topography and mimicry of a spin liquid on a triangular lattice

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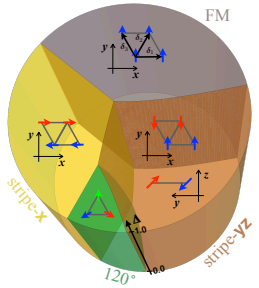
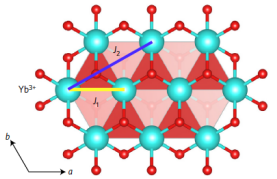
Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017); **120**, 207203 (2018)

plan

I. anisotropic **Δ**-antiferromagnets, **intro**





$YbMgGaO_4$

II. disorder-induced **mimicry** in YMGO

PRL **119,** 157201 (2017) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2017

Disorder-Induced Mimicry of a Spin Liquid in $YbMgGaO_4$

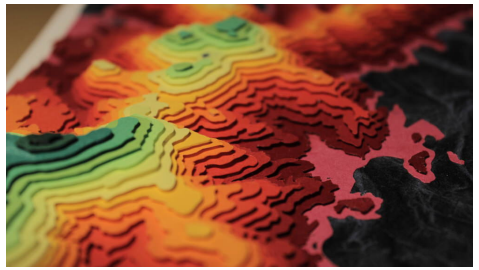
Zhenyue Zhu, P. A. Maksimov, Steven R. White, and A. L. Chernyshev

III. phase diagram and **topography** of spin-liquid phase

PHYSICAL REVIEW LETTERS **120,** 207203 (2018)

Topography of Spin Liquids on a Triangular Lattice

Zhenyue Zhu, P. A. Maksimov, Steven R. White, and A. L. Chernyshev



IV. duality, **truality** (= true reality), etc. [to be unpublished]

Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017); **120**, 207203 (2018)

credits

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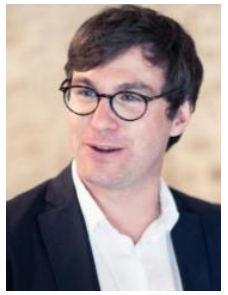
story

$$\mathcal{H} = \sum_{\langle ij \rangle} [J_{zz} S_i^z S_j^z + J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+) + J_{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) - \frac{iJ_{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)]$$

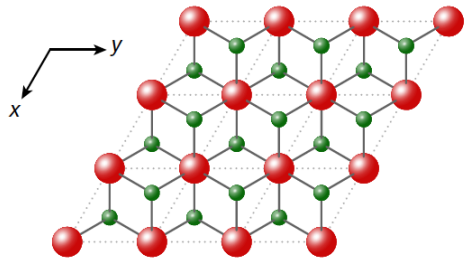
From: Martin Mourigal
Date: June 24, 2016 at 5:37:52 AM GMT+2
To: Sasha Chernyshev

Dear Sasha,
…
Also, **can I confidentially send you a manuscript on a triangular lattice compound that we are about to submit?**

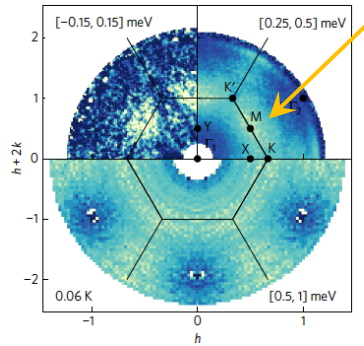
Best,
Martin

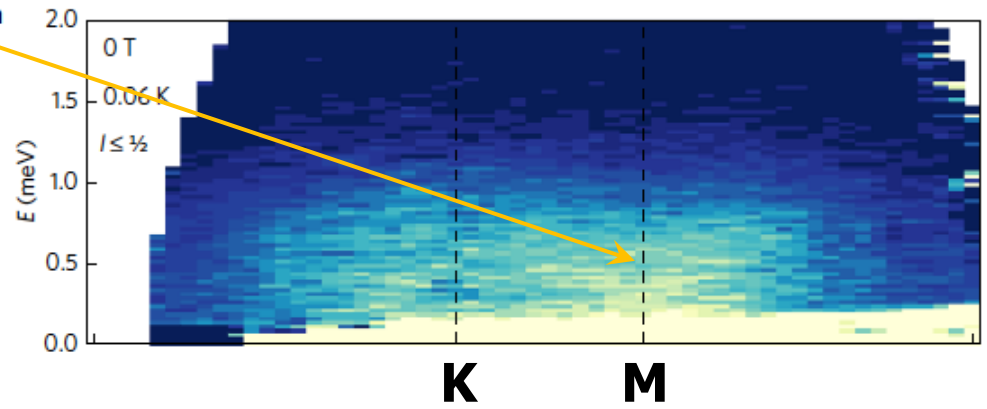


$YbMgGaO_4$



broad intensity at **M**-points

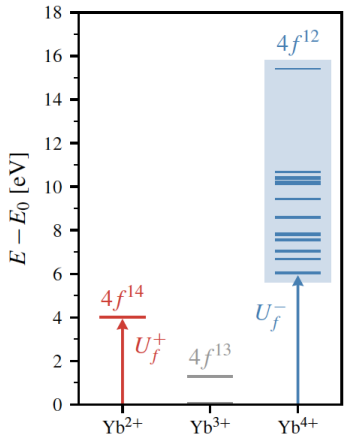


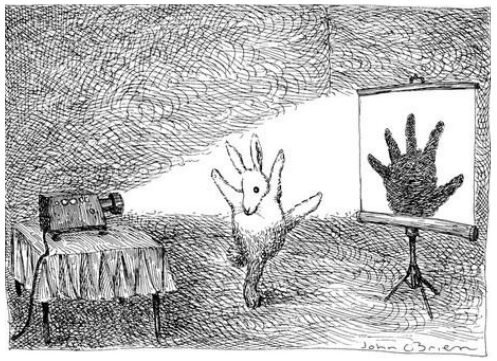


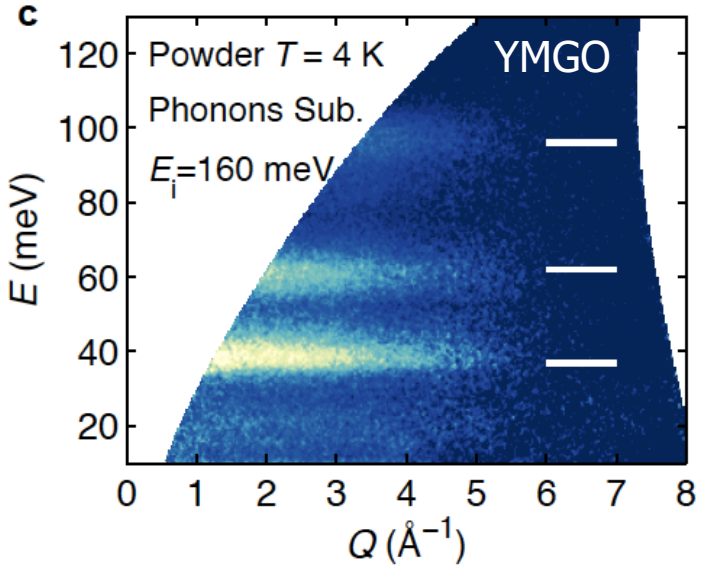
J. A. M. Paddison *etal*, Nat. Phys. **13**, 117 (2017).

is it crazy?

- rare-earth, Yb^{3+}, ***J=7/2***, + crystal-field splitting
- lowest doublet, effective *S=1/2*







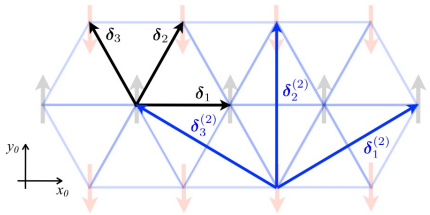
- **projection** of the large moment degrees of freedom onto the manifold of effective *S=1/2* states
- **agnostic approach:** spin-spin interactions = **anything** allowed by lattice symmetry & (mostly) nearest-neighbor, because *f*-electrons

J. A. M. Paddison *etal*, Nat. Phys. **13**, 117 (2017).

J. G. Rau and M. J. P. Gingras, arXiv:1802.03024

humanizing the hamiltonian, I

$J=2J_{\pm}$, $\Delta=J_{zz}/2J_{\pm}$



- triangular lattice symmetries ⇛ **four** terms
- XXZ part ⇛ friendlier form
- "extended" form ⇛ more intuition

[42] For a less humane form of (1), see

$$\mathcal{H}=\sum_{\langle ij\rangle} \boxed{J_{zz}S_i^zS_j^z+J_{\pm}\left(S_i^+S_j^-+S_i^-S_j^+\right)} \quad \text{XXZ}$$

$$\boxed{\gamma_{ij}=1,e^{2\pi i/3},e^{-2\pi i/3}}$$

$$+\boxed{J_{\pm\pm}\left[\gamma_{ij}S_i^+S_j^++\gamma_{ij}^*S_i^-S_j^-\right]-\frac{iJ_{z\pm}}{2}\left[\gamma_{ij}^*S_i^+S_j^z-\gamma_{ij}S_i^-S_j^z+(i\leftrightarrow j)\right]}$$

anisotropic, bond-dependent

[56] For a more humane form of (2), see

$$\mathcal{H}=\sum_{\langle ij\rangle} \boxed{J\left[S_i^xS_j^x+S_i^yS_j^y+\Delta S_i^zS_j^z\right]} \quad \text{XXZ}$$

$$\boxed{\tilde{\varphi}_\alpha=\{0,-2\pi/3,2\pi/3\}}$$

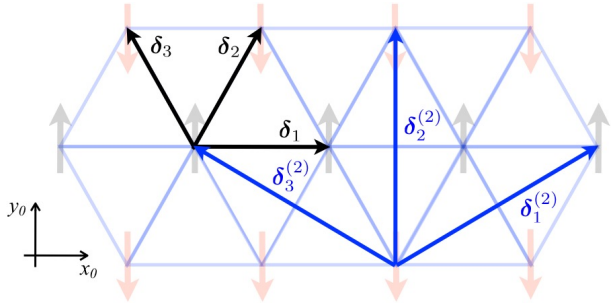
$$\boxed{+2J_{\pm\pm}\left[\cos\tilde{\varphi}_\alpha\left(S_i^xS_j^x-S_i^yS_j^y\right)-\sin\tilde{\varphi}_\alpha\left(S_i^xS_j^y+S_i^yS_j^x\right)\right]}$$

$$\boxed{+J_{z\pm}\left[\cos\tilde{\varphi}_\alpha\left(S_i^yS_j^z+S_i^zS_j^y\right)-\sin\tilde{\varphi}_\alpha\left(S_i^xS_j^z+S_i^zS_j^x\right)\right]}$$

anisotropic, bond-dependent

Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017); **120**, 207203 (2018)

humanizing the hamiltonian, II



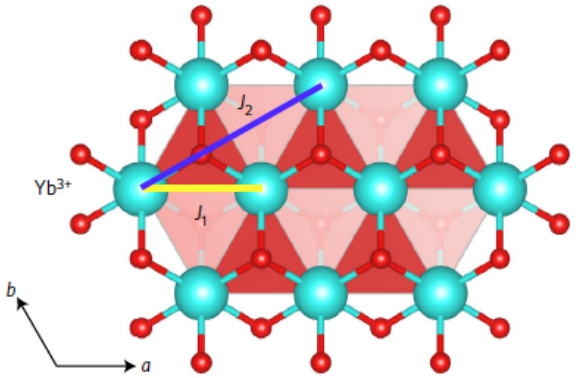
- triangular lattice symmetries ⇛ **four** terms
- parametrization of the exchange matrix

[*x*-bond] $\hat{\mathcal{H}}_{12} = \mathbf{S}_1^0 \begin{pmatrix} J_{xx} & J_{xy} & J_{xz} \\ J_{yx} & J_{yy} & J_{yz} \\ J_{zx} & J_{zy} & J_{zz} \end{pmatrix} \mathbf{S}_2^0 \quad \Rightarrow\!\!\!\Rightarrow \quad \hat{\mathcal{H}}_{12} = \mathbf{S}_1^0 \begin{pmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & J_{yz} \\ 0 & J_{zy} & J_{zz} \end{pmatrix} \mathbf{S}_2^0$

- parametrization: $J_{zz} = \Delta \cdot J_1\,,\; J_1 = (J_{xx} + J_{yy})/2,\; J_{\pm\pm} = (J_{xx} - J_{yy})/4\,,\; J_{zy} = J_{zy} = J_{z\pm}$

$$\mathcal{H} = \sum_{\langle ij \rangle} J\left[S_i^x S_j^x + S_i^y S_j^y + \Delta S_i^z S_j^z\right] + 2J_{\pm\pm}\left[\cos\tilde{\varphi}_\alpha \left(S_i^x S_j^x - S_i^y S_j^y\right) - \sin\tilde{\varphi}_\alpha \left(S_i^x S_j^y + S_i^y S_j^x\right)\right] + J_{z\pm}\left[\cos\tilde{\varphi}_\alpha \left(S_i^y S_j^z + S_i^z S_j^y\right) - \sin\tilde{\varphi}_\alpha \left(S_i^x S_j^z + S_i^z S_j^x\right)\right]$$

$\tilde{\varphi}_\alpha = \{0, -2\pi/3, 2\pi/3\}$

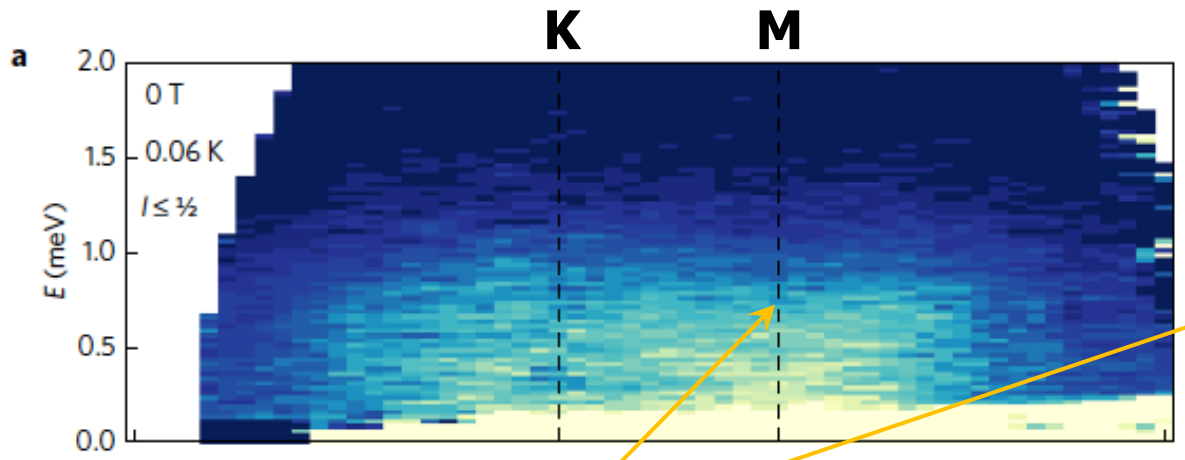


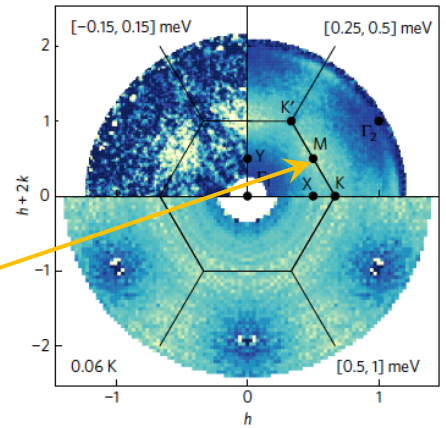
$YbMgGaO_4$

mimicry

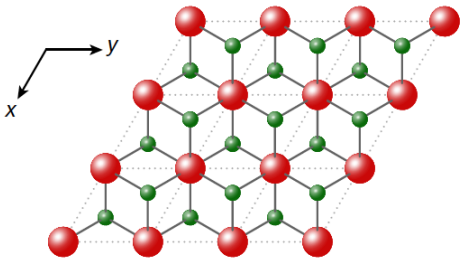
Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017).

