Gauge-frustrated Kitaev Spin Liquid

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arXiv:1901.05283

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Vetenskapsrådet

Outline

Frustration

Kitaev interactions in materials

‘Conventional’ Kitaev spin liquids

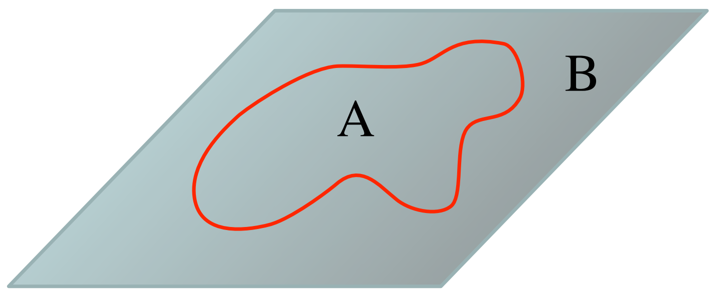
- Solving the Kitaev model
- Majorana metals
- Thermodynamic signatures

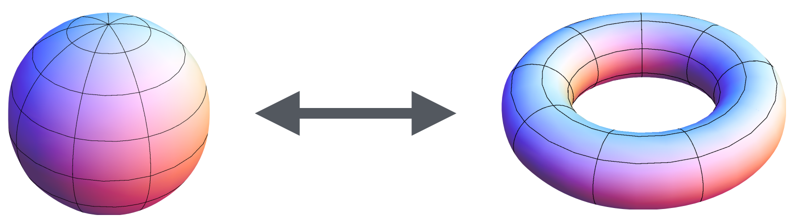
‘Gauge frustration’ – geometric frustration in the gauge sector

Thermodynamics

Quantum spin liquids

- no magnetic order
- strongly fluctuating spins down to zero temperature
- no long-range correlations, but long-range entanglement
- topological ground state degeneracy
- spin fractionalization



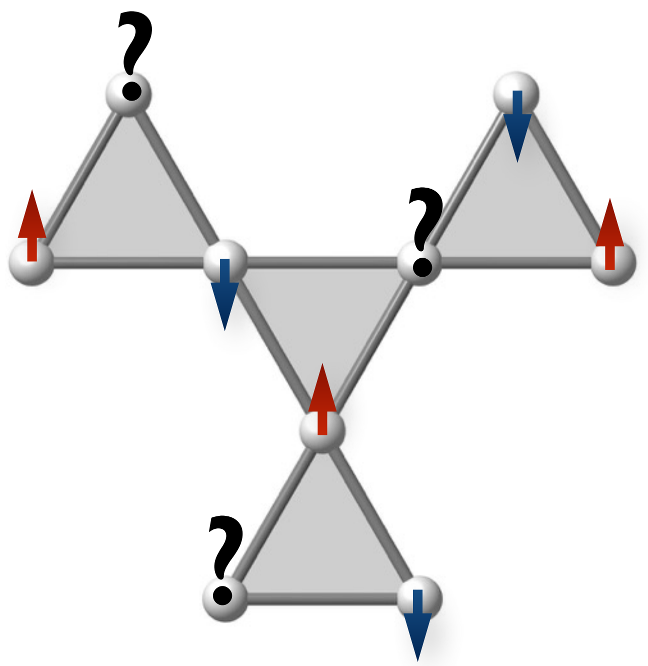


- elusive

- no experimentally verified candidates (no smoking gun signature)
- very few theoretical models, where QSL ground state is rigorously established – Kitaev spin liquids

Towards quantum spin liquids – frustration

geometric frustration



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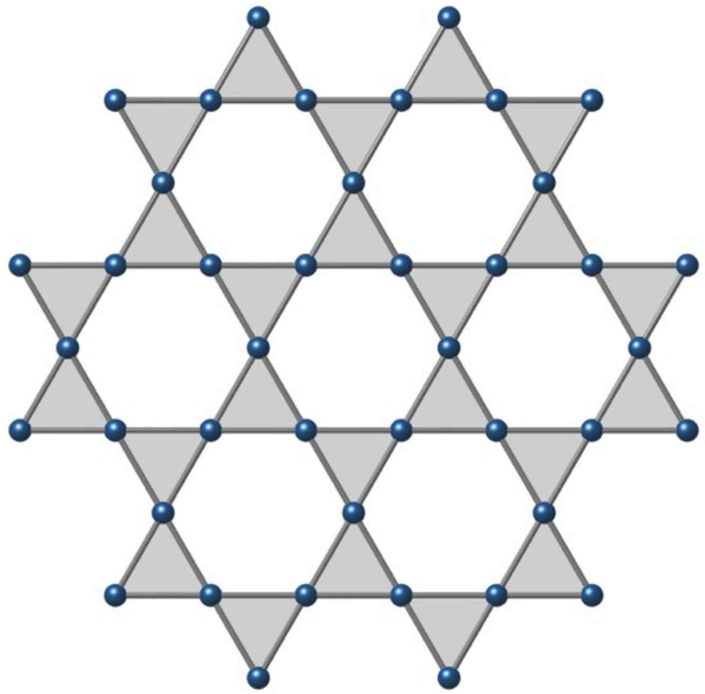

Herbertsmithite
$ZnCu_3(OH)_6CL_2$

Han et al., Nature (2012)

Towards quantum spin liquids – frustration

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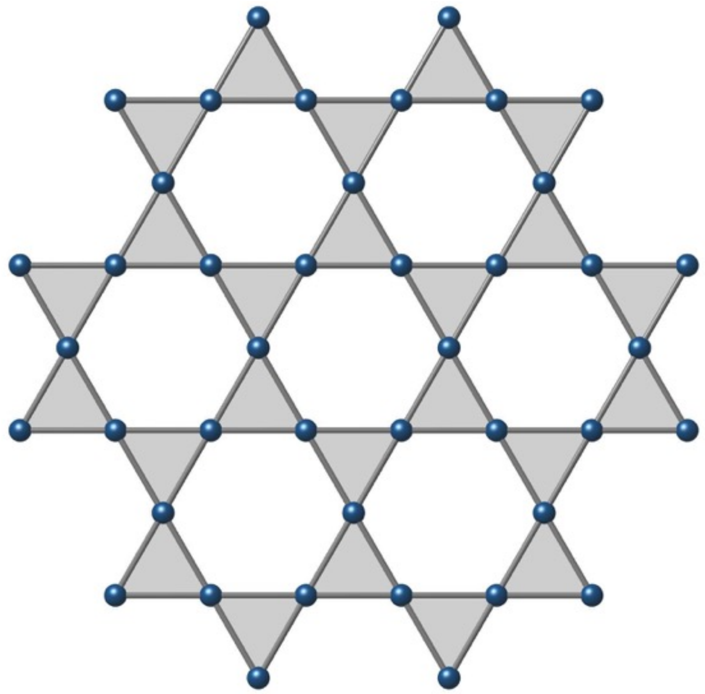

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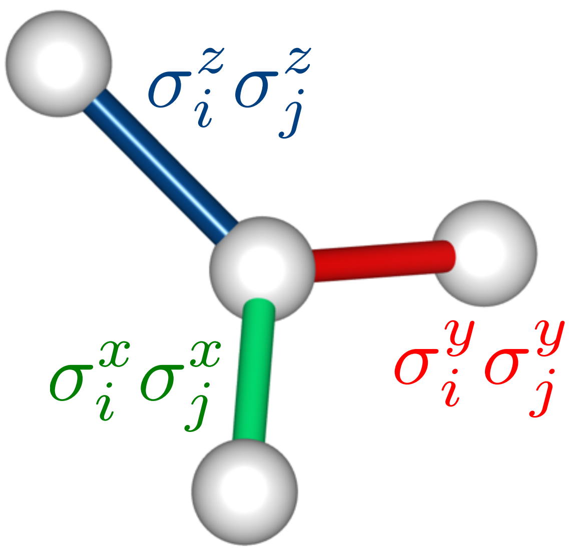
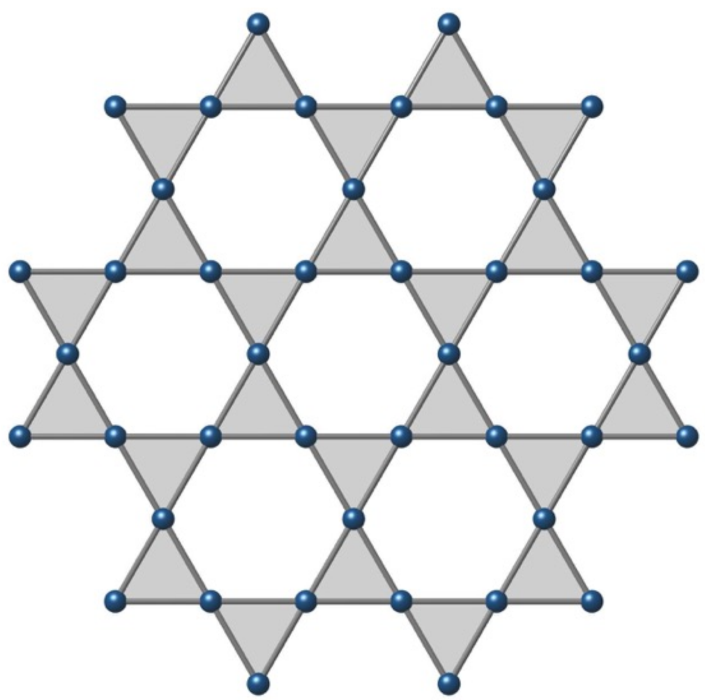
exchange frustration



