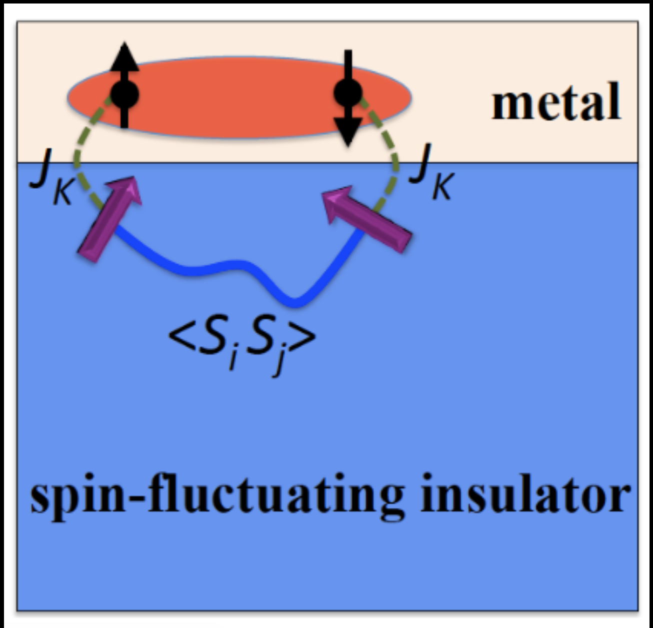
Topological Superconductivity in Metal/Quantum-Spin-Ice Heterostructures

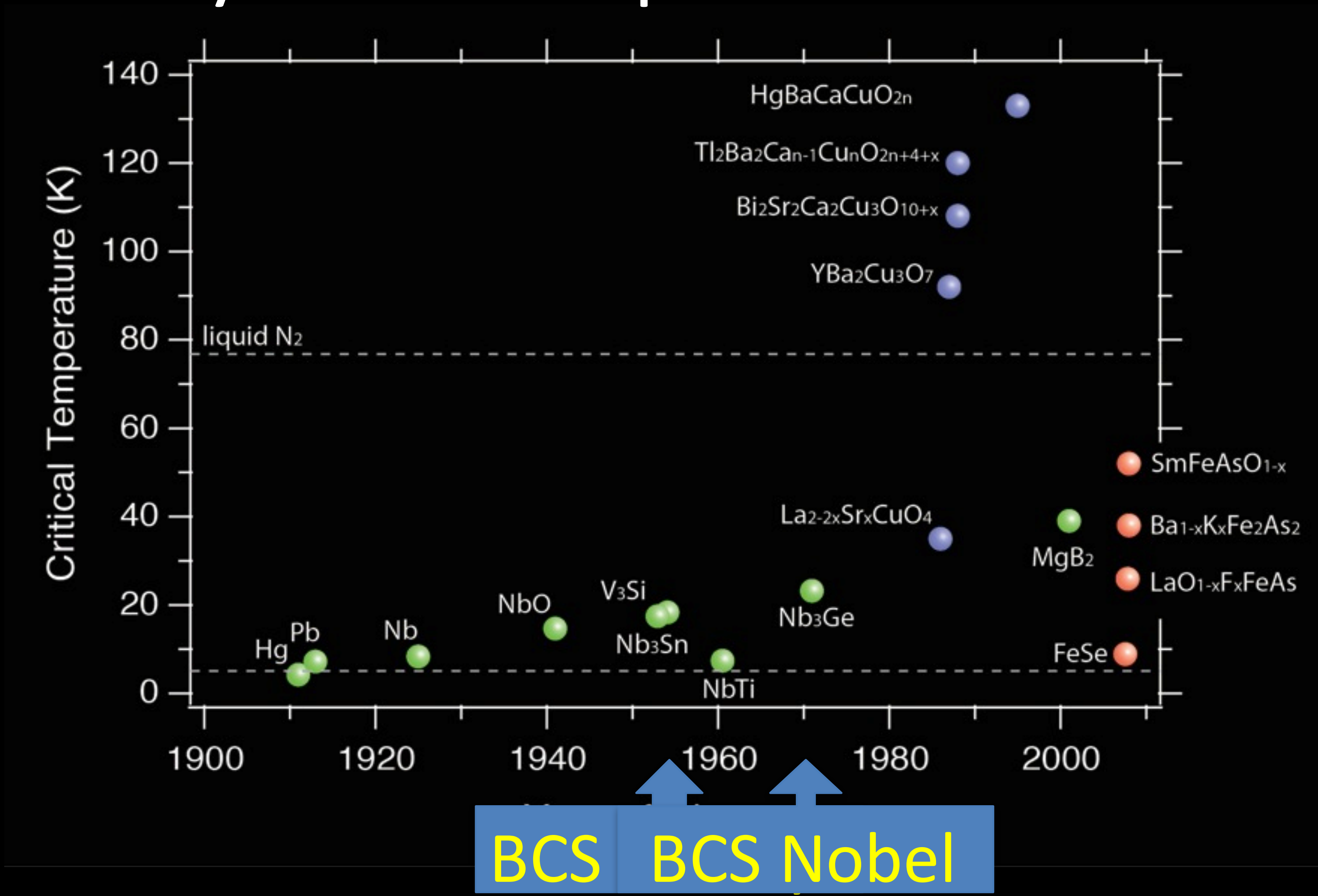


Eun-Ah Kim (Cornell)

UVA 11.05.2015

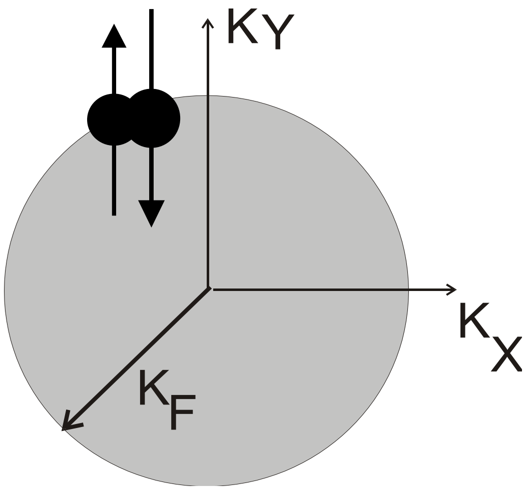
Q1. Can a theory guide discovery of a new superconductor?

