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DQMP Flat Club – 2D Magnets

Christian Rüegg :: Director :: PSI

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- Introduction: Physics, Materials and Experiments
- Dirac Magnons in $CrBr_3$ and their Damping — S. Nikitin *et al.*, Phys. Rev. Lett. **129**, 127201 (2022).
- Strong Spin-lattice Coupling in $LiCrO_2$ — S. Toth *et al.*, Nature Comm. **7**, 13547 (2016).
- Quantum Criticality and Dynamics in 2D — S. Allenspach *et al.,* Phys. Rev. Lett./Res. (2020/21).
- $SrCu_2(BO_3)_2$ Out-of-Equilibrium Magnons — F. Giorgianni *et al.,* Phys. Rev. B **107**, 184440 (2023).

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2D Materials – Physics, Magnets and Devices

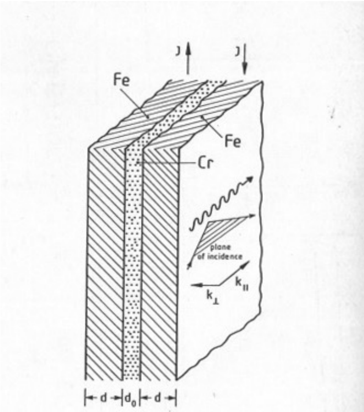
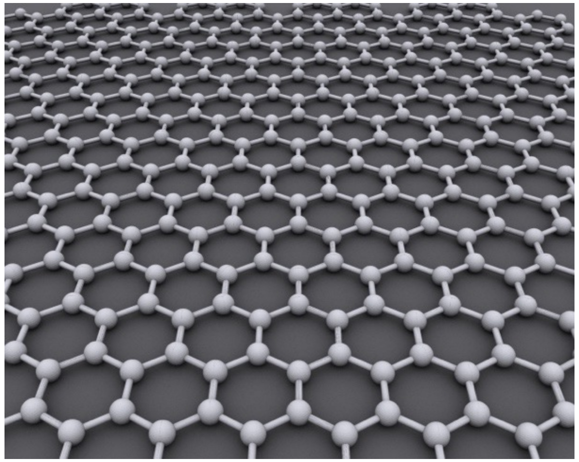
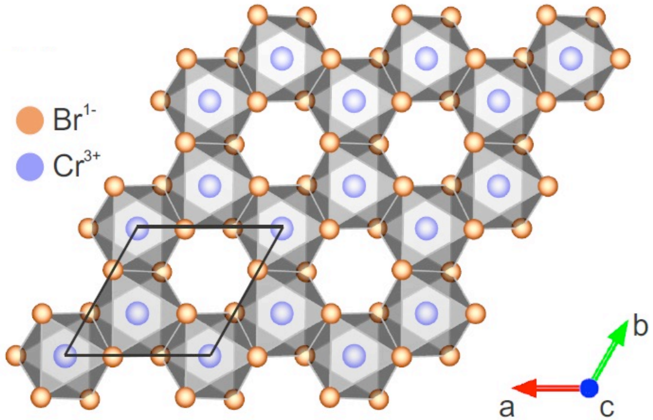


FIG. 1. Ferromagnetic double layer with antiparallel alignment of the magnetizations. Also indicated is the plane of incidence of the laser light for the observation of light scattering from spin waves and hysteresis curves via MOKE.

Nobel Prize 2007



Nobel Prize 2010



2D Metal Films
2D to 3D materials
Atomic control of thickness
Many applications (e.g. GMR)

Graphene
2D material
2D electronic states
Single layer, few layers and devices

2D Magnets (e.g. square, honeycomb)
2D sub-structure in 3D material
2D magnetic states (3D at T < T*)
Thin films, bulk and some applications

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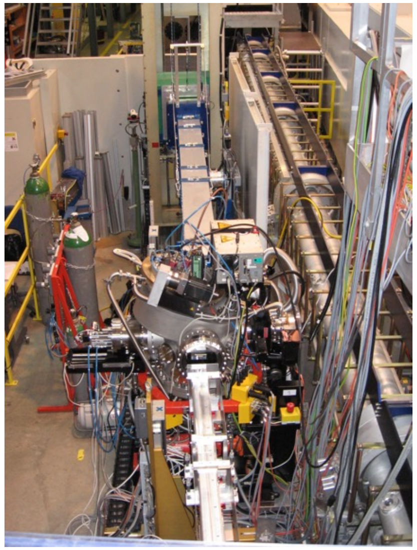
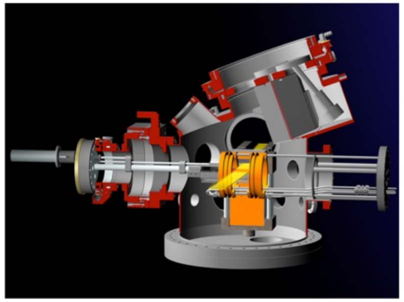
2D Materials – Magnetism of a single layer

In-situ sputtering of metallic thin films on the neutron reflectometer AMOR (SINQ)

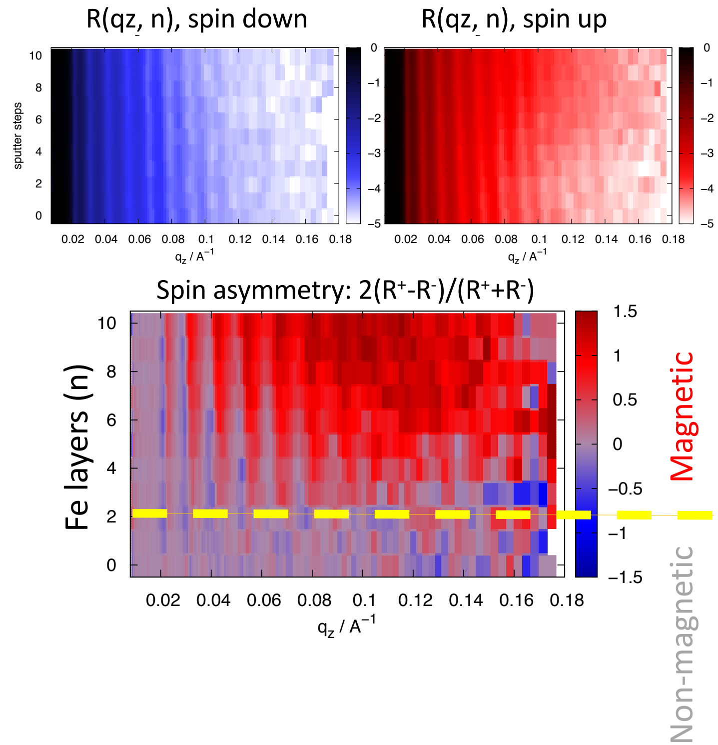
- Focusing guide based on elliptic Selene principle, sample size 2x20 mm^2 (now 1 mm^2)
- Polarized neutron beam, sensitivity: 1 layer
- Counting time: 30 m per layer (0.5 m in the future)





Sputtering chamber:

- Fe and other metals
- rotating gun
- in-situ sample positioning



Collaboration:

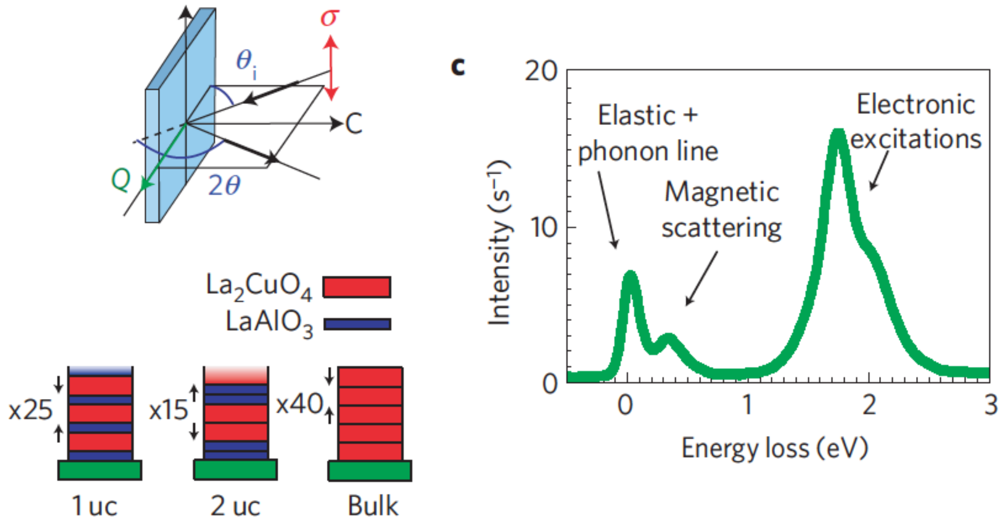
P. Böni, TU Munich; J. Mannhart, Univ. Augsburg; J. Stahn, PSI

2D Materials – Excitations of a single layer

LETTERS
PUBLISHED ONLINE: 2 SEPTEMBER 2012 | DOI: 10.1038/NMAT3409
nature materials

Spin excitations in a single La_2CuO_4 layer

M. P. M. Dean[1]★, R. S. Springell[2,3], C. Monney[4], K. J. Zhou[4†], J. Pereiro[1†], I. Božović[1], B. Dalla Piazza[5], H. M. Rønnow[5], E. Morenzoni[6], J. van den Brink[7], T. Schmitt[4] and J. P. Hill[1]★

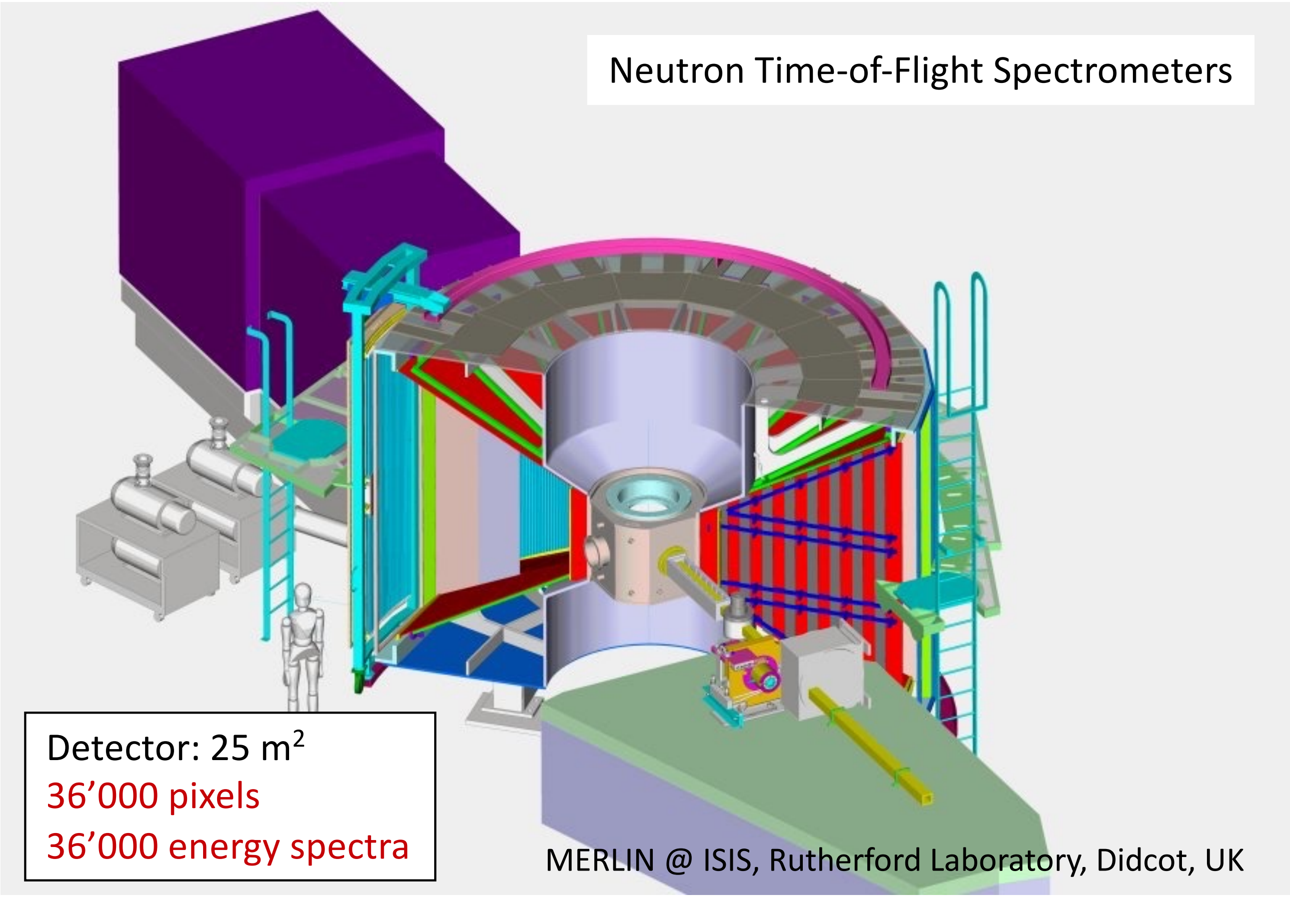


RIXS (ADDRESS Beamline at the SLS)

M.P.M. Dean *et al.*, Nature Materials **11**, 850 (2012).

