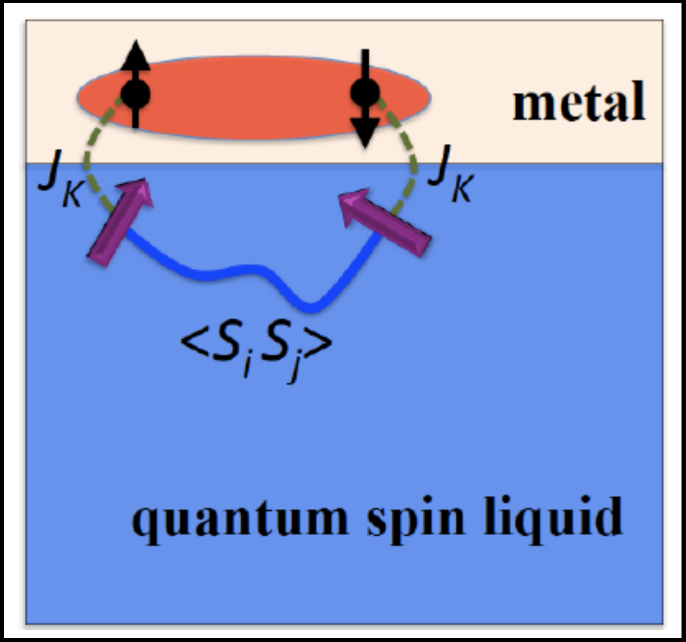
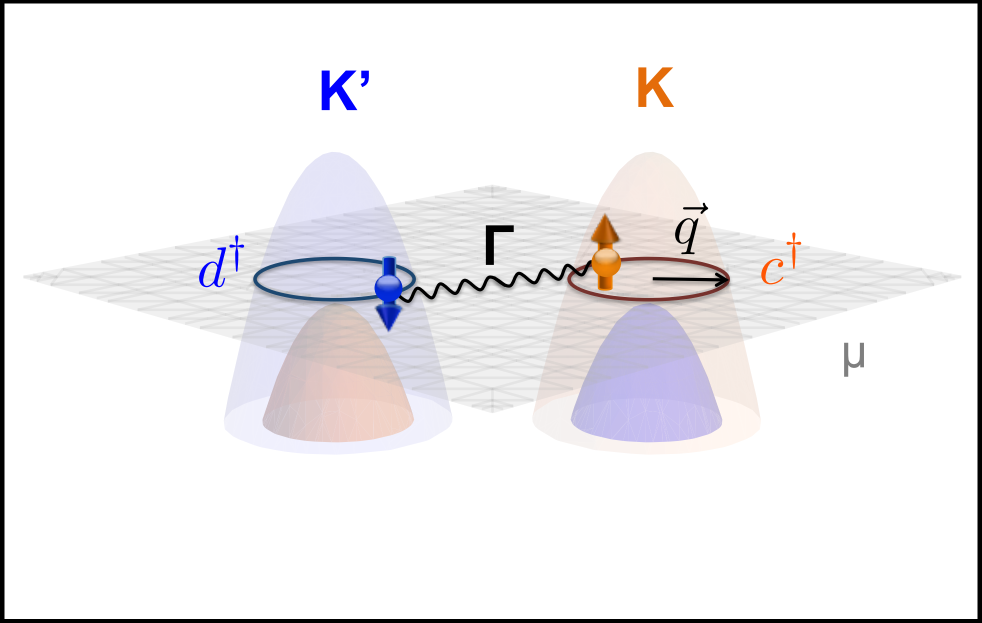
Designing 2D topological SC's





Eun-Ah Kim (Cornell)

IBS-CCES 12.17.2015

Q. Topological Superconductor material?

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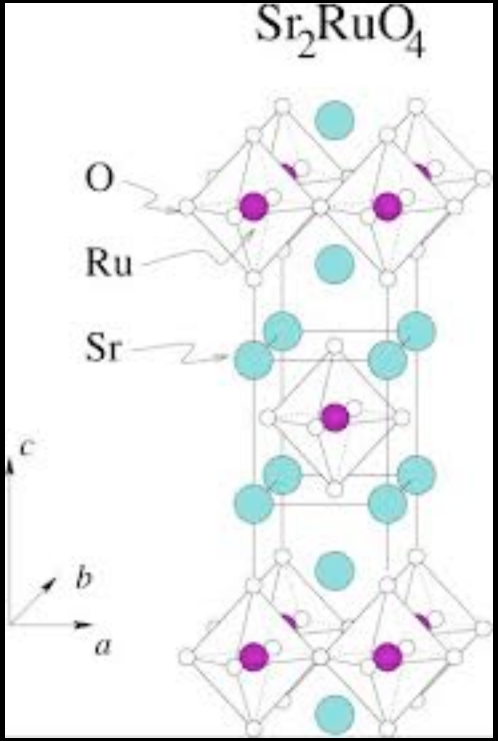
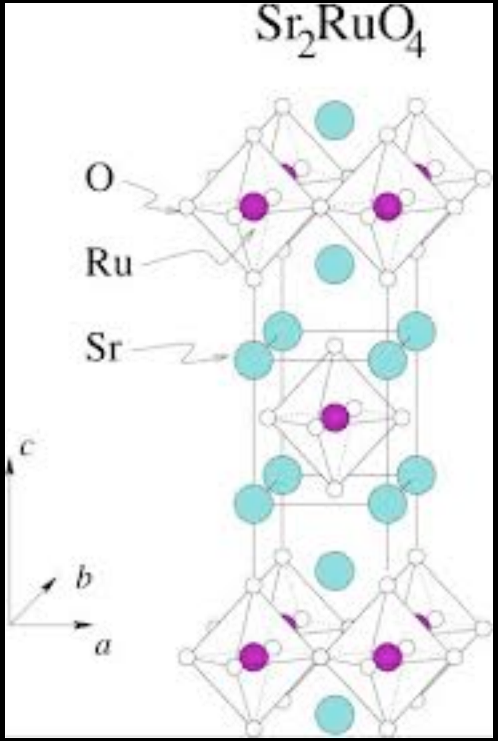
Bulk

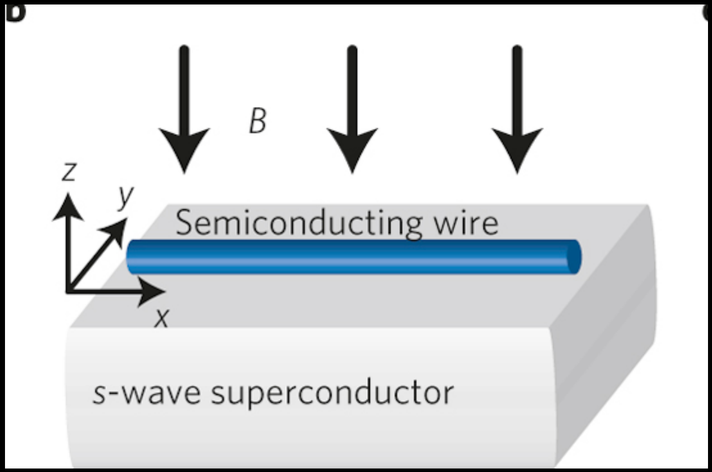


Q. Topological Superconductor material?

Bulk

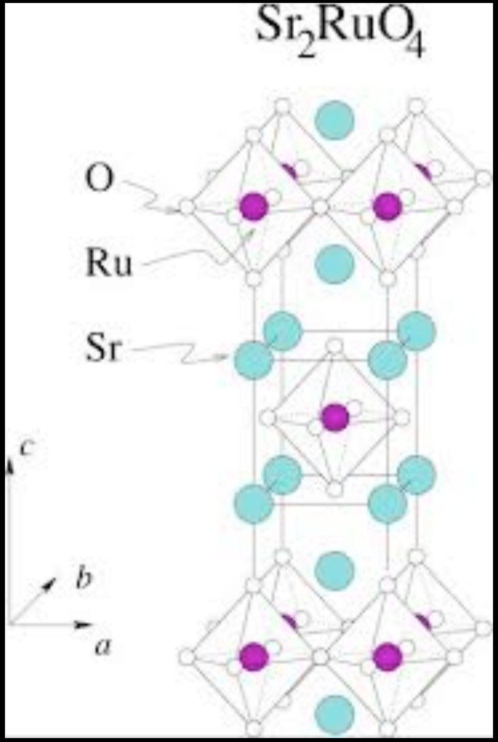


1D proximity

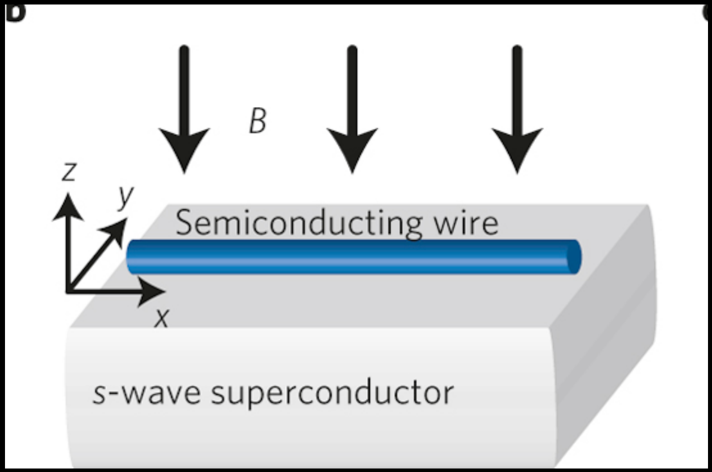


Q. Topological Superconductor material?

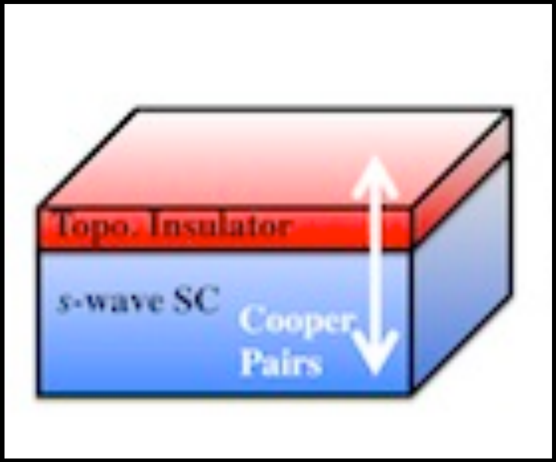
Bulk



1D proximity



2D proximity?



Designing 2D topological SC's

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- 2D topological SC
  - odd-parity SC of spinless fermions
  - Majorana bound state

Designing 2D topological SC's

- 2D topological SC
  - odd-parity SC of spinless fermions
  - Majorana bound state

- Strategies:

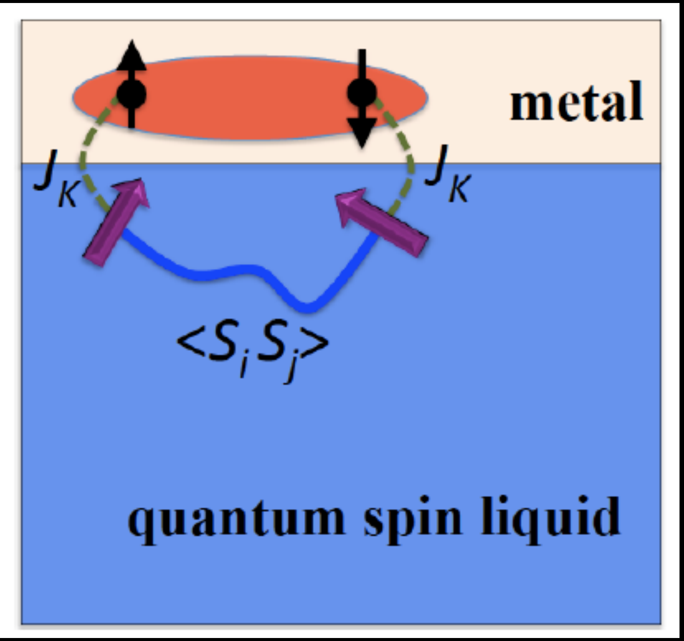
1) interaction,

2) spinlessness

Strategy I

- Manipulate the pairing interaction: target non-phononic mechanism

Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures



Jian-Huang She, Choonghyun Kim, Craig Fennie,
Michael Lawler, E-AK (in preparation, 2015)

Wanted: non-phononic mechanism


P.W.Anderson

Dope a Quantum spin liquid

Wanted: non-phononic mechanism

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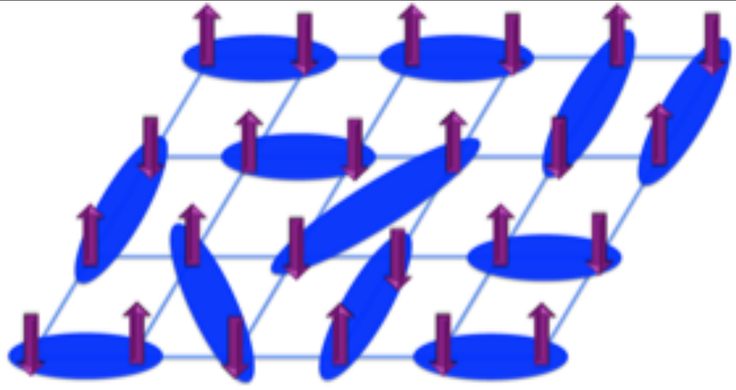
Dope a Quantum spin liquid



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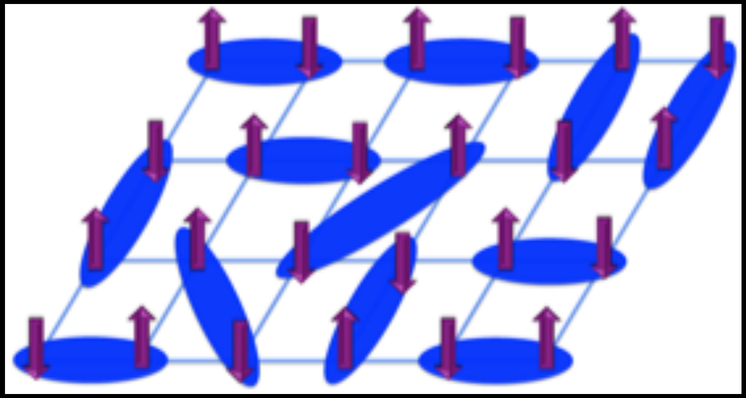

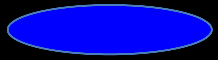

RVB singlet

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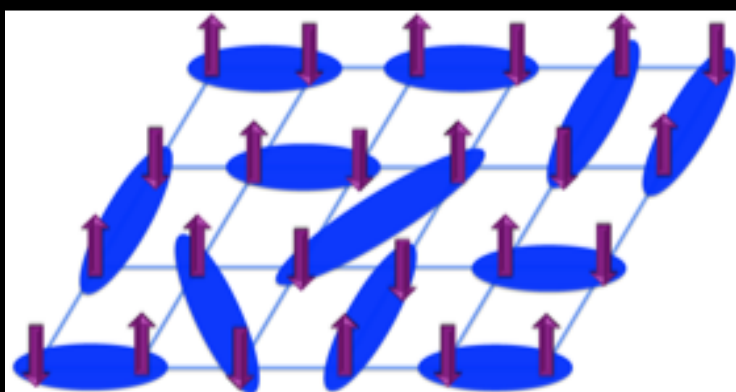
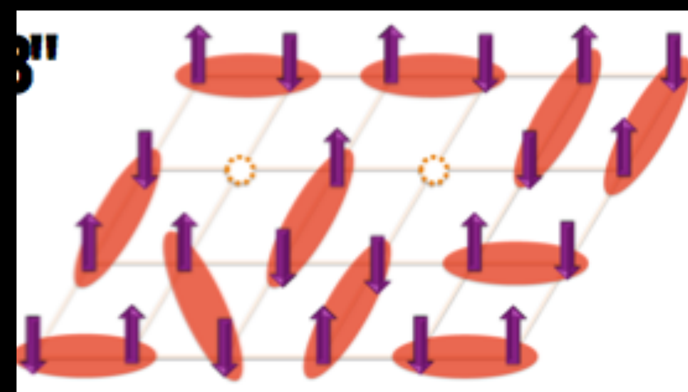
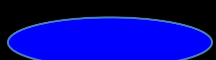
Dope a Quantum spin liquid







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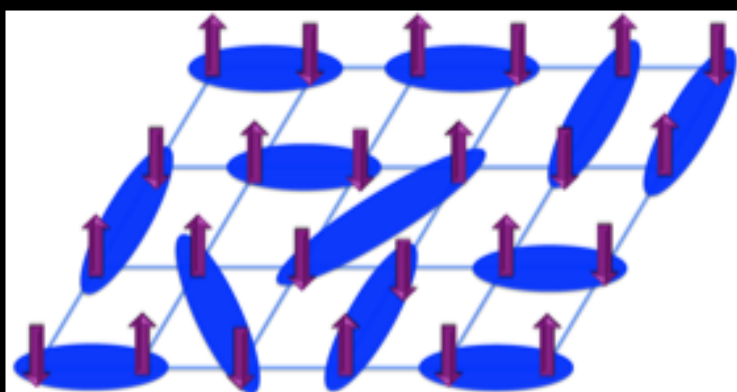
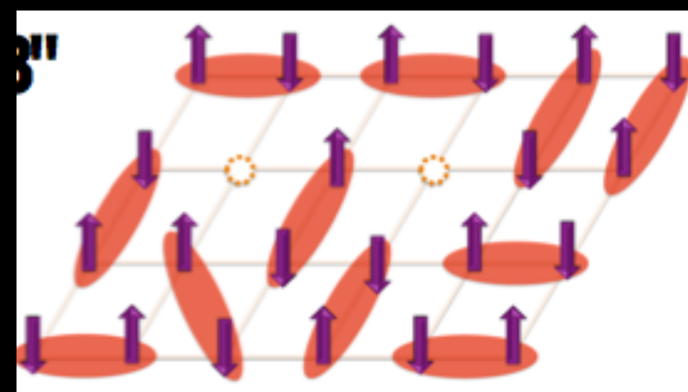


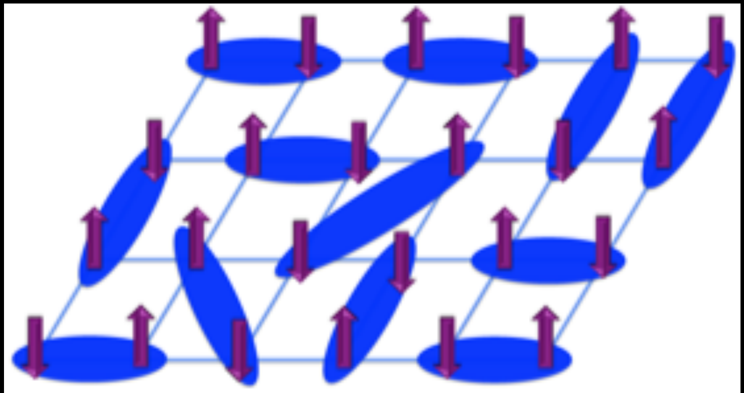


RVB singlet

Cooper pair singlet

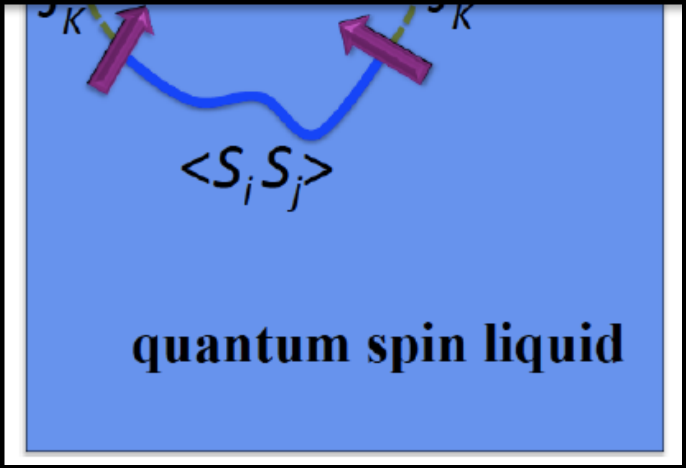
Wanted: non-phononic mechanism

Use Quantum spin liquid



Wanted: non-phononic mechanism

Use Quantum spin liquid



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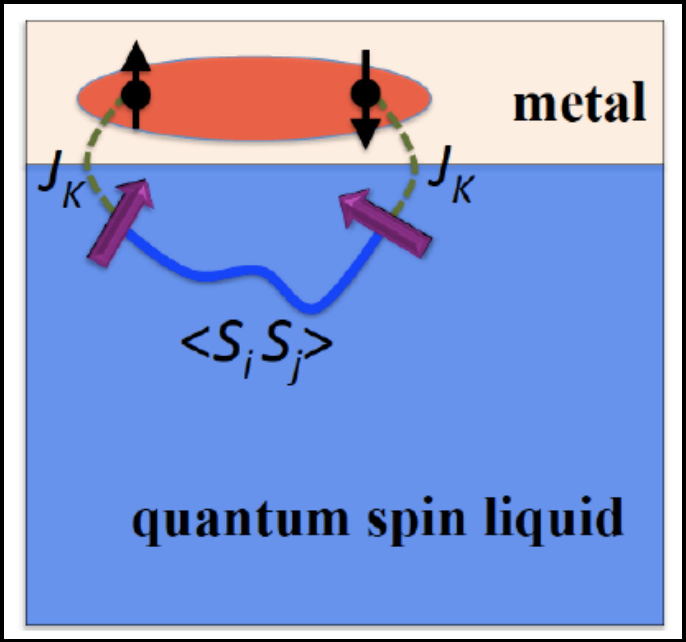
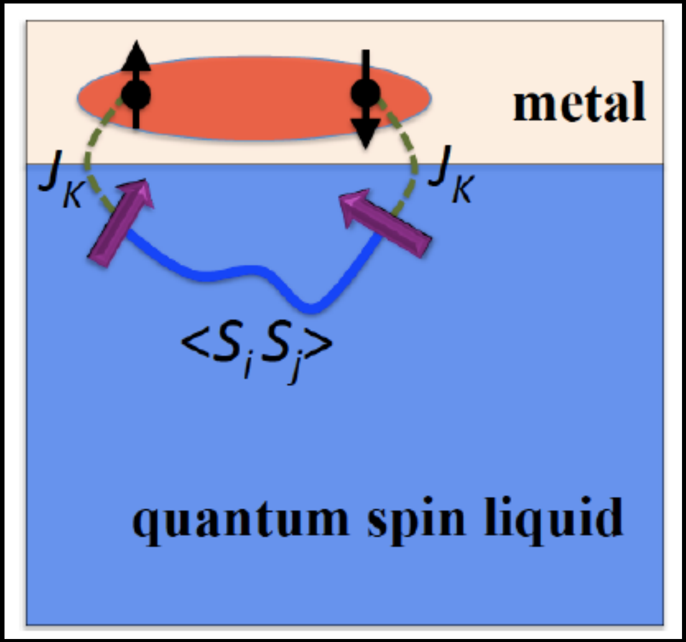


E_F

J_{ex}

Wanted: non-phononic mechanism

Use Quantum spin liquid



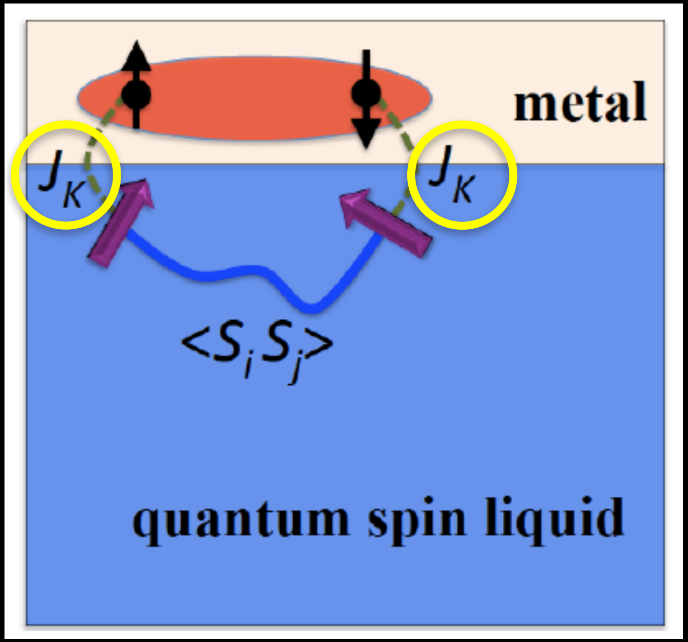
E_F

J_{ex}

- Characteristic energy scales:

