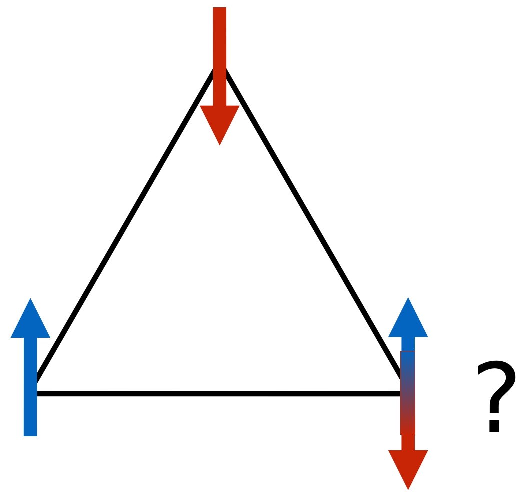
Frustrated magnetism and quantum computing

P.A. Maksimov

JINR, Dubna

DSPIN-23

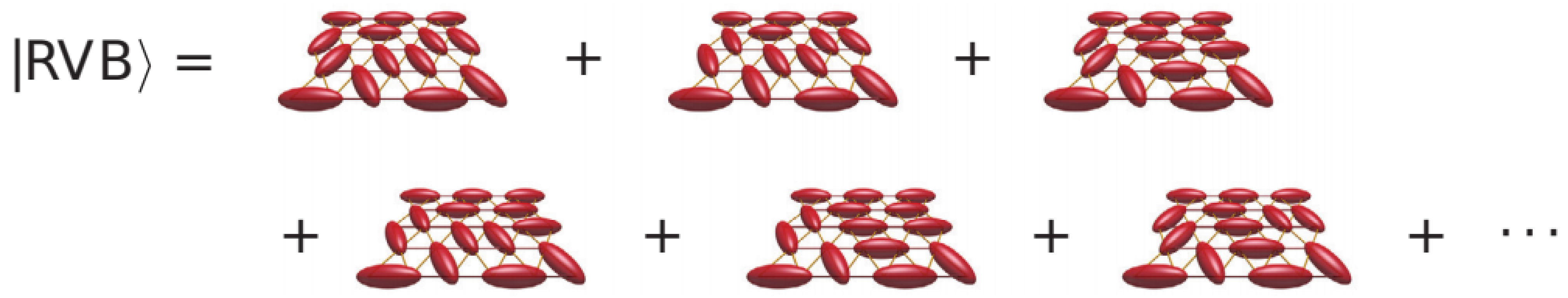
Frustrated magnets



G. H. Wannier, Physical Review 79, 357 (1950)

Classical degeneracy → Finite entropy at T=0

Resonating valence bond (RVB)



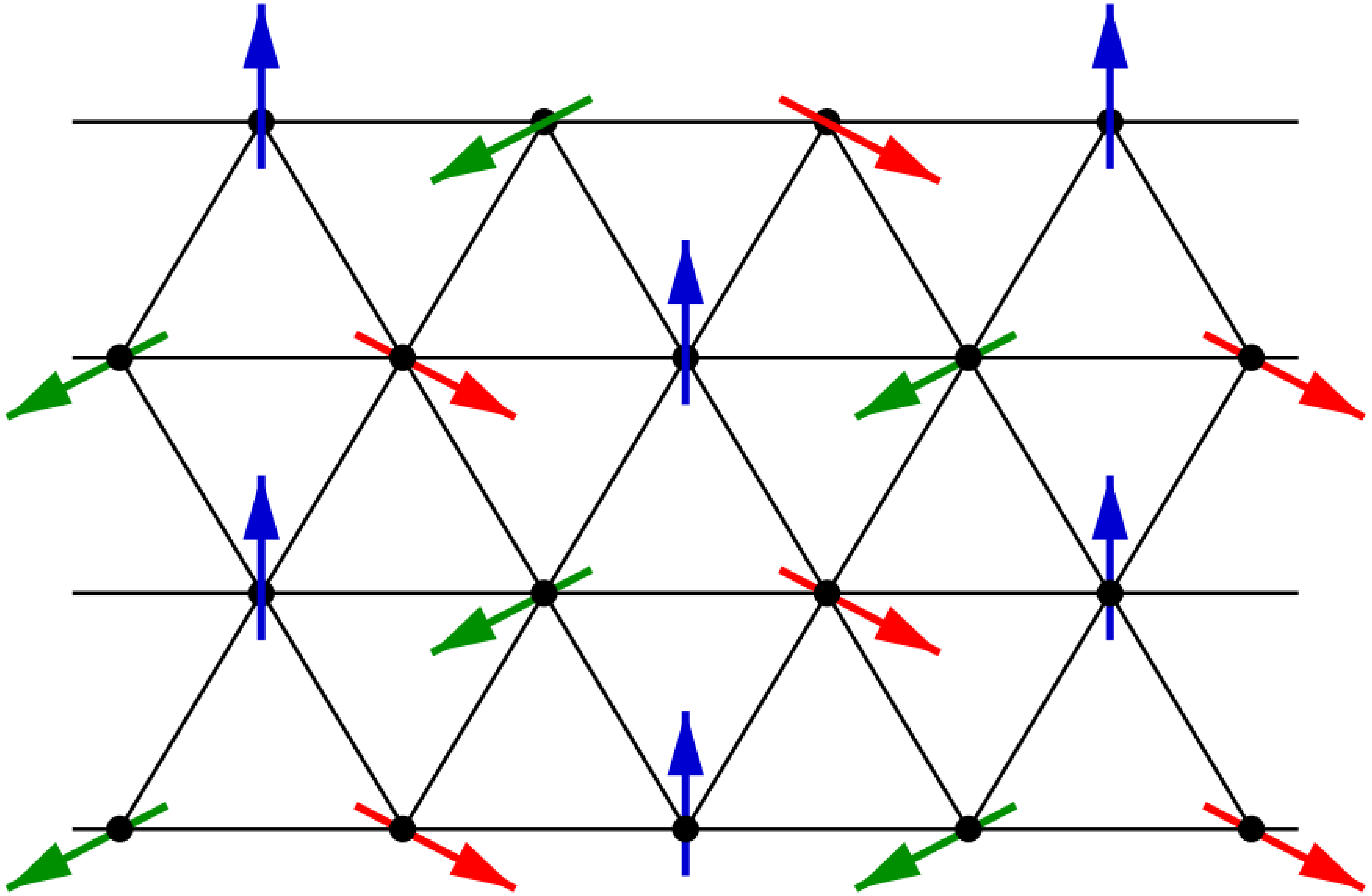
P. W. Anderson, Materials Research Bulletin 8, 153 (1973)

P. Fazekas and P. W. Anderson, Philosophical Magazine 30, 423 (1974)

Spin liquids: fractionalized excitations, topologocal properties

L. Savary and L. Balents, Reports on Progress in Physics 80, 016502 (2017)

Suppressed long-range order

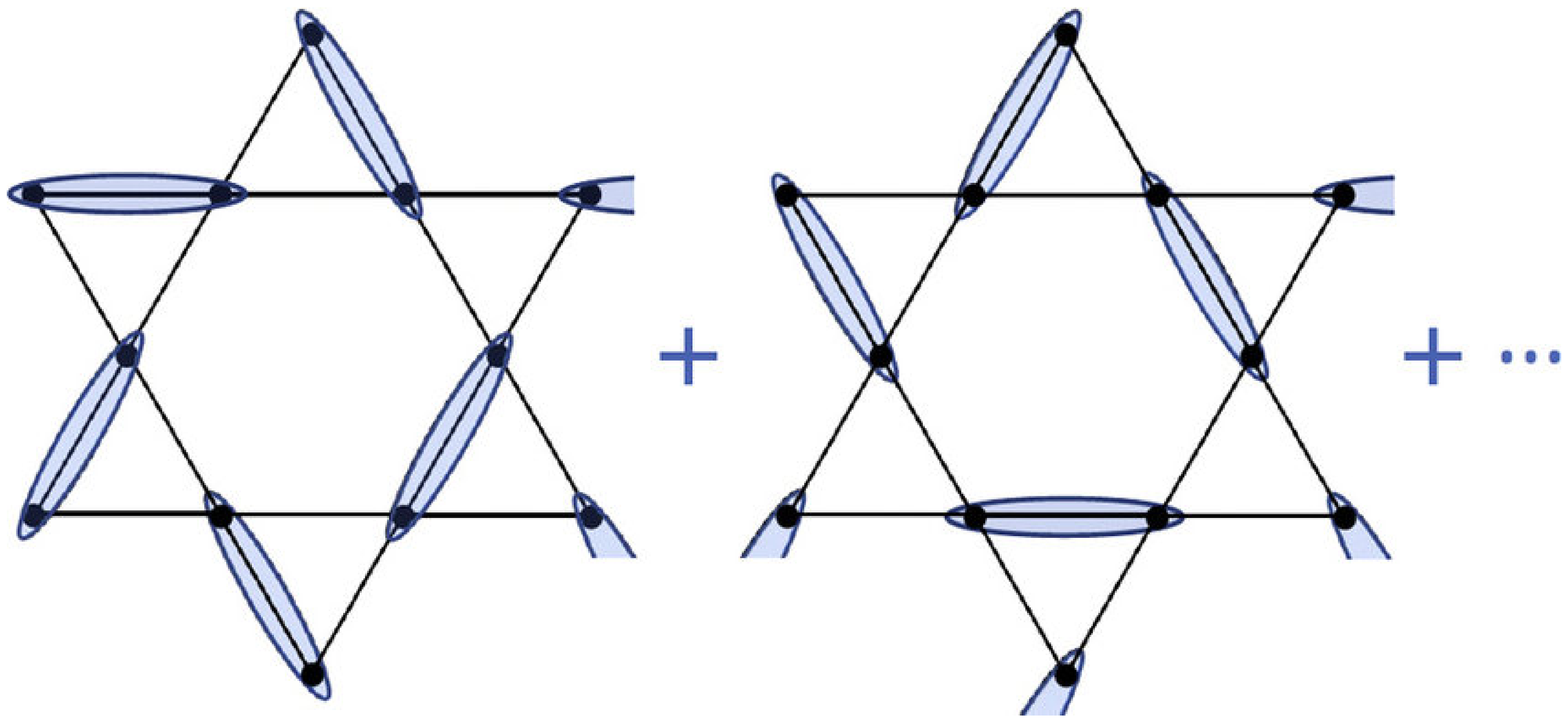


Strong magnetic moment renormalization because of frustration

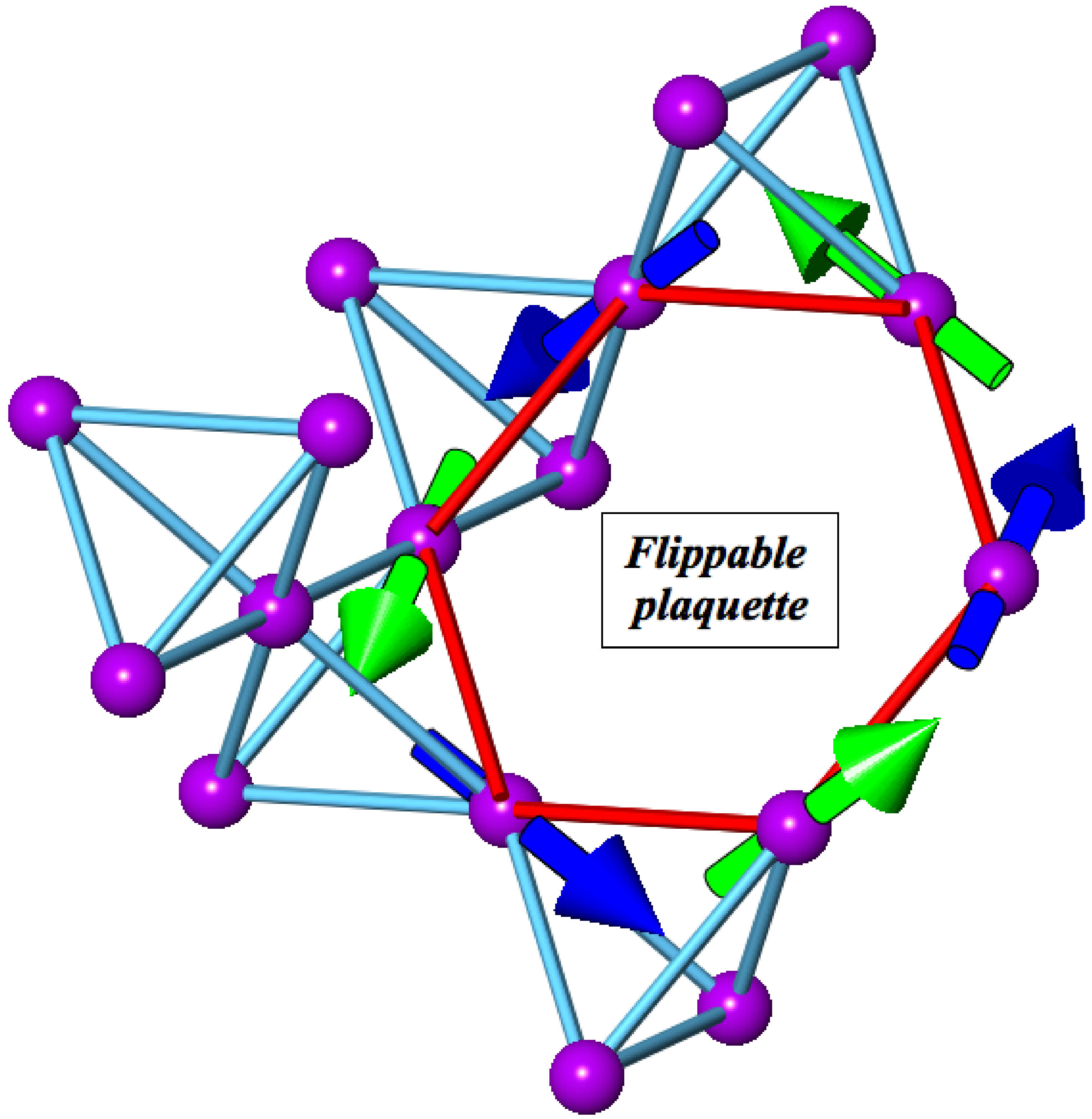
$$\langle S^z \rangle = S - 0.261$$

Th. Jolicoeur and J.C. Le Guillou, Phys. Rev. B 40, 2727 (1989)

Frustration from geometry: kagome and pyrochlore lattices



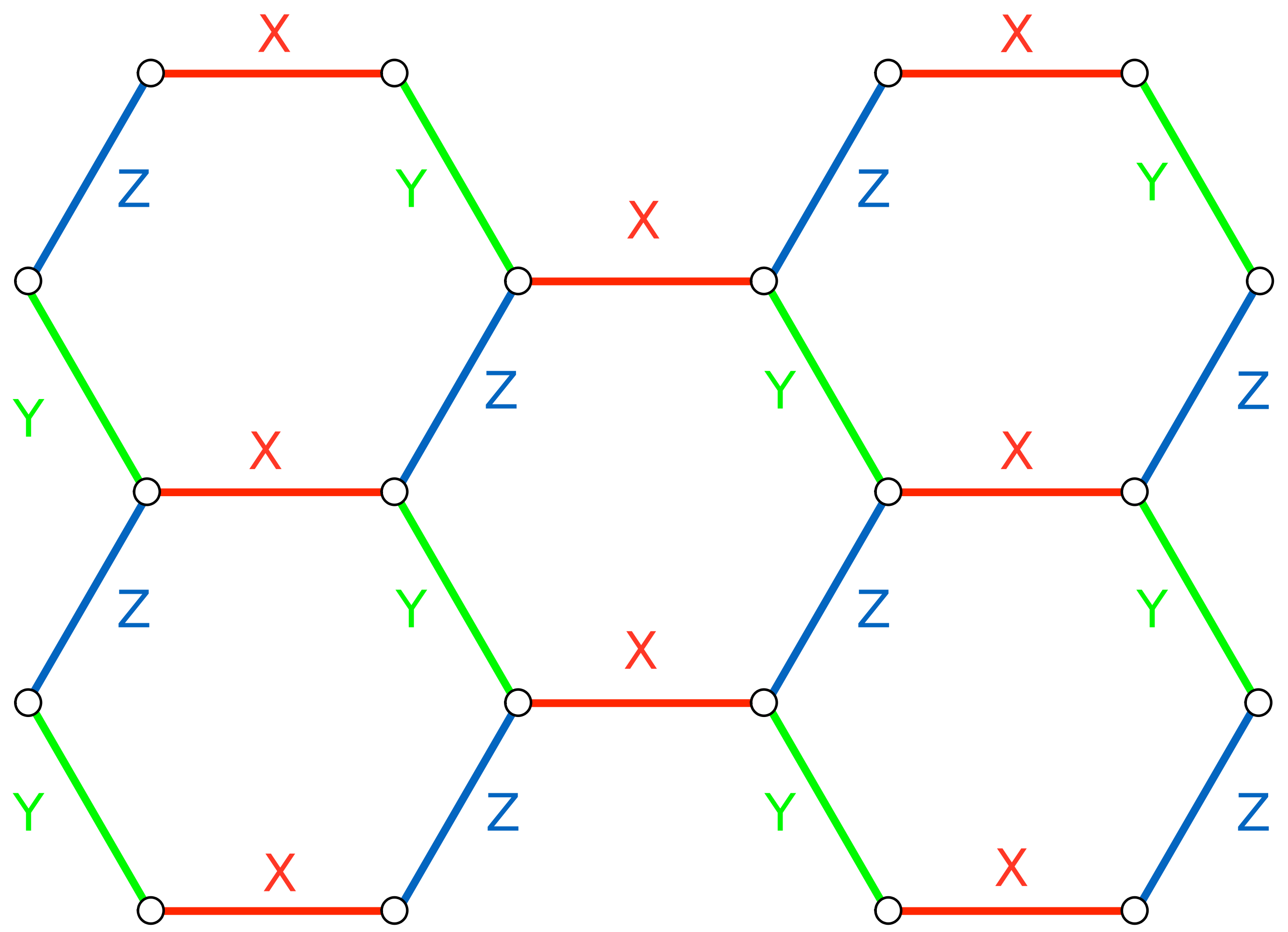
P. Mendels and F.Bert, Comptes Rendus Physique 17, 455 (2016)



M.J.P. Gingras and P.A. McClarty, Rep. Prog. Phys. 77, 056501 (2014)

Frustration from anisotropic interactions: Kitaev model

$$\mathcal{H} = K \sum_{\langle ij \rangle^{\gamma}} S_i^{\gamma} S_j^{\gamma} = K \sum_{\langle ij \rangle^{\mathrm{x}}} S_i^x S_j^x + K \sum_{\langle ij \rangle^{\mathrm{y}}} S_i^y S_j^y + K \sum_{\langle ij \rangle^{\mathrm{z}}} S_i^z S_j^z$$

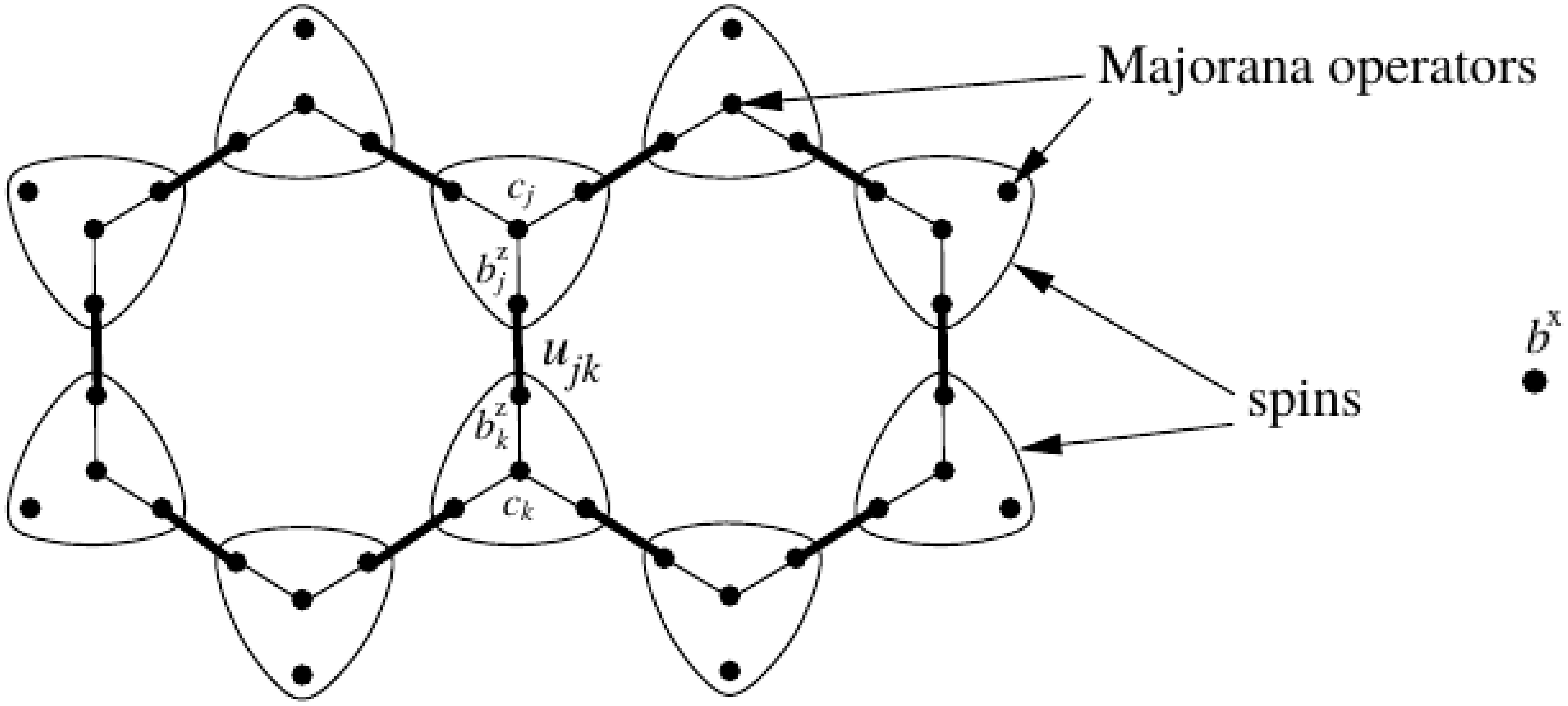


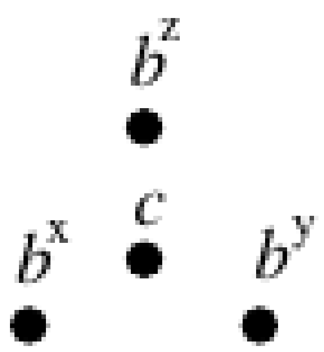
A. Kitaev, Annals of Physics 321, 2 (2006), January Special Issue

Exactly solvable for S=1/2, massive classical degeneracy

Kitaev model: Majorana fermions

$$\mathcal{H} = K \sum_{\langle ij \rangle^\gamma} S_i^\gamma S_j^\gamma = K \sum_{\langle ij \rangle^{\mathrm{x}}} S_i^x S_j^x + K \sum_{\langle ij \rangle^{\mathrm{y}}} S_i^y S_j^y + K \sum_{\langle ij \rangle^{\mathrm{z}}} S_i^z S_j^z$$





Free fermion solution!

$$S^x = ib^x c,\ S^y = ib^y c,\ S^z = ib^z c$$

Majorana fermions:

$$c_j^2 = 1,\ c_i c_j = -c_j c_i,\ i \neq j$$

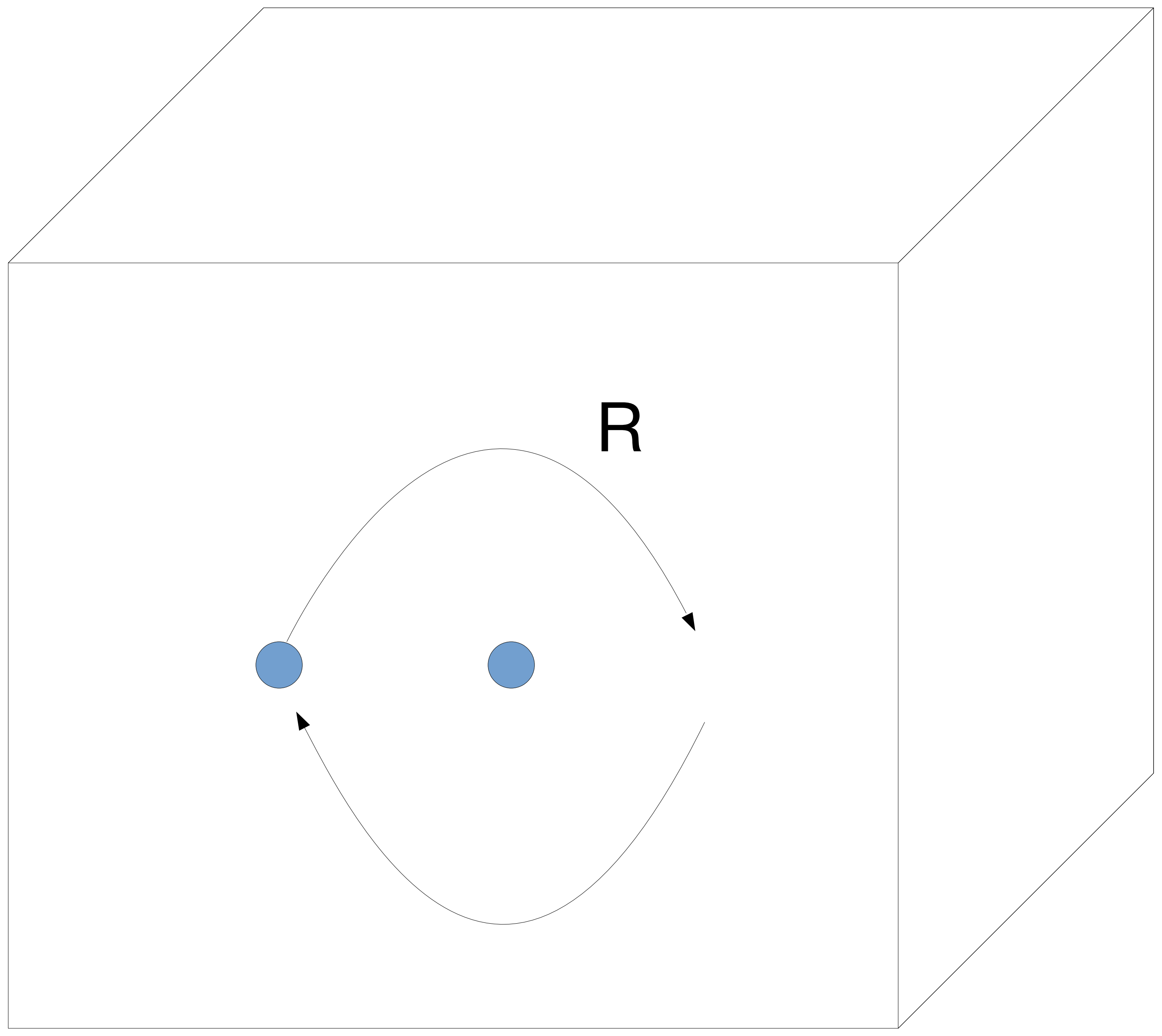
Non-abelian statistics in magnetic field: path to topological quantum computing

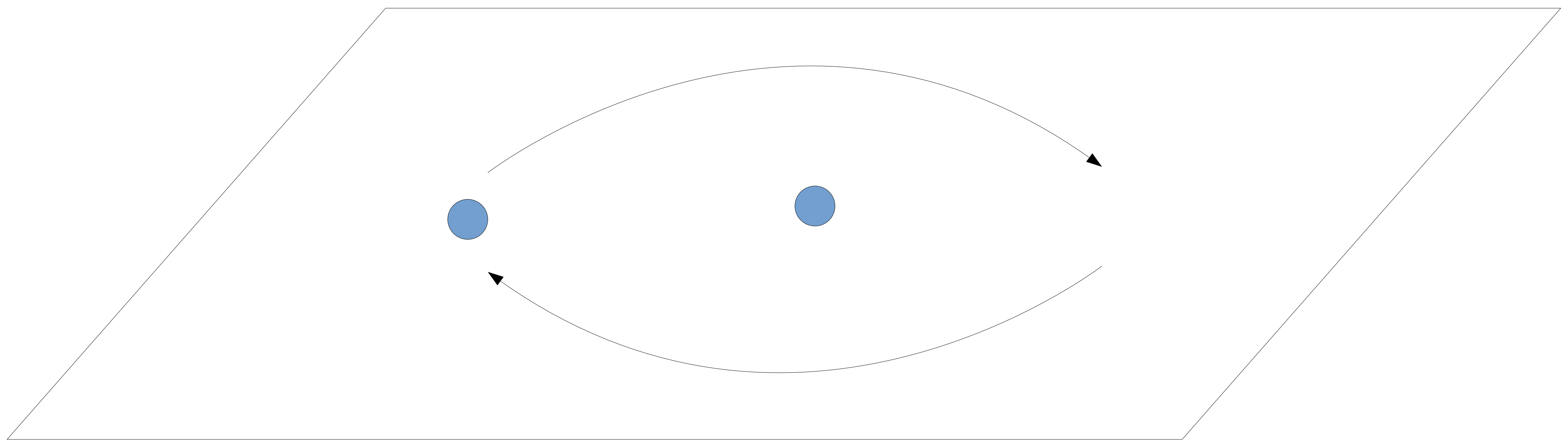
А. Китаев, А. Шень, М. Вялый

КЛАССИЧЕСКИЕ И КВАНТОВЫЕ ВЫЧИСЛЕНИЯ

4. Анионы. Анионы — это особые возбуждения в двумерных квантовых системах, в частности, в двумерной электронной жидкости в магнитном поле. Один из авторов (А. К.) считает этот подход наиболее интересным (поскольку он же его и придумал [32]), поэтому опишем его более подробно.