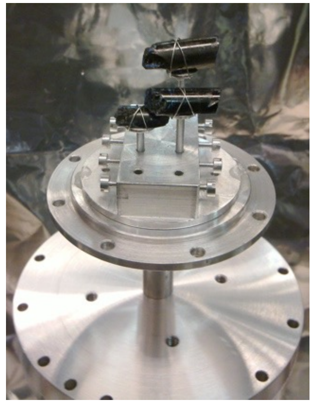
2D Materials – Excitations in bulk samples

Neutron Time-of-Flight Spectrometers



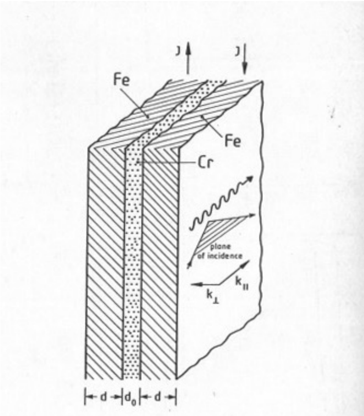
Detector: 25 m^2
36’000 pixels
36’000 energy spectra

MERLIN @ ISIS, Rutherford Laboratory, Didcot, UK



M. Mena *et al.*, Phys. Rev. Lett. **124**, 257201 (2020).

2D Materials – Physics, Magnets and Devices



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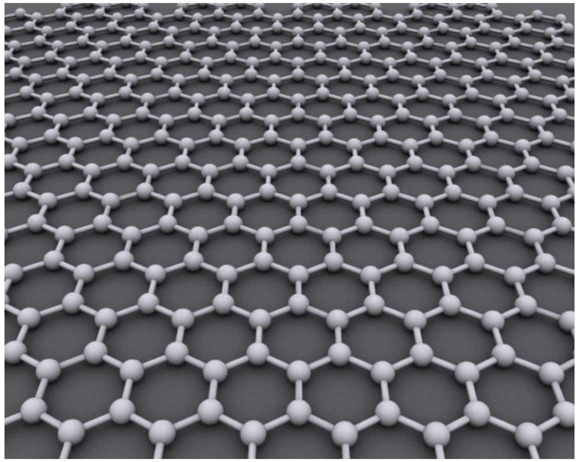
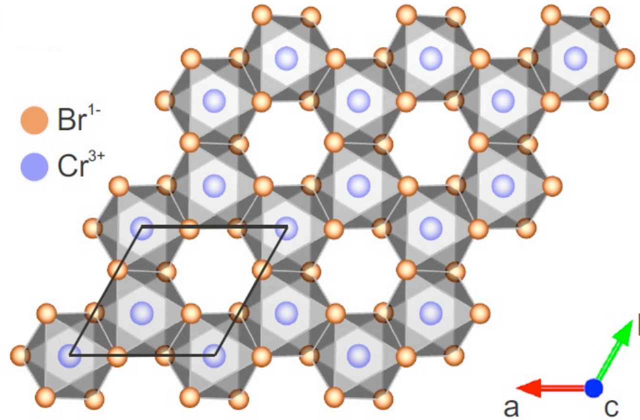
Nobel Prize 2007



Nobel Prize 2010



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2D sub-structure in 3D material
2D magnetic states (3D at T < T*)
Thin films, bulk and some applications

Experimental challenges? What information is missing from experiments?


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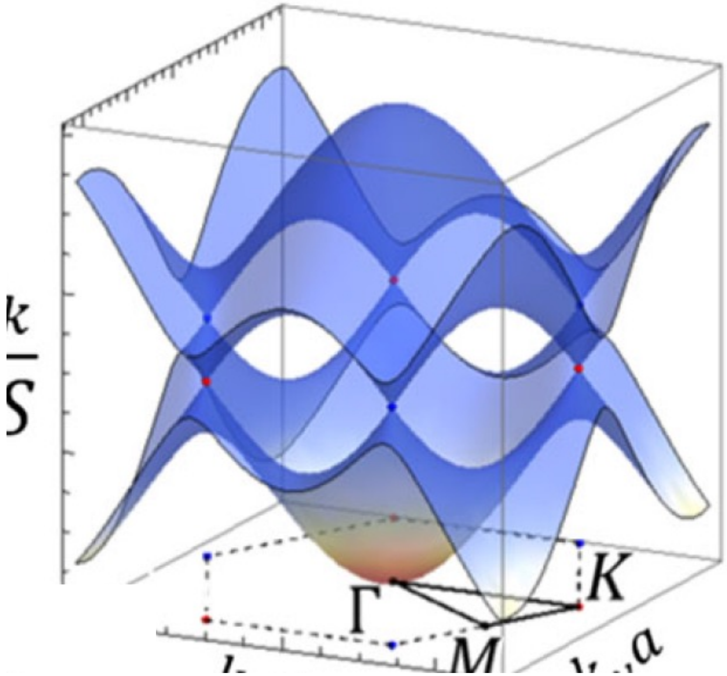
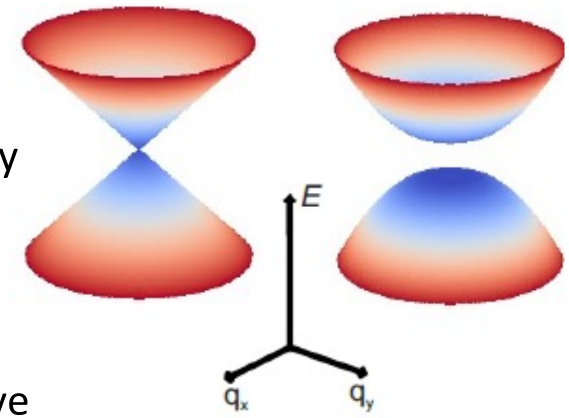
Dirac Magnons in $CrBr_3$ and their Damping

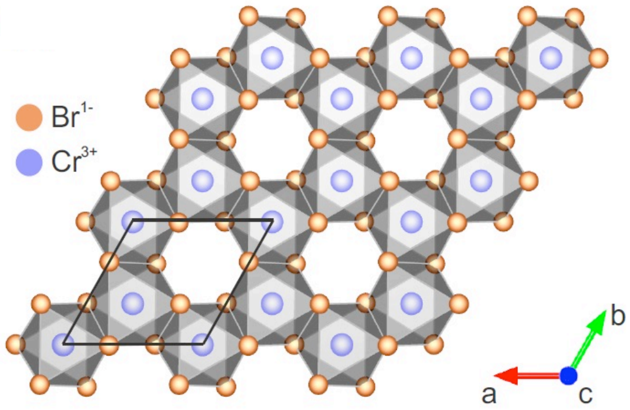
Spin Waves in a Honeycomb Ferromagnet



- Dirac cone at finite energy
- Spin gap opens if the inversion symmetry is broken
- Top and bottom band have Chern numbers of ±1



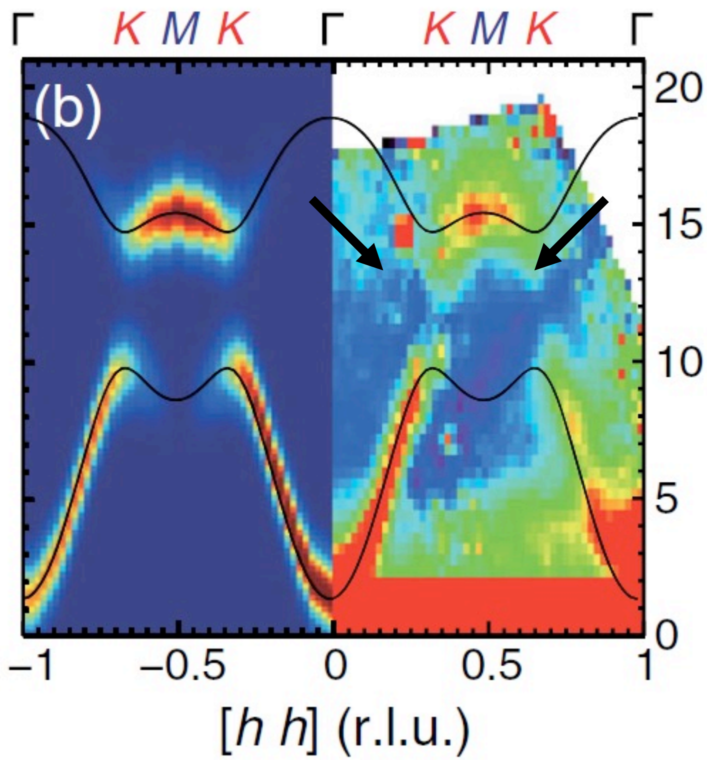
$$C_{\pm} = \frac{1}{2\pi}\int_{\mathrm{BZ}} d^2k\Omega_{\boldsymbol{k},\pm} = \mp 1,$$



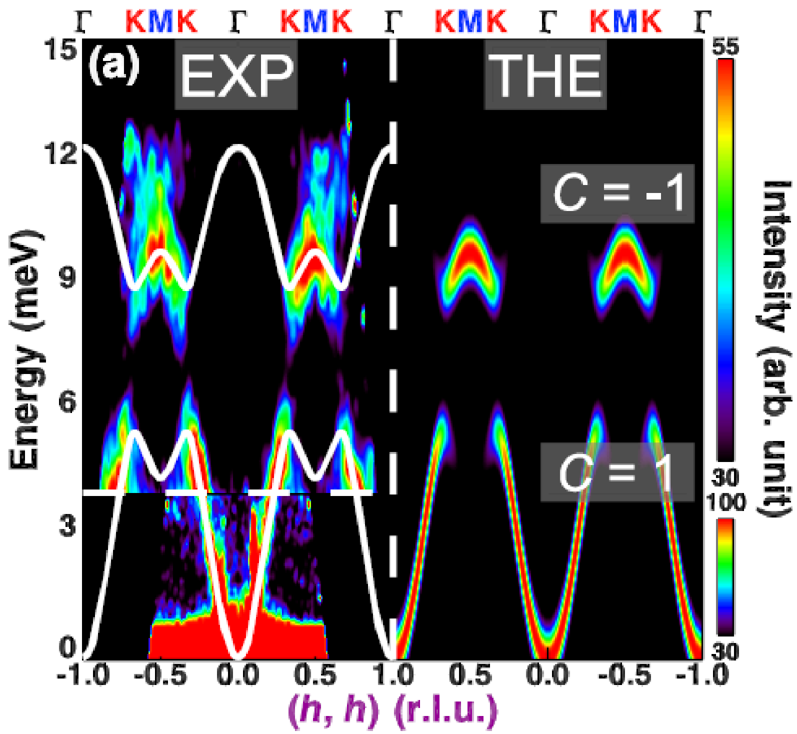
- S. S. Pershoguba *et al.*, PRX **8**, 011010 (2018).
- L. Chen *et al.*, PRX **8**, 041028 (2018).

