Quantum spin liquids and unconventional superconductivity in honeycomb materials

Jaime Merino

Universidad Autónoma de Madrid

In collaboration with: Manuel F. López, Universidad Autónoma de Madrid; Arnaud Ralko, Institut Néel, and Ben J. Powell, University of Queensland.

A. Ralko, and JM, PRL **124**, 217203 (2020); M. F. López, and JM, PRB (2020); JM, M. F. López, and B. J. Powell, PRB (2021).

IfiMAC Condensed Matter Physics Center

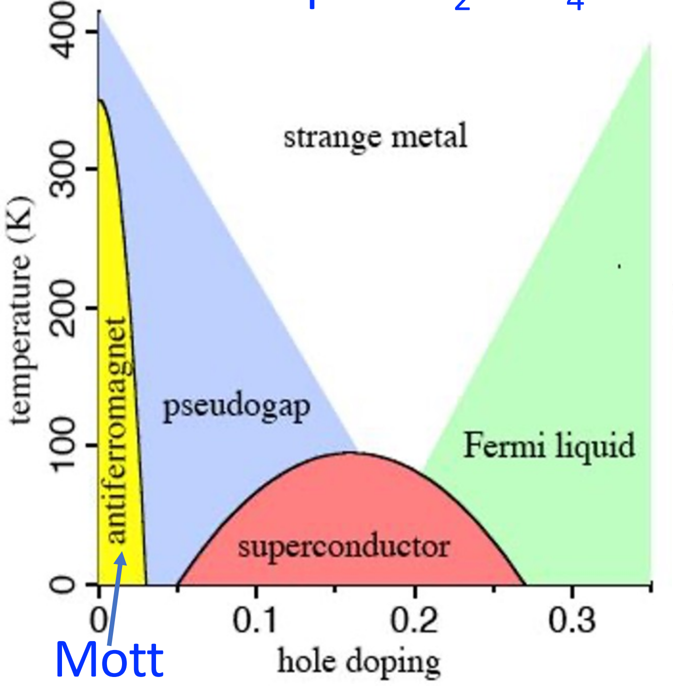
Supported by MINECO: RTI2018-098452-B-I00, PRX18/00070

Outline

- Motivation: unconventional superconductivity in strongly correlated 2D materials.
- Novel chiral quantum spin liquids in honeycomb Kitaev magnets.
- Unconventional superconductivity in decorated honeycomb materials.
- Conclusions and outlook.

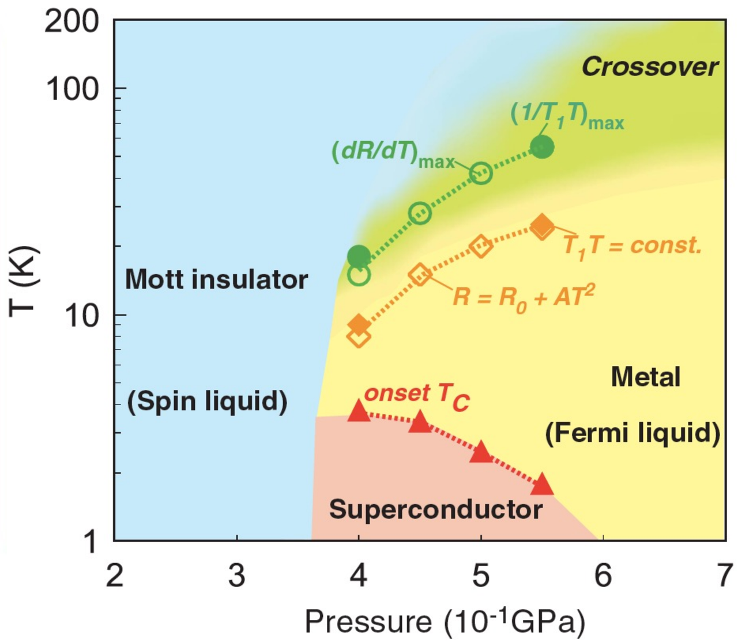
Superconductivity in strongly correlated 2D materials

Hole doped La_2CuO_4

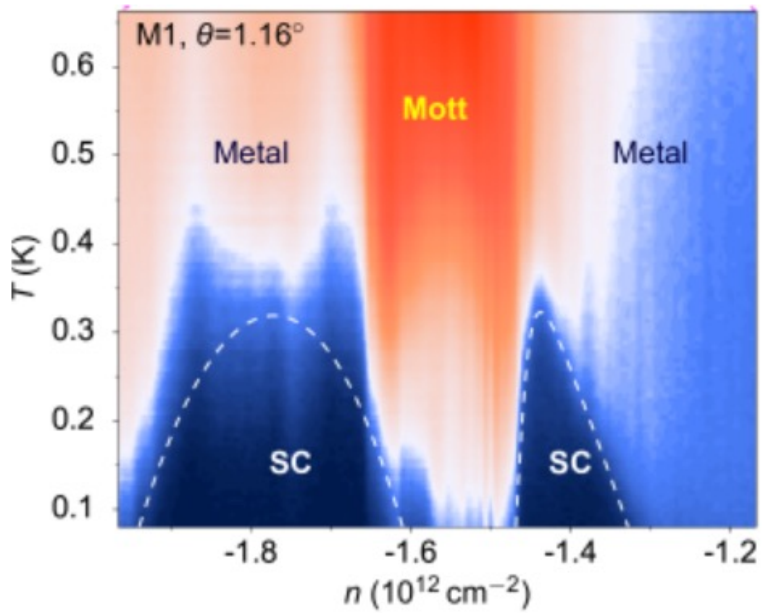


Mott insulator

κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$



Twisted bilayer graphene (TBG)

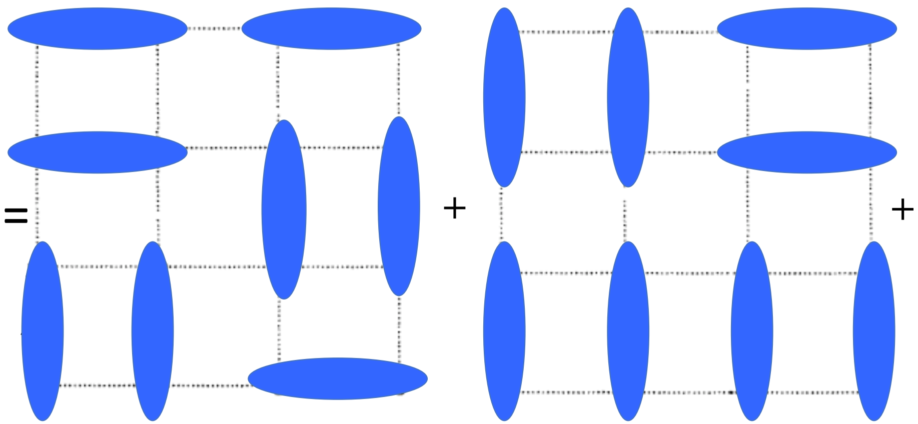


- Superconductivity arises in proximity to the Mott insulator: what is the mechanism?
- What is the connection (if any) between quantum spin liquids and superconductivity?
- Role of flat bands, Dirac points,…on electronic properties and superconductivity.

Anderson's RVB theory of cuprate superconductivity

Ground state of the Heisenberg model on a triangular lattice is an RVB state (1973):

$$\mathcal{H} = J \sum_{\langle j,k \rangle} \vec{S}_j \cdot \vec{S}_k$$

|RVB> =  + ...

 $= (ij) = 1/\sqrt{2}(|i\uparrow j\downarrow> - |i\downarrow j\uparrow>) = -(ji)$

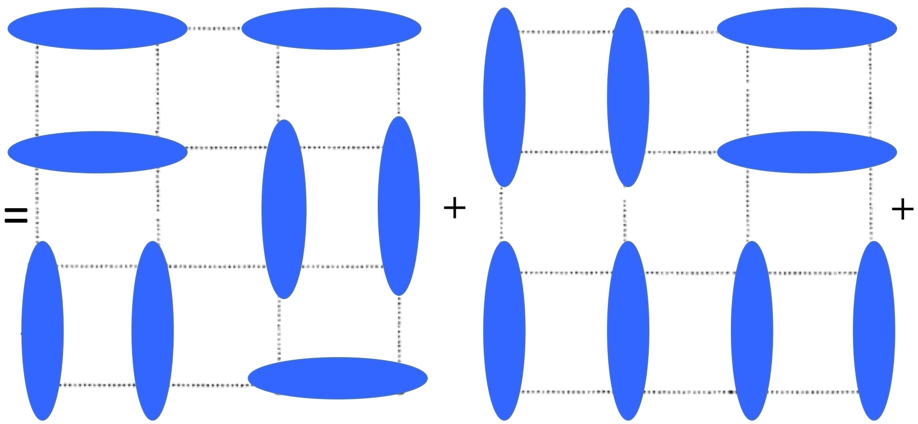
valence bond/singlet

RVB Mott insulator

Anderson’s RVB theory of cuprate superconductivity

Ground state of the Heisenberg model on a triangular lattice is an RVB state (1973):

$$\mathcal{H} = J \sum_{\langle j,k \rangle} \vec{S}_j \cdot \vec{S}_k$$

|RVB> =  + ...

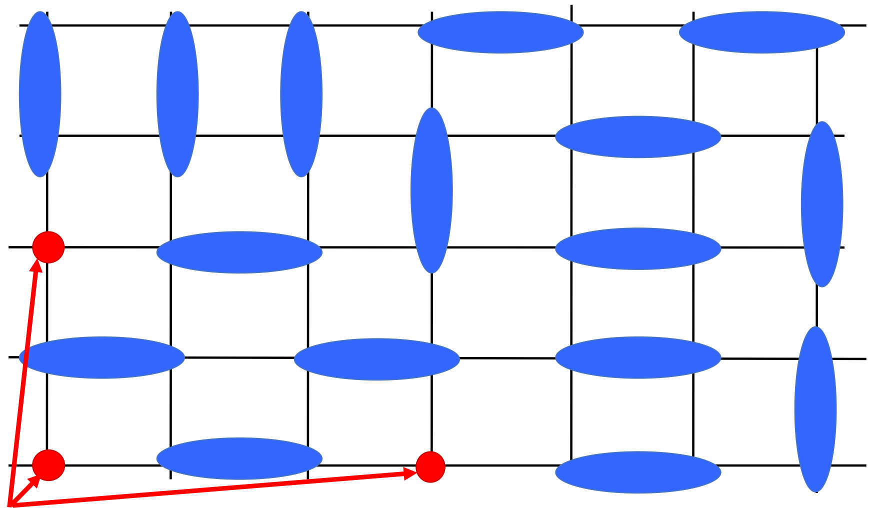
 $= (ij) = 1/\sqrt{2}(|i\uparrow j\downarrow> - |i\downarrow j\uparrow>) = -(ji)$

valence bond/singlet

RVB Mott insulator

Under hole doping, the ground state of the t-J model is a high-Tc superconductor (1987):

$$H_{t-J} = PTP + J\sum_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \quad P = \prod_i (1 - n_{i\uparrow} n_{i\downarrow})$$



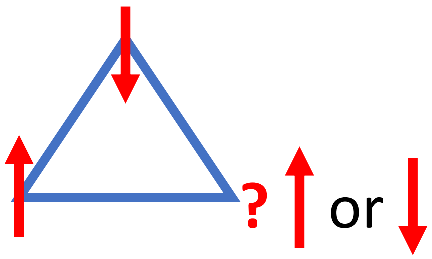
$$P\,|\Phi\rangle = P\left[\sum_{\vec{r},\vec{r}'} \varphi(\vec{r}-\vec{r}')c^\dagger_{\vec{r}\uparrow}c^\dagger_{\vec{r}'\downarrow}\right]^{N/2} |0\rangle$$

High-Tc superconductor

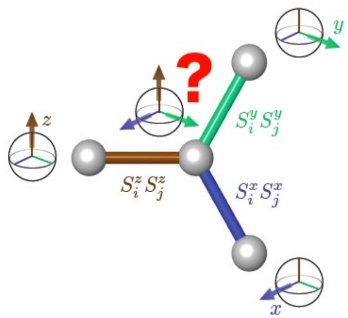
Key ingredients for quantum spin liquids

- Small spins, s=1/2 favor quantum fluctuations.

- Geometrical frustration:



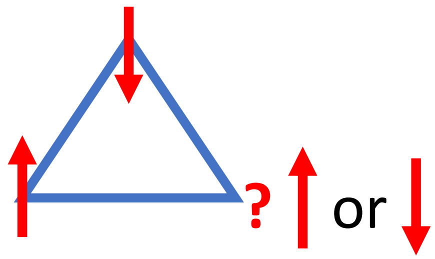
- Strong spin-orbit coupling:



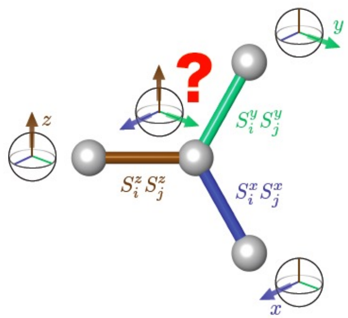
Broholm, et. al., Science (2020).
Savary and Balents, Rep. Prog. Phys. (2017).

Key ingredients for quantum spin liquids

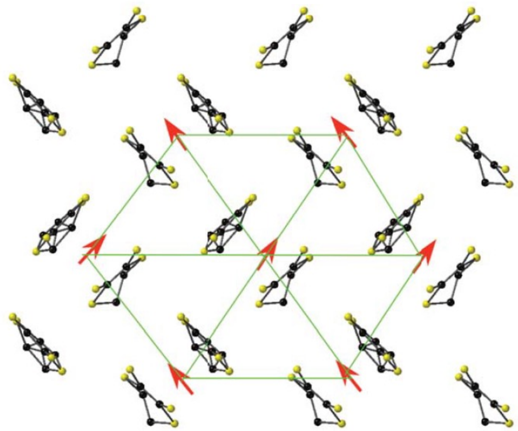
- Small spins, s=1/2 favor quantum fluctuations.
- Geometrical frustration:



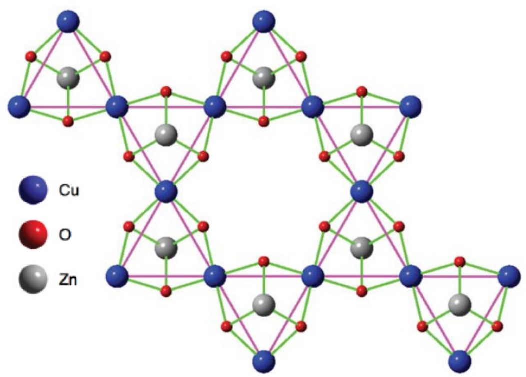
- Strong spin-orbit coupling:



Candidate spin liquid materials



s=1/2, triangular

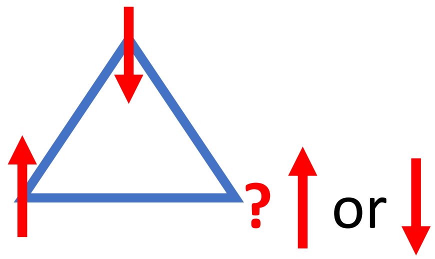


s=1/2, Kagomé

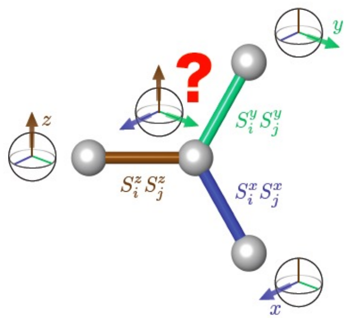
Broholm, et. al., Science (2020).
Savary and Balents, Rep. Prog. Phys. (2017).

