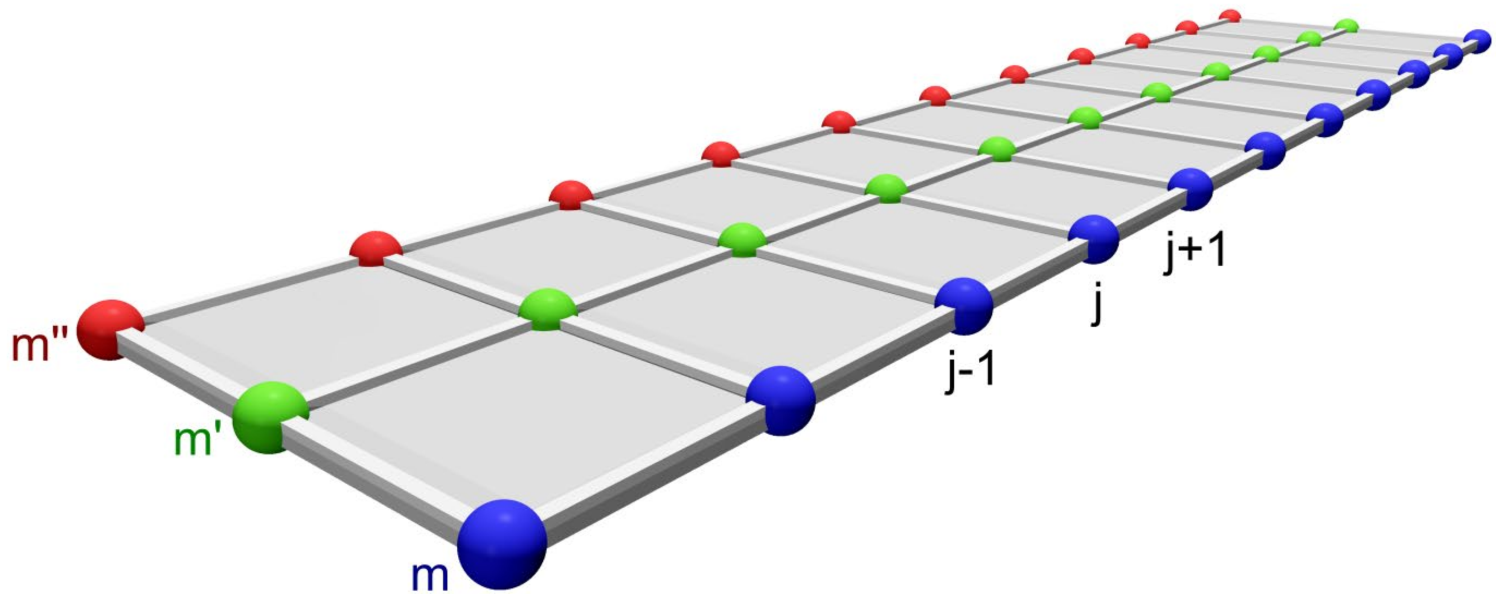
(stokes)

$$\Delta\phi = \frac{q}{\hbar}\left(\int_{\gamma_1} \vec{A}\cdot d\vec{r}\,' - \int_{\gamma_2} \vec{A}\cdot d\vec{r}\,'\right) = \frac{q}{\hbar}\oint \vec{A}\cdot d\vec{r}\,' = \frac{q}{\hbar}\int \vec{B}\cdot d\vec{S}$$

$$= \frac{q}{\hbar}\Phi(\vec{B}) = 2\pi\,\frac{\Phi(\vec{B})}{\Phi_0}$$

$$\Phi_0 = \frac{h}{q}$$ QUANTUM OF FLUX

A synthetic flux ladder

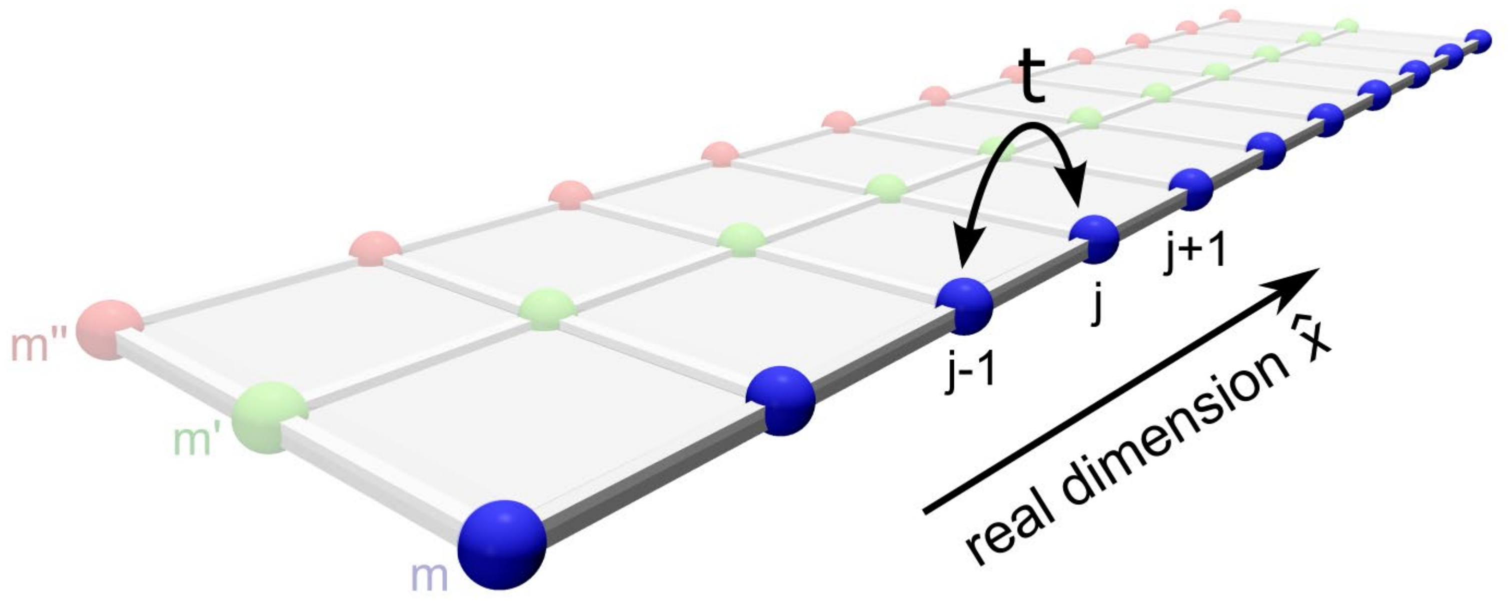


<u>1D real + 1D synthetic ladder</u>

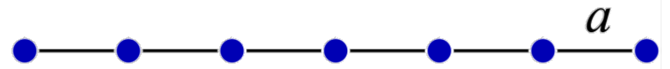
proposal:
A. Celi et al., *PRL* **112**, 043001 (2014)

experiment:
M. Mancini et al., *Science* **349**, 1510 (2015)
B. K. Stuhl et al., *Science* **349**, 1514 (2015)

A synthetic flux ladder



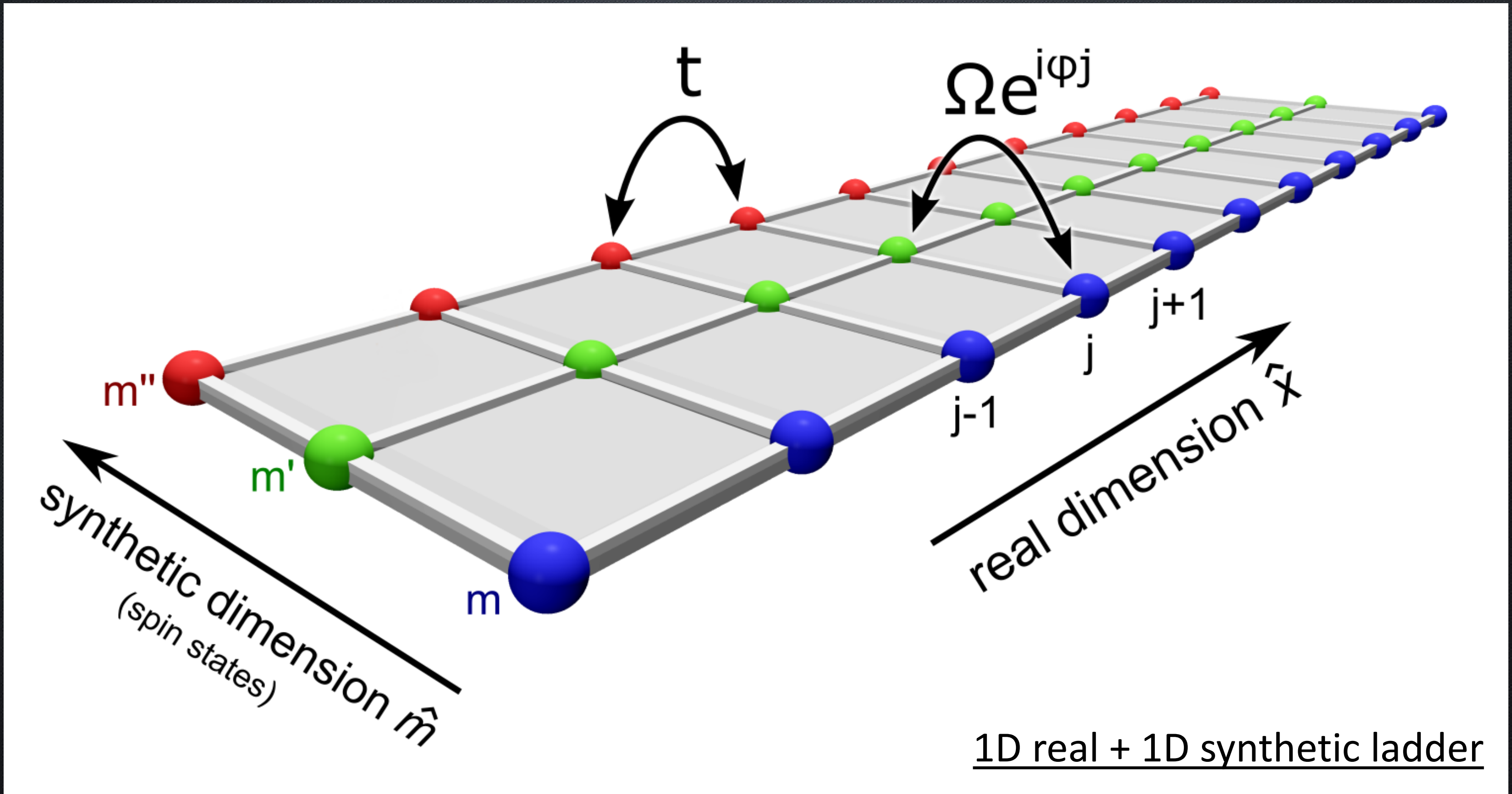
1D real + 1D synthetic ladder

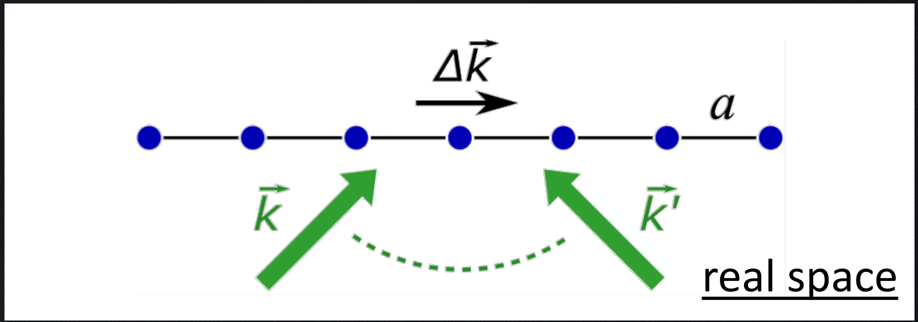


real space

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

A synthetic flux ladder





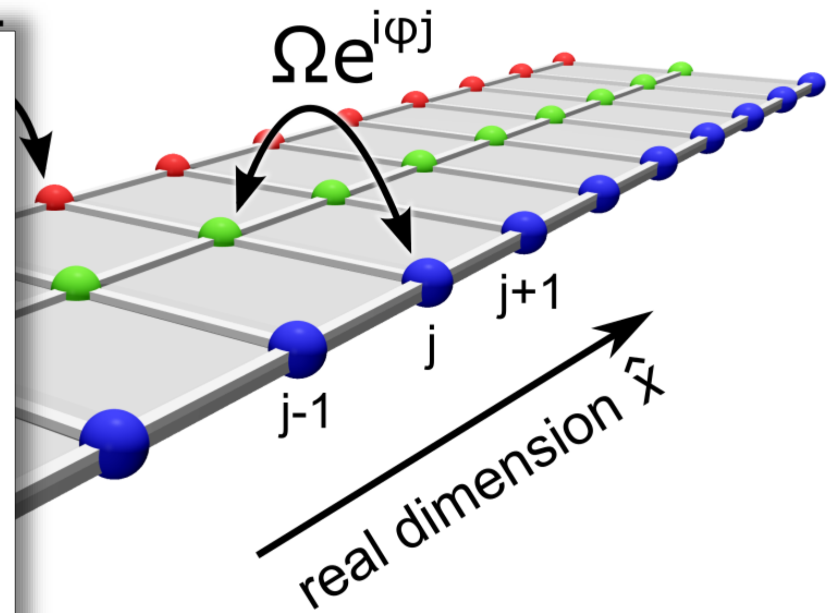
A synthetic flux ladder

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

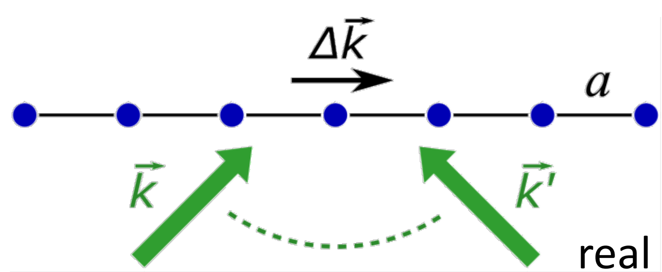
two-photon Rabi frequency:

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

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

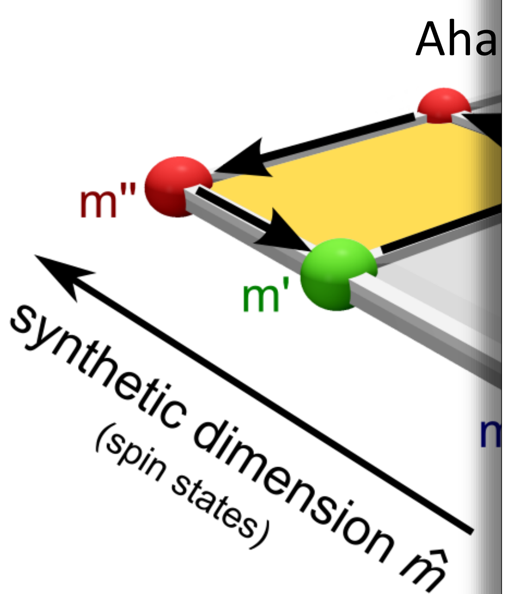


1D real + 1D synthetic ladder

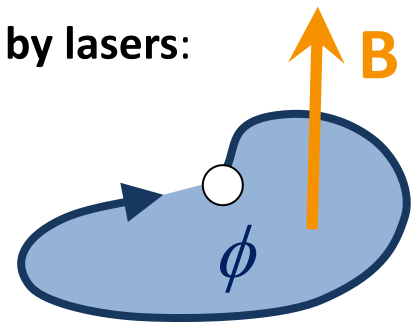


real space

A synthetic flux ladder



Aharonov-Bohm phase imprinted by lasers:



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

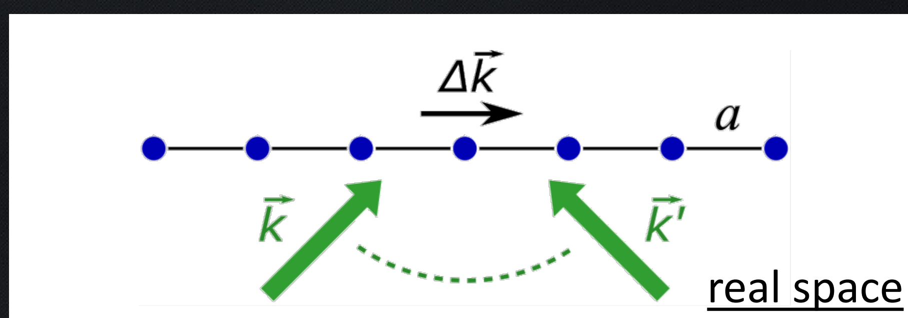
$$\phi = 2\pi \frac{\Phi(\mathbf{B})}{\Phi_0}$$

