Title: Kitaev spin liquids in spin-orbit coupled correlated materials

Speakers: Hae-Young Kee

Series: Condensed Matter

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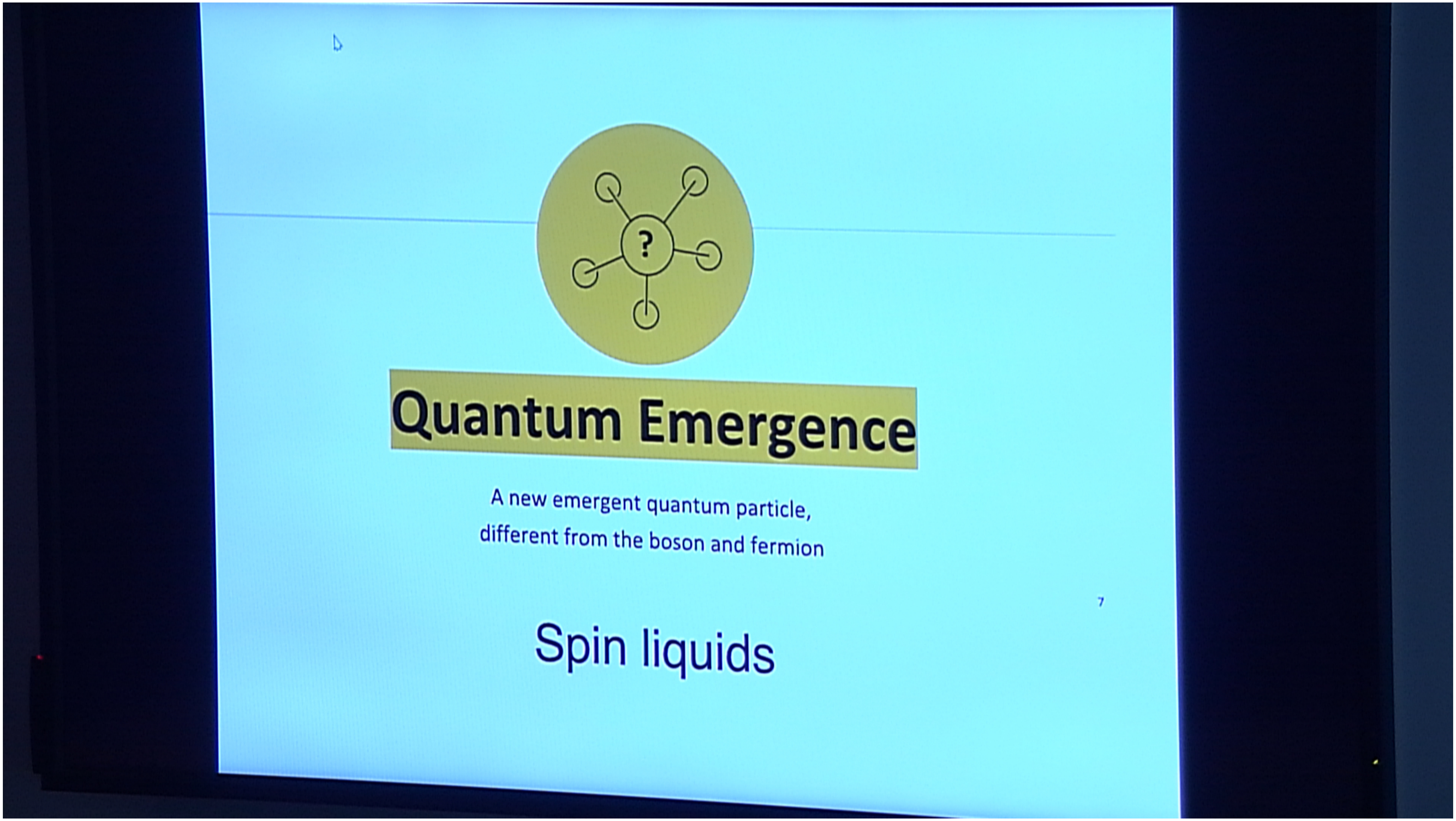
URL: http://pirsa.org/19050020

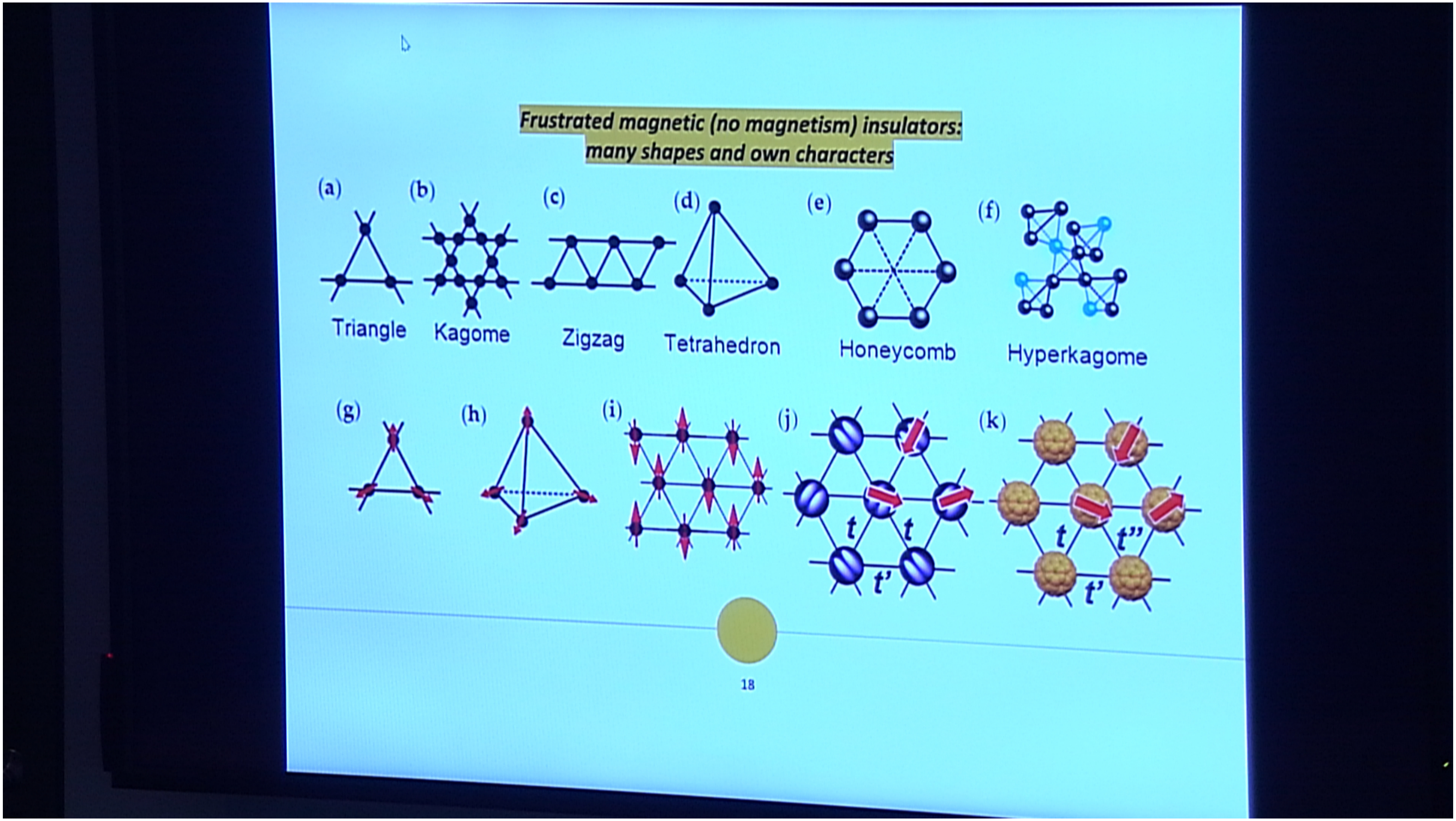
Abstract: Recently, a new family of correlated honeycomb materials with strong spin-orbit coupling have been promising candidates to realize the Kitaev spin liquid. In particular, a half-integer quantized thermal Hall conductivity was reported in alpha-RuCl3 under the magnetic field. Using a generic nearest neighbour spin model with bond-dependent interactions, I will present numerical evidence of an extended regime of quantum spin liquids. I will also discuss how to achieve a chiral spin liquid near ferromagnetic Kitaev interaction in the presence of the magnetic field leading to the quantized thermal Hall conductivity.



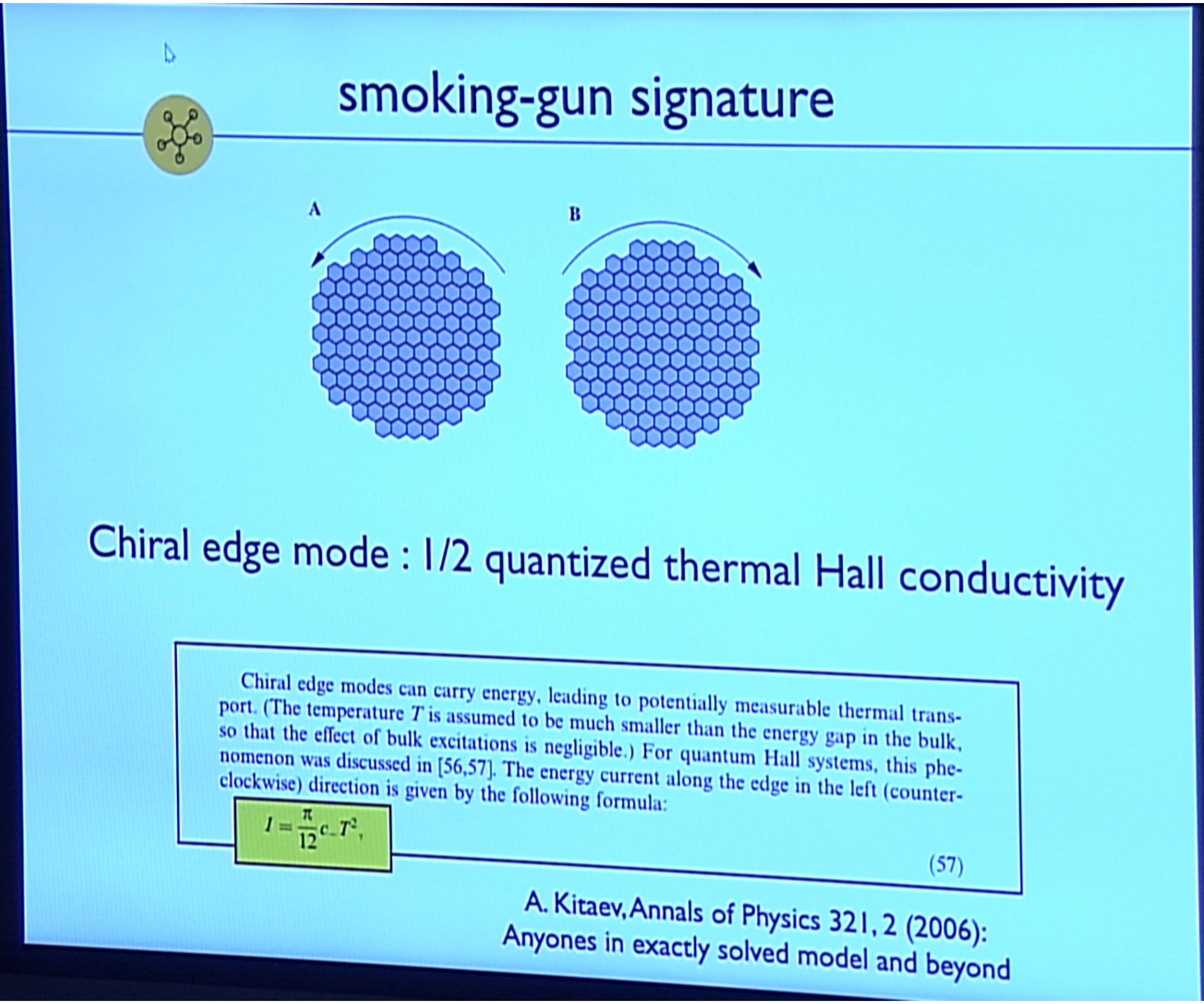
Quantum Emergence

A new emergent quantum particle,
different from the boson and fermion

Spin liquids



Frustrated magnetic (no magnetism) insulators: many shapes and own characters



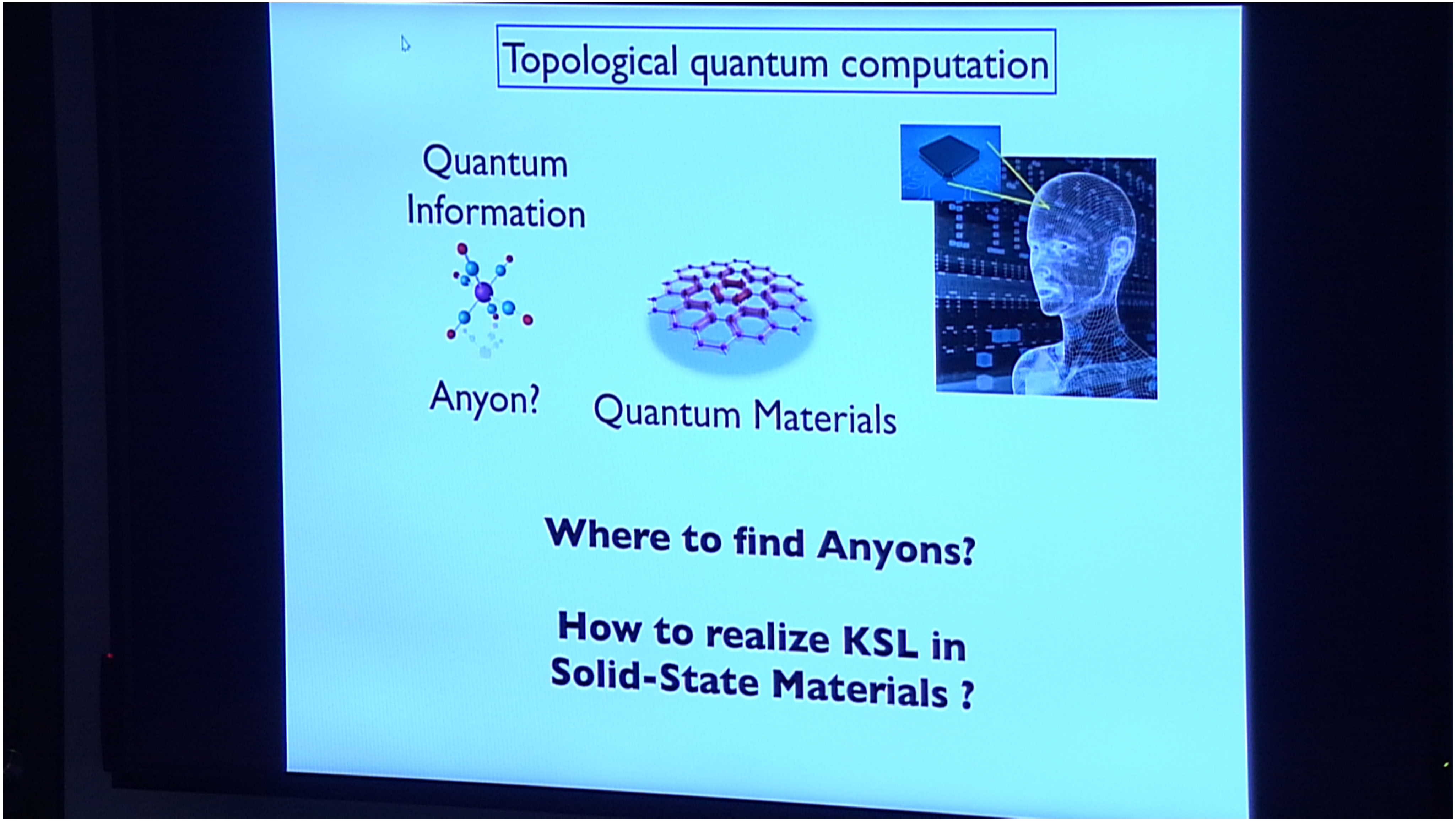
smoking-gun signature

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:

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

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



Topological quantum computation

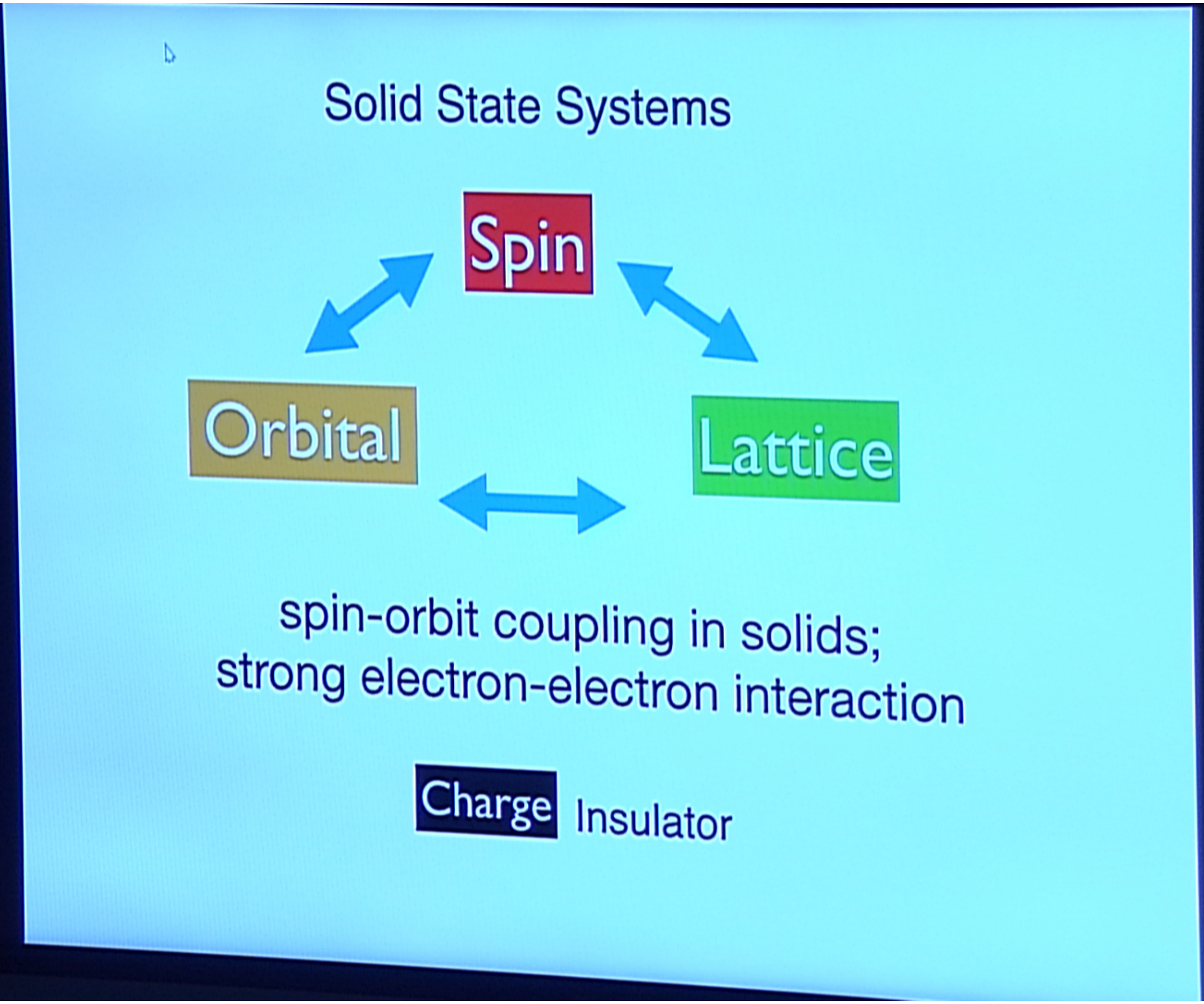
Quantum Information

Anyon?

Quantum Materials

Where to find Anyons?

How to realize KSL in Solid-State Materials ?



Solid State Systems

Spin

Orbital

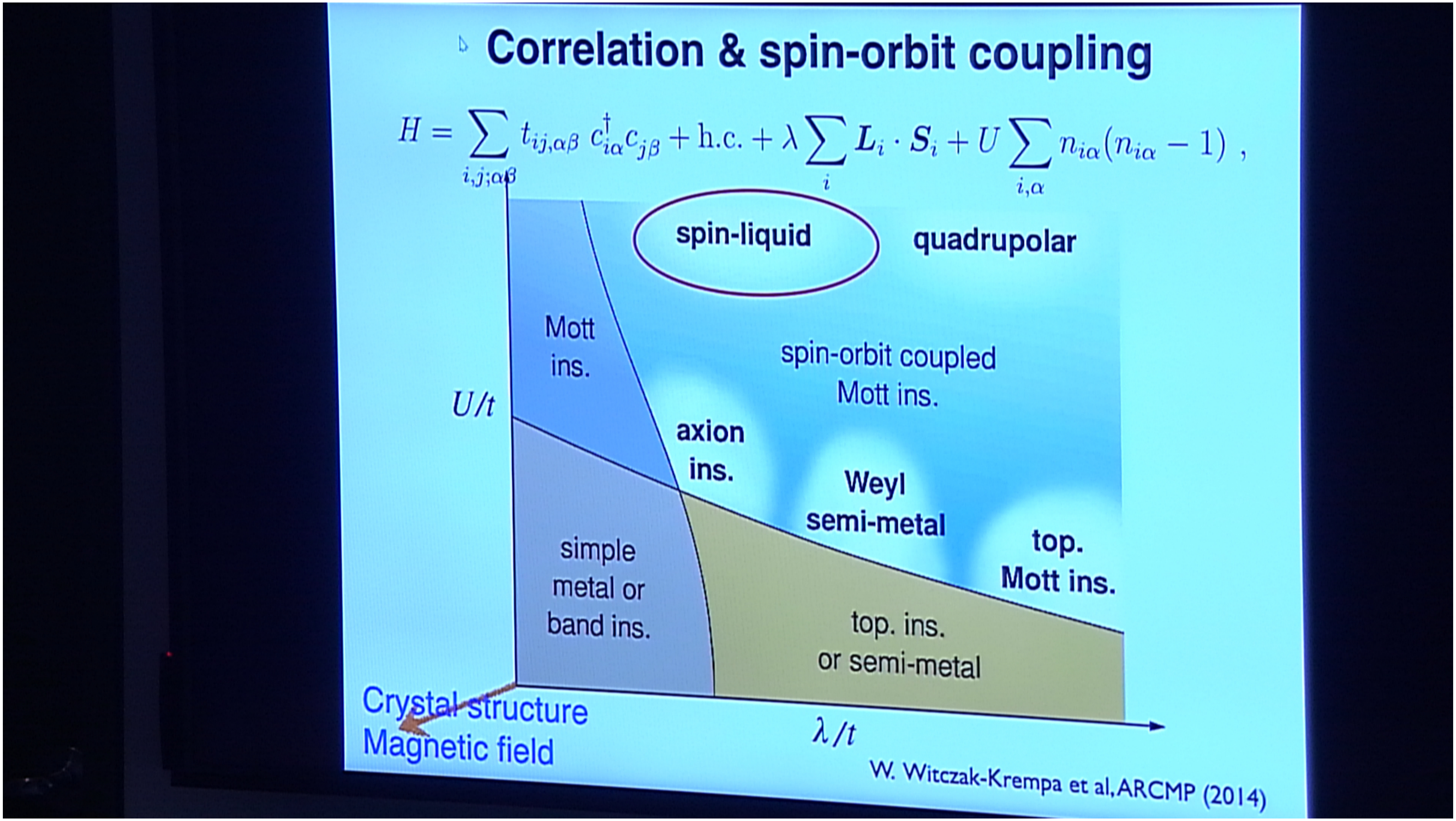
Lattice

spin-orbit coupling in solids;
strong electron-electron interaction

Charge Insulator

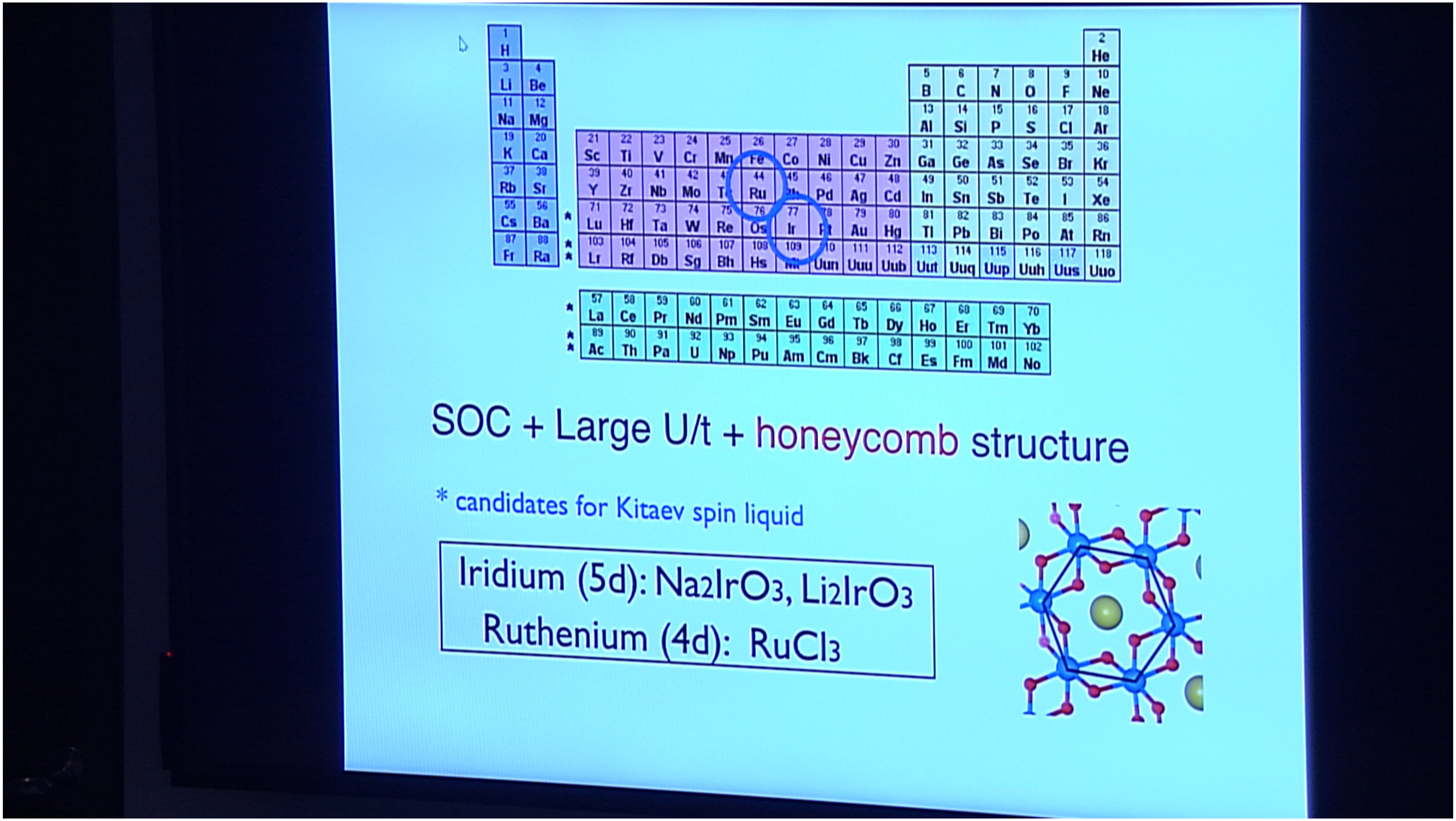
Correlation & spin-orbit coupling

$$H=\sum_{i,j;\alpha\beta} t_{ij,\alpha\beta}\, c^{\dagger}_{i\alpha} c_{j\beta} + \mathrm{h.c.} + \lambda \sum_{i} \boldsymbol{L}_i \cdot \boldsymbol{S}_i + U \sum_{i,\alpha} n_{i\alpha}(n_{i\alpha}-1)\ ,$$



Crystal structure
Magnetic field

W. Witczak-Krempa et al, ARCMP (2014)



1 H																		2 He
3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

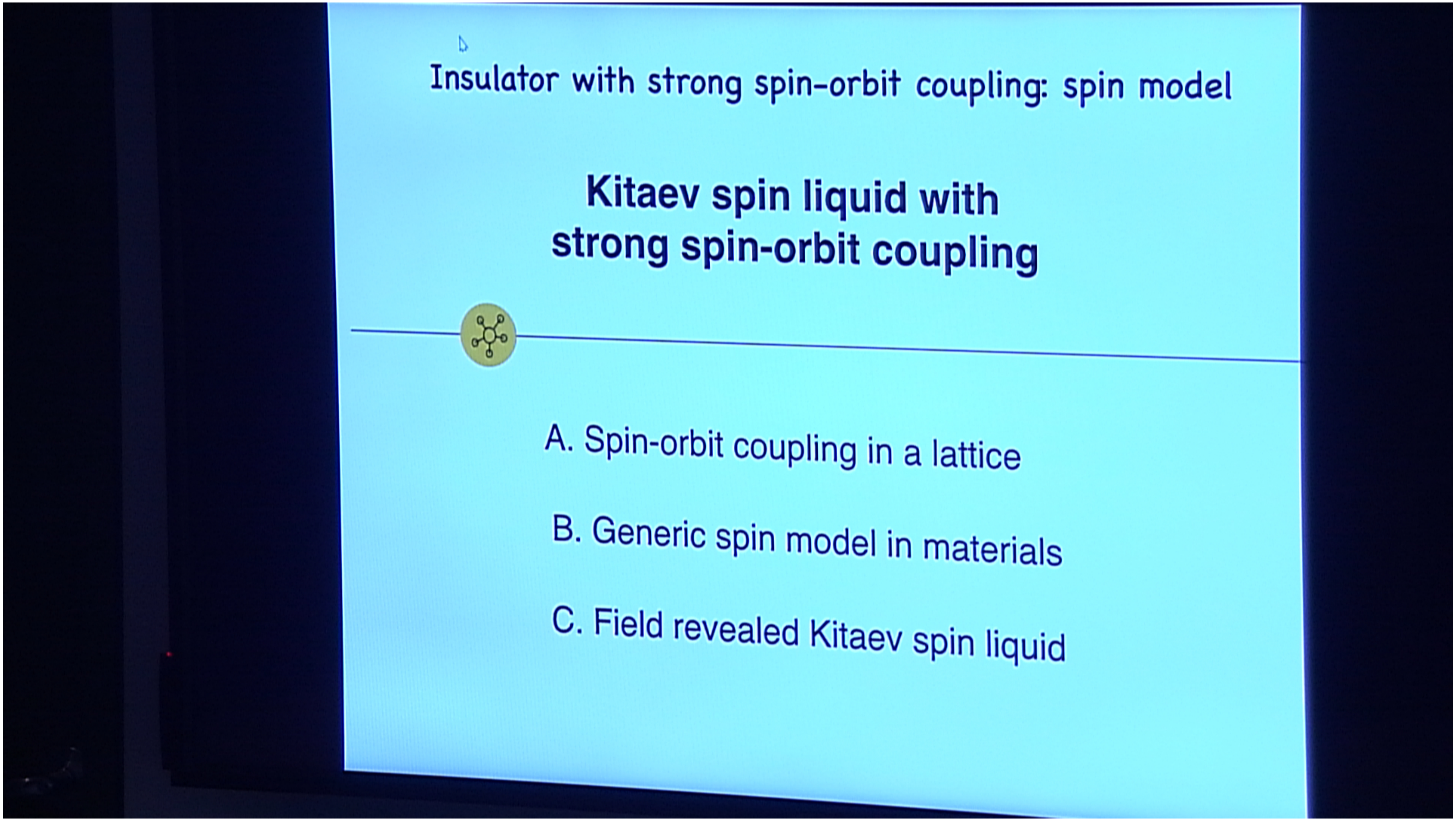
*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

