Macroscopic entanglement, spin liquids & Kitaev materials

Entanglement in Strongly Correlated Systems
Benasque, February 2020

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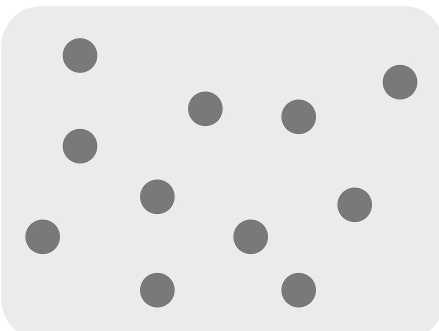
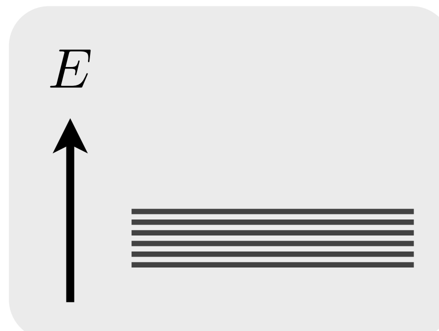
CRC183
ENTANGLED STATES OF MATTER

When do interesting things happen?

Some of the most intriguing phenomena in condensed matter physics arise from the splitting of **‘accidental’ degeneracies**.



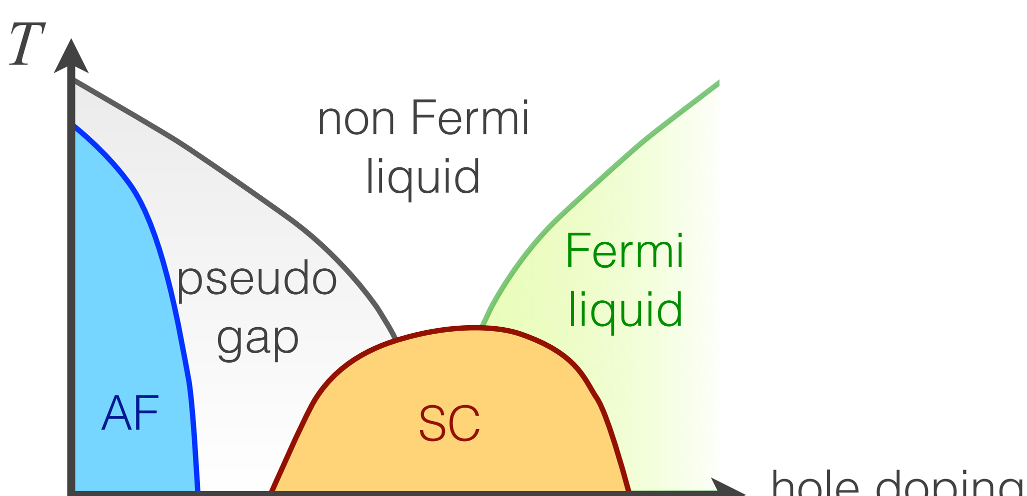
interacting
many-body system



‘accidental’
degeneracy

residual effects
select ground state

phase diagram of
cuprate superconductors



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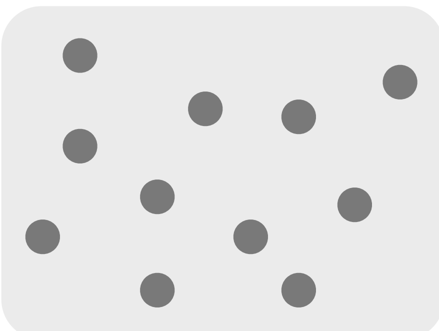
Some of the most intriguing phenomena in condensed matter physics arise from the splitting of **‘accidental’ degeneracies**.



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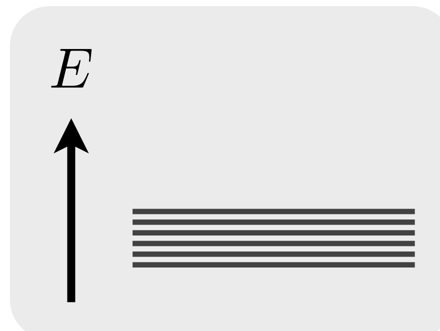


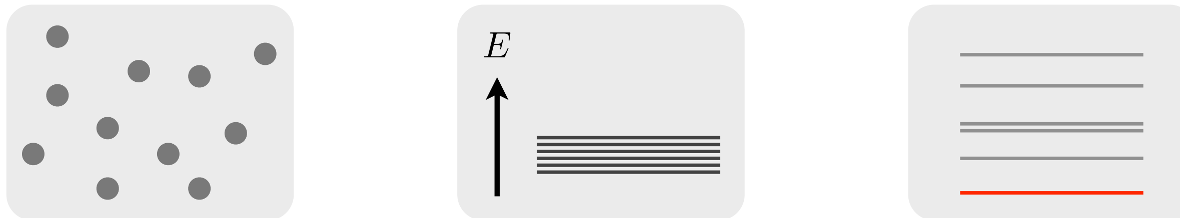
‘accidental’
degeneracy

residual effects
select ground state

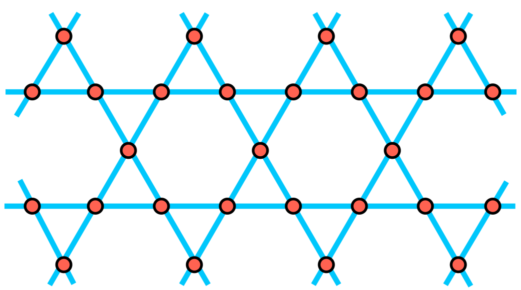
But they are also **notoriously difficult** to handle, due to

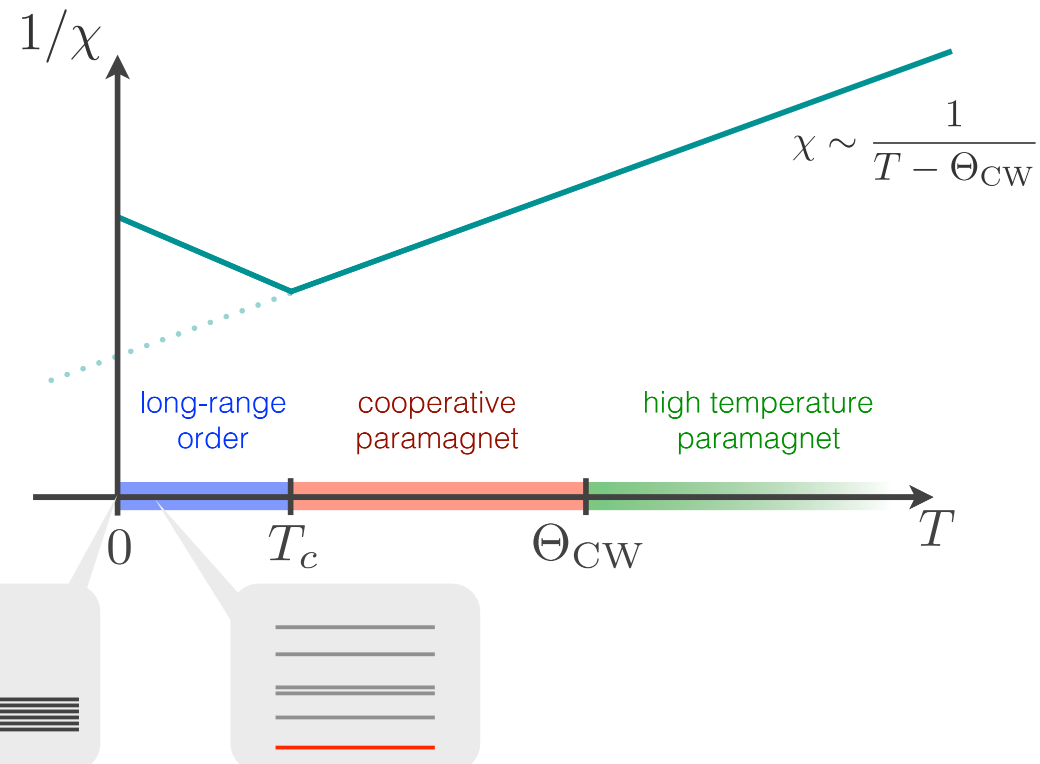
- multiple energy scales
- complex energy landscapes / slow equilibration
- strong coupling
- macroscopic entanglement

Example – frustrated magnets

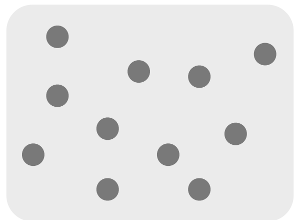


interacting many-body system | ‘accidental’ degeneracy | **residual effects** select ground state

