# TOPMAT 2018

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MPI - PKS Dresden

**Part I**

# New phase transitions of Composite Fermions

**Part II**

# Bosonization and shear sound in 2D Fermi liquids

# New phase transitions of Composite Fermions


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- Phase transition between Pfaffian and composite fermi liquid in bilayer graphene by turning magnetic field.
- Stoner transition of composite fermi liquids in AlAs (arXiv: 1802.02167).

# Zoo of fractionalized liquids

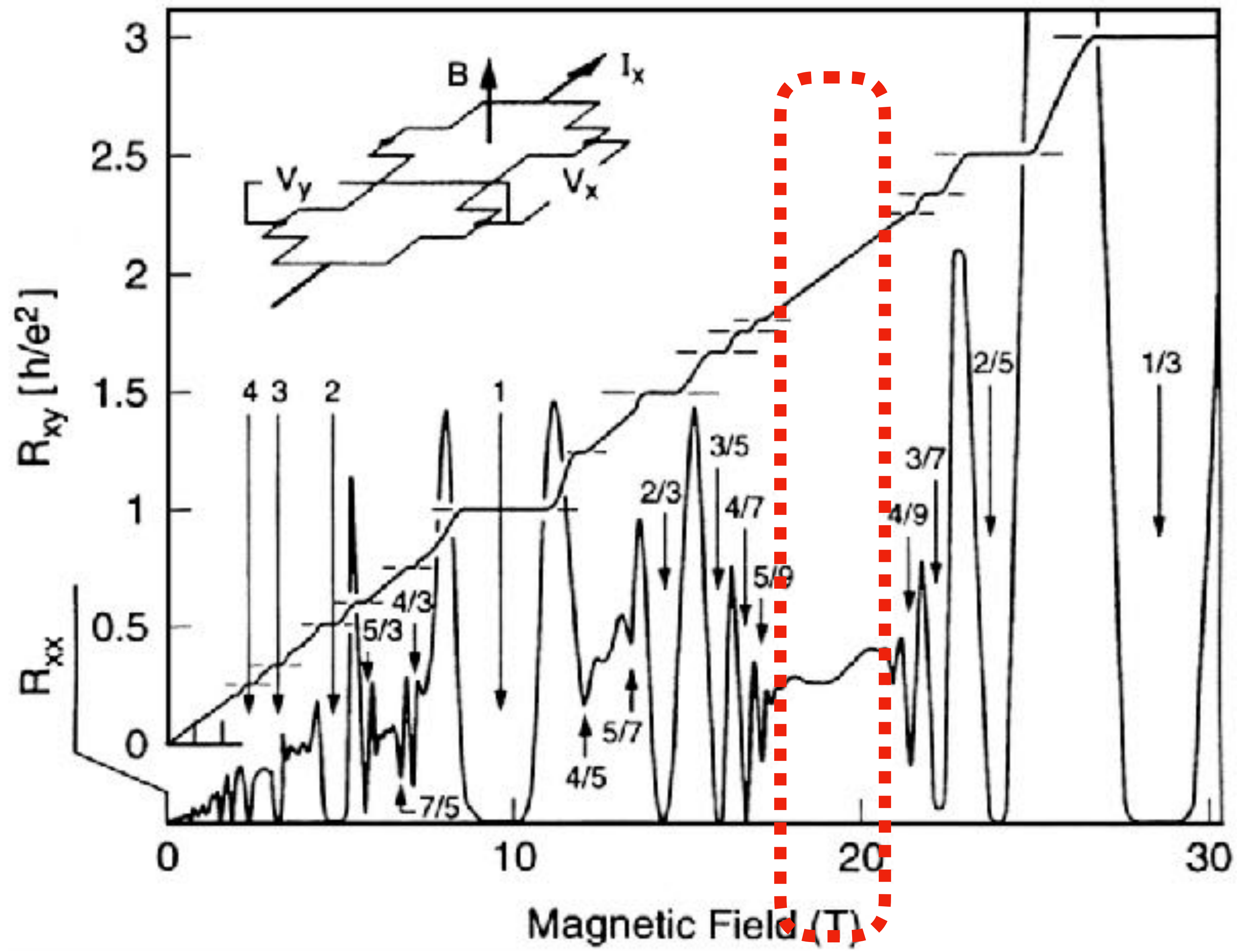
**A gift from nature:**

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

$$\sigma_{xx} = 0$$

**Any phase of matter with fractional $\nu$ must have fractionalized excitations**

**Gapless phases don't have quantised $\sigma_{xy}$**




$$\nu = \frac{1}{2}$$

**We believe this is a gapless fractionalized phase of matter:**

Composite Fermi Liquid

# The composite Fermi liquid

**Consider spin-full electrons at** $\nu = \frac{1}{2}$

**Slave-boson**

Spinful
neutral fermion
↓

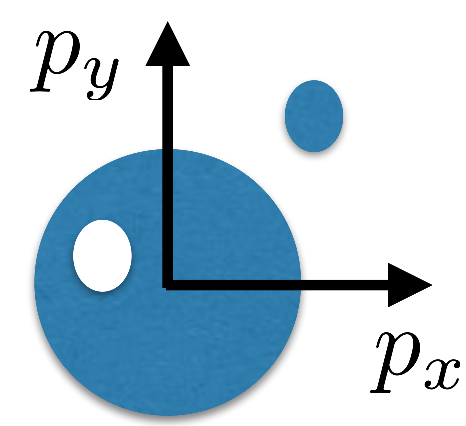
Electron ⟶ $c^\dagger_{\sigma r} = f^\dagger_{\sigma r} b^\dagger_r$ ⟵ Spinless
charged boson

**Boson forms Laughlin state:**

$$\nu_b = \nu_e = \frac{1}{2}$$

$$\Psi_b = \prod_{i<j} (z_i - z_j)^2 e^{-\frac{|z_i|^2}{4l^2}}$$

**Fermion forms fermi sea:**




**composite fermion fermi surface**

# The composite Fermi liquid

**Consider spin-full electrons at** $\nu = \frac{1}{2}$

**Slave-boson**

Spinfull neutral fermion

Electron $\longrightarrow$ $c^\dagger_{\sigma r} = f^\dagger_{\sigma r} b^\dagger_r$ $\longleftarrow$ Spinless charged boson

$$\nu_b = \nu_e = \frac{1}{2}$$

| **State of b** | **Mott - CDW** | **Laughlin state** |
|---|---|---|
| **Phase of electrons** | **U(1) spinon Fermi surface** | **Composite Fermi liquid** |
| **Name of f** | **Spinon** | **Composite fermion** |

# Wave function of Composite Fermi Liquid

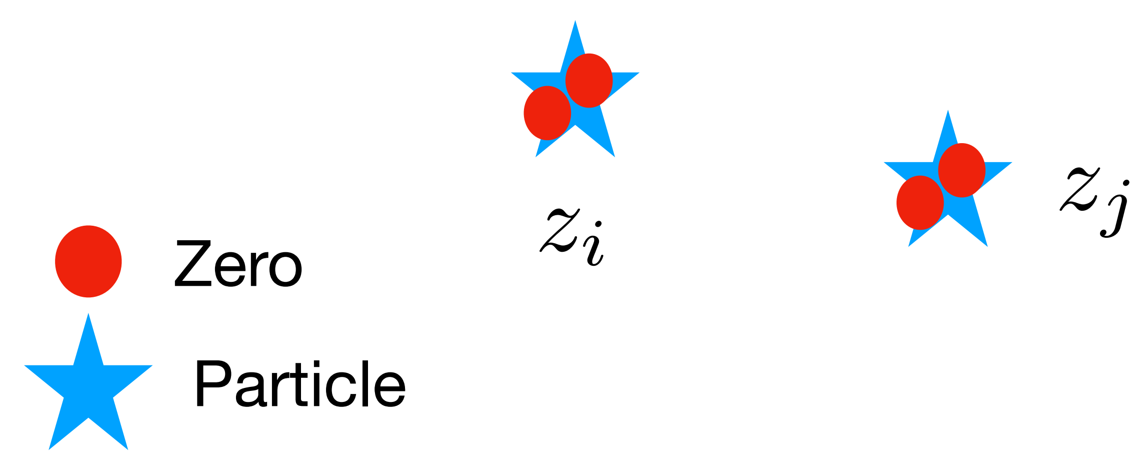
## The key to quantum Hall energetics

How to make particles stay as far way from each other as possible within a Landau level at filling $\nu$:

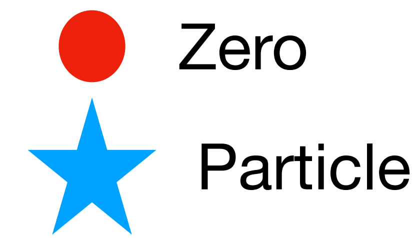
$$\Psi = \prod_{i<j} (z_i - z_j)^{\frac{1}{\nu}} \qquad\qquad z = x + iy$$

We get the bosonic Laughlin state at $\nu = \frac{1}{2}$

$$\Phi_{bose} = \prod_{i<j} (z_i - z_j)^2 e^{-\frac{|z_i|^2}{4l^2}}$$



# Wave function of Composite Fermi Liquid

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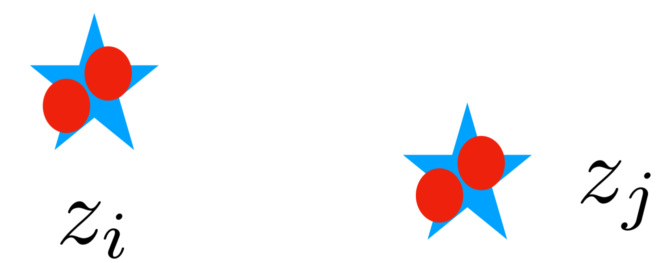
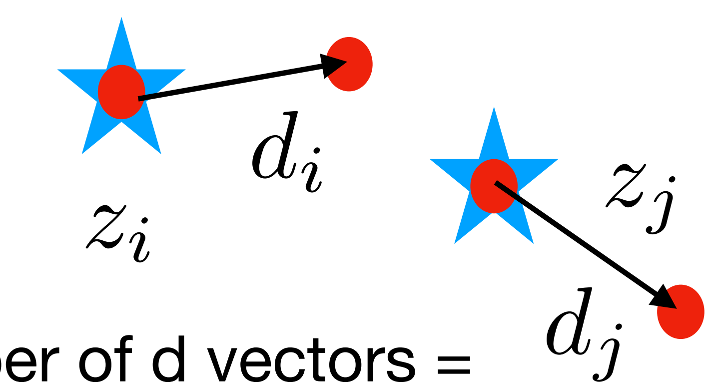
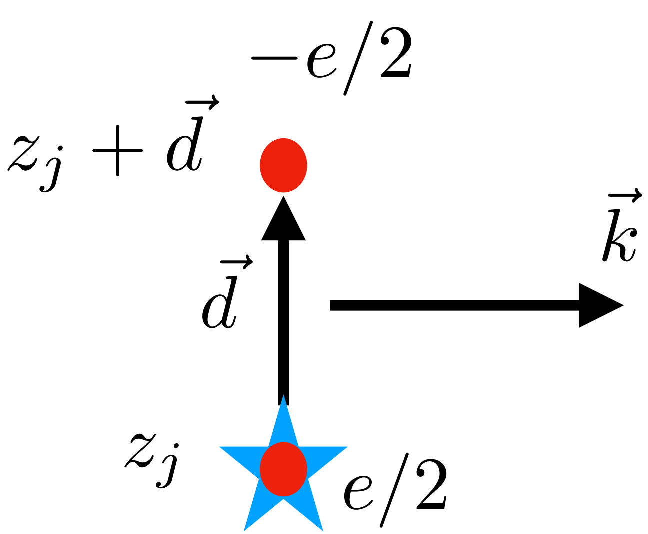
$$\Phi_{bose} = \prod_{i<j} (z_i - z_j)^2 e^{-\frac{|z_i|^2}{4l^2}}$$




To get fermions: displace the zeroes as little as possible to be able to anti-symmetrize

$$\Psi_{fermi} = \mathcal{A}\left( \prod_{i<j} (z_i - z_j)(z_i - z_j - d_i - d_j) e^{-\frac{|z_i|^2}{4l^2}} \right)$$




$$\mathbf{d}_i = -l^2 \hat{z} \times \mathbf{k}_i$$

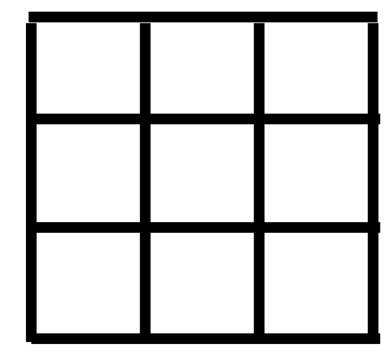
Number of d vectors =
Number of particles

N. Read, Semiconductor Science and Technology, 9, 1859 (1994).
J. K. Jain, Phys. Rev. Lett. 63, 199 (1989)
E. Rezayi and N. Read, Phys. Rev. Lett. 72, 900 (1994).
C. Wang and T. Senthil, Phys. Rev. B 94, 245107 (2016)

# Composite fermions on Torus

Single particle translations form a discrete lattice on a finite size torus

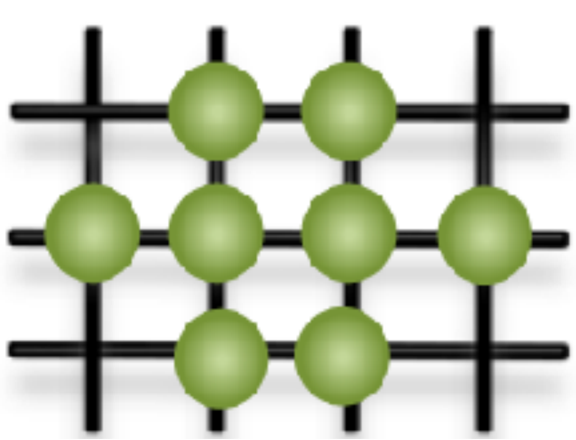
$$\mathbf{d} \in \frac{m_1\mathbf{L_1} + m_2\mathbf{L_2}}{N_\phi},\ m_{1,2} \in \mathbb{Z}\mathrm{mod}(N_\phi)$$



$\hat{t}_i(\mathbf{d})$ Translation of particle i by vector **d**

For any given set of N distinct $\{\mathbf{d}_i\}$

We can construct a Composite Fermion trial wave-function



$$|\Psi_{\mathrm{CFL}}(\{\mathbf{d}_i\})\rangle = \det(\hat{t}_j(\mathbf{d}_i))|\Phi^{\mathrm{Bose}}_{1/2}\rangle$$

$$\mathbf{d}_i = -l^2\hat{z} \times \mathbf{k}_i$$

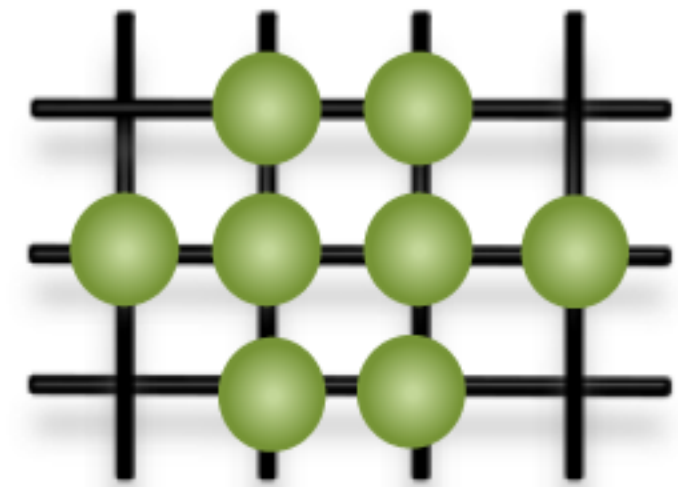
E. H. Rezayi and F. D. M. Haldane, Phys. Rev. Lett. **84**, 4685 (2000).

Shao, Kim, Haldane, & Rezayi, PRL (2015).