Key ingredients for quantum spin liquids

- Small spins, s=1/2 favor quantum fluctuations.
- Geometrical frustration:



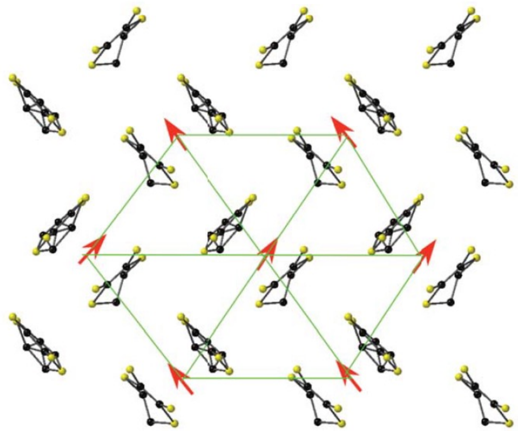
- Strong spin-orbit coupling:



Broholm, et. al., Science (2020).
Savary and Balents, Rep. Prog. Phys. (2017).

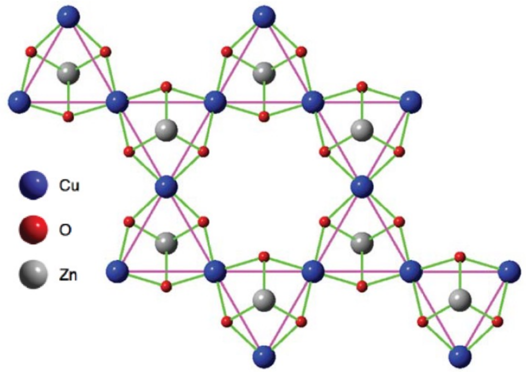
Candidate spin liquid materials

κ-$(ET)_2Cu_2(CN)_3$



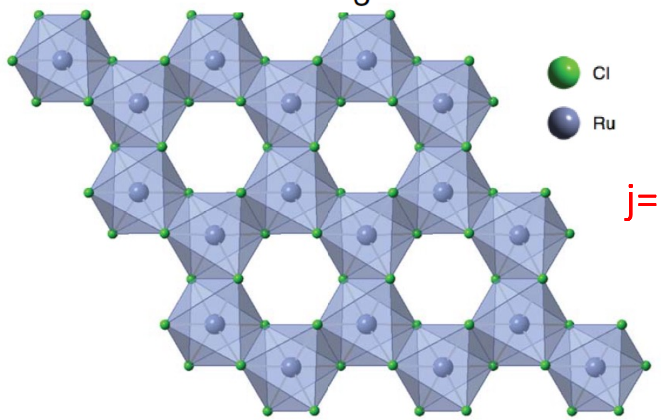
s=1/2, triangular

$ZnCu_3(OH)_6Cl_2$



s=1/2, Kagomé

α-$RuCl_3$

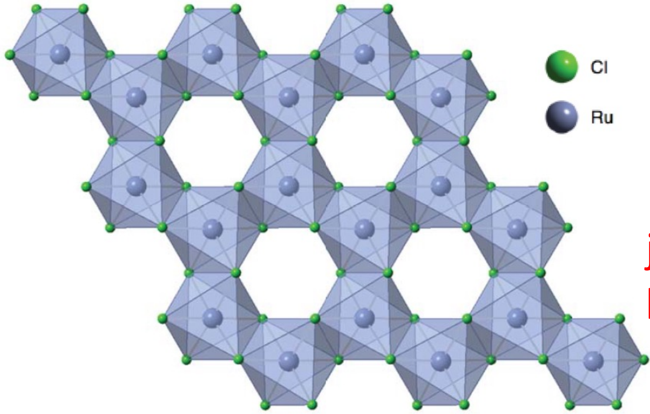


j=1/2, honeycomb

Quantum spin liquids in honeycomb materials

- Can novel chiral quantum spin liquids arise in Kitaev magnets?

α-$RuCl_3$

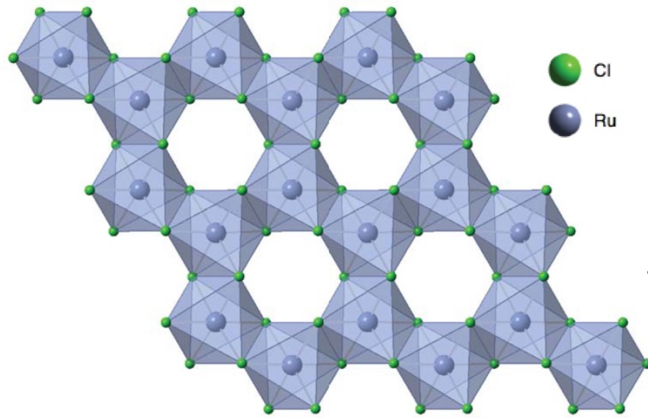


j=1/2,
honeycomb

Quantum spin liquids in honeycomb materials

- Can novel chiral quantum spin liquids arise in Kitaev magnets?

α-RuCl$_3$

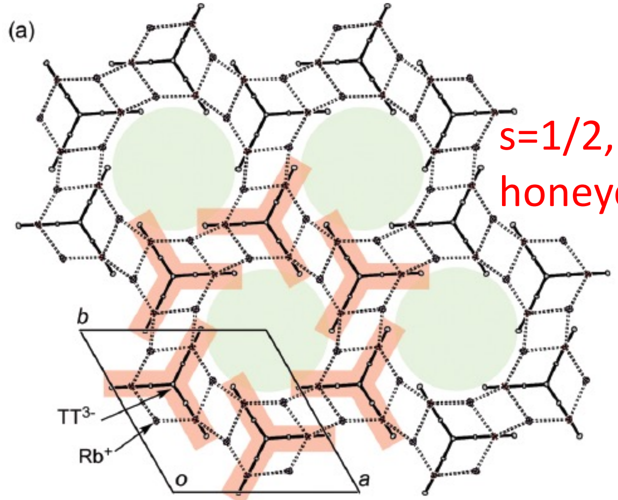


j=1/2, honeycomb

- Is there a quantum spin liquid in the Heisenberg model on the decorated honeycomb lattice?

- Can superconductivity arise by doping the half-filled decorated honeycomb lattice?

$Rb_3TT \cdot 2H_2O$



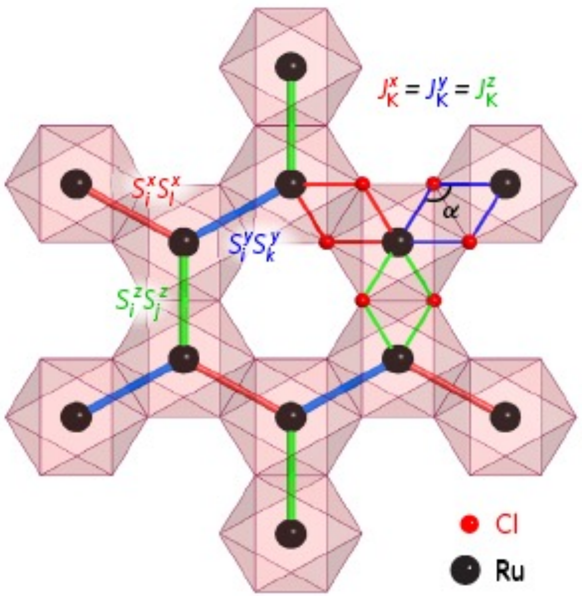
s=1/2, decorated honeycomb lattice

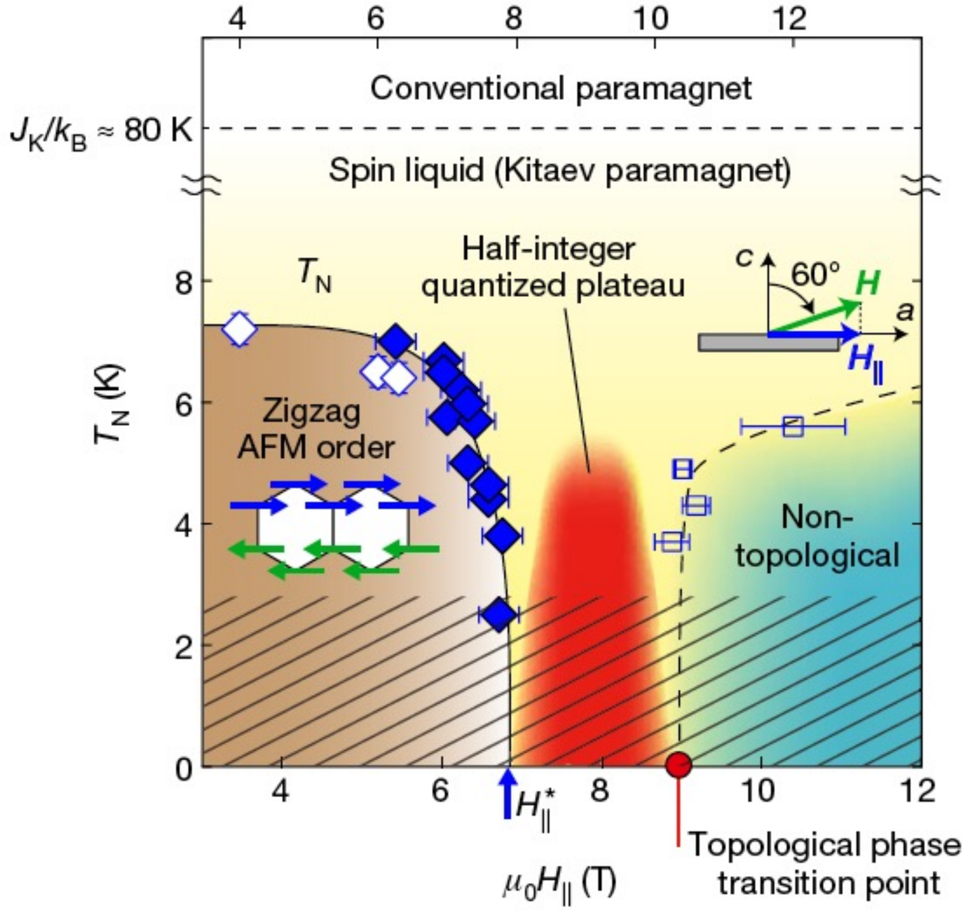
Novel chiral quantum spin liquids in Kitaev magnets

A. Ralko, and JM, PRL **124**, 217203 (2020).

Quantum spin liquid in α-$RuCl_3$

α-$RuCl_3$: $Ru^{3+}(4d^5)$



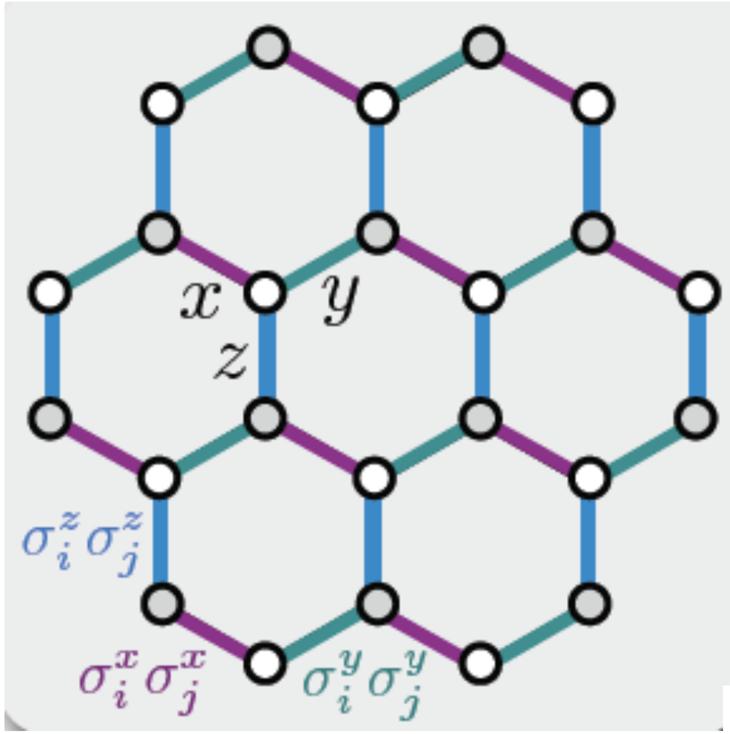


Y. Kasahara, et. al., Nature 559, (2018)

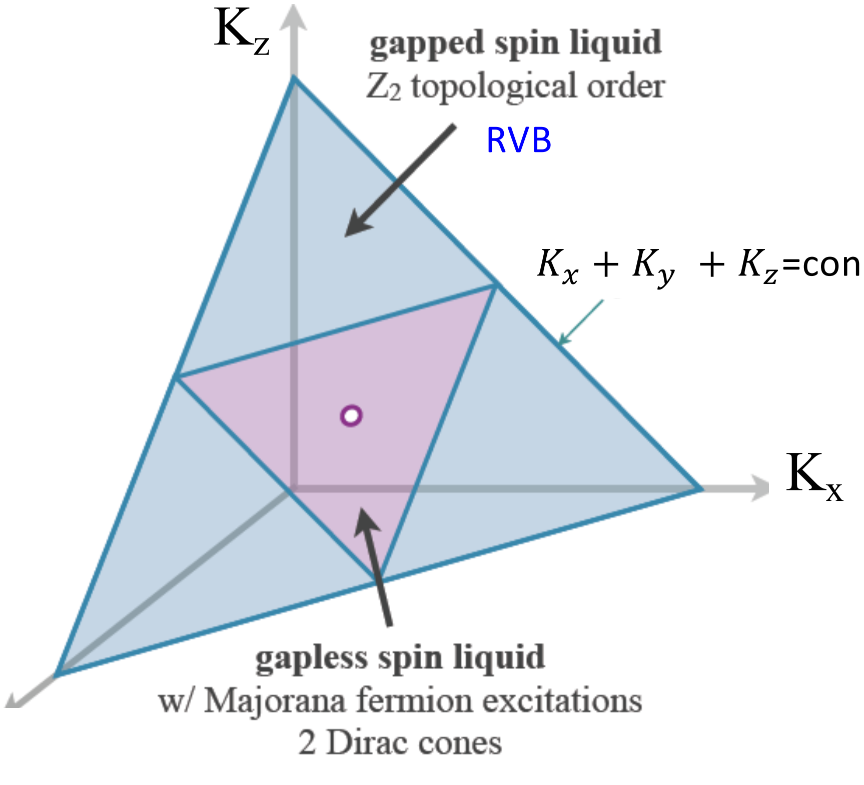
Kitaev spin model

$$H_K = \sum_{<ij>} K_\gamma \sigma_i^\gamma \sigma_j^\gamma = \sum_{<ij>} K_x \sigma_i^x \sigma_j^x + K_y\, \sigma_i^y \sigma_j^y + K_z\, \sigma_i^z \sigma_j^z$$

Bond dependent Ising exchange



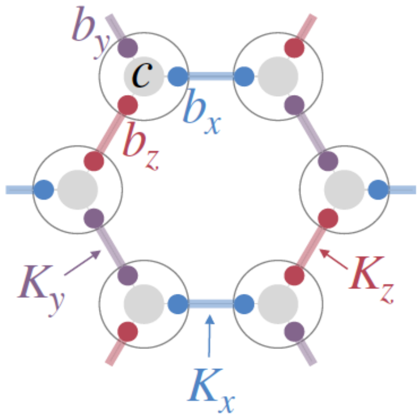
Exact ground state is a spin liquid!



A. Y. Kitaev, Ann. Phys. (2006).

Exact solution to the Kitaev model

Spins are represented through four Majorana fermions:



$b^x, b^y, b^z =$ bond Majorana fermion

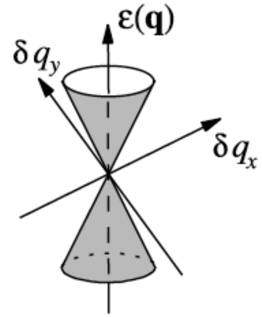
$c =$ matter Majorana fermion

$$\sigma^x = ib^x c$$
$$\sigma^y = ib^y c$$
$$\sigma^z = ib^z c$$

$$H_K = \frac{i}{4}\sum_{<ij>} \hat{A}_{ij} c_i c_j = \frac{i}{4}\sum_{<ij>} 2K_\gamma \hat{u}_{ij}^\gamma\, c_i c_j$$

$$\hat{u}_{ij}^\gamma = i b_i^\gamma b_j^\gamma,\ \hat{u}_{ji}^\gamma = -\,\hat{u}_{ij}^\gamma,\ \hat{A}_{ij} = -\hat{A}_{ji}$$

$$\left[\hat{u}_{ij}^\gamma, H_K\right] = 0,\ u_{ij} = \pm 1$$ Fix Z_2 gauge fields quadratic H!



