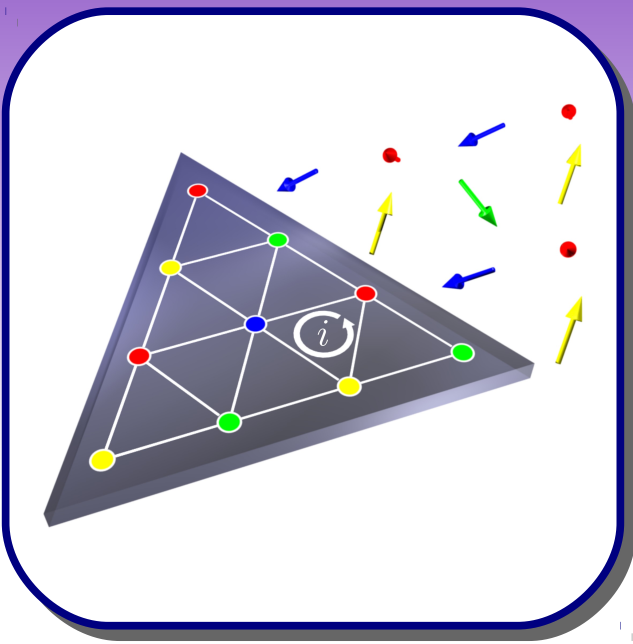
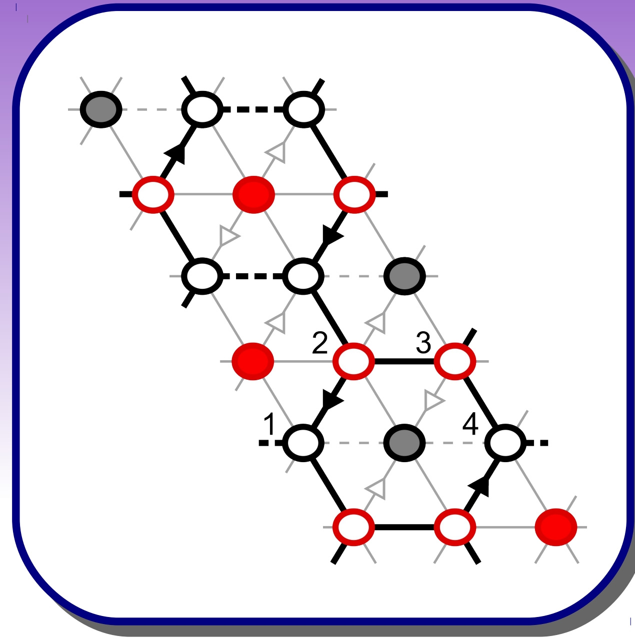




Strongly correlated topological states of spinless fermions in 2D lattices

Stefanos Kourtis

"Correlations, criticality, and coherence in quantum systems" – Évora, Portugal, 6/10/14

IFW
Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden

Work done in collaboration with:

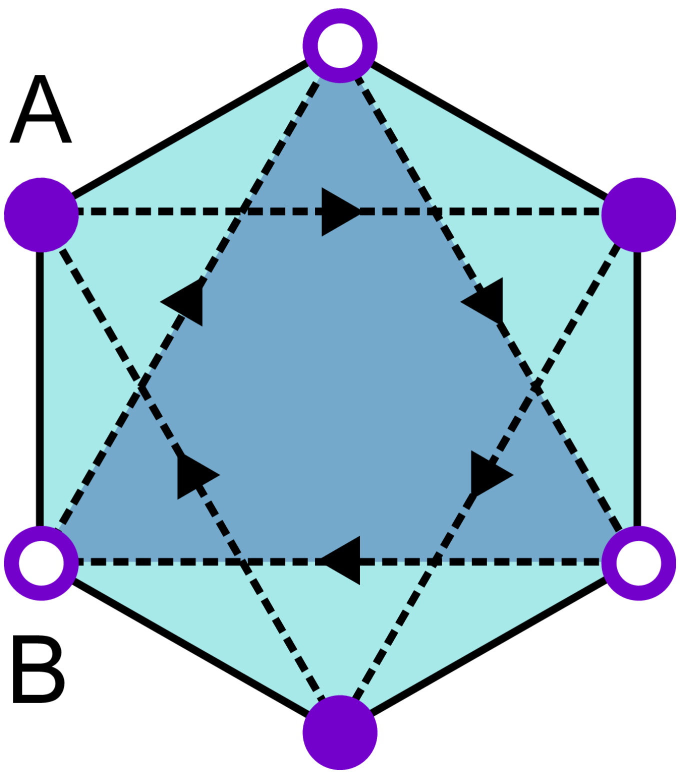
→ J. Venderbos (now @ MIT)
→ M. Daghofer
→ J. van den Brink
→ new: C. Loftin (UNC)
→ T. Neupert (Princeton)
→ C. Chamon (Boston U)
→ C. Mudry (PSI Villigen)

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

DAAD

FQHE in the Haldane model

(Neupert *et al.*, Sheng *et al.*, Regnault & Bernevig, ... , 2011)

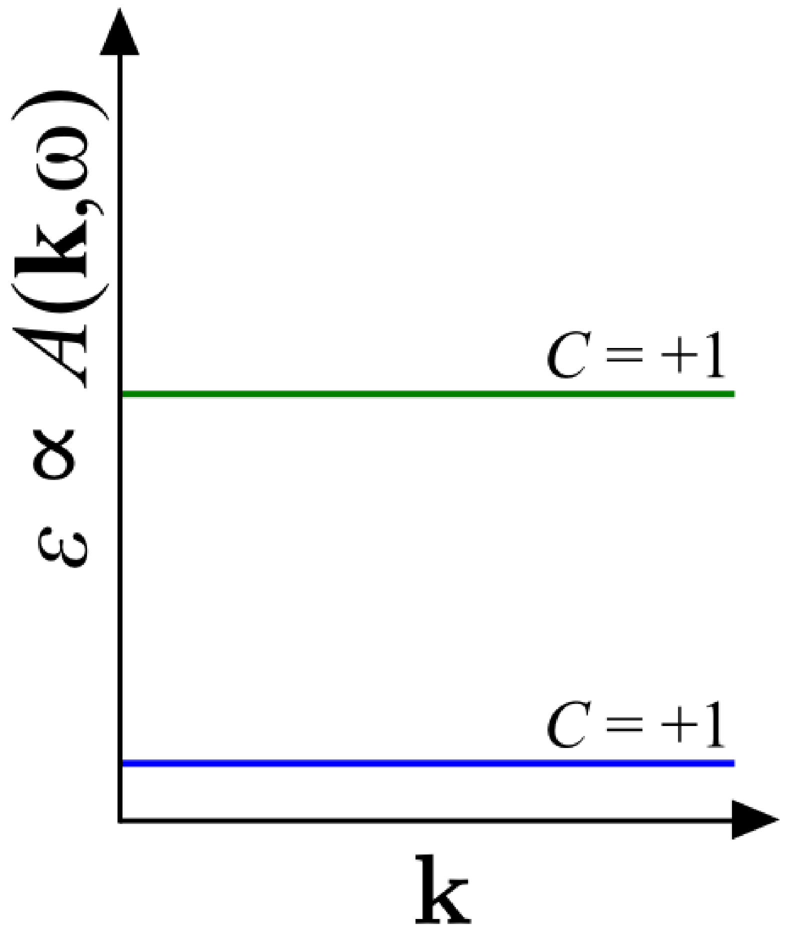


- spinless fermions
- filling fraction $\nu = p/q$
- no net flux through unit cell
- screened Coulomb repulsion
- Hall conductivity:

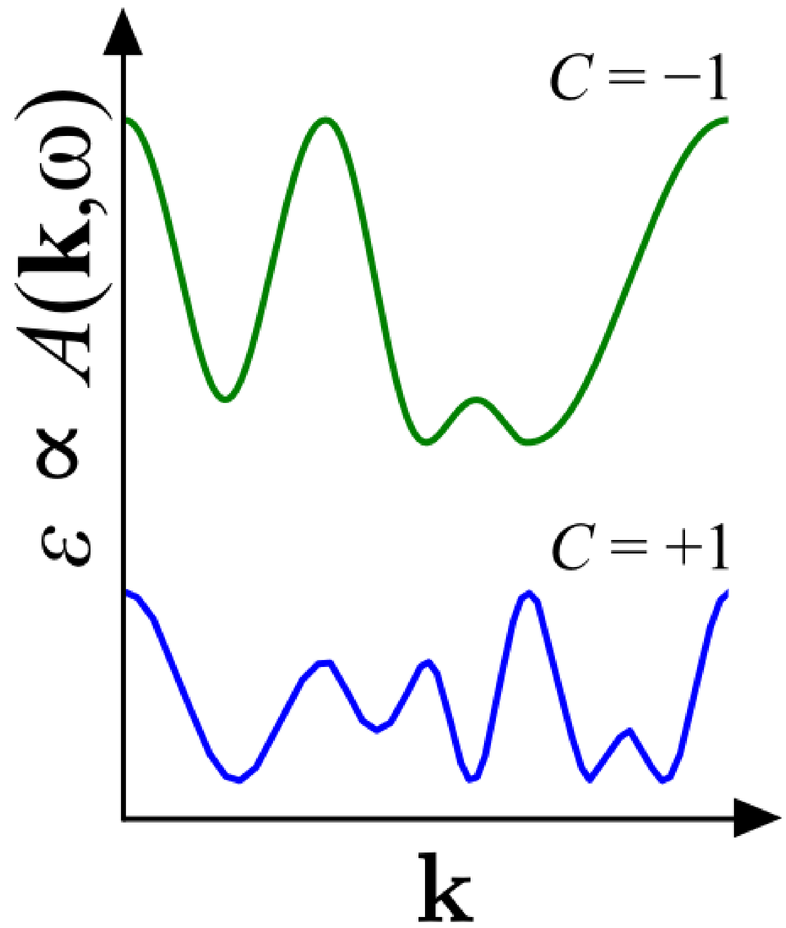
$$\sigma_{xy} = \frac{p}{q}\frac{e^2}{h}$$

