Exploring Synthetic Quantum Matter with Cold Atoms & Tensor Networks

Matteo Rizzi

Universität zu Köln & Forschungszentrum Jülich

Benasque, 27.02.2019

The Big Picture

<u>*Quantum Many-Body Systems:*</u>
usually very difficult problems
for classical math / algorithms

Classical Hardware reaching limit
& exploding Big Data:
demand for a new information age

new understanding of
entanglement properties:
<u>Tensor Networks</u>

HPC Numerical Methods
for strongly-correlated systems

Quantum Information Science

- Q-communication & Q-cryptography *[ready!]*
- Q-Computer (fully digital) *[long-time!]*
- Q-Simulator (analog) *[near-term!]*

Condensed Matter Physics

Among *many* recipes for qubits:
<u>topological states of matter</u>

Still difficult to access & control …

Quantum Optics & Atomic physics

Control of single quantum objects,
long coherence times, …

Geometrical constraints

(background) gauge fields

interaction range & strength

<u>Synthetic Quantum Matter</u>

The Big Picture

Quantum Simulation with Cold Atomic Gases

Geometrical constraints

(background) gauge fields ⟷ *interaction range & strength*

=

Access to synthetic topological matter & more !

Here:

Fermionic Models: studies via Mappings & Tensor Networks

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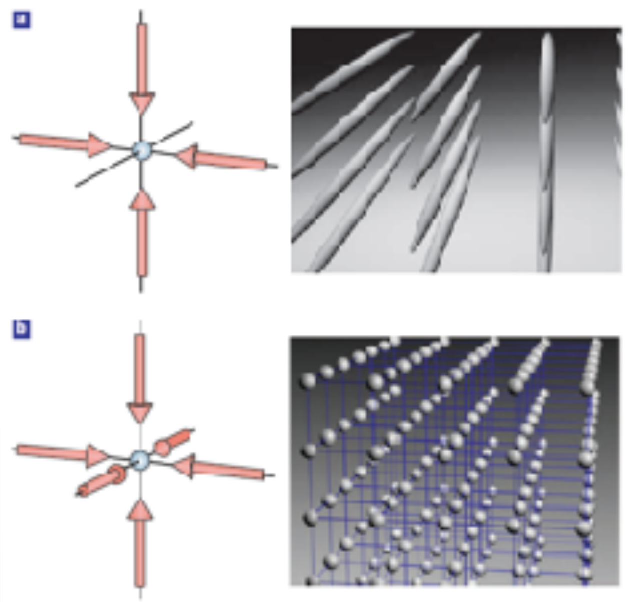
Synthetic Quantum Matter

Bottom-up engineering

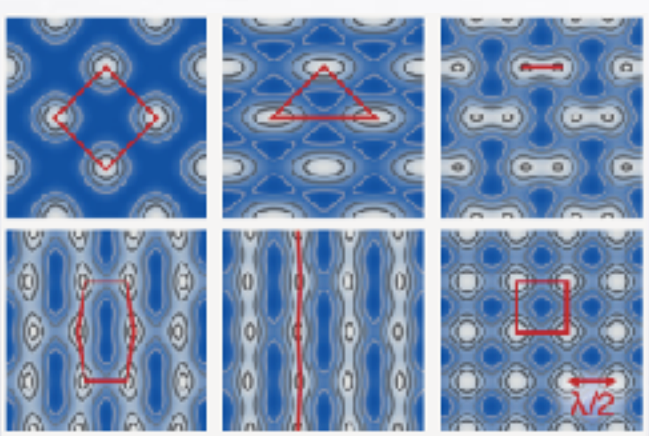
trapped ions, superconducting qubits, quantum dots, NV centers, etc.

Hamiltonian engineering

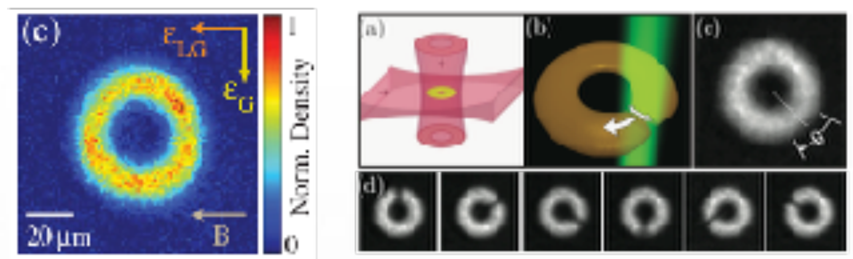
<u>cold atomic gases</u>, photonic systems, …



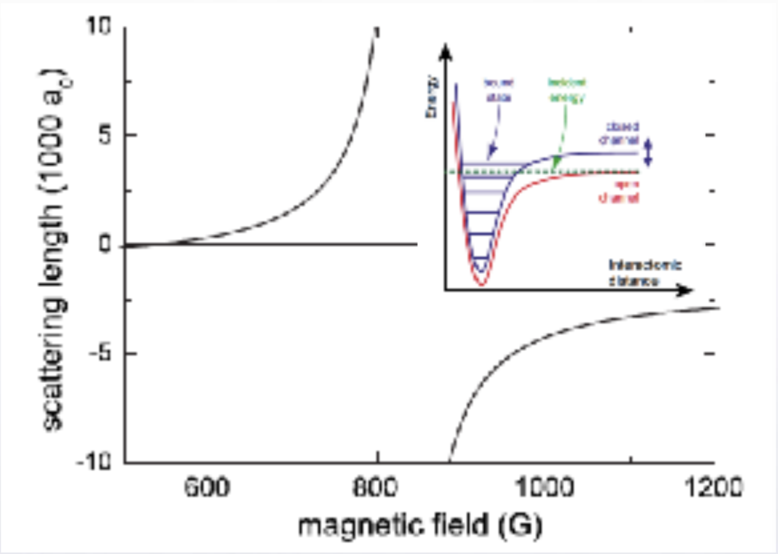
I. Bloch, et al. RMP **80**, 885 (2008)



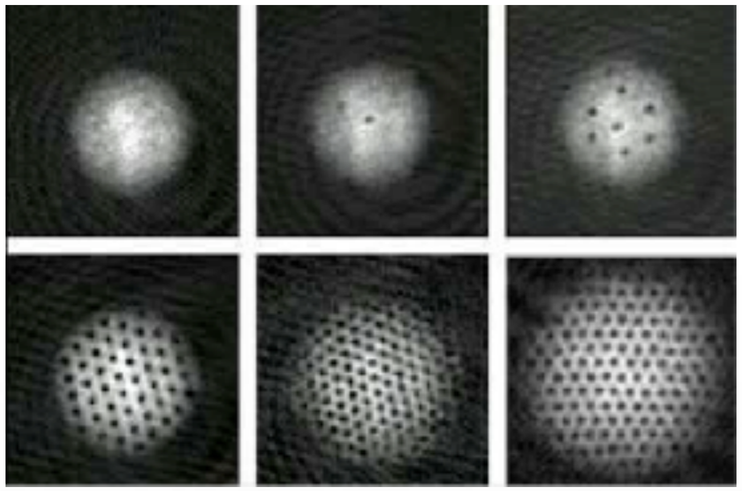
L. Tarruell, et al., Nature **483**, 302 (2012)



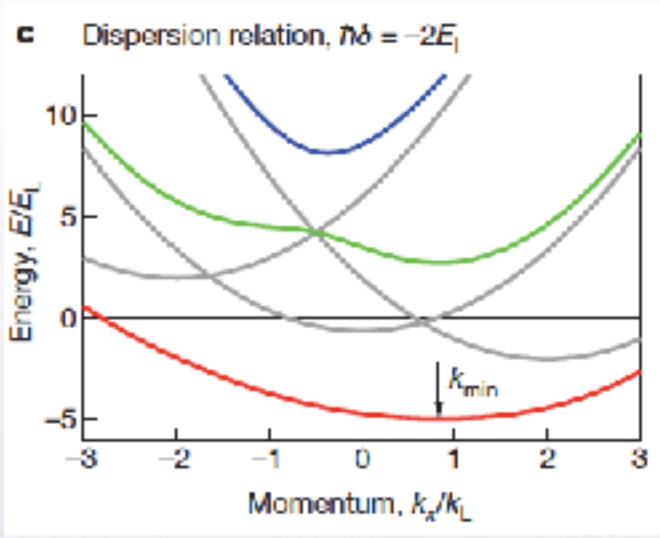
Ramanathan et al., PRL 106, 130401 (2011);



C.Chin,et al.,RMP **82**,1225 (2010)



A. Fetter, RMP **81**, 647 (2009)



J. Dalibard, et al., RMP **83**, 1523 (2011)
N. Goldman, et al., RPP **77**, 126401 (2014)

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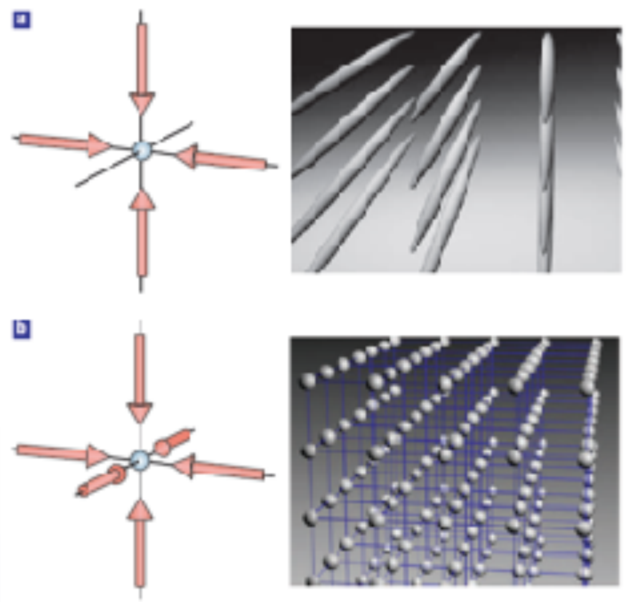

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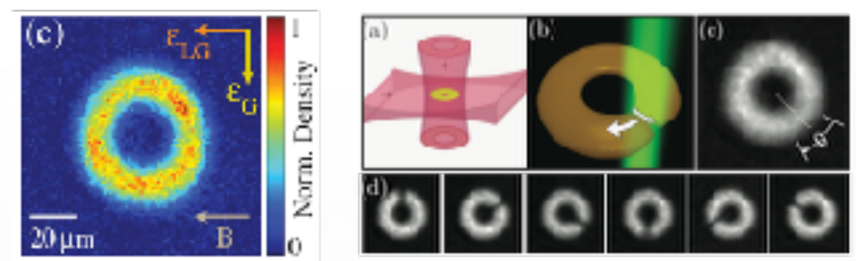

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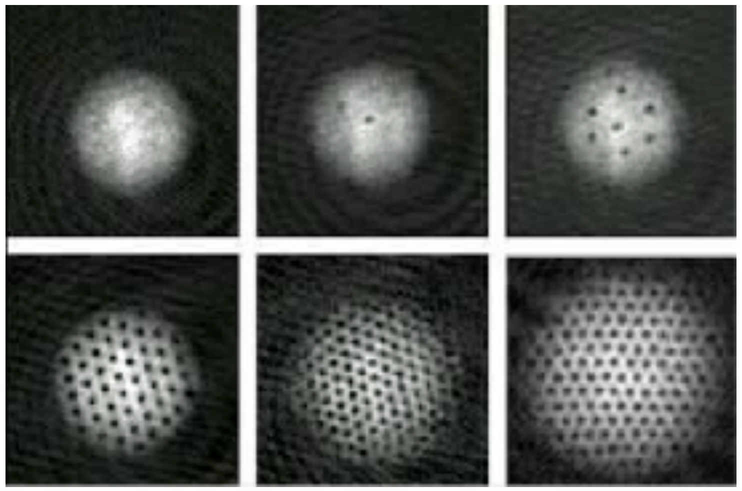

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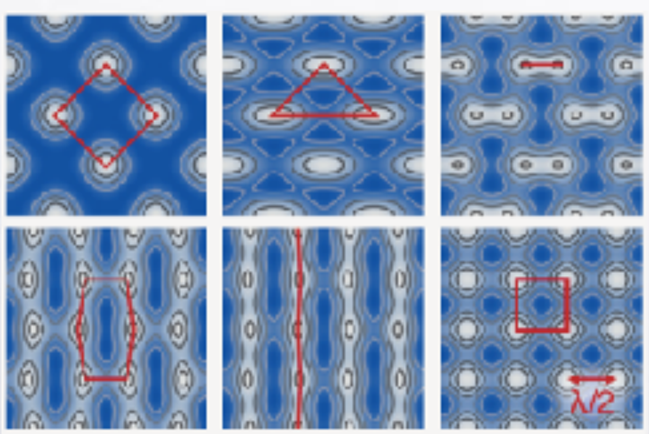

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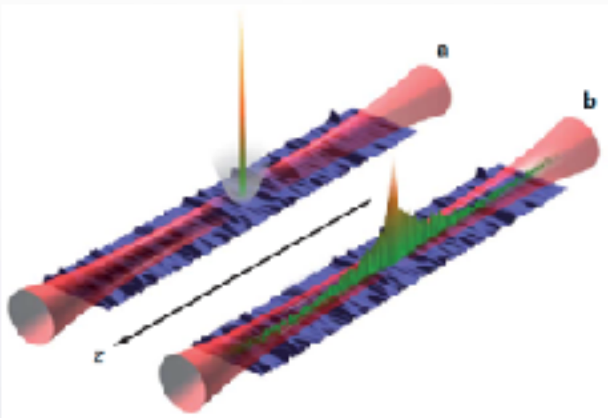
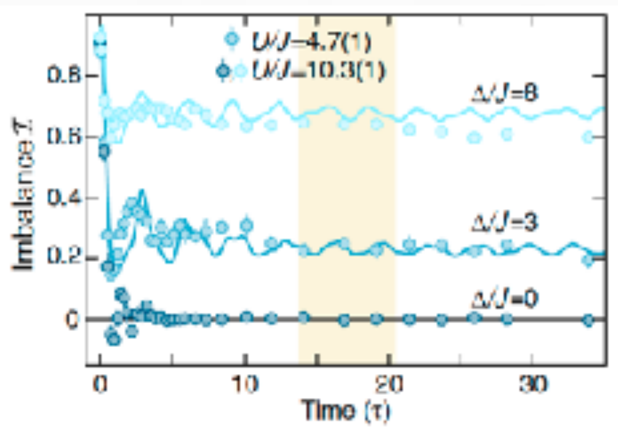
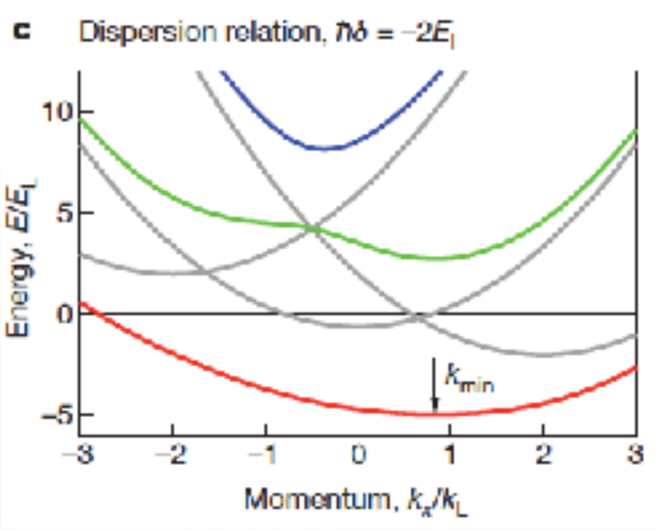


J. Billy, et al.,
Nature 453, 891 (2008)



M. Schreiber, et al.,
Science 349, 842 (2015)



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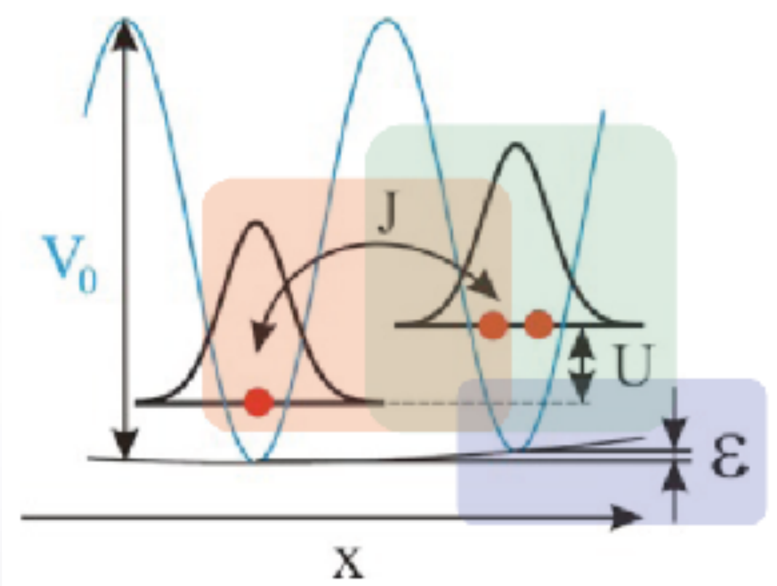
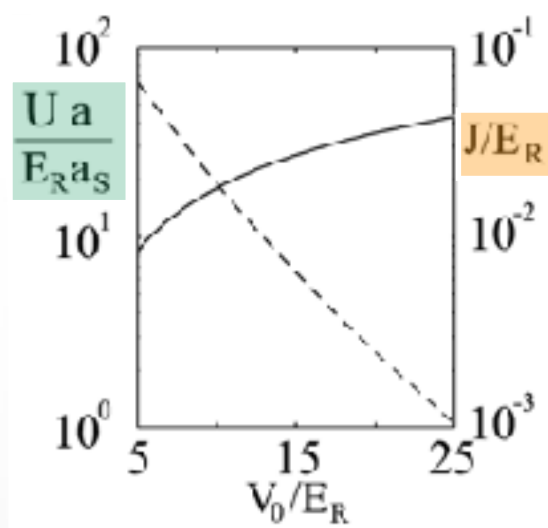
Hubbard models

Tight-binding model
out of localized
(single particle)
Wannier functions

$$H = -J \sum_{<i,j>} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i(\hat{n}_i - 1)$$

D. Jaksch et al., PRL **81** 3108 (1998)

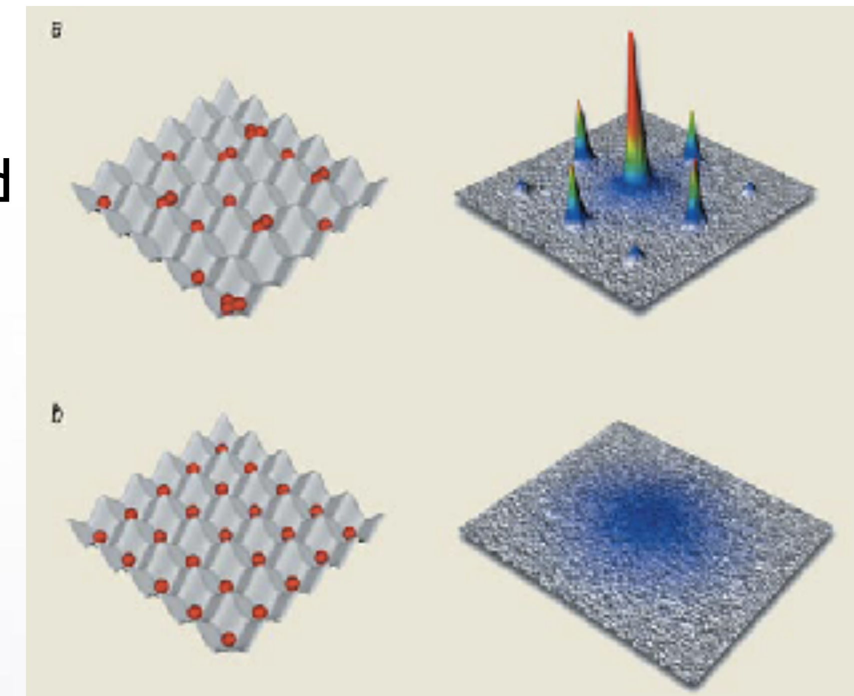




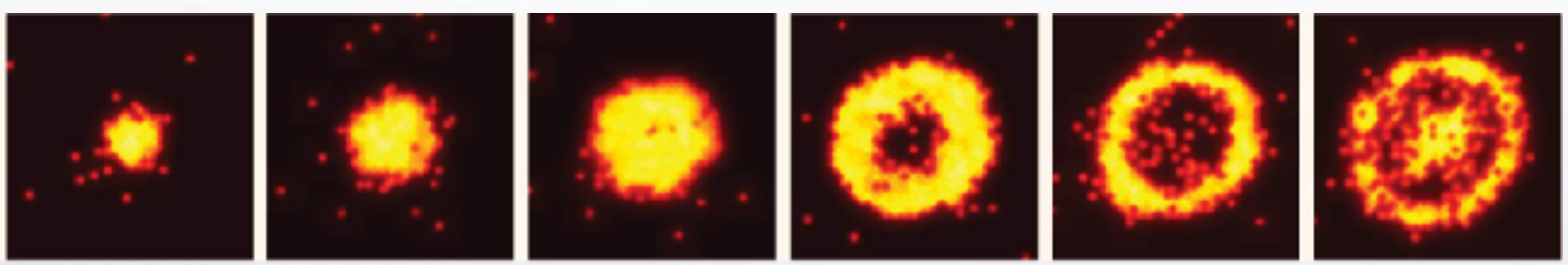
real space momentum space

Superfluid

Mott Insulator



M. Greiner, et al., Nature **415**, 39 (2002)



Sherson, et al. Nature **467**, 68 (2010).

nowadays: spectacular progresses with 2D Fermi-Hubbard!

e.g., Greiner & Bloch & Esslinger labs

Hubbard models

Tight-binding model out of localized (single particle) Wannier functions

$$H = -J \sum_{<i,j>} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

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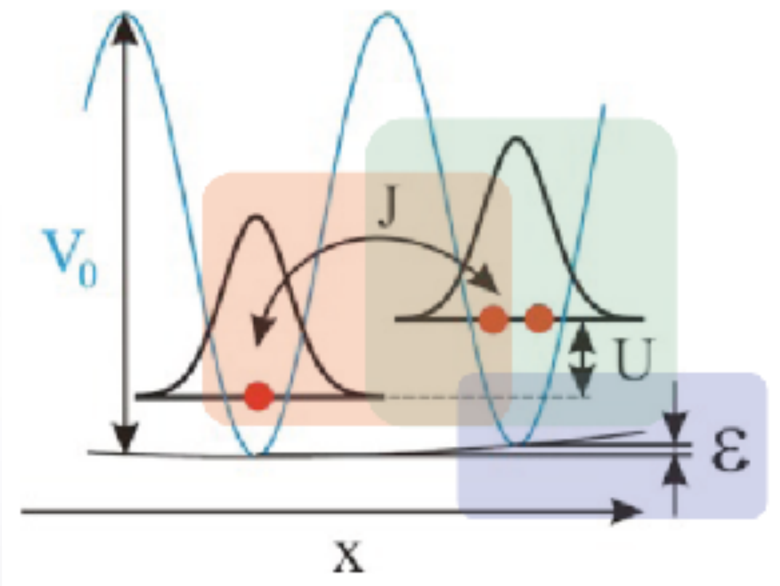
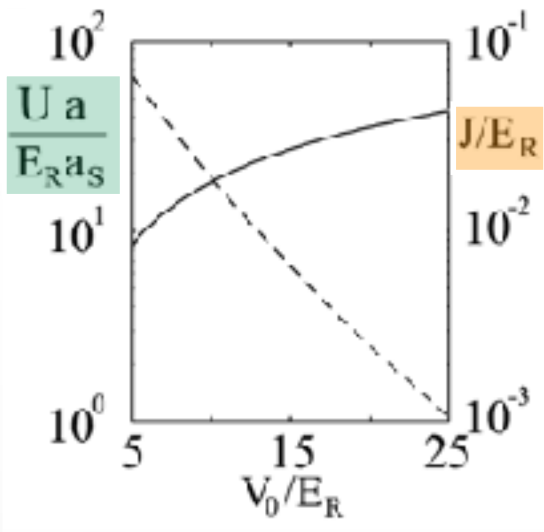
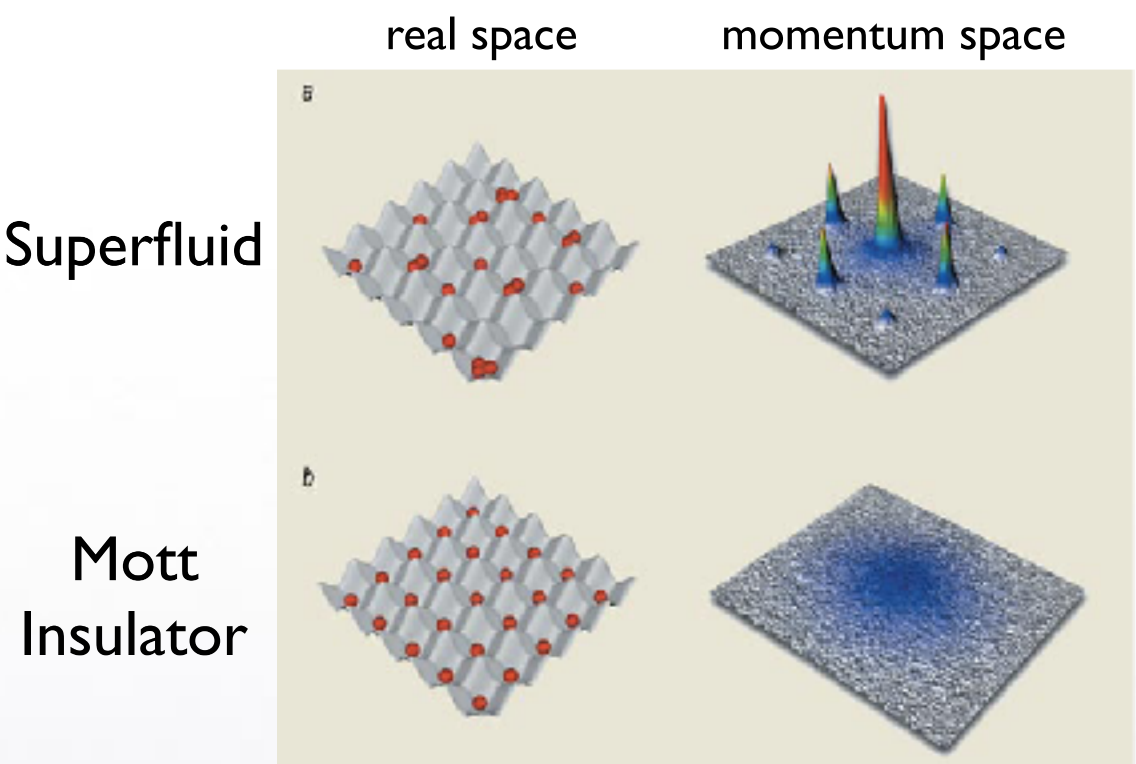






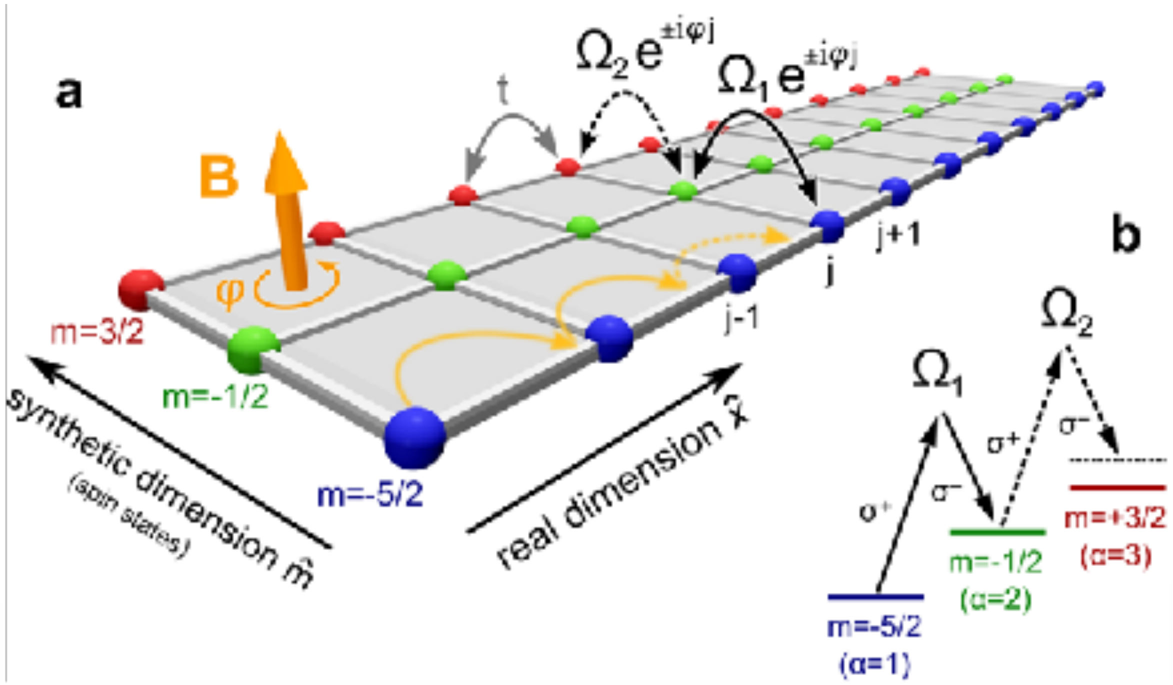
M. Greiner, et al., Nature **415**, 39 (2002)

nuclear / hyperfine levels → multi-flavor / multi-orbital Hubbard models

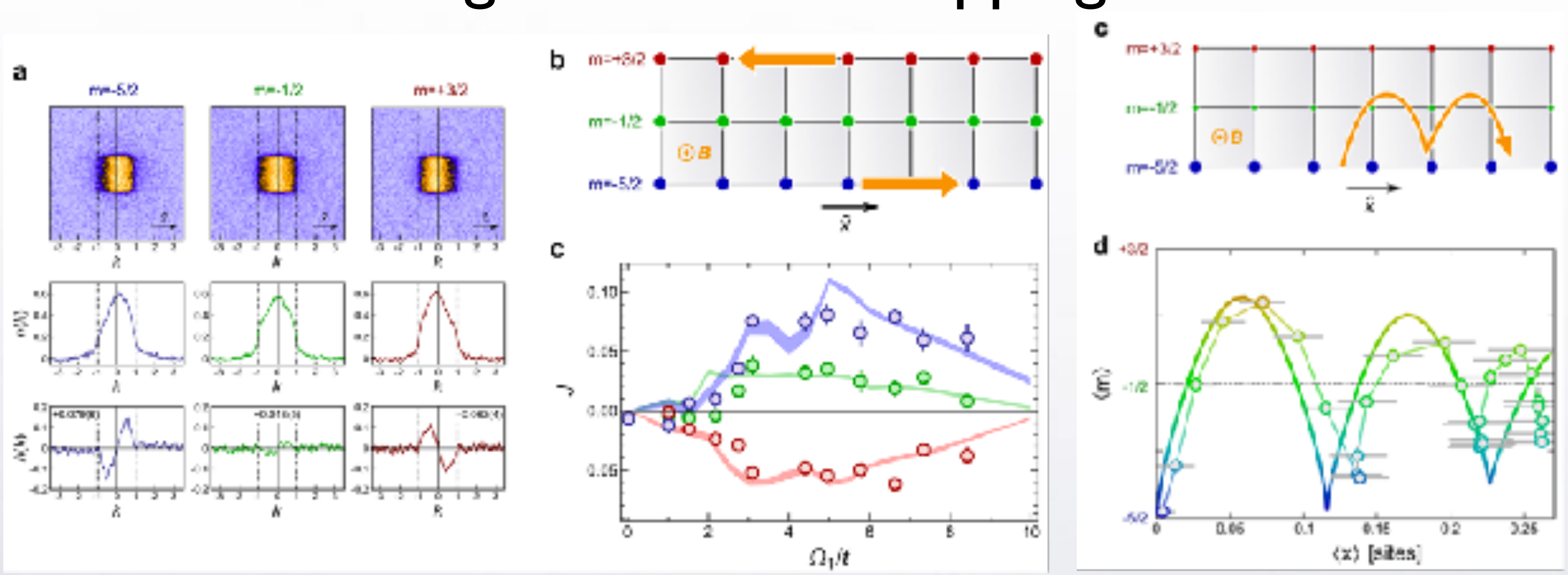
nuclear / hyperfine levels → *synthetic* (extra-)dimension

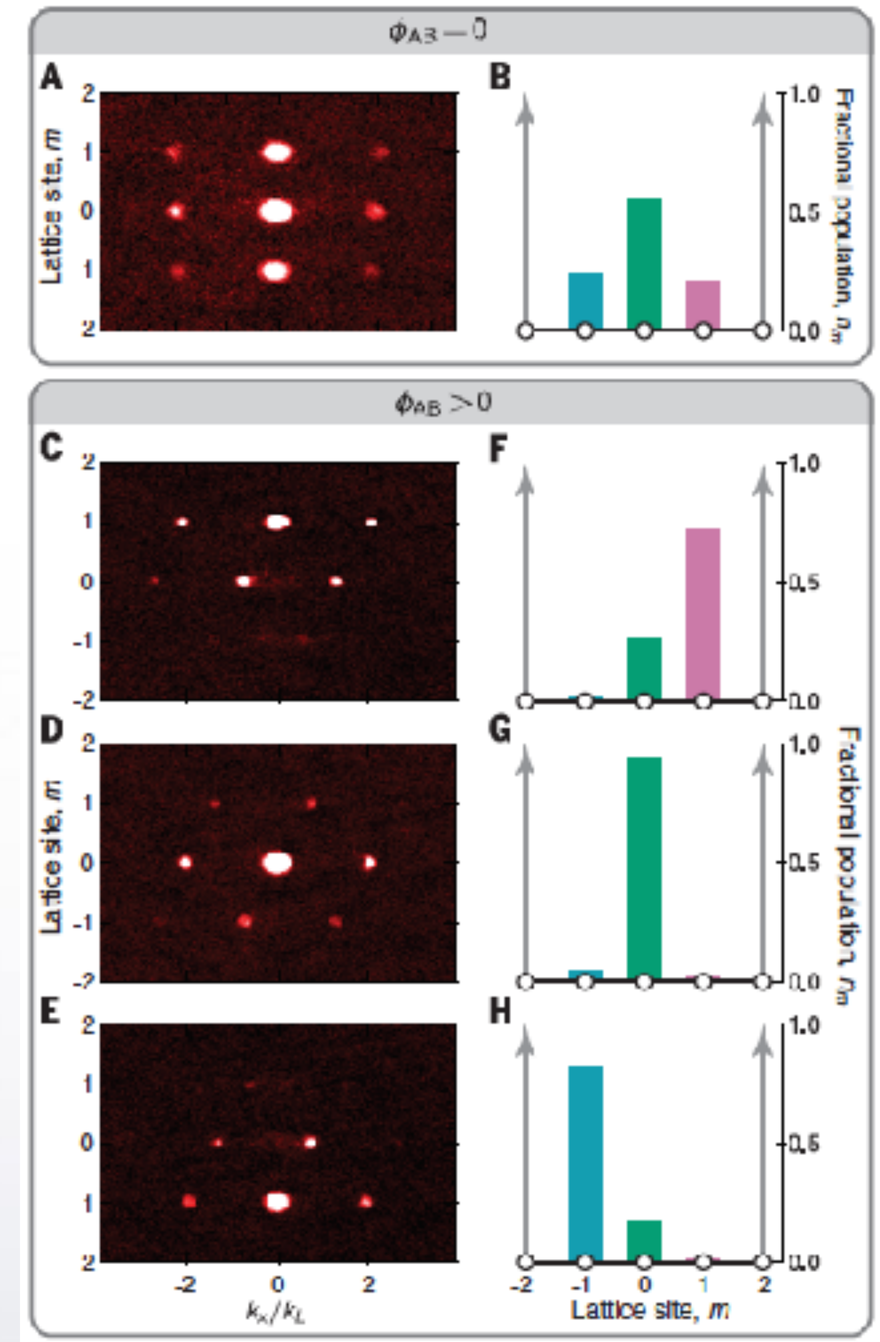
A. Celi et al., PRL **108**, 133001 (2012) & **112**, 043001 (2014)

Synthetic ladders



Chiral edge currents & skipping orbits





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

B.K. Stuhl, et al., Science **349**, 1514 (2015)

+ many more related experiments @ Harvard, MIT, Munich, Paris, etc.