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

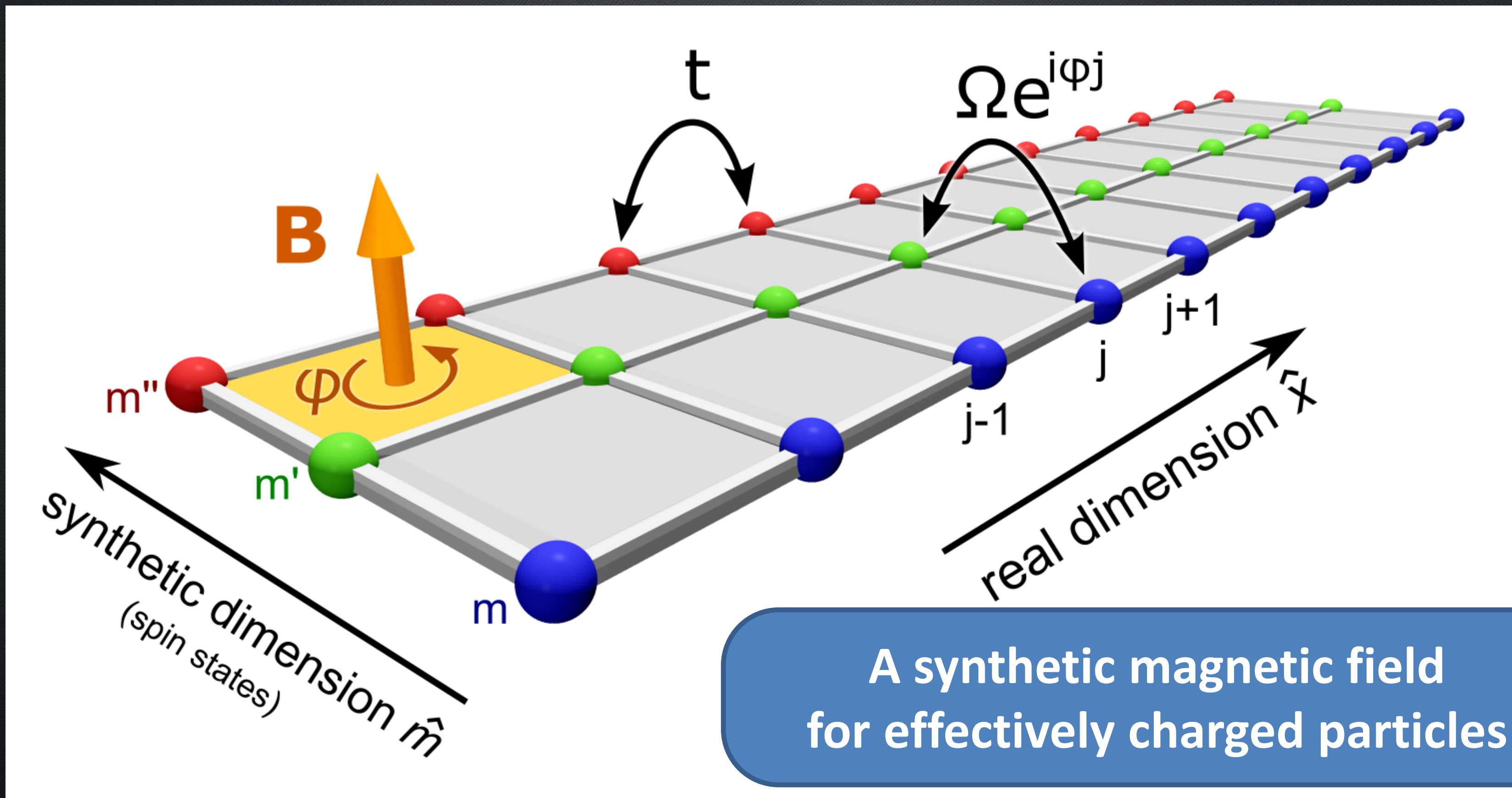
Reviews on gauge fields for ultracold atoms:

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

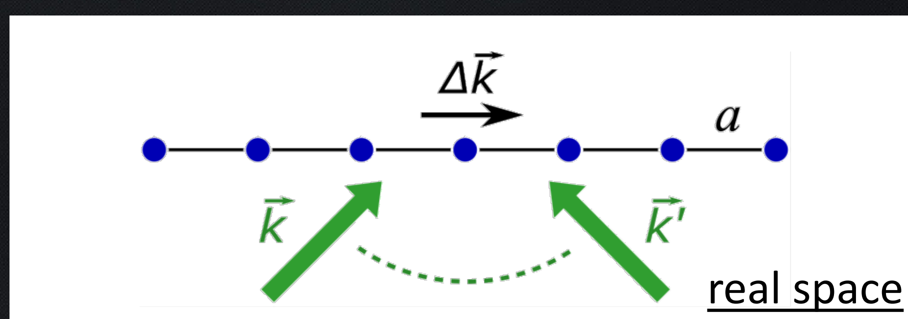
N. Goldman et al., Rep. Prog. Phys. **77**, 126401 (2014)



A synthetic flux ladder



A synthetic magnetic field for effectively charged particles



Lecture 1

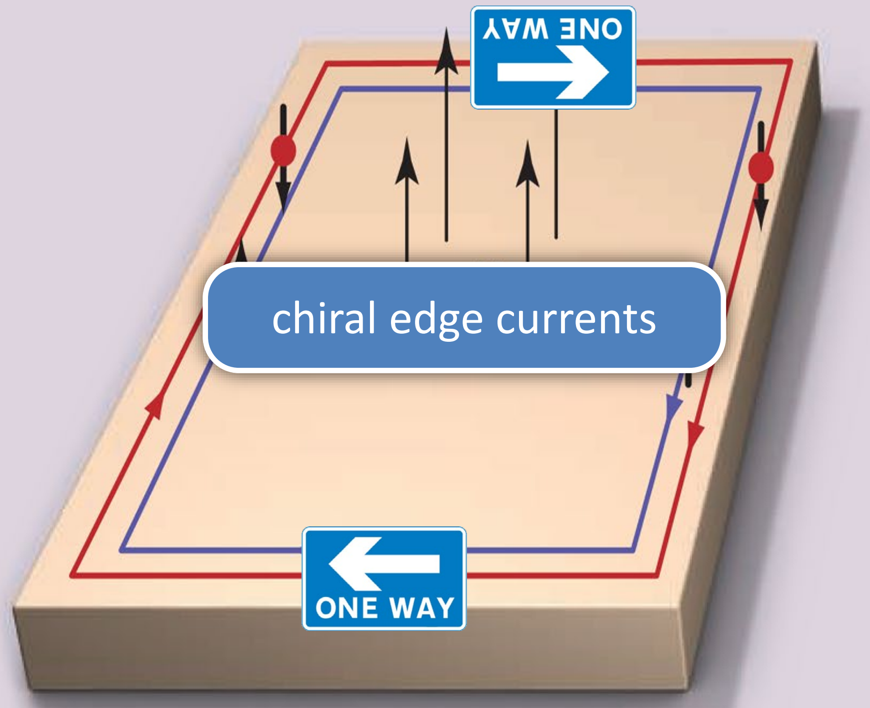
- Introduction to multicomponent quantum gases
- Interactions in two-electron fermions and SU(N) physics
- Experimental techniques
- **EXP**: SU(N) physics in low dimensions
- **EXP**: SU(N) Fermi-Hubbard and breaking SU(N) physics

Lecture 2

M. Mancini et al., Science **349**, 1510 (2015)
L. Livi et al., PRL **117**, 220401 (2016)

- Multicomponent systems with coherent coupling
- Synthetic dimensions and artificial magnetic fields
- **EXP**: Chiral edge currents in synthetic ladders
- **EXP**: Synthetic Hall effect

Edge states are a hallmark of **topological states of matter** (Nobel Physics 2016)



Quantum Hall

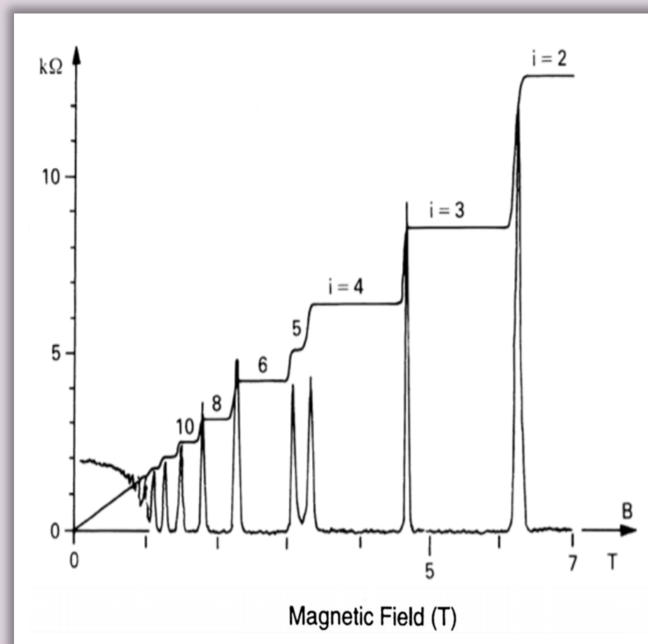
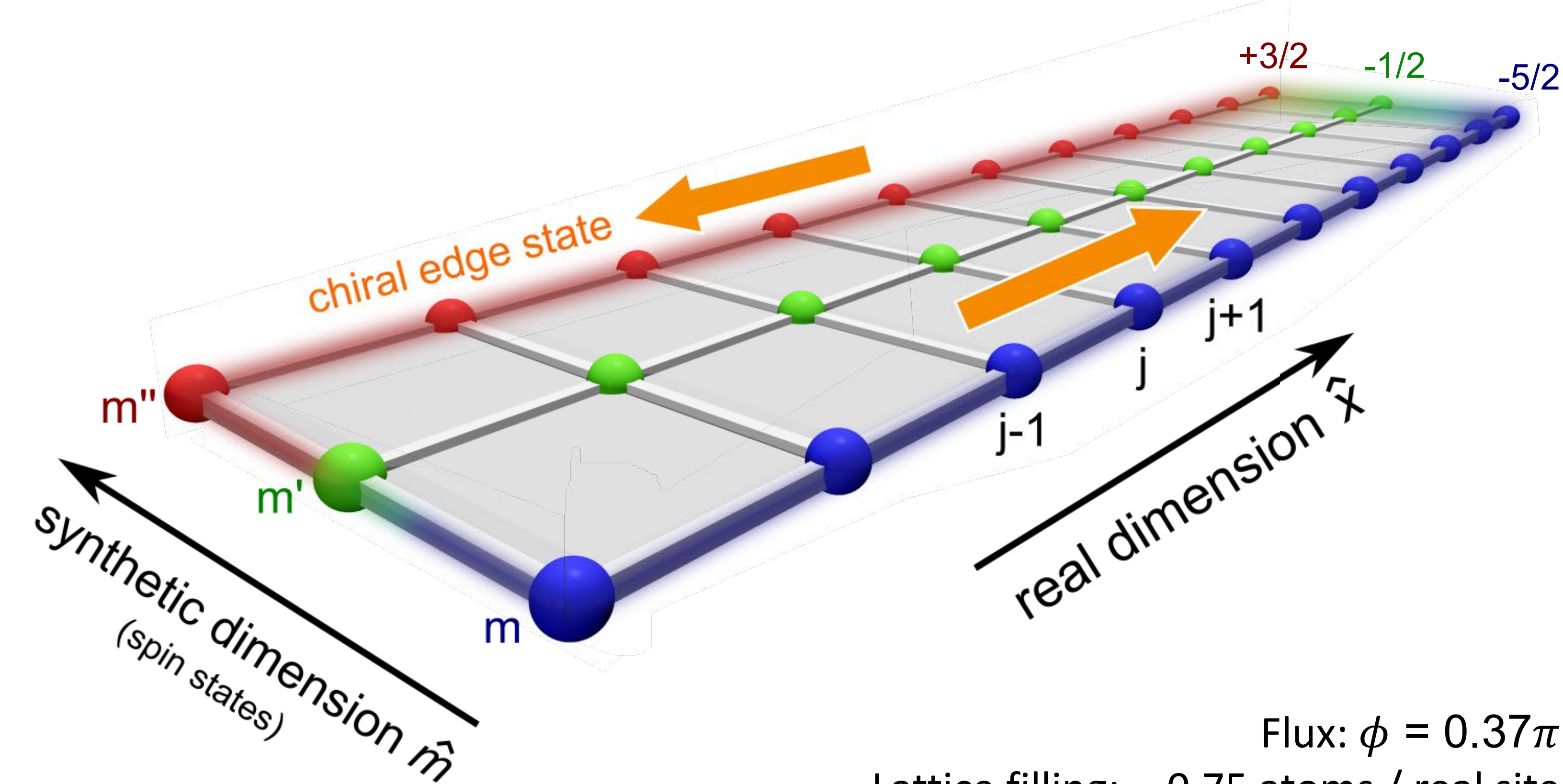


Figure from S. Oh, Science **340**, 153 (2013)

Observing chiral edge states

Adiabatic preparation of a Fermi gas in a 3-leg synthetic flux ladder



Flux: $\phi = 0.37\pi$

Lattice filling: ~ 0.75 atoms / real site

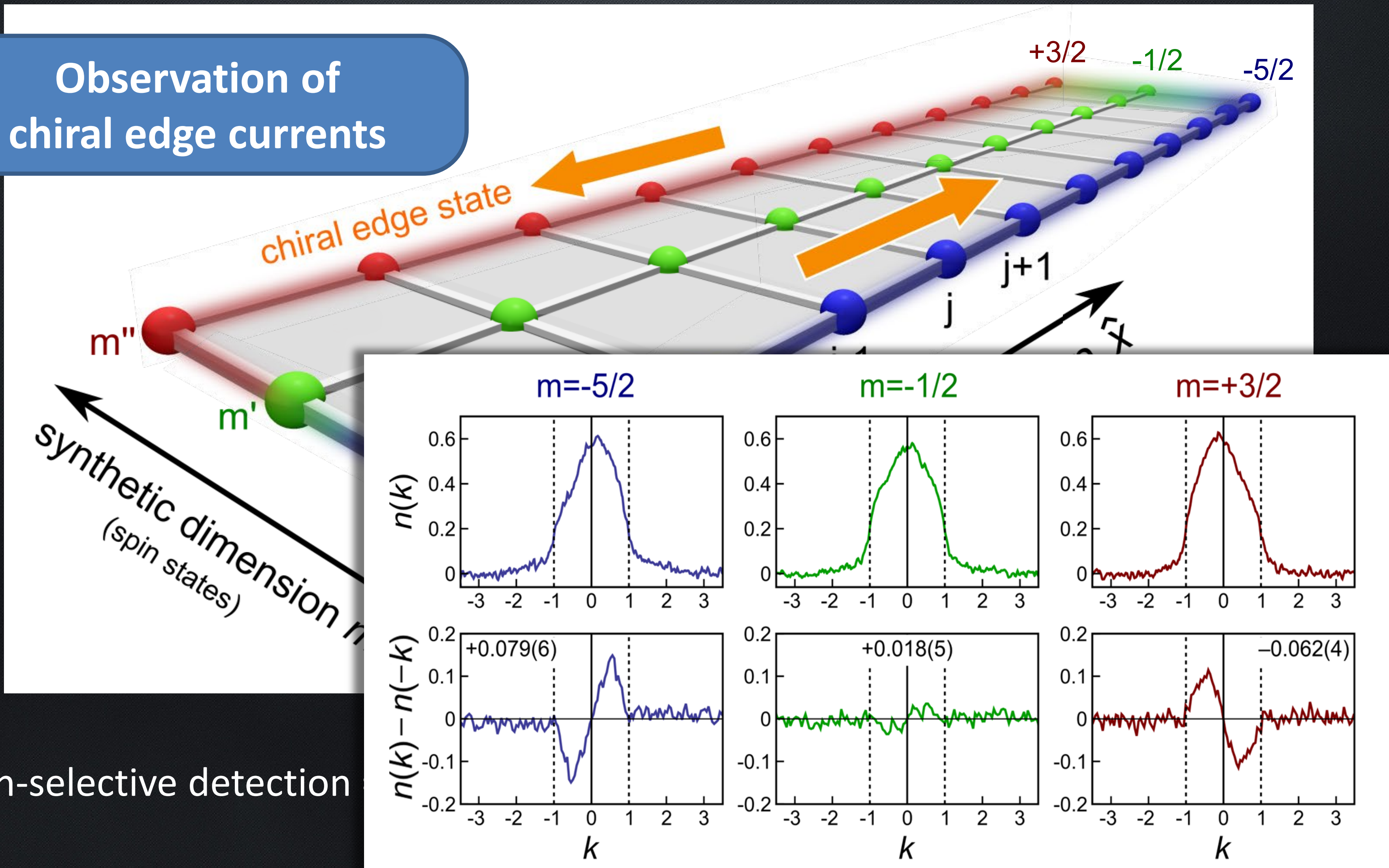
Spin-selective detection = single-site imaging in synthetic dimension

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

Observing chiral edge states

Adiabatic preparation of a Fermi gas in a 3-leg synthetic flux ladder

Observation of chiral edge currents

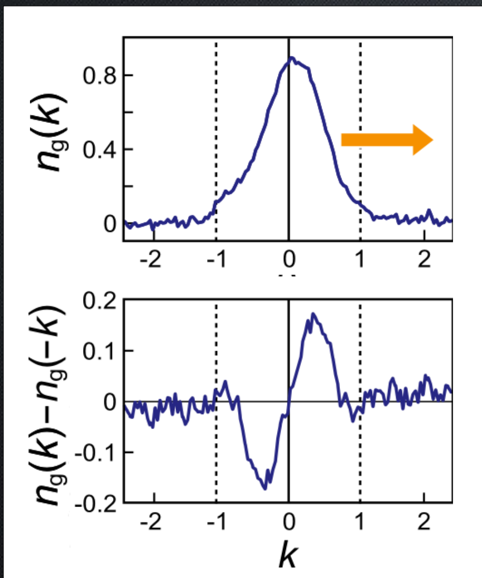


Spin-selective detection

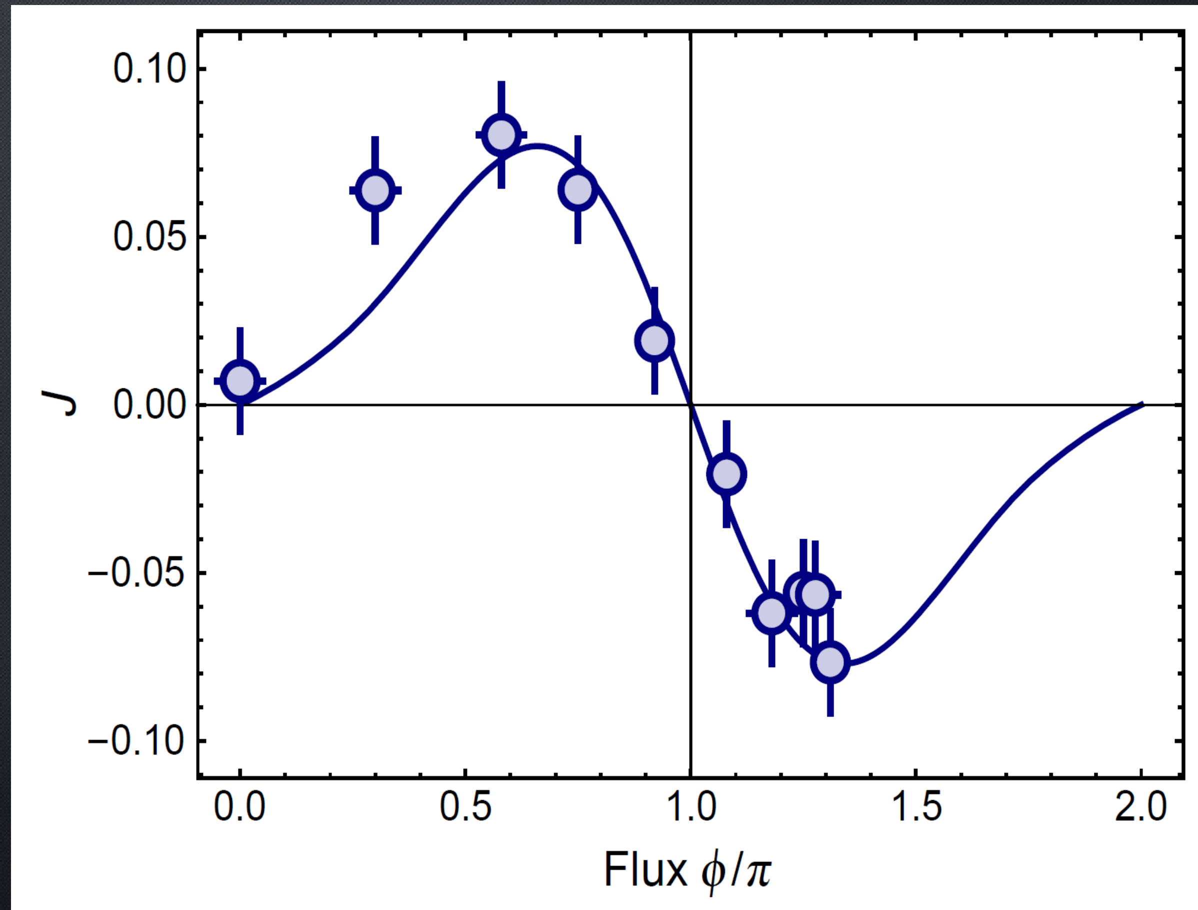
L. Livi et al., PRL **117**, 220401 (2016)