Spin Dynamics in CrX_3: DM Interaction matters?

CrI_3

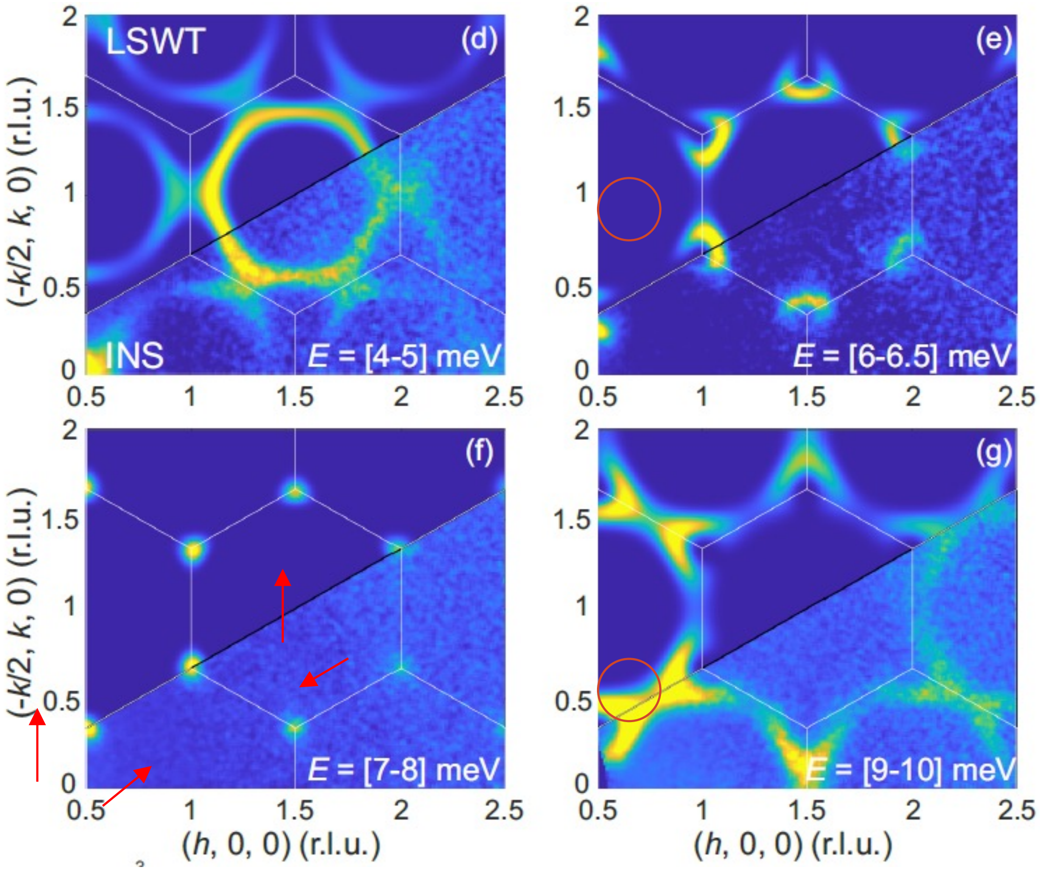


$CrBr_3$

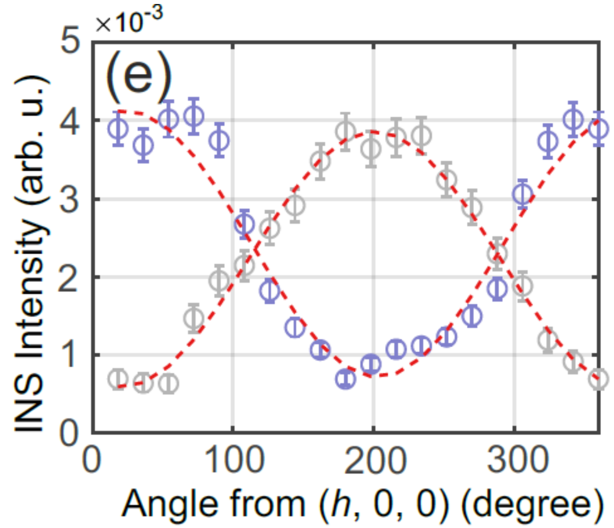


- Z. Cai *et al.*, PRB **104**, L020402 (2021).
- L. Chen *et al.*, PRX **8**, 041028 (2018).
- L. Chen *et al.*, PRX **11**, 031047 (2021).

INS-ToF Data: Constant-Energy Slices and LSWT

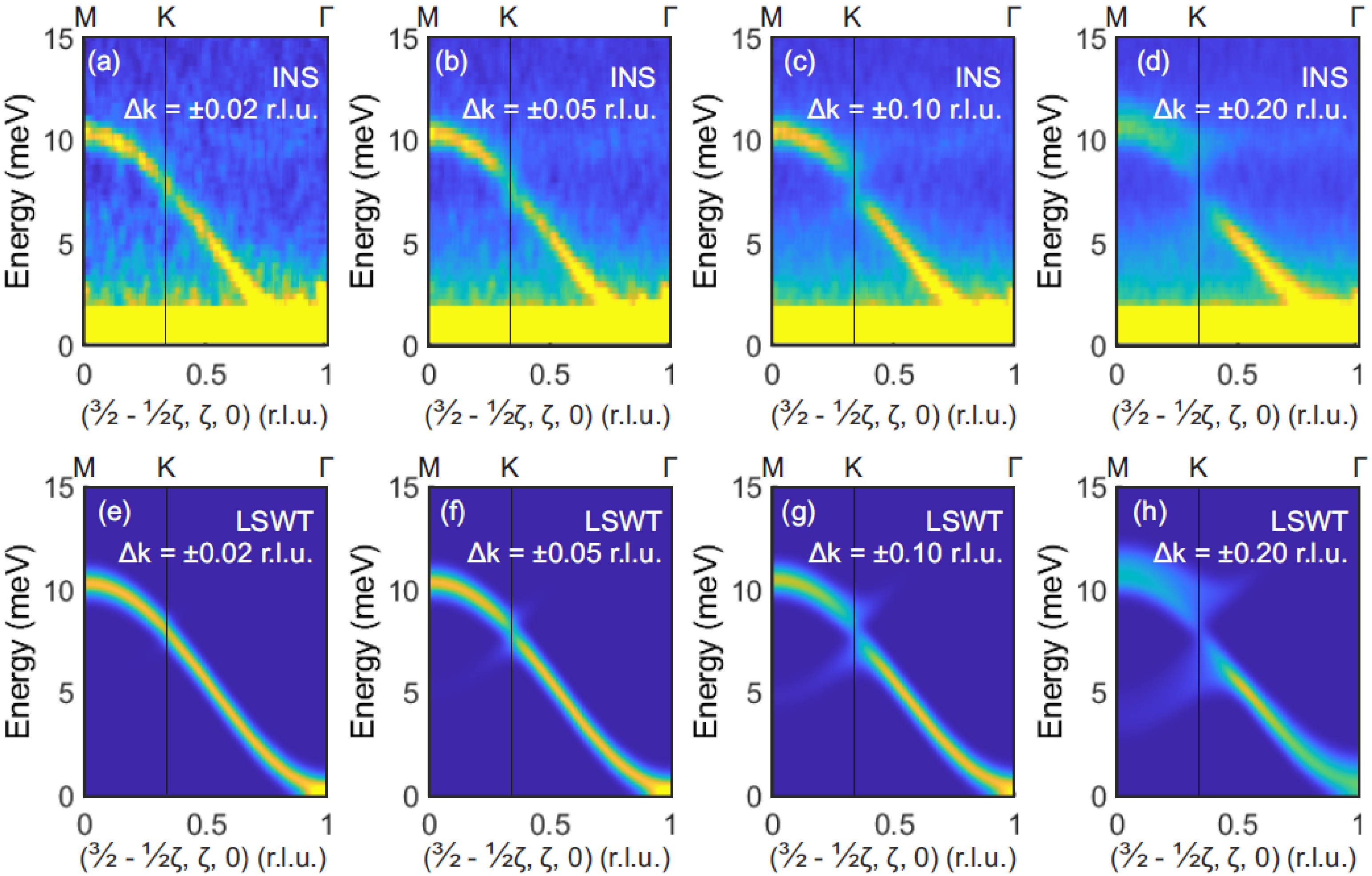


- Perfect quantitative agreement between INS and LSWT
- Clear intensity at the Dirac point
- Intensity winding around *K*-point



$$I = I_0[1 \pm \cos(\alpha - \alpha_0)]$$

Data Analysis – Momentum Integration Range



- S. Nikitin *et al.*, Phys. Rev. Lett. **129**, 127201 (2022).

Agree with results on $CrCl_3$ by S-H. Do *et al.*, Phys. Rev. B **106**, 060408 (2022).