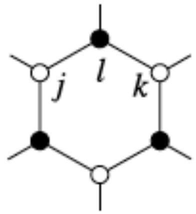
- Quantum spin liquid with gapless Majorana excitations and two Dirac cones.

Effect of a weak magnetic field

Applying a weak magnetic field to the Kitaev model:

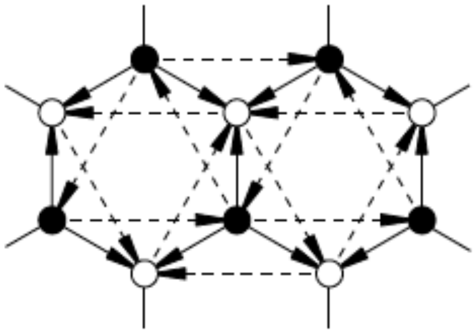
$$V = -\sum_j (h_x \sigma_j^x + h_y \sigma_j^y + h_z \sigma_j^z)$$

Leads up to third order in the field:



$$H_{\mathrm{eff}}^{(3)} \sim -\frac{h_x h_y h_z}{K^2} \sum_{j,k,l} \sigma_j^x \sigma_k^y \sigma_l^z,$$

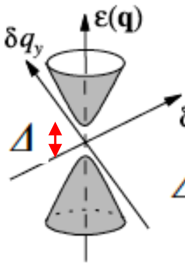
Majorana fermions on honeycomb lattice with n. n. n. chiral amplitudes:



$$H_{\mathrm{eff}} = \frac{\mathrm{i}}{4} \sum_{j,k} A_{jk} c_j c_k,$$

$$A = 2\,K(\longleftarrow) + 2\kappa\,(\leftarrow\!\text{- - -})$$

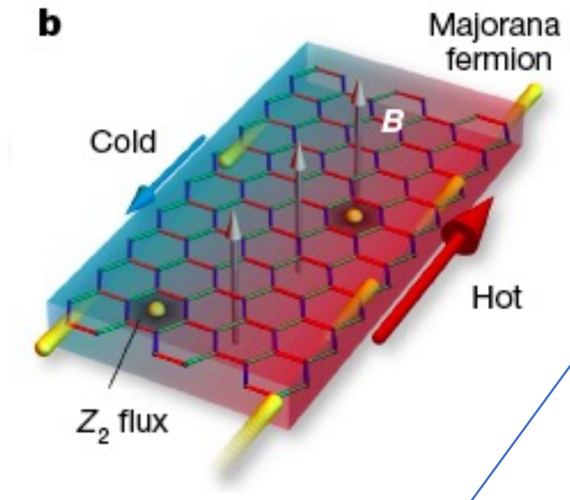
$$\kappa \sim \frac{h_x h_y h_z}{K^2}.$$



$$\Delta \sim \frac{h_x h_y h_z}{K^2}$$

- Gapped chiral quantum spin liquid with non-zero Chern number, $\nu = \pm 1$.
- Topological Majorana edge state gives rise to a half-quantized thermal conductivity.

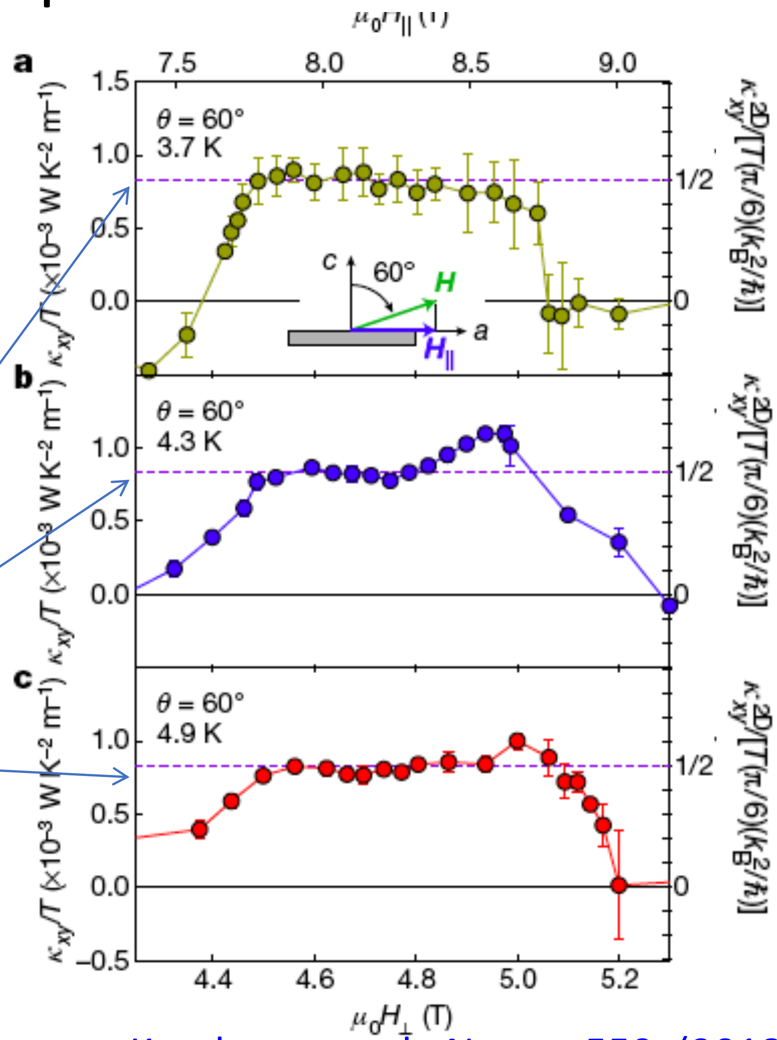
Thermal Hall experiments in α-$RuCl_3$



Half-quantization observed:

$$\kappa_{xy}/T = \nu \frac{\pi}{12} \frac{k_B^2}{\hbar d}$$

Kitaev QSL: ν=+1, $GQSL_{+1}$



Y. Kasahara, et. al., Nature 559, (2018)

Beyond the Kitaev model

- No exact solution to Kitaev model + moderate/strong magnetic fields, Heisenberg terms and/or the Dzyaloshinskii-Moriya contribution.

- We consider the general model:

$$H = H_K + H_{\mathrm{B}} + H_{\mathrm{DM}}$$

$$H_B = -\sum_i \mathbf{B} \cdot \mathbf{S}_i$$

$$H_{\mathrm{DM}} = \sum_{\langle\langle ij \rangle\rangle} \mathbf{D}_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j$$

A. Ralko, and J. Merino, PRL (2020).

Majorana mean-field theory

- We introduce a HF mean-field decoupling of the Majoranas:

$$(\sigma_i^\gamma \sigma_j^\gamma)_{HF} \approx \left\langle \frac{i}{2} b_i^\gamma c_i \right\rangle \frac{i}{2} b_j^\gamma c_j + \left\langle \frac{i}{2} b_j^\gamma c_j \right\rangle \frac{i}{2} b_i^\gamma c_i - \left\langle \frac{i}{2} b_i^\gamma c_i \right\rangle \left\langle \frac{i}{2} b_j^\gamma c_j \right\rangle$$

Magnetic channel

$$-\left\langle \frac{i}{2} b_i^\gamma b_j^\gamma \right\rangle \frac{i}{2} c_i c_j - \left\langle \frac{i}{2} c_i c_j \right\rangle \frac{i}{2} b_i^\gamma b_j^\gamma + \left\langle \frac{i}{2} b_i^\gamma b_j^\gamma \right\rangle \left\langle \frac{i}{2} c_i c_j \right\rangle +$$

Spin liquid channel

$$-\left\langle \frac{i}{2} b_i^\gamma c_j \right\rangle \frac{i}{2} b_j^\gamma c_i - \left\langle \frac{i}{2} b_j^\gamma c_i \right\rangle \frac{i}{2} b_i^\gamma c_j + \left\langle \frac{i}{2} b_i^\gamma c_j \right\rangle \left\langle \frac{i}{2} b_j^\gamma c_i \right\rangle$$

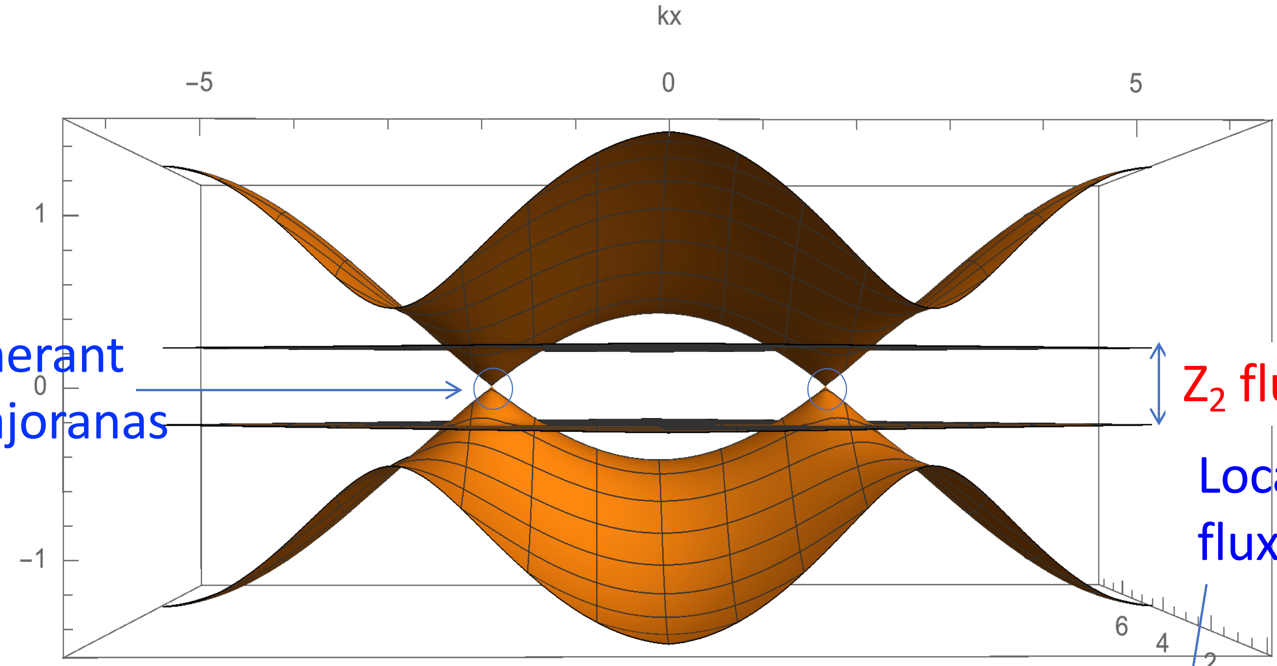
- Together with the constraints to recover actual spin Hilbert space:

$$b^z c + b^x b^y = 0$$
$$b^y c - b^x b^z = 0$$
$$b^x c + b^y b^z = 0$$

60 self-consistent non-linear coupled equations for Kitaev+Heisenberg+DM

Majorana mean-field theory

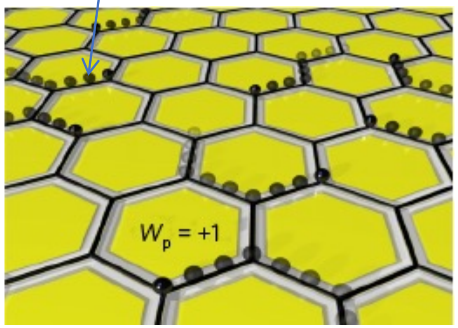
Spectrum of pure Kitaev model



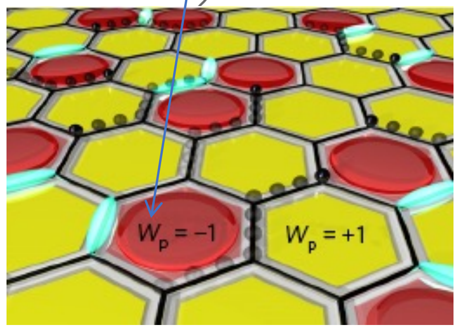
Itinerant Majoranas

Z_2 flux gap

Localized fluxes



MMFT recovers exact energy: E=-0.393649K.



Beyond the Kitaev model

- No exact solution to Kitaev model + moderate/strong magnetic fields, Heisenberg terms and/or Dzyaloshinskii-Moriya contribution.

- We consider the general model:

$$H = H_K + H_B + \cancel{H_{DM}}$$

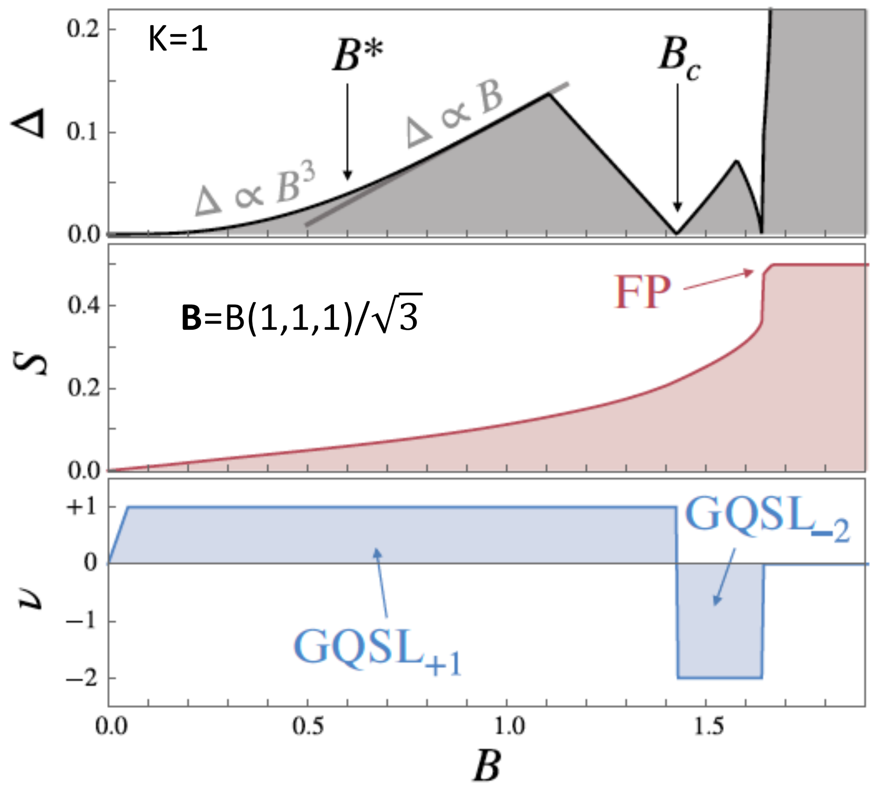
$$H_B = -\sum_i \mathbf{B} \cdot \mathbf{S}_i$$

$$\cancel{H_{DM} = \sum_{\langle\langle ij \rangle\rangle} \mathbf{D}_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j}$$

- Take magnetic field in the [1,1,1] direction: $\mathbf{B}=B(1,1,1)/\sqrt{3}$

Magnetic field dependence

Kitaev model under a magnetic field

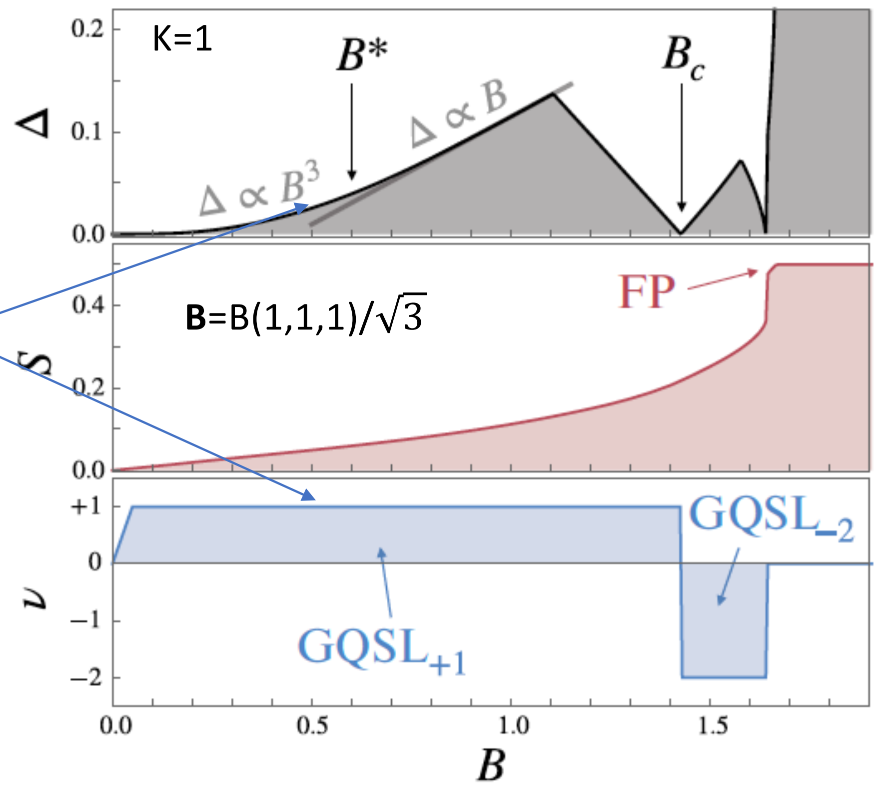


A. Ralko, and J. Merino, PRL (2020).

Magnetic field dependence

Kitaev model under a magnetic field

Kitaev gapped quantum spin liquid with $\nu = +1$.

