Frustrated metal $Pr_2Ir_2O_7$:
when Luttinger semimetal meets with ordered spin ice

Gang Chen
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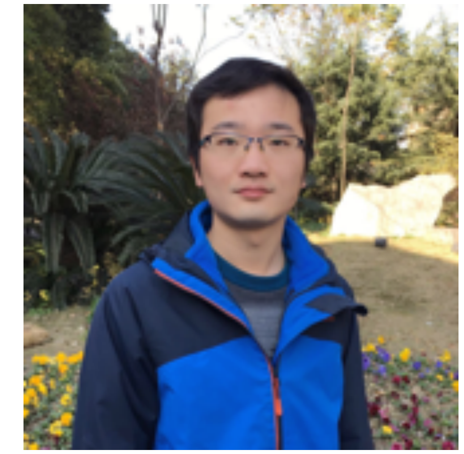
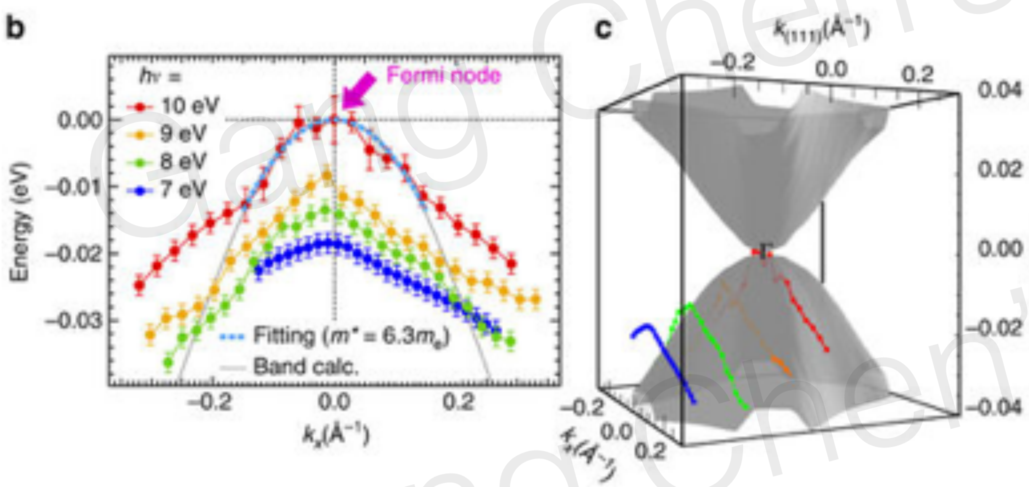


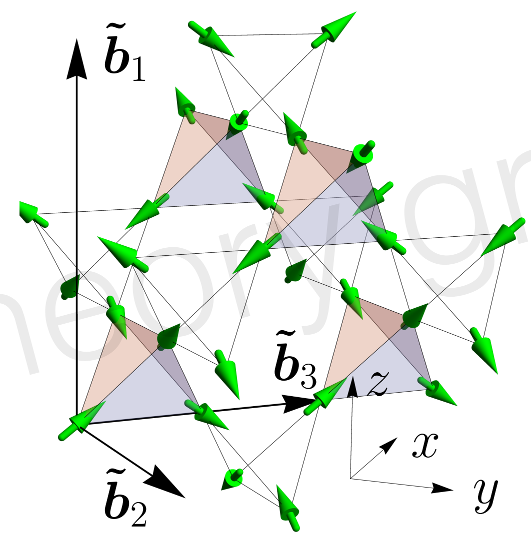
Xu-Ping Yao

When Luttinger semimetal meets Melko-Hertog-Gingras spin ice state in Pr2Ir2O7



Ir Luttinger semimetal

+

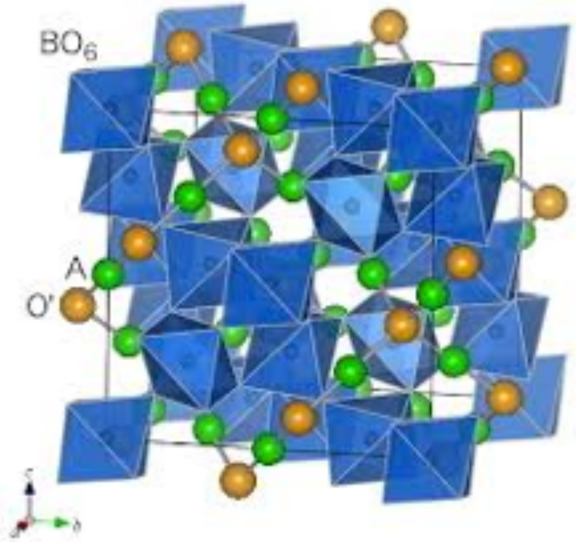


MHG spin ice state

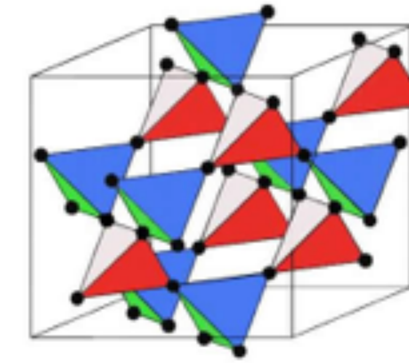
= ????

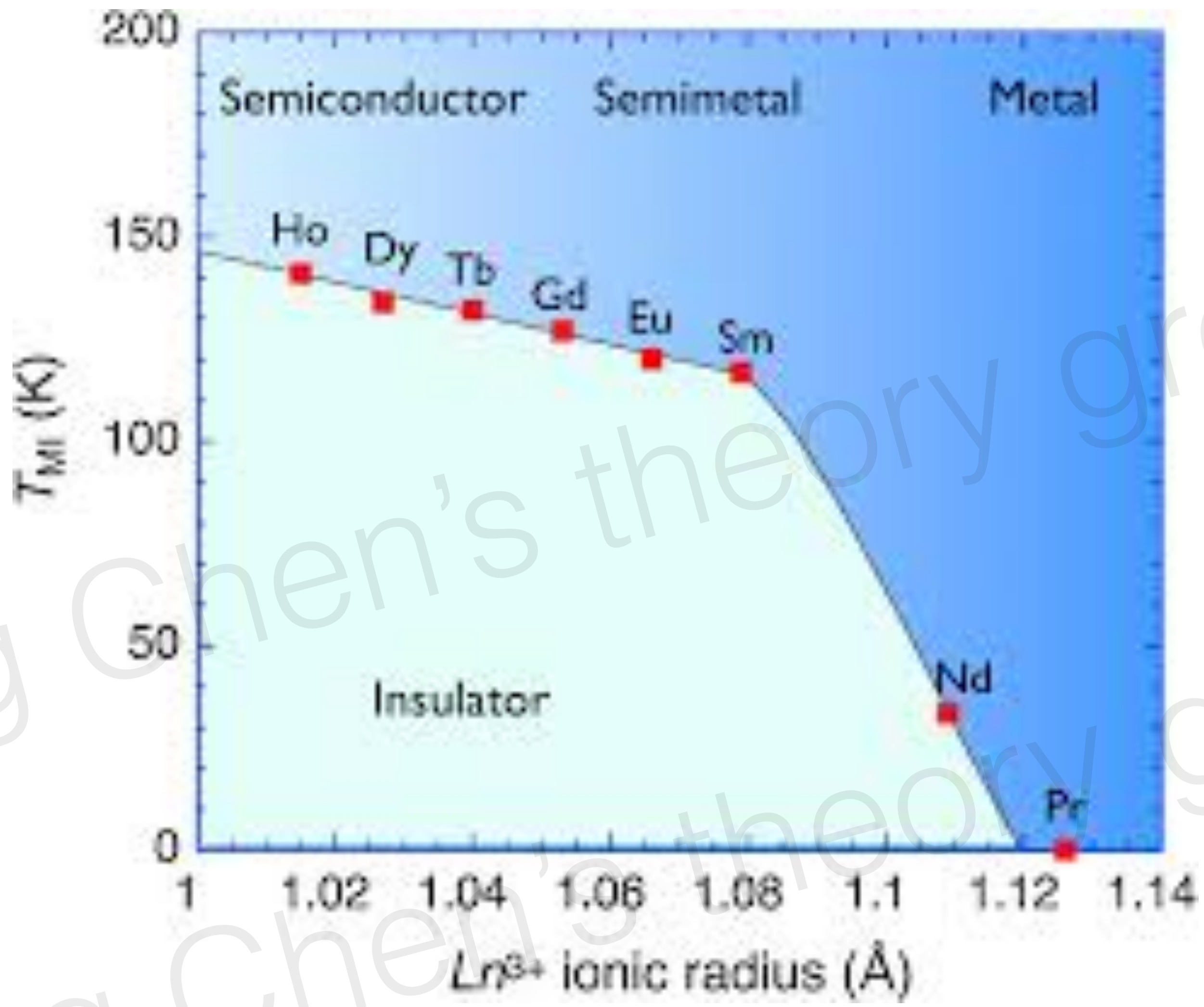
Xu-Ping Yao, GC, 1712.06534

Pyrochlore iridates



$R_2Ir_2O_7$

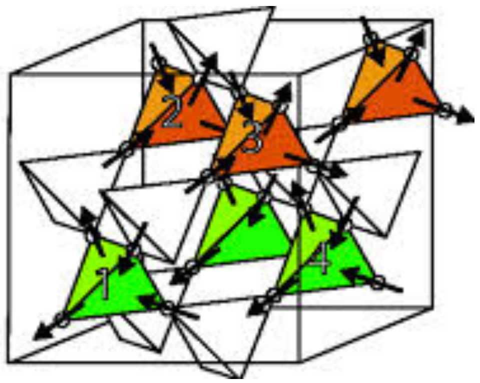




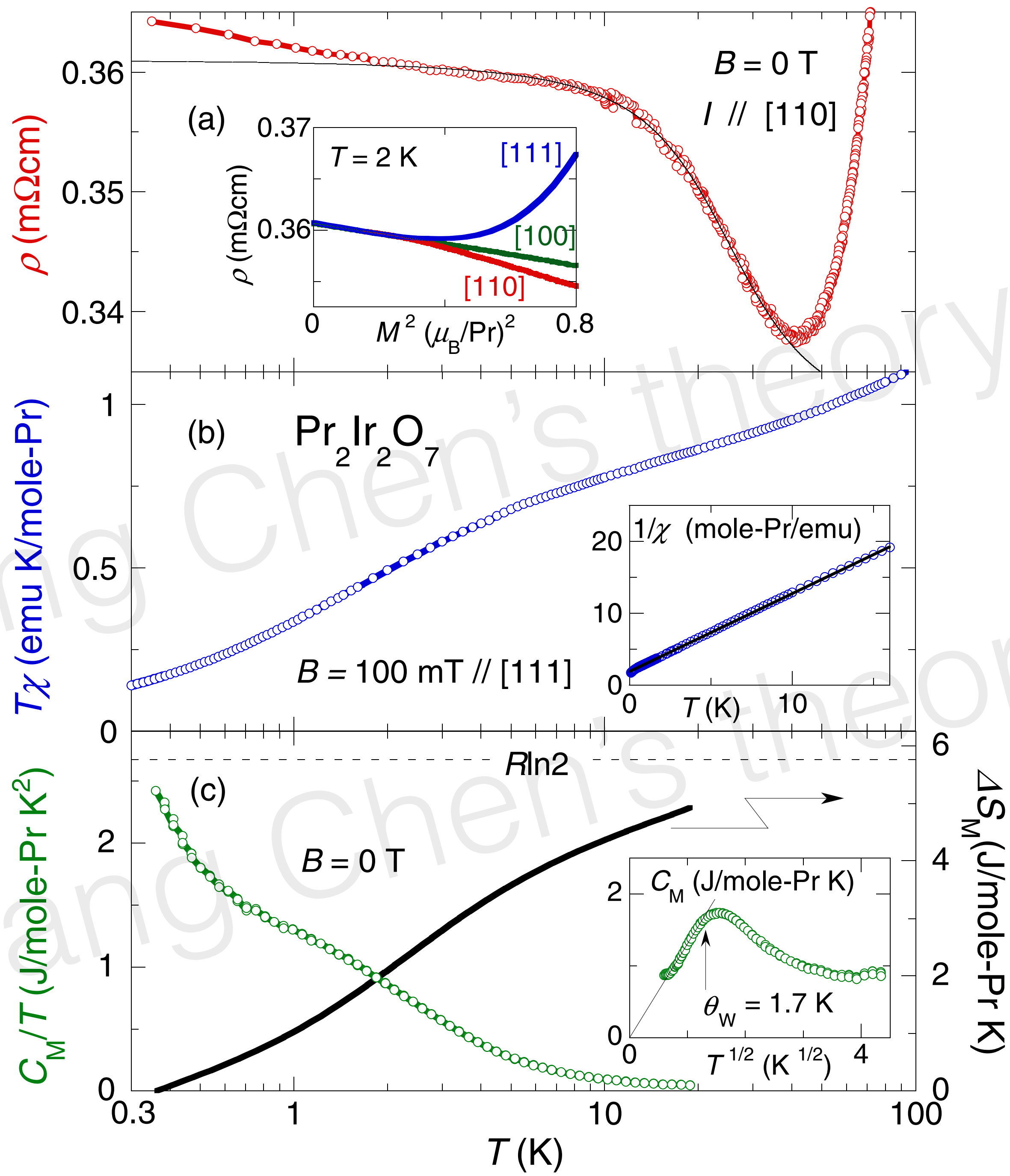
K Matsuhira, M Wakeshima,
Y Hinatsu, S. Takagi
JPSJ, 2011

