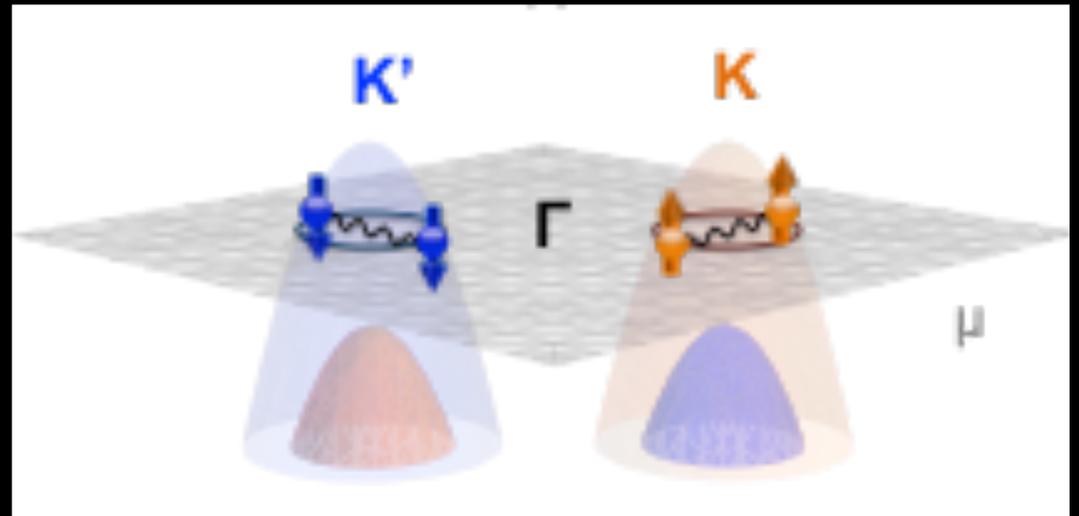
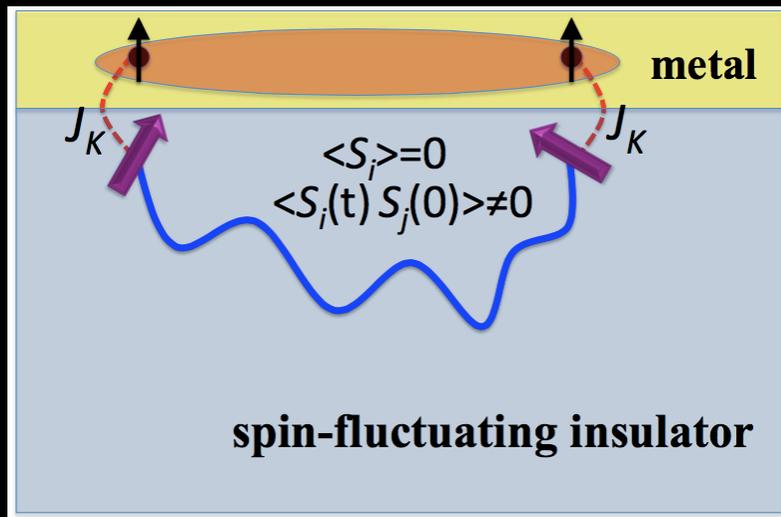


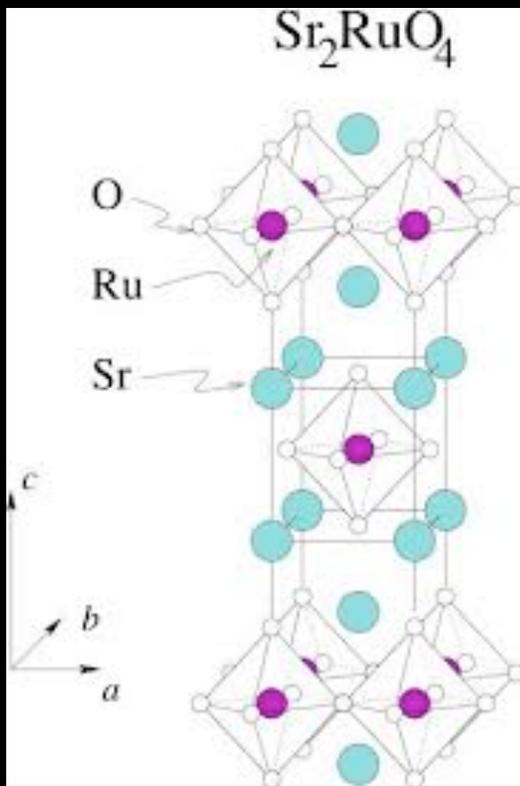
Designing 2D topological SC's



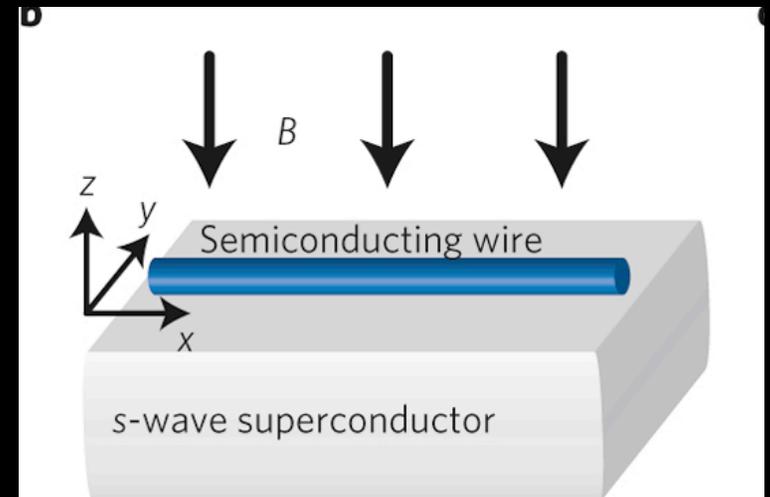
Eun-Ah Kim (Cornell)

Q. Topological Superconductor material?

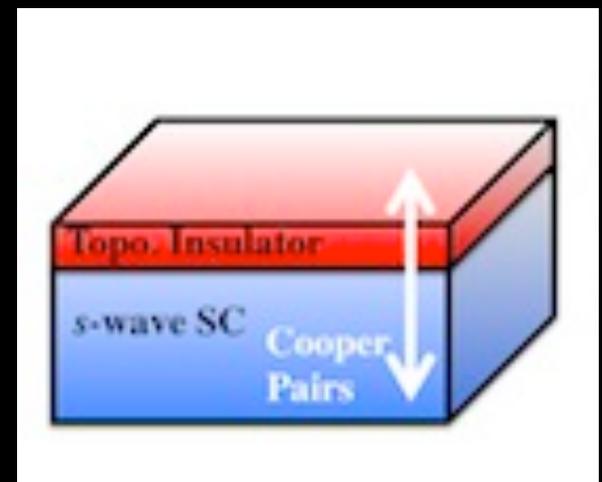
Bulk



1D proximity



2D proximity?



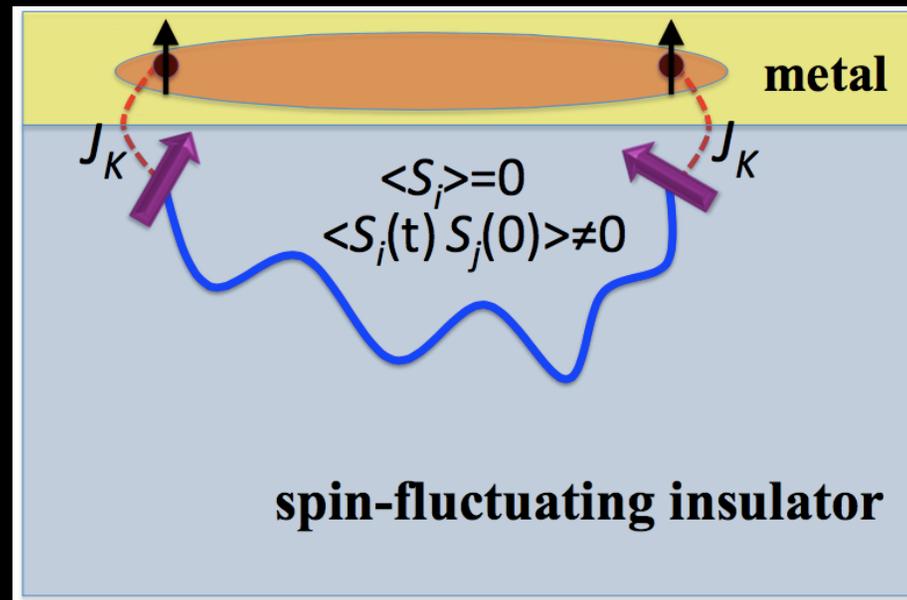
Designing 2D topological SC's

- 2D topological SC
 - odd-parity SC of spinless fermions
 - Majorana bound state
 - Strategies: 1) interaction, 2) spinlessness
- T-inv topo-SC at a Metal/Quantum Spin Ice interface
- Modulated topo-SC in group VI TMD (e.g., MoS₂)

Strategy I

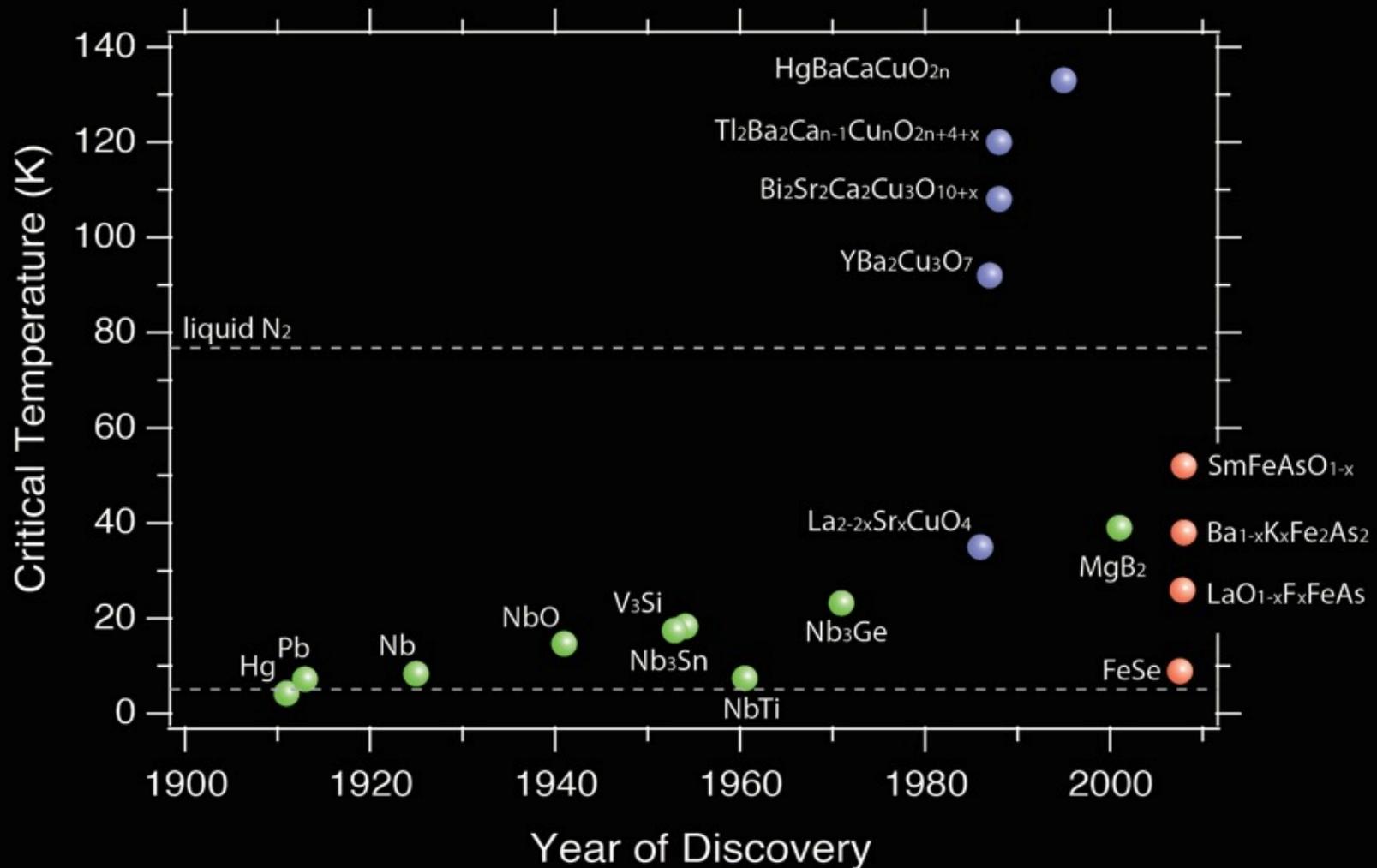
- Manipulate the pairing interaction:
target (ferromagnetic) spin
fluctuation

Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures



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

Q. Proof of principle for non-phonon mechanism?



Literature on spin-fluctuation mediated superconductivity

260,000 results on google scholar.....

The image shows a screenshot of a Google Scholar search interface. At the top left is the Google logo. To its right is a search bar containing the text "spin fluctuation". Below the search bar, the word "Scholar" is displayed in red, followed by the text "About 259,000 results (0.02 sec)". On the left side, there are navigation links: "Articles", "Case law", and "My library". Below these are filters for "Any time", "Since 2015", "Since 2014", "Since 2011", and "Custom range...". The main content area displays two search results. The first result is titled "Spin-fluctuation-mediated even-parity pairing in heavy-fermion superconductors" by K Miyake, S Schmitt-Rink, and CM Varma, published in Physical Review B in 1986. Its abstract states that anisotropic even-parity pairings are assisted and odd-parity pairings are impeded by antiferromagnetic spin fluctuations. The second result is titled "Anisotropic Superfluidity in He 3: A Possible Interpretation of Its Stability as a Spin-Fluctuation Effect" by PW Anderson and WF Brinkman, published in Physical Review Letters in 1973. Its abstract proposes that paramagnon effects enhance the critical temperature for triplet pairing in He 3.

Google

spin fluctuation

Scholar About 259,000 results (0.02 sec)

Articles

Case law

My library

Any time

Since 2015

Since 2014

Since 2011

Custom range...