Towards quantum spin liquids – frustration

geometric frustration



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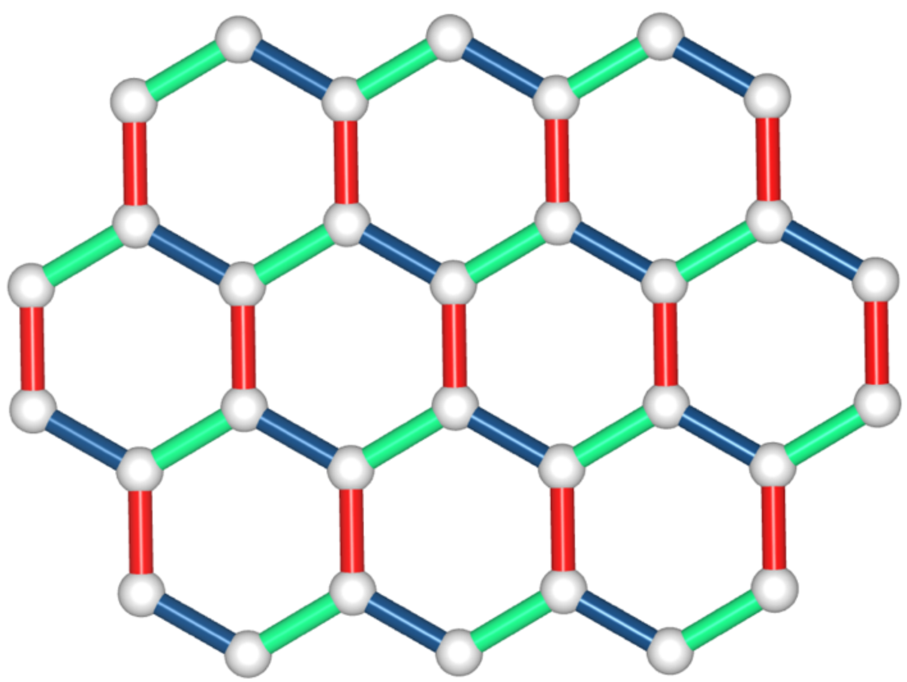
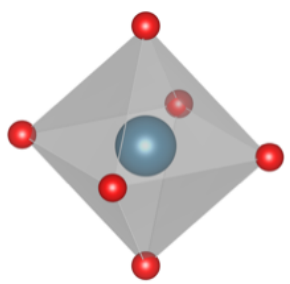


Kitaev honeycomb model
Iridates

Exchange Frustration in Iridates

G. Jackeli and G. Khaliullin, PRL **102**, 017205 (2009)



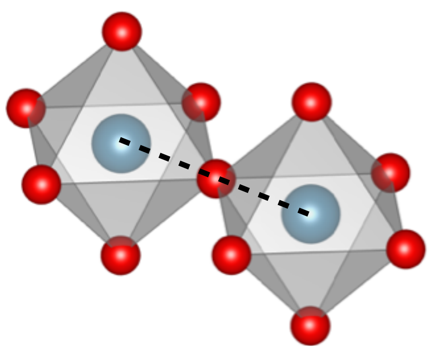
IrO_6

Interplay of
- octahedral crystal field
- spin-orbit coupling
- e^--e^- correlations

→ Mott insulator with spin-orbit-entangled spin-1/2 on Ir atom

Heisenberg exchange

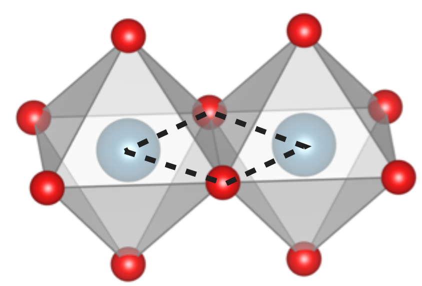
corner-sharing



Sr_2IrO_4

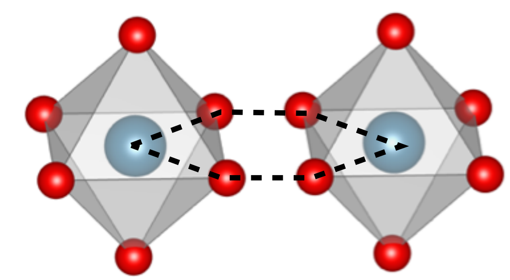
dominant Kitaev exchange

edge-sharing



Na_2IrO_3 / Li_2IrO_3

parallel edge-sharing

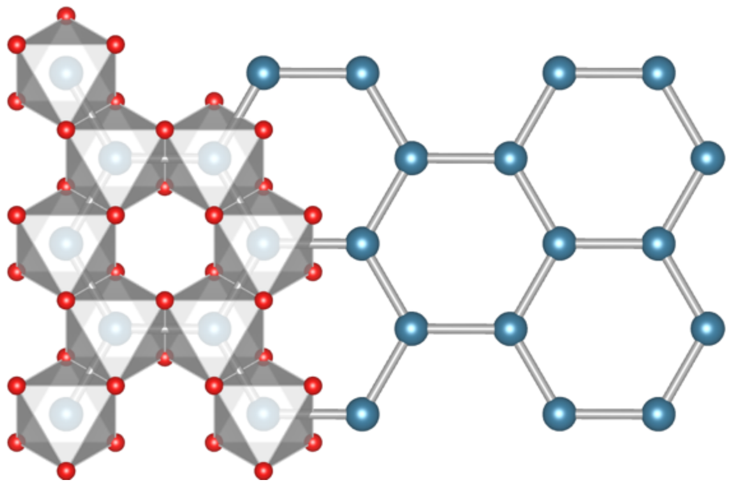


$Ba_3IrTi_2O_9$

$$H = J_K \sum_{\langle i,j\rangle \in \gamma} \sigma_i^\gamma \sigma_j^\gamma + J_H \sum_{\langle i,j\rangle \in \gamma} \vec{\sigma}_i \vec{\sigma}_j + \Gamma \sum_{\langle i,j\rangle \in \gamma} (\sigma_i^\alpha \sigma_j^\beta + \sigma_i^\alpha \sigma_j^\beta)$$

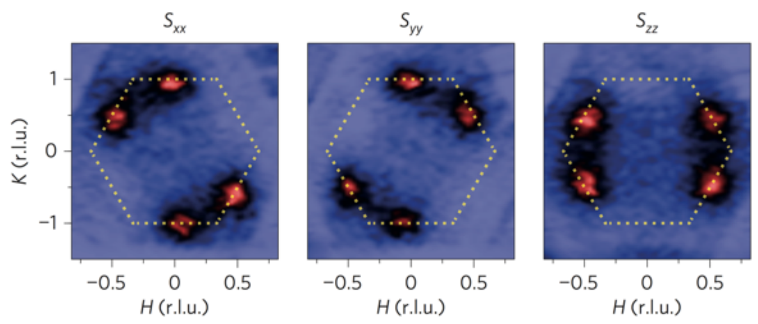
Materials – 2D

honeycomb



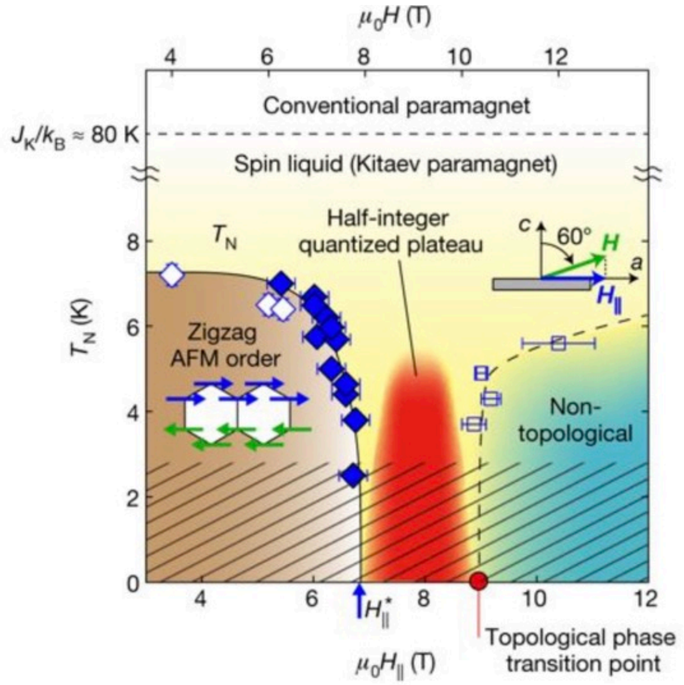
Kitaev interaction **dominant**

Chun et al., Nature Physics (2015)



quantized thermal Hall conductance

Kasahara et al. Nature (2018)

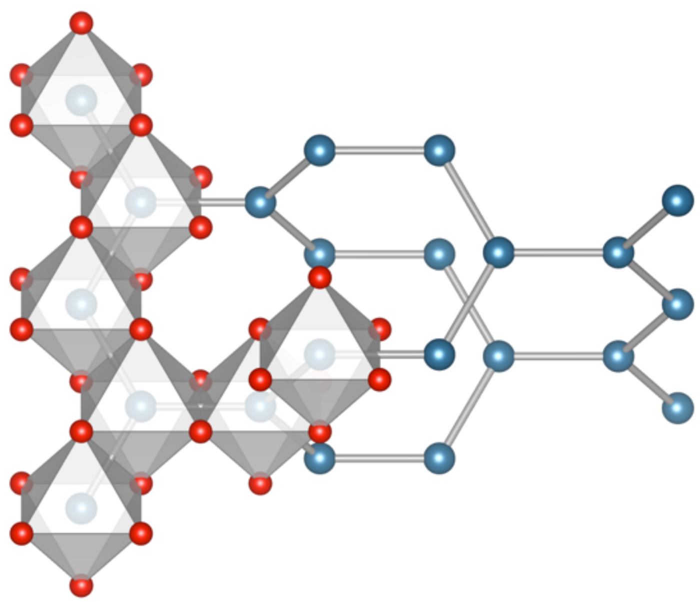


α-Li_2IrO_3, Na_2IrO_3 Singh et al. PRL (2012)

