Dimensional Tuninig Of Electronic States Under Strong And Frustrated Interactions

Kyoto Sangyo University

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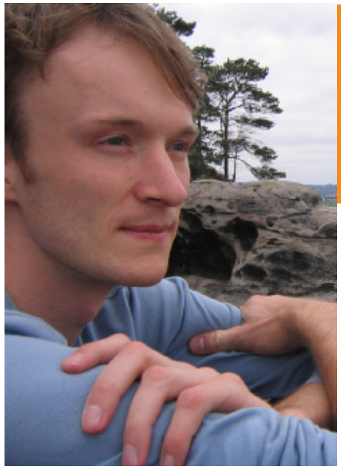
Outline

- Introduction to strongly correlated metals.

- Geometrically Frustrated Interactions play particular role in **the geometry of the Metallic state**.

I) anisotropic triangular lattice
II) anisotropic kagome lattice

C. H, F. Pollmann, arXiv:0711.3075v1



Frank Pollmann MPIPKS, Dresden

Strongly Correlated Metals

Metallicity

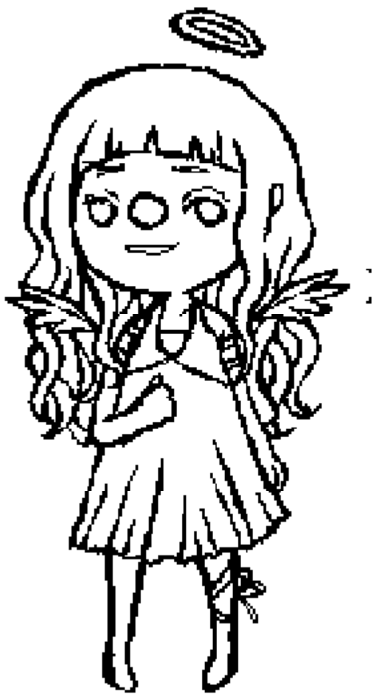
Electronic correlations

competition of two different energy scales

kinetic energy vs Coulomb energy

Strongly Correlated Metals

Metallicity



Small electronic correlations

↓

Just a renormalization of
Density of states

↓

Fermi Liquid picture

Electronic
correlations

Strongly Correlated Metals

Metallicity

Electronic correlations

Strong electronic correlations

↓

Density of states changes(collective excitations)

↓

Metallicity is either suppressed or modified much in space.

Insulator	non-Fermi liquid

In a class of strongly correlated electrons,
the effective geometry of metallicity is somewhat modified.

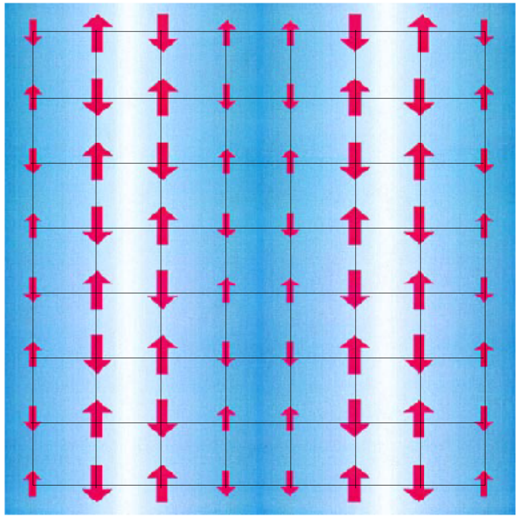
Strongly Correlated Metals: example1

Stripe phases in high-temperature superconductors

V. J. Emery, S. A. Kivelson†‡, and J. M. Tranquada**

*Department of Physics, Brookhaven National Laboratory, Upton, NY 11973-5000; and †Department of Physics, University of California, Los Angeles, CA 90095

Stripe phases are predicted and observed to occur in a class of strongly correlated materials describable as doped antiferromagnets, of which the copper-oxide superconductors are the most prominent representatives. The existence of stripe correlations necessitates the development of new principles for describing charge transport and especially superconductivity in these materials.



square lattice + correlation= stripe formation

1D propagation of carriers

Strongly Correlated Metals: example2

Science
AAAS

CORRELATED ELECTRON SYSTEMS

REVIEW

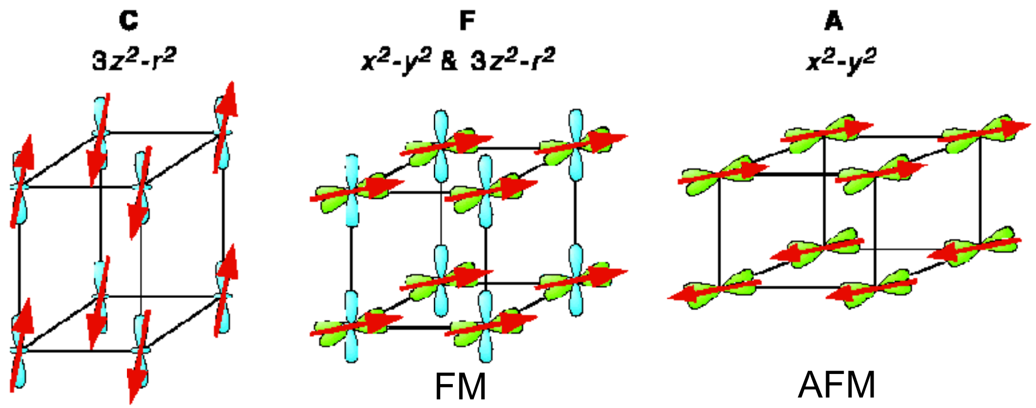
Orbital Physics in Transition-Metal Oxides

Y. Tokura[1,2] and N. Nagaosa[1]

An electron in a solid, that is, bound to or nearly localized on the specific atomic site, has three attributes: charge, spin, and orbital. The orbital represents the shape of the electron cloud in solid. In transition-metal oxides with anisotropic-shaped d-orbital electrons, the Coulomb interaction between the electrons (strong electron correlation effect) is of importance for understanding their metal-insulator transitions and properties such as high-temperature superconductivity and colossal magnetoresistance. The orbital degree of freedom occasionally plays an important role in these phenomena, and its correlation and/or order-disorder transition causes a variety of phenomena through strong coupling with charge, spin, and lattice dynamics. An overview is given here on this "orbital physics," which will be a key concept for the science and technology of correlated electrons.

Two degrees of freedom coupled:
Orbital + spin

e.g. Manganese Oxides



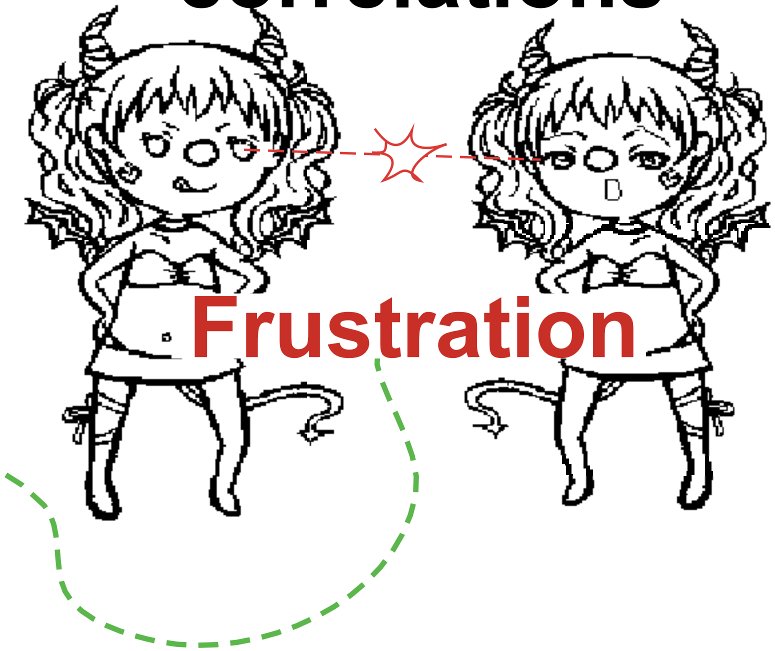
Kugel-Khomskii model

$$H = \sum_{ij} [J_{ij}(\vec{T}_i,\vec{T}_j)\vec{S}_i \cdot \vec{S}_j + K_{ij}(\vec{T}_i,\vec{T}_j)]$$

Strongly Correlated Metals

Metallicity

Electronic correlations



How about designing the effective geometry of metal
by using the geometrical frustration?

real space physics → reciprocal / k-space physics

DOS

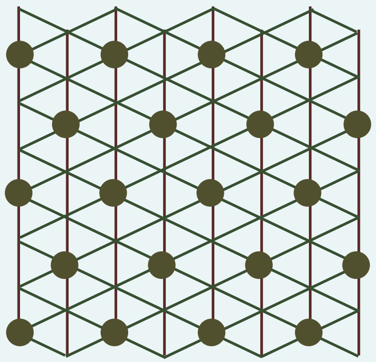
Strongly Correlated Metals: example3

Spinless Fermions on a Triangular Lattice

C.H, N.Furukawa ('06)

