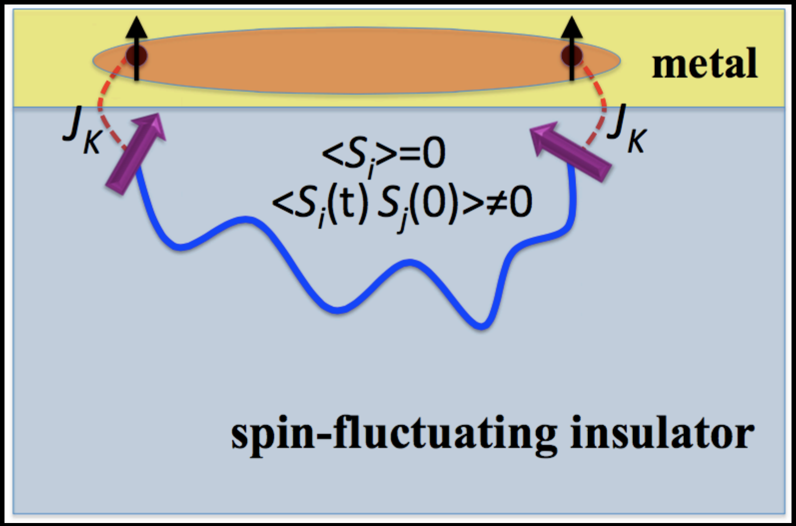
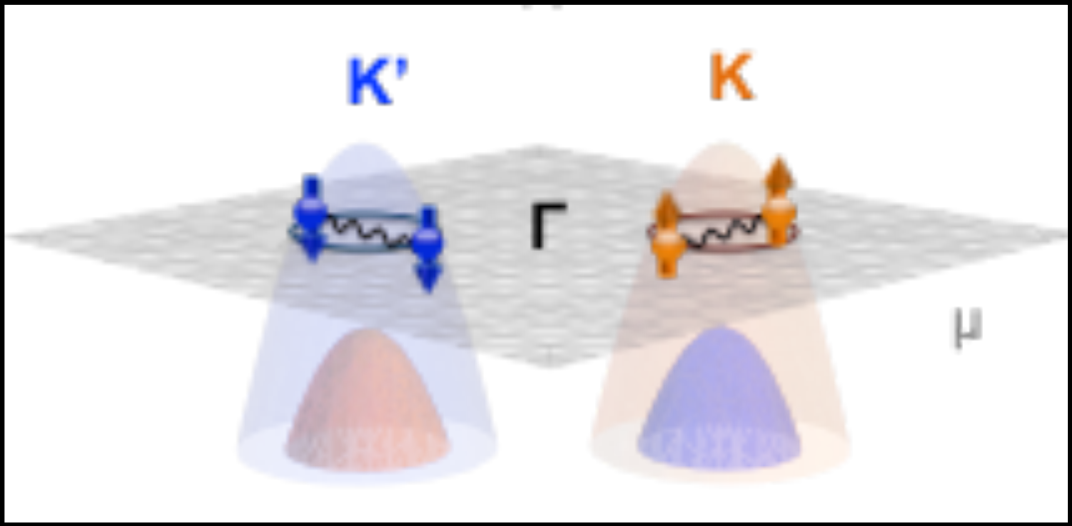
Designing 2D topological SC's



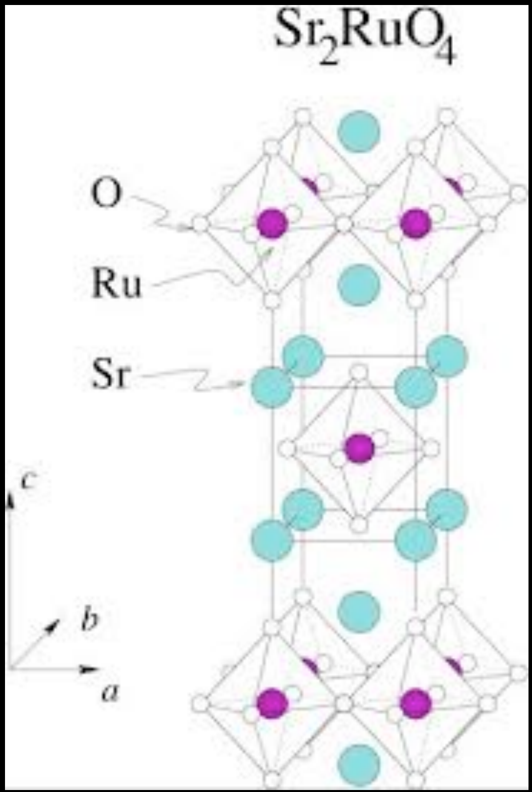


Eun-Ah Kim (Cornell)

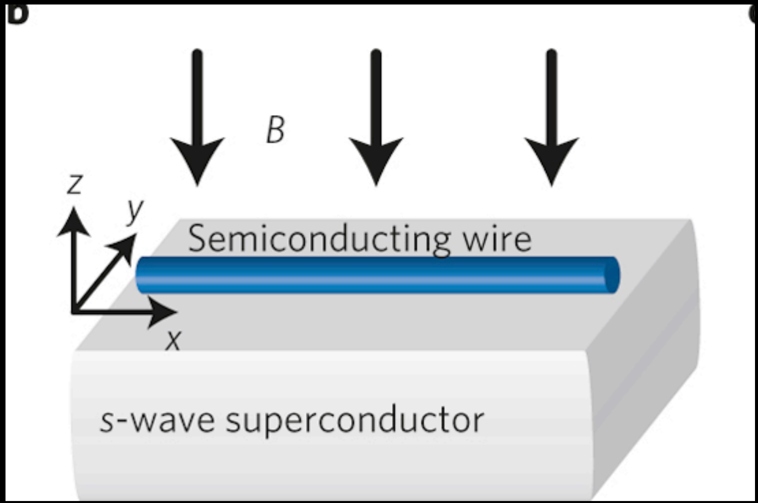
ICTP 08.11.2015

Q. Topological Superconductor material?

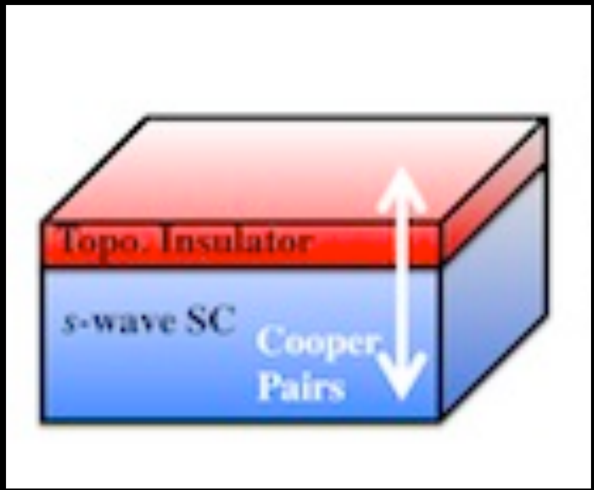
Bulk



1D proximity



2D proximity?



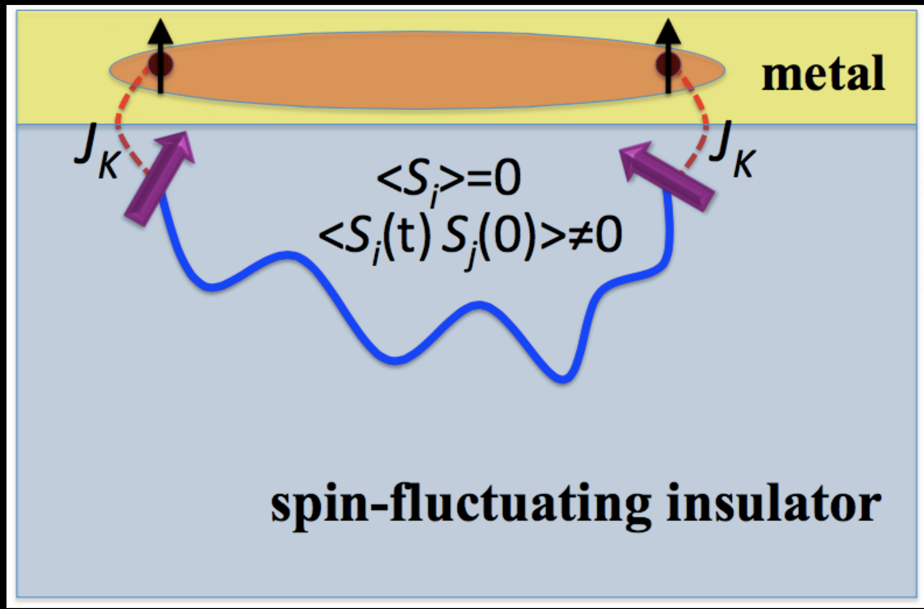
Designing 2D topological SC's

- 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

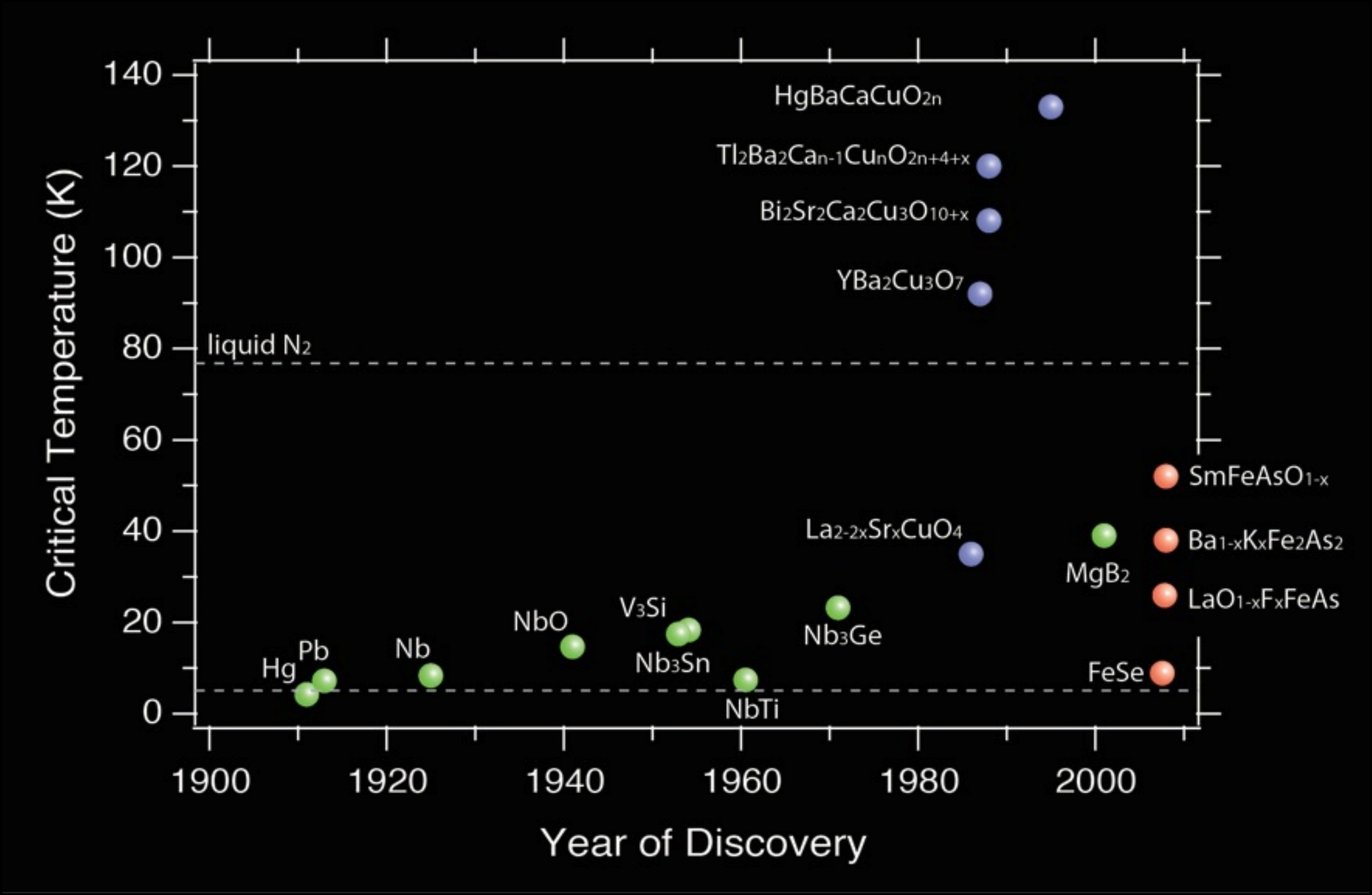
- Manipulate the pairing interaction: target (ferromagnetic) spin fluctuation

Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures



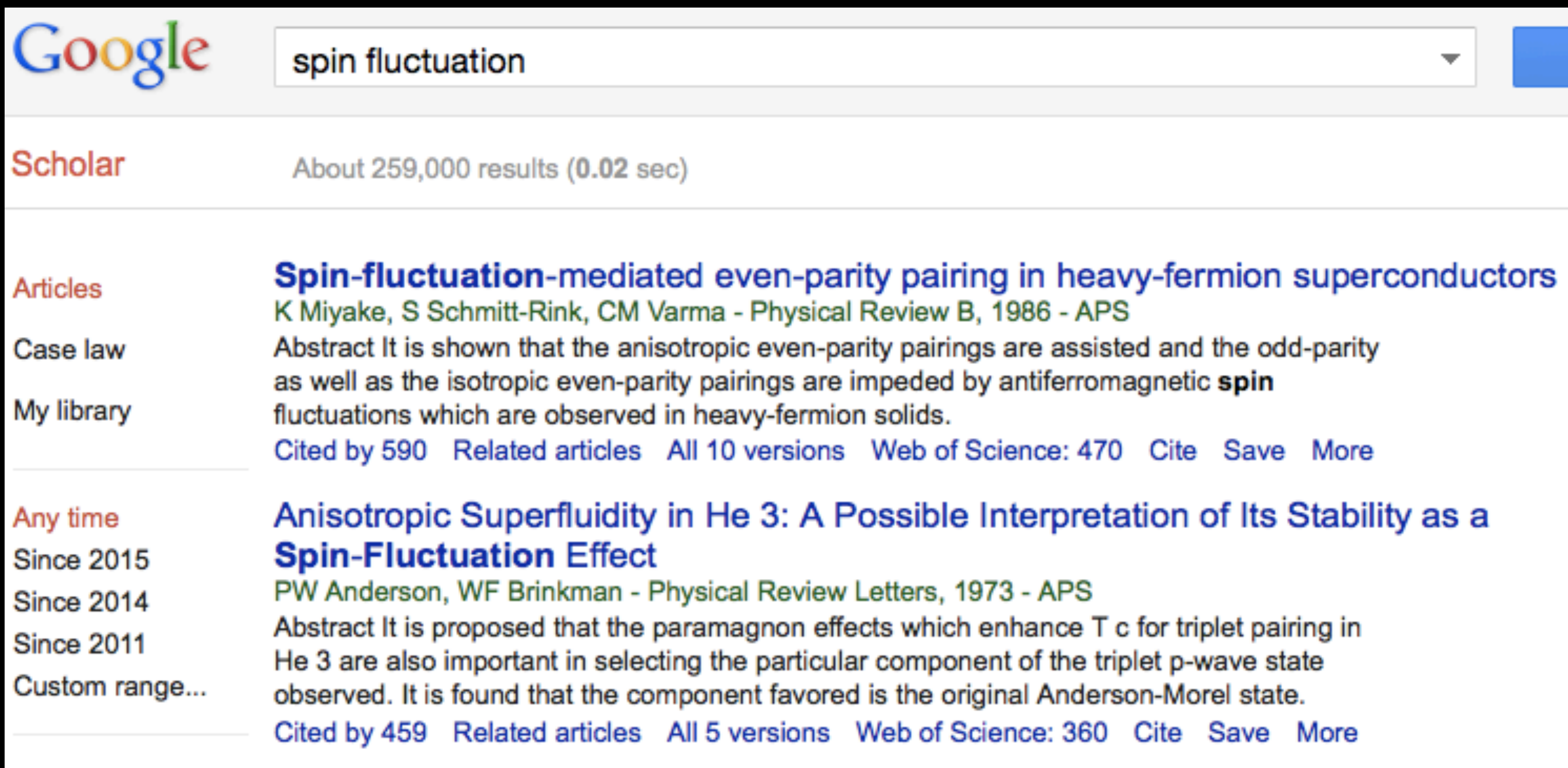
Jian-Huang She, Choonghyun Kim, Craig Fennie, Michael Lawler, E-AK (in preparation, 2015)

Q. Proof of principle for non-phonon mechanism?



Literature on spin-fluctuation mediated superconductivity

260,000 results on google scholar……

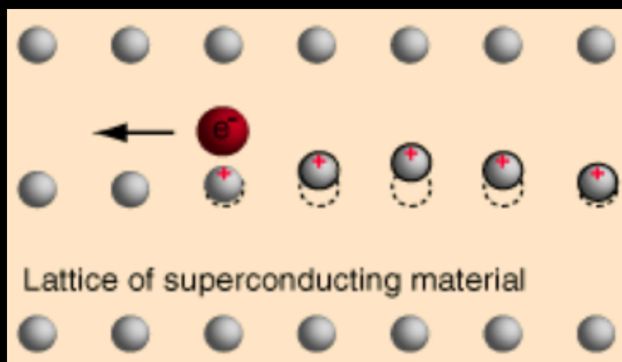


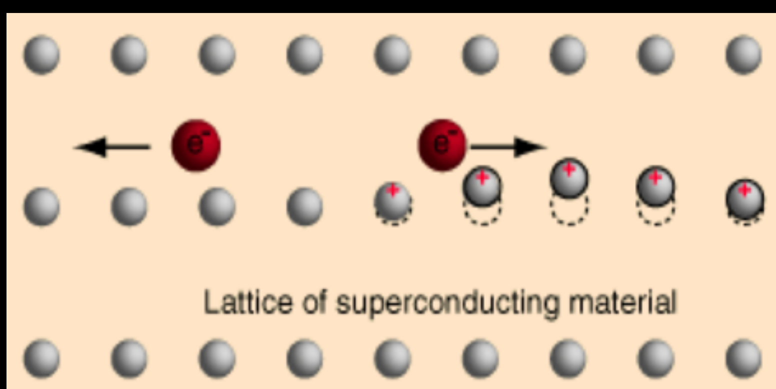
Proof of Principle Example for spin-fluctuation mediated SC?

0

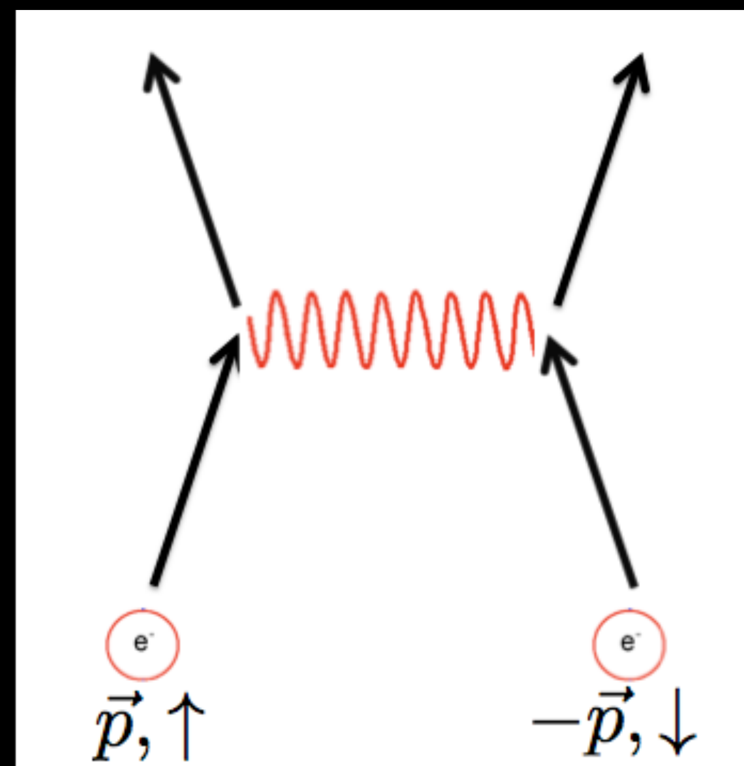
Fundamental Challenge of non-Phonon mechanism

Phonon driven





Spin-fluctuation driven



Absence of separation of scales!

Challenges

Experimental

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

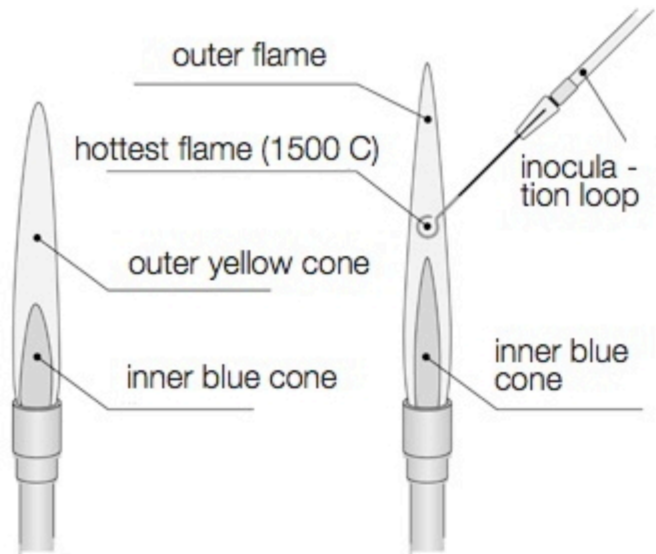
Theoretical

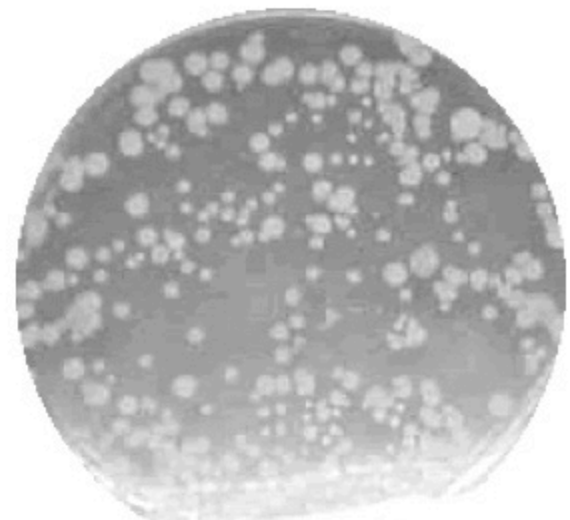
- Strongly correlated fermions, i.e. the sign problem.

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.

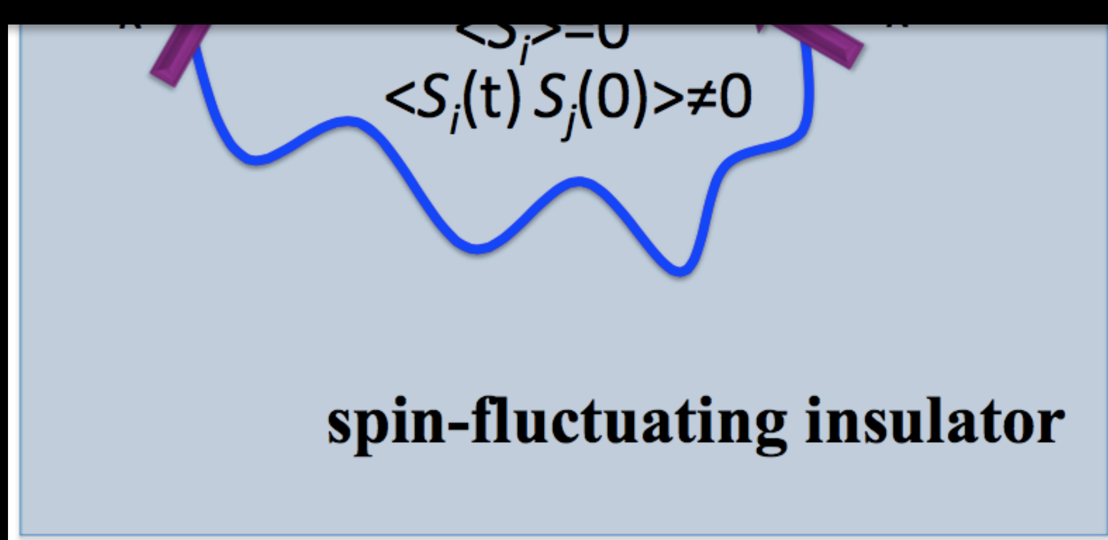




Strategy?

Separate the "glue" from "charge:

Heterostructure!



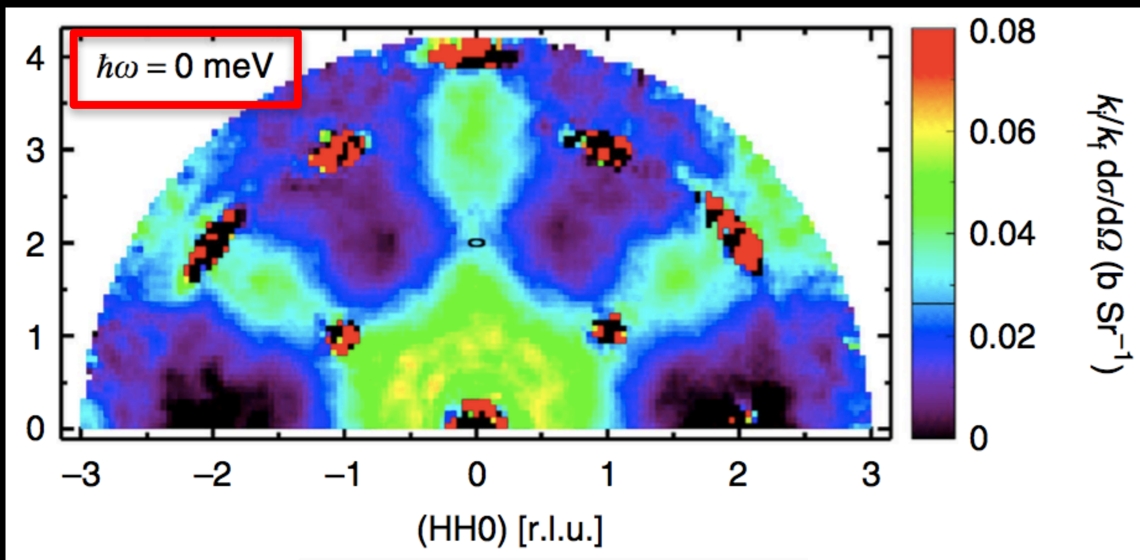
Criteria for the substrate

1. No long range order $<S>=0$
2. Strong dynamic spin fluctuation $<S_i S_j>$

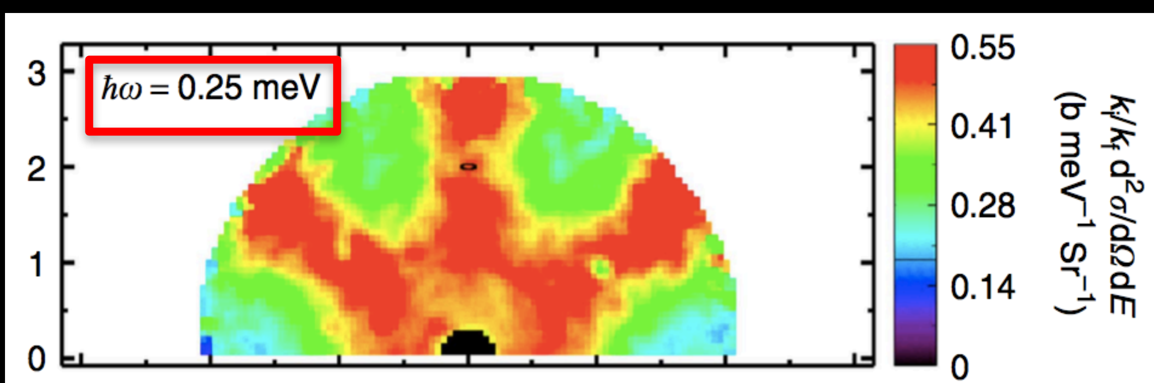
Received 20 Sep 2012 | Accepted 18 Apr 2013 | Published 17 Jun 2013
DOI: 10.1038/ncomms2914

