Observation of spinon Anderson localization in a spin-1/2 antiferromagnetic Heisenberg chain

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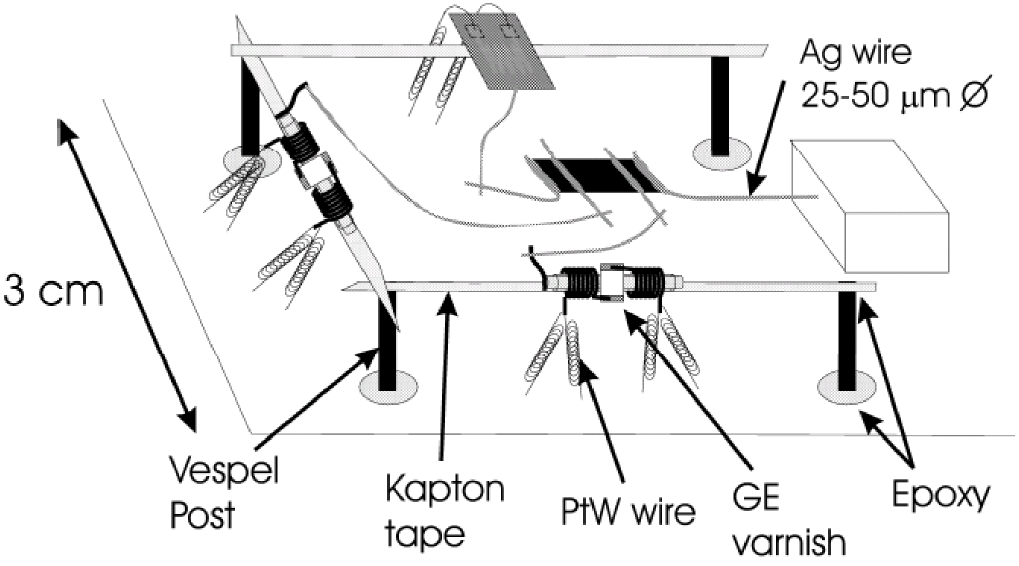
Outline：

1. Ultra-low-temperature heat transport measurement
2. Some examples of heat transport by magnetic excitations
3. Anderson localization of spinons in a spin-1/2 antiferromagntic Heisenberg chain
4. Unveiling the quantum critical point of an Ising chain in a transverse field
5. Summary

1. Ultra-low-temperature heat transport measurement



^{3}He-^{4}He dilution fridge

T→7 mK; H→17 T

$$\kappa = \alpha \frac{\dot{Q}}{\Delta T}$$

Heat transport: A tool to probe low-lying quasiparticles

$$\kappa = \kappa_{\text{electrons}} + \kappa_{\text{phonons}} + \kappa_{\text{magnons}} + \kappa_{\text{spinons}} \ldots$$

$$\kappa = 1/3\ C\ v\ l$$

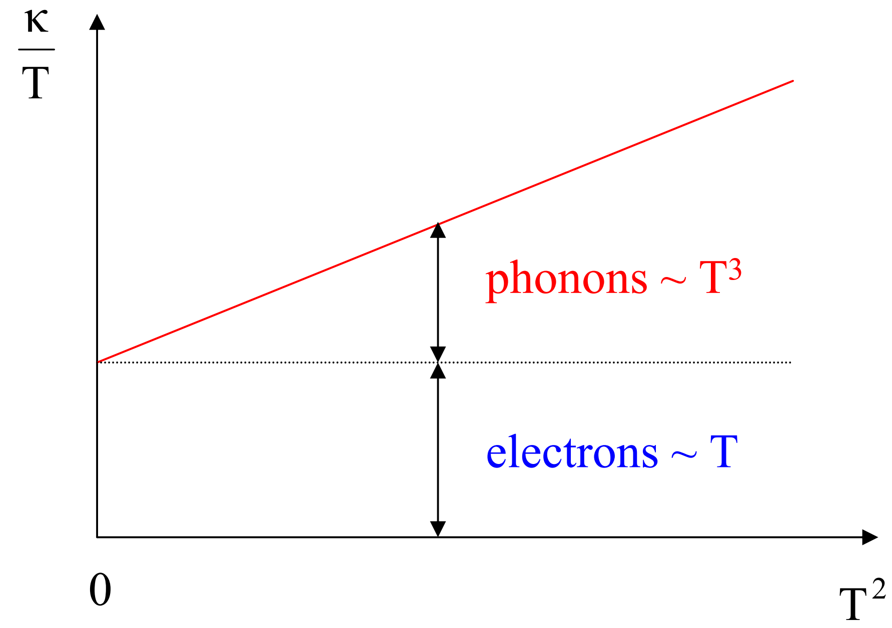
FERMIONS (Electrons)

$$\kappa \propto C_e \propto T$$

BOSONS (Phonons)

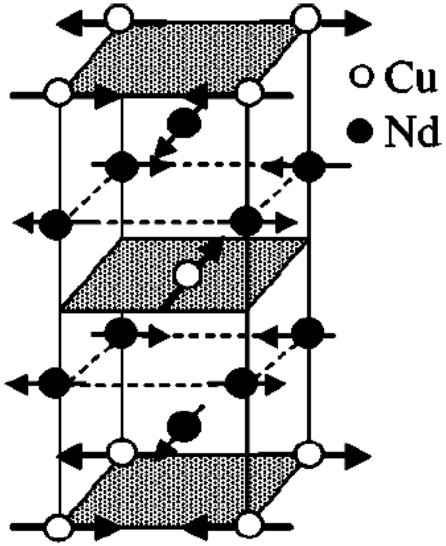
$$\kappa \propto C_{ph} \propto T^3$$

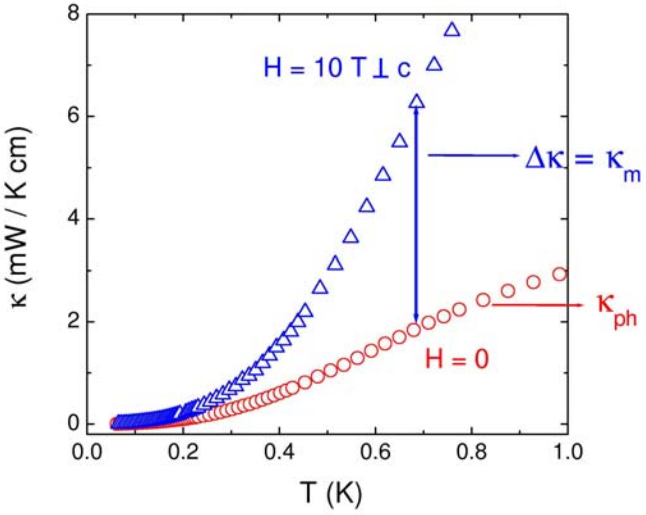
$$\kappa/T = A + BT^2$$

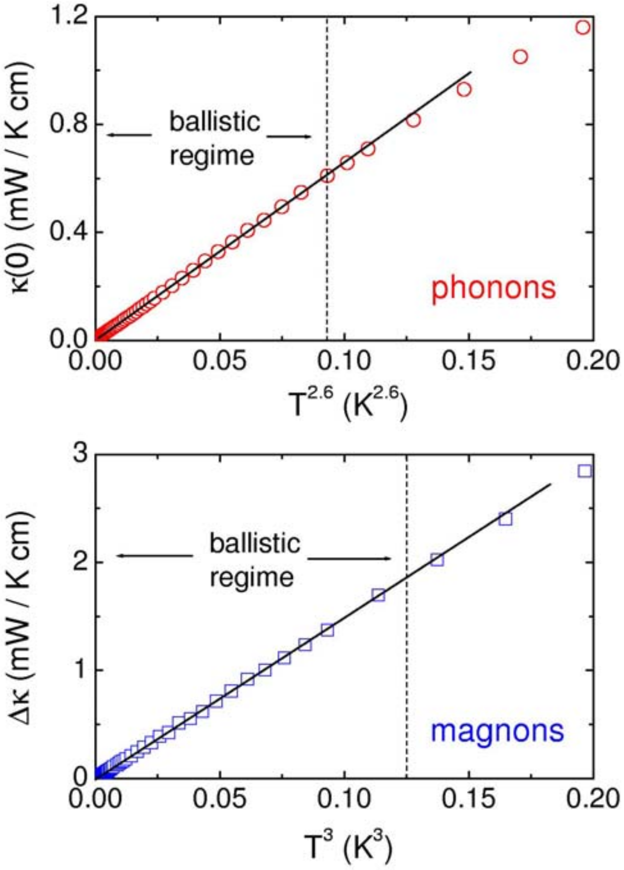


2. Some examples of heat transport by magnetic excitations

Example 1: AF magnon heat transport in Nd_2CuO_4



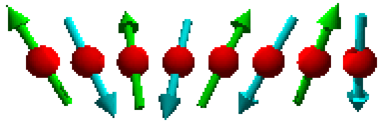




Spin-flop transition
in H ⊥ c

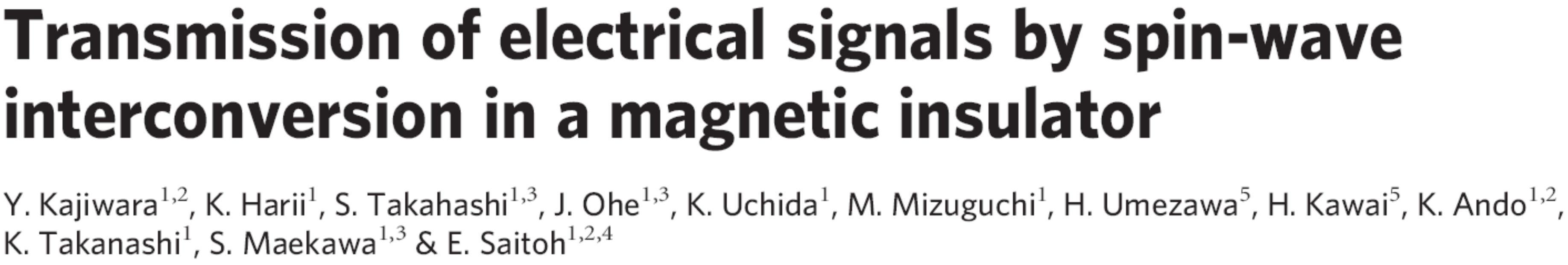
Switch on acoustic magnons

First observation of $\kappa \sim T^3$ AF magnon heat transport



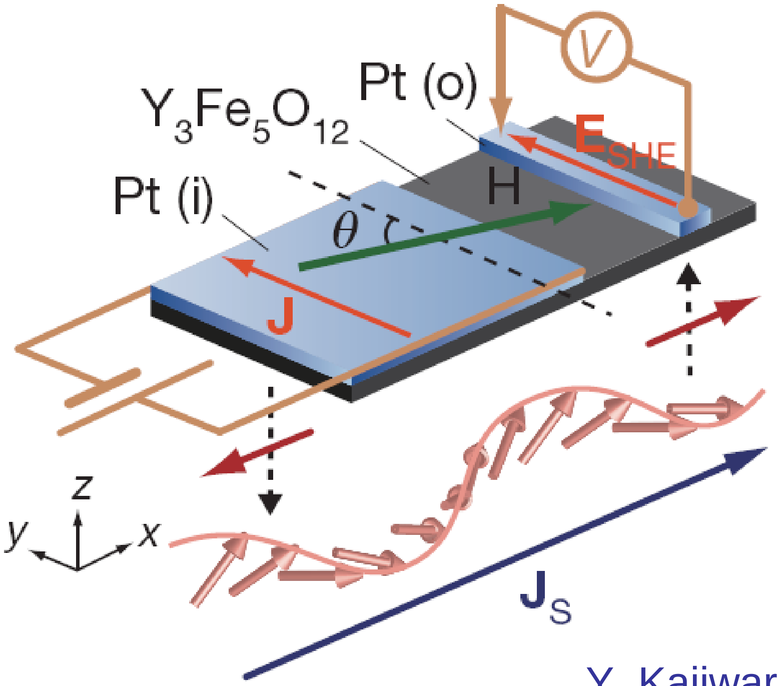
S. Y. Li, L. Taillefer *et al.*, PRL **95**, 156603 (2005)

Example 2: FM magnon heat transport in YIG



Transmission of electrical signals by spin-wave interconversion in a magnetic insulator

Y. Kajiwara[1,2], K. Harii[1], S. Takahashi[1,3], J. Ohe[1,3], K. Uchida[1], M. Mizuguchi[1], H. Umezawa[5], H. Kawai[5], K. Ando[1,2], K. Takanashi[1], S. Maekawa[1,3] & E. Saitoh[1,2,4]



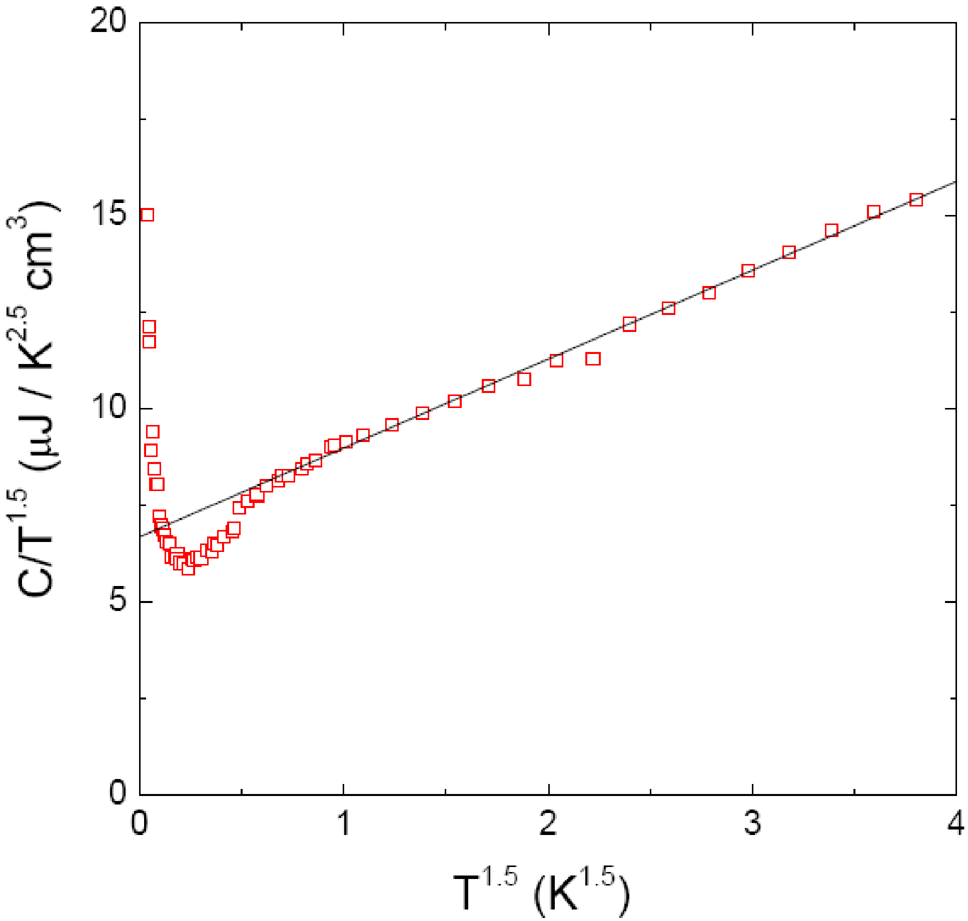
$Y_3Fe_5O_{12}$ (YIG)

typical ferrimagnet

Y. Kajiwara *et al.*, Nature **464**, 262 (2010)

Specific heat: FM magnon in YIG single crystal

2008/11/10



At not very low *T*: *E* = *Dk*^{2}

$$C_m(T) = \frac{15\zeta(5/2)k_B^{2.5}T^{1.5}}{32\pi^{1.5}D^{1.5}}$$

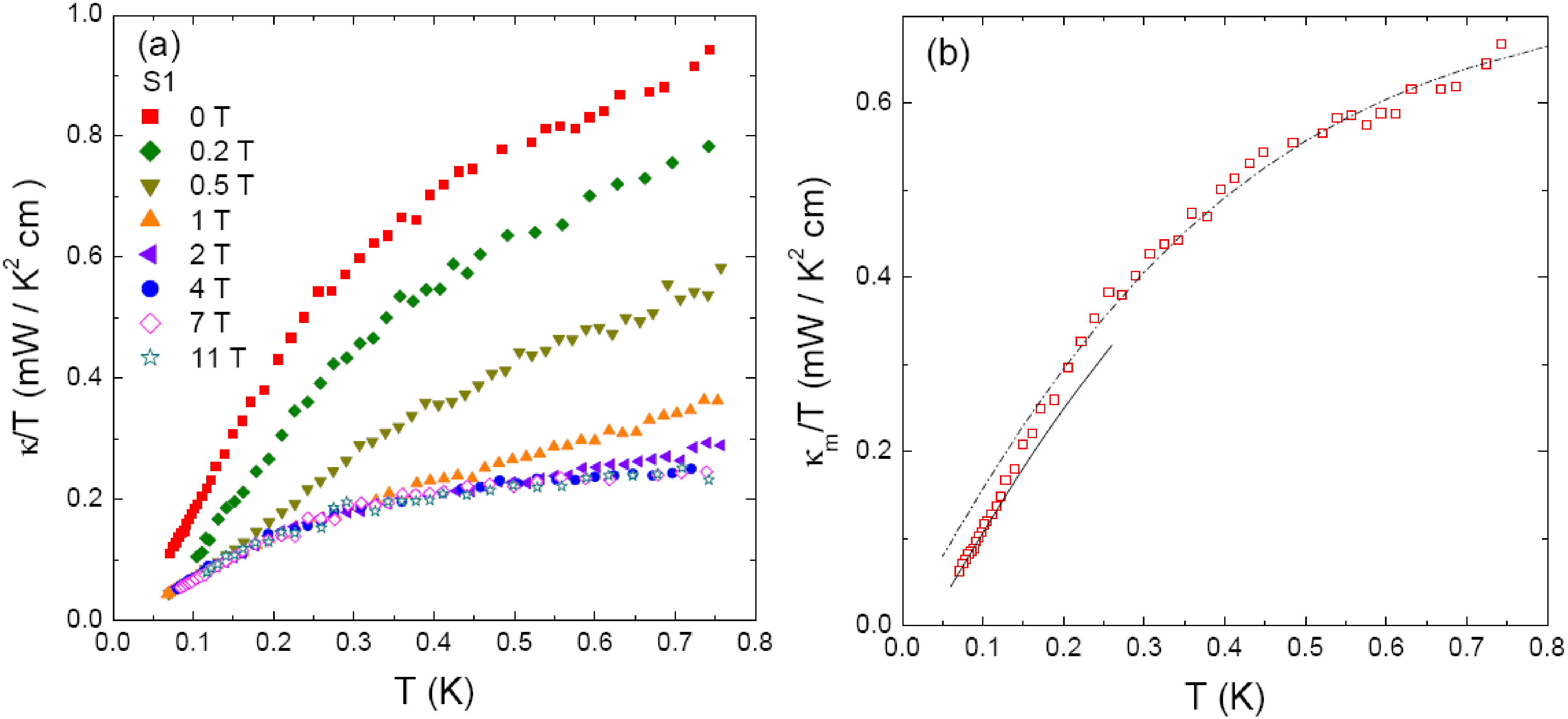
$$\kappa_m(T) = \frac{\zeta(3)k_B^3 L T^2}{\pi^2\hbar D}$$

0.77 K < T < 2.5 K: $C = 6.7T^{1.5} + 2.3T^3$

T < 0.77 K: dipole-dipole correction

B. Y. Pan, S. Y. Li *et al.*, arXiv:1302.6739

Thermal conductivity: FM magnon in YIG single crystal



Magnon gap in field: $\Delta = g\mu_B H$

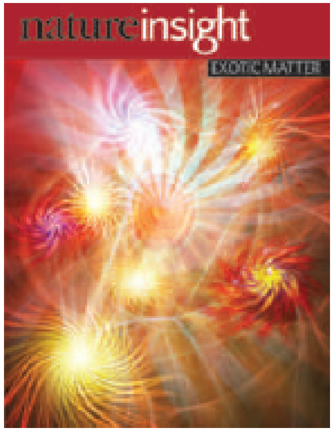
$\kappa_m = \kappa(0T) - \kappa(4T)$

If no corrections: $\kappa_m \sim T^2$

Our result suggests the corrections of defects and dipole-dipole interaction are needed.