Strong nearest neighbor repulsion $\frac{t}{V} \sim 0$

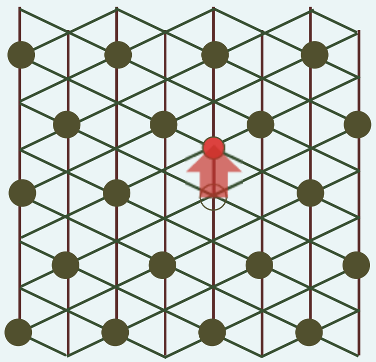
1/3 filling



Wigner X-tal

ground state

$E_V = 0$



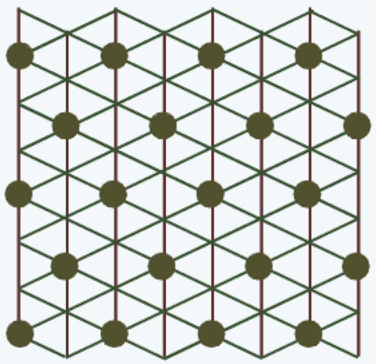
excited state

$E_V = 2V$

Spinless Fermions on a Triangular Lattice

Strong nearest neighbor repulsion $\frac{t}{V} \sim 0$

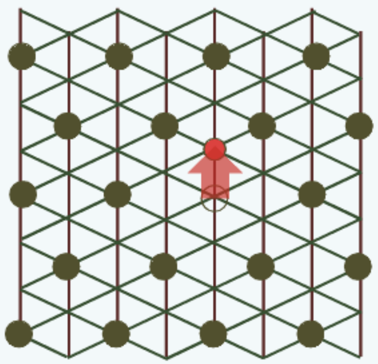
1/3 filling



Wigner X-tal

ground state

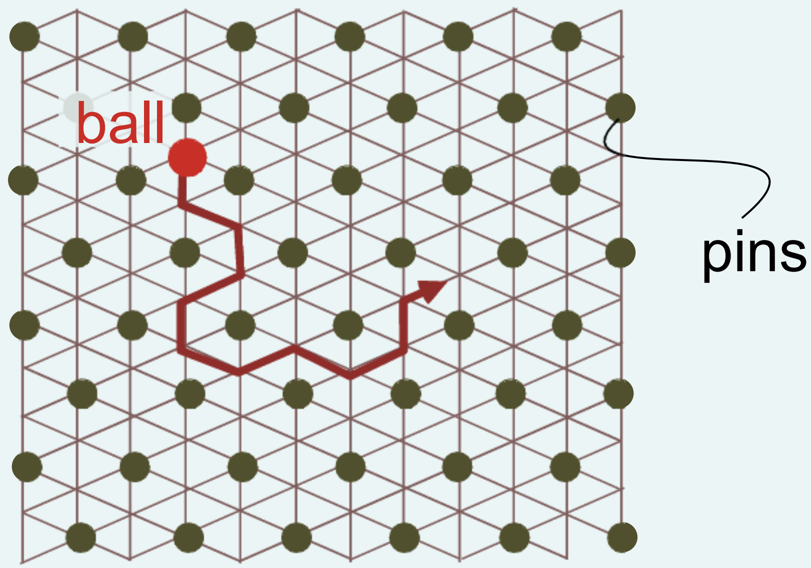
$E_V = 0$



excited state

$E_V = 2V$

1/3 filling +1 particle

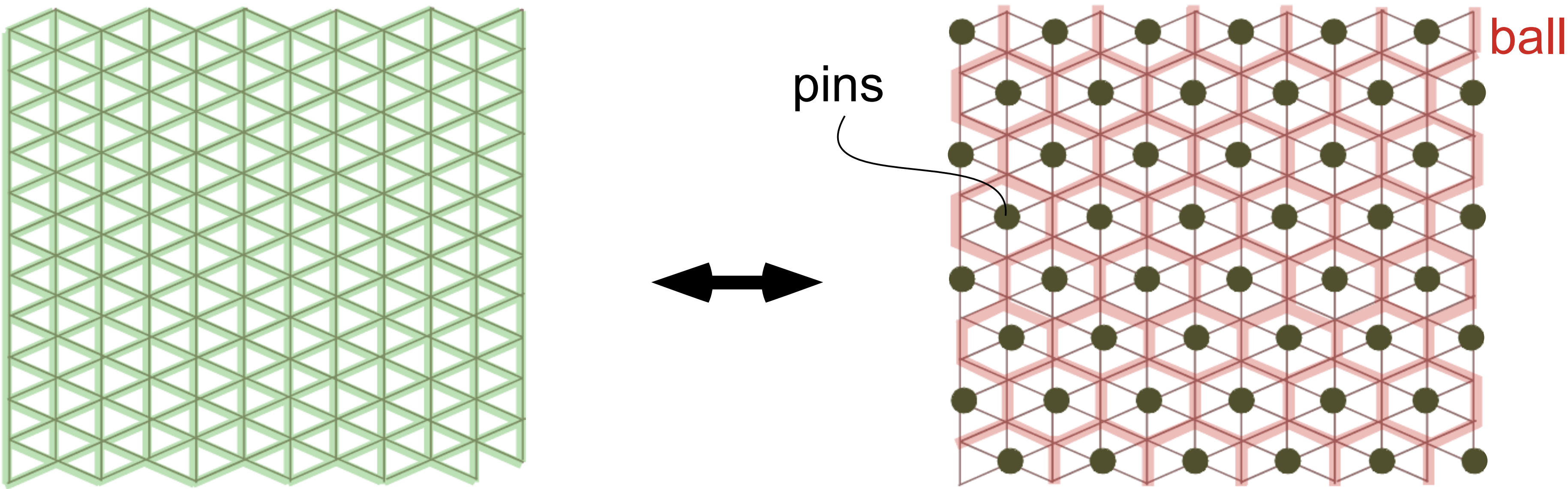


$E_V = 3V$

Charge order (solid) + Metal (liquid)

Geometry Modification of the “Lattice”

“pinball liquid“



triangle

Honeycomb

Fermi liquid

Weak coupling

Non Fermi liquid

Strong coupling

Related works

Experimental

Organic Solid θ-ET_2X

(1) Anisotropic triangular lattice

(2) Charge Ordering (CO)

due to strong nearest neighbor coulomb repulsion at 1/4-filling

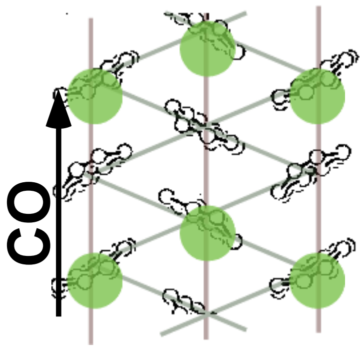
c.f. Mila-Zotos,Penc ('94)
Seo-Fukuyama ('97)

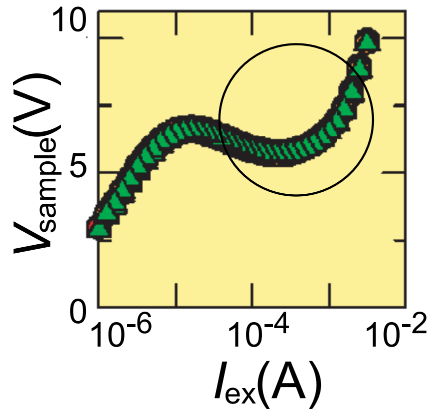
(3) Anomalous transport

An organic thyristor

Vol 437|22 September 2005|doi:10.1038/nature04087

F. Sawano[1], I. Terasaki[1], H. Mori[2,3], T. Mori[4], M. Watanabe[5], N. Ikeda[6], Y. Nogami[3,7] & Y. Noda[5]





Theoretical

tV- Model studies

- Pinballs — C.H, Furukawa,Nakagawa, Kubo('06)
- Variational MC — Miyazaki, et.al. ('07)
- 2D-DMRG — Nishimoto, et.al. ('07)

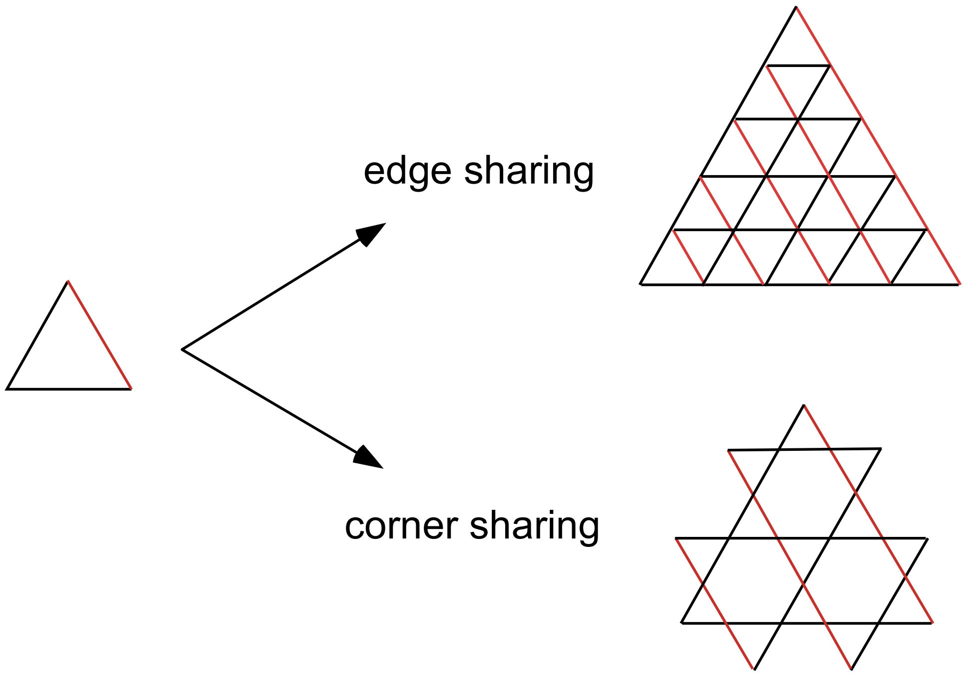
Hard core boson studies

Wessel-Troyer, Heidarian-Damle, Melko, et.al. ('05)