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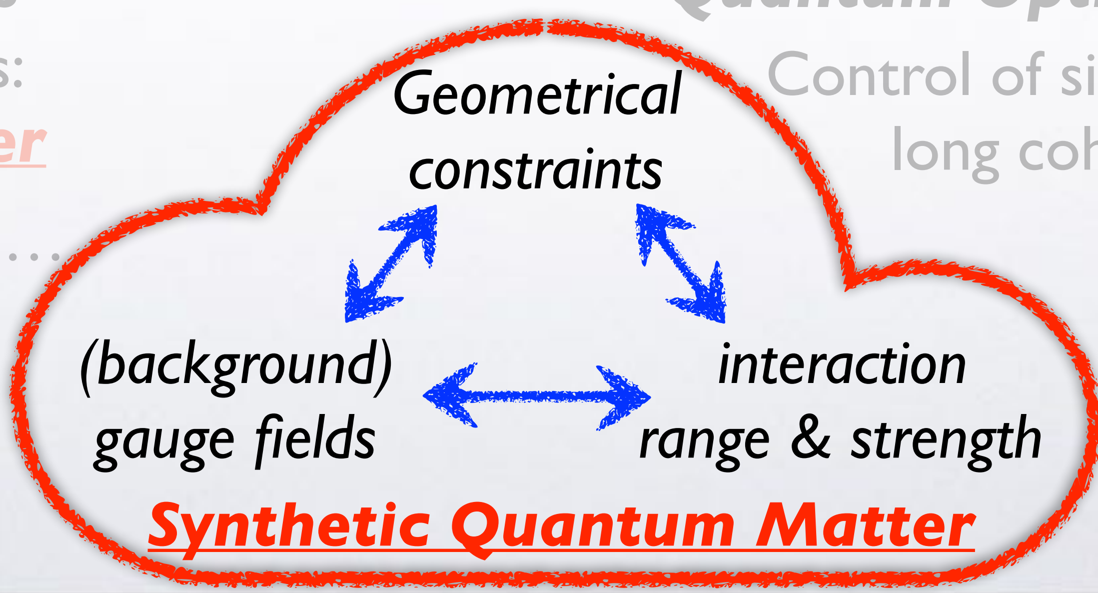

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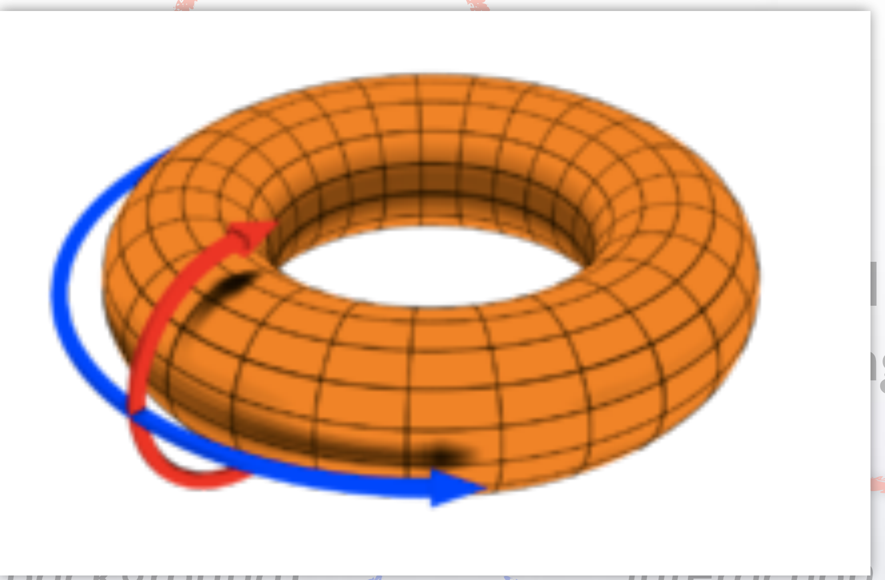

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gauge fields ↔ *range & strength*

Synthetic Quantum Matter

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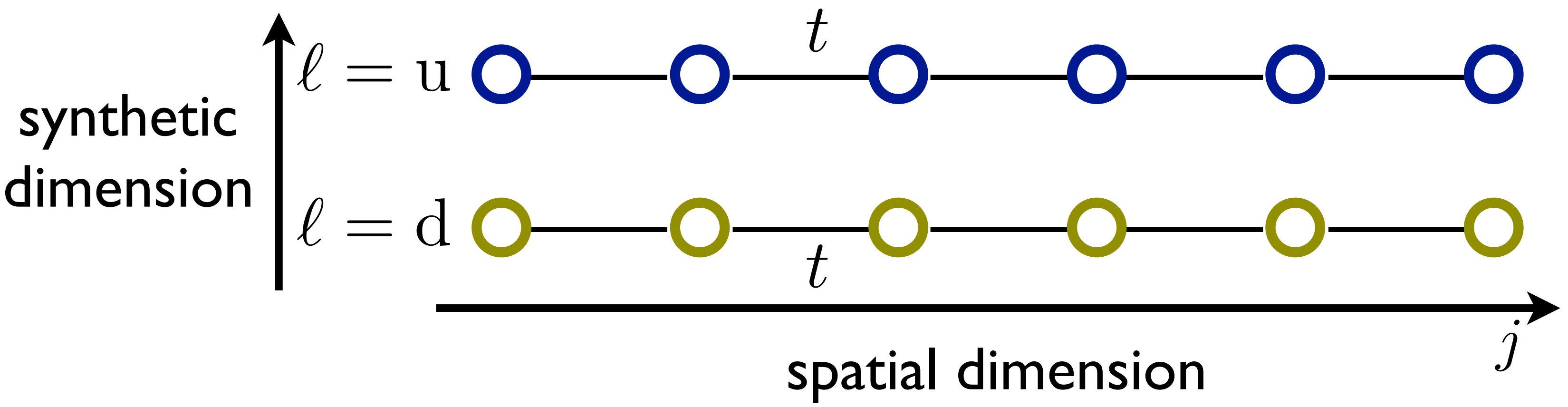
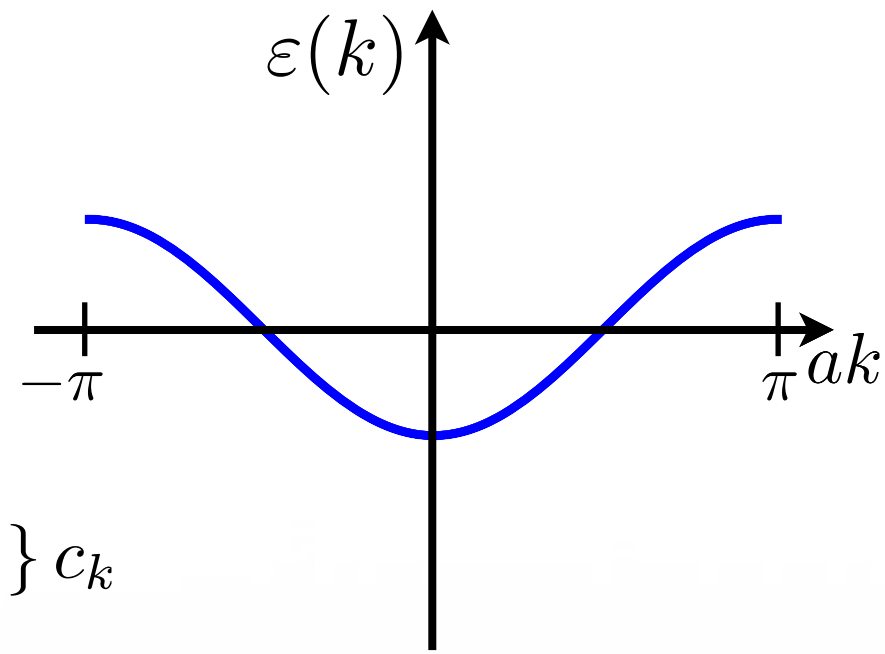
OUTLINE

- The Creutz-Hubbard Ladder: general features
  - Topology & Interactions
    - SPT vs orbital magnetism at half-filling
    - relation to high-energy models
    - interacting SPT phases at fractional filling
  - Tuning the Drude Weight of Dirac fermions
- Other related works & plans

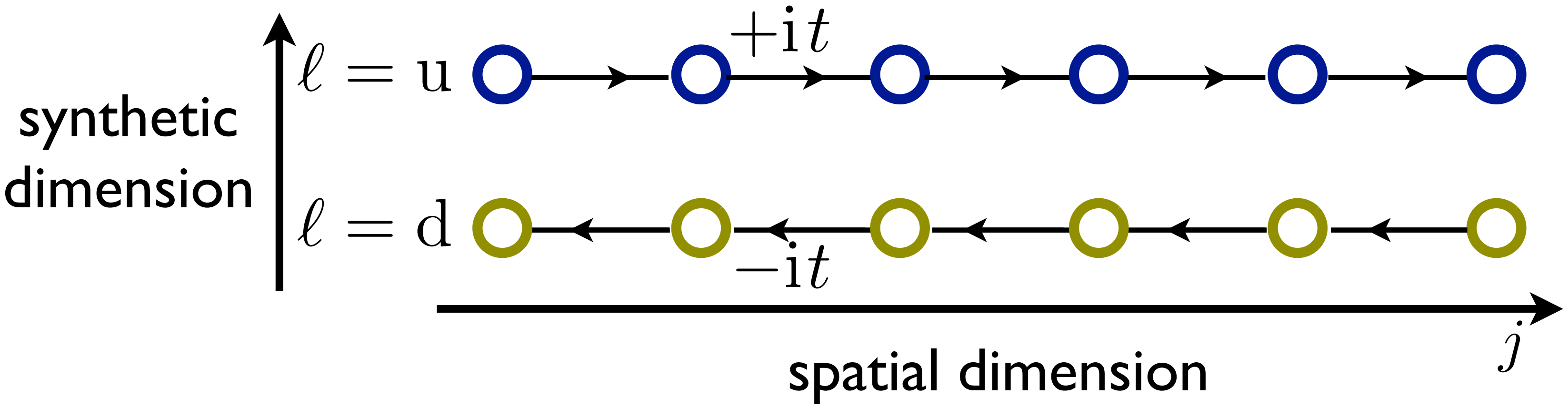
From standard to flat bands

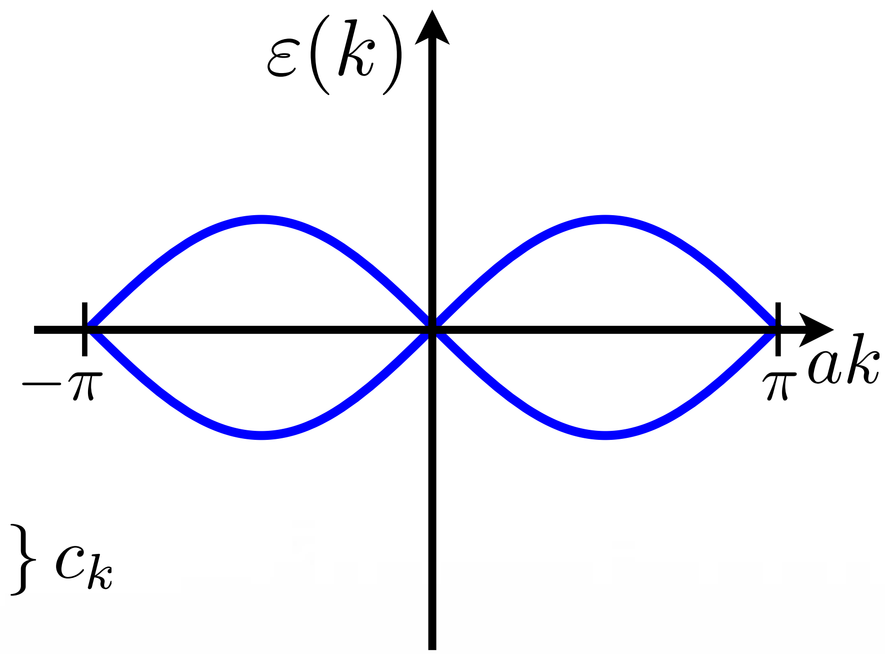




$$\mathcal{H}_0 = \sum_k c_k^\dagger \{ \quad -2t\cos(ak)\ \sigma_0 + \quad \} c_k$$

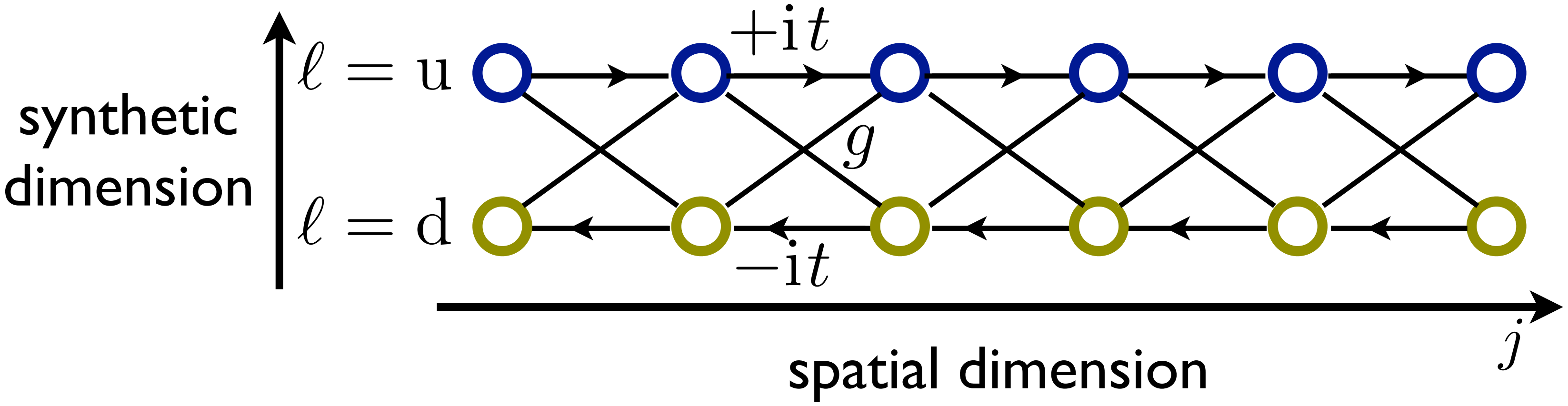
From standard to flat bands

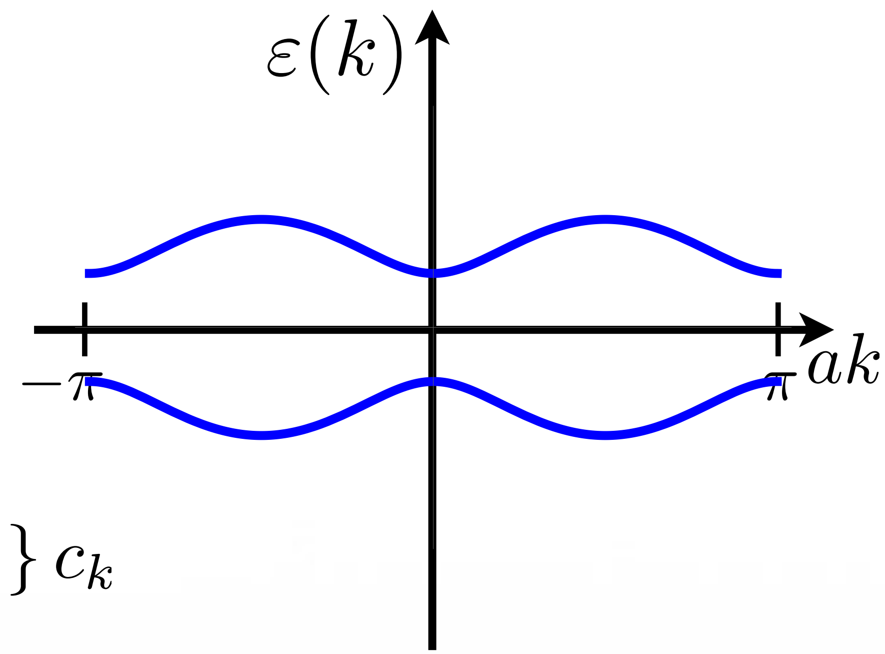




$$\mathcal{H}_0 = \sum_k c_k^\dagger \{[\quad + 2t \sin(ak)] \, \sigma_3 + \quad \} \, c_k$$

From standard to flat bands





$$\mathcal{H}_0 = \sum_k c_k^\dagger \{[\qquad + 2t\sin(ak)]\,\sigma_3 + [\qquad - 2g\cos(ak)]\,\sigma_1\}\, c_k$$

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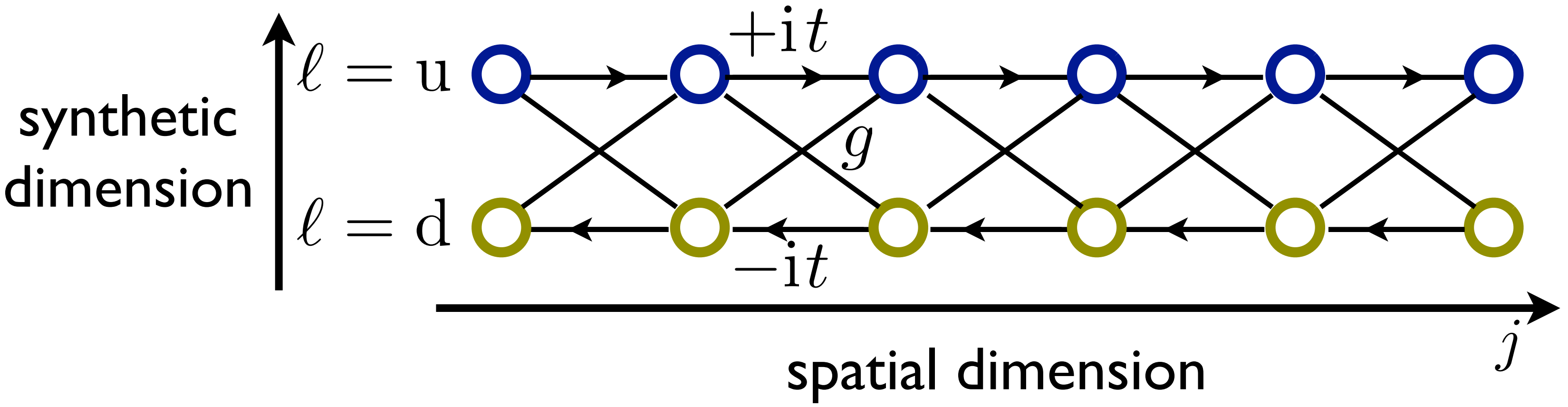

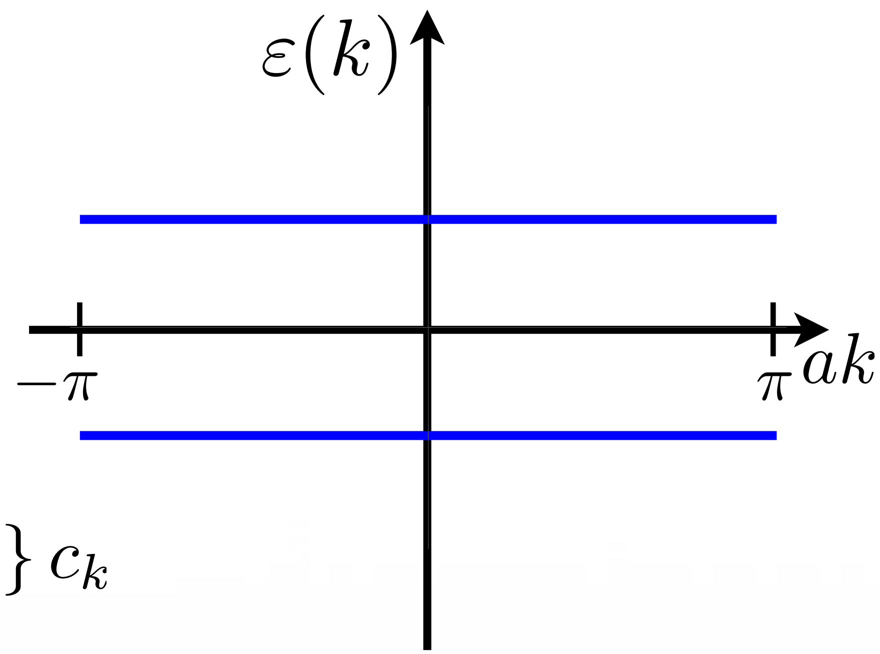

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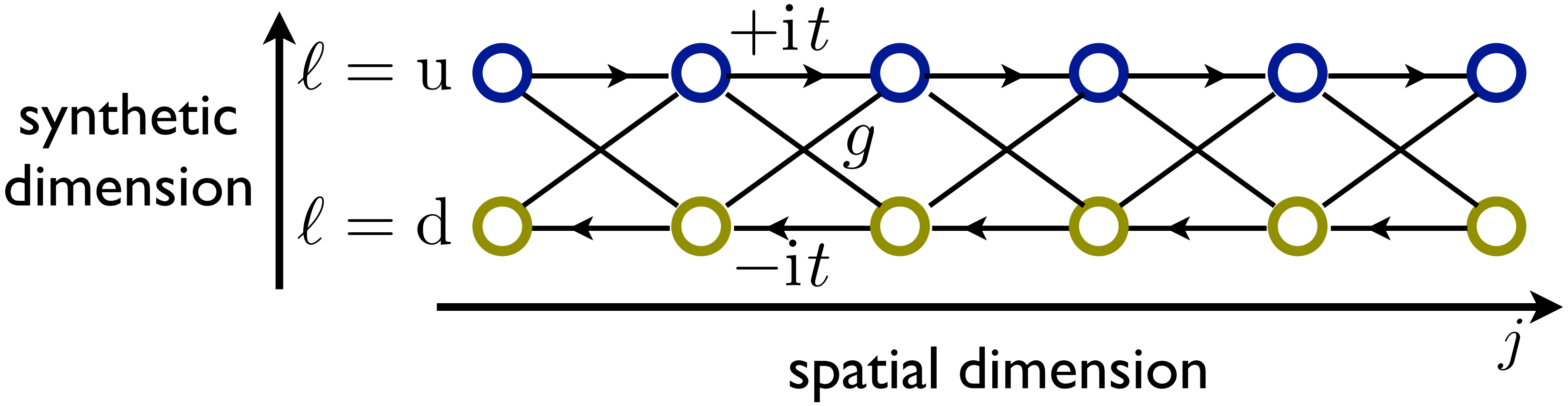
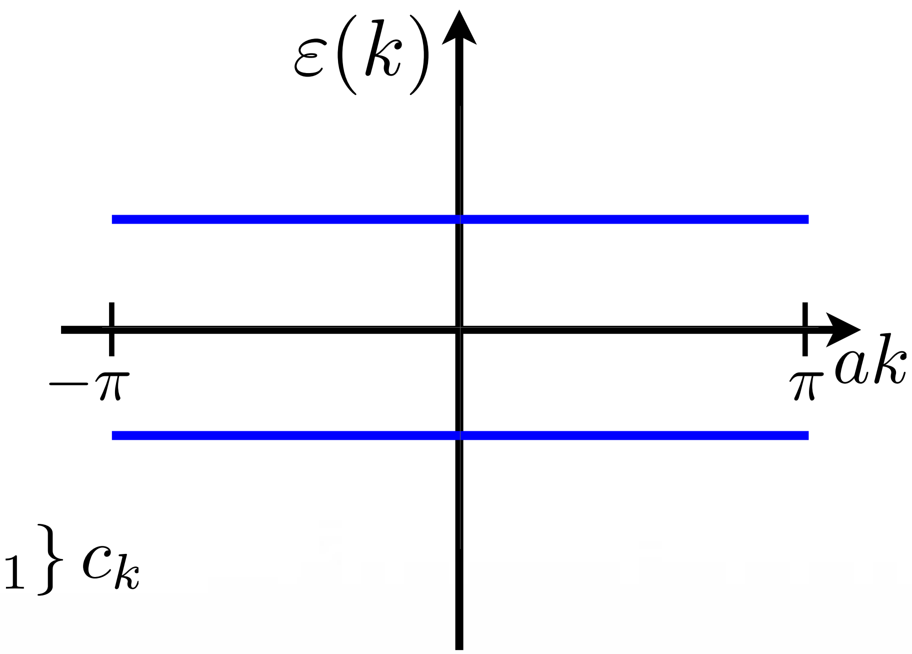
$g = t$ flat bands

Flat topological bands





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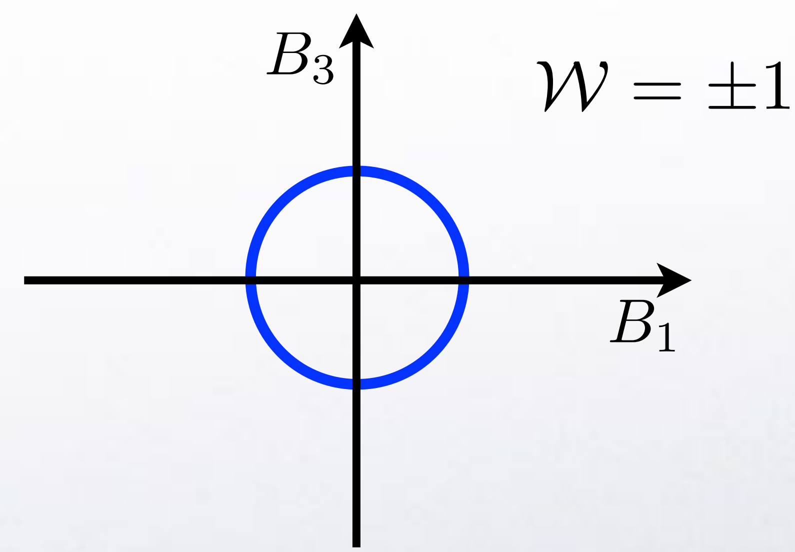
$g = t$ flat bands, with topological character!

$$\mathcal{H}_0 = \sum_{k \in \mathrm{BZ}} c_k^\dagger \{\mathbf{B}(k) \cdot \boldsymbol{\sigma}\}\, c_k$$

constrained in (B_1, B_3) plane by chiral symmetry:

$$\sigma_2 \mathcal{H}_0(k) \sigma_2 = -\mathcal{H}_0(k)$$



Symmetry Protected Topological (SPT) Order

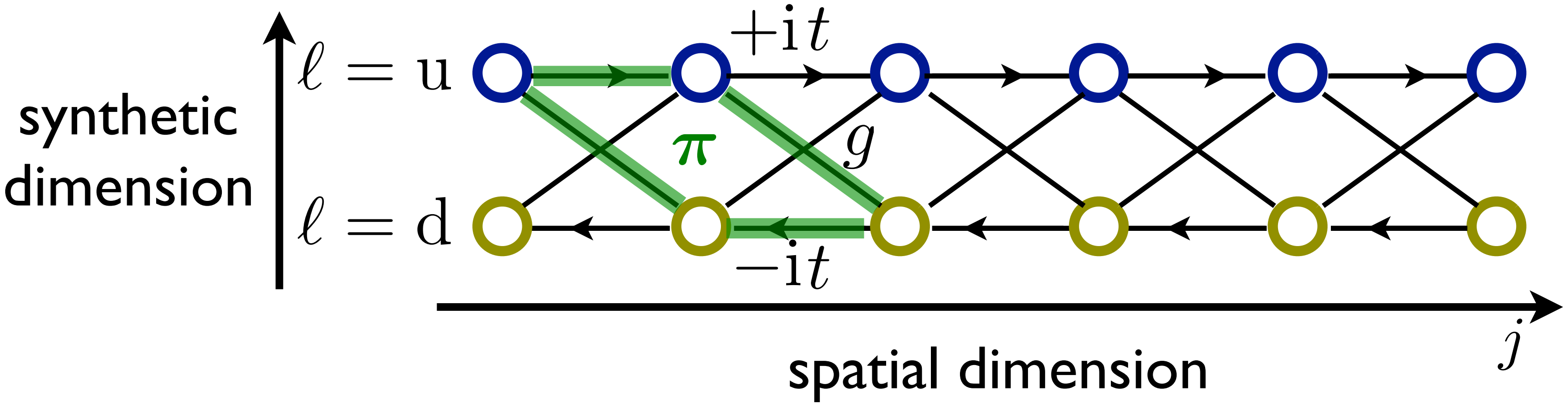
$$\mathcal{A}_\pm(k) = \langle \varepsilon_\pm(k) | \mathrm{i}\partial_k | \varepsilon_\pm(k) \rangle \qquad \varphi_{\mathrm{Zak},\pm} = \int_{\mathrm{BZ}} \mathrm{d}k\, \mathcal{A}_\pm(k) = \pi$$

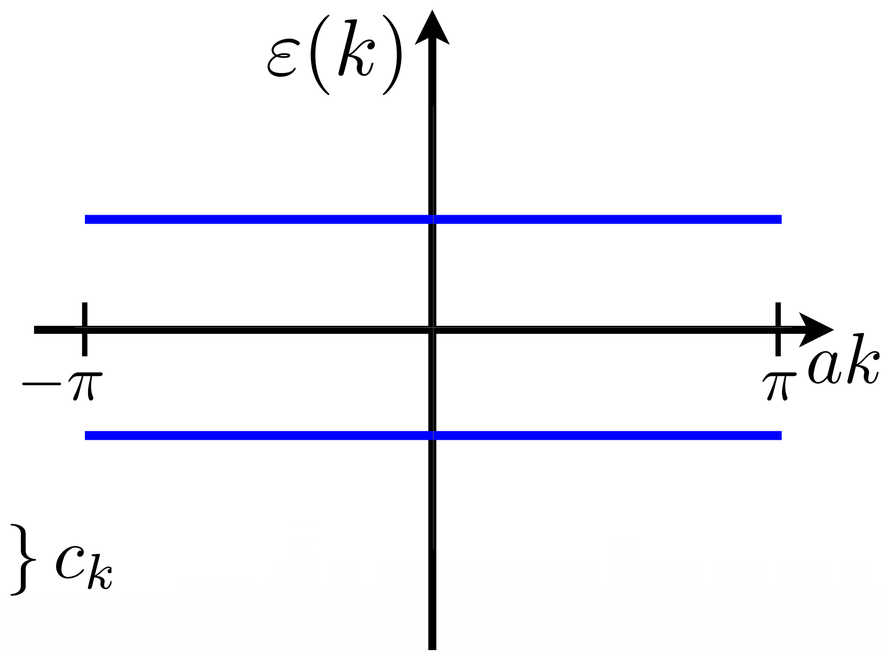
e.g., S. Ryu, et al., NJP **12**, 065010 (2010), D. Xiao, et al., RMP **82**, 1959 (2010)

φ_{Zak} measured in cold gases via Ramsey interferometry

M. Atala, et al., Nat. Phys. 9, 795 (2013)

Aharanov-Bohm cages





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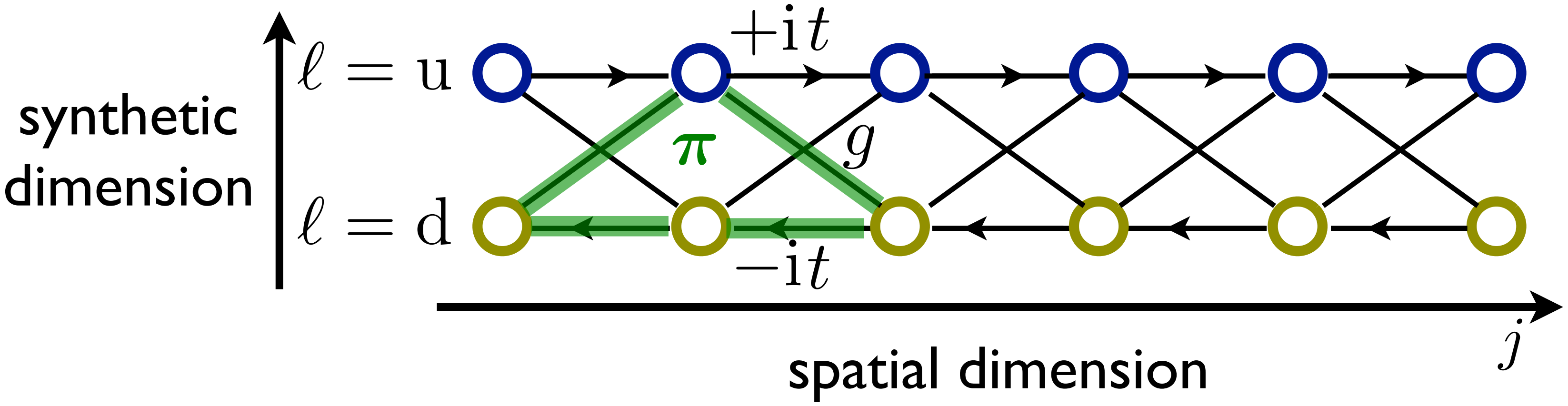

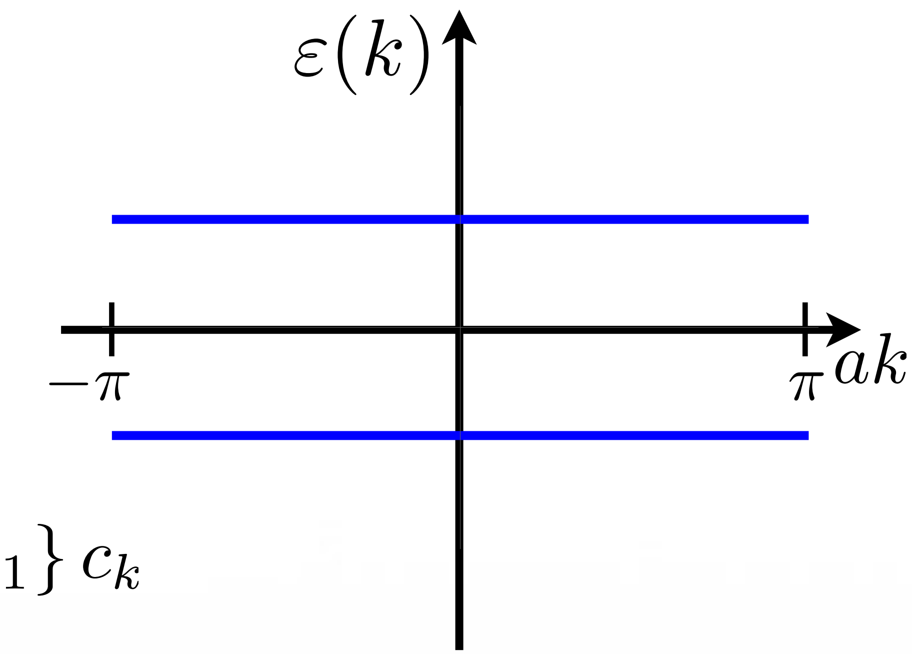

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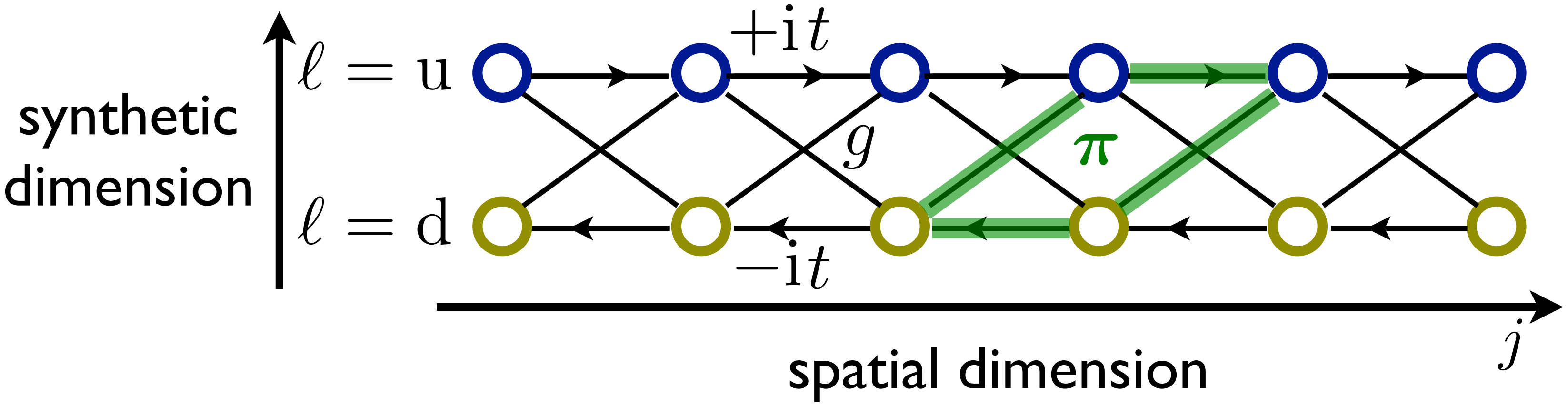

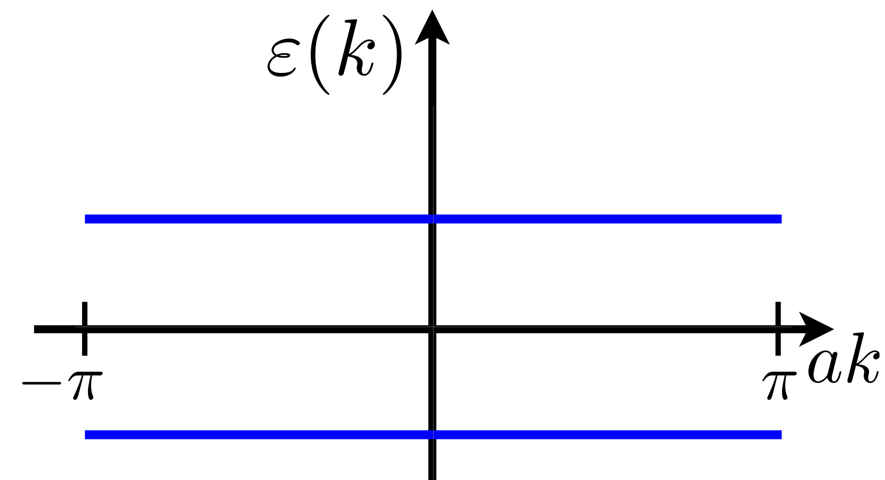

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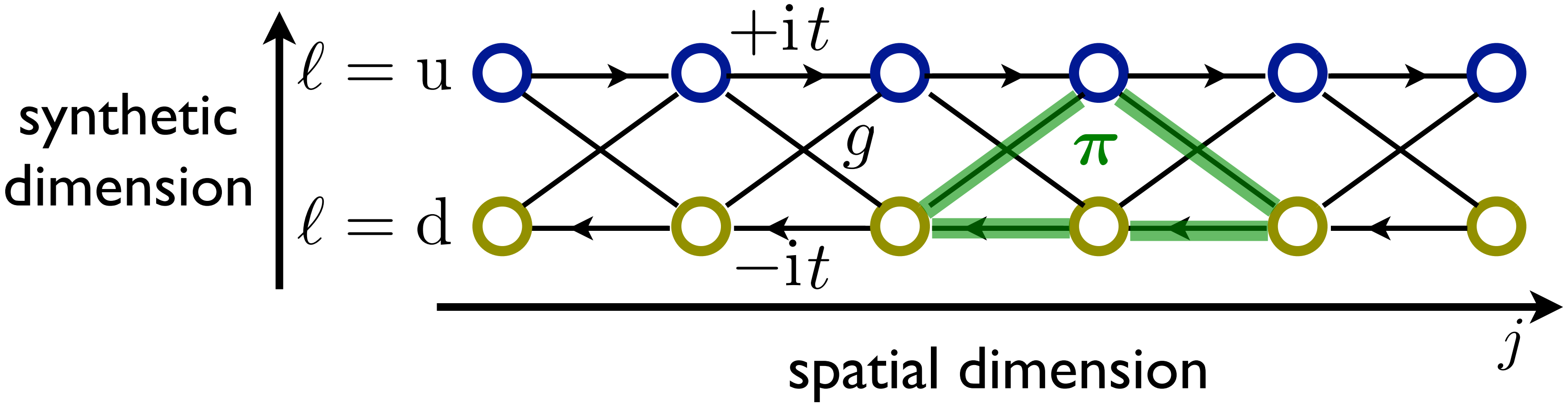

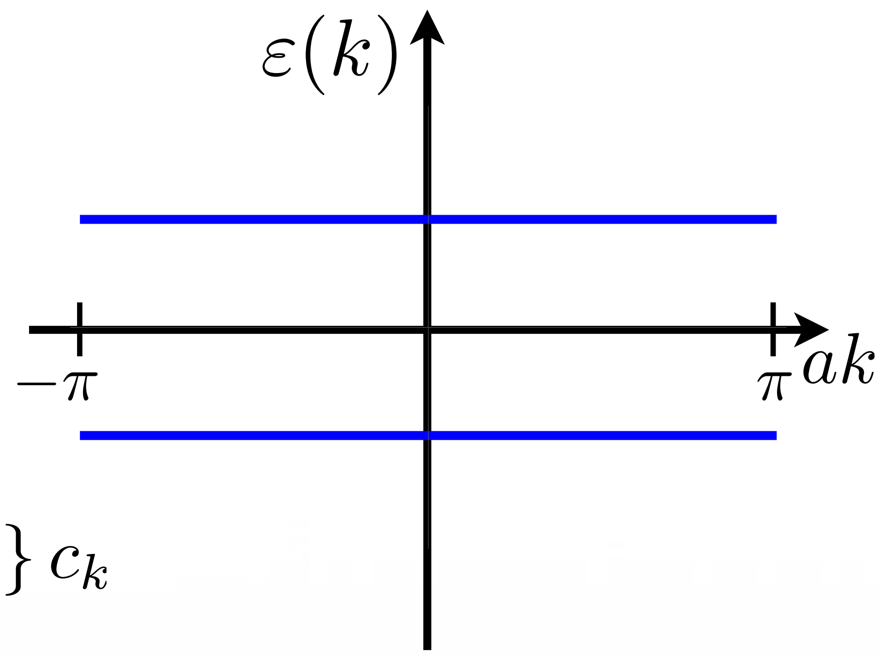

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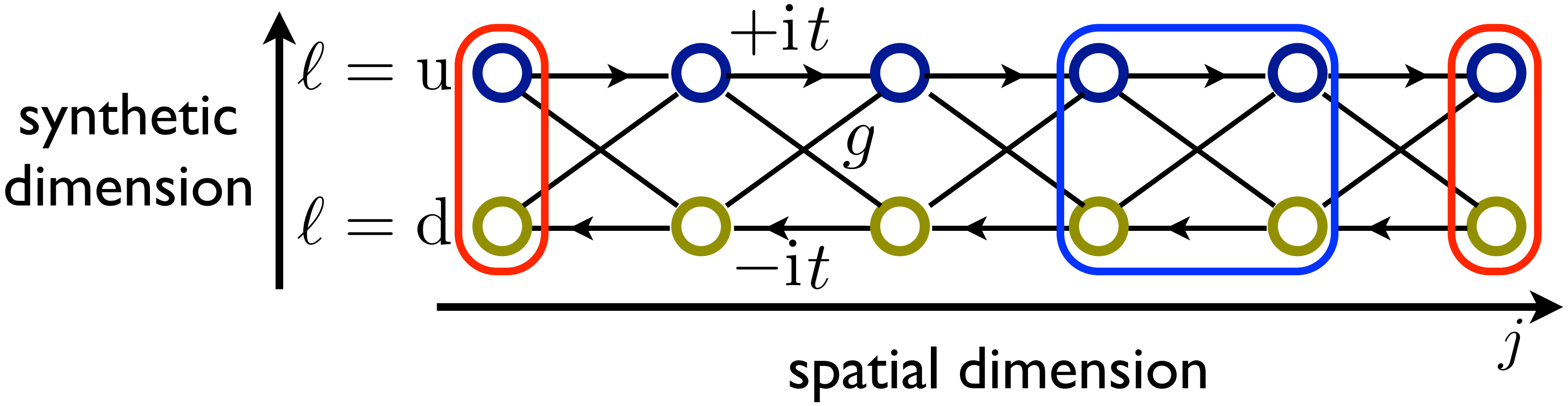