# Composite fermions on Torus

$$|\Psi_{\mathrm{CFL}}(\{\mathbf{d}_i\})\rangle = \det(\hat{t}_j(\mathbf{d}_i))|\Phi^{\mathrm{Bose}}_{1/2}\rangle, \ \mathbf{d}_i \equiv -l^2\hat{\mathbf{z}} \times \mathbf{k}_i$$

$$\mathbf{d} \in \frac{m_1\mathbf{L_1} + m_2\mathbf{L_2}}{N_\phi}, \ m_{1,2} \in \mathbb{Z}\mathrm{mod}(N_\phi)$$



Given a set of occupied states we can predict many body momenta

$$\mathbf{K} = \frac{\hat{\mathbf{z}}}{l^2} \times \sum_i \mathbf{d}_i = 2\pi\left(-\frac{\sum_i m_{2i}}{L_1}, \frac{\sum_i m_{1i}}{L_2}\right)$$

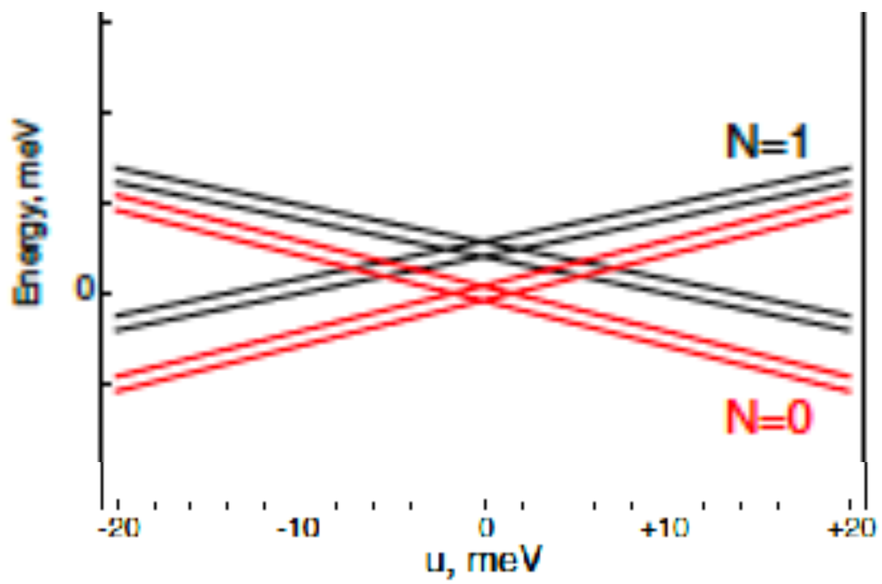
Composite fermion kinetic energy

$$E[\{\mathbf{k}_i\}] = E_0 + \frac{1}{N_e}\sum_{i<j}\epsilon(\mathbf{k}_i - \mathbf{k}_j)$$

$$\approx E_0 + \frac{1}{N_e}\sum_{i<j}\frac{|\mathbf{k}_i - \mathbf{k}_j|^2}{2m^*},$$

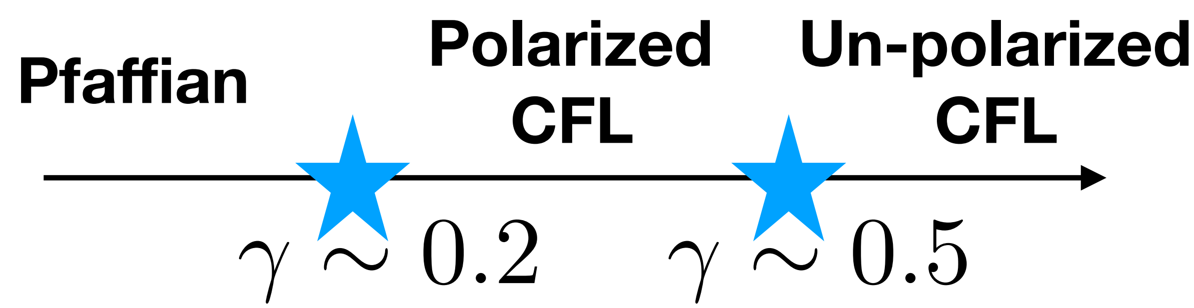
Shao, Kim, Haldane, & Rezayi, PRL (2015).

# A smoother transition between the Pfaffian and the CFL

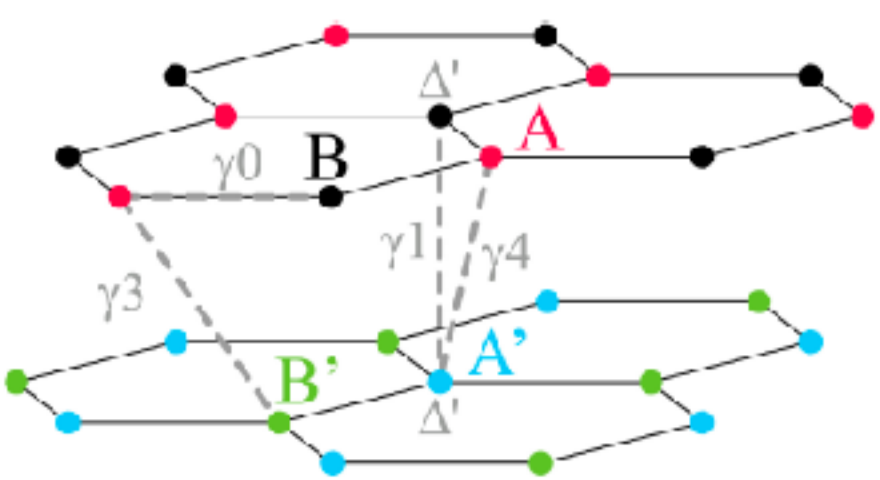



**Imagine 2 components continuously rotating from N=0 LL into a N=1LL**

$$|\gamma\rangle = \gamma|0,\uparrow\rangle + (1-\gamma)|1,\downarrow\rangle$$

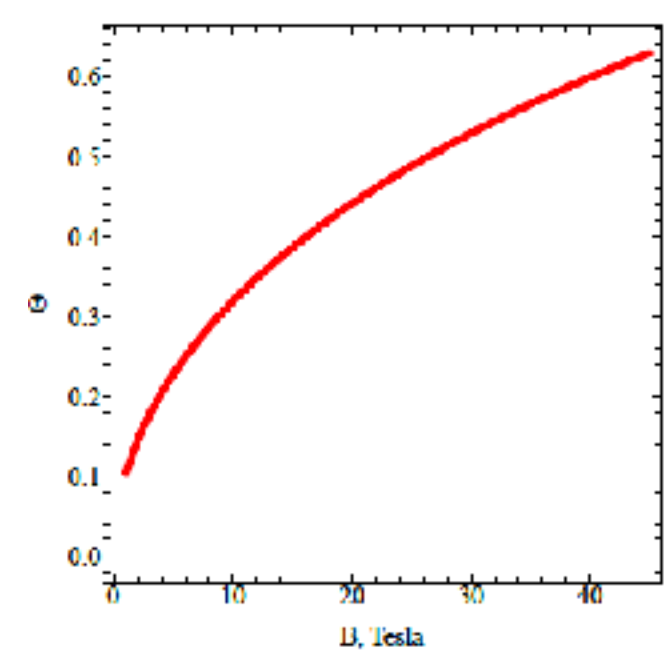



**In the N=1 LL of bilayer graphene one can achieve version of this:**



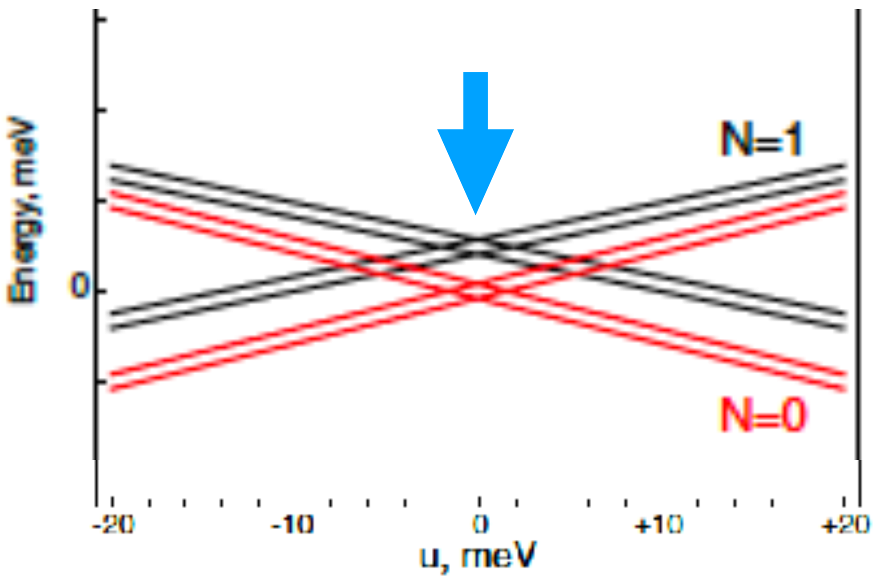

$$\psi_{1+} = \begin{pmatrix} \cos\Theta|1\rangle \\ 0 \\ \cos\Phi\sin\Theta|0\rangle \\ \sin\Phi\sin\Theta|0\rangle \end{pmatrix} \quad \begin{matrix} \textbf{A} \\ \textbf{B'} \\ \textbf{A'} \\ \textbf{B} \end{matrix}$$

$$\psi_{1-} = \begin{pmatrix} 0 \\ \cos\Theta|1\rangle \\ \sin\Phi\sin\Theta|0\rangle \\ \cos\Phi\sin\Theta|0\rangle \end{pmatrix}$$