SOC + Large U/t + honeycomb structure

* candidates for Kitaev spin liquid

Iridium (5d): Na_2IrO_3, Li_2IrO_3

Ruthenium (4d): $RuCl_3$



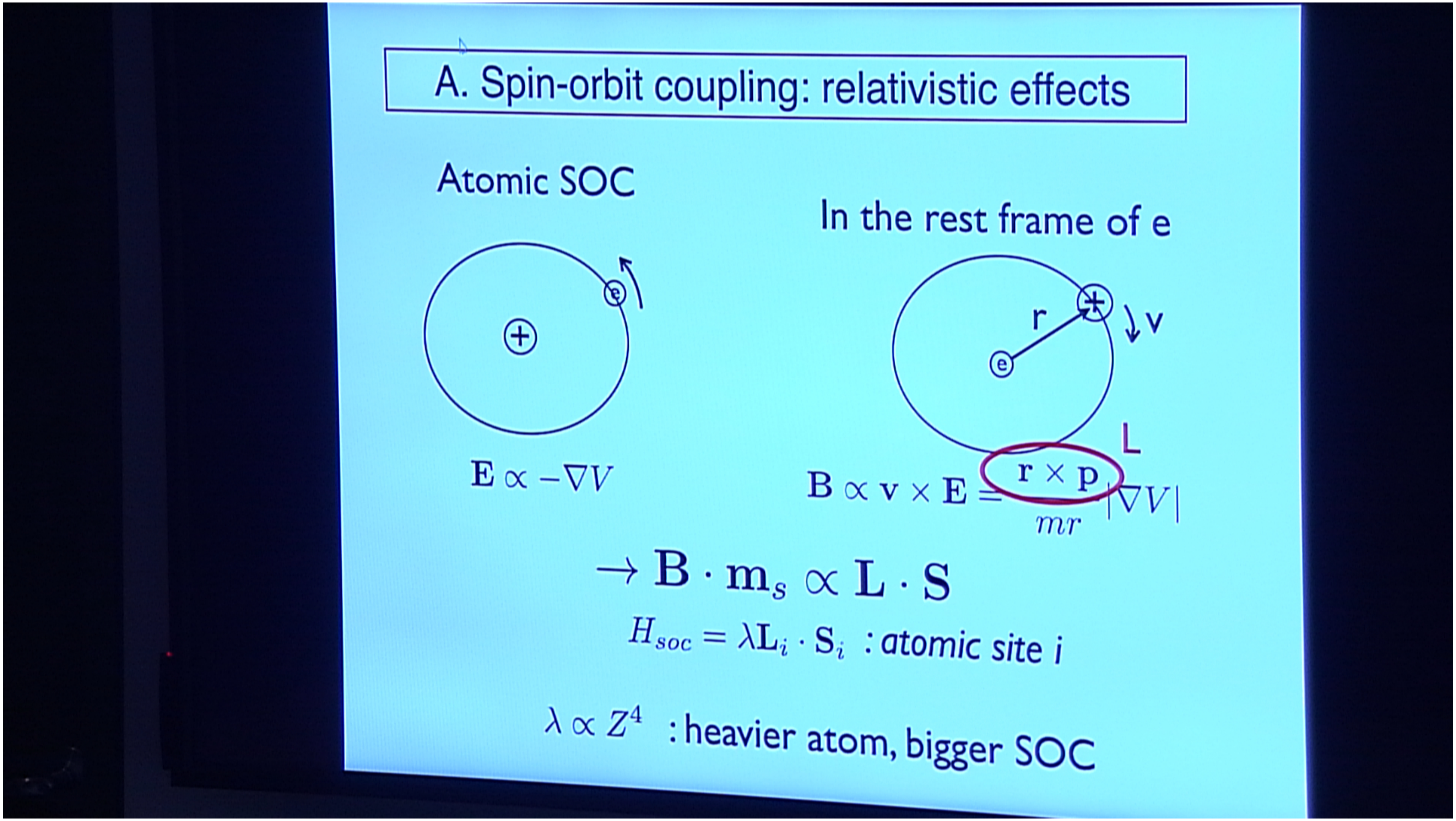
Insulator with strong spin-orbit coupling: spin model

Kitaev spin liquid with strong spin-orbit coupling

A. Spin-orbit coupling in a lattice

B. Generic spin model in materials

C. Field revealed Kitaev spin liquid



A. Spin-orbit coupling: relativistic effects

Atomic SOC

In the rest frame of e

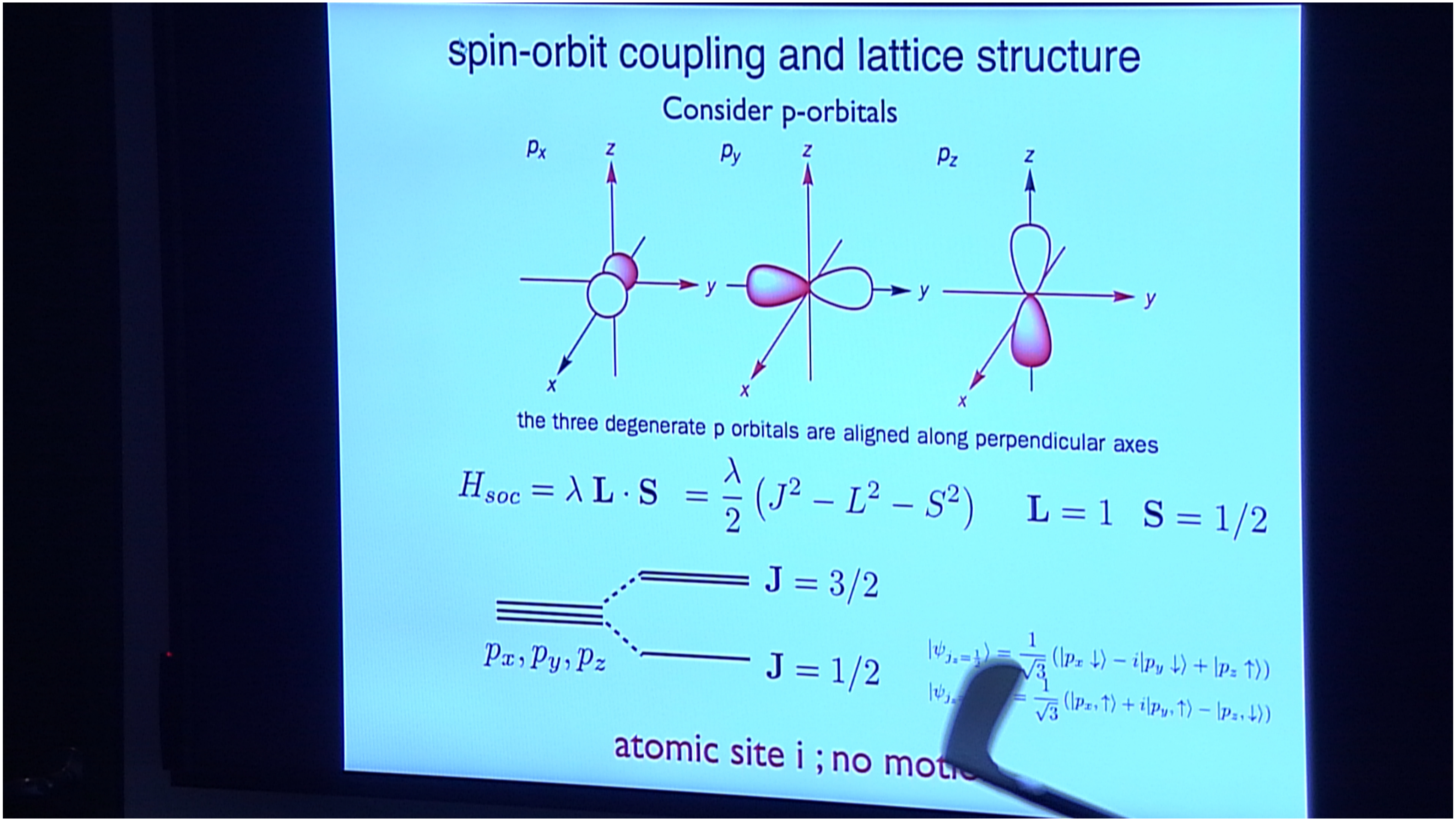
$$\mathbf{E} \propto -\nabla V$$

$$\mathbf{B} \propto \mathbf{v} \times \mathbf{E} = \frac{\overset{L}{\boxed{\mathbf{r} \times \mathbf{p}}}}{mr} |\nabla V|$$

$$\rightarrow \mathbf{B} \cdot \mathbf{m}_s \propto \mathbf{L} \cdot \mathbf{S}$$

$H_{soc} = \lambda \mathbf{L}_i \cdot \mathbf{S}_i$: *atomic site i*

$\lambda \propto Z^4$: heavier atom, bigger SOC



spin-orbit coupling and lattice structure

Consider p-orbitals

the three degenerate p orbitals are aligned along perpendicular axes

$$H_{soc} = \lambda\, \mathbf{L} \cdot \mathbf{S} \ = \frac{\lambda}{2}\left(J^2 - L^2 - S^2\right) \quad \mathbf{L} = 1 \ \ \mathbf{S} = 1/2$$

p_x, p_y, p_z

$\mathbf{J} = 3/2$

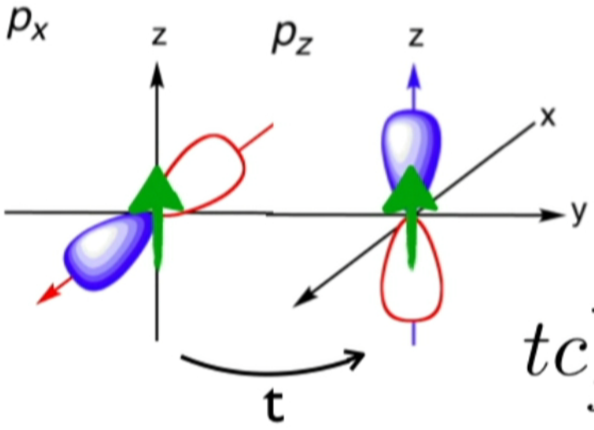
$\mathbf{J} = 1/2$

$$|\psi_{j_z=\frac{1}{2}}\rangle = \frac{1}{\sqrt{3}}\left(|p_x \downarrow\rangle - i|p_y \downarrow\rangle + |p_z \uparrow\rangle\right)$$

$|\psi_{j_z}$ [illegible] $= \frac{1}{\sqrt{3}}\left(|p_x, \uparrow\rangle + i|p_y, \uparrow\rangle - |p_z, \downarrow\rangle\right)$

atomic site i ; no moti

Let's consider two sites: effects of SOC on hopping



$$tc^{\dagger}_{j,p_z,\uparrow}c_{i,p_x,\uparrow} + h.c.$$

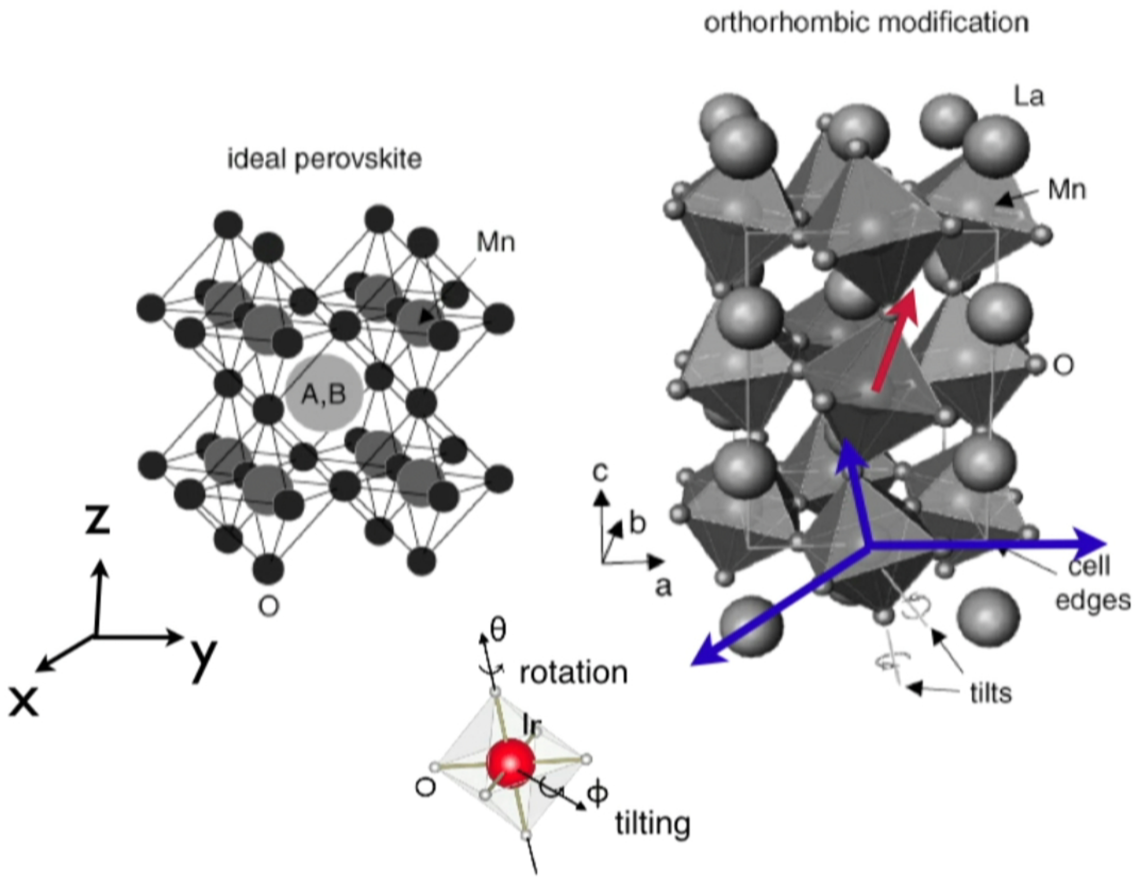
$$t_{i,j;p_z,p_x} = \int d^3\mathbf{r}\phi^*_{p_z}(\mathbf{r}-\mathbf{R}_i)\,\delta\mathcal{H}\,\phi_{p_x}(\mathbf{r}-\mathbf{R}_j)$$

