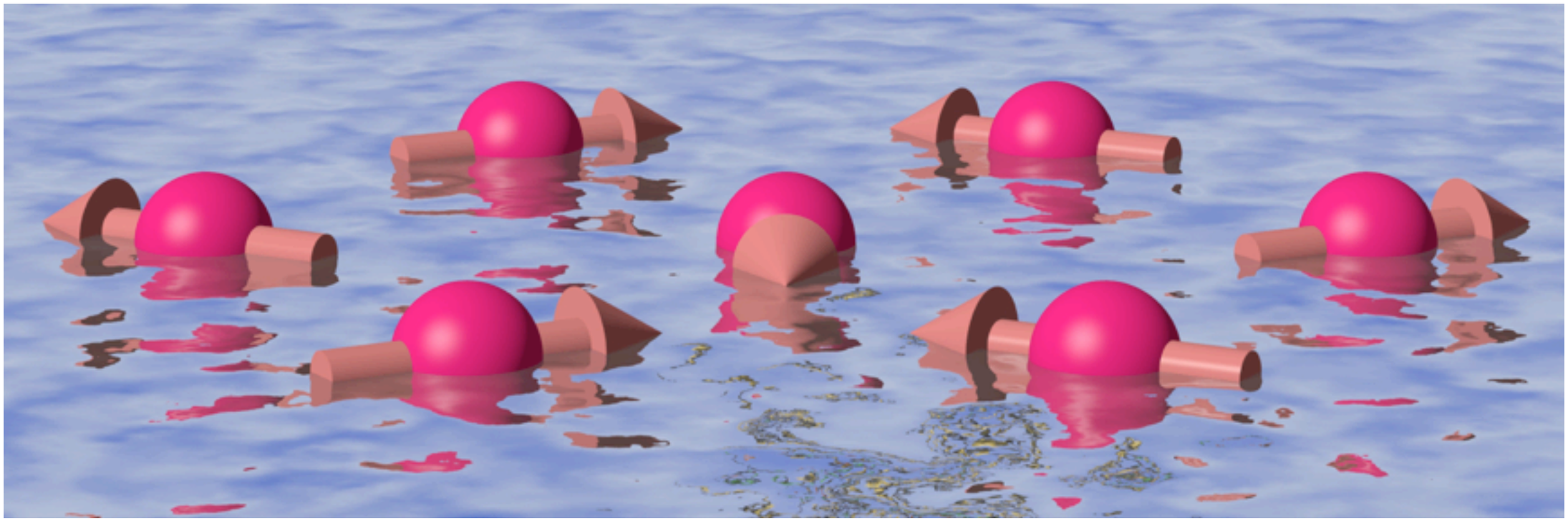
Breaking the spin waves: spinons in Cs_2CuCl_4 and *elsewhere*

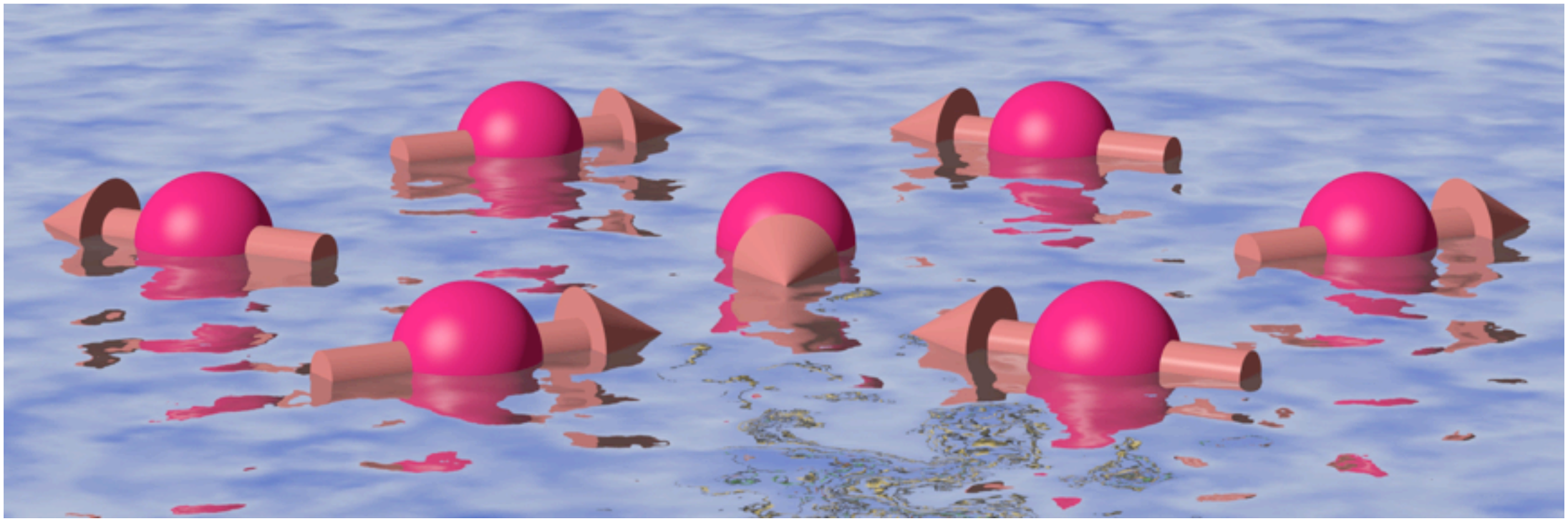


Oleg Starykh, University of Utah

Leon Balents, KITP
Hosho Katsura, Gakushuin U
Masanori Kohno, Tsukuba
Alexander Smirnov and
Kirill Povarov, Kapitza Institute

Iowa State U Colloquium, February 13, 2012

Breaking the spin waves: spinons in Cs_2CuCl_4 and *elsewhere*



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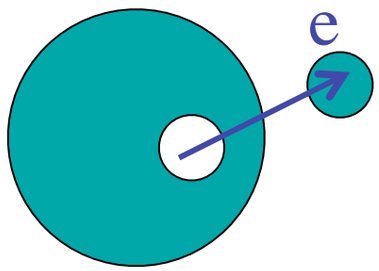
Outline

- Spin waves and *spinons*
- Experimental observations of spinons
  - ➡ neutron scattering, thermal conductivity, $2k_F$ oscillations
- Cs_2CuCl_4: spinon continuum, Dzyaloshinskii-Moriya and ESR
- ESR in the presence of uniform DM interaction
  - ESR in 2d electron gas with Rashba SOI
  - ESR in spin liquids with spinon Fermi surface
- Conclusions

Excitations: quasi-particles and their fractions

Conventional matter: quasi-particles = (renormalized) particles of underlying microscopic system

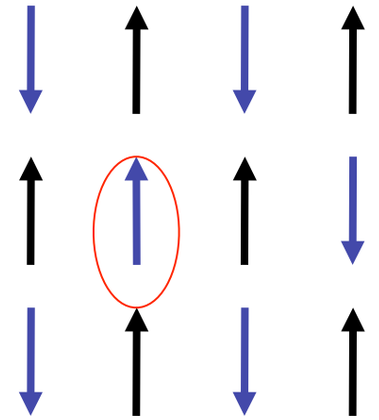
Fermi-liquid



Charge e, spin 1/2
but renormalized mass m^*

Neel state

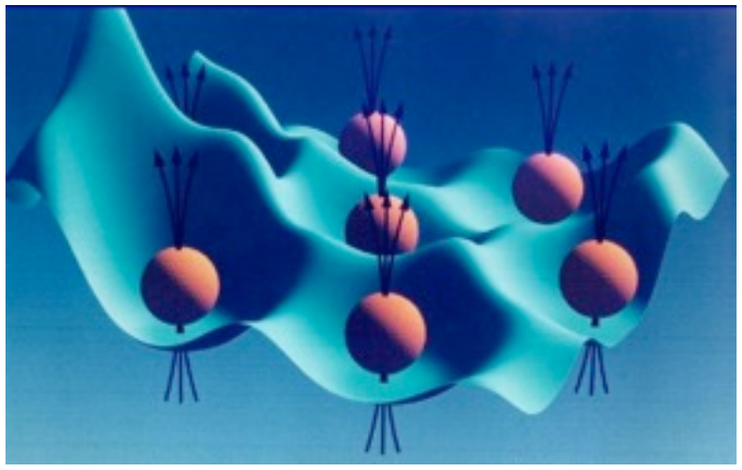
Spin-wave



Spin S=1
Adiabatically connected to spin-flip excitation of a single-spin in magnetic field

Strongly correlated matter: excitations carry a fraction of particle's quantum number

Quantum Hall effect

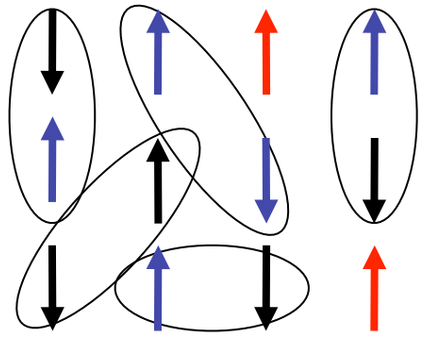


Tom Duff, Lucent

Charge e/3

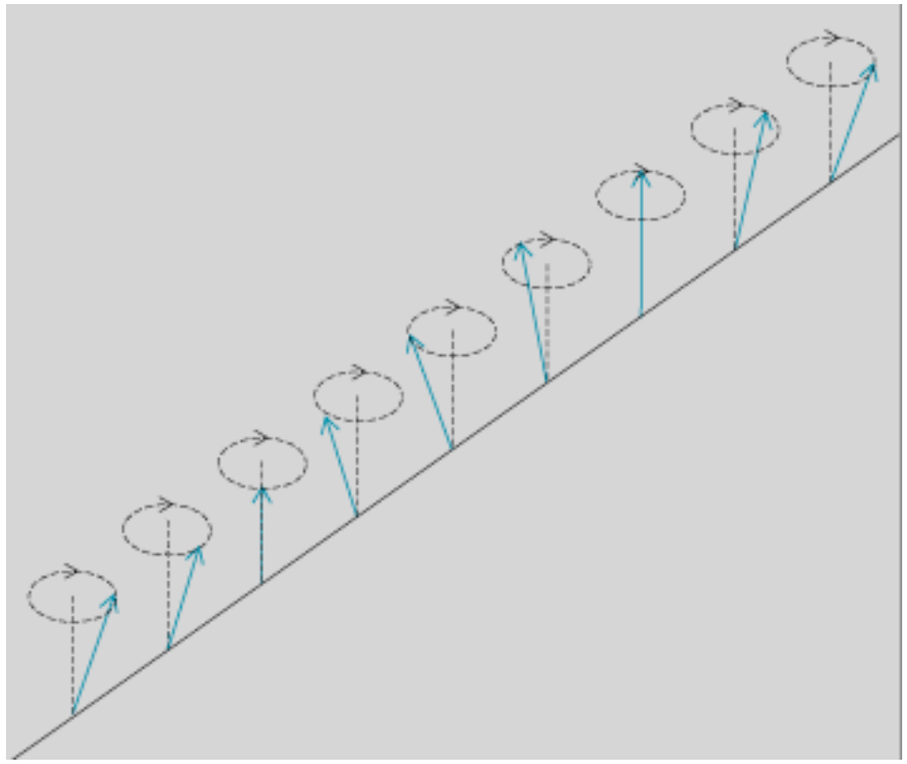
Spin liquid

Excitation -
broken valence bond:
two S=1/2 spinons



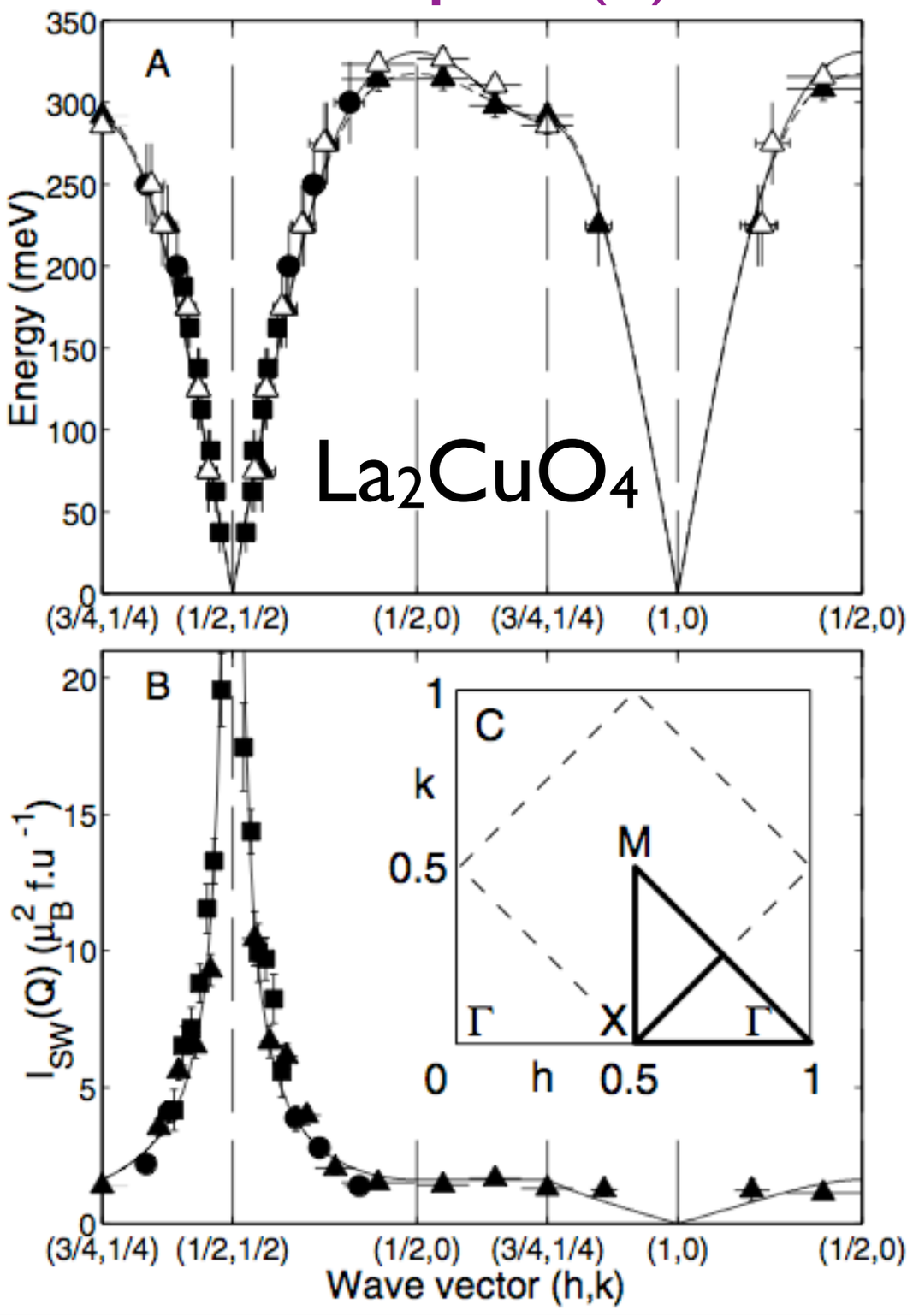
?

Spin wave or magnon = propagating disturbance in magnetically ordered state (ferromagnet, **antiferromagnet**, ferrimagnet...)



$\Sigma_r S^+_r e^{i\, k.r} |0\rangle$

sharp $\omega(k)$



Carries $S^z = 1$.
Observed via inelastic neutron scattering as a sharp single-particle excitation.

magnon is a boson

(neglecting finite dimension of the Hilbert space for finite S)

Coldea et al PRL 2001

But the *history* is more complicated

Regarding statistics of spin excitations:

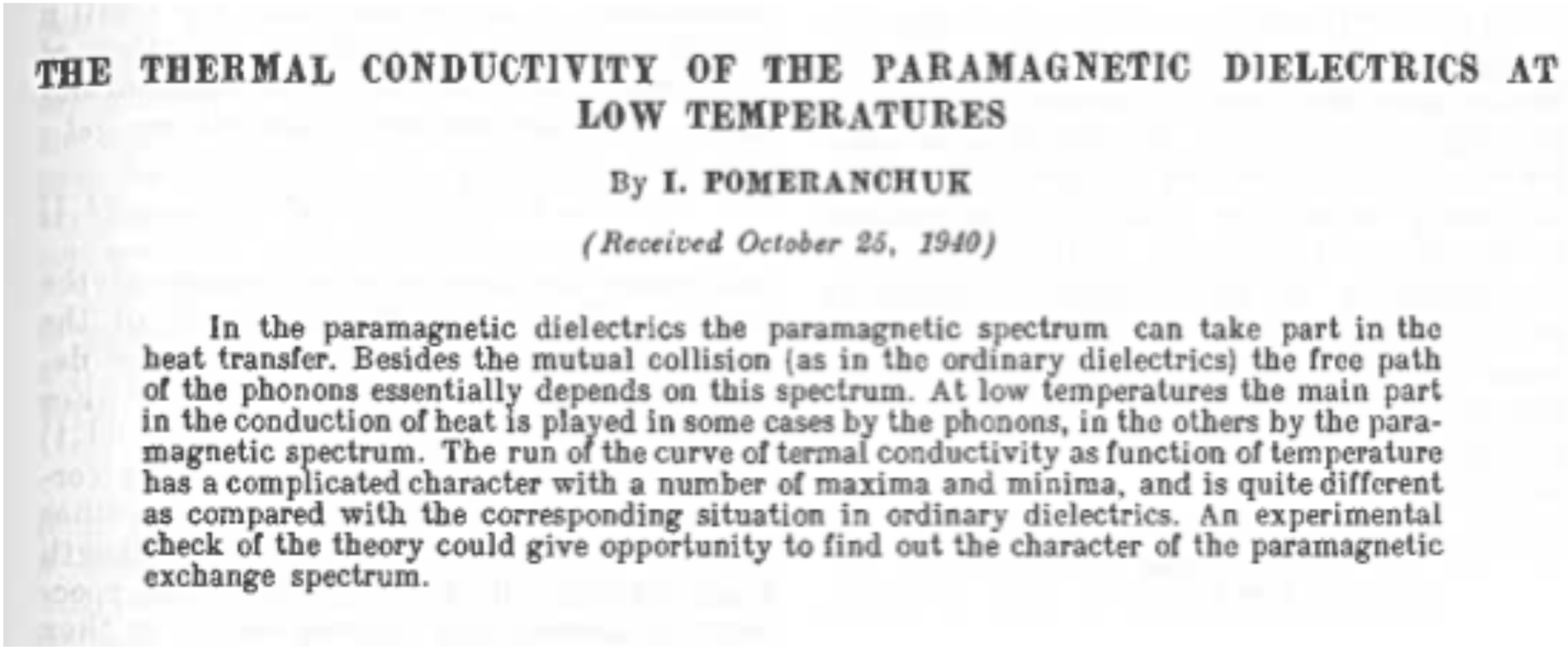
"The experimental facts available suggest that the magnons are submitted to the Fermi statistics; namely, when $T << T_{CW}$ the susceptibility tends to a constant limit, which is of the order of const/T_{CW} ([5]) [for $T > T_{CW}$, χ=const/$(T + T_{CW})$]. Evidently we have here to deal with the Pauli paramagnetism which can be directly obtained from the Fermi distribution. Therefore, we shall assume the Fermi statistics for the magnons."

But the *history* is more complicated

Regarding statistics of spin excitations:

"The experimental facts available suggest that the magnons are submitted to the Fermi statistics; namely, when $T << T_{CW}$ the susceptibility tends to a constant limit, which is of the order of const/T_{CW} ([5]) [for $T > T_{CW}$, χ=const/$(T + T_{CW})$]. Evidently we have here to deal with the Pauli paramagnetism which can be directly obtained from the Fermi distribution. Therefore, we shall assume the Fermi statistics for the magnons."

(5) A. Perrier and Kamerlingh Onnes, Leiden Comm. No.139 (1914)



THE THERMAL CONDUCTIVITY OF THE PARAMAGNETIC DIELECTRICS AT LOW TEMPERATURES

By I. POMERANCHUK

(Received October 25, 1940)

In the paramagnetic dielectrics the paramagnetic spectrum can take part in the heat transfer. Besides the mutual collision (as in the ordinary dielectrics) the free path of the phonons essentially depends on this spectrum. At low temperatures the main part in the conduction of heat is played in some cases by the phonons, in the others by the paramagnetic spectrum. The run of the curve of termal conductivity as function of temperature has a complicated character with a number of maxima and minima, and is quite different as compared with the corresponding situation in ordinary dielectrics. An experimental check of the theory could give opportunity to find out the character of the paramagnetic exchange spectrum.

I. Pomeranchuk, JETP 1940

FROM THE

PHYSICAL LABORATORY

OF THE

UNIVERSITY OF LEIDEN

BY

H. KAMERLINGH ONNES,

Director of the Laboratory.

N°. 139c.

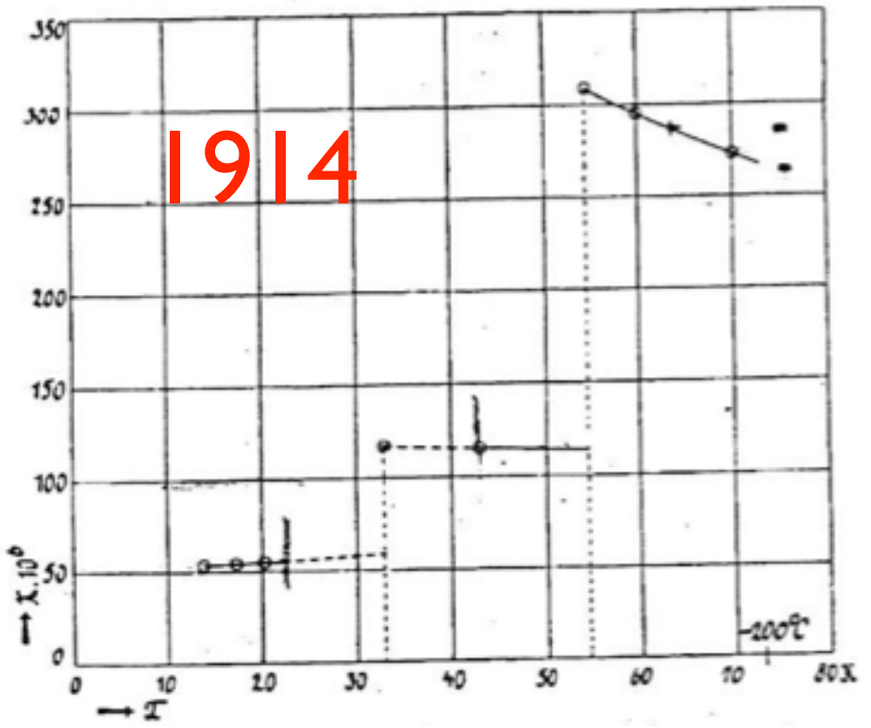
From the library of the Kapitza Institute
for Physical Problems, Moscow

ALBERT PERRIER and H. KAMERLINGH ONNES.