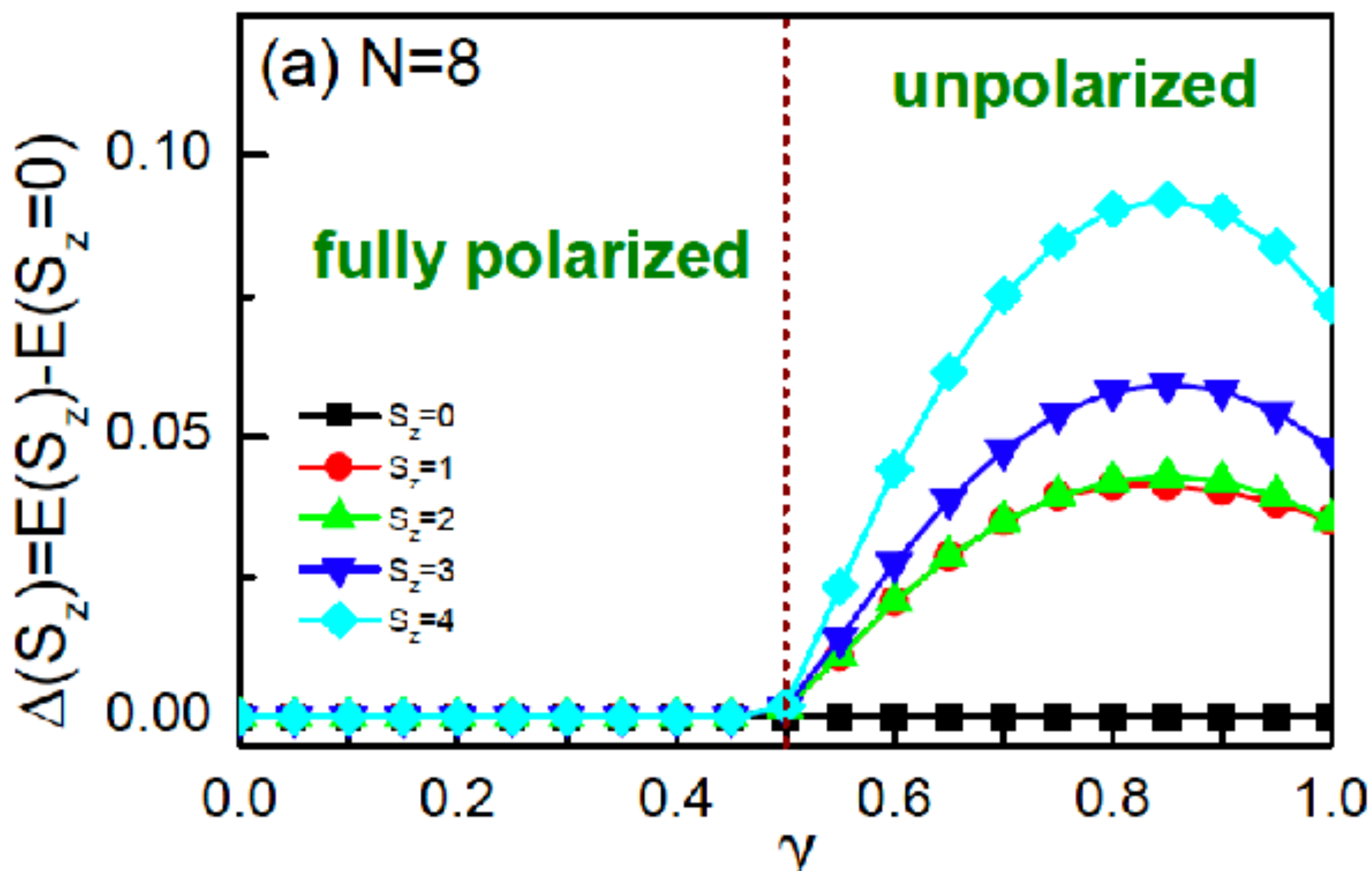
# SU(2) magnet to SU(2) singlet

**Consider SU(2) 2-component system:**



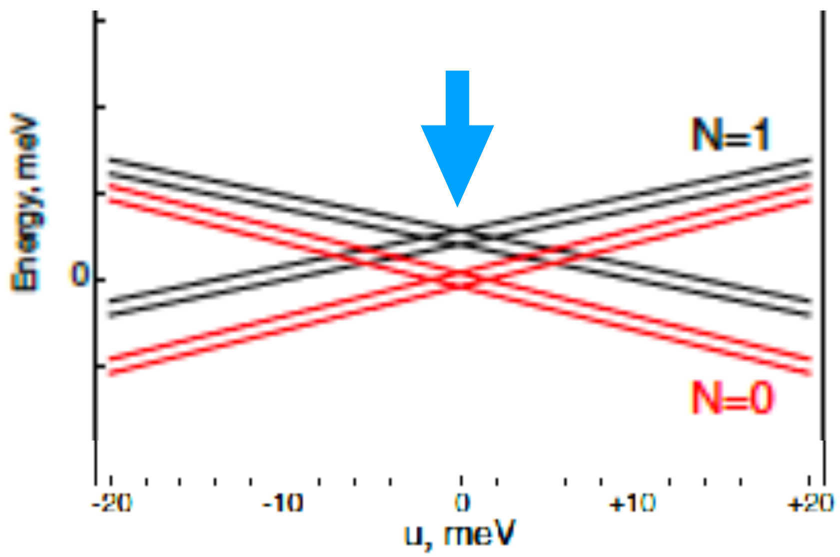

$$|\gamma\rangle = \gamma|0,\uparrow\rangle + (1-\gamma)|1,\downarrow\rangle$$

**ED Spectrum**
**Torus**



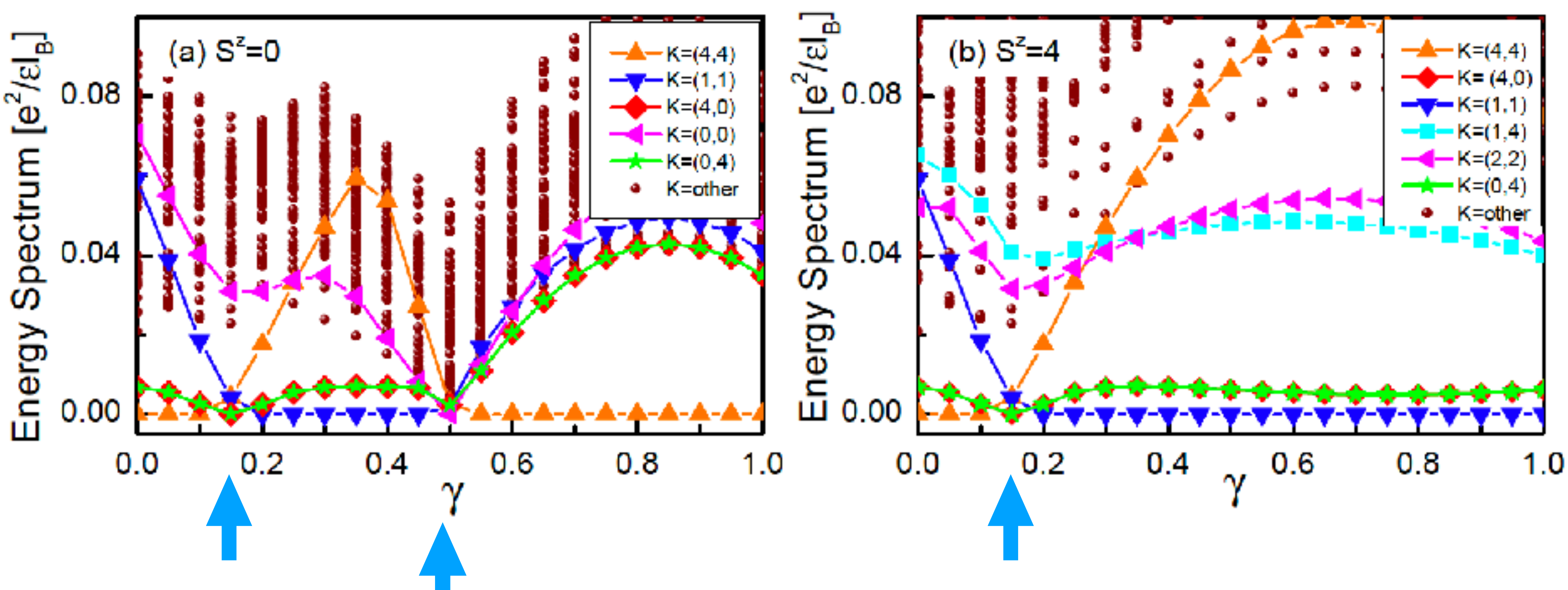
# Phase transition of polarized states

**Consider SU(2) 2-component system:**

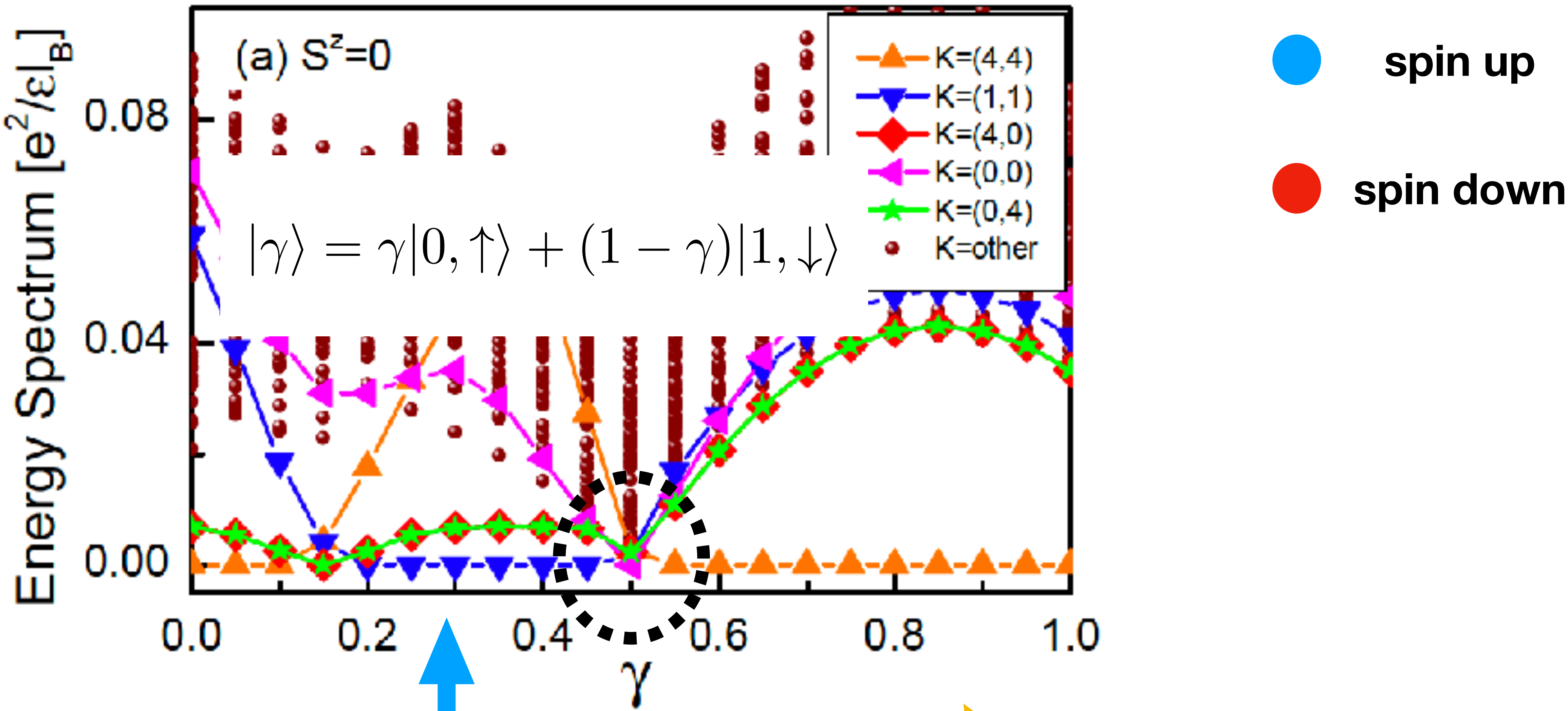



$$|\gamma\rangle = \gamma|0,\uparrow\rangle + (1-\gamma)|1,\downarrow\rangle$$

**ED Spectrum Torus**

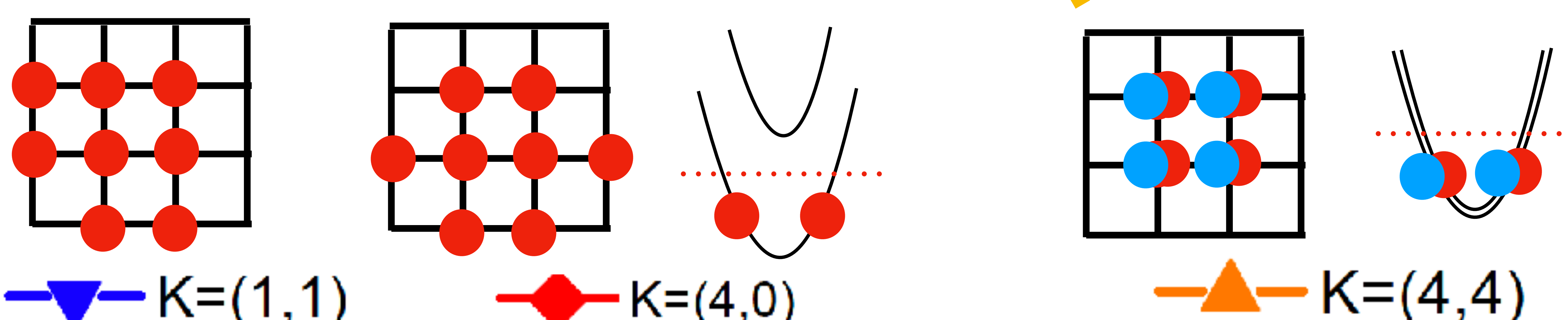


# Stoner transition of CFL states




$S^2 = S_z^{max}(S_z^{max}+1)$

$S^2 = 0$



# Pfaffian to CFL transition

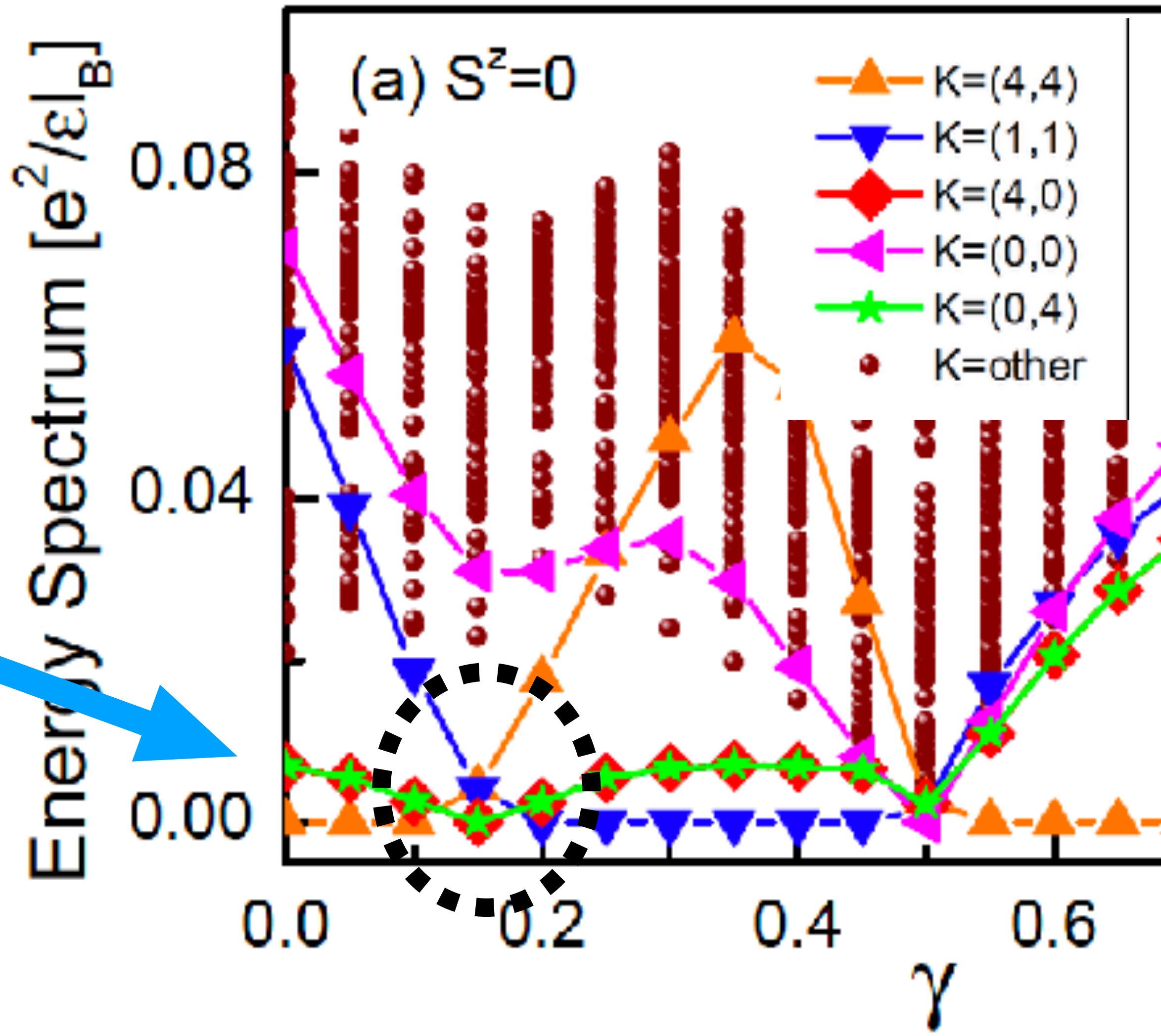
$$|\gamma\rangle = \gamma|0,\uparrow\rangle + (1-\gamma)|1,\downarrow\rangle$$

**3-fold (x 2) topological degeneracy of Moore-Read state**

K=(4,4) $(\pi, \pi)$

K=(4,0) $(\pi, 0)$

K=(0,4) $(0, \pi)$

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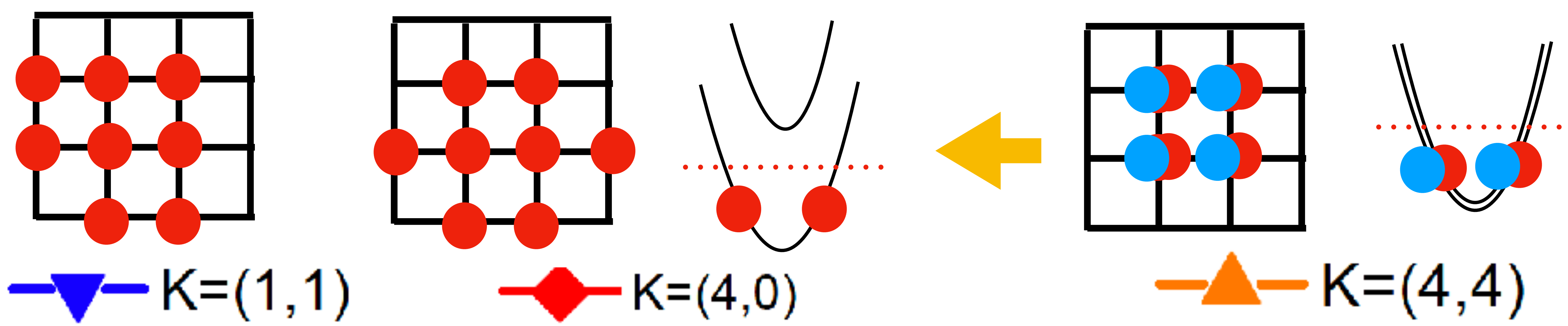
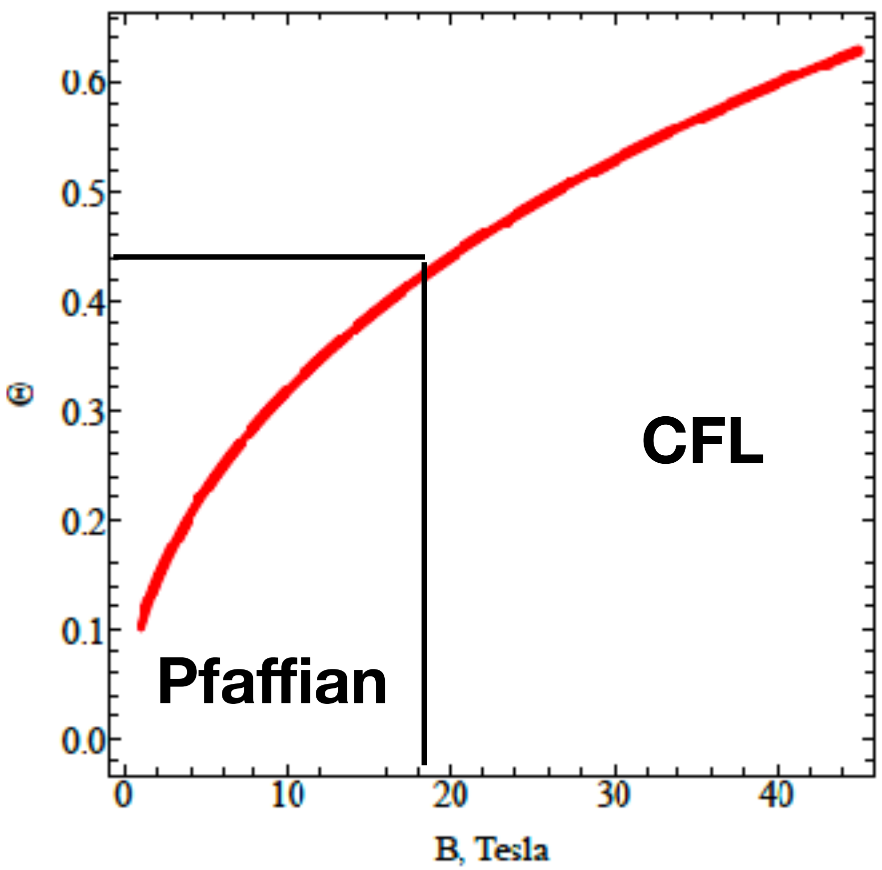
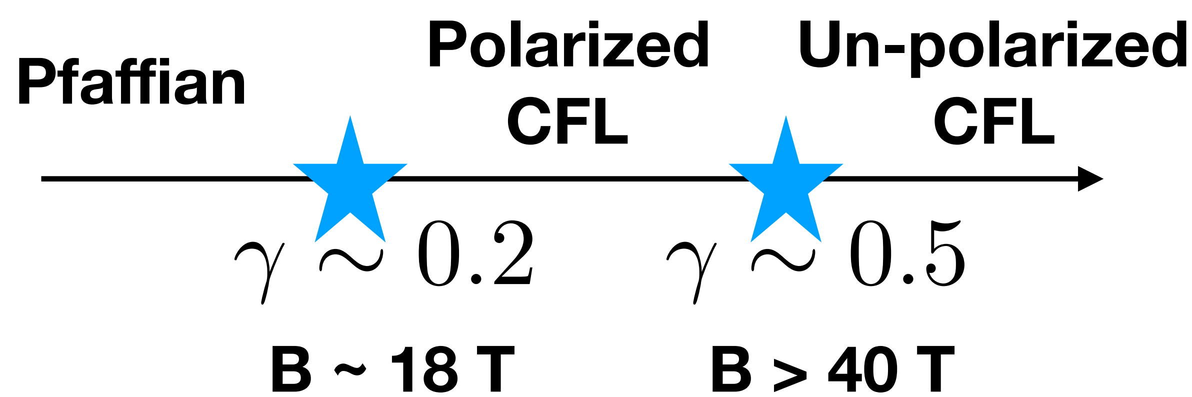


