order and excitations in large-*S* kagomé-lattice antiferromagnets

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Life and Death in Kagomé Flatland

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PRL **113,** 237202 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Quantum Selection of Order in an *XXZ* Antiferromagnet on a Kagome Lattice

A. L. Chernyshev[1] and M. E. Zhitomirsky[2]

- ☑ A. L. Chernyshev, arXiv:1507.04738 (→PRB)
- ☑ A. L. Chernyshev and M. E. Zhitomirsky, arXiv:1508.06632

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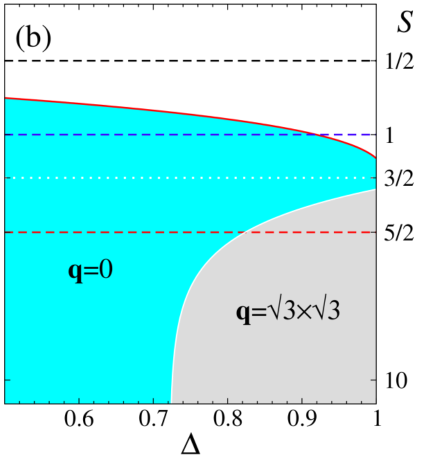
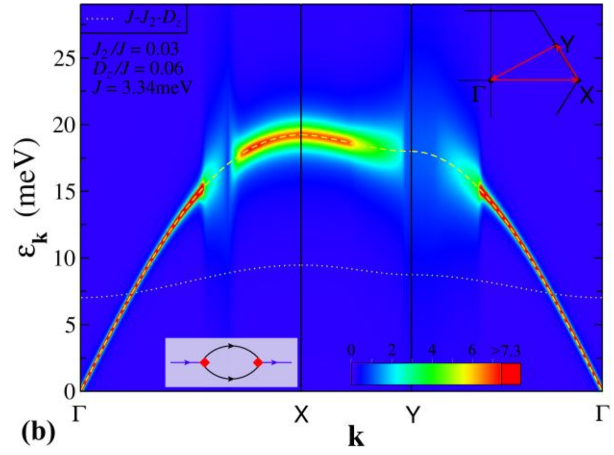
plan



I. quantum selection of the ground state

II. spectra of some real large-*S* kagomé AFs



history

- Ising case: residual entropy at *T=0*, as in the triangular lattice (Wannier, 1950)

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Progress of Theoretical Physics, Vol. VI, No. 3, May~June, 1951.

Statistics of Kagomé Lattice

Itiro Syôzi

Department of Physics, Osaka University

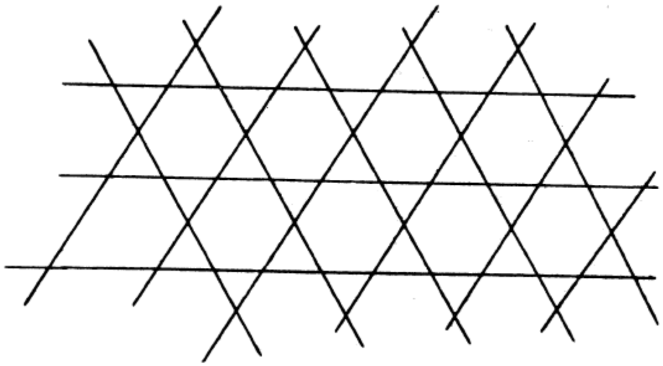


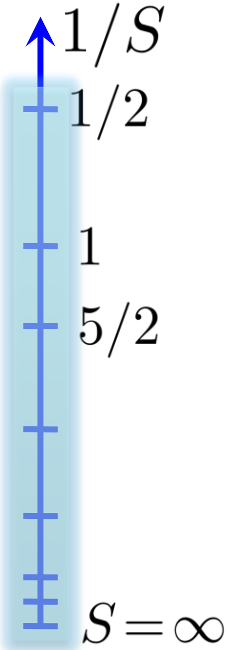
Fig. 1. Kagomé Lattice

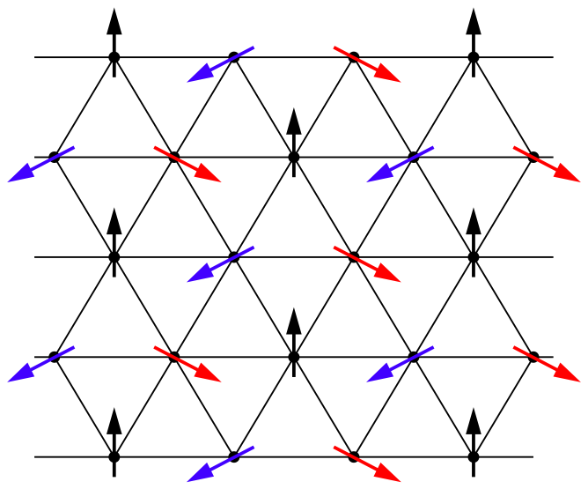
After the work of Onsager,[1] who solved exactly the problem of Ising model for the case of plane square lattice, the same problems for the honeycomb and triangular lattice were treated by several authors.[2] Other than these three types of lattices, there is left a lattice, called in Japanese kagomé (woven bomboo pattern), which consists exclusively of equivalent lattice points and equivalent bonds. Since the number of nearest neighbors of a lattice point is as many as

triangular vs kagomé, Heisenberg case

- vector spins: triangular lattice ⇛ a unique 120° order for all *S*

$$\mathcal{H} \Rightarrow \frac{J}{4}\sum_{\triangle}\mathbf{S}_{\triangle}^{2} - \frac{3J}{2}\sum_{i}\mathbf{S}_{i}^{2}$$





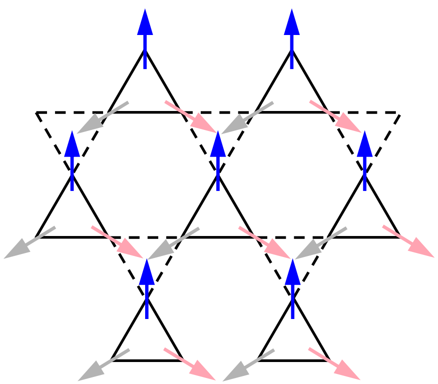
triangular vs kagomé, Heisenberg case

$$\mathcal{H} \Rightarrow \frac{J}{2}\sum_{\triangle}\mathbf{S}_{\triangle}^2 - J\sum_i \mathbf{S}_i^2$$

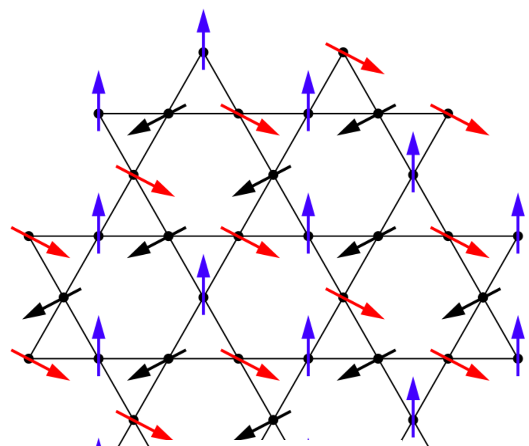
- kagomé lattice ⇛ classical energy is minimized by **any** 120° state with $\mathbf{S}_{\triangle}=0$
  ⇛ massive degeneracy within the 120° coplanar manifold

- fluctuations ⇛ order-by-disorder, "island of stability"*

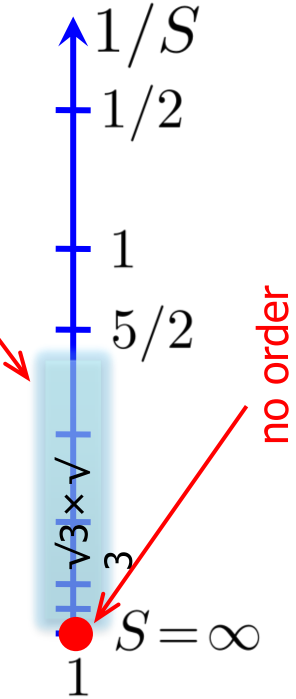
two main contenders
for the ordered state



q=0



√3 × √3



*A. V. Chubukov, PRL **69**, 832 (1992)

progress by Heisenberg ⇛ *XXZ*

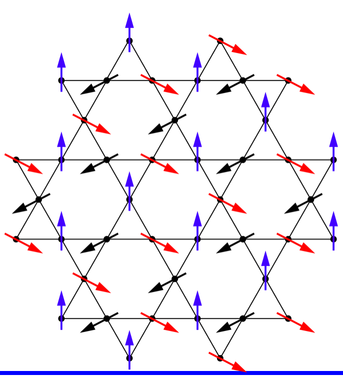
$$\mathcal{H} = J \sum_{\langle ij \rangle} \left(S_i^x S_j^x + S_i^y S_j^y + \Delta S_i^z S_j^z \right)$$

