TECHNISCHE UNIVERSITÄT DRESDEN

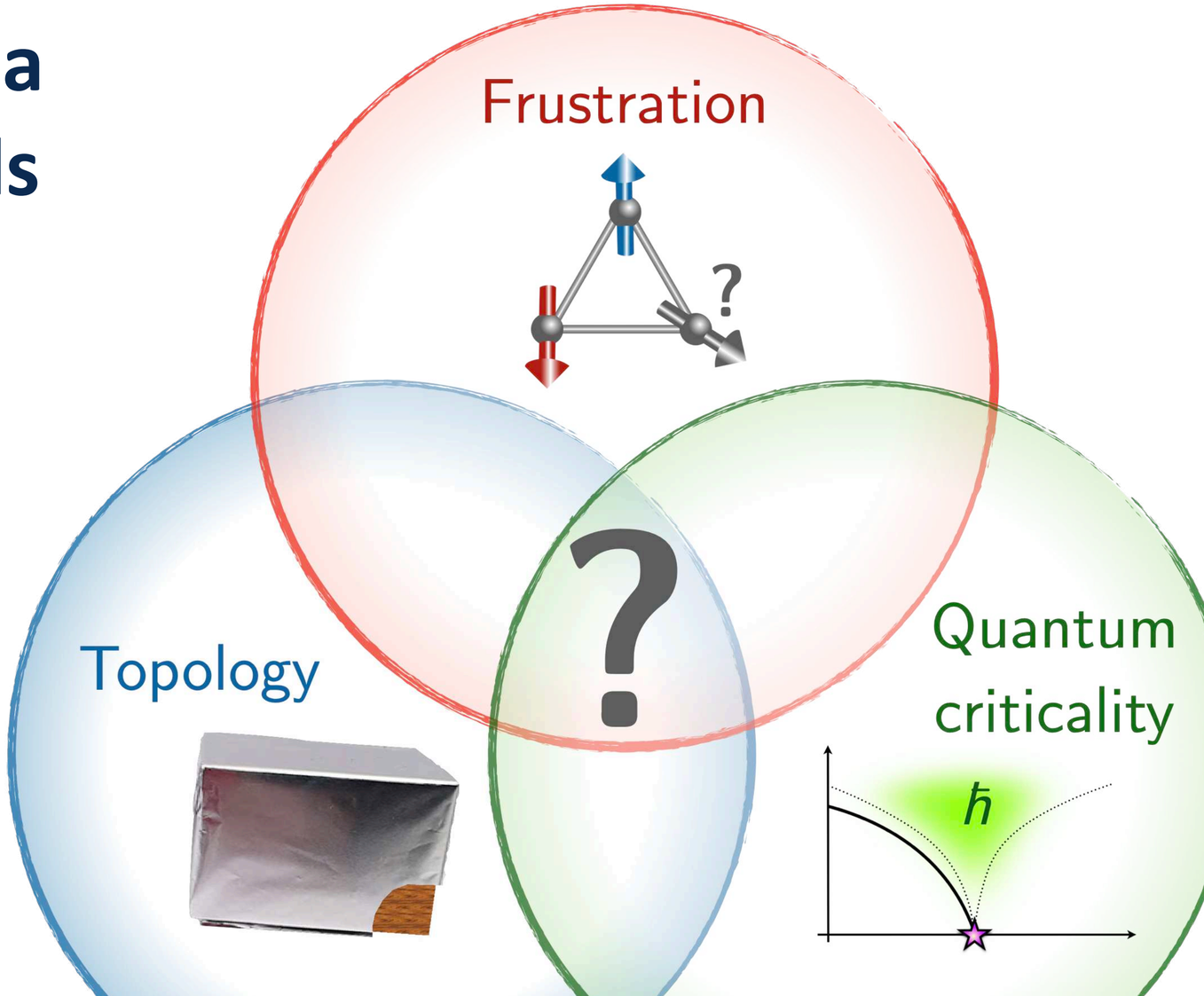
DRESDEN concept

Emergent Phenomena in Quantum Materials

Lukas Janssen

Wilhelm Krüger (Dresden)
David Moser (Dresden)
Shouryya Ray (Dresden → Odense)

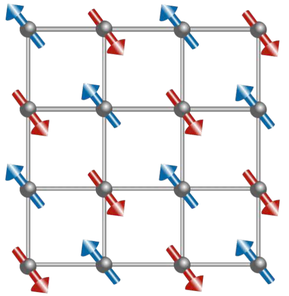
Fakher Assaad (Würzburg)
Zi Yang Meng (Hong Kong)
Zihong Liu (Würzburg → Dresden)
Jonas Schwab (Würzburg)
Urban Seifert (Santa Barbara)



Outline

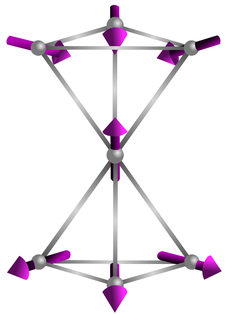
(1) Introduction

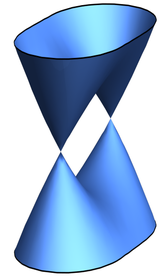
- Research Motivation
- Research Goals

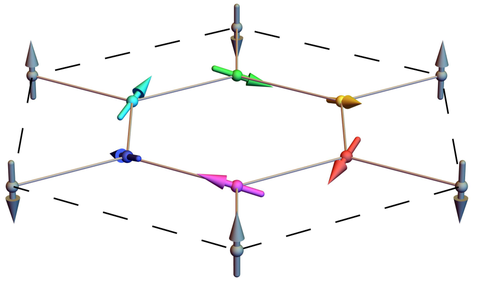


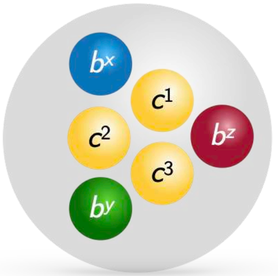
(2) Emergent Phenomena in Quantum Materials

- Emergent Symmetries
- Emergent Topology
- Emergent Orders
- Emergent Particles



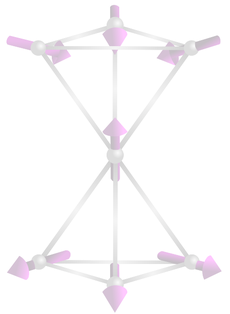


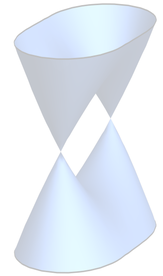


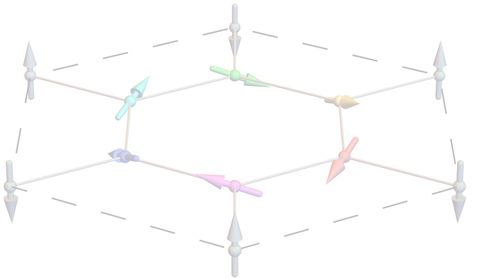


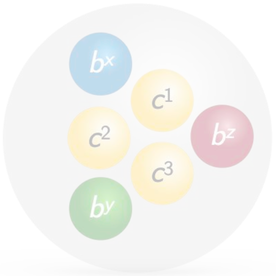
(3) Summary

Outline







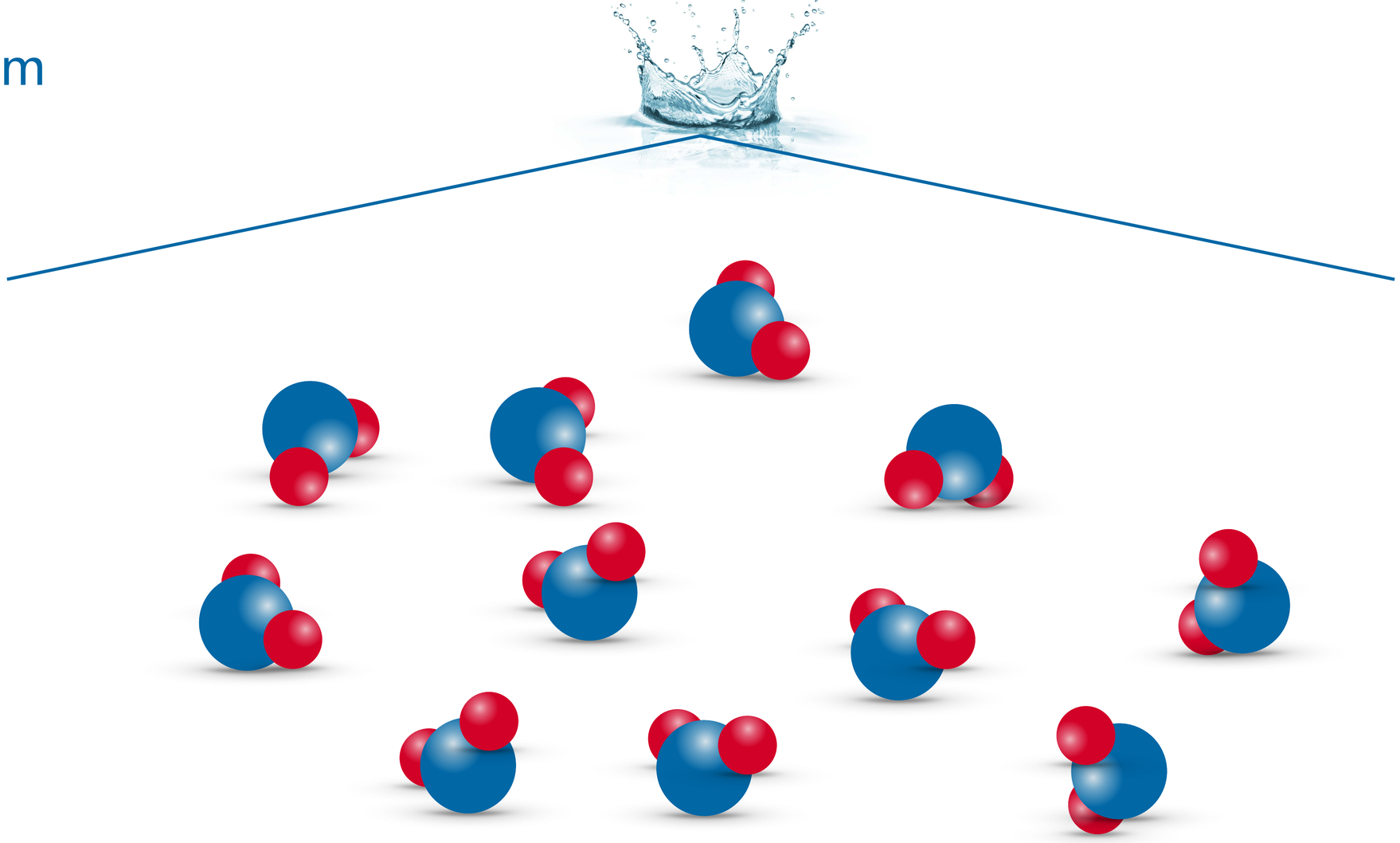


Reductionism

Matter

pinimg.com

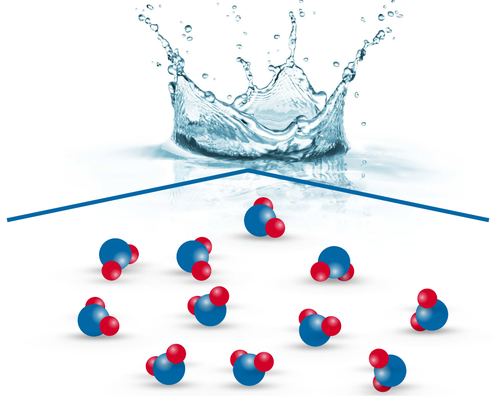
Reductionism



Matter

Molecules

Reductionism



Matter

Molecules

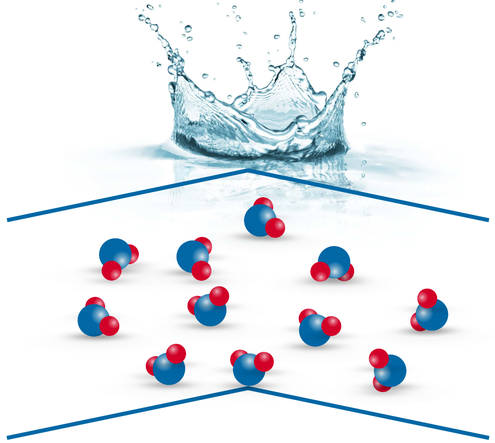
Atoms

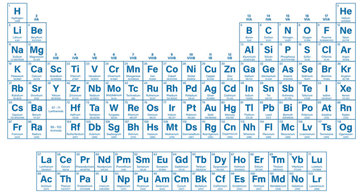
1																	2
H																	He
Hydrogen 1.008																	Helium 4.002602
3	4											13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	10
Li	Be											B	C	N	O	F	Ne
Lithium 6.94	Beryllium 9.0121831											Boron 10.81	Carbon 12.011	Nitrogen 14.007	Oxygen 15.999	Fluorine 18.998403163	Neon 20.1797
11	12	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13	14	15	16	17	18
Na	Mg											Al	Si	P	S	Cl	Ar
Sodium 22.98976928	Magnesium 24.305											Aluminium 26.9815385	Silicon 28.085	Phosphorus 30.973761998	Sulfur 32.06	Chlorine 35.45	Argon 39.948
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Potassium 39.0983	Calcium 40.078	Scandium 44.955908	Titanium 47.867	Vanadium 50.9415	Chromium 51.9961	Manganese 54.938044	Iron 55.845	Cobalt 58.933194	Nickel 58.6934	Copper 63.546	Zinc 65.38	Gallium 69.723	Germanium 72.630	Arsenic 74.921595	Selenium 78.971	Bromine 79.904	Krypton 83.798
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Rubidium 85.4678	Strontium 87.62	Yttrium 88.90584	Zirconium 91.224	Niobium 92.90637	Molybdenum 95.95	Technetium (98)	Ruthenium 101.07	Rhodium 102.90550	Palladium 106.42	Silver 107.8682	Cadmium 112.414	Indium 114.818	Tin 118.710	Antimony 121.760	Tellurium 127.60	Iodine 126.90447	Xenon 131.293
55	56	57 - 71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs	Ba	Lanthanoids	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Caesium 132.90545196	Barium 137.327		Hafnium 178.49	Tantalum 180.94788	Tungsten 183.84	Rhenium 186.207	Osmium 190.23	Iridium 192.217	Platinum 195.084	Gold 196.966569	Mercury 200.592	Thallium 204.38	Lead 207.2	Bismuth 208.98040	Polonium (209)	Astatine (210)	Radon (222)
87	88	89 - 103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr	Ra	Actinoids	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
Francium (223)	Radium (226)		Rutherfordium (267)	Dubnium (268)	Seaborgium (269)	Bohrium (270)	Hassium (269)	Meitnerium (278)	Darmstadtium (281)	Roentgenium (282)	Copernicium (285)	Nihonium (286)	Flerovium (289)	Moscovium (289)	Livermorium (293)	Tennessine (294)	Oganesson (294)

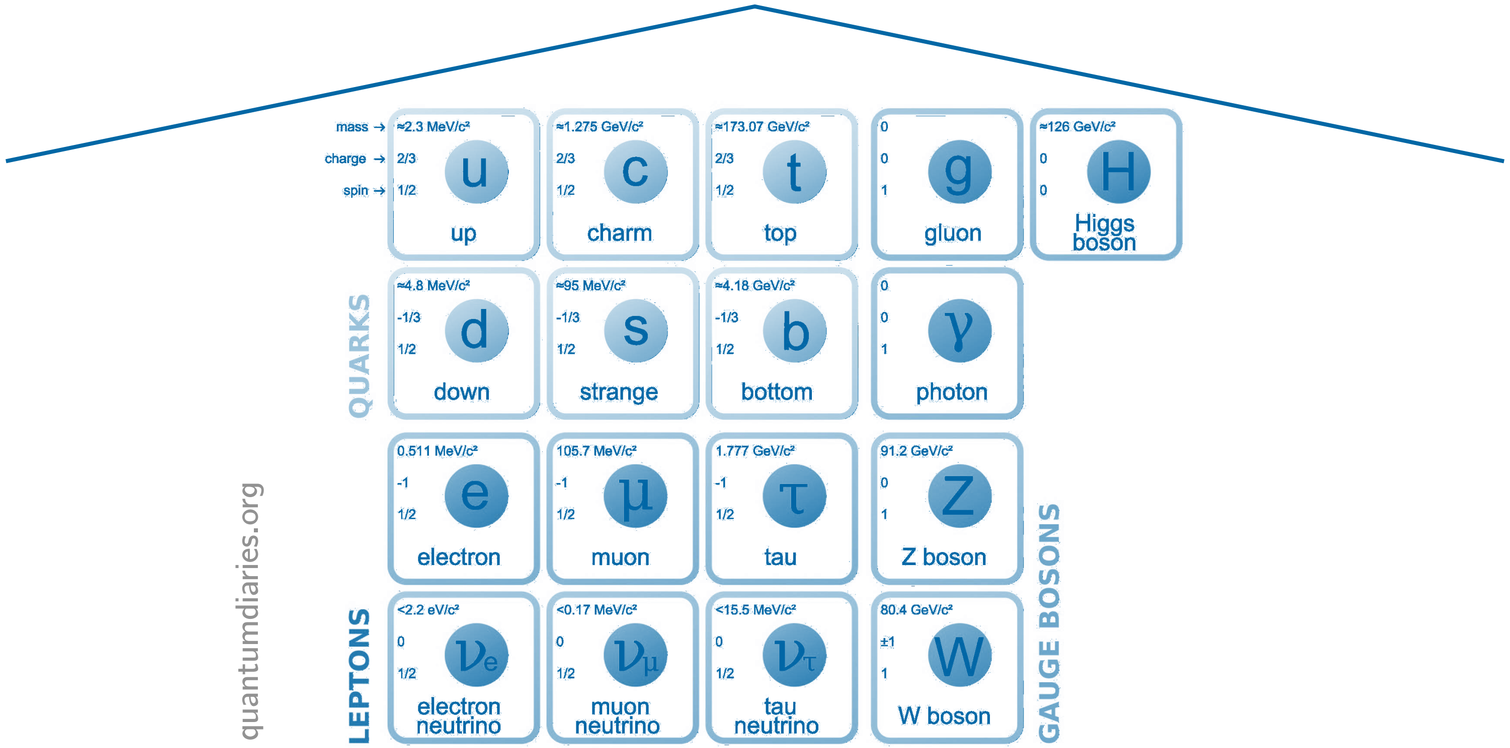
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum 138.90547	Cerium 140.116	Praseodymium 140.90766	Neodymium 144.242	Promethium (145)	Samarium 150.36	Europium 151.964	Gadolinium 157.25	Terbium 158.92535	Dysprosium 162.500	Holmium 164.93033	Erbium 167.259	Thulium 168.93422	Ytterbium 173.045	Lutetium 174.9668
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium (227)	Thorium 232.0377	Protactinium 231.03588	Uranium 238.02891	Neptunium (237)	Plutonium (244)	Americium (243)	Curium (247)	Berkelium (247)	Californium (251)	Einsteinium (252)	Fermium (257)	Mendelevium (258)	Nobelium (259)	Lawrencium (266)

philipharris.co.uk

Reductionism







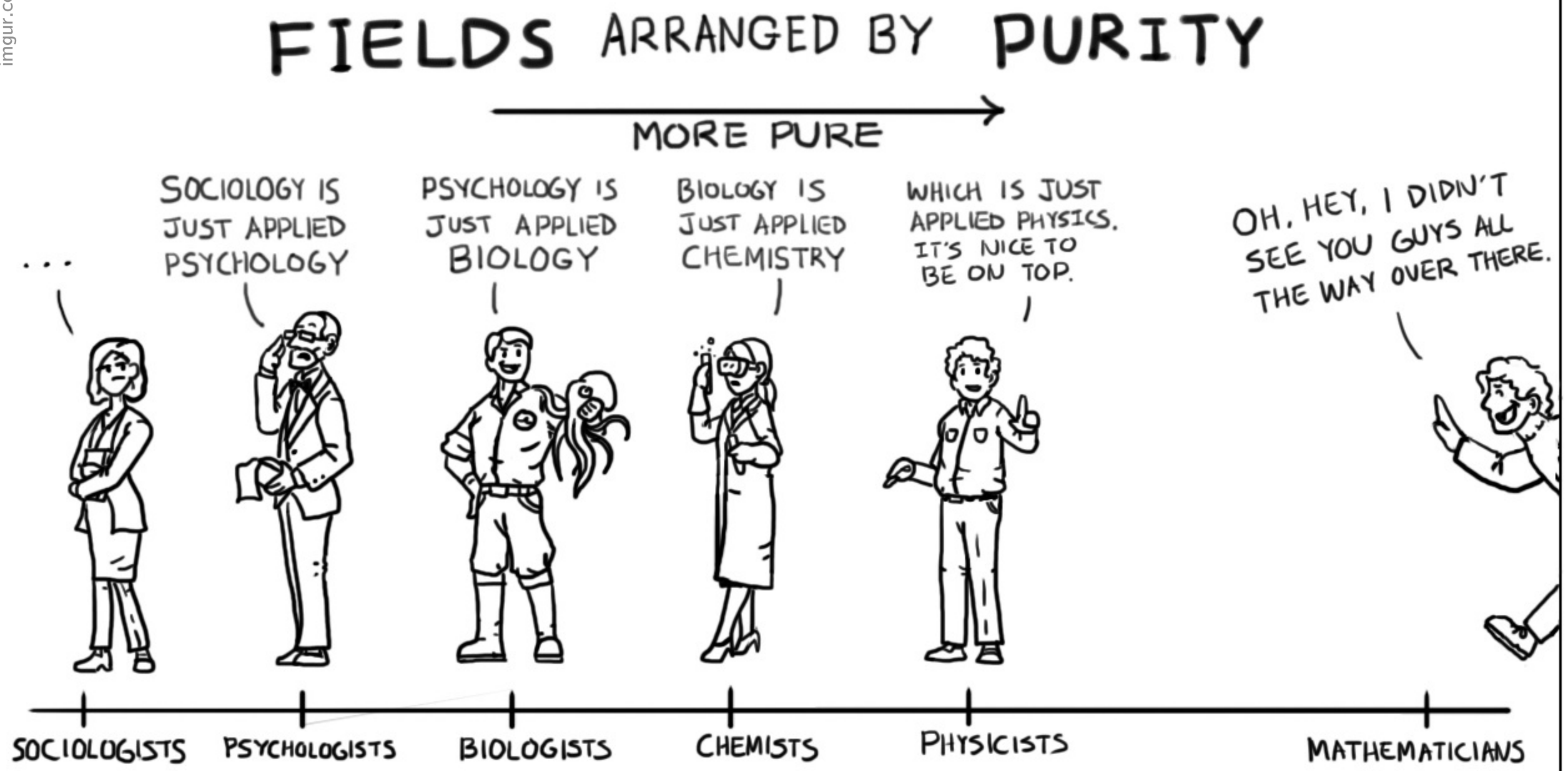
Matter

Molecules

Atoms

Elementary particles

FIELDS ARRANGED BY PURITY

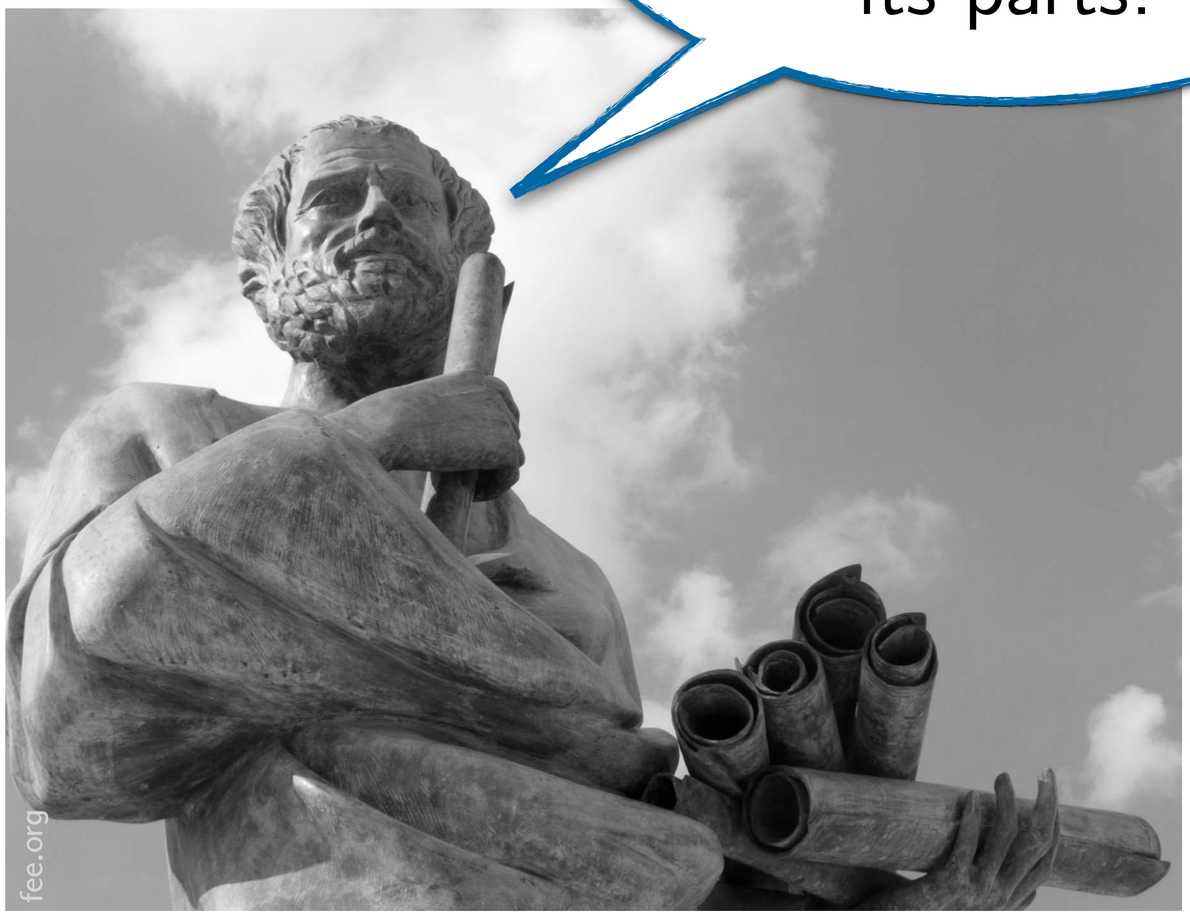


Complexity

quora.com

Emergence

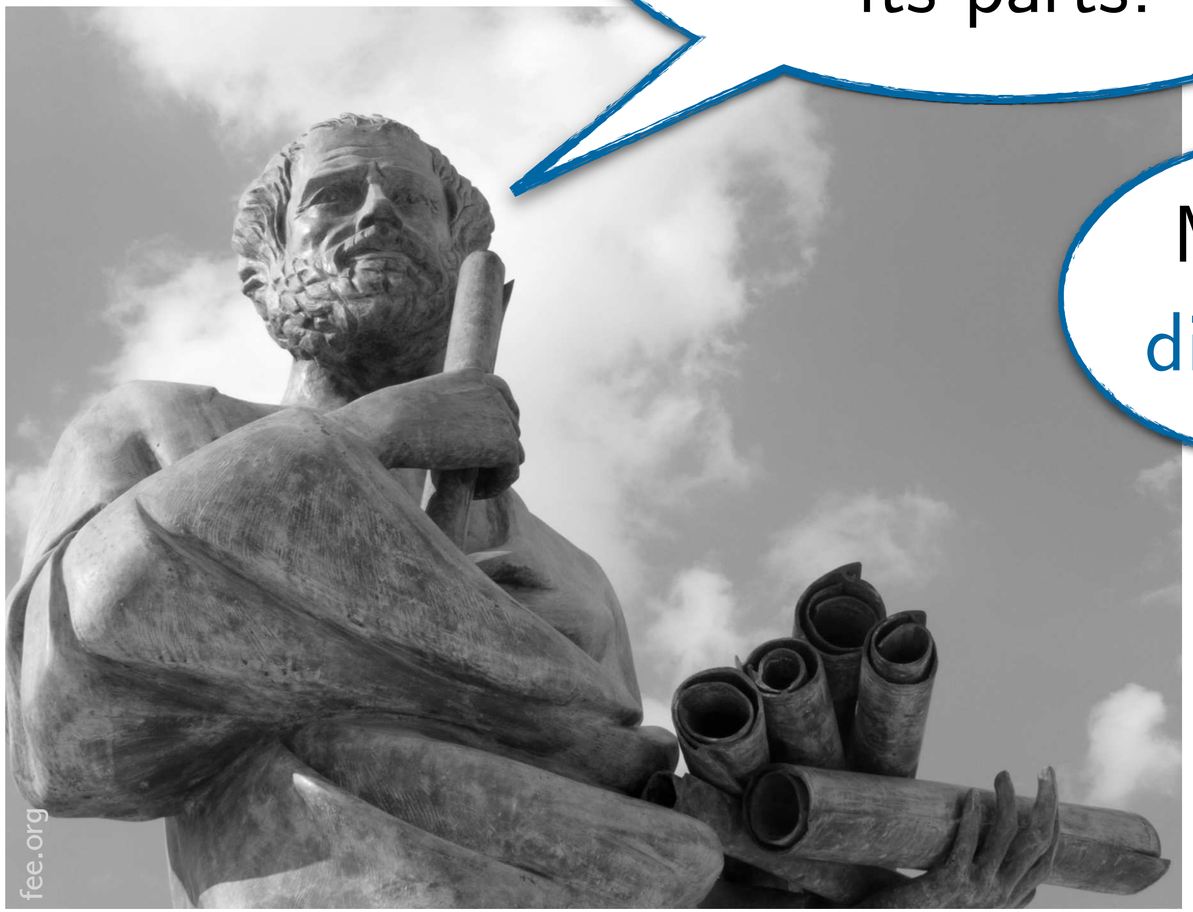
The whole is greater than the sum of its parts!



Aristotle, 385-322 BC

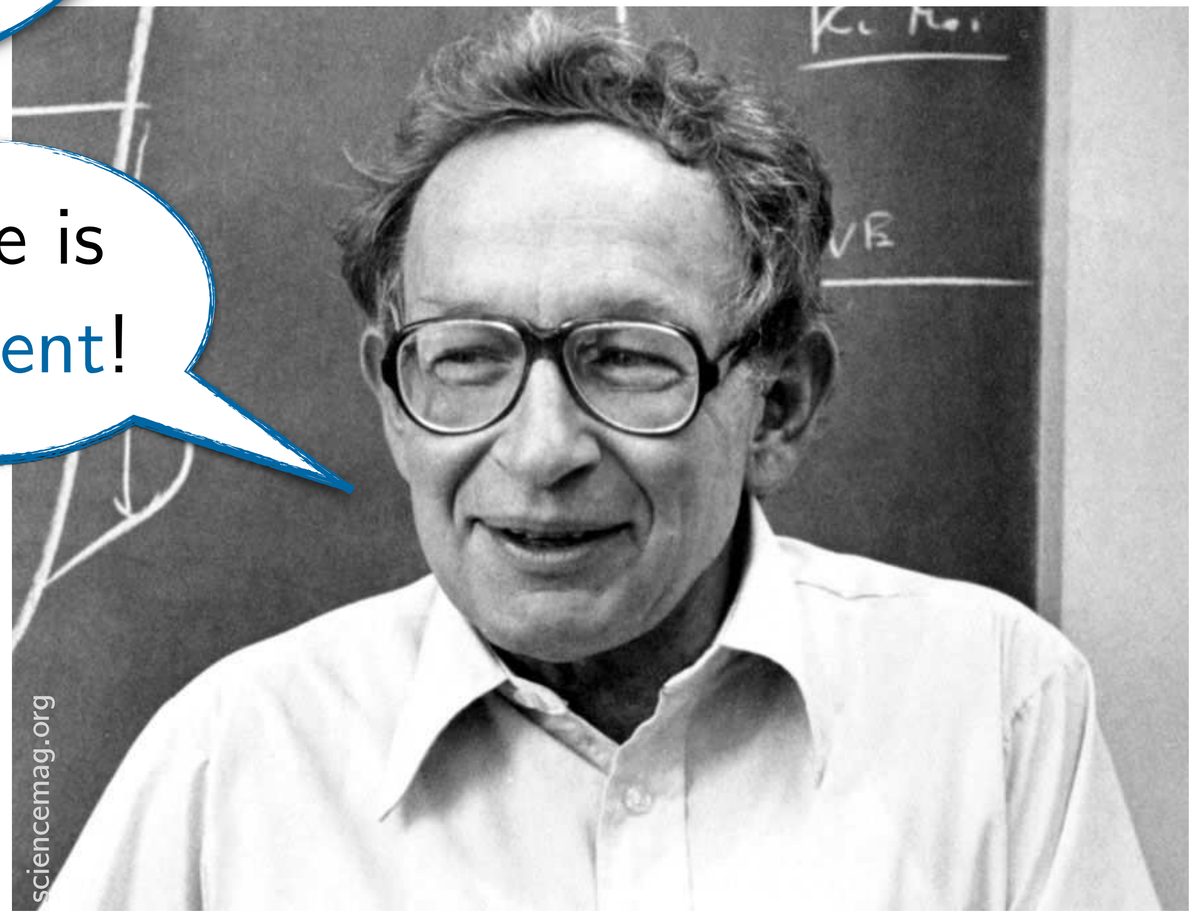
Emergence

The whole is greater than the sum of its parts!



Aristotle, 385-322 BC

More is different!



