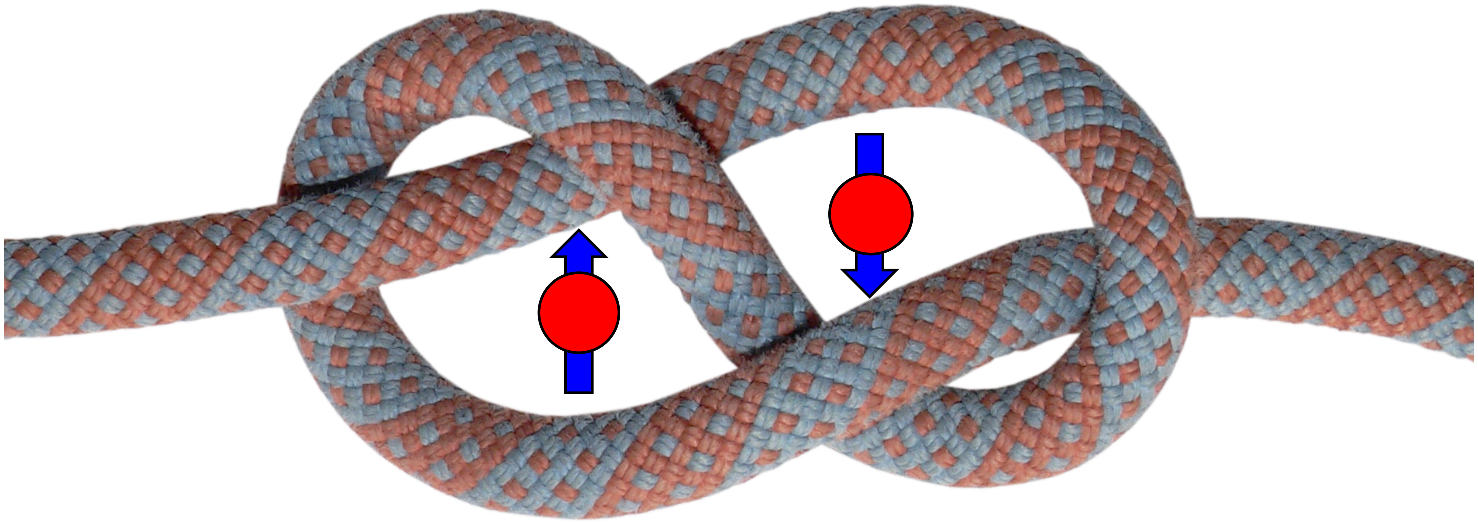
# Oxide Heterostructures
## A route to engineering topological phases of matter

**Arun Paramekanti**
**(University of Toronto)**



Seminar, College de France (Paris, 26 May 2016)

Funding: UNIVERSITY OF TORONTO NSERC CRSNG CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH

# Topology in Everyday Life

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**Football**

**Genus = 0**

# Topology in Everyday Life

**Football**

**Genus = 0**

**Toronto - Winter travel**

**Genus = 1**

# Topology in Everyday Life

**Football**

**Genus = 0**

**Toronto - Winter travel**

**Genus = 1**

**Breakfast**

**Genus = 1**

# Topology in Everyday Life

**Football**

**Genus = 0**

**Toronto - Winter travel**

**Genus = 1**

**Breakfast?**

**Genus = 1**

# Topology in Everyday Life

**Football**

**Genus = 0**

**Toronto - Winter travel**

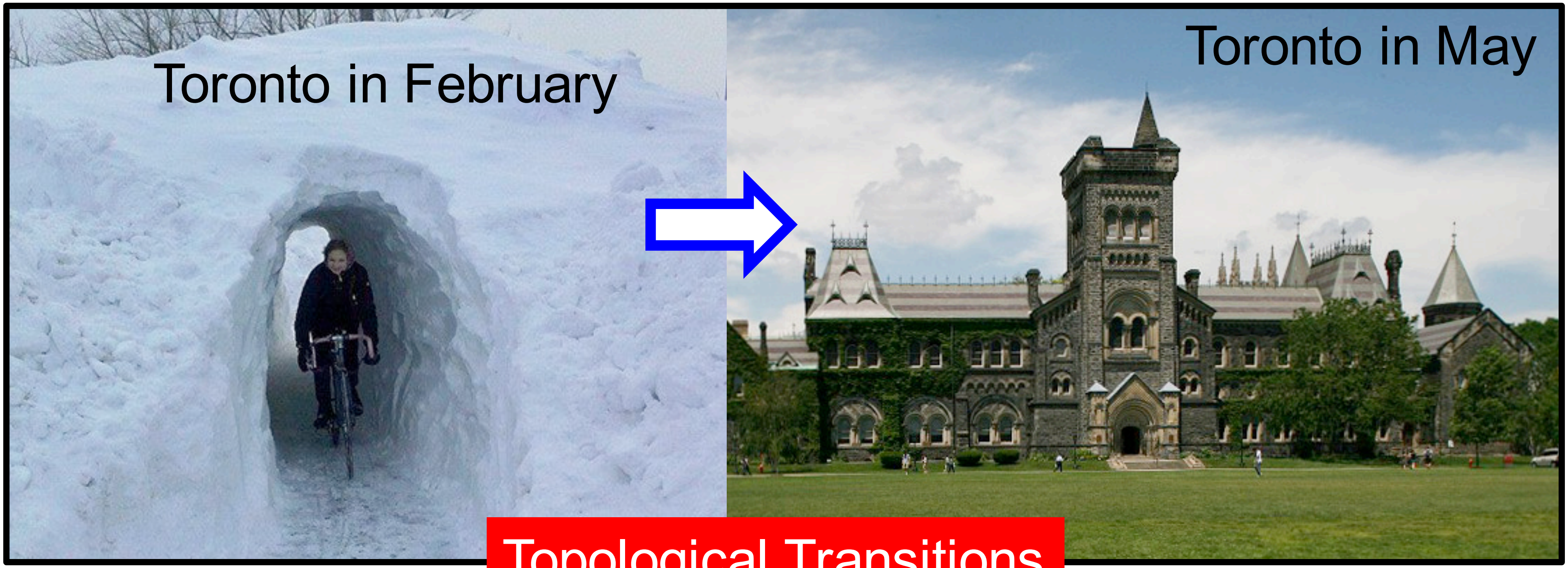
**Genus = 1**

**Breakfast**

Genus = 1

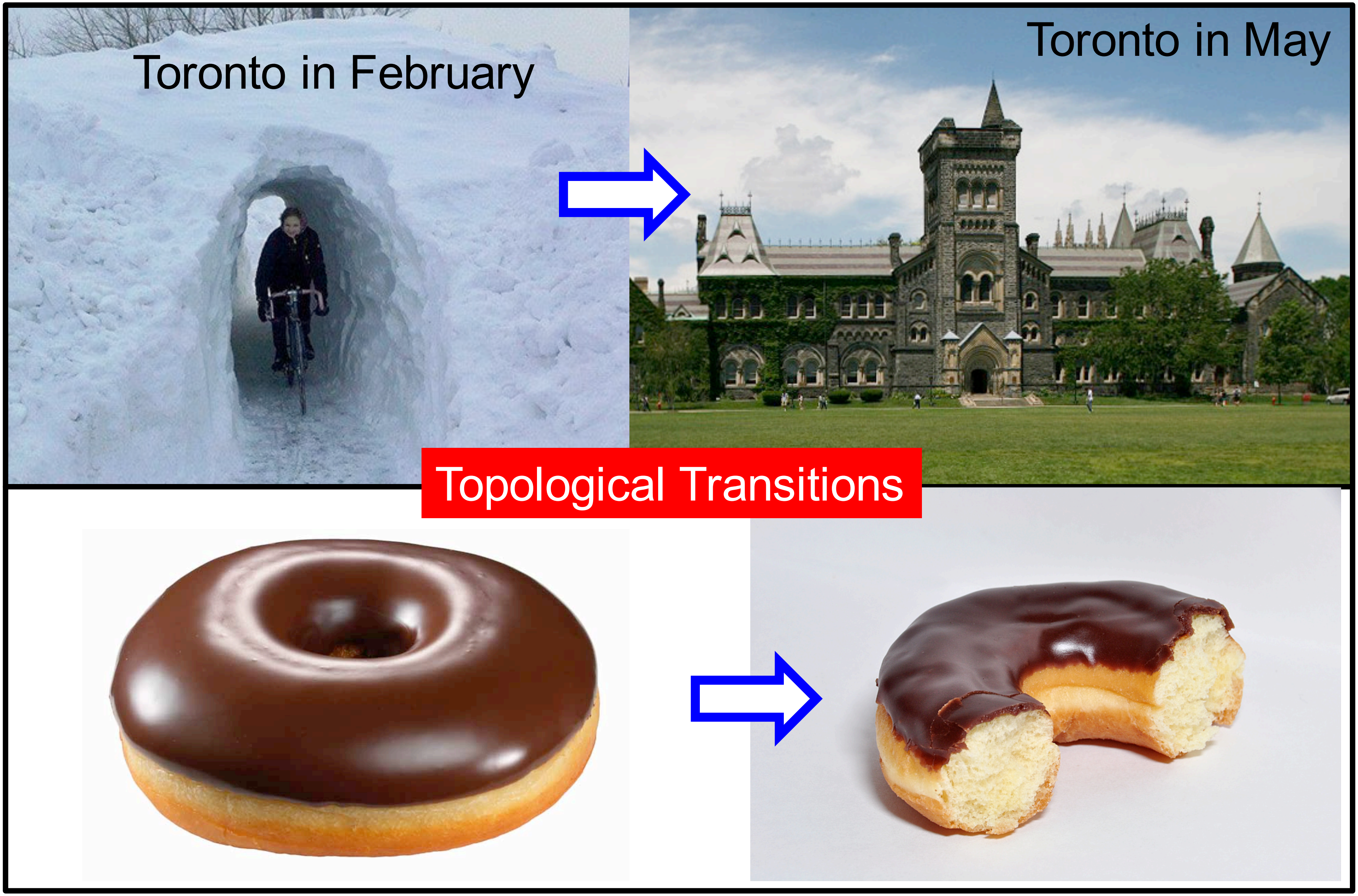
**Genus = 3**

# Topology in Everyday Life



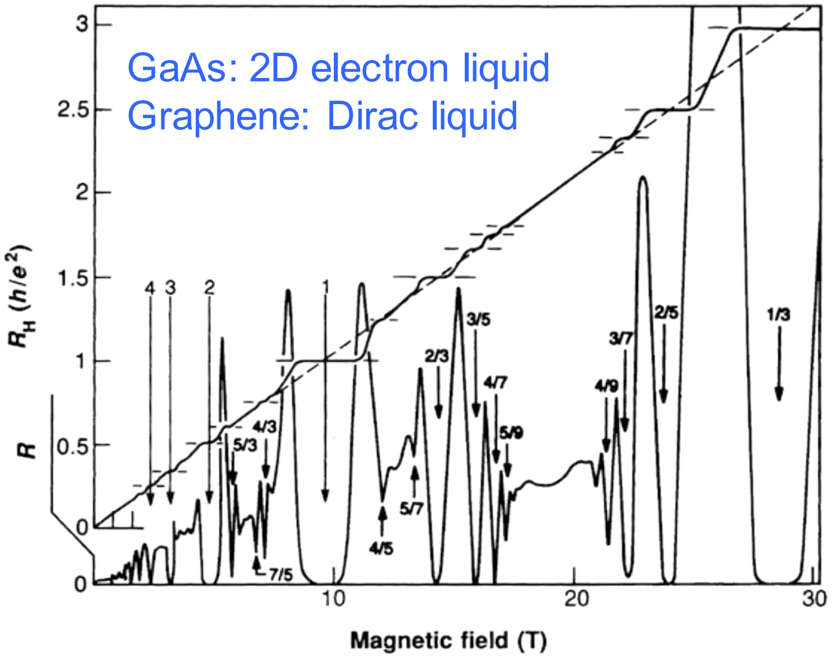
Topological Transitions

# Topology in Everyday Life

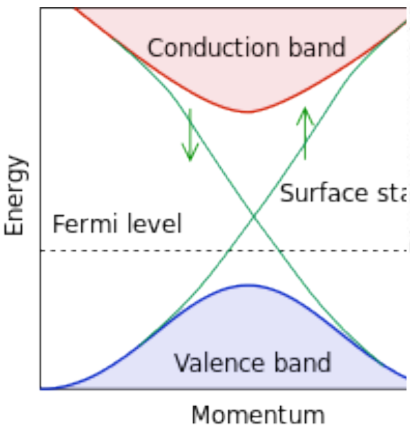


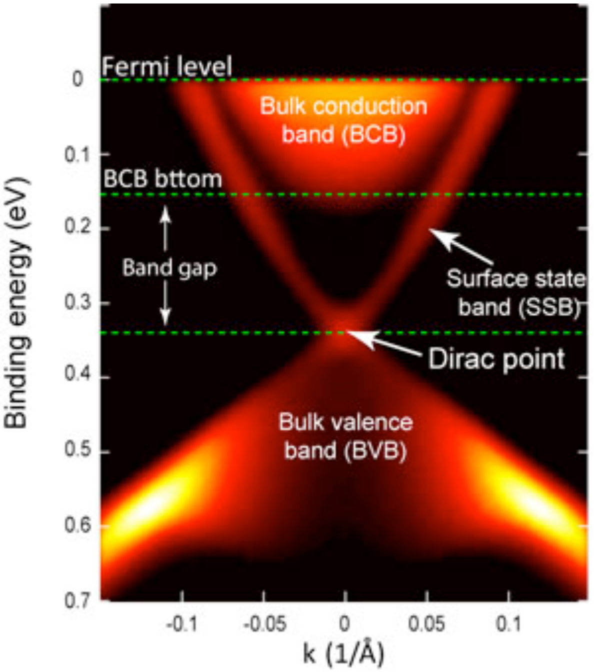
# Topological phases of quantum matter

Quantum Hall effects


GaAs: 2D electron liquid
Graphene: Dirac liquid

Topological insulators, top. crystalline insulators



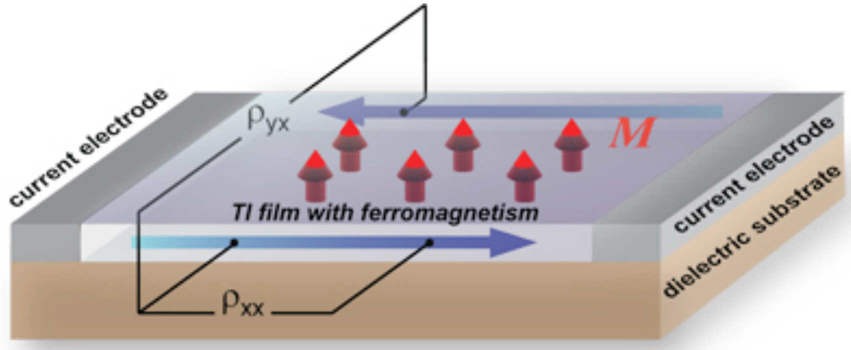


Quantum Hall effect
- Precise quantization of $\sigma_{xy}$
- Chiral edge states

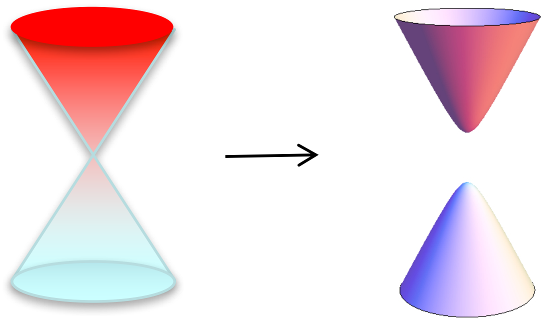
Topological insulators (3d)
- Precise $\vec{E} \cdot \vec{B}$ coefficient $\Theta = \pi$
- Chiral odd-# Dirac surface states

# Quantum anomalous Hall effect
# Magnetically doped topological insulators

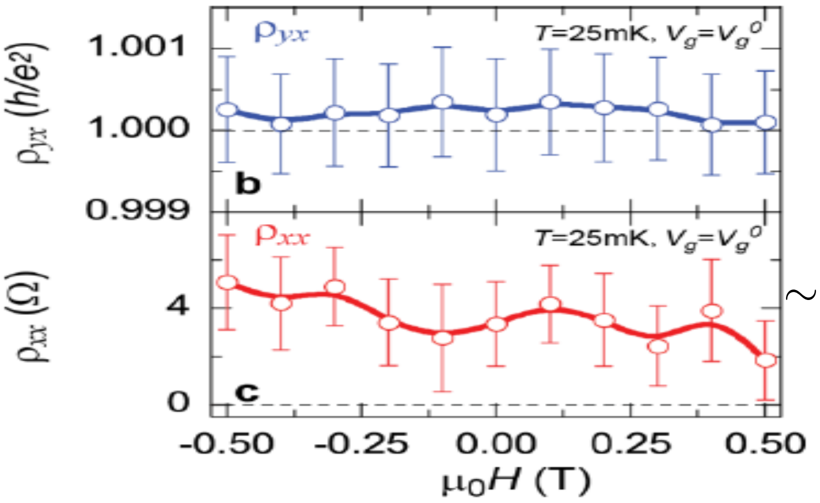
- Consider TIs near a band inversion transition (e.g., thin films)
- Breaking time-reversal strongly with dopant magnetization: QAH effect
- Spin orbit coupling is crucial