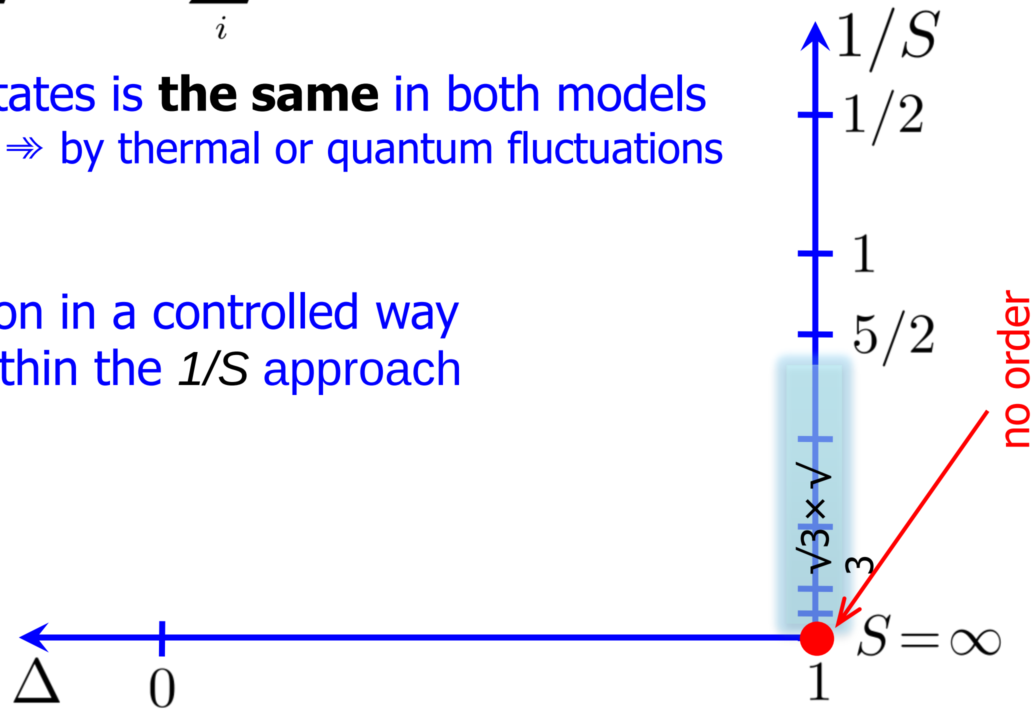
XXZ ⇛ analysis of what quantum fluctuations do, why/how

$$\mathcal{H} \Rightarrow \frac{J}{2} \sum_{\triangle} \mathbf{S}_{\triangle}^2 - J \sum_i \mathbf{S}_i^2$$

- degeneracy between **coplanar** states is **the same** in both models
  - *Heisenberg, coplanar structure ⇛ by thermal or quantum fluctuations
  - **XXZ* ⇛ anisotropy

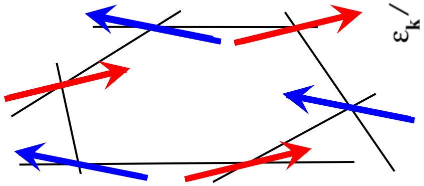
- *XXZ* ⇛ allows to study GS selection in a controlled way (perturbatively) within the *1/S* approach

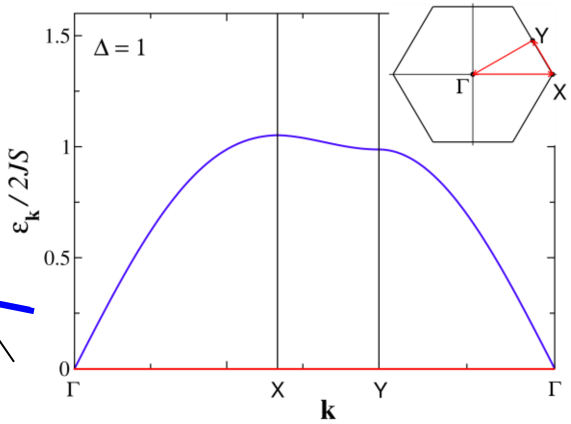




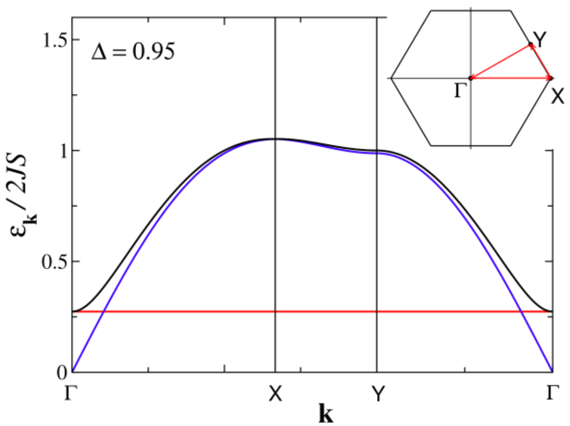
flat mode

- flat mode = local out-of-plane excitations
- Heisenberg limit*:
  - flat mode is at ω=0
  - *1/S* -expansion fails (1/0 = ∞)



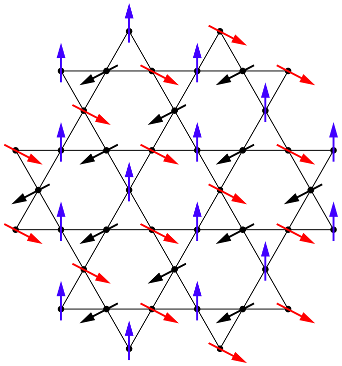


- *XXZ* case:
  - flat mode is gapped, $\omega \propto \sqrt{1-\Delta}$
  - *1/S* -expansion can be used



- *XXZ* ⇛ degeneracy is not lifted on the harmonic level, providing a more subtle case of order-by-disorder

$$\mathcal{H} = E_{\rm cl} + \mathcal{H}_2 + \ldots$$



*J. T. Chalker, P. C. W. Holdsworth, E. F. Shender, PRL **68**, 855 (1992)

non-linear terms …

… are responsible for the GS selection

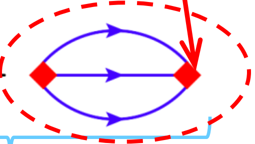
- in particular, the "cubic" terms

$$S^z = S - a^\dagger a\,,\quad S^x \approx \sqrt{S/2}\,(a^\dagger + a)$$

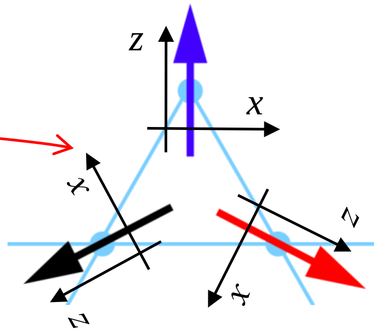
$$\hat{\mathcal{H}} = J \sum_{\langle ij \rangle} \Big(\Delta S_i^y S_j^y + \cos\theta_{ij}(S_i^x S_j^x + S_i^z S_j^z) + \sin\theta_{ij}(S_i^z S_j^x - S_i^x S_j^z) \Big)$$

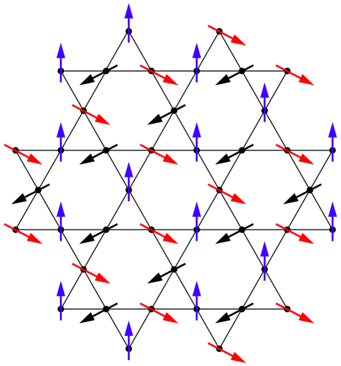
[*H* is in the local reference frame basis of a coplanar structure]

because for all 120° states all $\cos\theta_{ij} = -1/2$, but $\sin\theta_{ij} = \pm\sqrt{3}/2$

⇛ in the *1/S* -expansion of the GS $E = E_{\rm cl} + \langle \mathcal{H}_2 \rangle + \langle \mathcal{H}_4 \rangle +$ 

only the last term can be responsible for lifting GS degeneracy $\mathcal{O}(S^0)$





J. T. Chalker, P. C. W. Holdsworth, E. F. Shender, PRL **68**, 855 (1992)
A. V. Chubukov, PRL **69**, 832 (1992)

non-linear SWT

Harris etal (92)* ("two step" LSWT diagonalization for kagomé)

- we generalized it to XXZ and for non-linear (cubic) terms [elegant form]