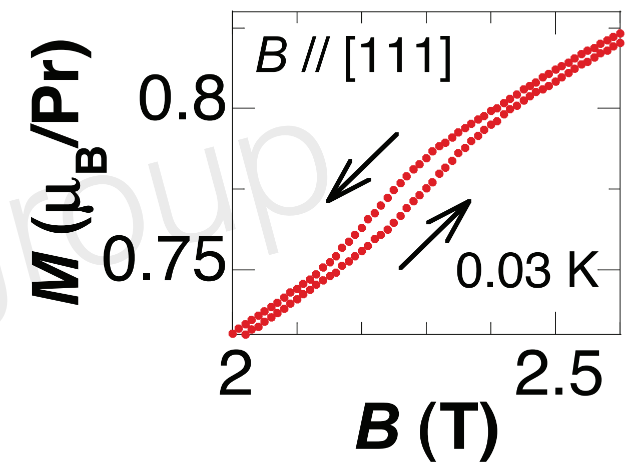
$Pr_2Ir_2O_7$ remains metallic and disordered,
all rest have metal-insulator transition with Ir magnetism

Early/pioneering theories: Leon Balents, Dima Pesin, Lucile Savary,
Sungbin Lee, Yong Baek Kim, et al



Peculiar one: $Pr_2Ir_2O_7$





metamagnetic transition

Nakatsuji, etc

PRL **96,** 087204 (2006)

Some $Pr_2Ir_2O_7$ sample does order magnetically

Unstable Spin-Ice Order in the Stuffed Metallic Pyrochlore $Pr_{2+x}Ir_{2-x}O_{7-\delta}$

D. E. MacLaughlin,[1,2,*] O. O. Bernal,[3] Lei Shu,[1,4,5] Jun Ishikawa,[2] Yosuke Matsumoto,[2]
J.-J. Wen,[6,†] M. Mourigal,[6,‡] C. Stock,[6,7,§] G. Ehlers,[8] C. L. Broholm,[6,7,8,9] Yo Machida,[2,¶]
Kenta Kimura,[2] Satoru Nakatsuji,[2,10,**] Yasuyuki Shimura,[2] and Toshiro Sakakibara[2]

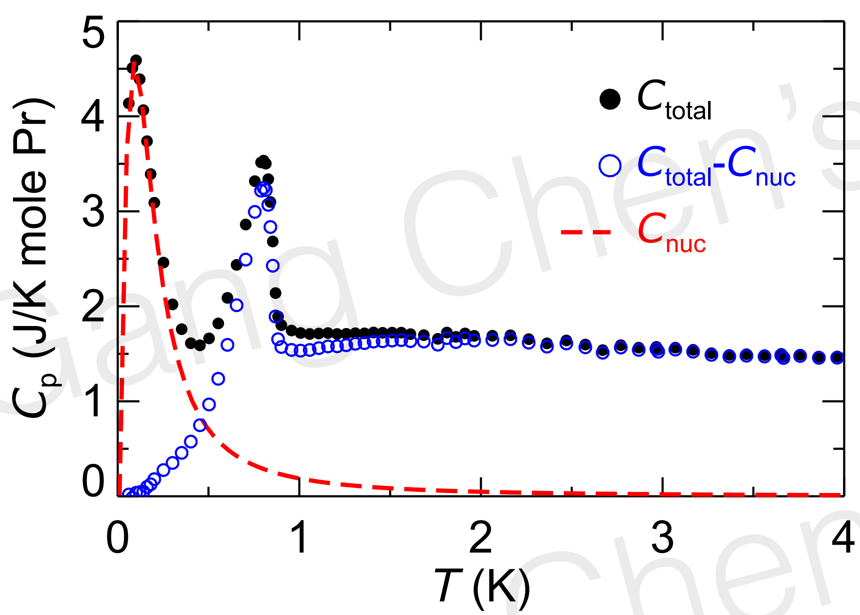


FIG. 1. (color online) Temperature dependence of the specific heat of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ in zero field. Filled circles: experimental total specific heat. Dashed curve: calculated specific

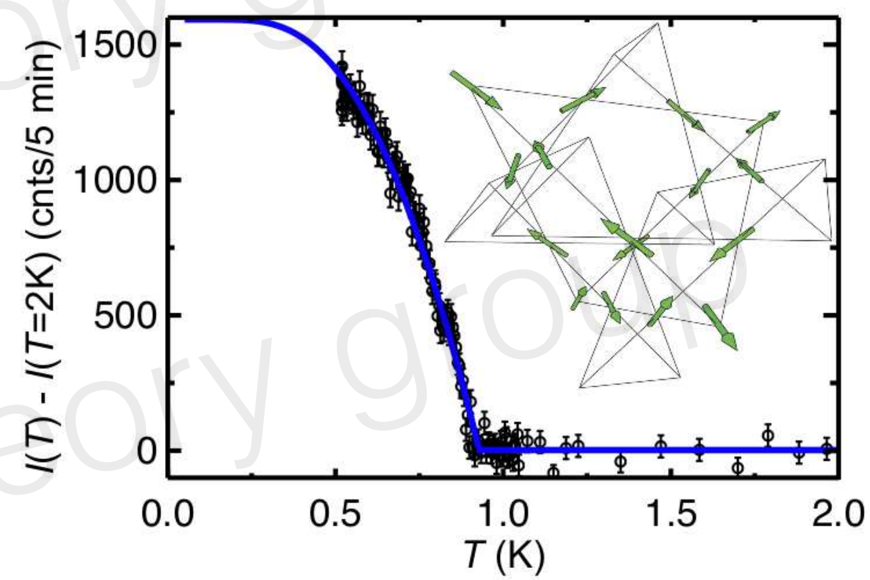
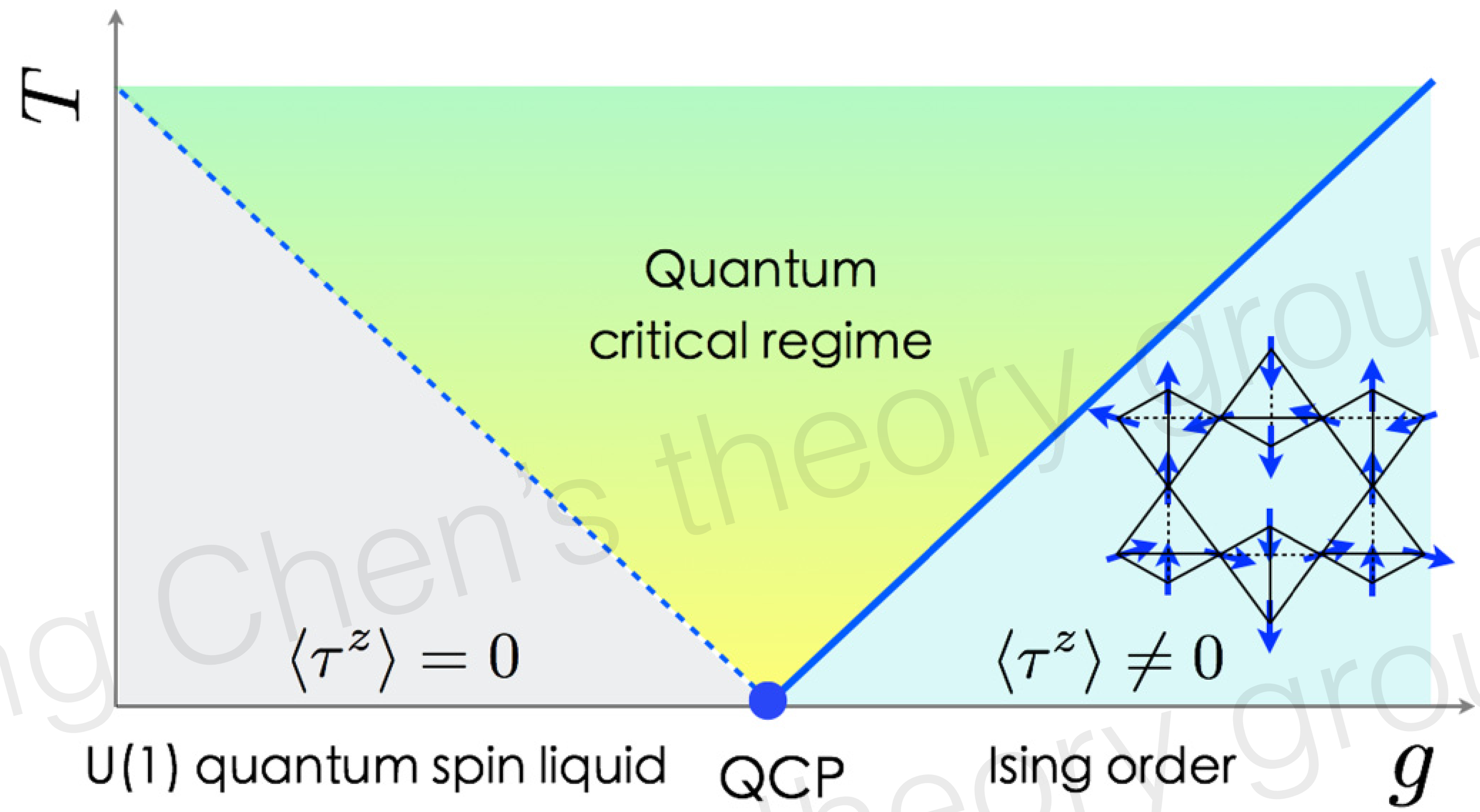


FIG. 2. (color online) Temperature dependence of elastic neutron scattering intensity of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ at the position of the $\mathbf{q}_m = (100)$ reflection. The intensity measured at $T = 2$ K

actually “Melko-Hertog-Gingras" spin state
(obtained numerically for a **different and classical** system)