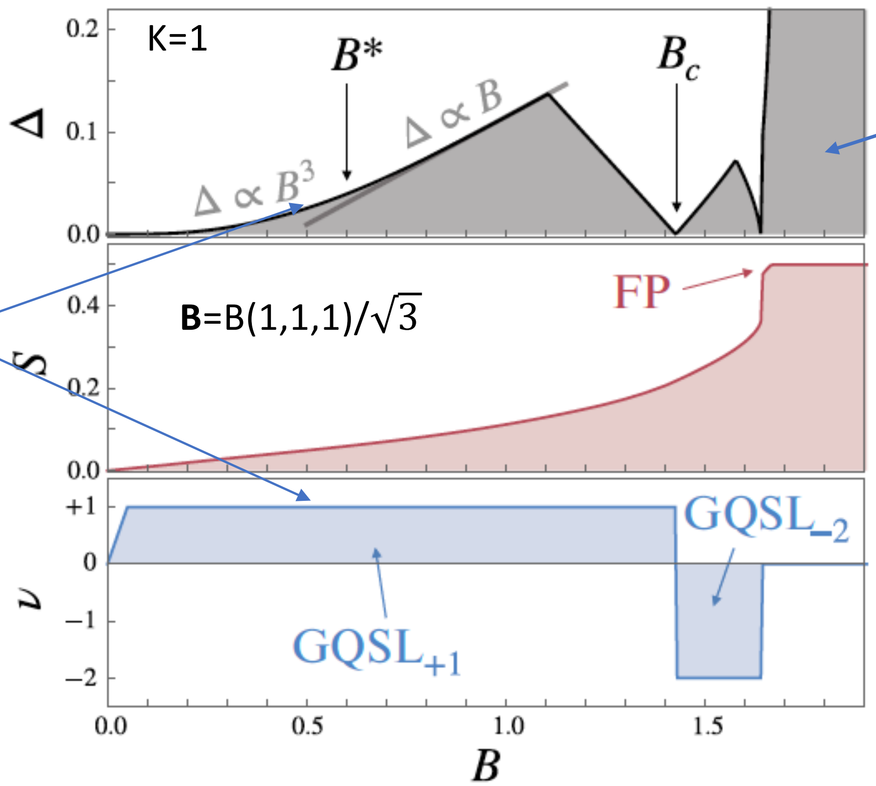


A. Ralko, and J. Merino, PRL (2020).

Magnetic field dependence

Kitaev model under a magnetic field

Kitaev gapped quantum spin liquid with $\nu = +1$.



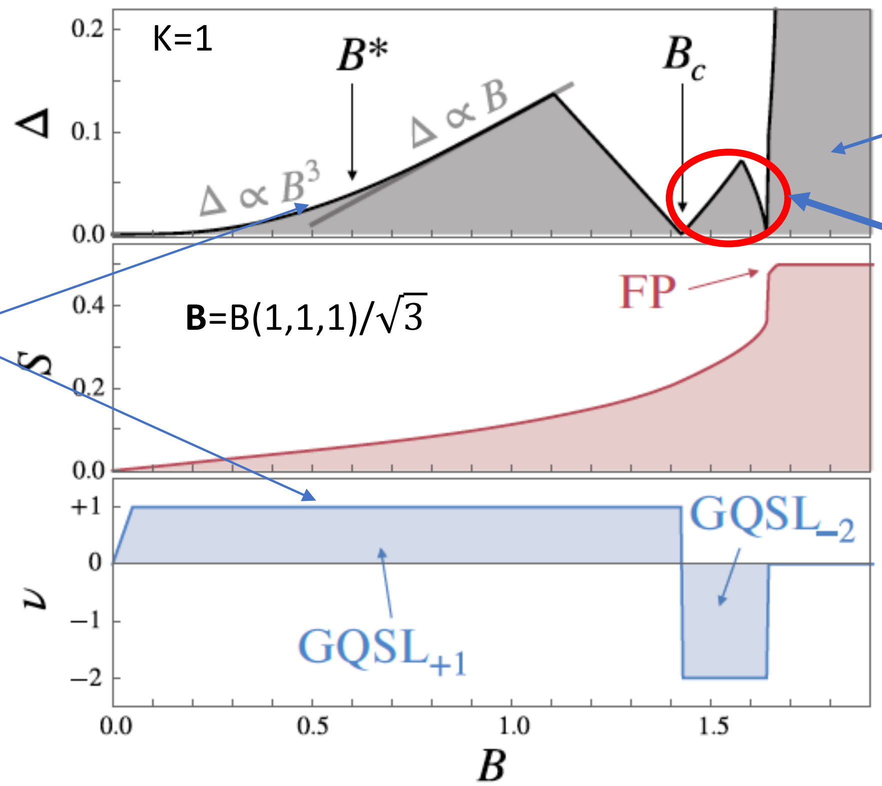
Gapped polarized phase $\nu = 0$.

A. Ralko, and J. Merino, PRL (2020).

Magnetic field dependence

Kitaev model under a magnetic field

Kitaev gapped quantum spin liquid with $\nu = +1$.



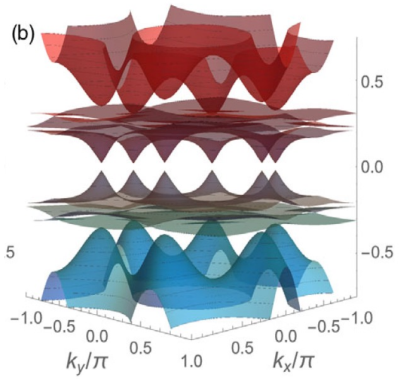
Gapped polarized phase $\nu = 0$.

Novel gapped quantum spin liquid with ν =-2 for 1.4 <B<1.64!

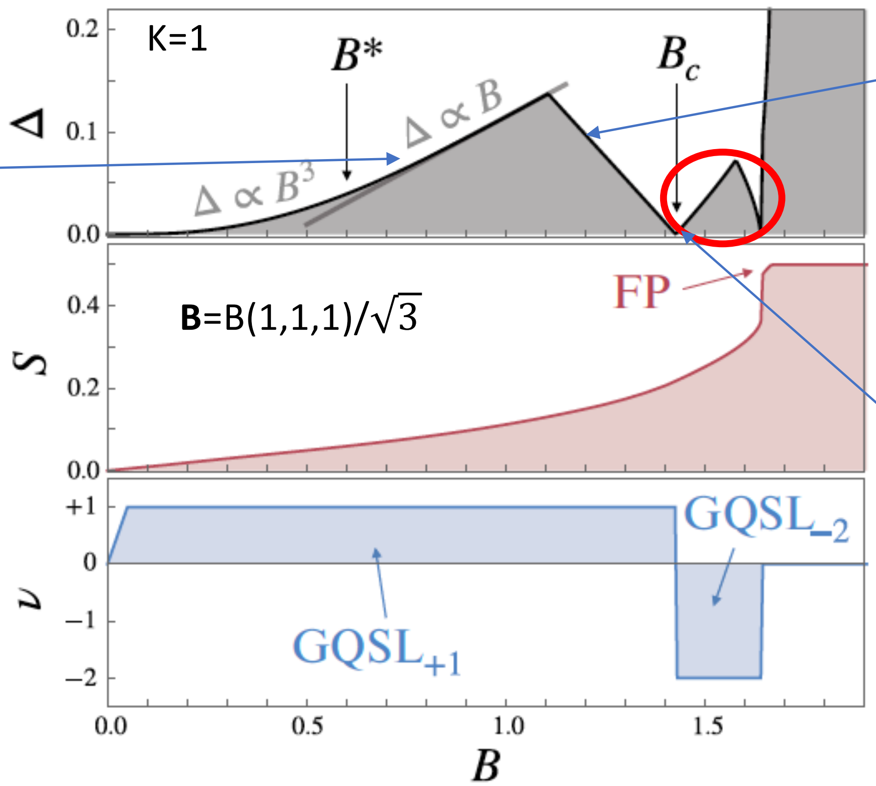
A. Ralko, and J. Merino, PRL (2020).

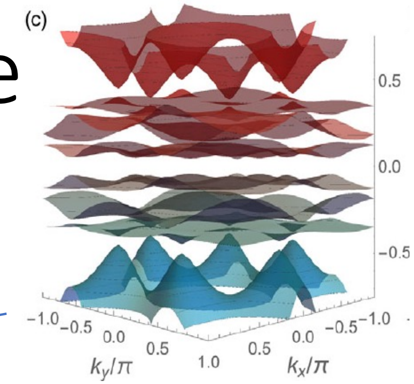
Magnetic field dependence

Kitaev model under a magnetic field

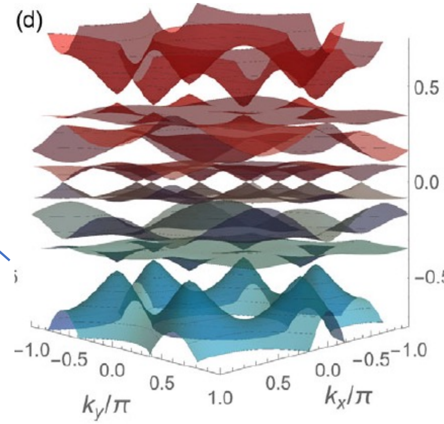


QSL gapped at
Dirac points.





Dirac cones are
washed out.



Gap closes at the
M-points.

A. Ralko, and J. Merino, PRL (2020).

Beyond the Kitaev model

- No exact solution to Kitaev model + moderate/strong magnetic fields, Heisenberg terms and/or Dzyaloshinskii-Moriya contribution.

- We consider the general model:

$$H = H_K + H_B + H_{DM}$$

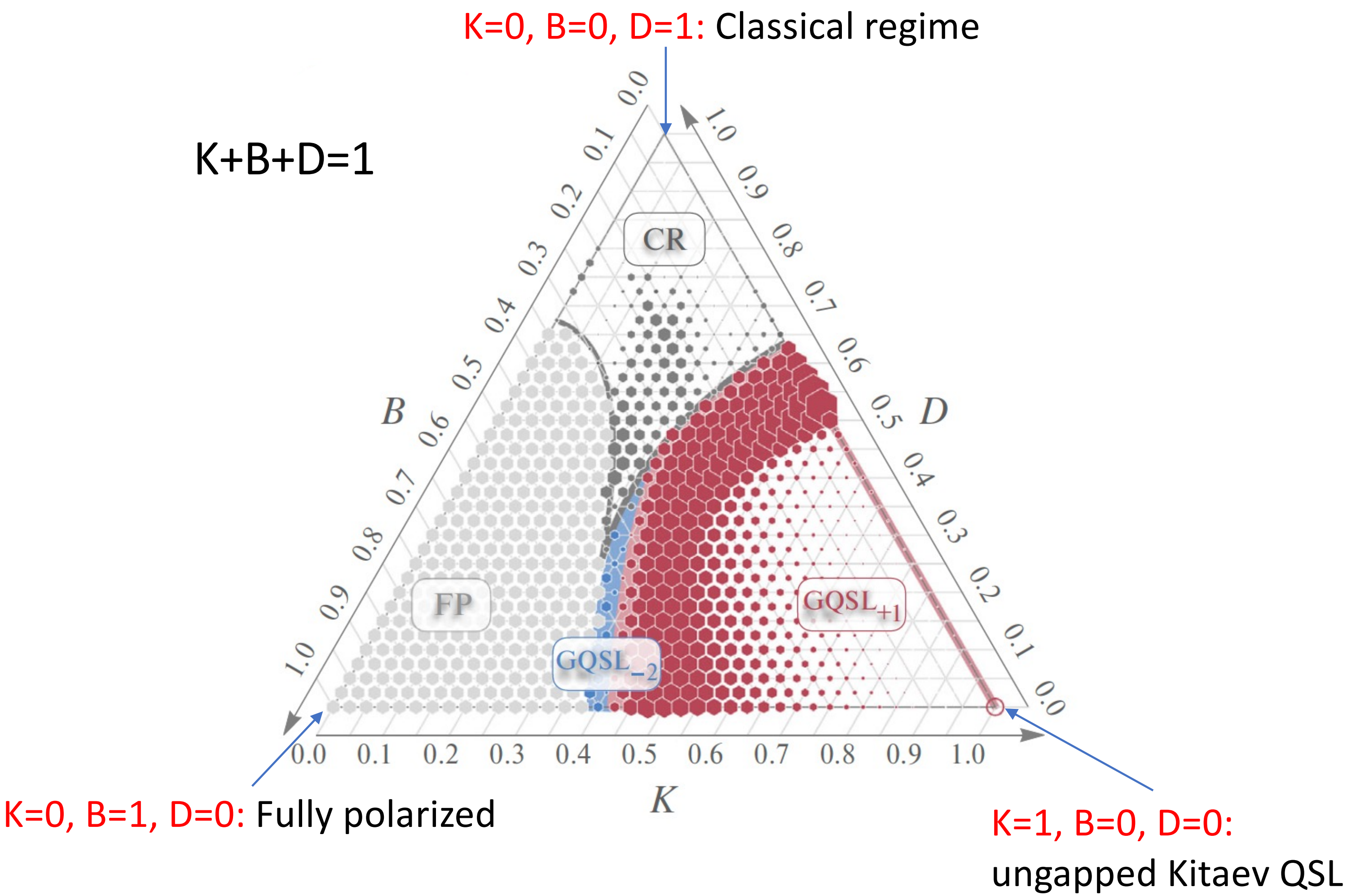
$$H_B = -\sum_i \mathbf{B} \cdot \mathbf{S}_i$$

$$H_{DM} = \sum_{\langle\langle ij \rangle\rangle} \mathbf{D}_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j$$

- We take the magnetic field in the [1,1,1] direction: **B**=B(1,1,1)/$\sqrt{3}$
- We take a DM field in the [0,0,1] direction: **D**=D(0,0,1)/$\sqrt{3}$
- Obtain K-B-D phase diagram.