experiments, I

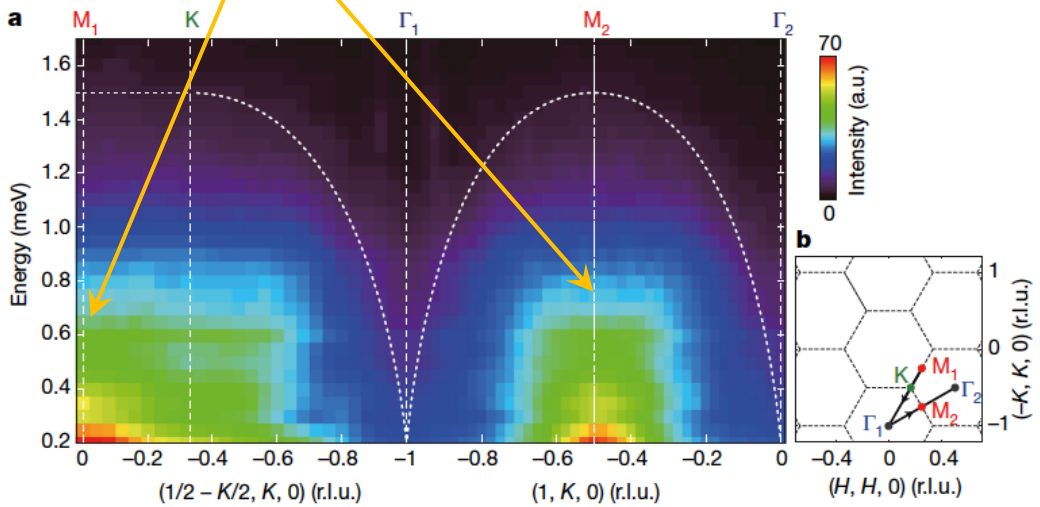




$YbMgGaO_4$



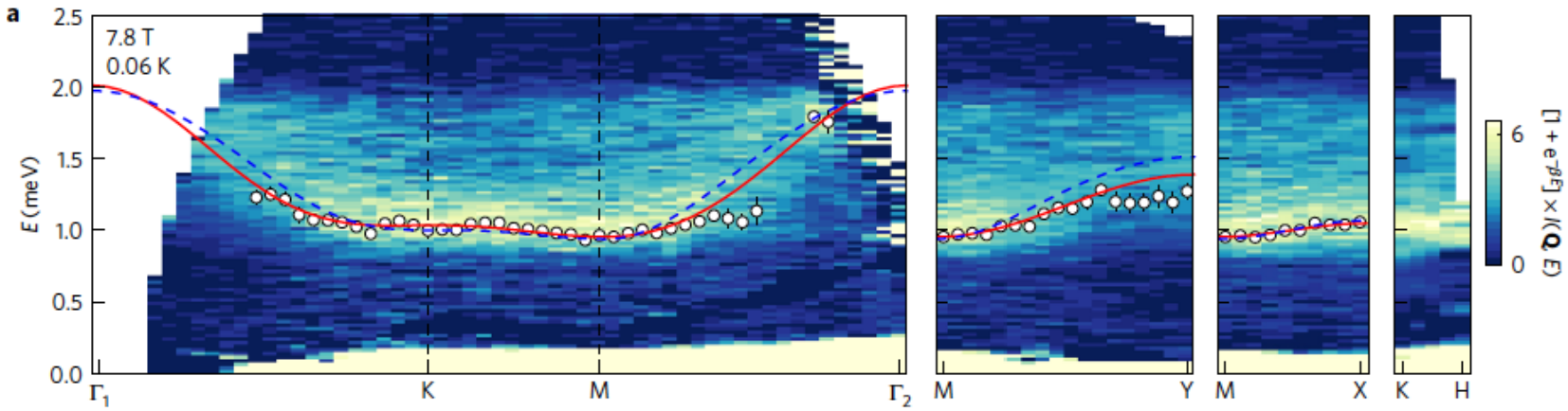
broad intensity at **M**-points

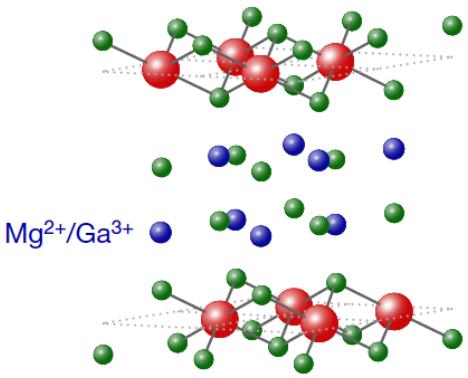


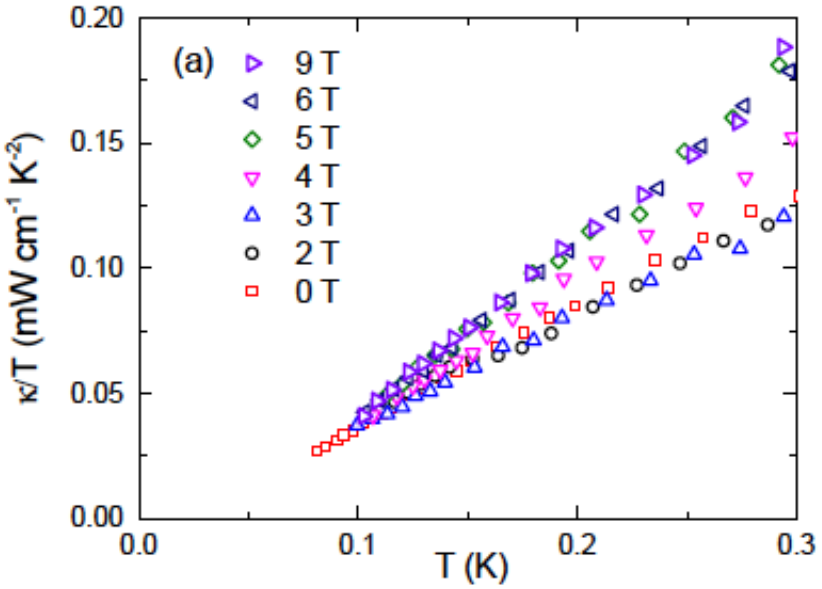
- no order
- broad features in $S(\boldsymbol{q},\omega)$
- **spin-liquid?**

Y. Shen *etal*, Nature **540**, 559 (2016); J. A. M. Paddison *etal*, Nat. Phys. **13**, 117 (2017).

experiments, II



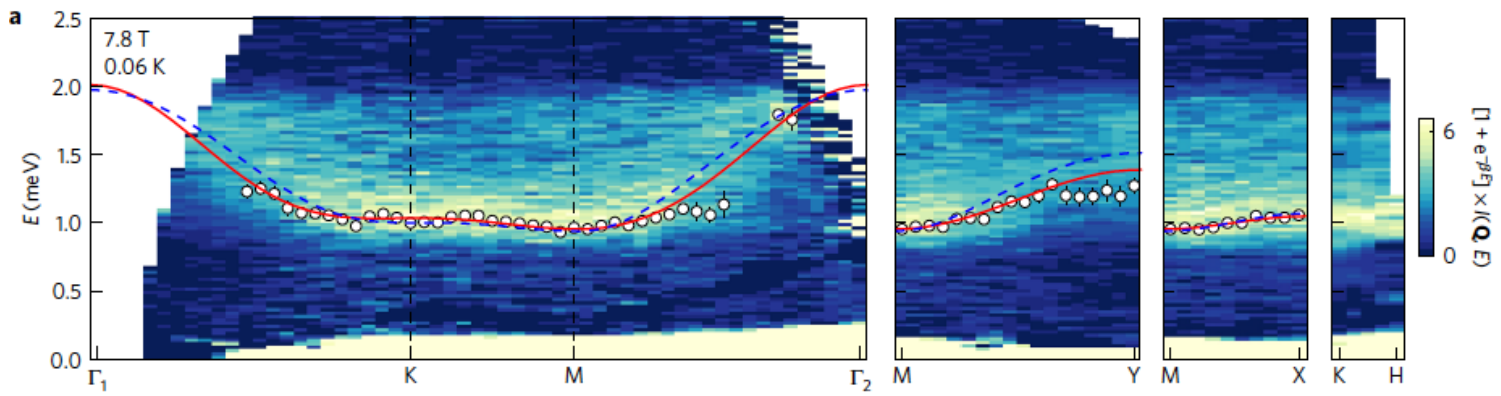




- features remain broad above saturation
- no thermal conductivity by spin excitations
- low-T freezing
- **disorder?** [mixing of interplane Ga^{3+} and Mg^{2+}]

$\mathcal{HJ}$ J. A. M. Paddison *etal*, Nat. Phys. **13**, 117 (2017); Y. Xu *etal*, PRL **117**, 267202 (2016); Z. Ma *etal*, PRL **120**, 087201 (2018).

(early) parameters: simpler model!



- **neutrons, ESR:** $J_1 = 0.218(8)$meV, Δ=0.58(2), $\boldsymbol{J_2 = 0.22(2) J_1}$, $J_{\pm\pm} = 0.06 J_1$, $J_{z\pm} \approx 0.0$
- **mostly J_1-J_2 XXZ** + **subleading** $J_{\pm\pm}$ + negligible $J_{z\pm}$

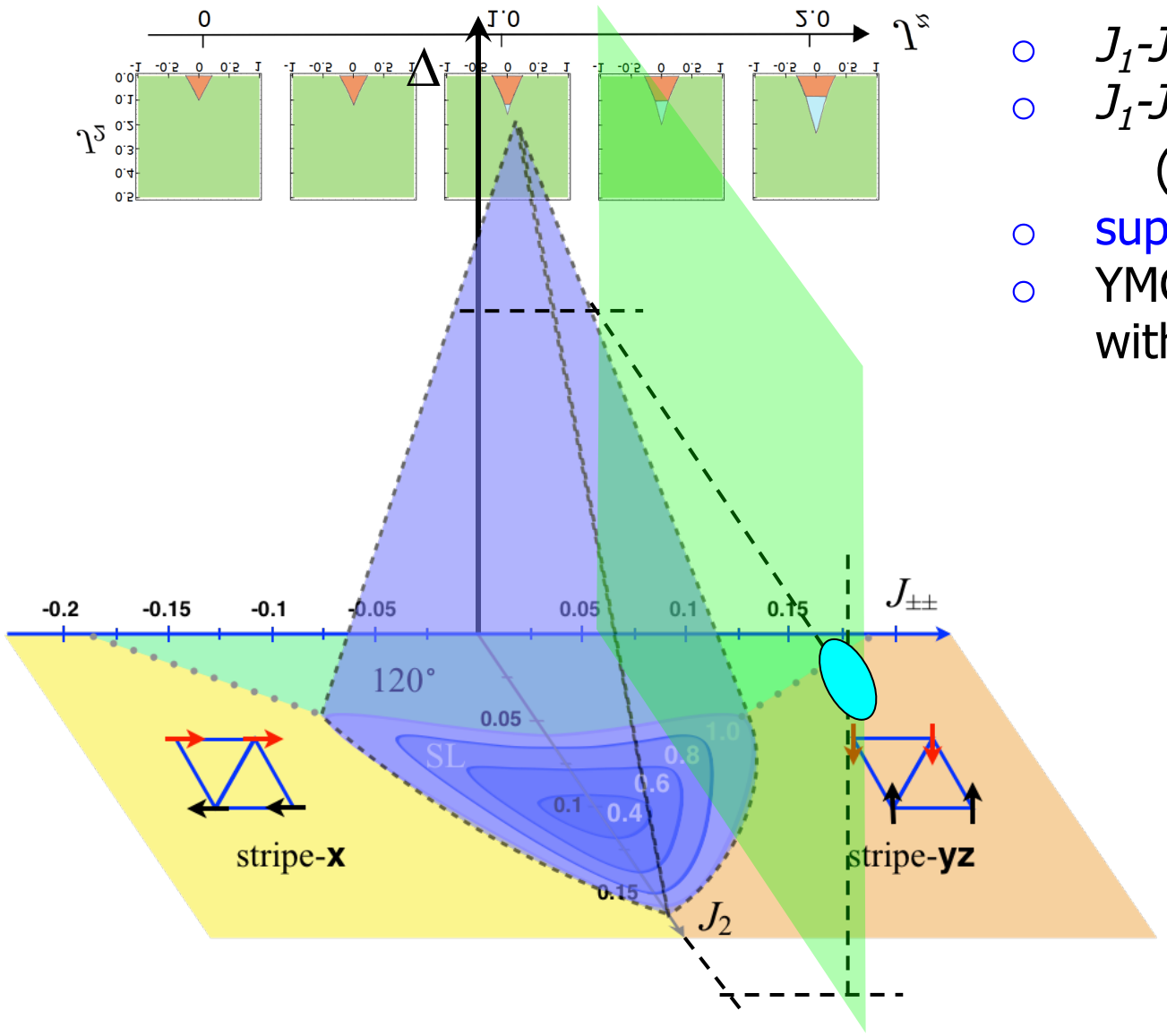
$$\mathcal{H} = \mathcal{H}_{\mathrm{XXZ}}^{J_1-J_2} + \mathcal{H}_{\mathrm{pd}}$$

$$\mathcal{H}_{\mathrm{XXZ}}^{J_1-J_2} = \sum_{\langle ij \rangle_n} J_n \left(S_i^x S_j^x + S_i^y S_j^y + \Delta S_i^z S_j^z \right)$$