Wanted: non-phononic mechanism

Use Quantum spin liquid



E_F

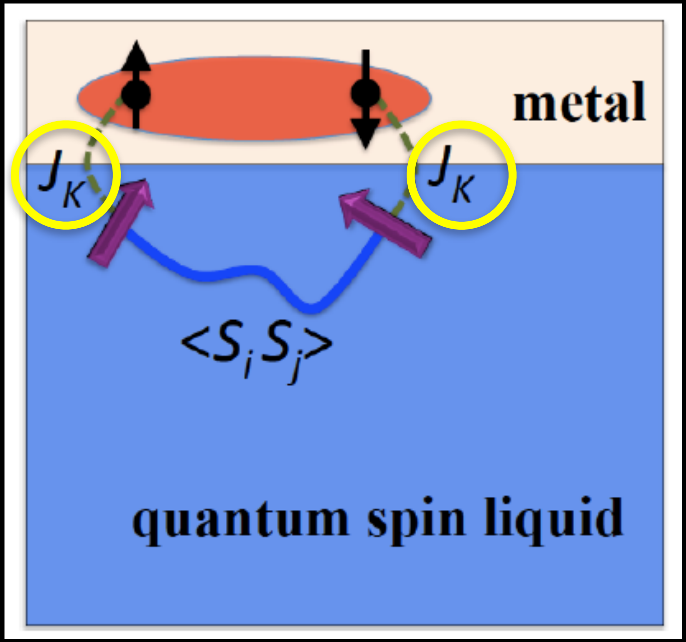
J_{ex}

- Characteristic energy scales:

  E_F, J_{ex}, J_K

Wanted: non-phononic mechanism

Use Quantum spin liquid



E_F

J_{ex}

- Characteristic energy scales:

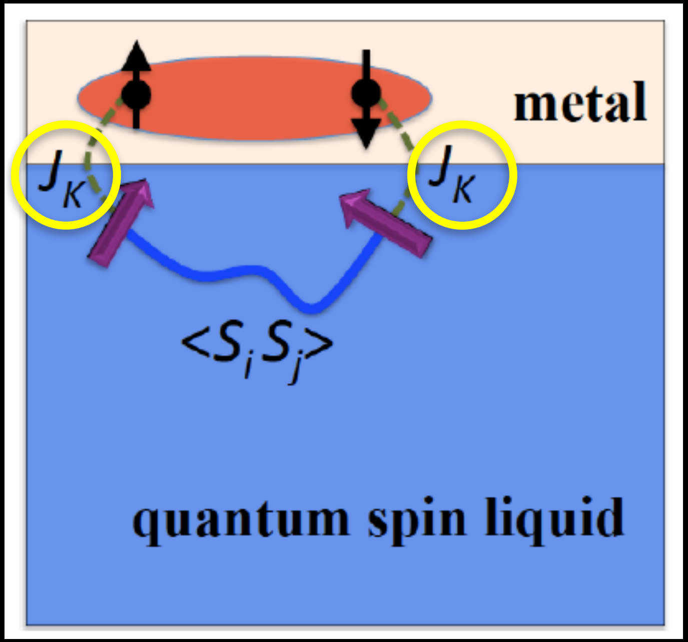
  $E_{F,}$ $J_{ex,}$ J_K

- Perturbative limit:

  $J_K / E_F << 1$

Wanted: non-phononic mechanism

Use Quantum spin liquid



E_F

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- Characteristic energy scales:

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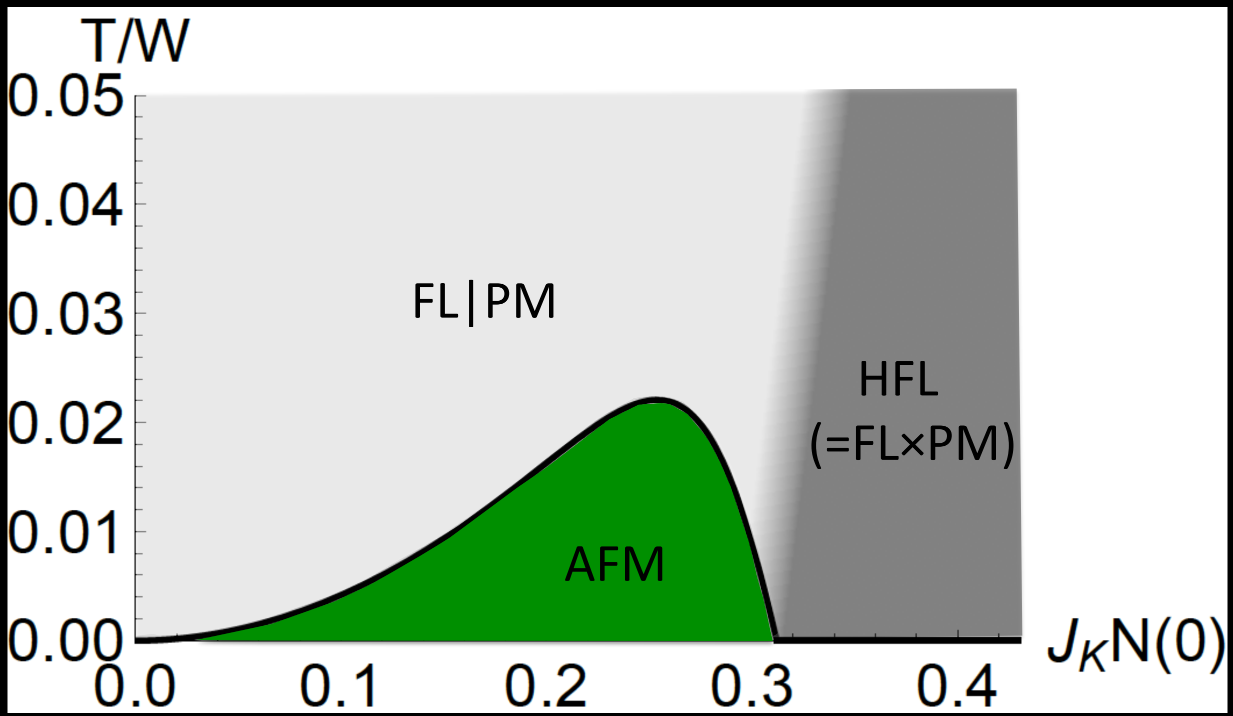
- Spin-fermion model

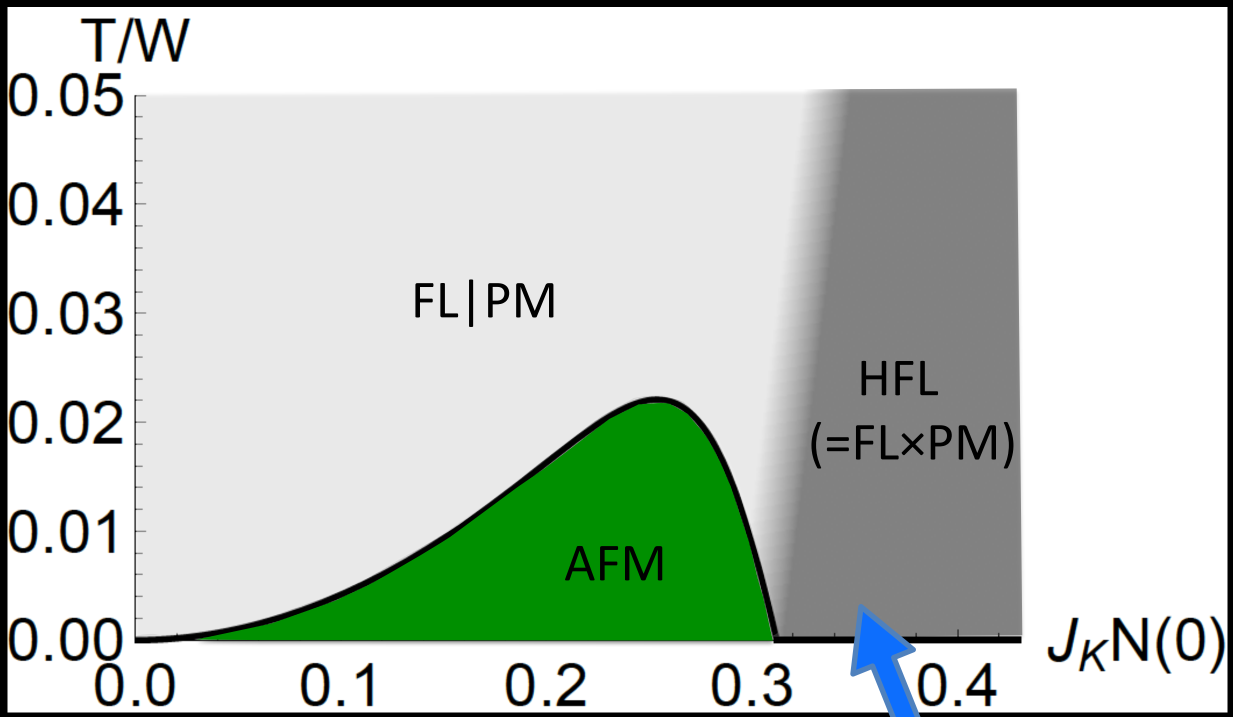
Spin-fermion model for J_{ex}=0

Spin-fermion model for J_{ex}=0



Doniach (1977)

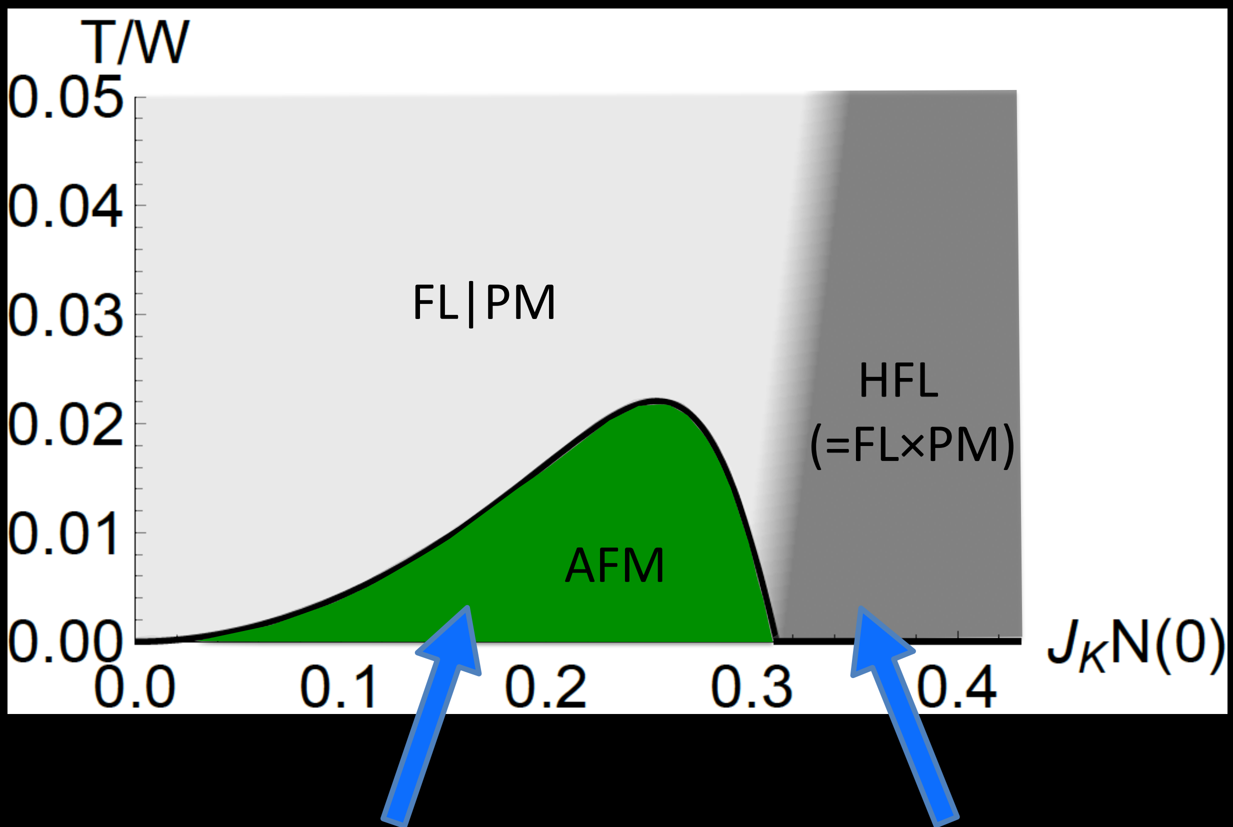
Spin-fermion model for J_{ex}=0



Kondo-Singlet

Doniach (1977)

Spin-fermion model for J_{ex}=0



RKKY interaction

Kondo-Singlet

Doniach (1977)

Spin-fermion model for J_{ex}+ Frustration

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For $J_{RKKY} \sim J_K^2 N(0) < J_{ex}$ AFM order suppressed.

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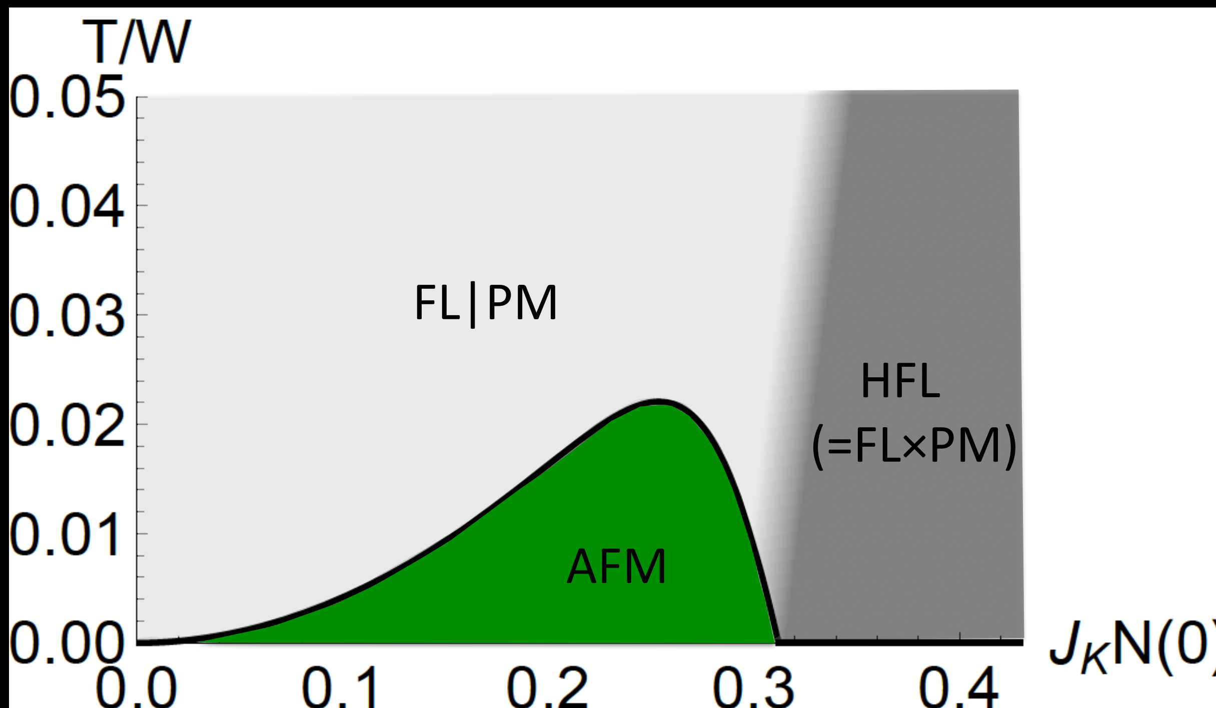

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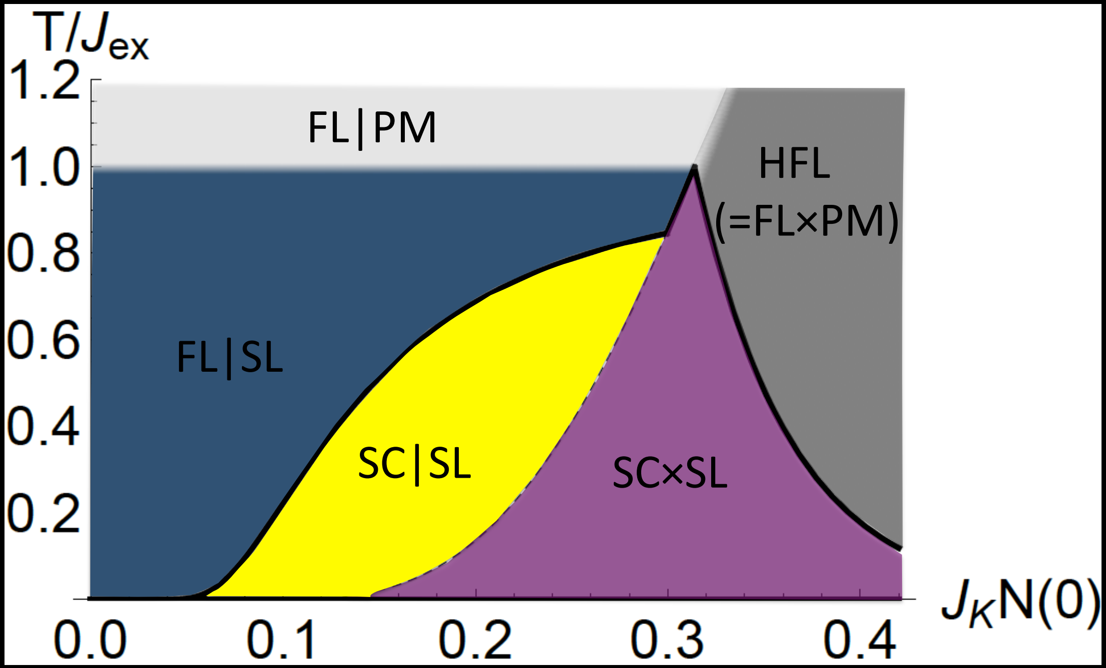

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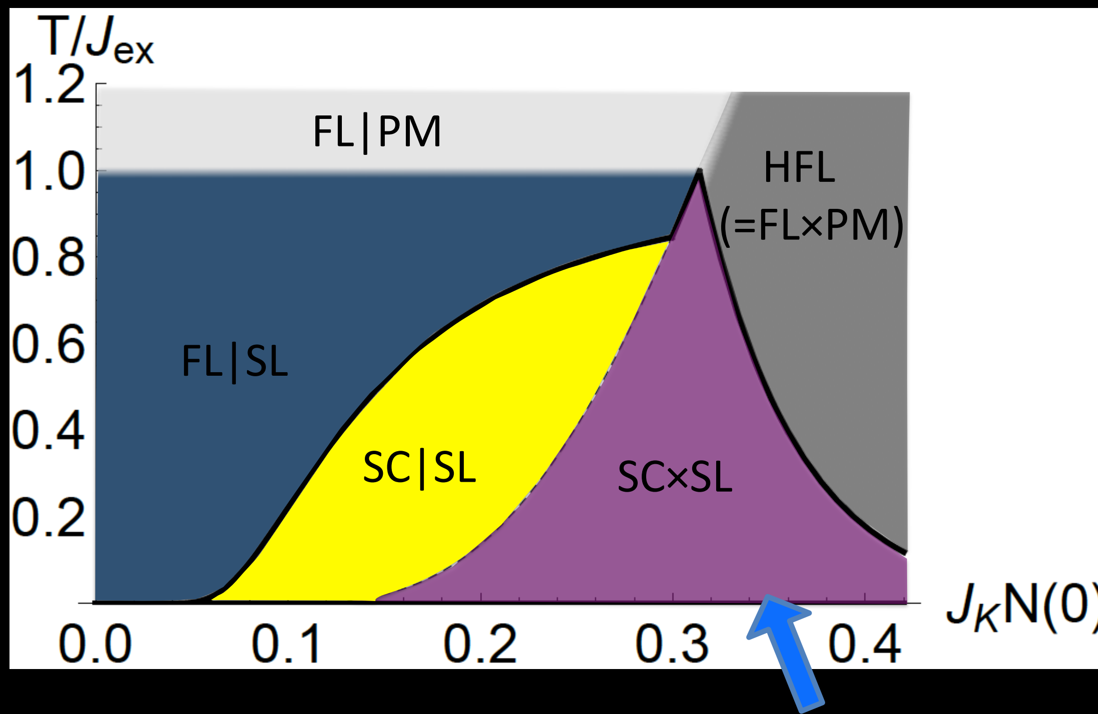


Kondo-Singlet + RVB singlet

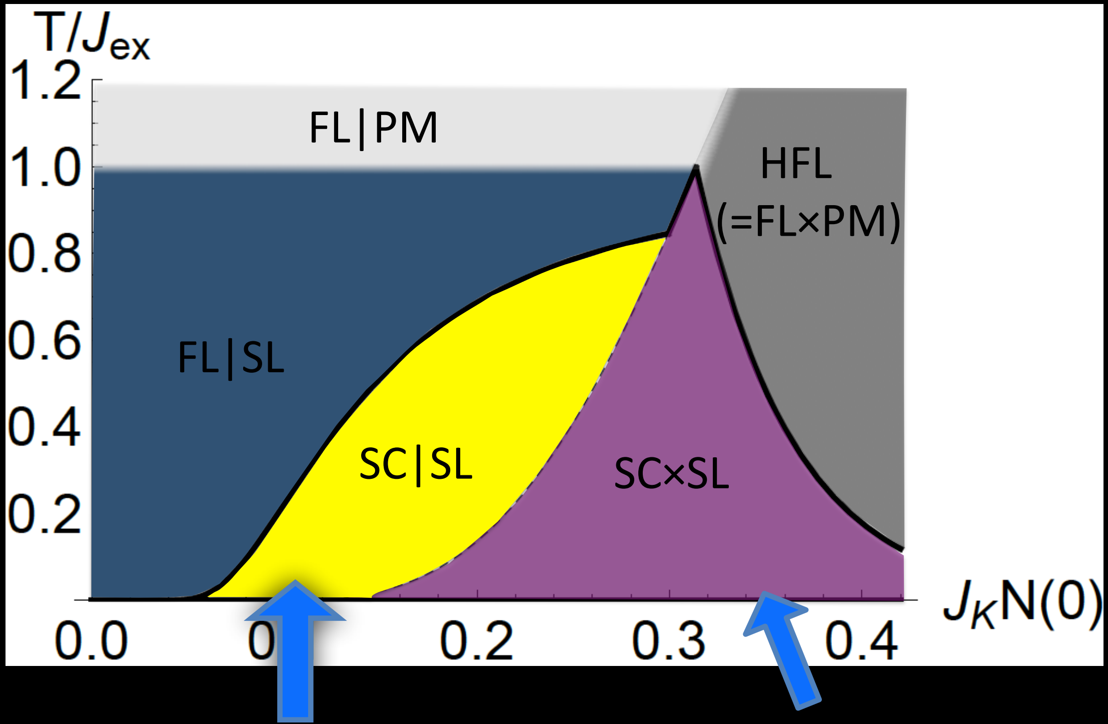
+Cooper pair singlet

Coleman & Andrei (XXXX)

Senthil, Vojta, Sachdev (XXXX)

Spin-fermion model for J_{ex} + Frustration

For $J_{RKKY} \sim J_K^2 N(0) < J_{ex}$ AFM order suppressed.