Full phase diagram

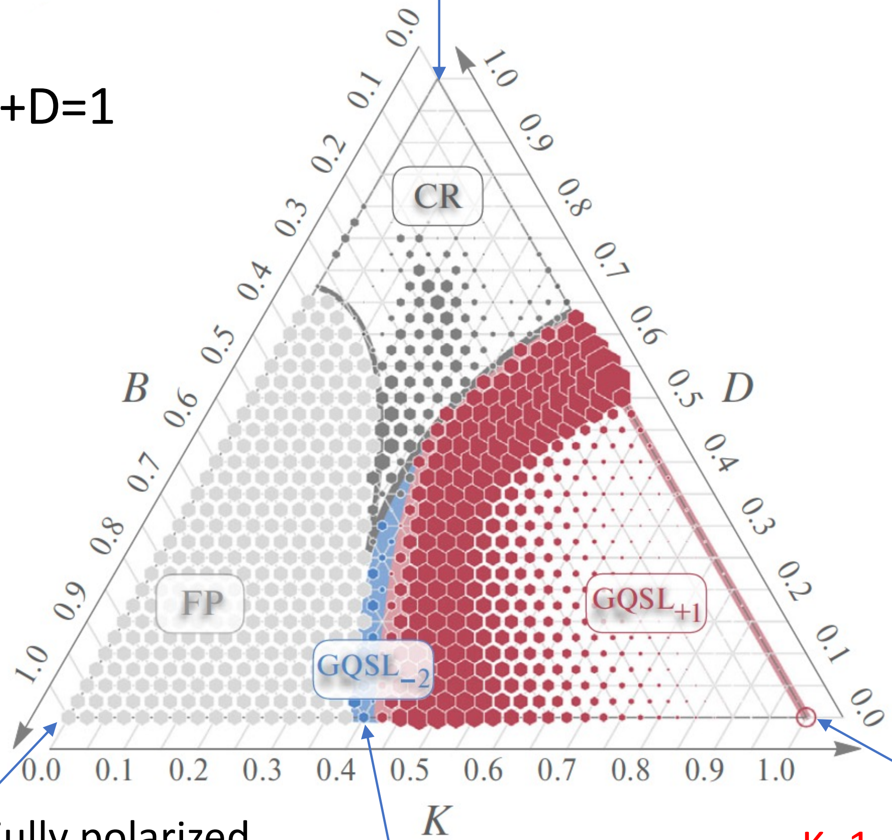
K+B+D=1



Full phase diagram

K=0, B=0, D=1: Classical regime

K+B+D=1



K=0, B=1, D=0: Fully polarized

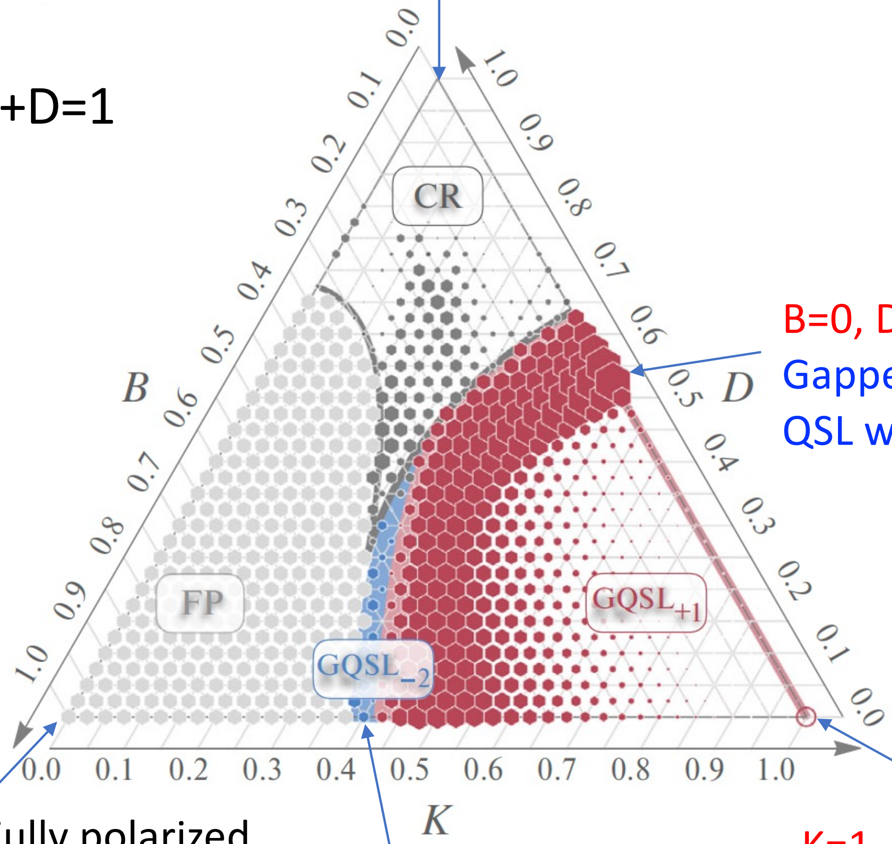
Gapped QSL with ν =-2

K=1, B=0, D=0:
ungapped Kitaev QSL

Full phase diagram

K=0, B=0, D=1: Classical regime

K+B+D=1



B=0, D $\neq$ 0:
Gapped chiral QSL with ν =1

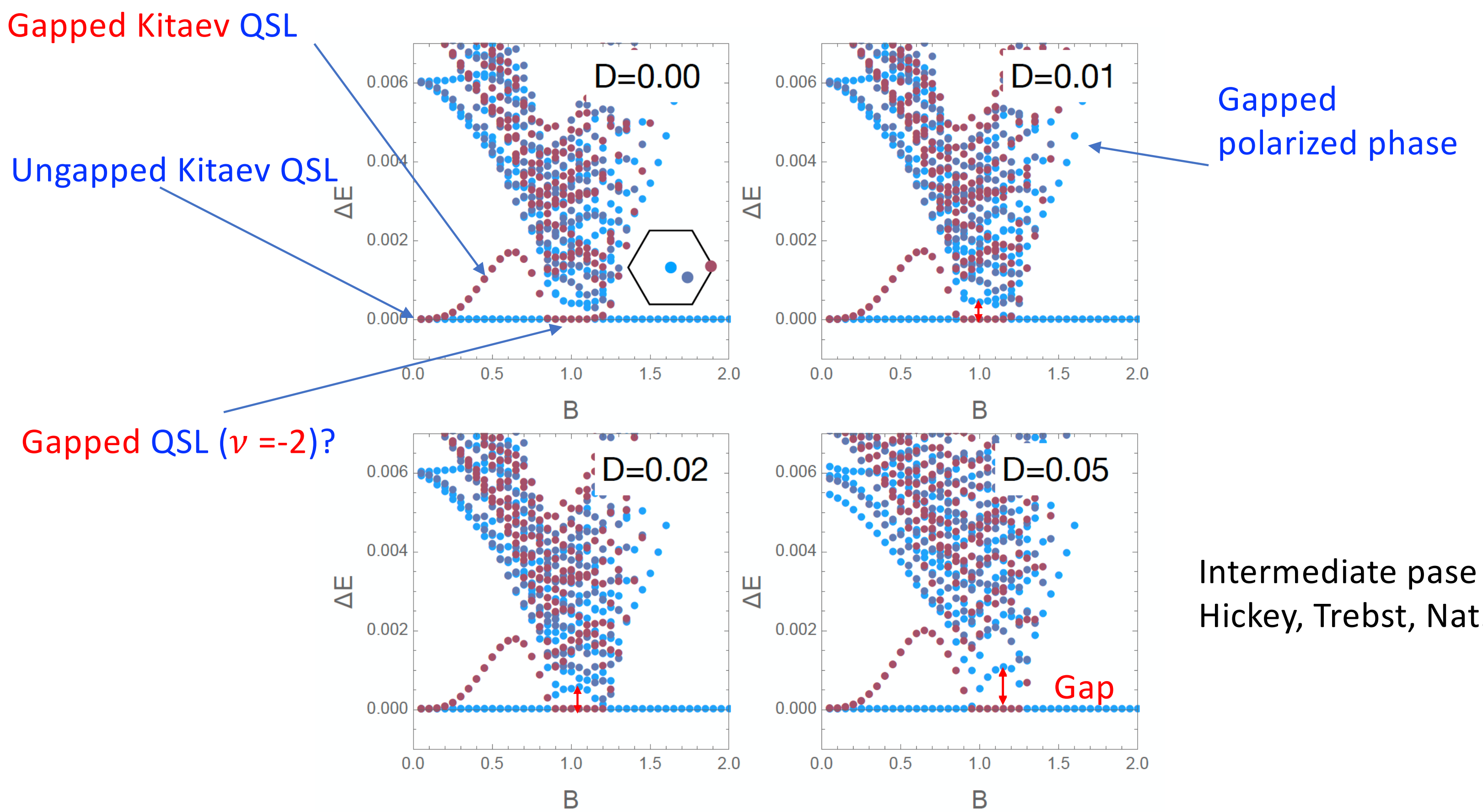
K=0, B=1, D=0: Fully polarized

Gapped QSL with ν =-2

K=1, B=0, D=0:
ungapped Kitaev QSL

Beyond MMFT: exact diagonalization of K-B-D model

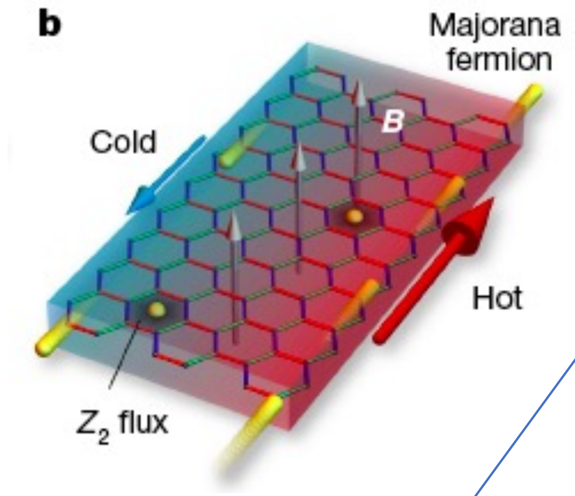
Exact eigenstates of Kitaev model+B+DM

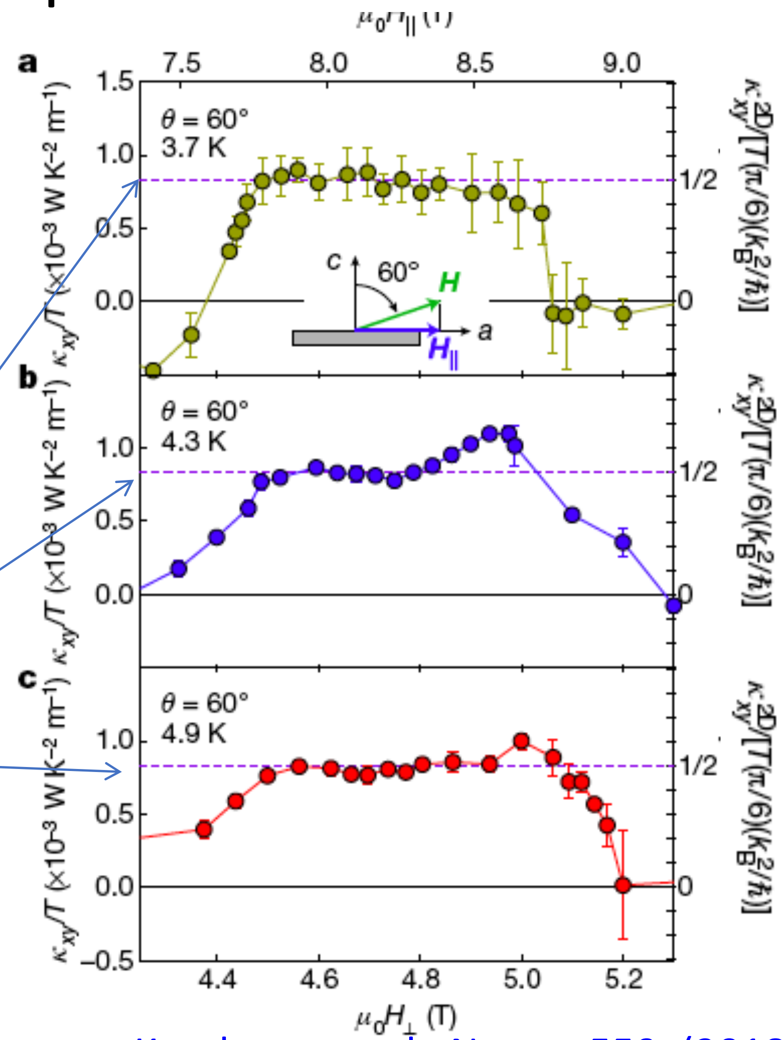


Intermediate pase consistent with Hickey, Trebst, Nat. Comm. (2019)

- An intermediate phase is found at sufficiently large: $B \sim K$
- Gap in intermediate phase is enhanced by the DM interaction.

Thermal Hall experiments in α-$RuCl_3$





Y. Kasahara, et. al., Nature 559, (2018)

Half-quantization observed:

$$\kappa_{xy}/T = \nu \frac{\pi}{12}\frac{k_B^2}{\hbar d}$$

Kitaev QSL: ν=+1, $GQSL_{+1}$

Can a novel ν=-2, $GQSL_{-2}$ be observed?

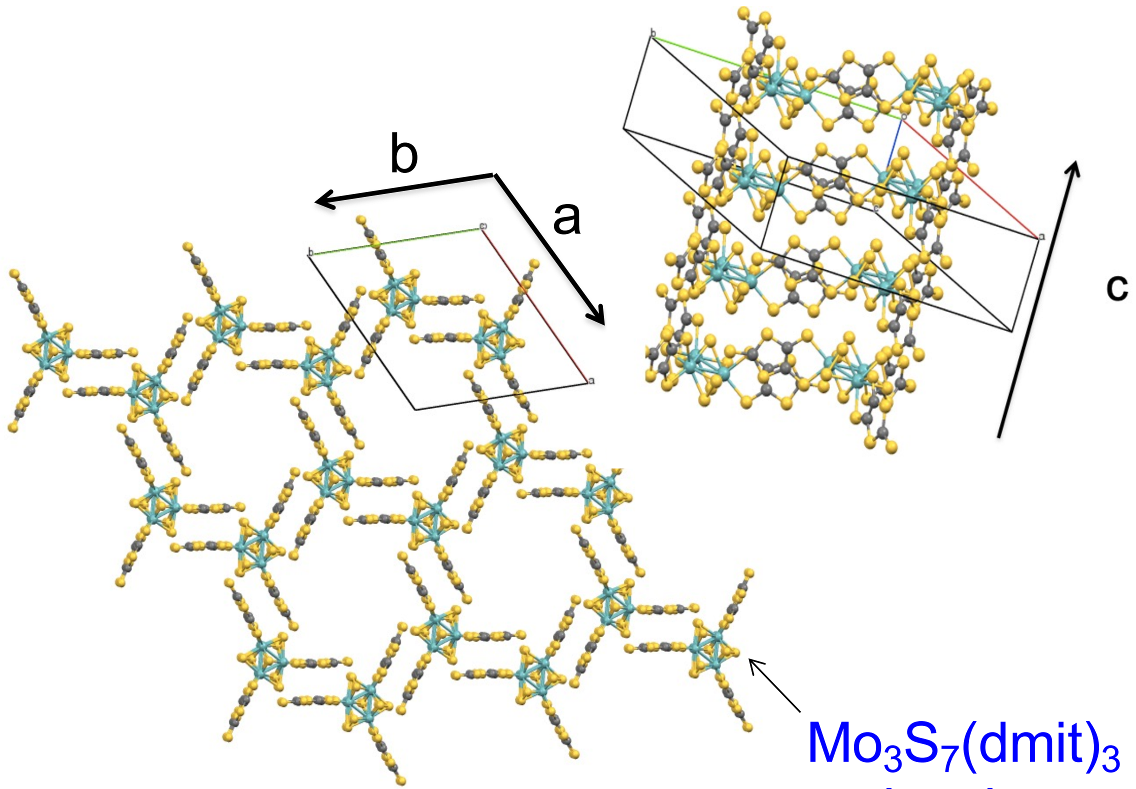
Unconventional superconductivity in decorated honeycomb materials

JM, M. F. López, and B. J. Powell, PRB (2021).