Topological quantum computing



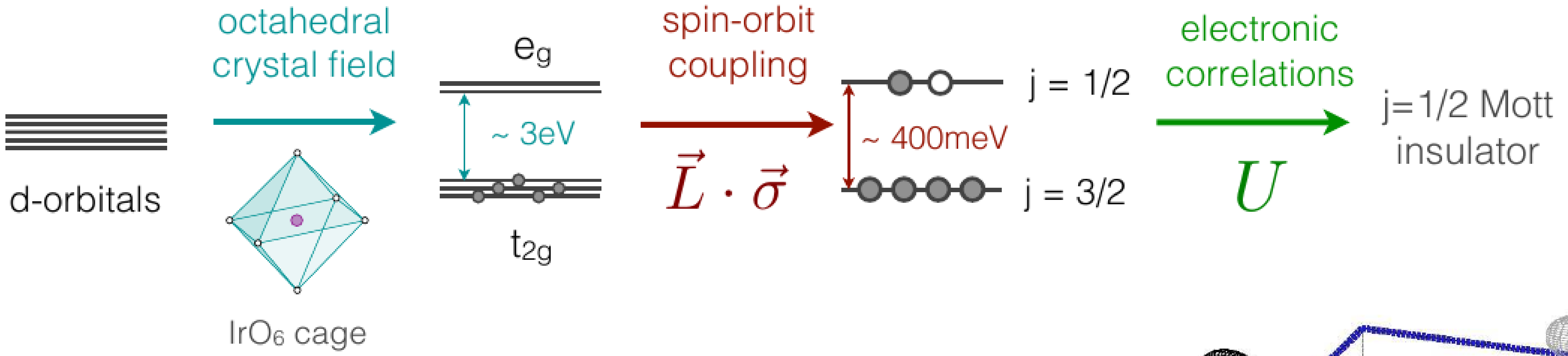


$$R = e^{i\theta}$$

$$R^2 = 1$$

$$R = \pm 1$$

Kitaev materials: d^5 ions



$$|j_{1/2}\rangle = \begin{cases} \frac{1}{\sqrt{3}}(-|xy,\uparrow\rangle - \mathrm{i}|xz,\downarrow\rangle - |yz,\downarrow\rangle) & (m_j = +\frac{1}{2}) \\ \frac{1}{\sqrt{3}}(|xy,\downarrow\rangle + i|xz,\uparrow\rangle - |yz,\uparrow\rangle) & (m_j = -\frac{1}{2}) \end{cases}$$

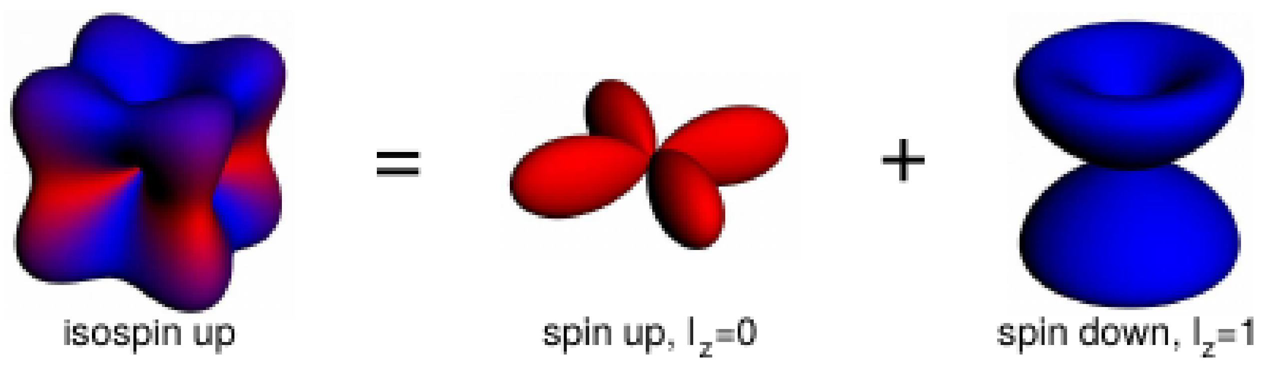
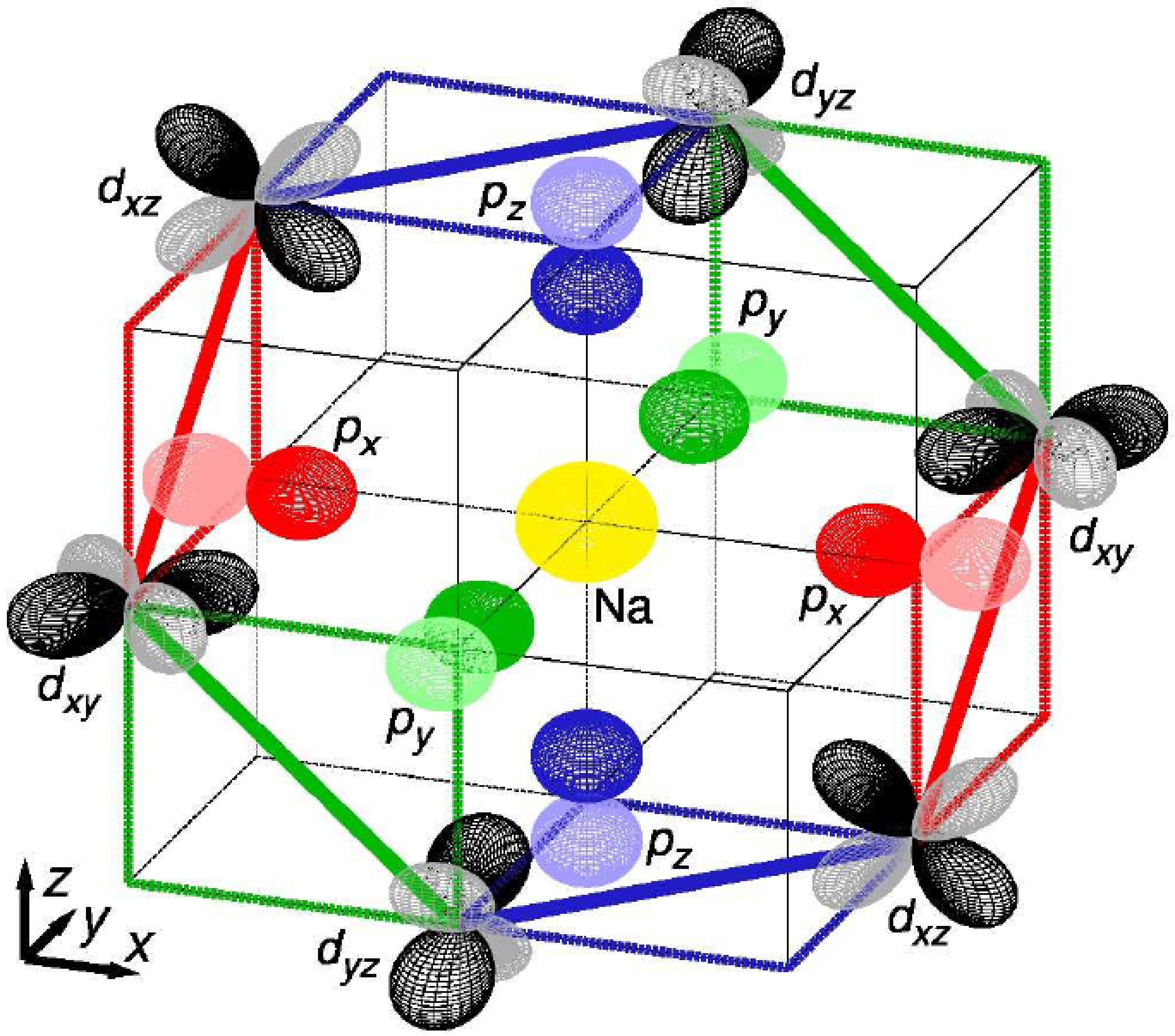


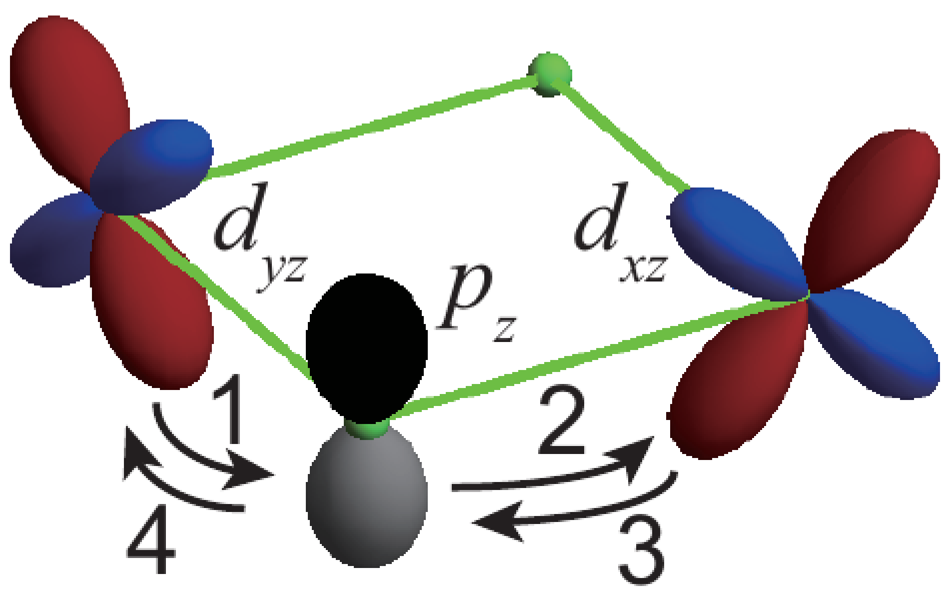
FIG. 1: (Color online) Density profile of a hole in the isospin up state (without tetragonal distortion). It is a superposition of a spin up hole density in $|xy\rangle$-orbital, $l_z = 0$, (middle) and spin down one in $(|yz\rangle + i|xz\rangle)$ state, $l_z = 1$, (right).



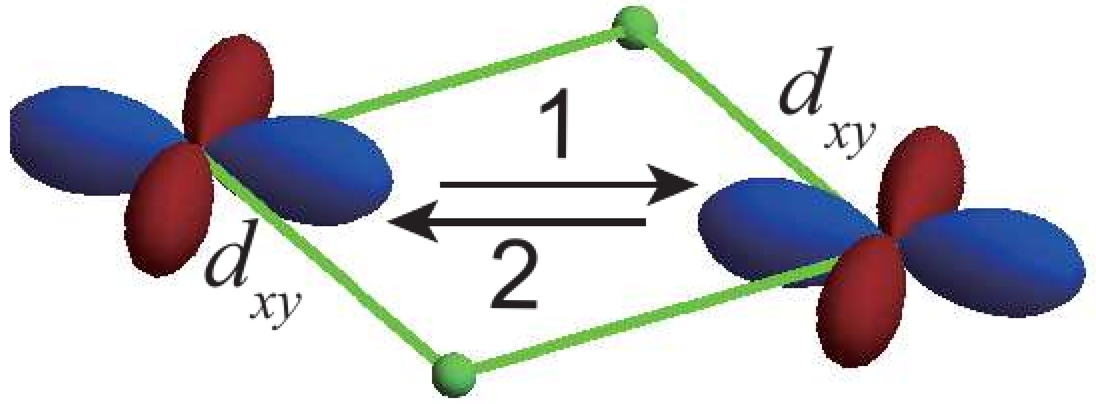
G. Jackeli and G. Khaliullin, Phys. Rev. Lett. 102, 017205 (2009)

Kitaev-Heisenberg model

Kitaev bond-dependent exchange K

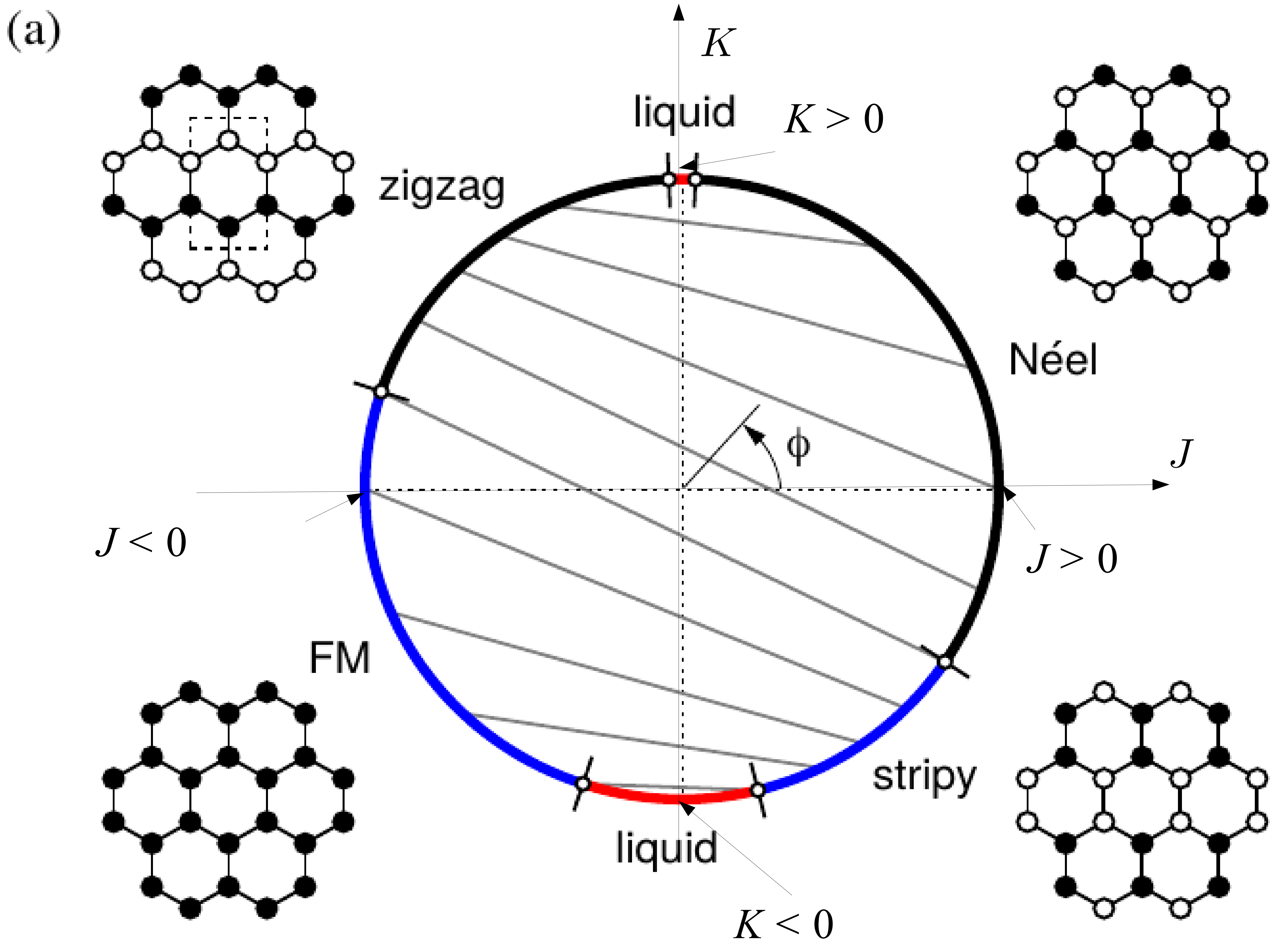


Heisenberg bond-independent exchange J



$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J \mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma$$

Kitaev-Heisenberg model phase diagram



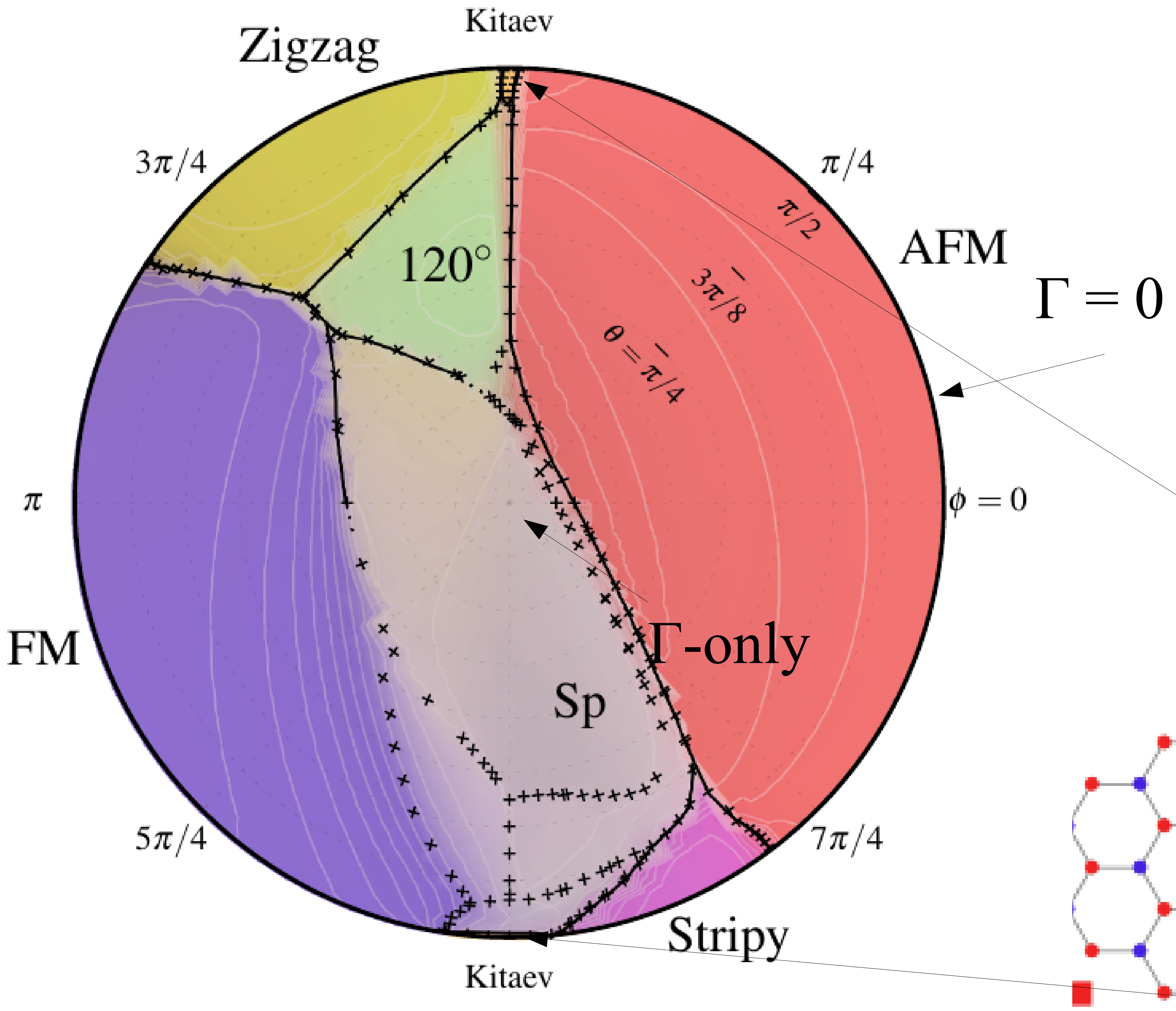
Jiří Chaloupka, George Jackeli, and Giniyat Khaliullin, Phys. Rev. Lett. 110, 097204 (2013)

$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J \mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma$$

$$J = \cos\phi, \;\; K = \sin\phi$$

Mostly — ordered states

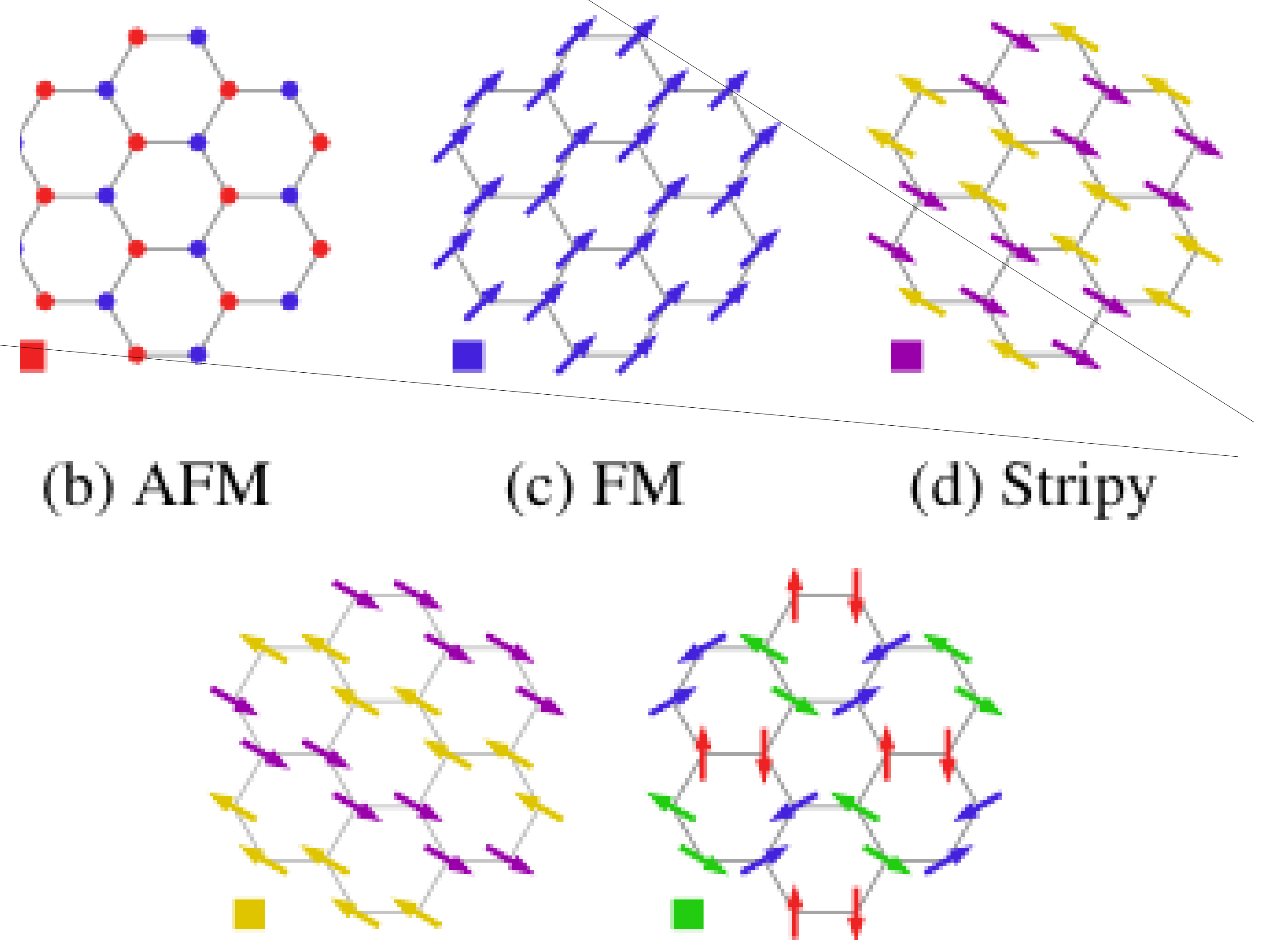
Extended Kitaev-Heisenberg model



S=1/2 phase diagram

$$\mathcal{H} = \sum_{\langle ij \rangle^{\gamma}} J\mathbf{S}_i \cdot \mathbf{S}_j + K S_i^{\gamma} S_j^{\gamma} + \Gamma \left(S_i^{\alpha} S_j^{\beta} + S_i^{\beta} S_j^{\alpha} \right)$$

$$J = \sin\theta\cos\phi,\ \ K = \sin\theta\sin\phi,\ \ \Gamma = \cos\theta$$



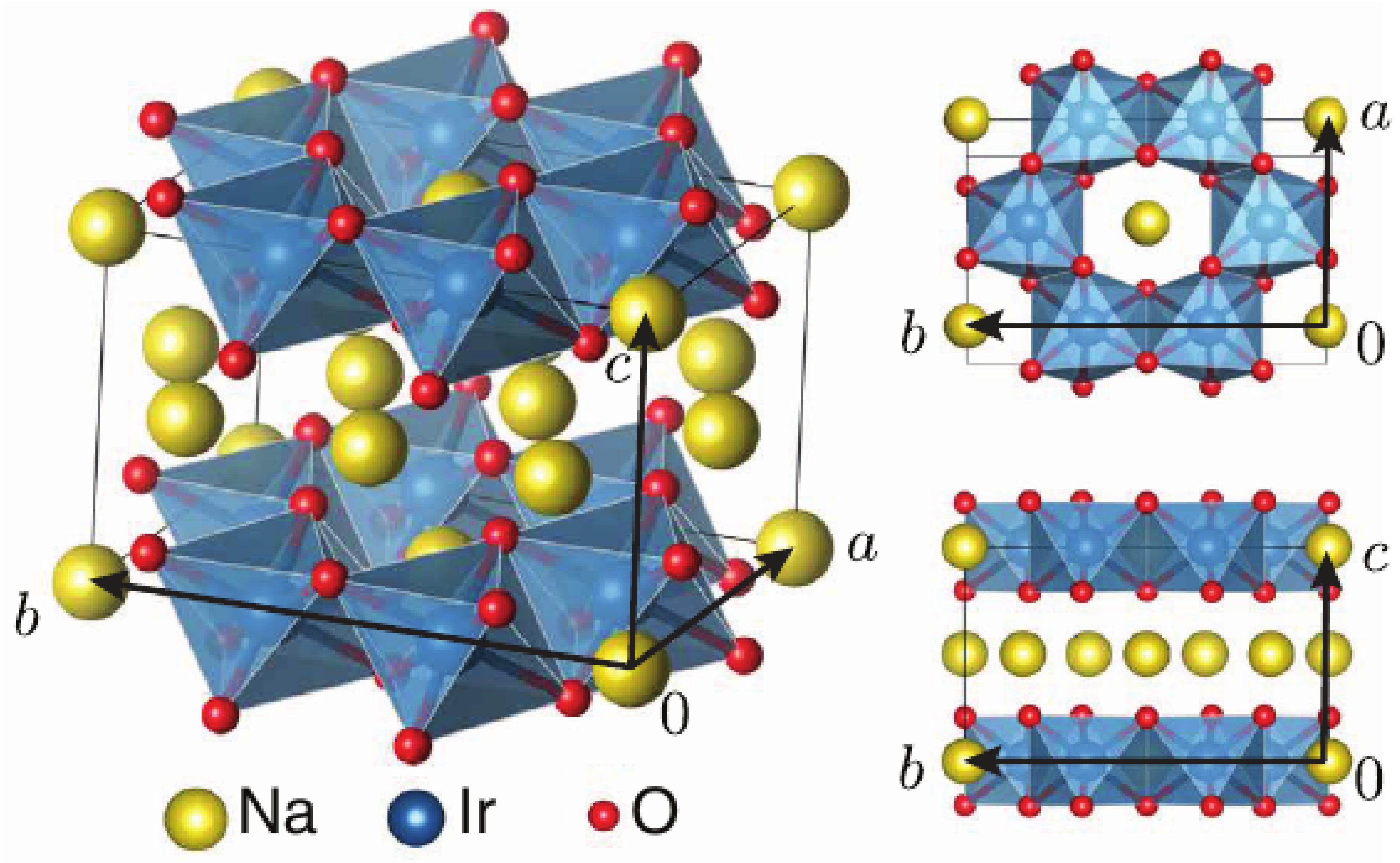
(b) AFM (c) FM (d) Stripy

(e) Zigzag (f) 120°

Spin liquid regions are extremely narrow

Jeffrey G. Rau, Eric Kin-Ho Lee, and Hae-Young Kee, Phys. Rev. Lett. 112, 077204 (2014)

Kitaev materials: Na2IrO3



Yogesh Singh, S. Manni, J. Reuther, T. Berlijn, R. Thomale, W. Ku, S. Trebst, and P. Gegenwart, Phys. Rev. Lett. 108, 127203 (2012)

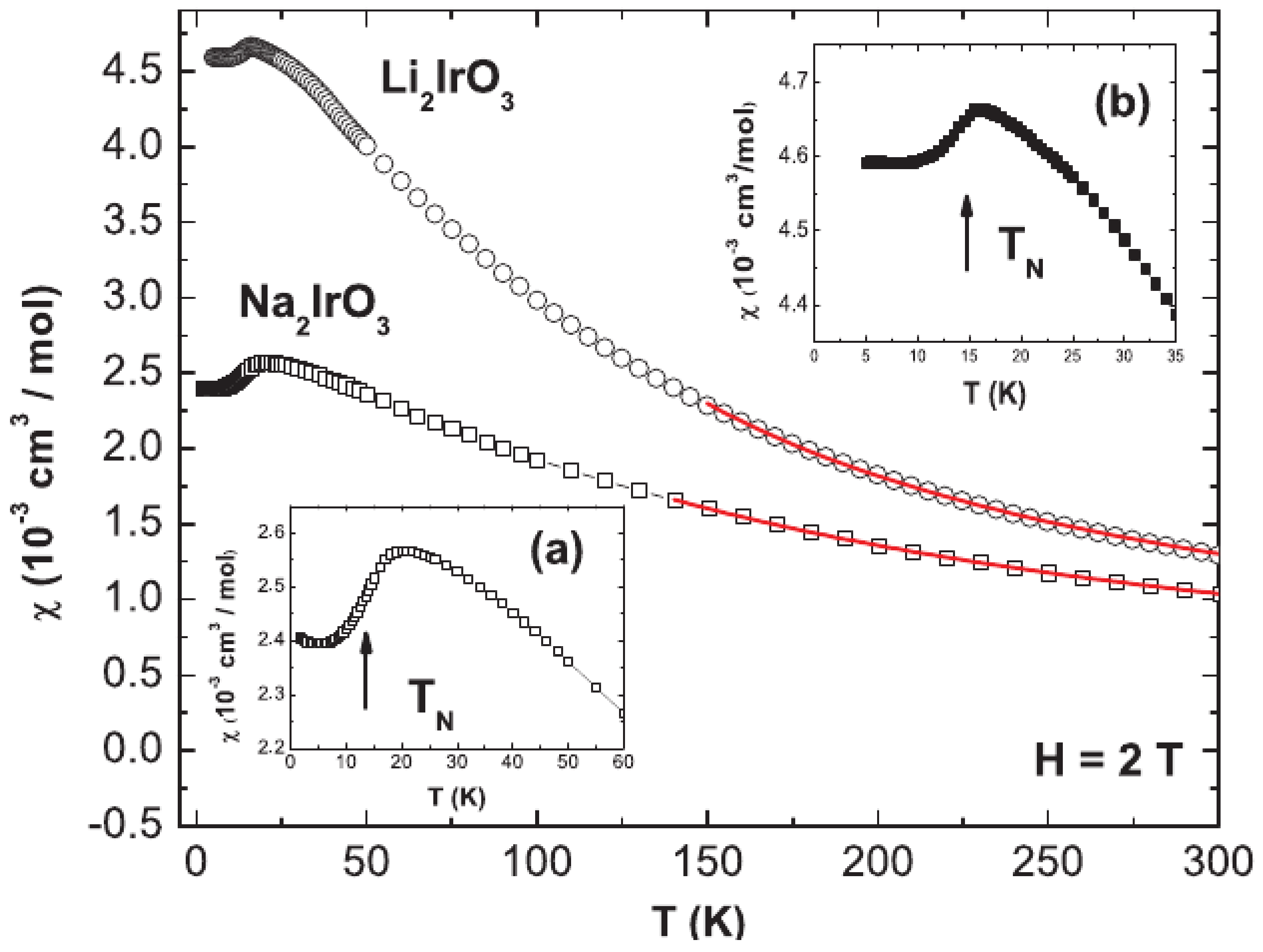


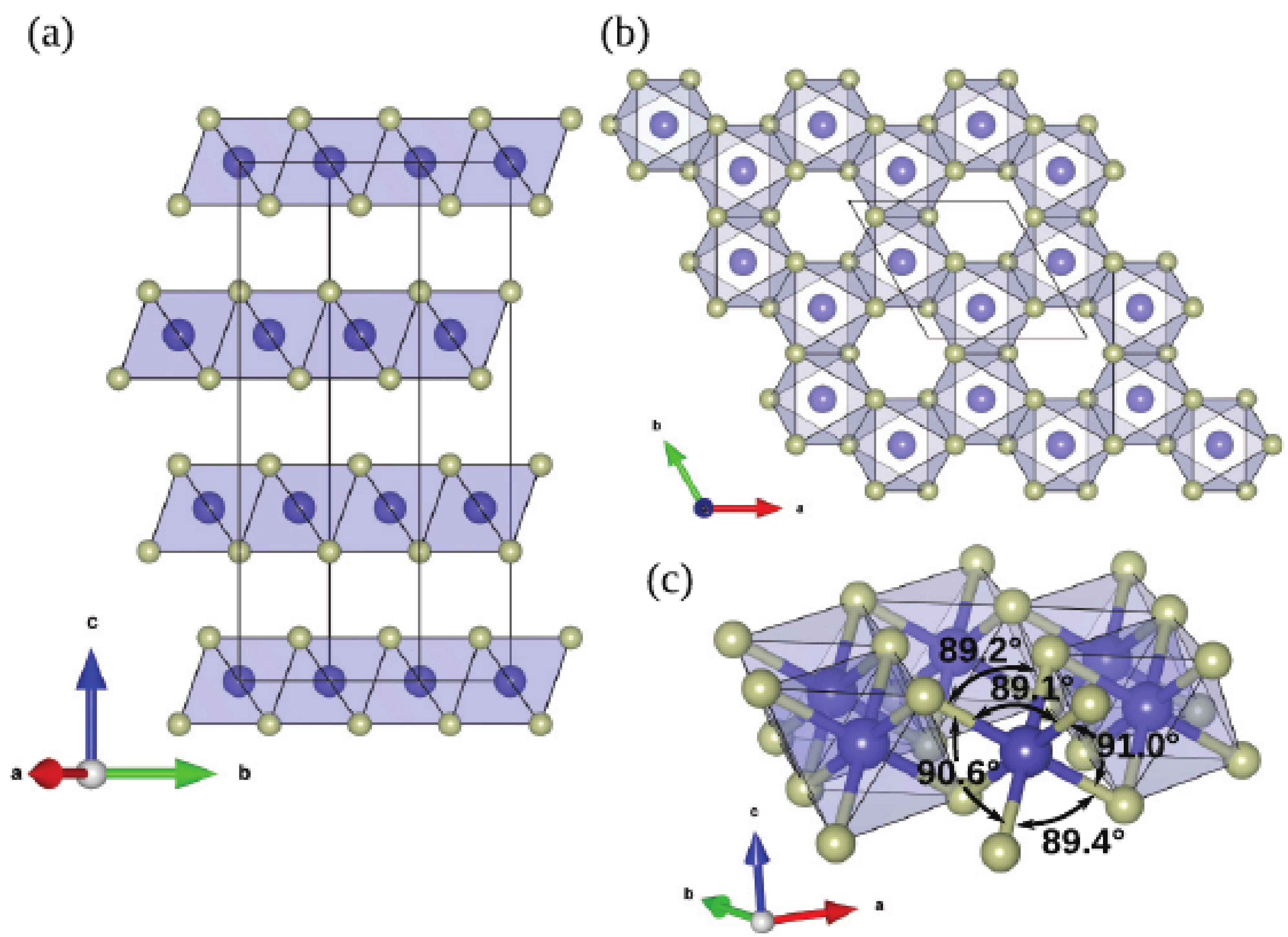
FIG. 1: (Color online) Magnetic susceptibility χ versus temperature T for A_2IrO_3 ($A =$ Na, Li). The fit by the Curie-Weiss (CW) expression $\chi = \chi_0 + C/(T - \theta)$ is shown as the curve through the data. The insets (a) and (b) shows the anomaly at the antiferromagnetic ordering for the Na and Li systems, respectively.