Landau levels vs Chern bands

Landau levels

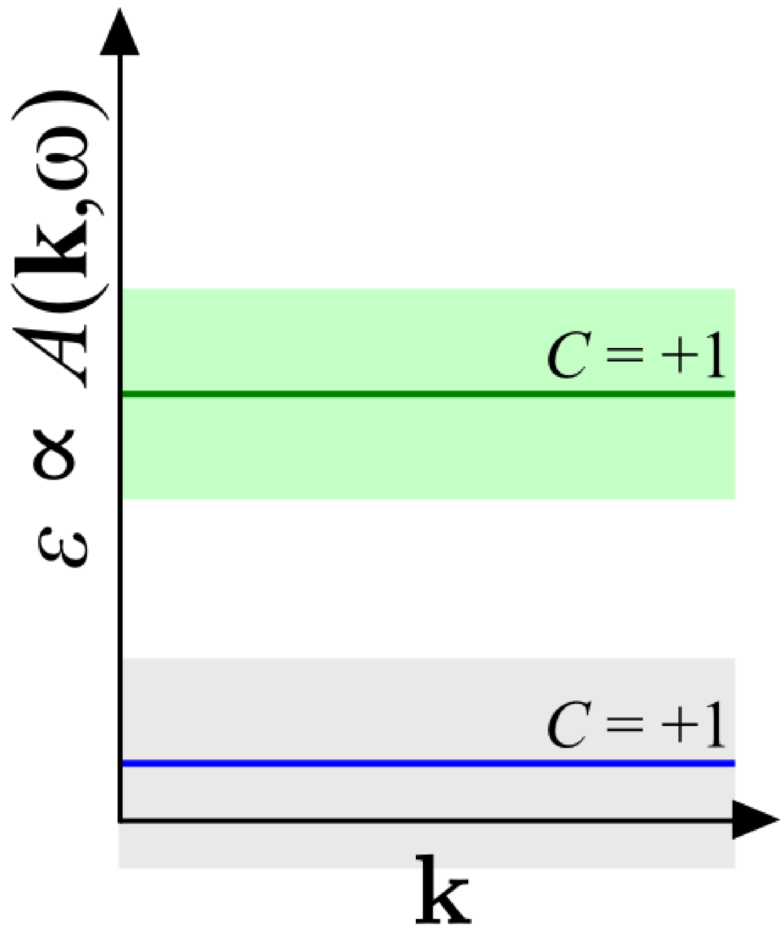


Chern bands

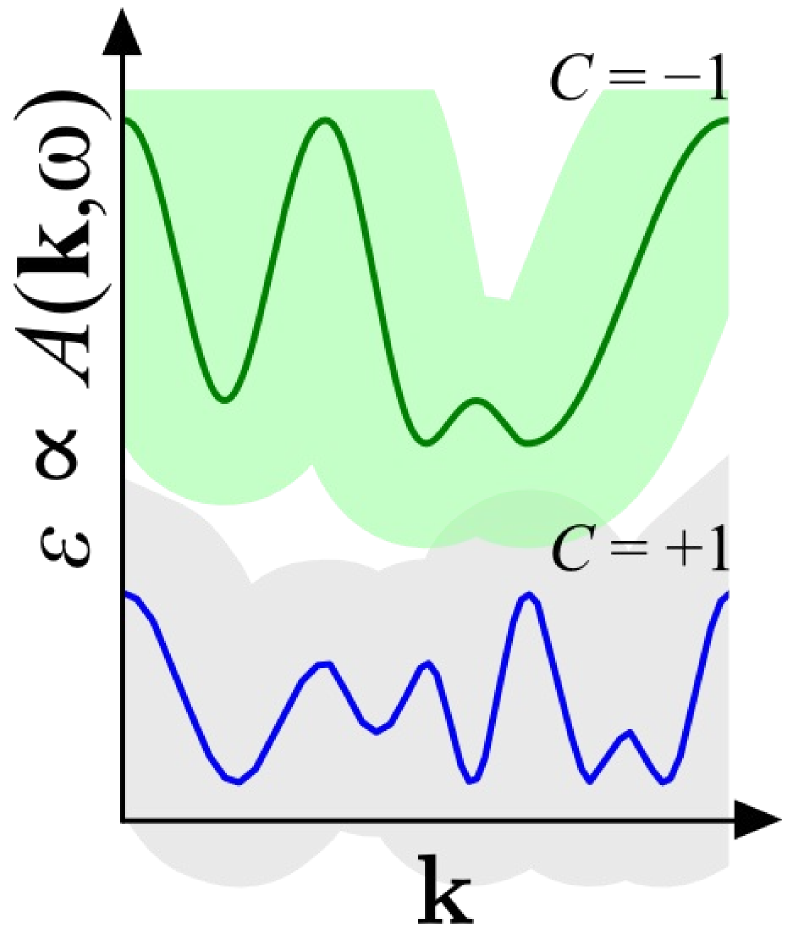


Landau levels vs Chern bands

Landau levels + V

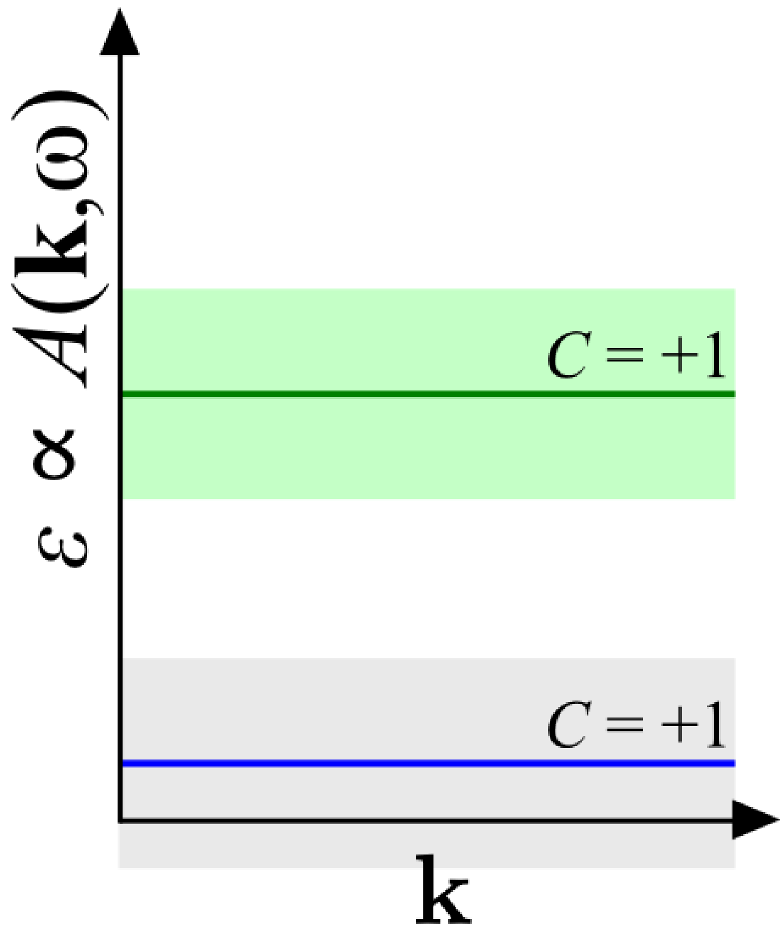


Chern bands + V

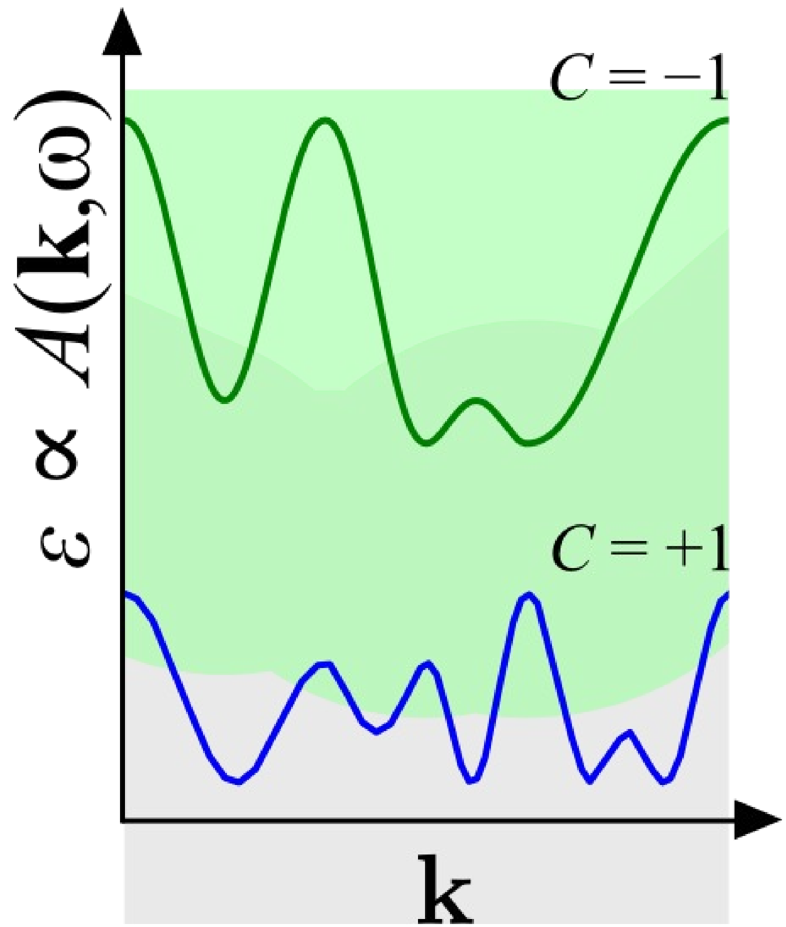


Landau levels vs Chern bands

Landau levels + V



Chern bands + large V



Correlations → topological order

Real bands are:

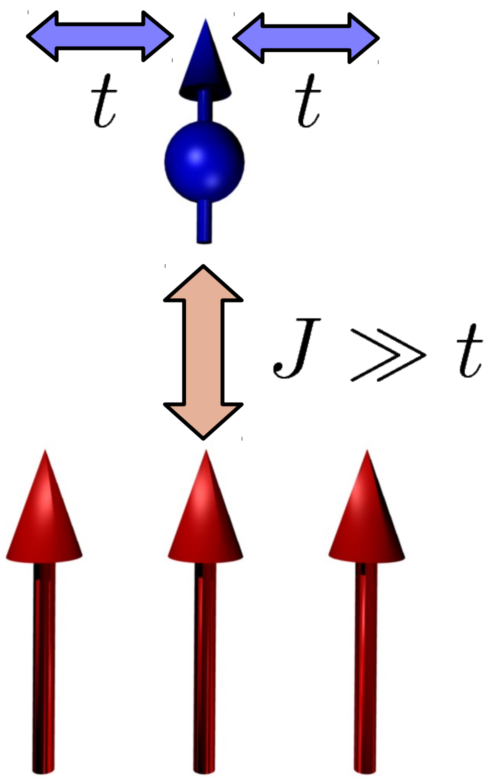
- multiple
- dispersive
- broadened / mixed by interactions

Can the addition of interactions in **real** bands:

- induce **FQH-like** physics?
- lead to correlated topological phases **w/o QH counterparts**?
  (topological order w/o underlying topological bands?)

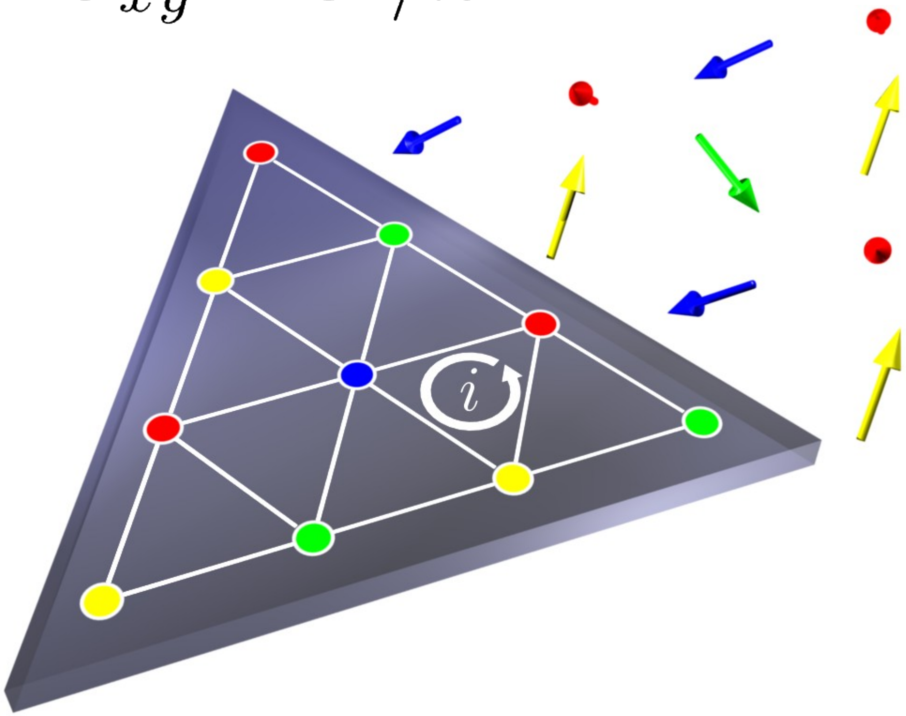
Chern insulator (CI) on the triangular lattice

Kondo-lattice model



Martin & Batista, 2008:

- at $\nu = 3/4$
  → chiral spin pattern
- $\sigma_{xy} = e^2/h$



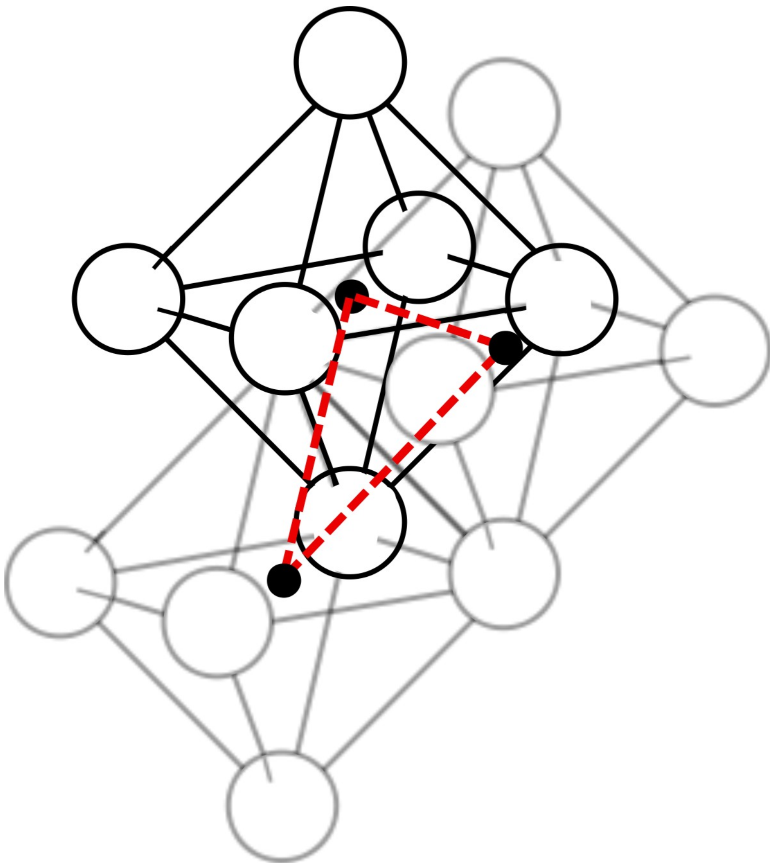
Also:

- Ohgushi, Murakami & Nagaosa, 2000

CI on triangular lattice of t_{2g} electrons

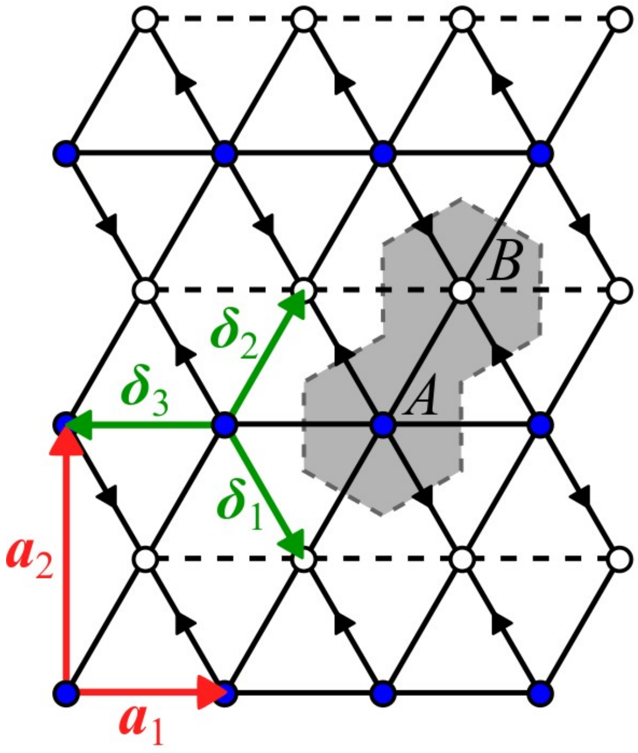
3-orbital Hubbard model

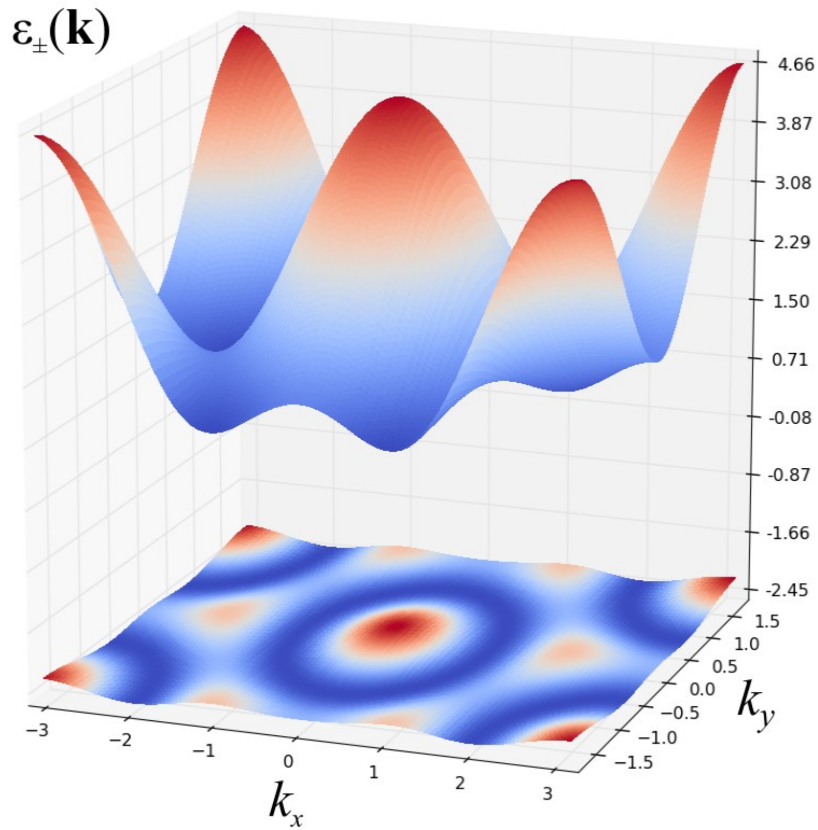
Venderbos *et al.*, 2011; 2012:



- strong on-site Coulomb effects
  → mapping to KLM
  → chiral spin pattern
- flat isolated single-orbital band
- $\sigma_{xy} = e^2/h$

Effective model on the triangular lattice



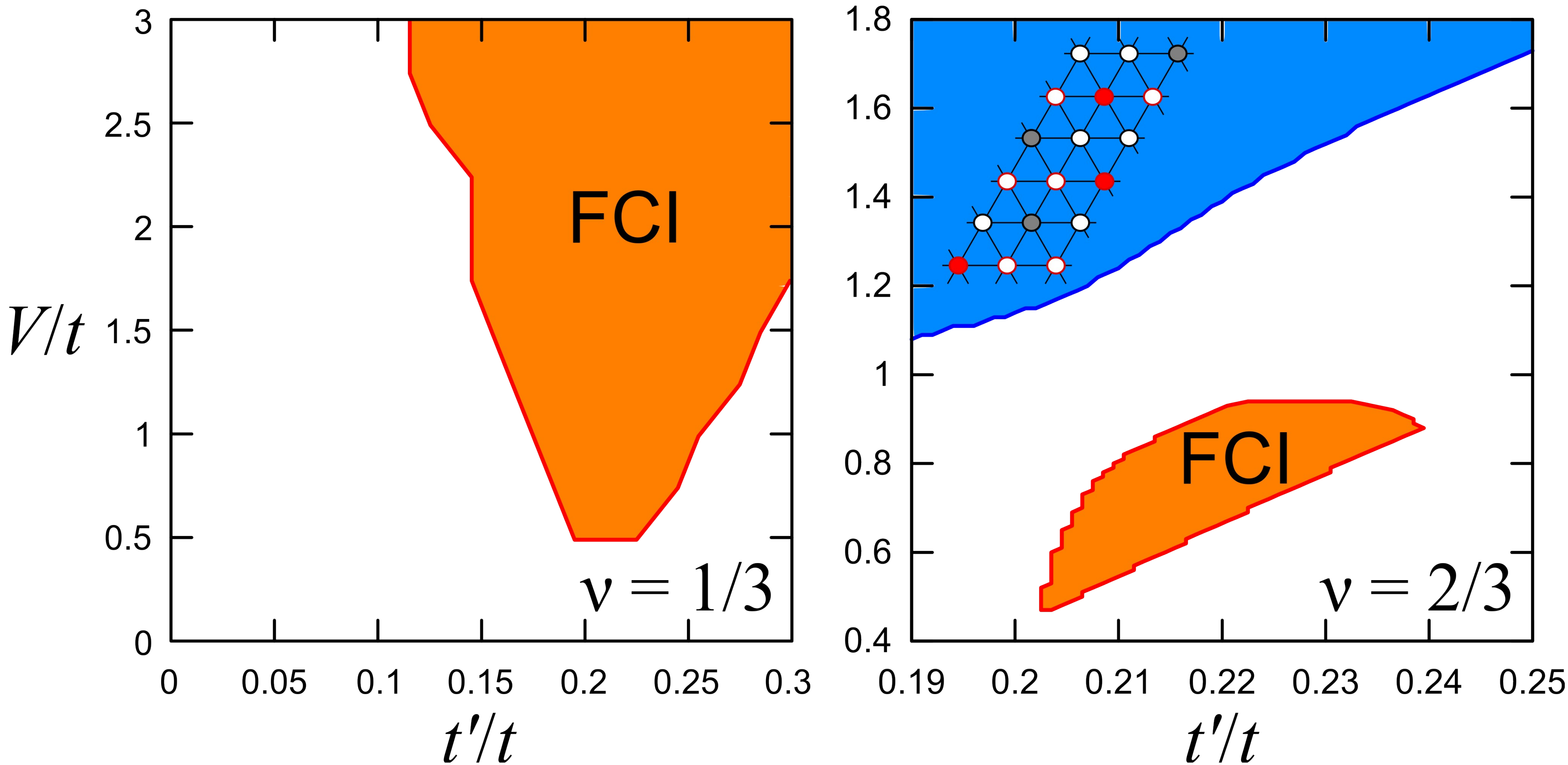


+ partially filled Chern band

+ nearest-neighbor Coulomb interaction V

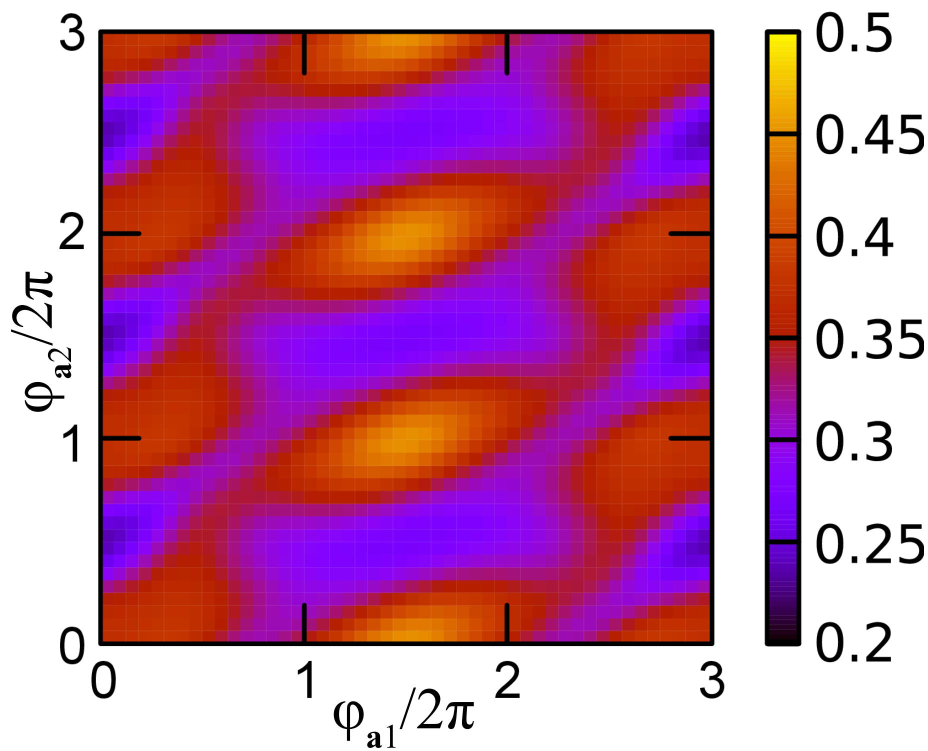
Phase diagram

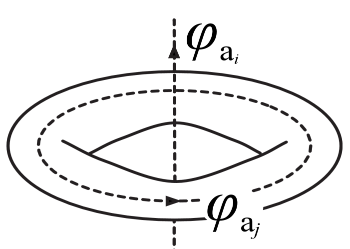
Exact diagonalization, 3x6-site cluster, PBC



Fractional Chern insulator

Topological invariant: σ_H → integral of **Berry curvature**

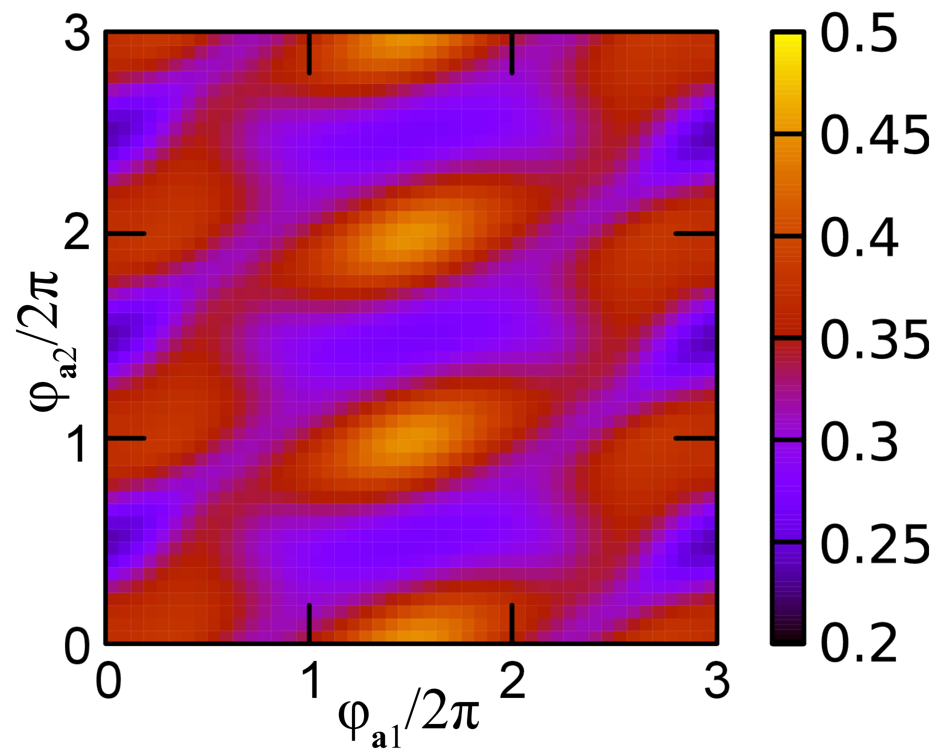




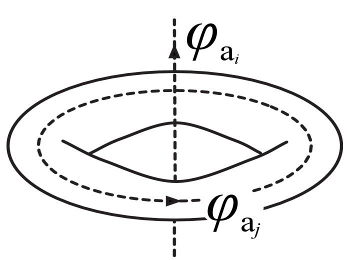
$$\sigma_{\mathrm{H}} = \frac{e^2}{h\pi q} \sum_{n=1}^{q} \iint_0^{2\pi} d\varphi_{\mathbf{a}_i} d\varphi_{\mathbf{a}_j} \Im \sum_{n' \neq n} \frac{\langle n | \frac{\partial H}{\partial \varphi_{\mathbf{a}_i}} | n' \rangle \langle n' | \frac{\partial H}{\partial \varphi_{\mathbf{a}_j}} | n \rangle}{(\epsilon_n - \epsilon_{n'})^2}$$

Fractional Chern insulator

Topological invariant: σ_H → integral of **Berry curvature**



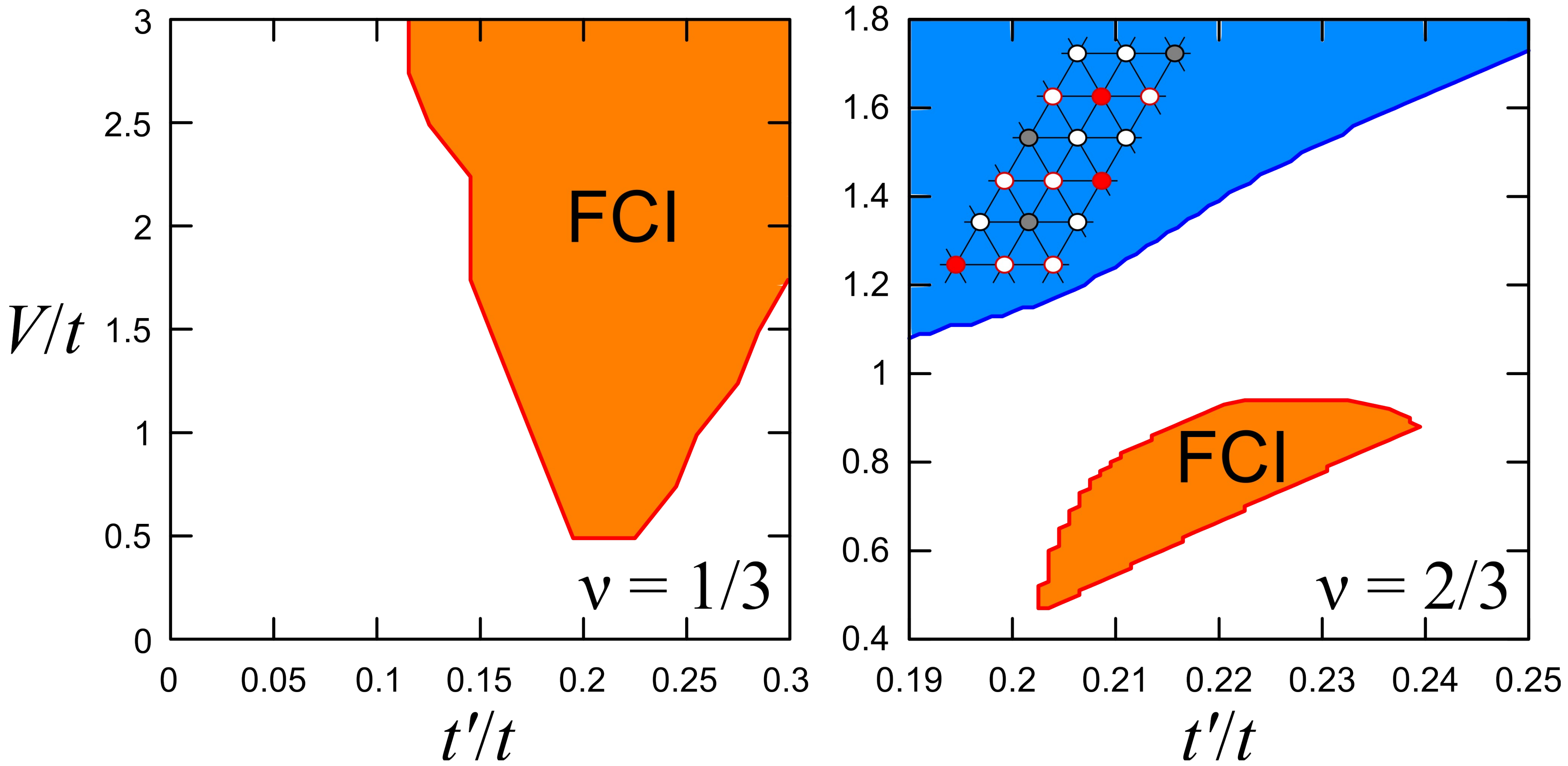
Very precise quantization of σ_H, even in finite-size numerics