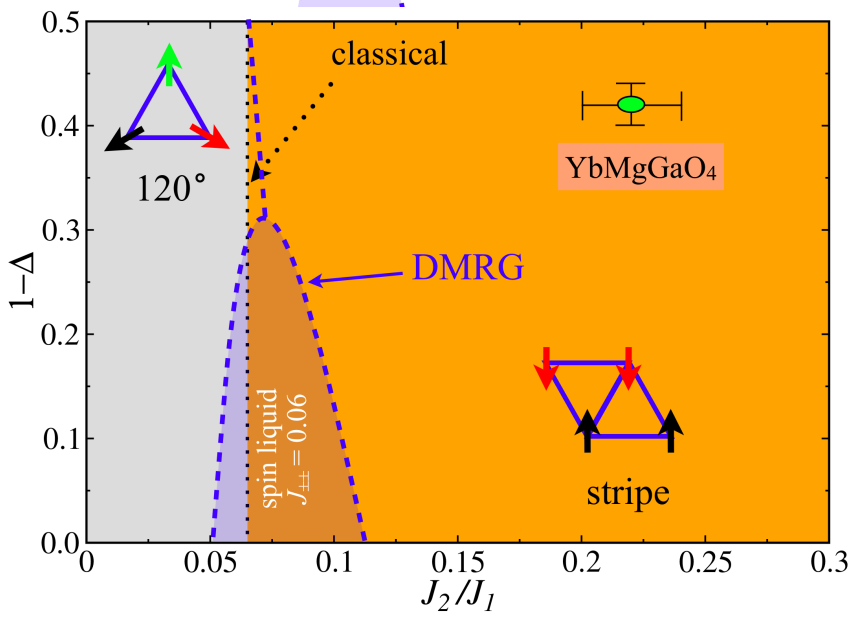
$$\mathcal{H}_{\mathrm{pd}} = J_{\pm\pm} \sum_{\langle ij \rangle} \left(e^{i\tilde{\varphi}_\alpha} S_i^+ S_j^+ + e^{-i\tilde{\varphi}_\alpha} S_i^- S_j^- \right)$$

J. A. M. Paddison *etal*, Nat. Phys. **13**, 117 (2017); Y. Li *etal*, PRL **115**, 167203 (2015).

J_1-J_2-XXZ-$J_{\pm\pm}$, DMRG?



- J_1-J_2 model has a spin liquid phase [J_2 =0.06 … 0.15]
- J_1-J_2-XXZ-$J_{\pm\pm}$ ⇛ **extended spin liquid phase**
  (extent in Δ=[1.0 … 0.3], $J_{\pm\pm}$=[-0.1 … 0.1])
- supported by variational MC (Iaconis *etal.*,'18)
- YMGO?: **well outside an SL, in a stripe phase** with a large ordered moment **⟨S⟩ ≈ 0.42 [DMRG]**



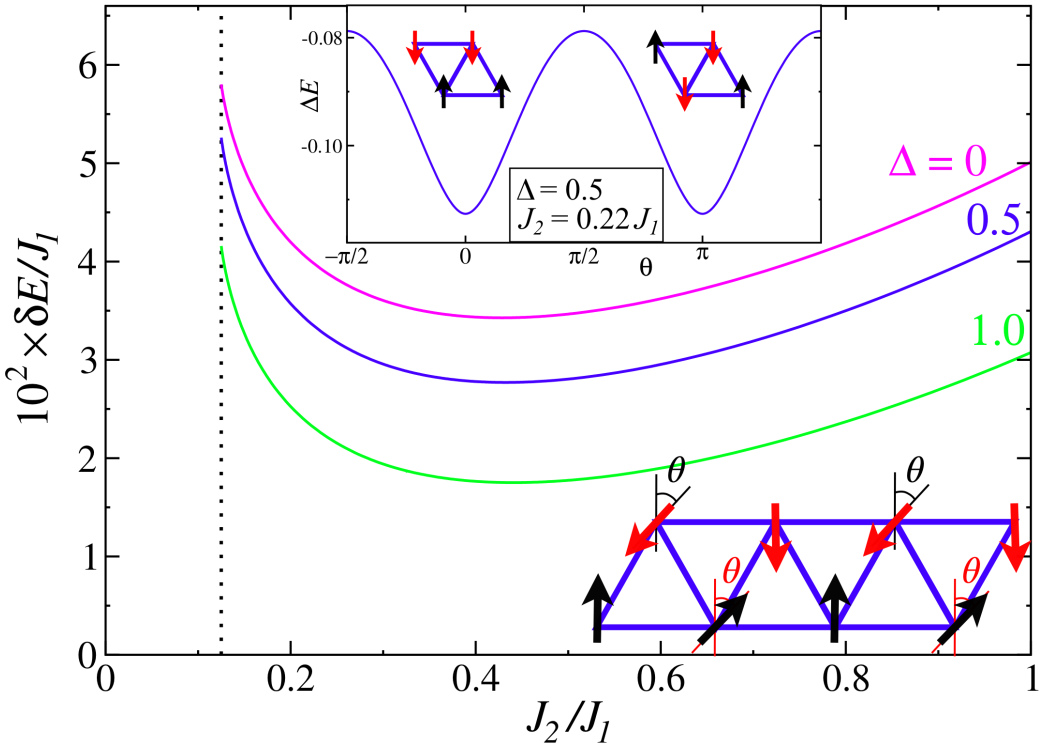
Z. Zhu and S. R. White, PRB **92**, 041105 (2015).

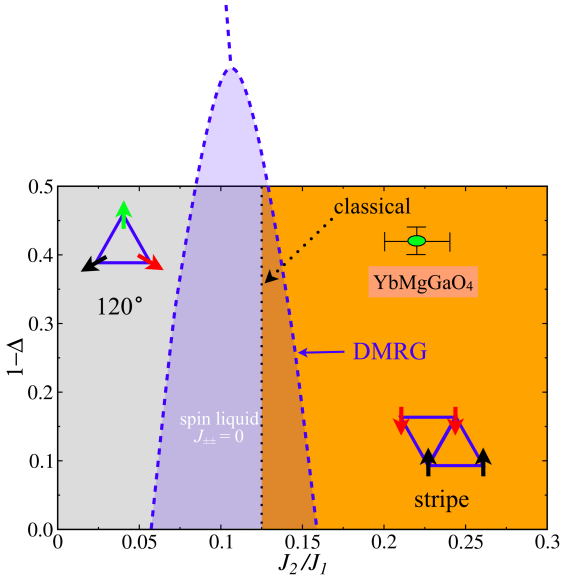
Z. Zhu, *etal*, PRL **119**, 157201 (2017); J. Iaconis *etal*, SciPost Phys. **4**, 3 (2018)

how can stripe look like an "SL"? a scenario:

- pure J_1-J_2-XXZ limit: stripes are selected by an order-by-disorder effect
  [from a classically degenerate manifold of (spiral) states]

- ⇛ tunneling barrier between stripe different phases: about $0.03J_1$ per spin





Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017).

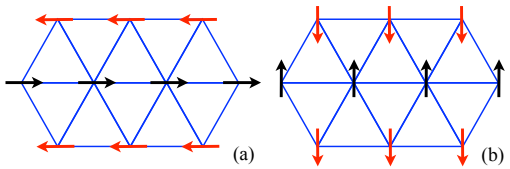
+ disorder … = SL **mimicry**

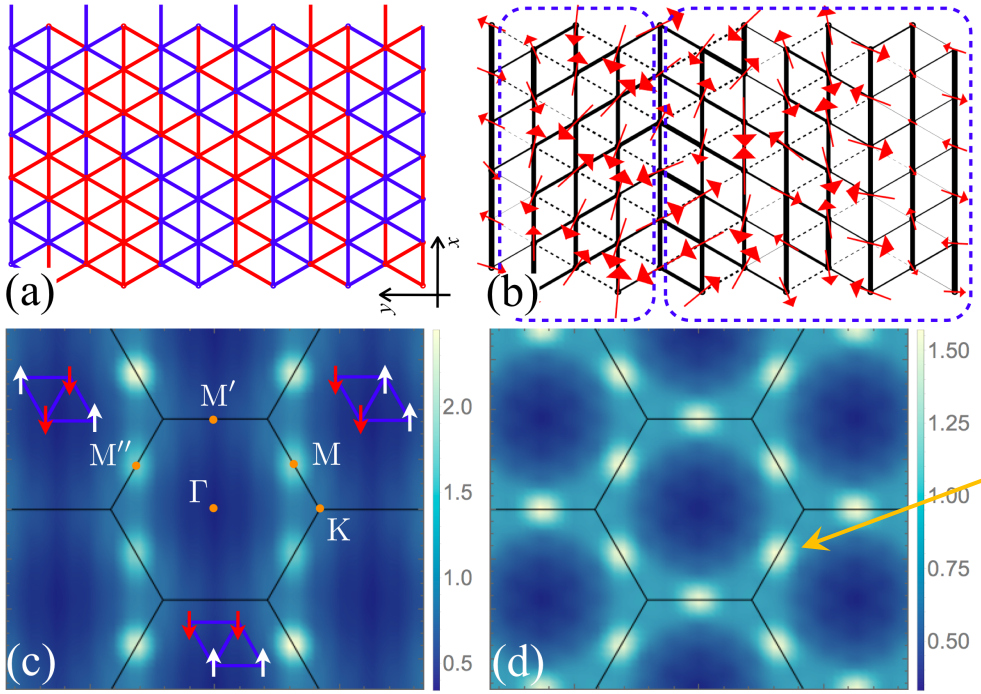
$$\hat{\mathcal{H}}_{12} = \mathbf{S}_1^0 \begin{pmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & J_{yz} \\ 0 & J_{zy} & J_{zz} \end{pmatrix} \mathbf{S}_2^0$$

$$J_{\pm\pm} = (J_{xx} - J_{yy})/4$$

- subleading $\boldsymbol{J_{\pm\pm}}$ terms are a (small) difference of the diagonal terms in the exchange matrix
- disorder in the latter (20%, consistent with experiments)
  ⇛ **random pinning fields for stripes**

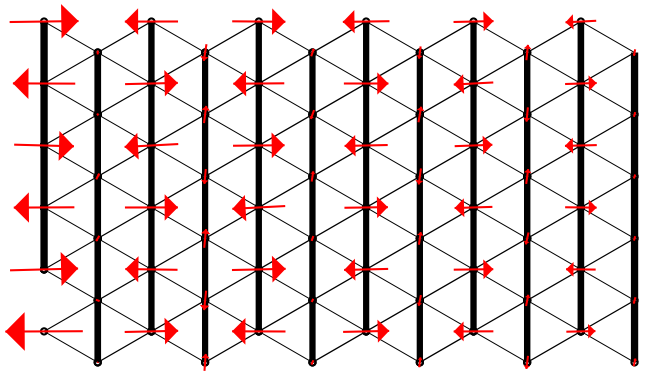
Y. Li *etal*, PRL **118**, 107202 (2017).





- DMRG ⇛ stripe clusters, or **stripe-superposed** states, yielding $S(\boldsymbol{q})$ similar to experiments

broad intensity at **M**-points;
short-range stripe order



see also E. Parker and L. Balents, PRB **97**, 184413 (2018);
Z. Ma *etal*, PRL **120**, 087201 (2018).

Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017).

YMGO is in a stripe phase with large ordered moment;
disorder makes it look like a spin-liquid

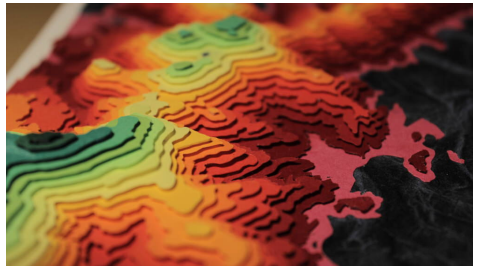
isomorphism

reincarnation

redemption

topography

holy grail



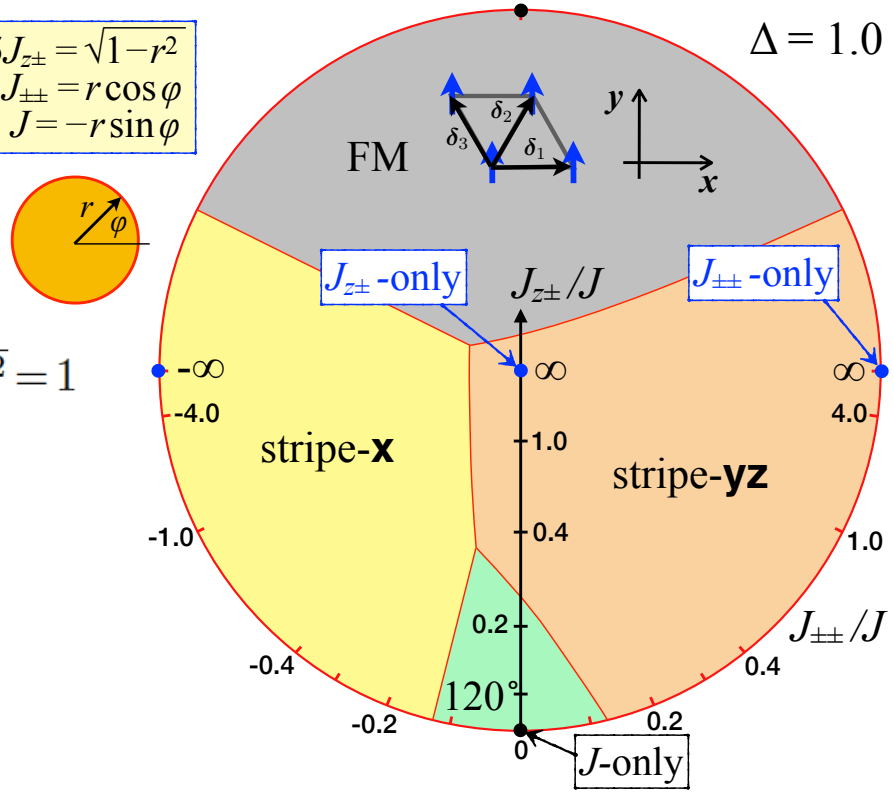
Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **120**, 207203 (2018)