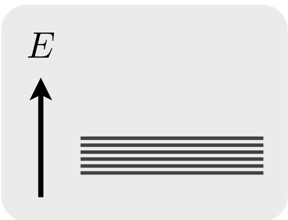




Example – quantum Hall liquids



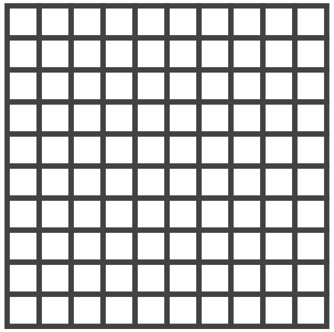
interacting
many-body system



'accidental'
degeneracy

residual effects
select ground state

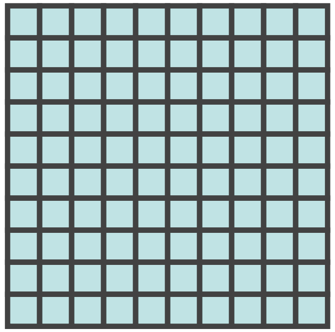
Landau level **degeneracy**



$$2\Phi/\Phi_0$$

orbital states

integer quantum Hall

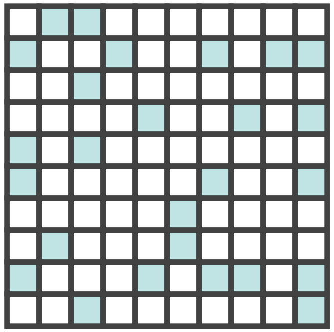


filled level

↓

incompressible liquid

fractional quantum Hall

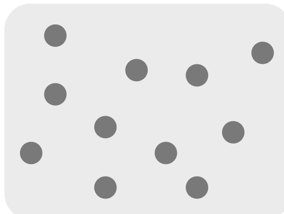


partially filled level

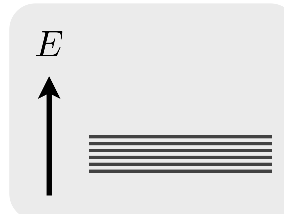
↓ Coulomb repulsion

incompressible liquid

Example – twisted bilayer graphene



interacting
many-body system



'accidental'
degeneracy

residual effects
select ground state

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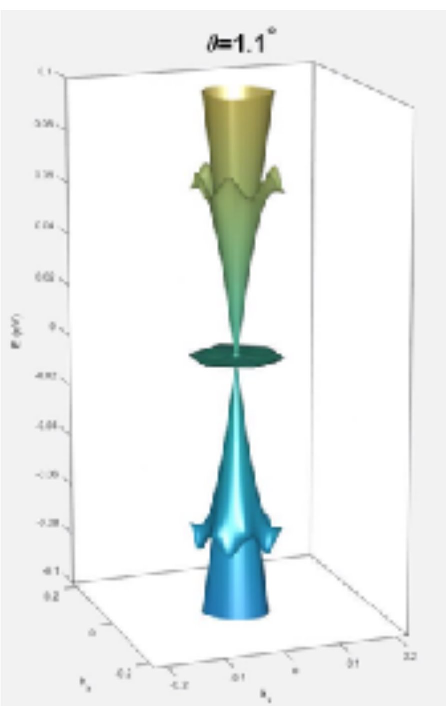
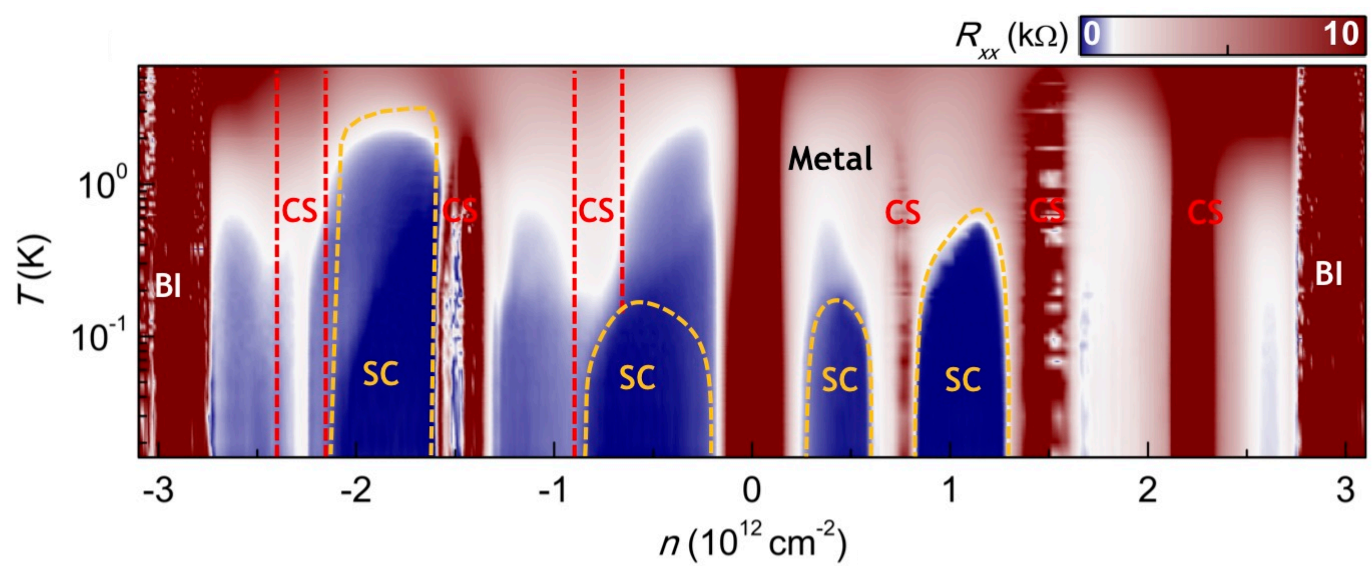
electronic band structure with a **flat band** in twisted bilayer graphene





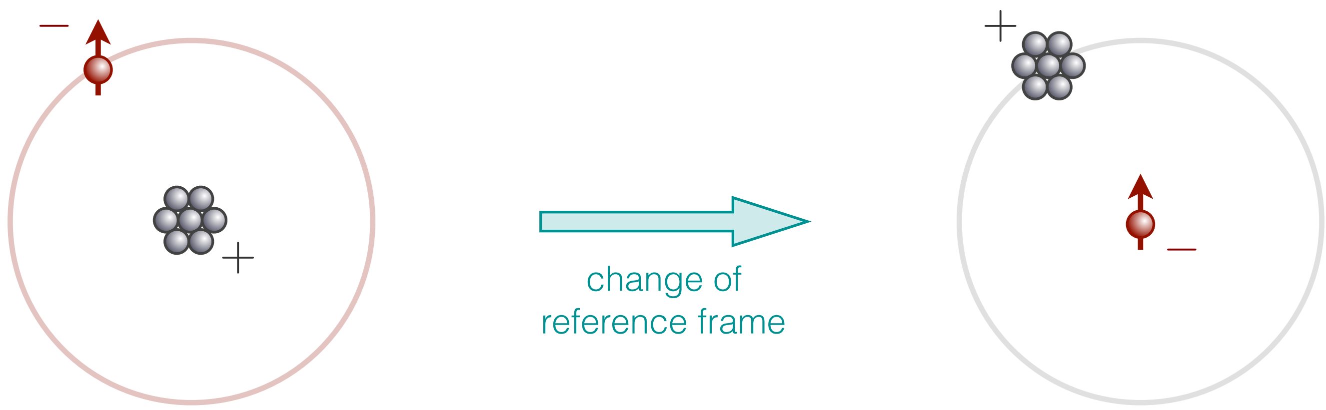
Efetov group, Nature **574**, 653(2019)

Jarillo-Herrero group, Nature **556**, 43 (April 2018)

spin-orbit materials

Spin-orbit coupling

Spin-orbit coupling 101 – quantum mechanics lecture

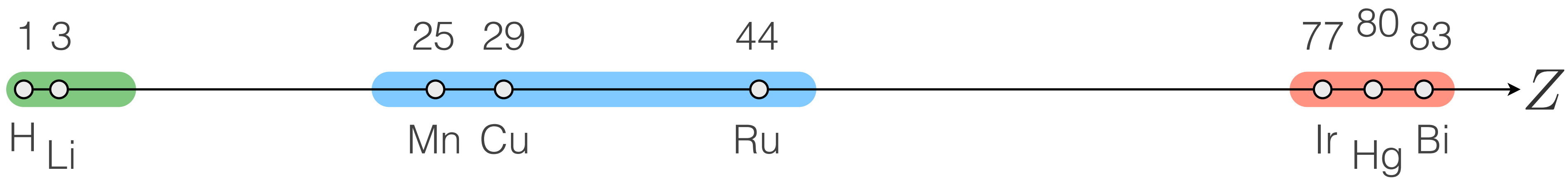


relativistic correction

$$\Delta E = \frac{\lambda}{\hbar^2}\,\vec{l}\cdot\vec{s} = \frac{\lambda}{2}\left[j(j-1) - l(l-1) - s(s-1)\right]$$

$$\lambda = \frac{Ze^2\mu_0\hbar^2}{8\pi m_e^2 r^3} \qquad r \propto 1/Z \qquad \lambda \propto Z^4$$

Spin-orbit coupling in condensed matter

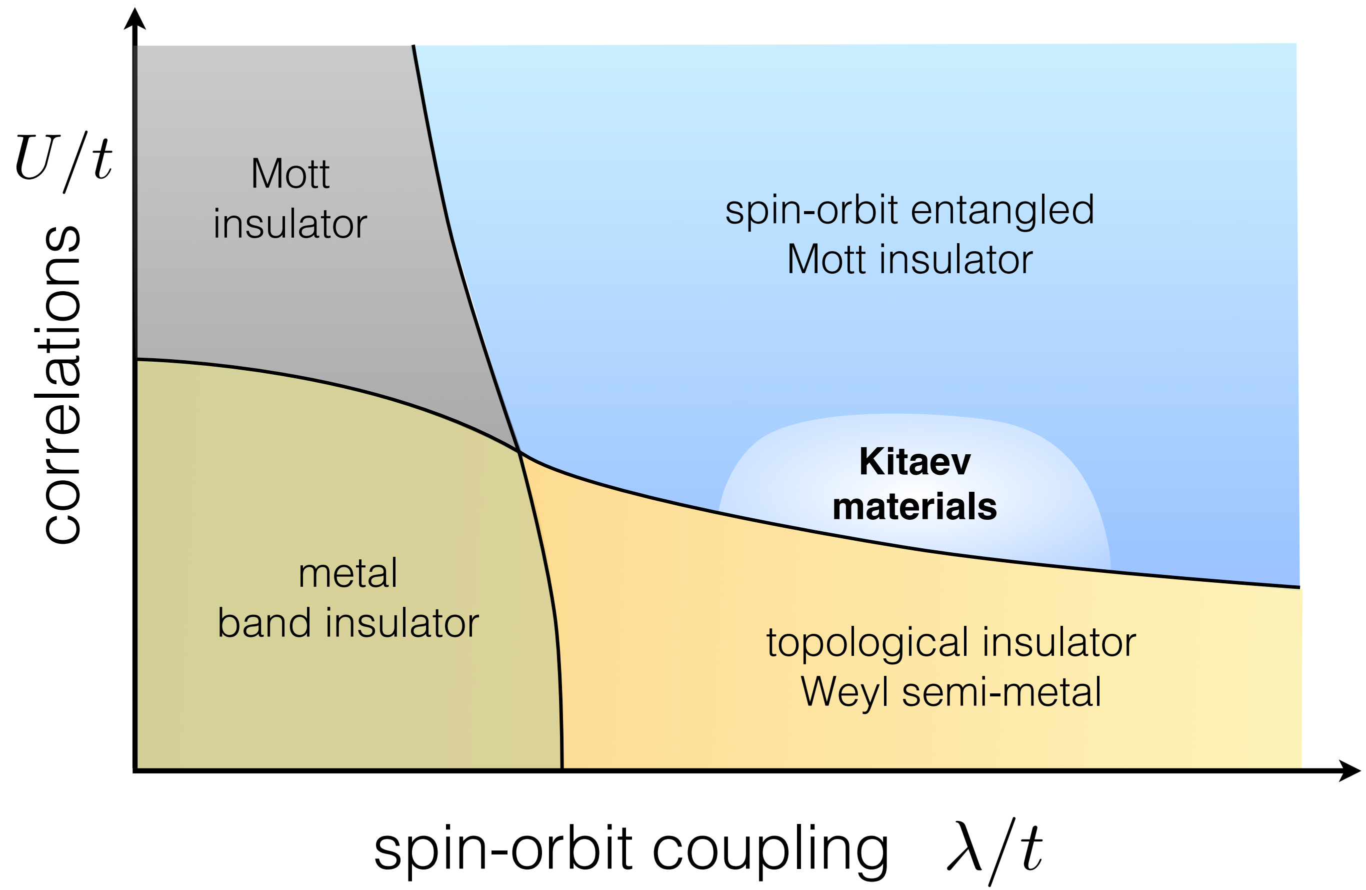


$\lambda \propto Z^4$ $\frac{1}{2}$ 1 5 50 58 67

weak SOC	moderate SOC		strong SOC	
atomic fine structure	multiferroics	unconventional superconductor	SO-assisted Mott physics	topological insulators
	$TbMnO_3$	Sr_2RuO_4	Sr_2IrO_4 $Na_4Ir_3O_8$ $(Na,Li)_2IrO_3$	HgTe Bi_2Se_3
	SOC induced DM interaction competes with **magnetic exchange**		SOC competes directly with **Hubbard physics**	

4d/5d transition metal compounds

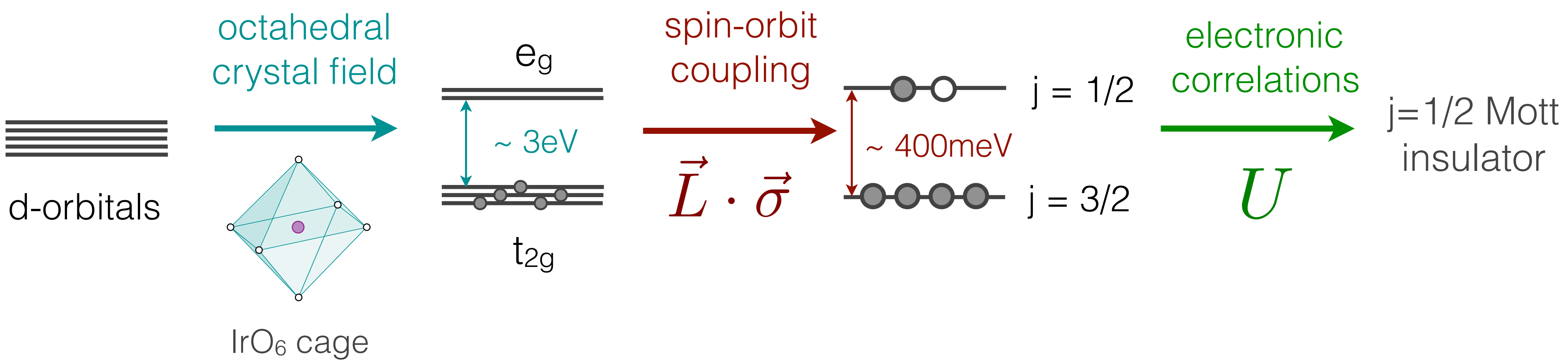
Transition metal oxides with **partially filled 4d/5d shells** exhibit an intricate interplay of **spin-orbit coupling**, **electronic correlations**, and **crystal field effects** resulting in a **broad variety of metallic and insulating states**.



