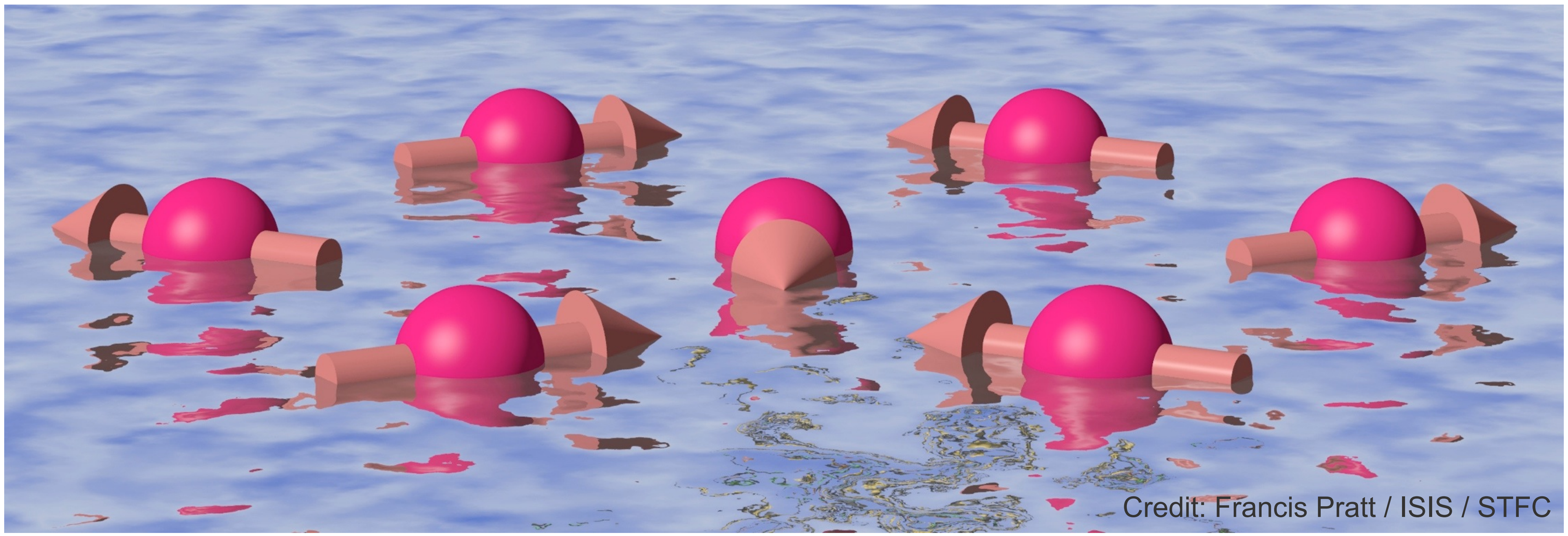
Two-magnon instabilities and other surprises in magnetized quantum antiferromagnets



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Conference on Field Theory Methods in Low-Dimensional Strongly Correlated Quantum Systems,
August 25-29, 2014, ICTP, Trieste, Italy

Outline

- Emergent Ising orders - a very brief history
- UUD magnetization plateau and its instabilities
- High-field phase diagram of a triangular antiferromagnet

VOLUME 52, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1984

Discrete-Symmetry Breaking and Novel Critical Phenomena in an Antiferromagnetic Planar (*XY*) Model in Two Dimensions

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and

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Order parameters: continuous $\vec{\psi} = \begin{pmatrix}\psi_{\parallel}\\ \psi_{\perp}\end{pmatrix} \equiv \frac{1}{N}\sum_{i=1}^{N} \exp(-i\vec{q}\cdot\vec{R}_i)\vec{s}_i$ and discrete spin chirality $\chi = \sum_{\text{triangle}} \vec{S}_i \times \vec{S}_j$

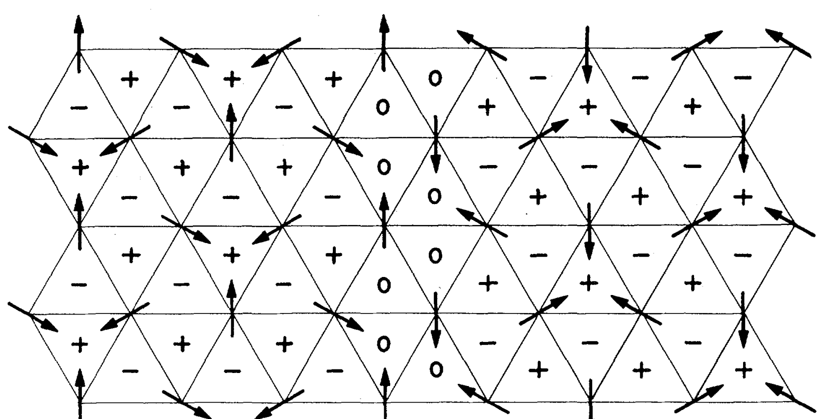
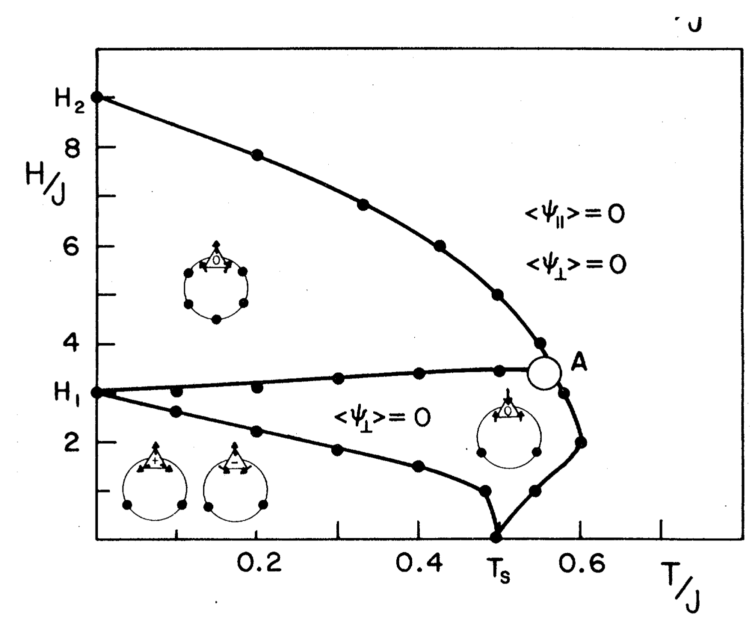


FIG. 1. Two ground states of opposite staggered helicity separated by a domain wall. The helicity of each triangle is indicated.



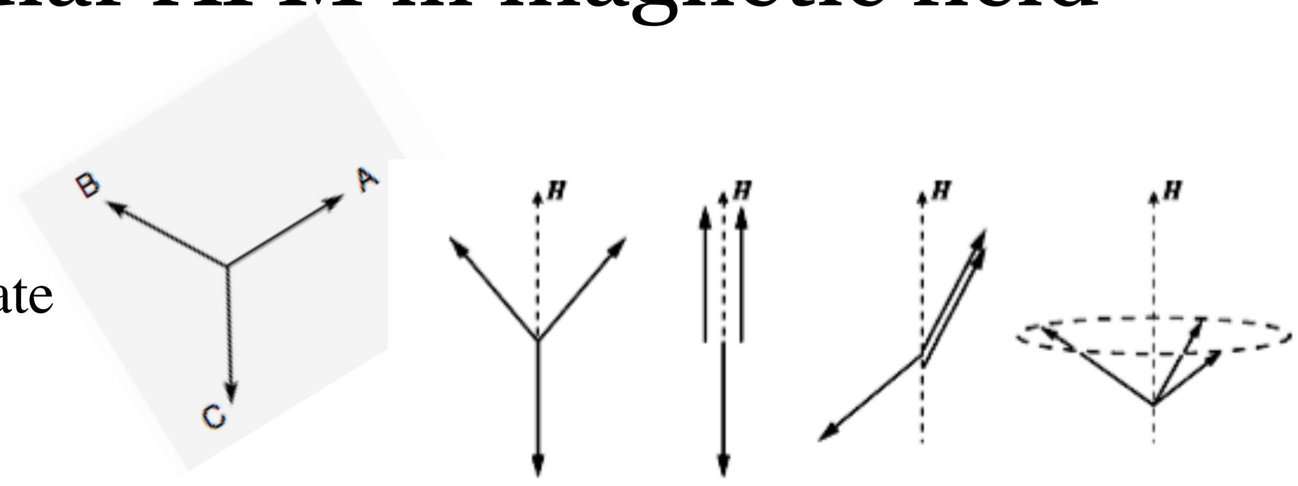
Two possibilities:

- *single* transition: both **spins** and **chiralities** order,
- *two* separate transitions: **Ising** (chirality) transition is followed by the **BKT** (spins)

"An exceedingly simple model leads to a surprising richness of phases and critical behavior. The underlying triangular lattice and the associated degeneracy play a crucial role in this physics."

[unfortunately, incorrect identification of spin configurations]

Classical isotropic triangular AFM in magnetic field



120° state — co-planar supersolid — non-coplanar superfluid

- Zero field: co-planar spiral (120 degree) state
- Magnetic field: **accidental degeneracy**

$$H = J\sum_{i,j}\vec{S}_i\cdot\vec{S}_j - \sum_i \vec{h}\cdot\vec{S}_i$$

$$H = \frac{1}{2}J\sum_{\triangle}\Big(\sum_{i\in\triangle}\vec{S}_i - \frac{\vec{h}}{3J}\Big)^2$$

- all states with $\vec{S}_{i1}+\vec{S}_{i2}+\vec{S}_{i3} = \frac{\vec{h}}{3J}$ form the lowest-energy manifold
- Accidental degeneracy
  - O(2) spins: 3 angles, 2 equations => 1 **continuous angle undetermined**
  - O(3) spins: 6 angles, 3 equations => **2 continuous angles** (upto global U(1) rotation about **h**)

J. Phys. C: Solid State Phys. **19** (1986) 5927–5935. Printed in Great Britain

Phase diagram of the antiferromagnetic *XY* model with a triangular lattice in an external magnetic field

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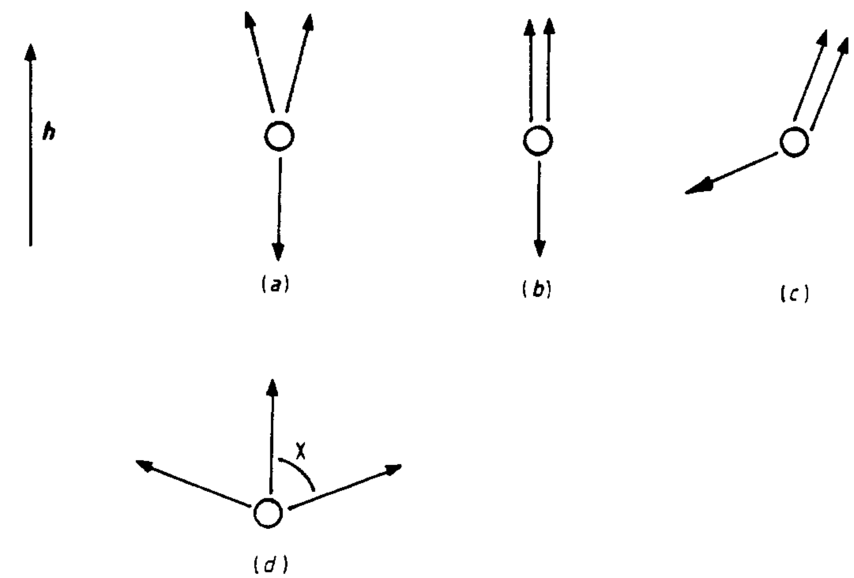
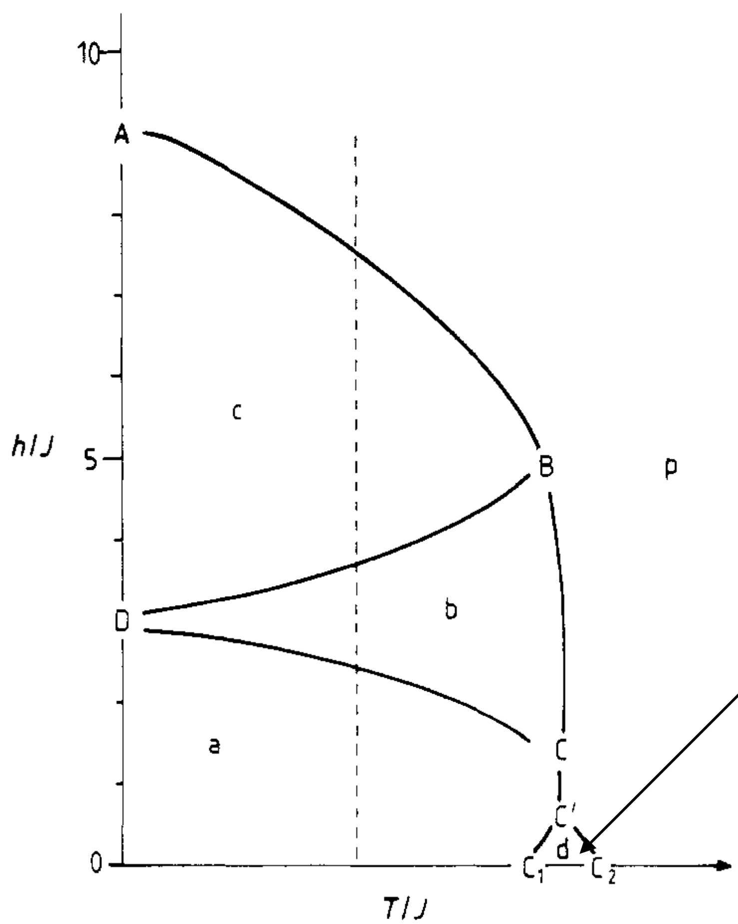


Figure 3. Configuration of spins of the three sublattices with the minimal spin wave free energy: (*a*), $0 < h < h_{c1}$; (*b*), $h = h_{c1}$; (*c*), $h_{c1} < h < h_{c2}$; (*d*), in the case of the opposite sign of the anisotropic part of the free energy.



Order of helicities (chiralities) only

Figure 4. Phase diagram of the AF *XY*(t) model in an external magnetic field. In phases a, b and c the mean magnetic moments of different sublattices form configurations similar to those shown in figures 3(*a*), 3(*b*) and 3(*c*) respectively. In phase d only the long-range order with respect to helicities is retained. Phase p is paramagnetic.