Chiral currents with tunable flux

Measurement of chiral current J vs ϕ



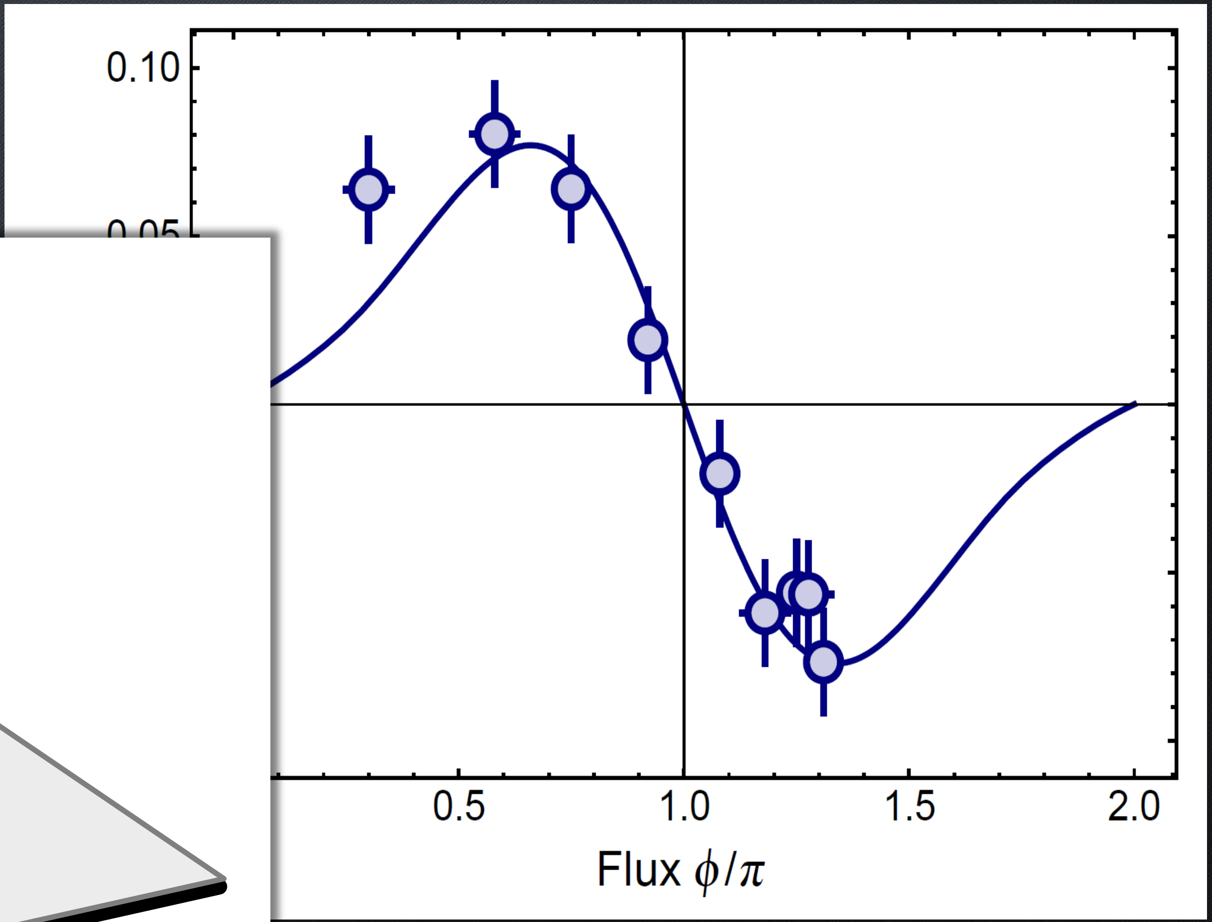
$$J = \int_0^1 [n_g(k) - n_g(-k)]\,dk$$

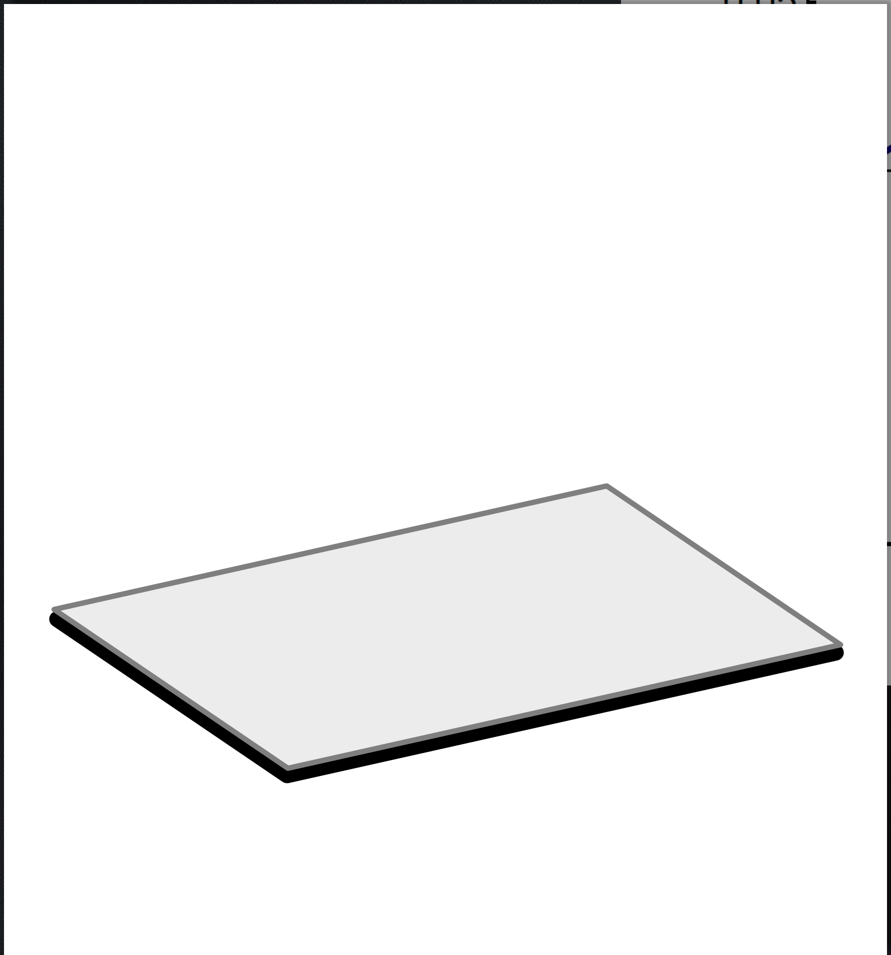


L. Livi et al., PRL **117**, 220401 (2016)

Chiral currents with tunable flux

Measurement of chiral current J vs ϕ





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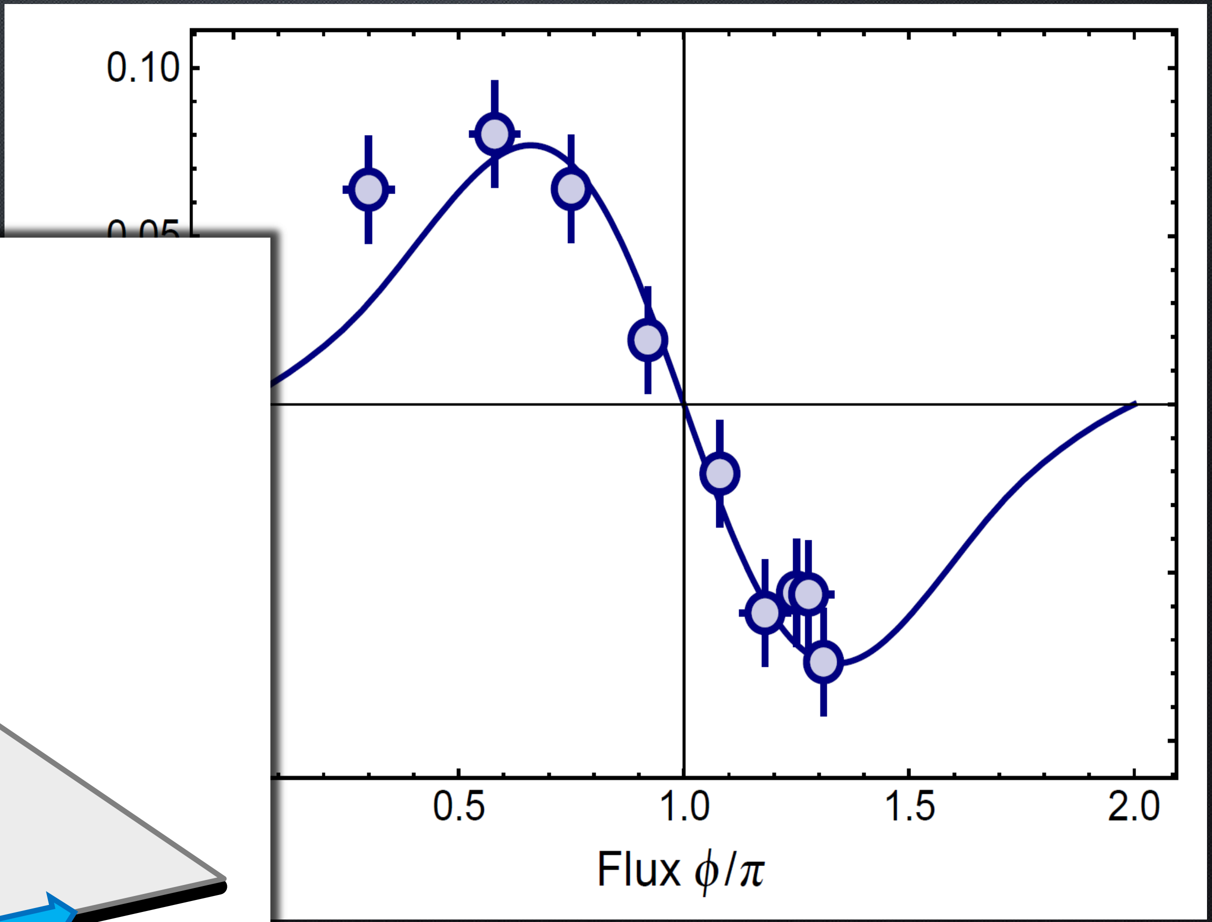
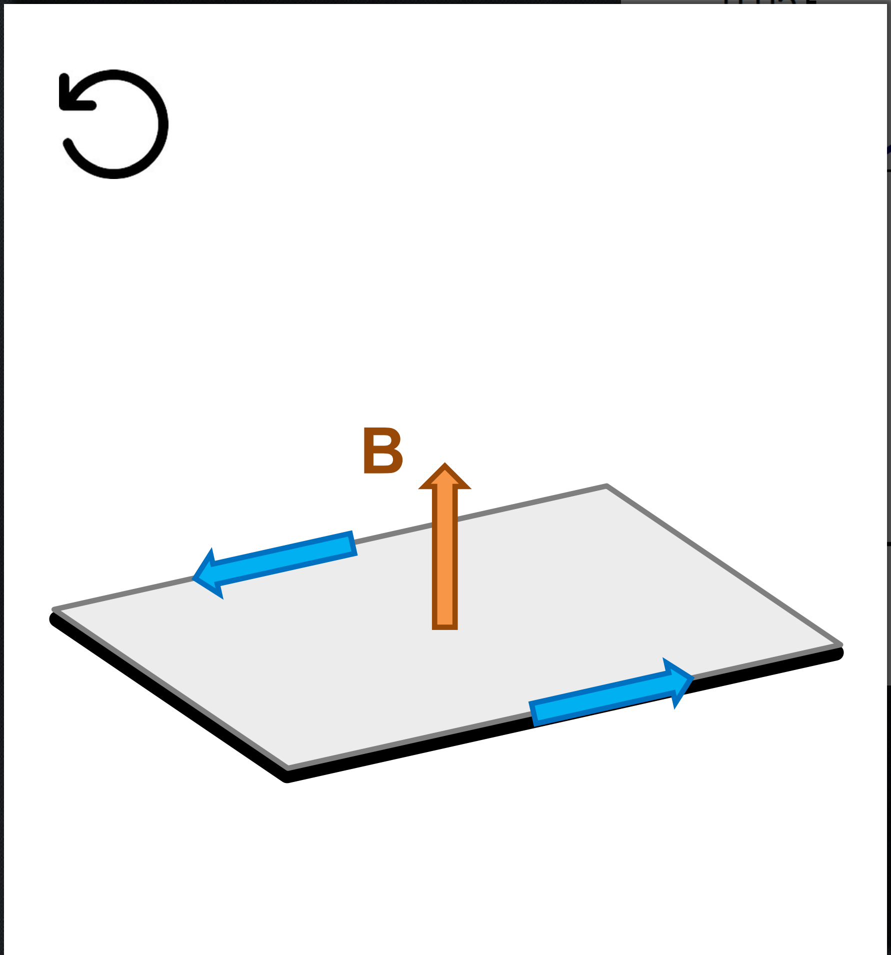
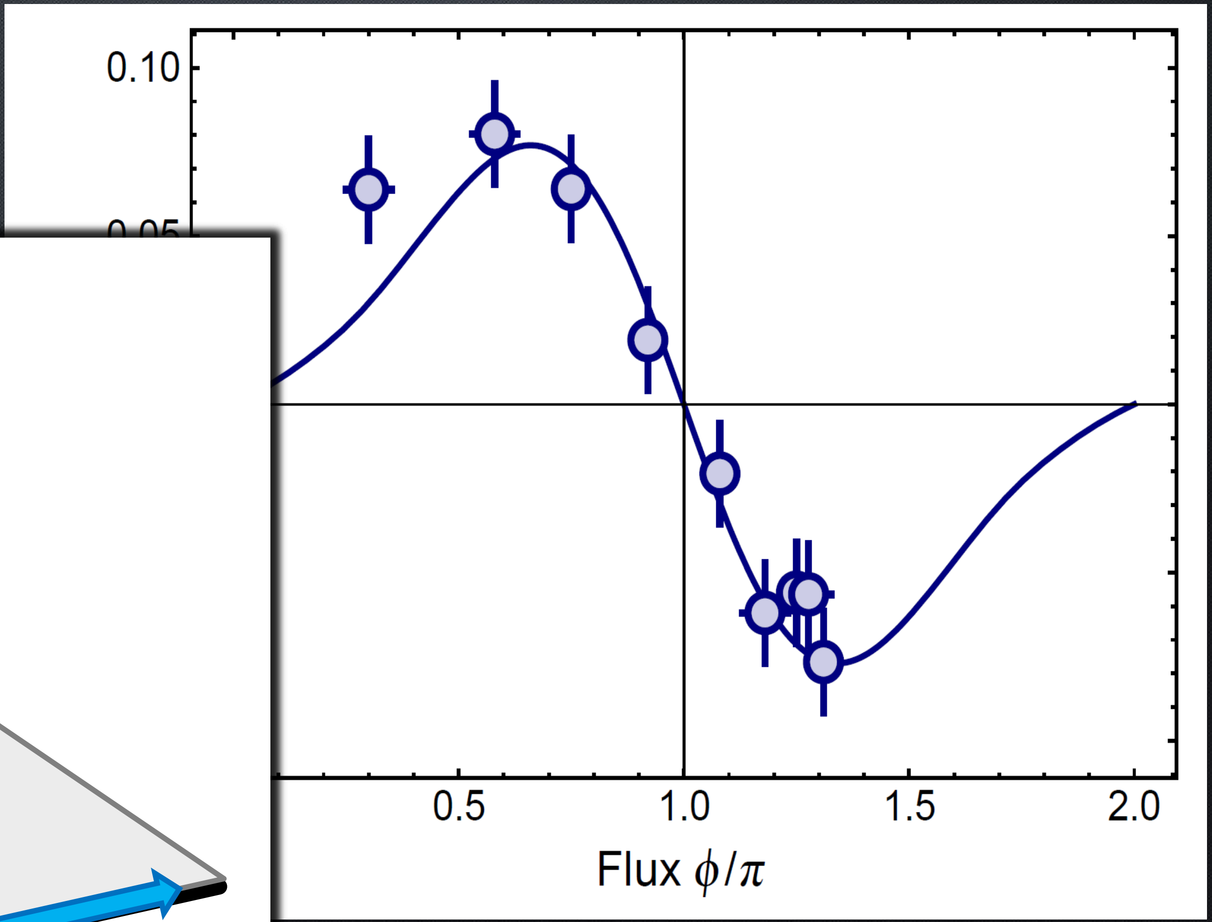
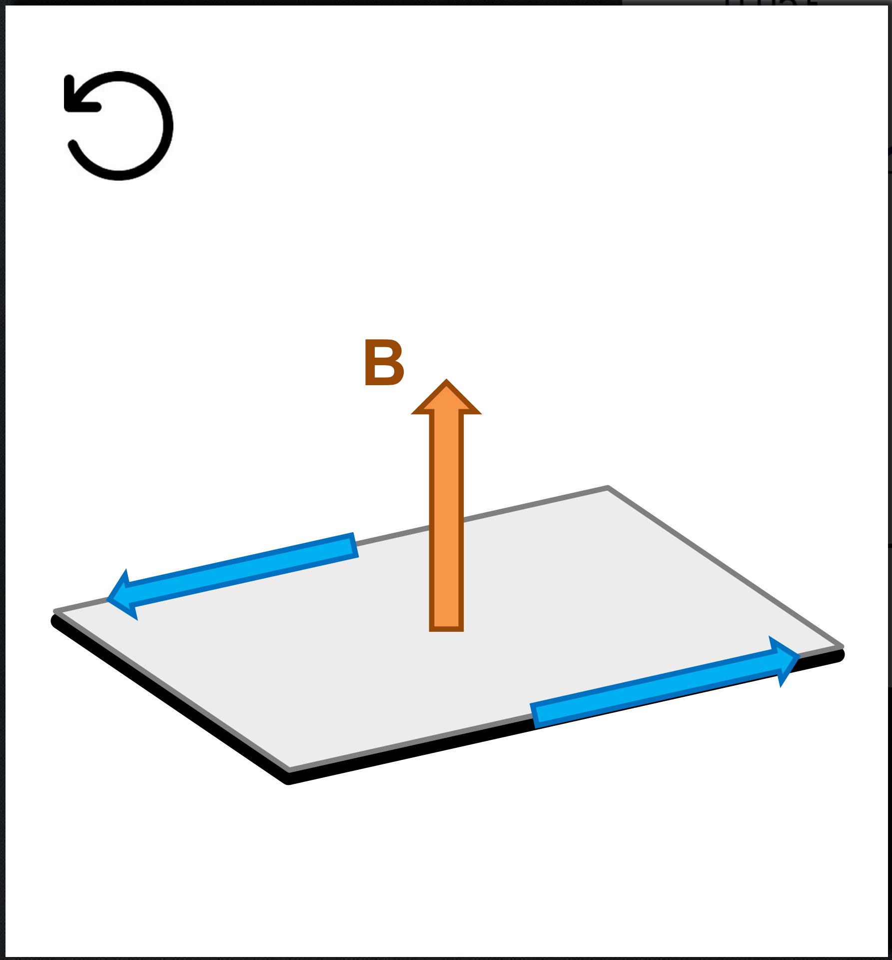