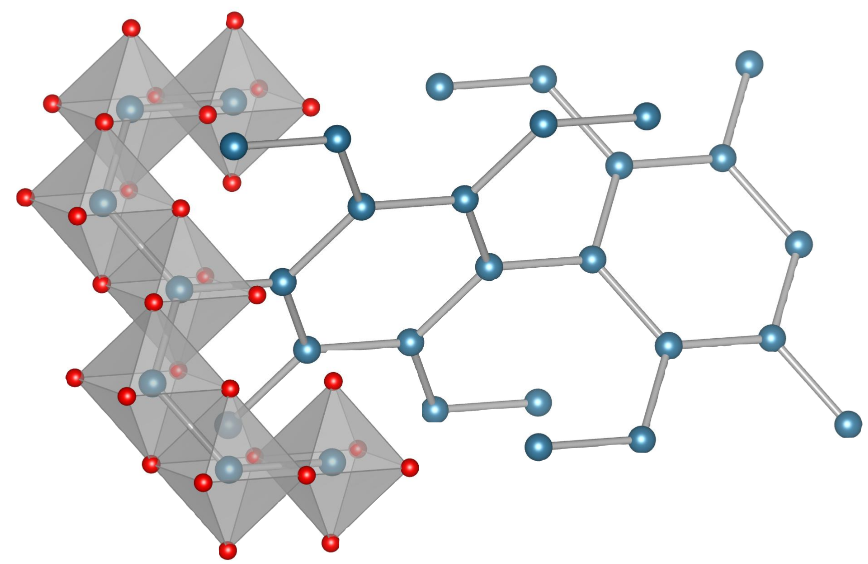
$RuCl_3$ Banerjee et al., Nat. Mat. (2016)

$H_3LiIr_2O_6$ Kitagawa et al. Nature (2018)

Materials – 3D



β-Li_2IrO_3 Takayama et al., PRL (2015)



γ-Li_2IrO_3 Modic et al., Nat. Comm. (2014)

Copper-Oxalate Framework

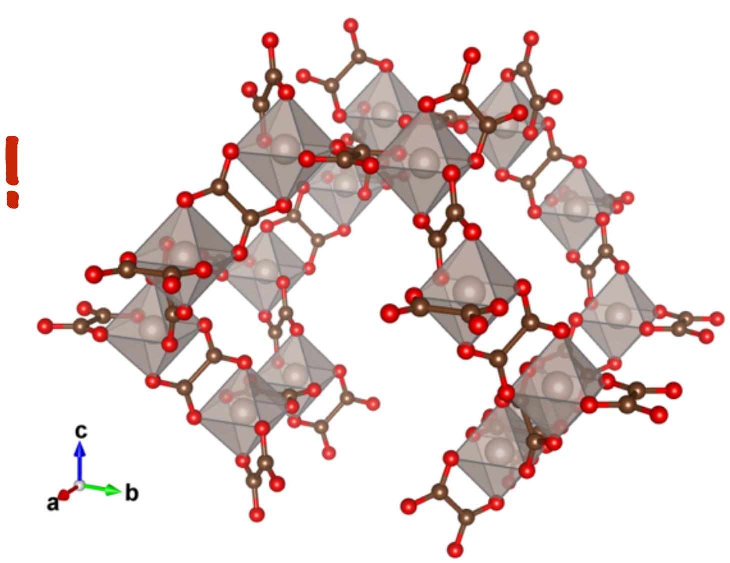
Zhang, J. Am. Chem. Soc. (2018)

→ learn more about **quantum spin liquids in 3D**

Can we realize many more 3D tri-coordinated lattice structures? yes!

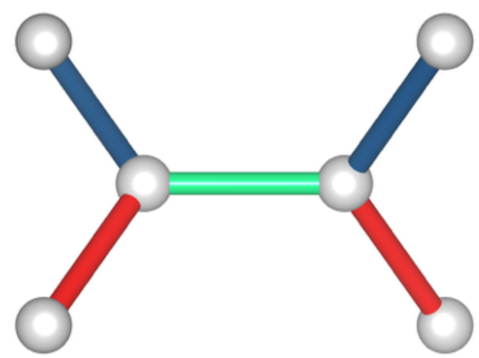
potential materials: *metal-organic-frameworks*

Yamada et al. PRL (2016)
Dwivedi et al. PRB (2017)



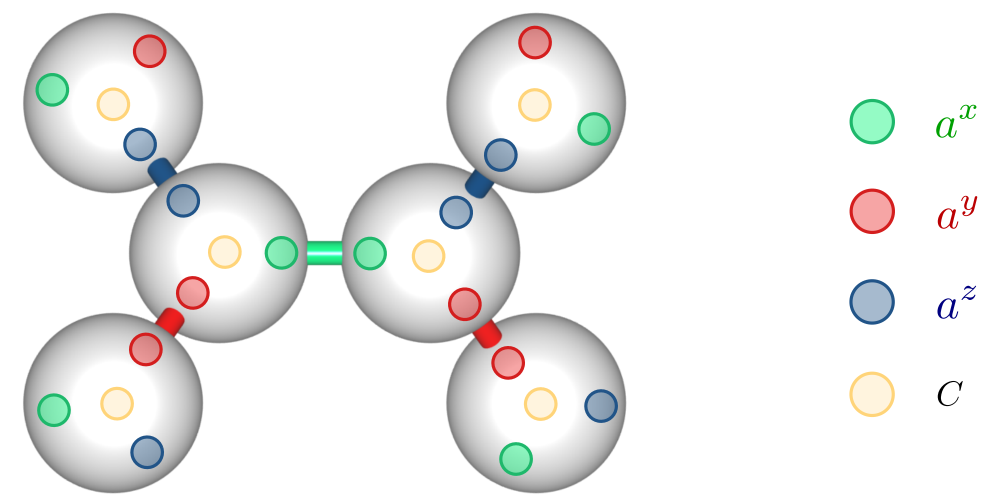
Spin fractionalization and Majorana fermions