R. Yu, et al (Science 2010)



Surface Dirac fermions get gapped



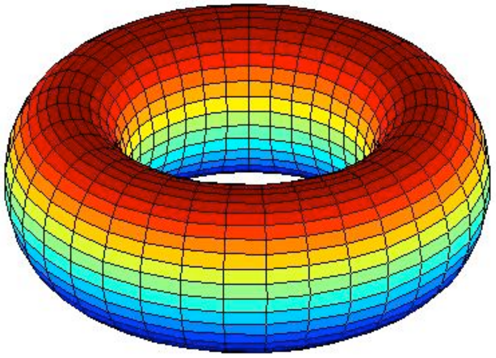
$\sim 10^{-4}\frac{h}{e^2}$

$(Bi,Sb)_2Te_3$ film doped with Cr or V atoms
Ferromagnetic Tc ~ 10-15K

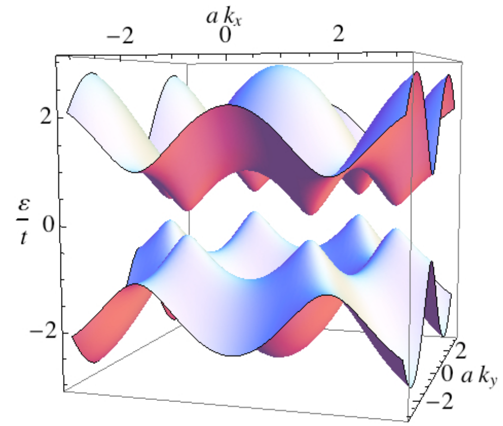
C.Z. Chang et al, Science 2013 (Xue group, Tsinghua)
C.Z. Chang et al, arXiv (M. Chan + J. Moodera groups, PSU/MIT)
A. J. Bestwick et al, arXiv (Goldhaber-Gordon group, Stanford)
A. Kandala, et al, arXiv (N. Samarth and C.X. Liu groups, PSU)

# Bands in Crystals – Momentum Space Topology

## Crystal momentum



2D Brillouin zone: Torus



k-space energy bands: $E_n(\mathbf{k})$

Bloch wavefunctions: $|\psi_n(\mathbf{k})\rangle$

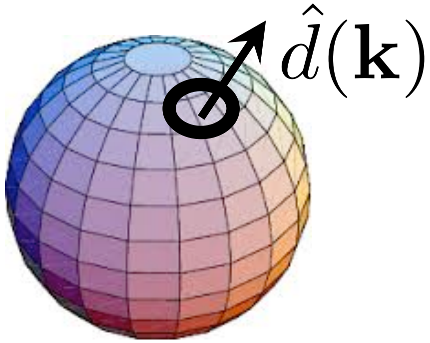
## Two-Band System

$$H(\mathbf{k}) = \vec{d}(\mathbf{k}) \cdot \vec{\sigma}$$

pseudospin

$$E_\pm(\mathbf{k}) = \pm|\vec{d}(\mathbf{k})|$$

“Bloch sphere”



$\hat{d}(\mathbf{k})$: Information about wavefunction

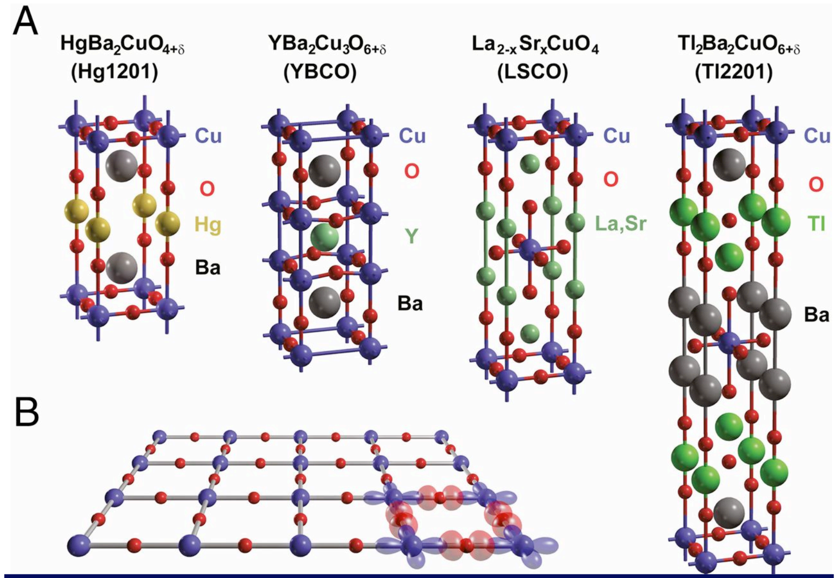
$$\boxed{\int \frac{dk_x dk_y}{4\pi} \hat{d}(\mathbf{k}) \cdot \partial_x \hat{d}(\mathbf{k}) \times \partial_y \hat{d}(\mathbf{k})}$$

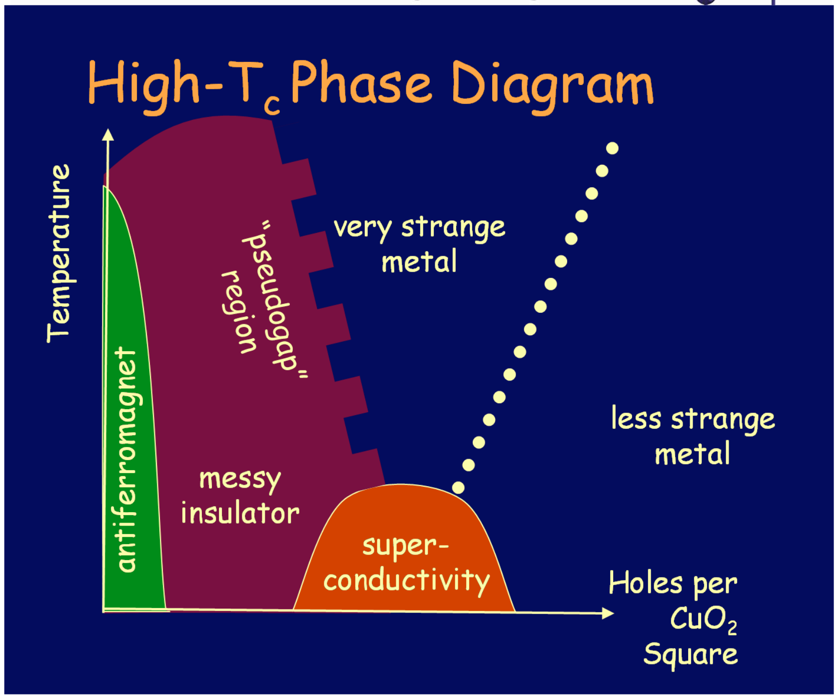
→ Topological invariant (Chern number)

Sample boundary: Change of topology leads to gapless edge states

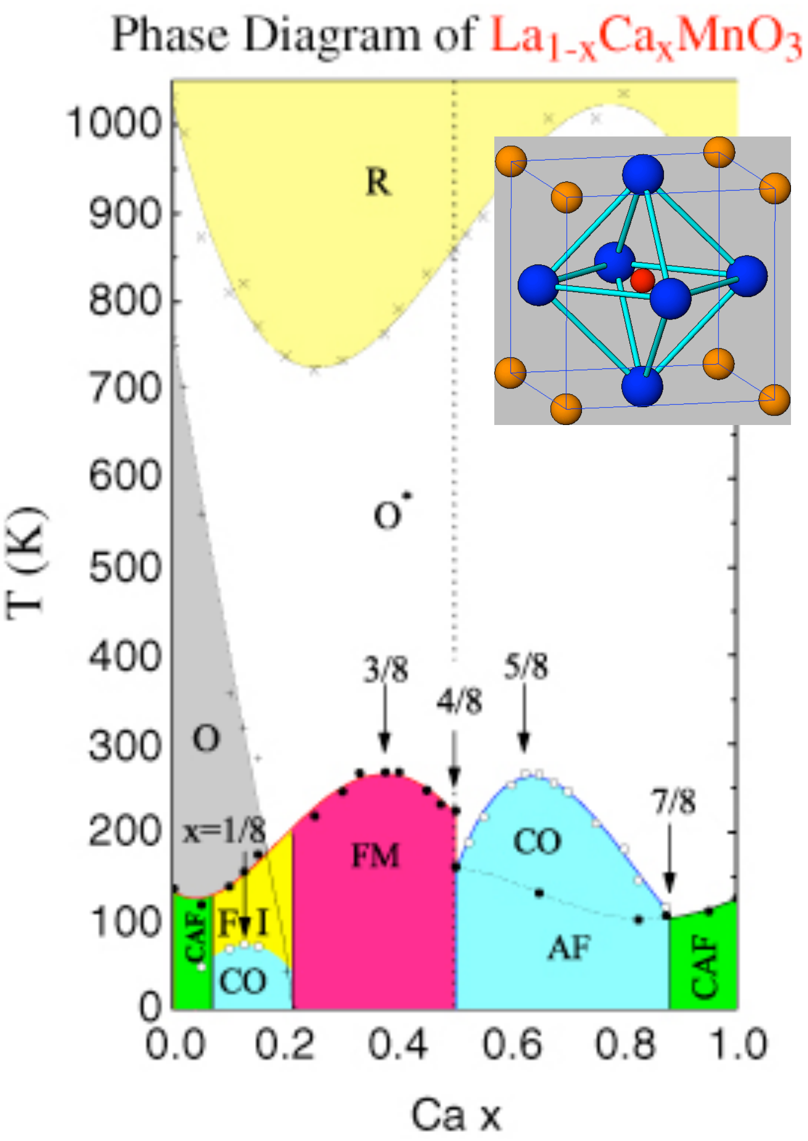
# Strong correlations can drive new phases of matter

## High temperature superconductivity





## Colossal magnetoresistive oxides

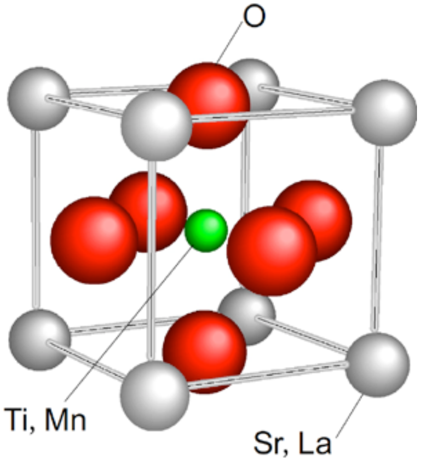


# Topology meets Strong Correlations

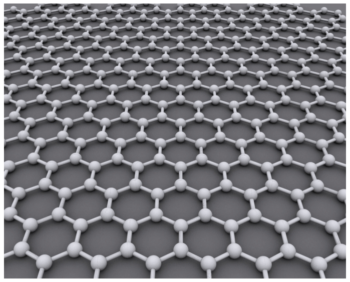
- Band topology - momentum space, global
- Strong correlations - real space, local

- How can we bring together strong correlations and band topology?
- Can strongly correlated materials display topological bands?
- Can we get new types of many-body topological properties?
- Does the interplay lead to new magnetic interactions and phases?
- What happens at an interacting topological transition?

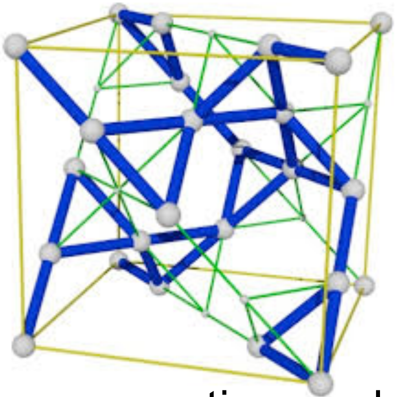
# Research interests



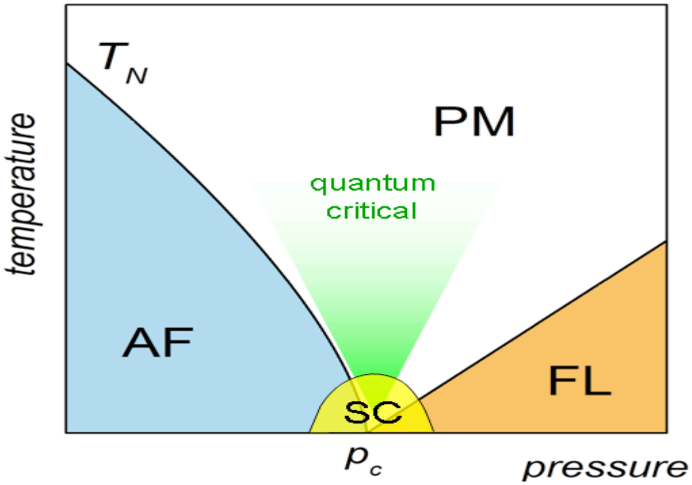
Transition metal oxides
and heterostructures:
Can they realize correlated
topological phases?



Graphene, TM dichalcogenides:
How to endow them with nontrivial
topological character?



Quantum magnetism and spin liquids:
Are there materials with spin liquid
phases and topological order?



Quantum phase transitions (QPTs):
What happens at topological phase
transitions?

# Collaborators

Ashley Cook
(PhD:Toronto -> U. Zurich)

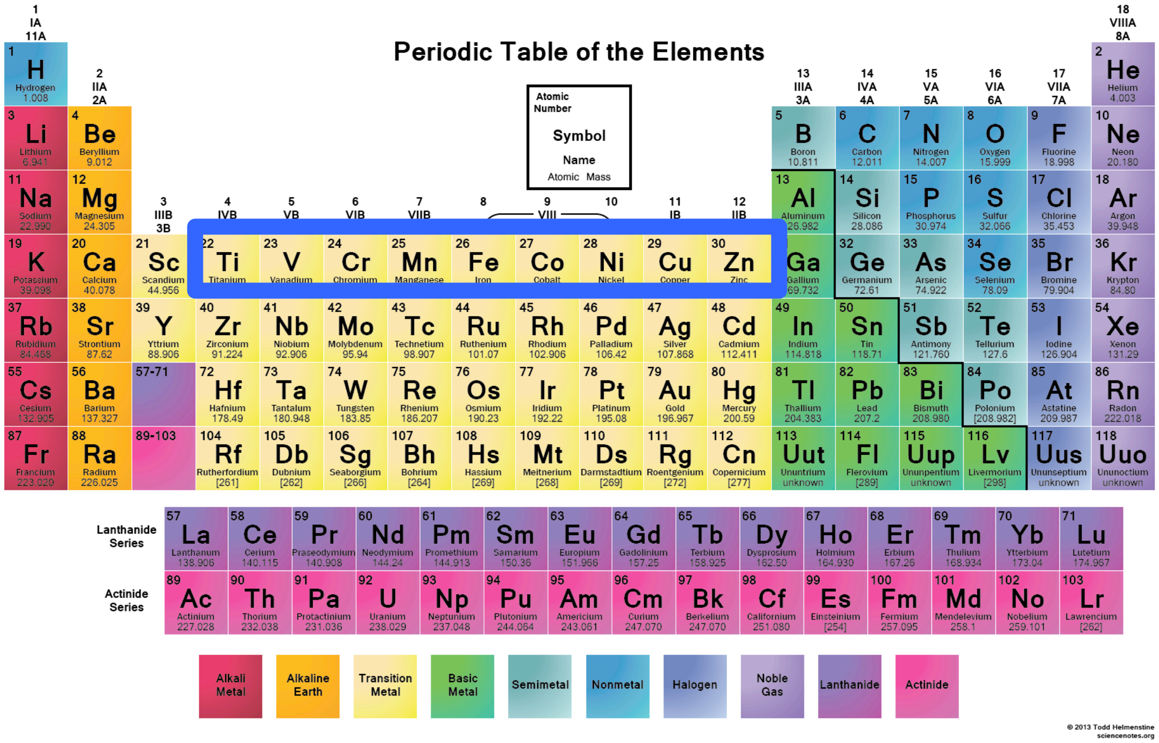
Ciaran Hickey
(PhD: Univ. Toronto)

- **Toronto: K. Plumb, J.P. Clancy, Young-June Kim**
- **SNU: B.-C. Jeon, T.-W. Noh**
- **ORNL: A.A. Aczel, G. Cao, T. J. Williams, S. Calder, A. Christianson, D. Mandrus. A. Kolesnikov**
- **India: Santu Baidya, Tanusri-Saha Dasgupta, Umesh Waghmare**