Phase diagram of the Heisenberg (XXX) model in the field

Journal of the Physical Society of Japan
Vol. 53, No. 12, December, 1984, pp. 4138–4154

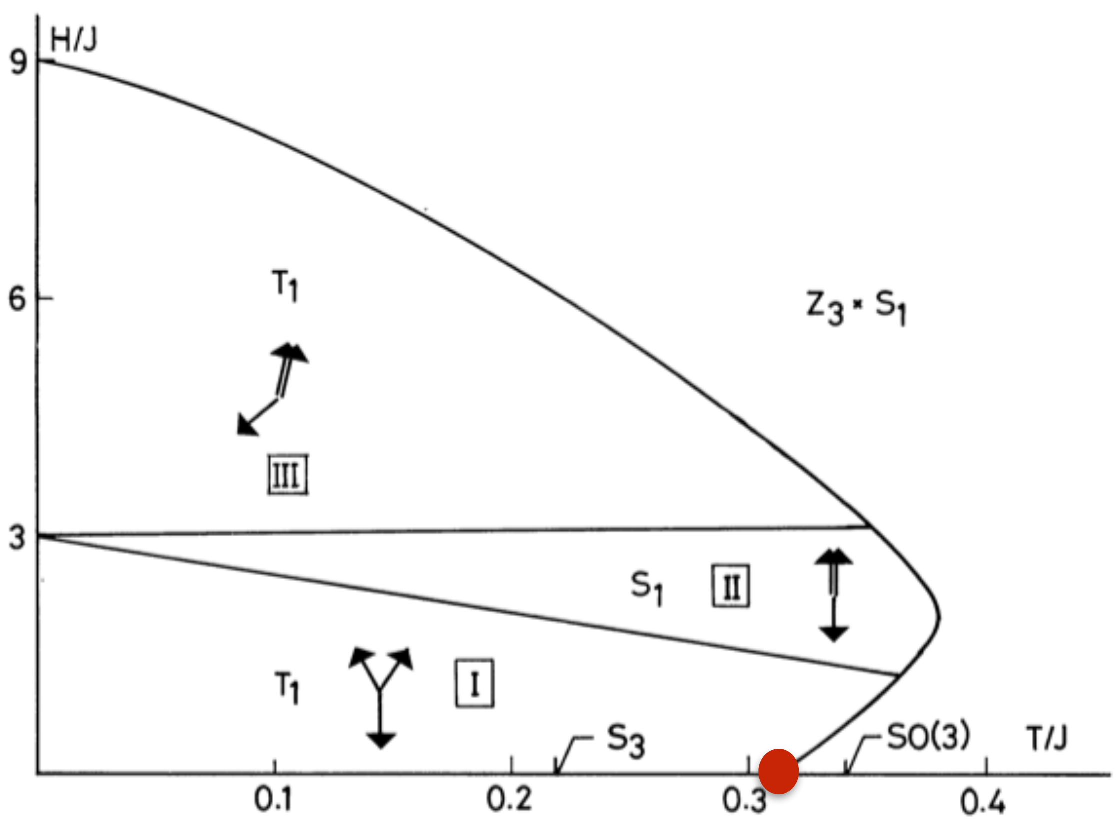
Phase Transition of the Two-Dimensional Heisenberg Antiferromagnet on the Triangular Lattice

Hikaru KAWAMURA and Seiji MIYASHITA†

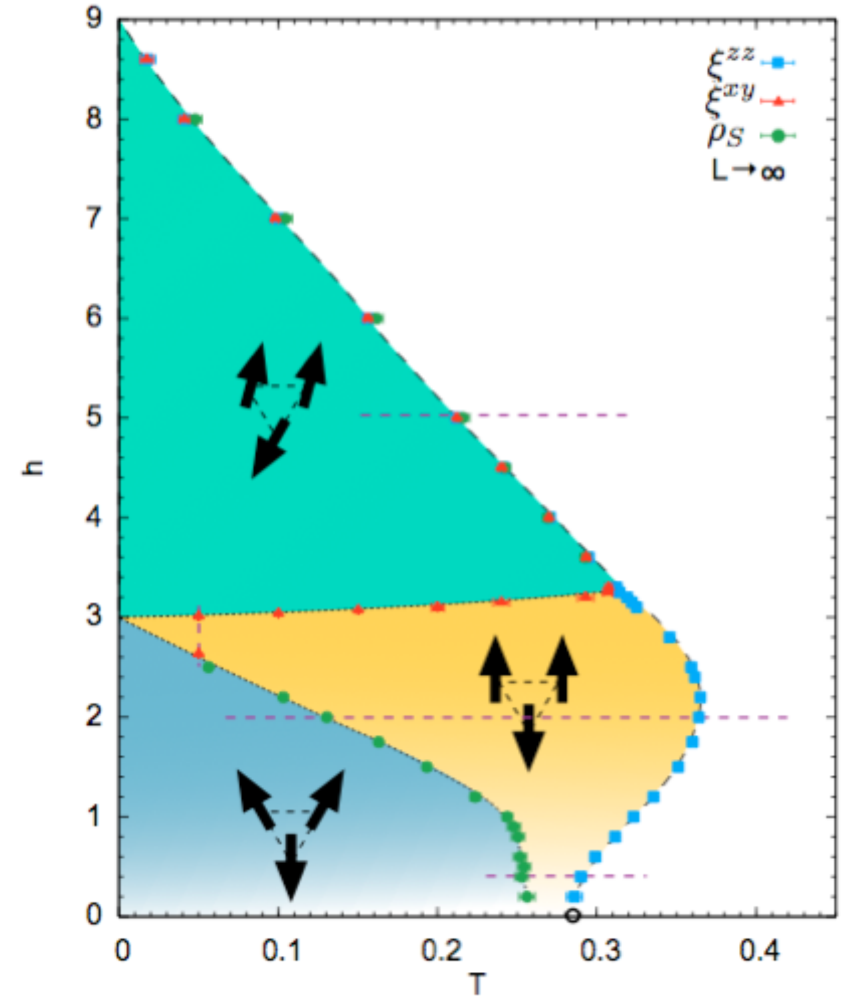
Journal of the Physical Society of Japan
Vol. 54, No. 12, December, 1985, pp. 4530–4538

Phase Transition of the Heisenberg Antiferromagnet on the Triangular Lattice in a Magnetic Field

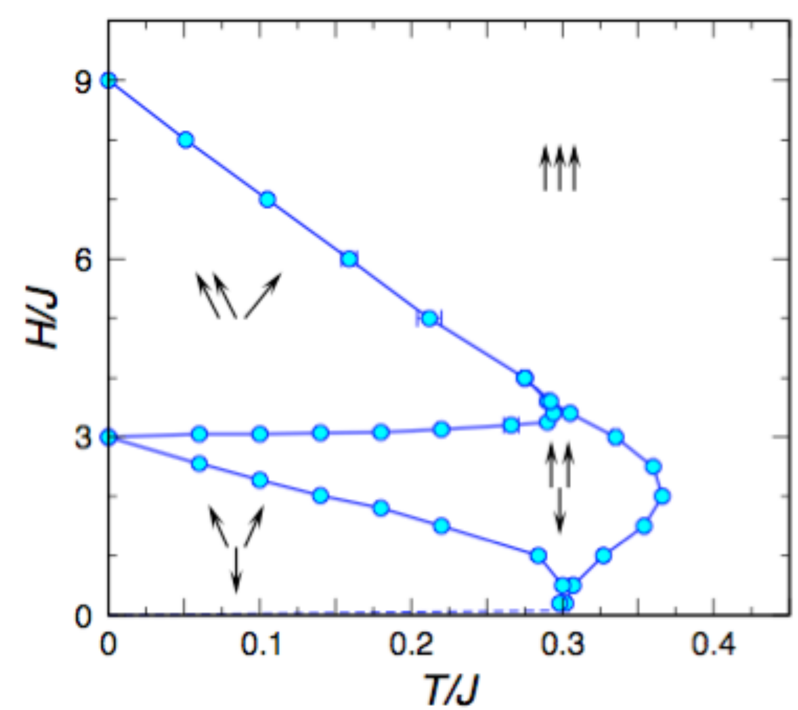
Hikaru KAWAMURA and Seiji MIYASHITA†



Z_2 vortex (chirality ordering) transition



Seabra, Momoi, Sindzingre, Shannon 2011



Gvozdikova, Melchy, Zhitomirsky 2010

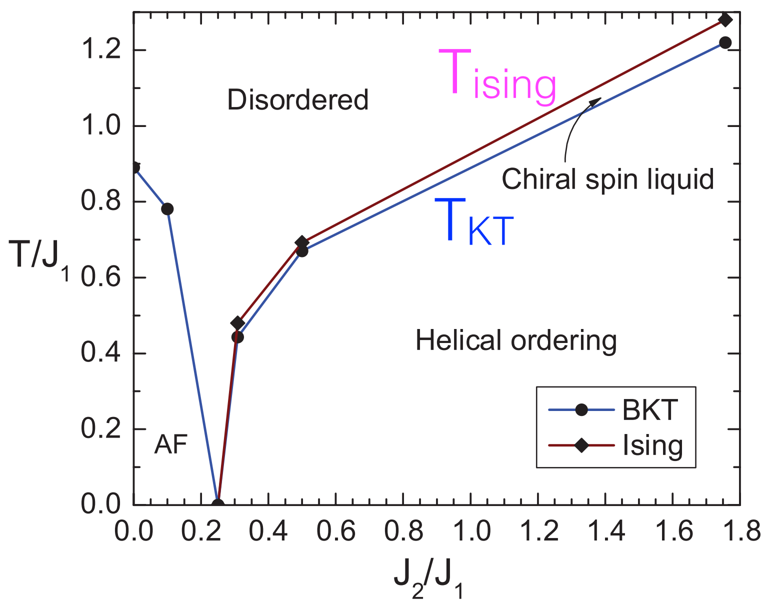
Emergent Ising order parameters

PHYSICAL REVIEW B **85**, 174404 (2012)

Chiral spin liquid in two-dimensional XY helimagnets

A. O. Sorokin[1,*] and A. V. Syromyatnikov[1,2,†]

$$H = \sum_{\mathbf{x}} (J_1 \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+a}}) + J_2 \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+2a}}) - J_b \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+b}})),$$



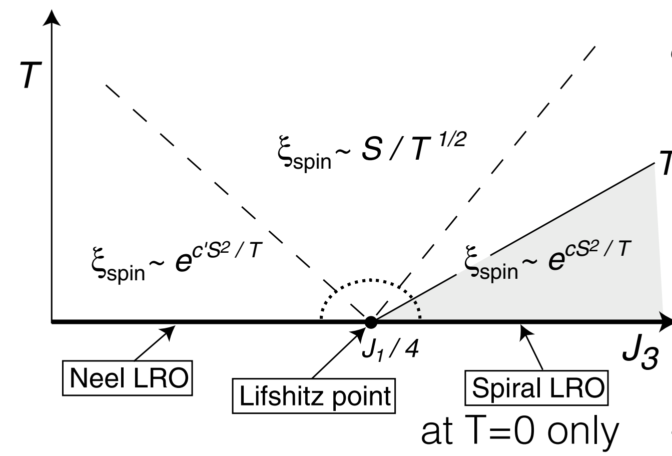
PRL **93**, 257206 (2004) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2004

Low-Temperature Broken-Symmetry Phases of Spiral Antiferromagnets

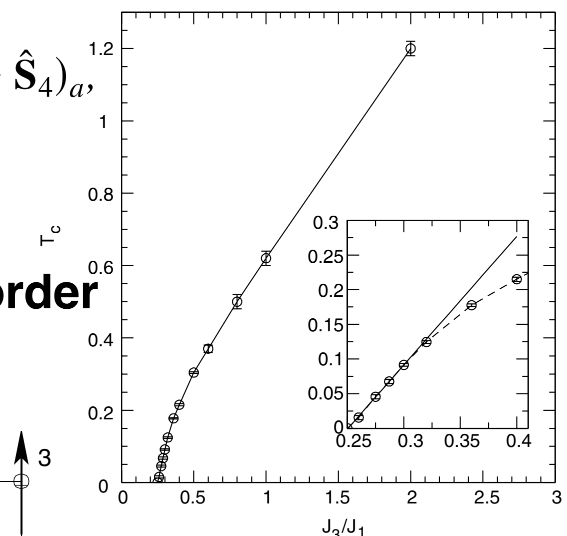
Luca Capriotti[1,2] and Subir Sachdev[2,3]

$$\hat{H} = J_1 \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j + J_3 \sum_{\langle\langle i,j \rangle\rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j,$$

$$\sigma_a = (\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_3 - \hat{\mathbf{S}}_2 \cdot \hat{\mathbf{S}}_4)_a,$$



Ising nematic order



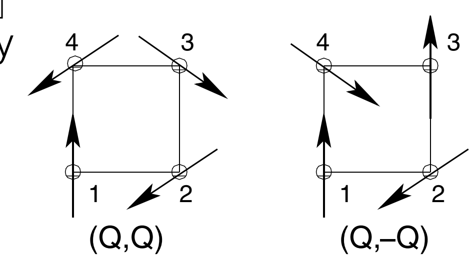
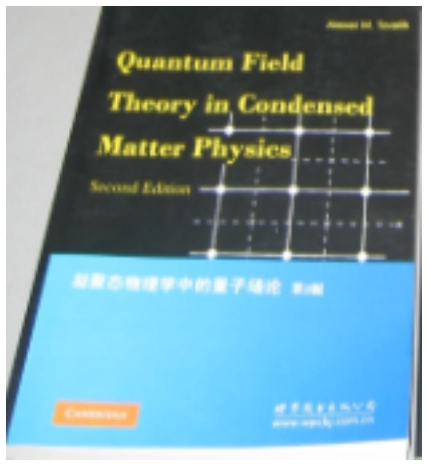


FIG. 2. The two different minimum energy configurations with magnetic wave vectors $\vec{Q} = (Q, Q)$ and $\vec{Q}^\star = (Q, -Q)$ with $Q = 2\pi/3$, corresponding to $J_3/J_1 = 0.5$.

Ising nematic in collinear spin system



VOLUME 64, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1990

Ising Transition in Frustrated Heisenberg Models

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$$\sigma = \vec{N}_1 \cdot \vec{N}_2 = \pm 1$$

VOLUME 91, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 24 OCTOBER 2003

Ising Transition Driven by Frustration in a 2D Classical Model with Continuous Symmetry

Cédric Weber,[1,2] Luca Capriotti,[3] Grégoire Misguich,[4] Federico Becca,[5] Maged Elhajal,[1] and Frédéric Mila[1]

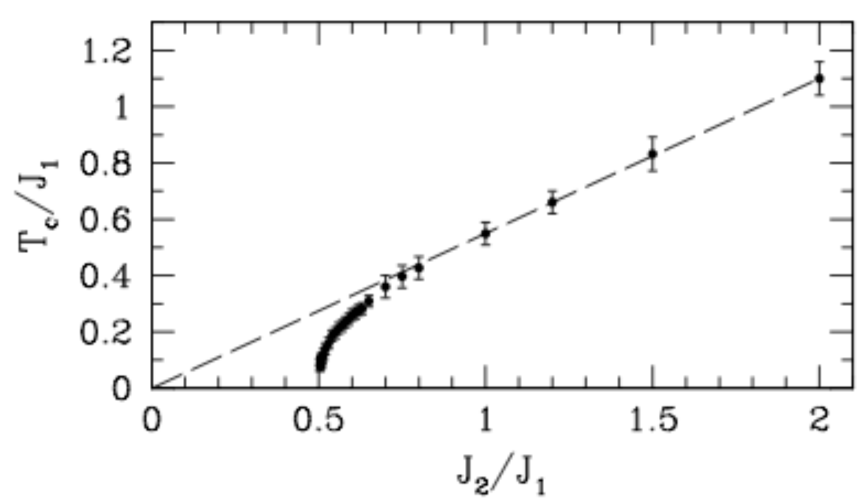
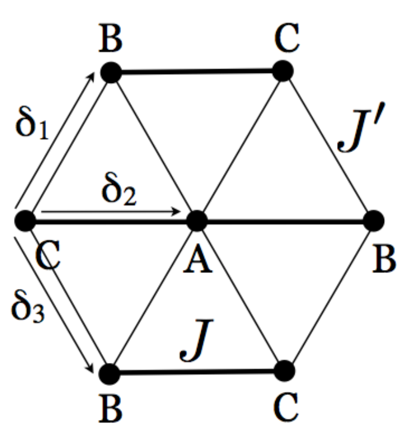


FIG. 4. Monte Carlo results for the critical temperature T_c as a function of the frustrating ratio J_2/J_1. The line is an extrapolation of the large J_2 data down to $J_2 = 0$ (see text).