Extended Hubbard Model studies

- Exact diagonalization — Merino-Seo-Ogata('05)
- Variational MC — Watanabe-Ogata('05)
- 2D-DMRG — Nishimoto-Ohta('07)
- DMFT — Merino,et.al.('07)

Spinless Fermions on the geometrically frustrated systems with anisotropy



(1) Triangular lattice

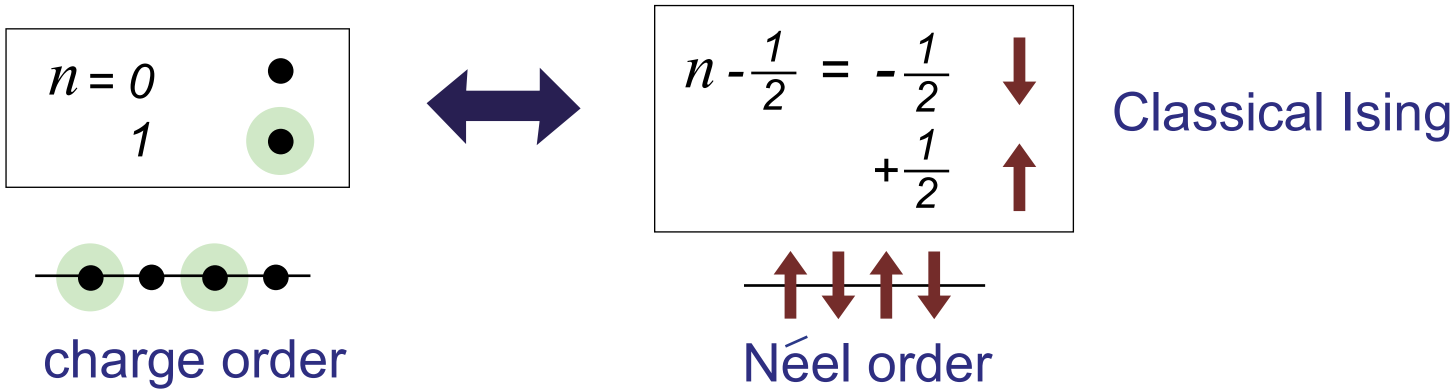
(2) Kagome lattice

t-V Model of Spinless Fermions

$$H=\sum_{<ij>}\left(-t_{ij}c_i^{\dagger}c_j+\mathrm{h.c.}\right)+\sum_{<ij>}V_{ij}\,n_i n_j$$

- **We start from the strong coupling limit (Classical limit)**

t=0

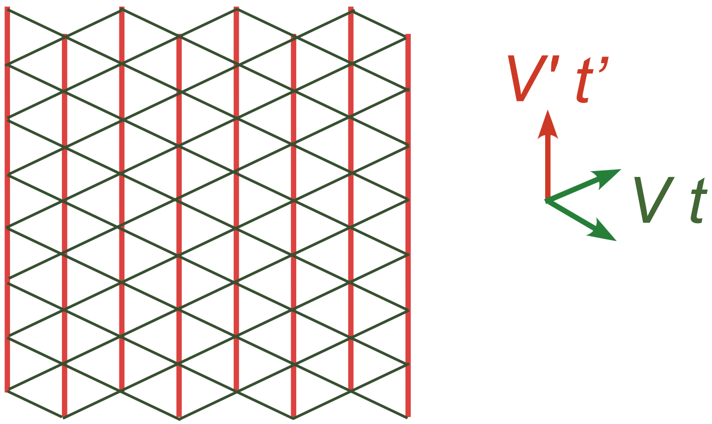


- **Same physics holds for two representative lattices.**

  I) Triangular lattice

  II) Kagome lattice

Lattice I. Anisotropic triangular lattice

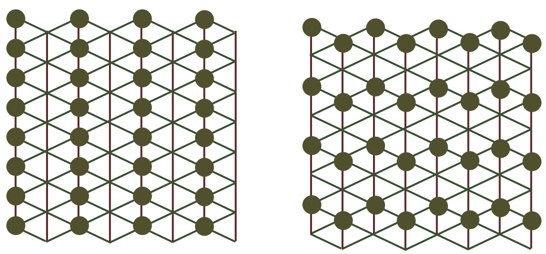


- **We focus on half-filling**

  1 fermion / site

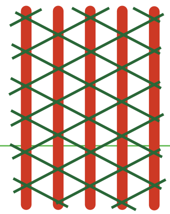
⇨ *ground state at large V is a striped charge ordered insulator*