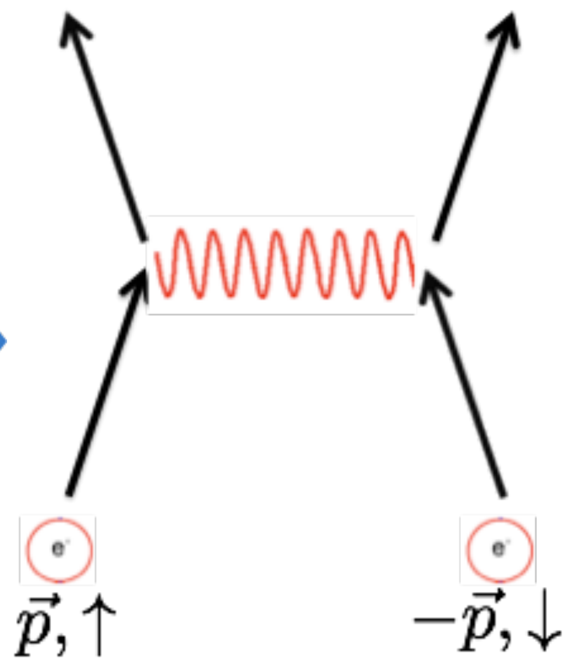
History of Serendipitous discoveries

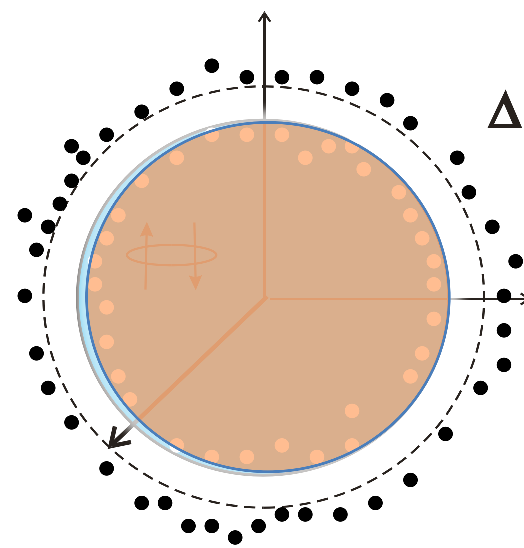


BCS theory

Normal State (Metal) | Weak coupling instability | Superconductor





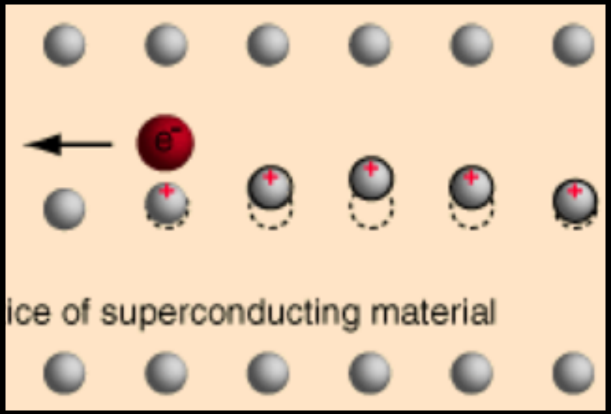


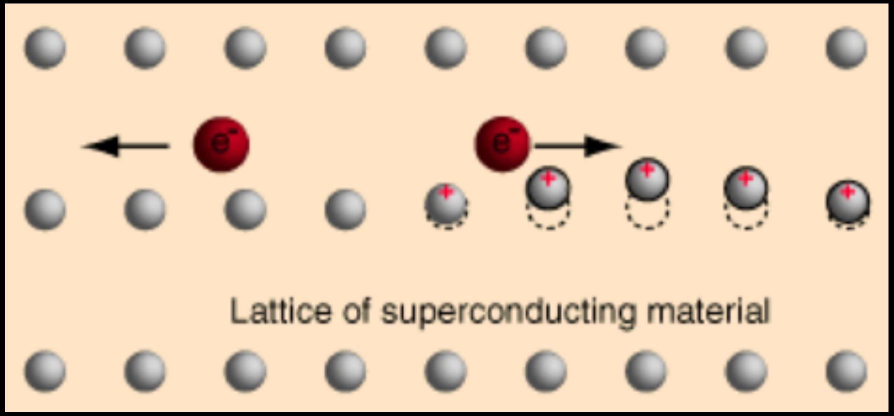
Degenerate
~free electron gas

Electrons interacting with
Lattice Vibration Mode

Gas of Cooper pairs

Magic ingredient of BCS theory





separation of scales:

$$\frac{\omega_D}{E_F} \ll 1$$

Migdal-Eliashberg theory

- Organize diagrams using $\frac{\omega_D}{E_F} \ll 1$
- Sum infinite number of leading diagrams.
- Result boils down to BCS mean-field theory

  when $\lambda \equiv V E_F < 1$

⇨ BCS mean-field theory is exact!!

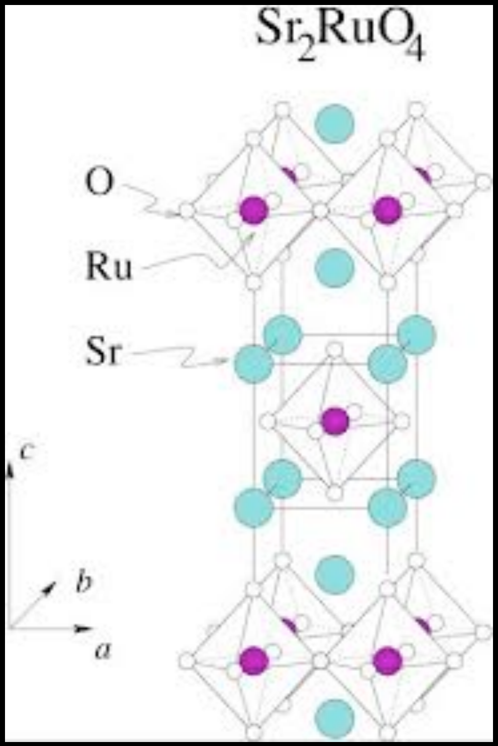
Electronic (non-phonon) Mechanisms

- Necessary for exotic (non-s-wave) SC.
- Give up separation of scales: $\frac{E_F}{E_F} = 1$

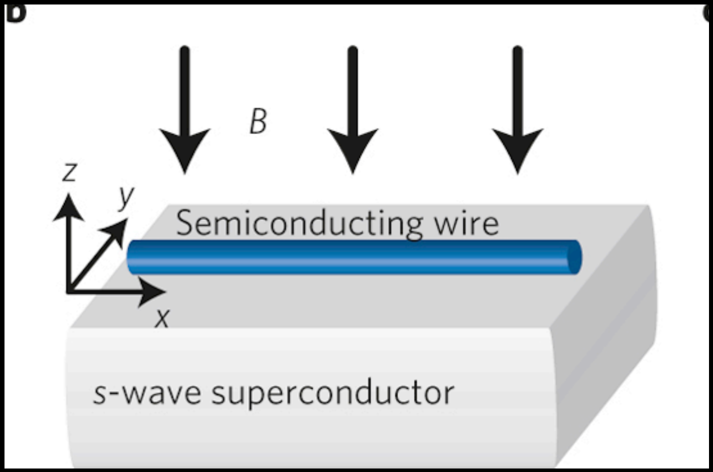
⇨ Untractable problem out of reach of BCS mean-field theory

Q. Topological Superconductor material?

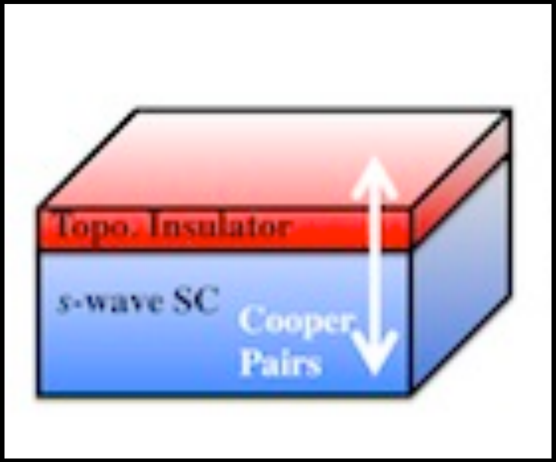
Bulk



1D proximity



2D proximity?

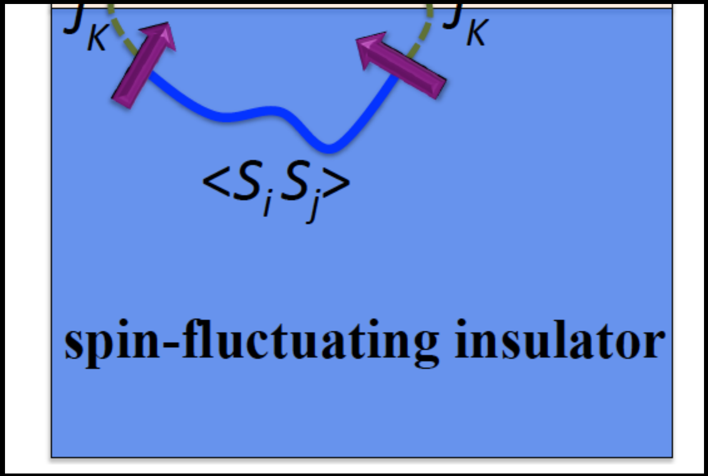


Anderson's proposal

: dope a quantum spin liquid (QSL)

QSL

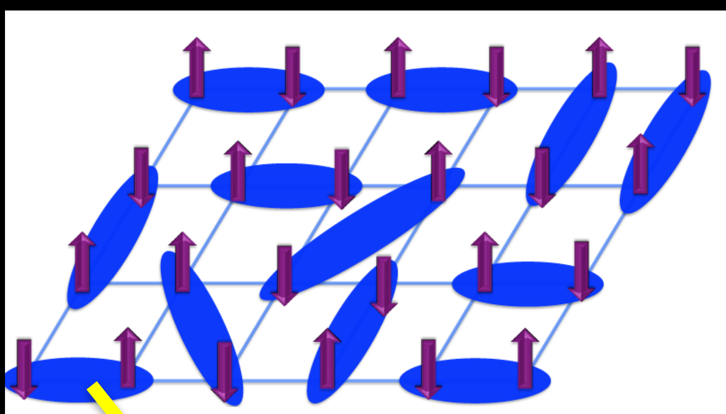
- Definition:
  - No magnetic order at T=0 $\langle \vec{s}_{\vec{q}} \rangle = 0$
  - Dynamic fluctuation $\langle \vec{s}_{-\vec{q}}(t) \vec{s}_{\vec{q}}(0) \rangle \neq 0$
  - Spin's are entangled.