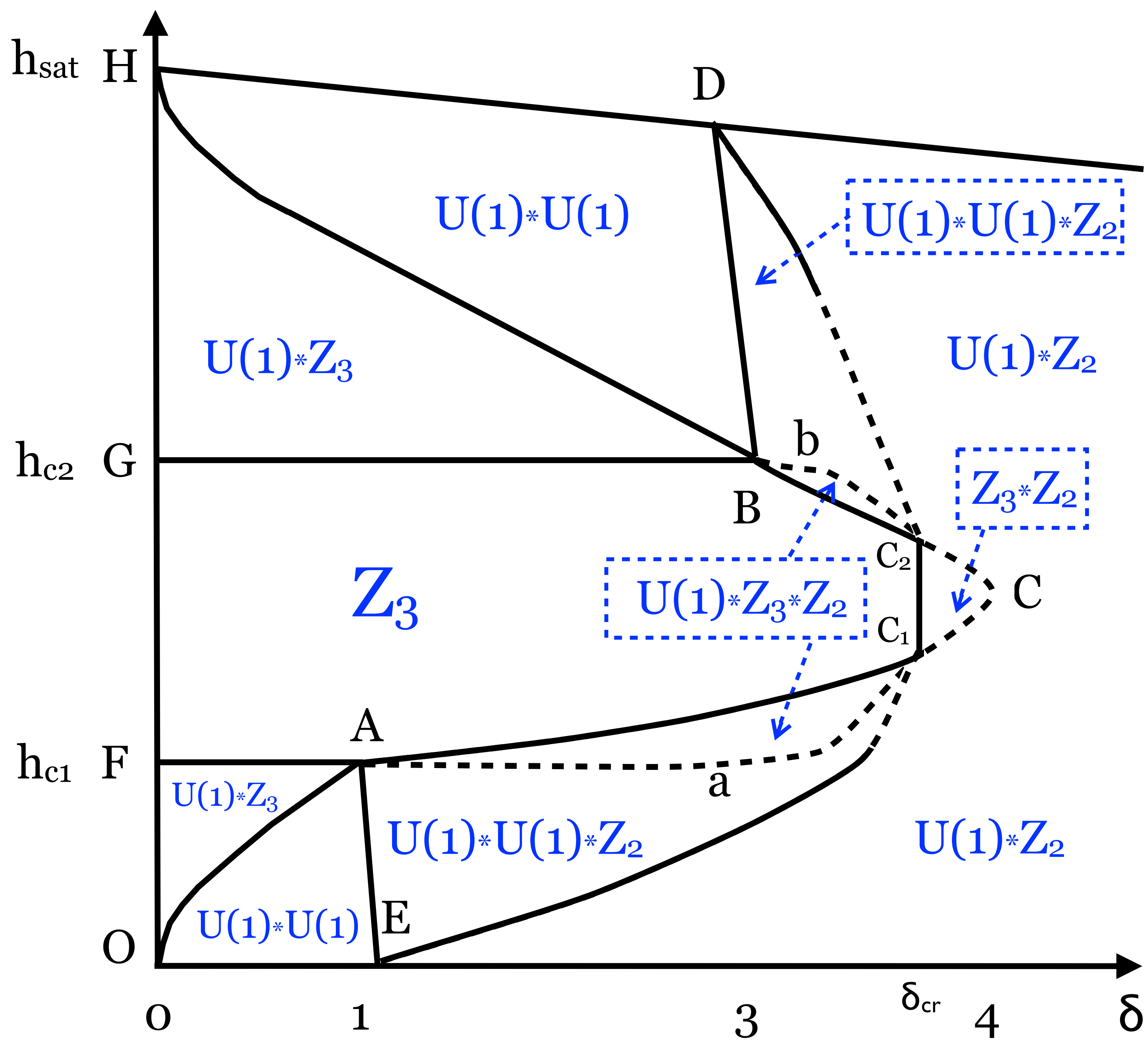
This talk:

Emergent Ising orders in quantum two-dimensional triangular antiferromagnet at T=0

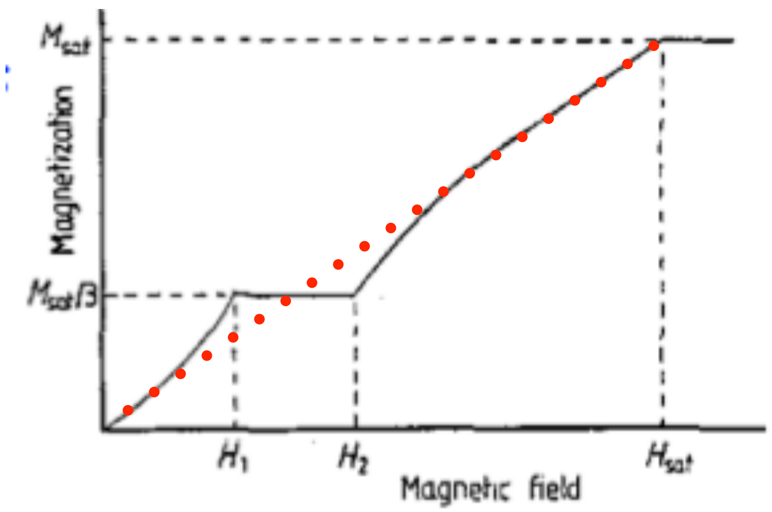
$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



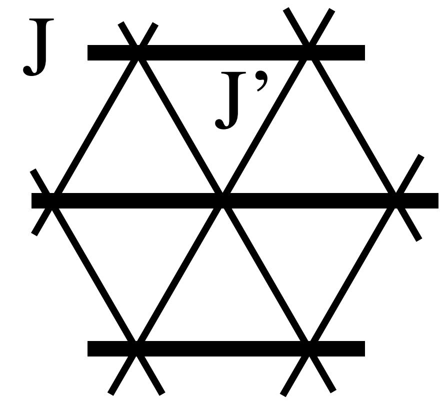
$$\delta = \frac{40}{3} S \Big(\frac{J - J'}{J} \Big)^2$$



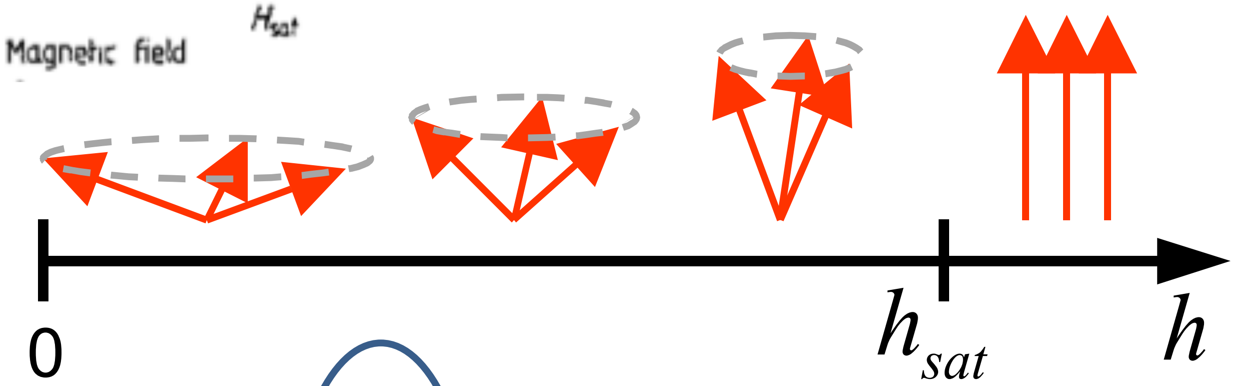
Spatially anisotropic model: classical vs *quantum*



$$H = \sum_{\langle ij \rangle} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j - h \sum_i \mathbf{S}_i^z$$



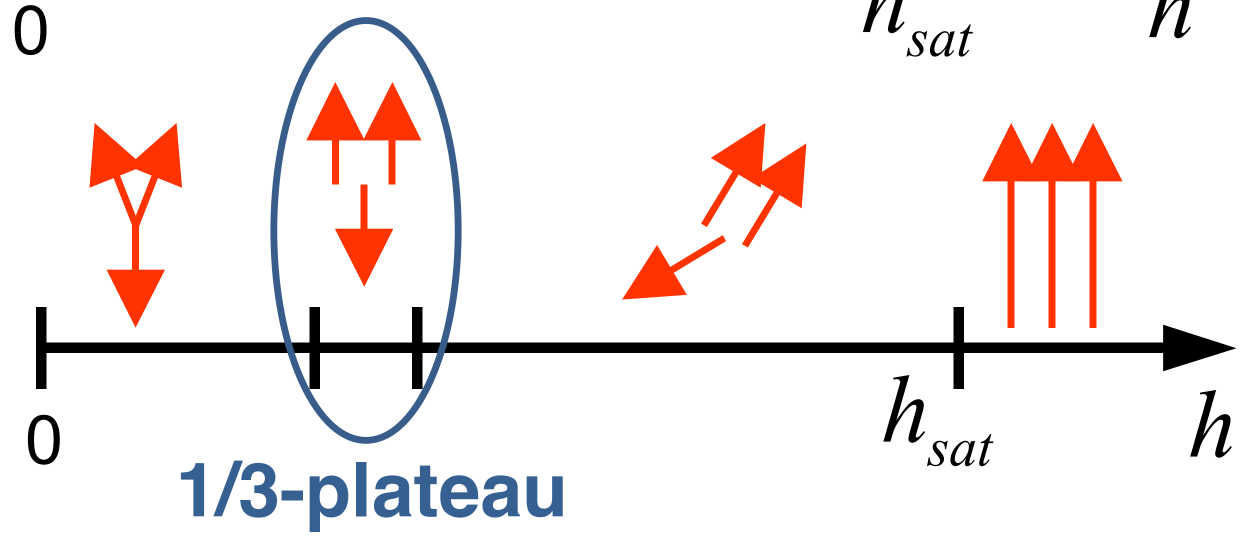
$S = \infty$



Umbrella state: favored classically; energy gain (J-J')^2/J

$$J' \neq J$$

$S = \frac{1}{2}$

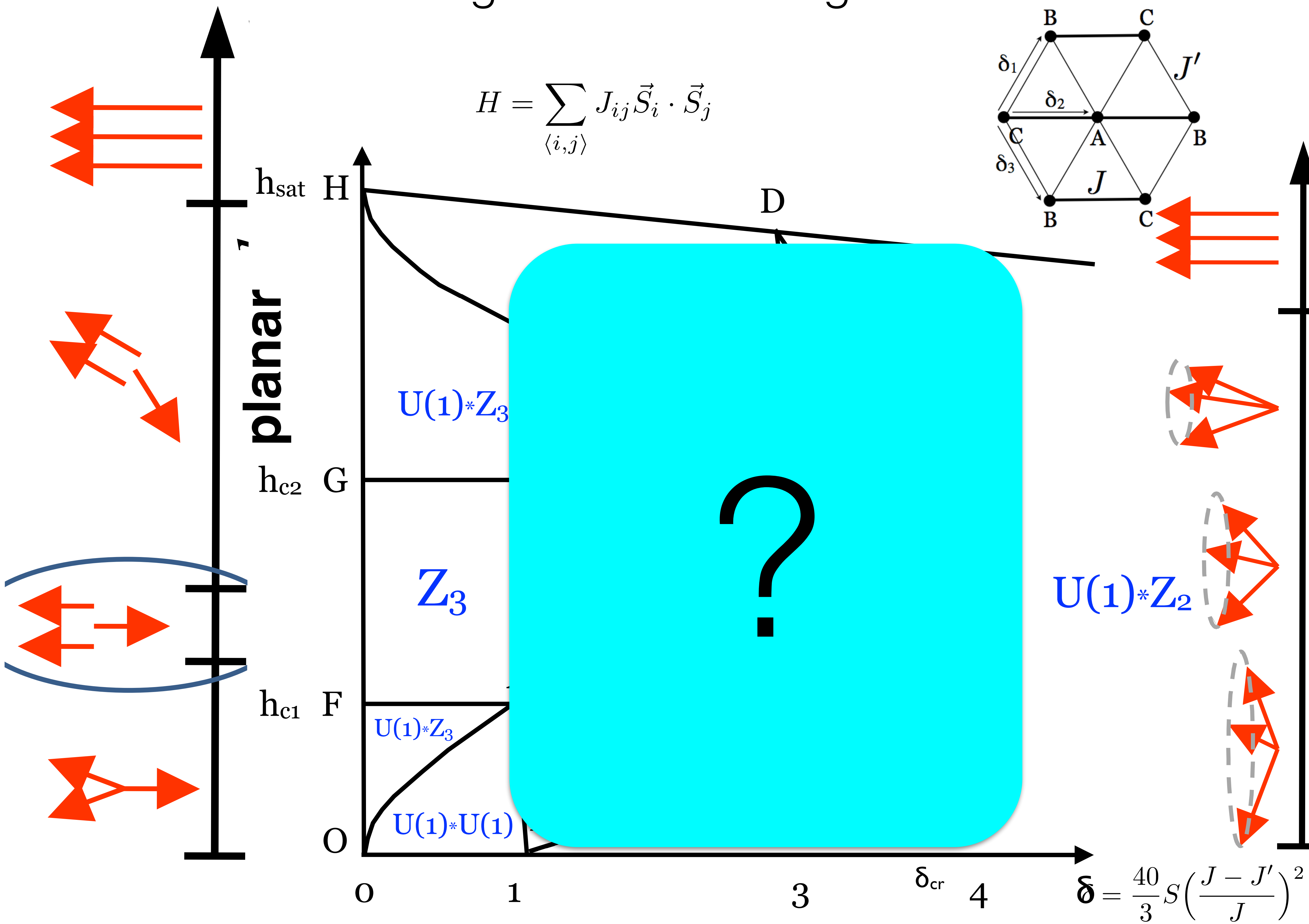


Planar states: favored by quantum fluctuations; energy gain J/S

The competition is controlled by dimensionless parameter

$$\delta = S(J - J')^2/J^2$$

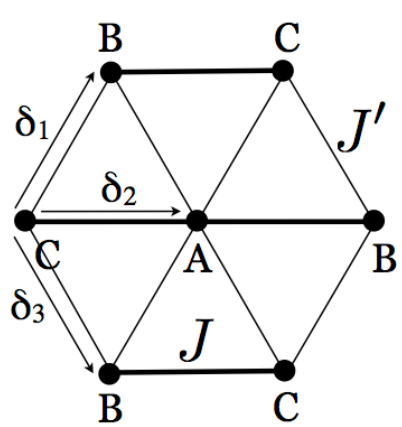
Emergent Ising orders in quantum two-dimensional triangular antiferromagnet at T=0



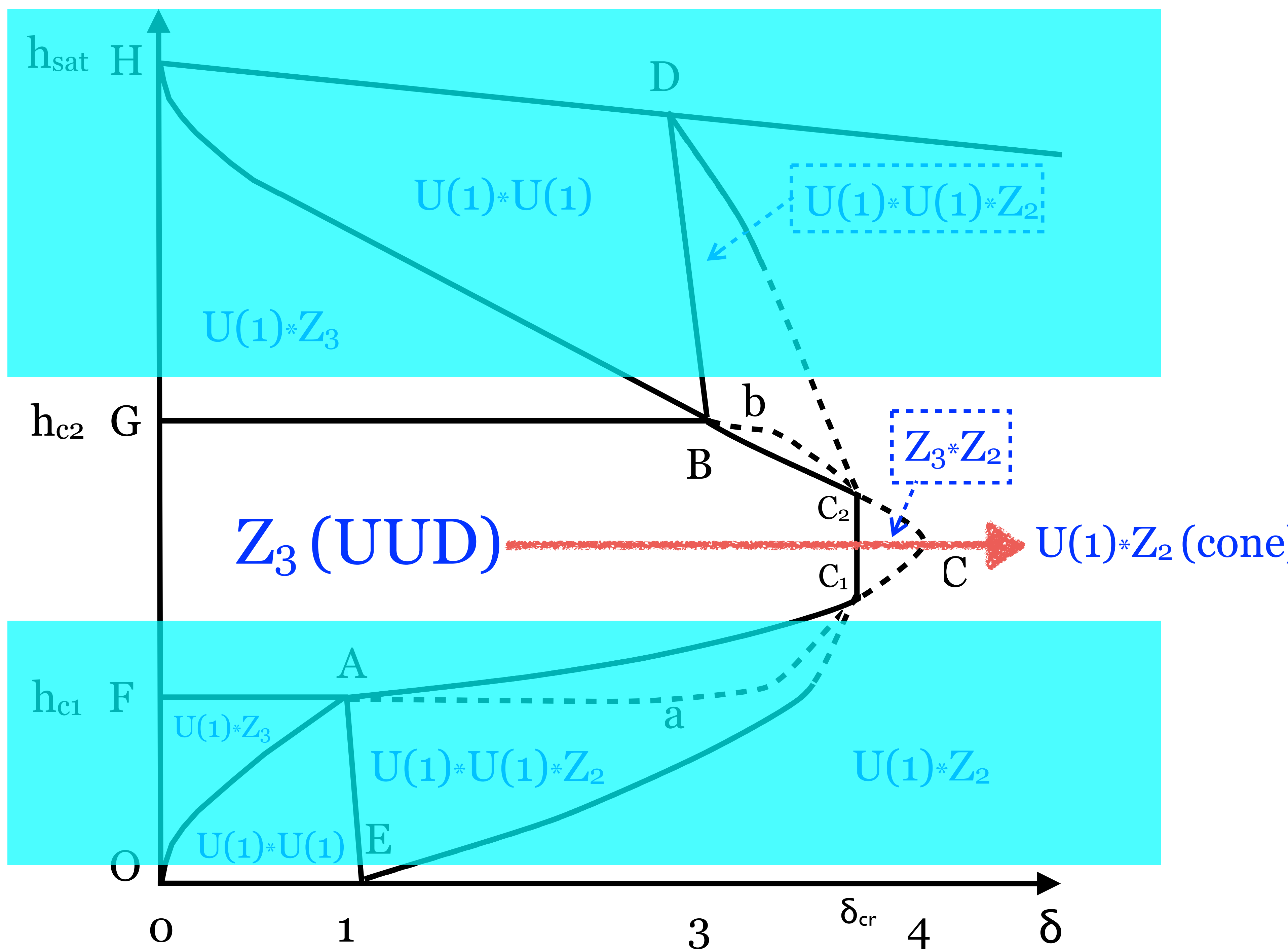
UUD-to-cone phase transition

$$Z_3 \to U(1) \times Z_2 \text{ or } Z_3 \to \text{smth else} \to U(1) \times Z_2?$$