B. Y. Pan, S. Y. Li *et al.*, arXiv:1302.6739

Example 3: Spinon heat transport in spin liquids



EXOTIC MATTER

Leon Balents, Nature **464**, 199 (2010)

Spin liquids in frustrated magnets

Leon Balents[1]

New magnetic ground state!

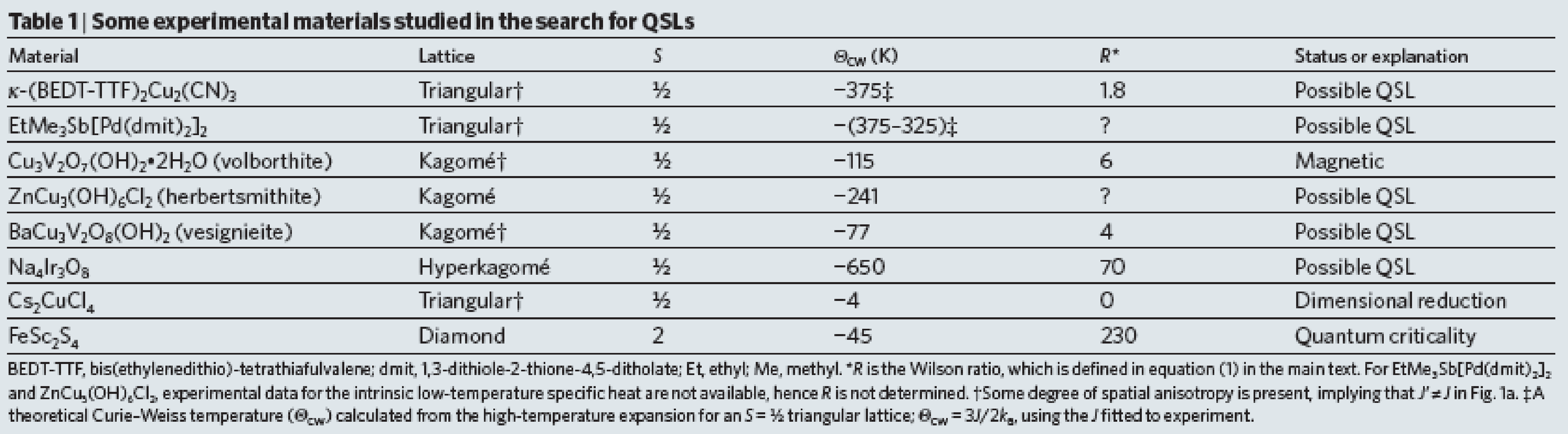
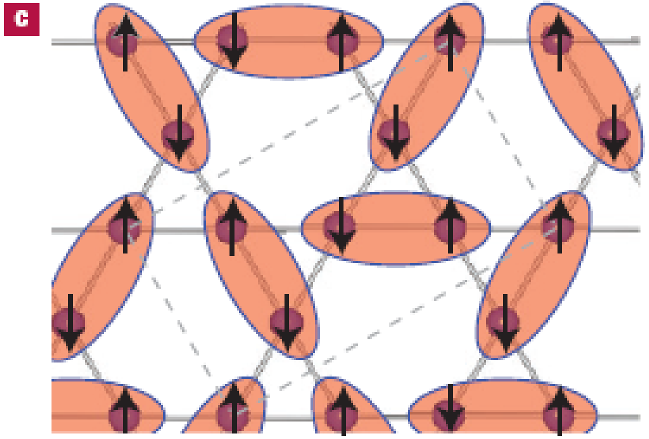


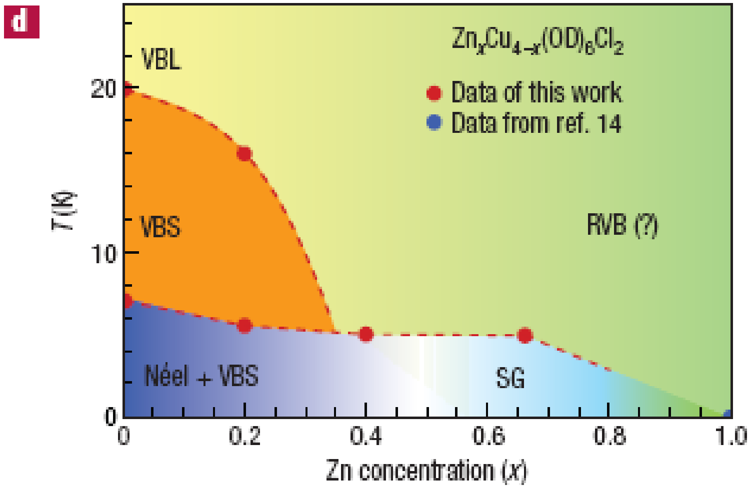
Table 1 | Some experimental materials studied in the search for QSLs

Material	Lattice	*S*	Θ_{CW} (K)	*R**	Status or explanation
κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$	Triangular†	½	−375‡	1.8	Possible QSL
EtMe$_3$Sb[Pd(dmit)$_2$]$_2$	Triangular†	½	−(375–325)‡	?	Possible QSL
Cu$_3$V$_2$O$_7$(OH)$_2$•2H$_2$O (volborthite)	Kagomé†	½	−115	6	Magnetic
ZnCu$_3$(OH)$_6$Cl$_2$ (herbertsmithite)	Kagomé	½	−241	?	Possible QSL
BaCu$_3$V$_2$O$_8$(OH)$_2$ (vesignieite)	Kagomé†	½	−77	4	Possible QSL
Na$_4$Ir$_3$O$_8$	Hyperkagomé	½	−650	70	Possible QSL
Cs$_2$CuCl$_4$	Triangular†	½	−4	0	Dimensional reduction
FeSc$_2$S$_4$	Diamond	2	−45	230	Quantum criticality

BEDT-TTF, bis(ethylenedithio)-tetrathiafulvalene; dmit, 1,3-dithiole-2-thione-4,5-ditholate; Et, ethyl; Me, methyl. **R* is the Wilson ratio, which is defined in equation (1) in the main text. For EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ and ZnCu$_3$(OH)$_6$Cl$_2$, experimental data for the intrinsic low-temperature specific heat are not available, hence *R* is not determined. †Some degree of spatial anisotropy is present, implying that $J' \neq J$ in Fig. 1a. ‡A theoretical Curie–Weiss temperature (Θ_{CW}) calculated from the high-temperature expansion for an $S = ½$ triangular lattice; $\Theta_{CW} = 3J/2k_B$, using the J fitted to experiment.

Quantum-spin-liquid states in the two-dimensional kagome antiferromagnets $Zn_xCu_{4-x}(OD)_6Cl_2$





Neutron scattering

S.-H. Lee, Nat. Mater. **6**, 853 (2007)

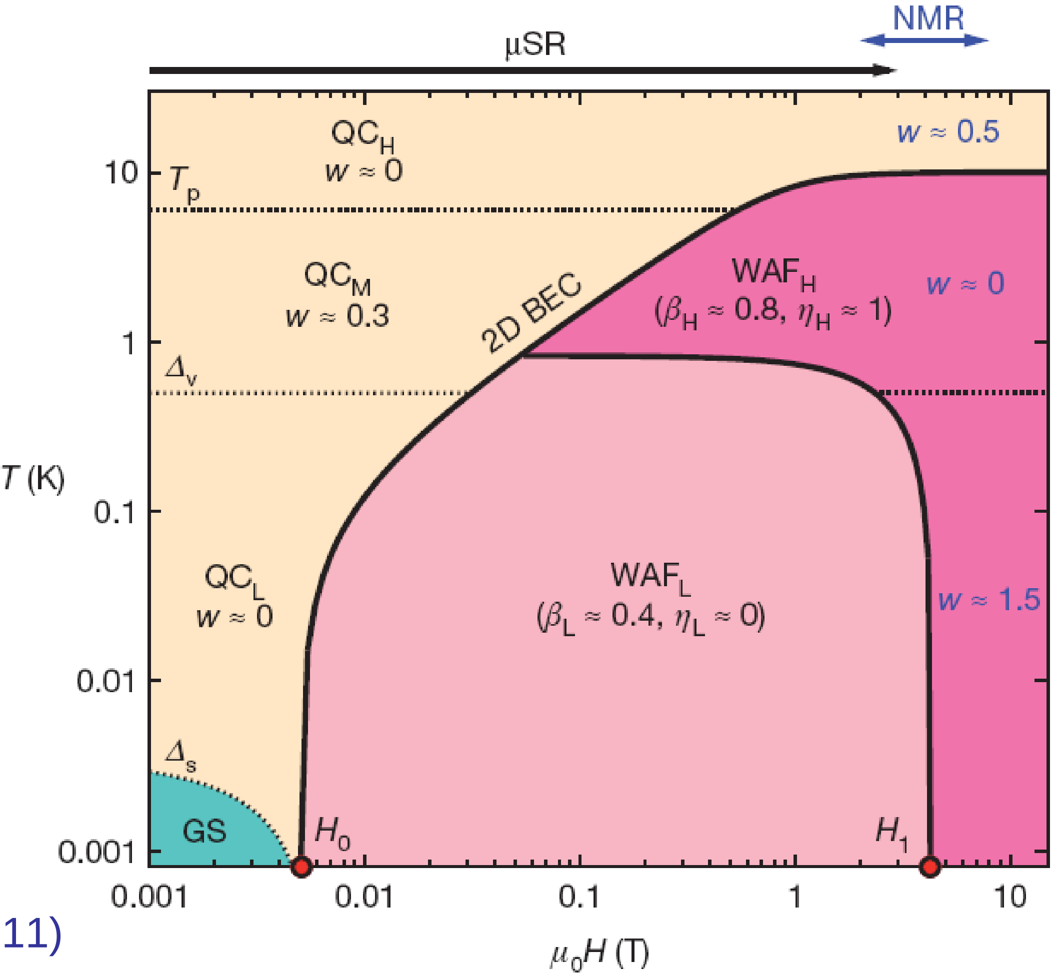
LETTER

doi:10.1038/nature09910

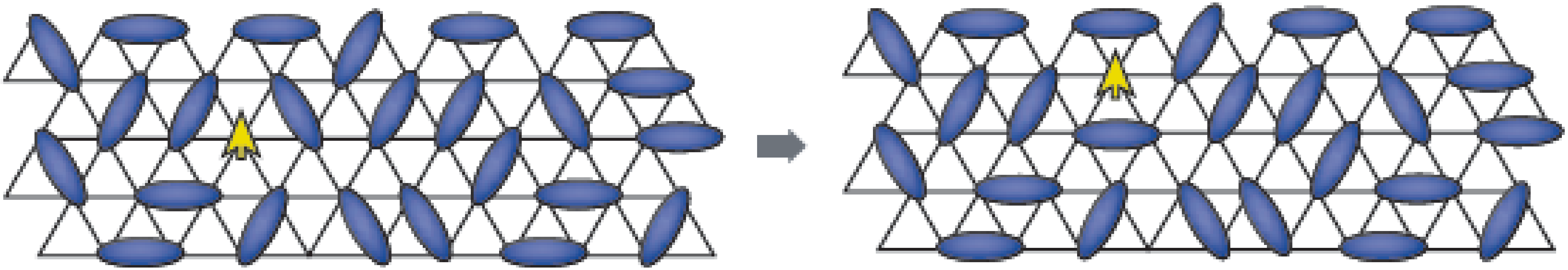
Magnetic and non-magnetic phases of a quantum spin liquid

μSR, NMR

κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$



F. L. Pratt et al., Nature **471**, 613 (2011)



Spinon excitation in a 2D QSL detected by heat transport

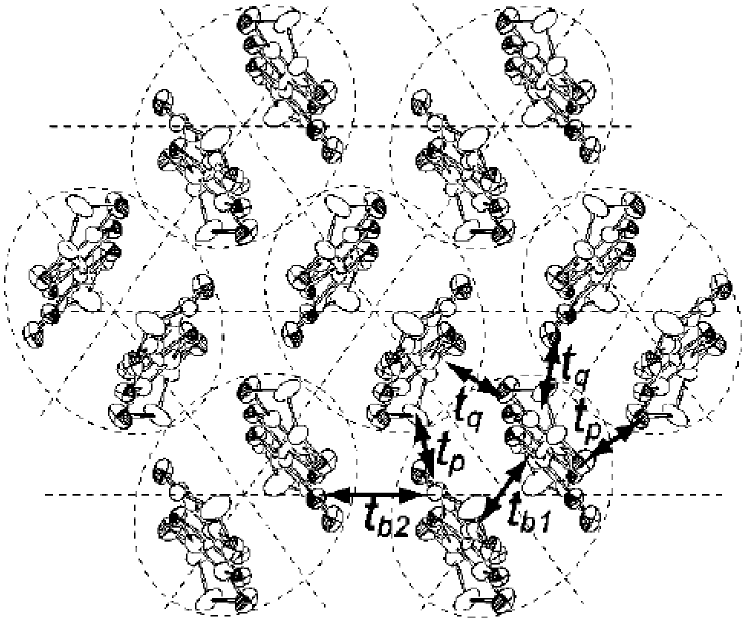
ARPES

Amperean Pairing Instability in the U(1) Spin Liquid State with Fermi Surface and Application to κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

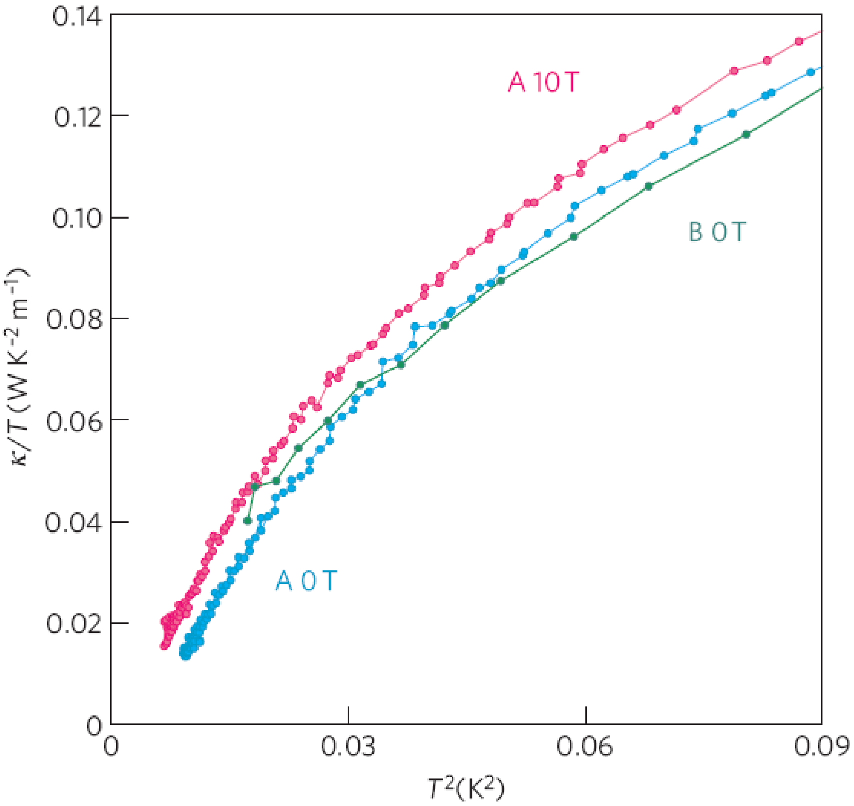
Sung-Sik Lee, Patrick Lee and T. Senthil, PRL **98**, 067006 (2007)