Spin-fluctuation-mediated even-parity pairing in heavy-fermion superconductors
K Miyake, S Schmitt-Rink, CM Varma - Physical Review B, 1986 - APS
Abstract It is shown that the anisotropic even-parity pairings are assisted and the odd-parity as well as the isotropic even-parity pairings are impeded by antiferromagnetic **spin** fluctuations which are observed in heavy-fermion solids.
Cited by 590 Related articles All 10 versions Web of Science: 470 Cite Save More

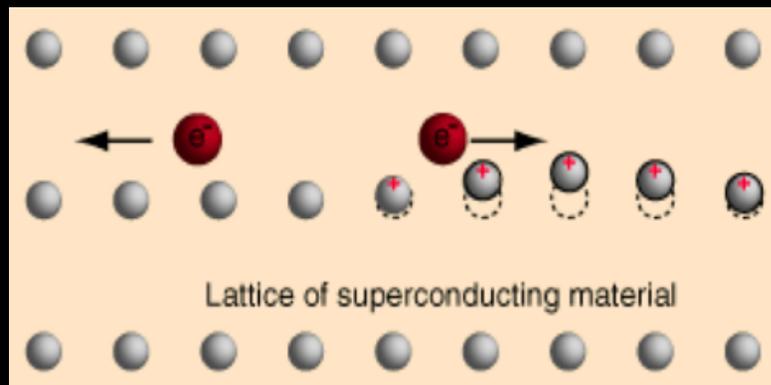
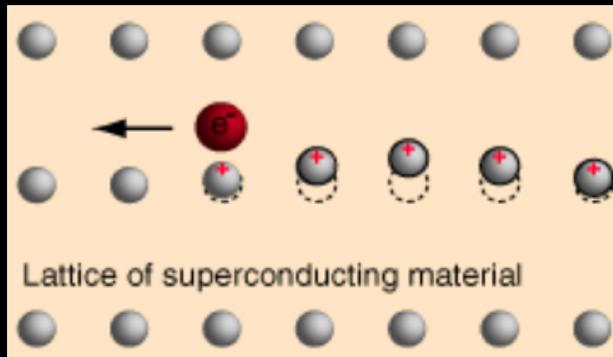
Anisotropic Superfluidity in He 3: A Possible Interpretation of Its Stability as a Spin-Fluctuation Effect
PW Anderson, WF Brinkman - Physical Review Letters, 1973 - APS
Abstract It is proposed that the paramagnon effects which enhance T_c for triplet pairing in He 3 are also important in selecting the particular component of the triplet p-wave state observed. It is found that the component favored is the original Anderson-Morel state.
Cited by 459 Related articles All 5 versions Web of Science: 360 Cite Save More

Proof of Principle Example for spin-fluctuation mediated SC?

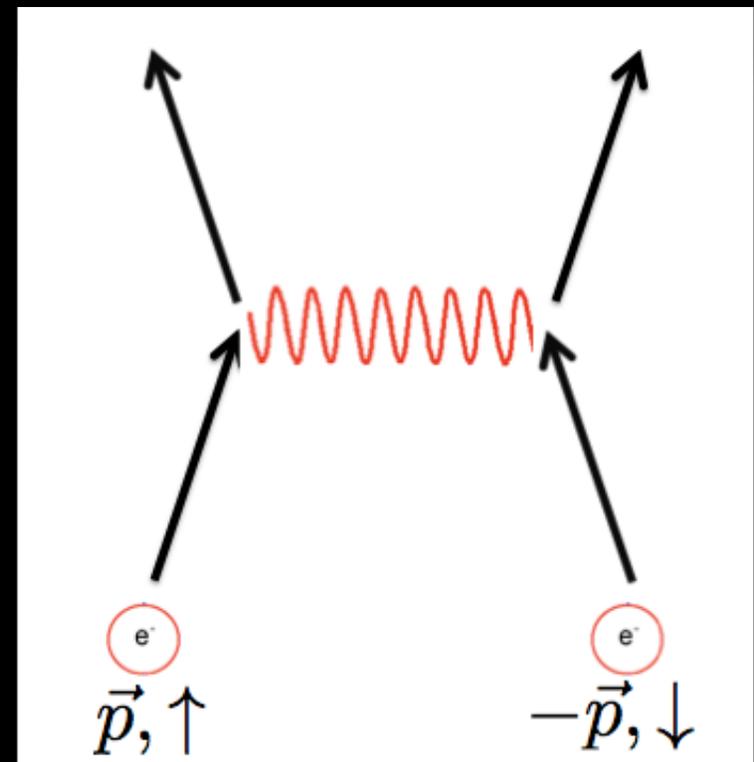
0

Fundamental Challenge of non-Phonon mechanism

Phonon driven



Spin-fluctuation driven



Absence of separation of scales!

Challenges

Experimental

- The electrons and the glue cannot be separately controlled.
- Other ordering phenomena.

Theoretical

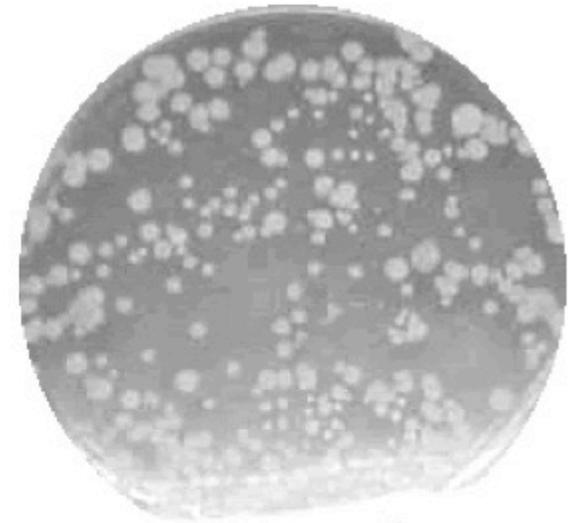
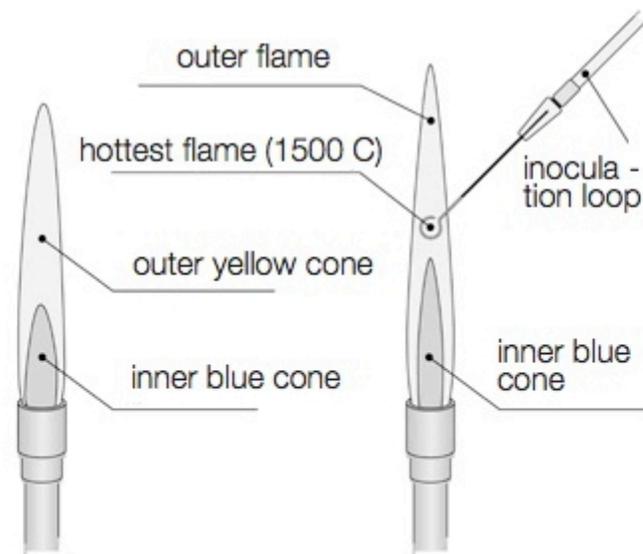
- Strongly correlated fermions, i.e. the sign problem.

Strategy?

The germ theory of disease. II.



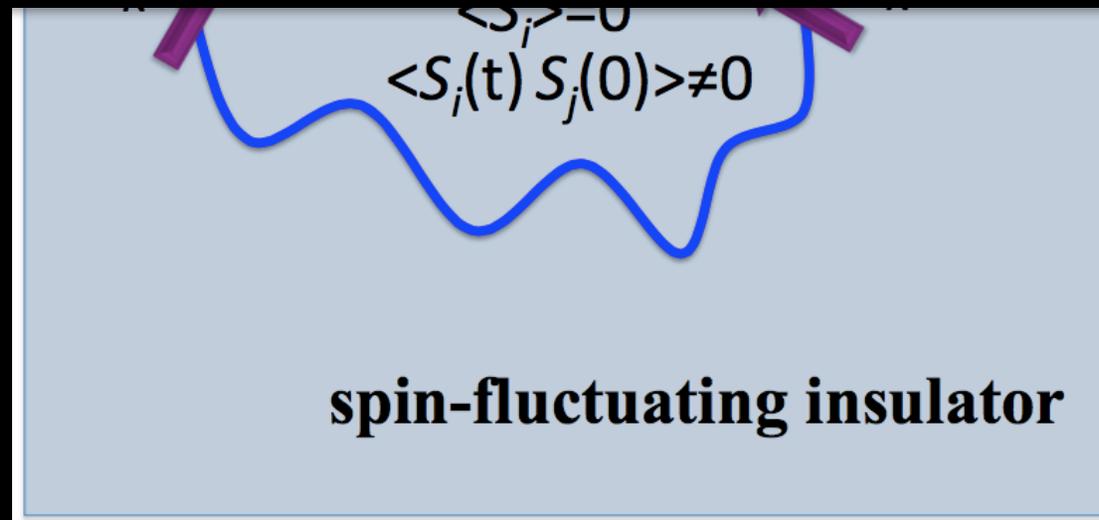
Koch develops through sterility techniques and semisolid media to facilitate **bacterial isolation**. He also introduces theoretical criteria to define the role of bacteria in disease.



Strategy?

Separate the "glue" from "charge":

Heterostructure!

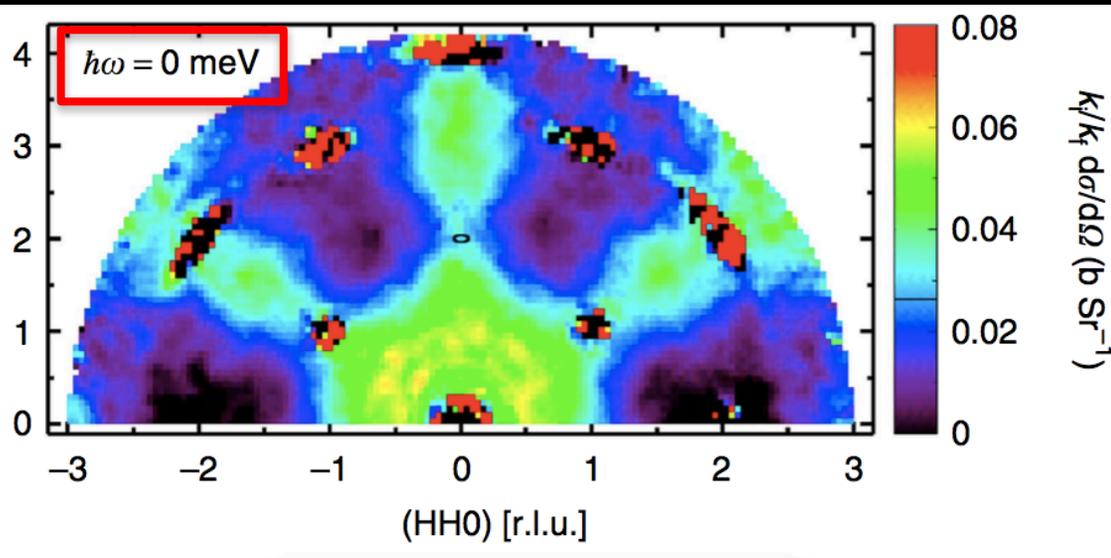


Criteria for the substrate

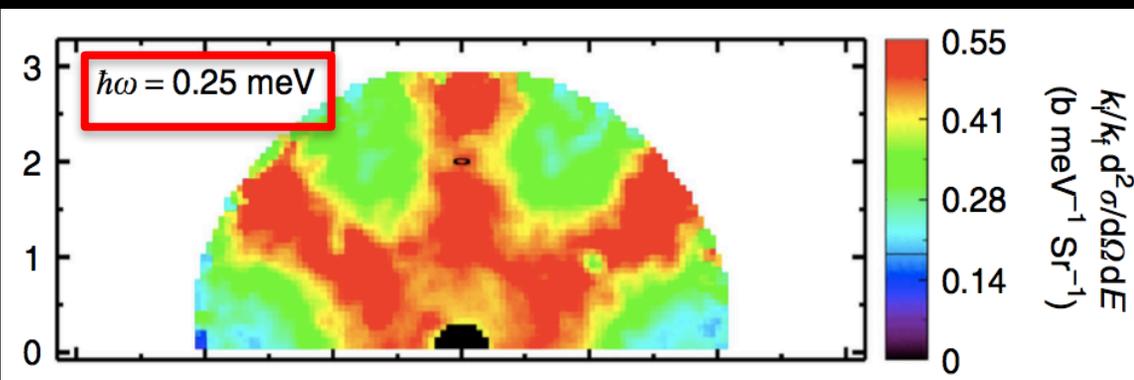
1. No long range order $\langle S \rangle = 0$
2. Strong dynamic spin fluctuation $\langle S_i S_j \rangle$

Quantum fluctuations in spin-ice-like $\text{Pr}_2\text{Zr}_2\text{O}_7$

K. Kimura¹, S. Nakatsuji^{1,2}, J.-J. Wen³, C. Broholm^{3,4,5}, M.B. Stone⁵, E. Nishibori⁶ & H. Sawa⁶



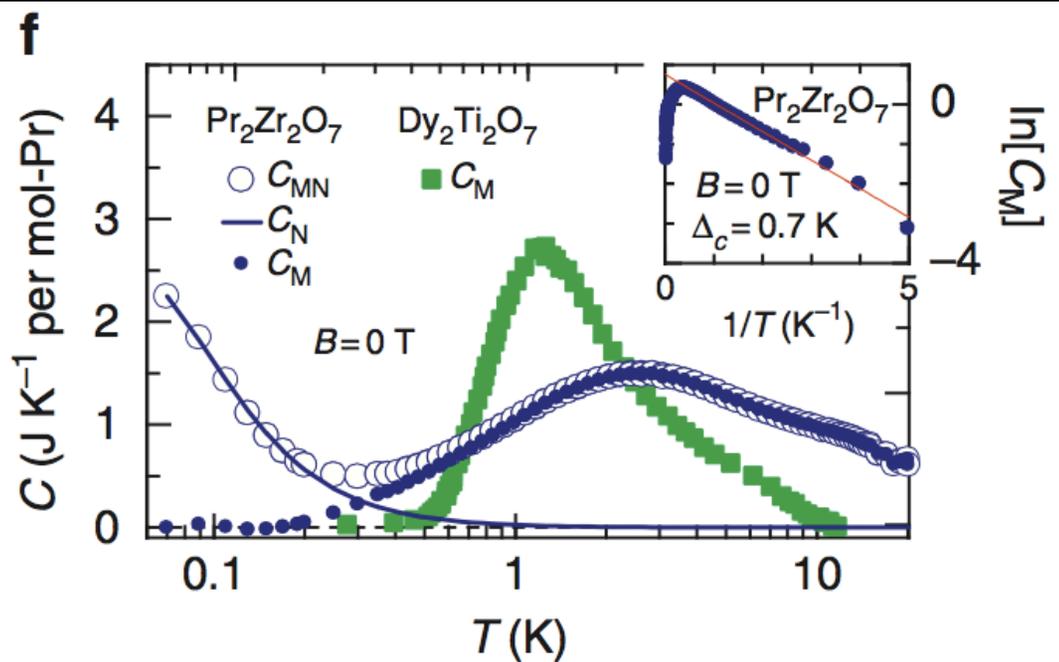
- Elastic neutron: pinch points (spin-ice like)



