Kitaev spin liquids in honeycomb materials

Hae-Young Kee
University of Toronto

SudipFest
April 5th, 2019

Canadian Institute for Advanced Research

NSERC CRSNG

CENTER FOR QUANTUM MATERIALS

High Tc

1. arXiv:0710.0608 [pdf, other] cond-mat.supr-con cond-mat.str-el doi 10.1073/pnas.0804002105

Fermi pockets and quantum oscillations of the Hall coefficient in high temperature superconductors

Authors: Sudip Chakravarty, Hae-Young Kee

Abstract: Recent quantum oscillation measurements in high temperature superconductors in high magnetic fields and low temperatures have ushered in a n
These experiments explore the normal state from which superconductivity arises and provide evidence of a reconstructed Fermi surface consisting of electro
hole pockets in a regime in which such a possibility was previously considered to be remot… ▽ More

Submitted 24 June, 2008; **v1** submitted 2 October, 2007; **originally announced** October 2007.

Comments: Final version with a correction of a minor typo; 6 pages, 2 figures

Journal ref: Proc. Natl. Acad. Sci. USA 105, 8835 (2008)

2. arXiv:cond-mat/0309209 [pdf] cond-mat.supr-con doi 10.1038/nature02348

An explanation for a universality of transition temperatures in families of copper oxide superconductors

Authors: Sudip Chakravarty, Hae-Young Kee, Klaus Voelker

Abstract: A remarkable mystery of the copper oxide high-transition-temperature (Tc) superconductors is the dependence of Tc on the number of CuO2 layers
the unit cell of a crystal. In a given family of these superconductors, Tc rises with the number of layers, reaching a peak at n=3, and then declines: the result is
shaped curve. Despite the ubiquity of this phenomenon, it is still poorly un… ▽ More

Submitted 4 March, 2004; **v1** submitted 9 September, 2003; **originally announced** September 2003.

Comments: 15 pages, 3 figures. The version published in Nature

Journal ref: Nature 428, 53 (2004)

3. arXiv:cond-mat/0211613 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1103/PhysRevB.67.100504

Condensation energy and the mechanism of superconductivity

Authors: Sudip Chakravarty, Hae-Young Kee, Elihu Abrahams

Abstract: Condensation energy in a superconductor cannot be precisely defined if mean-field theory fails to hold. This implies that in the case of high temperature superconductors, discussions of quantitative measures of condensation energy must be scrutinized carefully, because the normal state is anomalous and the applicability of a mean-field description can be questioned. A related issue discussed her… ▽ More

Submitted 26 November, 2002; **originally announced** November 2002.

Comments: 4 pages, 1 eps figure, revtex 4

Journal ref: Phys. Rev. B 67, 100504(R) (2003).

4. arXiv:cond-mat/0112109 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1142/S0217979202013778

Orbital Magnetism in the Cuprates

Authors: Sudip Chakravarty, Hae-Young Kee, Chetan Nayak

Abstract: The pseudogap phase of the cuprate superconductors is argued to be characterized by a hidden broken symmetry of d-wave character in the particle-hole channel that leads to staggered orbital magnetism. This proposal has many striking phenomenological consequences, but the most direct signature of this order should be visible in the neutron scattering experiments. The theoretical underpinning of t… ▽ More

Submitted 6 December, 2001; **originally announced** December 2001.

Comments: Invited talk at the PPHMF-IV meeting at Santa Fe; uses ws-p8-50x6-00.cls LaTex style file; 7 pages and 3 eps figures

Journal ref: in Physical Phenomena at High Magnetic Fields - IV, eds. G. Boebinger, Z. Fisk, L. P. Gorkov, A. Lacerda, J. R. Schrieffer (World Scientific, Singapore, 2002).

5. arXiv:cond-mat/0101204 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1142/S0217979201007002

Neutron Scattering Signature of d-density Wave Order in the Cuprates

Authors: Sudip Chakravarty, Hae-Young Kee, Chetan Nayak

Abstract: An ordered d-density wave (DDW) state has been proposed as an explanation of the pseudogap phase in underdoped high-temperature superconductors. The staggered currents associated with this order have signatures which are qualitatively different from those of ordered spins. We apply the order parameter theory to an orthorhombic bilayer system and show that the expected magnitude as well as the… ▽ More

Submitted 21 June, 2001; **v1** submitted 14 January, 2001; **originally announced** January 2001.

Comments: 5 pages, 1 figure

6. arXiv:cond-mat/0101027 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1103/PhysRevB.64.224516

Spin and Current Correlation Functions in the \bf d-density Wave State of the Cuprates

Authors: Sumanta Tewari, Hae-Young Kee, Chetan Nayak, Sudip Chakravarty

Abstract: We calculate the spin-spin and current-current correlation functions in states exhibiting d_{{x^2}-{y^2}}-density wave (DDW) order, d_{{x^2}-{y^2}} superconducting order (DSC), or both types of order. The spin-spin correlation functions in a state with both DDW and DSC order and in a state with DDW order alone, respectively, illuminate the resonant peak seen in the superconducting state of the u… ▽ More

Submitted 1 June, 2001; **v1** submitted 3 January, 2001; **originally announced** January 2001.

Comments: 9 pages, 4 figures

Journal ref: Phys. Rev. B 64, 224516 (2001).

7. arXiv:cond-mat/9908205 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1103/PhysRevB.61.14821

On Measuring Condensate Fraction in Superconductors

Authors: Sudip Chakravarty, Hae-Young Kee

Abstract: An analysis of off-diagonal long-range order in superconductors shows that the spin-spin correlation function is significantly influenced by the order if the order parameter is anisotropic on a microscopic scale. Thus, magnetic neutron scattering can provide a direct measurement of the condensate fraction of a superconductor. It is also argued that recent measurements in high temperature superco… ▽ More

Submitted 1 February, 2000; **v1** submitted 13 August, 1999; **originally announced** August 1999.

Comments: 4 pages, 1 eps figure, RevTex. A new possibility in the underdoped regime is added. Other corrections are minor

Journal ref: Phys. Rev. B 61, 14821 (2000).

8. arXiv:cond-mat/9811082 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el doi 10.1103/PhysRevLett.82.2366

Frustrated kinetic energy, the optical sum rule, and the mechanism of superconductivity

Authors: Sudip Chakravarty, Hae-Young Kee, Elihu Abrahams

Abstract: The theory that the change of the electronic kinetic energy in a direction perpendicular to the CuO-planes in high-temperature superconductors is a substantial fraction of the condensation energy is examined. It is argued that the consequences of this theory based on a rigorous c-axis conductivity sum rule are consistent with recent optical and penetration depth measurements.

Submitted 5 November, 1998; **originally announced** November 1998.

Comments: 4 pages (RevTeX) and 2 eps figures

Journal ref: Phys. Rev. Lett. 82, 2366 (1999).

Spin Liquid from High Tc

Quantum Spin liquids

: Long Range Entanglement
with fractional excitations

- Kitaev Spin liquids
- Toric code

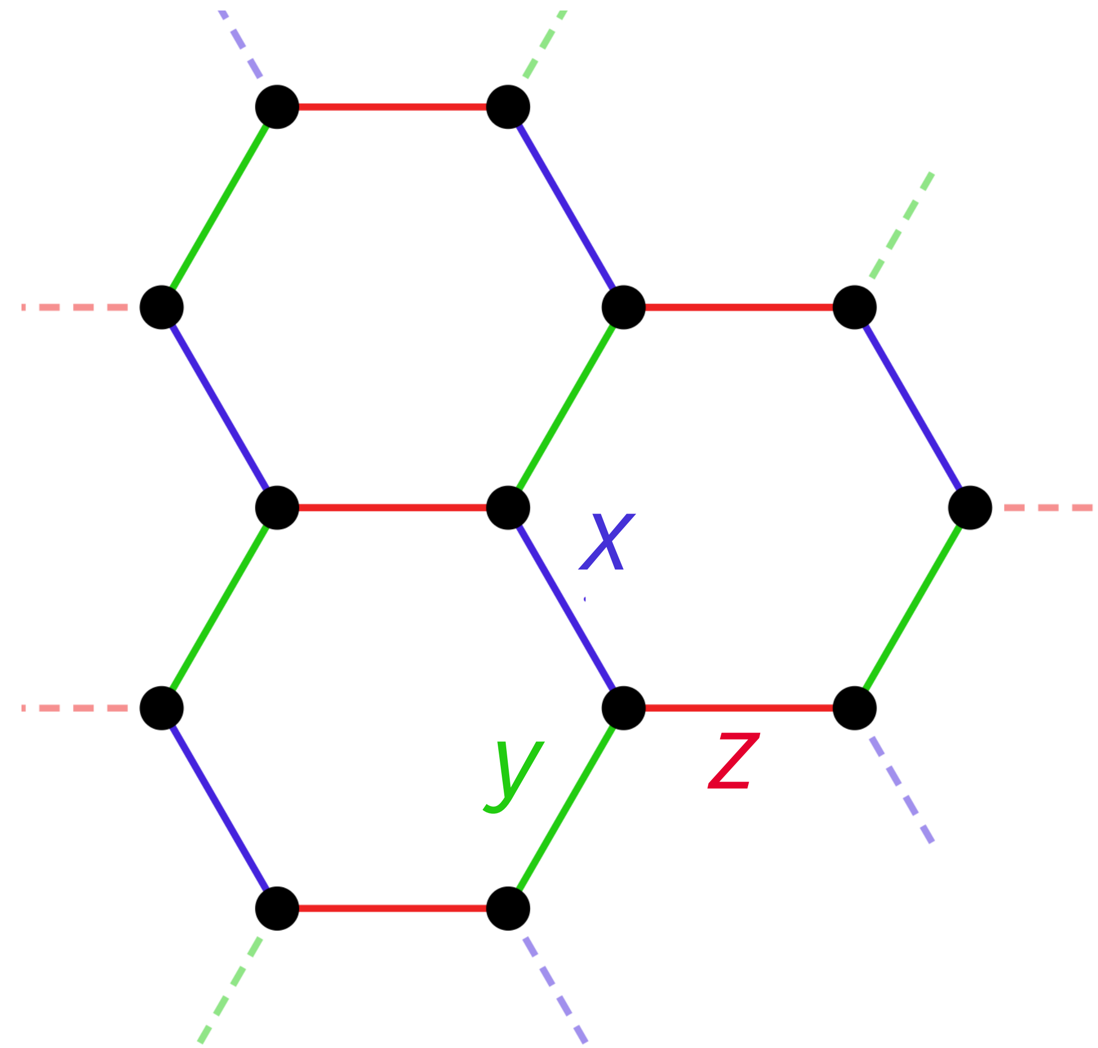
Kitaev spin liquid

Kitaev Exchange

$$K \sum_{\langle ij \rangle \in \gamma} S_i^\gamma S_j^\gamma$$

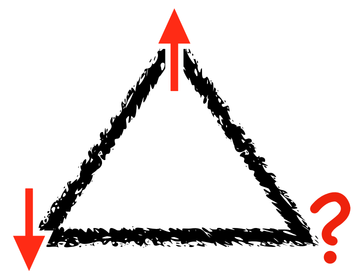
where $\gamma = x, y, z$

bond-dep. interaction



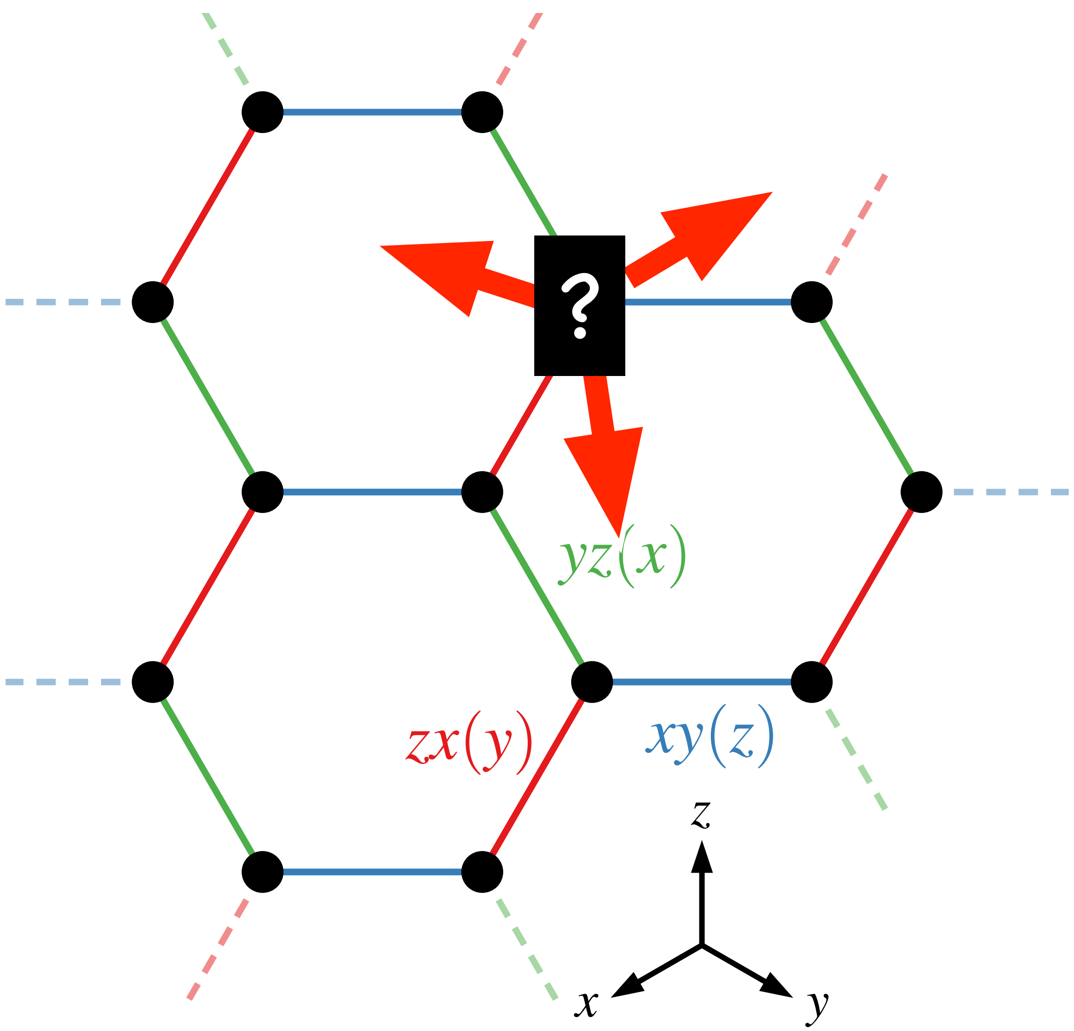
Exactly solvable: Z2 spin liquid ground state

A. Kitaev, Annals of Physics 321, 2 (2006):
Anyones in exactly solved model and beyond



~~geometrical frustration~~

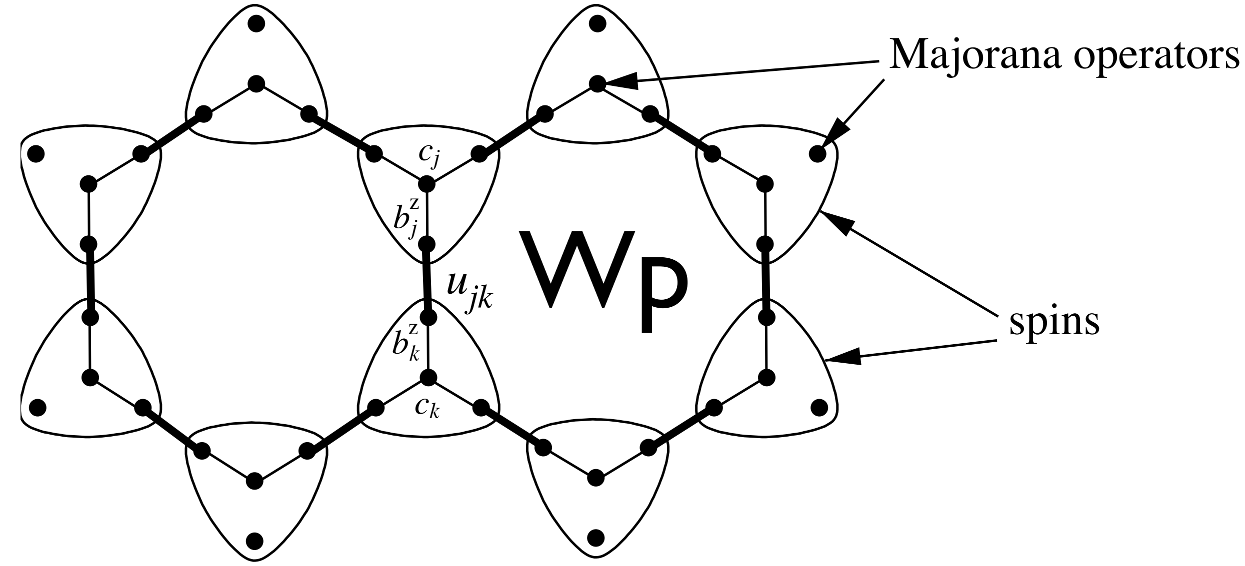
A new angle to frustration



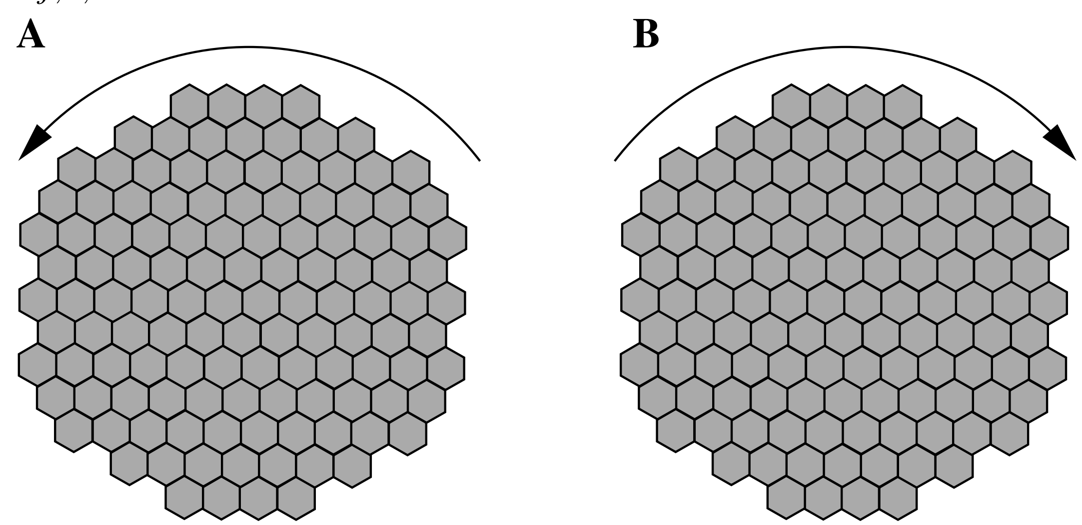
sing interaction on each bond:
bond dependant interaction:
each bond favors
different directions
of x,y,z

frustrated!

entropy is carried by emergent particles graphical representation of H



TRS breaking: $H_{\text{eff}}^{(3)} \sim -\frac{h_x h_y h_z}{J^2} \sum_{j,k,l} \sigma_j^x \sigma_k^y \sigma_l^z,$



Chiral edge modes can carry energy, leading to potentially measurable thermal transport. (The temperature T is assumed to be much smaller than the energy gap in the bulk, so that the effect of bulk excitations is negligible.) For quantum Hall systems, this phenomenon was discussed in [56,57]. The energy current along the edge in the left (counterclockwise) direction is given by the following formula:

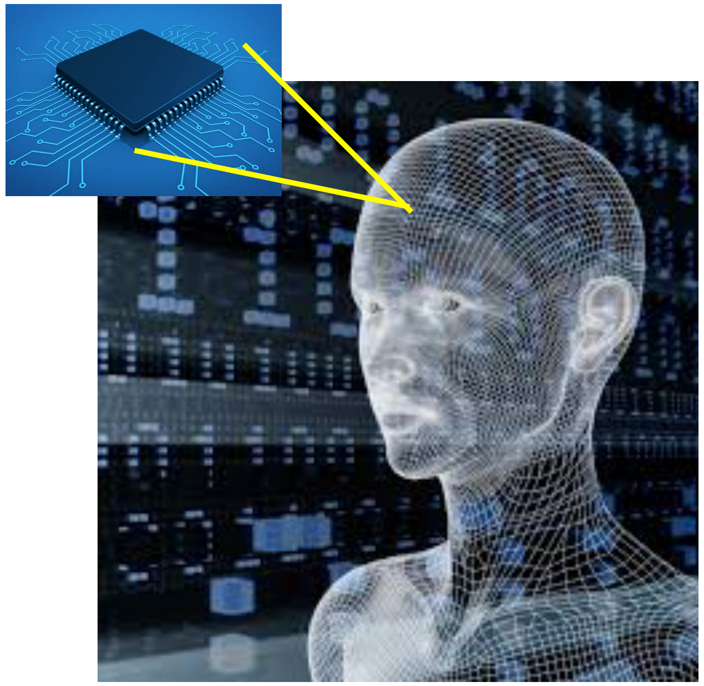
$$I = \frac{\pi}{12} c_- T^2, \quad (57)$$

A. Kitaev, Annals of Physics 321, 2 (2006):
Anyones in exactly solved model and beyond

Topological quantum computation

Quantum Information

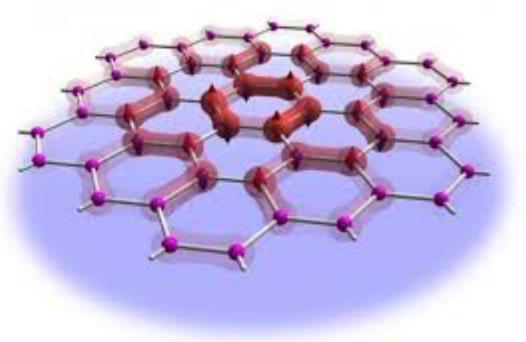
Anyon?



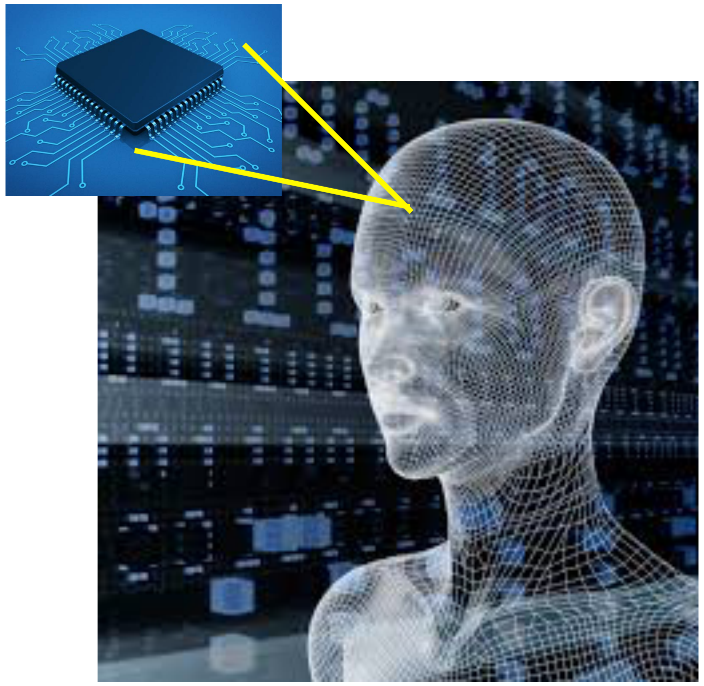
Topological quantum computation

Quantum Information

Anyon?



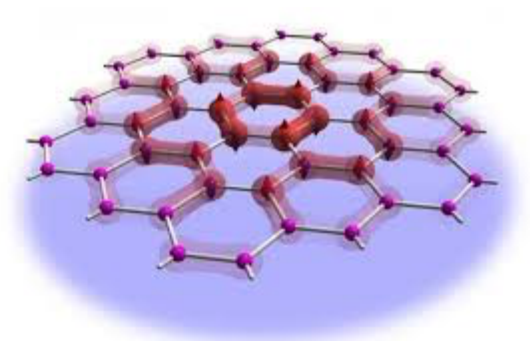
Quantum Materials



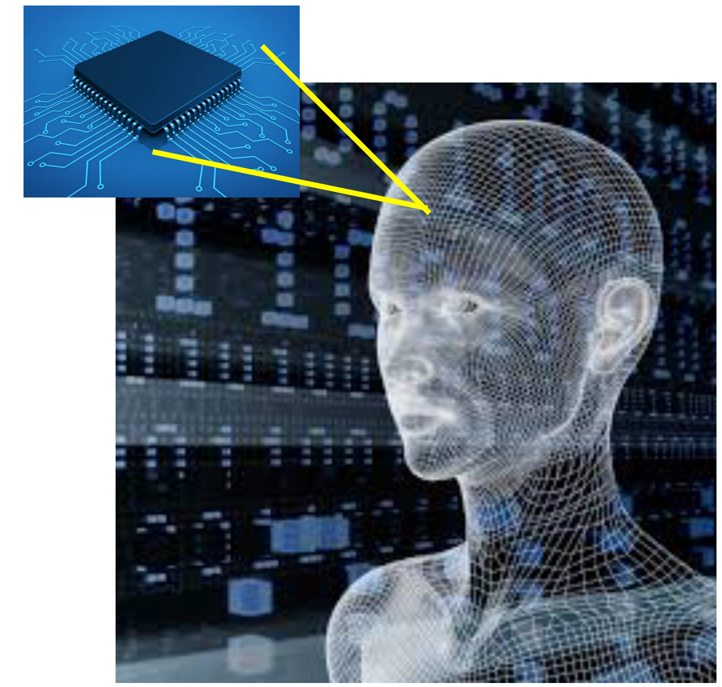
Topological quantum computation

Quantum Information

Anyon?

