Condensation of bosonic pairs in quantum magnets

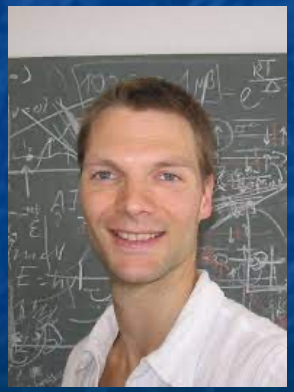
F. Mila
Ecole Polytechnique Fédérale de Lausanne
Switzerland

Theorists

Mithilesh Nayak (Lausanne → Fribourg)

Bruce Normand (PSI)

Brijesh Kumar (New Delhi)



Experimentalists

Ellen Fogh (Lausanne)

Henrik Rønnow (Lausanne)

and many more…

Scope

- Spin nematics
- Pair condensation in spin-1/2 systems

  → Below saturation: bound states of magnons

  → From gapped phase: bound states of triplons
- Bosonic language: condensation of Cooper pairs
- Experimental evidence: triplet gap at transition
- Shastry-Sutherland compound $SrCu_2(BO_3)_2$

  → Inelastic neutron scattering up to 26 T

  → Dynamical structure factor from t-dependent DMRG
- Conclusions

Spin nematics

- Broken SU(2) symmetry without magnetic order
- Spin-1 models with biquadratic interactions

  Blume and Hsieh, 1969
- General classification

  Andreev and Grishchuk, 1984
- Experimental realization in spin-1 systems?

  → $NiGa_2S_4$: spin-1 on triangular lattice Nakatsuji et al, 2005

  → Theory: Ferro- and AF- quadrupolar phases

  Arikawa-Tsunetsugu, 2006; Läuchli, FM, Penc, 2006

Pair condensation in S=1/2 systems

- Spin nematic below saturation if FM interactions
- Bound states of magnons condense first

  Shannon, Momoi, Sindzingre, 2006

  Zhitomirsky and Tsunetsugu, 2010
- NMR signature in $LiCuVO_4$

  → No shift below saturation

  → No magnetic order

  Orlova et al, 2017

Pair condensation in gapped AF

- Gapped antiferromagnets

  → Usually, gap closing = BEC of triplets

- Always? No!

  → If there is a spin-2 bound state below the two-triplet continuum, it will condense first

  → Non-zero magnetization, but no BEC of triplets

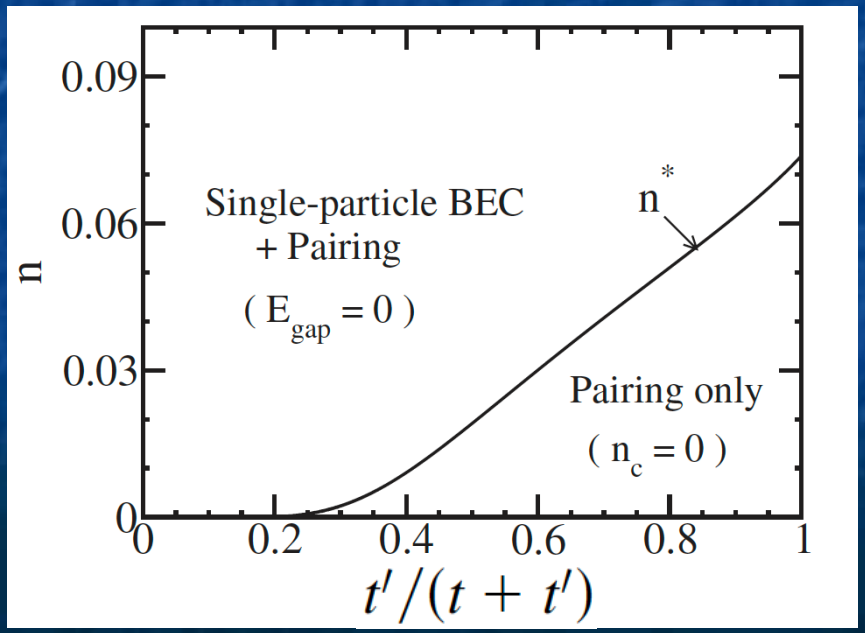
PRL 95, 110406 (2005) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2005

Absence of Single-Particle Bose-Einstein Condensation at Low Densities for Bosons with Correlated Hopping