- Inelastic neutron: over 90% weight

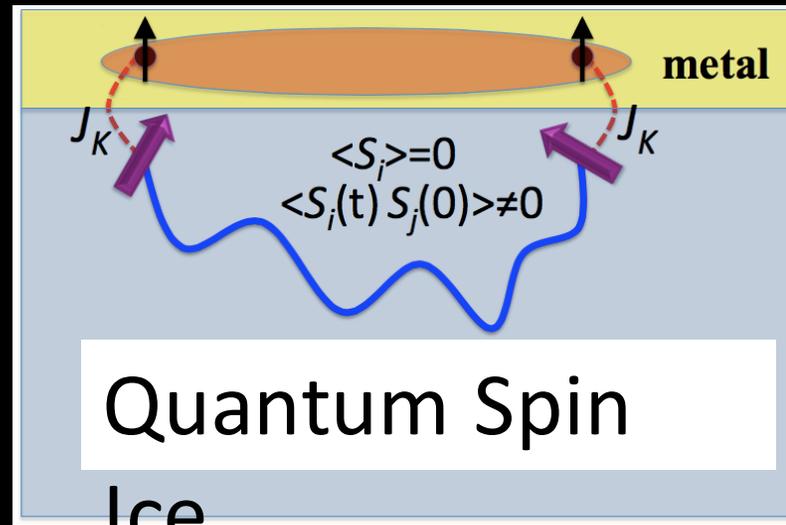
Quantum fluctuations in spin-ice-like $\text{Pr}_2\text{Zr}_2\text{O}_7$

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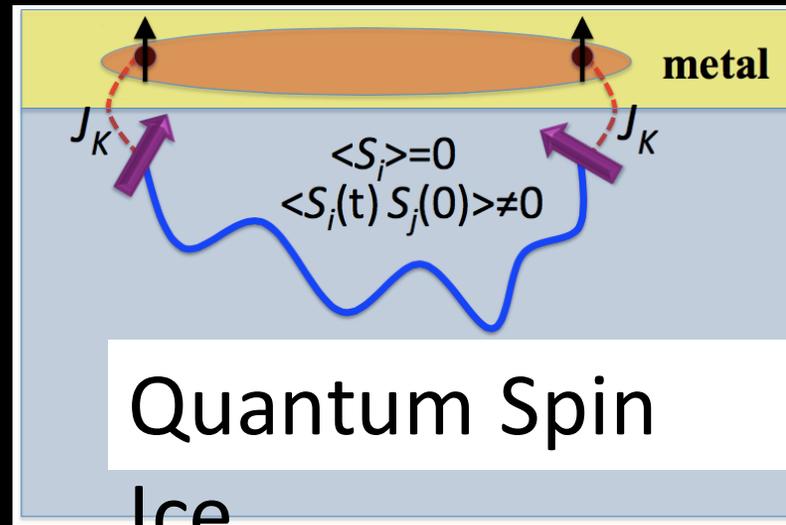
- No order down to 20mK
- Dynamic fluct. upto ~ 3 K

Structural Criteria for the Metal



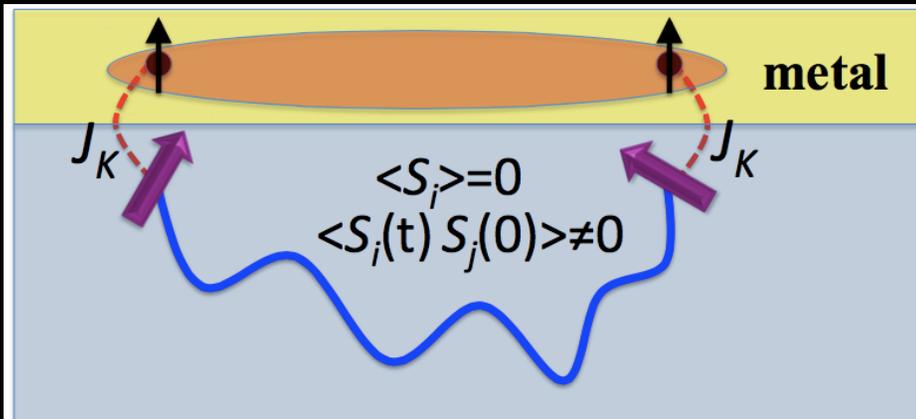
1. Chemical stability
2. Lattice matching: $A_2B_2O_7$
3. No orphan bonds: (111) direction

Electronic Criteria for the Metal



1. Simple metal without ordering possibilities.
2. Wave function penetration for coupling.
3. Odd # of Fermi surface around high symmetry points for Topo SC.

Effective Continuum Theory



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

$$H_K(t) = J_K v_{\text{cell}} \sum_{a\alpha\beta} \int d^2\mathbf{r} \psi_{\alpha}^{\dagger}(\mathbf{r}) \sigma_{\alpha\beta}^a \psi_{\beta}(\mathbf{r}) S_a(\mathbf{r}_{\perp} = \mathbf{r}, z = 0, t)$$

- Integrate out spins >> Effective e-e interaction

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

$$s_a(\mathbf{r}, t) = \sum_{\alpha\beta} \psi_{\alpha}^{\dagger}(\mathbf{r}, t) \sigma_{\alpha\beta}^a \psi_{\beta}(\mathbf{r}, t)$$

Dominant Pairing Channel

- Key properties of the static spin structure factor

$$S_{ab}(\mathbf{q}) = \delta_{ab} - \left(1 - \frac{1}{1+q^2\xi^2}\right) \frac{q_a q_b}{q^2}$$

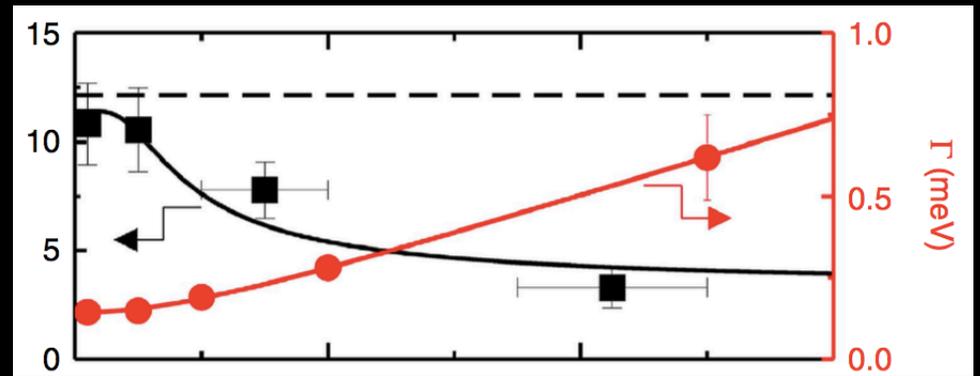
1. "spin-orbit" coupling
 2. $J_z = L_z + S_z$ conserved.
 3. spin "mirror" symm: $S_{ab}(\mathbf{q}) = S_{ba}(\mathbf{q})$
-> singlet - triplet decoupled.
- Purely repulsive interaction in the singlet channel

Transition Temperature

- Spin dynamics

$$T_c \sim \tau^{-1} e^{-1/\lambda}$$
$$\lambda \sim J_K^2 / (\bar{E}_F J_{\text{ex}})$$

$$\tau^{-1} \sim 2J_{\text{ex}} \sim 0.17 \text{ meV}$$

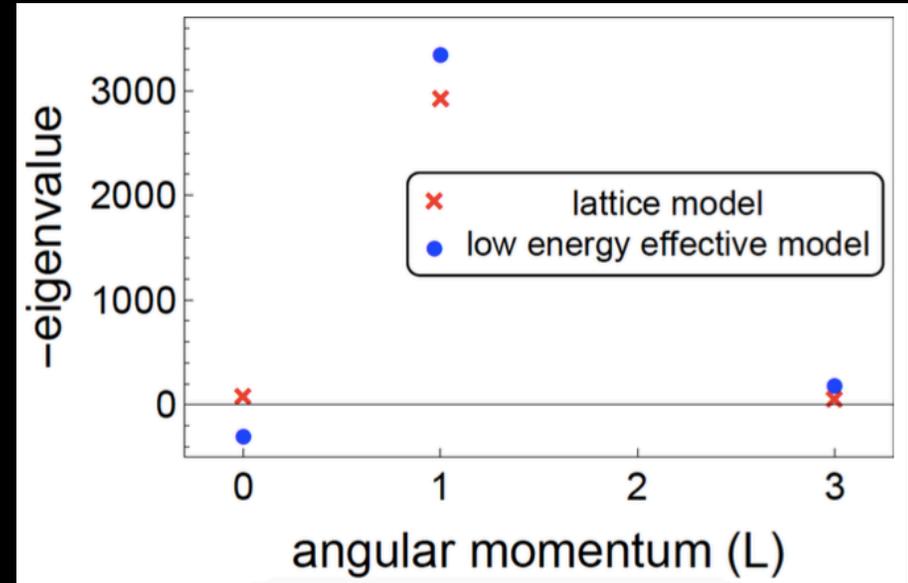
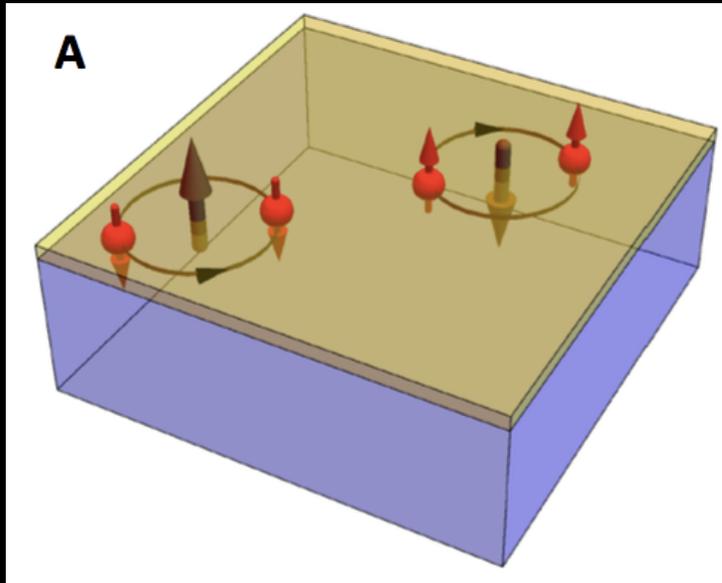


- Parameters for our proposal

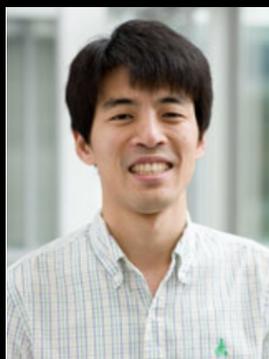
$$E_F \sim 300 \text{ meV}, \quad J_K \sim 10 \text{ meV}, \quad \lambda \sim O(1)$$

- $T_c \sim 1.5 \text{ K}$

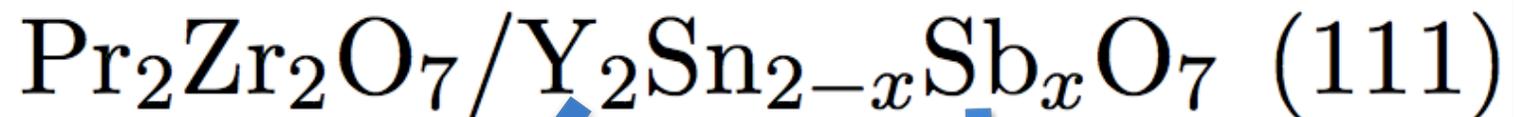
Dominant Pairing Channel



1. $^3\text{He-B}$ type but 2D.
2. Overwhelmingly dominant.

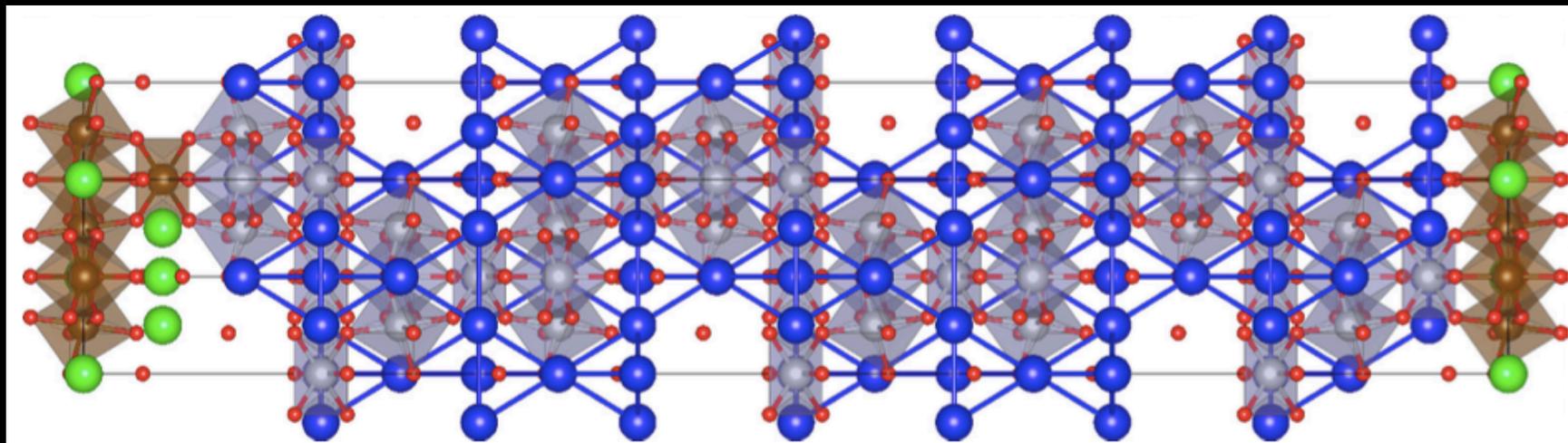


Microscopic Proposal



Non-magnetic

s-electrons:
large overlap,
isotropic FS.