Chiral currents with tunable flux

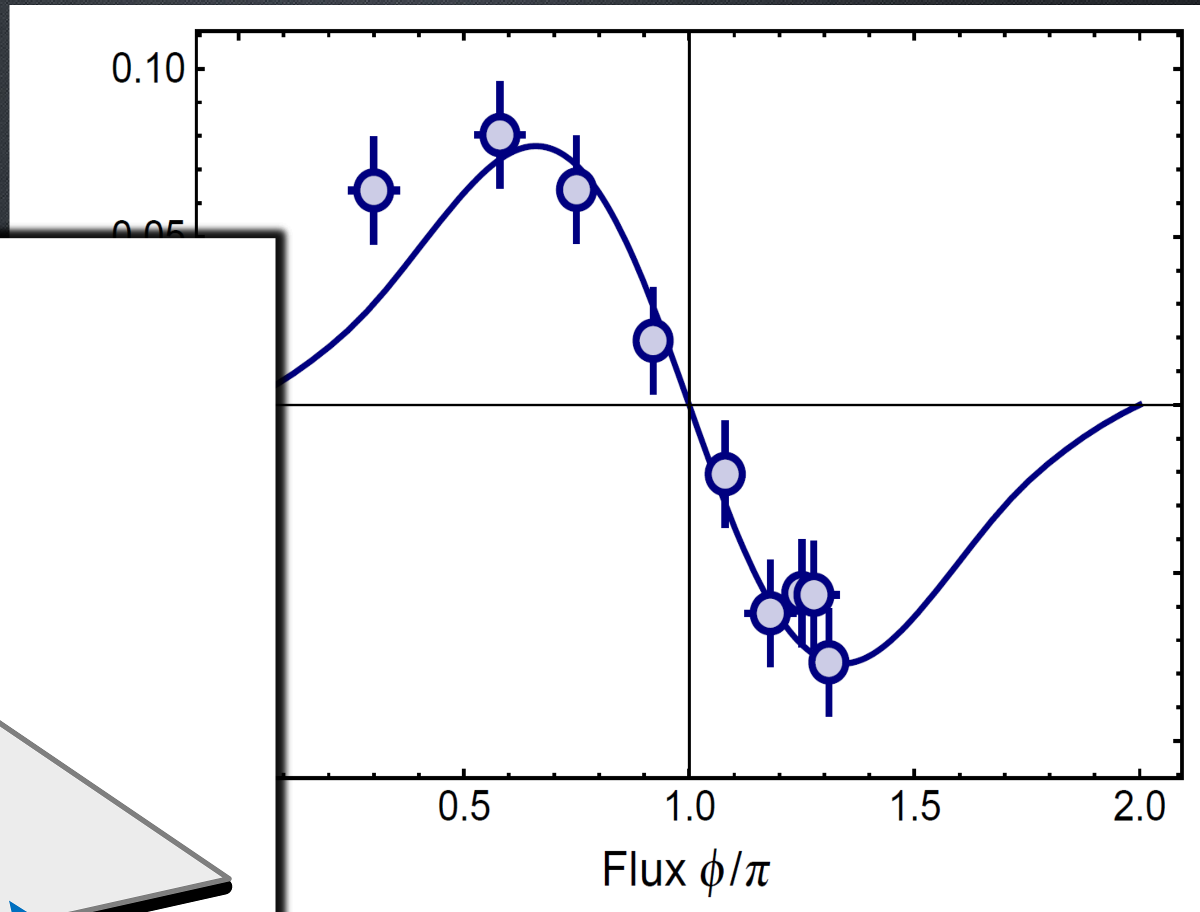
Measurement of chiral current J vs ϕ

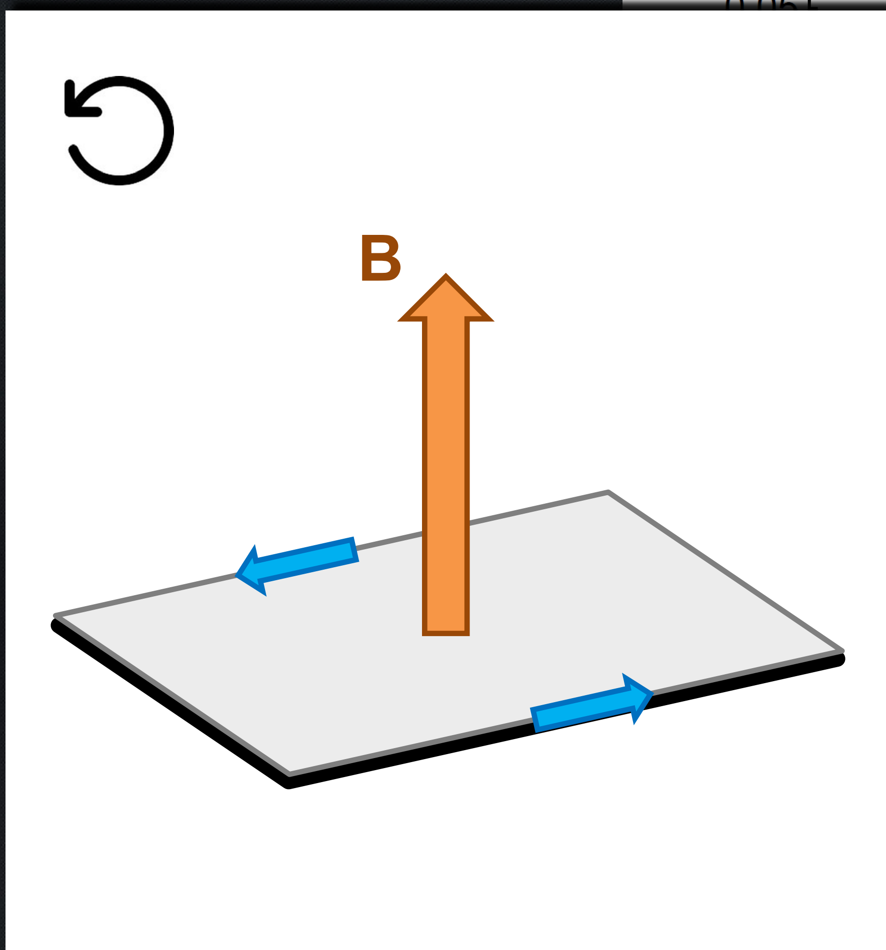




Chiral currents with tunable flux

Measurement of chiral current J vs ϕ





Chiral currents with tunable flux

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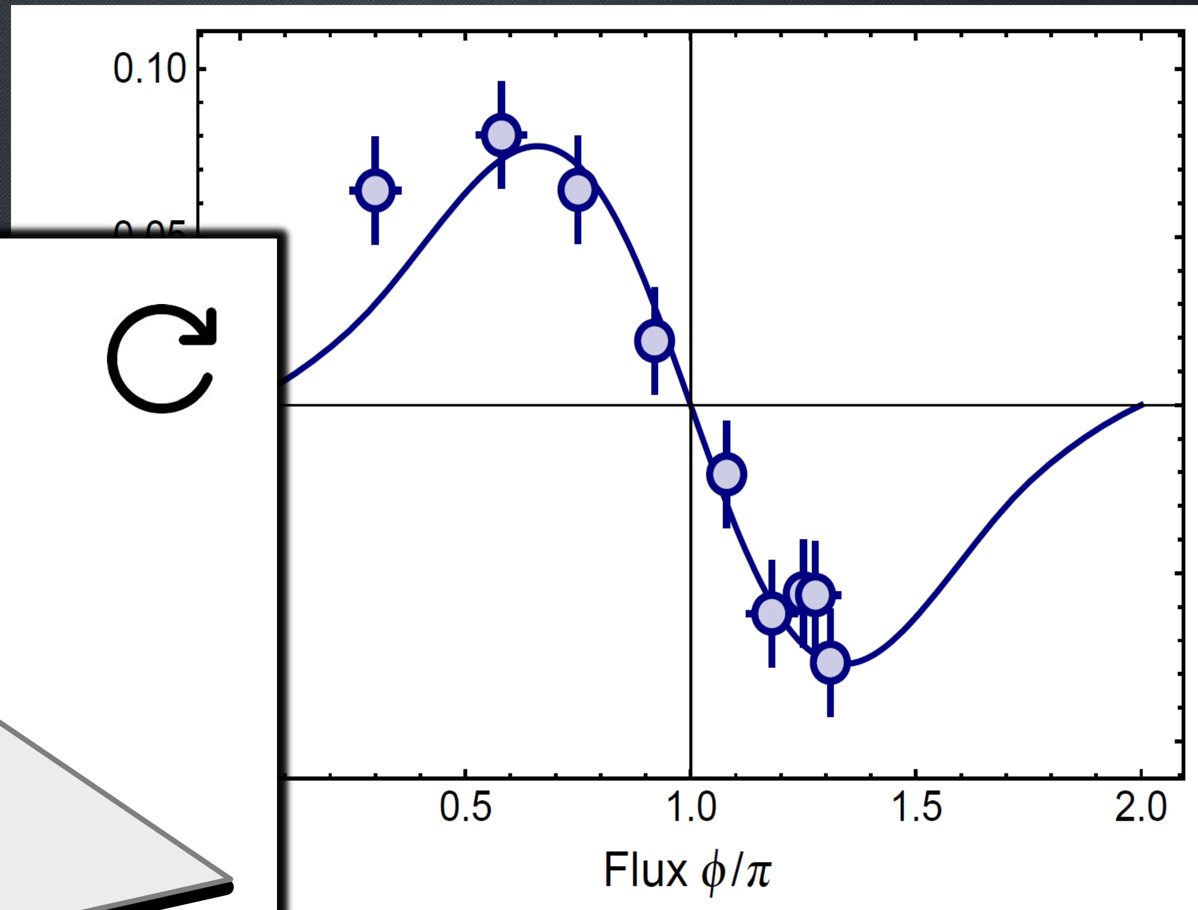
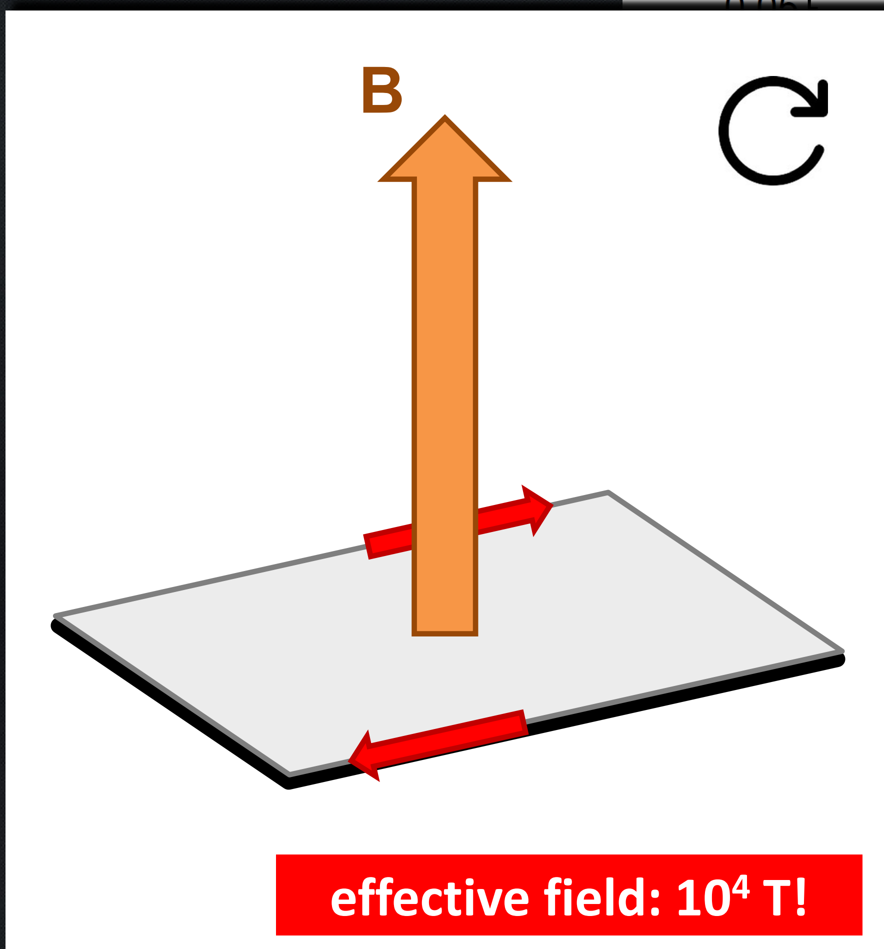




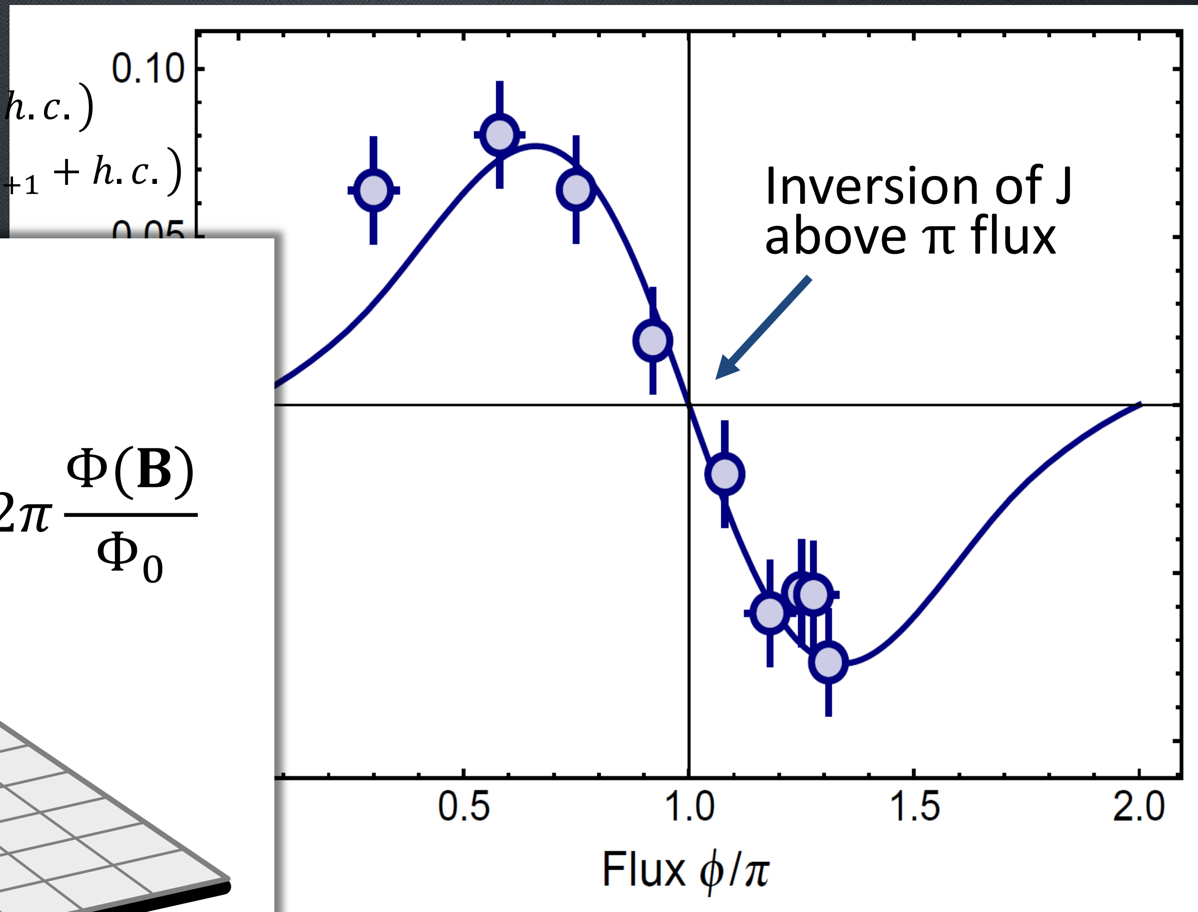
*L. Livi et al., PRL **117**, 220401 (2016)*