Our proposal for Pr subsystem

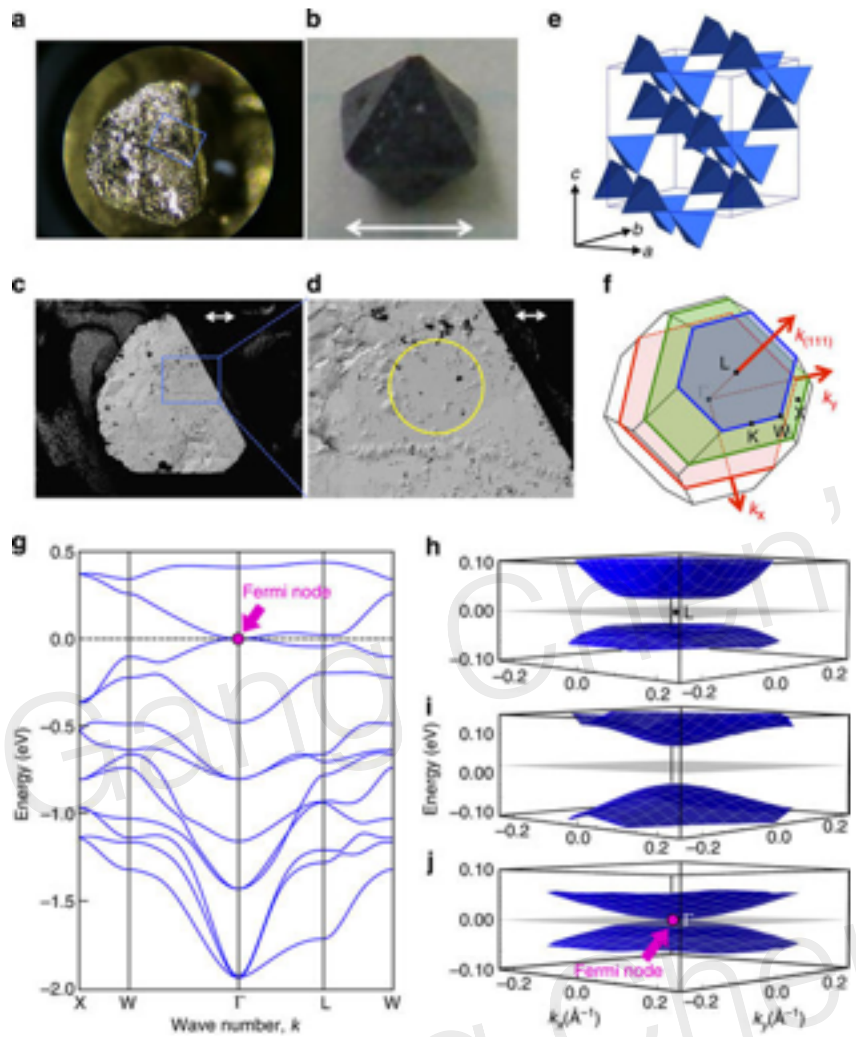


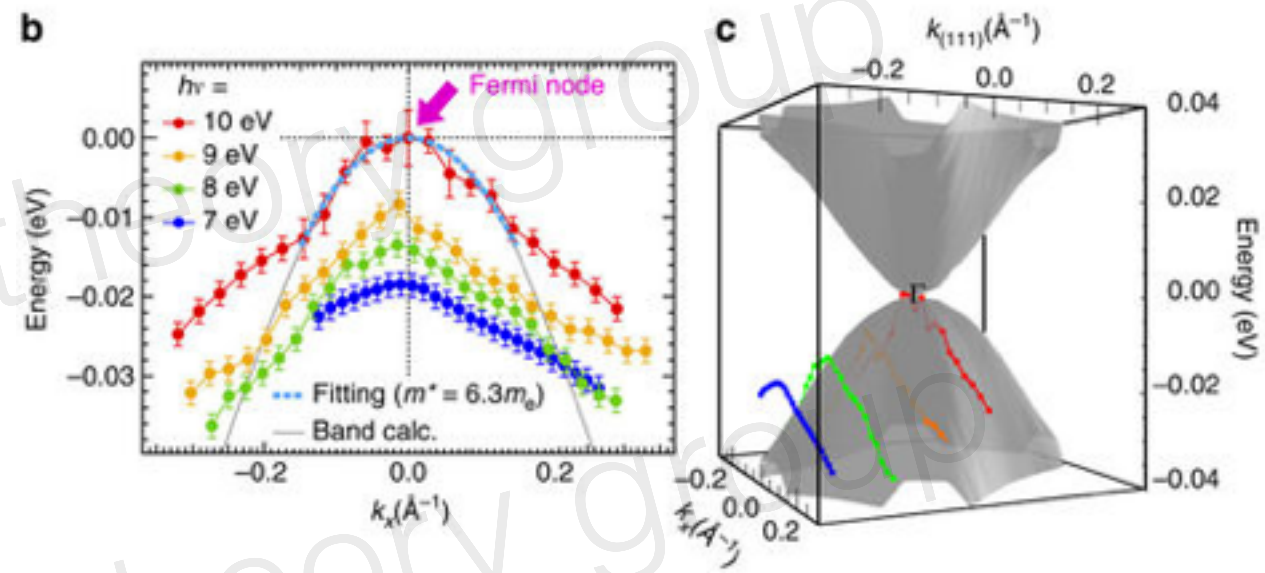
The Pr subsystem is proximate to a quantum phase transition from pyrochlore ice U(1) QSL to Ising magnetic order.

Microscopics: different samples have different Fermi energy, induces different RKKY interaction between Pr local moments.

Gang Chen, PRB 94, 205107 (2016)

Ir conduction electron: Luttinger semimetal



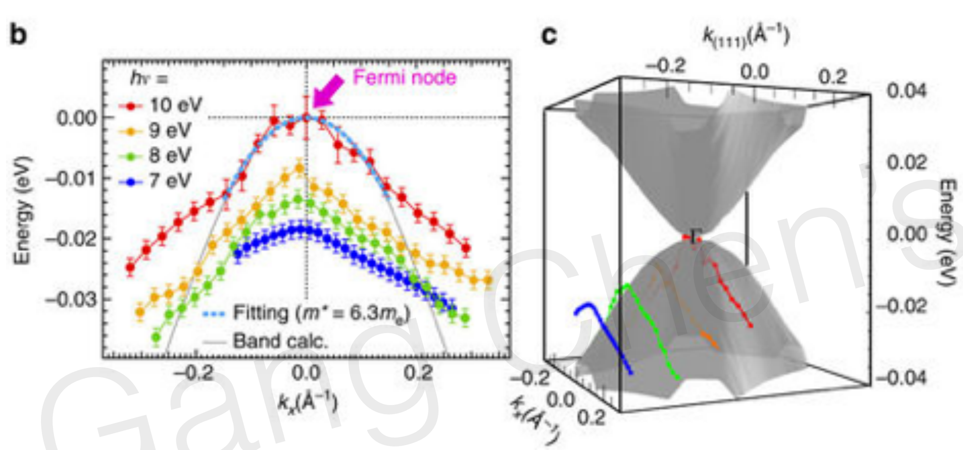


ARPES: Quadratic band touching

T Kondo, …Ru Chen, …, Nakatsuji, Balents, Shin
Nature Comm, 2015
P Amitage's optical measurement 2017
Correlation effect: EG Moon, L Savary, YB Kim, Cenke Xu, L Balents

Partial screening of long range Coulomb interaction

What is the impact of Pr magnetism
on Ir conduction electrons in the **ordered** regime?



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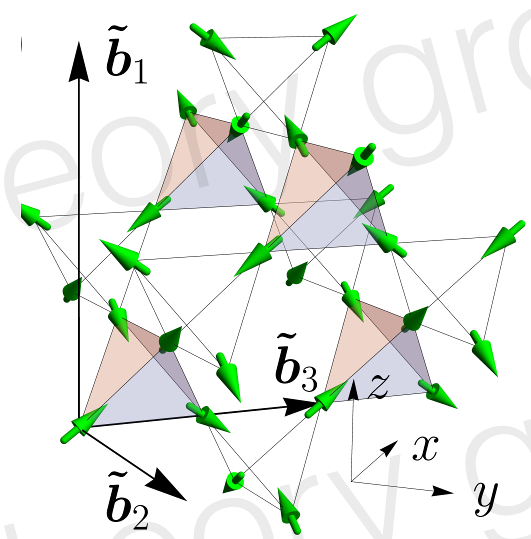


= ????

Ir Luttinger semimetal

MHG spin ice state

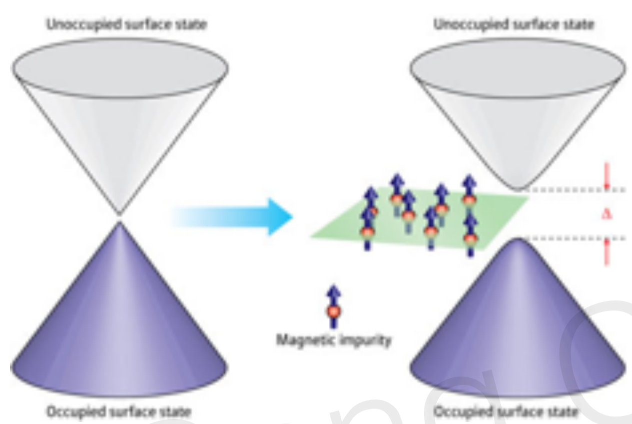
T Kondo, etc, 2015

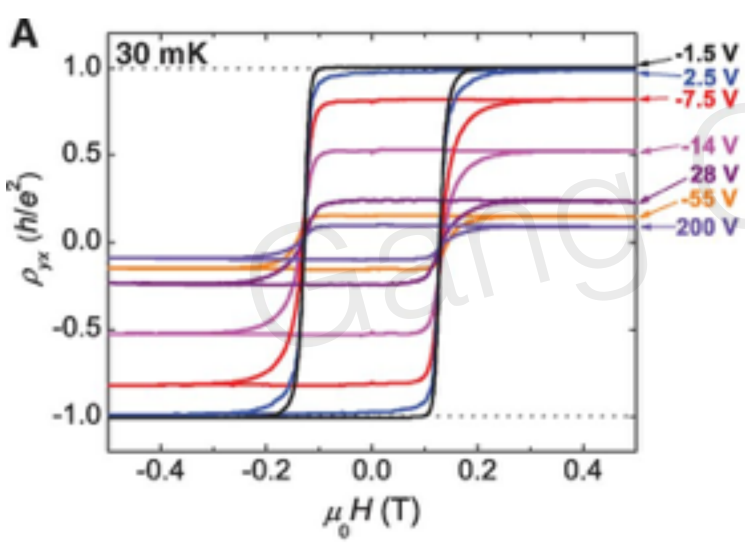
C Broholm, etc, 2015

When electron behaves as electron,
when spin behaves as spin !