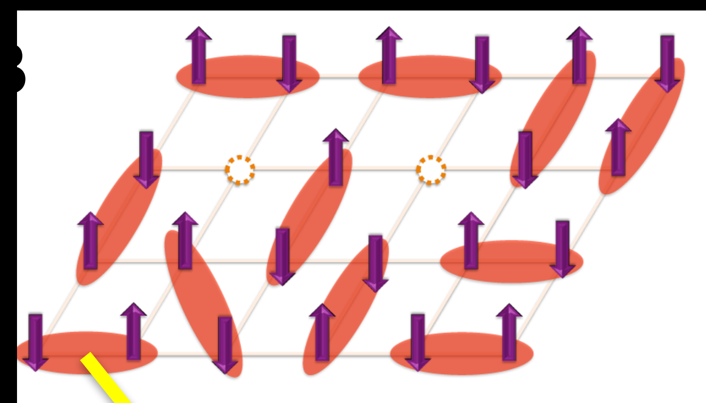
Anderson's conjecture

QSL = Resonating Valence Bond state

Exotic SC



Doping



RVB singlet

Cooper pair =mobile RVB singlet

P.W. Anderson, Science 1987

Challenges against Anderson's conjecture

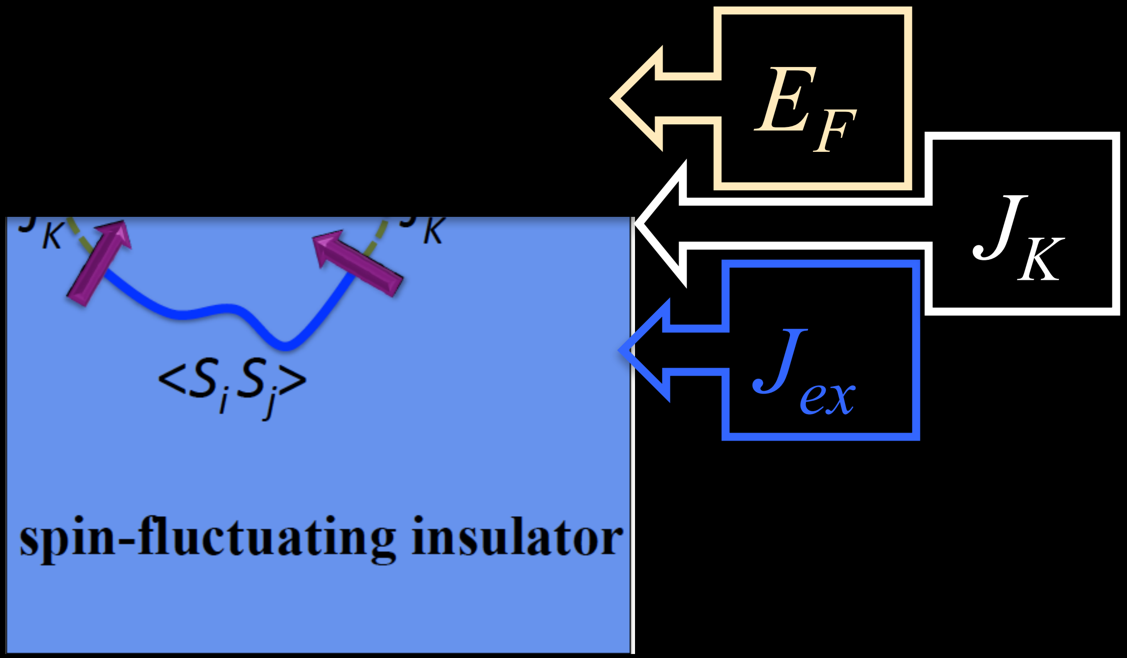
- Experimental:
  - Hard to dope QSL
- Theoretical:
  - No controlled theory
  - Predictions are based on faith and hope...

Q2. Can we exploit the spin entangement in QSL for SC?

A new approach

Keep the QSL and borrow the spin entanglement:

Heterostructure!



Challenges against Anderson's conjecture

- Experimental:
  - Hard to dope QSL
- Theoretical:
  - No controlled theory
  - Predictions are based on faith and hope...

Advantages of the Heterostructure route

- Experimental:
  - Accessible to current MBE technology
  - Hard to dope QSL
- Theoretical:
  - Separation of scales: $J_{ex}/E_F < 1$
  - A reliable prediction.
  - No controlled theory
  - Predictions are based on faith and hope...

Strategy

Effective Field theory

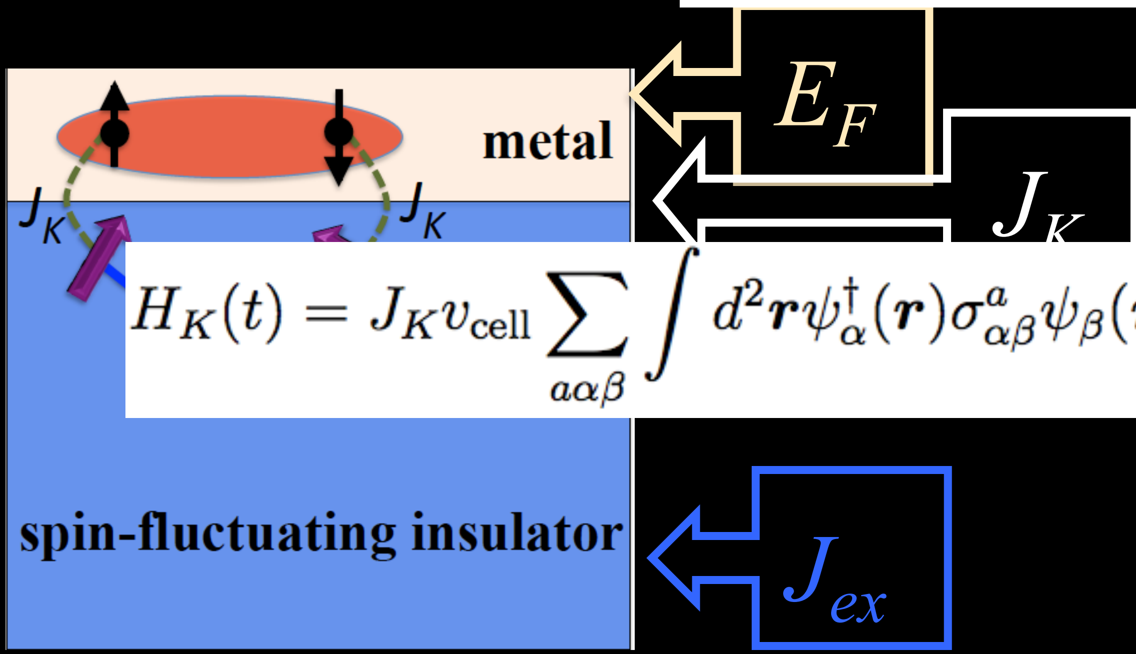
A microscopic theory for a concrete proposal

