Interplay of magnetic and electronic states in the pyrochlore iridates

Leon Balents, KITP, UCSB

- or -

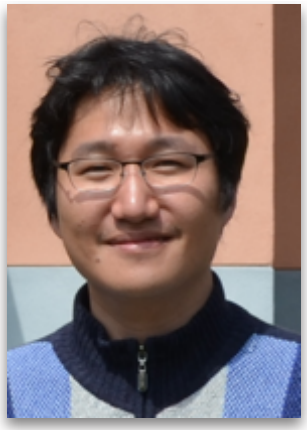
correlations versus topology

DPG meeting, Regensburg, March 2016

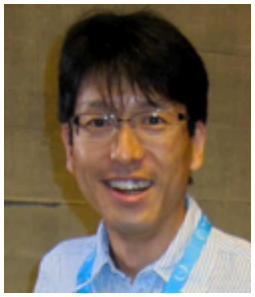
People

Ru Chen

Lucile Savary

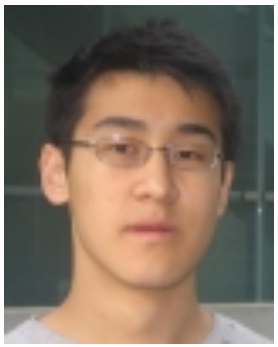


Eun-Gook Moon



S. Nakatsuji

T. Kondo

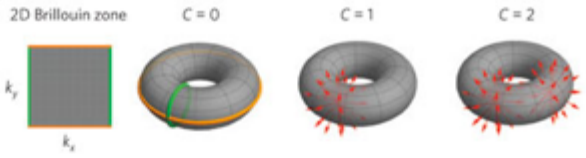


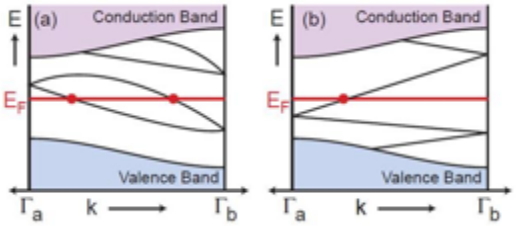
T. Hsieh

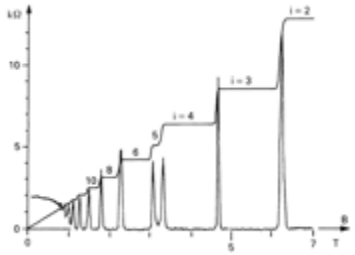
H. Ishizuka

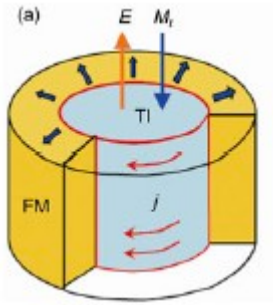
TIs

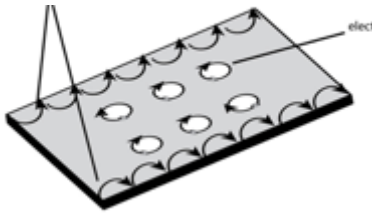
Broken TRS	with TRS
integer Chern number	Z_2 invariant
= Hall conductance	= M-E polarizability
chiral edge states	helical edge/ surface states

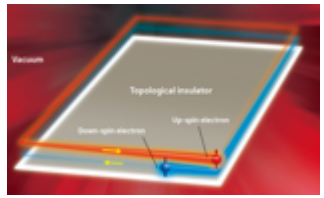










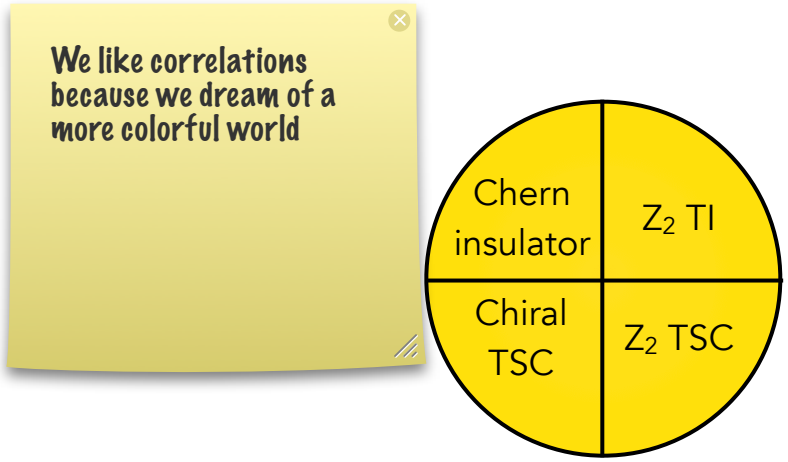


Topological everything

- Chern insulator
- Z_2 topological insulator
- topological crystalline insulators
- topological superconductors
- Dirac semi-metals
- Weyl semi-metals
- Line node semi-metals
- Fermi surface
- ...

Why correlations?

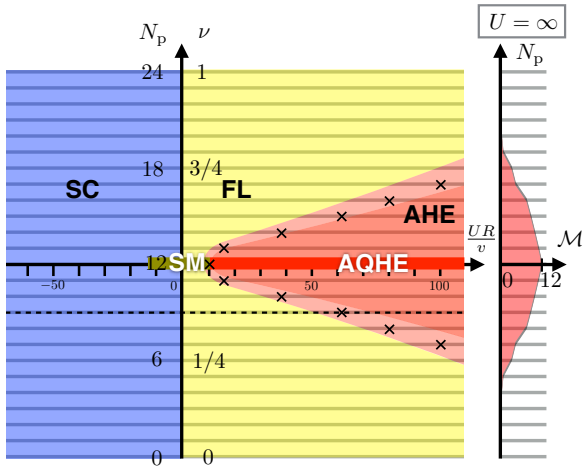
w/o interactions



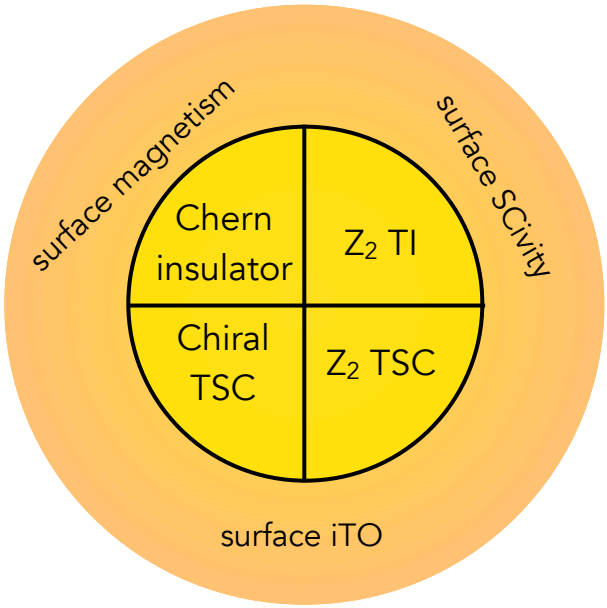
+ Weyl, Dirac...

Why correlations?