classical phase diagram

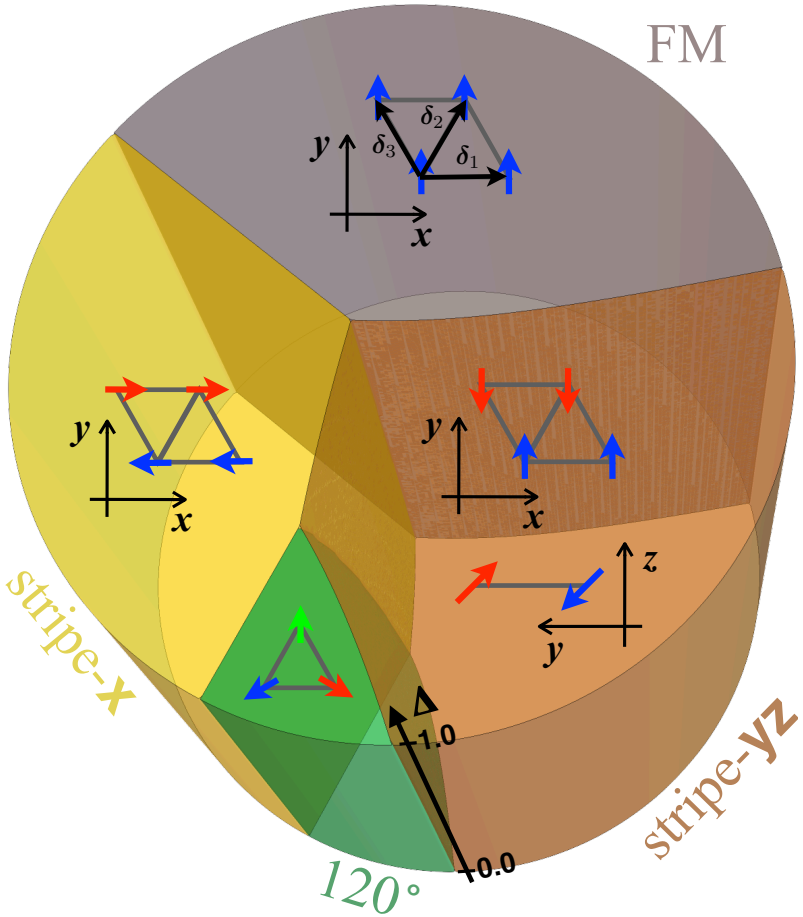
- **3D parameter space:** *XXZ*-Δ, $J_{\pm\pm}$, and $J_{z\pm}$
- ⇛ **mapping on a cylinder**, ["2" and "5" to exaggerate $J_{\pm\pm}\sim J_{z\pm}\sim J$ region]
- **FM, 120˚ , and stripe states*,** weak Δ-dependence (+ few subtleties)

top = Heisenberg
bottom = XY

$$5J_{z\pm}=\sqrt{1-r^2}$$
$$2J_{\pm\pm}=r\cos\varphi$$
$$J=-r\sin\varphi$$

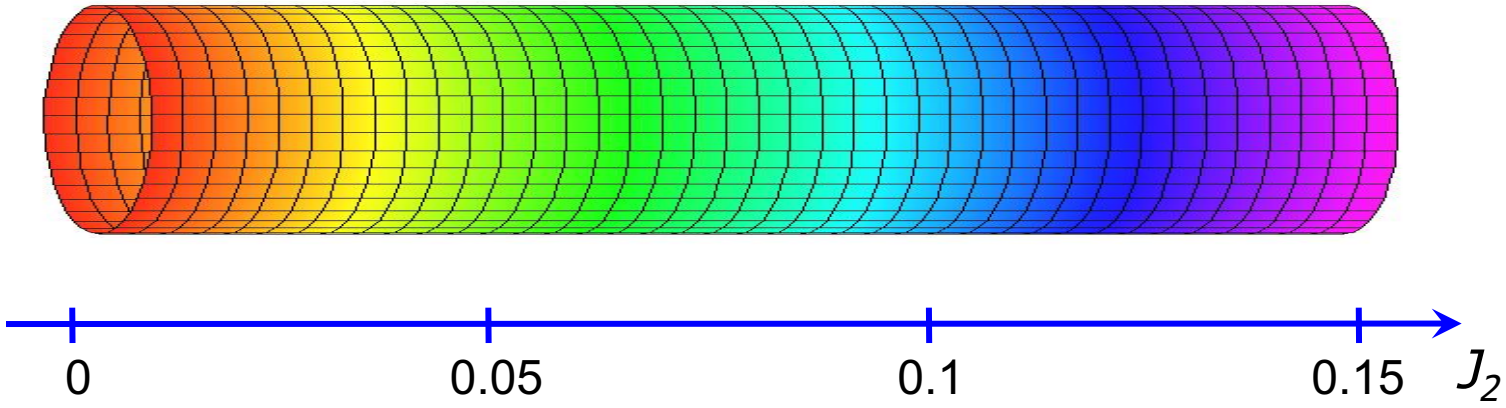


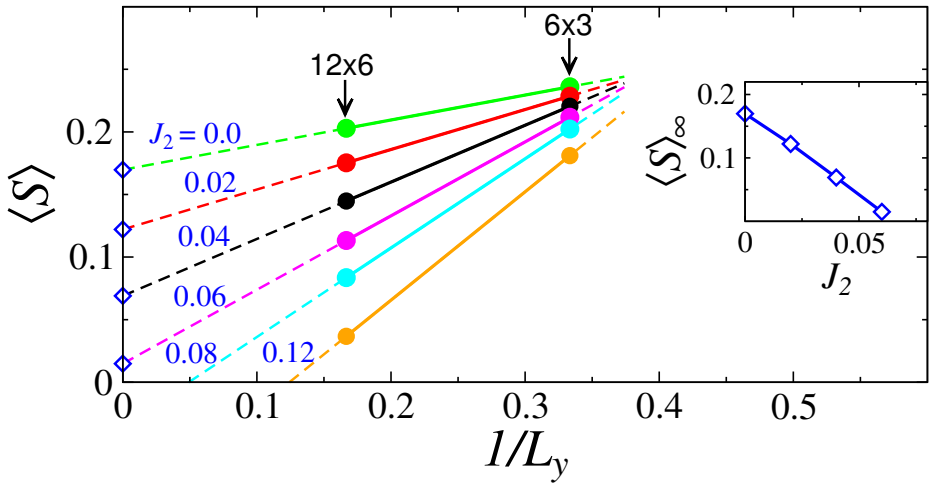
$$\sqrt{J_1^2+(2J_{\pm\pm})^2+(5J_{z\pm})^2}=1$$



*C. Liu, R. Yu, and X. Wang, Phys. Rev. B **95**, 174424 (2016).

S=1/2, DMRG: 3D phase space, how?





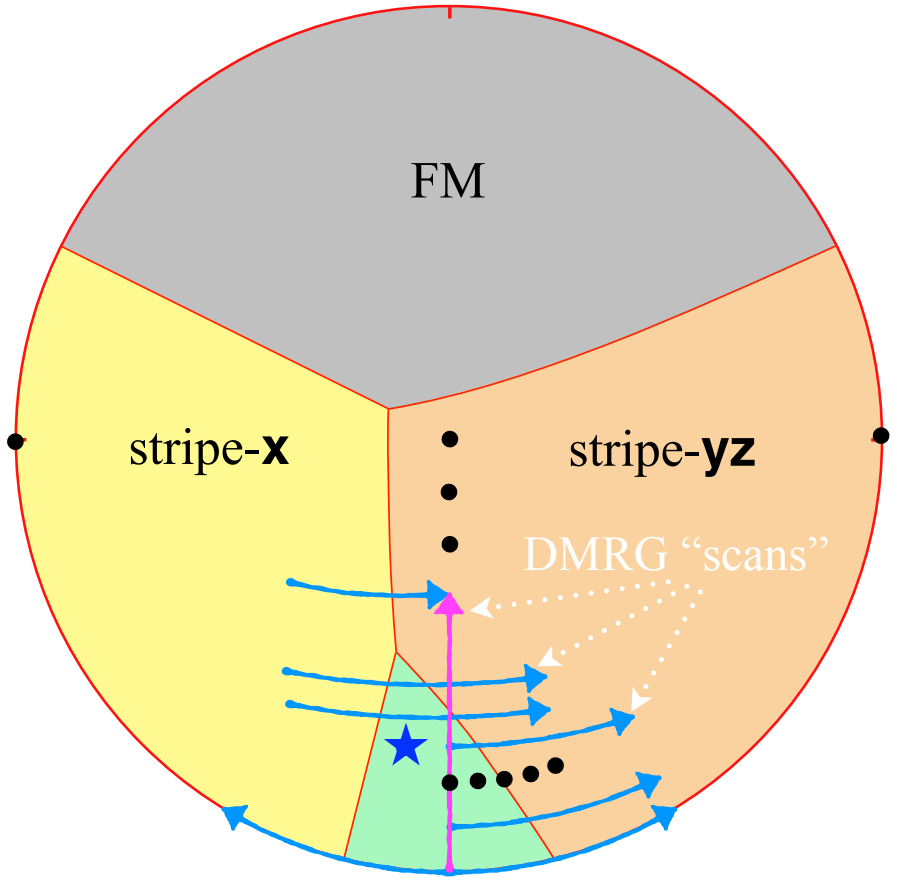
- **1D long-cylinder scans ["scans"]:** vary one parameter, play with BCs/range, read orders

- "all-fixed" parameters [**"non-scans"**], 12x6, 20x6 clusters
- $1/L_y$-scaling, fixed aspect-ratio clusters
- decay of correlations off boundary, exp vs power-law
- $S(\boldsymbol{q})$ structure factor

[S. R. White and SC, PRL 2007]

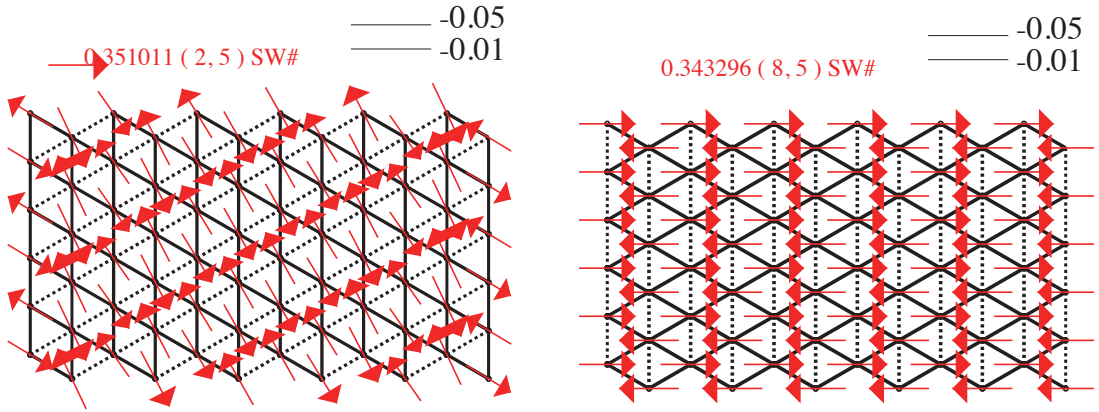
Z. Zhu and S. R. White, Phys. Rev. B **92**, 041105 (2015).

DMRG: scans, non-scans, large $J_{\pm\pm}$, $J_{z\pm}$



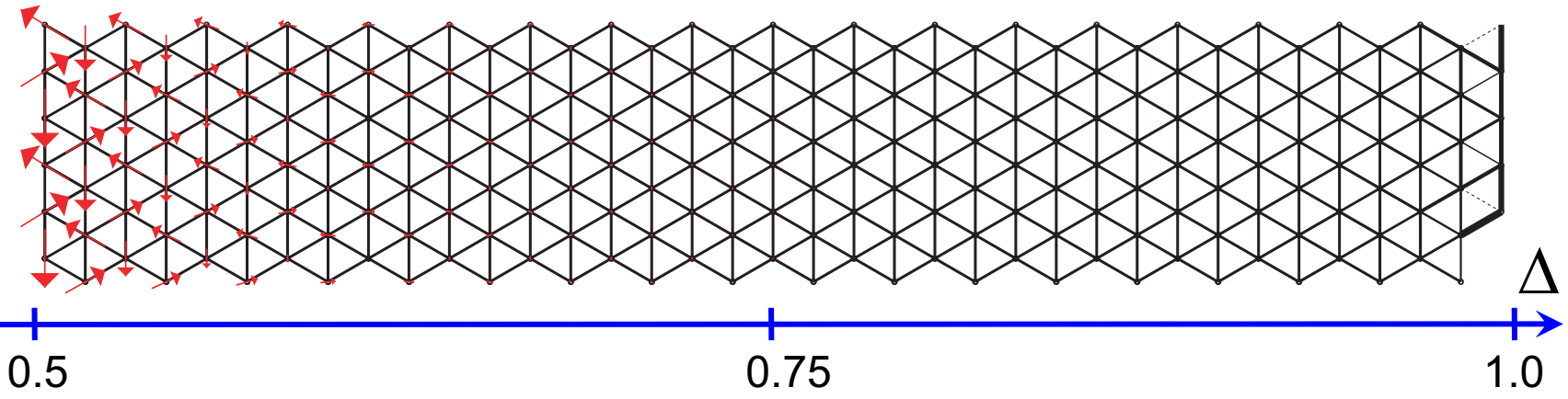
- some regions: obvious continuity
- strong stripe orders; little quantum fluctuations
- ⇛ potential spin liquid regions are near the 120° state
- ⇛ **SKIP MOST DMRG results …**