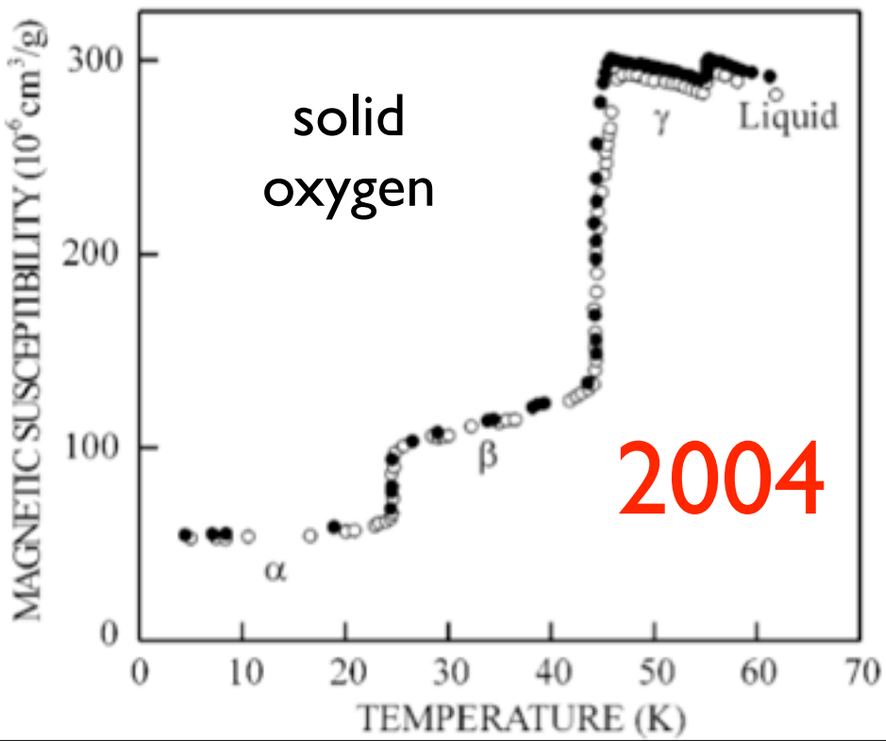
Magnetic researches. XII. The susceptibility of solid oxygen in two forms.

(*Translated from: Verslag van de Gewone Vergadering der Wis- en Natuurkundige Afdeeling der Kon. Akad. van Wetenschappen te Amsterdam*, 28 Februari 1914, p. 1004—1011.)

EDUARD IJDO — PRINTER — LEIDEN.



Yu.A. Freiman, H.J. Jodl / Physics Reports 401 (2004) 1–228



Solid oxygen phases:

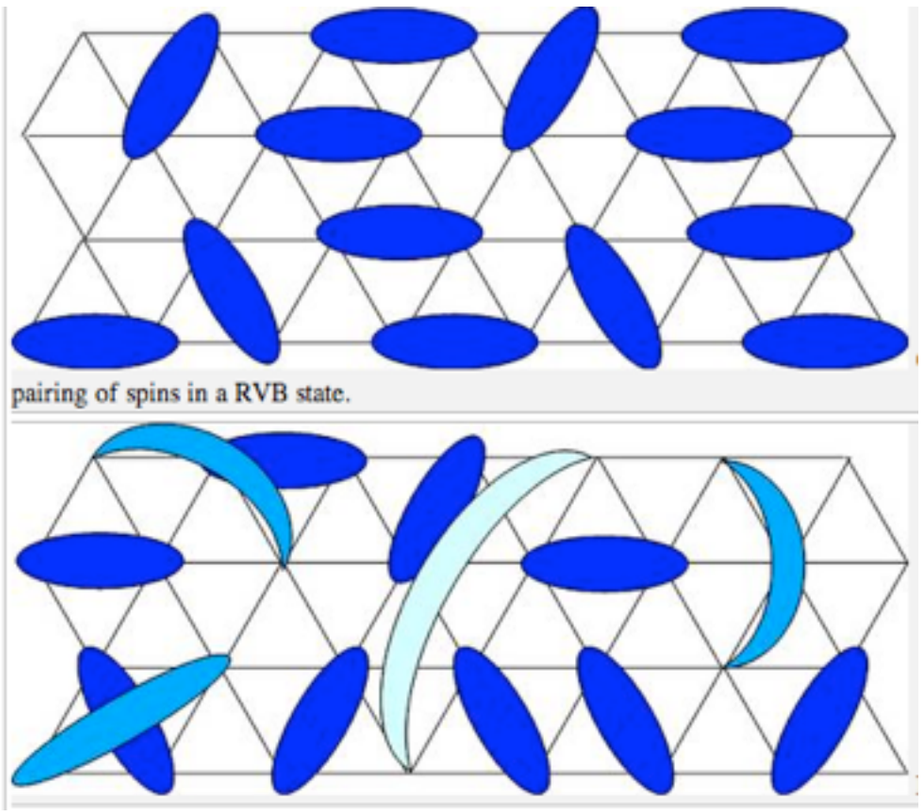
- S=1 triangular lattice antiferromagnet
- dimerized (formed by O_8 clusters)
- metal (@ 95 GPa)
- superconductor (>100 GPa, T_c = 0.6 K)

30+ years later

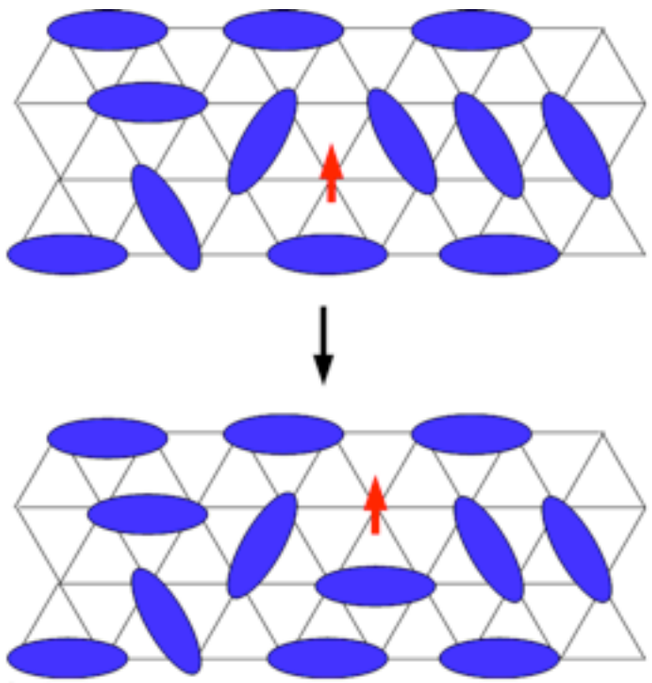
P. W. Anderson, *Resonating valence bonds: a new kind of insulator?* Mat. Res. Bul. (1973)

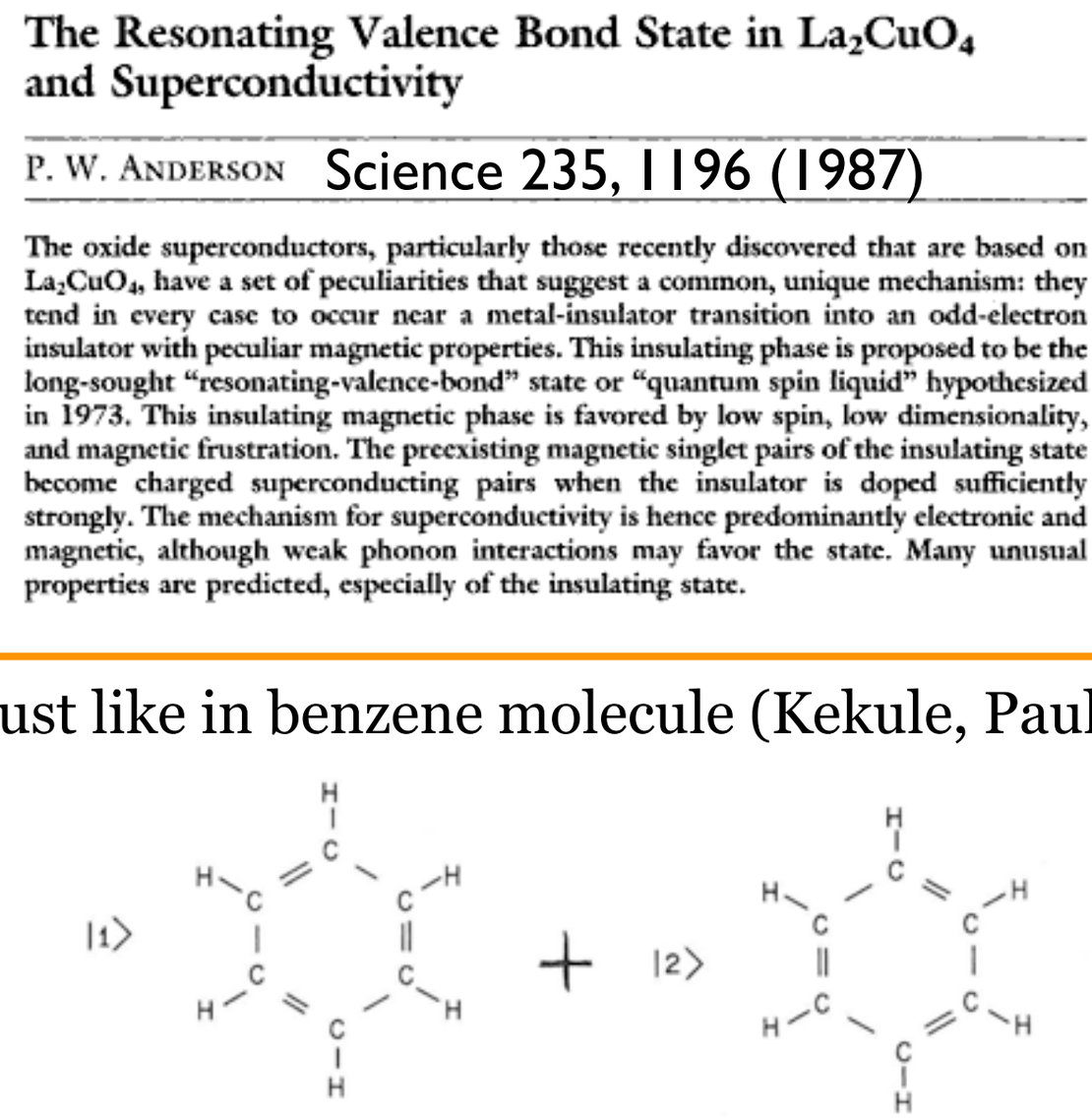
P. Fazekas and P. W. Anderson, Philos. Magazine (1974)

Science 235, 1196 (1987)



pairing of spins in a RVB state.





The Resonating Valence Bond State in La_2CuO_4 and Superconductivity

P. W. ANDERSON Science 235, 1196 (1987)

The oxide superconductors, particularly those recently discovered that are based on La_2CuO_4, have a set of peculiarities that suggest a common, unique mechanism: they tend in every case to occur near a metal-insulator transition into an odd-electron insulator with peculiar magnetic properties. This insulating phase is proposed to be the long-sought "resonating-valence-bond" state or "quantum spin liquid" hypothesized in 1973. This insulating magnetic phase is favored by low spin, low dimensionality, and magnetic frustration. The preexisting magnetic singlet pairs of the insulating state become charged superconducting pairs when the insulator is doped sufficiently strongly. The mechanism for superconductivity is hence predominantly electronic and magnetic, although weak phonon interactions may favor the state. Many unusual properties are predicted, especially of the insulating state.

Just like in benzene molecule (Kekule, Pauling)

excitations are obtained by breaking the singlet bond -- they are *spin-1/2 spinons*!

Spinons are natural in d=1

Bethe's solution: 1933
identification of spinons: 1981

doi:10.1016/0375-9601(81)90335-2 | How to Cite or Link Using DOI
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What is the spin of a spin wave?

L. D. Faddeev and L. A. Takhtajan

Leningrad Branch of the Steklov Mathematical Institute, Leningrad, USSR

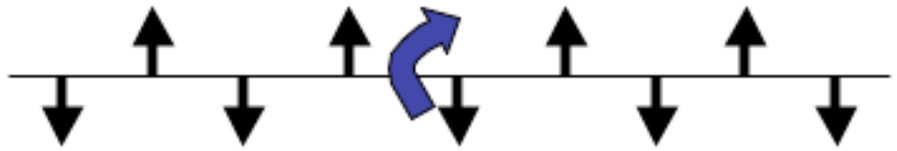
Received 15 July 1981. Available online 16 September 2002.

Abstract

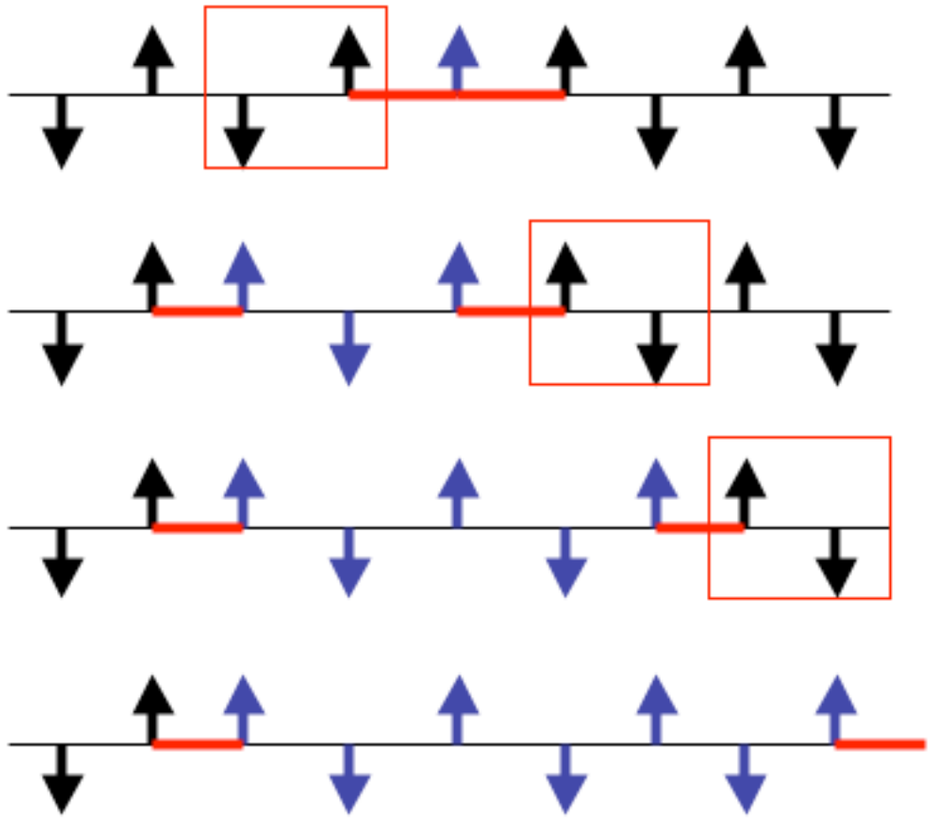
We argue that the spin of a spin wave in the Heisenberg antiferromagnetic chain of spins $\frac{1}{2}$ is equal to $\frac{1}{2}$ rather than 1 as is generally considered to be true.

Article Outline

• References

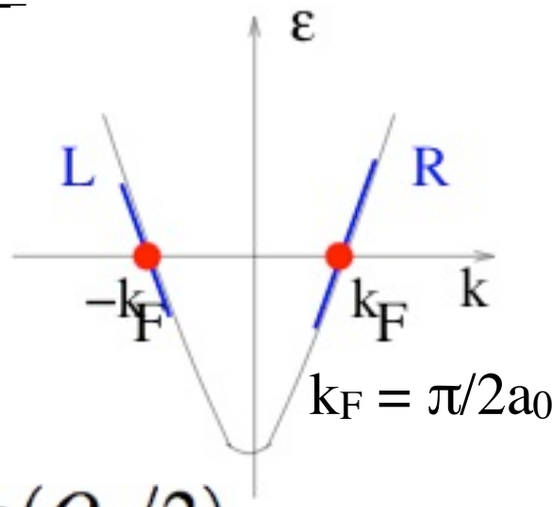


S=1 spin wave breaks into two domain walls / spinons: hence each is carrying S=1/2



Two-spinon continuum of spin-1/2 chain

Spinon energy $\omega(k_x) = \frac{\pi J}{2}|\sin(k_x)|$ de Cloizeaux-Peason dispersion, 1962



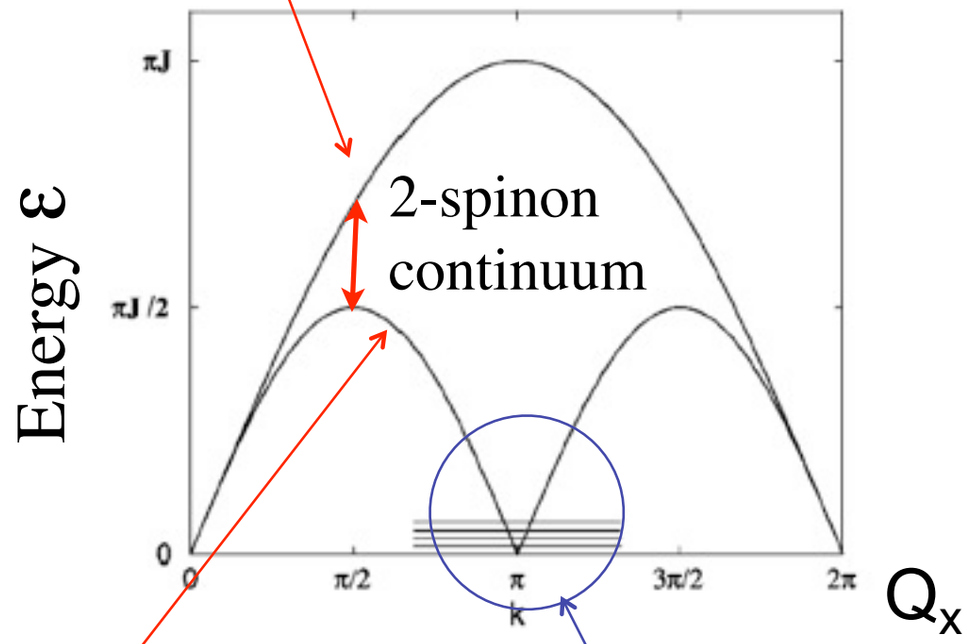
S=1 excitation $\begin{cases} \varepsilon = \omega(k_{x1}) + \omega(k_{x2}) \\ Q_x = k_{x1} + k_{x2} \end{cases}$

$$\varepsilon = \pi J \sin(\frac{Q_x}{2}) \cos(\frac{k_{x1} - k_{x2}}{2})$$

Variables:
k_{x1} and k_{x2}
or
ε and Q_x

$\omega_{2,\text{upper}} = \pi J \sin(Q_x/2)$
$k_{x1} = k_{x2} = Q_x/2$

Upper boundary

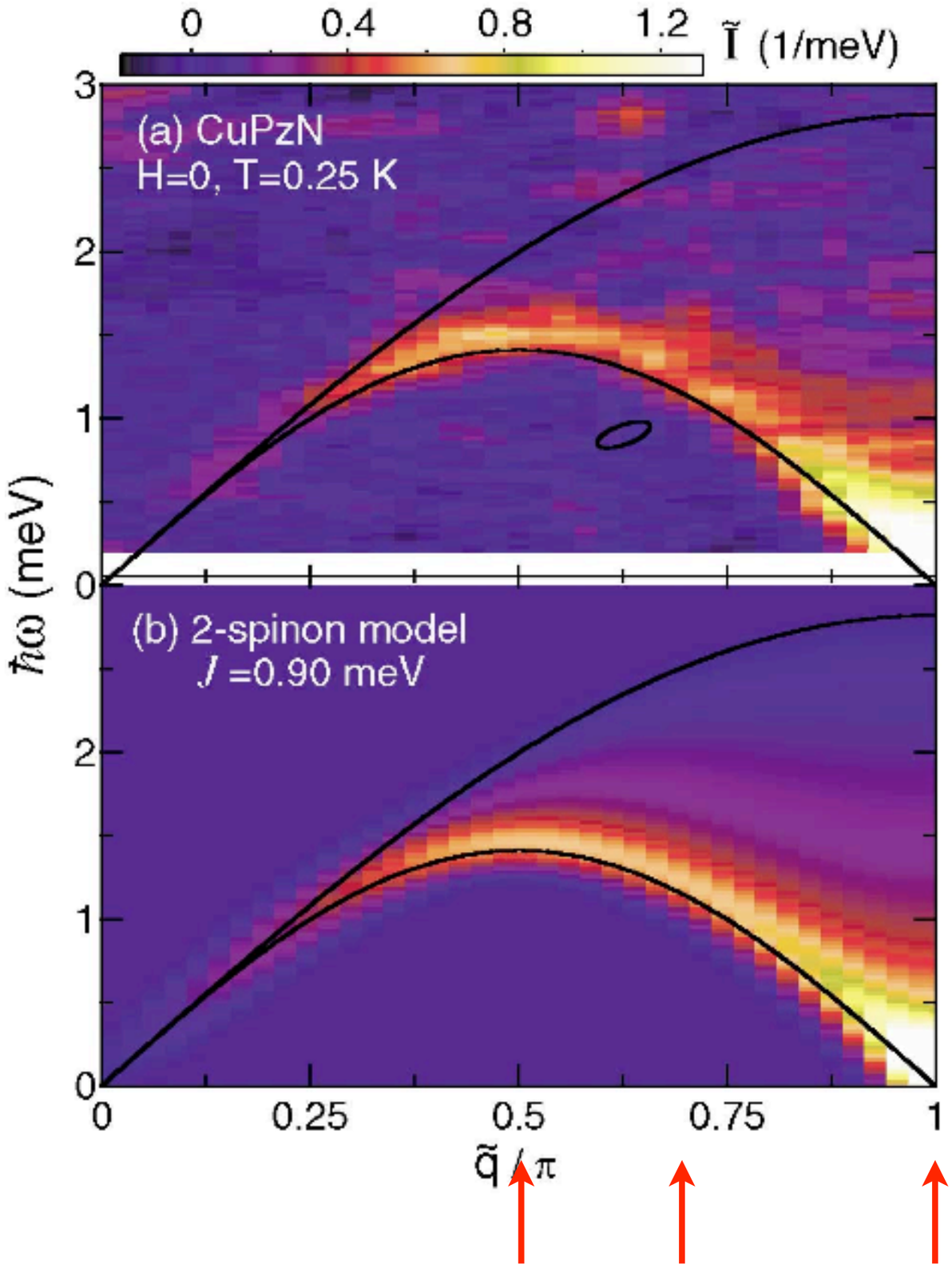


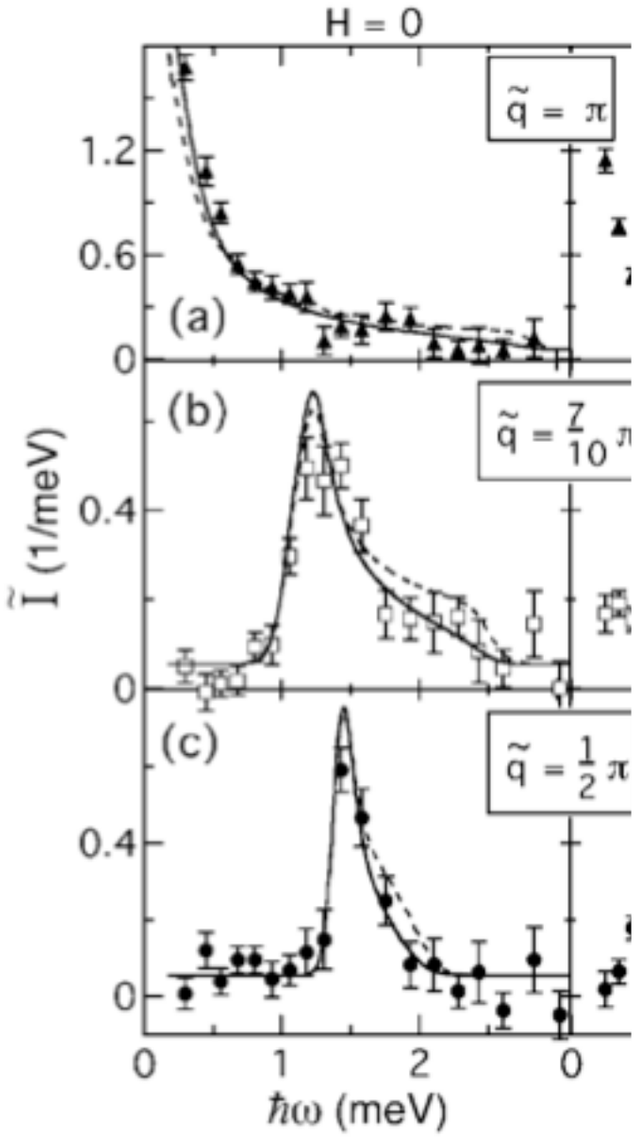
Lower boundary

Low-energy sector $Q_{AFM}=\pi$

$$\omega_{2,\text{lower}} = \frac{\pi J}{2}\sin(Q_x)$$
$$k_{x1} = 0, k_{x2} = Q_x$$