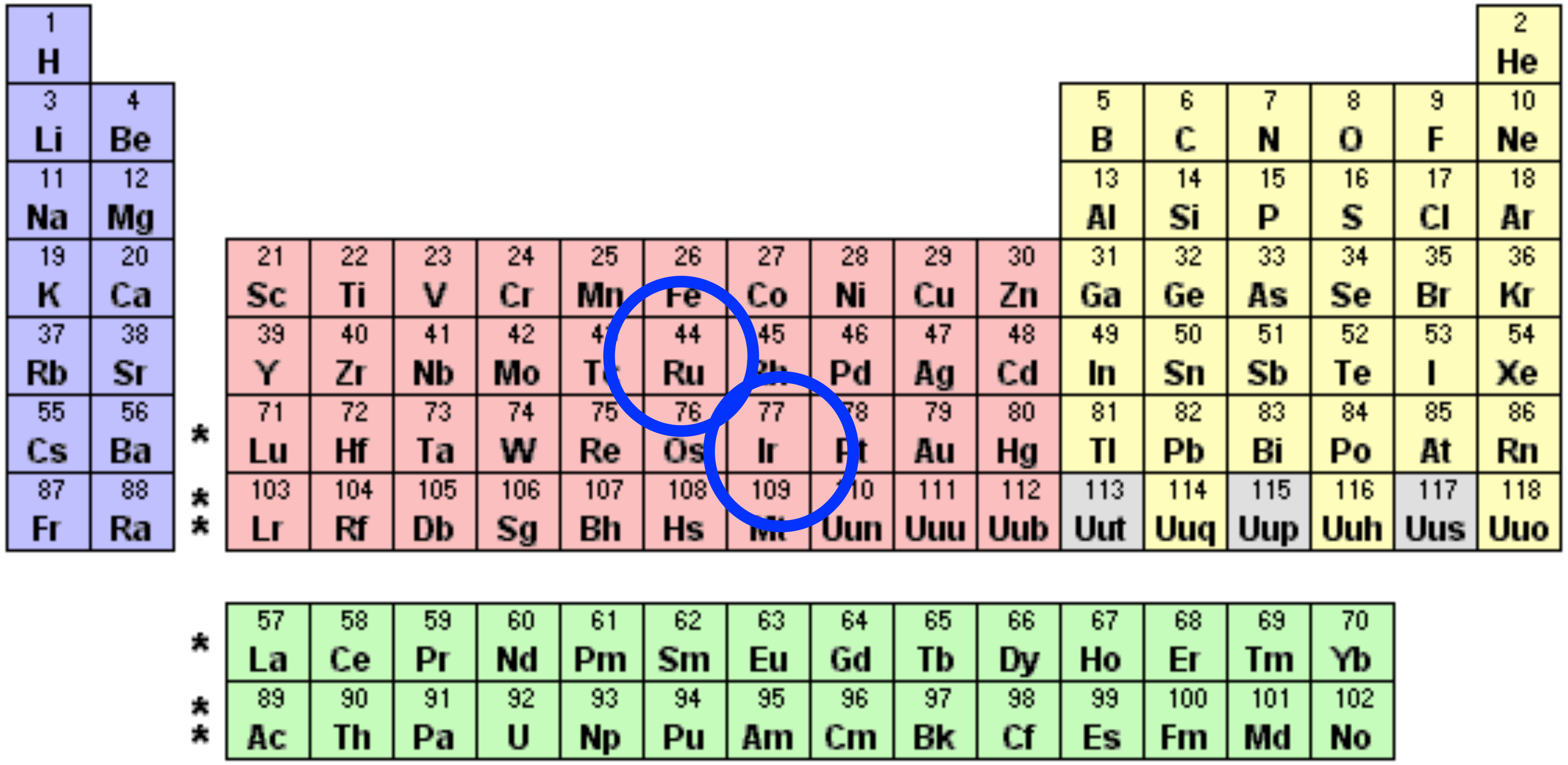


Quantum Materials



Where to find Anyons?

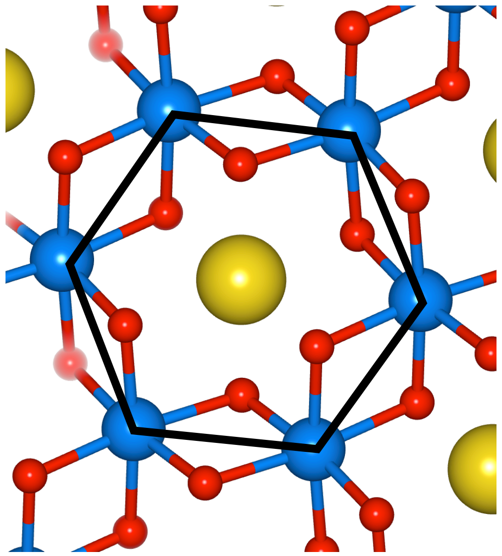
How to realize KSL in Solid-State Materials ?



* candidates for Kitaev spin liquid

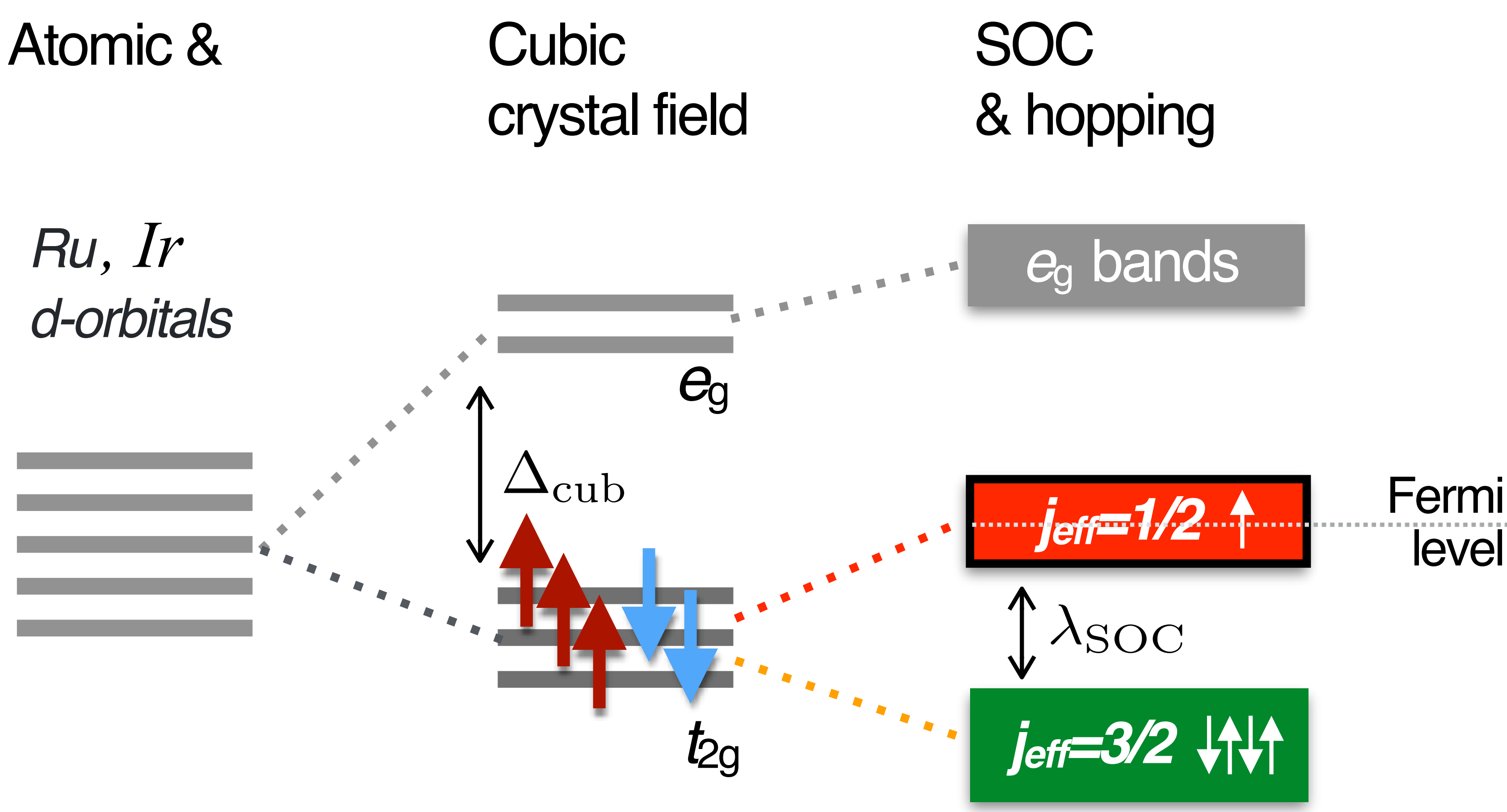
Iridium (5d): Na_2IrO_3, Li_2IrO_3

Ruthenium (4d): $RuCl_3$



Kitaev spin liquid in materials?

relevant orbitals & spin-orbit coupling (SOC):



d^5 -- half filled Jeff=1/2 bands

Sr2IrO4: Mott insulator, BJ Kim...W. Noh, PRL (2008);
B.J. Kim...H. Takagi, Science (2009)

J_{eff} = 1/2 basis

$$\left|+\tfrac{1}{2}\right\rangle = \sqrt{\frac{1}{3}}\left(|yz\rangle|\downarrow\rangle + i\,|zx\rangle|\downarrow\rangle + |xy\rangle|\uparrow\rangle\right)$$

$$= \sqrt{\frac{2}{3}}\,|1,+1\rangle|\downarrow\rangle - i\sqrt{\frac{1}{3}}\,|1,0\rangle|\uparrow\rangle$$

TR

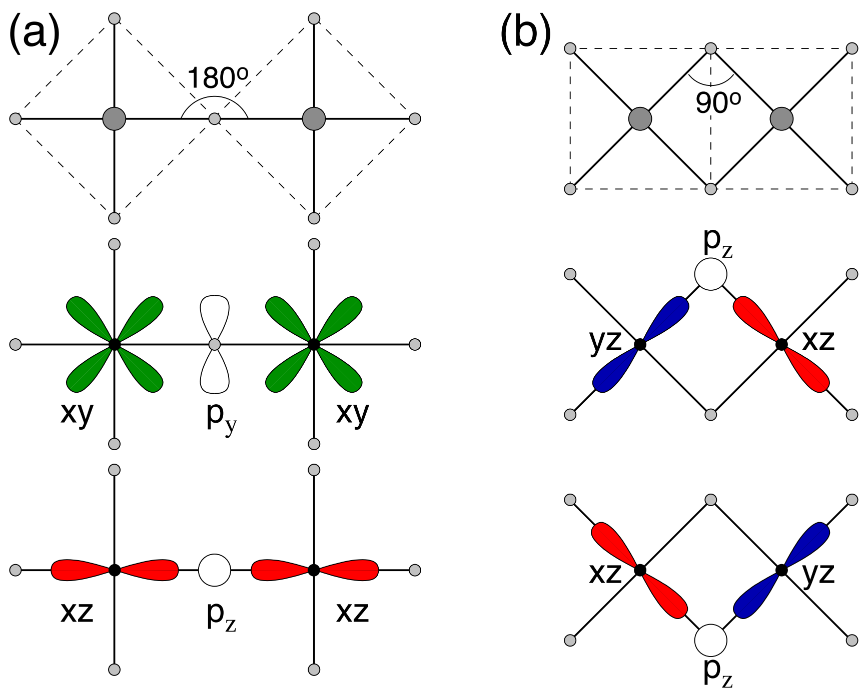
$$\left|-\tfrac{1}{2}\right\rangle = \sqrt{\frac{1}{3}}\left(|yz\rangle|\uparrow\rangle - i\,|zx\rangle|\uparrow\rangle - |xy\rangle|\downarrow\rangle\right)$$

$$= \sqrt{\frac{2}{3}}\,|1,-1\rangle|\uparrow\rangle + i\sqrt{\frac{1}{3}}\,|1,0\rangle|\downarrow\rangle$$

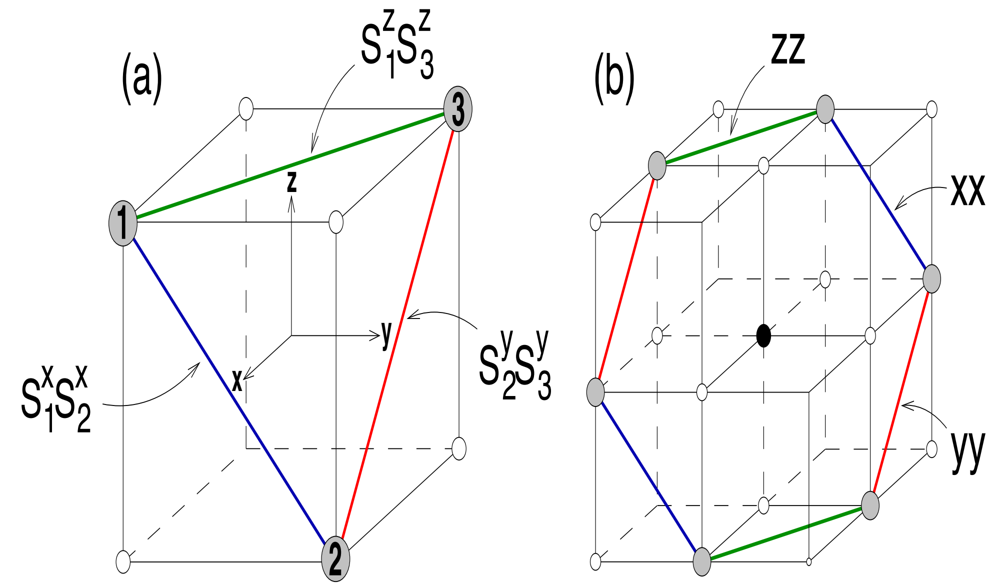
mixture of t2g orbitals and different spins

Compass model

Jackeli and Khaliullin, Phys. Rev. Lett. 102, 017205 (2009)



edge-shared octahedra



strong SOC in t2g states:

Kitaev-Heisenberg model

$$H_{ij}^{\gamma} = -K S_i^{\gamma} S_j^{\gamma} + J \mathbf{S}_i \cdot \mathbf{S}_j \quad \text{where} \quad \mathrm{K} = \frac{8 J_H t_0^2}{3U^2}$$

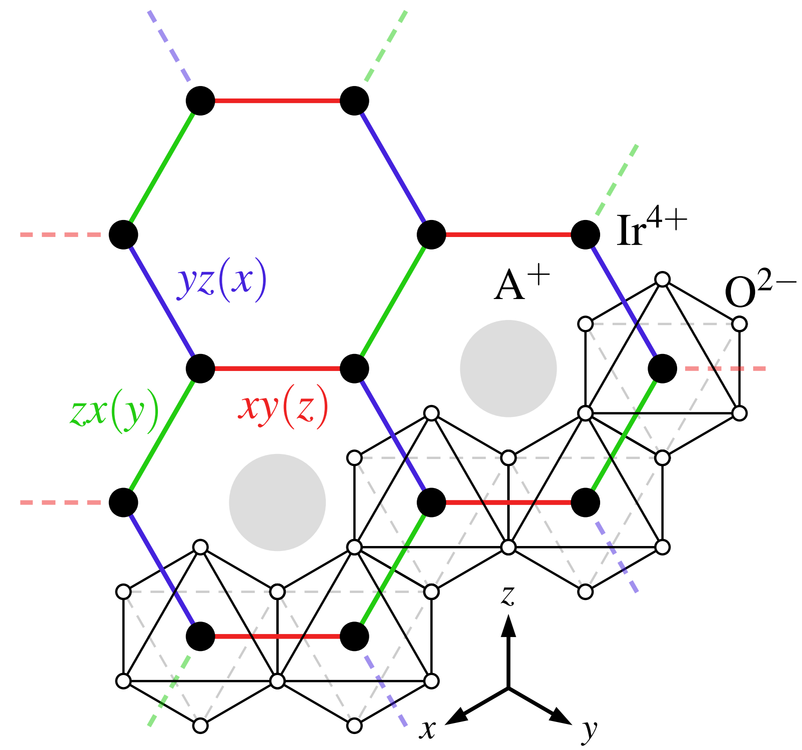
Material candidates: honeycomb Iridates (5d)

Na_2IrO_3, Li_2IrO_3

Generic Spin Model

nearest neighbour:
ideal honeycomb

$$H = \sum_{\gamma \in x,y,z} H^\gamma,$$



bond-dep. interaction

$$H^z = \sum_{\langle ij \rangle \in z-bond} [K_z S_i^z S_j^z + \Gamma_z (S_i^x S_j^y + S_i^y S_j^x)] + J\mathbf{S}_i \cdot \mathbf{S}_j$$

$$H^x = H^z (x \to y \to z \to x)$$

J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

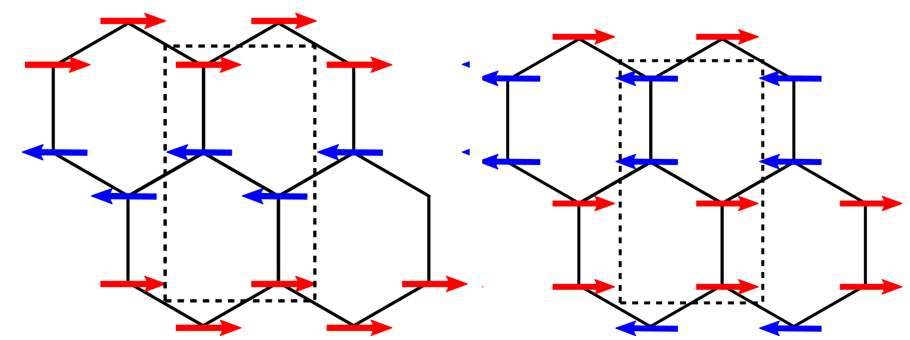
Ordered phases nearby KSL

ED 24-site cluster

For $+\Gamma$

+J

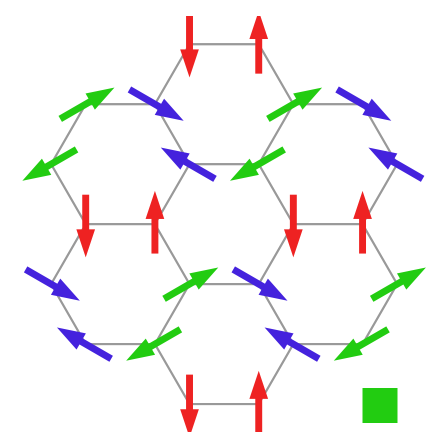
(J,K,Γ) = (sinθcosϕ,sinθsinϕ,cosθ)