W. Witczak-Krempa, G. Chen, Y. B. Kim, and L. Balents, Annual Review of Condensed Matter Physics 5, 57 (2014).

j=1/2 Mott insulators

most common **Iridium valence** Ir^{4+} $(5d^5)$

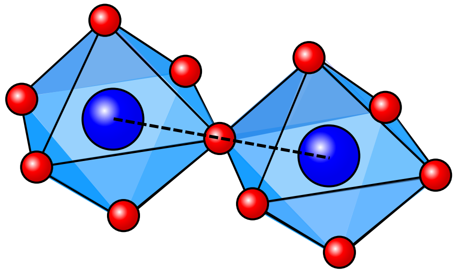


Why are these spin-orbit entangled j=1/2 Mott insulators **interesting?**

spin-orbit entangled Mott insulators

Why are these spin-orbit entangled j=1/2 Mott insulators **interesting?**

corner-sharing

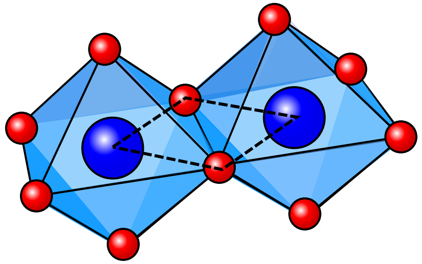


Sr_2IrO_4

exhibits cuprate-like magnetism
superconductivity?

B.J. Kim et al. PRL 101, 076402 (2008)
B.J. Kim et al. Science 323, 1329 (2009)

edge-sharing



$(Na,Li)_2IrO_3$
$RuCl_3$
$H_2LiIr_2O_6$
Cu_2IrO_3
...

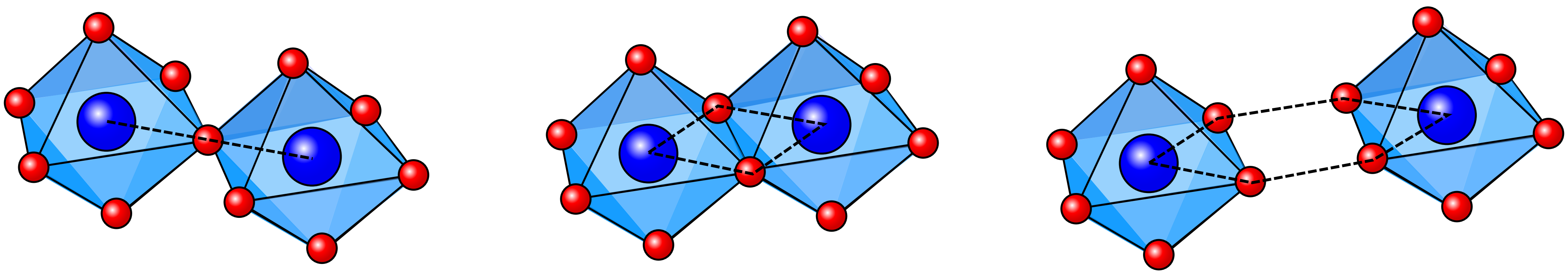
exhibit Kitaev-like magnetism
spin liquids?

G. Jackeli and G. Khaliullin, PRL 102, 017205 (2009)
J. Chaloupka, G. Jackeli, and G. Khaliullin, PRL 105, 027204 (2010)

bond-directional exchange

G. Jackeli and G. Khaliullin, PRL 102, 017205 (2009)
J. Chaloupka, G. Jackeli, and G. Khaliullin, PRL 105, 027204 (2010)

corner-sharing | **edge**-sharing | “**parallel edge**”-sharing



Sr_2IrO_4

$(Na,Li)_2IrO_3$
$RuCl_3$

$Ba_3IrTi_2O_9$

Heisenberg exchange

Heisenberg-Kitaev exchange

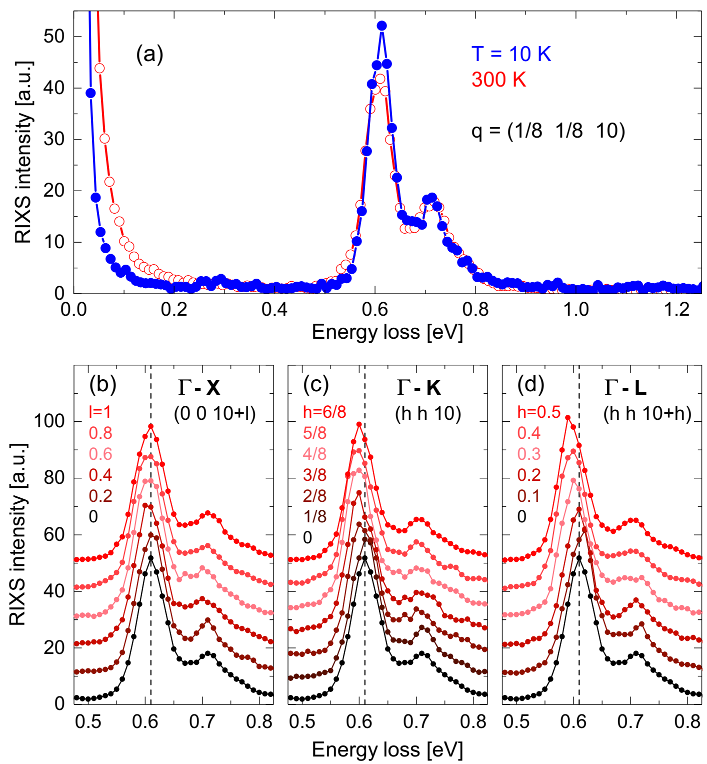
$$H = -\sum_{\gamma-\text{bonds}} J\, \mathbf{S}_i \mathbf{S}_j + K\, S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right)$$

spin-orbit entangled moments

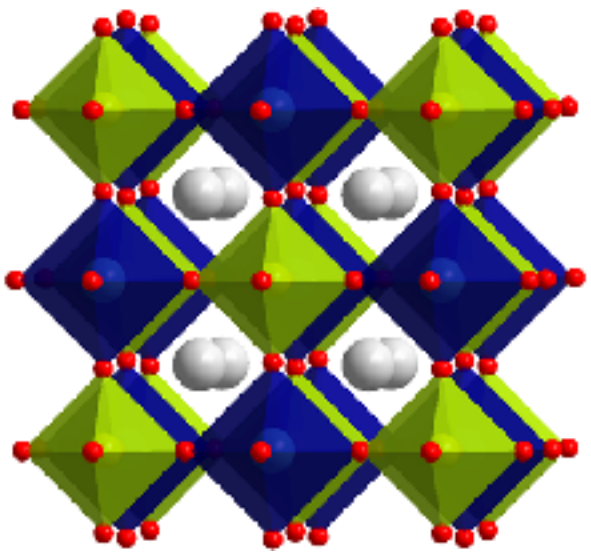
Ba_2CeIrO_6

Revelli *et al.*, PRB **100**, 085139 (2019)

The double perovskite Ba_2CeIrO_6
is the **best j=1/2 system** we have ever seen,
but not really a “Kitaev material”.



RIXS experiments



- pristine j=1/2 physics

$$|0\rangle = 0.991\left|\frac{1}{2},\frac{1}{2}\right\rangle - 0.130\left|\frac{3}{2},\frac{1}{2}\right\rangle$$

- frustrated FCC magnetism, but Kitaev interaction relieves frustration

- strong magneto-elastic effect

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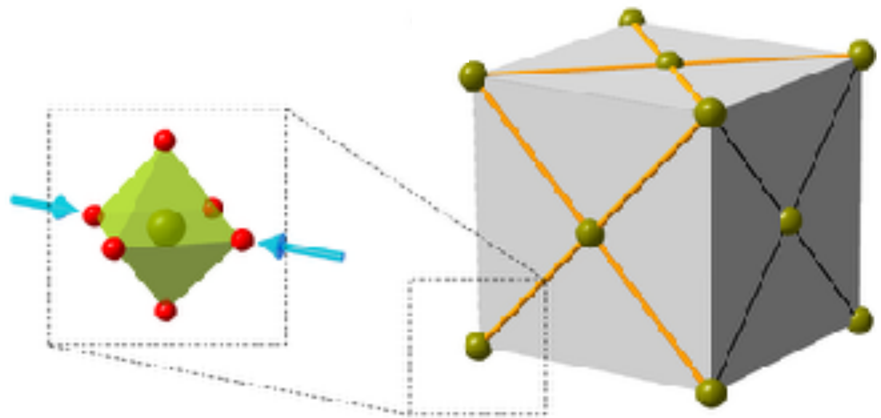