A. Kitaev, Annals of Physics (2006)



splitting spins

$$\sigma^\alpha = i a^\alpha c$$



$$H = -\sum_{\gamma-\text{bond}} J_\gamma \sigma_j^\gamma \sigma_k^\gamma$$

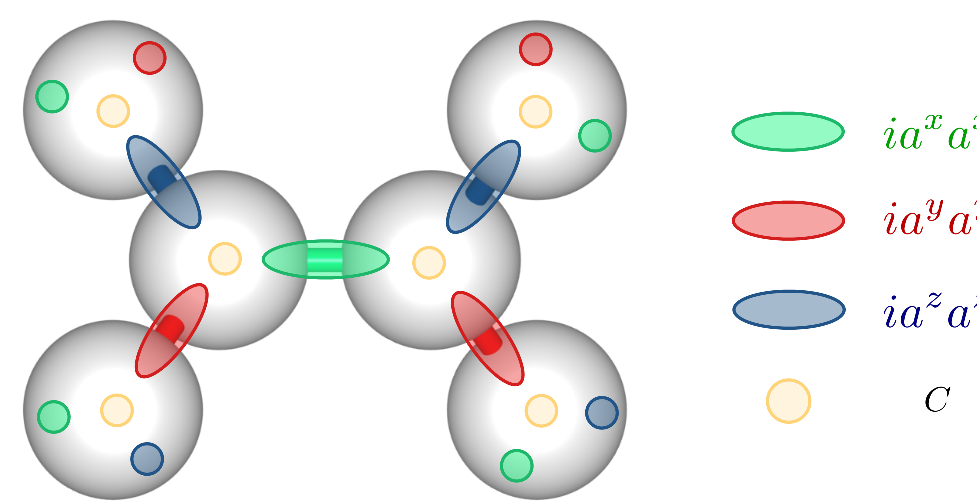
joining Majoranas

$$\hat{u}_{jk} = i a_j^\alpha a_k^\alpha$$

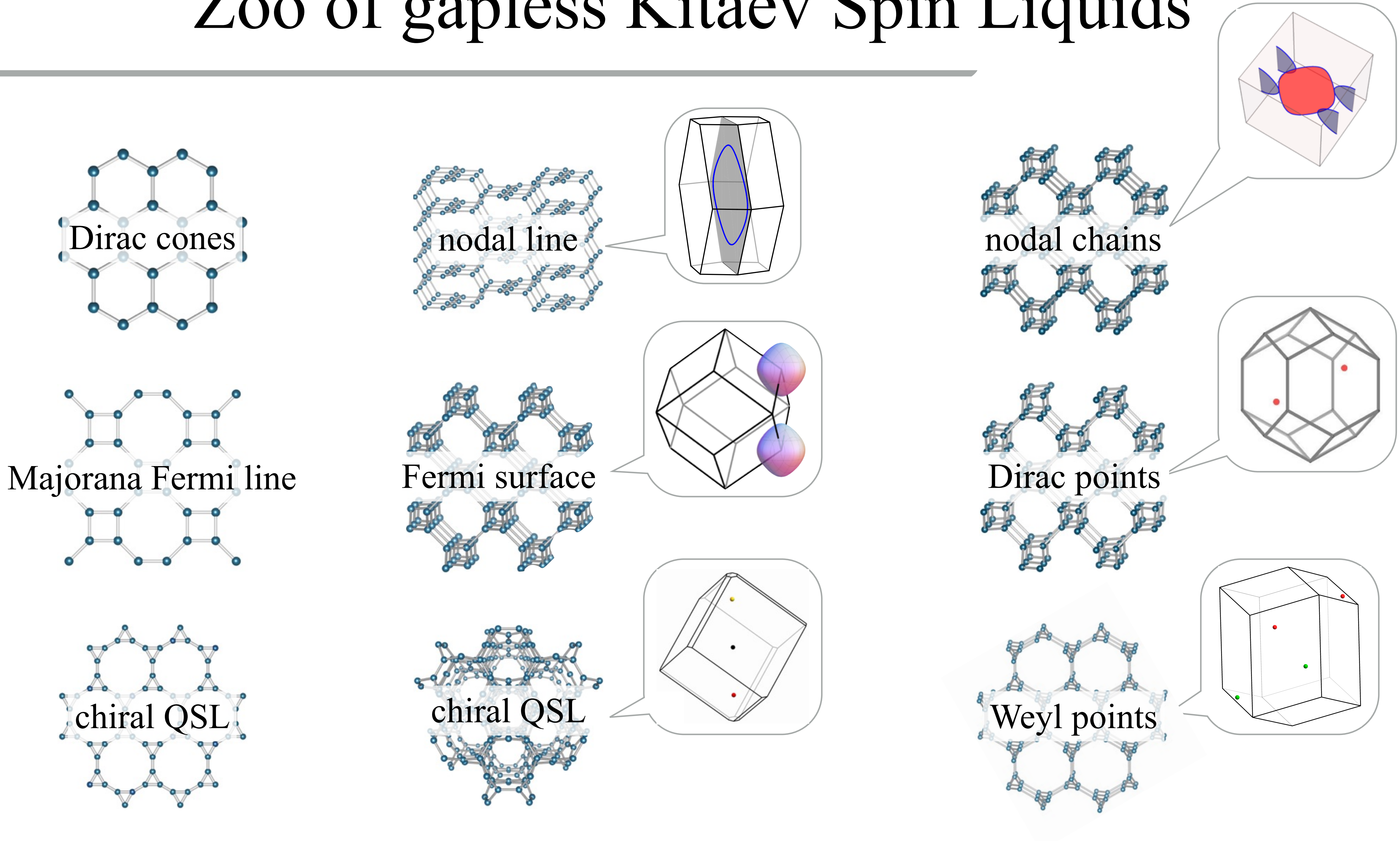
- represent spins by four **Majorana fermions**
- emergent **Z_2 gauge field** on bonds
- Hilbert space split into two separate sectors: $2^N = 2^{N/2} \times 2^{N/2}$

Majorana fermions c_j "**spinons**"

flux loops "**visons**" (static and gapped)



Zoo of gapless Kitaev Spin Liquids

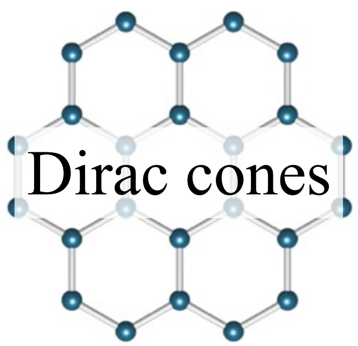


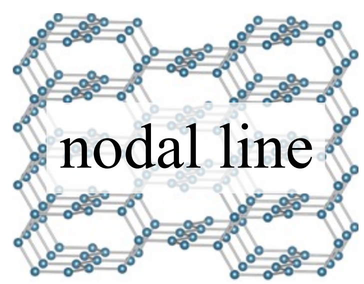
Kitaev, Annals of Physics (2006)
Yang et al. PRB (2007)
Yao and Kivelson, PRL (2007)

O'Brien, Hermanns, Trebst, PRB (2016)
Yamada, Dwivedi, Hermanns, PRB (2017)