zigzag stripe

+K

-K

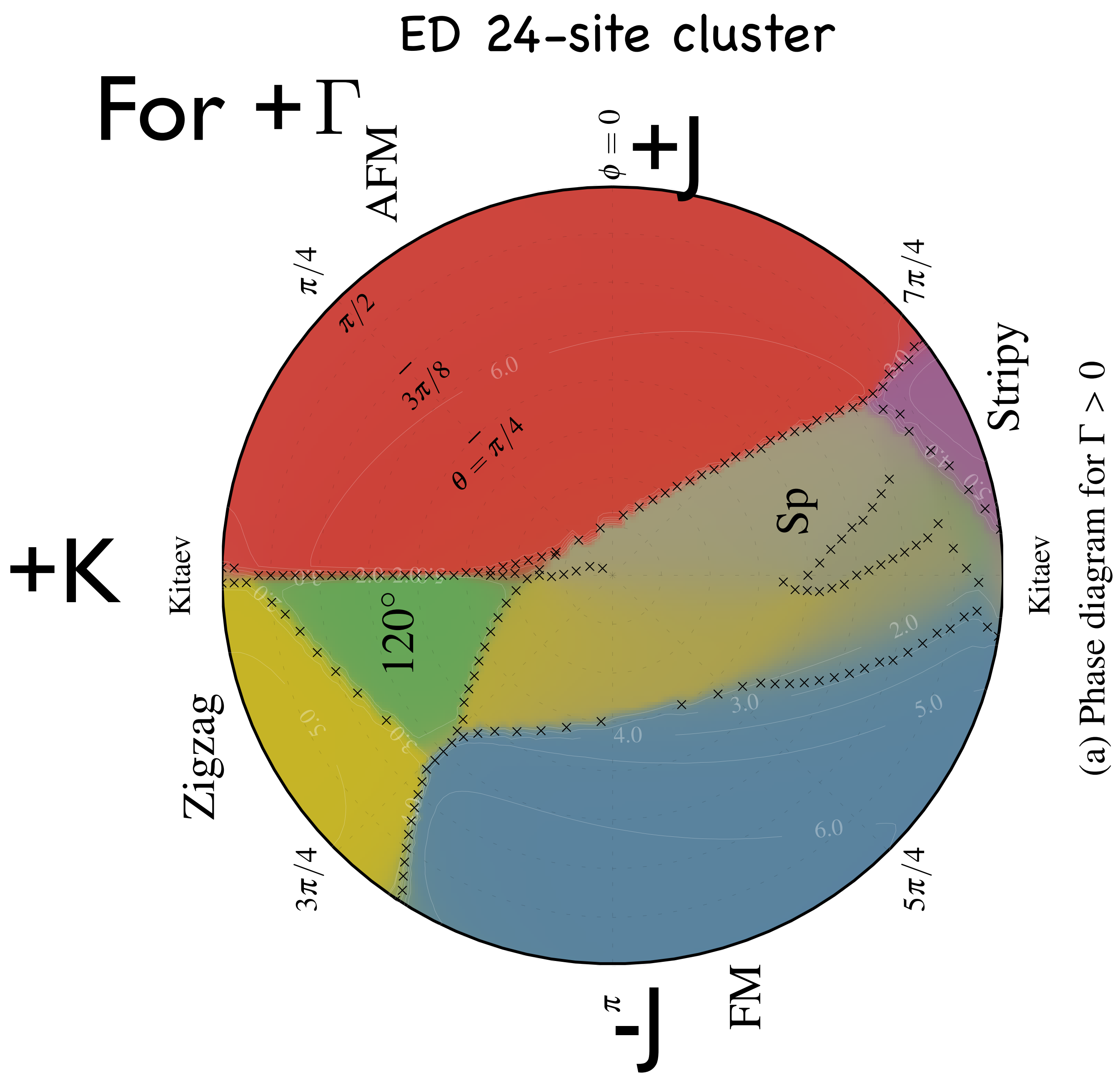


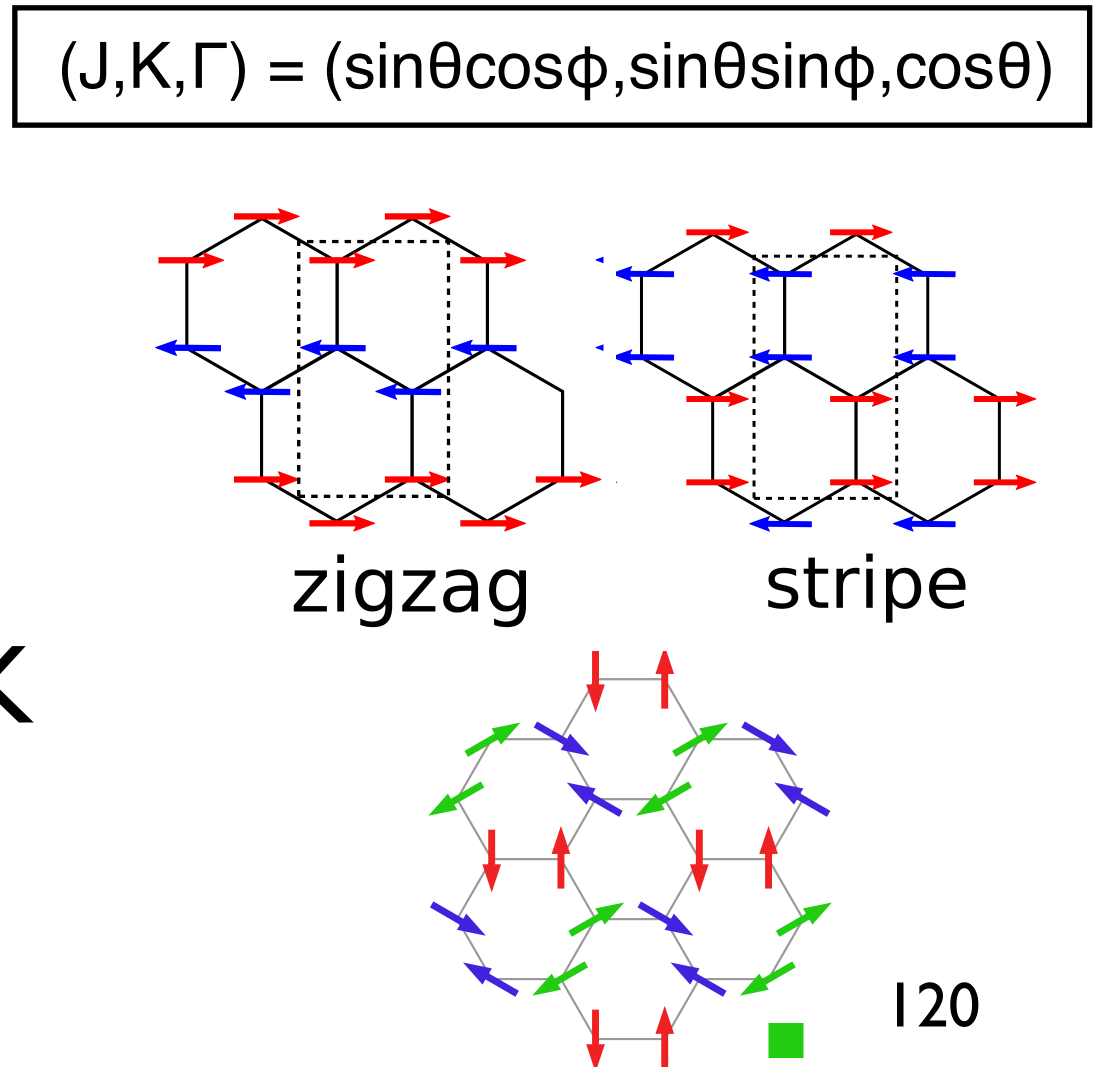
120

-J

J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Ordered phases nearby KSL



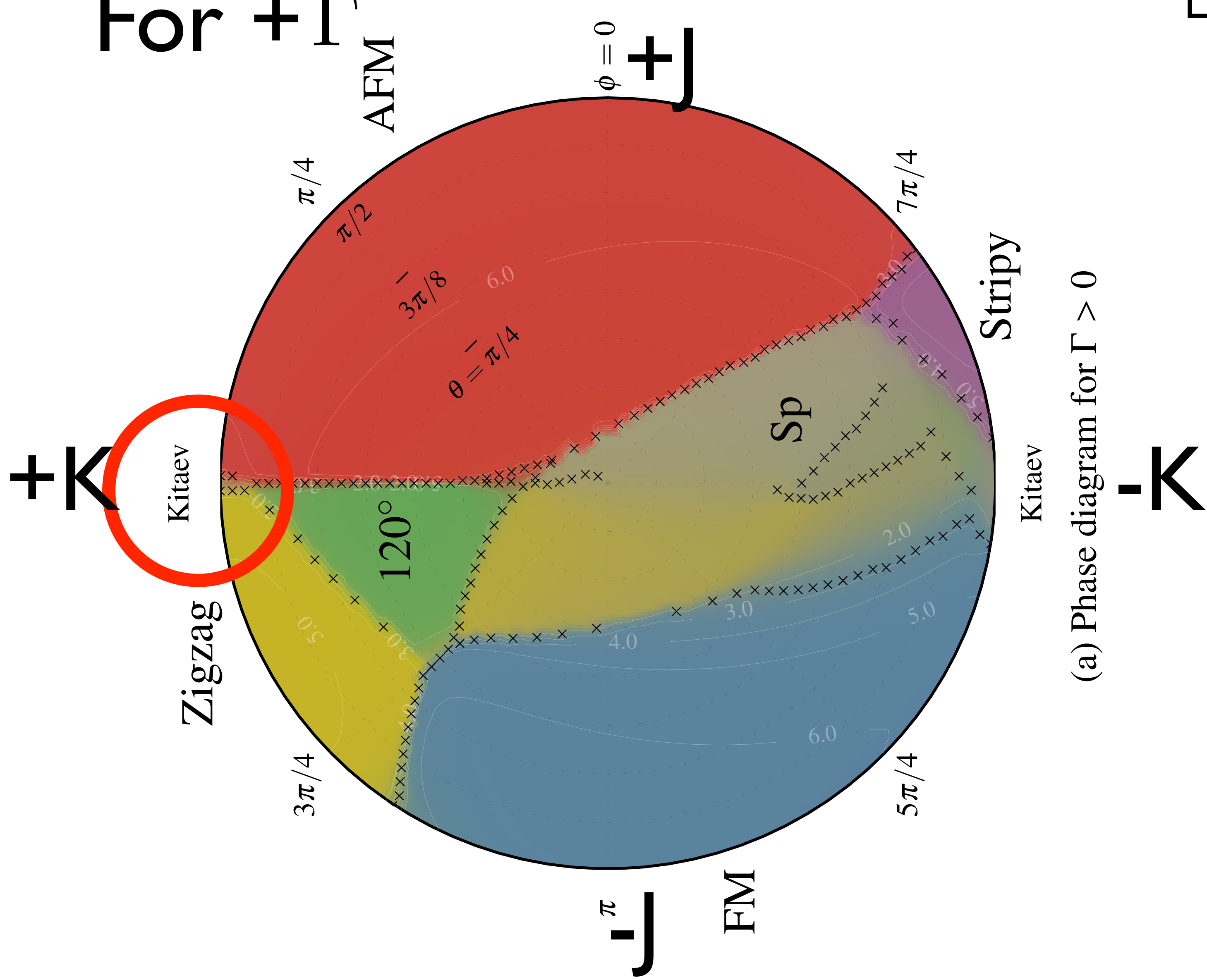


J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

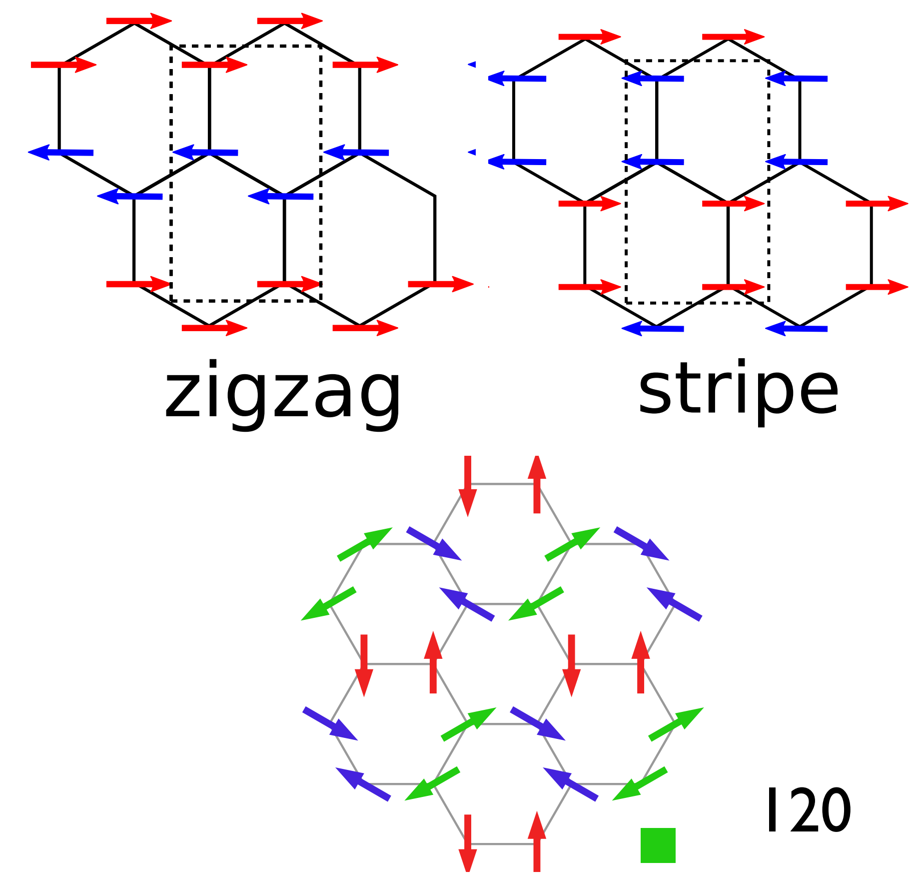
Ordered phases nearby KSL

ED 24-site cluster

For $+\Gamma$

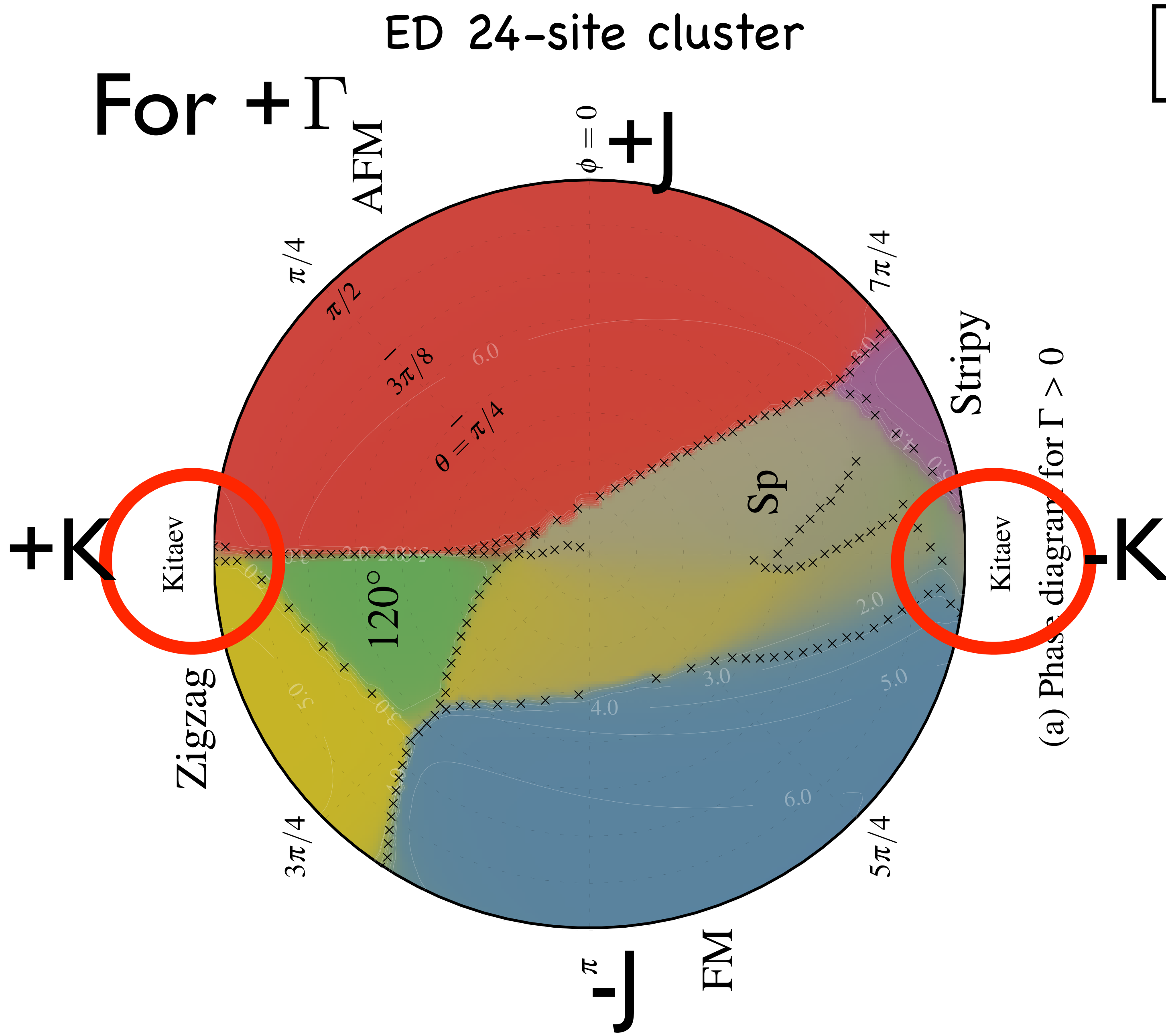


(J,K,Γ) = (sinθcosϕ,sinθsinϕ,cosθ)

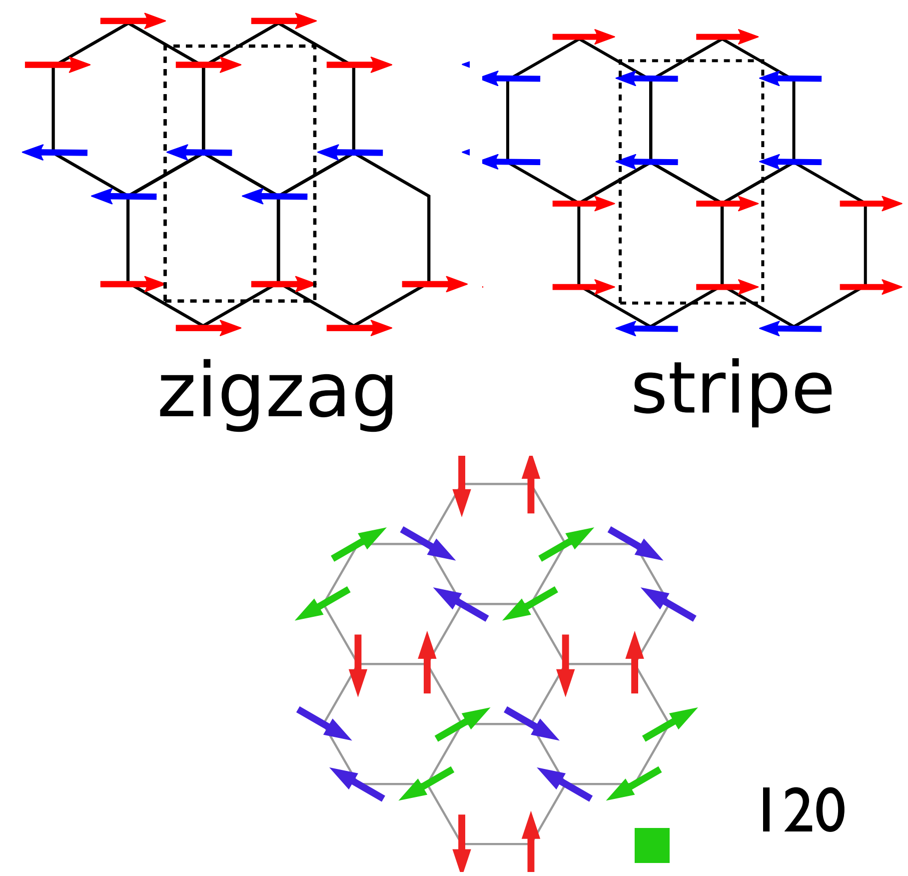


J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Ordered phases nearby KSL

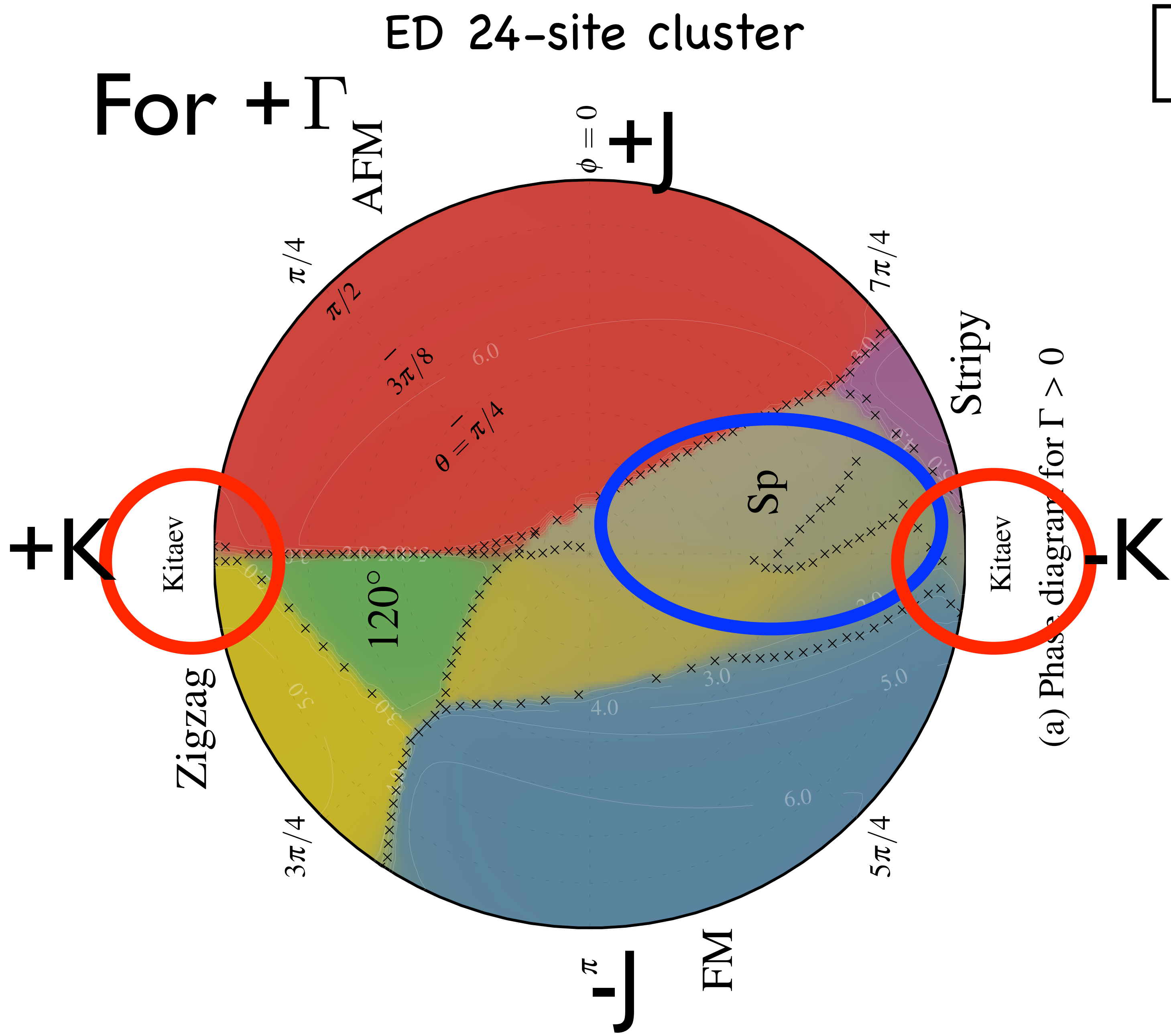


(J,K,Γ) = (sinθcosϕ,sinθsinϕ,cosθ)

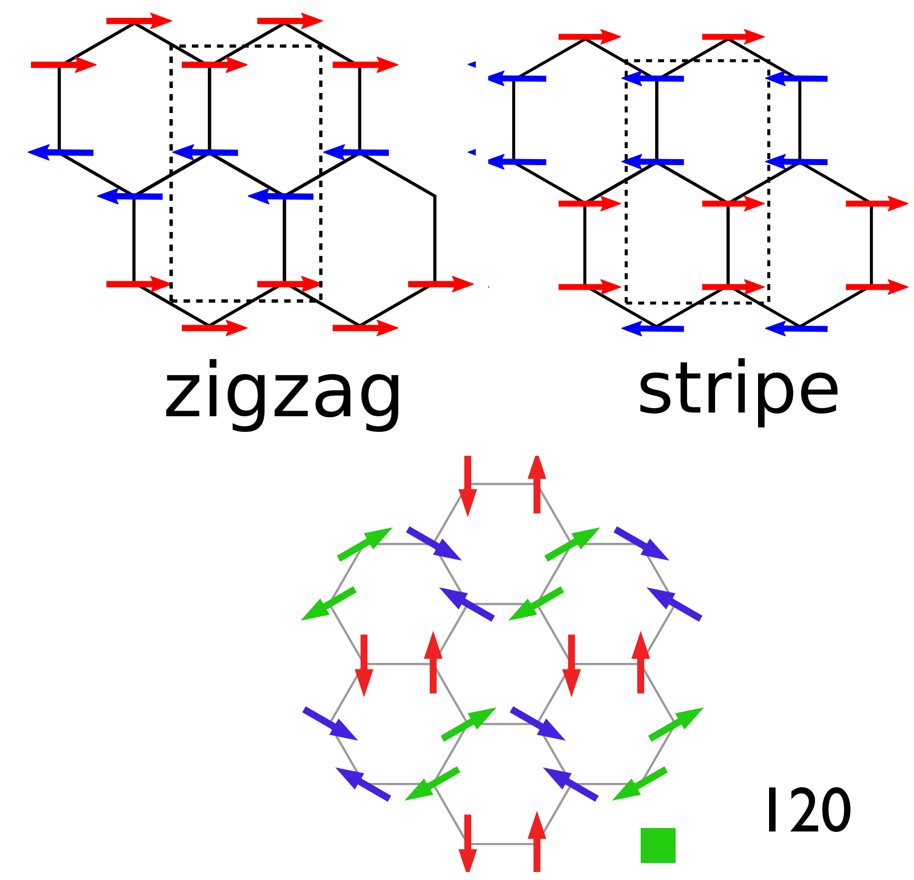


J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Ordered phases nearby KSL

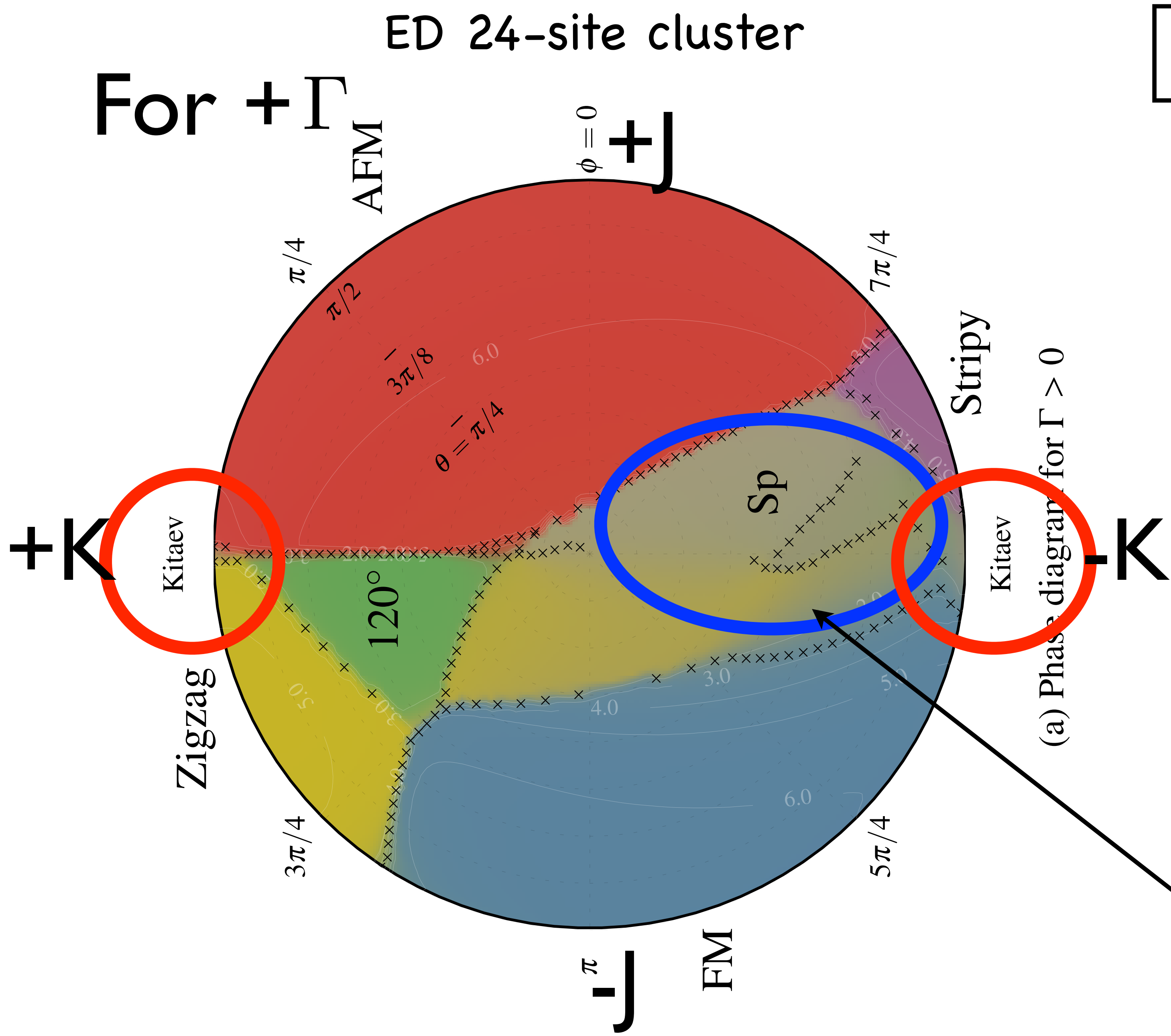


(J,K,Γ) = (sinθcosφ,sinθsinφ,cosθ)

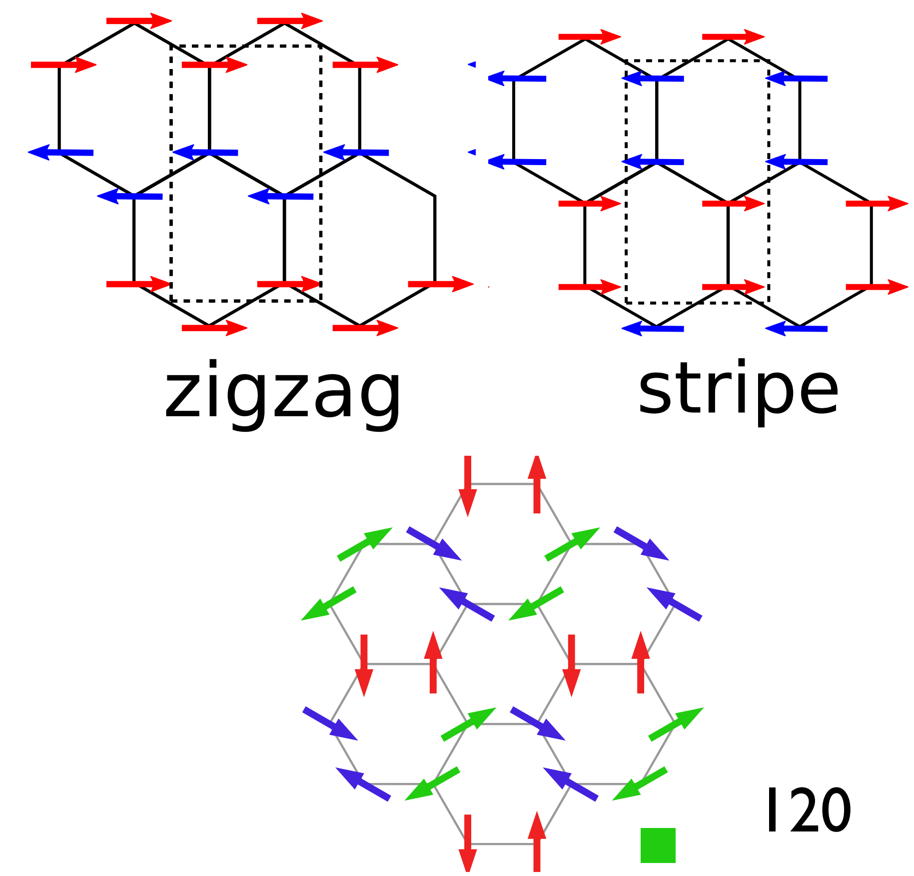


J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Ordered phases nearby KSL



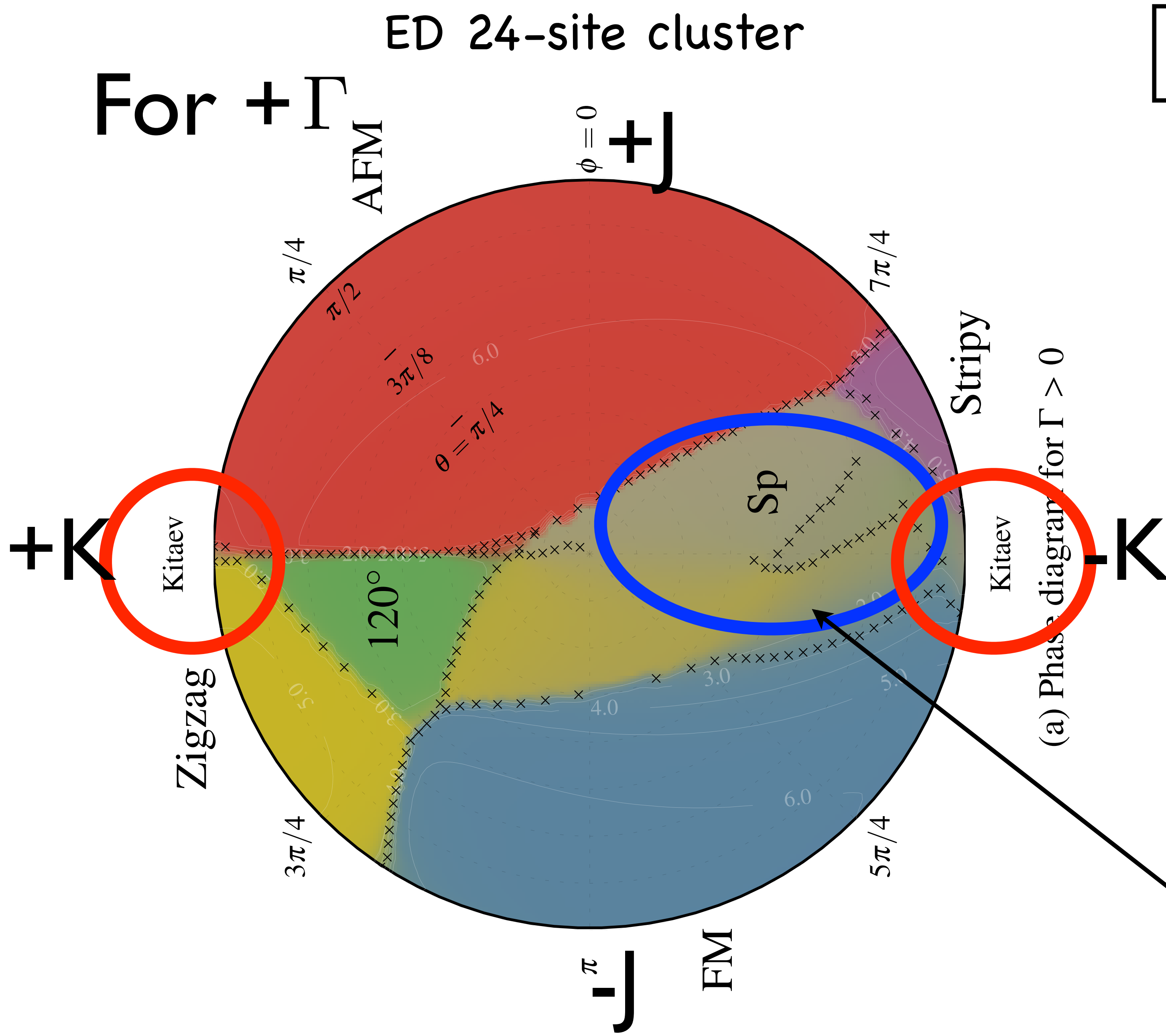
(J,K,Γ) = (sinθcosφ,sinθsinφ,cosθ)