Persuade experimentalists

Effective Field Theory

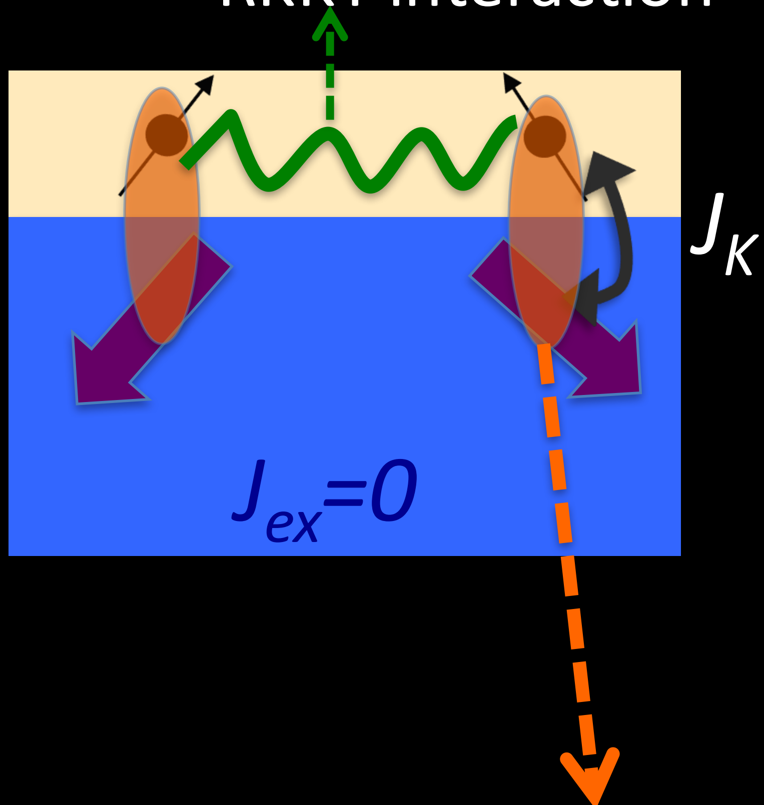
The starting point: Kondo-Heisenberg

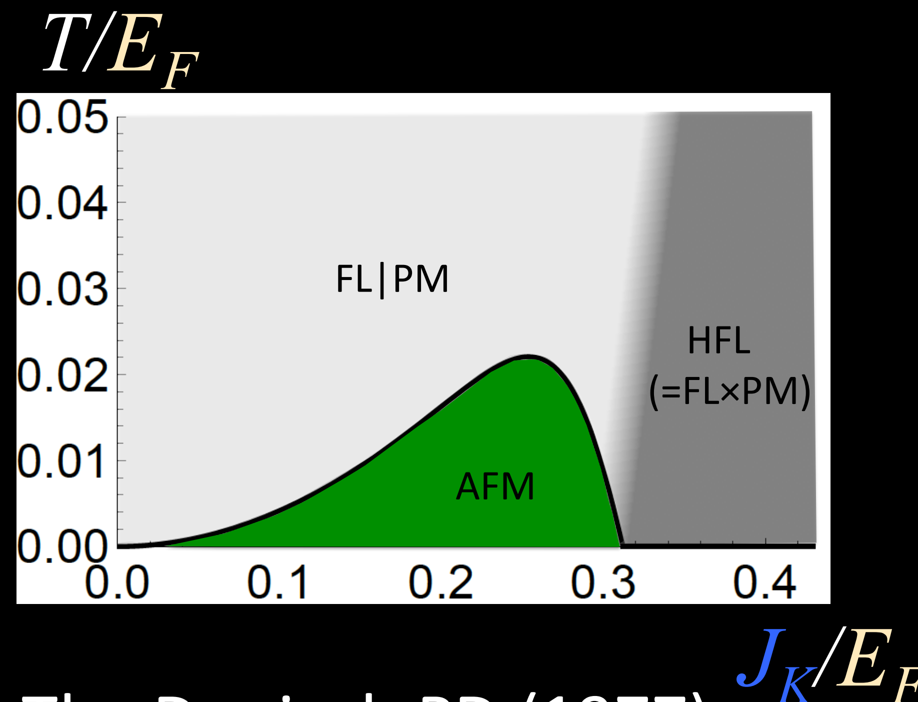
$$H_c = \sum_{\boldsymbol{k}\alpha} \left(\frac{\hbar^2 k^2}{2m} - E_F \right) \psi^\dagger_\alpha(\boldsymbol{k}) \psi_\alpha(\boldsymbol{k})$$



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

The starting point: Kondo

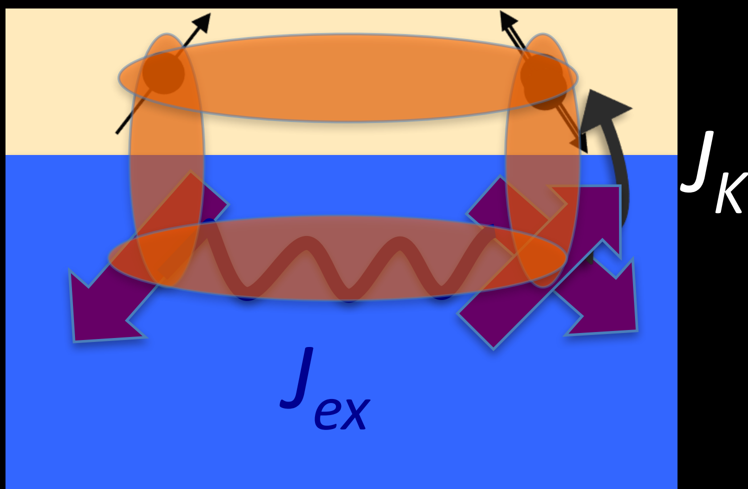


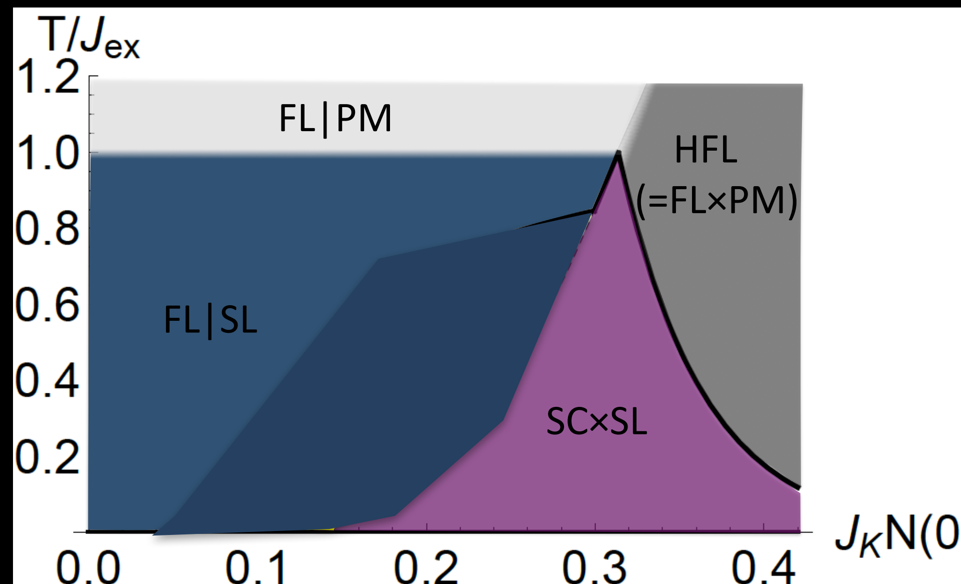


The Doniach PD (1977)

Kondo-singlet: Heavy Fermi Liquid
= Fermi liquid x Paramagnet

The starting point: Kondo-Heisenberg

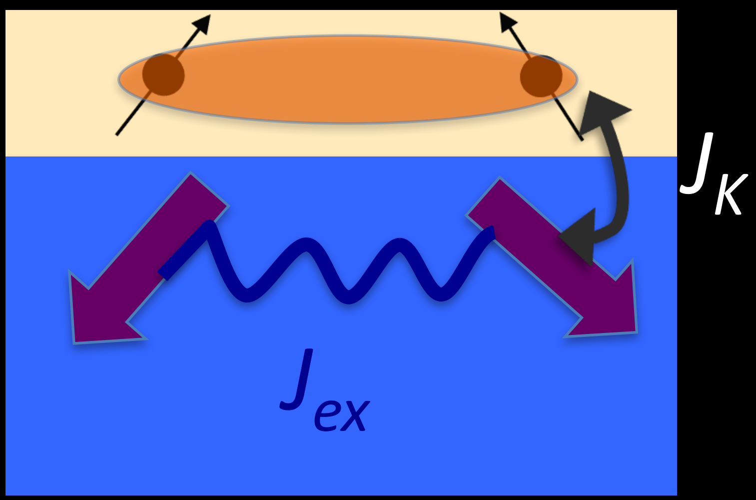


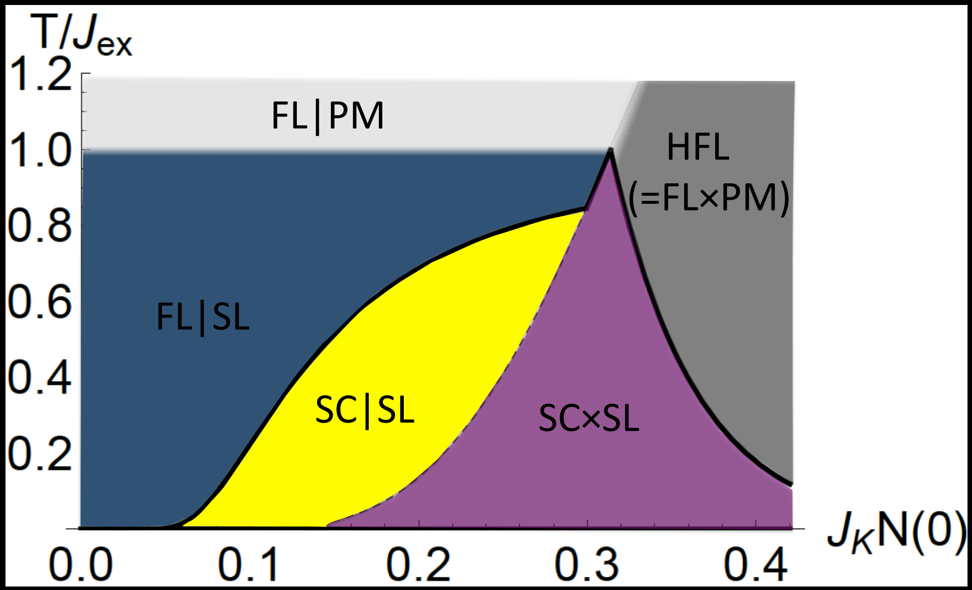


The PD at small J_{ex} large J_K

Coleman & Andrei (1989), Senthil, Sachdev, Vojta (2003)