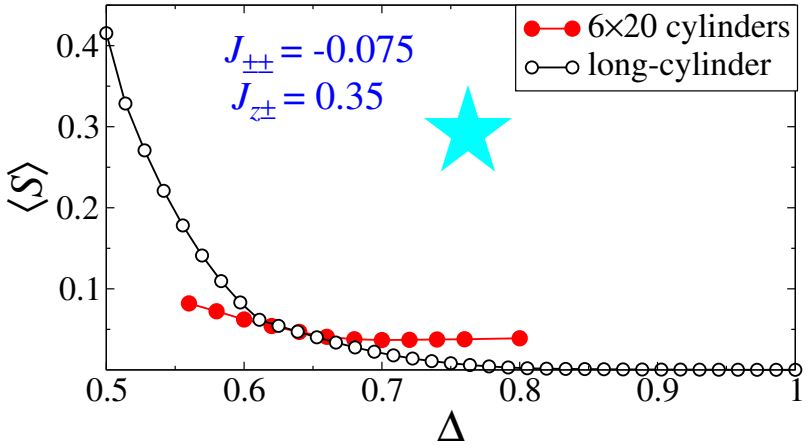
Δ=1.0, $J_{z\pm}$= 4.0, 8.0, ∞

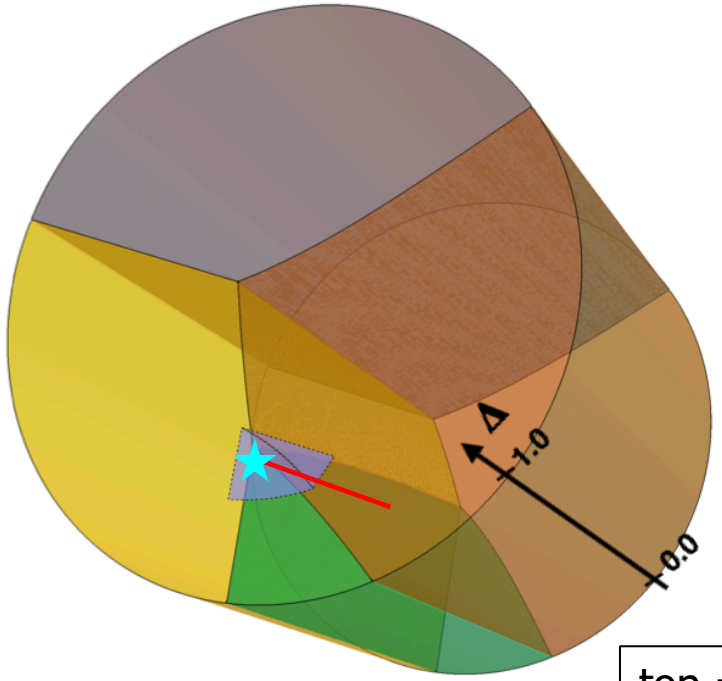


Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **120**, 207203 (2018)

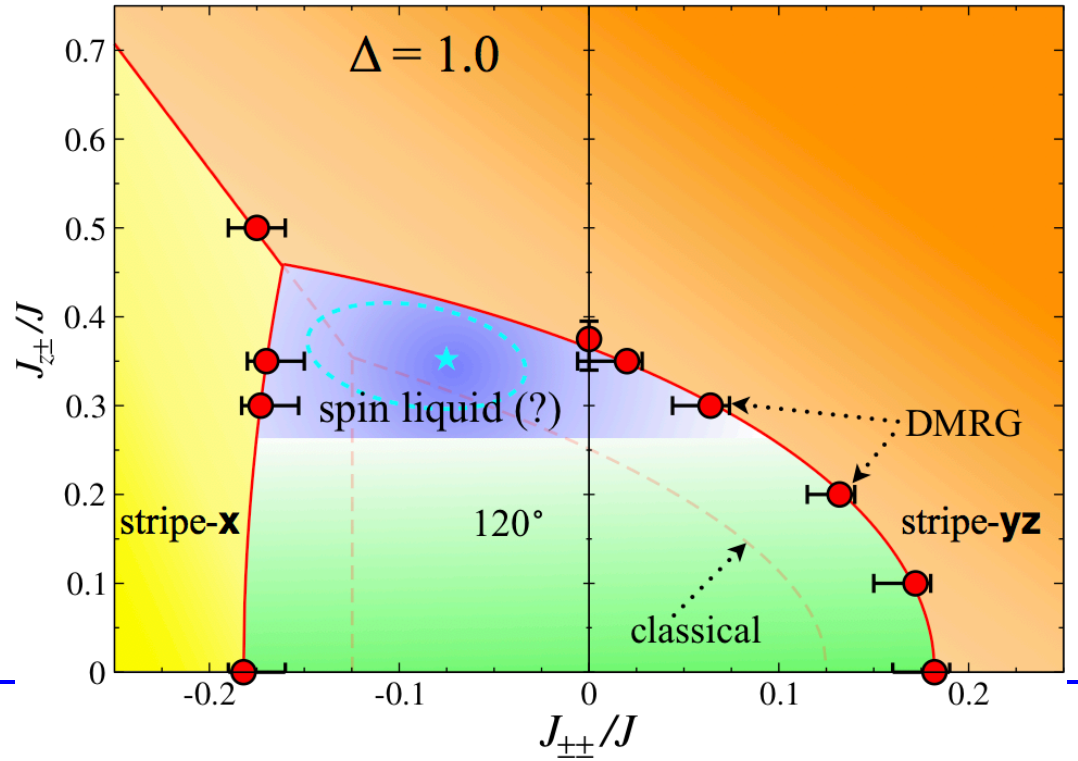
DMRG, spin liquid??



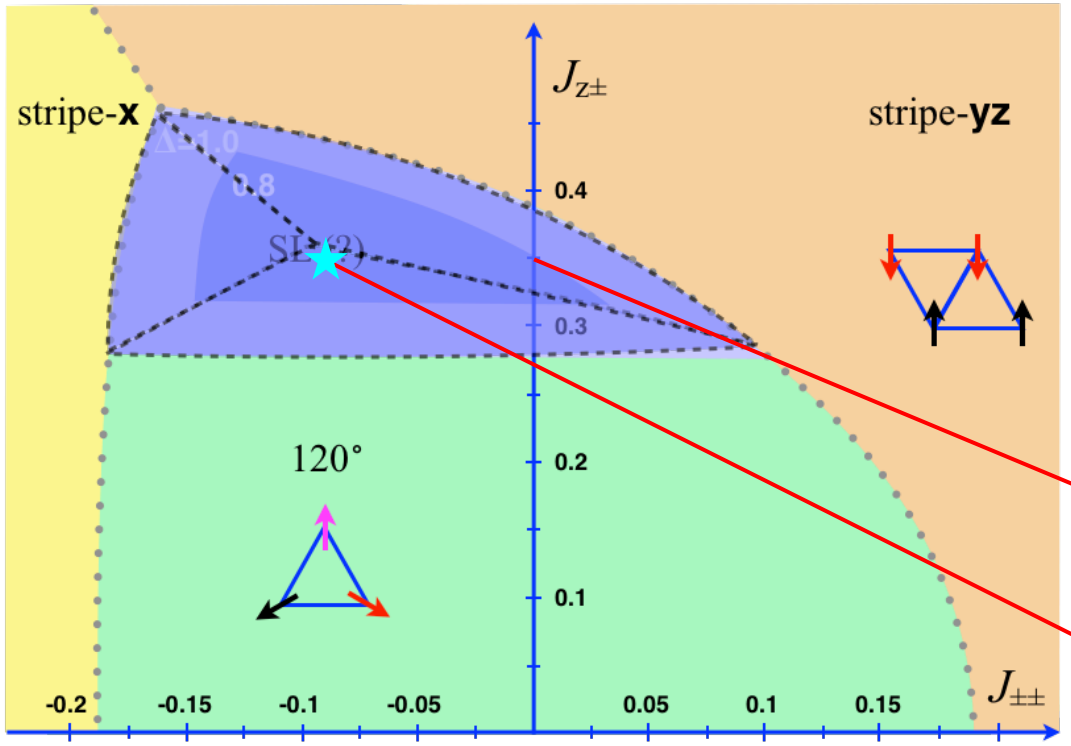




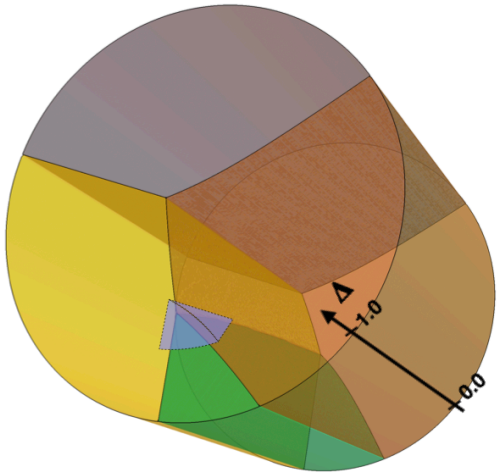
top = Heisenberg
bottom = XY



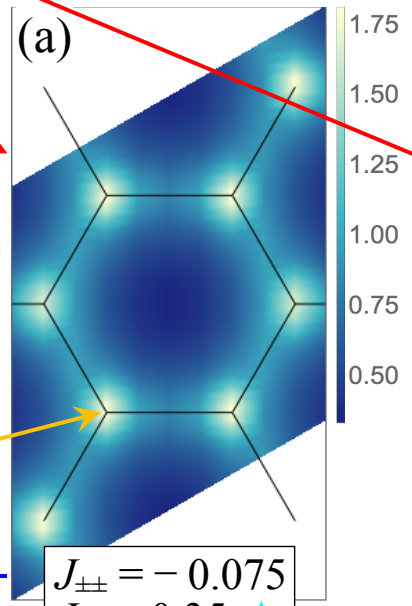
spin-liquid topographic map

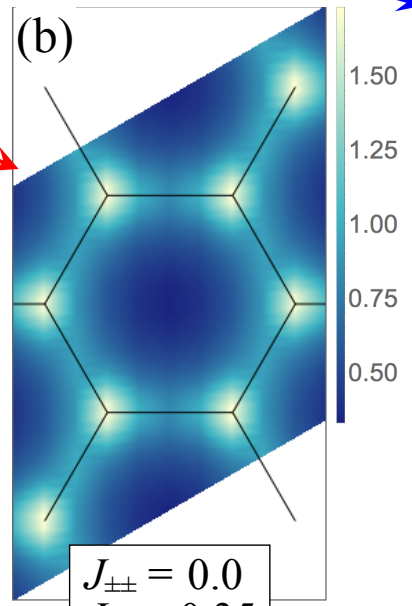


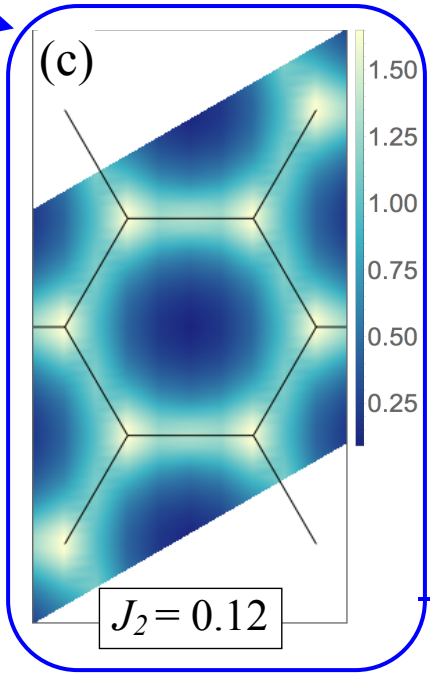
- strong evidence: region
  ($J_{z\pm}$≈[0.3…0.5], $J_{\pm\pm}$≈[-0.2…+0.1], Δ=[1.0…0.7])
  is a spin liquid
- **what kind of SL?**
- maximal at Δ=1.0 ⇛ **not** driven by anisotropic terms
- *S(**q**):* isotropic, no off-diagonal $S^{\alpha\beta}(\mathbf{q})$
- ***S(q)* is similar to J_1-J_2 SL region**



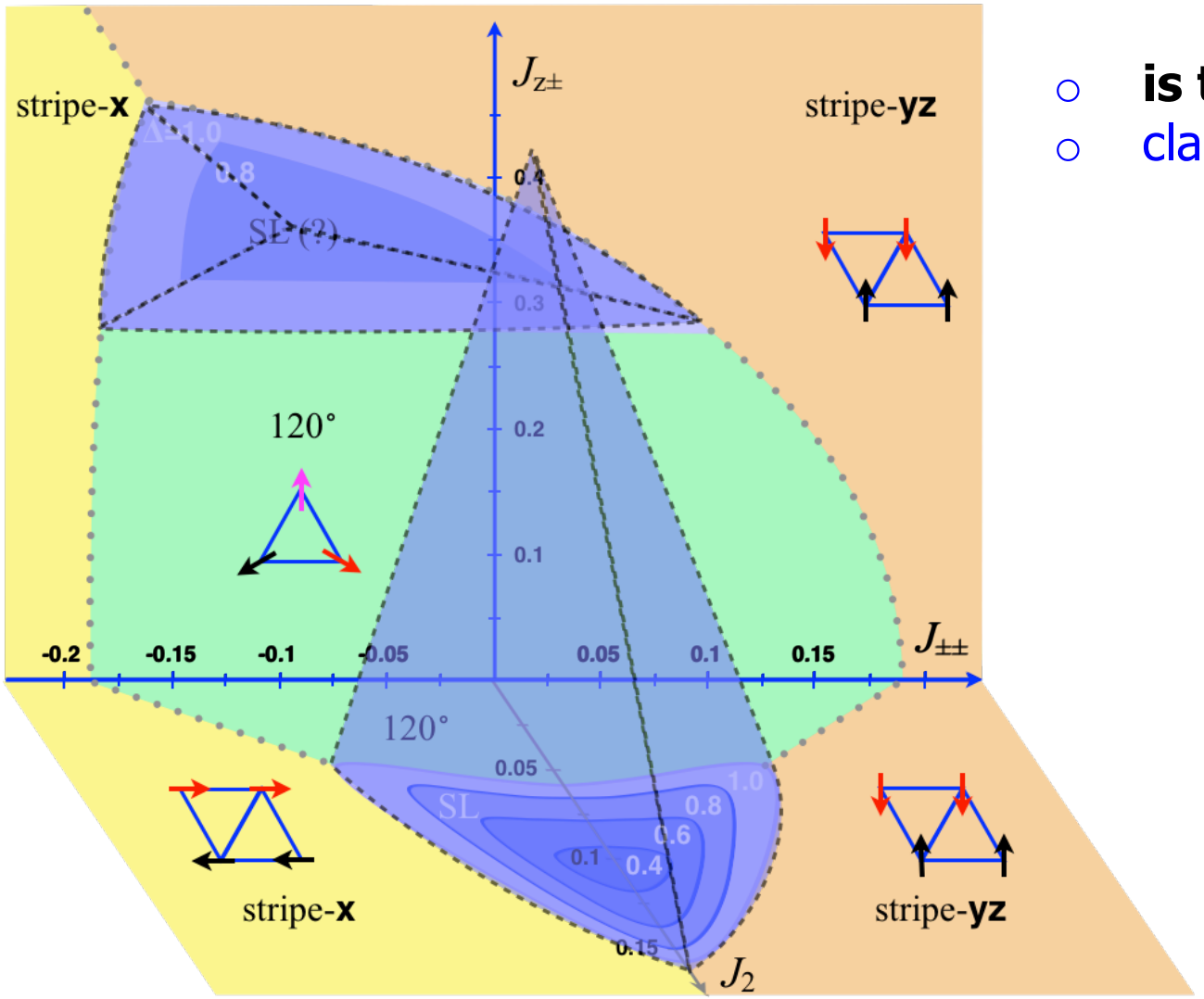
K-points



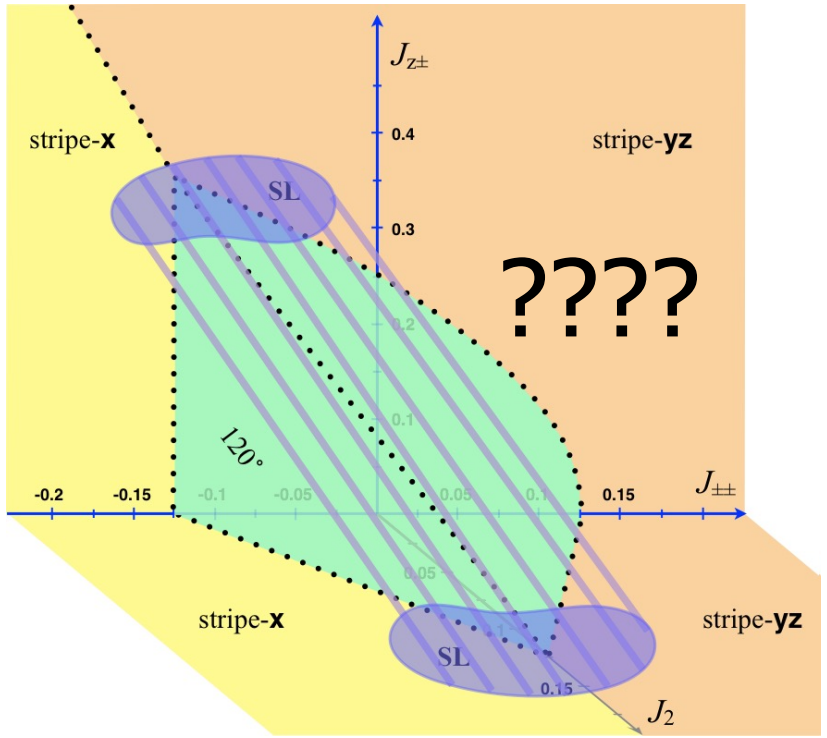




connection with the SL in J_1-J_2-XXZ-$J_{\pm\pm}$?