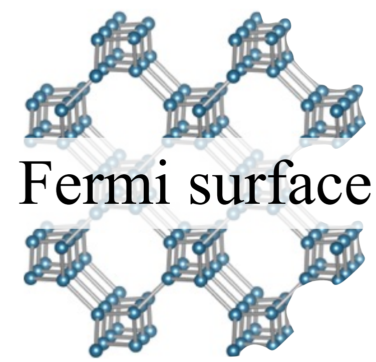
Zoo of gapless Kitaev Spin Liquids

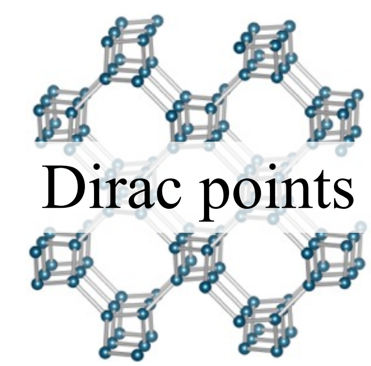
real

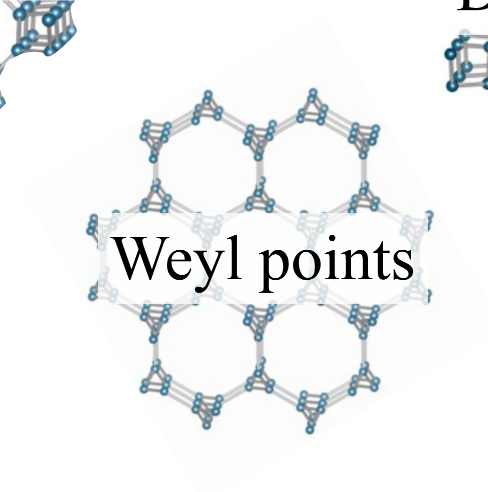




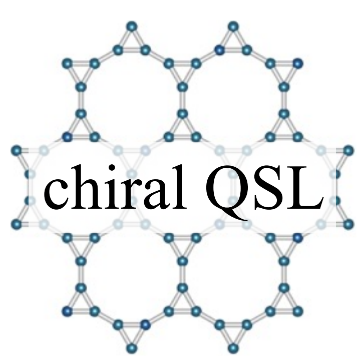
complex

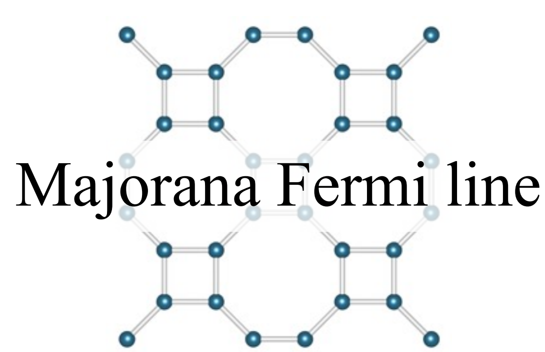


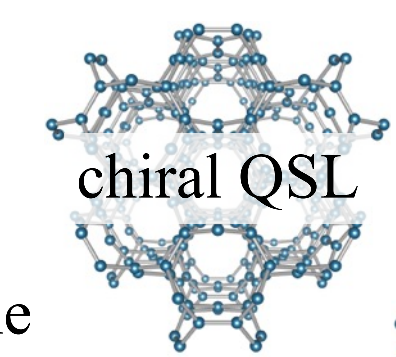


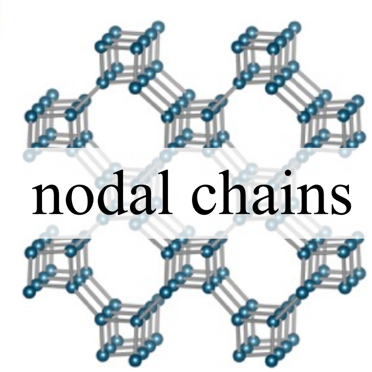


imaginary



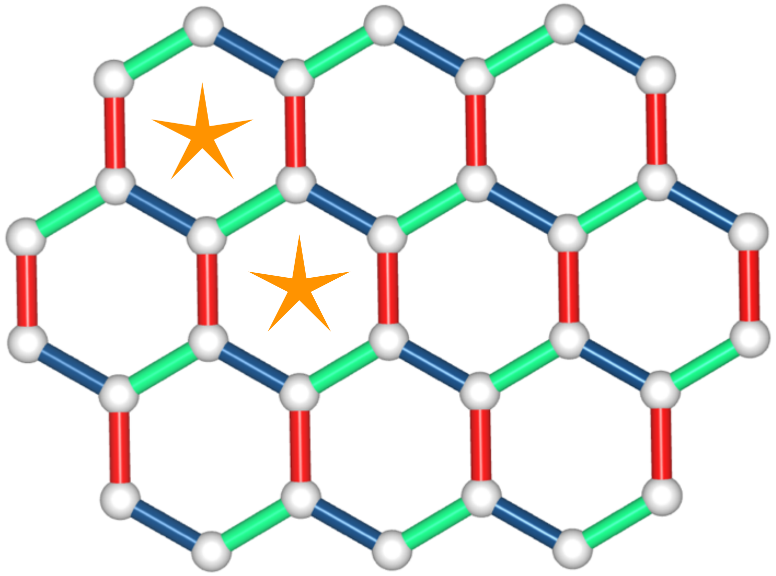






Z_2 gauge field – vison excitations

2D



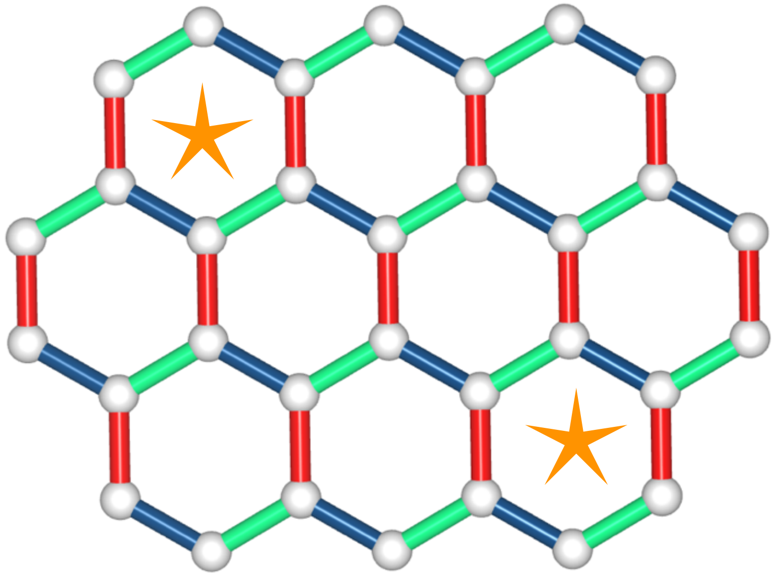
fluxes are point particles

deconfined

any finite temperature destroys the spin liquid

Z_2 gauge field – vison excitations

2D



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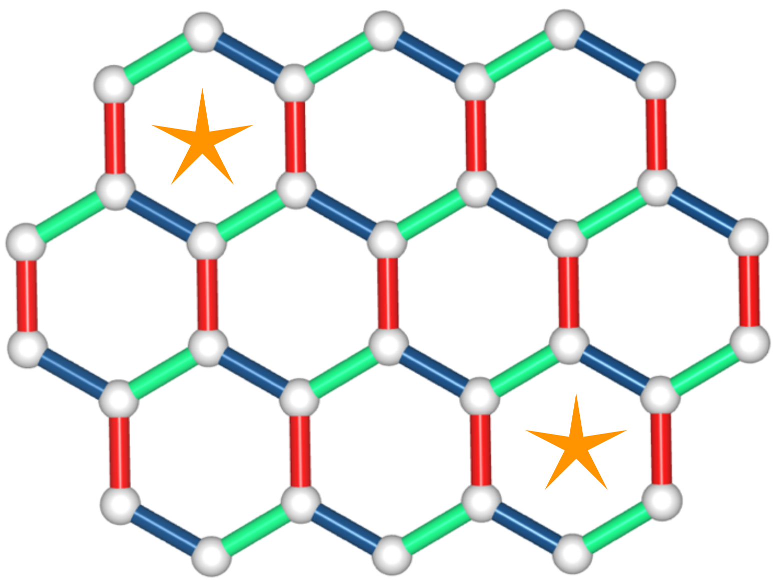
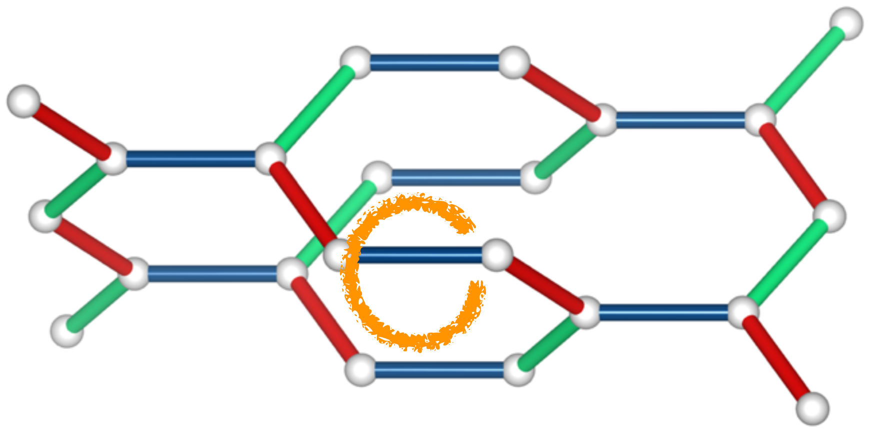


3D



fluxes are point particles

deconfined

any finite temperature destroys the spin liquid

fluxes form loops

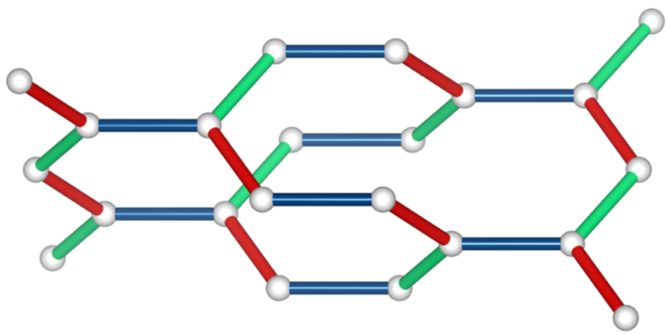
finite loop tension → confined at low temperatures

finite temperature transition

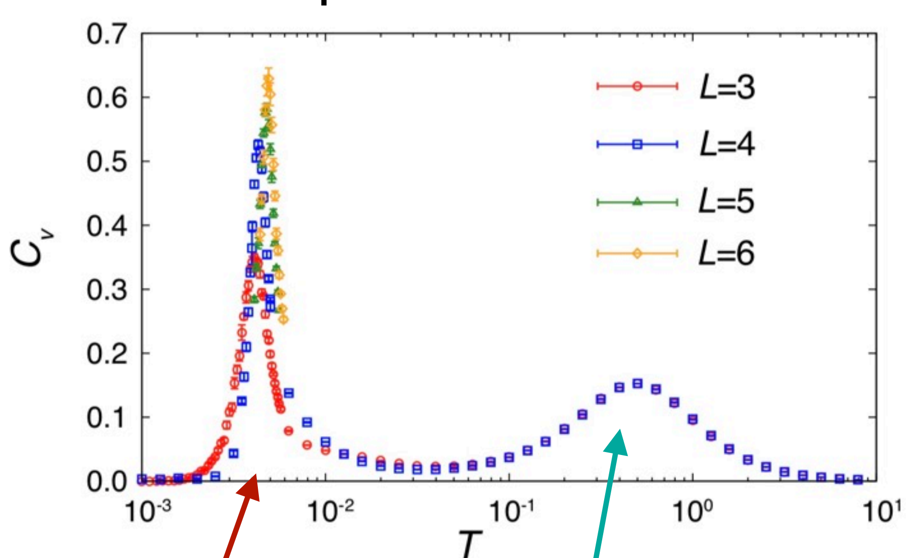
Thermodynamic Signatures

Nasu, Udagawa, Motome, PRL (2014)

(10,3)b ‘hyperhoneycomb’