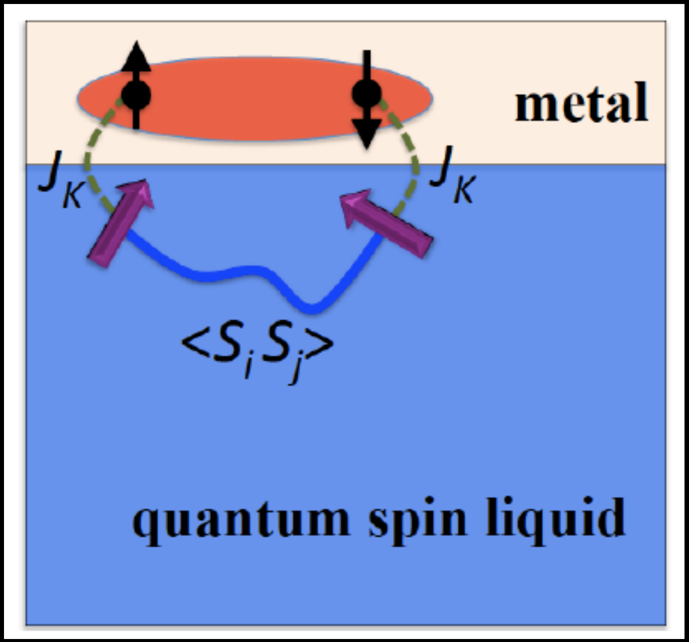
Superconductor "riding" on QSL

Kondo-Singlet + RVB singlet +Cooper pair singlet

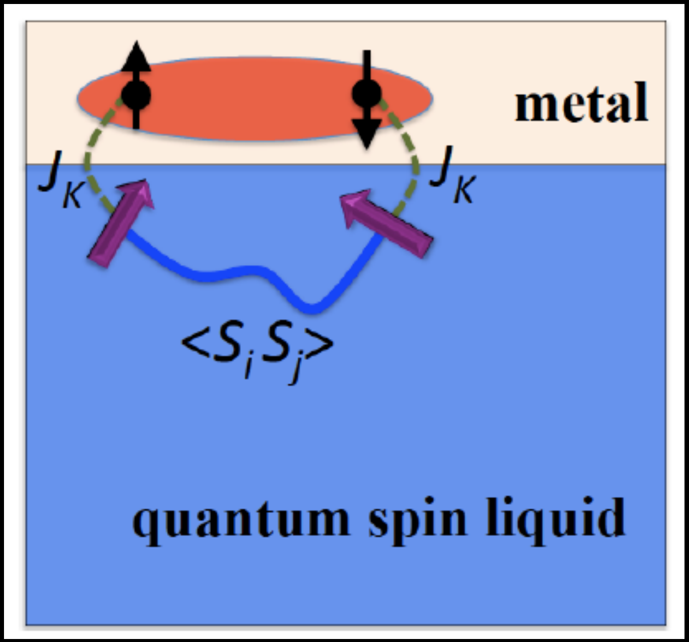
Coleman & Andrei (XXXX)

Senthil, Vojta, Sachdev (XXXX)

How to predictively materialize SC|QSL ?

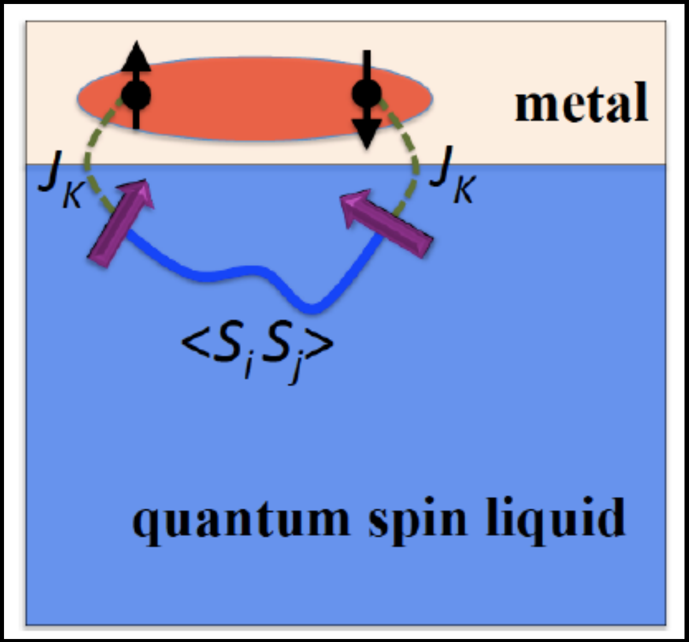


How to predictively materialize SC|QSL ?



Simple isotropic metal

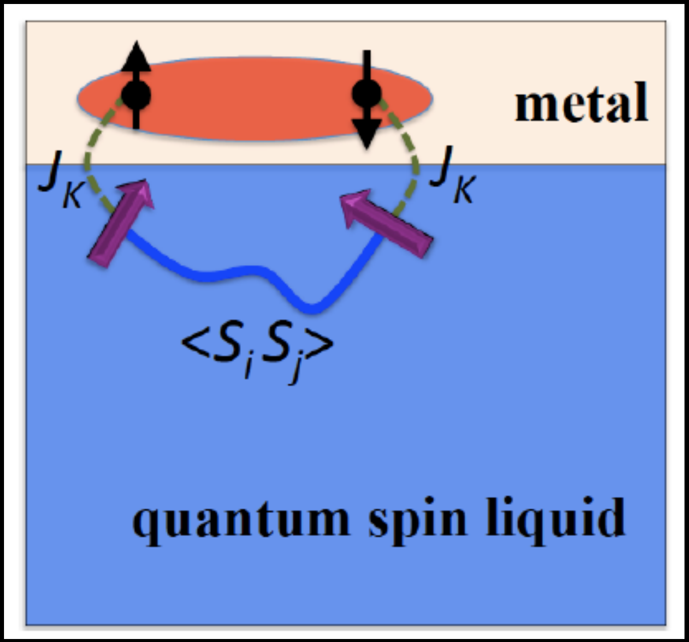
How to predictively materialize SC|QSL ?



Simple isotropic metal

1. $\langle S \rangle = 0$

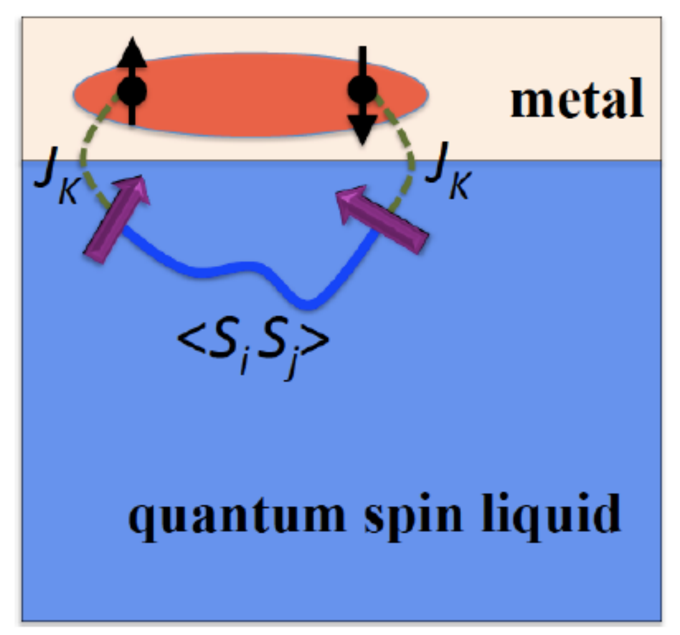
How to predictively materialize SC|QSL ?



Simple isotropic metal

1. $<S>=0$
2. Dynamic spin fluctuation $<S_i S_j>$

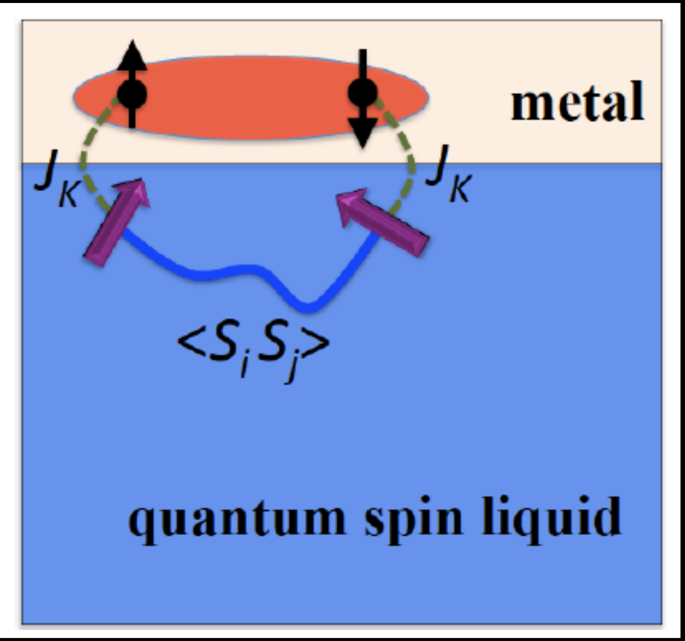
How to predictively materialize SC|QSL ?



Simple isotropic metal

1. **$<S>=0$**
2. **Dynamic spin fluctuation $<S_i S_j>$**
3. **Gapped spectrum**

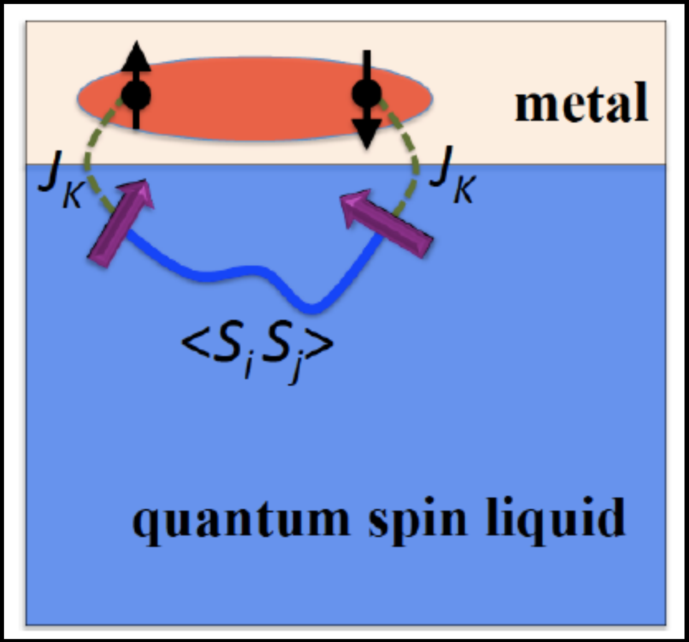
How to predictively materialize SC|QSL ?



Simple isotropic metal

1. **$\langle S\rangle=0$**
2. **Dynamic spin fluctuation $\langle S_iS_j\rangle$**
3. **Gapped spectrum**
4. **“Simple”**

How to predictively materialize SC|QSL ?



Simple isotropic metal

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➡ Quantum Spin Ice

Received 20 Sep 2012 | Accepted 18 Apr 2013 | Published 17 Jun 2013 DOI: 10.1038/ncomms2914

Quantum fluctuations in spin-ice-like $Pr_2Zr_2O_7$

K. Kimura[1], S. Nakatsuji[1,2], J.-J. Wen[3], C. Broholm[3,4,5], M.B. Stone[5], E. Nishibori[6] & H. Sawa[6]

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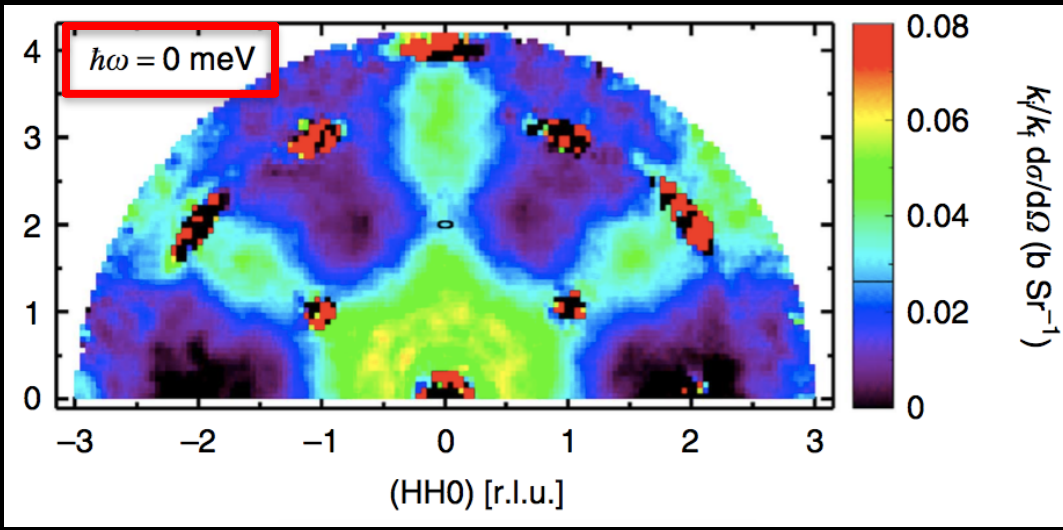

- Elastic neutron: pinch points (spin-ice like)

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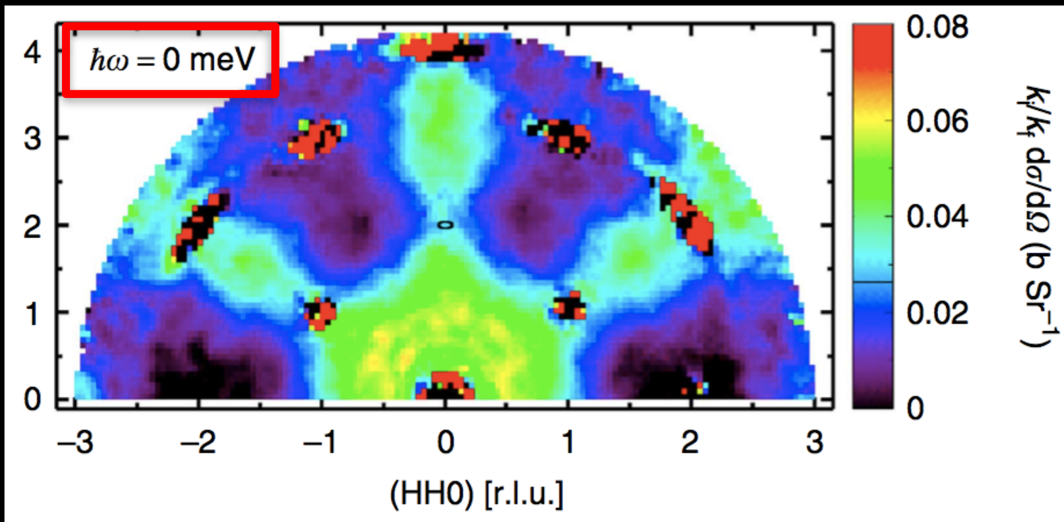

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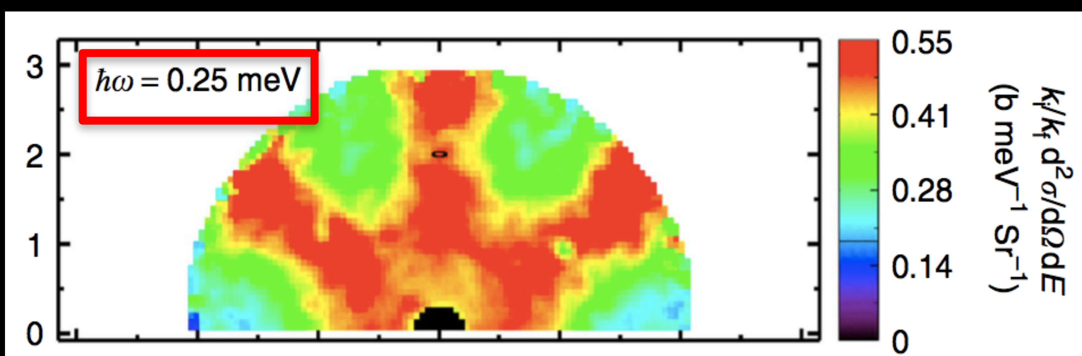

- Inelastic neutron: over 90% weight

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- No order down to 20mK

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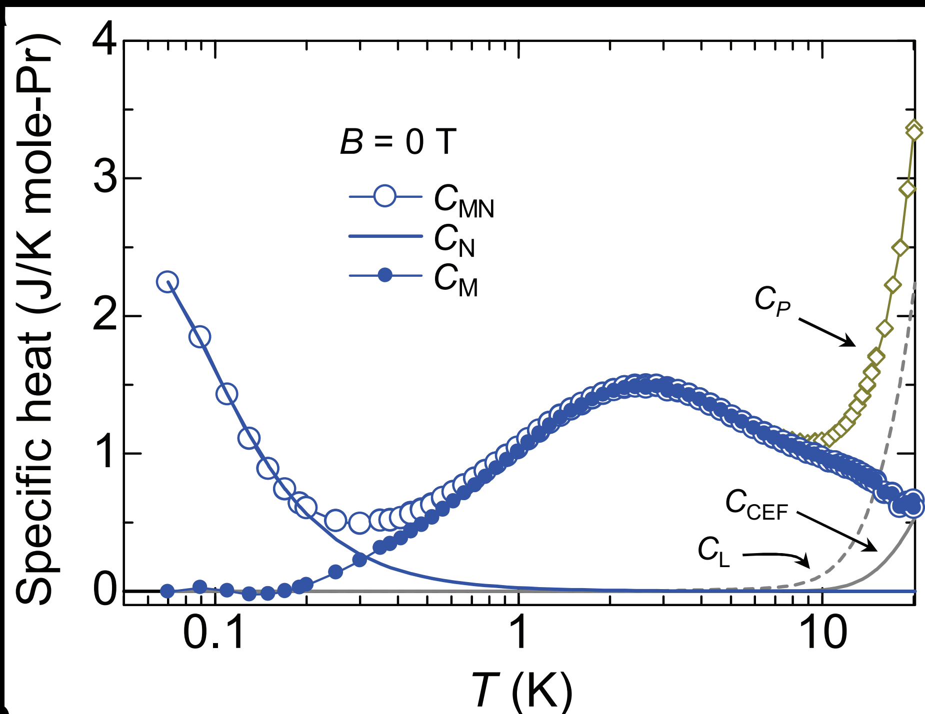

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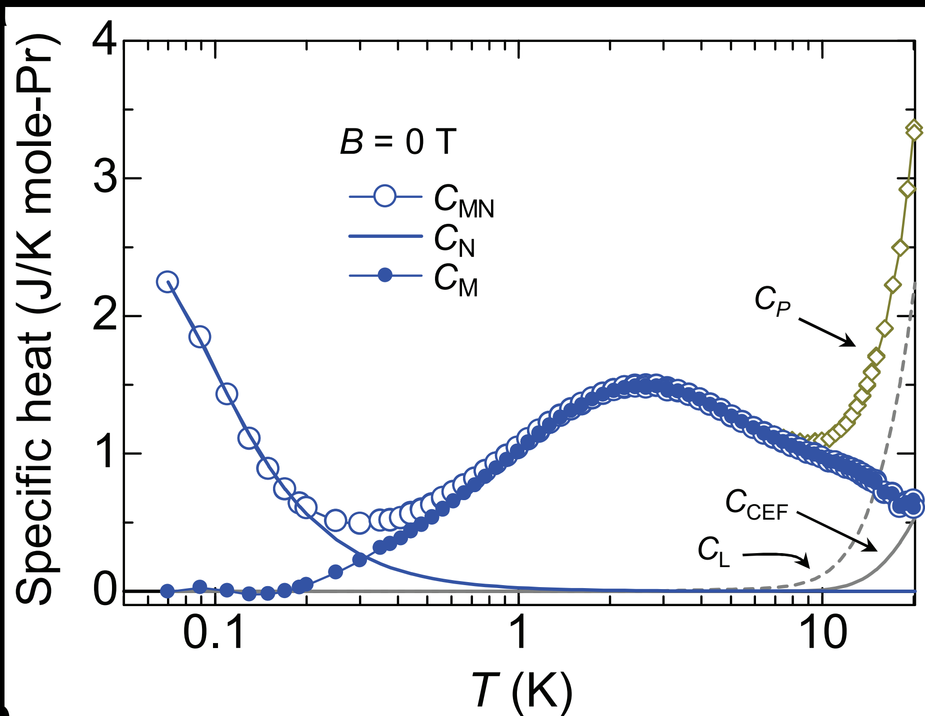

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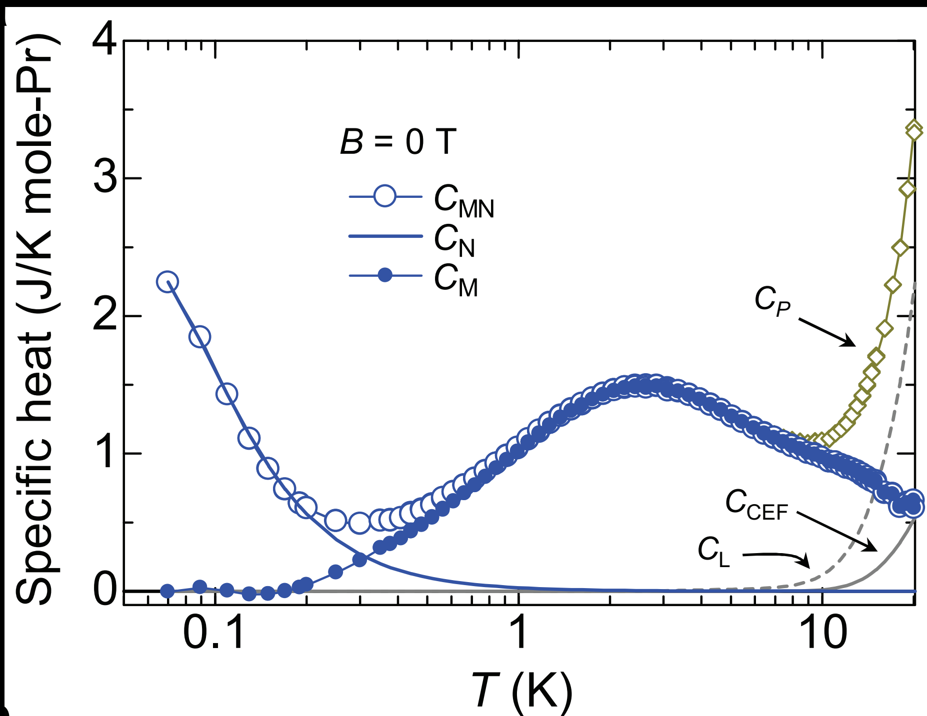
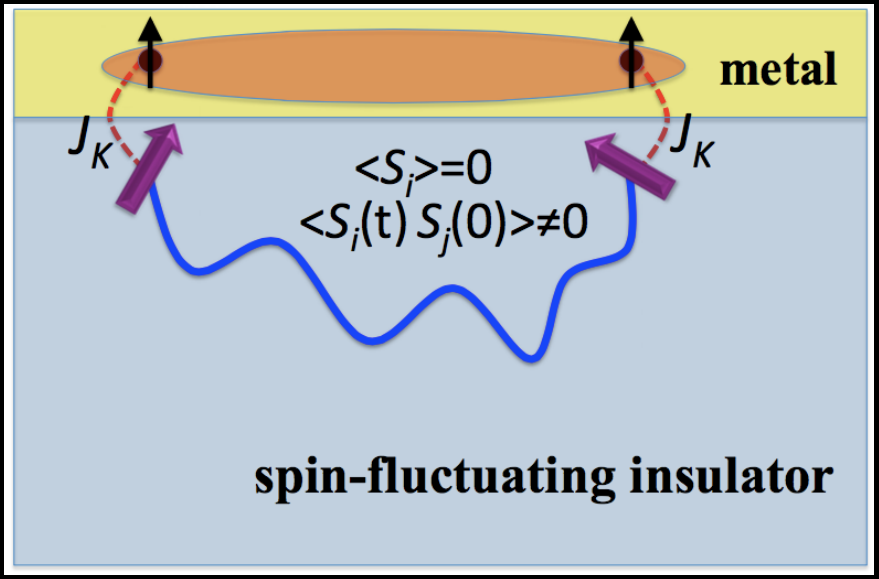