Rachel Bendjama, Brijesh Kumar,* and Frédéric Mila†

Mean-field theory

$$H = -t\sum_{\mathbf{r}}\sum_{\delta=\pm x,\pm y} b^{\dagger}_{\mathbf{r}+\delta} b_{\mathbf{r}} - \mu\sum_{\mathbf{r}} n_{\mathbf{r}}$$
$$- t'\sum_{\mathbf{r}}\sum_{\delta=\pm x}\sum_{\delta'=\pm y} n_{\mathbf{r}}\{b^{\dagger}_{\mathbf{r}+\delta} b_{\mathbf{r}+\delta'} + \text{H.c.}\},$$



Pair condensation without single particle condensation

(large enough correlated hopping and small density)

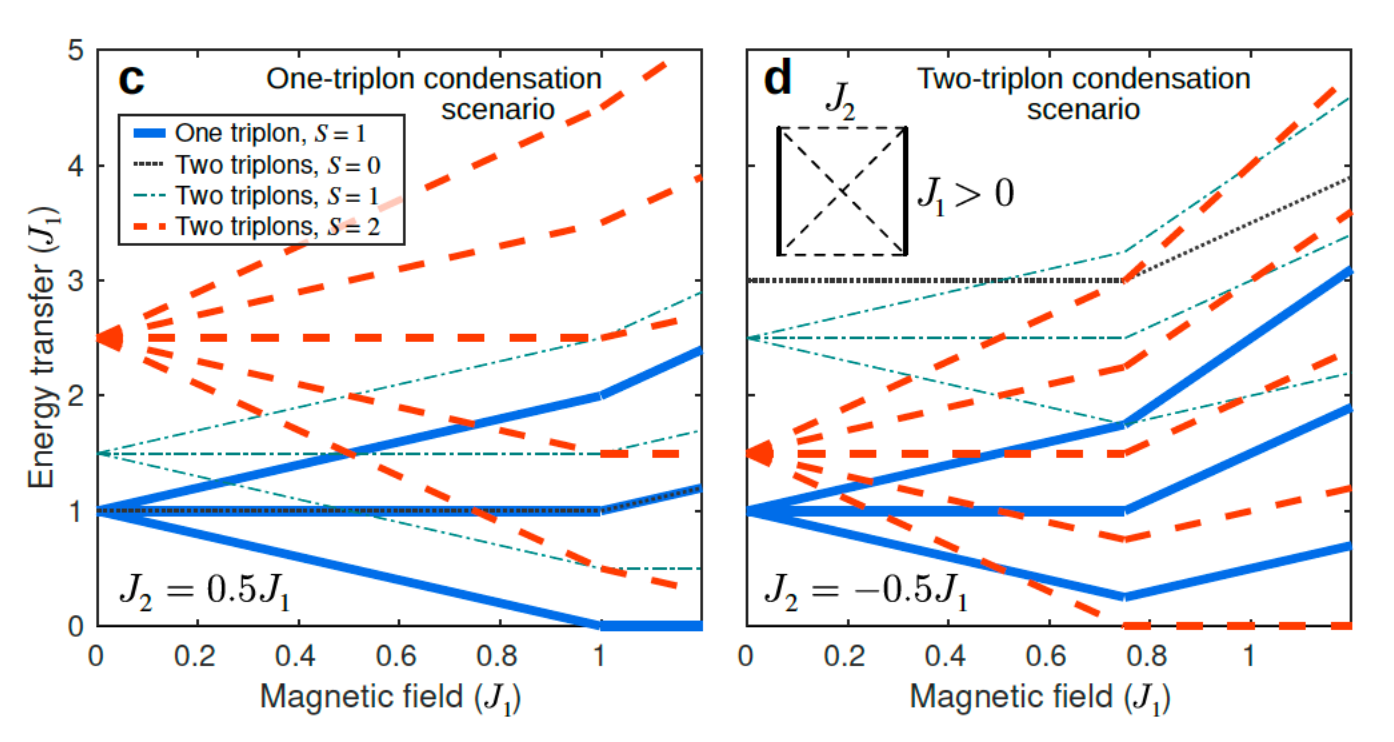
Experimental signature?