Prediction: $\kappa \sim T$, like electrons in a metal

Heat transport: A tool to probe spinons



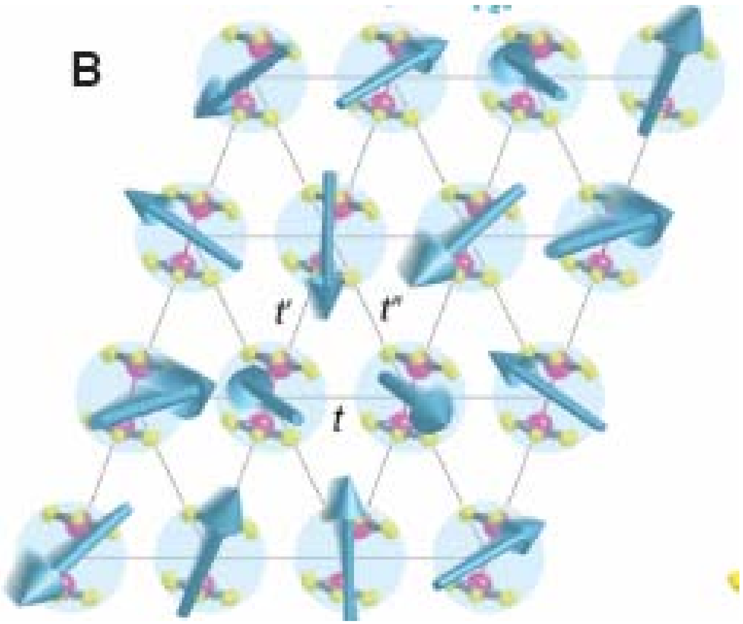
κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$



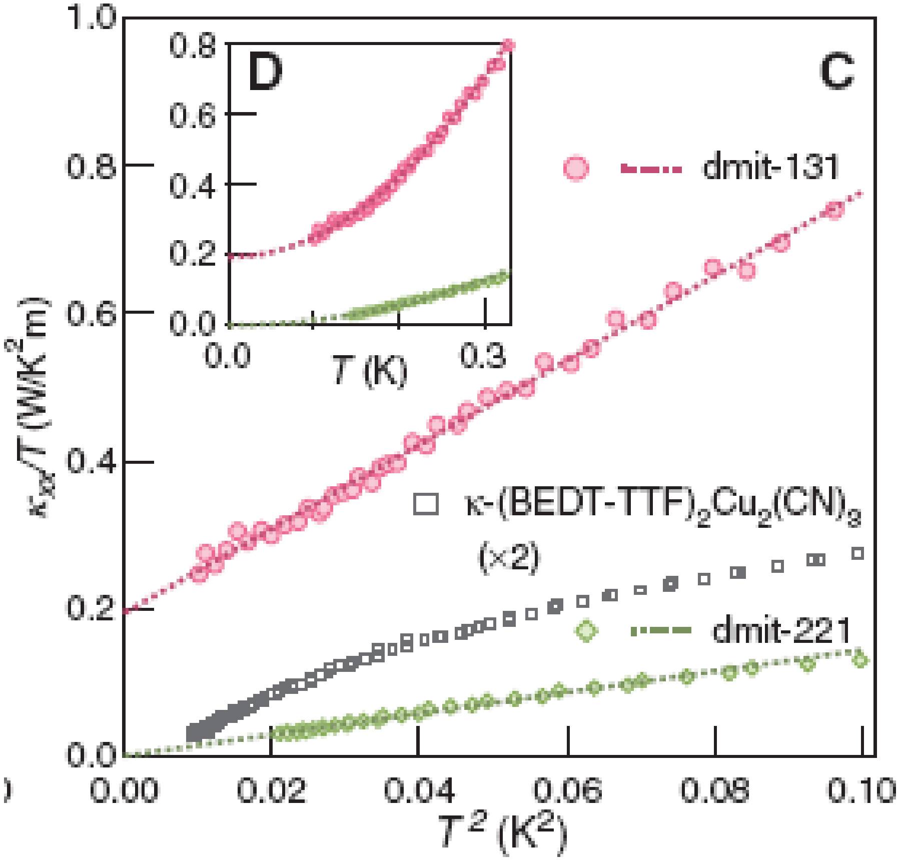
No κ_0/T: are spinons gapped?

M. Yamashita *et al.*, Nature Physics **5**, 44 (2008)

Heat transport: A tool to probe spinons



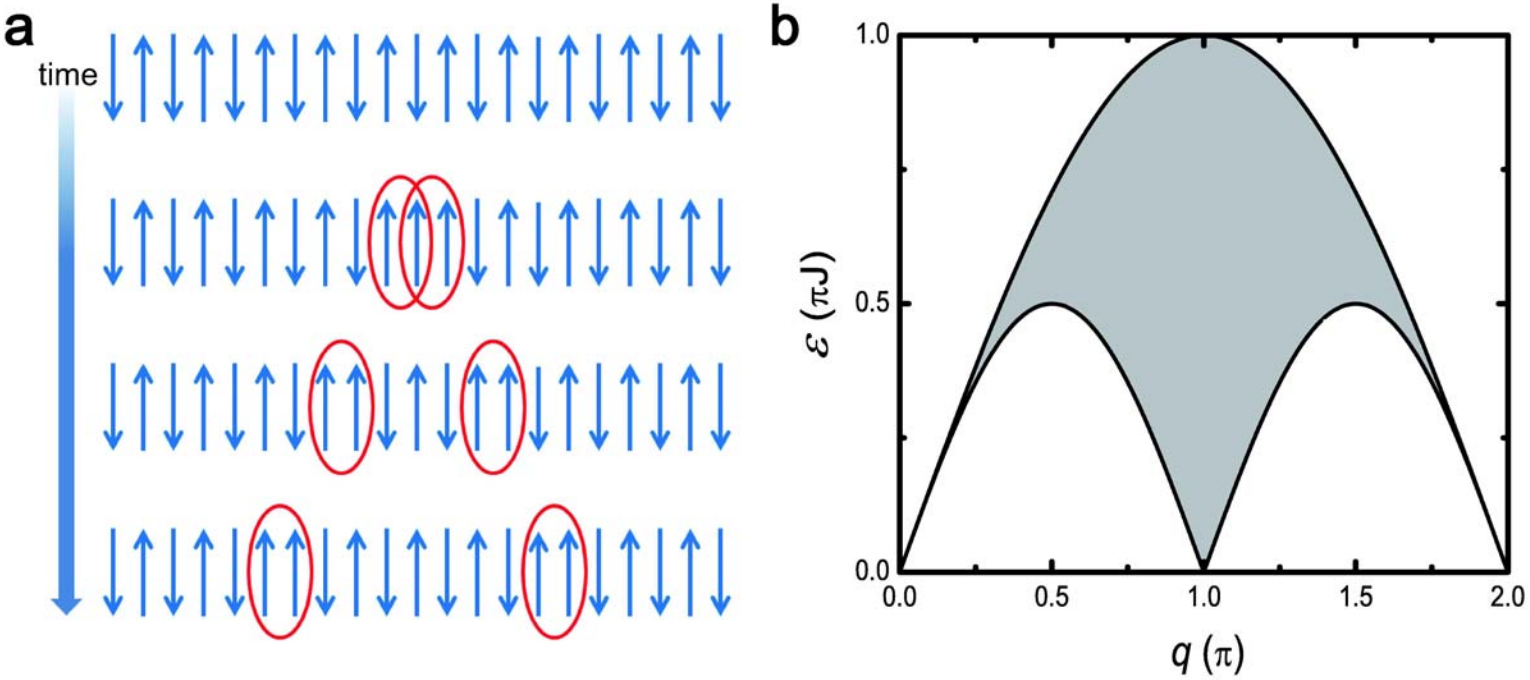
$EtMe_3Sb[Pd(dmit)_2]_2$: dmit-131



Significant κ_0/T: evidence for spinons in a spin-liquid candidate.

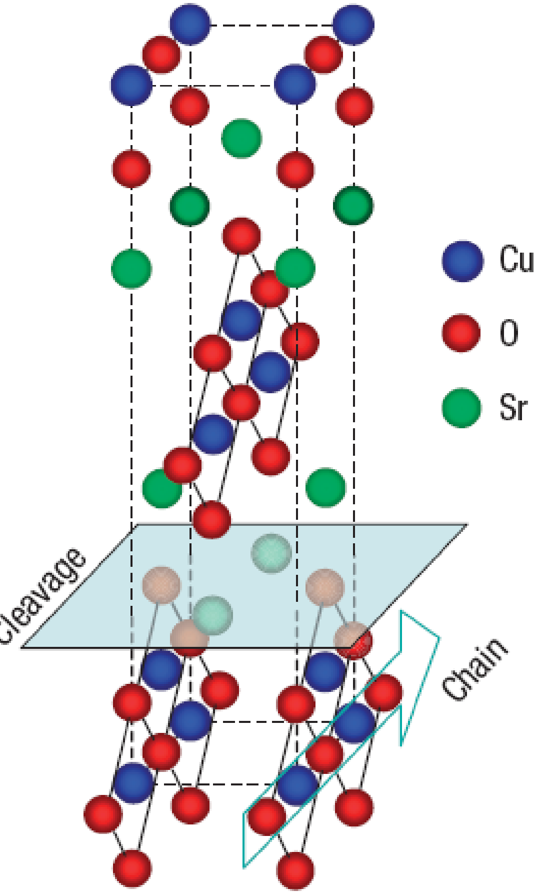
M. Yamashita *et al.*, Science **328**, 1246 (2010)

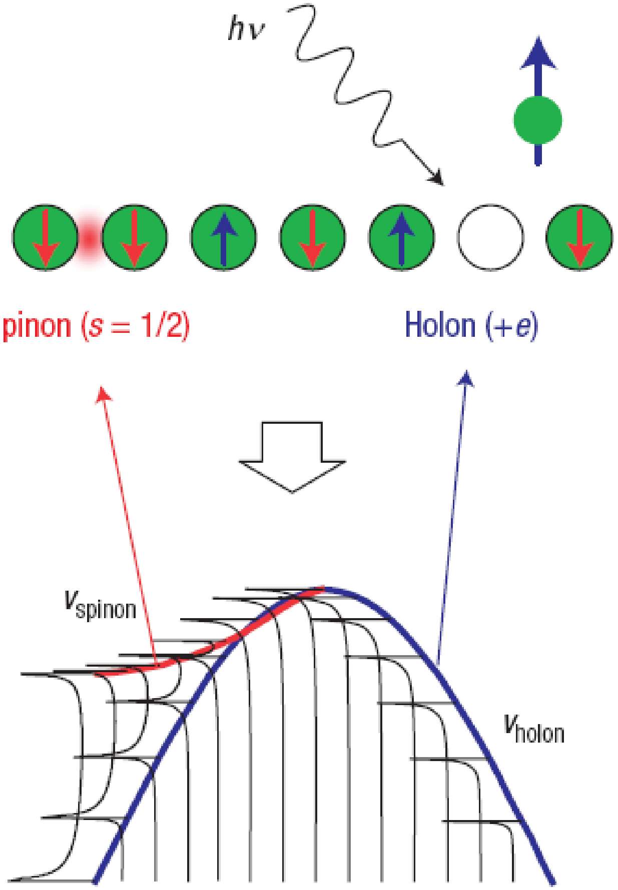
3、Anderson localization of spinons in a spin-1/2 antiferromagntic Heisenberg chain

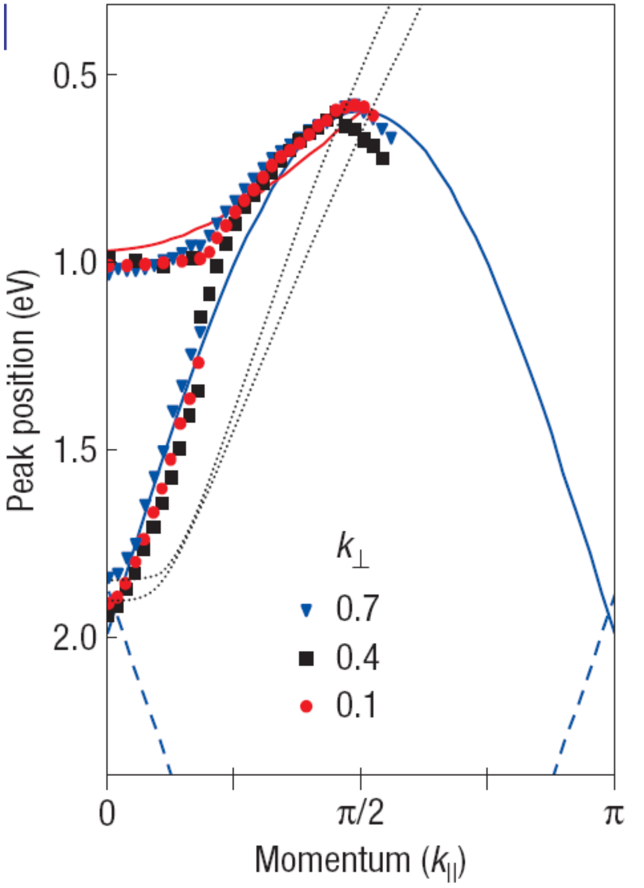


The model of spin-1/2 AF Heisenberg chain can be exactly solved，and the excitations are called spinon.