Highly 1d antiferromagnet CuPzN



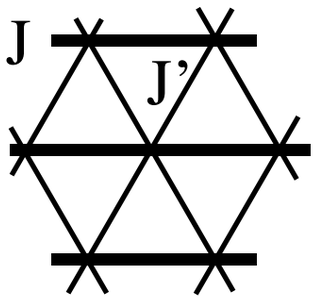


Stone et al, PRL 2003

$J'/J < 10^{-4}$

Experimental Realization of a 2D Fractional Quantum Spin Liquid

R. Coldea,[1,2] D. A. Tennant,[2,3] A. M. Tsvelik,[4] and Z. Tylczynski[5]

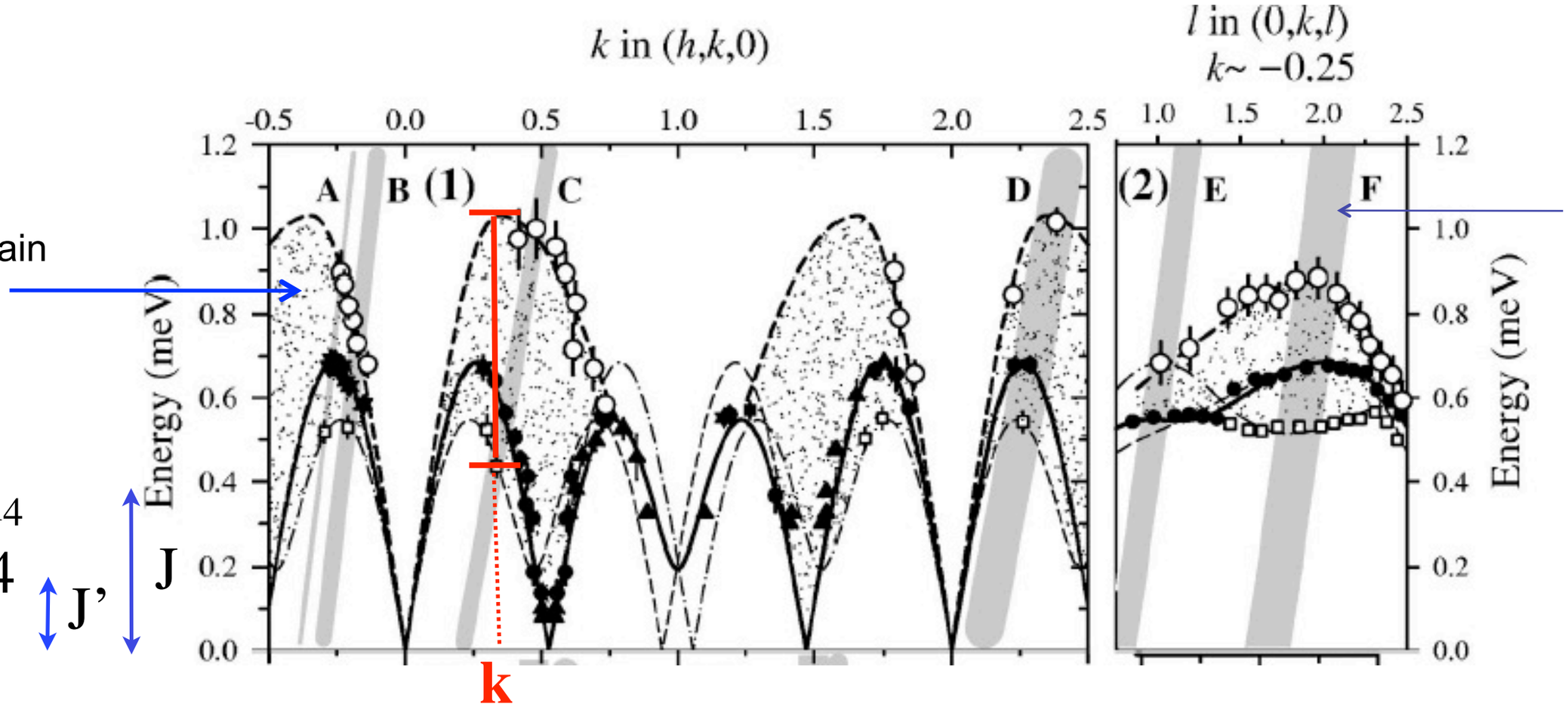


PHYSICAL REVIEW B 68, 134424 (2003)

Extended scattering continua characteristic of spin fractionalization in the two-dimensional frustrated quantum magnet Cs_2CuCl_4 observed by neutron scattering

R. Coldea,[1,2,3] D. A. Tennant,[1,3] and Z. Tylczynski[4]

Along the chain



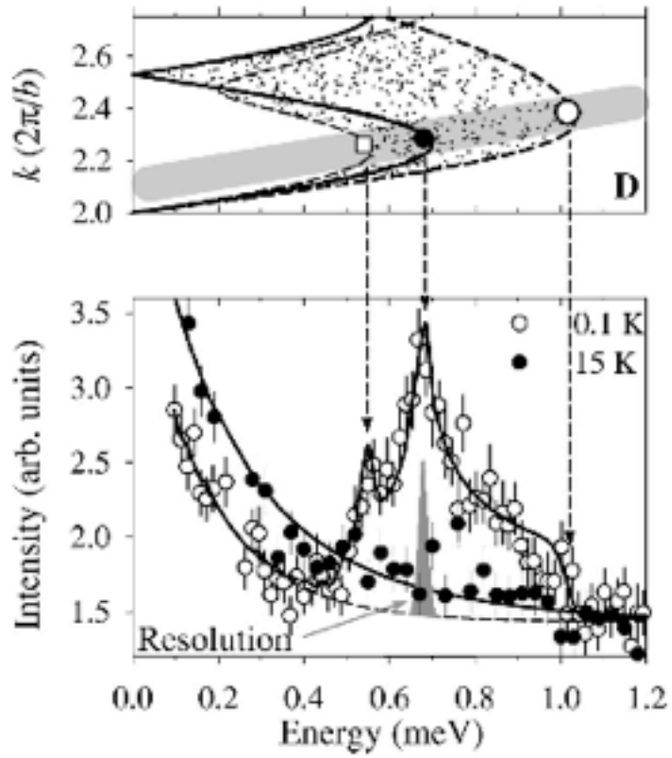
Cs_2CuCl_4
J'/J=0.34

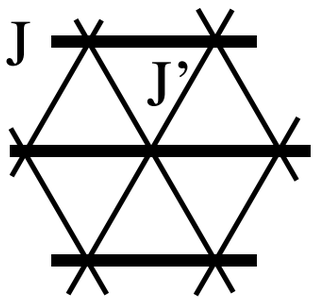
J' J

Very unusual response: broad and strong continuum; spectral intensity varies strongly with 2d momentum (k_x, k_y)

Experimental Realization of a 2D Fractional Quantum S

R. Coldea,[1,2] D. A. Tennant,[2,3] A. M. Tsvelik,[4] and Z. Tylczy



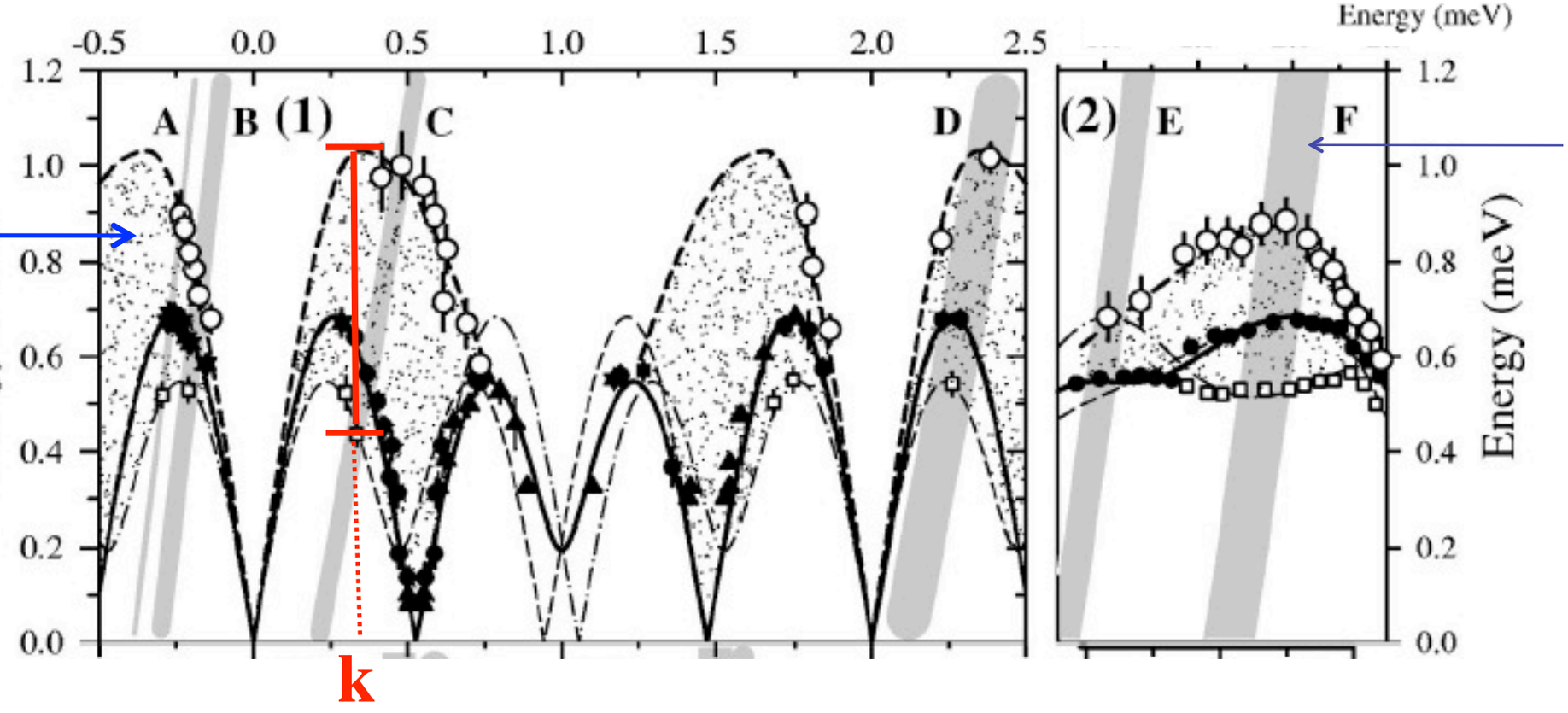


PHYSICAL REVIEW B 68, 134424 (2003)

Extended scattering continua characteristic of spin fractionalizatio frustrated quantum magnet Cs_2CuCl_4 observed by neut

R. Coldea,[1,2,3] D. A. Tennant,[1,3] and Z. Tylczynski[4]

k in $(h,k,0)$



Along the chain

transverse to chain

Cs_2CuCl_4

$J'/J=0.34$

J'

J

Very unusual response: broad and strong continuum; spectral intensity varies strongly with 2d momentum (k_x, k_y)

Effective Schrödinger equation in two-spinon basis (Kohno, OS, Balents: Nat. Phys. 2007)

- Study two spinon subspace

$$|k_x, k_y; \epsilon\rangle = \sum_y e^{ik_y y} |k_x, \epsilon\rangle_y \otimes_{y' \neq y} |0\rangle_{y'}$$

(two spinons on chain **y** with S^z_{tot} =+1)

  - Momentum conservation: 1d Schrödinger equation in ε space (**k** = (k_x, k_y))

$$\epsilon\psi_{\mathbf{k}}(\epsilon) + \int d\tilde{\epsilon} D_{k_x}(\tilde{\epsilon})\, J'(\mathbf{k}) A^*_{k_x}(\epsilon) A_{k_x}(\tilde{\epsilon})\, \psi_{\mathbf{k}}(\tilde{\epsilon}) = E\psi_{\mathbf{k}}(\epsilon)$$

- Crucial matrix elements known exactly

$$A_{k_x}(\epsilon) \equiv \frac{1}{\sqrt{2}} \langle 0 | S^-_{-k_x, y} | k_x, \epsilon \rangle_y$$

Bougourzi *et al*, 1996

Structure Factor

- Spectral Representation

J.S. Caux *et al*, 2006

$$S(k,\omega) \propto \sum_n \left|\langle n|S_k^+|0\rangle\right|^2 \delta(\omega - E_n)$$

Weight in 1d:
73% in 2 spinon states
99% in 2+4 spinons

– We derive closed-form expression for d=2 S(k,ω) in 2-spinon approximation [RPA-like form is a consequence of this]

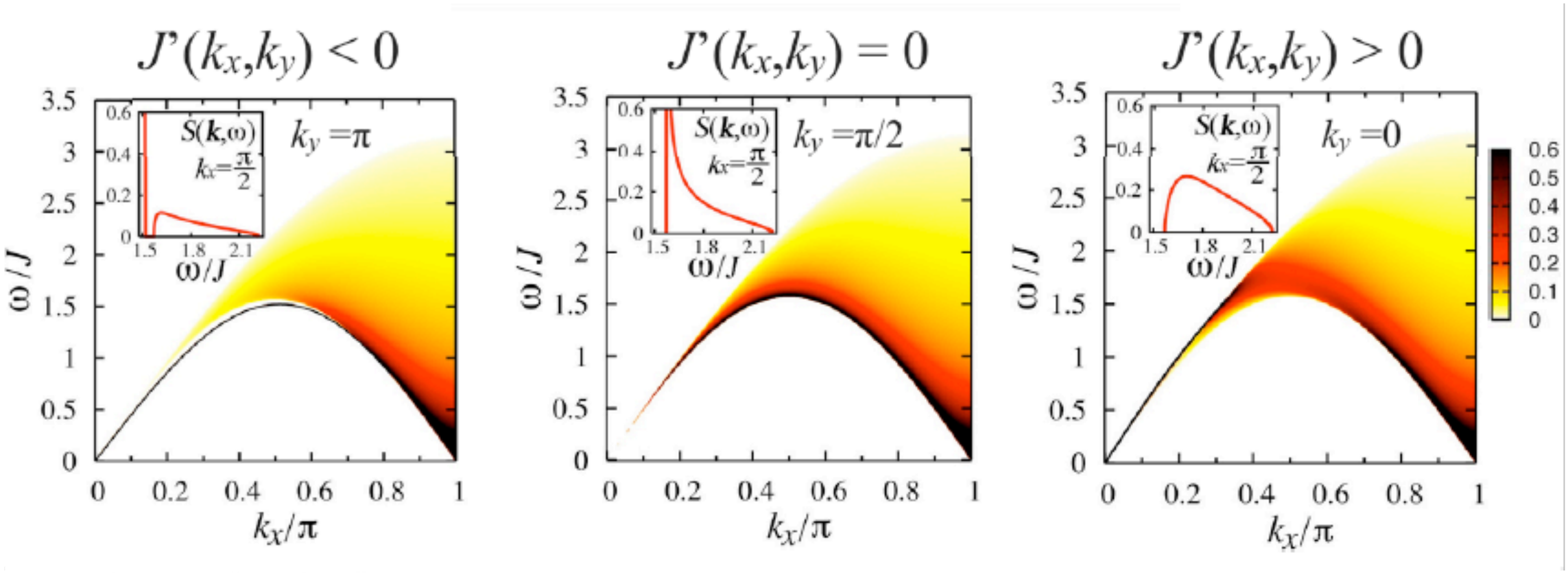
$$S(k,\omega) = \frac{S_{1d}(k,\omega)}{[1 + J'(k)\chi'_{1d}(k,\omega)]^2 + [\pi J'(k) S_{1d}(k,\omega)]^2}$$

$$S_{1d}(k,\omega) = |A_k(\omega)|^2 / \sqrt{\omega^2_{2,\text{upper}} - \omega^2} \qquad \chi'_{1d}(k,\omega) = P\int_0^\infty d\omega' \, \frac{S_{1d}(k,\omega')}{\omega' - \omega}$$

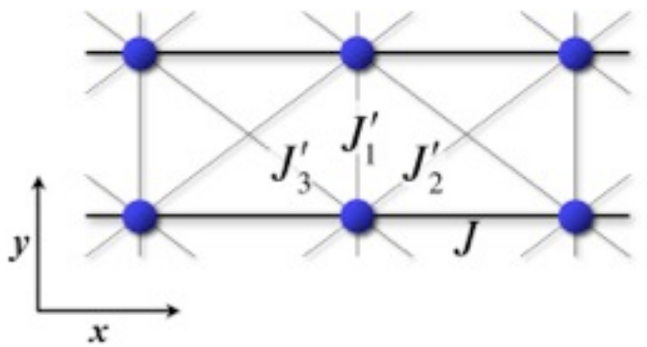
$$S_{1d}(k,\omega) = \frac{1}{2\pi} \frac{e^{-I(\rho(k,\omega))}}{\sqrt{\omega_U^2(k) - \omega^2}} \Theta[\omega_k^U - \omega]\Theta[\omega_k^L - \omega] \qquad I(\rho) = \int_0^\infty dt \, \frac{e^t}{t} \frac{\cosh(2t)\cos(4\rho t) - 1}{\cosh t \sinh(2t)} \qquad \rho(k,\omega) = \frac{4}{\pi} \text{acosh} \sqrt{\frac{\omega_U^2(k) - \omega_L^2(k)}{\omega^2 - \omega_L^2(k)}}$$

Types of behavior

- Behavior depends upon spinon interaction $J'(k_x,k_y)$



Bound “triplon”
(3-fold degenerate)