- Distinct surface states

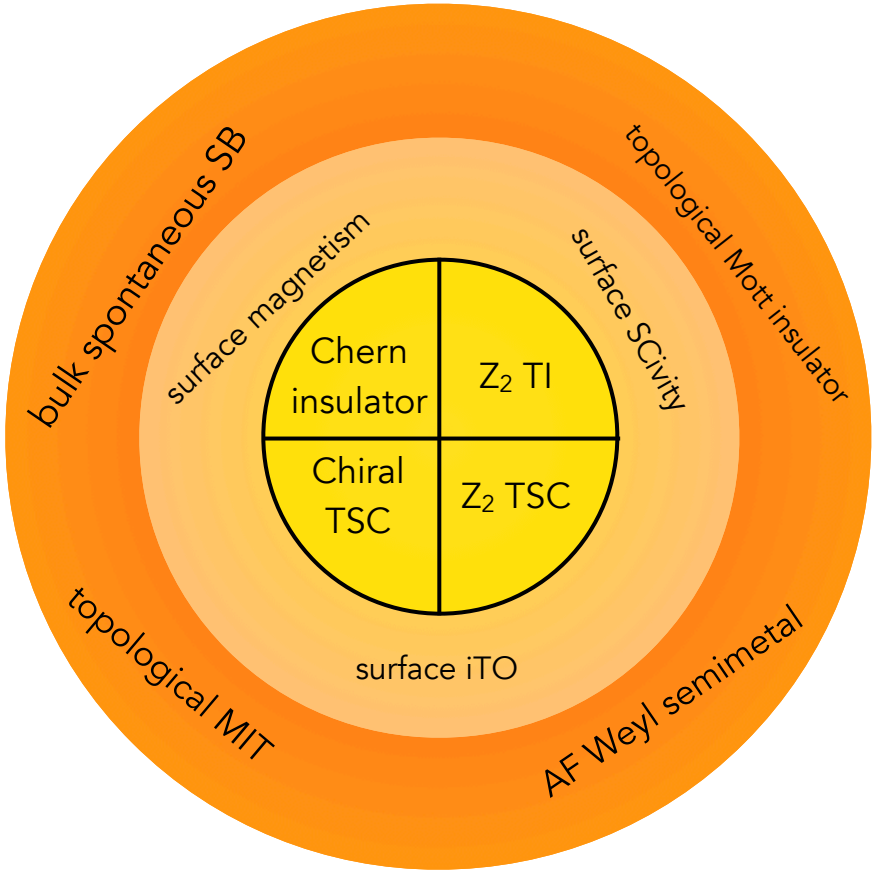


e.g. T. Neupert *et al, 2015*



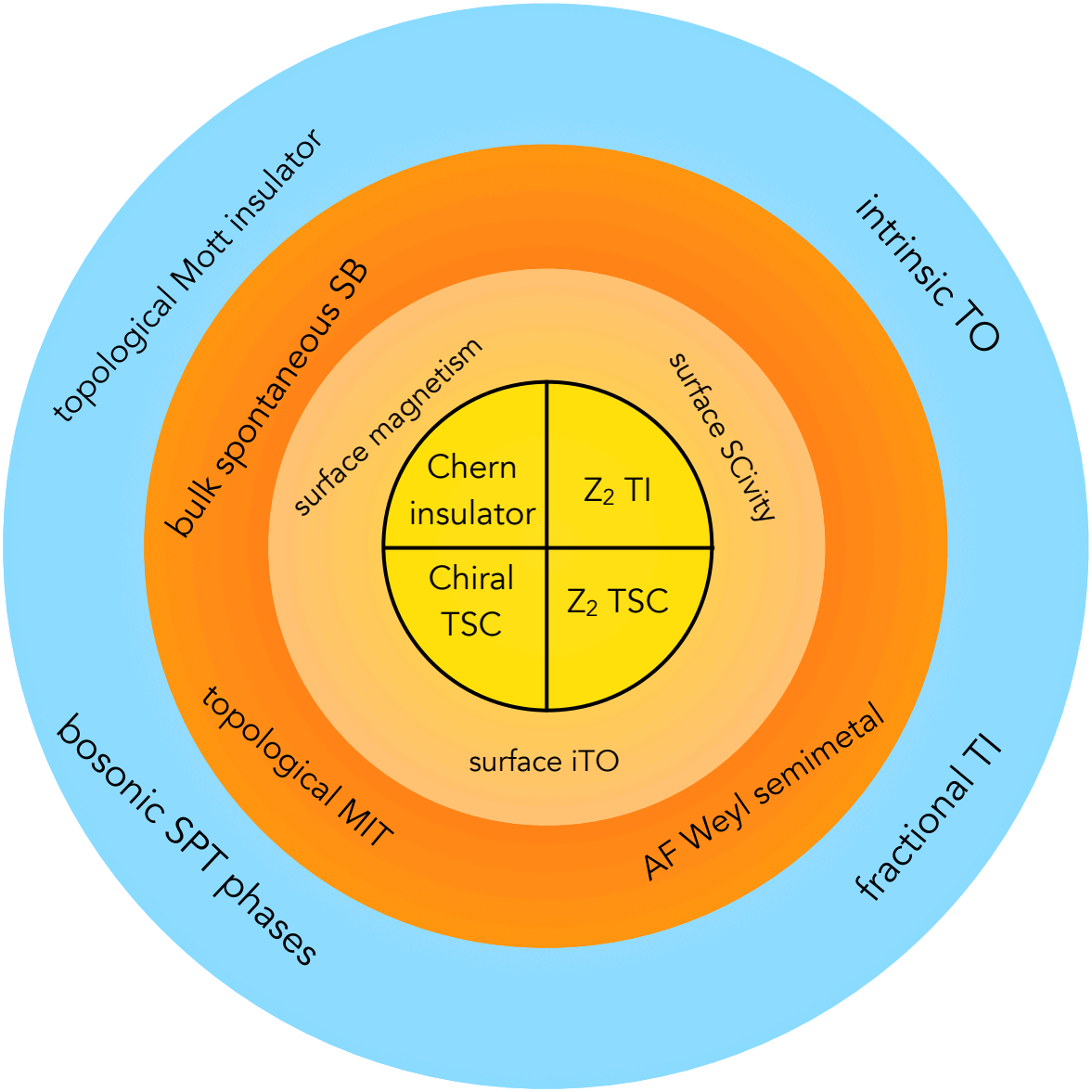
Why correlations?

- Distinct surface states
- Control of bulk topology by spontaneous symmetry breaking



Why correlations?

- Distinct surface states
- Control of bulk topology by spontaneous symmetry breaking
- Entirely new phases requiring strong interactions



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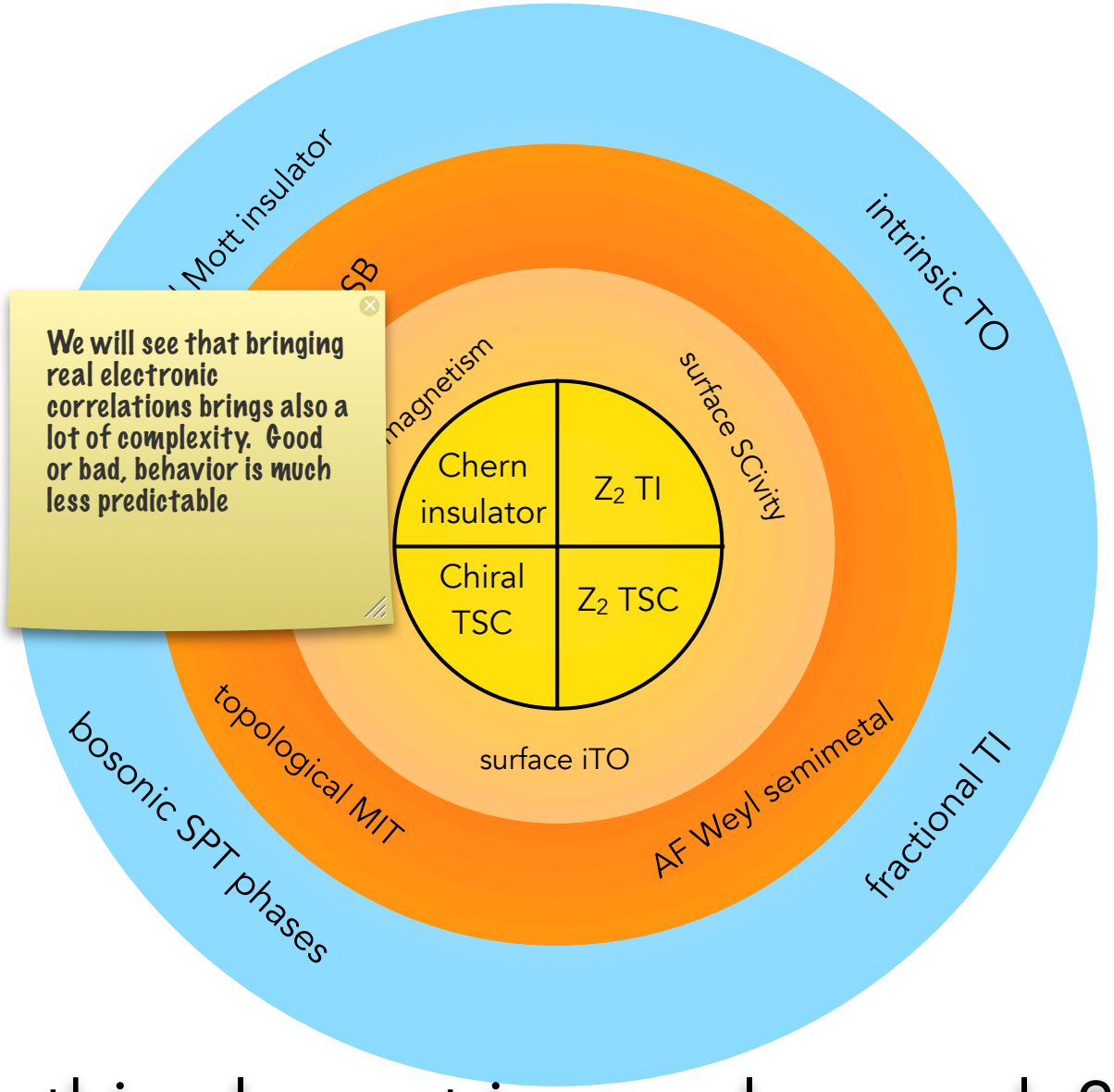
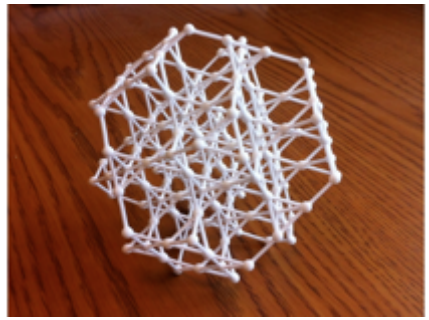
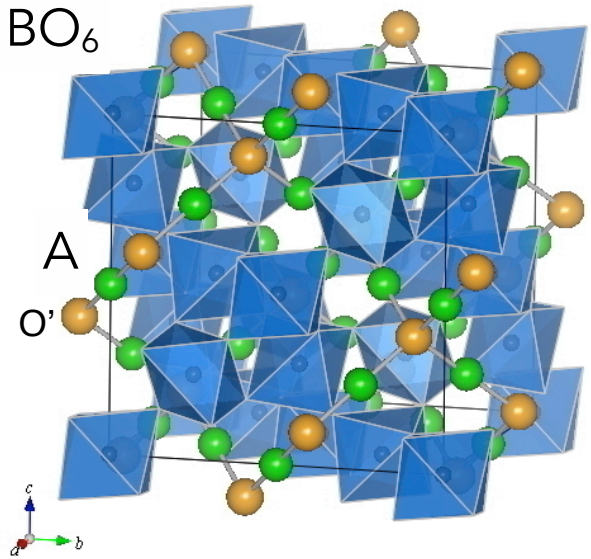


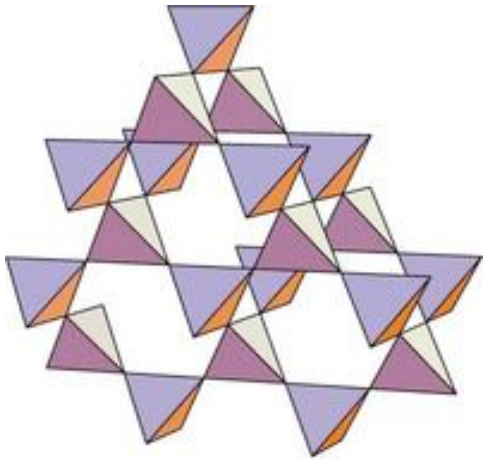
This talk: how does this play out in a real example?

Pyrochlores





$A_2B_2O_7$



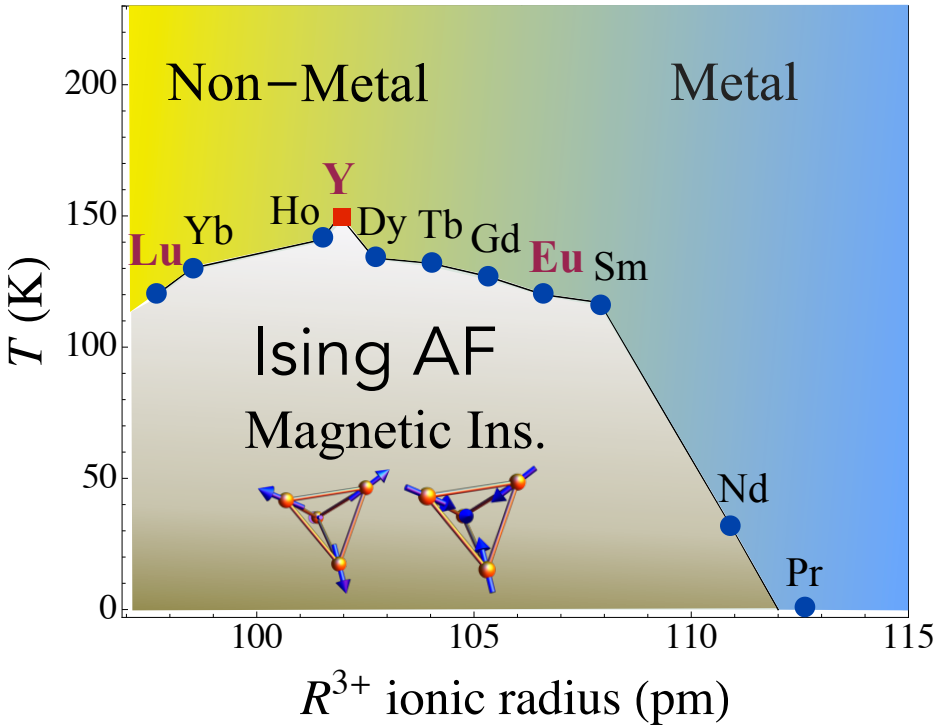
A (B) sublattice

A=Y,Ln ⟵ f-electron moments, except

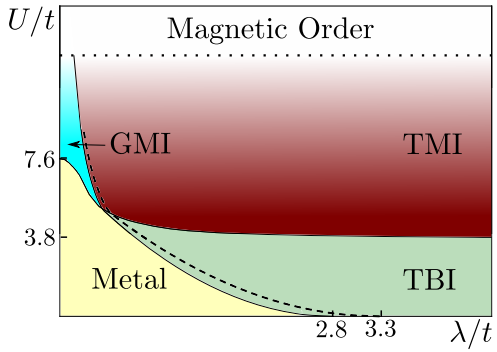
B = Ir when A = Y, Eu

Pyrochlore iridates

- Continuous magnetic/metal-insulator transitions (compatible with Ising)