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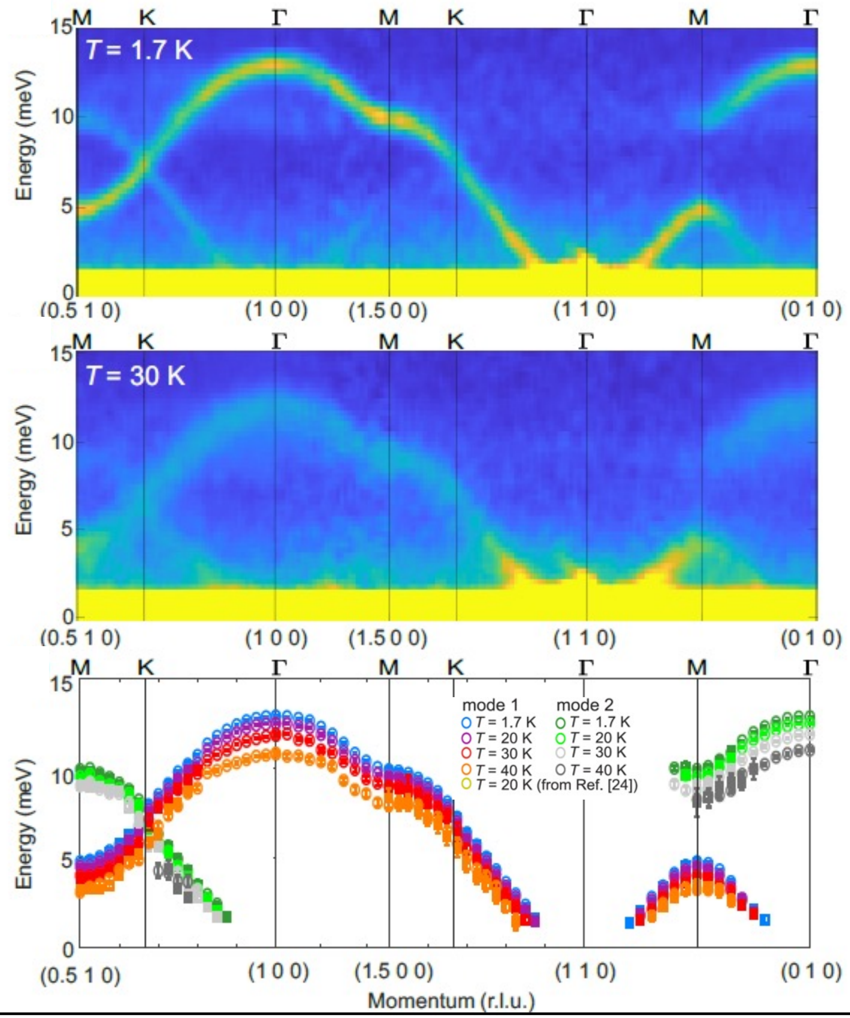
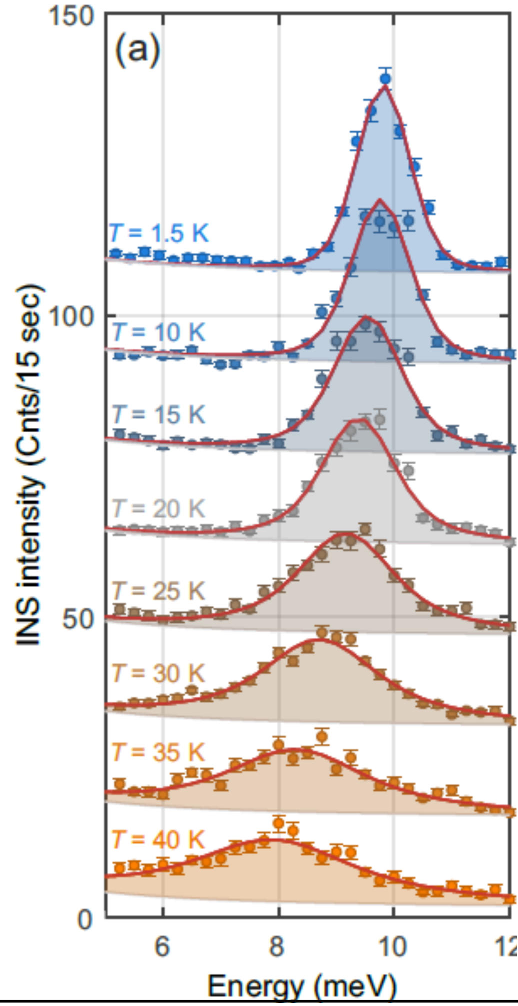
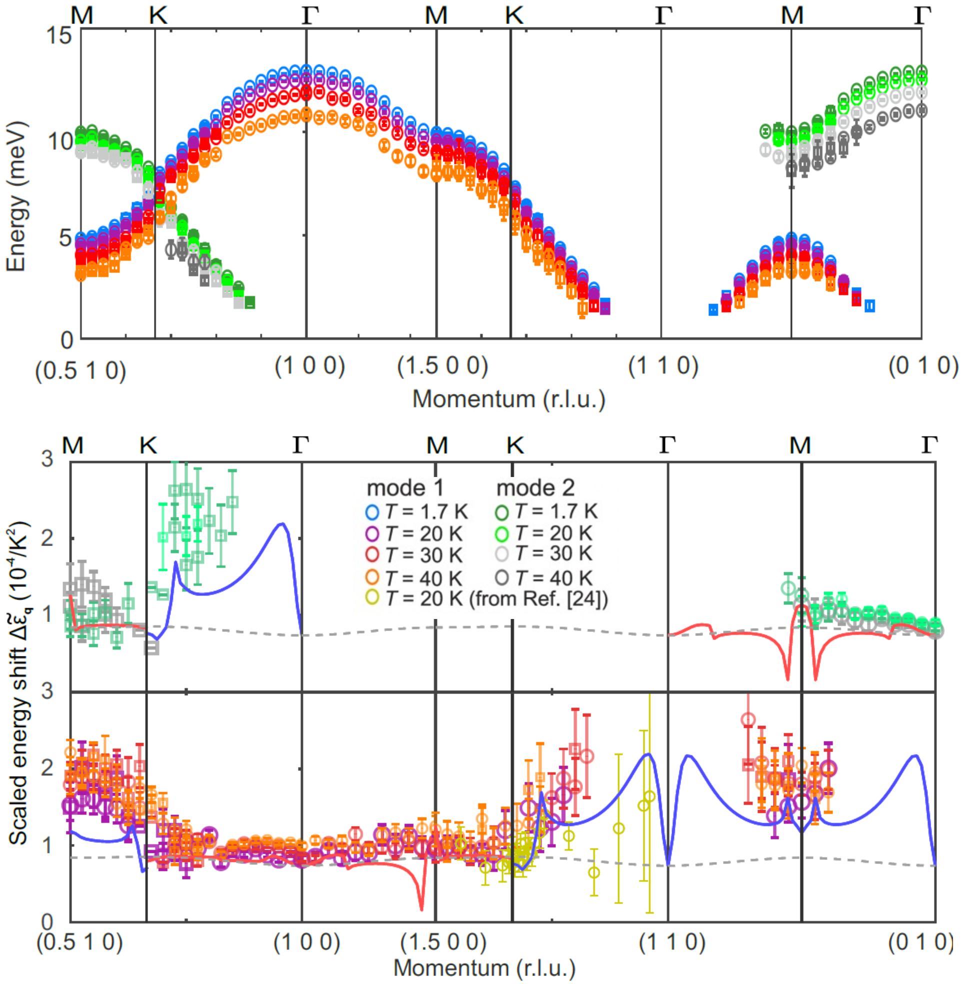
High-Temperature INS data





Temperature-induced Magnon Renormalization



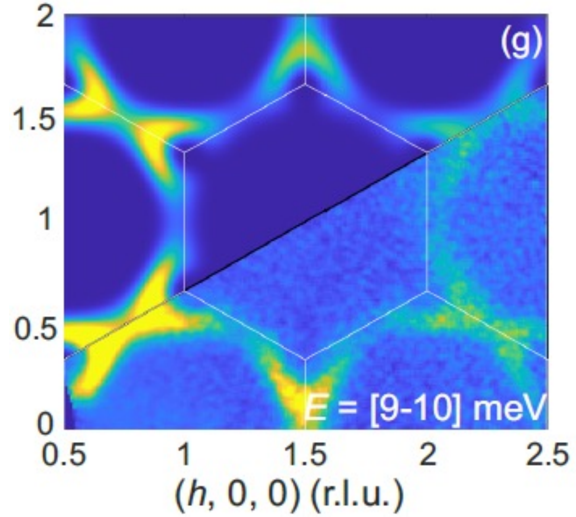
- Good collapse for T^2-scaling
- Renormalization is stronger for the down band (magnons below K-point)
- Renormalization for the up-band can be well described by Hartree term alone.
- **Q**-dependence is monotonic, sharp Van-Hove-like peaks are absent

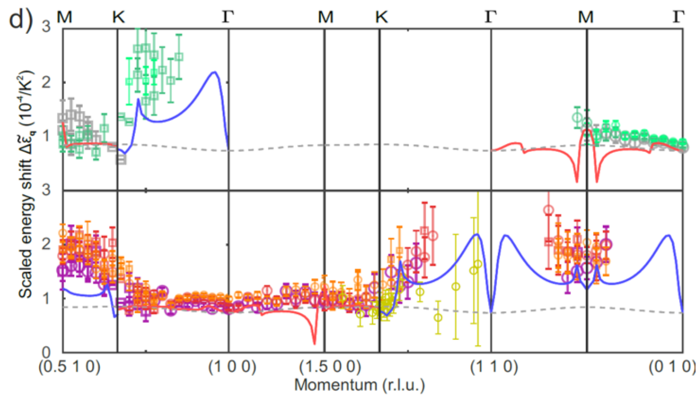
$$\Delta\tilde{\varepsilon}_{\mathbf{q}}(T) = \frac{\varepsilon_{\mathbf{q}}(0) - \varepsilon_{\mathbf{q}}(T)}{\varepsilon_{\mathbf{q}}(0)T^2}$$

cf. S. S. Pershoguba *et al.*, PRX **8**, 011010 (2018).

Dirac Magnons in $CrBr_3$

- $CrBr_3$ is a perfect realization of a quasi-two-dimensional honeycomb FM with Heisenberg exchange interactions
- Magnons show no gap at th K-point, and the previous report on the topological gap was most likely based on inaccurate data analysis of the TOF INS data
- The Dirac magnons at the K-point show clear winding of spectral intensity, predicted for nodal quasiparticles
- The linewidth and the dispersion bandwidth scale with T^2, in agreement with theory
- The measured **Q**-dependence of the linewidth and magnon renormalization lacks the predicted Van-Hove-like peaks indicating to the need for more sophisticated theoretical analysis





- S. Nikitin *et al.*, Phys. Rev. Lett. **129**, 127201 (2022).

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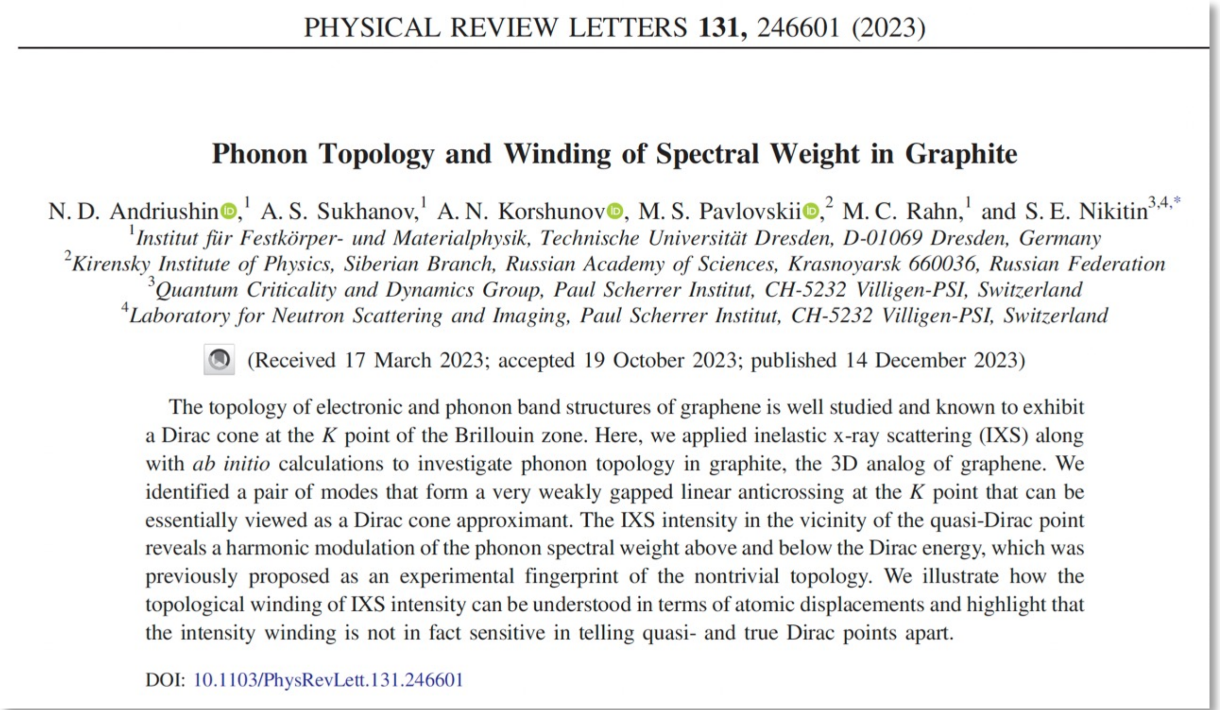
Phonon Spectral Weight and Winding in Graphite



PHYSICAL REVIEW LETTERS **131,** 246601 (2023)

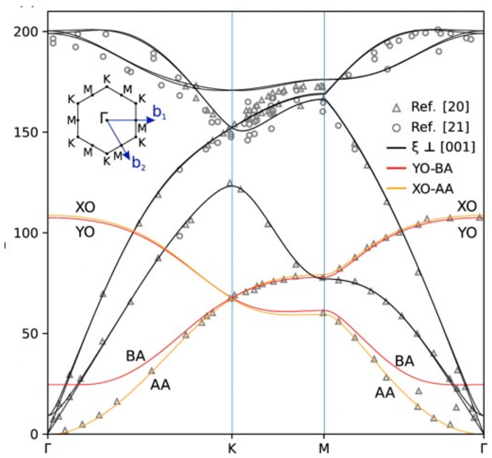
Phonon Topology and Winding of Spectral Weight in Graphite