M. F. López, and JM, PRB (2020).

$Mo_3S_7(dmit)_3$ and $Rb_3TT{\cdot}2H_2O$ materials

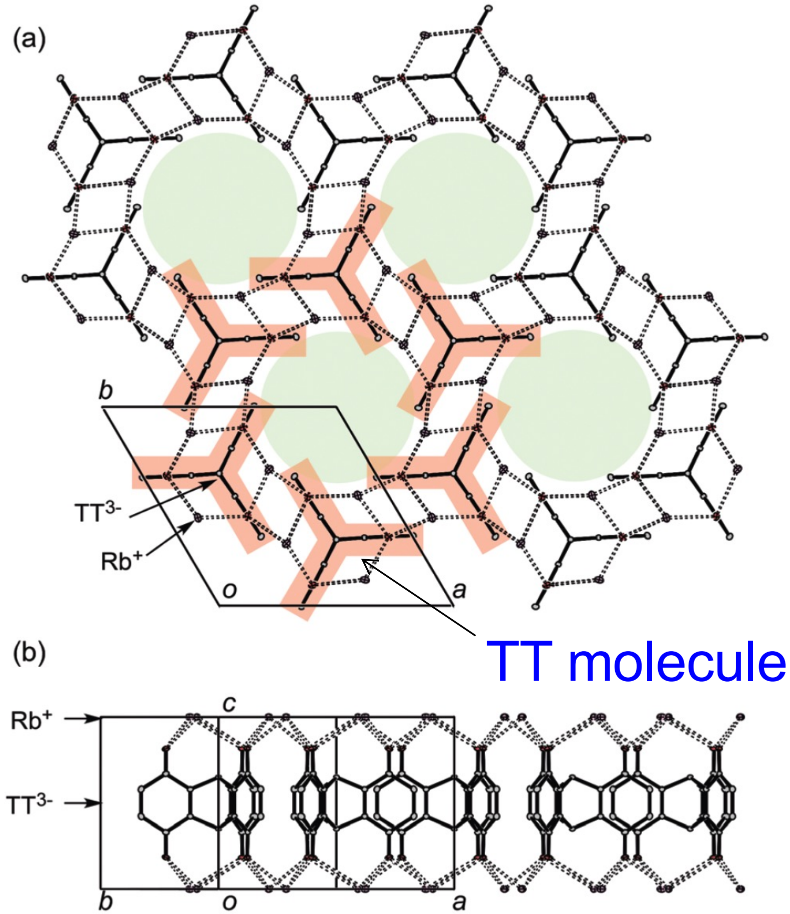
$Mo_3S_7(dmit)_3$



$Mo_3S_7(dmit)_3$ molecule

Rosa Llusar, et. al., JACS (2004).

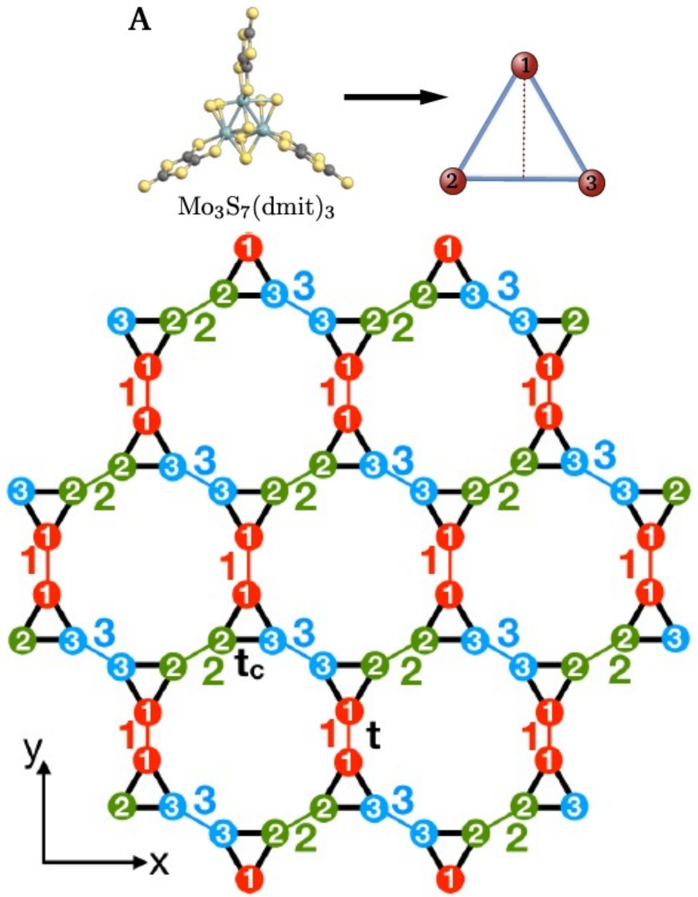
$Rb_3TT{\cdot}2H_2O$



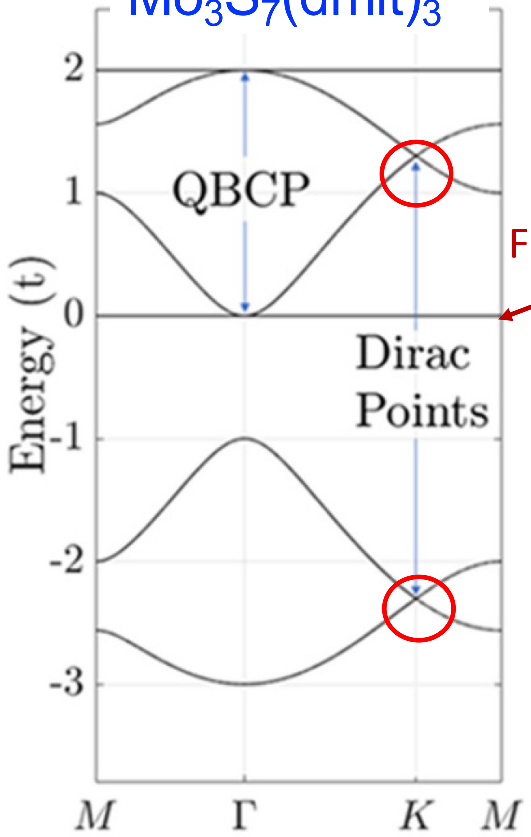
TT molecule

Y. Shuku et. al., Chem. Commun. (2018).

Tight-binding model for $Mo_3S_7(dmit)_3$ and $Rb_3TT{\cdot}2H_20$

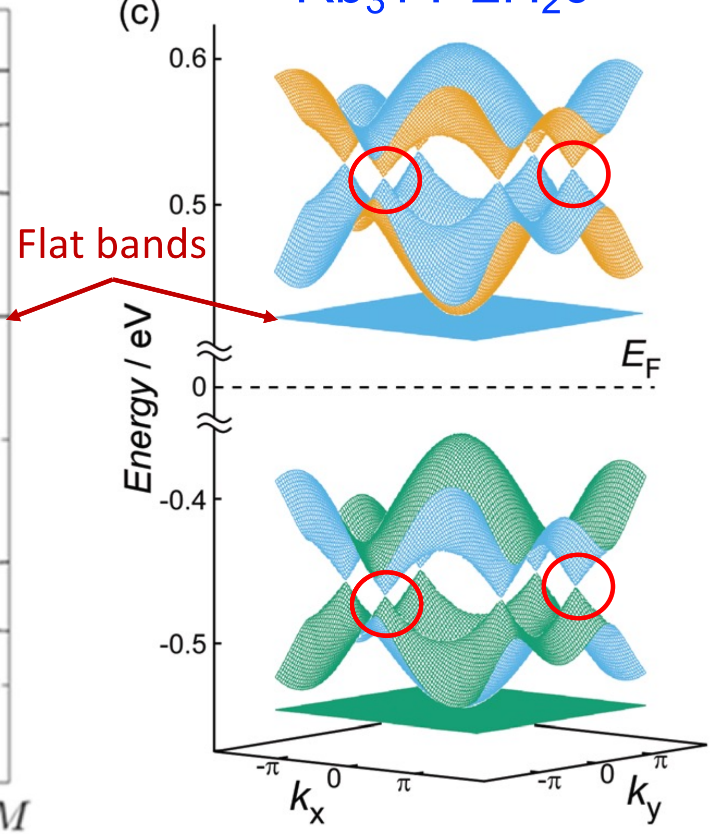


$Mo_3S_7(dmit)_3$



M. F. López, JM, PRB (2019)

$Rb_3TT{\cdot}2H_20$



Y. Shuku et. al., Chem. Comm. (2018)

- Dirac cones: non-trivial topology under significant spin-orbit coupling.
- Coulomb interaction effects enhanced in proximity to flat bands as in TBG.

Minimal strongly correlated model

Hubbard model on a decorated honeycomb lattice:

$$H = -t_c \sum_{<ij>,\sigma} (c_{i\sigma}^{\dagger} c_{j\sigma} + H.c.) - t \sum_{<ij>,\sigma} (c_{i\sigma}^{\dagger} c_{j\sigma} + H.c.) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

At half-filling and U, U>>t, t_c the Hubbard model maps onto:

$$\mathcal{H} = J \sum_{\langle j,k \rangle} \vec{S}_j \cdot \vec{S}_k$$

Is the ground state of the Heisenberg model on a decorated honeycomb a quantum spin liquid?

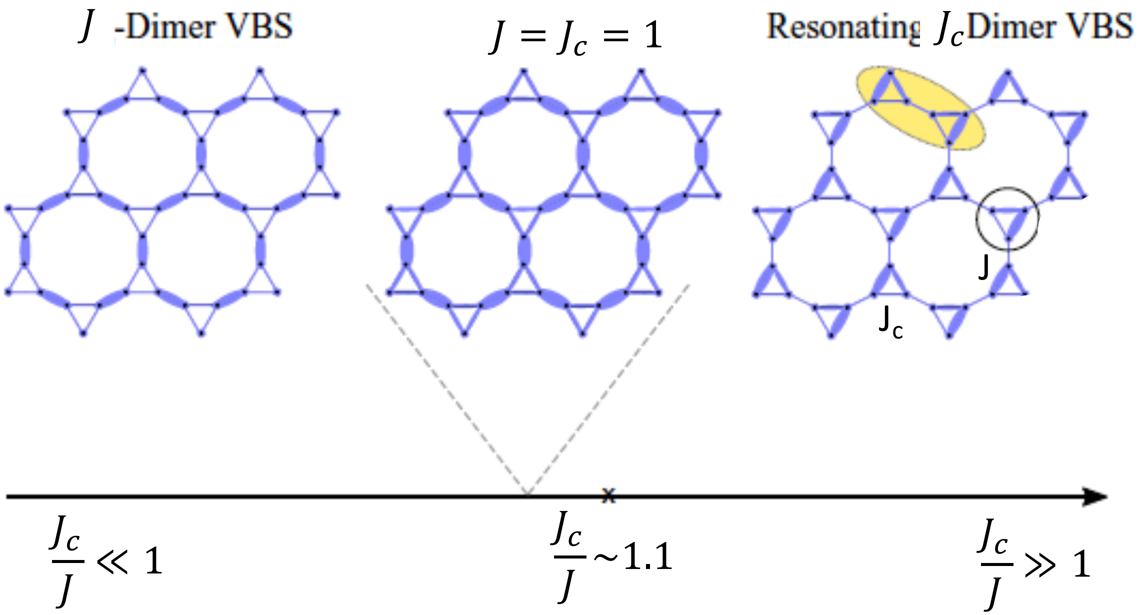
At finite hole doping consider the t-J model:

$$H = -t_c \sum_{<ij>,\sigma} P_G (c_{i\sigma}^{\dagger} c_{j\sigma} + H.c.) P_G - t \sum_{<ij>,\sigma} P_G (c_{i\sigma}^{\dagger} c_{j\sigma} + H.c.) P_G + J_c \sum_{<ij>,\sigma} \vec{S}_i \vec{S}_j + J \sum_{<ij>,\sigma} \vec{S}_i \vec{S}_j$$

Can unconventional superconductivity arise under hole doping? Which is the role played by the flat bands and the Dirac cones ?

RVB spin liquid on the decorated honeycomb lattice?

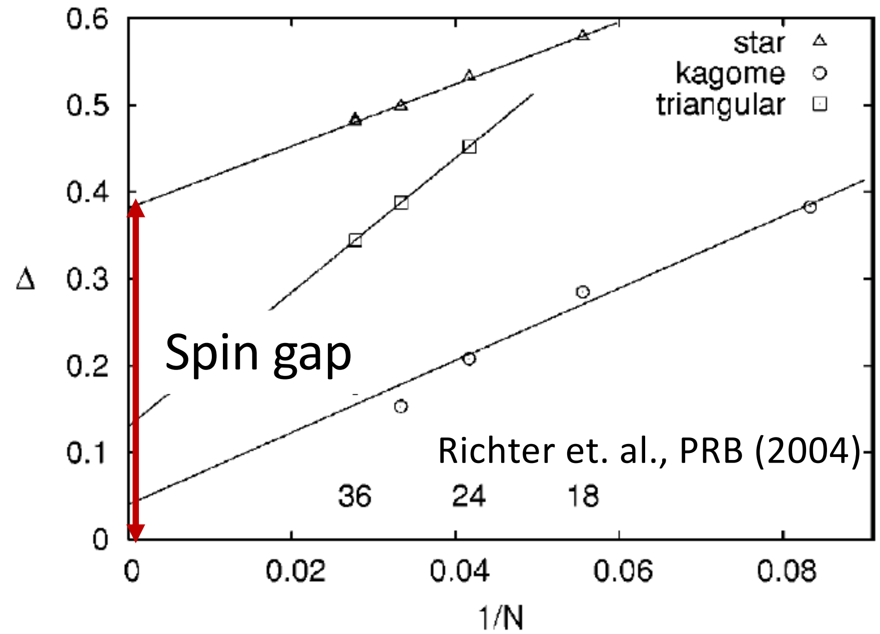
Tensor network T=0 phase diagram



Jahromi, Orus, PRB (2018)

Exact diagonalization 42-sites

Lattice	Triangular	Kagomé	Star
e_0	−0.1842	−0.2172	−0.3091
m^+/m^+_{class}	0.386	0.000	0.122

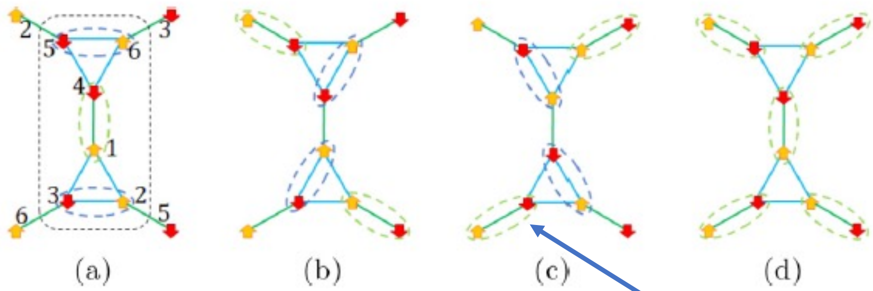


- Ground state at J=J_c is a spin disordered Valence Bond Solid.
- Strongly suppressed long range AF order with large singlet-triplet spin gap.

RVB spin liquid on the decorated honeycomb lattice?