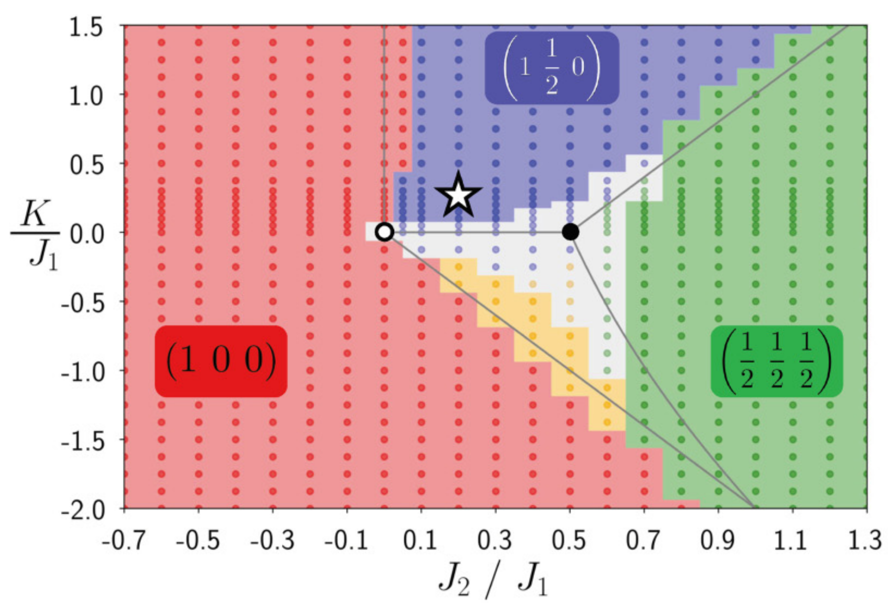

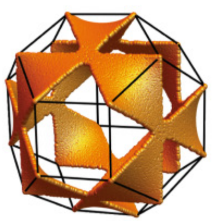

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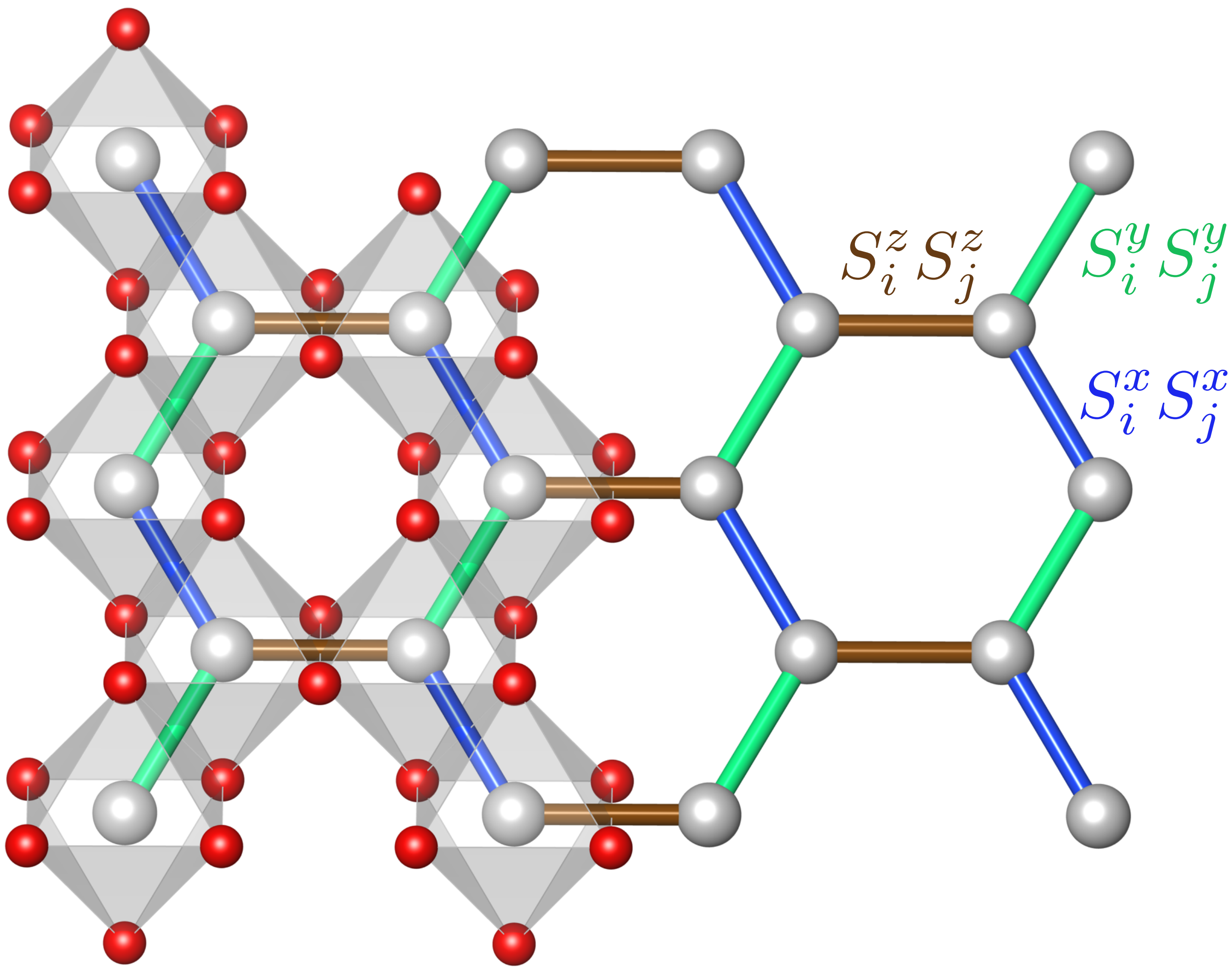
honeycomb
Kitaev materials

proximate spin liquids

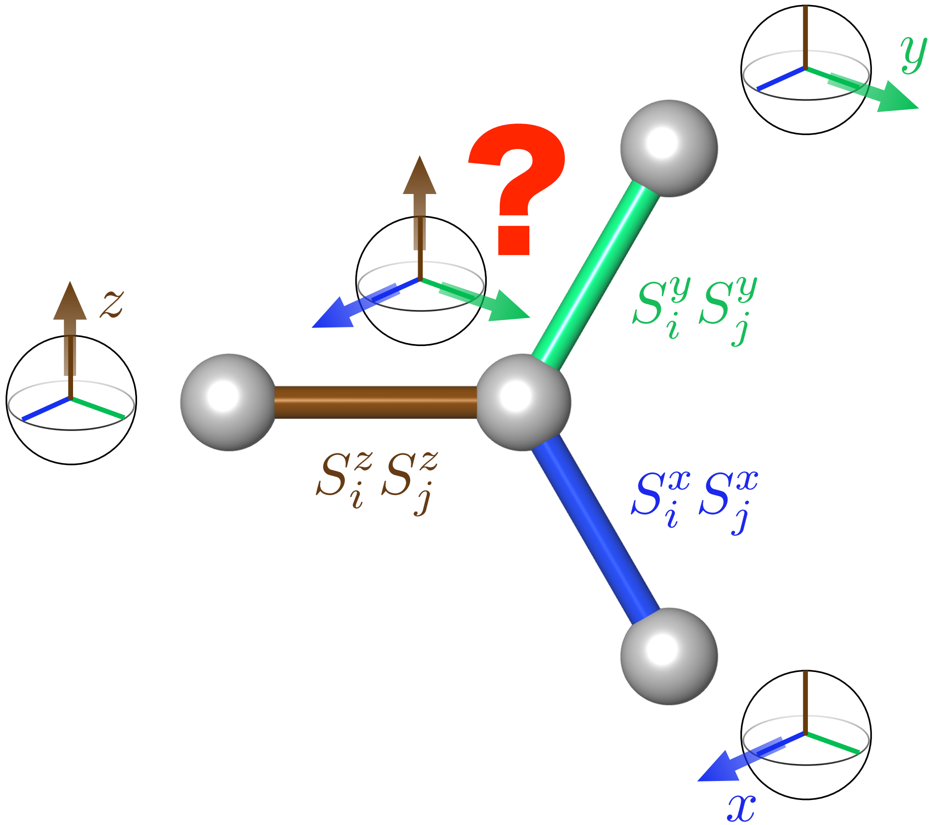
honeycomb Kitaev materials

Na_2IrO_3, α-Li_2IrO_3, $RuCl_3$, $H_2LiIr_2O_6$

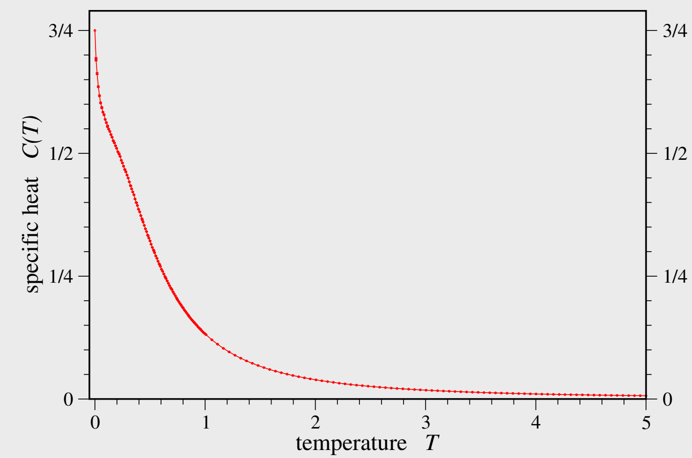


exchange frustration

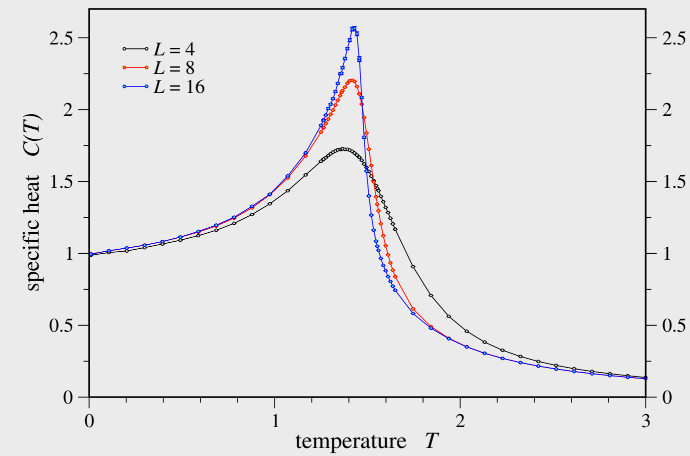
$$H = -\sum_{\gamma-\text{bonds}} J\,\mathbf{S}_i\mathbf{S}_j + K\,S_i^\gamma S_j^\gamma$$



classical Kitaev

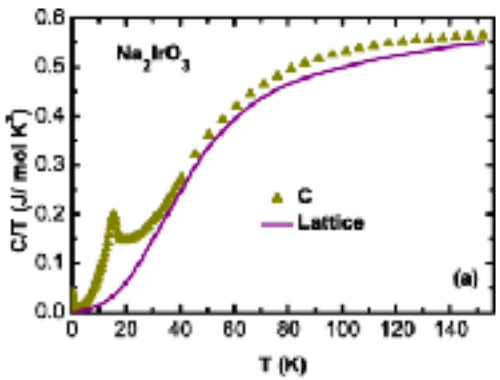


classical Heisenberg

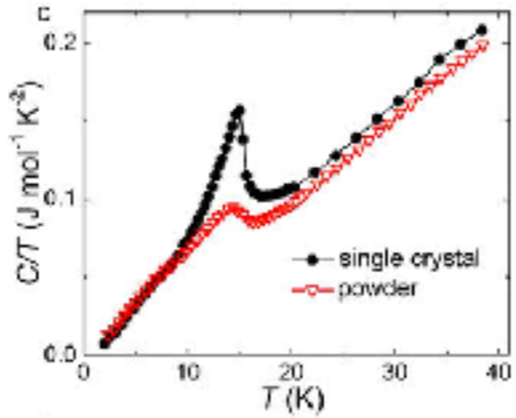


Kitaev materials – really?

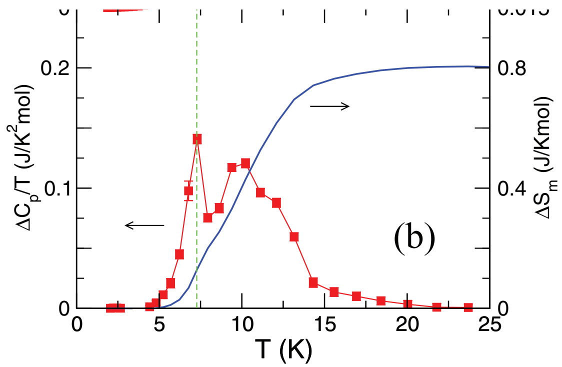
Na_2IrO_3



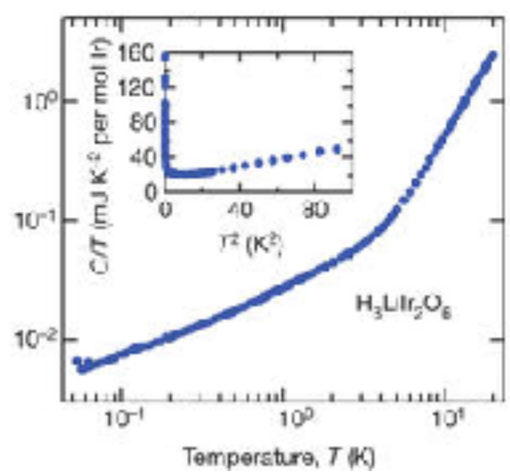
Li_2IrO_3



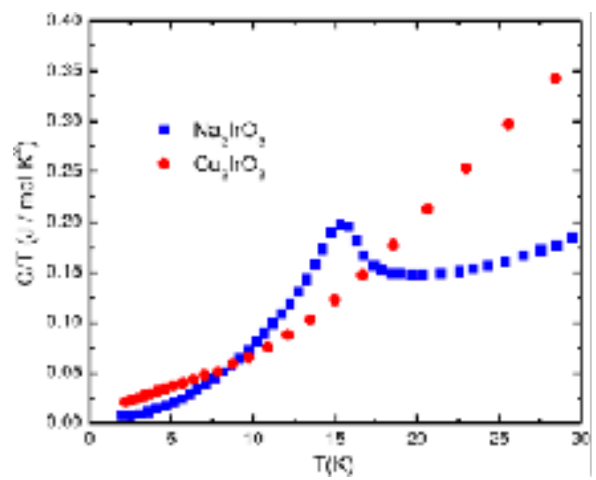
$RuCl_3$



$H_2LiIr_2O_6$



Cu_2IrO_3



Candidate materials tend to exhibit **magnetic ordering** at low T.

honeycomb Kitaev materials

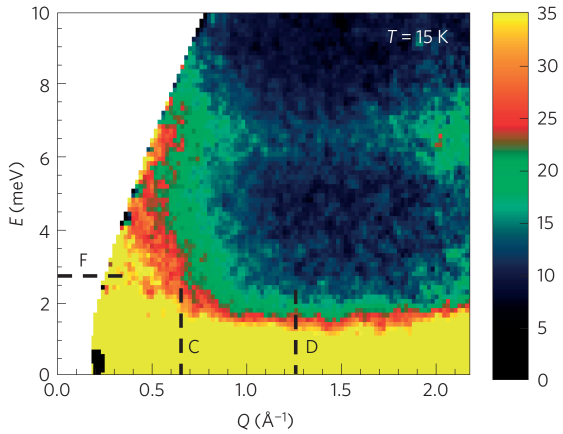
	magnetic moment $\mu_{\mathrm{eff}}/\mu_{\mathrm{B}}$	ordering temperature T_{N}	Curie-Weiss temperature Θ_{CW}
Na_2IrO_3	1.79(2)	15 K zig-zag order	-125 K
α-Li_2IrO_3	1.83(5)	15 K counterrotating spirals	-33 K
$RuCl_3$	2.2	7 K zig-zag order	-150 K
$H_2LiIr_2O_6$	?	—	?