- No order down to 20mK
- Gapped quantum paramagnet ω_s=0.17meV
- Inelastic spectra peaked at Q=0

Effective Continuum Theory



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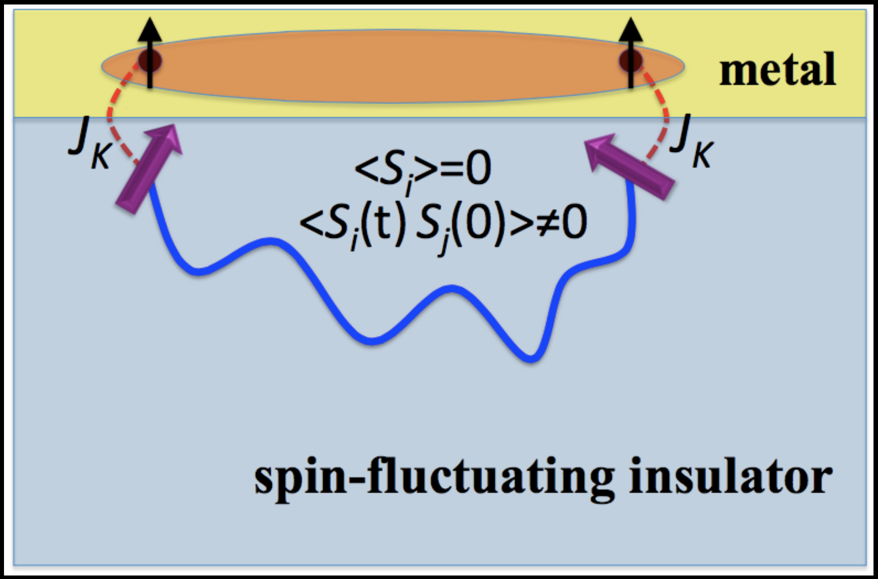
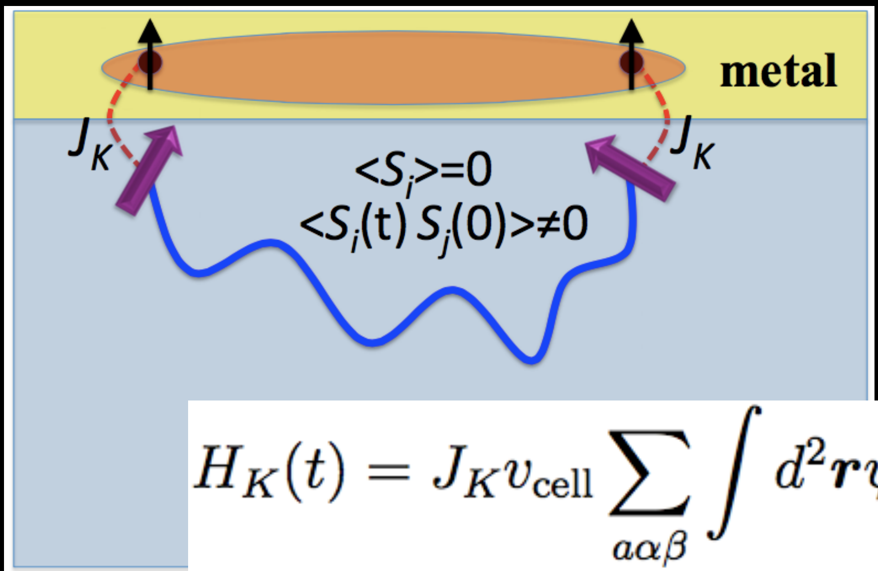


$$H_c = \sum_{\boldsymbol{k}\alpha} \left(\frac{\hbar^2 k^2}{2m} - E_F \right) \psi^\dagger_\alpha(\boldsymbol{k}) \psi_\alpha(\boldsymbol{k})$$

Effective Continuum Theory



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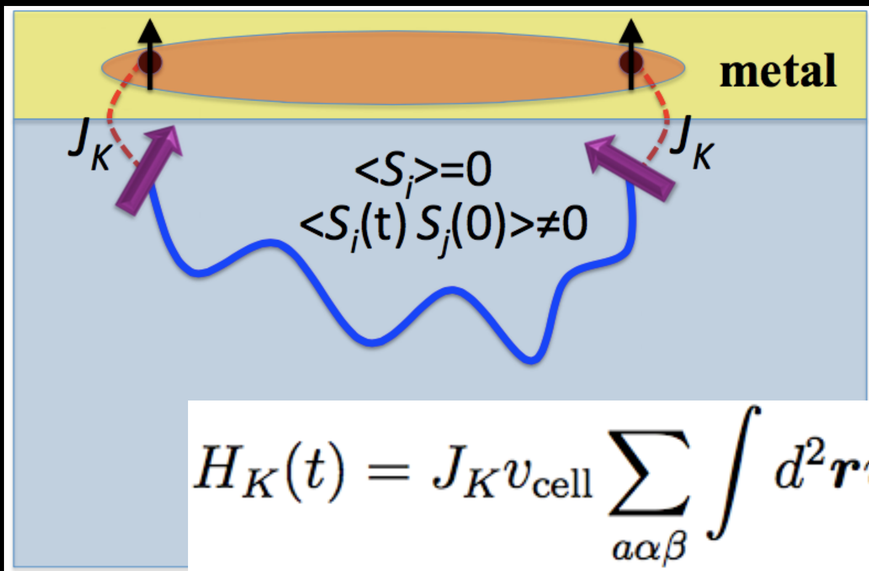
$$H_K(t) = J_K v_{\rm cell} \sum_{a\alpha\beta} \int d^2\boldsymbol{r}\, \psi^\dagger_\alpha(\boldsymbol{r}) \sigma^a_{\alpha\beta} \psi_\beta(\boldsymbol{r}) S_a(\boldsymbol{r}_\perp = \boldsymbol{r}, z = 0, t)$$

Effective Continuum Theory



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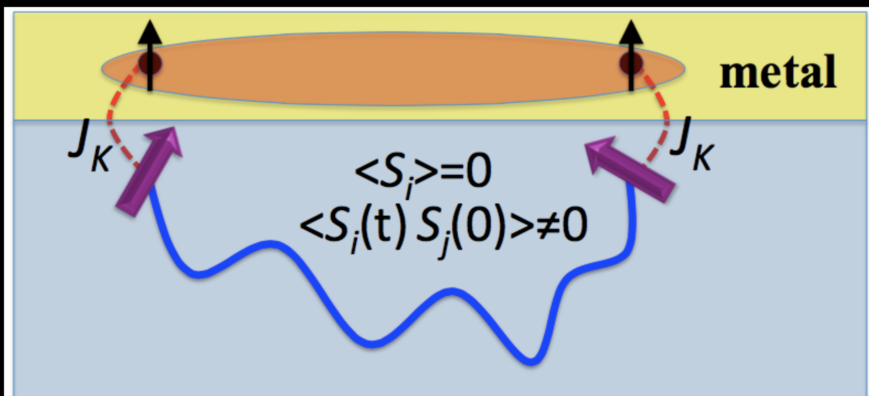
- Integrate out spins >> Effective e-e interaction

Effective Continuum Theory



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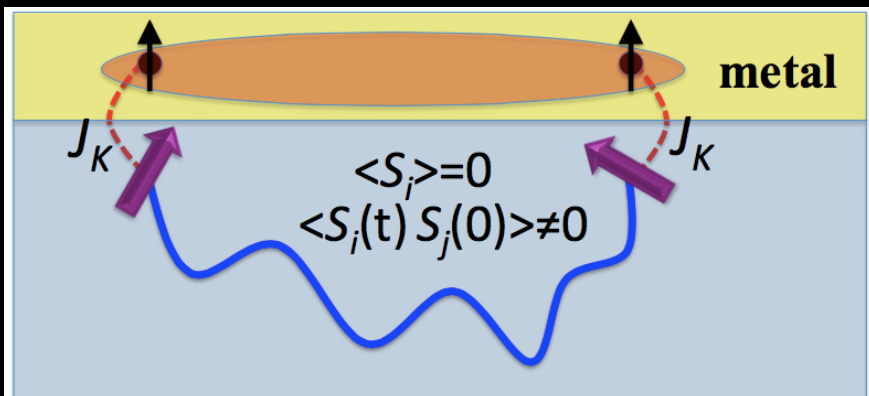
- Integrate out spins >> Effective e-e interaction

$$H_{\text{int}}(t) = -(J_K^2 v_{\text{cell}}^2 / 2\hbar) \sum_{ab} \int dt' \int d^2\boldsymbol{r} d^2\boldsymbol{r}' s_a(\boldsymbol{r}, t) \langle S_a(\boldsymbol{r}, 0, t) S_b(\boldsymbol{r}', 0, t') \rangle s_b(\boldsymbol{r}', t')$$

Effective Continuum Theory



$$H_c = \sum_{\boldsymbol{k}\alpha} \left(\frac{\hbar^2 k^2}{2m} - E_F \right) \psi^\dagger_\alpha(\boldsymbol{k}) \psi_\alpha(\boldsymbol{k})$$

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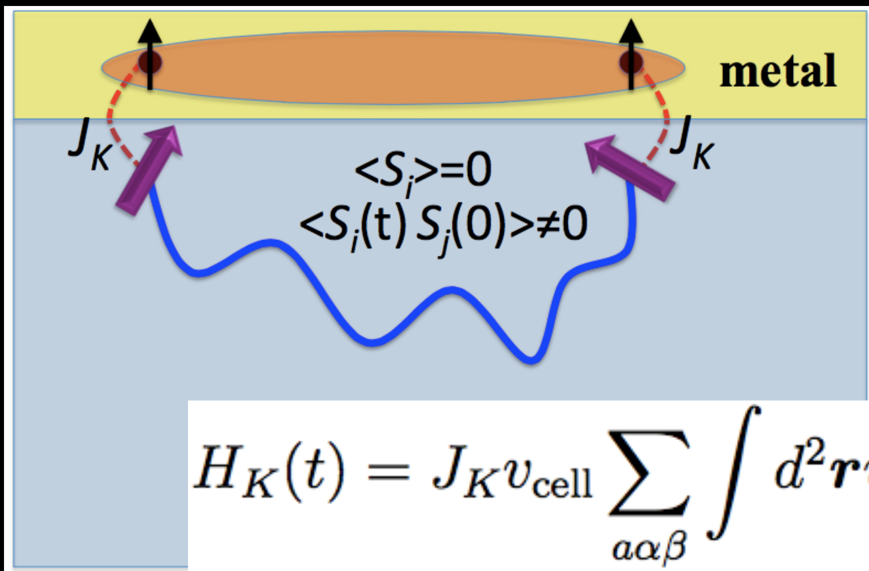

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➡"Migdal theorem"

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$$T_c \sim \omega_s e^{-1/\lambda}$$

Dominant Pairing Channel

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- Energy integrated spin structure factor

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2. Quantum #'s: $J_z=L_z+S_z$ & Parity
3. Resulting interaction suppresses even-parity states

Leading channels

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$$\hat{\Delta}^{(-)}_{j_z=0} \sim \begin{pmatrix} k_x - ik_y & 0 \\ 0 & k_x + ik_y \end{pmatrix}$$

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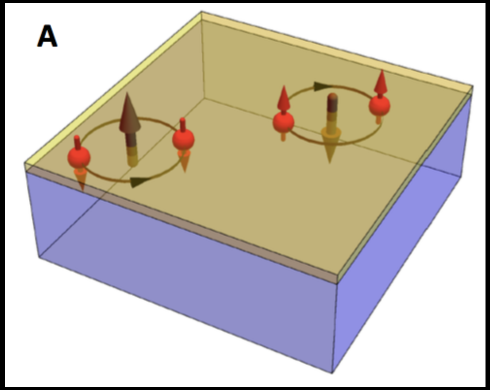

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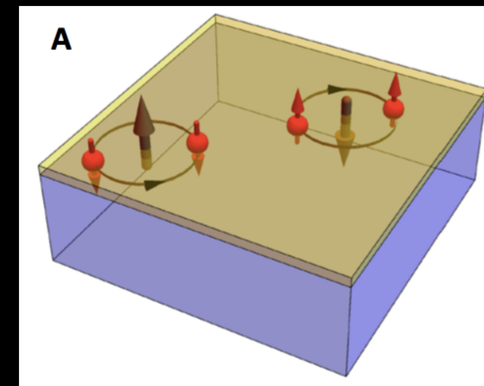

$$\hat{\Delta}^{(-)}_{j_z=\pm 1} \sim \begin{pmatrix} 0 & k_x \pm ik_y \\ k_x \pm ik_y & 0 \end{pmatrix}$$

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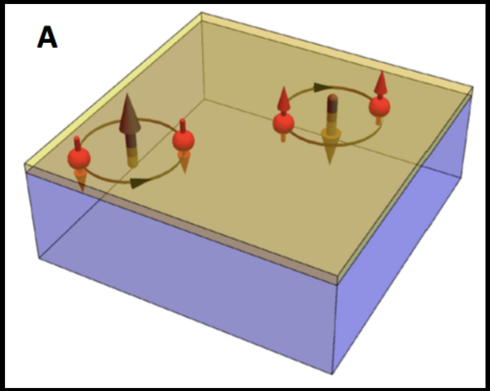

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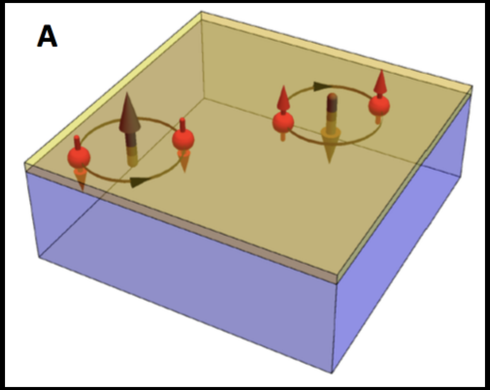

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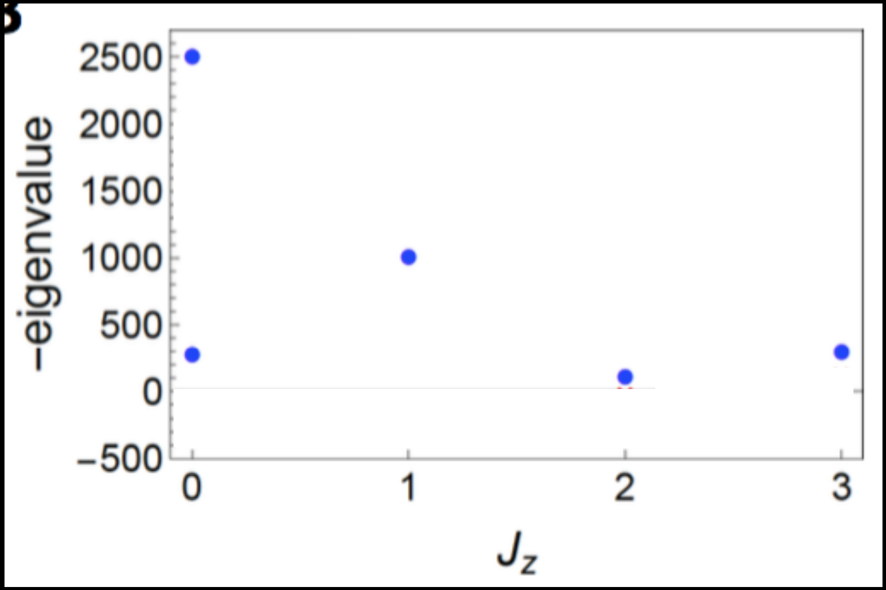

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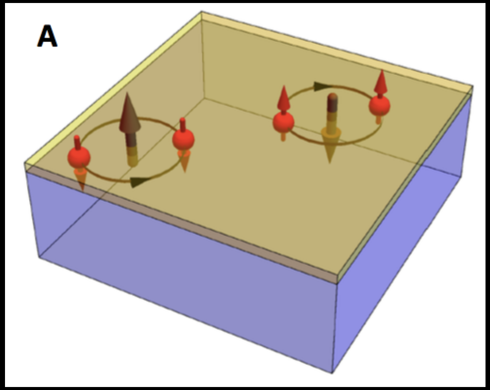

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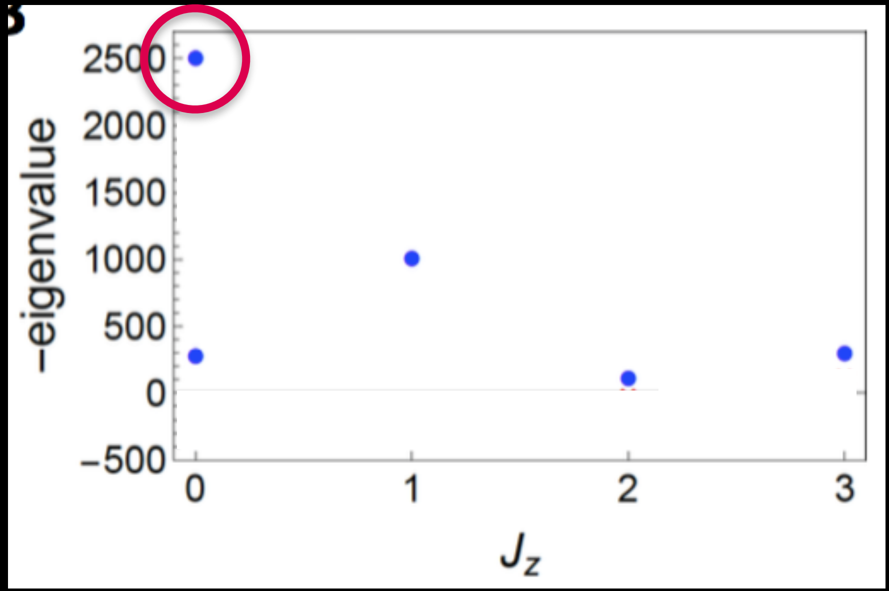

Can we persuade a material synthesis person?

Criteria for Metal

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- Structural
  - Lattice match
    - ➡ $A_2B_2O_7$
  - No orphan bonds

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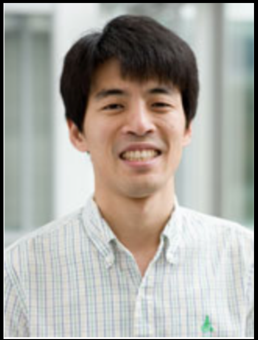
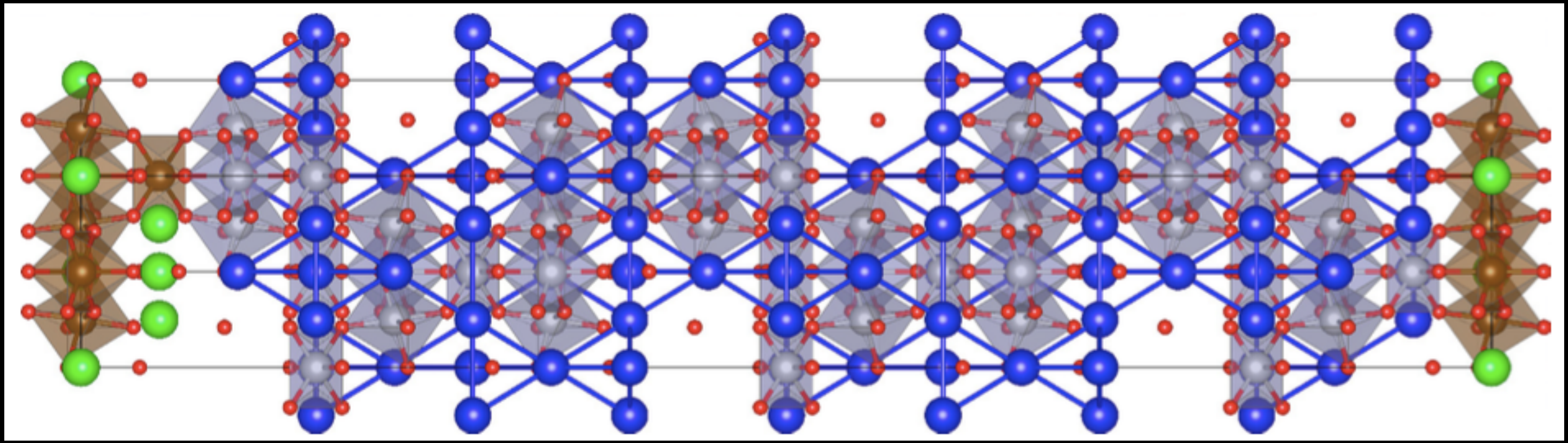
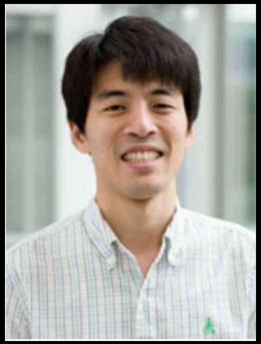
- Electronic
  - Simple isotropic Fermi surface
  - Wave function penetration
  - Odd-# FS around high symmetry points



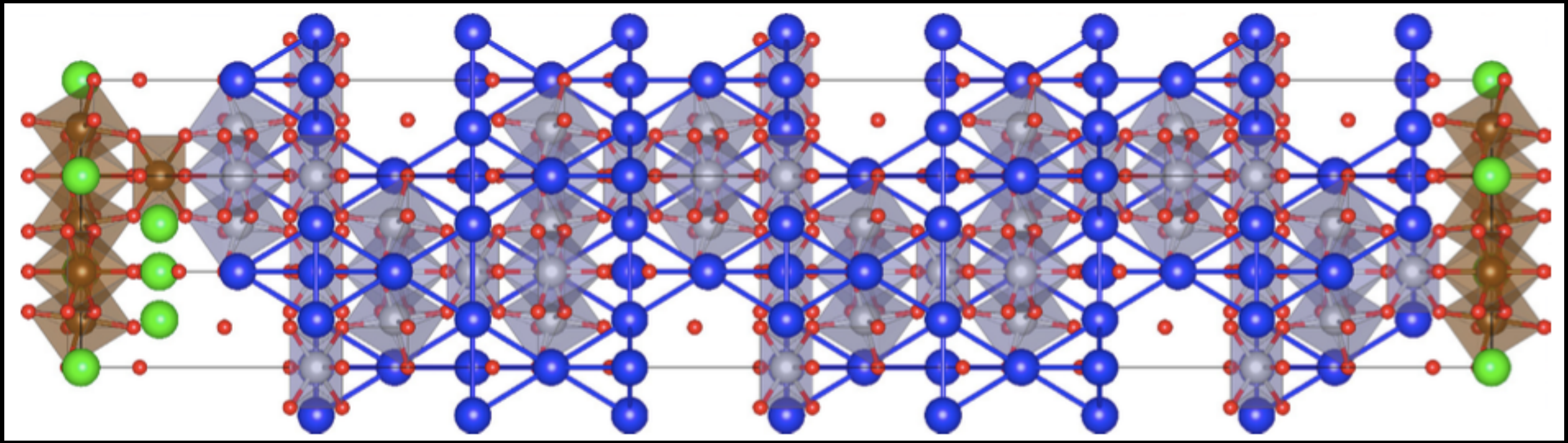
$Pr_2Zr_2O_7/Y_2Sn_{2-x}Sb_xO_7$ (111)

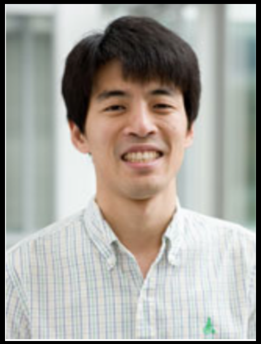




$Pr_2Zr_2O_7/Y_2Sn_{2-x}Sb_xO_7\ (111)$

Non-magnetic

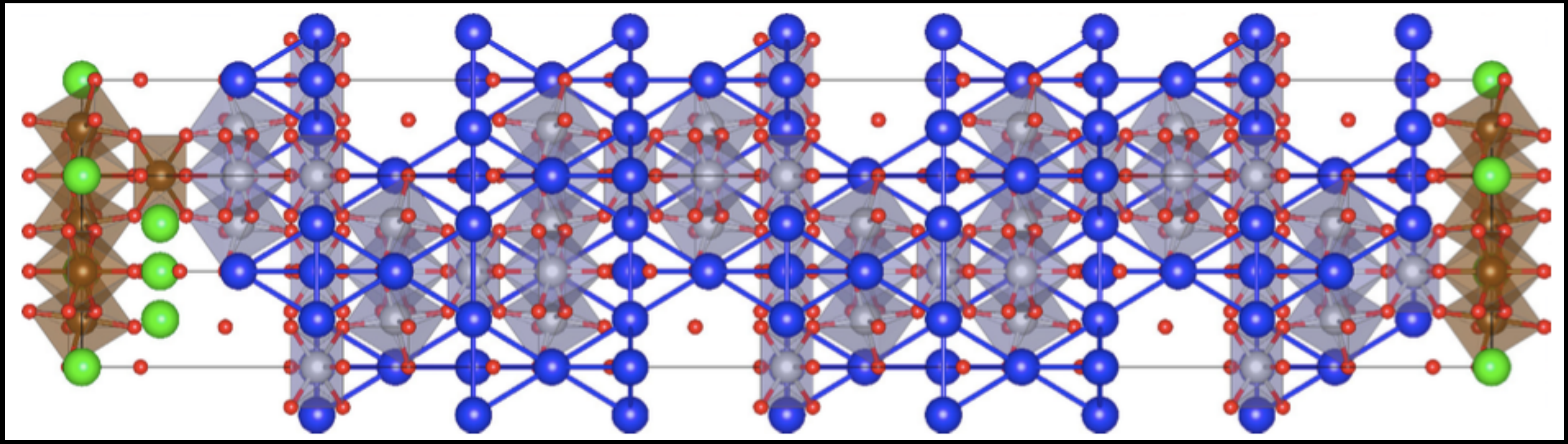




$$\mathrm{Pr_2Zr_2O_7/Y_2Sn_{2-x}Sb_xO_7}\ \ (111)$$

Non-magnetic

s-electrons:
large overlap,
isotropic FS.