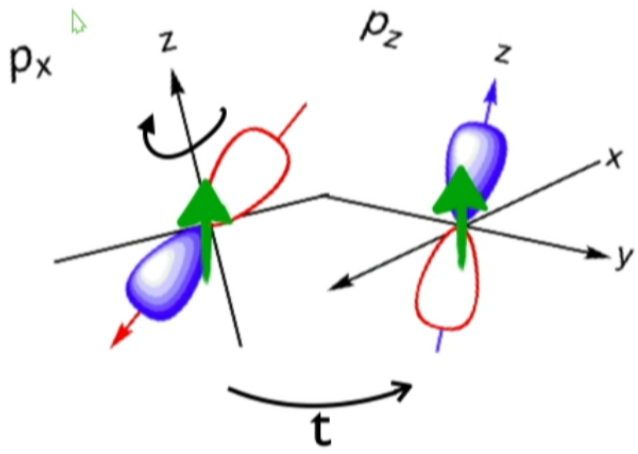
=0

because of symmetry: odd & even in mirror reflection z

when mirror symmetries broken $t \neq 0$

local axis is determined by other atoms inside the solids





$$tc^{\dagger}_{j,p_z,\uparrow}c_{i,p_x,\uparrow} + h.c.$$

$$\rightarrow tc^{\dagger}_{j,\boxed{j_z=\frac{1}{2}}}c_{i,\boxed{j_z=-\frac{1}{2}}} + h.c.$$

; pseudospin (strong SOC) flips over hopping

$$|\psi_{j_z=\frac{1}{2}}\rangle = \frac{1}{\sqrt{3}}\left(|p_x\downarrow\rangle - i|p_y\downarrow\rangle + \boxed{|p_z\uparrow\rangle}\right)$$

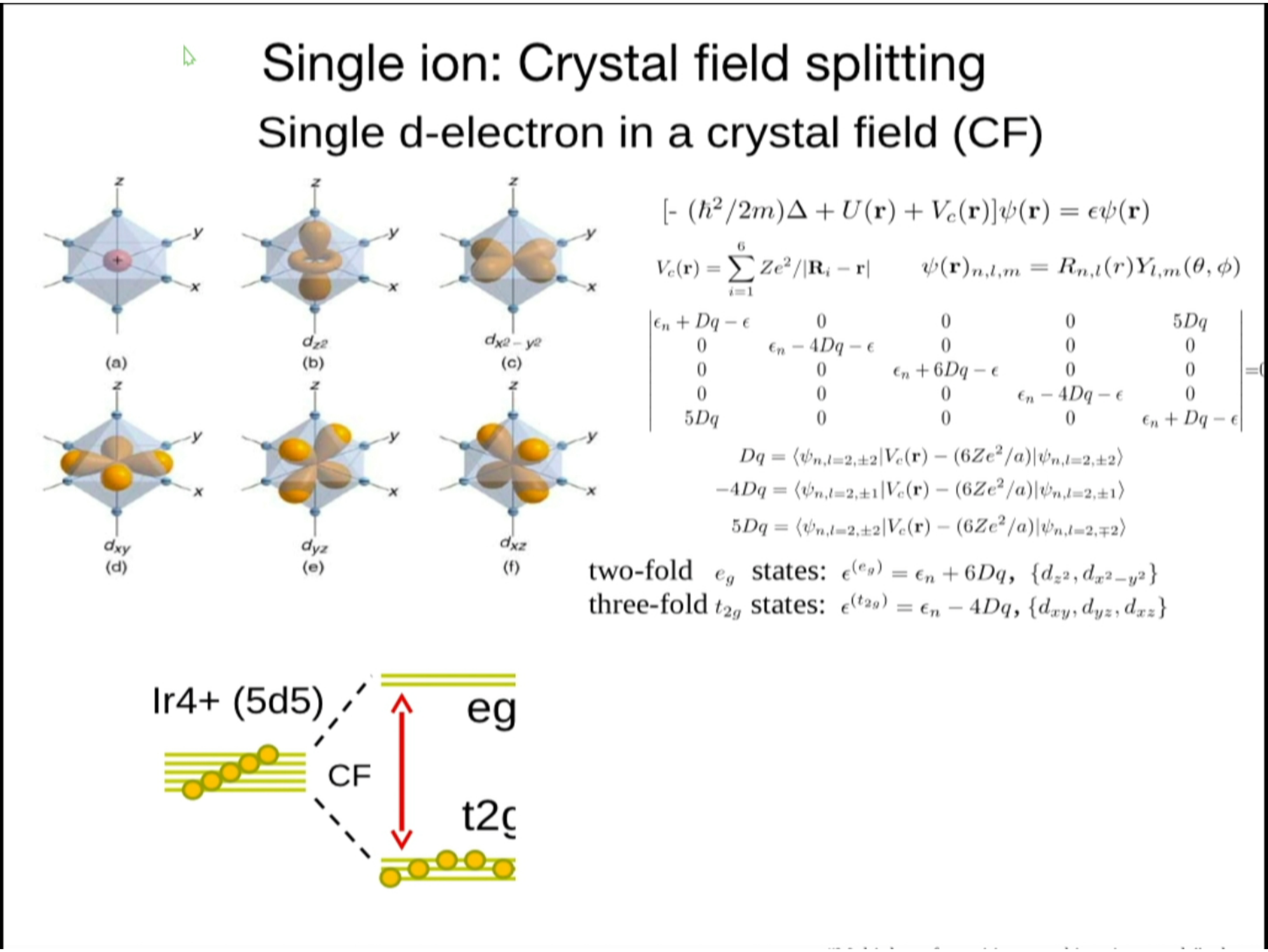
$$|\psi_{j_z=-1/2}\rangle = \frac{1}{\sqrt{3}}\left(\boxed{|p_x,\uparrow\rangle} + i|p_y,\uparrow\rangle - |p_z,\downarrow\rangle\right)$$

atomic SOC + crystal structure: Rashba-like SOC

$\boxed{i\cos(k_y)\sigma_y}$ with inversion symmetry

* inversion is broken : $\sin(k_y)\sigma_x$

$$\sin(k_y)\sigma_x - \sin(k_x)\sigma_y \sim (\mathbf{k}\times\vec{\sigma})\cdot\hat{z}$$



Single ion: Crystal field splitting

Single d-electron in a crystal field (CF)

$$[\text{-}\ (\hbar^2/2m)\Delta + U(\mathbf{r}) + V_c(\mathbf{r})]\psi(\mathbf{r}) = \epsilon\psi(\mathbf{r})$$

$$V_c(\mathbf{r}) = \sum_{i=1}^{6} Ze^2/|\mathbf{R}_i - \mathbf{r}| \qquad \psi(\mathbf{r})_{n,l,m} = R_{n,l}(r)Y_{l,m}(\theta,\phi)$$

$$\begin{vmatrix} \epsilon_n + Dq - \epsilon & 0 & 0 & 0 & 5Dq \\ 0 & \epsilon_n - 4Dq - \epsilon & 0 & 0 & 0 \\ 0 & 0 & \epsilon_n + 6Dq - \epsilon & 0 & 0 \\ 0 & 0 & 0 & \epsilon_n - 4Dq - \epsilon & 0 \\ 5Dq & 0 & 0 & 0 & \epsilon_n + Dq - \epsilon \end{vmatrix} =$$

$$Dq = \langle \psi_{n,l=2,\pm 2}|V_c(\mathbf{r}) - (6Ze^2/a)|\psi_{n,l=2,\pm 2}\rangle$$

$$-4Dq = \langle \psi_{n,l=2,\pm 1}|V_c(\mathbf{r}) - (6Ze^2/a)|\psi_{n,l=2,\pm 1}\rangle$$

$$5Dq = \langle \psi_{n,l=2,\pm 2}|V_c(\mathbf{r}) - (6Ze^2/a)|\psi_{n,l=2,\mp 2}\rangle$$

two-fold e_g states: $\epsilon^{(e_g)} = \epsilon_n + 6Dq$, $\{d_{z^2}, d_{x^2-y^2}\}$

three-fold t_{2g} states: $\epsilon^{(t_{2g})} = \epsilon_n - 4Dq$, $\{d_{xy}, d_{yz}, d_{xz}\}$

Crystal Field Splitting & Spin-orbit coupling (SOC)

$$H_{SOC} = \lambda \mathbf{l} \cdot \mathbf{s} = \lambda \sum_{a,\sigma} \sum_{b,\sigma'} \langle a\sigma | l_x s_x + l_y s_y + l_z s_z | b\sigma' \rangle d^{\dagger}_{a\sigma} d_{b\sigma'}$$

$$\begin{array}{rc} & \begin{array}{ccccc} d_{yz} & d_{zx} & d_{xy} & d_{z^2} & d_{x^2-y^2} \end{array} \\ l_x = & \left[\begin{array}{ccc|cc} 0 & 0 & 0 & -\sqrt{3}i & -i \\ 0 & 0 & i & 0 & 0 \\ 0 & -i & 0 & 0 & 0 \\ \hline \sqrt{3} & 0 & 0 & 0 & 0 \\ i & 0 & 0 & 0 & 0 \end{array}\right] \\ l_y = & \left[\begin{array}{ccc|cc} 0 & 0 & -i & 0 & 0 \\ 0 & 0 & 0 & \sqrt{3}i & -i \\ i & 0 & 0 & 0 & 0 \\ \hline 0 & -\sqrt{3}i & 0 & 0 & 0 \\ 0 & i & 0 & 0 & 0 \end{array}\right] \\ l_z = & \left[\begin{array}{ccc|cc} 0 & i & 0 & 0 & 0 \\ -i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2i \\ \hline 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -2i & 0 & 0 \end{array}\right] \end{array}$$

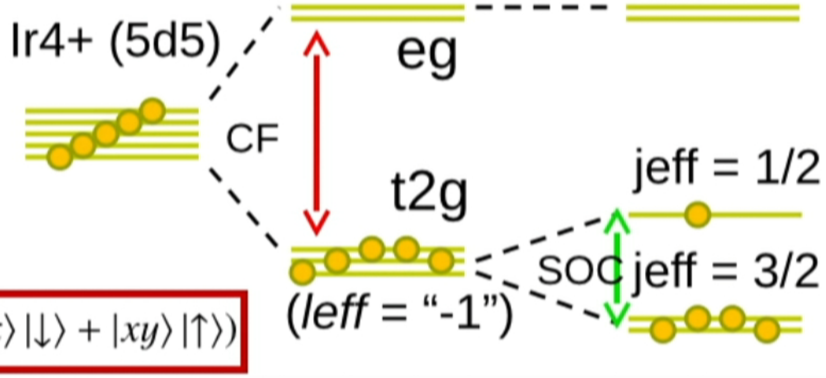
T-P equivalence

$$\Longleftrightarrow$$

$$\mathbf{l}(t_{2g}) = -\mathbf{l}(p)$$

$$l = 2 \qquad \boxed{l_{eff} = -1}$$

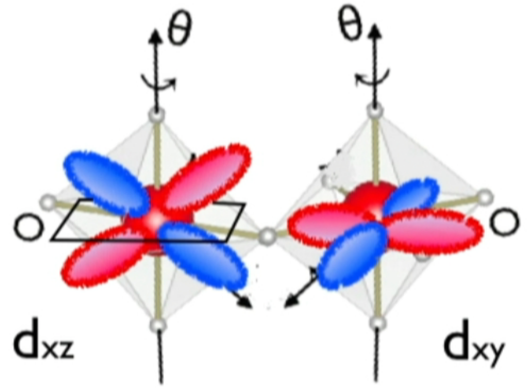
$$\begin{array}{rc} & \begin{array}{ccc} p_x & p_y & p_z \end{array} \\ l_x = & \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{bmatrix} \\ l_y = & \begin{bmatrix} 0 & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & 0 \end{bmatrix} \\ l_z = & \begin{bmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{array}$$



Jeff = 1/2 basis

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

SOC in Jeff=1/2 basis → pseudo-spin flip terms



bulk

$\mathrm{Sr_2IrO_4}$

only rotation

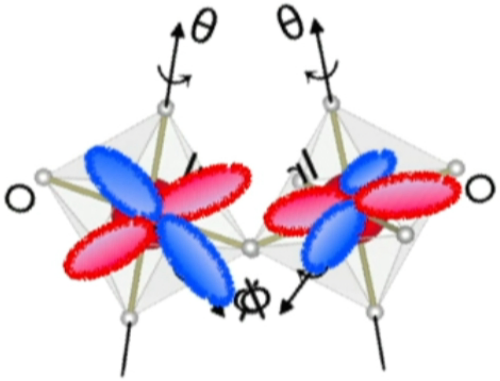
$$t = 0$$

$$|1/2\rangle \propto |yz\downarrow\rangle + i|zx\downarrow\rangle + \boxed{|xy\uparrow\rangle}$$

$$|-1/2\rangle \propto |yz\uparrow\rangle - \boxed{i|zx\uparrow\rangle} - |xy\downarrow\rangle$$

$$t\, d^{\dagger}_{i,xz,\uparrow} d_{j,xy,\uparrow}$$

$$\to t c^{\dagger}_{\boxed{j,j_z=\frac{1}{2}}} c_{i,\boxed{j_z=-\frac{1}{2}}} + h.c.$$

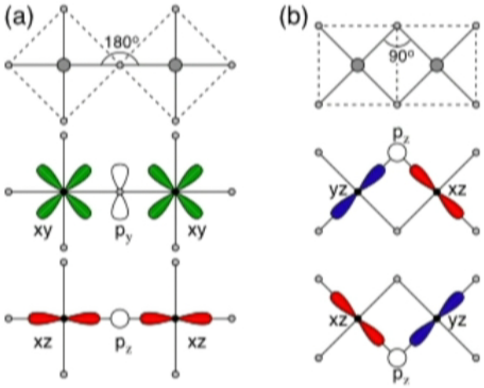


Orthorhombic lattice SrIrO3,
dxz and dxy hopping between nearest neighbour is allowed:

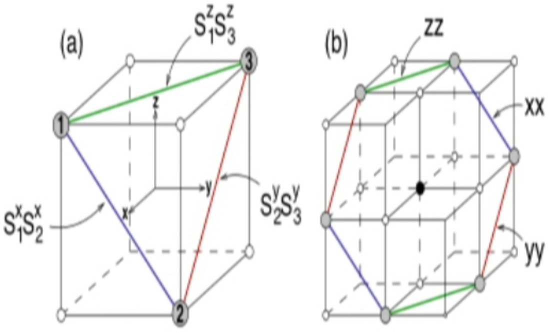
$$t \neq 0$$

Compass model (large U limit)

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



edge-shared octahedra



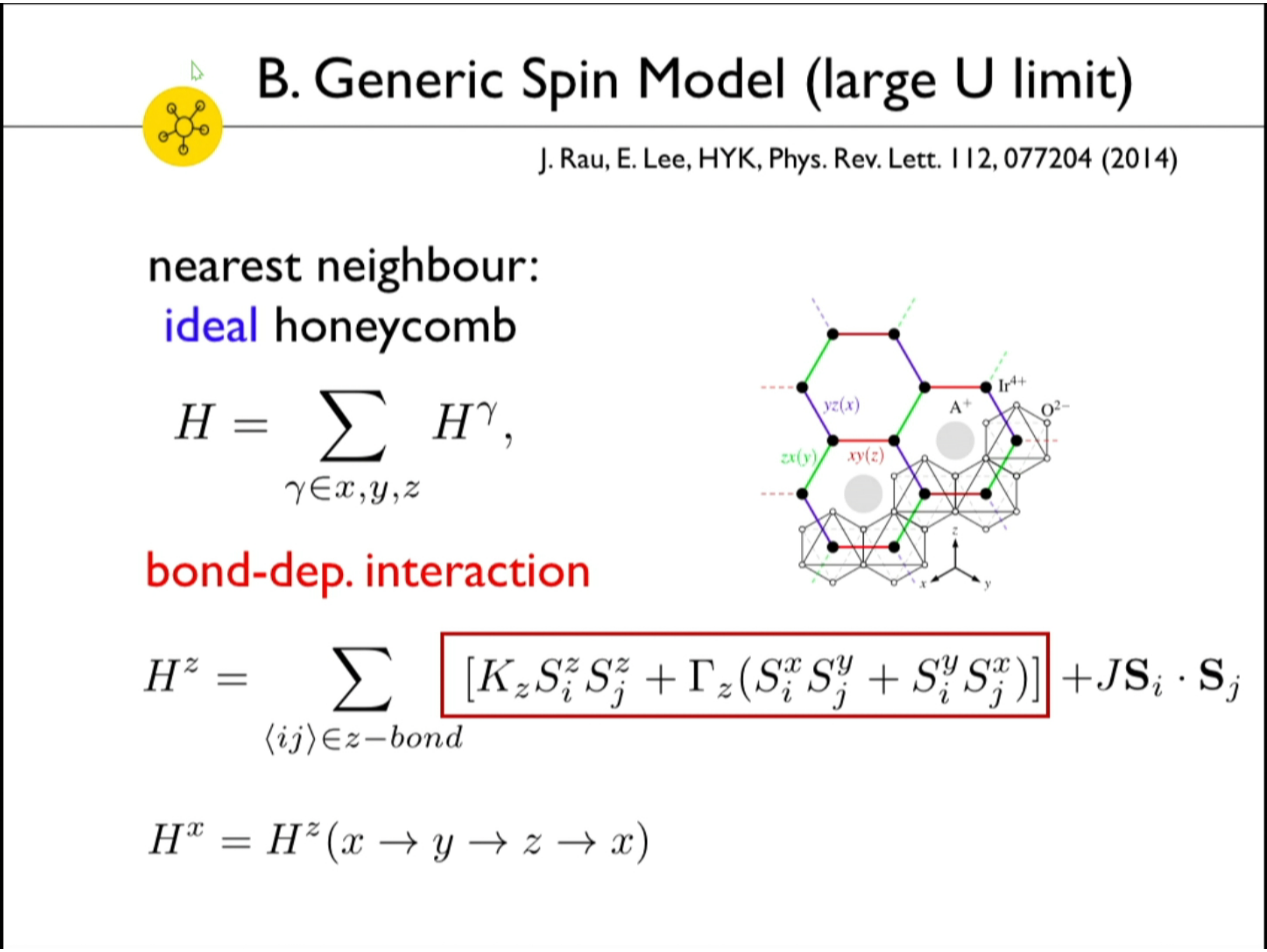
strong SOC in t2g states:

Kitaev-Heisenberg model

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

Material candidates: honeycomb Iridates (5d)

Na_2IrO_3, Li_2IrO_3



B. Generic Spin Model (large U limit)

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

nearest neighbour:
ideal honeycomb

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

bond-dep. interaction

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

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

Ordered phases nearby KSL

ED 24-site cluster

For $+\Gamma$

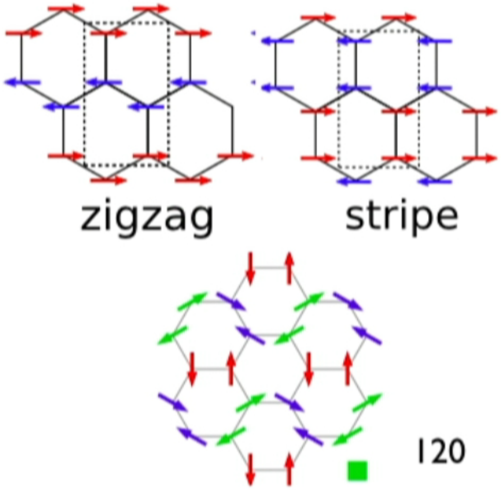
+J

+K

-K

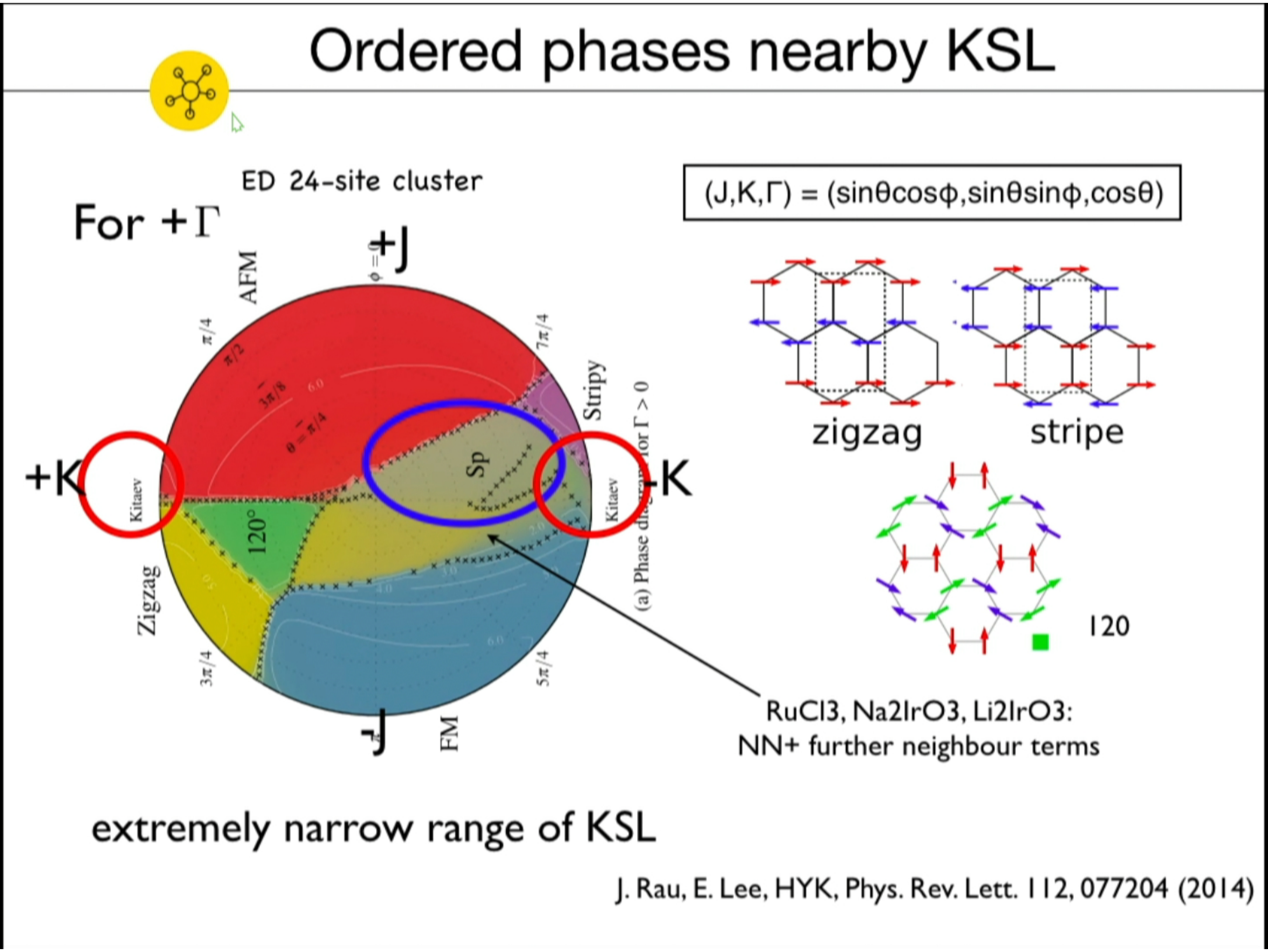
-J

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



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

Ordered phases nearby KSL



ED 24-site cluster

For $+\Gamma$

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

RuCl3, Na2IrO3, Li2IrO3:
NN+ further neighbour terms

extremely narrow range of KSL

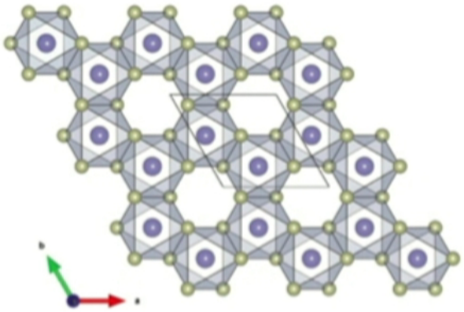
J. Rau, E. Lee, HYK, Phys. Rev. Lett. 112, 077204 (2014)

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

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

α-RuCl$_3$: A spin-orbit assisted Mott insulator on a honeycomb lattice

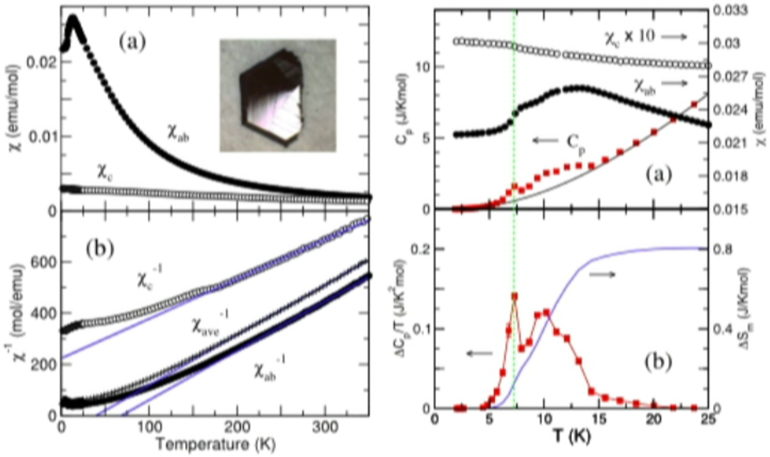
K. W. Plumb,[1] J. P. Clancy,[1] L. J. Sandilands,[1] V. Vijay Shankar,[1] Y. F. Hu,[2] K. S. Burch,[1,3]
Hae-Young Kee,[1,4] and Young-June Kim[1,*]

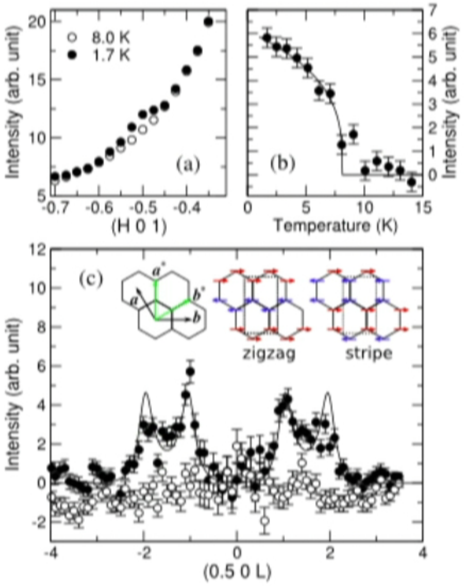


$$\boxed{\mathrm{Ru}^{3+} : 4d^5}$$

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].

Zigzag magnetic ordering below Tc





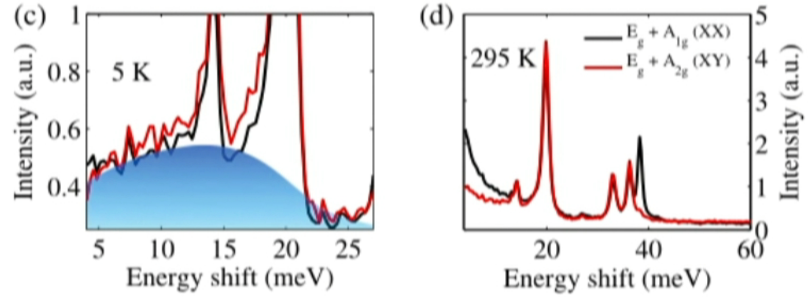
J. Sears et al, PRB 91, 144420 (2015)

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

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

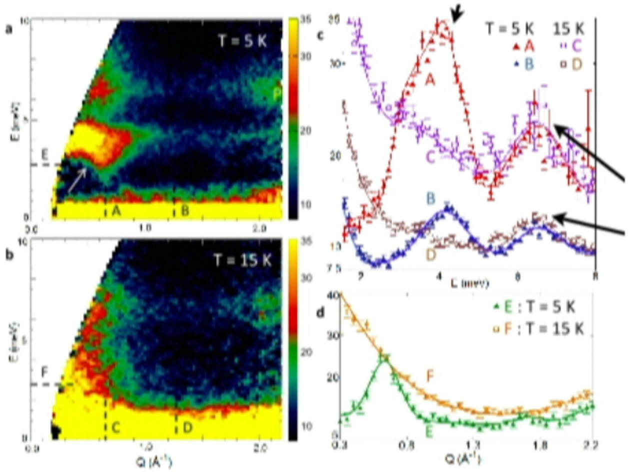
Proximate to Kitaev spin liquid

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)

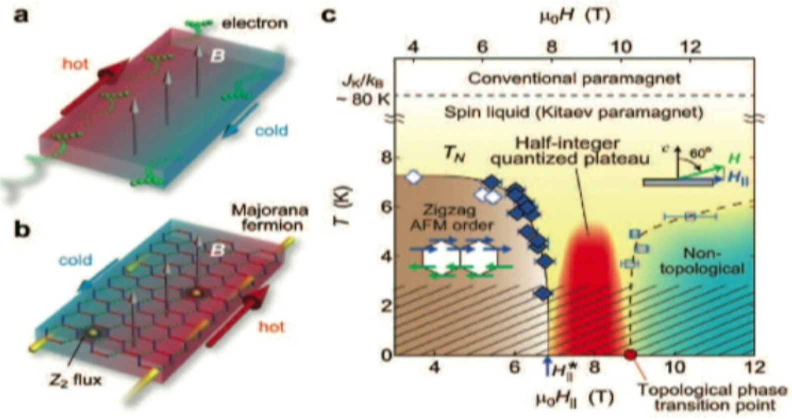
A. Banerjee... S. Nagler, Science (2017)

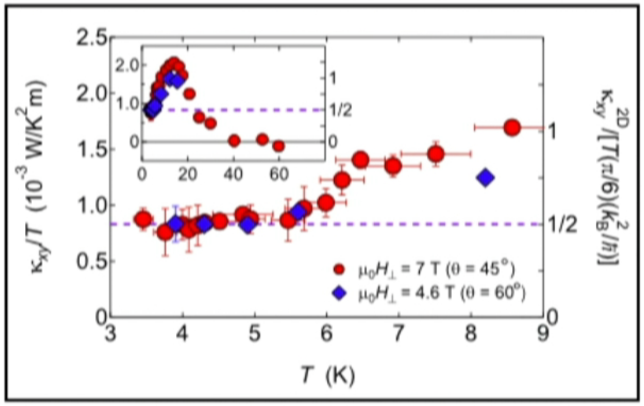
S.-H. Do, …, S. Ji, Nat. Phys. 13, 1079 (2017)

. . . . .