These eigenvectors define a unitary transformation of the original Holstein-Primakoff bosons to the new ones

$$a_{\alpha,\mathbf{k}} = \sum_{\nu} w_{\nu,\alpha}(\mathbf{k})\, d_{\nu,\mathbf{k}}\,, \quad d_{\nu,\mathbf{k}} = \sum_{\alpha} w_{\nu,\alpha}(\mathbf{k})\, a_{\alpha,\mathbf{k}}\,, \quad (42)$$

such that the harmonic Hamiltonian $\hat{\mathcal{H}}_2$ in the form of (9) with $\hat{\mathbf{A}}_{\mathbf{k}}$'s and $\hat{\mathbf{B}}_{\mathbf{k}}$'s from (14) with (21), (24), or (29) is turned into three independent Hamiltonians

$$\hat{\mathcal{H}}_2 = 2JS\sum_{\nu,\mathbf{k}}\Big[A_{\nu,\mathbf{k}} d^{\dagger}_{\nu,\mathbf{k}} d_{\nu,\mathbf{k}} - \frac{B_{\nu,\mathbf{k}}}{2}\big(d^{\dagger}_{\nu,\mathbf{k}} d^{\dagger}_{\nu,-\mathbf{k}} + \text{h. c.}\big)\Big].$$

$$\mathcal{H}_3 = \frac{1}{3!}\frac{1}{\sqrt{N}}\sum_{\mathbf{k},\mathbf{q}}\sum_{\nu\mu\eta} V^{\nu\mu\eta}_{\mathbf{qkp}}\, b^{\dagger}_{\nu,\mathbf{q}} b^{\dagger}_{\mu,\mathbf{k}} b^{\dagger}_{\eta,-\mathbf{p}} + \text{h.c.}, \quad (51)$$

$$+\frac{1}{2!}\frac{1}{\sqrt{N}}\sum_{\mathbf{k},\mathbf{q}}\sum_{\nu\mu\eta} \Phi^{\nu\mu\eta}_{\mathbf{qk;p}}\, b^{\dagger}_{\nu,\mathbf{q}} b^{\dagger}_{\mu,\mathbf{k}} b_{\eta,\mathbf{p}} + \text{h.c.}, \quad (52)$$

with the vertices for the "source" and the "decay" terms

$$V^{\nu\mu\eta}_{\mathbf{qkp}} = -J\sqrt{\frac{3S}{2}}\,\widetilde{V}^{\nu\mu\eta}_{\mathbf{qkp}}\,, \quad \Phi^{\nu\mu\eta}_{\mathbf{qk;p}} = -J\sqrt{\frac{3S}{2}}\,\widetilde{\Phi}^{\nu\mu\eta}_{\mathbf{qk;p}}\,, \quad (53)$$

where the symmetrized dimensionless vertices are

$$\begin{aligned}\widetilde{V}^{\nu\mu\eta}_{\mathbf{qkp}} &= F^{\nu\mu\eta}_{\mathbf{qkp}}(u_{\nu\mathbf{q}}+v_{\nu\mathbf{q}})(u_{\mu\mathbf{k}}v_{\eta\mathbf{p}}+v_{\mu\mathbf{k}}u_{\eta\mathbf{p}})\\ &+F^{\mu\eta\nu}_{\mathbf{kpq}}(u_{\mu\mathbf{k}}+v_{\mu\mathbf{k}})(u_{\nu\mathbf{p}}v_{\eta\mathbf{q}}+v_{\nu\mathbf{p}}u_{\eta\mathbf{q}})\\ &+F^{\eta\nu\mu}_{\mathbf{pqk}}(u_{\eta\mathbf{p}}+v_{\eta\mathbf{p}})(u_{\nu\mathbf{q}}v_{\mu\mathbf{k}}+v_{\nu\mathbf{q}}u_{\mu\mathbf{k}})\,,\end{aligned} \quad (54)$$

and

$$\begin{aligned}\widetilde{\Phi}^{\nu\mu\eta}_{\mathbf{qk;p}} &= F^{\nu\mu\eta}_{\mathbf{qkp}}(u_{\nu\mathbf{q}}+v_{\nu\mathbf{q}})(u_{\mu\mathbf{k}}u_{\eta\mathbf{p}}+v_{\mu\mathbf{k}}v_{\eta\mathbf{p}})\\ &+F^{\mu\eta\nu}_{\mathbf{kpq}}(u_{\mu\mathbf{k}}+v_{\mu\mathbf{k}})(u_{\nu\mathbf{p}}u_{\eta\mathbf{q}}+v_{\nu\mathbf{p}}v_{\eta\mathbf{q}})\\ &+F^{\eta\nu\mu}_{\mathbf{pqk}}(u_{\eta\mathbf{p}}+v_{\eta\mathbf{p}})(u_{\nu\mathbf{q}}v_{\mu\mathbf{k}}+v_{\nu\mathbf{q}}u_{\mu\mathbf{k}})\,,\end{aligned} \quad (55)$$

*A. B. Harris, C. Kallin, and A. J. Berlinsky, PRB **45**, 2899 (1992)

non-linear SWT

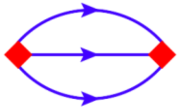
Harris etal (92)* ("two step" LSWT diagonalization for kagomé)

- we generalized it to XXZ and for non-linear (cubic) terms [elegant form]

q=0 $$F^{\nu\mu\eta}_{\mathbf{qkp}} = \sum_{\alpha\beta} \epsilon^{\alpha\beta\gamma} \cos(q_{\beta\alpha})\, w_{\nu,\alpha}(\mathbf{q}) w_{\mu,\beta}(\mathbf{k}) w_{\eta,\beta}(\mathbf{p}).$$

√3 × √3 $$F^{\nu\mu\eta}_{\mathbf{qkp}} = i \sum_{\alpha\beta} \epsilon^{\alpha\beta\gamma} \sin(q_{\beta\alpha})\, w_{\nu,\alpha}(\mathbf{q}) w_{\mu,\beta}(\mathbf{k}) w_{\eta,\beta}(\mathbf{p}).$$

- ⇛ energy correction



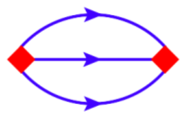
$$\delta E^{(3)} = -\frac{1}{6N} \sum_{\nu\mu\eta} \sum_{\mathbf{q},\mathbf{k}} \frac{\left|V^{\nu\mu\eta}_{\mathbf{q},\mathbf{k},-\mathbf{k}-\mathbf{q}}\right|^2}{\varepsilon^{\nu}_{\mathbf{q}} + \varepsilon^{\mu}_{\mathbf{k}} + \varepsilon^{\eta}_{-\mathbf{k}-\mathbf{q}}}$$

*A. B. Harris, C. Kallin, and A. J. Berlinsky, PRB **45**, 2899 (1992)

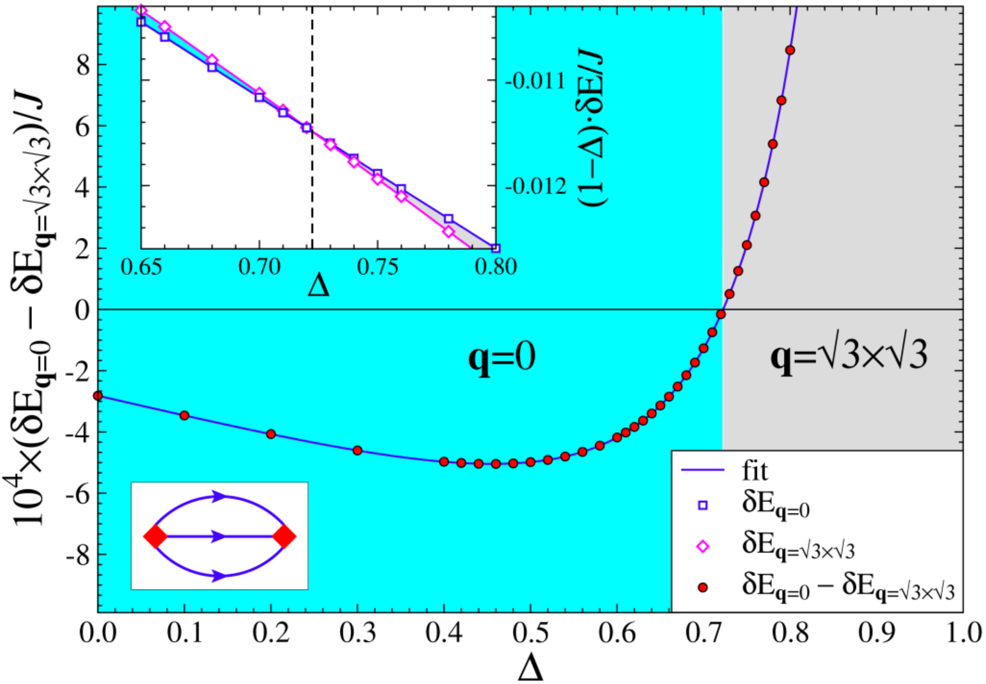
ground-state selection

- ⇛ energy correction*

  (*27 terms, 10 distinct)



$$\delta E^{(3)} = -\frac{1}{6N}\sum_{\nu\mu\eta}\sum_{\mathbf{q},\mathbf{k}}\frac{|V^{\nu\mu\eta}_{\mathbf{q},\mathbf{k},-\mathbf{k}-\mathbf{q}}|^2}{\varepsilon^{\nu}_{\mathbf{q}}+\varepsilon^{\mu}_{\mathbf{k}}+\varepsilon^{\eta}_{-\mathbf{k}-\mathbf{q}}}$$



- there is a transition from **q**=0 to √3 × √3 state at $\Delta_c \approx 0.72$
- different from thermal ObD selection
- small $\approx 3\cdot 10^{-4} J$ per spin
- diverges $\propto 1/(1-\Delta)$

(As far as we know, photo is public domain)

*SC and M. Zhitomirsky, PRL **113**, 237202 (2014)

why and how: real-space PT

how do quantum fluctuations select the GS?