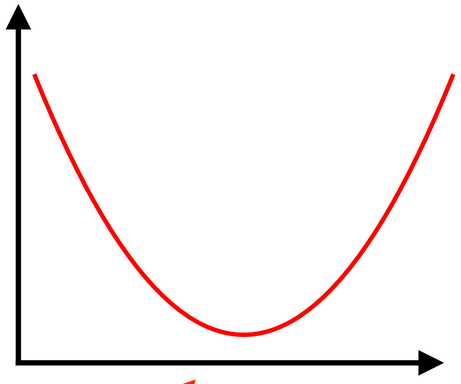
$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



$$\delta = \frac{40}{3} S \left(\frac{J - J'}{J} \right)^2$$



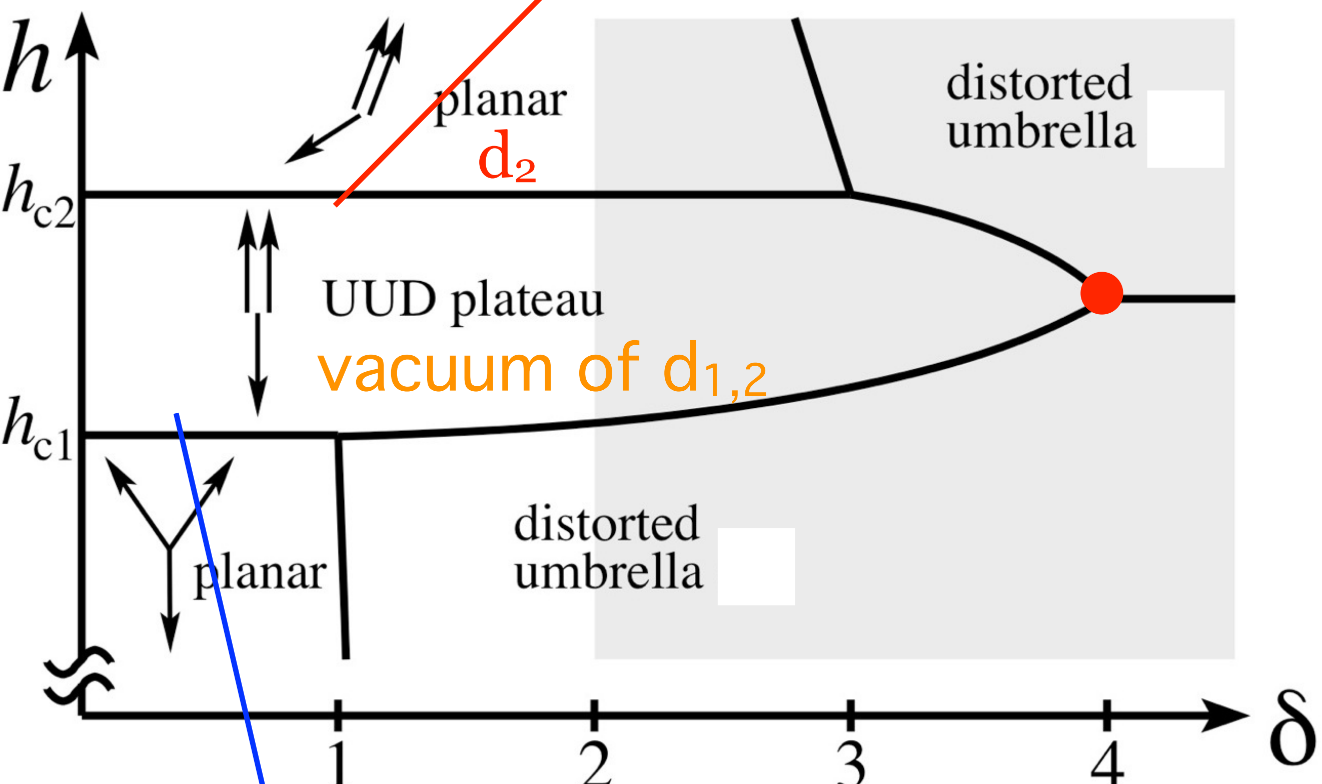
Low-energy excitation spectra



$$\epsilon_{d2} = h_{c2} - h + \frac{9Jk^2}{4}$$

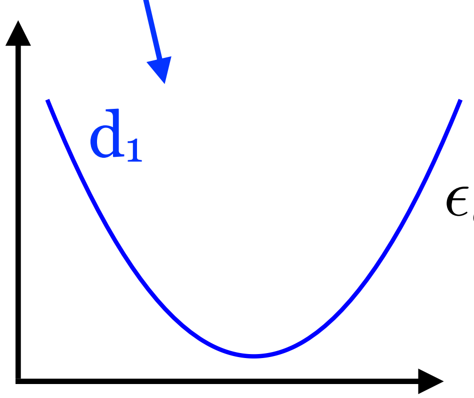
for δ < 3

Magnetization plateau is **collinear** phase: preserves O(2) rotations about magnetic field -- no gapless spin waves. Breaks only discrete Z_3. Hence, ***very stable***.



$$h_{c2} - h_{c1} = \frac{0.6}{2S} h_{\rm sat} = \frac{0.6}{2S}(9JS)$$

$$\delta = \frac{40\ S}{3}(1 - J'/J)^2$$



$$\epsilon_{d1} = h - h_{c1} + \frac{3Jk^2}{4}$$

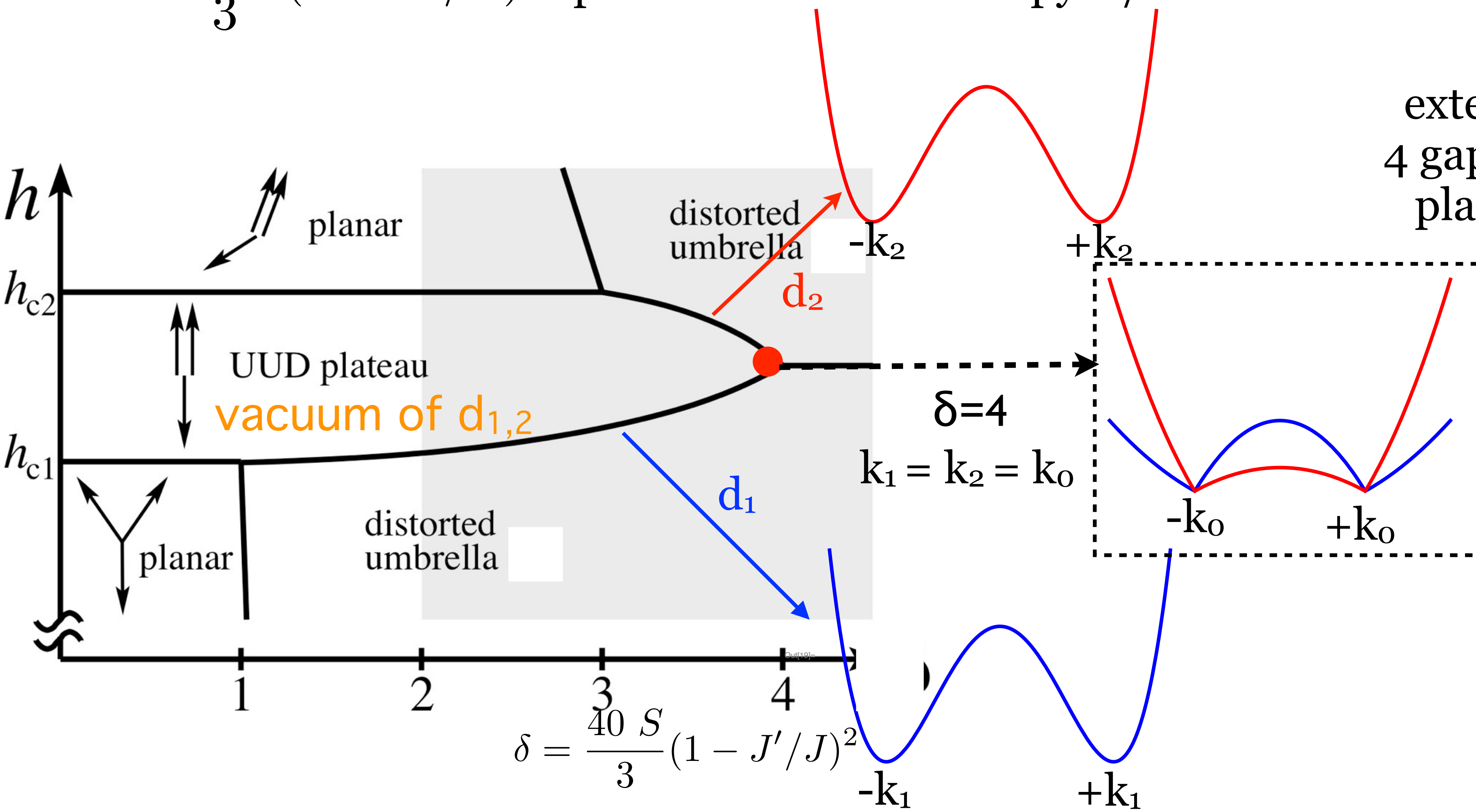
for δ < 1

Bose-Einstein condensation of d_1 (d_2) mode at k =0 leads to lower (upper) co-planar phase

Alicea, Chubukov, OS PRL 2009

Low-energy excitation spectra near the plateau's end-point

$$\delta = \frac{40\ S}{3}(1 - J'/J)^2$$ parameterizes anisotropy J'/J



extended symmetry:
4 gapless modes at the
plateau's end-point

$$k_0 = \sqrt{\frac{3}{10S}}$$

S>>1

Magnetization plateau is **collinear** phase: preserves O(2) rotations about magnetic field -- no gapless spin waves. Breaks only discrete Z_3.

Alicea, Chubukov, OS PRL 2009

Bosonization of 2d interacting magnons

$$\mathcal{H}^{(4)}_{d_1 d_2} = \frac{3}{N}\sum_{p,q}\Phi(p,q)\Big(d^\dagger_{1,\mathbf{k}_0+\mathbf{p}}d^\dagger_{2,-\mathbf{k}_0-\mathbf{p}}d_{1,-\mathbf{k}_0+\mathbf{q}}d_{2,\mathbf{k}_0-\mathbf{q}} - d^\dagger_{1,\mathbf{k}_0+\mathbf{p}}d^\dagger_{2,-\mathbf{k}_0-\mathbf{p}}d^\dagger_{1,-\mathbf{k}_0+\mathbf{q}}d^\dagger_{2,\mathbf{k}_0-\mathbf{q}}\Big) + \text{h.c.}$$

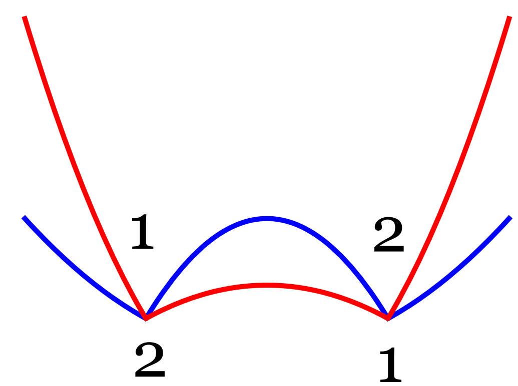
$$\Psi^\dagger_{1,p}\Psi_{2,q} \qquad \Psi^\dagger_{1,p}\Psi^\dagger_{2,q}$$

$$\Phi(p,q) \sim \frac{(-3J)k_0^2}{|\mathbf{p}||\mathbf{q}|}$$

singular magnon interaction

magnon pair operators

$$\begin{cases}\Psi_{1,p} = d_{1,k_0+p}d_{2,-k_0-p}\\ \Psi_{2,p} = d_{1,-k_0+p}d_{2,k_0-p}\end{cases}$$



Obey canonical Bose commutation relations in the UUD ground state

$$[\Psi_{1,\mathbf{p}},\Psi_{2,\mathbf{q}}] = \delta_{1,2}\delta_{\mathbf{p},\mathbf{q}}\Big(1 + d^\dagger_{1,\mathbf{k}_0+\mathbf{p}}d_{1,\mathbf{k}_0+\mathbf{p}} + d^\dagger_{2,\mathbf{k}_0+\mathbf{p}}d_{2,\mathbf{k}_0+\mathbf{p}}\Big) \to \delta_{1,2}\delta_{\mathbf{p},\mathbf{q}}$$

In the UUD ground state $\langle d_1^\dagger d_1\rangle_{\rm uud} = \langle d_2^\dagger d_2\rangle_{\rm uud} = 0$

★ Interacting magnon Hamiltonian in terms of $\mathbf{d}_{1,2}$ bosons = non-interacting Hamiltonian in terms of $\Psi_{1,2}$ magnon pairs

Chubukov, OS PRL 2013

Two-magnon instability

Magnon pairs $\Psi_{1,2}$ condense *before* single magnons $d_{1,2}$

Equations of motion for Ψ - Hamiltonian

$$\langle \Psi^\dagger_{1,\mathbf{p}} - \Psi_{1,\mathbf{p}} \rangle = \frac{6 J f_p^2}{\Omega_p} \frac{3}{N} \sum_q f_q^2 \langle \Psi^\dagger_{2,\mathbf{q}} - \Psi_{2,\mathbf{q}} \rangle$$

$$\langle \Psi^\dagger_{2,\mathbf{p}} - \Psi_{2,\mathbf{p}} \rangle = \frac{6 J f_p^2}{\Omega_p} \frac{3}{N} \sum_q f_q^2 \langle \Psi^\dagger_{1,\mathbf{q}} - \Psi_{1,\mathbf{q}} \rangle$$

\`Superconducting' solution with *imaginary* order parameter

$$\langle \Psi_{1,p} \rangle = \langle \Psi_{2,p} \rangle \sim i \frac{\Upsilon}{\mathbf{p}^2}$$