$SrCuO_2$: Spin-charge seperation by ARPES

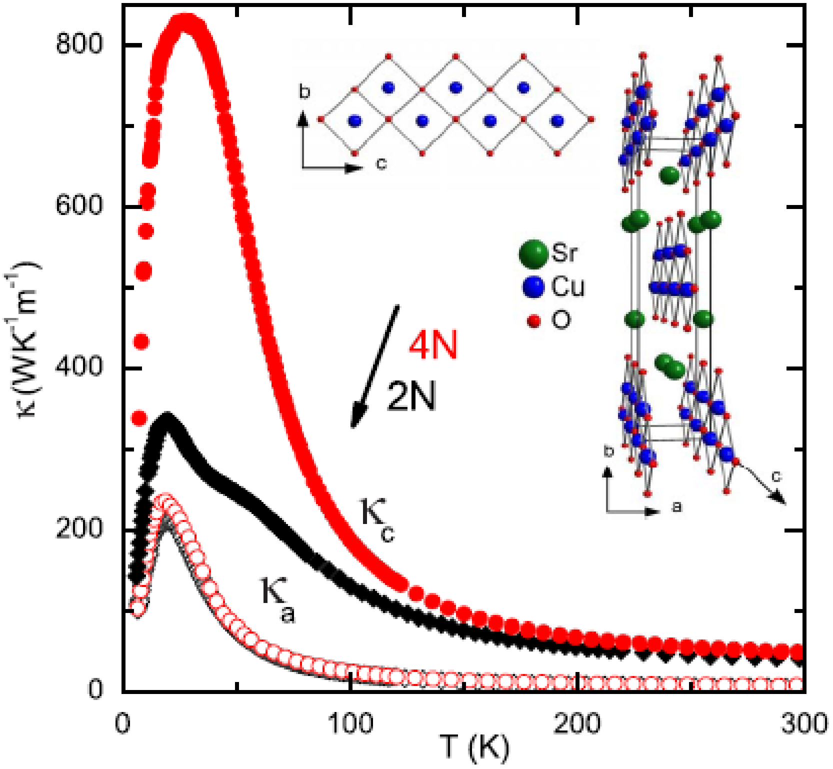


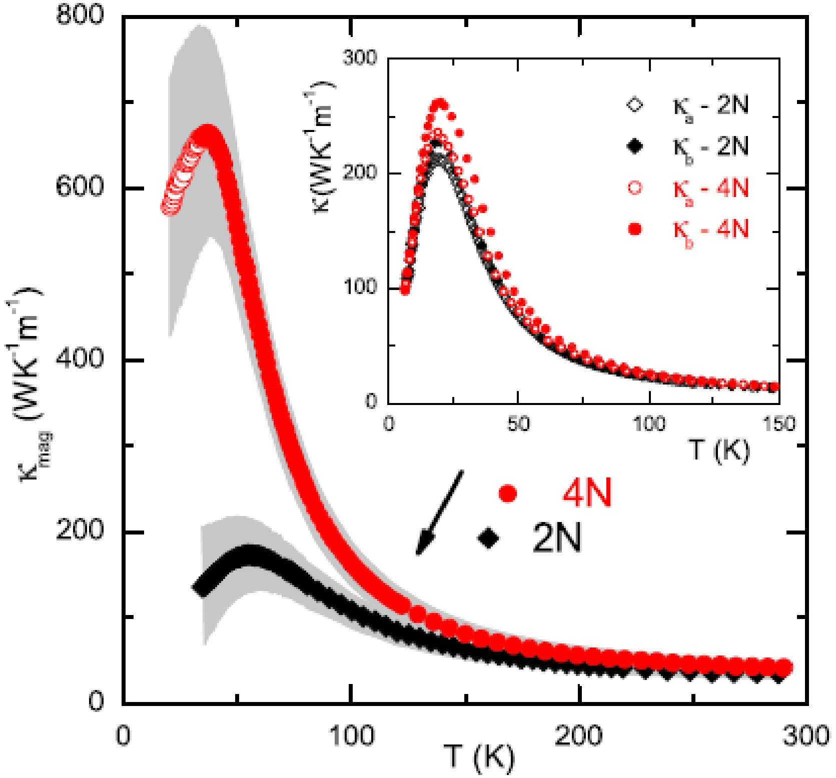




B. J. Kim *et al.*, Nature Phys. **2**, 397 (2006)

SrCuO$_2$: extra heat conduction along the chain

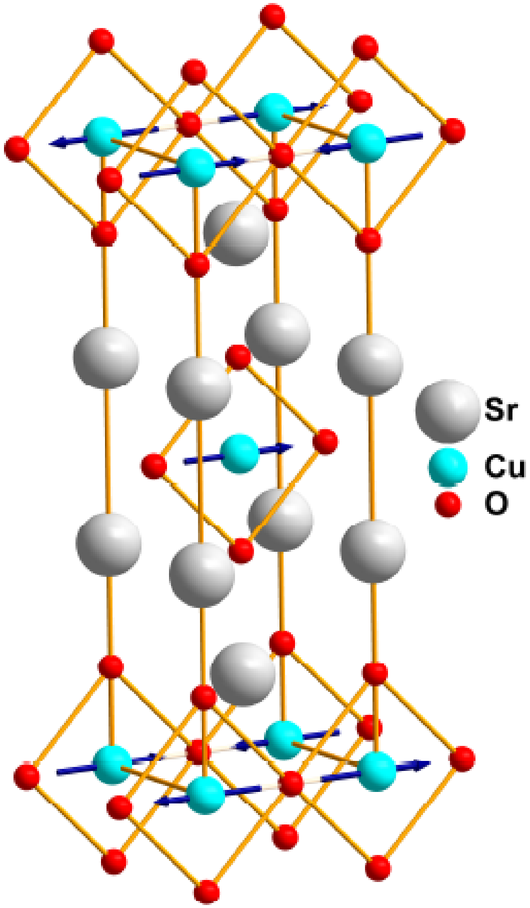




$$\kappa_{spinon} = \kappa_c - \kappa_a$$

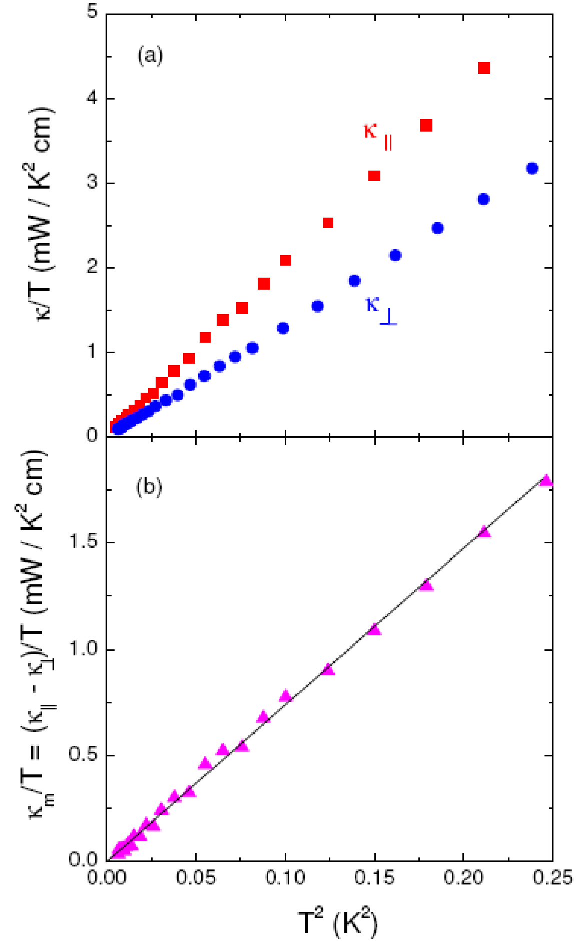
N. Hlubek *et al.*, Phys. Rev. B **81**, 020405(R) (2010)

Sr_2CuO_3: extra heat conduction along the chain



J ~ 2000 K

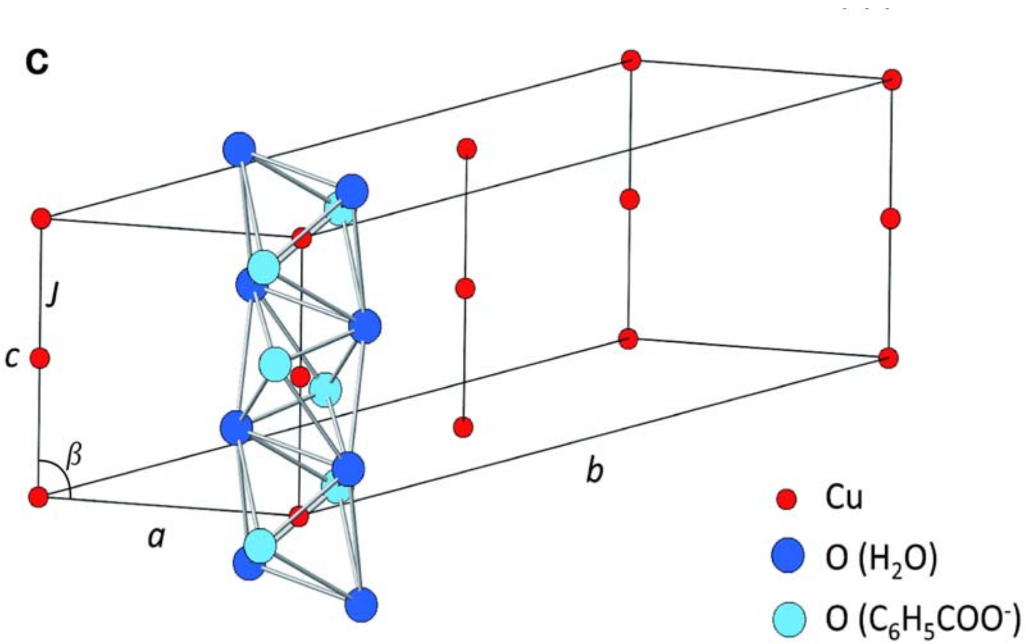
J’ ~ T_N = 5.4 K



$$\kappa_{magnon} = \kappa_{||} - \kappa_{\perp}$$

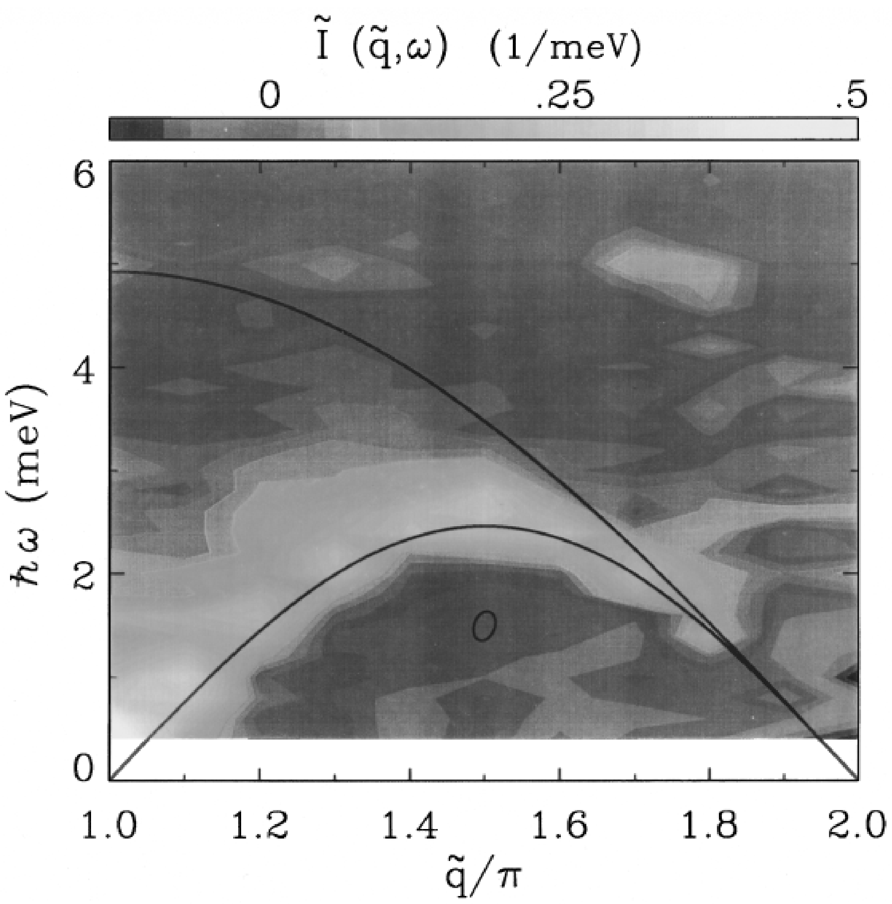
T. Y. Guan, S. Y. Li *et al.*, unpublished

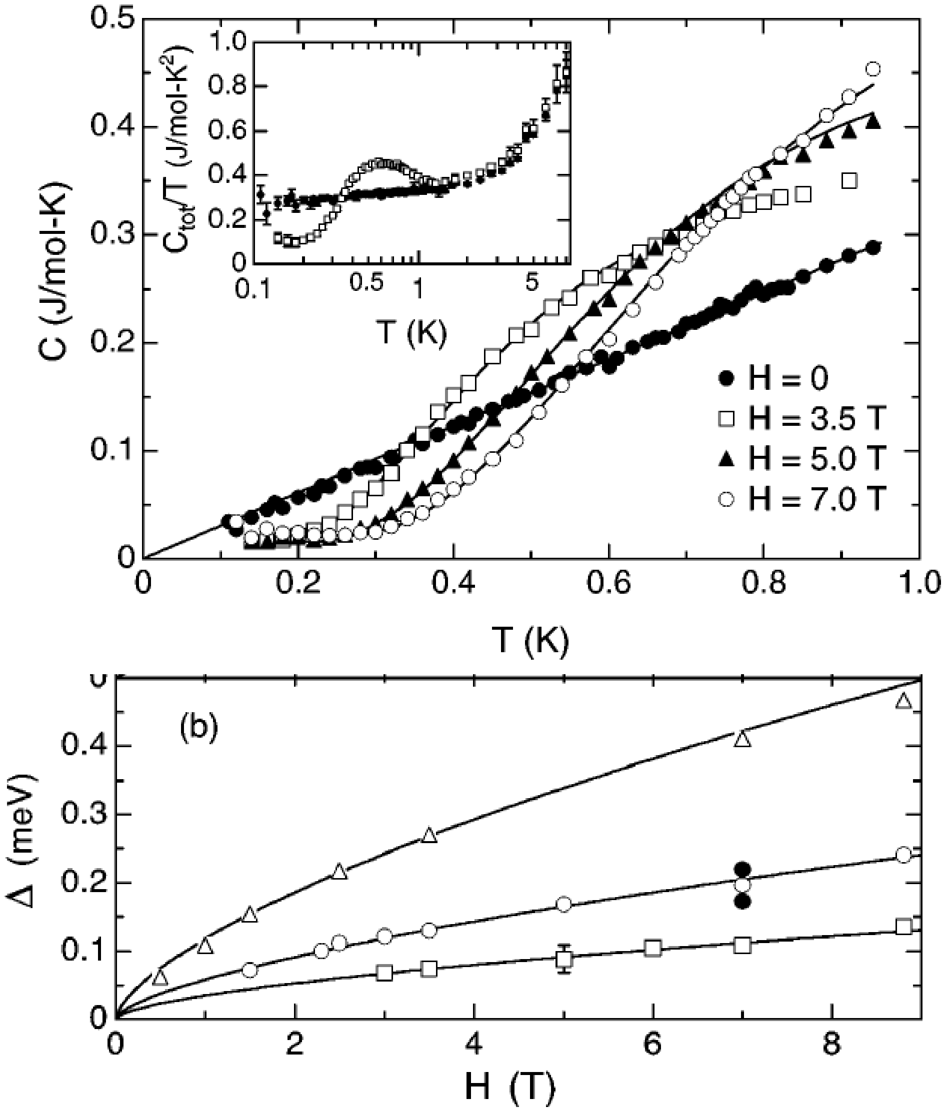
Cu Benzoate: an ideal spin-1/2 Heisenberg chain



$Cu(C_6H_5COO)_2 \bullet 3H_2O$: J ~ 18.6 K, J’ < 50 mK
no order down to 50 mK

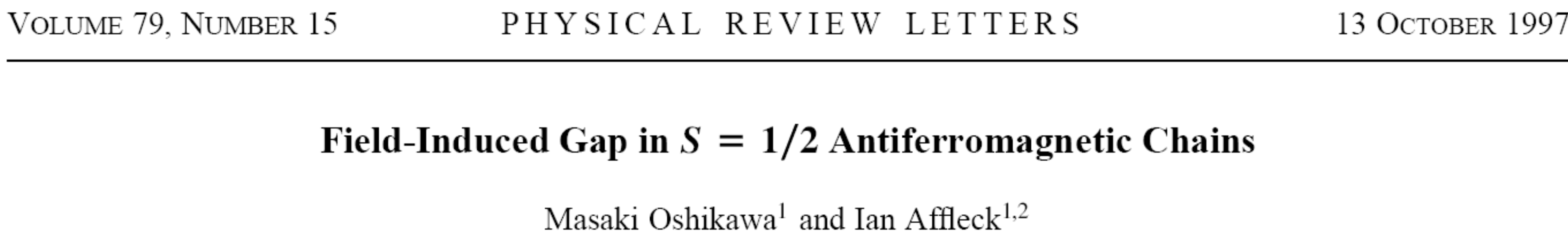
Cu Benzoate: an ideal spin-1/2 Heisenberg chain





D. C. Dender *et al.*, PRB **53**, 2583 (1996)

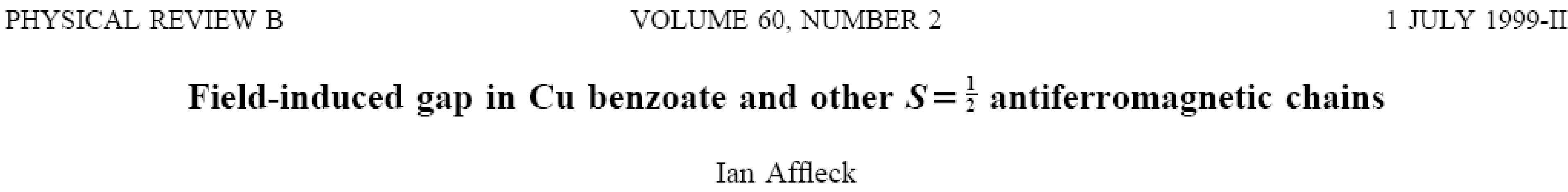
D. C. Dender *et al.*, PRL **79**, 1750 (1997)



VOLUME 79, NUMBER 15 PHYSICAL REVIEW LETTERS 13 OCTOBER 1997

Field-Induced Gap in $S = 1/2$ Antiferromagnetic Chains

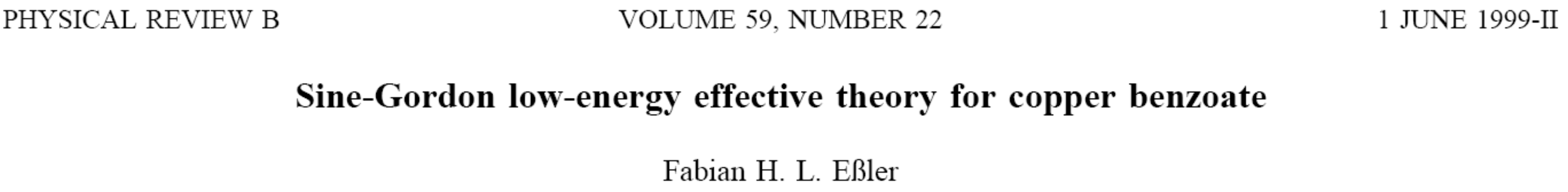
Masaki Oshikawa[1] and Ian Affleck[1,2]



PHYSICAL REVIEW B VOLUME 60, NUMBER 2 1 JULY 1999-II

Field-induced gap in Cu benzoate and other $S=\frac{1}{2}$ antiferromagnetic chains