- Follow spin-2 bound state up to condensation
  → tricky due to selection rules

- Follow the first-triplet excitation
  → gap does not close at the transition

(as the single particle gap in BCS theory)
  → kink at the transition

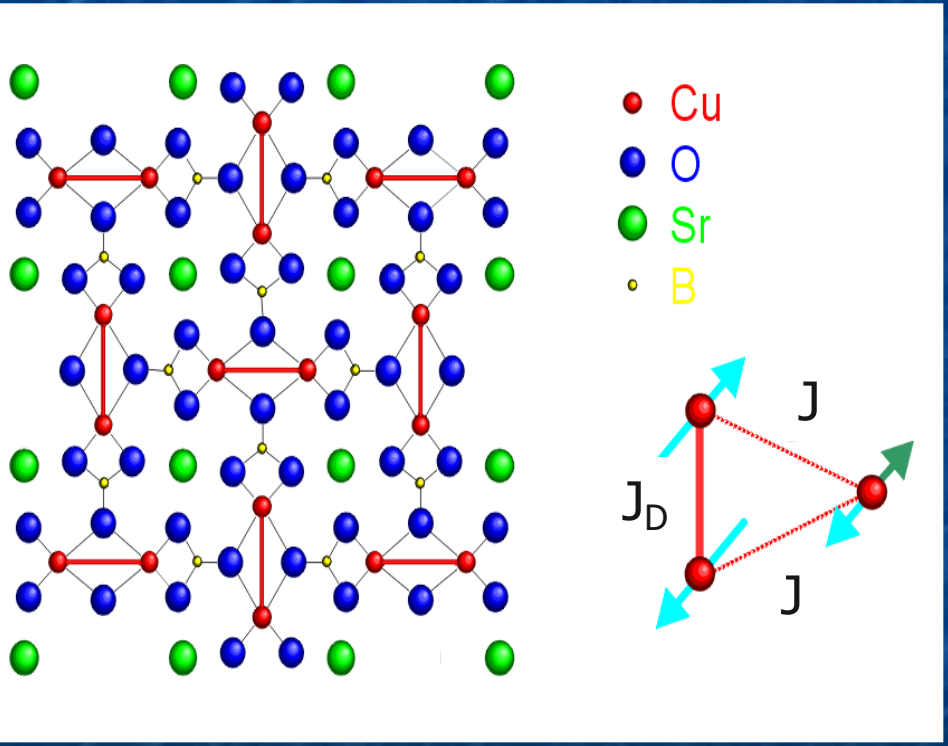
Toy model



Fogh, Nayak, … FM, Rønnow, 2023

$SrCu_2(BO_3)_2$

Smith and Keszler, JSSC 1991



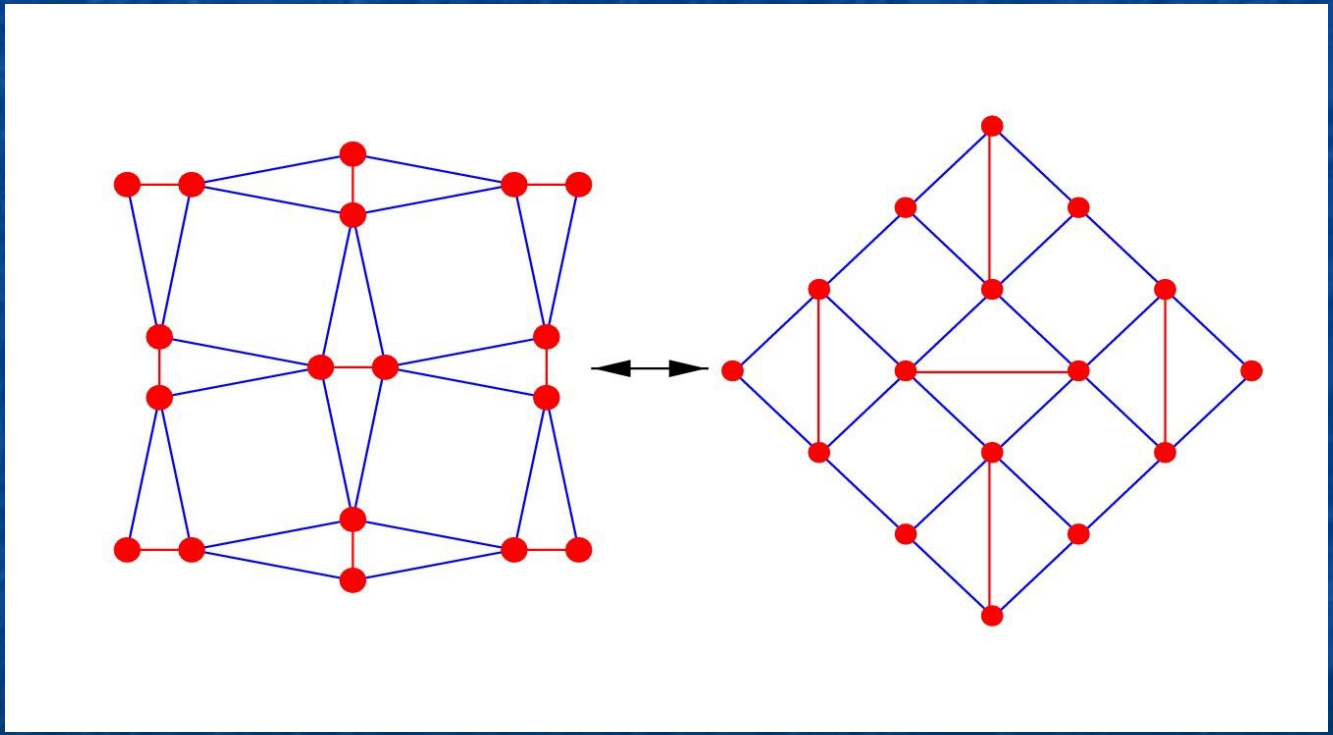
Cu^{2+} -> Spin 1/2

$J_D \approx 85$ K