CO

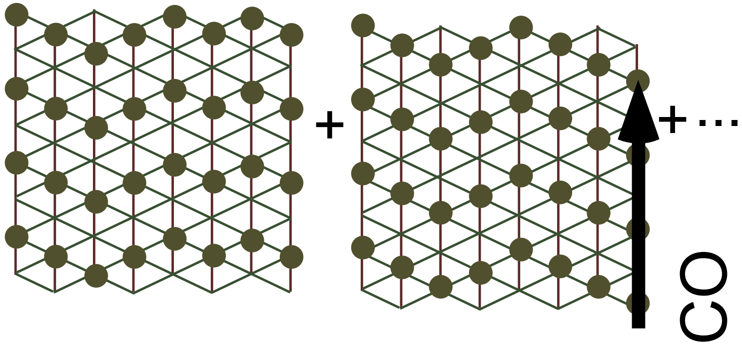


Classical limit *t=0* Ground state at half-filling

$V' > V$

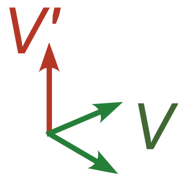


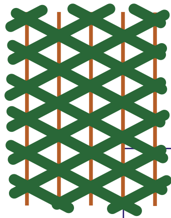
chain stripe



degenerate stripes

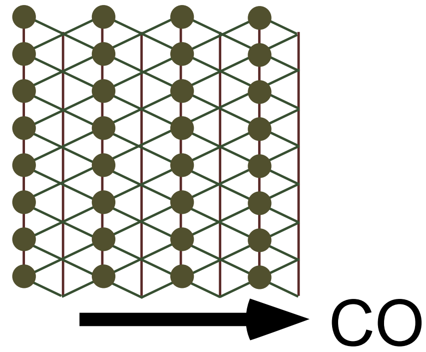
semi-macroscopic degeneracy $\sim 2^L$





$V' < V$

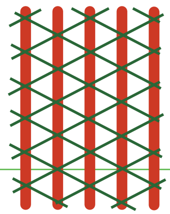
vertical stripe



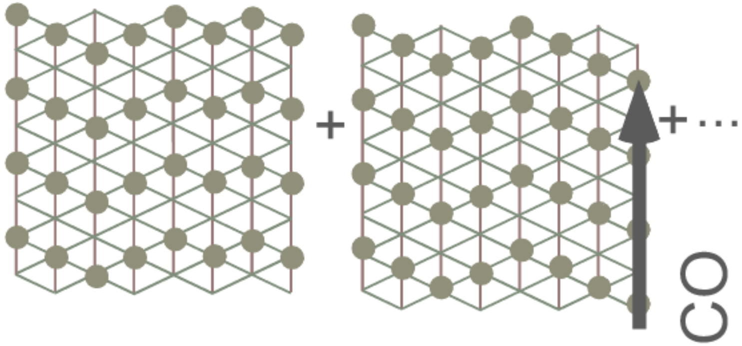
unique stripe

Classical limit + dynamics t

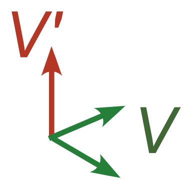
$V' > V$

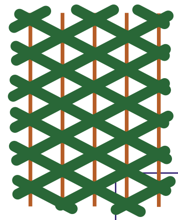


chain stripe



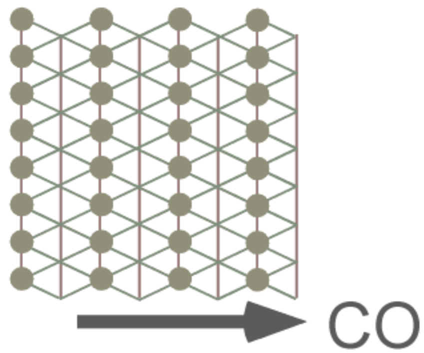
disordered stripes





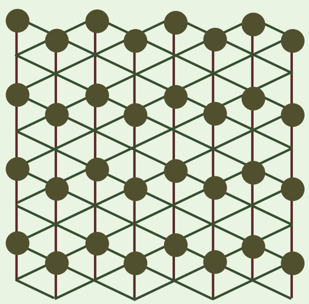
$V' < V$

vertical stripe



ordered stripe

+*t* **quantum dynamics**



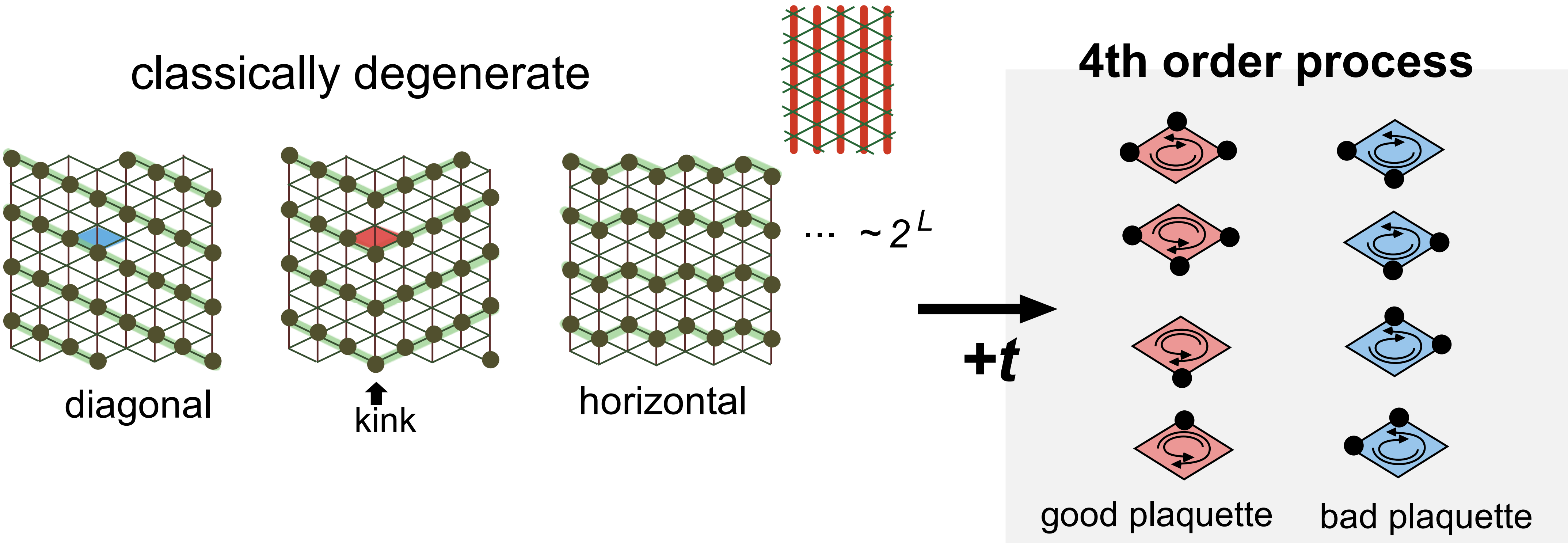
degeneracy is lifted

Horizontal stripe

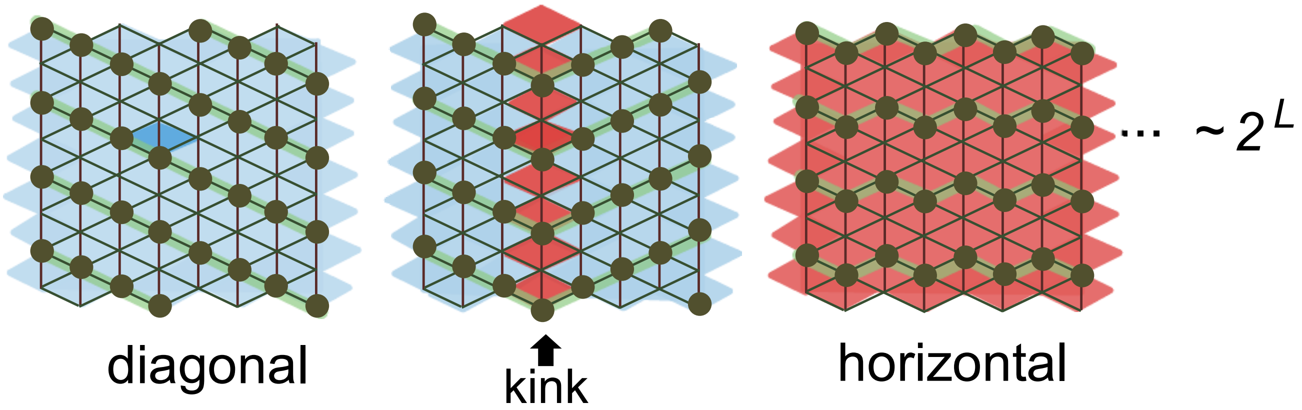
no intrinsic change
(just an exchange energy gain)