Yanagashima+Maeno, JPSJ 2001
K. Matsuhira et al, JPSJ 2011
W. Witczak-Krempa et al, ARCMP 2013



D. Pesin + LB, 2010
Topological MI?

Pyrochlore iridates

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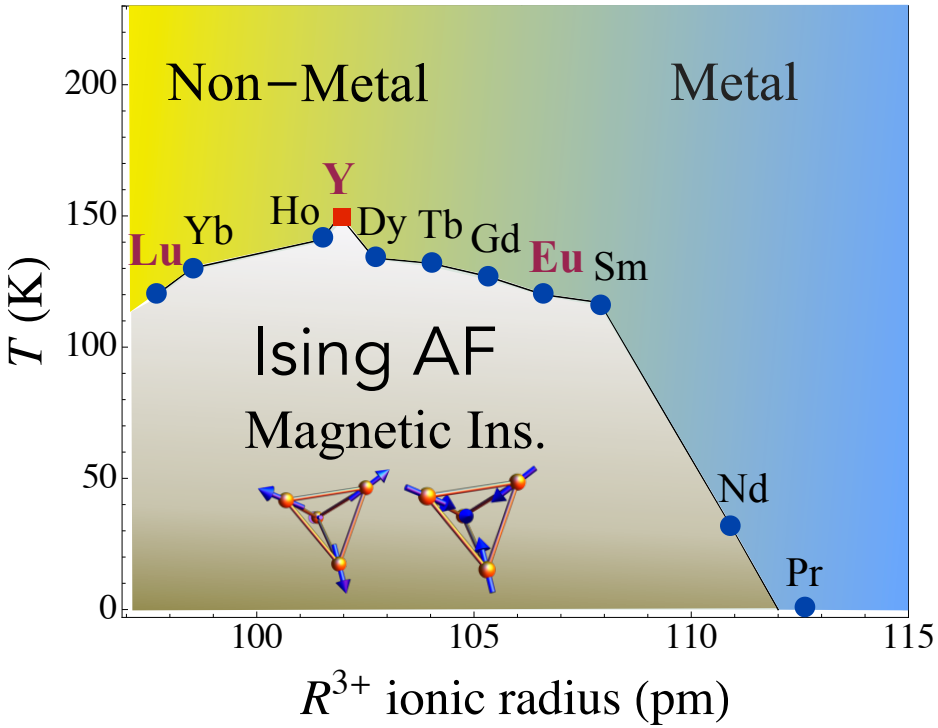

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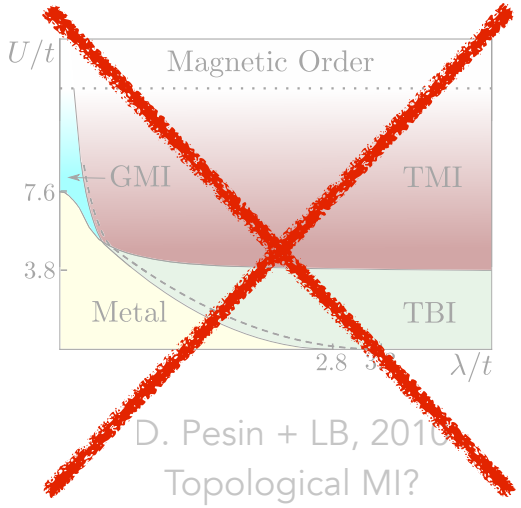

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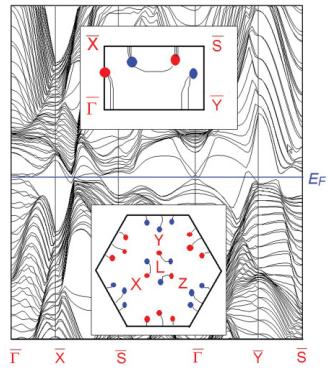
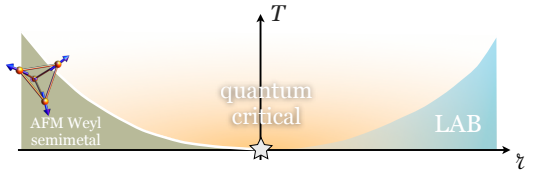


X. Wan *et al*, 2011
AF Weyl semimetal?

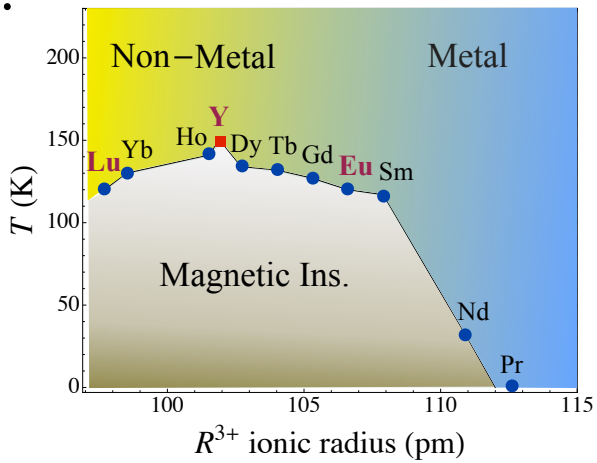


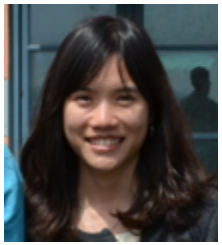
L. Savary *et al*, 2014 - topological QCP?

Ingredients of a theory

- Unusual electronic structure
- Ir e-e Hubbard interactions
- Rare earth moments?

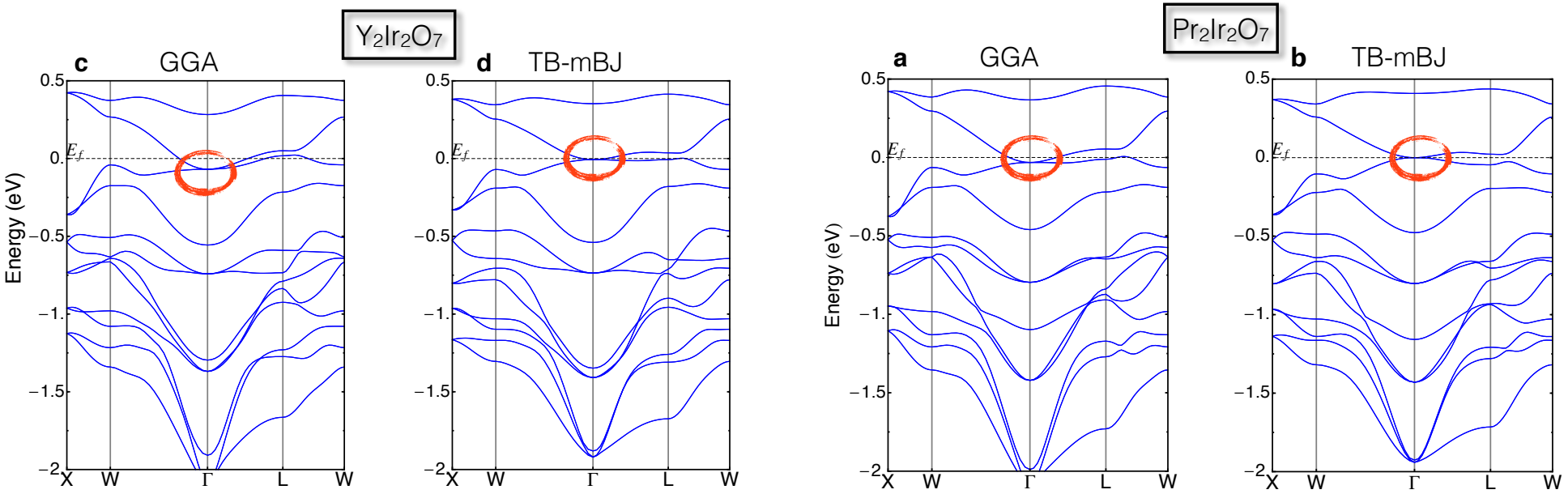
probably not?

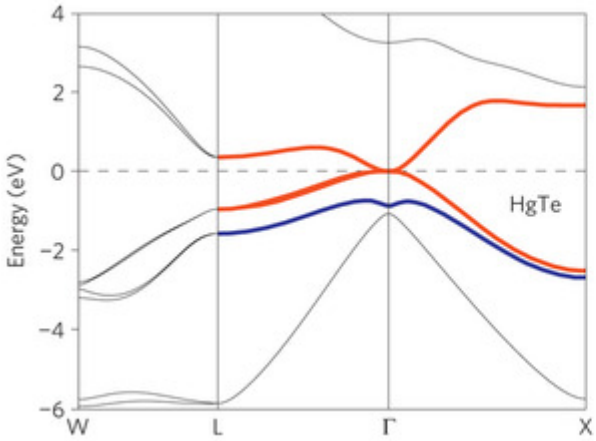




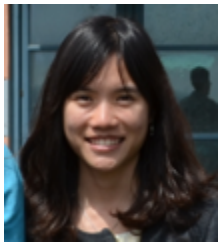
T. Kondo *et al*, Nat. Comm., 2015

Paramagnetic electronic structure



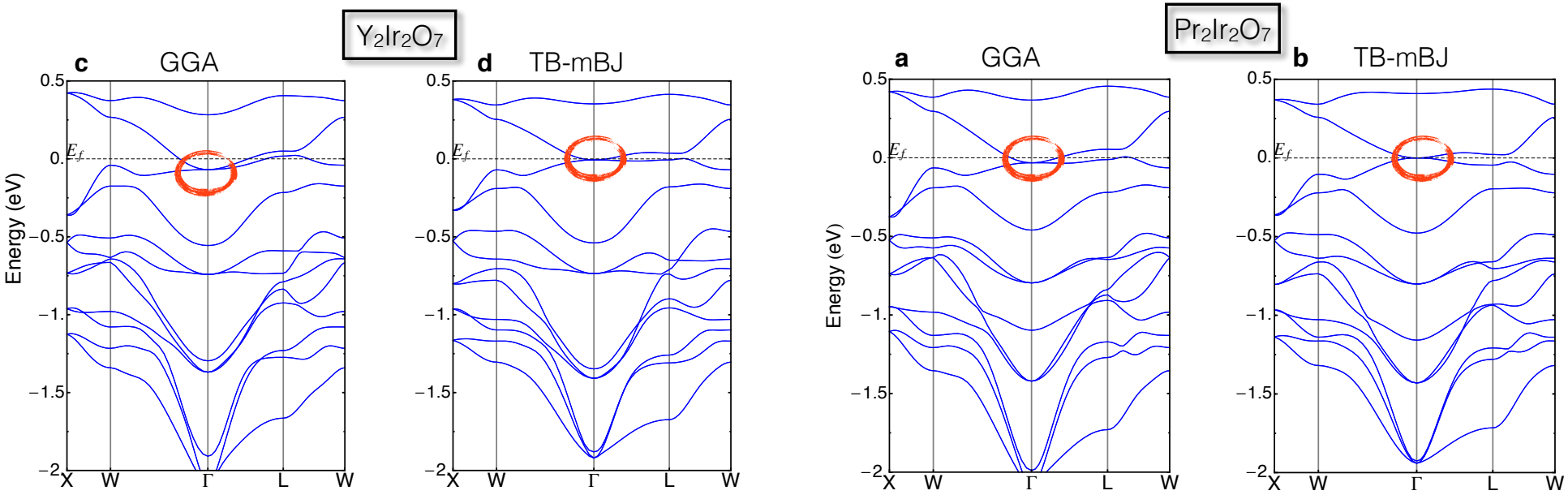


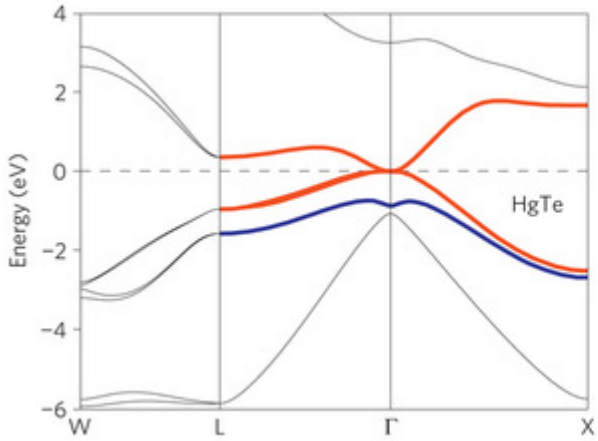
Γ_8 4-dimensional irrep guaranteed by cubic symmetry and time reversal