Digression: Quantum Anomalous Hall Effect

Qikun Xue's group



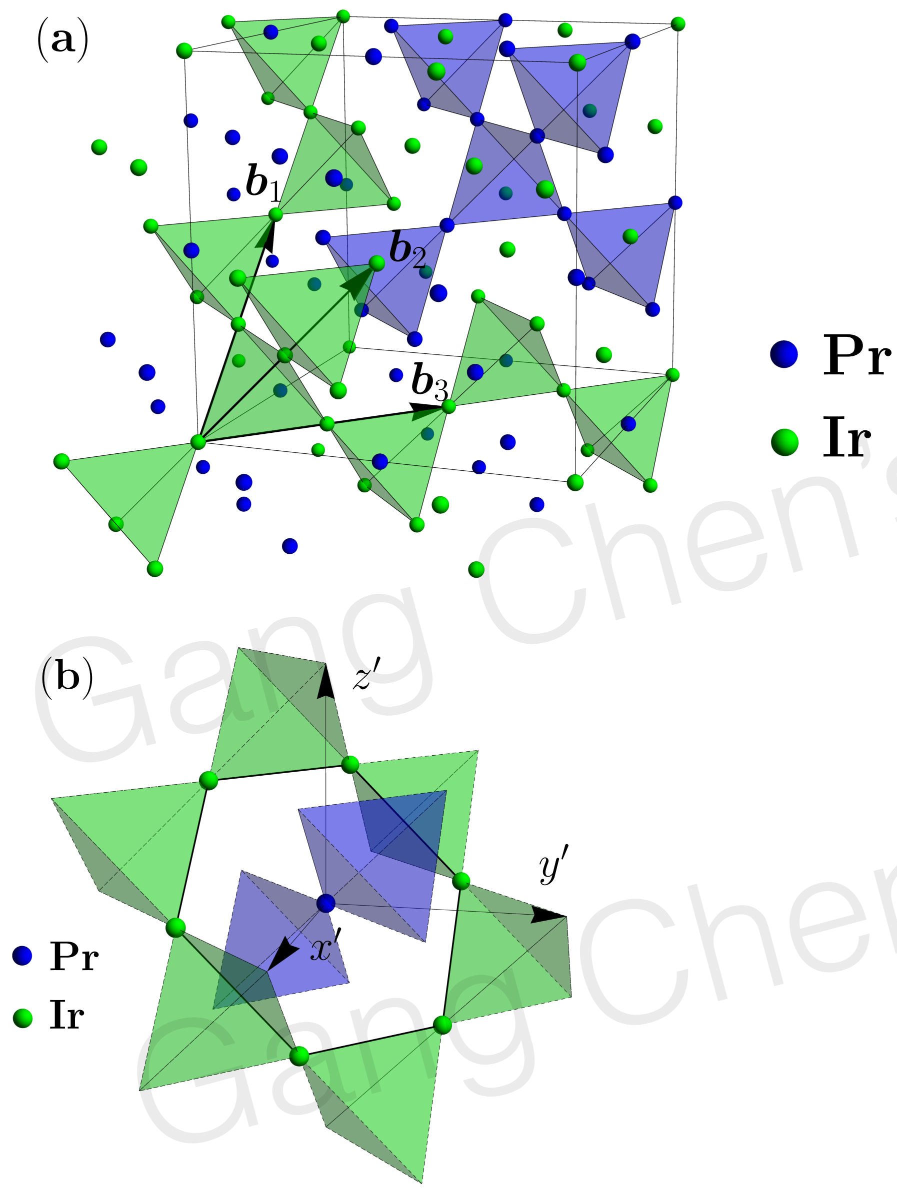


1. One understanding: TI -> Dirac cone ferromagnetism -> gapped Dirac fermion -> QAHE

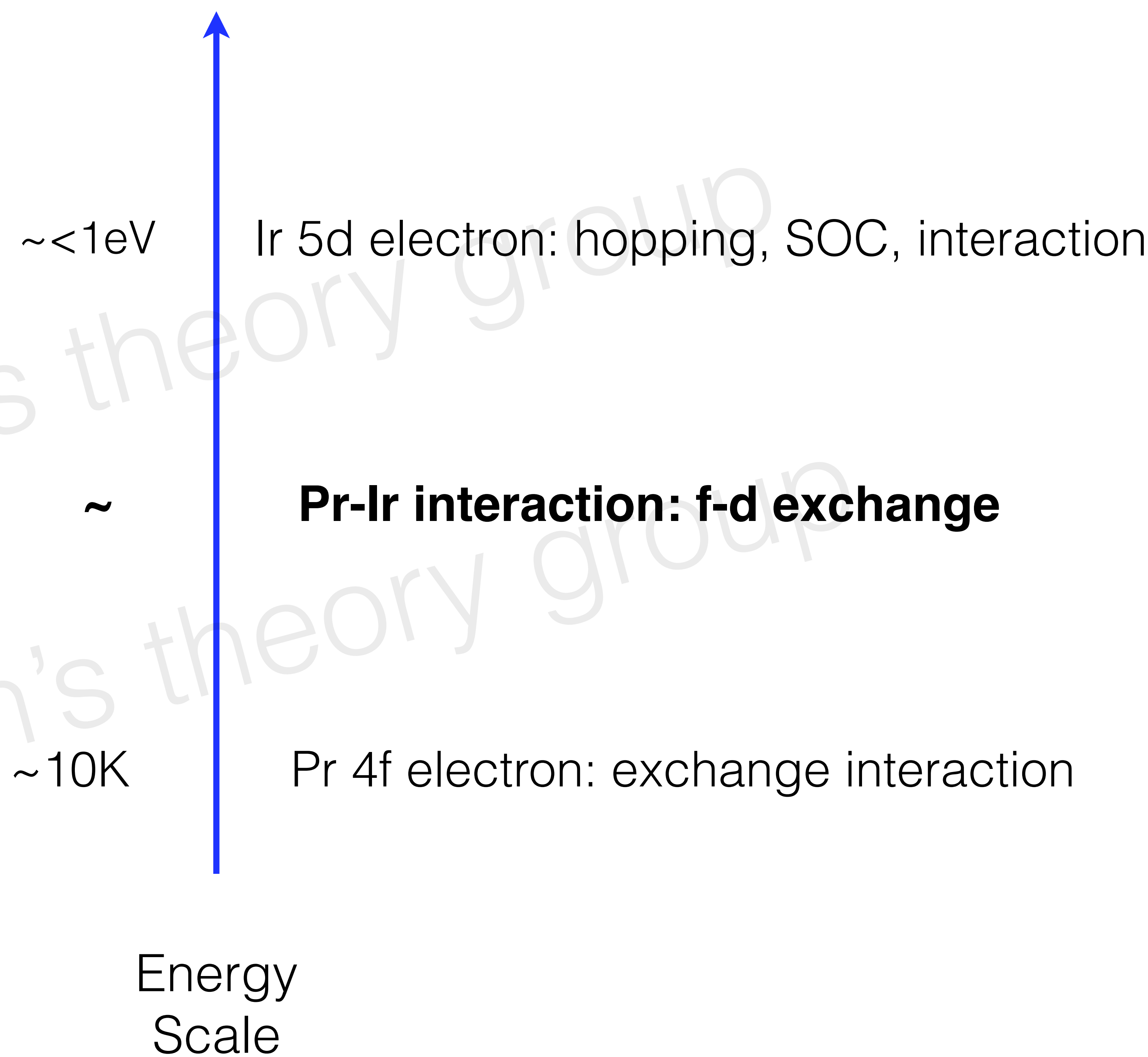
2. Our understand: QAHE is an example of interplay between conduction electron and local moments. Here in QAHE, itinerant electron band topology is modulated by magnetism, and magnetism is rather simple.

Here, we study the system with both local moments and itinerant electrons, trying to understand their interplay and interactions. How local moments influence conduction electrons, and ice versa.

Microscopics: Ir conduction electron + Pr local moments



GC, Hermele, PRB 2012
X-P Yao, GC, 1712.06534



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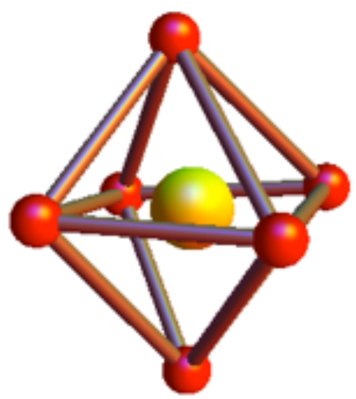
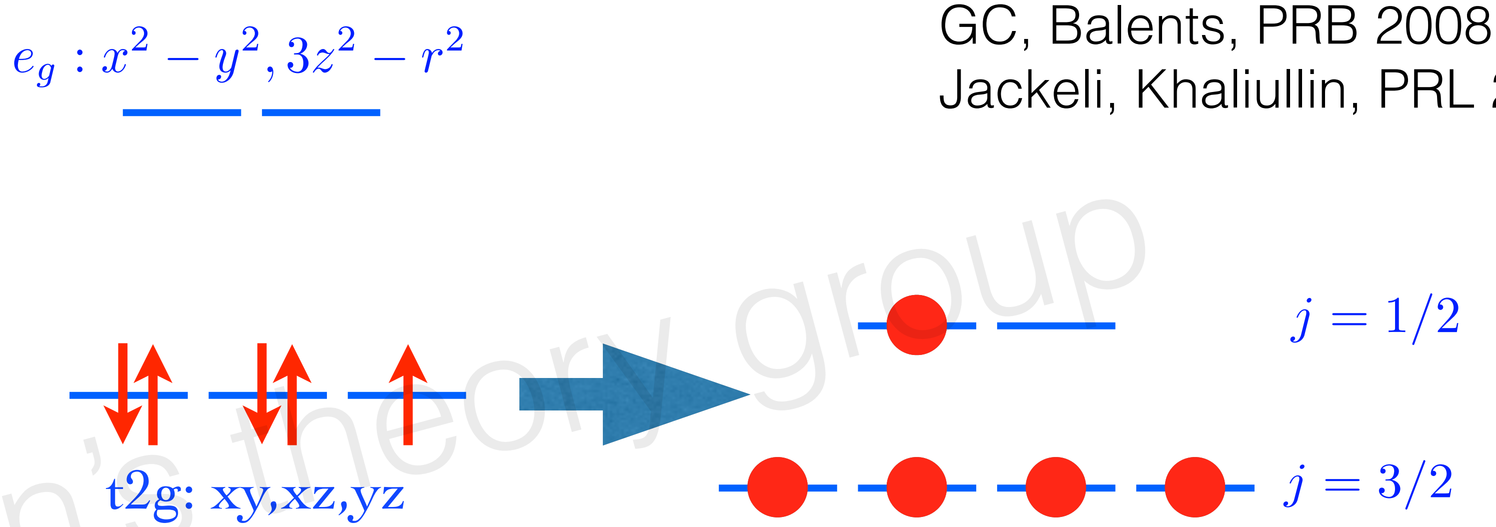
Ir 5d electron: SOC, hopping and correlation