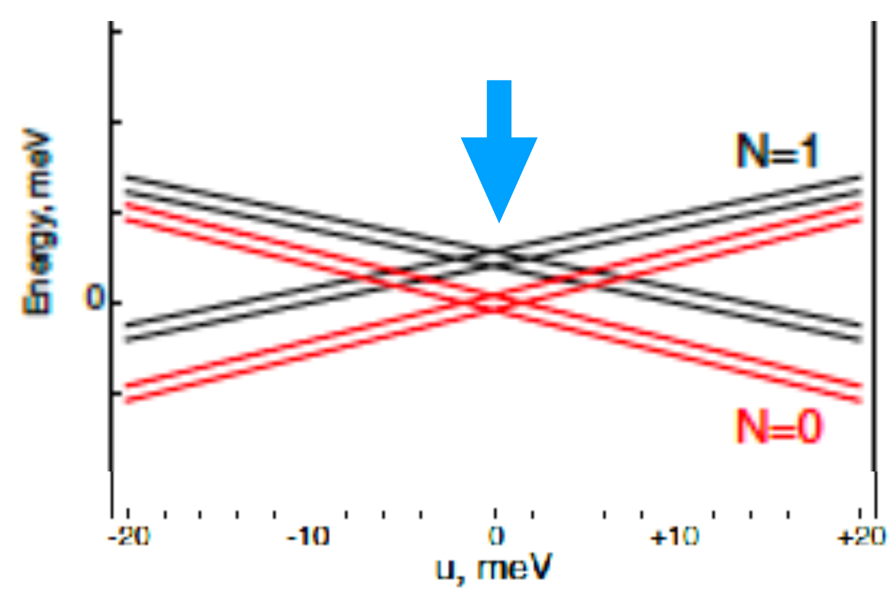
# Clean Pfaffian to CFL in bilayer graphene




**Continuously rotating the N=0 LL into a N=1LL with field**

$$|\gamma\rangle = \gamma|0,\uparrow\rangle + (1-\gamma)|1,\downarrow\rangle$$



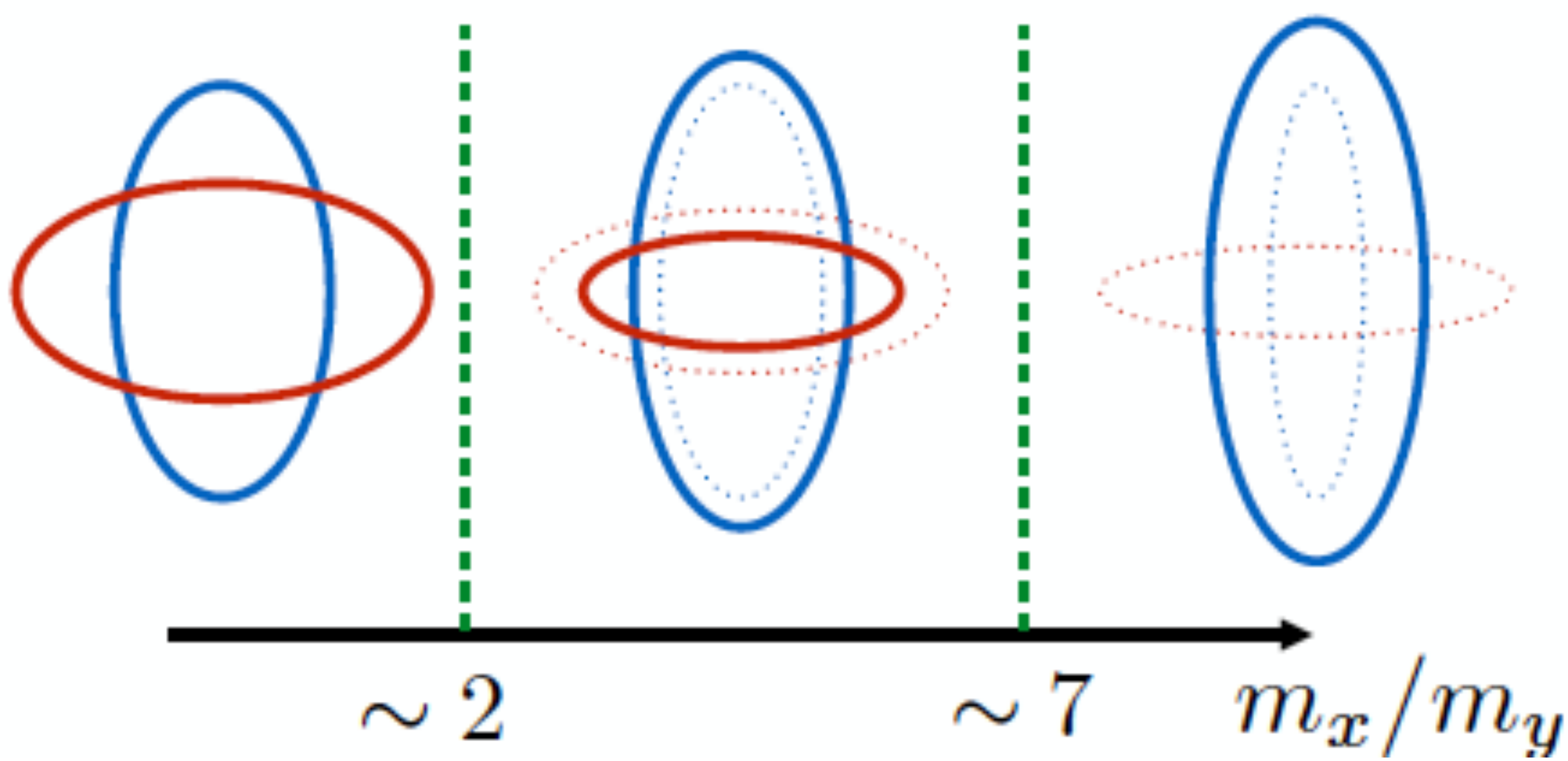




**It would be a Pfaffian with a twist**

**- SU(2) skyrmions and ferro-magnet coexisting with Pfaffian physics**

# Ising Stoner Instability of Composite Fermion Metal

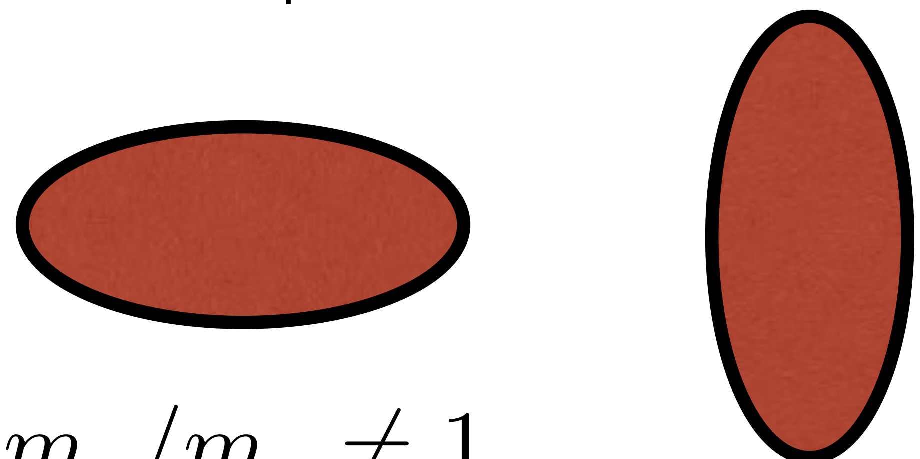
- Two components with rotated mass tensors rotated by $\pi/2$ undergo a an analogue of the Stoner transition:



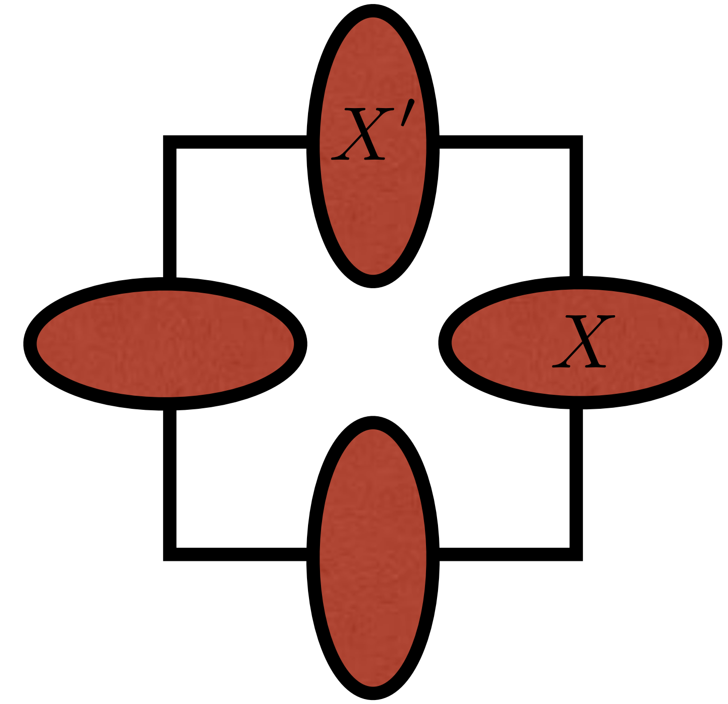

- Aluminum Arsenide $m_x/m_y \approx 5$

# The Hamiltonian of our study

Aluminum Arsenide: Two valleys
with anisotropic mass

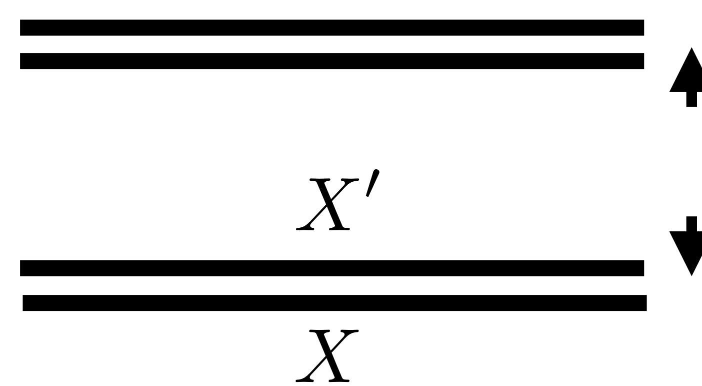


$m_x/m_y \neq 1$




$$\mathbf{p} \to \mathbf{p} + \mathbf{A}(\mathbf{r})$$

$N = 0LL$




$$\omega_c = \frac{B}{\sqrt{m_x m_y}}$$

Landau level projection endows electrons with a "shape"

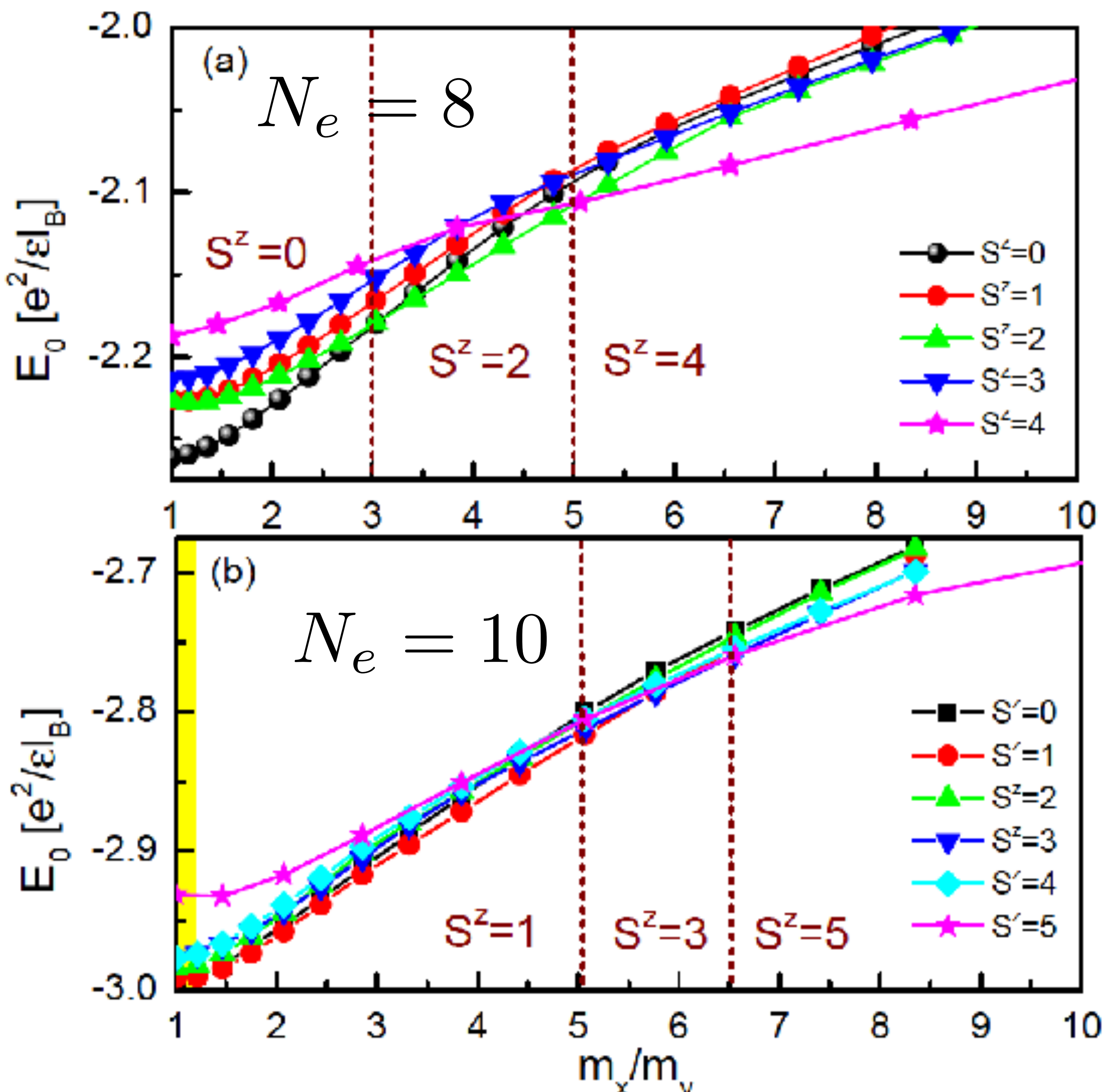
LL projection

$$v_0(q) = \frac{2\pi e^2}{\epsilon q} \quad \longrightarrow \quad v_{eff}(q) = \frac{2\pi e^2}{\epsilon q} F_i(q) F_j^*(q)$$