**Discussions:** Bruce Gaulin, John Greedan, , Y. B. Kim, M. Randeria, N. Trivedi, Pat Woodward, S. Trebst, G. Chen, L. Balents, S. Sachdev

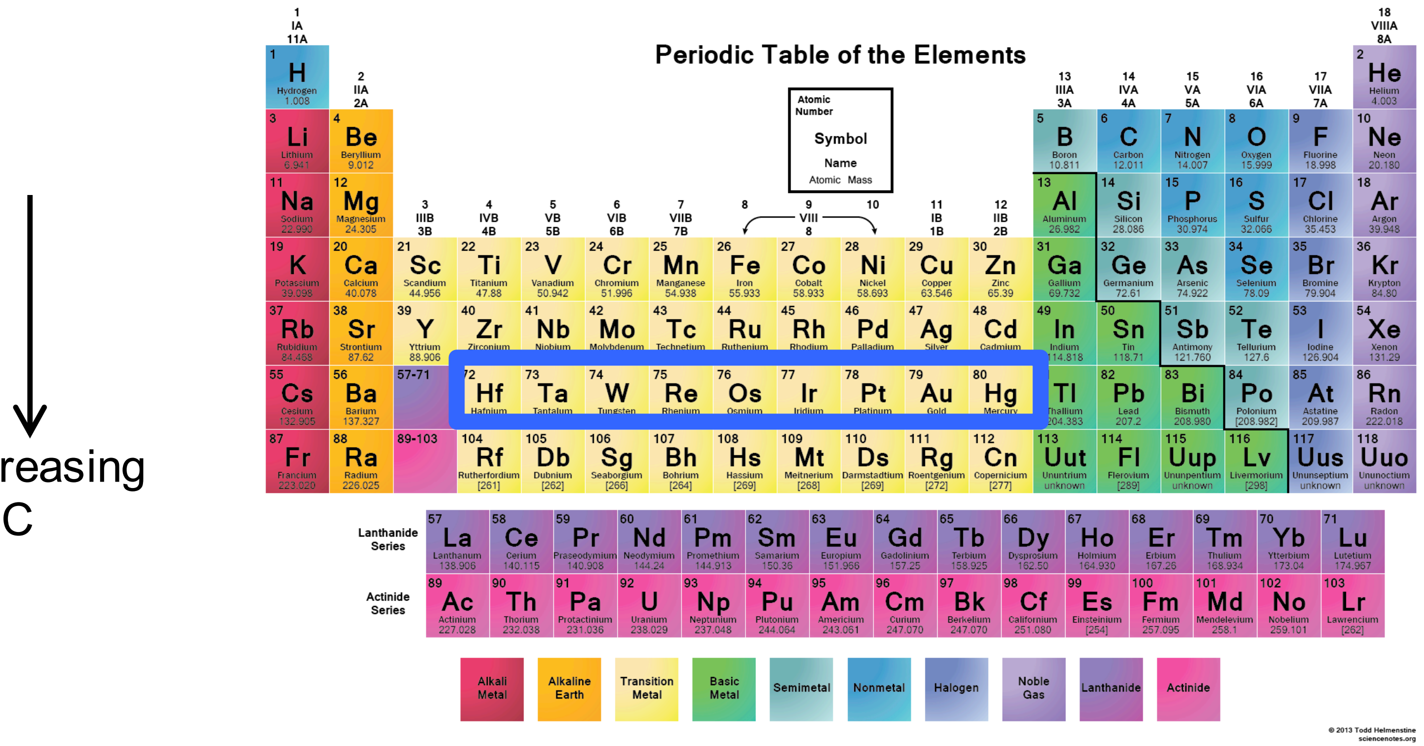
# (1) Strong correlations

- Brink of Mott localization or deep Mott insulator regime
- Common in 3d oxides: Kinetic energy ~ Interactions
- “High” energy/temperature scales for correlations/magnetism



# (2) **Band topology**

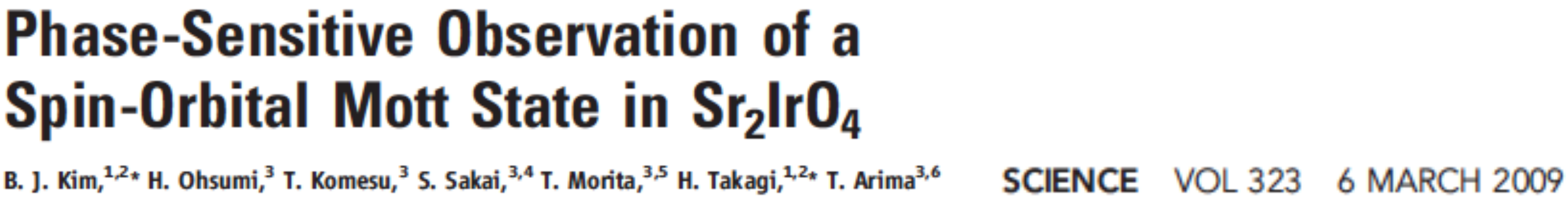
- Nontrivial band topology: SOC + conducting electron fluid
- Strong SOC needs heavy elements
- Expected in 4d/5d oxides (eg: Rhenium, Osmium, Iridium)



Increasing SOC

# Engineering topology + correlations in solids

## Layered complex oxides of 5d transition metals

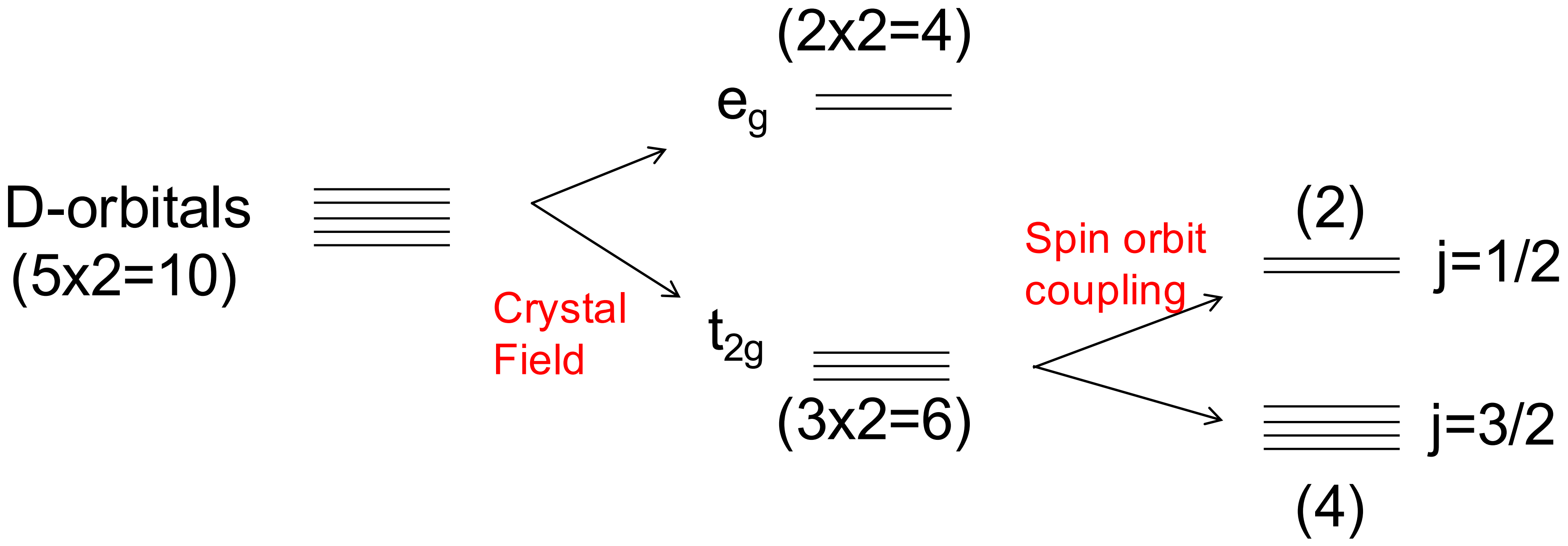


**Phase-Sensitive Observation of a Spin-Orbital Mott State in $Sr_2IrO_4$**

B. J. Kim,[1,2]* H. Ohsumi,[3] T. Komesu,[3] S. Sakai,[3,4] T. Morita,[3,5] H. Takagi,[1,2]* T. Arima[3,6]

SCIENCE VOL 323 6 MARCH 2009

Strong correlation effects needs <u>narrow</u> bands



D-orbitals

(5x2=10)

Crystal Field

(2x2=4)

$e_g$

$t_{2g}$

(3x2=6)

Spin orbit coupling

(2)

j=1/2

j=3/2

(4)

Spin orbit coupling can cause band narrowing!

# Engineering topology + correlations in solids

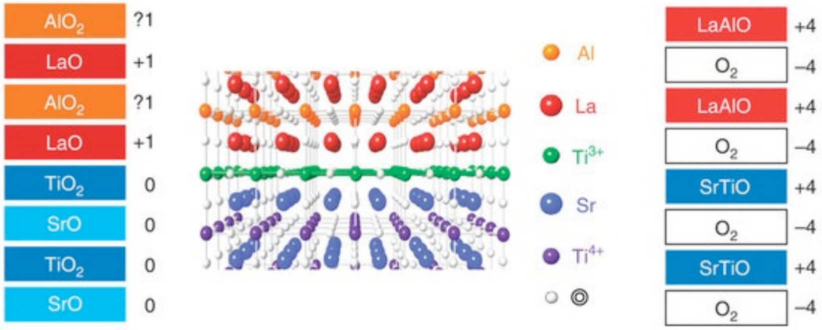
## Oxide heterostructures and superlattices

### LaAlO3/SrTiO3 interface [100]

H. Y. Hwang, J.M. Triscone, J. Mannhart,
R. Ashoori, K. A. Moler, ...

Basic physics: Magnetism + Superconductivity

Applications: Write/Erase circuits using electric field



### 3d-3d Superlattices along [111]

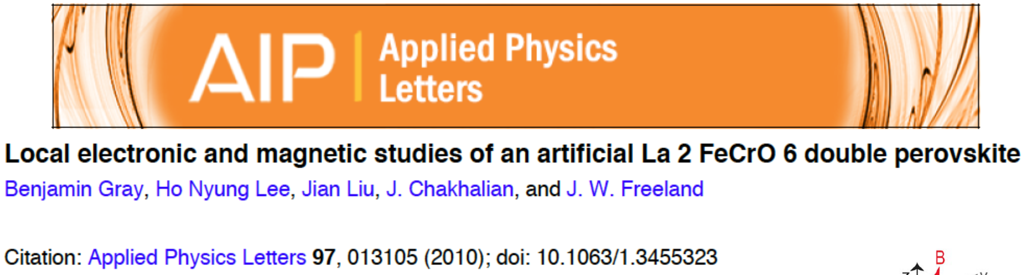
nature materials

LETTERS

PUBLISHED ONLINE: 22 JANUARY 2012 | DOI: 10.1038/NMAT3224

**Exchange bias in $LaNiO_3$–$LaMnO_3$ superlattices**

Marta Gibert[1]*, Pavlo Zubko[1], Raoul Scherwitzl[1], Jorge Íñiguez[2] and Jean-Marc Triscone[1]



AIP Applied Physics Letters

**Local electronic and magnetic studies of an artificial La 2 FeCrO 6 double perovskite**

Benjamin Gray, Ho Nyung Lee, Jian Liu, J. Chakhalian, and J. W. Freeland

Citation: Applied Physics Letters **97**, 013105 (2010); doi: 10.1063/1.3455323

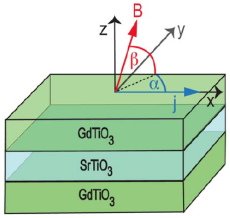
### 3d/5d Superlattices along [111]

H. Takagi group (APL 2015)

### Quantum Wells, Modulation Doping

S. Stemmer group (UCSB)

Confined 2DEGs, high mobilities, magnetism



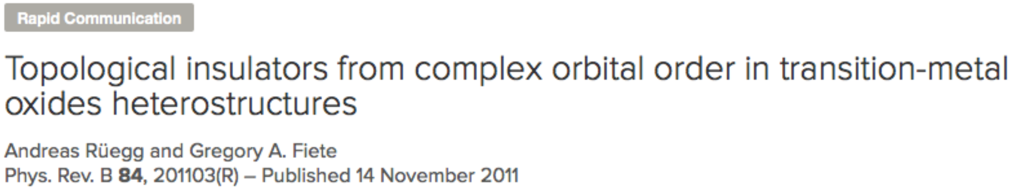
### Prediction of topological insulators in simple TMO bilayers

ARTICLE

Received 20 Jun 2011 | Accepted 18 Nov 2011 | Published 20 Dec 2011 DOI: 10.1038/ncomms1602

Interface engineering of quantum Hall effects in digital transition metal oxide heterostructures

Di Xiao[1], Wenguang Zhu[1,2], Ying Ran[3], Naoto Nagaosa[4,5] & Satoshi Okamoto[1]



Rapid Communication

Topological insulators from complex orbital order in transition-metal oxides heterostructures

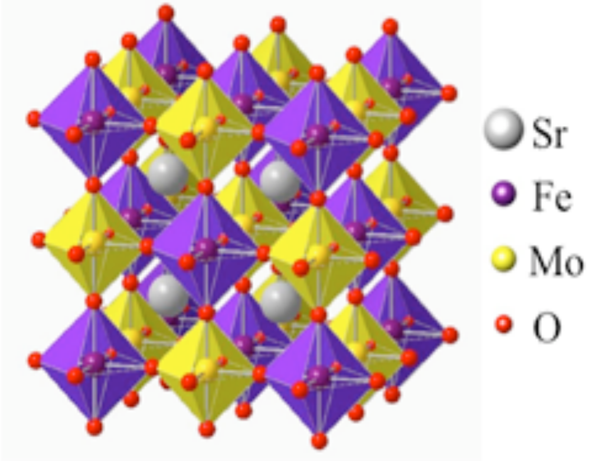
Andreas Rüegg and Gregory A. Fiete

Phys. Rev. B **84**, 201103(R) – Published 14 November 2011

# Double Perovskites: Mixing correlations and SOC

General formula: $A_2BB'O_6$ (B,B' = 3d, 4d, 5d)

Double perovskite lattice



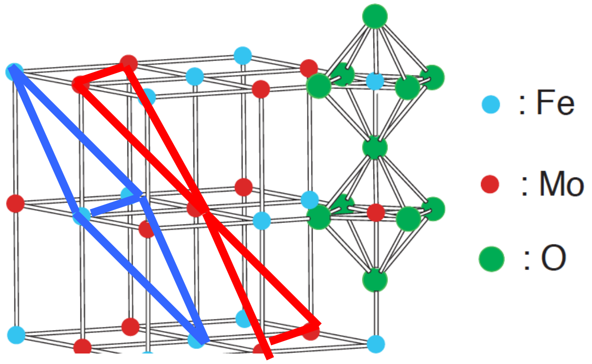
**Metallic systems**

B: Magnetism and B':Conduction electrons

. Half metallic ferrimagnets (eg:$Sr_2FeMoO_6$, $T_C$= 420K)

. Large polarization: good for spin injection

. Interplay of **Magnetism**, **SOC**, **Metallicity**



**Layered along [111]**

**Mott insulators**

B=magnetism, B'=inert or magnetism

. **Well isolated** TM-oxygen octahedra

. **Frustrated** fcc lattice (eg: $Ba_2YReO_6$)

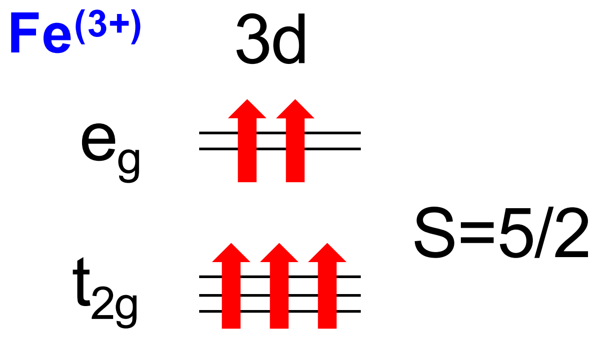
. Unusual spin-orbit coupled liquids?