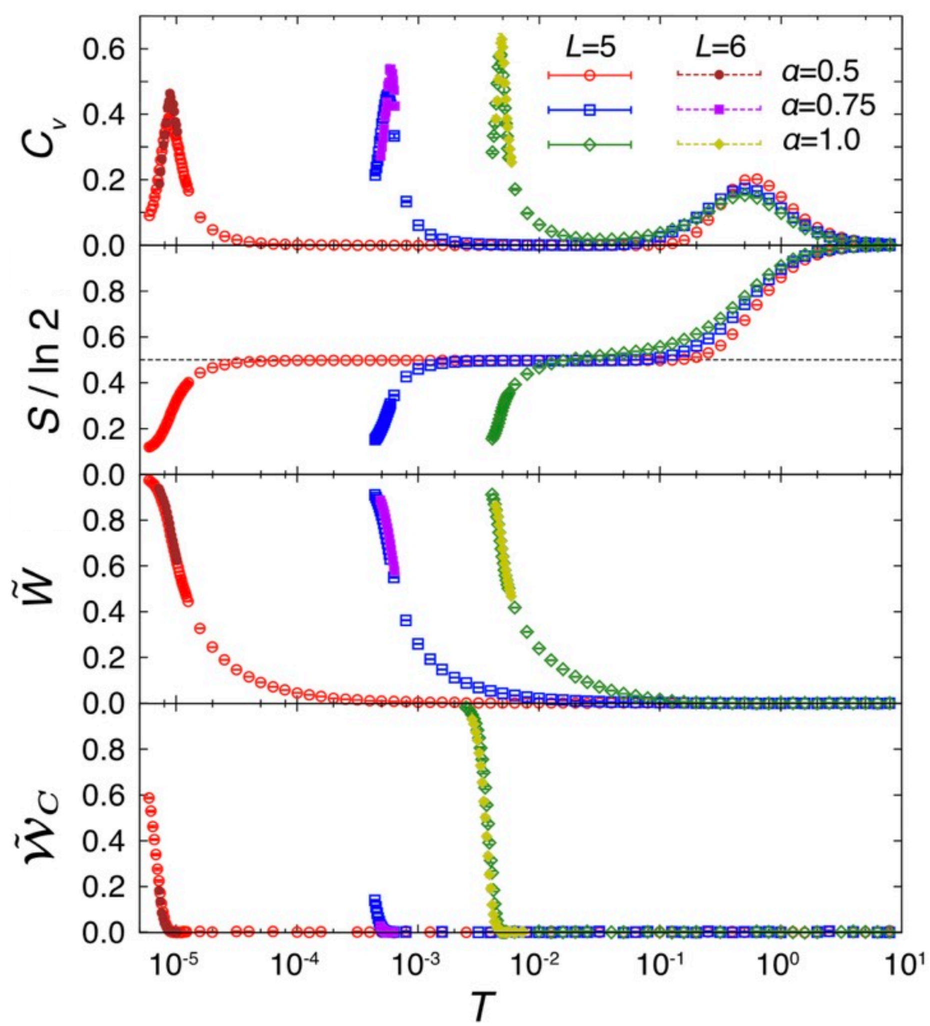
specific heat



fluxes order

local correlations build up

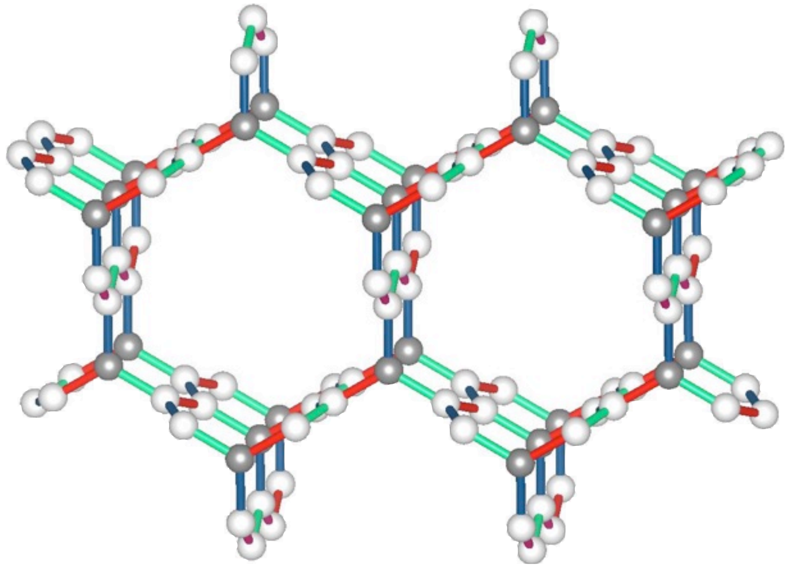
Tc set by vison gap

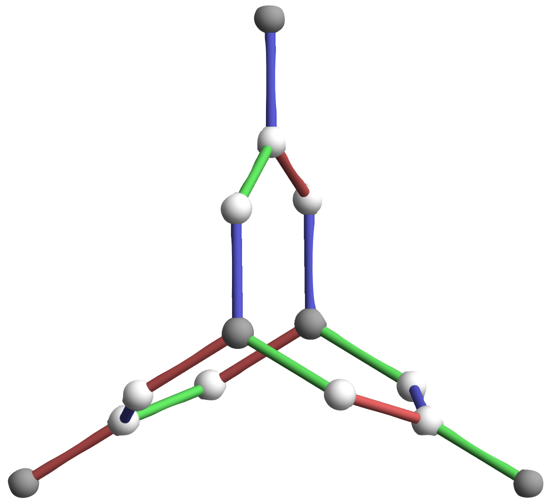


‘Gauge-frustration’

no Z_2 monopoles
(vison excitations form closed loops in 3D)

(8,3)c lattice





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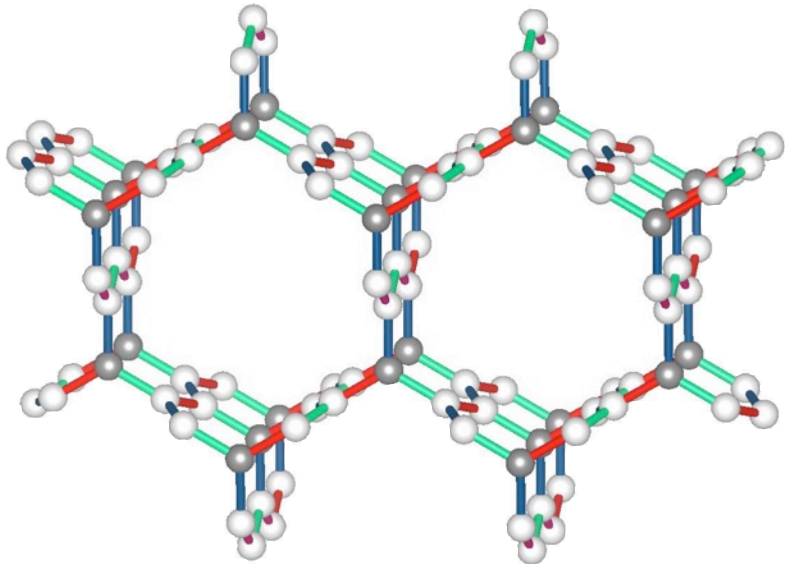
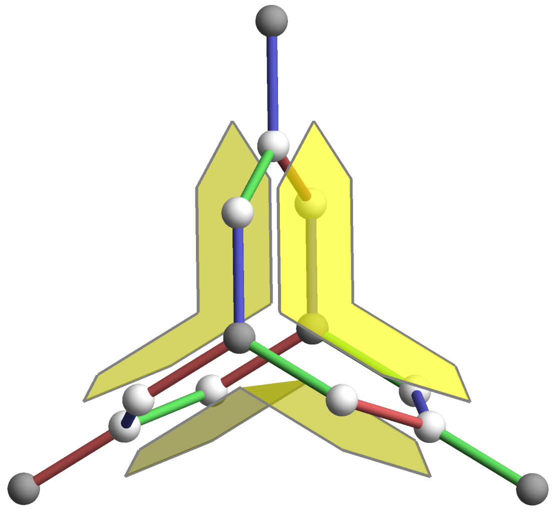
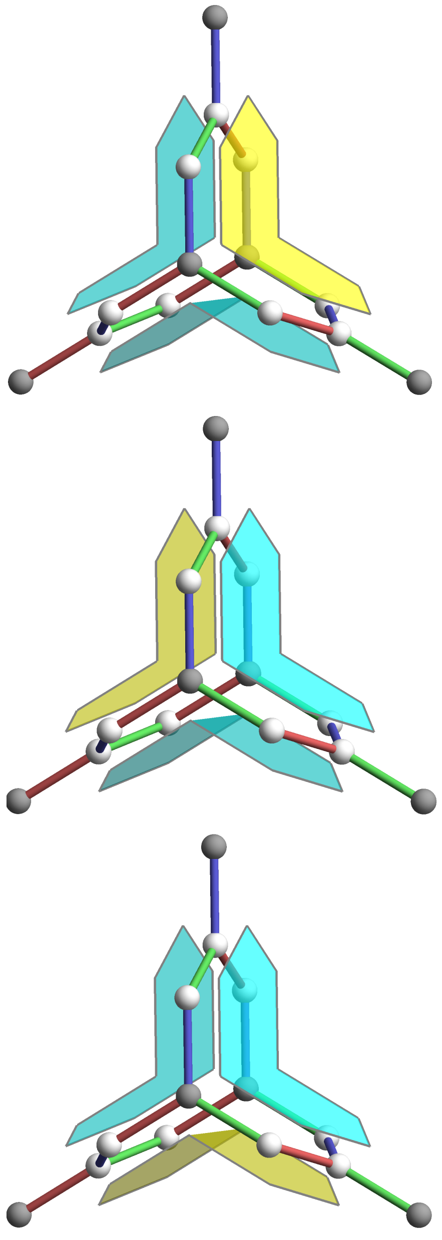