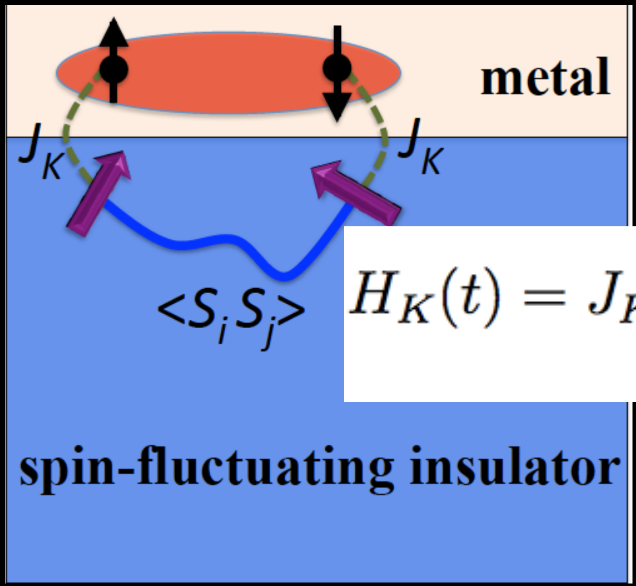
Heterostructure: Focus on small J_K/E_F





J.-H. She, C. Kim, C. Fennie, M. Lawler, EAK (2015)

Effective Theory for J_K/E_F<<1



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

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

- Integrate out spins >> Effective e-e interaction

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

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

spin entanglement imprints onto the effective e-e interaction

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

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

- "Designed" by the choice of QSL and its

$$\mathcal{S}_{ab}(\mathbf{q},\omega) \equiv \int dt \langle S_a(-\mathbf{q},t) S_b(\mathbf{q},0) \rangle e^{-i\omega t}$$

- Experimental knowledge of $\mathcal{S}_{ab}(\mathbf{q},\omega)$ is sufficient

Our first pass choice of QSL:
quantum spin ice

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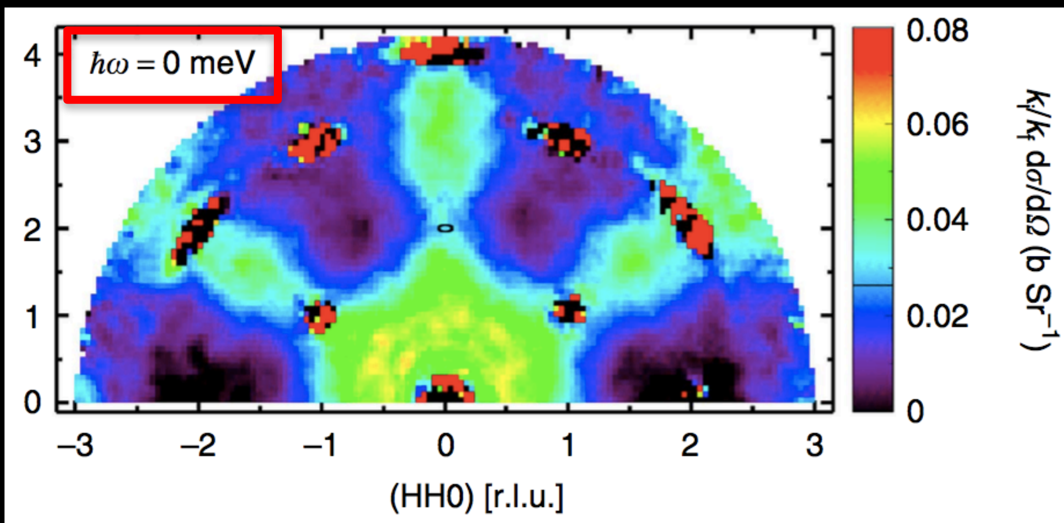
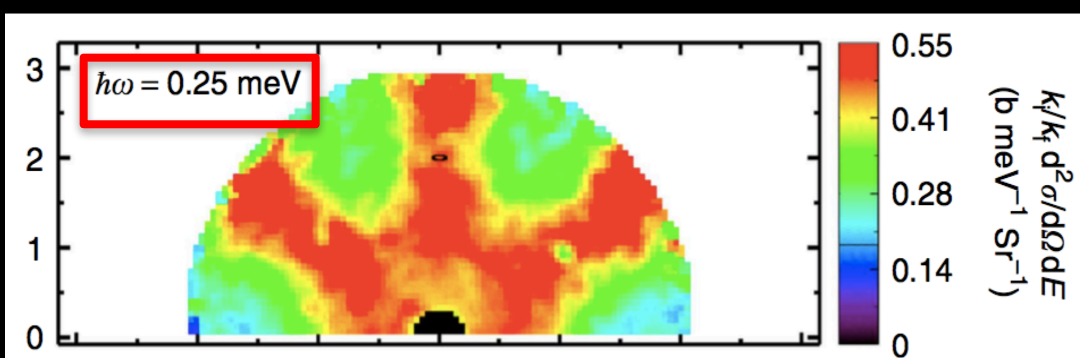
DOI: 10.1038/ncomms2914

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

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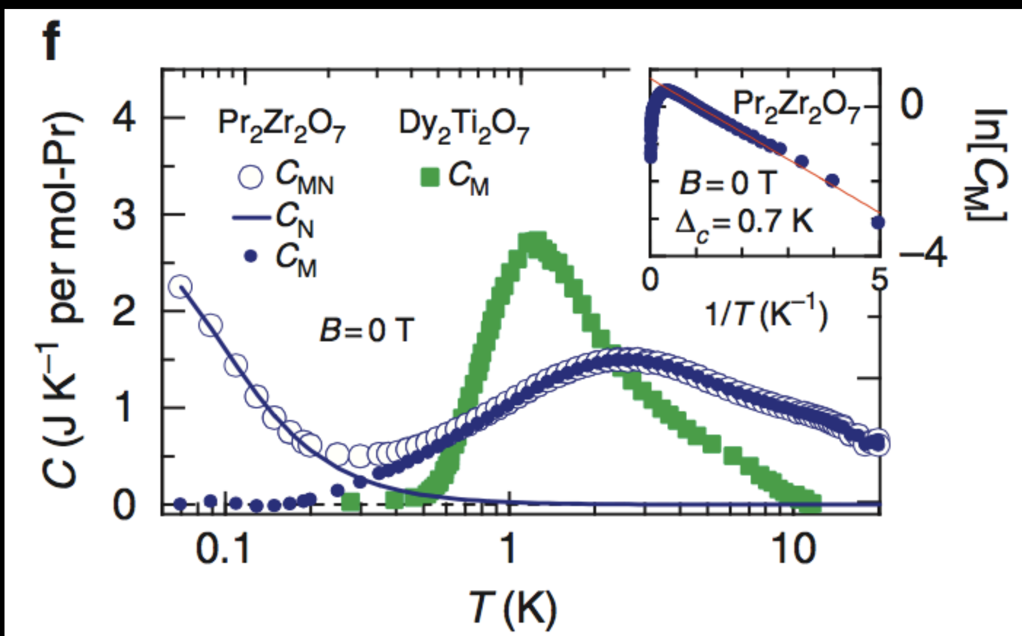

- No order down to 20mK
- Dynamic fluct. upto ~3K
- Gapped QSL!