Identical to 1D

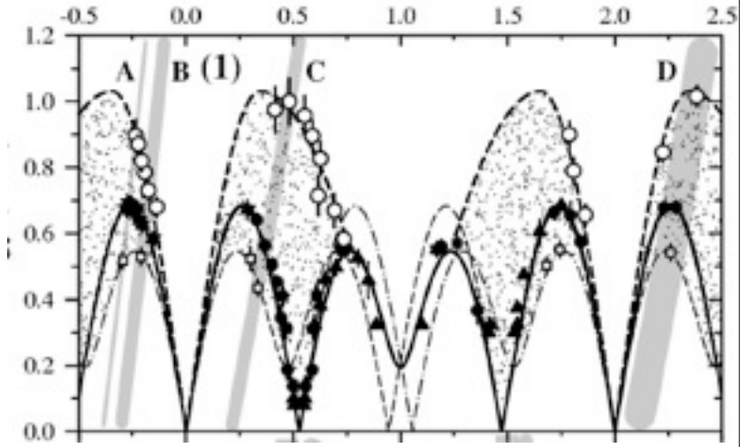
$J'(k) = 4J_1'\cos^2[k_x/2]\cos[k_y]$

$J'_2 = J'_3 = J'_1/2$

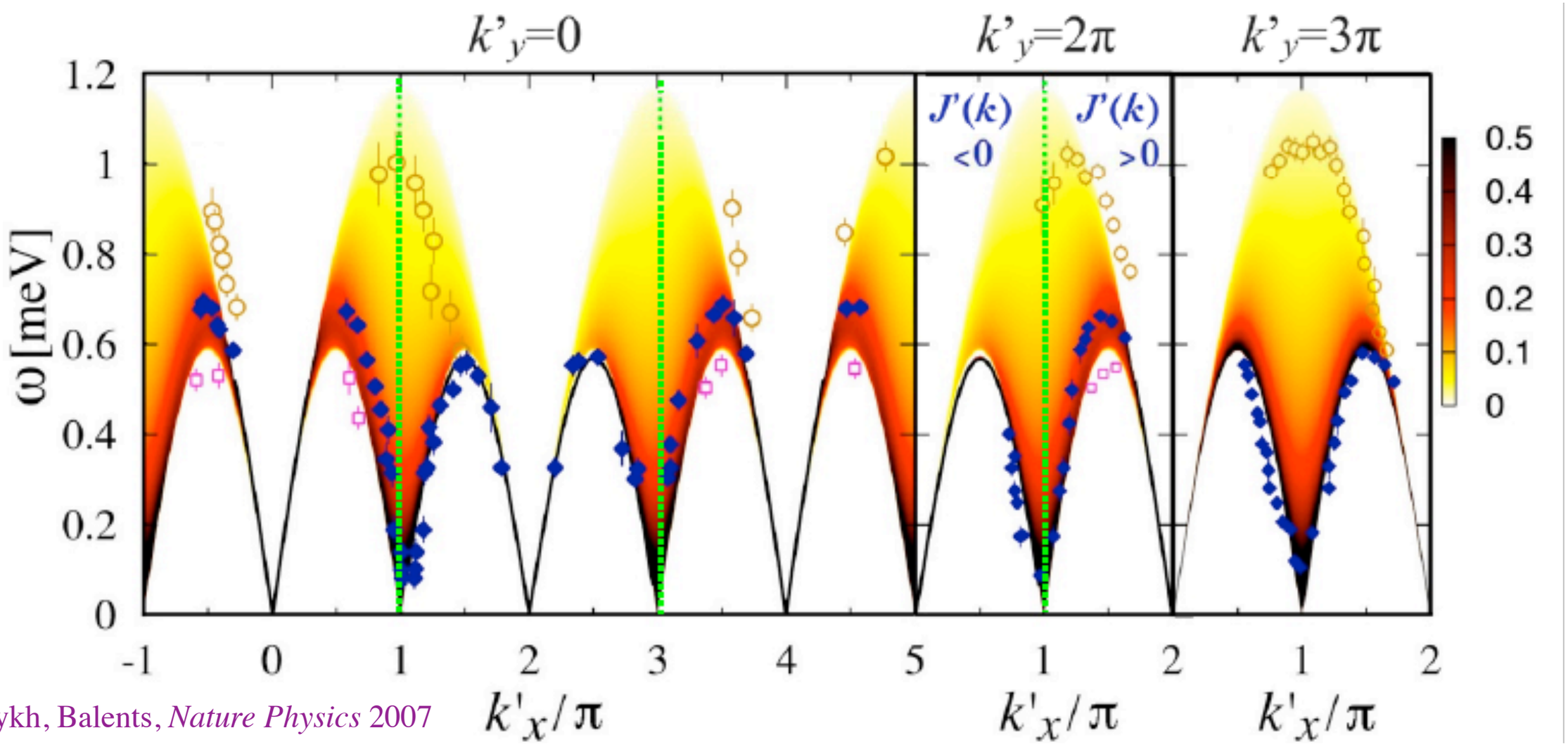
Upward shift of spectral weight. Broad resonance in continuum or anti-bound state (small k)

Explanation:

Dimensional reduction due to frustration:
spinons in Cs_2CuCl_4 are of 1d origin,
propagate between chains
by forming S=1 triplon pairs



The moral: effectively highly one-dimensional due to strong frustration



Kohno, Starykh, Balents, *Nature Physics* 2007

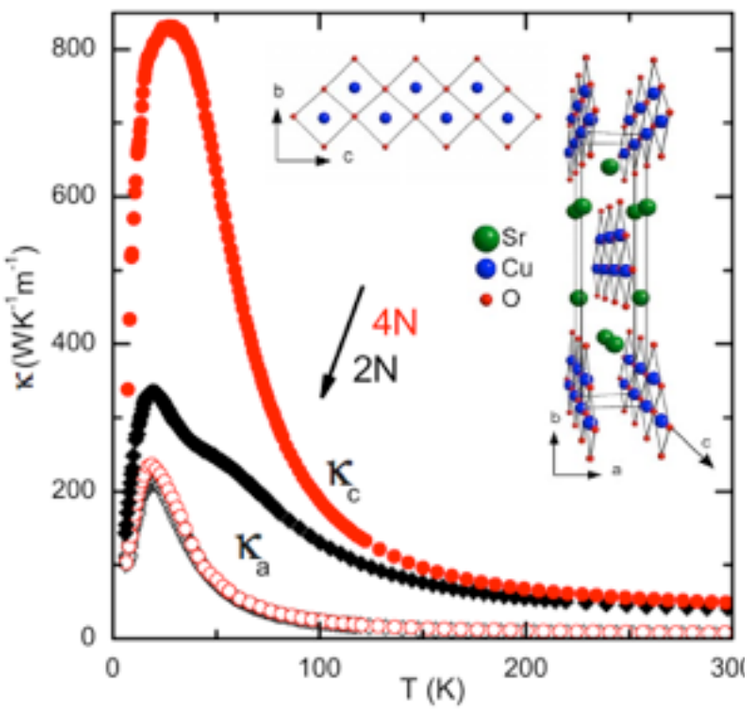
- Vertical green lines: $J'(k)=4J' \cos[k'_x/2] \cos[k'_y/2] = 0$.

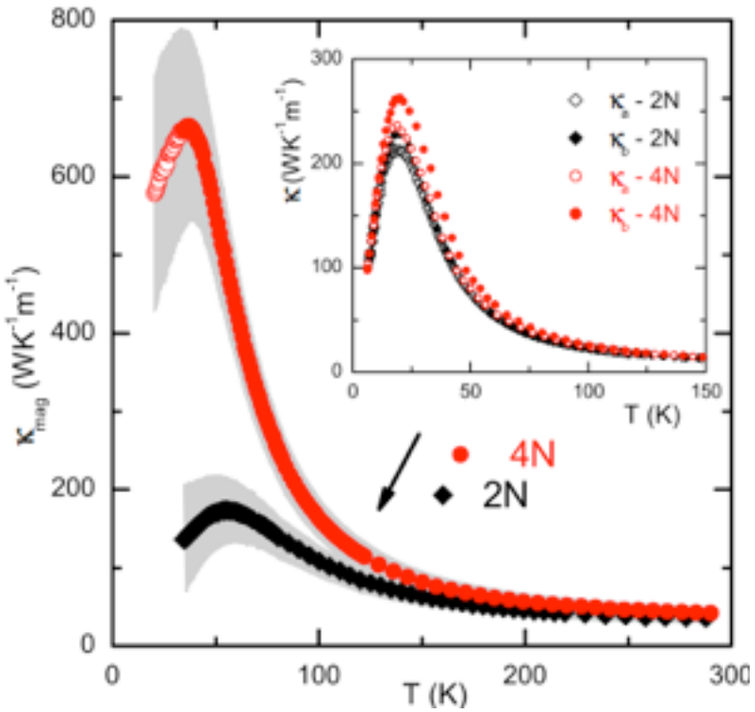
How else can we probe/see spinons?

PHYSICAL REVIEW B **81**, 020405(R) (2010)

Ballistic heat transport of quantum spin excitations as seen in $SrCuO_2$

N. Hlubek,[1] P. Ribeiro,[1] R. Saint-Martin,[2] A. Revcolevschi,[2] G. Roth,[3] G. Behr,[1] B. Büchner,[1] and C. Hess[1]
[1]*IFW-Dresden, Institute for Solid State Research, P.O. Box 270116, D-01171 Dresden, Germany*
[2]*Laboratoire de Physico-Chimie de L'Etat Solide, ICMMO, UMR 8182, Université Paris-Sud, 91405 Orsay, France*
[3]*Institut für Kristallographie der RWTH, D-52056 Aachen, Germany*
(Received 11 November 2009; published 11 January 2010)





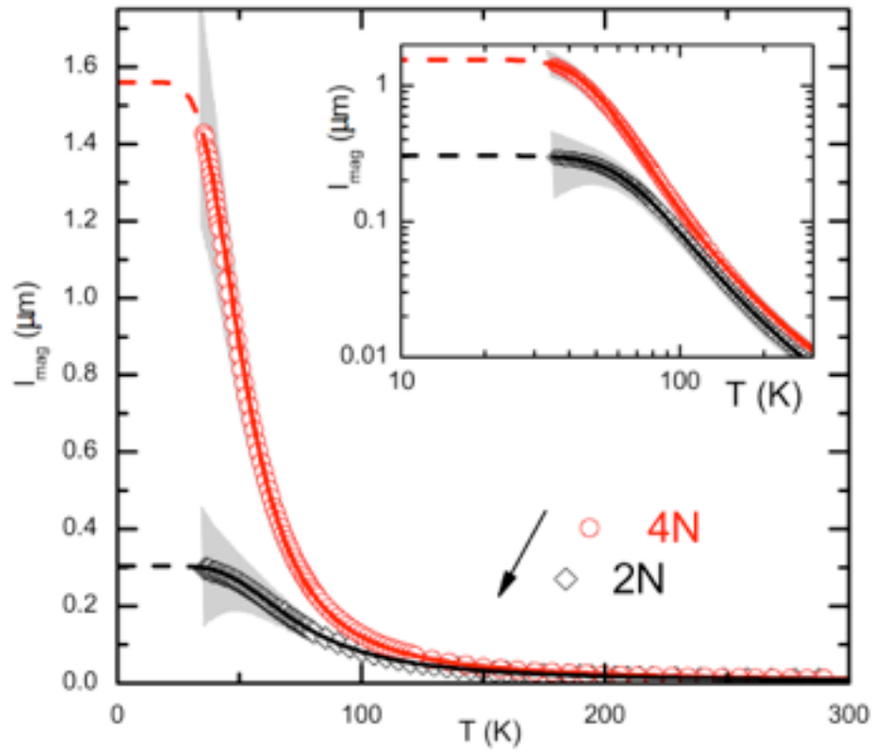


FIG. 3. (Color online) Magnetic mean-free paths of $SrCuO_2$ for different purities. The solid lines were calculated according to Eq. (2). The shaded area illustrates the uncertainty from the estimation of the phononic background.

mean-free path ~1 micron !

Highly 2d organic systems

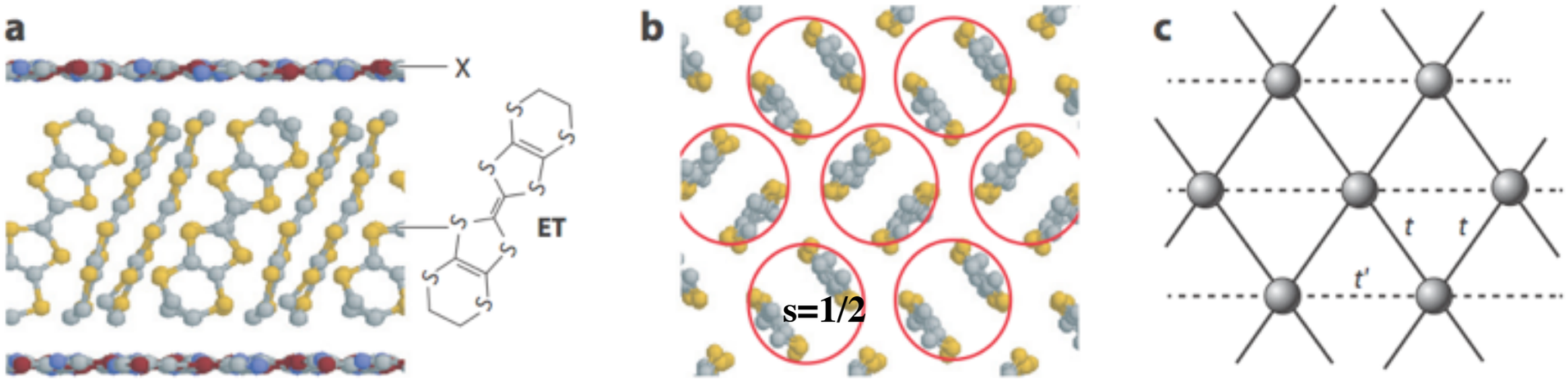


Figure 3

Structure of κ-$(ET)_2X$. (*a*) Side and (*b*) top view of the layer and (*c*) modeling the in-plane structure into an isosceles-triangular lattice with two kinds of transfer integrals.

ET = bis(ethylenedithio)tetrathiafulvalene

Kanoda and Kato, Annu. Rev. Condens. Matt.Phys (2011)

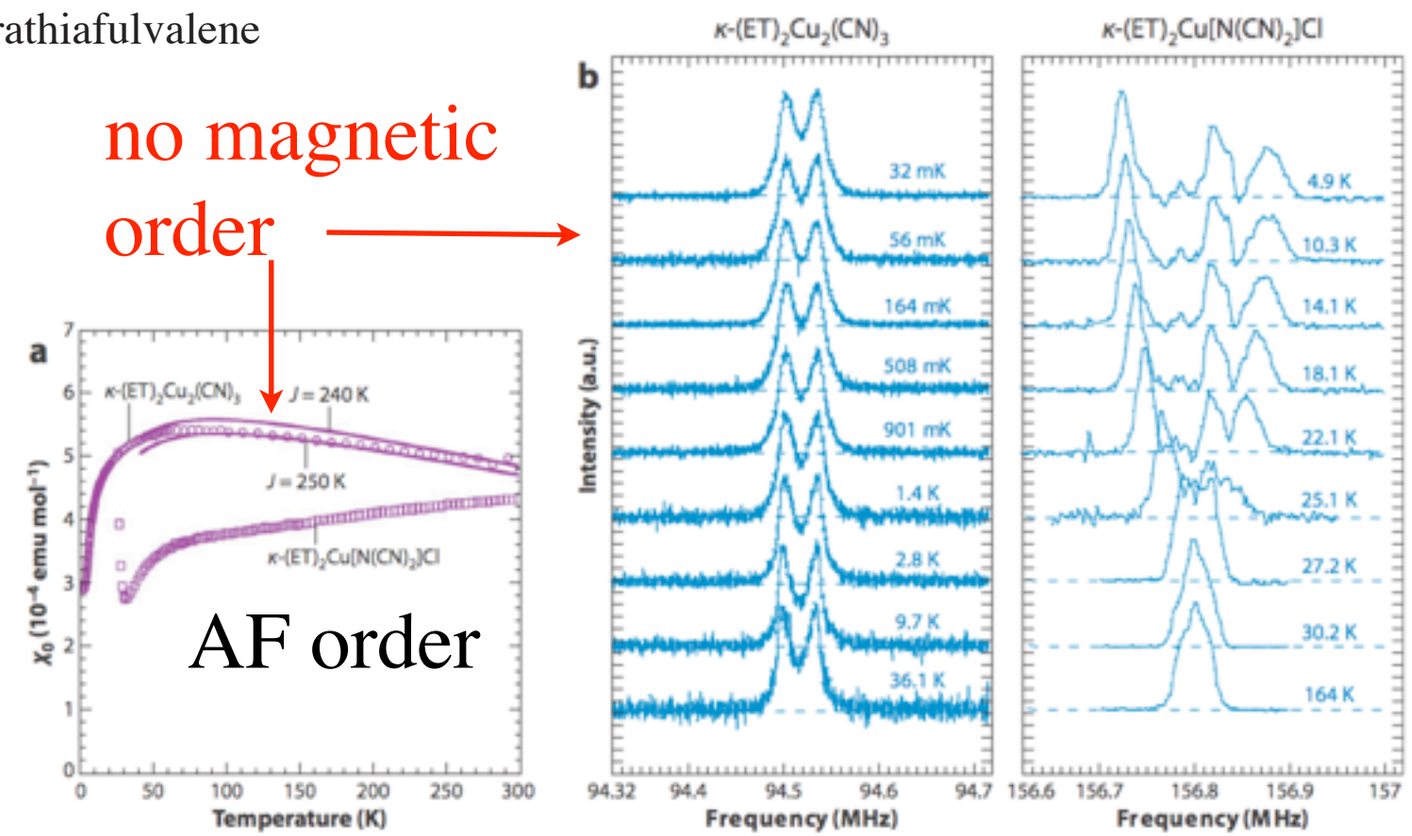
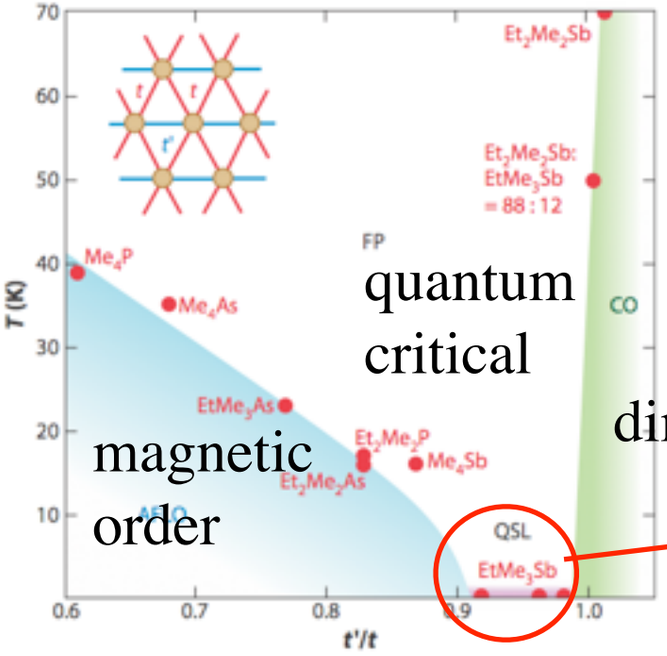


Figure 8

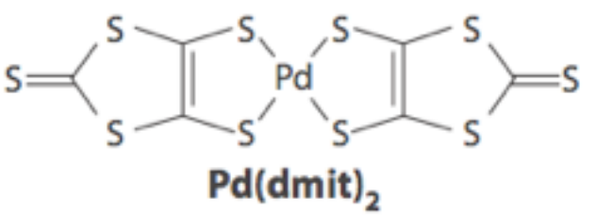
(*a*) Temperature dependences of spin susceptibilities of κ-$(ET)_2Cu_2(CN)_3$ and κ-$(ET)_2Cu[N(CN)_2]Cl$. The solid lines represent the results of the series expansion of the triangular-lattice Heisenberg model using [7,7] Pade approximation with $J = 240$ K and 250 K. (*b*) ^1H NMR spectra of single crystals of κ-$(ET)_2Cu_2(CN)_3$ (*left panel*) and κ-$(ET)_2Cu[N(CN)_2]Cl$ (*right panel*) under magnetic fields applied perpendicular to the conducting layer. Abbreviation: NMR, nuclear magnetic resonance.

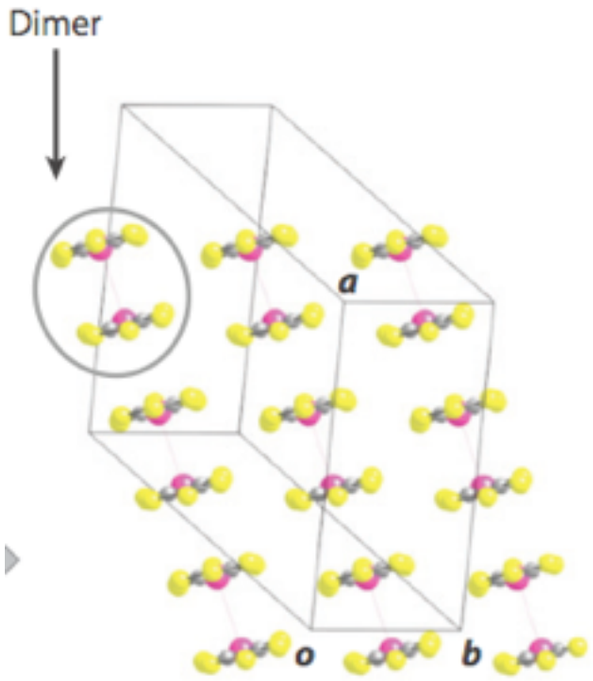
β’ - $Pd(dmit)_2$ salts

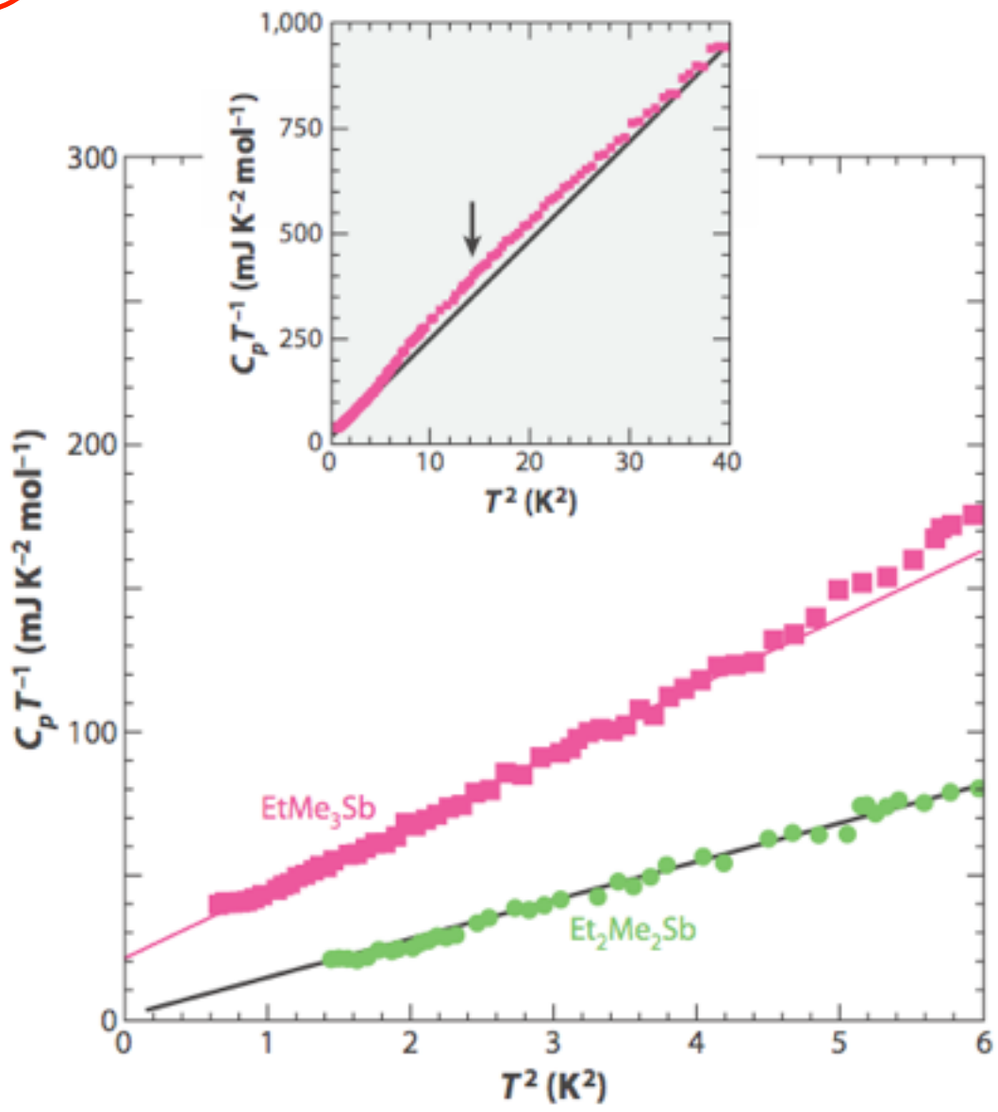
dmit = 1,3-dithiole-2-thione-4,5-dithiolate