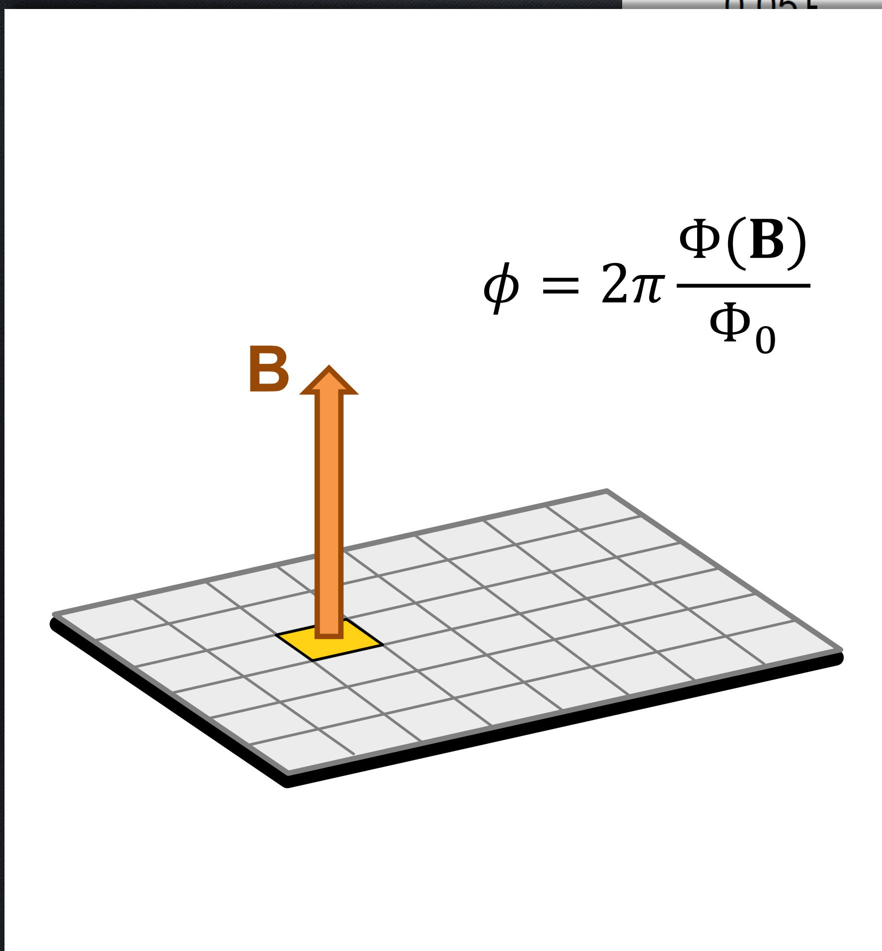
Chiral currents with tunable flux

Harper-Hofstadter model:

Measurement of chiral current J vs ϕ

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





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

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

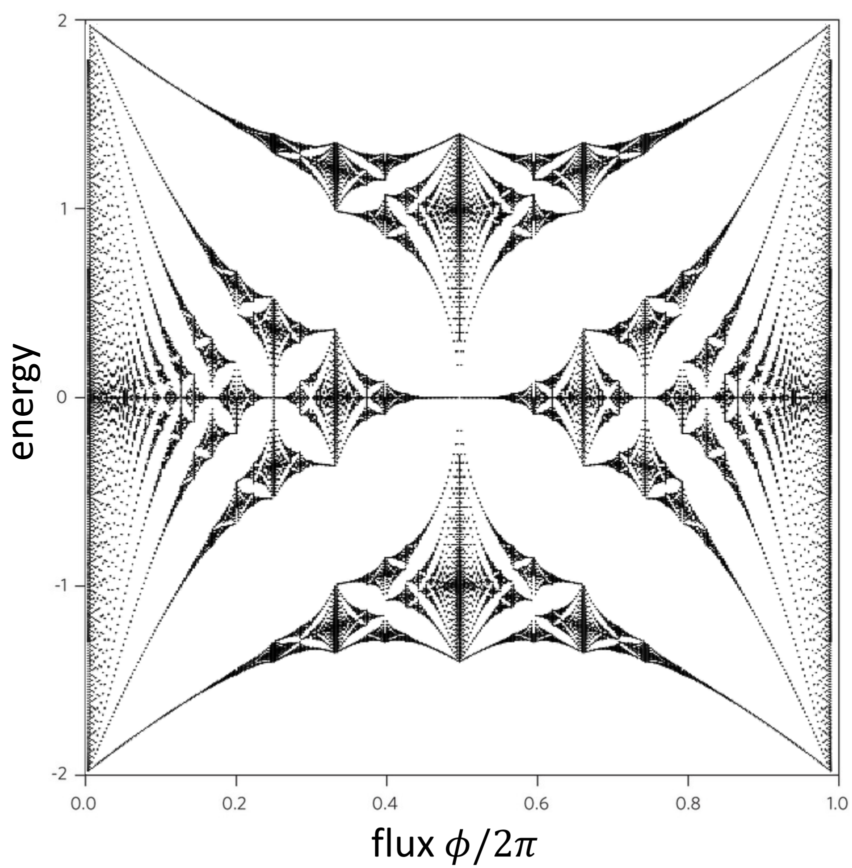
$J(\phi) = J(2\pi + \phi)$ lattice

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

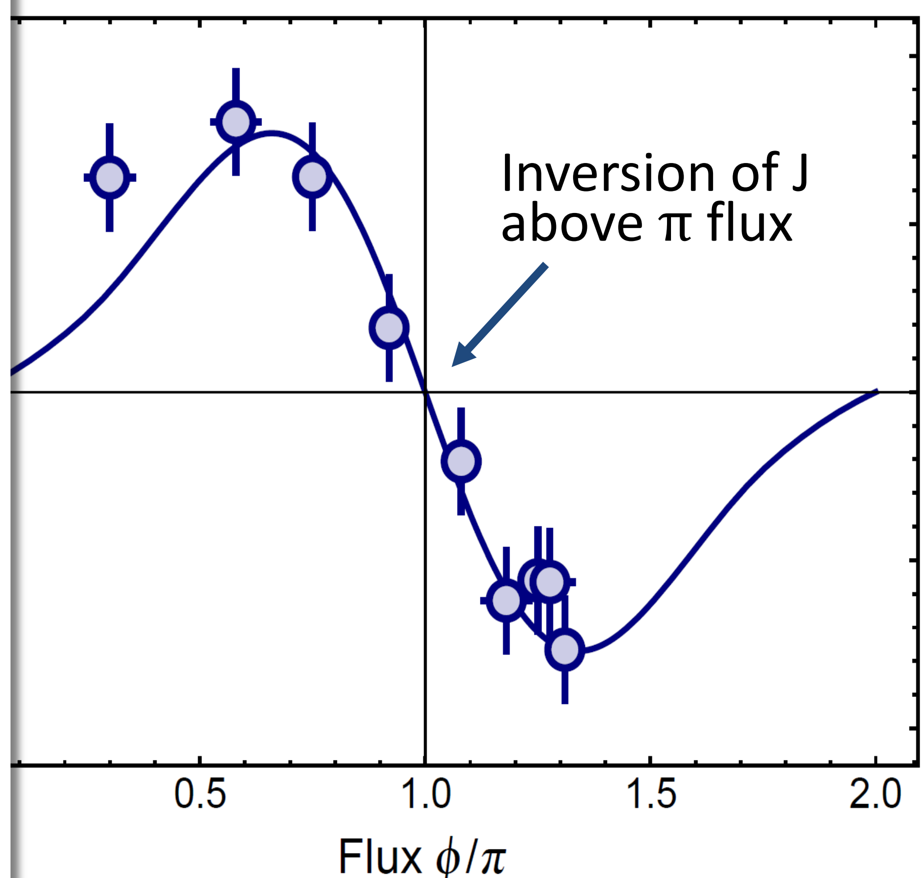
Chiral currents with tunable flux

Harper-Hofstadter model:

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



Hofstadter's butterfly



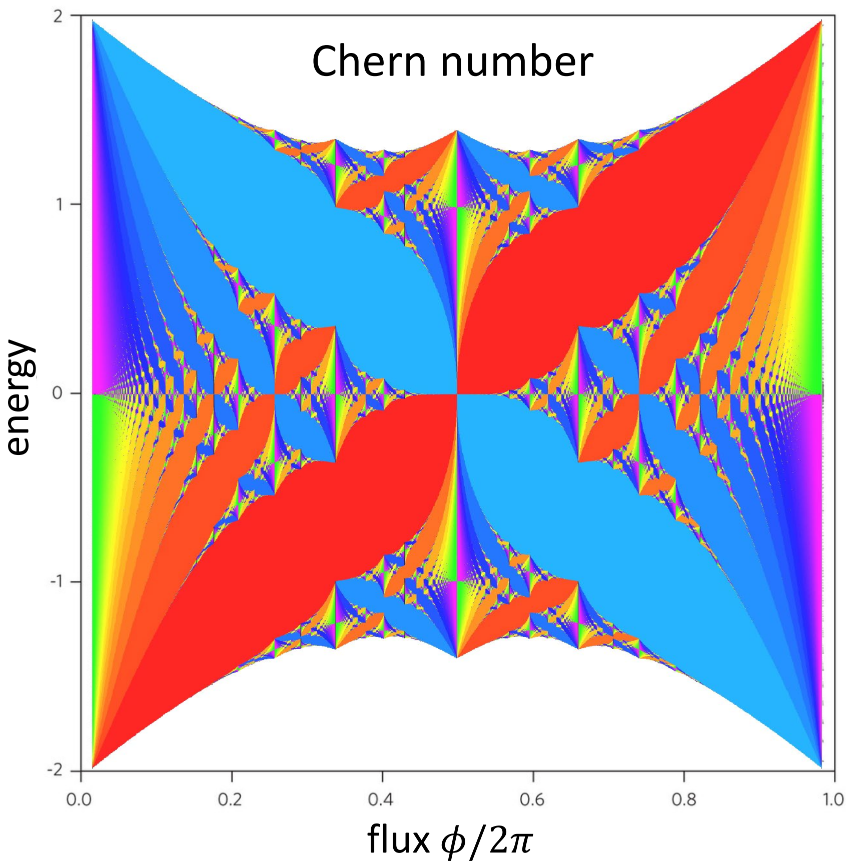
$J(\phi) = -J(-\phi)$ time-reversal

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

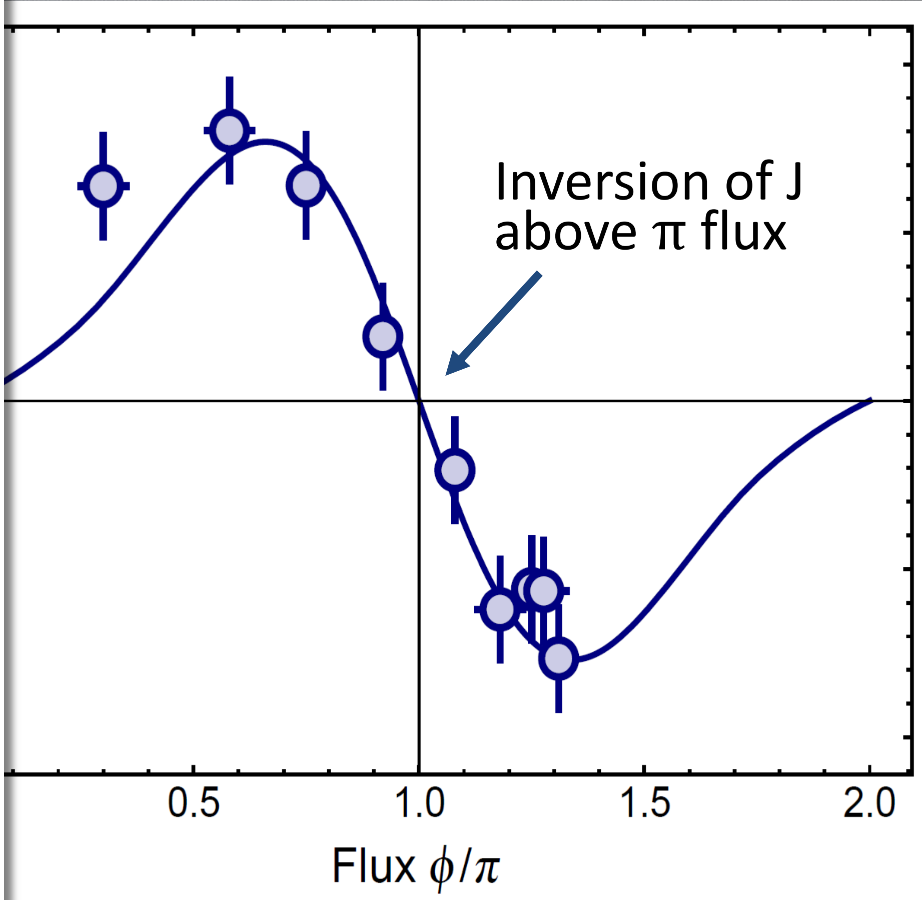
Chiral currents with tunable flux

Harper-Hofstadter model:

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



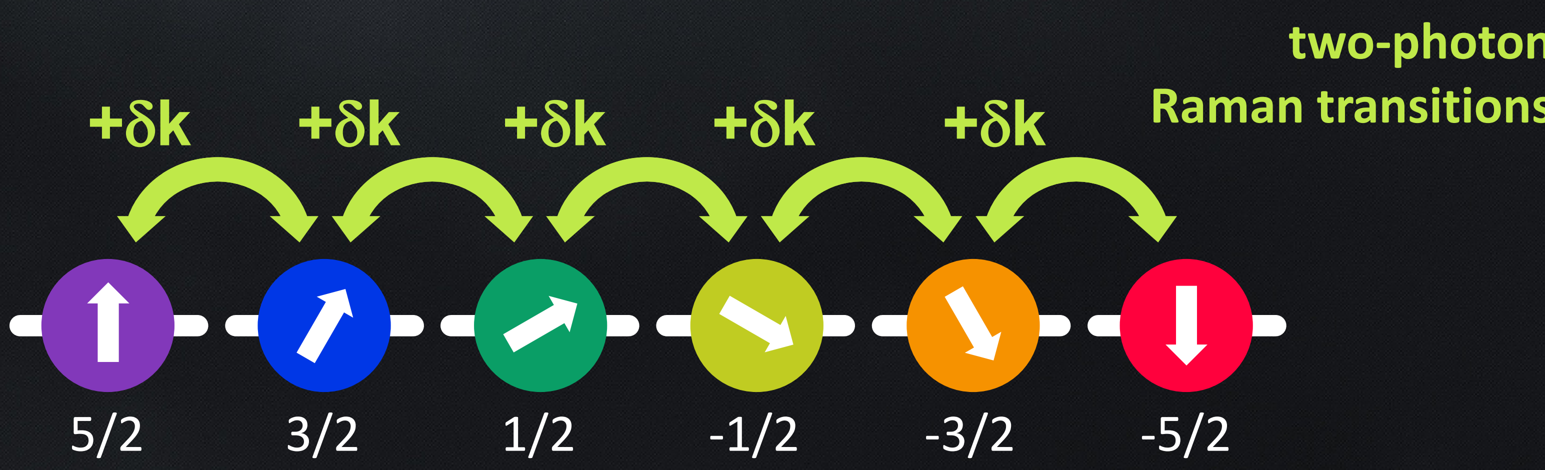
Hofstadter's butterfly



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

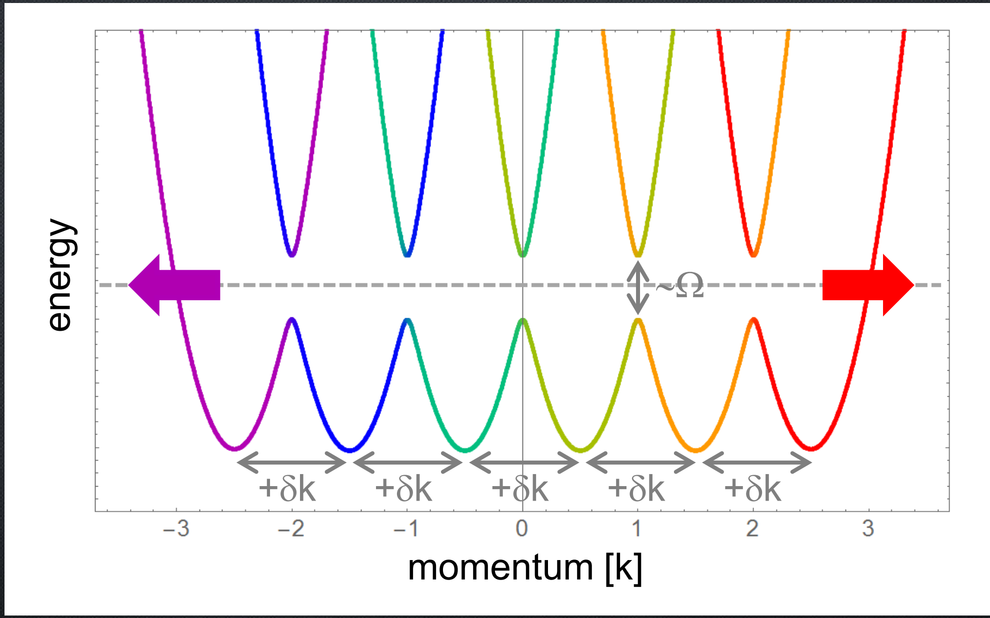
$J(\phi) = J(2\pi + \phi)$ lattice

Synthetic magnetic flux or spin-orbit coupling?