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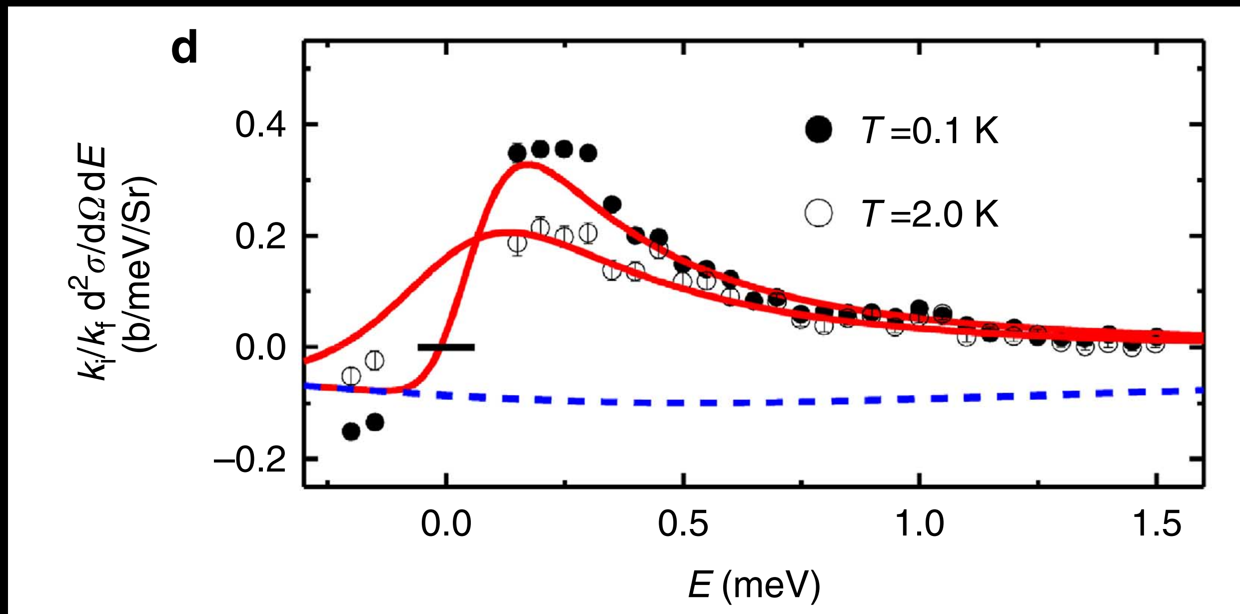
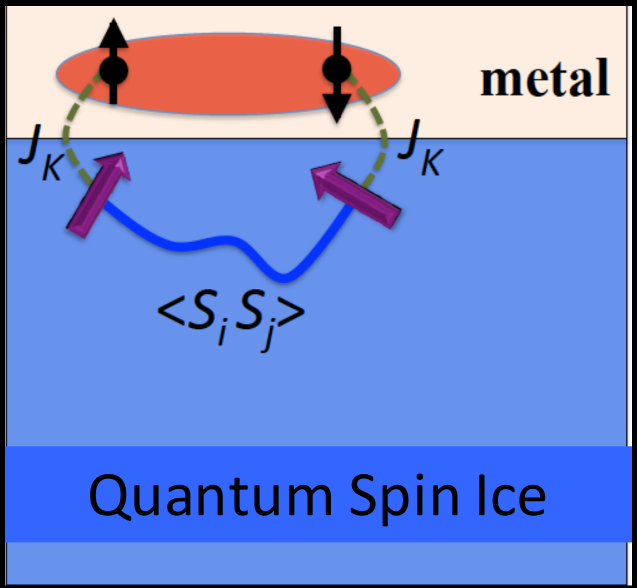


Relaxational Dynamics with $\tau^{-1}=2J_{ex}=0.17\mathrm{meV}$

Hierarchy of scales



- $J_K/E_F << 1$: perturbation theory on J_K
- $J_{ex}/E_F << 1$: "Migdal's thm", theoretically accessible
- $\lambda = J_K^2 / J_{ex} E_F < 1$: mean-field theory is "exact"

Mean-field theory
on the effective model

Dominant Pairing Channel

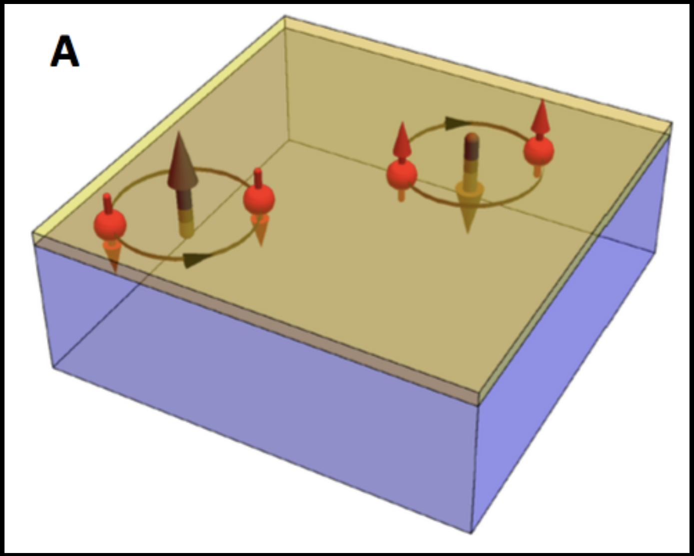
- Key properties of the static spin structure factor

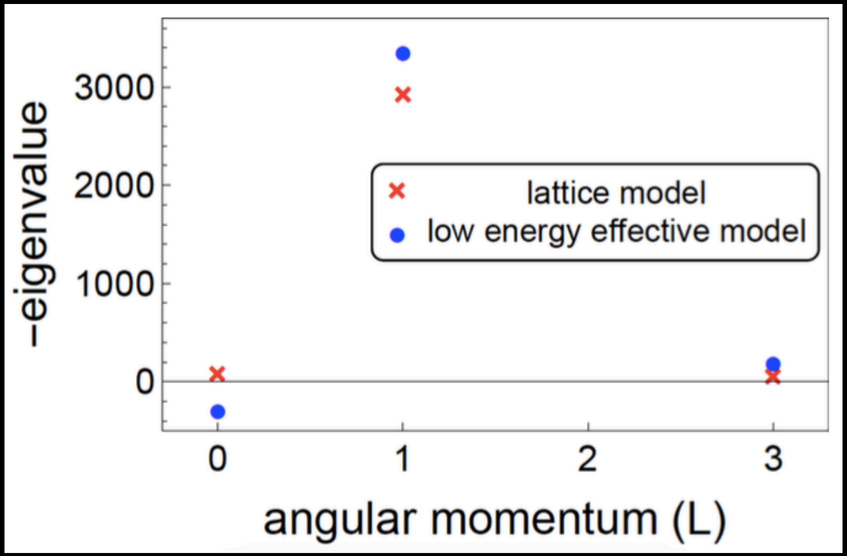
$$S_{ab}(\boldsymbol{q}) = \delta_{ab} - \left(1 - \frac{1}{1+q^2\xi^2}\right)\frac{q_a q_b}{q^2}$$

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

Dominant Pairing Channel





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

T_c

In analogy to phonon mediated BCS theory,

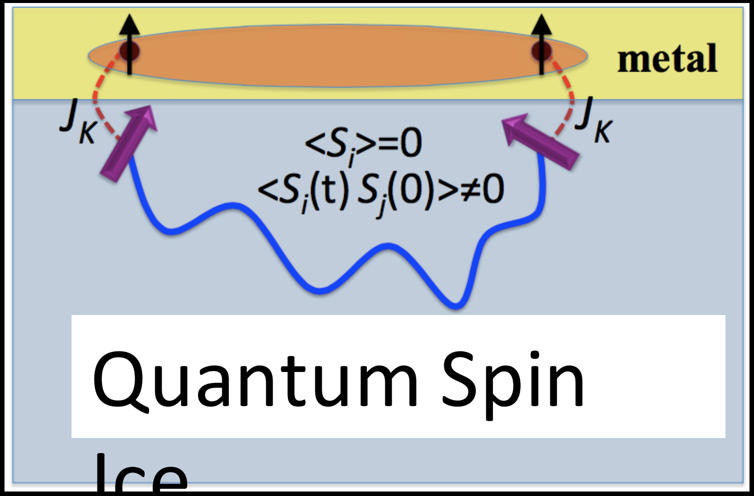
$$T_c \approx \tau^{-1} e^{-1/\lambda}$$

- $\tau^{-1} = 2J_{ex} = 0.17\text{meV}$
- $\lambda = V_{eff}/E_F = J_K{}^2/J_{ex}E_F$