Band structure for the Proposal

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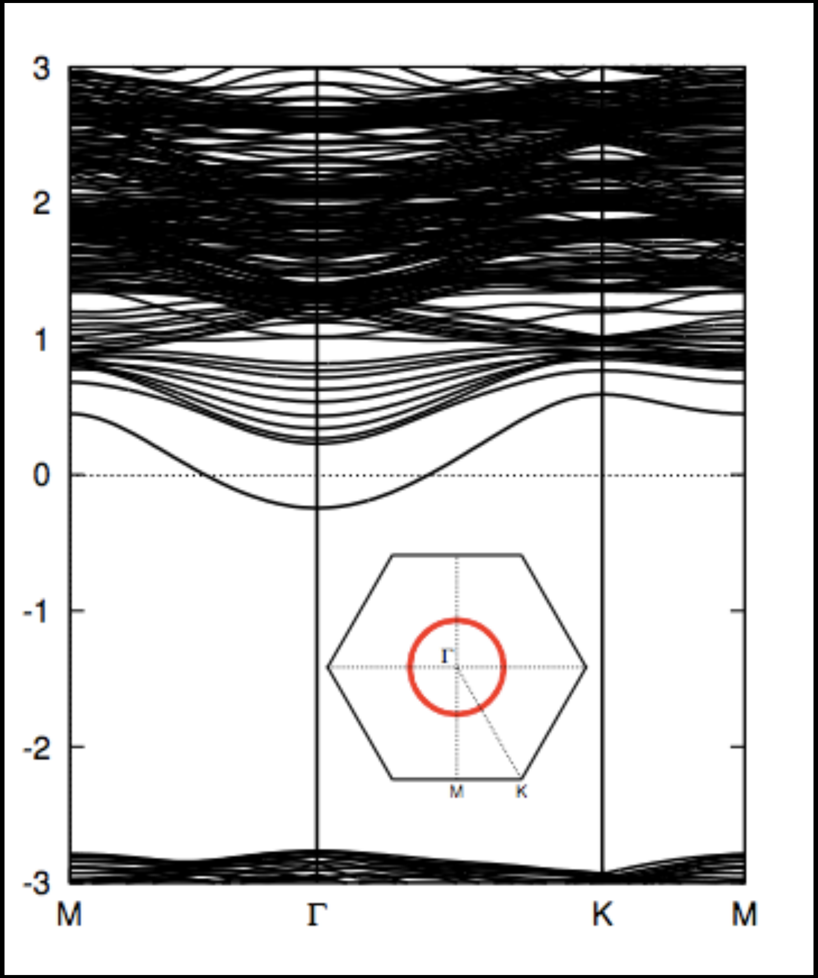

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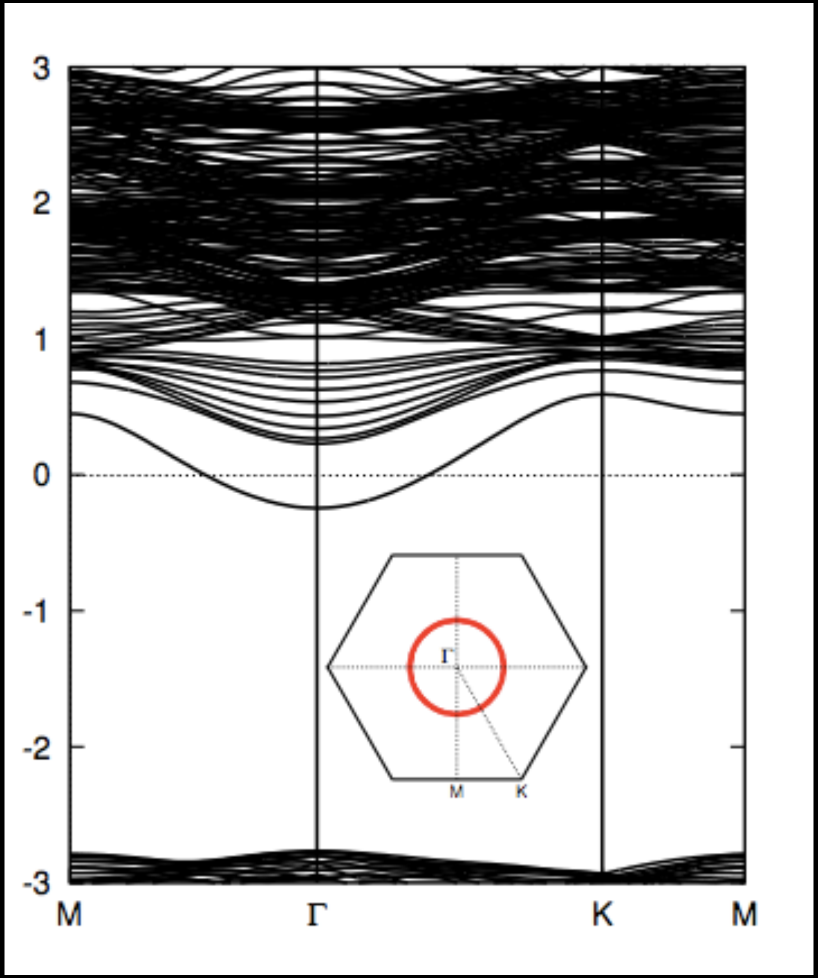
x=0.2

- Isotropic single pocket centered at Γ-point



Wave function penetration

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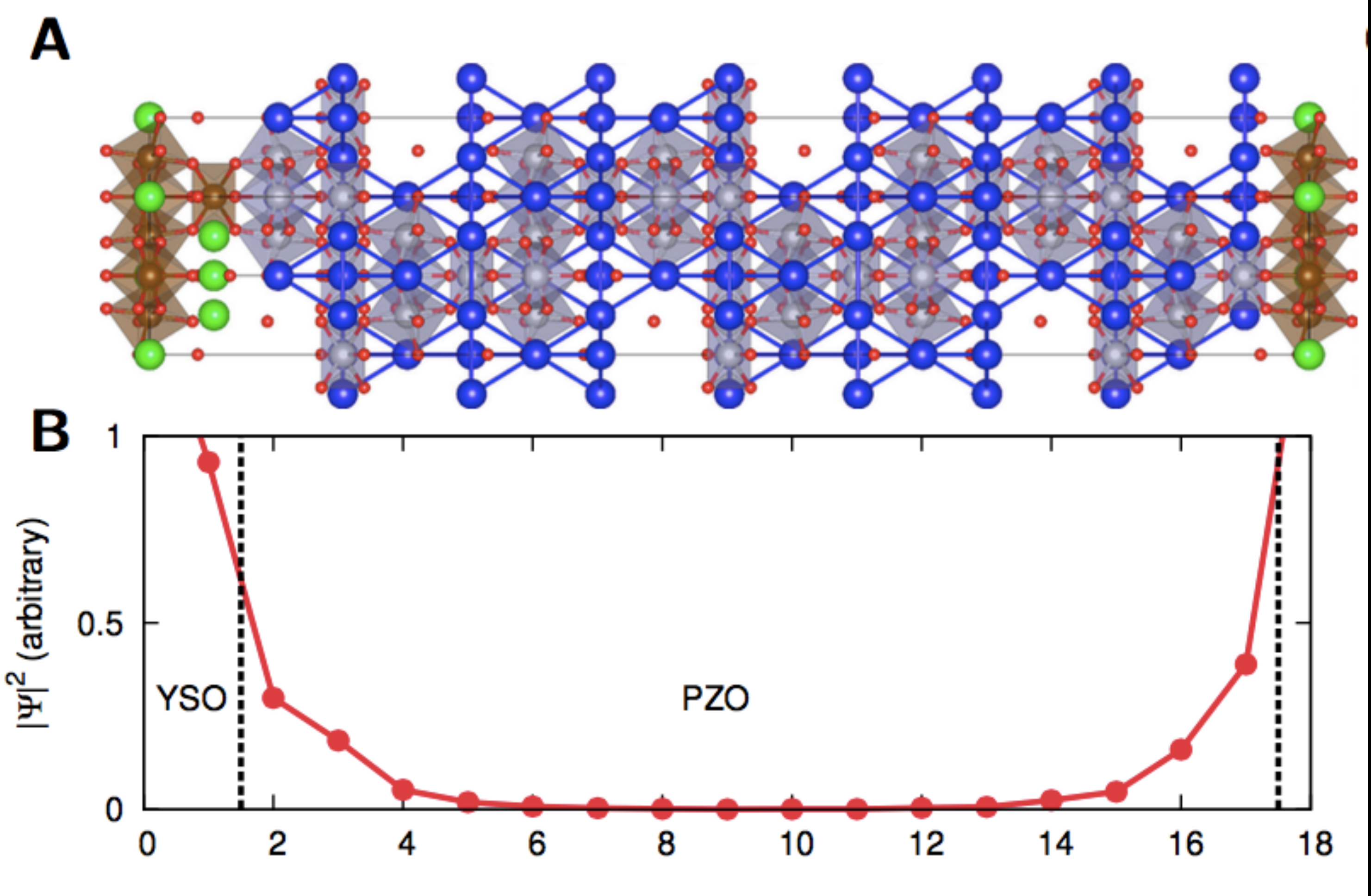

Earlier Proposal: Excitonic mechanism

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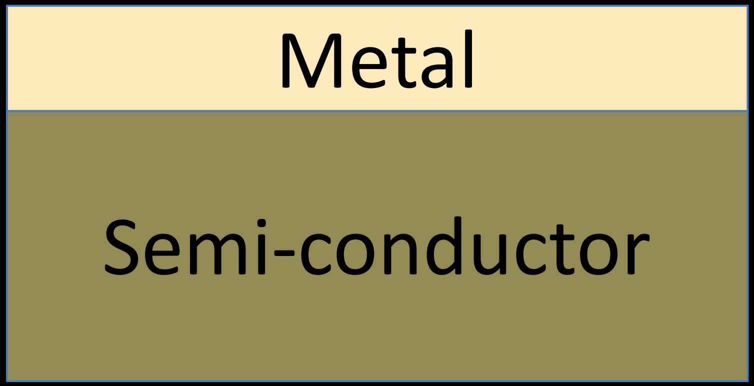

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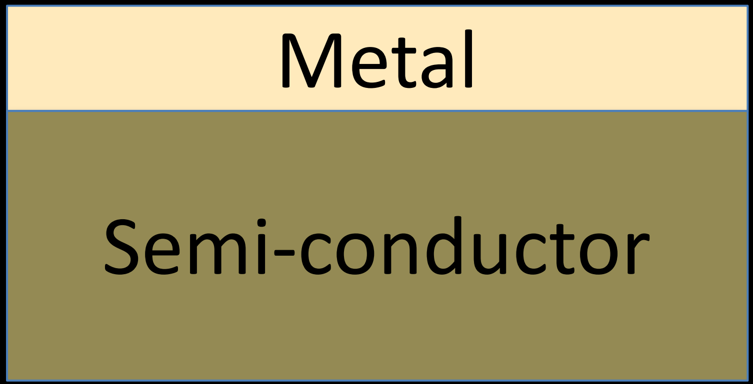

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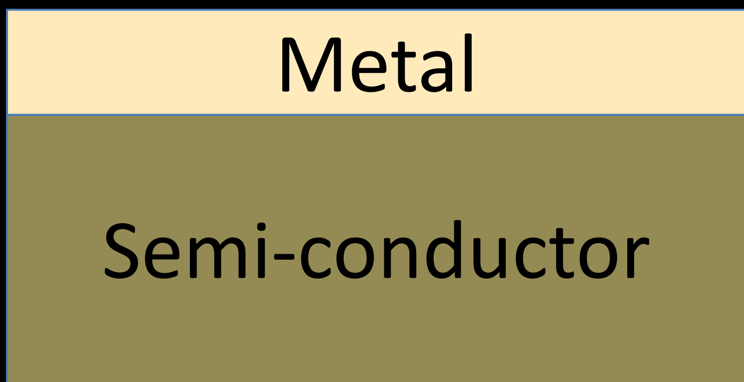
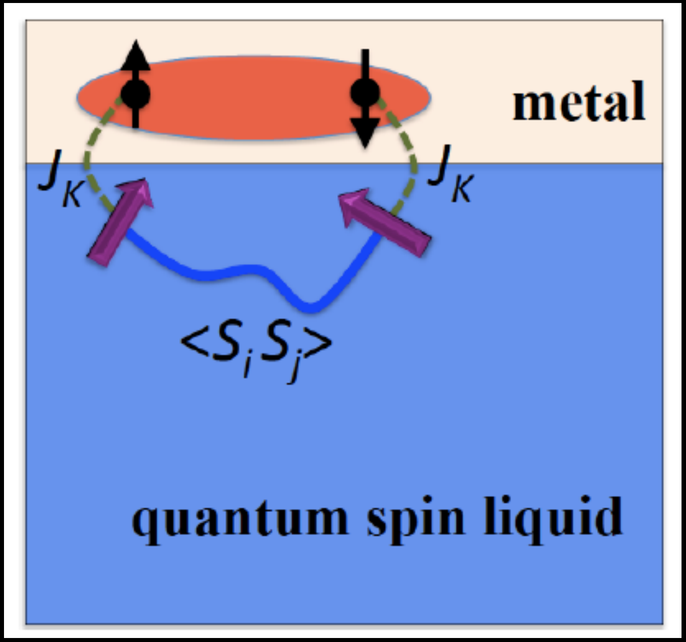


- Unstable against exchange.
- Intrinsically s-wave.

Little (64), Ginzburg (70), Bardeen (73)

Topological Superconductivity in Metal/ Quantum-Spin-Ice Heterostructures



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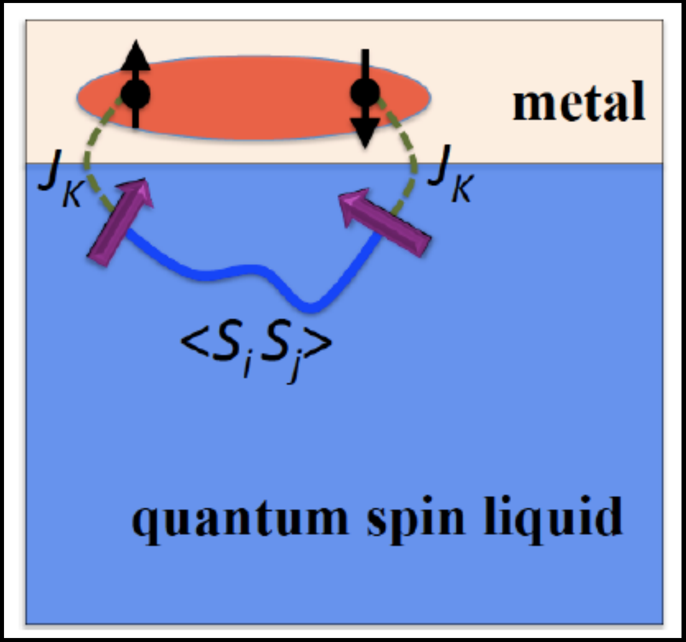

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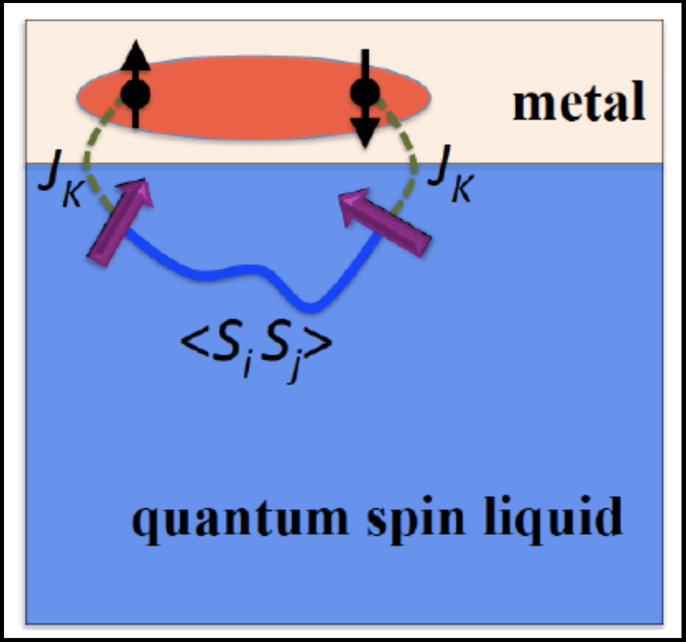

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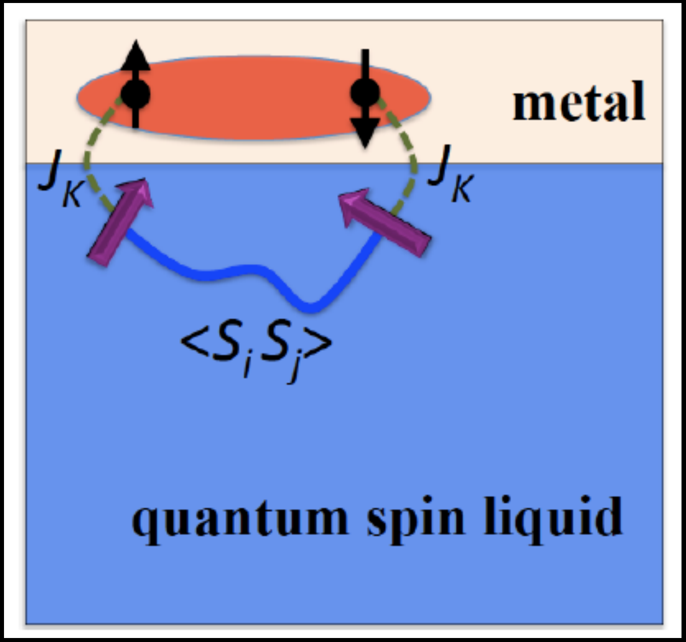

- Topological superconductor riding on QSL
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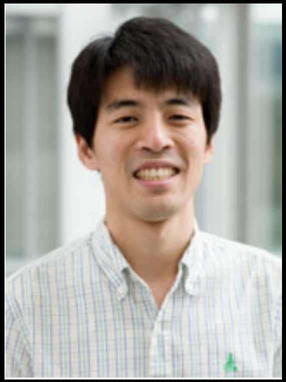
- Substantial phase space.

Acknowledgements

Jian-huang She



Choonghyun Kim

Criag Fennie

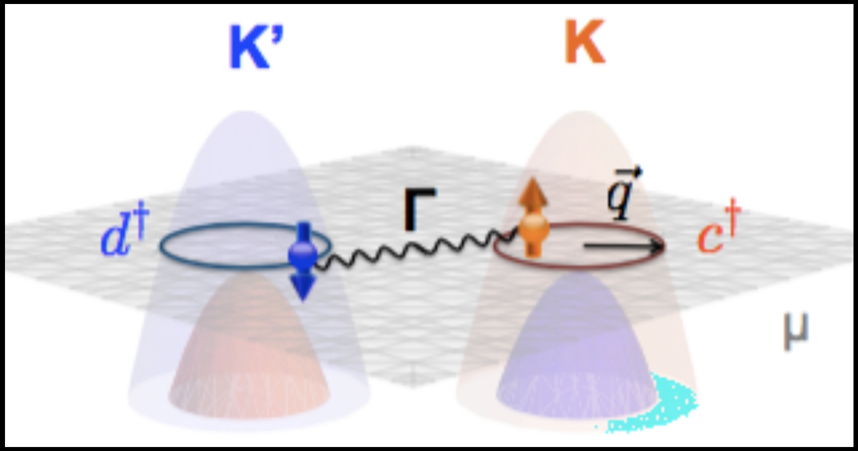
Michael Lawler

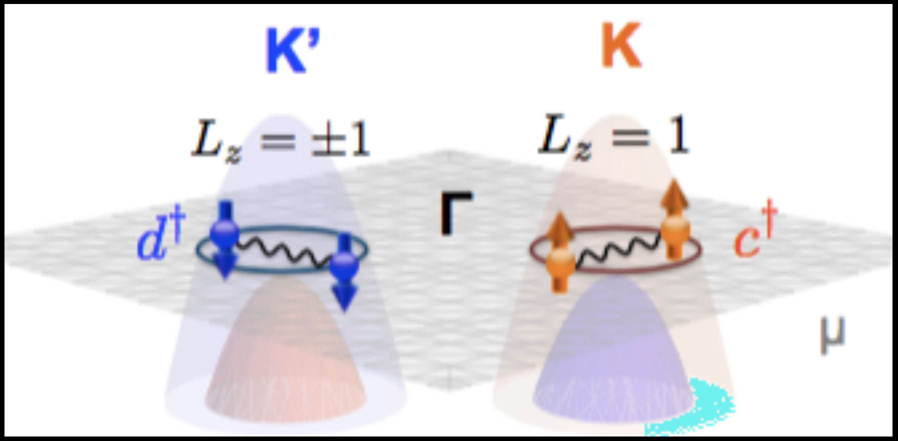
Funding: DOE, CCMR (NSF)

Strategy II

Manipulate the band structure

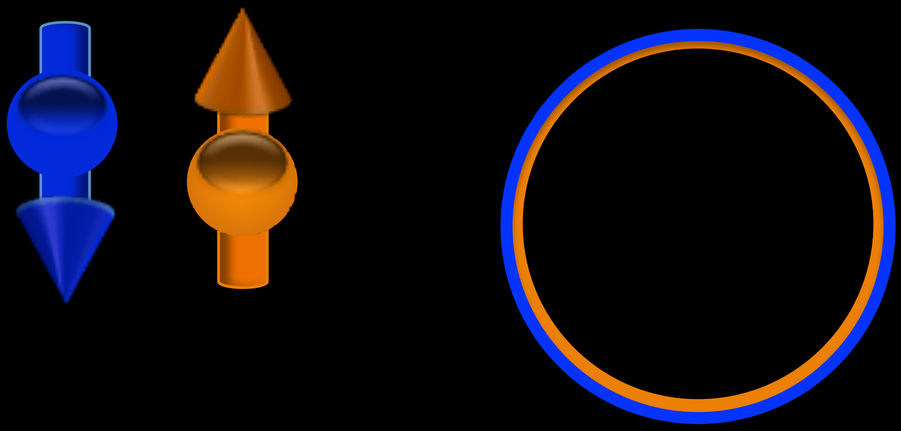
Topological superconductivity in group-VI TMDs