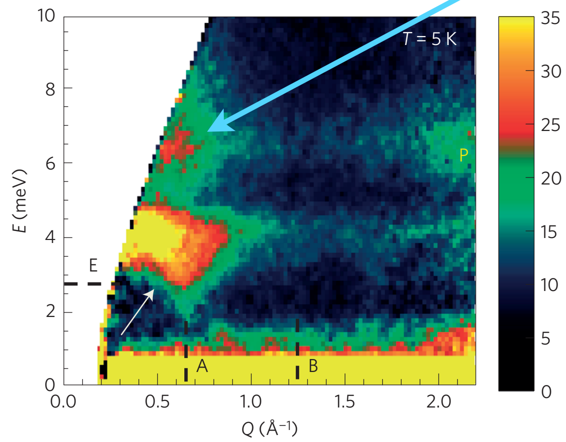
$RuCl_3$

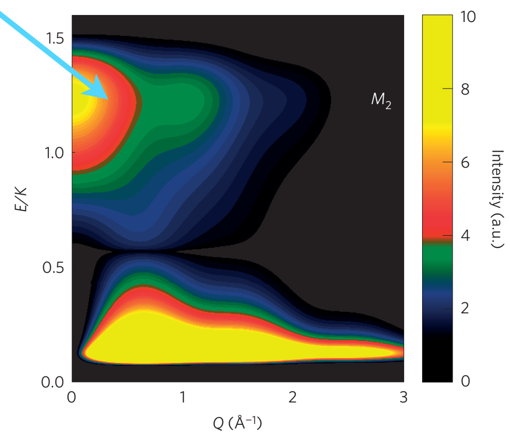
neutron scattering

Banerjee *et al.*, Nature Materials 4604 (2016)

broad **scattering continuum**



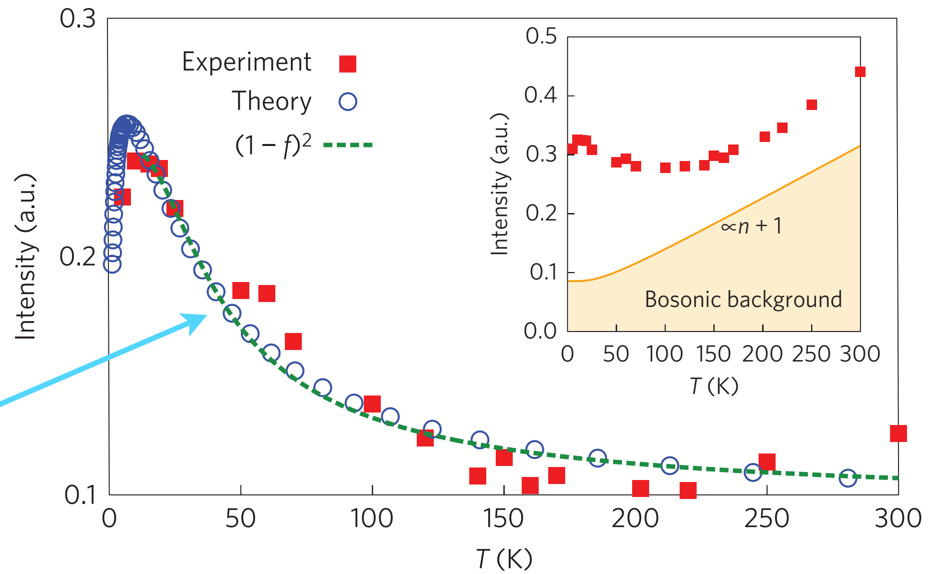




Raman scattering

Nasu *et al.*, Nature Physics **12**, 912 (2016)
Sandilands *et al.*, PRL **114**, 147201 (2015)

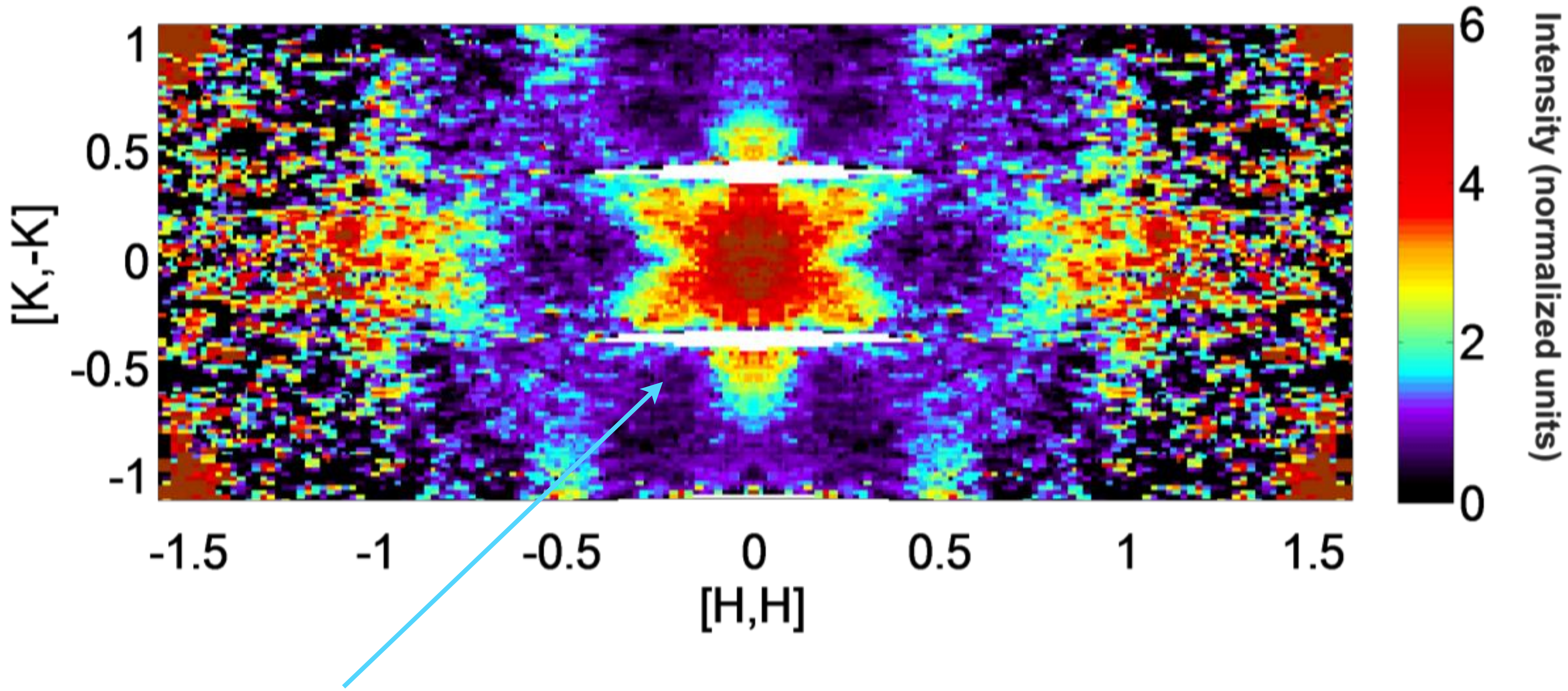
fermionic contribution



$RuCl_3$

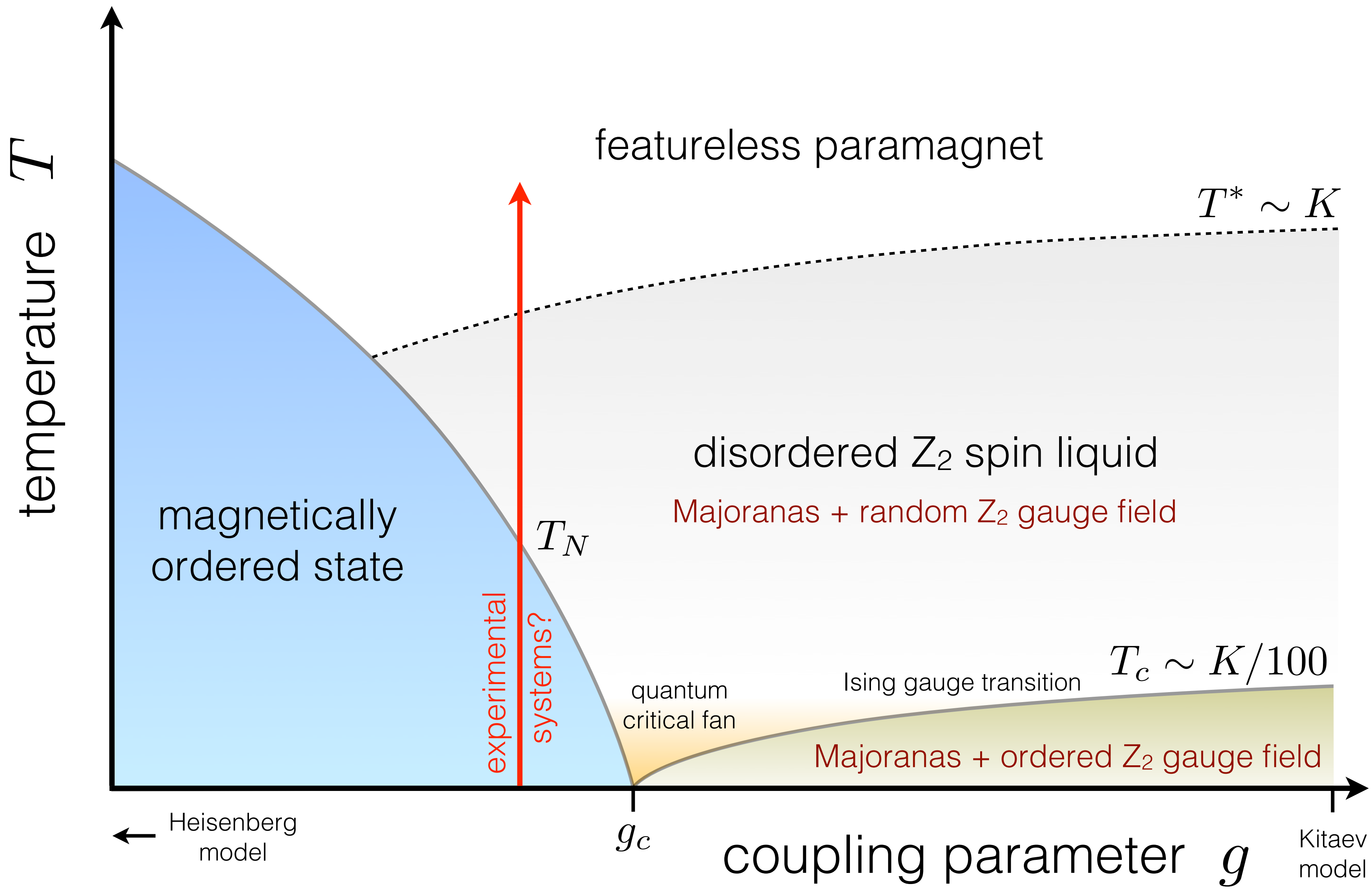
neutron scattering

Banerjee *et al.*, Nature Materials 4604 (2016)



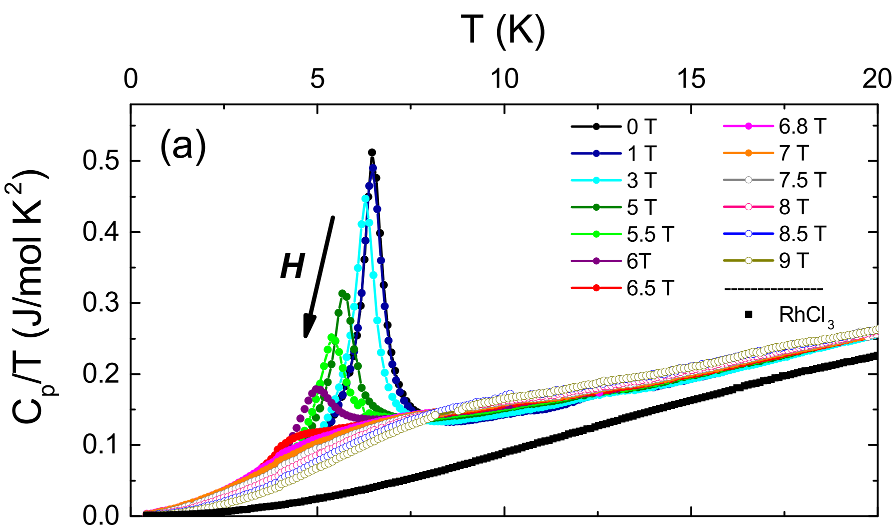
star-like feature arises from
interplay of spin-wave and spin liquids physics
at intermediate energy scales.