BJ Kim, etc 2008,
GC, Balents, PRB 2008
Jackeli, Khaliullin, PRL 2009



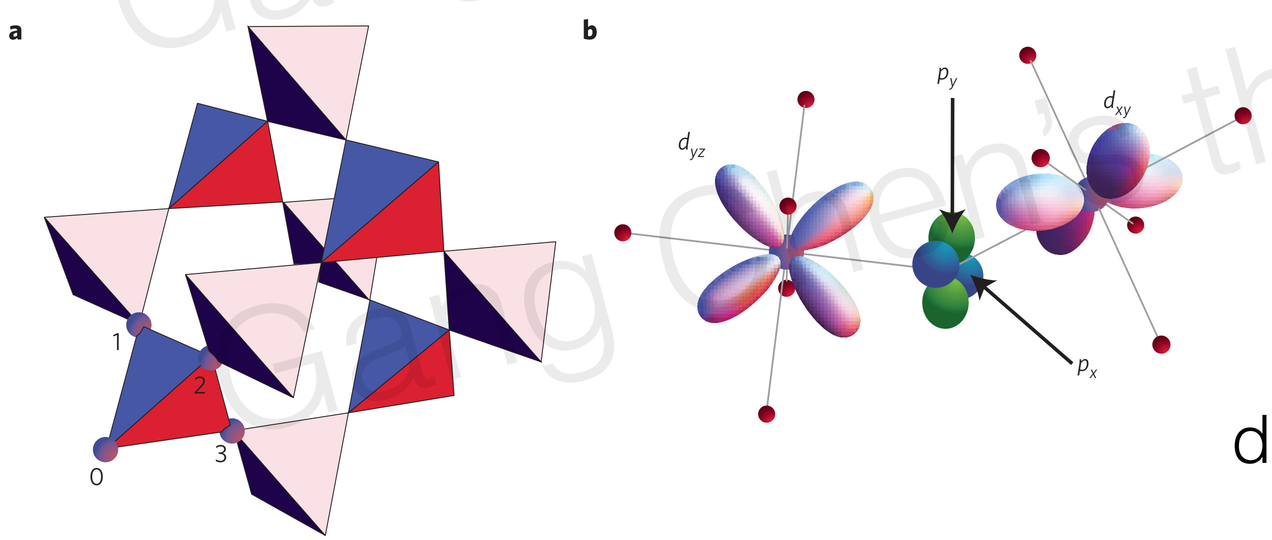
IrO6 octahedron

$\mathrm{Ir}^{4+} : 5d^5$



Crystal electric field

Spin-orbit coupling

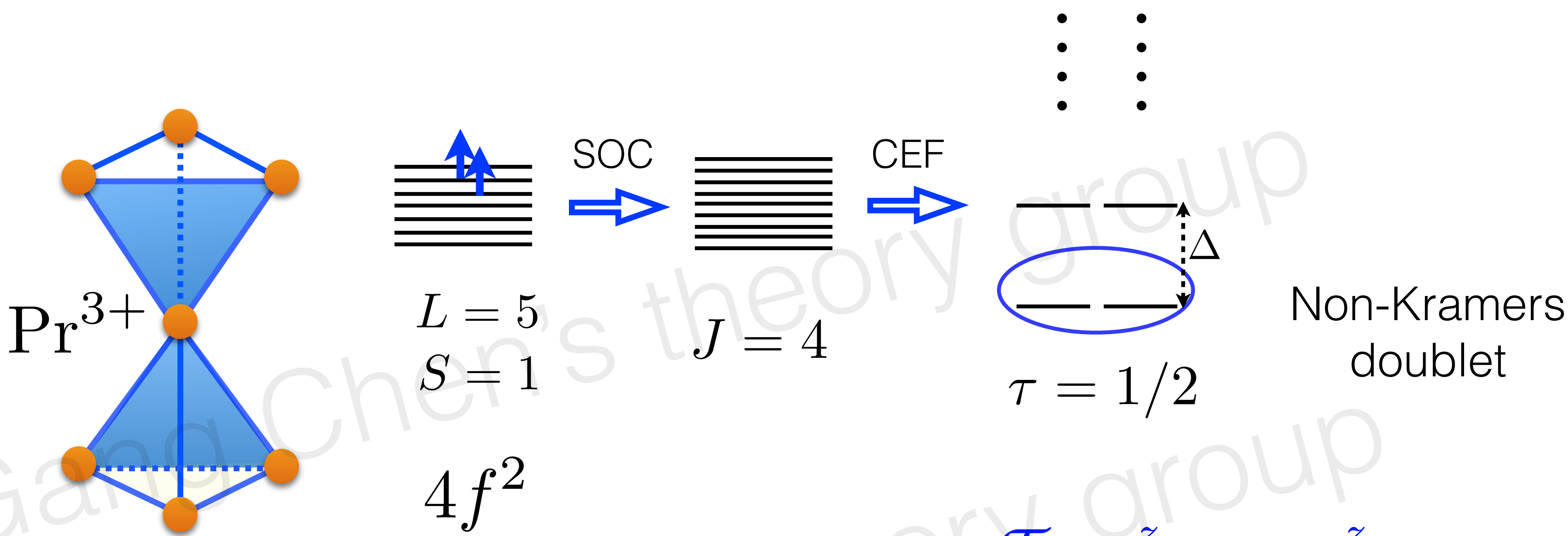


Besides Ir electron hopping via intermediate oxygens, there is direct electron hopping (Yong Baek Kim)

For $Pr_2Ir_2O_7$, correlation renormalizes the overall band width.

quickly skip

Pr local moments: non-Kramers dou



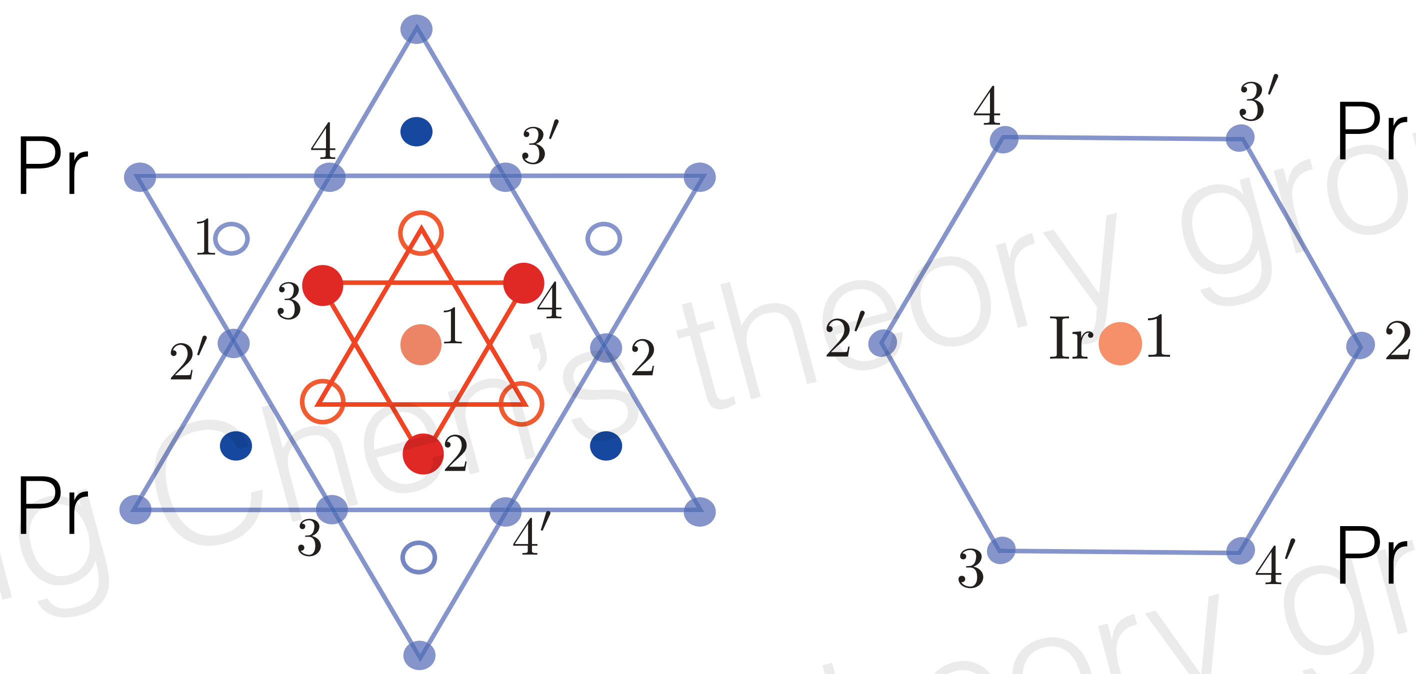
$$\mathcal{T} : \tau^z \rightarrow -\tau^z$$

$$\mathcal{T} : \tau^{x,y} \rightarrow +\tau^{x,y}$$

Indication:
1. Only z (or Ising) component couples to external magnetic field.
2. Magnetic order necessarily implies z (or Ising) component ordering.
3. Only z (or Ising) component couples to the Ir electron spin density.

Pr-Ir interaction: 4f-5d exchan

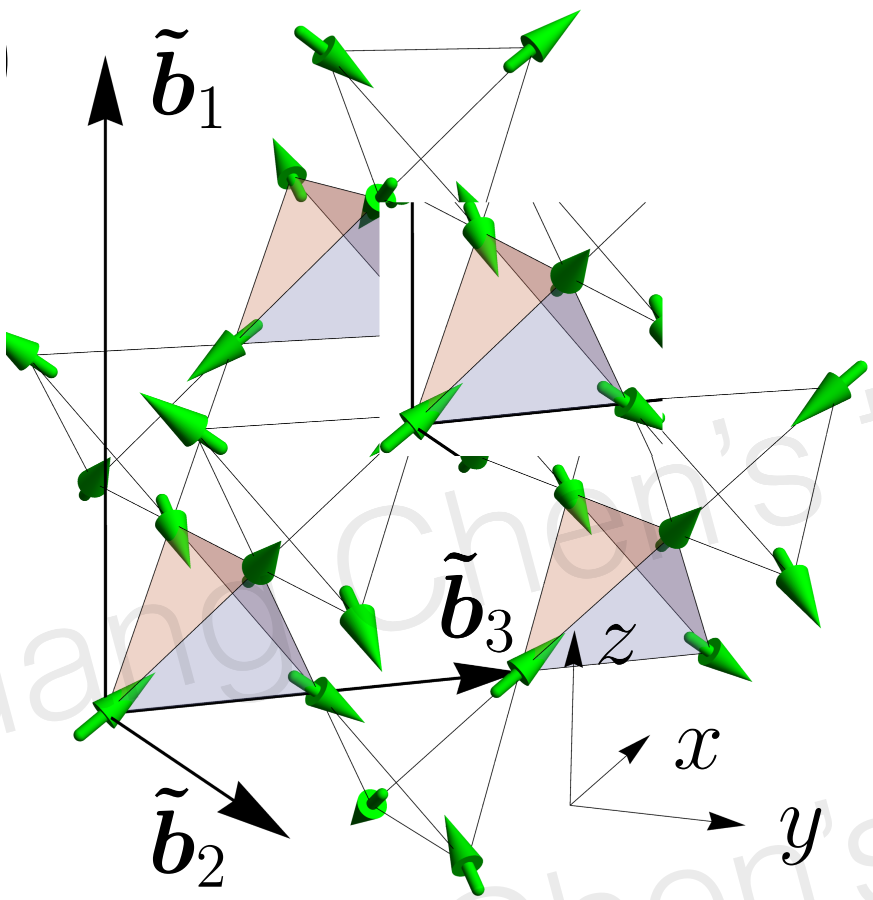
quickly skip



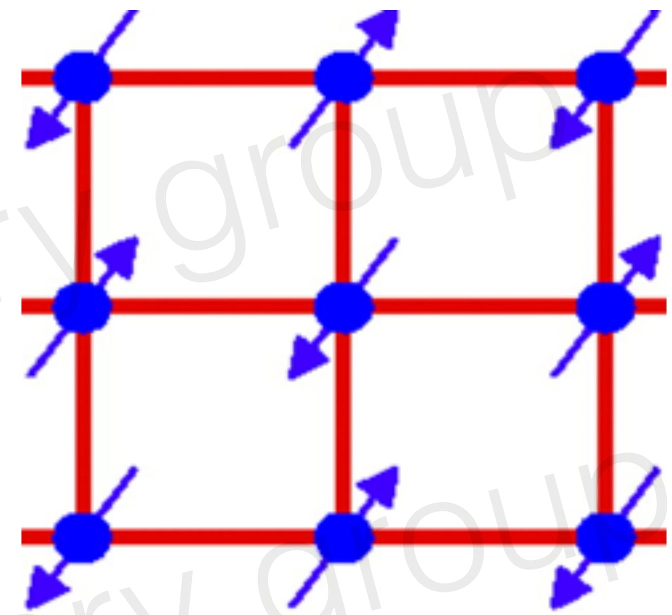
$$\mathcal{H}_{\rm fd} = \big[c_1 \tau_4^z - c_2\big(\tau_2^z + \tau_3^z\big)\big] j_1^x + \big[c_1 \tau_3^z - c_2\big(\tau_2^z + \tau_4^z\big)\big] j_1^y + \big[c_1 \tau_2^z - c_2\big(\tau_3^z + \tau_4^z\big)\big] j_1^z + [2 \leftrightarrow 2', 3 \leftrightarrow 3', 4 \leftrightarrow 4'],$$