T. Kondo *et al*, Nat. Comm., 2015

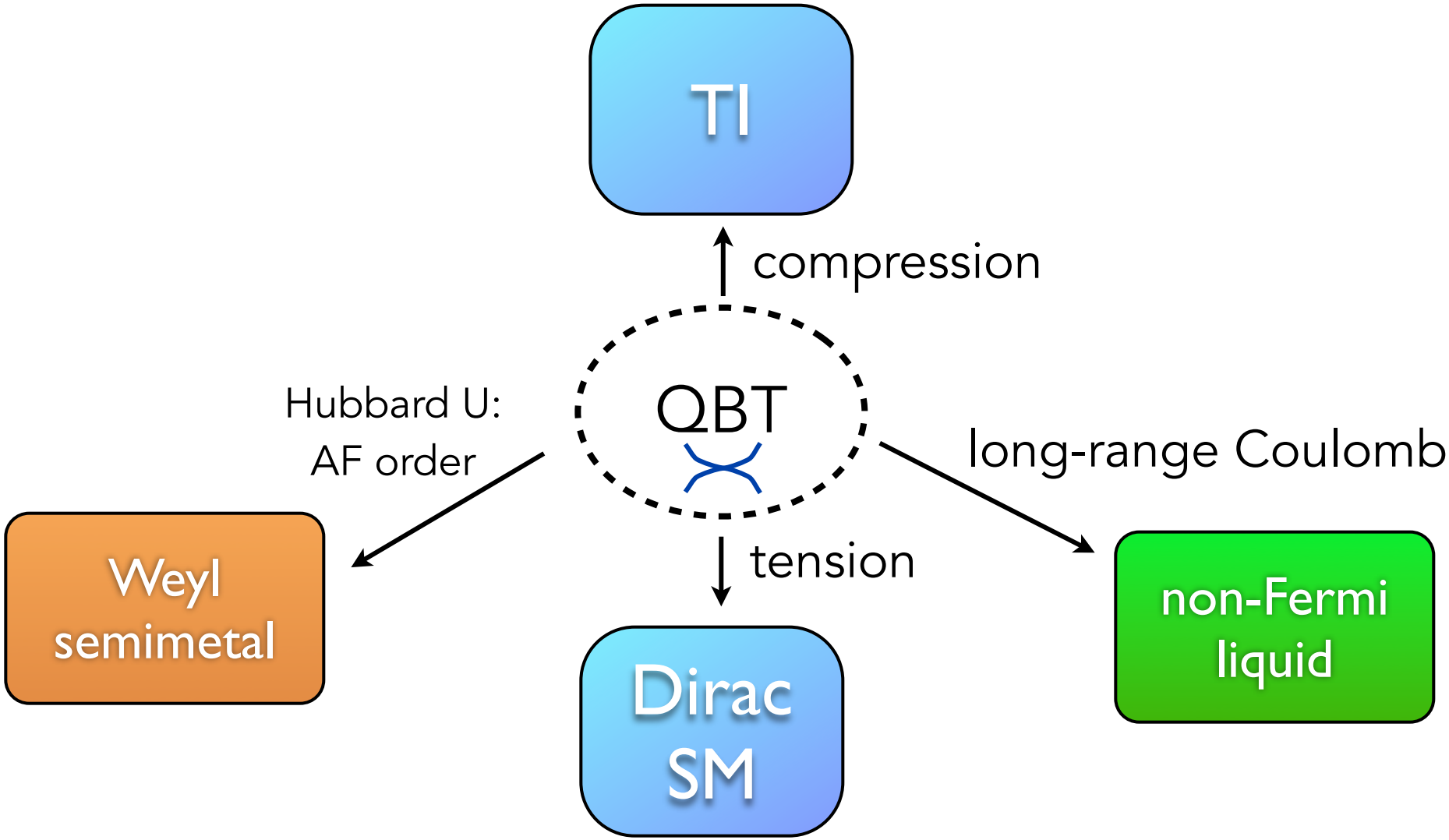
Paramagnetic electronic structure

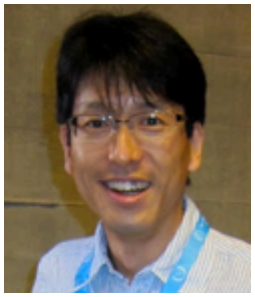




semi-metal is “easy” to convert to insulator: Mott transition can occur with weak order