NN-RVB on cluster

M. F. López, and JM, PRB (2020)



$$(ij) = \frac{1}{\sqrt{2}}(c^\dagger_{i\uparrow}c^\dagger_{j\downarrow} - c^\dagger_{i\downarrow}c^\dagger_{j\uparrow})|0\rangle$$

Spin singlet

$$|RVB\rangle = (14)(23)(56) + (13)(25)(46) + (12)(36)(45) - (14)(25)(36)$$

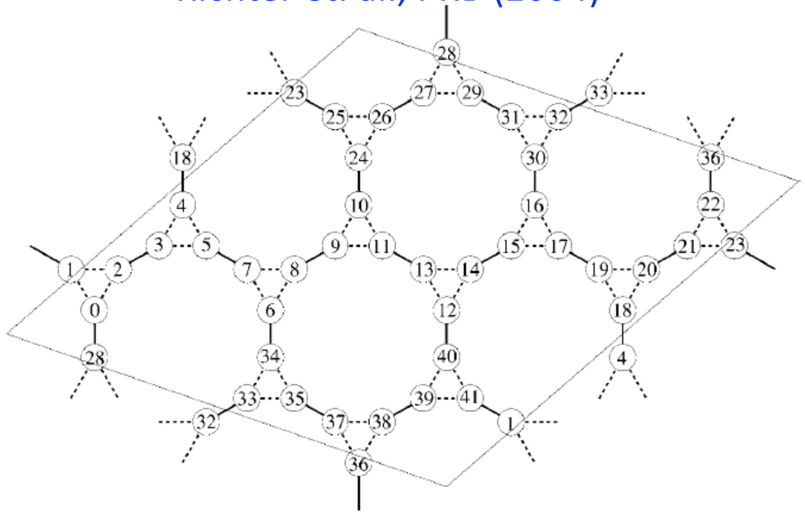
$$\langle RVB|\Psi_0\rangle = 0.9988$$

$$\langle \mathbf{S_i S_j}\rangle^{\Delta\rightarrow\Delta} = -0.573$$

$$\langle \mathbf{S_i S_j}\rangle^{\Delta} = -0.191$$

Exact diagonalization on 42-sites

Richter et. al., PRB (2004)



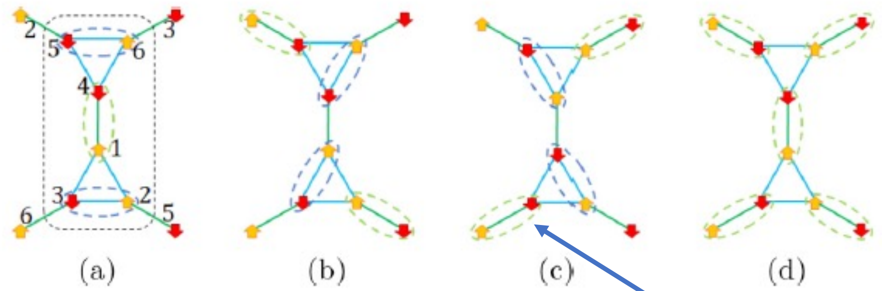
$$\langle \mathbf{S}_i\mathbf{S}_j\rangle^{\Delta\rightarrow\Delta} = -0.591$$

$$\langle \mathbf{S}_i\mathbf{S}_j^{\Delta}\rangle = -0.168$$

RVB spin liquid on the decorated honeycomb lattice?

NN-RVB on cluster

M. F. López, and JM, PRB (2020)



$$(ij) = \frac{1}{\sqrt{2}}(c^\dagger_{i\uparrow}c^\dagger_{j\downarrow} - c^\dagger_{i\downarrow}c^\dagger_{j\uparrow})|0\rangle$$

Spin singlet

$$|RVB\rangle = (14)(23)(56) + (13)(25)(46) + (12)(36)(45) - (14)(25)(36)$$

$$\langle RVB|\Psi_0\rangle = 0.9988$$

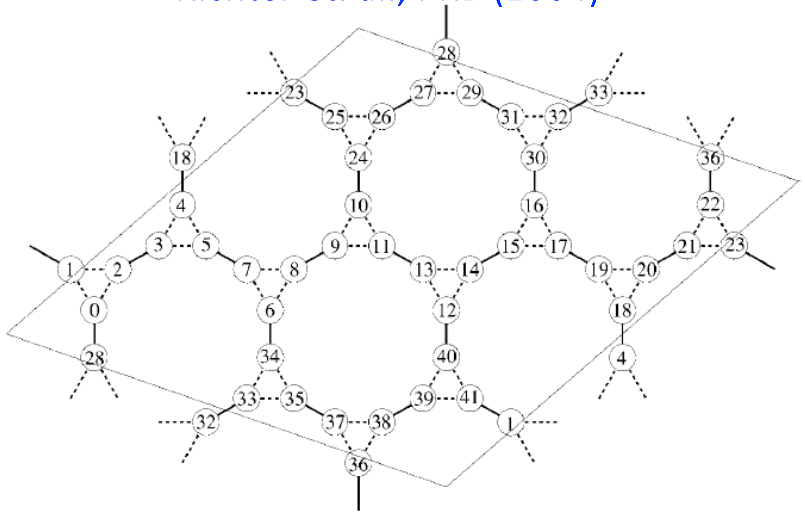
$$\langle \mathbf{S_i S_j}\rangle^{\Delta\to\Delta} = -0.573$$

$$\langle \mathbf{S_i S_j}\rangle^{\Delta} = -0.191$$

$$\boxed{|RVB\rangle = \sum_m a_m|m\rangle}$$

Exact diagonalization on 42-sites

Richter et. al., PRB (2004)



$$\langle \mathbf{S}_i\mathbf{S}_j\rangle^{\Delta\to\Delta} = -0.591$$

$$\langle \mathbf{S}_i\mathbf{S}_j^{\Delta}\rangle = -0.168$$

- NN-RVB state is a good candidate for the ground state of Heisenberg model on the DHL.

RVB theory of superconductivity on the DHL

At non-zero hole doping we explore the t_c-t-J_c-J model:

$$H = -t_c \sum_{\langle \alpha i, \alpha j\rangle \sigma} P_G(c^\dagger_{\alpha i\sigma} c_{\alpha j\sigma} + c^\dagger_{\alpha j\sigma} c_{\alpha i\sigma}) P_G \; - t \sum_{\langle Ai,\, Bi\rangle,\, \sigma} P_G(c^\dagger_{Ai\sigma} c_{Bi\sigma} + c^\dagger_{Bi\sigma} c_{Ai\sigma}) P_G$$

$$+ J_c \sum_{<\alpha i, \alpha j>} \left(\vec{S}_{\alpha i} \cdot \vec{S}_{\beta j} - \frac{n_{\alpha i} n_{\beta j}}{4} \right) + J \sum_{<Ai, Bi>} \left(\vec{S}_{Ai} \cdot \vec{S}_{Bi} - \frac{n_{Ai} n_{Bi}}{4} \right) \qquad P_G = \prod_i (1 - n_{i\uparrow} n_{i\downarrow})$$

Introducing bond singlet operators: $h^\dagger_{\alpha i, \beta j} = \frac{1}{\sqrt{2}} \left(c^\dagger_{\alpha i\uparrow} c^\dagger_{\beta j\downarrow} - c^\dagger_{\alpha i\downarrow} c^\dagger_{\beta j\uparrow} \right)$

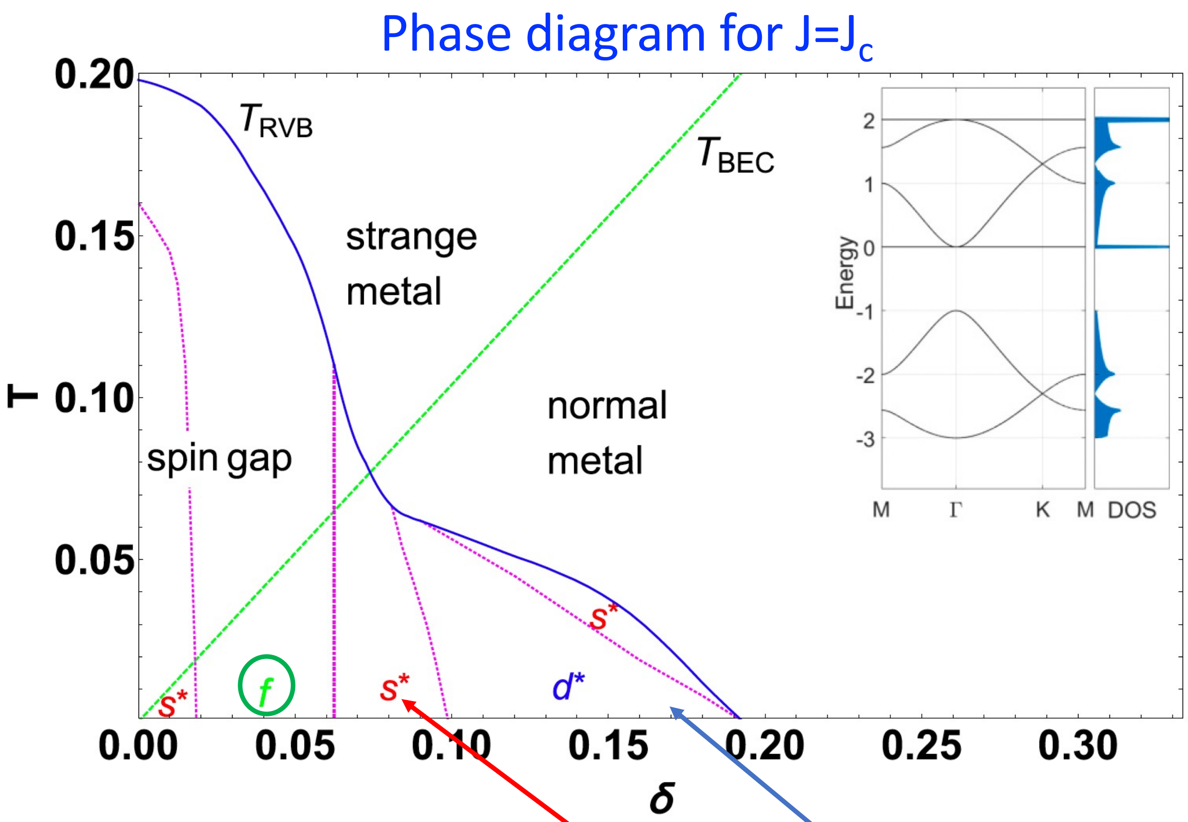
$$\sum_{<\alpha i, \beta j>} \left(\vec{S}_{\alpha i} \cdot \vec{S}_{\beta j} - \frac{n_{\alpha i} n_{\beta j}}{4} \right) = - \sum_{<\alpha i, \beta j>} h^\dagger_{\alpha i, \beta j} h_{\alpha i, \beta j}$$

Performing a Hartree-Fock-Bogoliubov decoupling of the free energy:

$$\Phi = -\frac{1}{\beta} \sum_{m, \mathbf{k}, \sigma} \ln\left(1 + e^{-\beta \omega_m(\mathbf{k})}\right) - \sum_{m, \mathbf{k}} \omega_m(\mathbf{k}) + 6 N_s \mu \; + \; \tilde{J}_c \sum_{\langle \alpha i, \alpha j\rangle} \left(|\Delta_{\alpha i, \alpha j}|^2 + |\chi_{\alpha i, \alpha j}|^2 \right) + \; \tilde{J} \sum_{\langle Ai, Bi\rangle} \left(|\Delta_{Ai, Bi}|^2 + |\chi_{Ai, Bi}|^2 \right)$$

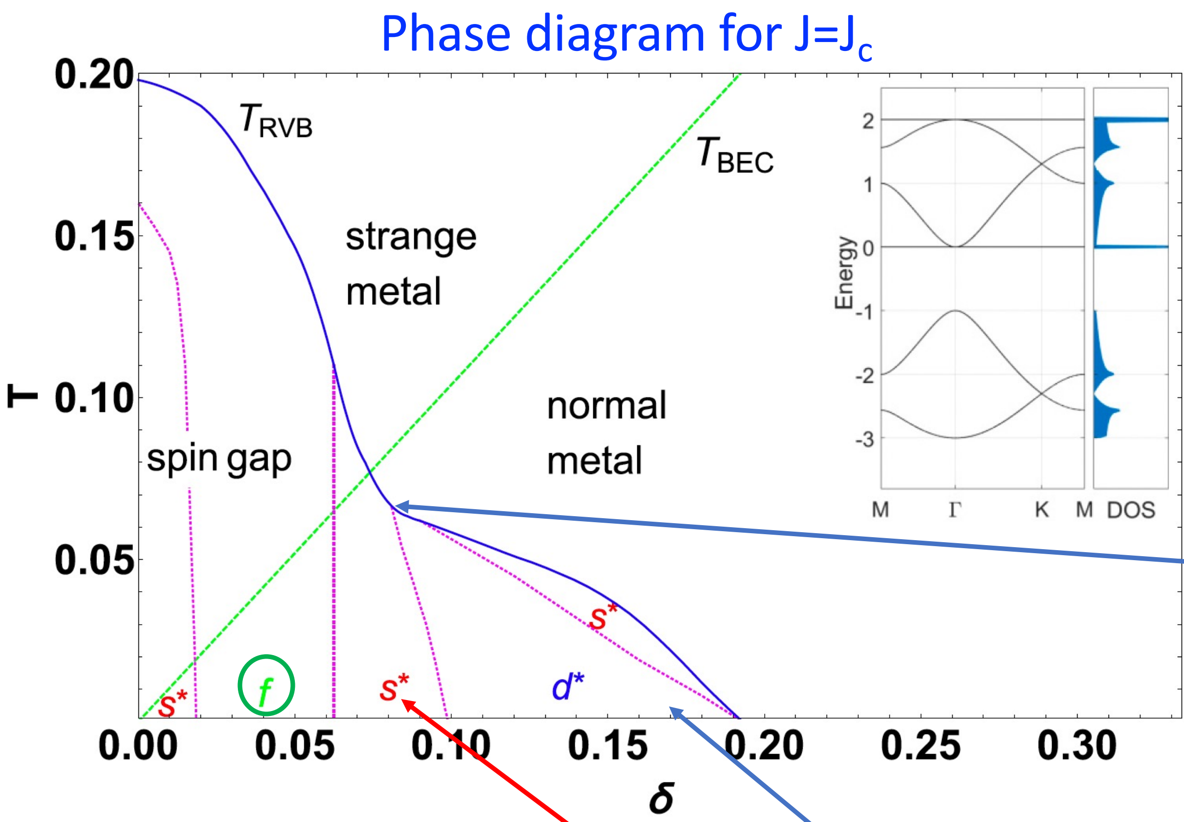
$\Delta_{\alpha i, \beta j} = \langle h_{\alpha i, \beta j} \rangle \quad \chi_{\alpha i, \beta j} = \langle h_{\alpha i, \beta j} \rangle$ Gutzwiller approx: $(J/t, J'/t) \to (\tilde{J}/\tilde{t}, \tilde{J}'/\tilde{t}) = \frac{2}{\delta(1+\delta)} (J/t, J'/t)$

RVB theory of superconductivity on the DHL



- Unconventional superconductivity: extended-s, extended-d and f-wave singlet pairing!

RVB theory of superconductivity on the DHL



At optimal doping (DHL):
$T_c = T_{BEC} = T_{RVB} \approx 0.075t$

Triangular lattice:
$T_c \sim 0.017t$

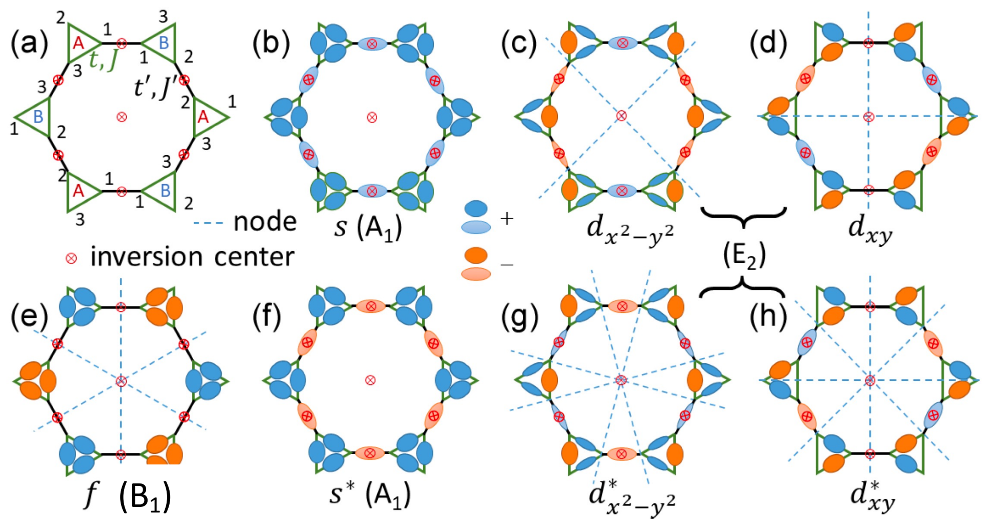
- Unconventional superconductivity: extended-s, extended-d and f-wave singlet pairing!