$$\sigma_{\rm H} = \frac{e^2}{h\pi q} \sum_{n=1}^{q} \iint_0^{2\pi} d\varphi_{\mathbf{a}_i} d\varphi_{\mathbf{a}_j} \Im \sum_{n' \neq n} \frac{\langle n | \frac{\partial H}{\partial \varphi_{\mathbf{a}_i}} | n' \rangle \langle n' | \frac{\partial H}{\partial \varphi_{\mathbf{a}_j}} | n \rangle}{(\epsilon_n - \epsilon_{n'})^2}$$

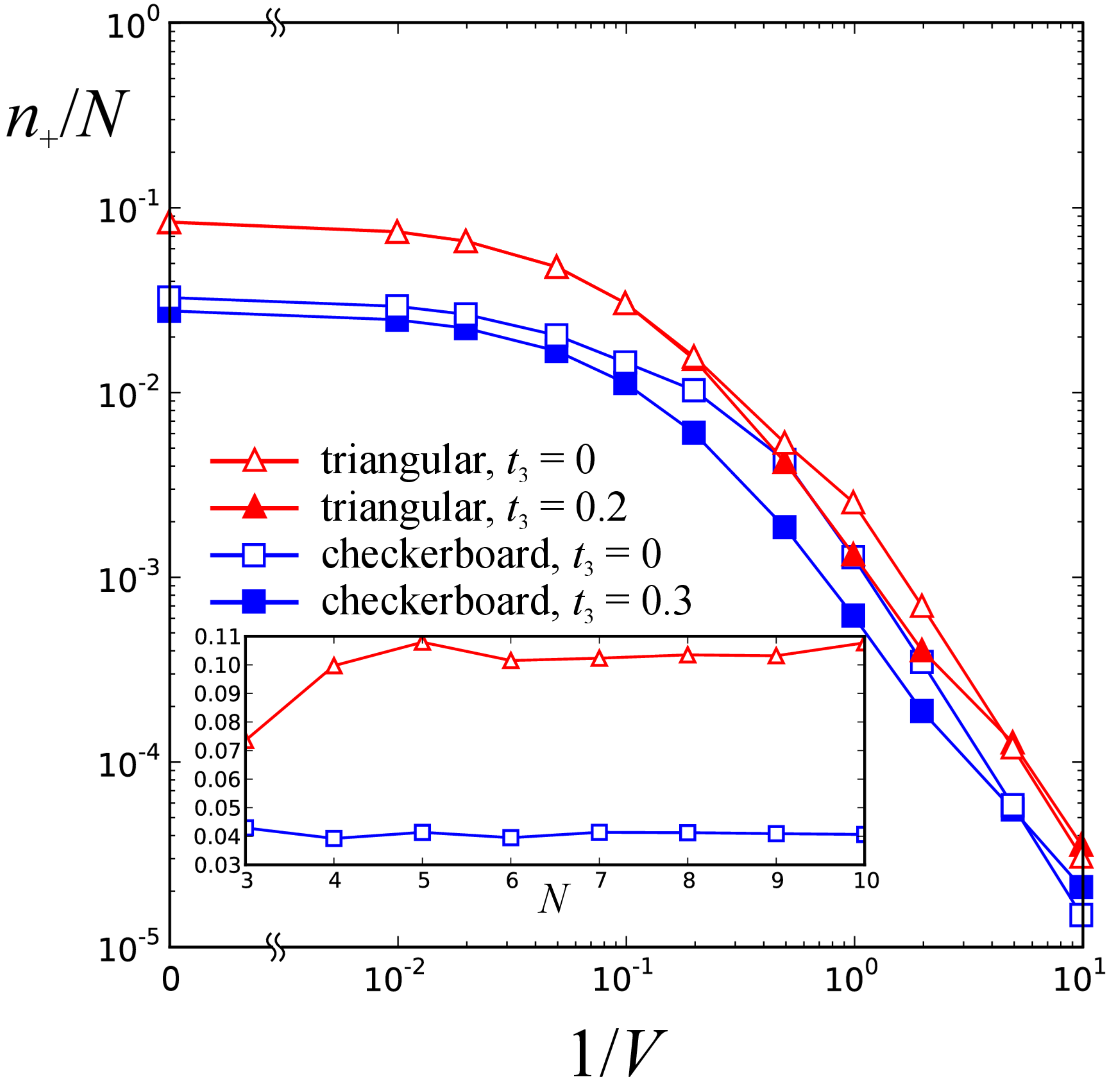
Phase diagram

Exact diagonalization, 3x6-site cluster, PBC



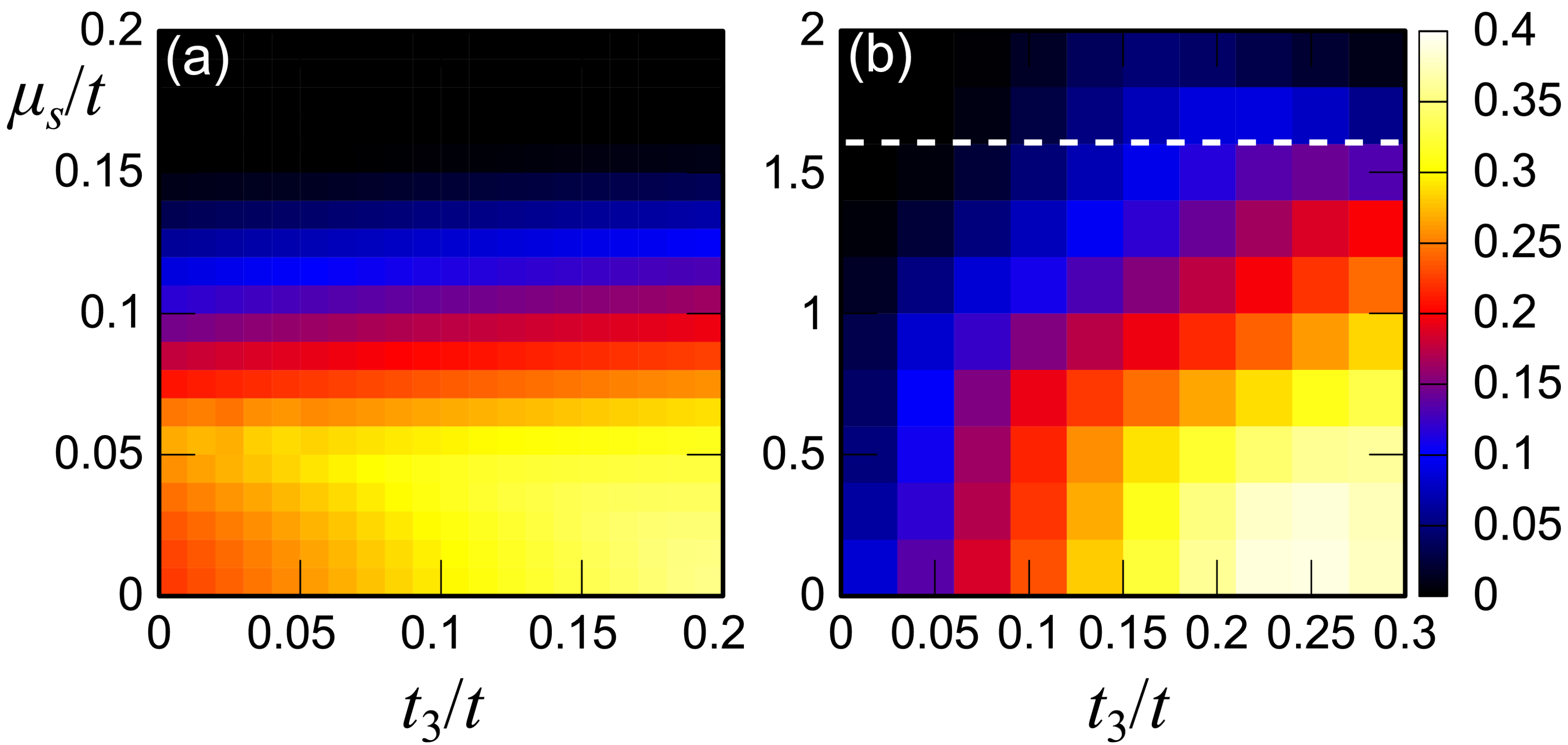
Upper-band character of FCI states

Exact diagonalization, 6x6-site cluster, PBC



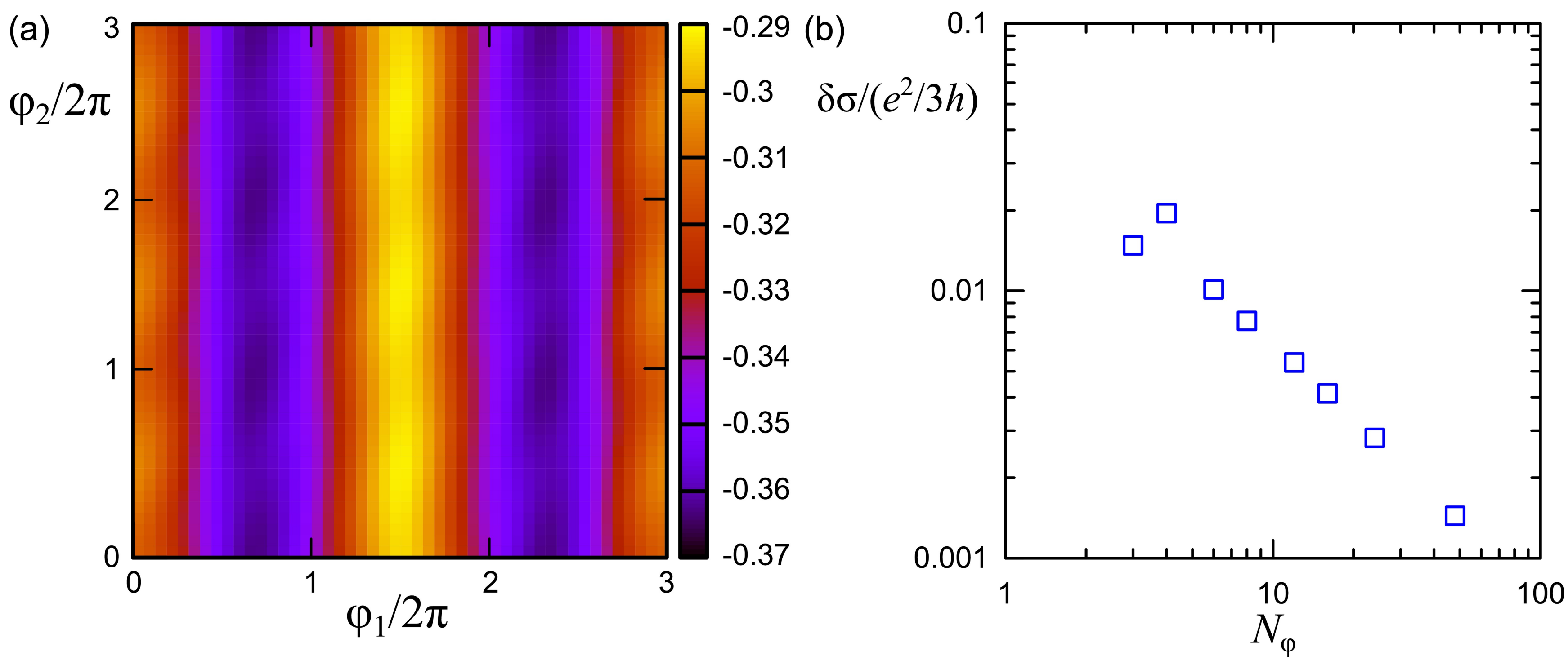
Phase diagram at V = infinity

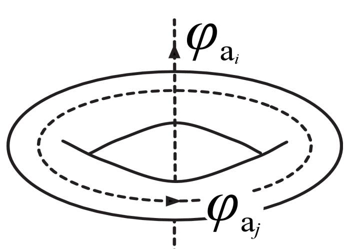
Exact diagonalization, 6x6-site cluster, PBC