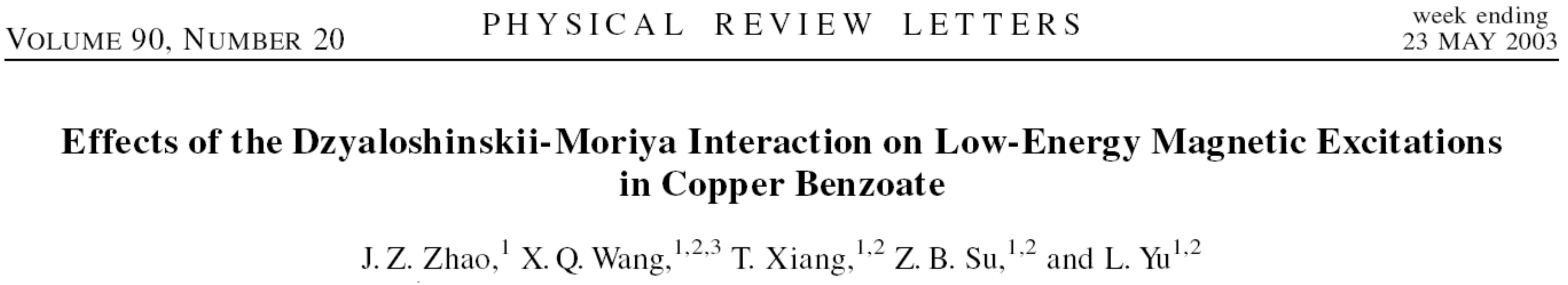
Ian Affleck



PHYSICAL REVIEW B VOLUME 59, NUMBER 22 1 JUNE 1999-II

Sine-Gordon low-energy effective theory for copper benzoate

Fabian H. L. Eßler

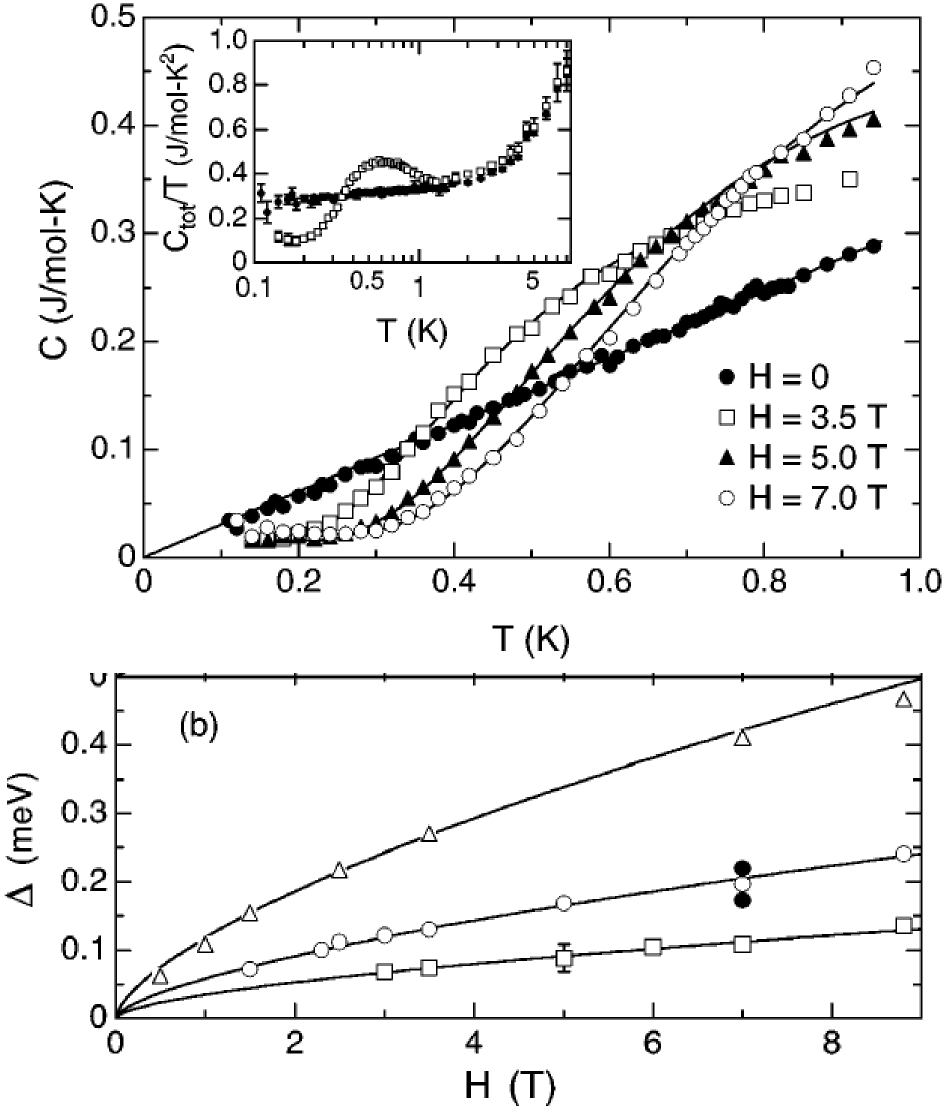


VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

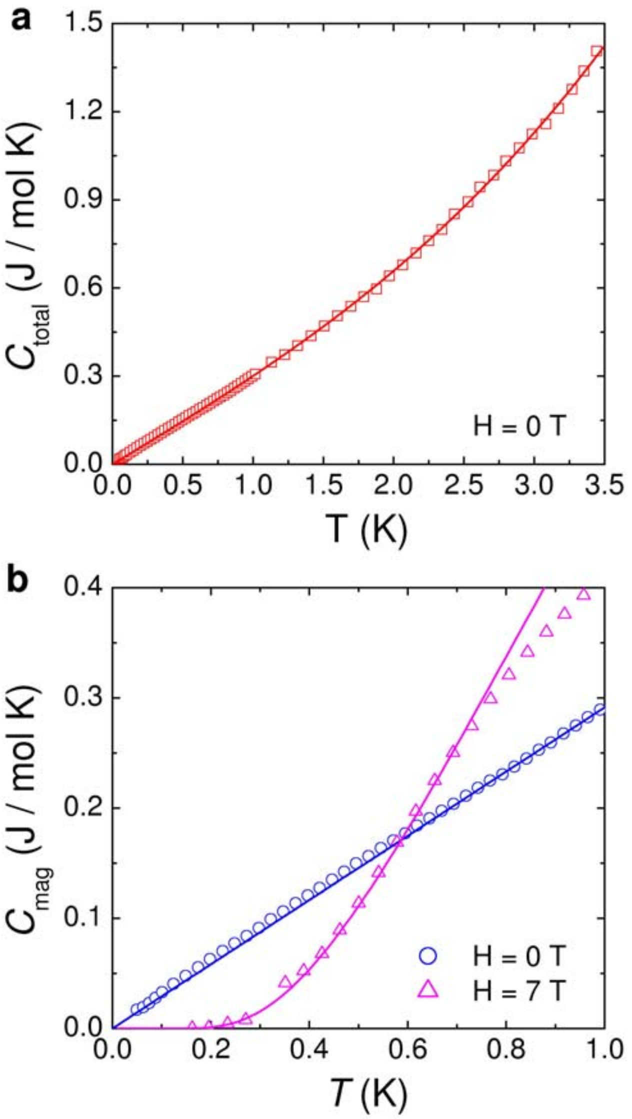
Effects of the Dzyaloshinskii-Moriya Interaction on Low-Energy Magnetic Excitations in Copper Benzoate

J. Z. Zhao,[1] X. Q. Wang,[1,2,3] T. Xiang,[1,2] Z. B. Su,[1,2] and L. Yu[1,2]

Cu Benzoate: spinon specific heat Cs ~ T

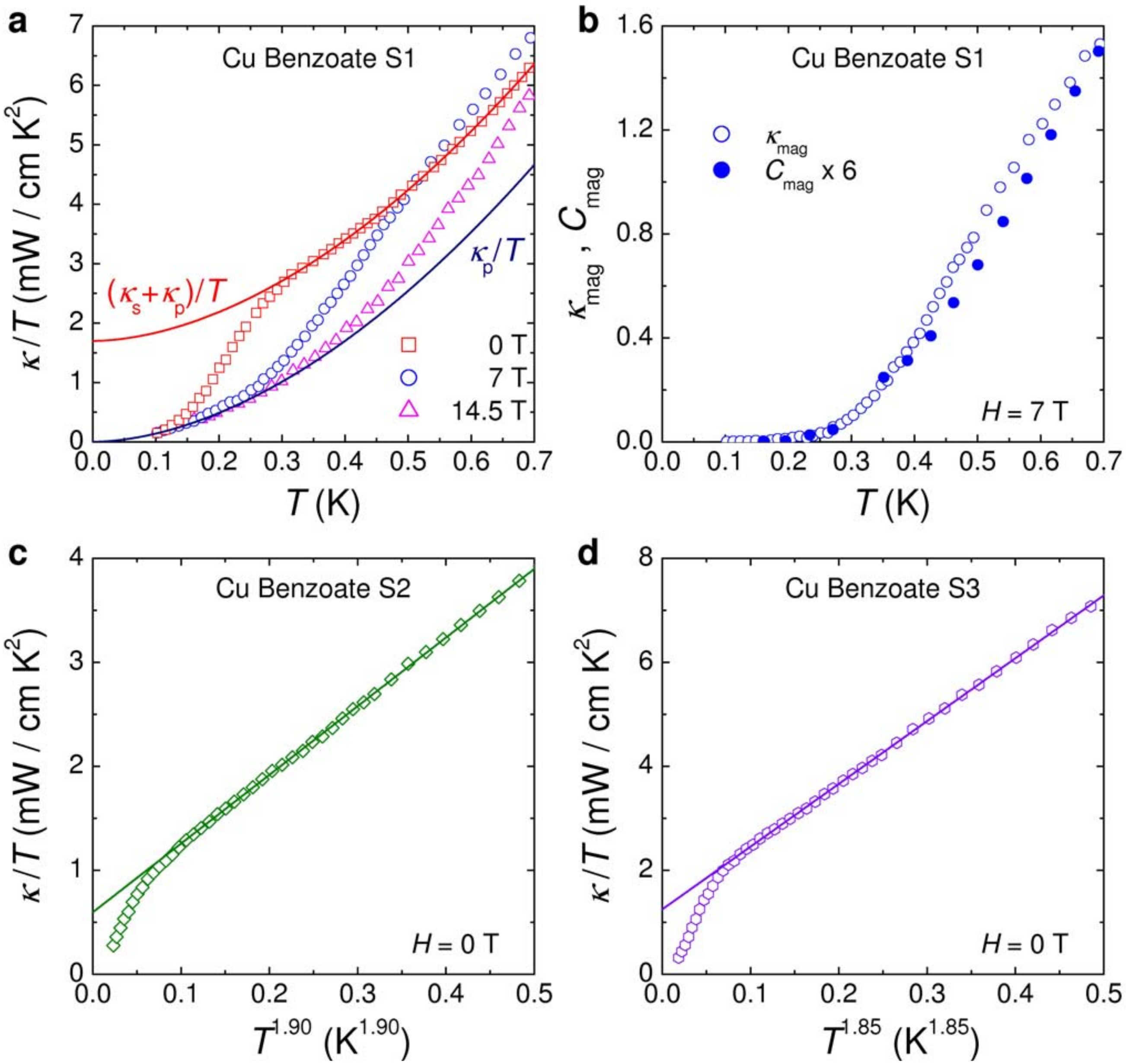


D. C. Dender *et al.*, PRL **79**, 1750 (1997)



B. Y. Pan, S. Y. Li *et al.*, arXiv:1208.3803

Cu Benzoate: thermal conductivity



$$\kappa = C\,v\,l$$

H = 0 T

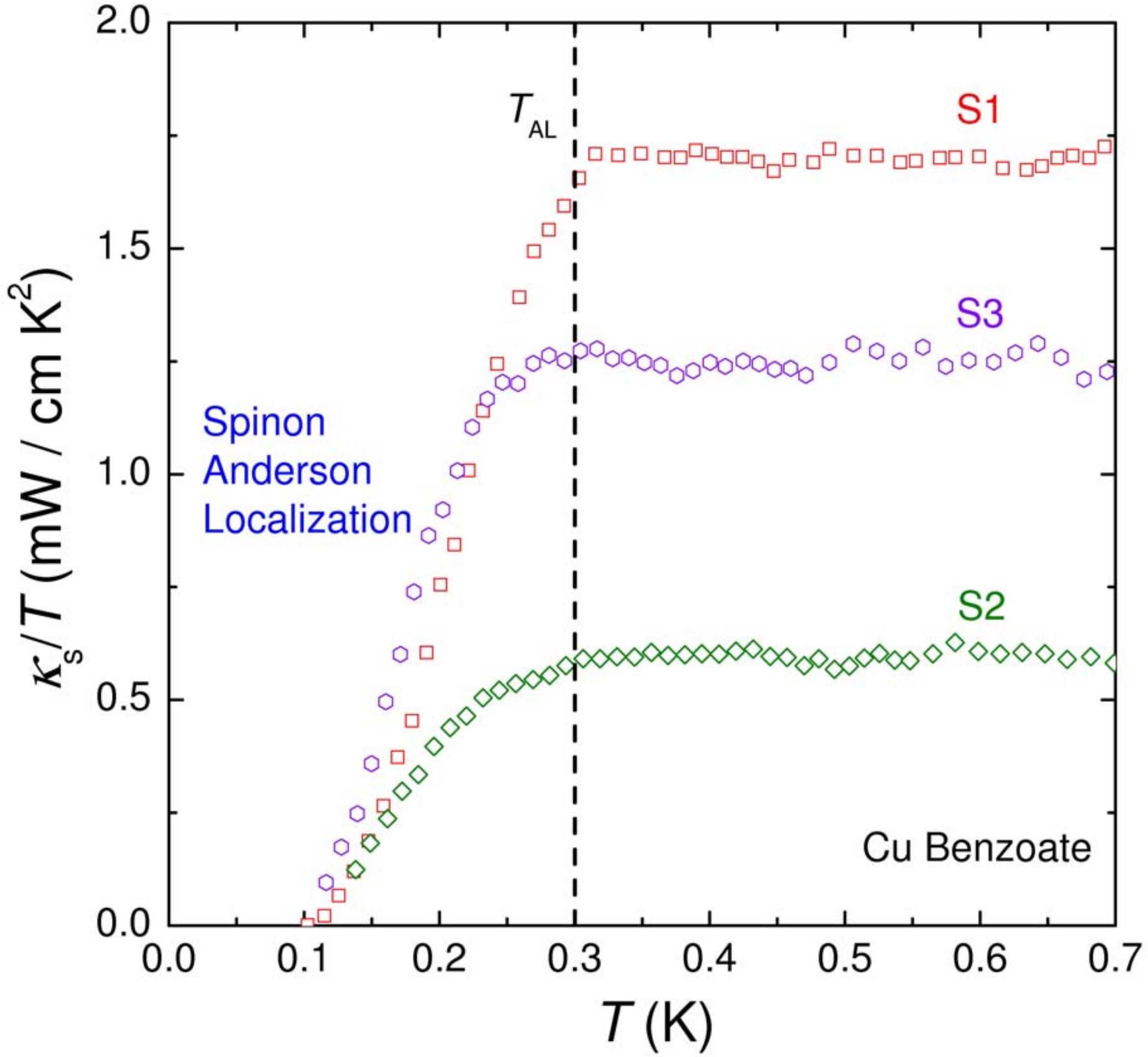
$\kappa_s \sim C_s \sim T$

H = 7 T

$\kappa_{mag} \sim C_{mag}$

B. Y. Pan, S. Y. Li *et al.*, arXiv:1208.3803

Cu Benzoate: spinon thermal conductivity



Linear term

Compare to electrons:

$\kappa_0/T = L_0/\rho_0$

1.7 mW/cmK^2

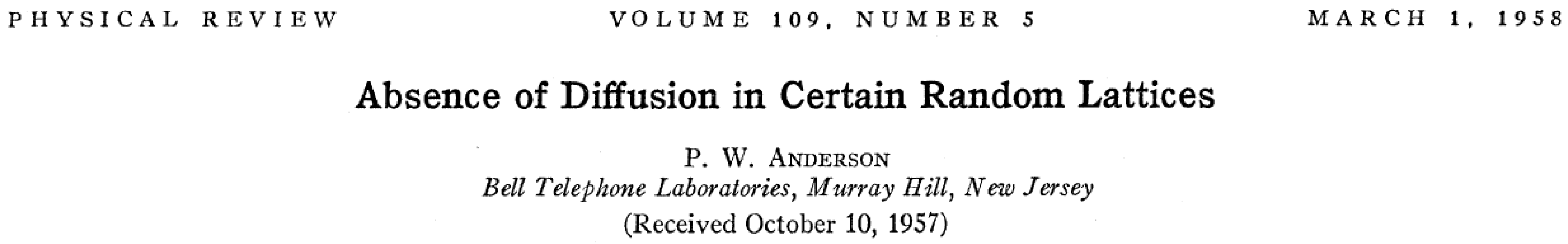
~ 15 $\mu\Omega$ cm

Compare to spinons in the spin liquid:

$\kappa_s/T \approx 2$ mW/cmK^2

B. Y. Pan, S. Y. Li *et al.*, arXiv:1208.3803

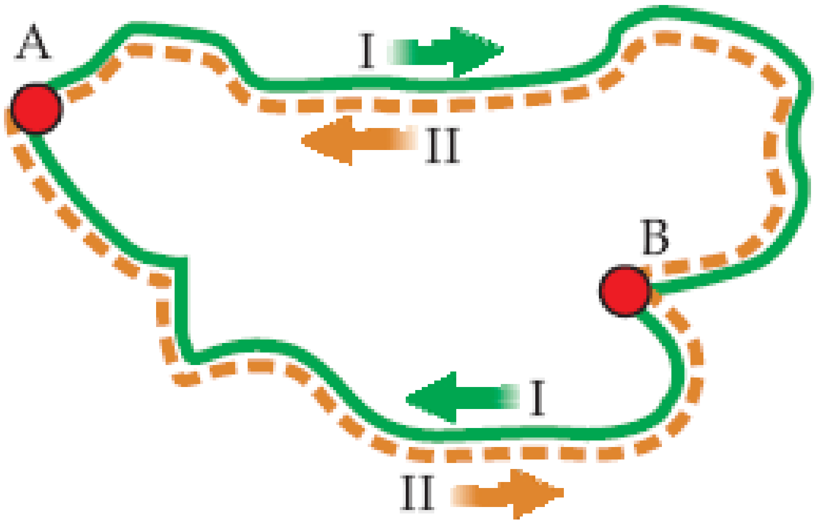
Anderson localization: a fundermental physics of waves



PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)



Anderson localization of waves in disordered systems originates from interference in multiple elastic scattering.