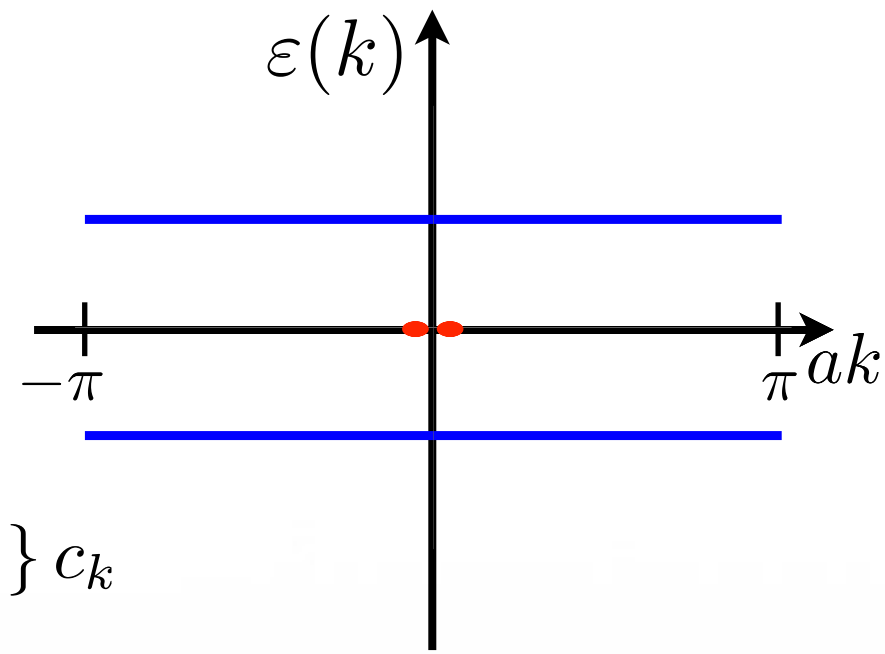

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Basis of localized states $w^\dagger_{j,\pm}$,
a.k.a. Aharanov-Bohm cages

Vidal, Mosseri, & Doucot, PRL **81**, 5888 (1998)

OBC: Mid-gap zero-energy edge states ($l^\dagger$,$r^\dagger$),
[bulk-edge correspondence]

S. Ryu and Y. Hatsugai, PRL **89**, 077002 (2002)
P. Delplace, et al., PRB **84**, 195452 (2011)

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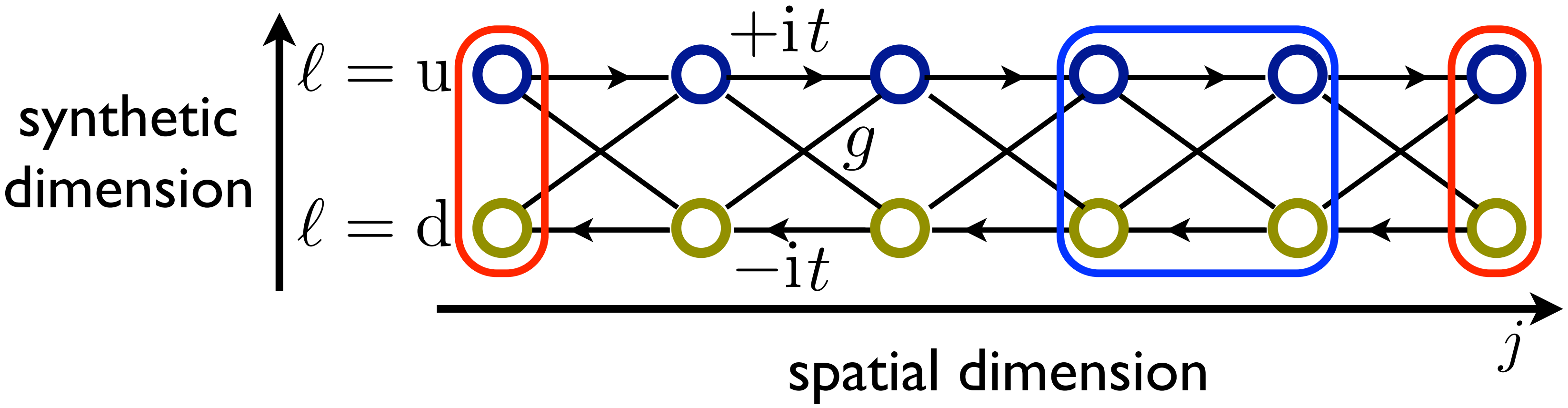

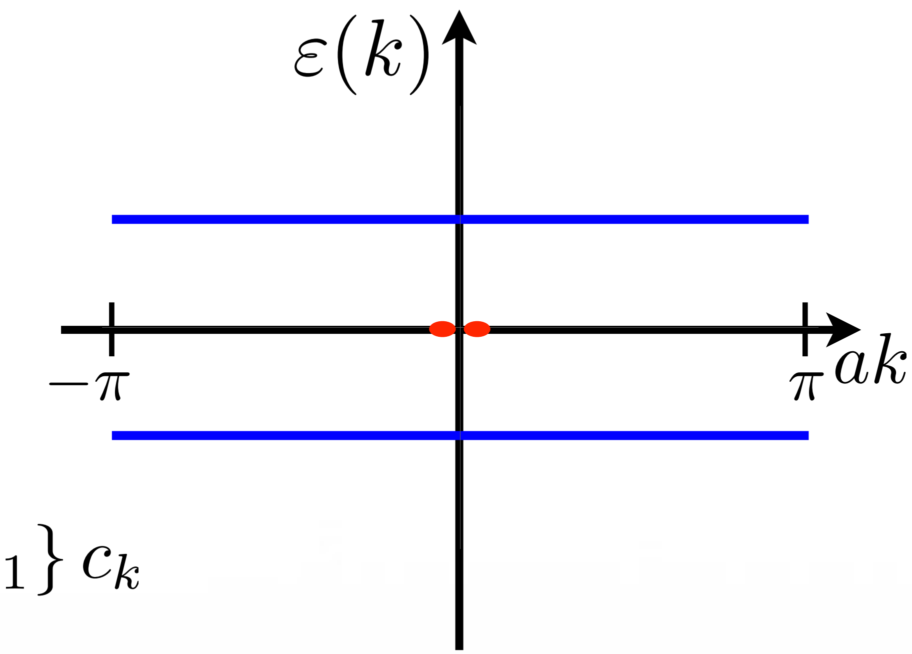

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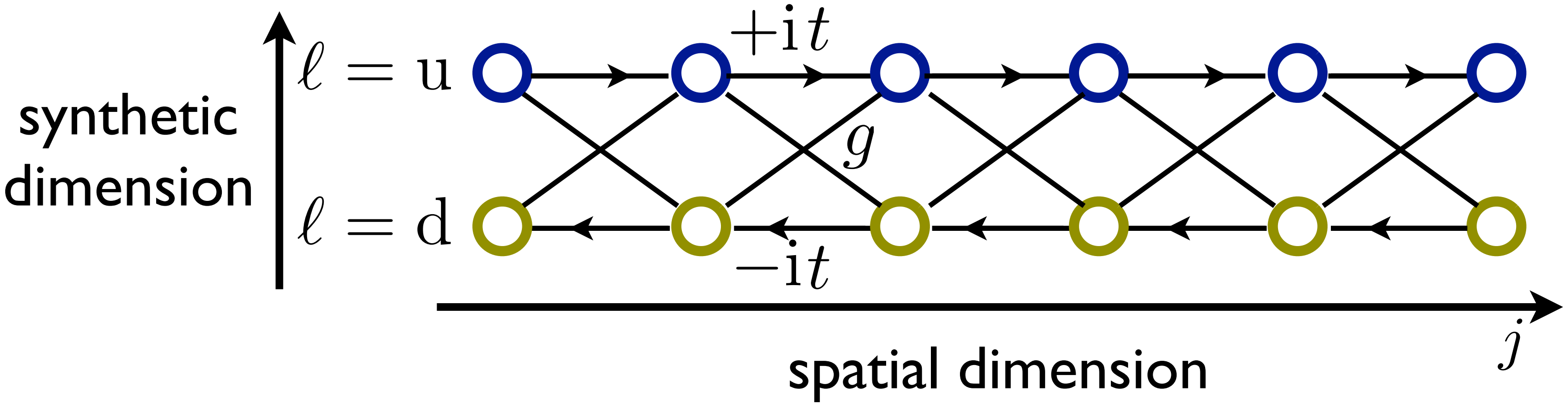
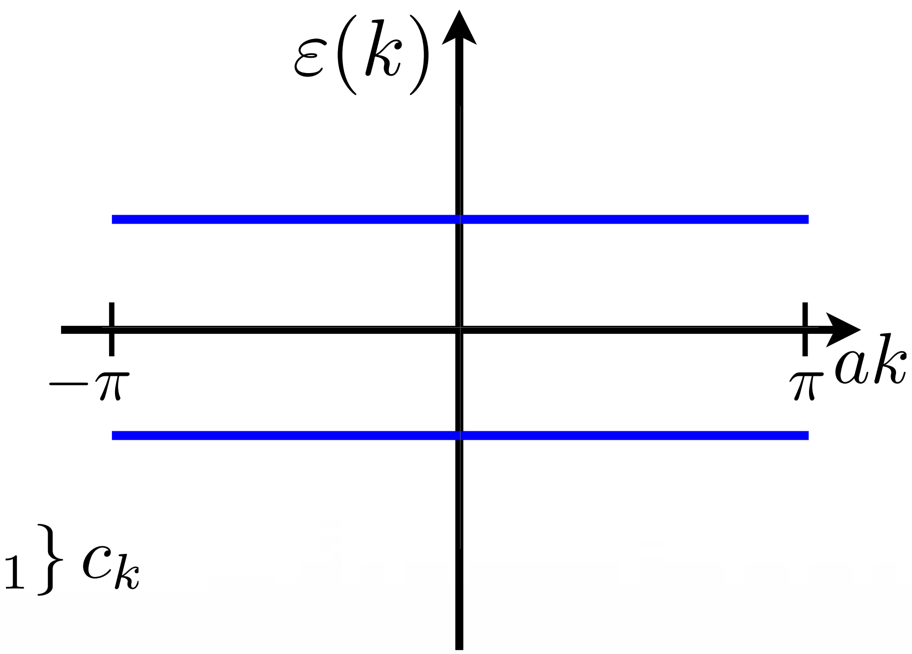
a *workhorse* for flat-band & SPT physics:
Tovmasyan, van Nieuwenburg, & Huber, PRB **88**, 220510(R) (2013)
Takayoshi, Katsura, Watanabe, & Aoki, PRA **88**, 063613 (2013)
Huber & Altman, PRB **82**, 184502 (2010)
Tovmasyan, Peotta, Törmä, & Huber, PRB **94**, 245149 (2016)
Sticlet, Seabra, Pollmann, & Cayssol, PRB **89**, 115430 (2014)

Bragg techniques
to measure edge states
in ultracold cold atoms
Goldman, Beugnon, Gerbier,
PRL 108, 255303 (2012)

SPT - Trivial transition





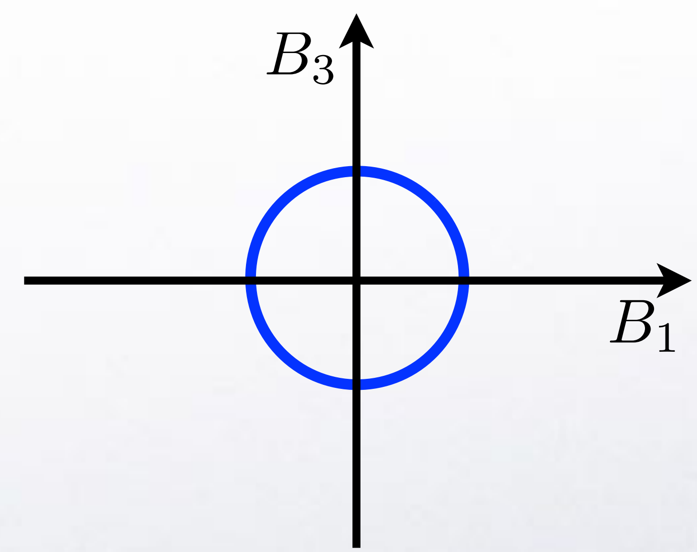
$$\mathcal{H}_0 = \sum_k c_k^\dagger \{[\qquad + 2t\sin(ak)]\,\sigma_3 + [\qquad - 2g\cos(ak)]\,\sigma_1\}\, c_k$$

$g = t$ flat bands, with topological character! *(SPT)*

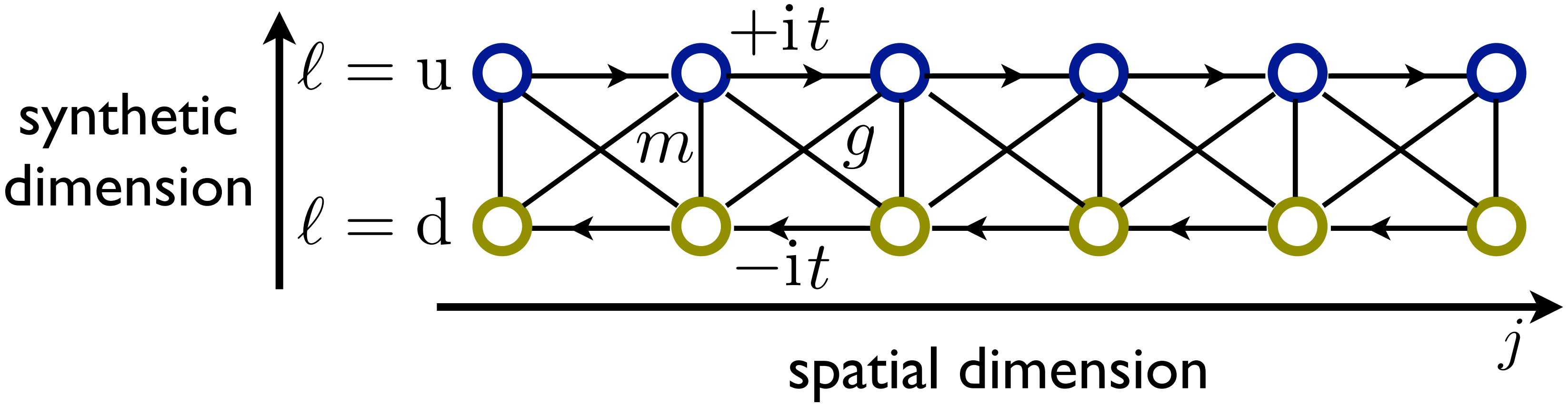
$$\mathcal{H}_0 = \sum_{k\in \mathrm{BZ}} c_k^\dagger \{\mathbf{B}(k)\cdot\boldsymbol{\sigma}\}\, c_k$$

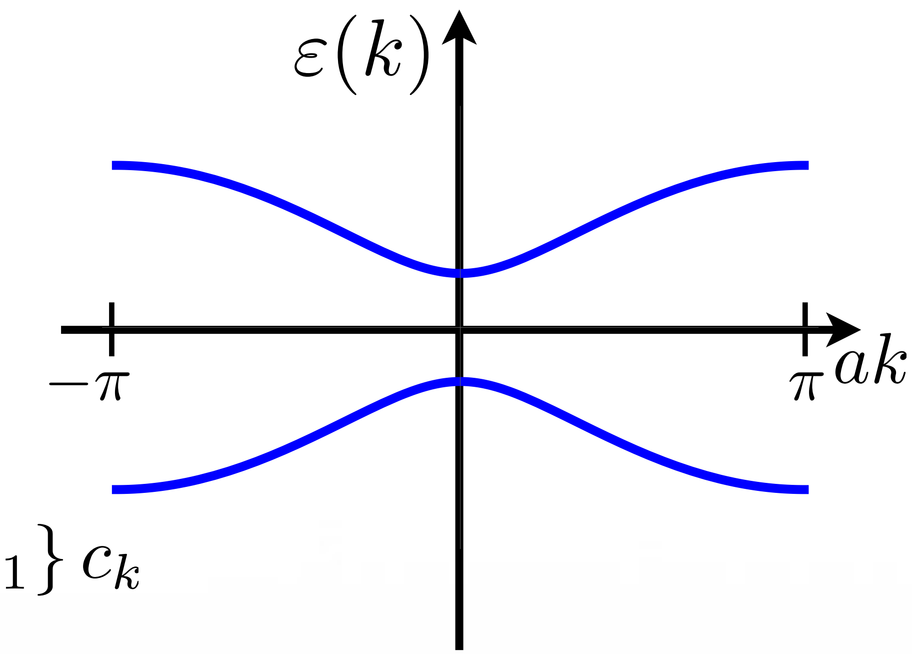
constrained in (B_1, B_3) plane by chiral symmetry:

$$\sigma_2\mathcal{H}_0(k)\sigma_2 = -\mathcal{H}_0(k)$$



SPT - Trivial transition





$$\mathcal{H}_0 = \sum_k c_k^\dagger \left\{ \left[\qquad + 2t\sin(ak) \right] \sigma_3 + \left[2m - 2g\cos(ak) \right] \sigma_1 \right\} c_k$$

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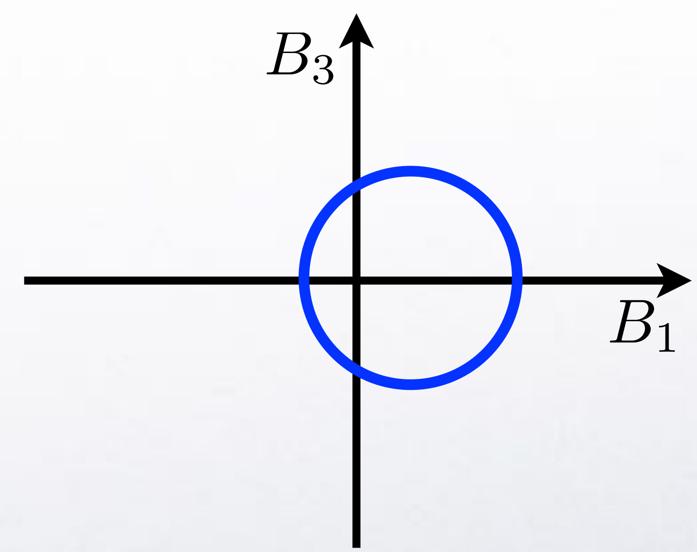
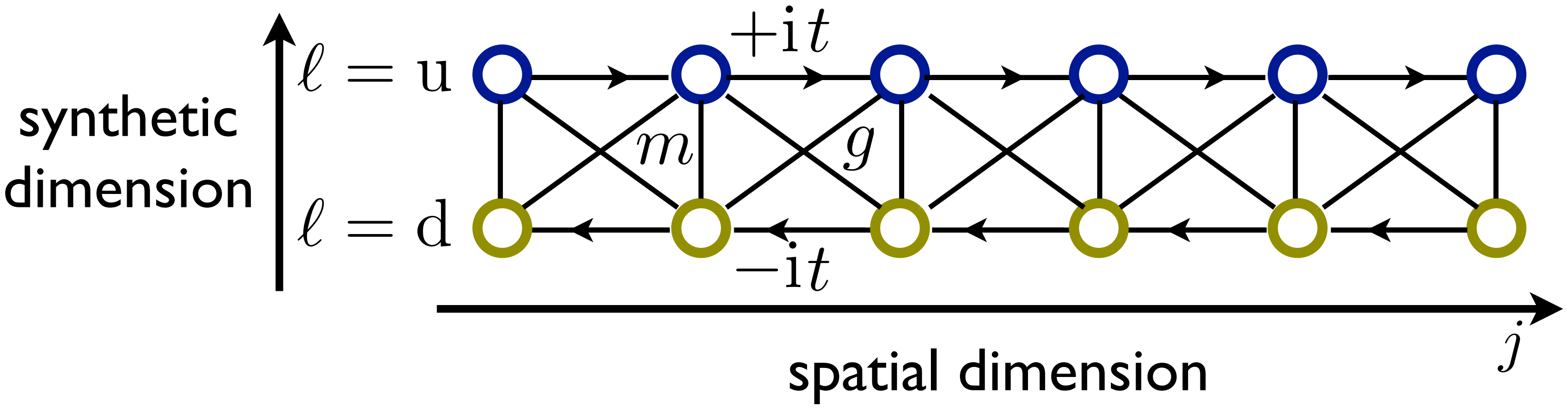


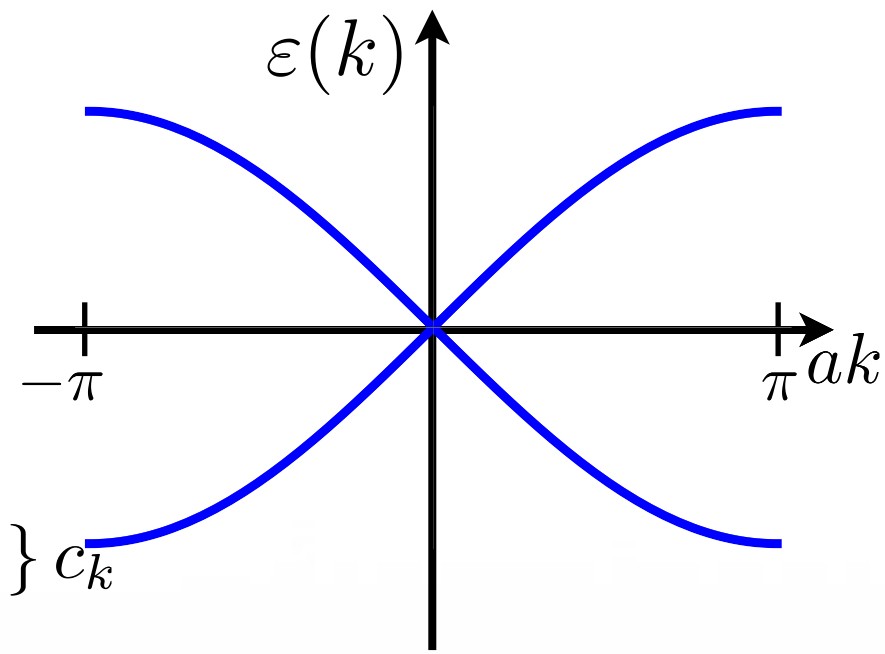
$$T: \ \sigma_1 \mathcal{H}_0^*(-k) \sigma_1 = +\mathcal{H}_0(k)$$
$$C: \ \sigma_3 \mathcal{H}_0^*(-k) \sigma_3 = -\mathcal{H}_0(k)$$

⇨ Class **BDI** of AZ table

Altland, Zirnbauer, PRB **55**, 1142 (1997)

SPT - Trivial transition





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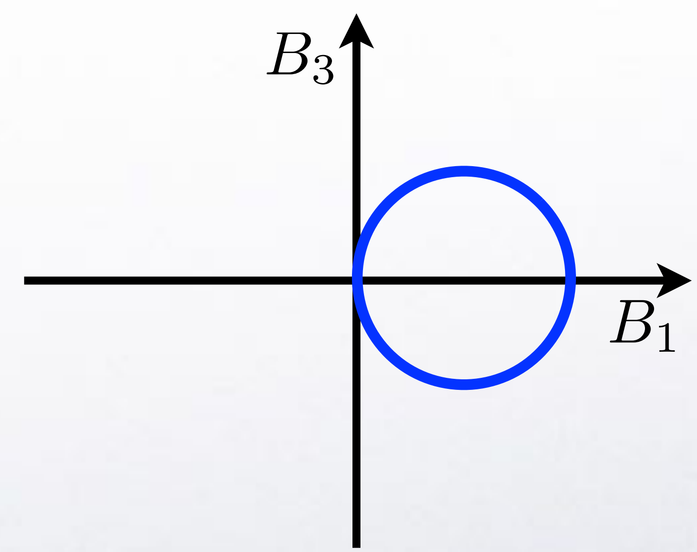
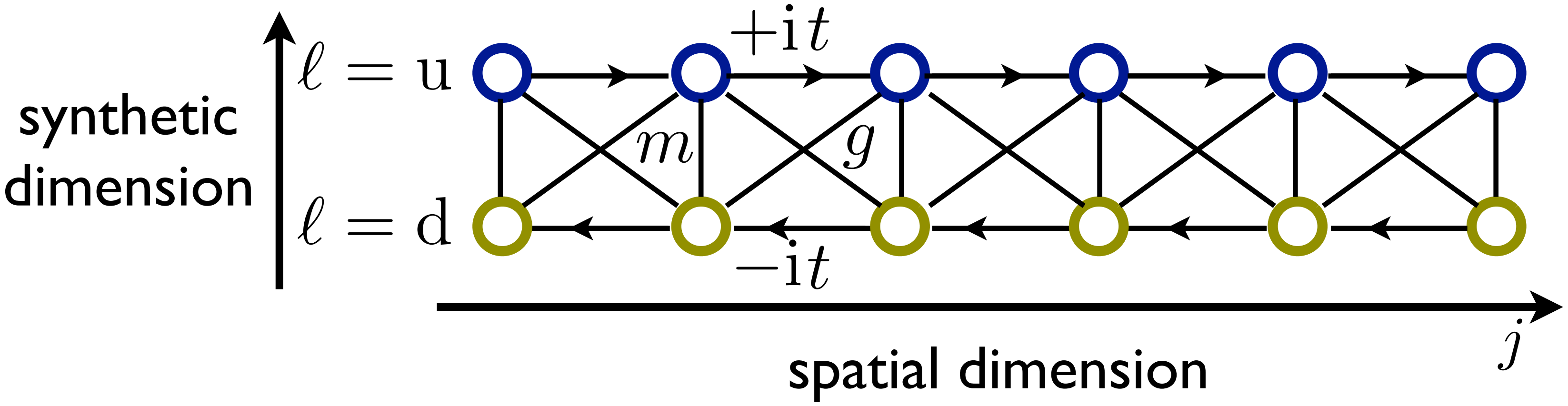


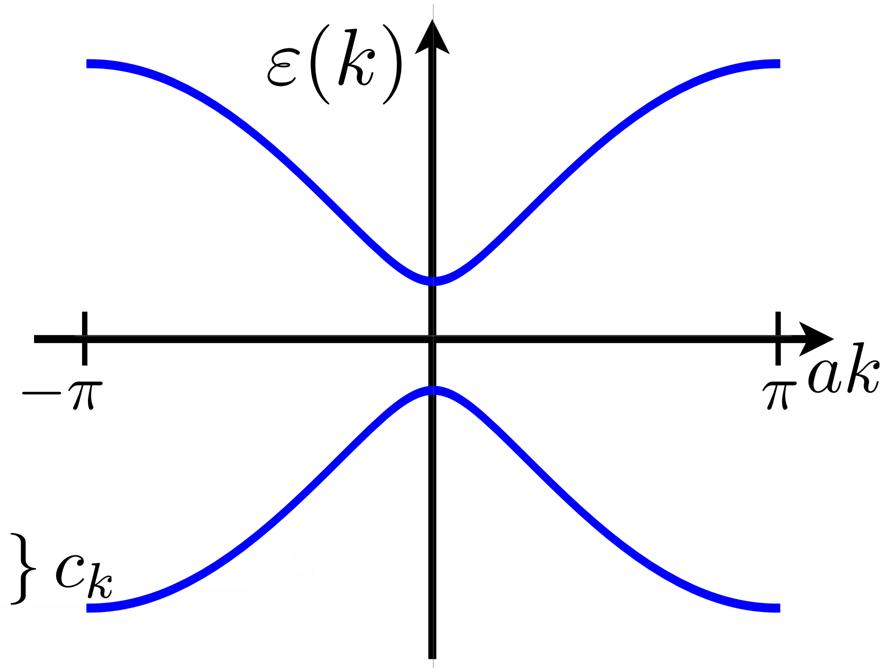
$m = g = t$ <u>isolated Dirac cone</u>

[no Fermion doubling]

Creutz, Horváth, PRD **50**, 2297 (1994)
Creutz, PRL **83**, 2636 (1999)

SPT - Trivial transition





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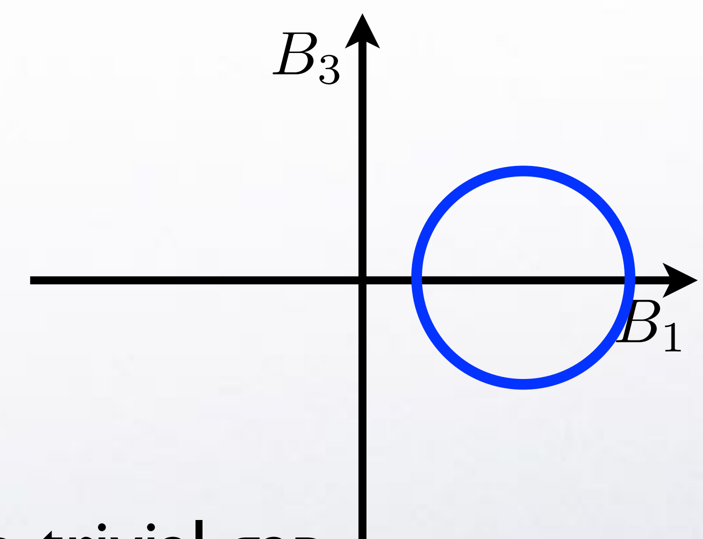
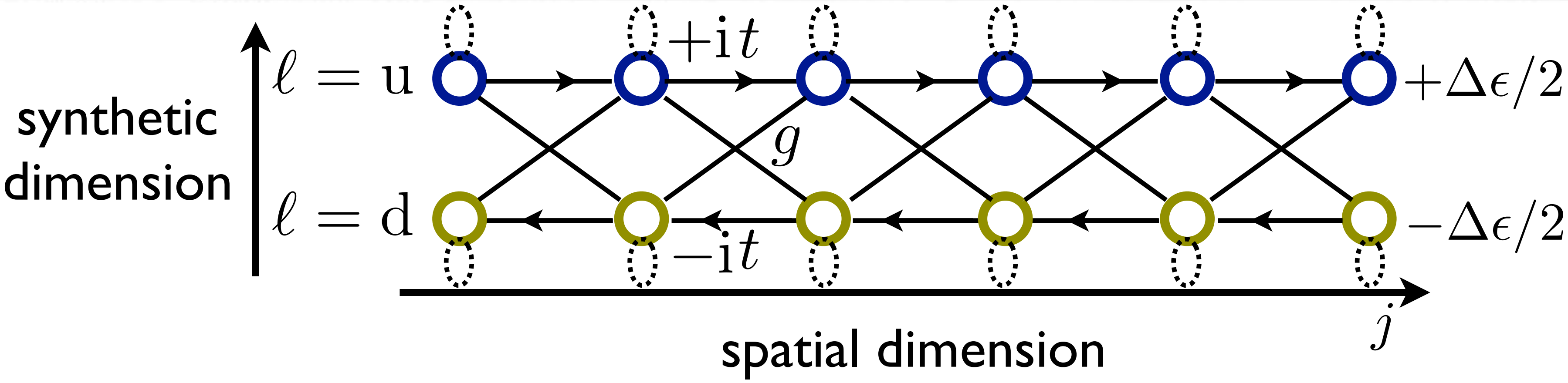


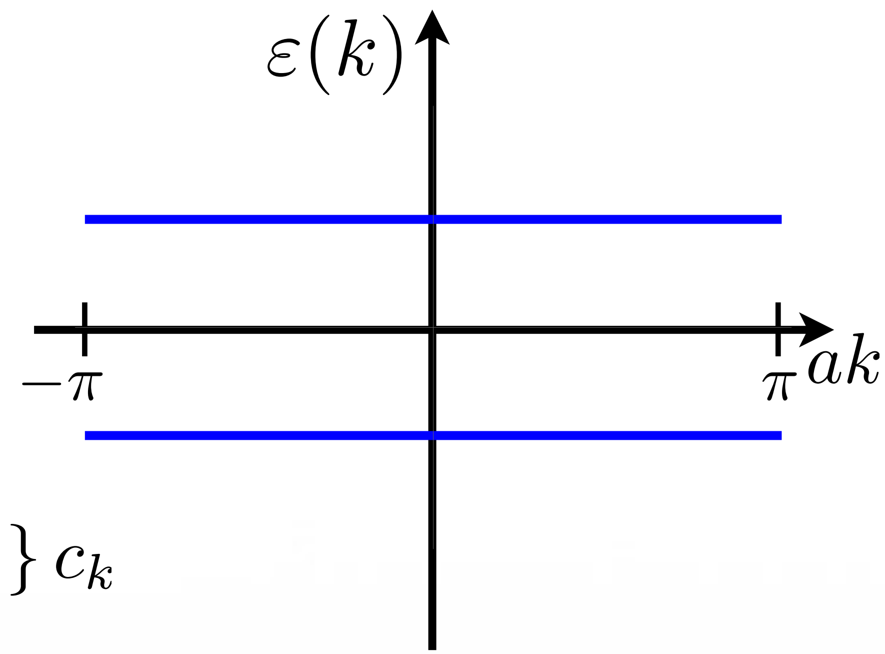
$m = g = t$ <u>isolated Dirac cone</u> *[no Fermion doubling]*

Creutz, Horváth, PRD **50**, 2297 (1994)
Creutz, PRL **83**, 2636 (1999)

$m > g = t$ transition to trivial gap
$\mathcal{W} = 0 \quad \varphi_{\mathrm{Zak}} = 0$
no more edge states

AIII SPT phase





$$\mathcal{H}_0 = \sum_k c_k^\dagger \left\{ [\Delta\epsilon/2 + 2t\sin(ak)]\,\sigma_3 + [\quad - 2g\cos(ak)]\,\sigma_1 \right\} c_k$$

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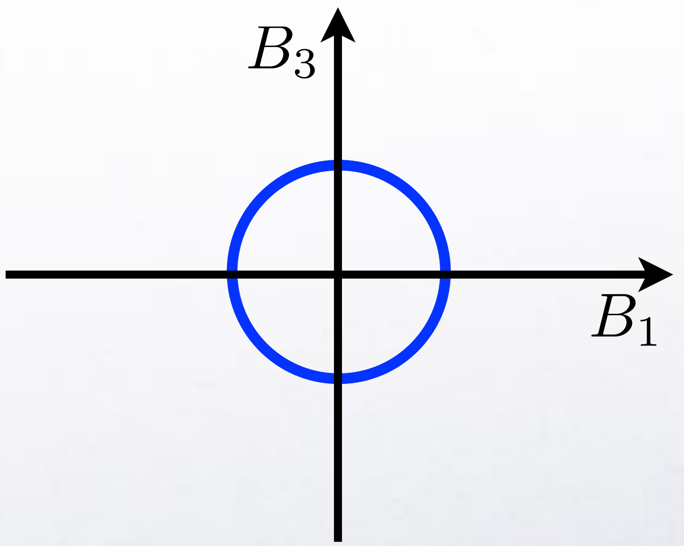

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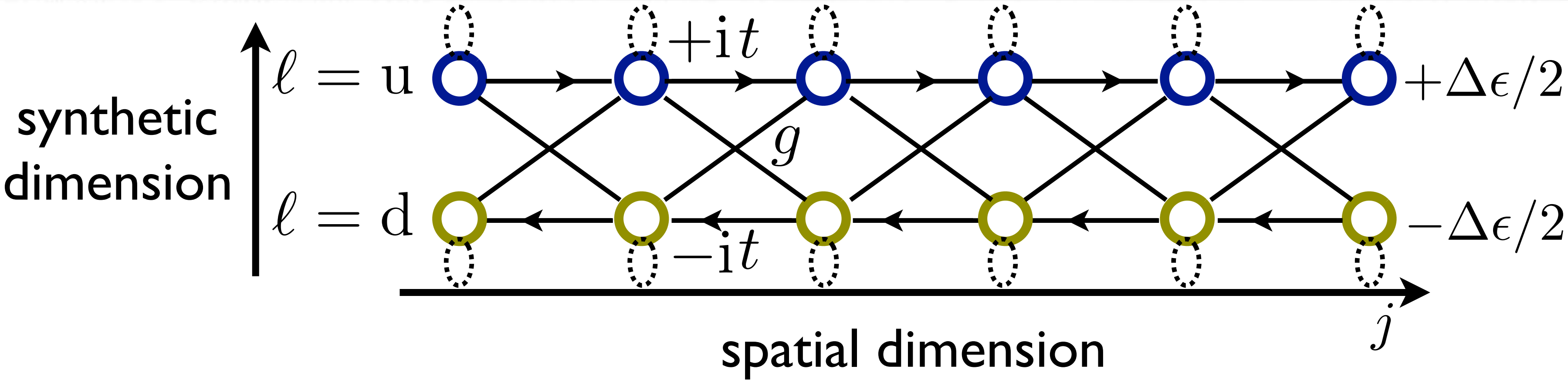
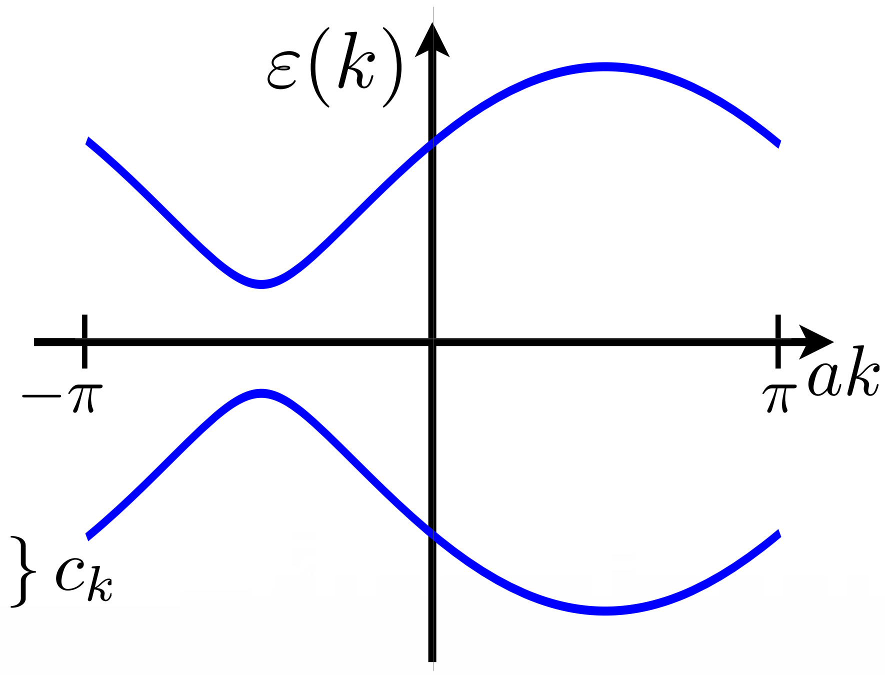
AIII SPT phase





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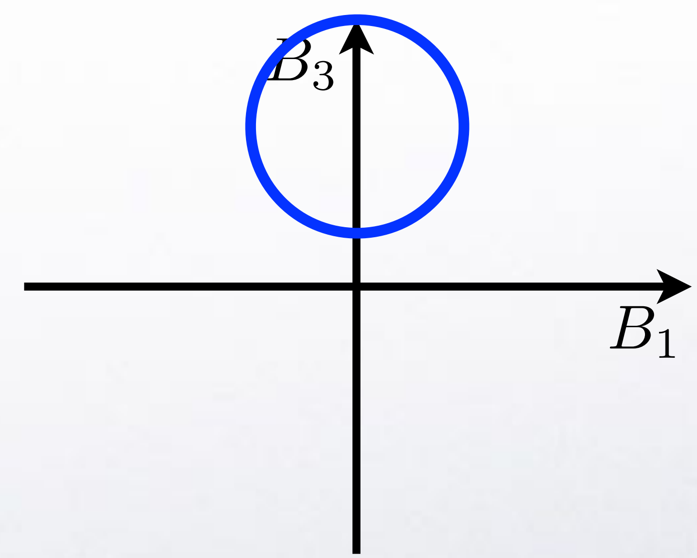


Zeeman $\Delta\epsilon$ breaks T & C symmetry!