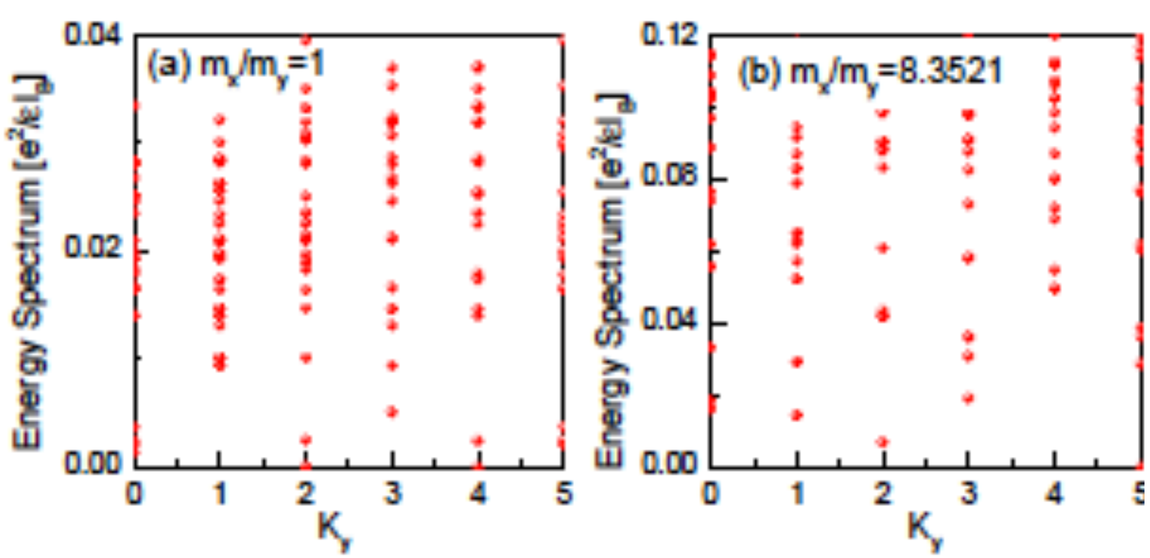
# Ground state polarization

$$S^z = \frac{N_1 - N_2}{2}$$

Exact diagonalization on torus



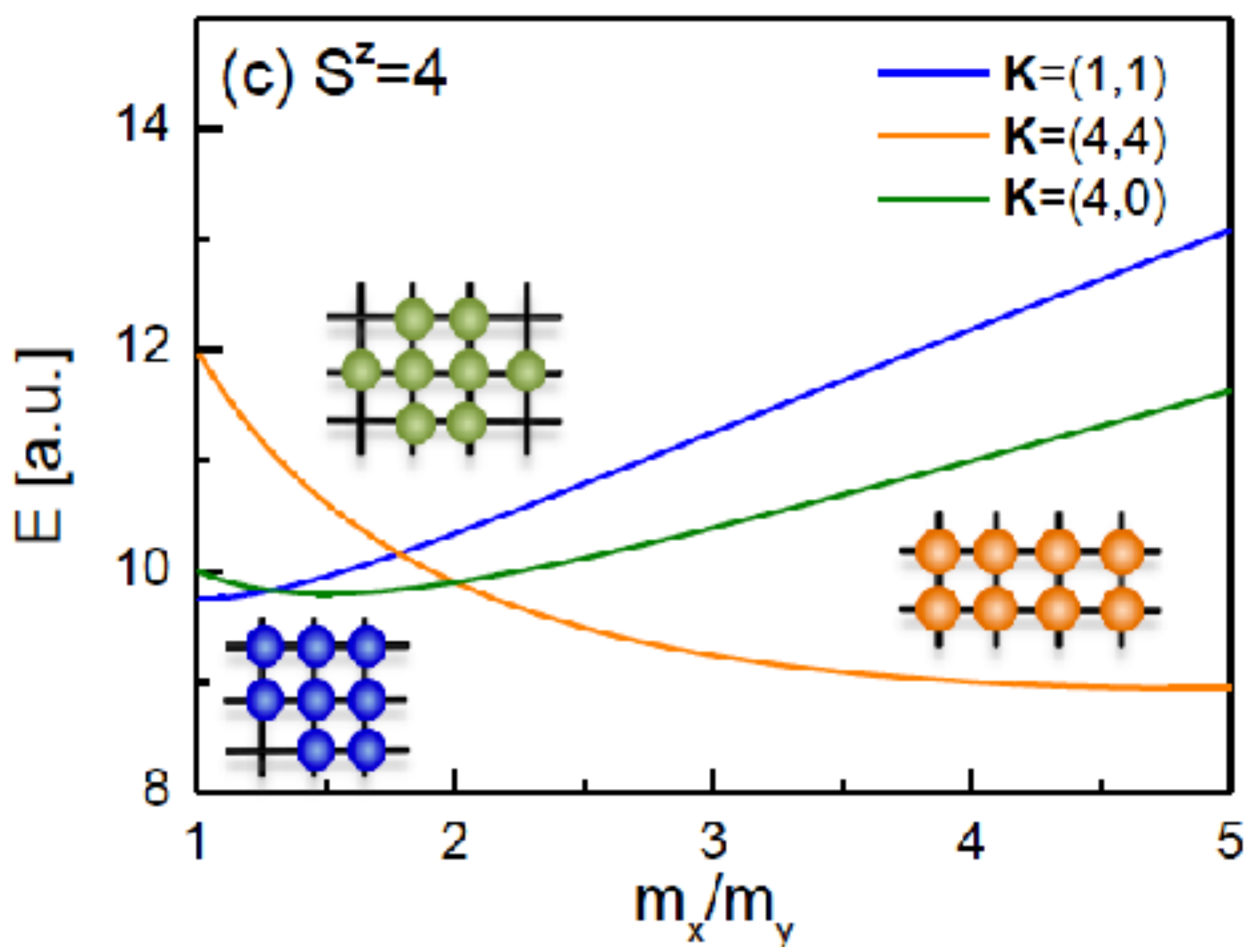

No clear gap in spectrum



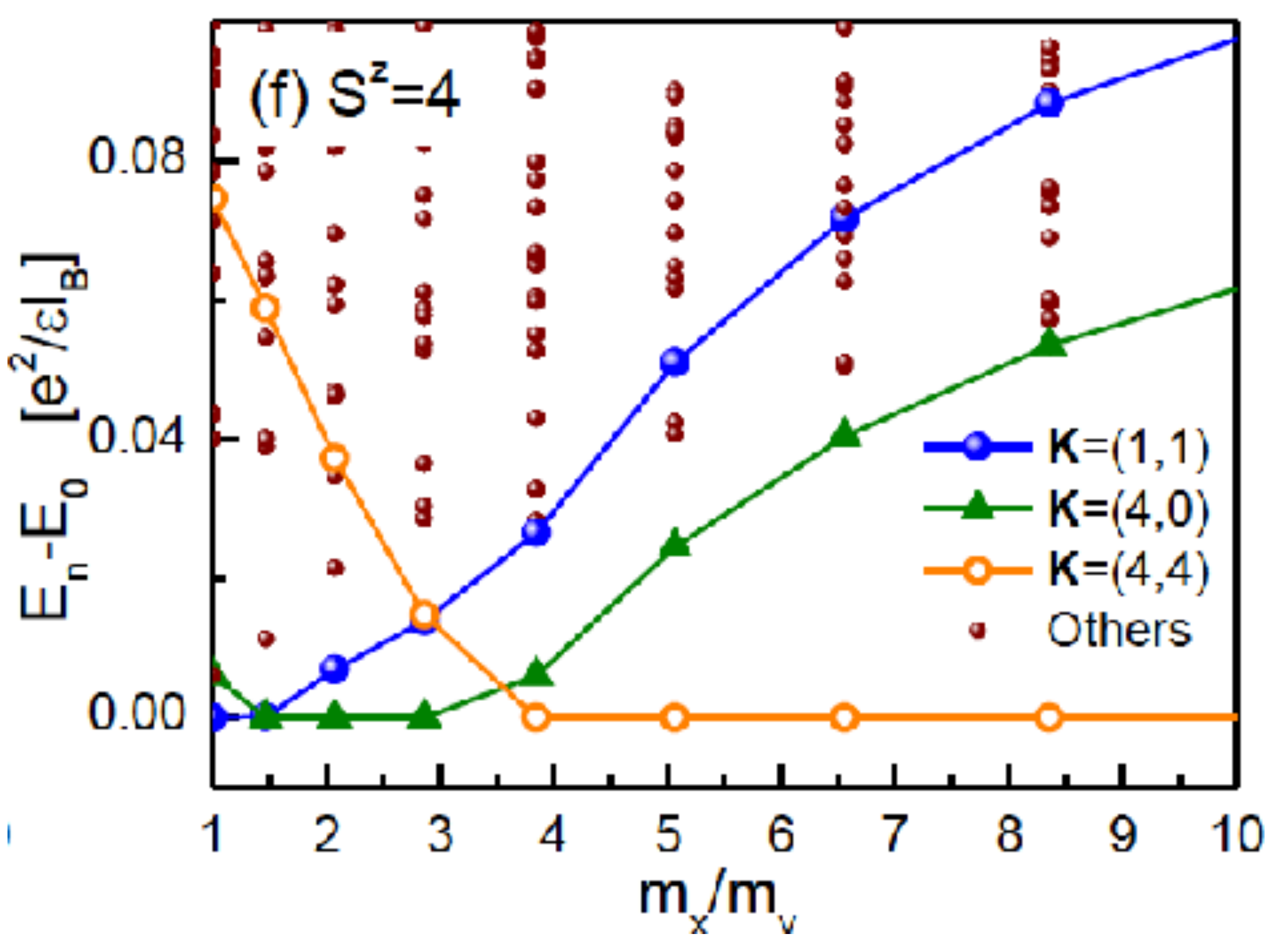
# Numerics vs simple model

$$|\Psi_{\rm CFL}(\{\mathbf{d}_{\mathbf{i}}^{\uparrow},\mathbf{d}_{\mathbf{i}}^{\downarrow}\})\rangle = \det(\hat{t}_j(\mathbf{d}_{\mathbf{i}}^{\uparrow}))\,\det(\hat{t}_j(\mathbf{d}_{\mathbf{i}}^{\downarrow}))|\Phi_{1/2}^{\rm Bose}\rangle$$