Proximate phases





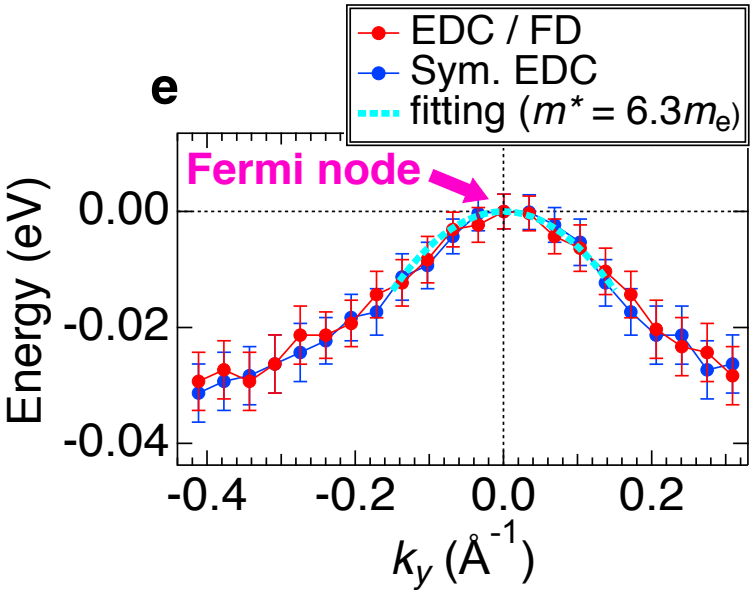
ARPES

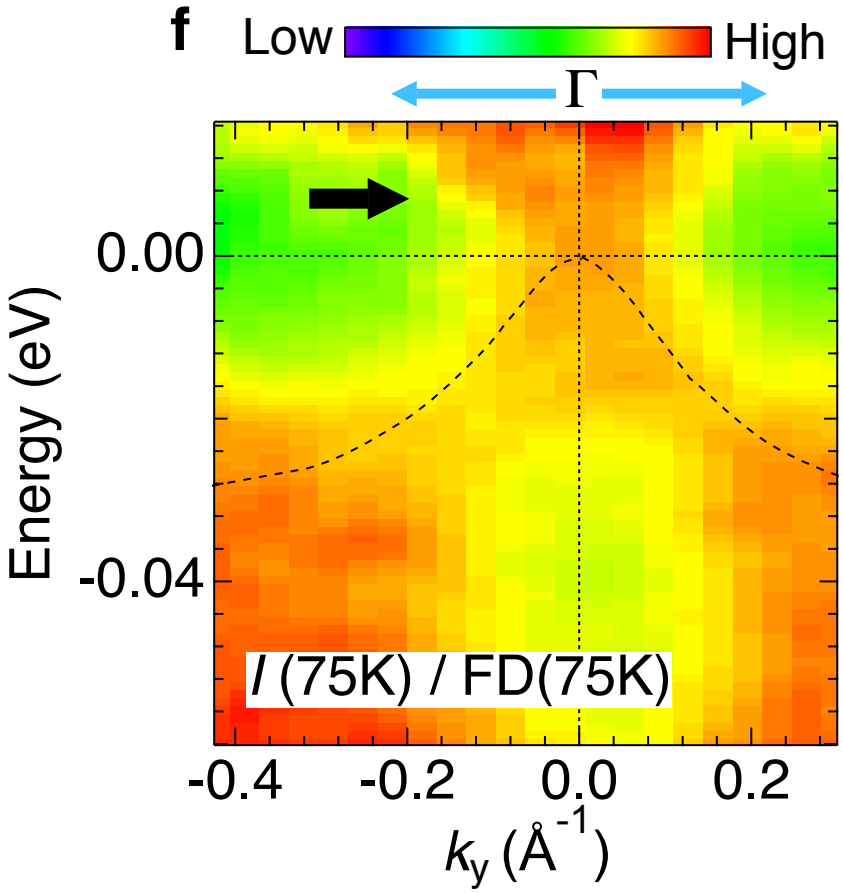
T. Kondo *et al*, Nat. Comm., 2015

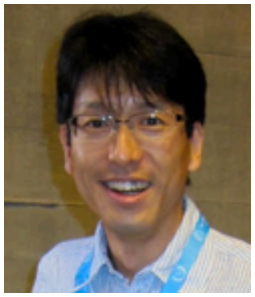
$Pr_2Ir_2O_7$ S. Nakatsuji

T. Kondo

S. Shin







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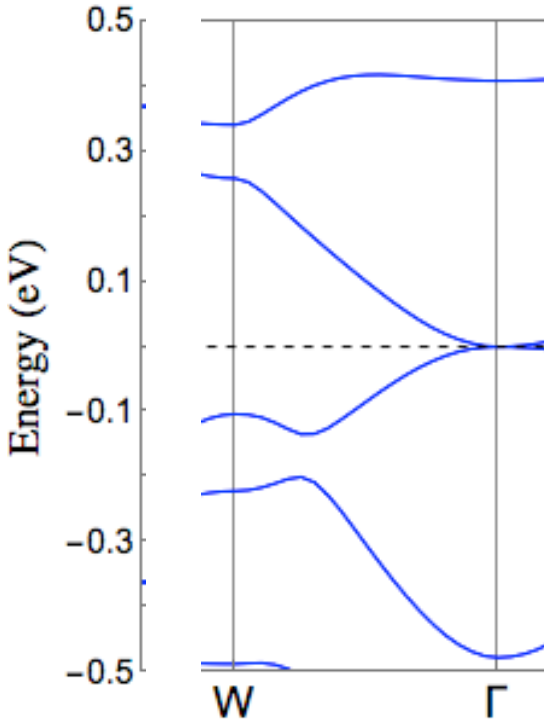
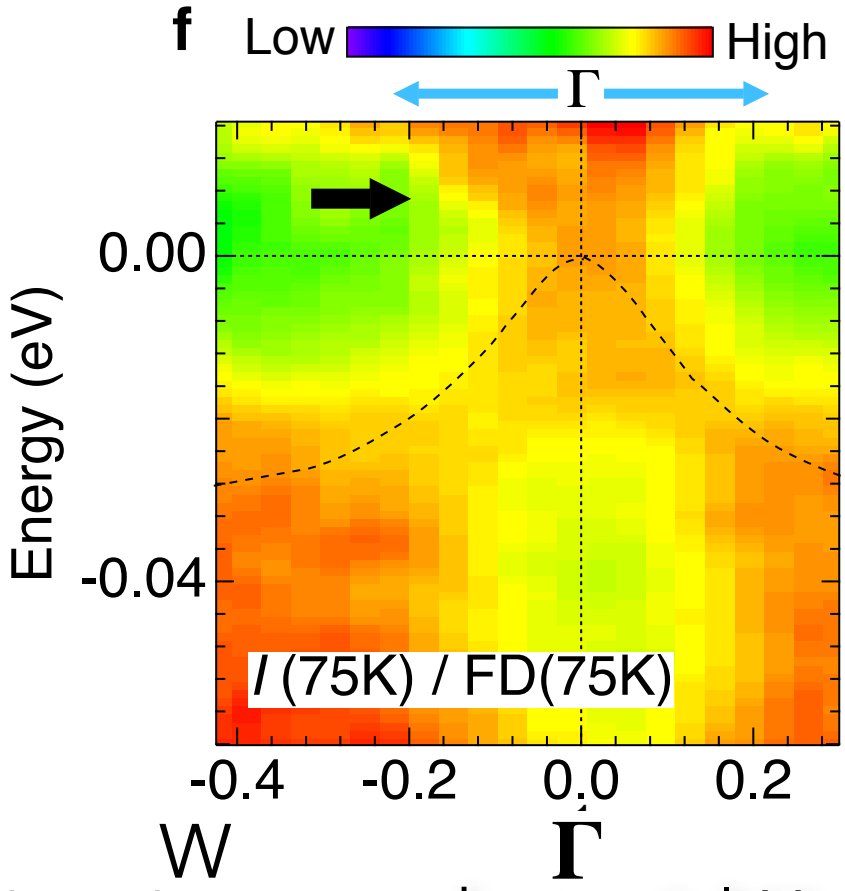
$Pr_2Ir_2O_7$ S. Nakatsuji T. Kondo S. Shin

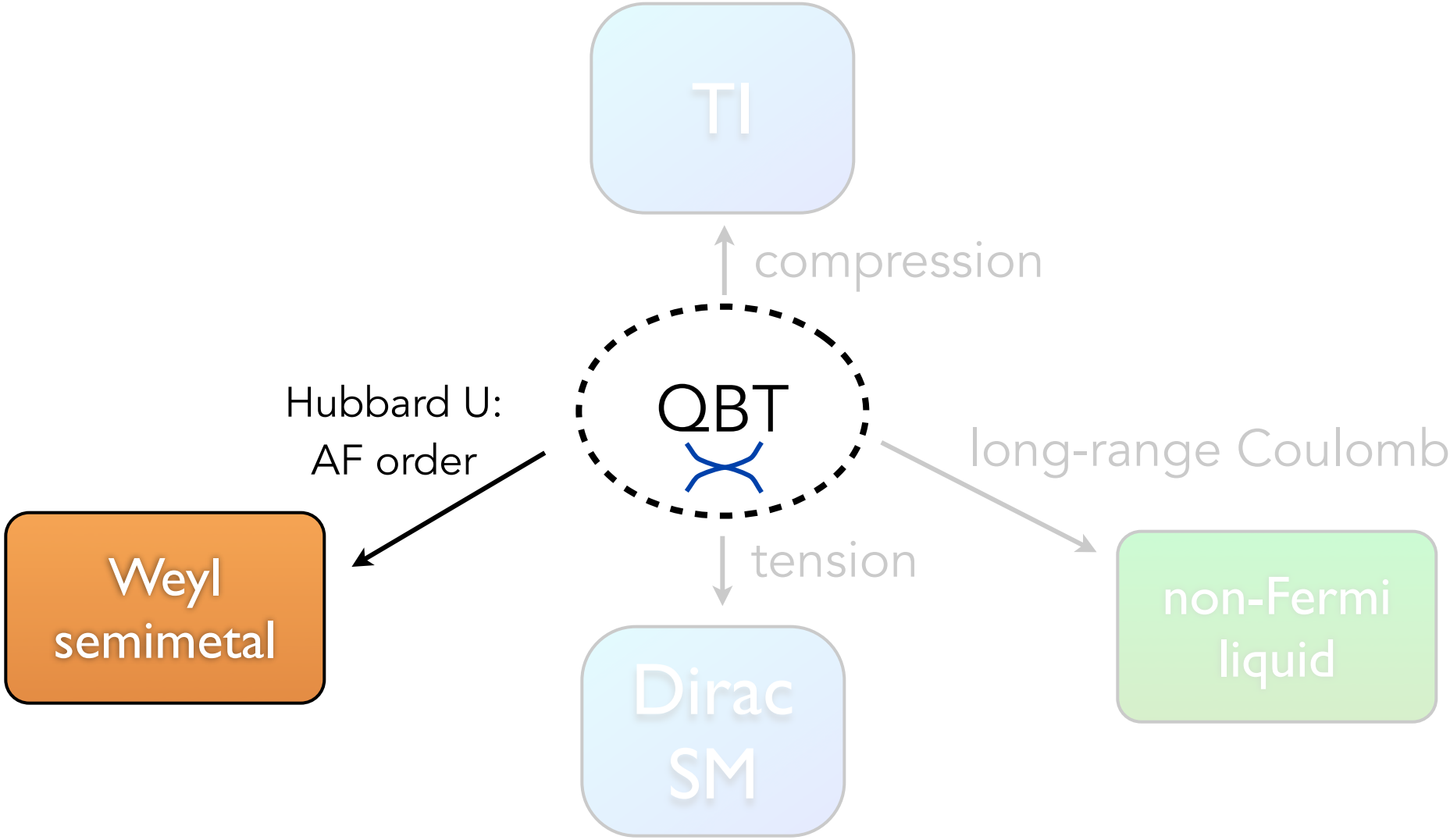




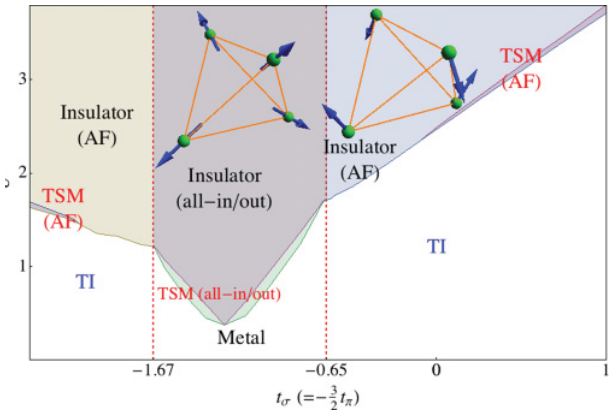
overall bandwidth ~ 3-5 times reduced!!

substantial U

Proximate phases

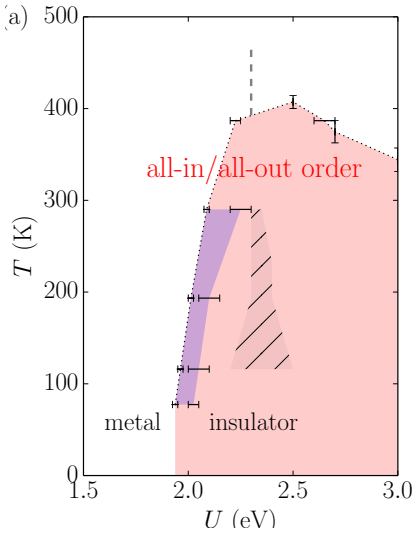


Ordering: theory



W. Witzak-Krempa + YB Kim, 2012

Hartree-Fock

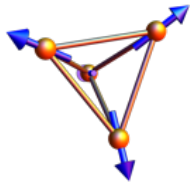


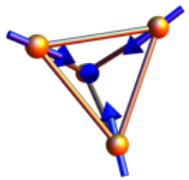
H. Shinaoka *et al*, 2015

DMFT

Jay-Z model

$$H = J_z \sum_{\langle i,j \rangle} S_i^z S_j^z$$





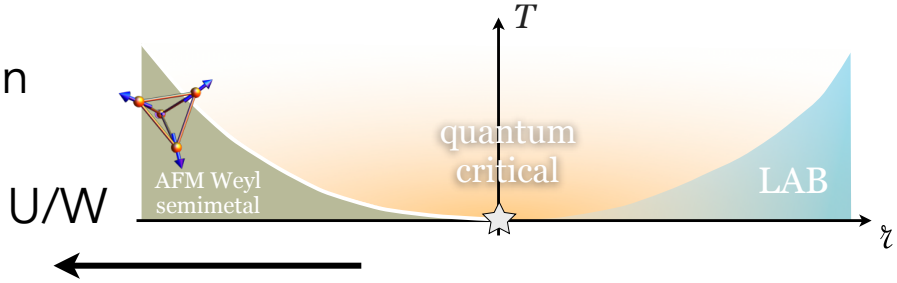
$J_z < 0$: all-in/all-out order

superexchange

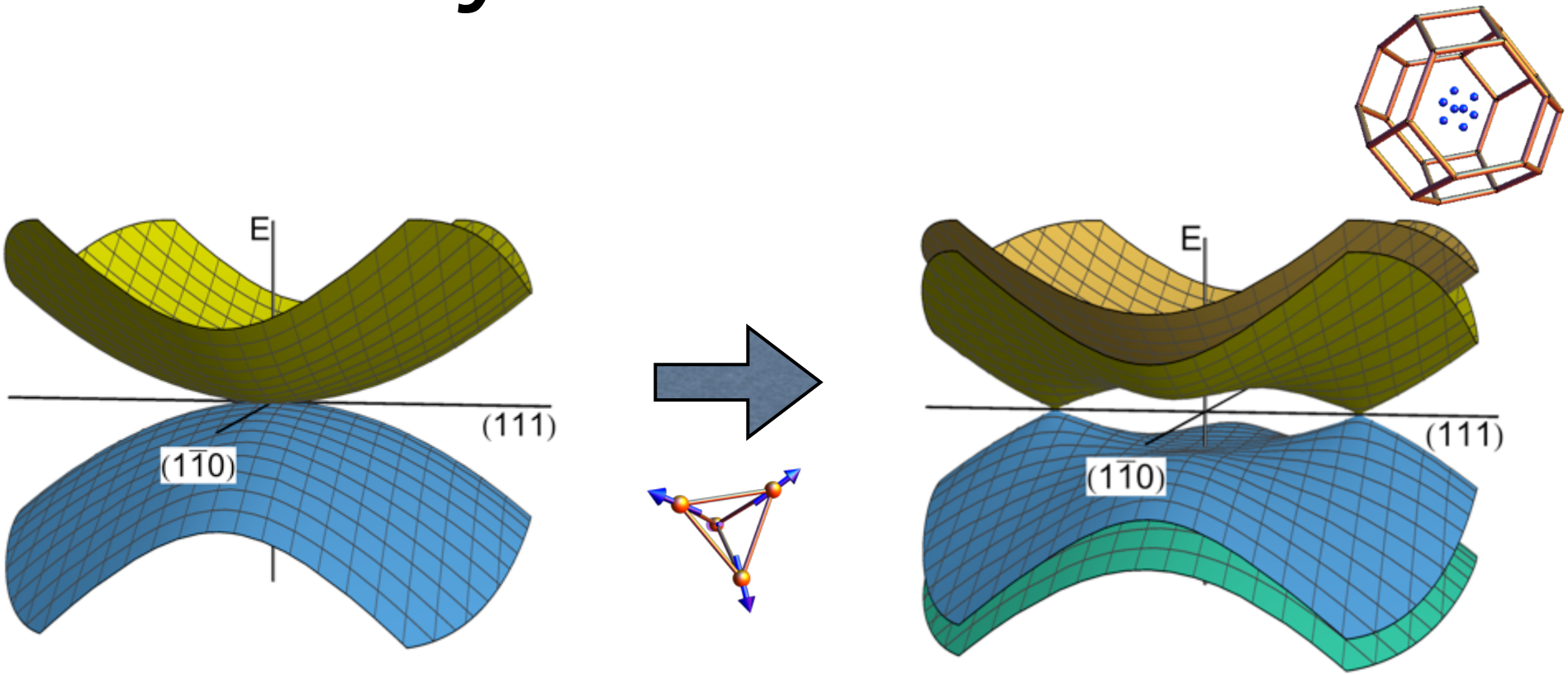
- General agreement: transition to AIAO Ising AF order