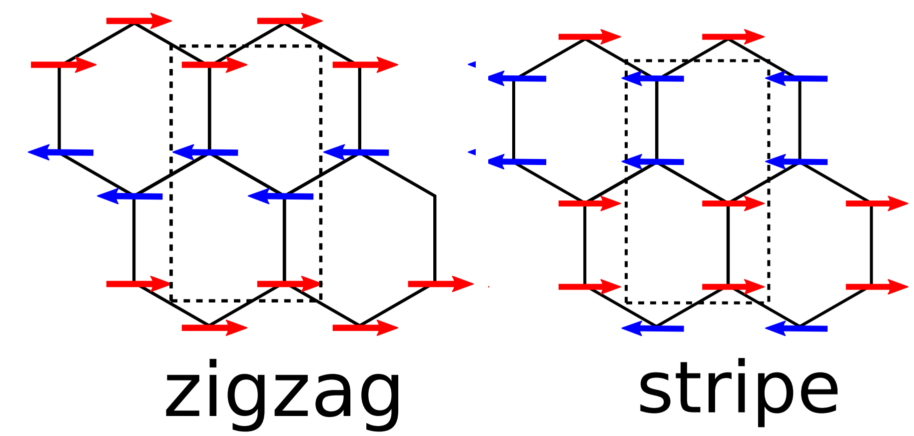
RuCl3, Na2IrO3, Li2IrO3:
NN+ further neighbour

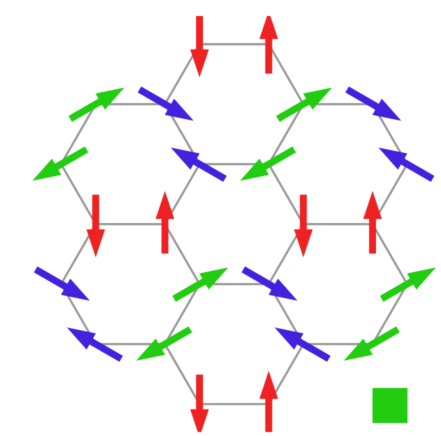
J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Ordered phases nearby KSL



(J,K,Γ) = (sinθcosϕ,sinθsinϕ,cosθ)





$RuCl_3$, Na_2IrO_3, Li_2IrO_3:
NN+ further neighbour

extremely narrow range of KSL

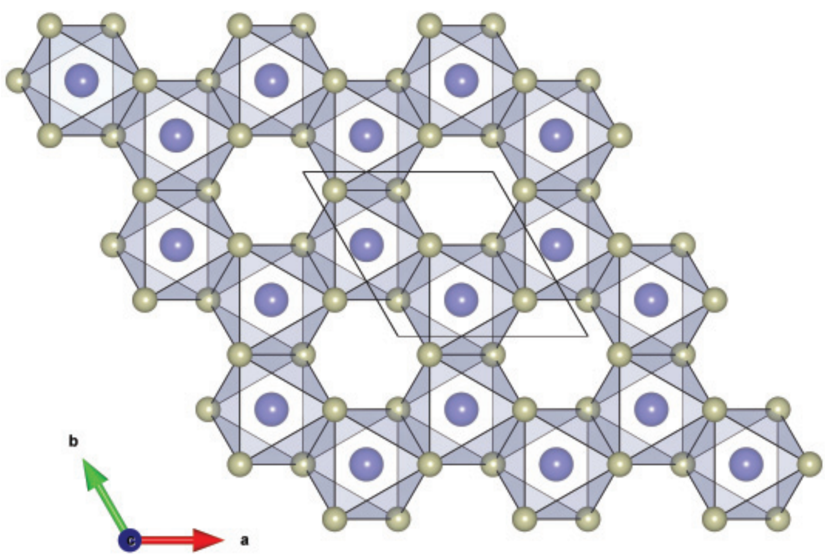
J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

Kitaev materials: extends to 4d $\alpha - RuCl_3$

PHYSICAL REVIEW B **90**, 041112(R) (2014)

α-$RuCl_3$: A spin-orbit assisted Mott insulator on a honeycomb lattice

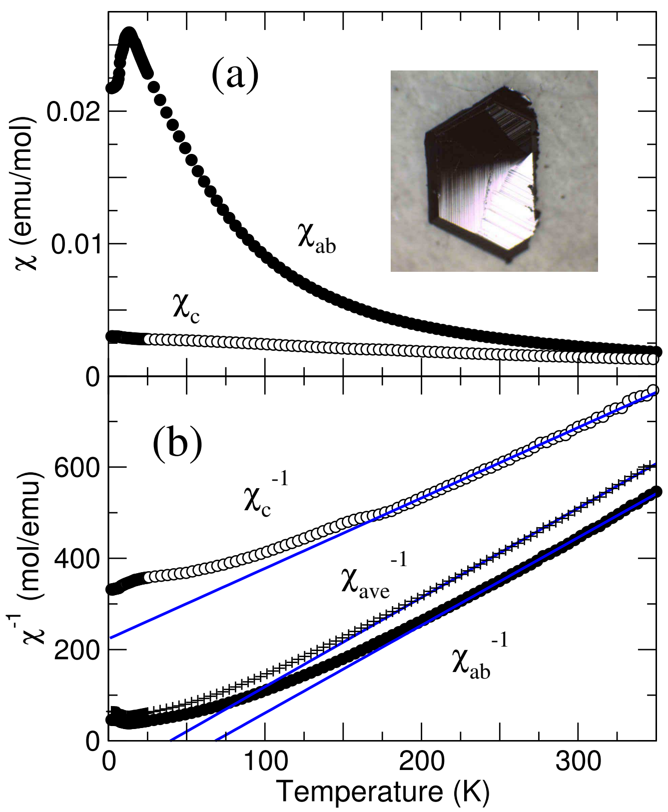
K. W. Plumb,[1] J. P. Clancy,[1] L. J. Sandilands,[1] V. Vijay Shankar,[1] Y. F. Hu,[2] K. S. Burch,[1,3] Hae-Young Kee,[1,4] and Young-June Kim[1,*]

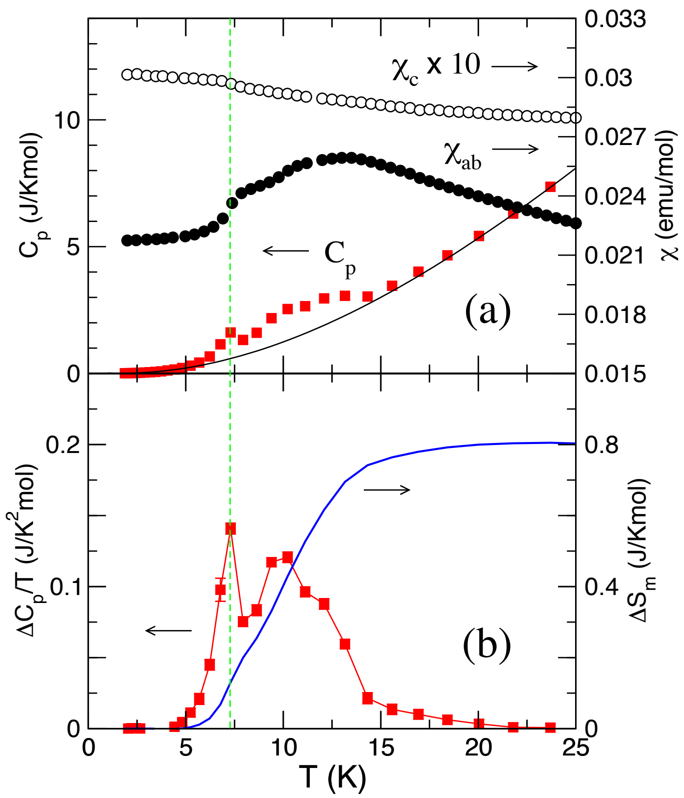


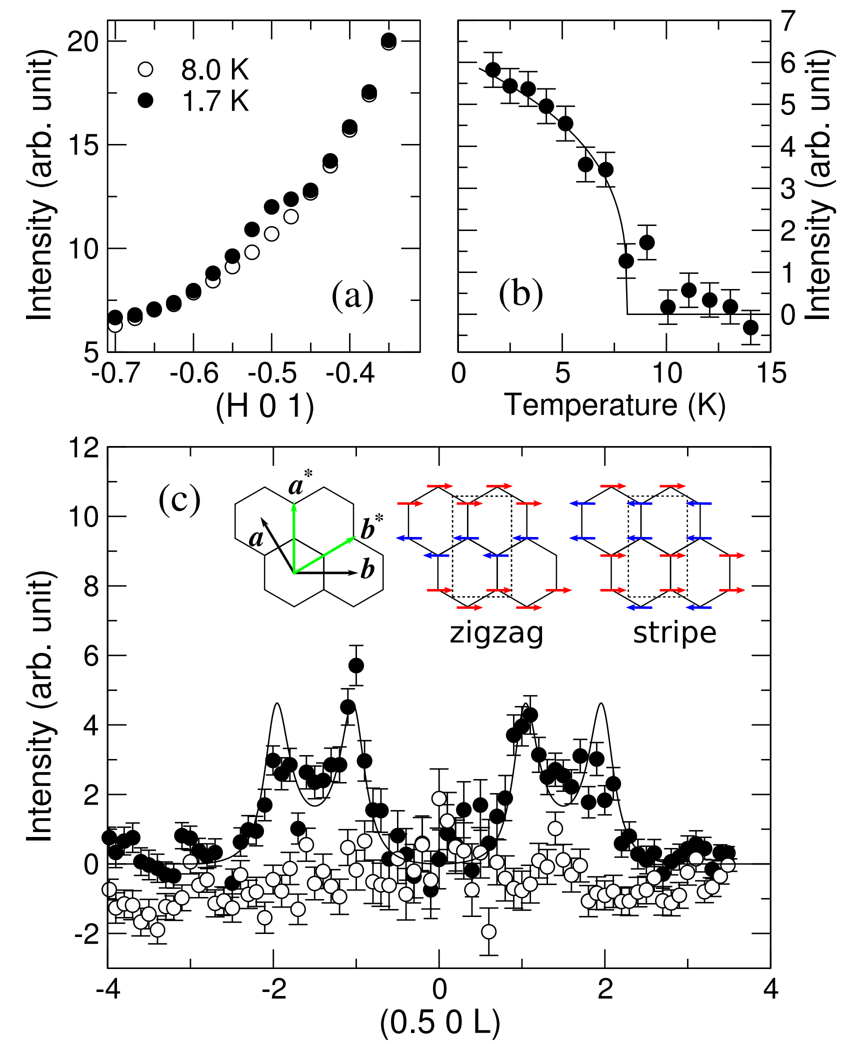
$Ru^{3+} : 4d^5$

process in α-$RuCl_3$. Then a microscopic spin model relevant for α-$RuCl_3$ should be composed of both the nearest-neighbor Heisenberg and bond-dependent exchange terms denoted by Kitaev K and Γ [44–46].

magnetic ordering below Tc





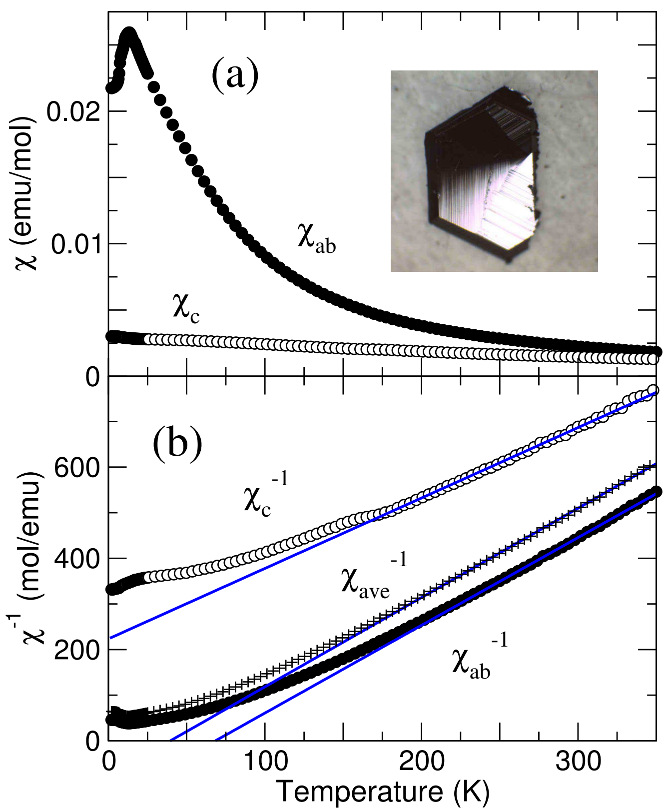


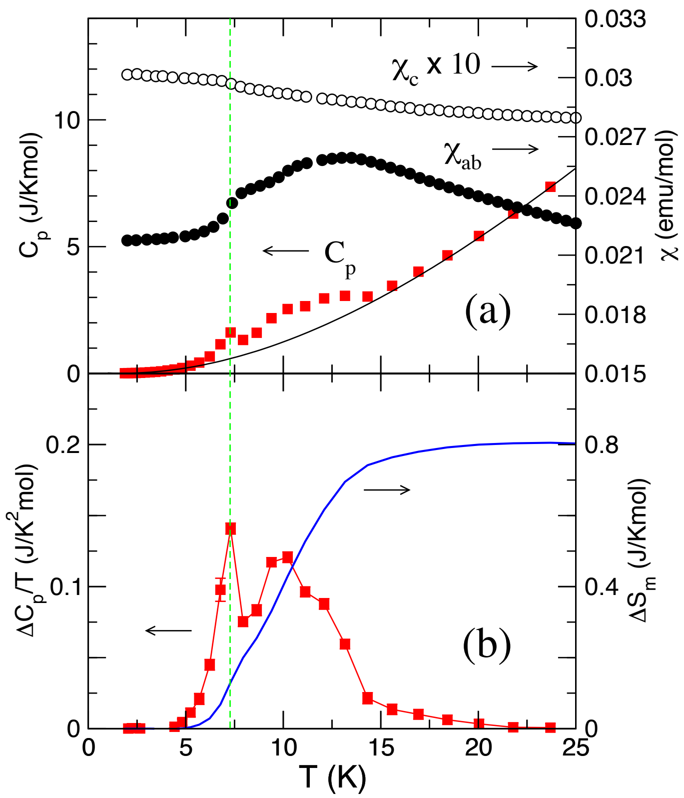
J. Sears et al, PRB 91, 144420 (2015)

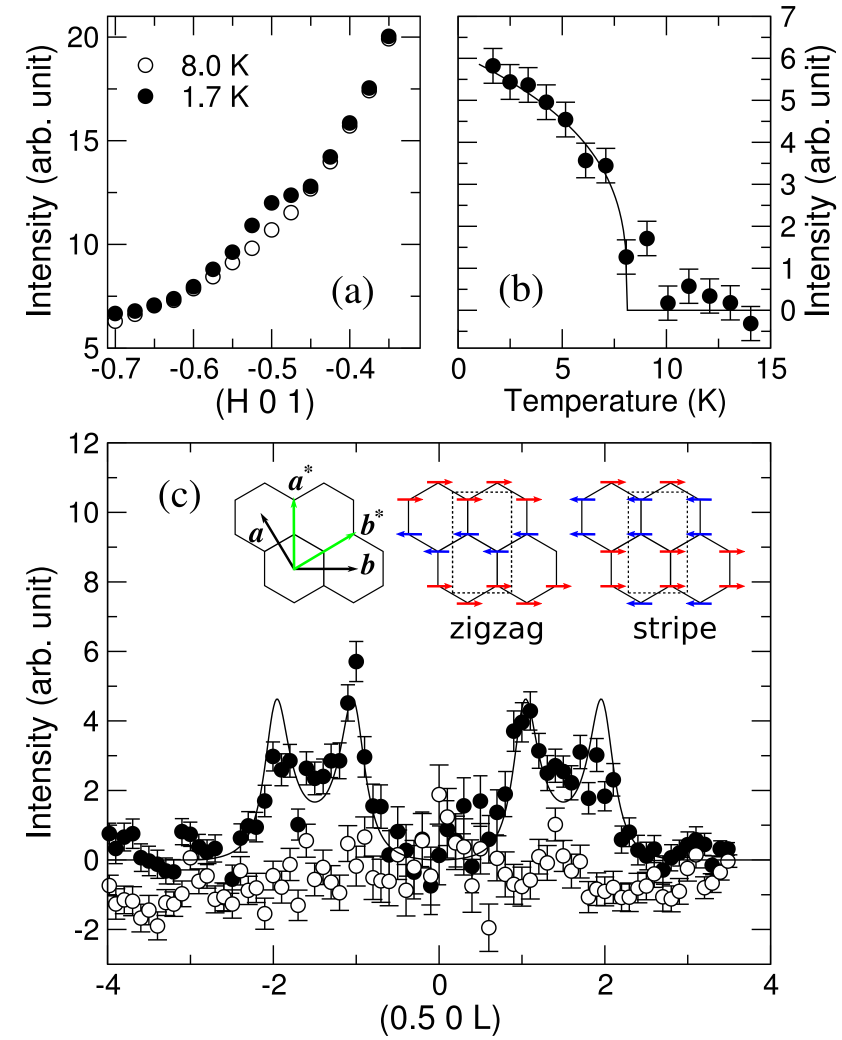
R. D. Johnson et al, Phys. Rev. B 92, 235119 (2015).

H. B. Cao et al, Phys. Rev. B 93, 134423 (2016); …….

magnetic ordering below Tc







J. Sears et al, PRB 91, 144420 (2015)

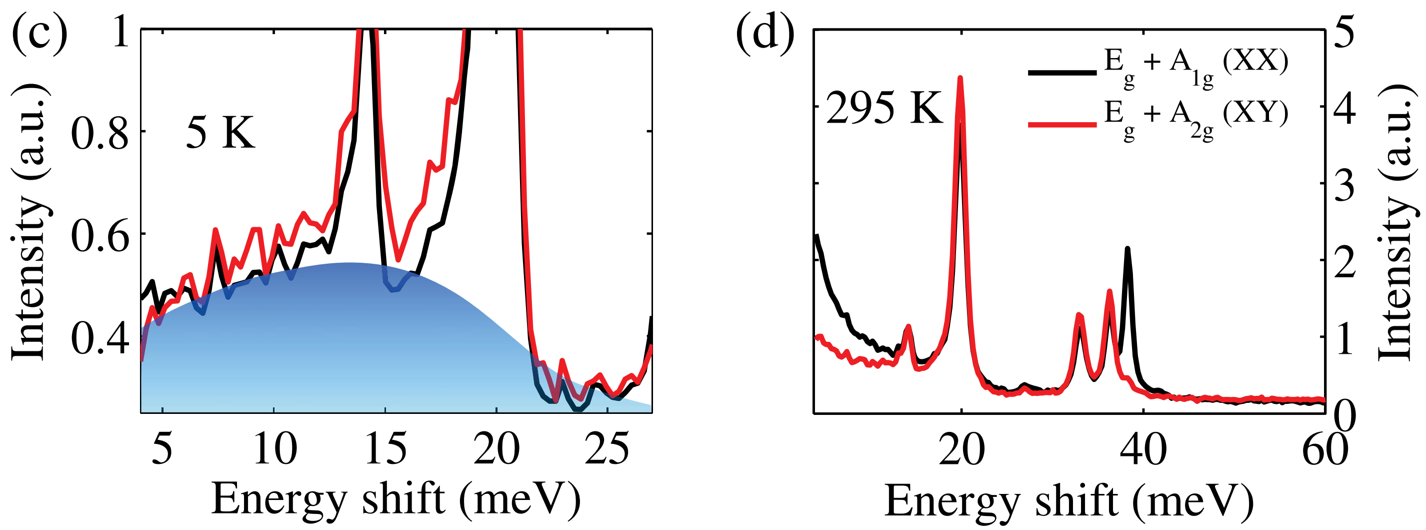
R. D. Johnson et al, Phys. Rev. B 92, 235119 (2015).

H. B. Cao et al, Phys. Rev. B 93, 134423 (2016); …….

What about above Tc or inelastic ?
Governed by Kitaev spin interaction?

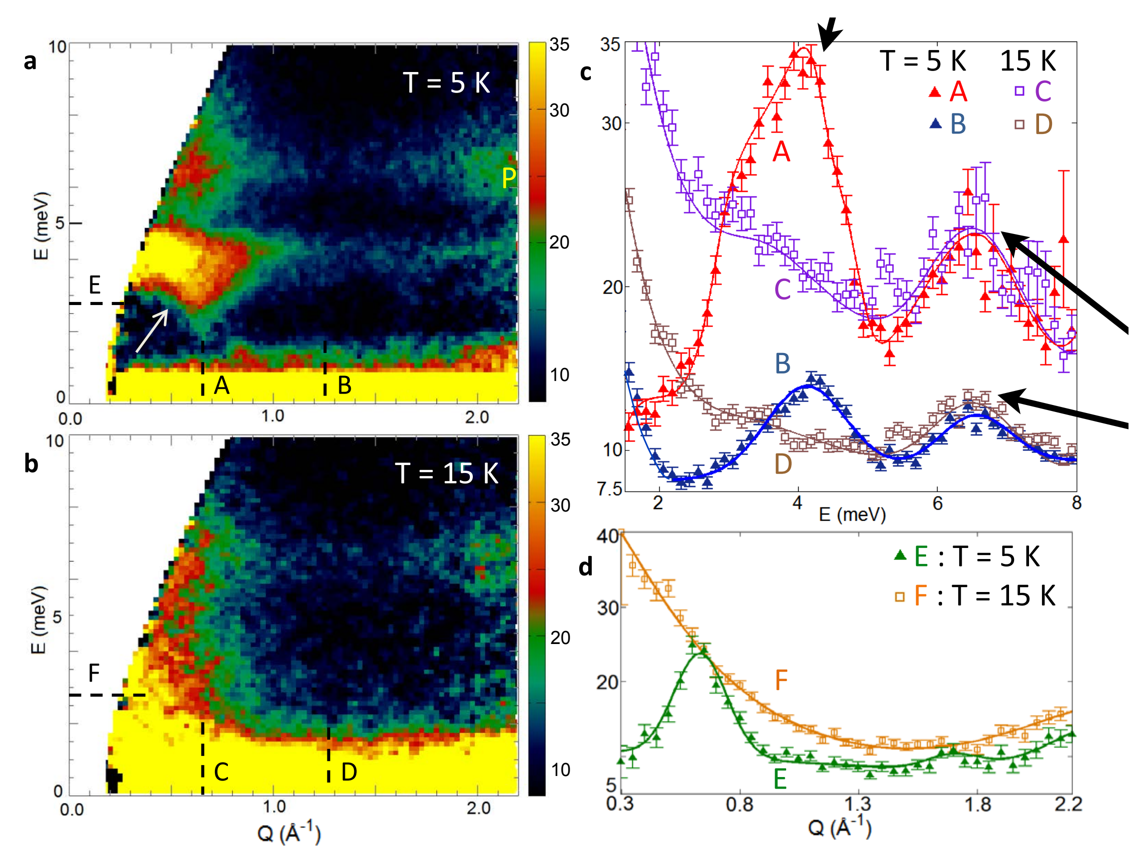
Proximate to Kitaev spin liquid

Raman spectrum



L. J. Sandilands et al, Phys. Rev. Lett. 114, 147201 (2015).

Magnetic excitations: inelastic neutron scattering



A. Banerjee... S. Nagler, Nat. Mat. 15, 733 (2016)

A. Banerjee... S. Nagler, Science (2017)

S.-H. Do, …, S. Ji, Nat. Phys. 13, 1079 (2017)

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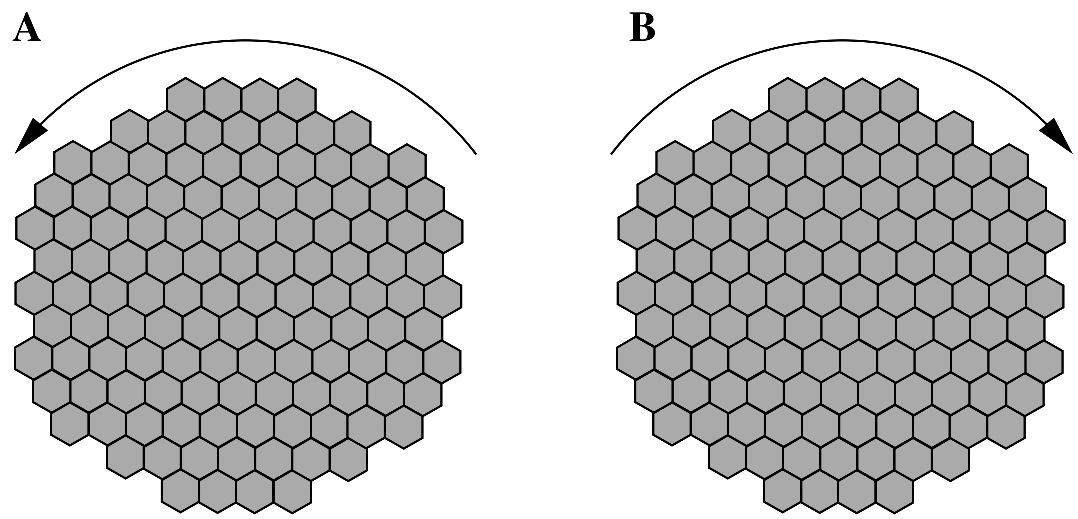
Indicate strong frustration: Kitaev contributions

smoking-gun signature



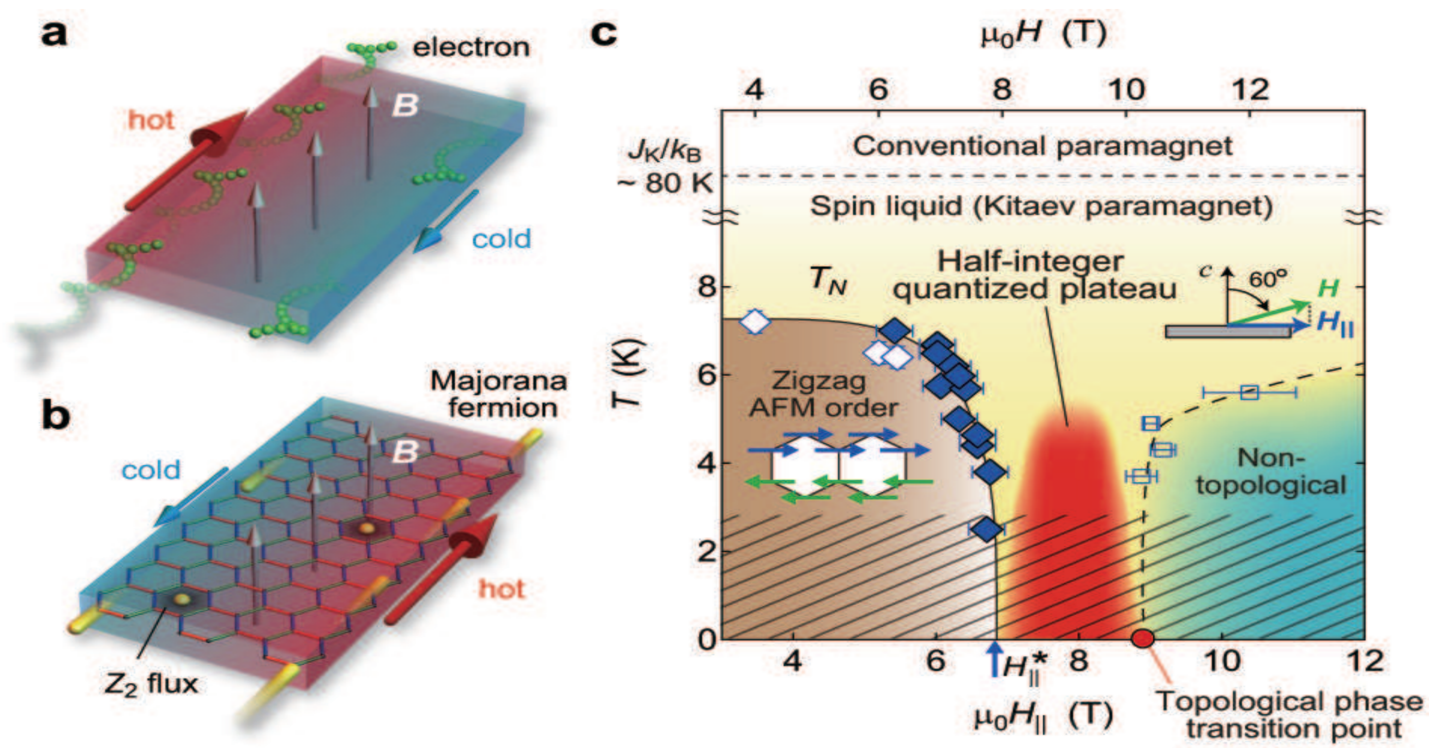
Chiral edge mode : 1/2 quantized thermal Hall conductivity