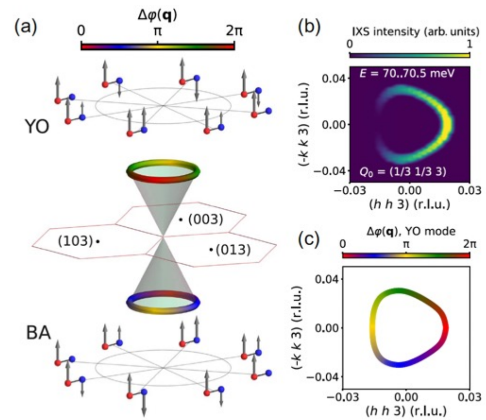
N. D. Andriushin,[1] A. S. Sukhanov,[1] A. N. Korshunov, M. S. Pavlovskii,[2] M. C. Rahn,[1] and S. E. Nikitin[3,4,*]
[1]*Institut für Festkörper- und Materialphysik, Technische Universität Dresden, D-01069 Dresden, Germany*
[2]*Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk 660036, Russian Federation*
[3]*Quantum Criticality and Dynamics Group, Paul Scherrer Institut, CH-5232 Villigen-PSI, Switzerland*
[4]*Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut, CH-5232 Villigen-PSI, Switzerland*

(Received 17 March 2023; accepted 19 October 2023; published 14 December 2023)

The topology of electronic and phonon band structures of graphene is well studied and known to exhibit a Dirac cone at the K point of the Brillouin zone. Here, we applied inelastic x-ray scattering (IXS) along with *ab initio* calculations to investigate phonon topology in graphite, the 3D analog of graphene. We identified a pair of modes that form a very weakly gapped linear anticrossing at the K point that can be essentially viewed as a Dirac cone approximant. The IXS intensity in the vicinity of the quasi-Dirac point reveals a harmonic modulation of the phonon spectral weight above and below the Dirac energy, which was previously proposed as an experimental fingerprint of the nontrivial topology. We illustrate how the topological winding of IXS intensity can be understood in terms of atomic displacements and highlight that the intensity winding is not in fact sensitive in telling quasi- and true Dirac points apart.

DOI: 10.1103/PhysRevLett.131.246601



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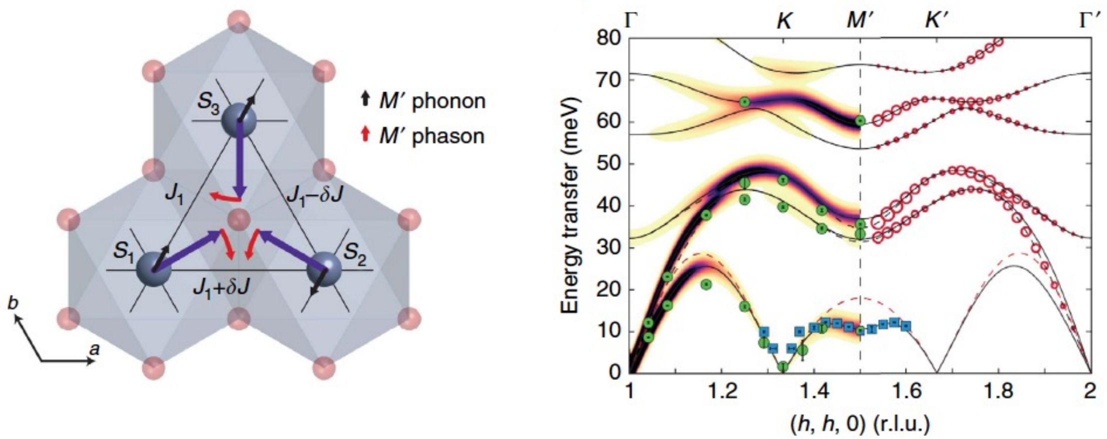
Strong Spin-Lattice Coupling in $LiCrO_2$

2D Triangular Lattice - Electromagnons

Strong coupling of magnetism and structure probed with meV resolution by non-resonant inelastic X-ray scattering

Interplay of magnetism and structural properties are believed to be a key ingredient for technological applications of materials e.g. in multiferroics.



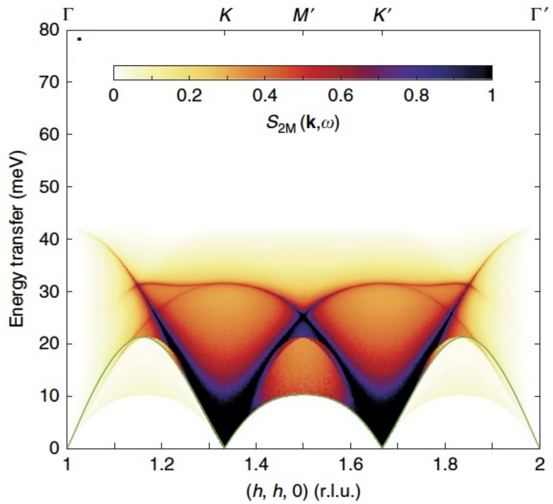
Electromagnon dispersion probed by inelastic X-ray scattering in $LiCrO_2$. S. Toth, B. Wehinger, K. Rolfs, U. Stuhr, H. Takatsu, K. Kimura, T. Kimura, H.M. Ronnow, Ch. Rüegg, Nature Comm. **7**, 13547 (2016).

2D Triangular Lattice - Electromagnons

Strong coupling of magnetism and structure probed with meV resolution by non-resonant inelastic X-ray scattering

Interplay of magnetism and structural properties are believed to be a key ingredient for technological applications of materials e.g. in multiferroics.

- Direct exchange in $LiCrO_2$
- Strong mixing of matrix elements up to 30% possible
- Resolution of 1 meV to probe magnetism on ultra-small samples (hard X-ray IXS)
- Can be applied to many systems to probe both one- and multi-magnon processes, magnetoelastic coupling, etc.



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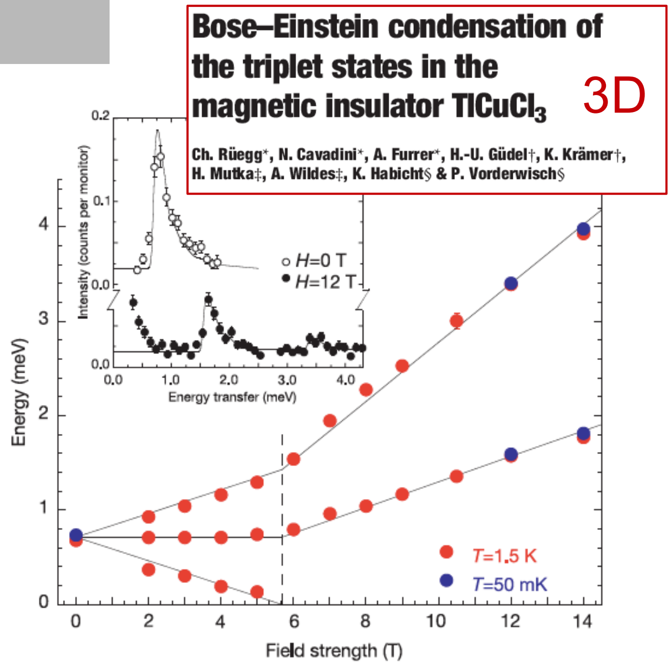
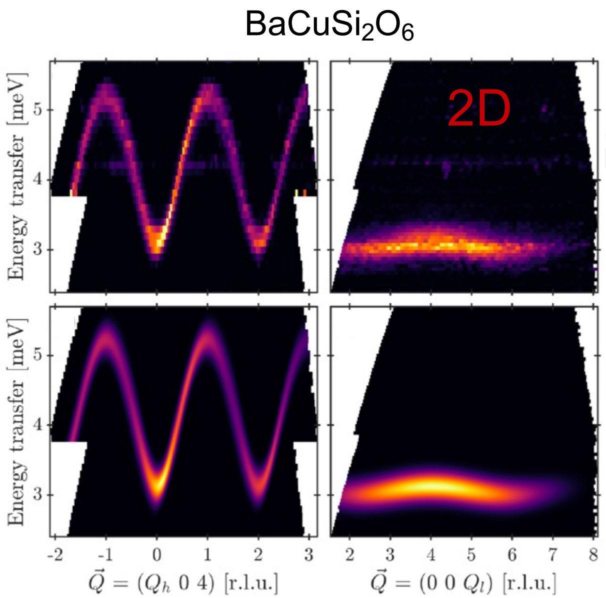
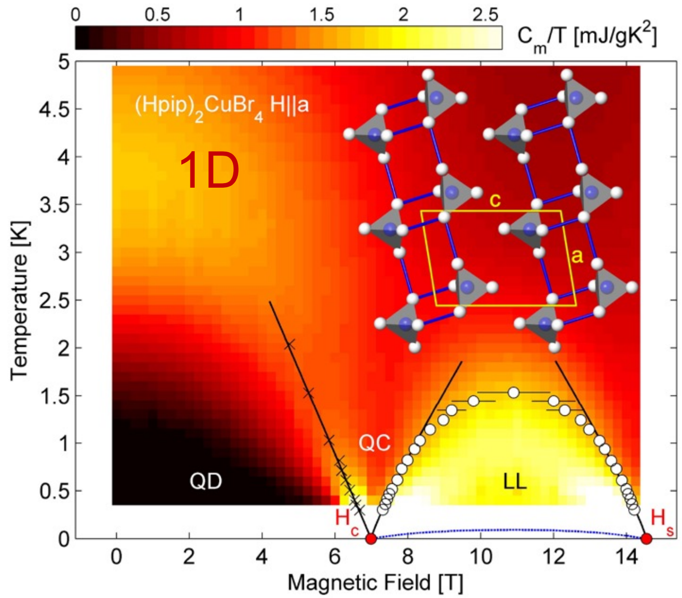
Quantum Criticality and Dynamics in 2D

Quantum Magnets – Criticality and Dynamics

Bose-Einstein Condensates, 1D, 2D, 3D Quantum Criticality, Spin Luttinger-liquids, Spin Liquids, etc