$\sim \frac{t^2}{V}$

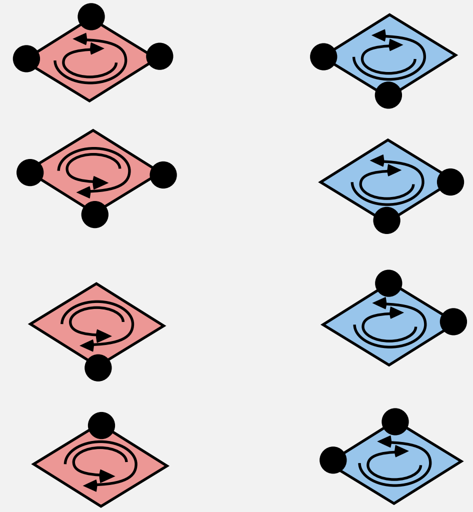
Quantum ground state *V'>V*



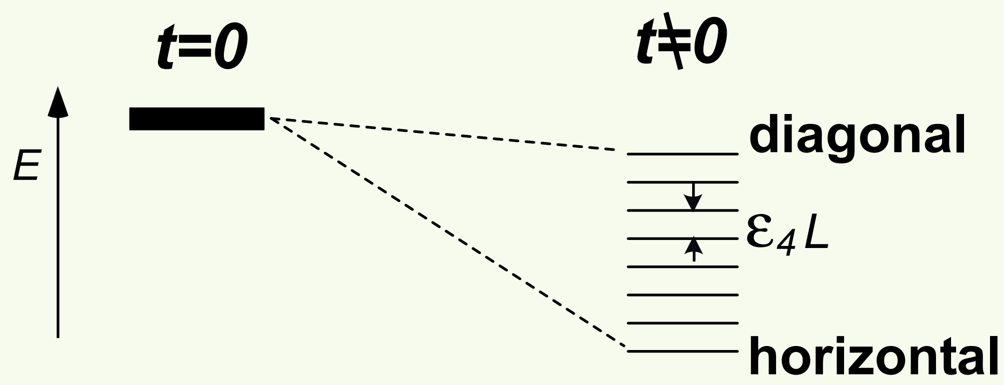
Quantum ground state *V'>V*



4th order process



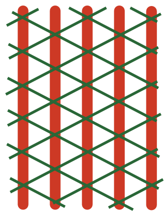
classical disorder **quantum order**

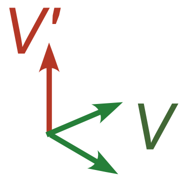


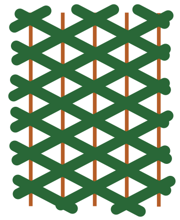
Half-filling + 1 Particle

V'>V

horizontal stripe

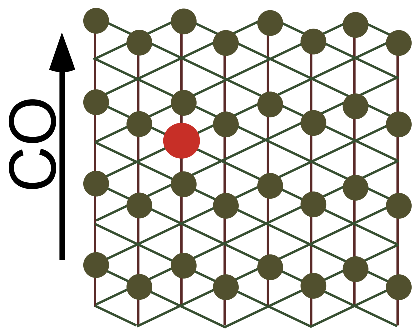


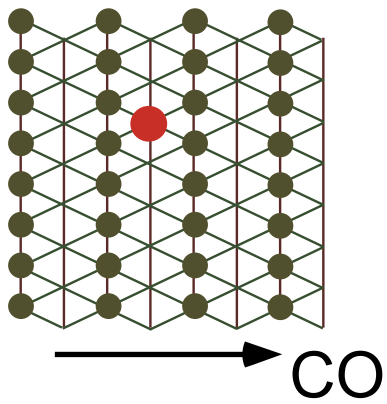




V'<V

vertical stripe

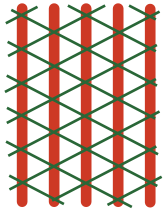


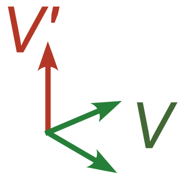


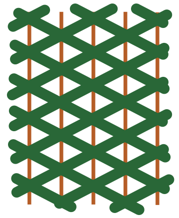
Half-filling + 1 Particle

V'>V

horizontal stripe

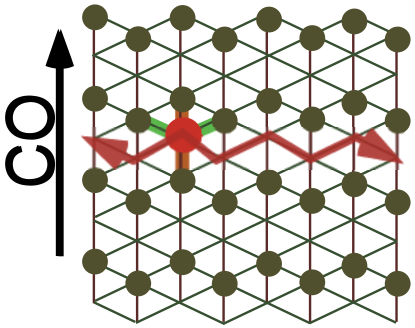


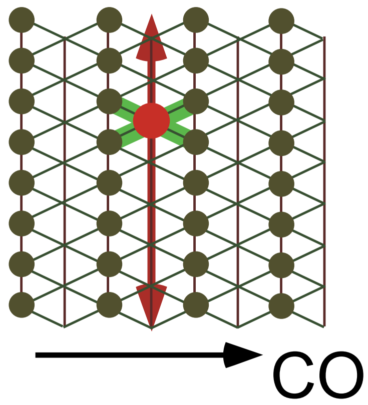


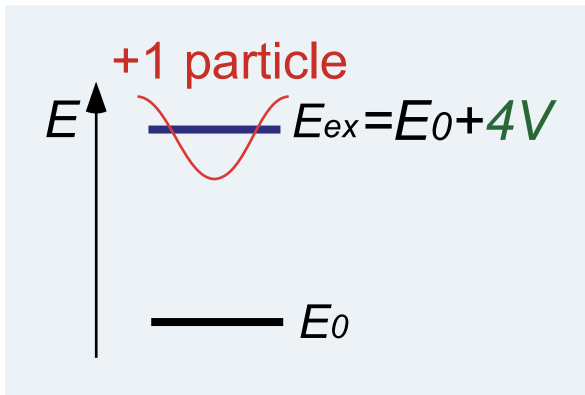


V'<V

vertical stripe





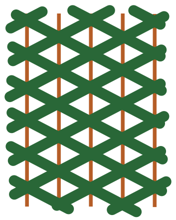


1D "confined state"

Particle cannot go over the CO walls..