Magnetic field - destroy the ordering?
Governed by Kitaev spin interaction?

Thermal Transport: alpha-RuCl3





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

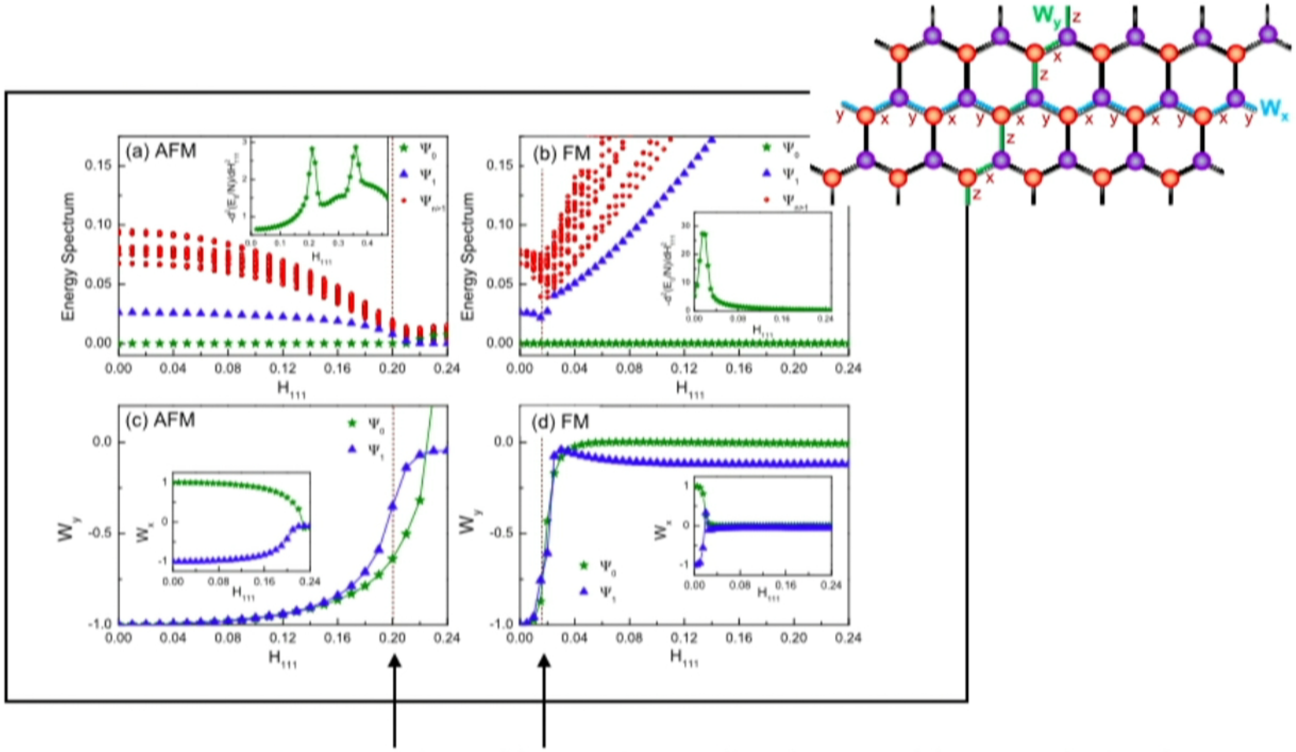
compare:

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

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

Real materials : not a pure Kitaev model (magnetic order at low T)

Pure Kitaev model cannot explain intermediate-field state



intermediate state?

Almost immediately unstable to polarized state

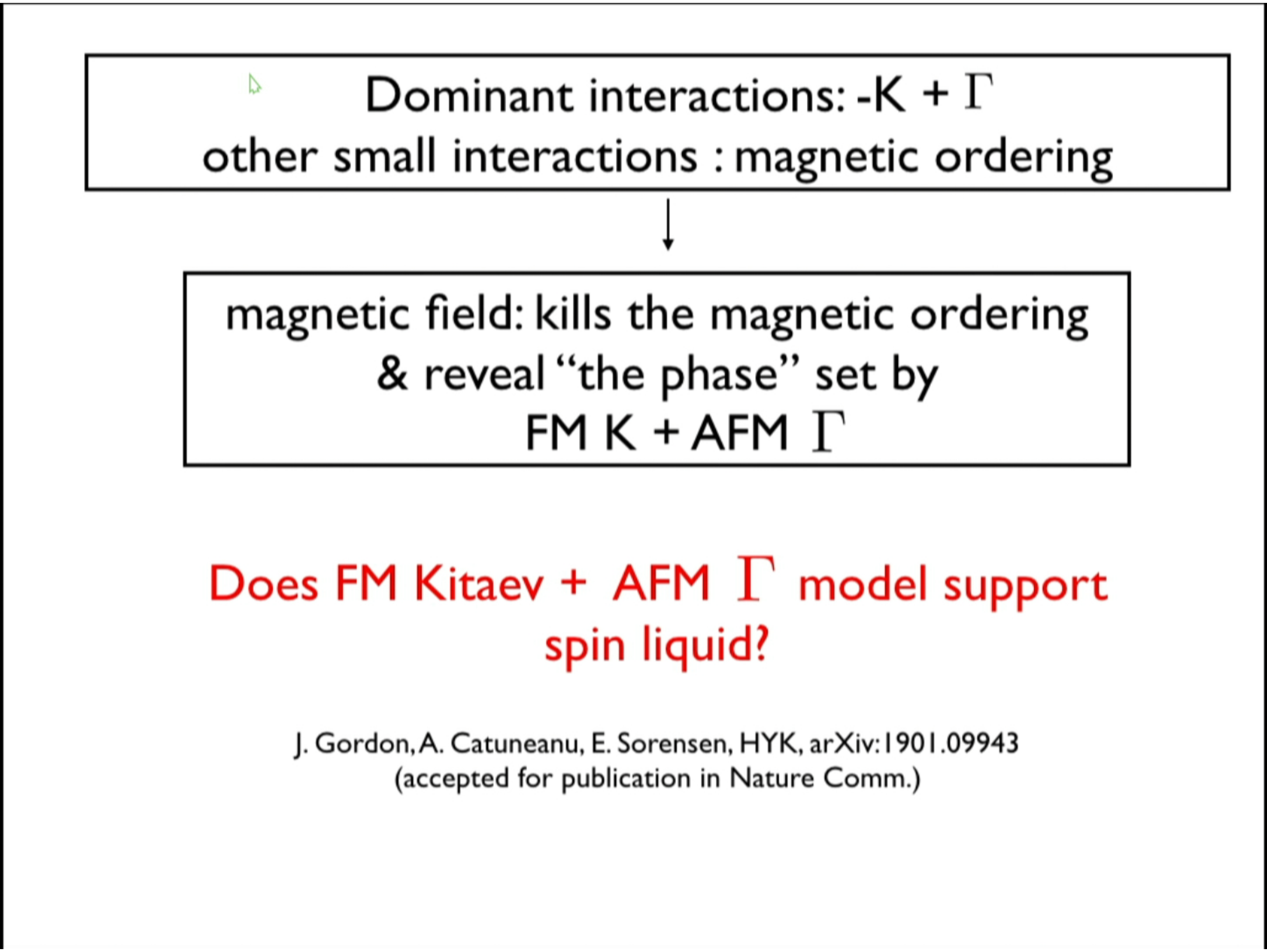
Z. Zhu, I. Kimchi, D. Sheng, L. Fu, PRB 97, 241110 (2018)

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



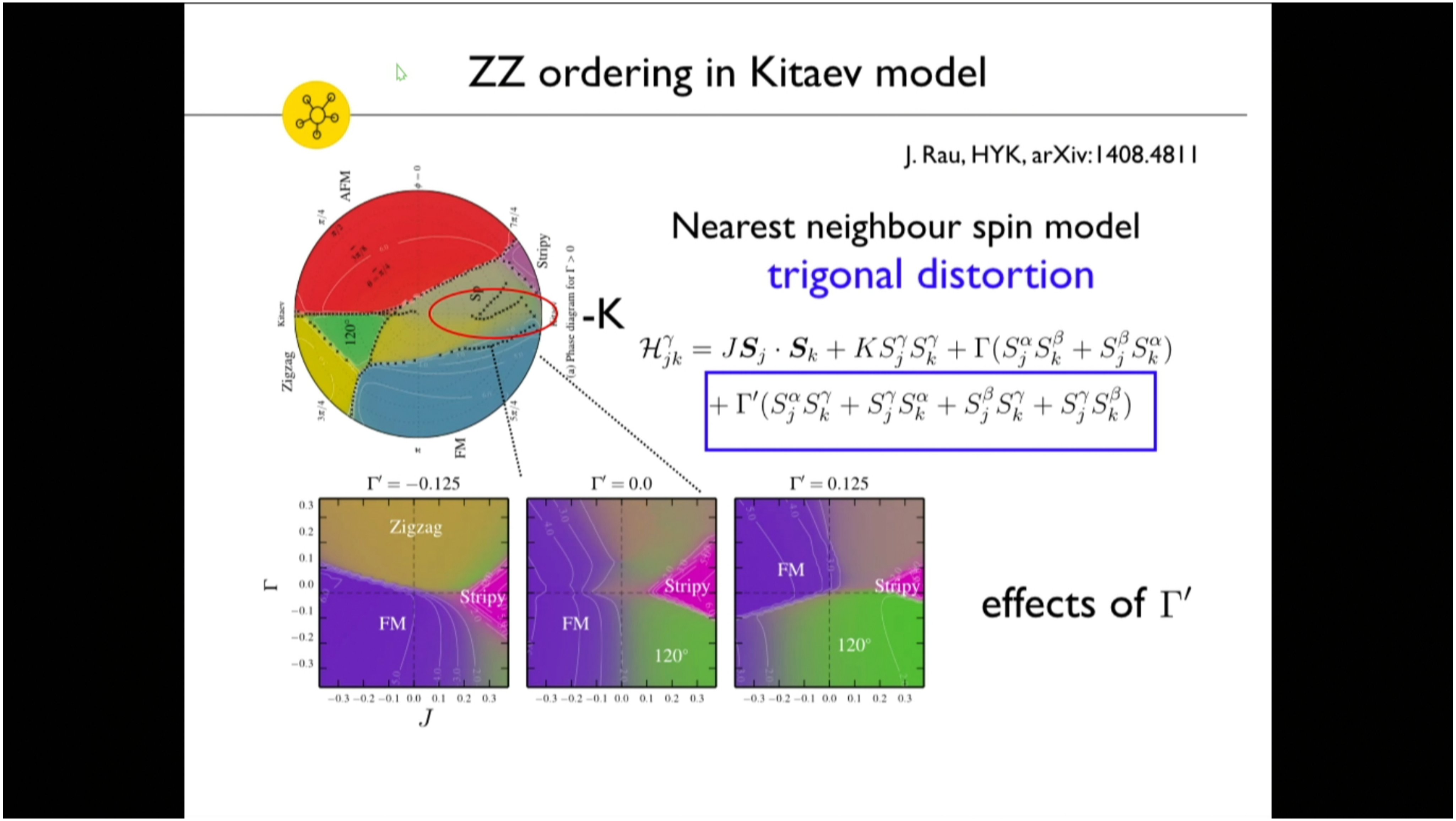
Dominant interactions: -K + Γ
other small interactions : magnetic ordering

↓

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
(accepted for publication in Nature Comm.)



ZZ ordering in Kitaev model

J. Rau, HYK, arXiv:1408.4811

Nearest neighbour spin model

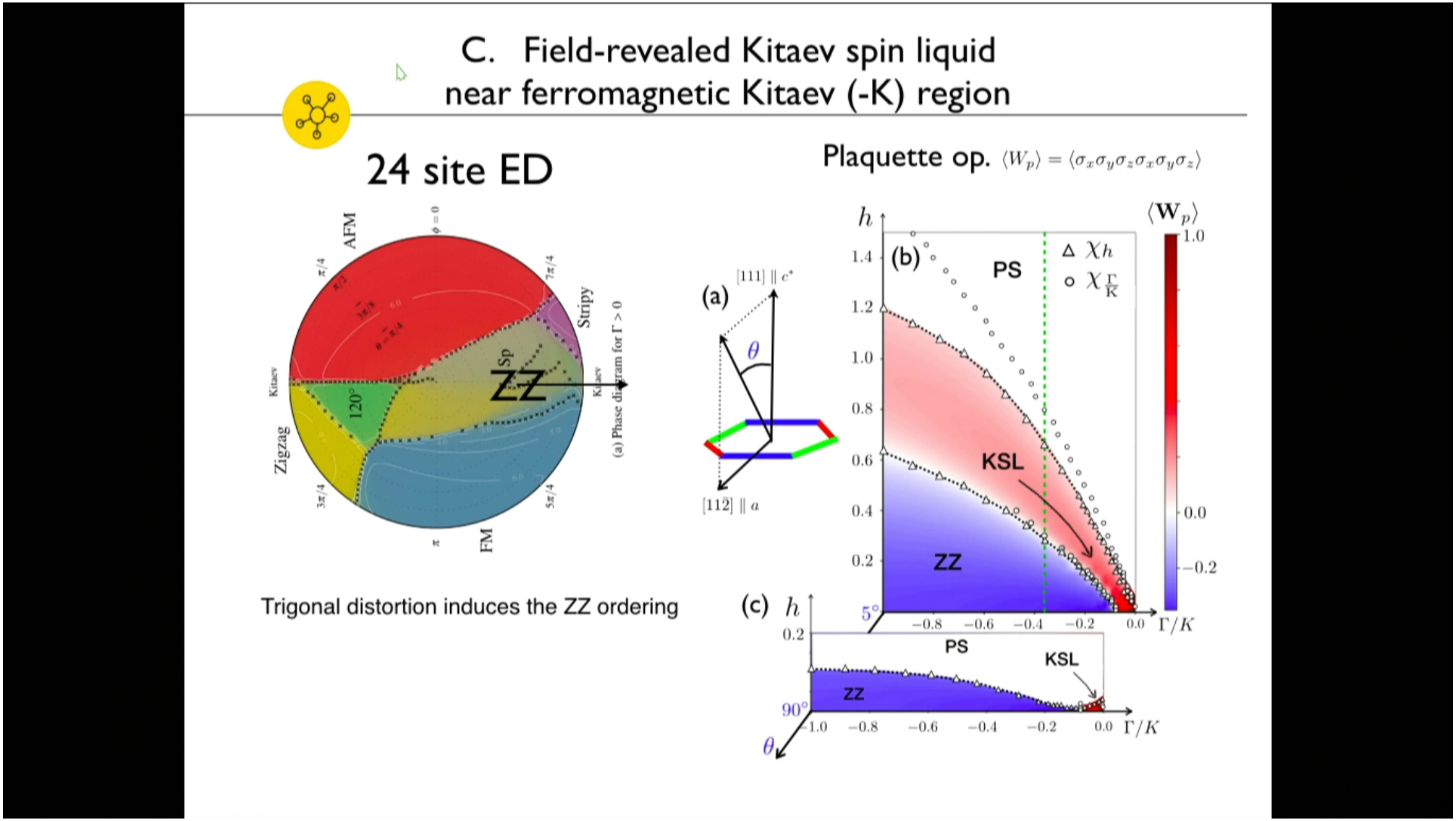
trigonal distortion

-K

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

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

effects of Γ'



