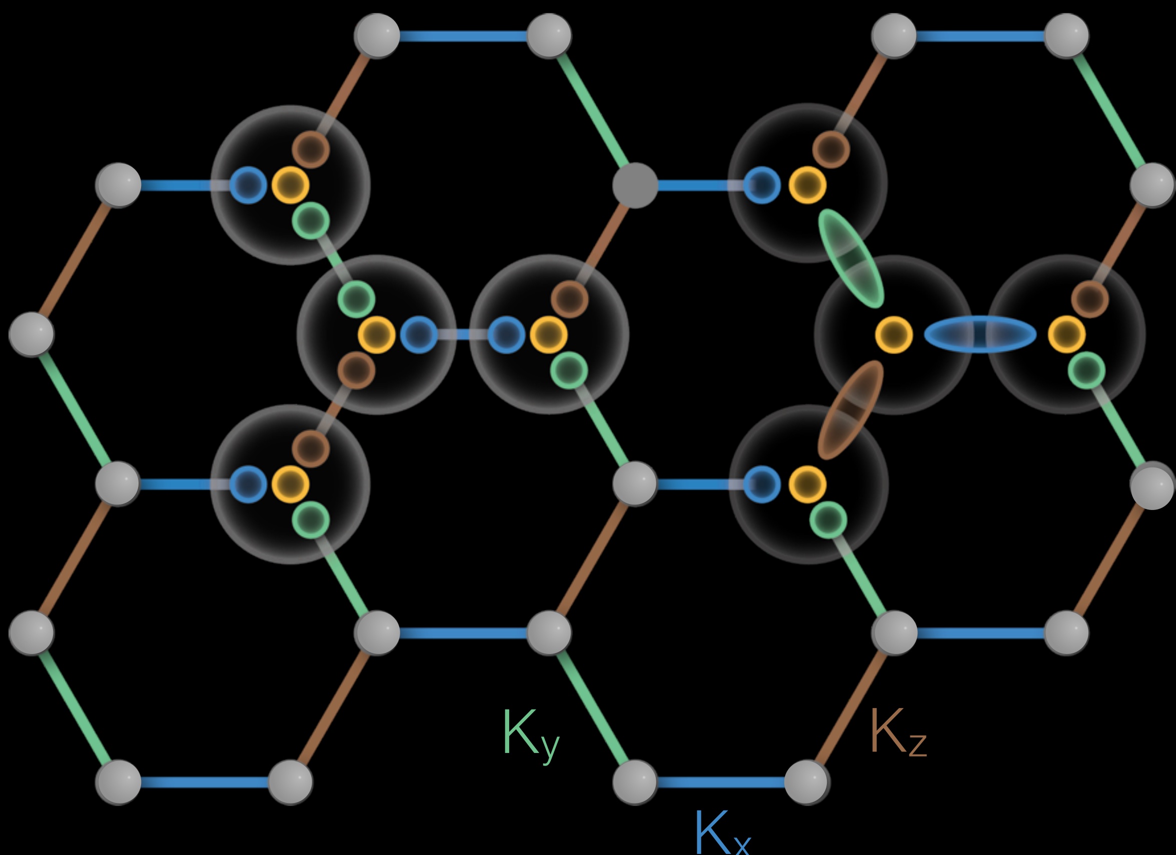
Field-driven Higgs transition in two-dimensional Kitaev materials

KhomskiiFest, Dresden
November 6th, 2018

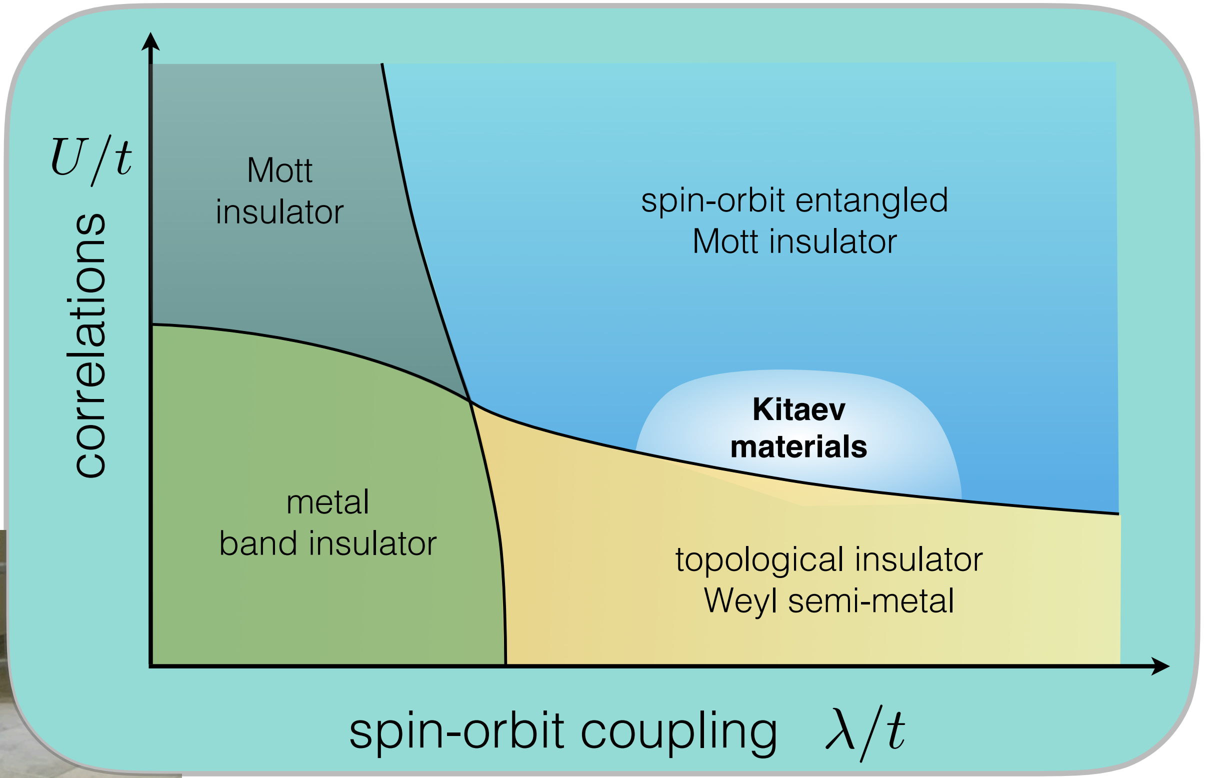


Simon Trebst
University of Cologne

CRC 1238
Control and Dynamics of Quantum Materials

SFB 1238
Bensberg conference,
September 2018

On Daniel's mind?