✦Quantum critical theory of this transition

L. Savary *et al*, 2014 - topological QCP



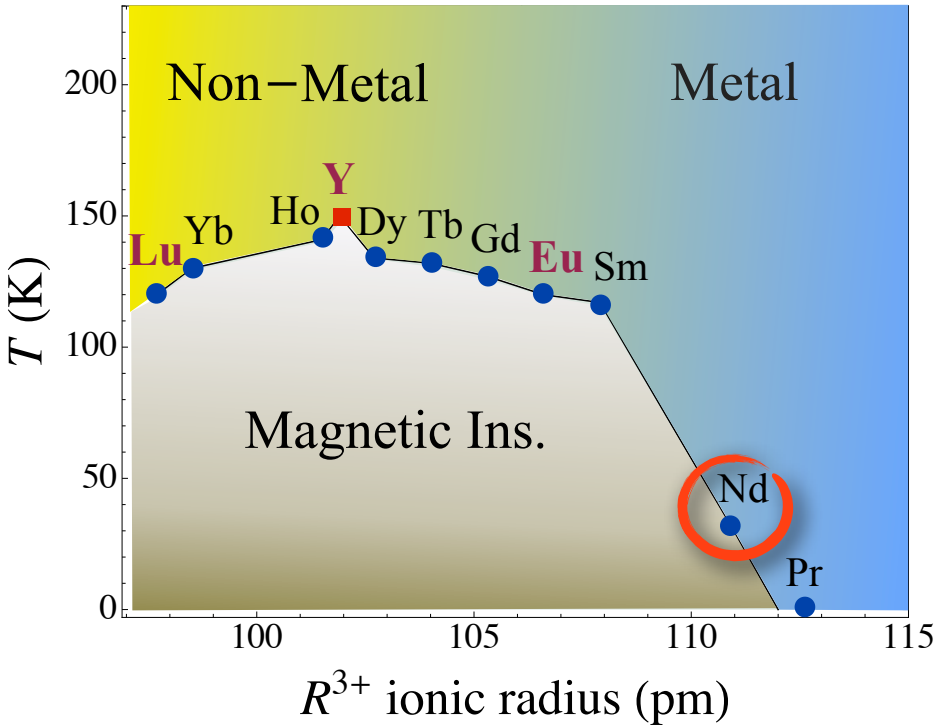
Weyl semimetal



If quasiparticle picture applies at low energy, a *weakly* ordered AIAO state *must* be a Weyl semimetal

Weyl?

- Weyl semimetal?

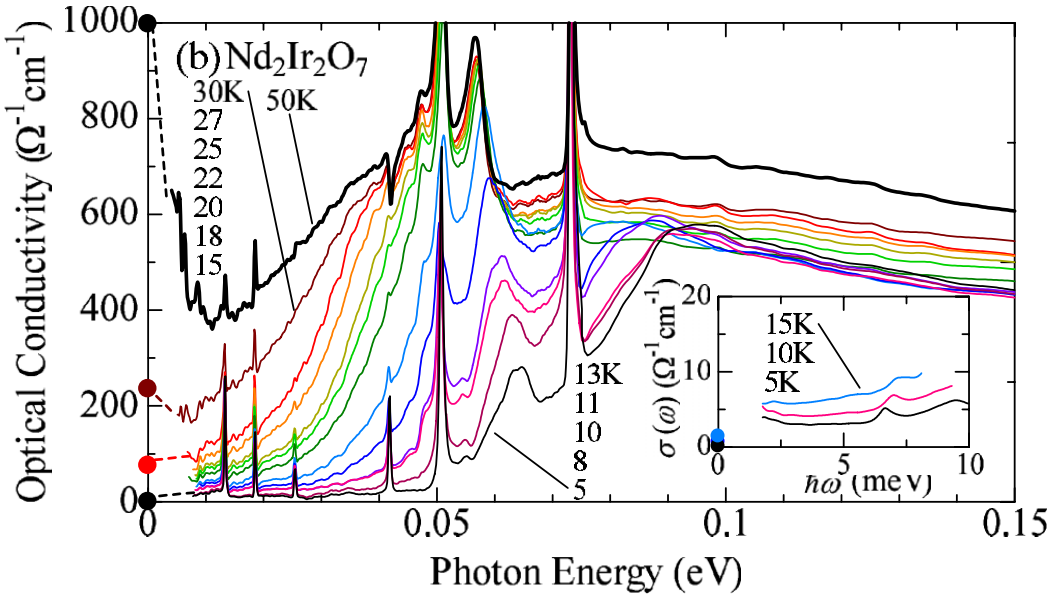


Yanagashima+Maeno, JPSJ 2001
K. Matsuhira et al, JPSJ 2011
W. Witczak-Krempa et al, ARCMP 2013

Best candidate should be $Nd_2Ir_2O_7$

Weyl not?

K. Ueda *et al*, 2012

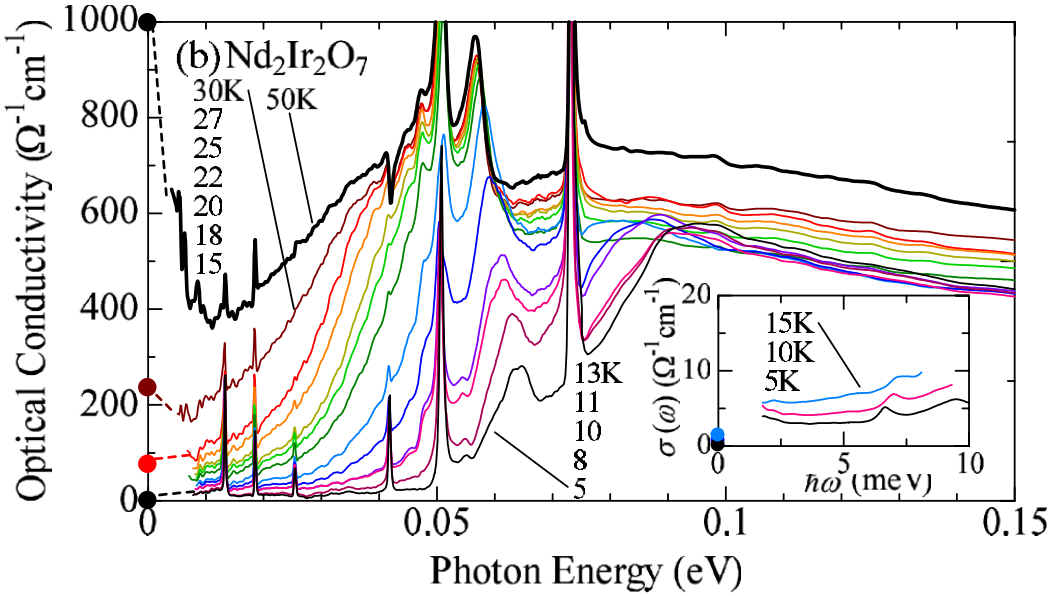


charge gap ~ 45meV

n.b. Gap ~ $18T_c$

Weyl not?

K. Ueda *et al*, 2012

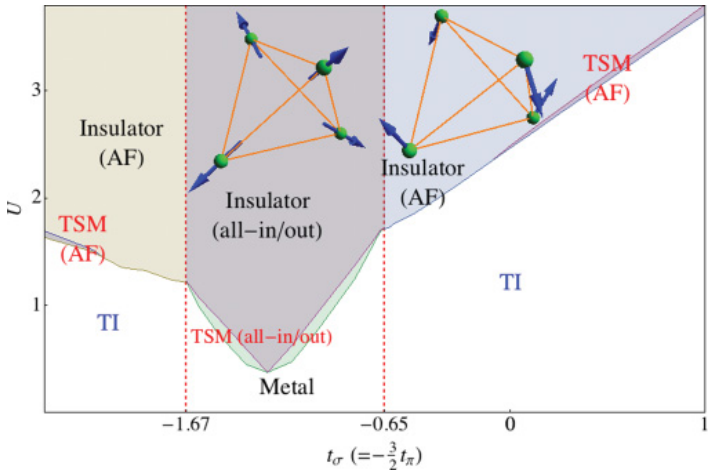


charge gap ~ 45meV

If quasiparticle picture applies at low energy, a *weakly* ordered AIAO state *must* be a Weyl semimetal

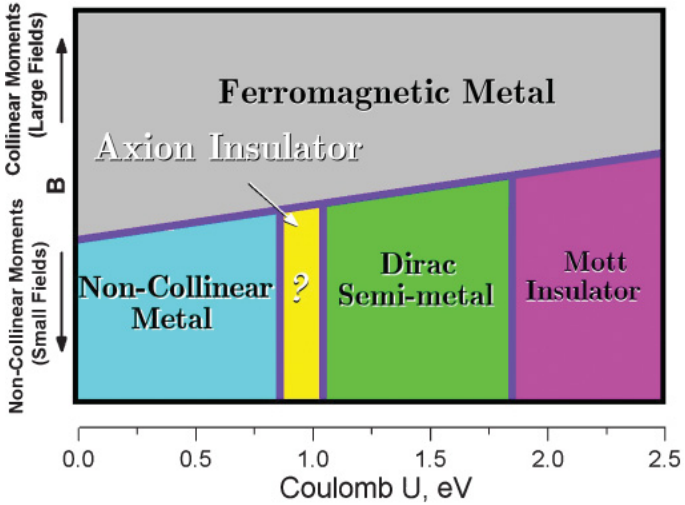
- ✦ Not weakly ordered?
- ✦ No quasiparticles?
- ✦ Weyl with very small DOS?

Weak or not?