- real-space perturbation theory* $\mathcal{H} \Rightarrow \frac{J}{2}\sum_{\triangle}\mathbf{S}_{\triangle}^2 - J\sum_i \mathbf{S}_i^2$

- expands around a manifold of classical 120° states with $\mathbf{S}_{\triangle} = 0$

- perturbations:

double flip: $V^{(1)} = -\frac{J}{4}\left(\Delta + \frac{1}{2}\right)\sum_{\langle ij\rangle}\left(S_i^+ S_j^+ + S_i^- S_j^-\right),$

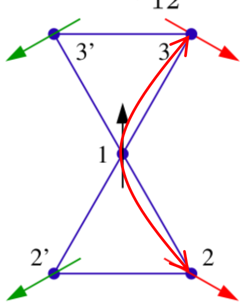
hopping: $V^{(2)} = \frac{J}{4}\left(\Delta - \frac{1}{2}\right)\sum_{\langle ij\rangle}\left(S_i^+ S_j^- + S_i^- S_j^+\right),$

cubic terms: $V^{(3)} = \frac{J}{2}\sum_{i,j}\sin\theta_{ij}\left(S - S_i^z\right)\left(S_j^+ + S_j^-\right),$

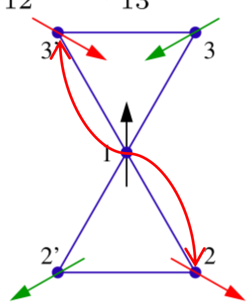
$V^{(4)} = -\frac{J}{2}\sum_{\langle ij\rangle}\left(S - S_i^z\right)\left(S - S_j^z\right)$

- the lowest-order (4th) correction fails to remove degeneracy (symmetry)
- first graph that does must have a non-trivial **topology** (around hexagon), ⇛ 7th (!) order

$V_{12}^{(1)} \to V_{13}^{(3)} \to V_{12}^{(3)} \to V_{13}^{(1)}$

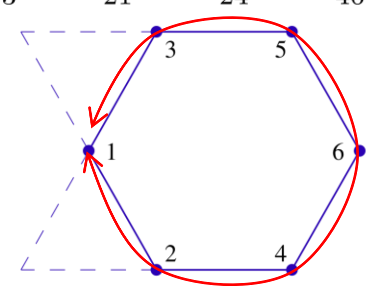


√3 × √3



q=0

$V_{12}^{(1)} \to V_{13}^{(3)} \to V_{21}^{(3)} \to V_{24}^{(2)} \to V_{46}^{(2)} \to V_{65}^{(2)} \to V_{35}^{(1)}$

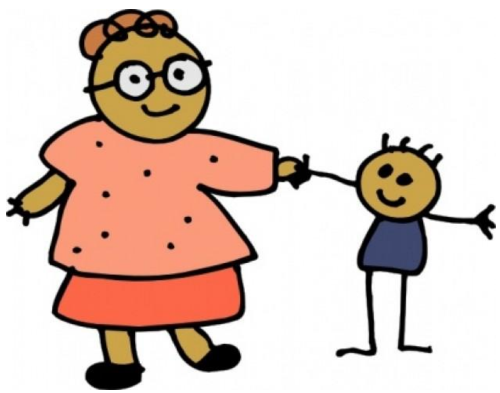


*M. W. Long, J. Phys.: CM **1**, 2857 (1989); M. T. Heinilä and A. S. Oja, PRB **48**, 7227 (1993);
B. Canals and M. E. Zhitomirsky, J. Phys.: CM **16**, S759 (2004); M.E. Zhitomirsky, J. Phys.: Conf. Ser. **592**, 012110 (2015).
D. L. Bergman, R. Shindou, G. A. Fiete, and L. Balents, PRB **75**, 094403 (2007); J. Phys.: CM **19**, 145204 (2007)

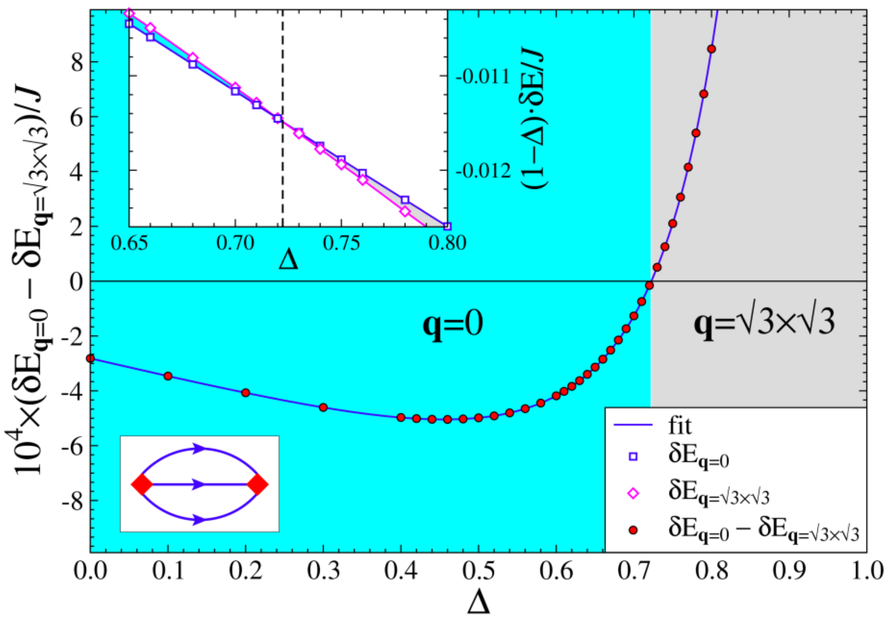
NLSWT vs RSPT

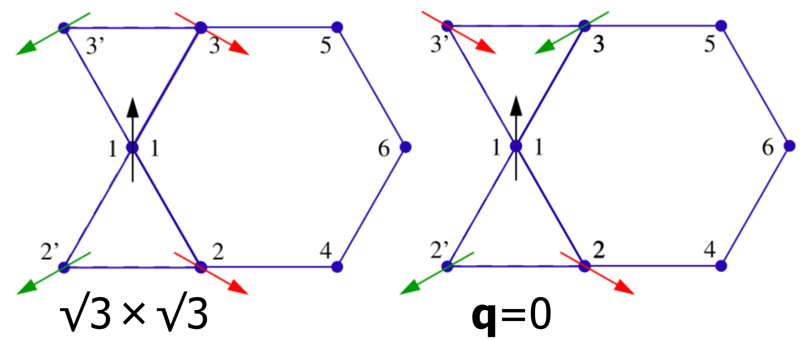
- ☑ 7th order $\delta E^{(7)} \propto \sin\theta_{12}\sin\theta_{13}$ ⇛ 2nd order in cubic terms, same as in NLSWT!
- ☑ coordination number expansion: $\delta E = 8J/z^7 \approx 5\cdot 10^{-4}J$ per spin ⇛ agree
- ☑ for Δ<1/2 **all** 7th order processes favor AF J_2 ⇛ **q**=0,

  for Δ>1/2 some switch sign ⇛ $\Delta_c > 1/2$ agree



NLSWT RSPT





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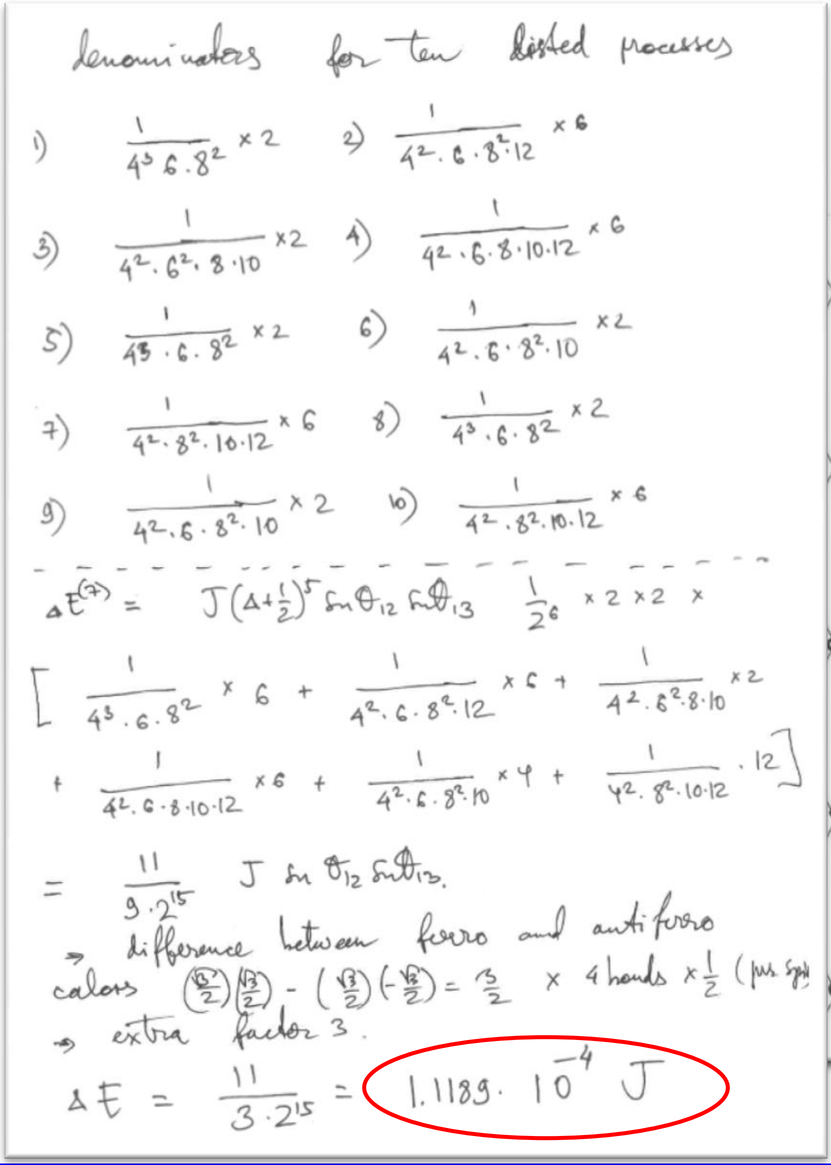
more RSPT


denominators for ten distinct processes

1) $\frac{1}{4^3\,6\cdot 8^2}\times 2$ 2) $\frac{1}{4^2\cdot 6\cdot 8^2\cdot 12}\times 6$