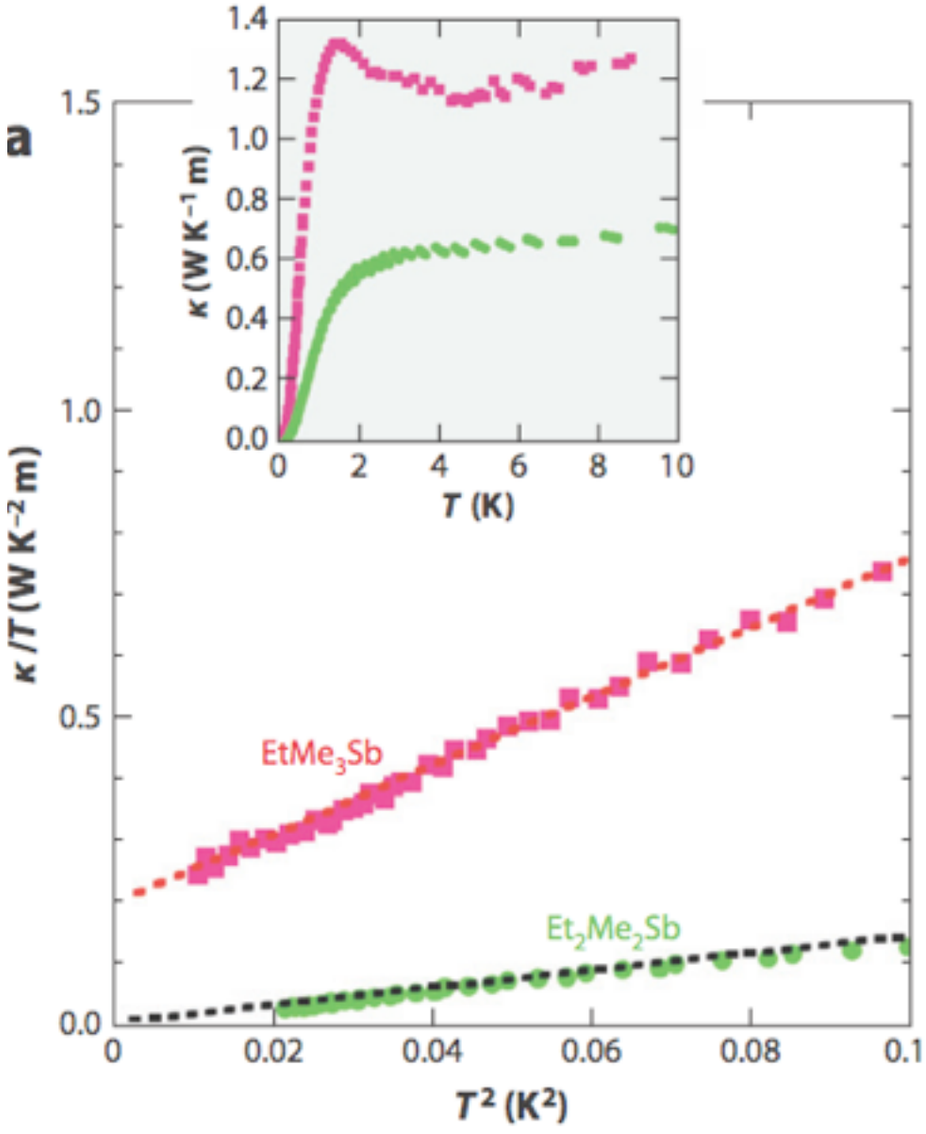


liquid ?!



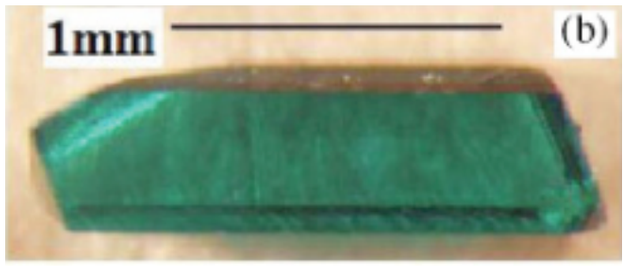


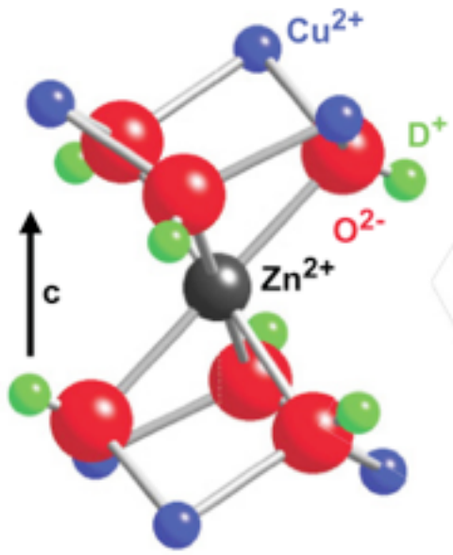


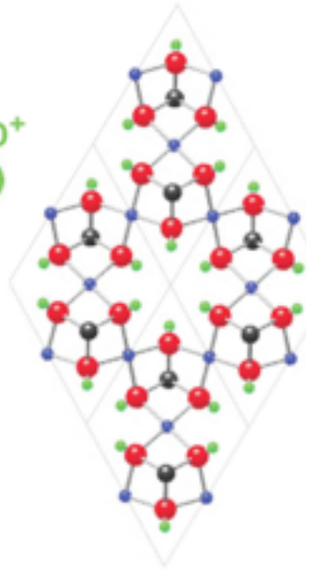


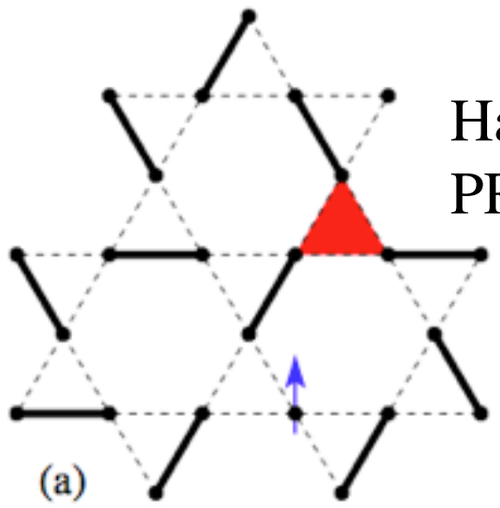
Even better: s=1/2 Kagome antiferromagnet $ZnCu_3(OH)_6Cl_2$

single crystals
become available
in 2011



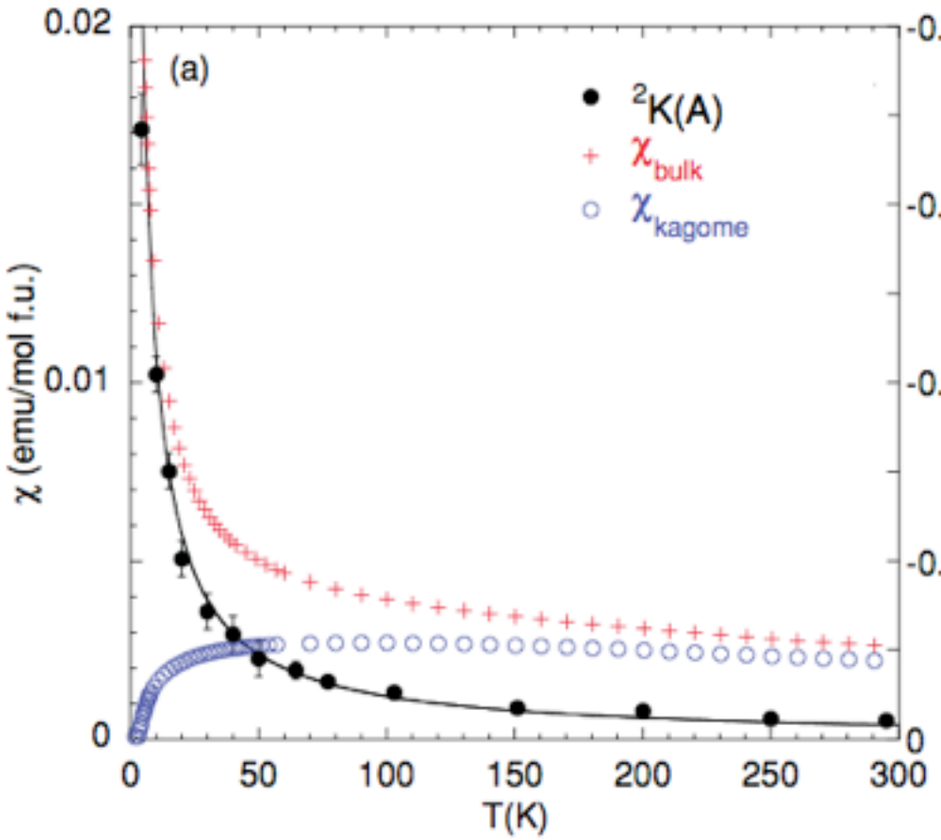


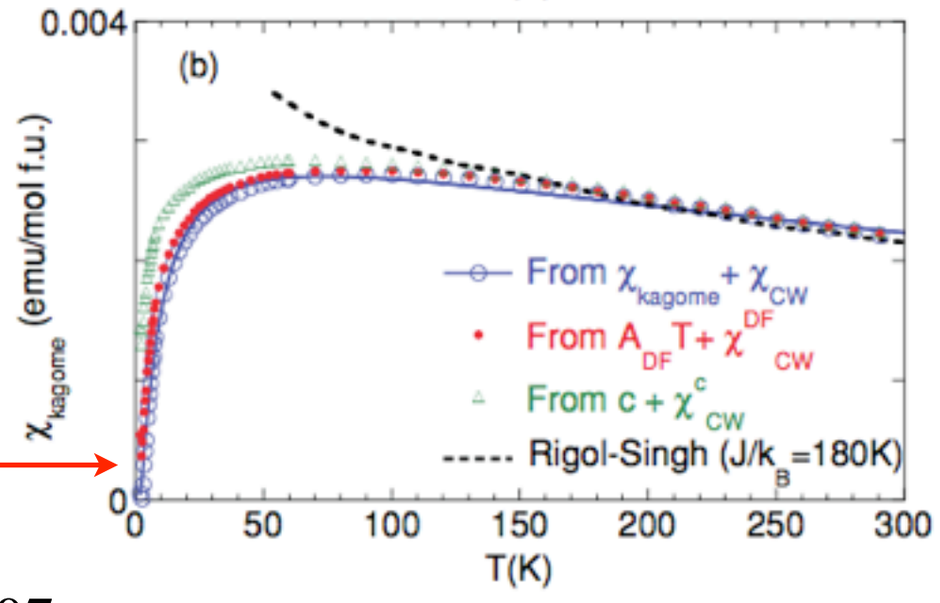




Hao, Tchernyshyov
PRL 2010

Semi-metal of neutral
spinons with Dirac dispersion
Ran, Hermele, Lee, Wen PRL 2007





Imai, Fu. Han, Lee
PRB 2011

Key features

- no long-range magnetic order
- finite (or power-law vanishing) spin susceptibility
- linear in T heat capacity
- (perhaps) linear in T thermal conductivity

?

P. W. Anderson (2010):

"*... a good effective low-energy theory is worth all of Monte Carlo with Las Vegas thrown in.*"

Key features

- no long-range magnetic order
- finite (or power-law vanishing) spin susceptibility
- linear in T heat capacity
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?

P. W. Anderson (2010):

"*... a good effective low-energy theory is worth all of Monte Carlo with Las Vegas thrown in.*"

- "Minimal" low-energy theory: Fermi-liquid of (charge-neutral) spinons !
  - theoretical caveat: there must also be an internal gauge field,

interaction with which may modifies naive "neutral fermi-liquid assumptions"

Having more conclusive experimental probes of the spinon Fermi surface would be nice

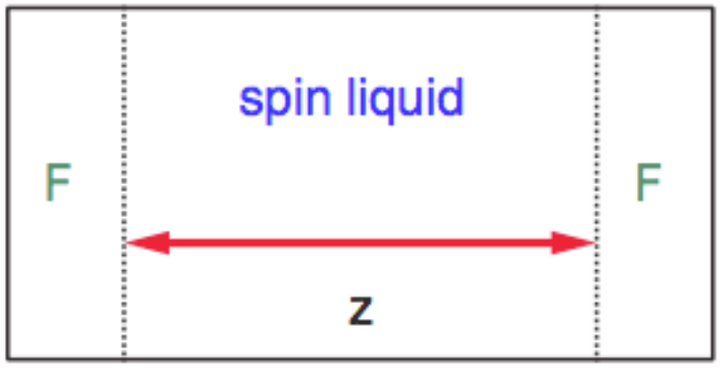
1. Friedel oscillations due to spinon Fermi surface

PRL **102,** 067204 (2009) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2009

How to Measure a Spinon Fermi Surface

M. R. Norman and T. Micklitz
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
(Received 15 September 2008; revised manuscript received 30 October 2008; published 12 February 2009)

RKKY like coupling mediated by spinons



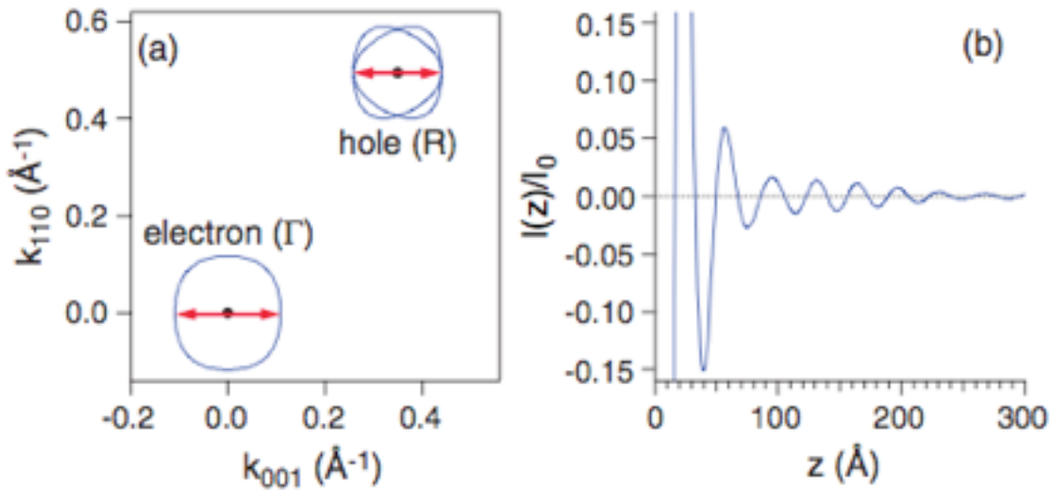


FIG. 3 (color online). (a) Spinon Fermi surface for $Na_4Ir_3O_8$ ($a = 8.985$ Å). Spanning vectors are indicated by arrows. (b) Calculated oscillatory response from Eq. (12).

- Also, *charge Friedel oscillations in a Mott insulator*, Mross and Senthil, PRB **84**, 041102 (2011)

2.

PRL **106,** 056402 (2011) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2011

Spinon Phonon Interaction and Ultrasonic Attenuation in Quantum Spin Liquids

Yi Zhou[1] and Patrick A. Lee[2]

ESR - electron spin resonance

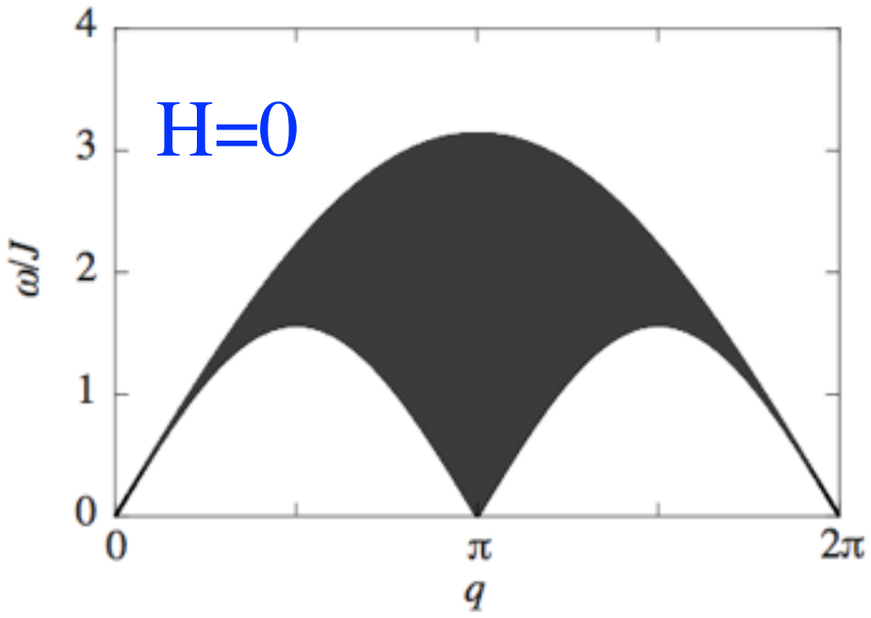
- Simple (in principle) and sensitive probe of magnetic *anisotropies* (and, also, **q=0** probe: $S = \Sigma_r S_r$)

$$I(h,\omega) = \frac{\omega}{4L}\int dt e^{i\omega t}\langle [S^+(t), S^-]\rangle$$

Zeeman **H** along **z**, microwave radiation **h** polarized perpendicular to it.

- For SU(2) invariant chain in paramagnetic phase

$I(H,\omega) \sim \delta(\omega\text{-}H)\ m(H)$ [Kohn's Th] Oshikawa, Affleck PRB 2002

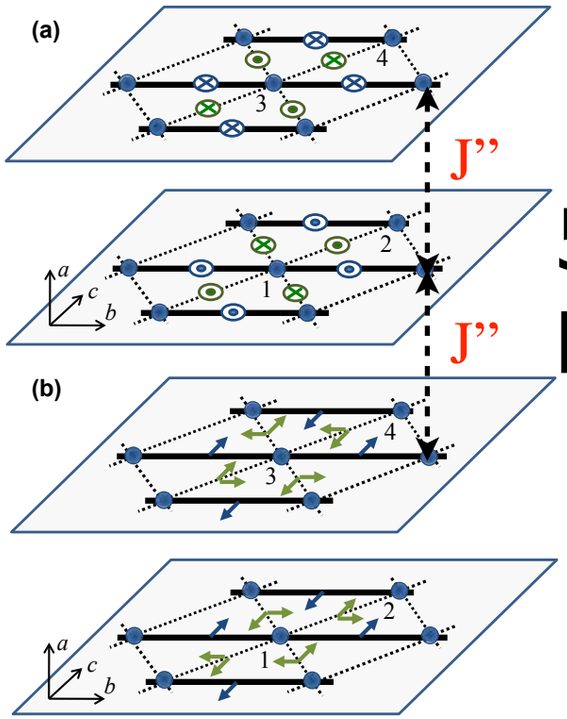


ESR in Cs_2CuCl_4: main source of anisotropy asymmetric Dzyaloshinskii-Moriya interaction

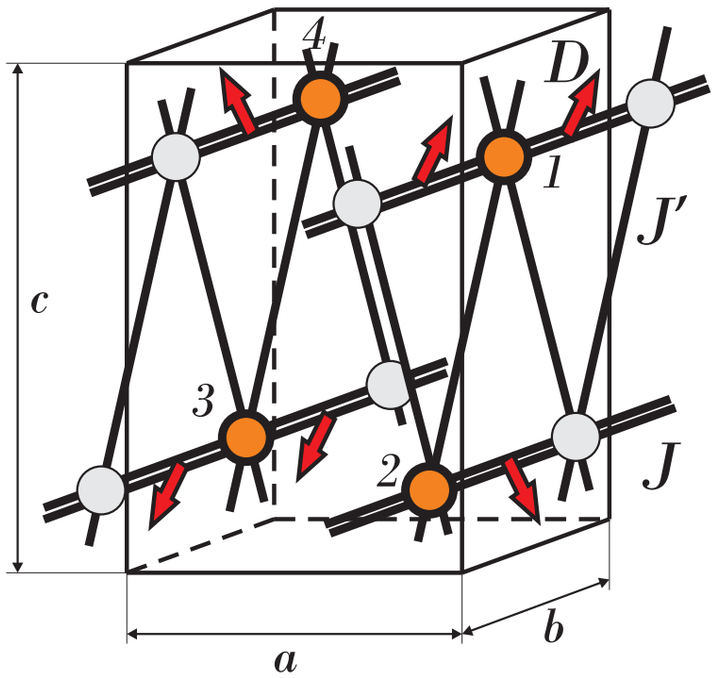
$$\vec{D}_{ij} \cdot \vec{S}_i \times \vec{S}_j$$