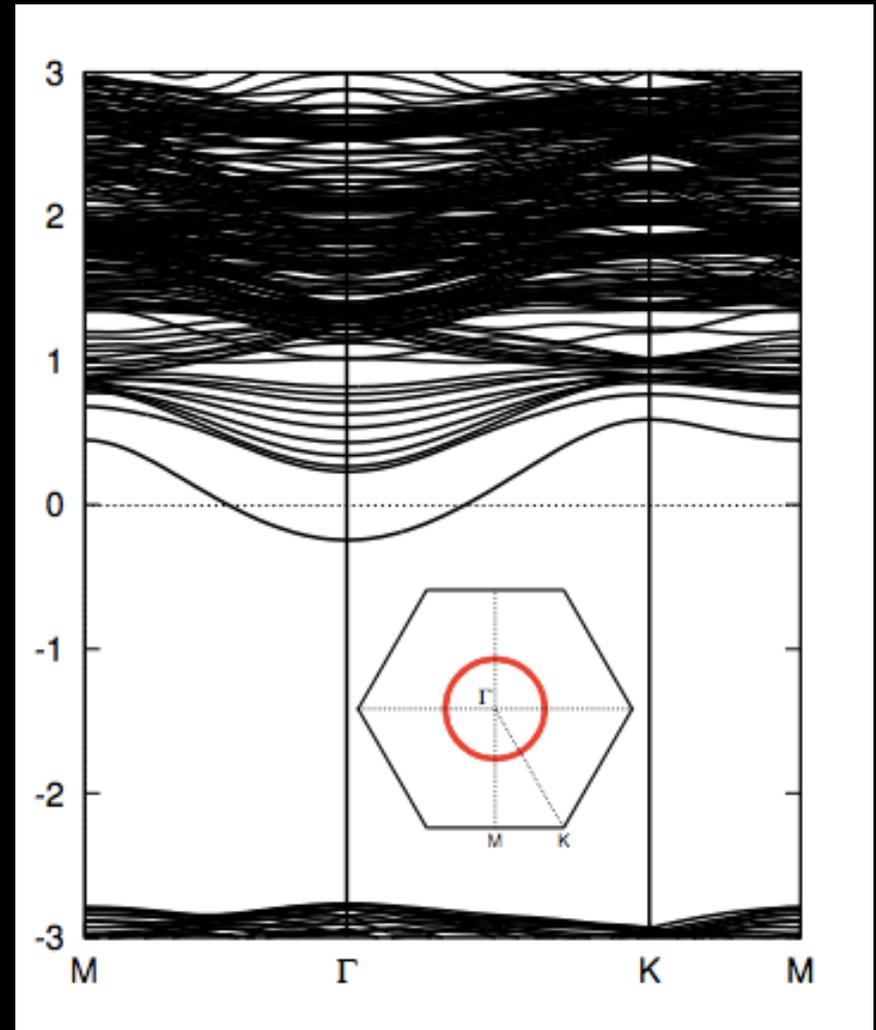


Band structure for the Proposal

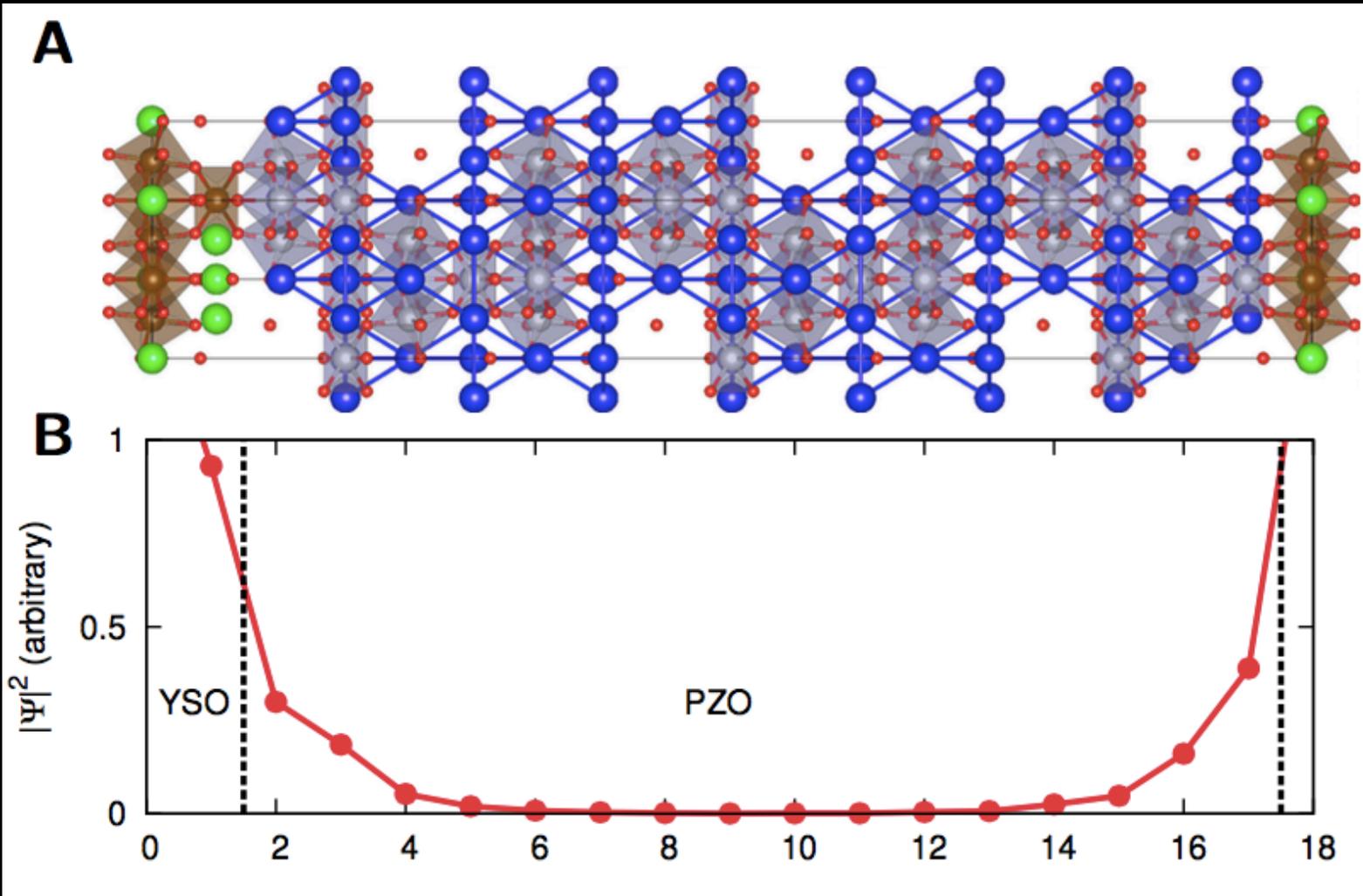
$\text{Pr}_2\text{Zr}_2\text{O}_7/\text{Y}_2\text{Sn}_{2-x}\text{Sb}_x\text{O}_7$ (111)

$x=0.2$

- Isotropic single pocket centered at Γ -point

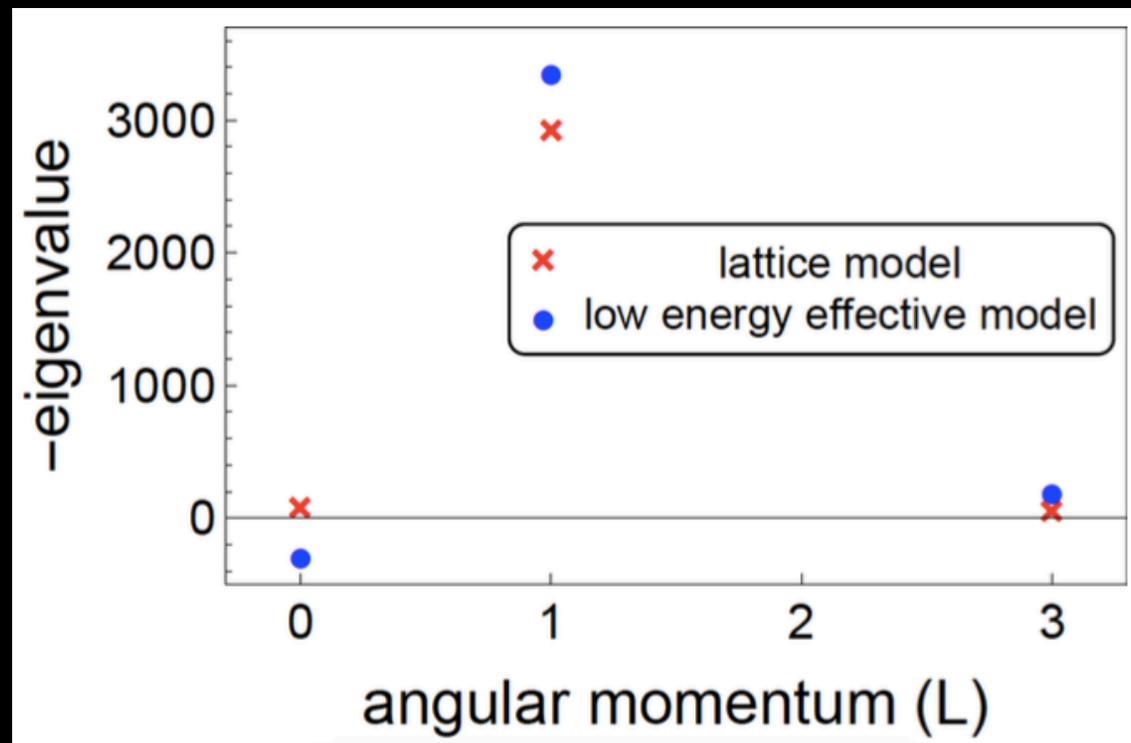


Wave function penetration



Full Lattice Model for the proposal

- Effective Continuum theory is valid.
- Ferromagnetic fluctuation is dominant.
- Overwhelmingly dominant p-wave instability.



Earlier Proposal: Excitonic mechanism

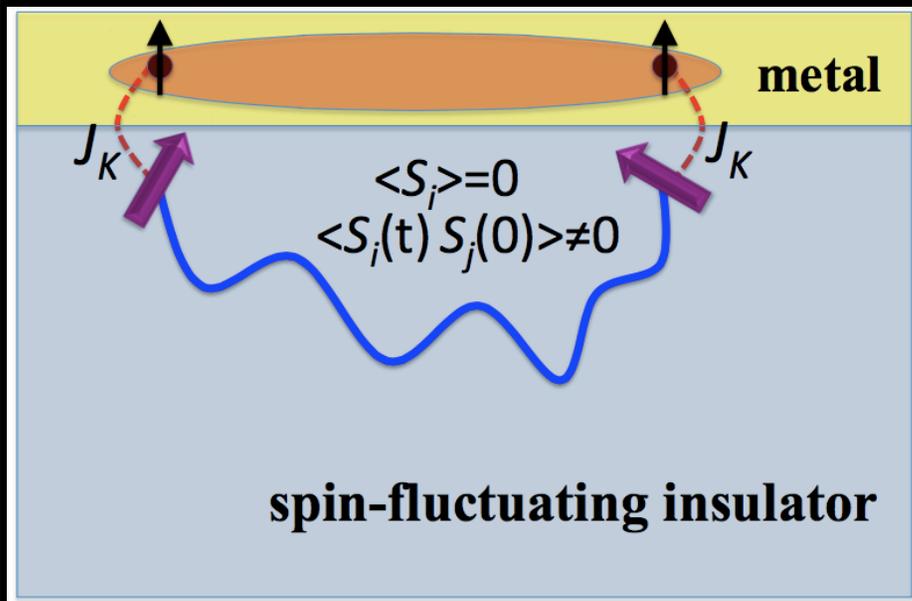
- Little (64), Ginzburg (70), Bardeen (73)

Metal

Semi-conductor

- Unstable against exchange.
- Intrinsically s-wave.

Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures

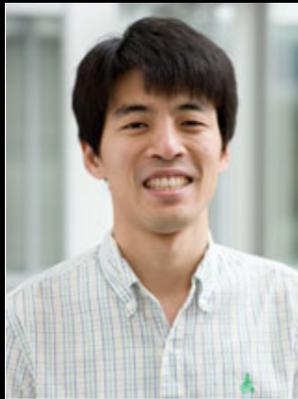


- Proof of principle for the spin-fluctuation SC.
- First T-inv Topo SC.
- Huge phase space.