$J/J_D \approx 0.63$

Famous for its magnetization plateaus

From orthogonal dimer to Shastry-Sutherland model



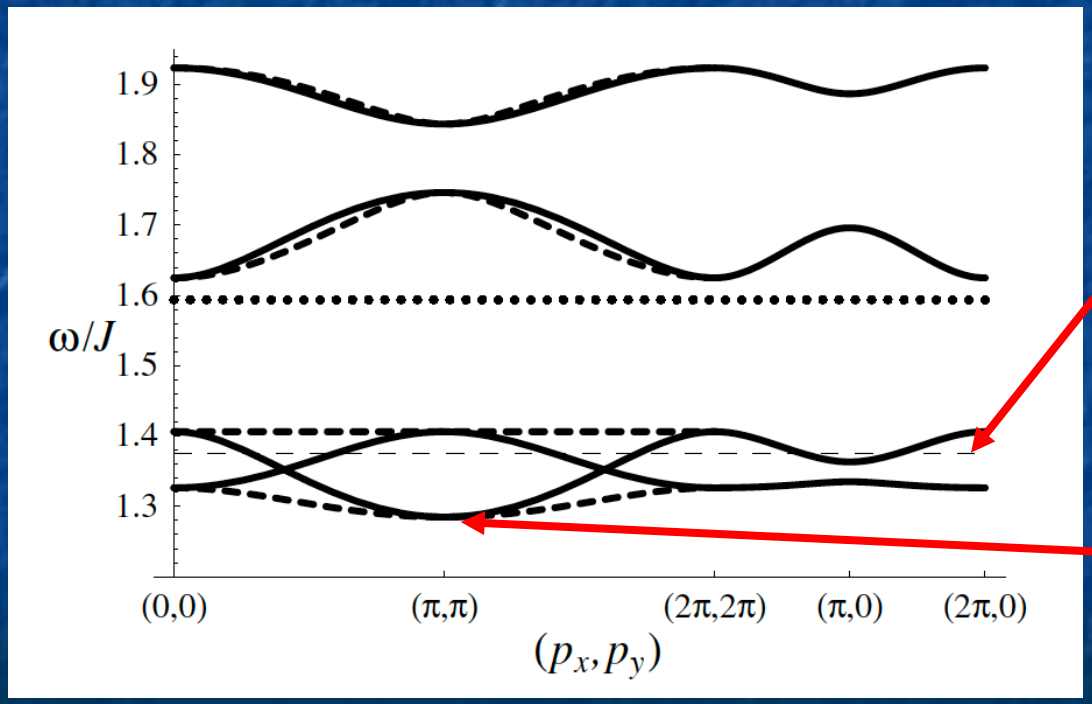
Shastry and Sutherland, 1981

VOLUME 86, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JANUARY 2001

Low-Lying Magnetic Excitation of the Shastry-Sutherland Model

K. Totsuka,[1,*] S. Miyahara,[2] and K. Ueda[2]

3rd order perturbation theory in J/J_D



Two-triplet continuum

Spin-2 bound state