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

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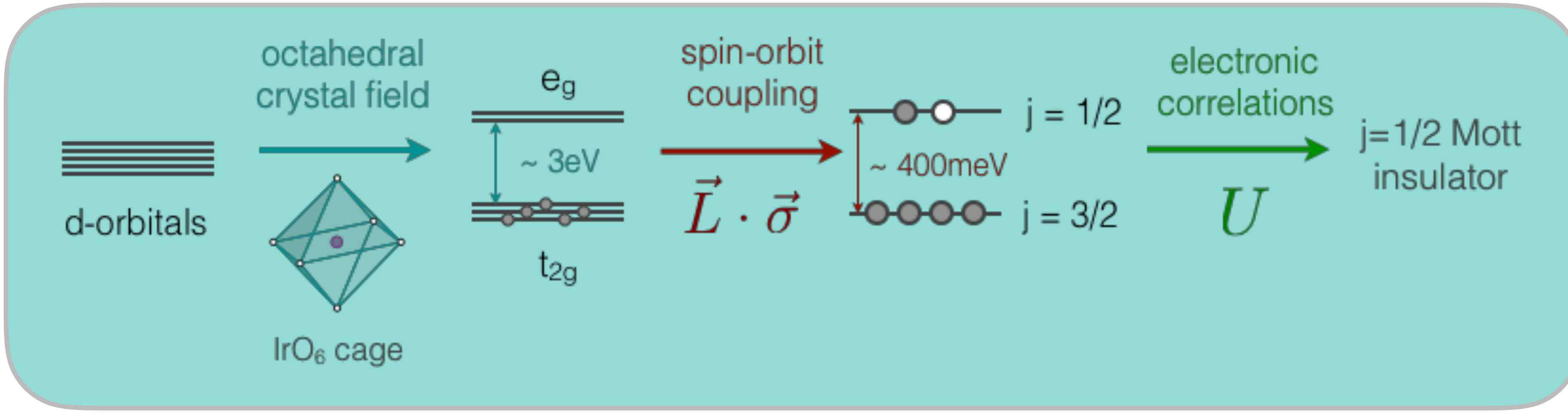
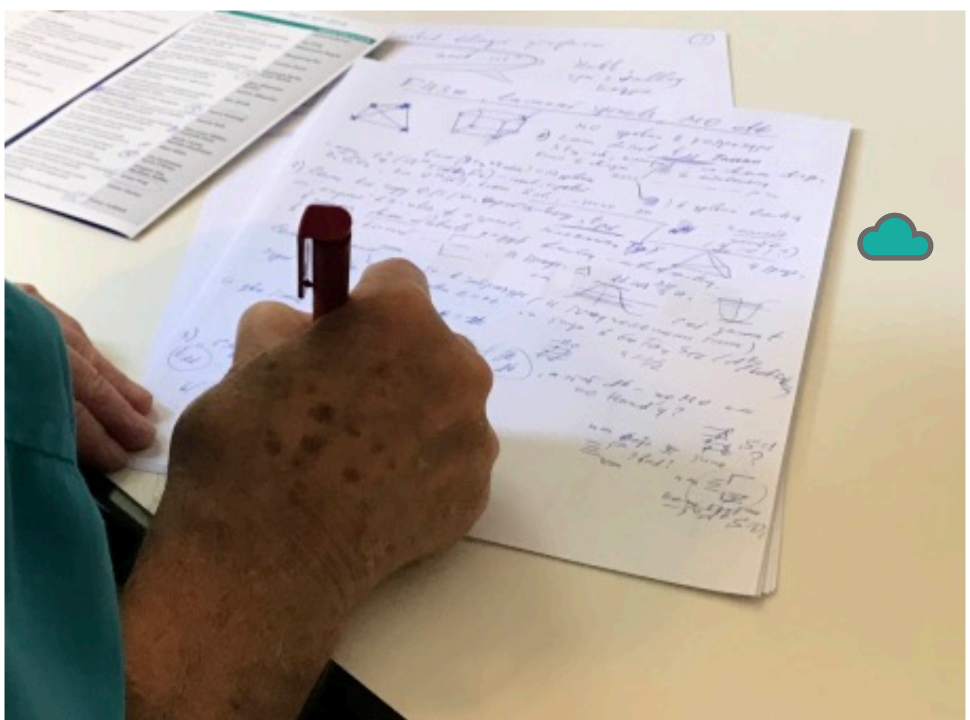
4d/5d transition metal compounds





At last – spin and orbital degrees of freedom truly entangle!

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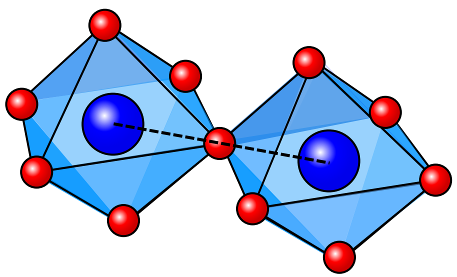
spin-orbit entangled Mott insulators

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

corner-sharing

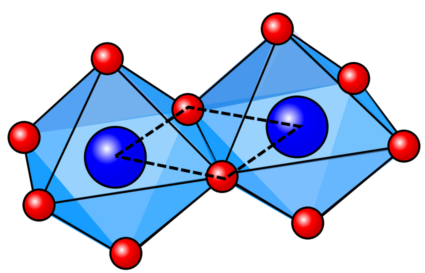


Sr_2IrO_4

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)



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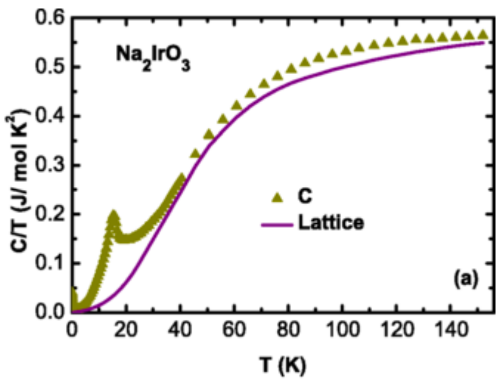
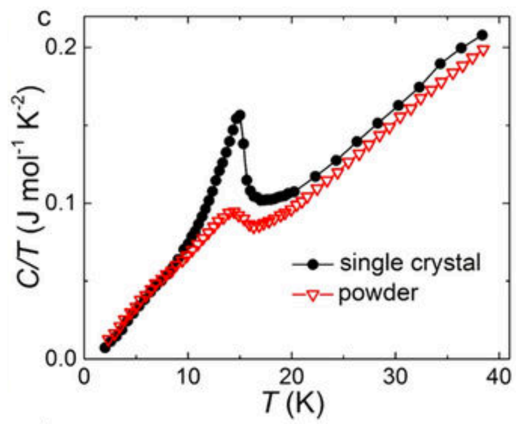
Kitaev materials – really?