Acknowledgements



Jian-huang She



Choonghyun Kim



Criag Fennie

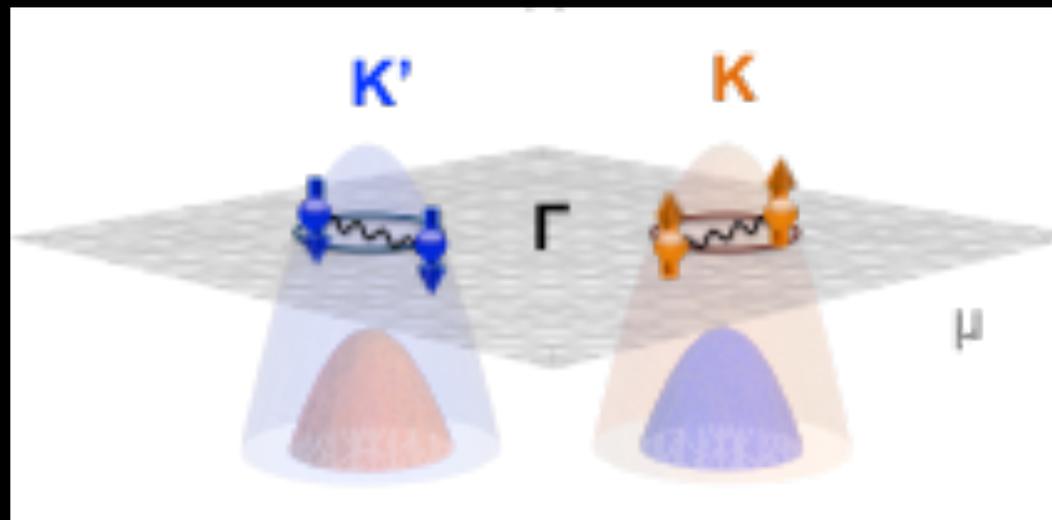


Michael Lawler

Strategy II

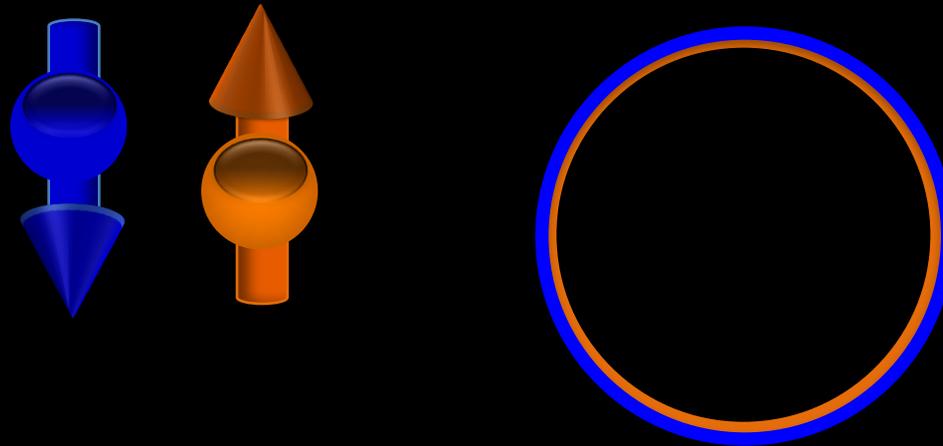
- Manipulate the band structure

Modulated topological superconductivity in group-VI TMDs



Yi-Ting Hsu, Abolhassan Vaezi, E-AK (in preparation, 2015)

Spin-degenerate Fermi surface

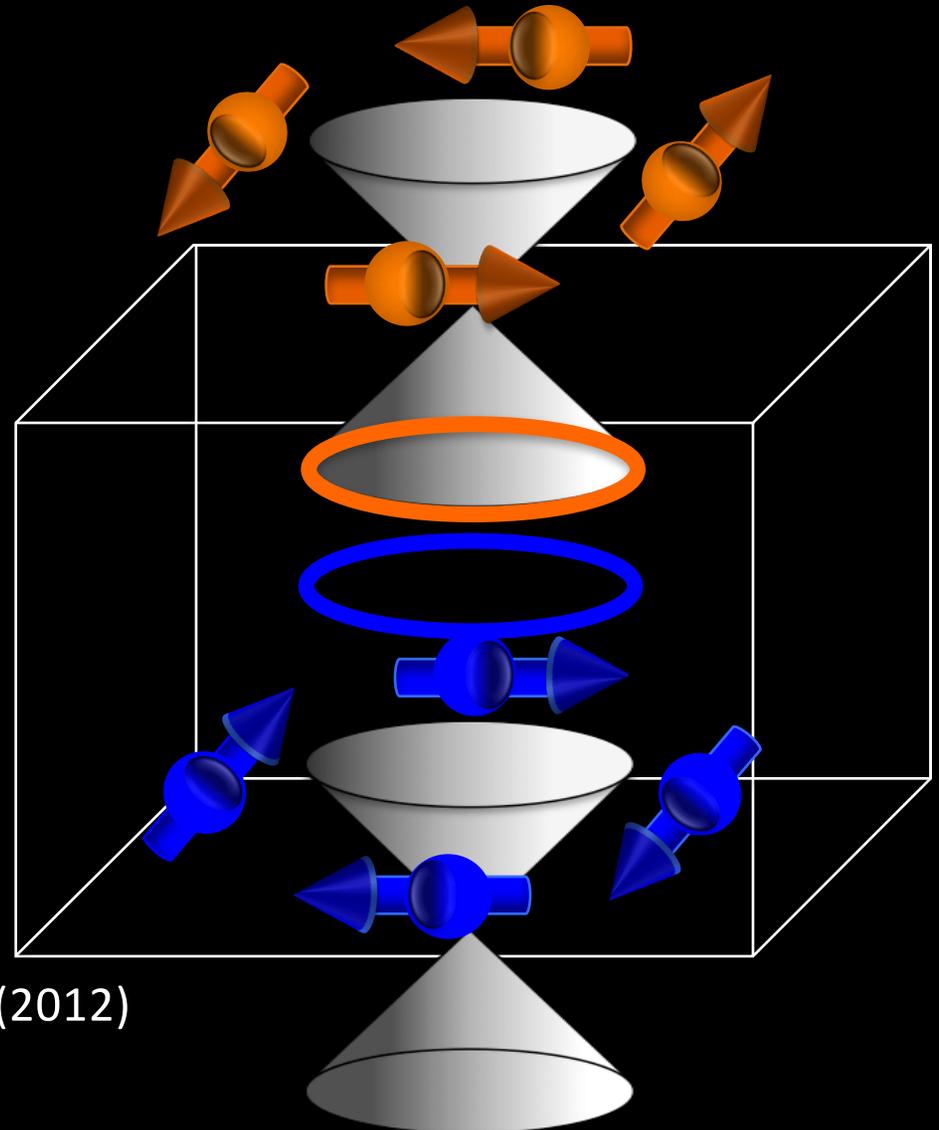


Singlet superconductor

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

Spinless fermion via **real space** splitting

- TI surface states
- Proximity induce topo SC

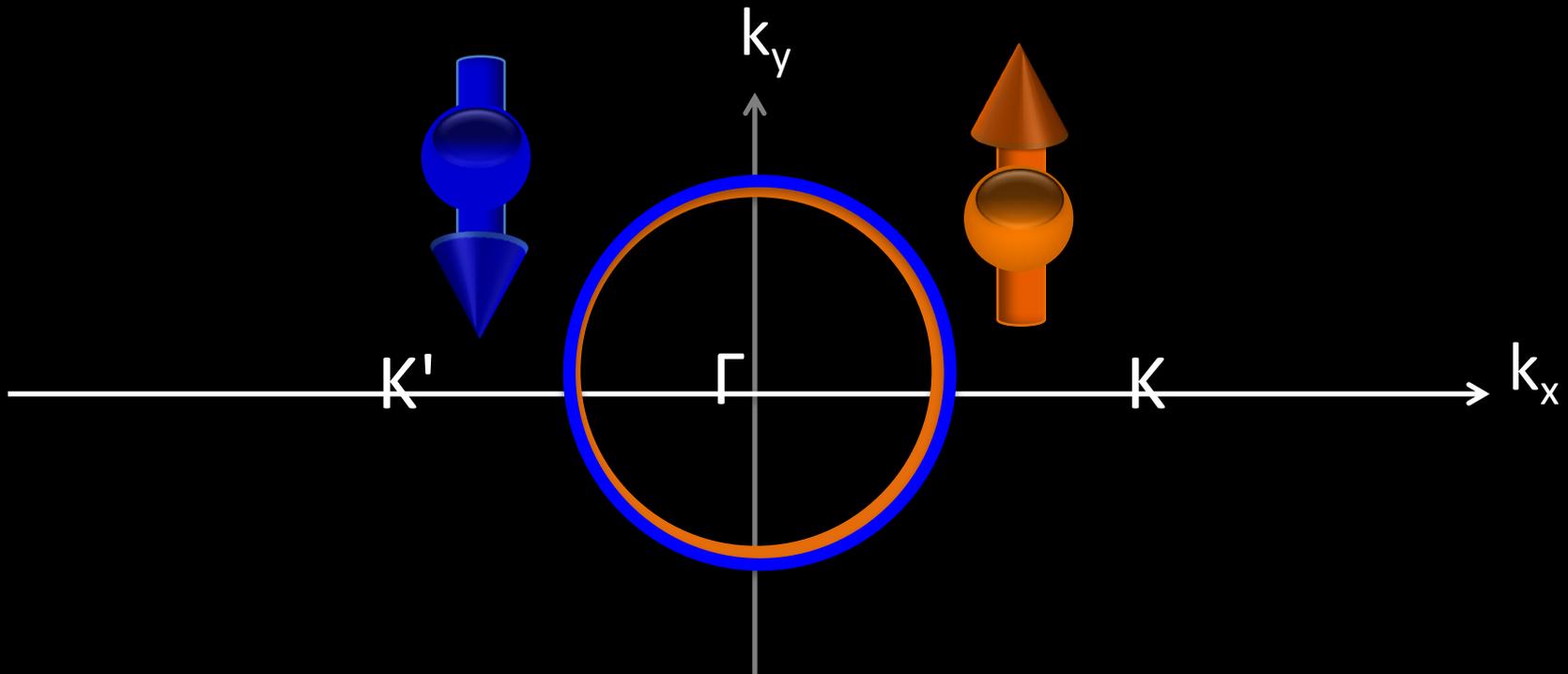


Fu & Kane, PRL (2008)

Experiments: Wang et al Science 336, 52 (2012)

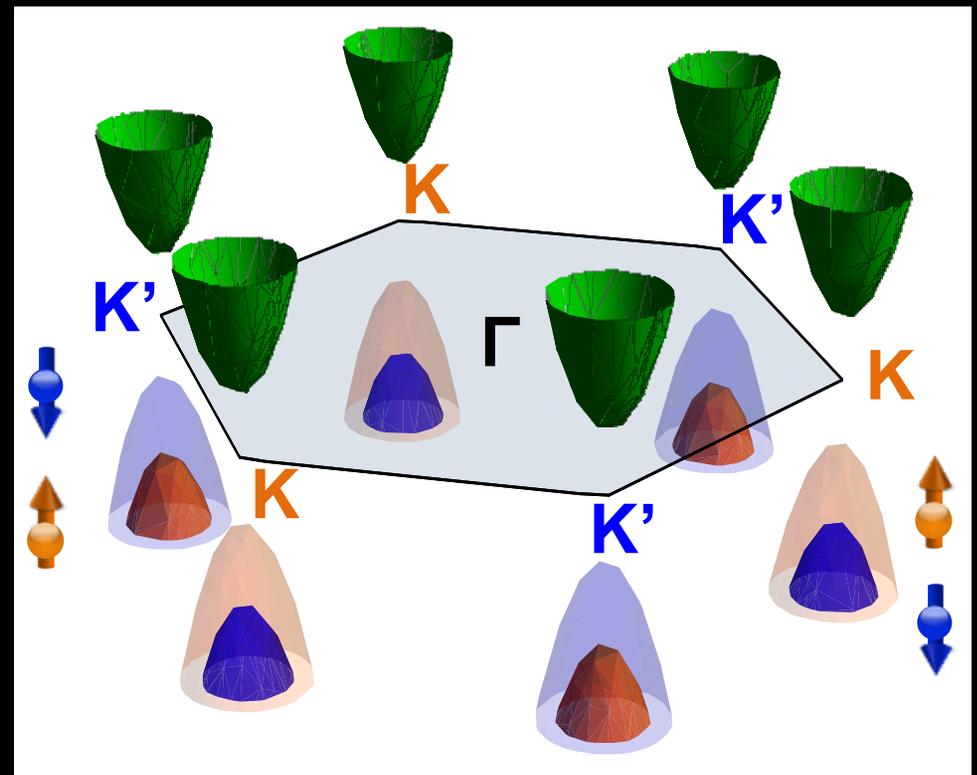
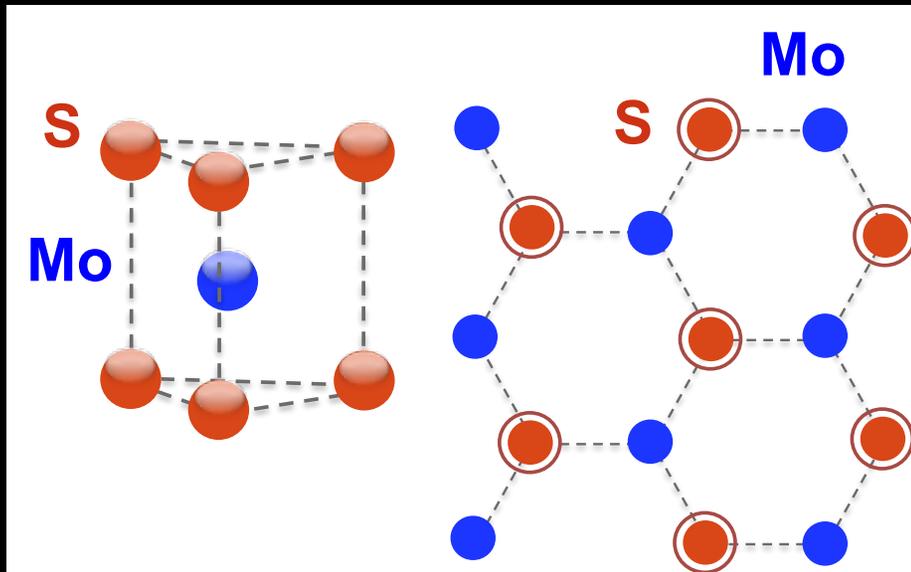
Xu et al, Nat.Phys 10, 943 (2014)

Spinless fermion via **k-space** splitting?