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]



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



- Inelastic neutron: over 90% weight

Received 20 Sep 2012 | Accepted 18 Apr 2013 | Published 17 Jun 2013
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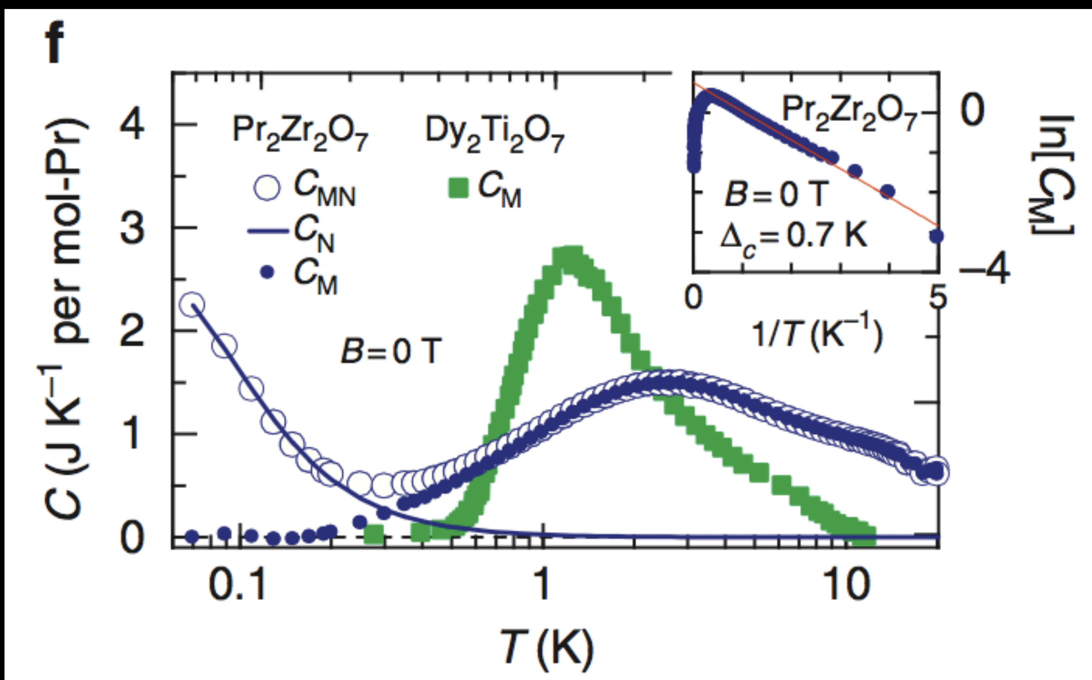
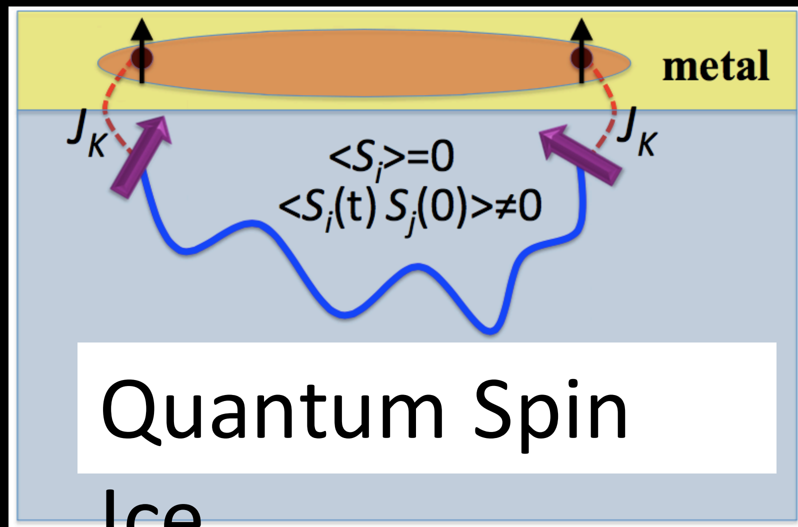


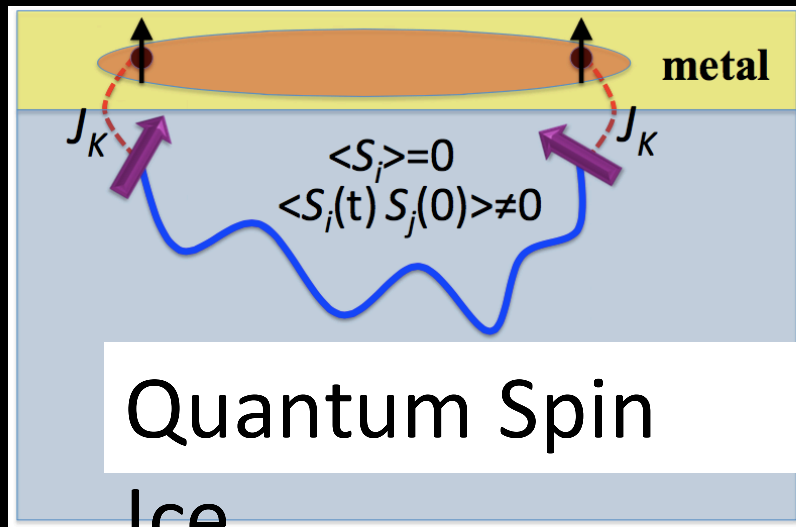
- No order down to 20mK
- Dynamic fluct. upto ~3K

Structural Criteria for the Metal



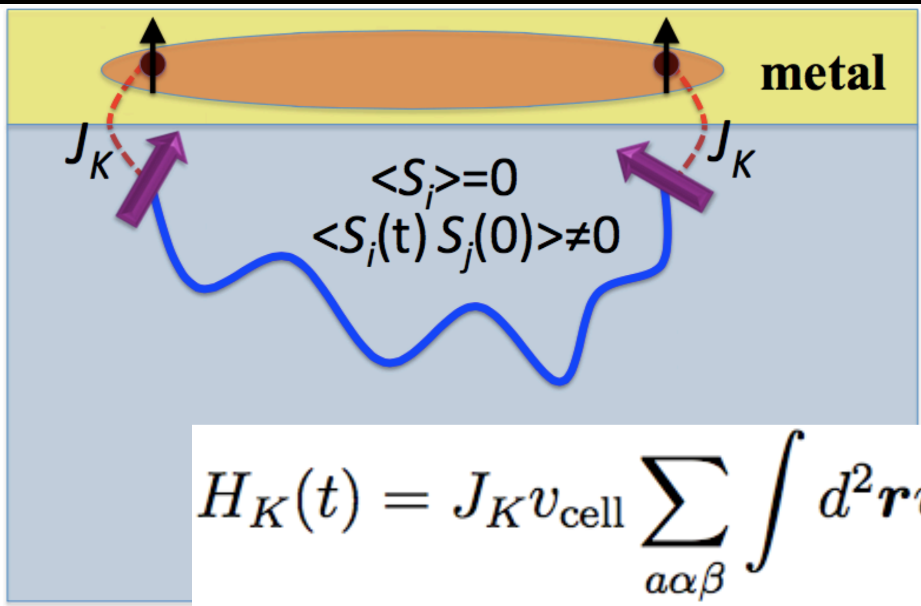
1. Chemical stability
2. Lattice matching: $A_2B_2O_7$
3. No orphan bonds: (111) direction

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



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

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

- Integrate out spins >> Effective e-e interaction

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

$$s_a(\boldsymbol{r}, t) \;=\; \sum_{\alpha\beta} \psi^\dagger_\alpha(\boldsymbol{r}, t) \sigma^a_{\alpha\beta} \psi_\beta(\boldsymbol{r}, t)$$

Dominant Pairing Channel

- Key properties of the static spin structure factor

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

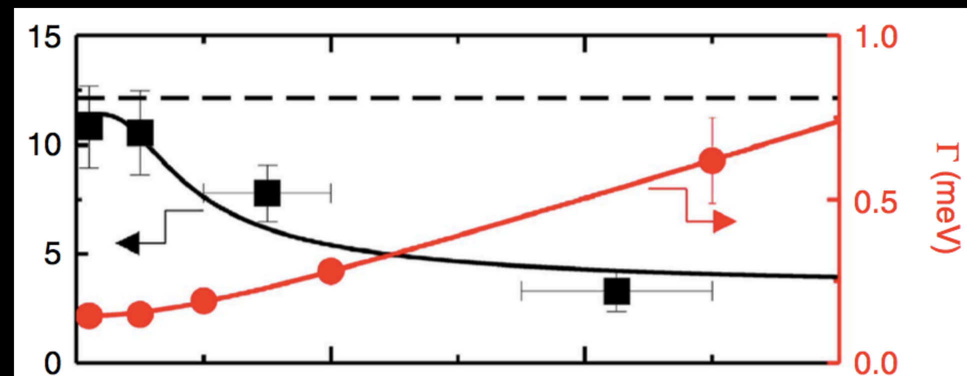
1. "spin-orbit" coupling
2. $J_z=L_z+S_z$ conserved.
3. spin "mirror" symm: $S_{ab}(\mathbf{q}) = S_{ba}(\mathbf{q})$
   -> singlet - triplet decoupled.

- Purely repulsive interaction in the singlet channel

Transition Temperature

- Spin dynamics

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



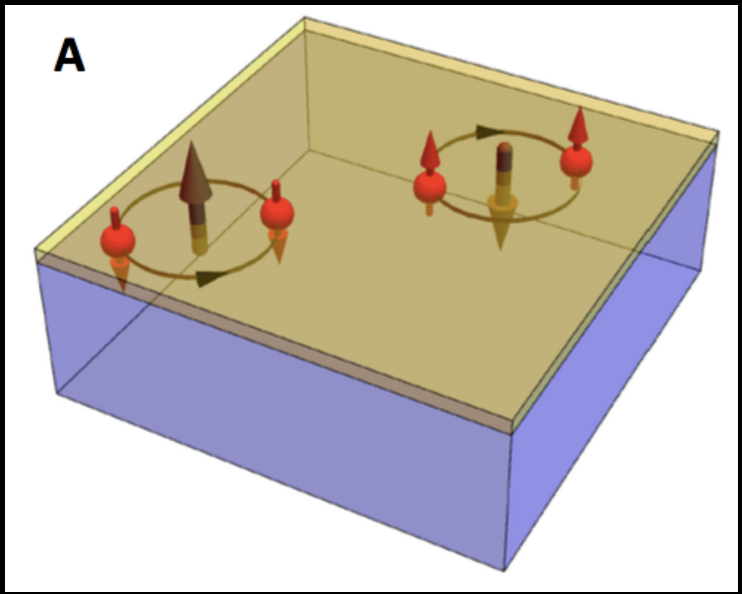
$\tau^{-1} \sim 2J_{ex} \sim 0.17$meV

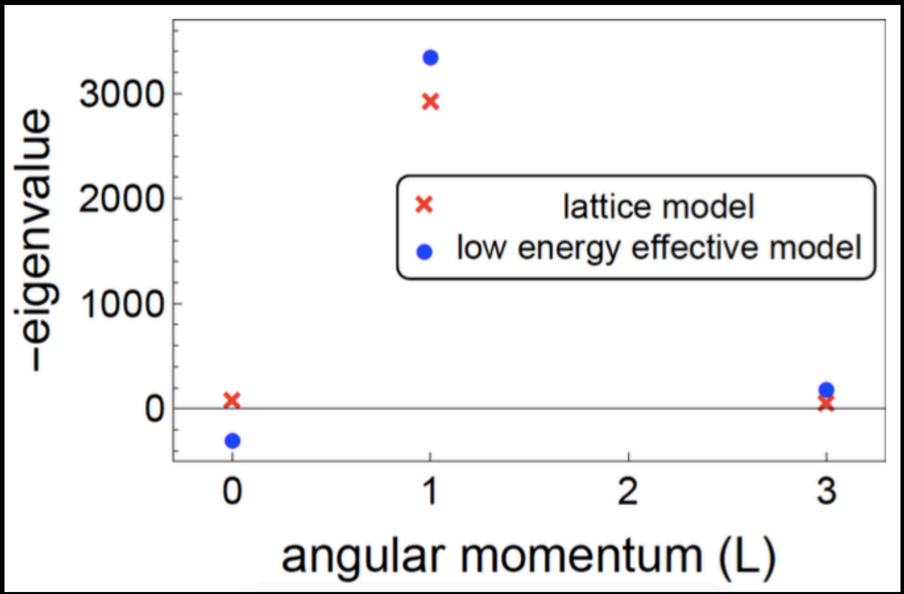
- Parameters for our proposal

$E_F \sim 300$meV, $J_K \sim 10$meV, $\lambda \sim O(1)$

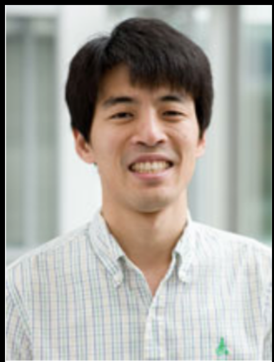
- $T_c \sim 1.5$K

Dominant Pairing Channel





1. ^{3}He-B type but 2D.
2. Overwhlemingly dominant.