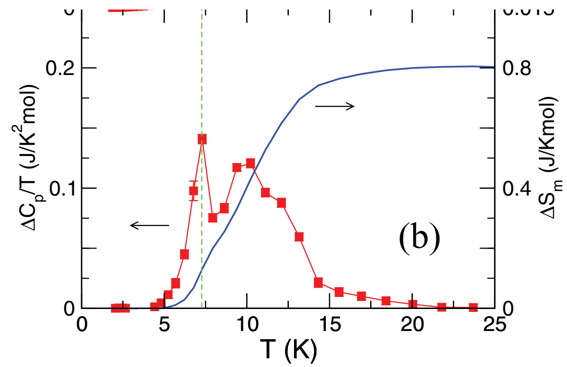
Na_2IrO_3



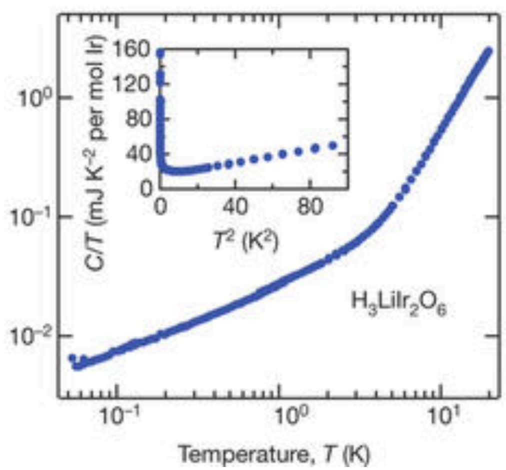
Li_2IrO_3



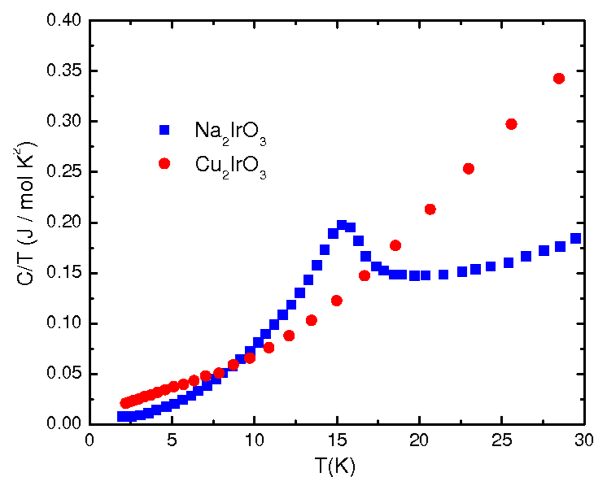
$RuCl_3$



$H_2LiIr_2O_6$



Cu_2IrO_3



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

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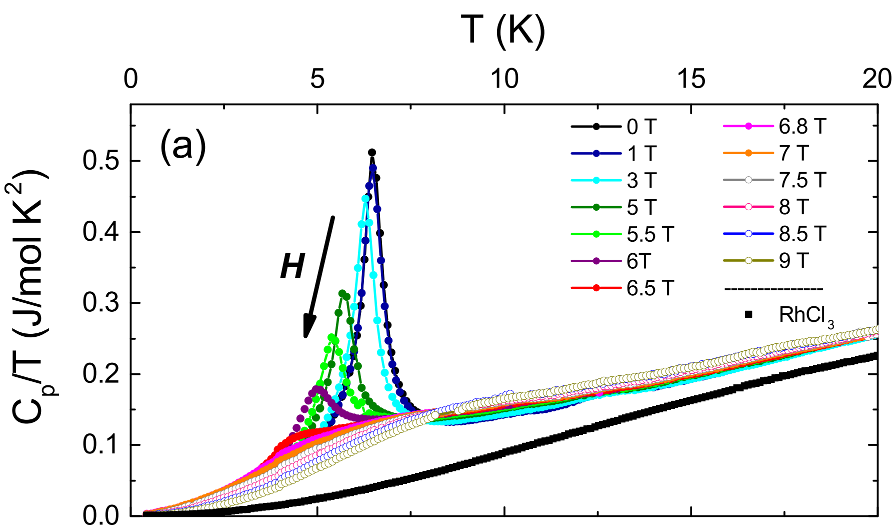
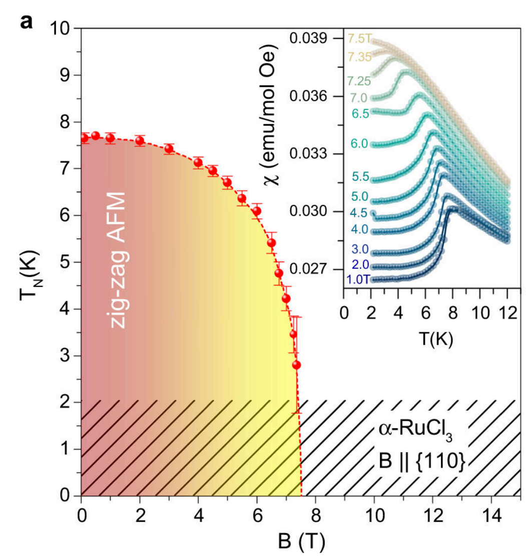
Spin liquids?!

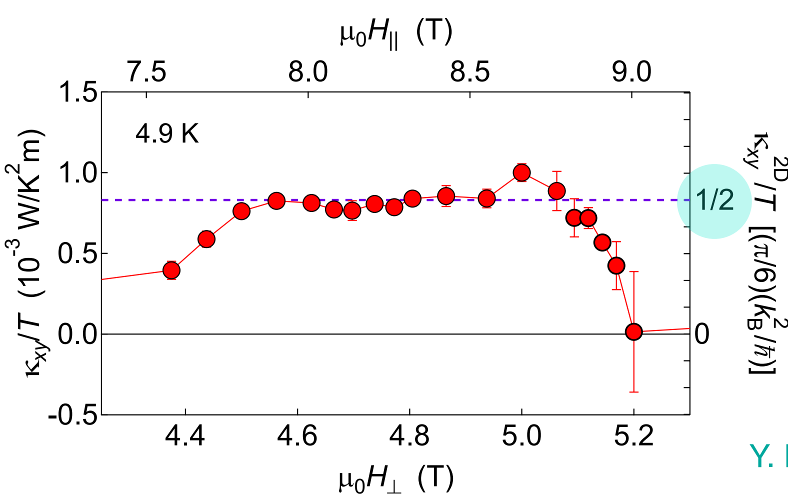
Something interesting happens for **$RuCl_3$ in a magnetic field**.



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)

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Ciarán Hickey

Kitaev spin liquids

magnetic field effects

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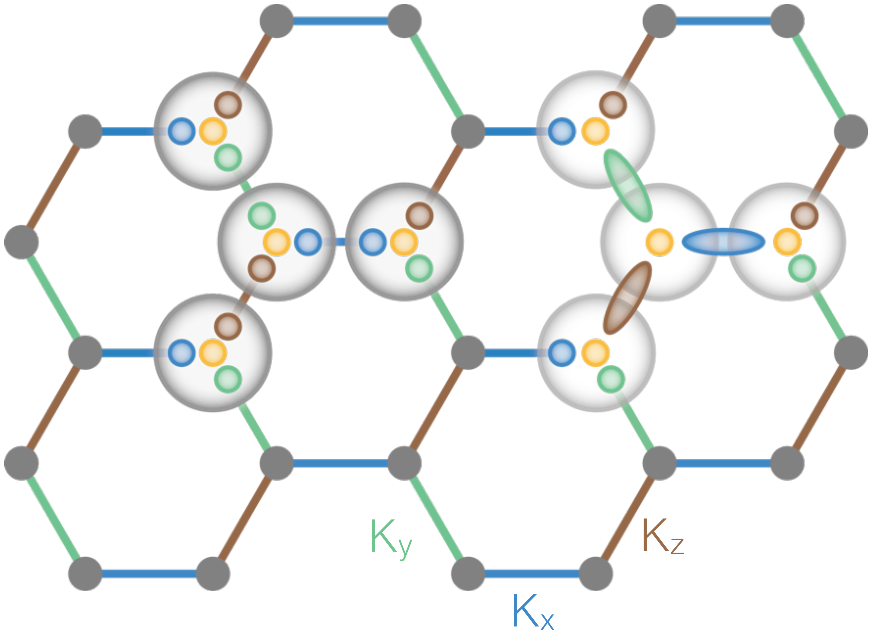
Kitaev model

$$\mathcal{H} = - \sum_{\gamma-\text{bonds}} K_\gamma \, S_i^\gamma S_j^\gamma$$

Represent spins in terms of four **Majorana fermions**

$$S_i^\gamma = i \; c_i \; c_i^\gamma$$

$$S_i^\alpha \to S_i^\alpha \qquad c_i^\alpha \to e^{-i\phi_i} c_i^\alpha \qquad c_i \to e^{i\phi_i} c_i$$



$$(c_i)^2 = 1 \to (e^{i\phi_i} c_i)^2 = 1 \qquad e^{i\phi_i} = \pm 1$$ **Z_2 redundancy**