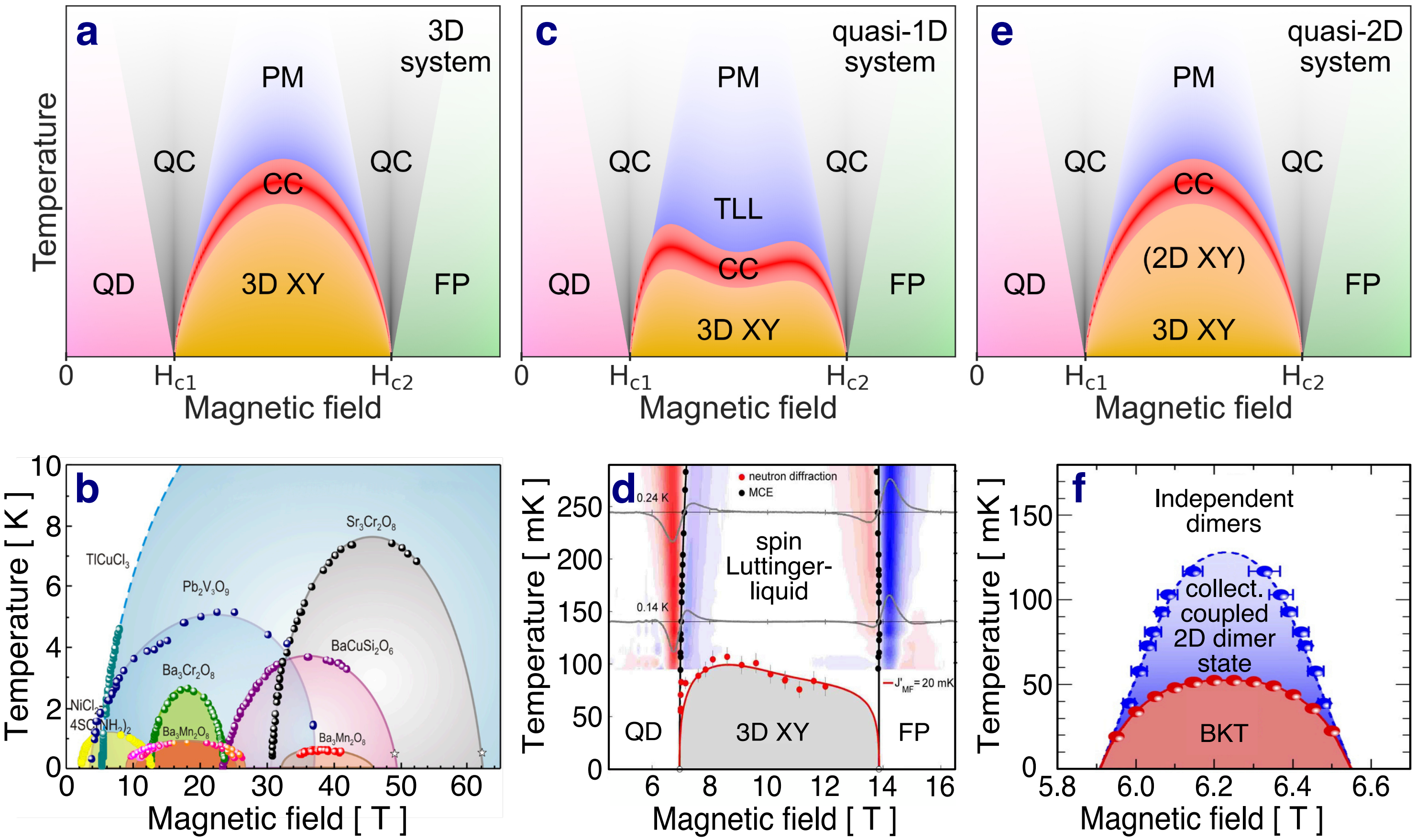


- Ch. Rüegg *et al.*, Nature **423**, 62 (2003).

- S. Allenspach *et al.*, Phys. Rev. Lett. **124**, 177205 (2020).
- S. Allenspach *et al.*, Phys. Rev. Research. **3**, 023177 (2021).
- S. Allenspach *et al.*, Phys. Rev. B **106**, 104418 (2022).

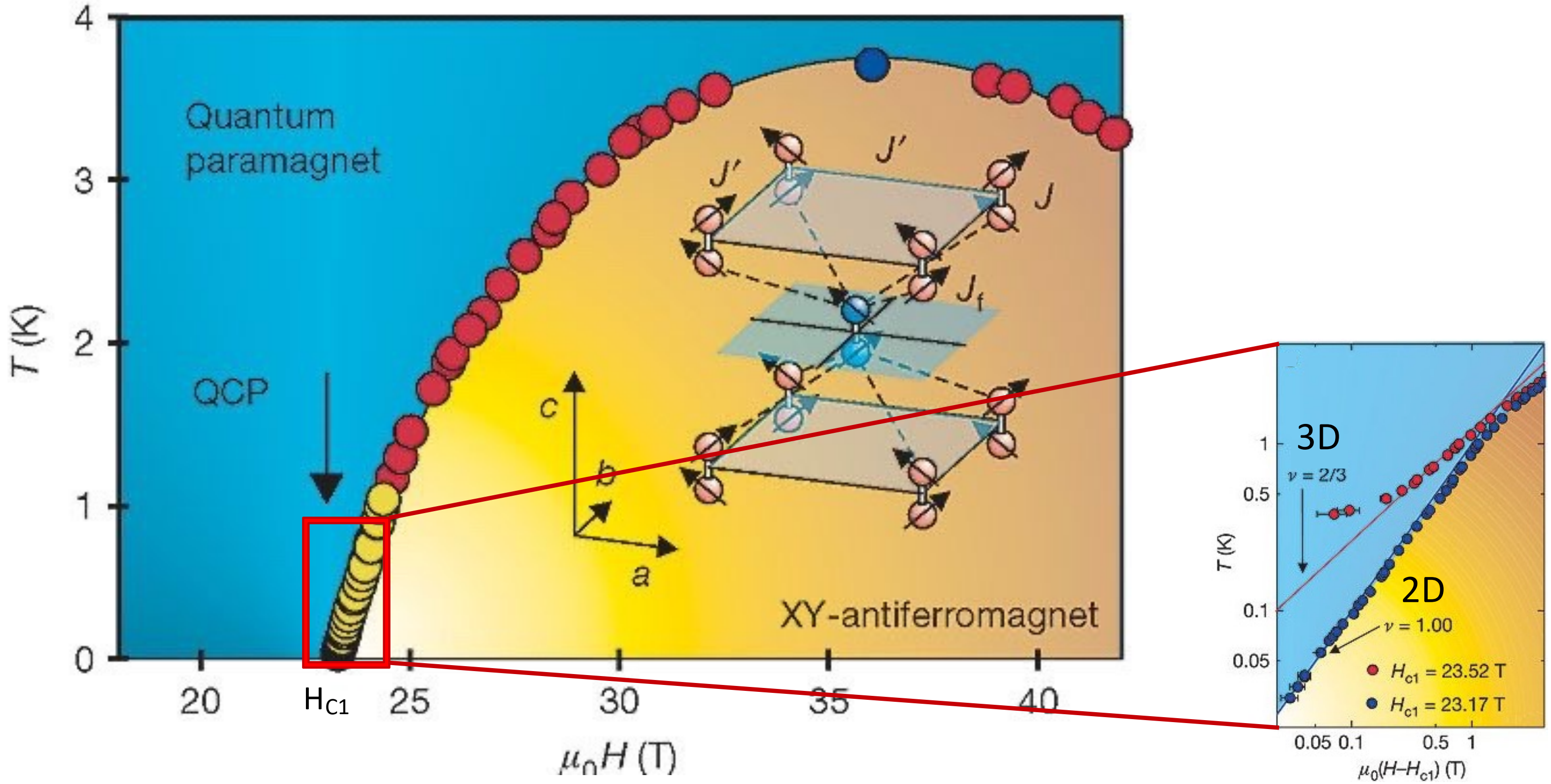
- Ch. Rüegg *et al.*, Phys. Rev. Lett. **101**, 247202 (2008).
- B. Thielemann *et al.*, Phys. Rev. B **79**, 020408(R) (2009).
- H. Ryll *et al.* Phys. Rev. B **89**, 144416 (2014).
- S. Ward *et al.* Phys. Rev. Lett. **118**, 177202 (2017).

Quantum Criticality in Spin-Dimer Systems



- V. Zapf et al., Rev. Mod. Phys. **86**, 563 (2014).
- B. Thielemann *et al.,* Phys. Rev. B **79**, 020408(R) (2009).
- U. Tutsch *et al.*, Nat. Commun. **5**, 5169 (2014).

Dimensional Reduction (?) – $BaCuSi_2O_6$

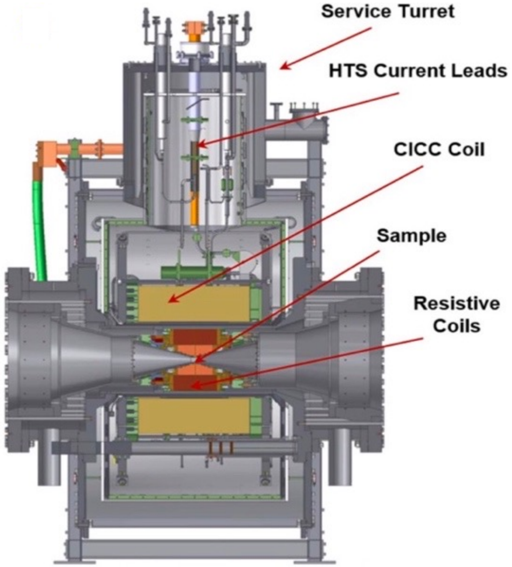


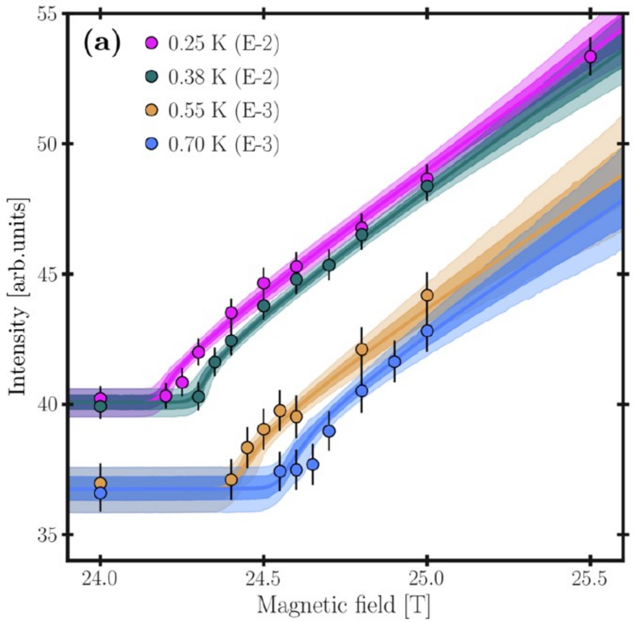
• S.E. Sebastian *et al.*, Nature **411**, 617 (2006).

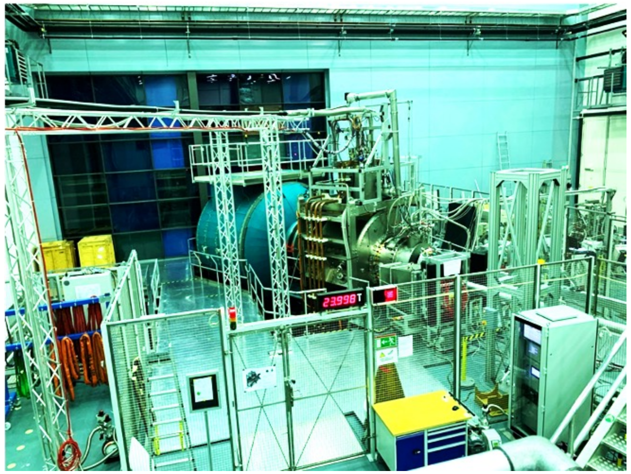
Magnetic Order Parameter in $BaCuSi_2O_6$

Investigating field-induced magnetic order in Han purple by neutron scattering up to 25.9 T

S. Allenspach,[1,2] A. Madsen,[1,3] A. Biffin,[4] M. Bartkowiak,[5] O. Prokhnenko,[5] A. Gazizulina,[6] X. Liu,[7] R. Wahle,[5] S. Gerischer,[5] S. Kempfer,[5] P. Heller,[5] P. Smeibidl,[5] A. Mira,[8,9] N. Laflorencie,[10] F. Mila,[11] B. Normand,[1,11] and Ch. Rüegg[1,2,11,12]



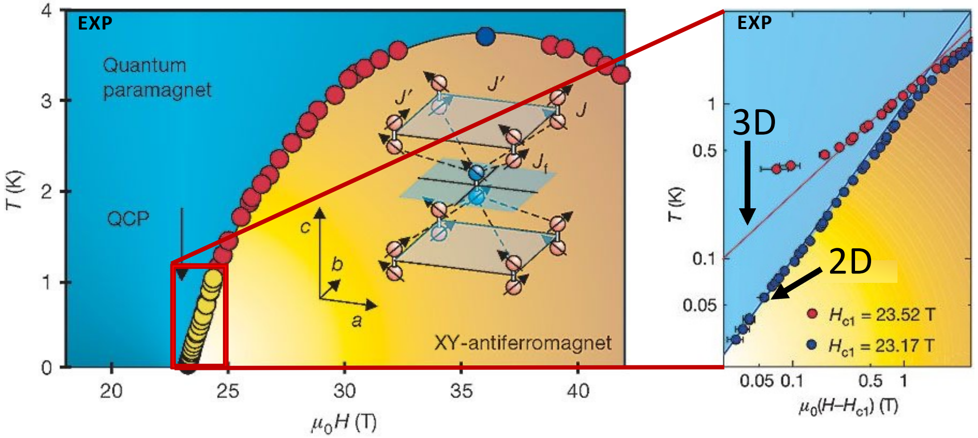




- S. Allenspach *et al.*, Phys. Rev. B **106**, 104418 (2022).