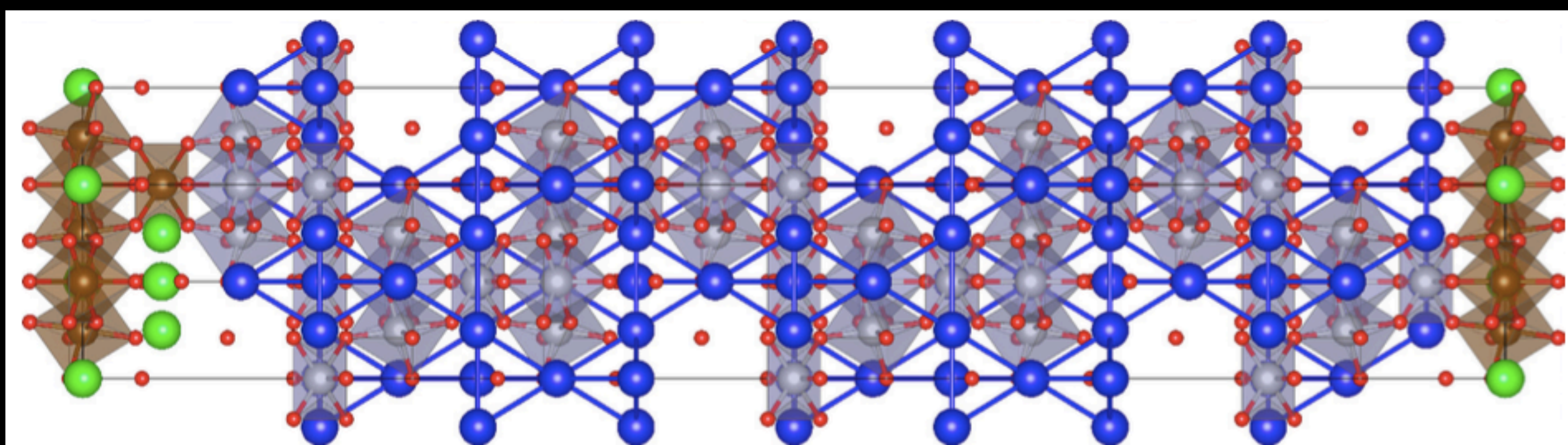


Microscopic Proposal

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

Non-magnetic

s-electrons:
large overlap,
isotropic FS.

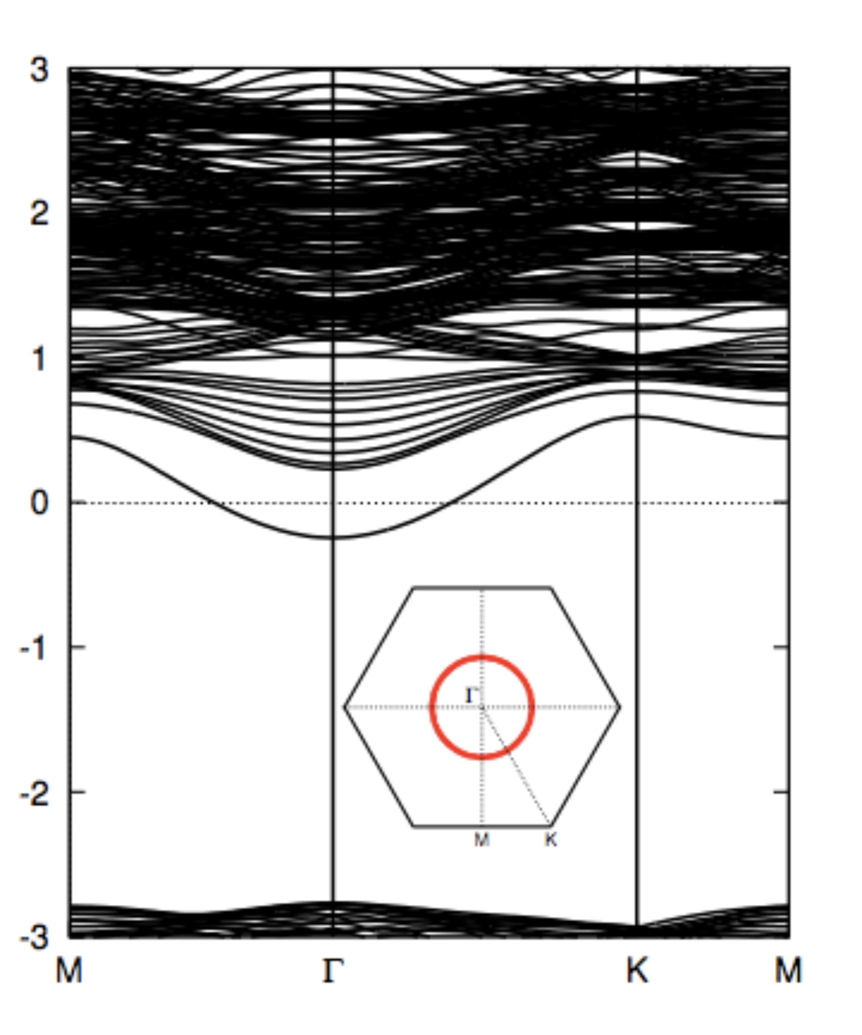


Band structure for the Proposal

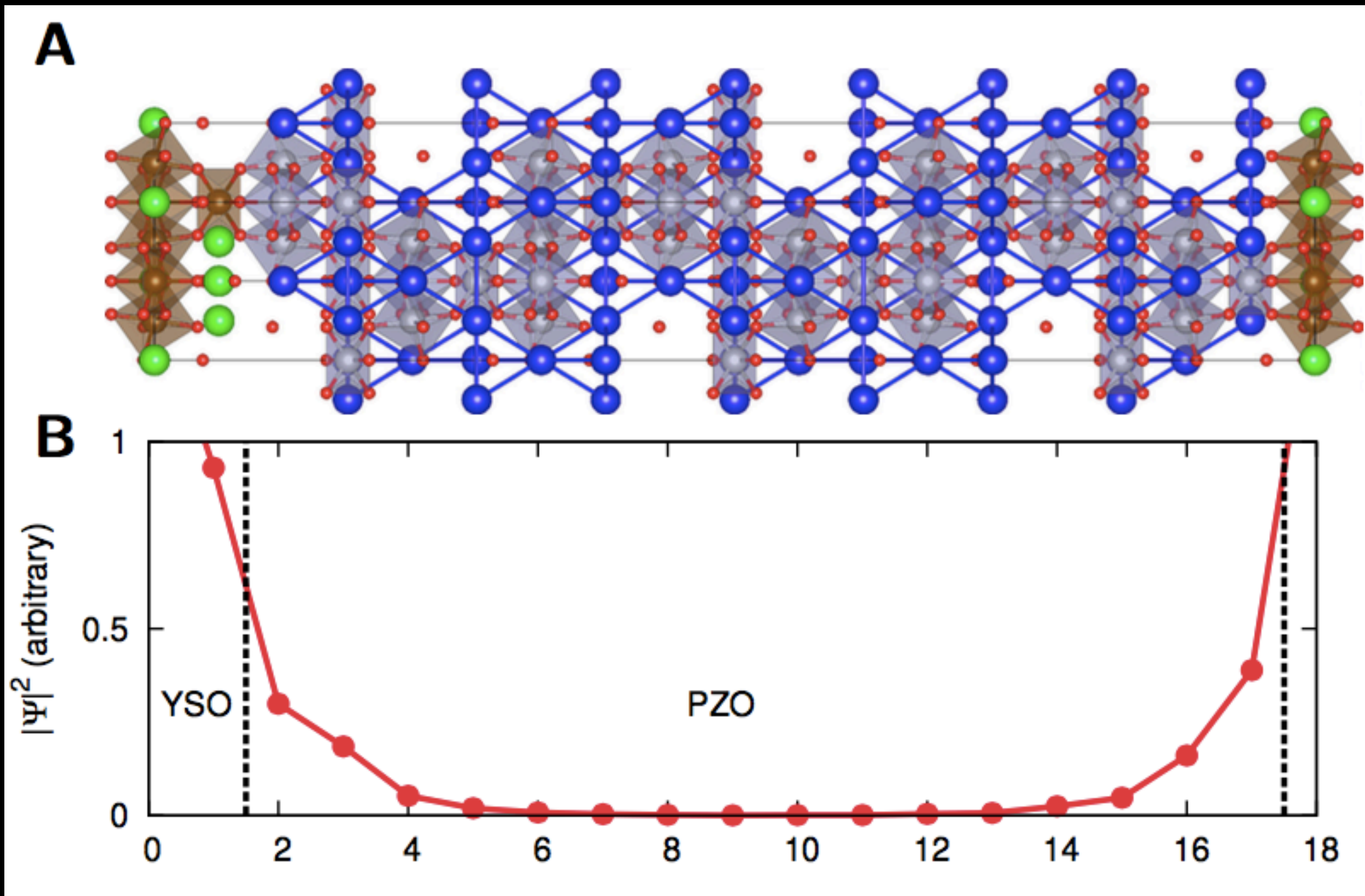
$Pr_2Zr_2O_7/Y_2Sn_{2-x}Sb_xO_7$ (111)

x=0.2

- Isotropic single pocket centered at Γ-point

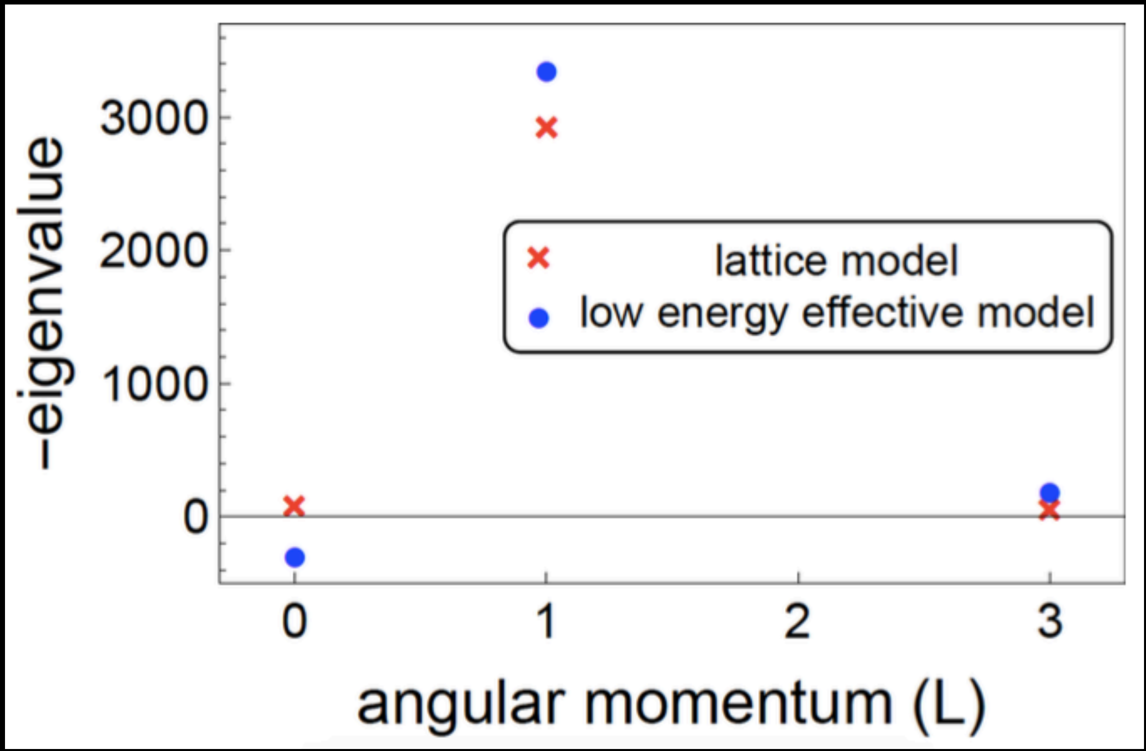


Wave function penetration



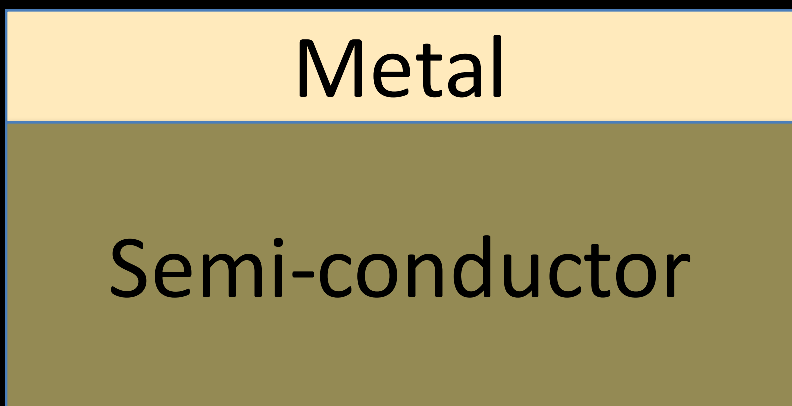
Full Lattice Model for the proposal

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



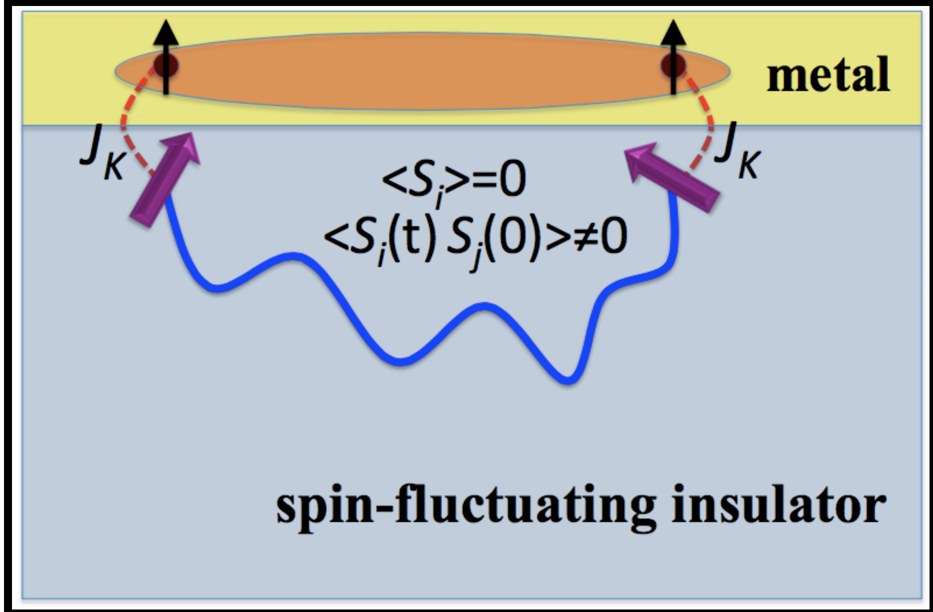
Earlier Proposal: Excitonic mechanism

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



- Unstable against exchange.
- Intrinsically s-wave.