- Is known from inelastic neutron scattering data (Coldea et al. 2001-03)
- 3D ordered state - determined by minute residual interactions - interplane and ***Dzyaloshinskii-Moriya*** (DM) OS, Katsura, Balents 2010

$$D_{y,z} = (-1)^y D_c \hat{c} + (-1)^z D_a \hat{a}$$



5 different DM terms allowed

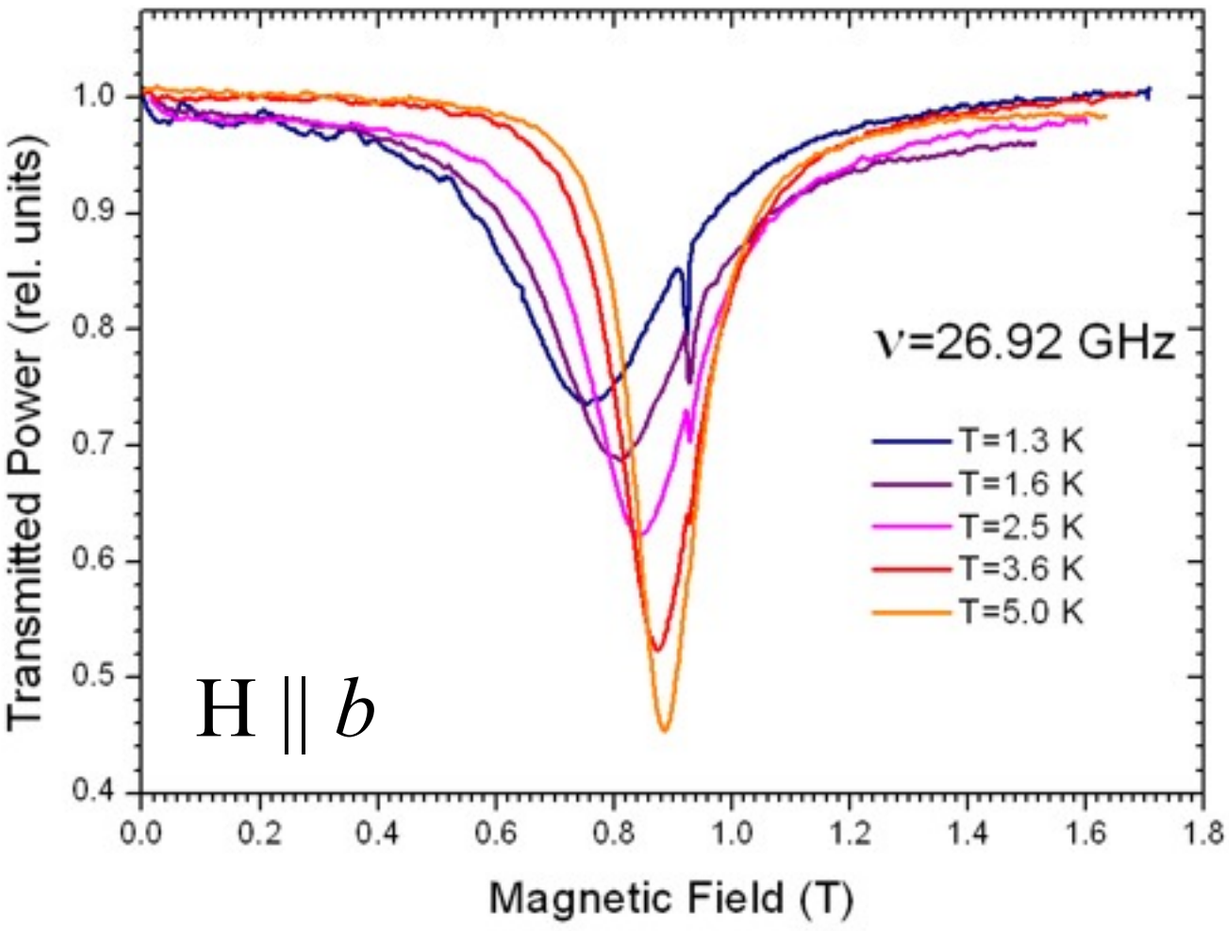


focus on the in-chain DM

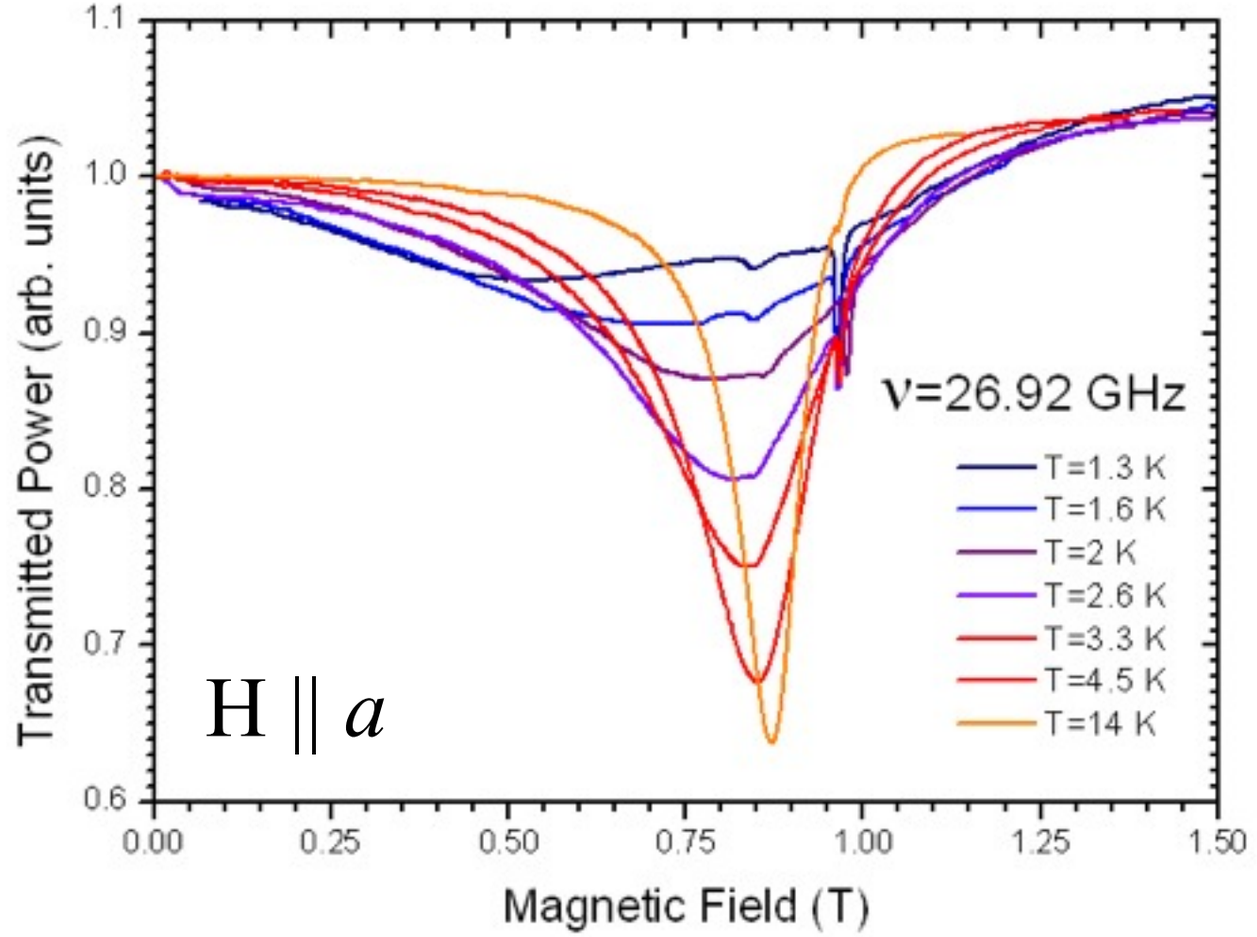
✶ Cs_2CuCl_4 is a very special material: possesses uniform along the chain DM interaction

ESR data

Shift for H || *b*



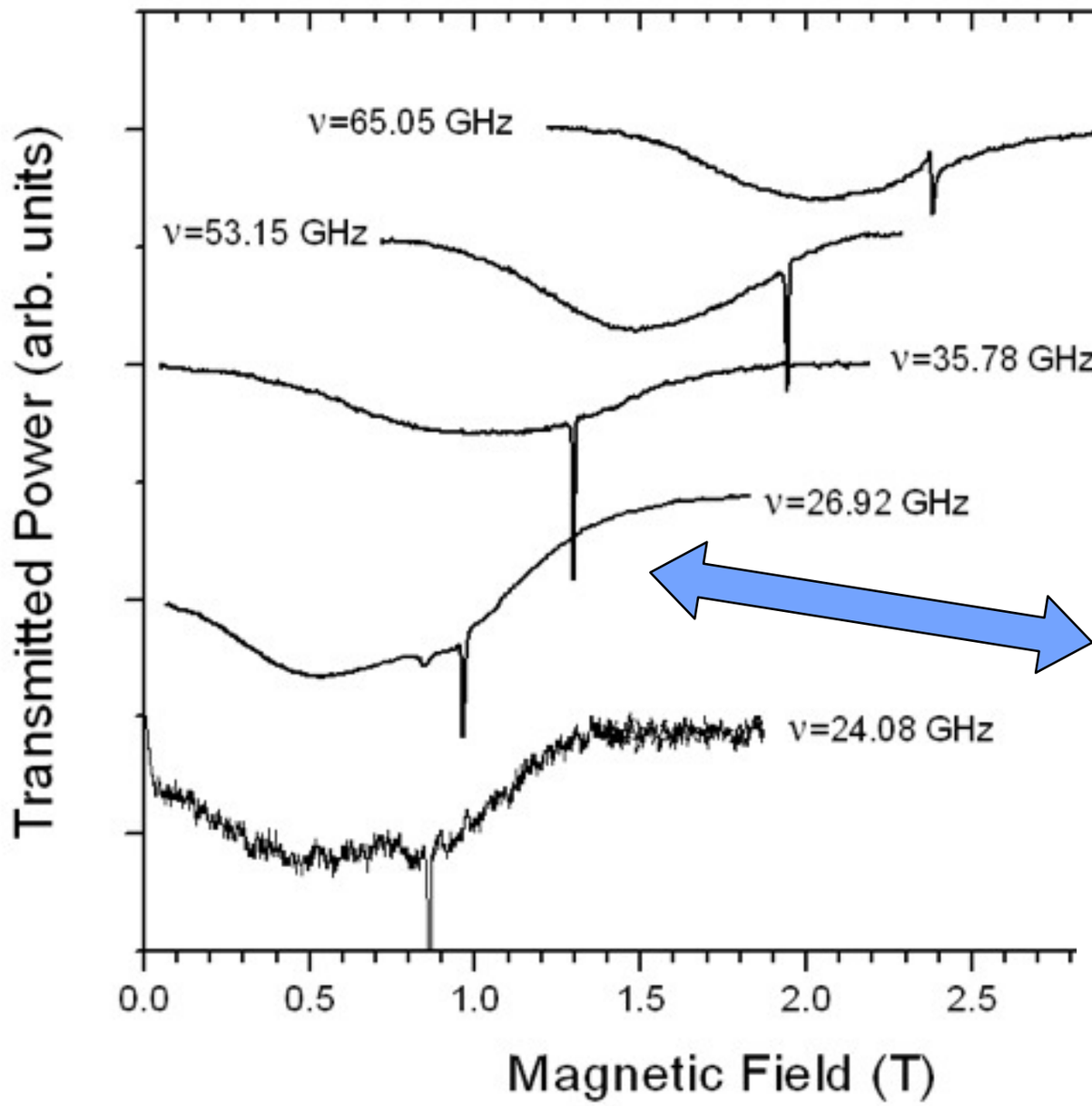
Shift and splitting for H || *a*, *c*



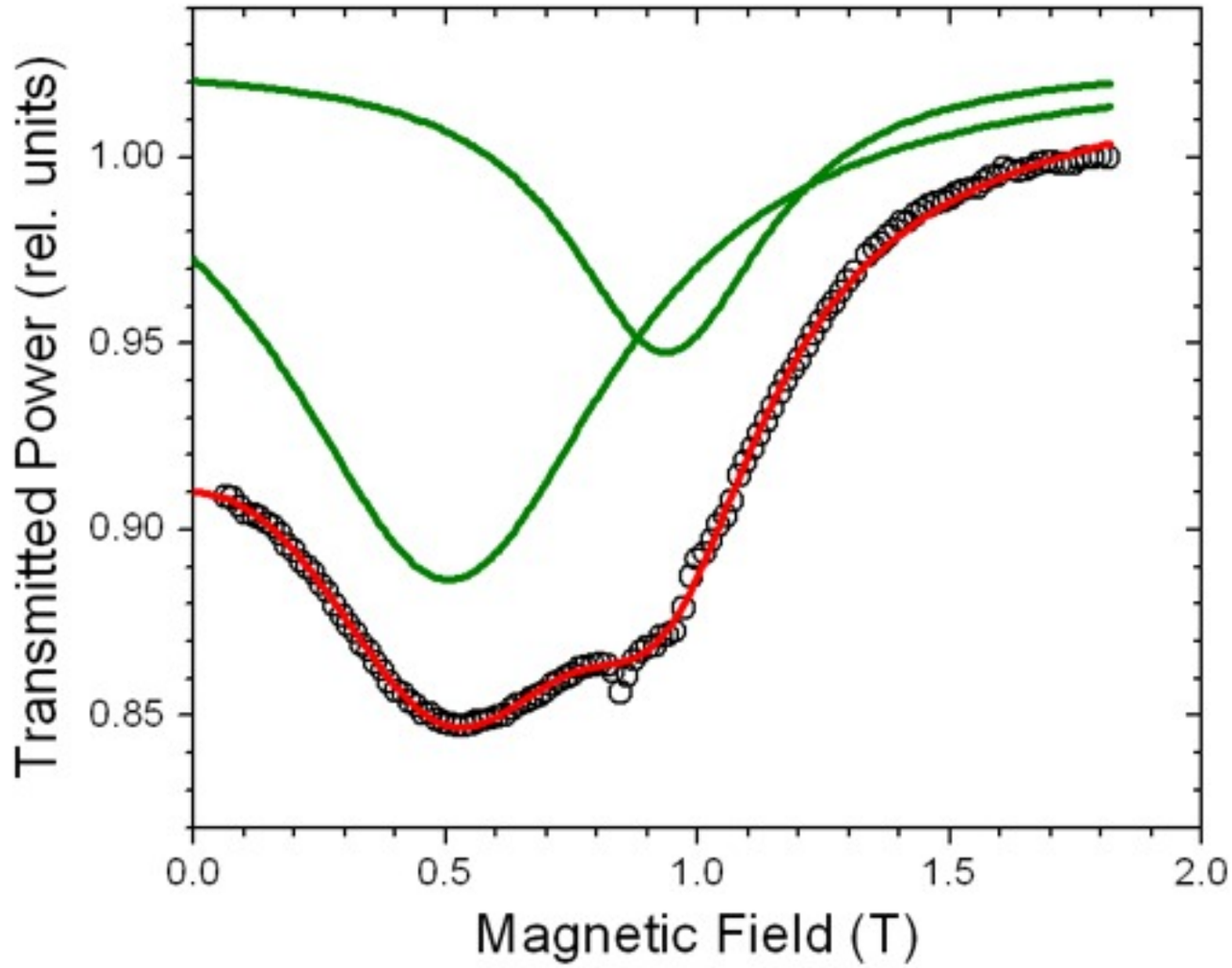
Resonance line is significantly modified with lowering the temperature; modification is strongly anisotropic with respect to field.