Table 3. Bond-averaged values of the largest magnetic interactions (in units of meV) within the plane for Na_2IrO_3 computed using various methods. 'Pert. Theo.' refers to second order perturbation theory (section 3.2), 'QC' = quantum chemistry methods, 'ED' = exact diagonalization.

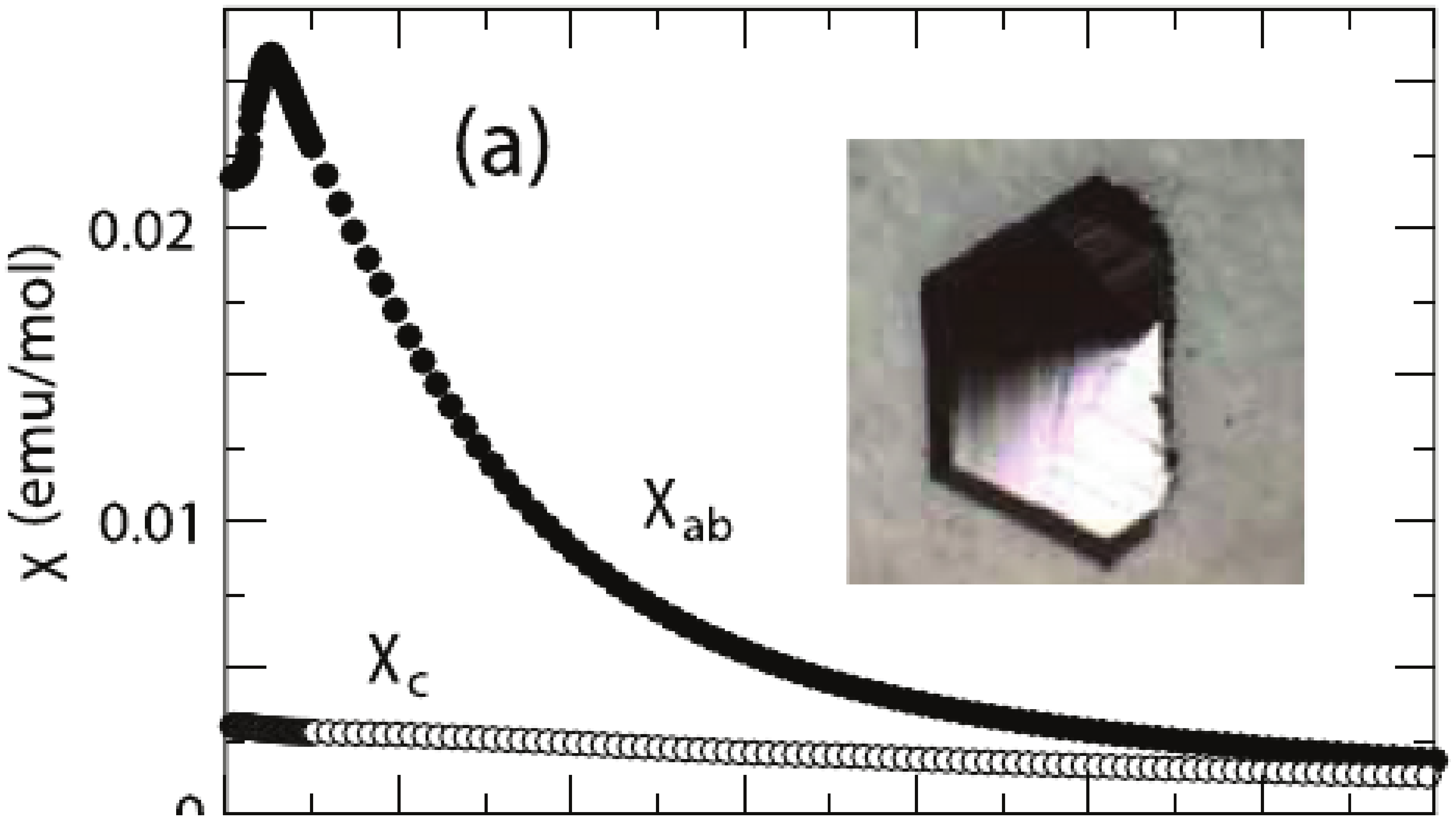
Method	J_1	K_1	Γ_1	Γ'_1	K_2	J_3
Pert. Theo. [44]	+3.2	−29.4	+1.1	−3.5	−0.4	+1.7
QC (2-site) [43]	+2.7	−16.9	+1.0	—	—	—
ED (6-site) [45]	+0.5	−16.8	+1.4	−2.1	−1.4	+6.7

Stephen M Winter et al, J. Phys.: Condens. Matter 29 493002 (2017)

Kitaev materials: RuCl3



K. W. Plumb, J. P. Clancy, L. J. Sandilands, V. Vijay Shankar, Y. F. Hu, K. S. Burch, Hae-Young Kee, and Young-June Kim, Phys. Rev. B 90, 041112(R) (2014)



J. A. Sears, M. Songvilay, K. W. Plumb, J. P. Clancy, Y. Qiu, Y. Zhao, D. Parshall, and Young-June Kim, Phys. Rev. B 91, 144420 (2015)

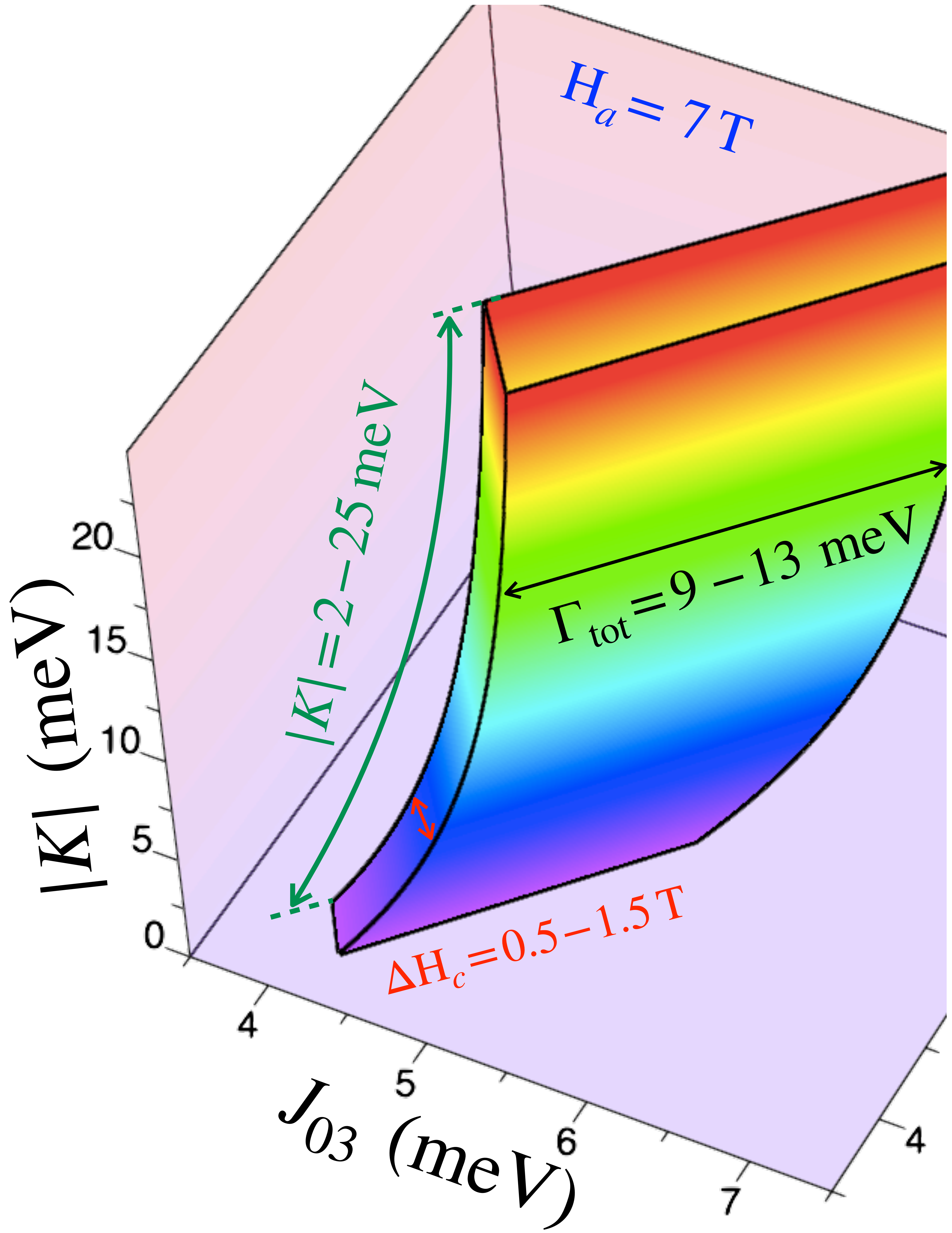
Zigzag state order at 7K

RuCl3 exchange parameters

Reference	Method	K	Γ	Γ'	J	J_3	Γ+2Γ'	J+3J_3
Banerjee et al. [22]	LSWT, INS fit	+7.0			-4.6			-4.6
Kim et al. [29]	DFT+t/U, $P3$	**-6.55**	**5.25**	-0.95	-1.53		3.35	-1.53
	DFT+SOC+t/U	**-8.21**	**4.16**	-0.93	-0.97		2.3	-0.97
	same+fixed lattice	-3.55	7.08	-0.54	**-2.76**		6.01	-2.76
	same+U+zigzag	+4.6	6.42	-0.04	**-3.5**		6.34	-3.5
Winter et al. [30]	DFT+ED, $C2$	**-6.67**	6.6	-0.87	-1.67	**2.8**	4.87	6.73
	same, $P3$	+7.6	8.4	+0.2	-5.5	**2.3**	**8.8**	+1.4
Yadav et al. [24]	Quantum chemistry	**-5.6**	-0.87		+1.2		-0.87	+1.2
Ran et al. [34]	LSWT, INS fit	**-6.8**	9.5				**9.5**	
Hou et al. [31]	DFT+t/U, U=2.5eV	-14.43	6.43		**-2.23**	**2.07**	6.43	+3.97
	same, U=3.0eV	-12.23	**4.83**		**-1.93**	1.6	4.83	+2.87
	same, U=3.5eV	**-10.67**	**3.8**		-1.73	1.27	3.8	+2.07
Wang et al. [32]	DFT+t/U, $P3$	**-10.9**	6.1		-0.3	0.03	6.1	-0.21
	same, $C2$	**-5.5**	7.6		+0.1	0.1	7.6	+0.4
Winter et al. [35]	*Ab initio*+INS fit	**-5.0**	2.5		-0.5	0.5	2.5	+1.0
Suzuki et al. [36]	ED, C_p fit	-24.41	**5.25**	-0.95	-1.53		3.35	-1.53
Cookmeyer et al. [37]	thermal Hall fit	**-5.0**	2.5		-0.5	0.11	2.5	-0.16
Wu et al. [38]	LSWT, THz fit	-2.8	2.4		-0.35	0.34	2.4	+0.67
Ozel et al. [39]	same, $K>0$	+1.15	2.92	+1.27	-0.95		5.45	-0.95
	same, $K<0$	-3.5	2.35		+0.46		2.35	+0.46
Eichstaedt et al. [33]	DFT+Wannier+t/U	-14.3	9.8	-2.23	-1.4	0.97	5.33	+1.5
Sahasrabudhe et al. [42]	ED, Raman fit	**-10.0**	3.75		-0.75	0.75	3.75	1.5
Sears et al. [40]	Magnetization fit	**-10.0**	10.6	-0.9	**-2.7**		**8.8**	-2.7
Laurell et al. [41]	ED, C_p fit	-15.1	10.1	-0.12	-1.3	0.9	**9.86**	+1.4

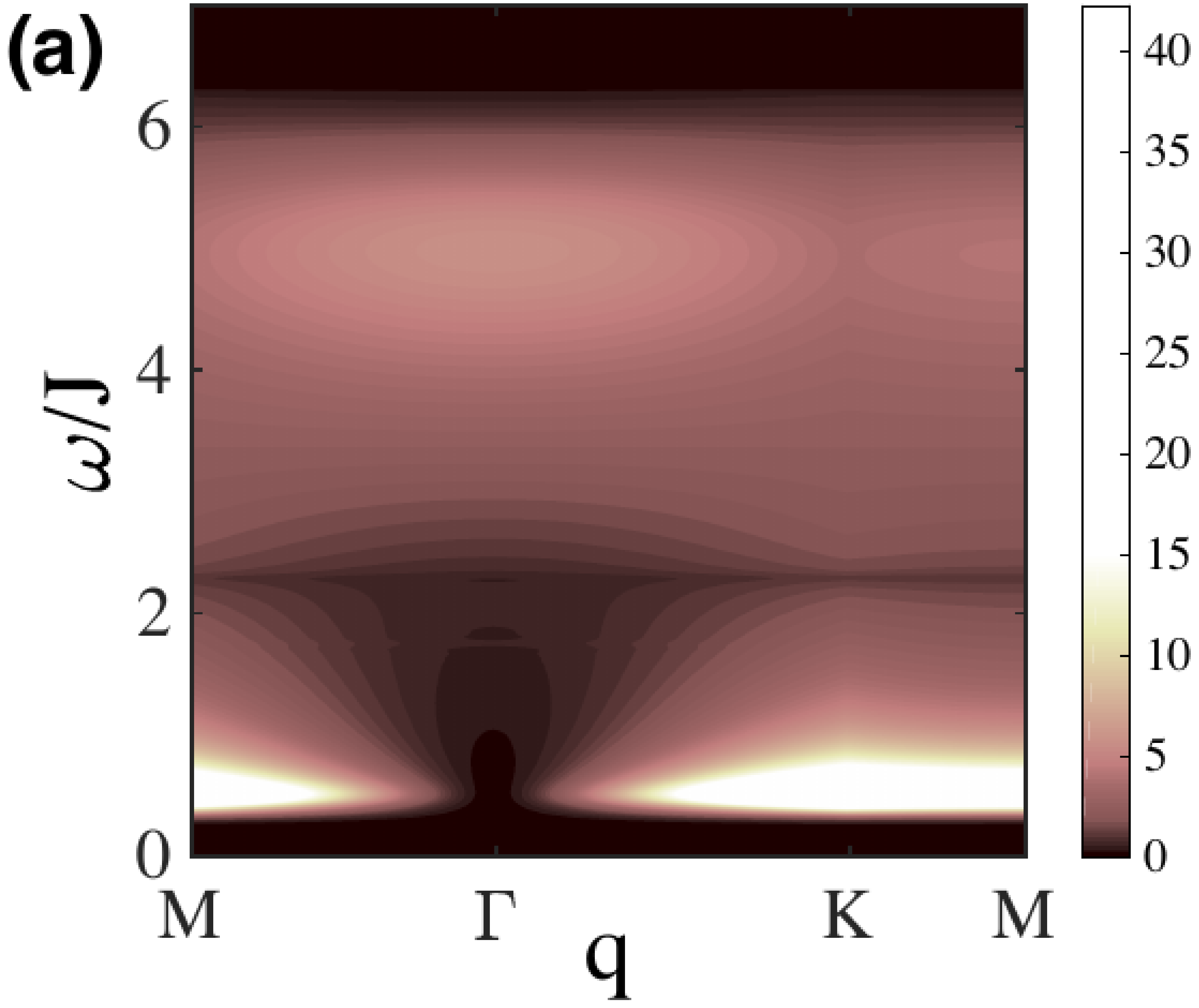
P. A. Maksimov and A. L. Chernyshev, Phys. Rev. Research 2, 033011 (2020)

RuCl3 exchange parameters



P. A. Maksimov and A. L. Chernyshev, Phys. Rev. Research 2, 033011 (2020)

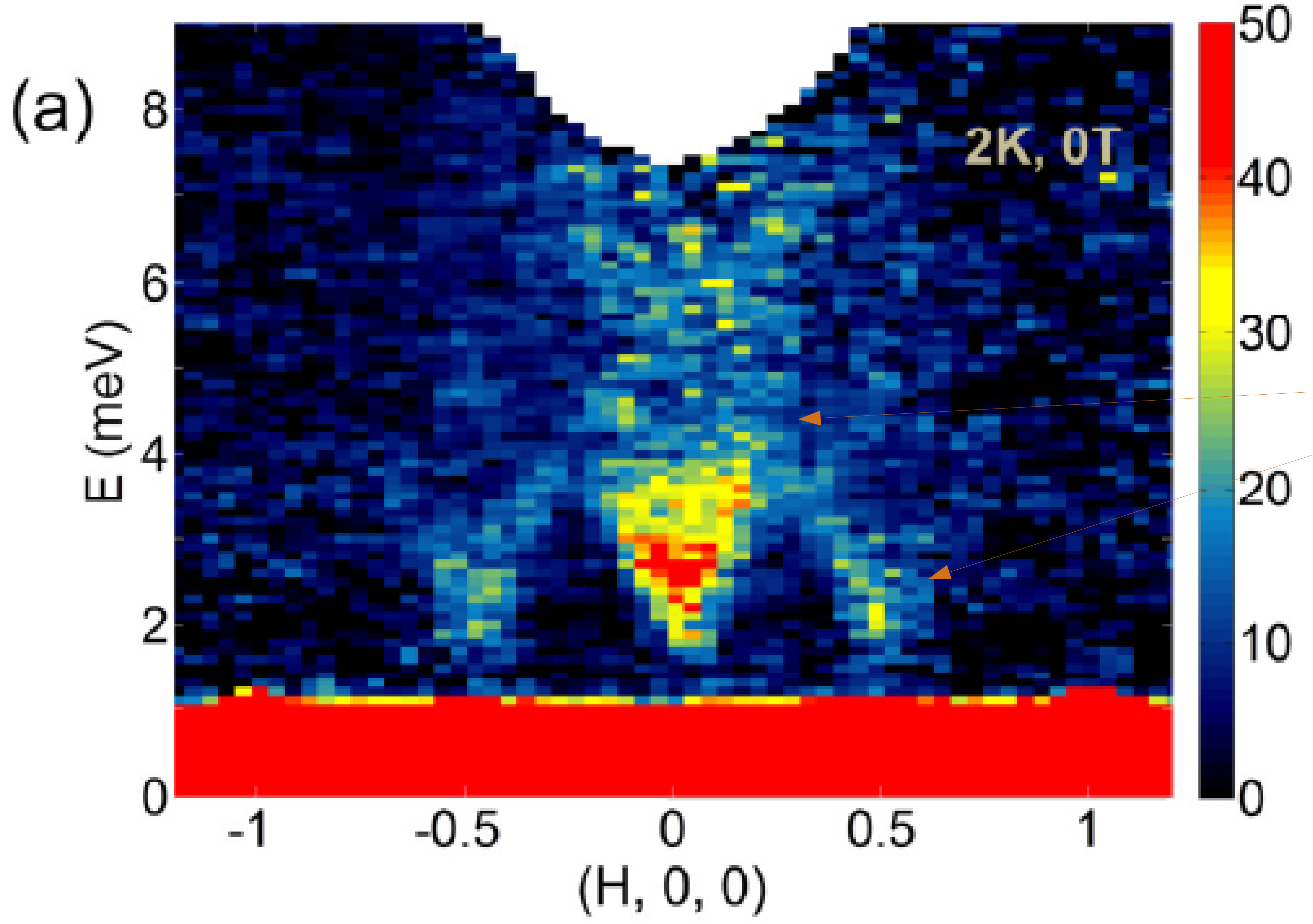
Fractionalization of excitations



- Kitaev model excitations have S=1/2
- One neutron (S=1) creates a pair of fermions
- Energy and momentum are split between two particles → broad continuum

J. Knolle, D. L. Kovrizhin, J. T. Chalker, and R. Moessner, Phys.Rev. B,92,115127 (2015)

Broadening of spectral peaks in a-RuCl$_3$

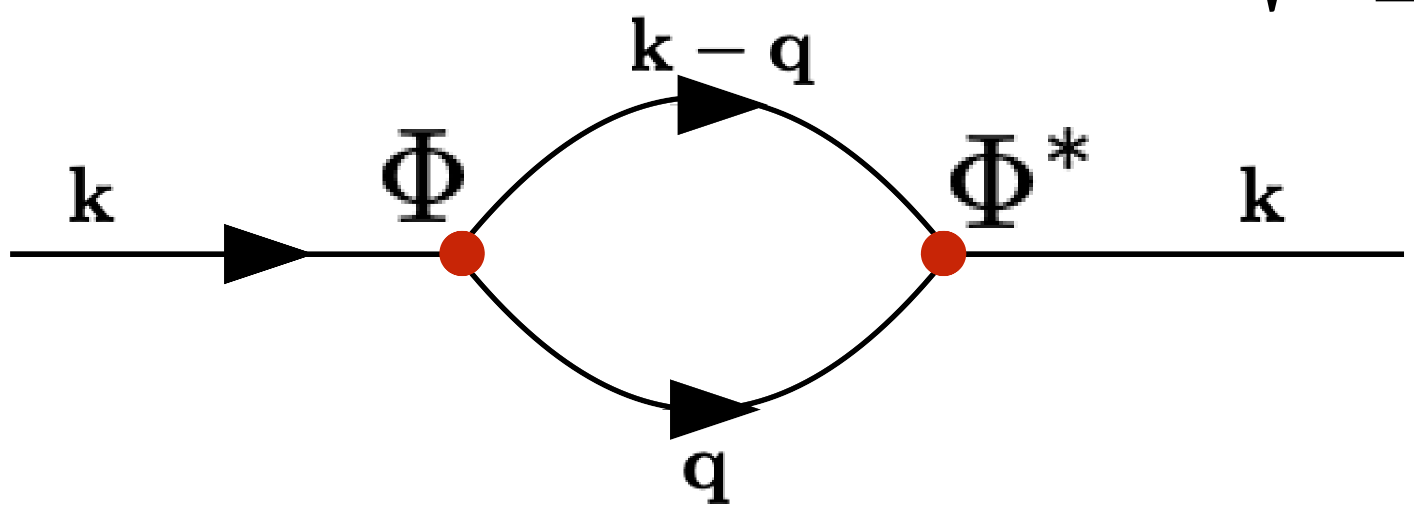


Banerjee, A., Lampen-Kelley, P., Knolle, J. et al., npj Quant Mater 3, 8 (2018)

- Coexistence of well-defined spin-waves and broad continuum
- Signatures of Majoranas

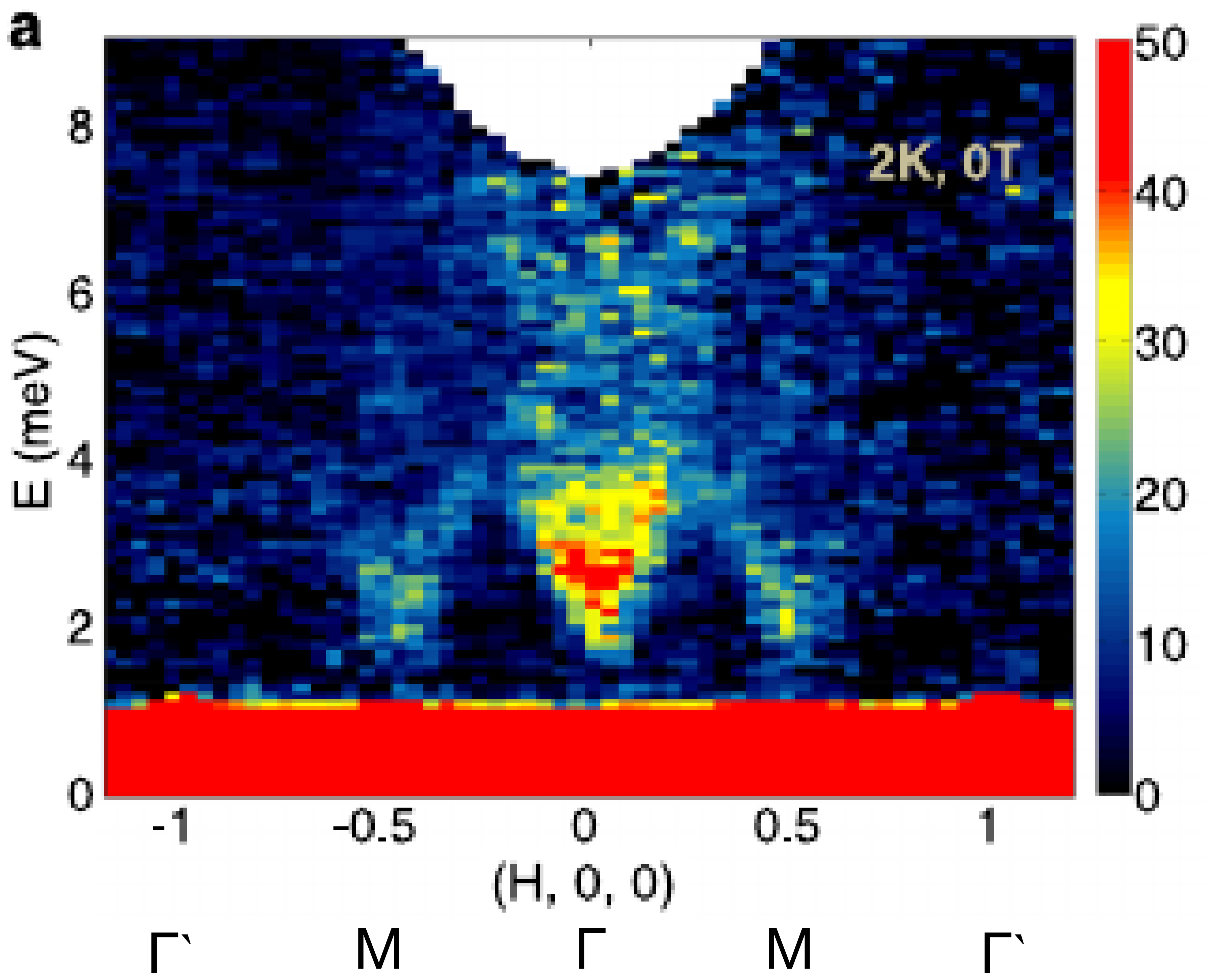
$$\mathcal{H} = \sum_{\langle ij \rangle \gamma} J\mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right)$$
$$+\Gamma' \left(S_i^\gamma S_j^\alpha + S_i^\gamma S_j^\beta + S_i^\alpha S_j^\gamma + S_i^\beta S_j^\gamma \right)$$

$$S^z = S - a^\dagger a \qquad S^x \approx \sqrt{\frac{S}{2}} \left(a + a^\dagger \right)$$



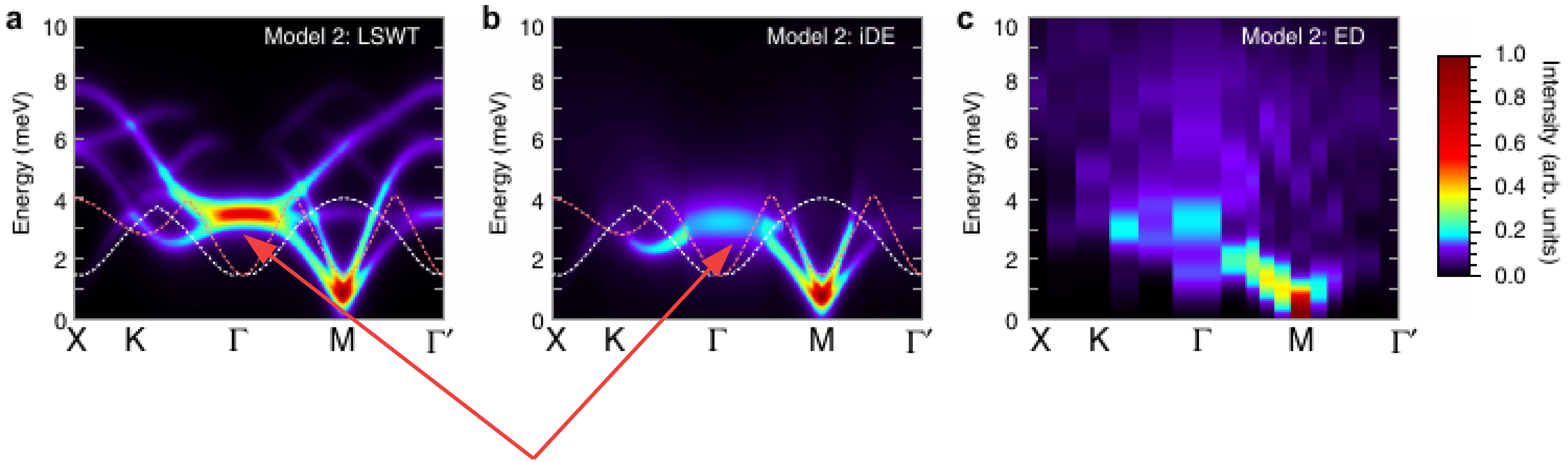
Broadening of spectral peaks in a-$RuCl_3$