Proximate spin liquids

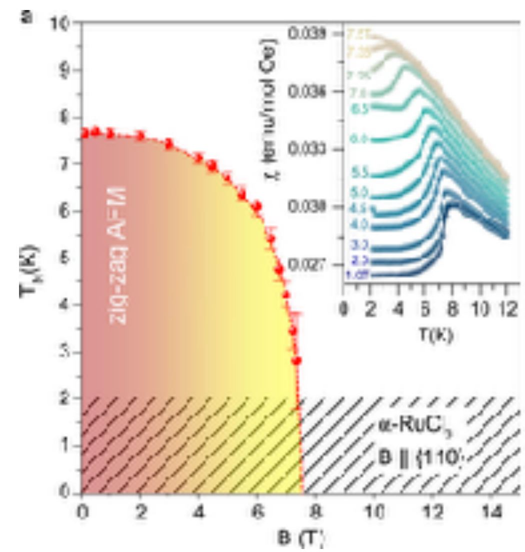


Spin liquids?!

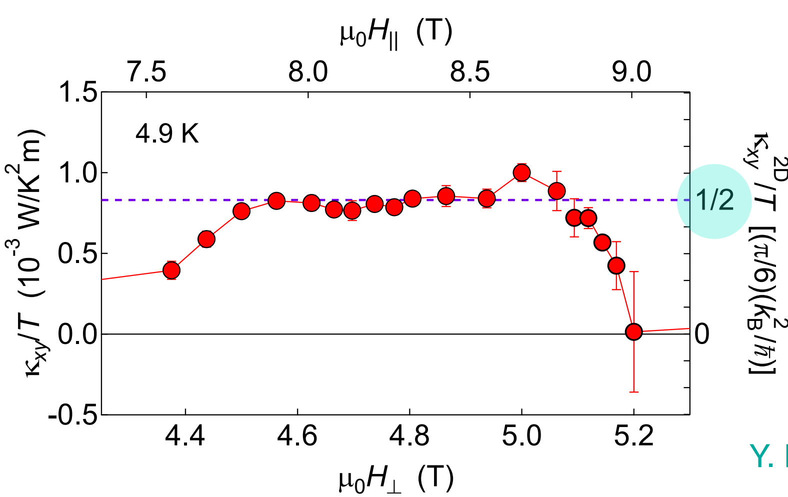
Something interesting happens for **$RuCl_3$ in a magnetic field**.



A. U. B. Wolter et al., PRB **96**, 041405(R) (2017)



A. Banerjee et al., npj Quantum Mater. **3**, 8 (2018)



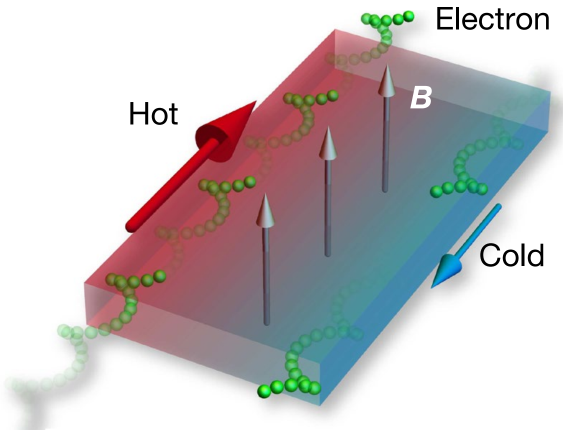
half-integer quantized
thermal Hall effect

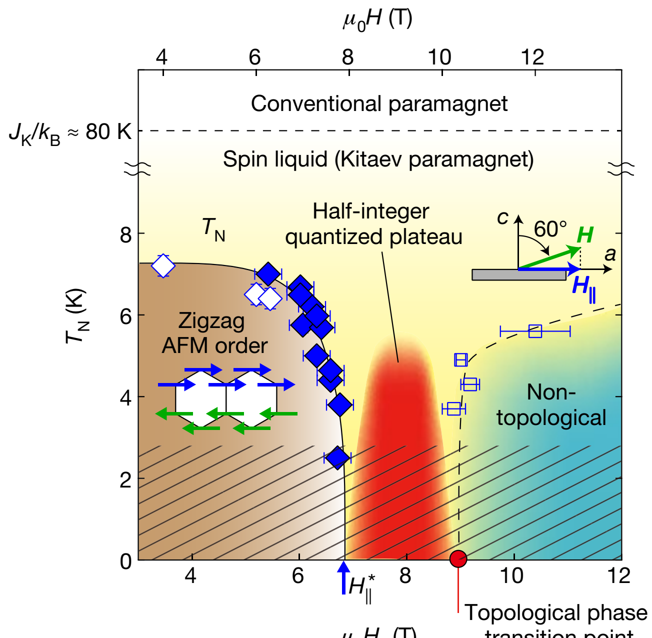
Y. Kasahara et al., Nature **559**, 227-231 (2018)

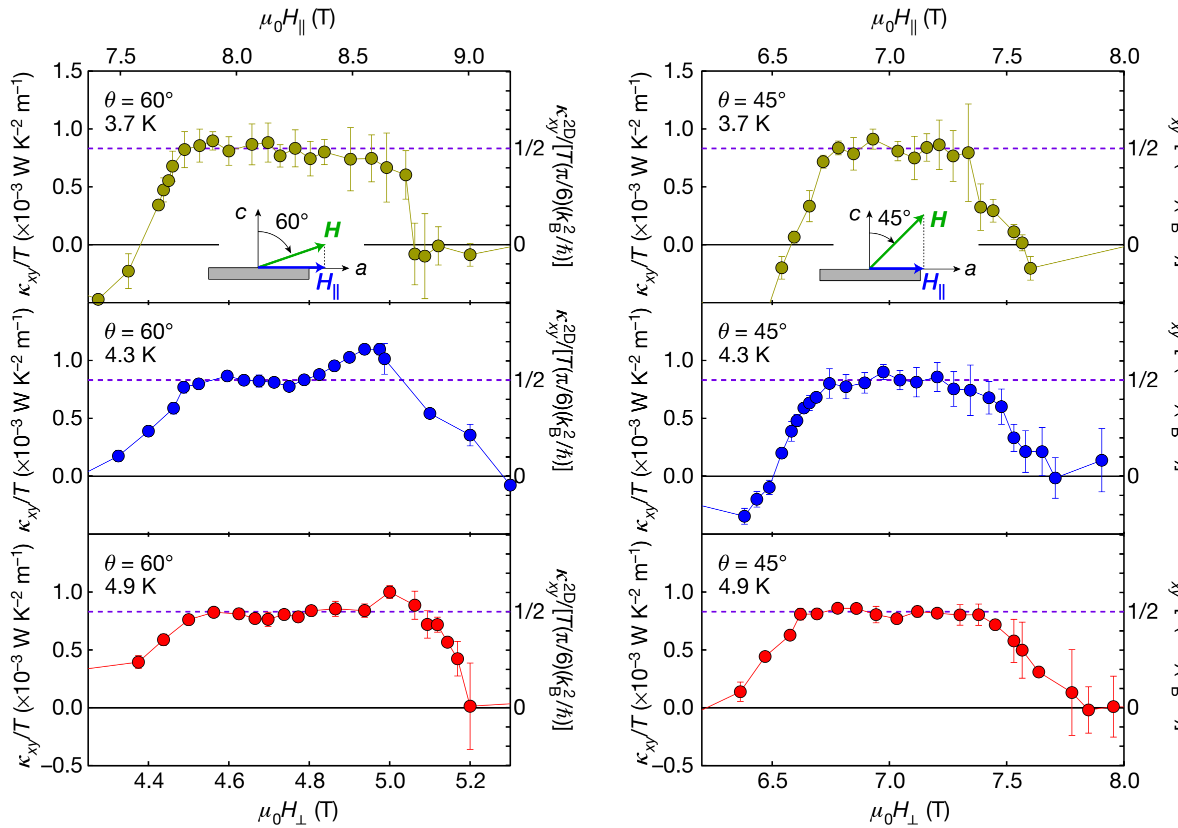
a new quantum Hall effect

S. Trebst & A. Rosch,
Physik-Journal (2018)

Something interesting happens for **$RuCl_3$ in a magnetic field**.







Y. Kasahara et al., Nature **559**, 227-231 (2018)

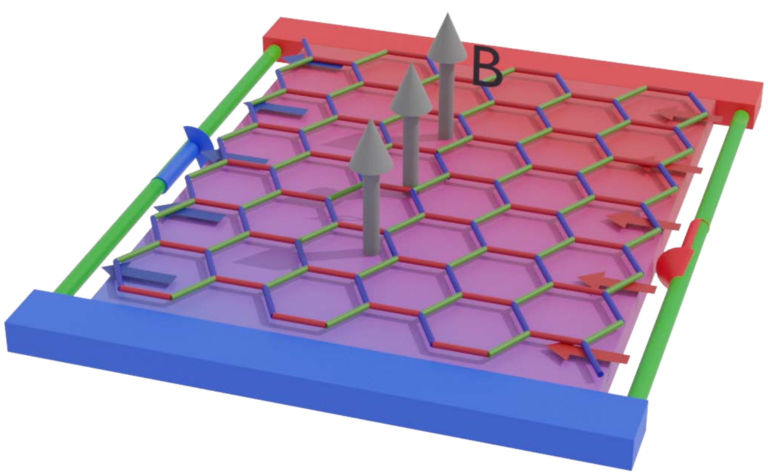
Why does this work in the presence of phonons?

Y. Vinkler-Aviv & A. Rosch, PRX **8**, 031032 (2018)
M. Ye, G. Halász, L. Savary, and L. Balents, PRL **121**, 147201 (2018)

thermal Hall effect in $RuCl_3$

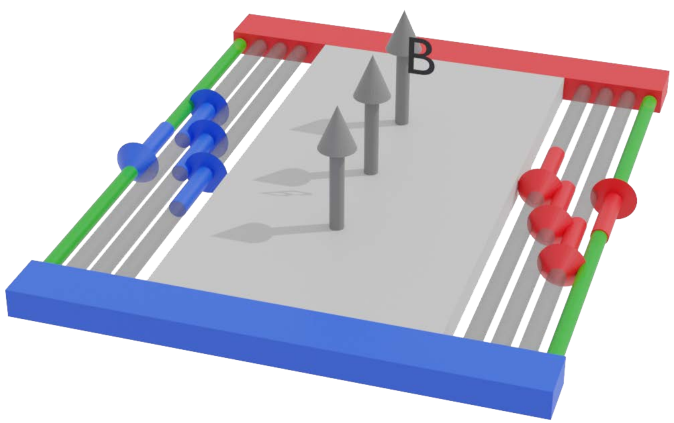
$$\kappa_{xy} = \frac{n}{2} \cdot \frac{\pi}{3} \frac{k_B^2 T}{\hbar}$$

A **half-quantized thermal Hall response** is direct evidence for gapless **Majorana modes**.