. Insulating ferrimagnets (eg: $Sr_2CrOsO_6$, $T_C$=725K)

# Single atom physics

**Nominal valence:** $Ba_2^{(2+)}Fe^{(3+)}Re^{(5+)}O_6^{(2-)}$

$Sr_2^{(2+)}Fe^{(3+)}Mo^{(5+)}O_6^{(2-)}$

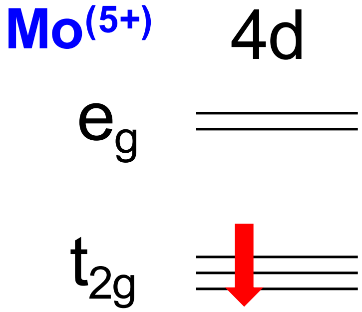


**$Fe^{(3+)}$** 3d

$e_g$

$t_{2g}$

S=5/2



**$Mo^{(5+)}$** 4d

$e_g$

$t_{2g}$

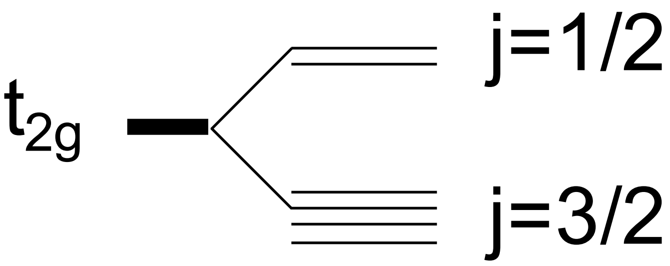
Hund's coupling > crystal field

SOC: λ ~100meV

## Re: Spin orbit coupling in $t_{2g}$ (L=1)

$$P_{t_{2g}} \vec{L} P_{t_{2g}} = -\vec{\ell} \qquad (\ell = 1)$$

$$H_{\mathrm{s.o.}} = -\lambda \vec{\ell} \cdot \vec{s}$$



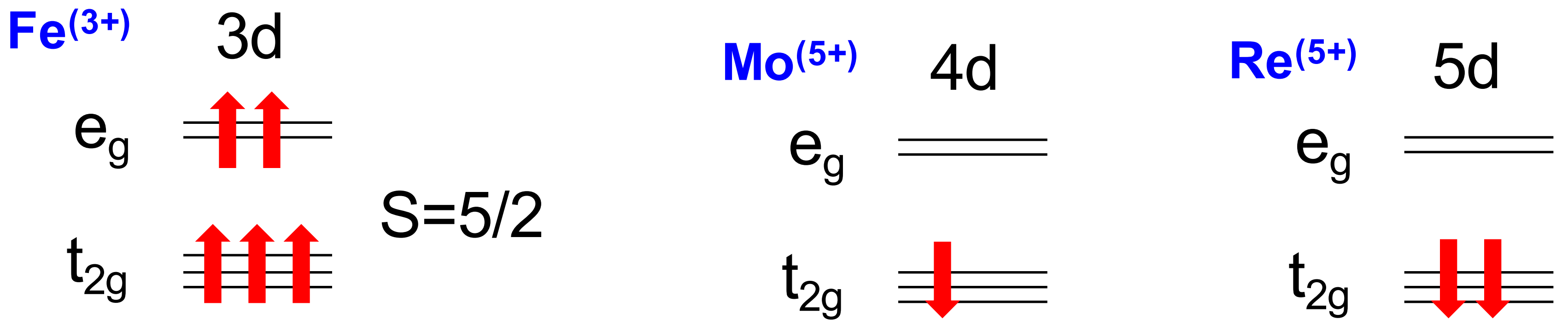
$t_{2g}$

j=1/2

j=3/2

# Single atom physics

**Nominal valence:** $Ba_2^{(2+)}Fe^{(3+)}Re^{(5+)}O_6^{(2-)}$
$Sr_2^{(2+)}Fe^{(3+)}Mo^{(5+)}O_6^{(2-)}$



Hund's coupling > crystal field

SOC: λ ~100meV

SOC: λ ~ 500 meV
Hubbard U
important

## Re: Spin orbit coupling in $t_{2g}$ (L=1)

$$P_{t_{2g}} \vec{L} P_{t_{2g}} = -\vec{\ell} \qquad (\ell = 1)$$

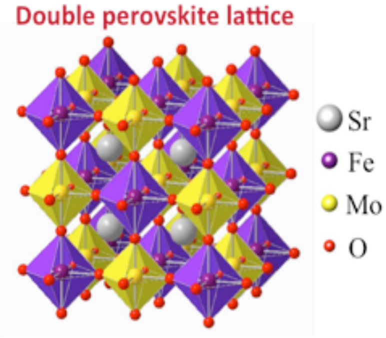
$$H_{\text{s.o.}} = -\lambda \vec{\ell} \cdot \vec{s}$$

## Re: Interactions in $t_{2g}$

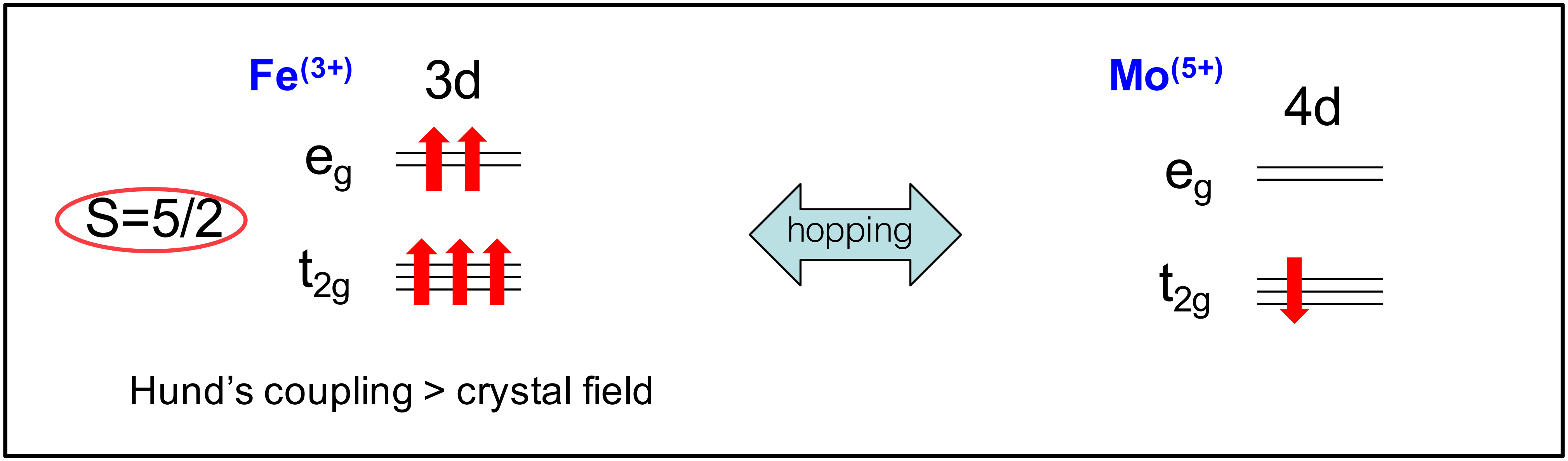
$$H_{\text{int}} = U \sum_{\alpha} n_{\alpha\uparrow} n_{\alpha\downarrow} + (U - 5\frac{J_H}{2}) \sum_{\alpha<\beta} n_\alpha n_\beta$$
$$-2J_H \sum_{\alpha<\beta} \vec{S}_\alpha \cdot \vec{S}_\beta + J_H \sum_{\alpha\neq\beta} d^\dagger_{\alpha\uparrow} d^\dagger_{\alpha\downarrow} d_{\beta\downarrow} d_{\beta,\uparrow}$$

(Kanamori)

# Double perovskites: Itinerant perspective


Double perovskite lattice

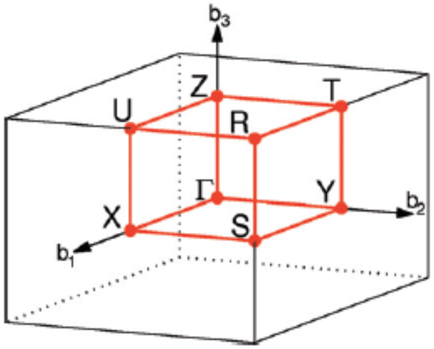
## Origin of half-metallicity



Hund’s coupling > crystal field

D.D. Sarma, et al (PRL 2000); S. Di Matteo, G.Jackeli, N.Perkins (2003); G. Jackeli (PRB 2003); P. Sanyal, P. Majumdar (PRB 2009); O. Erten, O. Nganba-Meetei, M. Randeria, N. Trivedi, P. Woodward, (2011, 2013)

# Electronic model for $Ba_2FeReO_6$: Hartree theory



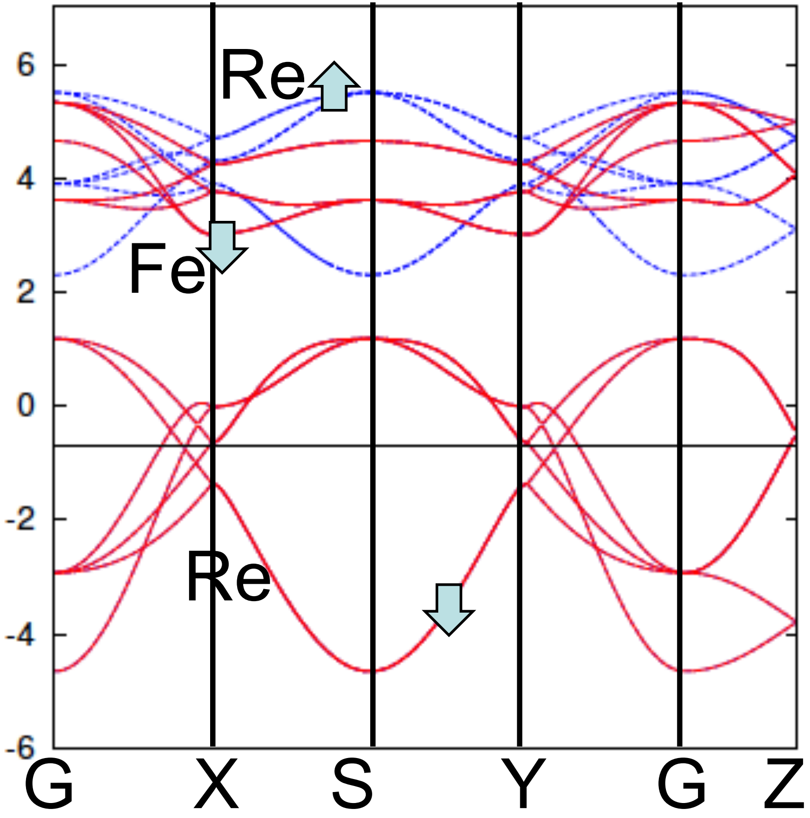
Correlation on Re: Stabilizes half-metallic state

Keep only intra-orbital U

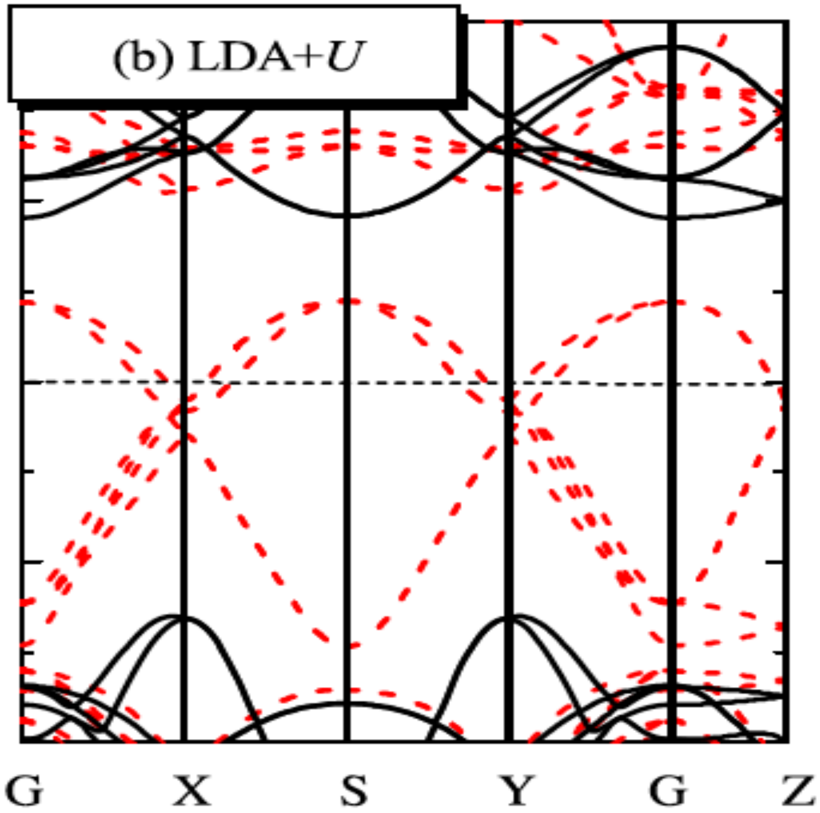
$t_{Fe\text{-}Re} \sim 330$ meV, $U \sim 2.5$eV, $\Delta_{CT} \sim 1$ eV

$t_{Re\text{-}Re} \sim 100$ meV, Other hoppings small < 50 meV

## Comparing Hartree-corrected dispersion with LDA+U



A. Cook, AP (PRB 2013)



B.C. Jeon, T.W. Noh, et al, (JPCM, 2010)

# Incorporating SOC and Hartree Mean Field Interactions

## Non-Interacting

Sz (Fe) ~ +2.40 (i.e., 4.8 $\mu_B$)
Sz (Re) ~ -0.15
Lz (Re) ~ -0.09
(Recall - L flipped in projecting to $t_2$g)

Ordered J (Re) ~ 0.24

## With Hartree

Sz (Fe) ~ +2.30 (i.e., 4.6 $\mu_B$)
Sz (Re) ~ -0.78
Lz (Re) ~ -0.48
(Recall - L flipped in projecting to $t_2$g)

Ordered J (Re) ~ 1.2

Important for correct $m_{sat} = 3.4\ \mu_B$

## Comparison with XMCD data

Theory: $(\mu_{orb}/\mu_{spin})$ ~ -0.31

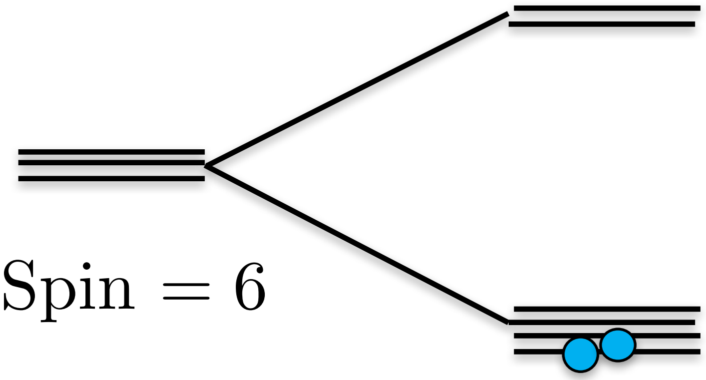
XMCD expt: $(\mu_{orb}/\mu_{spin})$ ~ -0.29