Pair condensation in $SrCu_2(BO_3)_2$

- Inelastic neutron scattering

  → need data above 23 T

  → only possible a few years ago in Berlin and for a very limited period of time

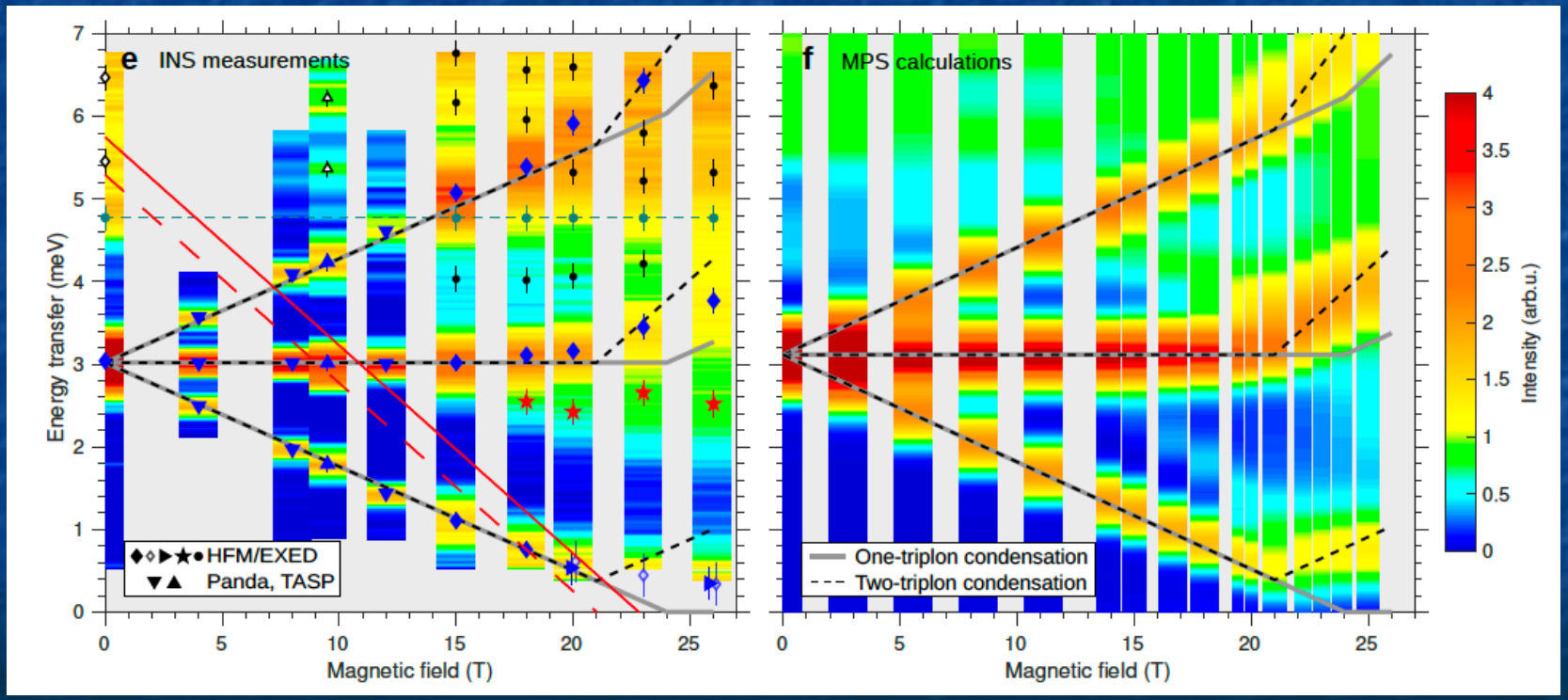
- Time-dependent DMRG on cylinders

  → good approximation to dynamical structure factor of 2D systems

Field-induced bound-state condensation and spin-nematic phase in $SrCu_2(BO_3)_2$ revealed by neutron scattering up to 25.9 T