Monolayer group VI TMD's

MoS_2 , WS_2 , MoSe_2 , WSe_2



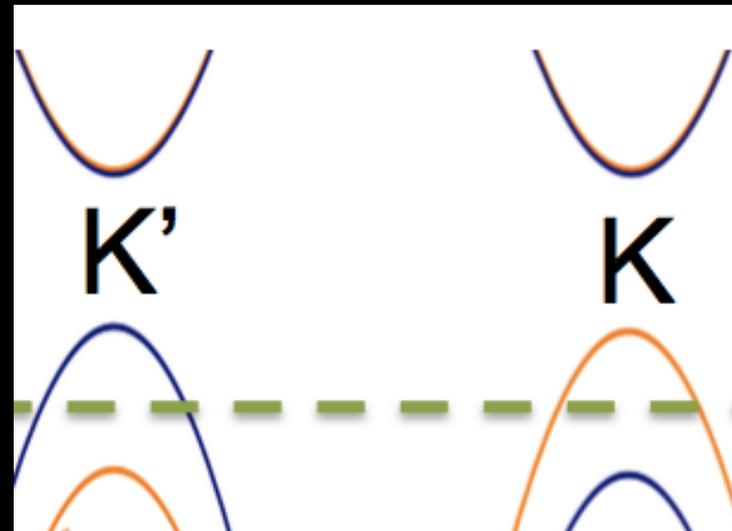
No inversion center! \Rightarrow Gap $\sim 2\text{eV}$, spin-orbit coupling

Band-selective spin-splitting

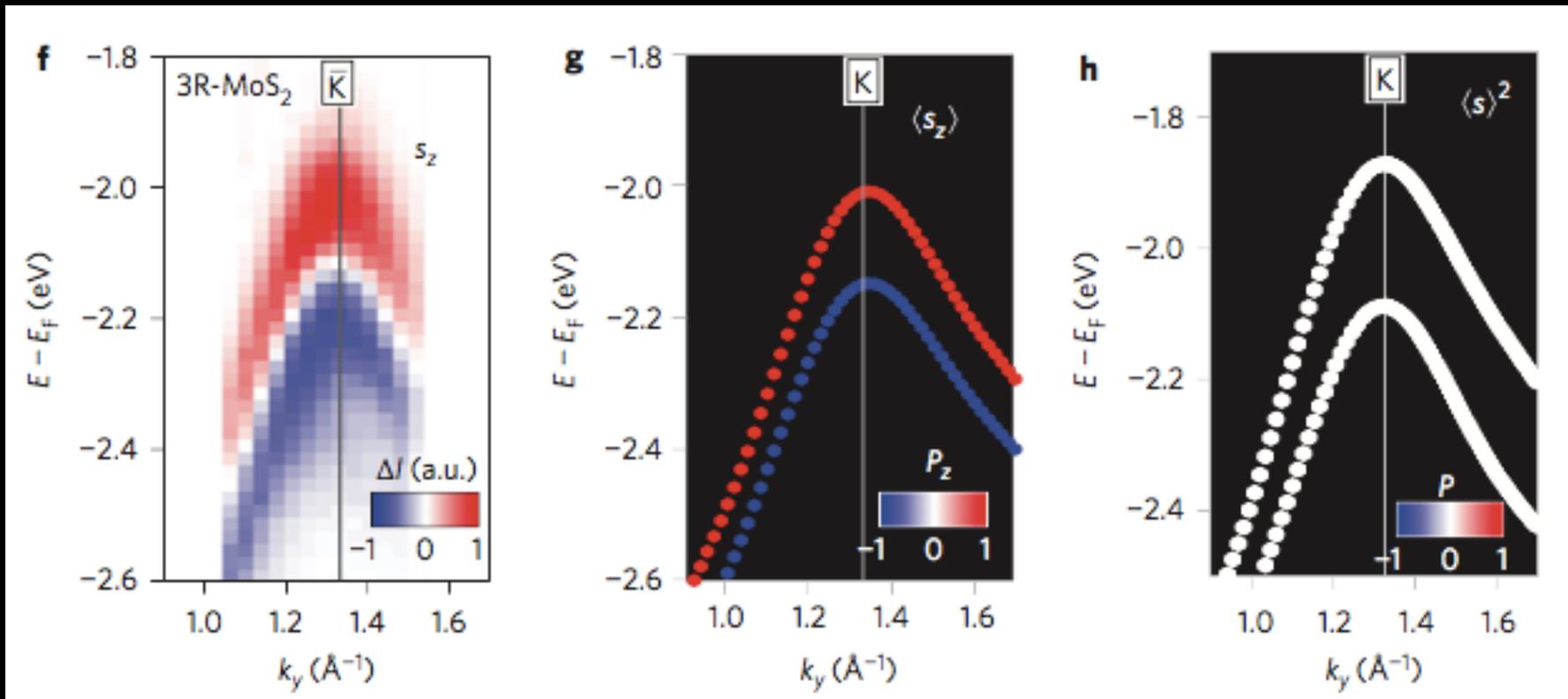
- Partially filled crystal-field-split d-bands
 - Conduction band $|d_{z^2}\rangle : l_z=0$
 - Valence band $\frac{1}{\sqrt{2}}(|d_{x^2-y^2}\rangle \mp i|d_{xy}\rangle) : l_z = \mp 1$
- Spin-orbit coupling

$$\vec{L} \cdot \vec{S}$$

150~460meV



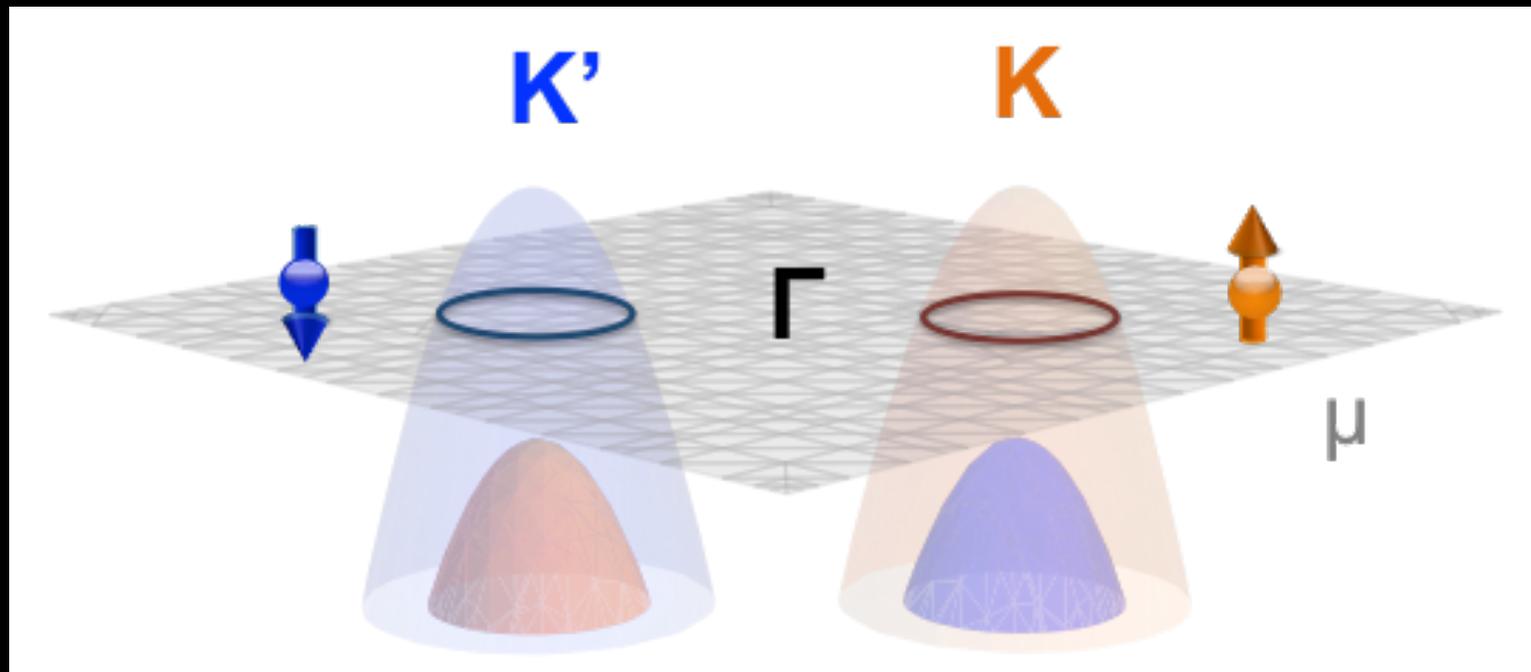
Confirmation of the band structure



Iwasa group N. Nano (2014)

k-space spin-split FS?

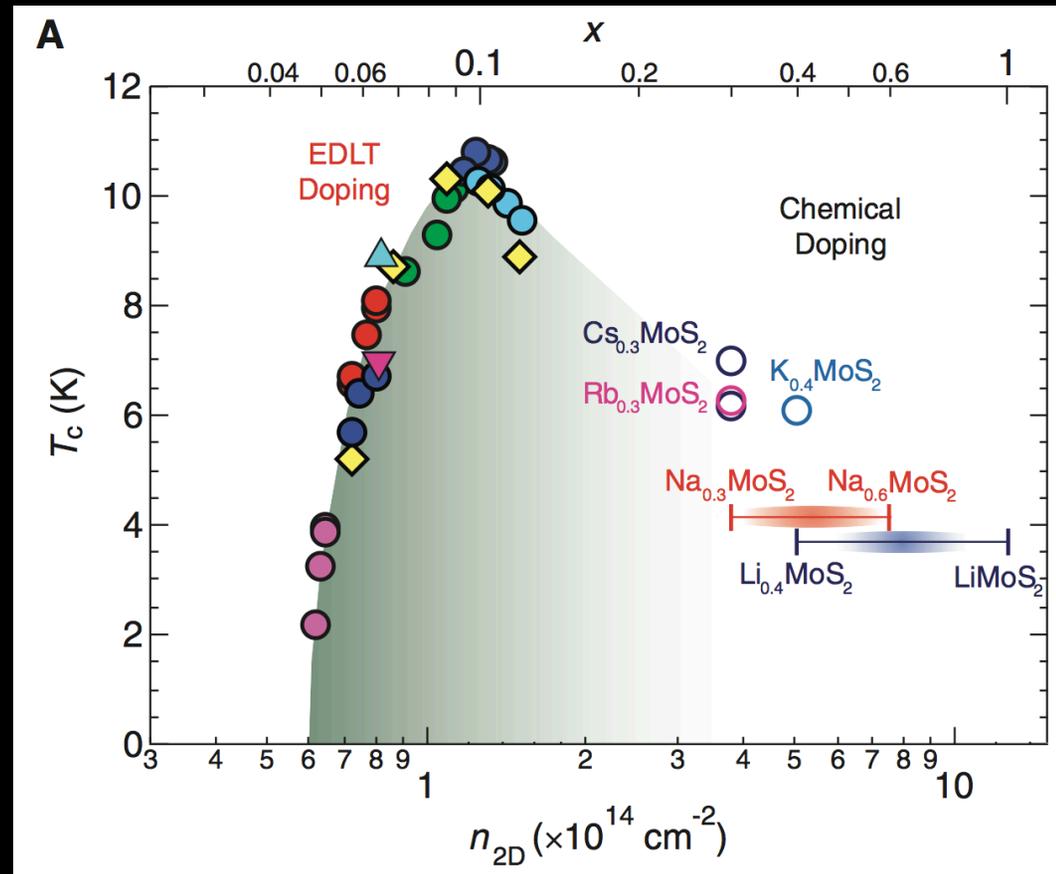
p-doped group VI- TMD!



Juice for superconductivity?

- d electrons => expect correlation effects
- n-doped TMD's

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

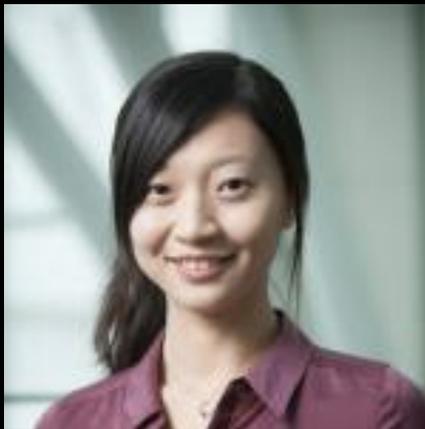


p-doped TMD

Moderate correlation (d-electron)

+

k-space spin-split Fermi surfaces



Yi-Ting Hsu

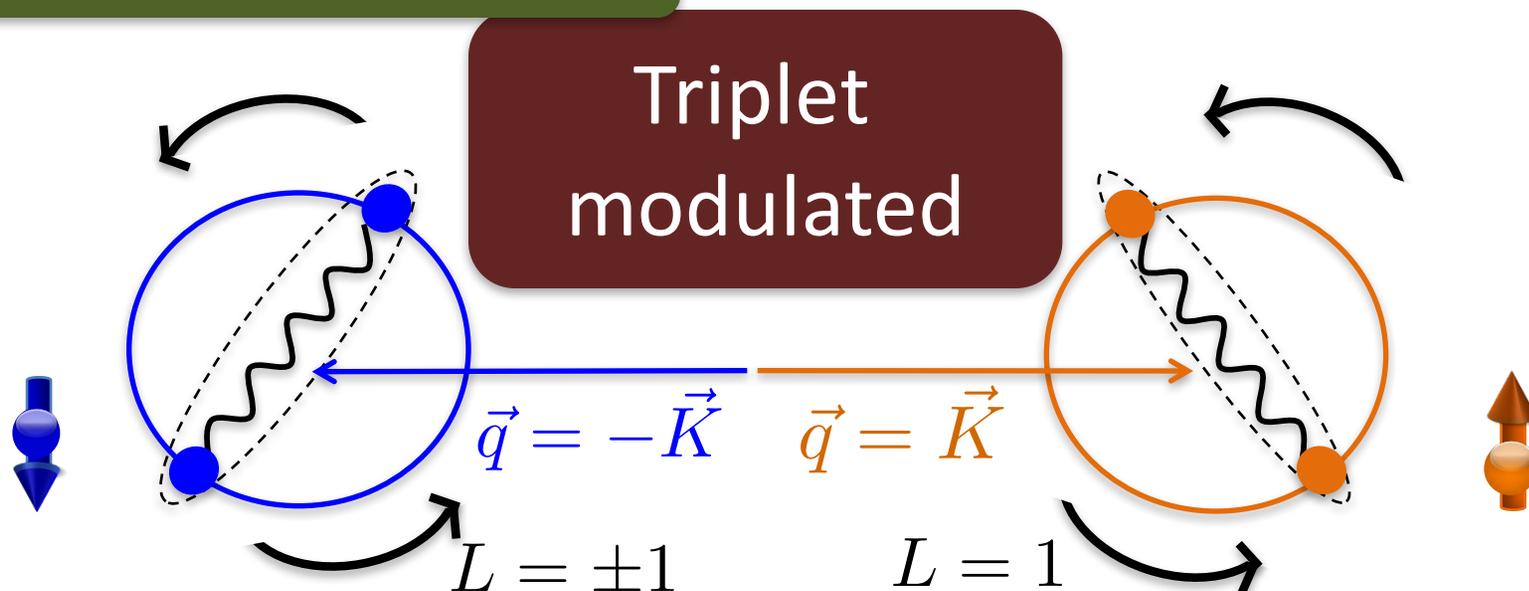
Topological SC?