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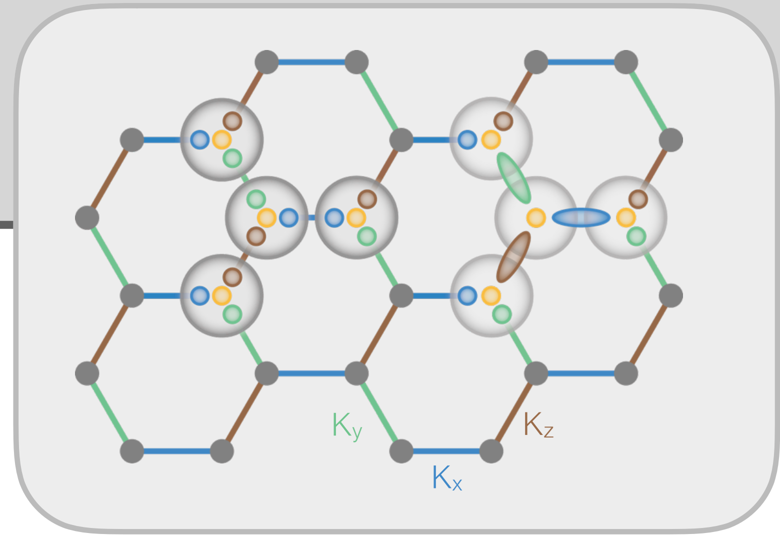
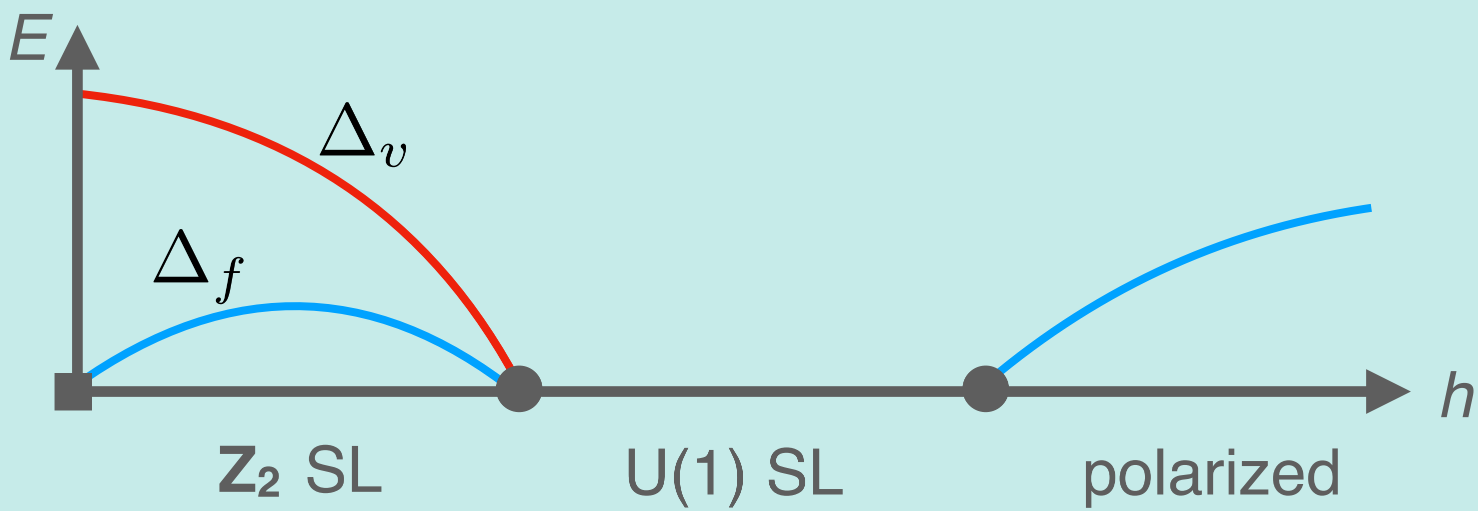
Kitaev spin liquids



$$\mathcal{H} = -\sum_{\gamma-\text{bonds}} K_\gamma \, S_i^\gamma S_j^\gamma$$

Kitaev spin liquids are textbook examples of **Z_2 spin liquids.**

For strong magnetic fields, this picture no longer holds.
The Kitaev model exhibits a **gauge transition** to a **U(1) spin liquid.**



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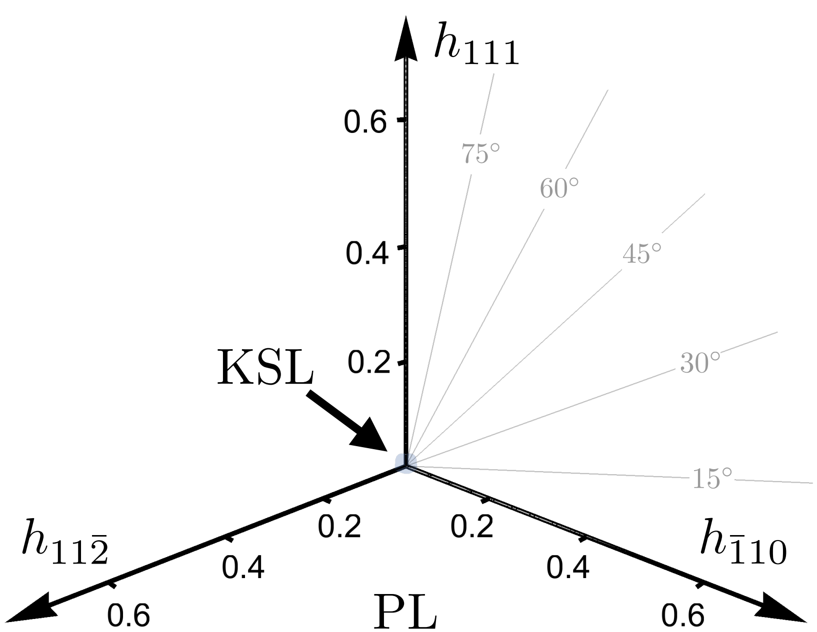
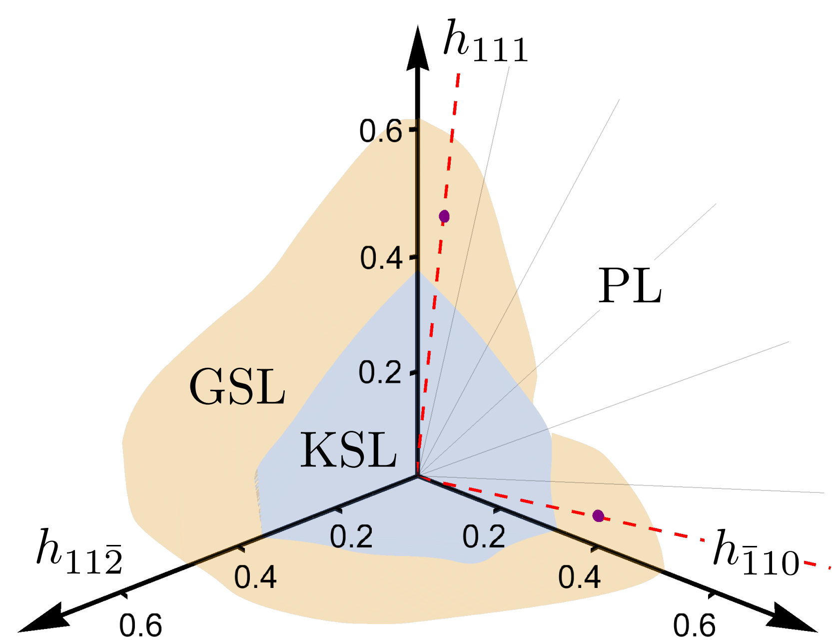
Kitaev model – magnetic field effects