Ellen Fogh,[1,*] Mithilesh Nayak,[2,*] Oleksandr Prokhnenko,[3] Maciej Bartkowiak,[3,4] Koji Munakata,[5] Jian-Rui Soh,[1] Alexandra A. Turrini,[6,1] Mohamed E. Zayed,[7] Ekaterina Pomjakushina,[8] Hiroshi Kageyama,[9] Hiroyuki Nojiri,[10] Kazuhisa Kakurai,[5] Bruce Normand,[1,11] Frédéric Mila,[2] and Henrik M. Rønnow[1]

Nature Communications, in press



Neutron scattering DMRG

Discussion I

- Momentum integrated results

  → Better statistics

  → Small dispersion, so not a major problem

- DMRG

  → Width 4 for most results, some benchmarks at width 6

  → No adjustable parameters – all taken from previous experiments, including DM interactions

- Minimum of triplet branch due to DM interactions?

  → The minimum should occur at 24 T, where the triplet gap would close, not at 21 T

Discussion II

- Red line: spin-2 mode detected in ESR Nojiri et al , 2003

  → Would cross the singlet too late

  → Dashed-red line: our guess for the lowest spin-2 bound state

  → Not seen probably because of A_2 symmetry

  Wang and Batista, 2018

- Three-triplet excitations

  → Expected when exciting a triplet in a sea of 2-triplet bound states

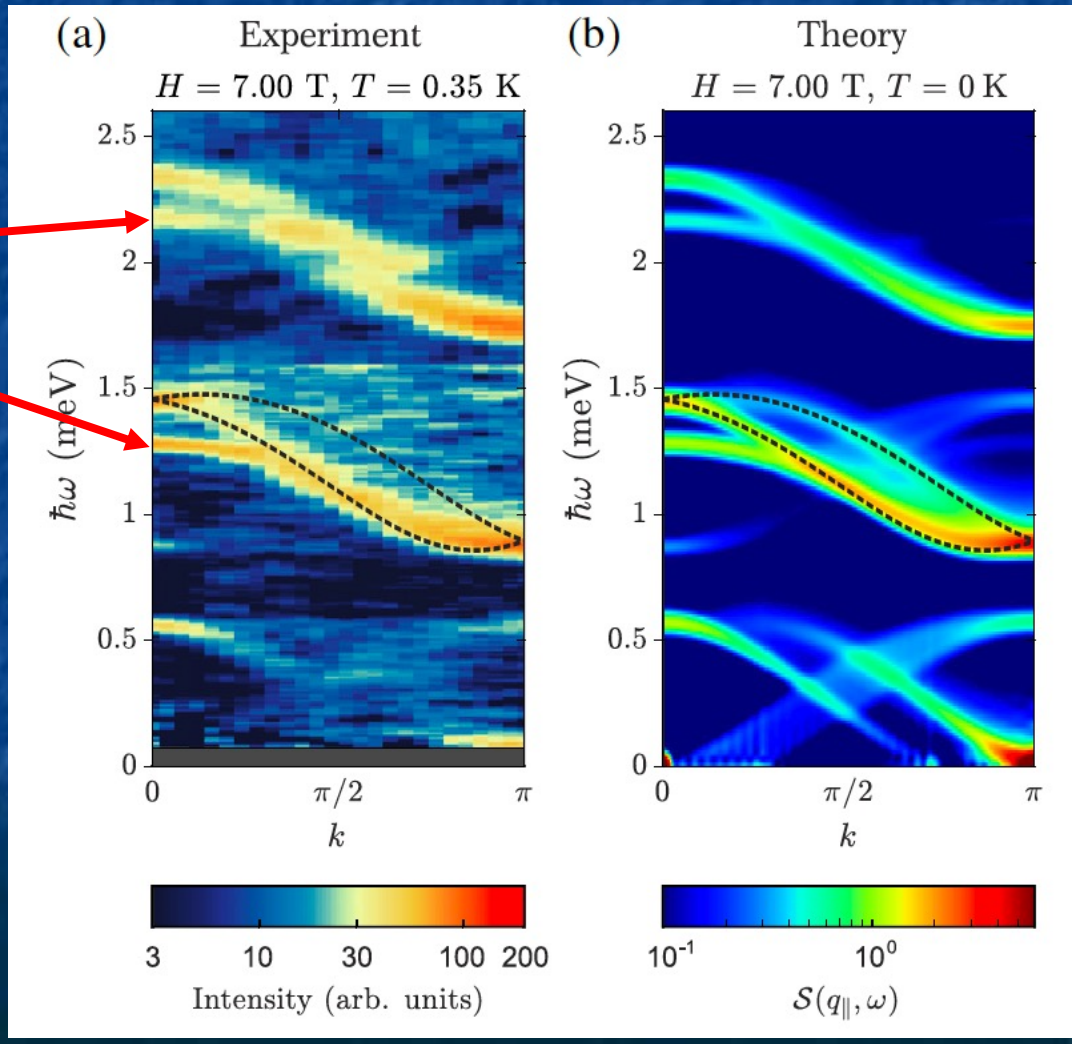
  → Cannot be resolved with current accuracy