$\nexists U_{T/C}$ s.t. $U_\alpha \mathcal{H}_0^*(-k) U_\alpha^\dagger = \pm \mathcal{H}_0(k)$ ⇨

Class **AIII** of AZ table

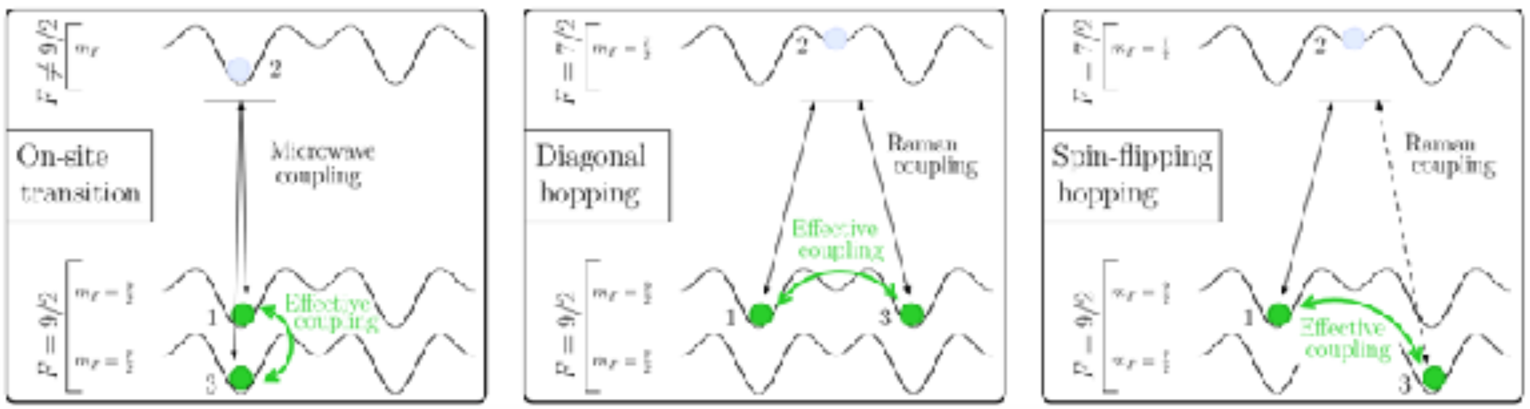
Altland, Zirnbauer, PRB **55**, 1142 (1997)

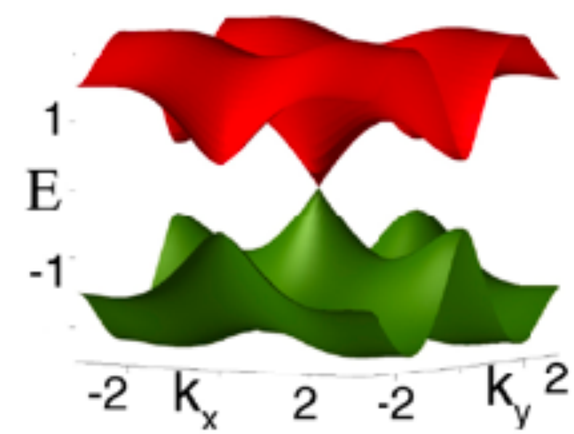
[another scheme Velasco, Paredes, PRL **119**, 115301 (2017)]

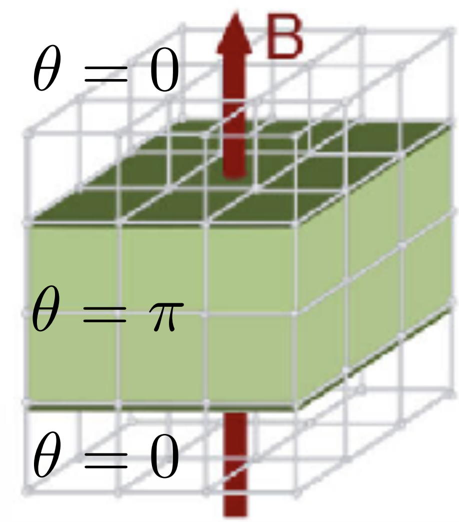
Experimental schemes

An optical-lattice-based quantum simulator for relativistic field theories and topological insulators

A. Bermudez, et al., PRL **105**, 190404 (2010);
L. Mazza, et al., NJP **14** 015007 (2012);
MR, PoS - SISSA **193**, 036 (2014)





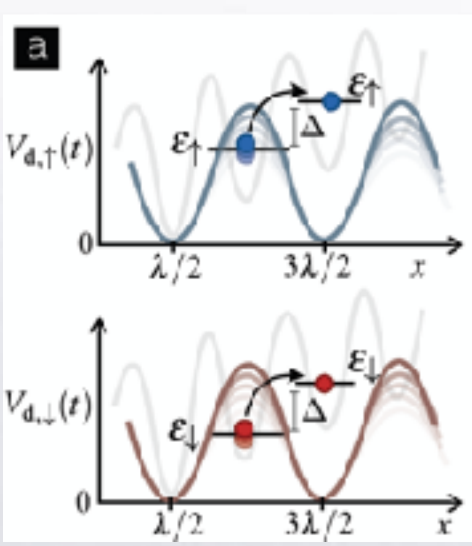


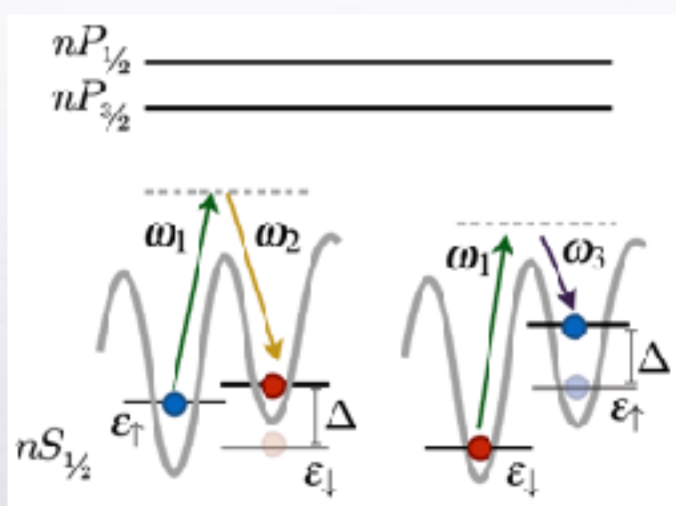
A shaken lattice proposal for the Creutz ladder

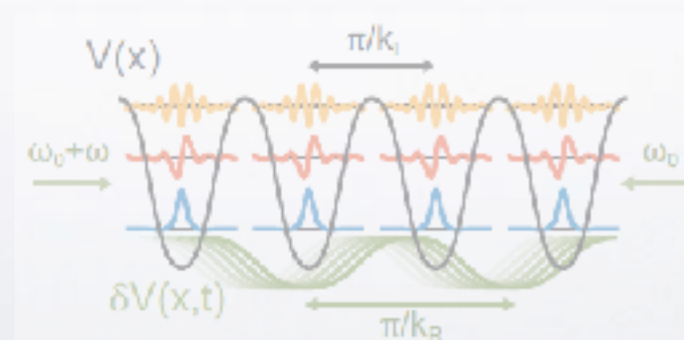
J. Jünemann, et al., PRX **7**, 031057 (2017)

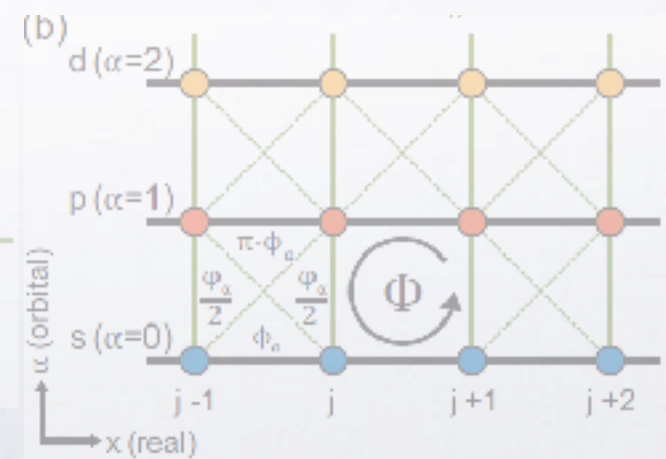
Realization of a cross-linked chiral ladder by orbital-momentum coupling

J.H. Kang, J.H. Han, & Y. Shin, arXiv:1807.01444



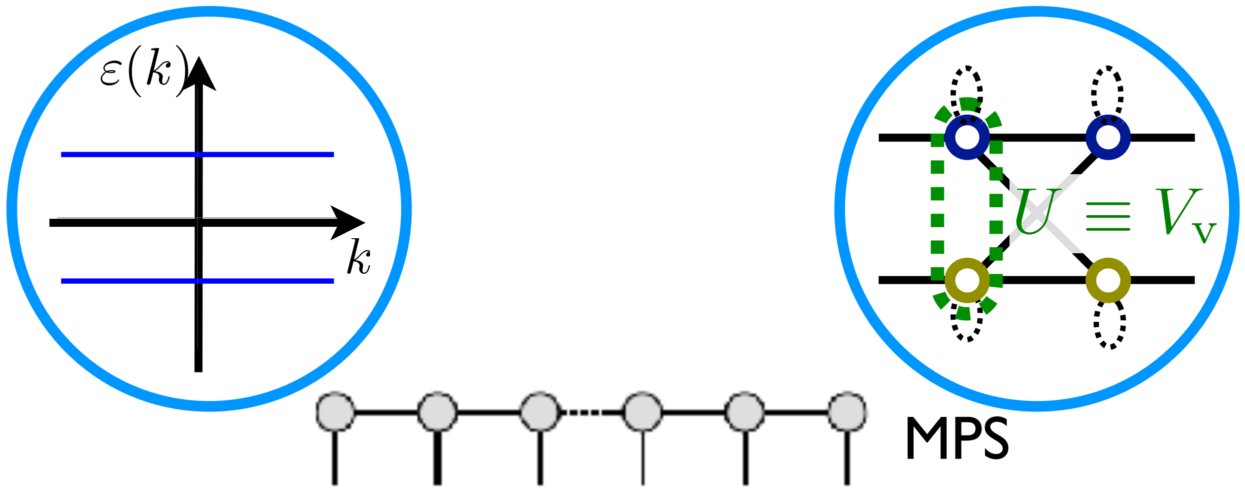


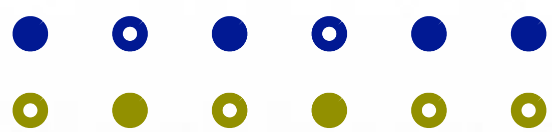




on-going collaboration with LENS, Florence

Interaction effects





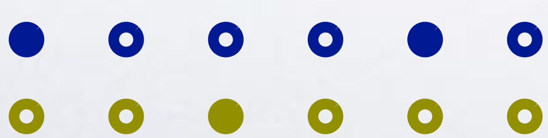
half-filling

Topological Phase vs. Orbital Magnetism

Jünemann, et al., PRX **7**, 031057 (2017)

Gross-Neveu-Wilson model

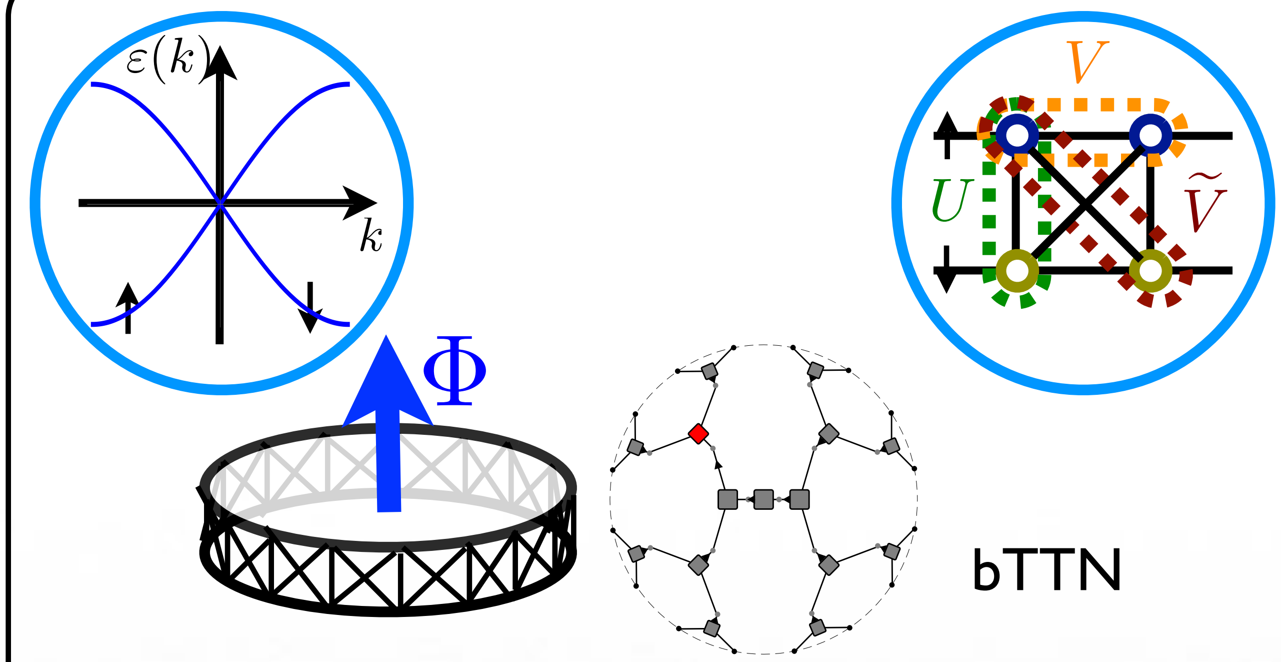
Bermudez, et al., Ann. Phys. **339**, 149 (2018)



quarter-filling

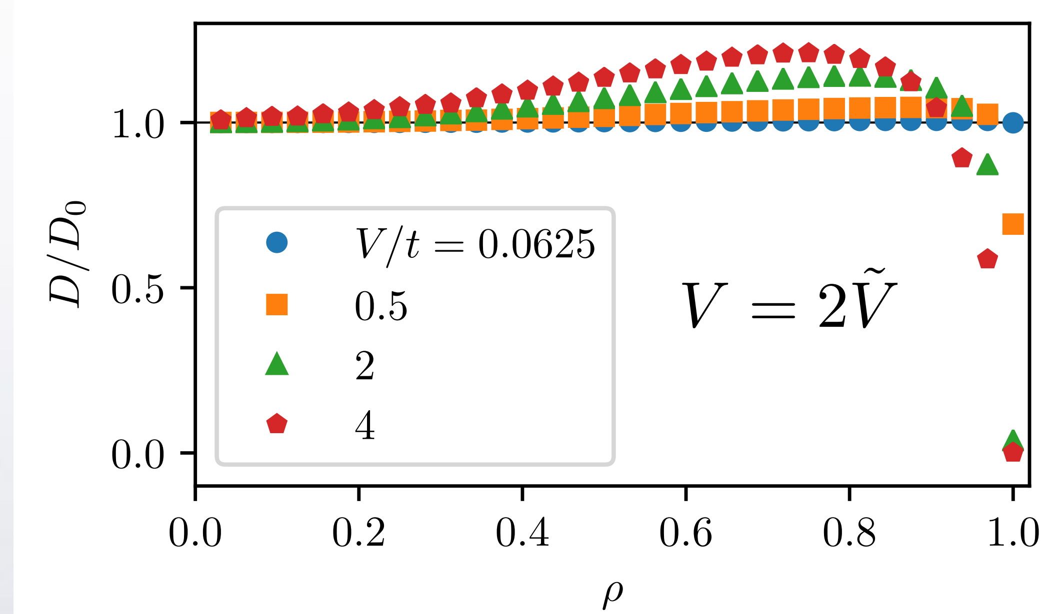
Fractional topological phases

Barbarino, et al., arXiv:1810.02337



Tunable Drude Weight of Dirac Fermions

Bischoff, et al. (MR), PRB **96**, 241112(R) (2017)

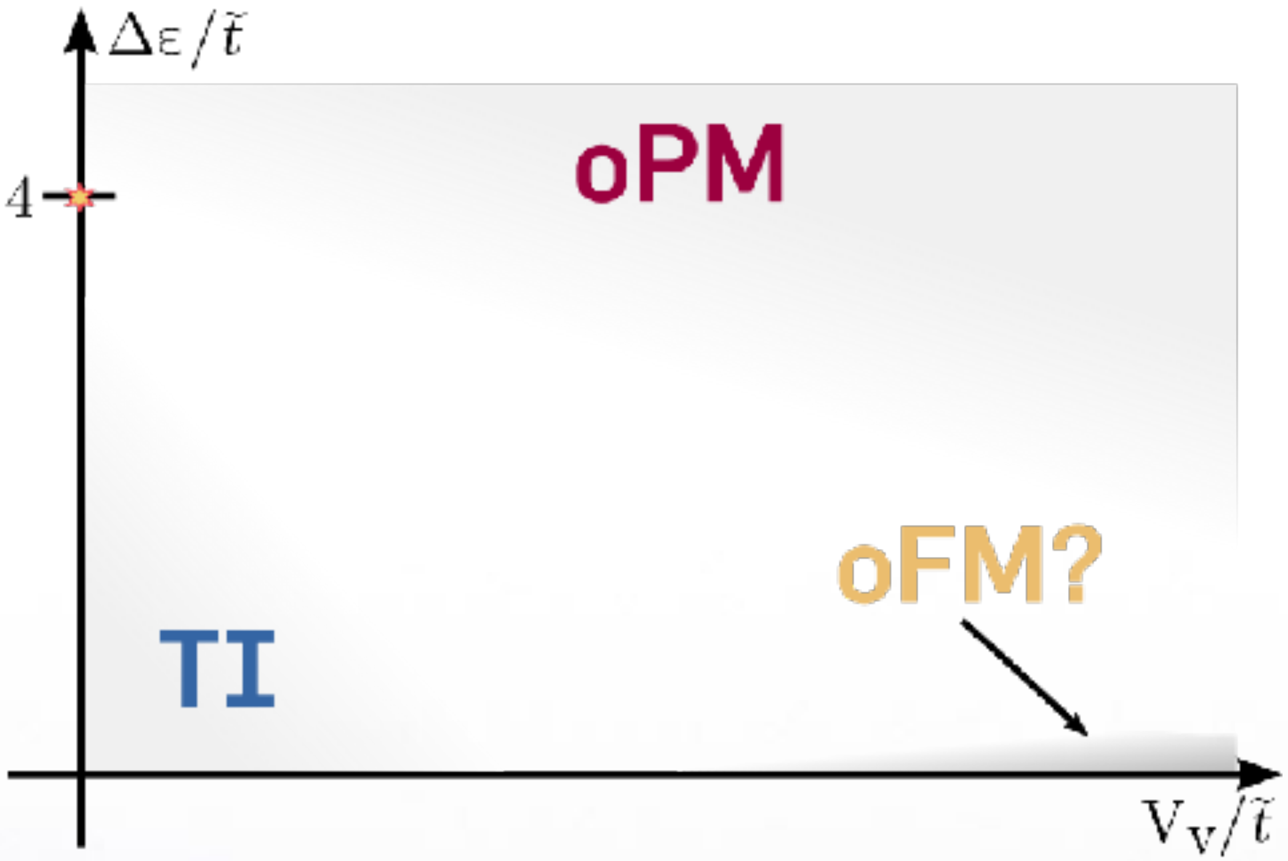


OUTLINE

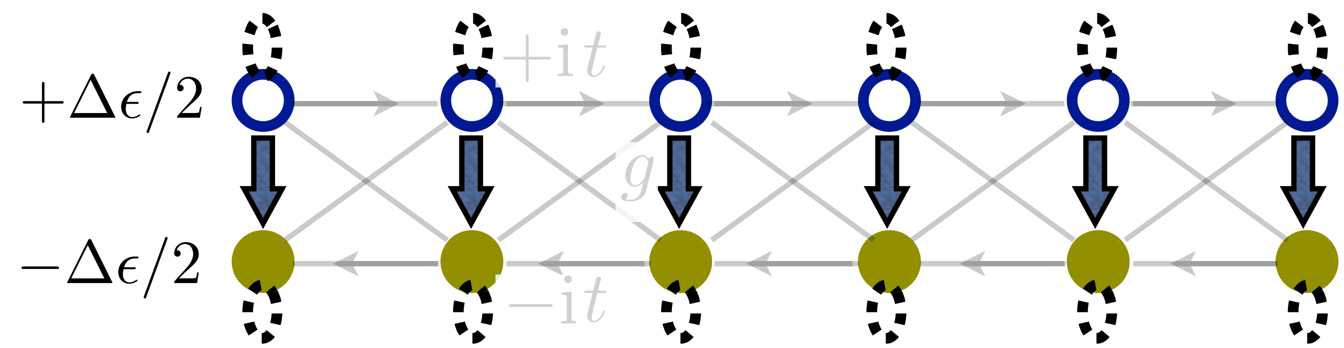
- The Creutz-Hubbard Ladder: general features
  - Topology & Interactions
    - SPT vs orbital magnetism at half-filling
    - relation to high-energy models
    - interacting SPT phases at fractional filling
  - Tuning the Drude Weight of Dirac fermions
- Other related works & plans

matteo.rizzi@fz-juelich.de

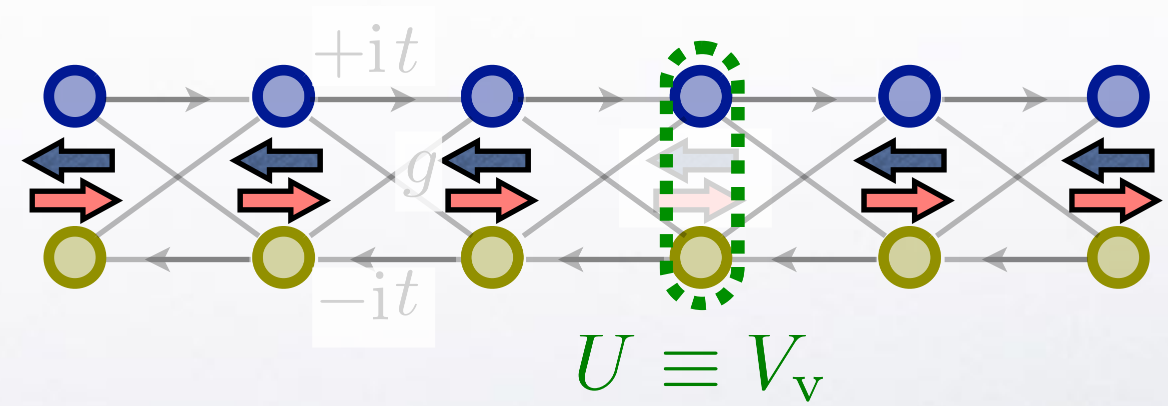
Phase diagram (half-filling)



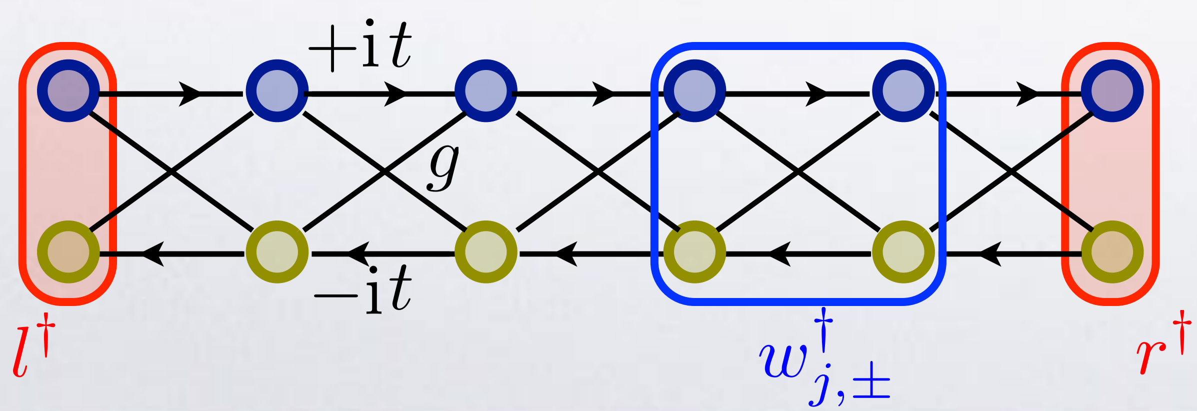
(trivial) Orbital ParaMagnet (**oPM**)



Orbital FerroMagnet (**oFM**)



Flat-band SPT topological insulator (**TI**)

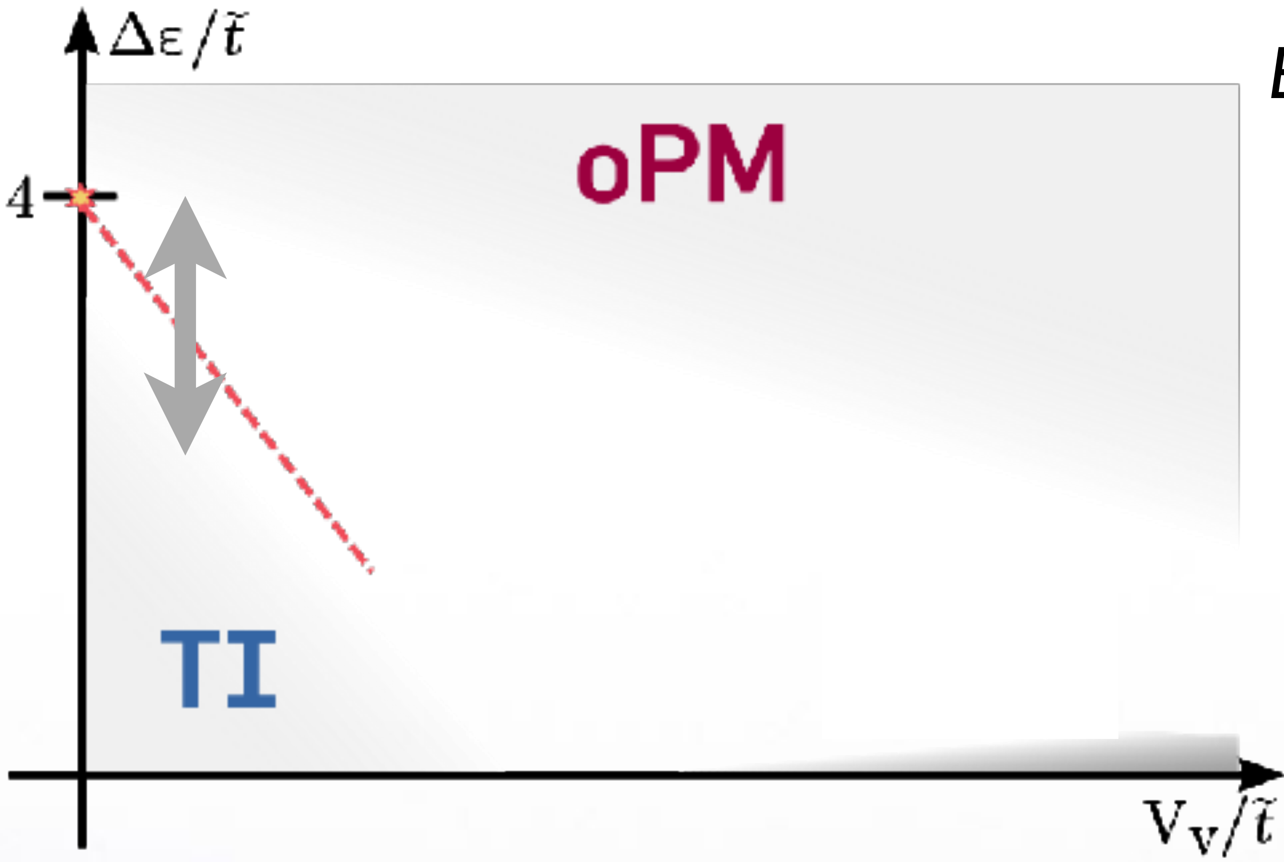


Weak interactions

Exact (non-local) mapping of non-interacting H onto ***two Ising models***

$$H_{\pi\mathrm{C}} = \sum_j \sum_{n=1,2} \left(-\tilde{t}\tau^x_{j,n}\tau^x_{j+1,n} + \frac{\Delta\varepsilon}{4}\tau^z_{j,n} \right)$$

Weak interactions



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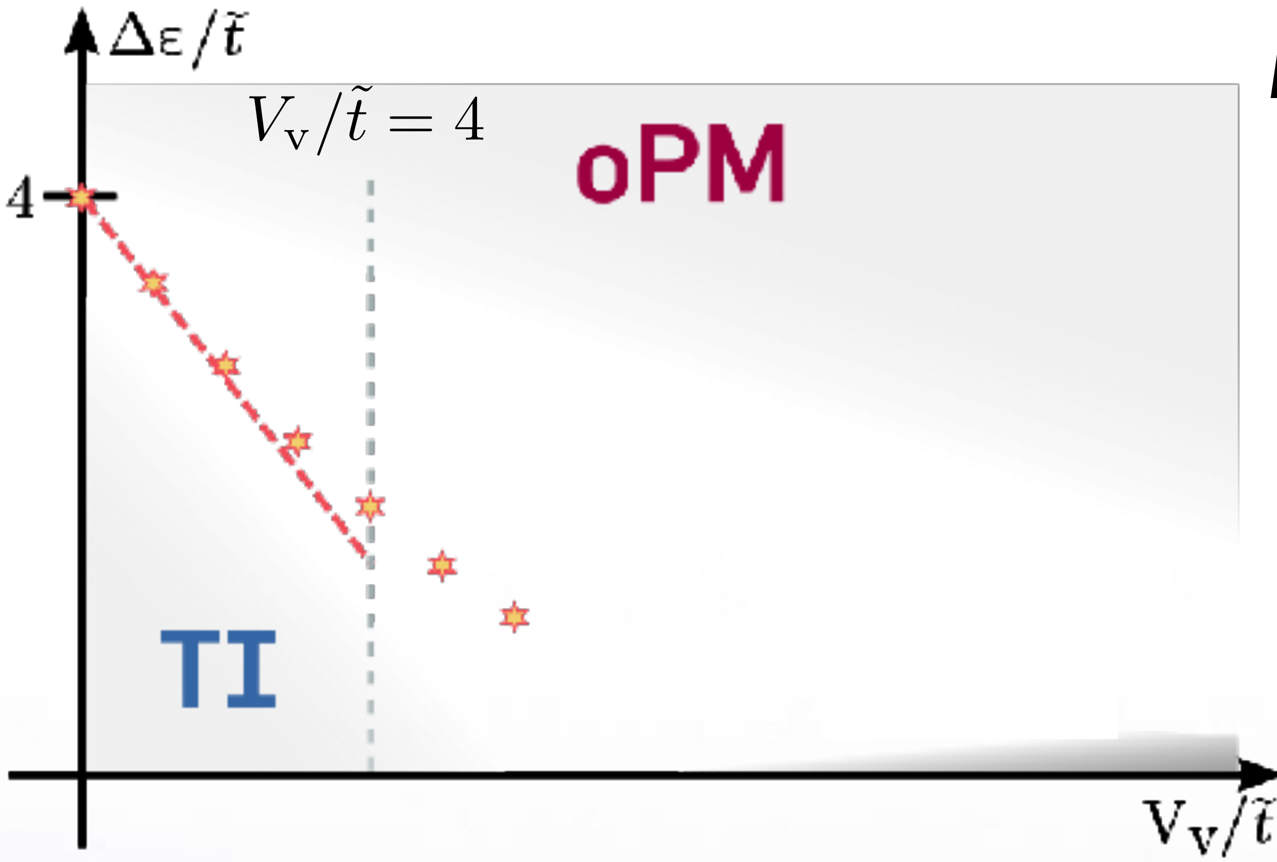
$$V_{\text{Hubb}} = -\frac{V_{\text{v}}}{4}\sum_j \tau^z_{j,1}\tau^z_{j,2} + \text{const.}$$

$$\frac{\Delta\epsilon}{\tilde{t}} = 4 - \frac{2}{\pi}\frac{V_{\text{v}}}{\tilde{t}} + \mathcal{O}\left(\frac{V_{\text{v}}^2}{\tilde{t}^2}\right)$$

For a more complete **RG treatment** (possibly extensible to more than 1D)

Tirrito, et al. (MR), arXiv:1812.05973 - PRB in press

Weak interactions



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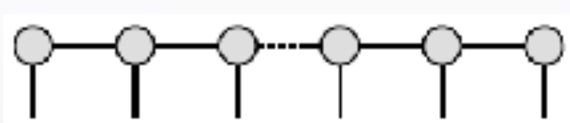
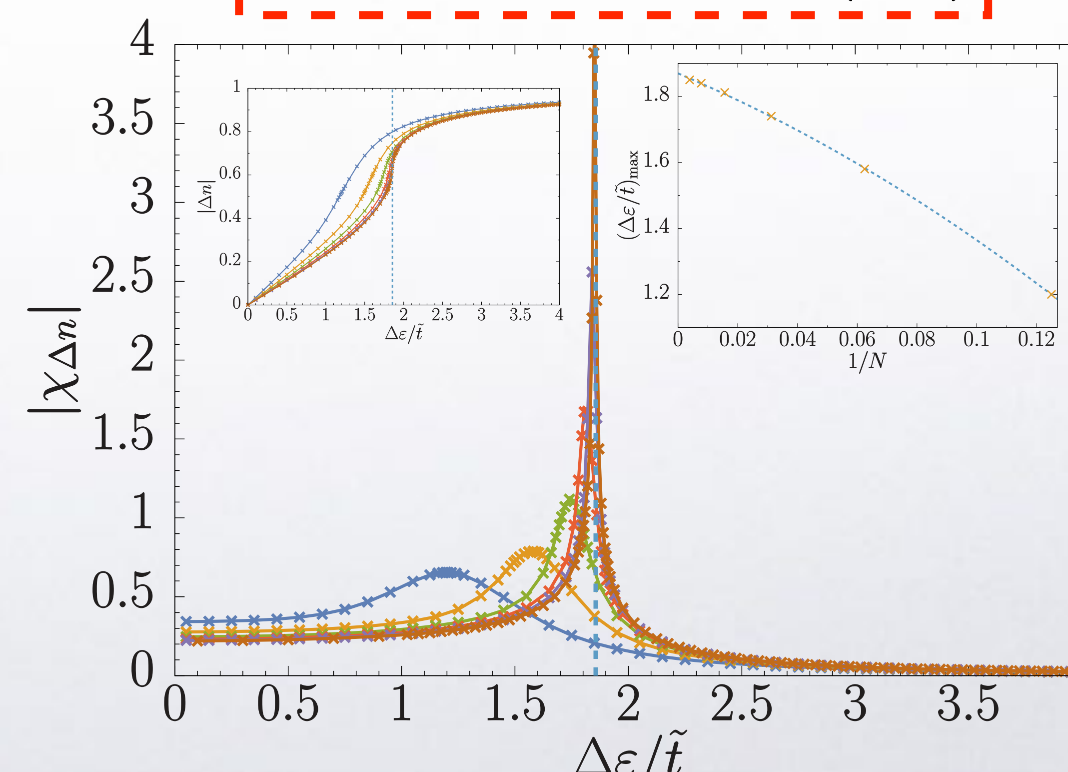
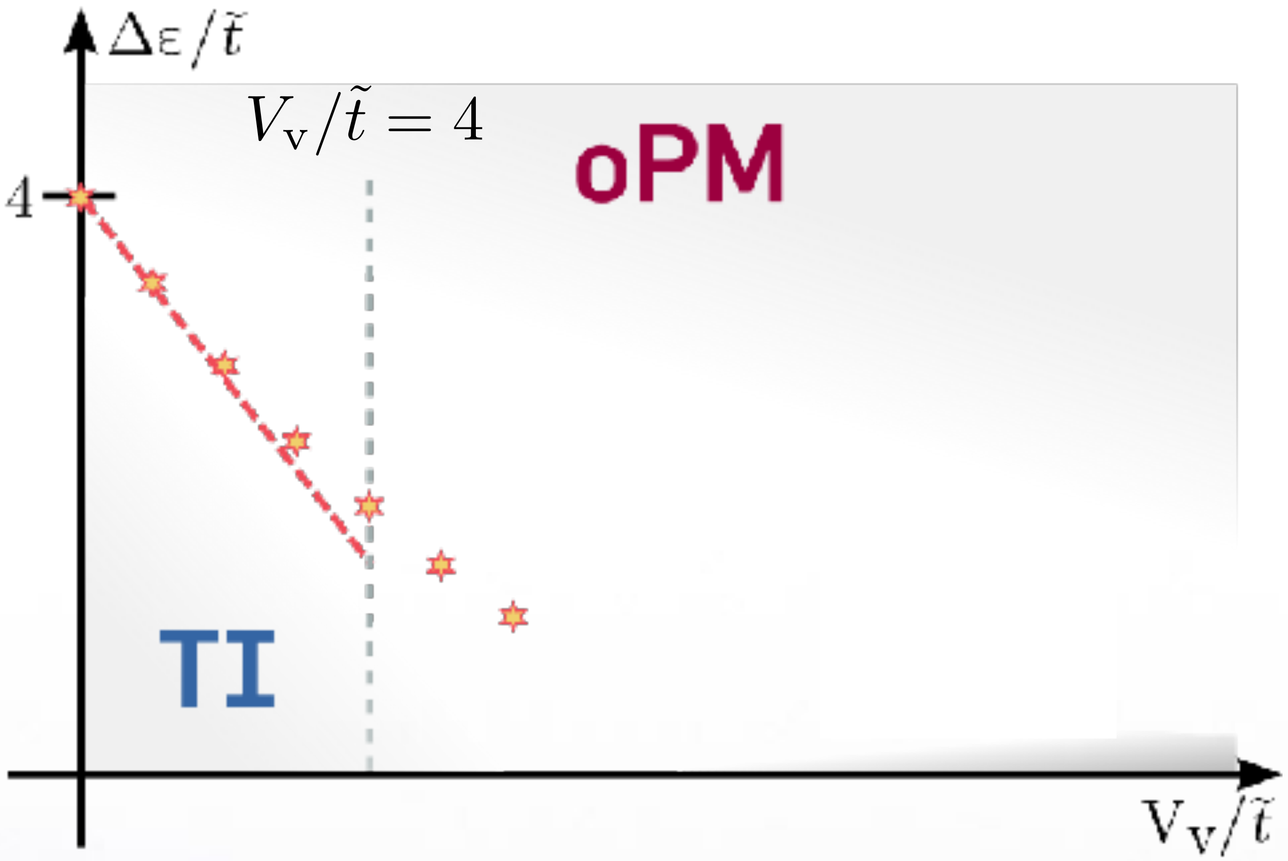
MPS calculations $N = 8 \dots 256$





$$T^z \equiv \Delta n \equiv n_{\rm u} - n_{\rm d} = \tfrac{1}{2}\langle \tau^z_1 + \tau^z_2 \rangle$$