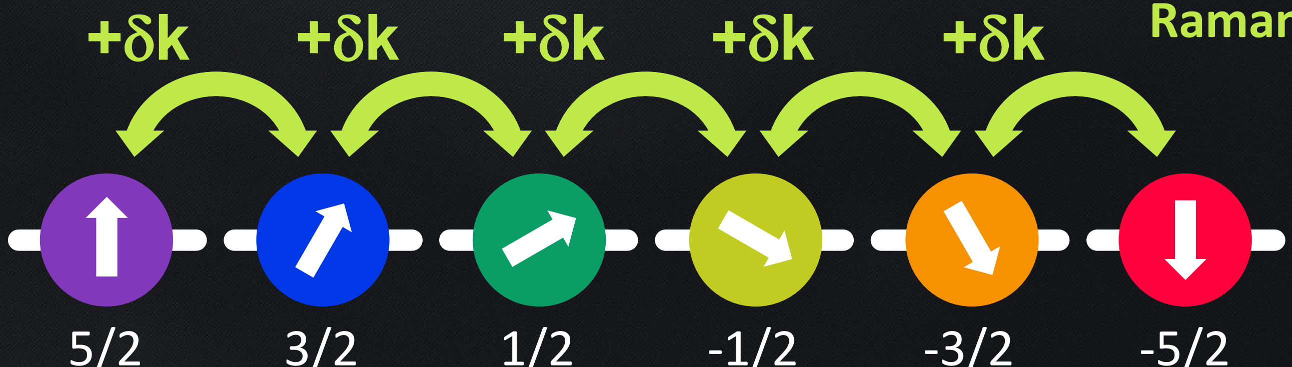


Synthetic magnetic flux or spin-orbit coupling?

spin-orbit coupling in real space

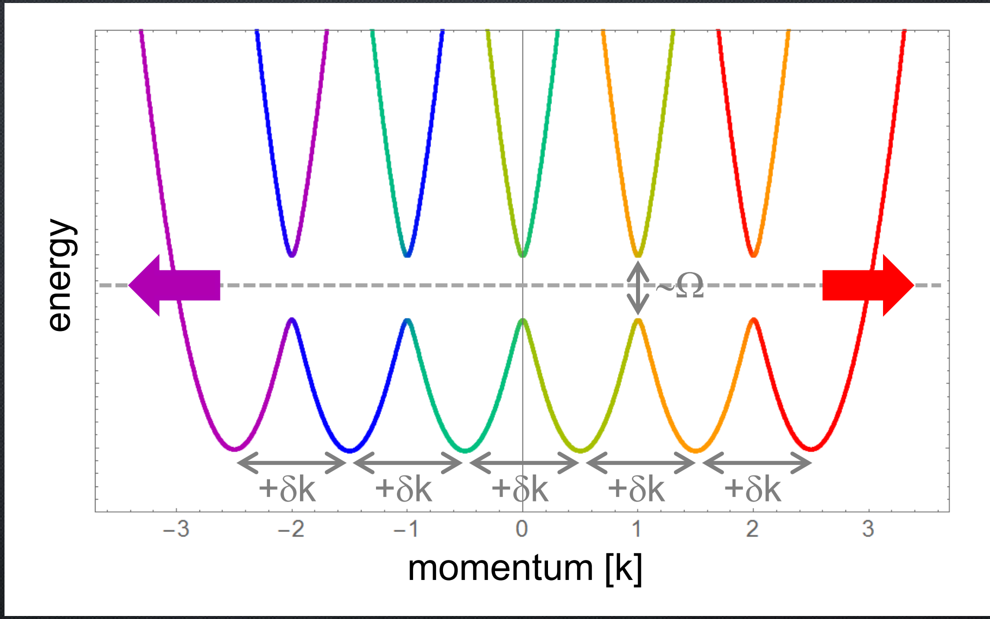


two-photon Raman transitions

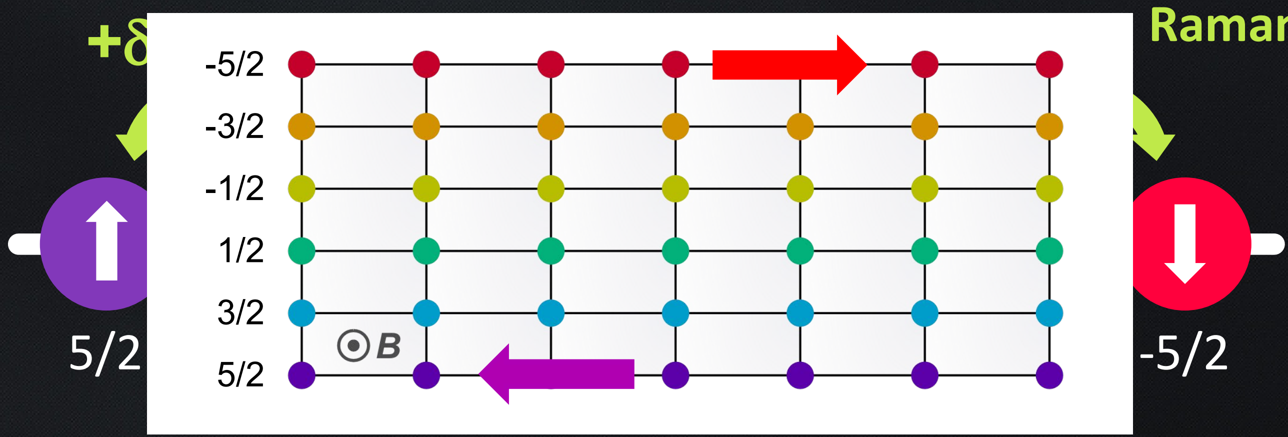


Synthetic magnetic flux or spin-orbit coupling?

spin-orbit coupling in real space



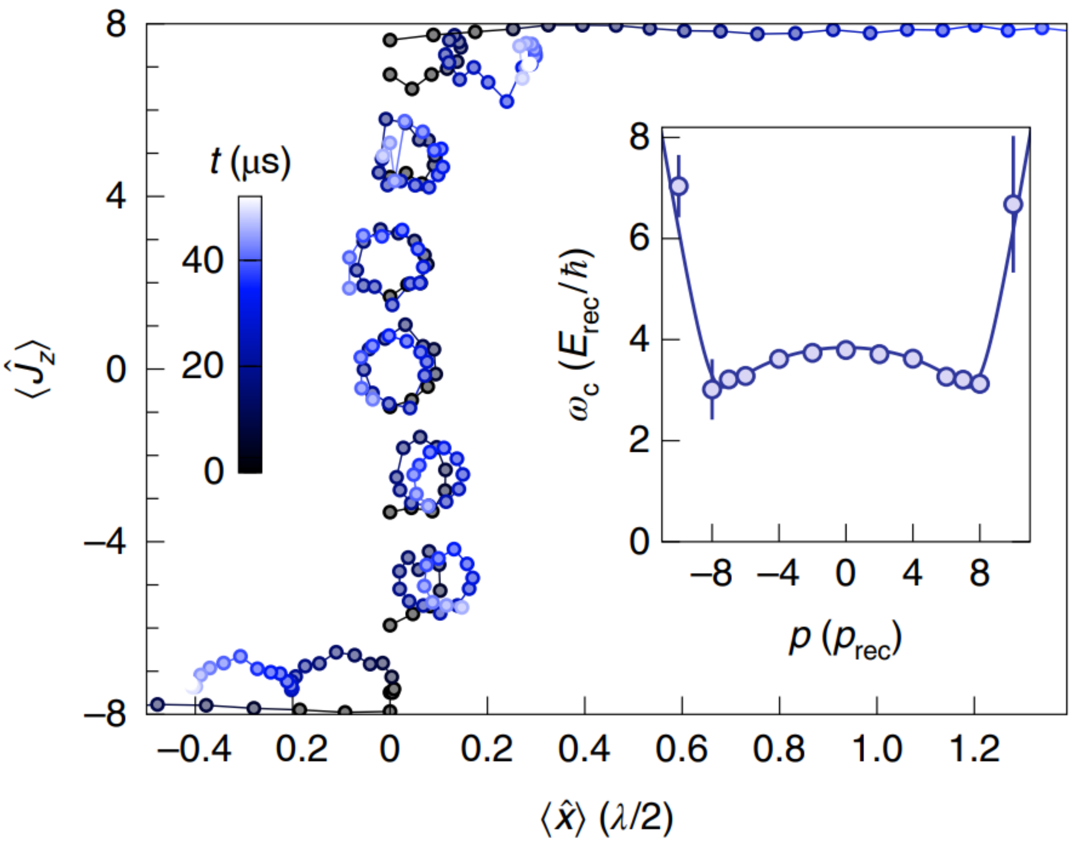
two-photon
Raman transitions



Larger synthetic dimensions

Probing chiral edge dynamics and bulk topology of a synthetic Hall system

Thomas Chalopin[1,3], Tanish Satoor[1,3], Alexandre Evrard[1], Vasiliy Makhalov[1,2], Jean Dalibard[1], Raphael Lopes[1] and Sylvain Nascimbene[1]



^{162}Dy atoms

F=8

2F+1=17 sites

Lecture 1

- Introduction to multicomponent quantum gases
- Interactions in two-electron fermions and SU(N) physics
- Experimental techniques
- **EXP**: SU(N) physics in low dimensions
- **EXP**: SU(N) Fermi-Hubbard and breaking SU(N) physics

Lecture 2

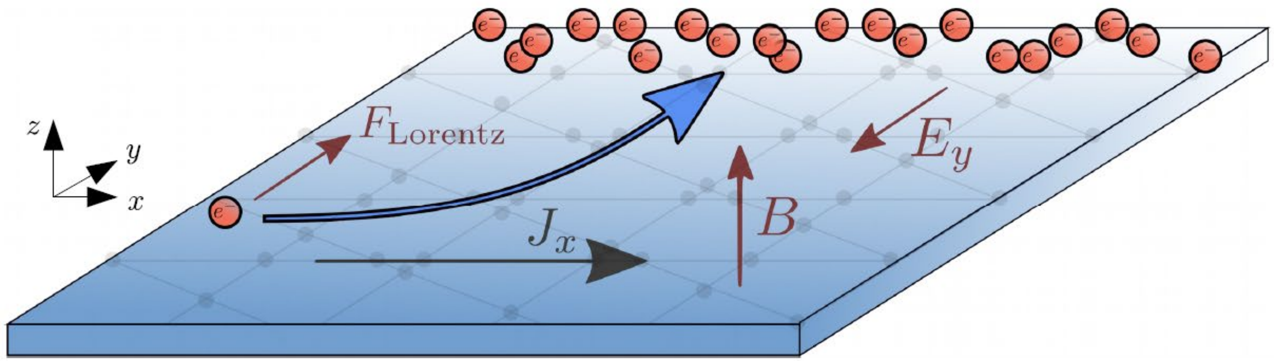
Observation of Universal Hall response
T. Zhou et al., arXiv:2205.13567

- Multicomponent systems with coherent coupling
- Synthetic dimensions and artificial magnetic fields
- **EXP**: Chiral edge currents in synthetic ladders
- **EXP**: Synthetic Hall effect

Hall effect

Classical picture of the Hall effect

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



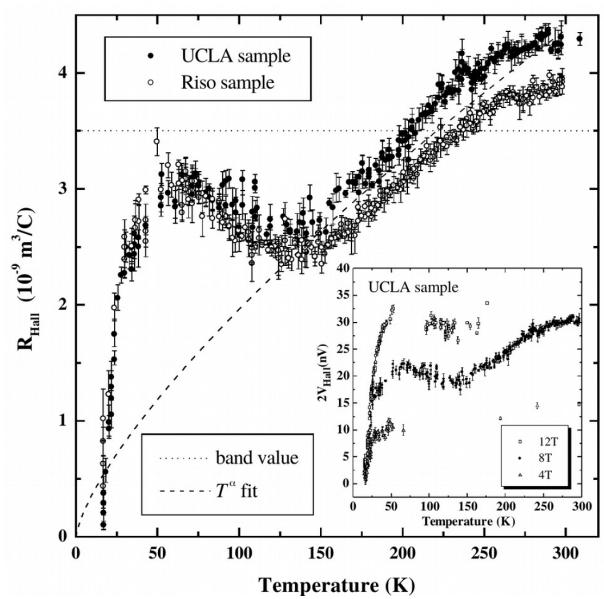
Well understood for noninteracting electrons in the continuum

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

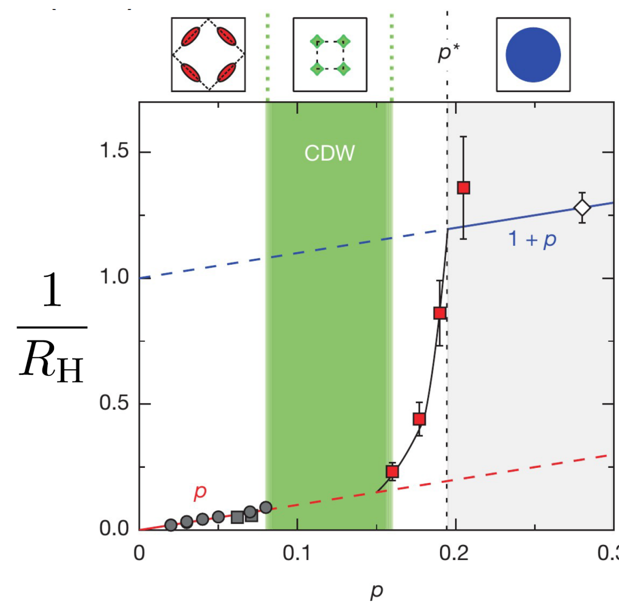
large B / quantum: $R_{\mathrm{H}} B = \frac{h}{e^2} \frac{1}{\nu} \quad \nu \in \boldsymbol{Z}$ quantization, metrology (resistance standards), …

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: $R_H = \frac{E_y}{B \cdot J_x} \sim \cancel{\frac{-1}{nq}}$ temperature dependence, change of sign, …

large B / quantum: $R_H B = \frac{h}{e^2}\frac{1}{\nu} \quad \nu \in \cancel{Z}$ Q fractional quantum Hall fractional statistics, …

Hall effect in synthetic ladders

How to measure the Hall response for strongly interacting atomic systems?

PHYSICAL REVIEW LETTERS **122,** 083402 (2019)

Editors' Suggestion

Universal Hall Response in Interacting Quantum Systems

Sebastian Greschner, Michele Filippone, and Thierry Giamarchi
Department of Quantum Matter Physics, University of Geneva, 1211 Geneva, Switzerland

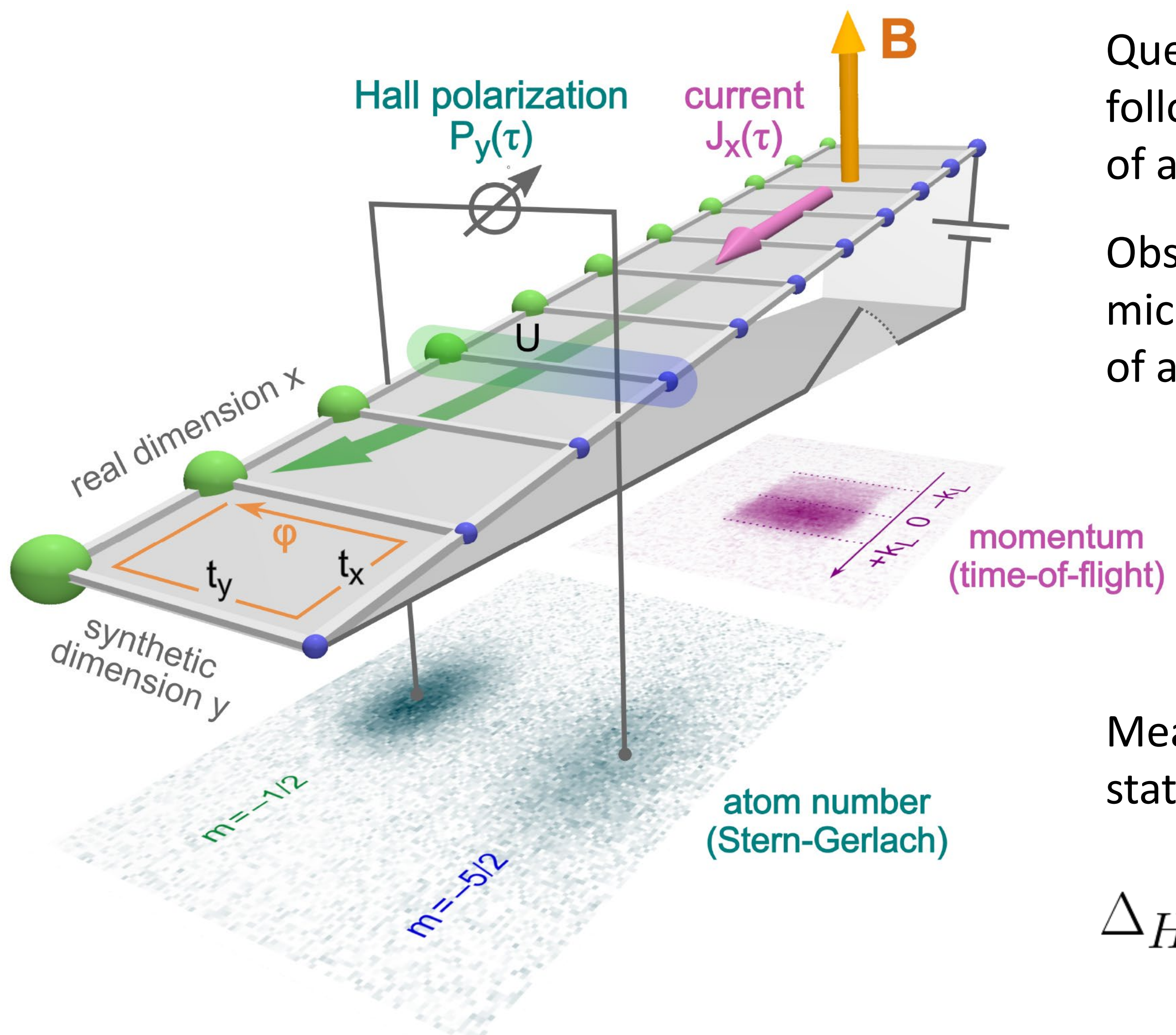
(Received 5 October 2018; published 28 February 2019)

We theoretically study the Hall effect on interacting M-leg ladder systems, comparing different measures and properties of the zero temperature Hall response in the limit of weak magnetic fields. Focusing on $SU(M)$ symmetric interacting bosons and fermions, as relevant for, e.g., typical synthetic dimensional quantum gas experiments, we identify an extensive regime in which the Hall imbalance Δ_H is universal and corresponds to a classical Hall resistivity $R_H = -1/n$ for a large class of quantum phases. Away from this high symmetry point we observe interaction driven phenomena such as sign reversal and divergence of the Hall response.