Inelastic neutron scattering



Banerjee, A., Lampen-Kelley, P., Knolle, J. et al., npj Quant Mater 3, 8 (2018)

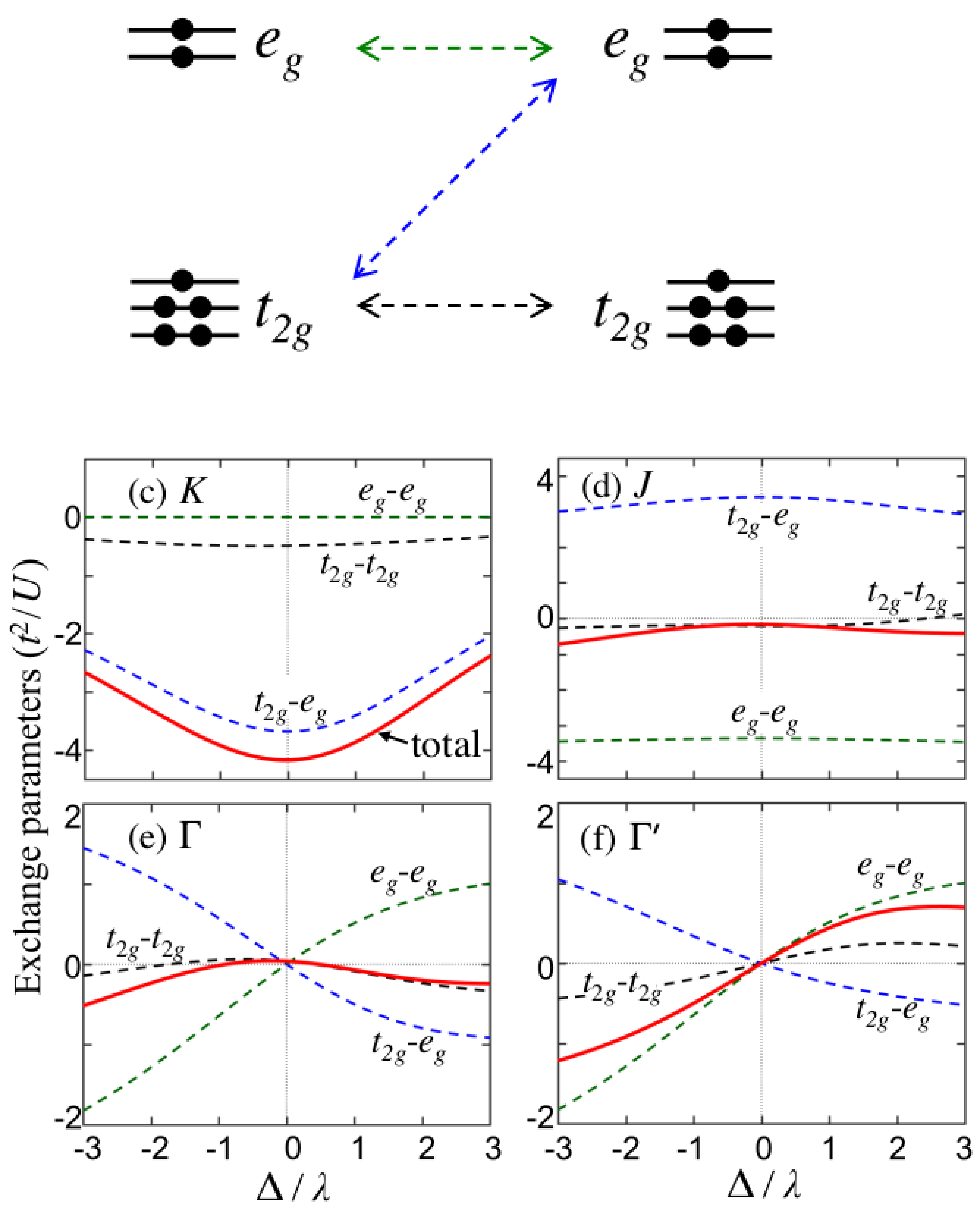
Non-interacting magnons Interacting magnons Exact diagonalization

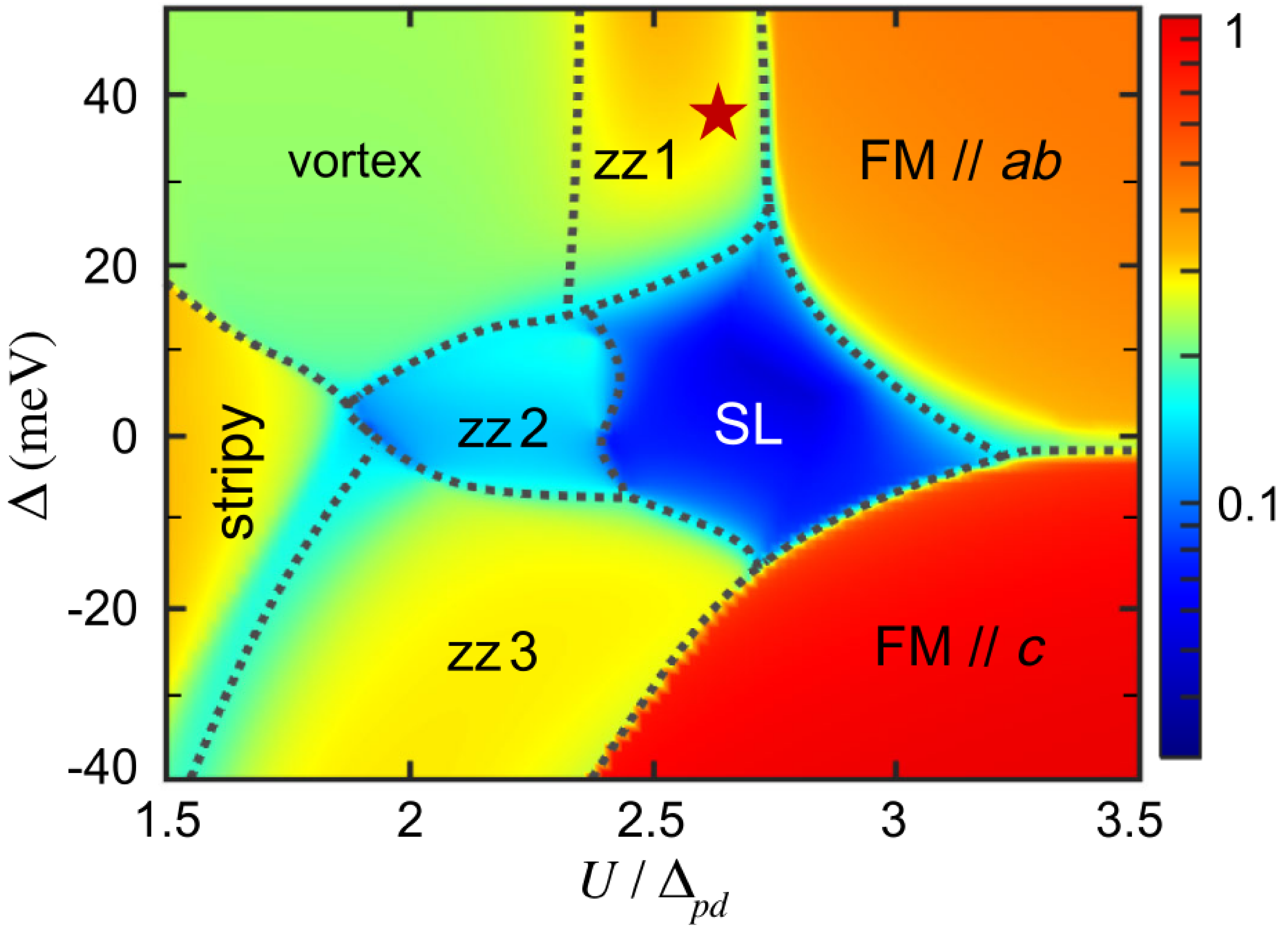


Broadening due to magnon decays

Winter, S.M., Riedl, K., Maksimov, P.A. et al., Nat. Commun 8, 1152 (2017)

Kitaev materials: d^7 ions - Co^{2+}



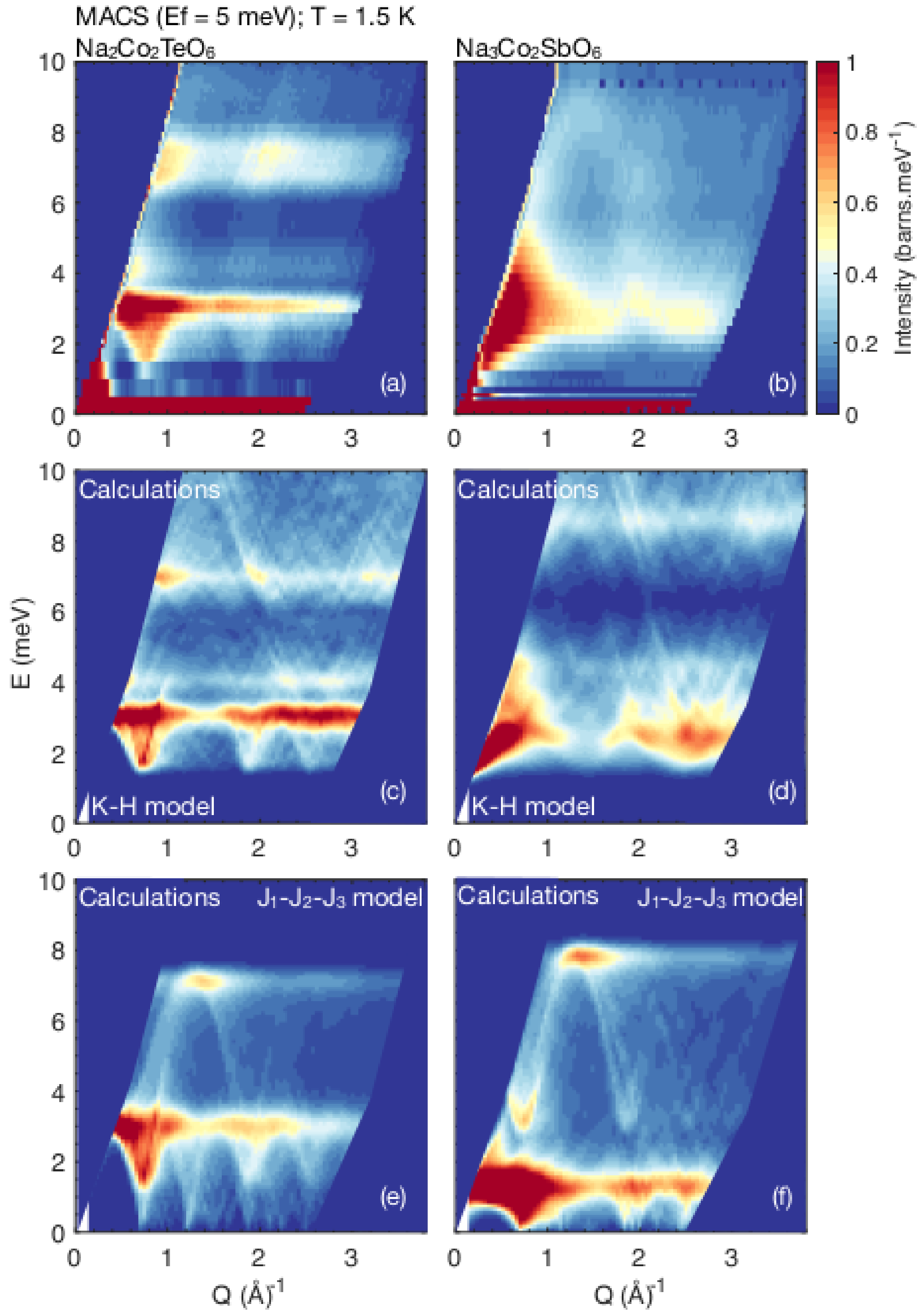


H. Liu and G. Khaliullin, Phys. Rev. B 97, 014407 (2018)

R. Sano, Y. Kato and Y. Motome, Phys. Rev. B 97, 014408 (2018)

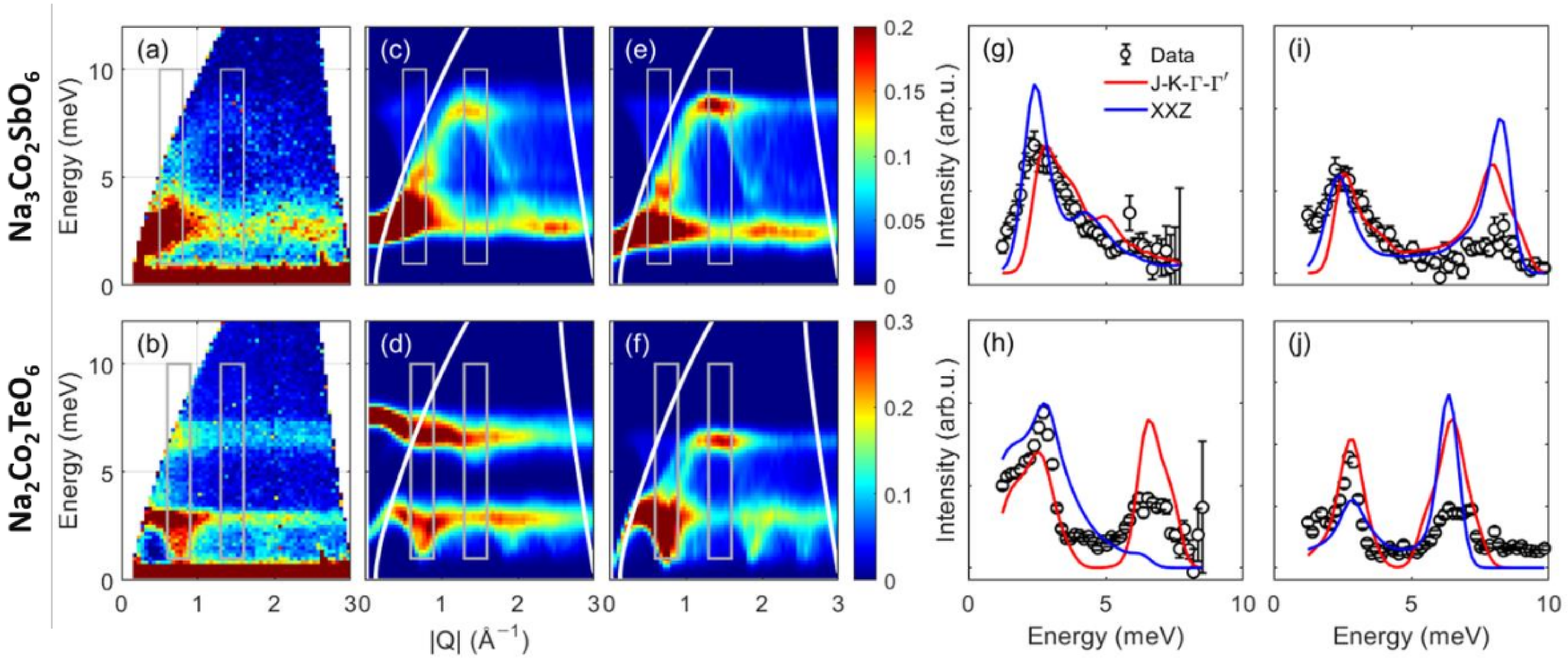
H. Liu, J. Chaloupka and G. Khaliullin, Phys. Rev. Lett. 125, 047201 (2020)

Kitaev materials: d^7 ions

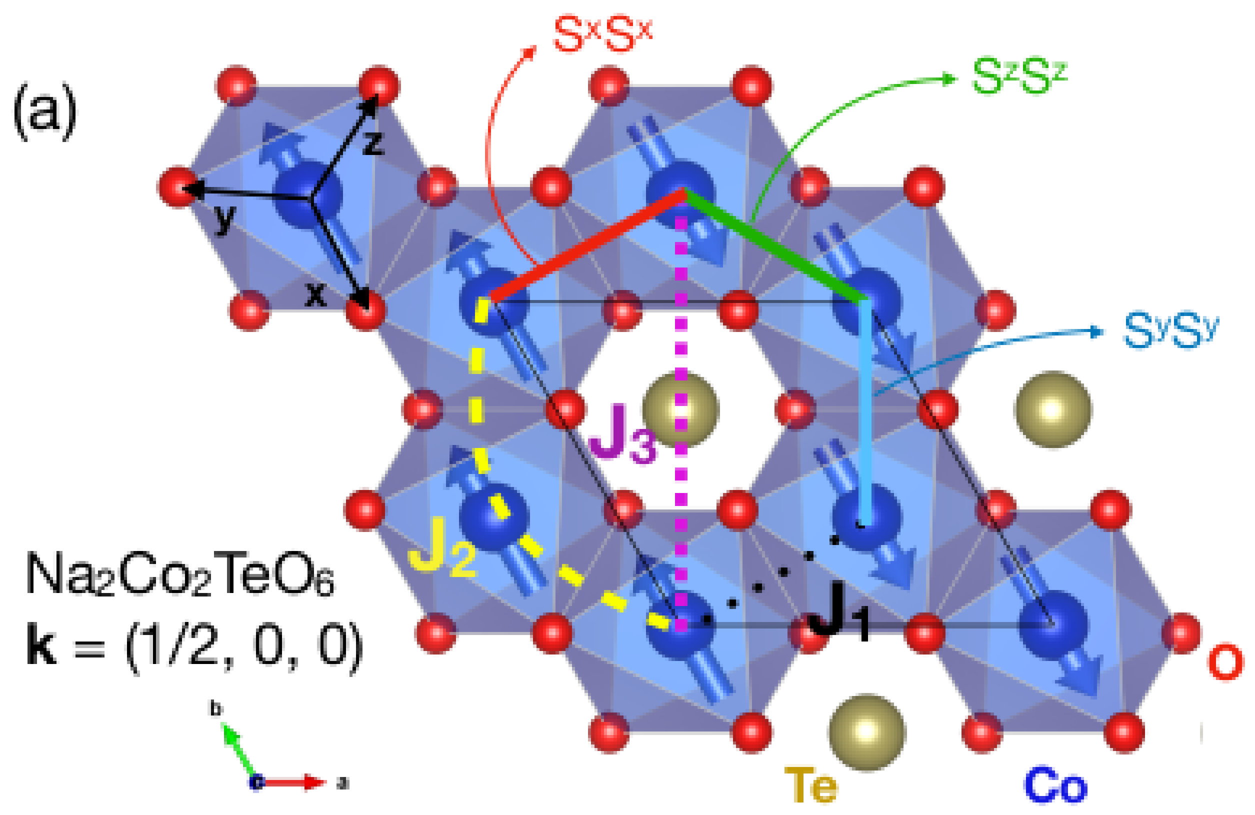


M. Songvilay et al., Phys. Rev. B 102, 224429 (2020)

Several families:
$Na_3Co_2SbO_6$
$Ag_3Co_2SbO_6$
$CoPS_3$
$BaCo_2(AsO_4)_2$

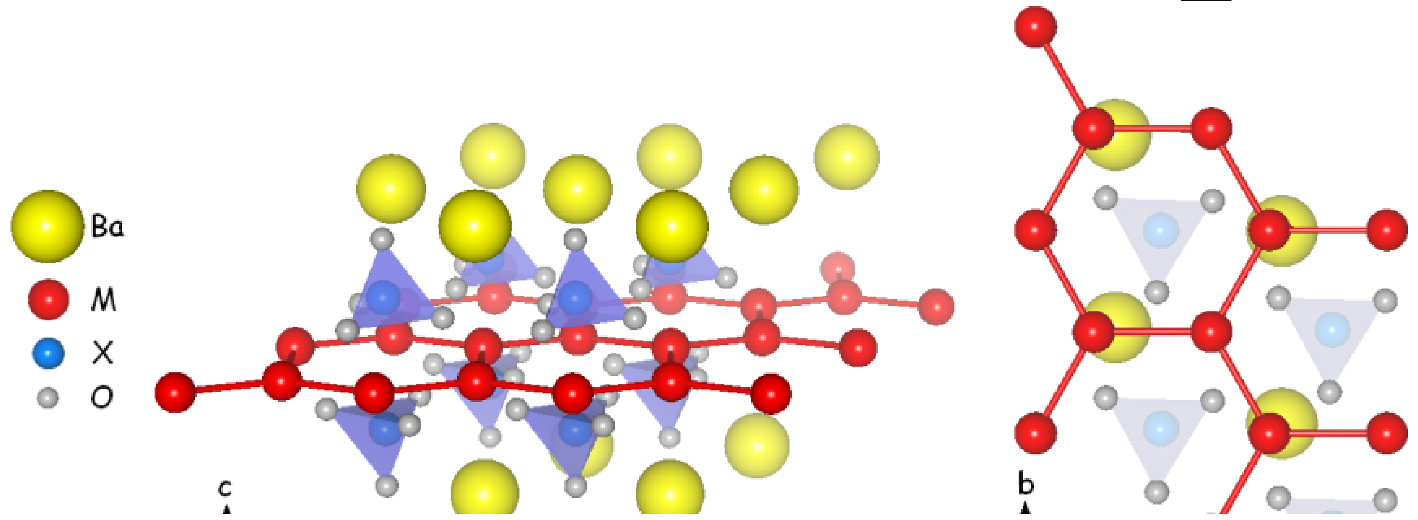


C. Kim et al., J. Phys.: Condes. Matter 34 045802 (2022)



- Zigzag ground state
- Spin-wave spectrum can be fit with Kitaev model with subleading Γ, Γ` terms

$BaCo_2(AsO_4)_2$: «double-zigzag»



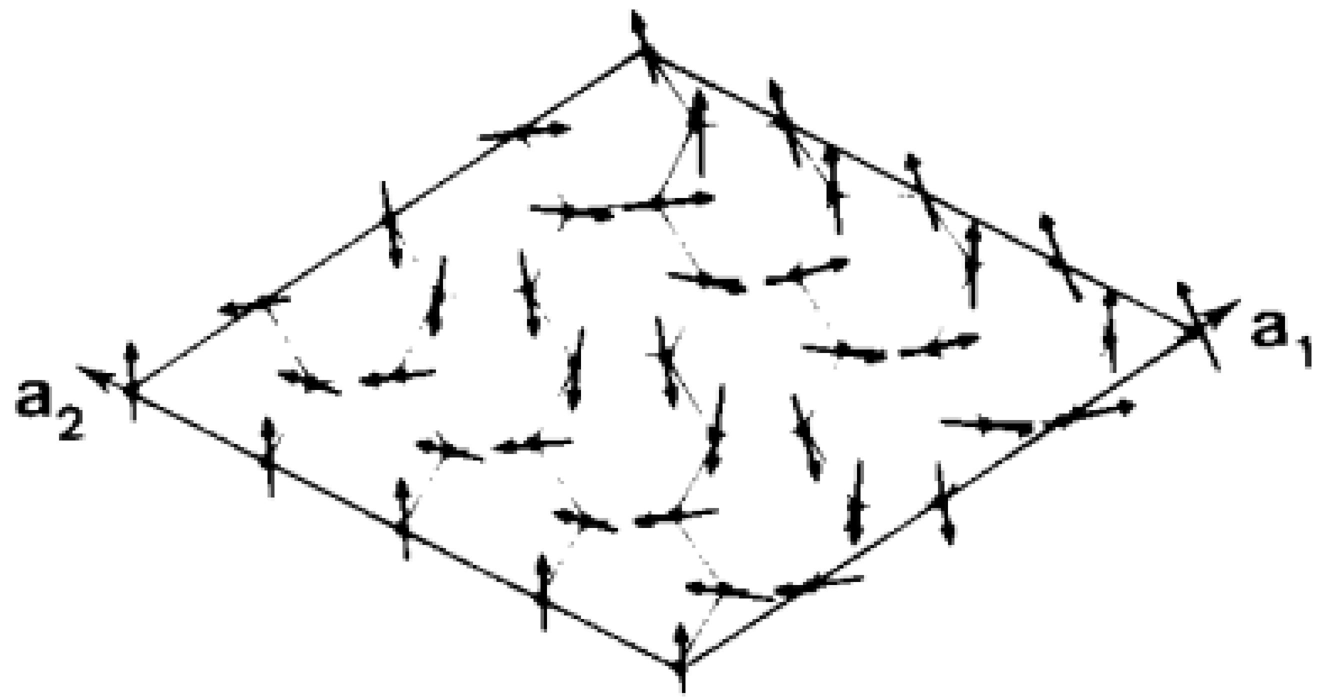
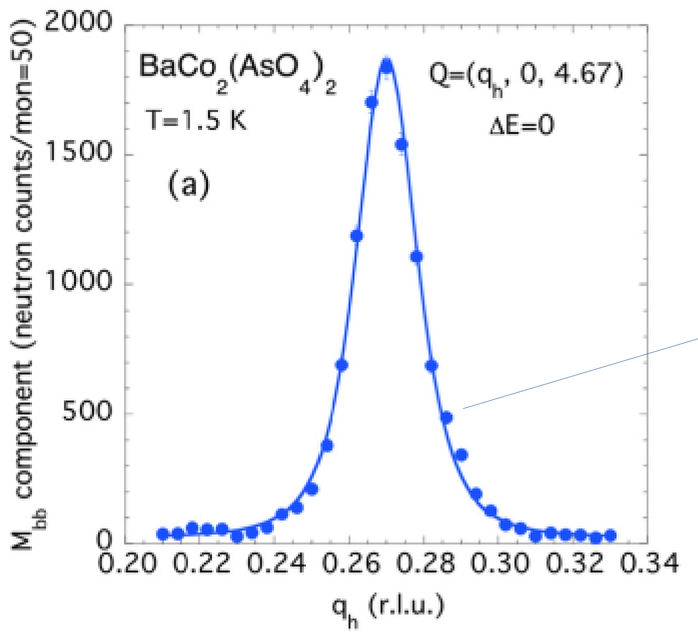
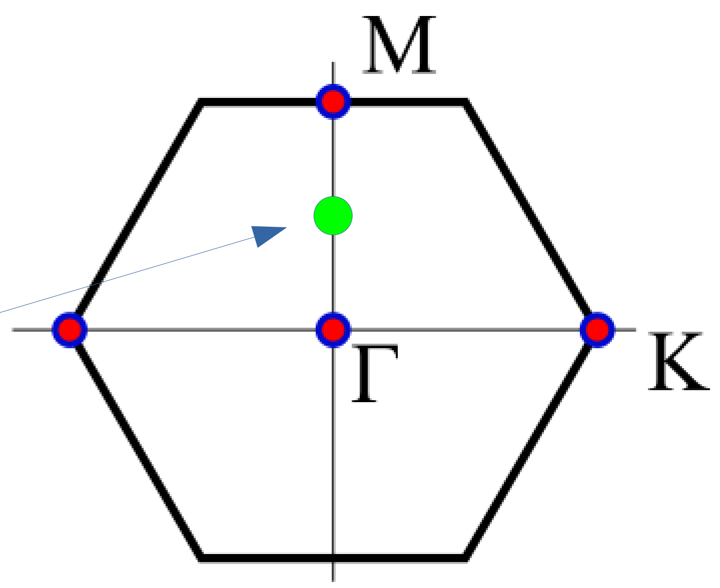
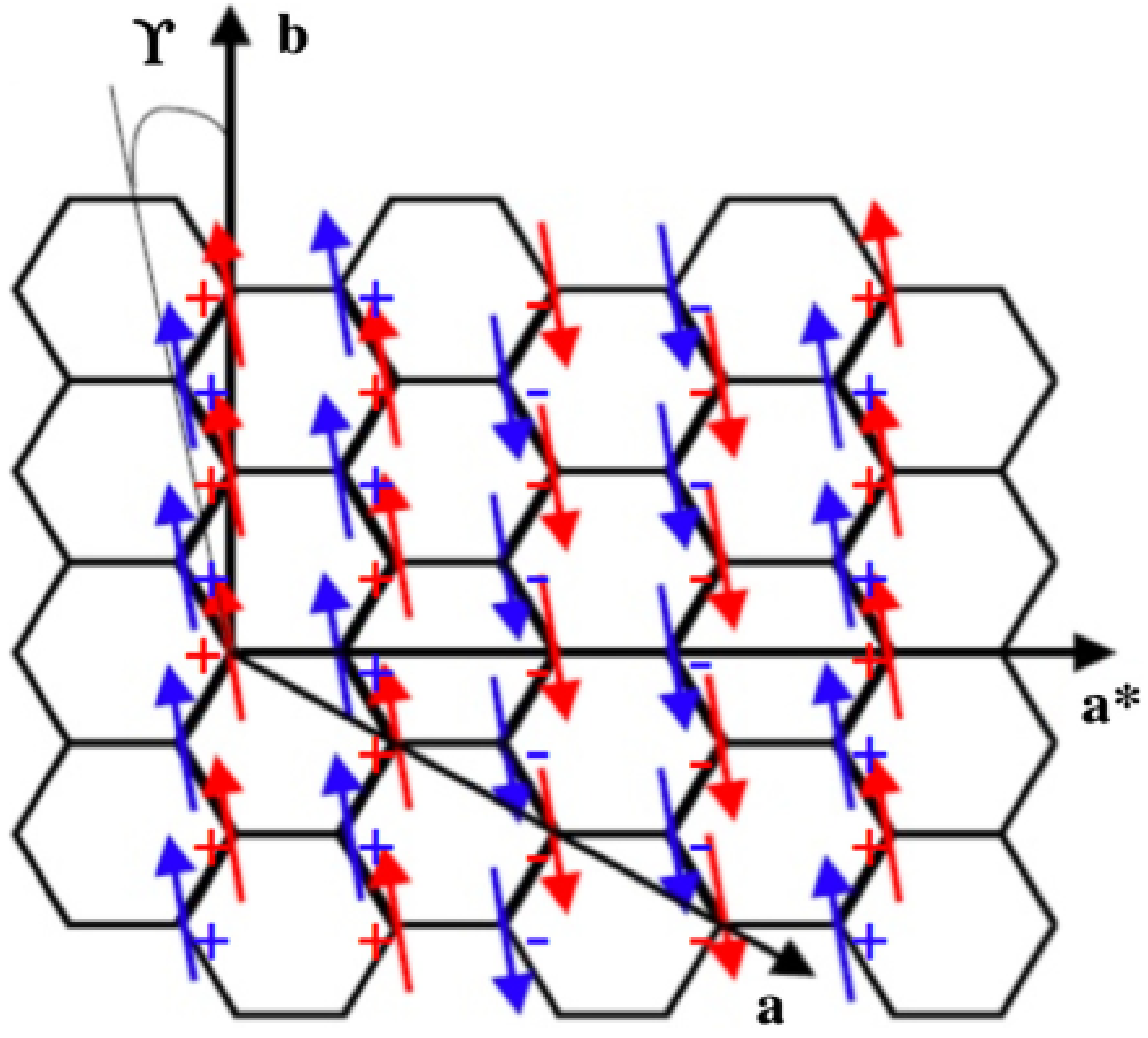


Fig. 2. In-plane magnetic order of Co^{2+} moments in $BaCo_2(AsO_4)_2$.