3) $\frac{1}{4^2\cdot 6^2\cdot 8\cdot 10}\times 2$ 4) $\frac{1}{4^2\cdot 6\cdot 8\cdot 10\cdot 12}\times 6$

5) $\frac{1}{4^3\cdot 6\cdot 8^2}\times 2$ 6) $\frac{1}{4^2\cdot 6\cdot 8^2\cdot 10}\times 2$

7) $\frac{1}{4^2\cdot 8^2\cdot 10\cdot 12}\times 6$ 8) $\frac{1}{4^3\cdot 6\cdot 8^2}\times 2$

9) $\frac{1}{4^2\cdot 6\cdot 8^2\cdot 10}\times 2$ 10) $\frac{1}{4^2\cdot 8^2\cdot 10\cdot 12}\times 6$

$$\Delta E^{(7)} = J(\Delta+\tfrac{1}{2})^5 \sin\theta_{12}\sin\theta_{13}\,\frac{1}{2^6}\times 2\times 2\times$$

$$\Big[\frac{1}{4^3\cdot 6\cdot 8^2}\times 6 + \frac{1}{4^2\cdot 6\cdot 8^2\cdot 12}\times 6 + \frac{1}{4^2\cdot 6^2\cdot 8\cdot 10}\times 2 + \frac{1}{4^2\cdot 6\cdot 8\cdot 10\cdot 12}\times 6 + \frac{1}{4^2\cdot 6\cdot 8^2\cdot 10}\times 4 + \frac{1}{4^2\cdot 8^2\cdot 10\cdot 12}\cdot 12\Big]$$

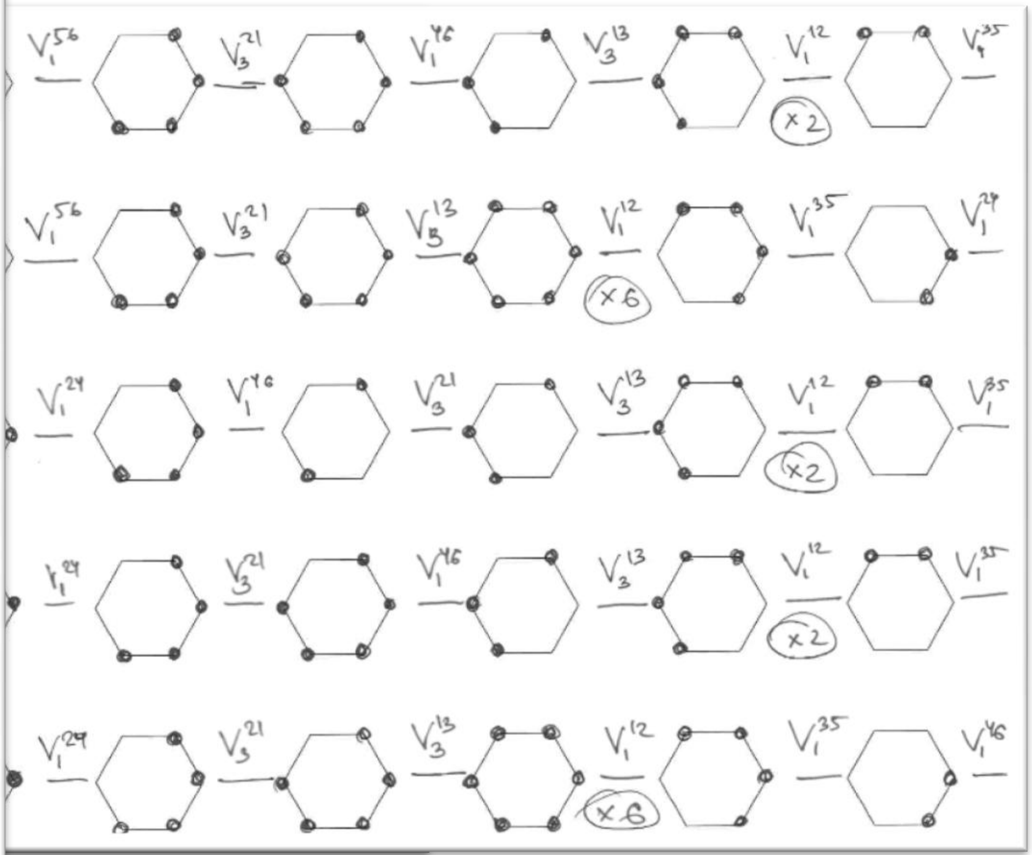
$$= \frac{11}{9\cdot 2^{15}}\, J \sin\theta_{12}\sin\theta_{13}$$

→ difference between ferro and antiferro colors $\left(\frac{\sqrt3}{2}\right)\left(\frac{\sqrt3}{2}\right) - \left(\frac{\sqrt3}{2}\right)\left(-\frac{\sqrt3}{2}\right) = \frac{3}{2}$ × 4 bonds × $\frac{1}{2}$ (plus sgn

→ extra factor 3.

$$\Delta E = \frac{11}{3\cdot 2^{15}} = 1.1189\cdot 10^{-4}\, J$$

☑ for Δ=1/2 can count **all** 7th order processes



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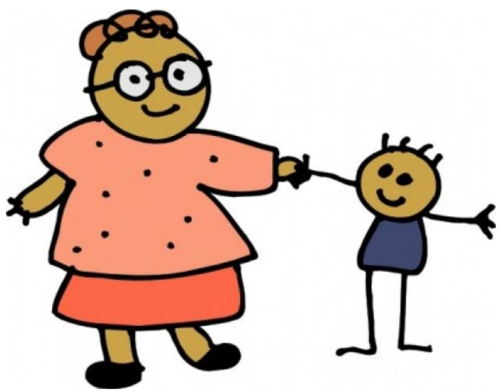
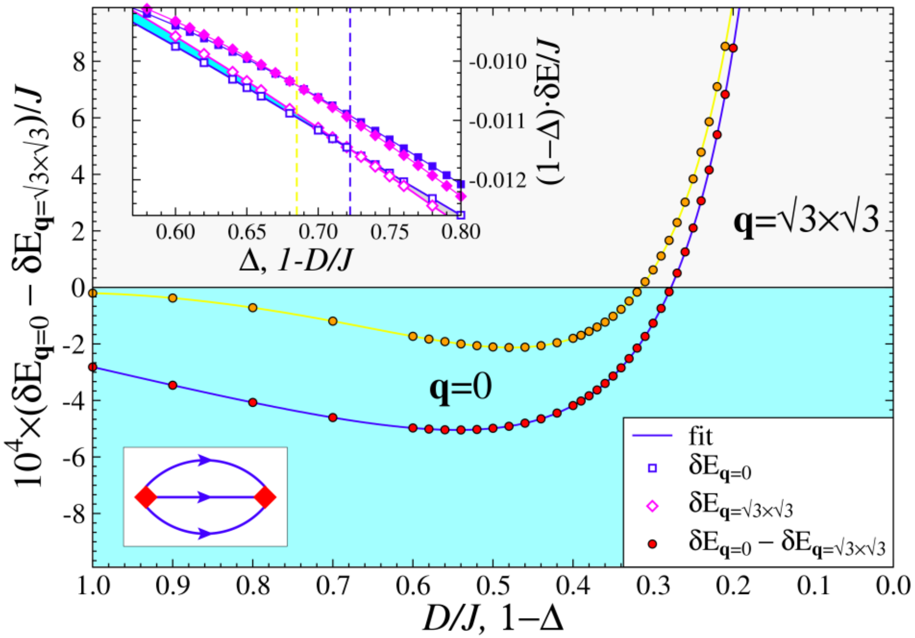
other *XXZ's*

- ☑ single-ion anisotropy, *D>0*, same effect, same qualitative GS selection
- ☑ however, local spin-flips = different, more local, require higher-order process

coordination number expansion: $\delta E \propto 1/z^8$ ⇛ agree

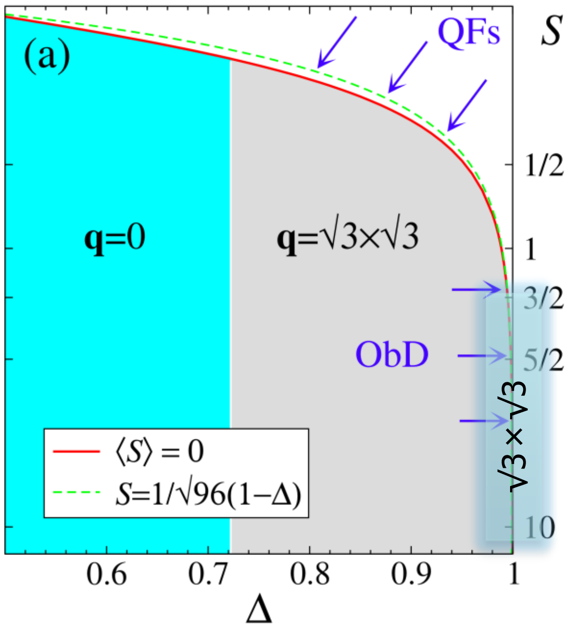
$$\mathcal{H} = J\sum_{\langle ij\rangle} \mathbf{S}_i\cdot\mathbf{S}_j + D\sum_i \left(S_i^z\right)^2$$