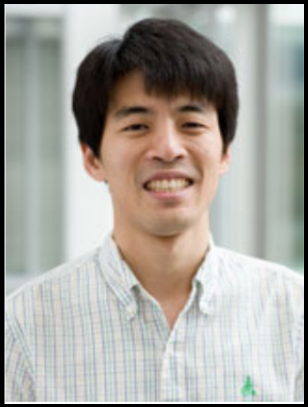
Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures



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

Acknowledgements

Jian-huang She



Choonghyun Kim

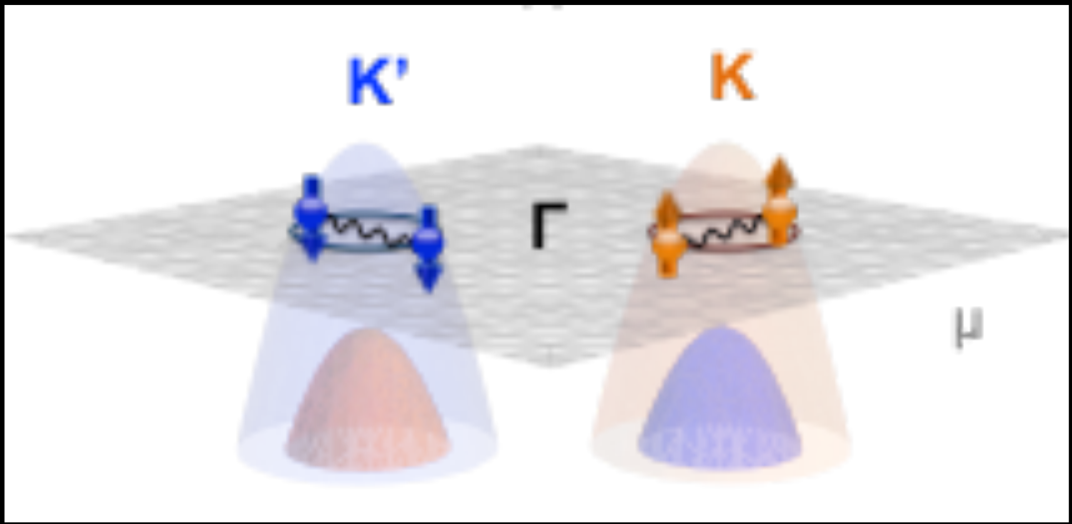
Criag Fennie

Michael Lawler

Strategy II

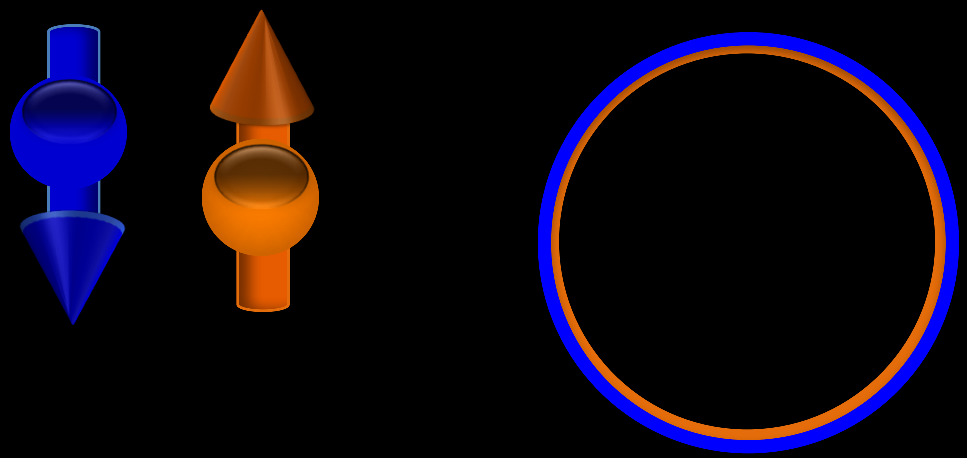
- Manipulate the band structure

Modulated topological superconductivity in group-VI TMDs



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

Spin-degenerate Fermi surface

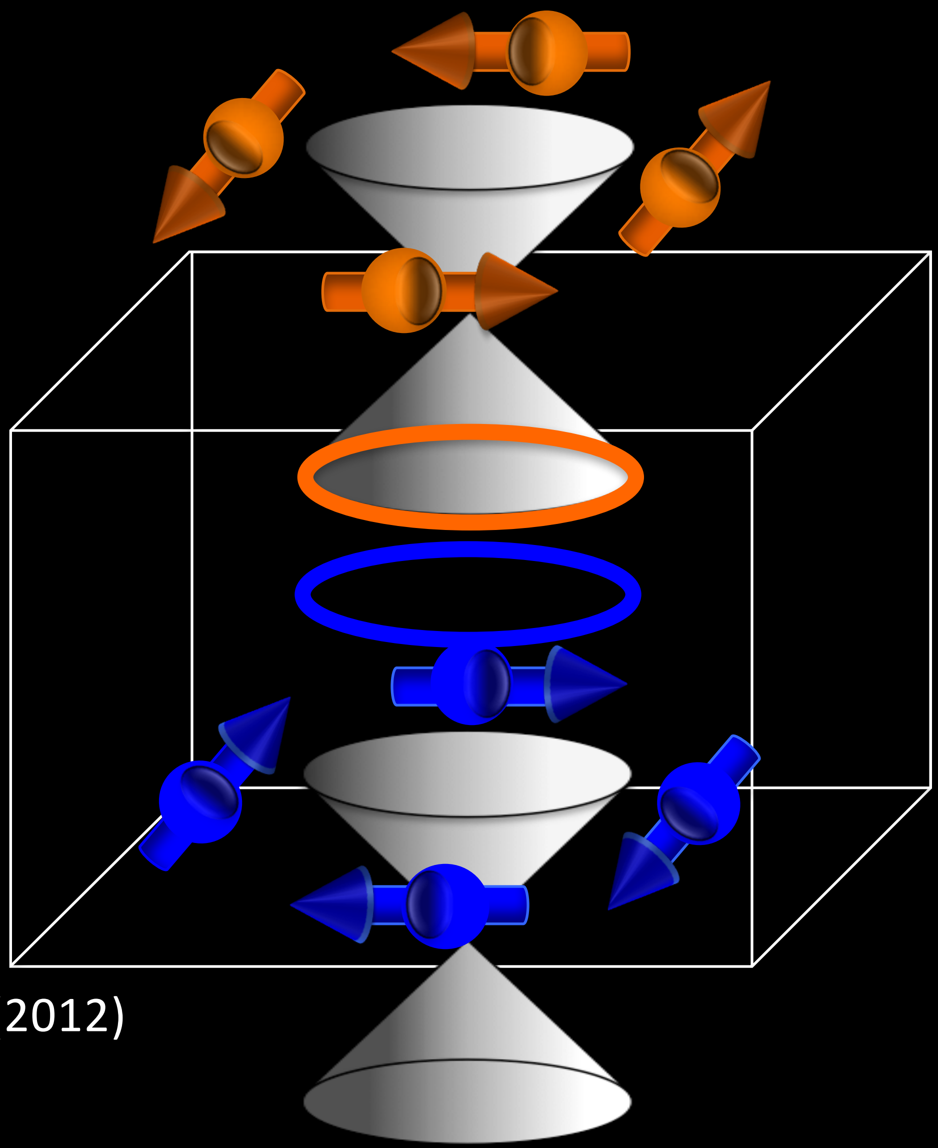


Singlet superconductor

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

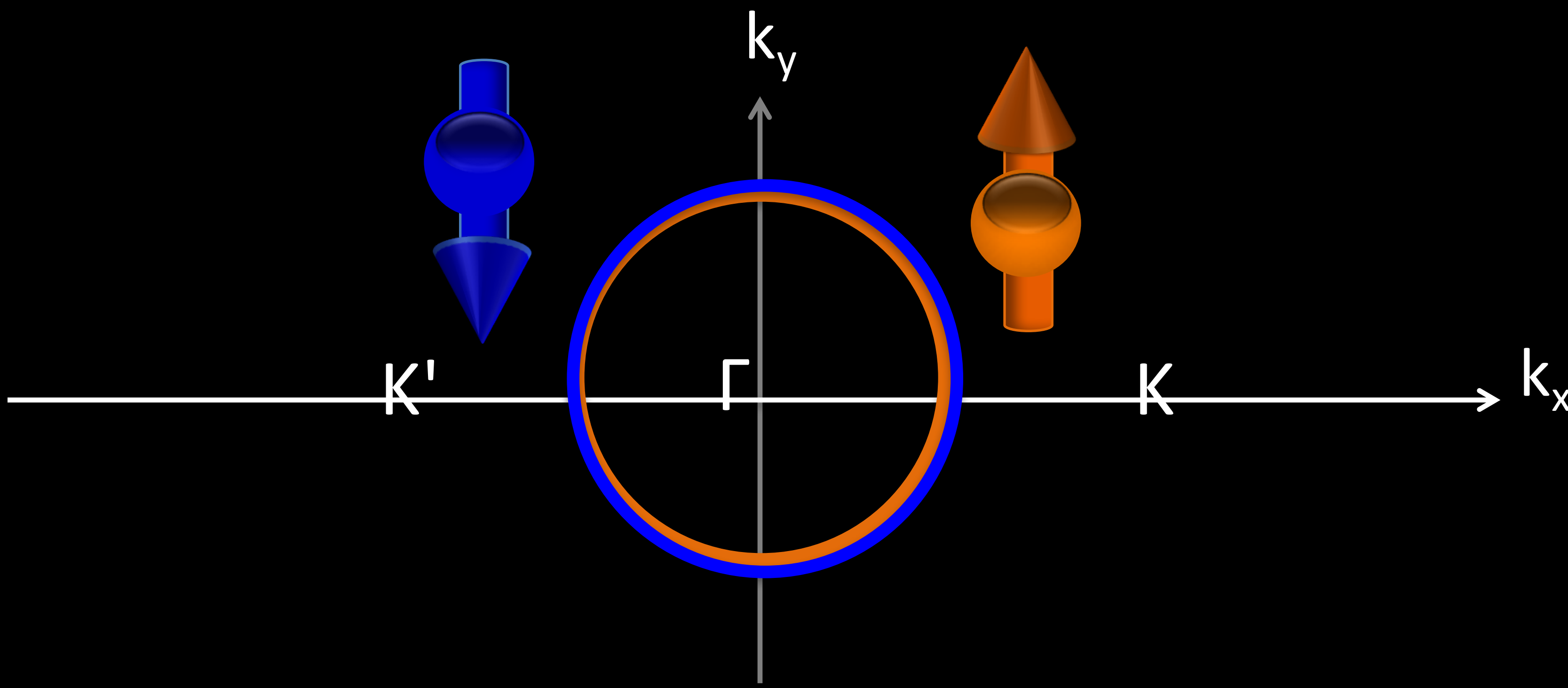
Spinless fermion via real space splitting

- TI surface states
- Proximity induce topo SC



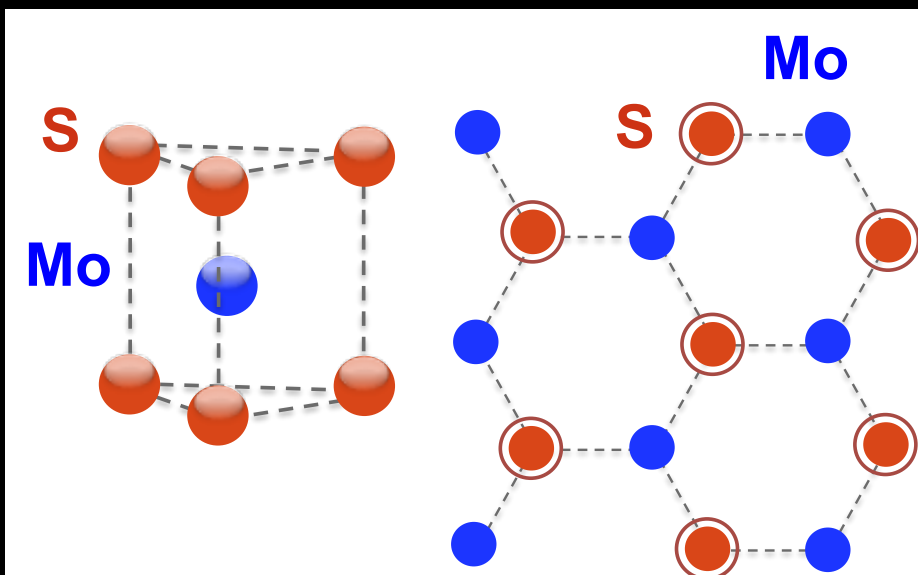
Fu & Kane, PRL (2008)
Experiments: Wang et al Science 336, 52 (2012)
Xu et al, Nat.Phys 10, 943 (2014)