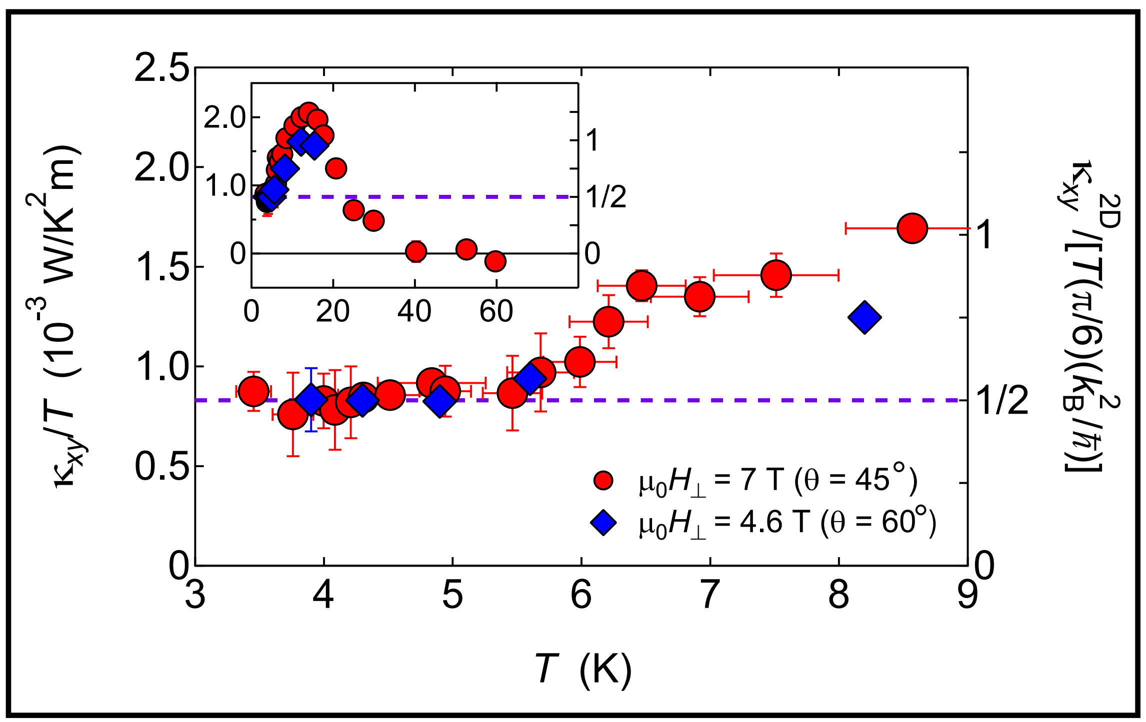
Chiral edge modes can carry energy, leading to potentially measurable thermal transport. (The temperature T is assumed to be much smaller than the energy gap in the bulk, so that the effect of bulk excitations is negligible.) For quantum Hall systems, this phenomenon was discussed in [56,57]. The energy current along the edge in the left (counterclockwise) direction is given by the following formula:

$$I = \frac{\pi}{12} c_{-} T^2, \tag{57}$$

A. Kitaev, Annals of Physics 321, 2 (2006):
Anyones in exactly solved model and beyond

Thermal Transport: alpha-RuCl3





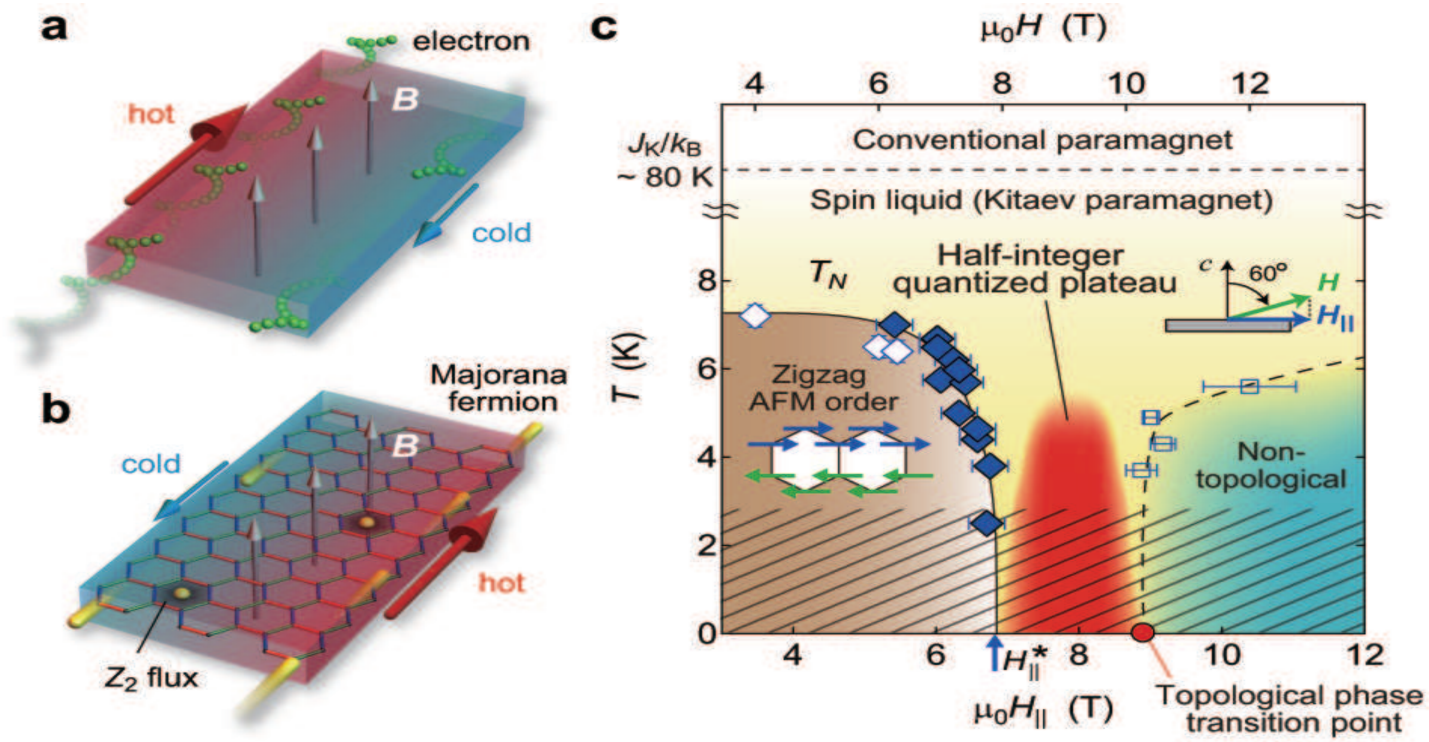
$$\frac{\kappa_{xy}^{2D}}{T} = c\,\frac{\pi}{6}\,\frac{k_B^2}{\hbar}$$

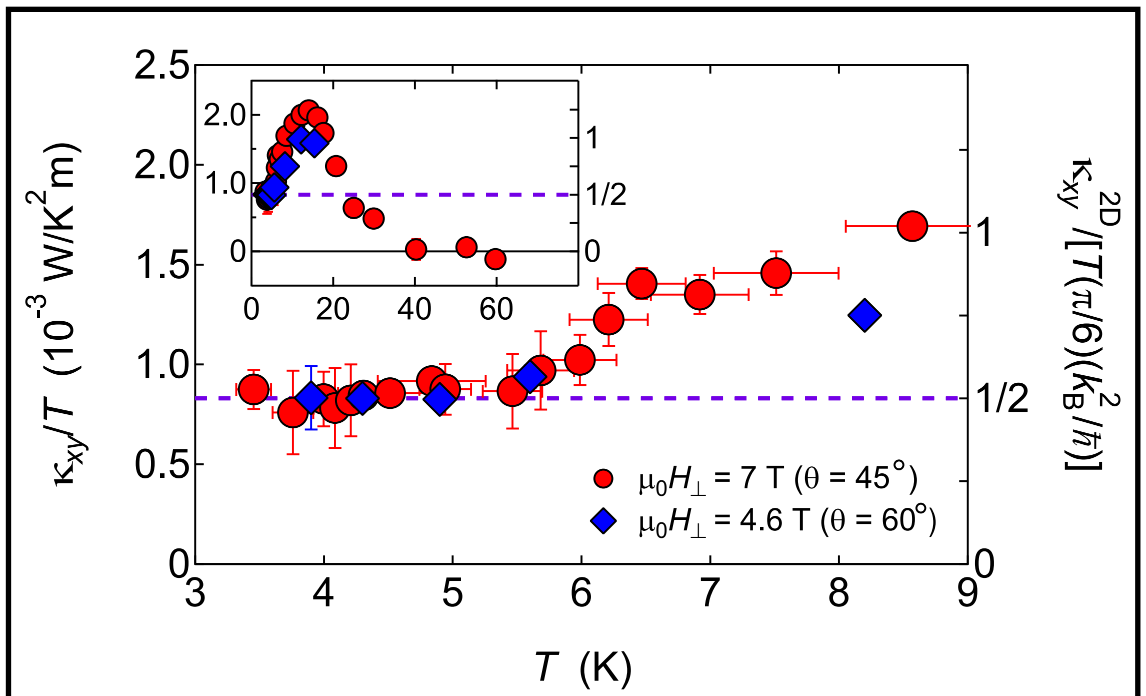
compare:

$$\sigma_{xy}^{QH} = \nu\,\frac{e^2}{h}$$

Kasahara,.. Y. Matsuda, Nature (2018)

Thermal Transport: alpha-RuCl3





$$\frac{\kappa_{xy}^{2D}}{T} = c\frac{\pi}{6}\frac{k_B^2}{\hbar}$$

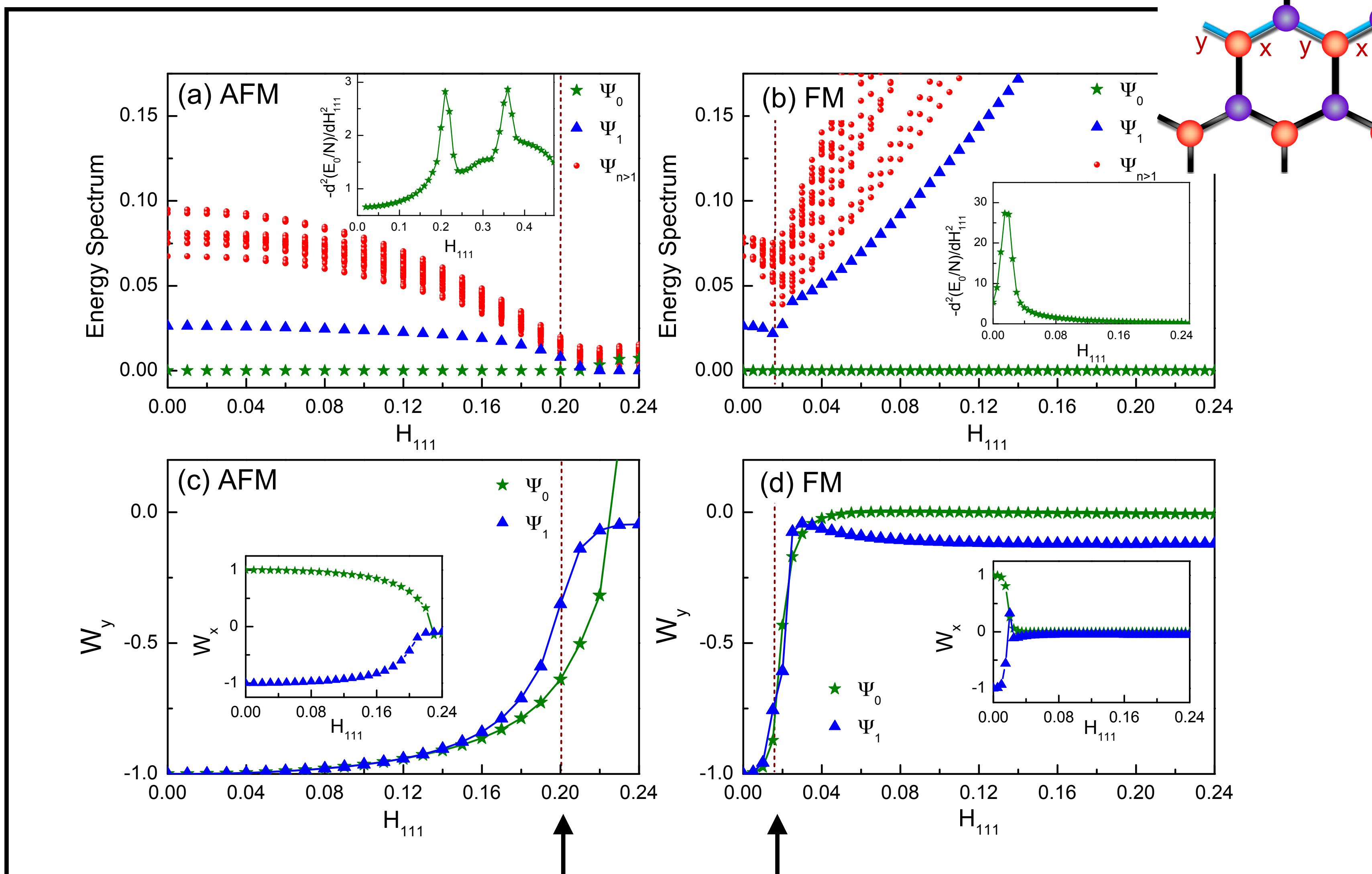
compare:

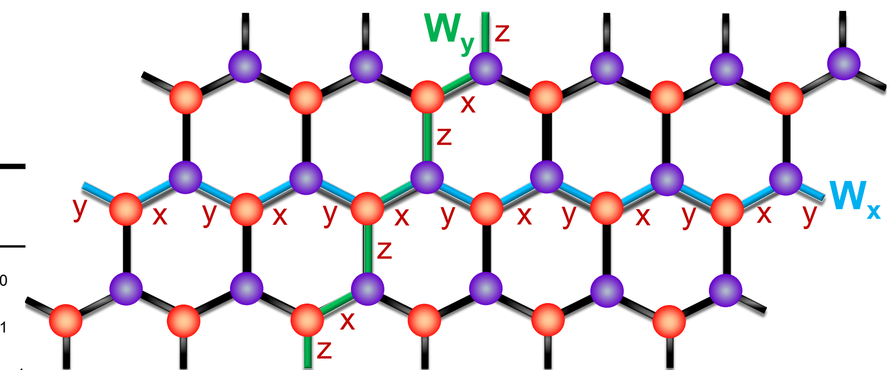
$$\sigma_{xy}^{QH} = \nu \frac{e^2}{h}$$

Real materials: not a pure K model!

Kasahara,..Y. Matsuda, Nature (2018)

Pure Kitaev model cannot explain intermediate-field state





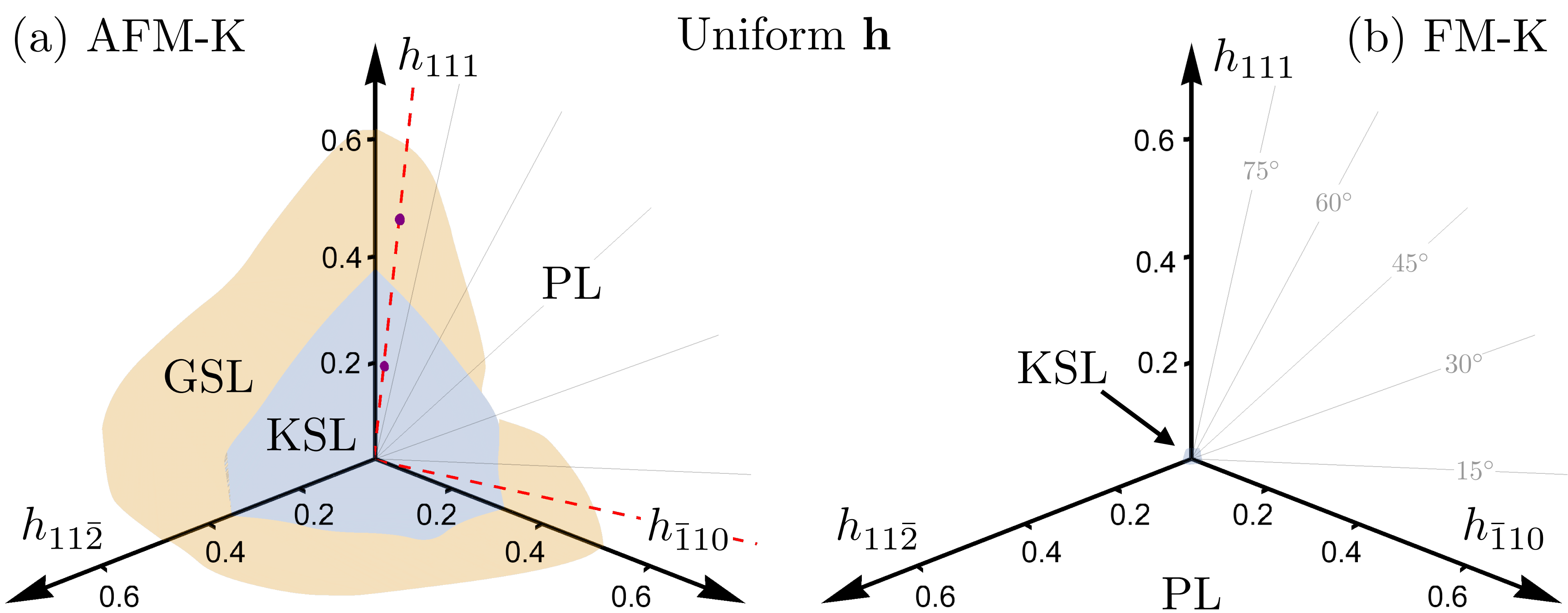
intermediate state?

Almost immediately unstable to polarized state

Z. Zhu, I. Kimchi, D. Sheng, L. Fu, PRB 97, 241110 (2018)

Field-driven U(1) spin liquid: transition from Kitaev to U(1) spin liquid near antiferromagnetic Kitaev region

C. Hickey, S. Trebst, Nat. Comm. 10, 530 (2019)



fascinating result, but cannot explain 1/2 quantized thermal Hall: the intermediate-field state in RuCl3

Recent magnetic field studies on RuCl3:

Ravi Yadav, et al Scientific Reports 6, 37925 (2016);
P. Lampen-Kelley et al, arXiv:1807.06192;
Zheng-Xin Liu and B. Normand, Phys. Rev. Lett. 120, 187201 (2018);
S.-H. Baek et al, Phys. Rev. Lett. 119, 037201 (2017);
U. B. Wolter et al, Phys. Rev. B 96, 041405 (2017);
Jiacheng Zheng et al, Phys. Rev. Lett. 119, 227208 (2017);
J. A. Sears et al, Phys. Rev. B 95, 180411(R) (2017);
R. Hentrich et al, Phys. Rev. Lett. 120, 117204 (2018);
A. N. Ponomaryov et al, Phys. Rev. B 96, 241107(R) (2017);
Y. Kasahara et al, Nature 559, 227–231 (2018);
Yuval Vinkler-Aviv and Achim Rosch, Phys. Rev. X 8, 031032 (2018);
Jonathan Cookmeyer and Joel E. Moore, Phys. Rev. B 98, 060412 (2018);
Hong-Chen Jiang et al, Phys. Rev. B 83, 245104 (2011);
Zheng Zhu et al, Phys. Rev. B 97, 241110 (2018);
Shuang Liang et al, Phys. Rev. B 98, 054433 (2018);
Matthias Gohlke et al, Phys. Rev. B 98, 014418 (2018);
Joji Nasu et al, Phys. Rev. B 98, 060416 (2018);
Nejc Jansa et al, Nat. Phys. 14, 786 (2018);
Ciar´an Hickey and Simon Trebst, Nat. Comm. (2019);
D. Ronquillo, A. Vengal, N. Trivedi, arXiv:1805.03722;
Hong-Chen Jiang et al, arXiv:1809.08247;
Liujun Zou and Yin-Chen He,, arXiv:1809.09091;
N. D. Patel and Nandini Trivedi, arXiv:1812.06105;
C. Balz et al, arXiv:1903.00056
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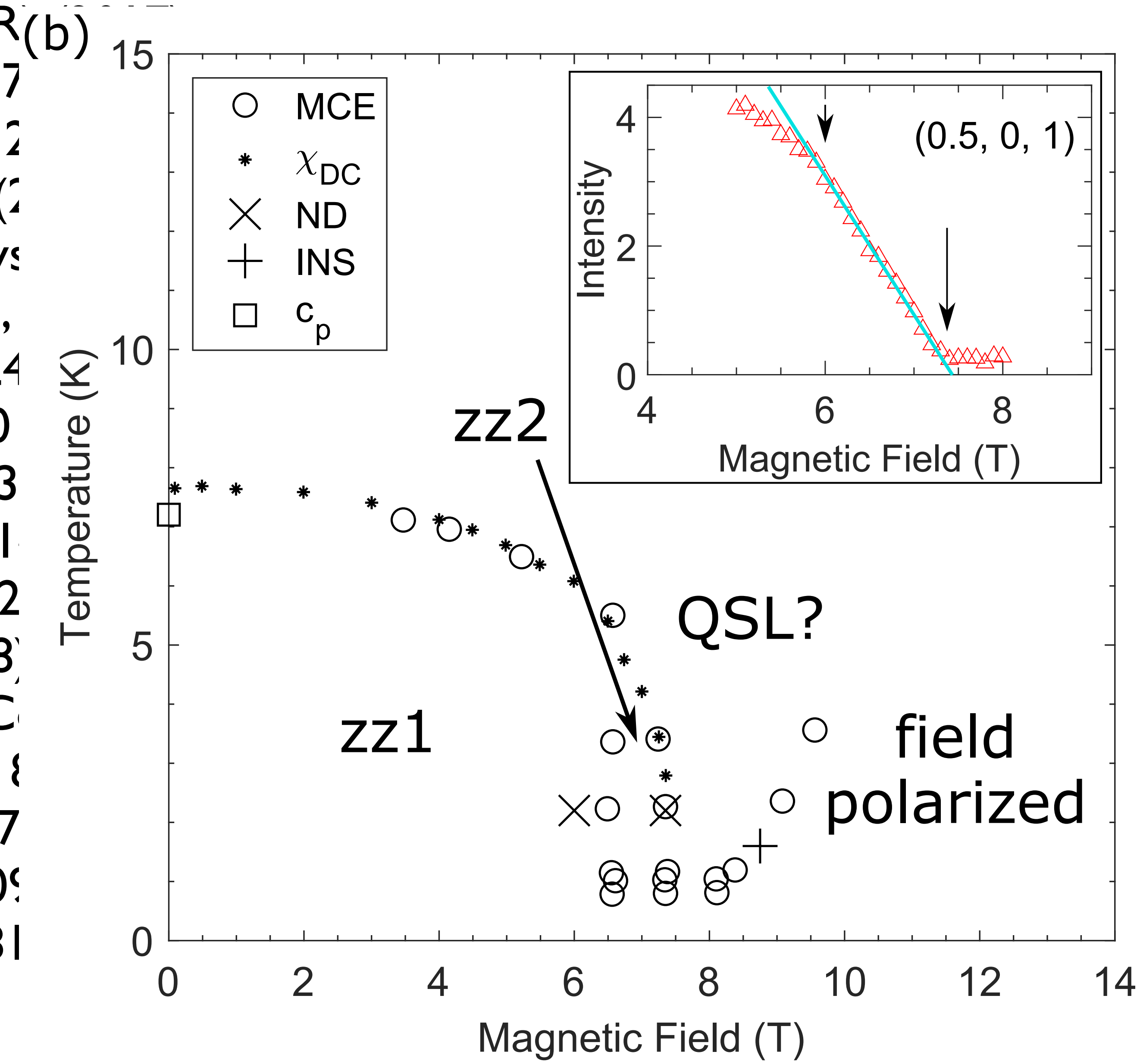
J. A. Sears et al, Phys. Rev. B 95, 180411(R
R. Hentrich et al, Phys. Rev. Lett. 120, 117
A. N. Ponomaryov et al, Phys. Rev. B 96, 2
Y. Kasahara et al, Nature 559, 227–231 (2
Yuval Vinkler-Aviv and Achim Rosch, Phys
Jonathan Cookmeyer and Joel E. Moore,
Hong-Chen Jiang et al, Phys. Rev. B 83, 24
Zheng Zhu et al, Phys. Rev. B 97, 241110
Shuang Liang et al, Phys. Rev. B 98, 05443
Matthias Gohlke et al, Phys. Rev. B 98, 01
Joji Nasu et al, Phys. Rev. B 98, 060416 (2
Nejc Jansa et al, Nat. Phys. 14, 786 (2018)
Ciar´an Hickey and Simon Trebst, Nat. C
D. Ronquillo, A. Vengal, N. Trivedi, arXiv:18
Hong-Chen Jiang et al, arXiv:1809.08247
Liujun Zou and Yin-Chen He,, arXiv:1809
N. D. Patel and Nandini Trivedi, arXiv:181
C. Balz et al, arXiv:1903.00056
……………..