Anderson, 1923-2020 AD

[Anderson, Science '72]

Living Bridges

quantamagazine.org

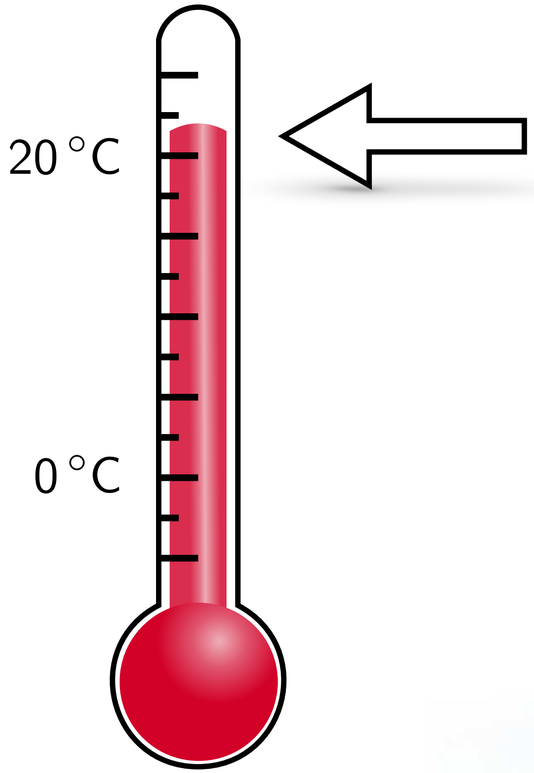
[Reid *et al.*, PNAS '15]

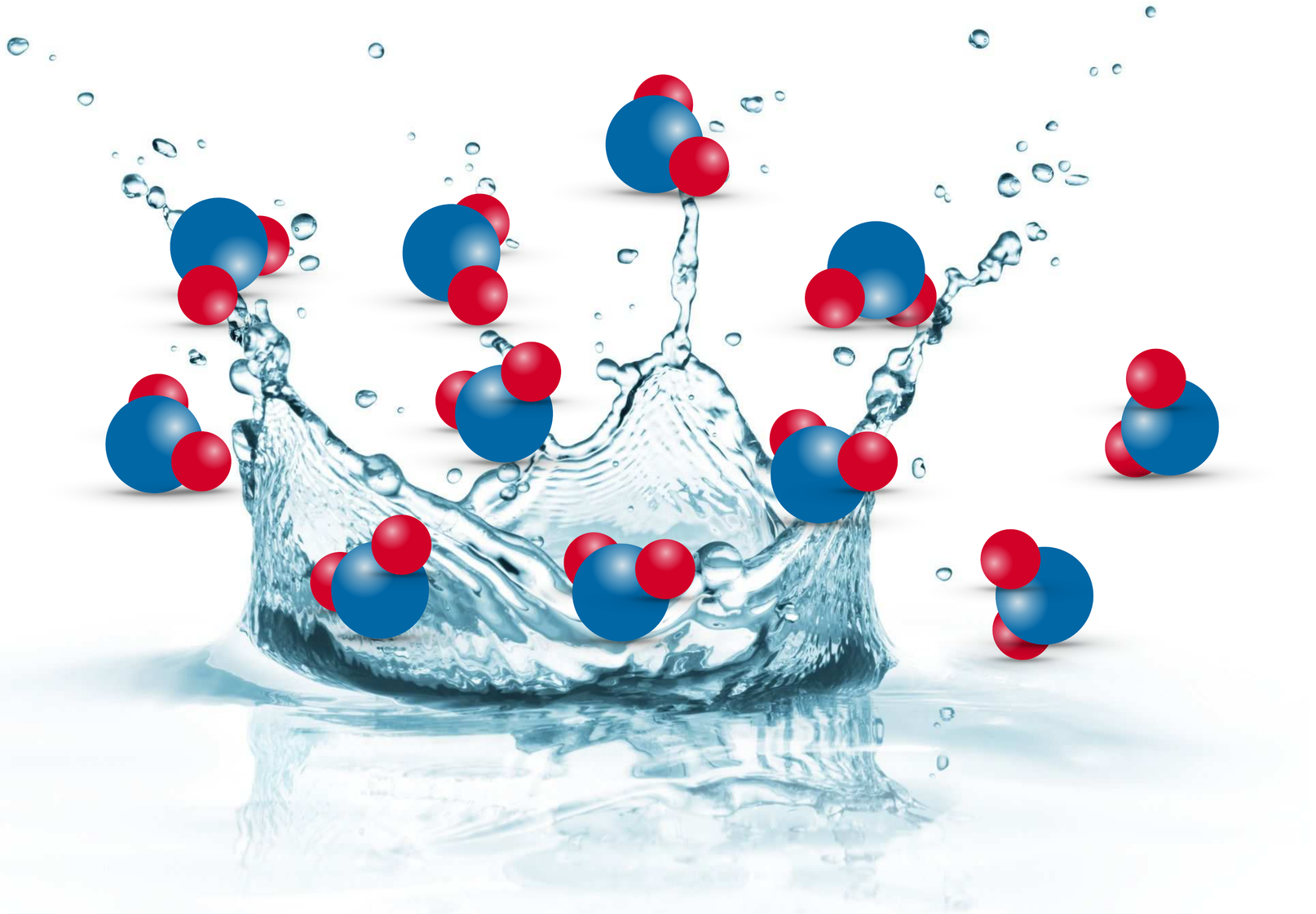
Living Bridges

quantamagazine.org

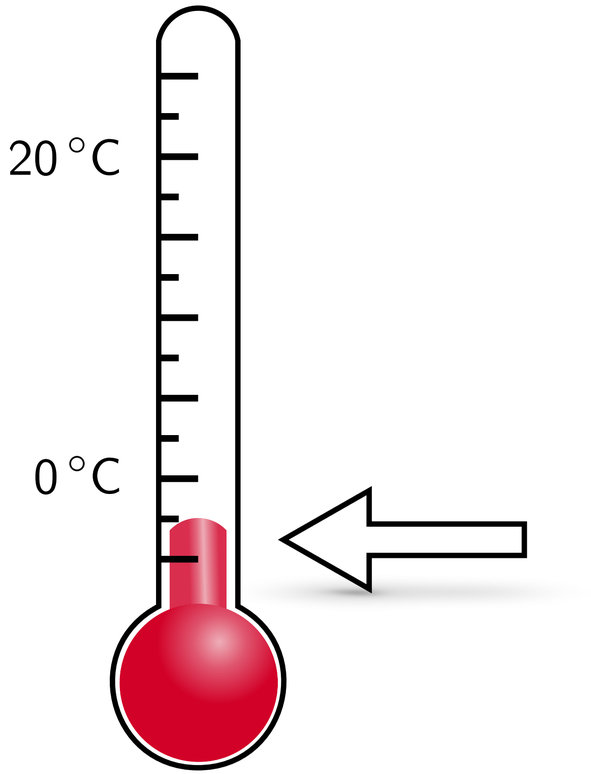
[Reid *et al.*, PNAS '15]

Snowflakes

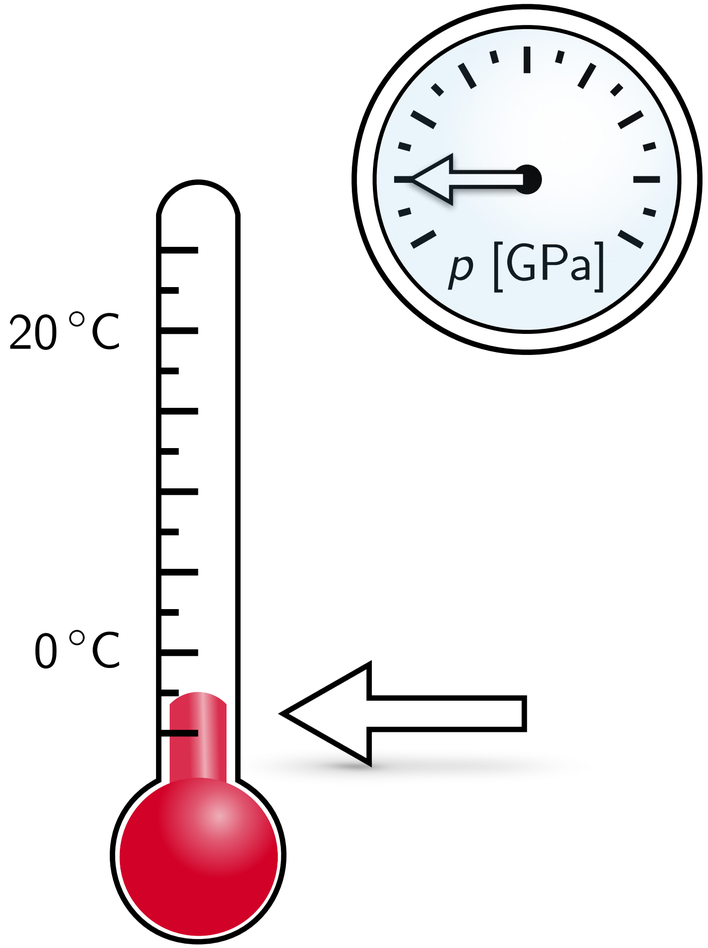




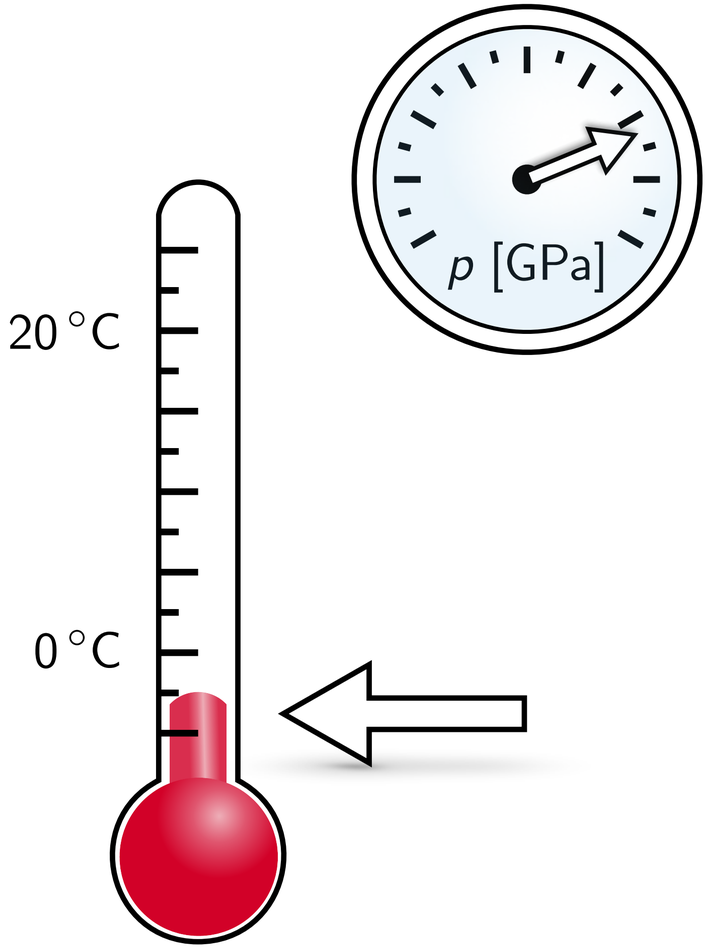
Snowflakes

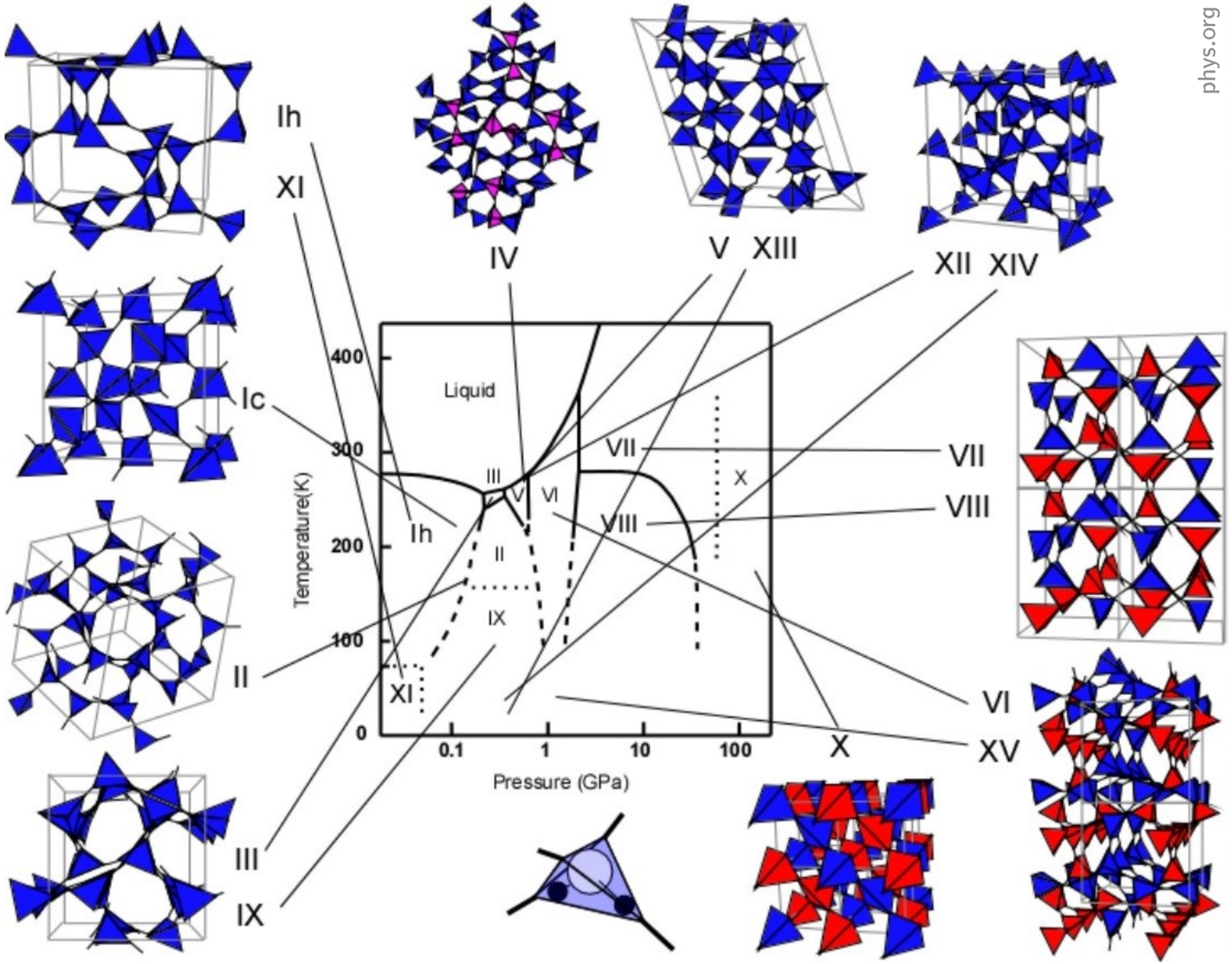


Phases of Ice



Phases of Ice

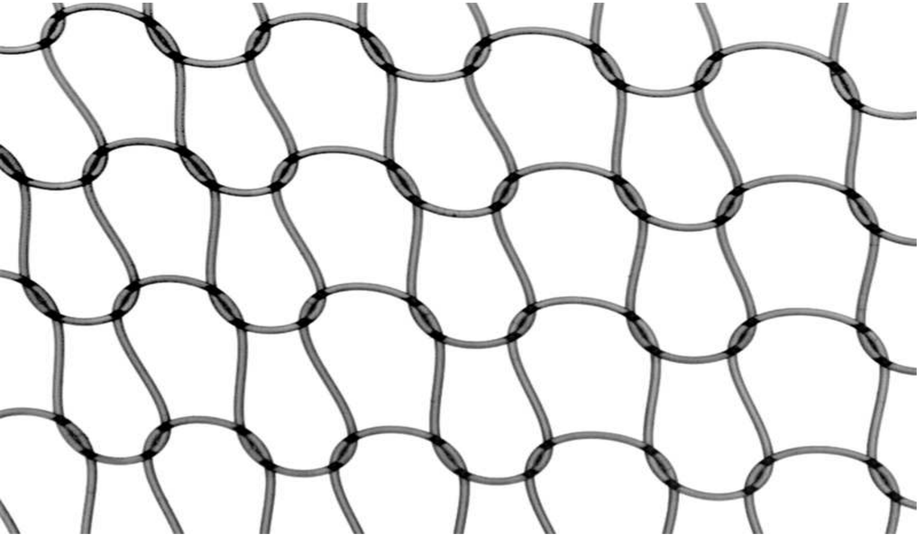




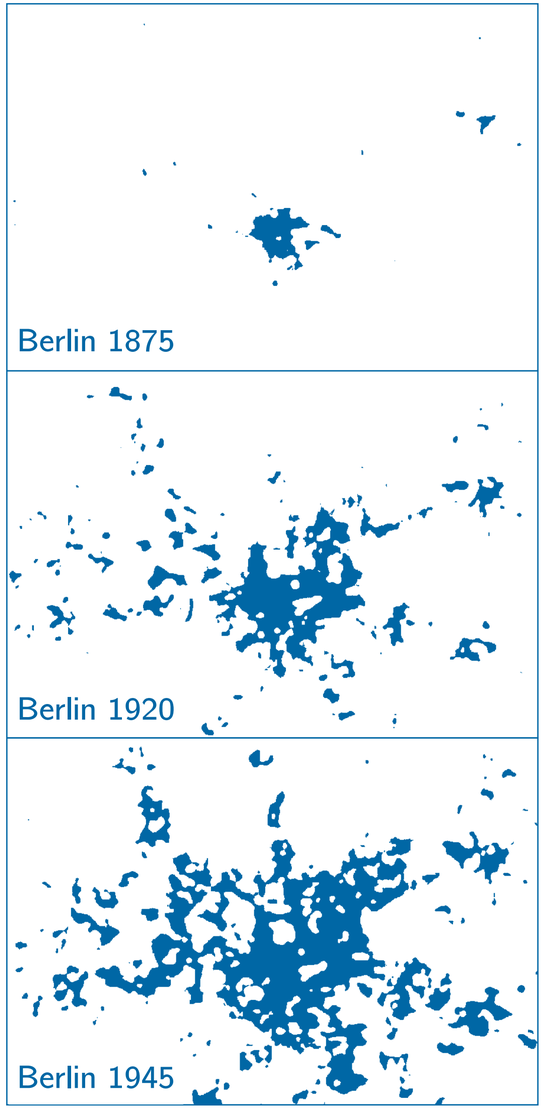
[Del Rosso *et al.*, Nat. Mat. '20]

Emergent Phenomena

[Portugal *et al.*, Nature '14]



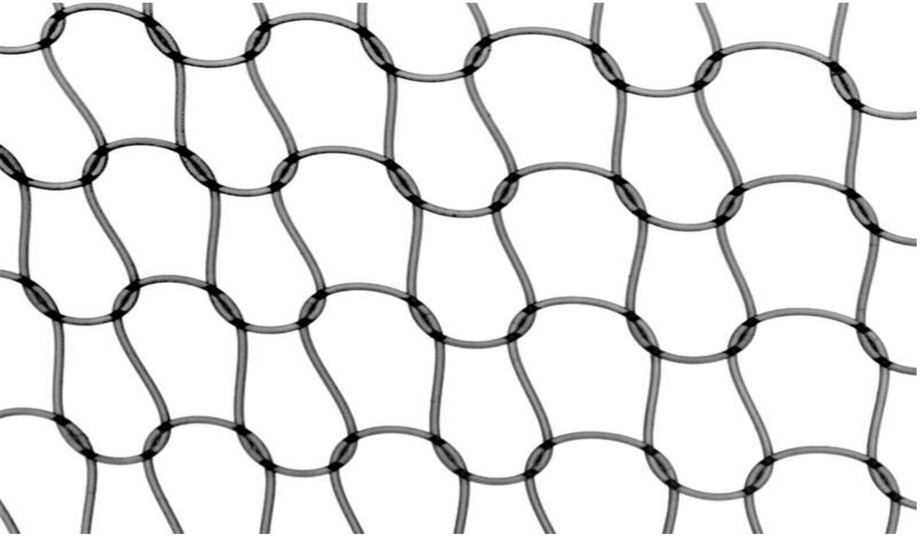
[Poincloux *et al.*, PRX '18]



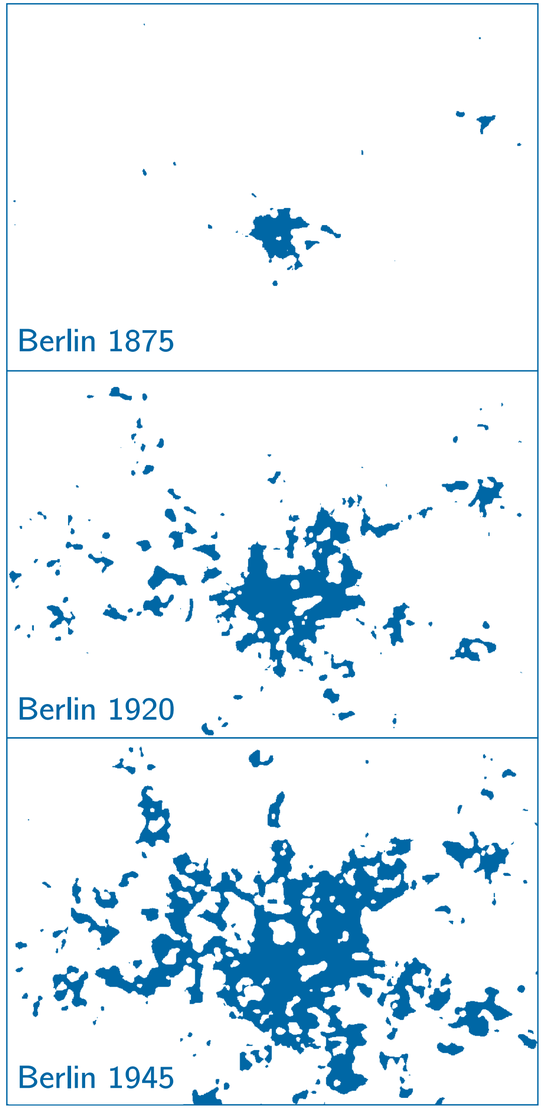
[Makse *et al.*, Nature '95]

Emergent Phenomena

[Portugal *et al.*, Nature '14]



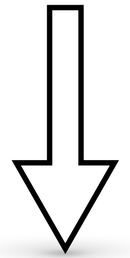
[Poincloux *et al.*, PRX '18]



[Makse *et al.*, Nature '95]

Many constituents

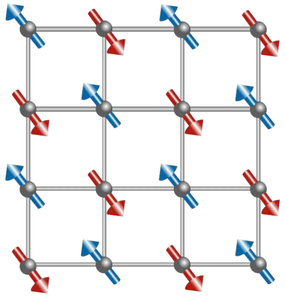
with simple rules

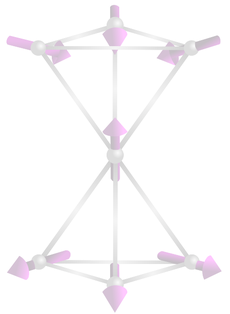


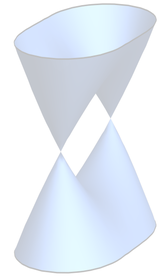
Complex structures

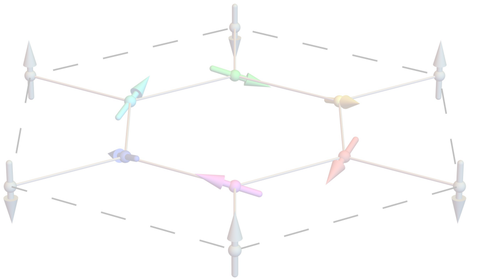
with new properties

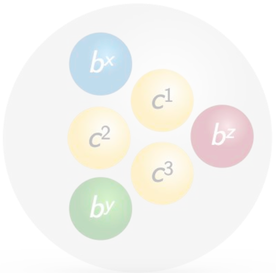
Outline





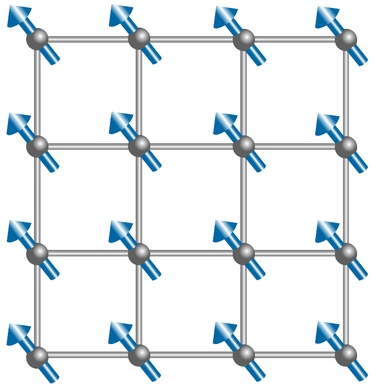






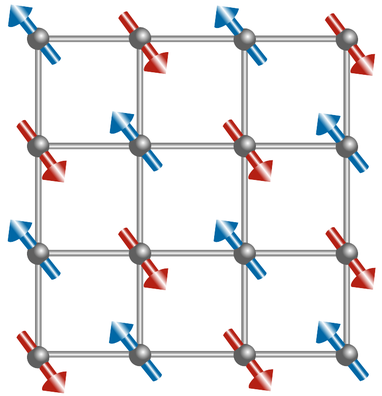
Possible States of Matter?

Symmetry classification:



Ferromagnet

Spin: $\mathrm{SU}(2) \to \mathrm{U}(1)$



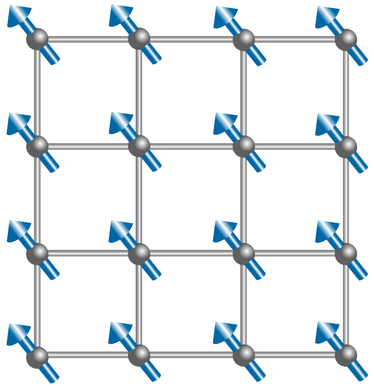
Antiferromagnet

Spin: $\mathrm{SU}(2) \to \mathrm{U}(1)$

Lattice: $T_a \to T_{2a}$

Possible States of Matter?

Symmetry classification:



Ferromagnet

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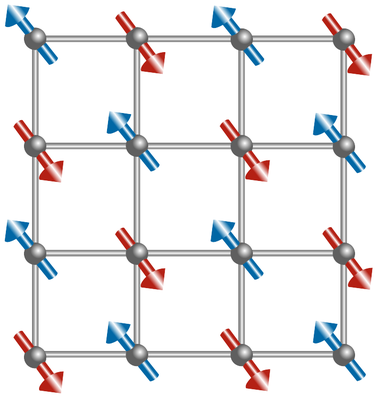
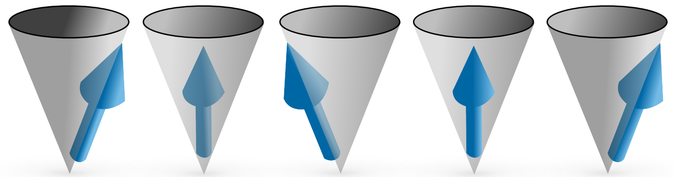


Antiferromagnet

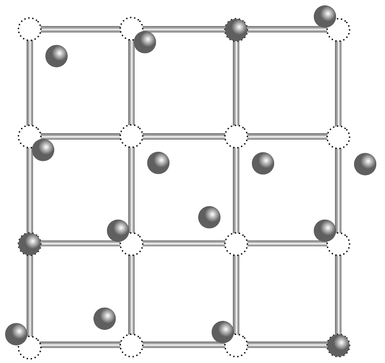
Spin: $\mathrm{SU}(2) \to \mathrm{U}(1)$

Lattice: $T_a \to T_{2a}$

Effective excitations: Quasiparticles



Spin: Magnons



Lattice: Phonons

Ingredient #1: Topology

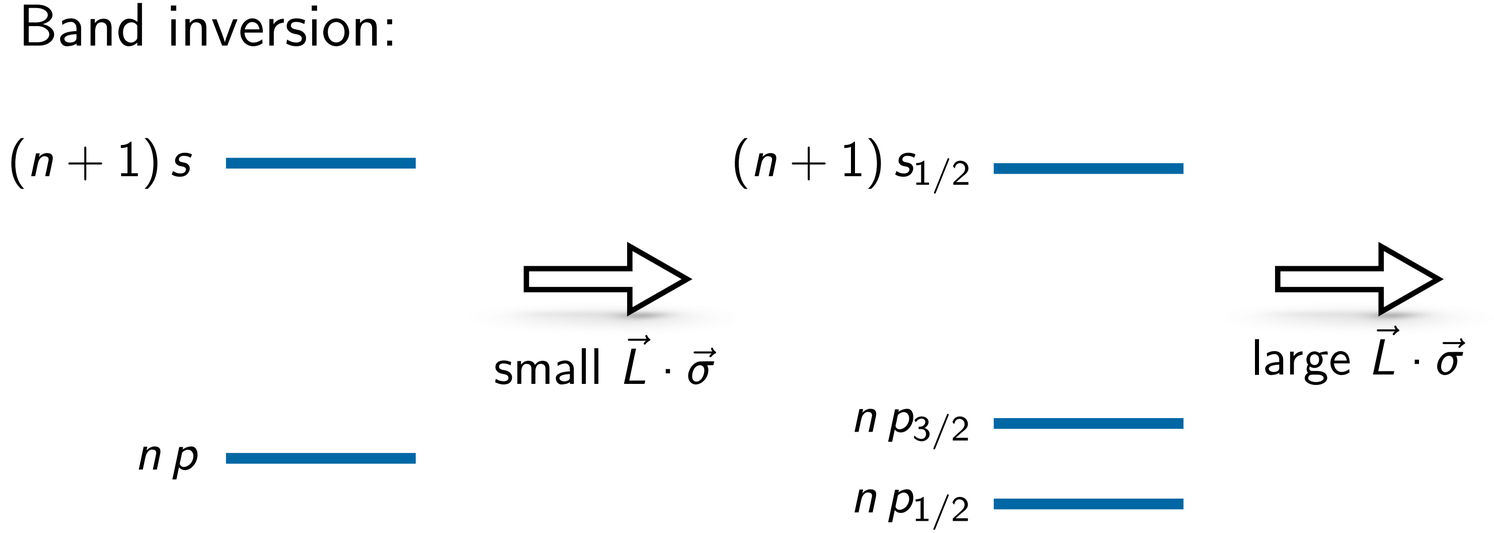
Topological insulator:

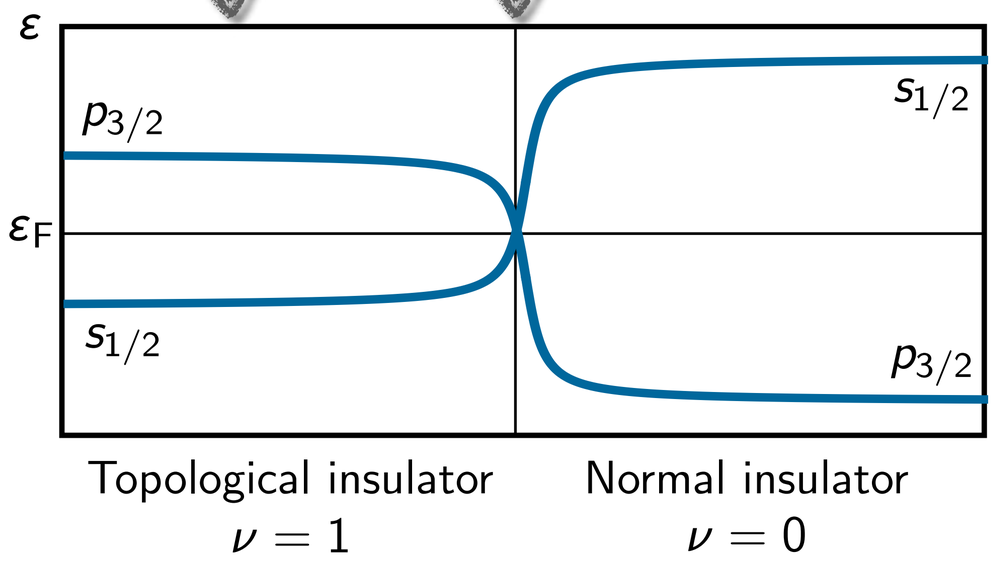
[Kane & Mele, PRL '05]
[König *et al.*, Science '07]

Ingredient #1: Topology

Topological insulator:

Band inversion:



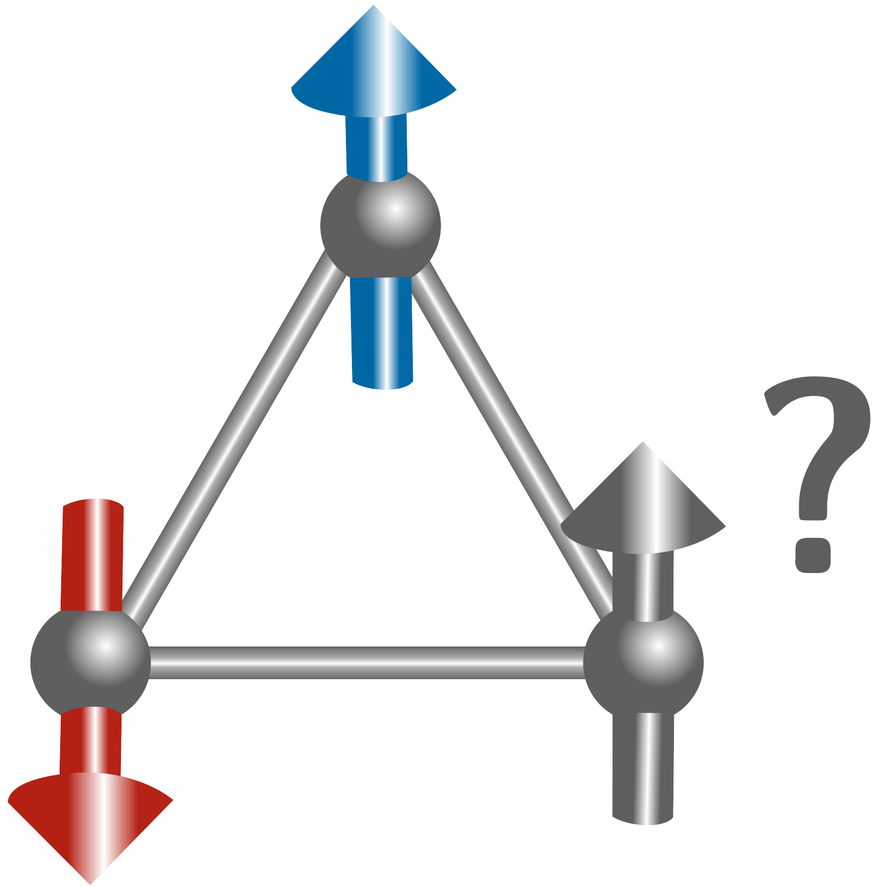


[Kane & Mele, PRL '05]
[König *et al.*, Science '07]

Ingredient #2: Frustration

Antiferromagnetic interaction:

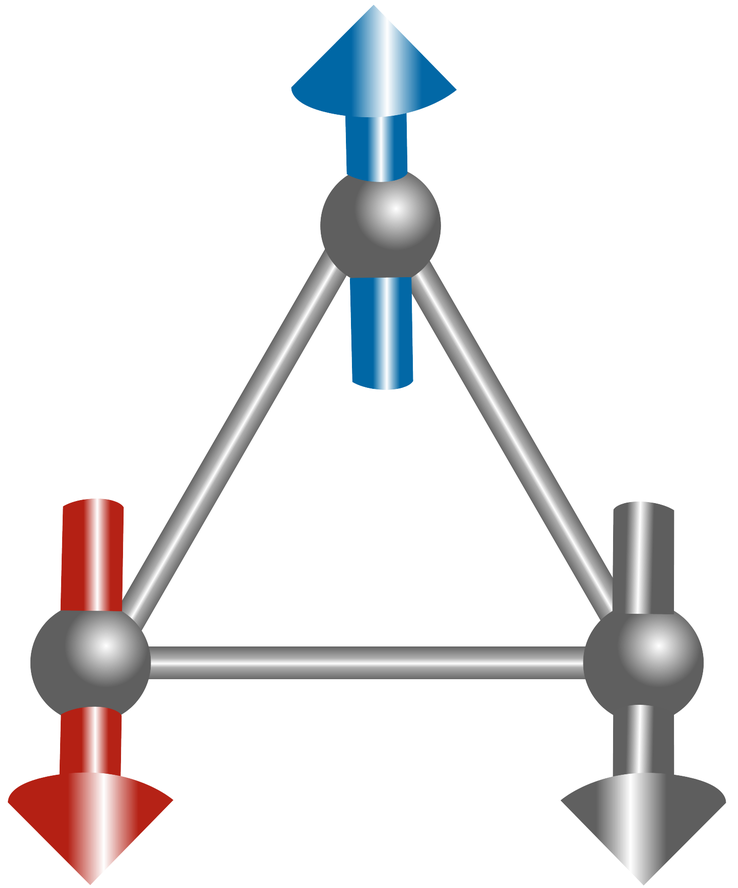
$$\mathcal{H}_{ij} = JS_i^z S_j^z \qquad\qquad J > 0$$



Ingredient #2: Frustration

Antiferromagnetic interaction:

$$\mathcal{H}_{ij} = JS_i^z S_j^z \qquad\qquad J > 0$$



?