Instability = softening of two-magnon mode @ $\delta_{cr} = 4 - O(1/S^2)$

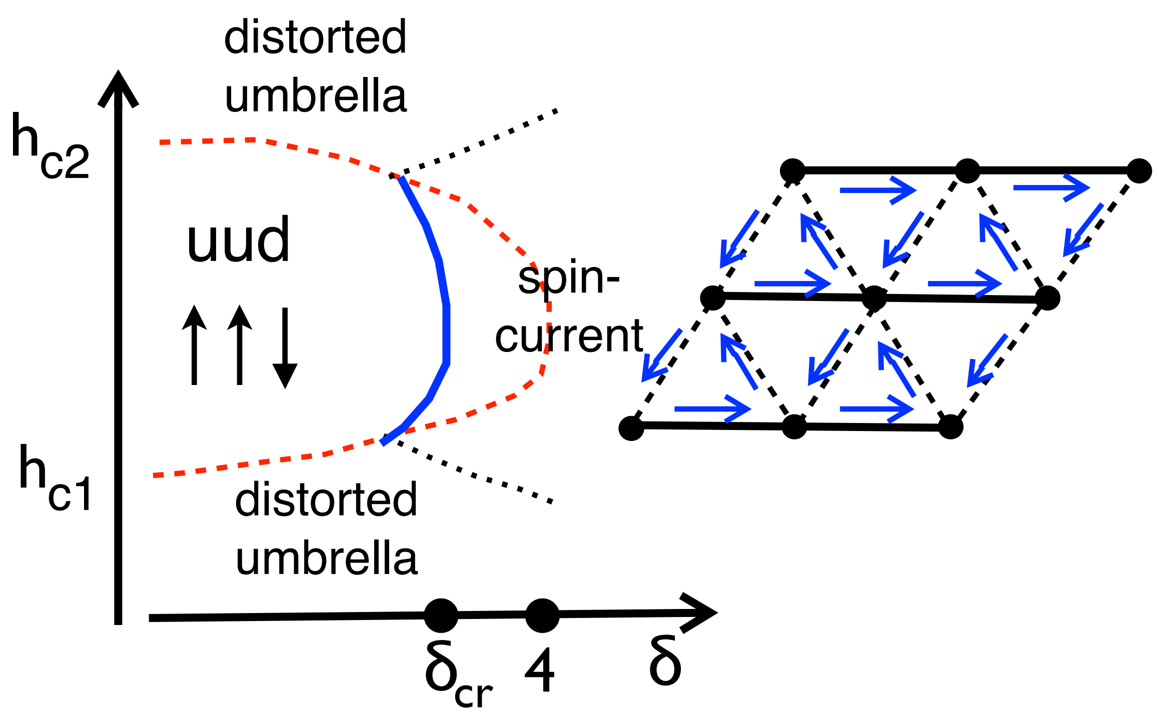
$$1 = \frac{1}{S} \frac{1}{N} \sum_p \frac{k_0}{\sqrt{|\mathbf{p}|^2 + (1 - \delta/4) k_0^2}}$$

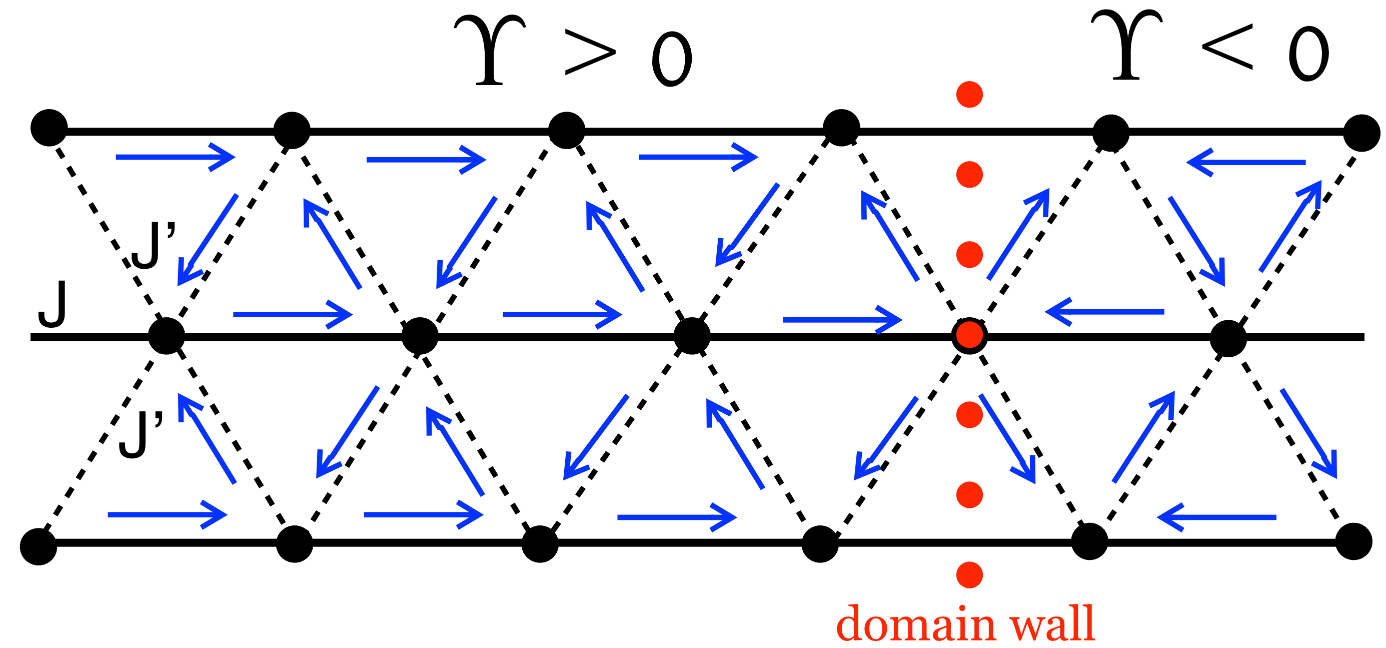
no single particle condensate

$$\langle d_1 \rangle = \langle d_2 \rangle = 0$$

Chubukov, OS PRL 2013

Two-magnon condensate = Spin-current nematic state





no transverse magnetic order $\langle \mathbf{S}_r^{x,y} \rangle = 0$ $\langle \mathbf{S}_r \cdot \mathbf{S}_{r'} \rangle$ is not affected

Finite scalar (and vector) chiralities. Sign of Υ determines sense of spin-current circulation

$$\langle \hat{z} \cdot \mathbf{S}_A \times \mathbf{S}_C \rangle = \langle \hat{z} \cdot \mathbf{S}_C \times \mathbf{S}_B \rangle = \langle \hat{z} \cdot \mathbf{S}_B \times \mathbf{S}_A \rangle \propto \Upsilon$$

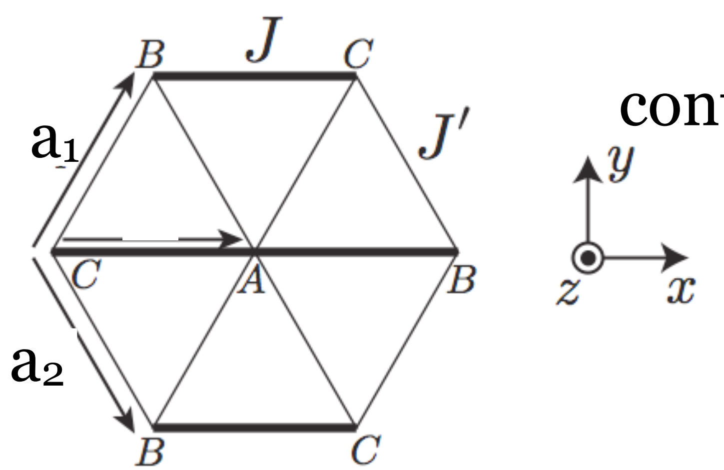
Spontaneously broken Z_2 -- spatial inversion [in addition to broken Z_3 inherited from the UUD state]

Leads to **spontaneous generation of Dzyaloshisnkii-Moriya interaction**

Chubukov, OS PRL 2013

Spontaneous generation of Dzyaloshinskii-Moriya interaction

$$\mathcal{H}^{(4)}_{d_1 d_2} \propto \frac{1}{N}\sum_{k\in +k_0} \frac{-ik_0}{\sqrt{(k-k_0)^2+(1-\delta/4)k_0^2}}(d^\dagger_{1,\mathbf{k}} d^\dagger_{2,-\mathbf{k}} - d_{1,\mathbf{k}} d_{2,-\mathbf{k}}) \sum_{p\in -k_0} \frac{-ik_0}{\sqrt{(p+k_0)^2+(1-\delta/4)k_0^2}}(d^\dagger_{1,\mathbf{p}} d^\dagger_{2,-\mathbf{p}} - d_{1,\mathbf{p}} d_{2,-\mathbf{p}})$$



continuum limit of DM in triangular lattice

$$\sum_{\mathbf{r}} \hat{z}\cdot \mathbf{S_r} \times (\mathbf{S_{r+a_1}} + \mathbf{S_{r+a_2}})$$

B || z

Mean-field approximation:

$$\mathcal{H}^{(4)}_{d_1 d_2} \to D \sum_k \left(\frac{k_0}{|k-k_0|} + \frac{k_0}{|k+k_0|}\right)(d^\dagger_{1,\mathbf{k}} d^\dagger_{2,-\mathbf{k}} - d_{1,\mathbf{k}} d_{2,-\mathbf{k}})$$

$$D \sim \Upsilon$$

spin currents appear due to **spontaneously generated DM**
(similar to Lauchli et al (PRL 2005) for Heis.+ring exchange model;
also ‘chiral Mott insulator’, Dhar et al, PRB 2013; Zaletel et al, 2013)

VOLUME 81, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1998

Incommensurate Spin Correlations in Spin-1/2 Frustrated Two-Leg Heisenberg Ladders

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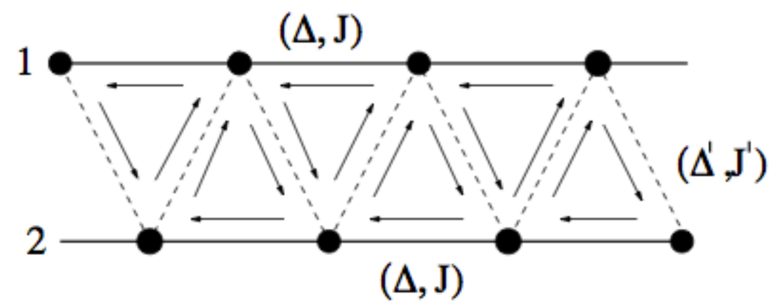

FIG. 3. Structure of the spin currents in the spin nematic phase.

PHYSICAL REVIEW B **87**, 174501 (2013)

Chiral Mott insulator with staggered loop currents in the fully frustrated Bose-Hubbard model

Arya Dhar,[1] Tapan Mishra,[2] Maheswar Maji,[3] R. V. Pai,[4] Subroto Mukerjee,[3,5] and Arun Paramekanti[2,3,6,7]

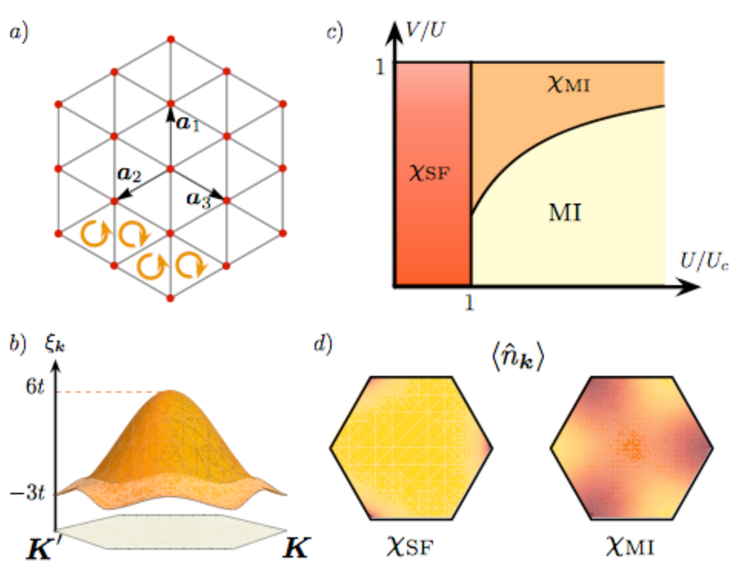

FIG. 1. **Bosons on the Frustrated Triangular Lattice.** (a) Lattice, coordinate system and sample current pattern in the χMI; (b) single-particle dispersion ξ_k, with minima at the K, K' points of the BZ; (c) Variational mean-field phase diagram showing χSF, χMI and MI phases tuned by the on site repulsion U and nearest neighbor repulsion V; (d) Momentum distribution $\langle \hat{n}_k \rangle$ for the chiral phases.

PHYSICAL REVIEW B **89**, 155142 (2014)

Chiral bosonic Mott insulator on the frustrated triangular lattice

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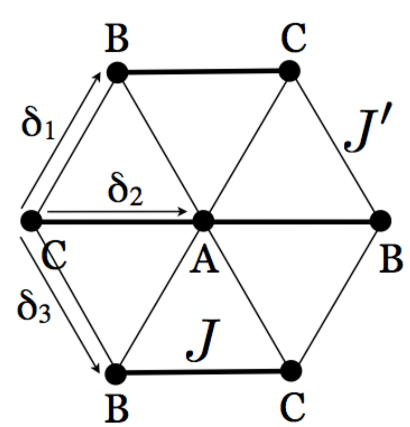
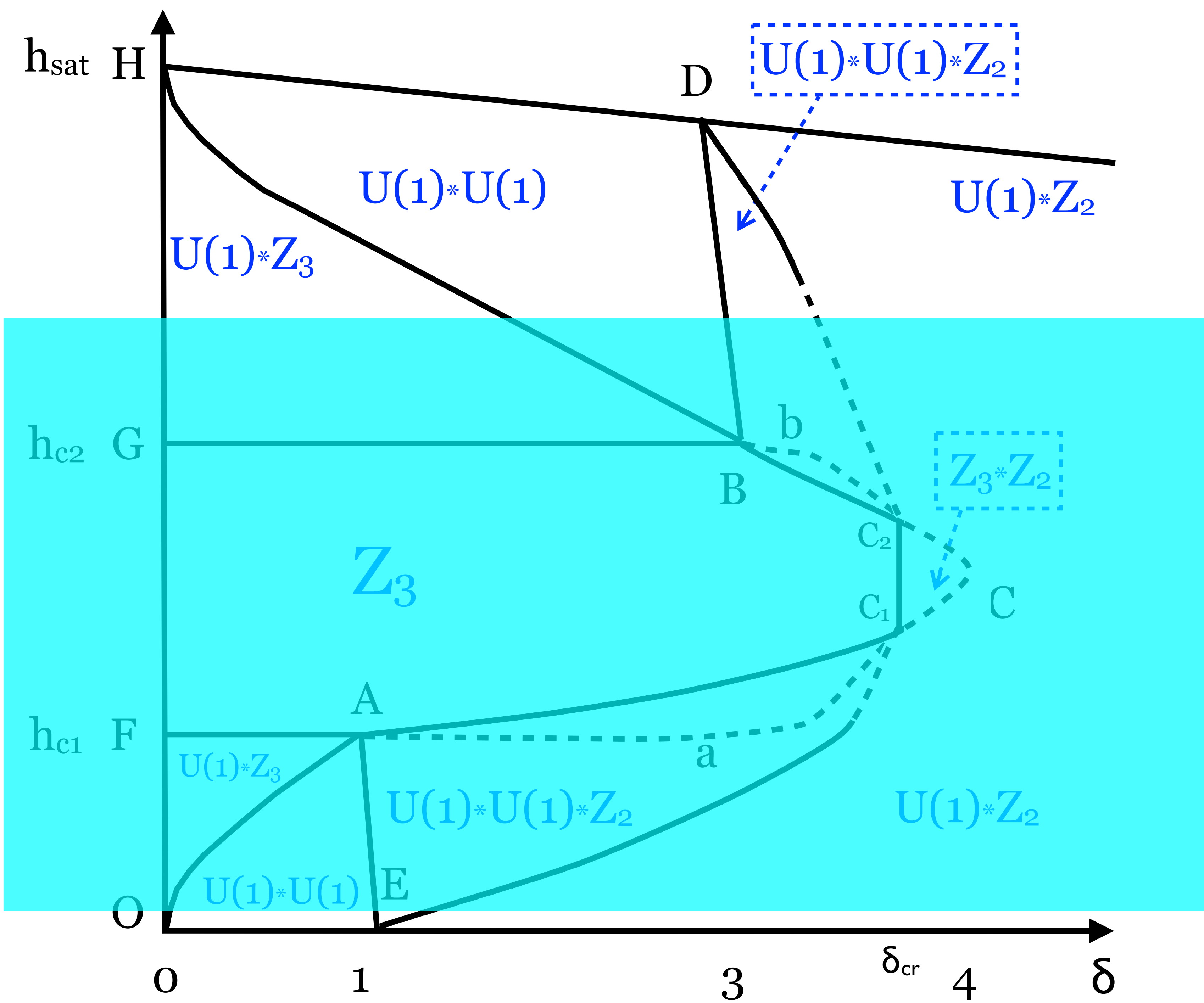
gapped single particles;
but
spontaneously broken time-reversal
= spontaneous circulating
currents