Weak interactions



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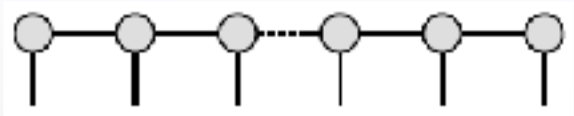
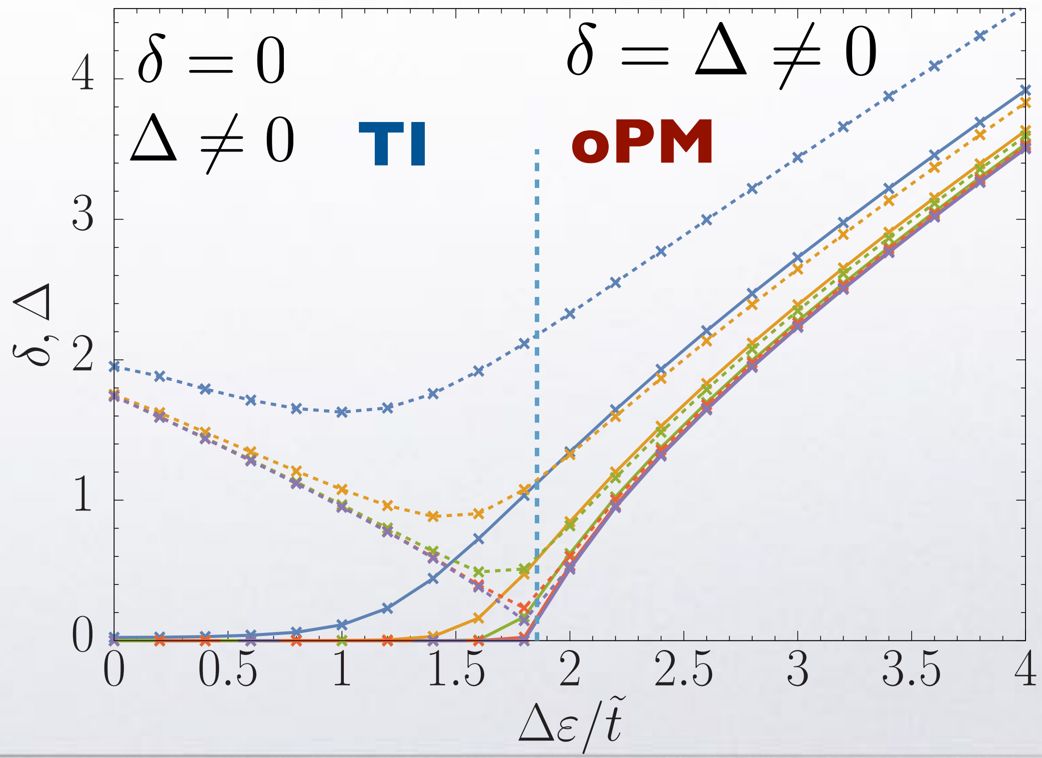


zero-energy edge modes

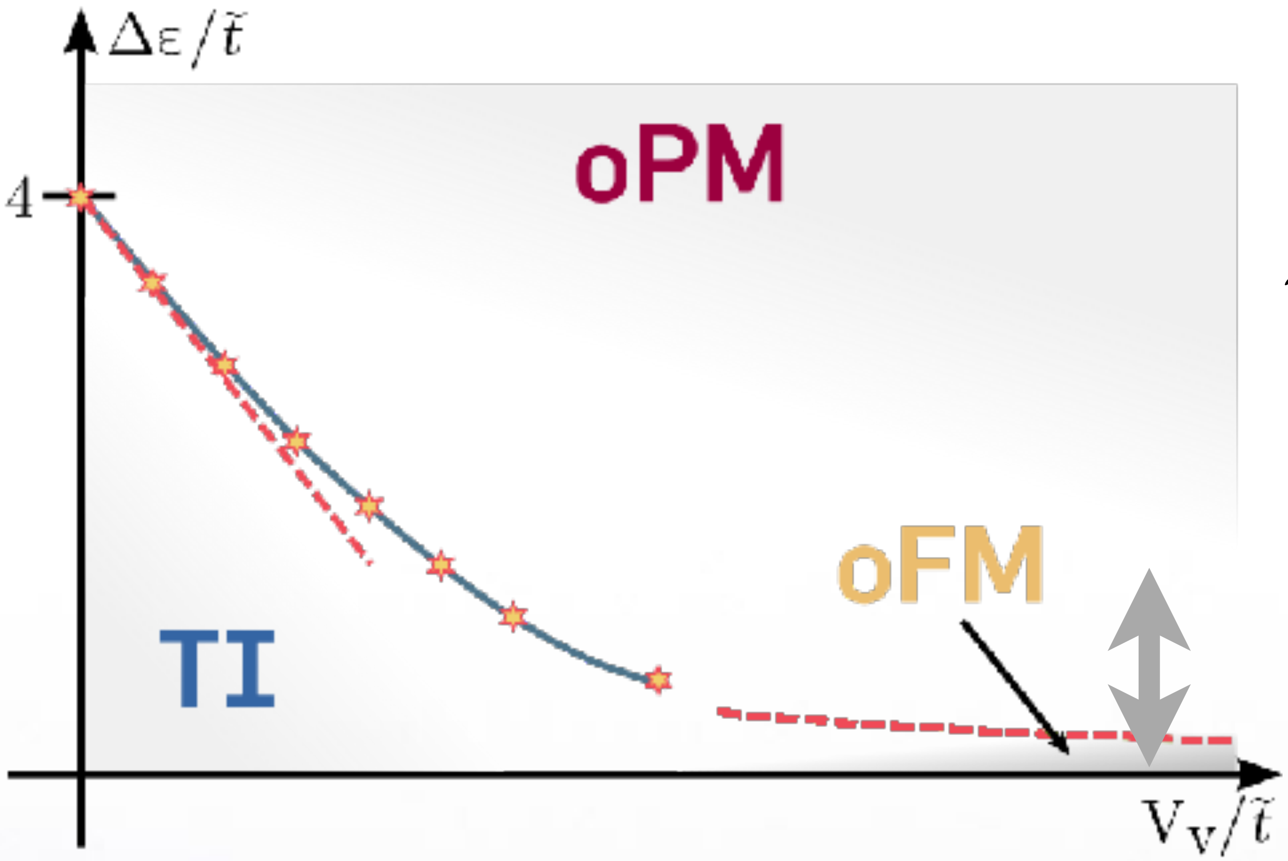
vs. compressibility gap

$$\delta = \lim_{N\to\infty} [E(N+1) + E(N-1) - 2E(N)]$$

$$\Delta = \lim_{N\to\infty} \tfrac{1}{2} [E(N+2) + E(N-2) - 2E(N)]$$



Strong interactions



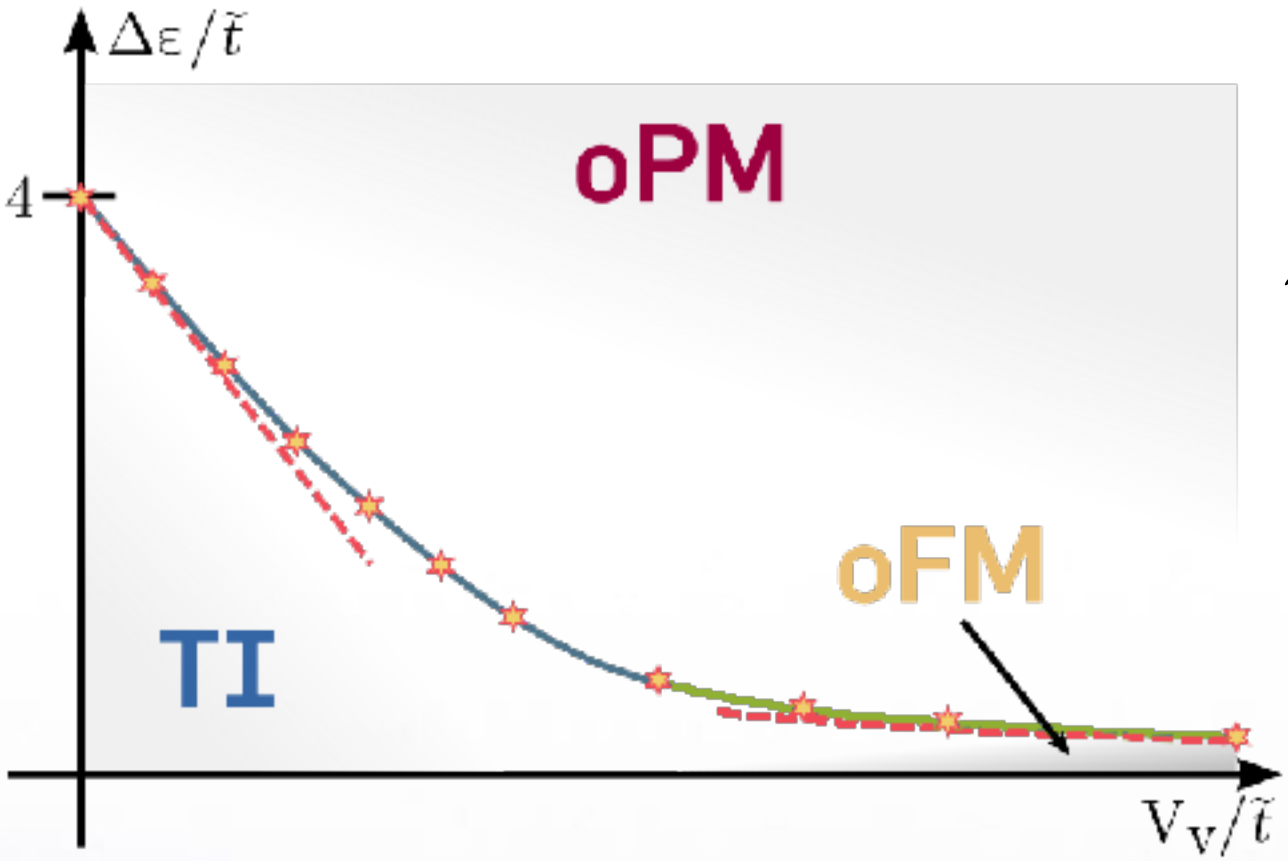
2[nd]-order *perturbation theory* [singly occ. rungs] gives **single Ising model**

$$\mathcal{P}_{\rm r} H_{\pi\rm CH} \mathcal{P}_{\rm r} = \frac{1}{4} J N + J \sum_i T_i^y T_{i+1}^y + \Delta\epsilon \sum_i T_i^z$$

$$J = -8\tilde{t}^2/V_{\rm v} \qquad T_j^\alpha = \frac{1}{2} c_j^\dagger \sigma^\alpha c_j$$

critical line $\frac{2\Delta\epsilon}{|J|} = 1 \iff \frac{\Delta\epsilon}{\tilde{t}} = \frac{4\tilde{t}}{V_{\rm v}}$

Strong interactions



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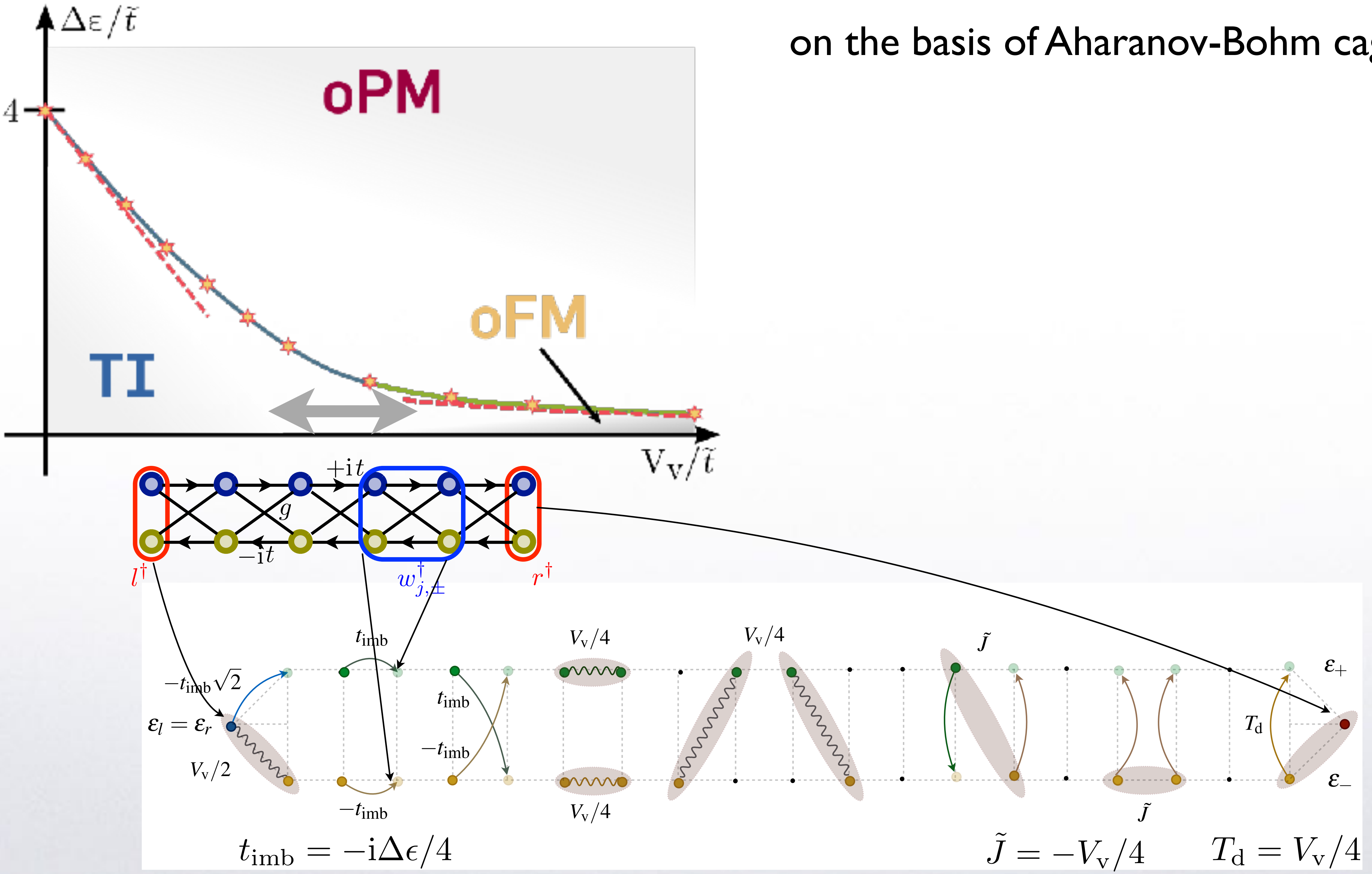
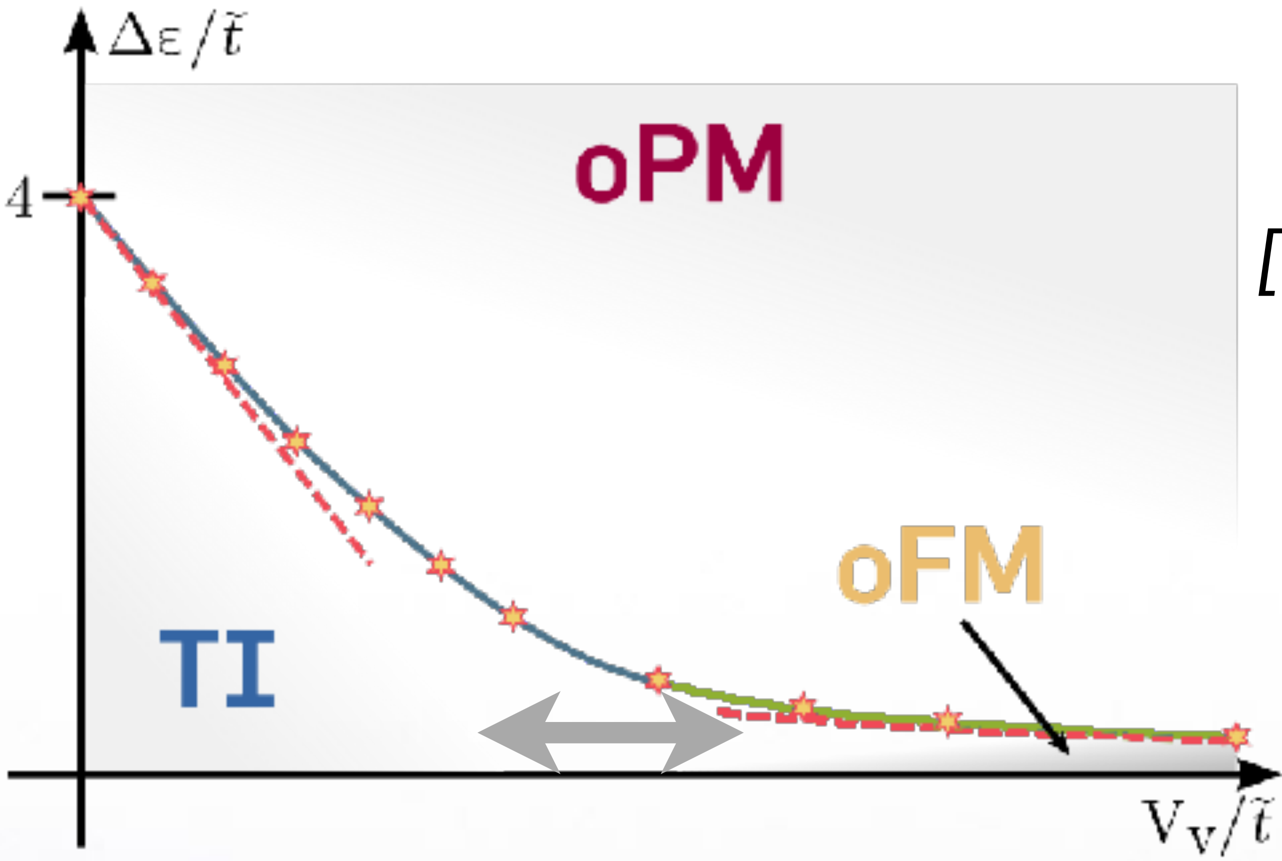
Weak imbalance

on the basis of Aharanov-Bohm cages



Weak imbalance

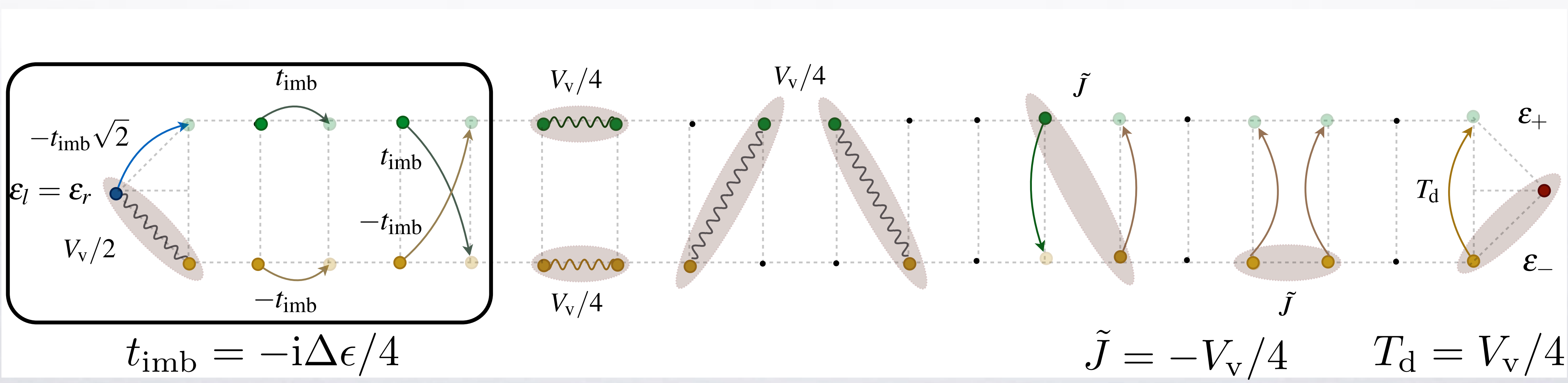


on the basis of Aharanov-Bohm cages

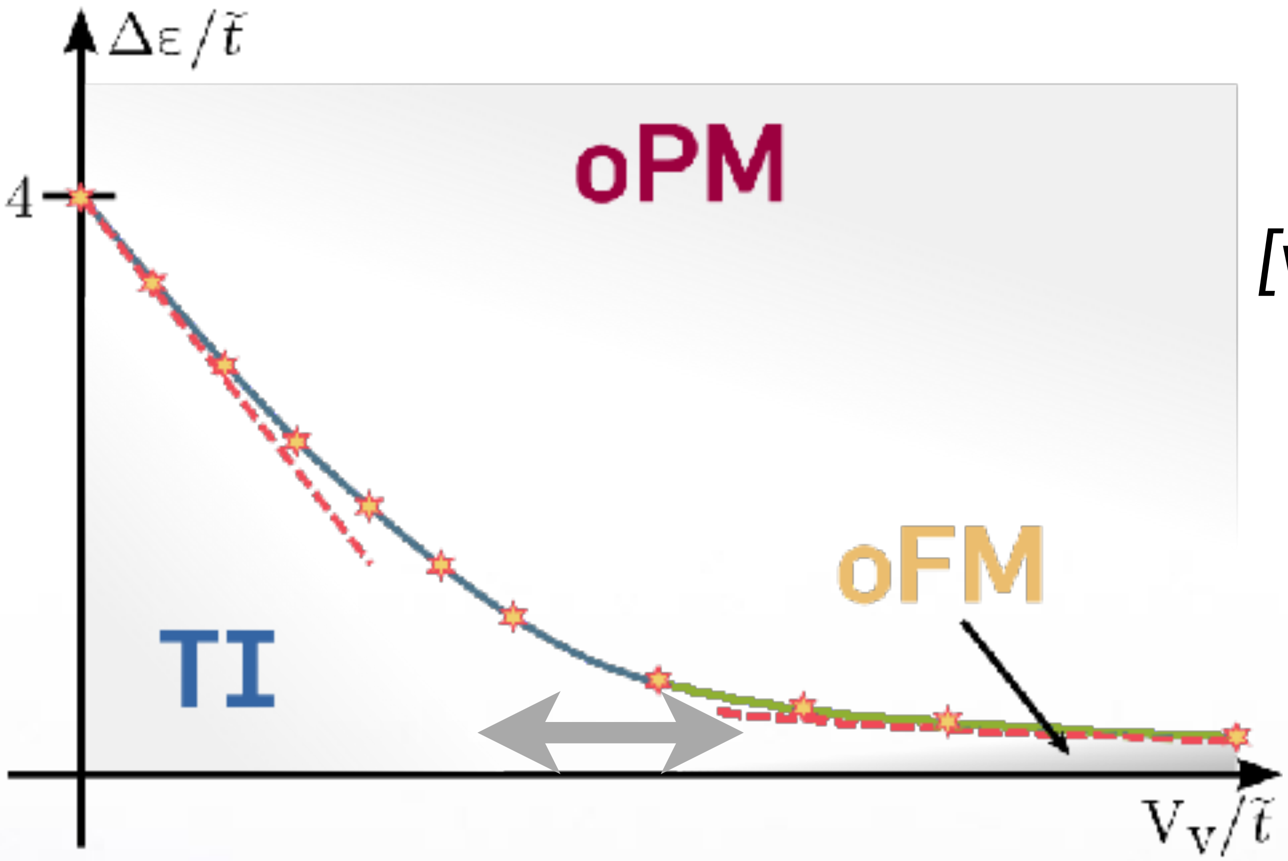
exotic Hubbard model

[without dipolar atoms or other "strange" schemes]

- imbalance induced hopping
- n.n. interactions
- pair tunnelling
- density-assisted tunnelling



Weak imbalance



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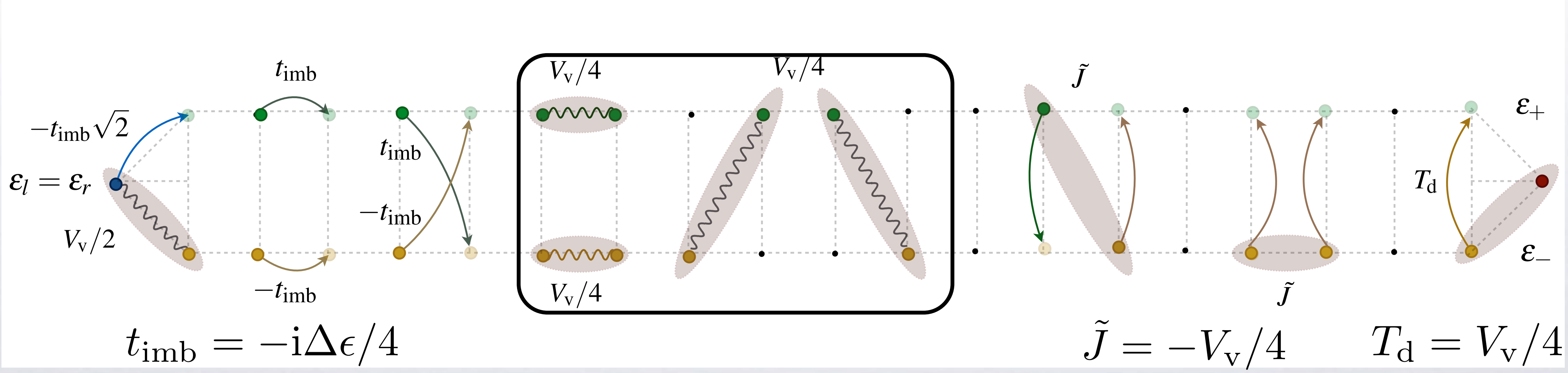
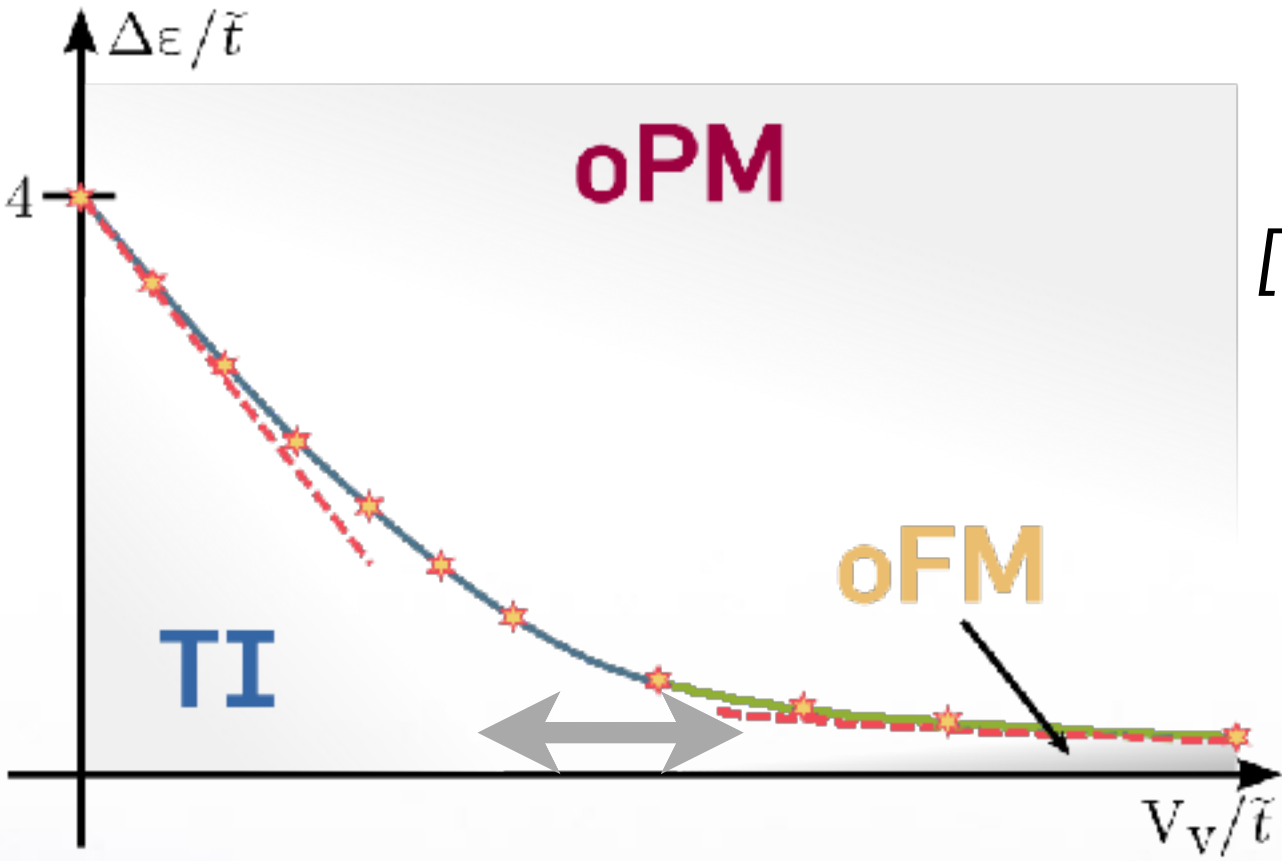
- pair tunnelling
- density-assisted tunnelling



Weak imbalance



on the basis of Aharanov-Bohm cages

exotic Hubbard model

[without dipolar atoms or other "strange" schemes]

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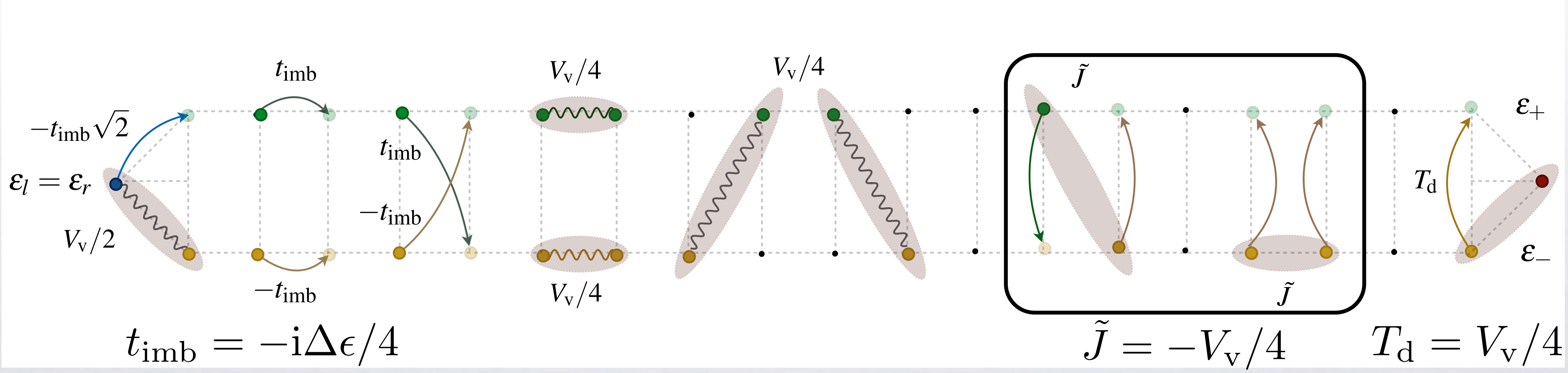

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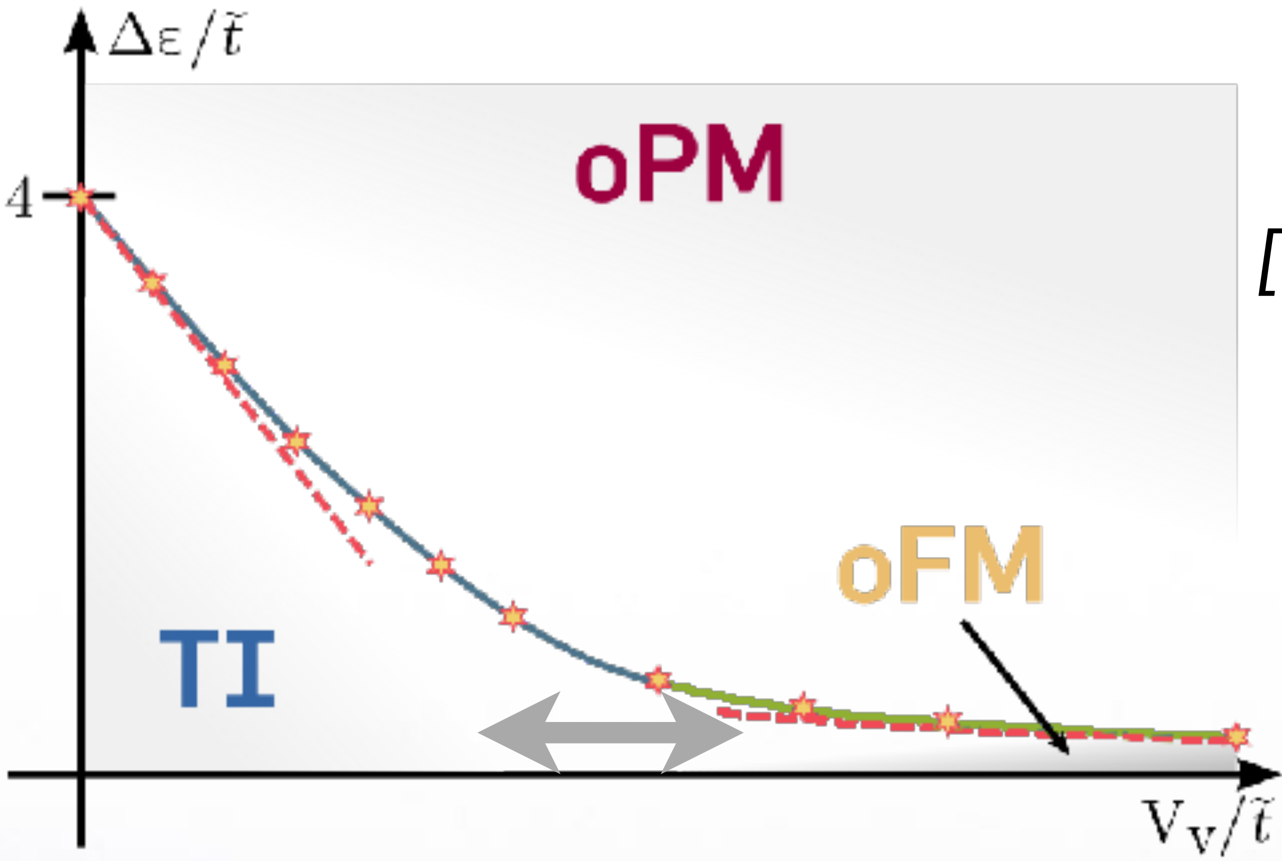

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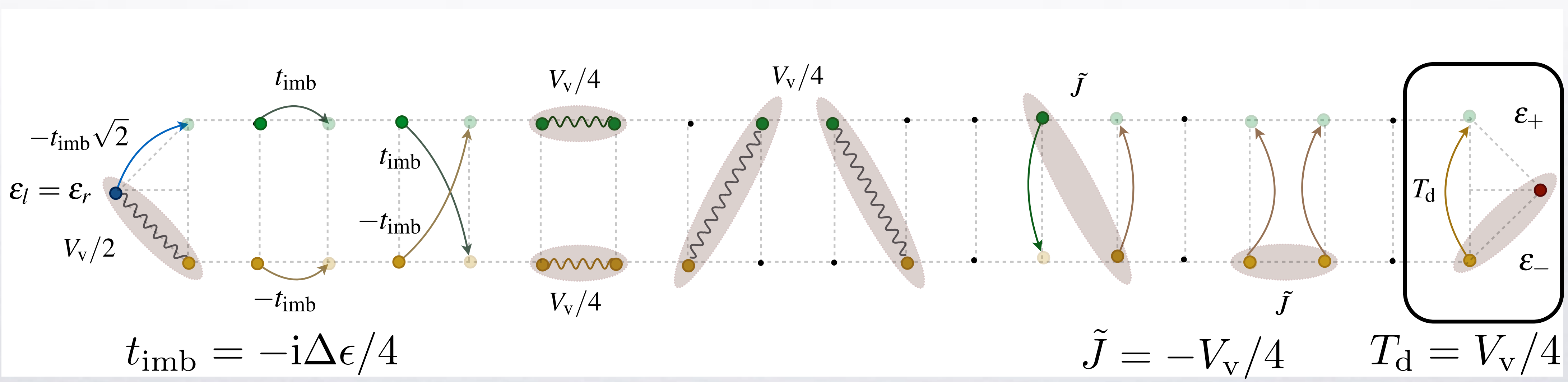