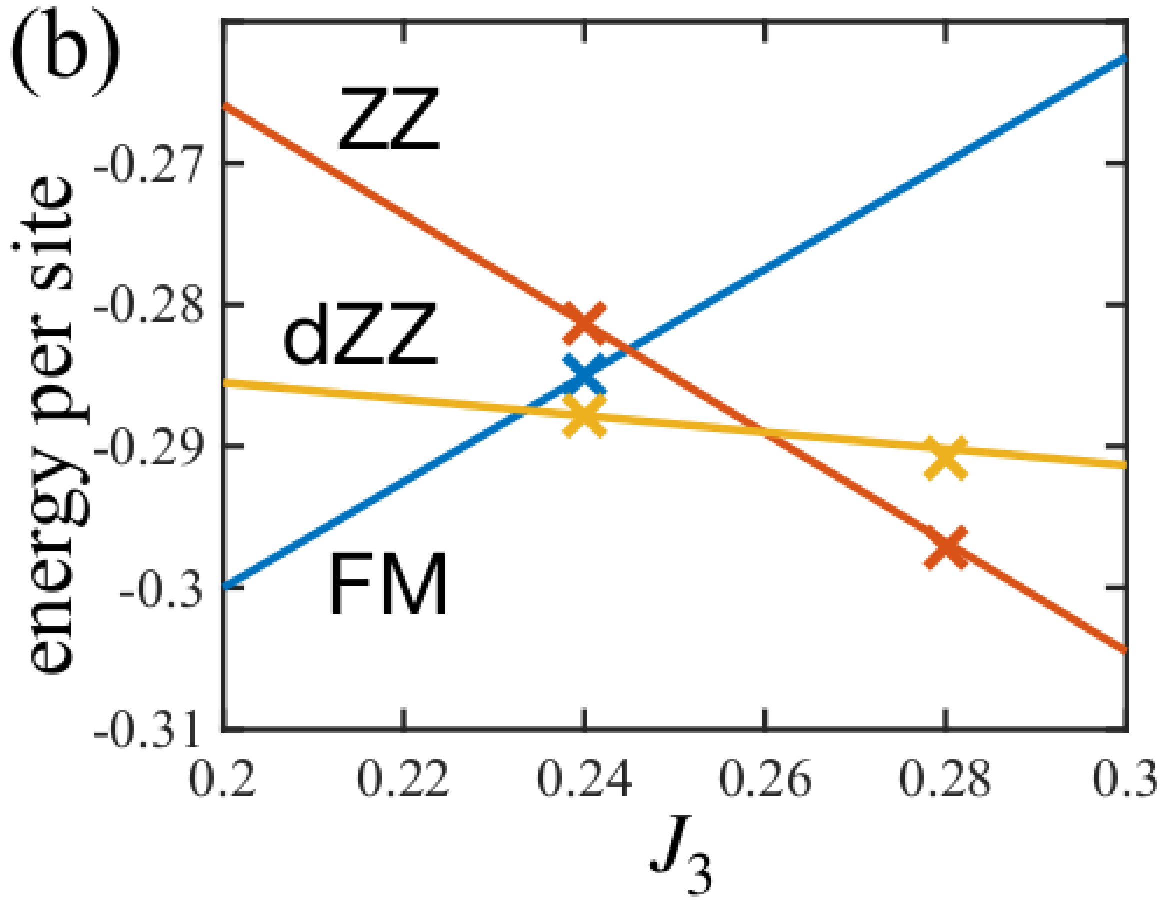




L.P. Regnault et al., Physica B+C 86, 660 (1977)



L.P. Regnault et al., Heliyon 4, e00507 (2018)

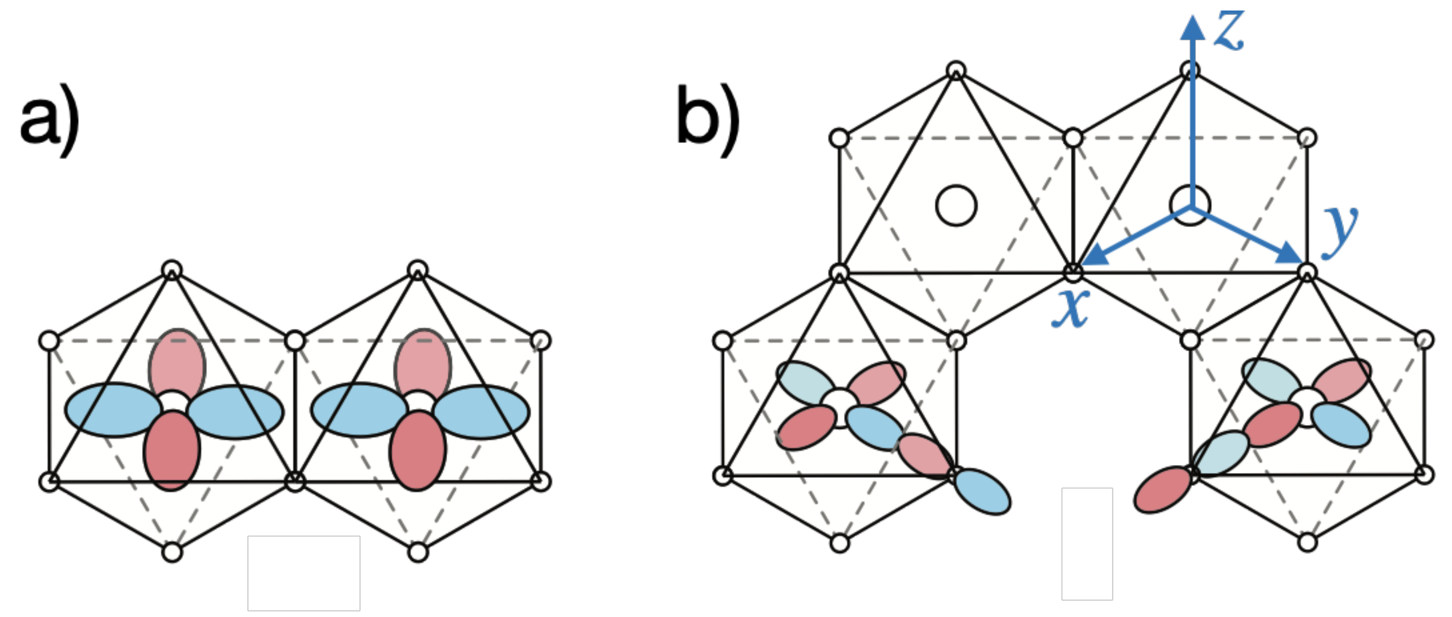


Jiang et al., arxiv 2304.06062

- Need exchanges beyond Heisenberg
- Kitaev model?

$BaCo_2(AsO_4)_2$: *ab initio* exchanges

DFT /A. Ushakov, Z. Pchelkina, S. Streltsov (ИФМ УрО РАН)/
(total energy method)



Direct hopping t`~ −300 meV is larger than through xz, yz orbitals, t ~ 50 meV

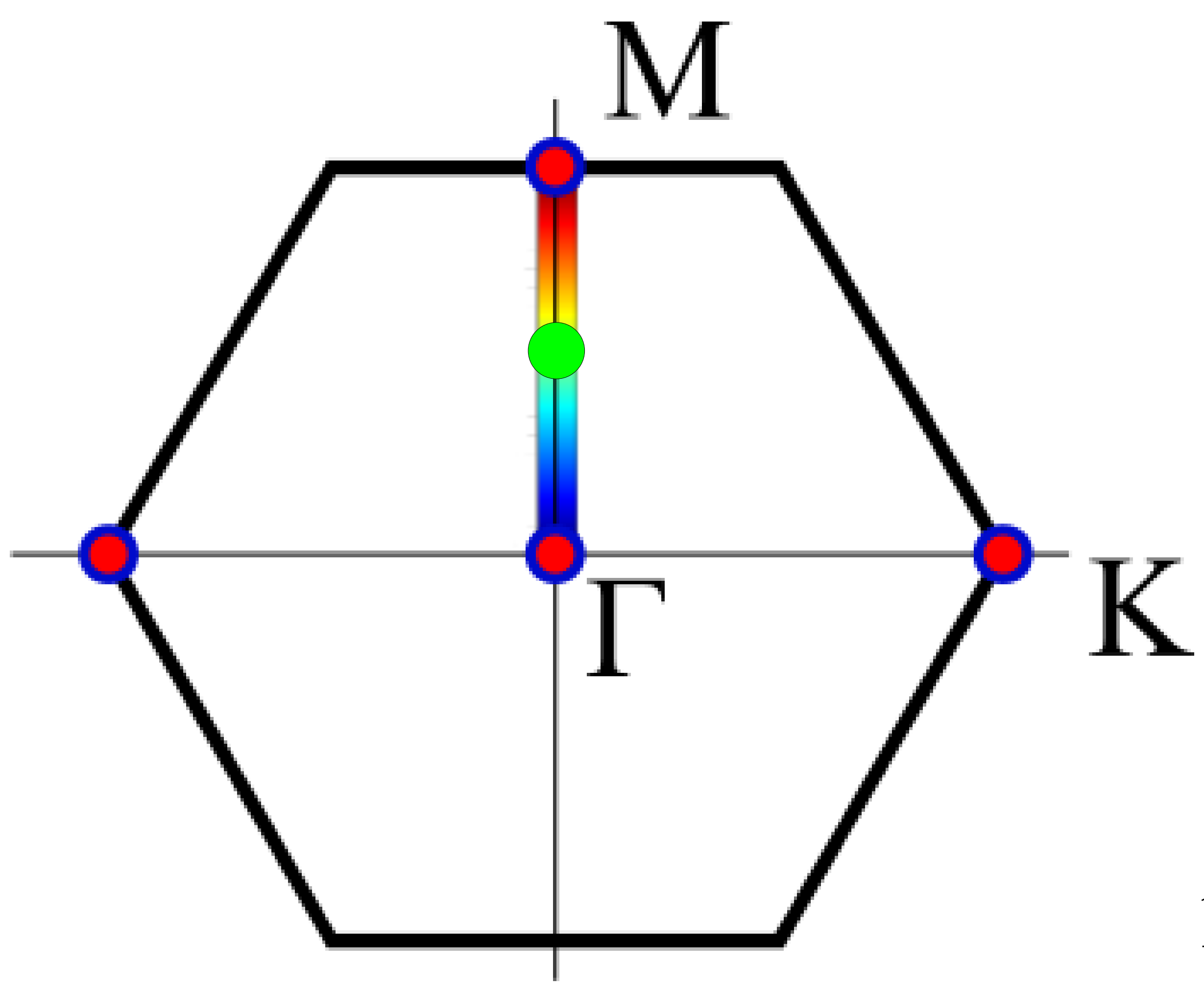
Strong overlap of third-neighbor orbitals
t_3=124meV

ED /S.Winter, Y. Li (Wake Forest)/
(2-site Exact Diagonalization)

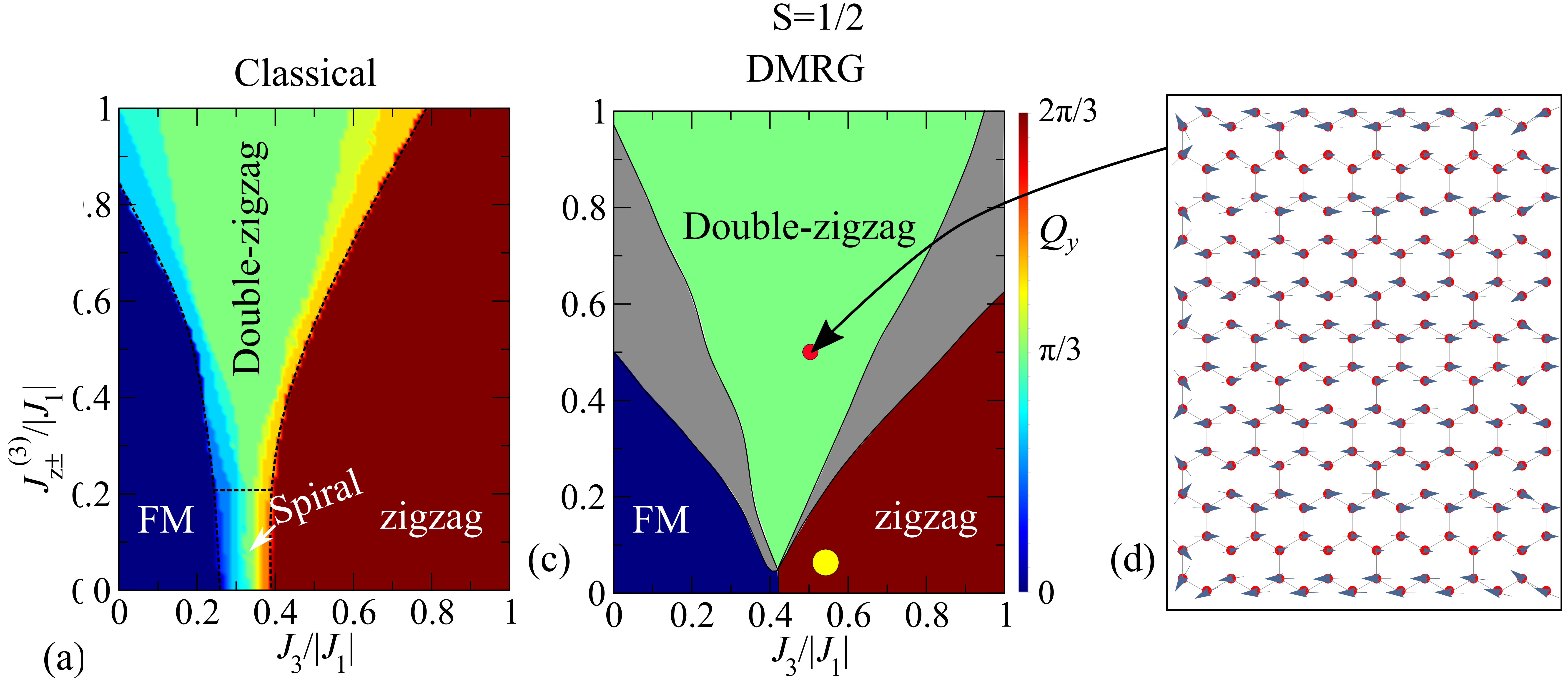
U	5 eV	6 eV	7 eV
J_1 (K)	-61.0	-40.9	-37.6
K_1 (K)	0.3	2.2	5.3
Γ_1 (K)	-2.2	-1.7	-1.8
Γ'_1 (K)	5.1	4.0	3.2
J_3 (K)	31.4	24.6	18.7
K_3 (K)	-0.2	0.2	-0.2
Γ_3 (K)	-4.5	-6.0	-4.5
Γ'_3 (K)	-3.6	-2.3	-1.8

$J_{H,t_{2g}}$	0.7 eV		0.9 eV	
U	3.25 eV	5 eV	6 eV	7 eV
J_1 (K)	-107 (-127)	-37 (-57)	-18 (-38)	-8.8 (-29)
K_1 (K)	32	13	6.5	3.4
Γ_1 (K)	28 (35)	14 (21)	8.0 (15)	4.8 (12)
Γ'_1 (K)	9.4 (16)	7 (14)	4.0 (11)	2.4 (9)
J_3 (K)	43	30	27	24
K_3 (K)	-0.6	-0.4	-0.3	-0.3
Γ_3 (K)	-20	-12	-10	-8.9
Γ'_3 (K)	-21	-12	-11	-9.2

Double-zigzag state in $BaCo_2(AsO_4)_2$

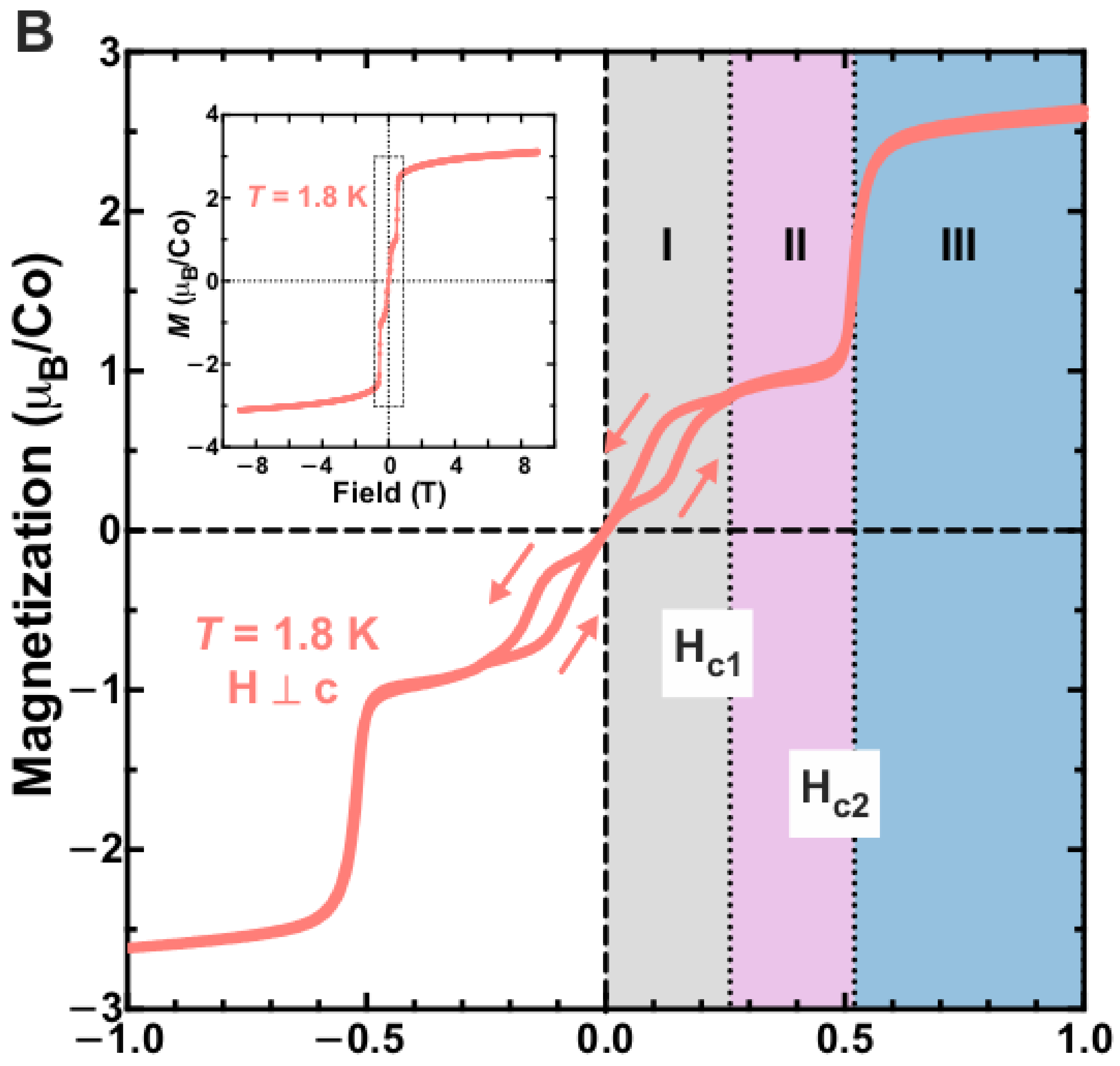


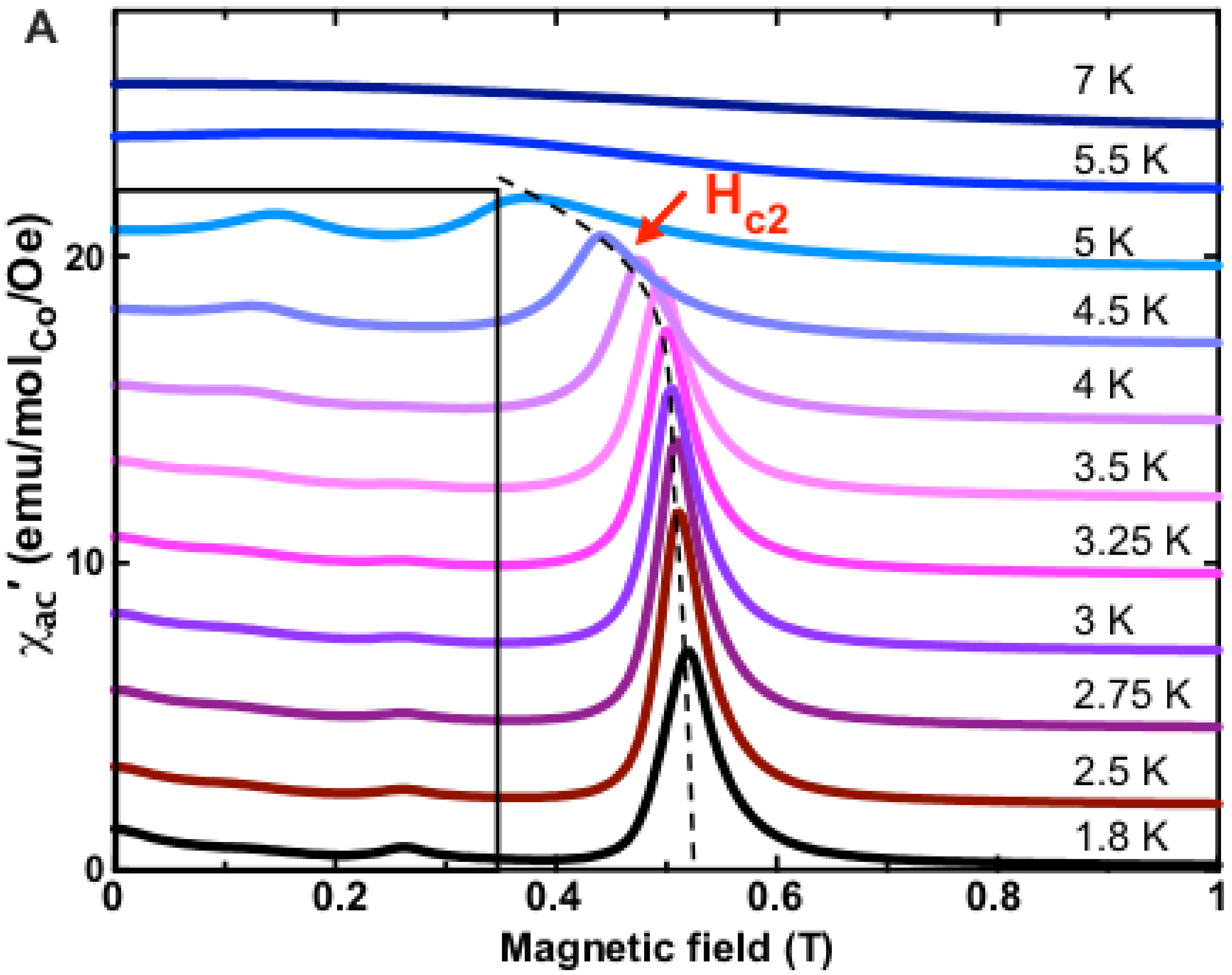
$$H_{\min} = \sum_{\langle ij\rangle_1} J_1\left(S_i^x S_j^x + S_i^y S_j^y\right) + J_3 \sum_{\langle ij\rangle_3}\left(S_i^x S_j^x + S_i^y S_j^y\right)$$
$$- J_{z\pm}^{(3)}\left(\left(S_i^x S_j^z + S_i^z S_j^x\right)c_\alpha + \left(S_i^y S_j^z + S_i^z S_j^y\right)s_\alpha\right),$$



P. A. Maksimov, Alexey V. Ushakov, Zlata V. Pchelkina, Ying Li, Stephen M. Winter, and Sergey V. Streltsov, Phys. Rev. B 106, 165131 (2022)

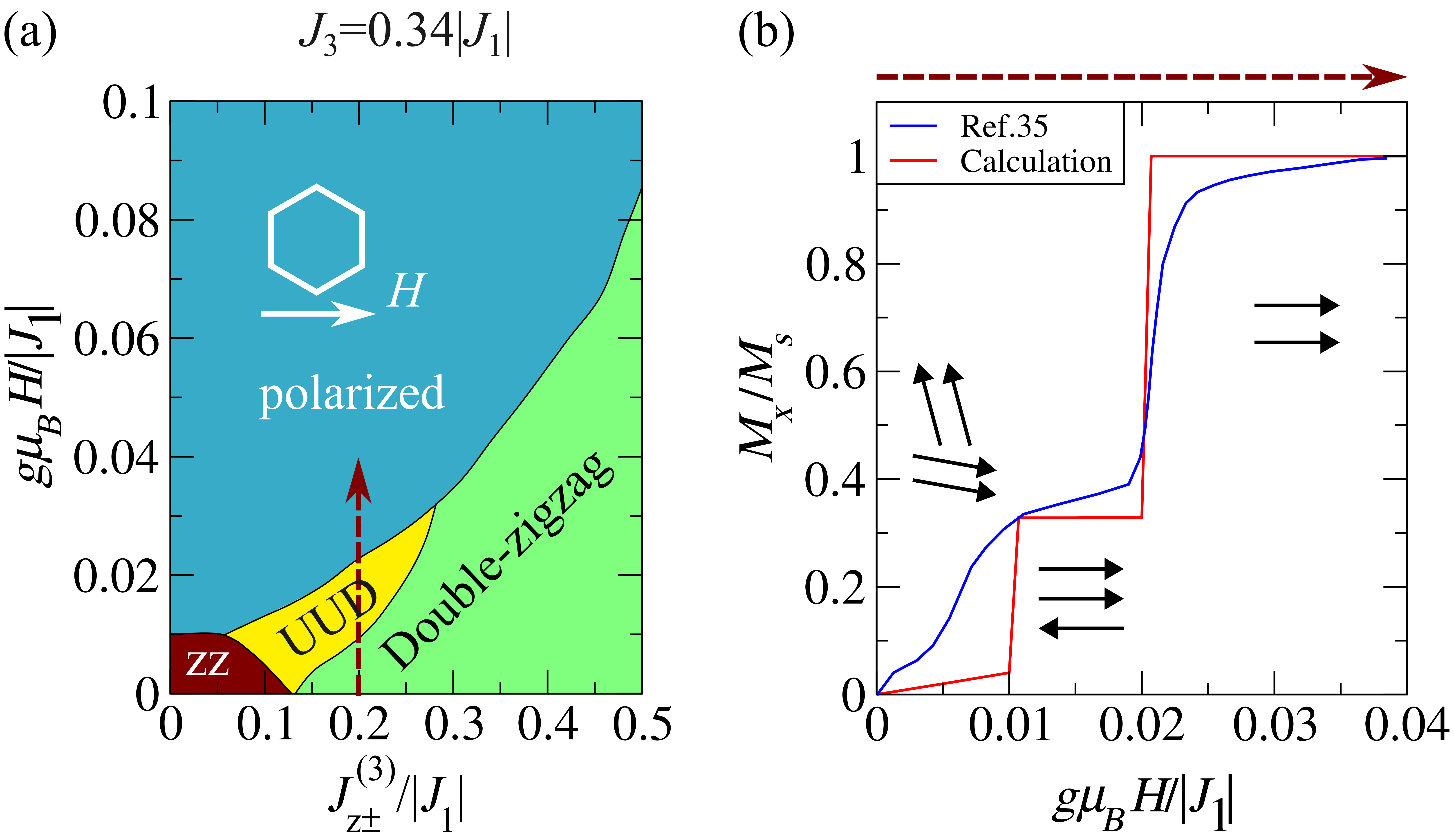
Field-induced transitions in $BaCo_2(AsO_4)_2$

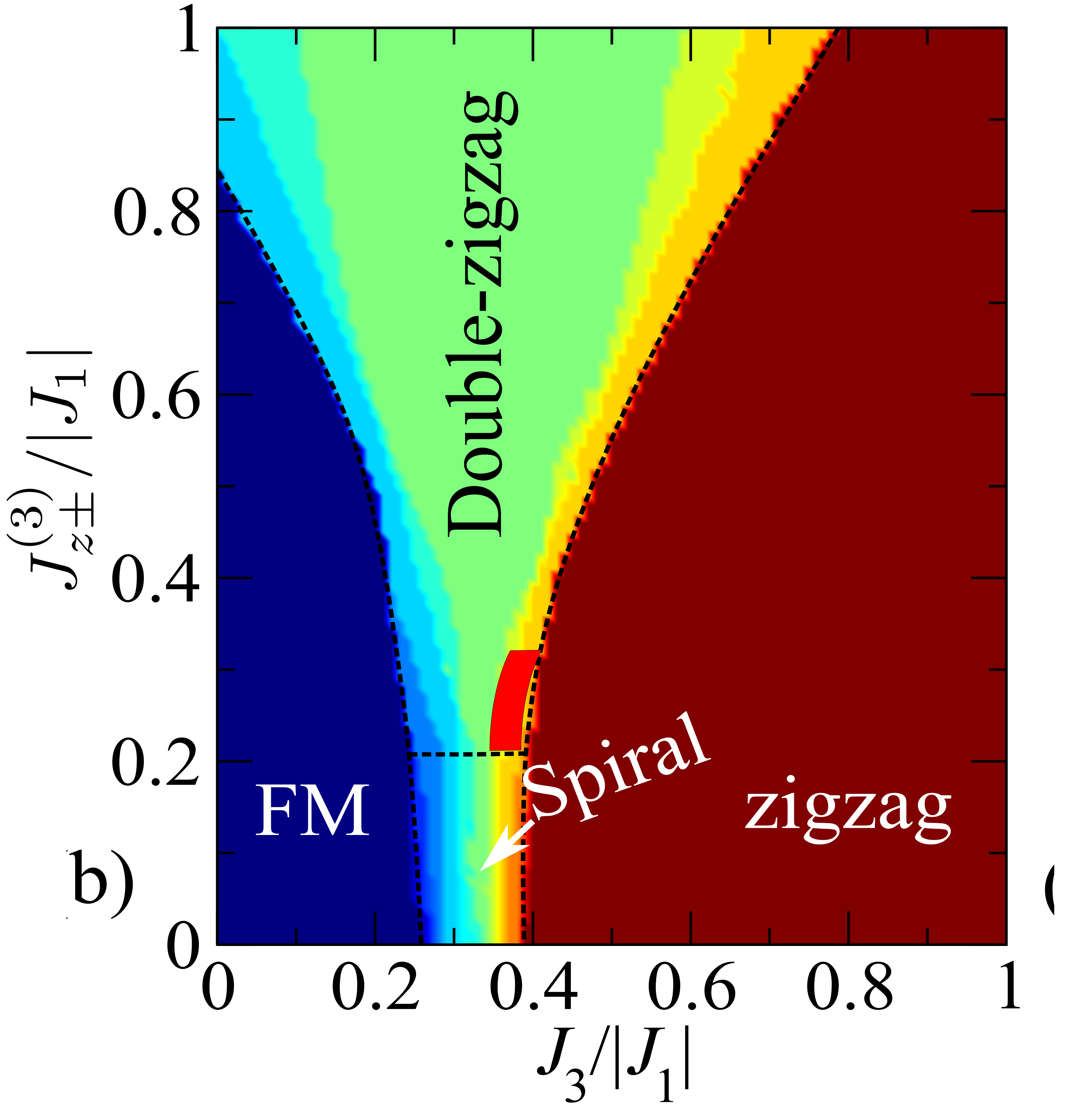




R. Zhong, T. Gao, N. P. Ong, and R. J. Cava, Sci. Adv. 6, eaay6953 (2020)

Field-induced transitions in $BaCo_2(AsO_4)_2$





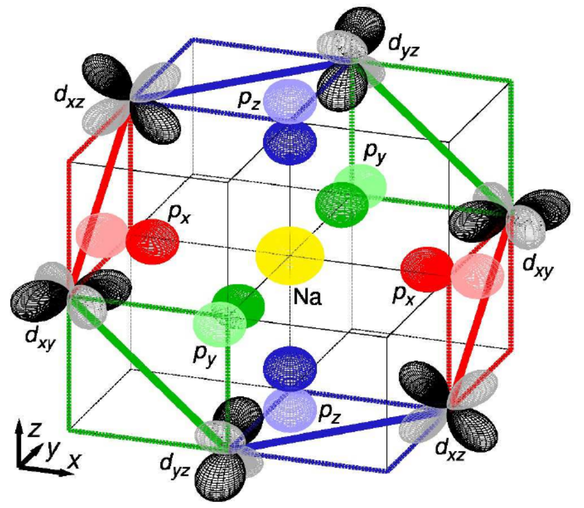
R. Zhong, T. Gao, N. P. Ong, and R. J. Cava, Sci. Adv. 6, eaay6953 (2020)