RVB theory of superconductivity on the DHL

Character table of C_{6v} symmetry point group

Irrep.	E	$2C_6$	$2C_3$	C_2	$3\sigma_v$	$3\sigma_d$	Superconducting order
A_1	1	1	1	1	1	1	s, s^*
A_2	1	1	1	1	−1	−1	-
B_1	1	−1	1	−1	1	−1	$f_{x(3y^2-x^2)}$
B_2	1	−1	1	−1	−1	1	$f_{y(3x^2-y^2)}$
E_1	2	1	−1	−2	0	0	(p_x, p_y)
E_2	2	−1	−1	2	0	0	$(d_{x^2-y^2}, d_{xy})$, $(d^*_{x^2-y^2}, d^*_{xy})$

Real space pairing states



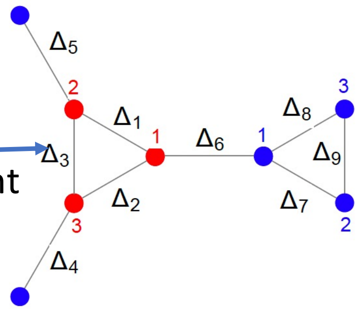
- In the honeycomb lattice s* and d-wave singlet pairing occur. (Black-Schaffer, Doniach PRB(2007))
- In the decorated honeycomb lattice f-wave singlet pairing is allowed by the decoration.

RVB theory of superconductivity on the DHL

From the linearized gap equations, at T_c:

$$\Gamma \boldsymbol{\Delta} = \frac{1}{J} \boldsymbol{\Delta}$$

9-component vector



we obtain the pairing solutions:

$$\Delta_f = \frac{1}{\sqrt{6}}[(1,1,1),(0,0,0),(-1,-1,-1)]^T, g = \frac{1}{a_s - c_s}$$

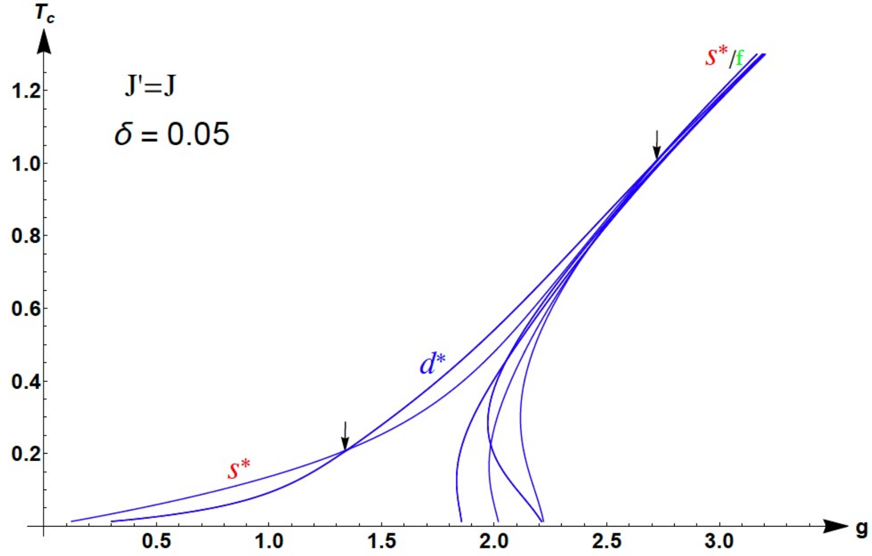
$$\Delta_{p_x} = \frac{1}{2\sqrt{3}}[(1,1,-2),(0,0,0),(-1,-1,2)]^T, g = \frac{1}{a_{d_{x^2-y^2}} - c_{d_{x^2-y^2}}}$$

$$\Delta_{p_y} = \frac{1}{2}[(1,-1,0),(0,0,0),(-1,1,0)]^T, g = \frac{1}{a_{d_{xy}} - c_{d_{xy}}}$$

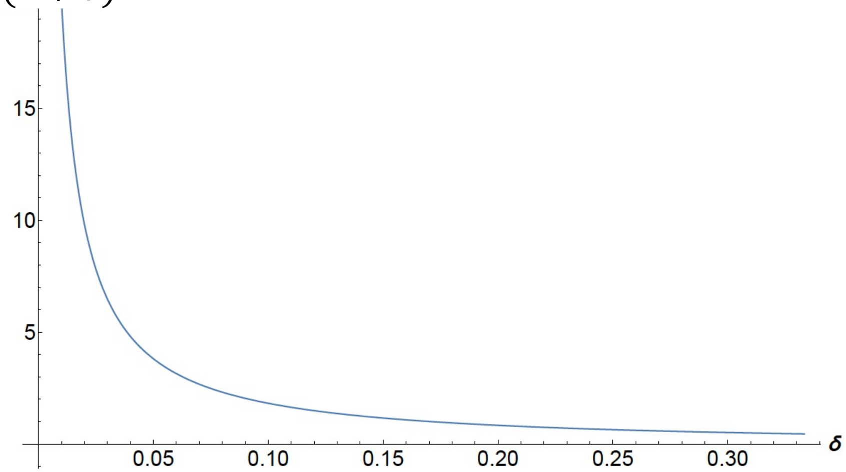
$$\Delta_{d^{\pm}_{x^2-y^2}} = \frac{1}{\sqrt{12 + 6(\beta_{d^{\pm}_{x^2-y^2}})^2}}[(1,1,-2),\beta^{\pm}_{d_{x^2-y^2}}(1,1,-2),(1,1,-2)]^T, g = J_{d^{\pm}_{x^2-y^2}}$$

$$\Delta_{d^{\pm}_{xy}} = \frac{1}{\sqrt{4 + 2(\beta_{d^{\pm}_{xy}})^2}}[(1,-1,0),\beta^{\pm}_{d_{xy}}(1,-1,0),(1,-1,0)]^T, g = J_{d^{\pm}_{xy}}$$

$$\Delta_{s^{\pm}} = \frac{1}{\sqrt{6 + 3(\beta^{\pm}_s)^2}}[(1,1,1),\beta^{\pm}_s(1,1,1),(1,1,1)]^T, g = J_{s^{\pm}}.$$



$$g = \tilde{J}/\tilde{t} = \frac{2}{\delta(1+\delta)}$$

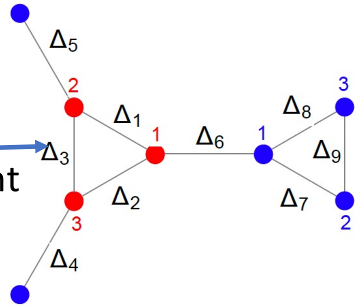


RVB theory of superconductivity on the DHL

From the linearized gap equations, at T_c:

$$\Gamma \boldsymbol{\Delta} = \frac{1}{J} \boldsymbol{\Delta}$$

9-component vector



we obtain the pairing solutions:

$$\Delta_f = \frac{1}{\sqrt{6}}[(1,1,1),(0,0,0),(-1,-1,-1)]^T, g = \frac{1}{a_s - c_s}$$

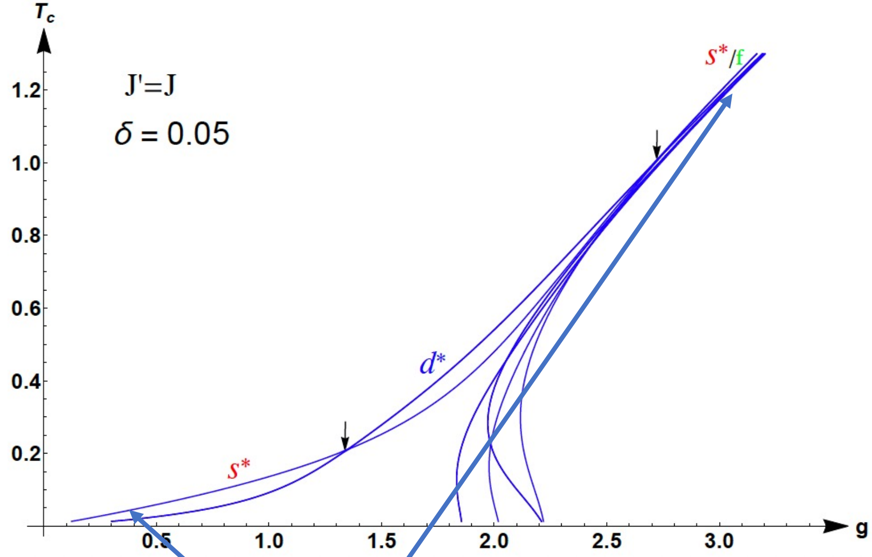
$$\Delta_{p_x} = \frac{1}{2\sqrt{3}}[(1,1,-2),(0,0,0),(-1,-1,2)]^T, g = \frac{1}{a_{d_{x^2-y^2}} - c_{d_{x^2-y^2}}}$$

$$\Delta_{p_y} = \frac{1}{2}[(1,-1,0),(0,0,0),(-1,1,0)]^T, g = \frac{1}{a_{d_{xy}} - c_{d_{xy}}}$$

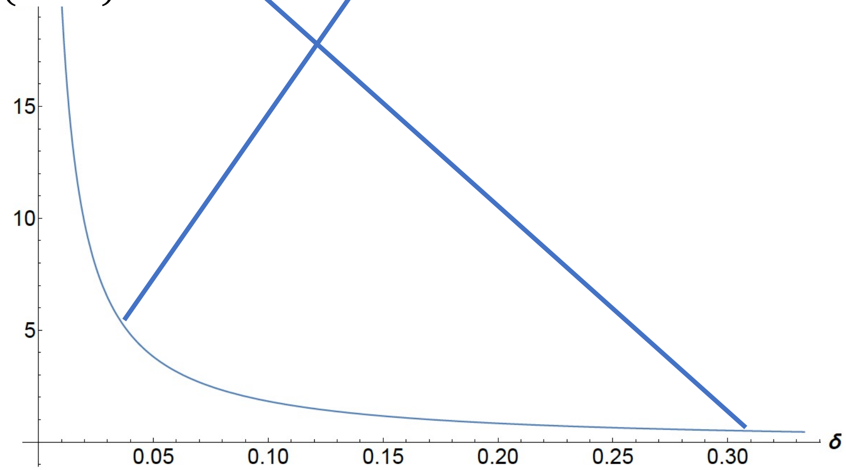
$$\Delta_{d^{\pm}_{x^2-y^2}} = \frac{1}{\sqrt{12+6(\beta_{d^{\pm}_{x^2-y^2}})^2}}[(1,1,-2),\beta^{\pm}_{d_{x^2-y^2}}(1,1,-2),(1,1,-2)]^T, g = J_{d^{\pm}_{x^2-y^2}}$$

$$\Delta_{d^{\pm}_{xy}} = \frac{1}{\sqrt{4+2(\beta_{d^{\pm}_{xy}})^2}}[(1,-1,0),\beta^{\pm}_{d_{xy}}(1,-1,0),(1,-1,0)]^T, g = J_{d^{\pm}_{xy}}$$

$$\Delta_{s^{\pm}} = \frac{1}{\sqrt{6+3(\beta^{\pm}_s)^2}}[(1,1,1),\beta^{\pm}_s(1,1,1),(1,1,1)]^T, g = J_{s^{\pm}}.$$



$$g = \tilde{J}/_{\tilde{t}} = \frac{2}{\delta(1+\delta)}$$

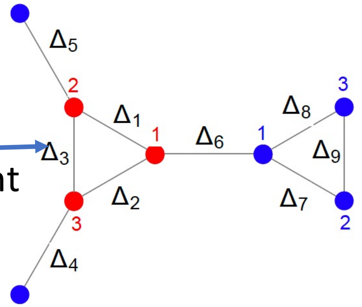


RVB theory of superconductivity on the DHL

From the linearized gap equations, at T_c:

$$\Gamma \boldsymbol{\Delta} = \frac{1}{J} \boldsymbol{\Delta}$$

9-component vector



we obtain the pairing solutions:

$$\Delta_f = \frac{1}{\sqrt{6}}[(1,1,1),(0,0,0),(-1,-1,-1)]^T, g = \frac{1}{a_s - c_s}$$

$$\Delta_{p_x} = \frac{1}{2\sqrt{3}}[(1,1,-2),(0,0,0),(-1,-1,2)]^T, g = \frac{1}{a_{d_{x^2-y^2}} - c_{d_{x^2-y^2}}}$$

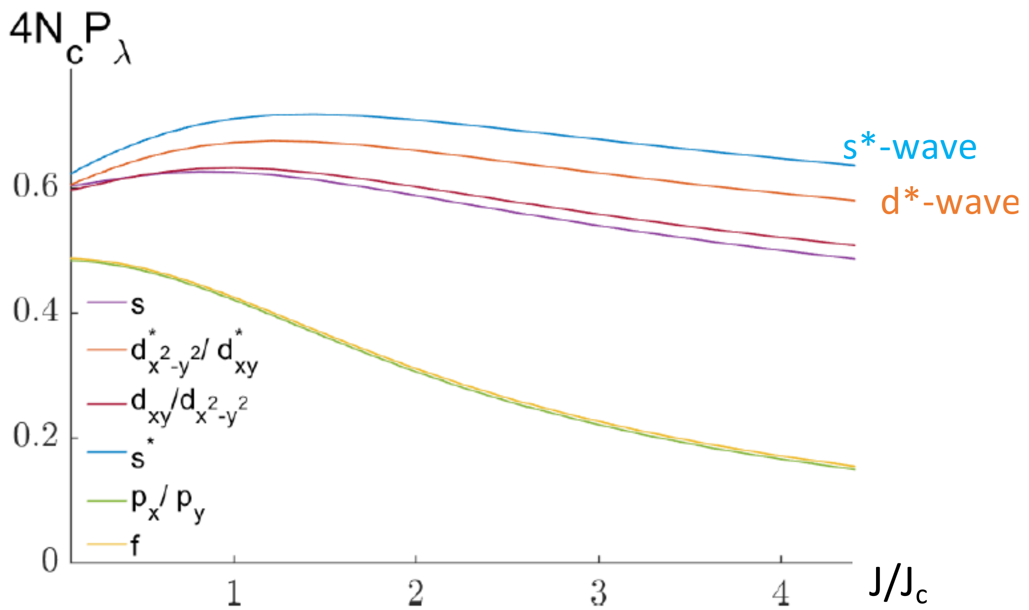
$$\Delta_{p_y} = \frac{1}{2}[(1,-1,0),(0,0,0),(-1,1,0)]^T, g = \frac{1}{a_{d_{xy}} - c_{d_{xy}}}$$

$$\Delta_{d^{\pm}_{x^2-y^2}} = \frac{1}{\sqrt{12+6(\beta_{d^{\pm}_{x^2-y^2}})^2}}[(1,1,-2),\beta^{\pm}_{d_{x^2-y^2}}(1,1,-2),(1,1,-2)]^T, g = J_{d^{\pm}_{x^2-y^2}}$$

$$\Delta_{d^{\pm}_{xy}} = \frac{1}{\sqrt{4+2(\beta_{d^{\pm}_{xy}})^2}}[(1,-1,0),\beta^{\pm}_{d_{xy}}(1,-1,0),(1,-1,0)]^T, g = J_{d^{\pm}_{xy}}$$

$$\Delta_{s^{\pm}} = \frac{1}{\sqrt{6+3(\beta^{\pm}_s)^2}}[(1,1,1),\beta^{\pm}_s(1,1,1),(1,1,1)]^T, g = J_{s^{\pm}}.$$

Consistent with exact diagonalization at half-filling:



$$P_\lambda = \frac{1}{4N_c}\sum_{\langle \alpha i, \beta j\rangle}\sum_{\langle \gamma k, \delta l\rangle} \Delta_\lambda(\alpha i,\beta j)\Delta_\lambda(\gamma k,\delta l)\left(\langle c^\dagger_{\alpha i\uparrow}c^\dagger_{\beta j\downarrow}c_{\gamma k\uparrow}c_{\delta l\downarrow}\rangle - \langle c^\dagger_{\alpha i\uparrow}c_{\gamma k\uparrow}\rangle\langle c^\dagger_{\beta j\downarrow}c_{\delta l\downarrow}\rangle\right)$$

Conclusions

- Kitaev magnets under magnetic fields and /or DM can host novel chiral quantum spin liquids.

- An RVB quantum spin liquid is a good candidate for the ground state of the Heisenberg model on the decorated honeycomb lattice.

- Extended s*, d* and f-wave singlet superconductivity can arise in decorated honeycomb lattices under hole doping.

Outlook:

- Theory: analyze rich variety of superconducting pairing states emerging in decorated lattices.

- Experiments: search for unconventional superconductivity in DHLs under doping!

Thank you for your attention!