Berry curvature at V = infinity

Exact diagonalization, 6x6-site cluster, PBC

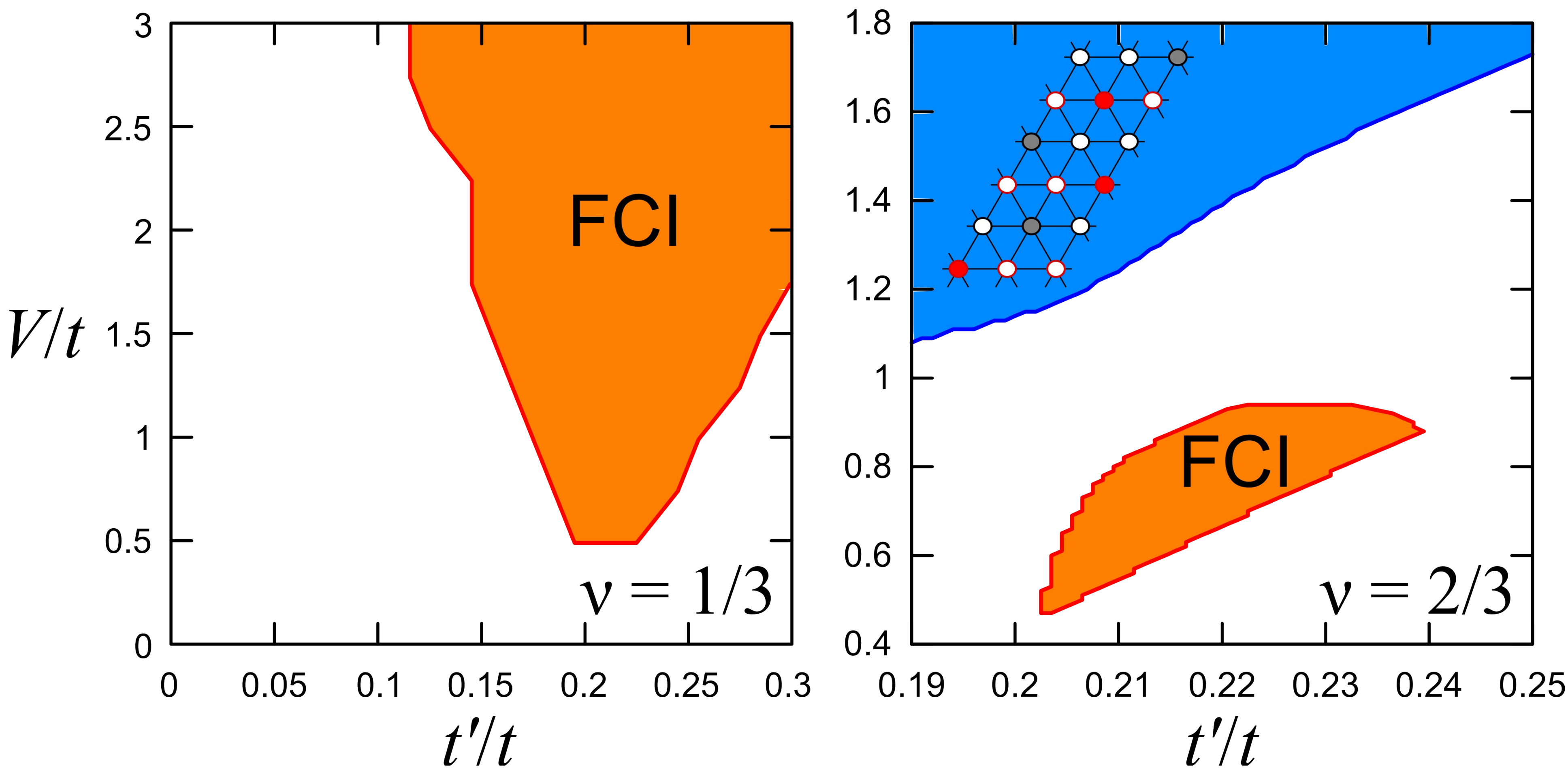




$$\sigma_{\mathrm{H}} = \frac{e^2}{h\pi q} \sum_{n=1}^{q} \iint_0^{2\pi} d\varphi_{\mathbf{a}_i} d\varphi_{\mathbf{a}_j} \Im \sum_{n' \neq n} \frac{\langle n | \frac{\partial H}{\partial \varphi_{\mathbf{a}_i}} | n' \rangle \langle n' | \frac{\partial H}{\partial \varphi_{\mathbf{a}_j}} | n \rangle}{(\epsilon_n - \epsilon_{n'})^2}$$