P.A. Maksimov, arxiv 2308.10672

Conclusions

- Kitaev model is exactly solvable and its excitations can be used for topological QC
- Kitaev model can be realized in transition metal compounds with strong SOC
- Additional interactions are allowed by symmetry and lead long-range order
- Phase diagram of extended Kitaev-Heisenberg model exhibits a plethora of exotic states

$$S^x = ib^x c,\ \ S^y = ib^y c,\ \ S^z = ib^z c$$



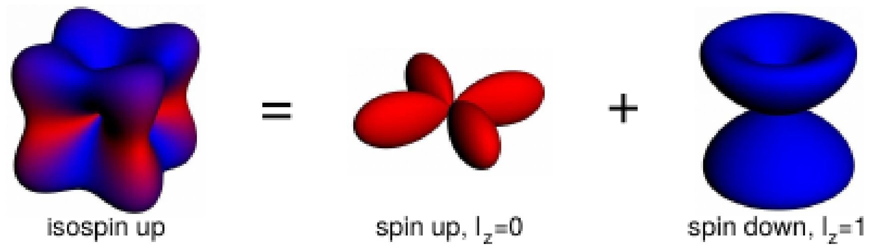
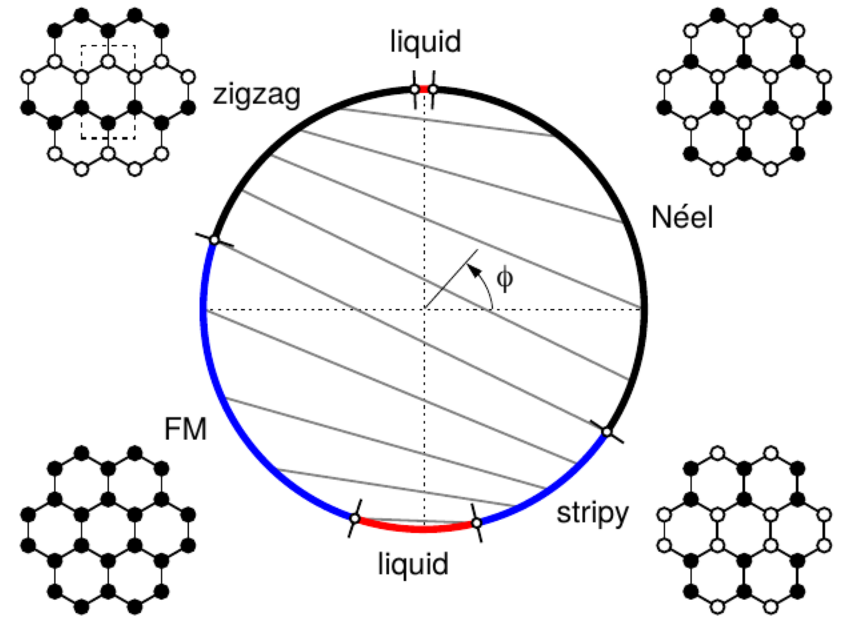
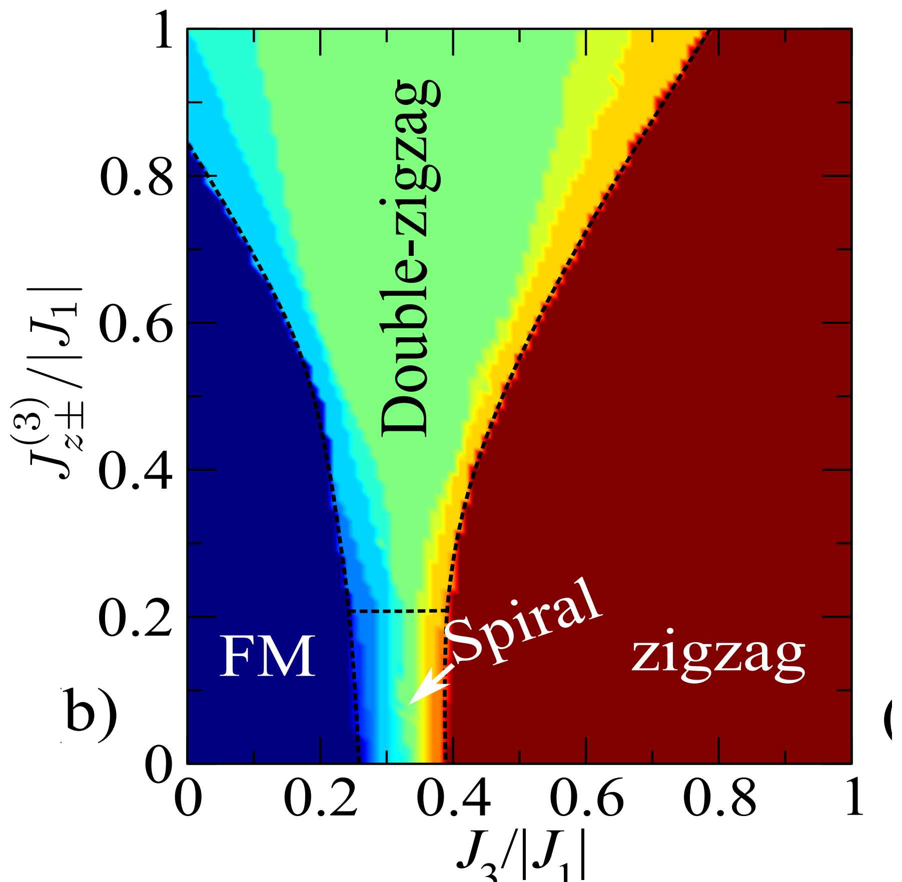


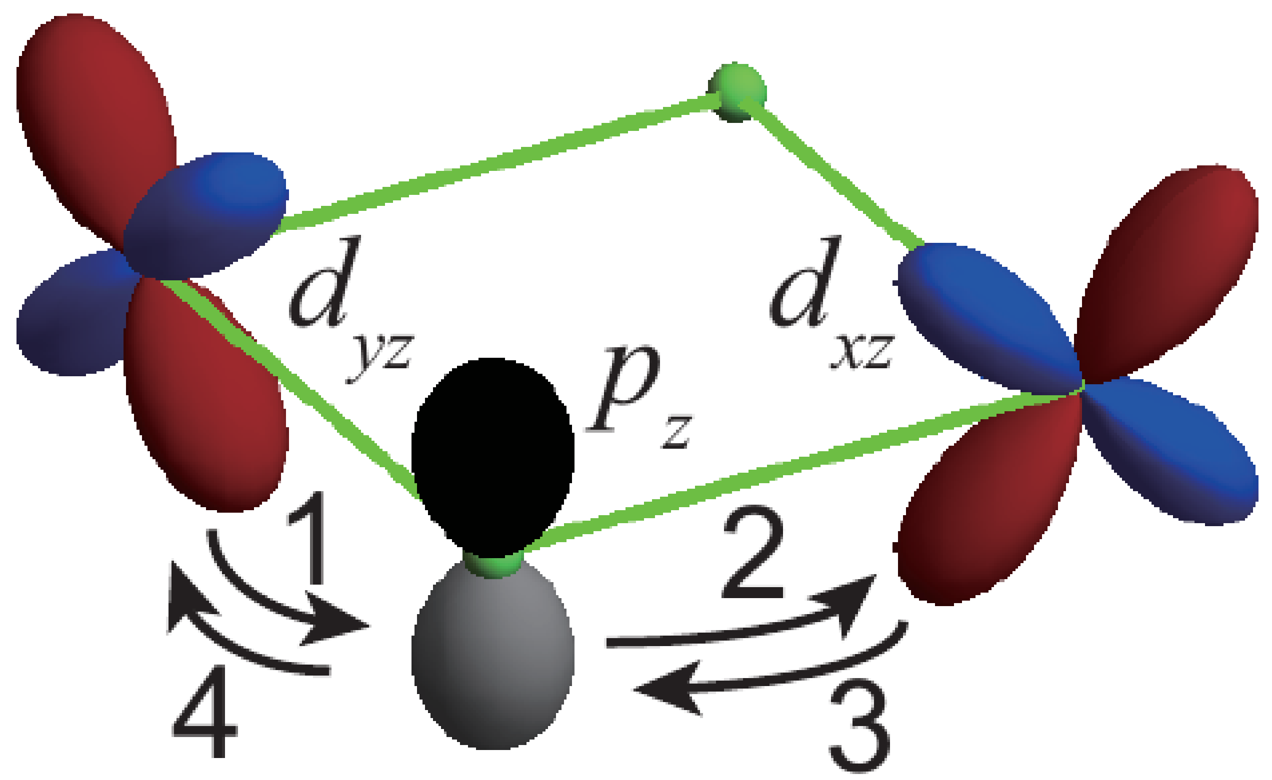
FIG. 1: (Color online) Density profile of a hole in the isospin up state (without tetragonal distortion). It is a superposition of a spin up hole density in $|xy\rangle$-orbital, $l_z = 0$, (middle) and spin down one in $(|yz\rangle + i|xz\rangle)$ state, $l_z = 1$, (right).

(a)

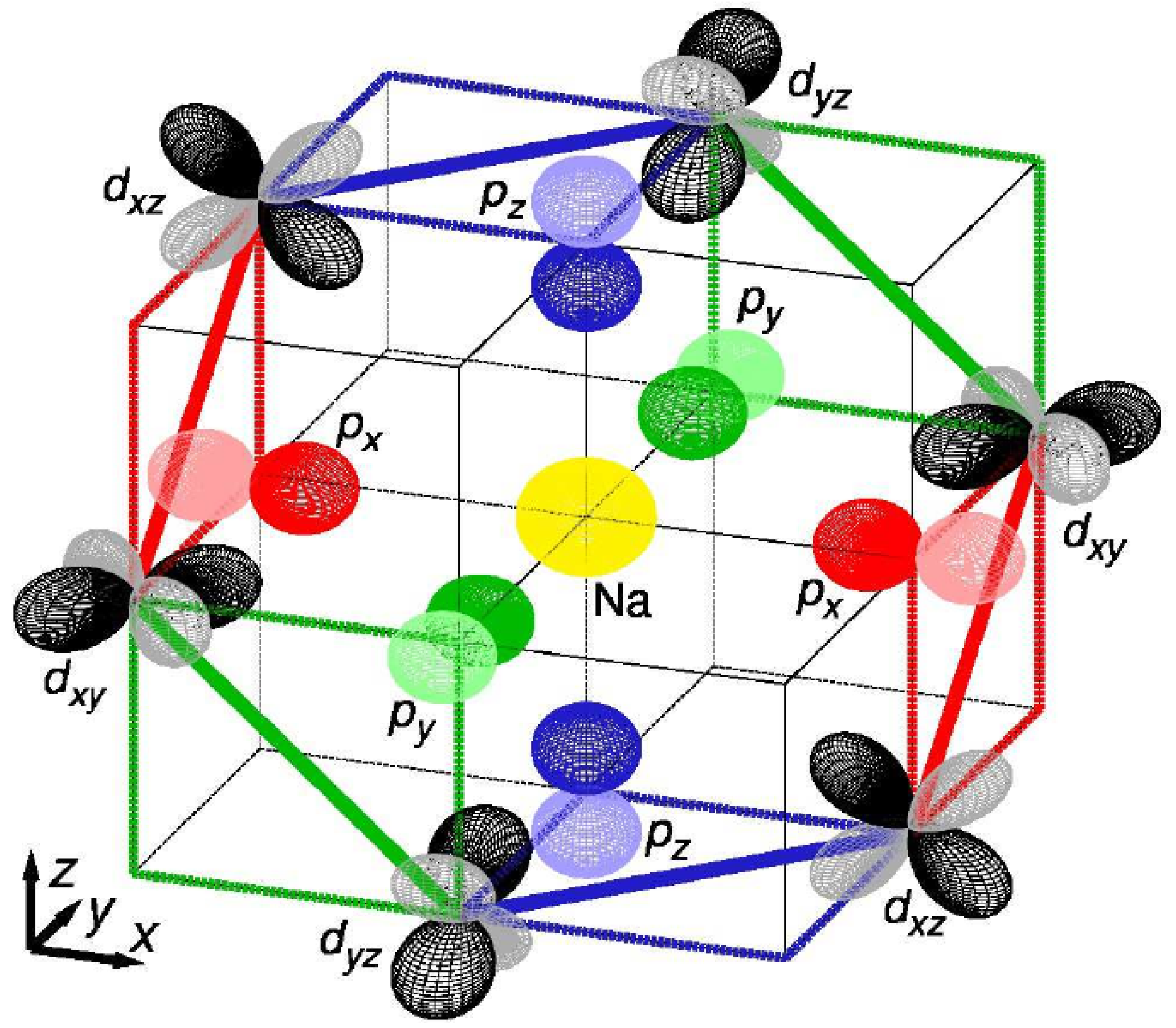


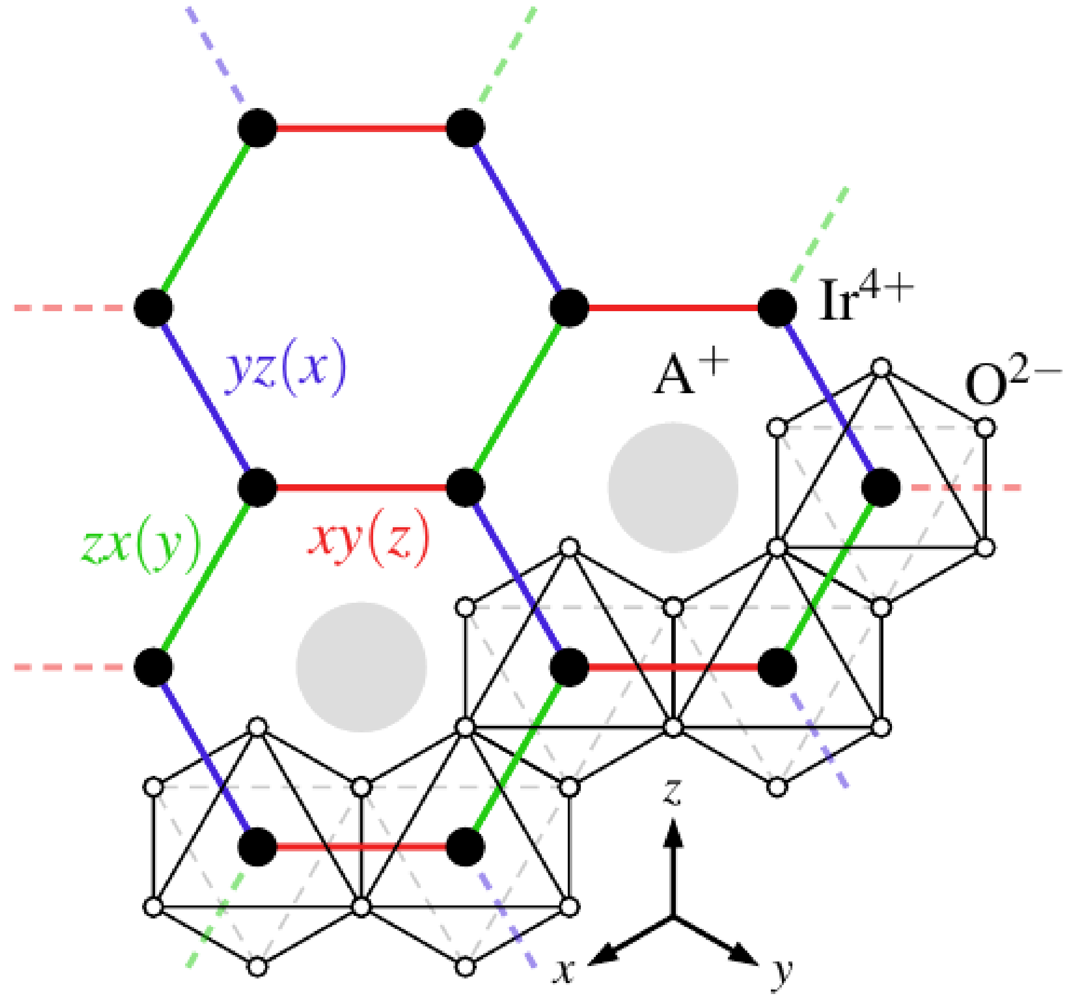


Реализация в материалах: d^5 металлы



Взаимодействует только z-компонента псевдоспина





$$\mathcal{H} = K \sum_{\langle ij \rangle^\gamma} S_i^\gamma S_j^\gamma$$

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

Реализация в материалах: d^5 металлы

$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J \mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma$$

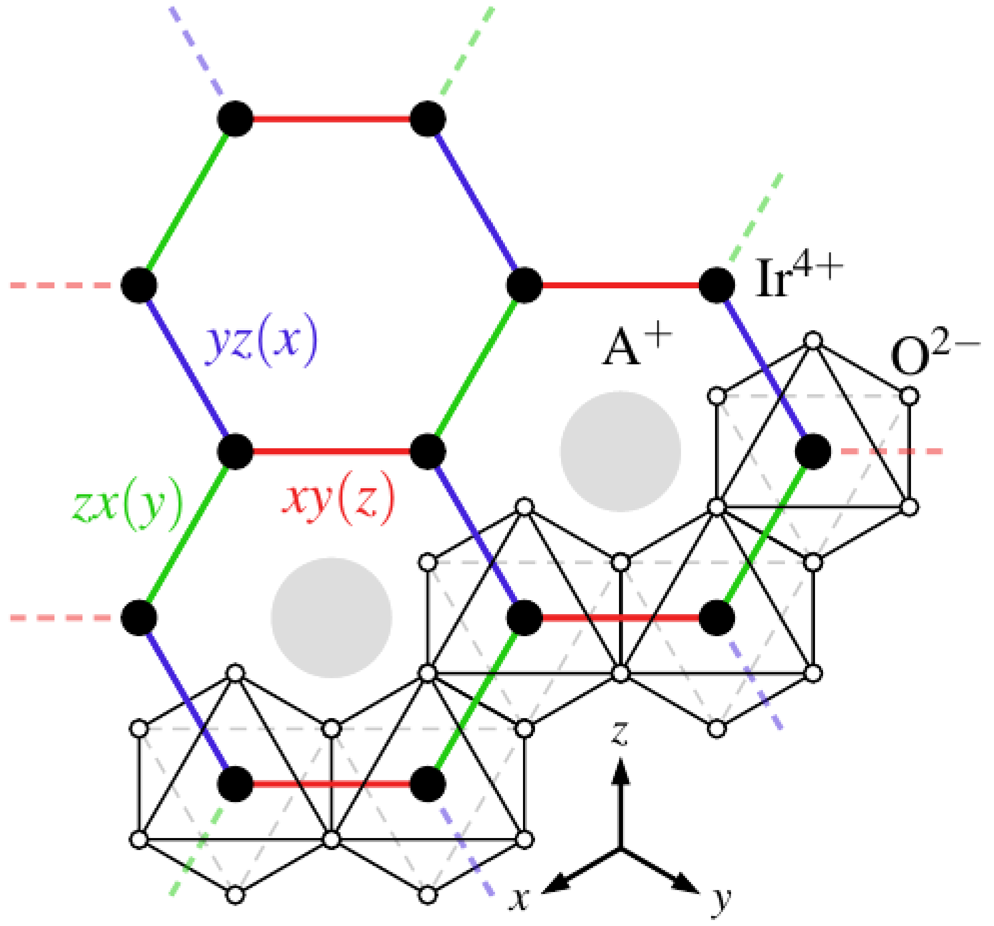
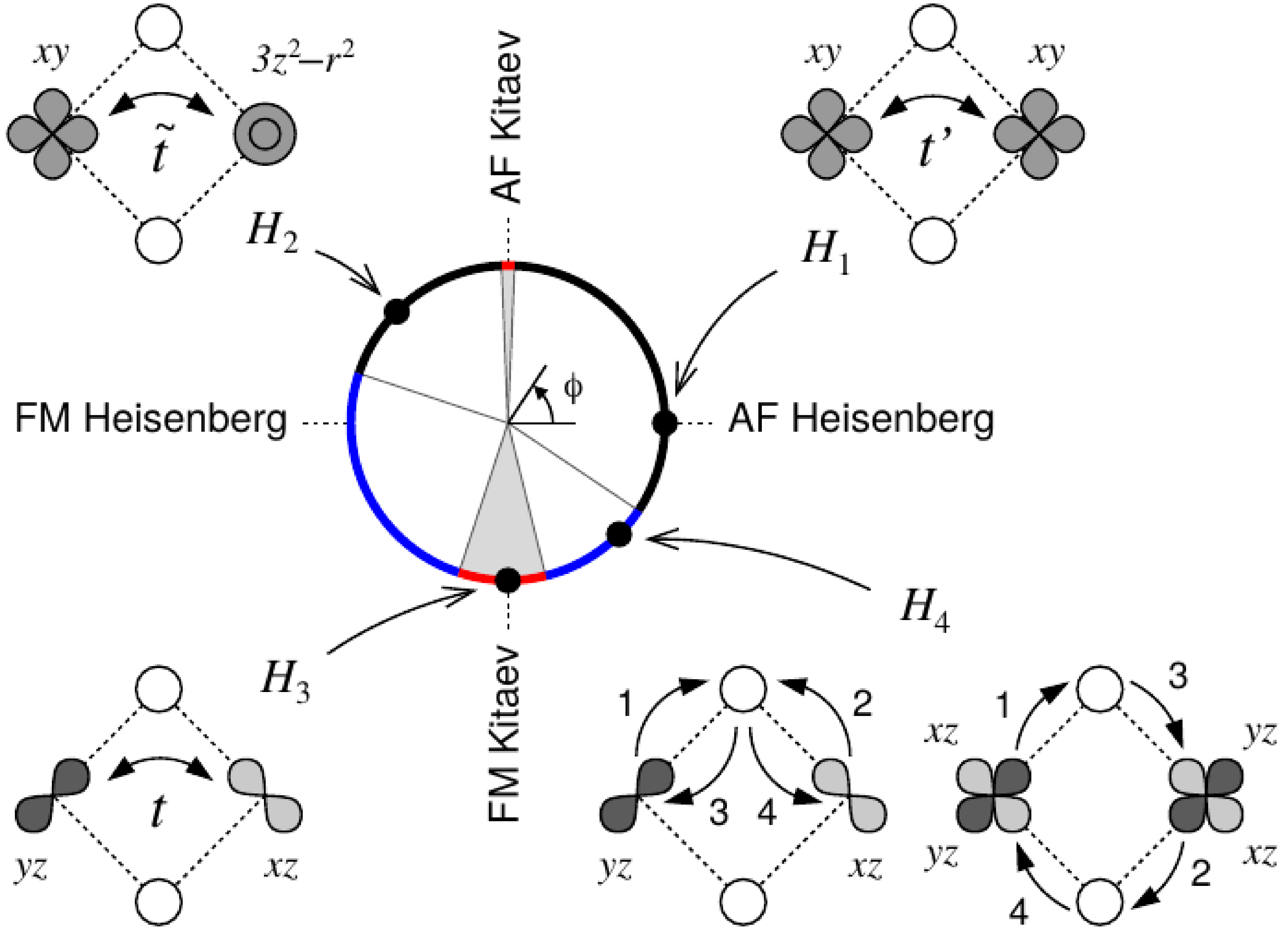


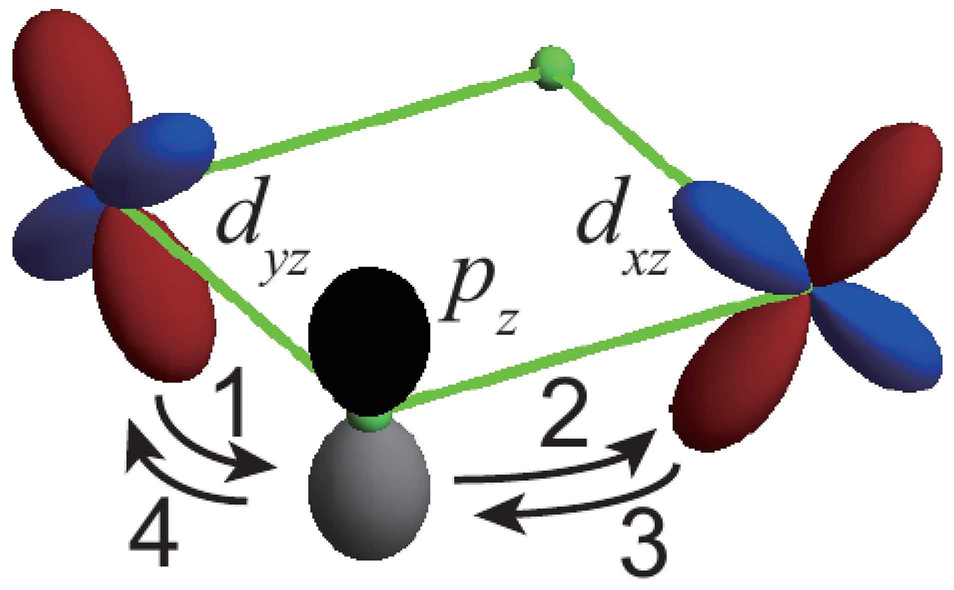
FIG. 1: Crystal structure of the honeycomb iridates A_2IrO_3 with Ir^{4+} in black, O^{2-} in white, and A = Na^+, Li^+ in gray. For the Kitaev and bond-dependent exchanges we have denoted the $yz(x)$ bonds blue, the $zx(y)$ bonds green and the $xy(z)$ bonds red.



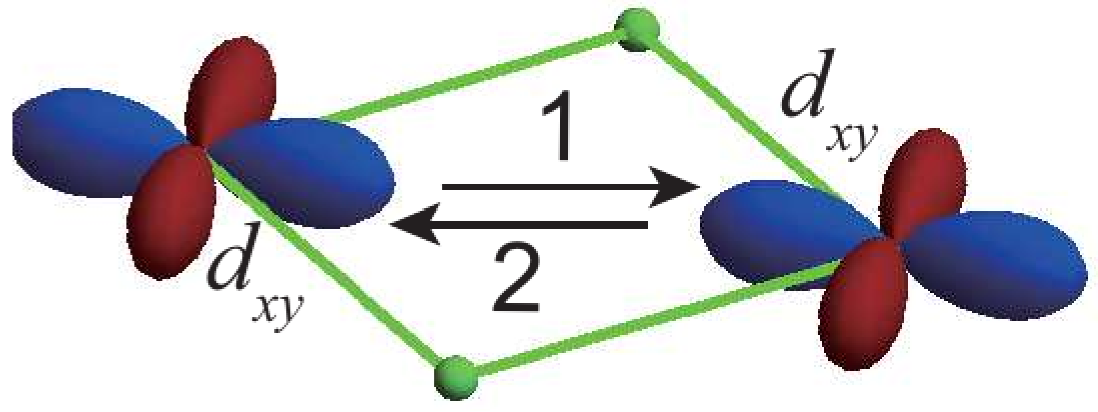
$$J = \cos\phi, \;\; K = \sin\phi$$

Расширенная модель Китаева-Гейзенберга

Китаевское взаимодействие K

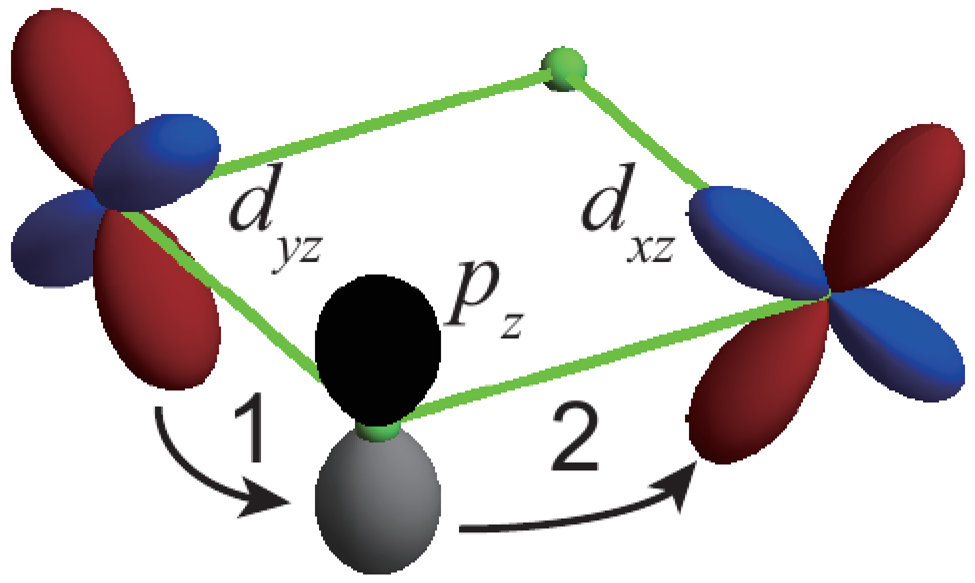


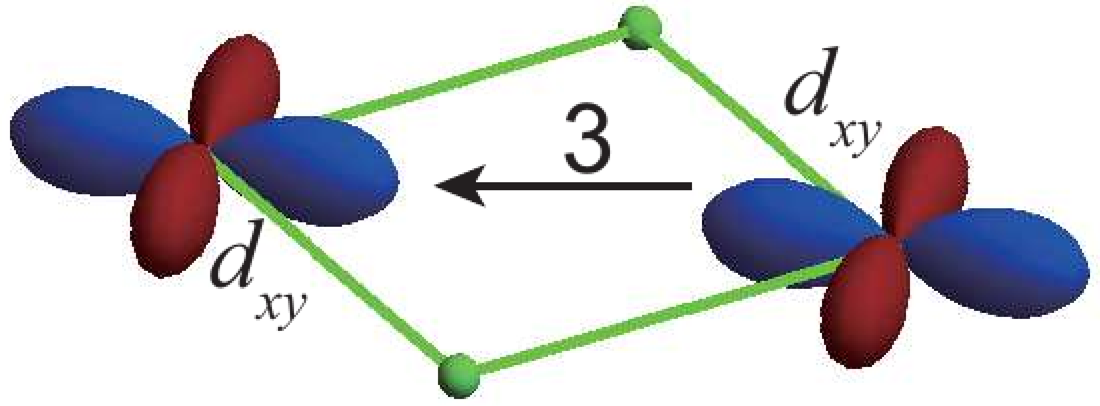
Гейзенберговское J



$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J\mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right)$$