DOI: 10.1103/PhysRevLett.122.083402

T. Zhou et al., arXiv:2205.13567

Measurement of Hall response



Quenched dynamics following the activation of a longitudinal field

Observation of the microscopic build-up of a Hall response

Measurement of a stationary Hall imbalance

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

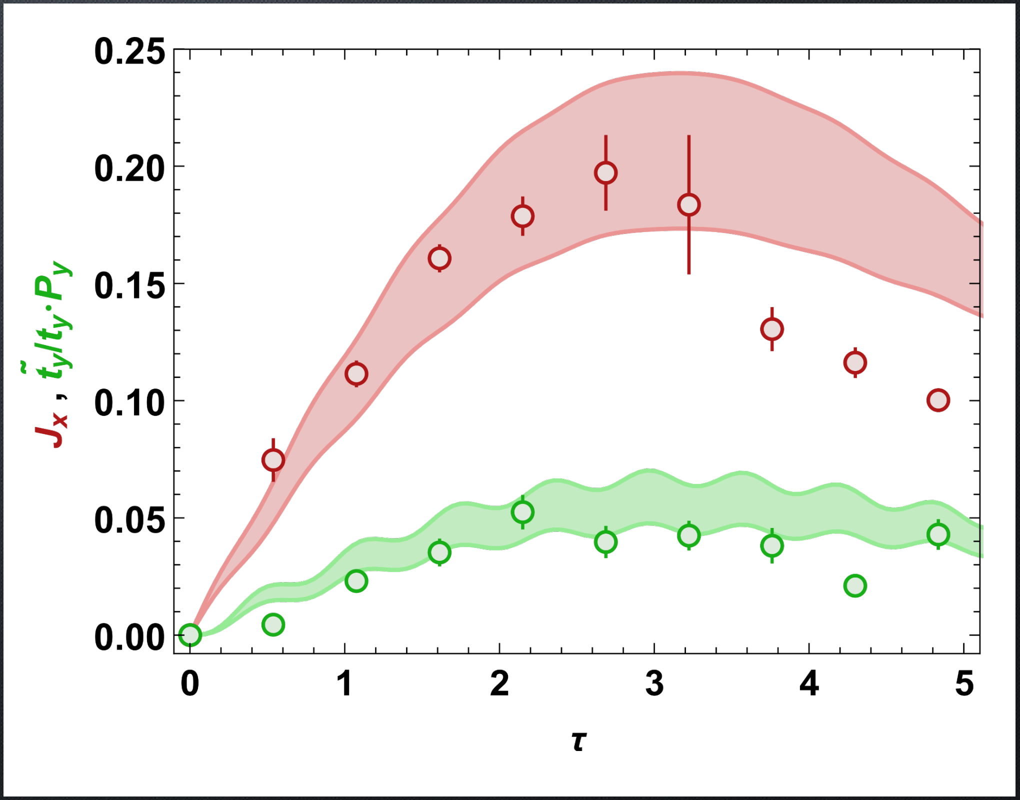
Hall effect in synthetic ladders

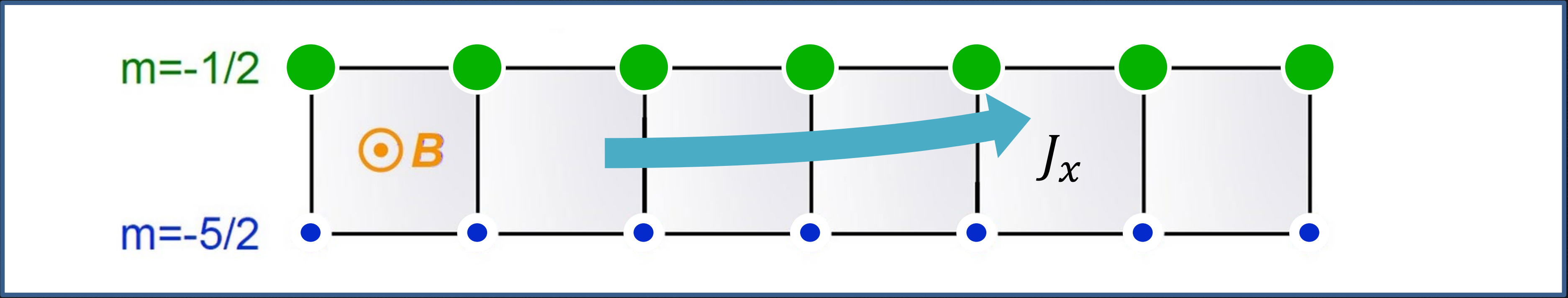
Optical gradient along x induces a longitudinal current

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

and a time-dependent polarization (Hall response)

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





Hall effect in synthetic ladders

Optical gradient along x induces a longitudinal current

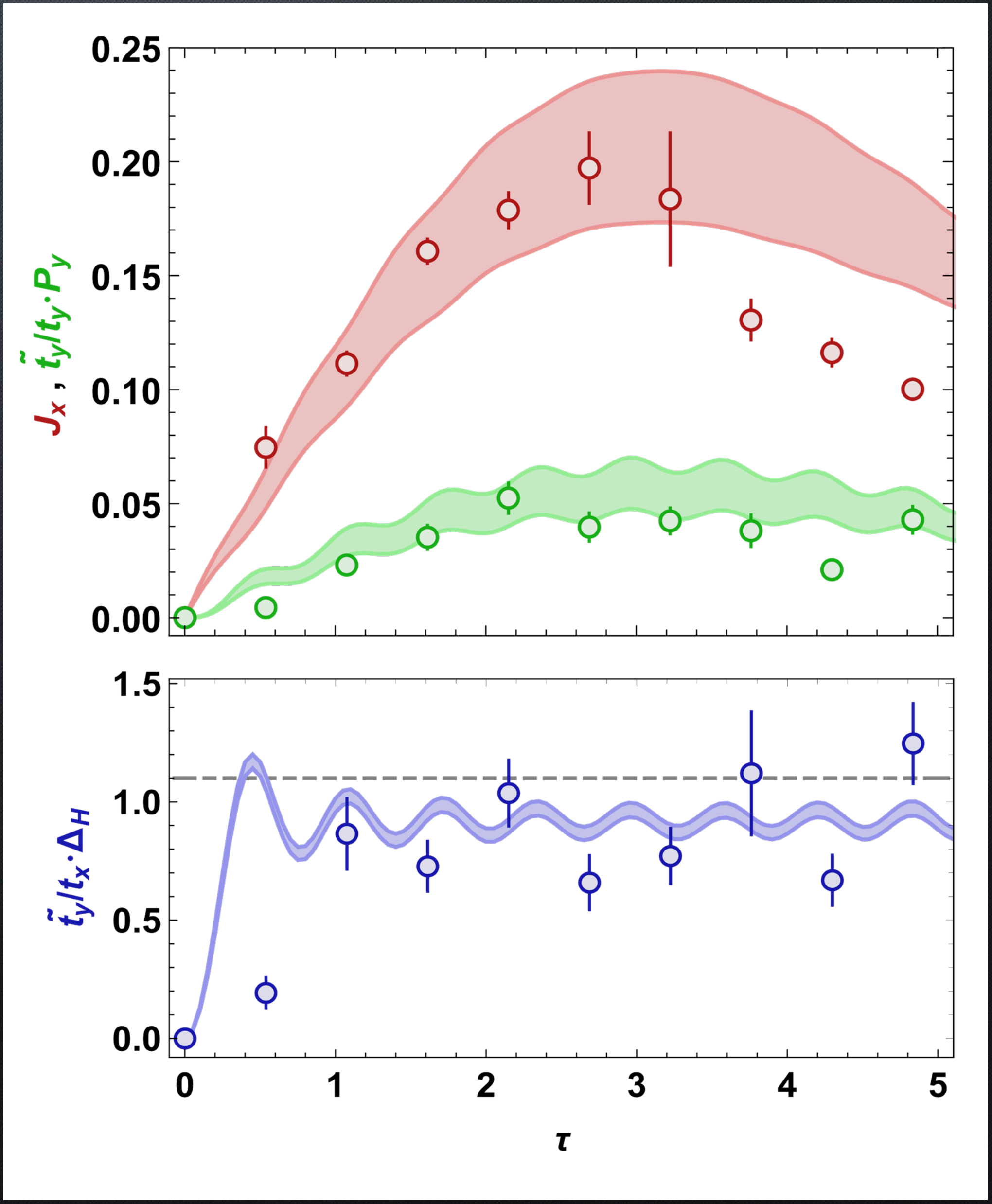
$$J_x = \sum_m \int \sin(k) n_m(k) dk$$

and a time-dependent polarization (Hall response)

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

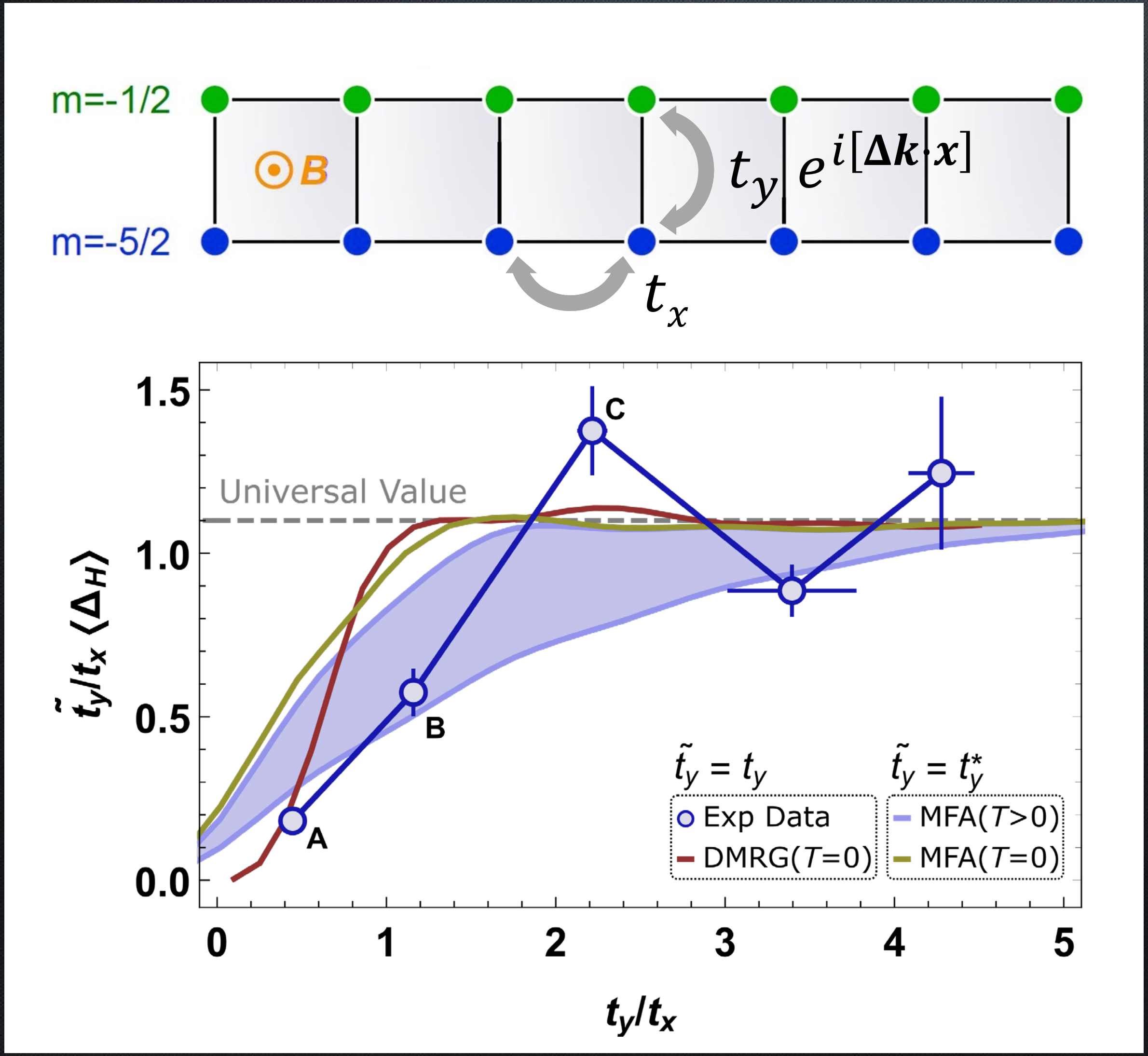
The **Hall imbalance** rapidly approaches a stationary regime