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

FM Kitaev coupling



AFM Kitaev coupling



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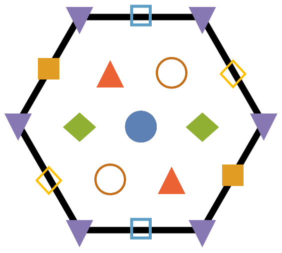
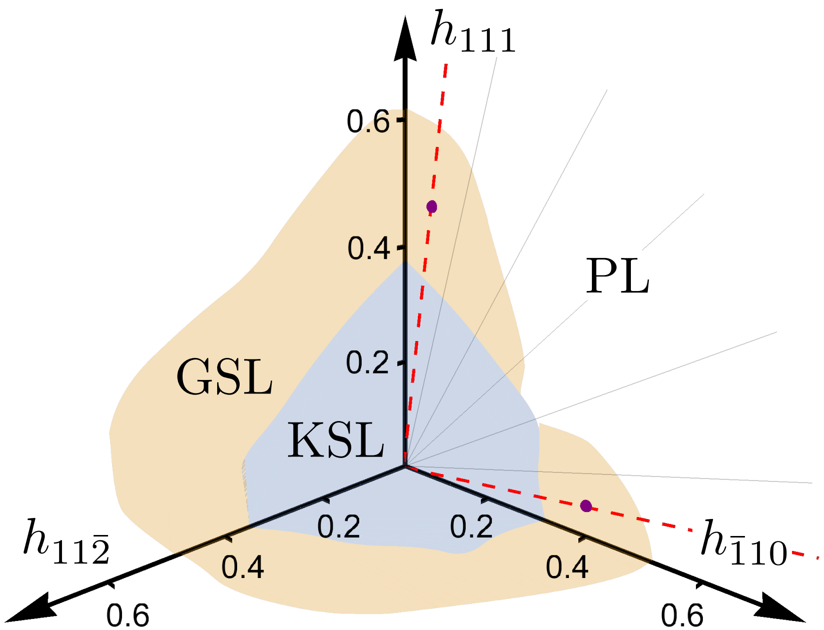
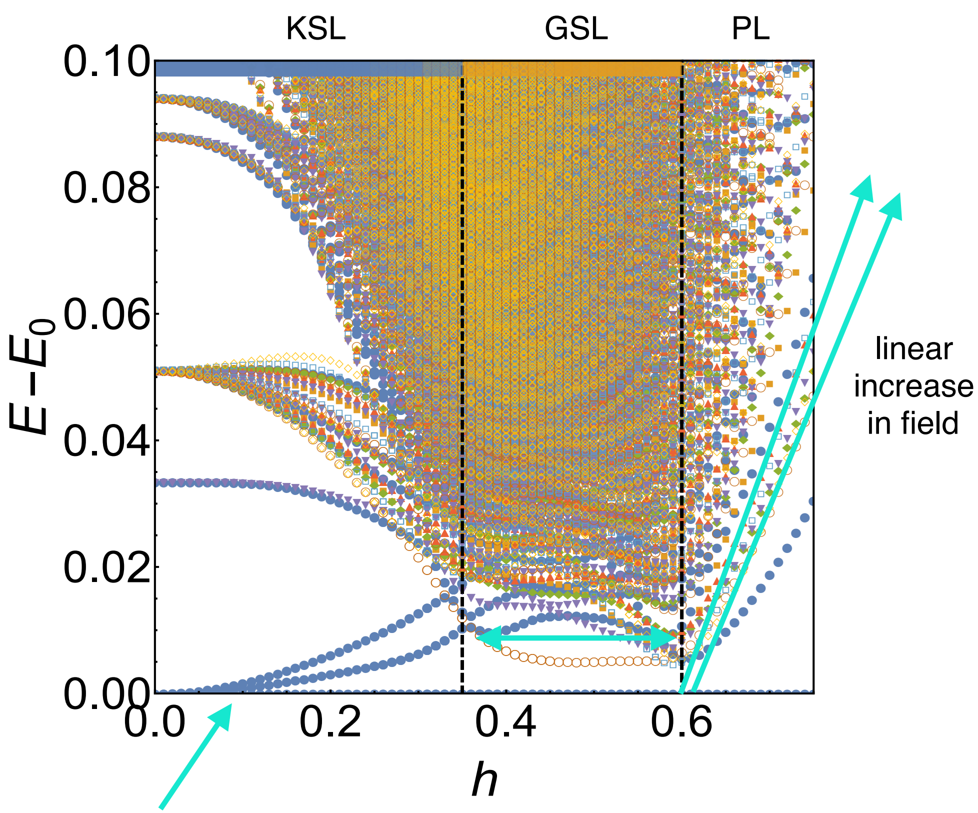
Kitaev model – magnetic field effects

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



AFM Kitaev coupling





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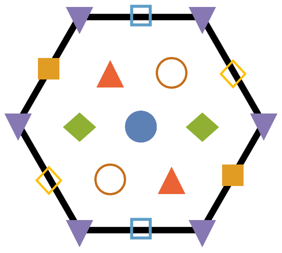
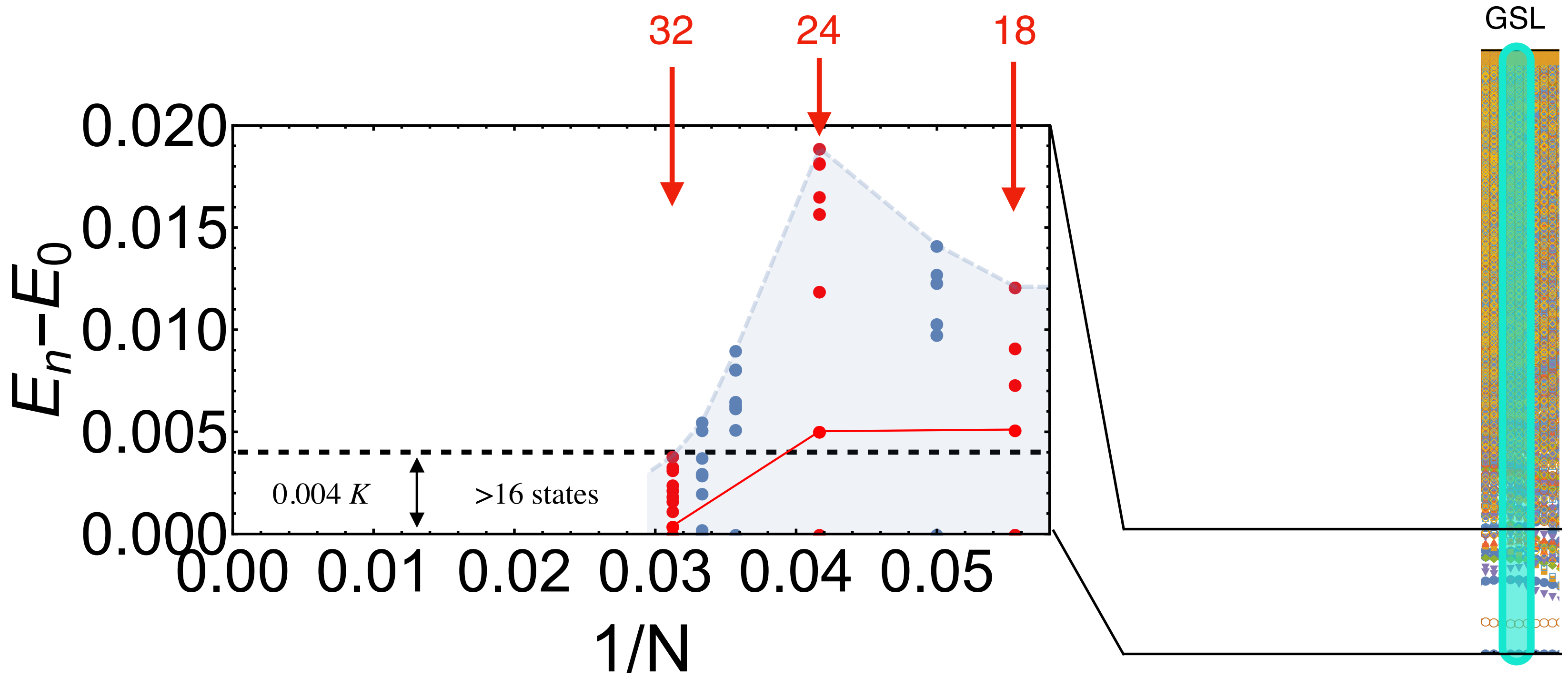
Kitaev model – magnetic field effects