Ingredient #2: Frustration

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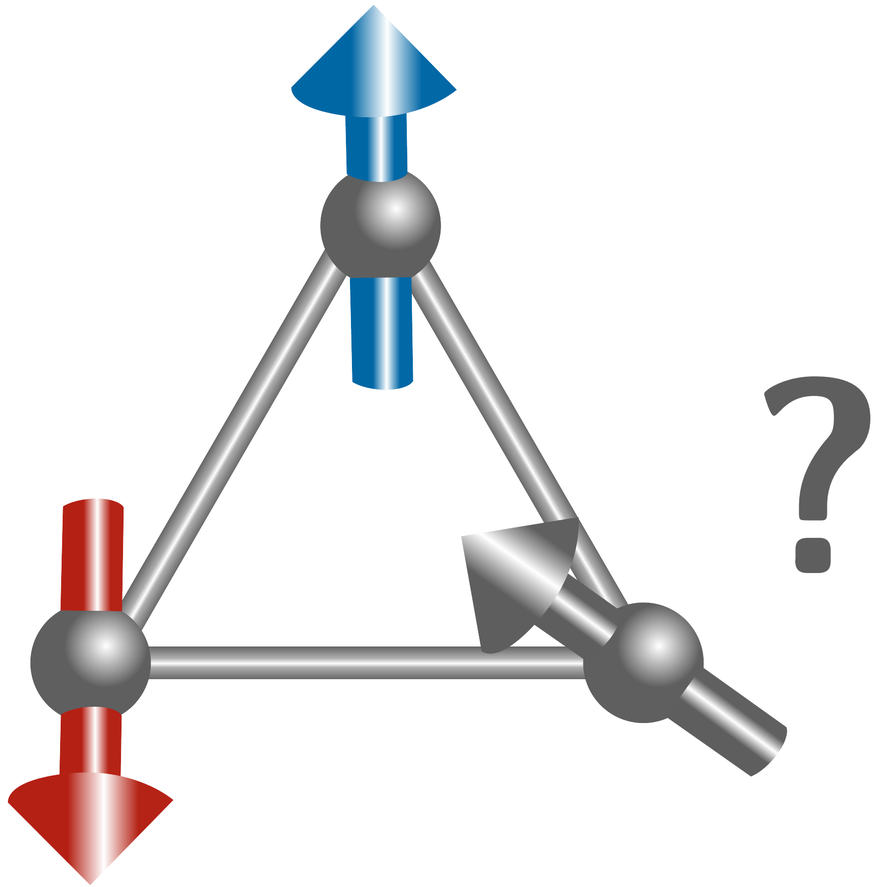

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Frustration:

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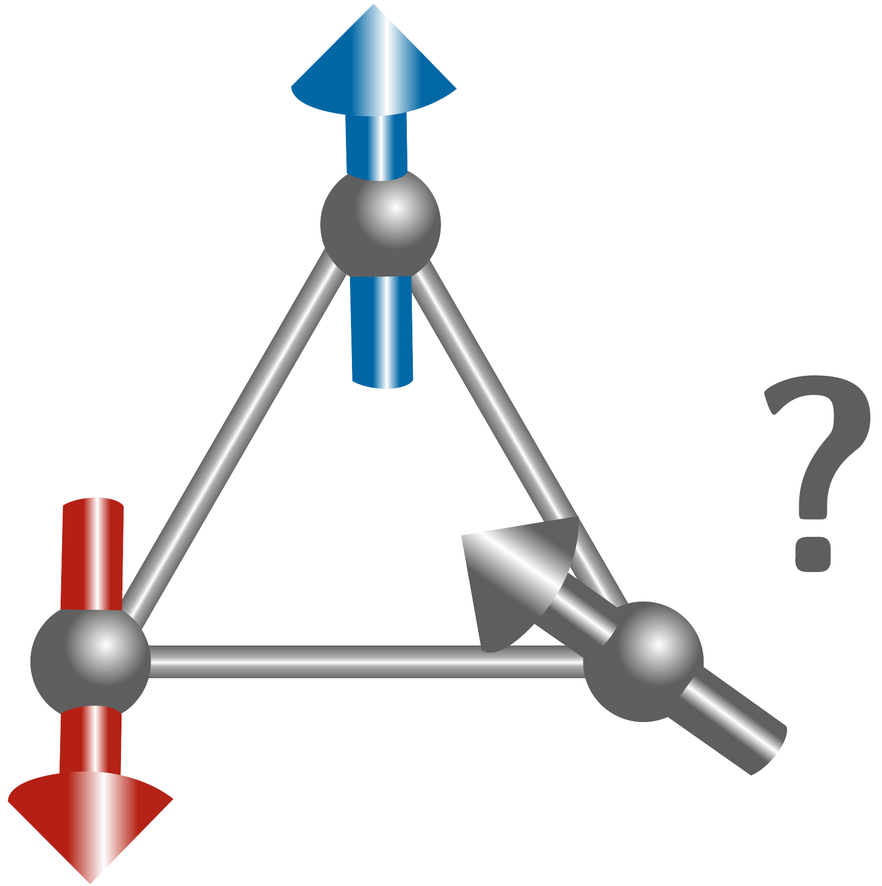


Ingredient #2: Frustration

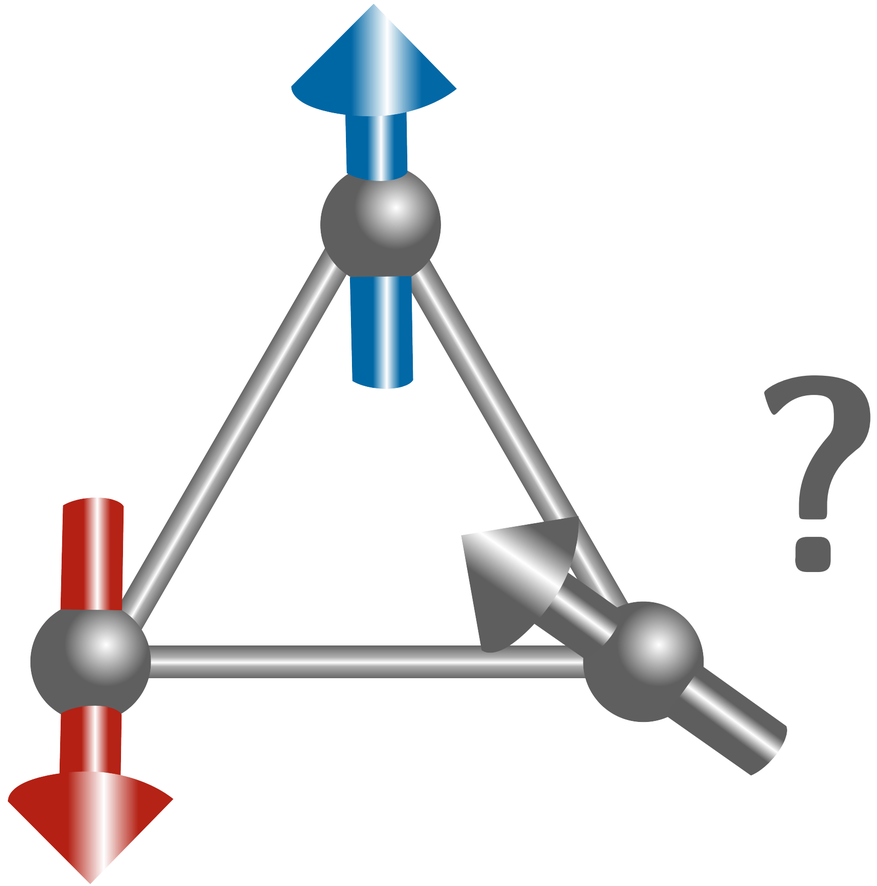
Antiferromagnetic interaction:

$$\mathcal{H}_{ij} = J S_i^z S_j^z \qquad J > 0$$

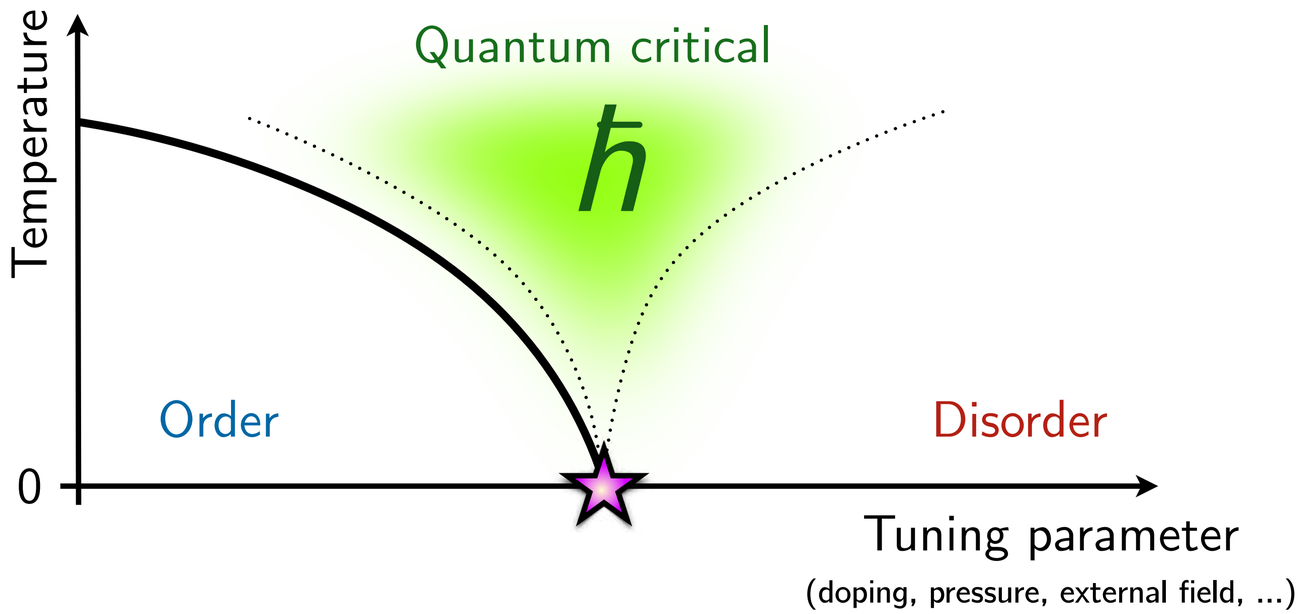
Frustration:

Incompatible interactions

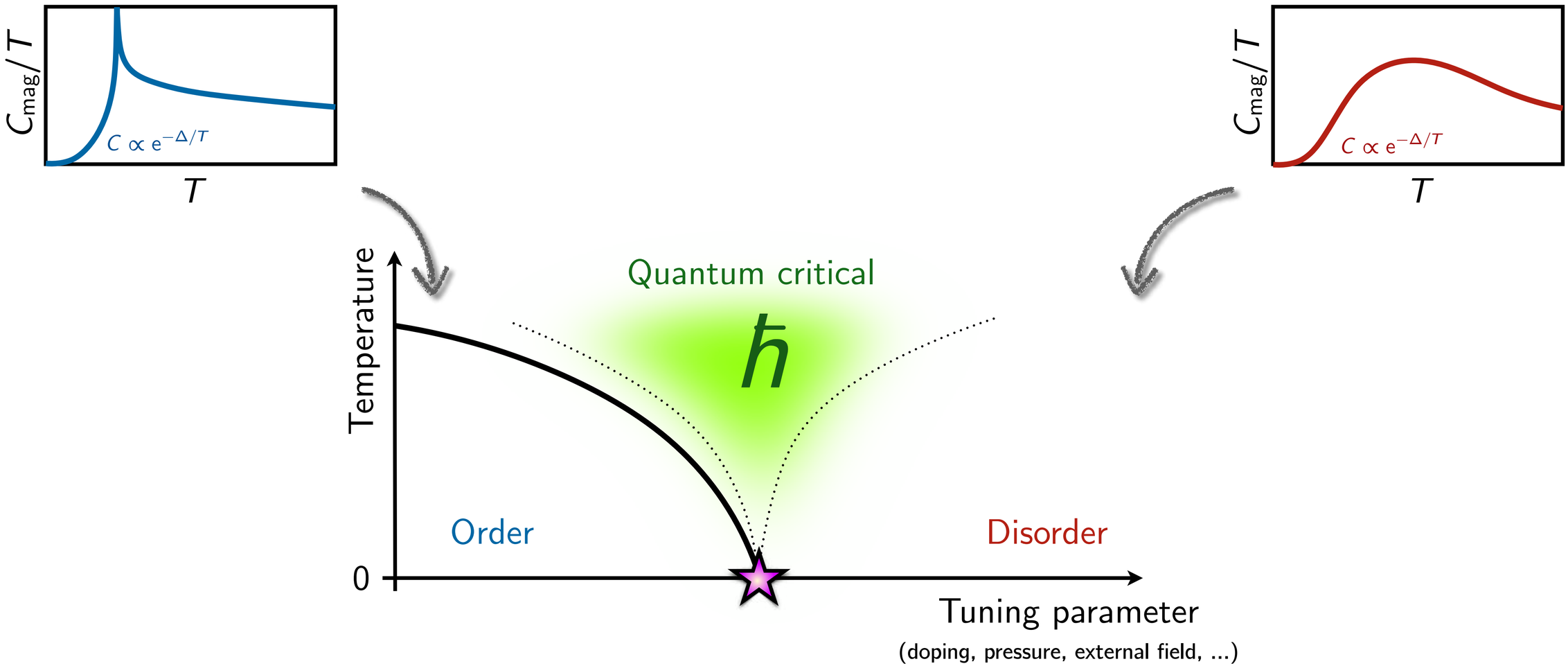
New states of matter
with exotic excitations?



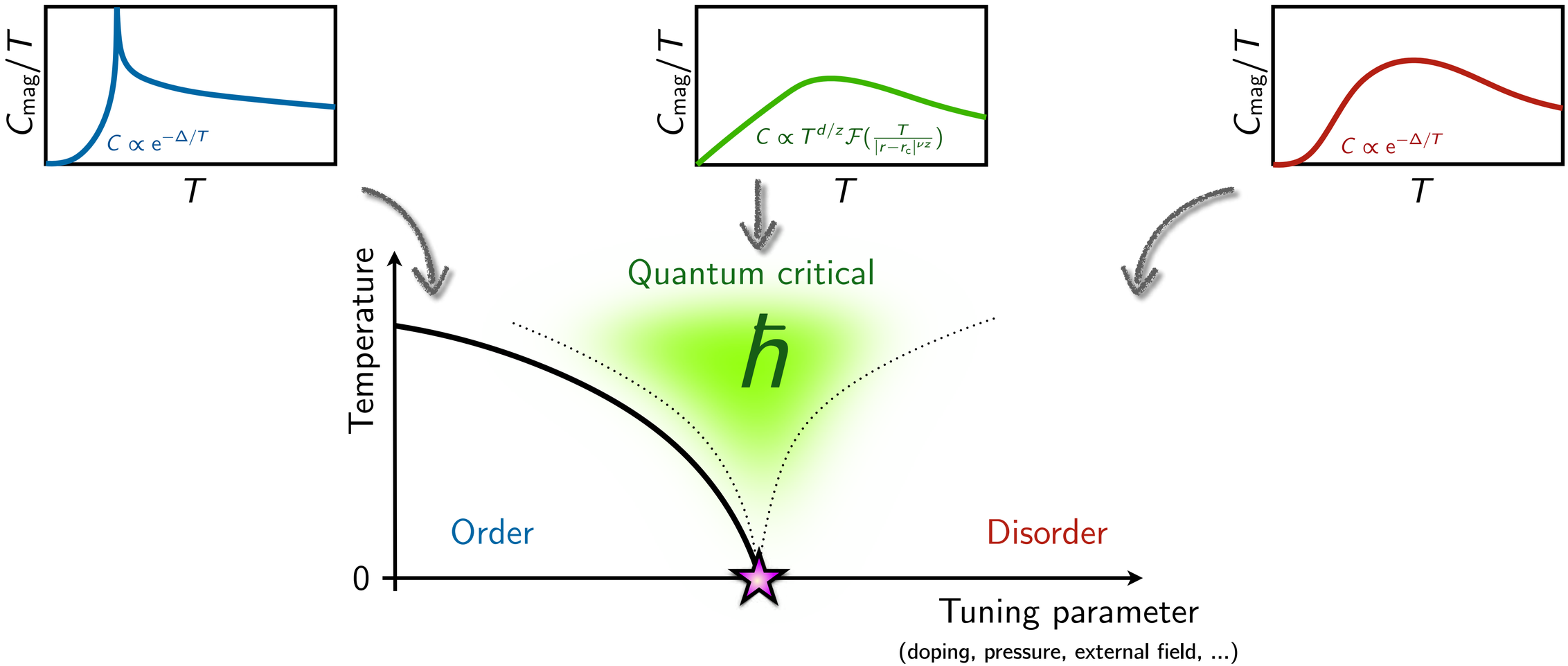
Ingredient #3: Quantum Criticality



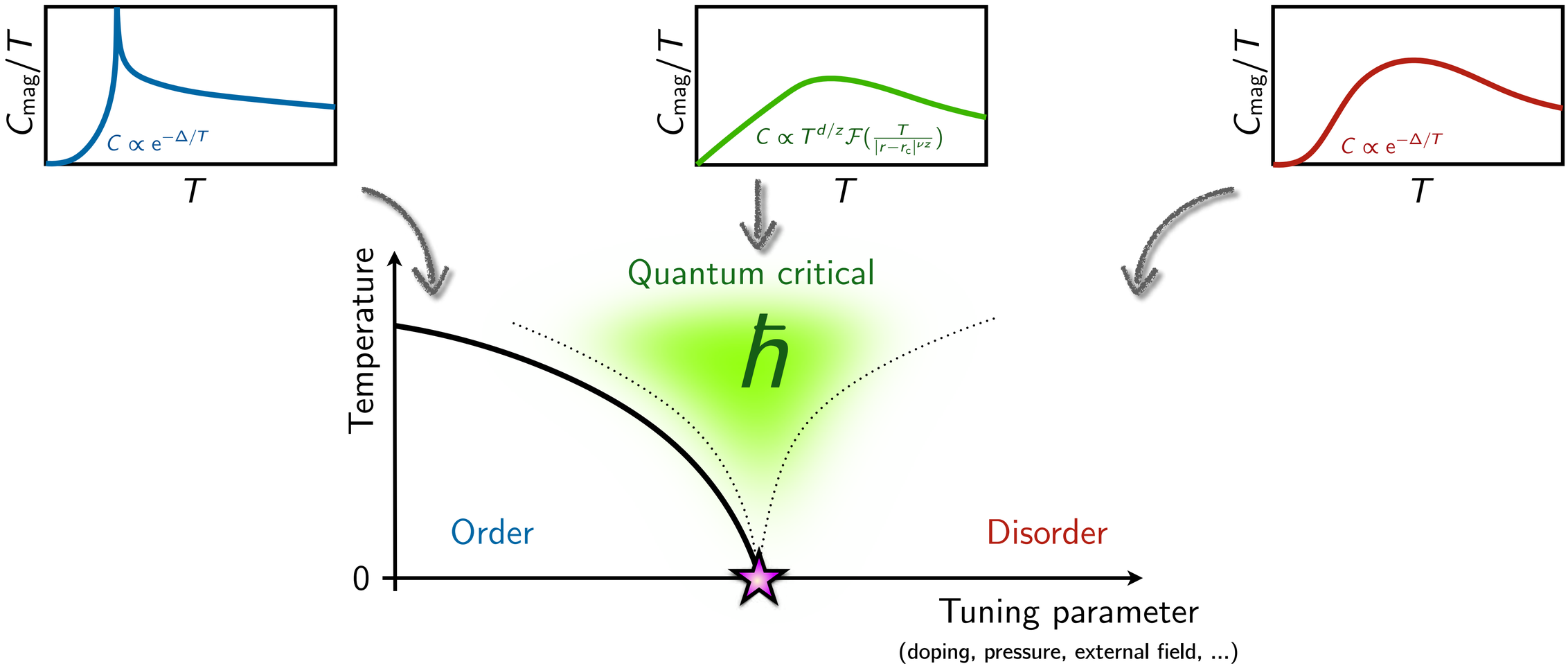
Ingredient #3: Quantum Criticality



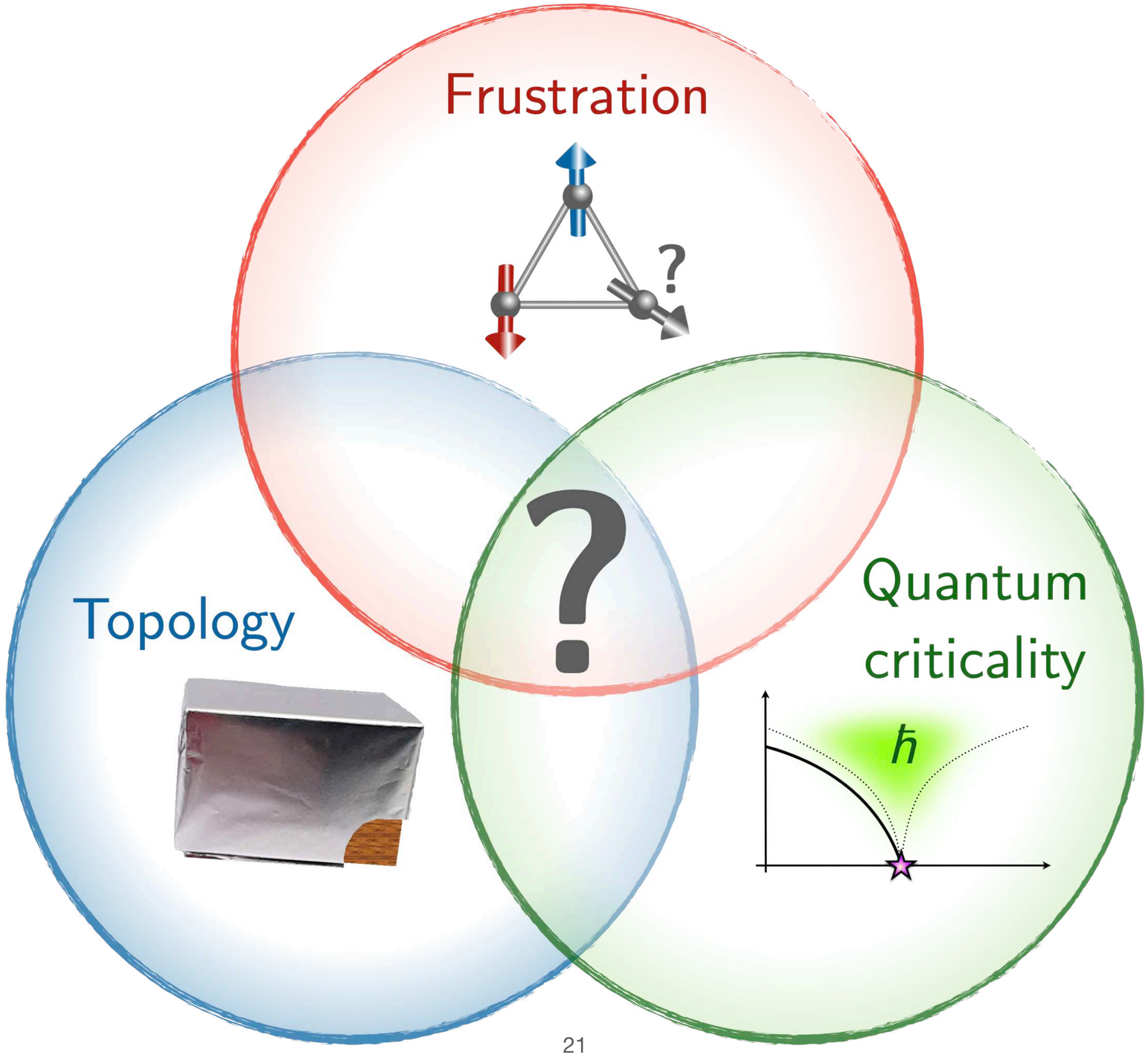
Ingredient #3: Quantum Criticality



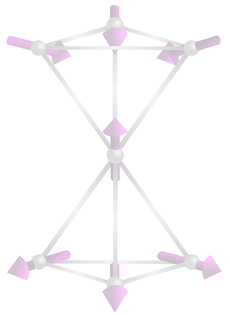
Ingredient #3: Quantum Criticality

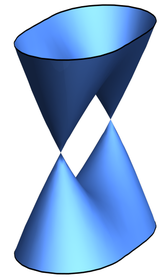


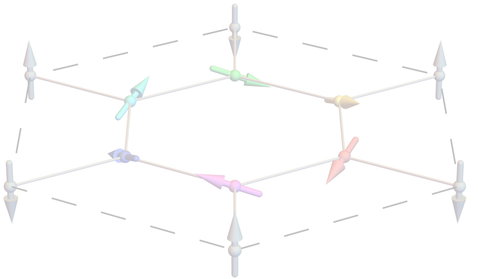
Strong correlations ⇒ Novel states without conventional quasiparticles?

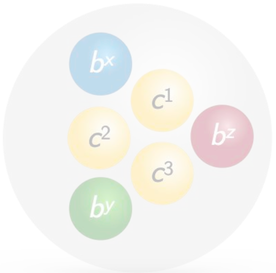

Frustration
?
Topology
?
Quantum
criticality
ħ

Outline

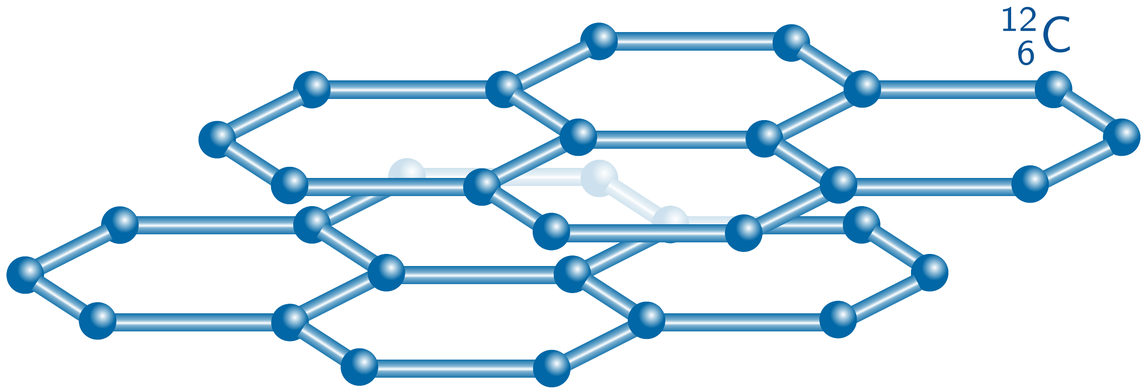


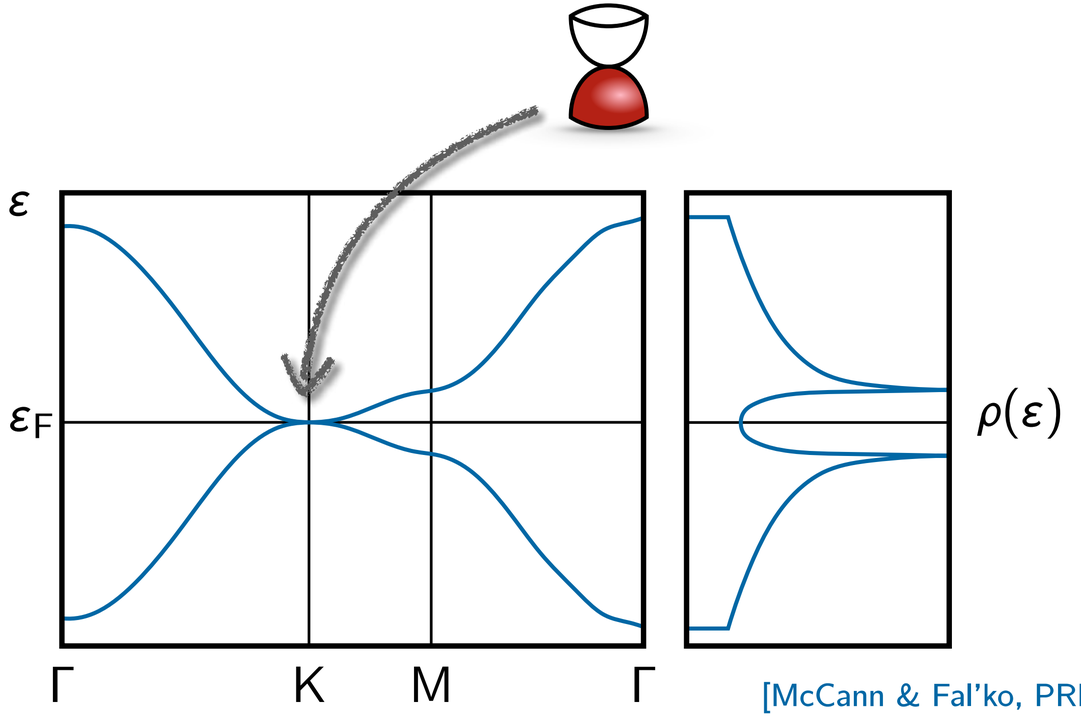






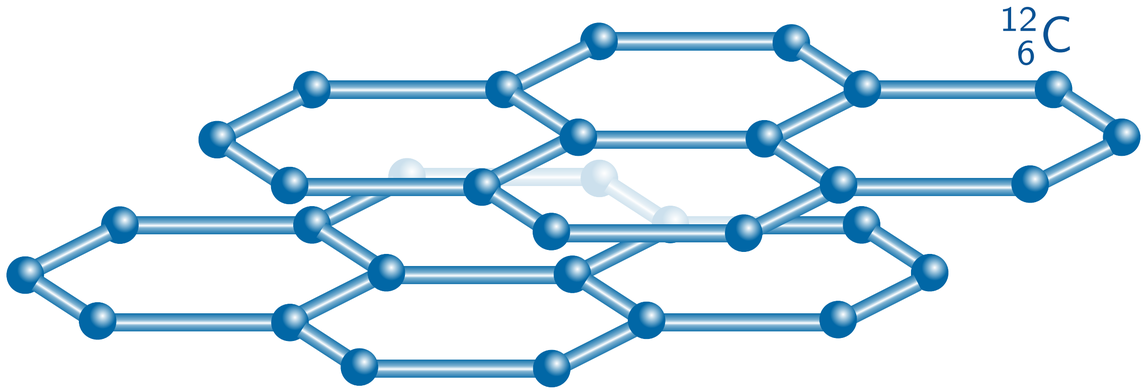
Example #1: Bilayer Graphene

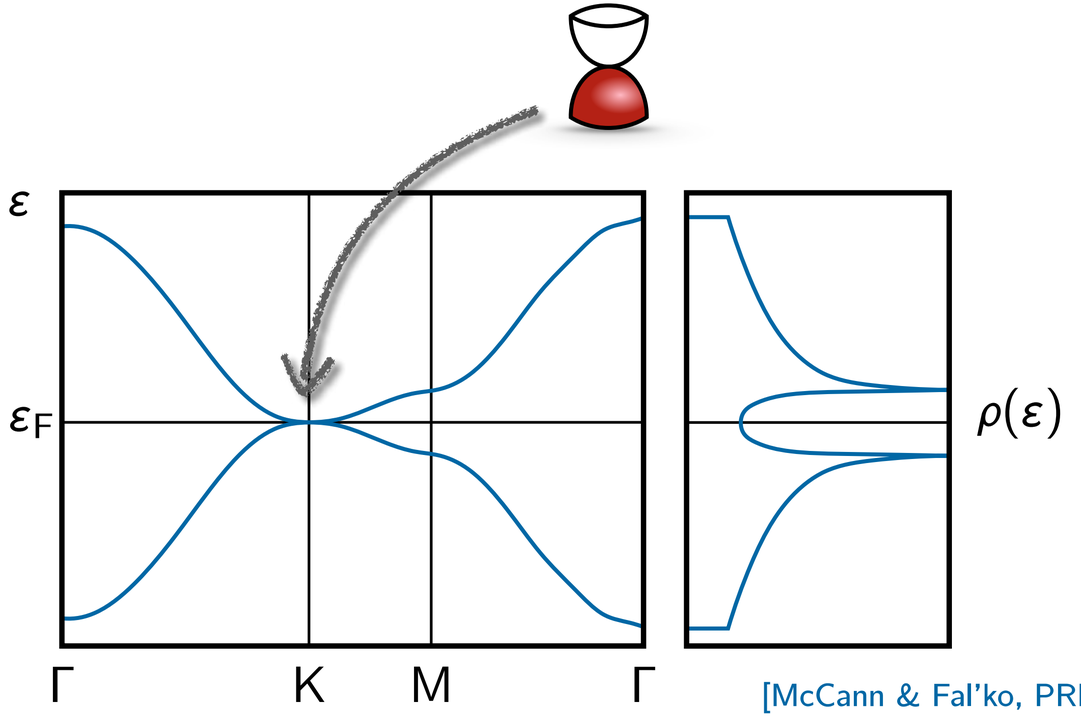




[McCann & Fal'ko, PRL '06]

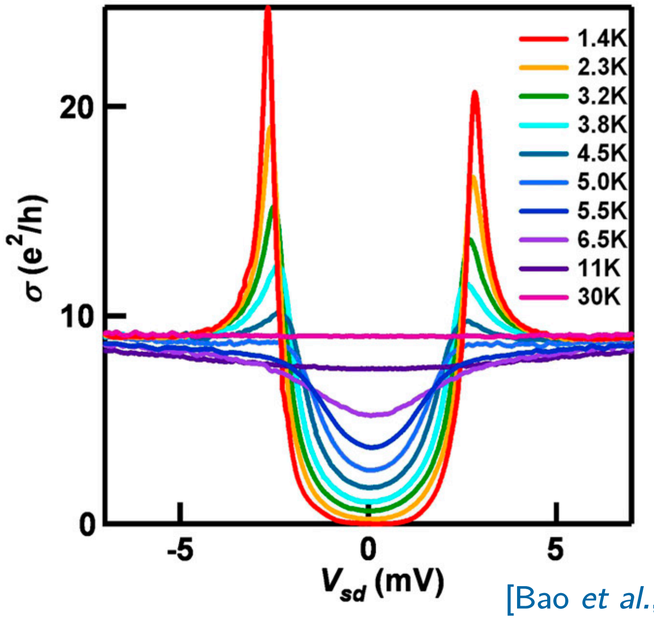
Example #1: Bilayer Graphene



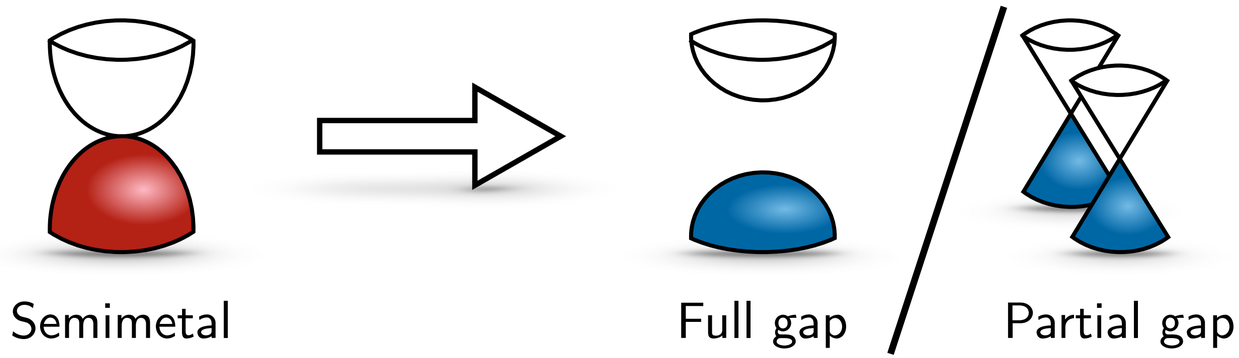


[McCann & Fal'ko, PRL '06]

Instability:

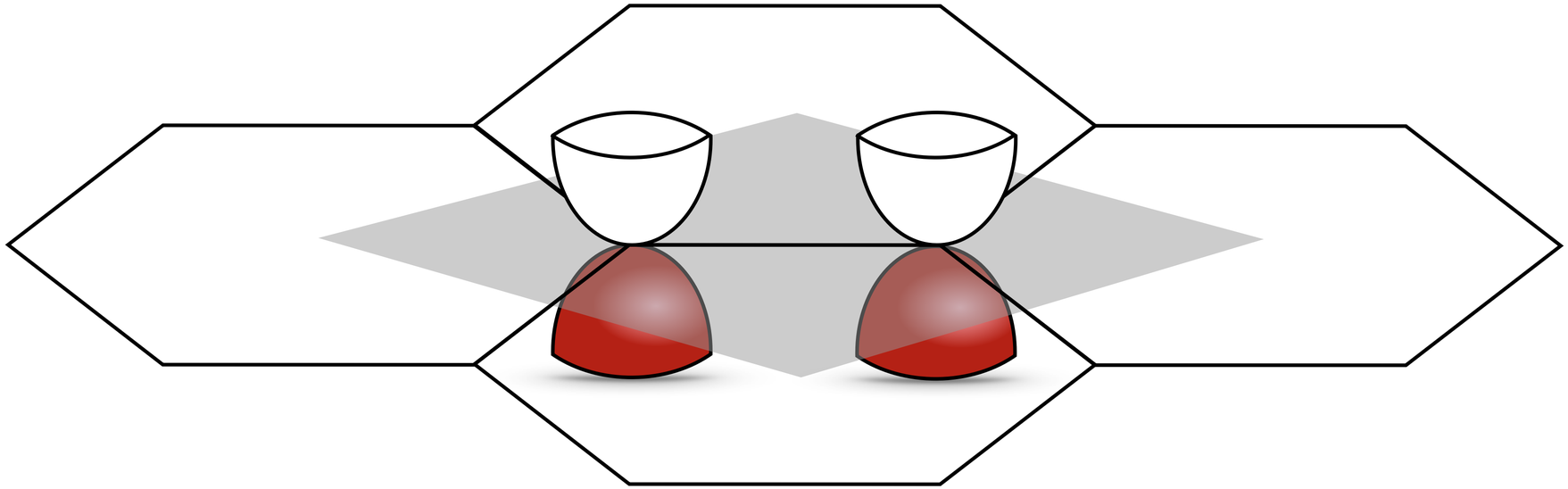


[Bao *et al.*, PNAS '12]

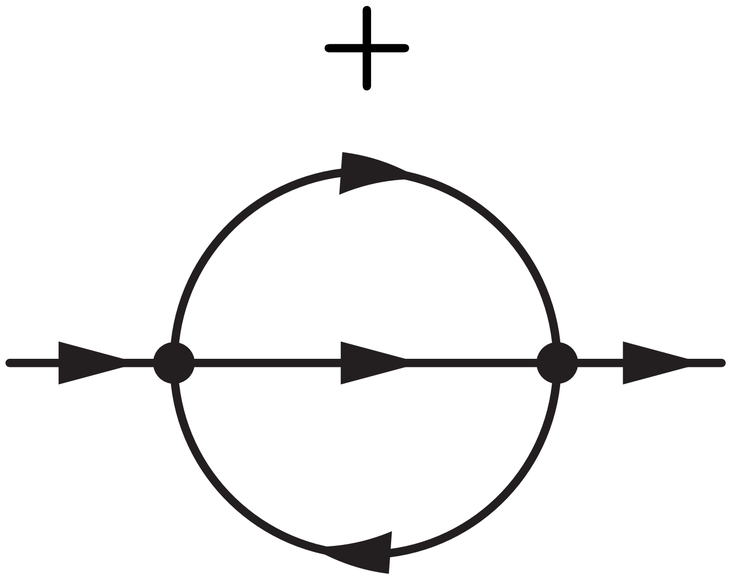


[Velasco *et al.*, Nat. Nano. '12]
[Freitag *et al.*, PRL '12]
[Mayorov *et al.*, Science '11]