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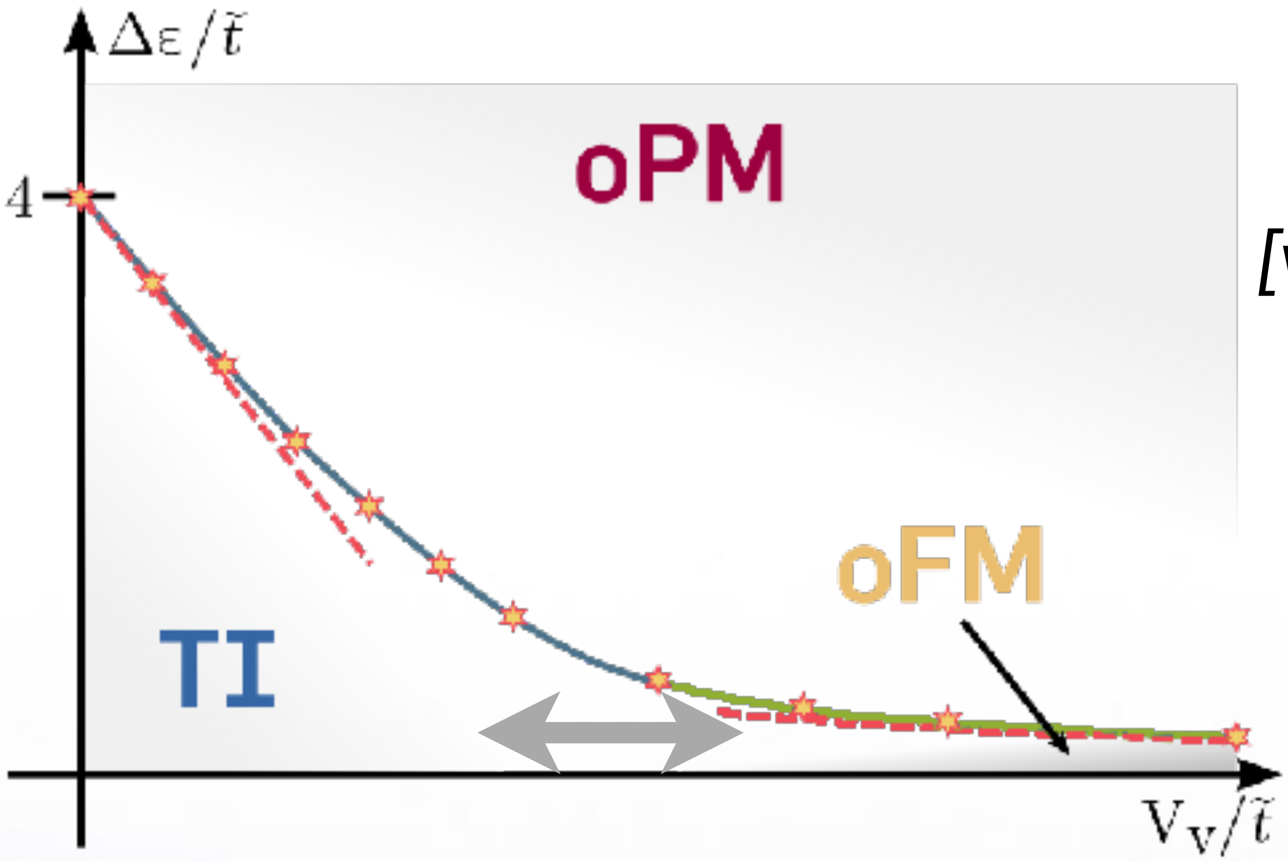

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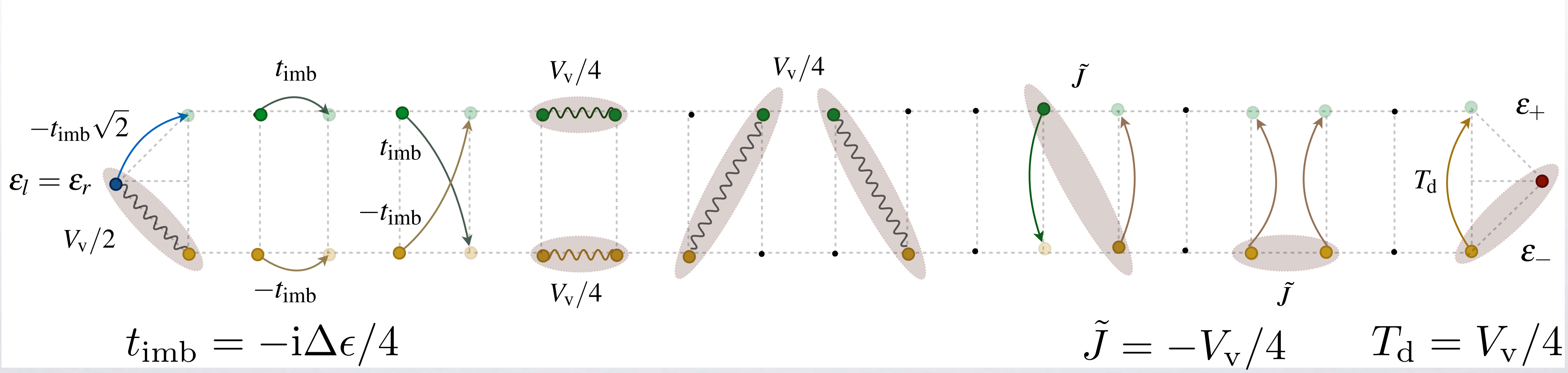

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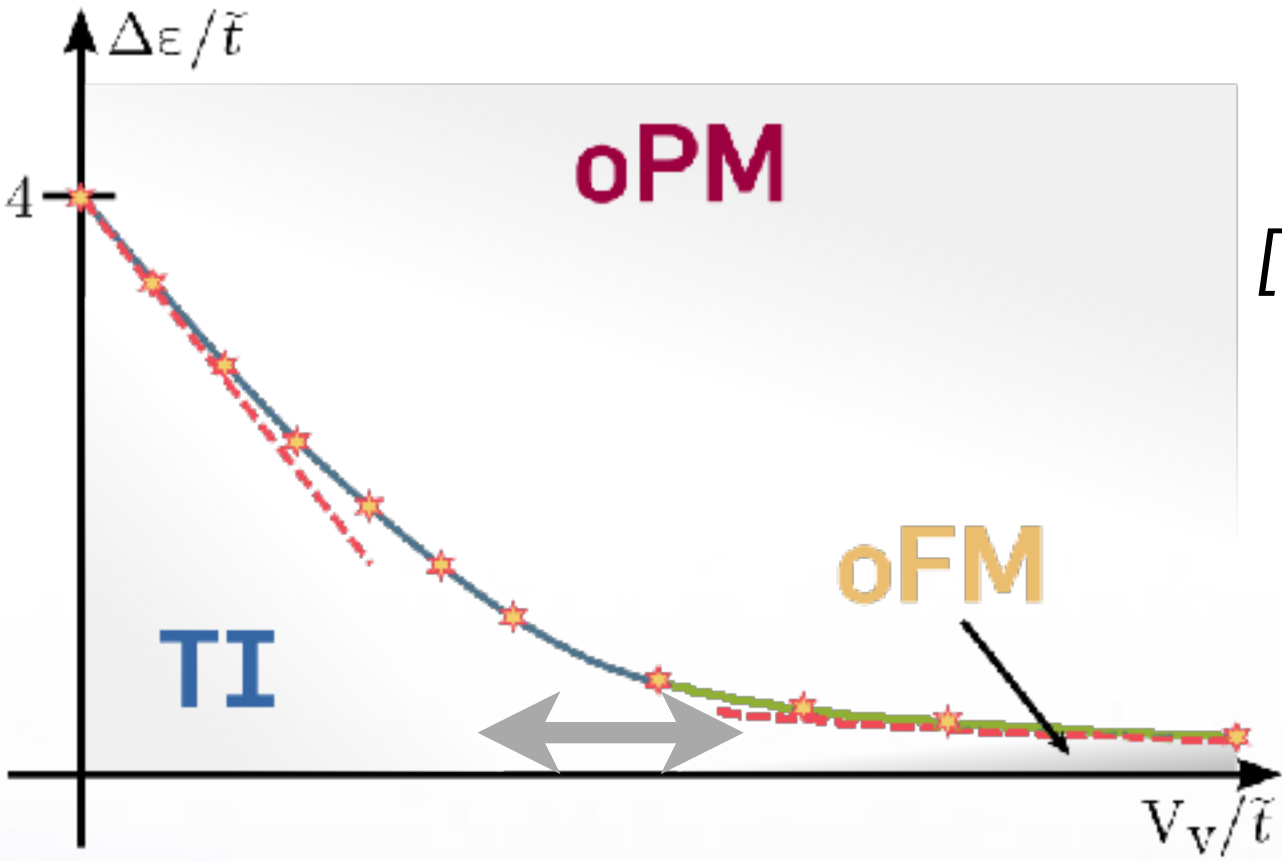

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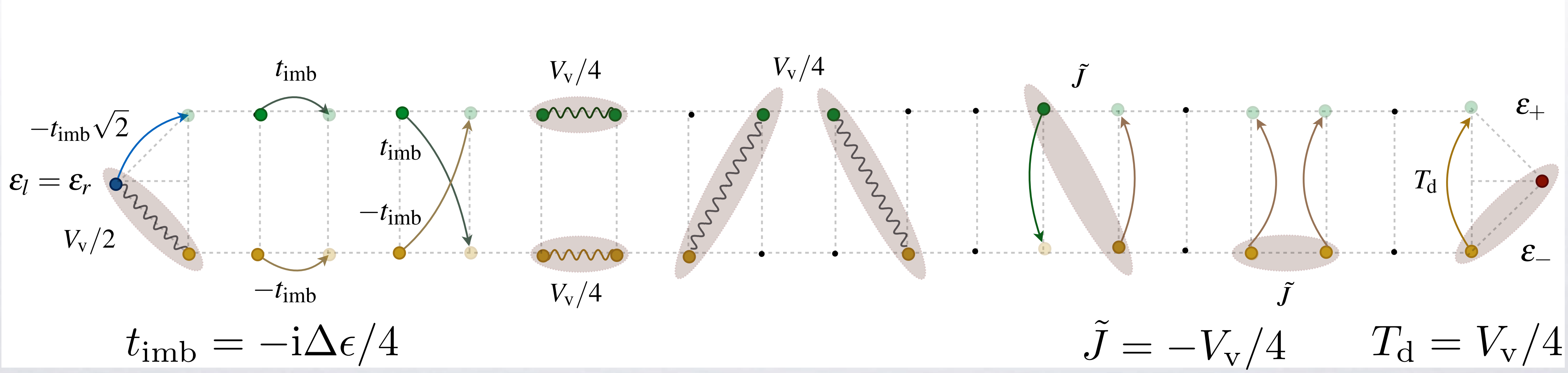
bulk-mediated *[à la Fano-Anderson]*

edge-edge interactions



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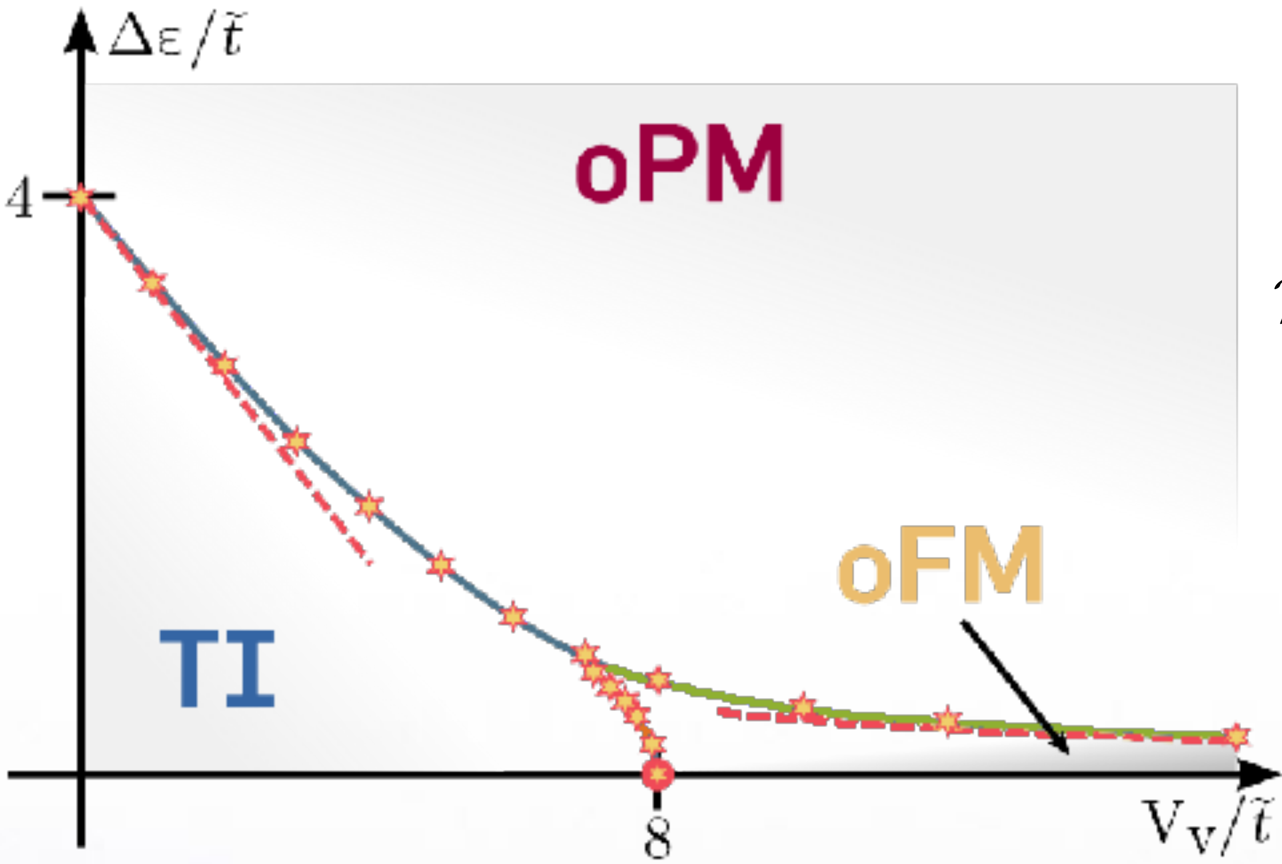


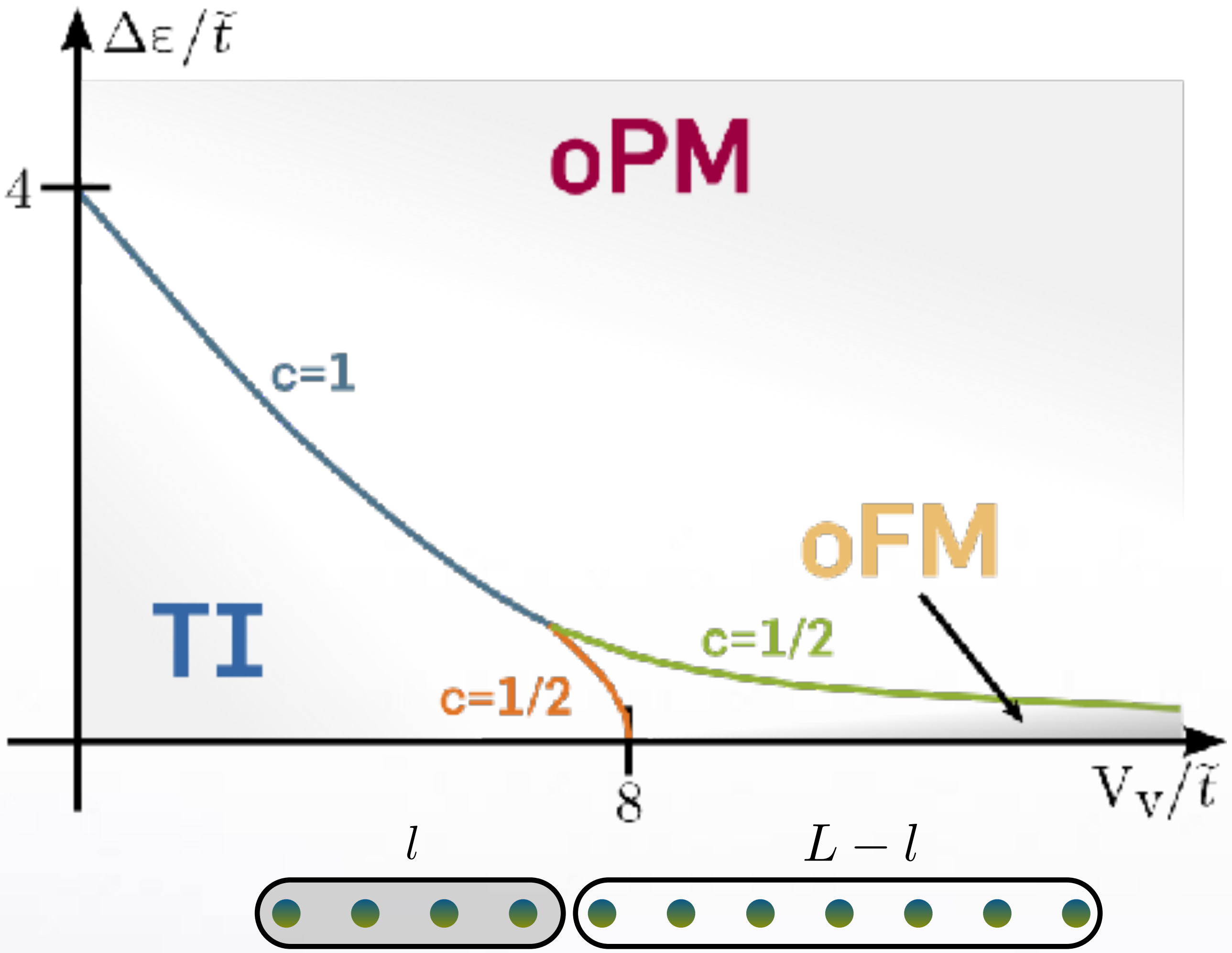
rewriting on singly-occupied AB cages gives **single Ising model**

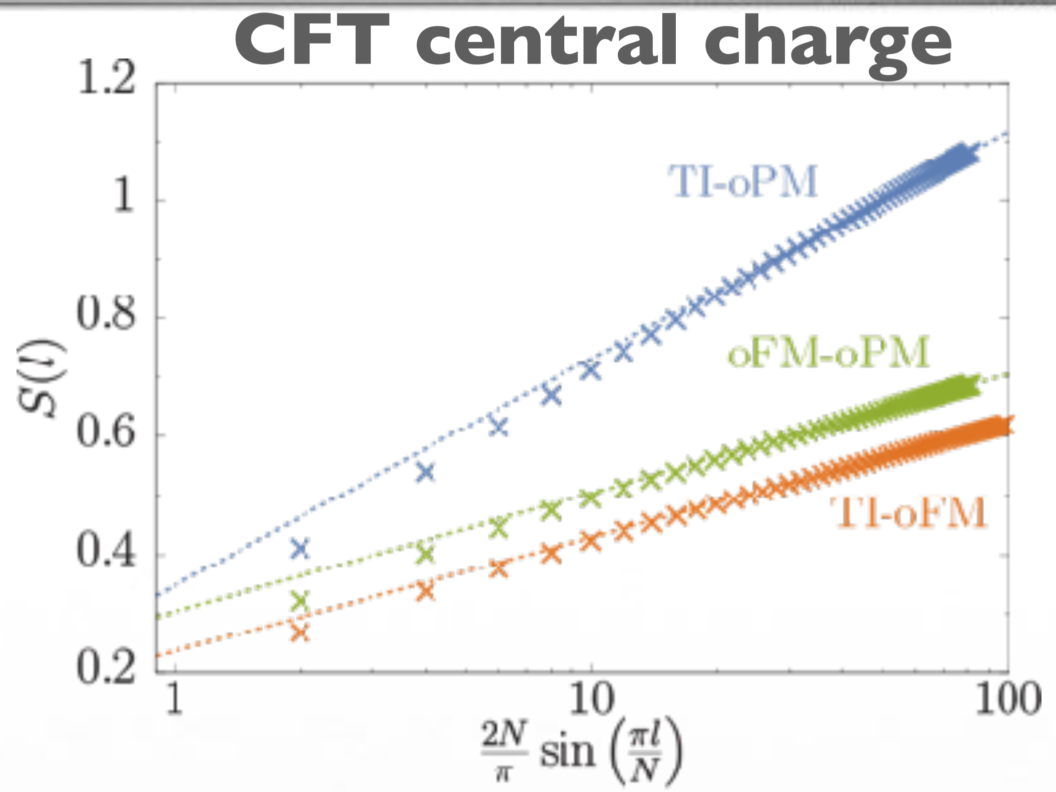
$$\mathcal{P}_c H_{\text{bulk}} \mathcal{P}_c = \frac{V_{\text{v}}}{4} N + 4\tilde{t} \sum_i \tilde{T}_i^z + 4\tilde{J} \sum_i \tilde{T}_{i-1}^x \tilde{T}_i^x$$

$$\tilde{J} = -V_{\text{v}}/4 \qquad \widetilde{T}_i^\alpha = \frac{1}{2} w_i^\dagger \widetilde{\sigma}^\alpha w_i$$

critical point $\dfrac{2\tilde{t}}{|\tilde{J}|} = 1 \iff \dfrac{V_{\text{v}}}{\tilde{t}} = 8$

Entanglement analysis via MPS





$$S(l) = -\mathrm{Tr}\{\rho_l \log \rho_l\} \simeq \frac{c}{6} \ln\left(\frac{2L}{\pi}\sin\frac{\pi l}{L}\right) + a$$

Vidal, Latorre, Rico & Kitaev, PRL **90**, 227902 (2003)
Calabrese & Cardy, JSTAT P06002 (2004)

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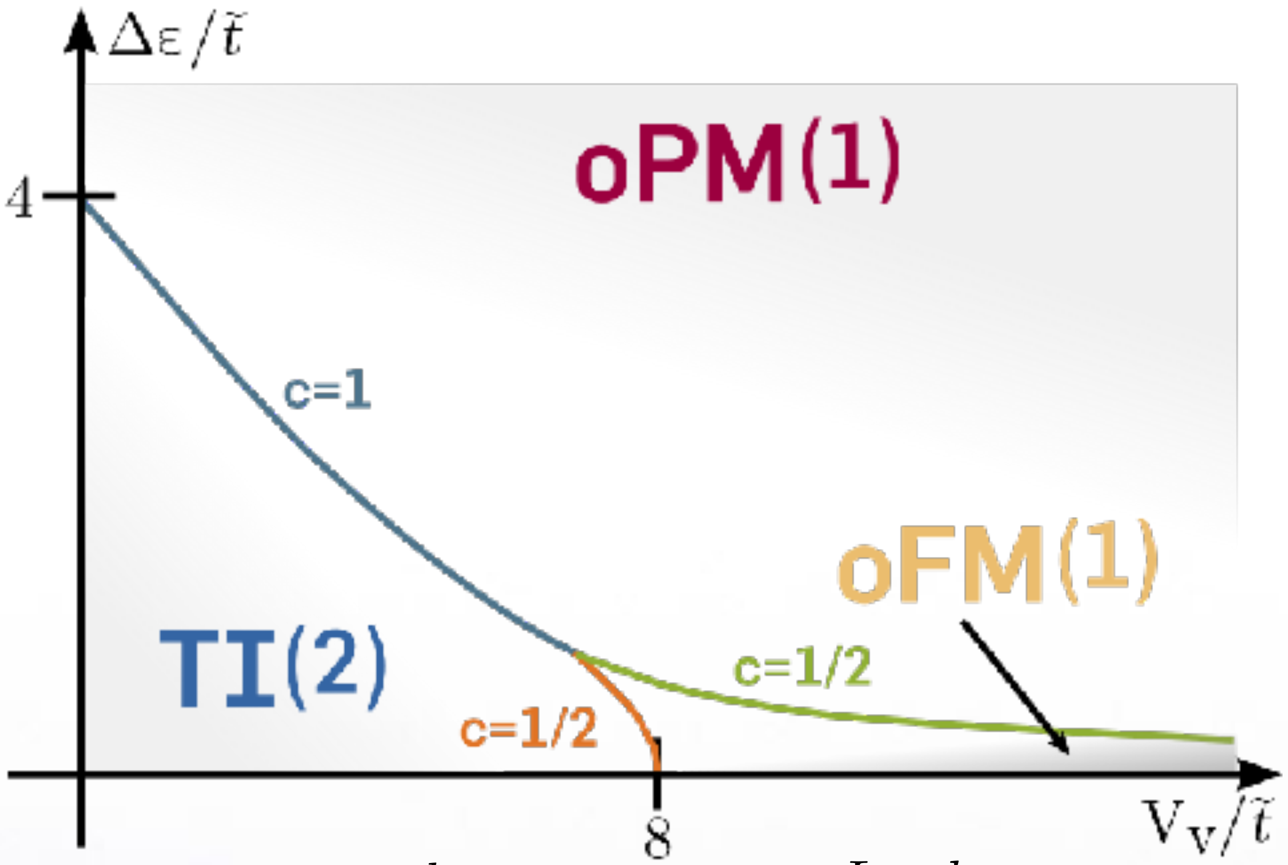

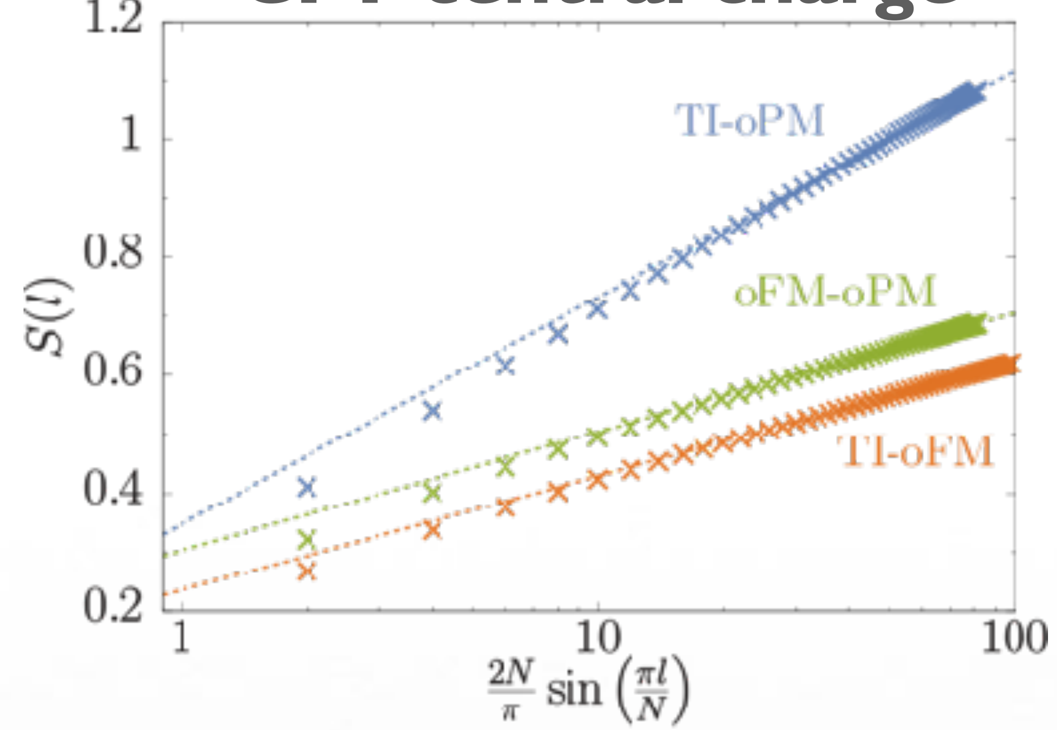

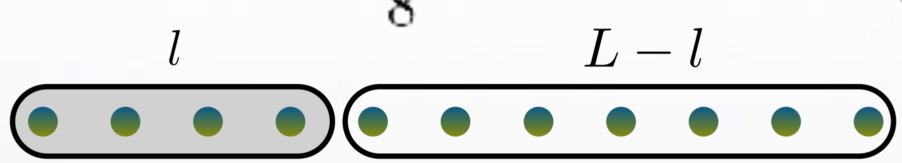

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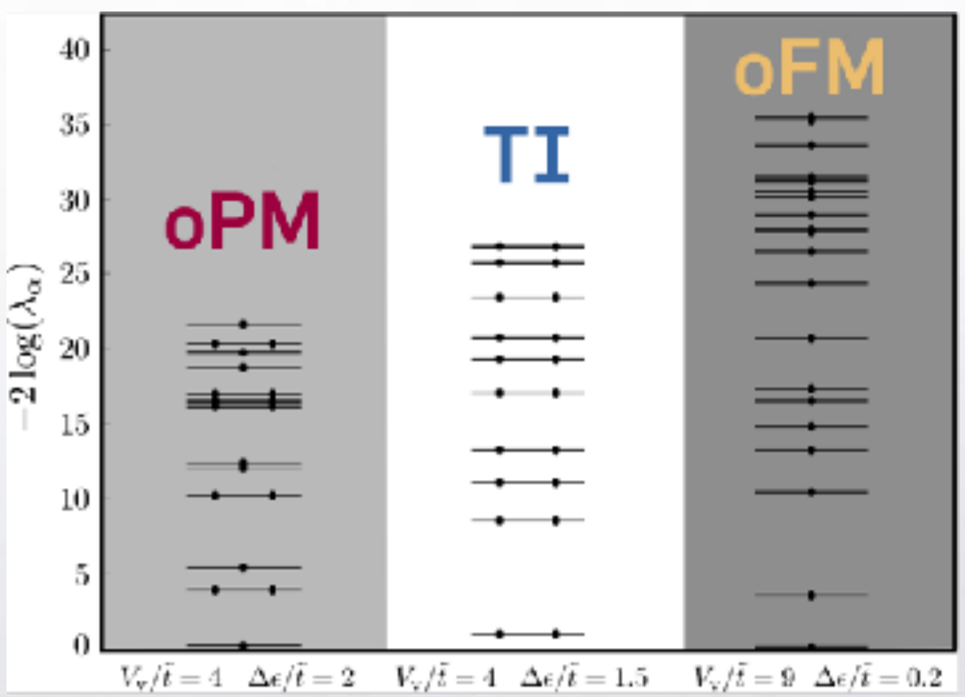
$$|\psi\rangle = \sum_i \lambda_i \, |\psi_l^i\rangle \otimes |\psi_{L-l}^i\rangle$$

Li & Haldane, PRL **101** 010504 (2015)
F. Pollmann, et al, PRB **81** 064439 (2010)

entanglement spectrum (SPT)



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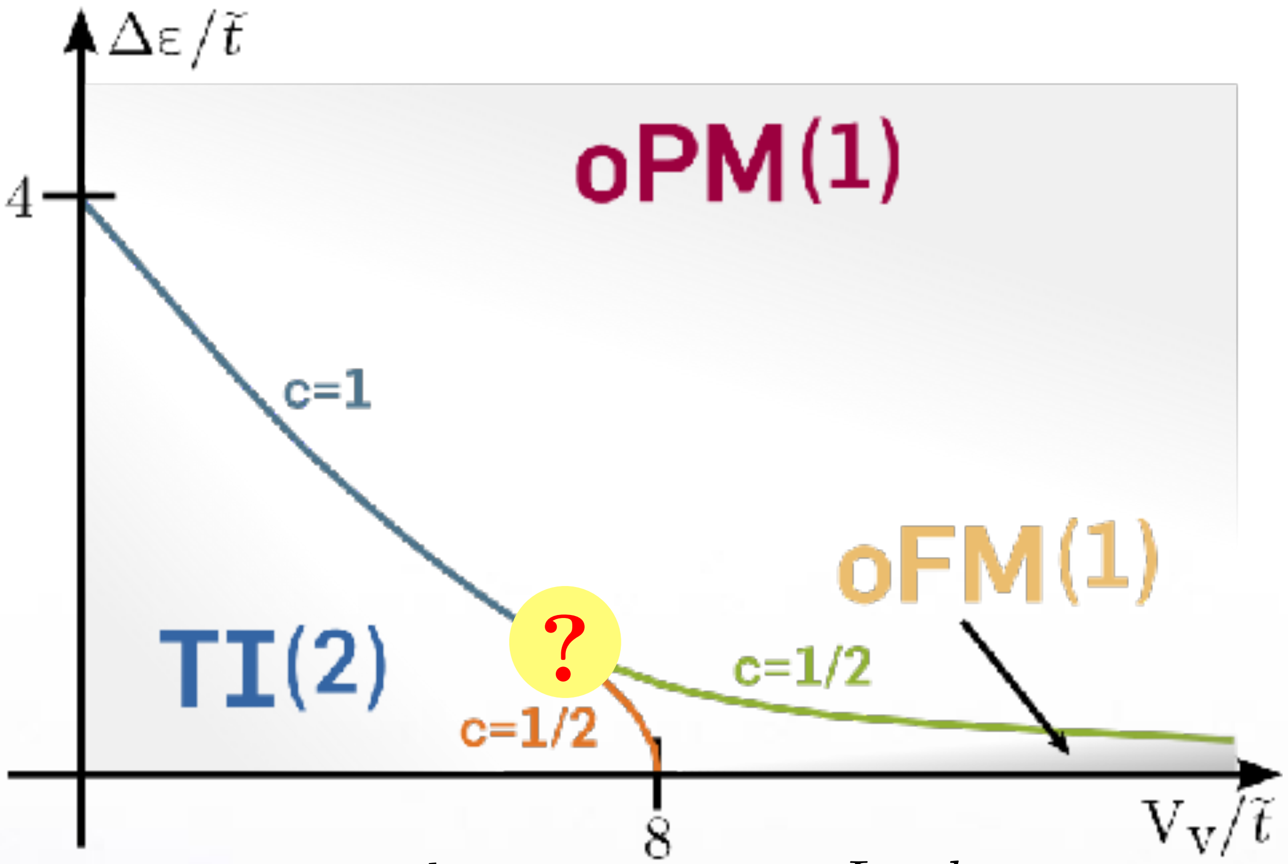

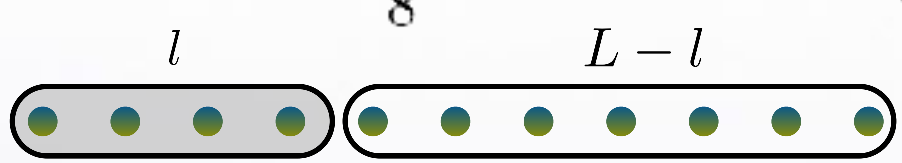

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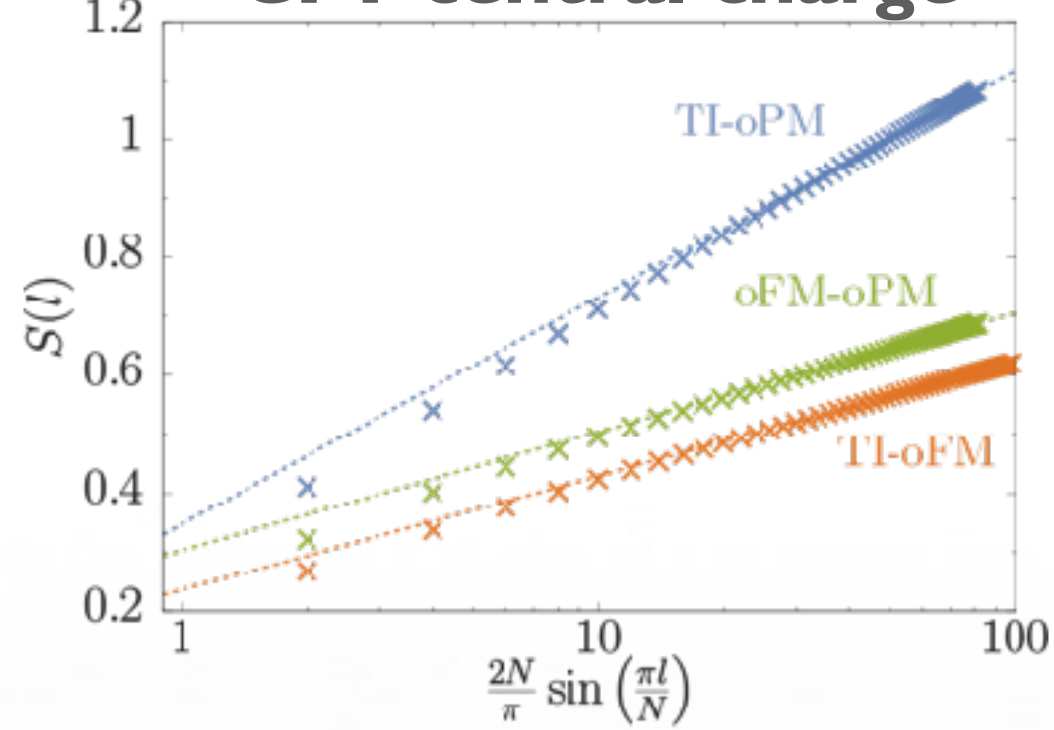
CFT central charge



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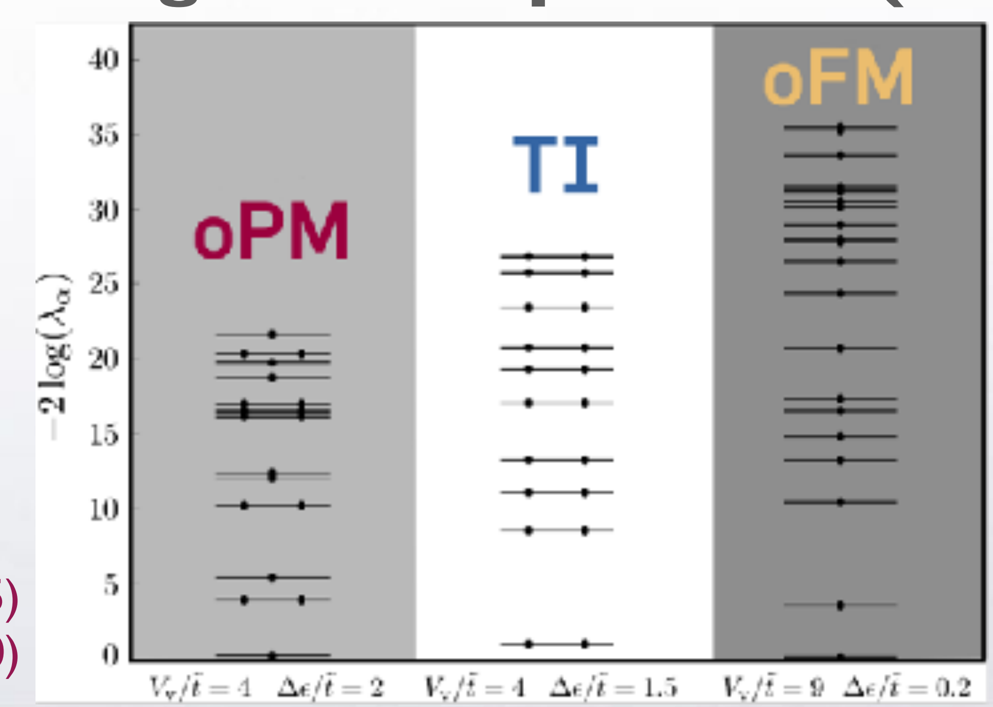

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Gross-Neveu model

(1+1)D toy model for QCD

D.J. Gross and A. Neveu, PRD **10**, 3235 (1974)

$\gamma^0 = \sigma^z \qquad \gamma^1 = \mathrm{i}\sigma^y \qquad \gamma^5 = \gamma^0\gamma^1 = \sigma^x$

$\Psi(x) = (\psi_1(x)\dots\psi_N(x))^t \qquad \overline{\psi}_n = \psi_n^\dagger\gamma^0$

$$\mathcal{H} = -\overline{\Psi}(x)\left(\mathbb{I}_N \otimes \mathrm{i}\gamma^1\right)\partial_x\Psi(x) - \frac{g^2}{2N}\left(\overline{\Psi}(x)\Psi(x)\right)^2$$

asymptotic freedom & dynamical mass generation *without* non-Abelian gauge fields!