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





The intermediate phase has the **smallest finite-size gap** ever seen!

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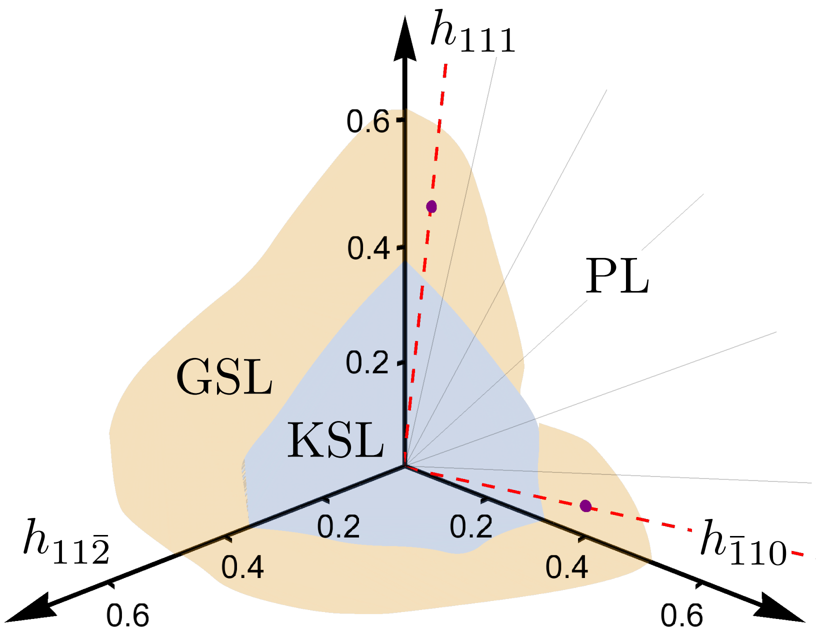
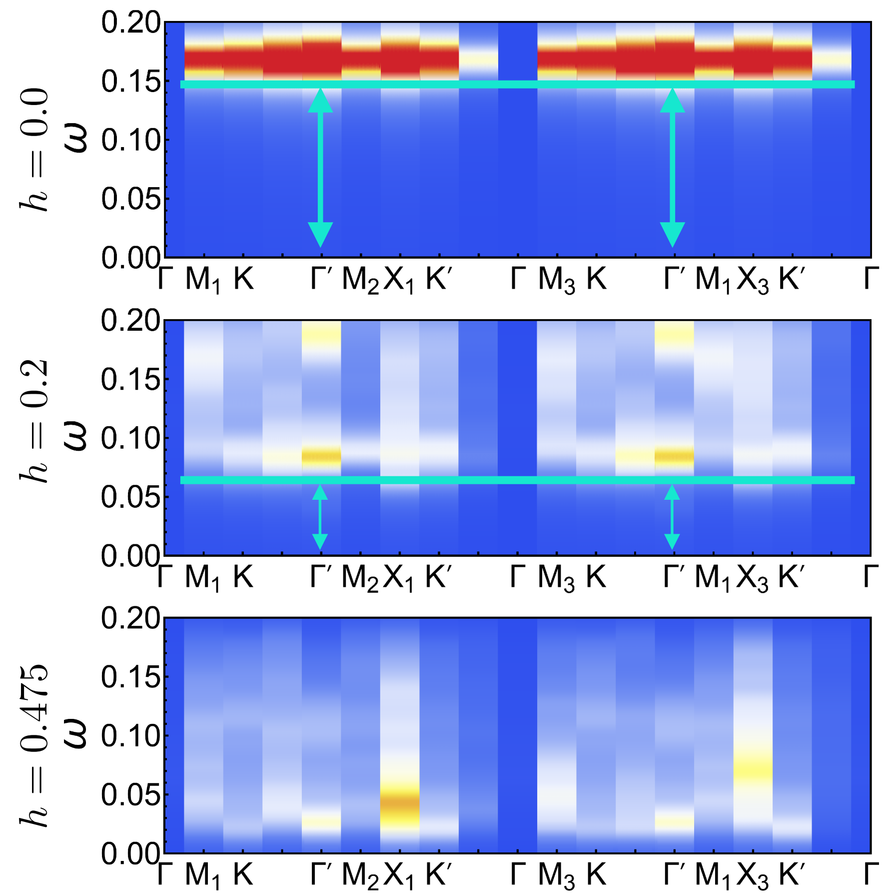
dynamical structure factor