Kitaev material $RuCl_3$

Y. Kasahara et al., Nature **559**, 227-231 (2018)



ν=5/2 FQH state in a 2DEG

M. Banerjee et al., Nature **559**, 205–210 (2018)

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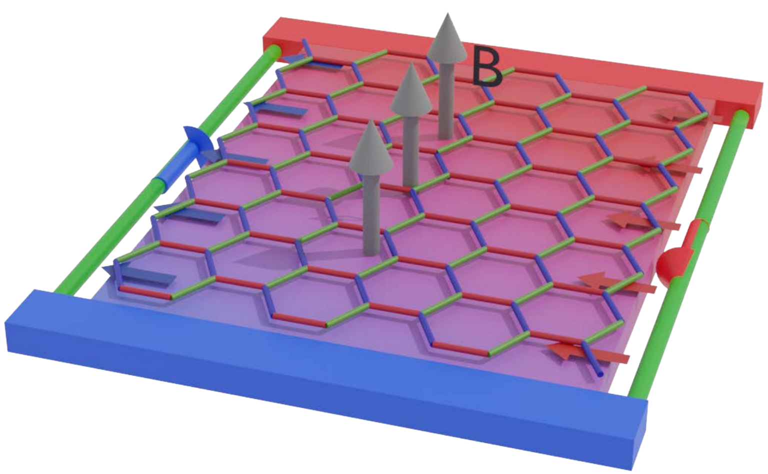
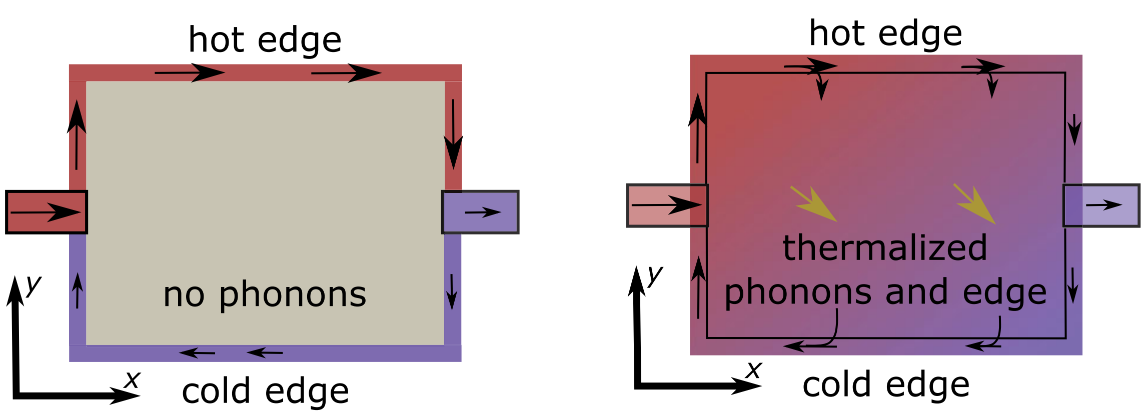
M. Ye, G. Halász, L. Savary, and L. Balents, PRL **121**, 147201 (2018)



Kitaev material $RuCl_3$

Y. Kasahara et al., Nature **559**, 227-231 (2018)

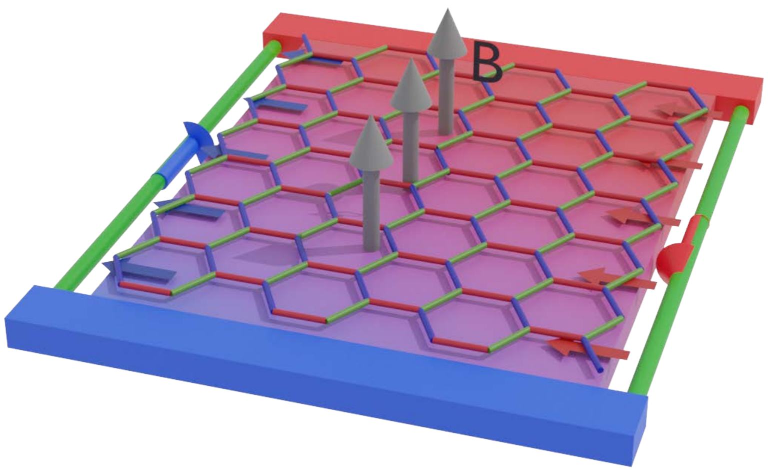
But why is it quantized in the first place?
Why is there no leakage into the bulk,
via gapless acoustic phonons?



thermal Hall effect in $RuCl_3$

A **half-quantized thermal Hall response**
is direct evidence for gapless **Majorana modes**.

Y. Vinkler-Aviv & A. Rosch, PRX **8**, 031032 (2018)
M. Ye, G. Halász, L. Savary, and L. Balents, PRL **121**, 147201 (2018)



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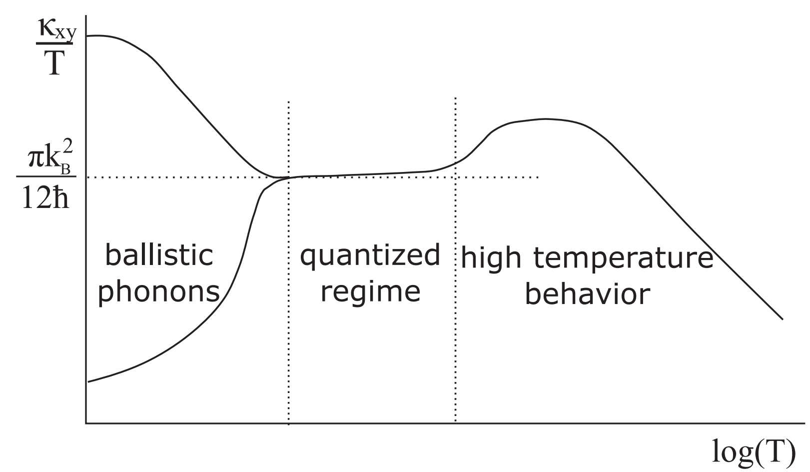
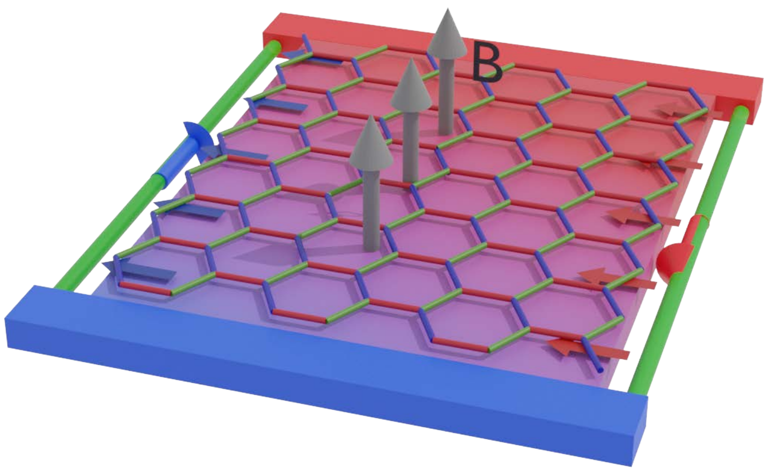


thermal Hall effect in $RuCl_3$

A **half-quantized thermal Hall response**
is direct evidence for gapless **Majorana modes**.

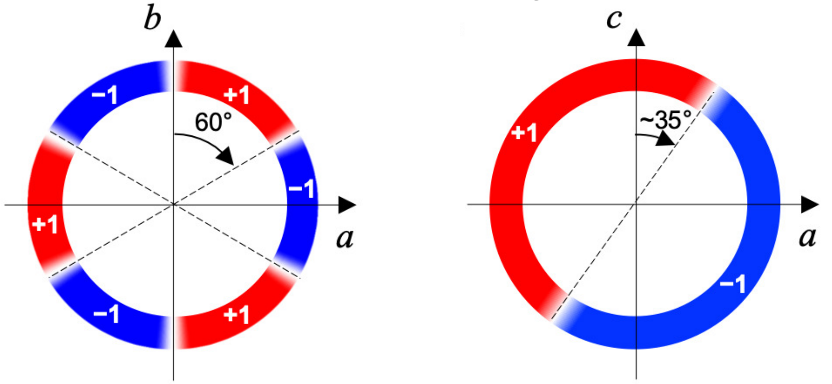
How can we distinguish whether the quantized thermal Hall effect arises from the formation of **Landau levels** or a non-trivial **Chern insulator**?



Kitaev material $RuCl_3$

Y. Kasahara et al., Nature **559**, 227-231 (2018)

The Kitaev spin liquid is a **chiral spin liquid**,
a Chern insulator of Majoranas.



Its Hall quantization is **angle-dependent** and occurs even for an in-plane field (**anomalous thermal Hall effect**).

T. Yokoi et al., arXiv:2001.01899

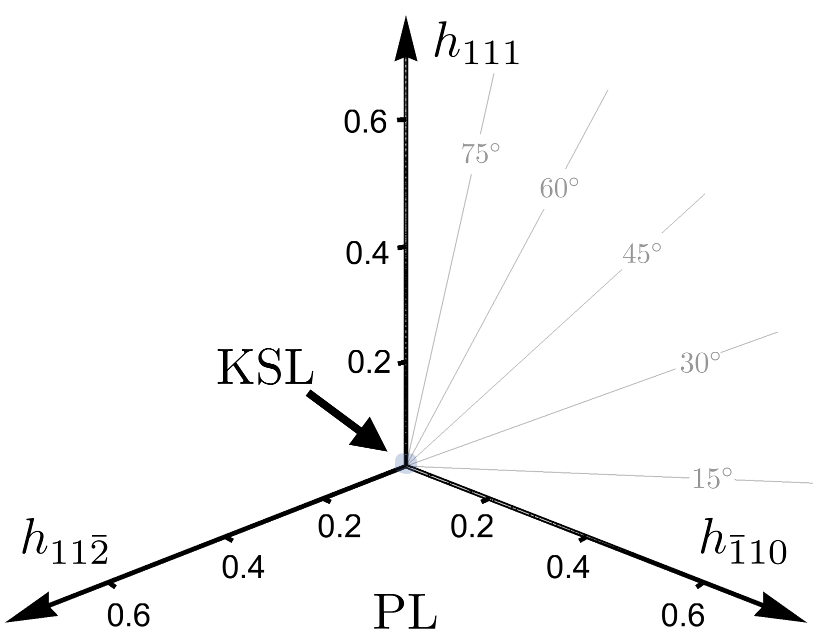
back to the Kitaev model

microscopic relevance

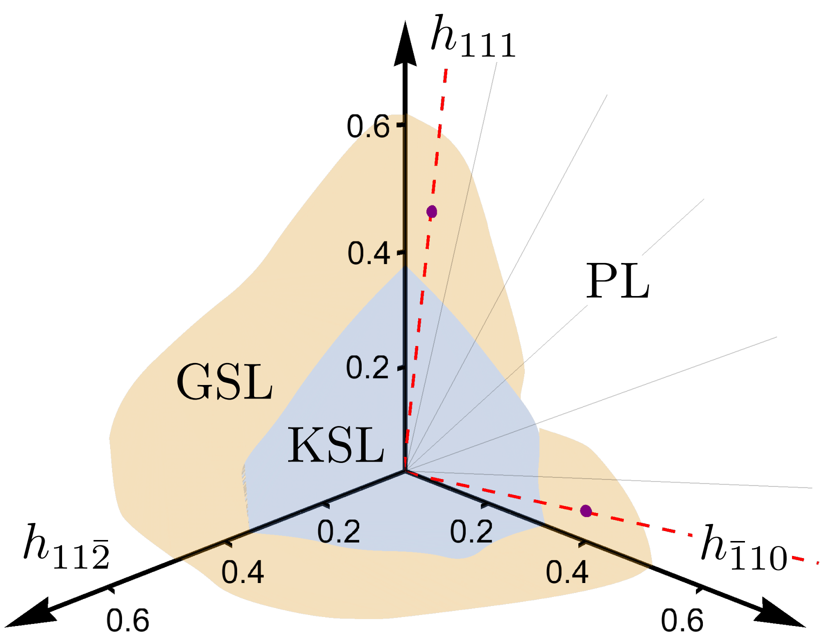
Kitaev model – magnetic field effects

$$\mathcal{H} = -\sum_{\gamma-\text{bonds}} K_\gamma S_i^\gamma S_j^\gamma - \sum_i \mathbf{h} \cdot \mathbf{S}_i$$