RG treatment exact in $N \to \infty$ limit: *what about finite N?*

Wilson lattice discretization, to avoid doublers(!) $h_k = \left(m + \frac{1-\cos ka}{a}\right)\gamma^0 - \frac{\sin ka}{a}\gamma^5$

Kogut & Susskind, PRD **11**, 395 (1975); K.Wilson (1977); Nielsen & Ninomiya, Nuc. Phys. B **185**, 20 & **193**, 173 (1981)

is essentially a Creutz-ladder

up to a rotation $\Psi(x) \longrightarrow \mathrm{e}^{-\mathrm{i}\frac{\pi}{2a}x}\Psi(x)$

$h_k^{\mathrm{CL}} = \left(\frac{\Delta\epsilon}{2} + 2\tilde{t}\sin k\right)\gamma^0 - 2\tilde{t}\cos k\,\gamma^5$

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for N=1 it is the same!!!

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chiral condensate	pseudo-scalar cond.
$\sigma_0 \equiv \langle\overline{\Psi}(x)\Psi(x)\rangle \neq 0$	$\Pi_0 \equiv \langle\overline{\Psi}(x)\mathrm{i}\gamma^5\Psi(x)\rangle \neq 0$

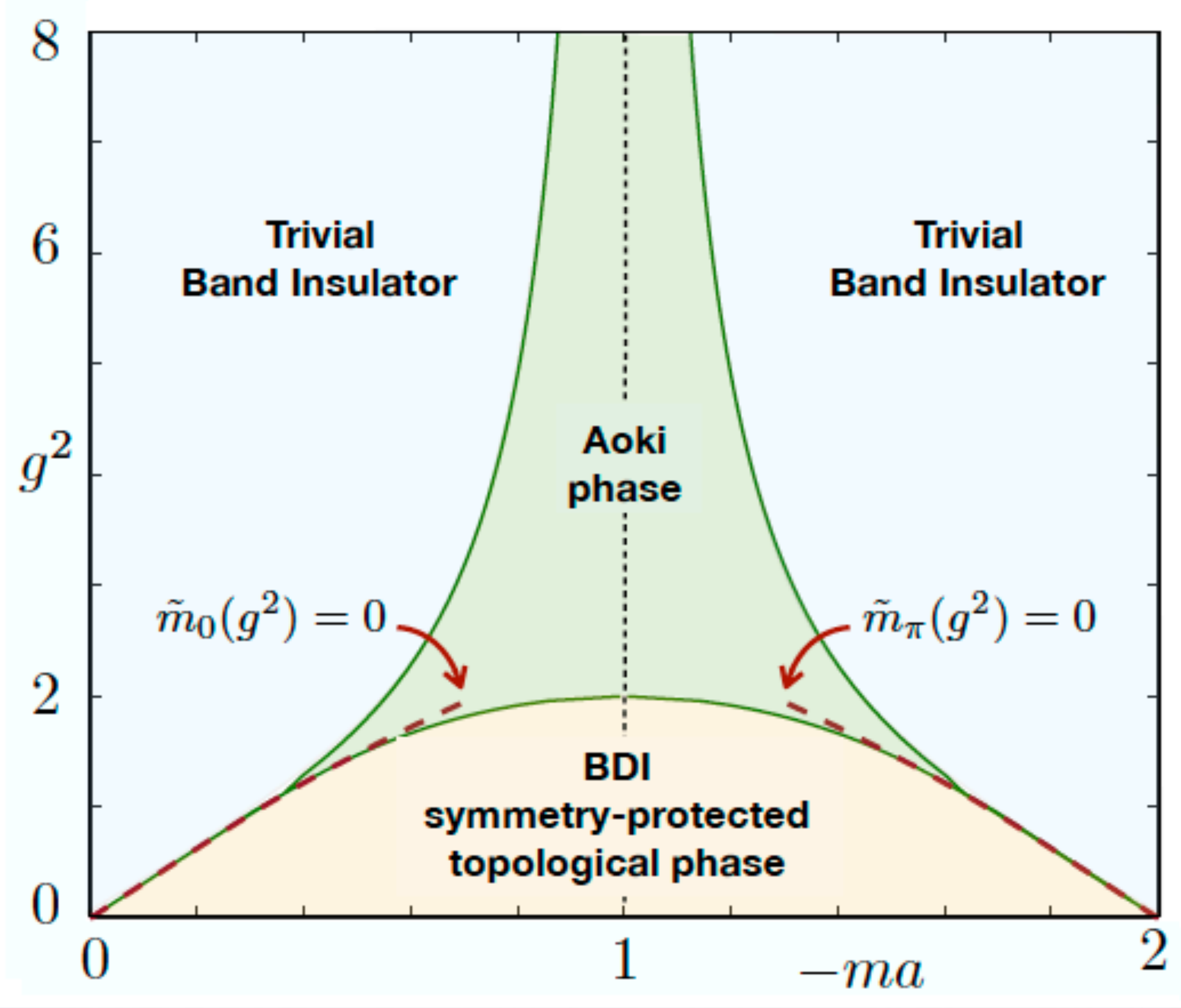
S. Aoki, PRD **30**, 2653 (1984); Izubuchi, Noaki, Ukawa, PRD **58**, 114507 (1998)

Gross-Neveu model

Various methods at hand, nowadays:
lattice QMC, large-N expansion, MPS for small N, quantum simulation with atoms, …

$$\tilde{m}_0(g^2) = m + \sigma_0$$

$$\sigma_0 \simeq \frac{g^2}{\pi a} + \frac{8}{a} \mathrm{e}^{-2\pi/g^2}$$



$$ma = \frac{\Delta\epsilon}{4\tilde{t}} - 1$$

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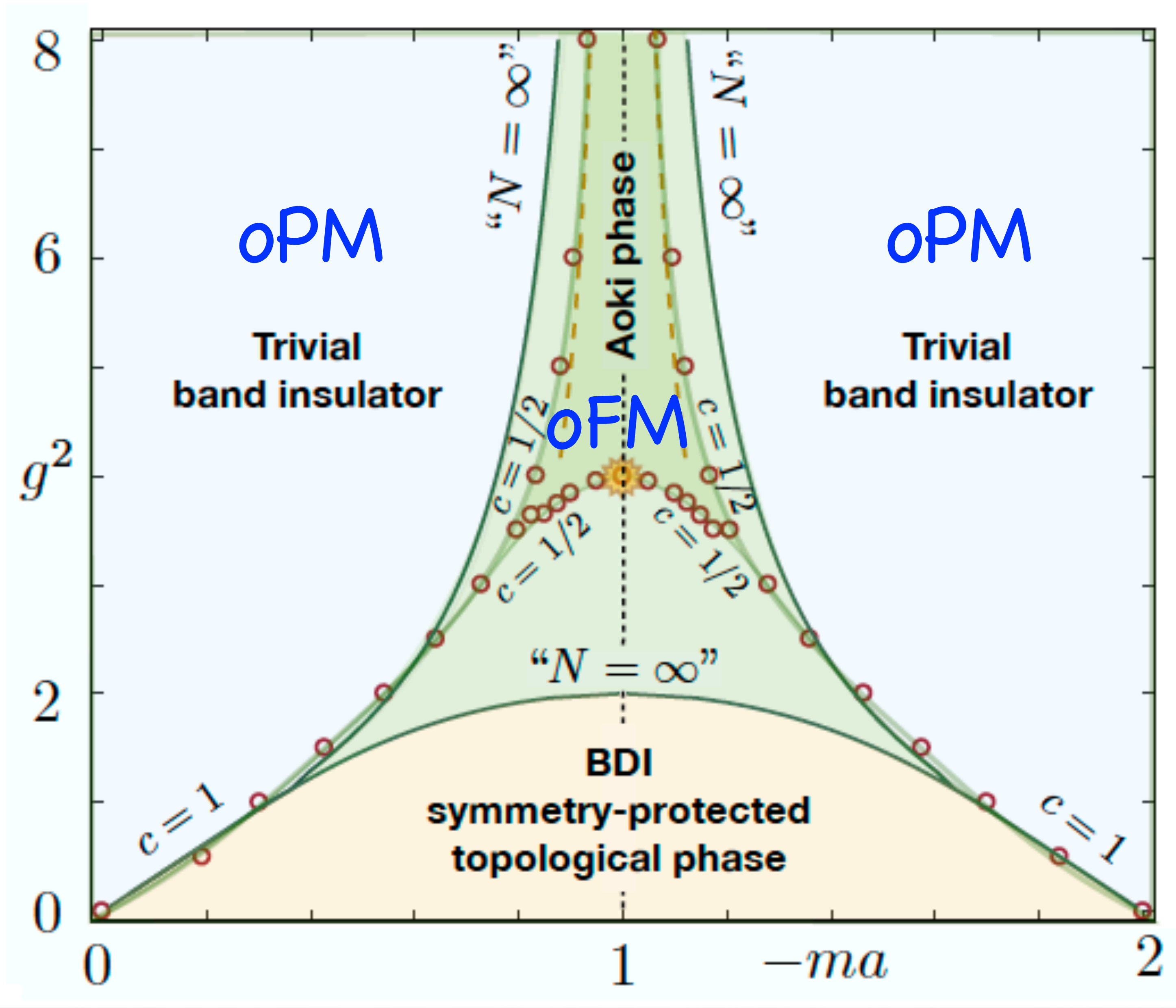

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Explanation of cond-mat results by hep-th language
+
New perspective on quant. simul. of hep-th models with low-N

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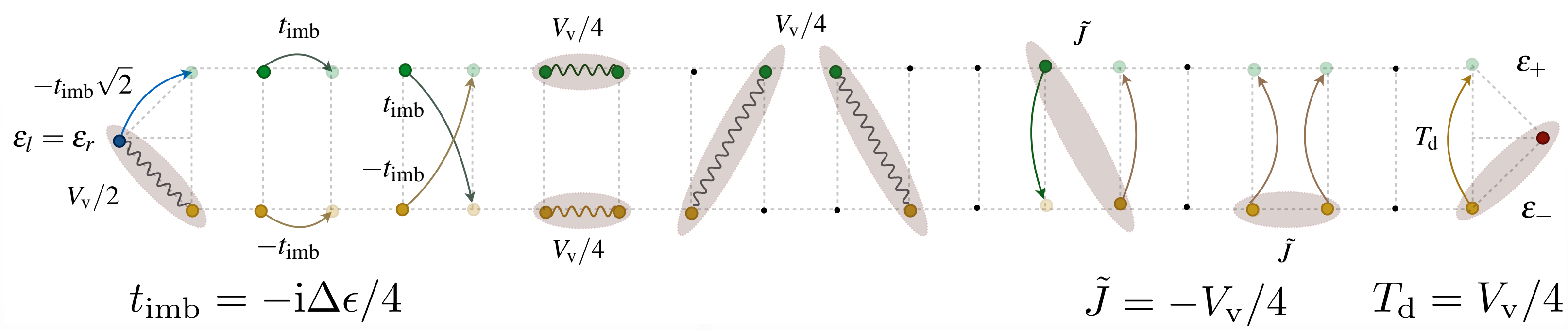
Topological CDW

Can intrinsically interacting SPT phases arise
at $\nu = N/L \neq 1$ for which non-interacting system is trivial?

<u>Creutz-Hubbard ladder</u>

↓

Projection on lowest band
& approximate cage basis:
… n.n. interactions …



↓

gapped phase at $\nu = \frac{1}{2}$ & critical U/t

$$\delta_{\rm charge} = E_1(N) - \frac{1}{2}\left[E_1(N+1) + E_1(N-1)\right]$$

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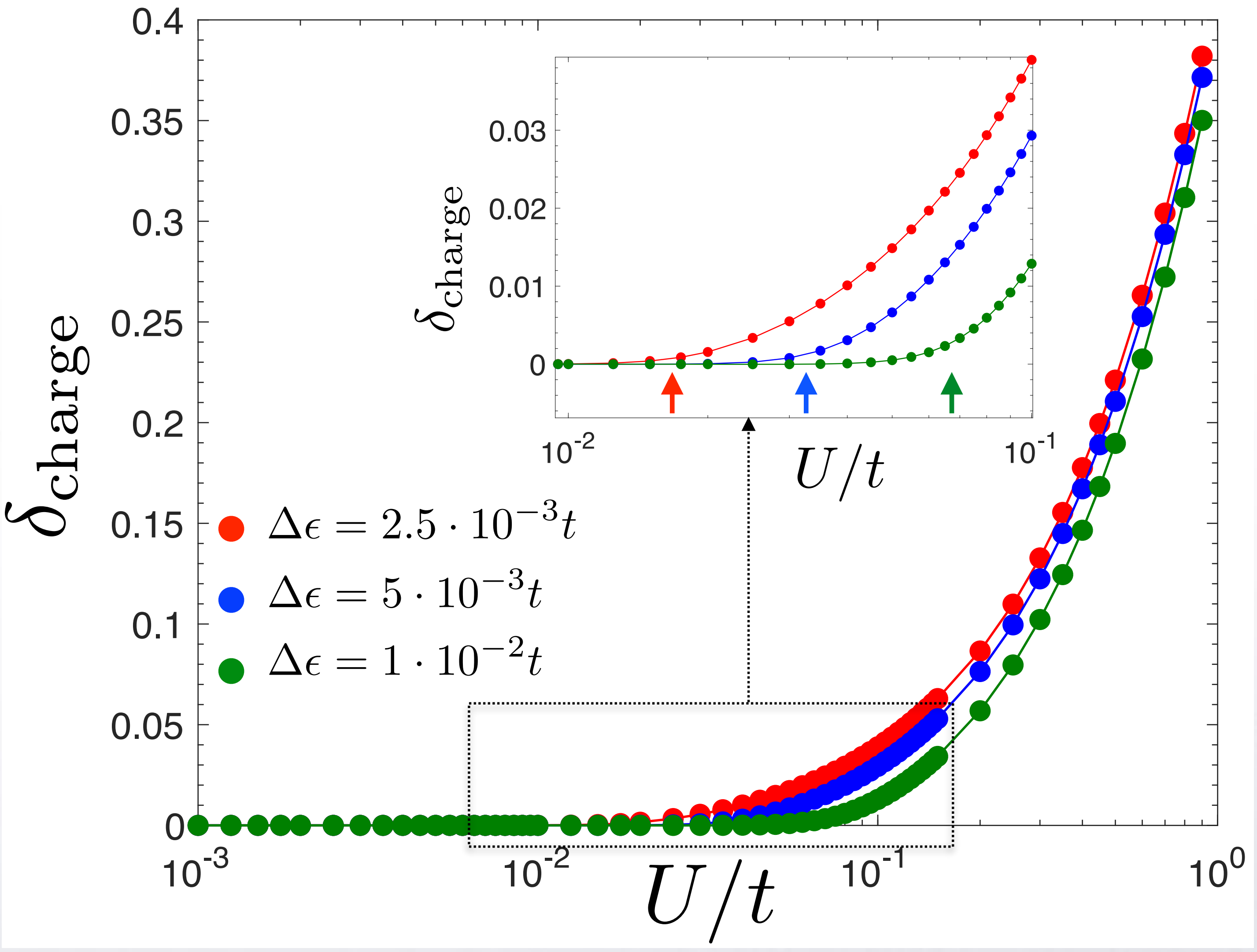
$$\delta_{{\rm spin},\alpha} = E_\alpha(N) - E_1(N)$$



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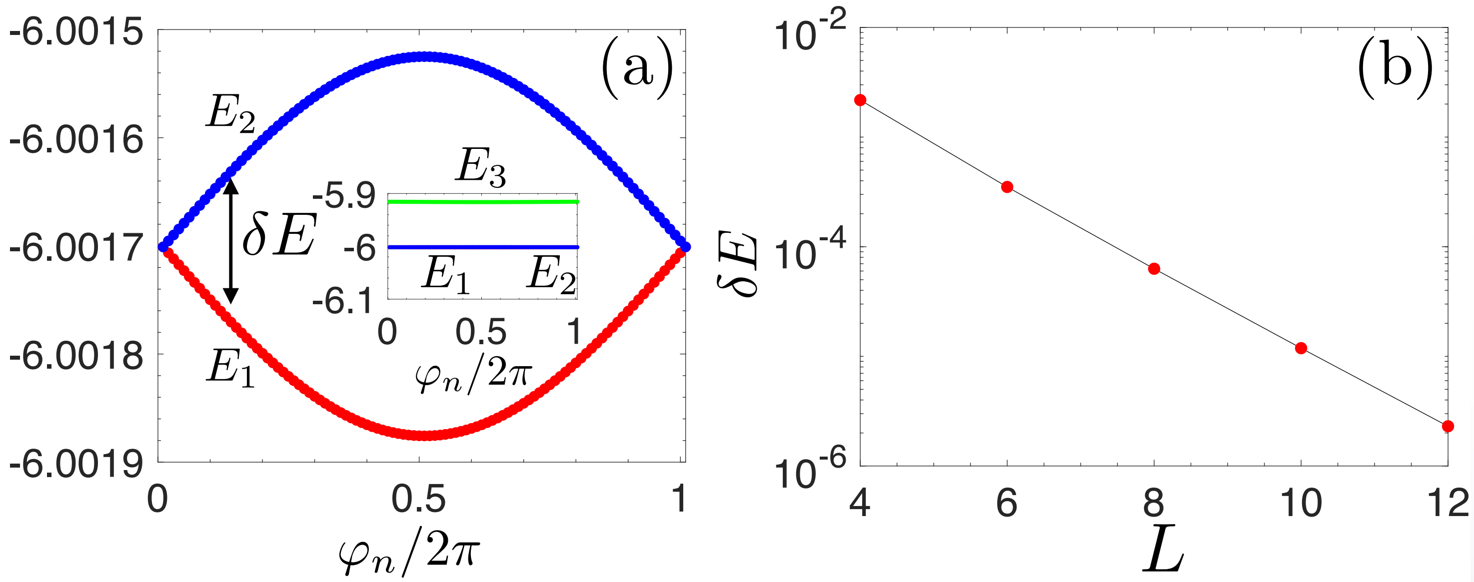

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Twisted PBC $t \to t\exp(i\varphi/L)$

Topological CDW

generalized SPT invariant

$$\mathcal{W} = \frac{i}{\pi} \int_0^{2\pi} d\varphi \, \mathrm{Tr}\left[\langle \Psi_\alpha(\varphi) | \partial_\varphi | \Psi_\beta(\varphi) \rangle\right]$$

F. Wilczek & A. Zee., PRL **52**, 2111 (1984)

destroyed by

$$\hat{H}_{\mathrm{SB}} = iM \sum_j \left(\hat{c}^\dagger_{j,\uparrow} \hat{c}_{j,\downarrow} - \mathrm{H.c.}\right) \propto \sigma_y$$

explicitly breaking chiral symm.

$$U_S = \sigma_y \qquad U_S H_0(k) U_S^\dagger = -H_0(k)$$

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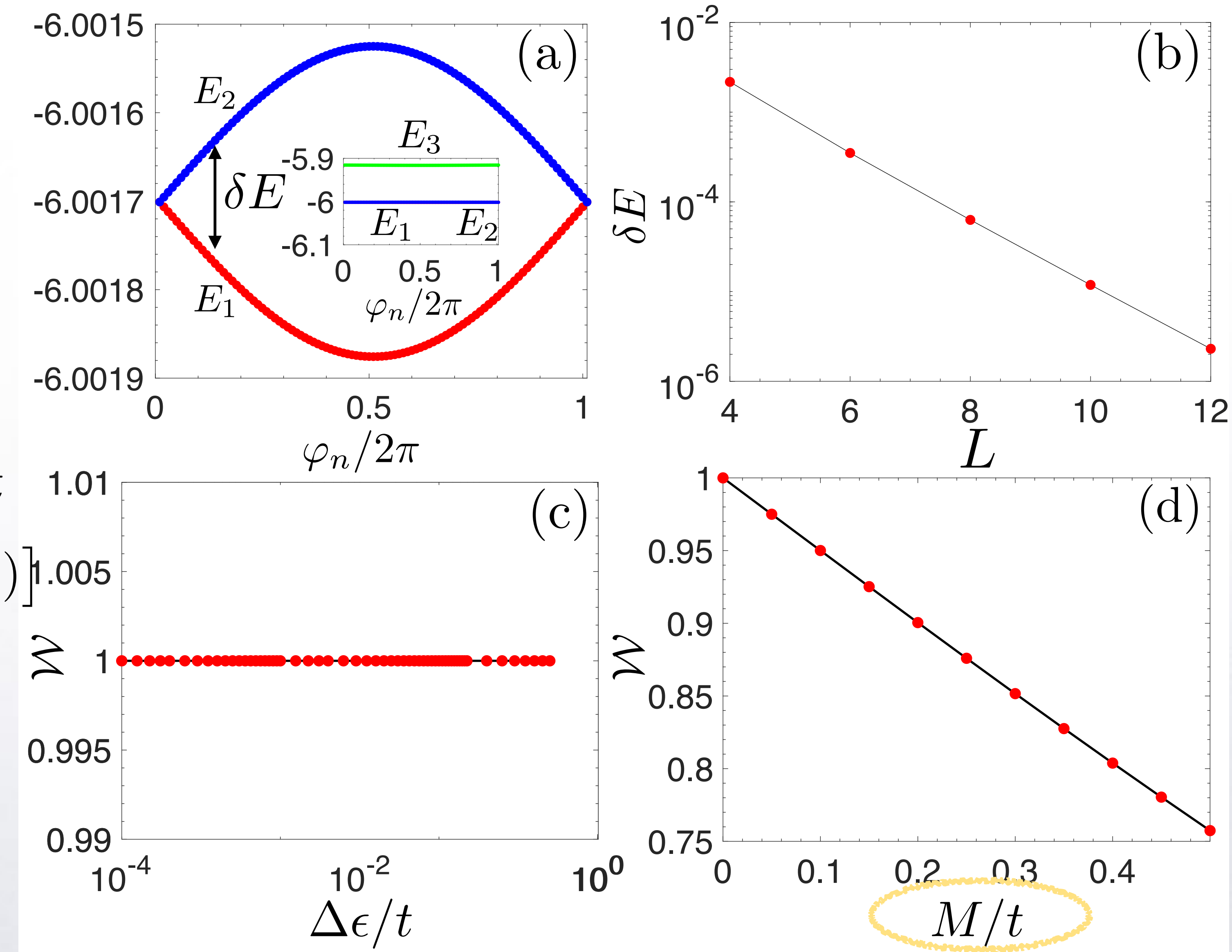

Topological CDW

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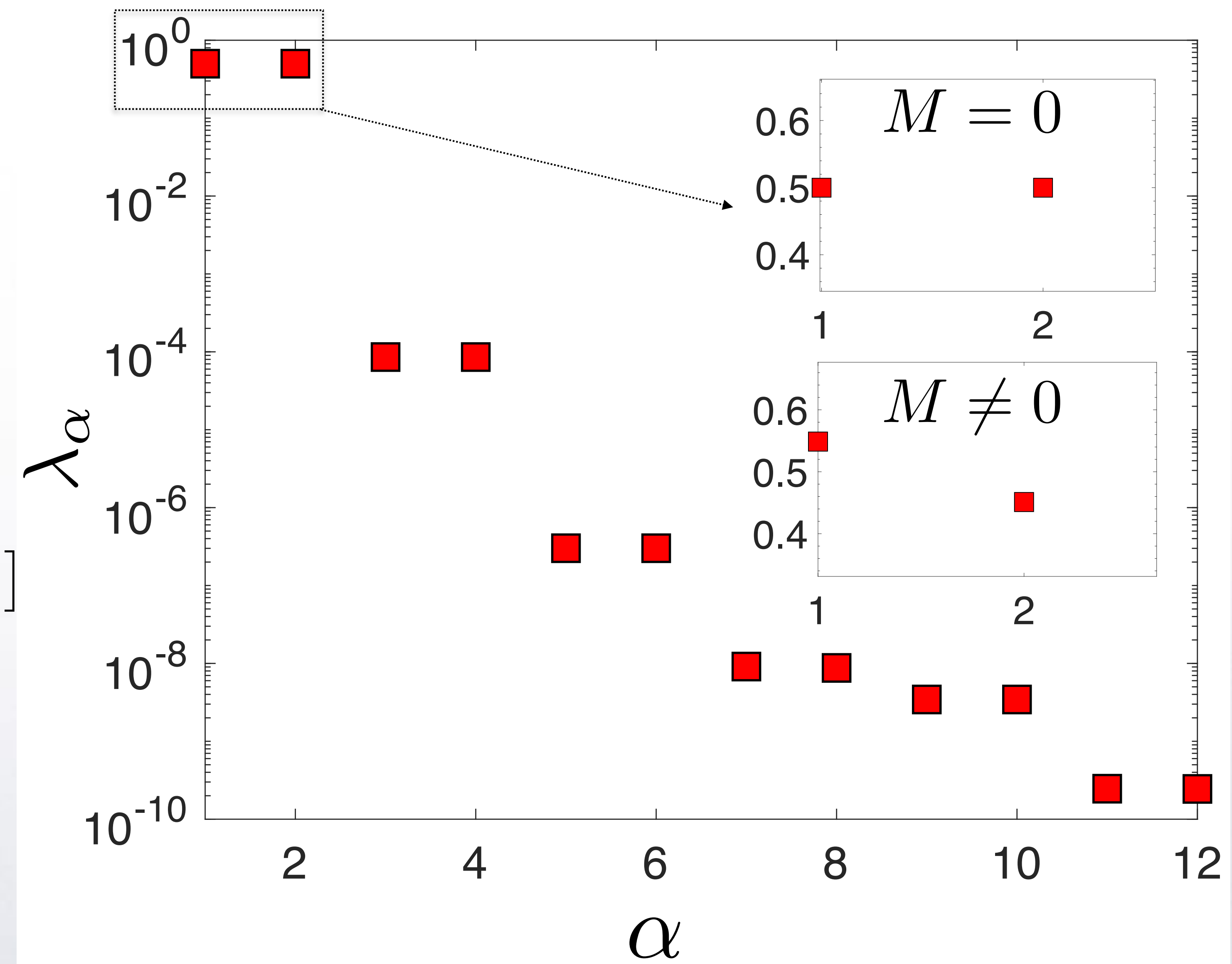
Same happens for
for entanglement spectrum!



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arXiv:1810.02337

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Dirac Fermions

For graphene (i.e., 2D Dirac Fermions), interactions give **positive** correction to magnetic susceptibility $\chi_{\rm orb}$!

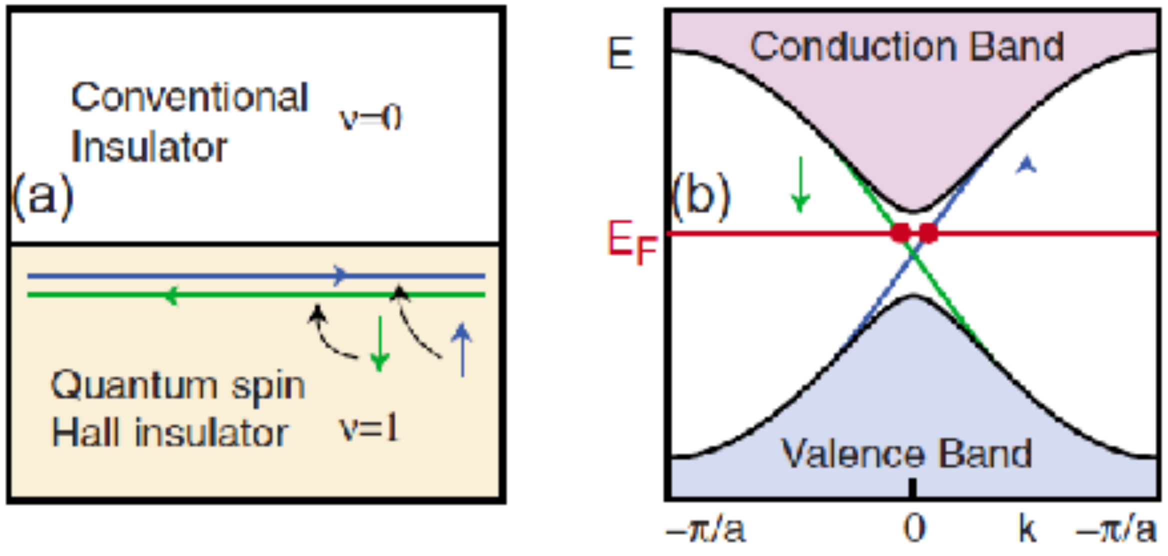
McClure, PR **104**, 666 ('56) & PR **119**, 606 ('60)
Sharma, Johnson, and McClure, PRB **9**, 2467 ('74)

Principi, et al., PRL 104, 225503 ('10)
& many more!!!

1D Systems:

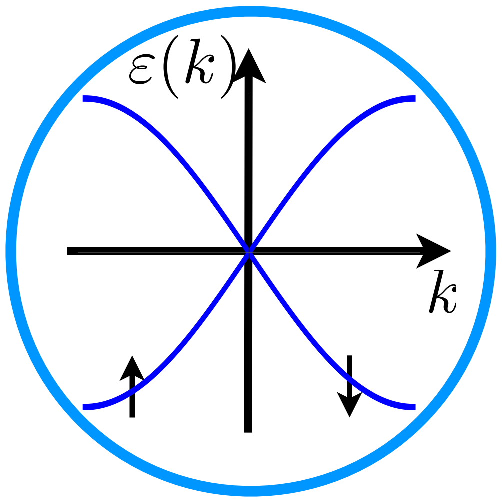
- Dirac-like dispersions possible, too
  M.Z. Hasan and C.L. Kane, RMP 82, 3045 ('10)
  X.-L. Qi and S.-C. Zhang, RMP 83, 1057 ('11)
- no *true* electric/magnetic field distinction

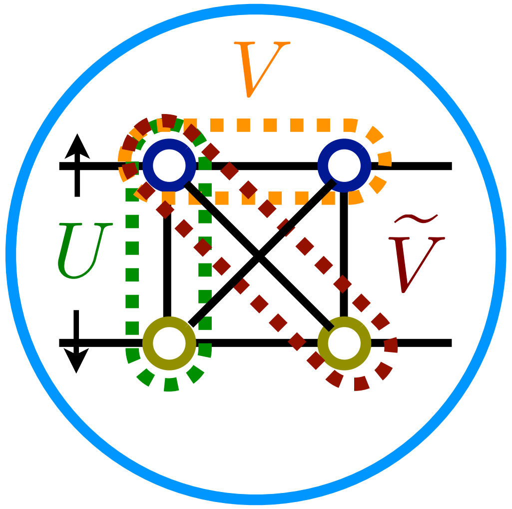
$D \simeq \chi_{\rm orb}$ $\qquad$ $\sigma_1(\omega) = D\,\delta(\omega) + \sigma_1^{\rm reg}(\omega)$

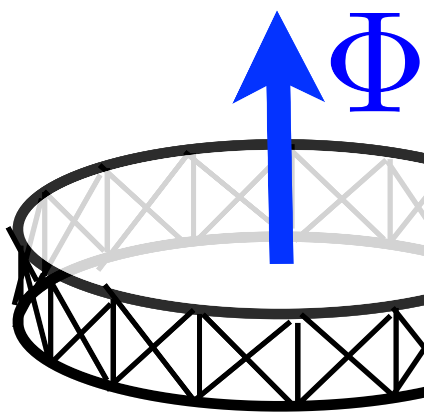


QUESTION HERE:
do many-body effects (i.e., interactions) lead to a ***qualitative*** change of the transport properties of 1D Dirac Fermions?

Model & Methods



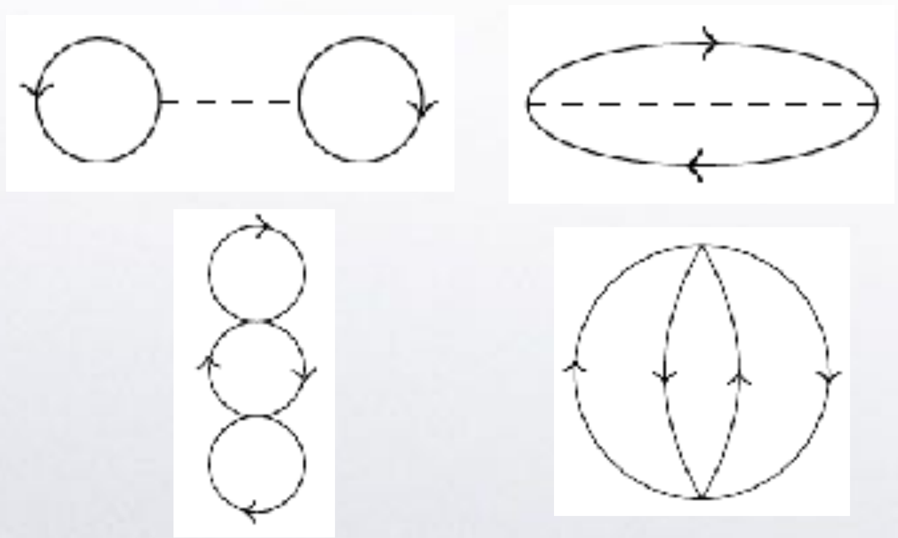




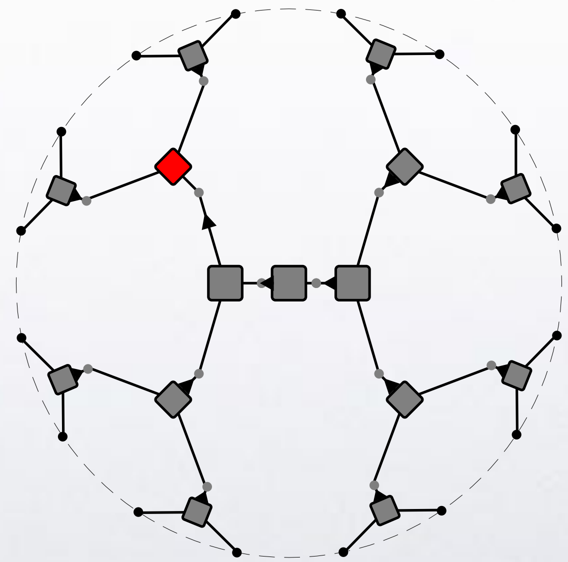
Rings are not essential to measure transport, e.g., D from quenches

C. Karrasch, et al., PRB **95**, 060406(R) (2017)

$$\varphi = \frac{2\pi}{L}\frac{\Phi}{\Phi_0}$$ Persistent Current $$I(\Phi) = -\frac{\partial E}{\partial \Phi}$$ Drude Weight $$D = \frac{L}{2\pi}\left.\frac{\partial^2 E}{\partial \Phi^2}\right|_{\Phi=0}$$



Perturbative calculations

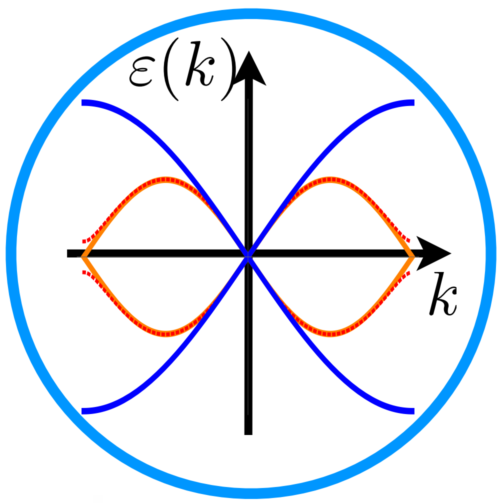


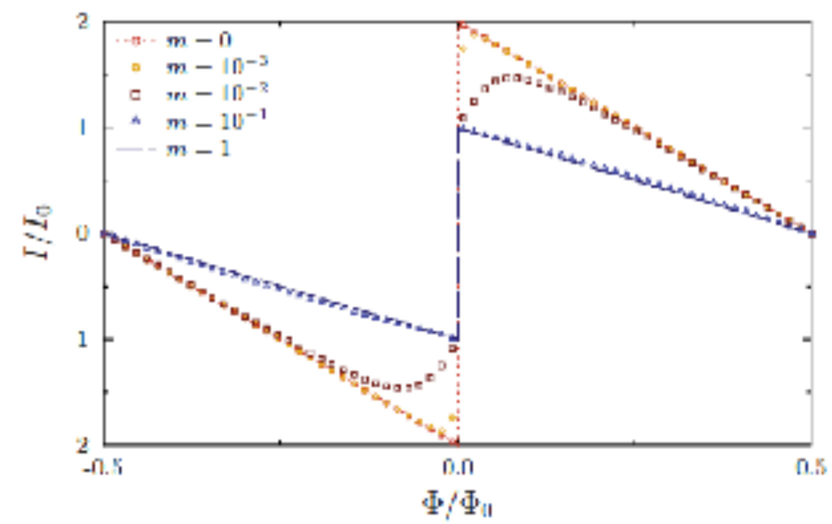
M. Gerster, MR, et al. , PRB 90, 125154 ('15) NJP 18, 015015 ('16) PRB 96, 195123 (2017)

P. Silvi, MR, et al. , arXiv:1710.03733v1

Tree Tensor Networks DMRG calculations

Key Results



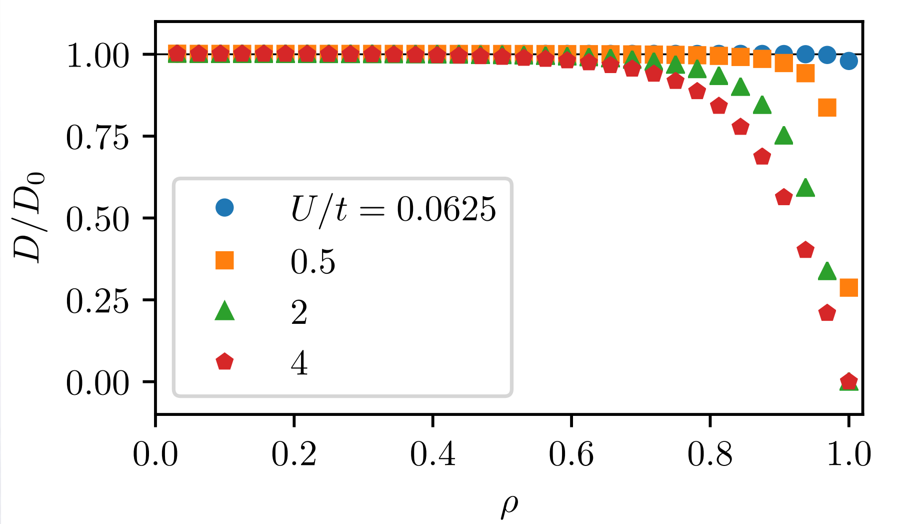


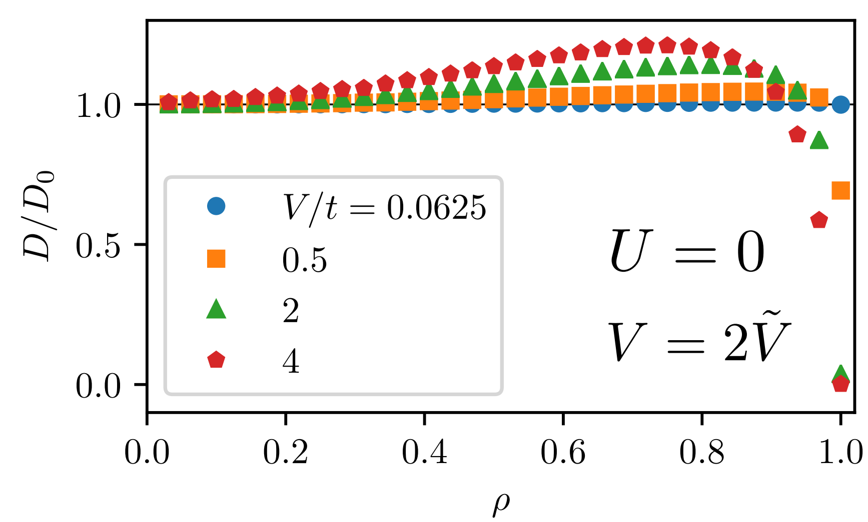
Non-interacting:
just a factor 2 (# lin. disp.)
w.r.t. Hubbard U=0

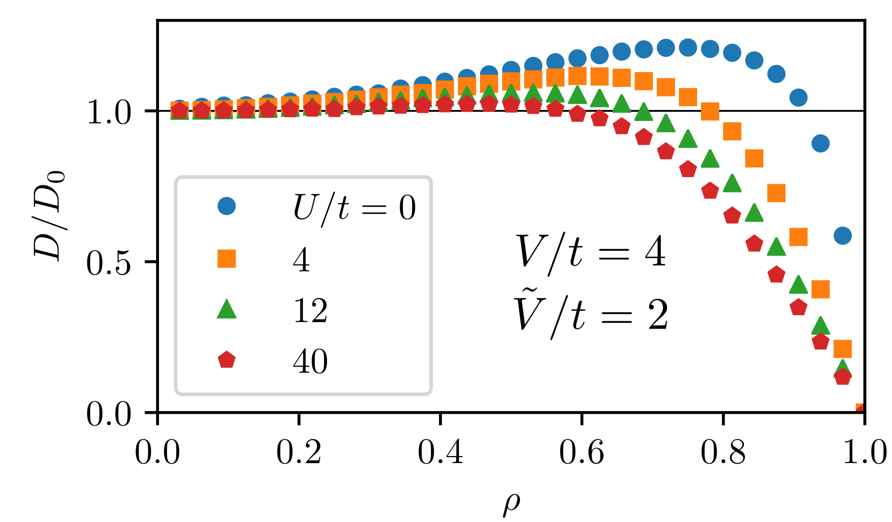
Sticlet, Dóra, Cayssol, PRB 88, 205401 ('13)

$$D/D_0 = \left(1 + \frac{4\sin^3\left(\frac{\pi\rho}{2}\right)}{3\pi}(V - \widetilde{V}) - \left[U^2 \frac{\sin^4\left(\frac{\pi\rho}{2}\right)}{32\pi^2\cos\left(\frac{\pi\rho}{2}\right)} \int_{\pi(1-\rho)}^{\pi} \frac{\cos(k)+3}{\sin\left(\frac{k}{2}\right)} \mathrm{d}k + \tilde{V}^2 \ldots + \ldots\right]\right)$$

[on-going bosonization with M. Filippone @ UniGe.ch]







Onsite-interacting:
analogue to Hubbard,
Drude Weight suppression!