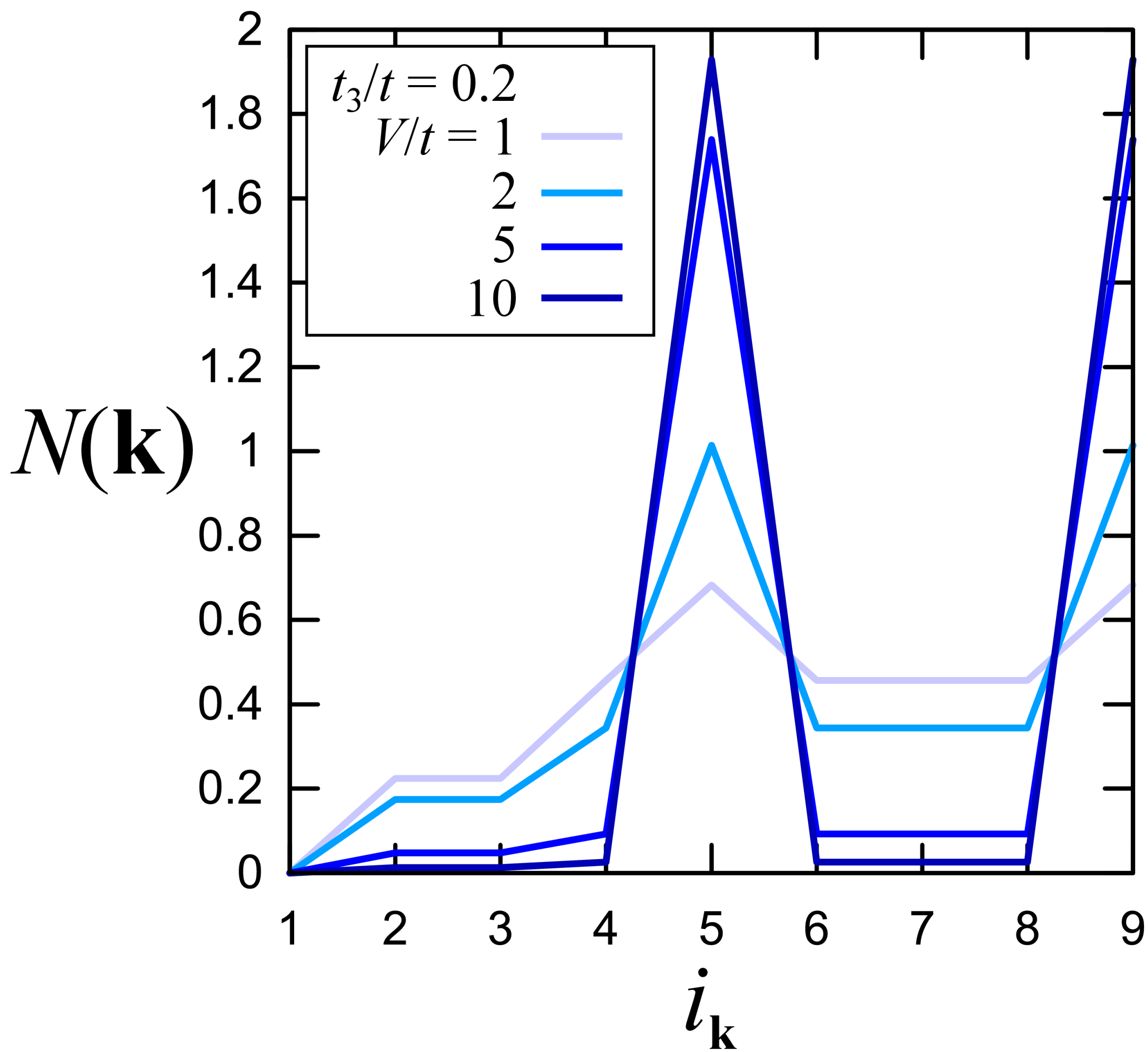
Phase diagram

Exact diagonalization, 3x6-site cluster, PBC

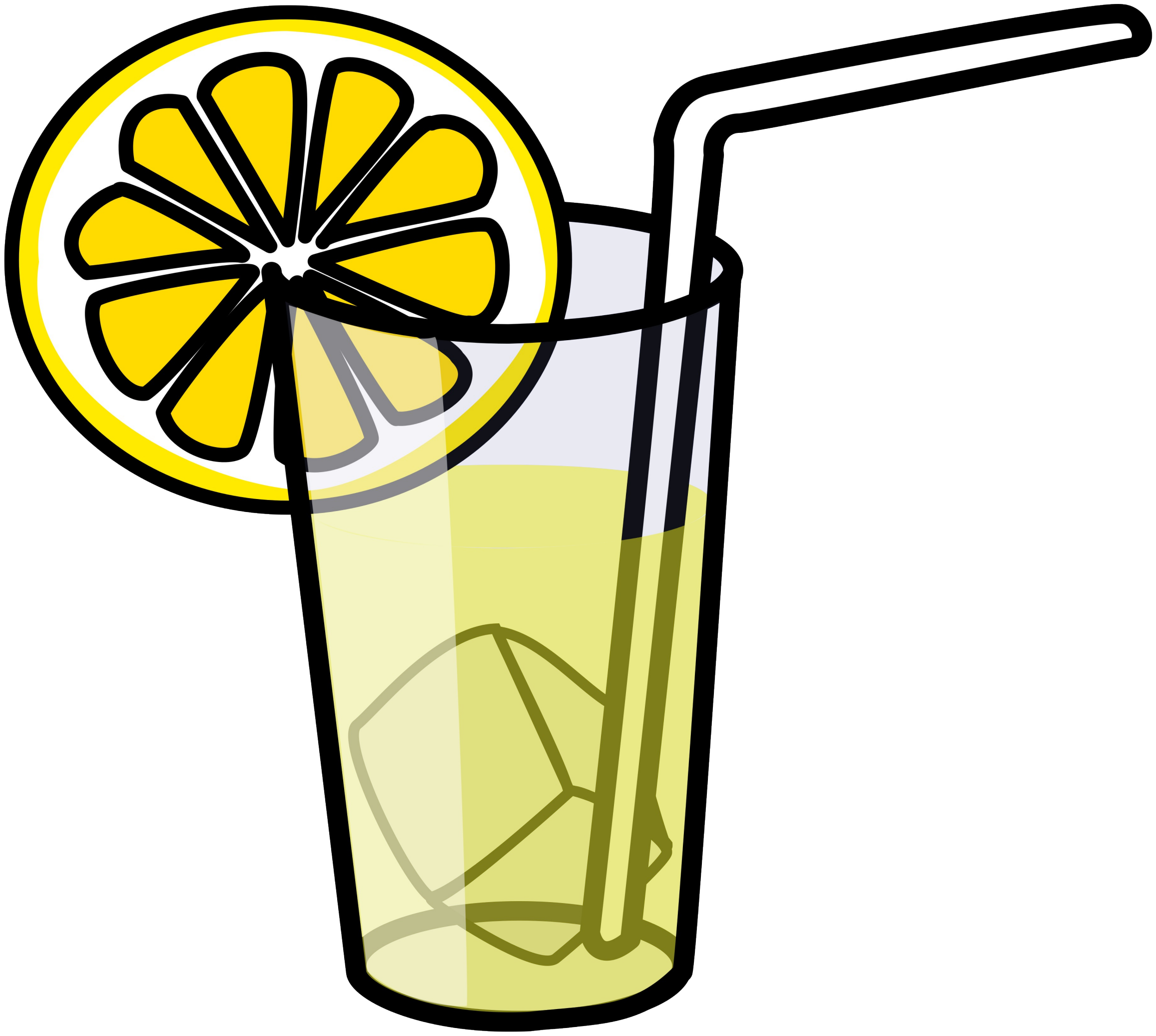


Charge-density wave

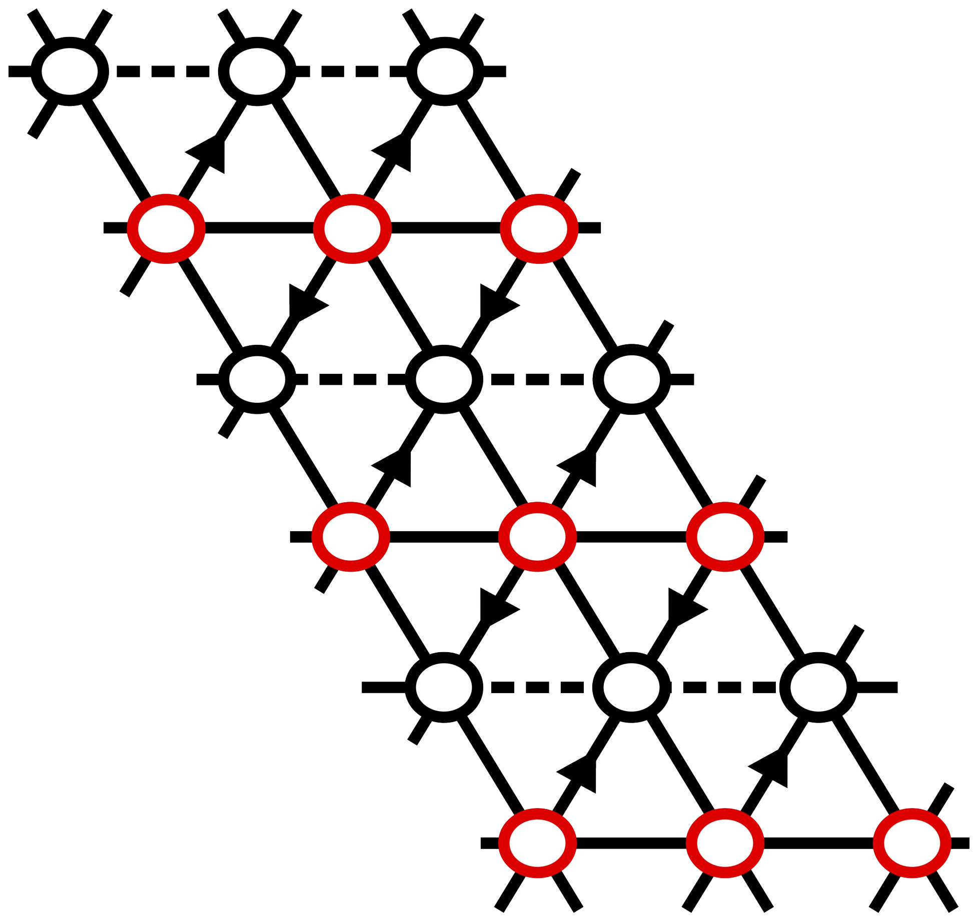
Static charge-structure factor



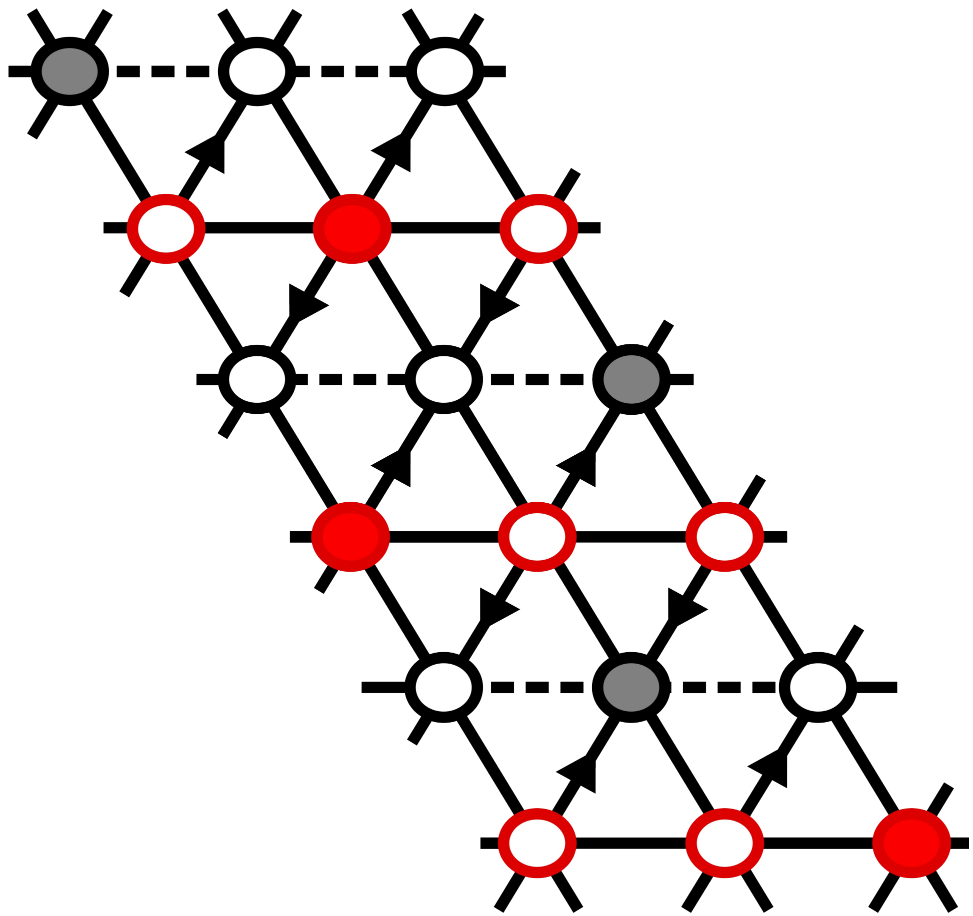
IFW



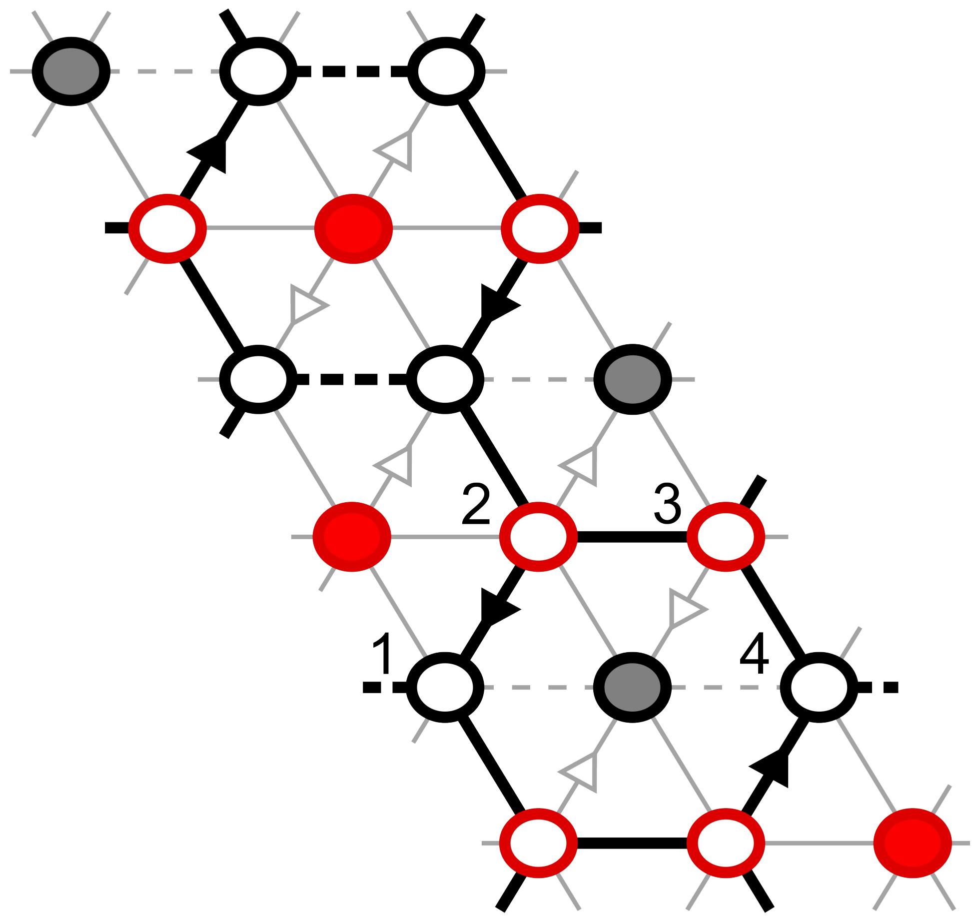
Topological & Landau order



Topological & Landau order

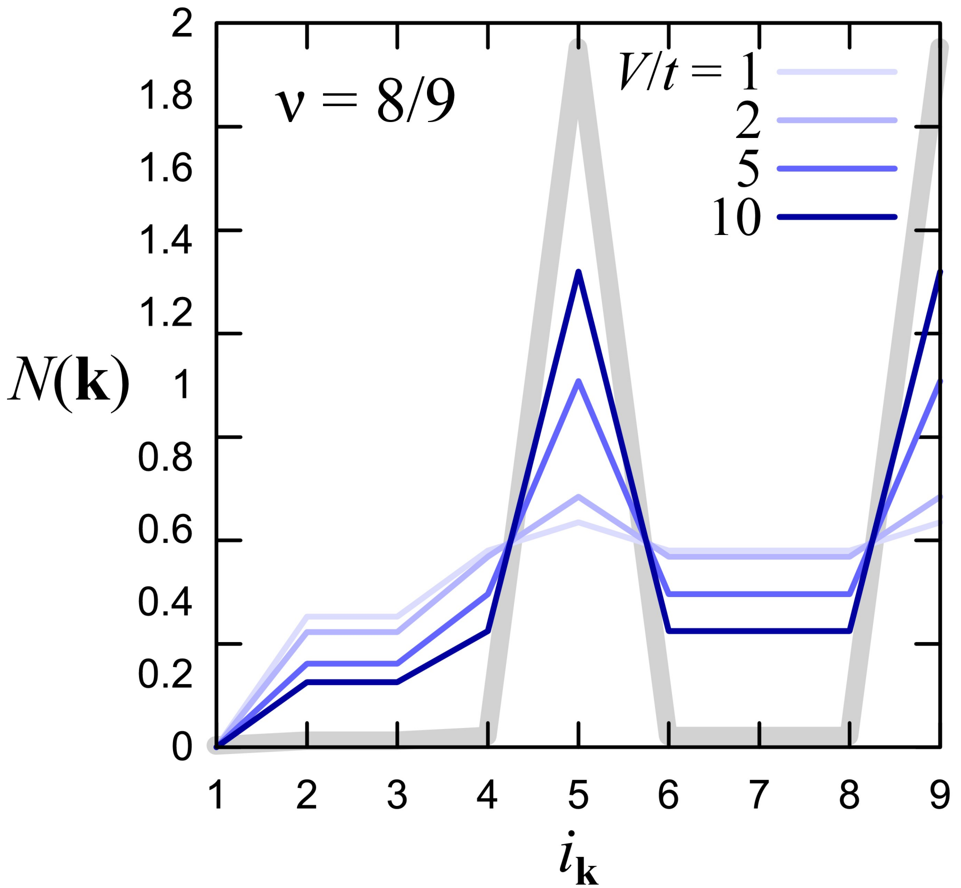


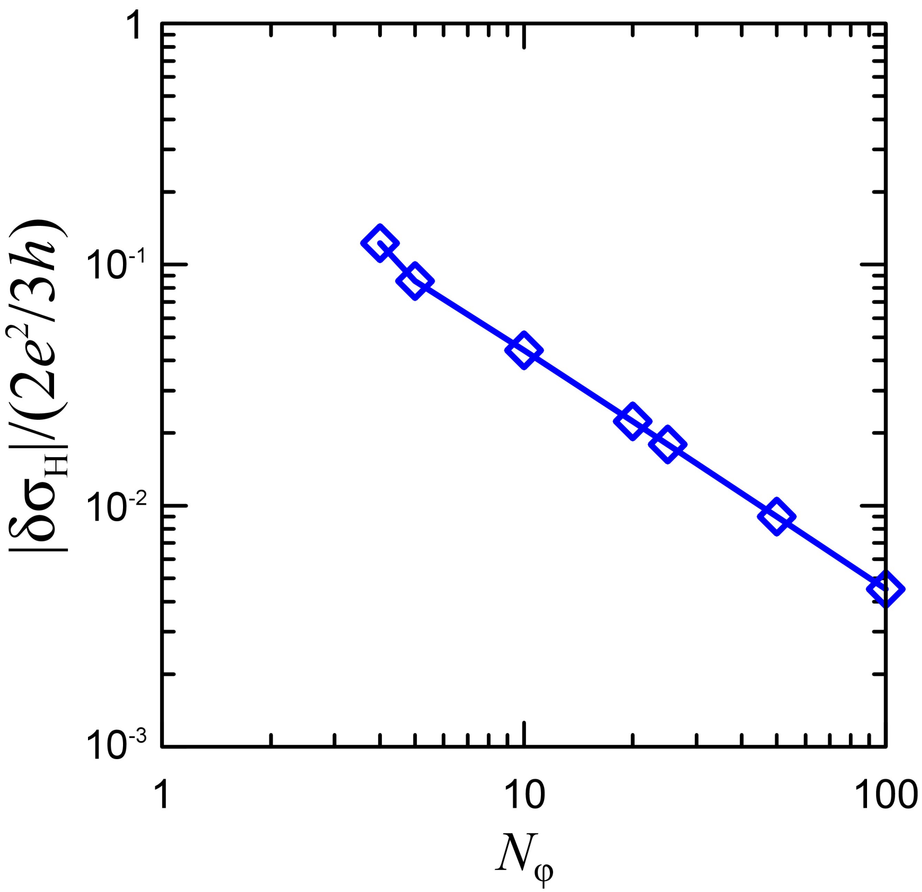
Topological & Landau order



Similar to pinball liquid → Hotta & Furukawa, PRB **74**, 193107 (2006)

Topological pinball liquid





→ Charge order-induced topological order

Conclusions

- FCI states for **arbitrarily strong repulsion...**

- ... going **beyond** traditional FQH physics (**FCI ≠ FQHE**)

  J. Venderbos, S. Kourtis, J. ven den Brink, and M. Daghofer, Phys. Rev. Lett. **108**, 126405

  S. Kourtis, J. Venderbos, and M. Daghofer, Phys. Rev. B **86**, 235118

  S. Kourtis, T. Neupert, C. Chamon & C. Mudry, Phys. Rev. Lett. **112**, 126806

- **combined** topological & Landau order

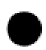
  (potential for topological states from interactions in trivial bands)

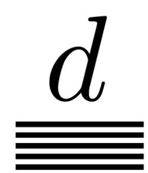
  S. Kourtis & M. Daghofer, arXiv:1305.6948 + work in progress...