GC, Hermele, PRB 2012

Magnetic translation of MHG spin ice state

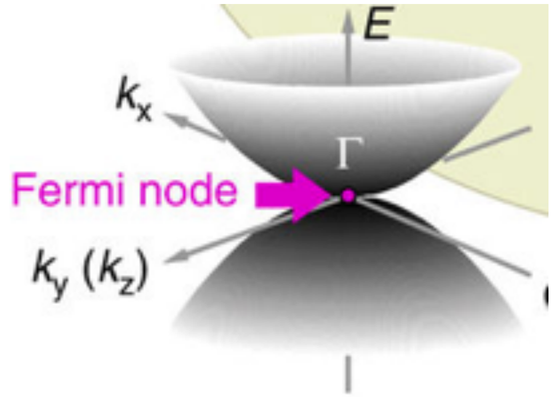


$$\tilde{\mathcal{T}} \equiv \mathcal{T} \circ t$$

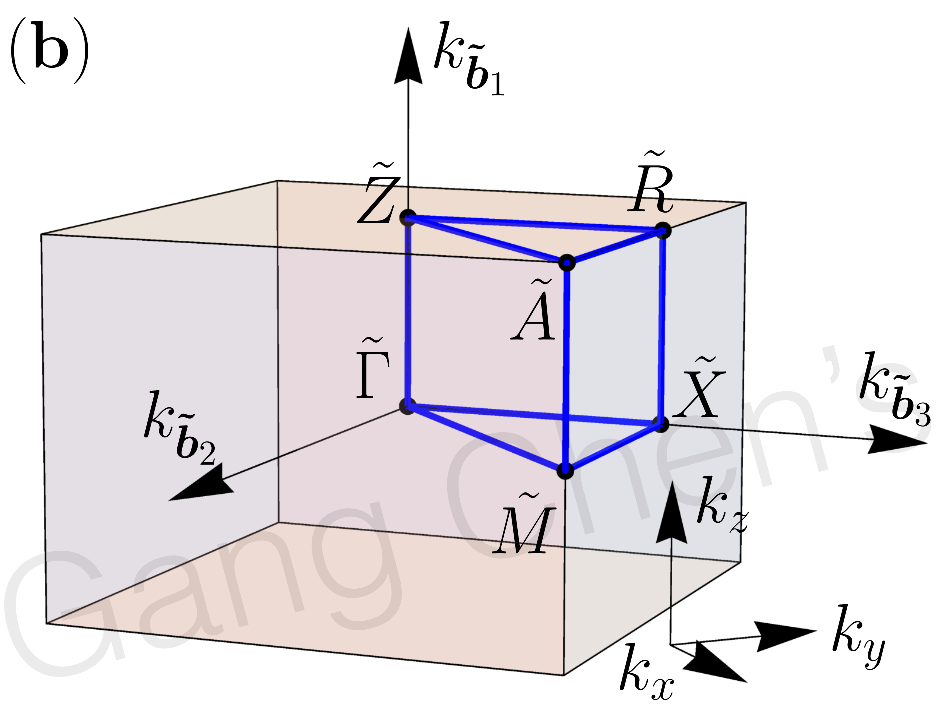


Neel state on square lattice

3D analogue of the magnetic translation for Neel state

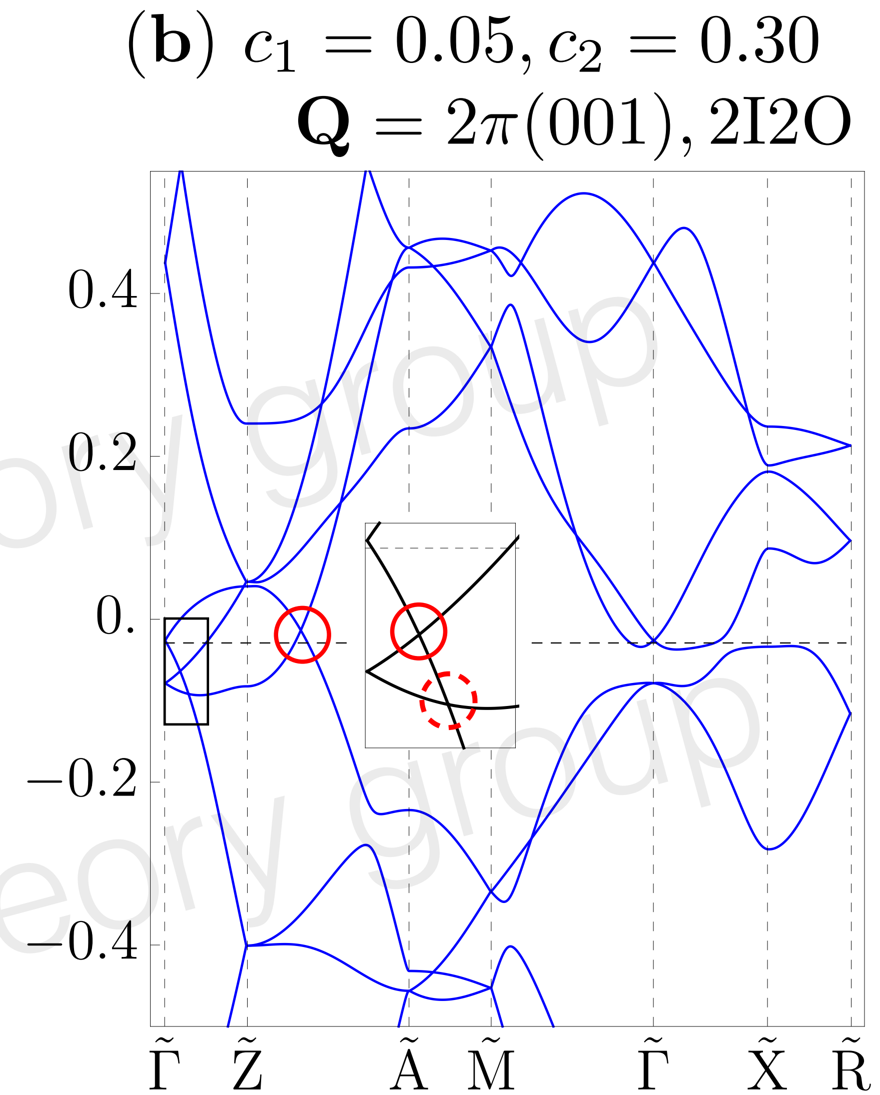


Symmetry protected Dirac band touching



magnetic Brillouin zone

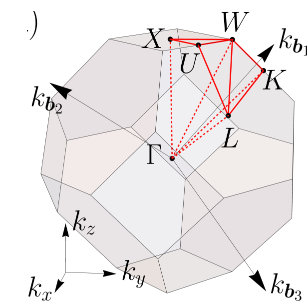
$\tilde{\mathcal{T}}^2 = -1$ at $\tilde{\Gamma}$ point

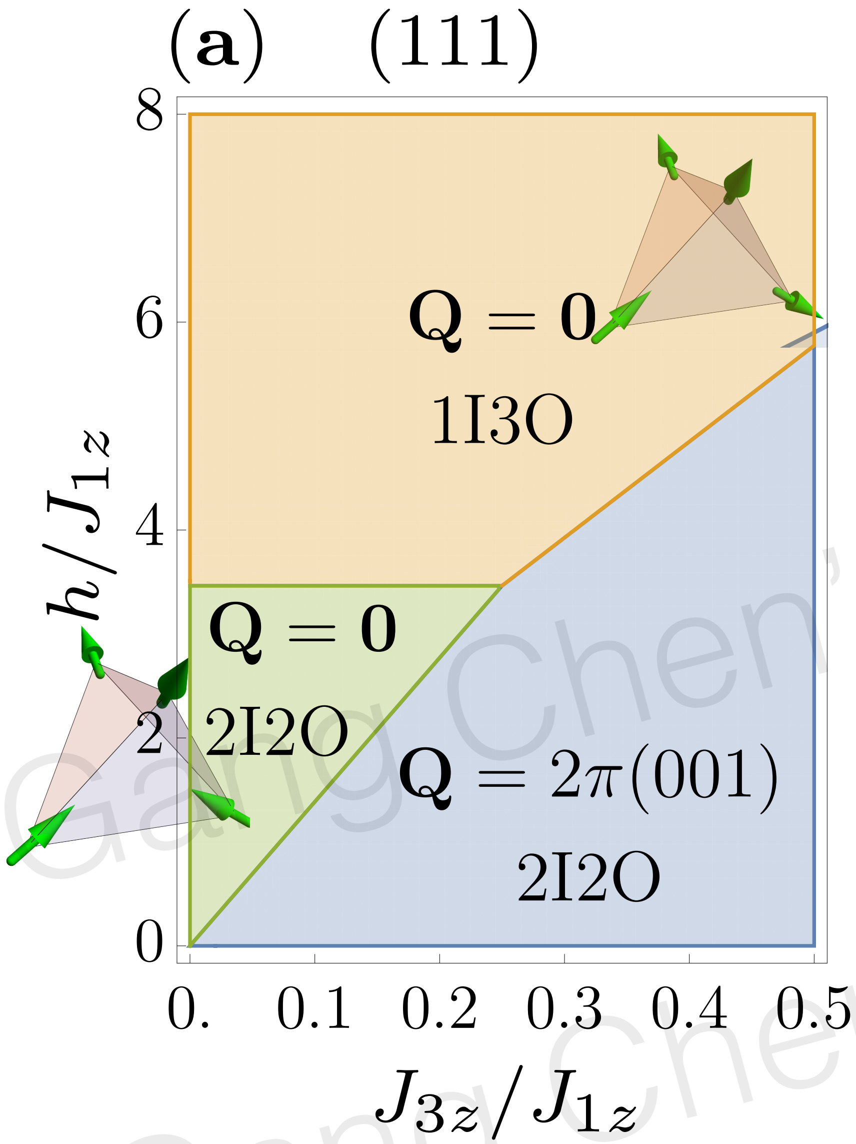


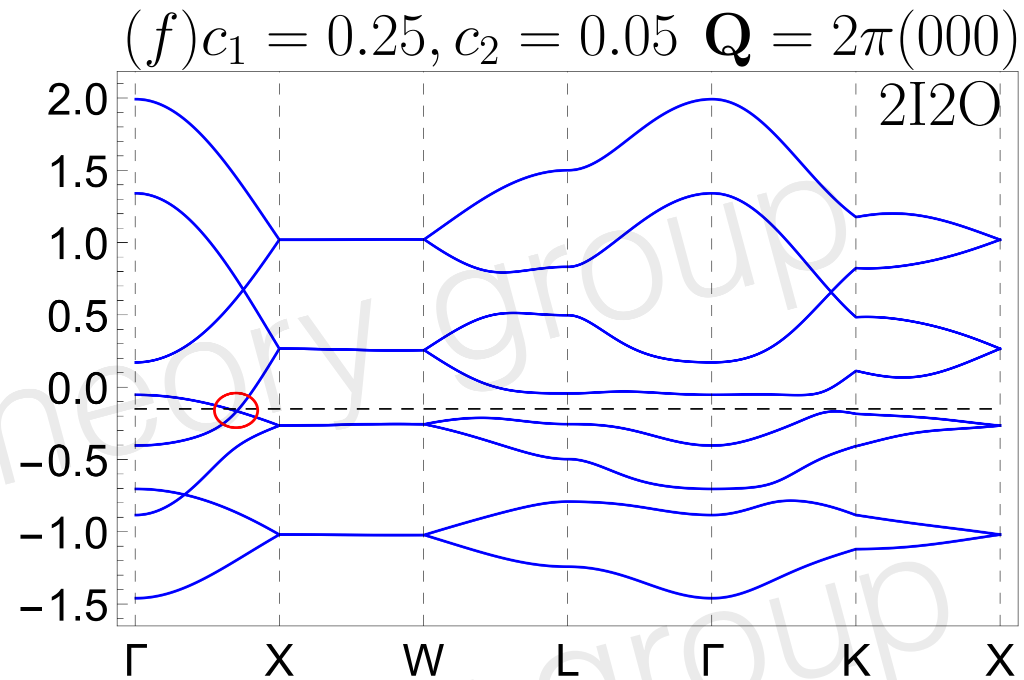
in addition, there are Weyl nodes
whose existence does not require symmetry

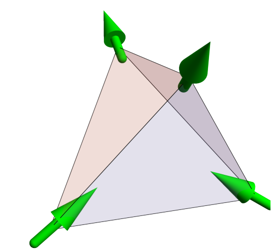
Pr magnetic order transfers its time reversal
symmetry breaking to Ir Luttinger semimetal.