PHYSICAL REVIEW LETTERS 124, 087203 (2020)

Magnetic-Field-Induced Bound States in Spin-$\frac{1}{2}$ Ladders

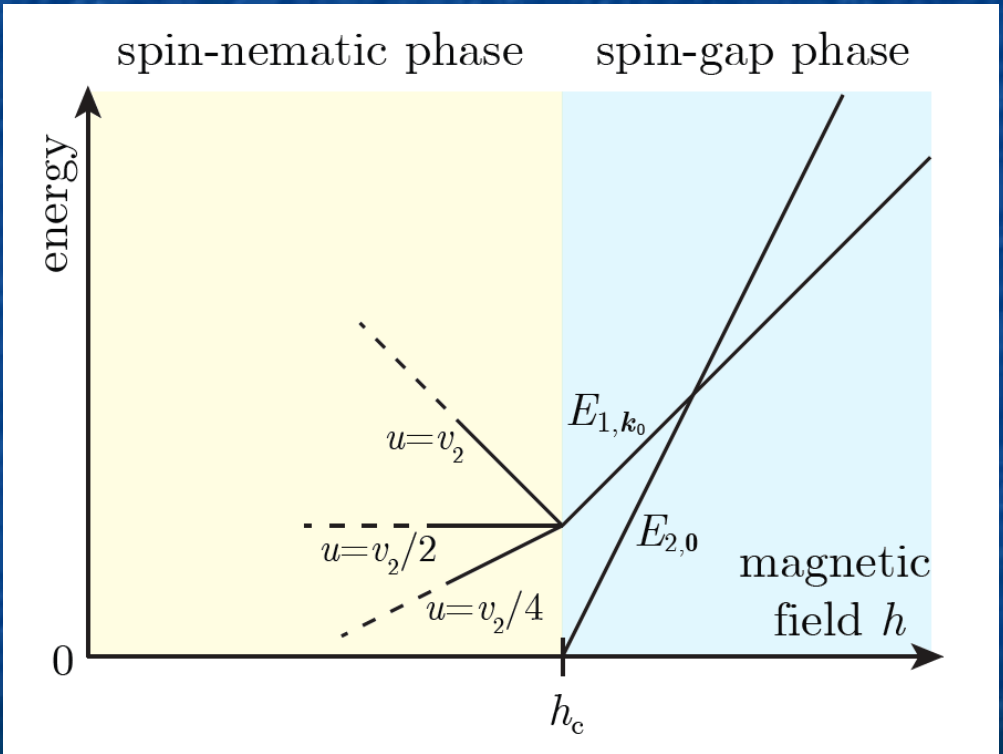
Mithilesh Nayak,[1,*] Dominic Blosser,[2,†] Andrey Zheludev,[2] and Frédéric Mila[1]

2-triplet bound states between a condensed triplet and a triplet created by a neutron



Kink of triplet branch

Condensation of bound state
of magnons below saturation



u, v_2: interaction
parameters

Momoi, arXiv:2308.12569

Conclusions

- Spin nematics

  → Growing evidence in various systems

- $SrCu_2(BO_3)_2$

  → First example when closing the gap in a gapped AF

  → First evidence of a persistent gap in the triplet spectrum and of a kink in its field dependence

- Other properties?

  → $\Delta S=2$ steps in magnetization (hard to observe in macroscopic samples)

  → Transitions between different phases, as in superfluid Helium 3?

More about DMRG results