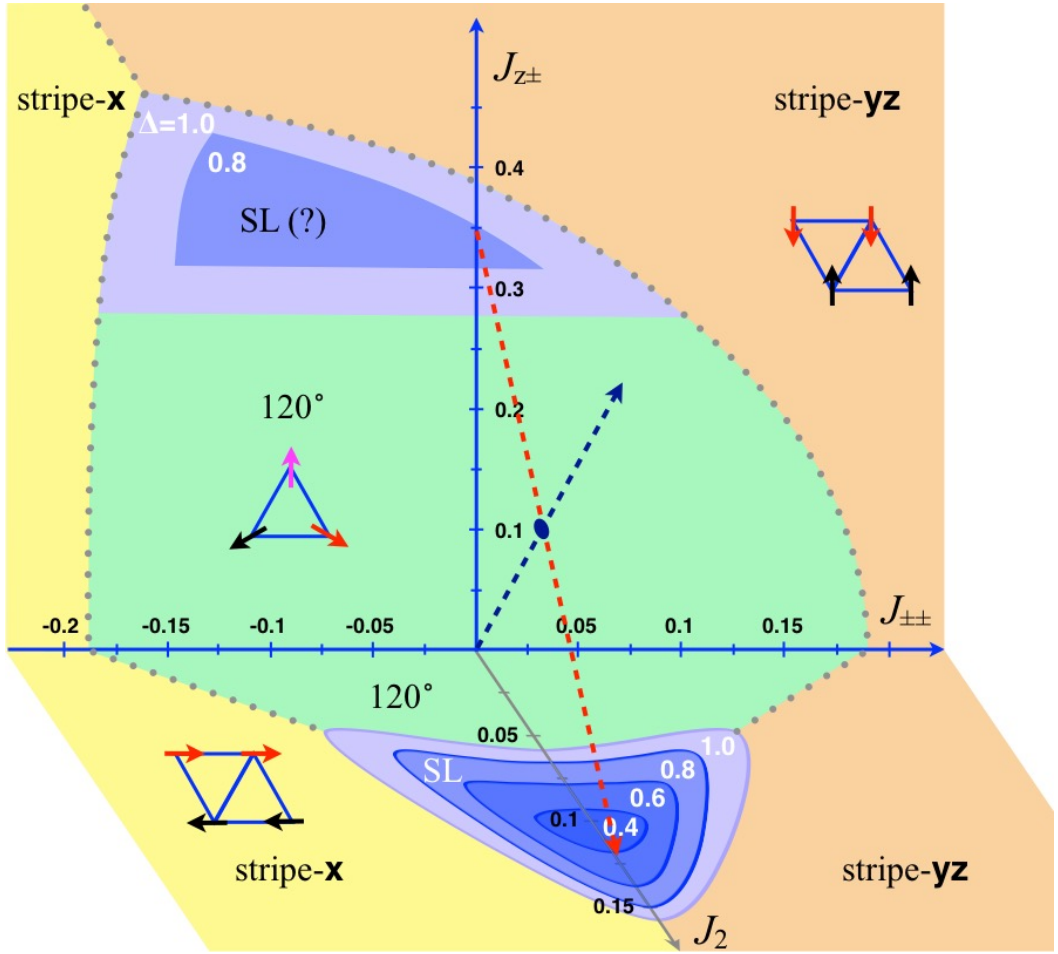
- **is there a connection between SL phases?**
- classically, connection along the rim of the 120 phase



Z. Zhu and S. R. White, PRB **92**, 041105 (2015).

Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **119**, 157201 (2017).

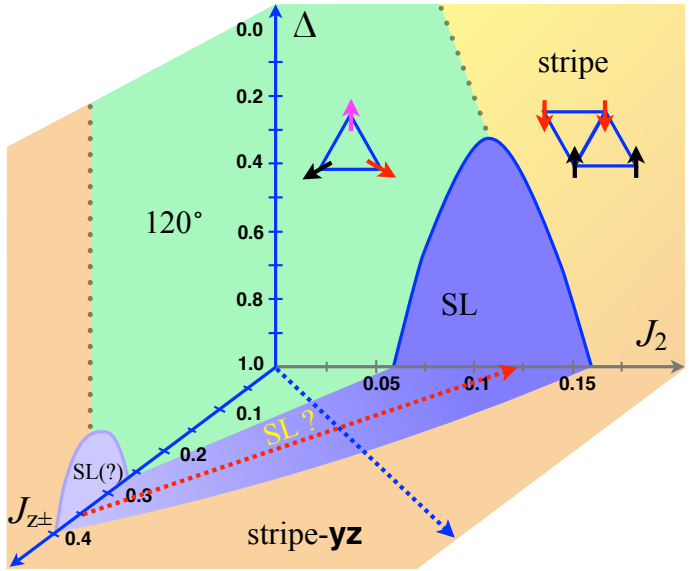
4D-extension, from SL to SL

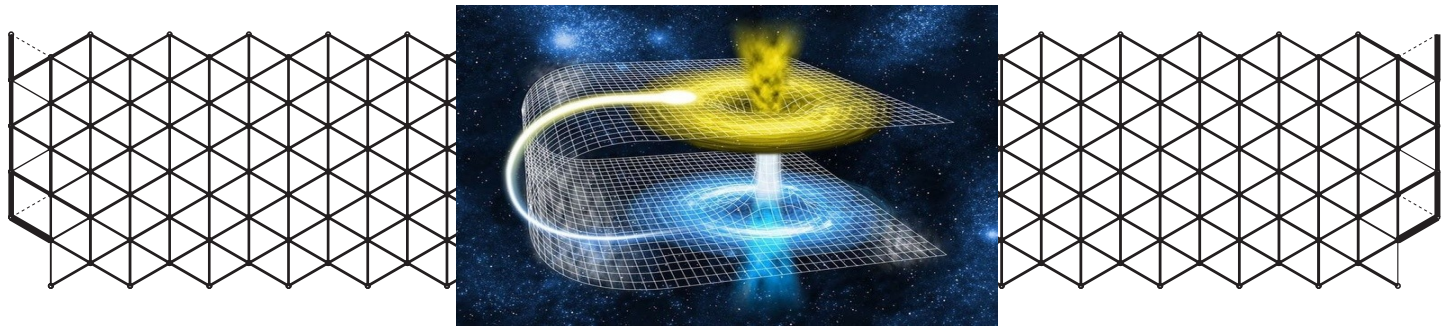


- **a DMRG scan from "anisotropic" SL to J_1-J_2 SL**

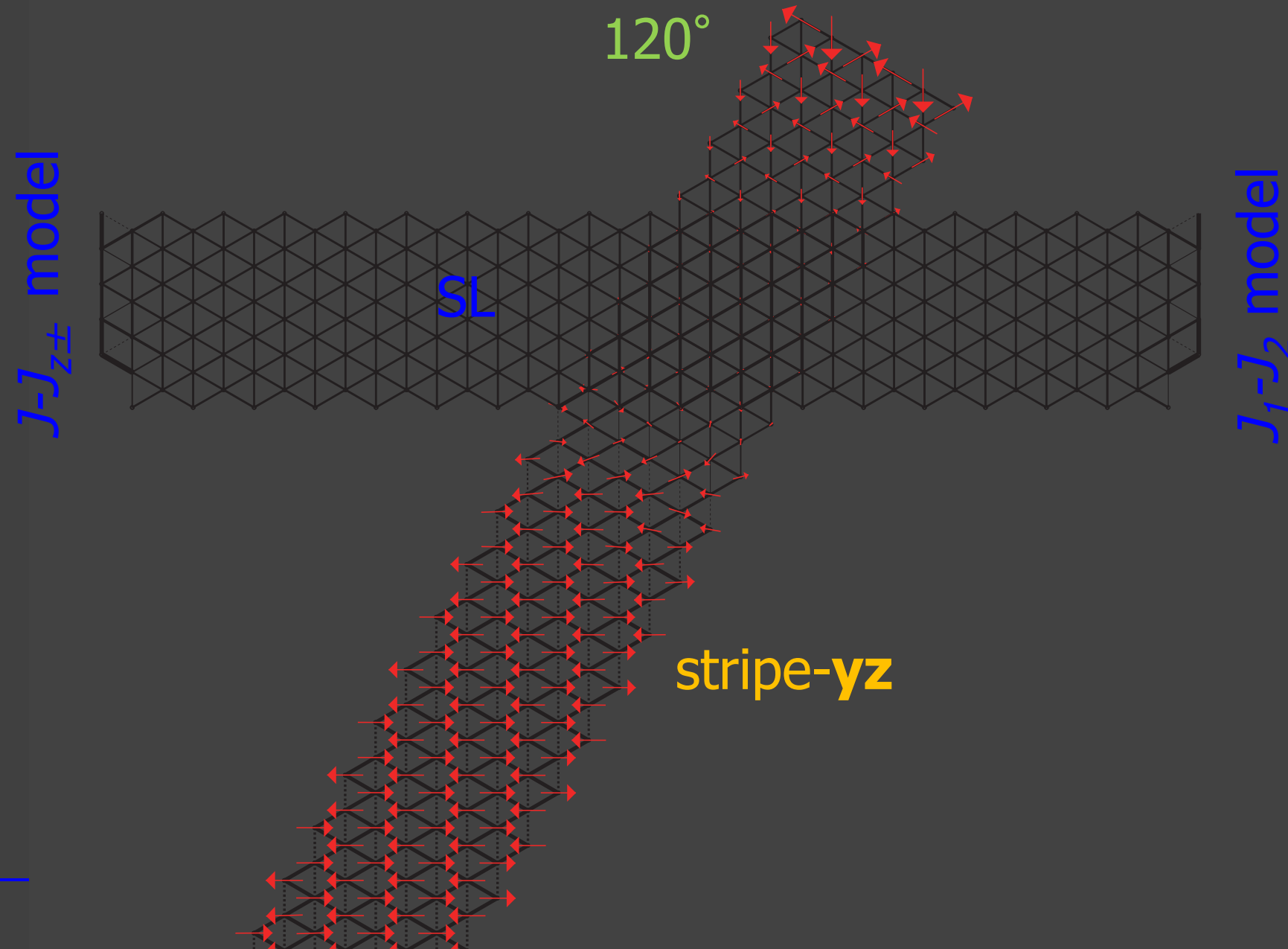
what happens when two spin liquids meet?