Trial wave function

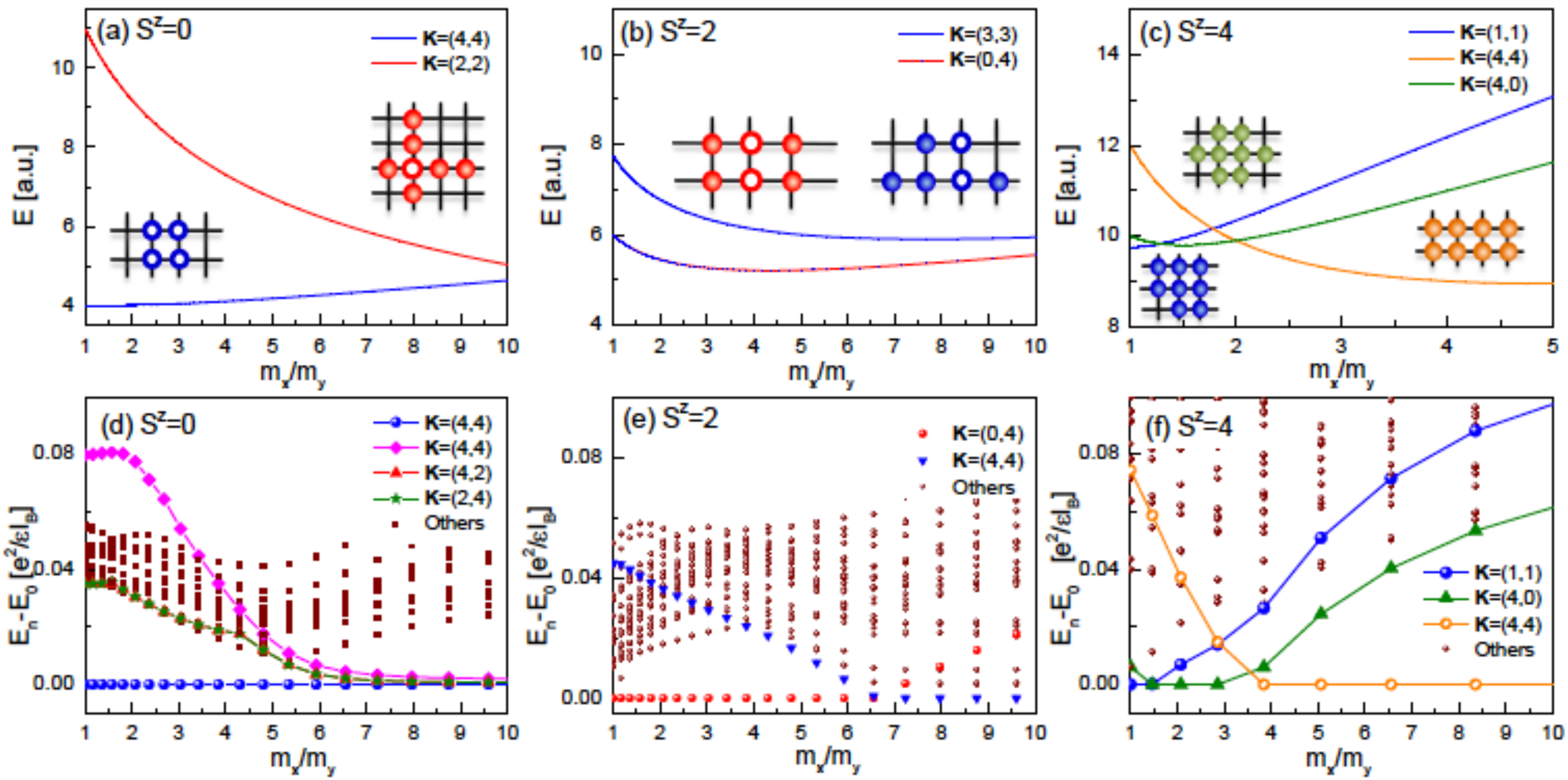



Exact diagonalization



# Numerics vs simple model

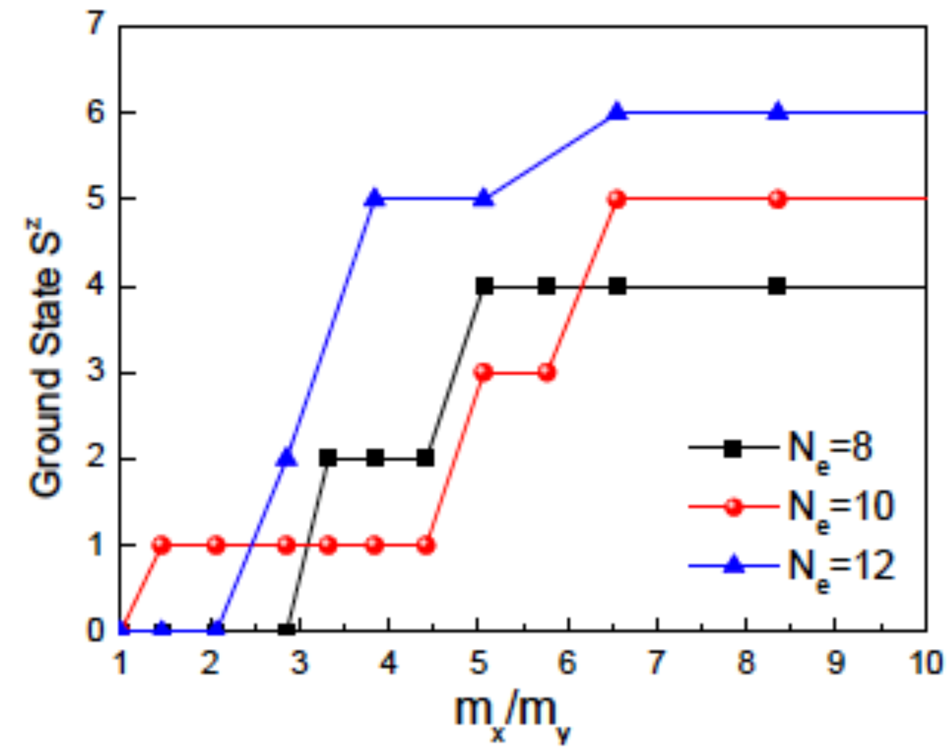
Trial wave function



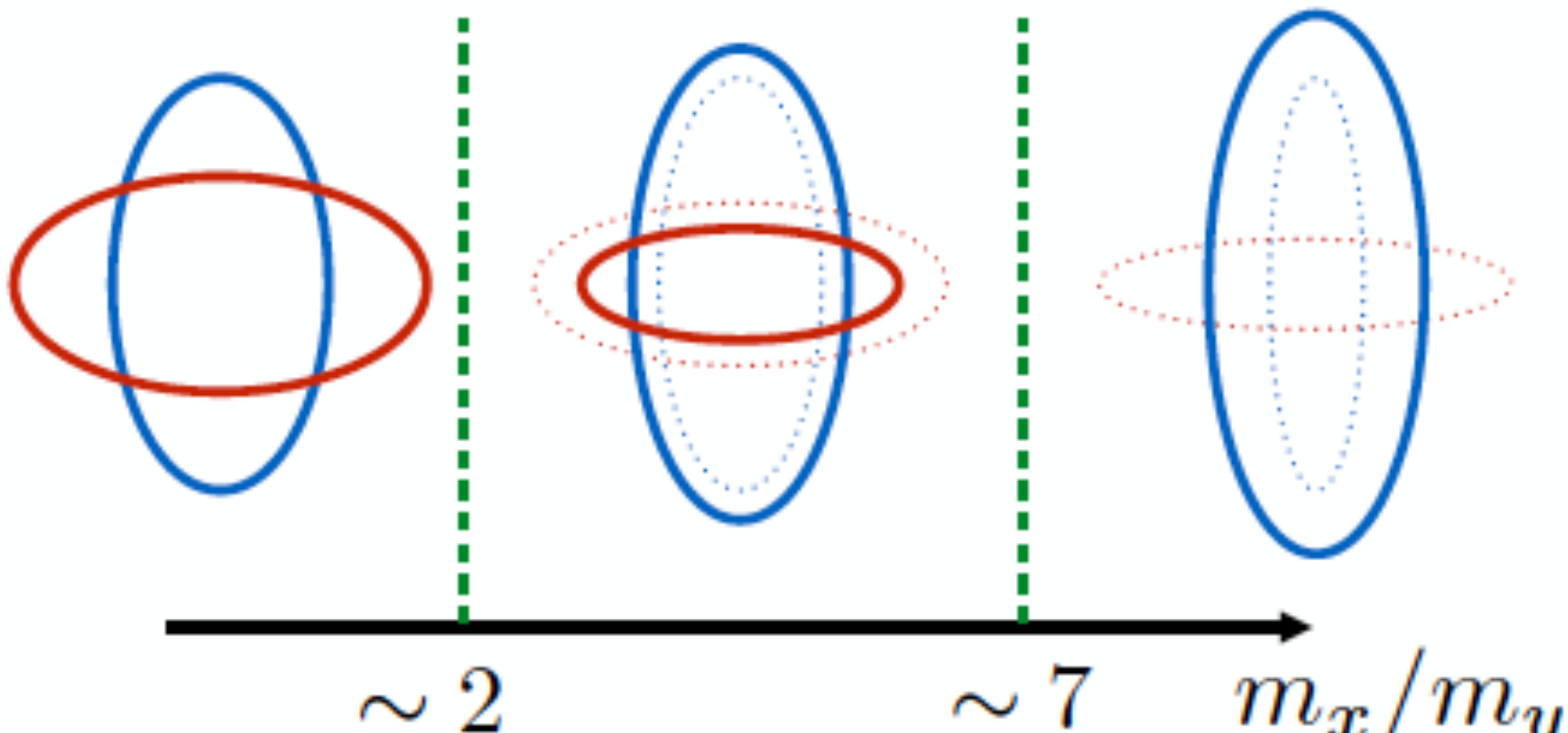

Exact diagonalization

# DMRG phase diagram

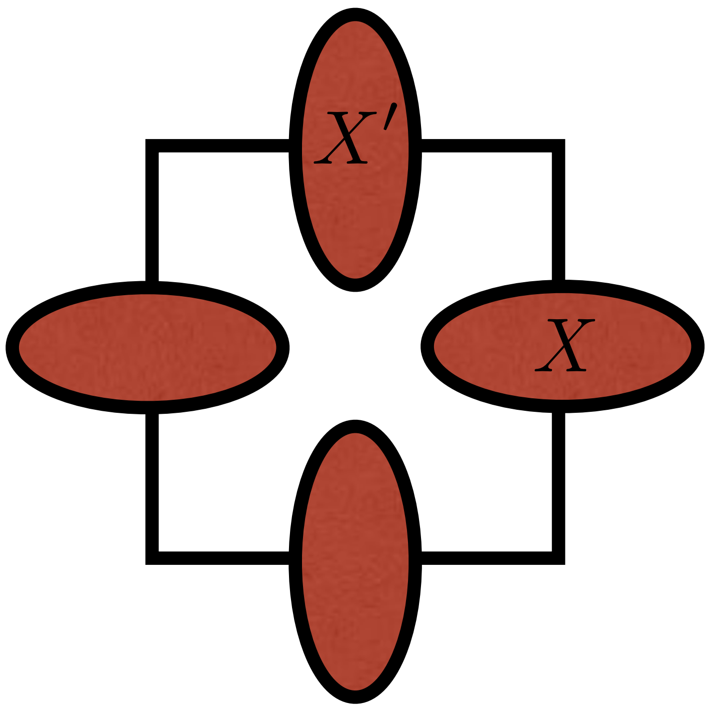
DMRG results:

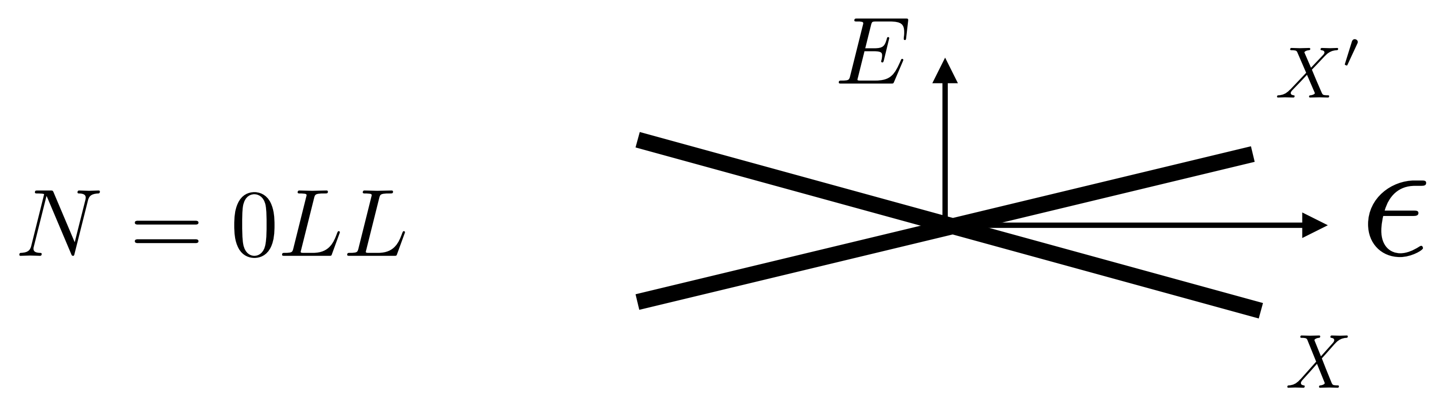



Valley Stoner magnet:



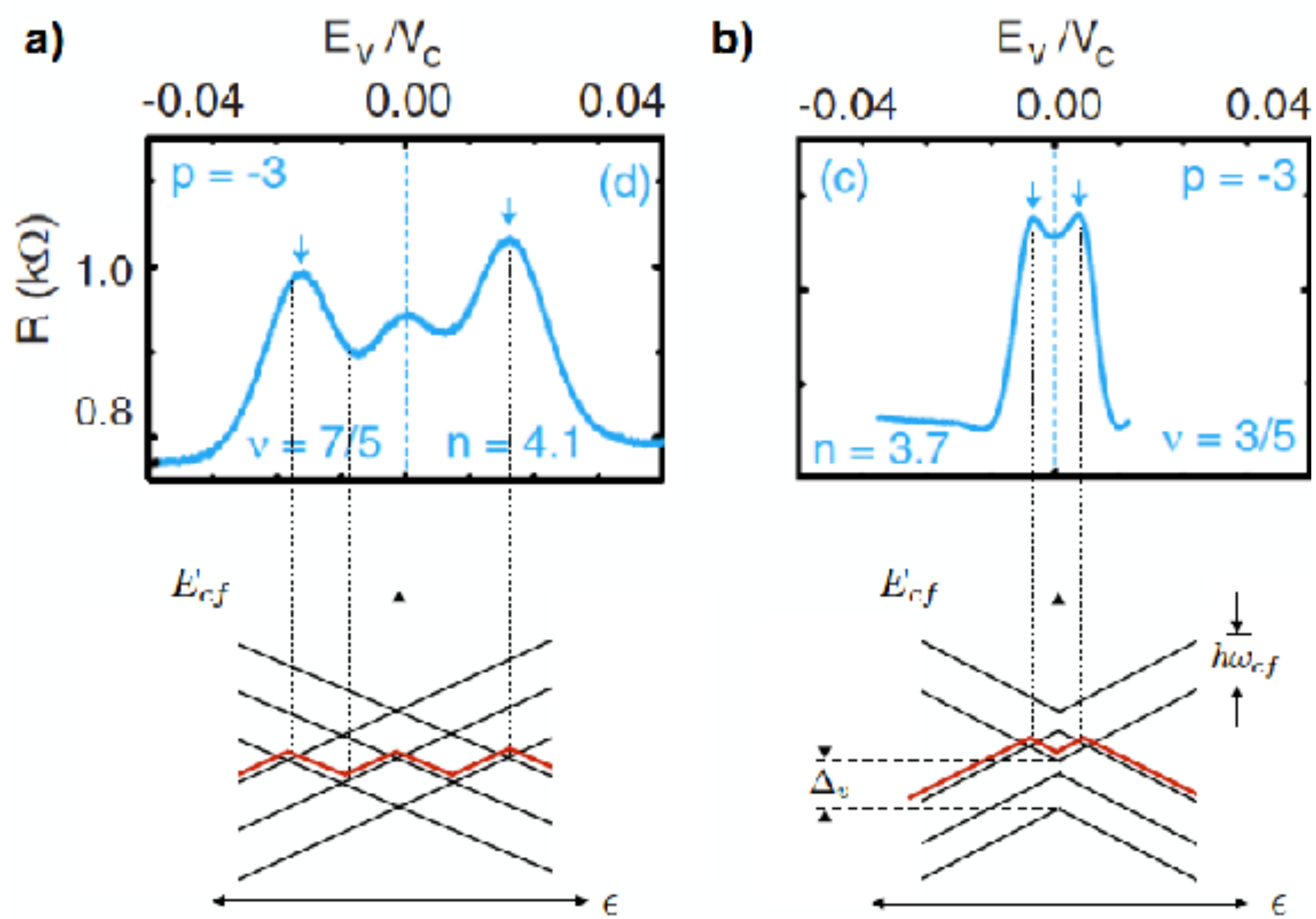
# Connections with Aluminum Arsenide




$$\nu = 1/2$$

Nearby FQH states appear to have spontaneous valley polarization:




Padmanabhan, Gokmen, and Shayegan PRB (2010)

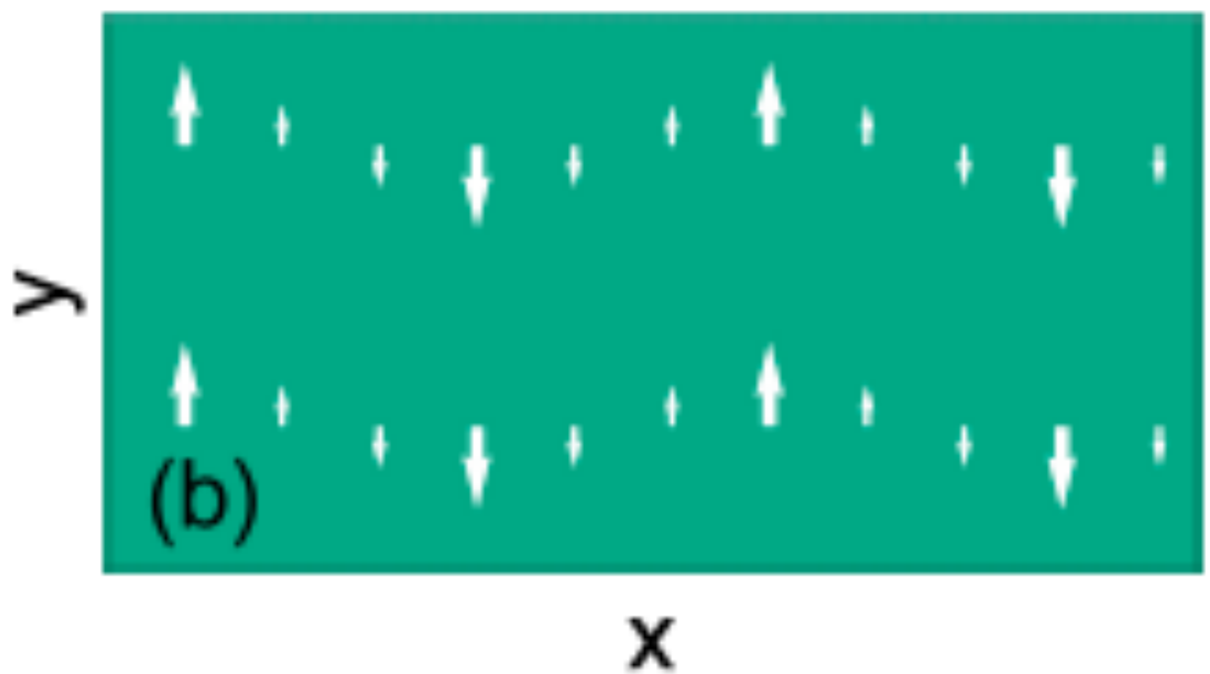
# Summary

Alternative platforms for fractional quantum Hall physics like Graphene, ZnO, AlAs, allow to realise a wealth of phase transitions between fractionalized phases of matter.

- Stoner transition of composite fermi liquids in AlAs (arXiv:1802.02167).
- Quantum phase transition between Pfaffian and composite fermi liquid might be realisable in bilayer graphene with perpendicular field.
- Sequence of phase transitions in ZnO (arXiv:1804.04565) and bilayer graphene (Nature 549, 360 (2017)) for a level crossing between N=0 and N=1 Landau levels.

# Bosonization and shear sound in 2D Fermi liquids

**Shear sound of interacting Fermi liquids**




Jun Yong Khoo
*MIT*

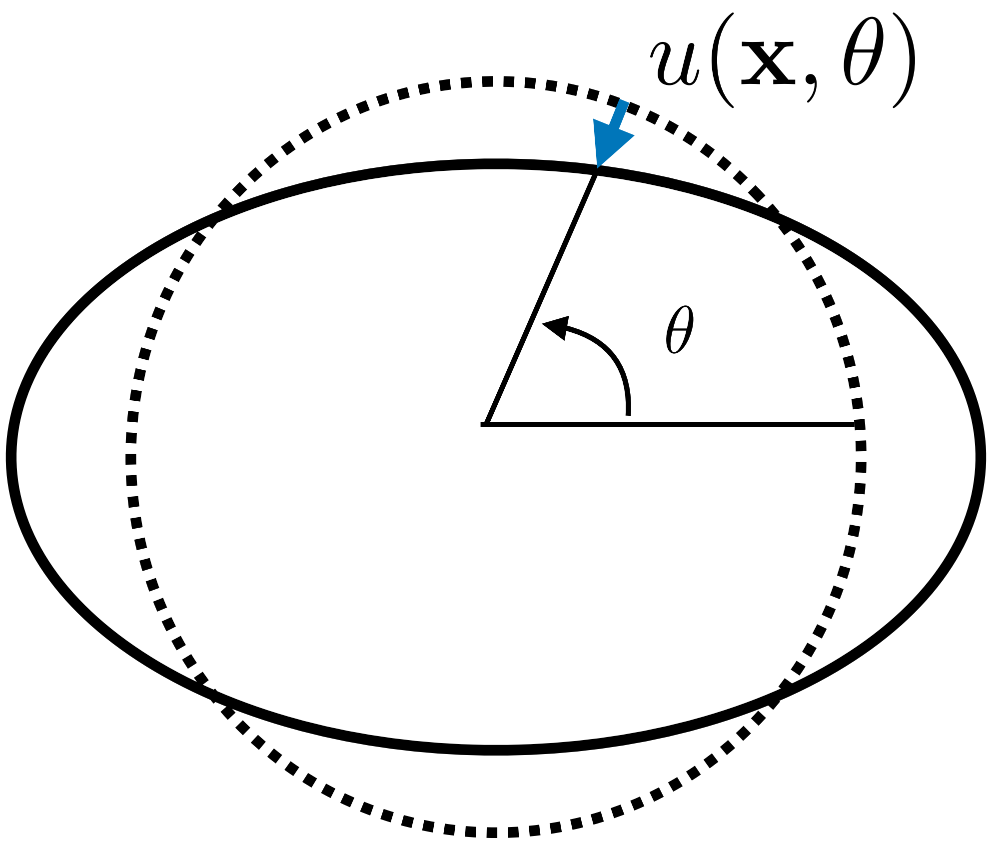
**Should appear rather generically in 2D Fermi liquids when quasiparticles become twice as heavy as bare**

$$m^* > 2m_0$$

**arXiv:1806.04157**

# Bosonization of 2D Fermi liquids

**2D Fermi liquids have an infinite number of slow variables**




**State is parametrized by space-time dependent Fermi radius**

$$p_F(\mathbf{x}, \theta) = p_{F0} + u(\mathbf{x}, \theta)$$

**Radius has commutation relations analogous to 1D**

$$\partial_n = \hat{\mathbf{p}}_\theta \cdot \partial_{\mathbf{x}}$$

$$[\hat{u}_{\mathbf{x},\theta}, \hat{u}_{\mathbf{x}',\theta'}] = \frac{(2\pi)^2}{i p_{\mathrm{F}}} \delta(\theta - \theta') \partial_n \delta(\mathbf{x} - \mathbf{x}') + O(\hat{u})$$