Not bad for a topological superconductor

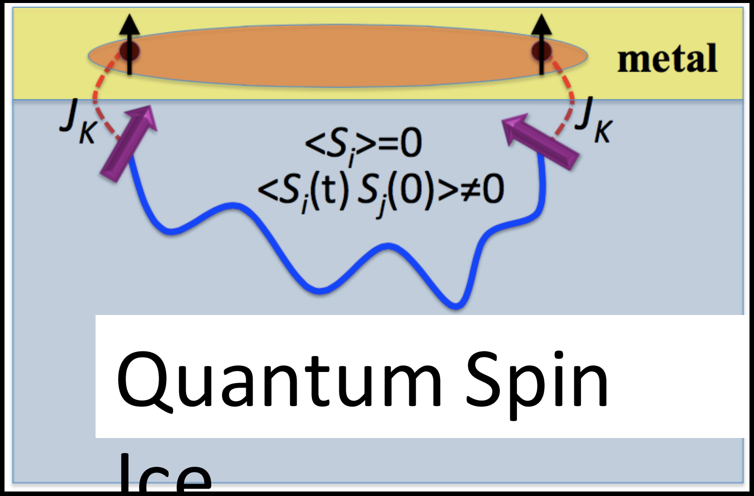
Microscopic Proposal

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

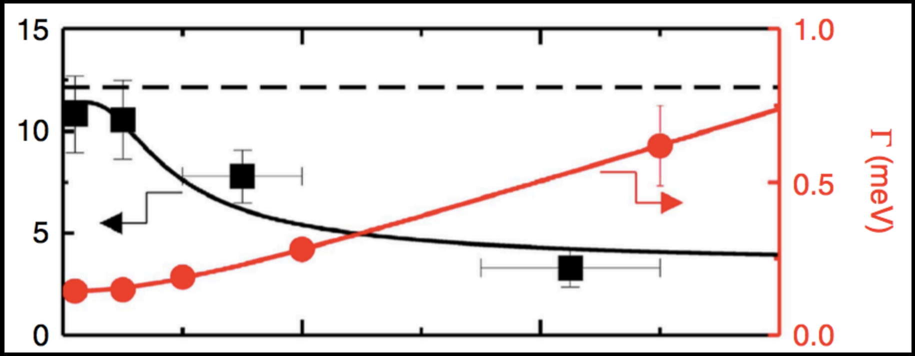


1. Simple metal without ordering possibilities.
2. Wave function penetration for coupling.
3. Odd # of Fermi surface around high symmetry points for a Topo SC.

Transition Temperature

- Spin dynamics

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

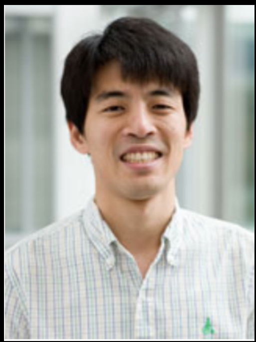


$\tau^{-1} \sim 2J_{ex} \sim 0.17\text{meV}$

- Parameters for our proposal

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

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

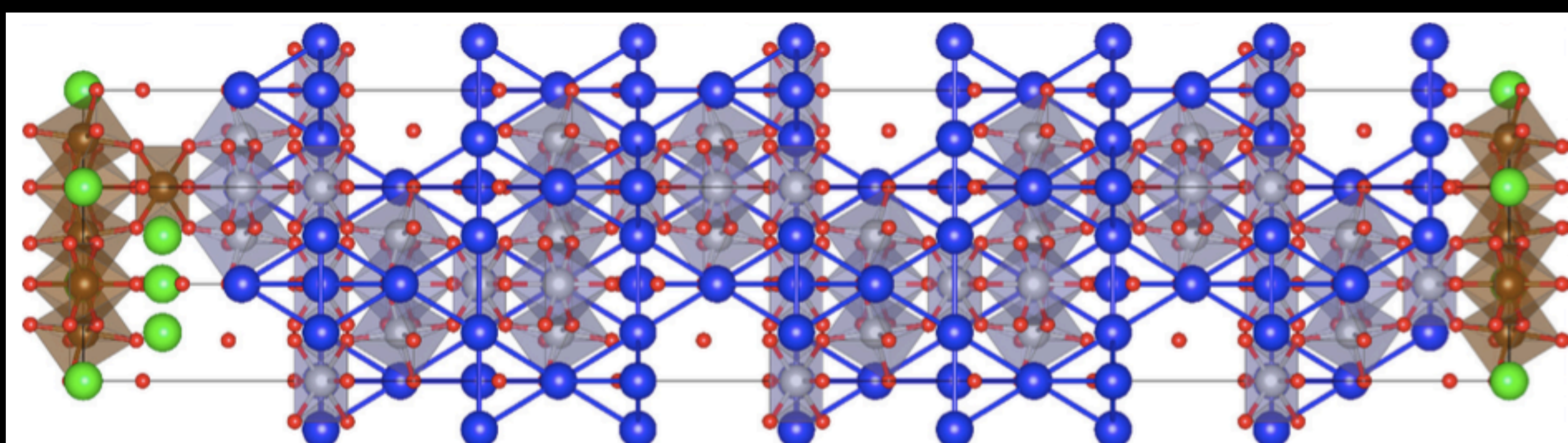


Microscopic Proposal

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

Non-magnetic

s-electrons:
large overlap,
isotropic FS.