Yi-Ting Hsu, Abolhassan Vaezi, E-AK (in preparation)

Spin-degenerate Fermi surface



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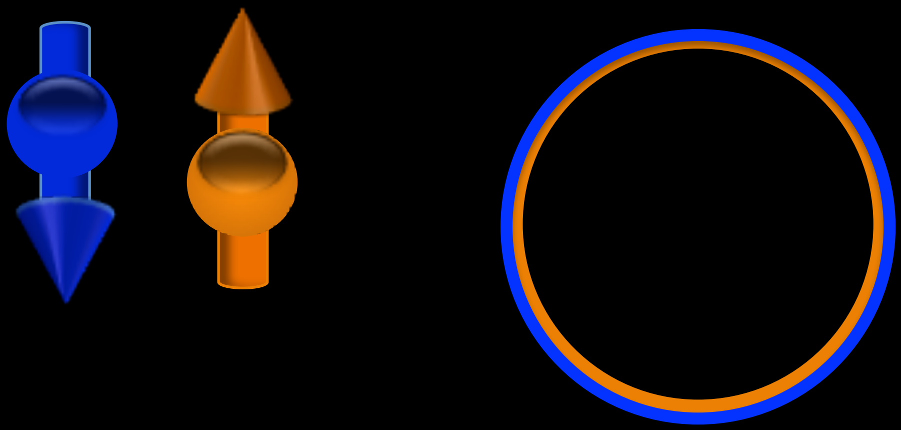

Singlet superconductor

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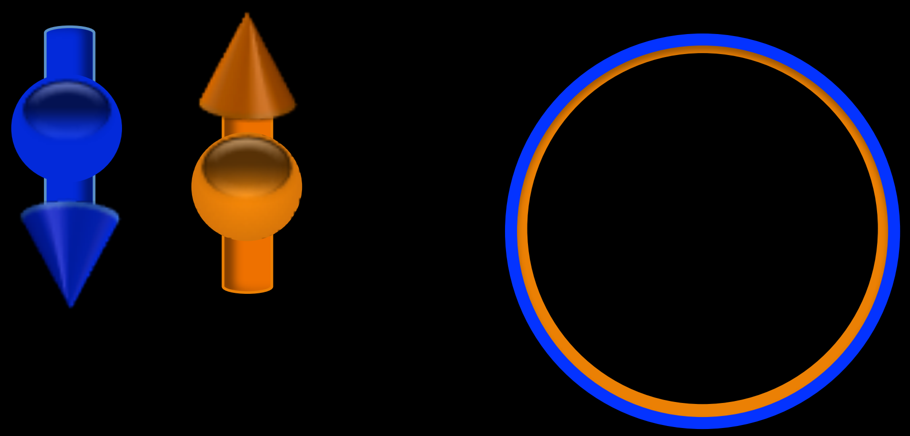

Singlet superconductor

Q. What if the band structure is spin-split?

Spinless fermion via real space splitting

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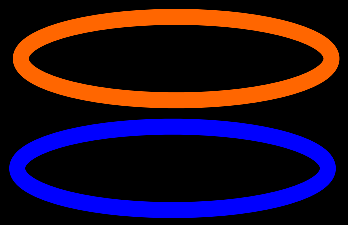

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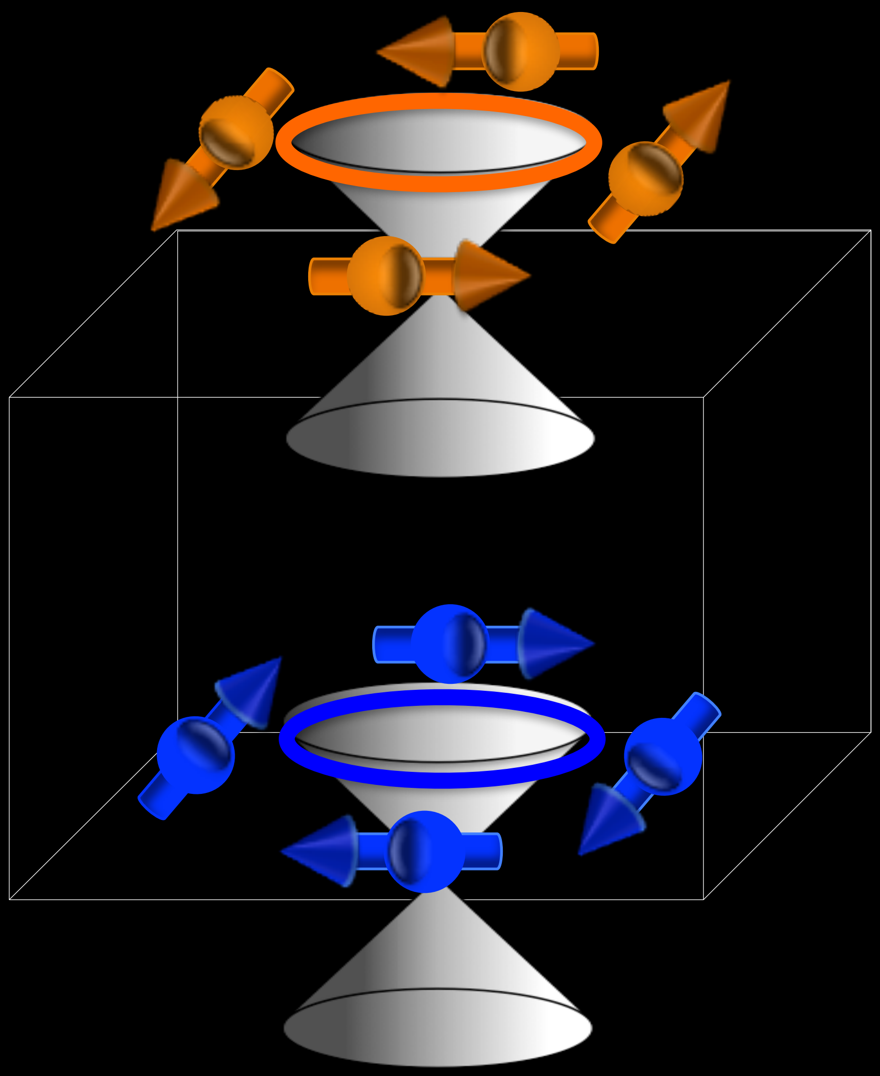
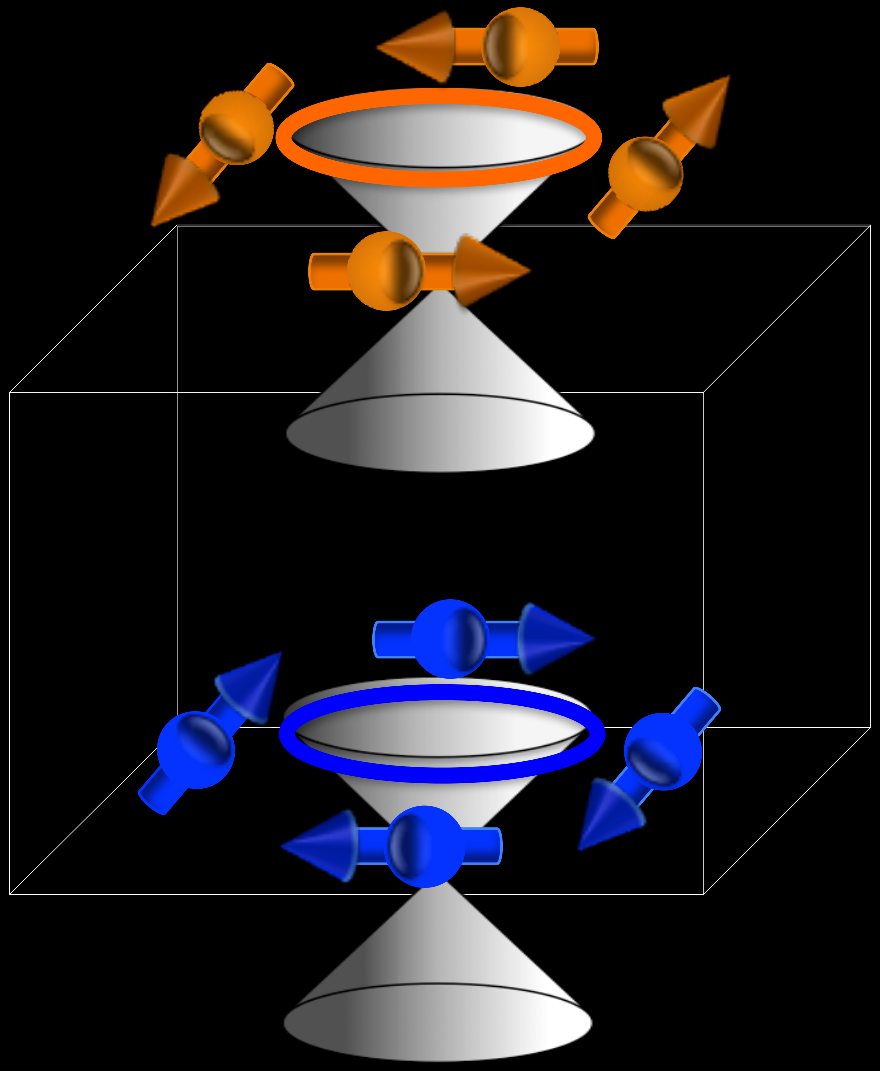


Spinless fermion via real space splitting

- TI surface states



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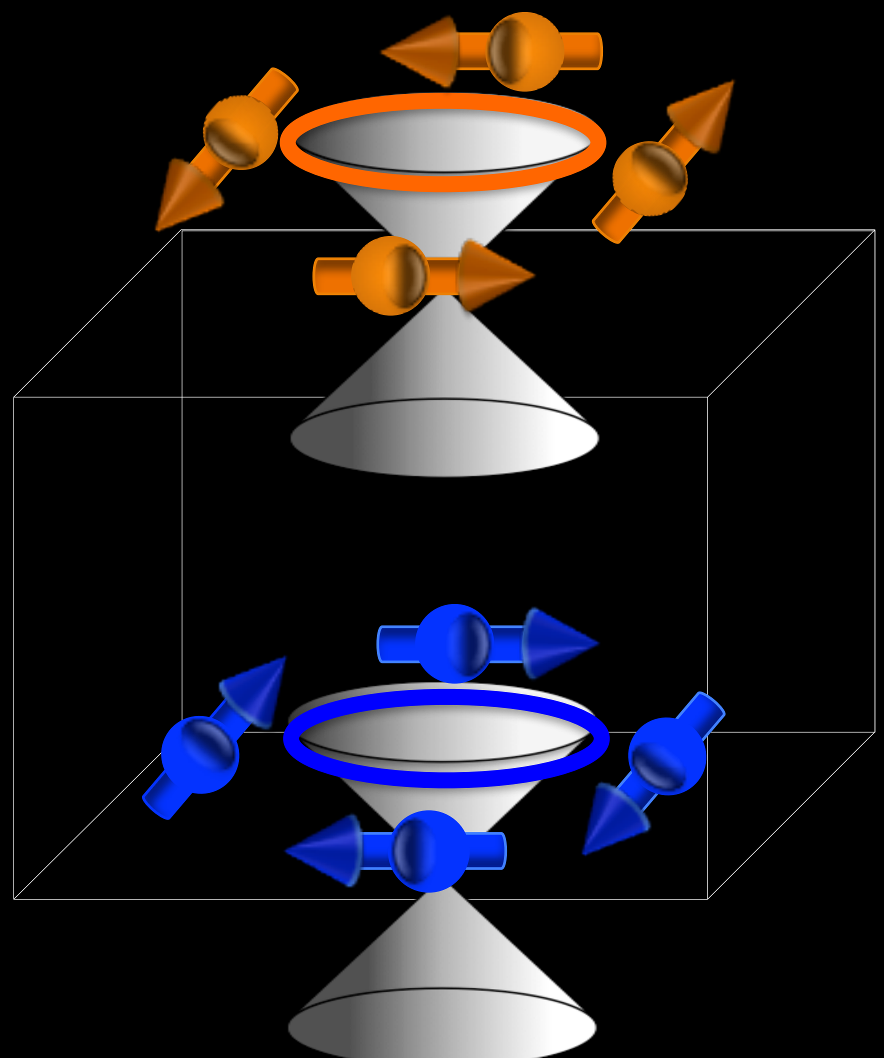

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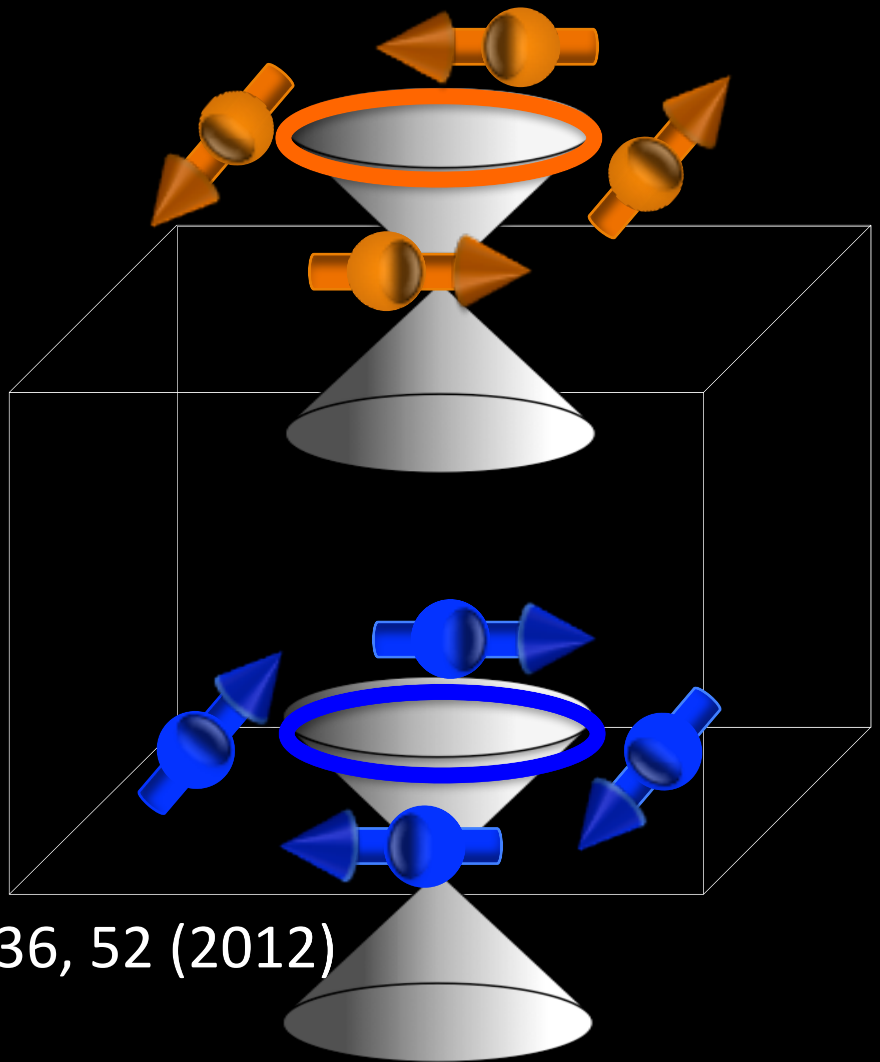
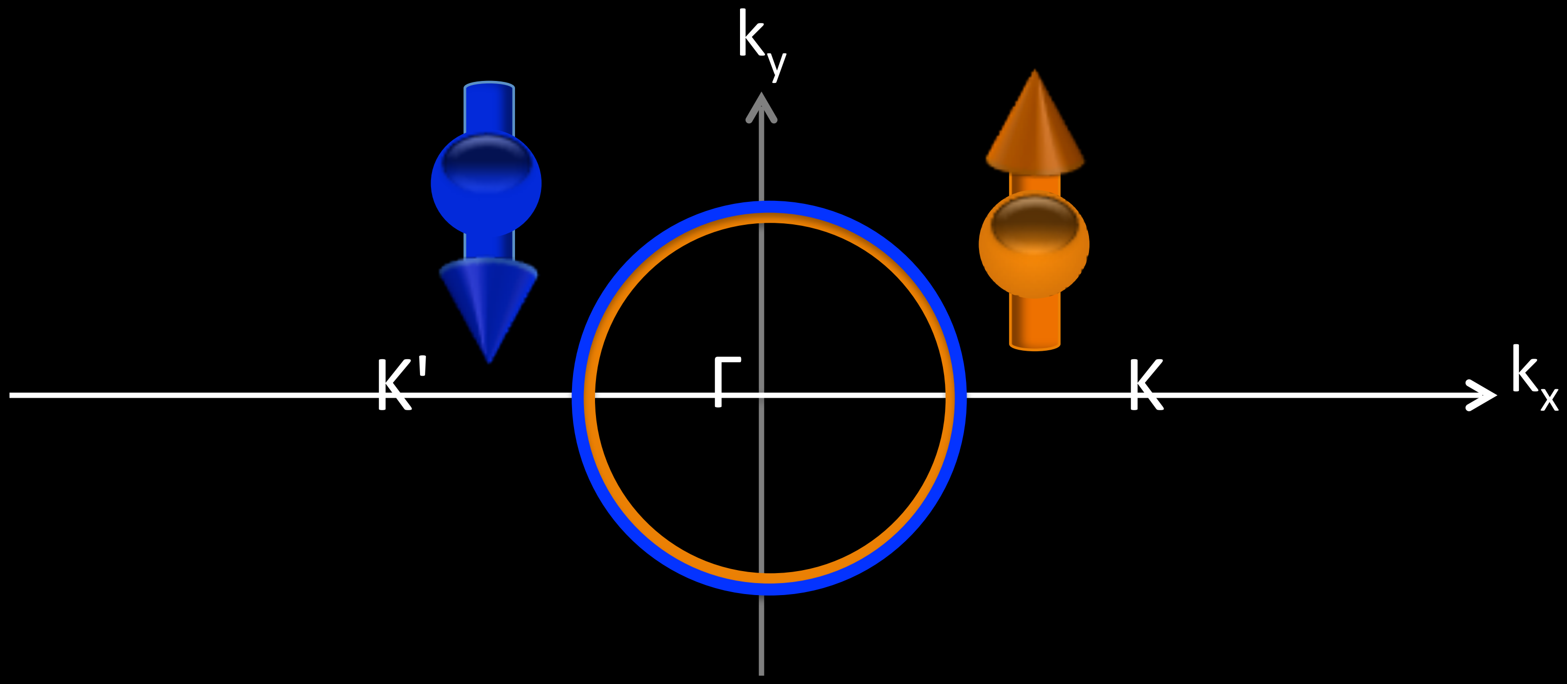
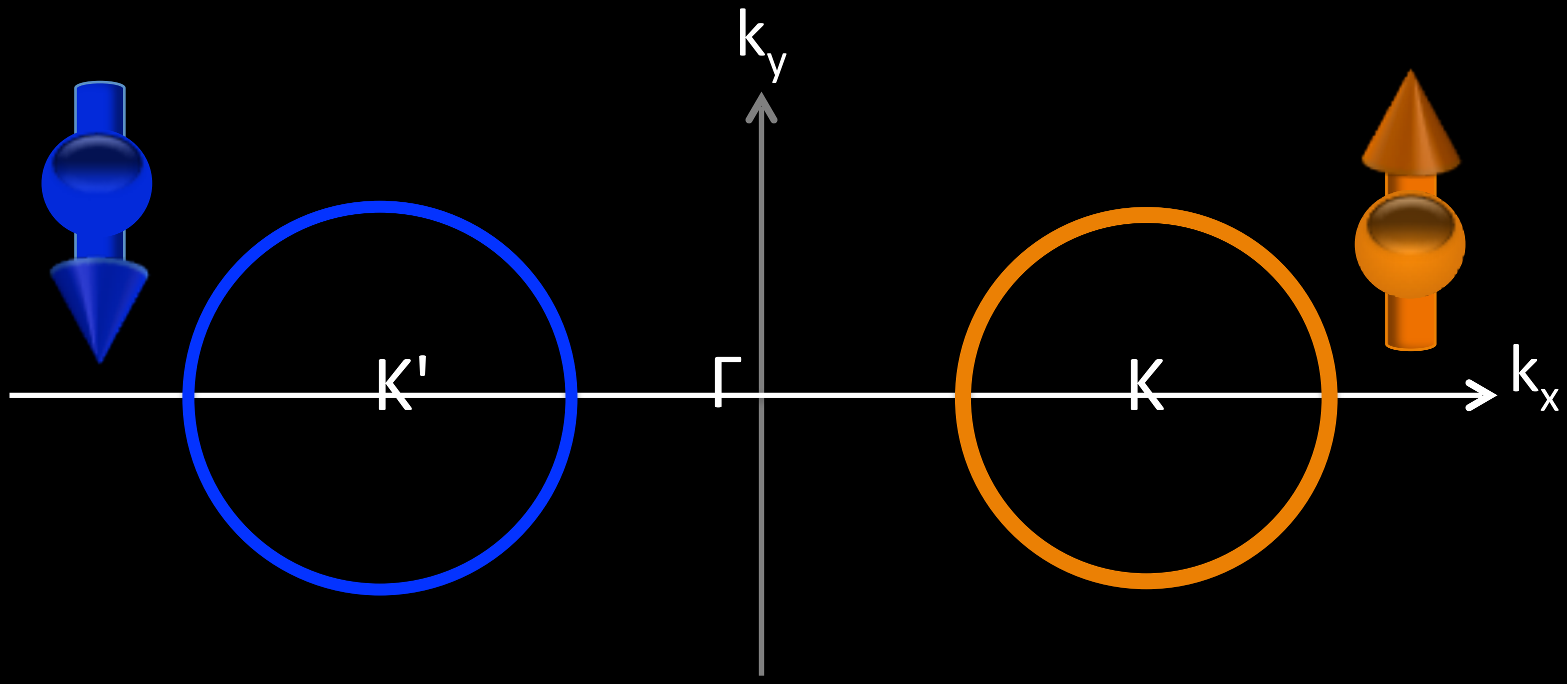


Fu & Kane, PRL (2008)
Experiments: Wang et al Science 336, 52 (2012)
Xu et al, Nat.Phys 10, 943 (2014)

Spinless fermion via k-space splitting?



Spinless fermion via k-space splitting?