Band engineering by external magnetic field





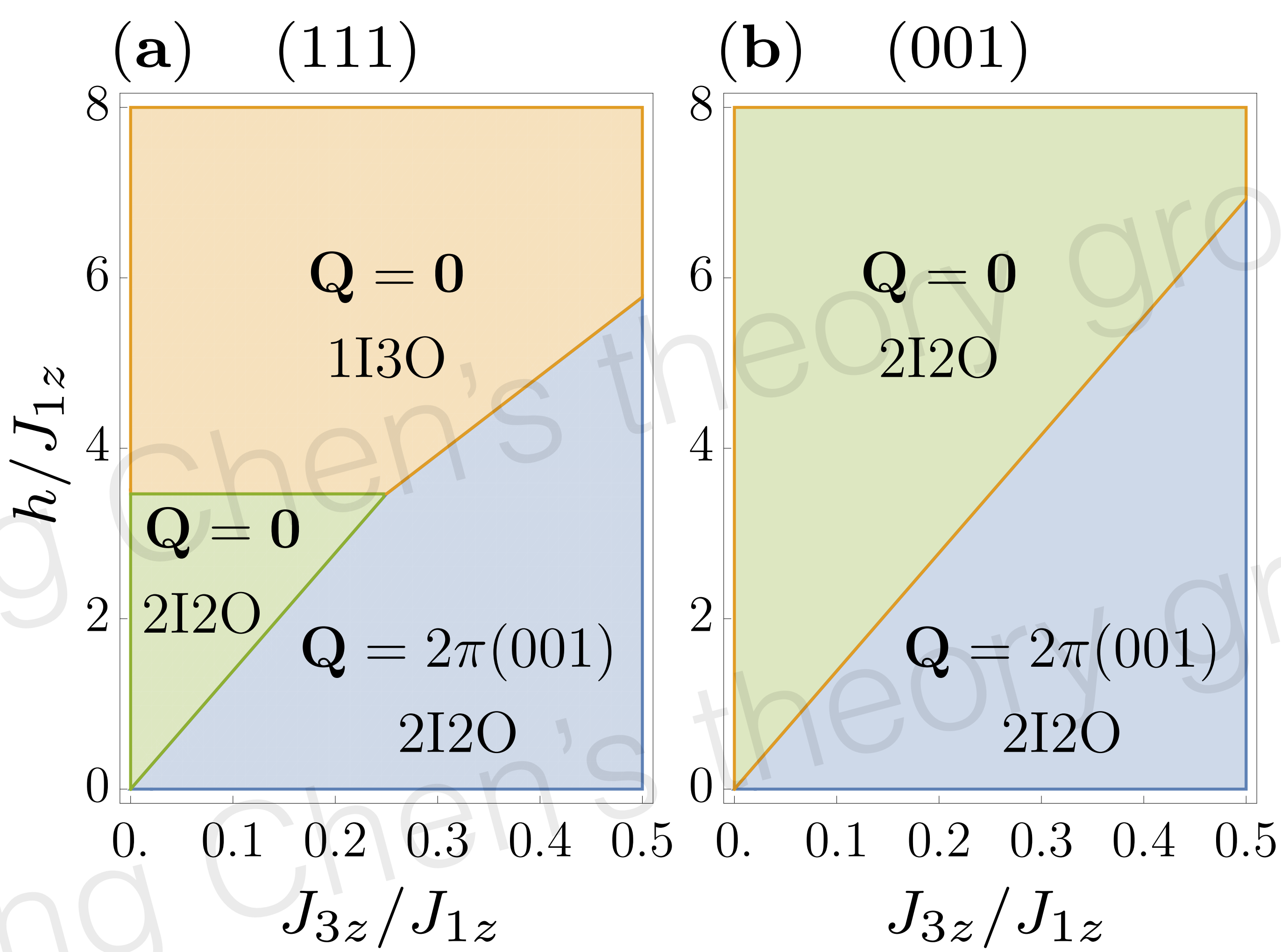




example: double Weyl nodes

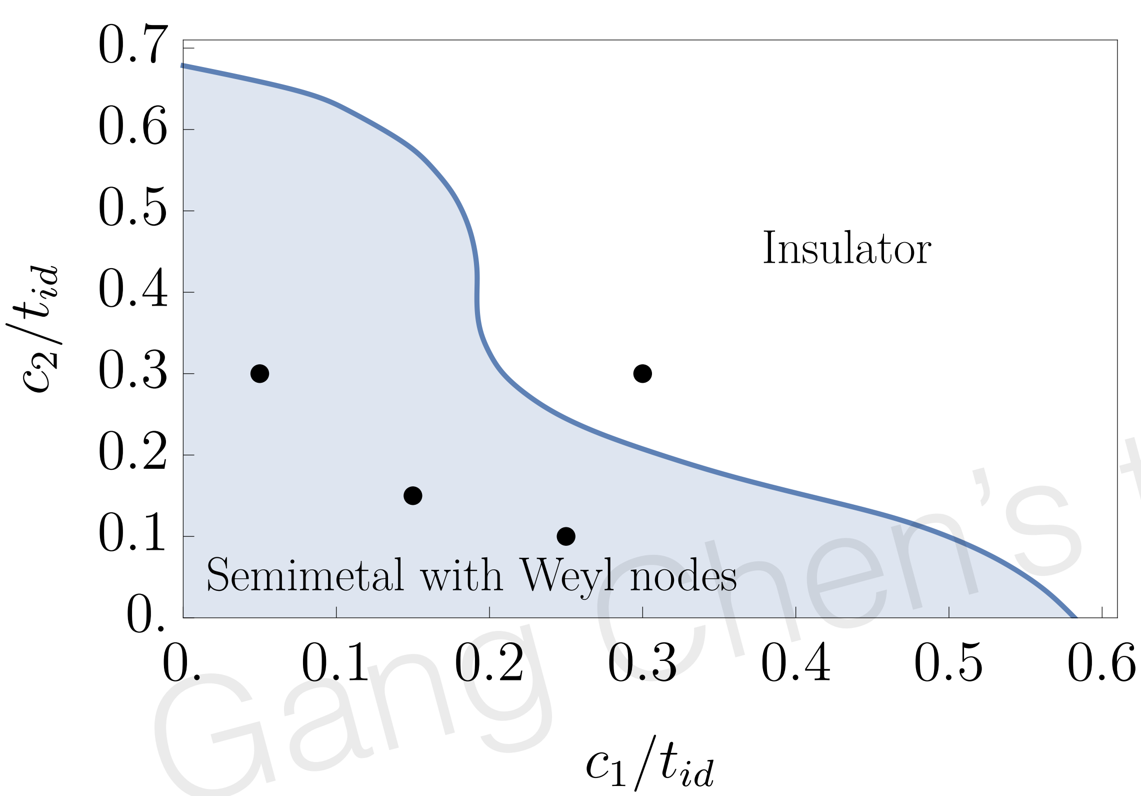
1. Magnetic field primarily couples to Pr moments, modifies Pr spin state, thereby indirectly influence the Ir band structure,
2. Field immediately removes the Dirac band touching,
3. Field induces Weyl nodes on the Ir band structure as well, anomalous Hall effect

Quantum control under magnetic field

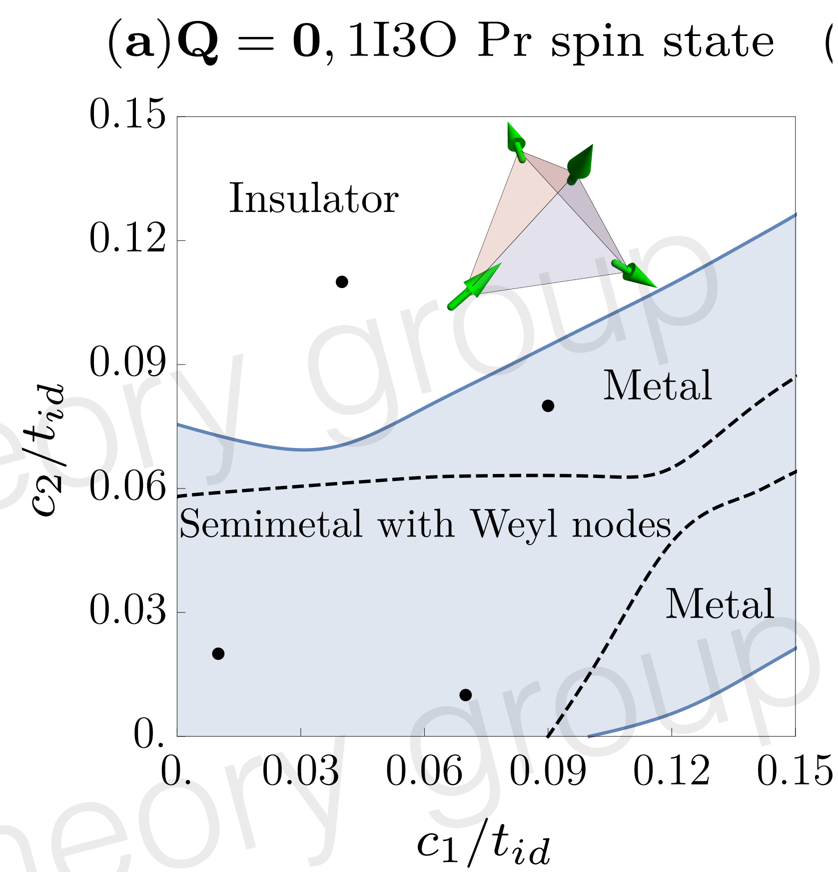


The Pr magnetic state under
different direction magnetic field

Ir band property under 111 field



zero field



finite field

Magnetic field modifies the Pr magnetic structure, thereby modifies the Ir band structure.

We predict that external magnetic field destroy the symmetry protected Dirac band touching, and Weyl nodes still persist and give to anomalous Hall effect.

Xu-Ping Yao, Gang Chen, arXiv 1712.06534

Summary

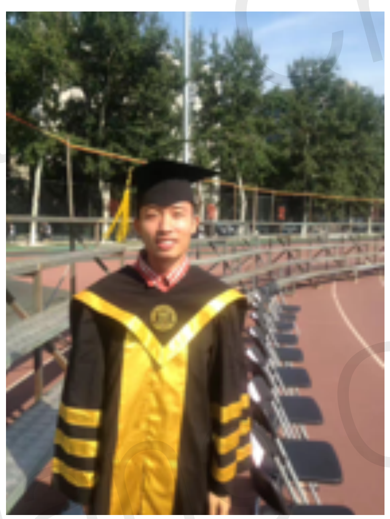
1. We point out the Pr local moment is proximate to a quantum phase transition from U(1) QSL to the Ising magnetic order in $Pr_2Ir_2O_7$.

2. We predict the band structure reconstruction of the Ir conduction electrons by the Pr magnetic order. We predict symmetry protected Dirac band touching and topologically protected Weyl nodes.

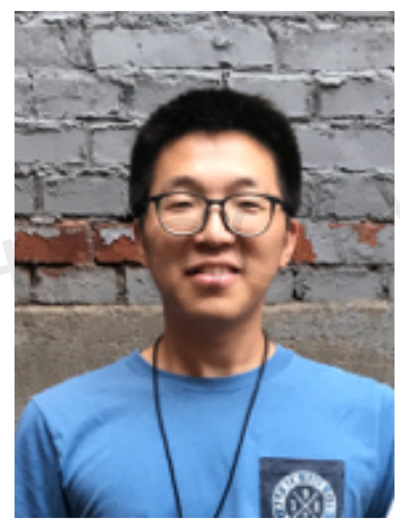
3. This work points out the interesting interplay of conduction electron and local moments in **hybrid quantum materials**.