A. Luther, Phys. Rev. B **19**, 320 (1979).

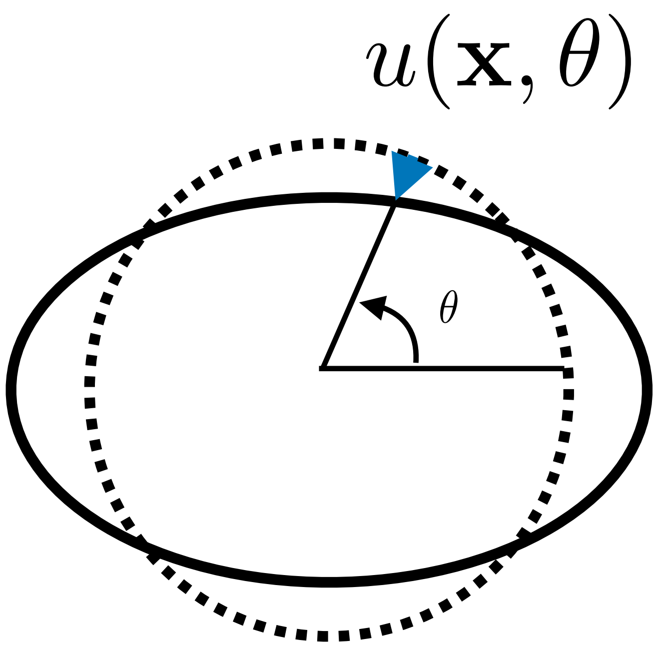
F. D. M. Haldane, eprint arXiv:cond-mat/0505529

A. H. Castro Neto and E. Fradkin, Phys. Rev. Lett. **72**, 1393 (1994).

D. F. Mross and T. Senthil, Phys. Rev. B **84**, 165126 (2011).

S. Golkar, D. X. Nguyen, M. M. Roberts, and D. T. Son, Phys. Rev. Lett. **117**, 216403 (2016).

# Bosonization of 2D Fermi liquids




$$\partial_n = \hat{\mathbf{p}}_\theta \cdot \partial_{\mathbf{x}}$$

$$[\hat{u}_{\mathbf{x},\theta}, \hat{u}_{\mathbf{x}',\theta'}] = \frac{(2\pi)^2}{ip_{\mathrm{F}}}\delta(\theta-\theta')\partial_n\delta(\mathbf{x}-\mathbf{x}') + O(\hat{u})$$

$$\hat{H} = \int d^2\mathbf{x}\ \hat{u}^\dagger_{\mathbf{x},\theta} h_{\theta,\theta'} \hat{u}_{\mathbf{x},\theta'}$$

$$h_{\theta,\theta'} = \frac{v_F p_F}{2}\left(\delta(\theta'-\theta) + \frac{F(\theta'-\theta)}{2\pi}\right)$$

**Landau function:**

$$F(\theta'-\theta)$$

**Quantum version of kinetic equation:**

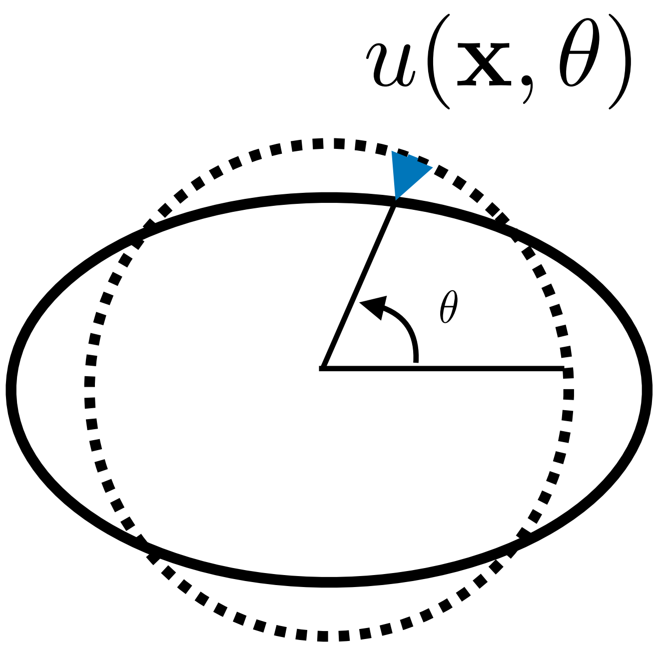
$$\hat{u}_{\mathbf{q},\theta} \equiv \int d^2\mathbf{x}\ \hat{u}_{\mathbf{x},\theta} e^{-i\mathbf{q}\cdot\mathbf{x}}$$

$$i\partial_t \hat{u}_{\mathbf{q},\theta} = \left[\hat{u}_{\mathbf{q},\theta}, \hat{H}\right] = K_{\theta,\theta'}\hat{u}_{\mathbf{q},\theta'},$$

$$K(\theta,\theta') = v_{\mathrm{F}}\mathbf{q}\cdot\hat{\mathbf{p}}_\theta\left(\delta(\theta-\theta') + \frac{1}{2\pi}F(\theta-\theta')\right)$$

$$v^\dagger_\theta G_{\theta,\theta'} w_{\theta'} \equiv \int \frac{d\theta d\theta'}{(2\pi)^2} v(\theta) G(\theta,\theta') w(\theta')$$

# Mapping classical to quantum



**Quantum version of kinetic equation:**

$$i\partial_t \hat{u}_{\mathbf{q},\theta} = \left[\hat{u}_{\mathbf{q},\theta}, \hat{H}\right] = K_{\theta,\theta'}\hat{u}_{\mathbf{q},\theta'},$$

$$K(\theta,\theta') = v_{\mathrm{F}}\mathbf{q}\cdot\hat{\mathbf{p}}_\theta \left(\delta(\theta-\theta') + \frac{1}{2\pi}F(\theta-\theta')\right)$$

$$K = TK^\dagger T^{-1}, \;\; T_{\theta,\theta'} = \frac{(2\pi)^2\mathbf{q}\cdot\hat{\mathbf{p}}_\theta}{p_{\mathrm{F}}}\delta(\theta-\theta')$$

**For every classical eigen-function of the kinetic Equation:**

$$K_{\theta,\theta'}\psi_{\lambda,\mathbf{q},\theta'} \;=\; E_\lambda\psi_{\lambda,\mathbf{q},\theta}$$

**We can construct a quantum bosonic eigen-mode:**

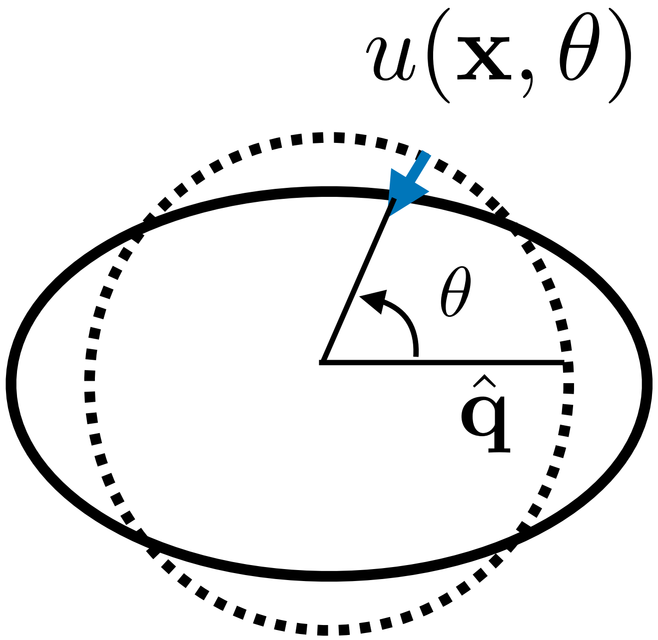
$$\hat{\psi}_{\lambda,\mathbf{q}} = \psi^\dagger_{\lambda,\mathbf{q},\theta}T^{-1}_{\theta,\theta'}\hat{u}_{\mathbf{q},\theta'}$$

**Canonical normalisation:**

$$\psi^\dagger_{\lambda,\mathbf{q},\theta}T^{-1}_{\theta,\theta'}\psi_{\lambda',\mathbf{q},\theta'} \;=\; \mathrm{sgn}(E_\lambda)\delta_{\lambda,\lambda'}$$

$$v^\dagger_\theta G_{\theta,\theta'}w_{\theta'} \equiv \int\frac{d\theta d\theta'}{(2\pi)^2}v(\theta)G(\theta,\theta')w(\theta')$$

# Mapping classical to 1D tight binding




**Mirror symmetry:**

$$F(\theta) = F(-\theta), \; K_{\theta,\theta'} = K_{-\theta,-\theta'}$$

**Even and Odd modes:** $\sigma = \pm$

$$\psi^{\sigma}_{\lambda,\mathbf{q},\theta} = \sigma \psi^{\sigma}_{\lambda,\mathbf{q},-\theta}$$

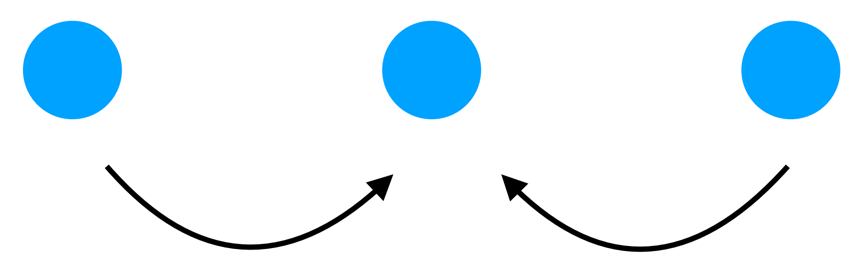
**Angular momentum:**

$$F(\theta) = F_0 + \sum_{l=1}^{\infty} 2F_l \cos(l\theta)$$

$$\psi^{+}_{\lambda,\theta} = \psi^{+}_{\lambda,0} + \sum_{l=1}^{\infty} 2\psi^{+}_{\lambda,l} \cos(l\theta),$$

$$\psi^{-}_{\lambda,\theta} = \sum_{l=1}^{\infty} 2\psi^{-}_{\lambda,l} \sin(l\theta).$$

$$E^{\sigma}_{\lambda} \psi^{\sigma}_{\lambda,l+1} = t_l \psi^{\sigma}_{\lambda,l} + t_{l+2} \psi^{\sigma}_{\lambda,l+2}$$



$$t_l = v_{\mathrm{F}} q (1 + F_l)/2$$

# Mapping classical to 1D tight binding

**Angular momentum:**

$$F(\theta) = F_0 + \sum_{l=1}^{\infty} 2F_l \cos(l\theta)$$

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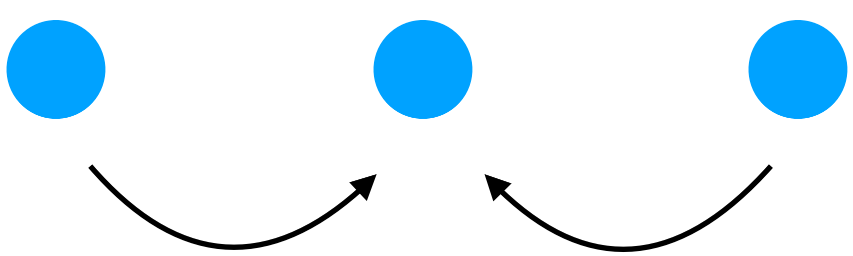
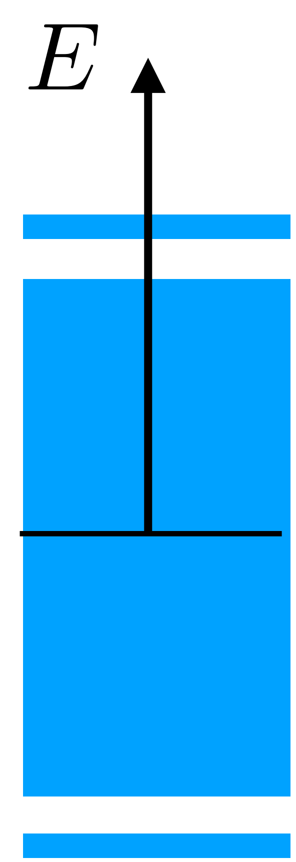


$$t_l = v_{\mathrm{F}} q(1 + F_l)/2$$

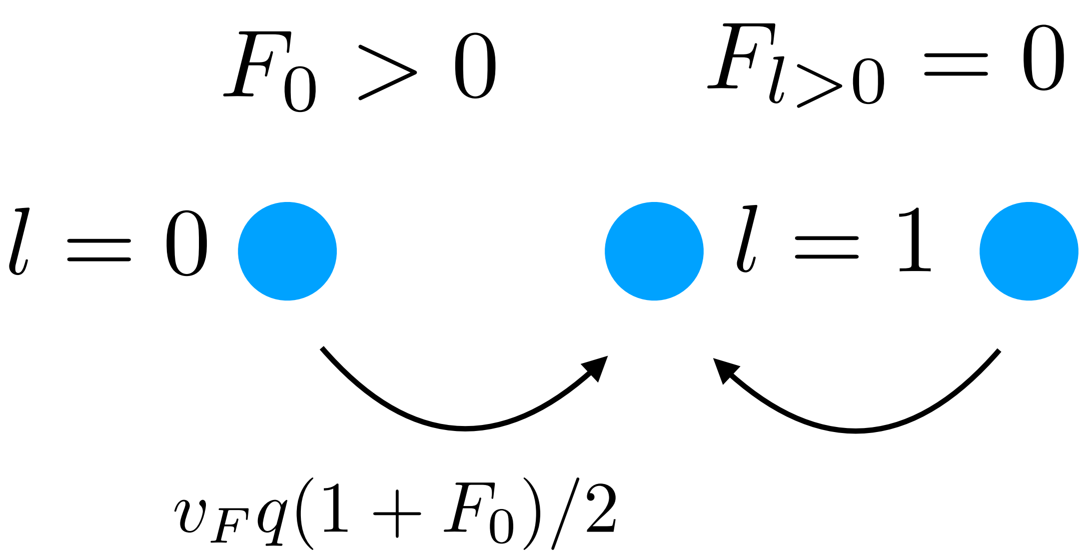
**Landau parameters
play role of bond disorder**




A. Kumar and D. L. Maslov, Phys. Rev. B 95, 165140 (2017).

# Another sound

**Only one bond is defective:**




$$E^{\sigma}_{\lambda}\psi^{\sigma}_{\lambda,l+1} = t_l\psi^{\sigma}_{\lambda,l} + t_{l+2}\psi^{\sigma}_{\lambda,l+2}$$