Monolayer group VI TMD's

- **Non-centro symmetric**

➡ Direct Gap ~2eV
➡ Dresselhaus spin-orbit

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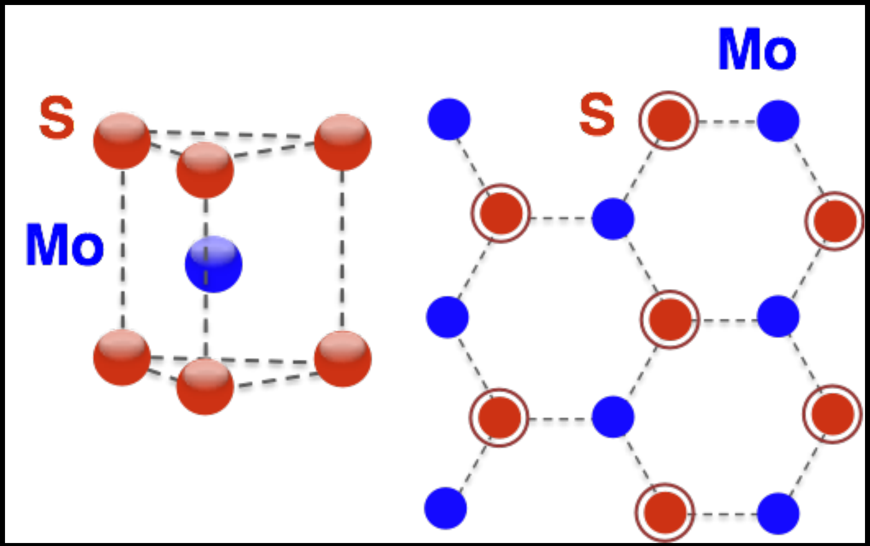

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- Spin-orbit coupling $\vec{L} \cdot \vec{S}$

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- Partially filled crystal-field-split d-bands
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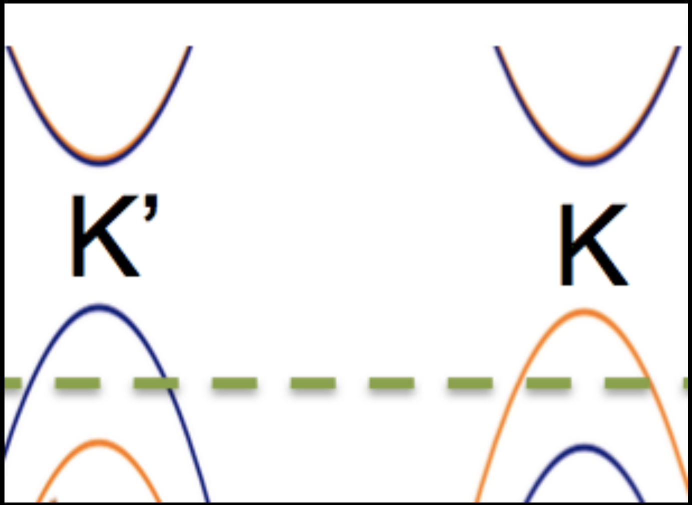
  - Valence band $\frac{1}{\sqrt{2}}(|d_{x^2-y^2}\rangle \mp i|d_{xy}\rangle)$: $l_z = \mp 1$

- Spin-orbit coupling $\vec{L} \cdot \vec{S}$



Band-selective spin-splitting

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  - Conduction band $|d_{z^2}\rangle : l_z = 0$
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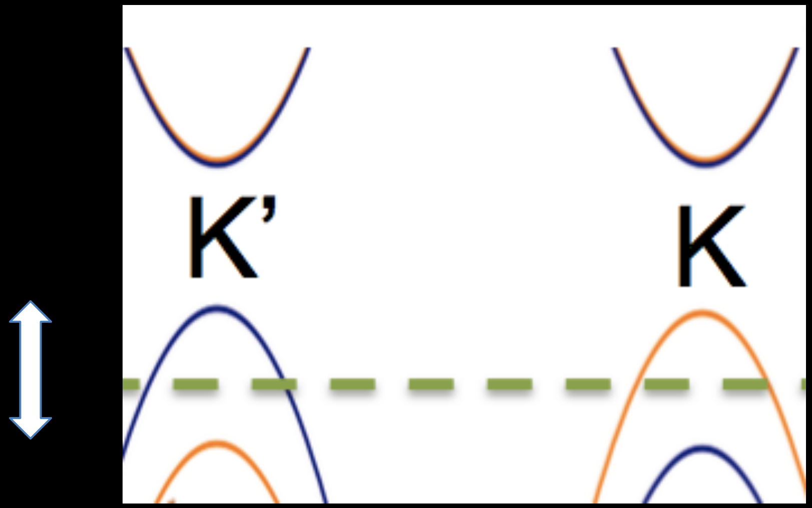
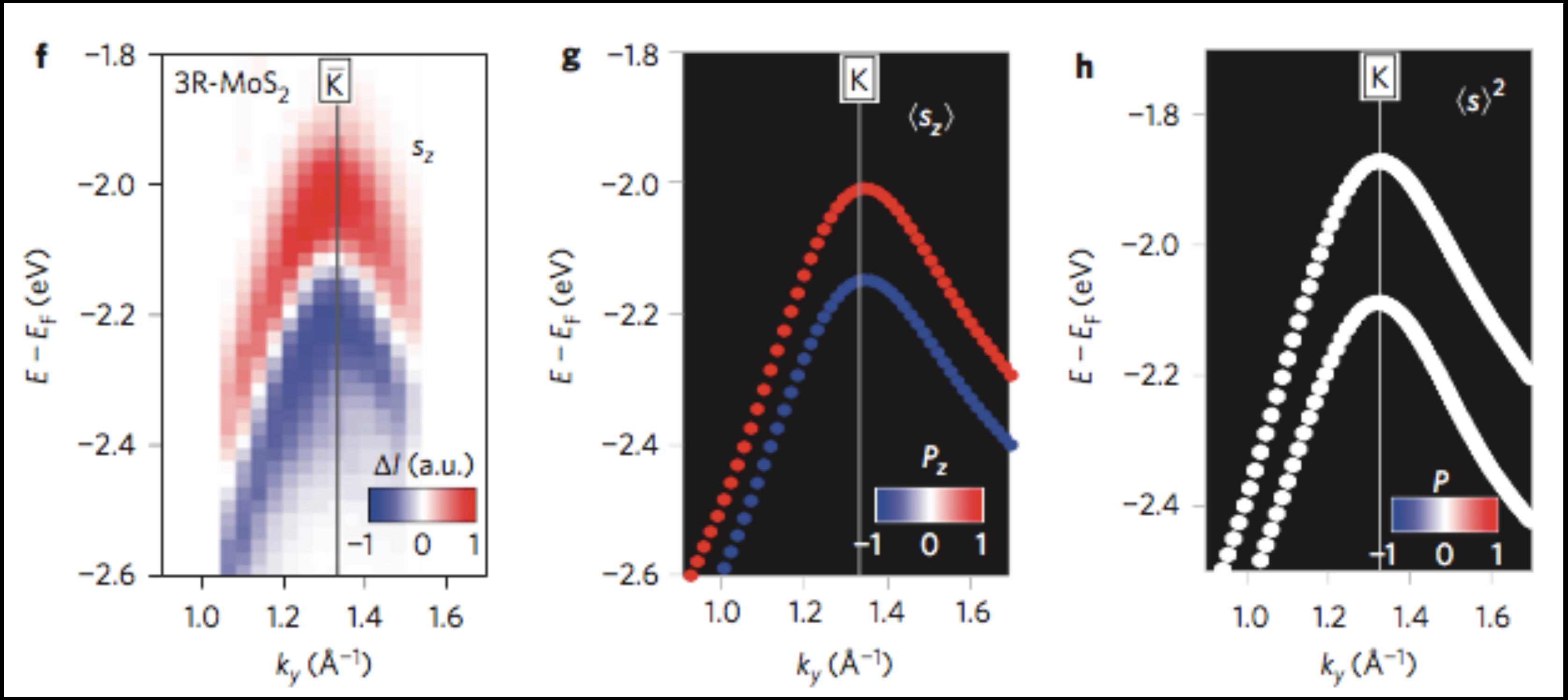
- Spin-orbit coupling $\vec{L} \cdot \vec{S}$

150~460meV





Iwasa group N. Nano (2014)

k-space spin-split FS?

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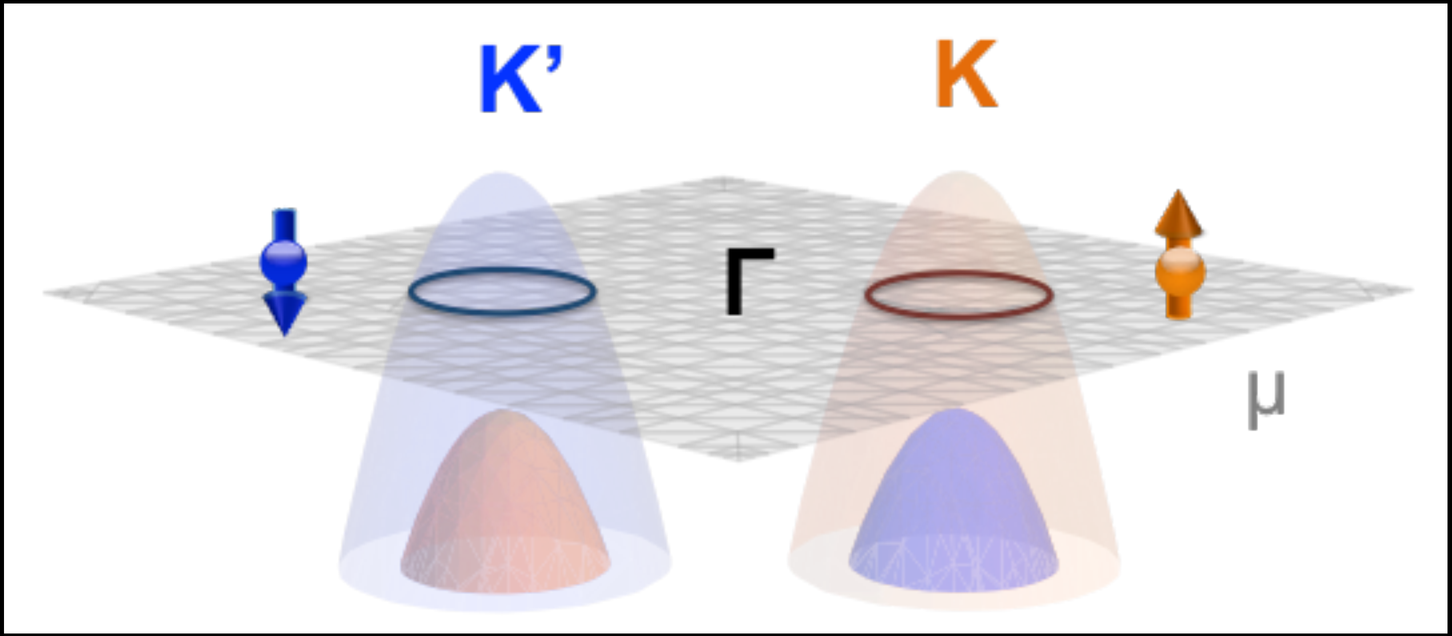
p-doped group VI- TMD!



Juice for superconductivity?

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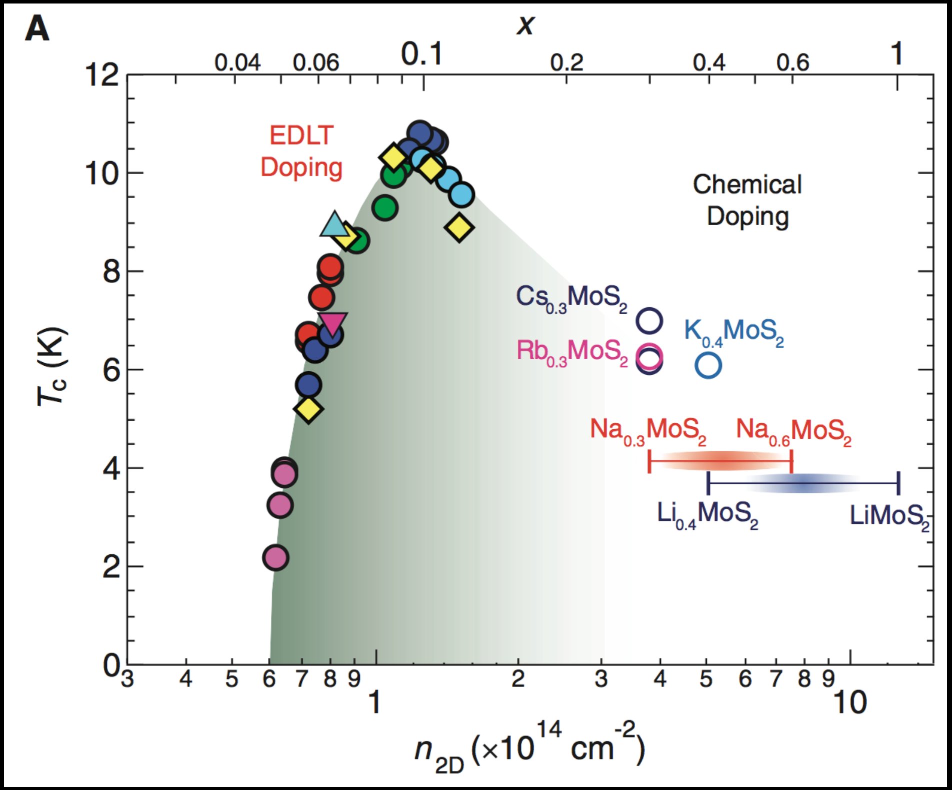
- d electrons => expect correlation effects

Juice for superconductivity?

- d electrons => expect correlation effects

- n-doped TMD's

  J.T.Ye *et al.* (Science 2012)



p-doped TMD

k-space spin-split Fermi surfaces

+

Moderate correlation (d-electron)

p-doped TMD

k-space spin-split Fermi surfaces

+

Moderate correlation (d-electron)

↓

Topological SC?

Yi-Ting Hsu

Mark Fischer

Abolhassan Vaezi

Model

- Kinetic term

$$H_0(\vec{q}) = at(\tau q_x \hat{\sigma_x} + q_y \hat{\sigma_y}) + \frac{\Delta}{2}\hat{\sigma_z} - \lambda\tau\hat{s_z} \otimes \frac{\hat{\sigma_z} - 1}{2}$$

- Repulsive interaction term

$$H'(W) = \sum_i U n_{i,\uparrow} n_{i,\downarrow}$$

Model

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Band-basis

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Band-basis

Spin-basis

- Repulsive interaction term

$$H'(W) = \sum_i U n_{i,\uparrow} n_{i,\downarrow}$$

Superconductivity out of repulsive interaction?

(Kohn &Luttinger 1965)

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- Kohn-Luttiger: singularity in scattering amplitude $\Gamma(\vec{q})$

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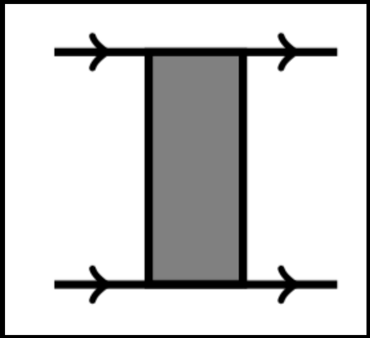

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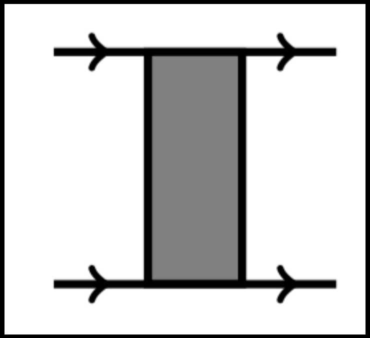

➡Non-s wave

(Kohn &Luttinger 1965)

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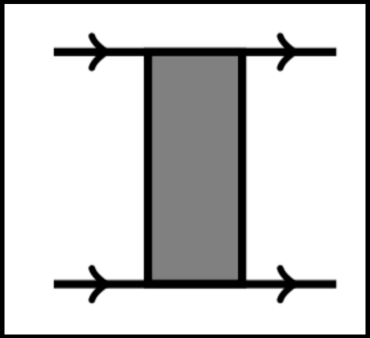

➡Non-s wave

(Kohn &Luttinger 1965)

- Two-step RG formulation
  : Fe-based SC, doped graphene, SrRuO

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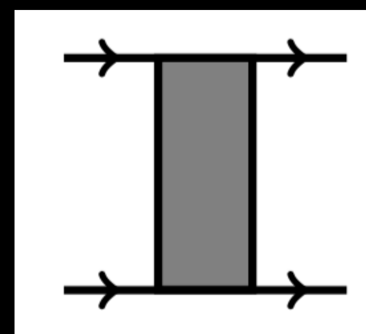


➡Non-s wave

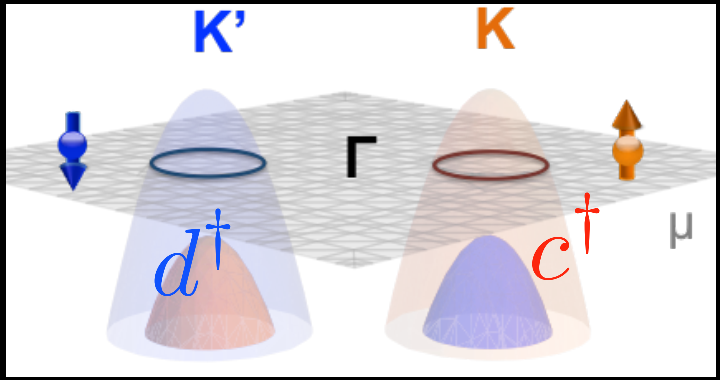
(Kohn &Luttinger 1965)

- Two-step RG formulation
  : Fe-based SC, doped graphene, SrRuO

  Chubukov & Nandkishore, Raghu & Kivelson (2008 - 2012)

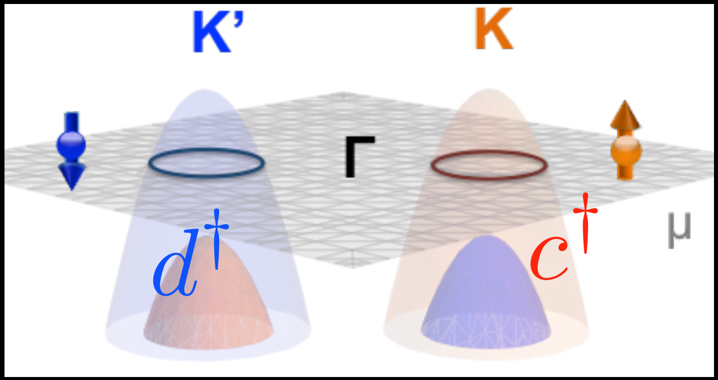
Two-step RG on p-doped TMD

Step I: W -> Λ_0



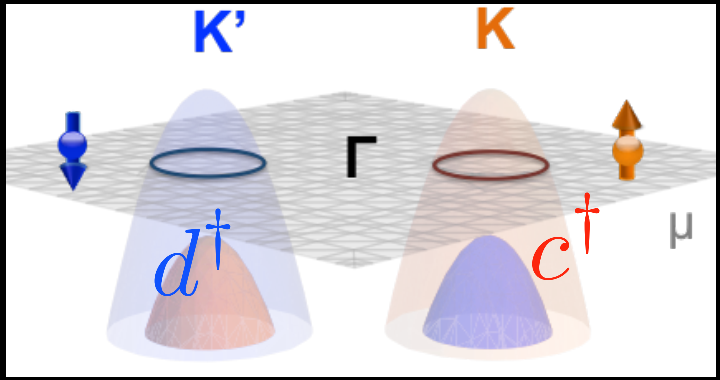
- At scale Λ_0: Effective model

Step I: W -> Λ_0



- At scale W: Microscopic model
- At scale Λ_0: Effective model

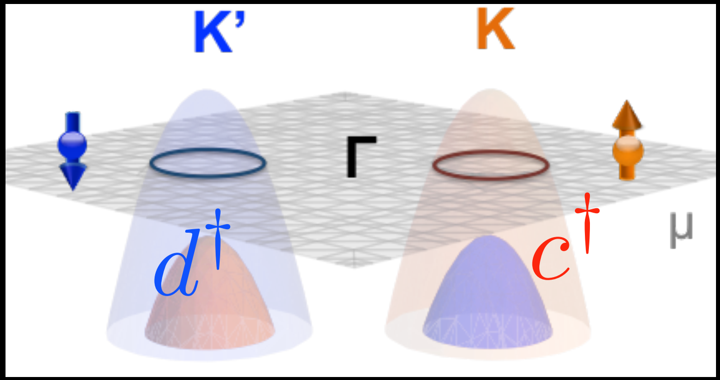
Step I: W -> Λ_0



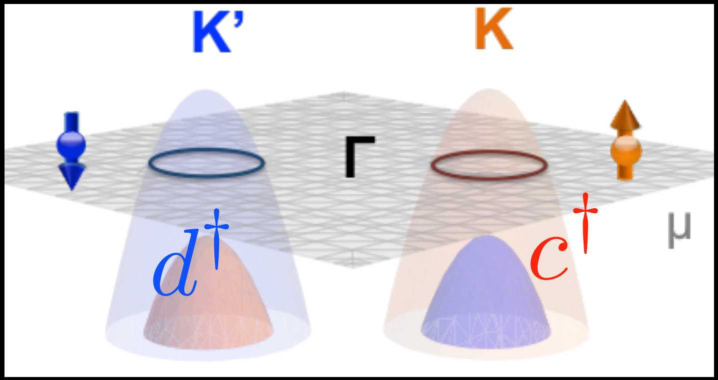
- At scale W: Microscopic model
- At scale Λ_0: Effective model

$$H'_{eff}(\Lambda_0) = \sum_{\vec{q},\vec{q}'}{}' g^{(0)}_{\text{inter}}(\vec{q},\vec{q}')c^\dagger_{\vec{q}'}d^\dagger_{-\vec{q}'}d_{-\vec{q}}c_{\vec{q}} + g^{(0)}_{\text{intra}}(\vec{q},\vec{q}')d^\dagger_{\vec{q}'}d^\dagger_{-\vec{q}'}d_{-\vec{q}}d_{\vec{q}} + (c \leftrightarrow d)$$

Step I: W -> Λ_0

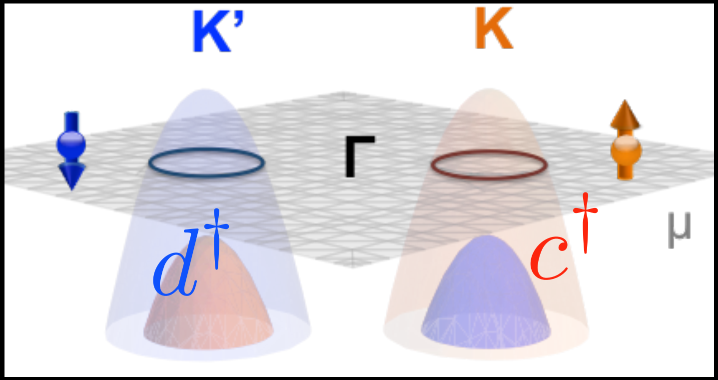


Step I: W -> Λ_0



- $g_{intra,0}$ and $g_{inter,0}$ at two-loop

Step I: W -> Λ_0



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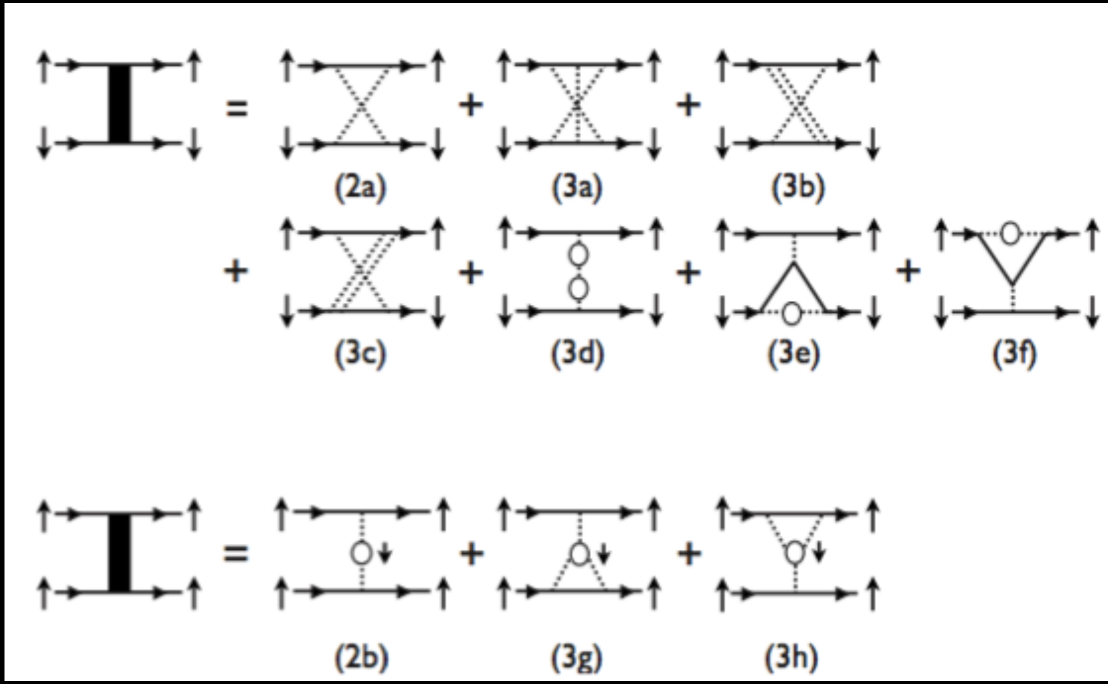
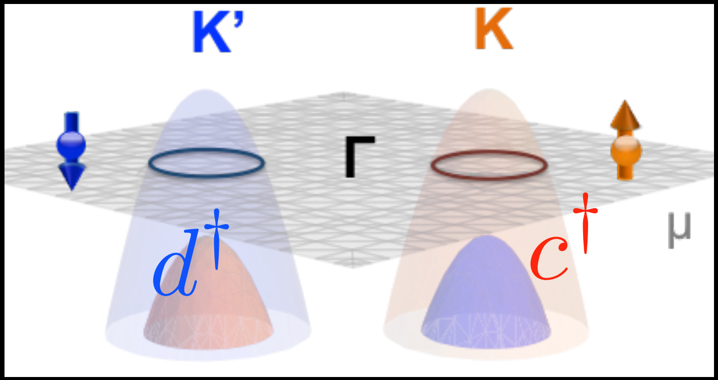