List of proposed parameter sets

L.Janssen, E. Andrade, M. Vojta, PRB (2017)

Set	Material	J_1 [meV]	K_1 [meV]	Γ_1 [meV]	J_2 [meV]	K_2 [meV]	J_3 [meV]	Method	Ref.	Year
1	✔ α-$RuCl_3$	-4.6	$+7.0$	—	—	—	—	fit to neutron scattering	34, 35	2016
1'	Na_2IrO_3	-4.0	$+10.5$	—	—	—	—	fit to susceptibility & neutron scattering	29	2013
1+Γ	✔ α-$RuCl_3$	-12	$+17$	$+12$	—	—	—	DFT + t/U expansion	41	2015
2	Na_2IrO_3	0	-17	0	0	—	$+6.8$	DFT + exact diagonalization	31	2016
2+Γ	Na_2IrO_3	$+3$	-17	$+1$	-3	$+6$	$+1$	DFT + t/U expansion, direction of moments	39, 42	2016
(2+Γ)'	Na_2IrO_3	$+3$	-17.5	-1	$+5$	—	$+5$	MRCI, fit to θ_{CW}	44	2014
(2+Γ)"	α-$RuCl_3$	$+1.2$	-5.6	-1	$+0.3$	—	$+0.3$	MRCI, fit to magnetization	13	2016
2/3	α-$RuCl_3$	-1.7	-6.6	$+6.6$	0	—	$+2.7$	DFT + exact diagonalization	31	2016
3	α-$RuCl_3$	—	-6.8	$+9.5$	—	—	—	fit to neutron scattering	32	2017
3'	α-$RuCl_3$	—	-5.5	$+7.6$	—	—	—	DFT + t/U expansion	33	2016
3"	α-$RuCl_3$	-1	-8	$+4$	—	—	—	DFT + t/U expansion	✔ 37	2016
3+J_3	α-$RuCl_3$	-0.5	-5.0	$+2.5$	—	—	$+0.5$	fit to neutron scattering	38	2017

FM Kitaev and AFM Γ : starting point

Dominant interactions: -K + Γ
other small interactions : magnetic ordering

↓

Dominant interactions: -K + Γ
other small interactions : magnetic ordering

↓

magnetic field: kills the magnetic ordering
& reveal "the phase" set by
FM K + AFM Γ

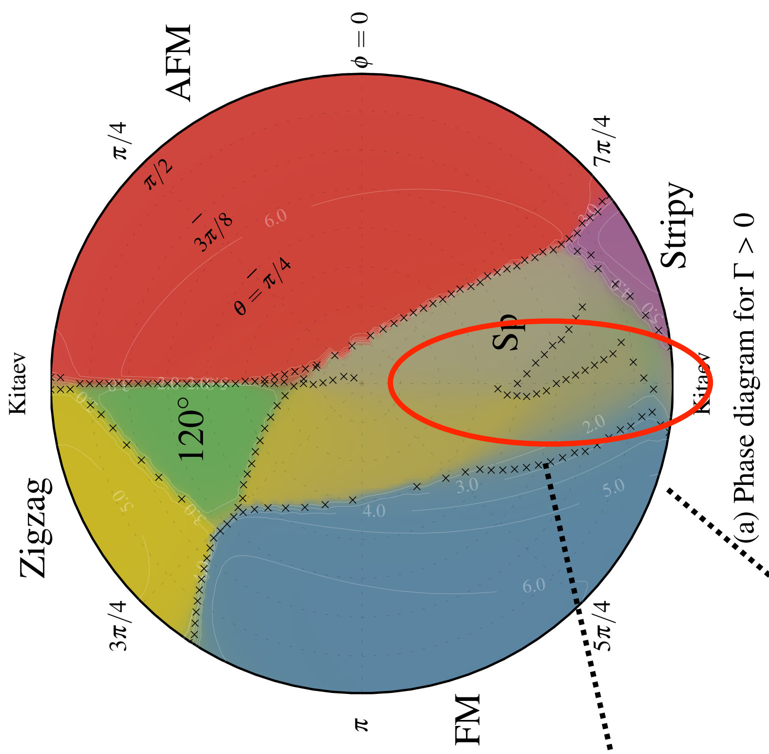
Does FM Kitaev + AFM Γ model support spin liquid?

J. Gordon, A. Catuneanu, E. Sorensen, HYK, arXiv:1901.09943,

Field-revealed Kitaev spin liquid

J. Gordon, A. Catuneanu, E. Sorensen, HYK, arXiv:1901.09943

Nearest neighbour spin model

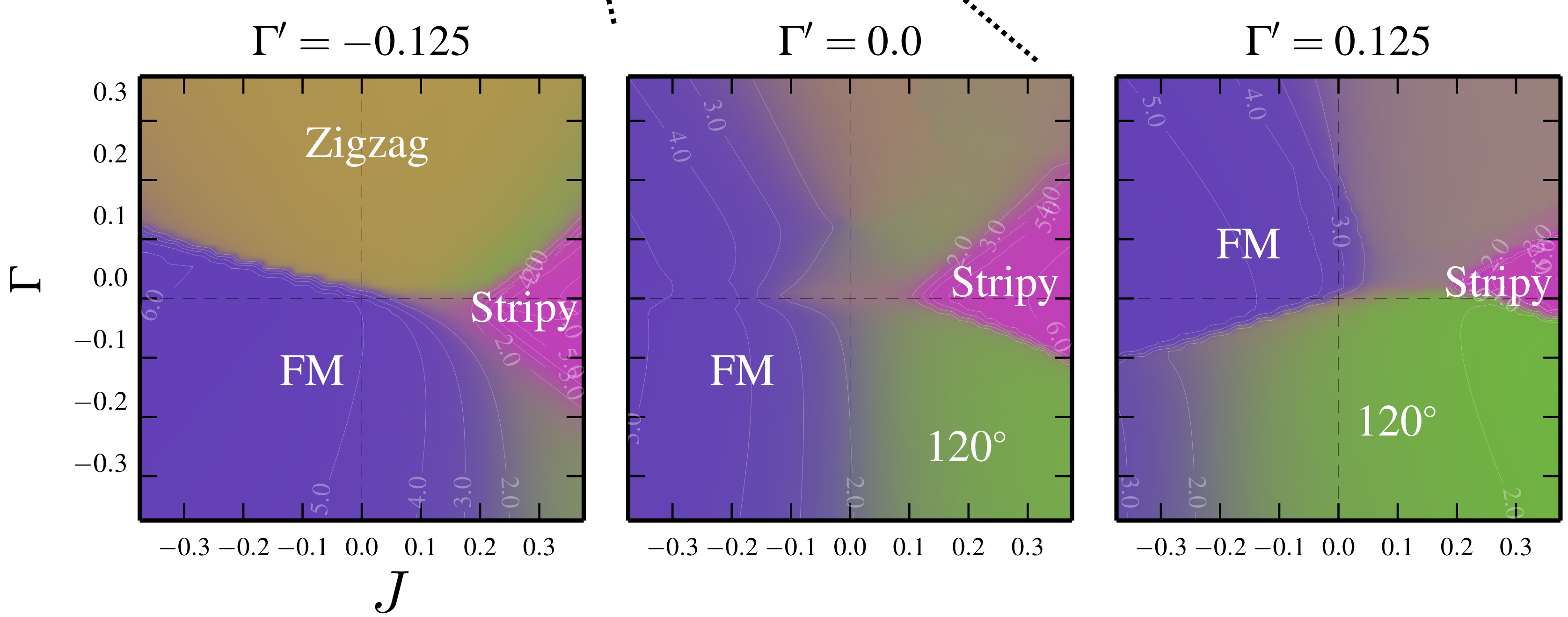


-K

trigonal distortion

$$\mathcal{H}_{jk}^{\gamma} = J\boldsymbol{S}_j \cdot \boldsymbol{S}_k + K S_j^{\gamma} S_k^{\gamma} + \Gamma(S_j^{\alpha} S_k^{\beta} + S_j^{\beta} S_k^{\alpha})$$

$$+\Gamma'(S_j^{\alpha} S_k^{\gamma} + S_j^{\gamma} S_k^{\alpha} + S_j^{\beta} S_k^{\gamma} + S_j^{\gamma} S_k^{\beta})$$

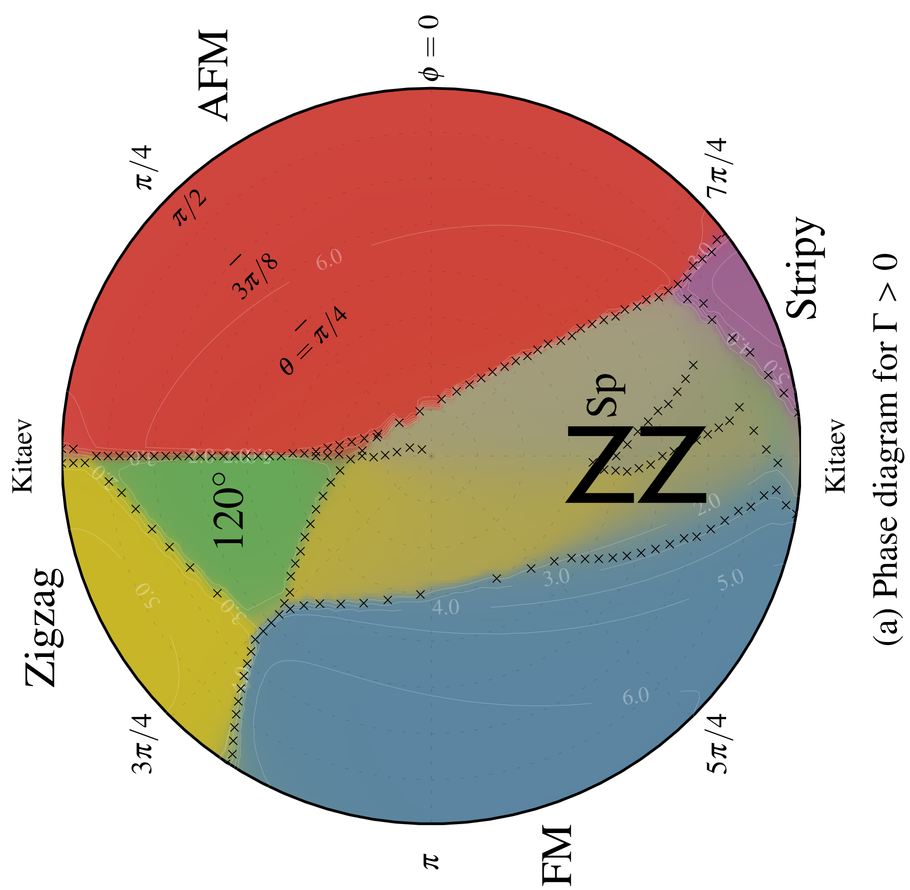


effects of Γ'

J. Rau, HYK, arXiv:1408.4811

Field-revealed Kitaev spin liquid near ferromagnetic Kitaev (-K) region

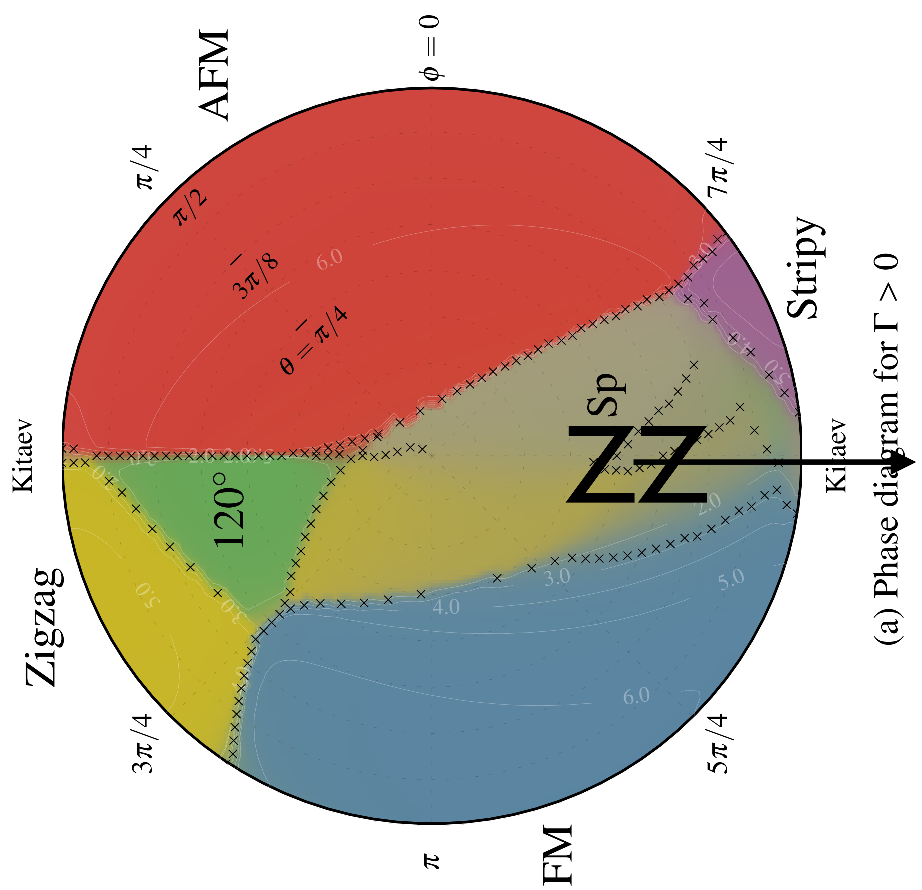
24 site ED



Γ' induces ZZ

Field-revealed Kitaev spin liquid near ferromagnetic Kitaev (-K) region

24 site ED



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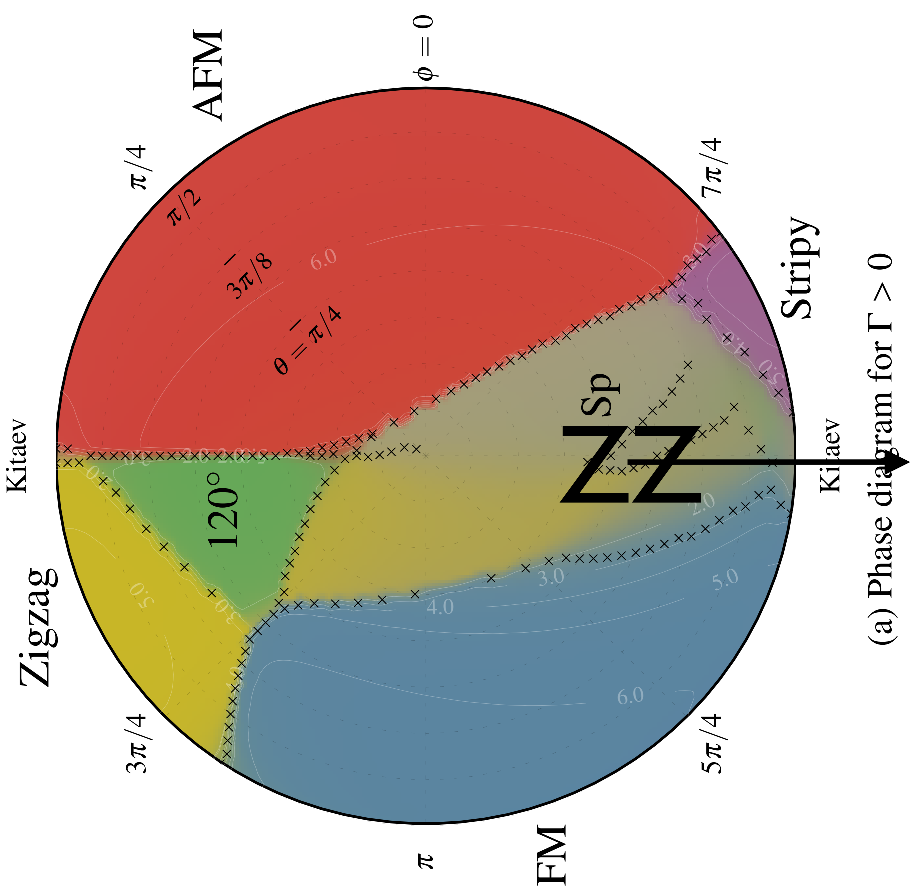
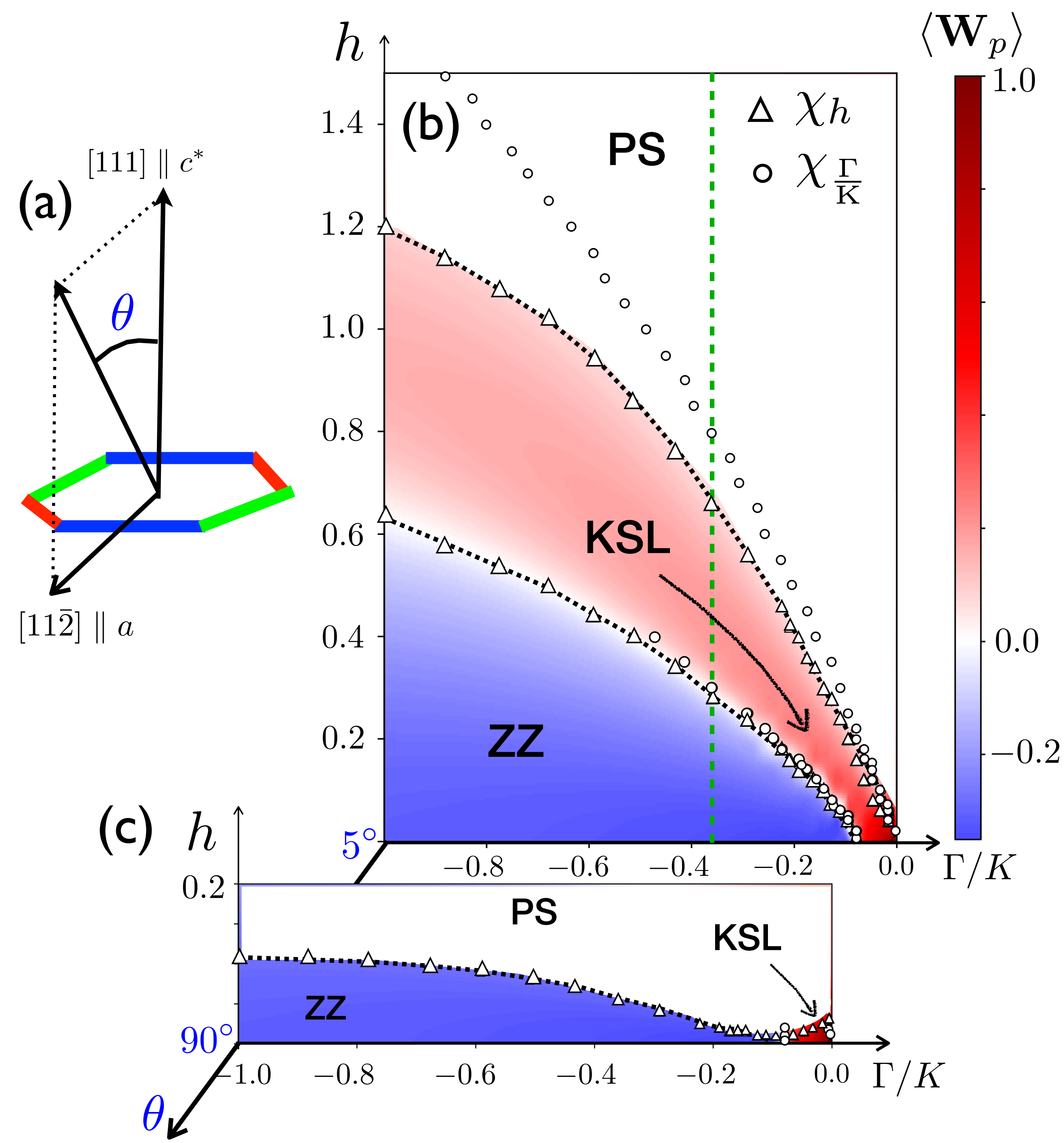


Γ' induces ZZ

Plaquette op. $\langle W_p \rangle = \langle \sigma_x \sigma_y \sigma_z \sigma_x \sigma_y \sigma_z \rangle$



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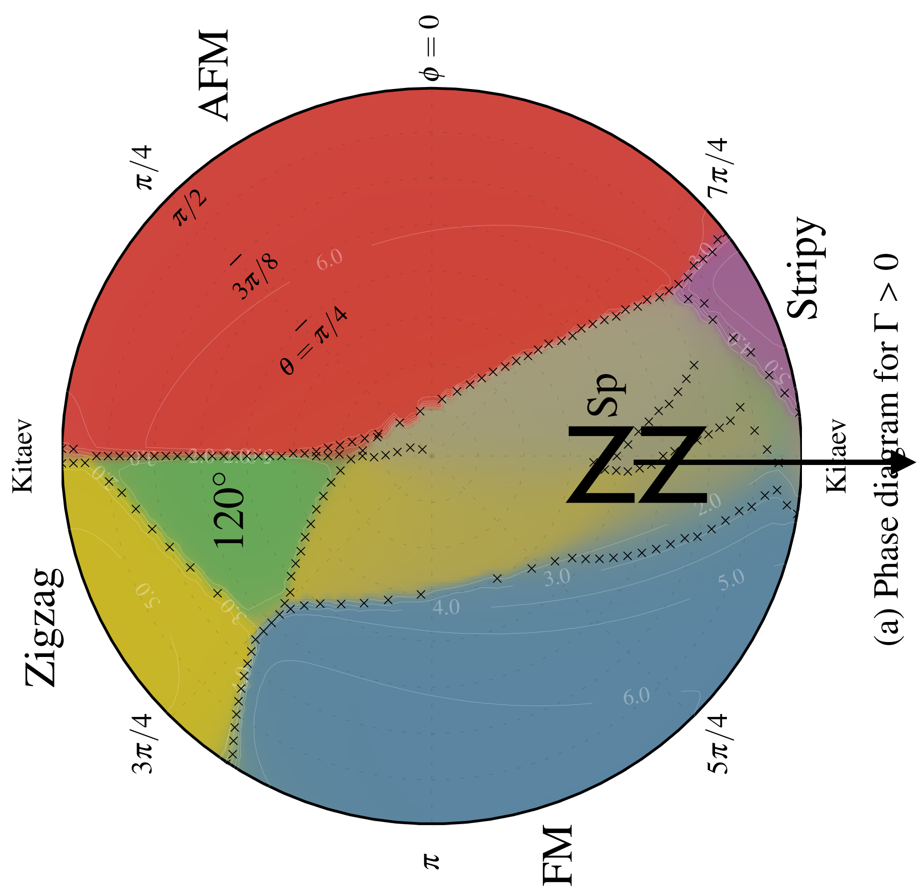
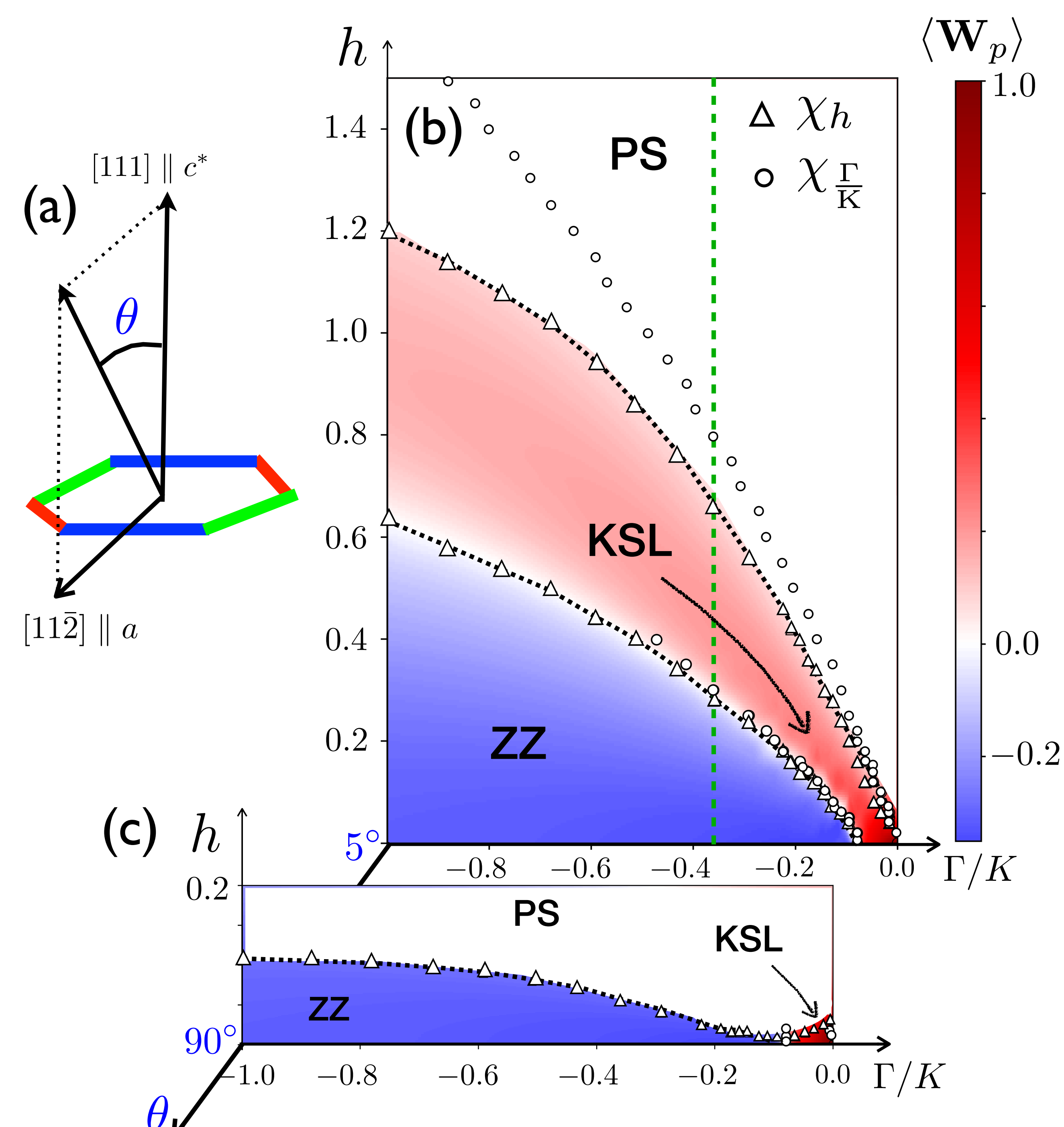