Phases of a triangular-lattice antiferromagnet near saturation

$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



$$\delta = \frac{40}{3} S \left(\frac{J - J'}{J} \right)^2$$



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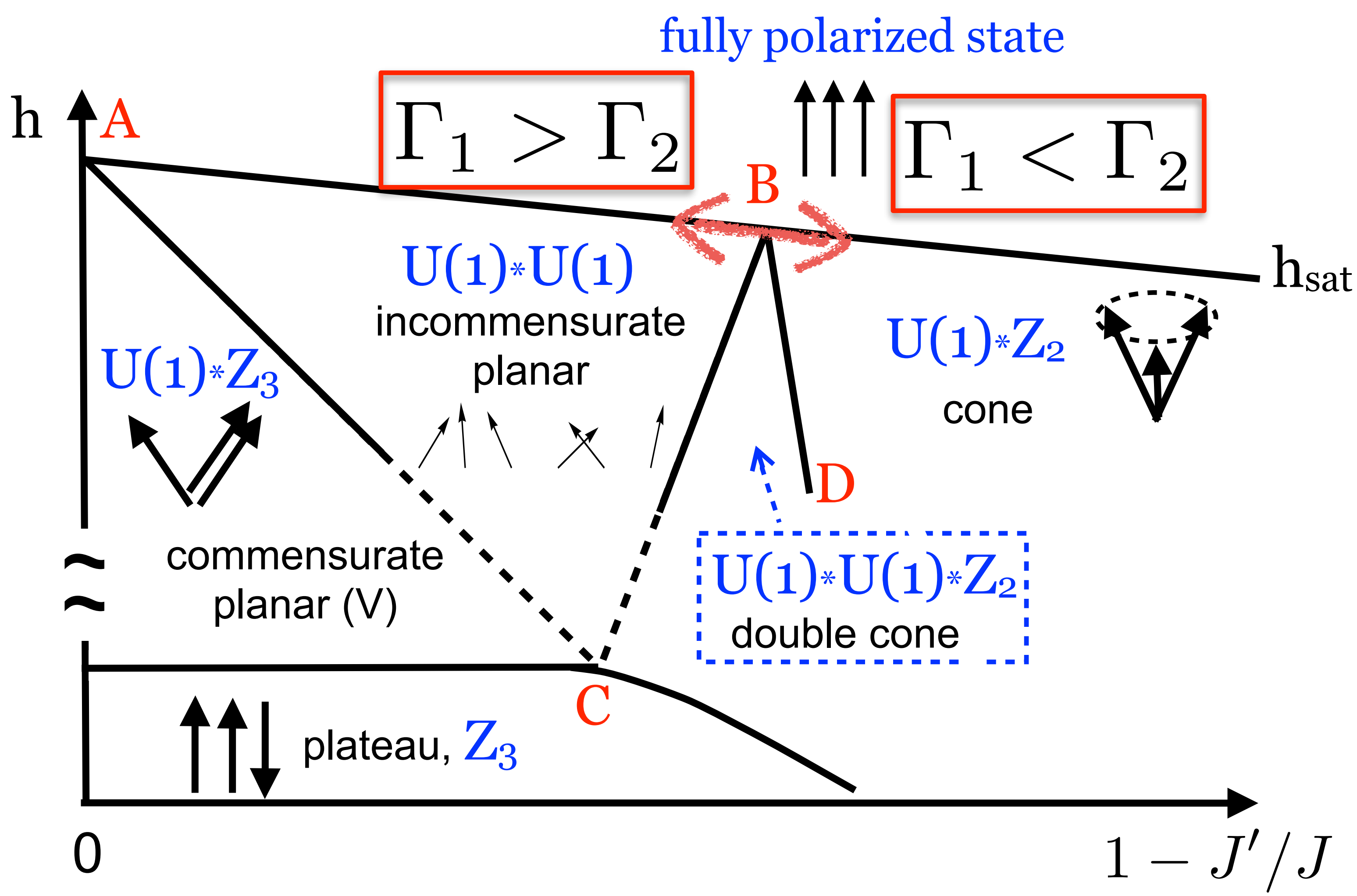
High-field phases: from **cone** to **incommensurate planar** at h = h_{sat}



Low-density expansion

$$E_0/N = -\mu(|\psi_1|^2 + |\psi_2|^2) + \frac{1}{2}\Gamma_1(|\psi_1|^4 + |\psi_2|^4) + \Gamma_2|\psi_1|^2|\psi_2|^2$$

$$\Delta\Gamma = \Gamma_2 - \Gamma_1 = \Delta\Gamma^{(0)} + \Delta\Gamma^{(1)} = \frac{9(\delta J)^2}{J} - \frac{1.6J}{S}$$

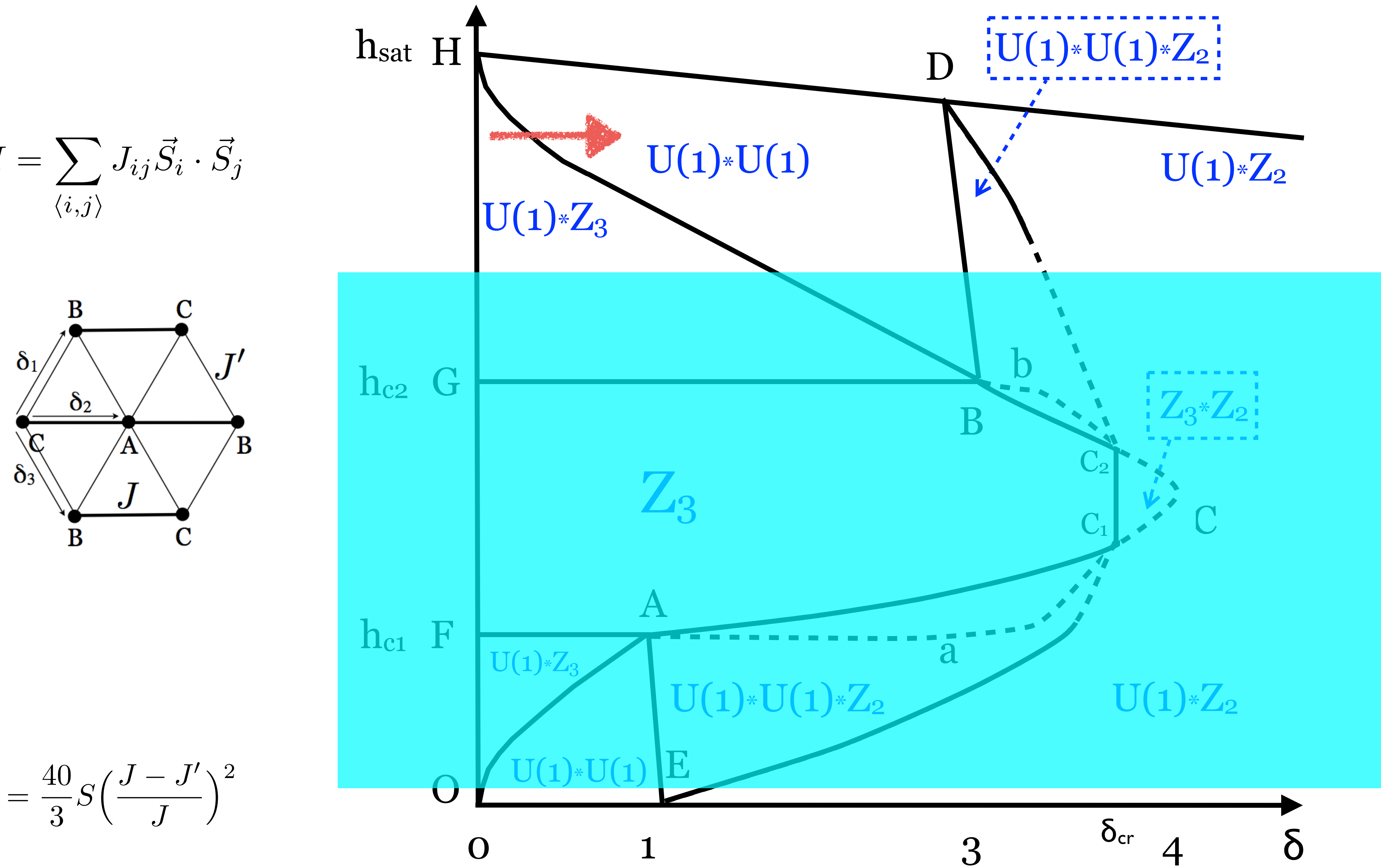
$$\Delta\Gamma^{(1)} = \frac{1}{16S}\sum_{\mathbf{k}\in \mathrm{BZ}}\left(\frac{(J_0 + 5J_{\mathbf{k}})^2}{J_0 - J_{\mathbf{k}}} - \frac{(J_0 - 4J_{\mathbf{Q}+\mathbf{k}})^2}{J_{\mathbf{Q}+\mathbf{k}} - J_{\mathbf{Q}}}\right) + \frac{3J}{8S} \approx -\frac{1.6J}{S}$$

Phases of a triangular-lattice antiferromagnet near saturation

$$U(1) \times Z_3 \to U(1) \times U(1)$$

$$Q = (4\pi/3, 0) \to Q_{\rm i} = \text{incommensurate}$$

$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



$$\delta = \frac{40}{3} S \left(\frac{J - J'}{J} \right)^2$$

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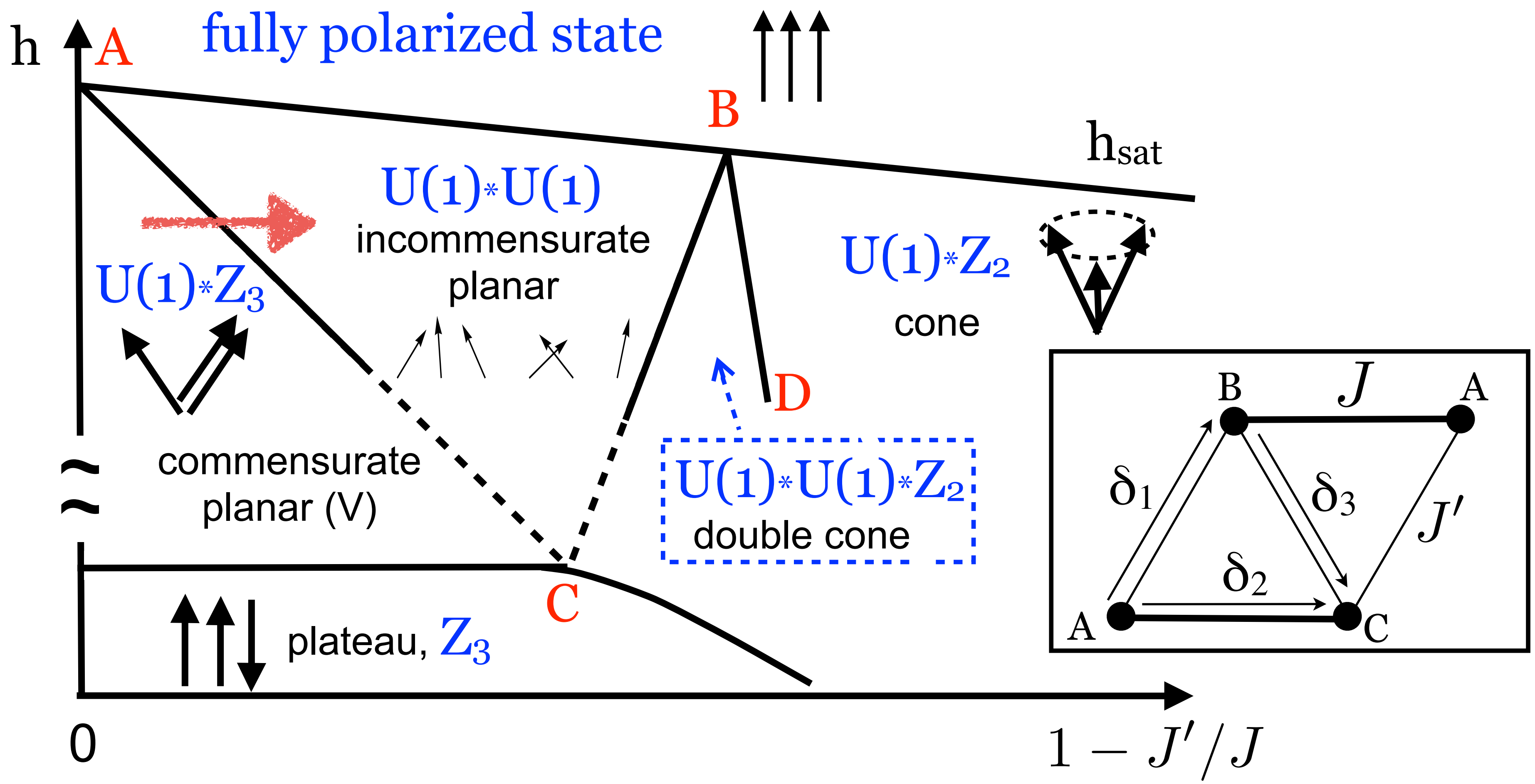
High-field phases: commensurate-incommensurate transition

$$Q = (4\pi/3, 0) \rightarrow Q_{\mathrm{i}} = \text{incommensurate}$$



Low-density expansion -> classical sine-Gordon model of the (relative) phase fluctuations

$$E_0/N = -\mu(|\psi_1|^2 + |\psi_2|^2) + \frac{1}{2}\Gamma_1(|\psi_1|^4 + |\psi_2|^4)$$
$$+\Gamma_2|\psi_1|^2|\psi_2|^2 + \Gamma_3((\bar{\psi}_1\psi_2)^3 + \text{h.c.})...$$

$$e^{i3\mathbf{Q}\cdot\mathbf{r}} = 1$$

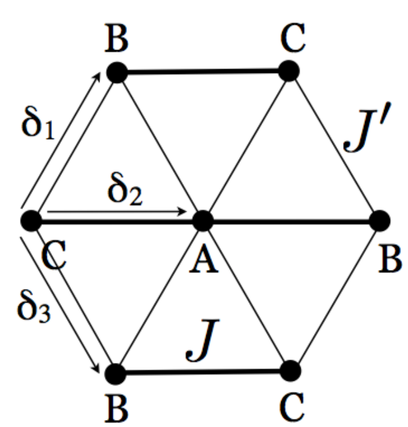
$$\longrightarrow \mathcal{E}_\theta = \frac{3JS^2\mu}{4h_{\text{sat}}}(\partial_x\theta)^2 + \frac{\sqrt{3}\delta JS^2\mu}{h_{\text{sat}}}\partial_x\theta + S\frac{\Gamma_3 S^2}{4}\frac{\mu^3}{h_{\text{sat}}^3}\cos[6\theta]$$

first calculation of $\Gamma_3 = \frac{3}{32S^2}\sum_{\mathrm{k}\in\mathrm{BZ}}\left(\frac{(5J_{\mathbf{k}}+J_0)(5J_{\mathbf{Q}+\mathbf{k}}+J_0)J_{\mathbf{Q}-\mathbf{k}}}{(J_0-J_{\mathbf{k}})(J_0-J_{\mathbf{Q}+\mathbf{k}})} - \frac{(5J_{\mathbf{k}}+J_0)(J_{\mathbf{k}}+J_0)}{2(J_0-J_{\mathbf{k}})}\right) + \frac{3J_0}{64S^2} \approx -\frac{0.69J}{S^2}$