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



T. Zhou et al., arXiv:2205.13567

Universal regime of Hall response

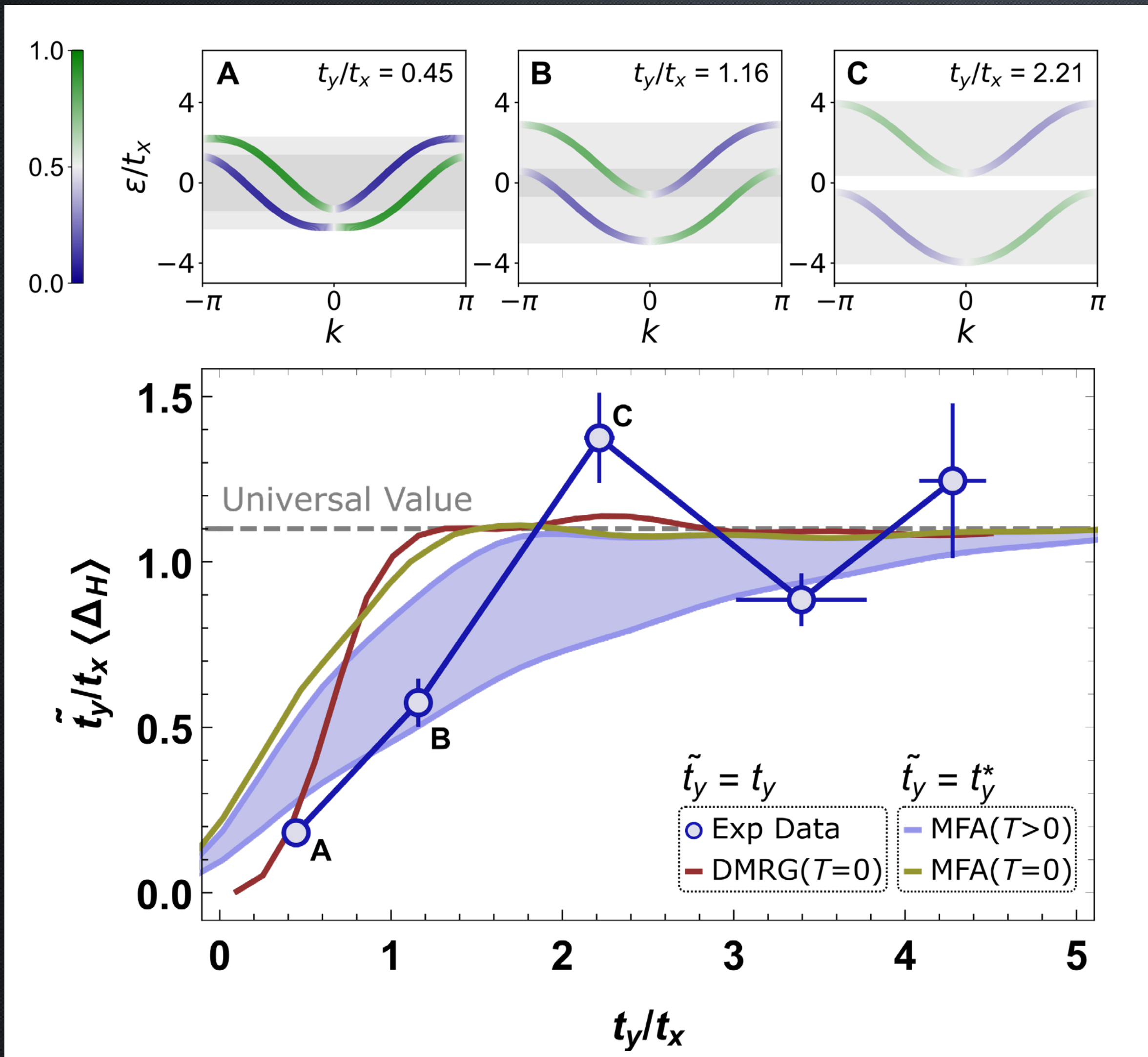


Dependence of the Hall imbalance on the transverse hopping t_y

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

T. Zhou et al., arXiv:2205.13567

Universal regime of Hall response



Dependence of the Hall imbalance on the transverse hopping t_y

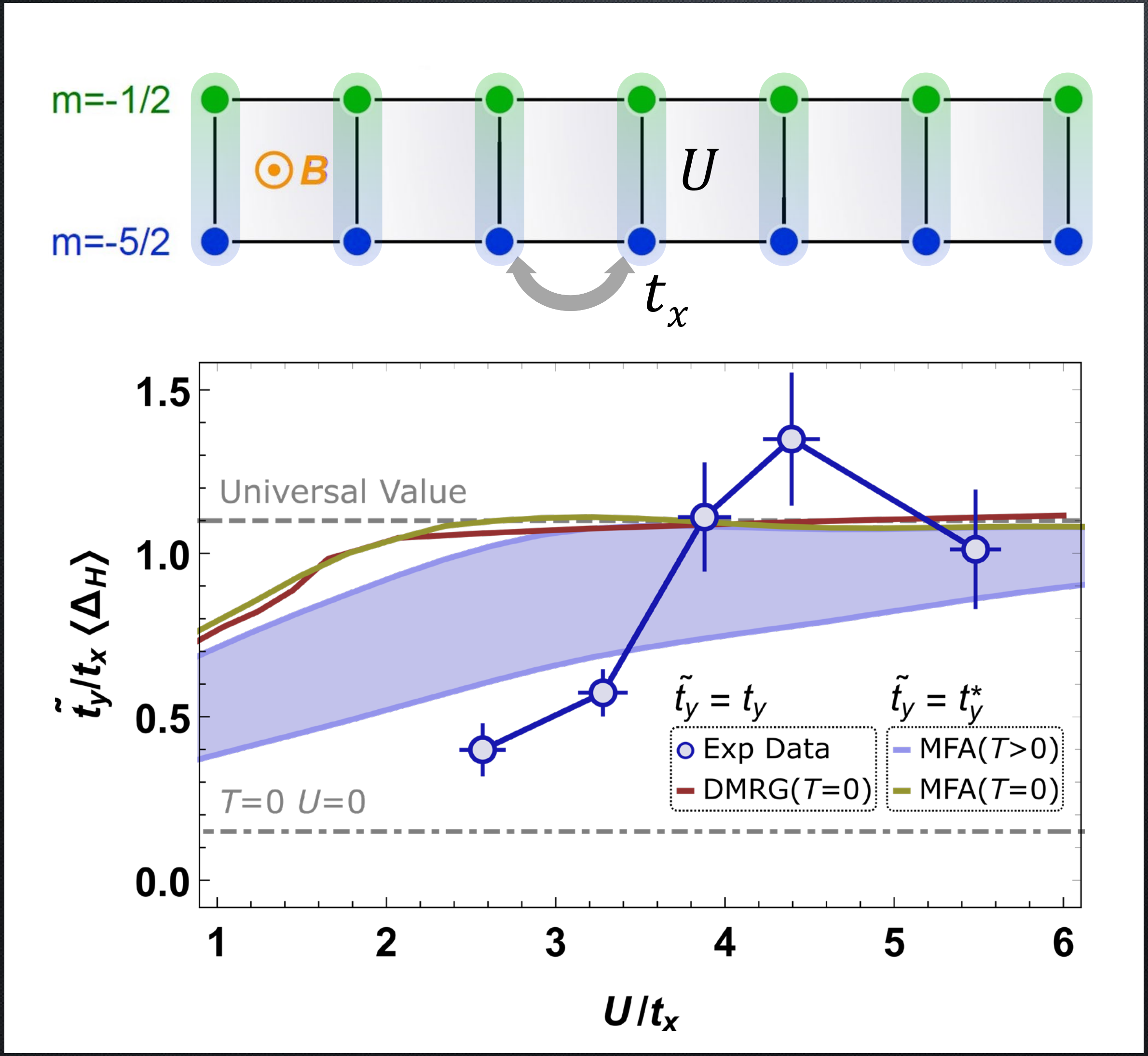
A large t_y opens a gap between the two bands, stabilizing a single-band metal where Δ_H takes the universal value

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

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

T. Zhou et al., arXiv:2205.13567

Universal regime of Hall response



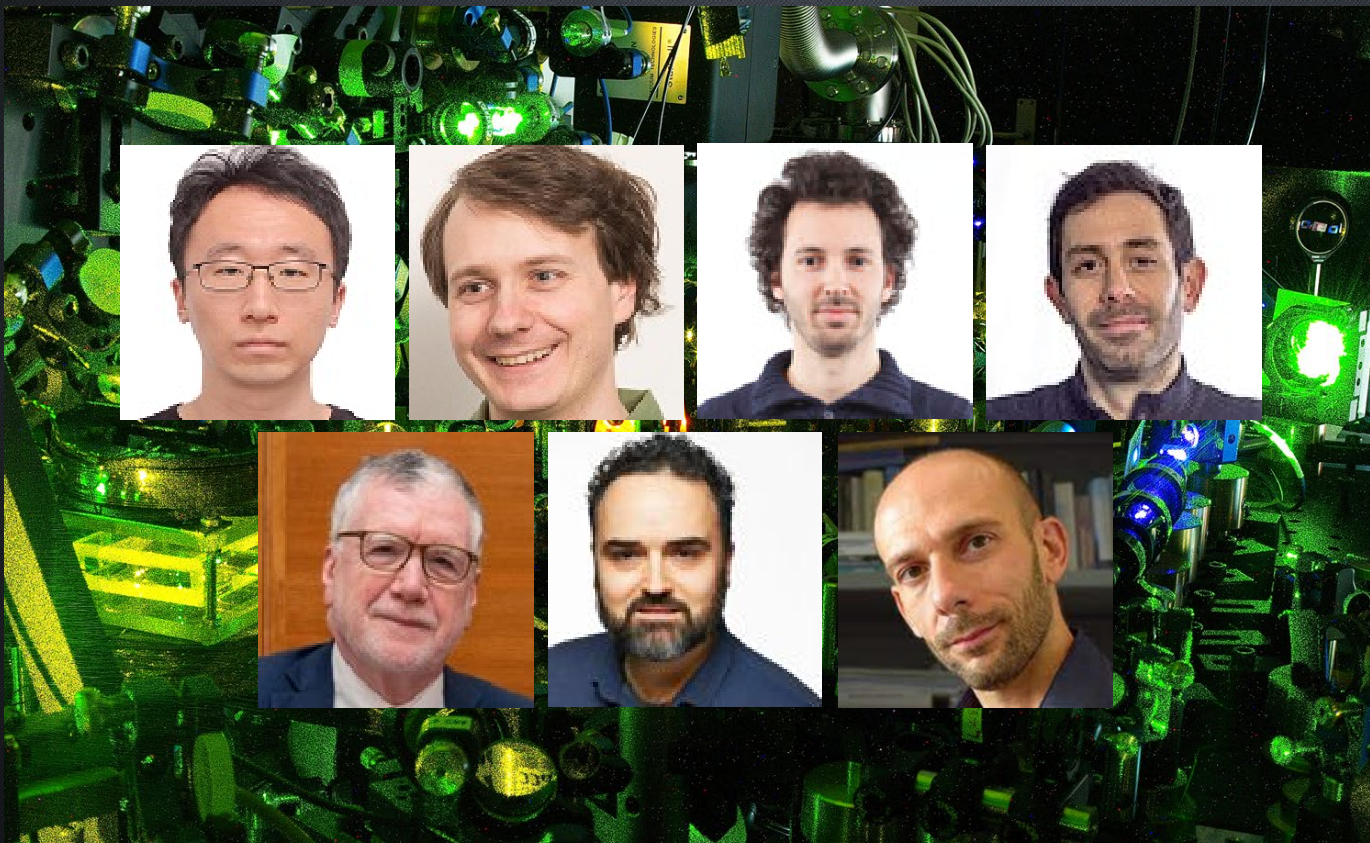
Dependence of the Hall imbalance on the interaction strength U

Clear effect of atom-atom interactions on Hall dynamics

Increasing U leads to a robust single-band metallic state characterized by the universal Hall imbalance

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

Credits



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L. F.

Former members:

Lorenzo Franchi
Lorenzo Livi
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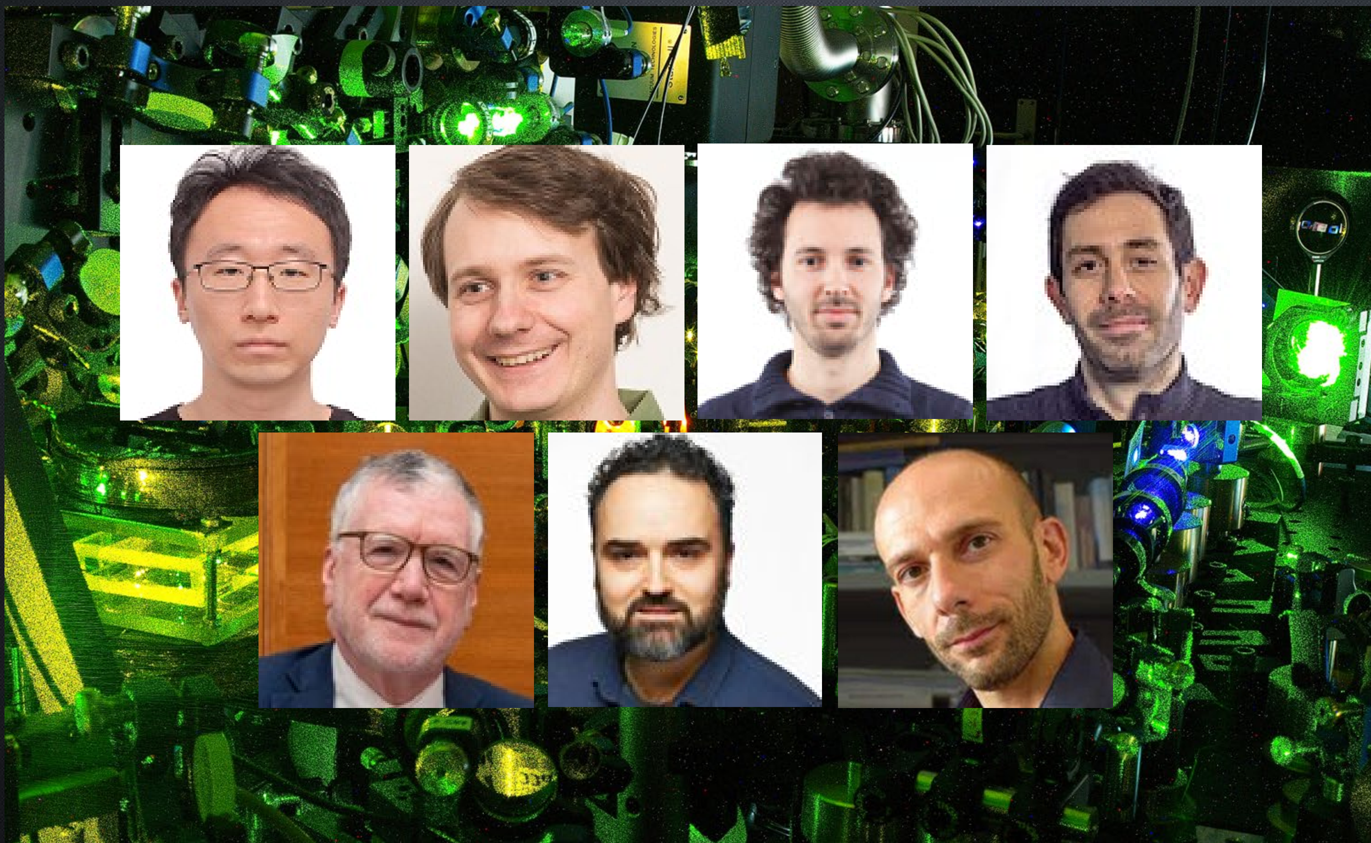
Pietro Lombardi
Guido Pagano
Florian Schafer
Carlo Sias
Daniele Tusi

€€€: ERC (TOPSIM), QUANTERA (QTFLAG), MIUR (FARE+PRIN), INFN (FISH)

Credits



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Theory:

L. Del Re
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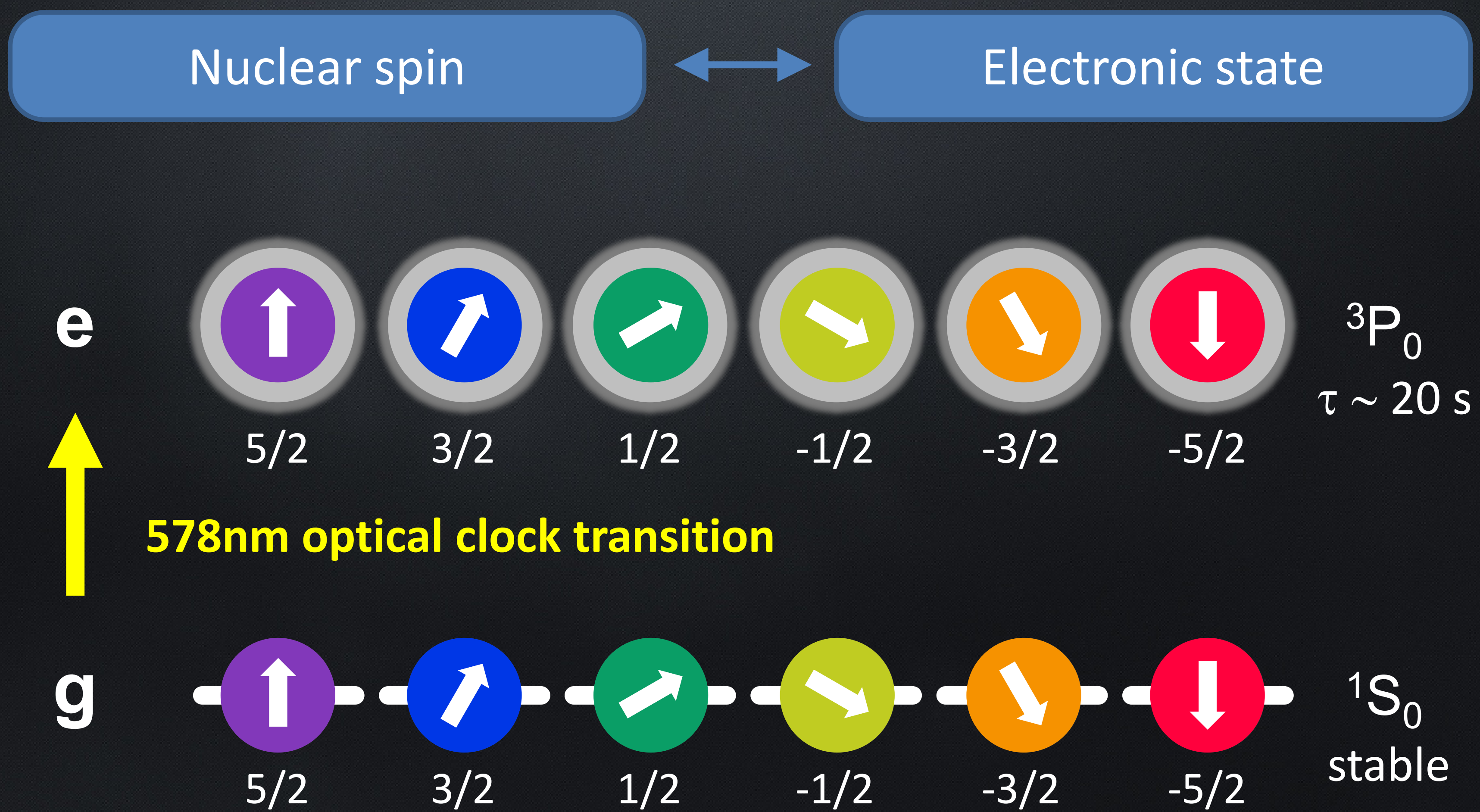
T. Giamarchi

€€€: ERC (TOPSIM), QUANTERA (QTFLAG), MIUR (FARE+PRIN), INFN (FISH)

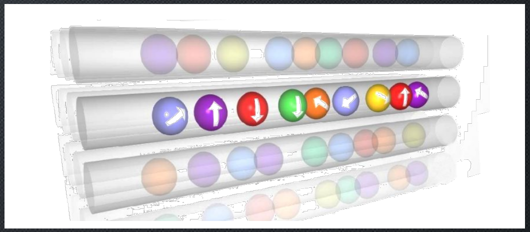
Nuclear spin and electronic state

Two internal degrees of freedom with long coherence times:

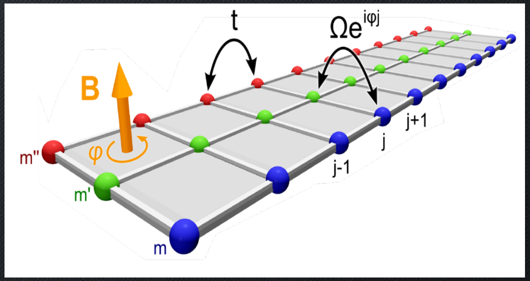


Thank you!

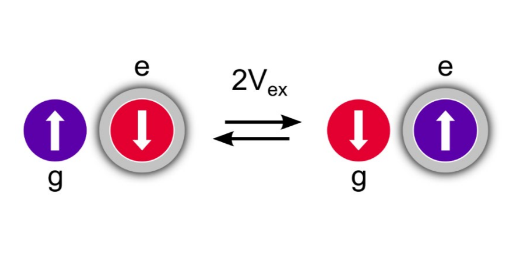
LECTURE 1
Strongly interacting SU(N) fermions
G. Pagano et al., *Nature Phys.* **10**, 198 (2014)
D. Tusi et al., arXiv:2104.13338 (2021)

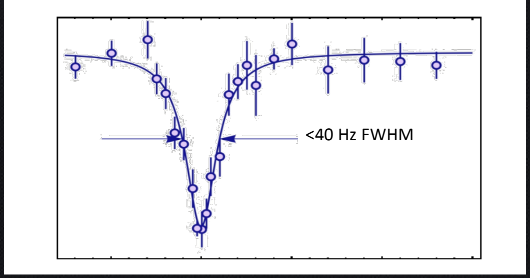


LECTURE 2
Synthetic dimensions and gauge fields
M. Mancini et al., *Science* **349**, 1510 (2015)
L. F. Livi et al., *PRL* **117**, 220401 (2016)
T. Zhou et al., arXiv:2205.13567 (2022)



EXTRA
Mixtures of nuclear spin and electronic states
Control of inter-orbital interactions:
G. Cappellini et al., *PRL* **113**, 120402 (2014)
G. Pagano et al., *PRL* **115**, 265301 (2015)
G. Cappellini et al., *PRX* **9**, 011028 (2019)





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