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

AFM Kitaev coupling





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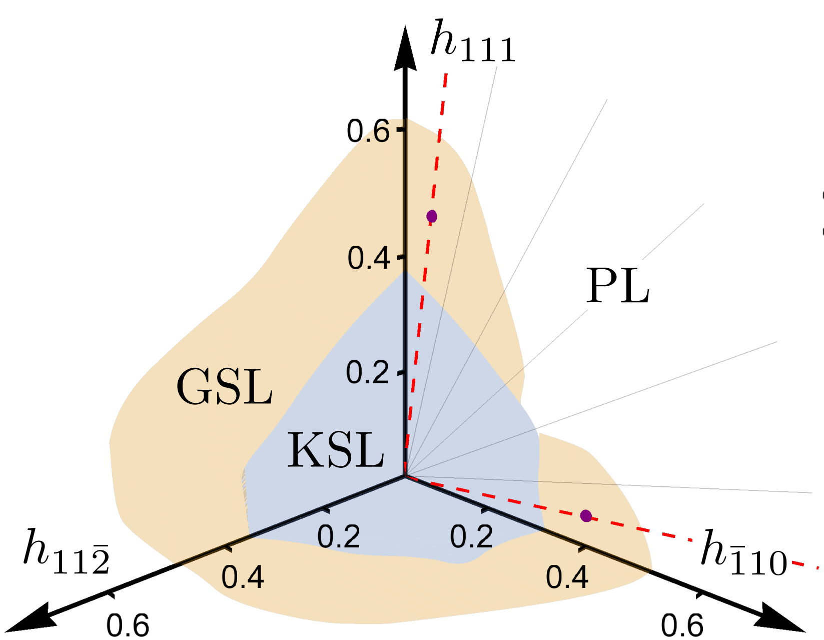
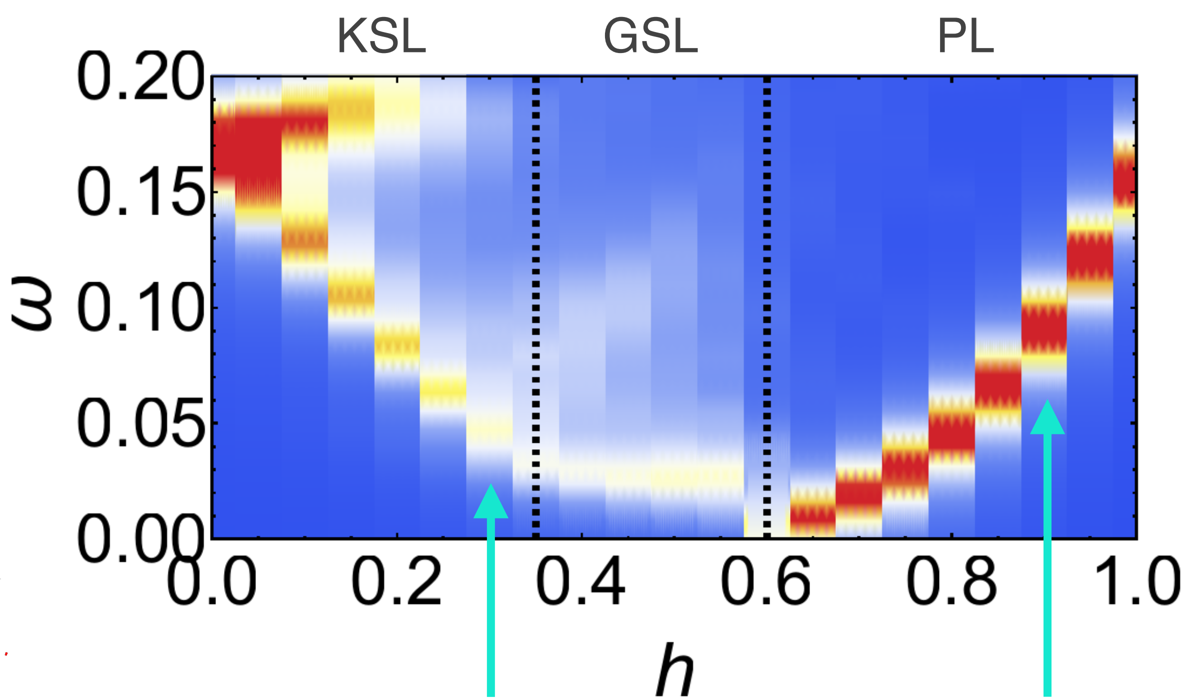
dynamical structure factor

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

AFM Kitaev coupling





flux gap closes

magnon excitation

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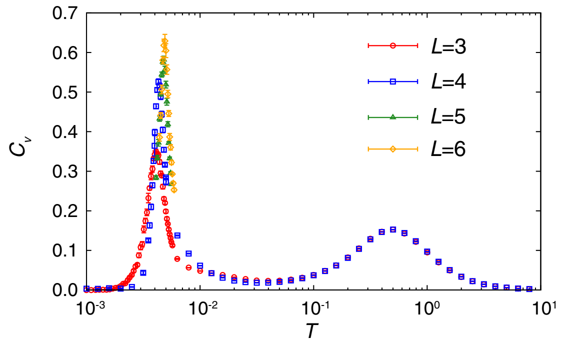
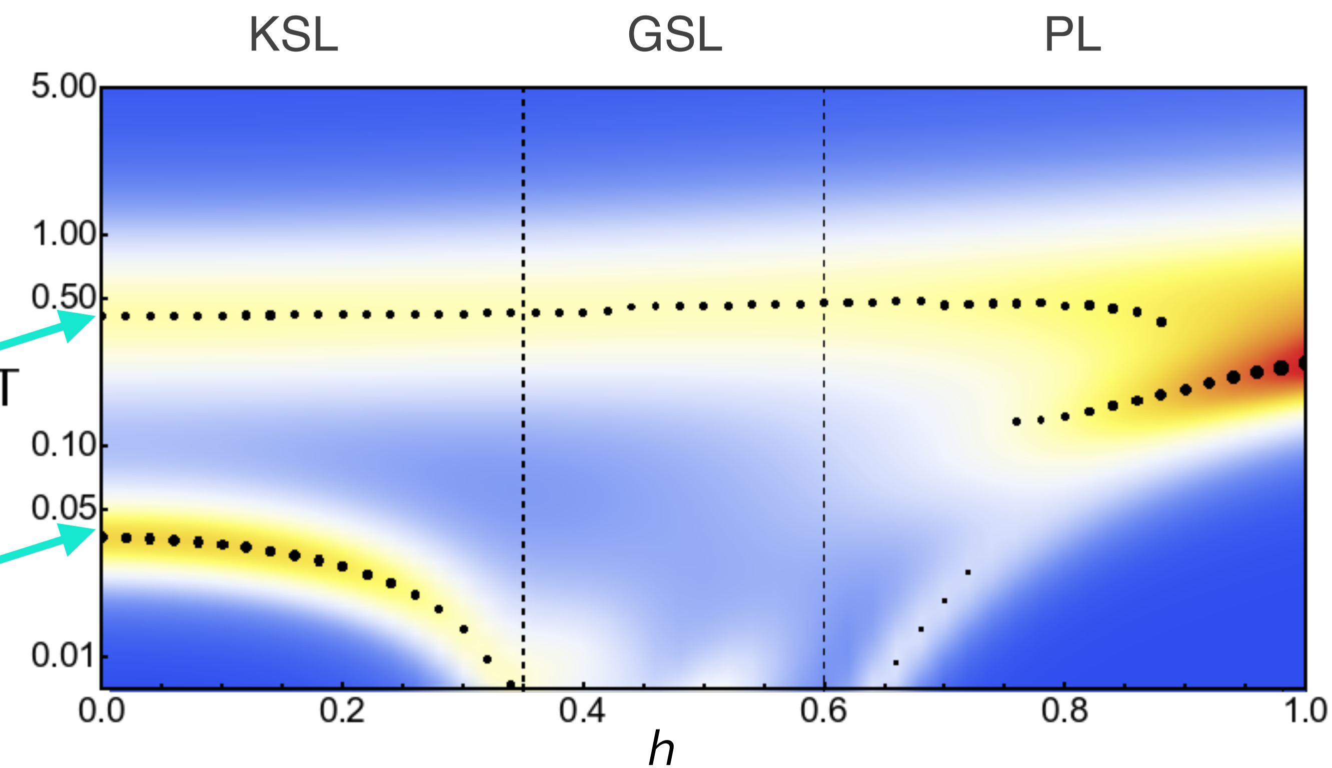
specific heat