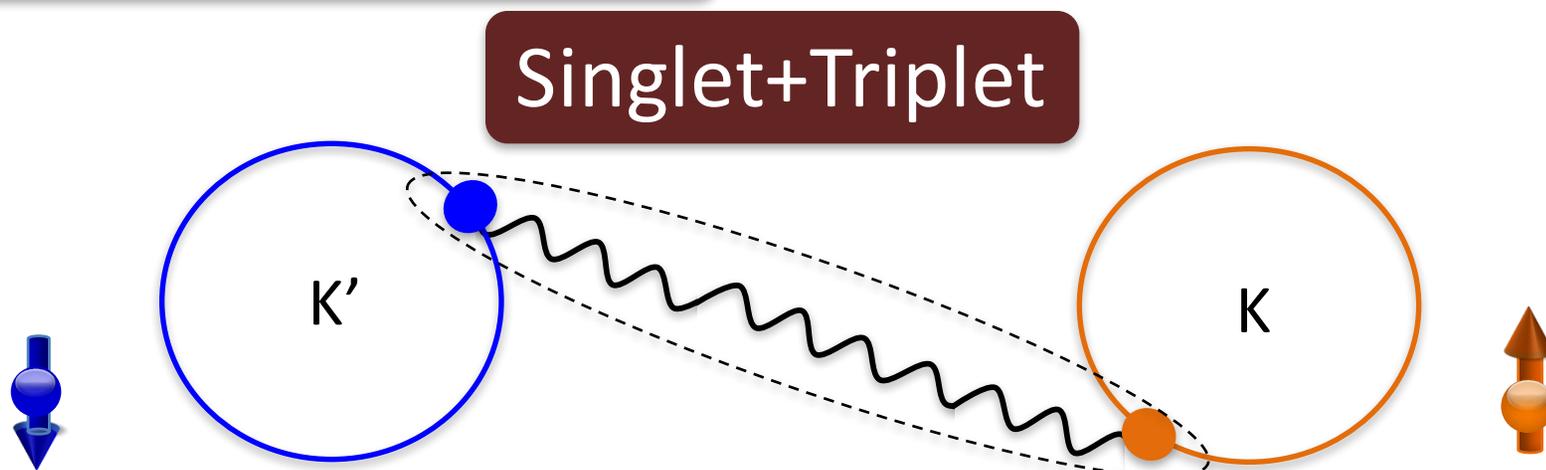
Abolhassan Vaezi

Top view

Intra-pocket pairing

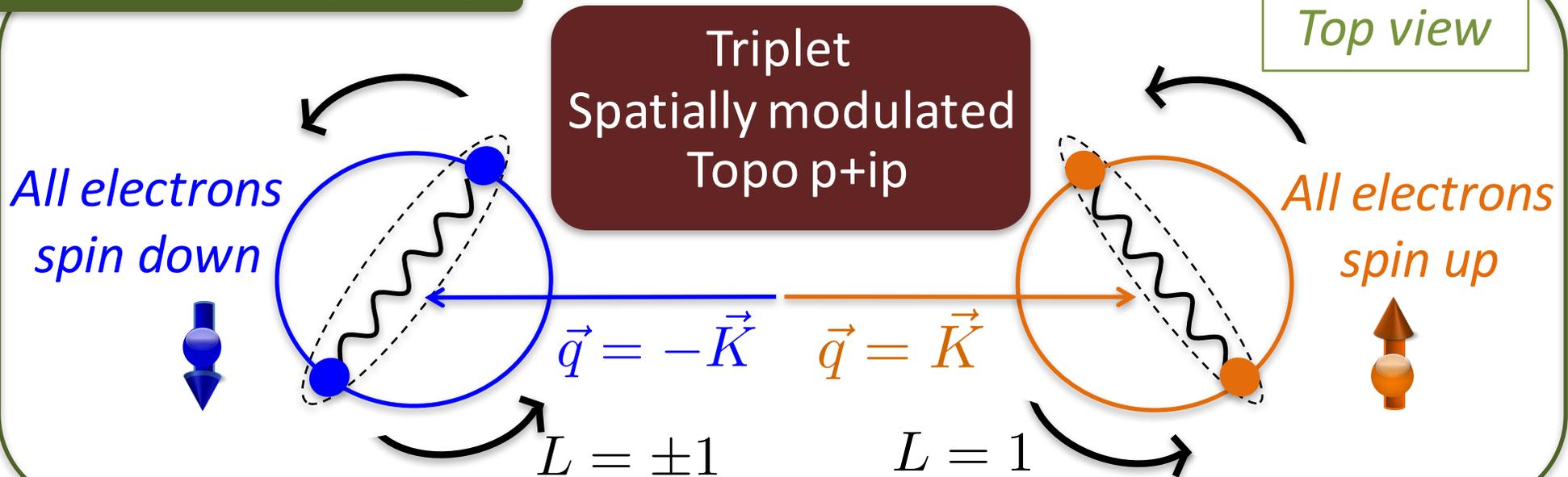


Inter-pocket pairing

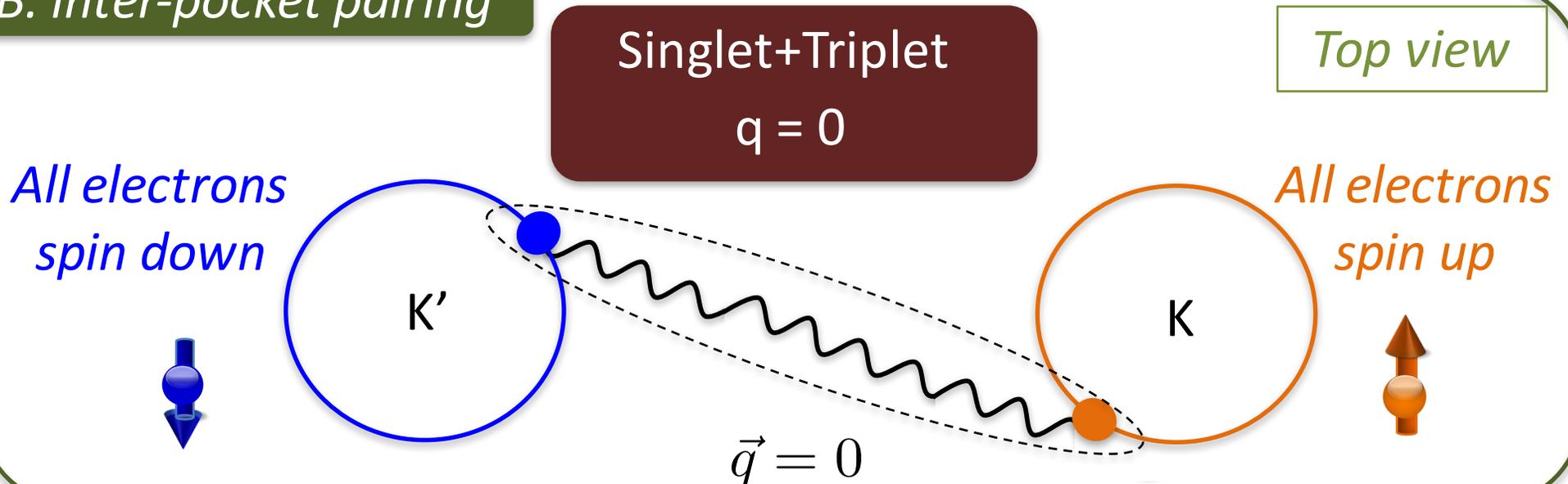


Possible ground states

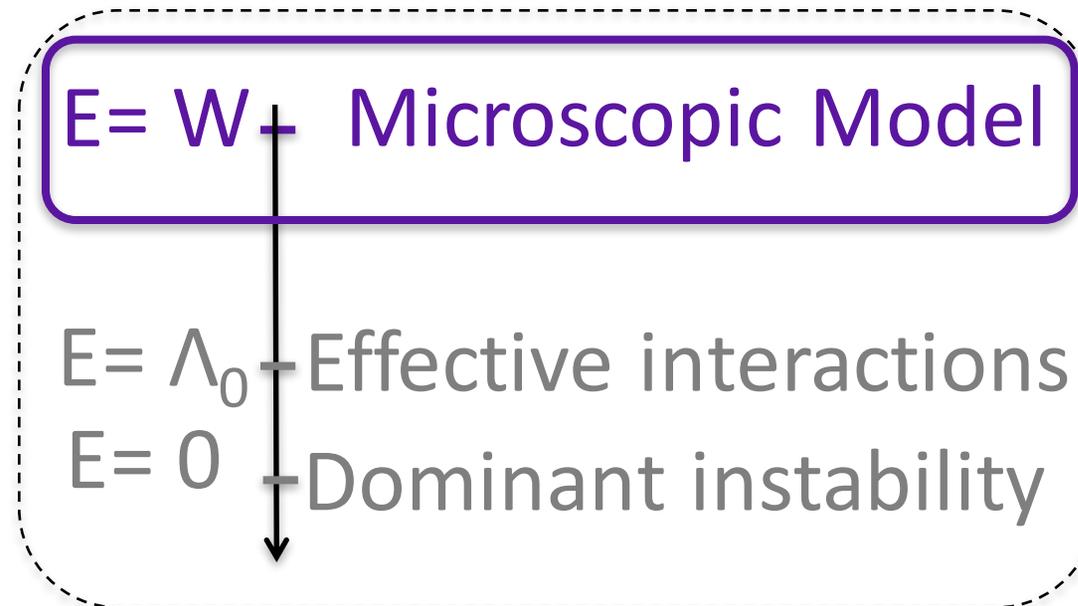
A. intra-pocket pairing



B. inter-pocket pairing



Perturbative Renormalization Group

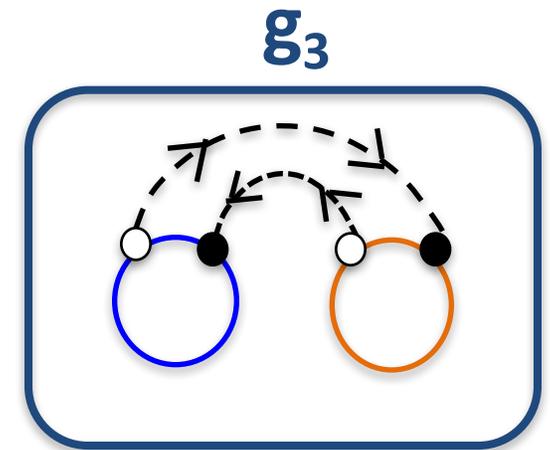
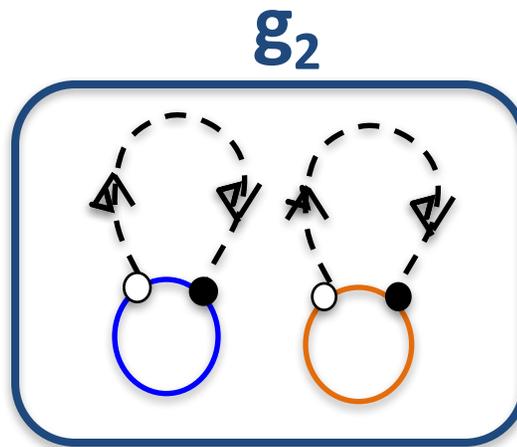
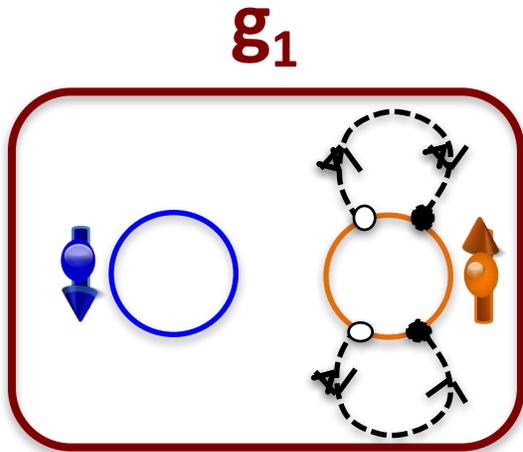
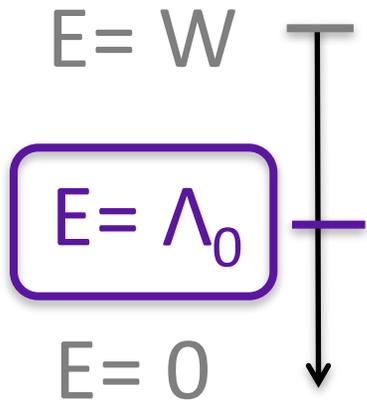


- Microscopic interaction
@ the UV limit:

On-site repulsion U (e-e)
+
Electron-phonon (e-ph)