- **domain wall?**
- entangled state?
- black hole?
- **wormhole???**

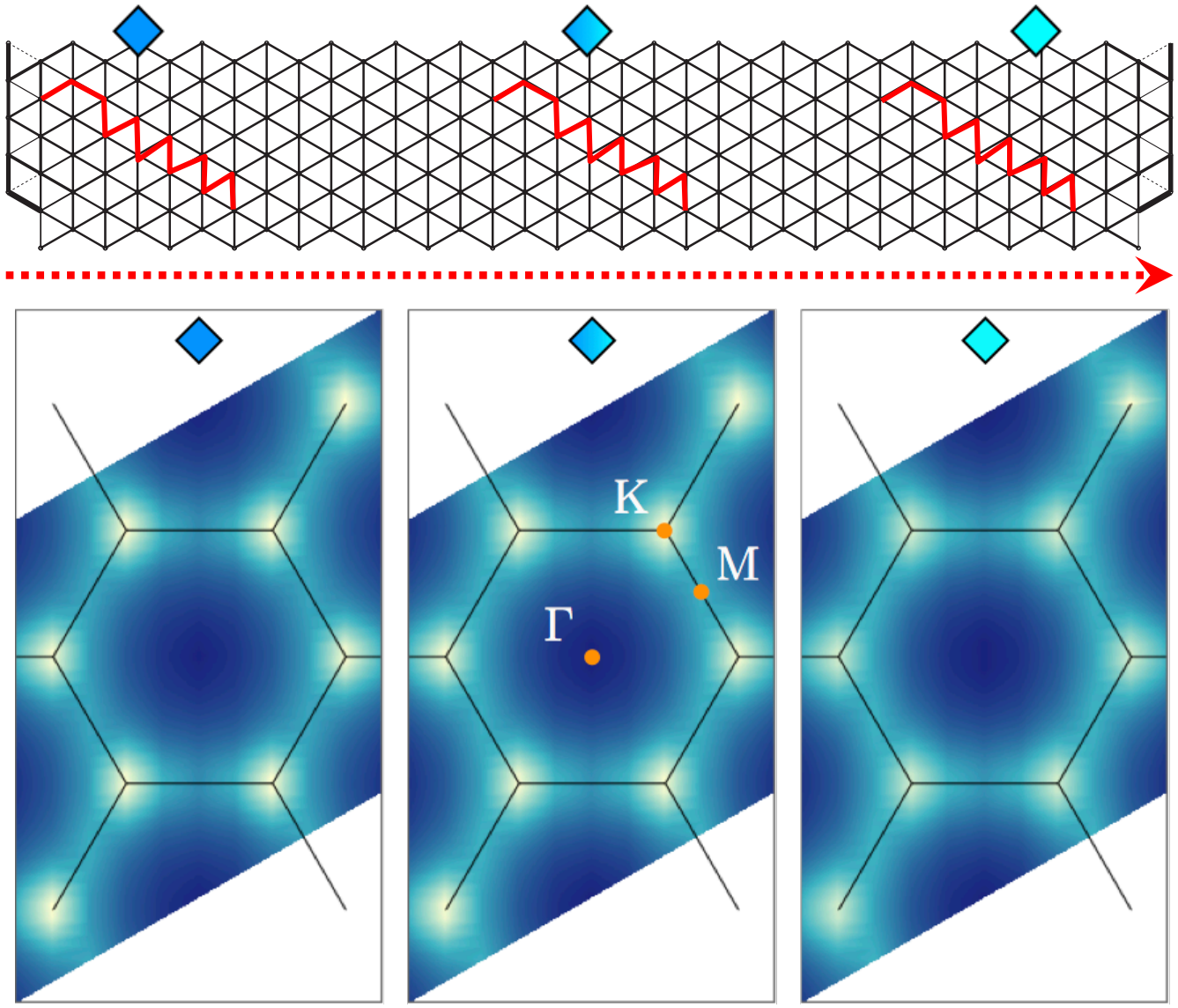




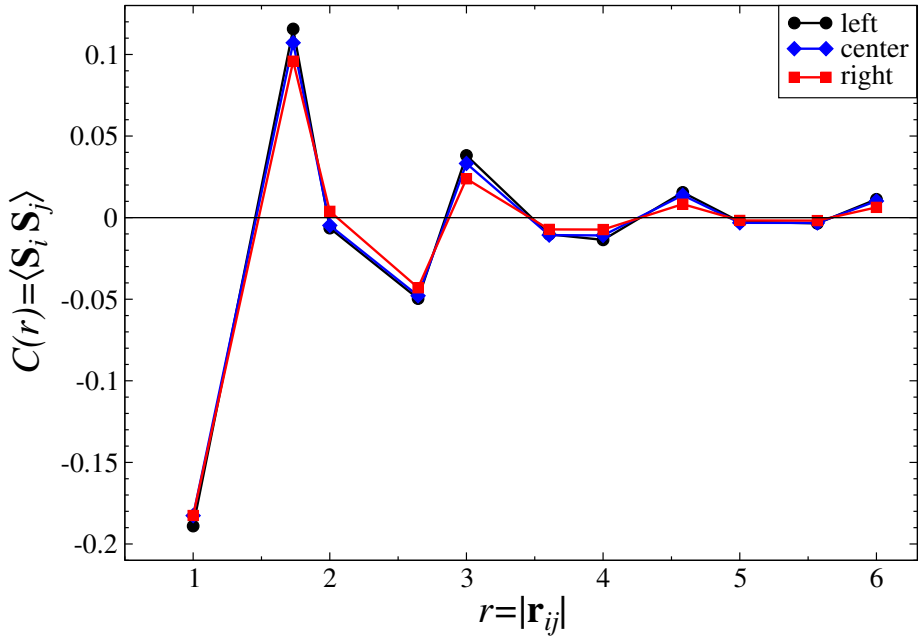
Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **120**, 207203 (2018)


120°
SL
J-$J_{z\pm}$ model
J_1-J_2 model
stripe-**yz**

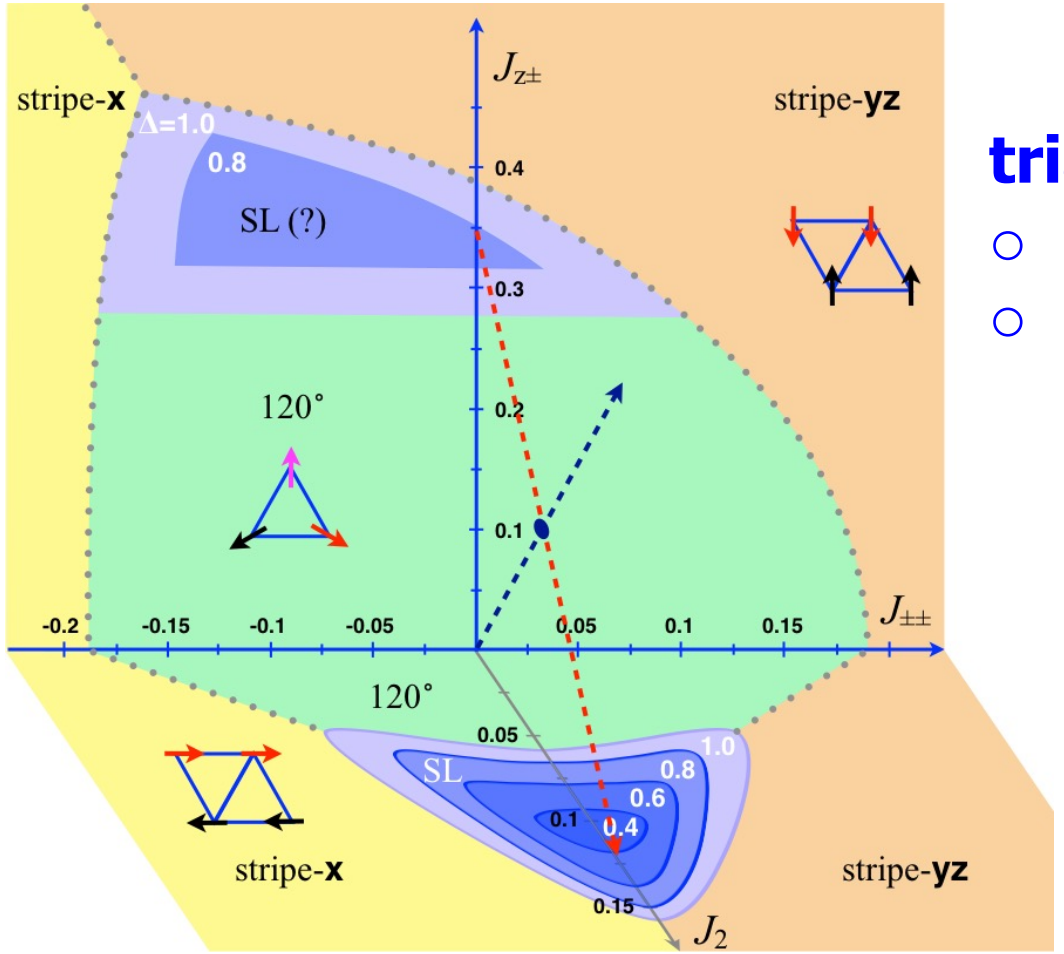
spin-liquid isomorphism



- no order all the way through the "SL scan"
  [**no** VBS or chiral order too]
- bonds = n.-n. $\langle \mathbf{S}_i \mathbf{S}_j \rangle$, no transition
- $S(\boldsymbol{q})$ is nearly identical [<5% variation]
- real-space correlations are the same
- ⇛ **spin liquids are isomorphic**
  (= same phase)

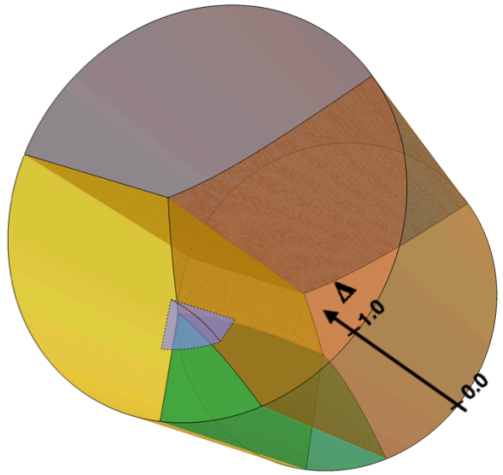


Z. Zhu, P. A. Maksimov, S. R. White, and SC, PRL **120**, 207203 (2018)



triangular lattice:

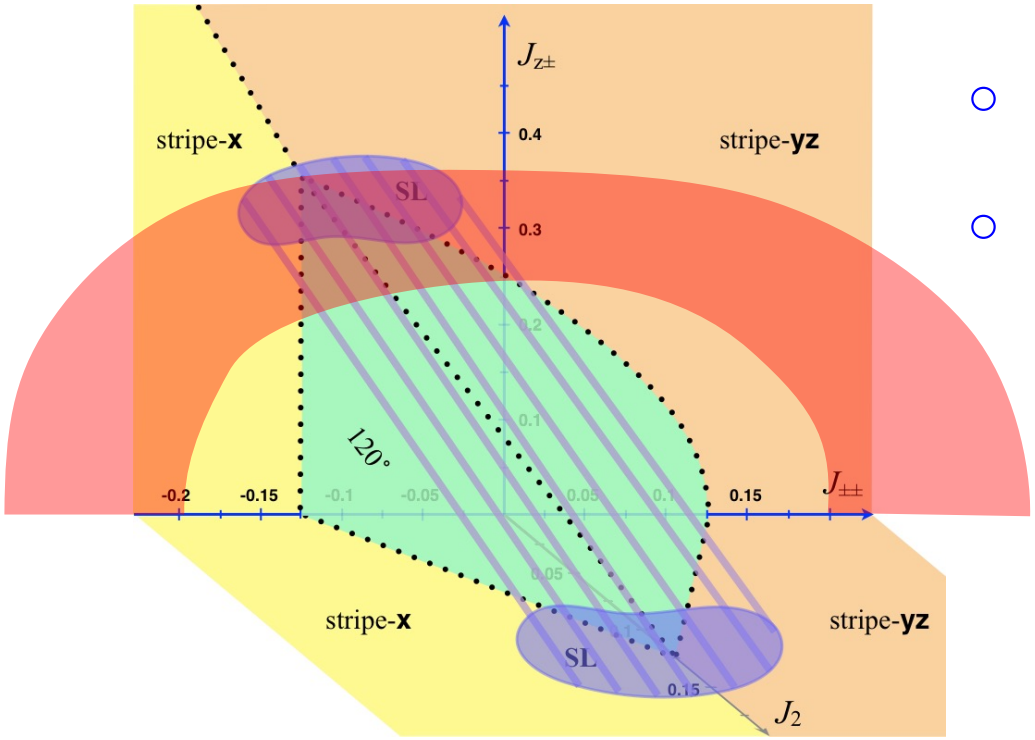
- **new SL in anisotropic-exchange n-n model**
- **it is isomorphic to the one in the J_1-J_2 model**



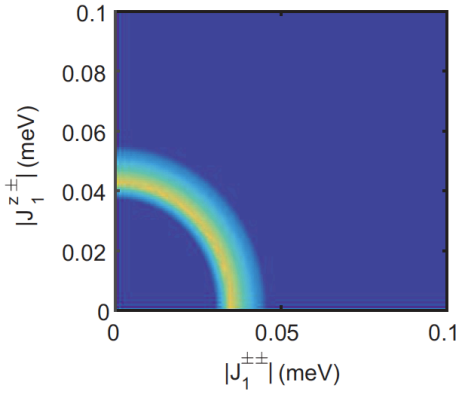
"where is disorder-free YMGO?", II

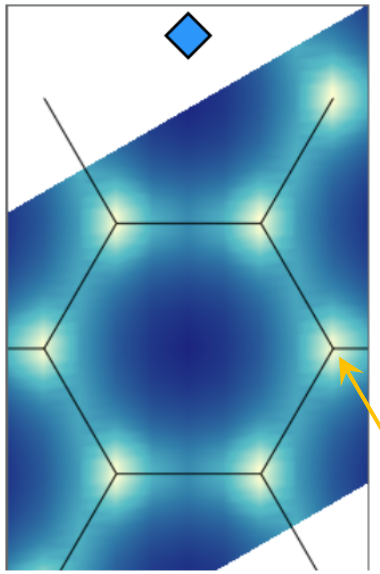
$$J_1^{zz} = 0.13(1)\ \text{meV}, \quad J_1^{\pm} = 0.08(1)\ \text{meV},$$
$$J_2/J_1 = 0.18(7), \quad \sqrt{|J_1^{\pm\pm}|^2 + |J_1^{z\pm}|^2} \lesssim 0.05\ \text{meV}$$

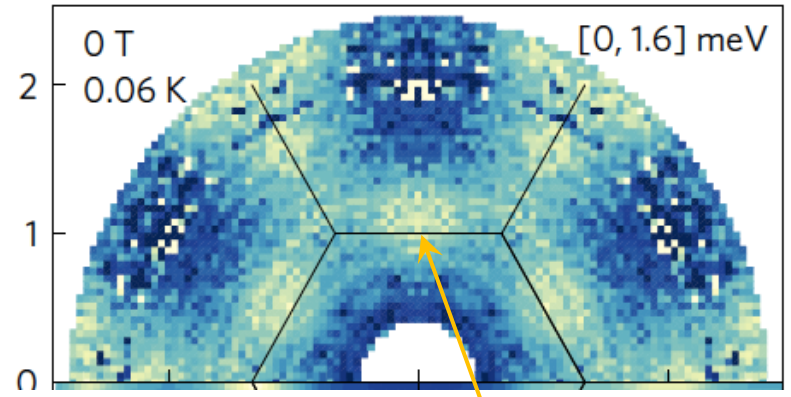
⇛ Δ=0.8(1), J_2 = 0.18(7)J_1 , $J_{\pm\pm}$≈ 0.2-0.3 , $J_{z\pm}$≈ 0.25-0.35



- closer to isotropic *XXZ*, larger bond-dependent terms, tied in a "ring of fire"
- **outside SL, deep in the stripe phase**
- **even if: wrong SL!** [*S*(***q***) different]