FM Kitaev coupling



AFM Kitaev coupling

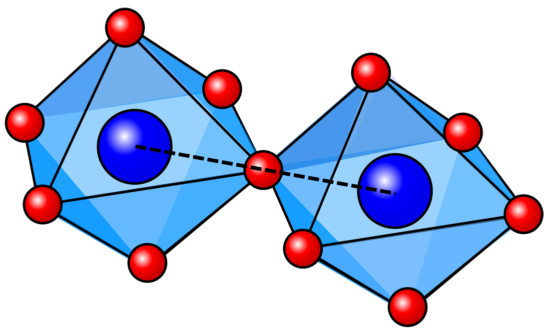


bond-directional exchange



G. Jackeli and G. Khaliullin, PRL 102, 017205 (2009)
J. Chaloupka, G. Jackeli, and G. Khaliullin, PRL 105, 027204 (2010)

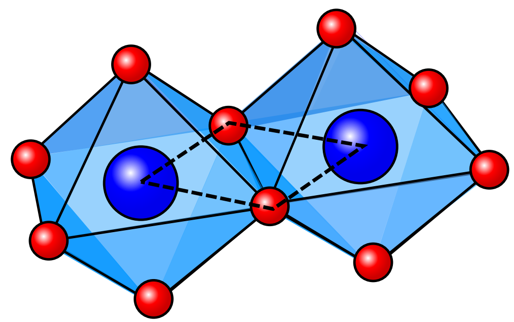
corner-sharing



Sr_2IrO_4

Heisenberg exchange

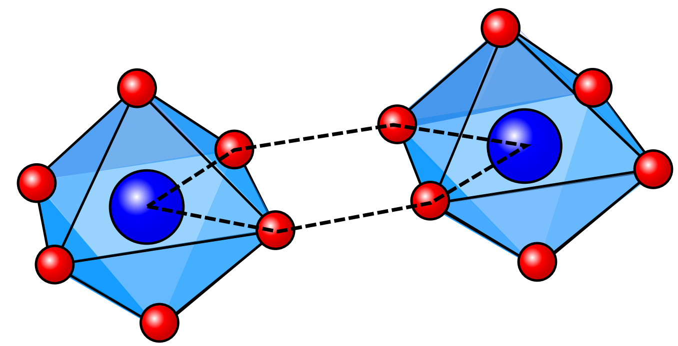
edge-sharing



$(Na,Li)_2IrO_3$
$RuCl_3$

Heisenberg-Kitaev exchange

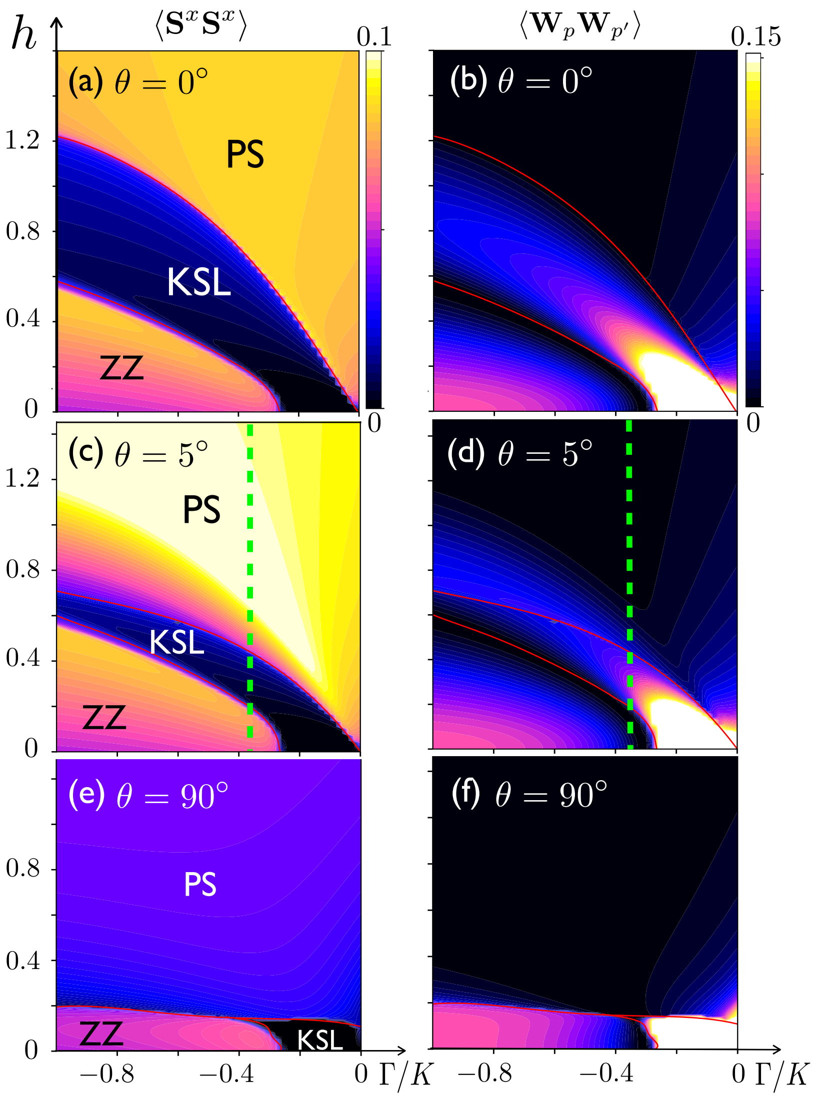
"**parallel edge**"-sharing



$Ba_3IrTi_2O_9$

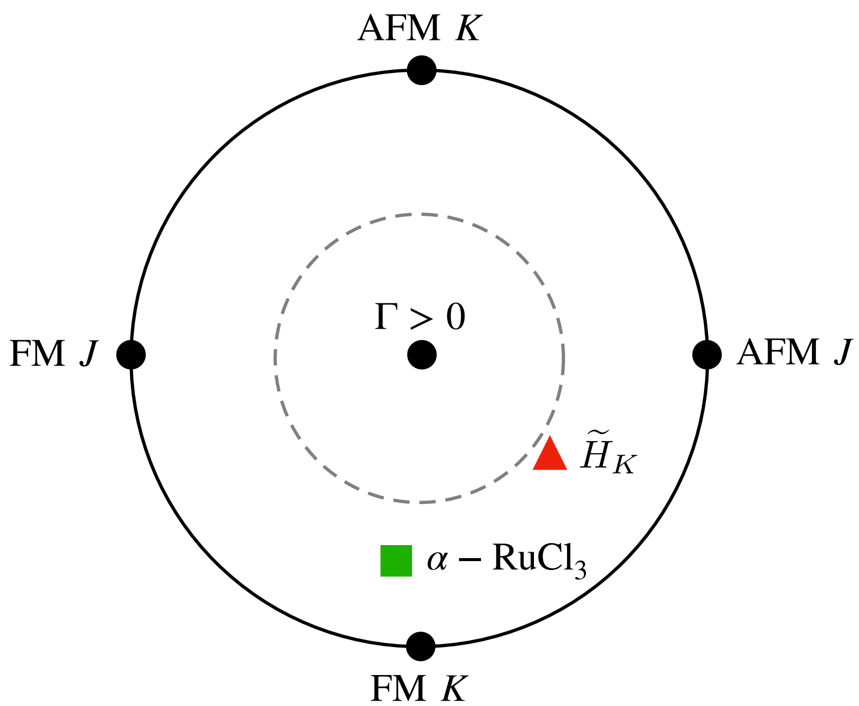
$$H = - \sum_{\gamma-\mathrm{bonds}} J\, \mathbf{S}_i \mathbf{S}_j + K\; S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right)$$

Microscopic relevance to $RuCl_3$



AFM off-diagonal coupling

Gordon et al., Nature Comm. **10**, 2470 (2019)

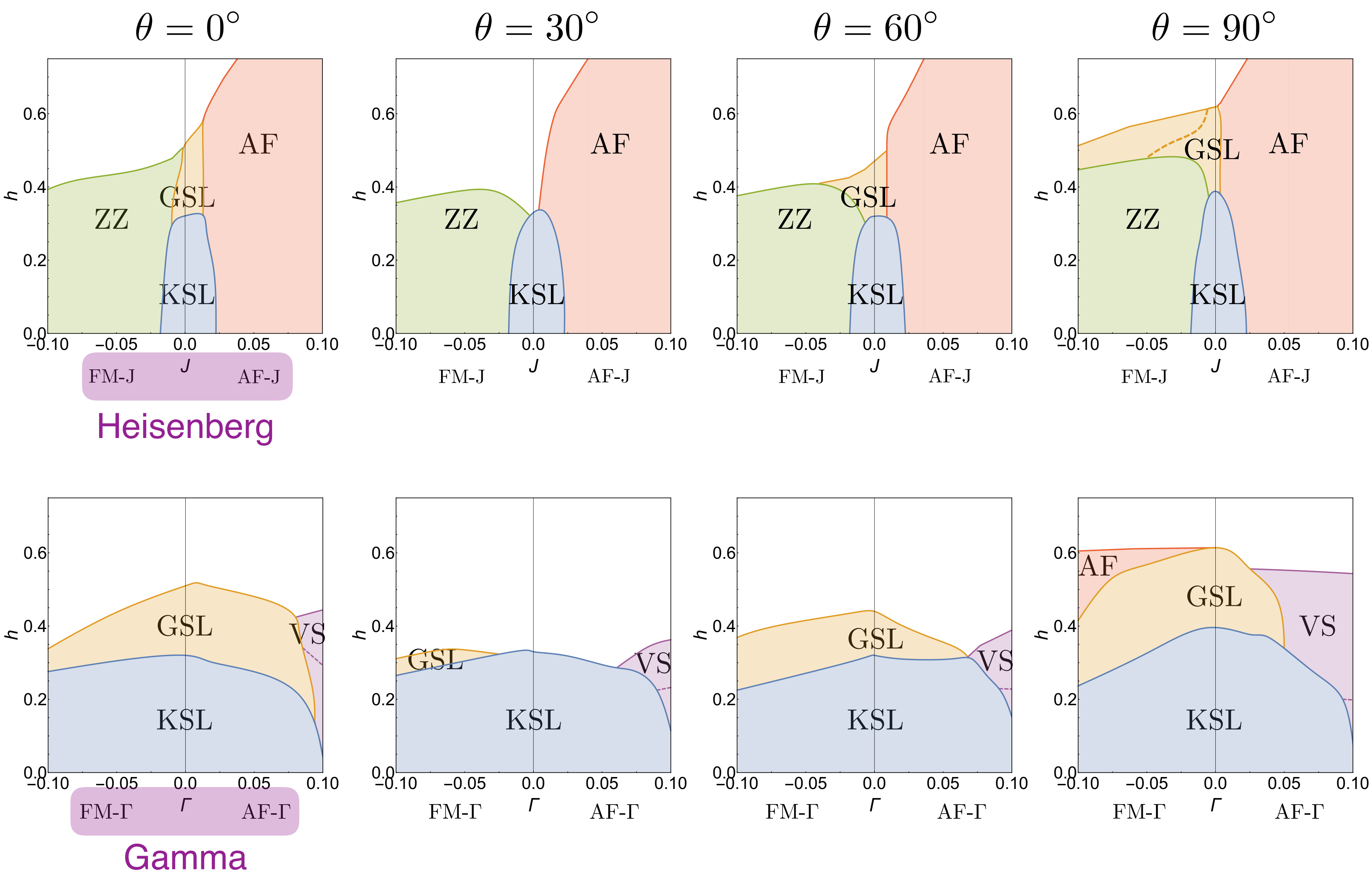


“hidden” AFM Kitaev model

(via Klein duality)

Kaib, Winter & Valenti, PRB **100**, 144445 (2019)

Higgsed U(1) spin liquid?



Summary

lecture notes
arXiv:1701.07056

Kitaev materials

- a family of spin-orbit assisted j=1/2 Mott insulators
- bond-directional exchange induces frustration
- unconventional forms of magnetism

Bond-directional exchange

- (proximate) spin liquids
- signatures of Majorana fermions and Z_2 gauge field
- spin textures

Family of lattice geometries

- honeycomb – Na_2IrO_3, α-Li_2IrO_3, $(H_{3/4}Li_{1/4})_2IrO_3$, $RuCl_3$
- triangular – $Ba_3IrTi_2O_9$, $Ba_3Ir_2TiO_9$, $Ba_3Ir_2InO_9$
- 3D – β-Li_2IrO_3, γ-Li_2IrO_3, metal-organic compounds

Thanks!