Longer-range & Spin-dep.:
qualitative difference,
tunable Drude Weight !

Robust effect
against on-site terms!

OUTLINE

- The Creutz-Hubbard Ladder: general features
- Topology & Interactions
  - SPT vs orbital magnetism at half-filling

    Jünemann, et al., PRX 7, 031057 (2017)
  - relation to high-energy models

    Bermudez, et al., Ann. Phys. 339, 149 (2018)
  - interacting SPT phases at fractional filling

    Barbarino, et al., arXiv:1810.02337
- Tuning the Drude Weight of Dirac fermions

  Bischoff, et al., PRB 96, 241112(R) (2017)
- Other related works & plans

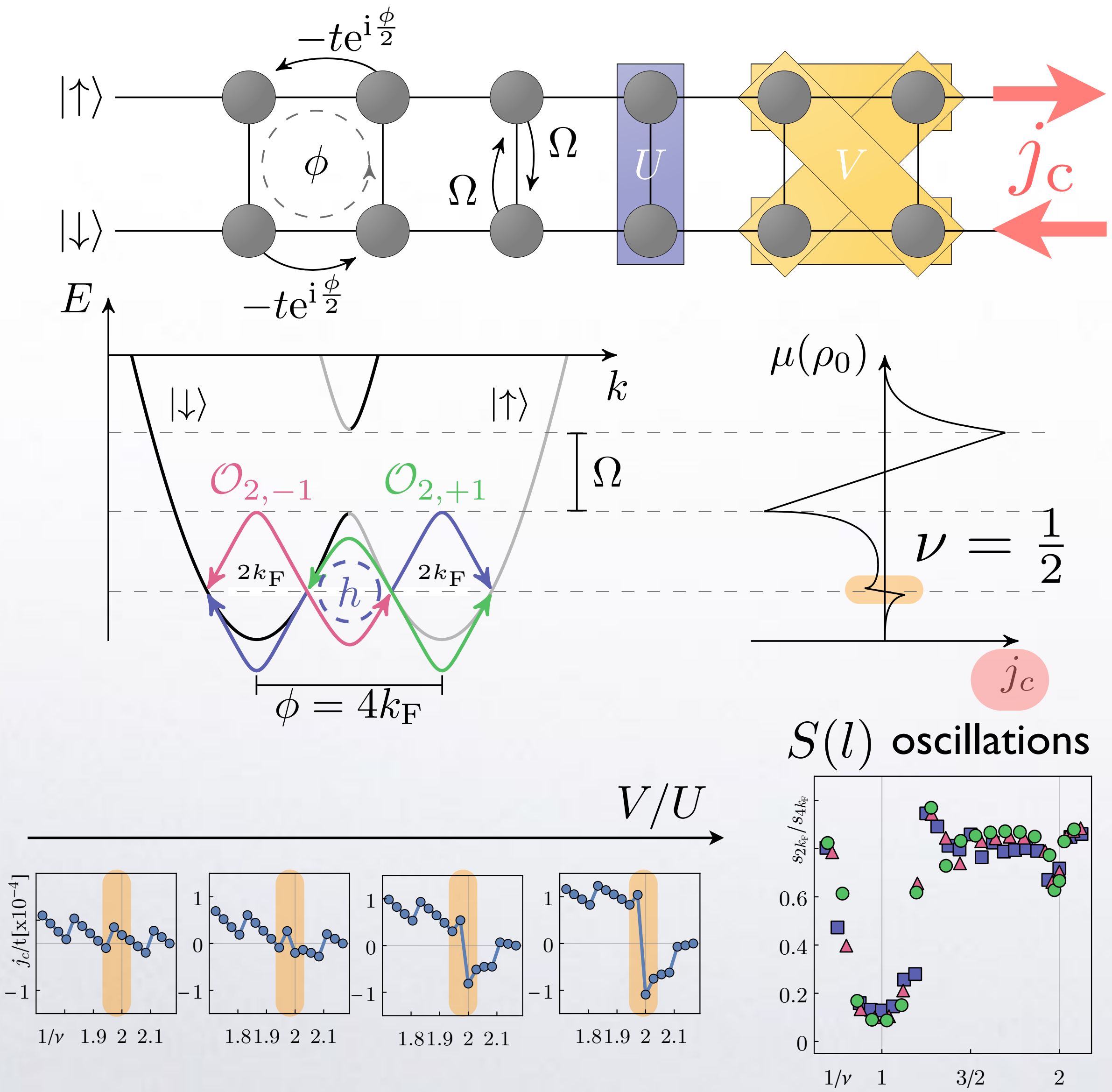
matteo.rizzi@fz-juelich.de

Other related works

topological states

… in quantum ladders

A. Haller, MR, M. Burrello,
New J. Phys. **20**, 053007 (2018)



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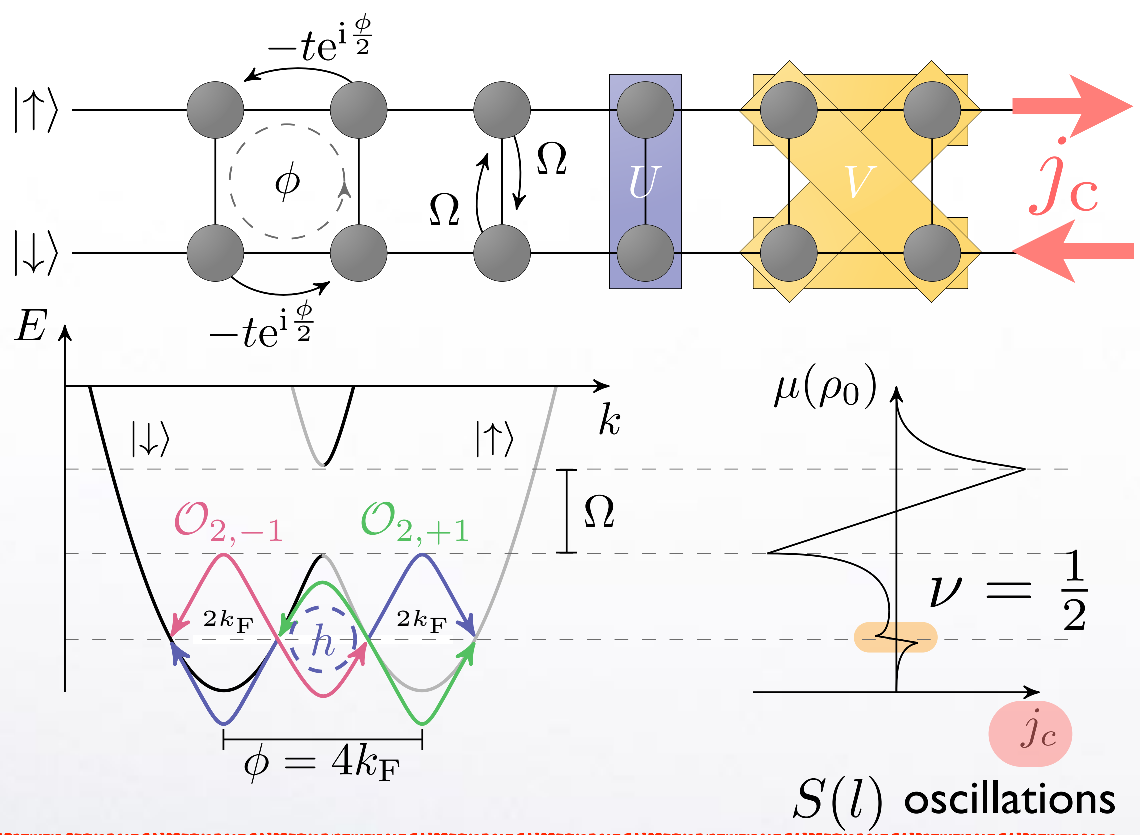

multi-leg ladders + density-assisted hoppings to go towards Majorana & "parafermions"

with M. Burrello (Copenhagen) & L. Mazza (Paris)

Other related works

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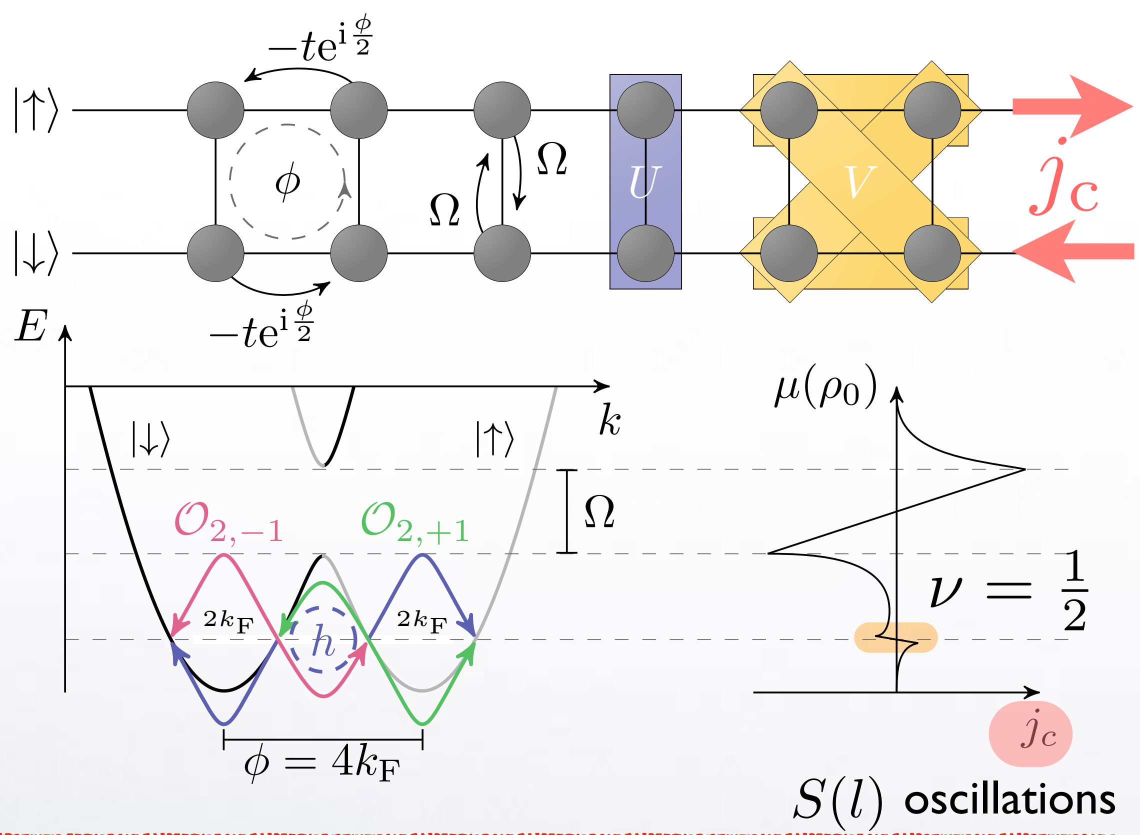

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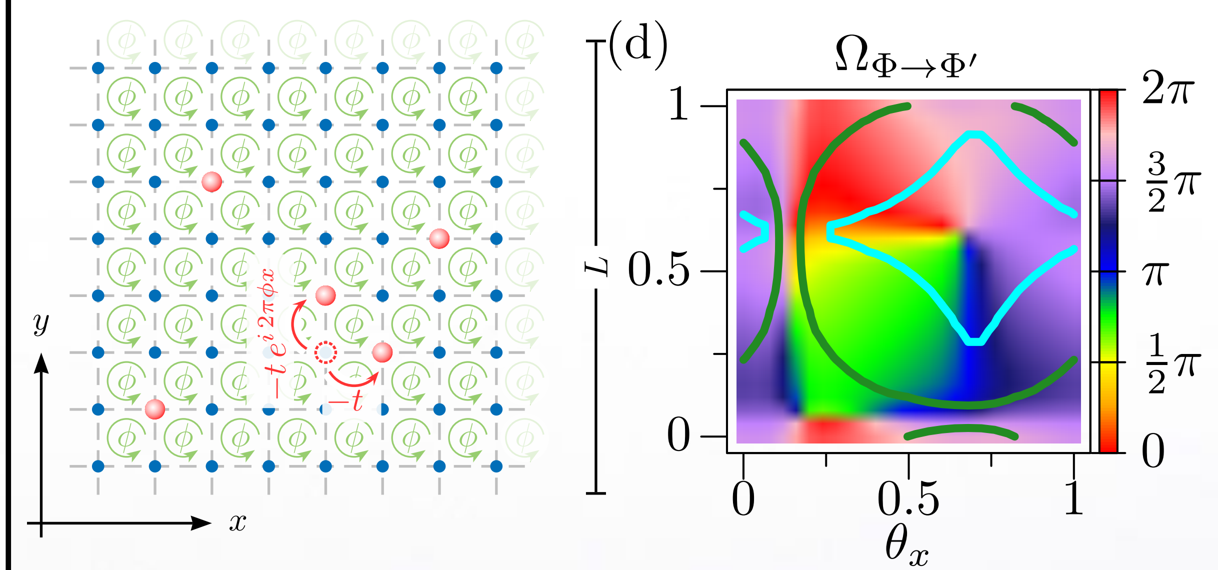
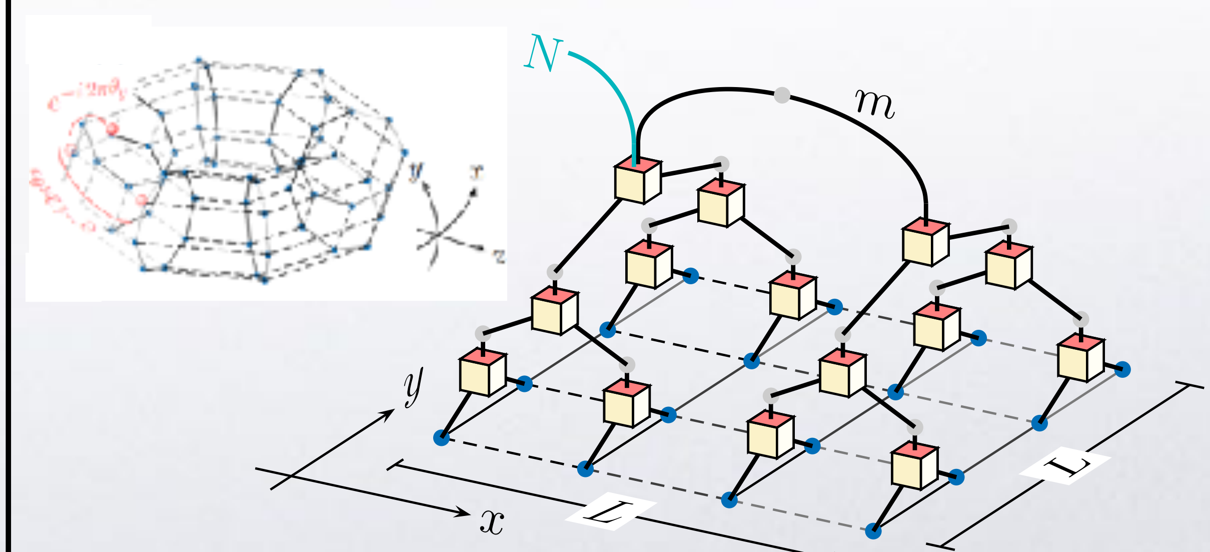
… in 2D Harper-Hofstadter

M. Gerster, et al. (MR) PRB **96**, 195123 (2017)





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topological states

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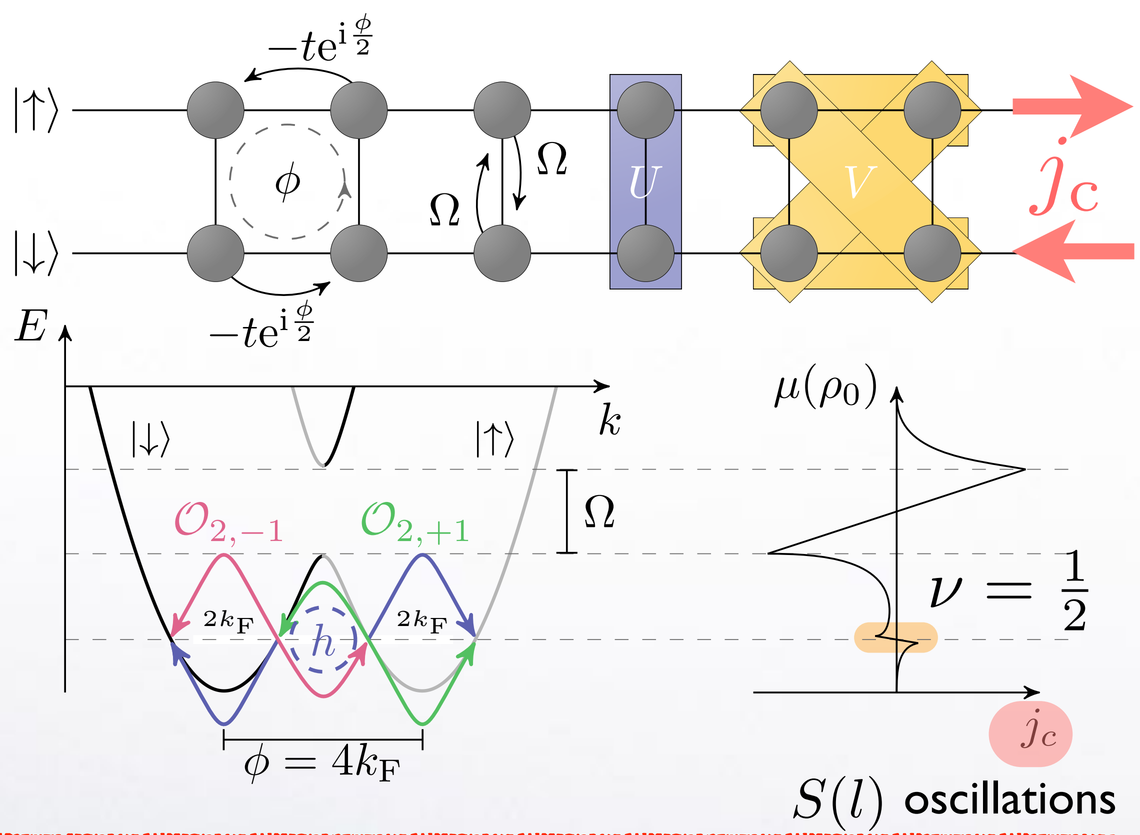

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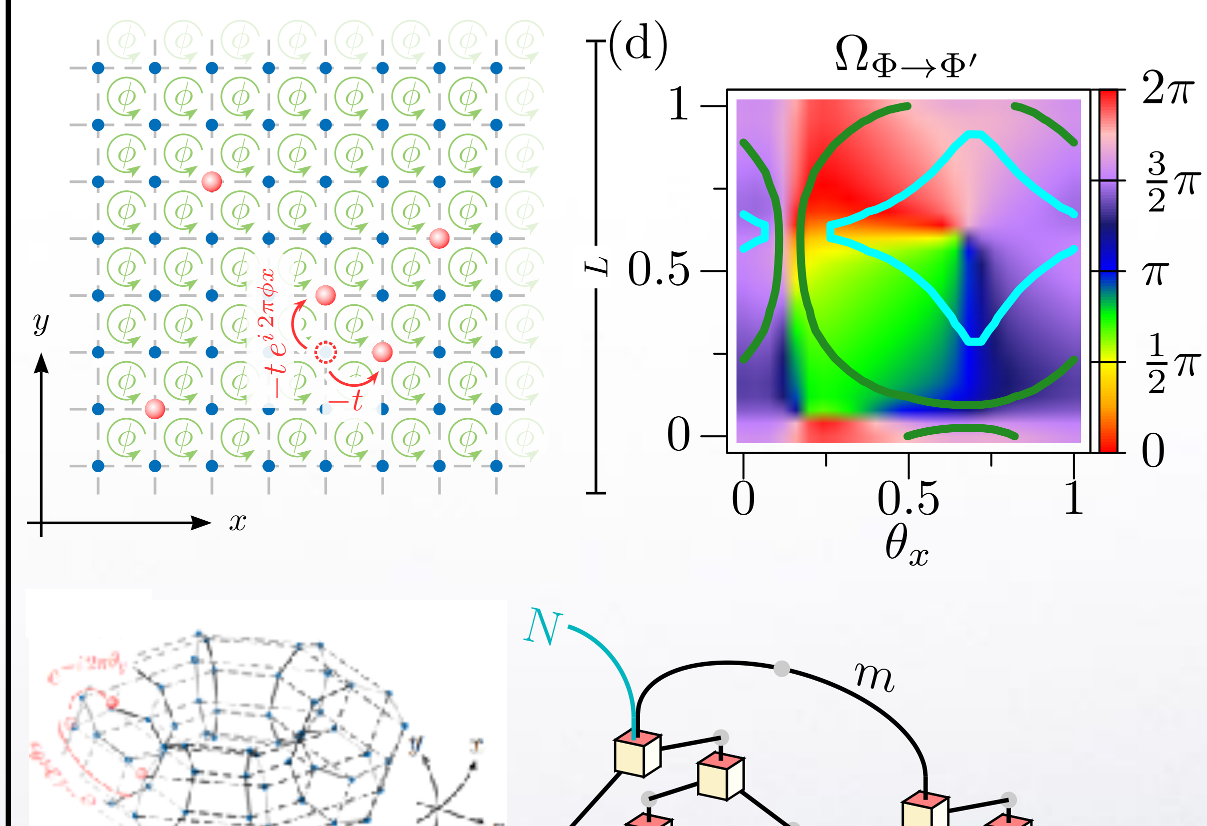


detection schemes for cold atoms?
pinning strategies of quasi-holes?

with I. Carusotto (Trento)

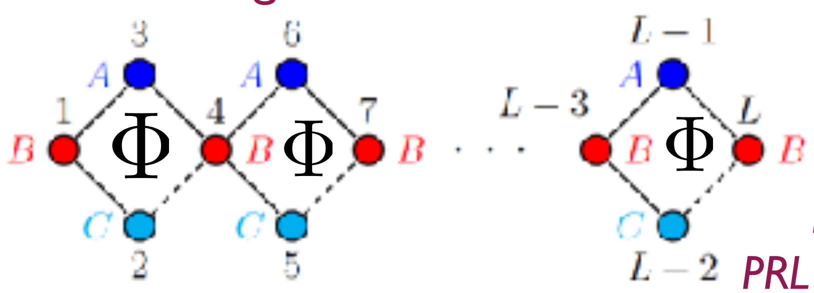
Other related works

flat-band bosonic systems

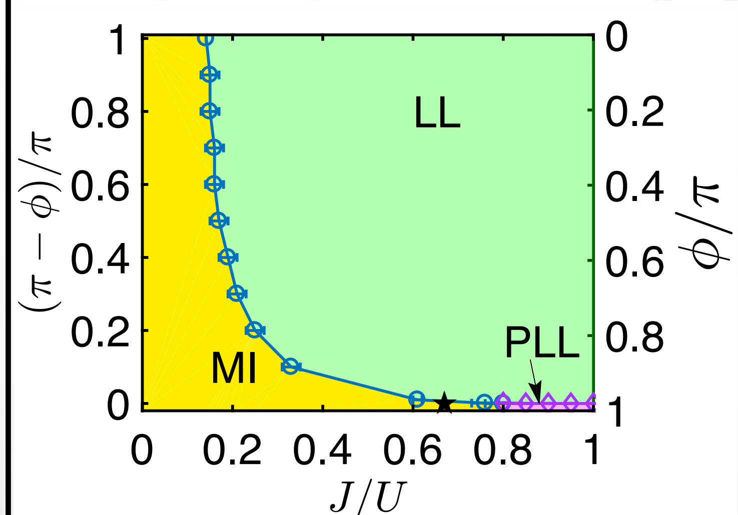
Robustness(?) of Pair Luttinger Liquid

MR, Cataudella, Fazio PRB **73**, R100502 & 144511 ('06)

C. Cartwright, G. deChiara, MR PRB **98**, 184508 ('18)

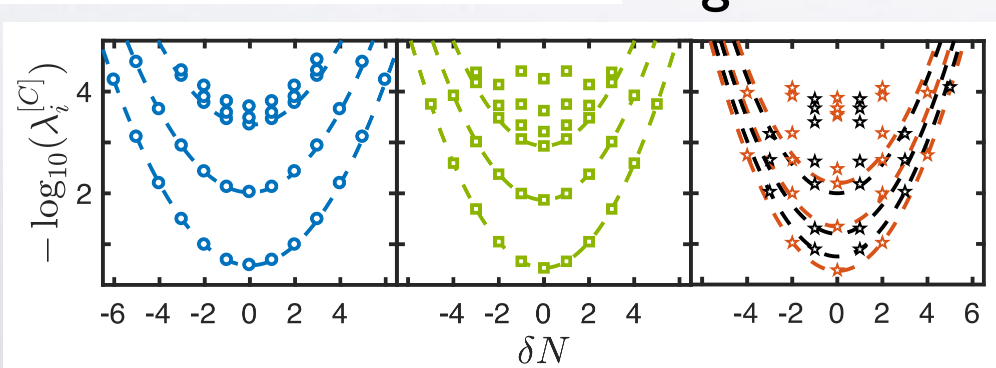


*B. Doucot, J. Vidal, PRL **88**, 227005 (2002)*



AB caging
+
emerging
Z_2 local sym.

signature in ES ?



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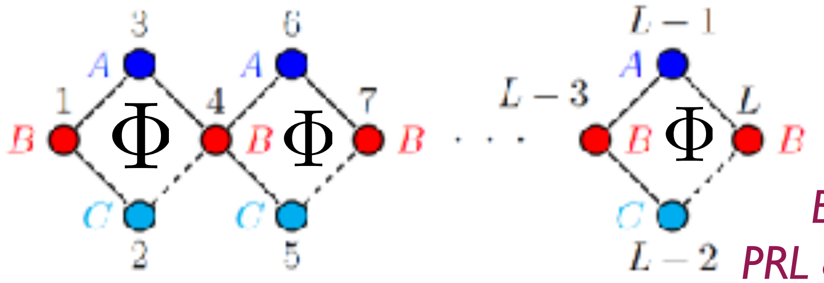


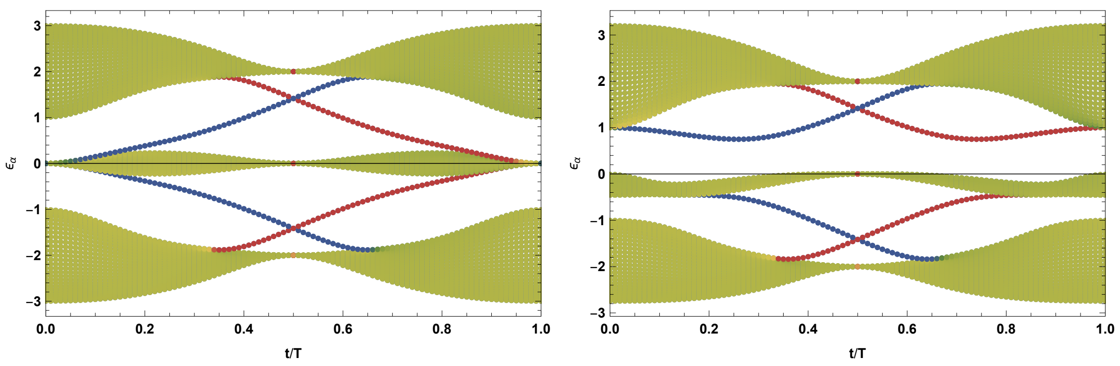
*B. Doucot, J. Vidal, PRL **88**, 227005 (2002)*

Square-Root TI: quantized pumping?

$$\mathcal{H}_{\diamond\pi} \longrightarrow \gamma_{\rm Zak} \notin \{0, \pi\}$$

$$\mathcal{H}^2_{\diamond\pi} = \mathcal{H}_{\rm trivial} \oplus \mathcal{H}_{\rm SSH}$$

M. Kremer, et al., 1805.05209



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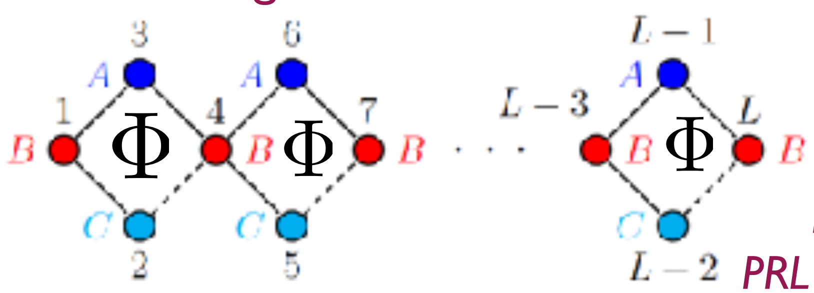

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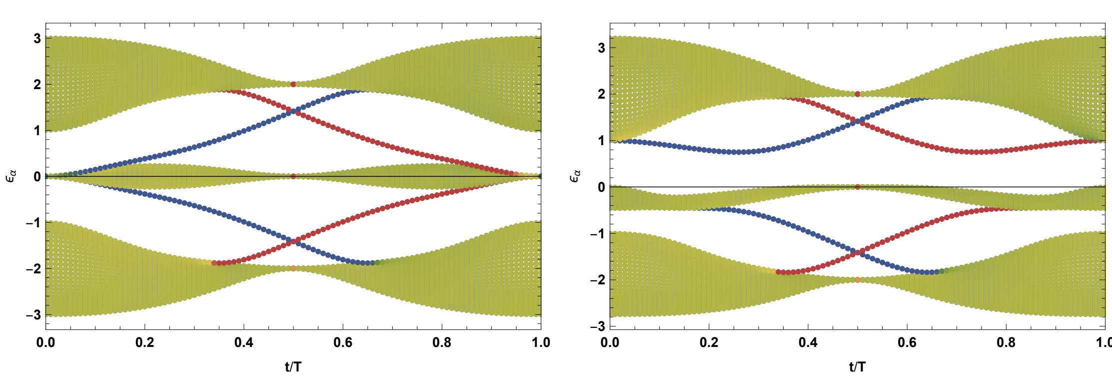
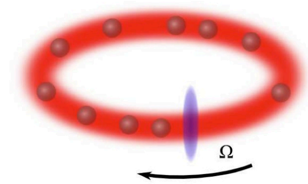


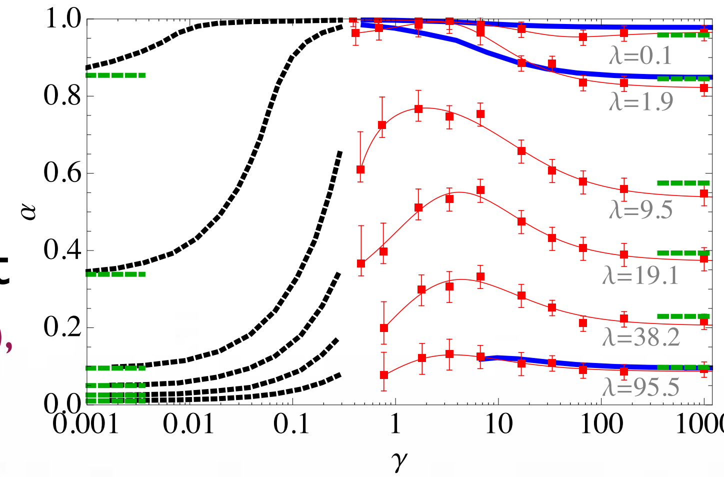
persistent currents

"optimal" interactions vs quantum fluctuations



"atomtronics" qubit

D. Aghamalyan, et al. (MR), NJP 17, 045023 (2015)



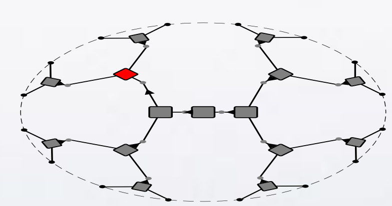
cMPS study

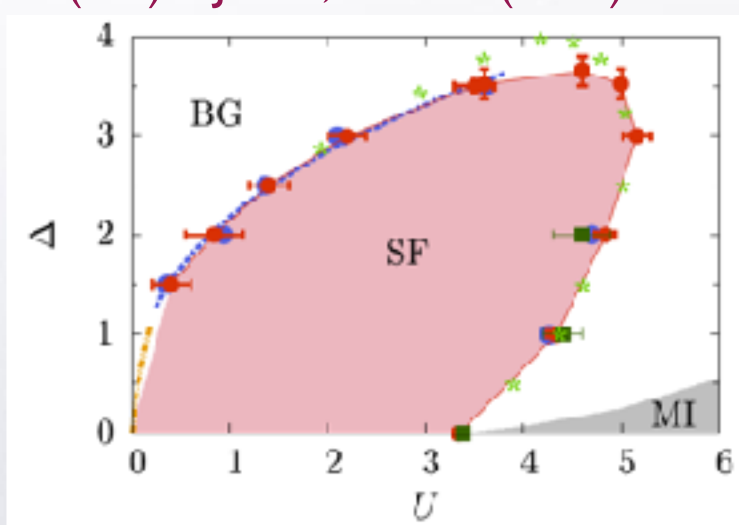
D. Draxler, et al. (MR), PRB **95**, 045145 (2017)

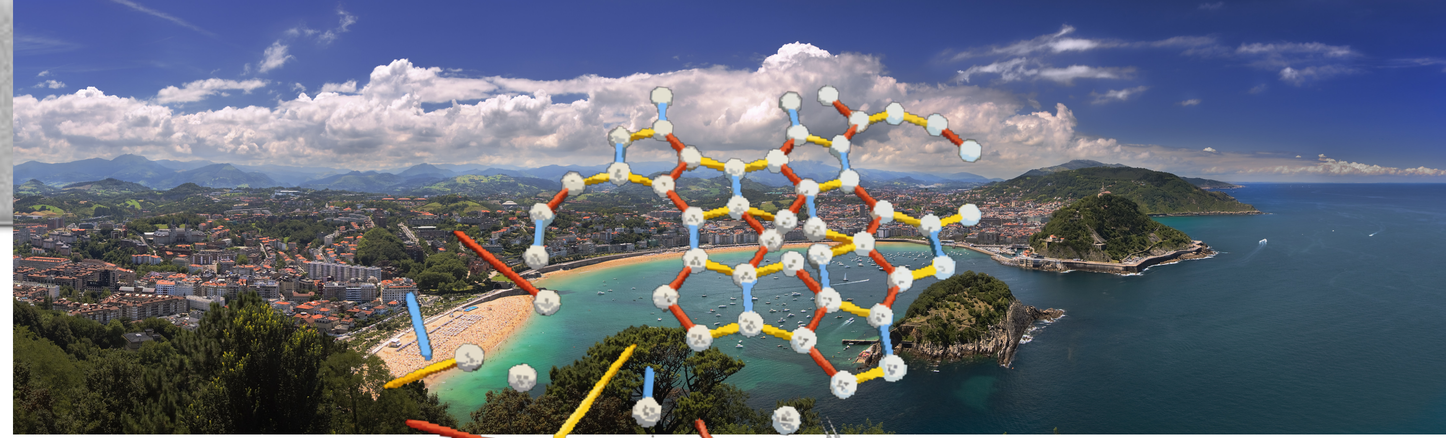
M. Cominotti, et al. (MR), PRL **113**, 025301 (2014)

1D disordered Bose-Hubbard: Bose Glass…

M. Gerster, et al. (MR) NJP **18**, 015015 (2016)







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Rainer Blatt (Innsbruck)
Immanuel Bloch (Munich)
Jacqueline Bloch (Paris)
Tilman Esslinger (Zurich)
Steven Girvin (Yale)
Hari C. Manoharan (Stanford)
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Matteo Rizzi
University of Cologne & Forschungszentrum Jülich

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University of Utrecht

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DFG

Studienstiftung des deutschen Volkes

My team @ JGU

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M. Bischoff

A. Haller

+ N. Tausendpfund & J. Nothhelfer

My collaborators:

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P. Silvi (Ulm > IQOQI Innsbruck)

M. Lewenstein (ICFO)

E. Tirrito (ICFO)

A. Bermudez (CSIC Madrid)

M. Polini (IIT Genova)

M. Burrello (NBI Copenhagen)

D. Rossini (Uni Pisa)

M. Dalmonte (ICTP Trieste)

R. Fazio (ICTP Trieste)

S. Barbarino (SISSA Trieste)

M. Filippone (Uni Geneva)

L. Mazza (Paris-Sud)

R. Orus (Mainz > Donostia)

all of you for your attention!

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