S-Δ PhD, I

naive, but honest …



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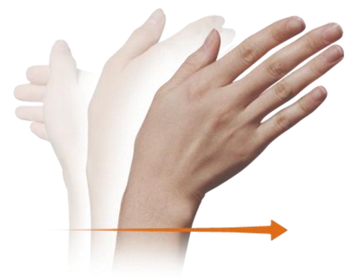
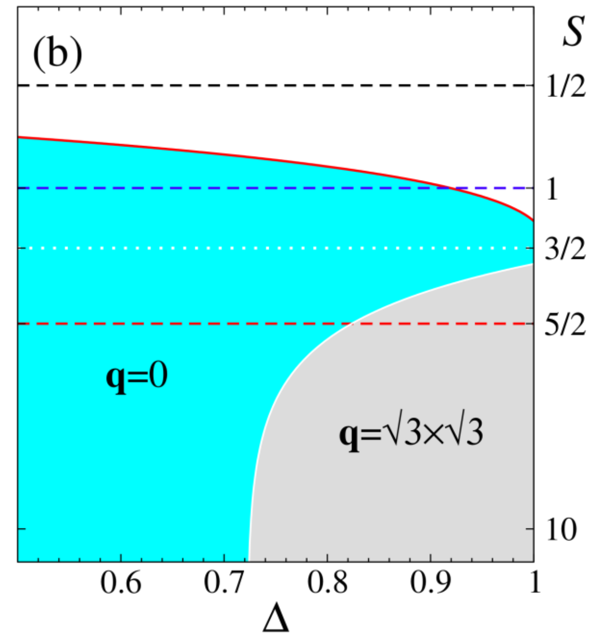


⇛



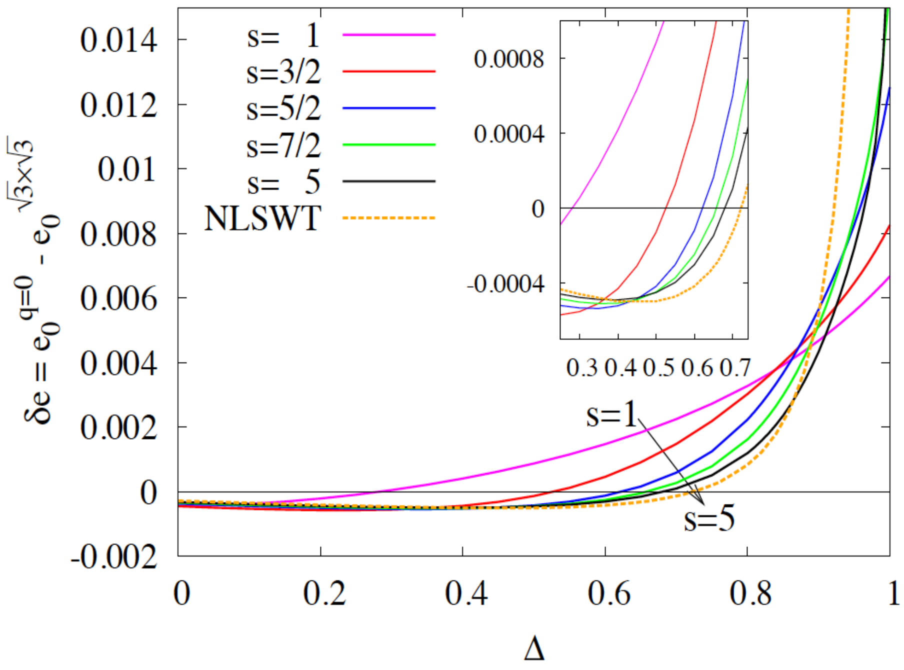
- *S*-Δ phase diagram from LSWT $\langle S \rangle = 0$, neglects tunneling effects, etc.
- **q**=0 to √3 × √3 transition from NLSWT results

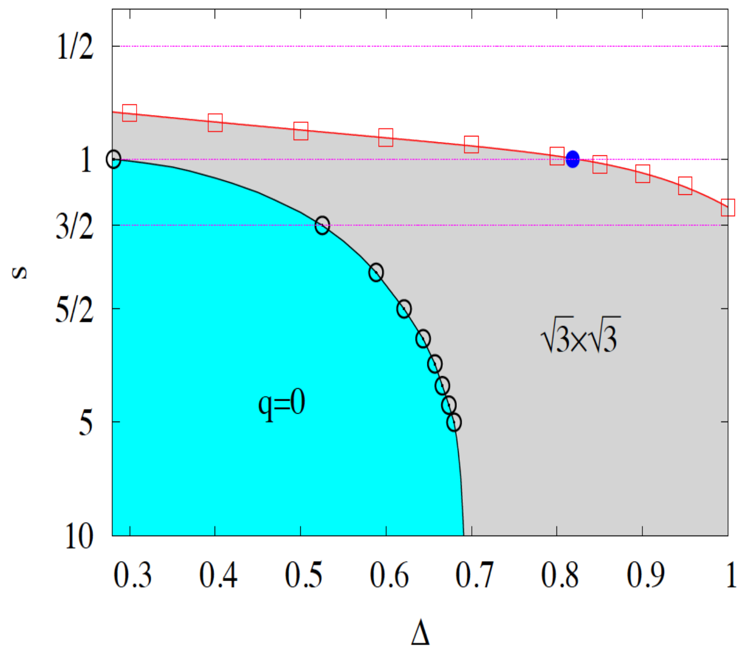
anticipated trends …

- QFs will suppress ordered region [*DMRG]
- ObD will create "island of stability" [**numerics: ⇛ island is big!]
- **q**=0 to √3 × √3 boundary? [***hints from self-consistent SWT]

*Y.-C. He and Y. Chen, PRL **114**, 037201 (2015); A. M. Läuchli; S. R. White, [private communications]
O. Gotze, D. J. J. Farnell, R. F. Bishop, P. H. Y. Li, and J. Richter, PRB **84, 224428 (2011)
***A. V. Chubukov, PRL **69**, 832 (1992)

PhD, II





- numerical method, similar to RSPT, qualitative and quantitative agreement
- different trend for **q**=0 to $\sqrt{3}\times\sqrt{3}$ boundary

O. Götze, J. Richter, PRB **91**, 104402 (2015)

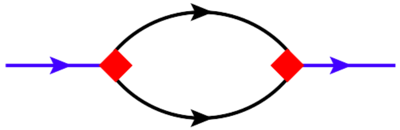
spectrum

spectrum

what happens with the spectrum due to non-linear terms?

two crucial ingredients:

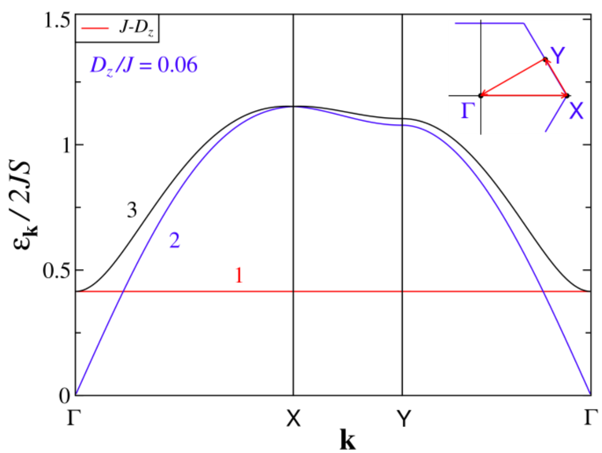
- noncollinear spin structure ⇛ 120° state ⇛ decays*

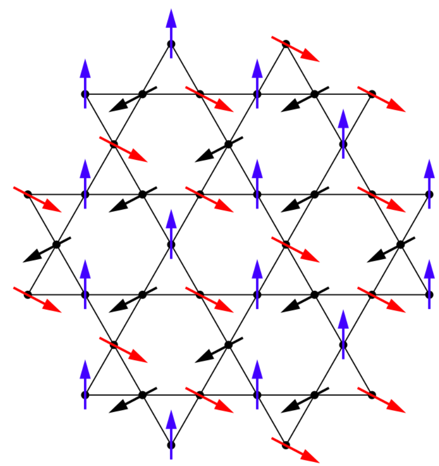


$$\hat{\mathcal{H}}_3 = \frac{1}{3!}\frac{1}{\sqrt{N}}\sum_{\mathbf{k},\mathbf{q}}\sum_{\nu\mu\eta} V^{\nu\mu\eta}_{\mathbf{qkp}}\, b^\dagger_{\nu,\mathbf{q}} b^\dagger_{\mu,\mathbf{k}} b^\dagger_{\eta,-\mathbf{p}} + \text{h.c.},$$

$$+\frac{1}{2!}\frac{1}{\sqrt{N}}\sum_{\mathbf{k},\mathbf{q}}\sum_{\nu\mu\eta} \Phi^{\nu\mu\eta}_{\mathbf{qk;p}}\, b^\dagger_{\nu,\mathbf{q}} b^\dagger_{\mu,\mathbf{k}} b_{\eta,\mathbf{p}} + \text{h.c.},$$

- flat mode(s)





*M. Zhitomirsky and **SC**, **RMP 85**, 219 (2013)

1/S or not 1/S ?

what's new when the flat mode is present?