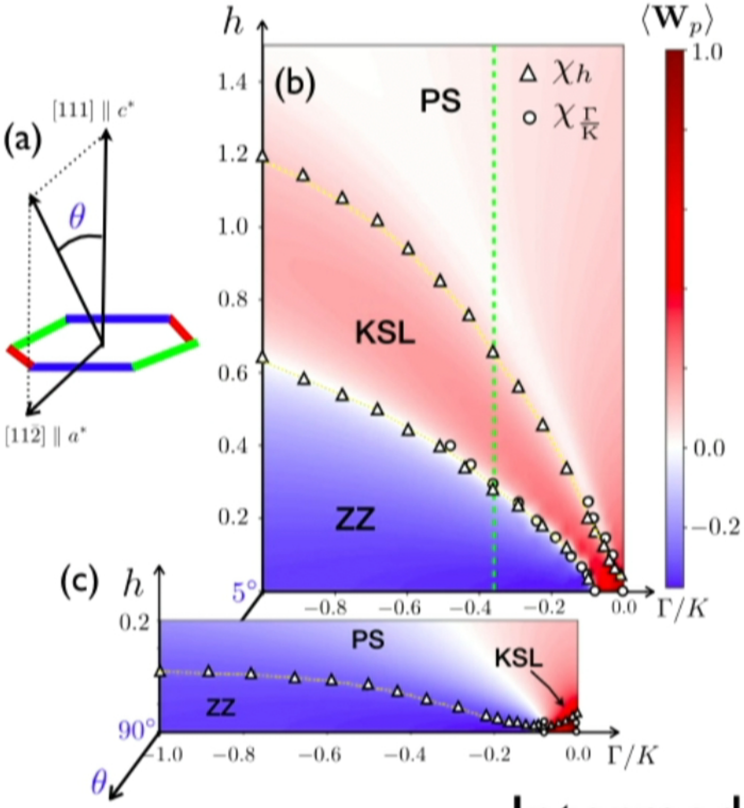
C. Field-revealed Kitaev spin liquid near ferromagnetic Kitaev (-K) region

24 site ED

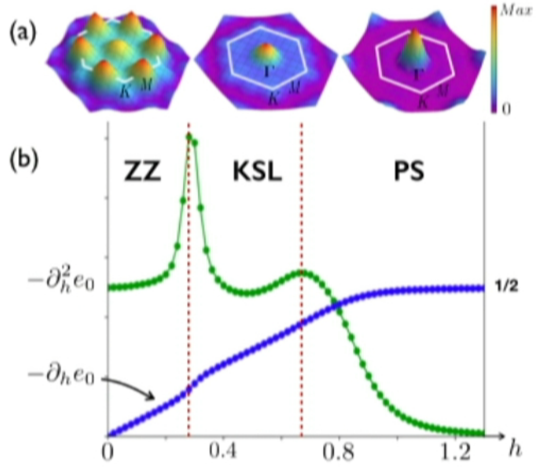
Plaquette op. $\langle W_p \rangle = \langle \sigma_x \sigma_y \sigma_z \sigma_x \sigma_y \sigma_z \rangle$

Trigonal distortion induces the ZZ ordering

24 site ED

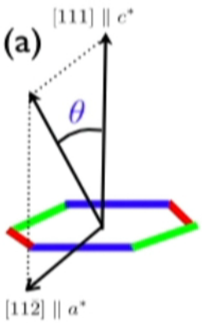


Set J=0 & Gamma' = -0.03

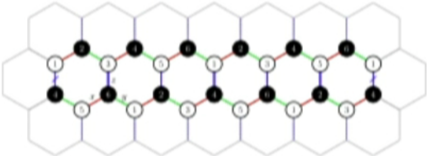


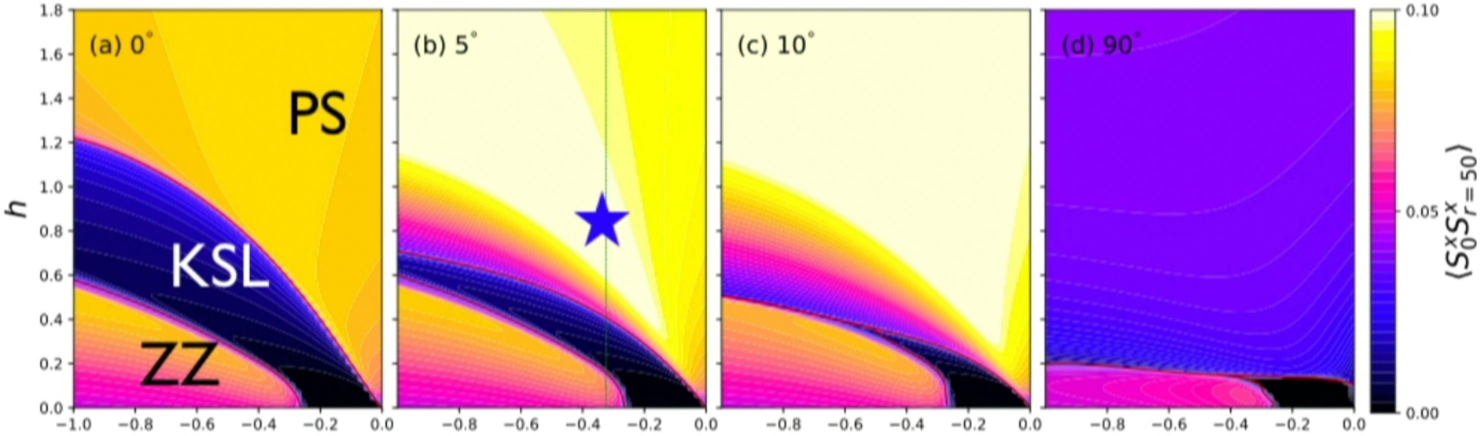
Intermediate field KSL is found when Gamma is finite

DMRG results on stripy geometry



Set J=0 & Γ'= -0.1

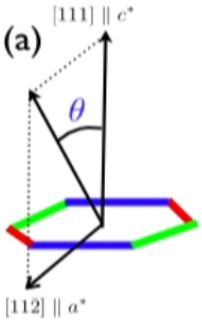




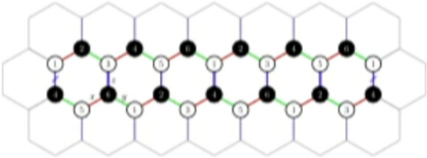
Strong field-angle dependence

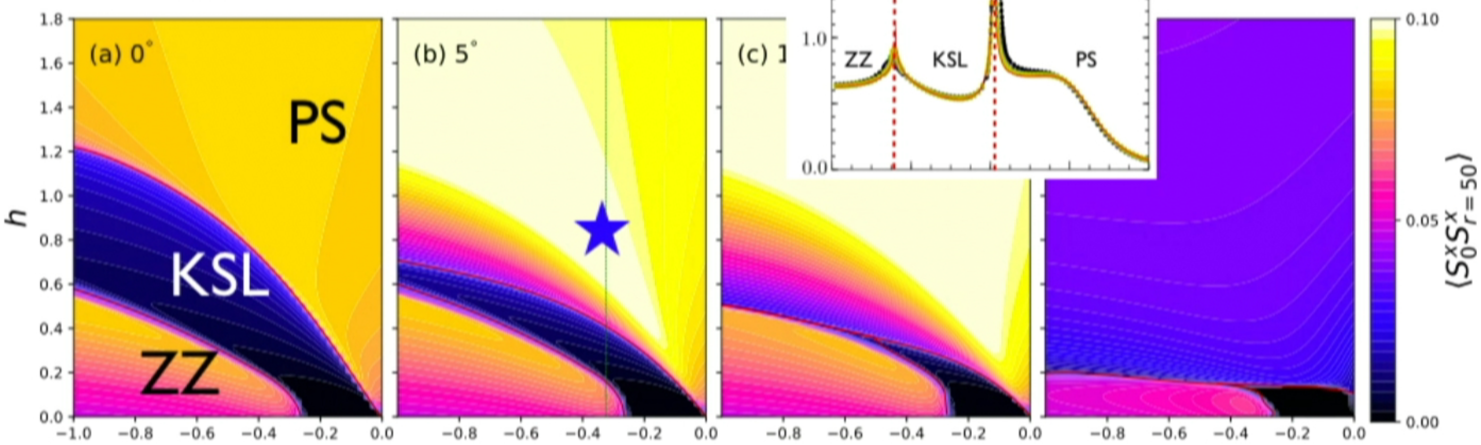
★ strong spin fluctuations in PS in high field regime

DMRG results on stripy geometry



Set J=0 & Γ'= -0.1



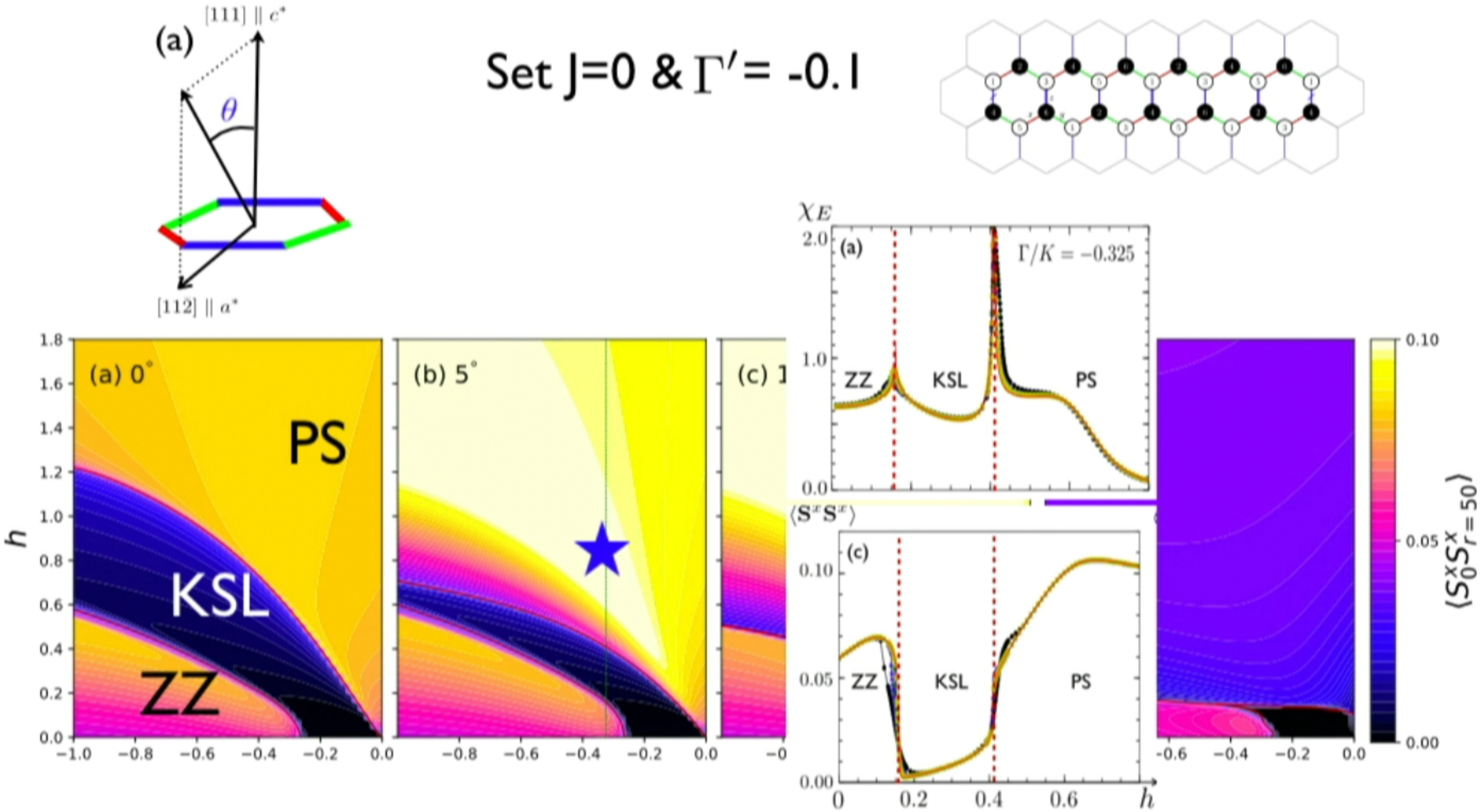


Strong field-angle dependence

★ 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

Another spin liquid nearby Kitaev spin liquid near ferromagnetic Kitaev (-K) region?