Anderson localization: Light

Localization of light in a disordered medium

Nature **390**, 671 (1997)

Statistical signatures of photon localization

Nature **404**, 850 (2000)

Transport and Anderson localization in disordered two-dimensional photonic lattices

Nature **446**, 52 (2007)

Anderson localization: Ultrasound

LETTERS

Localization of ultrasound in a three-dimensional elastic network

HEFEI HU[1]*, A. STRYBULEVYCH[1], J. H. PAGE[1†], S. E. SKIPETROV[2] AND B. A. VAN TIGGELEN[2]

[1] Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[2] Université Joseph Fourier, Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS, 25 Rue des Martyrs, BP 166, 38042 Grenoble, France
*Present address: Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801-3080, USA
† e-mail: jhpage@cc.umanitoba.ca

Nature Physics **4**,945 (2008)

Anderson localization: Ultracold atoms

Direct observation of Anderson localization of matter waves in a controlled disorder

Nature **453**, 891 (2008)

Anderson localization of a non-interacting Bose–Einstein condensate

Nature **453**, 895 (2008)

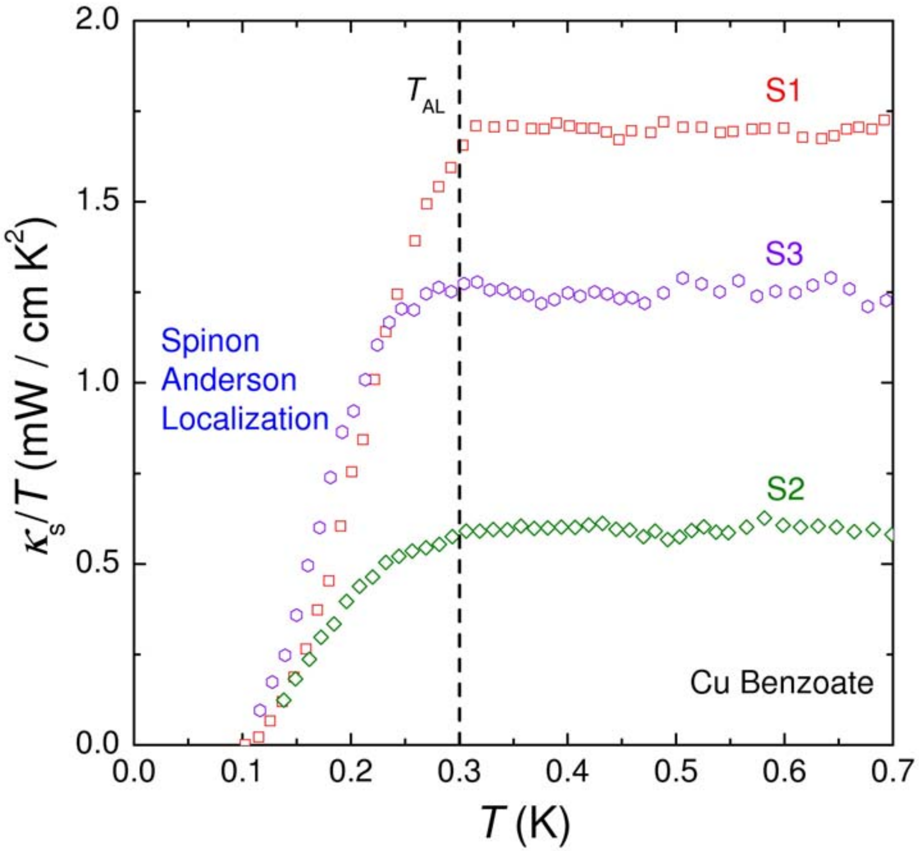
Three-Dimensional Anderson Localization of Ultracold Matter

Science **333**, 66 (2011)

Three-dimensional localization of ultracold atoms in an optical disordered potential

Nature Physics **8**, 398 (2012)

Anderson localization: Spinon

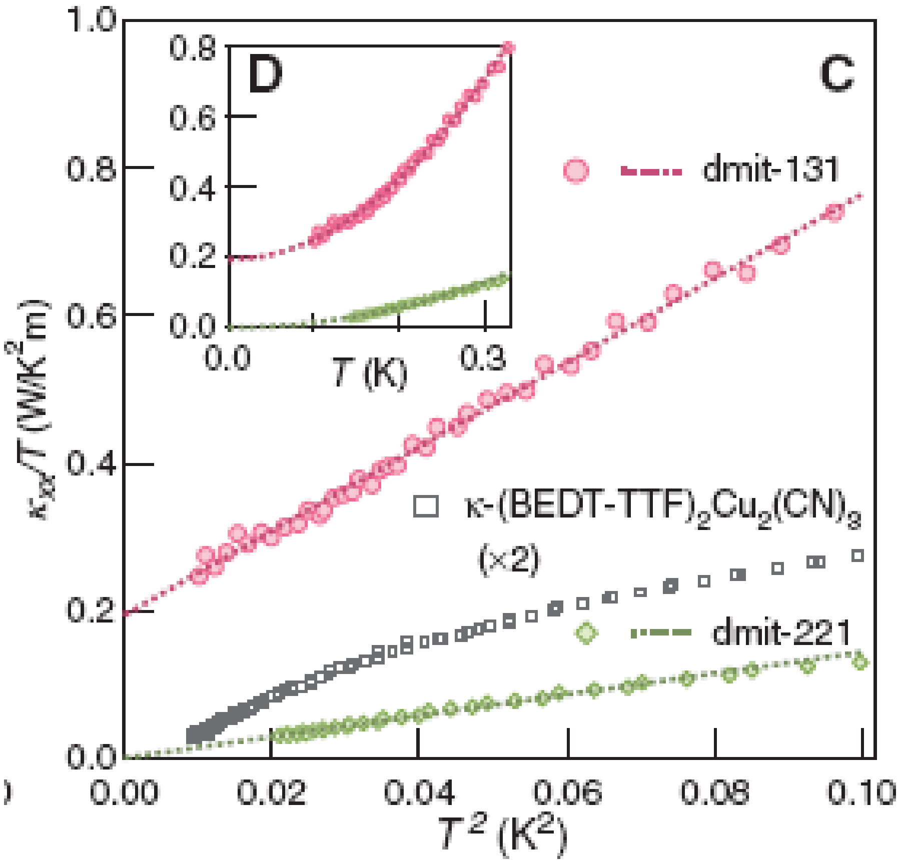


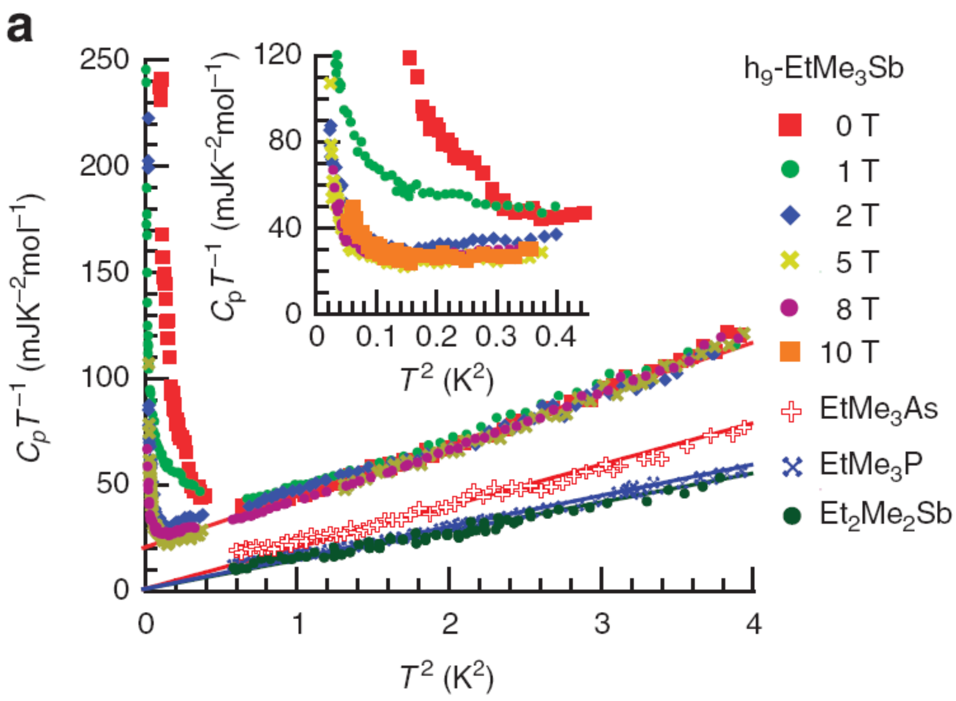
First observation of Anderson localization of magnetic excitations.
1D system is the best place for Anderson localization to occur.

B. Y. Pan, S. Y. Li *et al.*, arXiv:1208.3803

Spin liquid: Spinons

$EtMe_3Sb[Pd(dmit)_2]_2$: dmit-131

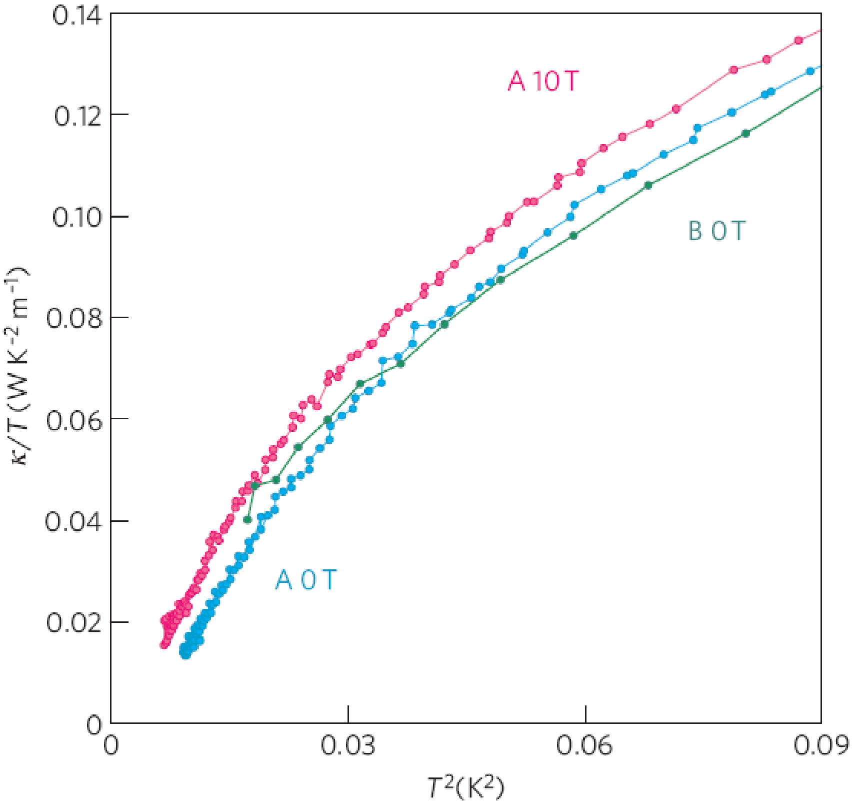




M. Yamashita *et al.*, Science **328**, 1246 (2010)   S. Yamashita *et al.*, Nat. Commun. **2**, 275 (2011)

Spin liquid: Spinons

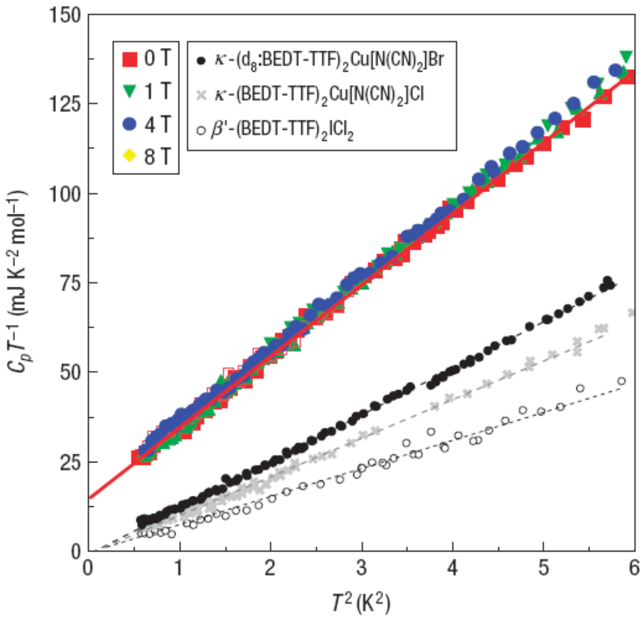
κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

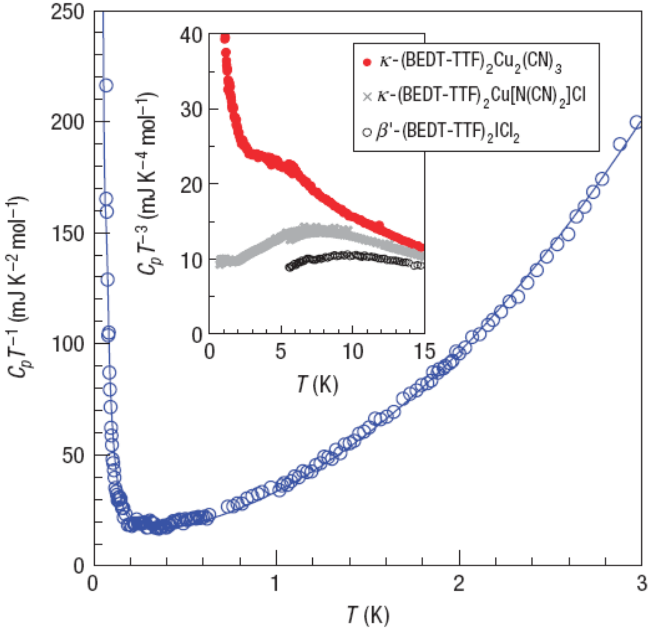


No κ_0/T: Gapped? Localized?

M. Yamashita *et al.*, Nature Physics **5**, 44 (2008)

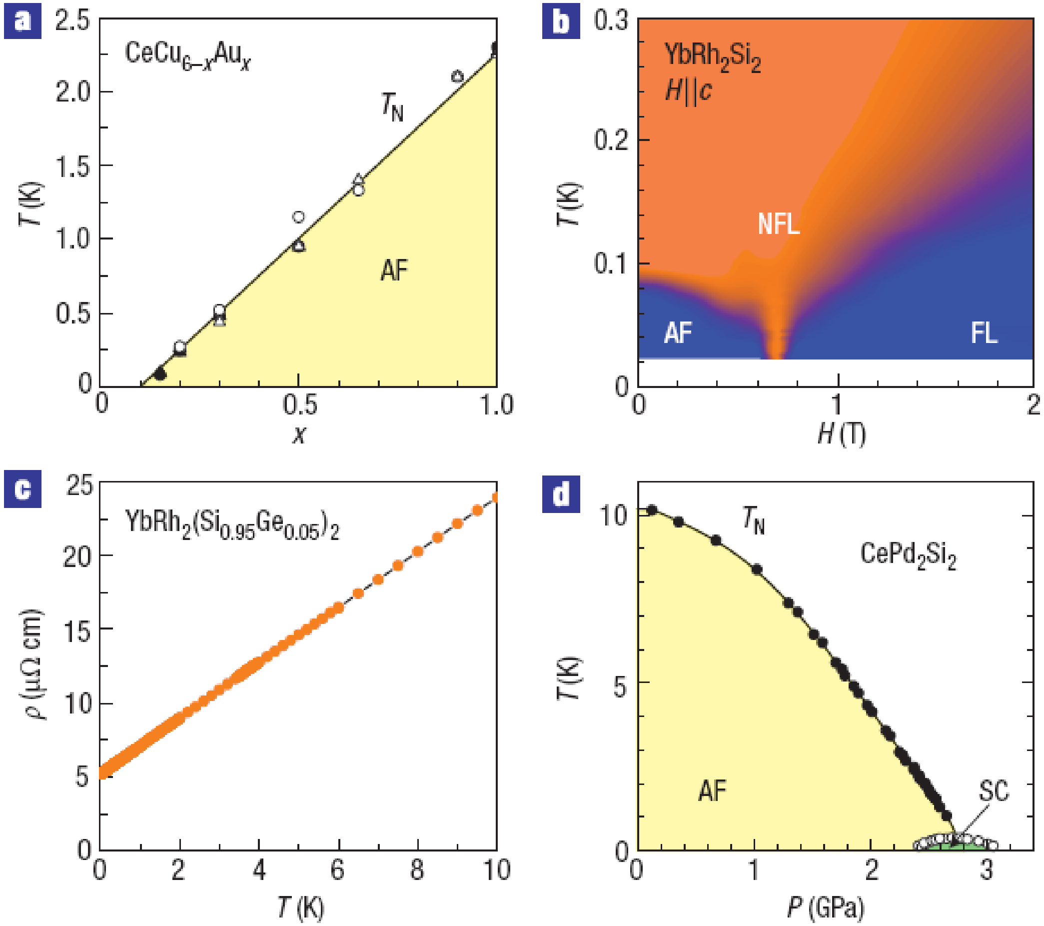
S. Yamashita *et al.*, Nature Physics **4**, 459 (2008)





4. Unveiling the quantum critical point of an Ising chain in a transverse field

Quantum Phase Transition: big issue in condensed matter physics

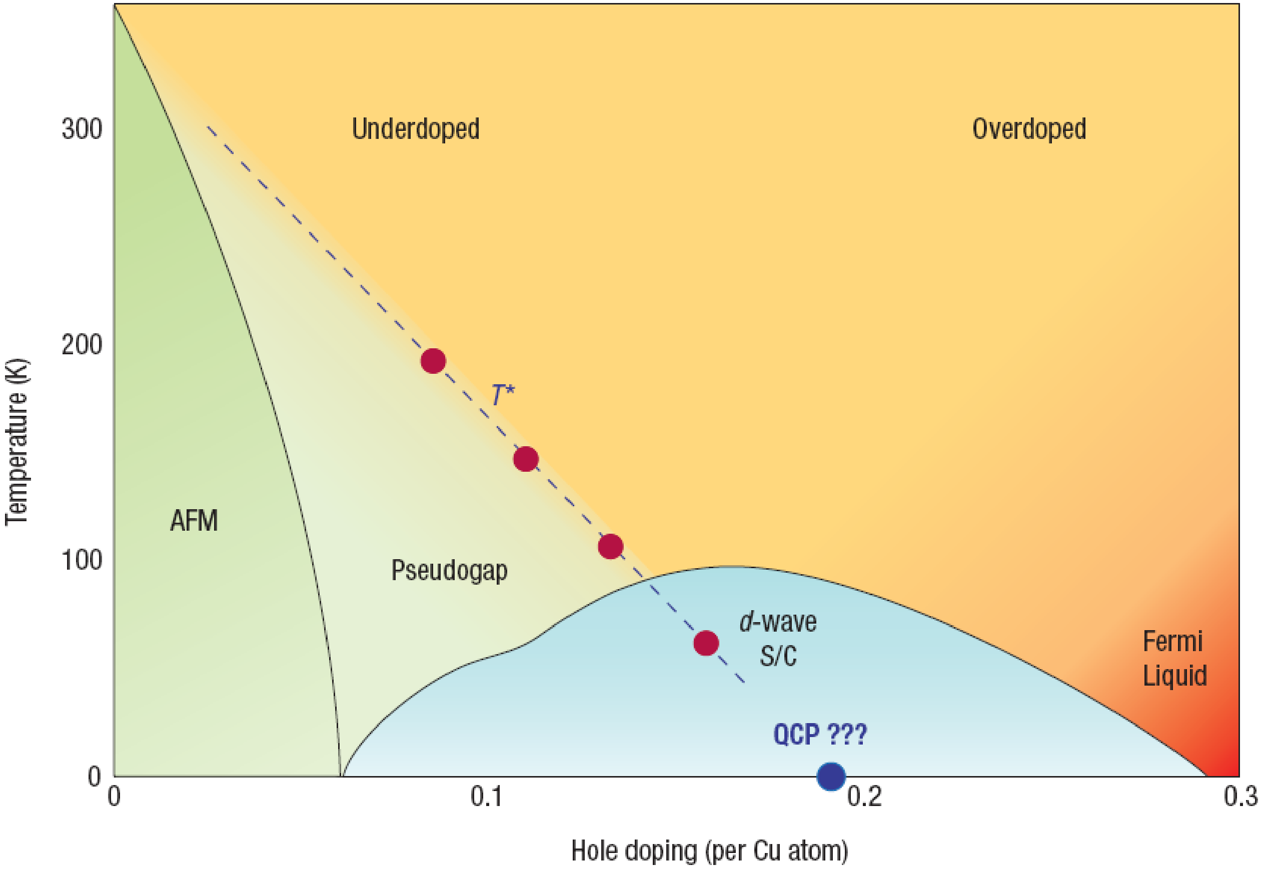


Heavy-fermion systems

QPT occurs at zero temperature, tuned by nonthermal parameters: chemical doping, magnetic field, pressure ...