Phase Diagram from Quantum Monte Carlo

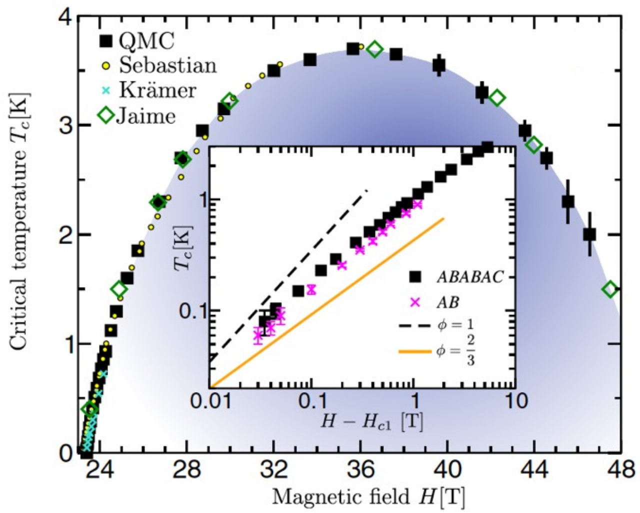
Experimental
Phase Diagram



- S.E. Sebastian *et al.*, Nature, **411**, 617 (2006).

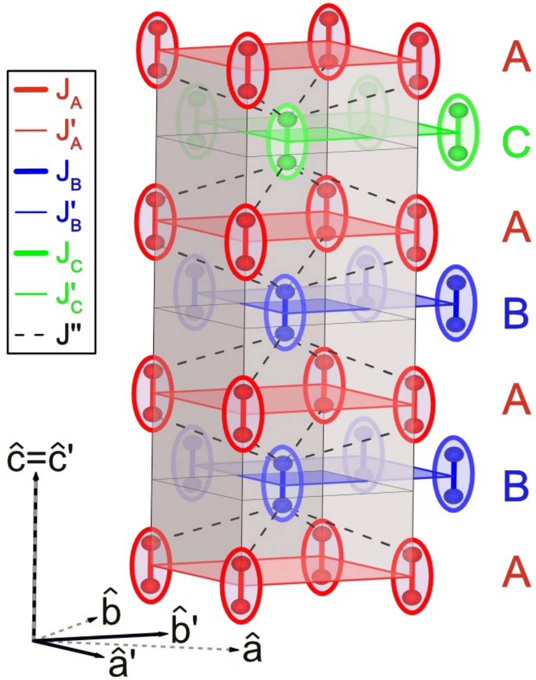
Quantum Monte Carlo
Phase Diagram

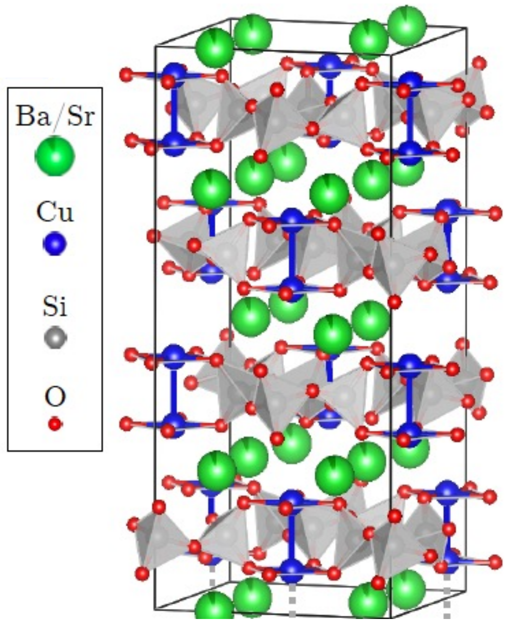
⇨ FM $J_{\text{intra-bilayer}}$
⇨ FM $J_{\text{inter-bilayer}}$
⇨ 3 dimer types with stacking

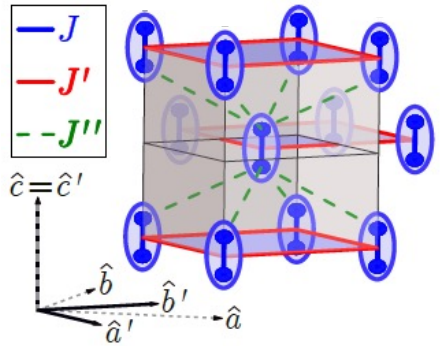


- S. Allenspach *et al.*, Phys. Rev. Lett. **124**, 177205 (2020).

Sr/Ba Substitution in $BaCuSi_2O_6$







- S. Allenspach *et al.*, Phys. Rev. B **106**, 104418 (2022).
- S. Allenspach *et al.*, Phys. Rev. Lett. **124**, 177205 (2020).
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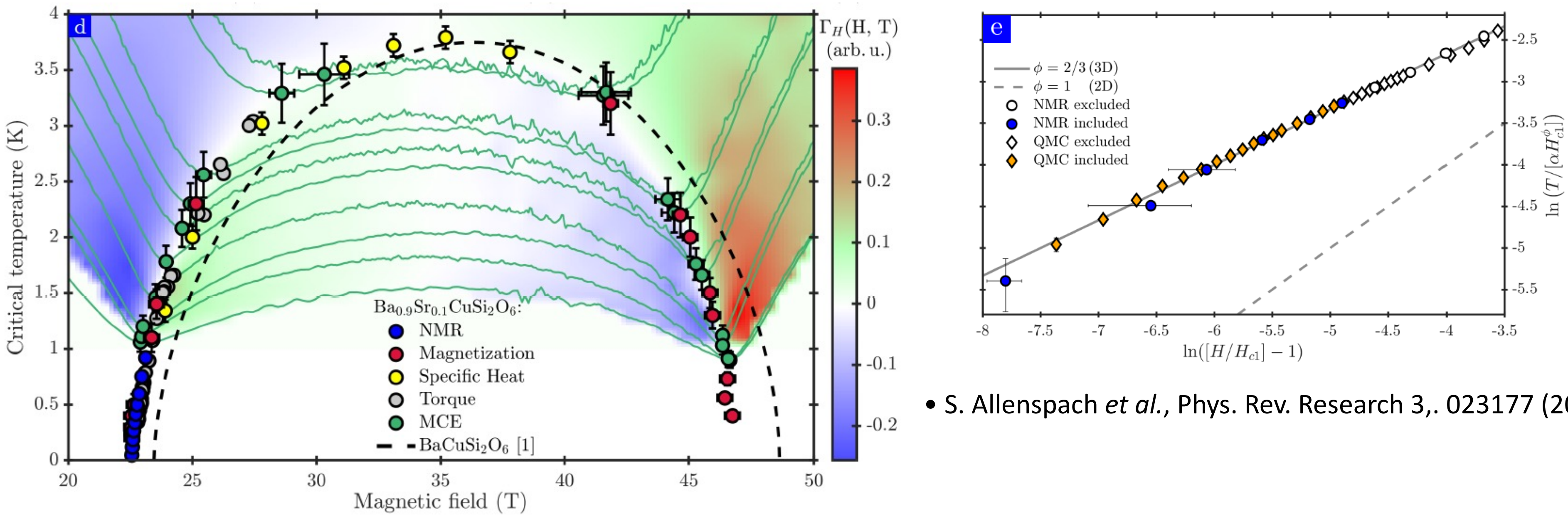
3D Quantum Criticality in $Ba_{0.9}Sr_{0.1}CuSi_2O_6$

Revealing three-dimensional quantum criticality by Sr substitution in Han purple

Stephan Allenspach,[1,2] Pascal Puphal,[3,4,5] Joosep Link,[6] Ivo Heinmaa,[6] Ekaterina Pomjakushina,[3] Cornelius Krellner,[4] Jakob Lass,[7,8] Gregory S. Tucker,[7,9] Christof Niedermayer,[7] Shusaku Imajo,[10] Yoshimitsu Kohama,[10] Koichi Kindo,[10] Steffen Krämer,[11] Mladen Horvatić,[11] Marcelo Jaime,[12] Alexander Madsen,[1,13] Antonietta Mira,[13,14] Nicolas Laflorencie,[15] Frédéric Mila,[9] Bruce Normand,[1,9,16] Christian Rüegg,[1,2,9,17] Raivo Stern,[6] and Franziska Weickert[18]



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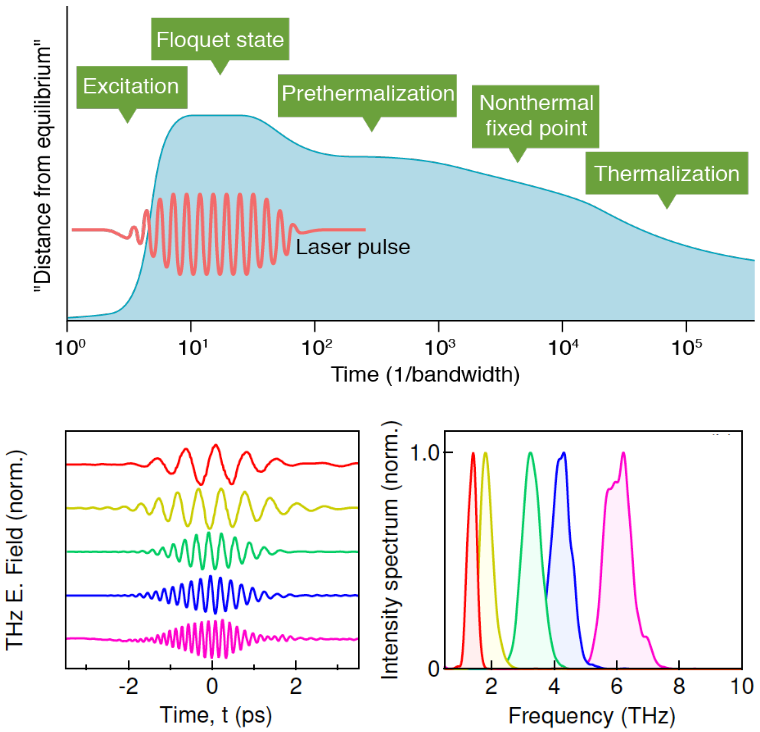
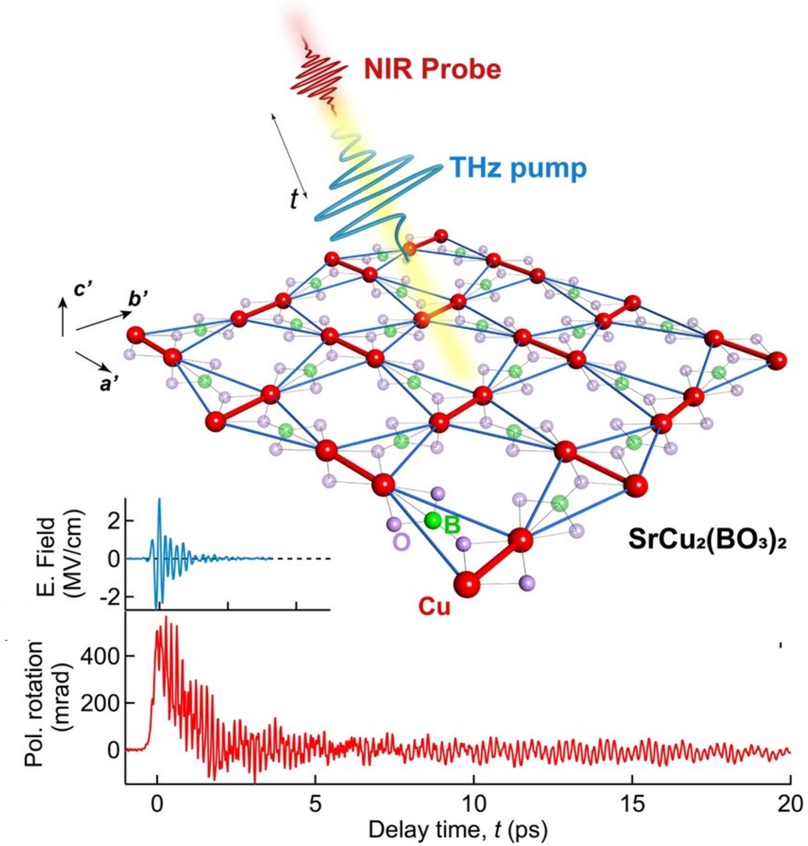
2D Quantum Magnets beyond Equilibrium