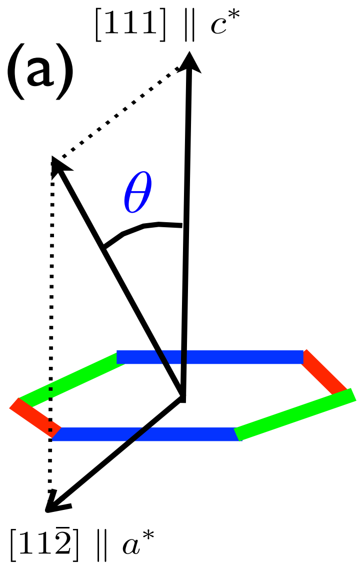
Γ' induces ZZ

Intermediate-field KSL is found when Γ is finite

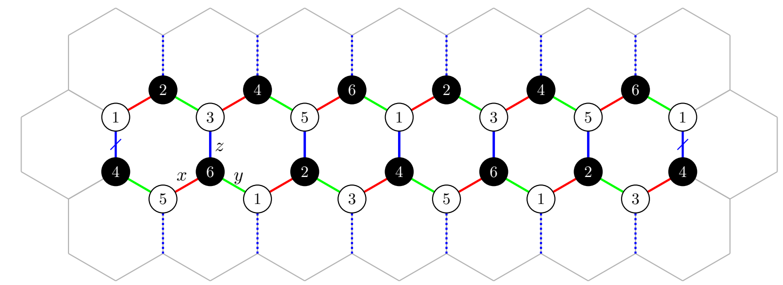
Plaquette op. $\langle W_p \rangle = \langle \sigma_x \sigma_y \sigma_z \sigma_x \sigma_y \sigma_z \rangle$

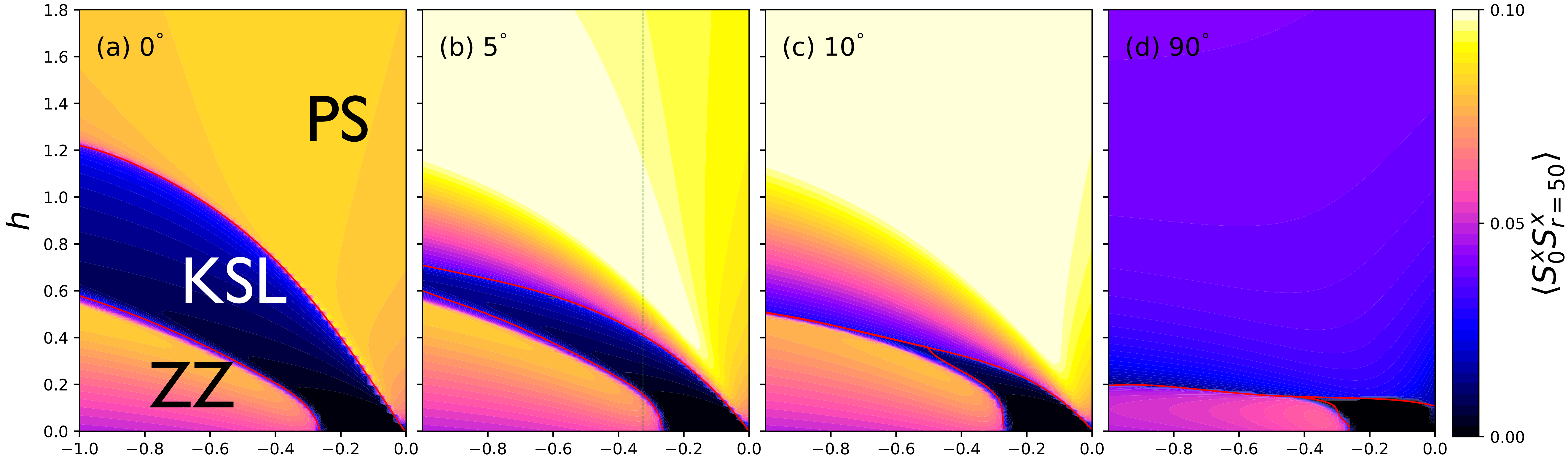


DMRG results on stripy geometry



Set J=0 & Γ'= -0.1

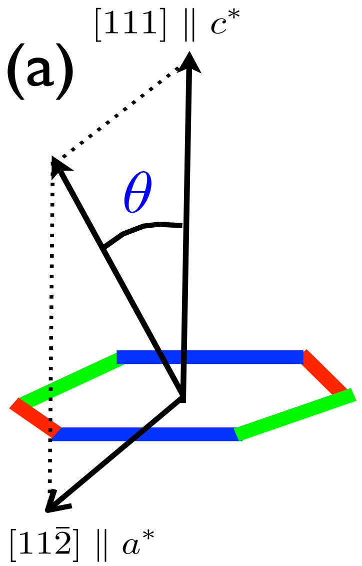




Strong field-angle dependence

★ strong spin fluctuations in PS in high field regime

DMRG results on stripy geometry



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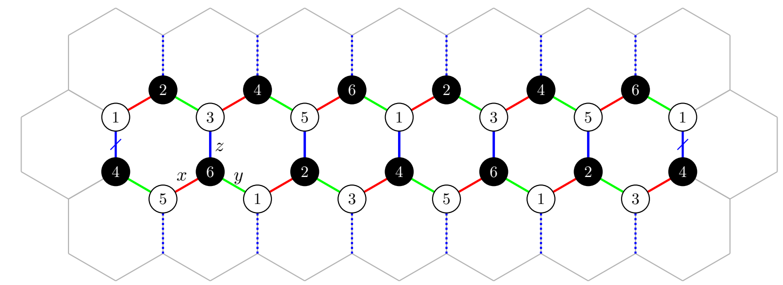

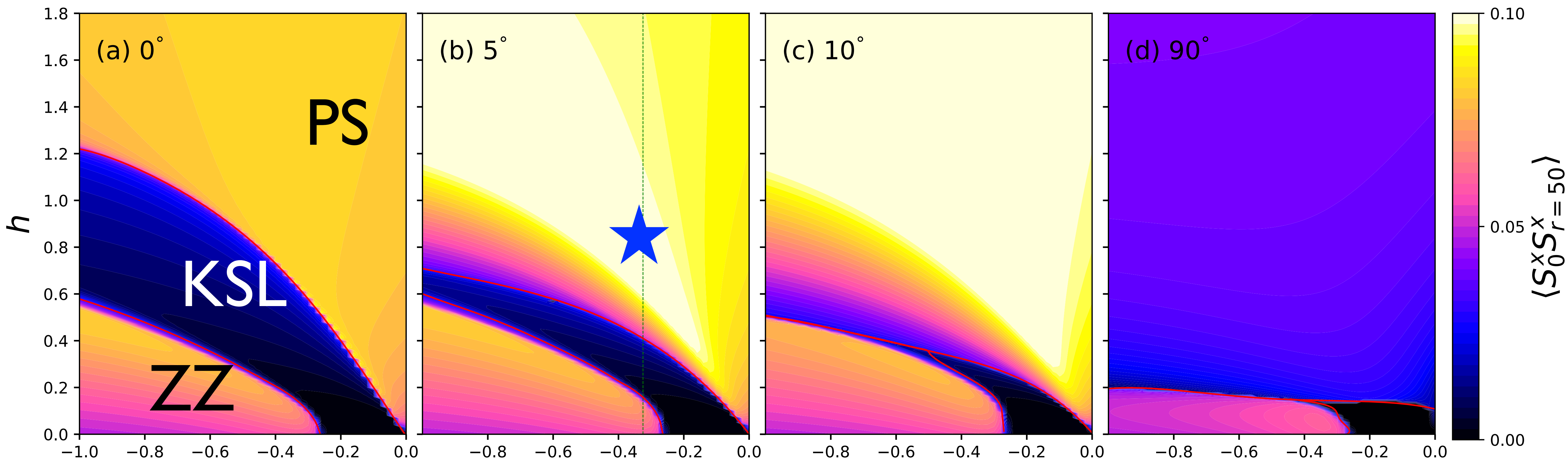

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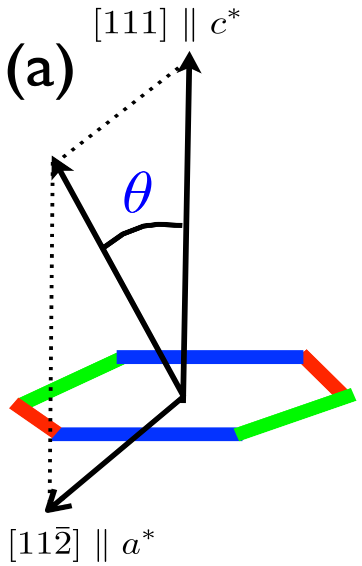

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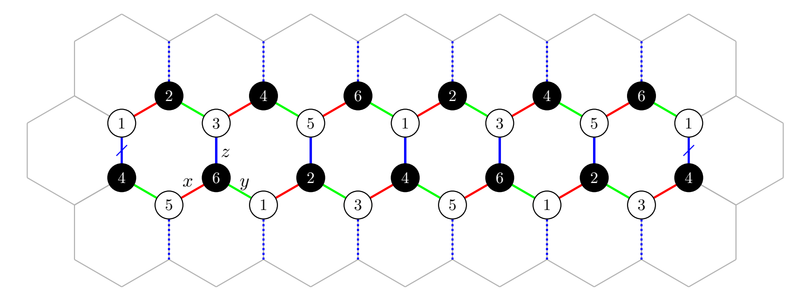
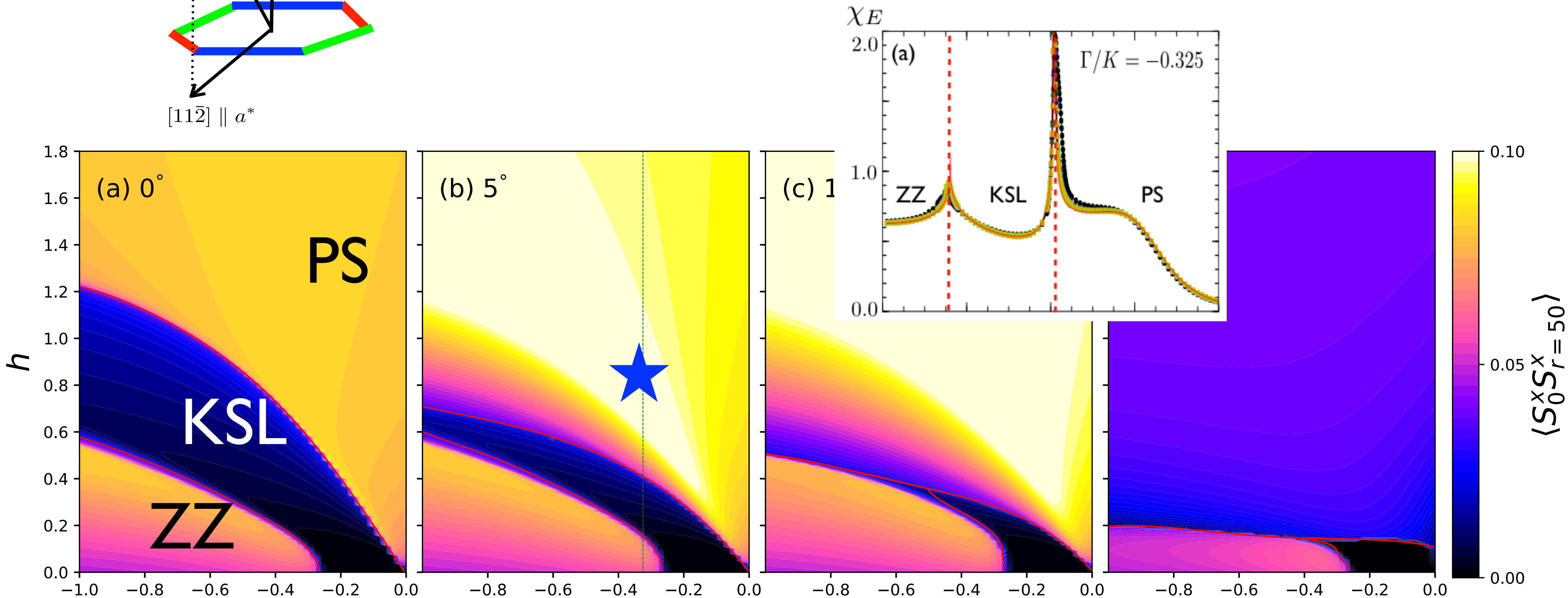


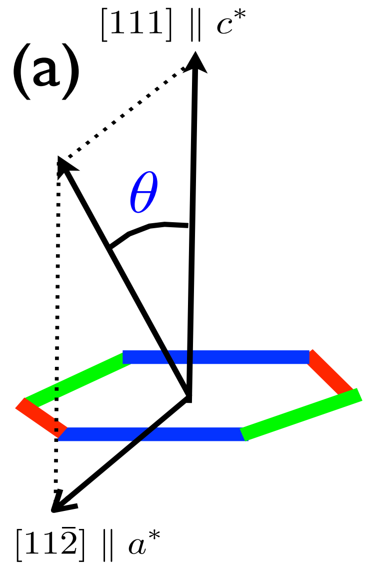


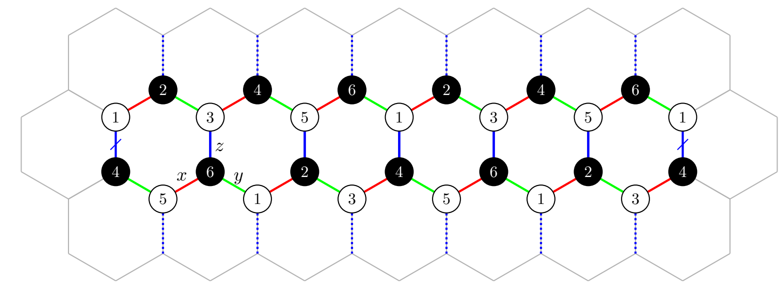
Strong field-angle dependence

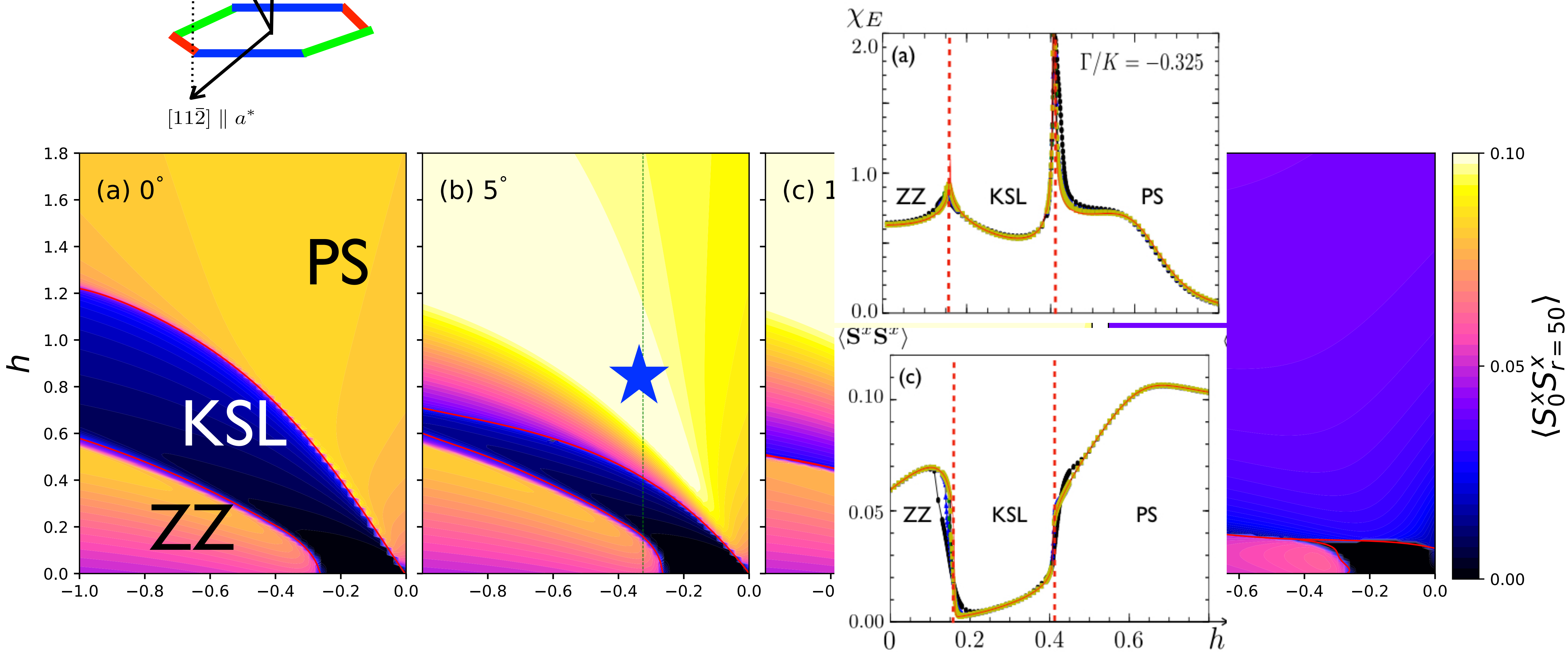
★ strong spin fluctuations in PS in high field regime

DMRG results on stripy geometry

Set J=0 & Γ' = -0.1







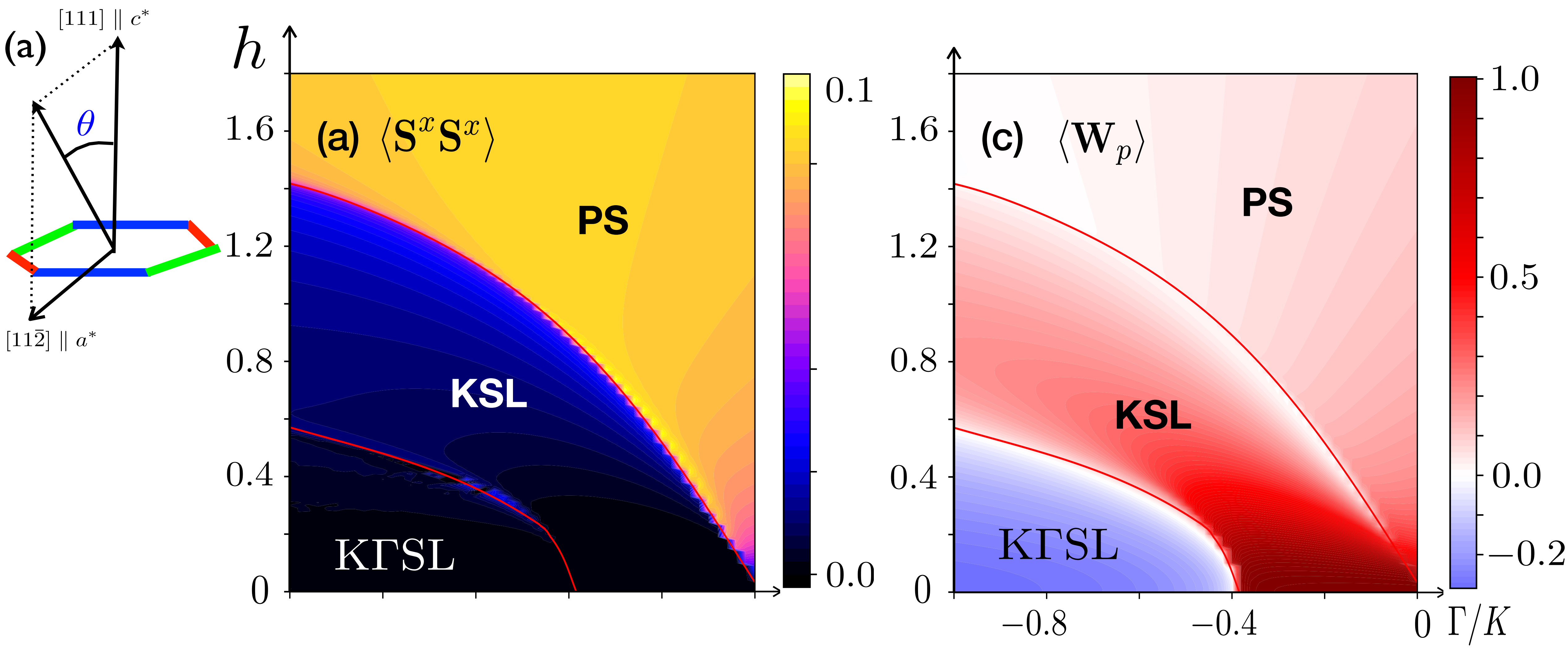
Strong field-angle dependence

★ strong spin fluctuations in PS in high field regime

What is the phase without ZZ ordering?

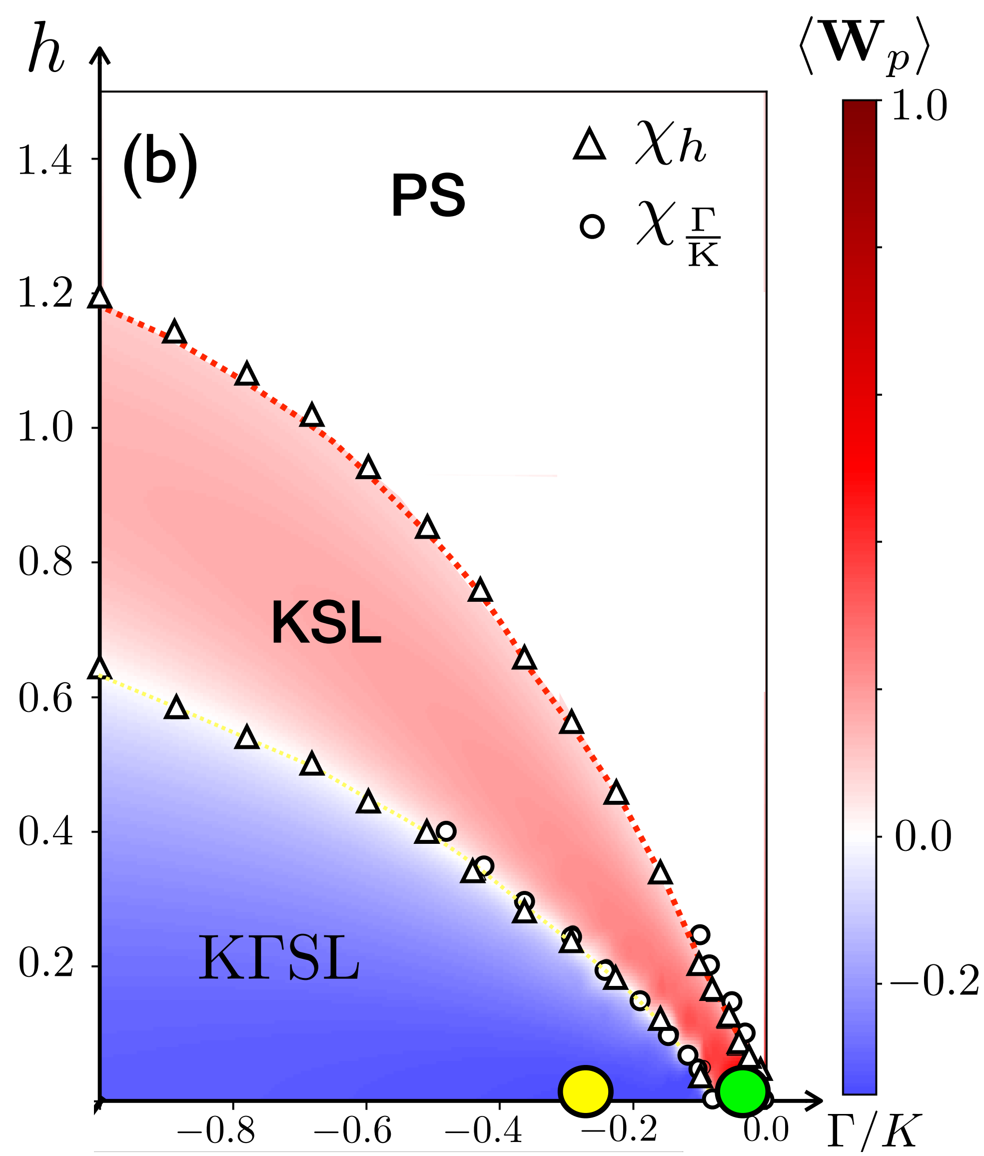
DMRG results on stripy geometry

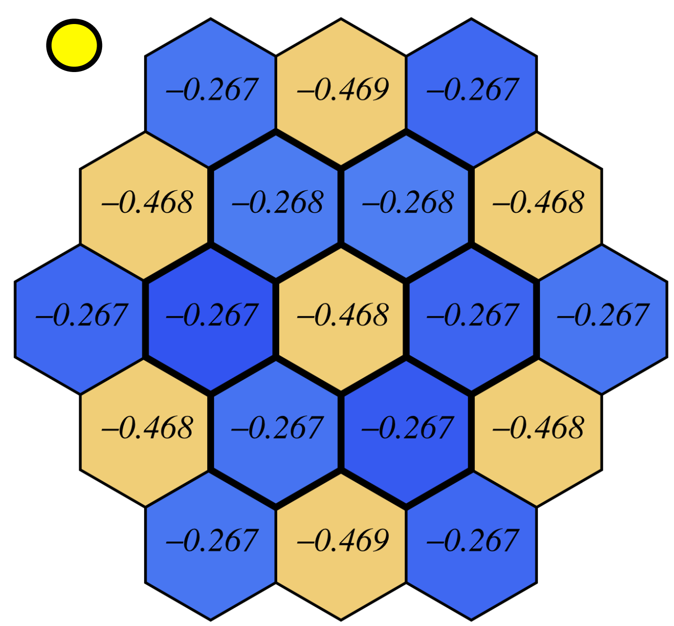
Set J=0 & θ =0 & Γ' =0

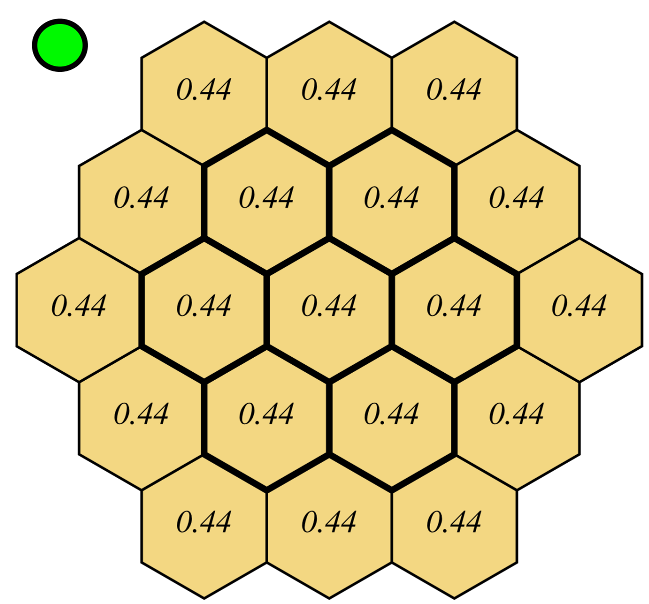


What is KGSL ? back to 24-site ED

Two spin liquids (unpublished)