Gegenwart, Si, & Steglich, Nature Phys. **4**, 186 (2008)

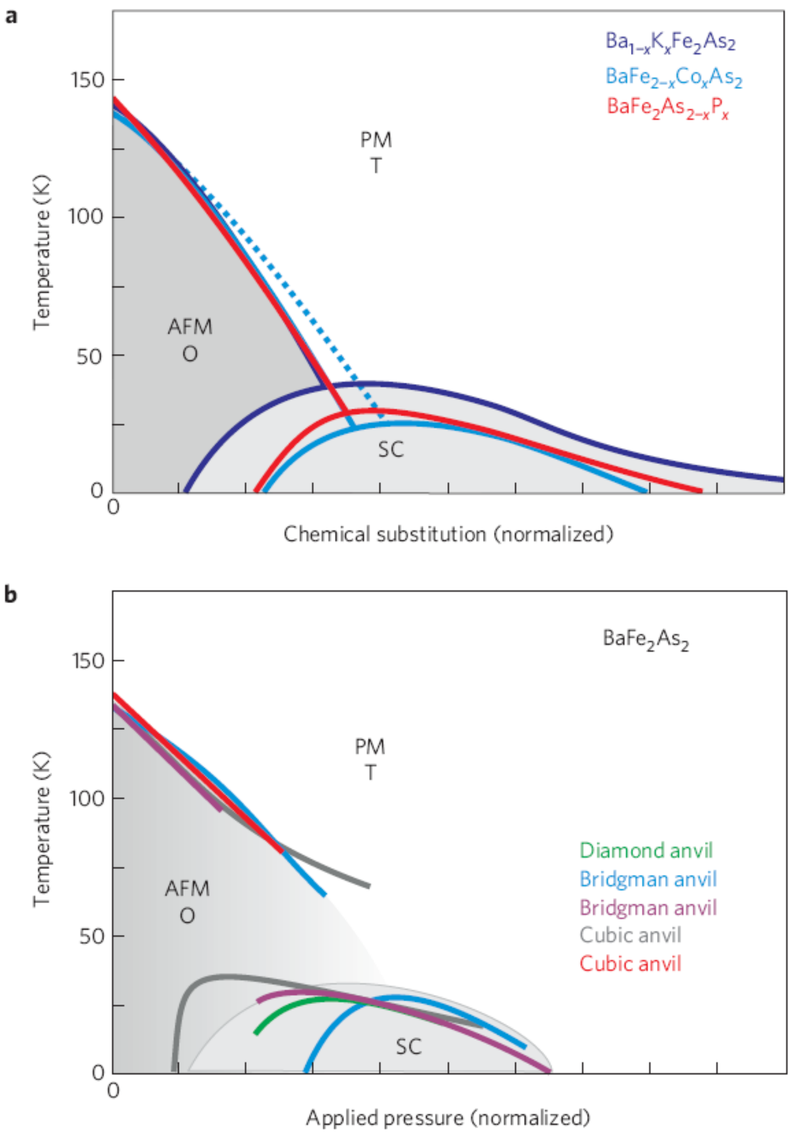
Quantum Phase Transition: big issue in condensed matter physics



Cuprates

D. M. Broun, Nature Phys. **4**, 170 (2008)

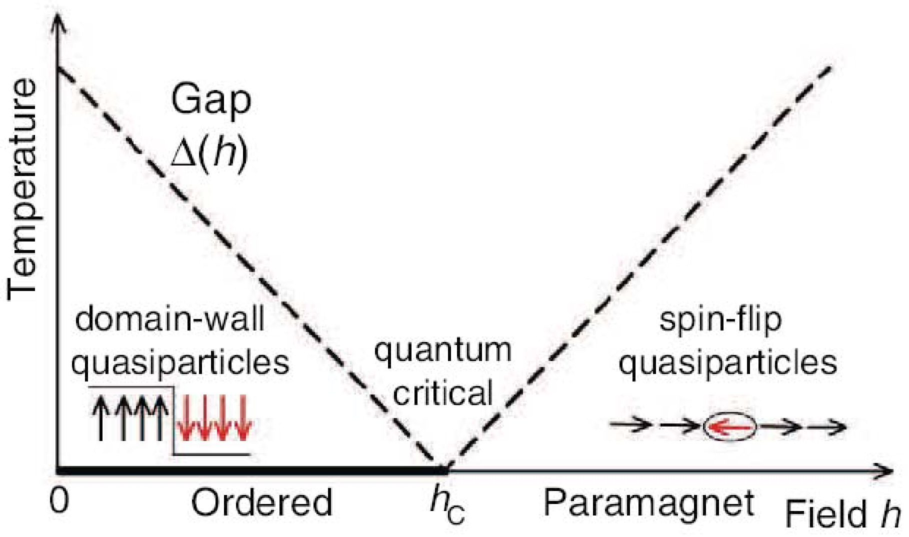
Quantum Phase Transition: big issue in condensed matter physics



Iron pnictides

Paglione & Greene, Nature Phys. **6**, 645 (2010)

TFIC: a relatively simple model undergoing QPT



Hamitonian:

$$H = -J\sum_i (\hat{\sigma}_i^z \hat{\sigma}_{i+1}^z - h\hat{\sigma}_i^x)$$

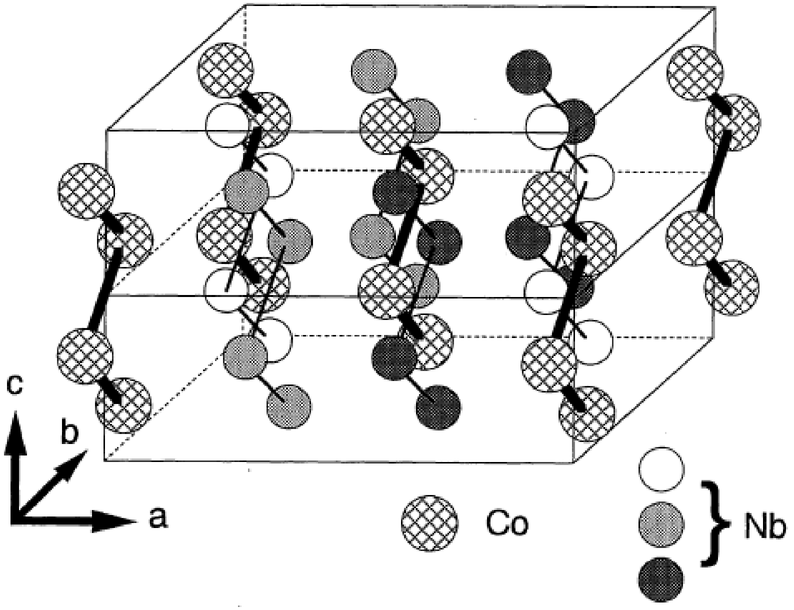
The Ising chain in a transverse field (TFIC):
one of the most-studied model in condensed matter physics.

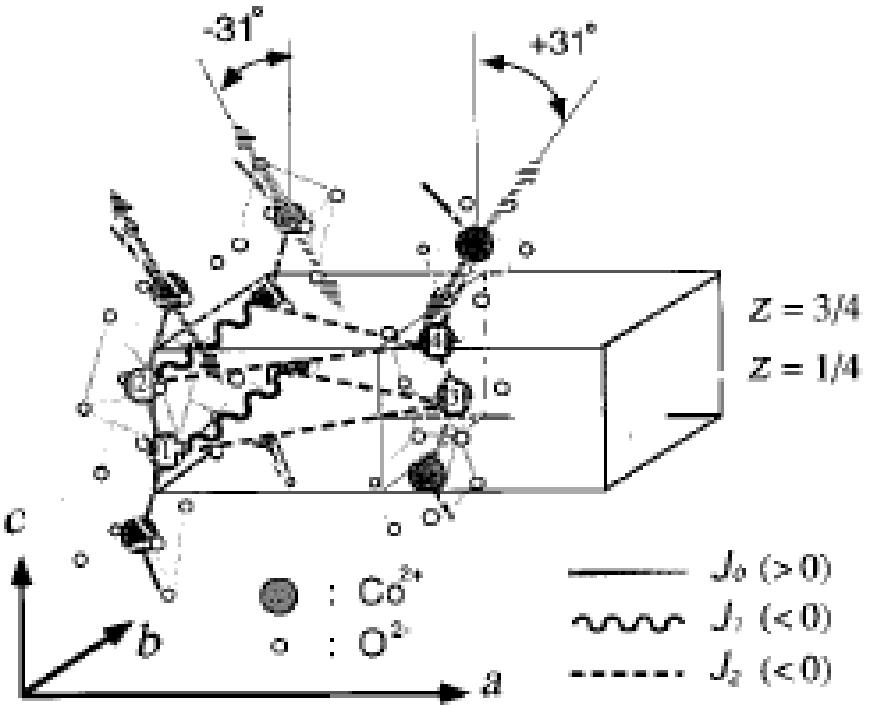
By using the Jordan-Wigner transfermation, the spins can be transformed to noninteracting spinless fermions, and this model can be exactly solved.

The minimum single-particle excitation energy, or the energy gap: $\Delta = 2J|1-h|$
Quantum critical point: $h = 1$, $\Delta = 0$

Subir Sachdev, *Quantum Phase Transitions*, (1999)

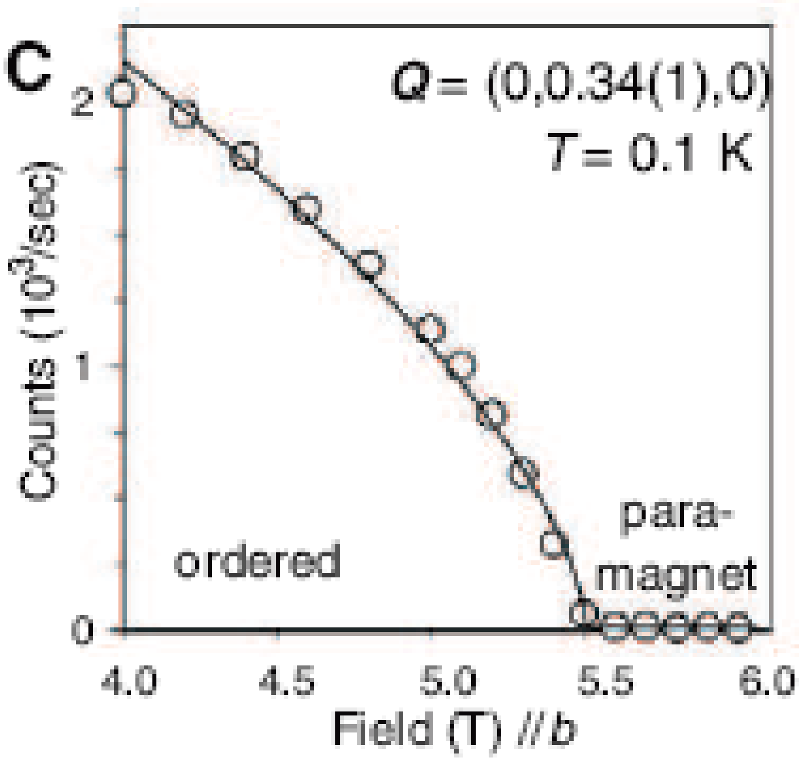
CoNb$_2$O$_6$: a rare experimental realization of the TFIC model





Strong easy-axis anisotropy due to CFEs: easy-axis in ac plane, ±31° to c-axis
Intrachain coupling J > 0: favors FM ordering along c-axis
Interchain coupling J1, J2 < 0, J1, J2 << J: favors AF ordering between chains

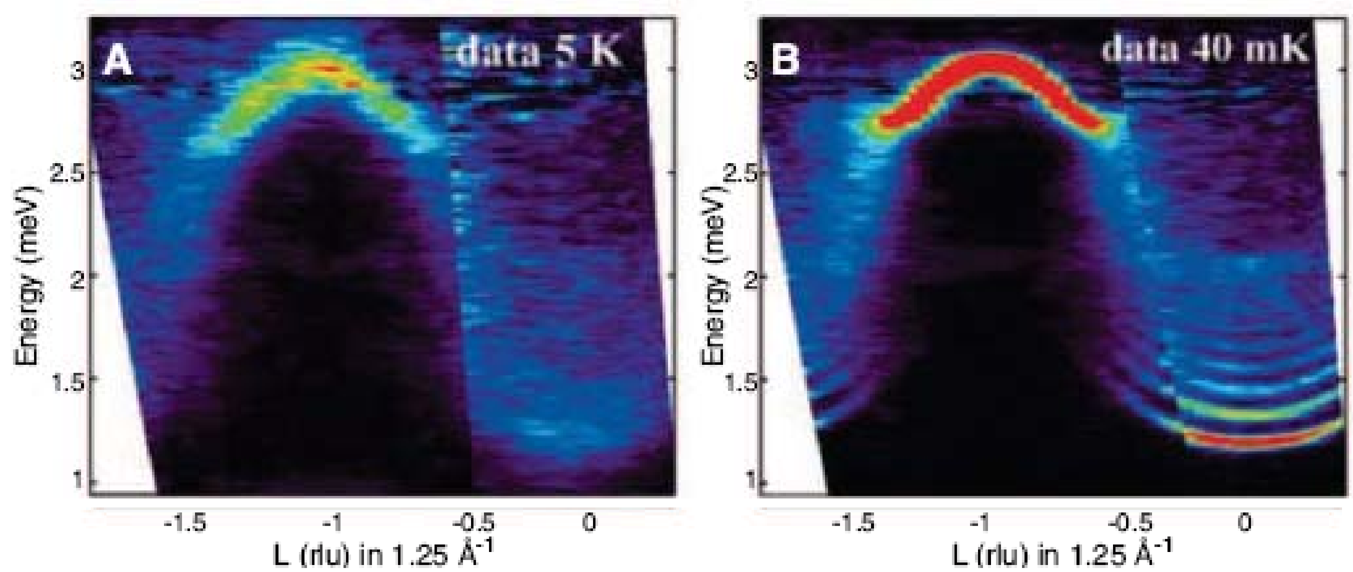
$CoNb_2O_6$: neutron scattering experiments in a transverse field

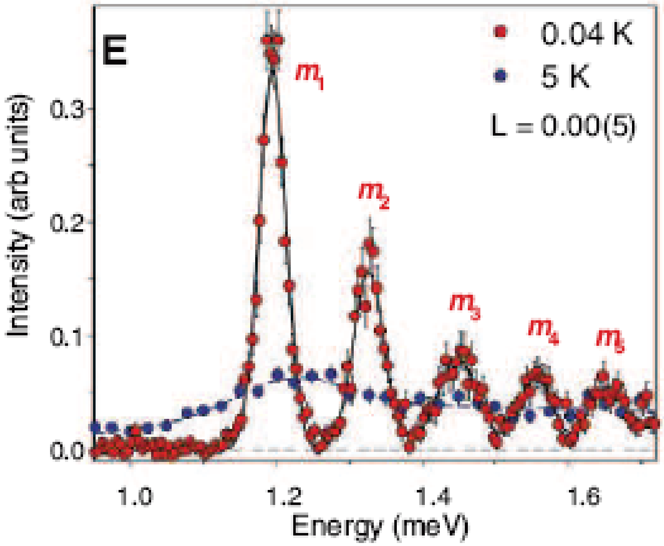


Elastic scattering in H || b: QPT at H = 5.5 T.