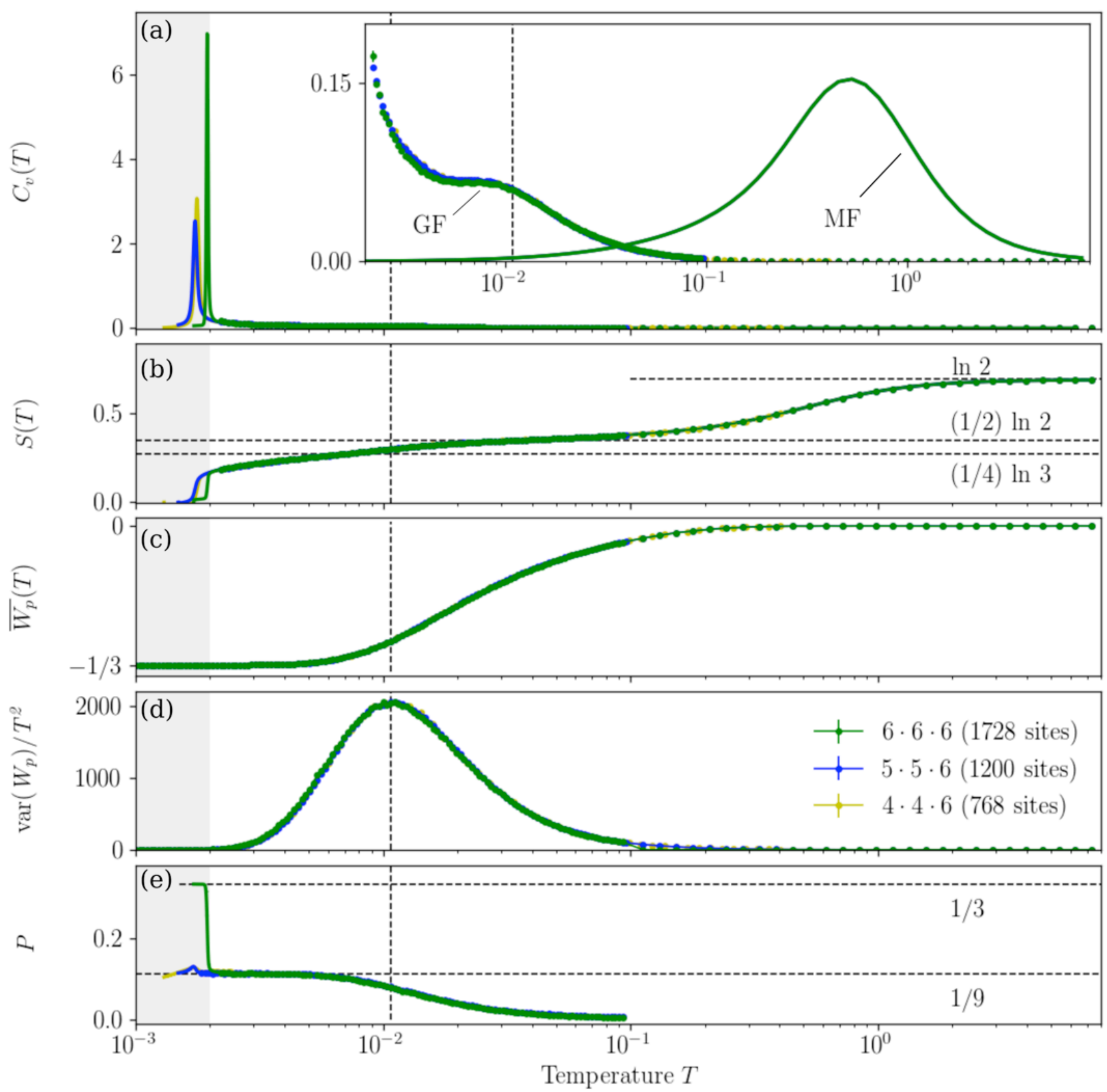
Lieb theorem→ π flux per plaquette

local constraints

extensive degeneracy

(partially) lift degeneracy by altering the coupling strenghts

Thermodynamics of gauge-frustrated KSL



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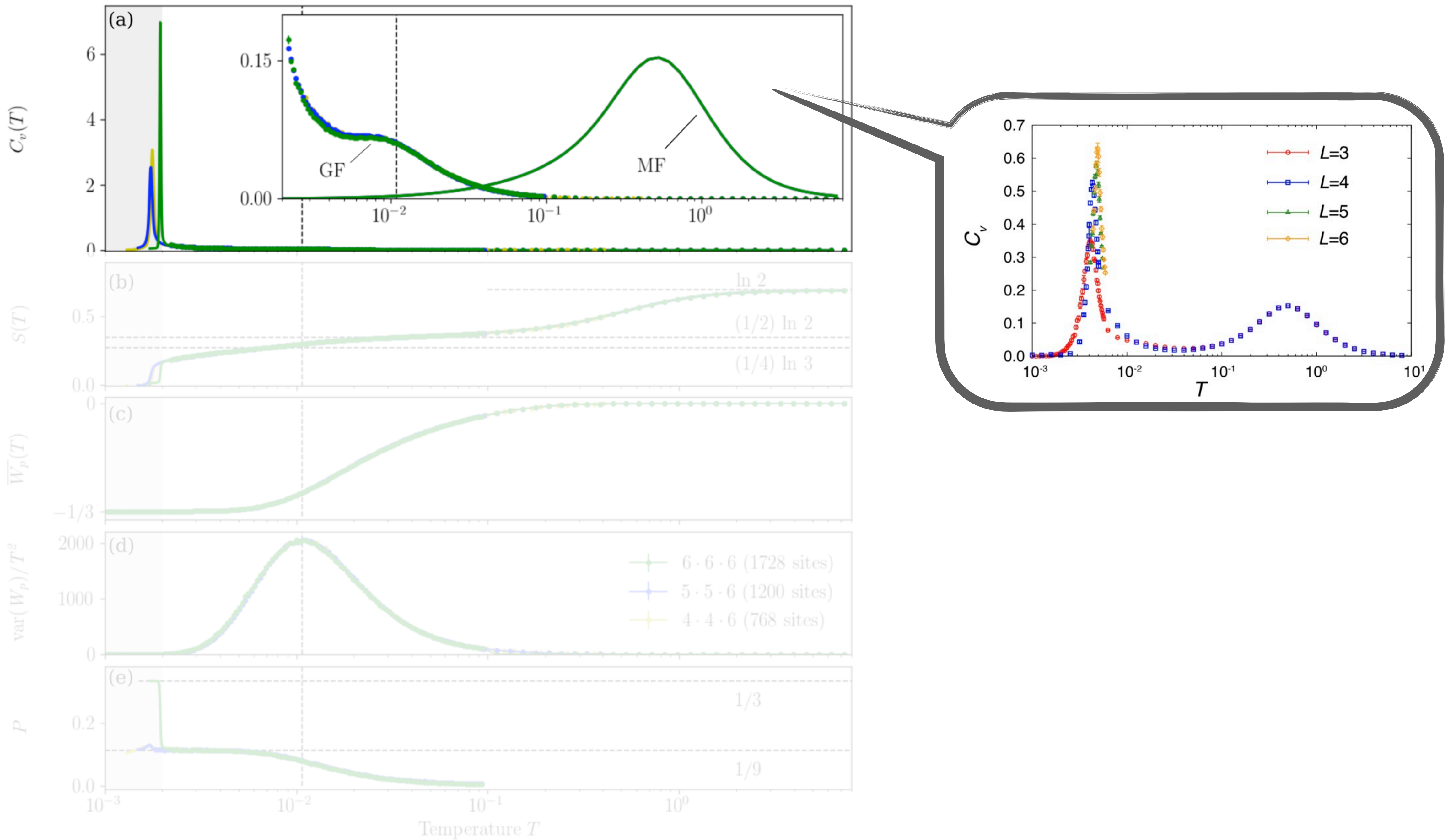

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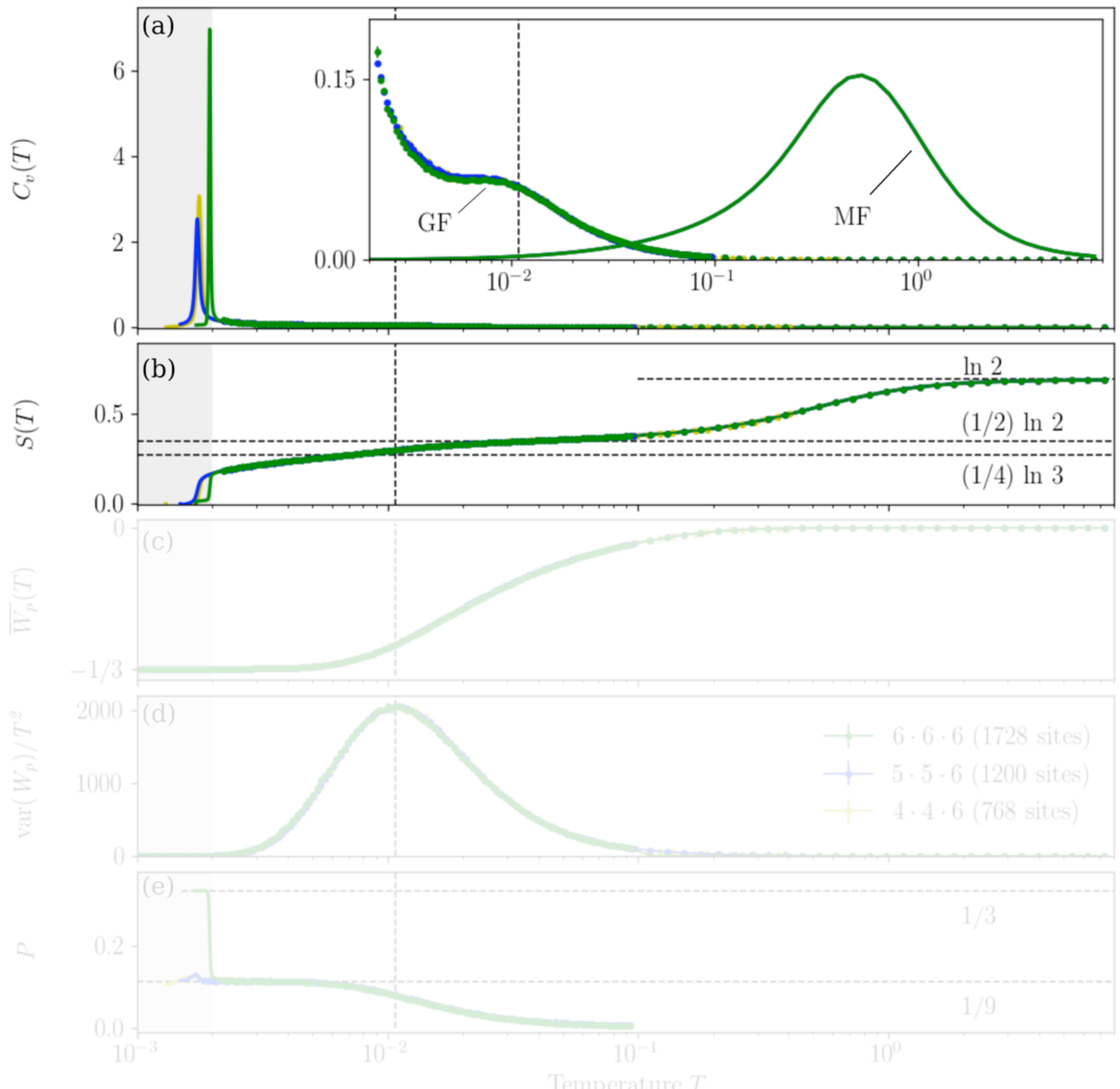
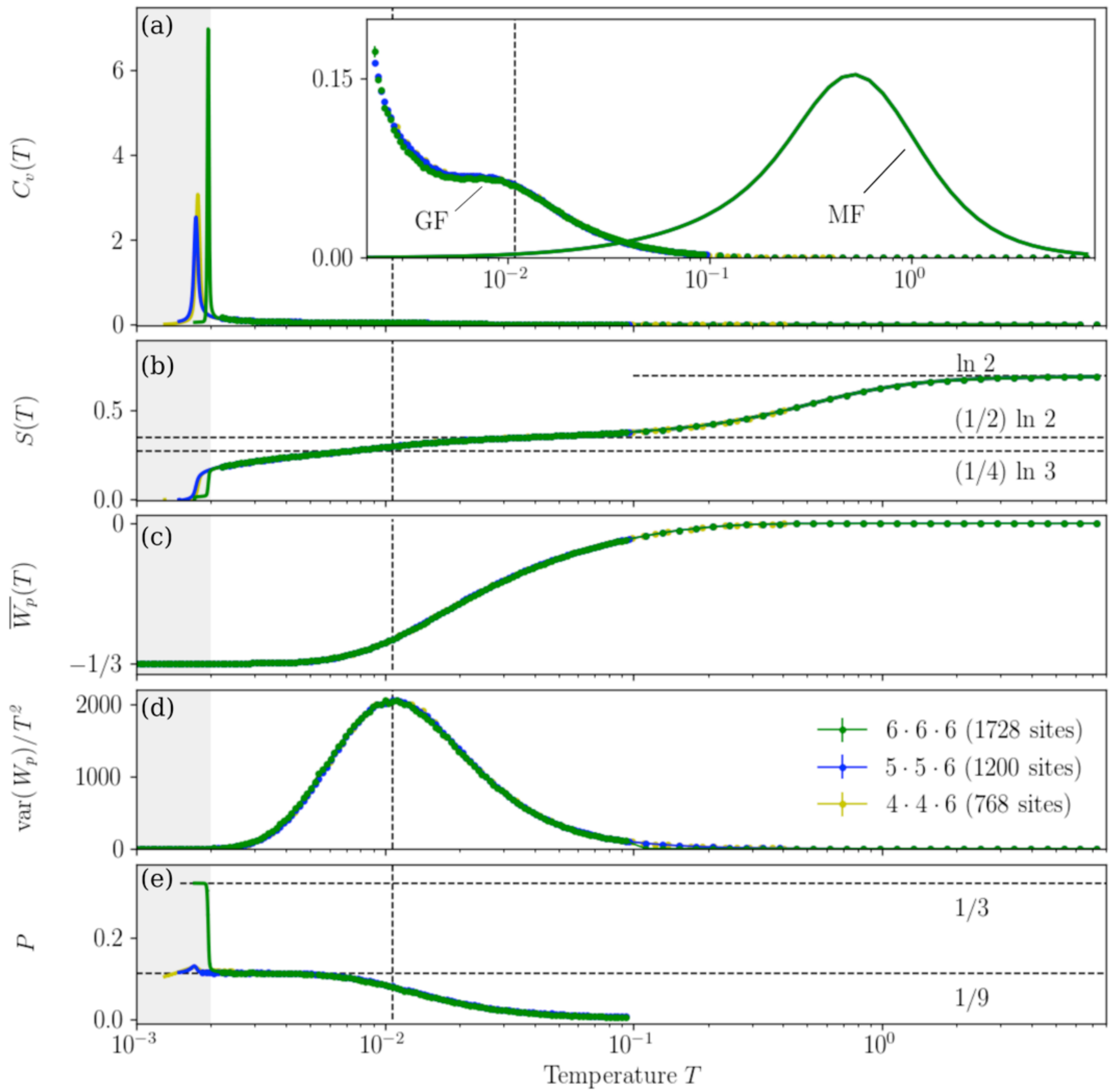
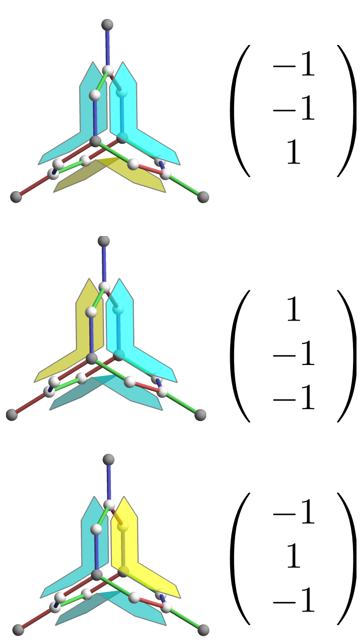