Недиагональное взаимодействие Γ





Реальные системы с взаимодействием Китаева

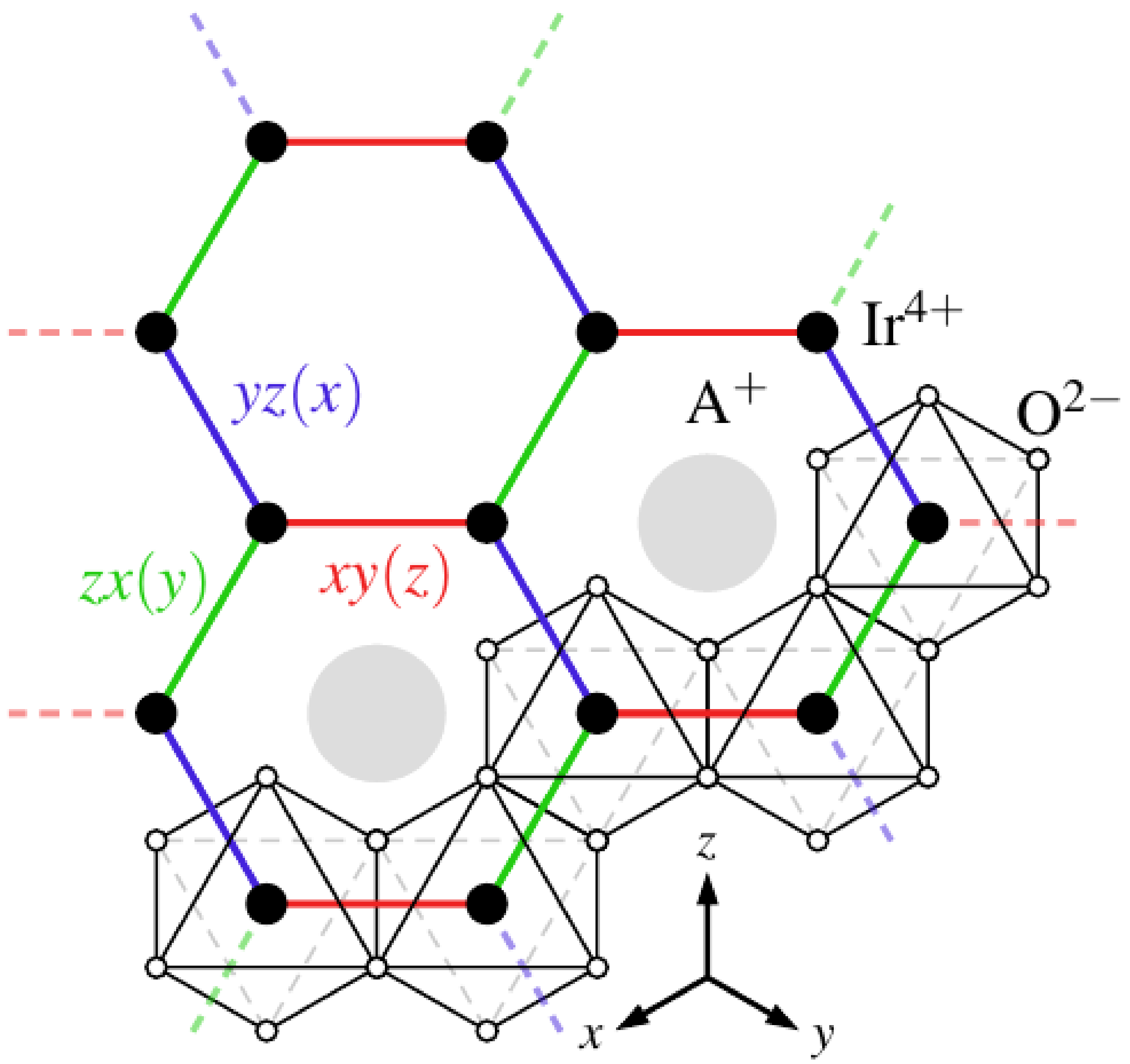


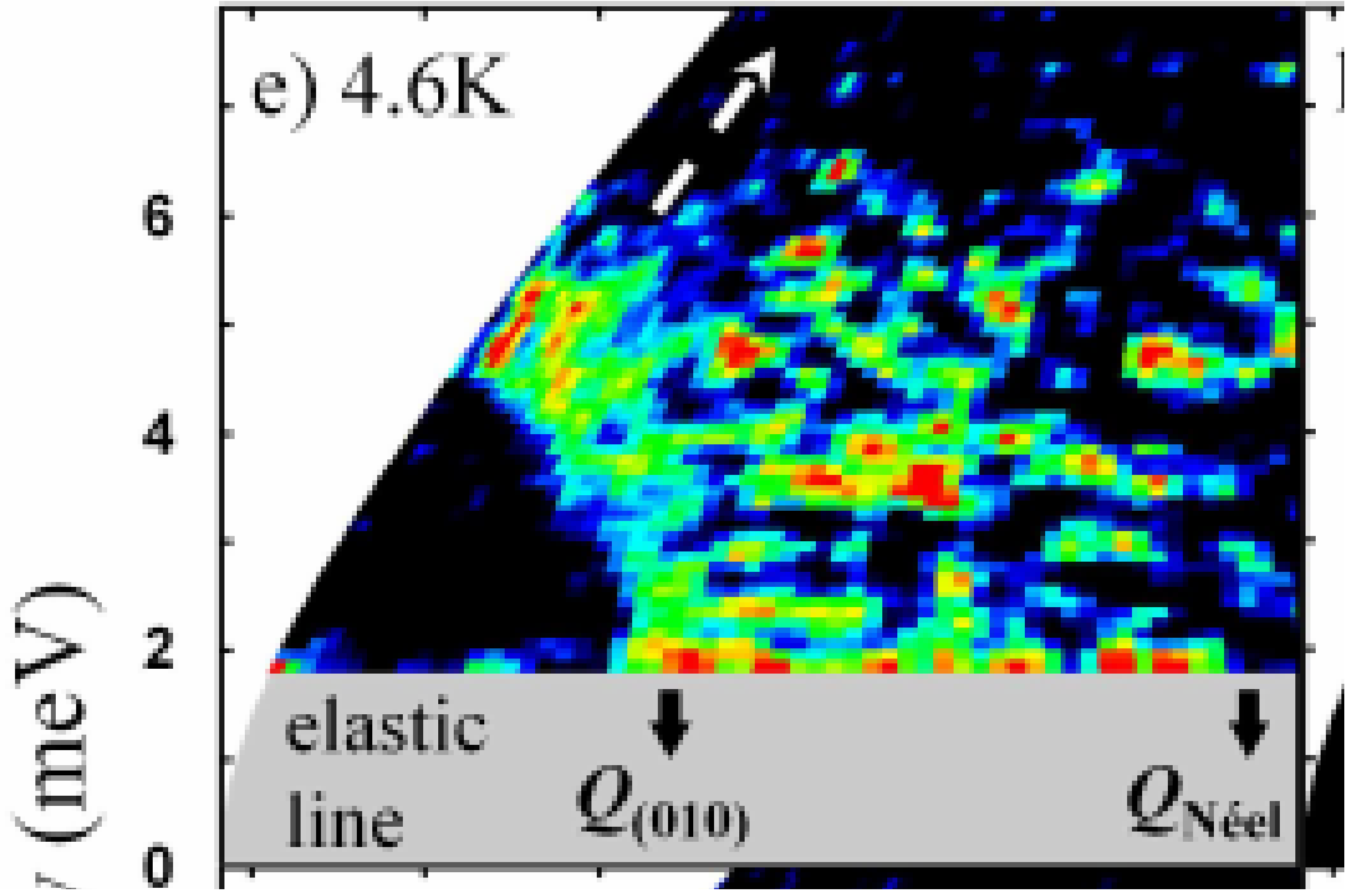
FIG. 1: Crystal structure of the honeycomb iridates A_2IrO_3 with Ir^{4+} in black, O^{2-} in white, and A = Na^+, Li^+ in gray. For the Kitaev and bond-dependent exchanges we have denoted the $yz(x)$ bonds blue, the $zx(y)$ bonds green and the $xy(z)$ bonds red.

При тригональном искажении октаэдров возможен еще дополнительный член. Тогда полный гамильтониан содержит 4 члена:

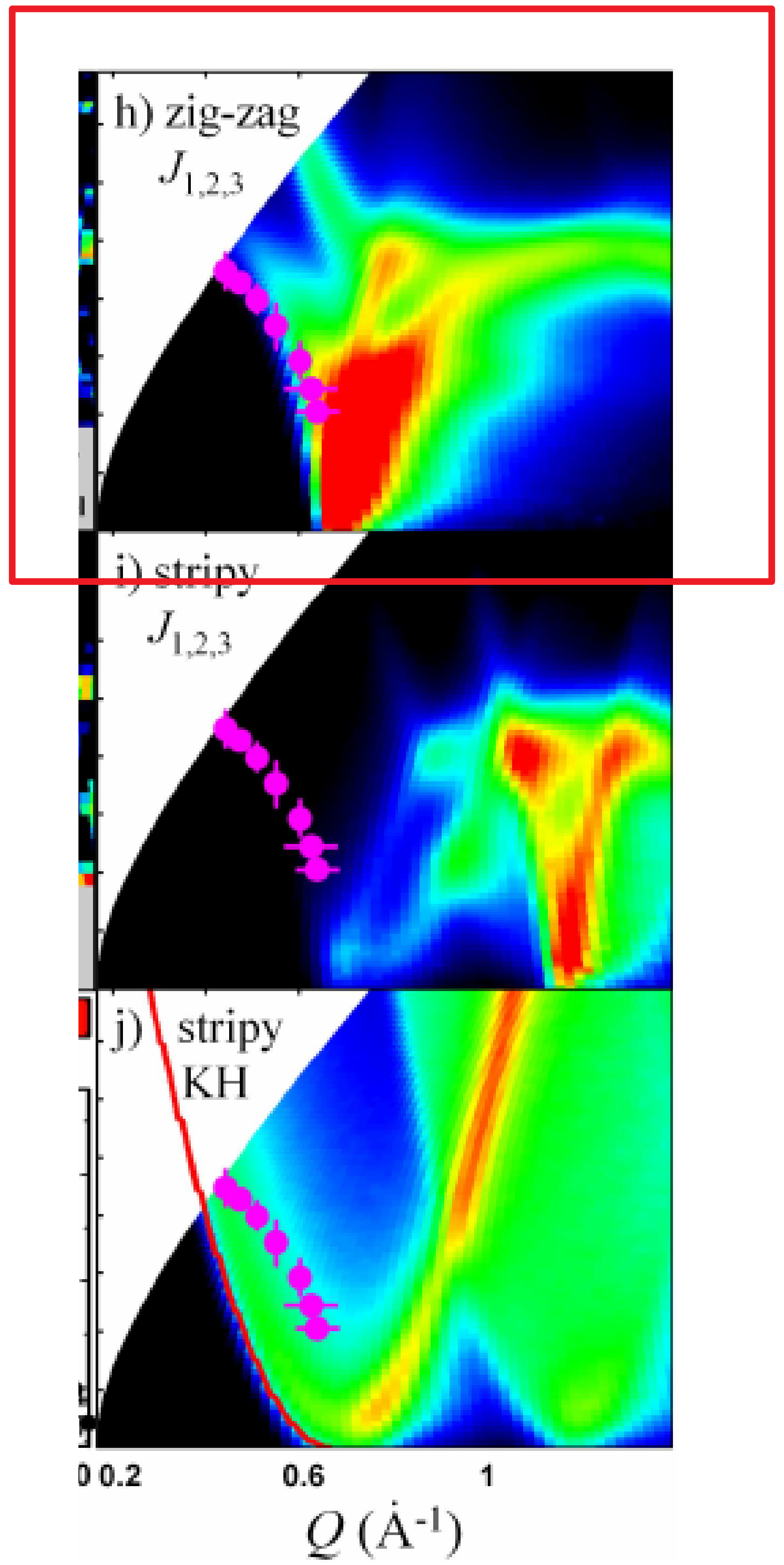
$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J\mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma + \Gamma \left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha \right) + \Gamma' \left(S_i^\gamma S_j^\alpha + S_i^\gamma S_j^\beta + S_i^\alpha S_j^\gamma + S_i^\beta S_j^\gamma \right)$$

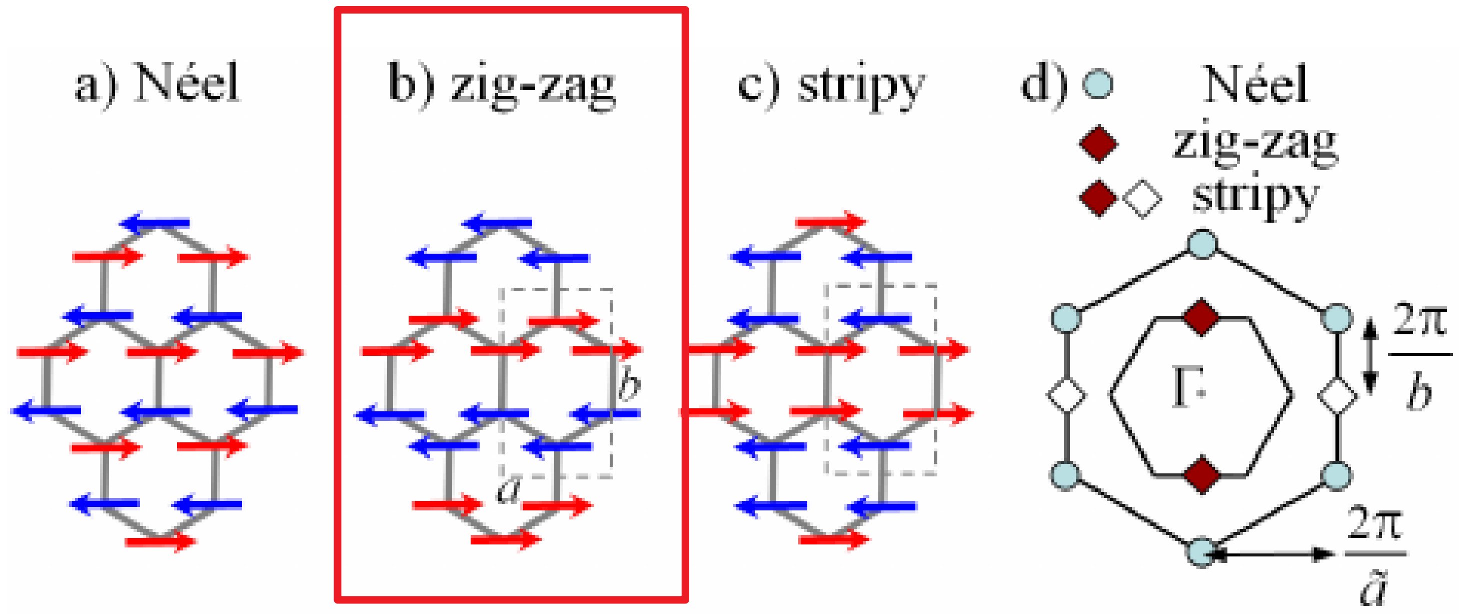
Основное состояние иридата натрия

Возможные состояния



Эксперимент по неупругому рассеянию нейтронов

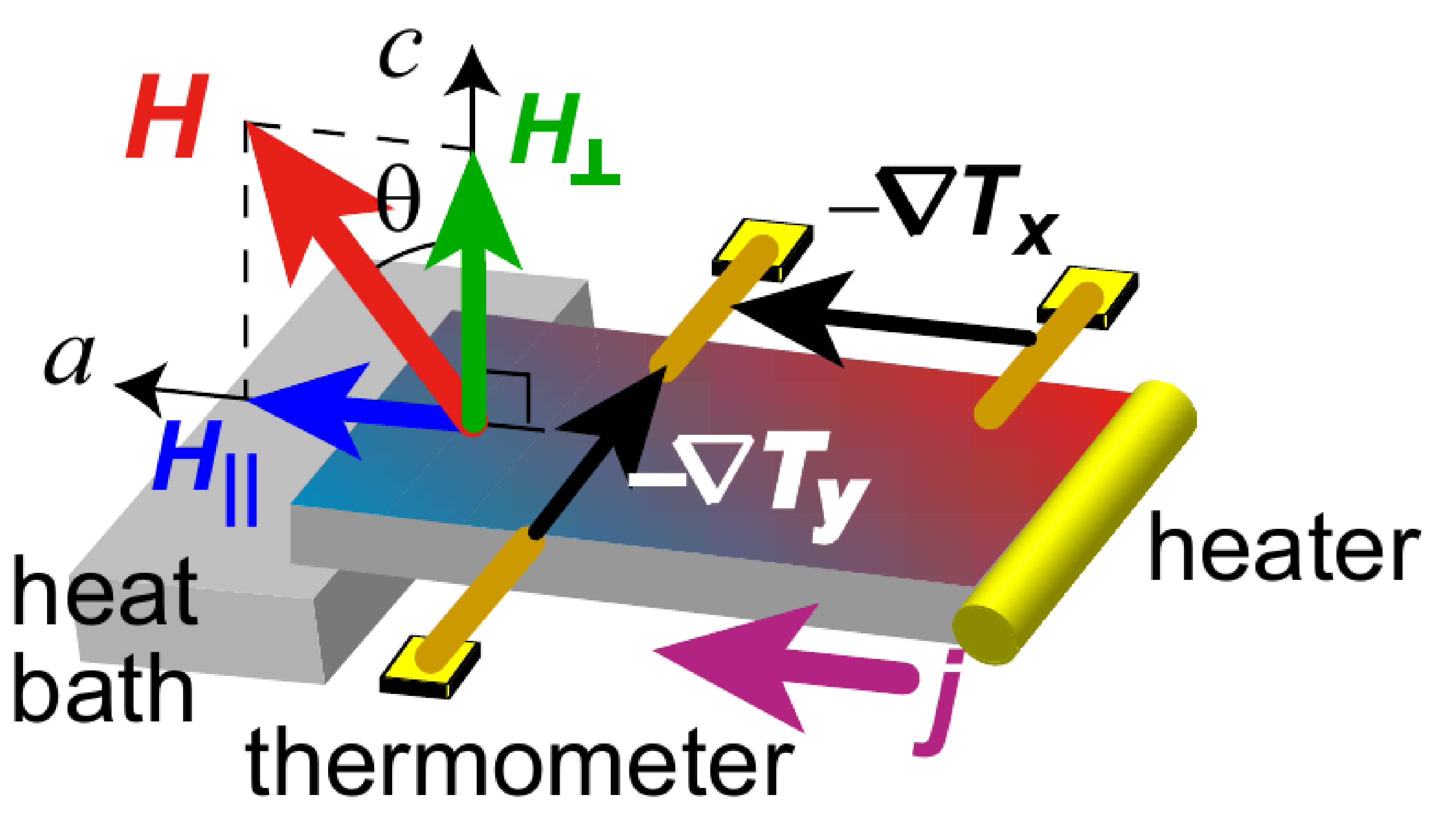


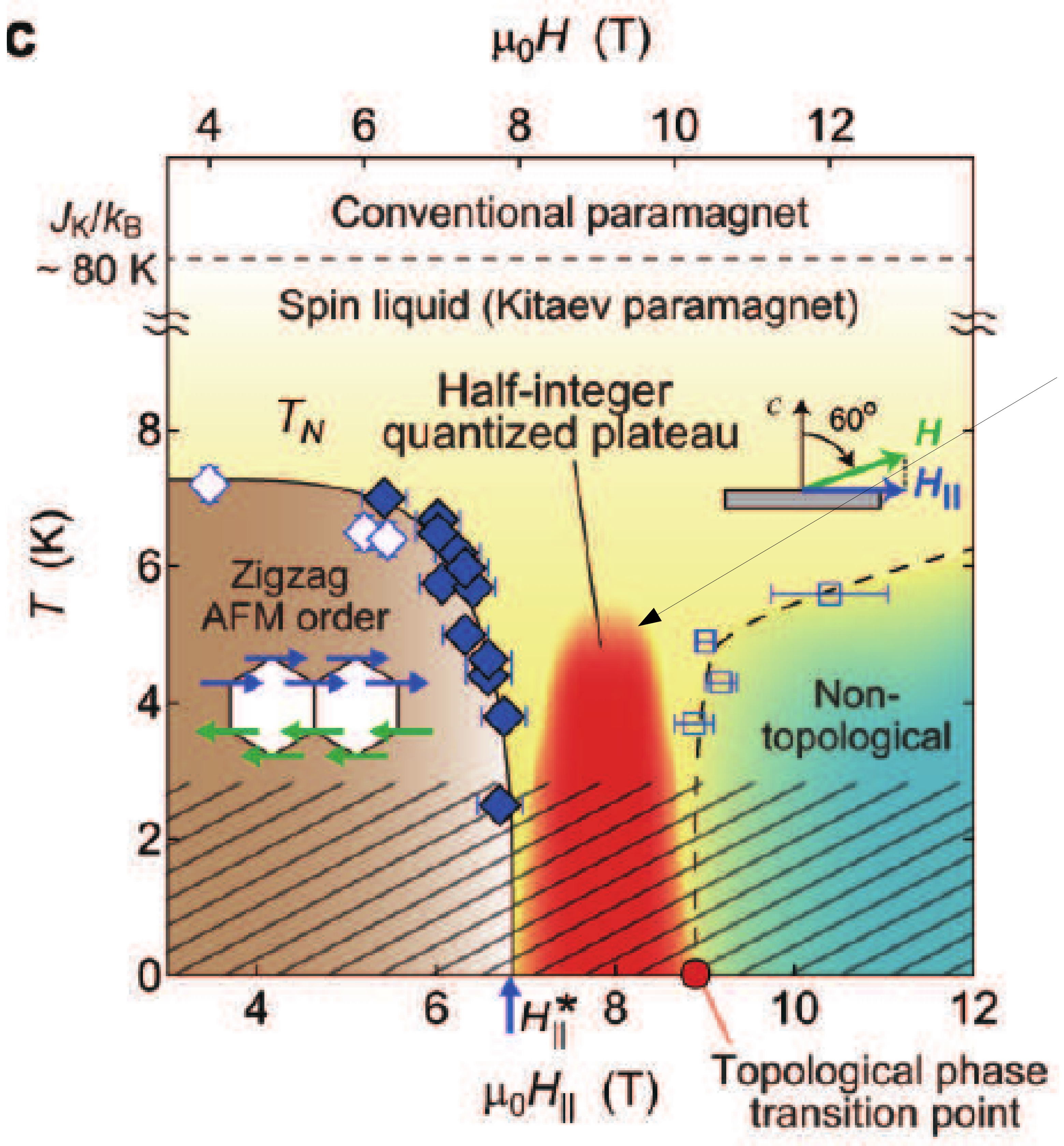


S. K. Choi et al, Phys. Rev. Lett. 108, 127204 (2012)

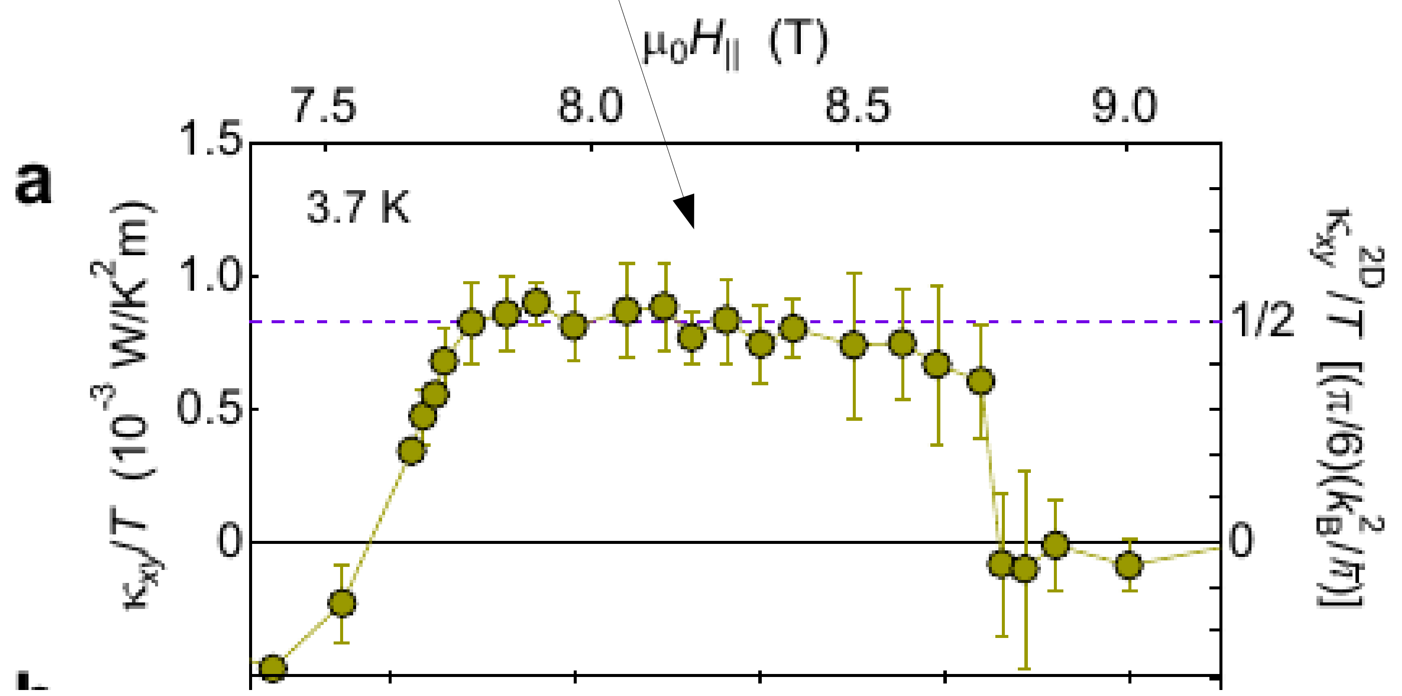
Реальные системы с взаимодействием Китаева: хлорид рутения RuCl3

Поперечная теплопроводность





Возможная топологическая фаза в магнитном поле с квантованной поперечной теплопроводностью



Kasahara, Y., Ohnishi, T., Mizukami, Y. et al., Nature 559, 227 (2018)

Редкоземельные системы с взаимодействием Китаева: A2PrO3

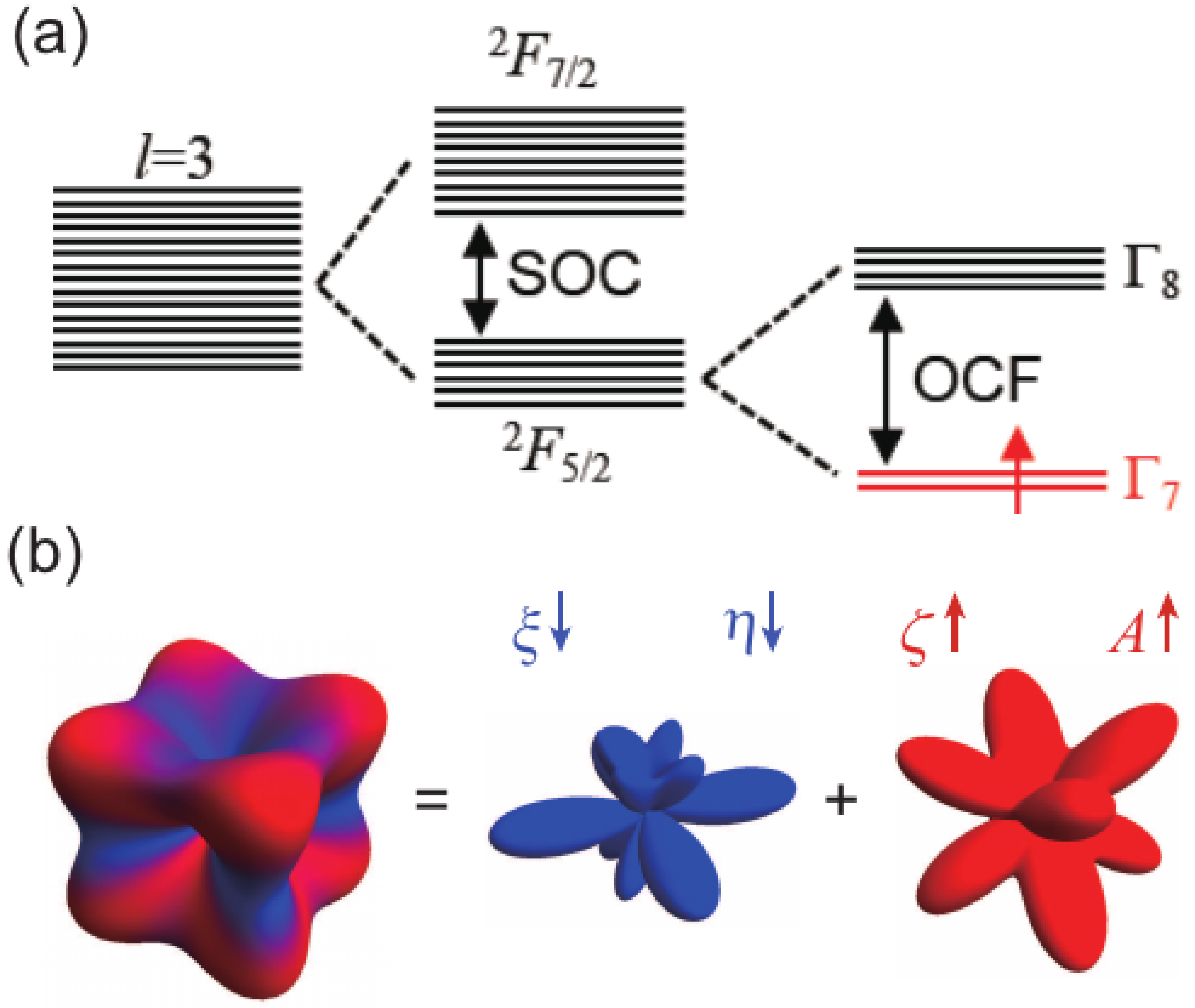
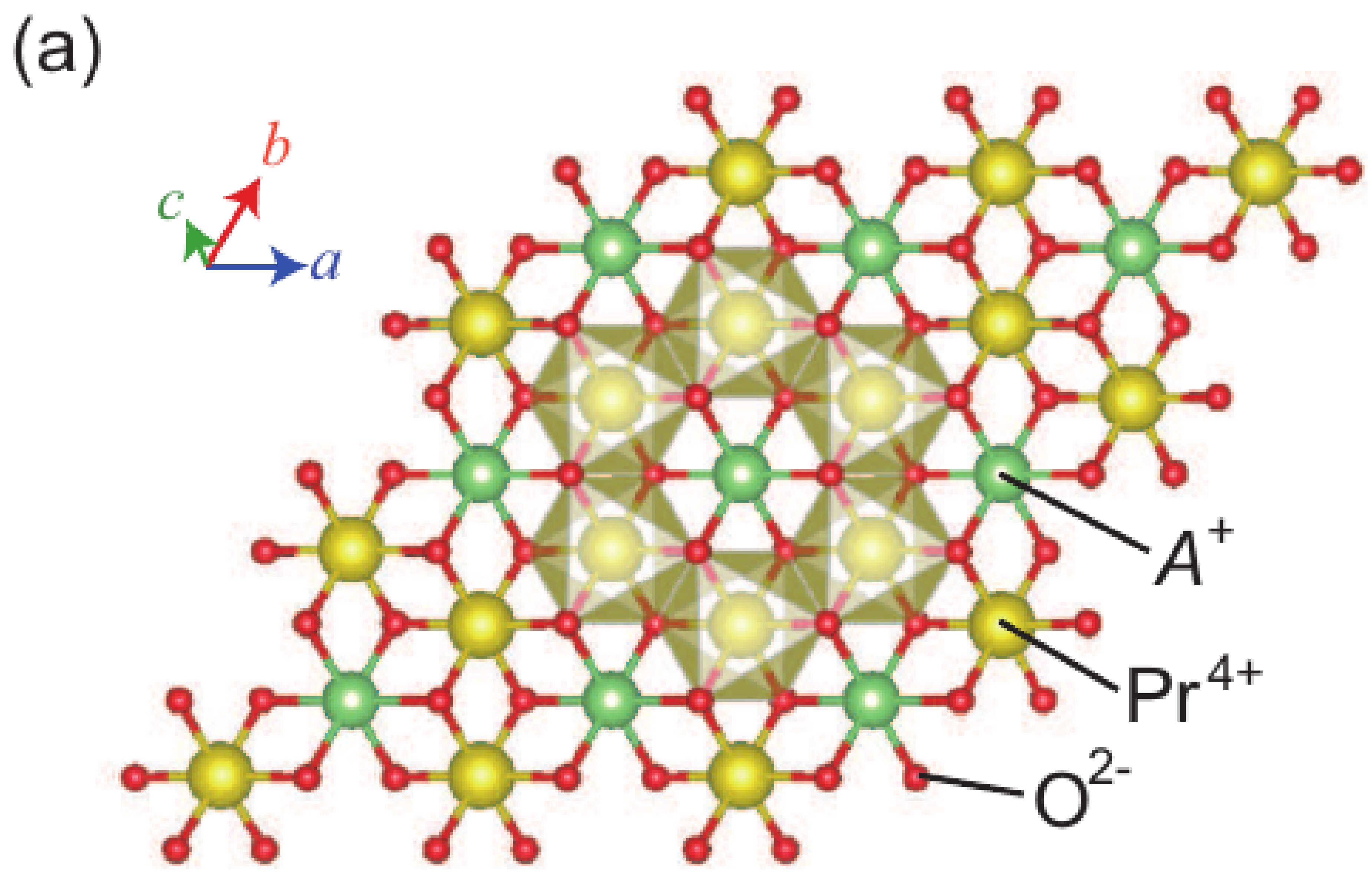
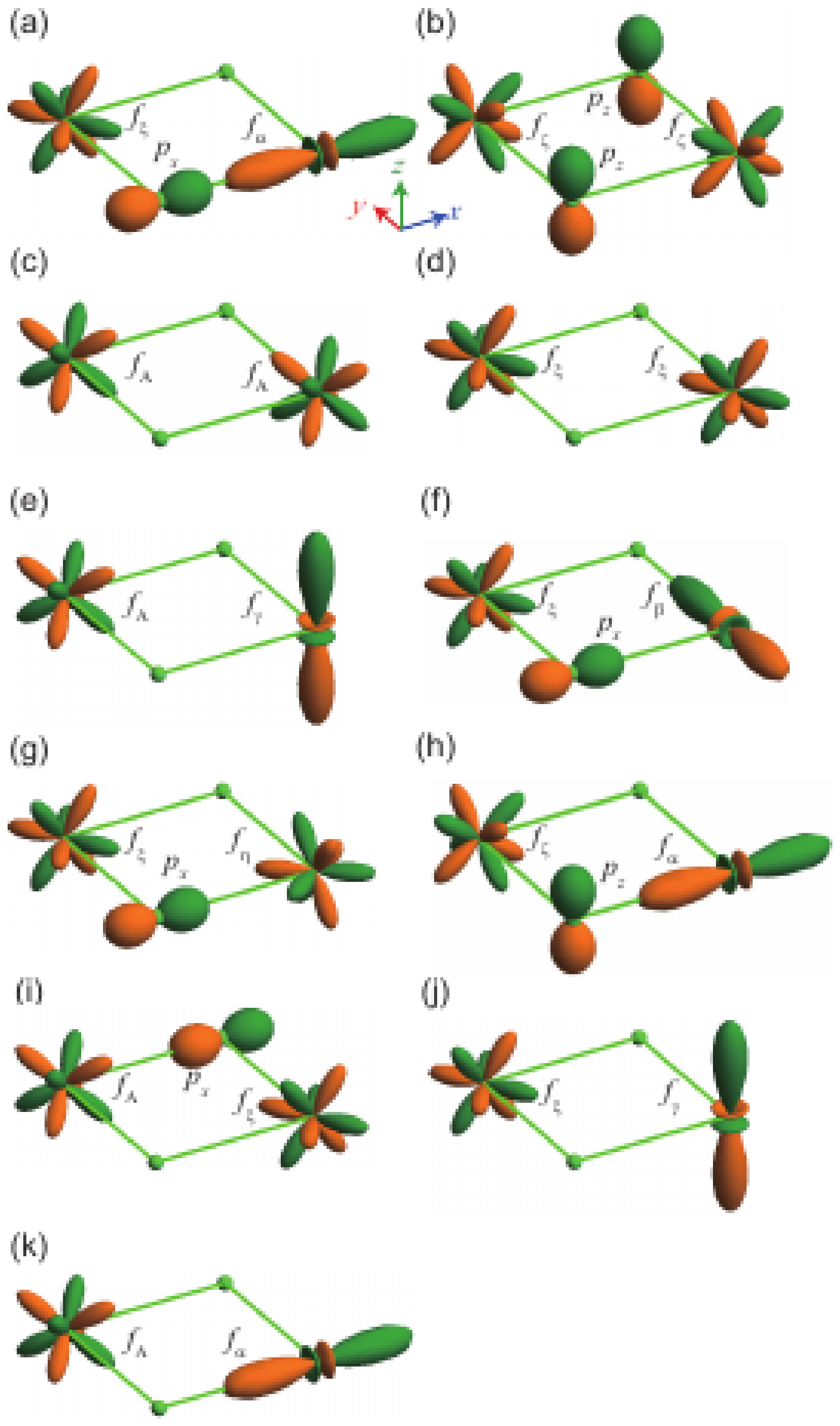