R. Coldea *et al.*, Science **327**, 177 (2010)

CoNb$_2$O$_6$: neutron experiments in zero field

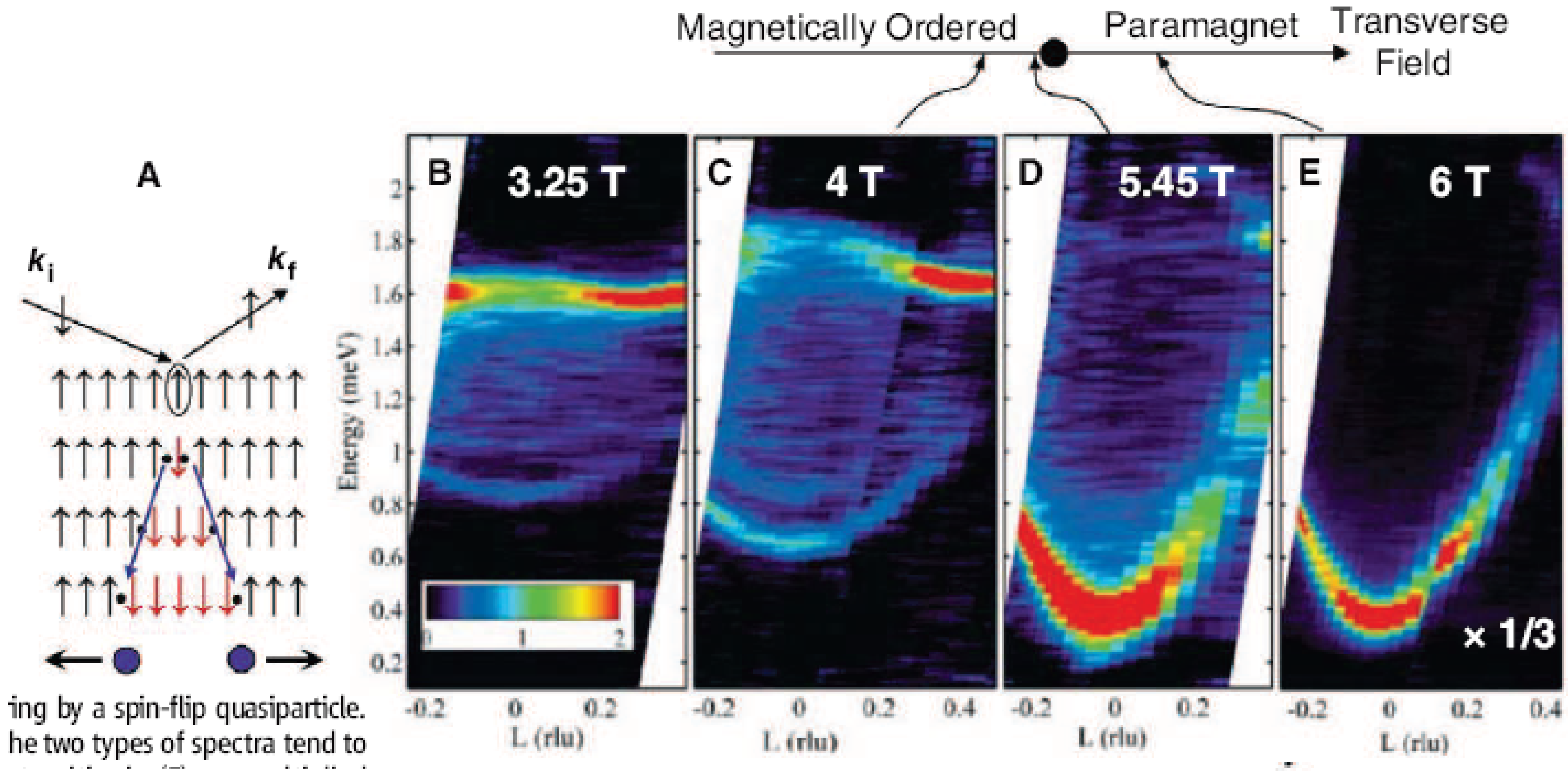




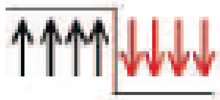
Inelastic scattering in H = 0 and at 40 mK:
a few bound states m$_1$, m$_2$, m$_3$, ...
(domain-wall quasiparticles)

R. Coldea *et al.*, Science **327**, 177 (2010)

$CoNb_2O_6$: neutron experiments in a transverse field



domain-wall quasiparticles



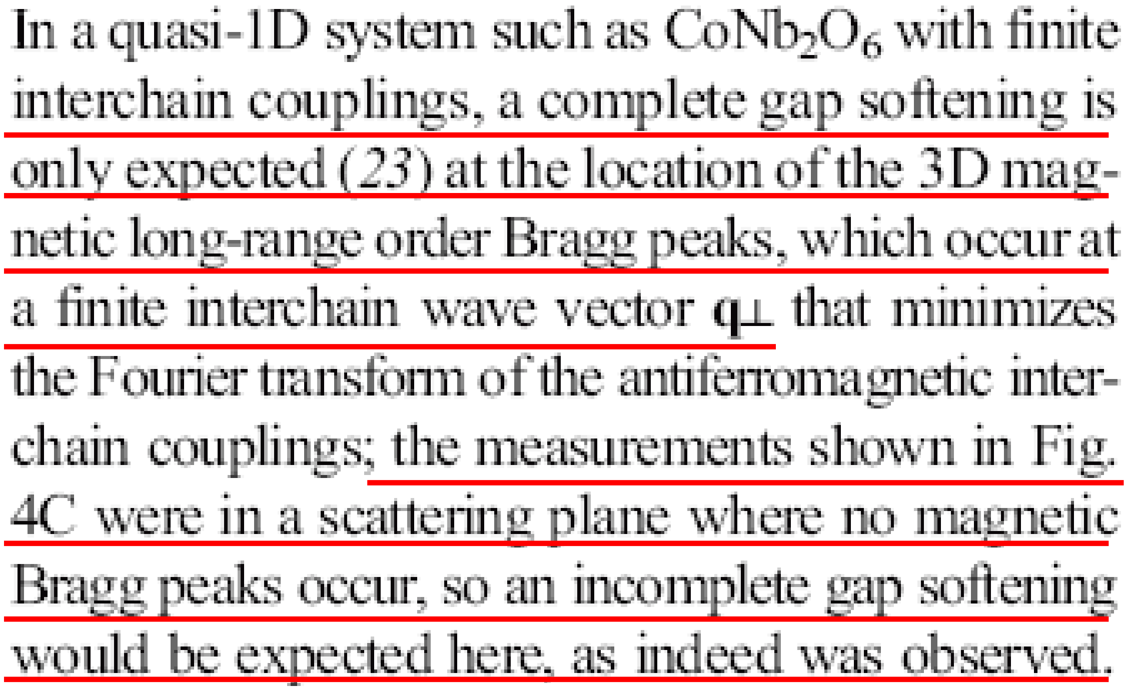
Inelastic scattering at 0.1 K:

domain-wall quasiparticles for H < 5.5 T

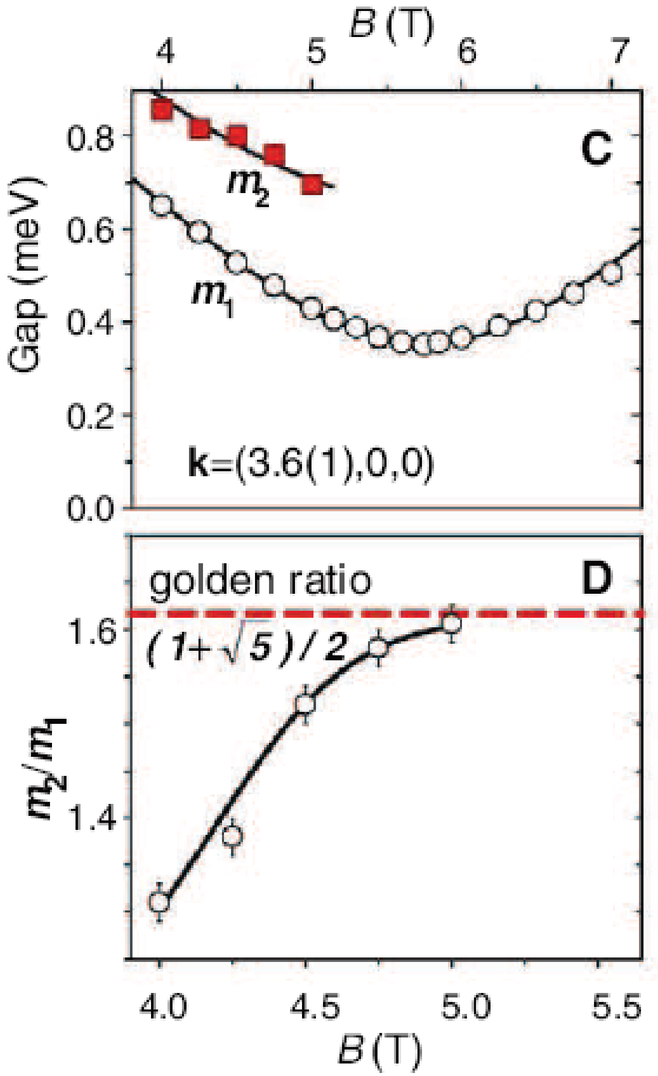
spin-flip quasiparticles for H > 5.5 T.

spin-flip quasiparticles

Our idea: Probe the low-lying magnetic excitation in CoNb$_2$O$_6$



In a quasi-1D system such as CoNb$_2$O$_6$ with finite interchain couplings, a complete gap softening is only expected (*23*) at the location of the 3D magnetic long-range order Bragg peaks, which occur at a finite interchain wave vector **q**⊥ that minimizes the Fourier transform of the antiferromagnetic interchain couplings; the measurements shown in Fig. 4C were in a scattering plane where no magnetic Bragg peaks occur, so an incomplete gap softening would be expected here, as indeed was observed.



QCP: Δ = 0

Technical difficulties for neutron scattering to probe the QCP with Δ = 0.

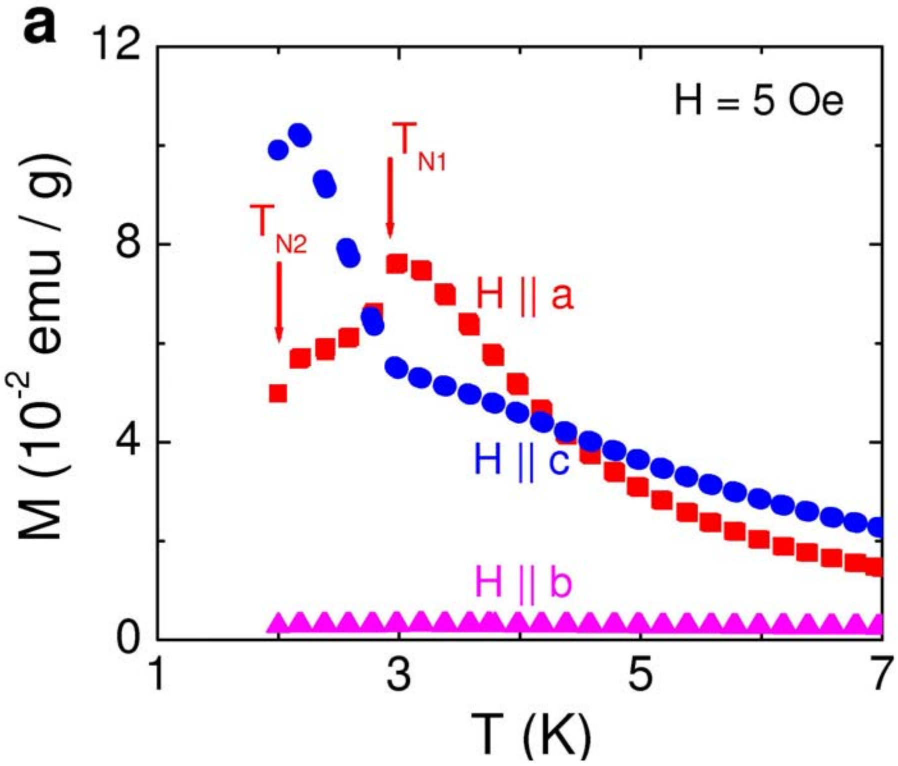
Heat transport should be able to detect the low-energy quasiparticals near the QCP.

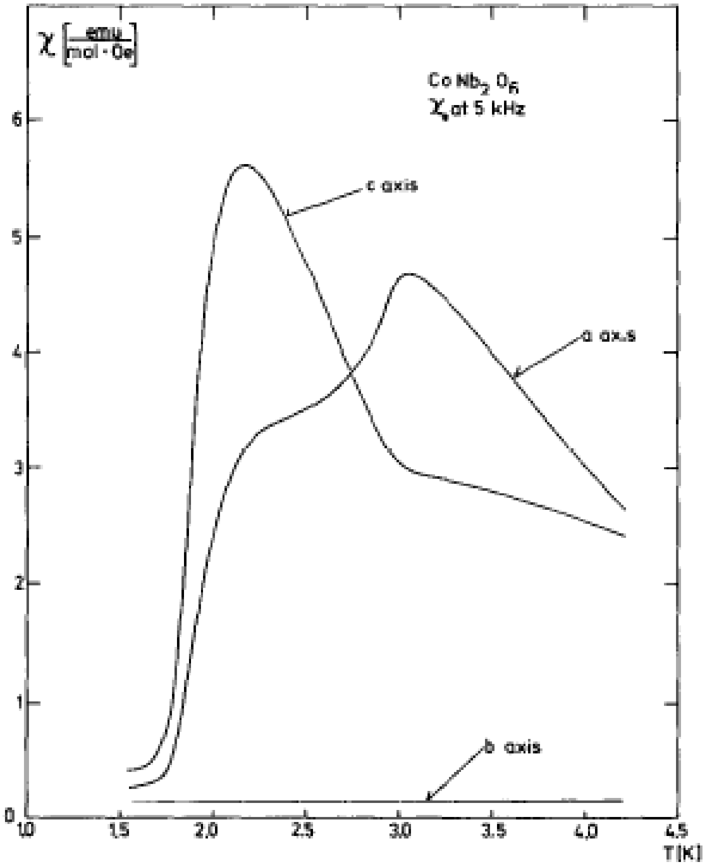
$CoNb_2O_6$: Single crystal growth

2008/11/10

Floating-zone
optical furnace

CoNb$_2$O$_6$: Magnetizations of our sample





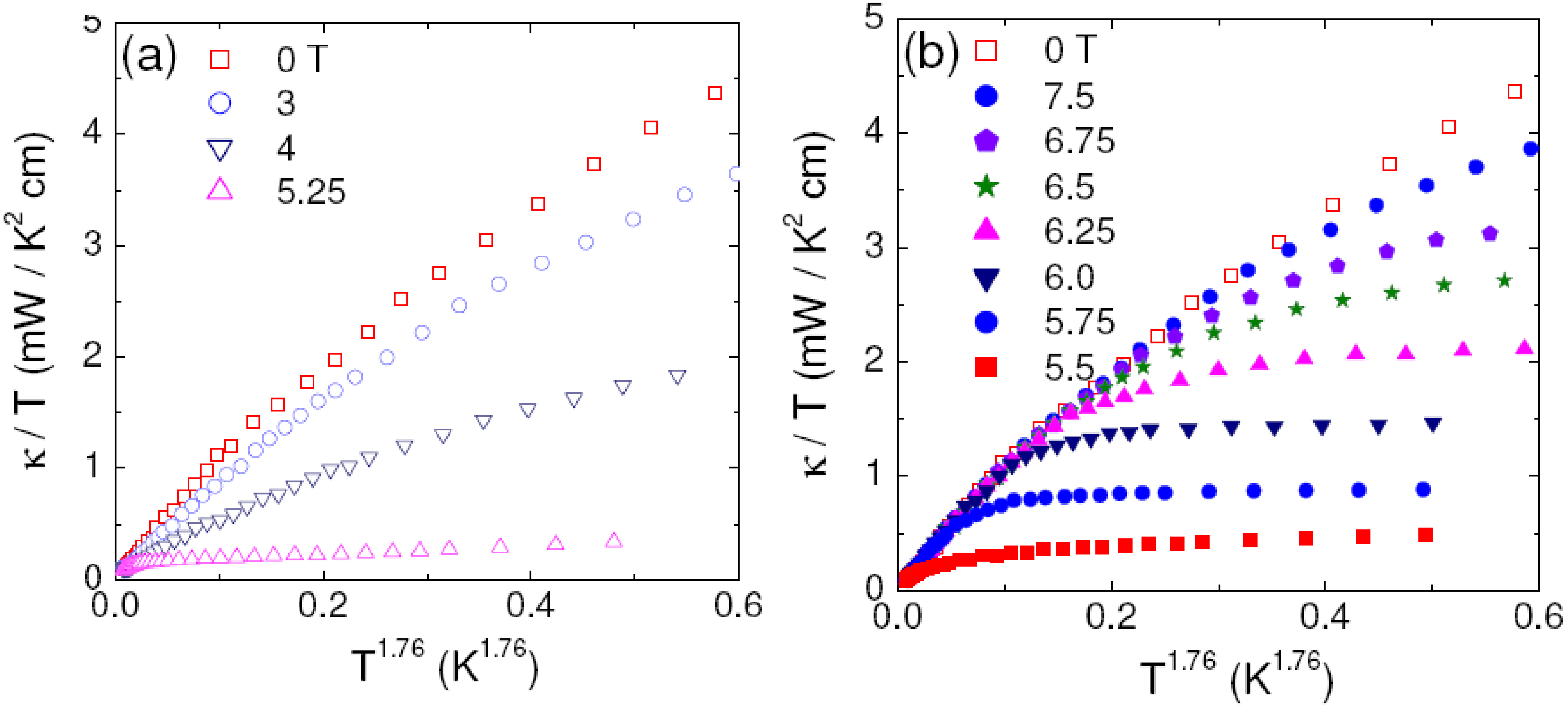
The interchain couplings: two 3D transitions

T_{N1} = 2.95 K: incommensurate SDW transition

T_{N2} = 1.97 K: commensurate AF transition

W. Scharf *et al.*, JMMM **13**, 121 (1979)

$CoNb_2O_6$: κ(H)/T in transverse fields H || b



1) No significant positive contribution to κ/T by magnetic excitations, likely due to low J. The suppression of κ/T is due to the scattering of phonons by these magnetic excitations.

2) At the left of QCP, there are some gapless excitations (AF magnons?).

3) At the QCP, some gapless excitations strongly scatter phonons.

4) At the right of QCP, the gap develops with increasing magnetic field.

Y. F. Dai, S. Y. Li *et al.*, unpublished

Summary

Low-T thermal conductivity and specific heat are nice tools to probe low-lying magnetic excitations in quantum magnets:

1、AFM magnons in 3D Nd_2CuO_4: $\kappa_m \sim T^3$

2、FM magnons in 3D YIG: $C_m \sim T^{1.5}$+correction; $\kappa_m \sim T^2$+corrections

3、Spinons is 2D spin liquid: $C_s \sim T$; $\kappa_s \sim T$

4、Spinons in 1D spin-1/2 Heisenberg chain Cu Benzoate: $C_s \sim T$ down to 50 mK, $\kappa_s \sim T$ down to 300 mK，observing Anderson localization of spinons at lower temperature.

5、Quasi-1D Ising chain $CoNb_2O_6$ in a transverse field: the magnetic excitations strongly scatter phonons, which unveils the QCP.