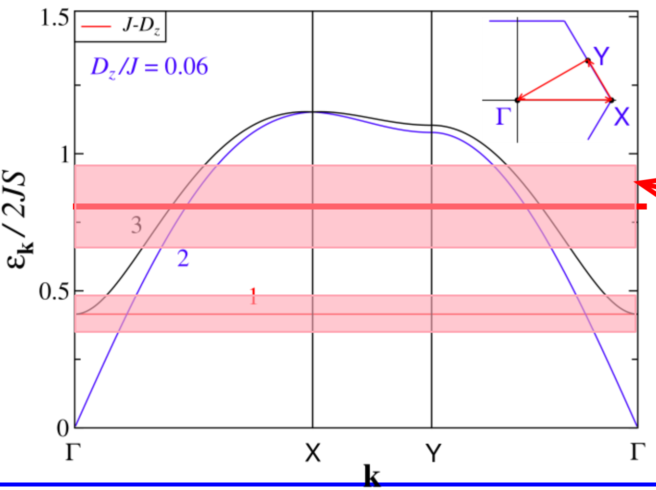
$S^z = S - a^\dagger a\,,$
$S^x \approx \sqrt{S/2}\,(a^\dagger + a)$

- usually, for decays from higher-energy states to lower ones

$$\Gamma_{\mathbf{k}} \propto J\,S \sum_{\mathbf{q}} \left|\Phi_{\mathbf{k},\mathbf{q}}\right|^2 \delta\left(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{q}} - \varepsilon_{\mathbf{k}-\mathbf{q}}\right) \qquad \varepsilon_{\mathbf{q}} \propto J\,S$$

$$\Rightarrow \quad \Gamma_{\mathbf{k}} \propto J \qquad \Rightarrow \quad \frac{\Gamma_{\mathbf{k}}}{\varepsilon_{\mathbf{k}}} \propto \frac{1}{S}$$

- flat mode ⇛ **resonant-like** decays at twice its energy ⇛ singularity



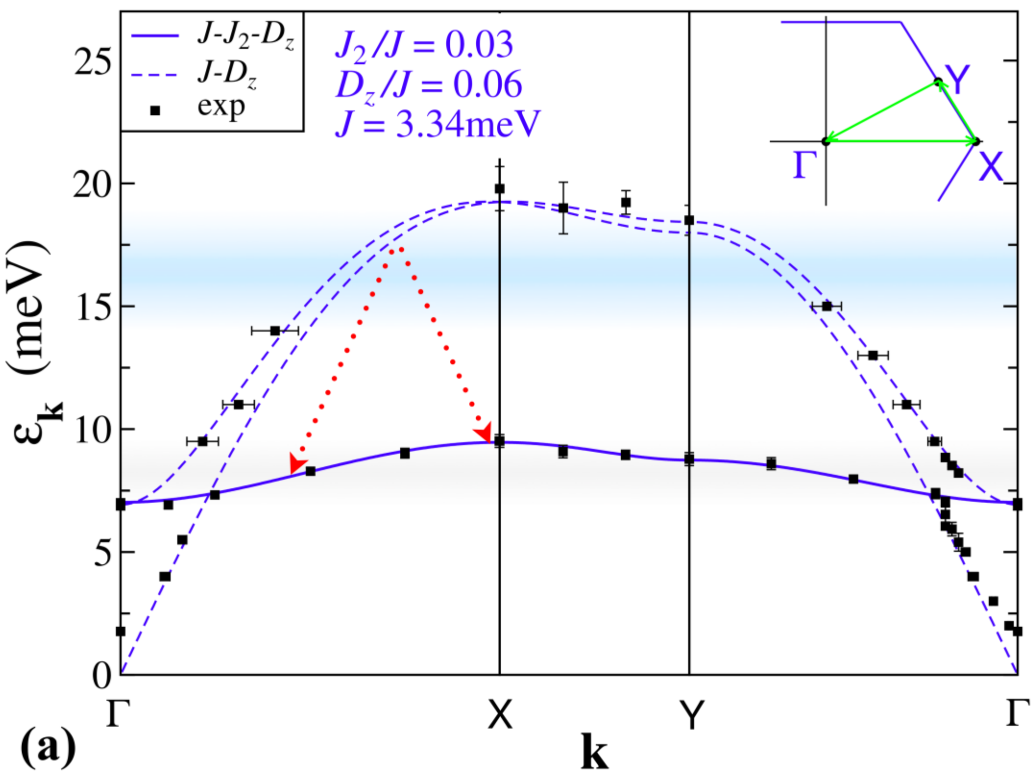
- *1/S* fluctuations **warp** the flat mode and regularize singularity
- fluctuation-induced dispersion is **spin-independent** $\delta\varepsilon_{\mathbf{k}} \propto J$
- decay rate $\Gamma_{\mathbf{k}} \propto S\,J$ **not** *1/S*-effect ⇛ not small even for large spins!

SC and M. Zhitomirsky, arXiv:1508.06632

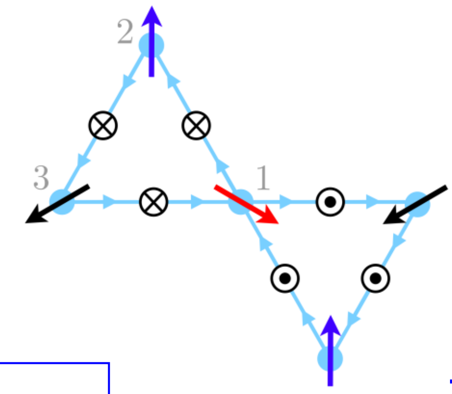
Fe-jarosite

$$\mathcal{H} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

almost classical, *S=5/2*, kagome-lattice antiferromagnet



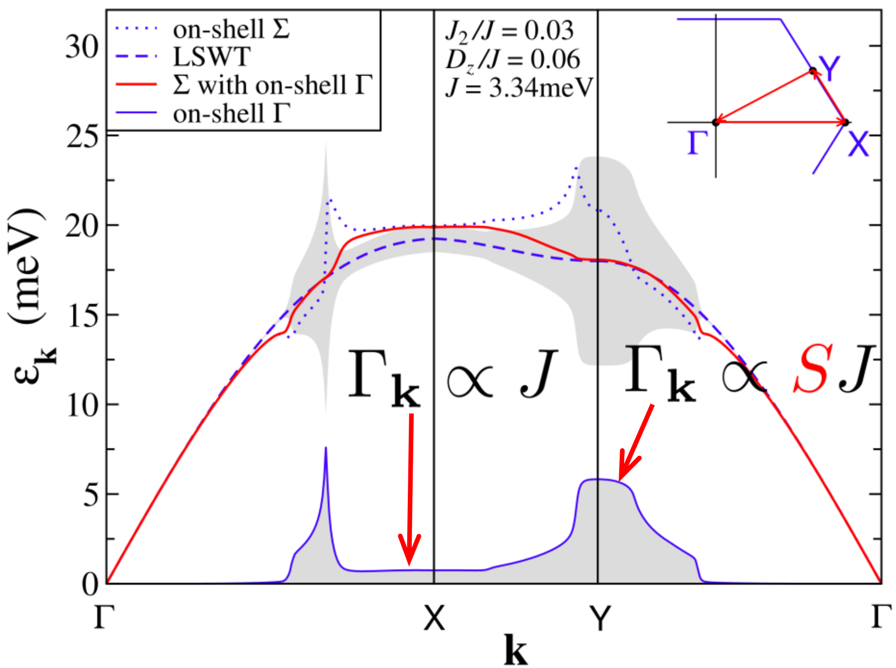
- DM, out-of-plane, gaps flat mode
- dispersion in the flat mode, J_2?
- “missing” data at twice flat mode?
- resonant-like decays?