The lowest temperature T=1.3 K is still twice higher than ordering T_N

Line splitting



T=1.3 K
ν=26.92 GHz
H || a

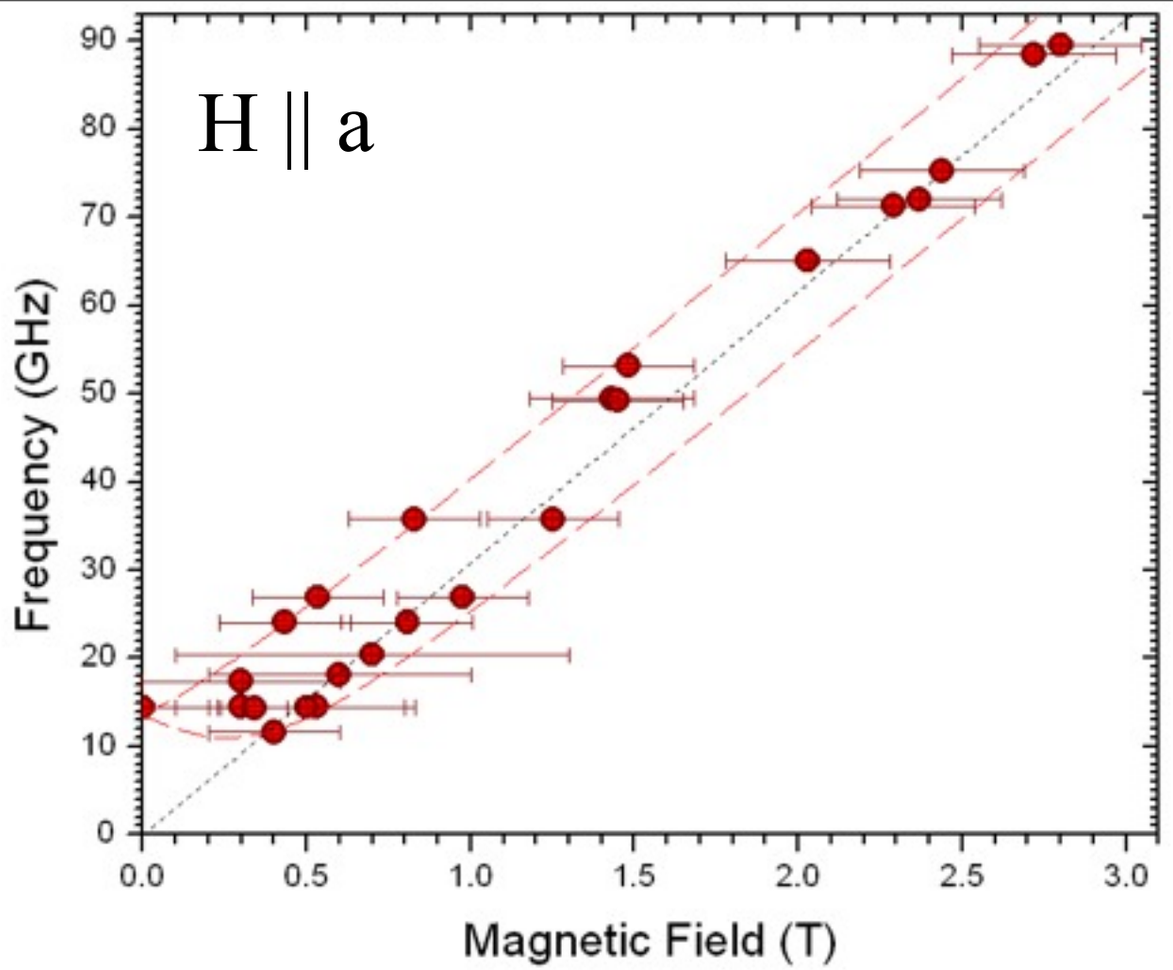


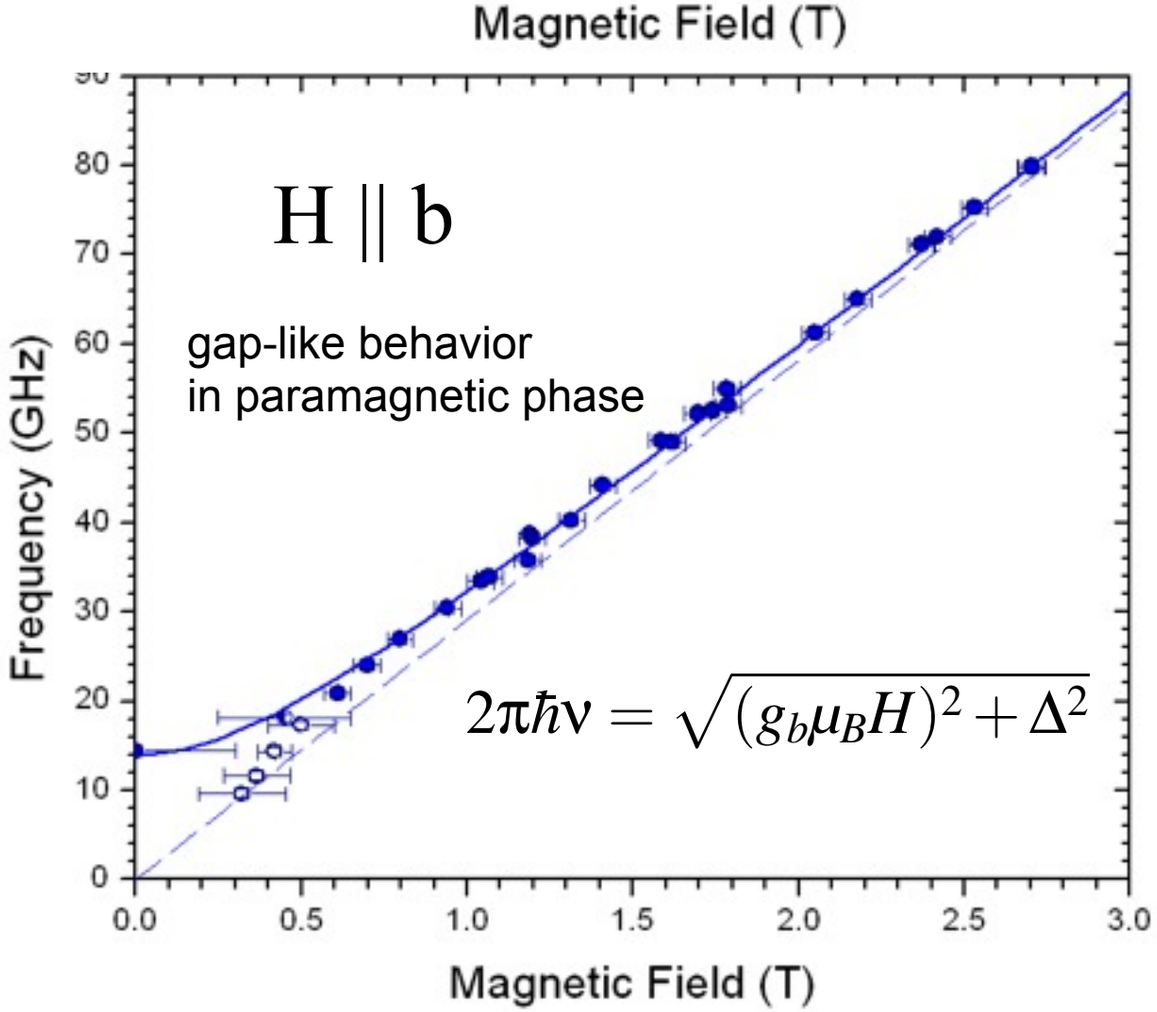
Spectra

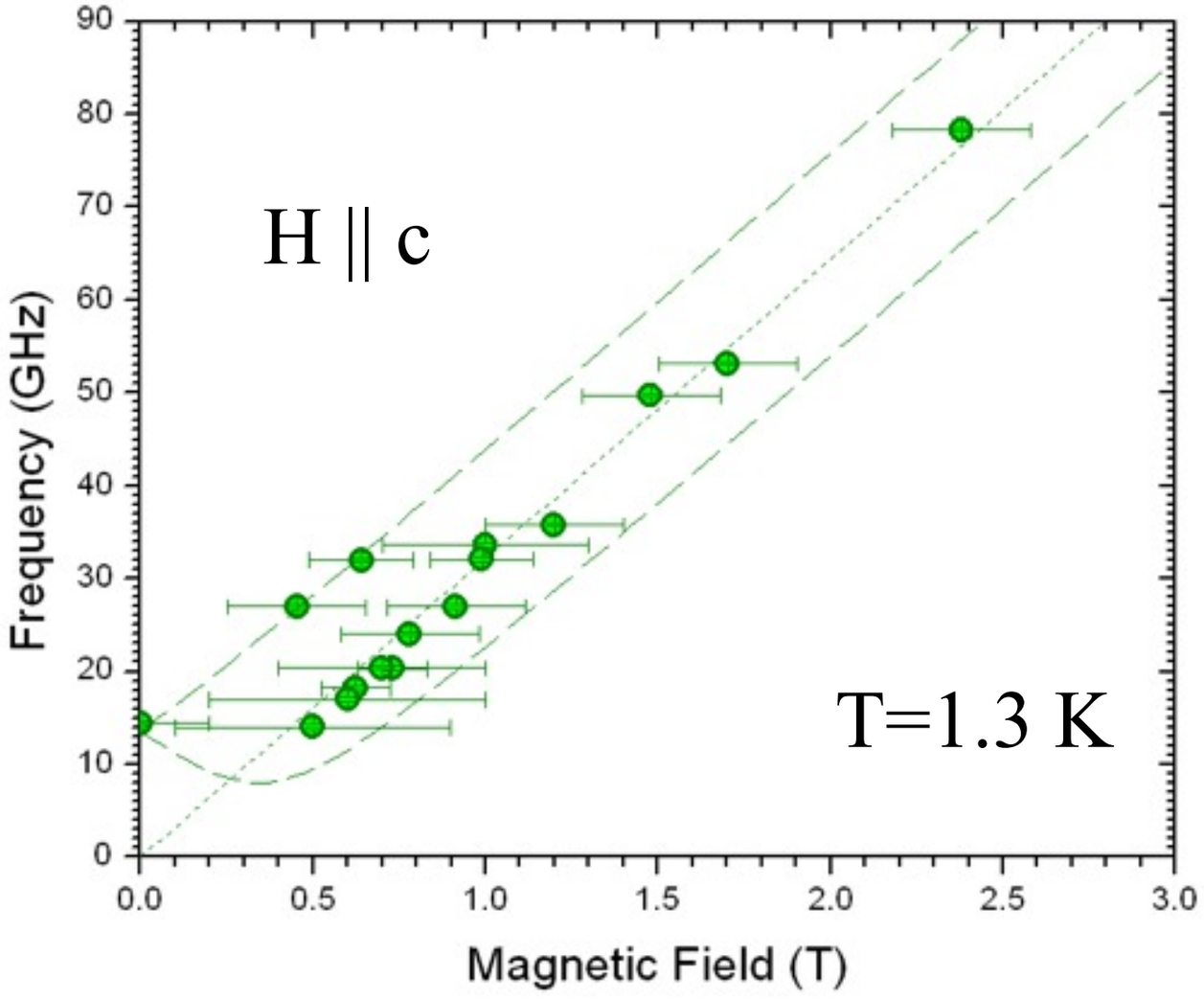
Line **splits** for H || *a*, *c*

Single but shifted line for H || *b*
(losses intensity at low frequency)

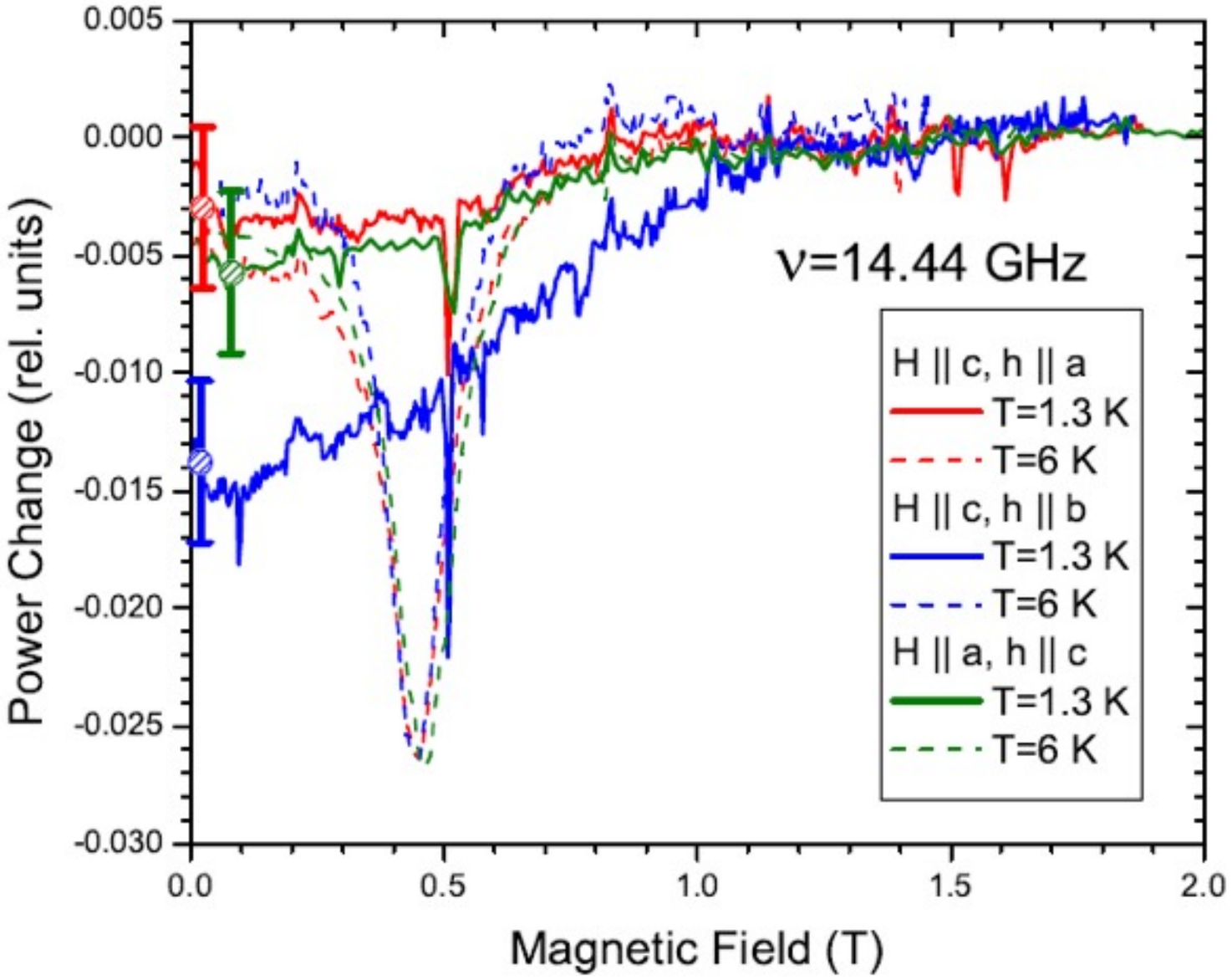
T=1.3 K

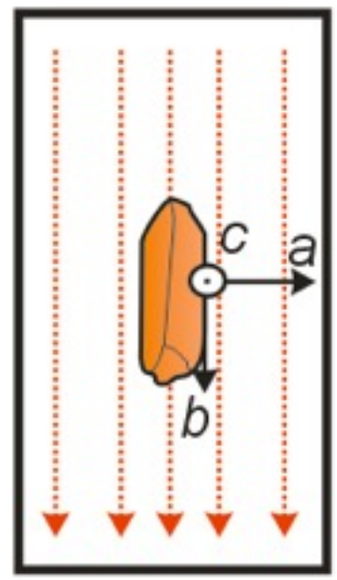




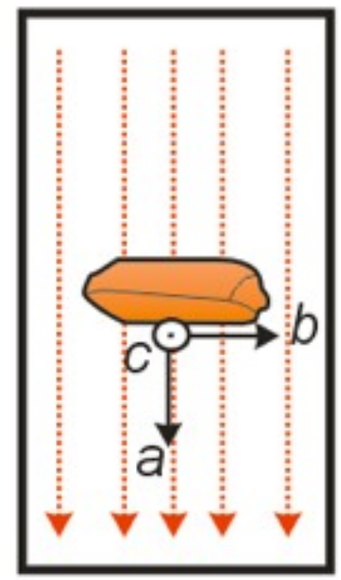


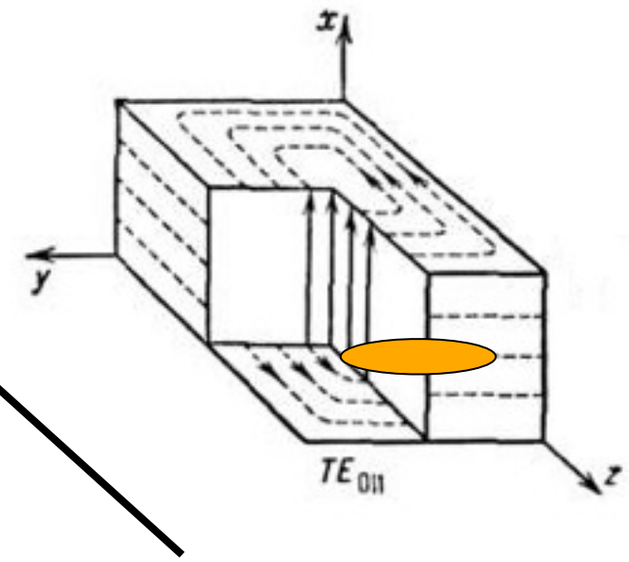
Polarization dependence in zero external field





h





The largest absorption occurs when microwave field h(t) is lined along crystal b-axis, h || *b*

Temperature regimes

Paramagnetic

individual spins

universal quasi-classical regime

J S

correlated spins (high T field theory)

spin-correlated (spin liquid)

well-developed correlations along chains;
but little correlations between chains

$T_0 \sim J\, e^{-2\pi S}$

Haldane scale does exist for S=1/2 chains: different response for S=1 and S=1/2 chains below this temperature

spinons

(low T field theory)

ordered phase

strongly coupled chains;
2d (or 3d) description

$T_N = 0.6$ K

spin waves

(at low energy)

ESR



single line



two lines

AFMR

Povarov et al, PRL 2011
Smirnov et al, 2012

C. Buragohain, S. Sachdev
PRB 59 (1999)

Observed behavior comes from decoupled chains !

Temperature regimes

ESR

Paramagnetic

individual spins

universal quasi-classical regime

J S

correlated spins (high T field theory)



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(at low energy)

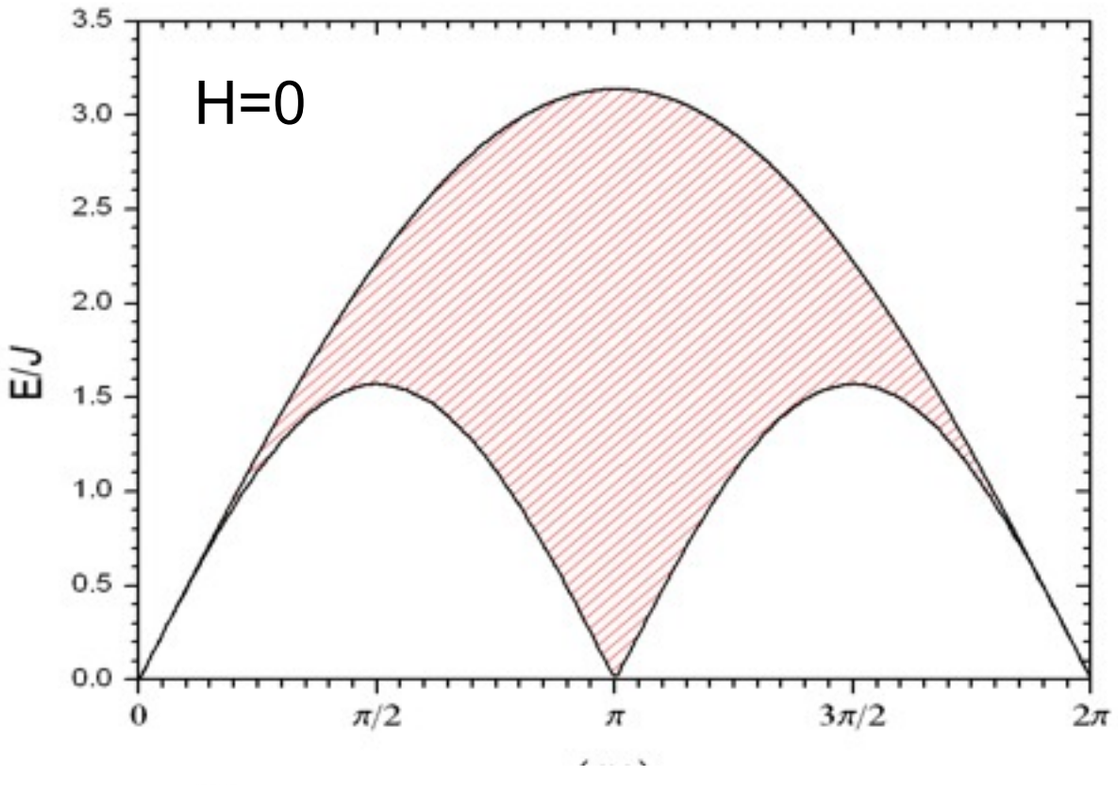
AFMR

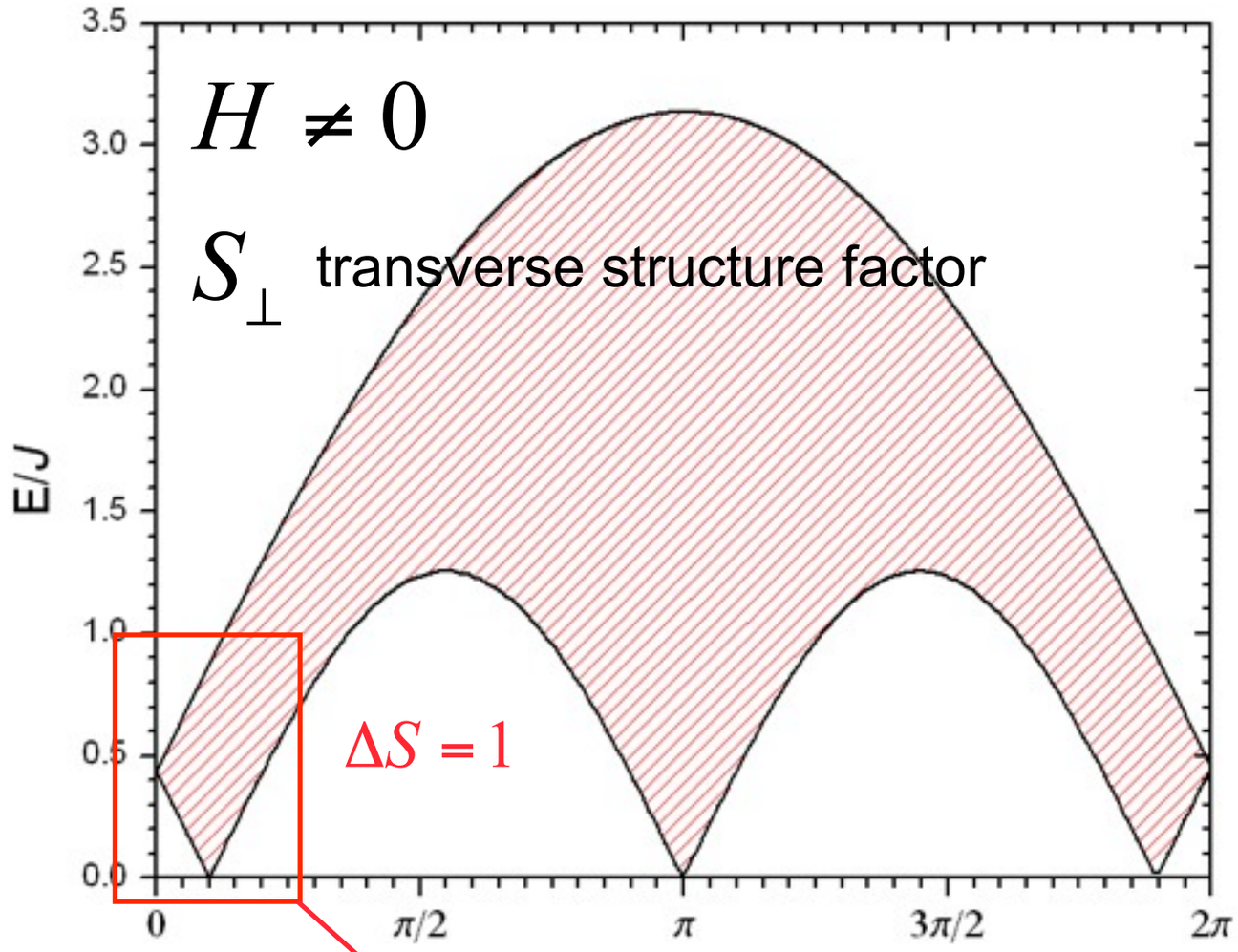
Povarov et al, PRL 2011
Smirnov et al, 2012

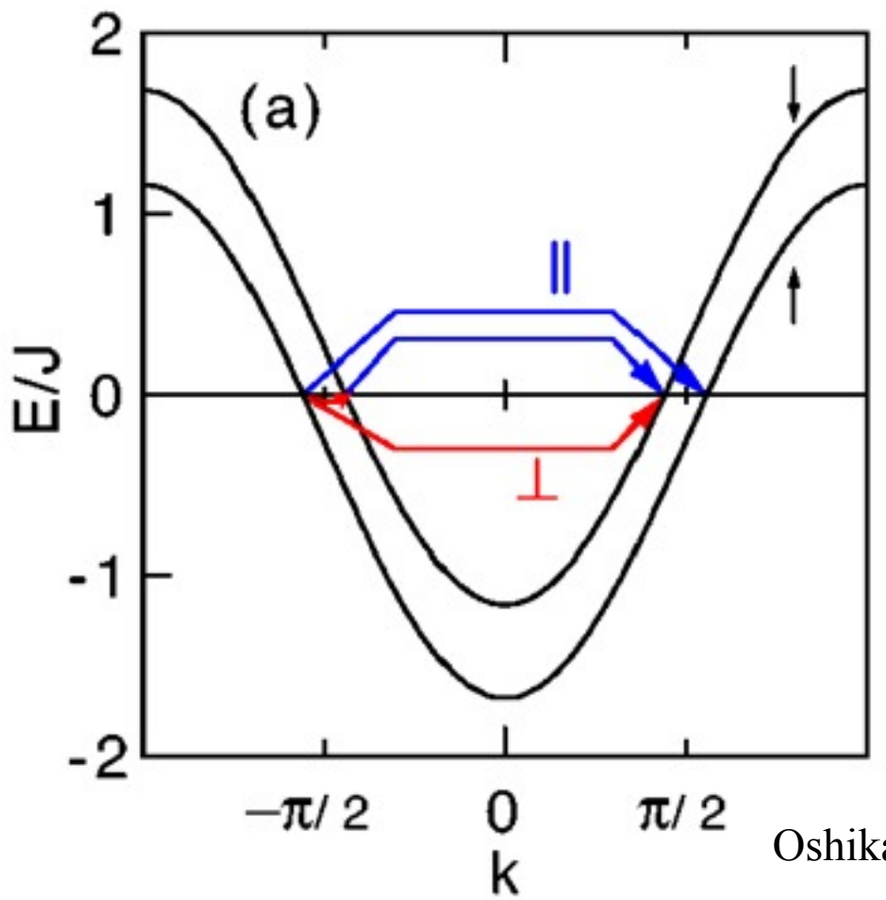
C. Buragohain, S. Sachdev
PRB 59 (1999)

Observed behavior comes from decoupled chains !