CI on triangular lattice of t_{2g} electrons

TM ion

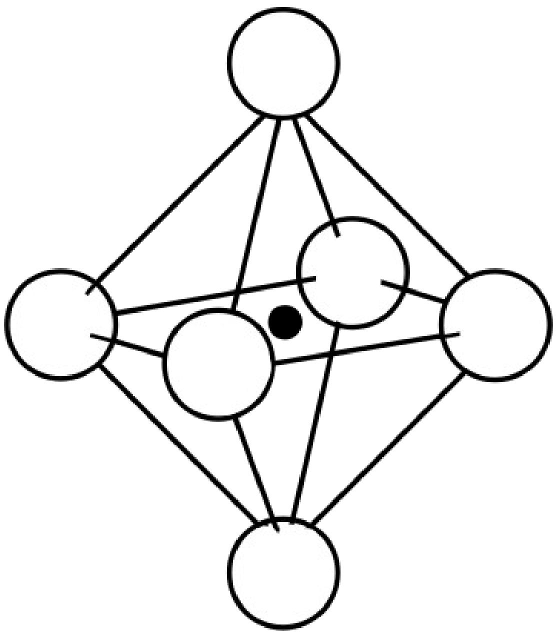
Partially occupied d-shell



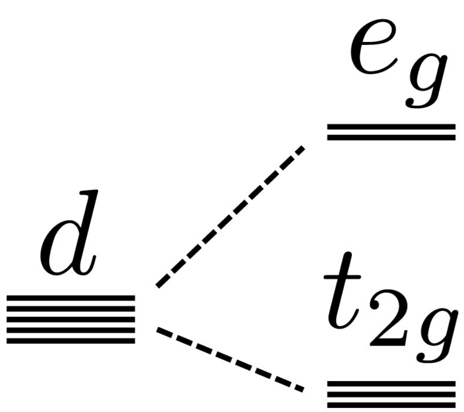


CI on triangular lattice of t_{2g} electrons

TM oxide

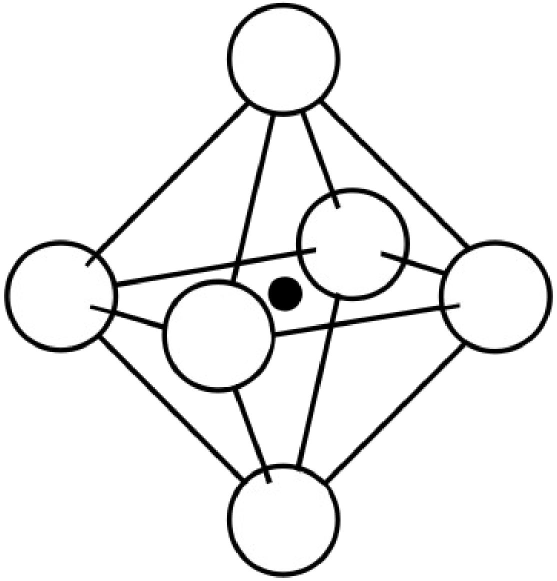


Symmetry lowering

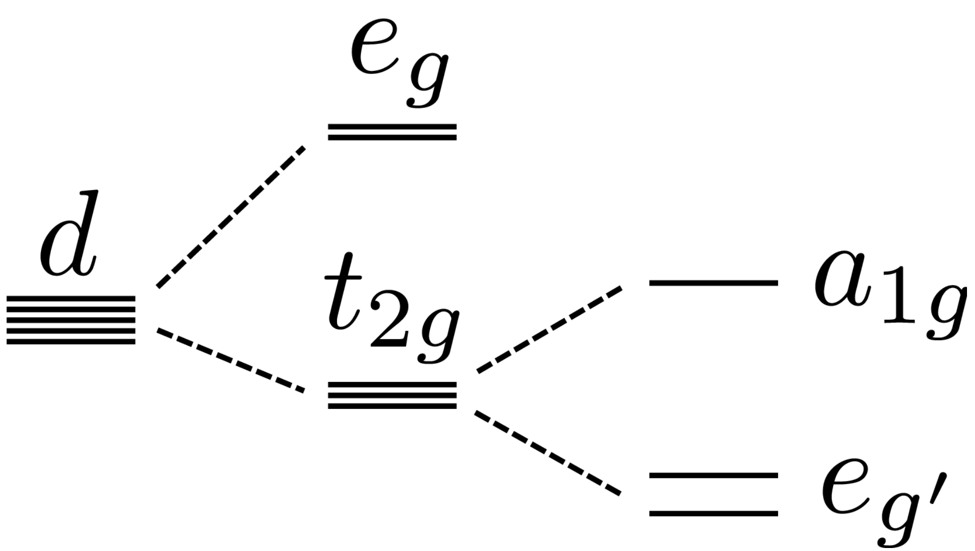


CI on triangular lattice of t_{2g} electrons

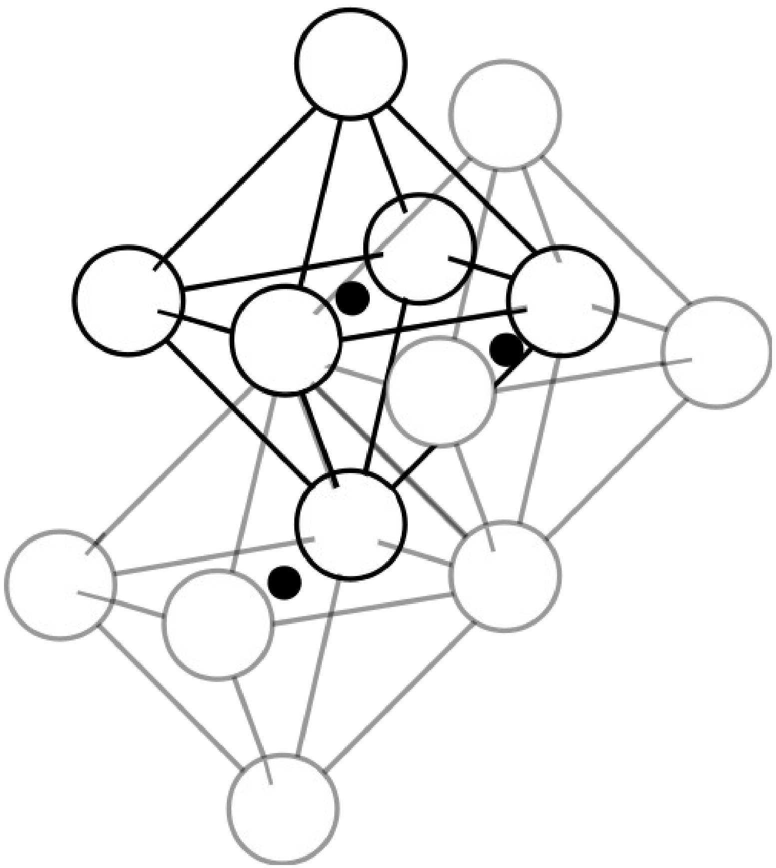
Crystal-field distortion

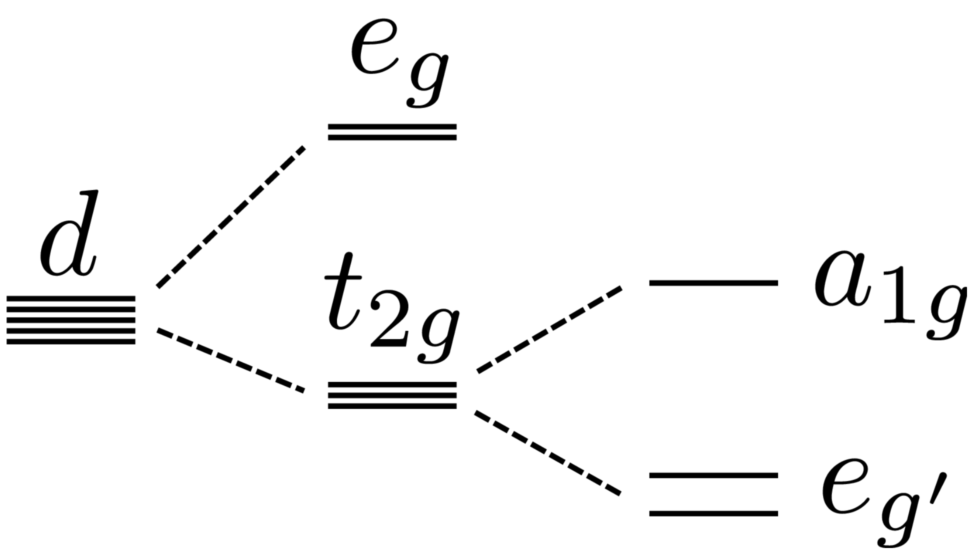


Levels split further

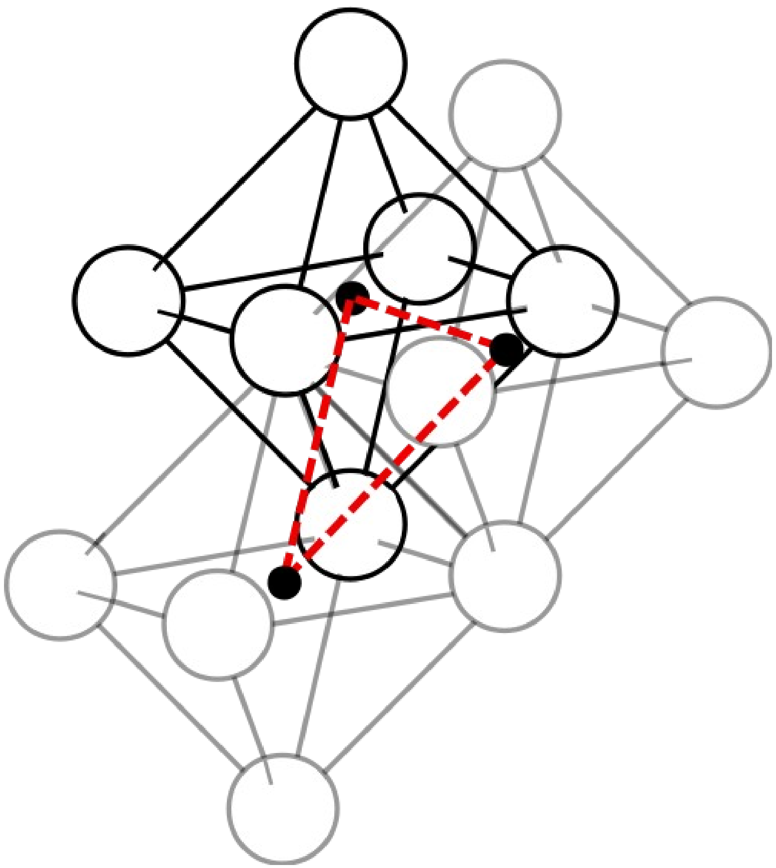


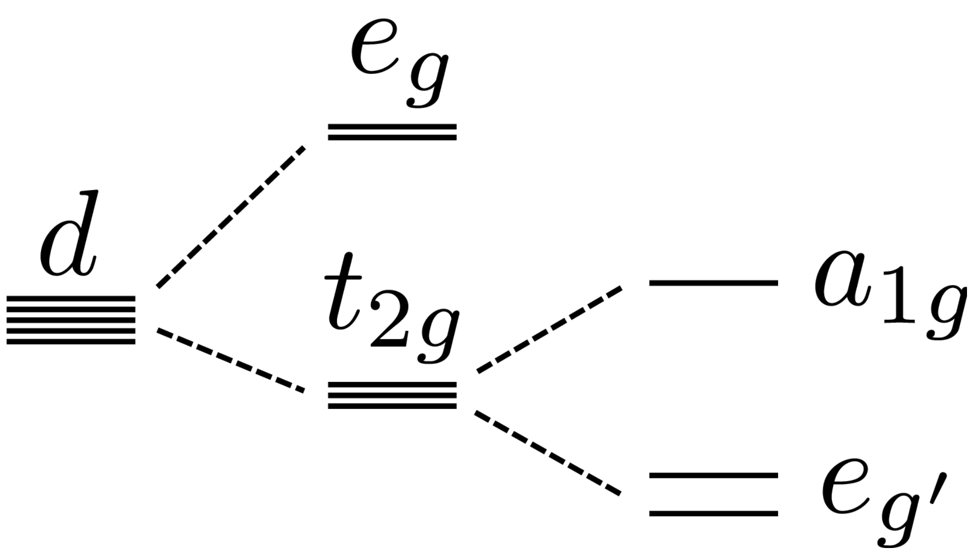
CI on triangular lattice of t_{2g} electrons





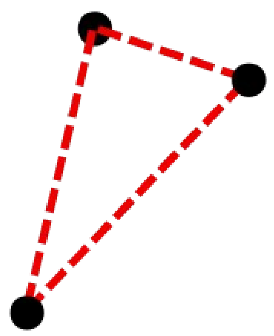
CI on triangular lattice of t_{2g} electrons