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





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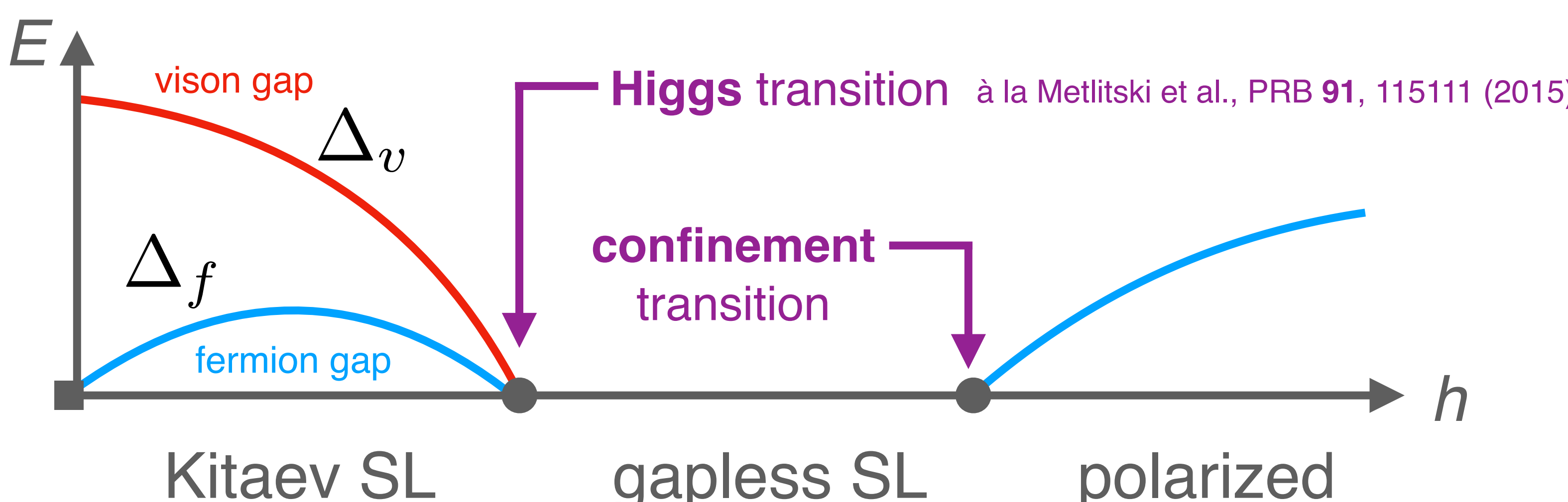
Kitaev unHiggsed!

Synopsis: for strong magnetic fields, the Kitaev model exhibits a **Higgs transition** to a gapless U(1) spin liquid.

Represent spins in terms of **complex fermions** $S_i^\alpha = f_{i,\mu}^\dagger \sigma_{\mu\nu}^\alpha f_{i,\nu}$

F. J. Burnell and C. Nayak, PRB **84**, 125125 (2011)

fermions	gapped topological SC	gapless Fermi surface	gapped trivial insulator
gauge field	Z_2 (Higgsed)	U(1)	U(1) [confined]



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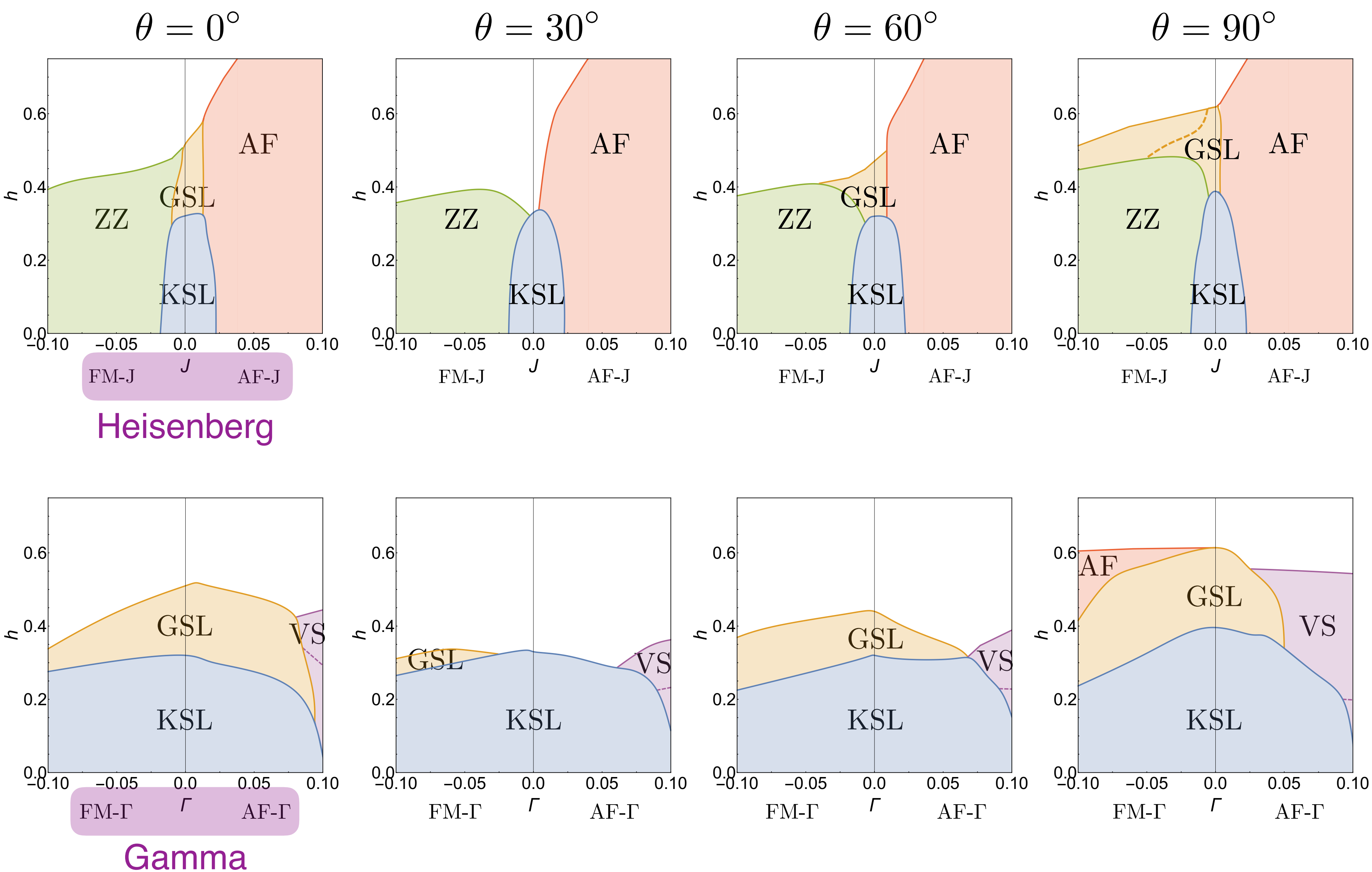
Stability of U(1) spin liquid



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Summary

C. Hickey and ST
arXiv:1805.05953

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

Kitaev spin liquids are textbook examples of **Z_2 spin liquids.**

For AFM Kitaev couplings and strong magnetic fields, a **Higgs transition** to a gapless **U(1) spin liquid** occurs.

The U(1) spin liquid is probably the generic high-field phase, and **parent phase** to the KSLs, but also all kinds of magnetic order.

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Thanks!