Emergent Lorentz Symmetry I

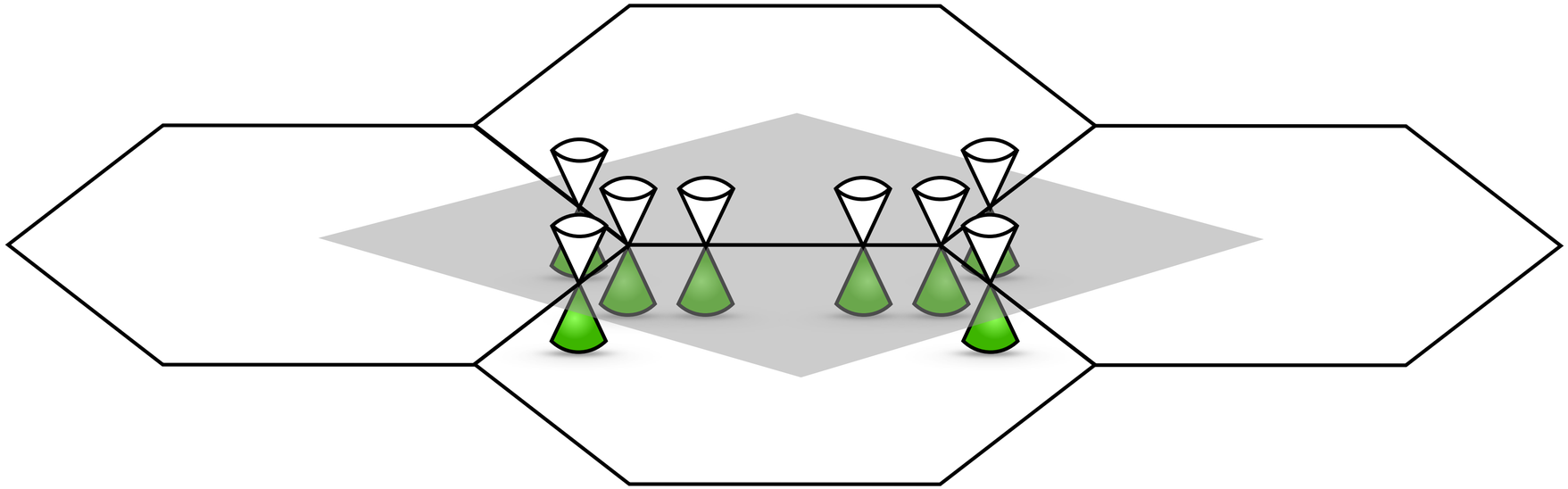


Shouryya Ray



[Ray, Vojta, LJ, PRB '18 (Editors' Suggestion)]

Emergent Lorentz Symmetry I



Shouryya Ray

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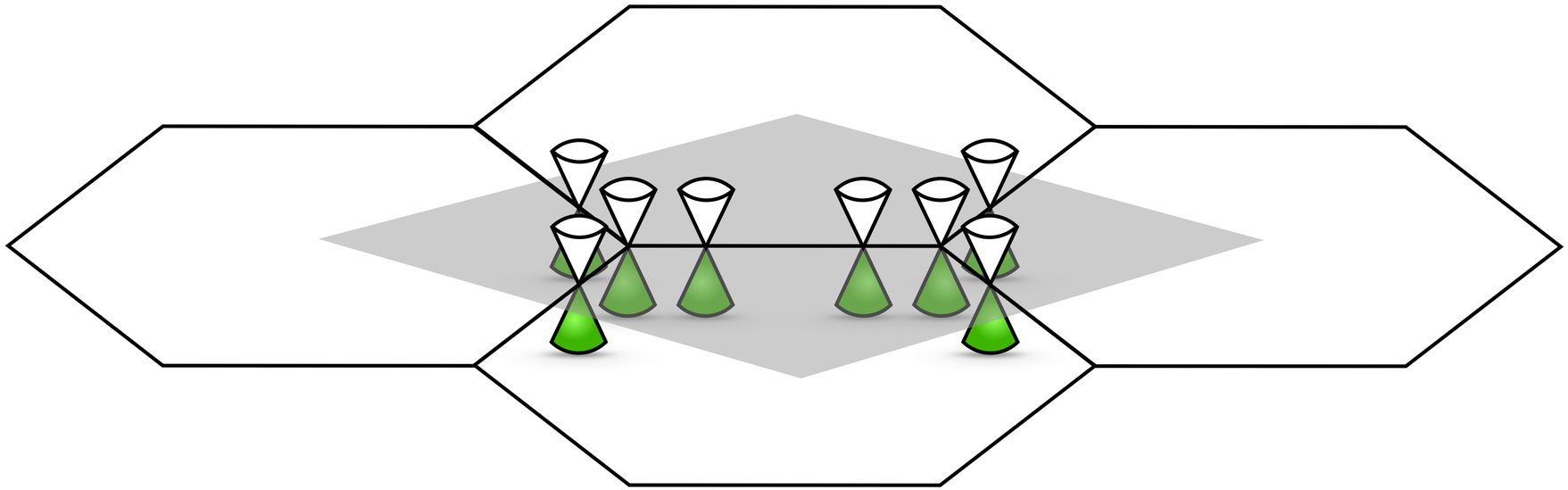
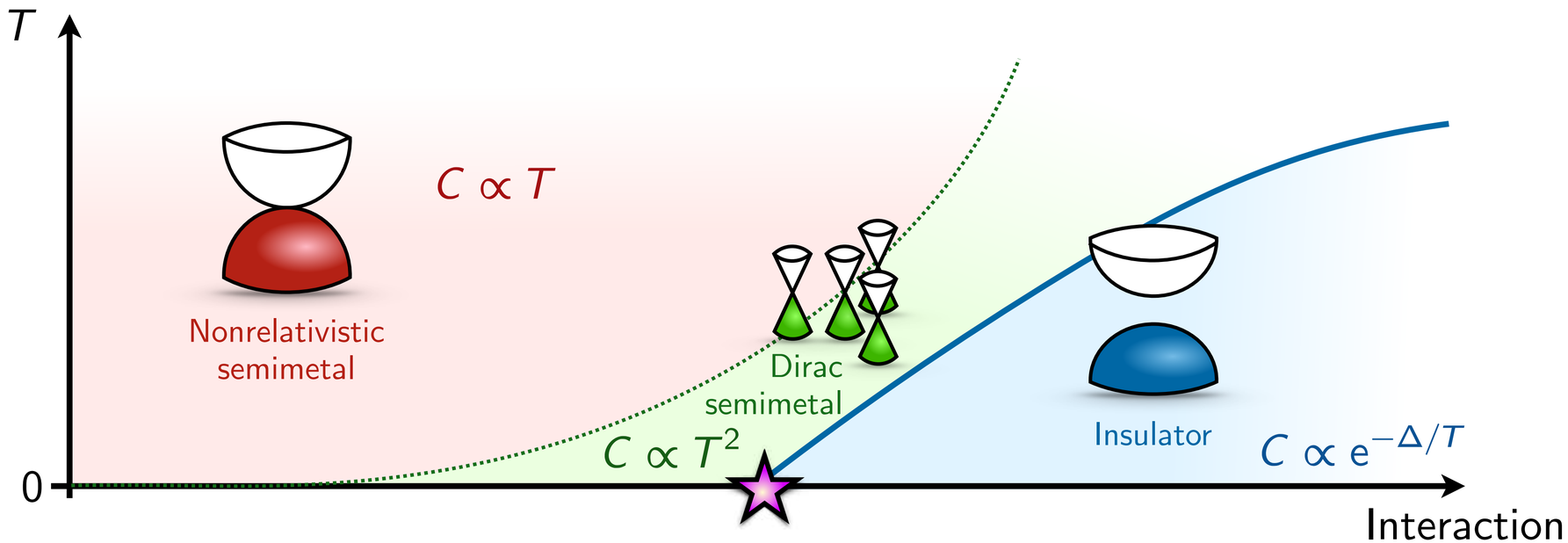


Shouryya Ray



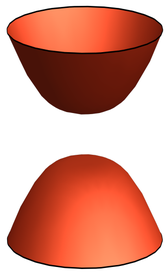
[Ray, Vojta, LJ, PRB '18 (Editors' Suggestion)]

see also: [Pujari, Lang, Murthy, Kaul, PRL '16]

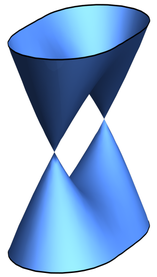
Emergent Lorentz Symmetry II

Lagrangian:

$$\mathcal{L} = \psi^\dagger[\partial_\tau + d_a(-i\nabla)(\Gamma_a \otimes \mathbb{1}_2)]\psi$$
$$- g[\psi^\dagger(\Gamma_z \otimes \vec{\sigma})\psi]^2 - g'[\psi^\dagger(\Gamma_a \otimes \mathbb{1}_2)\psi]^2$$



Antiferromagnetic insulator



Nematic semimetal

Shouryya Ray

[Ray & LJ, PRB '21]

Emergent Lorentz Symmetry II

Shouryya Ray

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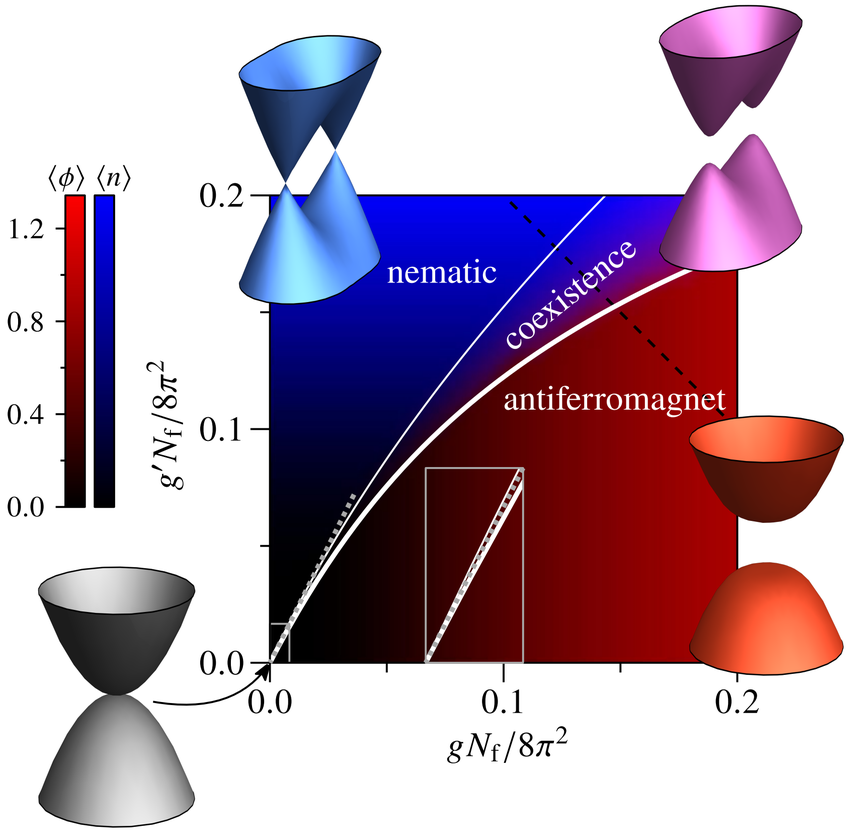
Phase diagram:



[Ray & LJ, PRB '21]

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Shouryya Ray

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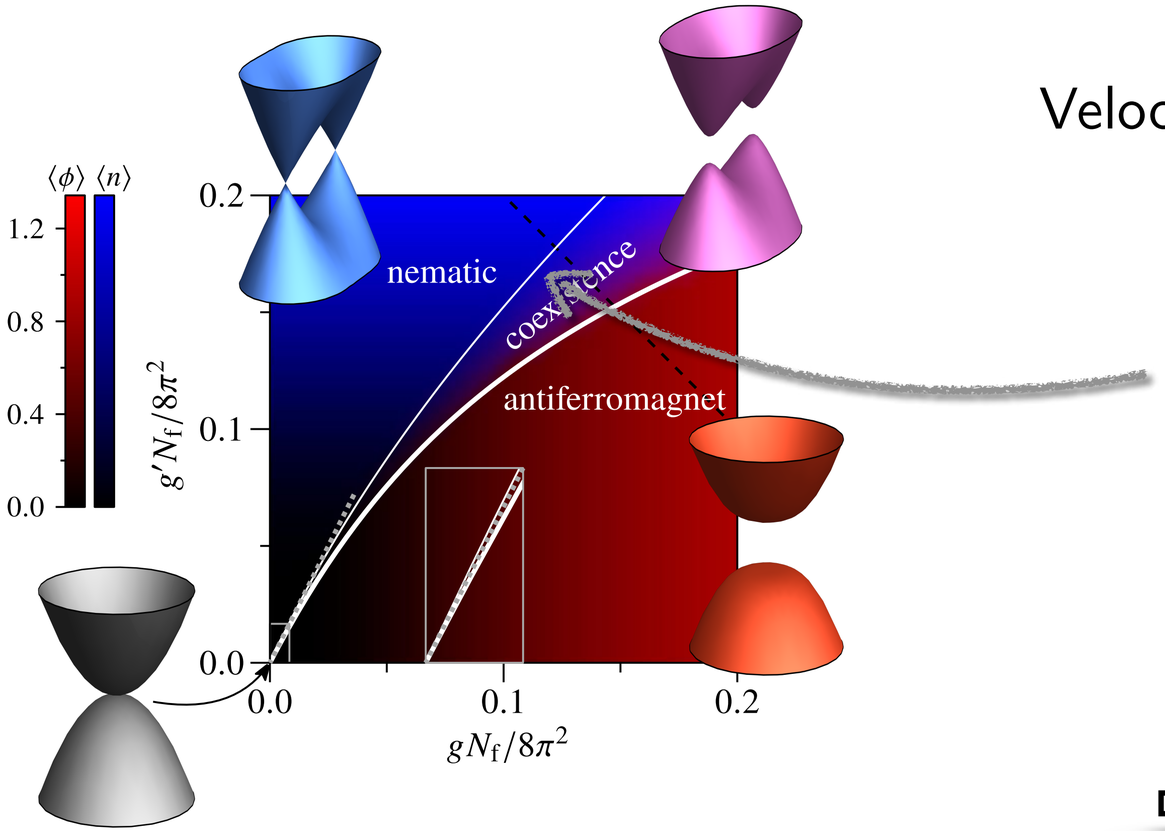
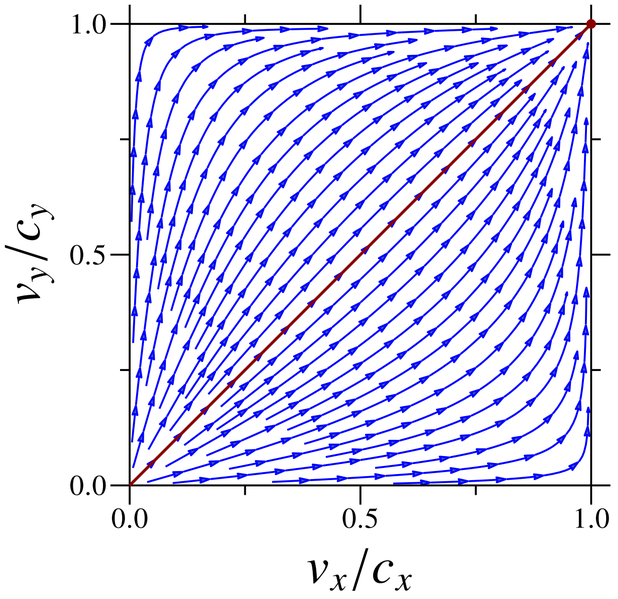


Velocity flow:

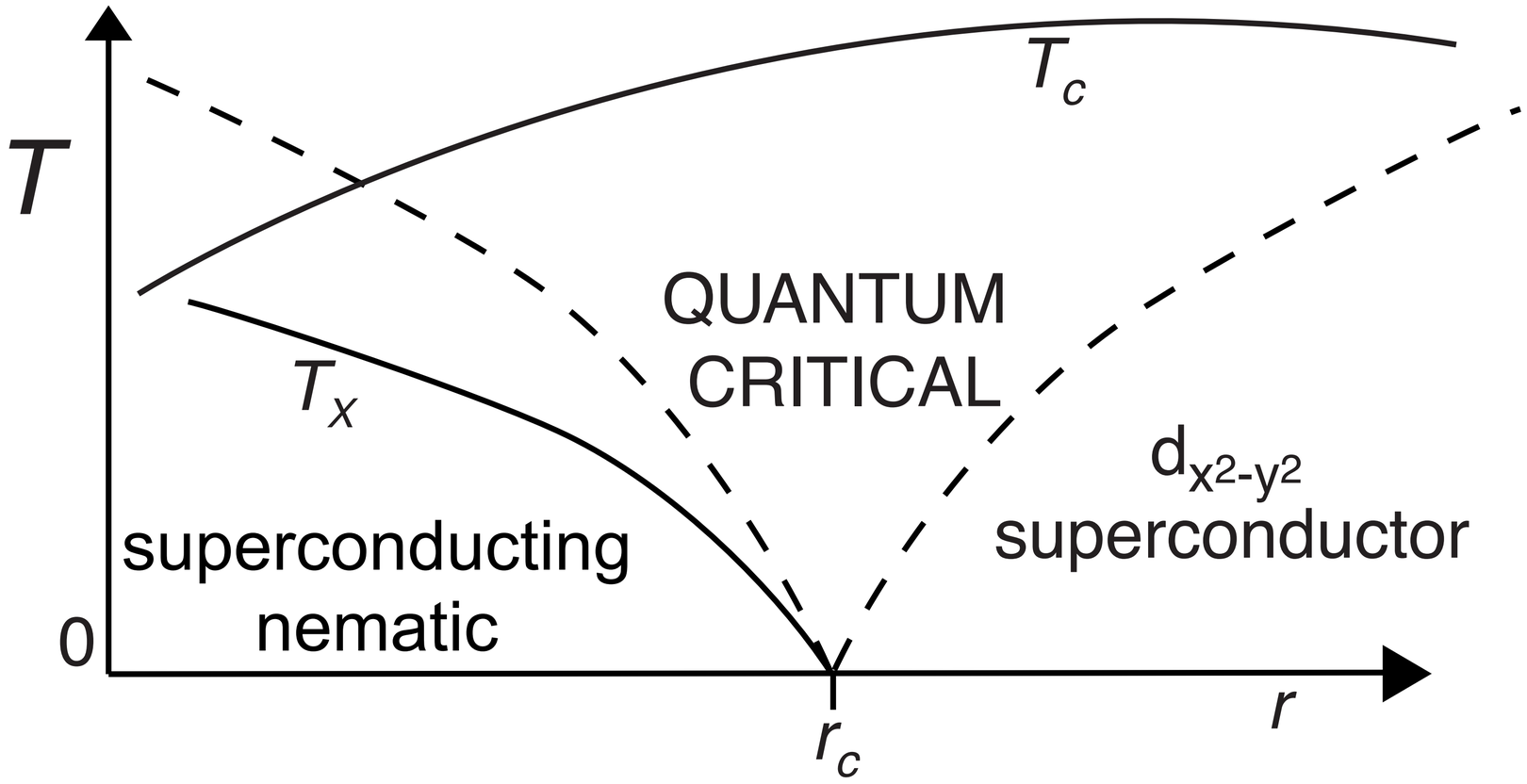


⇨ emergent Lorentz symmetry!

[Ray & LJ, PRB '21]

Counterexample: Emergent Anisotropy

Phase diagram of a *d*-wave superconductor:

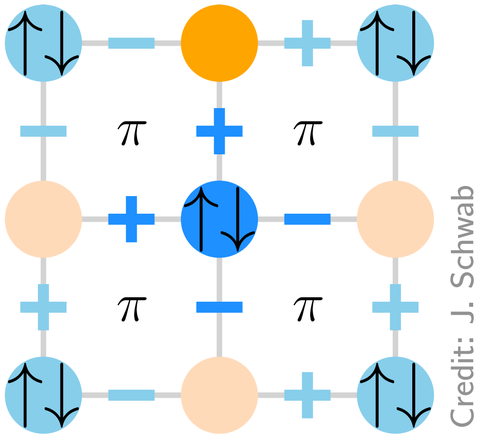


[Vojta, Zhang, Sachdev, PRL '00]

Counterexample: Emergent Anisotropy

Hamiltonian:

$$\mathcal{H} = -\sum_{\langle ij \rangle} (t_{ij} + \xi_{ij} S_i^z) c_i^\dagger c_j + \text{h.c.}$$
$$- J \sum_{\langle\langle i,i' \rangle\rangle} S_i^z S_{i'}^z - h \sum_{i \in A} S_i^x$$



Credit: J. Schwab

[Schwab, LJ, Sun, Meng, *et int.*, Assaad, PRL '22]

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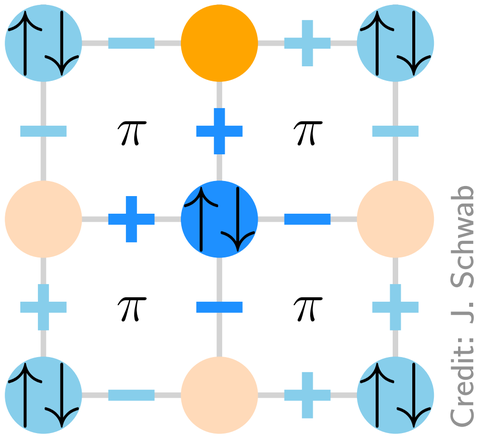

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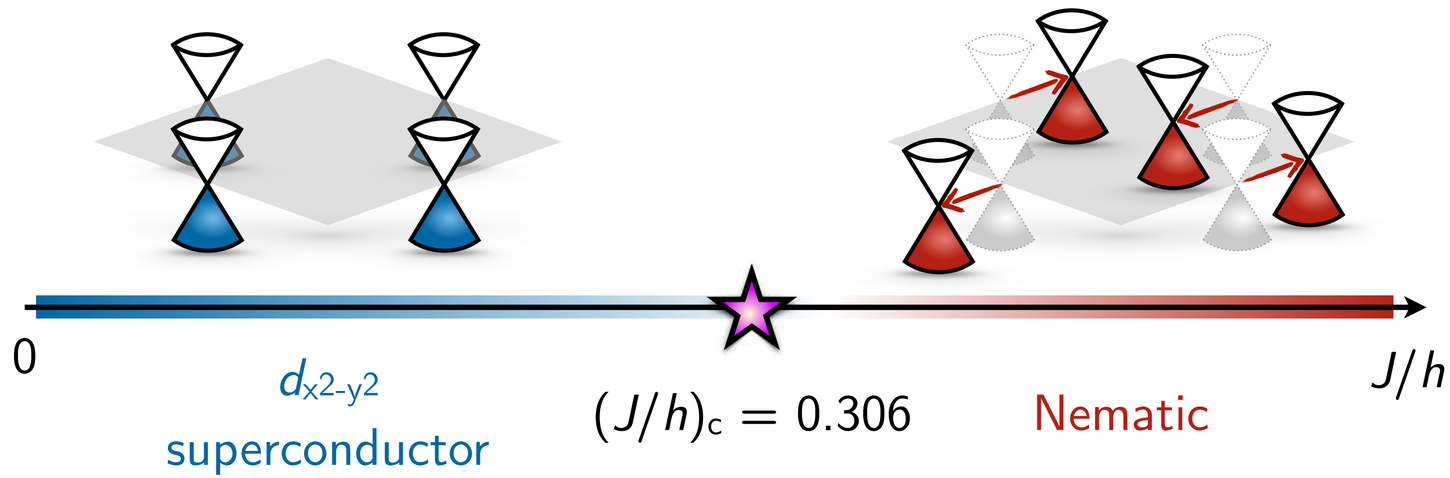
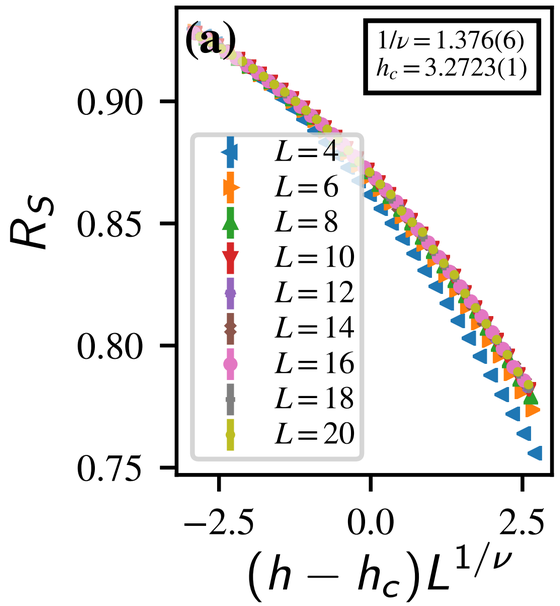


[Schwab, LJ, Sun, Meng, *et int.*, Assaad, PRL '22]

Counterexample: Emergent Anisotropy

Correlation ratio:

$$R_S = 1 - \frac{S(\Gamma + d\vec{k})}{S(\Gamma)}$$



Continuous transition ...

[Schwab, LJ, Sun, Meng, *et int.*, Assaad, PRL '22]

Counterexample: Emergent Anisotropy

Algorithms Lattice Fermions

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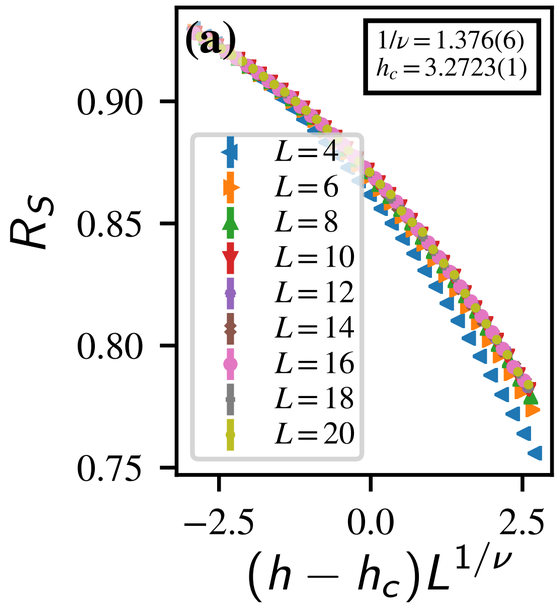
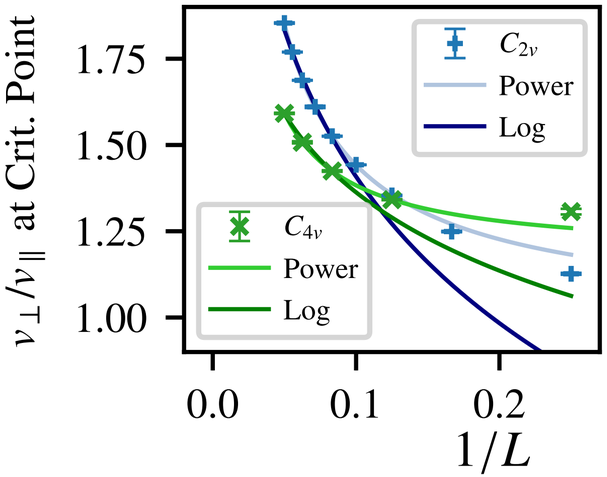


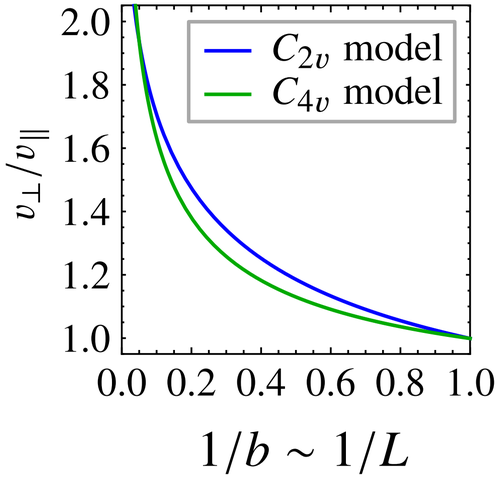
Continuous transition ...

... with emergent anisotropy!

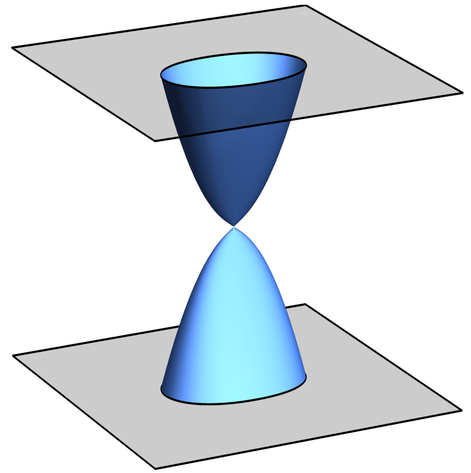
Velocity flow:



Quantum Monte Carlo

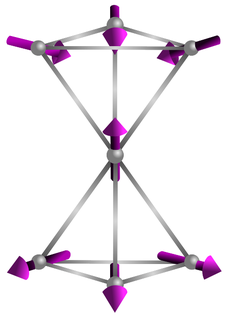


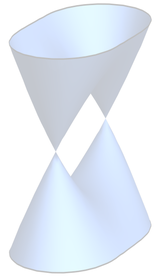
ε expansion

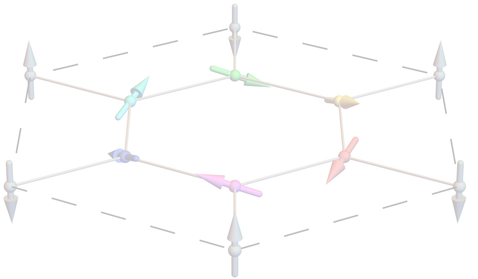


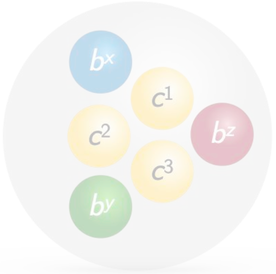
[Schwab, LJ, Sun, Meng, *et int.*, Assaad, PRL '22]

Outline

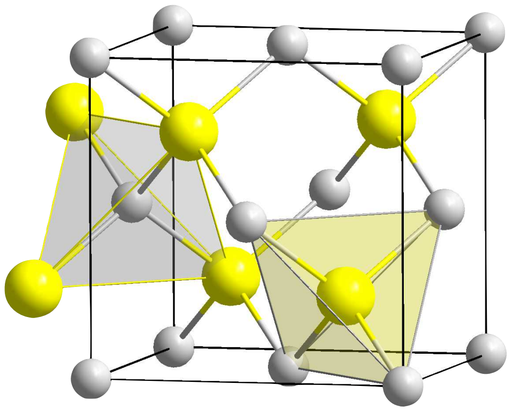




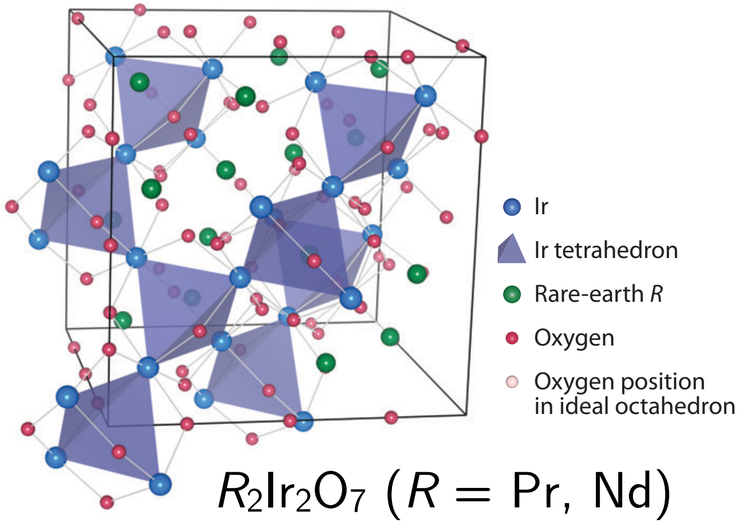




Example #2: Luttinger Semimetals

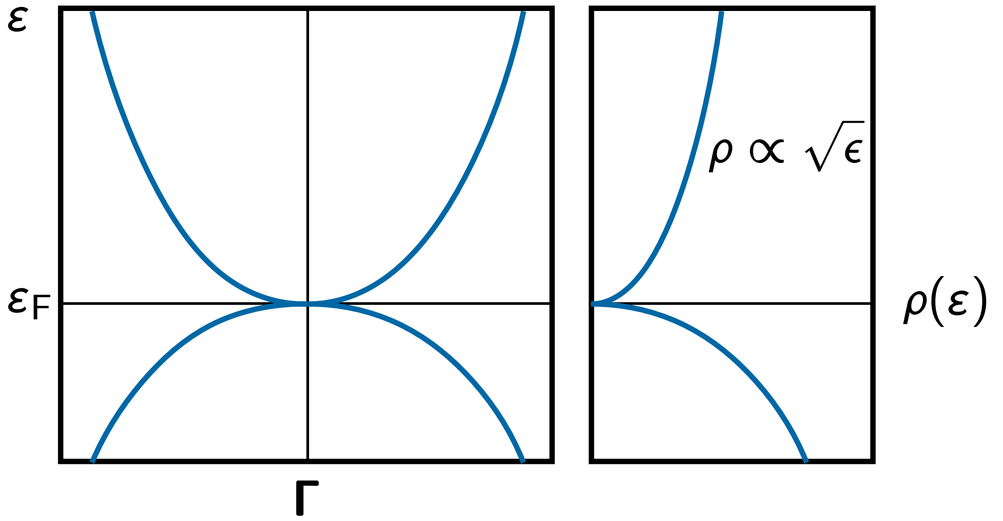


α-Sn, HgTe



$R_2Ir_2O_7$ (R = Pr, Nd)

[Kondo *et al.*, Nat. Comm. '15]
[Wang *et al.*, Nat. Phys. '20]



[Witczak-Krempa *et al.*, ARCMP '14]
[Armitage, Mele, Vishwanath, RMP '18]

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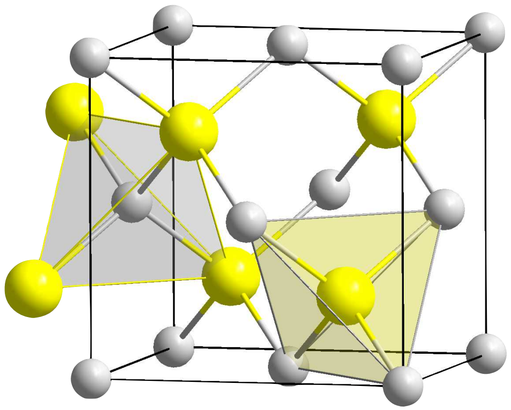

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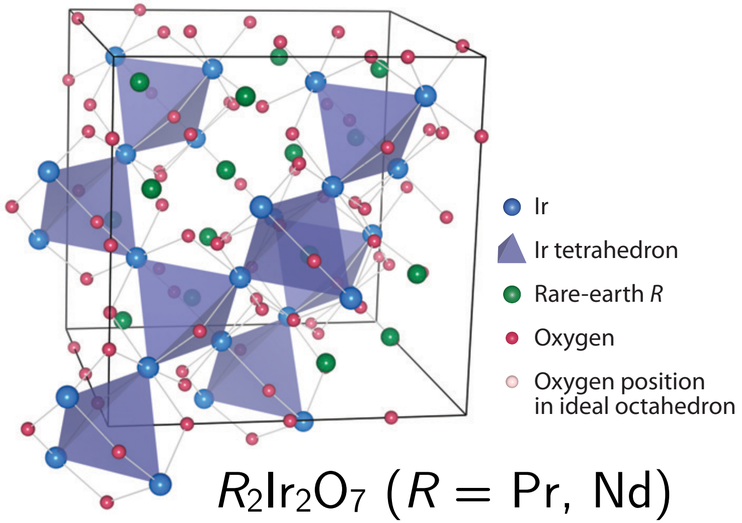

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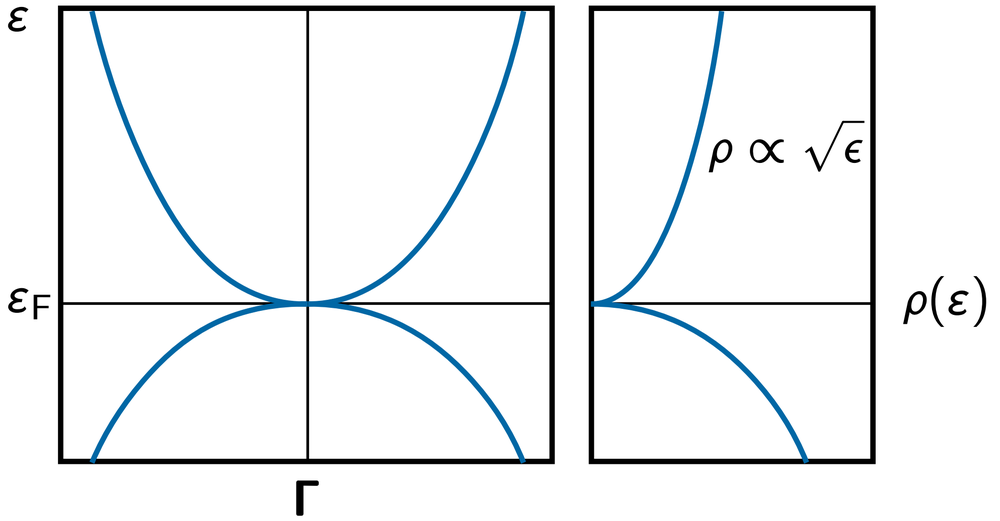