Thermodynamics of gauge-frustrated KSL



$$P = \frac{4}{3N}\sum_j \langle \mathbf{W}_0 \cdot \mathbf{W}_j \rangle$$

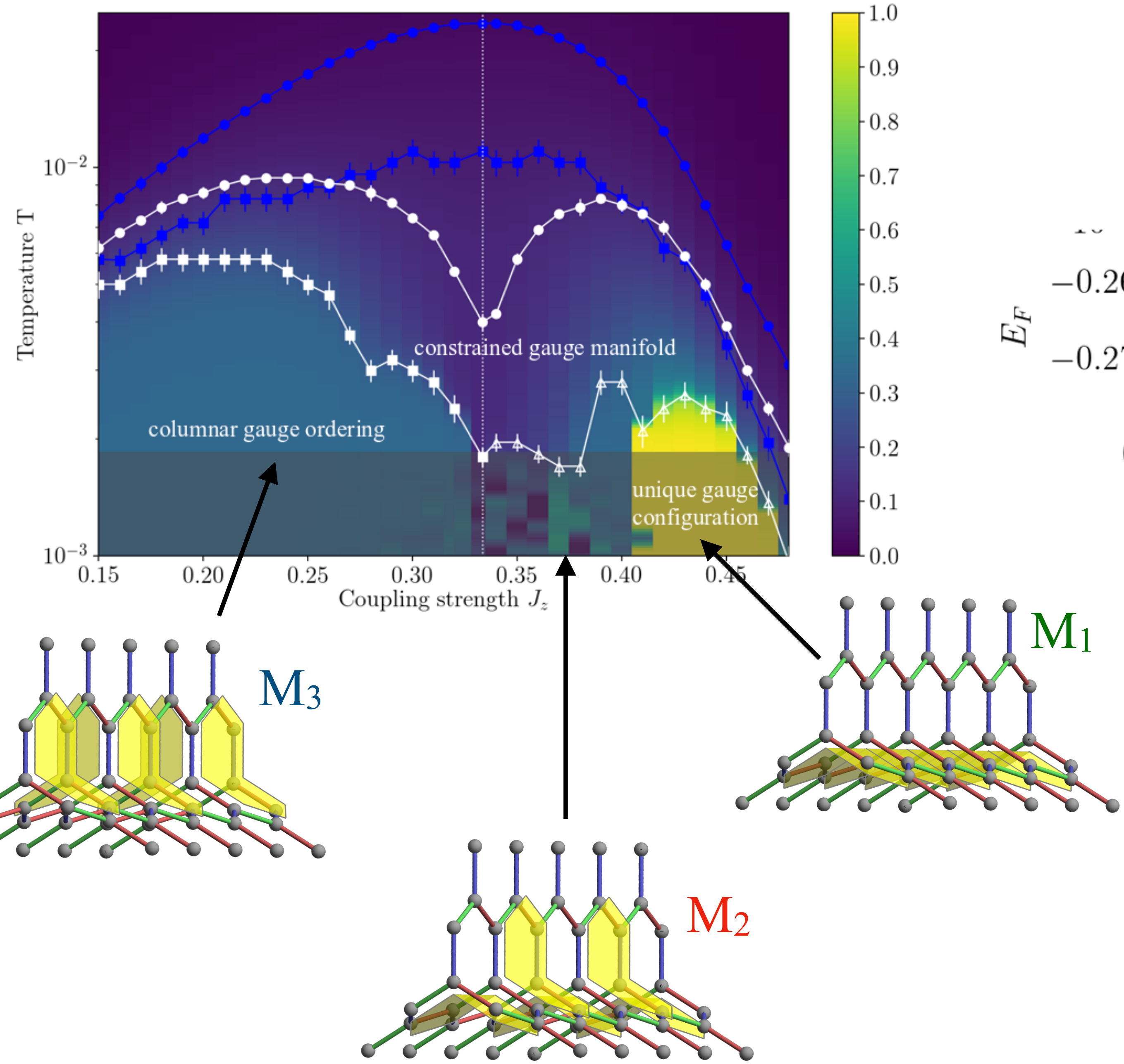
pseudospin vector of fluxes around 'star'

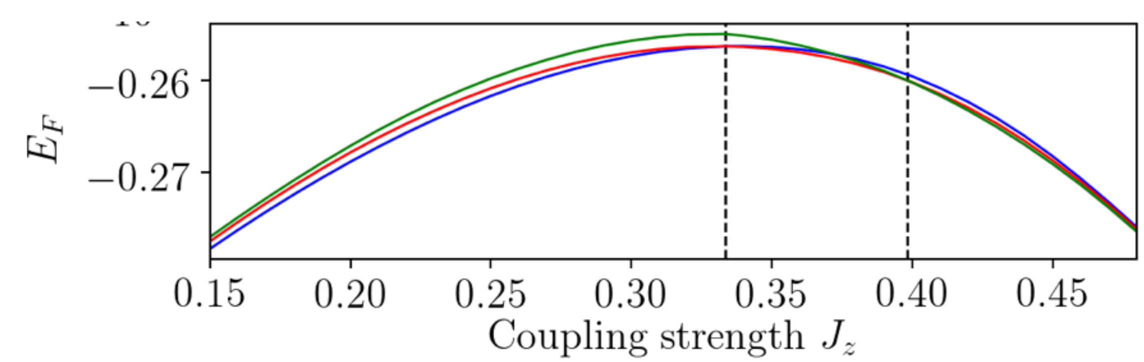


Interplay of Majoranas and fluxes

Ordering the Z_2 fluxes

phase diagram for $J_x = J_y$





Conclusions

Kitaev spin liquids and materials

‘Gauge-frustration’

extensive residual entropy arising in the gauge sector

interplay of Majoranas and gauge field leads to ordering of the fluxes and formation of a Majorana metal