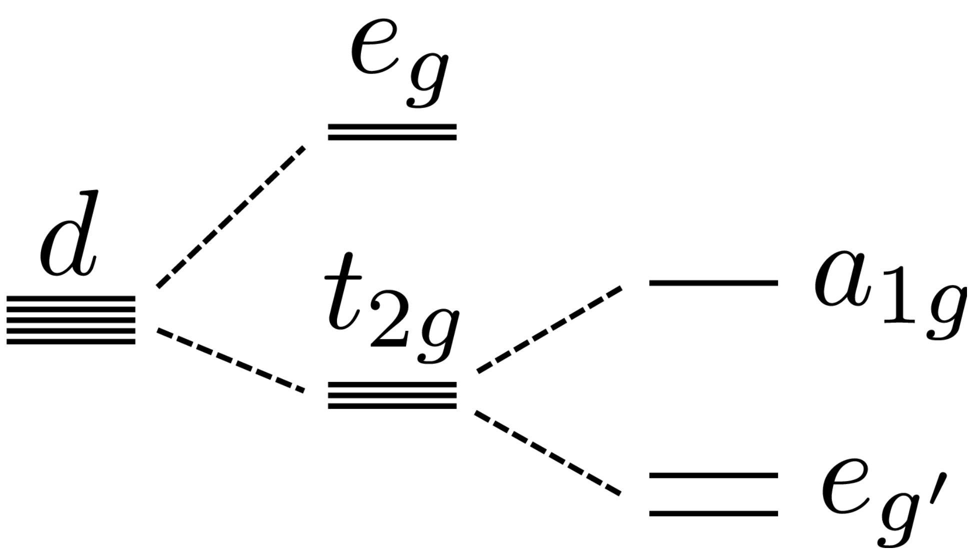


CI on triangular lattice of t_{2g} electrons

Triangular lattice

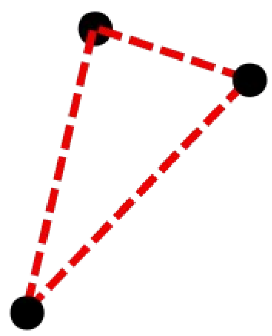


3 orbitals per site



CI on triangular lattice of t_{2g} electrons

Triangular lattice



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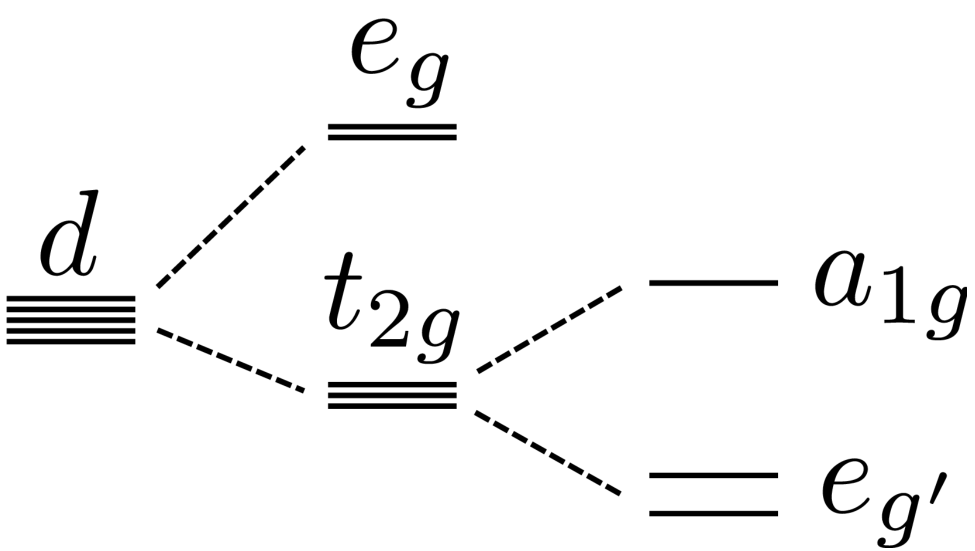
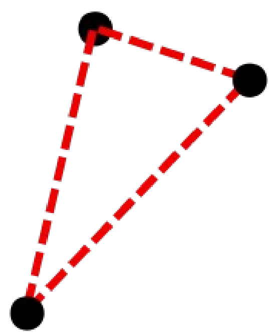


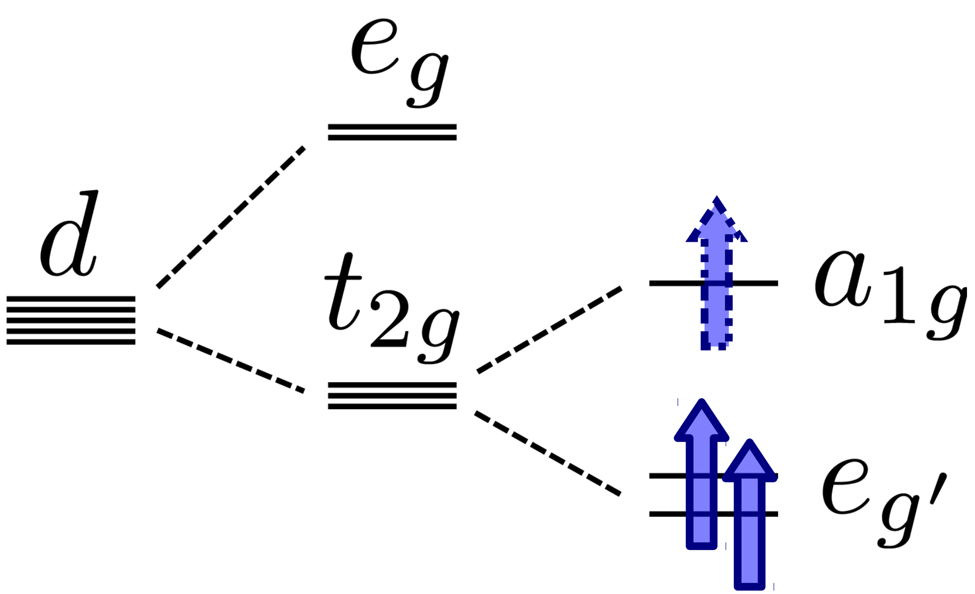
+ on-site Coulomb repulsion
+ Hund's rule coupling
+ $n = 2.5\ e^{-}/\mathrm{site}$

CI on triangular lattice of t_{2g} electrons

Triangular lattice



3 orbitals per site



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CI on triangular lattice of t_{2g} electrons

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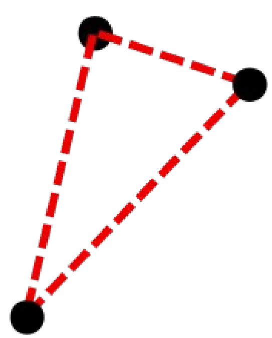
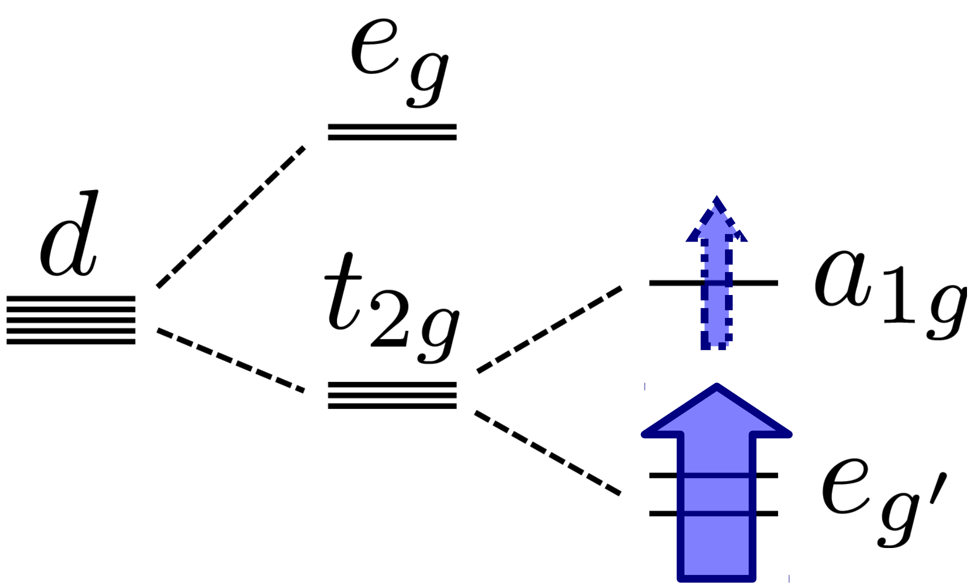


3 orbitals per site



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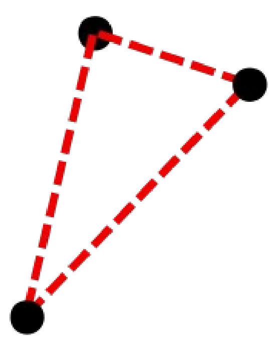
CI on triangular lattice of t_{2g} electrons

Triangular lattice

Kondo-lattice model



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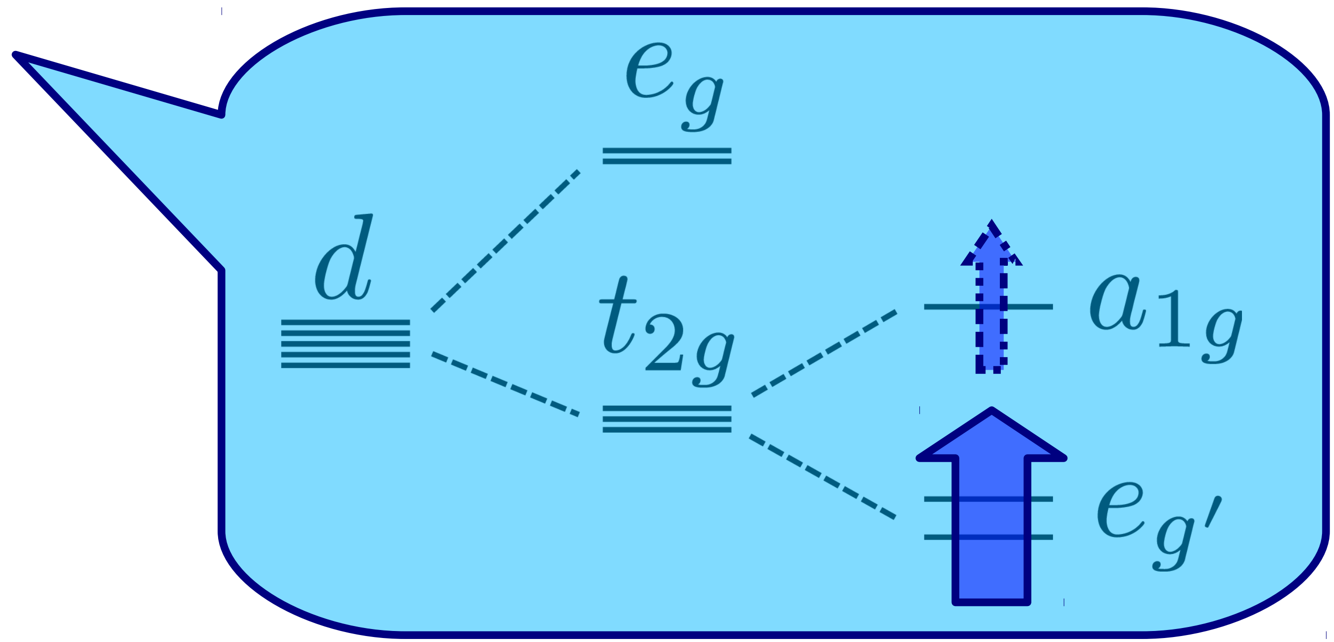

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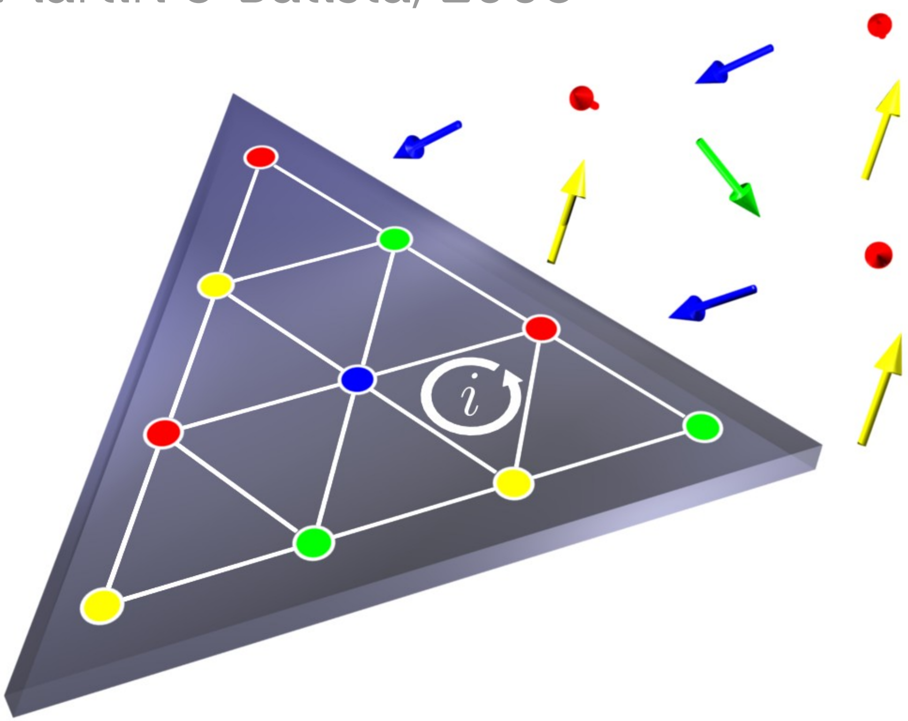
CI on triangular lattice of t_{2g} electrons

Triangular lattice

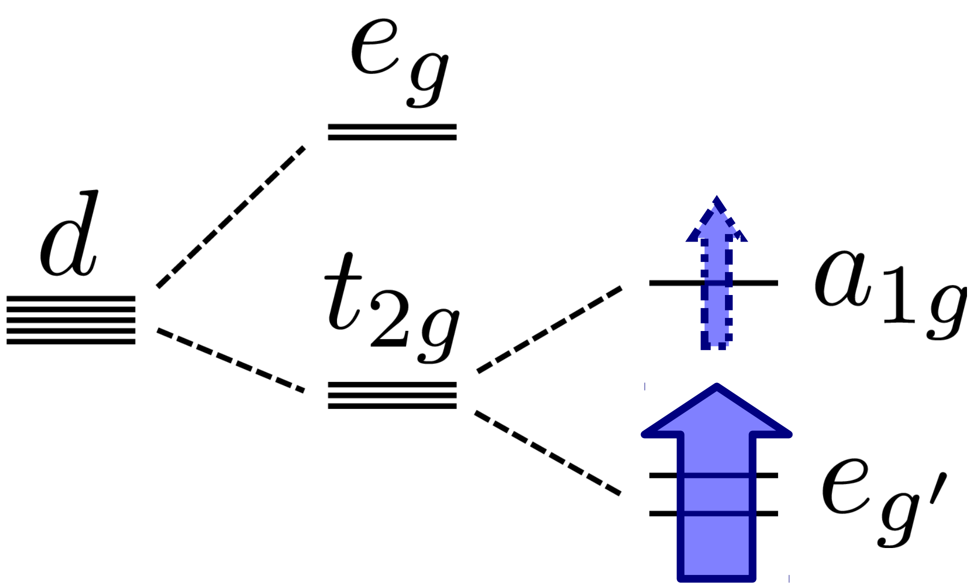
Kondo-lattice model

→ chiral spin pattern

Martin & Batista, 2008



3 orbitals per site



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