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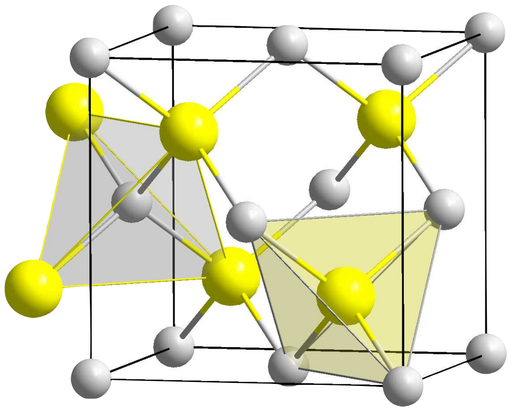
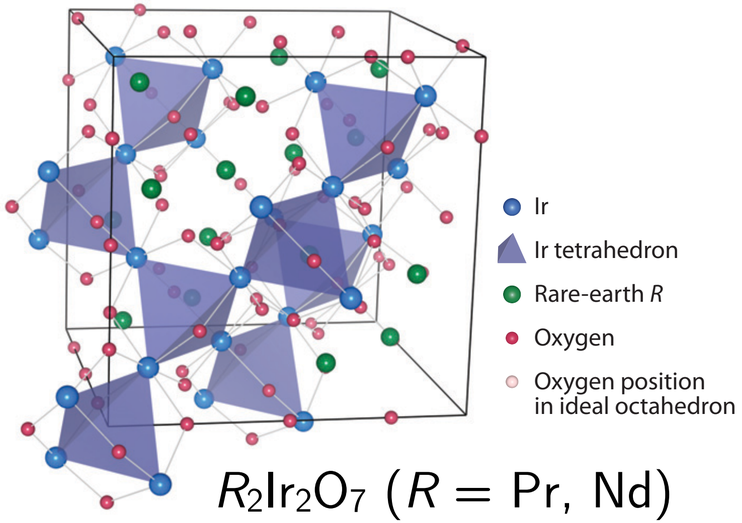
[Armitage, Mele, Vishwanath, RMP '18]

Short-range interactions: Irrelevant

Example #2: Luttinger Semimetals

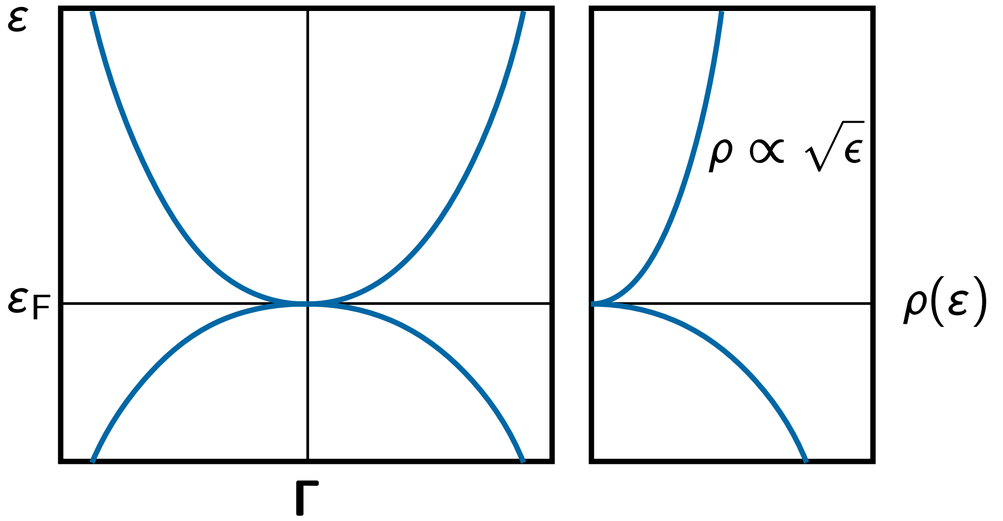


α-Sn, HgTe



$R_2Ir_2O_7$ (R = Pr, Nd)

[Kondo *et al.*, Nat. Comm. '15]
[Wang *et al.*, Nat. Phys. '20]



[Witczak-Krempa *et al.*, ARCMP '14]
[Armitage, Mele, Vishwanath, RMP '18]

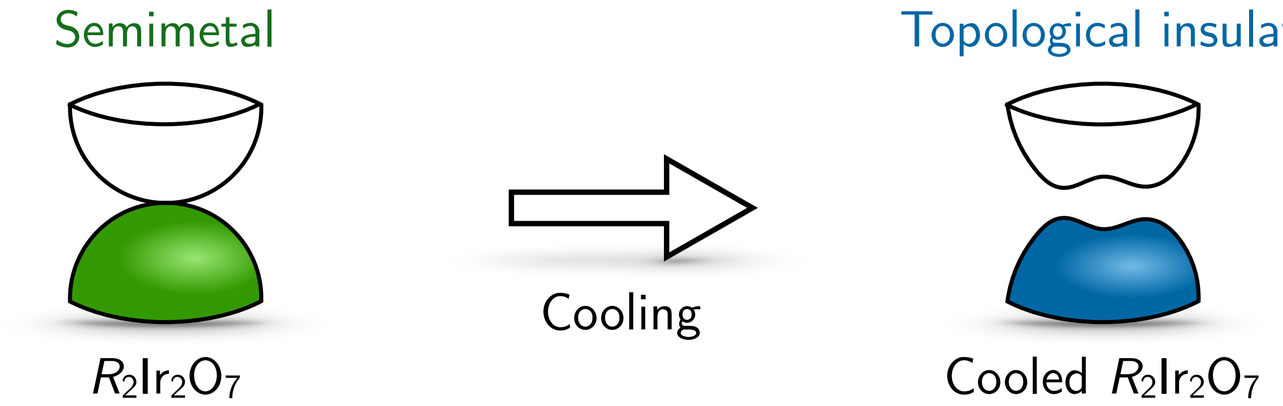
Short-range interactions: Irrelevant

Coulomb interaction: $V_0(r) \propto \frac{1}{r} \quad \rightarrow \quad V_{\text{eff}} \propto \frac{1}{r^z}, \quad z \approx 1.8$

[Moon, Xu, Kim, Balents, PRL '13]

Emergent Topological Phases

Coulomb-driven instability:



[Herbut & LJ, PRL '14]
[LJ & Herbut, PRB '17]

Emergent Topological Phases

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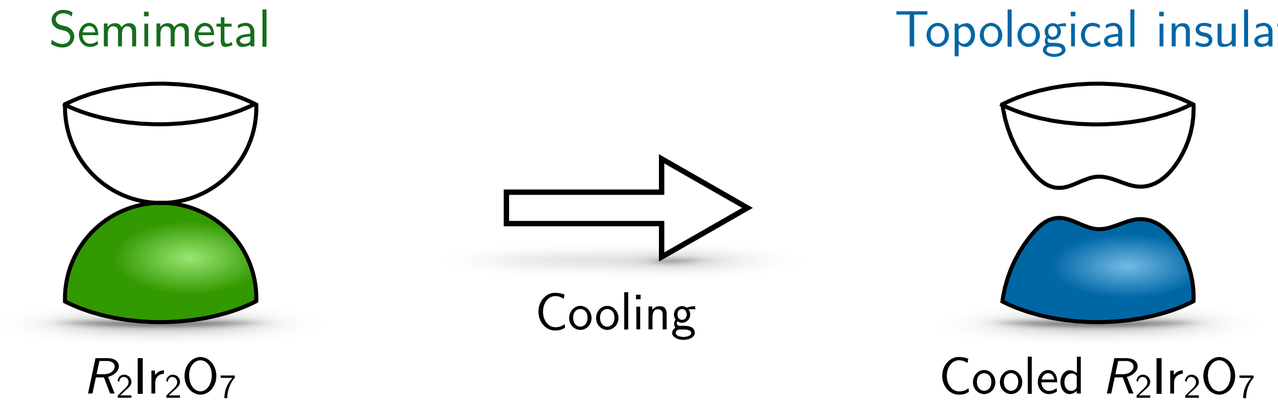
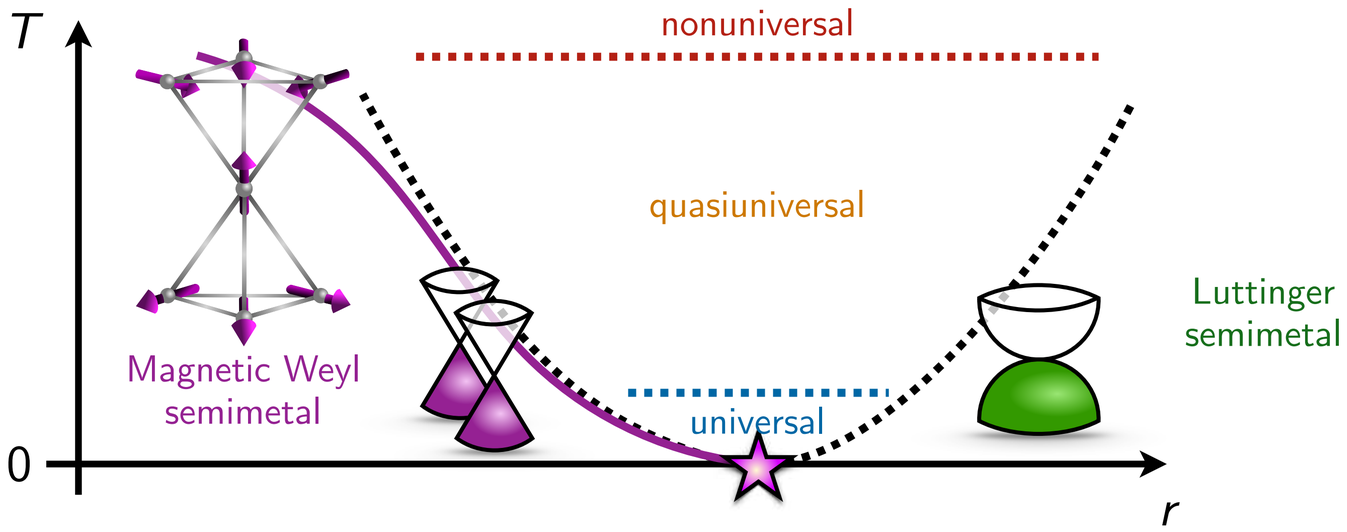


[Herbut & LJ, PRL '14]
[LJ & Herbut, PRB '17]

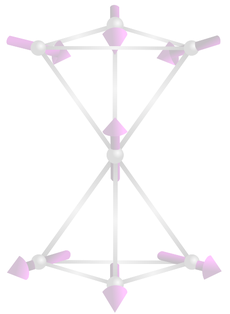
Strong short-range interactions:

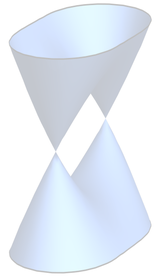


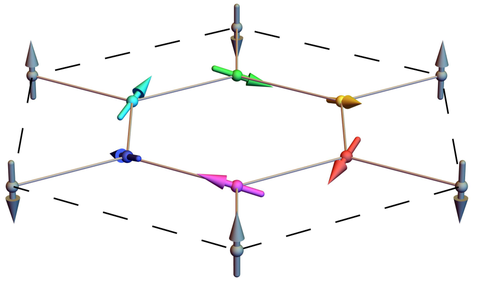
David Moser

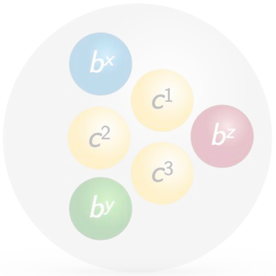
[Moser & LJ, *in preparation*]
see also: [Boettcher & Herbut, PRB '17]

Outline





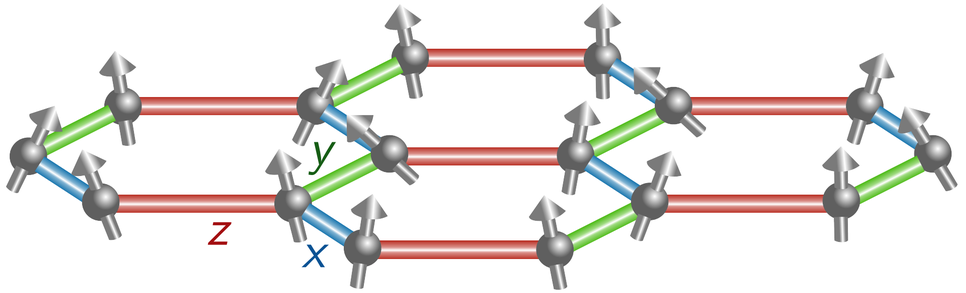




Example #2: Kitaev magnets

Hamiltonian:

$$\mathcal{H} = K \left(\sum_{\langle ij \rangle_x} S_i^x S_j^x + \sum_{\langle ij \rangle_y} S_i^y S_j^y + \sum_{\langle ij \rangle_z} S_i^z S_j^z \right)$$



[Kitaev, Ann. Phys. '06]

Review: [LJ & Vojta, JPCM '19]

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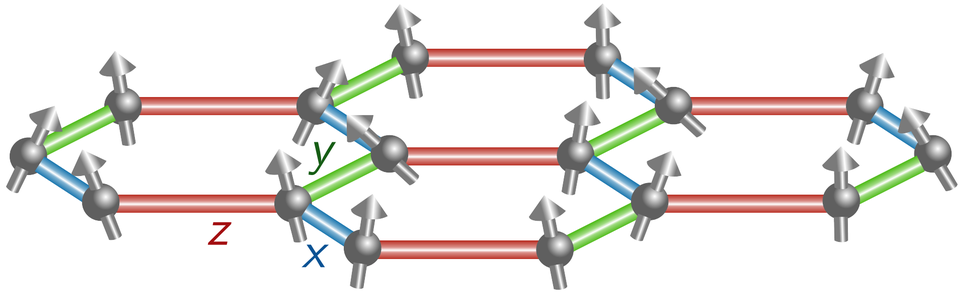

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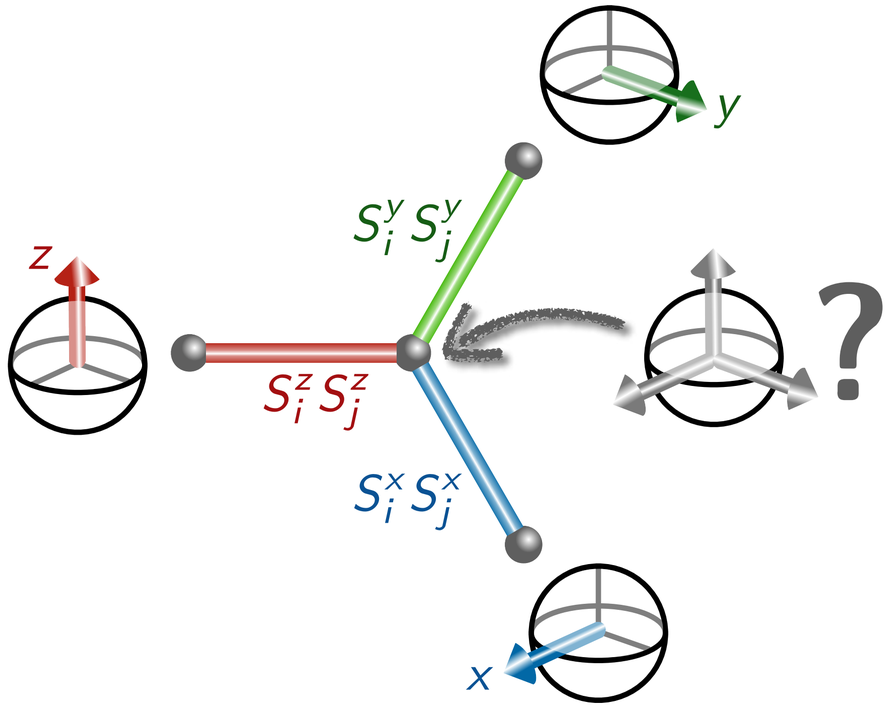
[Kitaev, Ann. Phys. '06]

Frustration:



Review: [LJ & Vojta, JPCM '19]

Kitaev-Heisenberg Physics in Magnetic Fields

Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\alpha} S_i^\alpha S_j^\alpha + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j - \vec{h} \cdot \sum_i \vec{S}_i$$

$$J = A \cos \varphi$$
$$K = 2A \sin \varphi$$

[LJ, Andrade, Vojta, PRL '16]
[Cônsoli, LJ, Vojta, Andrade, PRB '20]

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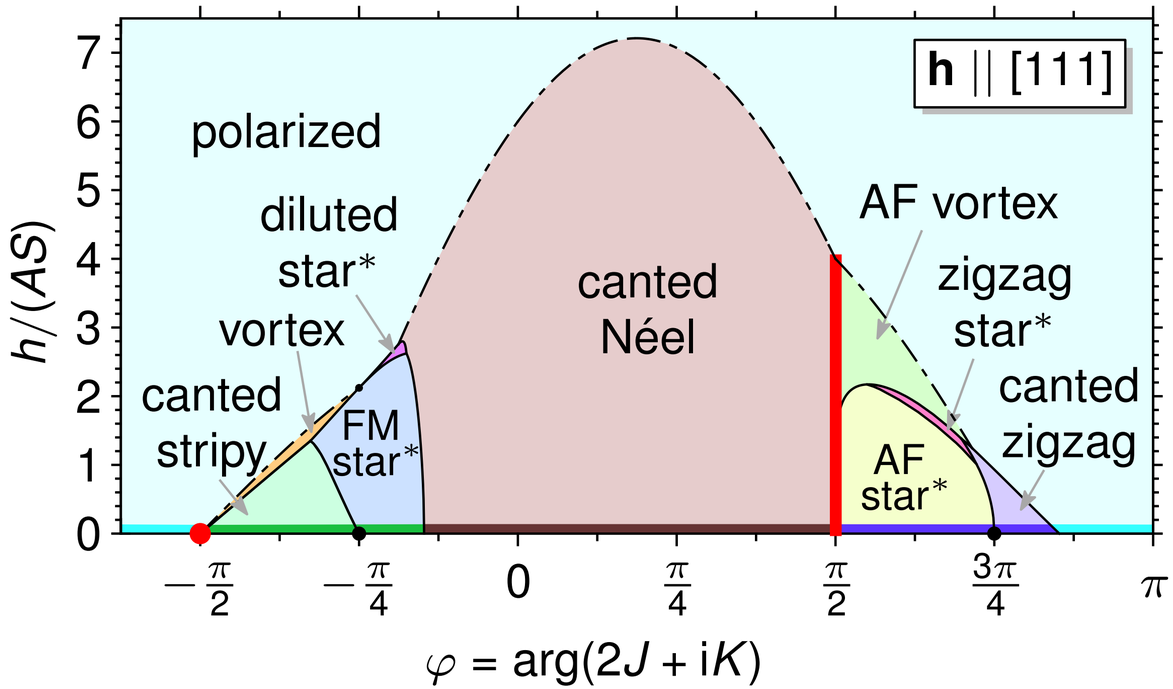

[LJ, Andrade, Vojta, PRL '16]
[Cônsoli, LJ, Vojta, Andrade, PRB '20]

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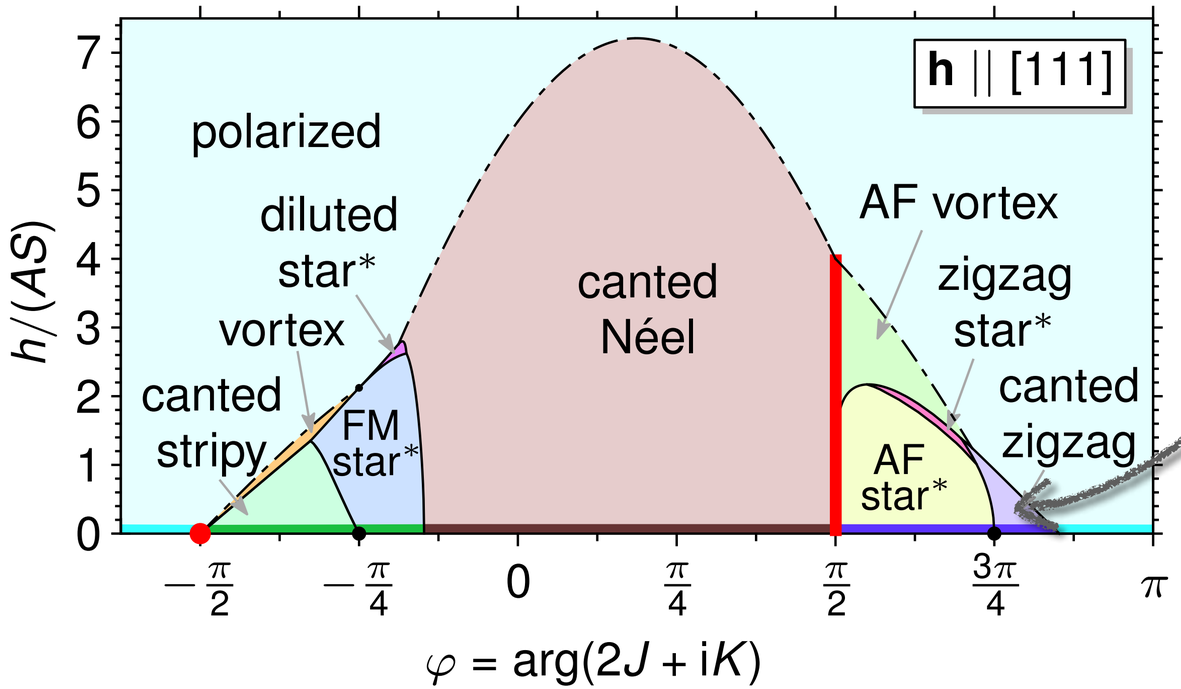

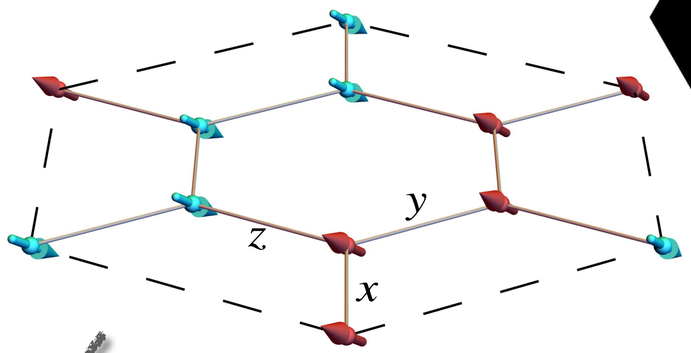

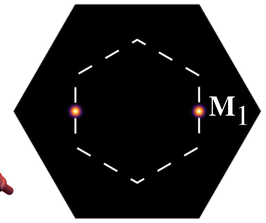

zigzag

[LJ, Andrade, Vojta, PRL '16]
[Cônsoli, LJ, Vojta, Andrade, PRB '20]

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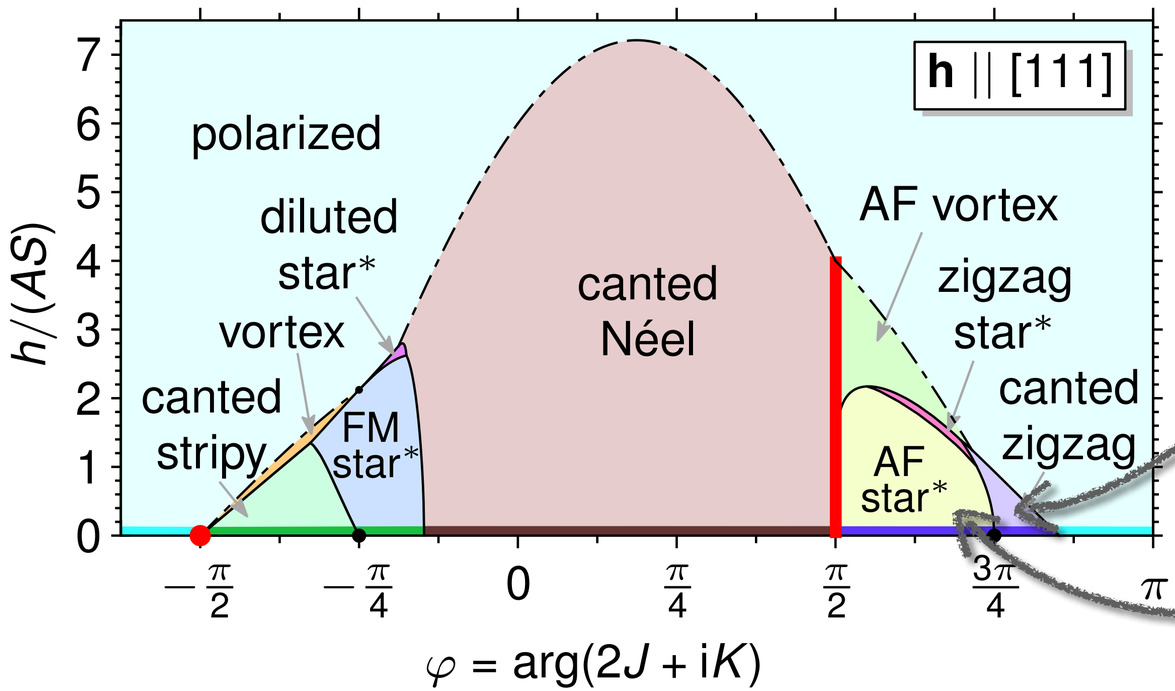
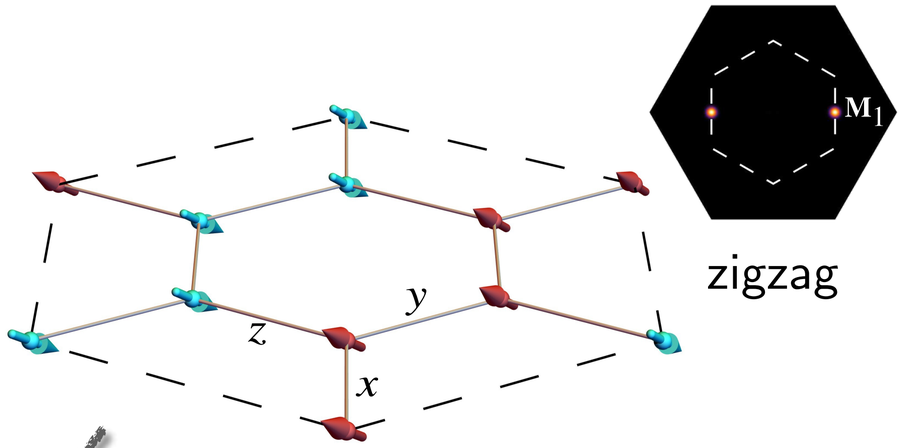
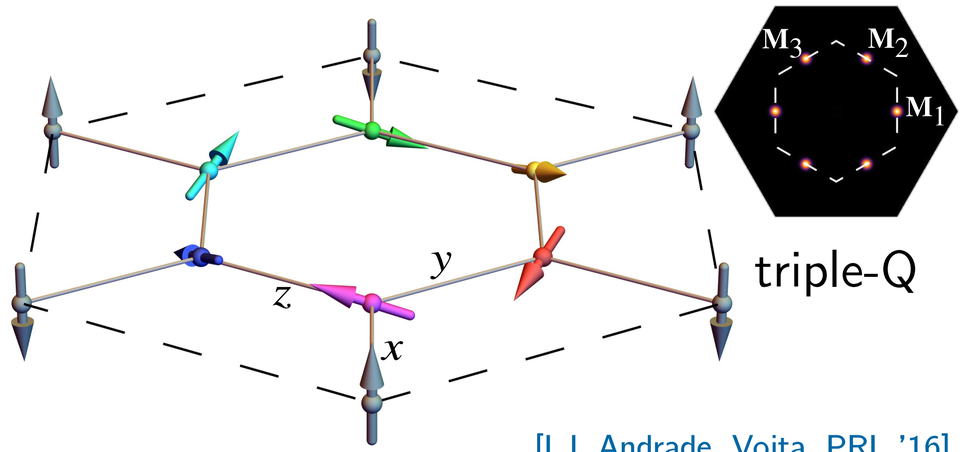




zigzag

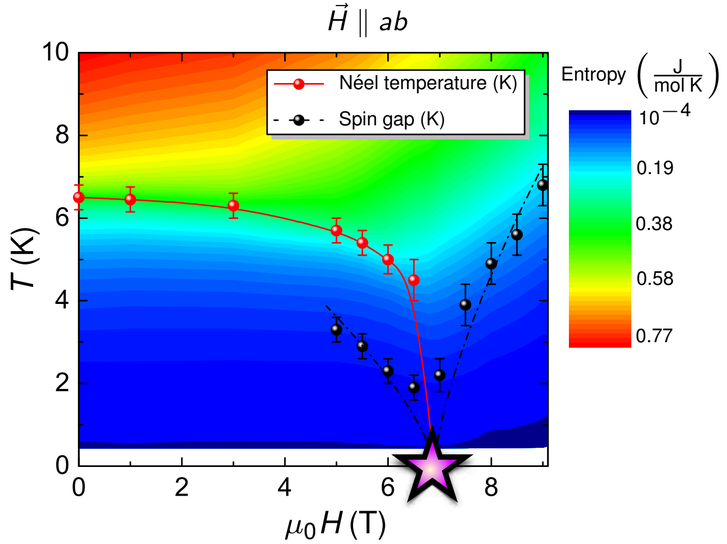


triple-Q

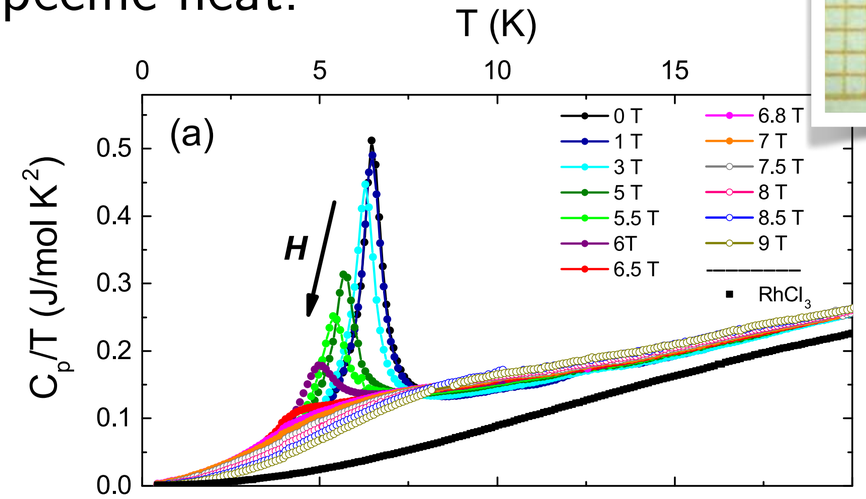
[LJ, Andrade, Vojta, PRL '16]
[Cônsoli, LJ, Vojta, Andrade, PRB '20]

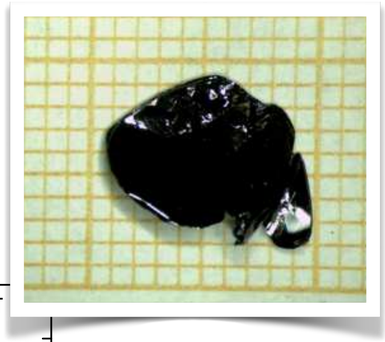
α-$RuCl_3$ in Magnetic Field

Phase diagram:



Specific heat:

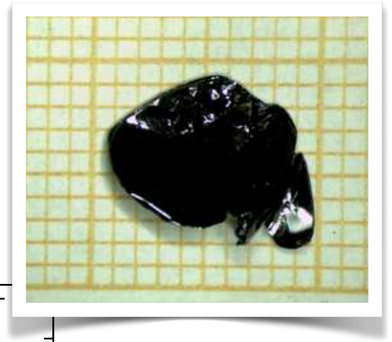




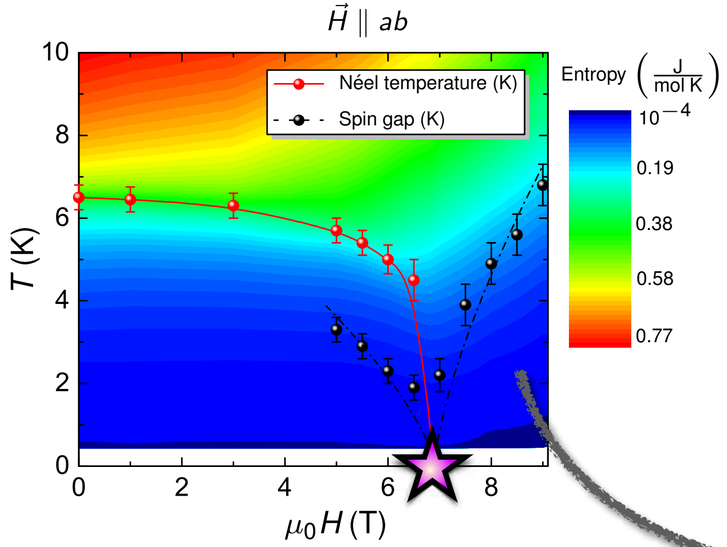
Credit: S. Wurmehl

[Wolter, Corredor, LJ, *et al.*, PRB '17]

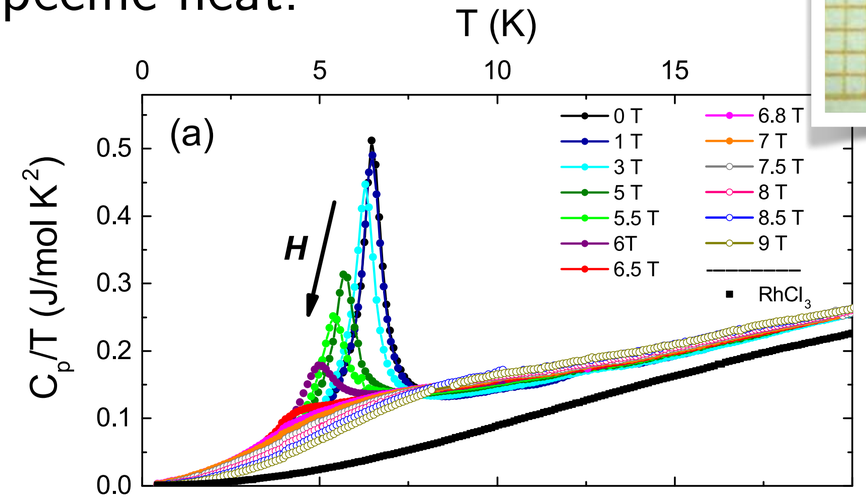
α-$RuCl_3$ in Magnetic Field



Phase diagram:

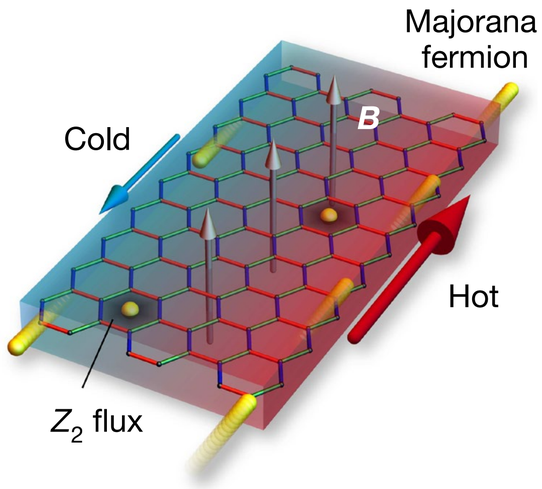


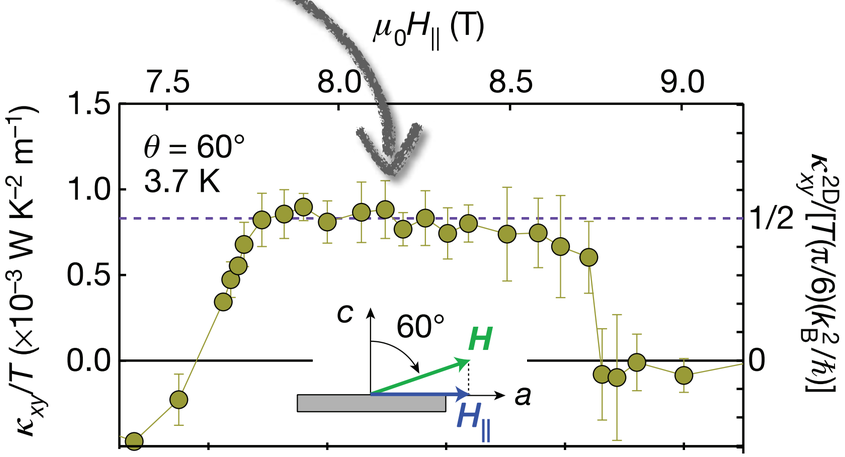
Specific heat:



[Wolter, Corredor, LJ, *et al.*, PRB '17]