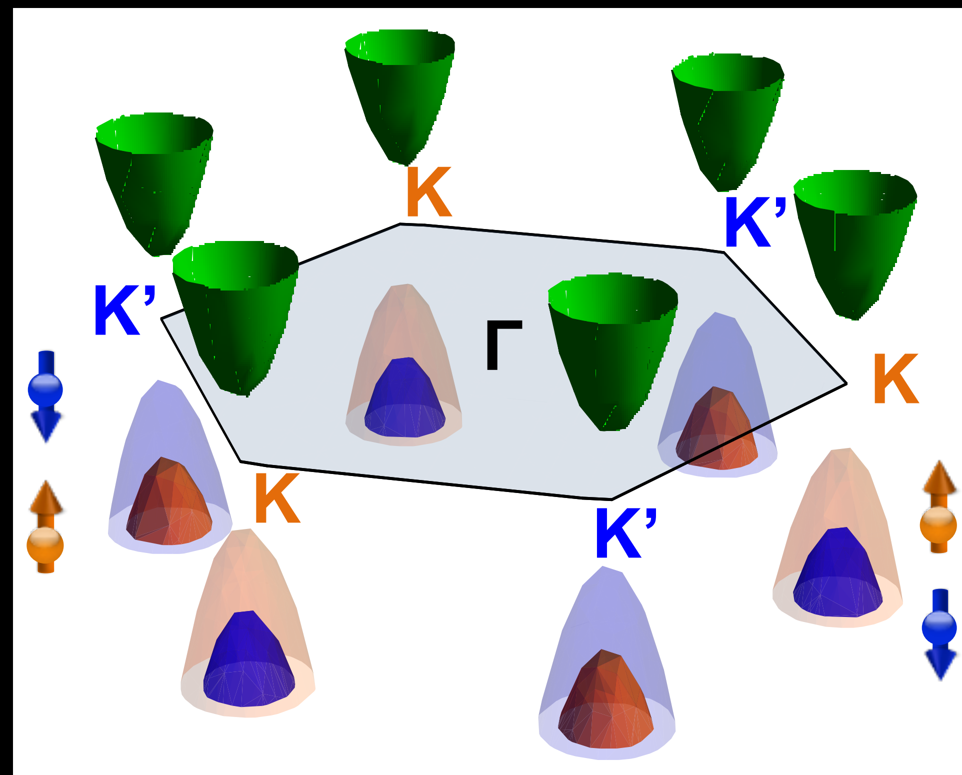
Spinless fermion via k-space splitting?



Monolayer group VI TMD's

MoS_2, WS_2, $MoSe_2$, WSe_2





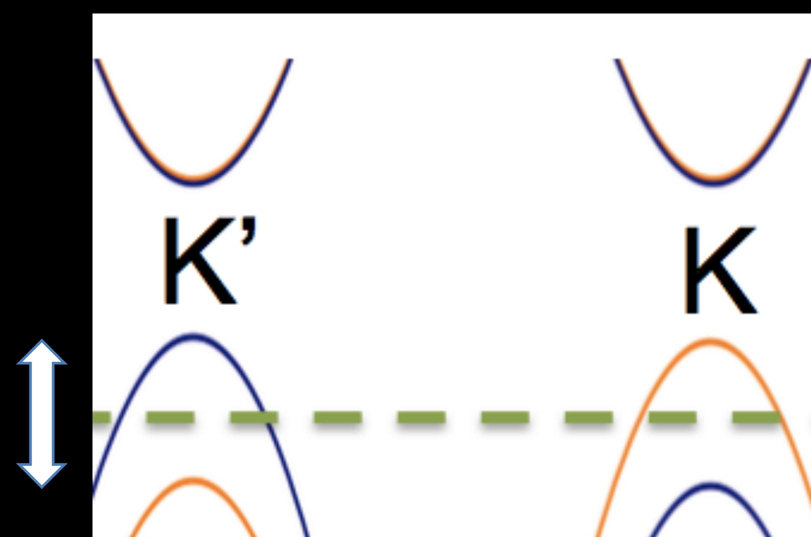
No inversion center! => Gap ~2eV, spin-orbit coupling

Band-selective spin-splitting

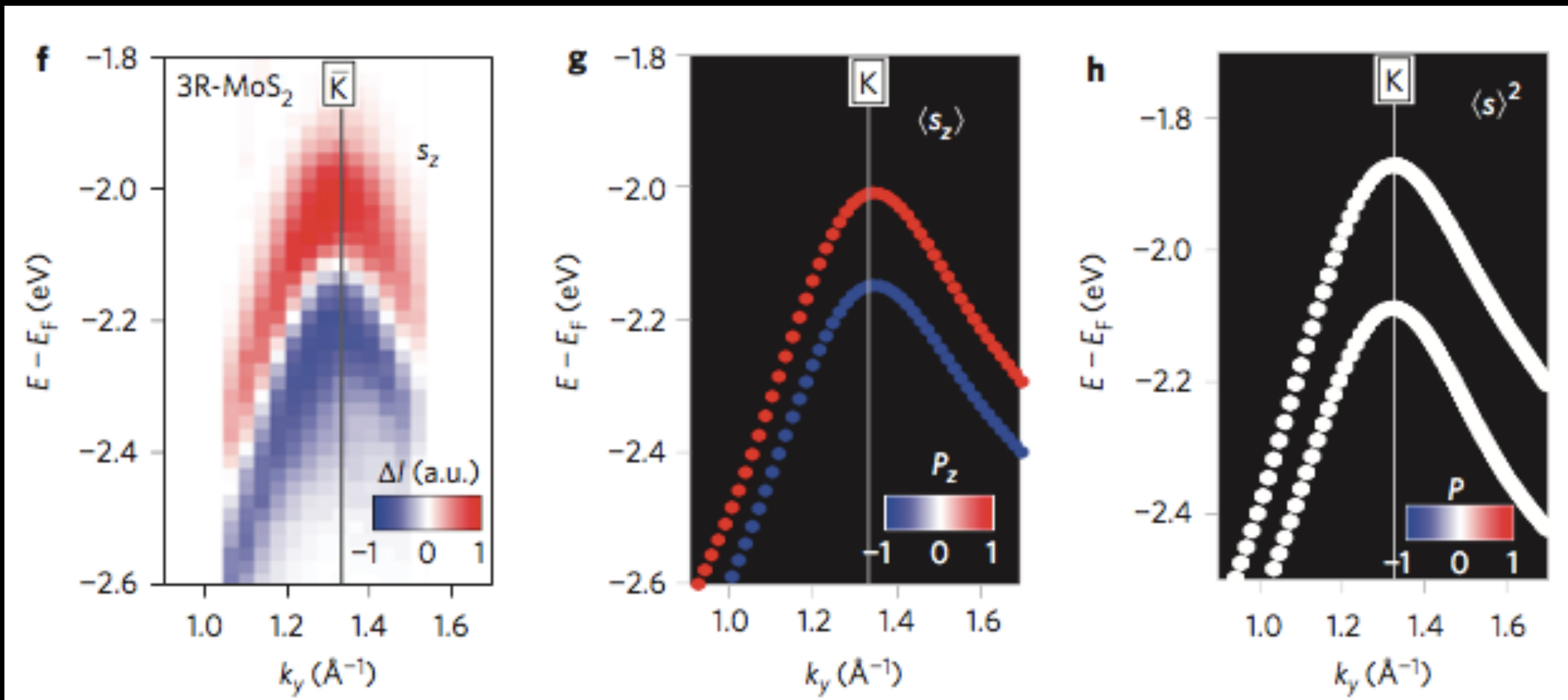
- Partially filled crystal-field-split d-bands
  - Conduction band $|d_{z^2}\rangle : l_z = 0$
  - Valence band $\frac{1}{\sqrt{2}}(|d_{x^2-y^2}\rangle \mp i|d_{xy}\rangle) \;: l_z = \mp 1$
- Spin-orbit coupling

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

150~460meV



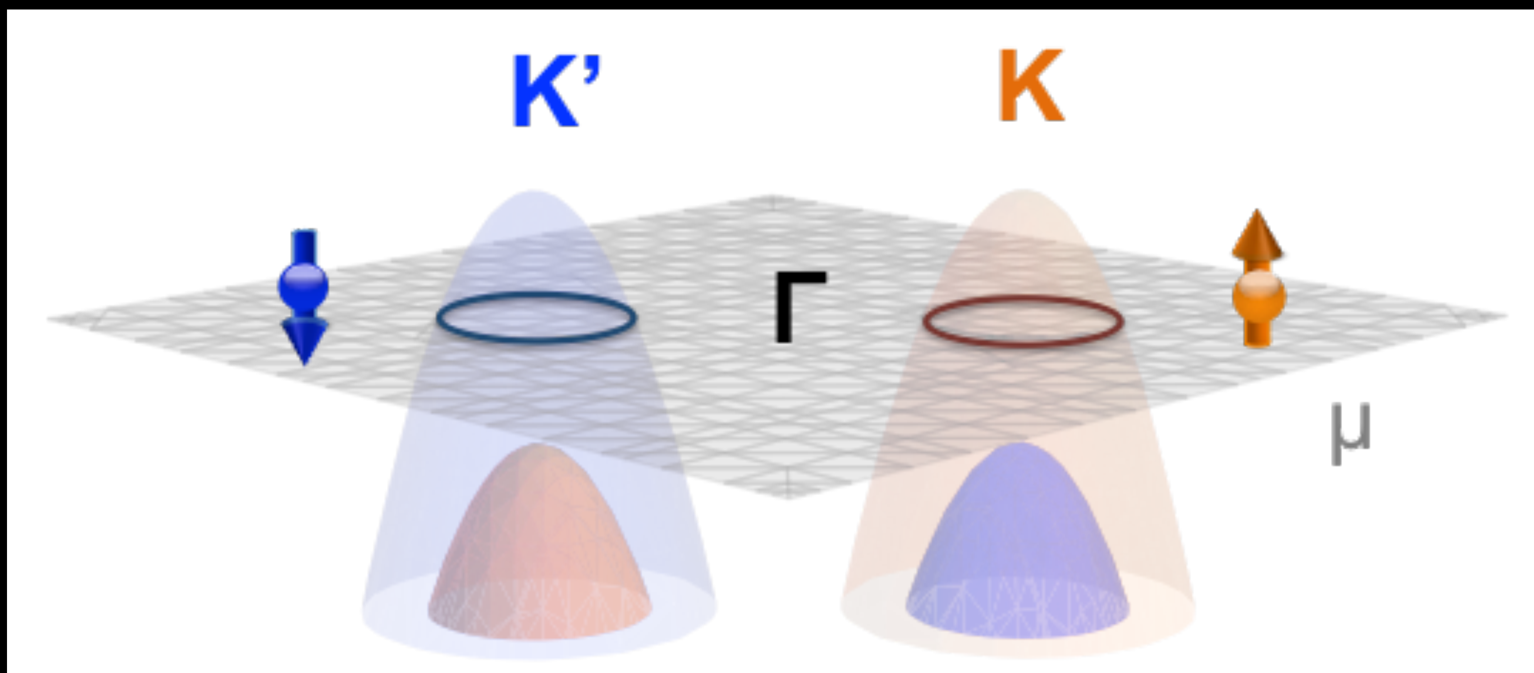
Confirmation of the band structure



Iwasa group N. Nano (2014)

k-space spin-split FS?

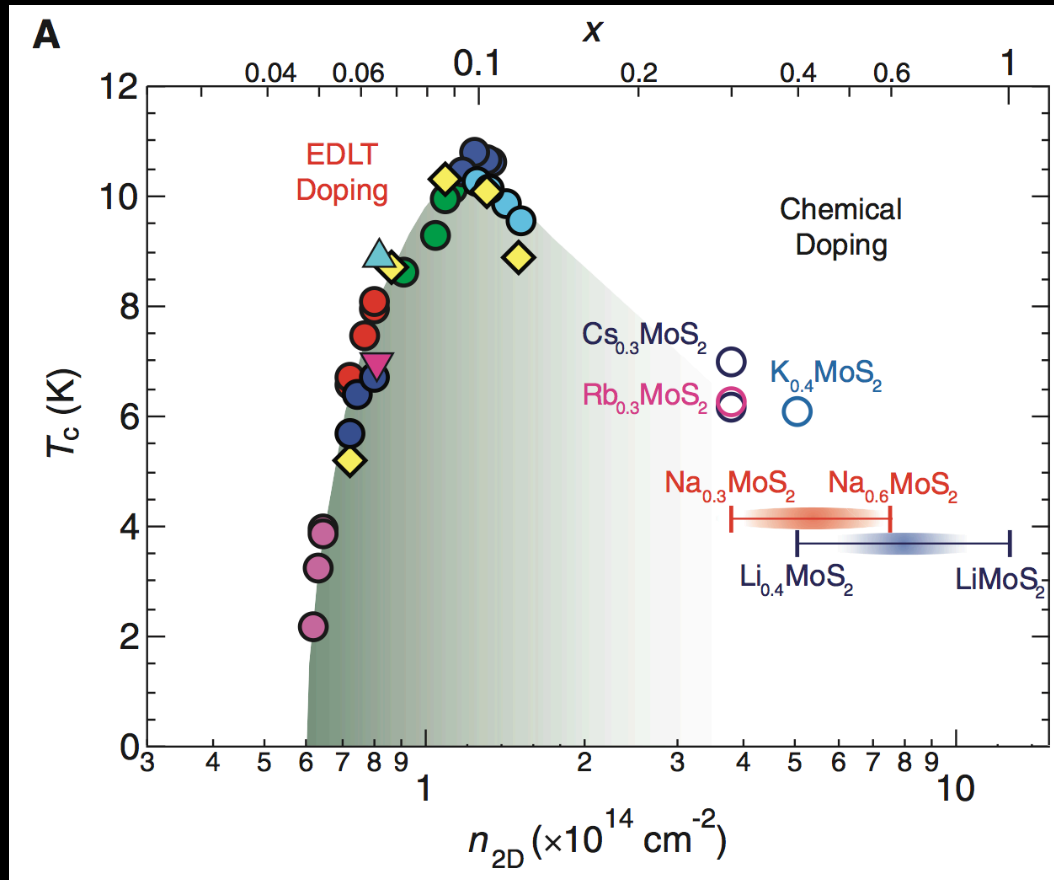
p-doped group VI- TMD!