Quantum magnets beyond equilibrium

Physics beyond Equilibrium





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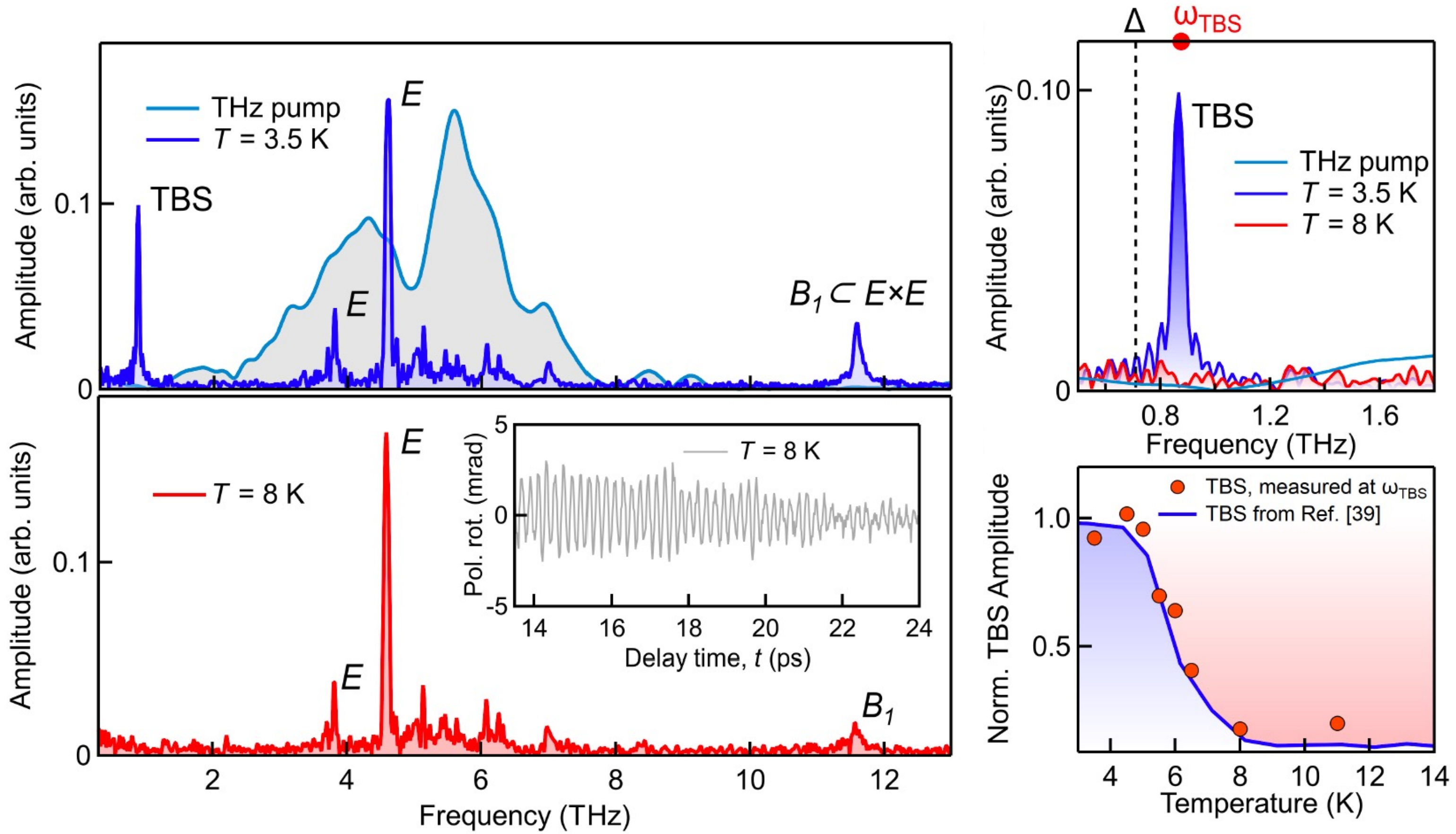
Magnetophononics in $SrCu_2(BO_3)_2$



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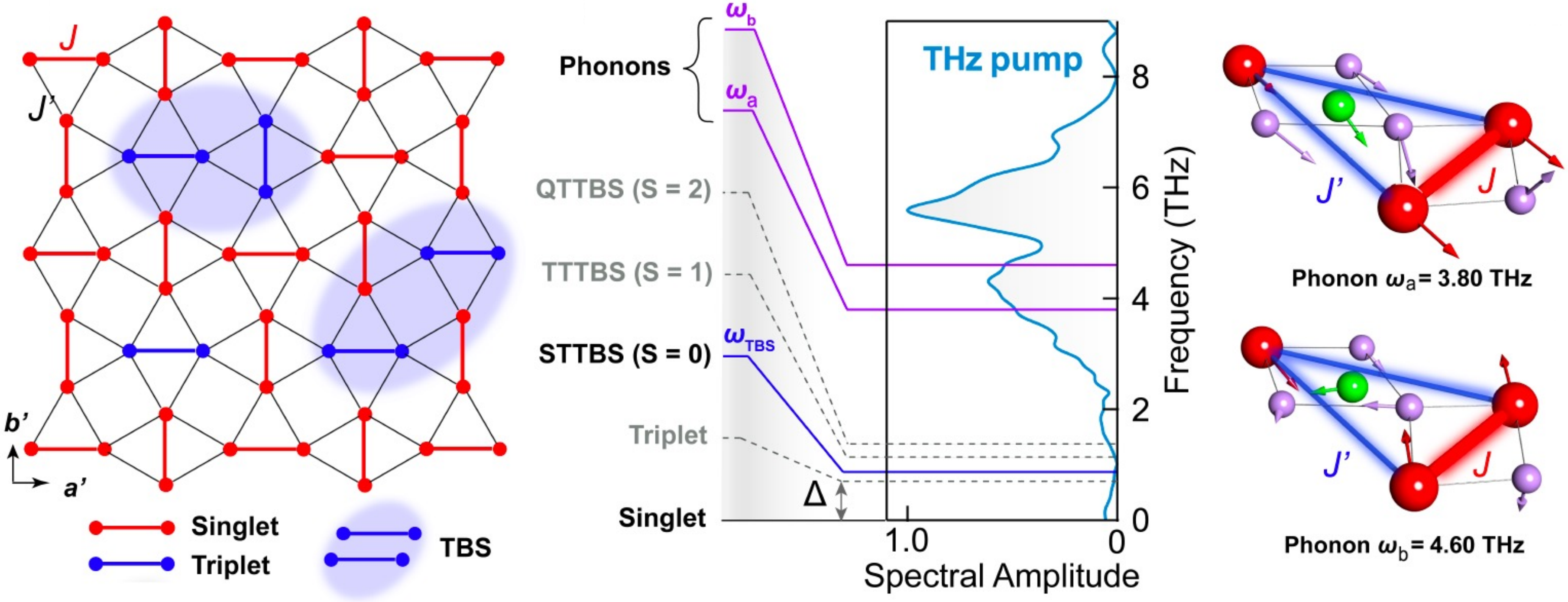
Magnetophononics in $SrCu_2(BO_3)_2$



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Devices from Quantum Magnets

Quantum Magnets – Transport and Applications ?

LETTERS
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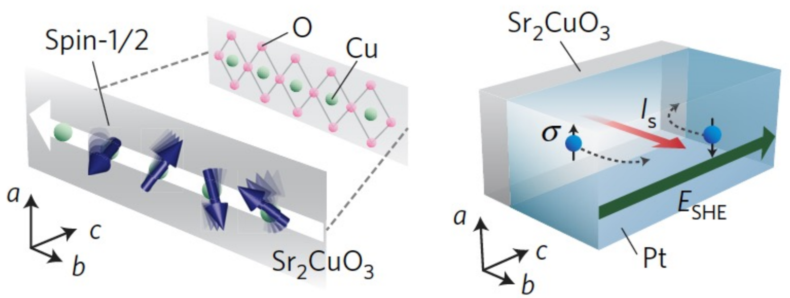
nature physics

One-dimensional spinon spin currents

Daichi Hirobe[1]*, Masahiro Sato[2,3†], Takayuki Kawamata[4], Yuki Shiomi[1,2], Ken-ichi Uchida[1,5], Ryo Iguchi[1,2], Yoji Koike[4], Sadamichi Maekawa[2,3] and Eiji Saitoh[1,2,3,6]*



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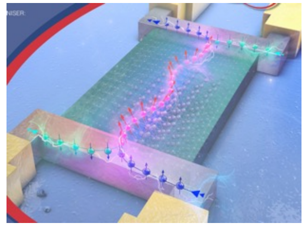
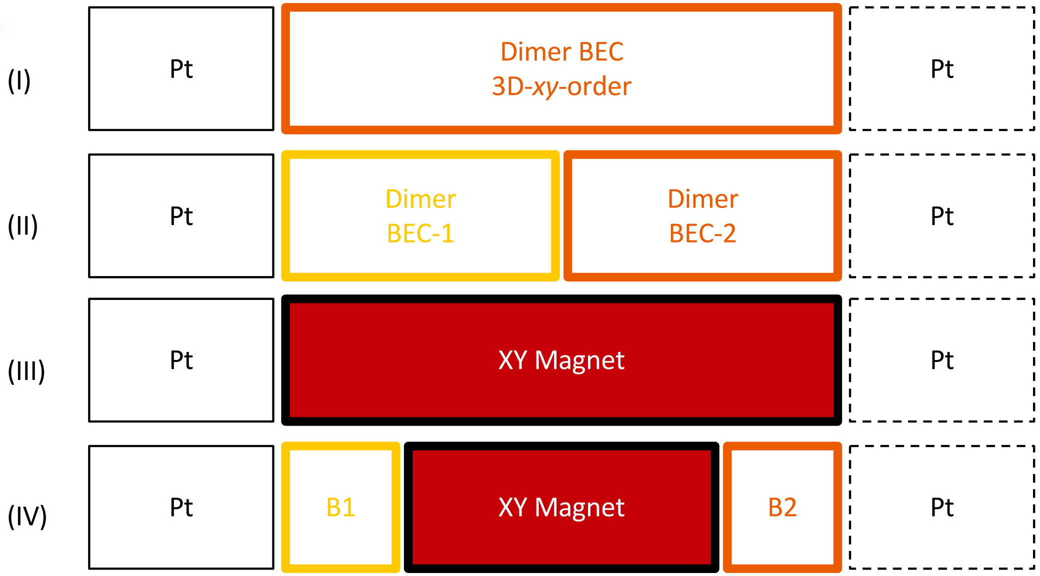
Switches for Quantum Spintronics ?





For (III) cf. D. Loss, Y. Tserkovnyak *et al.*

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