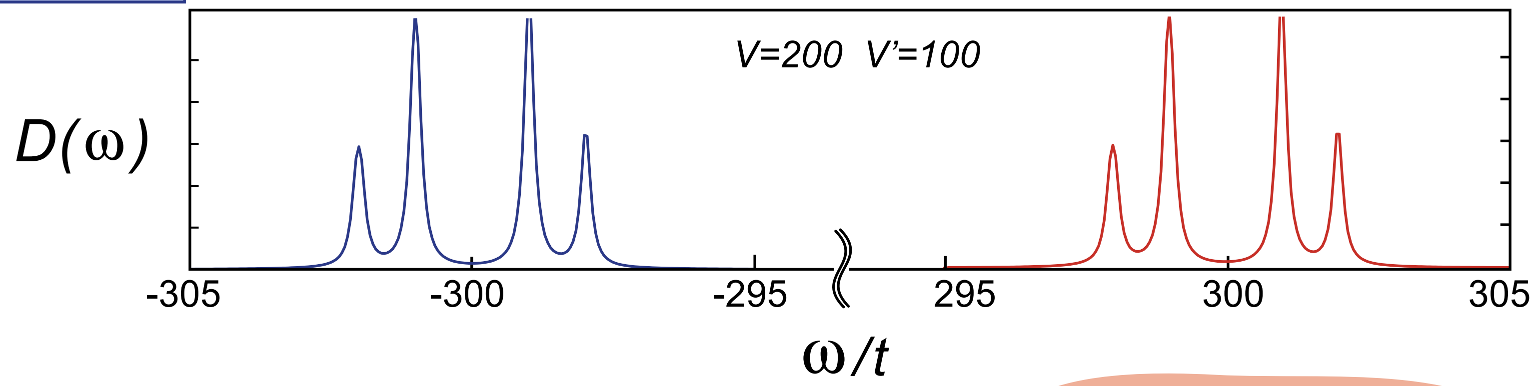
Spectral Function: *tV* model

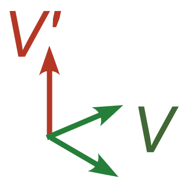
vertical stripe



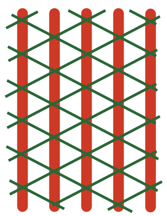
V'<V

1D free particle

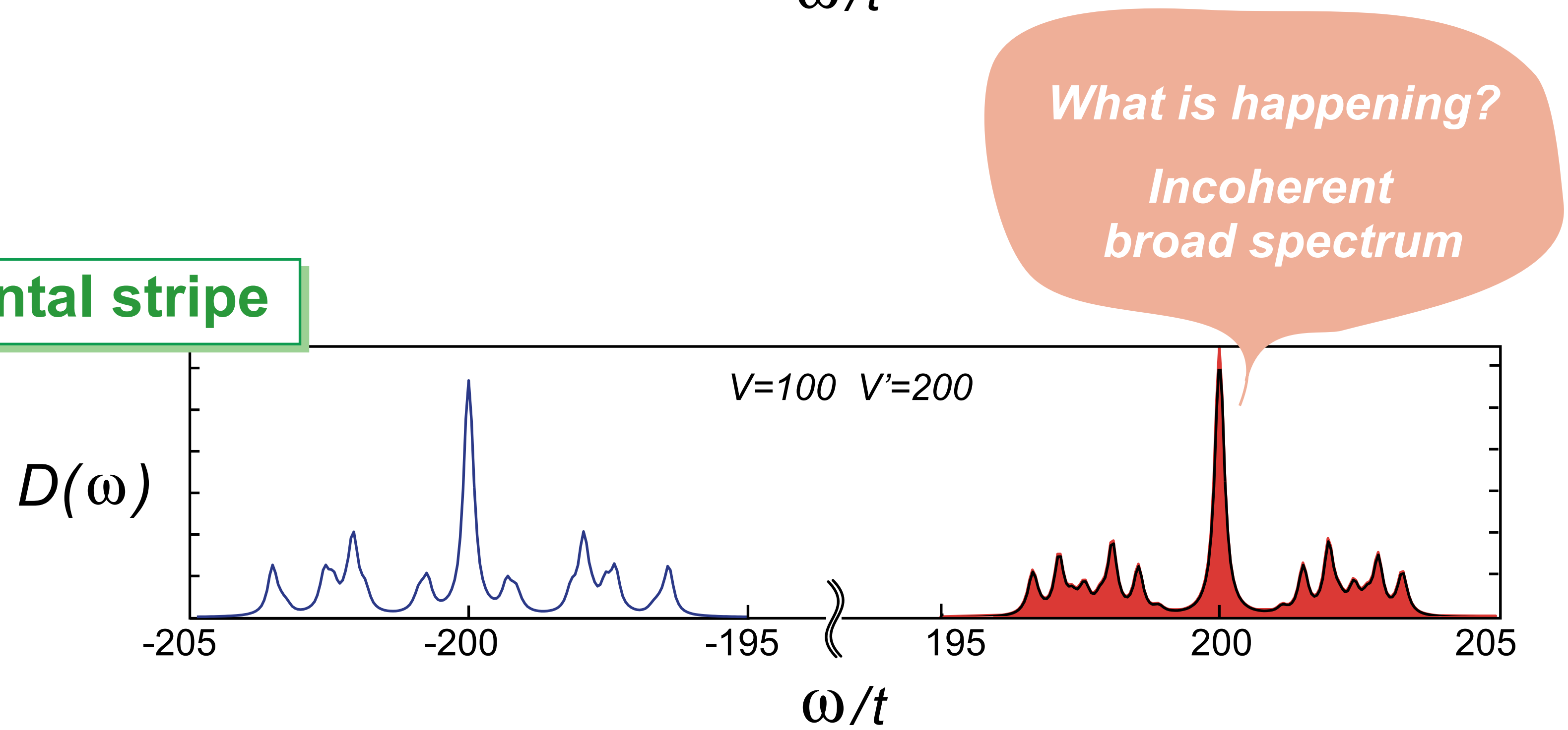




horizontal stripe



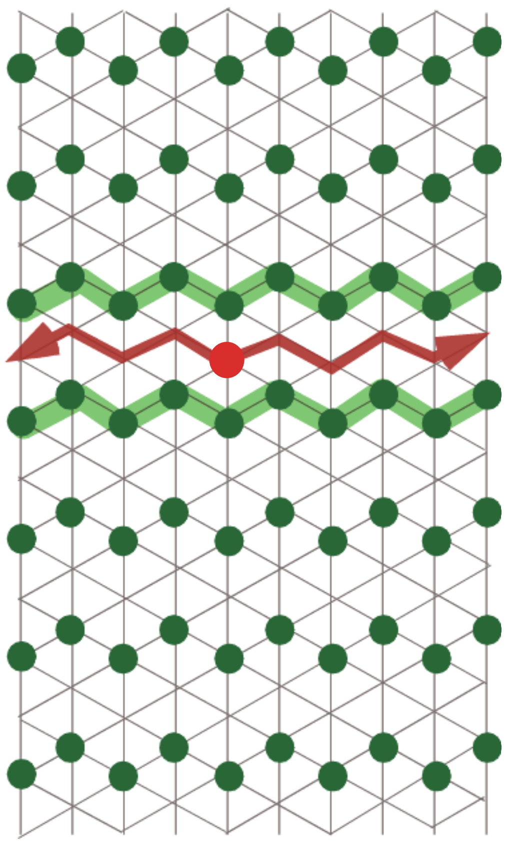
V'>V



Horizontal Stripe + 1Particle

V'>V

(1) Propagete along the CO walls. *x*-direction

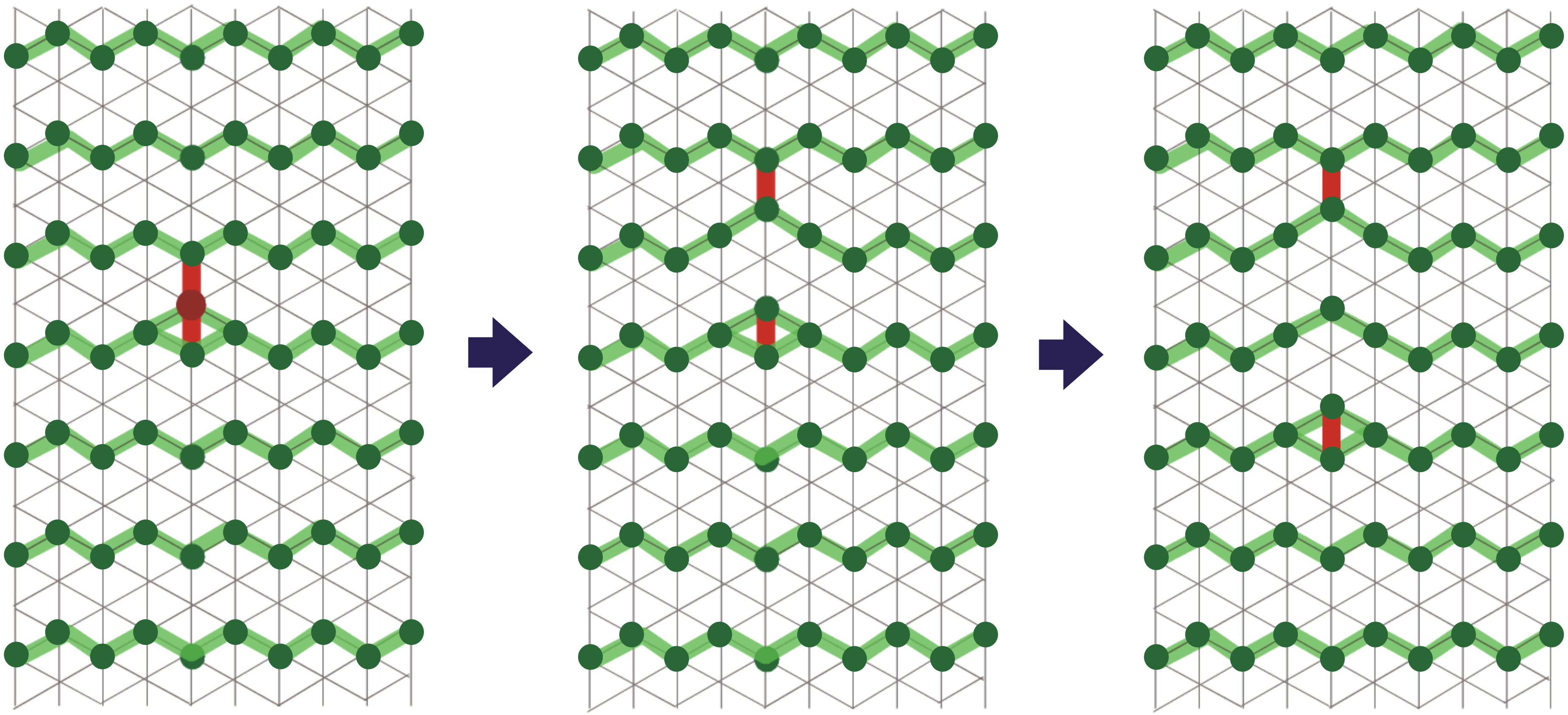


Horizontal Stripe + 1Particle

V'>V

(1) Propagete along the CO walls.

(2) Bonds move separately *y*-direction



Horizontal Stripe + 1Particle

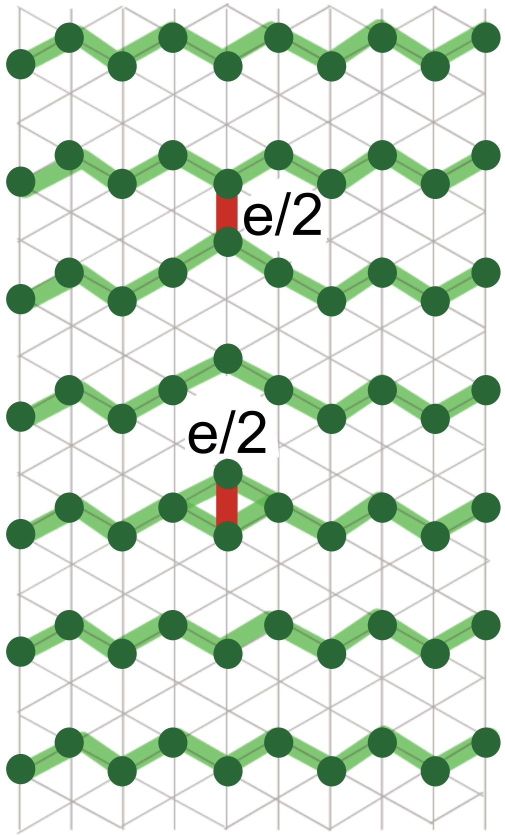
V'>V

(1) Bonds propagate together along the CO walls

(2) Bonds can **separate** in the direction perpendicular to the wall.

" fractional charge"

$$e \longrightarrow \frac{e}{2} + \frac{e}{2}$$



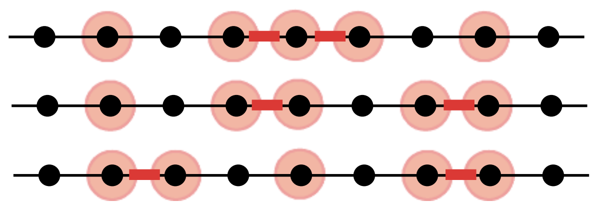
Fractional Charge $V' > V \gg t, t'$

effective model at $V \sim \infty$

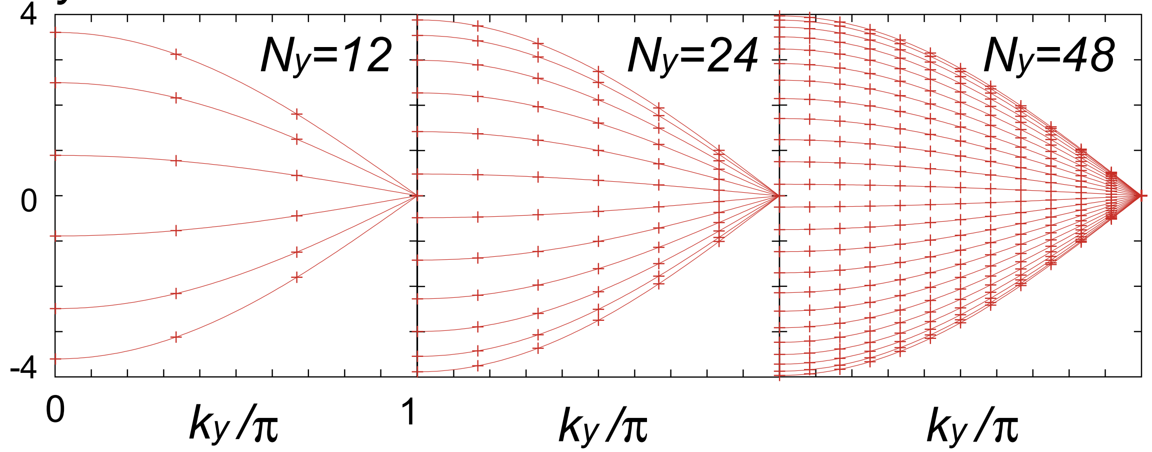
$$\mathcal{H}_{\mathcal{P}} = \sum_{\langle ij \rangle} \mathcal{P}\left(t_{ij} c_i^{+} c_j + \mathrm{h.c.}\right)\mathcal{P}$$

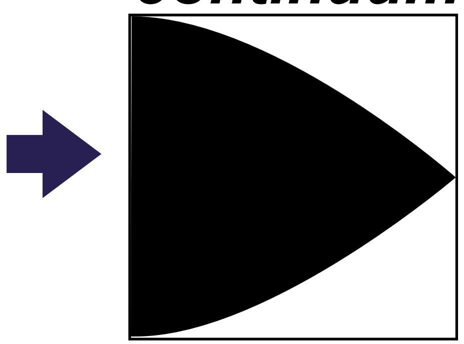
projector onto
the Ising ground states

P. Horsch, et.al.('05)



Dispersion (1st order)