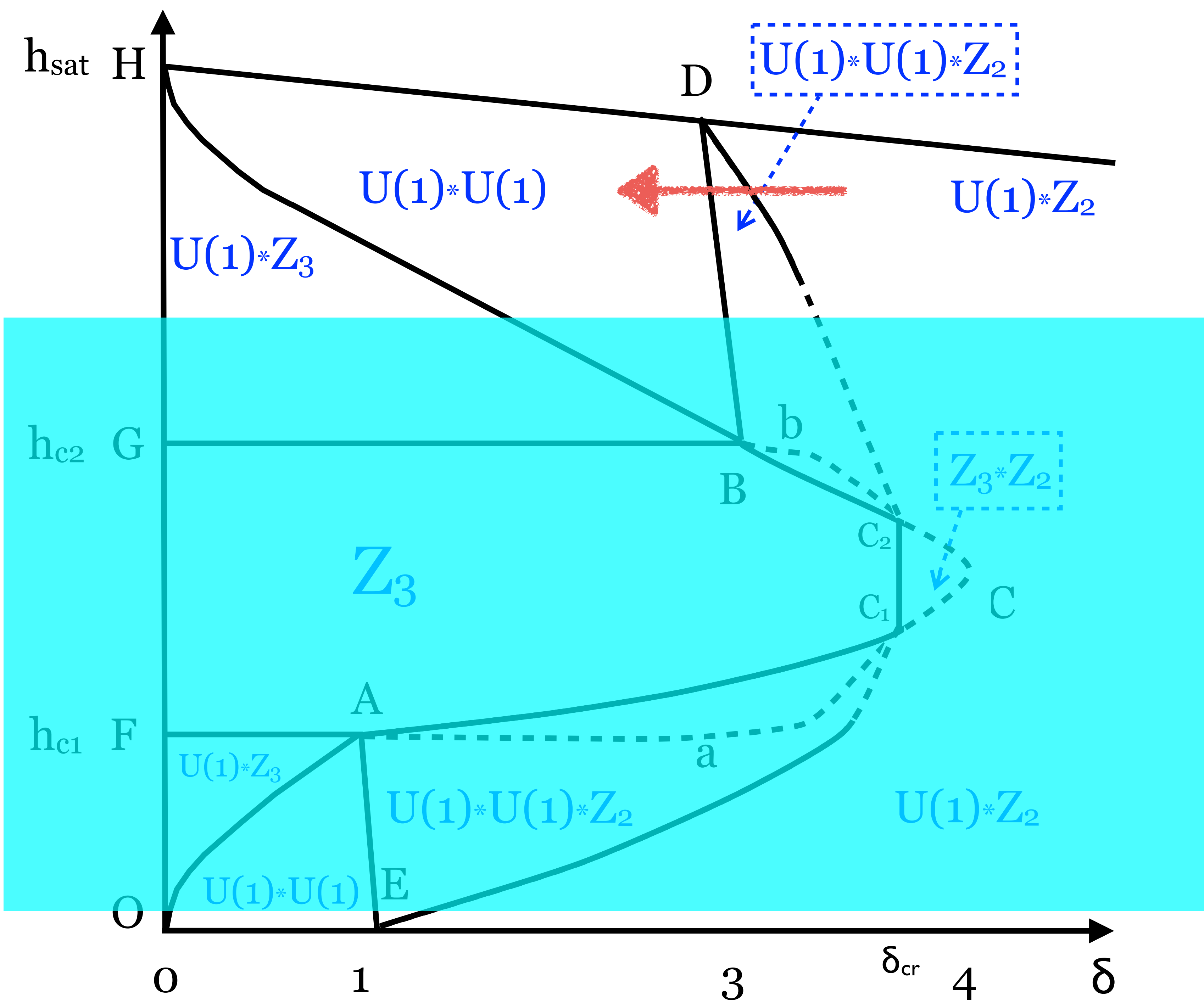
Phases of a triangular-lattice antiferromagnet near saturation

$$U(1) \times U(1) \to U(1) \times Z_2 \text{ or } U(1) \times U(1) \to \text{smth else} \to U(1) \times Z_2?$$

$$H = \sum_{\langle i,j \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



$$\delta = \frac{40}{3} S \left(\frac{J - J'}{J} \right)^2$$



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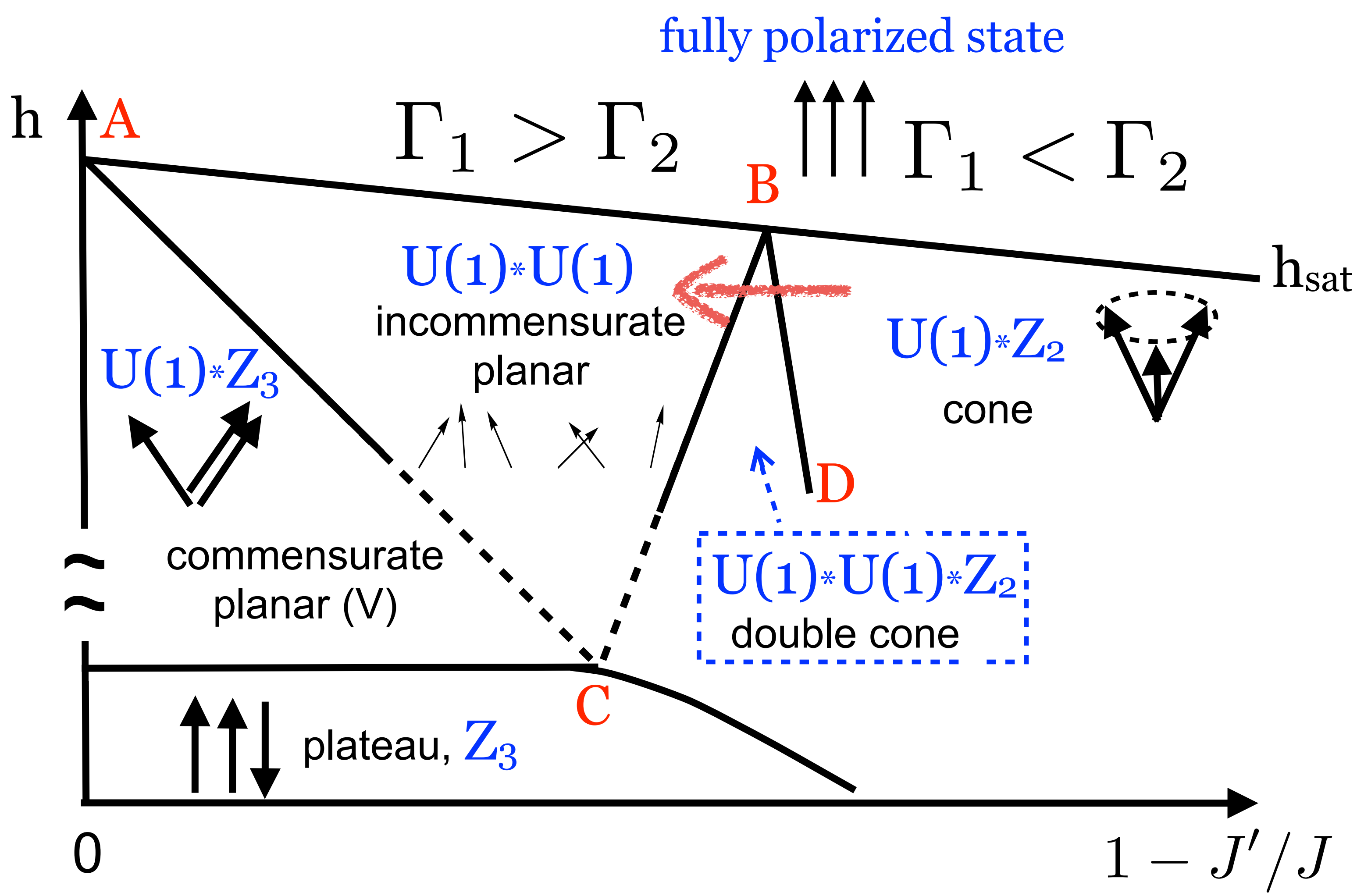
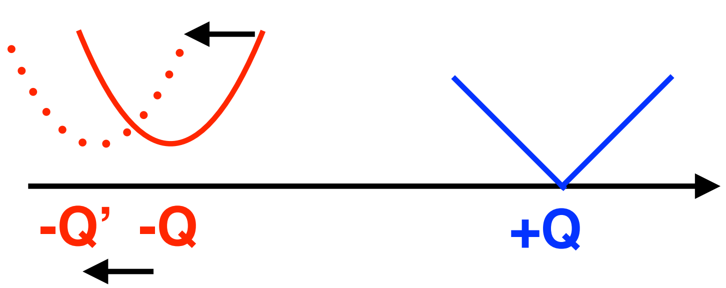
High-field phases: from **cone** to **incommensurate planar** at finite density



Elementary excitation spectrum of the cone phase: Goldstone mode at k = +Q, gapped at $-Q' \neq -Q$

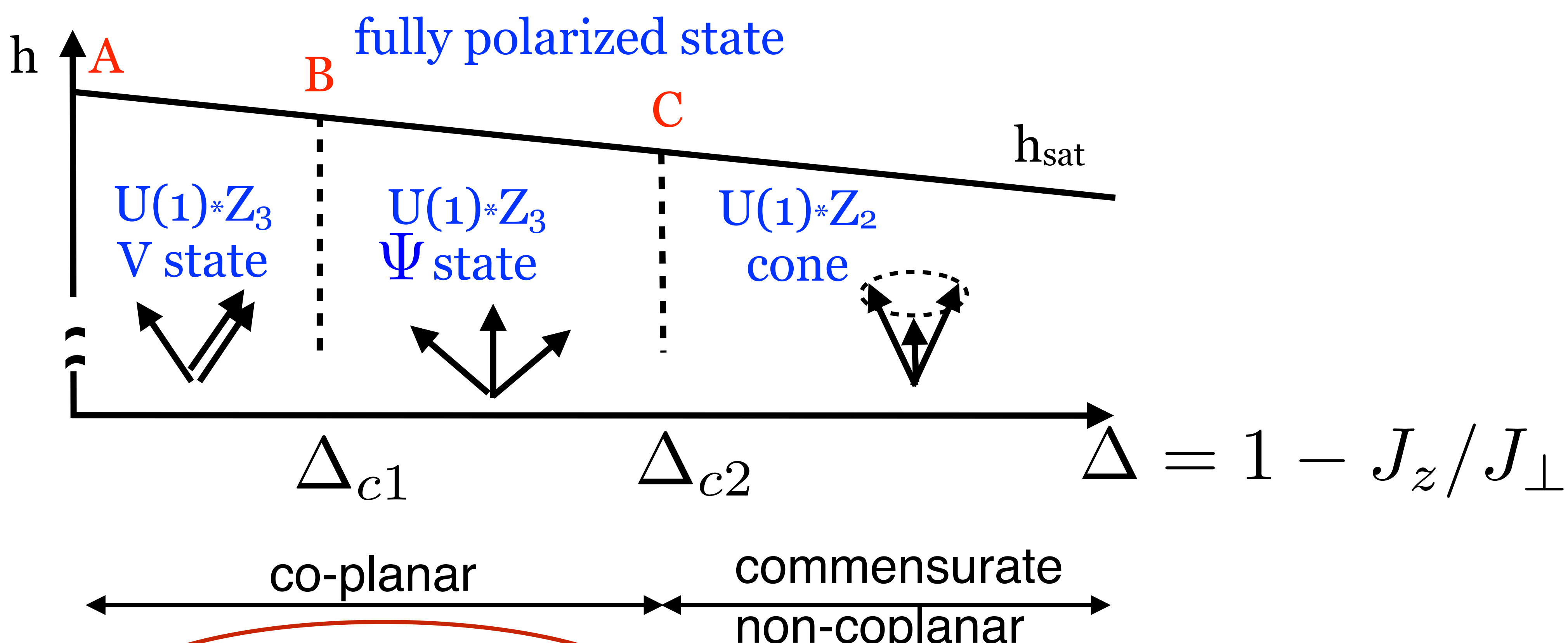
Transition at **BD**: softening of the mode at -Q'



$$Q' = Q + \frac{1.45(h_{\rm sat} - h)}{h_{\rm sat}\sqrt{S}}$$

High-field phases, XXZ model: commensurate-commensurate transitions

$$H_{\rm XXZ} = \sum_{\langle i,j \rangle} J(S_i^x S_j^x + S_i^y S_j^y) + J_z S_i^z S_j^z - h \sum_j S_j^z$$



$$\Delta_{\rm c1} = 0.45/S$$
$$\Delta_{\rm c2} = 0.53/S$$

$$\Gamma_3 = \frac{3J\Delta}{2S} - \frac{0.69J}{S^2}$$

$$\mathcal{E}_\theta = \frac{3JS^2}{4h_{\rm sat}}(\partial_x\theta)^2 + S\Gamma_3\frac{\mu^3}{h_{\rm sat}^3}\cos[6\theta]$$

Solid-Solid transition due to the sign change of Γ

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Conclusions

Emergent Ising orders

Two-dimensional chiral spin-current phase $Z_3 * Z_2$

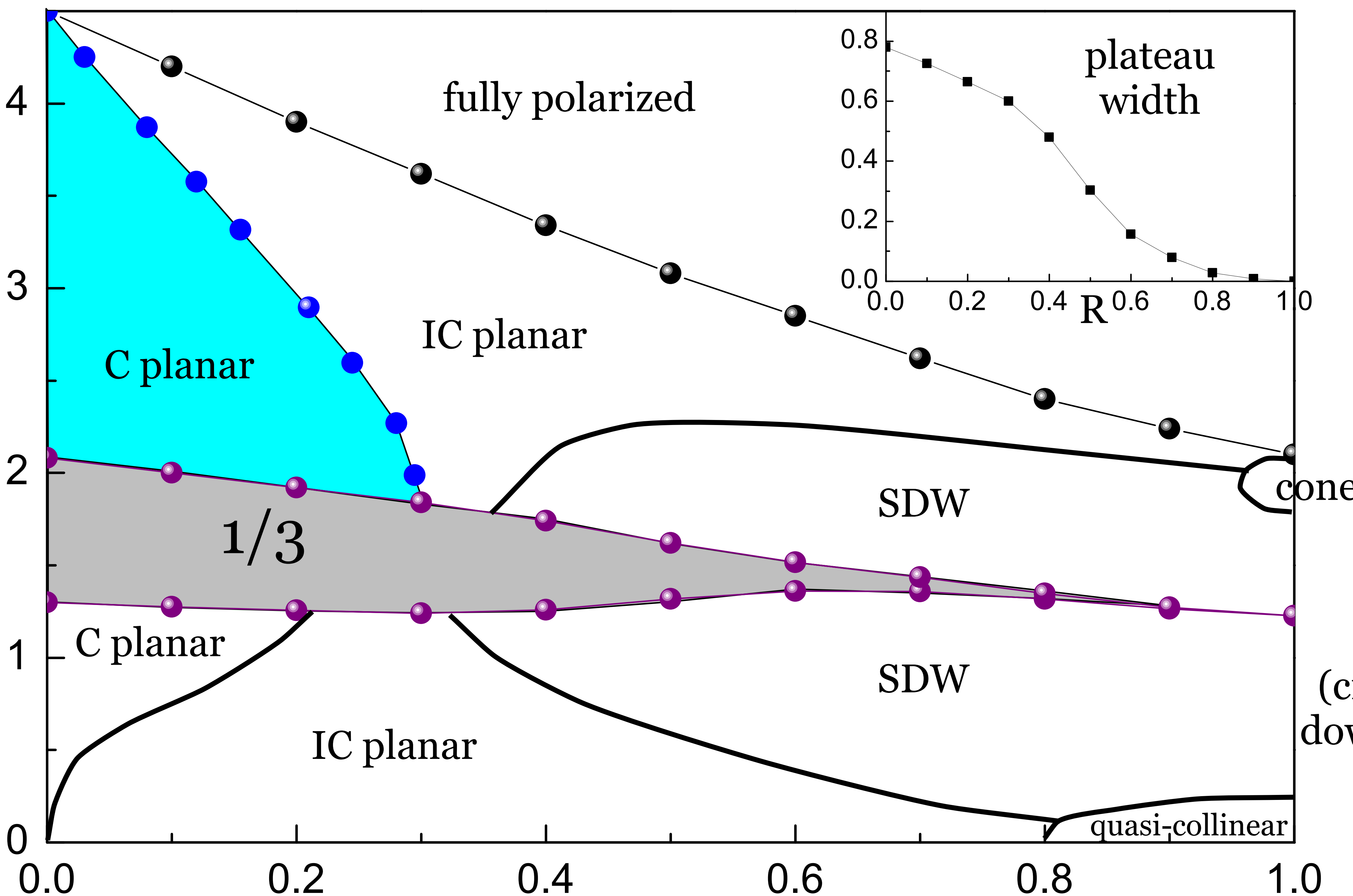
High-field phases of triangular antiferromagnet $U(1) * U(1) * Z_2$

"An exceedingly simple model leads to a surprising richness of phases and critical behavior.
The underlying triangular lattice and the associated degeneracy play a crucial role in this physics."