Juice for superconductivity?

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

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



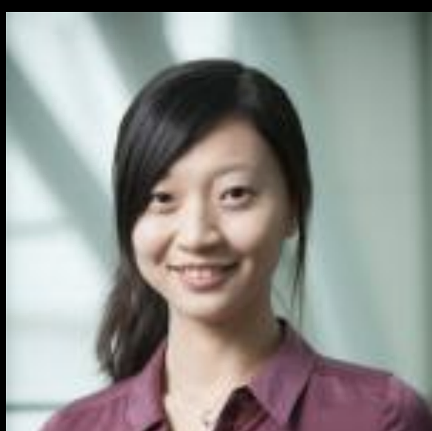
p-doped TMD

Moderate correlation (d-electron)

+

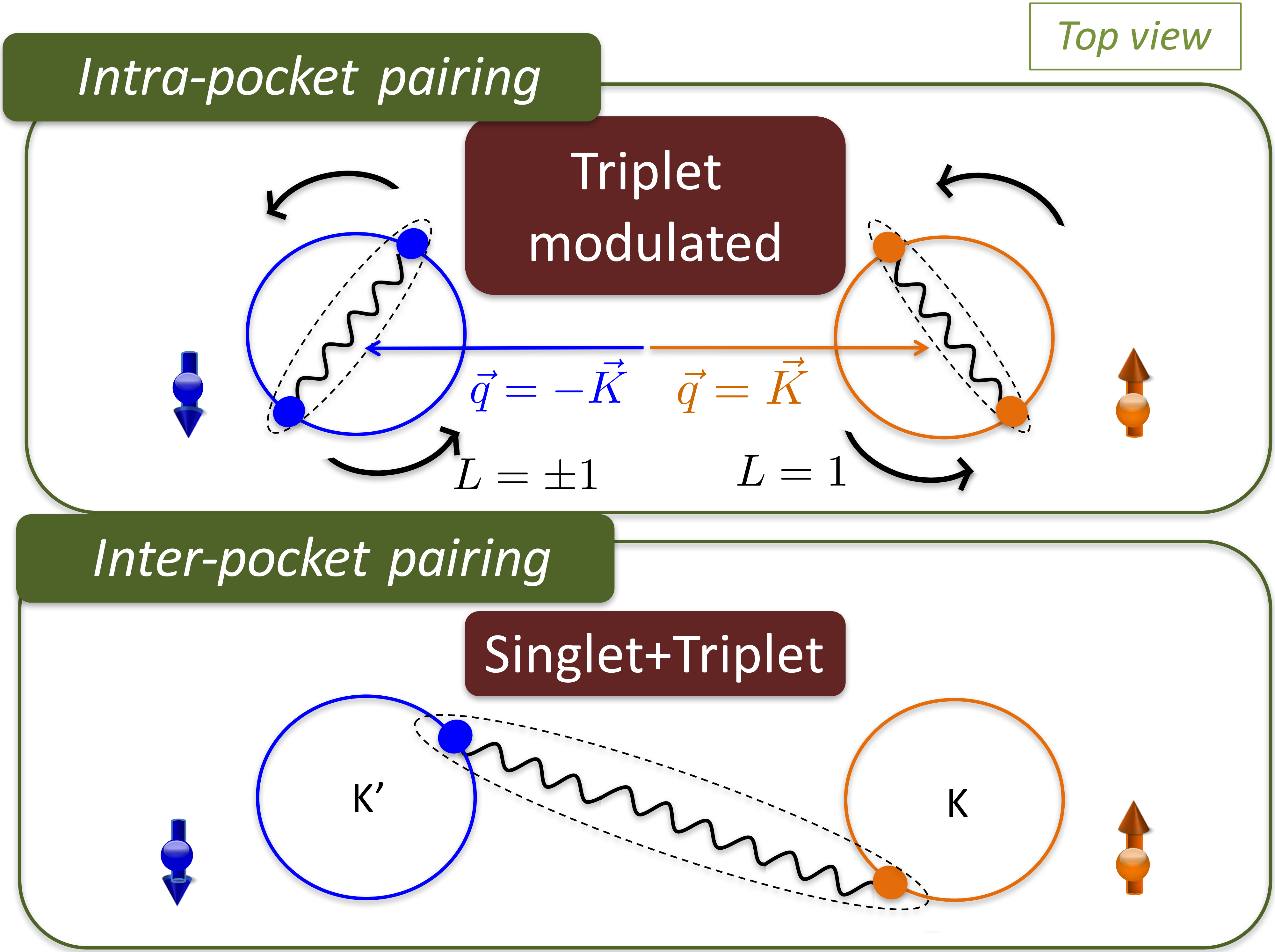
k-space spin-split Fermi surfaces

Topological SC?

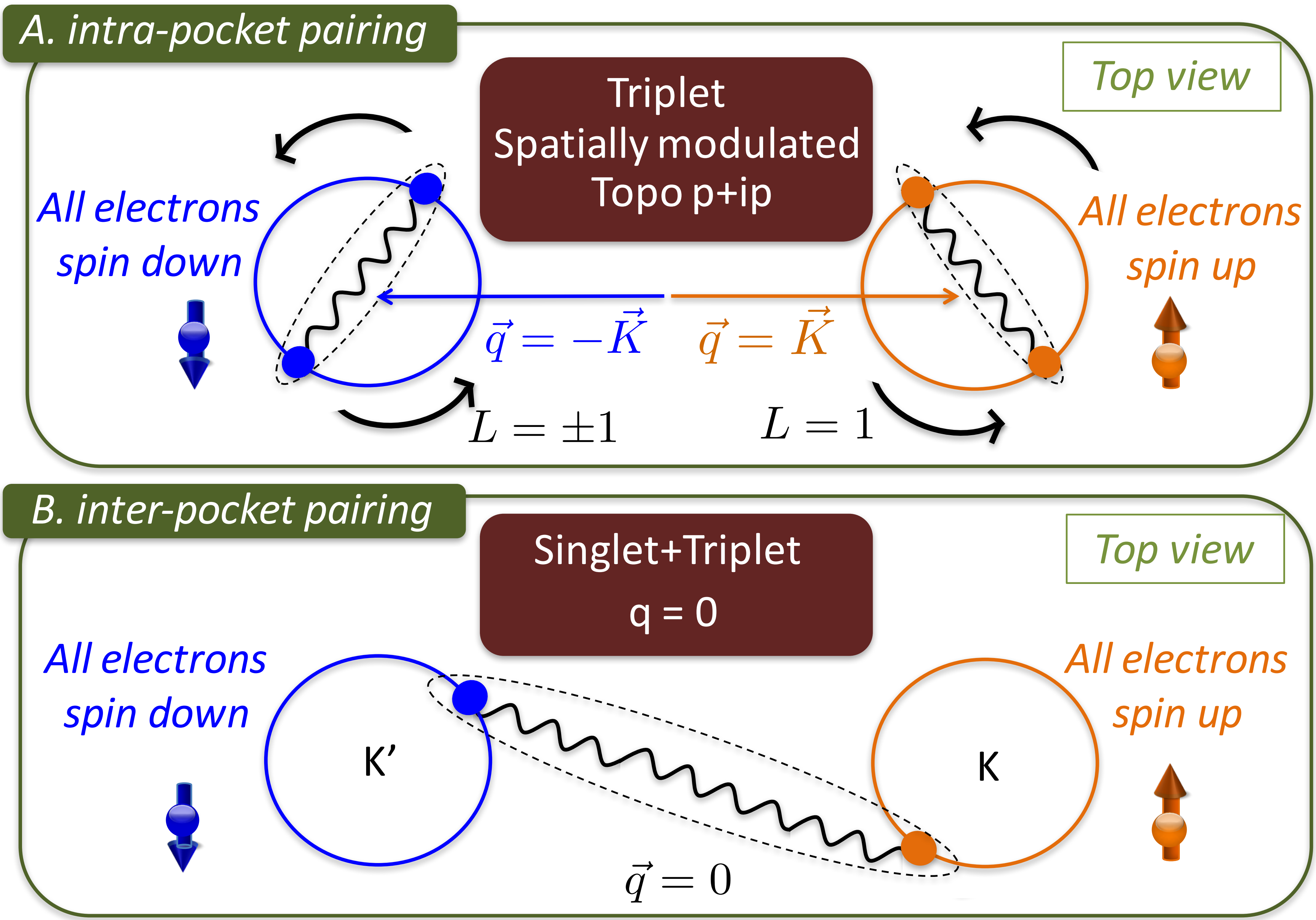


Yi-Ting Hsu

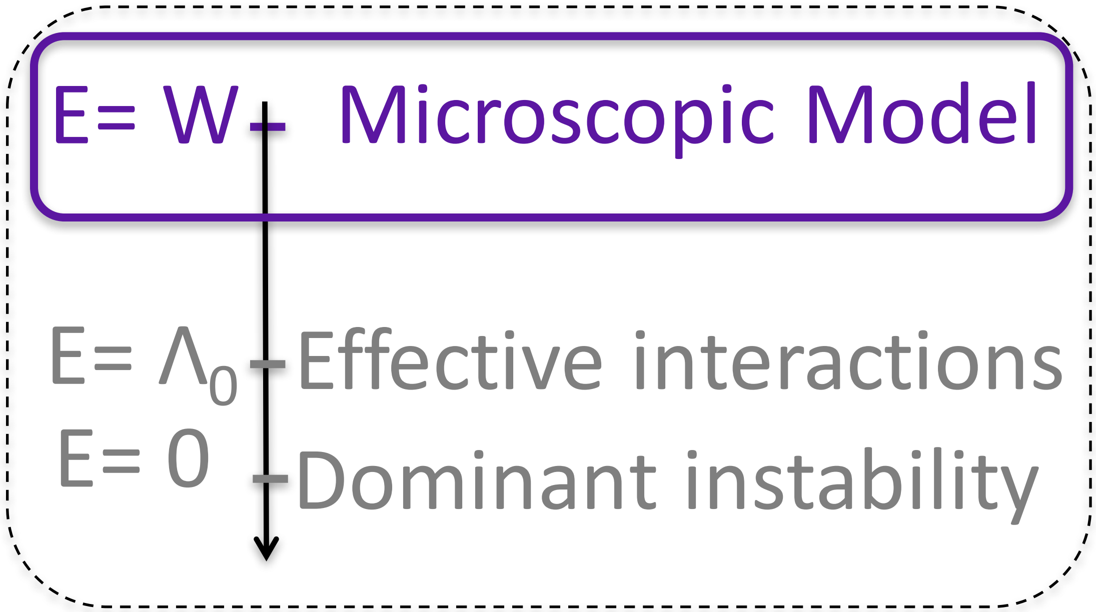
Abolhassan Vaezi


Top view
Intra-pocket pairing
Triplet modulated
$\vec{q} = -\vec{K}$
$\vec{q} = \vec{K}$
$L = \pm 1$
$L = 1$
Inter-pocket pairing
Singlet+Triplet
K'
K

Possible ground states



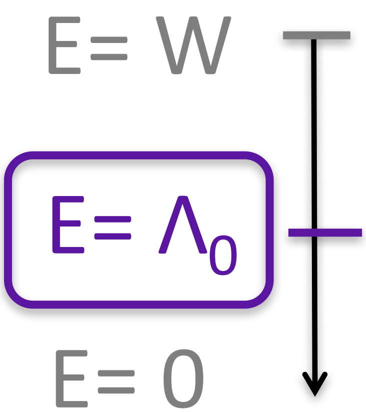
Perturbative Renormalization Group

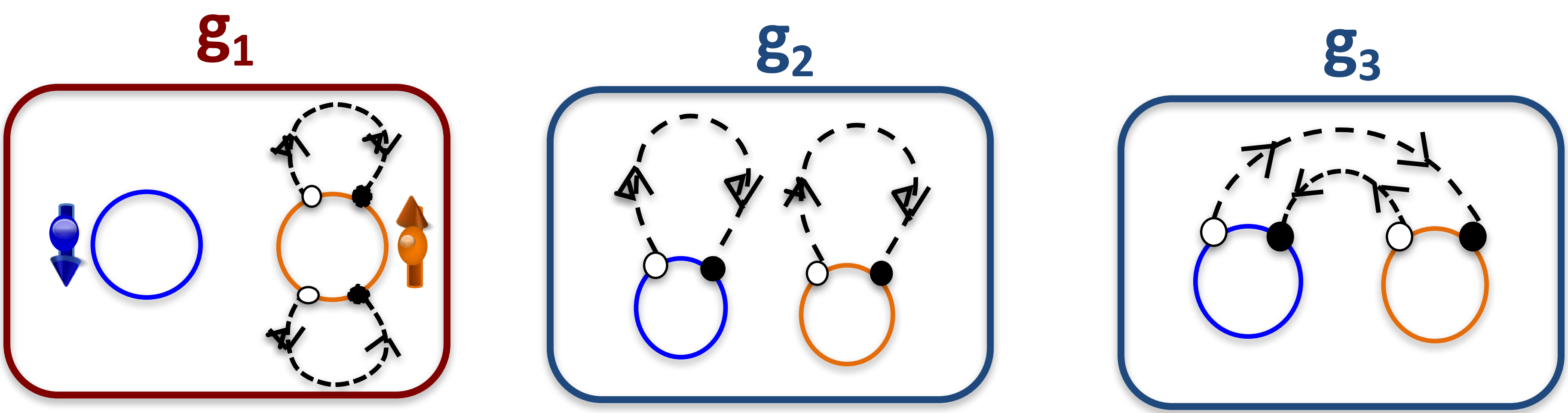


- Microscopic interaction @ the UV limit:

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

Effective interactions @ $E=\Lambda_0<W$

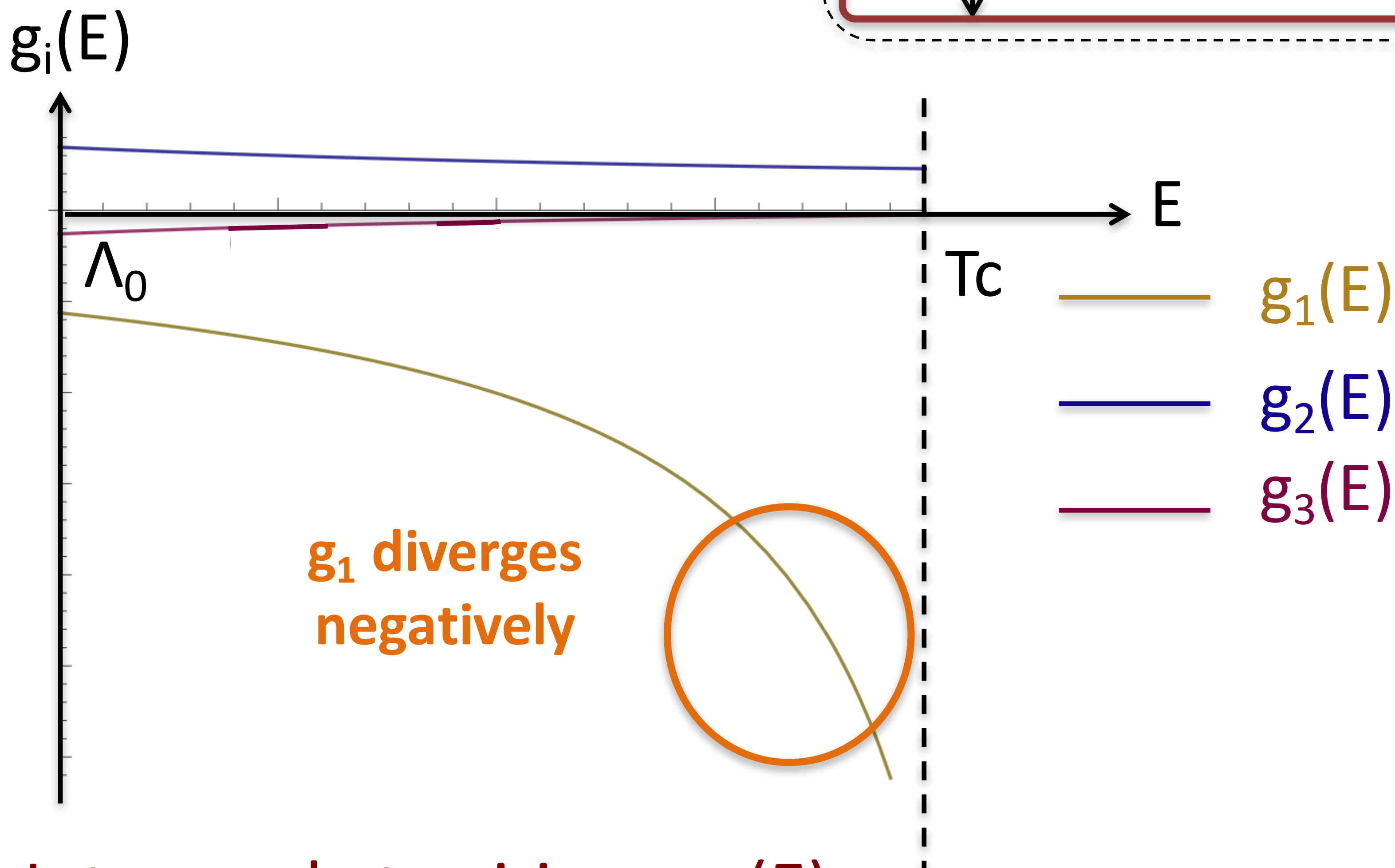




Pairing interaction for intra-pocket pair: $g_1(E)$

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

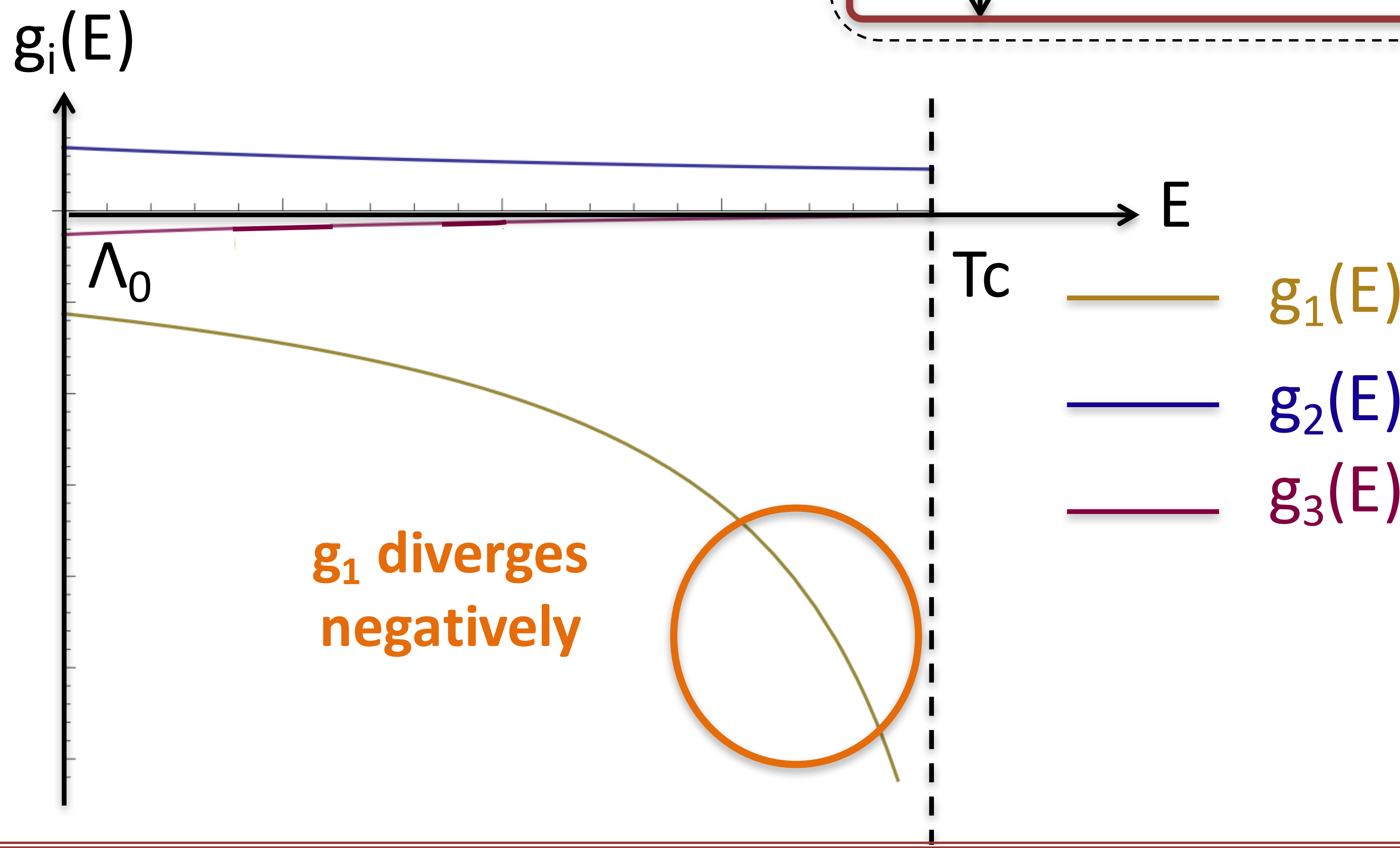
U > e-ph case RG flow



Intra-pocket pairing: $g_1(E)$

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

U > e-ph case RG flow

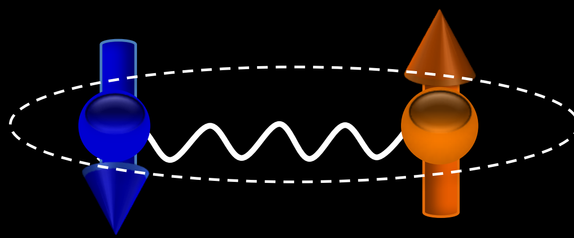


Intra-pocket pairing is dominant

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 > e-ph => 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

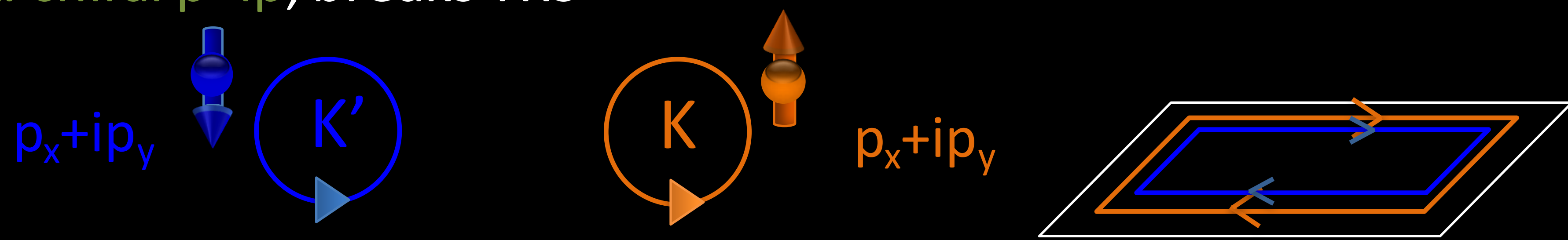
Transition metal dichalcogenides

	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

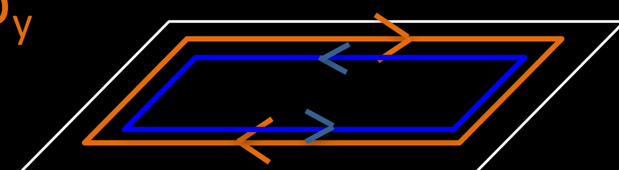
A. chiral p+ip, breaks TRS



Z-type topo sc:

integer spin degenerate edge modes

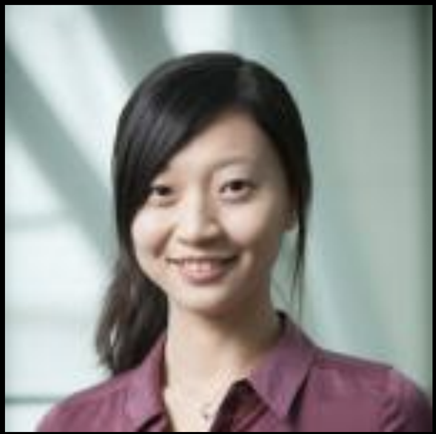
B. non-chiral p+ip, preserves TRS



=> Z_2-type topo sc protected by TRS:

counter-propagating edge modes with spin up and down

Acknowledgements

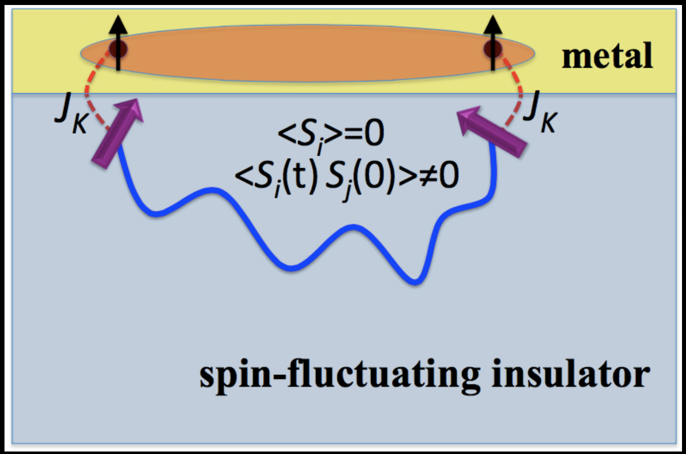


Yi-Ting Hsu

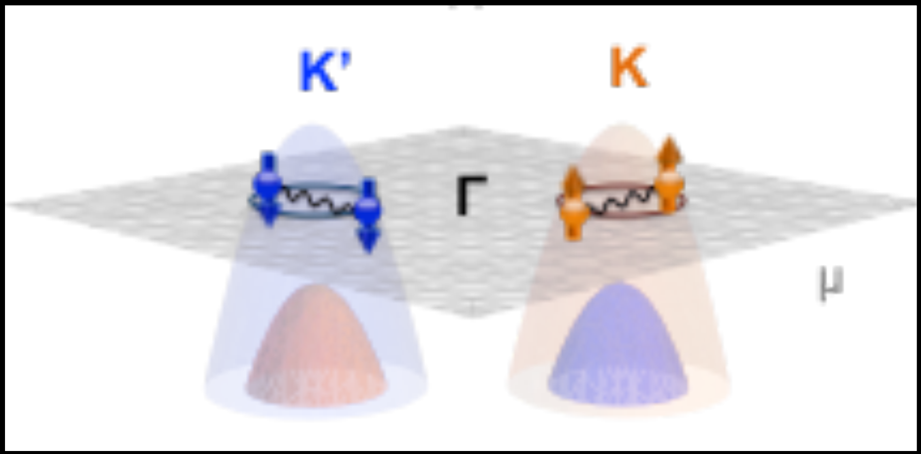
Abolhassan Vaezi

Designing 2D topological SC's

- Control interaction



- Spinless fermion through k-space splitting



Funding