Fractional Charge $V' > V \gg t, t'$

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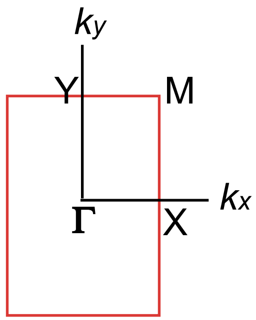
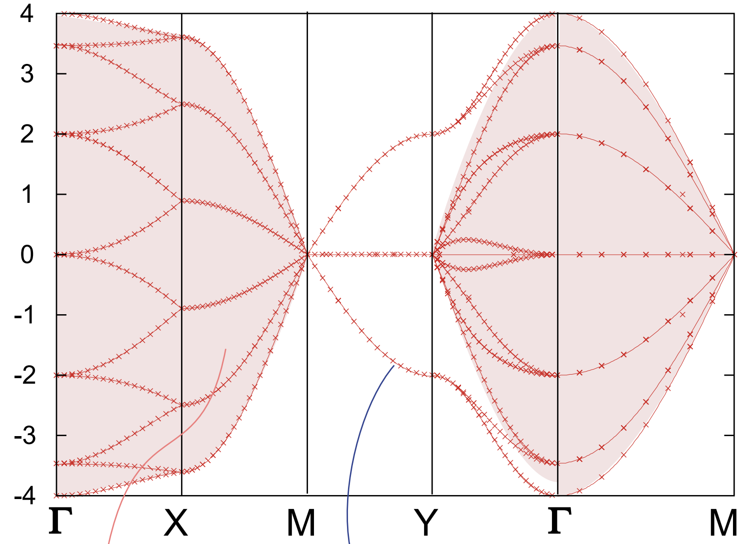
projector onto
the Ising ground states



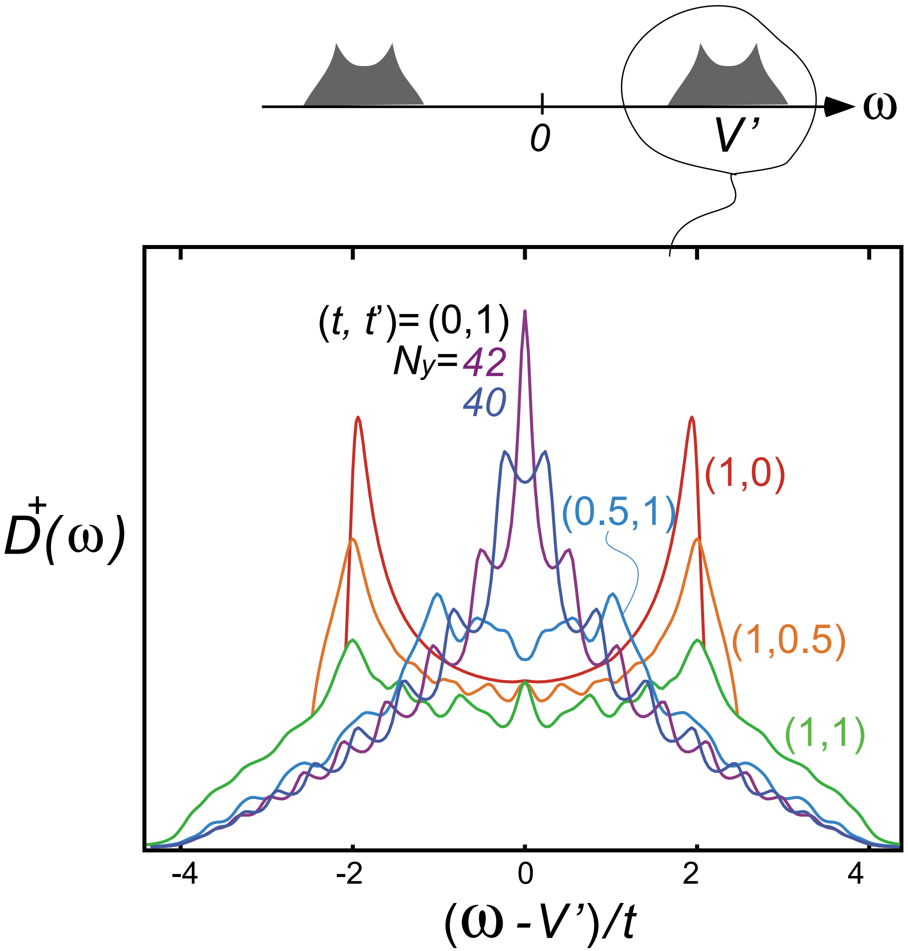


collective mode

1D free particle

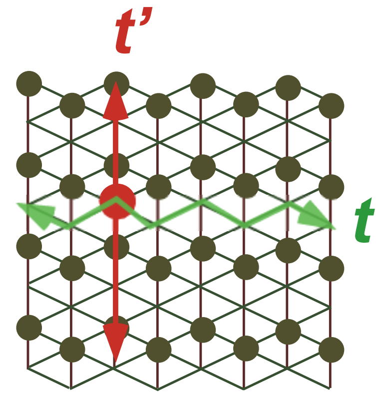
We find a characteristic dispersion which is the 1+1 combination
free particle motion (non-fractionalized)
\+ fractionalized collective mode.

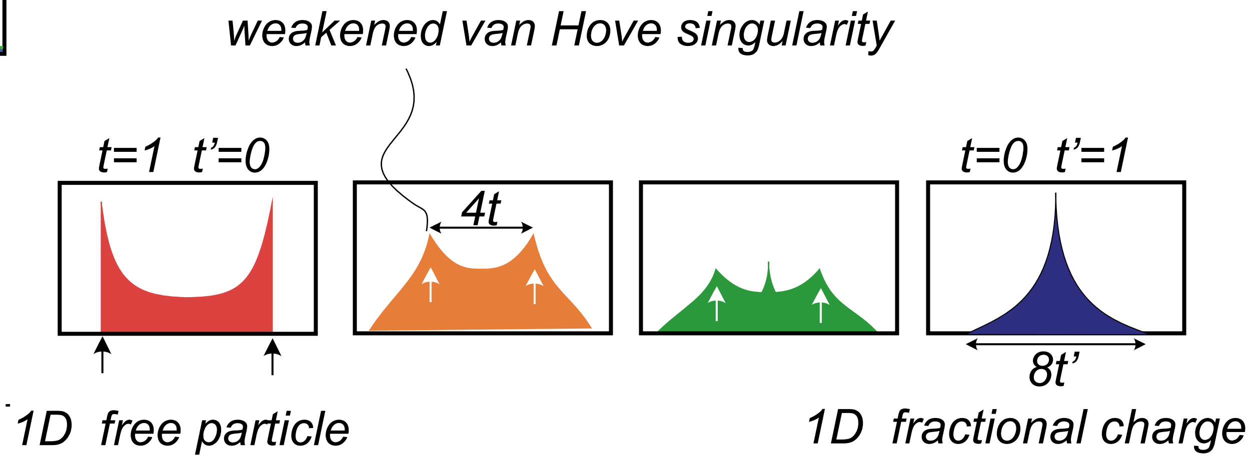
Spectral Function: projection model



Fractional Charge

V'>V

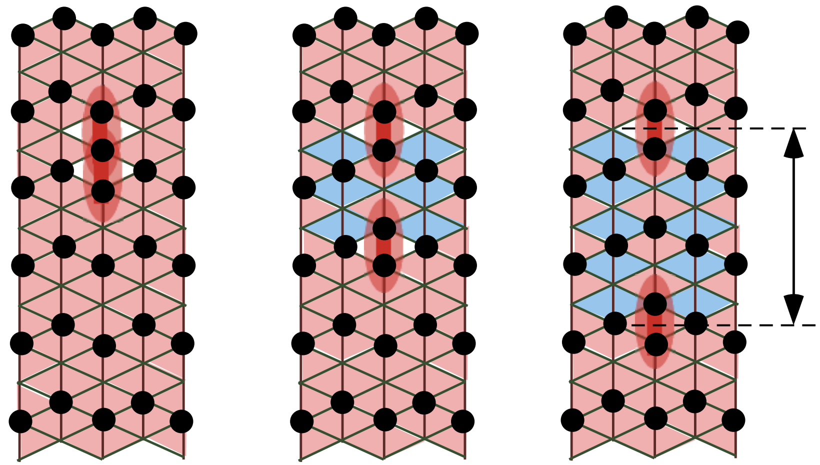




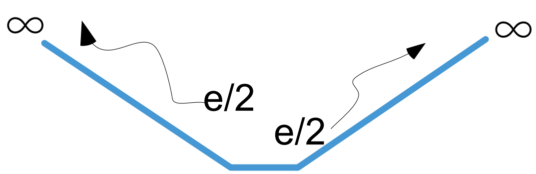
Fractional Charge $V' > V \gg t, t'$

Confinement (4th order)