C. Azimonte, et al, PRL **98**, 017204 (2007)

A. Cook, AP (PRB 2013)

# Single atom physics: Hund's coupling and SOC

Consider rhenates 5d$^2$

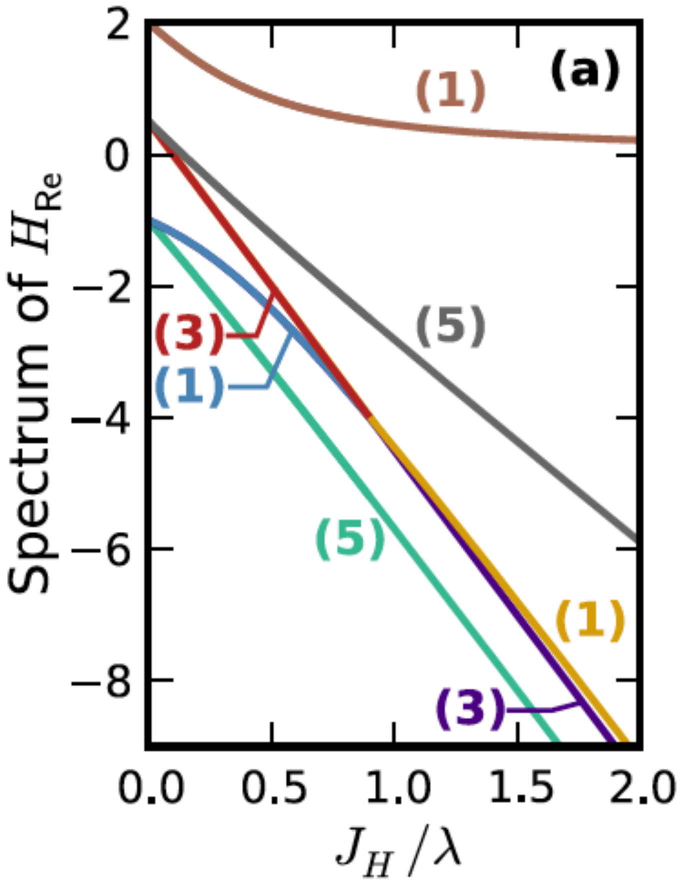


$t_{2g}$

$\mathrm{Orbital} \times \mathrm{Spin} = 6$

Solve "atomic" Kanamori interaction

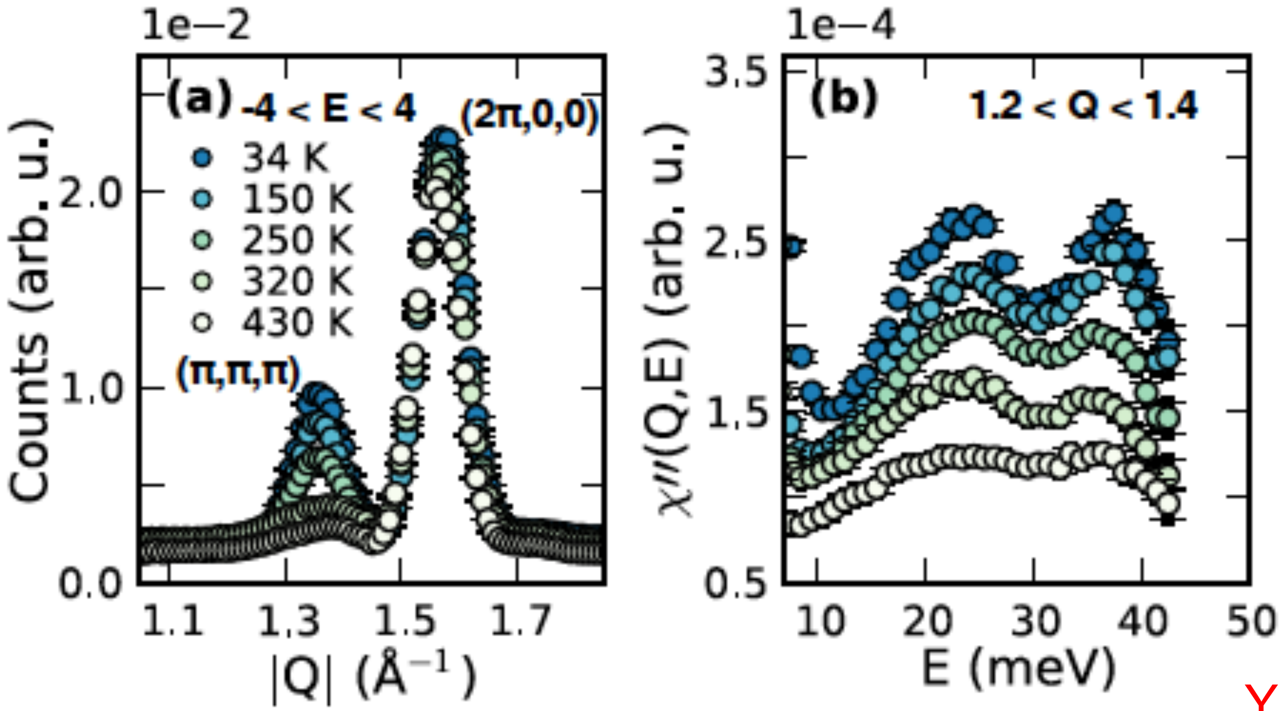
$$H_{\rm int} = \frac{U-3J_H}{2} n_{\rm tot}^2 - 2J_H \vec{S}_{\rm tot}^2 - \frac{J_H}{2} \vec{L}_{\rm tot}^2$$



- Weak interactions: Fill up j-manifold
- Strong interactions: Effective j=2 "spin"

# Magnetic fluctuations in bulk $Ba_2FeReO_6$

## Inelastic neutron spectrum

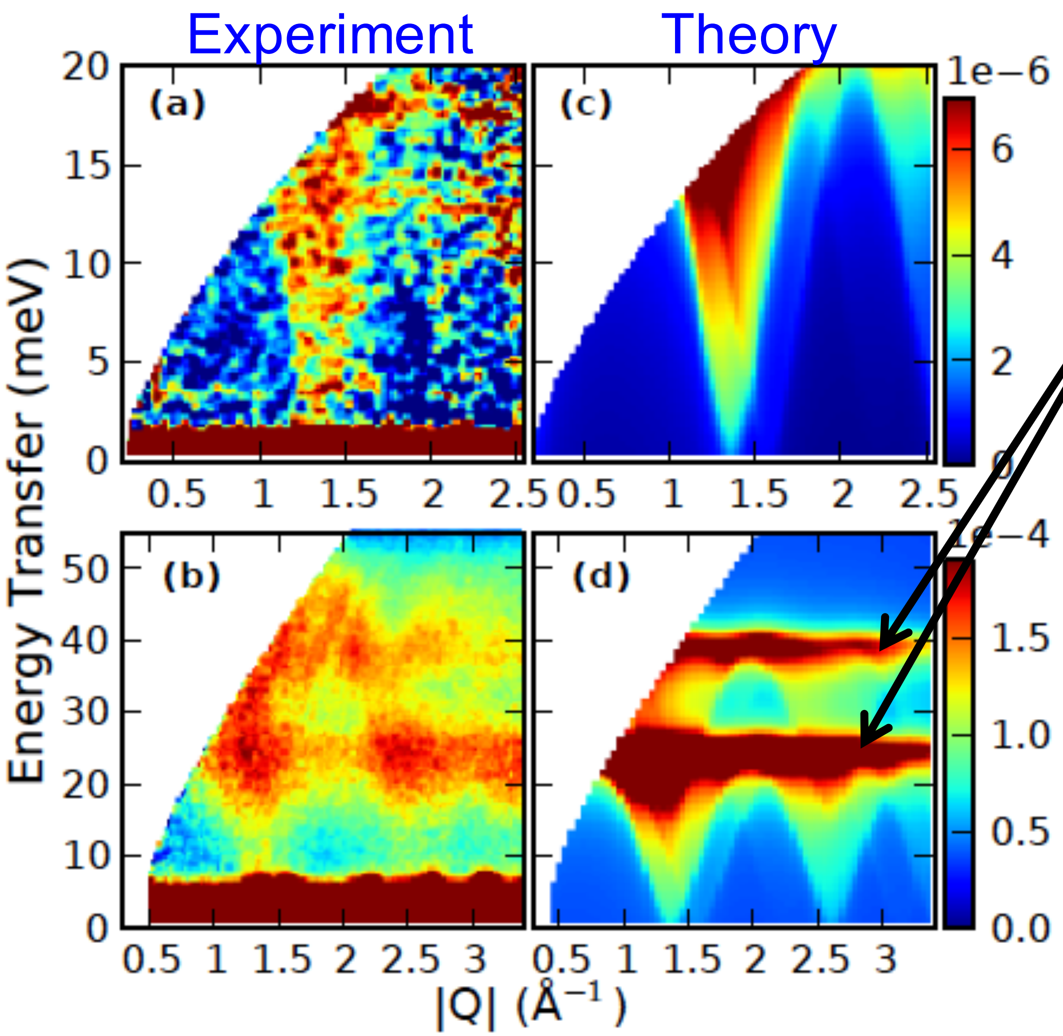


Y.J. Kim group

- Evidence for scattering at the magnetic Bragg peak
- Evidence for signal disappearing near magnetic Tc
- Confirm with Q-dependence of signal over wider range
  - weaker at large Q, unlike phonons

K. Plumb, A. Cook, et al, PRB 87,184412 (2013)

# Magnetic fluctuations in bulk $Ba_2FeReO_6$: Local moment perspective



Zone boundary energy ratio: $\mathcal{F}/\mathcal{R}$

Experimental estimate

$$\mathcal{F}/\mathcal{R} \approx 1.6$$

“Mean field” estimate

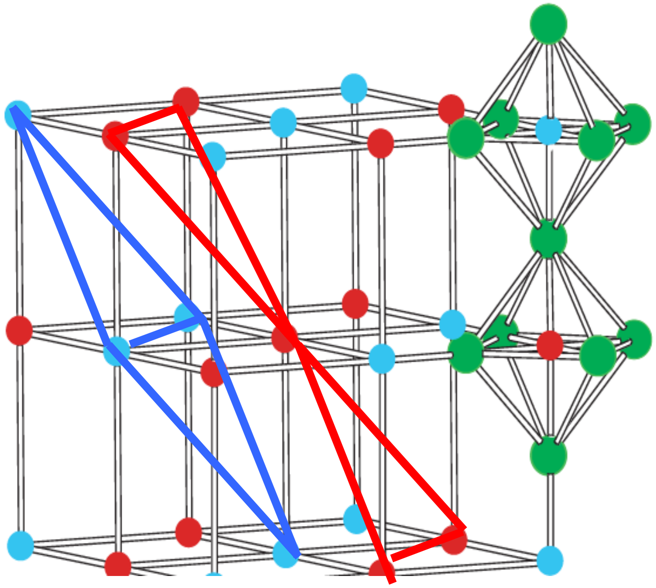
$$\mathcal{F}/\mathcal{R} \approx 1.9$$

K. Plumb, A. Cook, et al (PRB 2013)

- Assuming F=2.1-2.3, find R ~ 1.3-1.4 (i.e., R>1)
- Indicative of orbital moments participating in dynamics
- Estimated Re-Fe exchange coupling ~ 3 meV

# Ultrathin double perovskite films

- What if we dimensionally confine the half-metal to 2D?



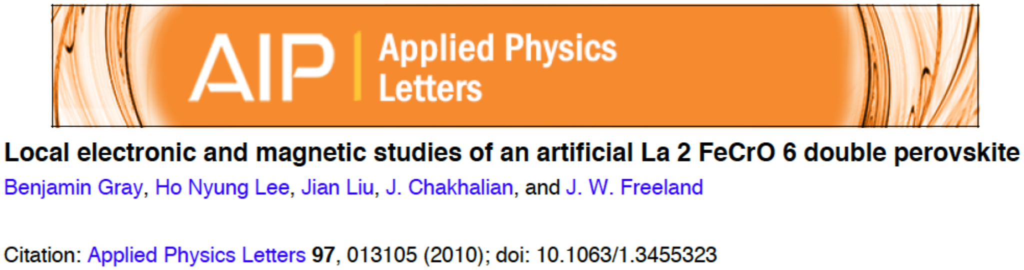
nature materials

LETTERS

PUBLISHED ONLINE: 22 JANUARY 2012 | DOI: 10.1038/NMAT3224

**Exchange bias in $LaNiO_3$–$LaMnO_3$ superlattices**

Marta Gibert[1]*, Pavlo Zubko[1], Raoul Scherwitzl[1], Jorge Íñiguez[2] and Jean-Marc Triscone[1]



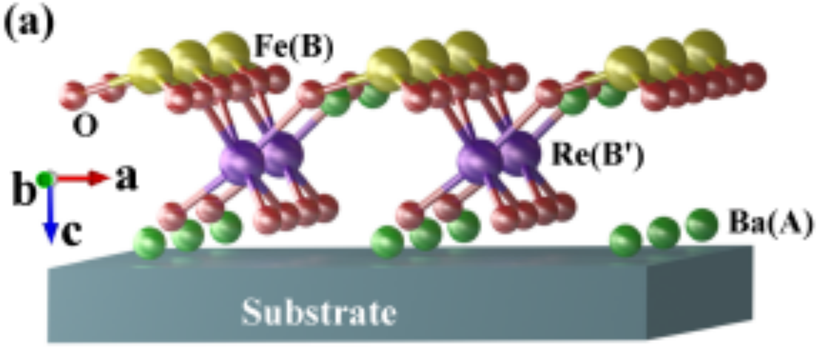
AIP Applied Physics Letters

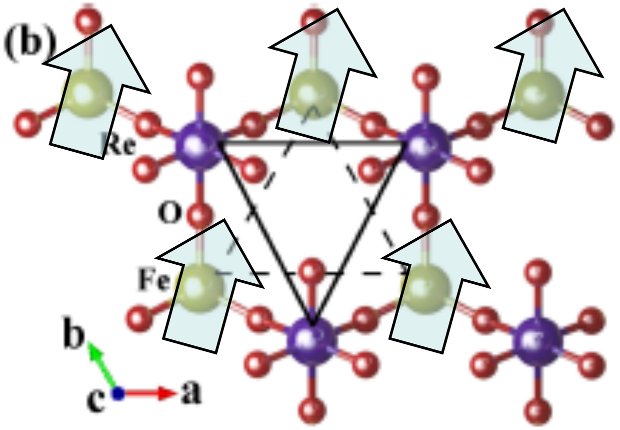
**Local electronic and magnetic studies of an artificial La 2 FeCrO 6 double perovskite**