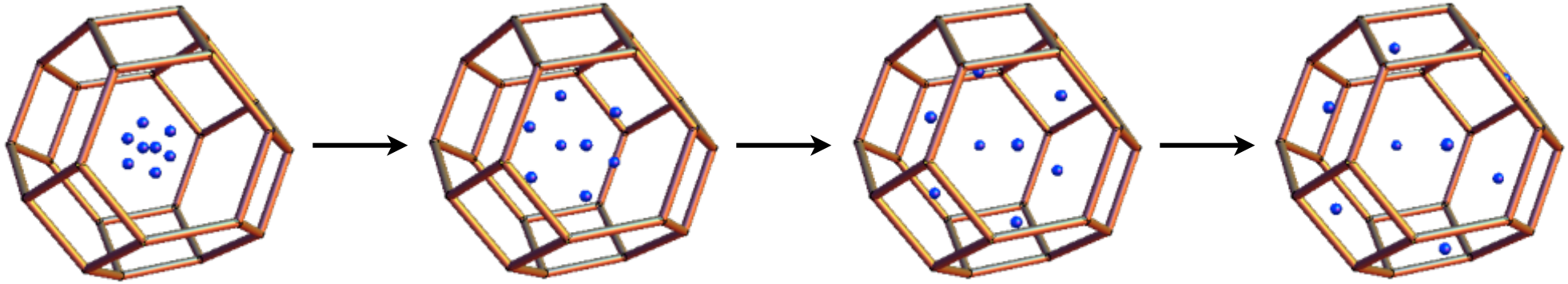
W. Witzak-Krempa + YB Kim, 2012

vs

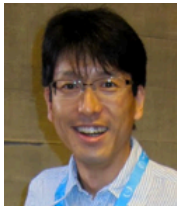


X. Wan *et al*, 2011

Weyl points move to zone boundary and annihilate with increasing order?

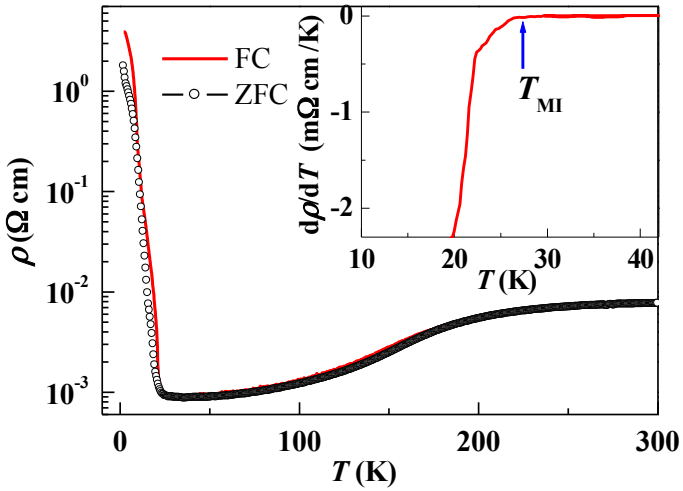


Could this have happened already for Nd?



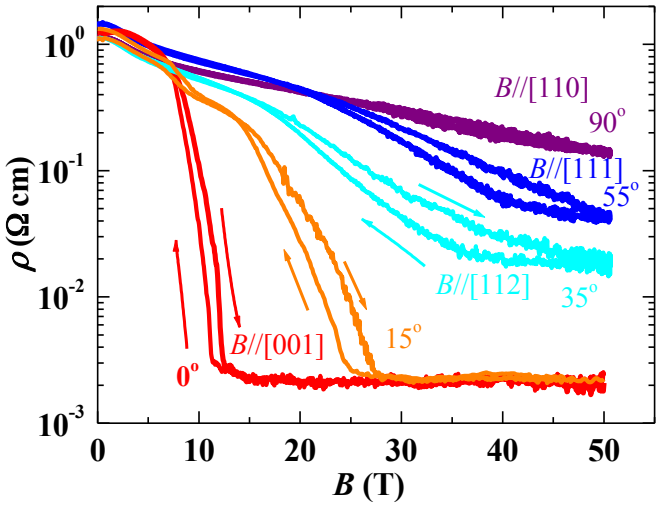
Zhaoming Tian *et al*, Nature Physics, 2015

Transport



To explore this in more detail, let's look at transport

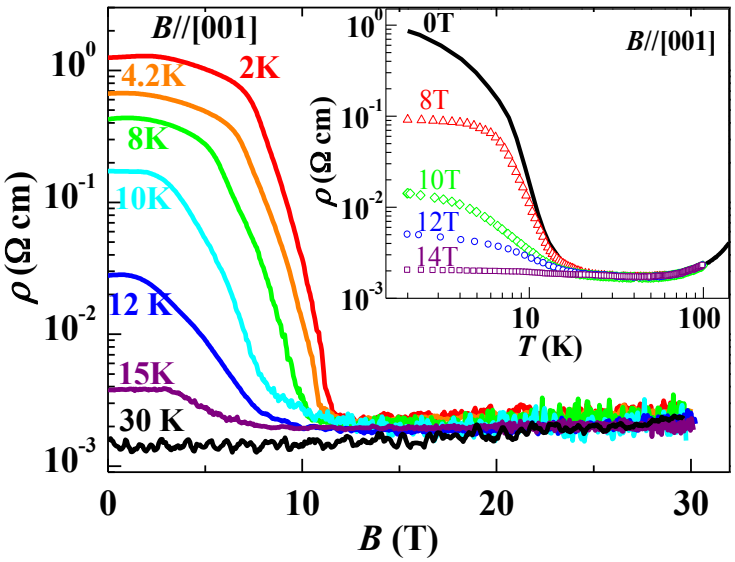
- Seems to b with hard gap
- thermal tra continuous

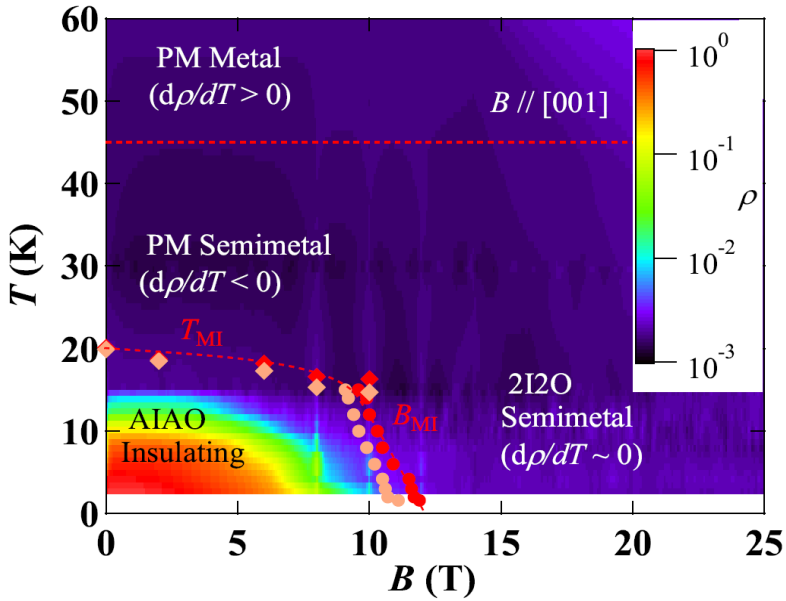


- However, abrupt first order transition appears at low T in a field
- Insulator-metal transition *only* occurs for fields along (100)

Zhaoming Tian *et al*, Nature Physics, 2015

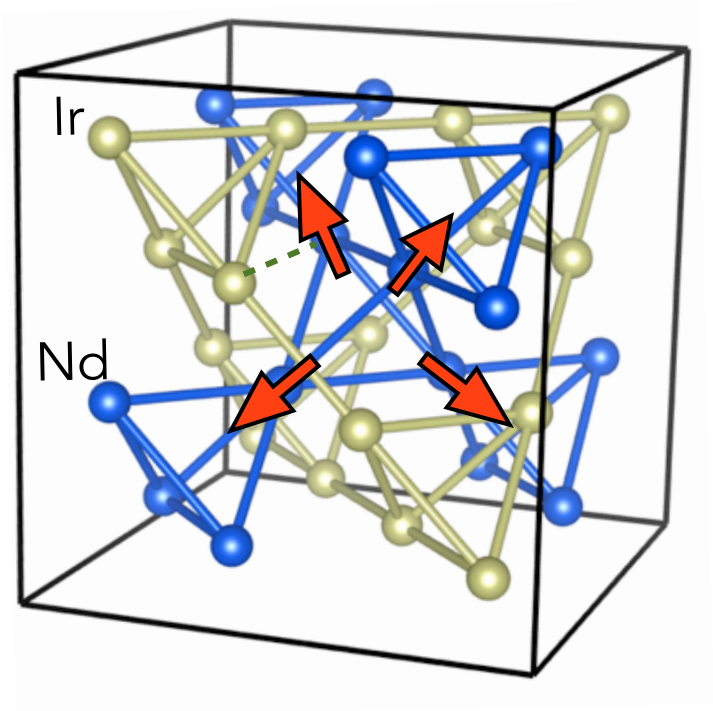
Metal-Insulator Transition



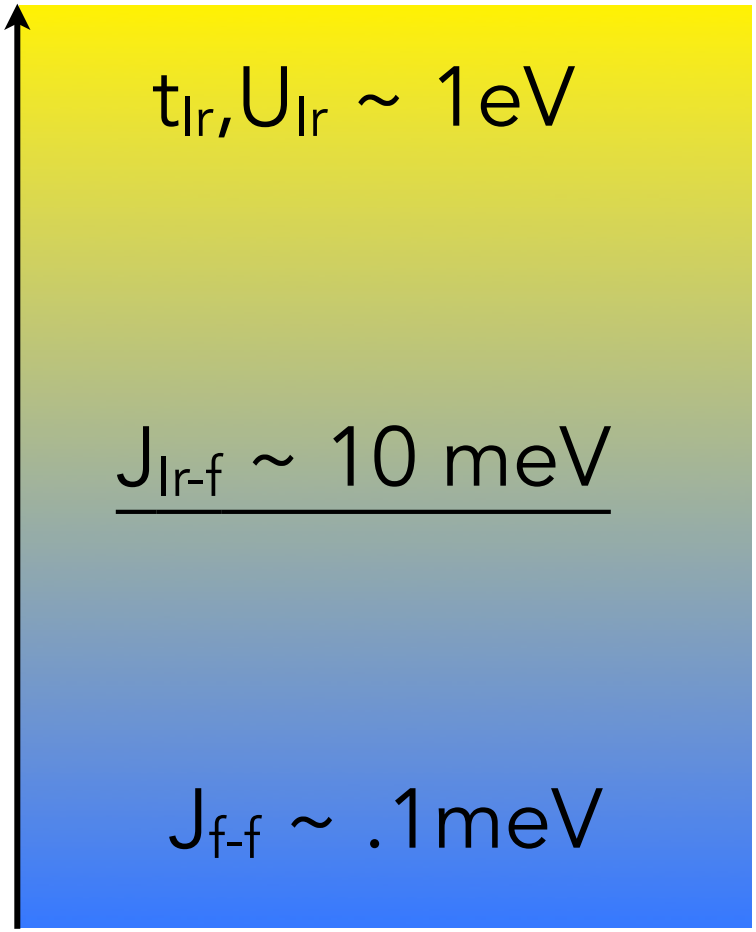


- First order transition at low temperature: mechanism of MIT is vanishing of condensation energy, not gap closing.
- Anisotropy: clear indication that Nd plays a direct role in the MIT - probably this is a unique feature for R=Nd

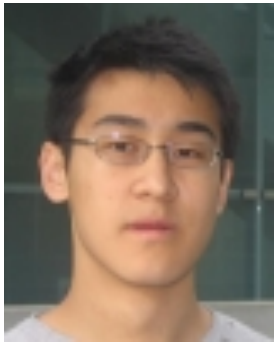
Nd physics



- Much of gap (45meV) is *due* to Nd-Ir exchange
- Intrinsic g-tensor anisotropy of Nd explains anisotropy of MIT



(100) field achieves maximum Nd polarization of 2in-2out type, "opposite" to AIAO Ising order