FIG. 1. (a) f^1 level splitting by the spin-orbit coupling (SOC) and the octahedral crystal field (OCF). (b) Density profile of an electron in the pseudospin up state $|+\rangle$ for the Γ_7 doublet; see Eq. (1).

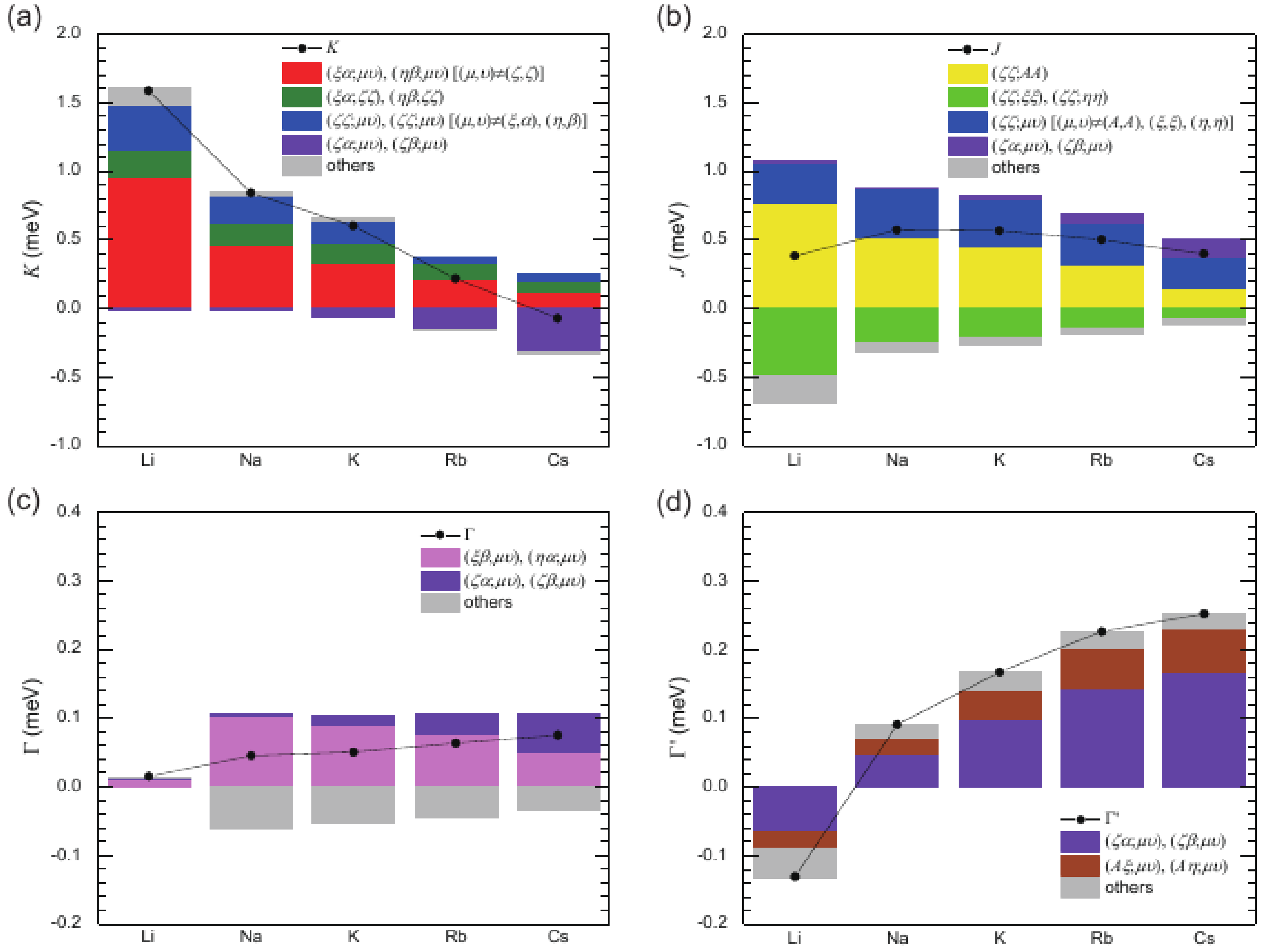


Seong-Hoon Jang, Ryoya Sano, Yasuyuki Kato, and Yukitoshi Motome, Phys. Rev. B 99, 241106(R) (2019)

Редкоземельные системы с взаимодействием Китаева: A2PrO3

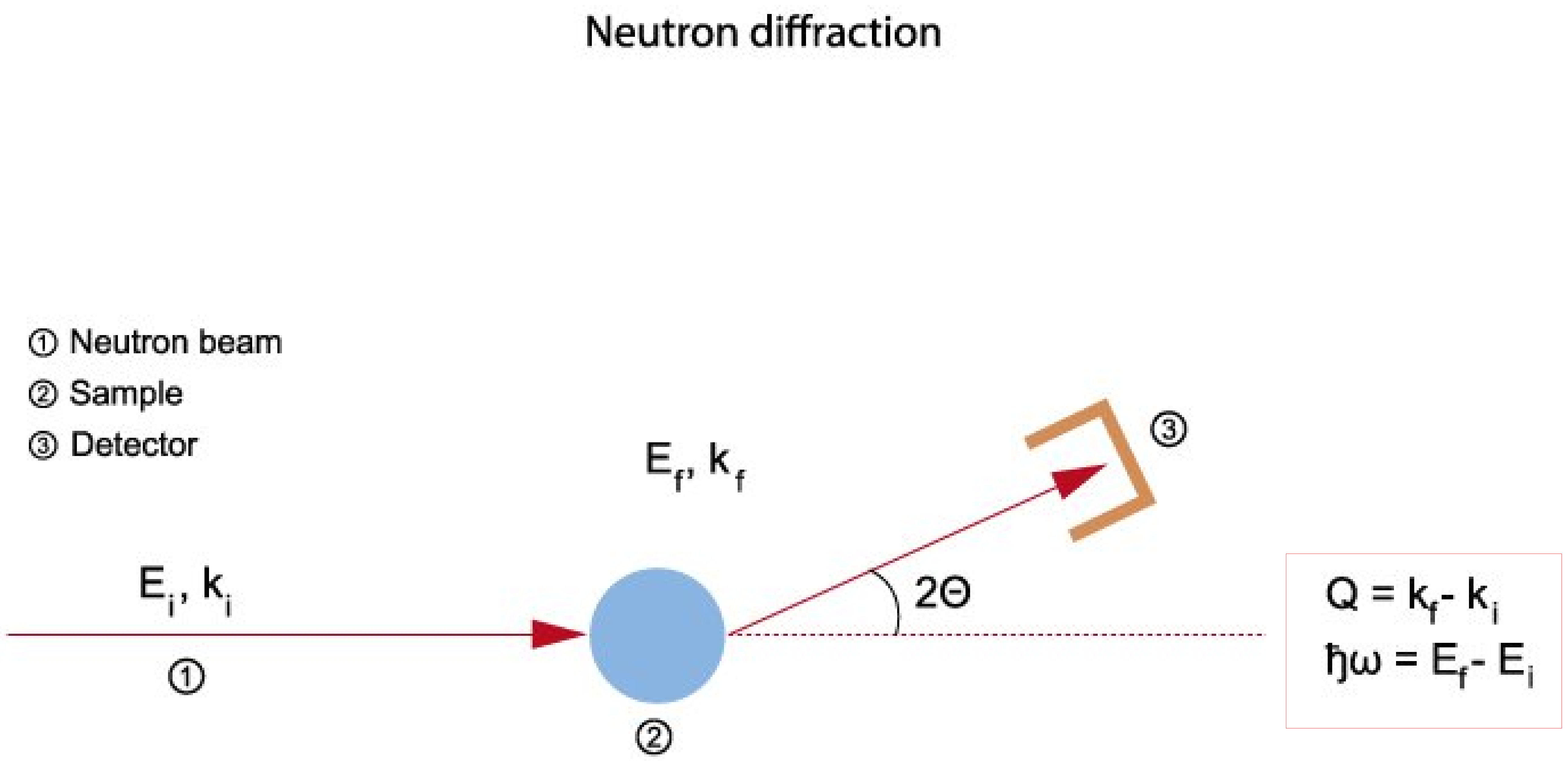


Перескоки, ведущие к анизотропному обменному Гамильтониану



Параметры Гамильтониана

Нейтронный сигнал в упорядоченных и неупорядоченных состояниях



Определяет импульс и энергию возбуждения

Нейтронный сигнал в упорядоченных состояниях

ФМ

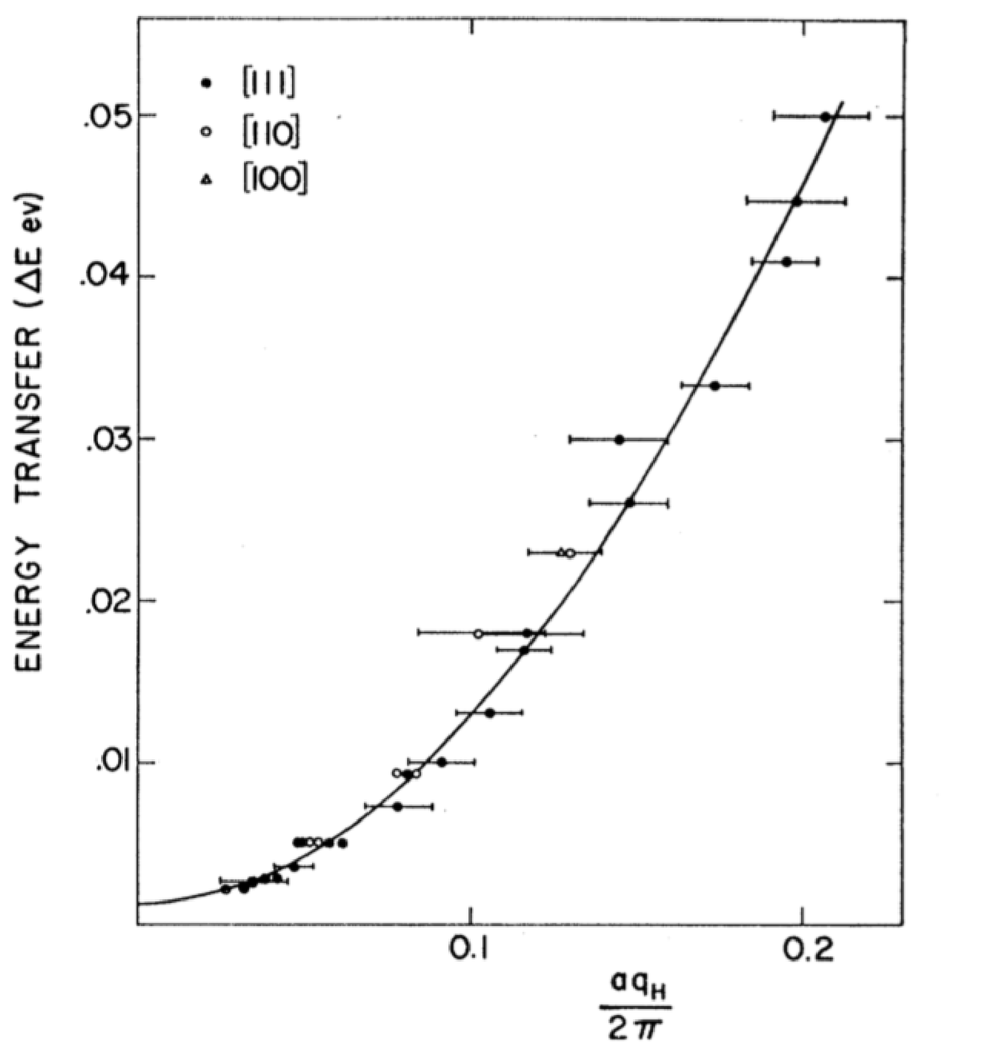
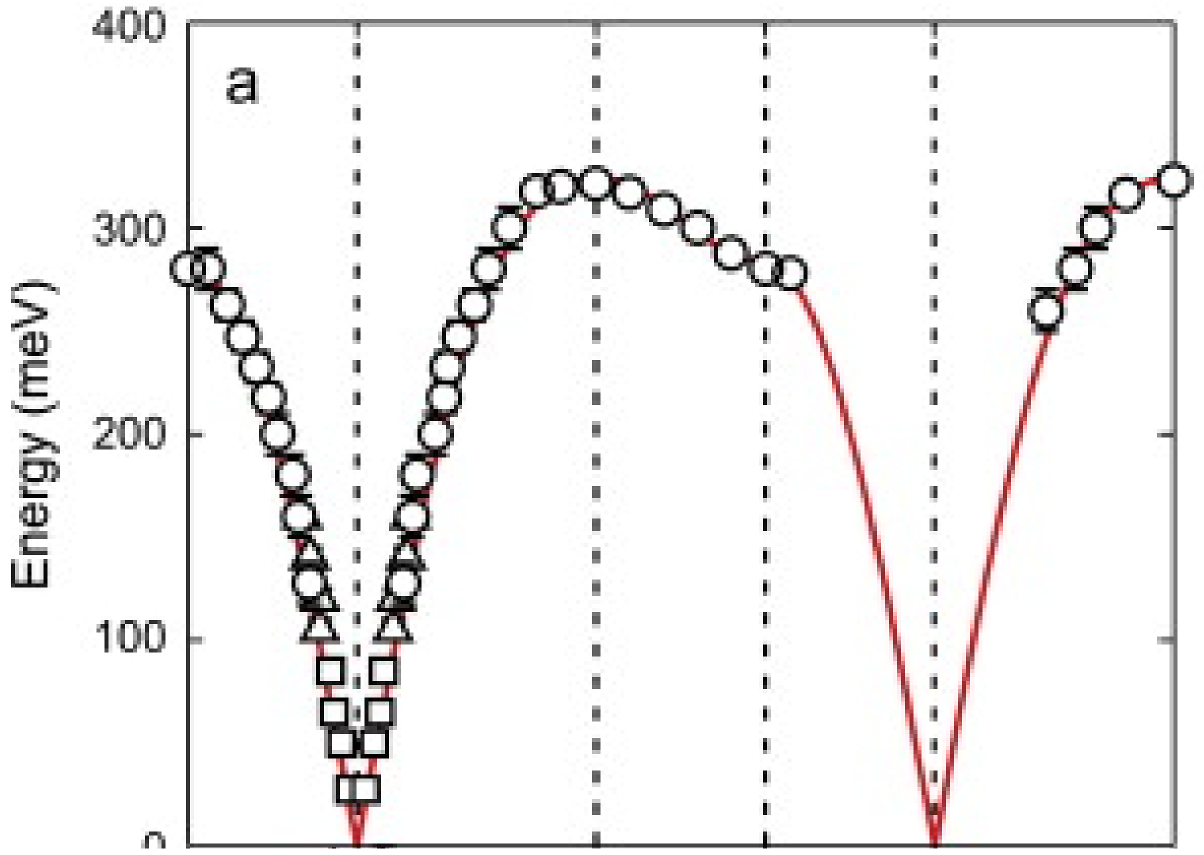


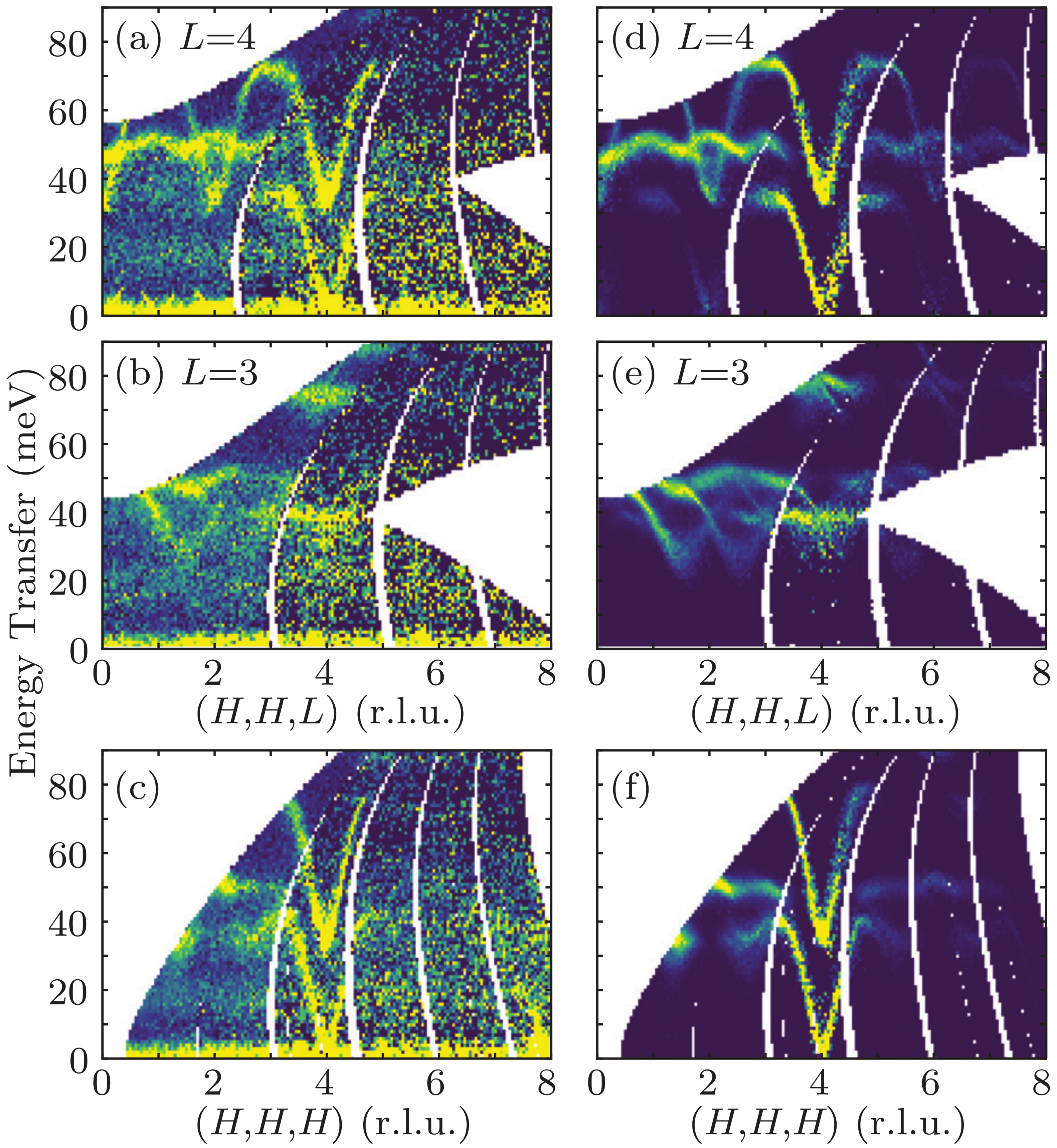
Fig. 2. The energy transfer ΔE as a function of the reduced vector of the spin waves. The error bars are about half of the full width at half maximum of the neutron groups. The solid line is the best fit to Eq. (3).

- Магнон, переворот спина, имеет момент S=1
- Нейтрон рождает один магнон

$$I(\mathbf{k},\omega) \propto \delta(\omega - \varepsilon_{\mathbf{k}})$$

АФМ

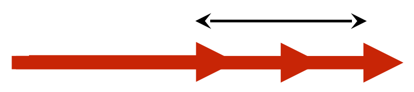




Эксперимент Расчет

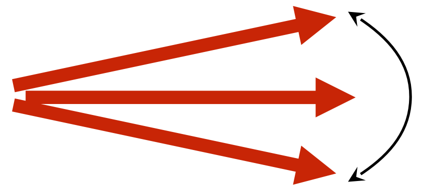
A. J. Princep et. Al, NPJ Quant. Mat. (2017)

Трехмагнонное взаимодействие



Продольные колебания (двухмагнонные, четные по вращению вокруг оси z)

$$S^z = S - a^\dagger a$$



Поперечные колебания (одномагнонные, нечетные по вращению вокруг оси z)

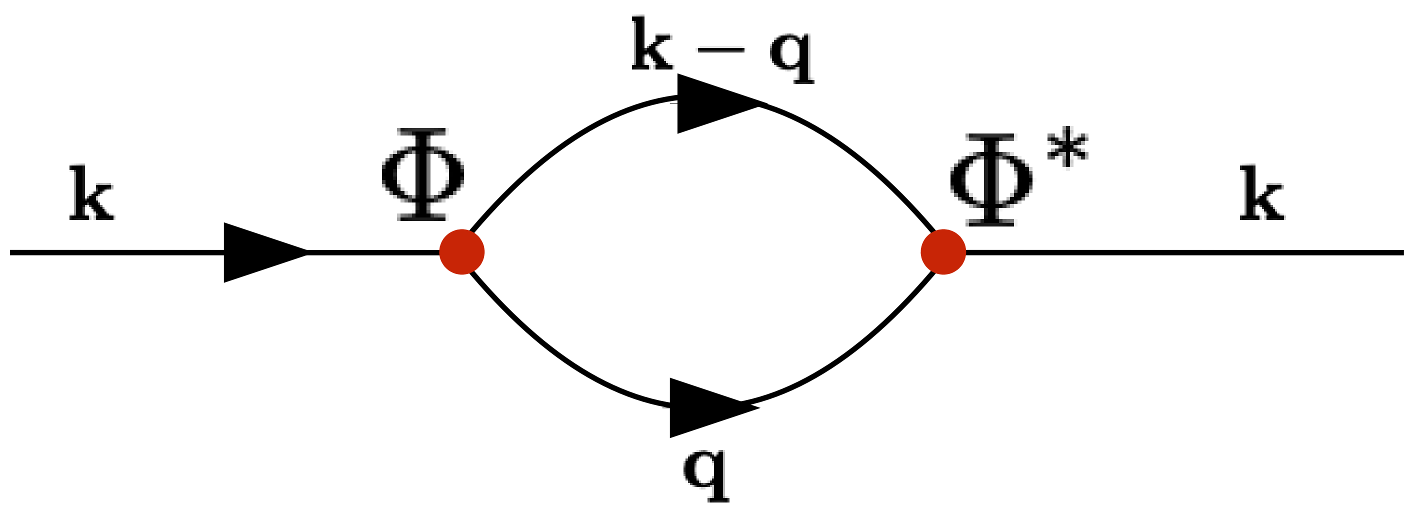
$$S^x \approx \sqrt{\frac{S}{2}}\left(a + a^\dagger\right)$$

Анизотропное взаимодействие

$$\hat{\mathcal{H}} = ...S_i^x S_j^z + S_i^z S_j^x...$$

$$\mathcal{H} = \sum_{\langle ij \rangle^\gamma} J\mathbf{S}_i \cdot \mathbf{S}_j + K S_i^\gamma S_j^\gamma + \Gamma\left(S_i^\alpha S_j^\beta + S_i^\beta S_j^\alpha\right)$$
$$+\Gamma'\left(S_i^\gamma S_j^\alpha + S_i^\gamma S_j^\beta + S_i^\alpha S_j^\gamma + S_i^\beta S_j^\gamma\right)$$

Распад магнонов

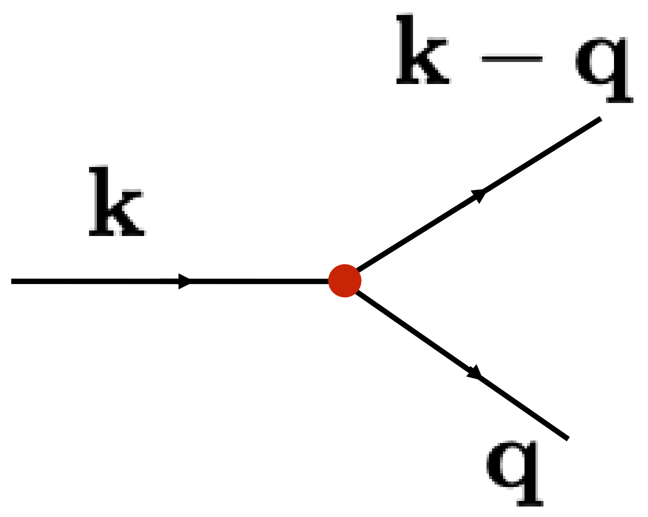


$$\Sigma(\mathbf{k},\omega) = \frac{1}{2}\sum_{\mathbf{q}} \frac{|\Phi(\mathbf{q},\mathbf{k})|^2}{\omega - \varepsilon_{\mathbf{k}-\mathbf{q}} - \varepsilon_{\mathbf{q}} + i0}$$

Борновское приближение: $\Gamma_{\mathbf{k}} = \frac{\pi}{2}\sum_{\mathbf{q}} |\Phi(\mathbf{q},\mathbf{k})|^2\, \delta\left(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}-\mathbf{q}} - \varepsilon_{\mathbf{q}}\right)$

Закон сохранения энергии и импулься:

$$\varepsilon_{\mathbf{k}} = \varepsilon_{\mathbf{q}} + \varepsilon_{\mathbf{k}-\mathbf{q}}$$



Обзоры

Модель Китаева и материалы

A. Kitaev, Annals of Physics 321, 2 (2006), January Special Issue

Models and materials for generalized Kitaev Magnetism, Stephen M Winter et al, J. Phys.: Condens. Matter 29 493002 (2017)

Kitaev Materials, Simon Trebst, 2017, arxiv:1701.07056

Materials design of Kitaev spin liquids beyond the Jackeli-Khaliullin mechanism, Motome et al., 2020, arxiv:2001.03731

Спиновые жидкости

Lucile Savary and Leon Balents, Rep. Prog. Phys. 80 016502 (2017)

M J P Gingras and P A McClarty, Rep. Prog. Phys. 77 056501 (2014)

Коррелированные системы со спин-орбитальным взаимодействием

William Witczak-Krempa, Gang Chen, Yong Baek Kim, Leon Balents, Annual Review of Condensed Matter Physics, 5:1, 57 (2014)

Магнонные распады

M. E. Zhitomirsky and A. L. Chernyshev, Rev. Mod. Phys. 85, 219 (2013)