Benjamin Gray, Ho Nyung Lee, Jian Liu, J. Chakhalian, and J. W. Freeland

Citation: Applied Physics Letters **97**, 013105 (2010); doi: 10.1063/1.3455323

- Bilayer: Buckled honeycomb lattice



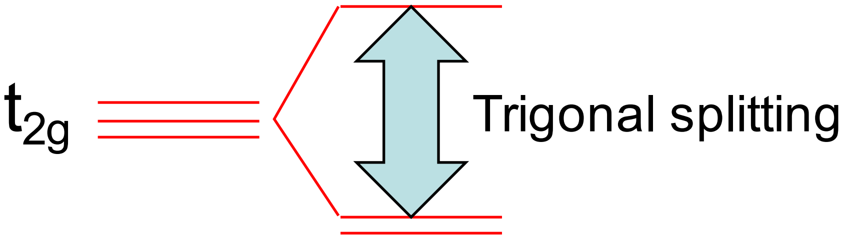


**Re: Triangular lattice**

# Ultrathin double perovskite films

- Triangular half-metal

$$L_z = 0 : \; d_{3z^2-r^2}$$

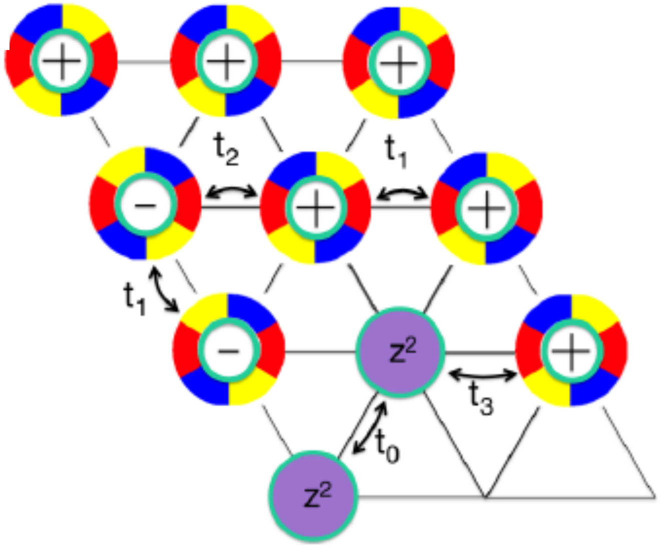


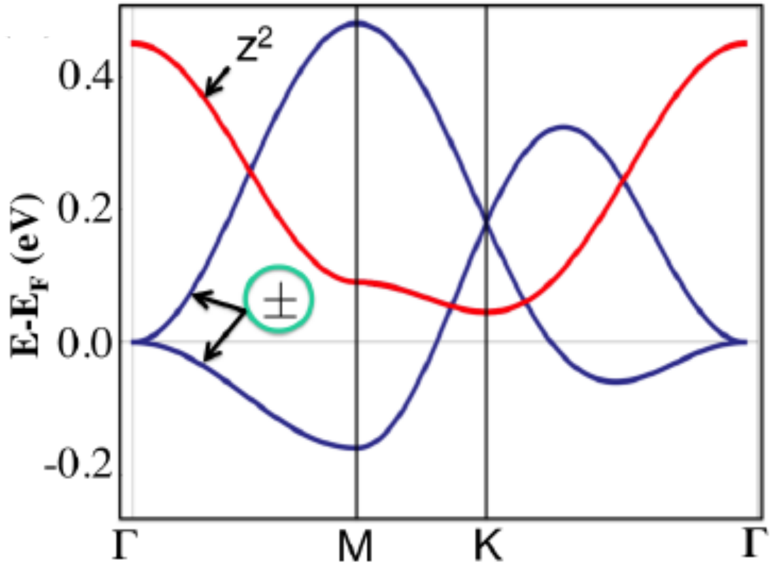
$t_{2g}$

Trigonal splitting

$$L_z = \pm 2 : d_{x^2-y^2} \pm i d_{xy}$$

Non-Kramers doublet

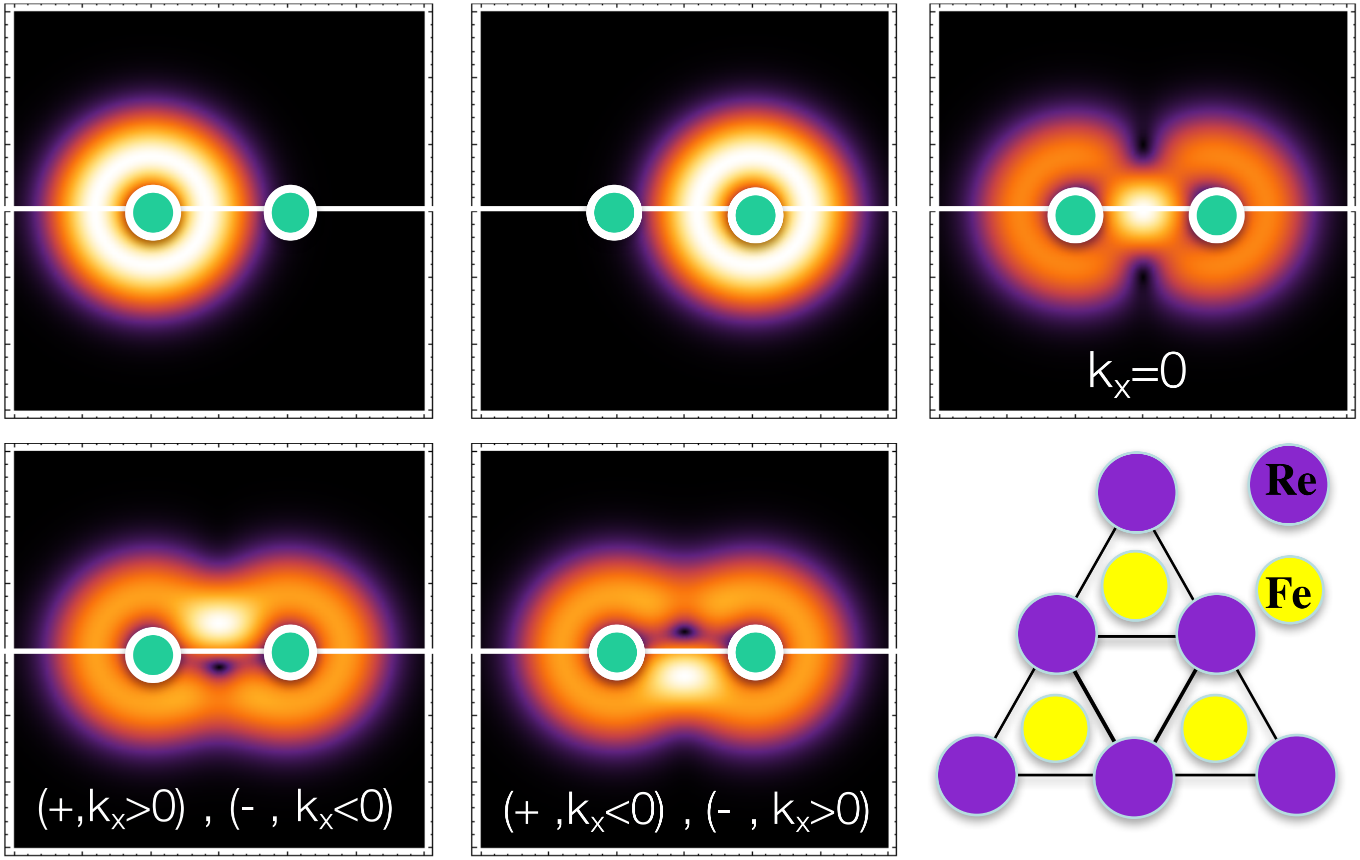




Dirac points at K: Inversion + “Time-reversal”
Quadratic band touching at Γ: C3 + “Time reversal”

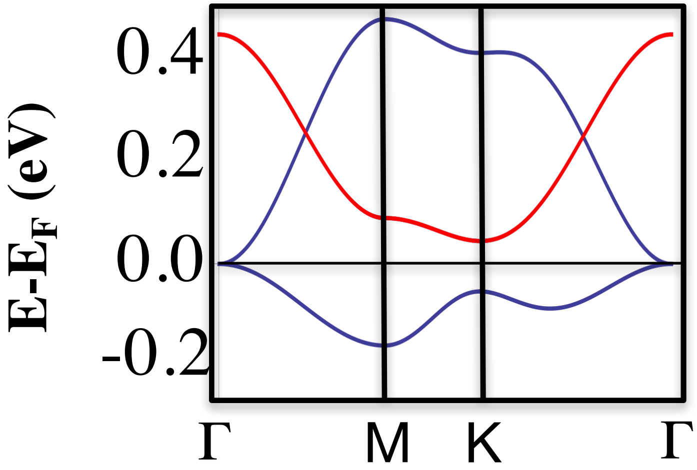
S. Baidya, U. Waghmare, AP, T. Saha-Dasgupta (to appear)

# “Orbital Dipoles” and the “Orbital Rashba effect”

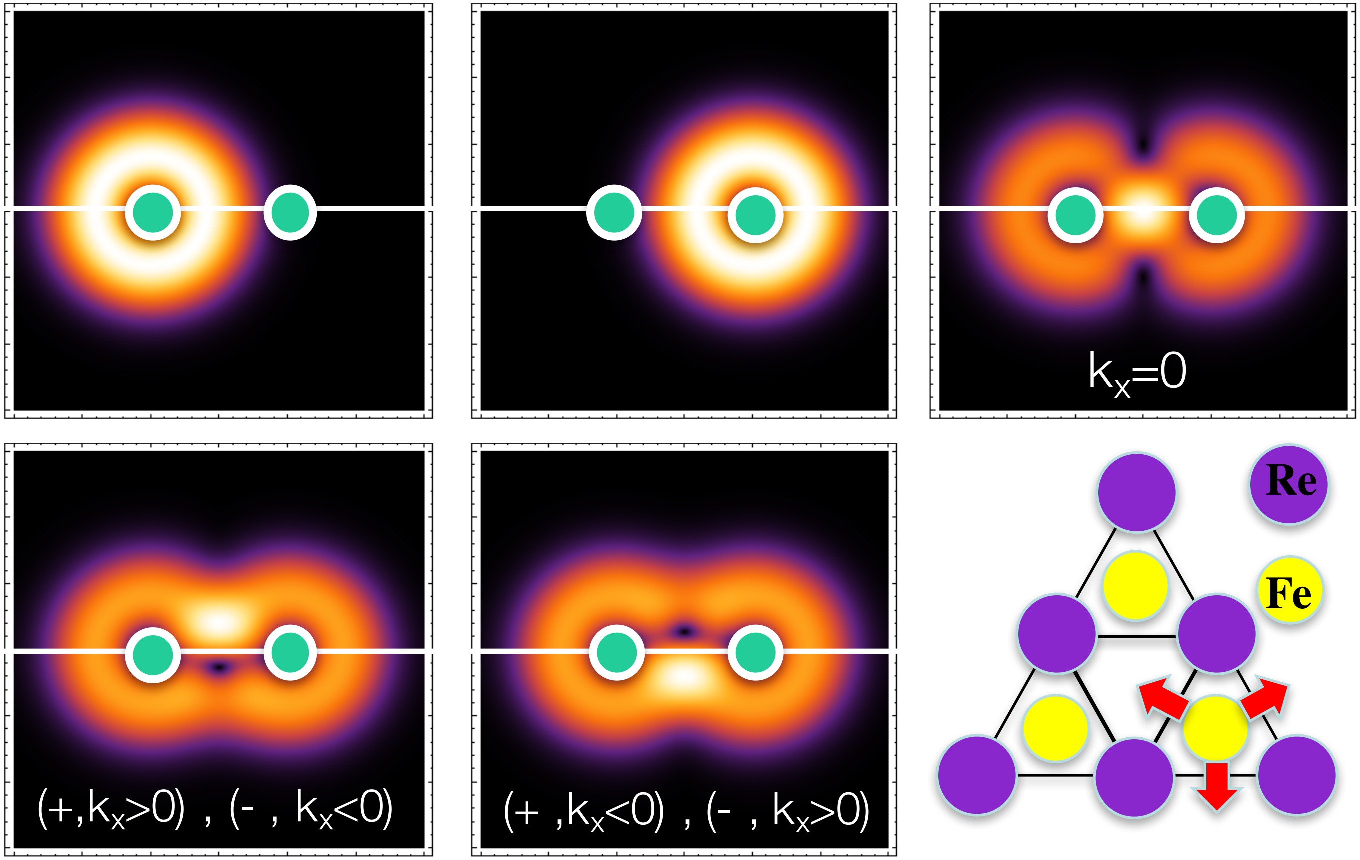


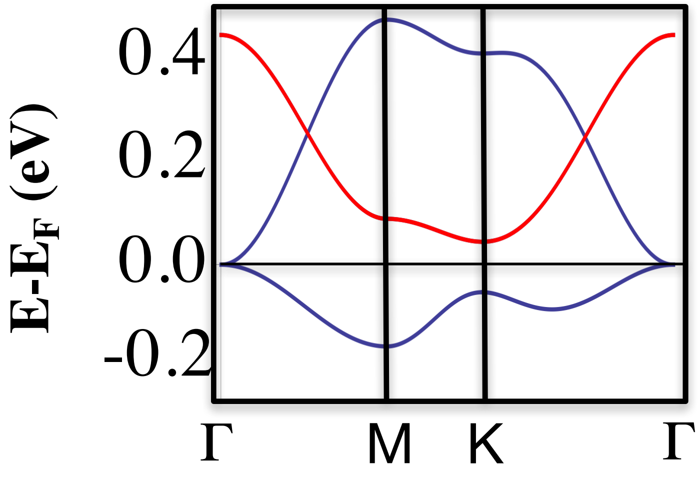
Inversion-symmetry breaking

- “Orbital Rashba” effect gaps out K Dirac point
- Half-semimetal



# “Orbital Dipoles” and the “Orbital Rashba effect”

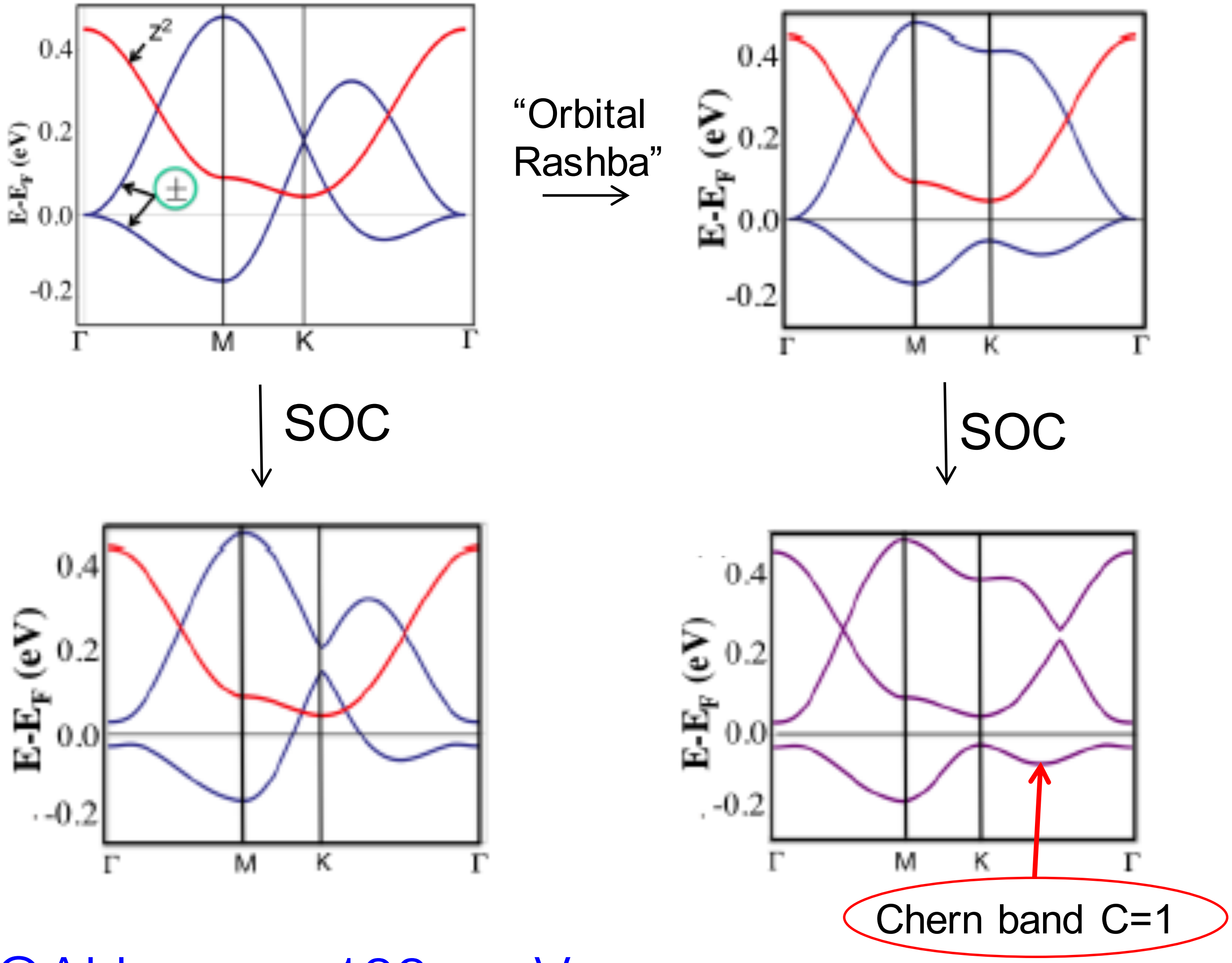




Inversion-symmetry breaking

- “Orbital Rashba” effect gaps out K Dirac point
- Half-semimetal

# Large gap quantum anomalous Hall insulator



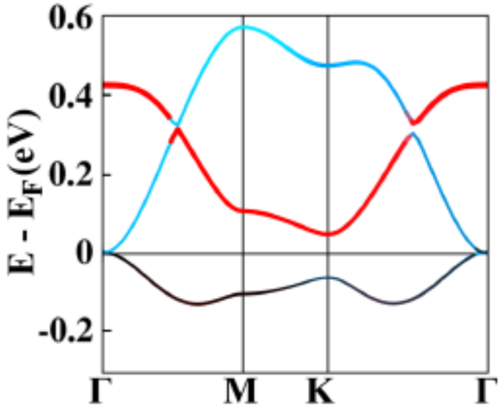
“Orbital Rashba”

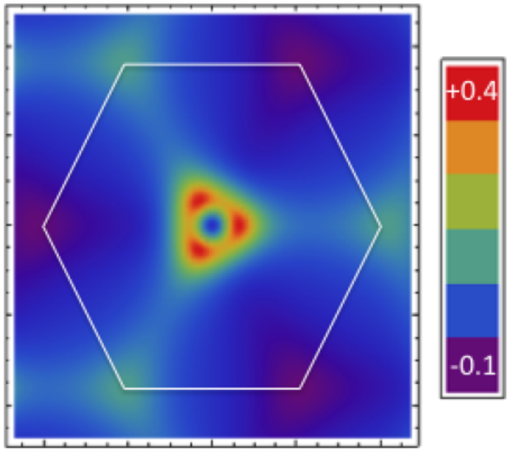
SOC

SOC

Chern band C=1

*DFT calculations*





Berry curvature

QAH gap ~ 100 meV

Ferromagnetic Tc ~ 250-300 K

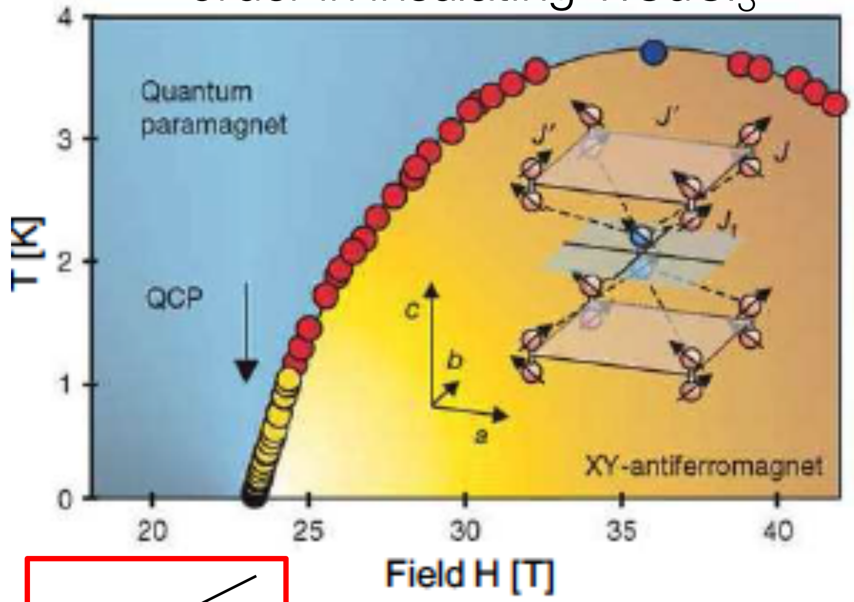
S. Baidya, U. Waghmare, AP, T. Saha-Dasgupta (to appear)

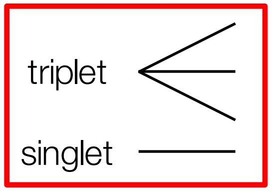
# Can interactions drive new phases at **topological** critical points?