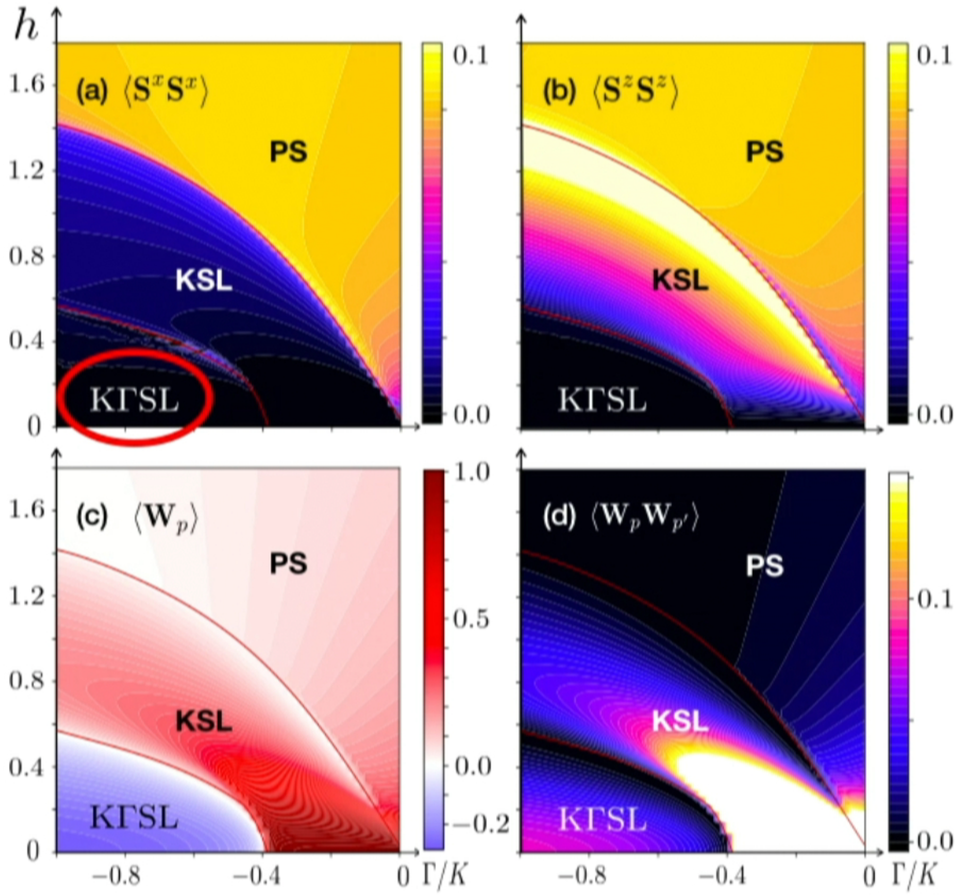
When Γ' =0

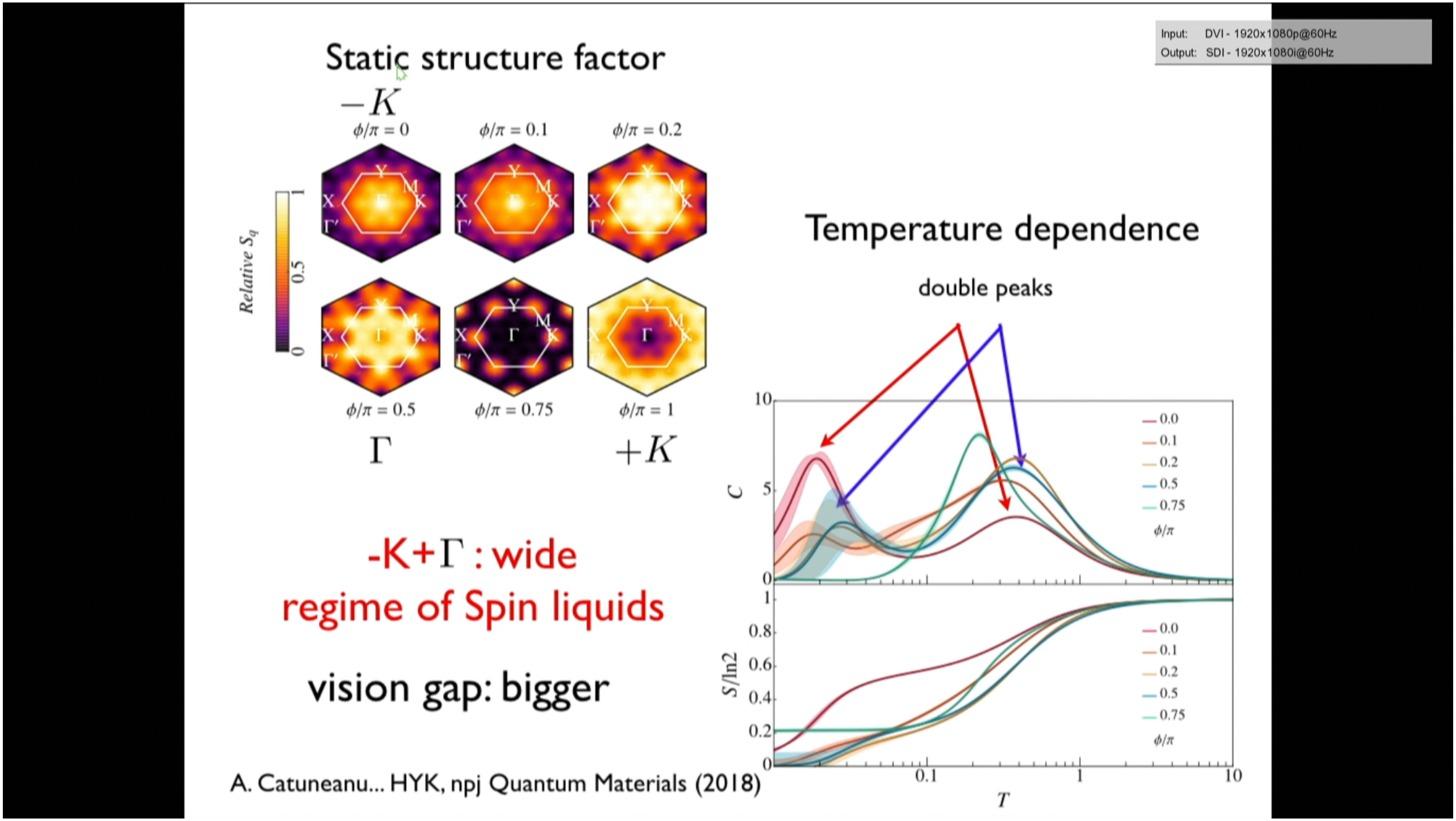
: no ZZ ordering

: What is the phase set by -K + Gamma?

DMRG results on 2 leg stripy geometry

Set J=0 & θ =0 & Γ' =0 without ZZ ordering





Static structure factor

-K+Γ : wide regime of Spin liquids

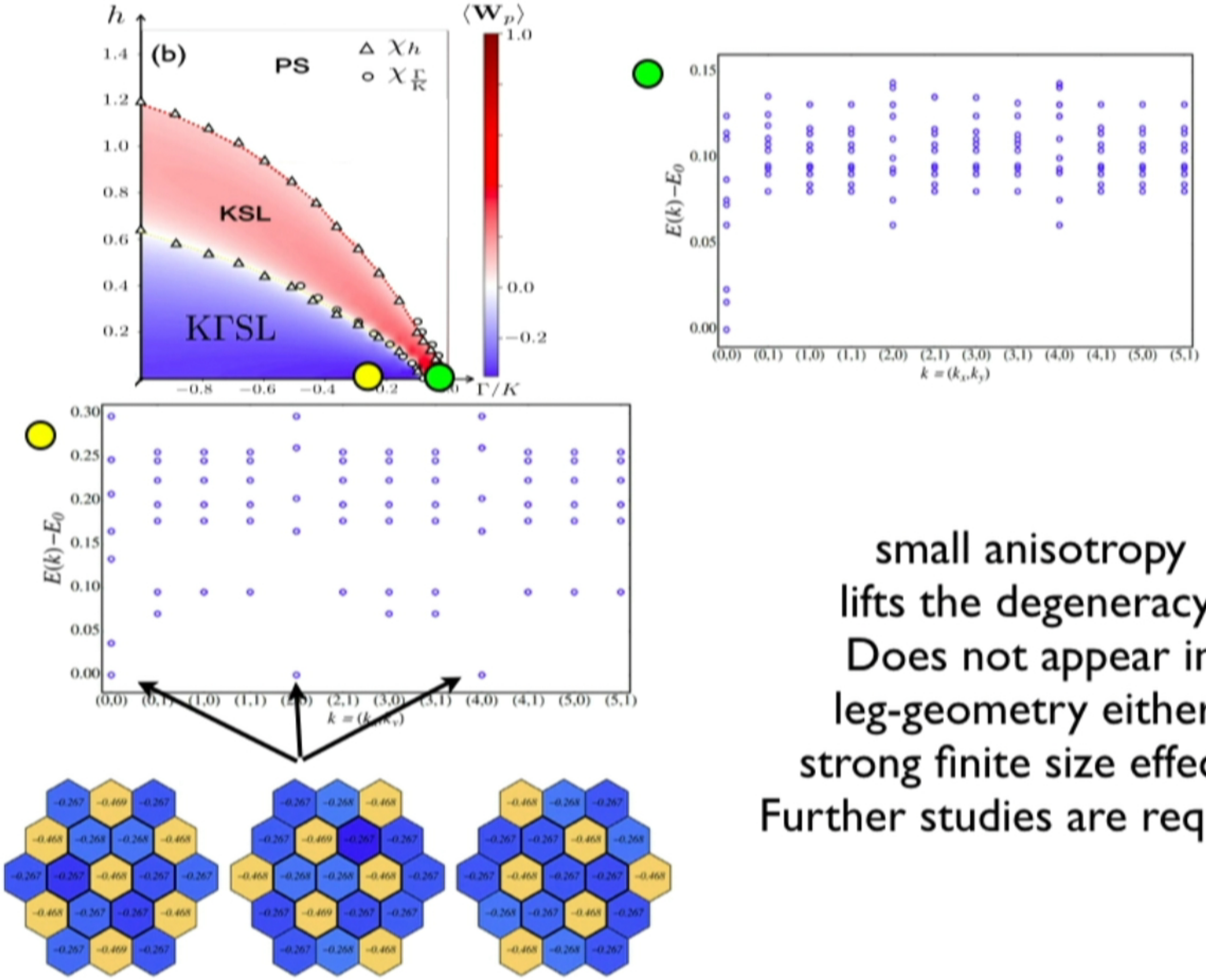
vision gap: bigger

A. Catuneanu... HYK, npj Quantum Materials (2018)

Temperature dependence

double peaks

3-fold degenerate: vortex crystal spin liquid (24 site ED)



small anisotropy
lifts the degeneracy:
Does not appear in
leg-geometry either:
strong finite size effects:
Further studies are required

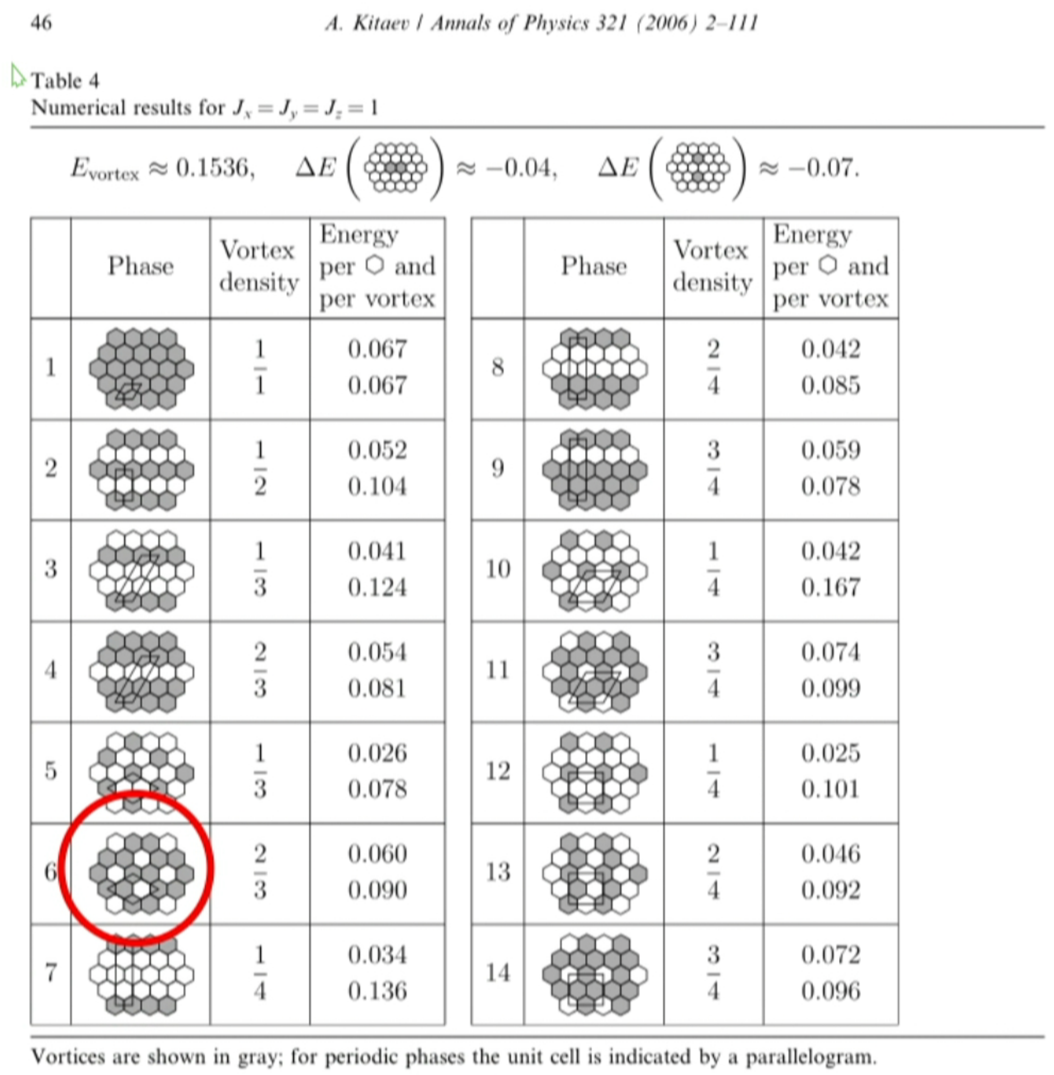


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Table 4
Numerical results for $J_x = J_y = J_z = 1$

$$E_{\text{vortex}} \approx 0.1536, \quad \Delta E\left(\quad\right) \approx -0.04, \quad \Delta E\left(\quad\right) \approx -0.07.$$

	Phase	Vortex density	Energy per ⬡ and per vortex		Phase	Vortex density	Energy per ⬡ and per vortex
1		$\frac{1}{1}$	0.067 0.067	8		$\frac{2}{4}$	0.042 0.085
2		$\frac{1}{2}$	0.052 0.104	9		$\frac{3}{4}$	0.059 0.078
3		$\frac{1}{3}$	0.041 0.124	10		$\frac{1}{4}$	0.042 0.167
4		$\frac{2}{3}$	0.054 0.081	11		$\frac{3}{4}$	0.074 0.099
5		$\frac{1}{3}$	0.026 0.078	12		$\frac{1}{4}$	0.025 0.101
6		$\frac{2}{3}$	0.060 0.090	13		$\frac{2}{4}$	0.046 0.092
7		$\frac{1}{4}$	0.034 0.136	14		$\frac{3}{4}$	0.072 0.096

Vortices are shown in gray; for periodic phases the unit cell is indicated by a parallelogram.

RuCl3 near Spin Liquid (possibly two spin liquids)

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

hyperhoneycomb spiral - near SU(2) $K = \Gamma$: L37.00012
Session L37: Iridates - honeycomb lattice & other geometries

higher-spin Kitaev materials: arXiv:1903.00011
P37.00006 by P. Stavropoulos
Session P37: Honeycomb lattice and other low-D models

doping: topological superconductor

strain induced phase transitions