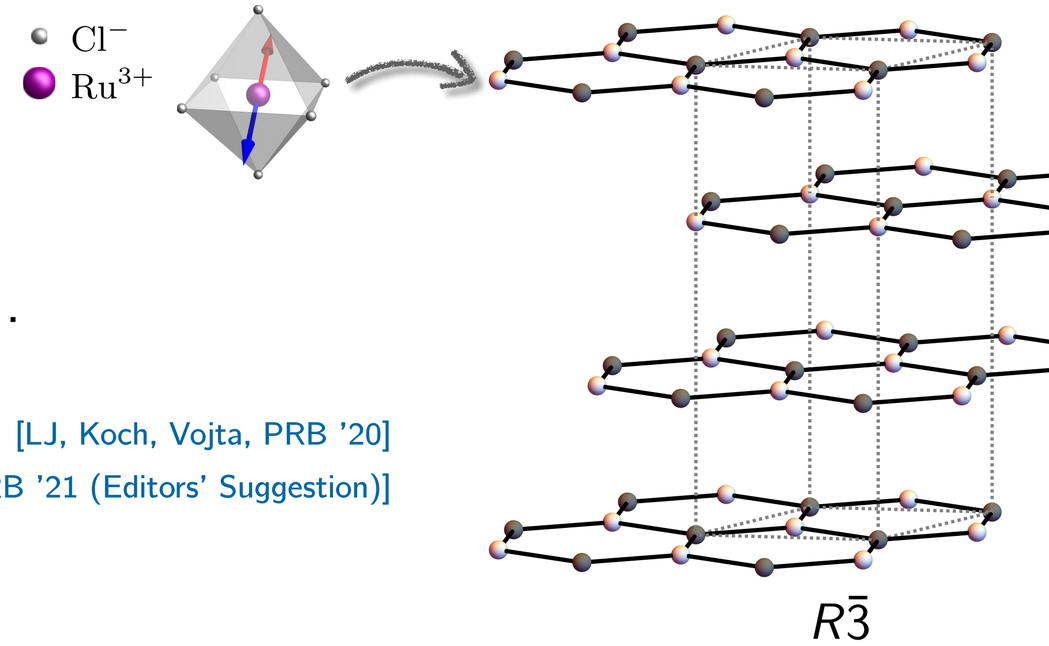
Half-integer quantum Hall effect:





[Kasahara *et al.*, Nature '18]
[Yokoi *et al.*, Science '21]

α-$RuCl_3$: Zigzag



Hamiltonian:

$$\mathcal{H}_{3D} = \mathcal{H}_{2D} + J_\perp \sum_{\langle ni,mi\rangle} \vec{S}_{n,i} \cdot \vec{S}_{m,i} + \dots$$

[LJ, Koch, Vojta, PRB '20]

[Balz, LJ, *et int.*, Nagler, PRB '21 (Editors' Suggestion)]

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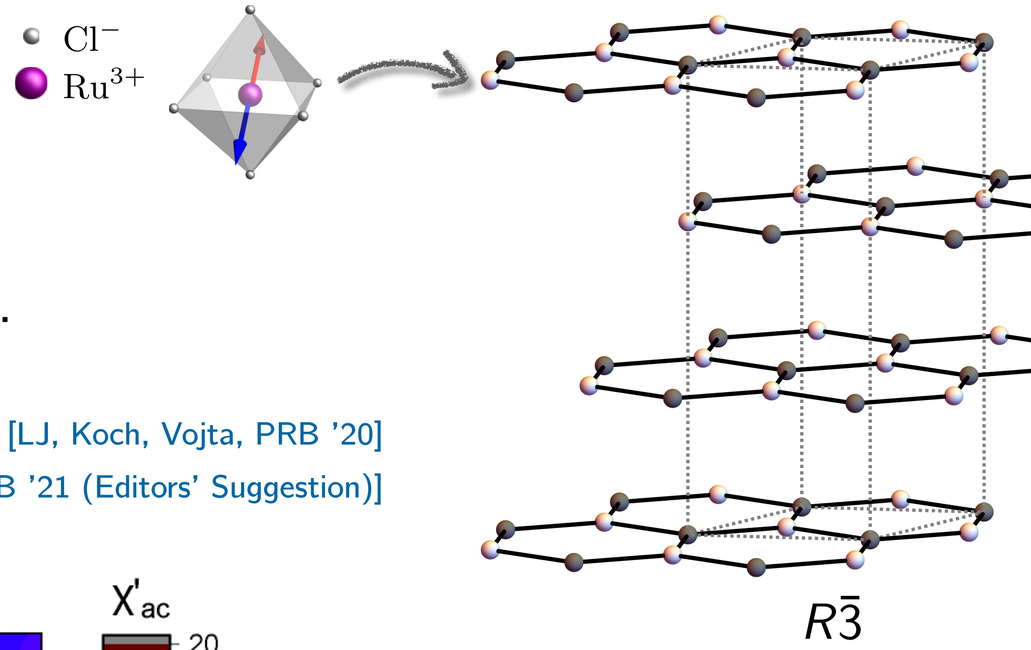

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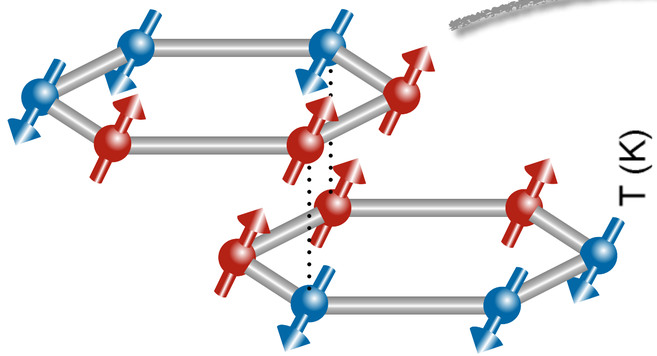
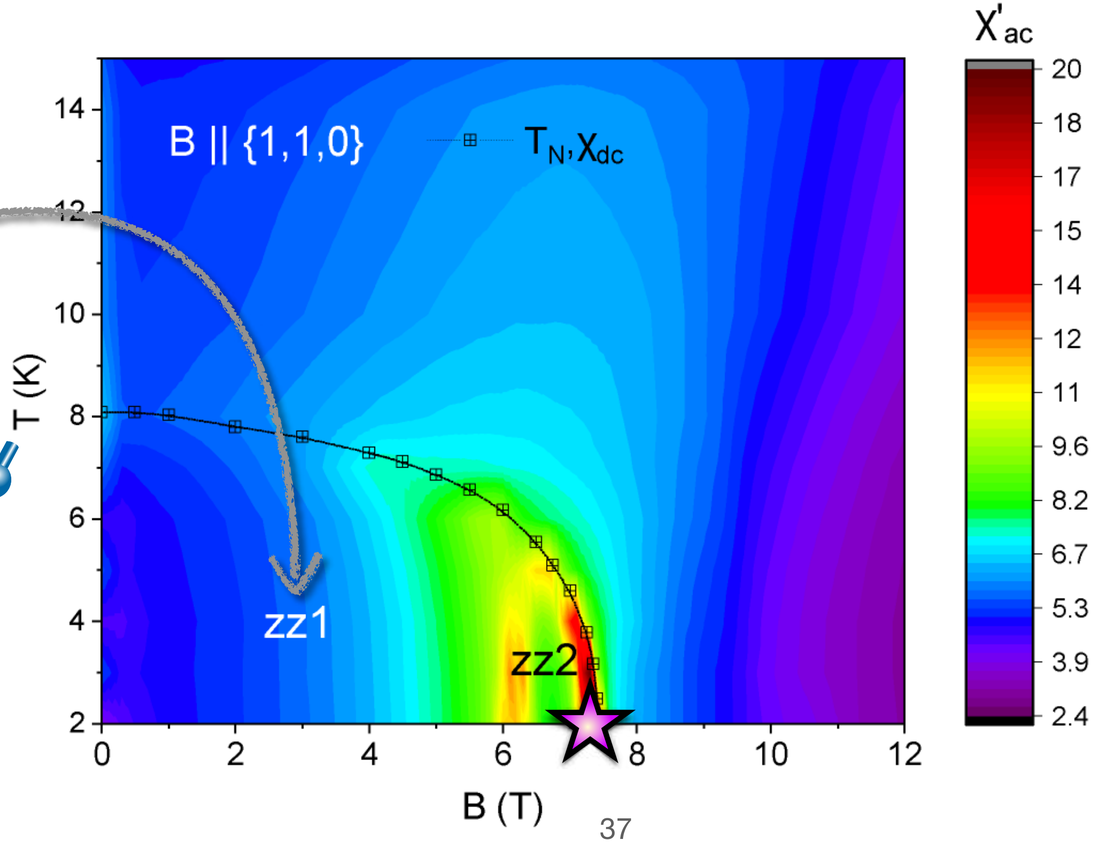


3-fold zigzag



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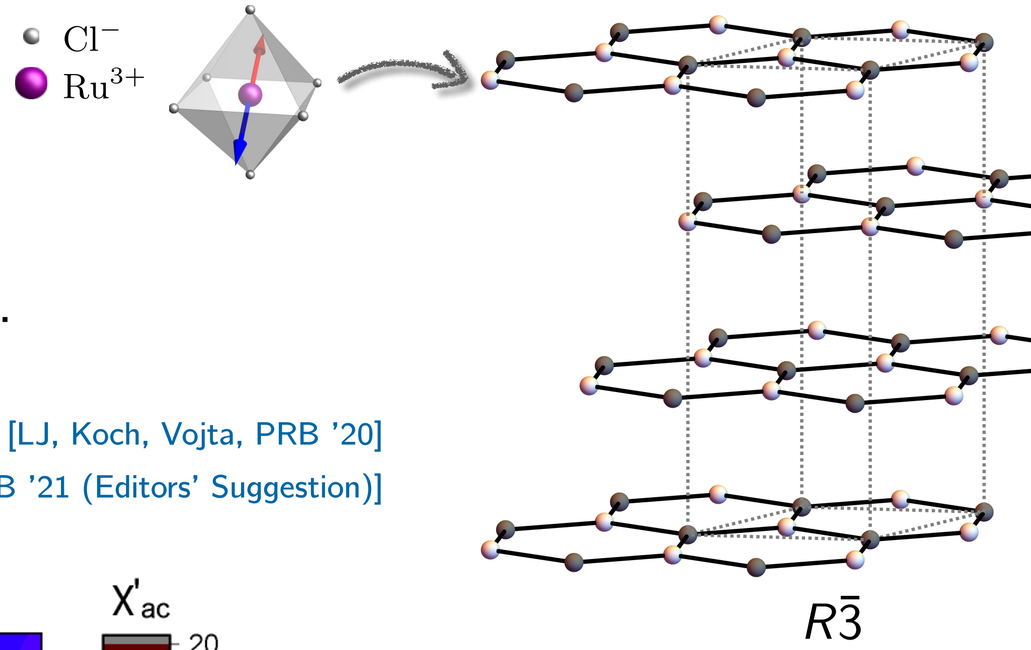

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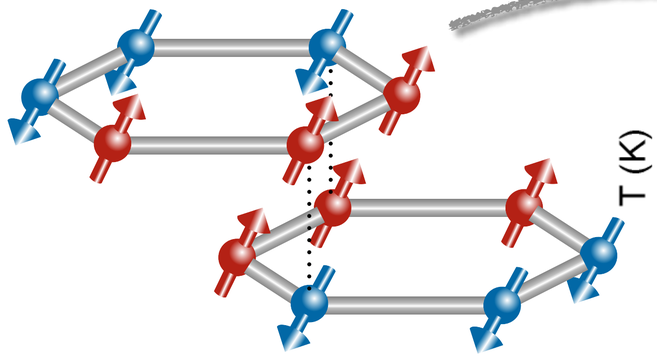

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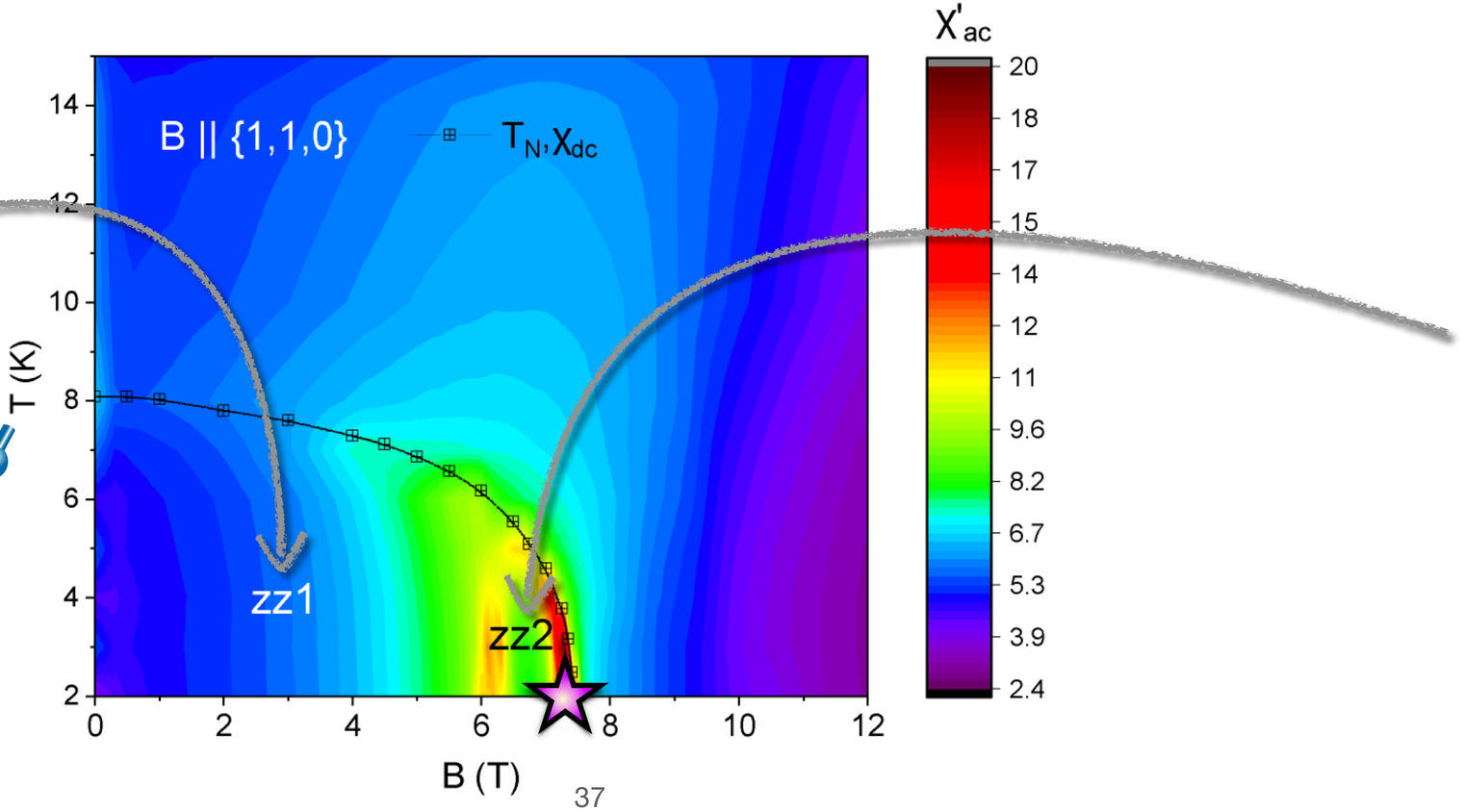

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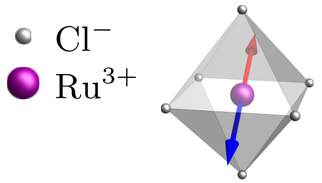

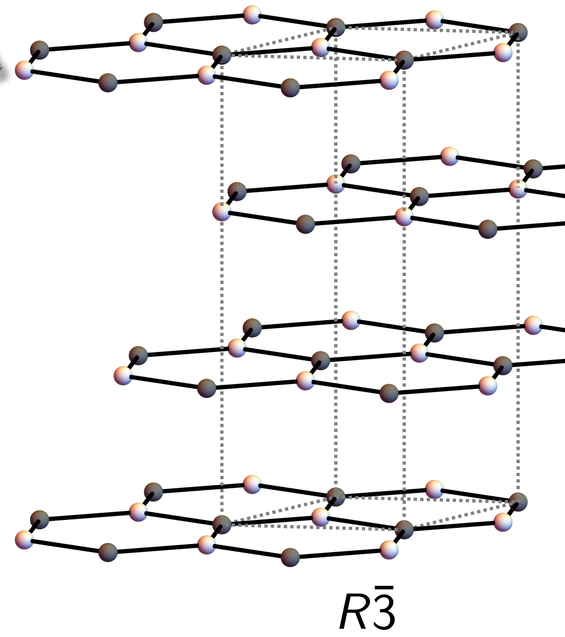

$R\bar{3}$

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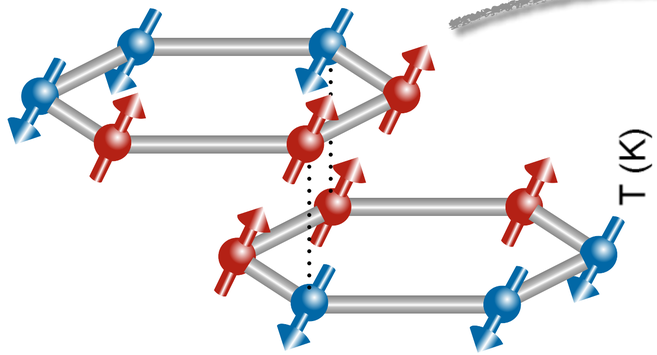

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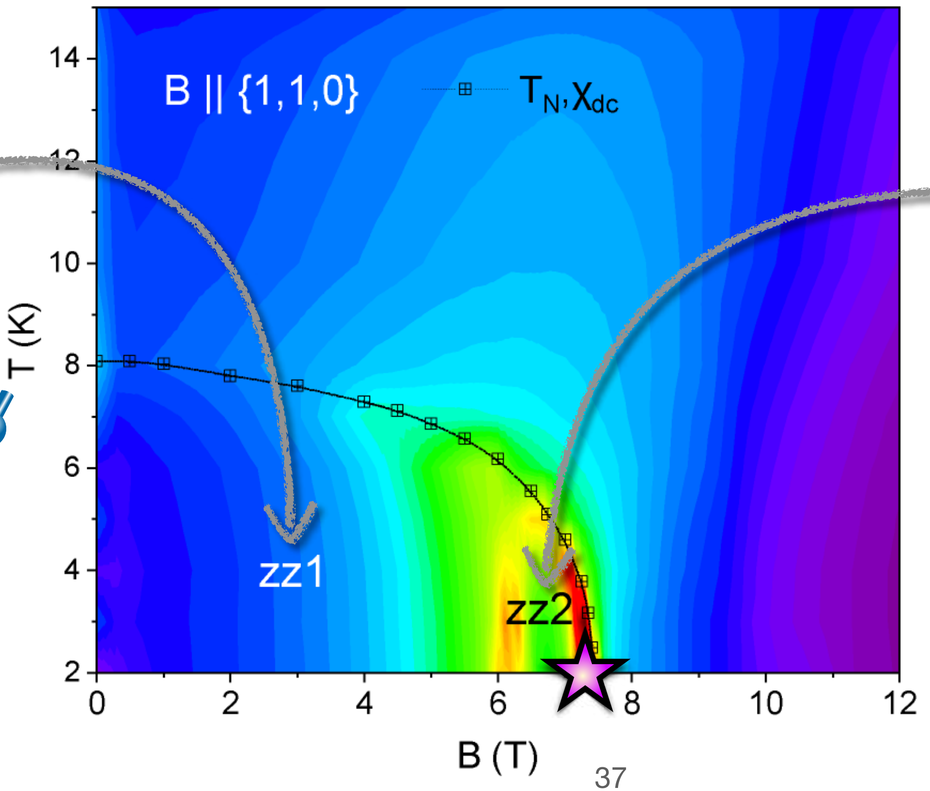

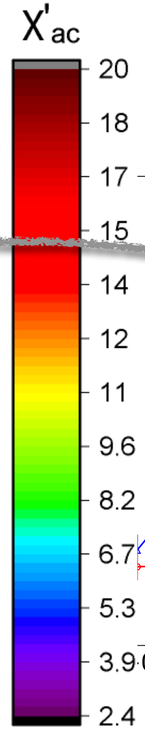

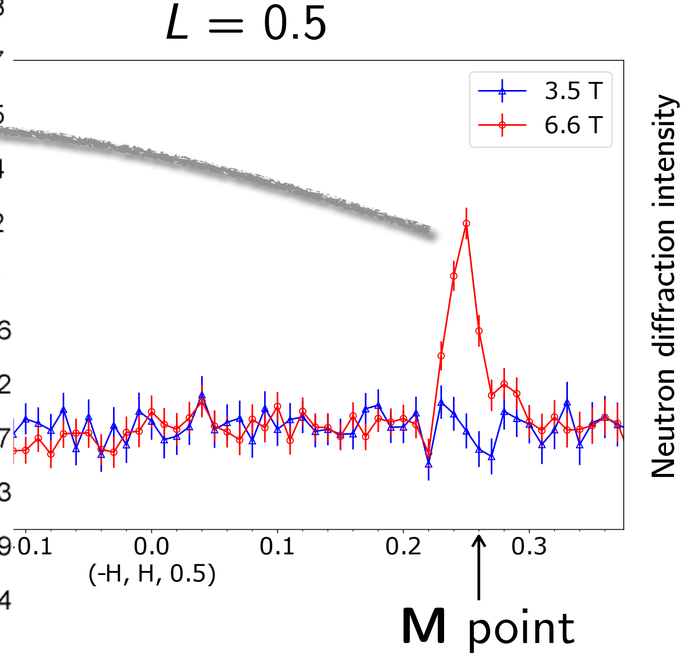

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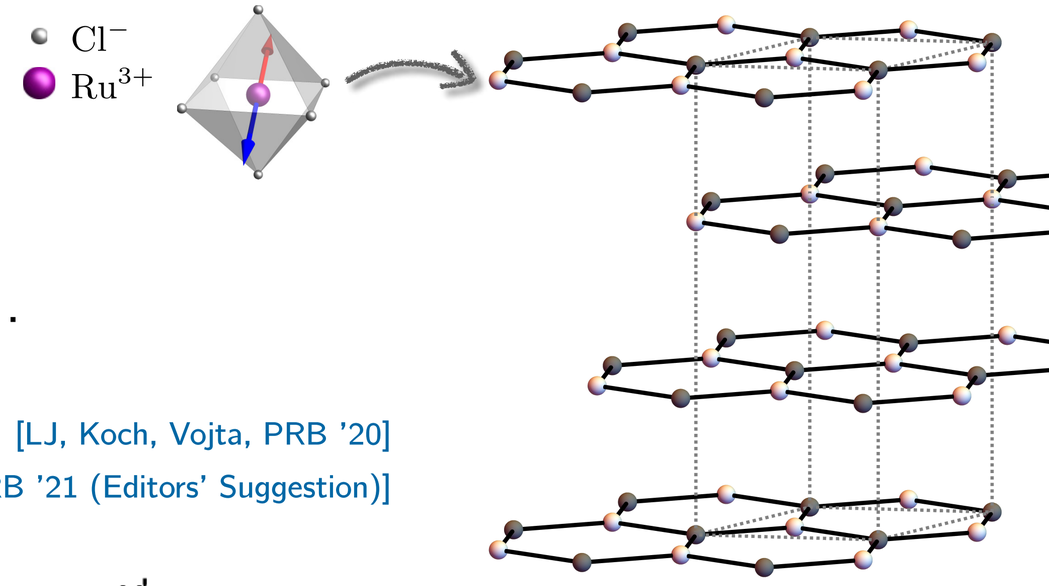

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[Balz, LJ, *et int.*, Nagler, PRB '21 (Editors' Suggestion)]

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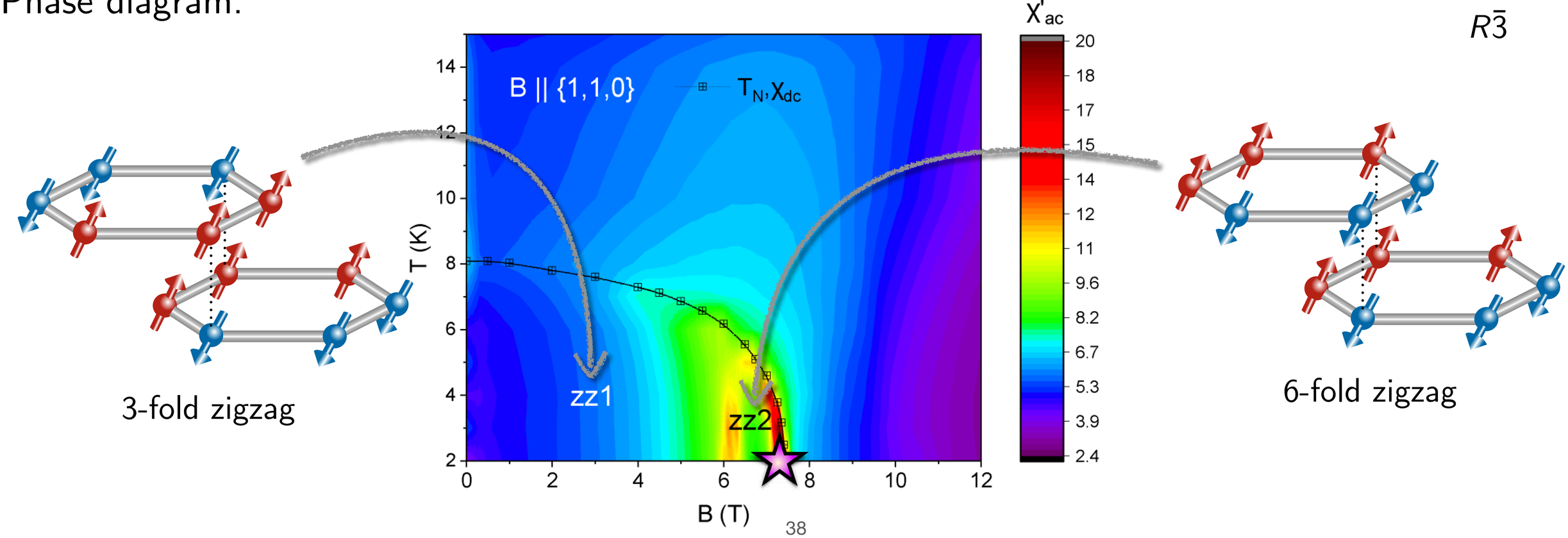
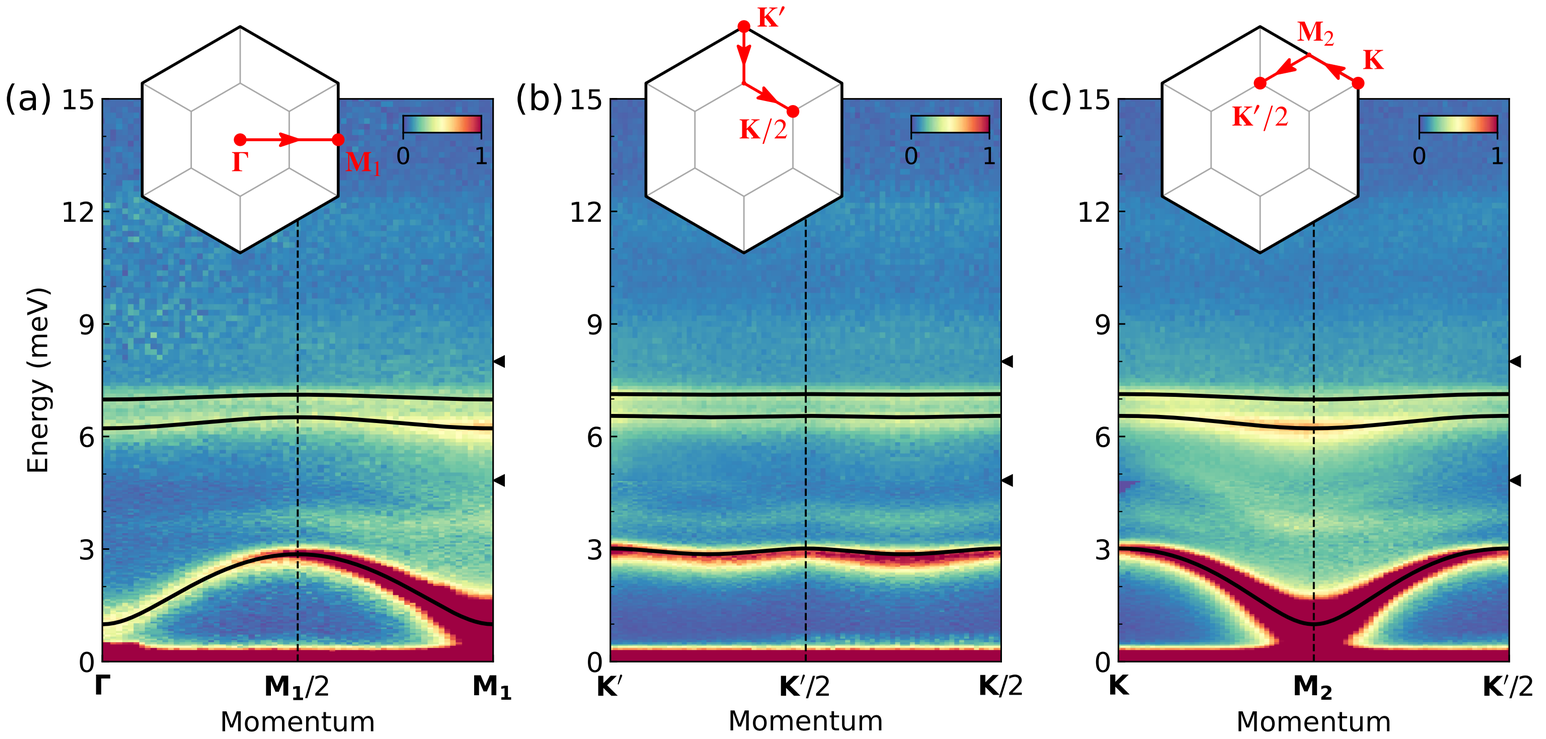
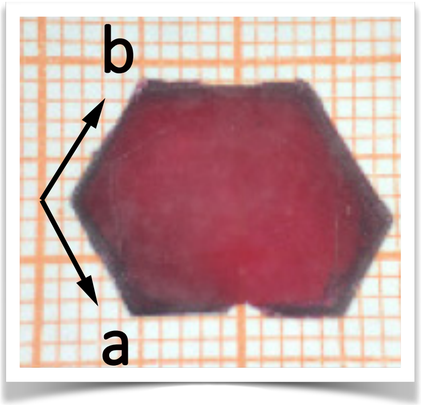


$Na_2Co_2TeO_6$: Triple-Q

Inelastic neutron spectrum:





Credit: Yuan Li

Wilhelm Krüger

[Krüger, Chen, Jin, Li, LJ, arXiv:2211.16957]

$Na_2Co_2TeO_6$: Triple-Q

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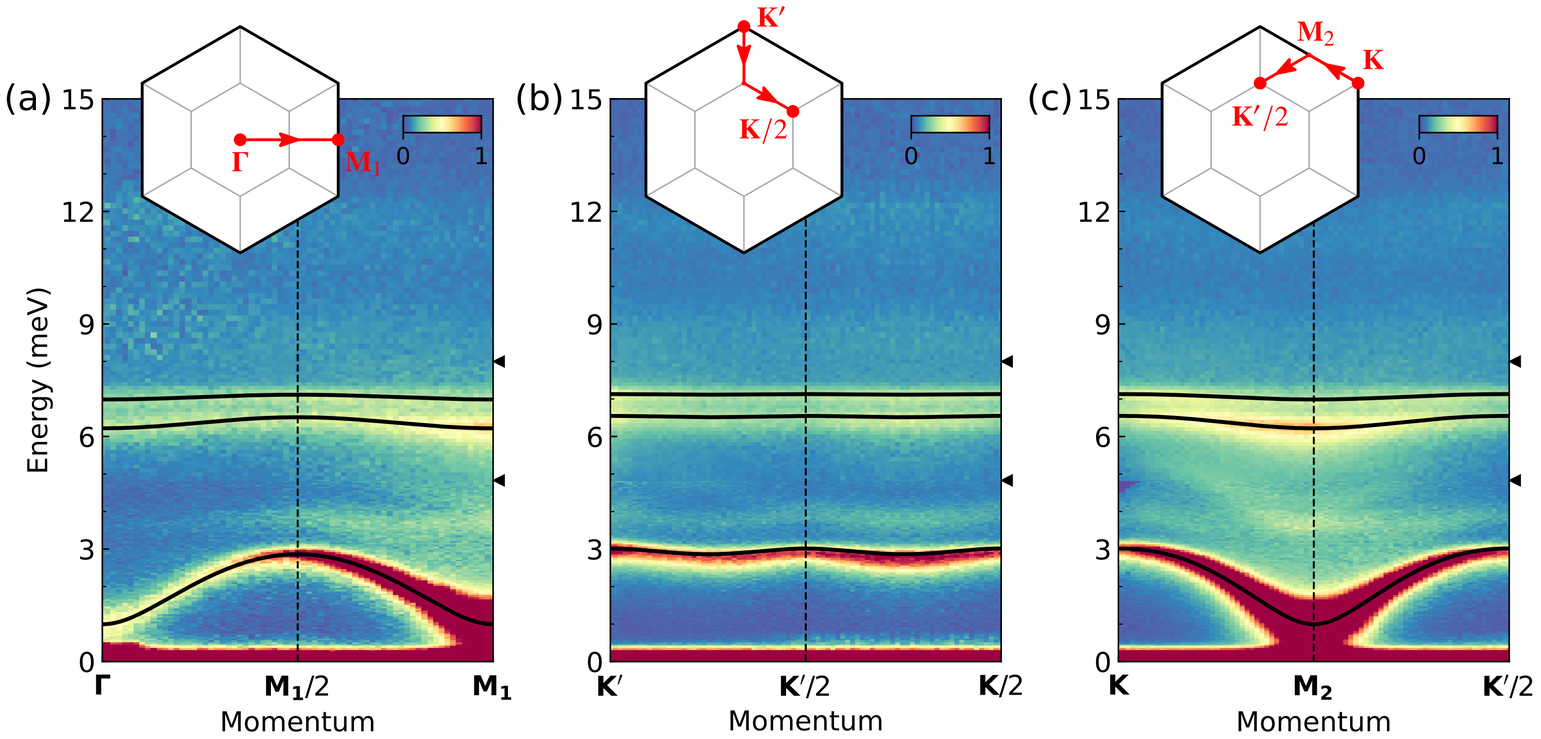
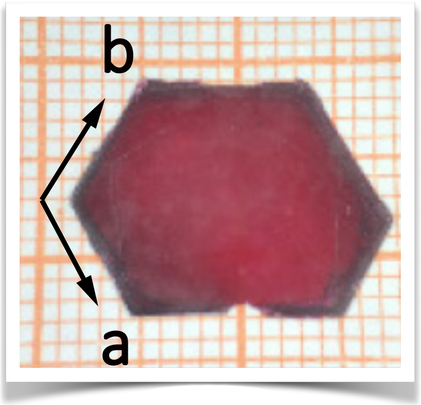
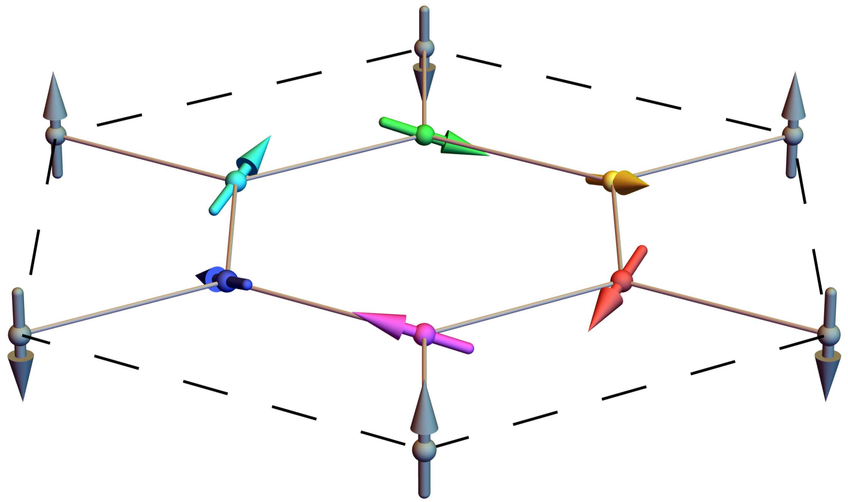




Credit: Yuan Li

Wilhelm Krüger

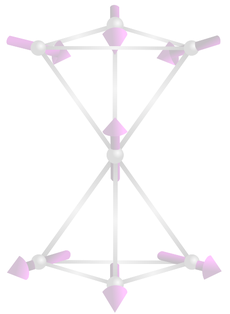
Ground state:

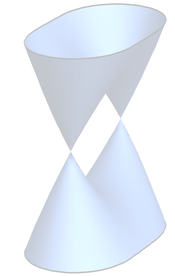


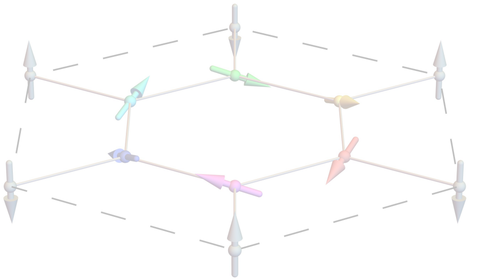
⇨ triple-Q order

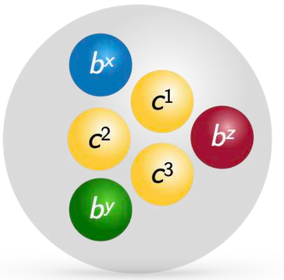
[Krüger, Chen, Jin, Li, LJ, arXiv:2211.16957]

Outline

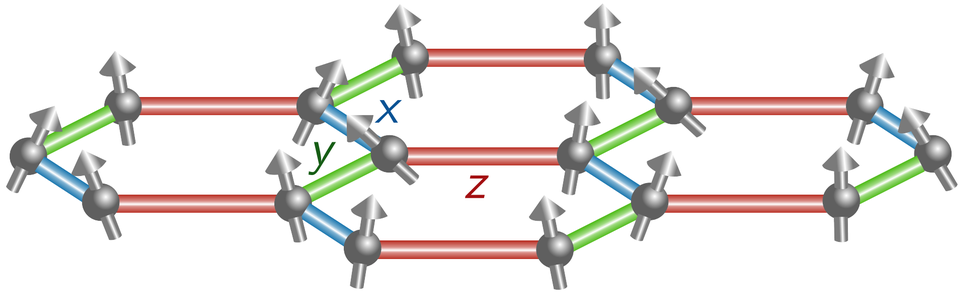








Example #3: Fractionalized Systems

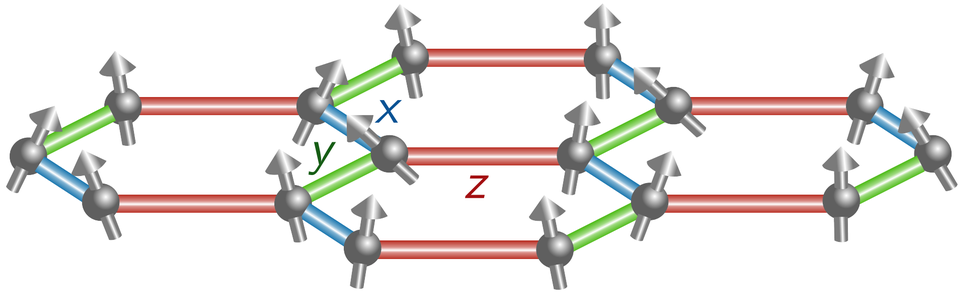


Kitaev spin-1/2 model:

$$\mathcal{H} = K \left(\sum_{\langle ij \rangle_x} \sigma_i^x \sigma_j^x + \sum_{\langle ij \rangle_y} \sigma_i^y \sigma_j^y + \sum_{\langle ij \rangle_z} \sigma_i^z \sigma_j^z \right)$$

[Kitaev, Ann. Phys. '06]

Example #3: Fractionalized Systems



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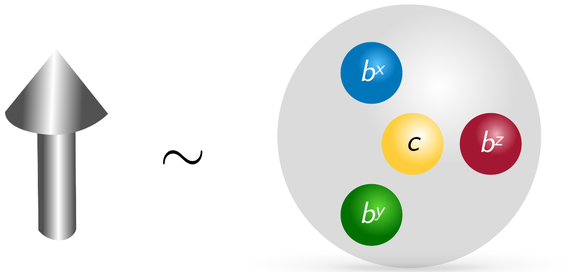
Majorana representation:

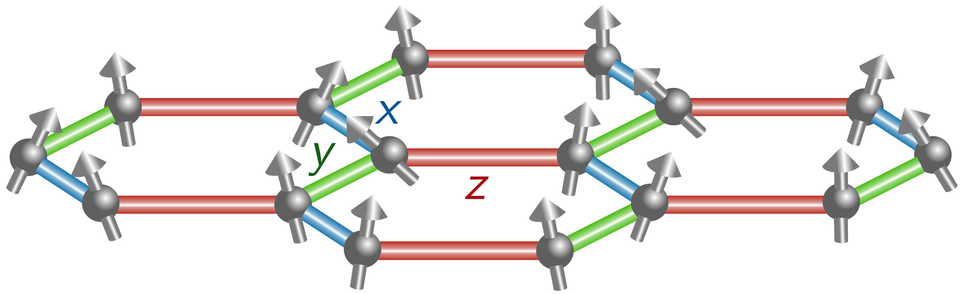
$$\sigma^x \sim i b^x c$$
$$\sigma^y \sim i b^y c$$
$$\sigma^z \sim i b^z c$$



spin $\sim$ 4 Majoranas with gauge constraint

[Kitaev, Ann. Phys. '06]

Example #3: Fractionalized Systems



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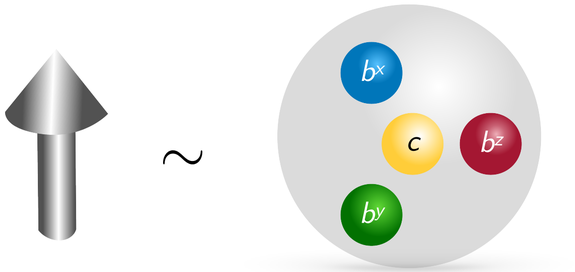


spin ∼ 4 Majoranas with gauge constraint

Fractionalization:

$$\mathcal{H} \sim iK \sum_{\langle ij \rangle_\alpha} \underbrace{(i b_i^\alpha b_j^\alpha)}_{\equiv \hat{u}_{ij} = \hat{u}_{ij}^\dagger} c_i c_j$$

with $\left[\hat{u}_{ij}, \tilde{\mathcal{H}} \right] = 0 \quad \Rightarrow \quad$ static $\mathbb{Z}_2$ gauge field!

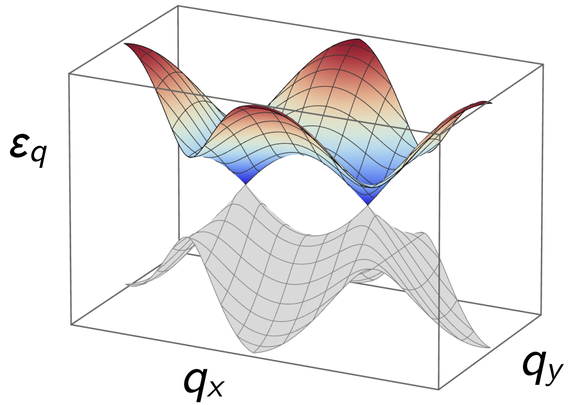
[Kitaev, Ann. Phys. '06]

Kitaev quantum spin liquid

Ground state:

$$\hat{u}_{ij} \mapsto u_{ij} \equiv 1 \quad \Longrightarrow \quad \mathcal{H} \sim \mathrm{i}K \sum_{\langle ij \rangle} c_i c_j$$

Majorana spectrum:



[Kitaev, Ann. Phys. '06]

Kitaev quantum spin liquid

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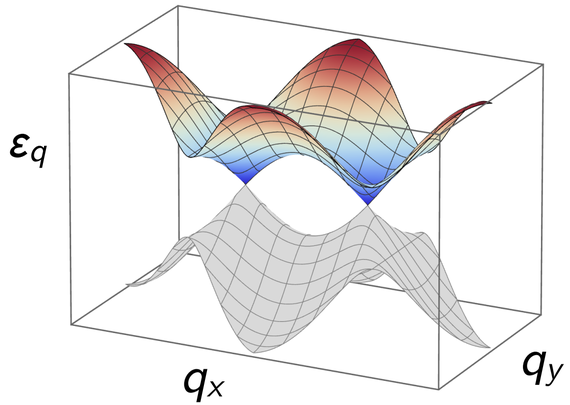
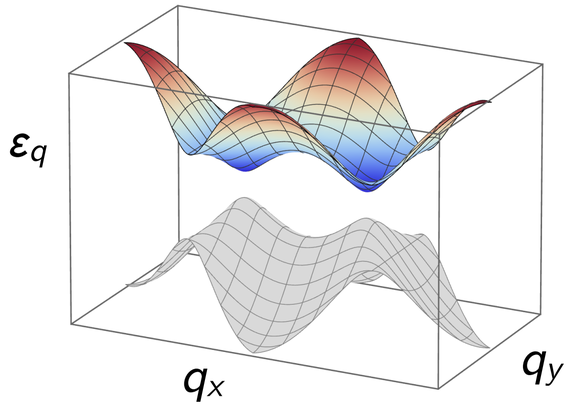
$$\hat{u}_{ij} \mapsto u_{ij} \equiv 1 \quad \Longrightarrow \quad \mathcal{H} \sim \mathrm{i}K \sum_{\langle ij \rangle} c_i c_j$$

External field $\vec{h} \parallel [111]$:

$$\mathcal{H} \mapsto \mathcal{H} - \vec{h} \cdot \sum_i \vec{\sigma}_i$$

Majorana spectrum:





with $\nu = 1$!

[Kitaev, Ann. Phys. '06]

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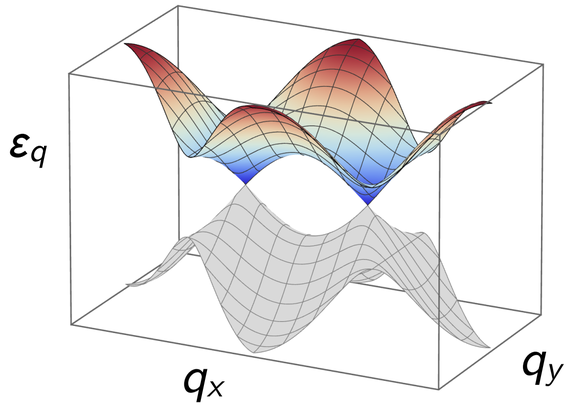

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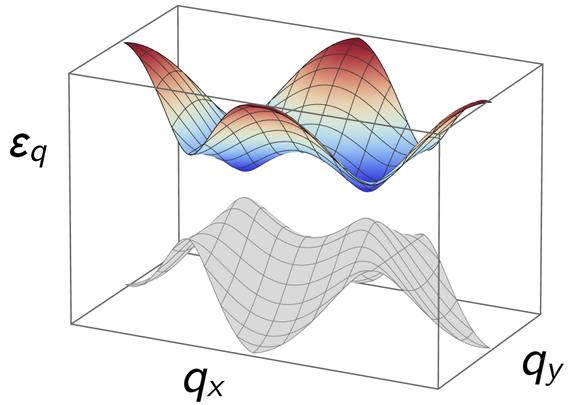
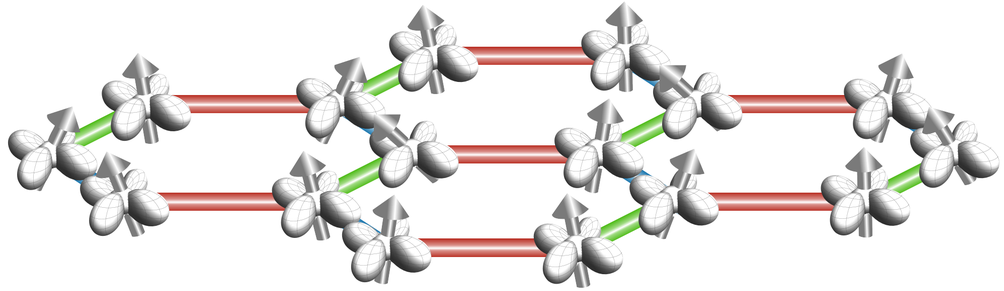


with $\nu = 1$!

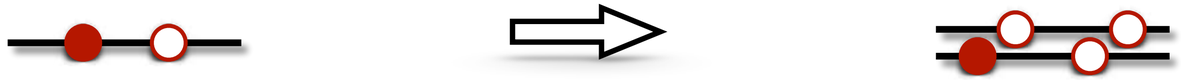
$\Longrightarrow$ Fractionalized version of topological insulator!

[Kitaev, Ann. Phys. '06]

Beyond Kitaev spin-1/2



Spin-orbital generalization:



$\sigma^\alpha \quad 2\times 2$ $\qquad$ $\gamma^i = \sigma^\alpha \otimes \tau^\beta \quad 4\times 4$

spin $\sim$ 4 Majoranas with gauge constraint

spin + orbital $\sim$ 6 Majoranas with gauge constraint

[Chulliparambil, *et int.*, LJ, Tu, PRB '20]

Kitaev-Heisenberg spin-orbital models

Hamiltonian:

$$\mathcal{H} = K \sum_{\langle ij \rangle_\alpha} \underbrace{\vec{\sigma}_i \cdot \vec{\sigma}_j \otimes \tau_i^\alpha \tau_j^\alpha}_{\mapsto \ \hat{u}_{ij} c_i^\top c_j} + J \sum_{\langle ij \rangle} \underbrace{\vec{\sigma}_i \cdot \vec{\sigma}_j \otimes \mathbb{1}_i \mathbb{1}_j}_{\mapsto \ \frac{1}{4}(c_i^\top \vec{L} c_i) \cdot (c_j^\top \vec{L} c_j)}$$

spin-1 matrices

with $[\hat{u}_{ij}, \mathcal{H}] = 0$ still static!

[Seifert, Dong, *et int.*, LJ, PRL '20]

Kitaev-Heisenberg spin-orbital models

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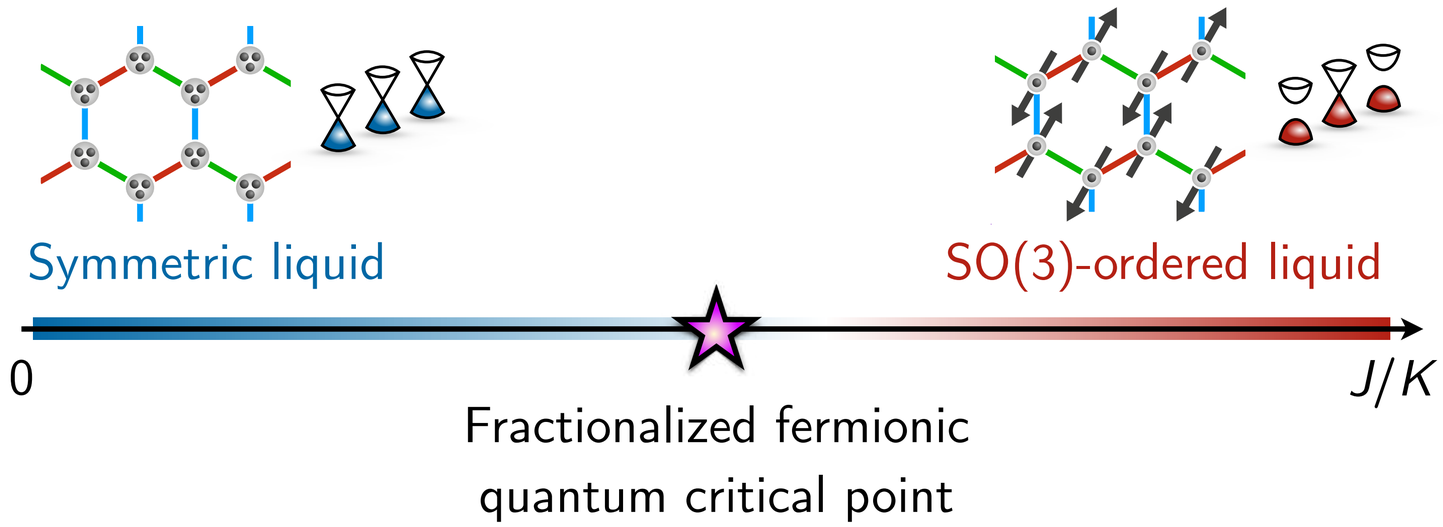
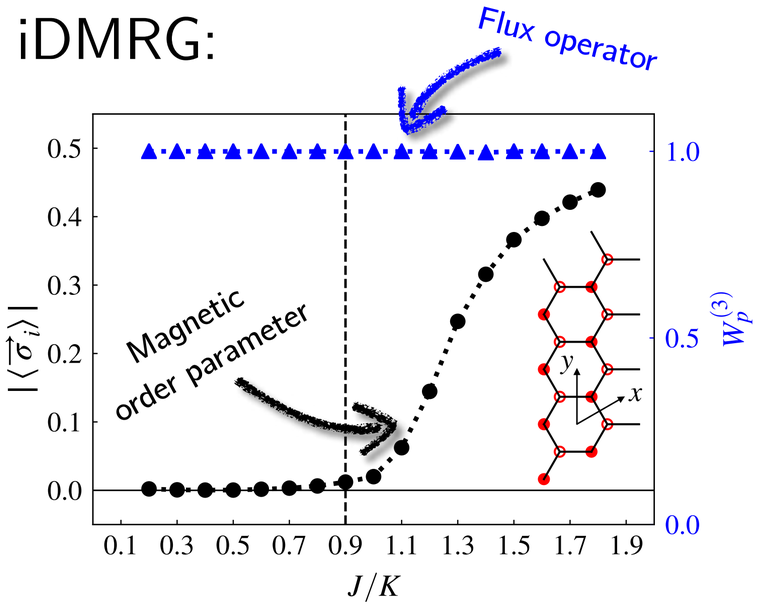
spin-1 matrices

with $[\hat{u}_{ij}, \mathcal{H}] = 0$ still static!

Phase diagram:



iDMRG:

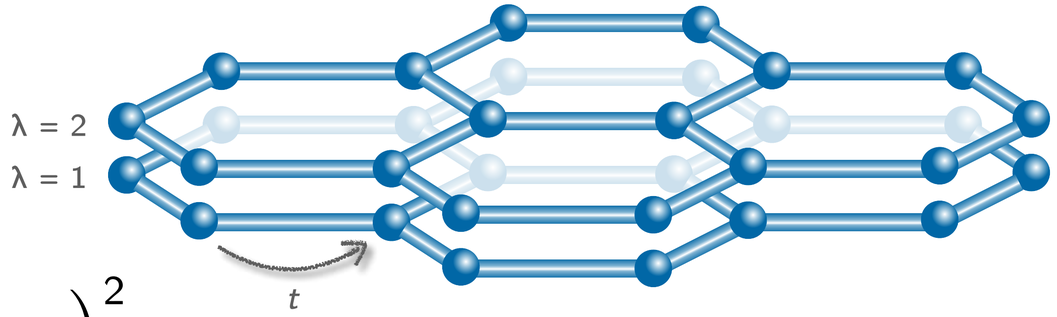


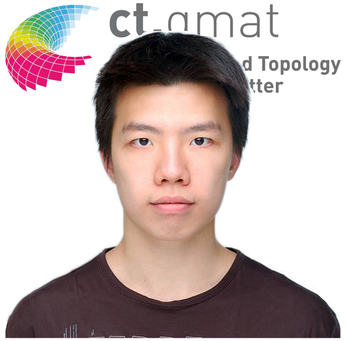
[Seifert, Dong, *et int.*, LJ, PRL '20]

Effective low-energy model

Hamiltonian:

$$\mathcal{H} = -t \sum_{\langle ij \rangle} c^\dagger_{i\lambda} c_{j\lambda} - J \sum_i \left(c^\dagger_{i\lambda} \vec{L} \tau^z_{\lambda\lambda'} c_{i\lambda'} \right)^2$$

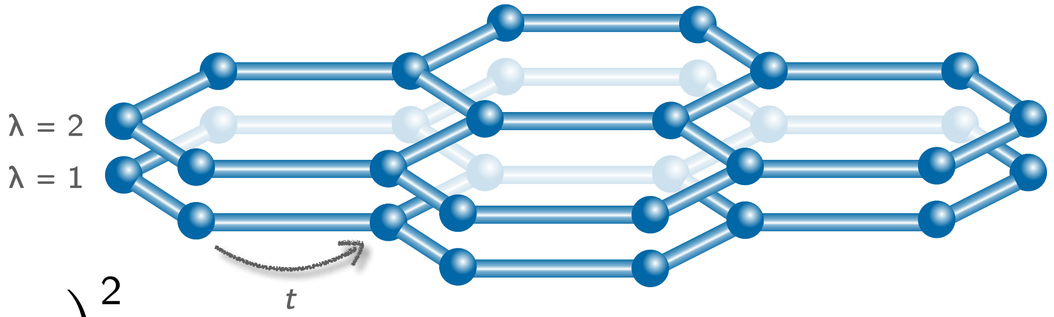


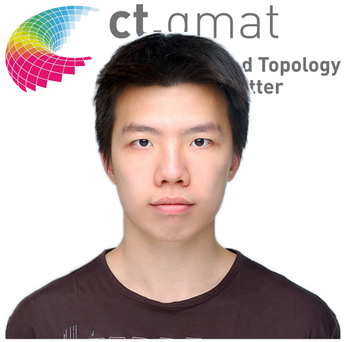


Zihong Liu

[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

Effective low-energy model





Zihong Liu

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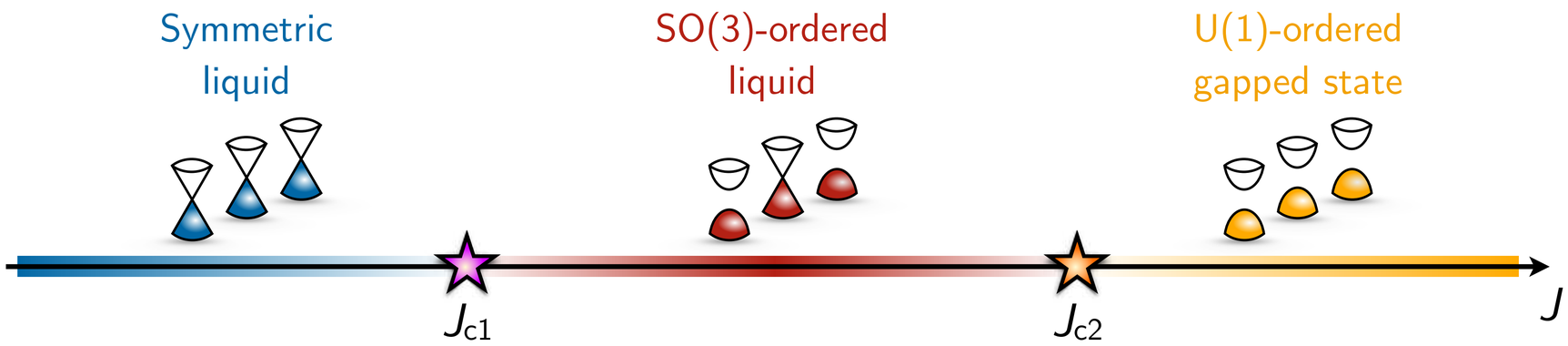
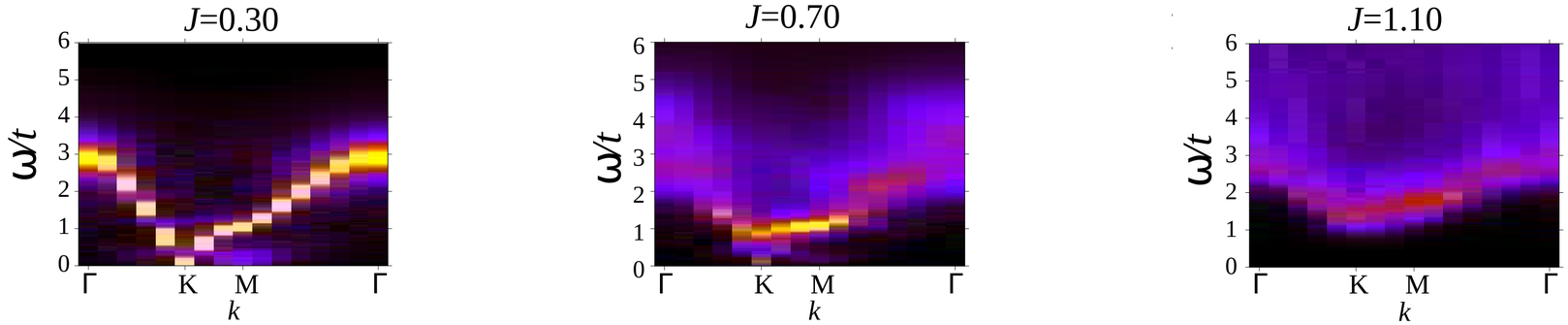
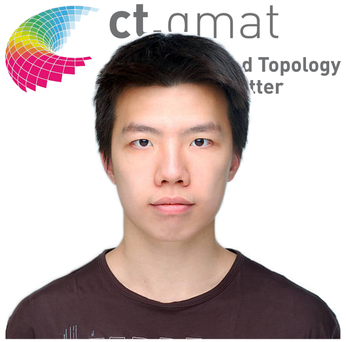


Fermion spectral function:



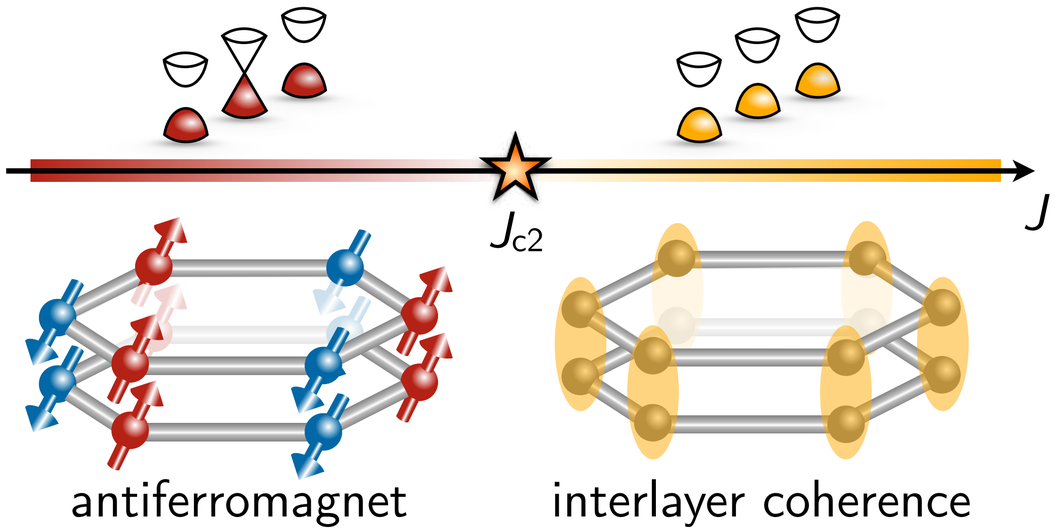
[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

Deconfined Metal-Insulator Transition



Zihong Liu

Competing orders:



[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

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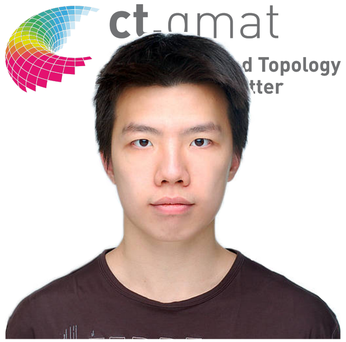

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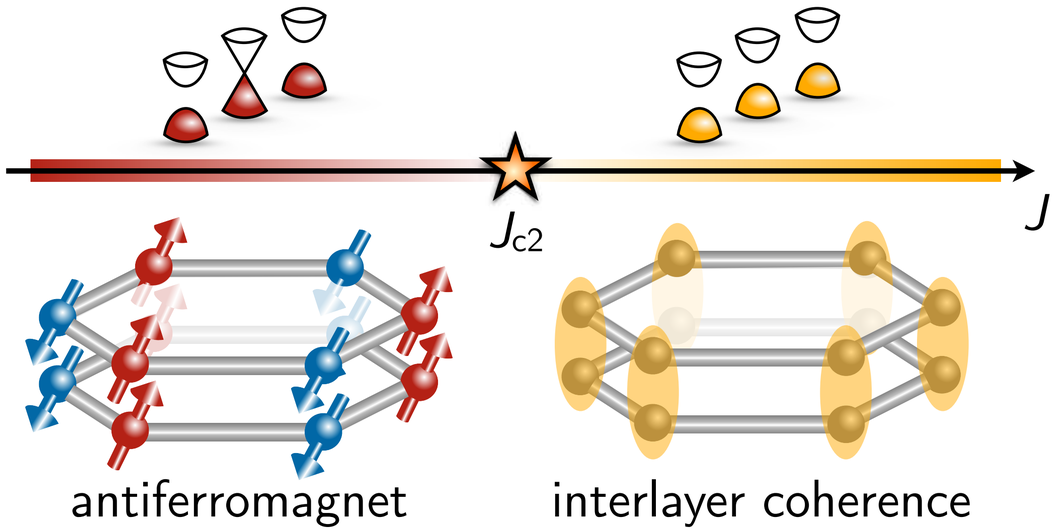
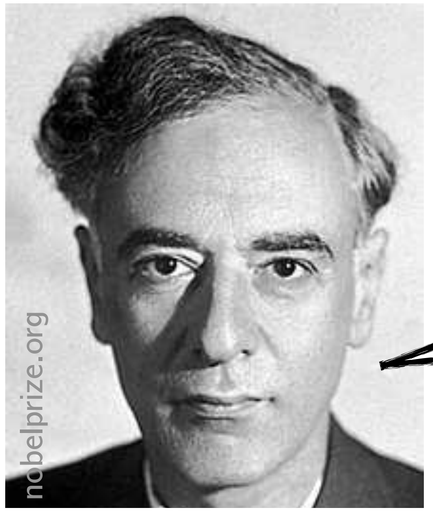
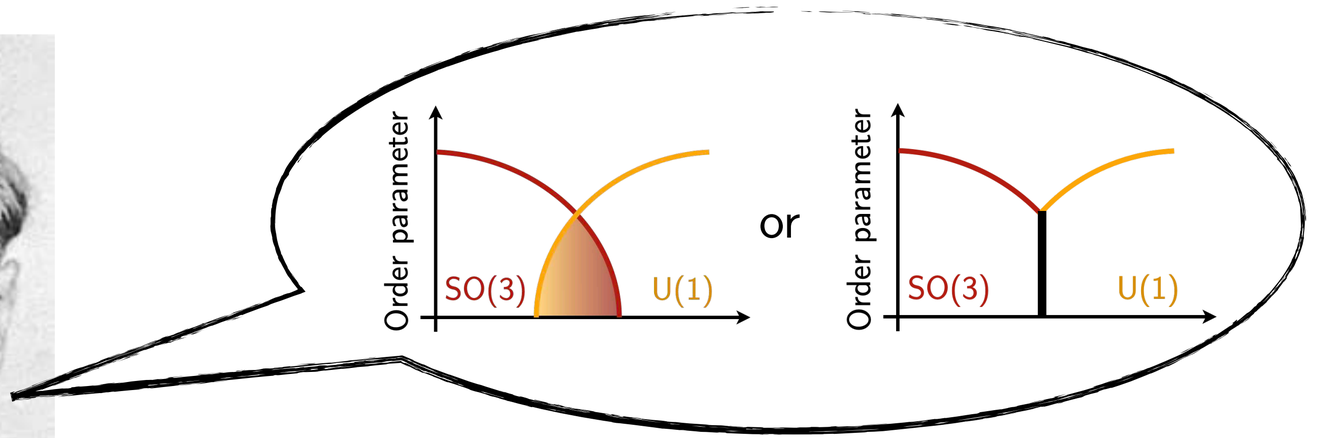




Landau



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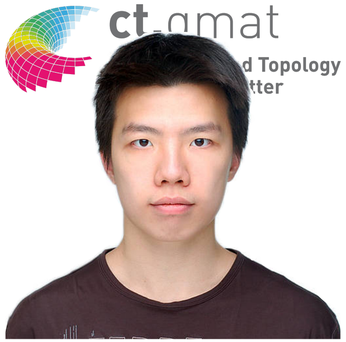

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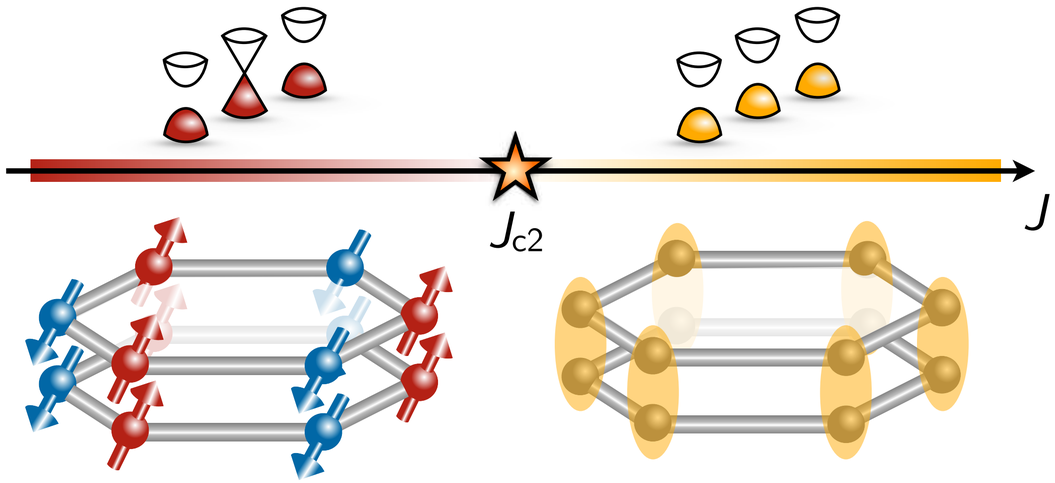
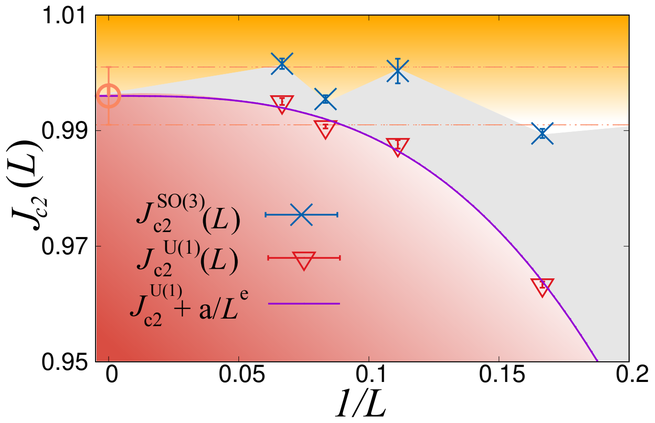
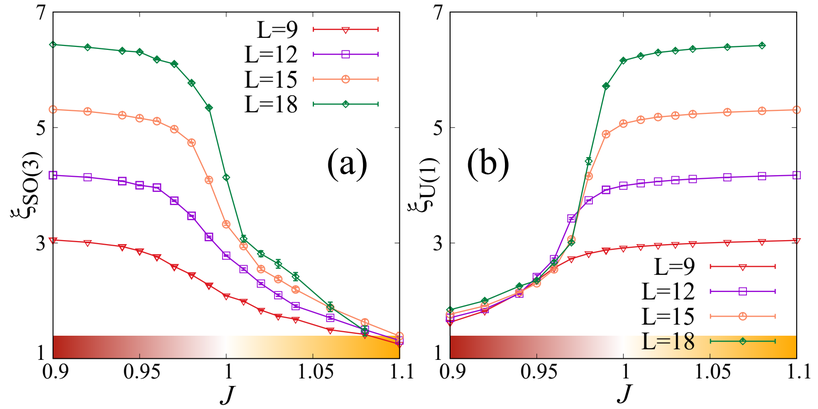


Quantum Monte Carlo:



direct ...