## Quantum critical points in “gapped” systems

**Quantum phase transitions**

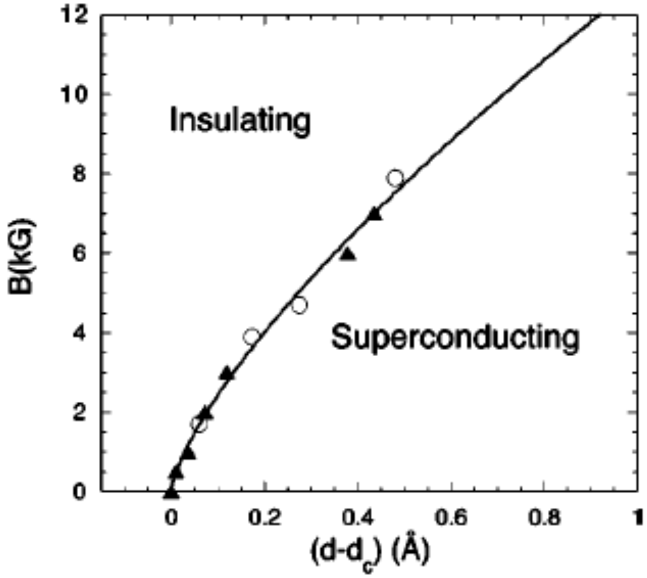
B-field induced magnetic order in insulating $TlCuCl_3$

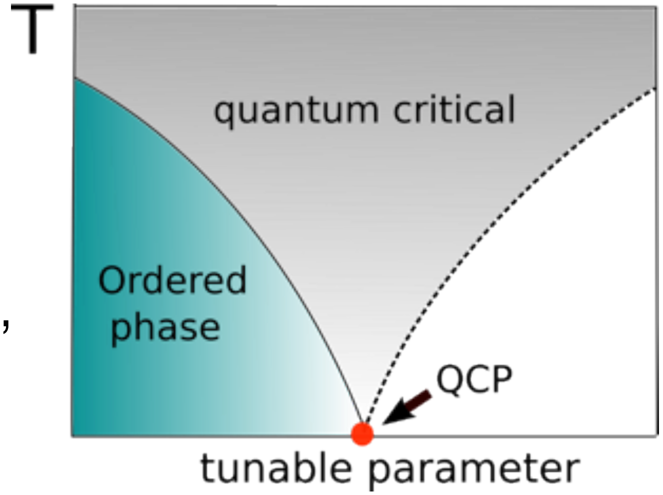




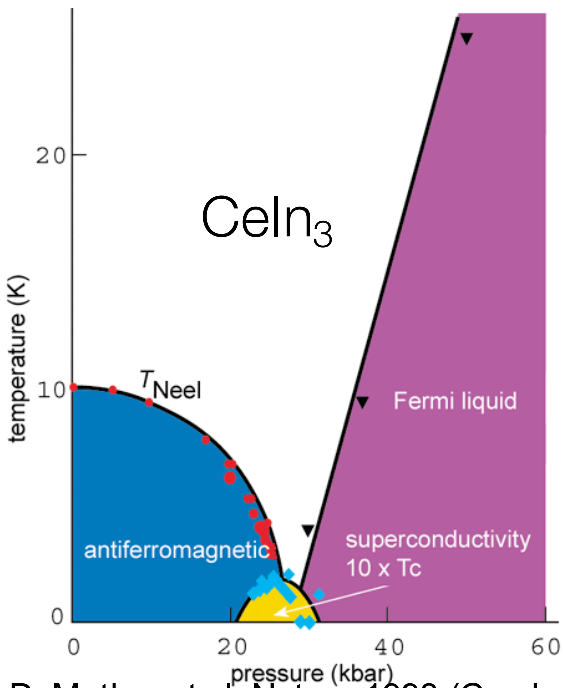
- Sharp change in ground state with tuning parameter at T=0
- Finite T crossovers: “critical fan”

Disorder tuned or B-field tuned Superconductor-insulator transition

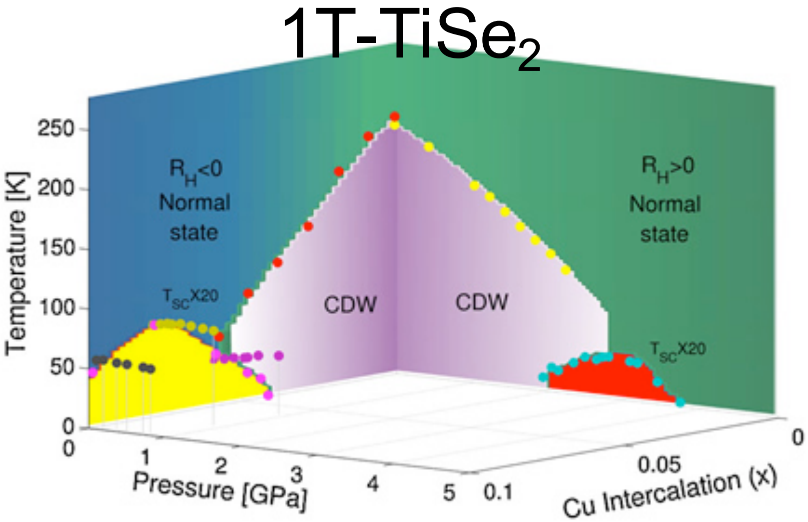




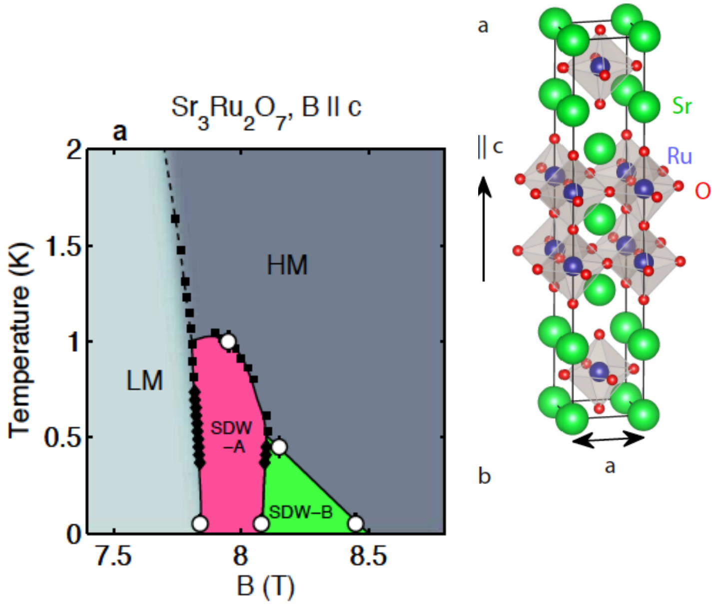
# Quantum critical points in metals - “emergent” phases



N.D. Mathur et al, Nature 1998 (Cambridge)
+ Grenoble group results



A.F. Kusmartseva, et al, PRL 2009

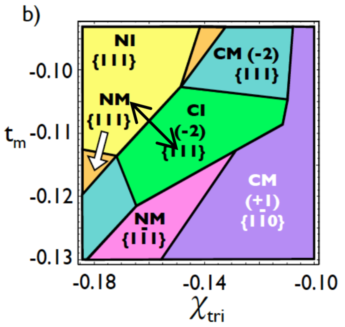


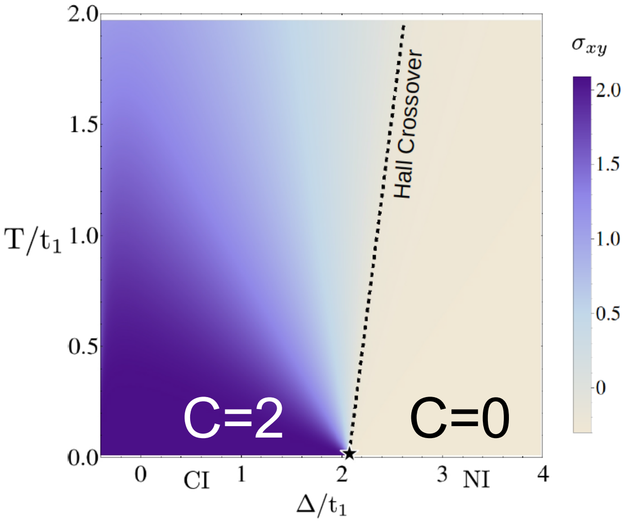
C.Lester, et al, Nat. Mat. 2015

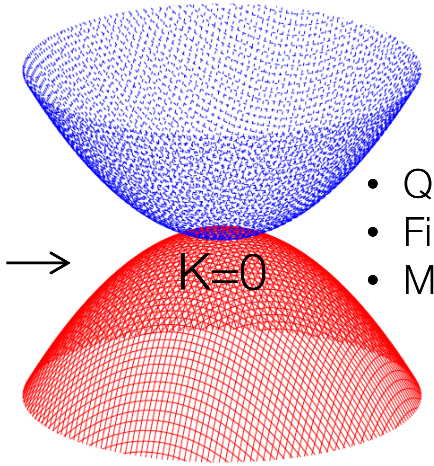
- Critical point involves Fermi surface reconstruction
- General overview: “Hot spots” on the Fermi surface could lead to new instabilities

(Metlitski, Sachdev, 2010; Berg,Metlitski, Sachdev, 2011)

# Can interactions drive new phases at **topological** critical points?







- QCP: Quadratic band touching
- Finite density of states
- Marginally relevant interactions

K. Sun, H. Yao, E. Fradkin, S. Kivelson (PRL 2009)

$$H=-\sum_{\langle ij\rangle} t_{ij}^{\alpha\beta}c_{i\alpha}^{\dagger}c_{j\beta}+\Delta\sum_i(n_{i\uparrow}-n_{i\downarrow})+U\sum_i n_{i\uparrow}n_{i\downarrow}$$

## RG flow

$$\left.\begin{aligned}
H_{\Gamma}^{\text{low}}&=\begin{pmatrix}\frac{3}{2}(t_2+t_1)k^2+r & \frac{3}{4}t_3(k_x-ik_y)^2\\ \frac{3}{4}t_3(k_x+ik_y)^2 & \frac{3}{2}(t_2-t_1)k^2-r\end{pmatrix}\\
S_{\text{int}}&=u\int_0^{\beta}d\tau\sum_i\bar{\psi}_{i\uparrow}(\tau)\bar{\psi}_{i\downarrow}(\tau)\psi_{i\downarrow}(\tau)\psi_{i\uparrow}(\tau)
\end{aligned}\right\}
\quad
\begin{aligned}
\frac{dr}{d\ell}&=2r+\frac{u\Lambda^2}{4\pi}\frac{t_1}{\sqrt{t_1^2+t_3^2/4}}\\
\frac{du}{d\ell}&=\frac{u^2}{6\pi}\frac{1}{\sqrt{t_1^2+t_3^2/4}}.
\end{aligned}$$

- Single “hot spot”
- Single marginally relevant coupling

# Chern transition and “emergent” phases

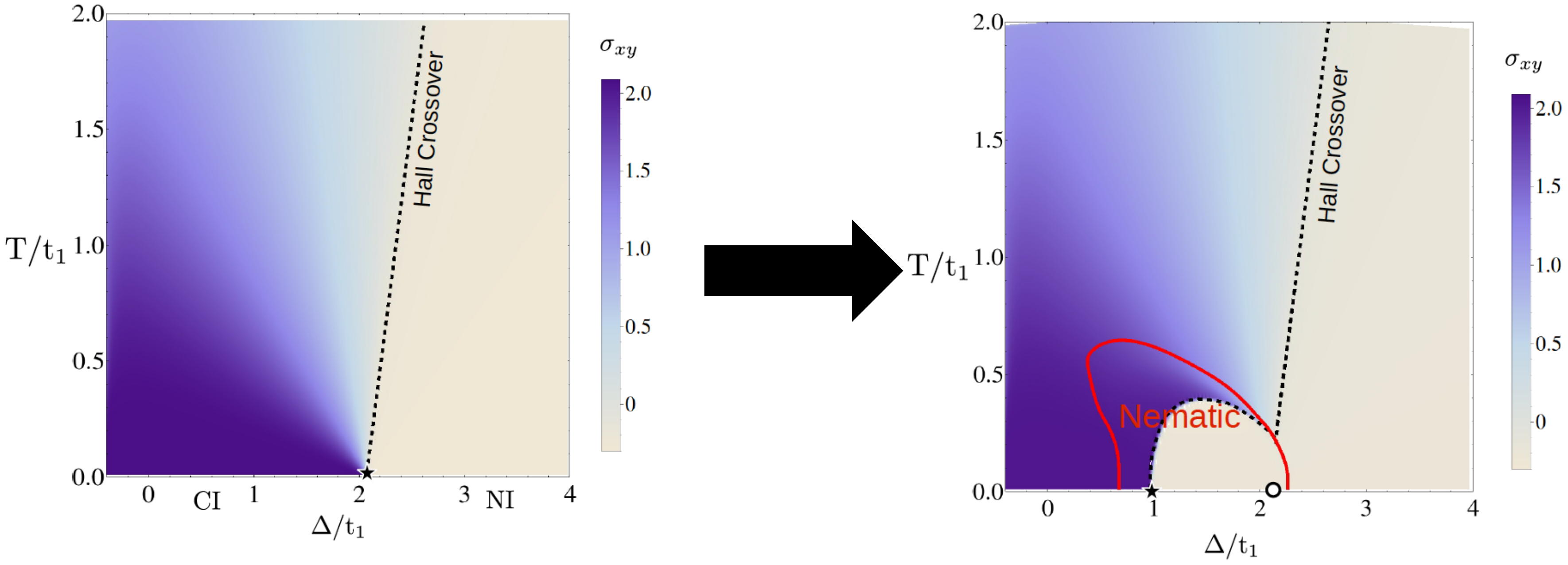
$$\vec{m} = \frac{1}{2N}\sum_{\mathbf{k}}\langle c^{\dagger}_{\mathbf{k}\alpha}\vec{\sigma}_{\alpha\beta}c_{\mathbf{k}\beta}\rangle$$

$e^{i2\theta_{\mathbf{k}}}$

Breaks rotational symmetry
- Emergent “nematic order”

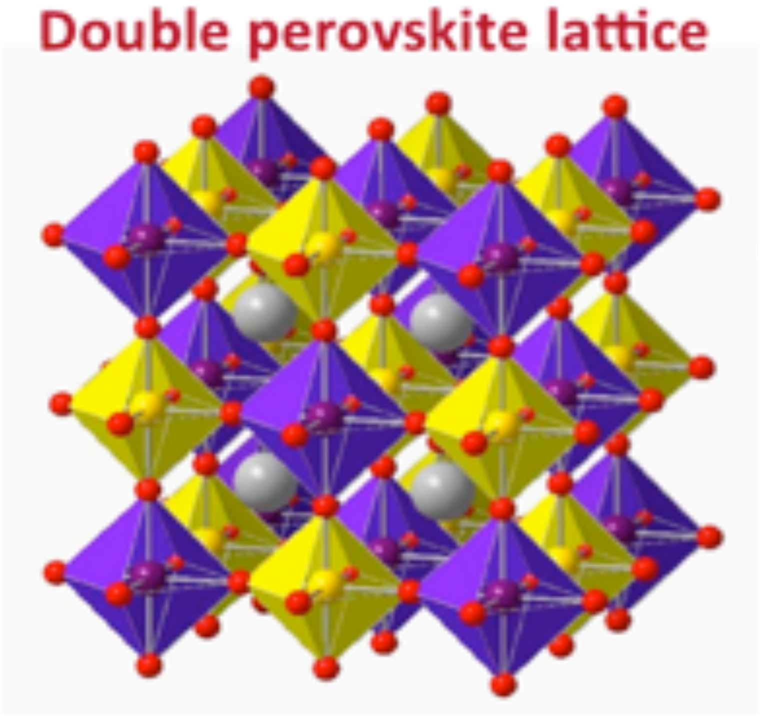
$$H_{\mathrm{mf}}(\mathbf{k})=\begin{pmatrix} A_{\mathbf{k}}-\mu-Um_z & D_{\mathbf{k}}-U(m_x-im_y) \\ D^{*}_{\mathbf{k}}-U(m_x+im_y) & B_{\mathbf{k}}-\mu+Um_z \end{pmatrix}$$

Quadratic band touching point splits into two Dirac nodes



Interactions give rise to an emergent liquid crystal!