Effective interactions @

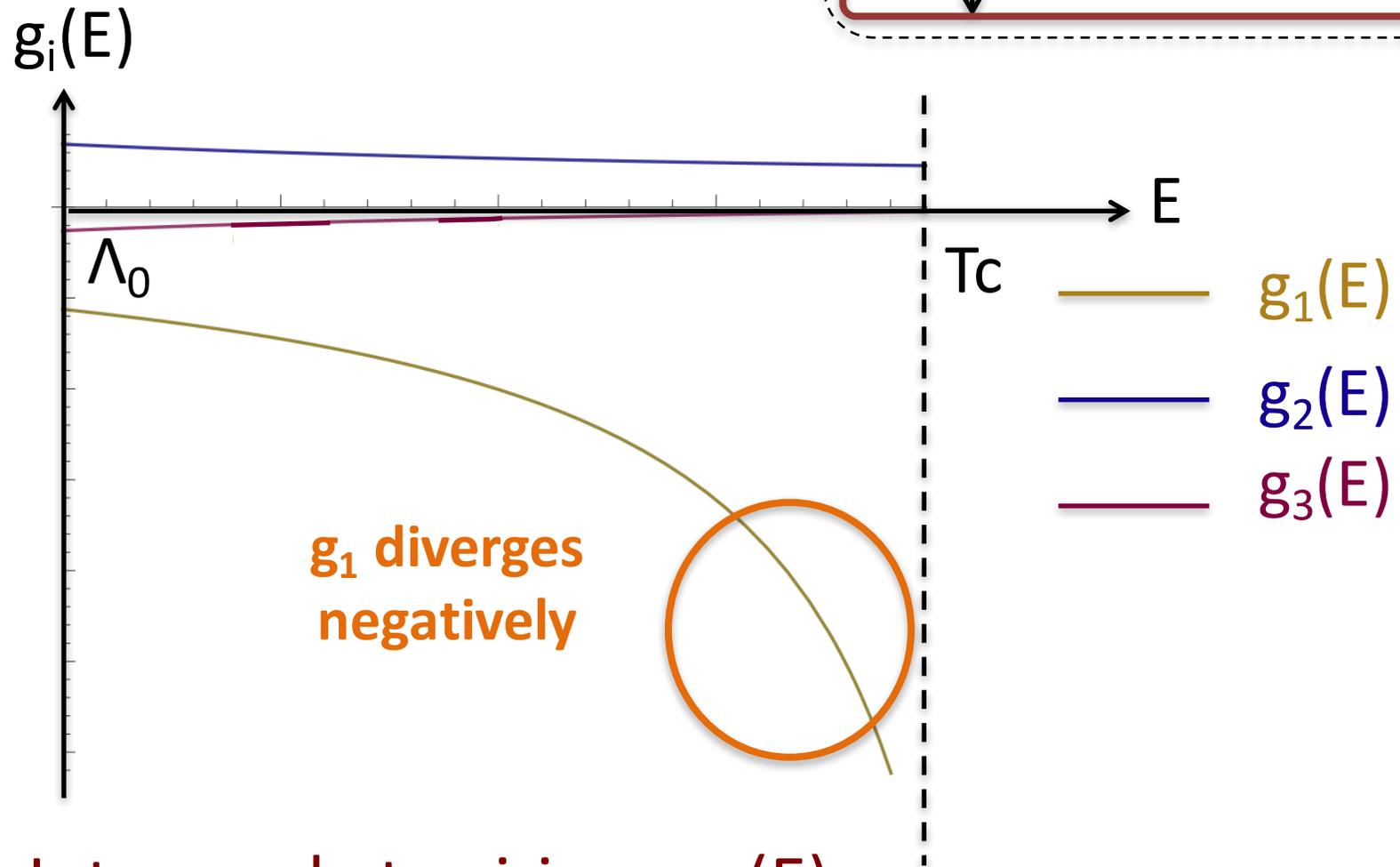
$$E = \Lambda_0 < W$$



Pairing interaction for intra-pocket pair: $g_1(E)$

Pairing interaction for inter-pocket pair: $g_2(E) \pm g_3(E)$

$U > e\text{-ph}$ case RG flow



Intra-pocket pairing: $g_1(E)$

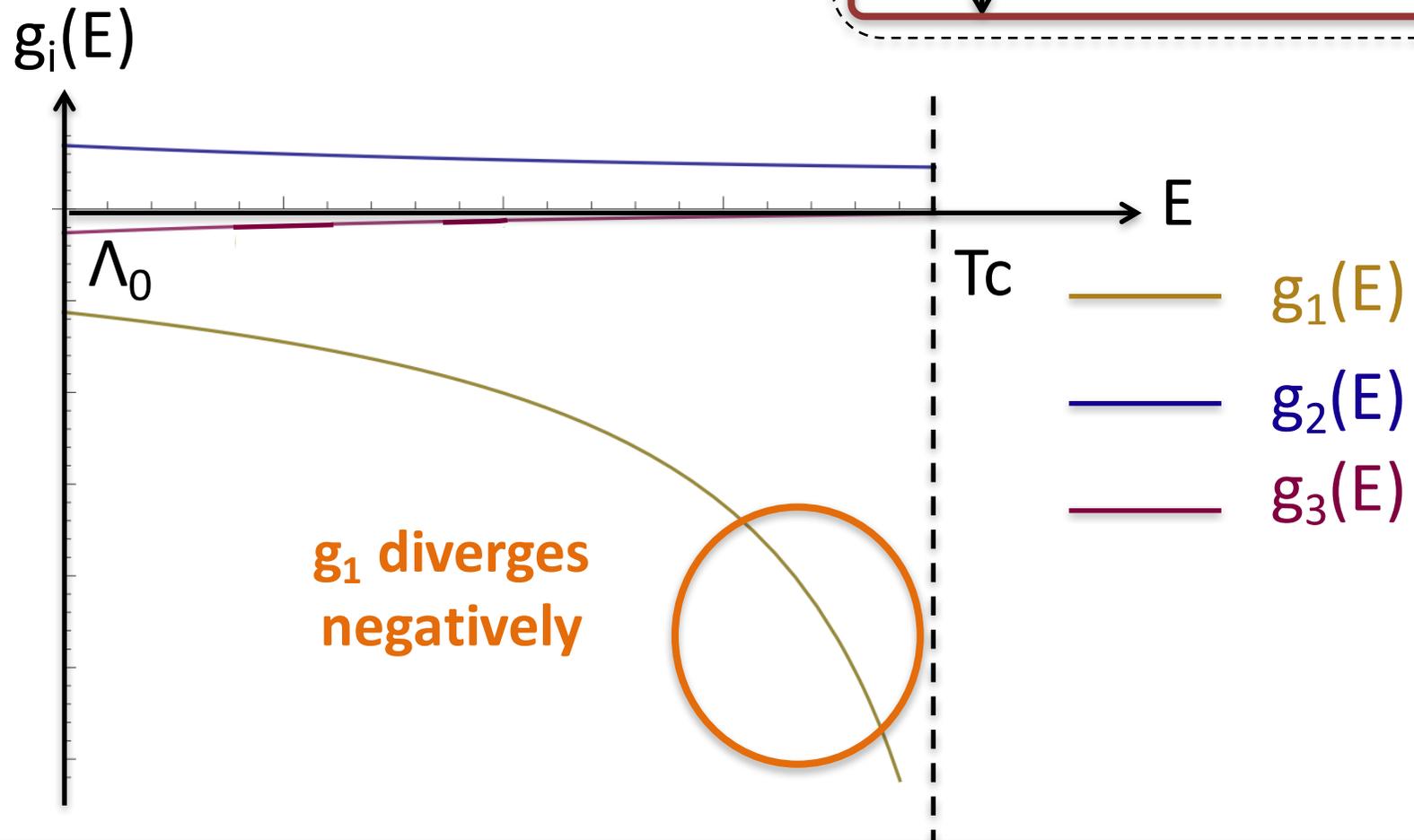
Inter-pocket pairing: $g_2(E) \pm g_3(E)$

$U > e\text{-ph}$ case RG flow

$E = W$ — Microscopic interactions

$E = \Lambda_0$ — Effective interactions

$E \rightarrow 0$ — Dominant instability



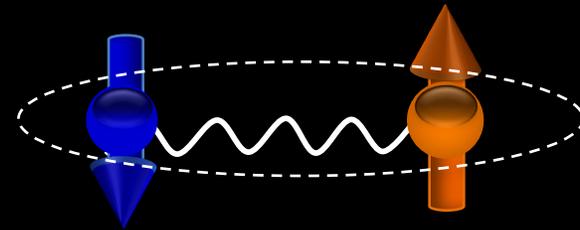
g_1 diverges negatively

Intra-pocket pairing is dominant

Intra- v.s. Inter- pocket pairing

↔ e-e repulsion v.s. e-ph interaction

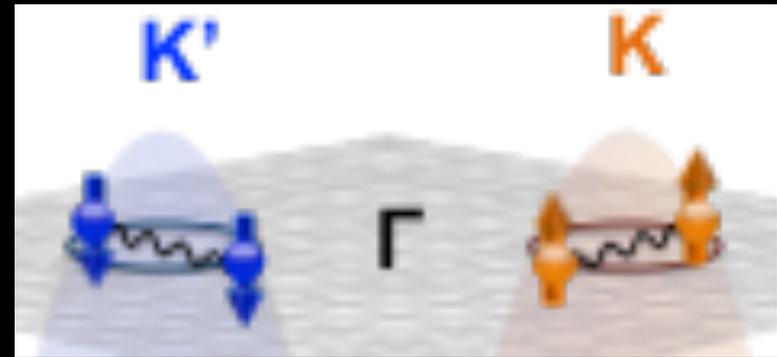
- U only only harms



- e-ph usually gives $q=0$ pairing

$U > \text{e-ph} \Rightarrow \text{intra-pocket pairing wins!}$

Signature of



1. Spatially modulated phase (FF)
: phase sensitive measurement
2. Triplet spin response: Knight shift
3. Majorana bound state and edge states

Possible Materials

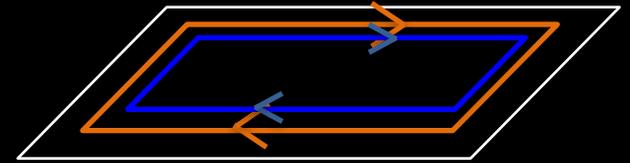
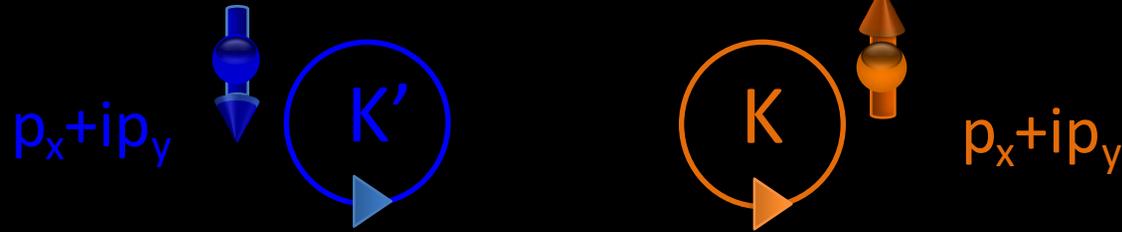
Transition metal dichalcogenides

	a	Δ	t	2λ
MoS ₂	3.193	1.66	1.10	0.15
WS ₂	3.197	1.79	1.37	0.43
MoSe ₂	3.313	1.47	0.94	0.18
WSe ₂	3.310	1.60	1.19	0.46

SOC-induced spin split

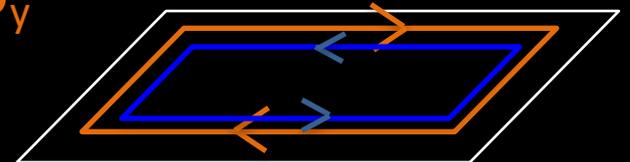
Topological properties for intra-pocket pairing

A. chiral $p+ip$, breaks TRS



 Z-type topo sc:
integer spin degenerate edge modes

B. non-chiral $p+ip$, preserves TRS



\Rightarrow Z_2 -type topo sc protected by TRS:
counter-propagating edge modes with spin up and down

Acknowledgements



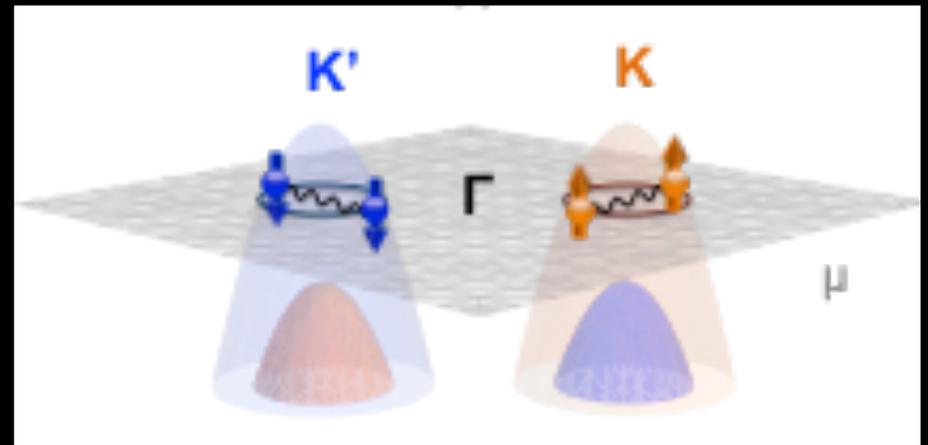
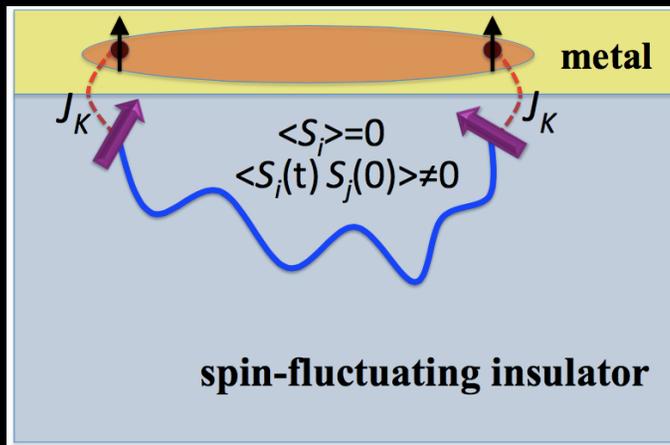
Yi-Ting Hsu



Abolhassan Vaezi

Designing 2D topological SC's

- Control interaction
- Spinless fermion through k-space splitting



Funding