Discovery of intertwined multipolar order in TmMgGaO4

(to appear soon)



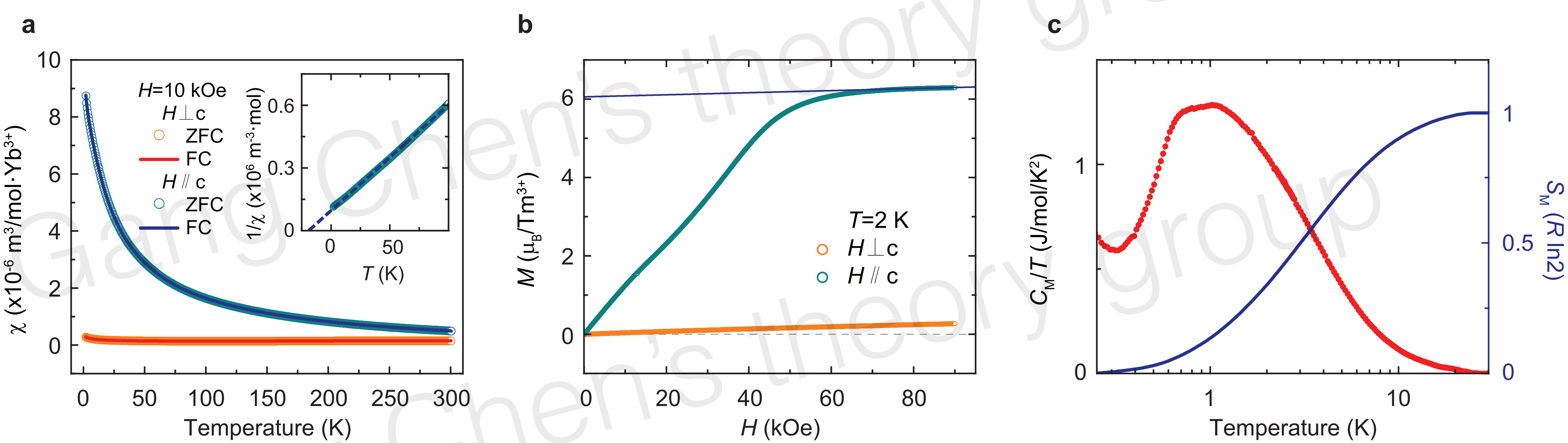
Changle Liu
(Fudan)



Yao Shen
(Fudan)

Jun Zhao
(Fudan)

approximately thought as non-Kramers doublets



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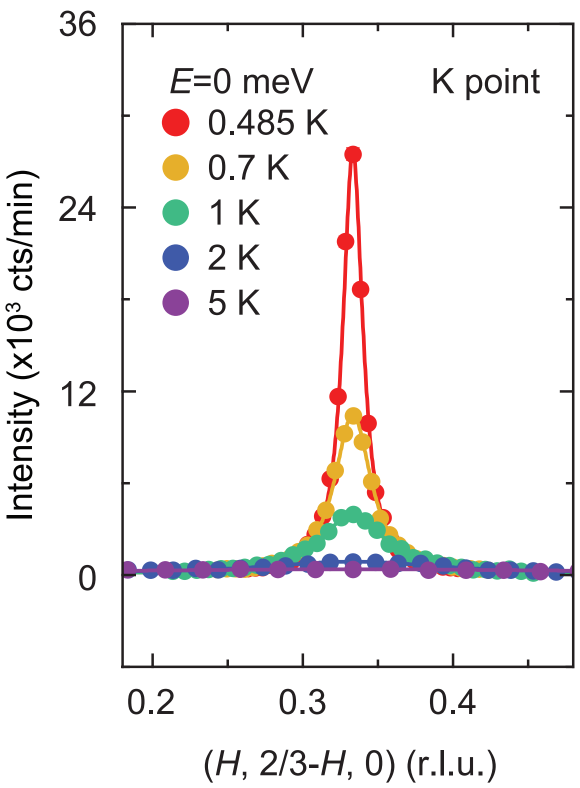
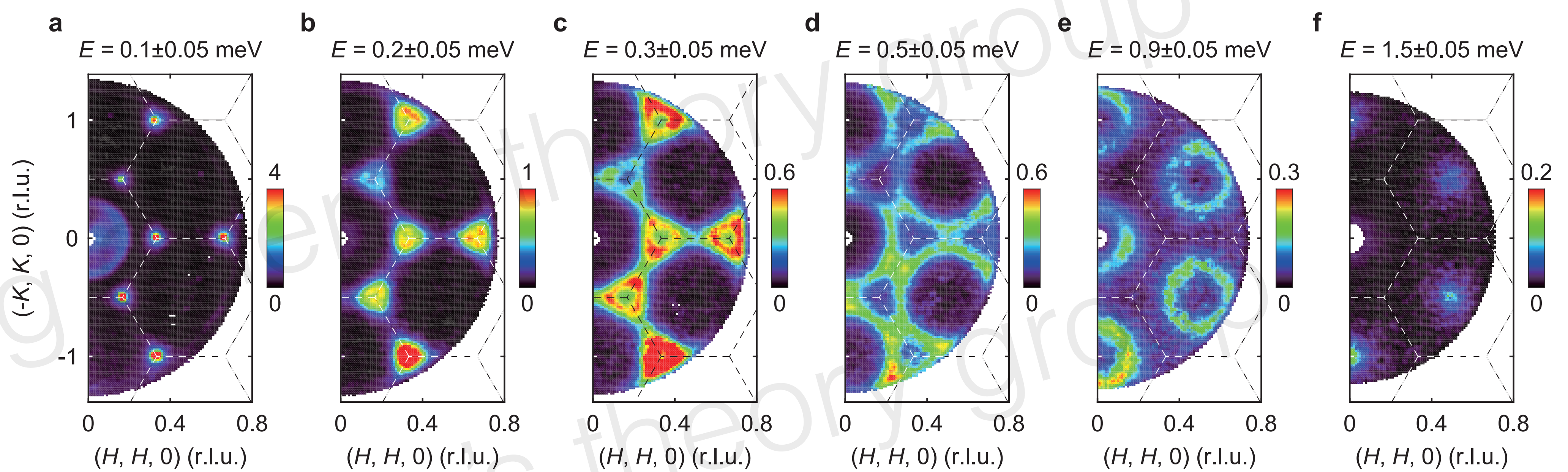
Well-defined spin wave





The presence of well-defined spin wave indicates
the presence of the hidden order !

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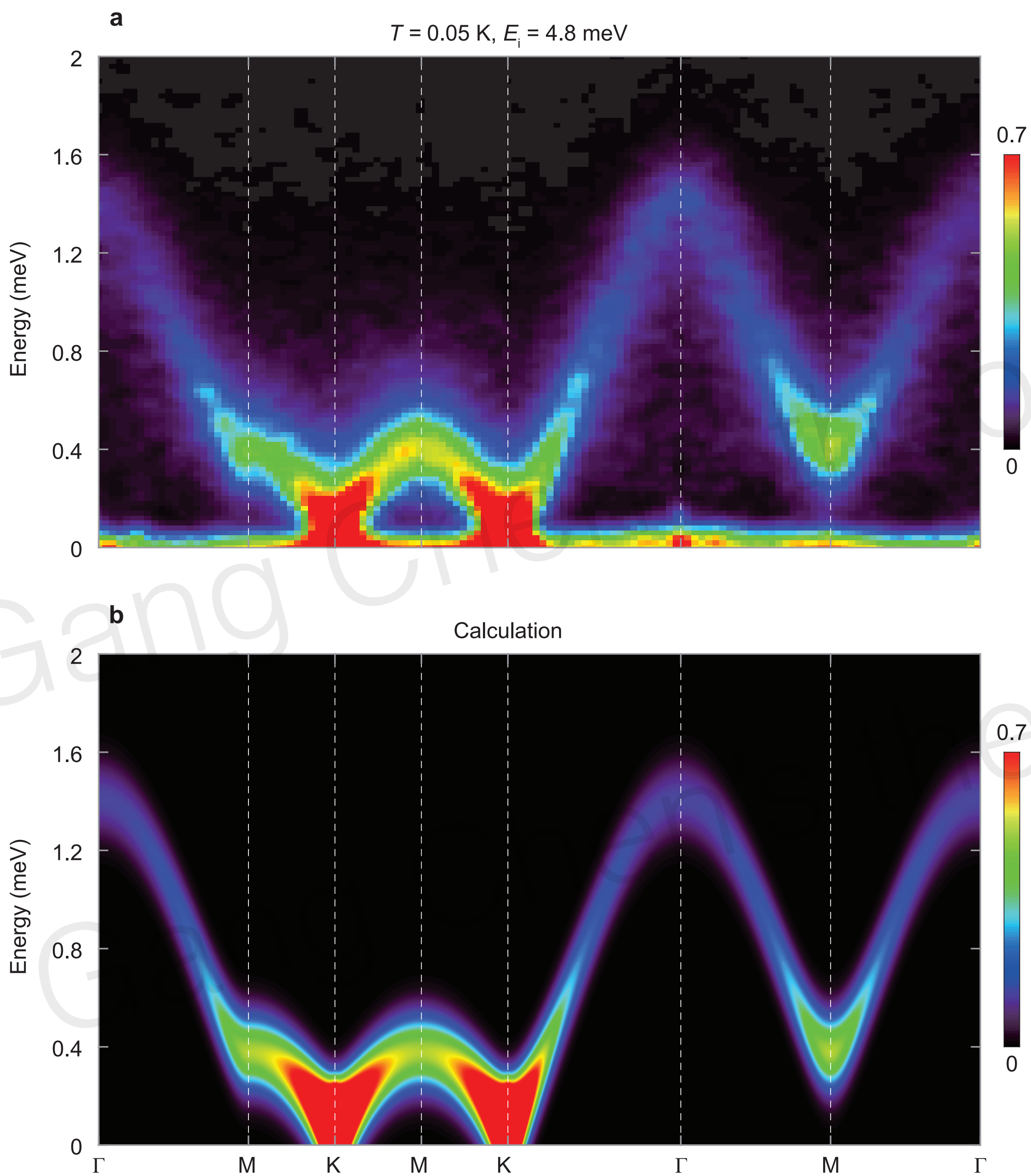
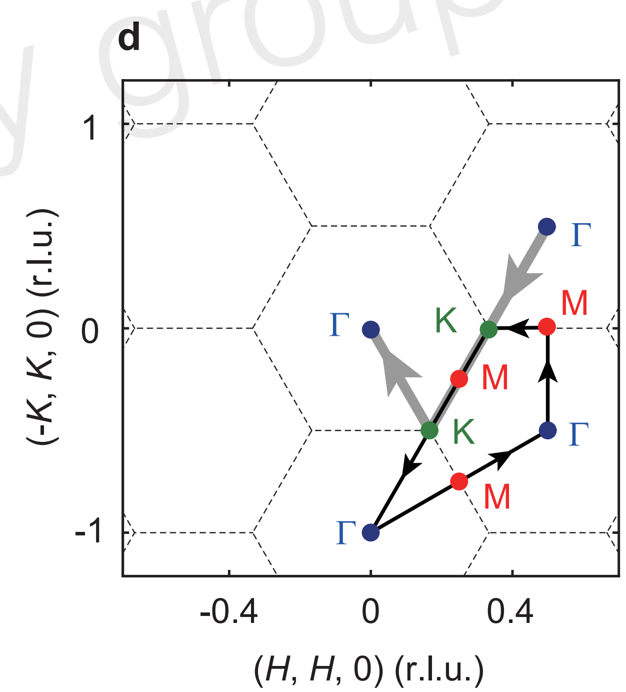
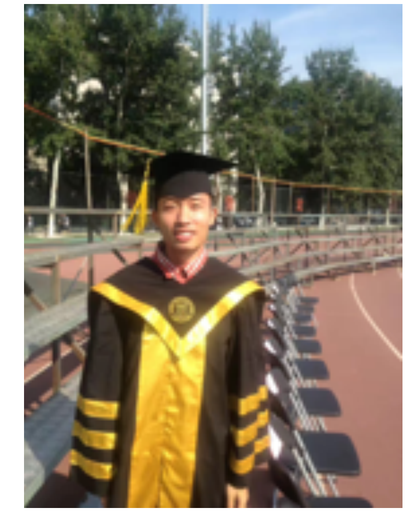
Comparison with theory







Changle Liu

Summary