# Mott insulating double perovskites: FCC lattice iridates



Mott insulating double perovskites

A sublattice: Inert closed shell atom

B sublattice: Magnetic ion

- Atoms farther apart, suppresses delocalization
- Rich variety of fcc lattice Mott insulators

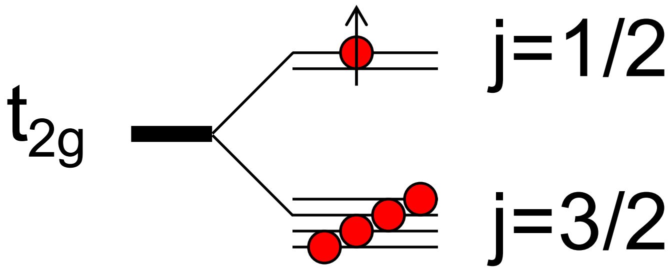
$Ba_2YMoO_6$, $Sr_2YReO_6$, $Sr_2YIrO_6$, $La_2MgIrO_6$, …

# Mott insulating double perovskites: FCC lattice iridates

**$La_2ZnIrO_6$ , $La_2MgIrO_6$** [G. Cao, et al, PRB 2013]

- Insulating DPs, $Zn^{2+}$/$Mg^{2+}$ are nonmagnetic
- $Ir^{4+}$ is in $5d^5$ configuration: j=1/2 moment
- Oxygen octahedra nearly perfect, small tilts/rotations

(G. Cao et al, PRB 2013; Battle and Gore, J. Mater. Chem 1996;
Currie et al., J. Sol. St. Chem, 1995)



j=1/2 Mott insulator

Other well studied examples of j=1/2 Mott insulators

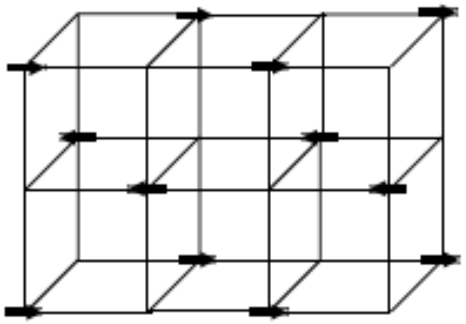
Perovskite, $Sr_2IrO_4$ - B. J. Kim, et al, Science 2009

Honeycomb, $Na_2IrO_3$ - Y. Singh and P. Gegenwart PRB 2010 (“Kitaev material”)

**Opportunity to explore magnetism of SOC moments on the frustrated fcc lattice**

# Magnetic order and spin dynamics

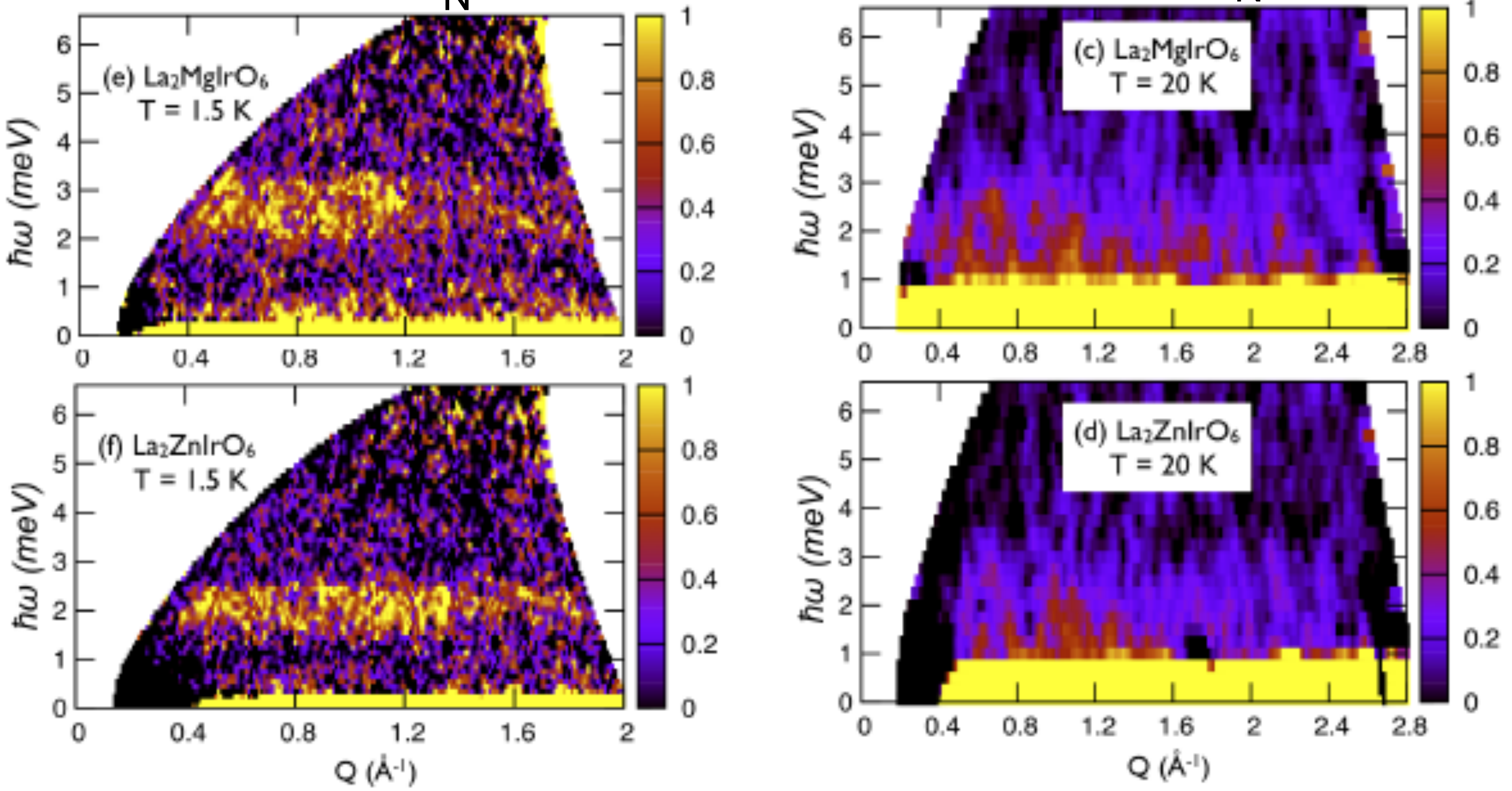
Magnetic order: Type I AFM
$\Theta/T_N < 2$ (weak frustration)



AFM A–II

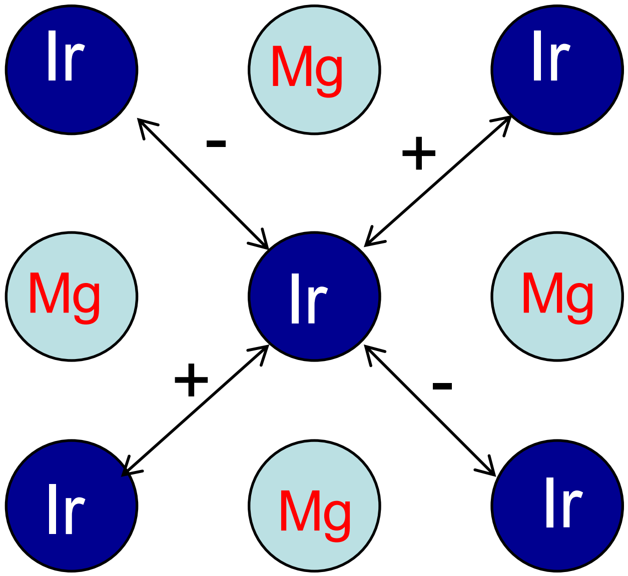
**Inelastic neutron scattering (ORNL)**

$T < T_N$ $T > T_N$



Band of gapped magnon excitations - Is this just a boring “Ising” model?

# Magnetic Hamiltonian: Symmetry analysis of ideal fcc lattice



$$H_{xy} = J_H \vec{S}_1 \cdot \vec{S}_2 + J_K S_1^z S_2^z \pm \Gamma(S_1^x S_2^y + S_1^y S_2^x)$$

$$H_{yz} = J_H \vec{S}_1 \cdot \vec{S}_2 + J_K S_1^x S_2^x \pm \Gamma(S_1^y S_2^z + S_1^z S_2^y)$$

$$H_{xz} = J_H \vec{S}_1 \cdot \vec{S}_2 + J_K S_1^y S_2^y \pm \Gamma(S_1^x S_2^z + S_1^z S_2^x)$$

H. Ishizuka, L. Balents (PRB 2014)
A. Cook, S. Matern, C. Hickey, A. A. Aczel, AP (PRB 2015)

Important conclusion:

**Uniaxial Ising interaction forbidden on ideal fcc lattice**

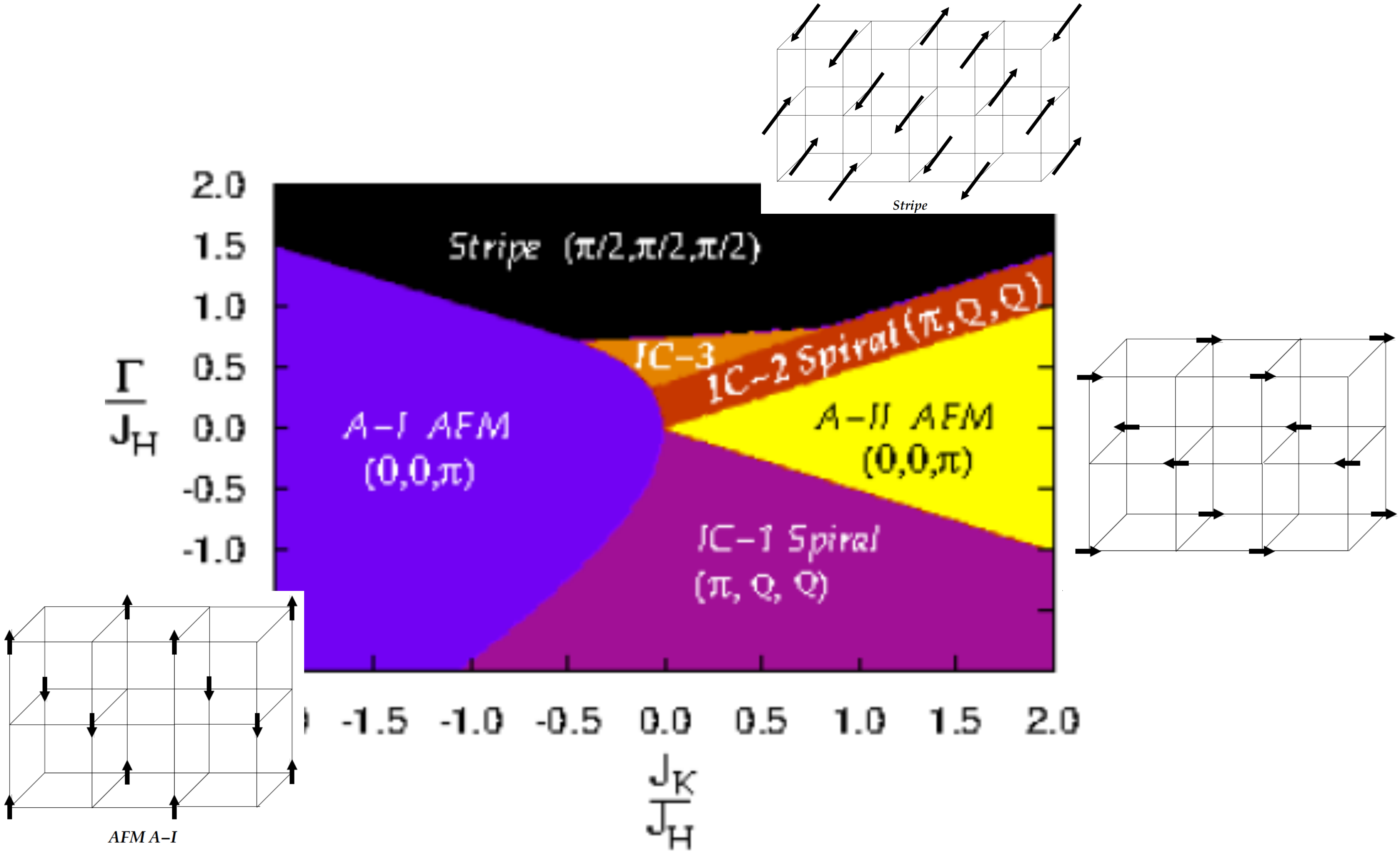
Kitaev++ models in iridate materials

2d/3d Honeycomb lattice: Kitaev model leads to a quantum spin liquid with topological order

Honeycomb $\alpha$-$Na_2IrO_3$/$Li_2IrO_3$
Jackeli, Khaliullin, Chaloupka (2011,2012) – Kitaev Hamiltonian
J. Rau, H. Y. Kee (PRL+PRB 2014) – Beyond Kitaev

Hyper-honeycomb $\beta/\gamma$– $Li_2IrO_3$
Takagi group (2014), J. Analytis group (2014) – 3D Kitaev generalization
I.Kimchi, R. Coldea, A. Vishwanath (2014); E.K.H.Lee, Y.B.Kim (2014)

# Luttinger-Tisza phase diagram



Small frustration parameter and measured order A-II suggests large $J_K$>0

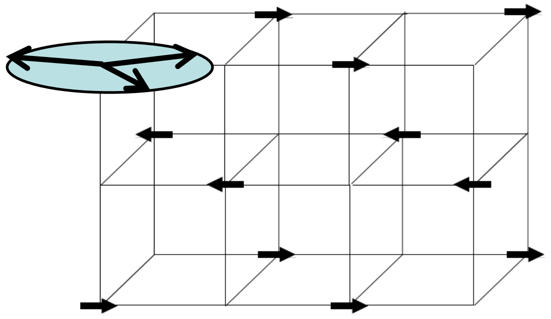
A. Cook, S. Matern, C. Hickey, A. A. Aczel, AP (PRB 2015)

# Spin dynamics

- Minimal Hamiltonian: “Kitaev model”

$$H_K = J_K \sum_{\langle \mathbf{rr'}\rangle_{xy}} S^z_{\mathbf{r}} S^z_{\mathbf{r'}} + J_K \sum_{\langle \mathbf{rr'}\rangle_{yz}} S^x_{\mathbf{r}} S^x_{\mathbf{r'}} + J_K \sum_{\langle \mathbf{rr'}\rangle_{xz}} S^y_{\mathbf{r}} S^y_{\mathbf{r'}}$$

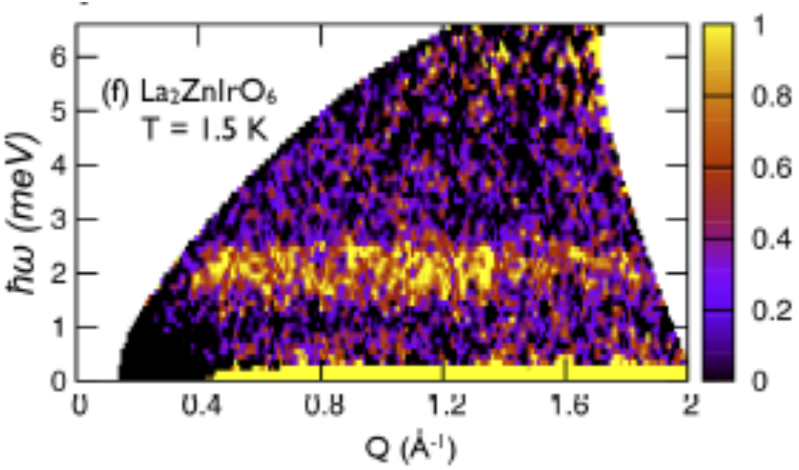
- Thermodynamic studies: $J_K$ ~ 24K



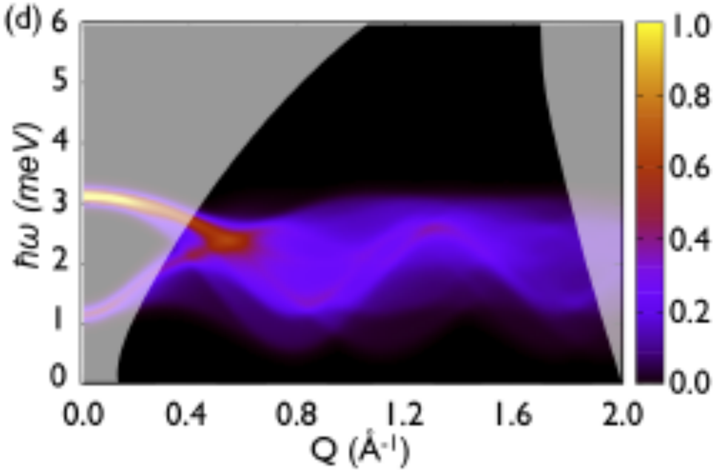
Classically: Spins can point anywhere in XY plane

- **Quantum order by disorder**: **Pins moments** to point along Ir-O bond direction
- **Magnon interactions important**: **Leads to a gap** in the spin wave spectrum
- Incorporate weak second neighbor ferromagnetism

Data for $La_2ZnIrO_6$



Theory for $La_2ZnIrO_6$



$J_K$ ~ + 0.7 meV; $J_2$ ~ - 0.2 $J_K$

Heterostructures could realize engineered topological 2D Kitaev models

# Summary

- 2D/3D double perovskites: $Sr_2FeMoO_6$, $Ba_2FeReO_6$
  - Topological phases including emergent Chern bands
  - C=1 quantum anomalous Hall insulators

- Emergent nematic order at topological quantum critical points

- Mott insulating double perovskites: $La_2ZnIrO_6$, $La_2MgIrO_6$
  - Spin Hamiltonian with unusual non-Heisenberg interactions
  - Heterostructures might realize 2D Kitaev models: Topological physics?