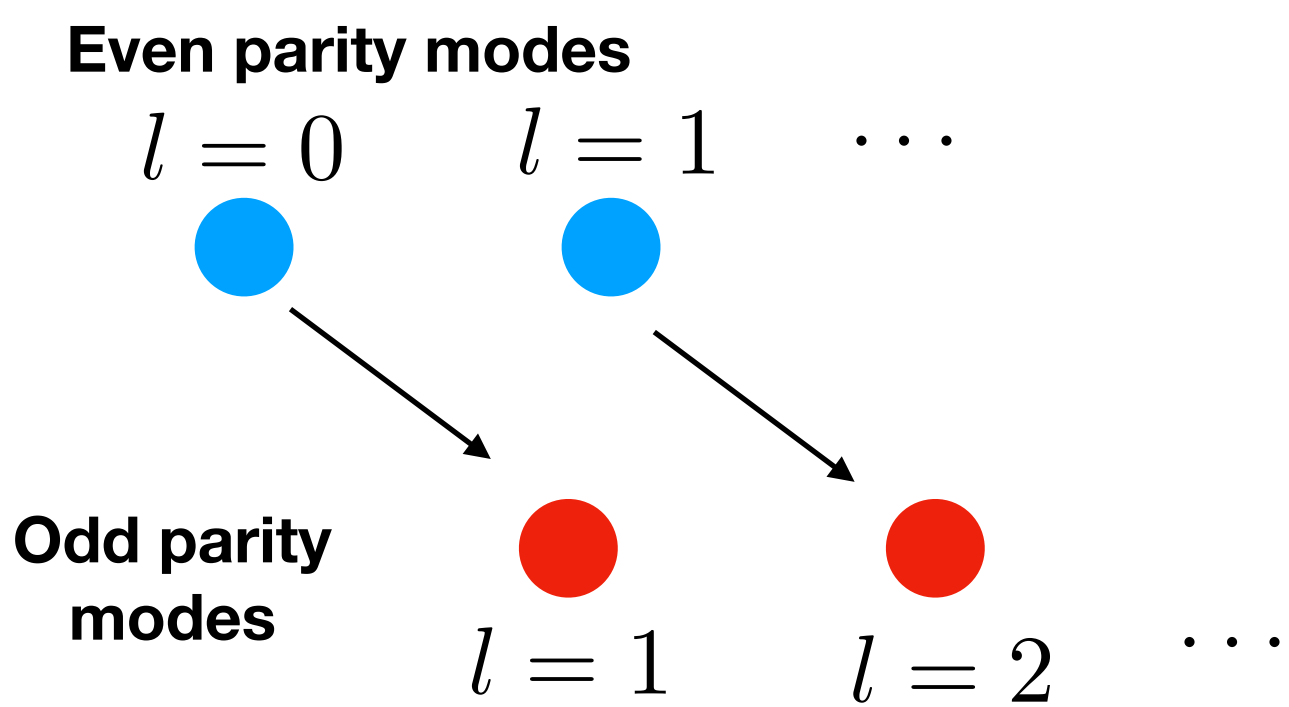
$$t_l = v_{\mathrm{F}} q(1 + F_l)/2$$

**Mapping between even and odd sector problems**

$$l \to l + 1$$

$$F'_{l+1} = F_l \quad \text{for } l \geq 1$$

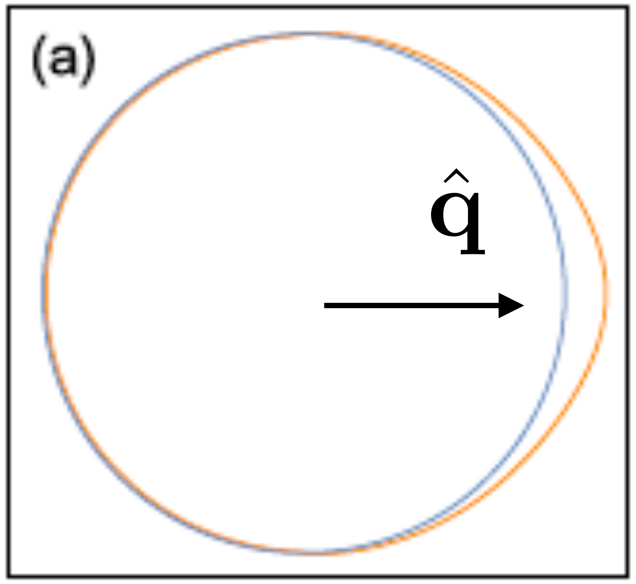
$$F'_1 = 1{+}2F_0$$

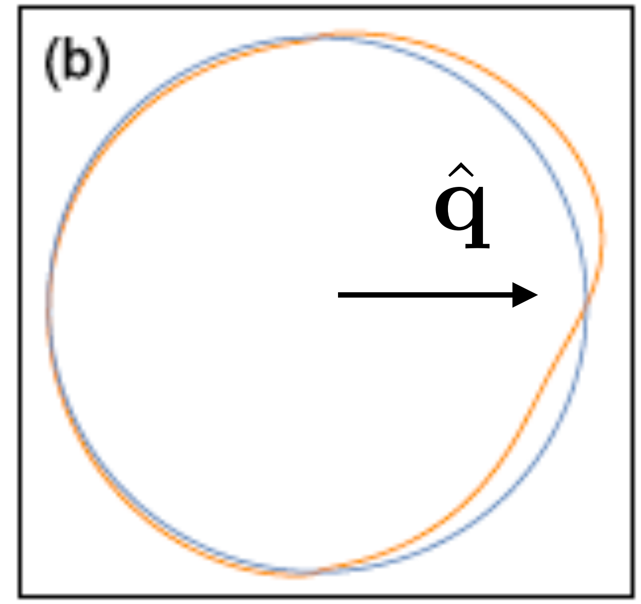



**Implies existence of collective mode other than zero sound in model with non-zero:**

$$\{F_0, F_1\}$$

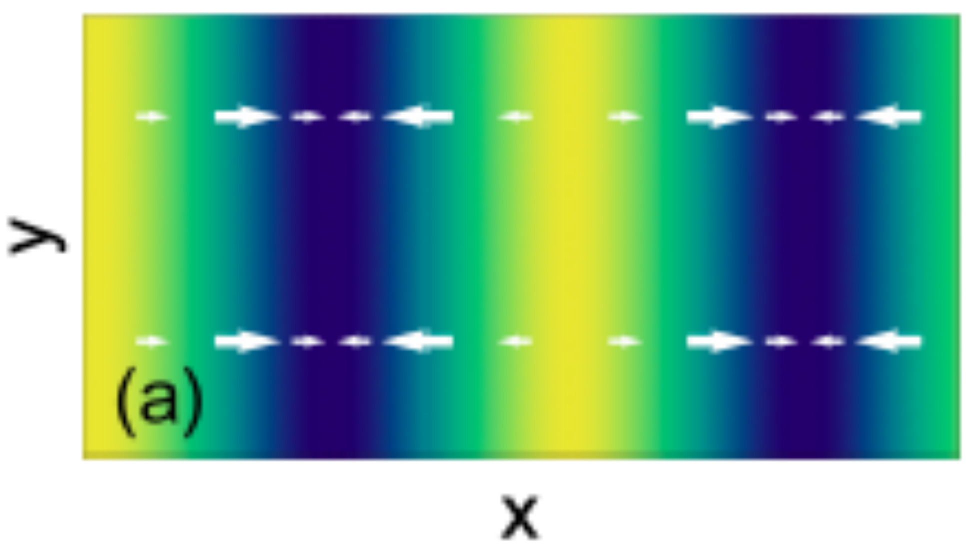
# Shear vs zero sound



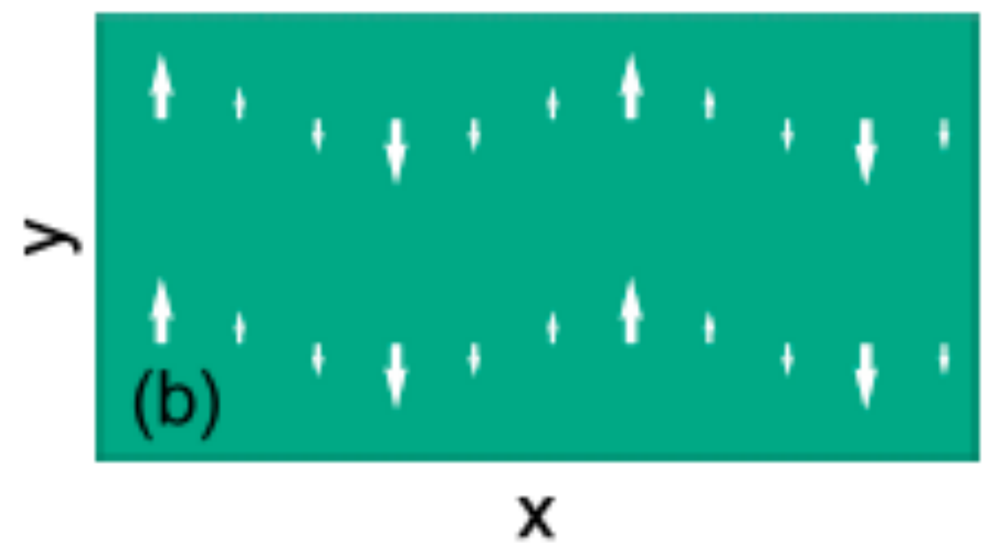




**Zero sound is longitudinal**

**Shear sound is purely transverse**




$$\mathbf{j} \parallel \mathbf{q}$$




$$\mathbf{j} \perp \mathbf{q}$$

**In metals zero sound is transformed into plasma mode**

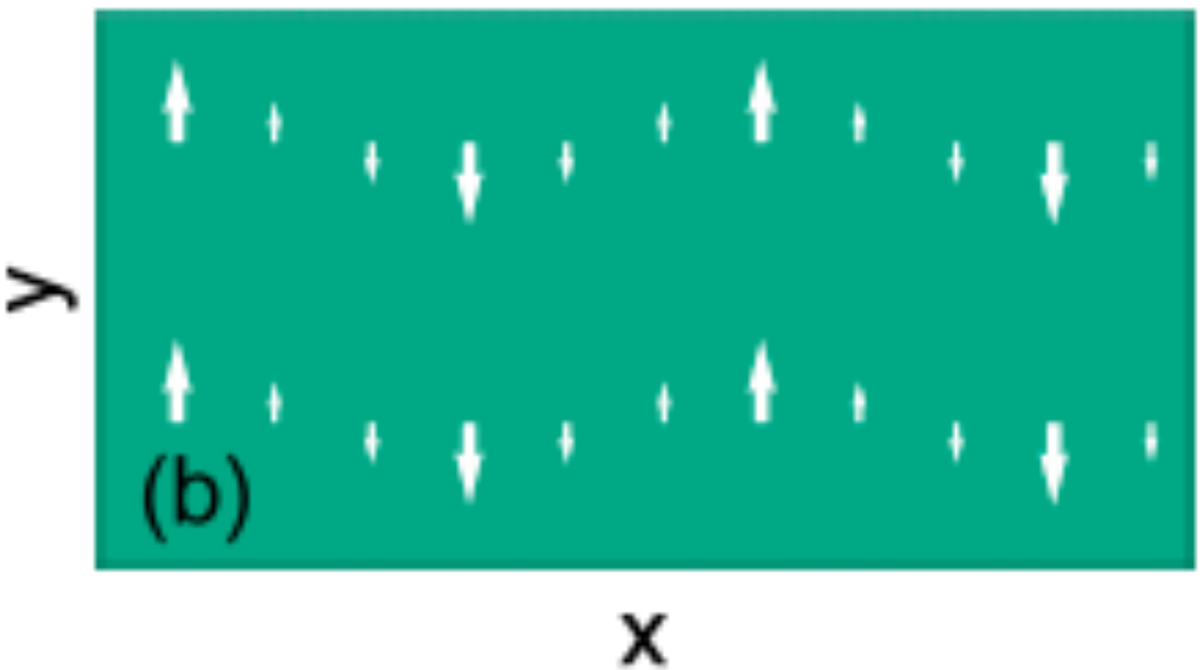
$$E \propto \sqrt{|\mathbf{q}|}$$

**Shear sound remains linearly dispersing in metals**

$$E = v_{\perp}|\mathbf{q}|$$

# Shear sound and mass renormalization

**Mode is Landau damped in weakly interacting Fermi liquids**




**Mode is expected to appear out of continuum when:**

$$F_1 > 1$$

**Mode is expected to appear when quasiparticles become twice as heavy:**

$$\frac{v_{F0}}{v_F} = \frac{m^*}{m_0} = 1 + F_1$$

**Large variety of systems with mass enhancement near critical points could host undamped shear sound:**

- He3 adsorbed on graphite — M. Neumann, J. Nyéki, B. Cowan, and J. Saunders, Science **317**, 1356 (2007).
- kappa-ET and dmit on the pressure induced metal side — Y. Zhou, K. Kanoda, and T.-K. Ng, Rev. Mod. Phys. **89**, 025003 (2017).
- Quasi-2D heavy fermion materials (e.g. CeCoIn5) — Settai et al. Journal of Physics: Condensed Matter 13, L627 (2001)
- Overdoped metal in iron based superconductors (cuprates?) — Hashimoto et al. Science **336**, 1554 (2012).

# Response functions

$$\hat{\mathcal{O}}_{\mathbf{q}} = \int d\theta O(\mathbf{q},\theta)\hat{u}_{\mathbf{q},\theta} = \sum_{\lambda} O_{\lambda,\mathbf{q}}\hat{\psi}_{\lambda,\mathbf{q}}$$

$$\rho_{\lambda,\mathbf{q}} = \mathrm{sgn}(E_\lambda)\frac{p_{\mathrm{F}}}{2\pi}\psi^{+}_{\lambda,0}$$

$$\mathbf{j}_{\lambda,\mathbf{q}} = \mathrm{sgn}(E_\lambda)\frac{v_{0\mathrm{F}}p_{\mathrm{F}}}{2\pi}(\psi^{+}_{\lambda,1}\hat{\mathbf{q}} + \psi^{-}_{\lambda,1}\hat{\mathbf{q}}_{\perp})$$

**Density** $l=0$

**Longitudinal Current** $l=1$

**Even Modes**

**Transverse Current** $l=1$

**Odd modes**

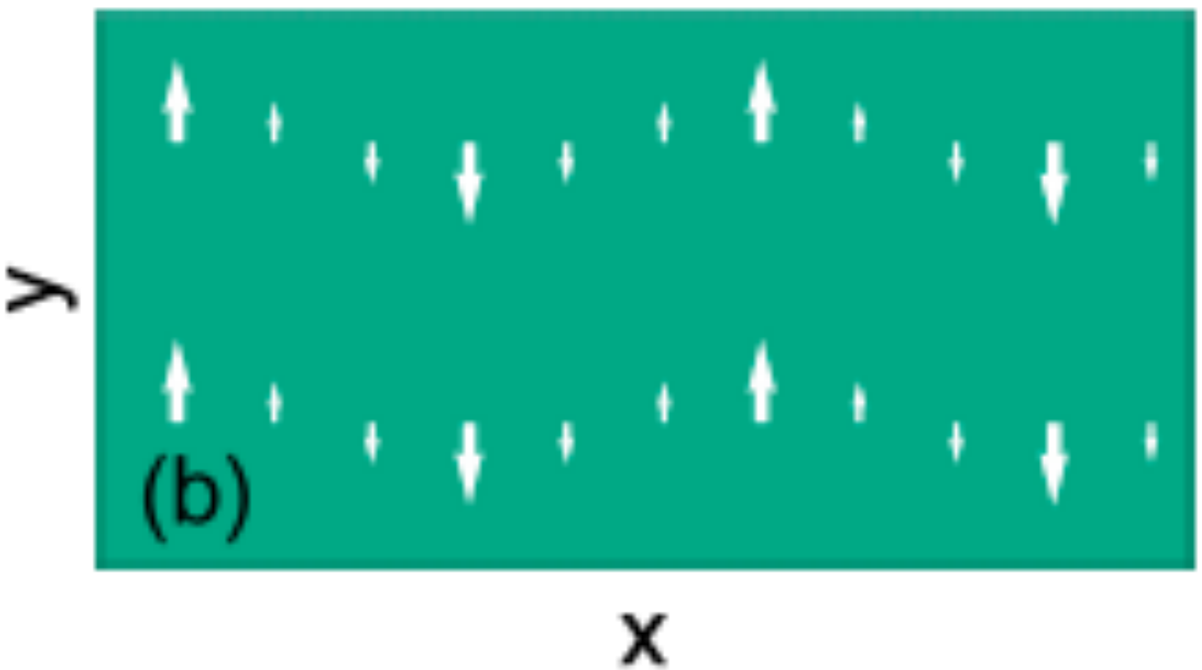
**Sharp peak in the transverse current-current correlation function with spectral weight:**

$$w_{j_\perp j_\perp} = \frac{p_{\mathrm{F}} q v_{0\mathrm{F}}^2}{16}\frac{F_1 - 1}{F_1^{3/2}} \qquad \text{vanishes as } F_1 \to 1$$

$$\mathrm{Im}\chi_{j_\perp j_\perp}(\mathbf{q},\omega) = -\mathcal{A}\frac{\pi v_{0\mathrm{F}}^2 p_{\mathrm{F}}^2}{(2\pi)^2}\sum_i \left|\psi^{-}_{i,1}\right|^2 \mathrm{sgn}(E_i)\delta(\omega - E_i^{-})$$

# Summary

**Mode is Landau damped in weakly interacting Fermi liquids**

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**arXiv:1806.04157**

# Stoner