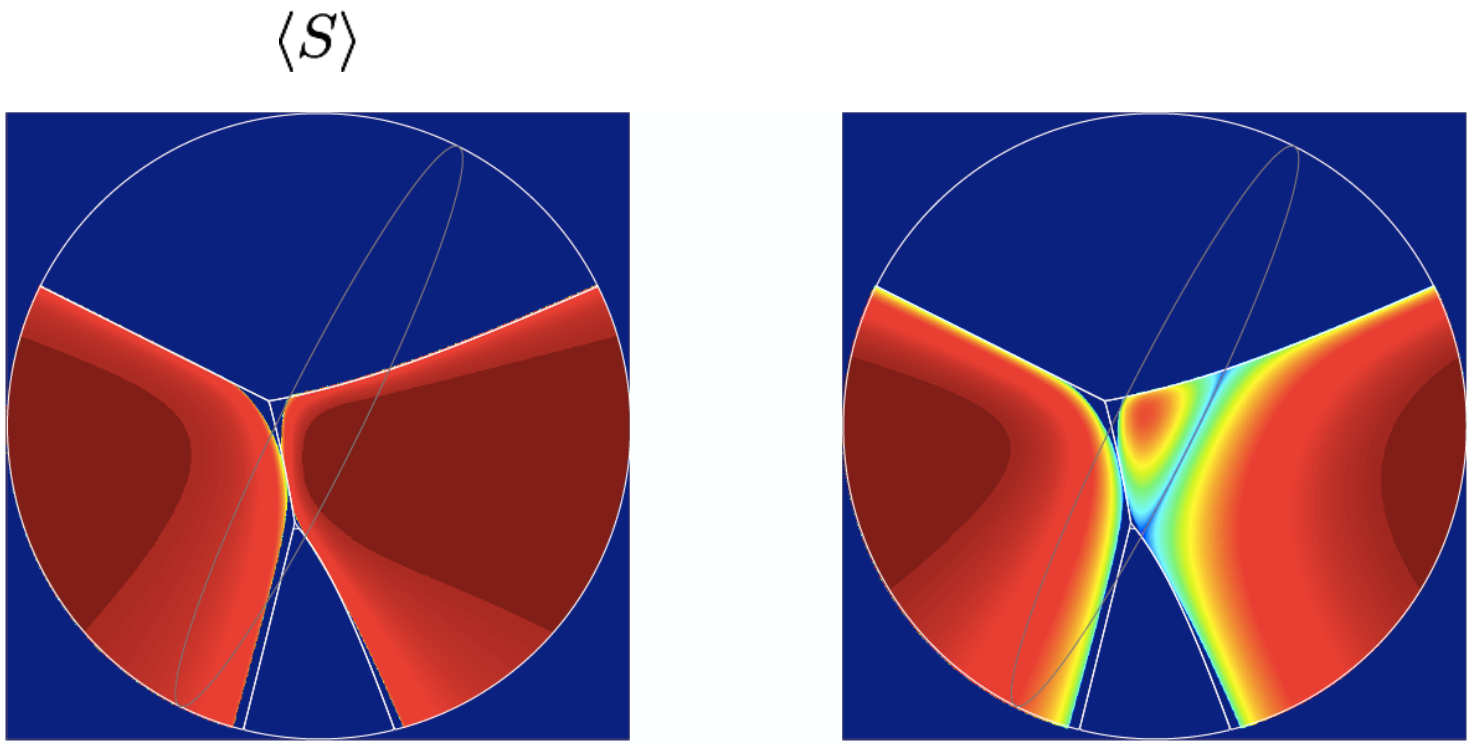
K-points

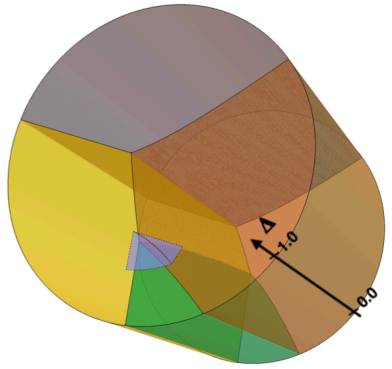
M-points

X. Zhang *etal*, arXiv:1708.07503

truality

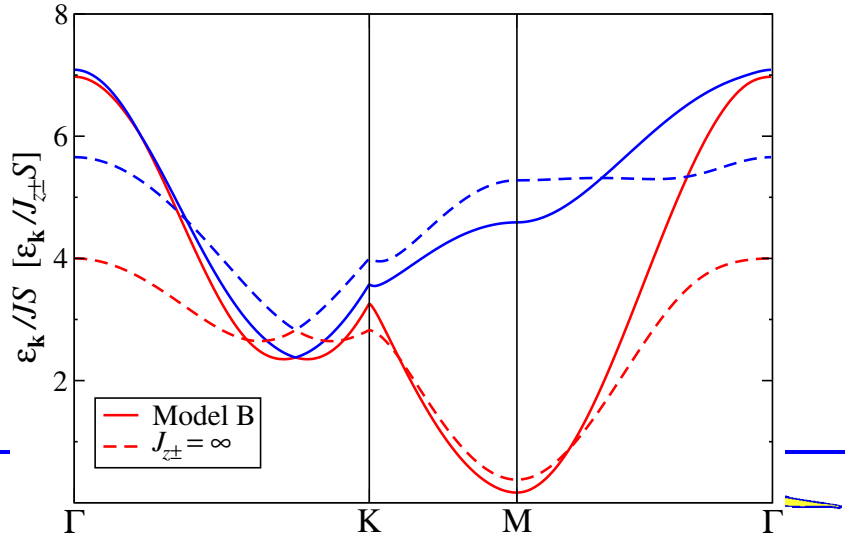
stripe phases, ordered moment vs T_N



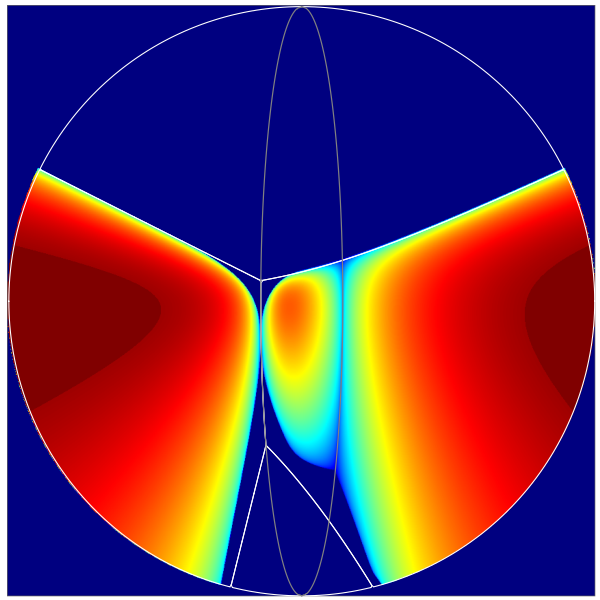


$\Delta = 0.0$

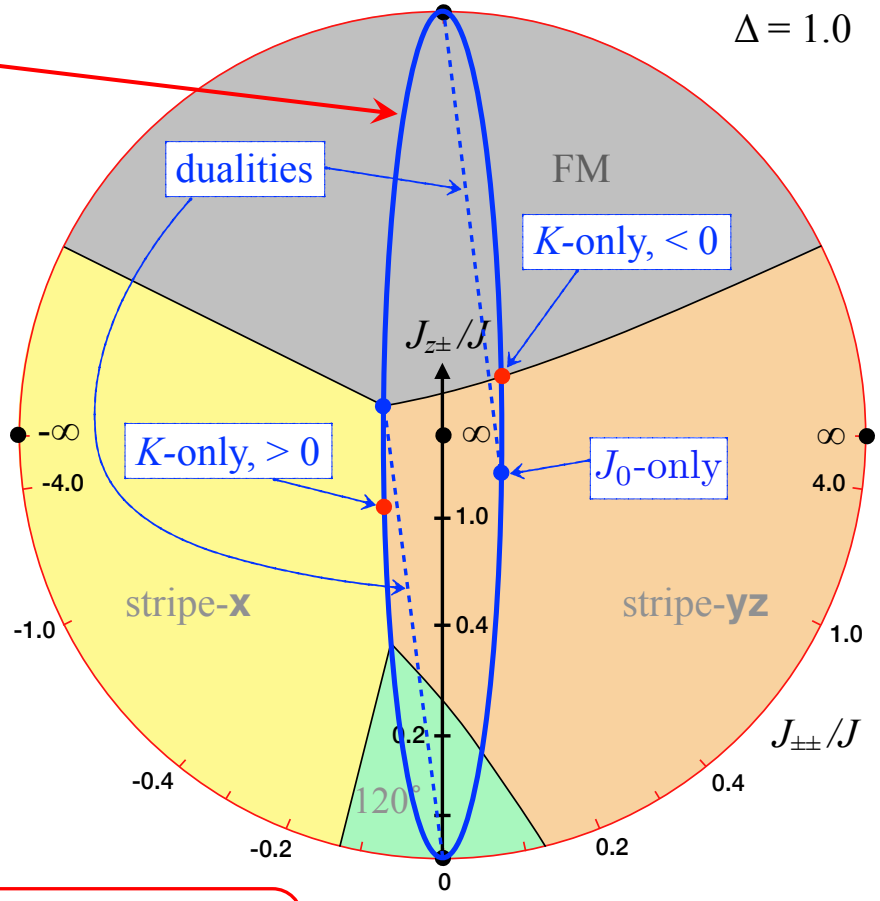
- **stripe phases:**
  ordered moment is nearly classical
- **Neel temperature is strongly suppressed around a weird line**
- **spectrum has a pseudo-Goldstone mode along it**
- **similar for other Δ's**



J-K-Γ-Γ′ model correspondence



- for Δ=**1.0** and $J_{z\pm}=2\sqrt{2}J_{\pm\pm}$ **line** the model becomes ***J-K*** model
- **hence, pseudo-goldstone modes**
- **yz**-stripe sector ⇛ **duality to FM** ⇛ nearly classical state
- **elsewhere (not on that line)**: ⇛ equivalent to ***J-K-Γ-Γ′*** model



$$\mathcal{H} = \sum_{\langle ij\rangle}[J_{zz}S_i^zS_j^z + J_{\pm}(S_i^+S_j^- + S_i^-S_j^+) + J_{\pm\pm}(\gamma_{ij}S_i^+S_j^+ + \gamma_{ij}^*S_i^-S_j^-) - \frac{iJ_{z\pm}}{2}(\gamma_{ij}^*S_i^+S_j^z - \gamma_{ij}S_i^-S_j^z + \langle i\leftrightarrow j\rangle)]$$

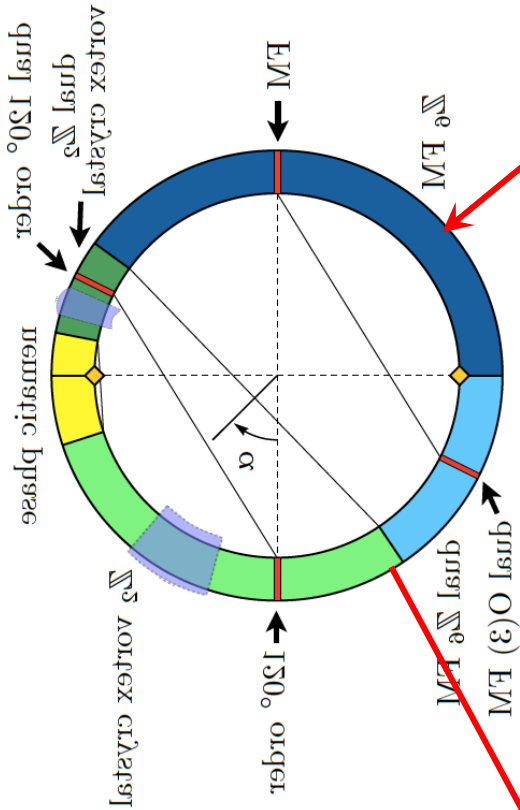
$$\Rightarrow \quad \mathcal{H} = -\tilde{J}\sum_{\langle ij\rangle}\mathbf{S}_i\cdot\mathbf{S}_j - K\sum_{\gamma\parallel\langle ij\rangle}S_i^\gamma S_j^\gamma$$

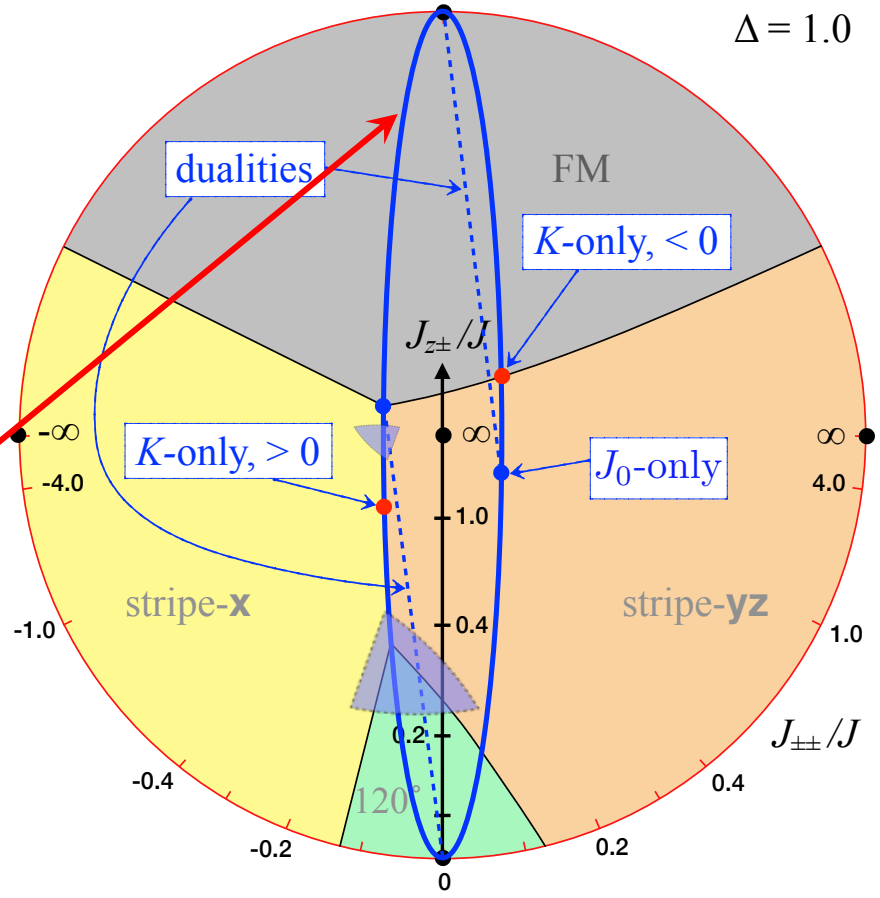
N. Perkins, discussion; I. Kimchi, private communication; J. G. Rau and M. J. P. Gingras, arXiv:1802.03024

dualities

- triangular-lattice ***J-K*** model:
  no Kitaev-like solution, still an SL phase
- ***J-K*** model on triangular lattice has been studied before
  [missed SL]
- there should exist a **dual SL phase**

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





I. Rousochatzakis *etal*, PRB **93**, 104417 (2016); M. Becker *etal*, PRB **91**, 155135 (2015)

conclusions

- ☑ **emergent consensus**: YMGO spin-liquid-like response is disorder-induced, not intrinsic ⇛ [generic for ObD, + plain=strong disorder]

- ☑ **3D/4D quantum phase diagram**: SL phase, ⇛ isomorphism to J_1-J_2 SL state; framework for the triangular-lattice based systems

- ☑ ***J-K* correspondence**: "dual SL"; suppressed T_N

- ☑ life does not end where spin-liquid does