HB2U, Alyosha!

two-dimensional

Schematic phase diagram for spin-1/2 triangular lattice AFM



R=1-J'/J

plateau for all J'/J (crystal of spin-downs; end-point at J'=0)

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Ground states of spin-$\frac{1}{2}$ triangular antiferromagnets in a magnetic field

Ru Chen,[1] Hyejin Ju,[1] Hong-Chen Jiang,[2] Oleg A. Starykh,[3] and Leon Balents[2]
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[2]*Kavli Institute of Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California, 93106, USA*
[3]*Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112, USA*

spin-current state does not apply directly to s=1/2 model

Compare with:

PHYSICAL REVIEW B **87**, 060407(R) (2013)

Quantum stabilization of classically unstable plateau structures

Tommaso Coletta,[1] M. E. Zhitomirsky,[2] and Frédéric Mila[1]

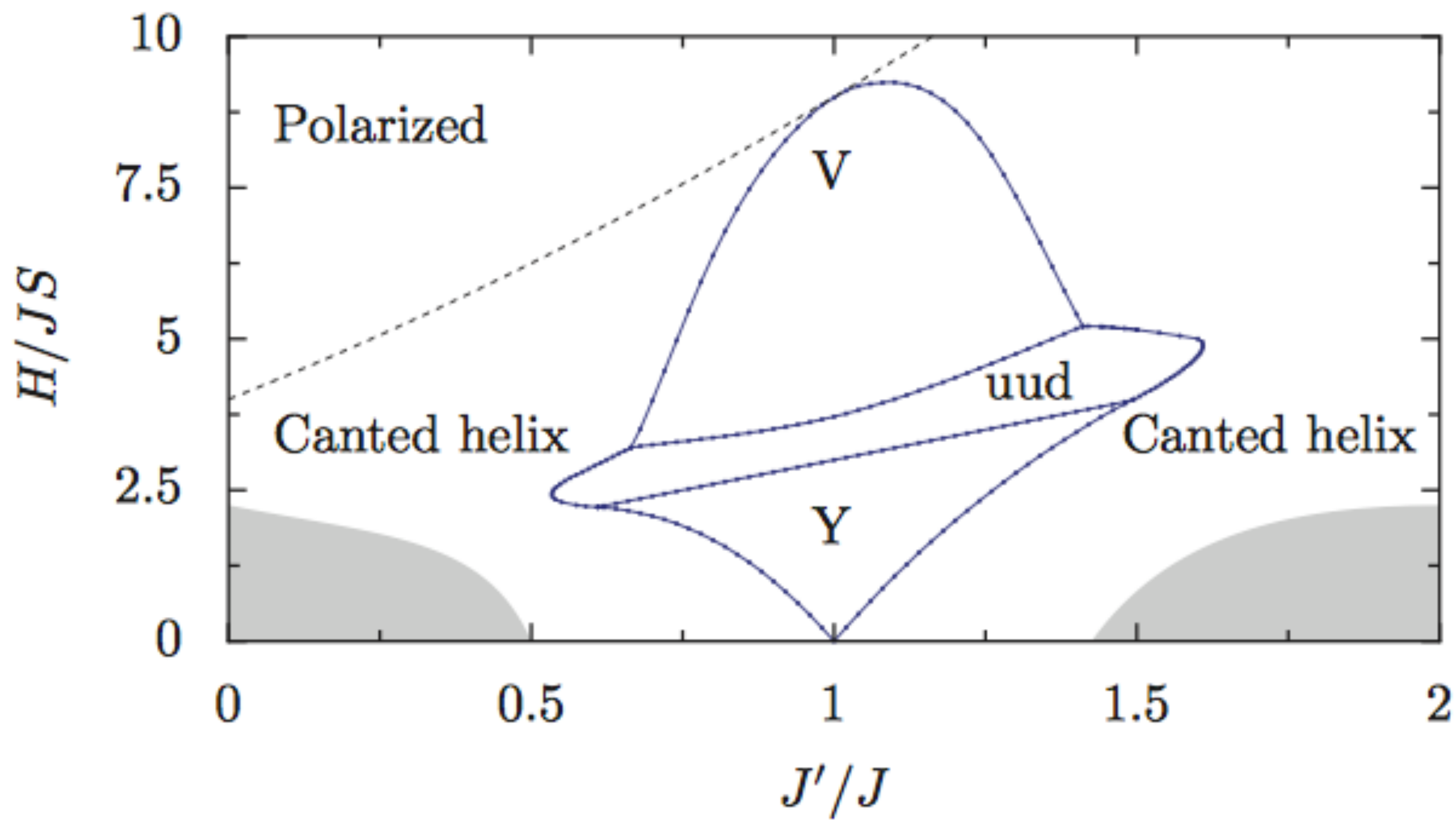

FIG. 4. (Color online) Phase diagram of the spin-1/2 anisotropic triangular lattice in magnetic field. Y and V regions denote three-sublattice planar states. The dashed line is the classical saturation field. The gray shading denotes regions where phases other than the canted helical states may be expected.

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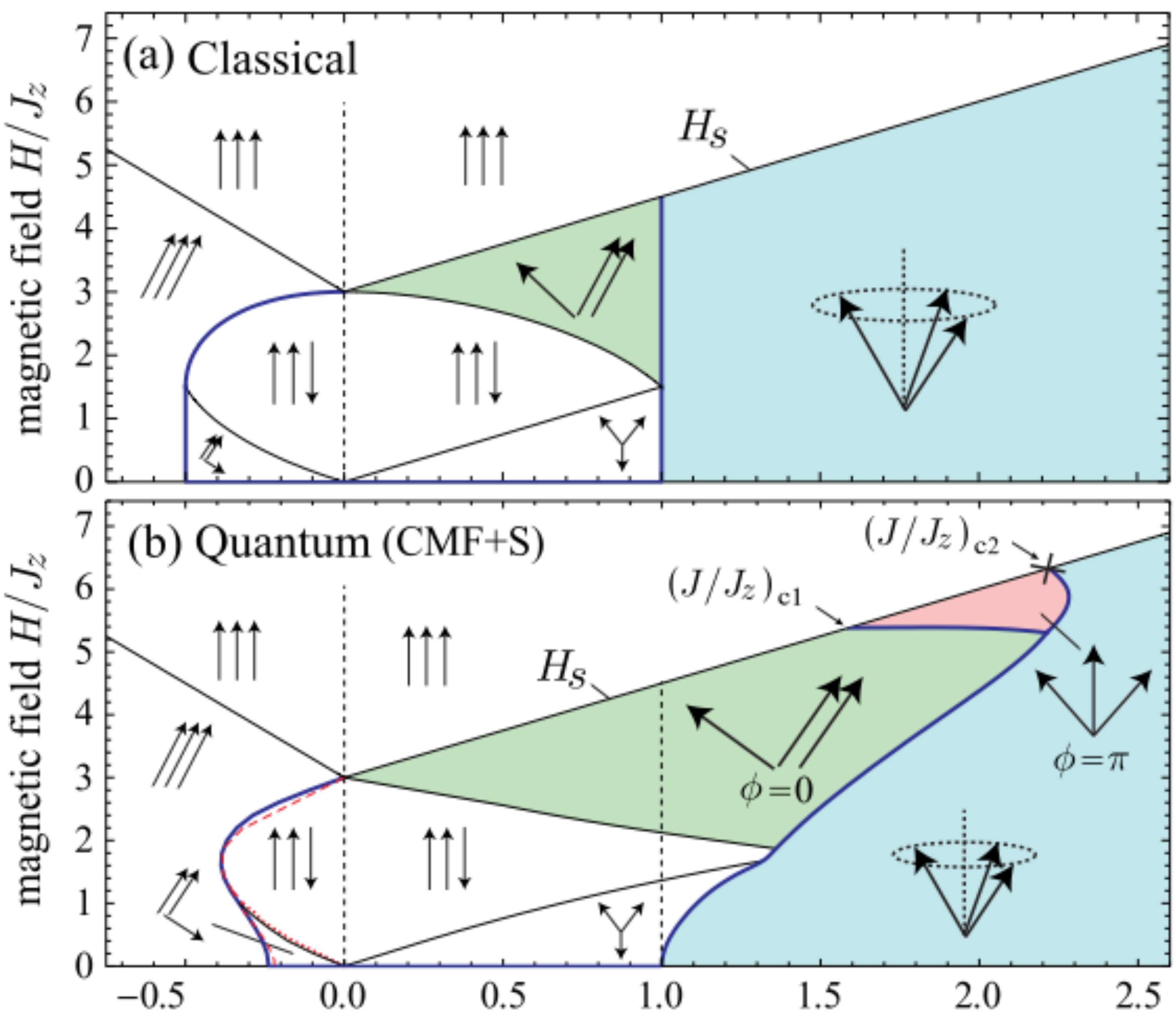
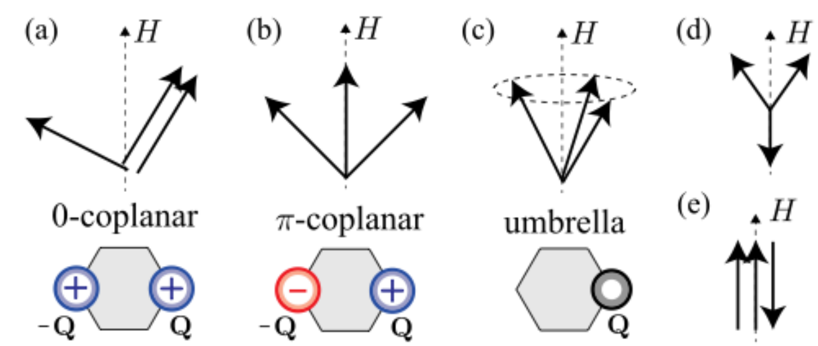
Quantum Phase Diagram of the Triangular-Lattice *XXZ* Model in a Magnetic Field

Daisuke Yamamoto,[1] Giacomo Marmorini,[1,2] and Ippei Danshita[3]

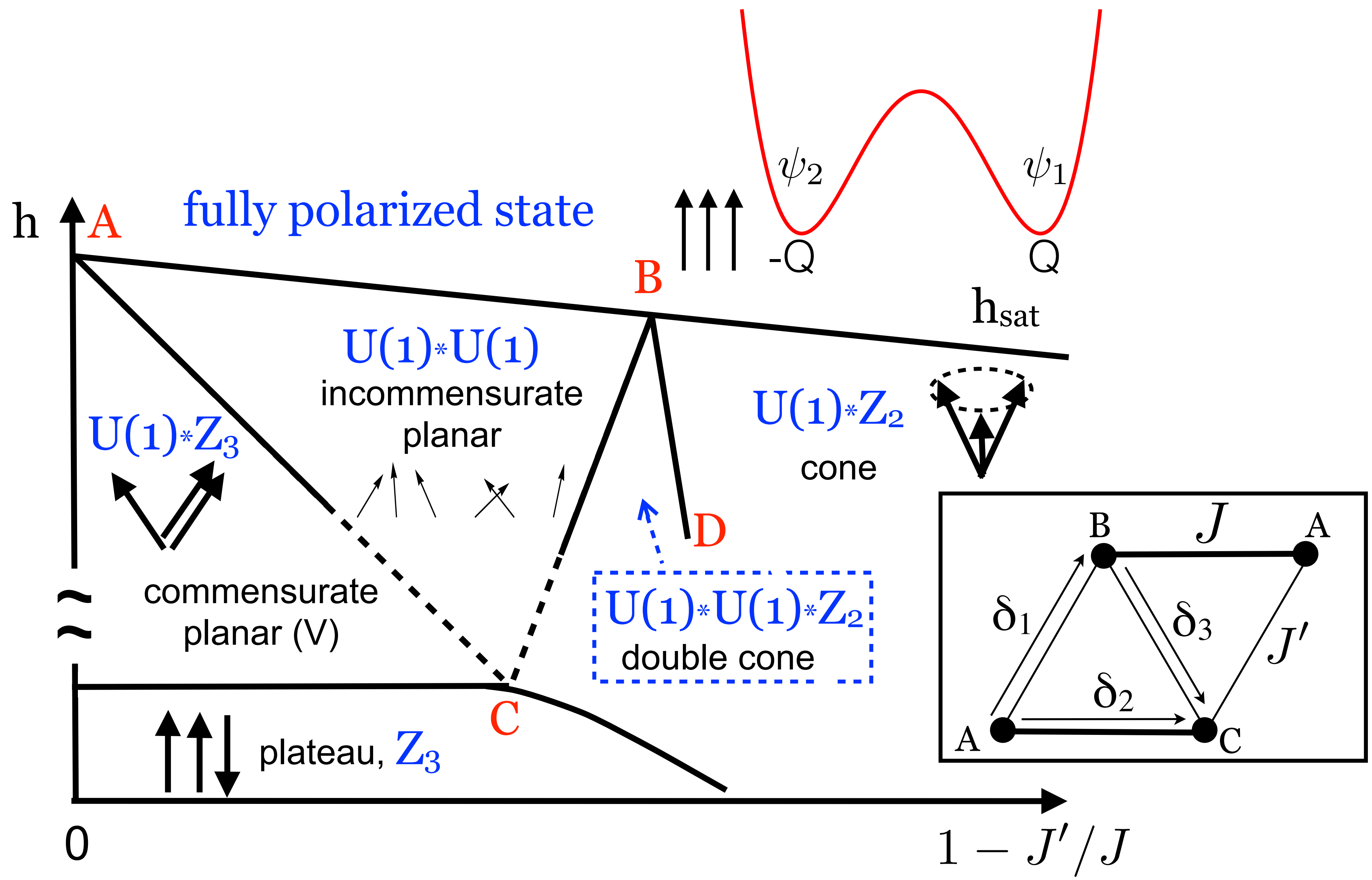




Cluster mean-field theory:
direct 1st order transition
between the UUD and the cone phases.

Can there be an intermediate
spin-current (chiral Mott) phase
with broken $Z_3 * Z_2$?

High-field phases, J-J' model



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