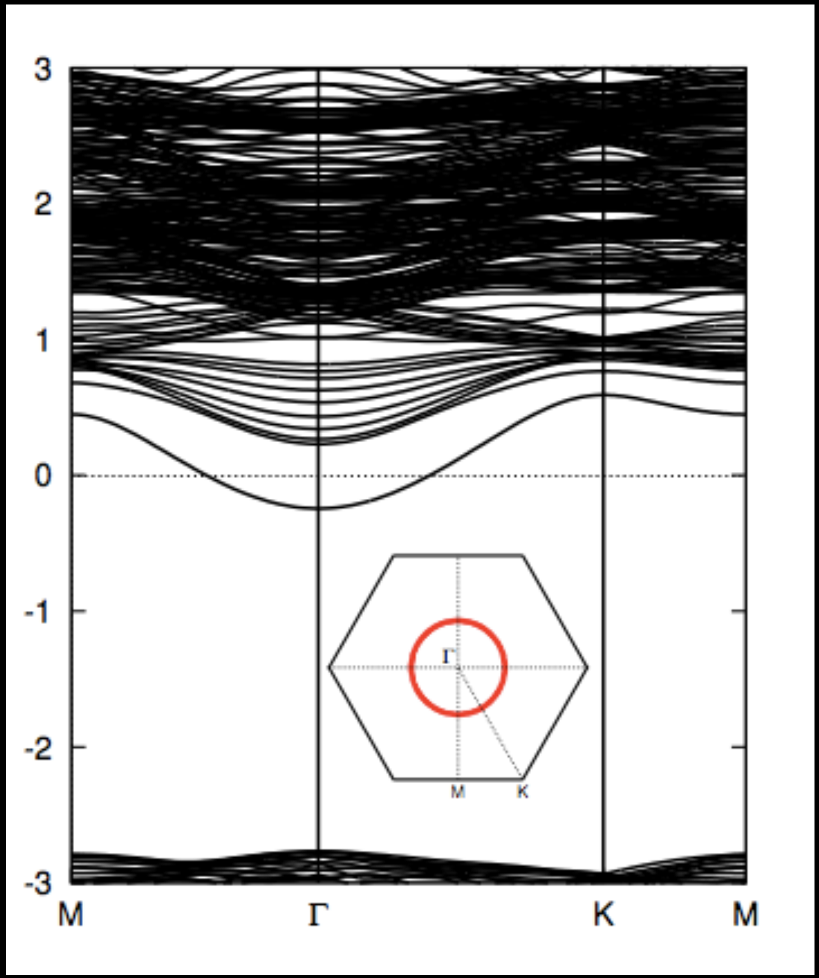


Band structure for the Proposal

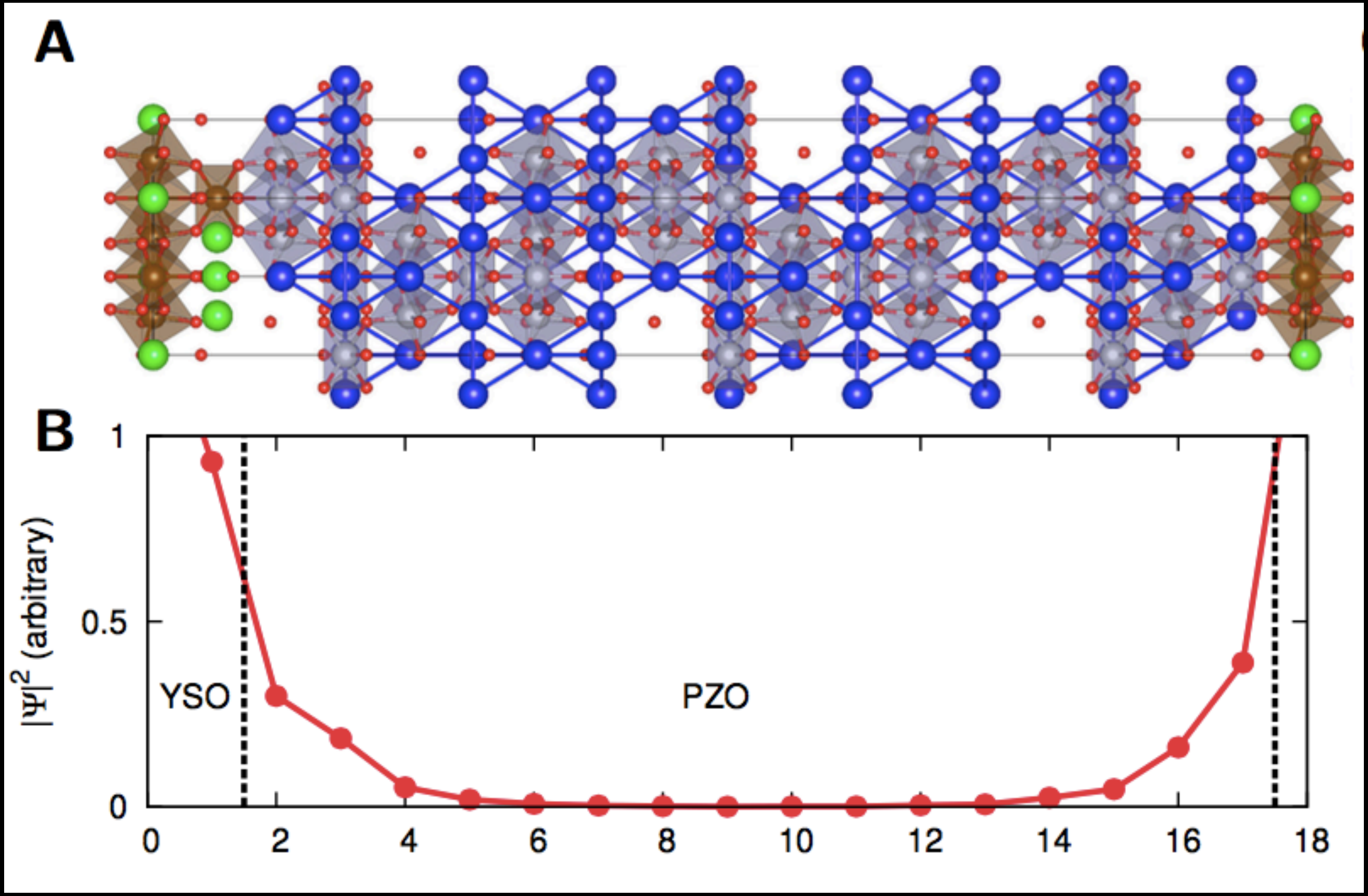
$Pr_2Zr_2O_7/Y_2Sn_{2-x}Sb_xO_7$ (111)

x=0.2

- Isotropic single pocket centered at Γ-point

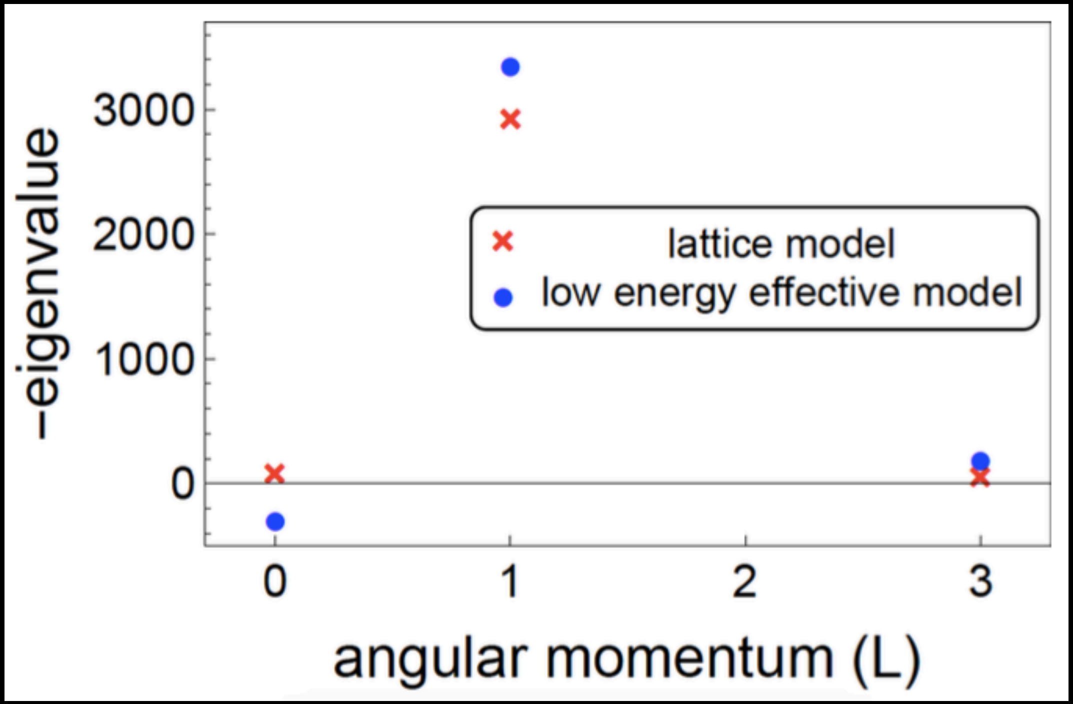


Wave function penetration



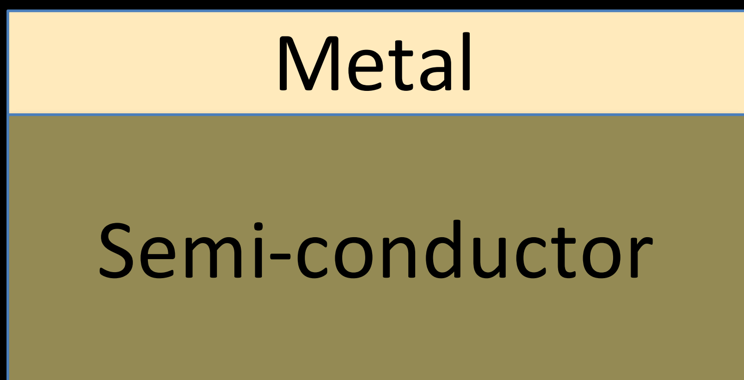
Full Lattice Model for the proposal

- 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.

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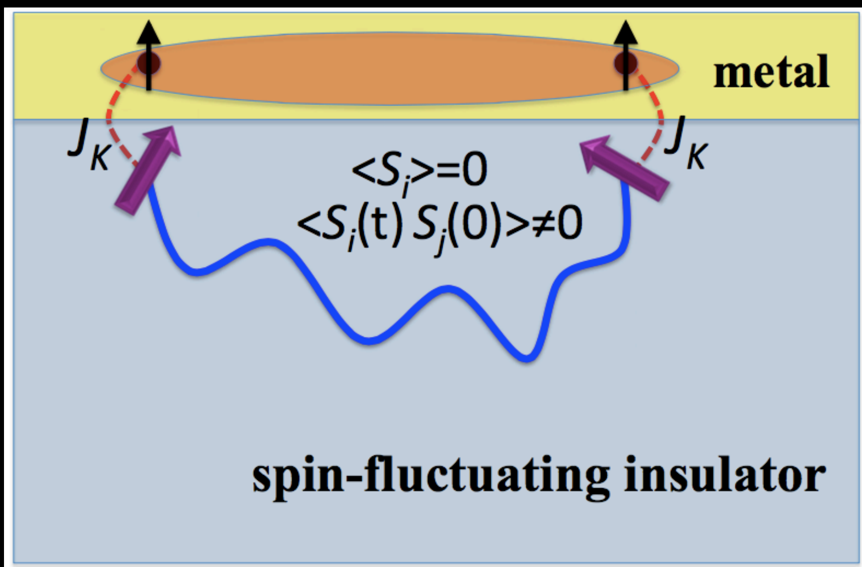
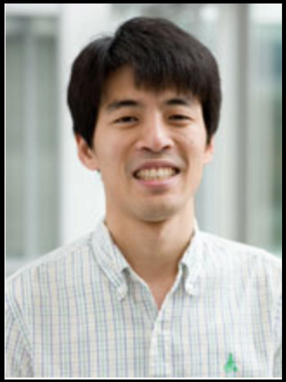


- A new strategy for exploiting spin entanglement of QSL.
- Non-trivial, but tame.
- First T-inv Topo SC.
- Huge phase space.

Acknowledgements

Jian-huang She



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Criag Fennie

Michael Lawler

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