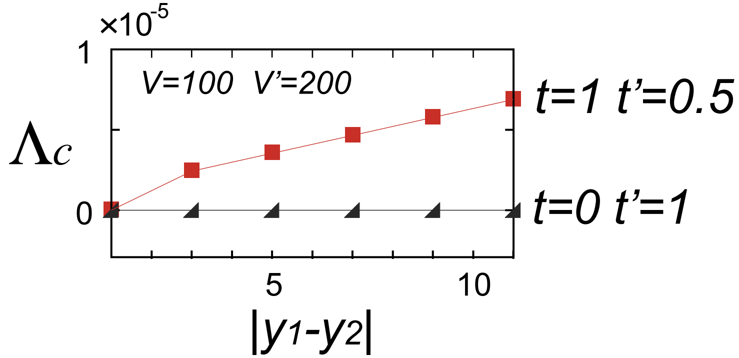
bad — good plaquette = $\varepsilon_4 = \dfrac{5t^4}{(2V'-V)^2 V'}$



Good plaquettes are replaced by the **bad** ones



fractions moving in the linear potentials

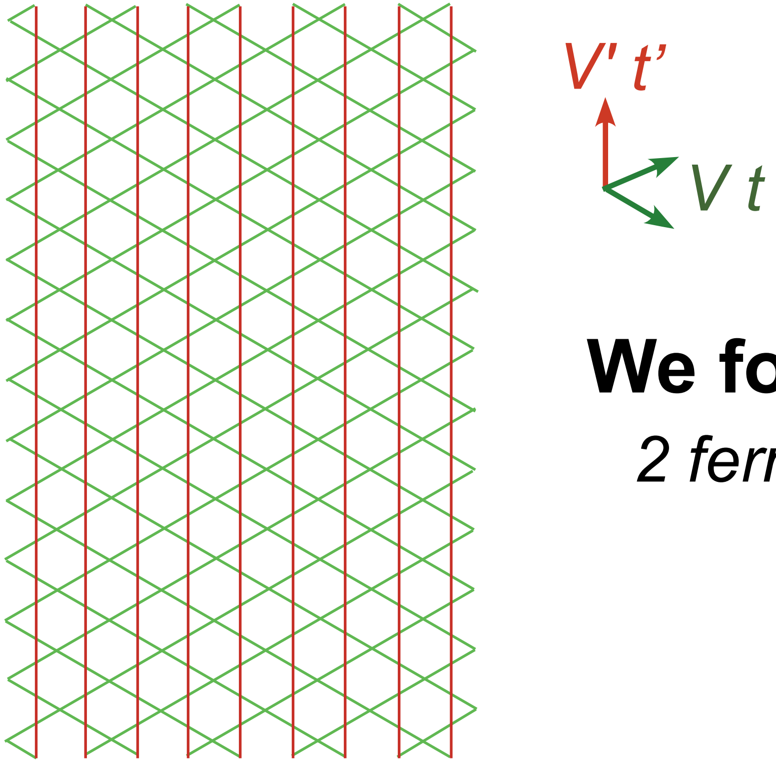


Distance between fractions

fractions never separate to infinite distance

coherence length $\sim t/\varepsilon_4 \sim (V/t)^3$

Lattice II.   Anisotropic Kagome lattice



We focus on 2/3-filling

2 fermion / 3site

⇨ *ground state at large V is a striped charge ordered insulator*

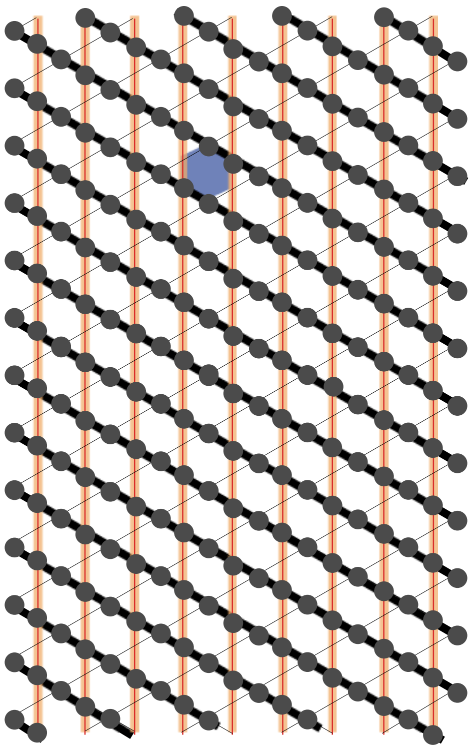
Anisotropic Kagome lattice

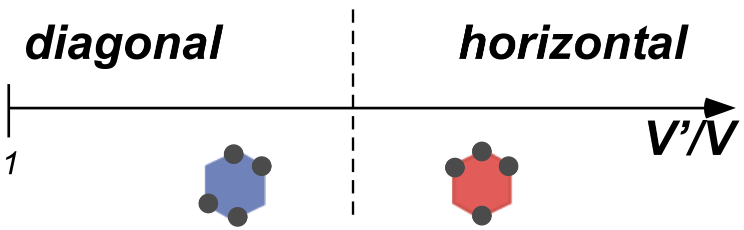
2/3-filling *2 fermion / 3site*

Ground state = classically degenerate

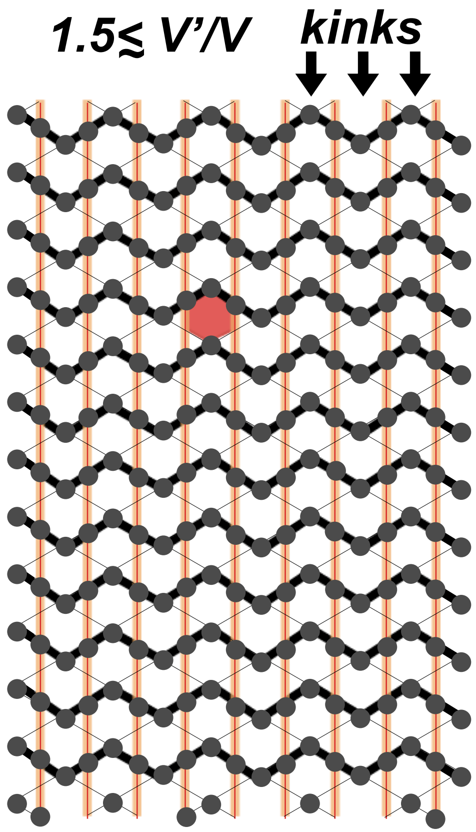
Unique ground state is selected from degenerate stripes ~ 2^L
by 6th order ring exchange of t around the hexagons.

$1 < V'/V \lesssim 1.5$



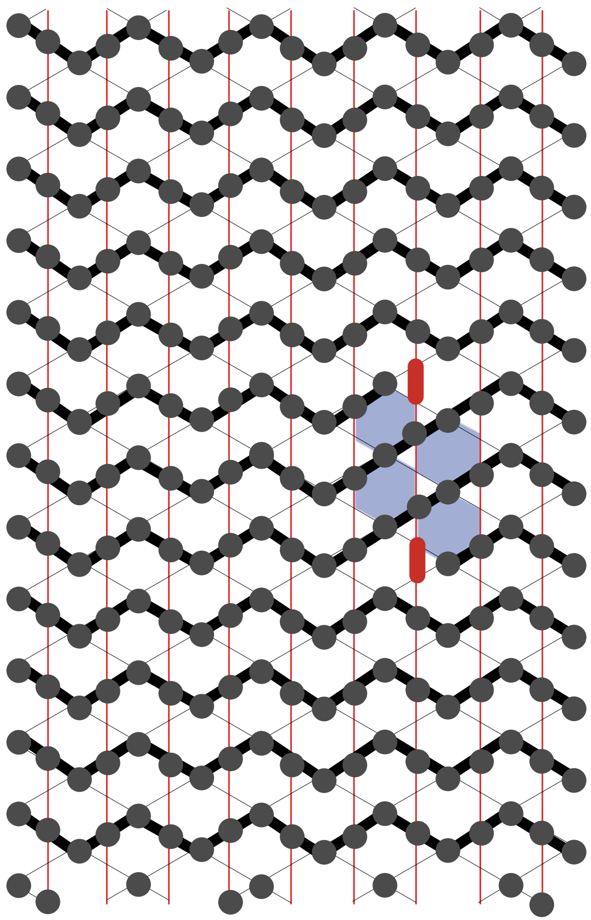


$1.5 \lesssim V'/V$



Anisotropic Kagome lattice

2/3-filling + 1hole



For both horizontal and diagonal stripes, doping of hole yields...

- fractionalization of charge perpendicular to the stripe
- free propagation along the stripe

Confinement of two fractions :

coherence length ~ $(V / t)^5$

linear potential at the 6th order of *t*.

good hexagons replaced by bad ones

Summary

- Strong coupling stories of interacting fermions.

  $V' \mp V \gg t, t'$

- **Partially frustrated lattices** (triangular & kagome) yield exotic **tuning of electronic propagation** in the vicinity of insulating state (particle doping).

  - **Fractionalization**
  - **non-fractionalized free propagation**

  dimension $1 \otimes 1 < 2$

- Hard core bosons also have such state.

  Geometry and the degree of cofinement differs a bit due to statistics.
  (fermionic exchange sign).