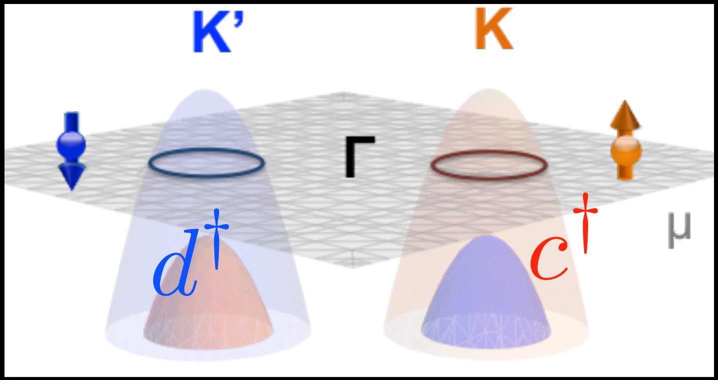
Step I: W -> Λ_0



- $g_{intra,0}$ and $g_{inter,0}$ at two-loop

$$g^{(0)}_{inter}(\vec{q},\vec{q}') = U + U^3 f_{inter}(\vec{q},\vec{q}')$$

Step I: W -> Λ_0



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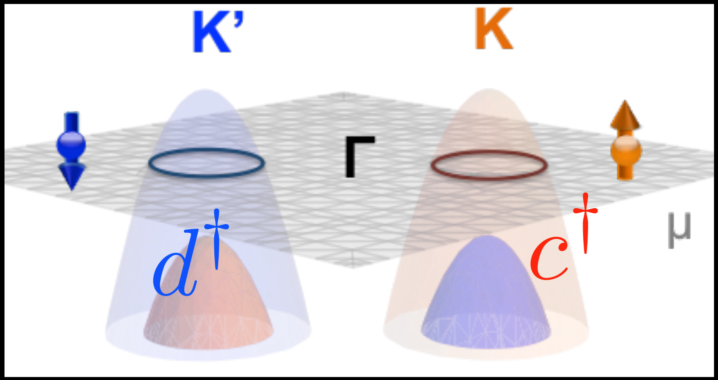
Step I: W -> Λ_0



- $g_{intra,0}$ and $g_{inter,0}$ at two-loop

$$g^{(0)}_{inter}(\vec{q},\vec{q}') = U + U^3 f_{inter}(\vec{q},\vec{q}')$$

$$g^{(0)}_{intra}(\vec{q},\vec{q}') = U^3 f_{intra}(\vec{q},\vec{q}')$$

- f's <0 -> $g^{(0)}$'s<0 in anisotropic channel

Step I: $\Lambda_0 \to 0$

- RG flow

- Divergence if $\lambda^{(0)} < 0$

Step I: Λ_0 ->0

- RG flow $$\frac{d\lambda}{dy} = -\lambda^2$$

$$y \equiv \nu_0 \mathrm{Log}(\Lambda_0/\mathrm{E})$$

- Divergence if $\lambda^{(0)} < 0$

Step I: Λ_0 ->0

- RG flow $$\frac{d\lambda}{dy} = -\lambda^2 \quad \Rightarrow \quad \lambda(y) = \frac{\lambda^{(0)}}{1+\lambda^{(0)} y}$$

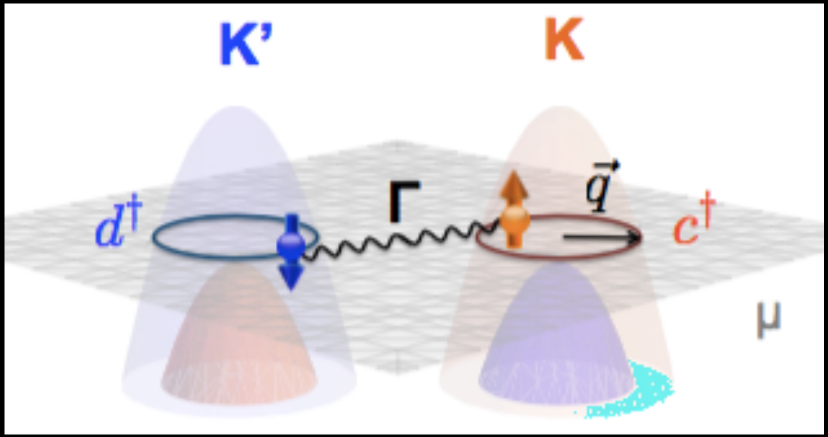
$$y \equiv \nu_0 \mathrm{Log}(\Lambda_0/\mathrm{E})$$

- Divergence if $\lambda^{(0)} < 0$

Two degenerate possibilities

Two degenerate possibilities

- Intra-pocket p+ip



Two degenerate possibilities

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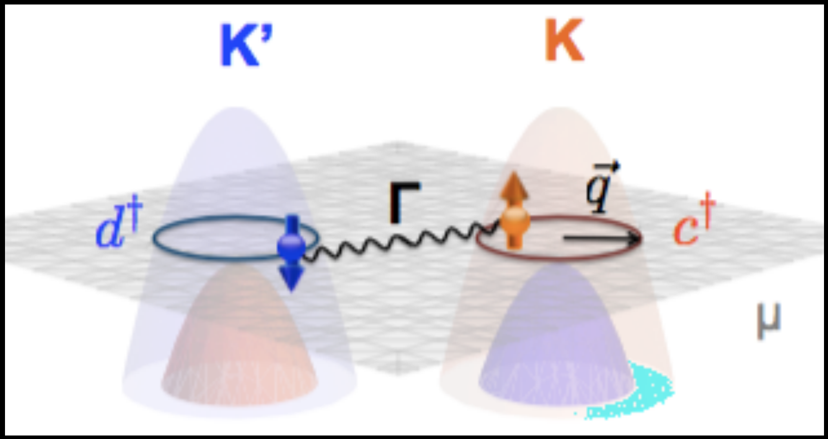
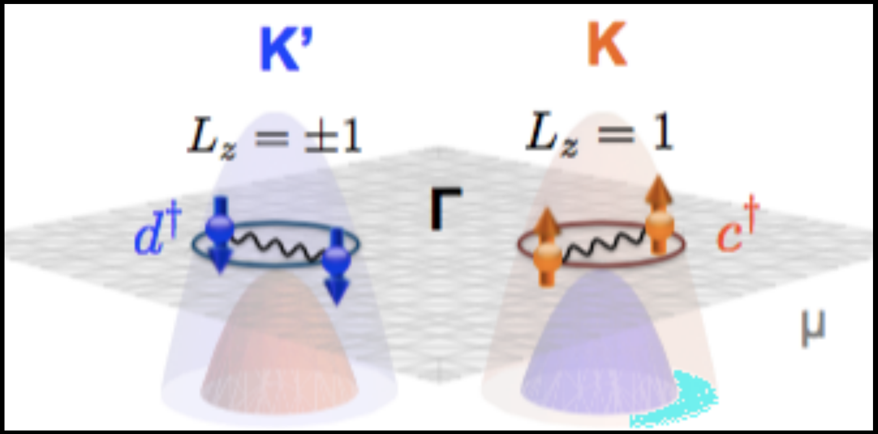


- Inter-pocket p'wave



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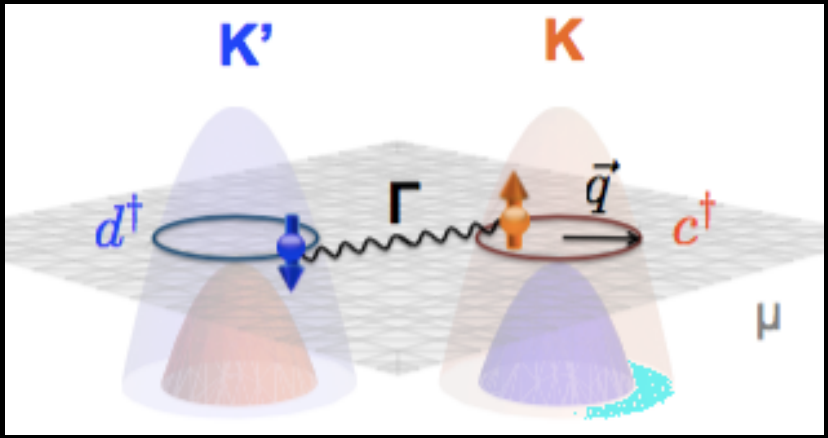

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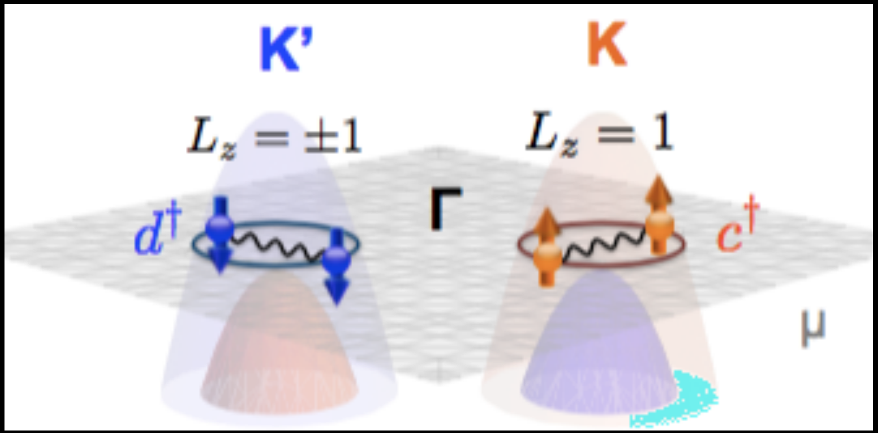
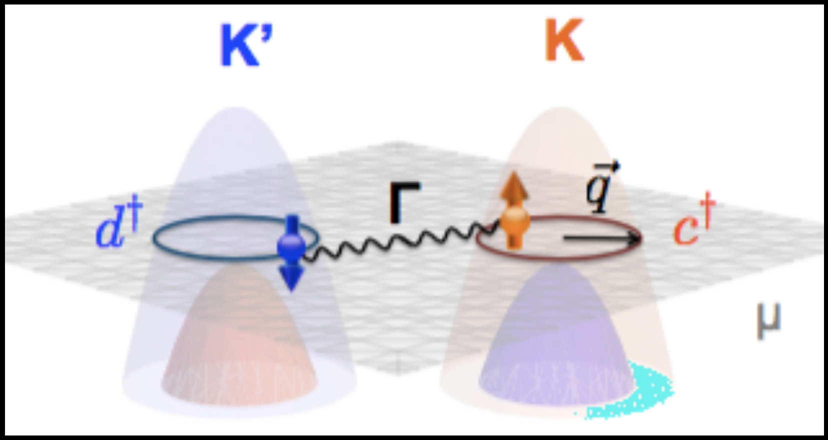


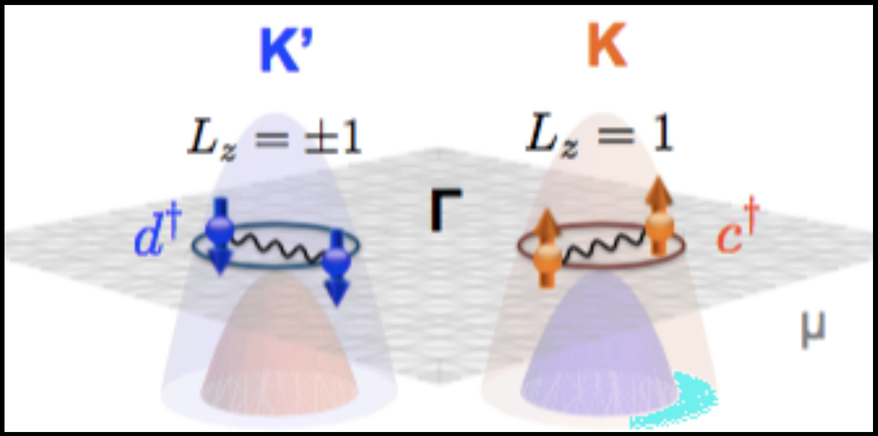
-T-breaking

Two degenerate possibilities

- Intra-pocket p+ip



- Inter-pocket p'wave

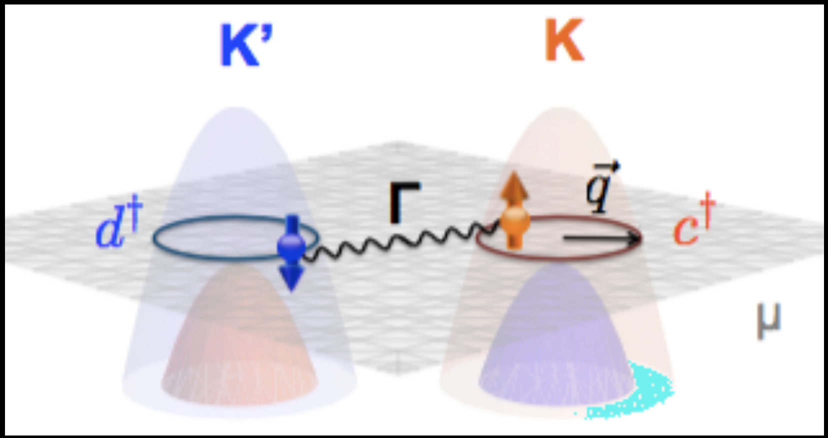


-T-breaking

-Analogous to Sr2RuO4

Two degenerate possibilities

- Intra-pocket p+ip



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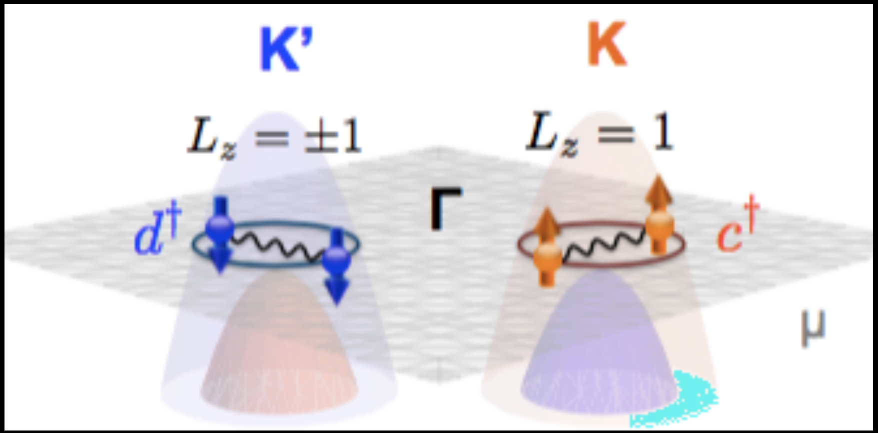


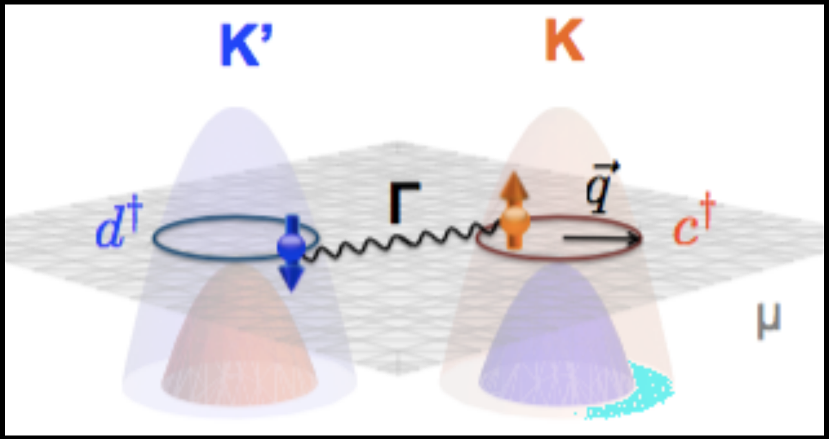
-T-breaking

-Analogous to Sr2RuO4

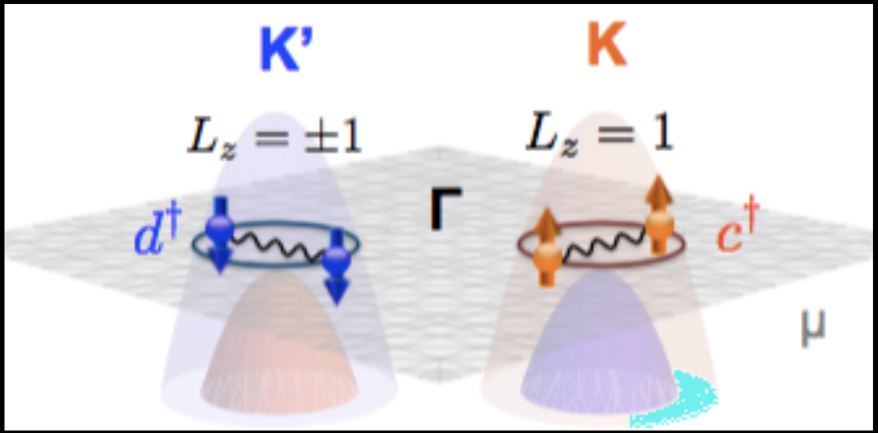
-Modulated

Two degenerate possibilities

- Intra-pocket p+ip



- Inter-pocket p'wave



-T-breaking

- C=1

-Analogous to Sr_2RuO_4

-Modulated

Two degenerate possibilities

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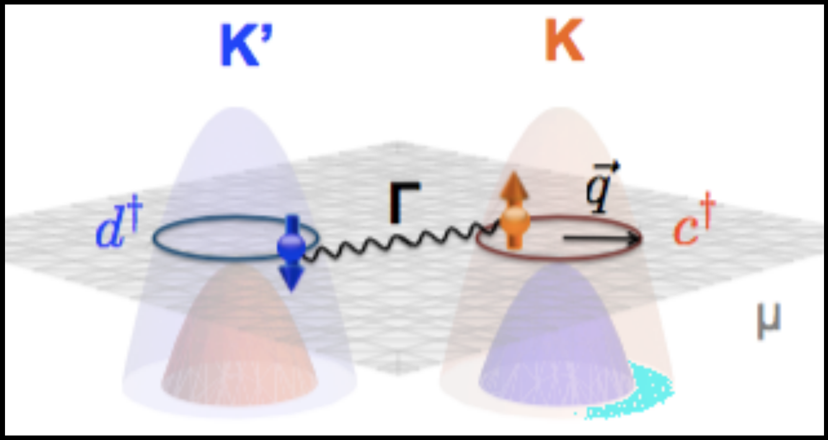
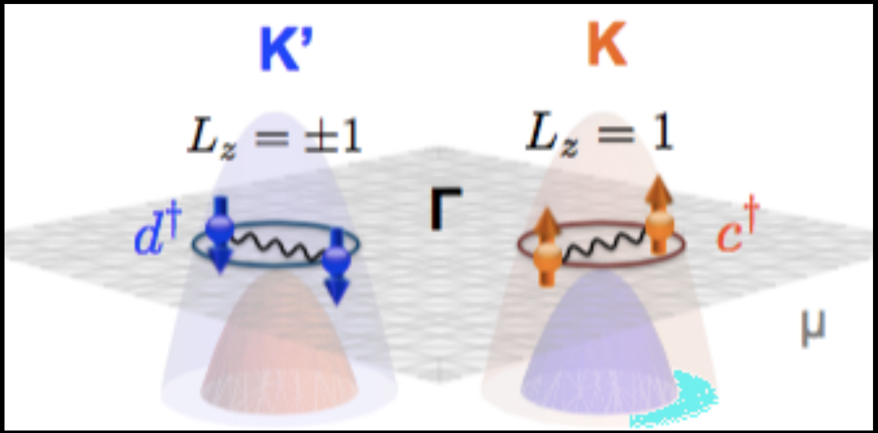


-T-breaking

- C=1

-Analogous to Sr2RuO4

- Inter-pocket p'wave

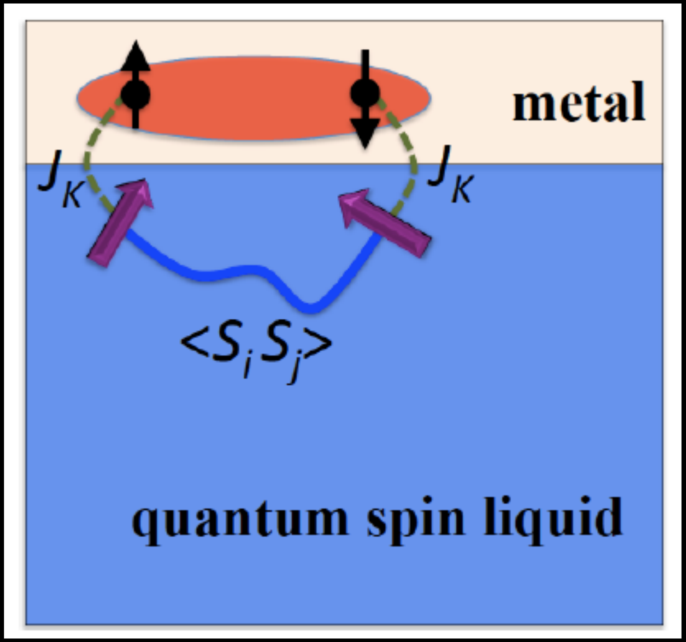


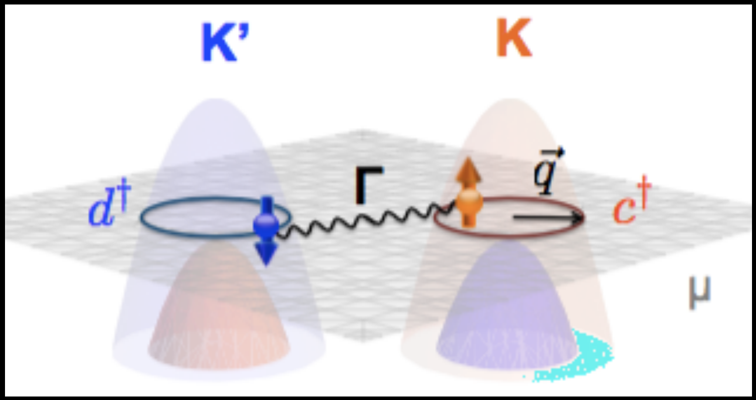
-Modulated

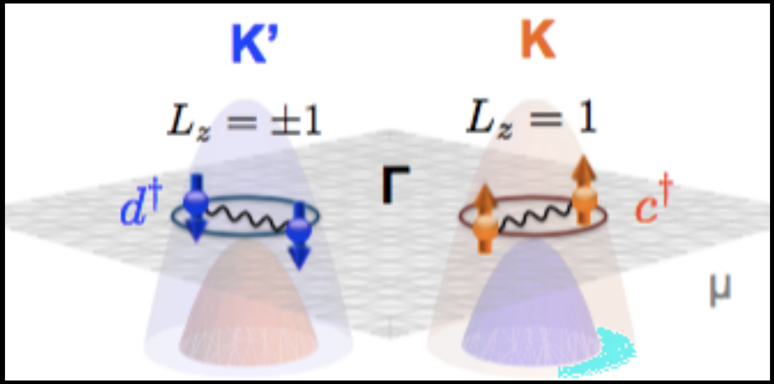
-C=\pm 1 per pocket

Designing 2D topological SC's

- Control interaction
- k-space spin split TMD







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