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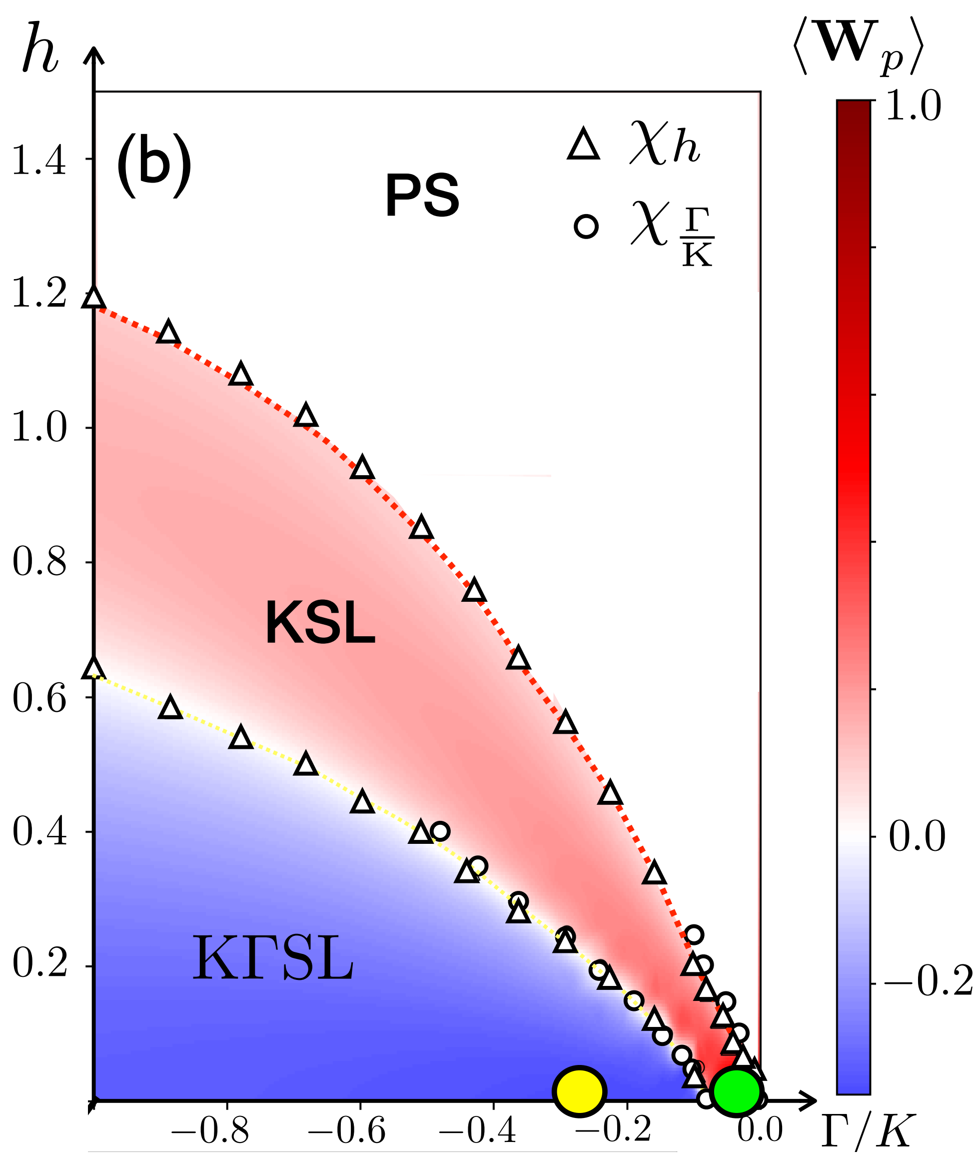
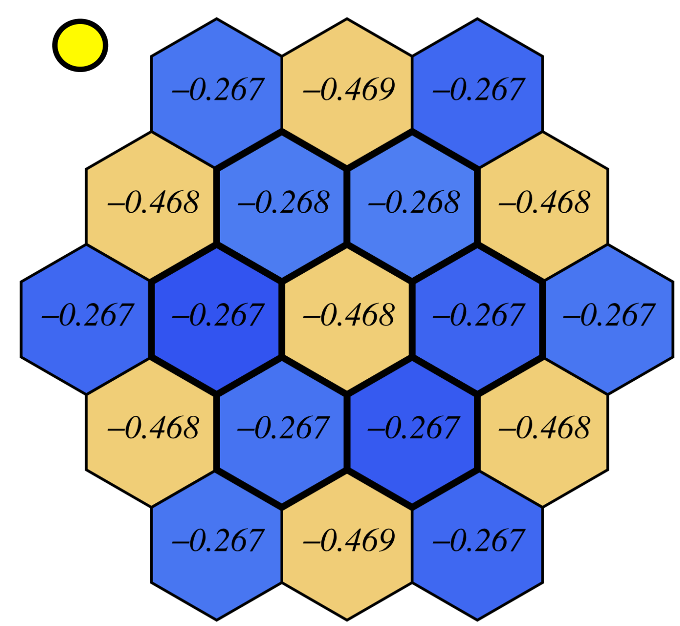
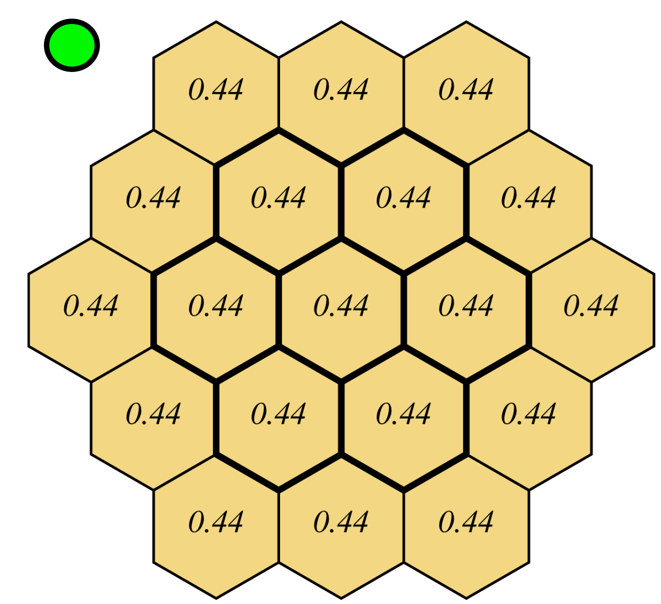
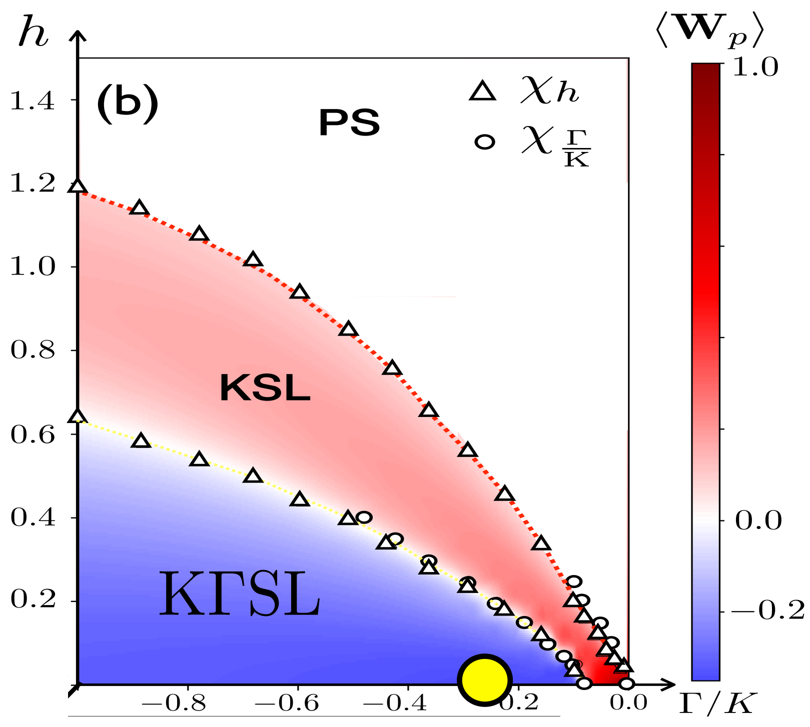


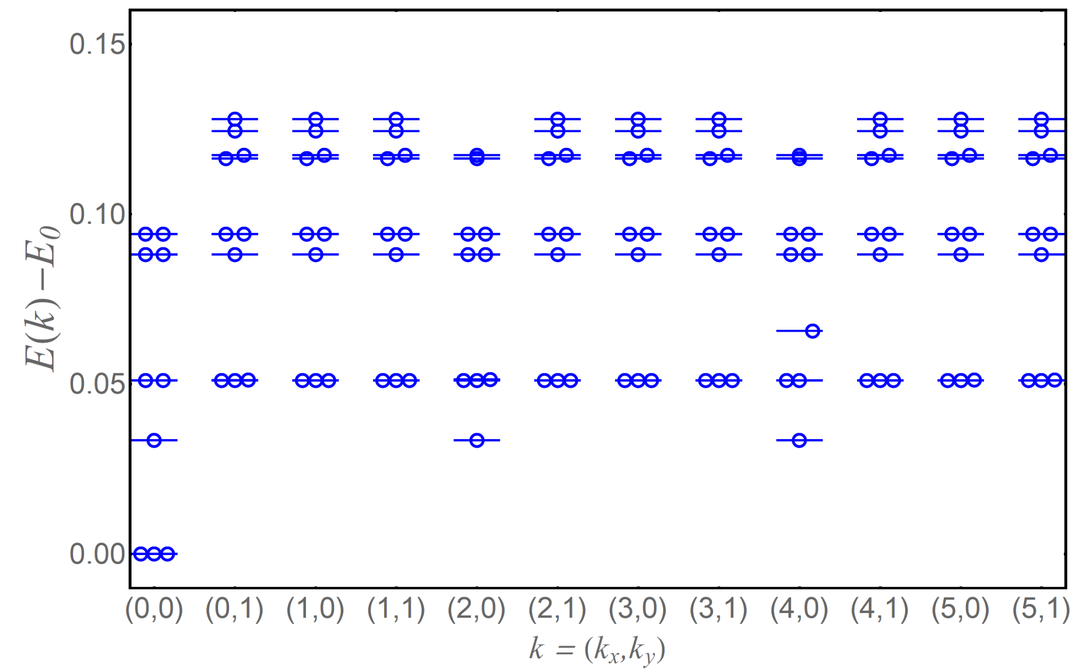


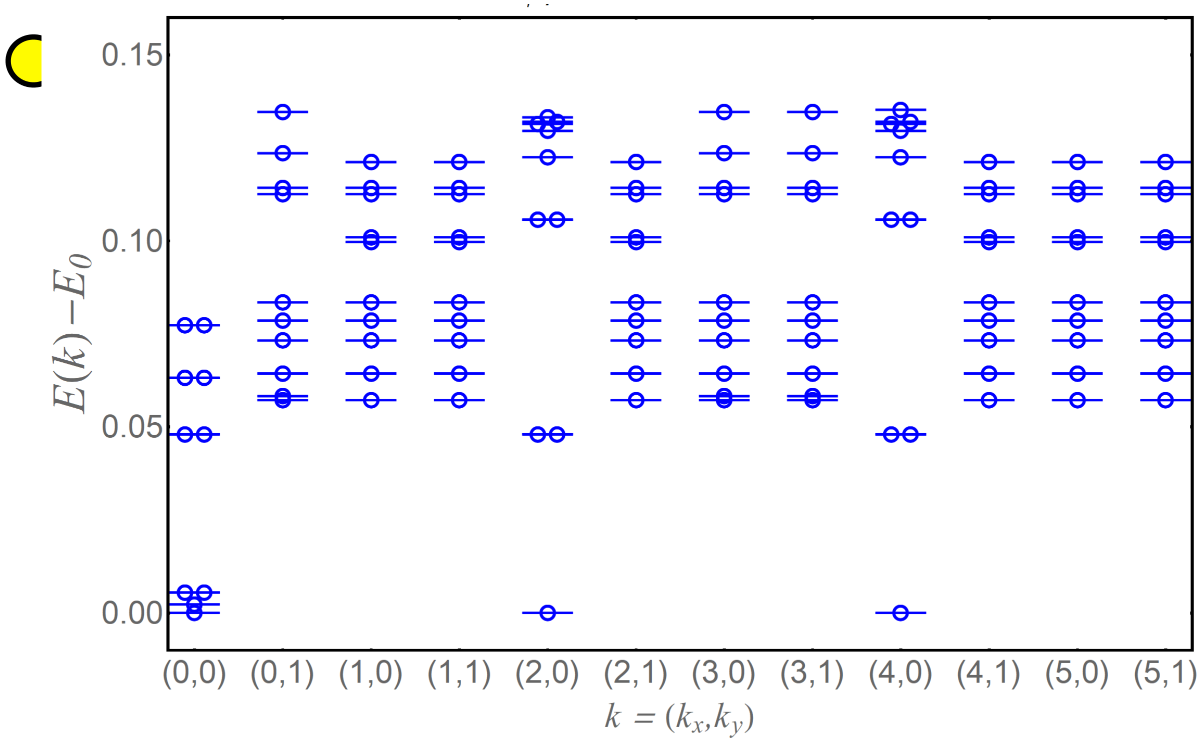


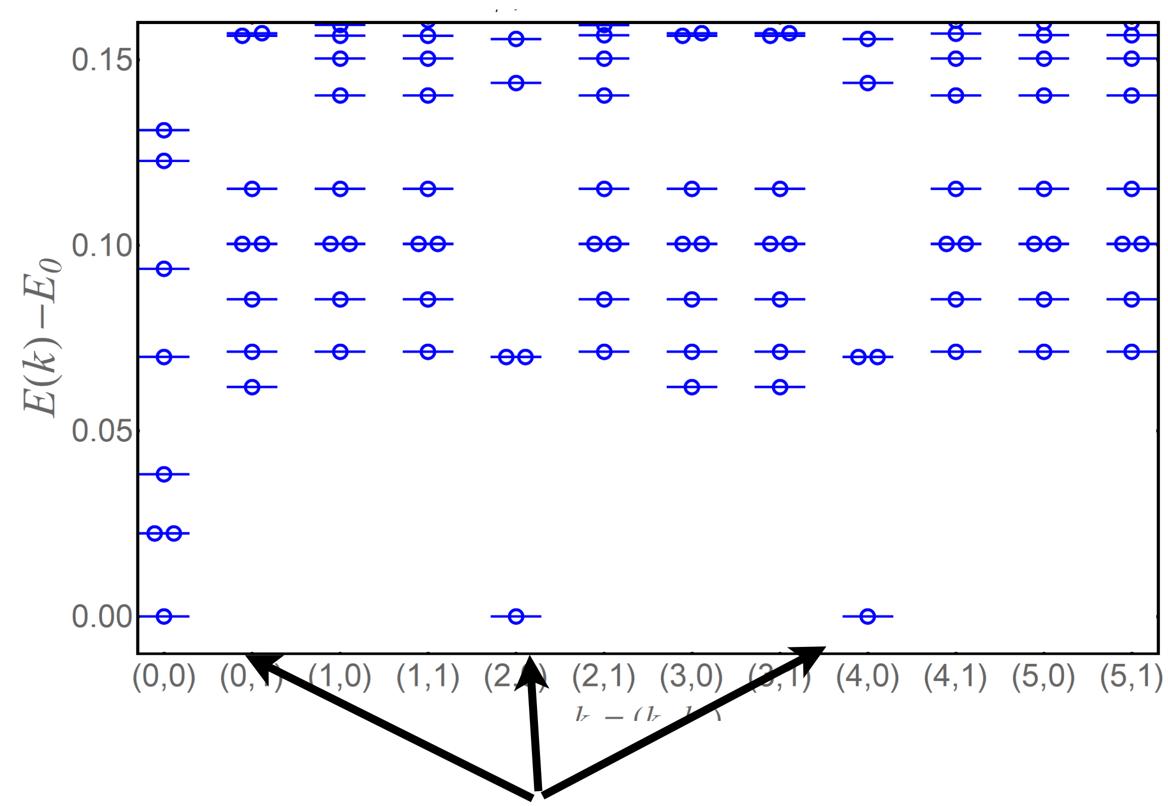
vison crystal spin liquid?

translation symmetry broken: vison crystal spin liquid









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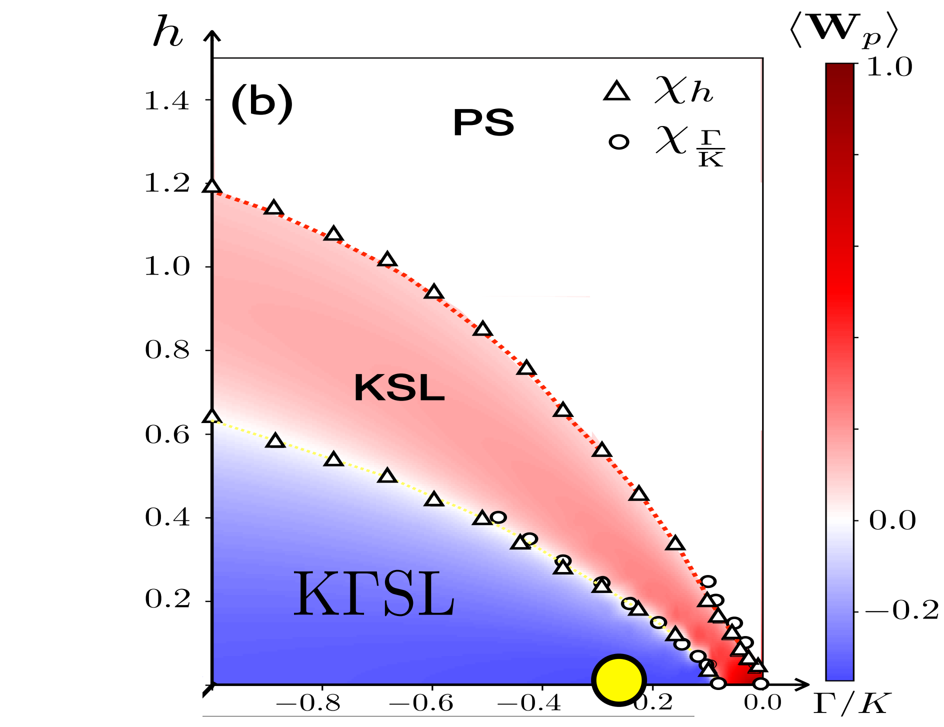

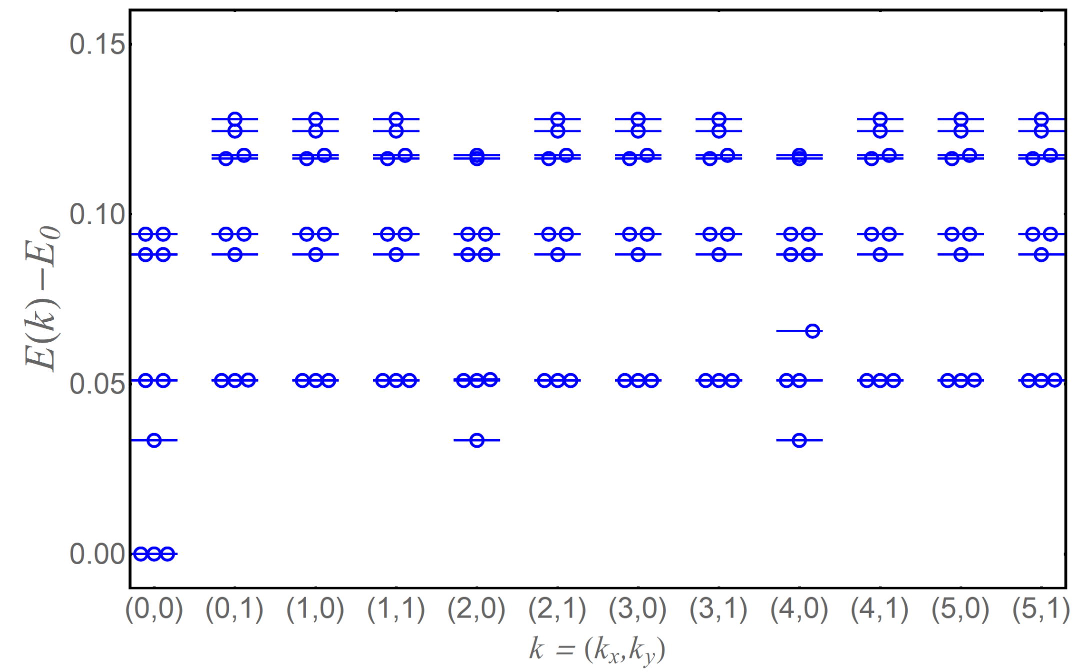

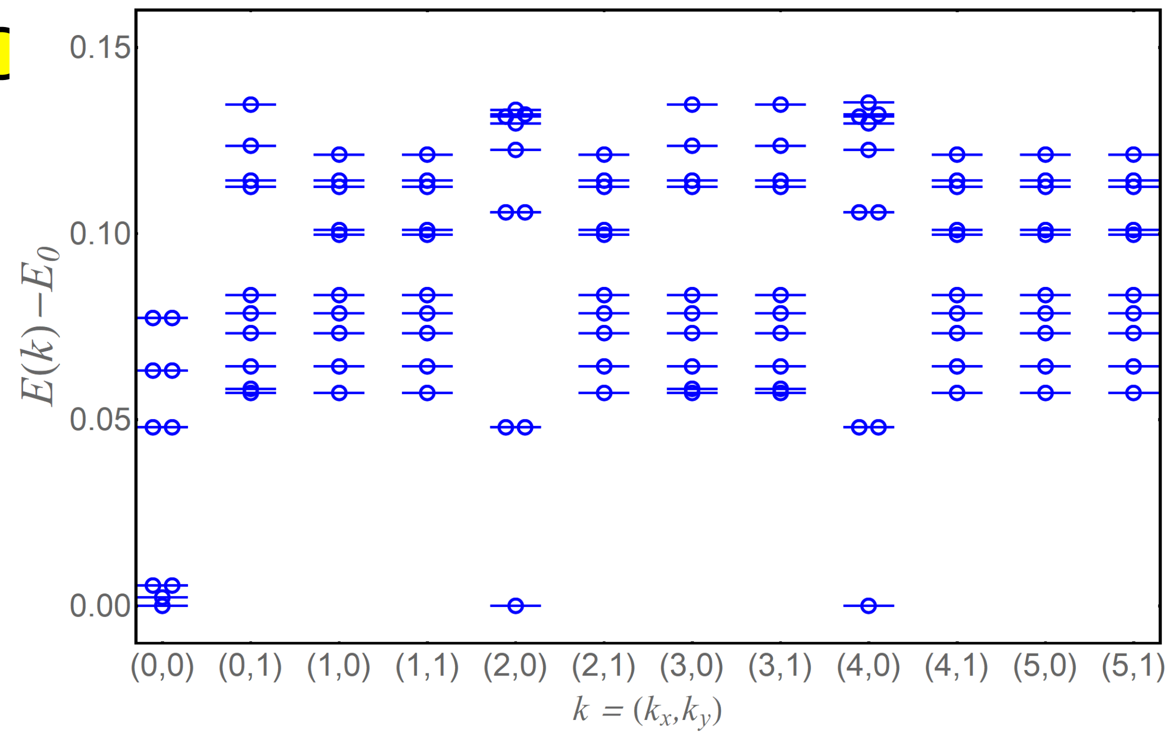

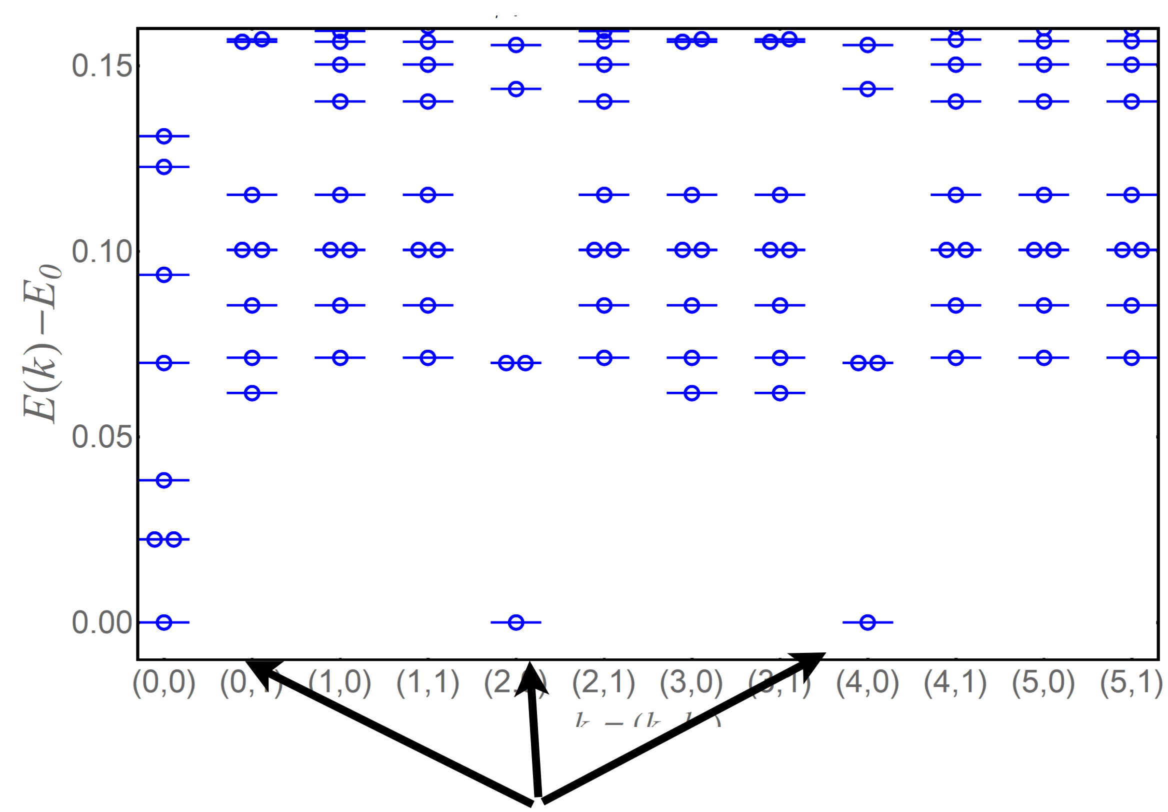

small anisotropy lifts the degeneracy: does not appear in leg-geometry either:Further studies are required

Specific predictions for RuCl3

Sign change of thermal Hall:
in-plane field direction changes

Wide range of KSL in the field perp. to the honeycomb plane

RuCl3: near Spin Liquid

Majorana fermions & Z2 are coupled via Γ interaction,
but the phase is adiabatically connected to pure Kitaev under the field

Outlook

Kitaev materials: SOC + honeycomb Mott insulator

—- higher-spin Kitaev materials: arXiv:1903.00011

doping: topological superconductor

strain induced phase transitions

Thank you Sudip and Nancy for
your inspiration, guidance, and friendship!