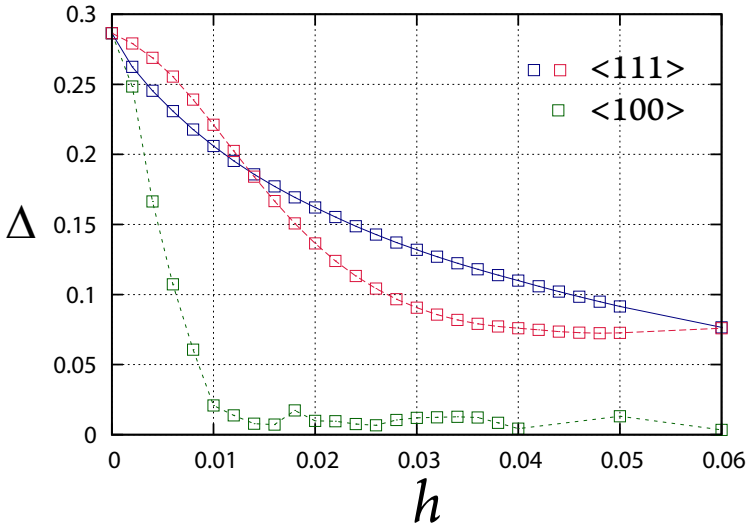


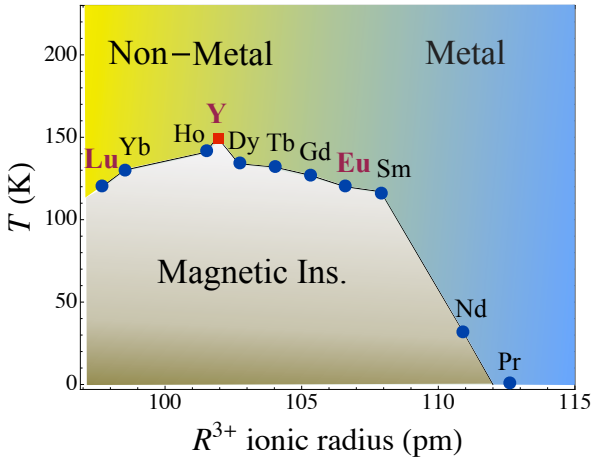
Anisotropy

- Nd sensitivity to direction is transferred to Ir

$$H_K = \sum_{ia} \vec{S}_i \cdot \mathrm{J}_{ia} \cdot \vec{\tau}_a$$

acts like h_{eff} ~10meV local field on Ir



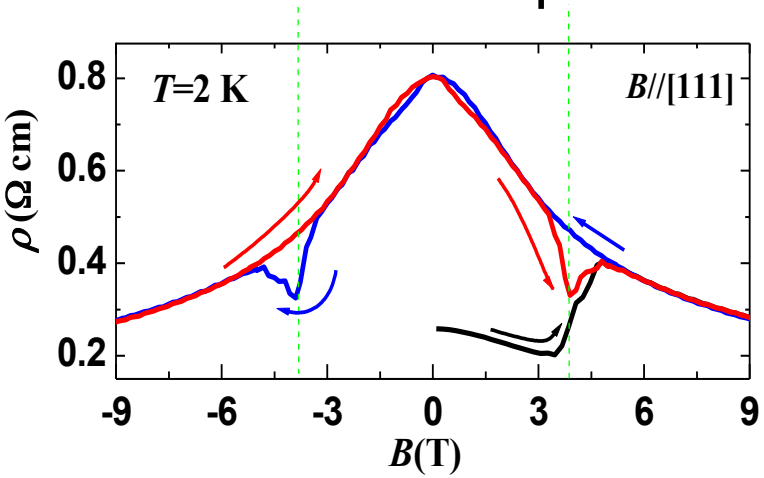


Hartree-Fock on Hubbard +Kondo lattice model

- h_{eff} is significant for Nd case
- can explain the anisotropy

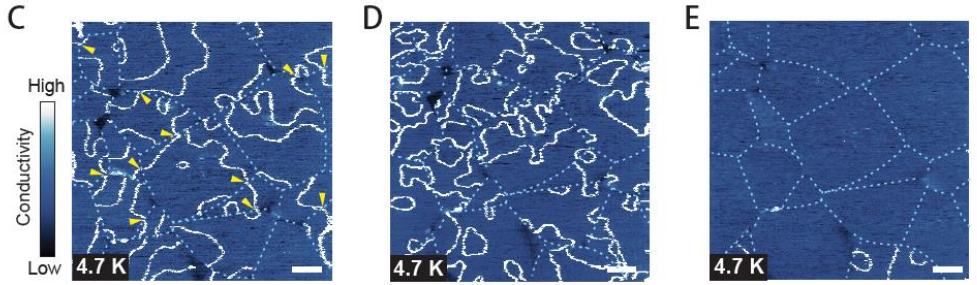
Domains

- Large magnetic moment of Nd allows manipulation of domains



Z. Tian *et al*, 2015

c.f. K. Ueda *et al* (2014)



local conductivity

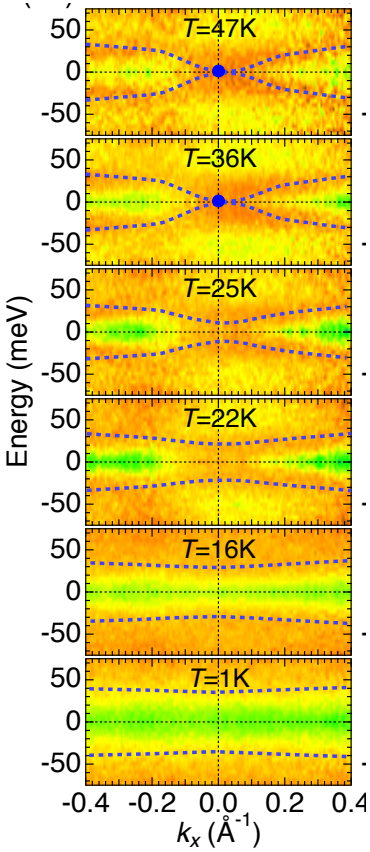
E. Y. Ma *et al*, 2015

conducting domain walls!

M. Nakayama *et al*, unpublished-- coming soon!

Quasiparticles?

- Already observed bandwidth reduction in $Pr_2Ir_2O_7$ - what happens for Nd?



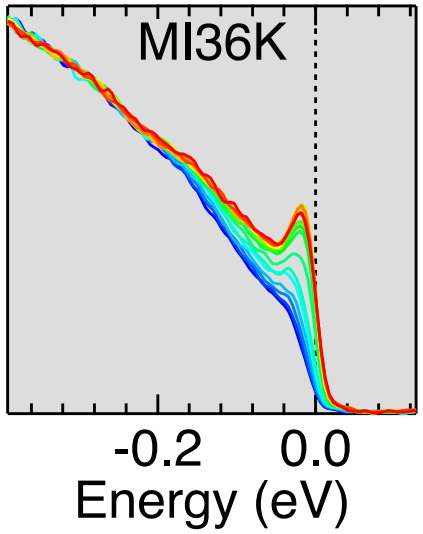
$T>T_c$: like Pr

$T=T_c$: no precursor - Slater

$T < T_c$: gap developing

Slater to Mott crossover?

$T << T_c$: remarkably flat

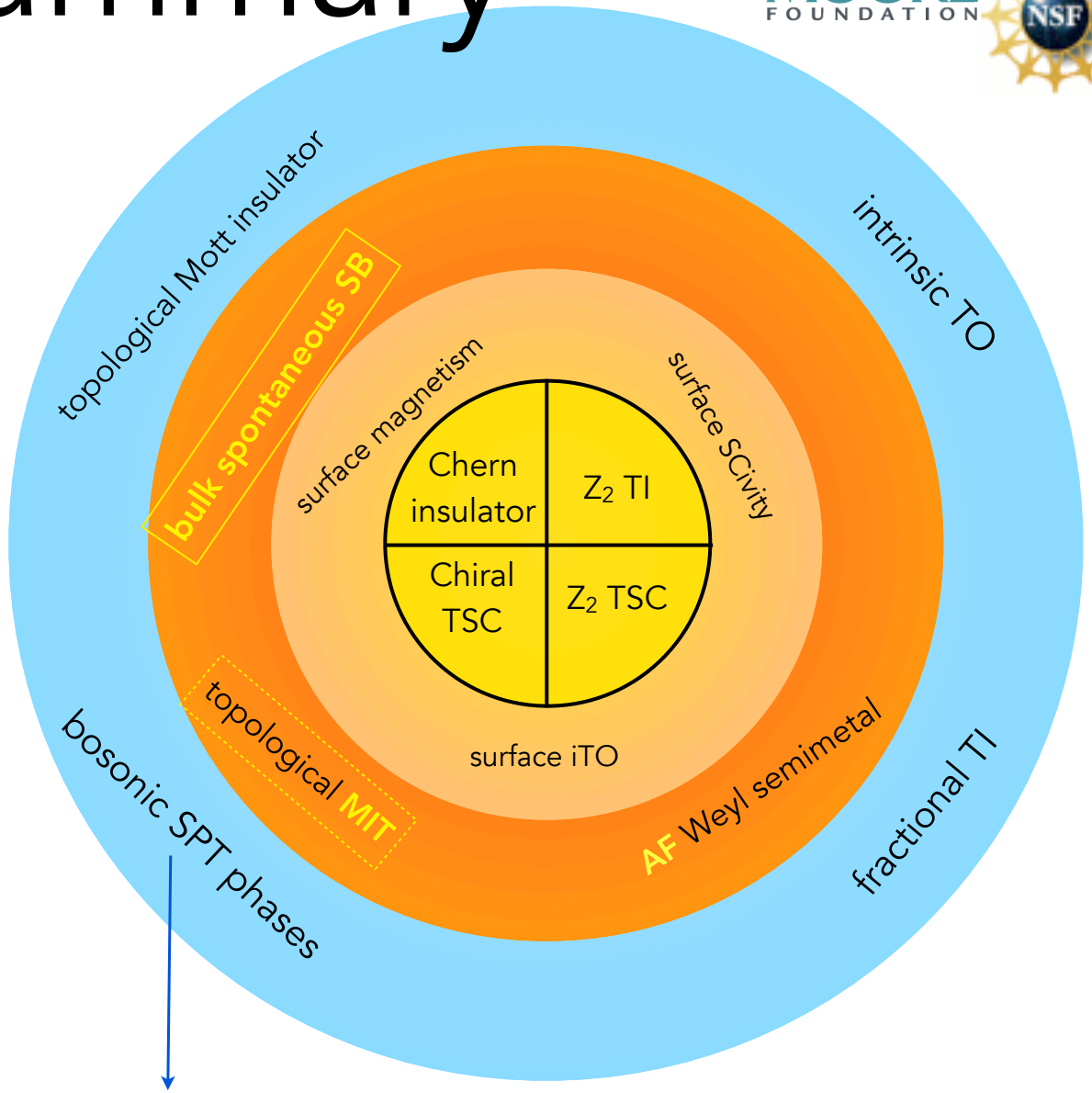


loss of quasiparticle peak

In strong Mott localized regime non-trivial band topology is unlikely

Summary

- Pyrochlore iridates show a rich phenomenology with nodal and gapped states, metal-insulator transitions, and strong anisotropic response
- Correlations induce antiferromagnetism but also Mott localization, which, helped by Nd f-moments, seems to subdue the Weyl fermions expected from the former alone
- Quite a bit still to explore! Correlated materials prove surprising and challenging



Advertisement: Zhen Bi *et al* , arXiv:1602.03190