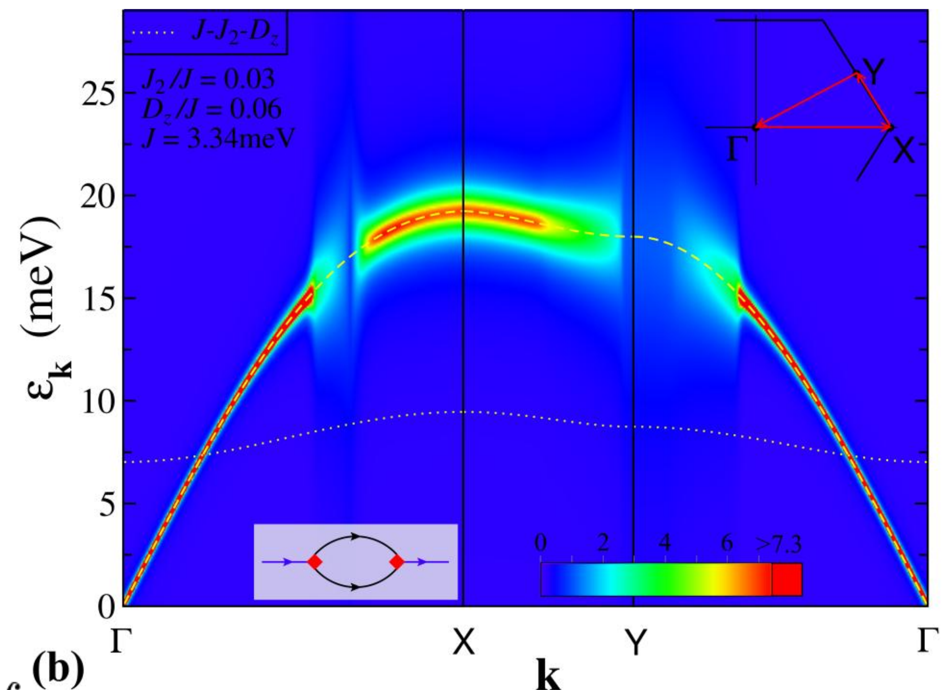


K. Matan *etal*, PRL **96**, 247201 (2006)
T. Yildirim and A. B. Harris, PRB **73**, 214446 (2006)

spectral signatures of resonant decays

- outside the resonance region $\Gamma_{\mathbf{k}} \approx 0.2 - 0.3J$
- inside of it, it is about 5 (*=2S* for FeJ) times larger, in agreement with expectations
- very strong quantum effect in an almost classical antiferromagnet





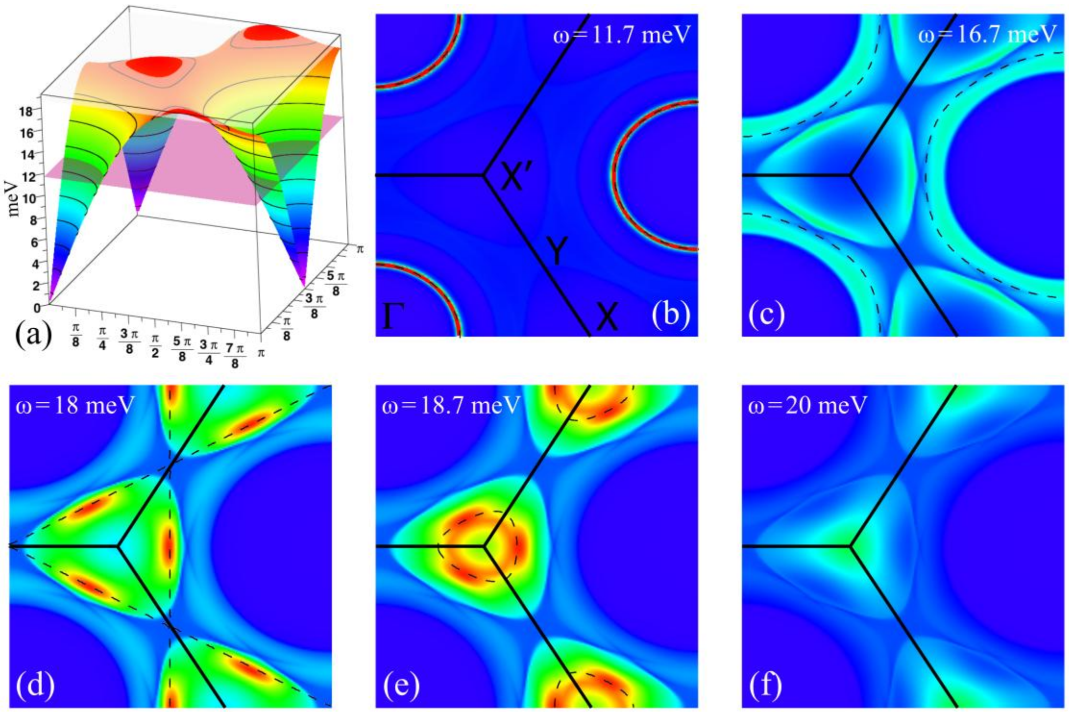
(b)

$$\mathcal{S}^{\alpha\alpha}(\mathbf{q},\omega) \propto \int dt\, e^{i\omega t} \langle S^{\alpha}_{\mathbf{q}}(t) S^{\alpha}_{-\mathbf{q}} \rangle \propto \sum_{\nu} F^{\alpha}_{\nu\mathbf{q}} A_{\nu}(\mathbf{q},\omega)$$

SC, arXiv:1507.04738, **SC** and M. Zhitomirsky, arXiv:1508.06632

constant-energy cuts of $A(q,\omega)$

- wipeout of the (portions of the) spectrum
- strong spectral weight redistribution
- features reminiscent of the quasiparticle breakdown in spin-1/2 systems

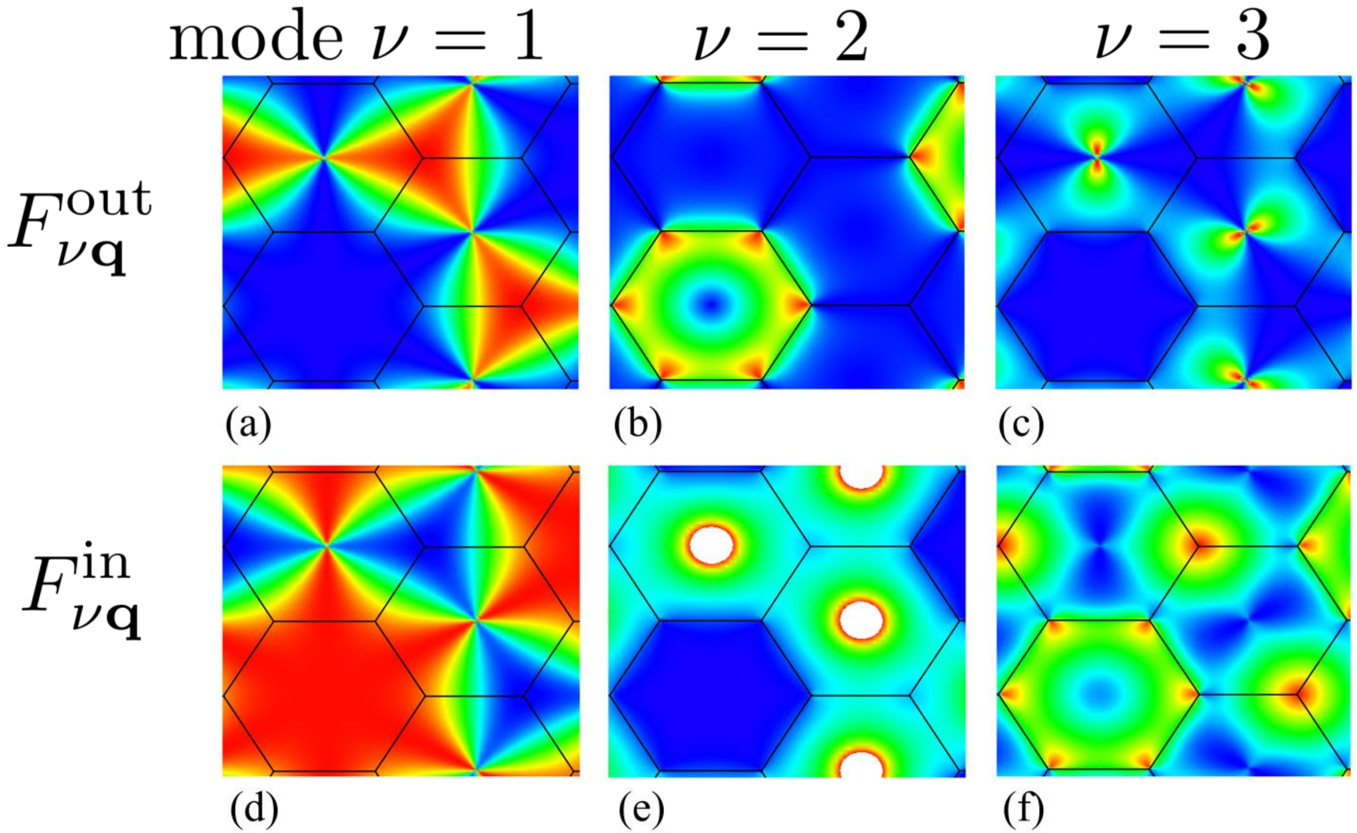


SC, arXiv:1507.04738, **SC** and M. Zhitomirsky, arXiv:1508.06632

"masks" in $S(q,\omega)$

- "kinematic formfactors" are suppressed in one BZ zones and are maximal in others ➔ characteristic to the non-Bravais lattices (a la Bragg peak extinction)

$$\mathcal{S}^{\text{in(out)}}(\mathbf{q},\omega) \approx \sum_{\nu} F^{\text{in(out)}}_{\nu\mathbf{q}} A_\nu(\mathbf{q},\omega)\,,$$



SC, arXiv:1507.04738, **SC** and M. Zhitomirsky, arXiv:1508.06632

conclusions

kagomé-lattice AFs ⇛ still many surprises

☑ “if you don’t expect the unexpected – you just don’t get it!”

quantum selection of **q**=0: a rare case of QObD different from thermal; uses topologically nontrivial tunneling paths to select the ground state

☑ very strong anomalous spectral features even in large-*S* AFs