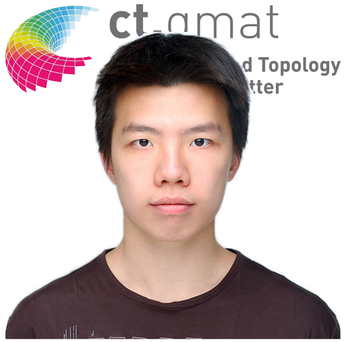
&



... continuous

[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

Deconfined Metal-Insulator Transition



Zihong Liu

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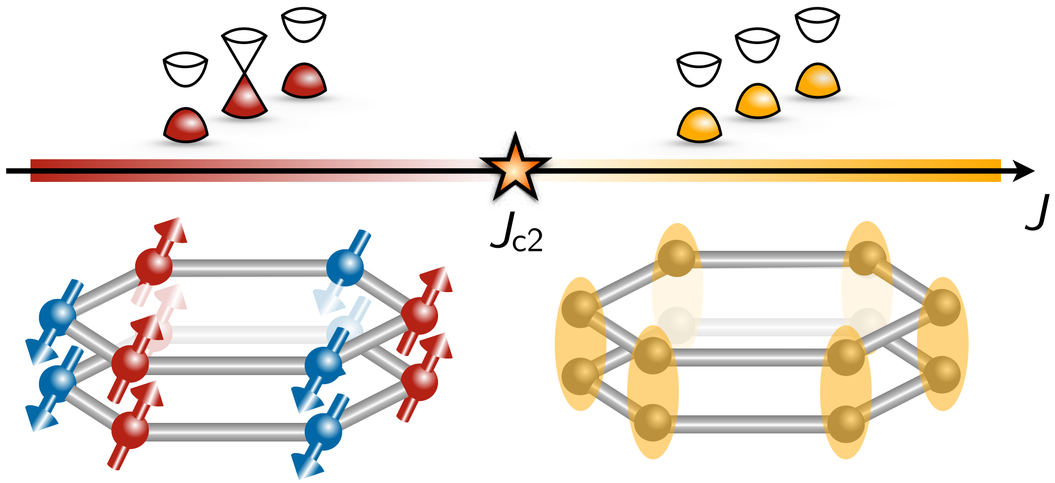

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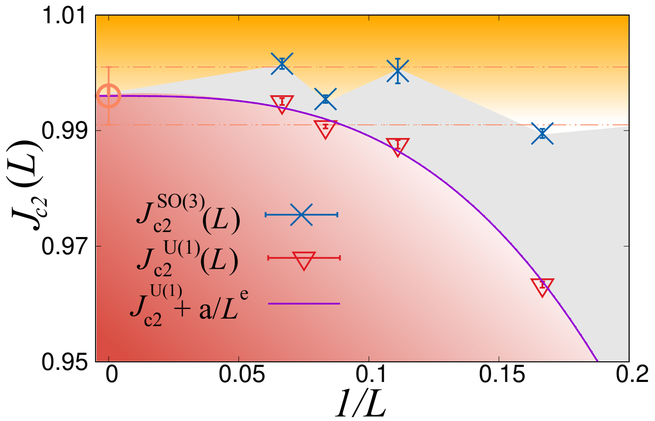
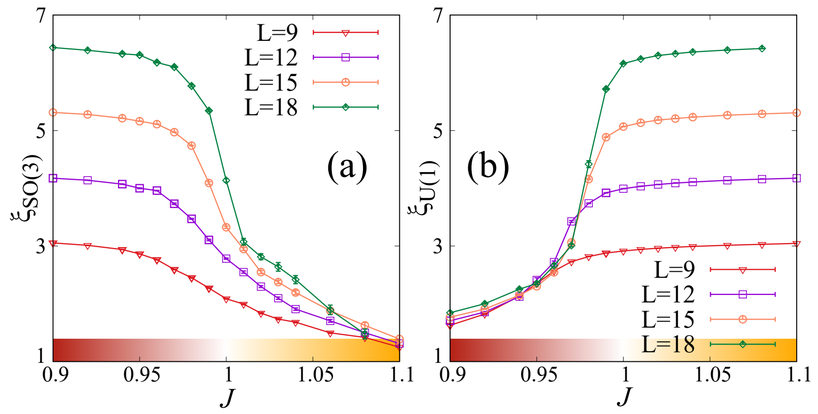


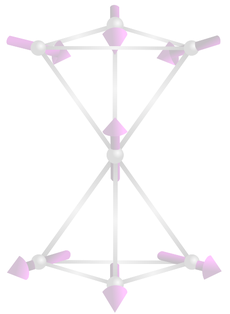


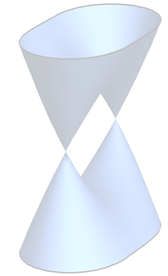
direct ... & ... continuous

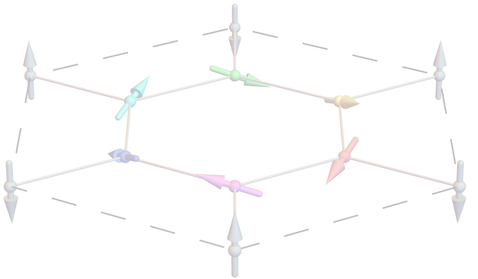
⇨ Metallic deconfined quantum critical point!

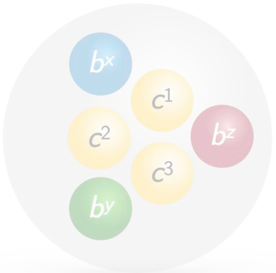
[Liu, Vojta, Assaad, LJ, PRL '22 (Editors' Suggestion)]

Outline

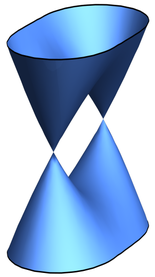




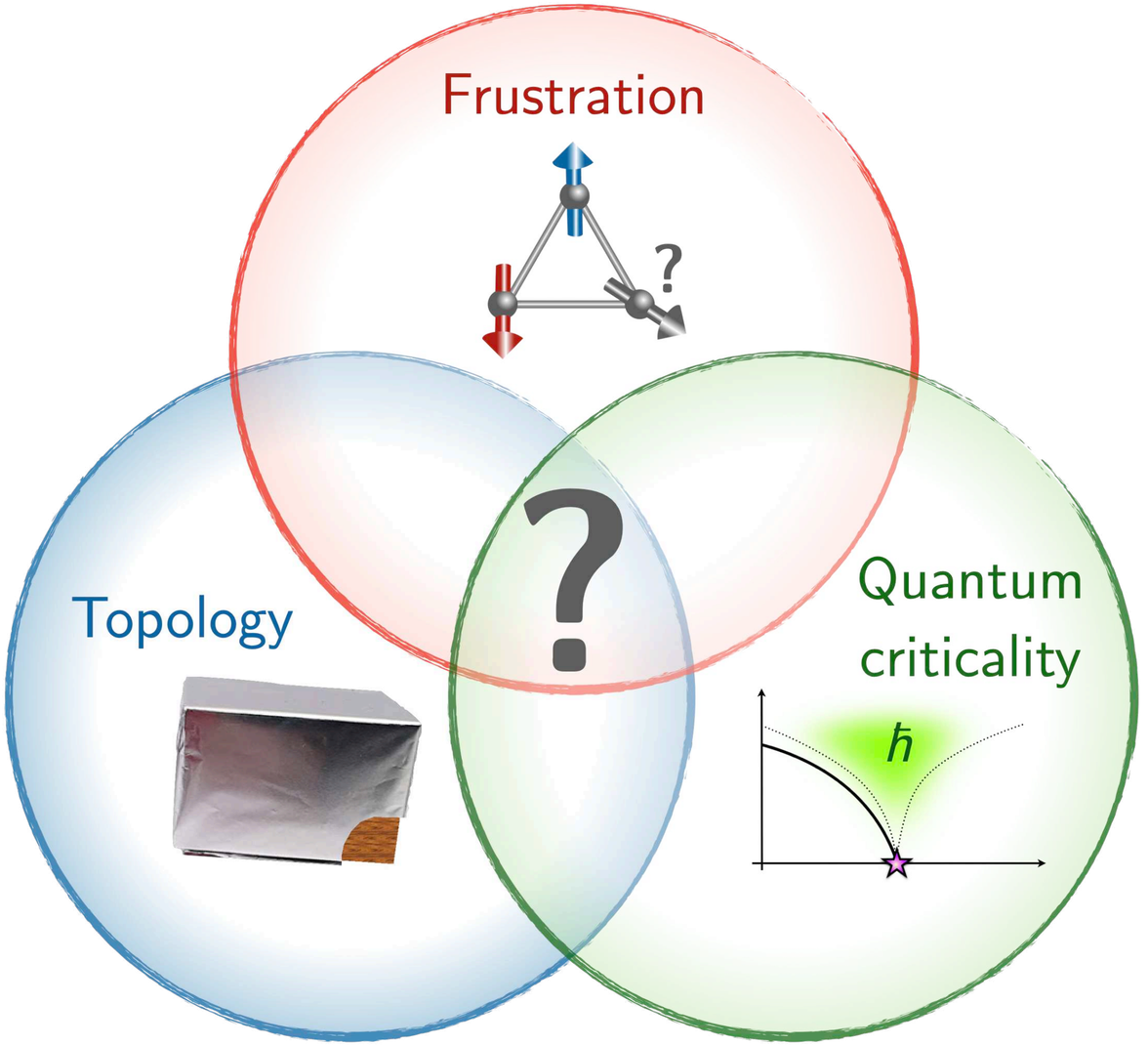


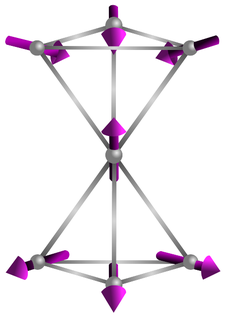


Emergent Phenomena in Quantum Materials

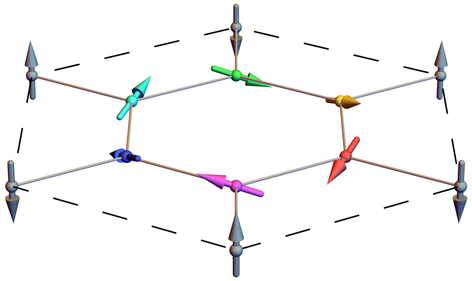


Emergent symmetries

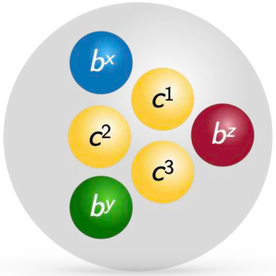




Emergent topology



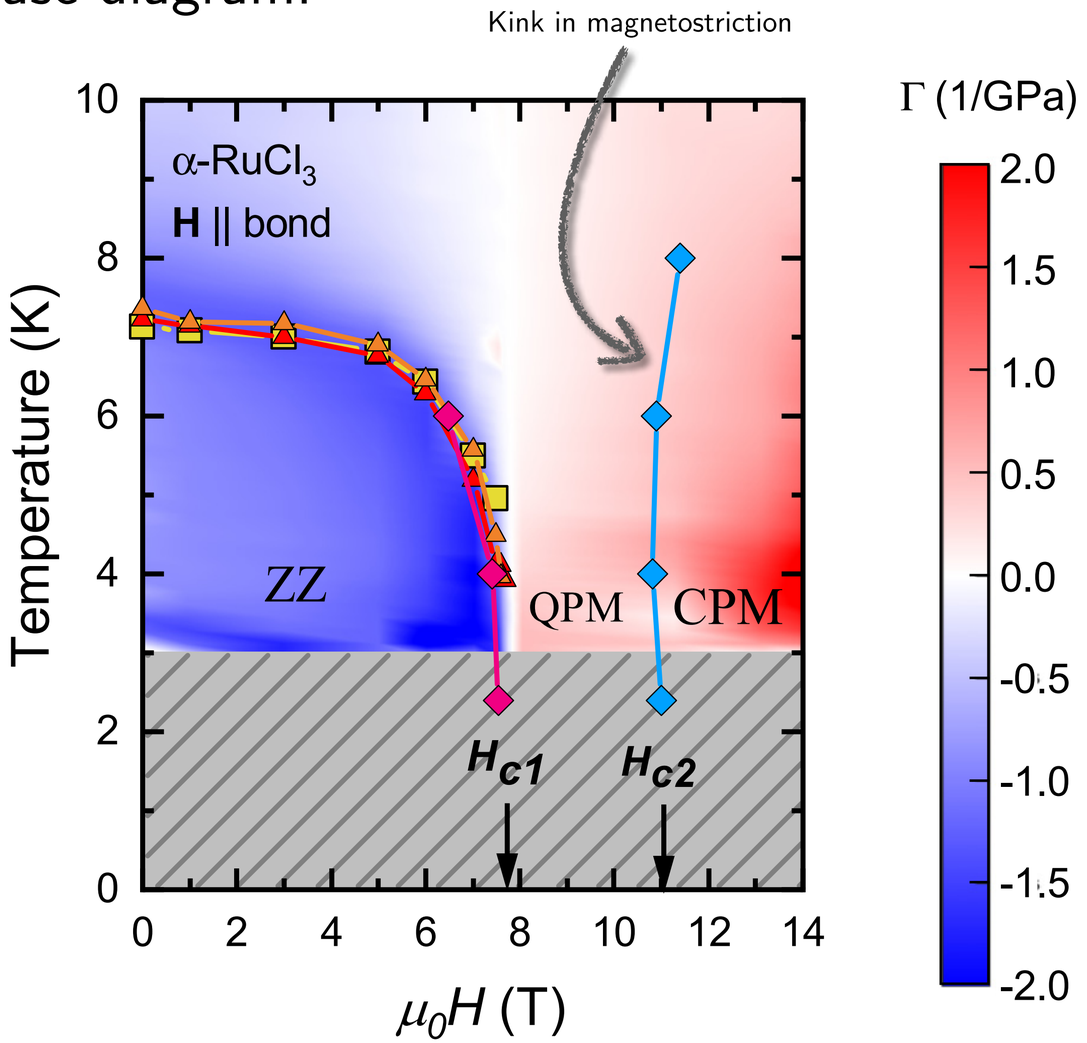
Emergent orders



Emergent particles

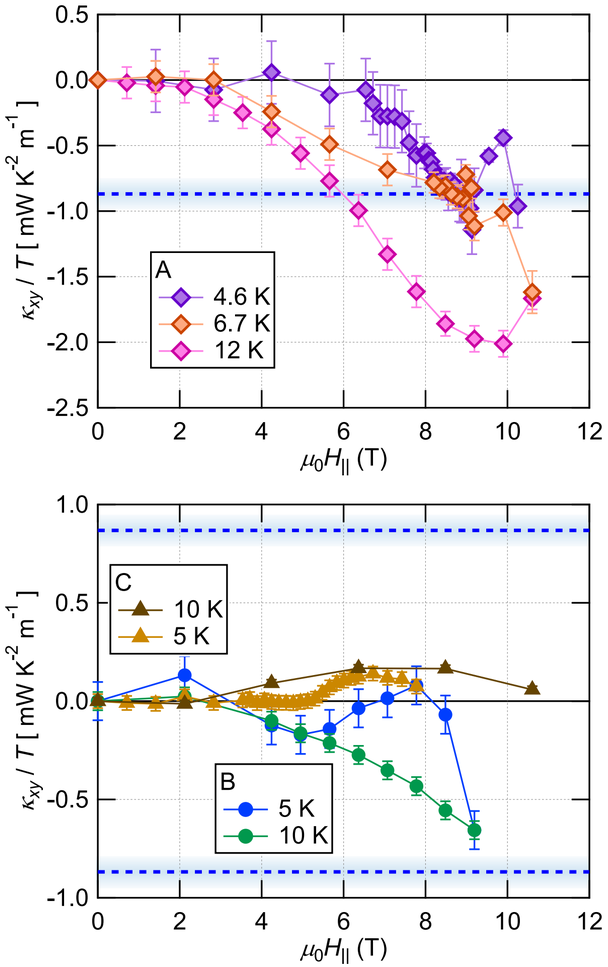
Field-Induced Quantum Paramagnet in α-$RuCl_3$

Phase diagram:



[Gass, *et int.*, LJ, *et al.*, PRB '20]

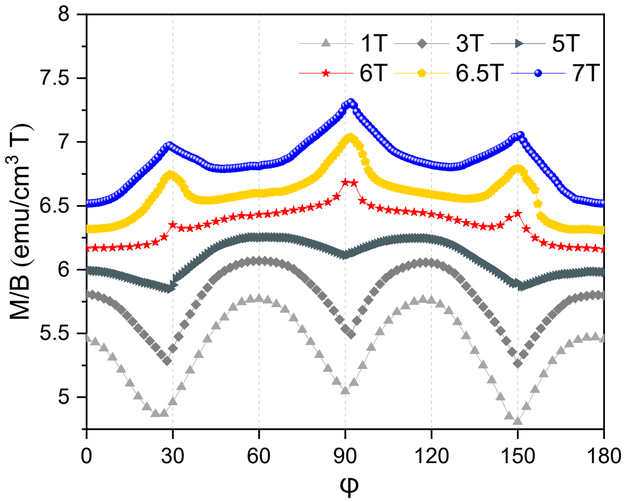
Sample dependence:



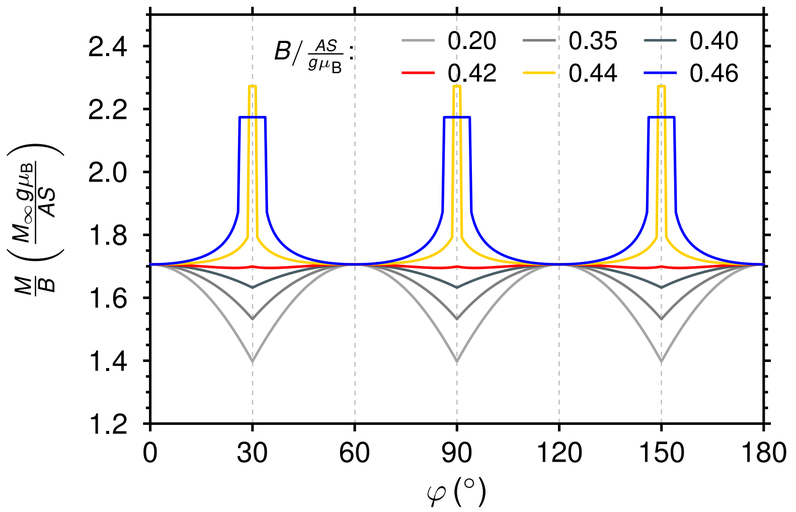
[Yamashita *et al.*, PRB '20]

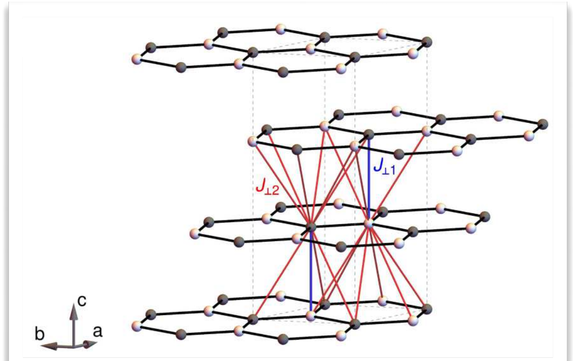
Magnetic Anisotropy in α-$RuCl_3$

Susceptibility:



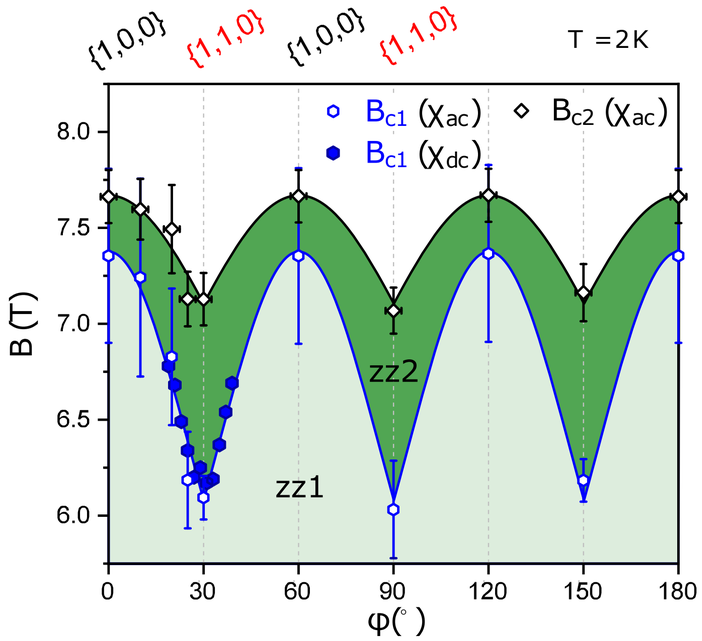
$(J_1, K_1, \Gamma_1, J_3) = (-0.1, -1, 0.5, 0.1)A$
$|K_\perp|, |J_\perp| \ll A$



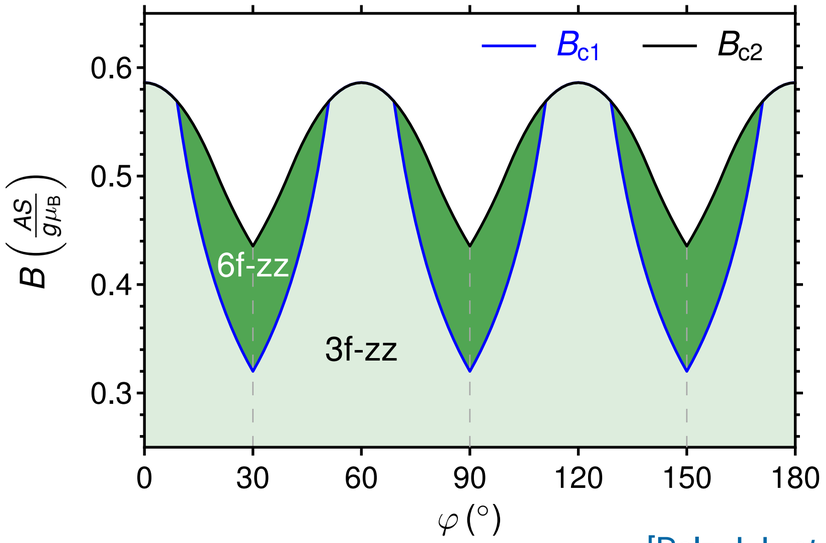


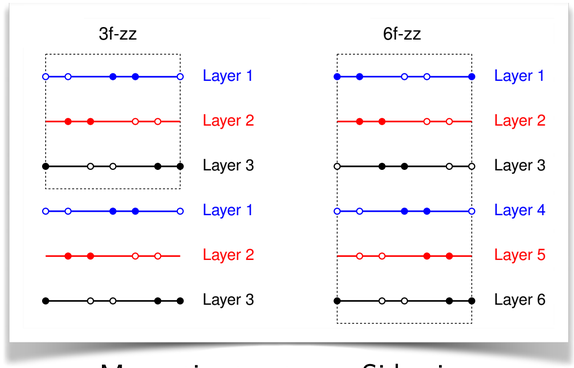
$R\bar{3}$ crystal structure

Phase diagram:



$(J_1, K_1, \Gamma_1, J_3) = (-0.1, -1, 0.5, 0.1)A$
$K_\perp/J_\perp = -1.14, \quad J_\perp > 0$

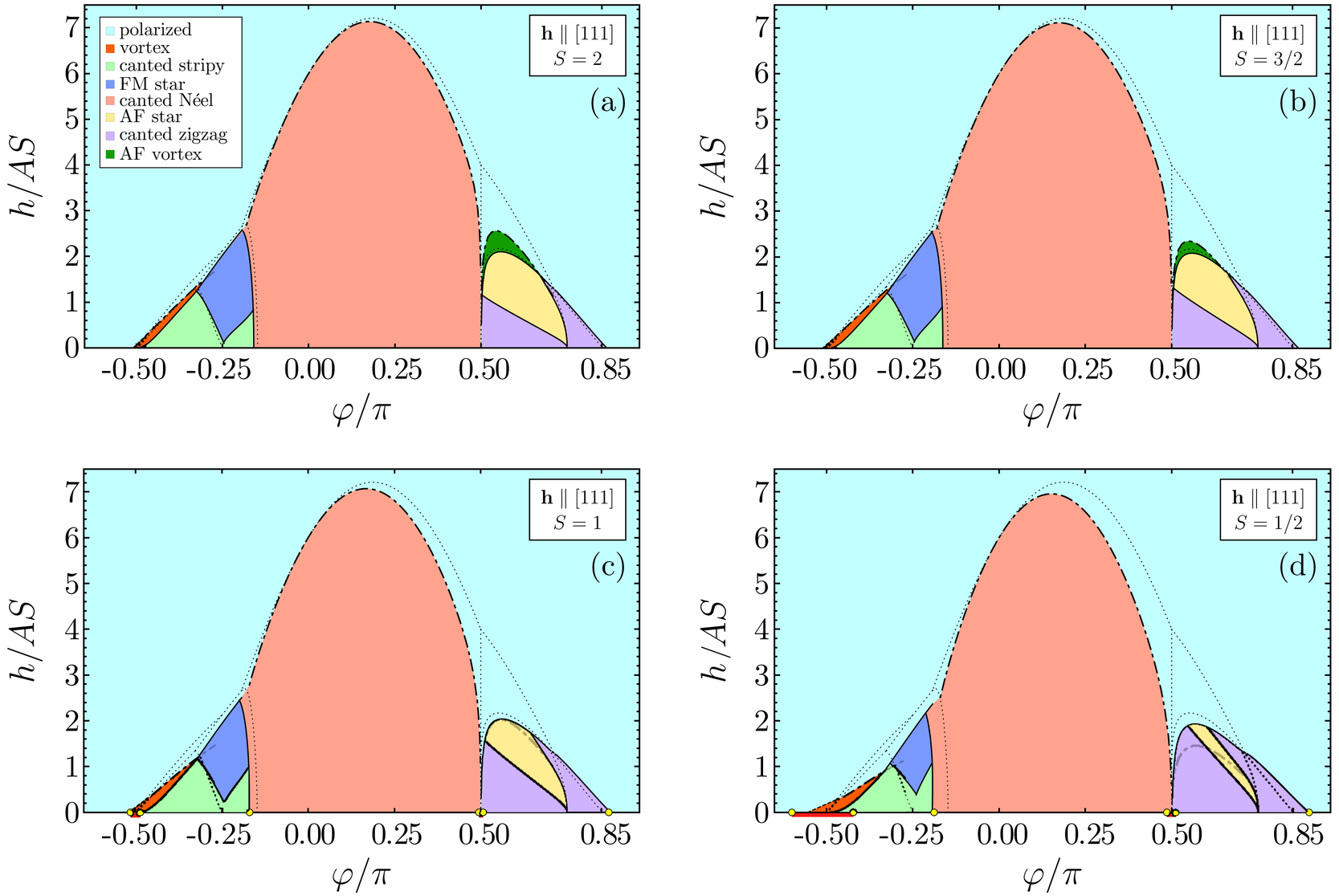




Magnetic structures: Side view

[LJ, Koch, Vojta, PRB '20]
[Balz, LJ, *et int.*, Nagler, PRB '21 (Editors' Suggestion)]

Kitaev-Heisenberg model in external field: $1/S$ expansion

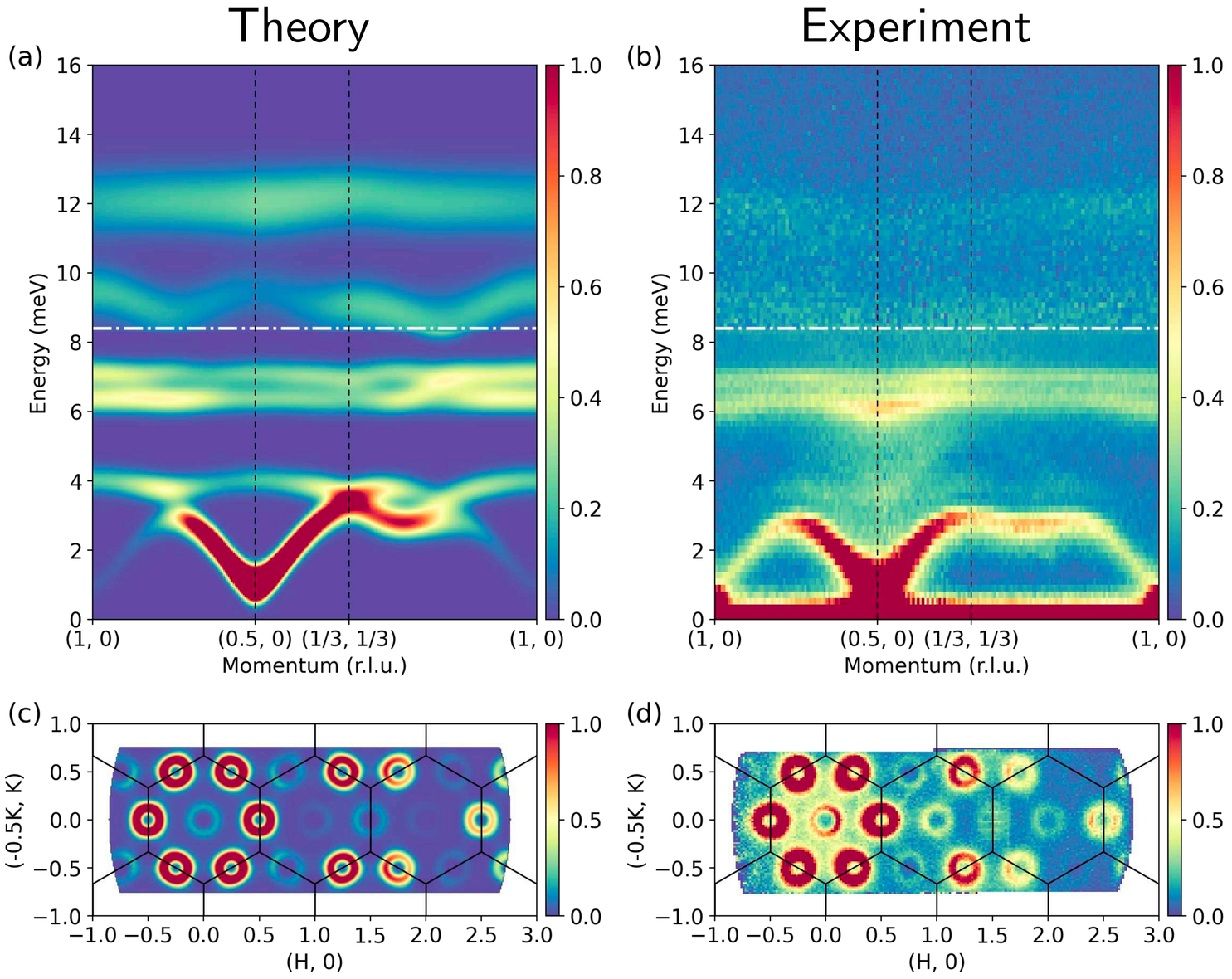


$$J = A\cos\varphi$$
$$K = 2A\sin\varphi$$

[Cônsoli, LJ, Vojta, Andrade, PRB '20]

$Na_2Co_2TeO_6$: Inelastic Neutron Spectrum

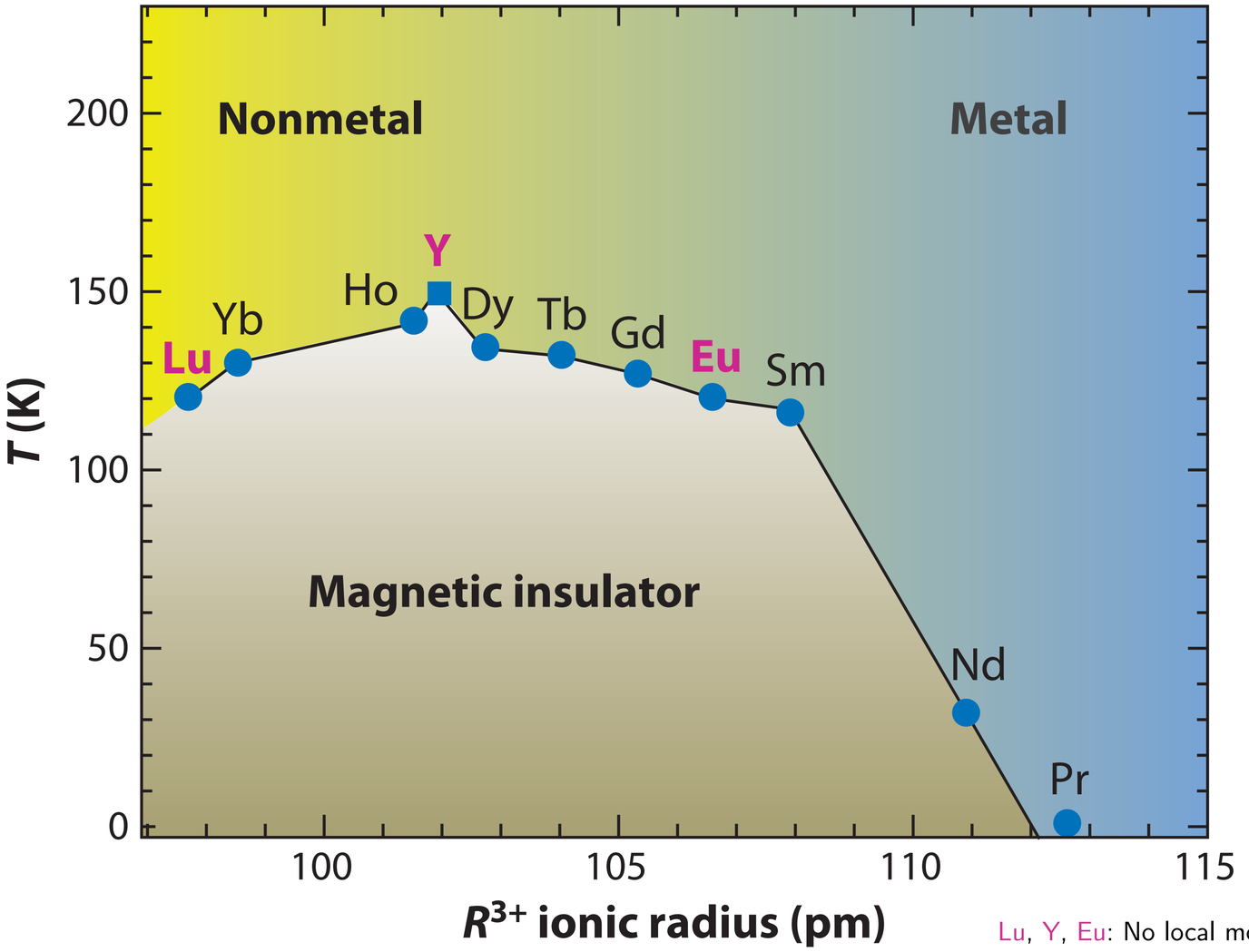
$$(J, K, \Gamma, \Gamma') = (1.2, -8.3, 1.9, -2.3, 0.5)\,\text{meV}$$
$$(J_3, J_2^A, J_2^B) = (1.5, 0.32, -0.24)\,\text{eV}$$
$$+ \text{ ring exchange}$$



[Krüger, Chen, Jin, Li, LJ, arXiv:2211.16957]

[Yao *et al.*, arXiv:2203.00282]

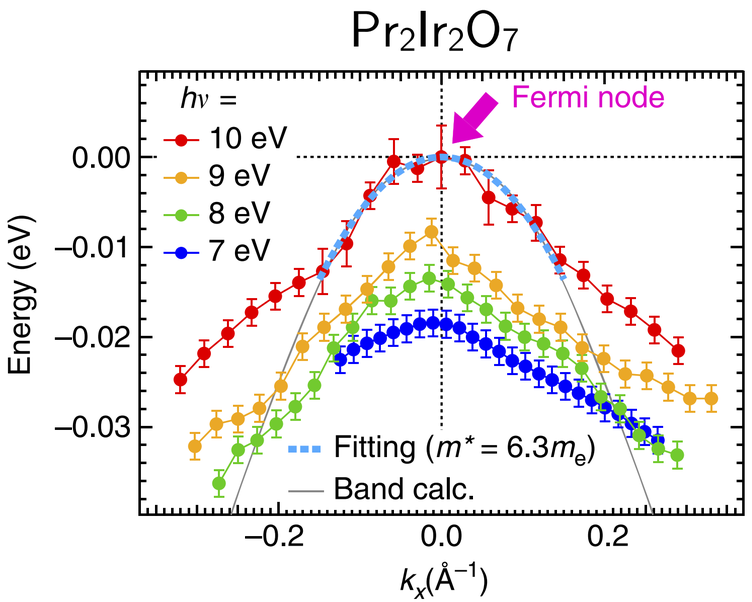
Phase diagram of $R_2Ir_2O_7$



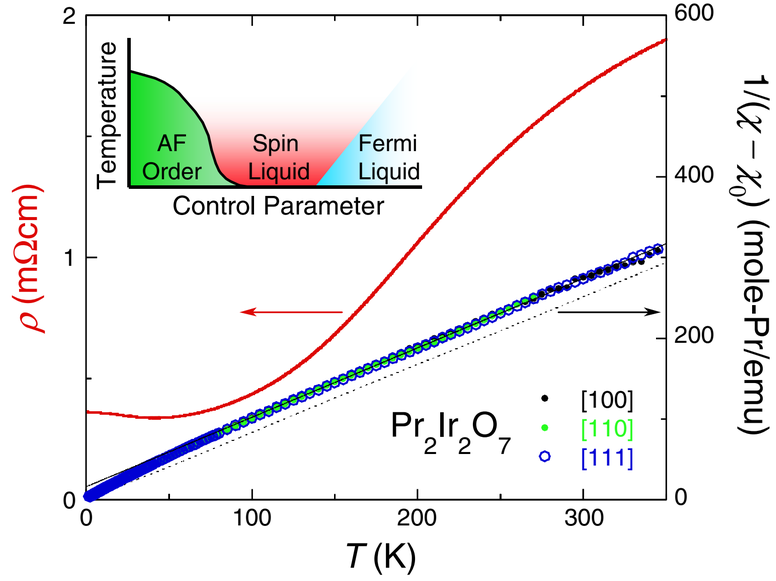
Lu, Y, Eu: No local moment

Y: Non-lanthanoide rare earth

[Witczak-Krempa *et al.*, ARCMP '14]



[Kondo *et al.*, Nat. Comm. '15]



[Nakatsuji *et al.*, PRL '06]