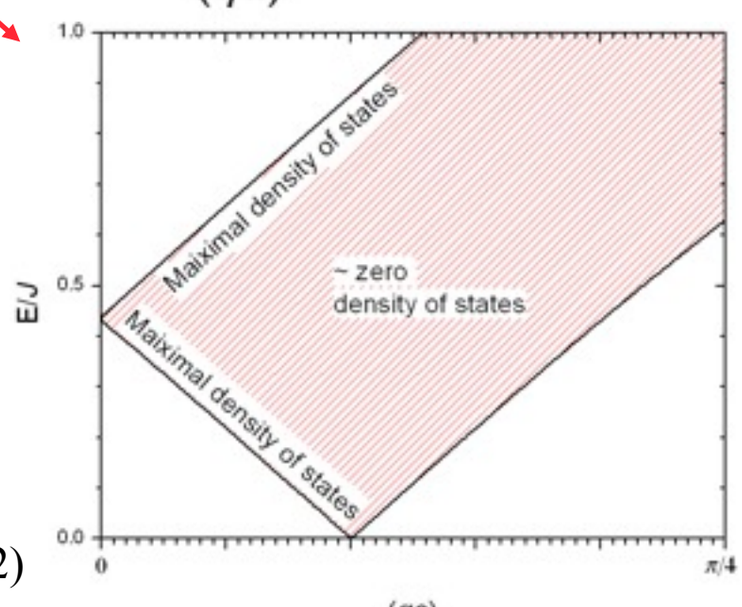
Spinon continuum in magnetic field







Zeeman-split FS



Oshikawa, Affleck, PRB **65** 134410 (2002)

Theory I: H along DM axis

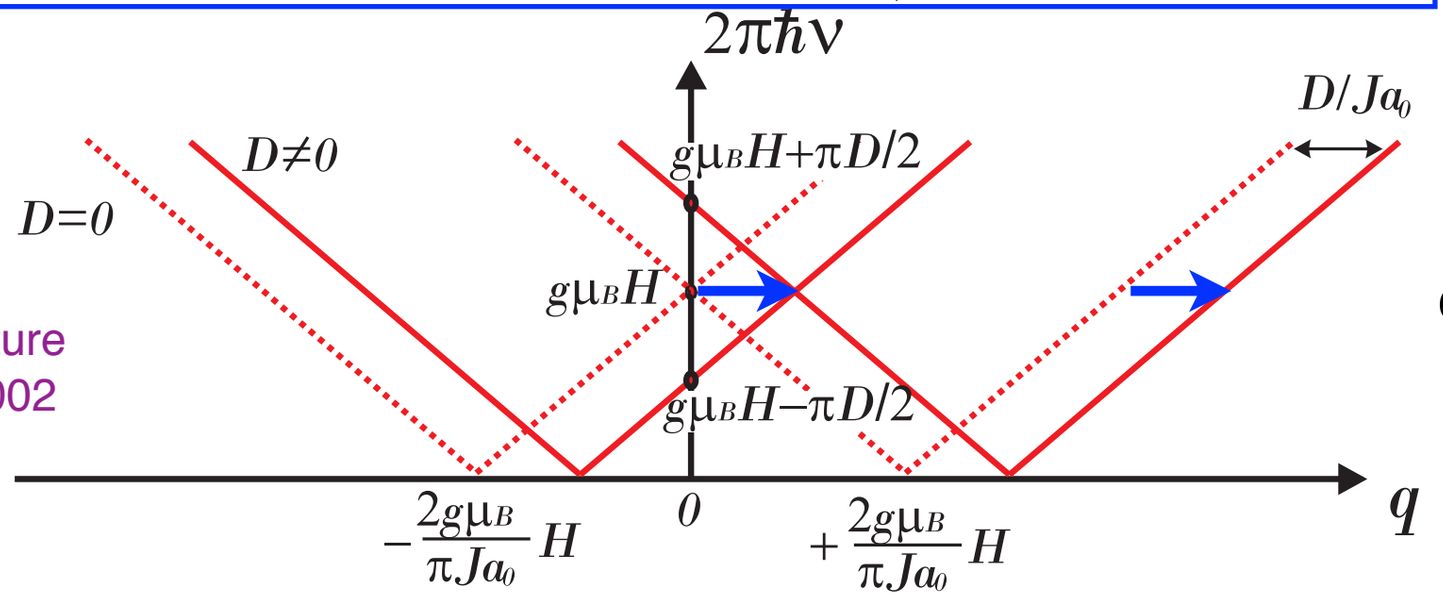
$$H = \sum_{x,y,z} \boxed{JS_{x,y,z} \cdot S_{x+1,y,z}} - \boxed{D_{y,z} \cdot S_{x,y,z} \times S_{x+1,y,z}} - g\mu_B H \cdot S_{x,y,z}$$

chain — uniform DM along the chain — magnetic field

! Unitary rotation about **z**-axis $S^+(x) \rightarrow S^+(x)e^{i(D/J)x}, S^z(x) \rightarrow S^z(x)$

- removes DM term from the Hamiltonian (to D^2 accuracy)
- ***boosts*** momentum to $D/(J\,a_0)$

$$q = 0 \rightarrow q = D/(Ja_0) \Rightarrow 2\pi\hbar\nu_{R/L} = g\mu_B H \pm \pi D/2$$



dotted lines: D=0 picture
Oshikawa, Affleck 2002

rotated basis: q=0
original basis: q=D/J

Chiral probe: **ESR probes *right*- and *left*-moving modes (spinons) independently**

Theory II: arbitrary orientation (cont'd)

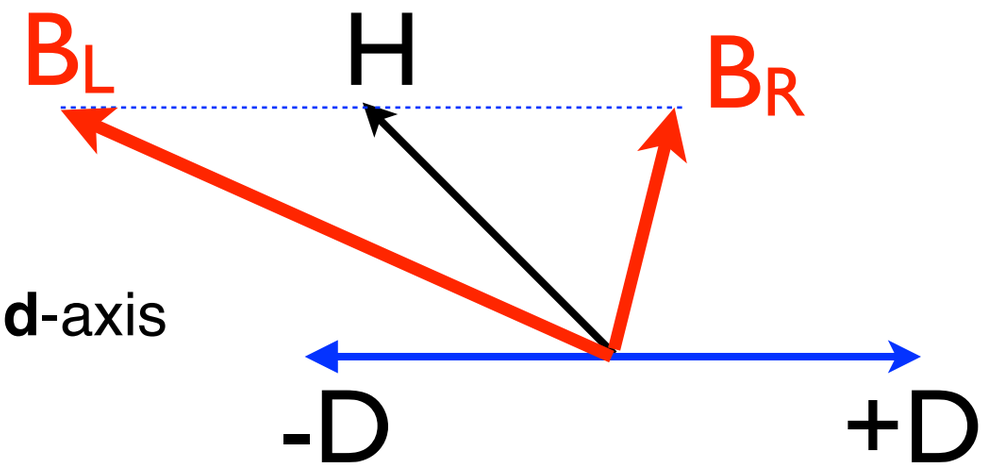
$$H = \frac{2\pi v}{3}[(\vec{M}_R)^2 + (\vec{M}_L)^2] \quad -\frac{vD}{J}[M_R^d - M_L^d] \quad -g\mu_B H[M_R^z + M_L^z]$$

unperturbed chain

uniform DM along the chain

magnetic field

Low-energy description in terms of spin currents $M_{R,L}$



Uniform DM produces internal momentum-dependent magnetic field along **d**-axis

- Total field acting on right/left movers $g\mu_B\vec{H} \pm \hbar v\vec{D}/J$
- Hence ESR signals at $2\pi\hbar\nu_{R/L} = |g\mu_B\vec{H} \pm \hbar v\vec{D}/J|$
- Polarization: for H=0 maximal absorption when microwave field h_{mw} is perpendicular to the internal (DM) one. Hence **h_{mw} ll b** is most effective.

Gangadharaiah, Sun, OS, PRB 2008

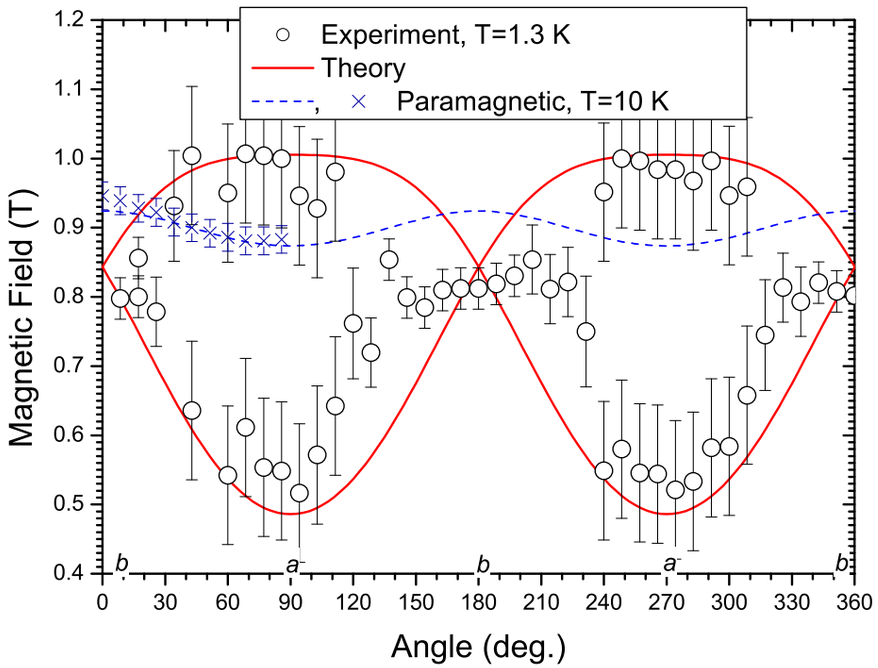
Explanation III: arbitrary orientation

- General orientation of H and D

$$(2\pi\hbar\nu_{\mathrm{R}})^2 = (g_b\mu_B H_b)^2 + (g_a\mu_B H_a + (-1)^z \pi D_a/2)^2 + (g_c\mu_B H_c + (-1)^y \pi D_c/2)^2,$$

$$(2\pi\hbar\nu_{\mathrm{L}})^2 = (g_b\mu_B H_b)^2 + (g_a\mu_B H_a - (-1)^z \pi D_a/2)^2 + (g_c\mu_B H_c - (-1)^y \pi D_c/2)^2,$$

a-b plane



$$D_a/(4\hbar) = 8 \text{ GHz}$$

$$D_c/(4\hbar) = 11 \text{ GHz}$$

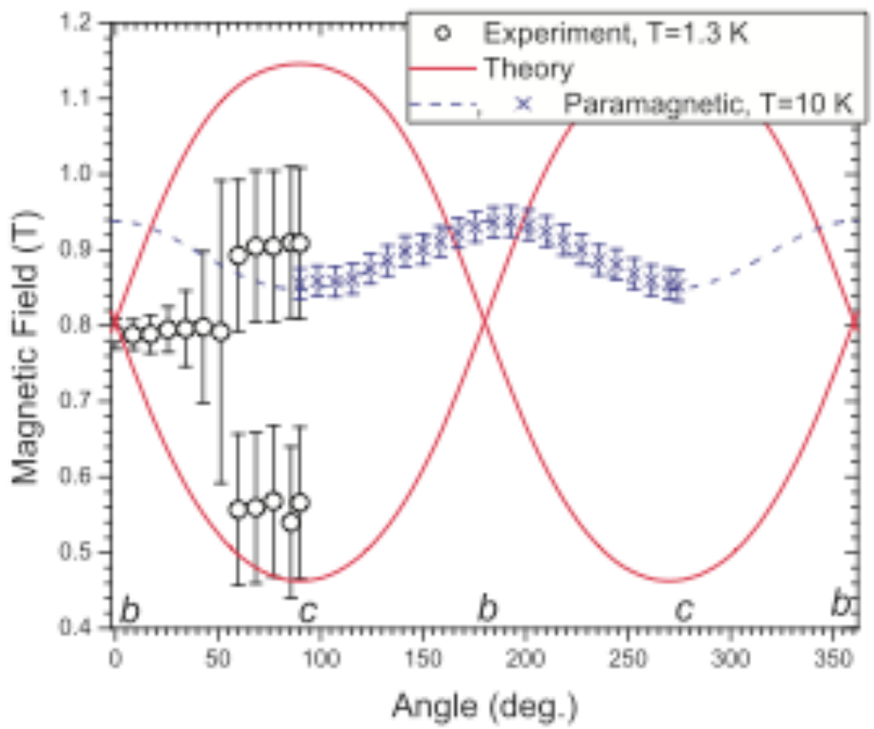
0.3 Tesla
0.4 Tesla

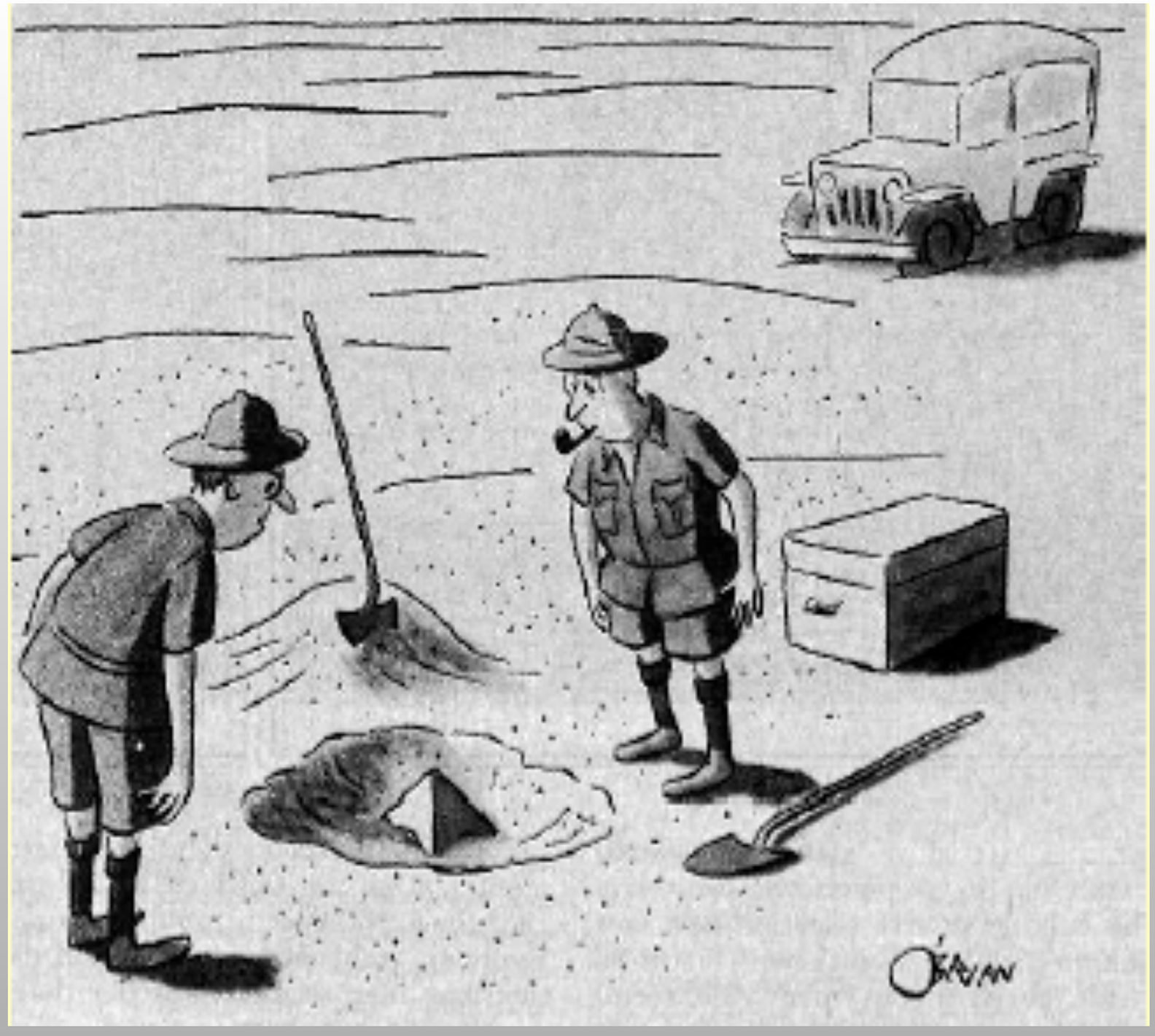
D ~ J/10

- for H along b-axis only: the "gap" is determined by the DM interaction strength

$$\Delta = \frac{\pi}{2}\sqrt{D_a^2 + D_c^2} \rightarrow (2\pi\hbar)13.6 \text{ GHz}$$

b-c plane





"This could be the discovery of the century. Depending, of course, on how far down it goes"

Can this reasoning be extended to higher dimensions?

Manipulating ESR by current in 2d conductor with Rashba Spin-Orbit interaction

PRL 98, 187203 (2007) PHYSICAL REVIEW LETTERS week ending 4 MAY 2007

g-Factor Tuning and Manipulation of Spins by an Electric Current

Zbyslaw Wilamowski,[1,2] Hans Malissa,[1] Friedrich Schäffler,[1] and Wolfgang Jantsch[1]
[1]*Institut für Halbleiter- und Festkörperphysik, Johannes Kepler Universität, A-4040 Linz, Austria*
[2]*Institute of Physics, Polish Academy of Sciences, Warsaw, and Faculty of Mathematics and Computer Sciences, UWM Olsztyn, Poland*
(Received 2 October 2006; published 3 May 2007)

We investigate the Zeeman splitting of the two-dimensional electron gas in an asymmetric silicon quantum well, performing electron-spin-resonance (ESR) experiments. Applying a small dc current we observe a shift in the resonance field due to the additional current-induced Bychkov-Rashba type of spin-orbit field. We also show that a high frequency current may induce electric dipole spin resonance very efficiently. We identify different contributions to this type of ESR signal.

Original suggestion:
Kalevich, Korenev
JETP Lett 52, 230 (1990)

$$\alpha_R(p_x\sigma_y - p_y\sigma_x) \longrightarrow \alpha_R j_x\,\sigma_y$$

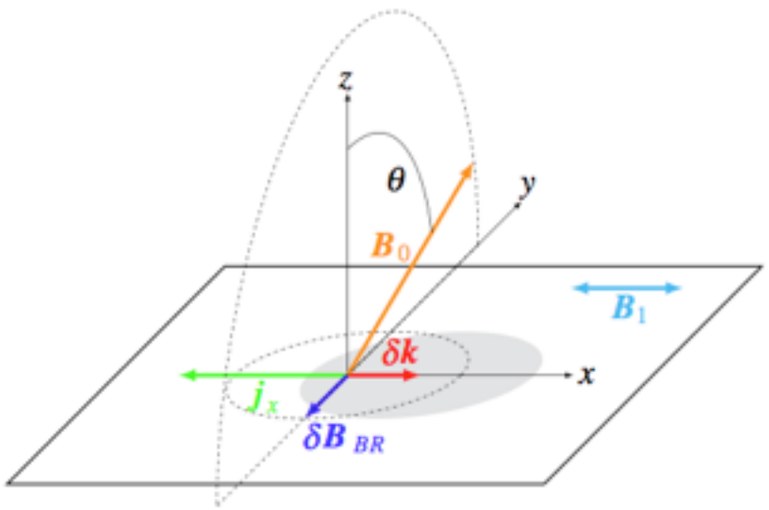


FIG. 1 (color online). A current j_x passes through a 2DEG (x-y plane). The Fermi circle (momentum distribution, dashed for $j_x = 0$, gray for $j_x \neq 0$), shifts by an amount $\hbar\delta\mathbf{k}$. Within this approximation, each electron experiences a Bychkov-Rashba field $\delta B_{\mathrm{BR},y}$ in addition to that resulting from its momentum $\hbar\mathbf{k}$. The static field B_0 (not drawn to scale) is applied in the y-z plane to enable ESR measurements.

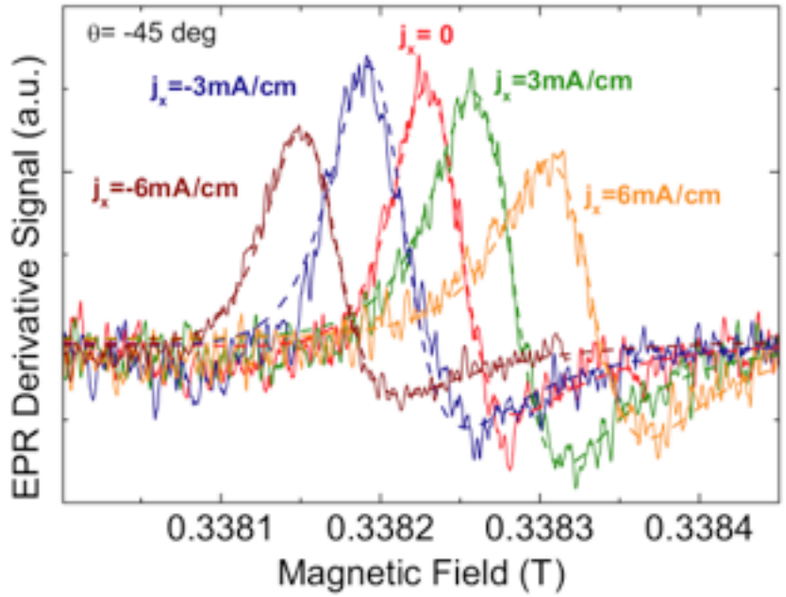


FIG. 2 (color online). ESR spectra of a 2DEG in a Si quantum well for various values of an electric current density passing a 3 mm wide sample. Measurements were performed with B_0 tilted by $\theta = -45°$ from the direction perpendicular to the sample plane at a microwave frequency of 9.4421 GHz.

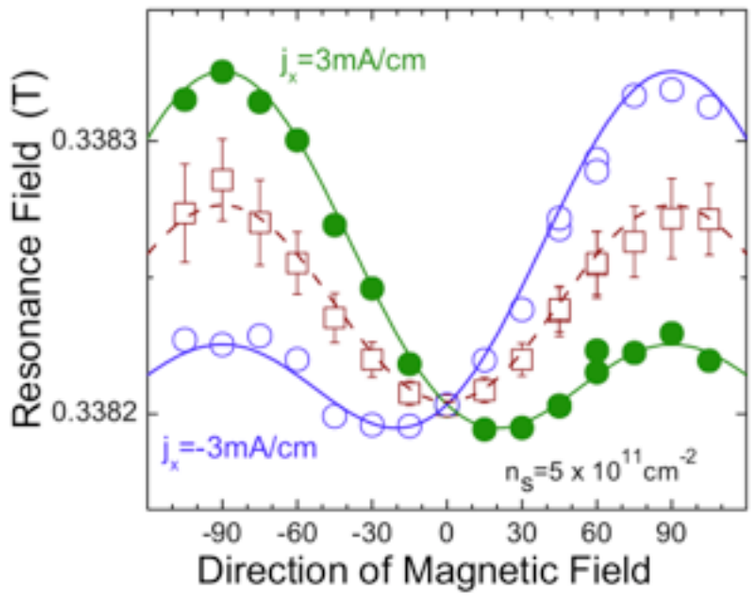


FIG. 4 (color online). Angular dependence of the ESR field for a current density $j = 0$ (squares) and ± 3 mA/cm (open and solid circles, respectively). The electron concentration is $n_S = 5 \times 10^{15}$ m^{-2} and the sample width 3 mm. Error bars correspond to 20% of the resonance linewidth.

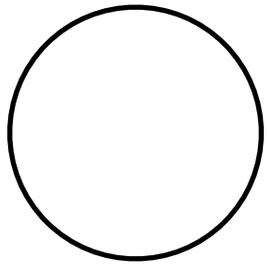
Analogy between DM in insulator and S-O interaction in 2d electron gas

- 2d gas: dc current produces static Rashba field B_R (due to drift velocity) which adds to external B_0
- 1d AFM: uniform DM interaction produces **k**-dependent internal magnetic field which adds to external B_0
- But note that in 1d antiferromagnet the ***spinons*** are ***neutral fermions***
- Crucial ingredient: Fermi surface !
- Key point: DM in antiferromagnetic insulator with spinon FS plays the role of spin-orbit interaction for neutral fermions (spinons).
- Hence, question:

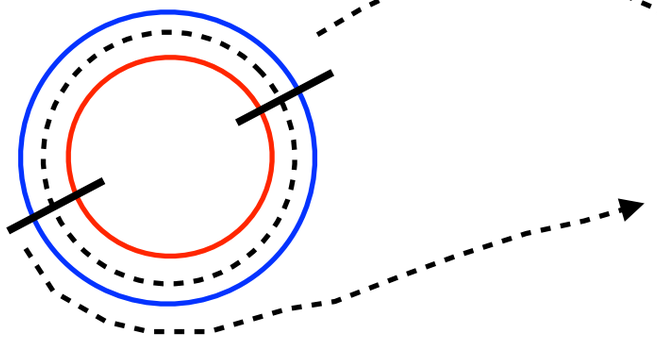
  What is ESR lineshape in the 2d Fermi gas with spin-orbit interaction and subject to uniform magnetic field?

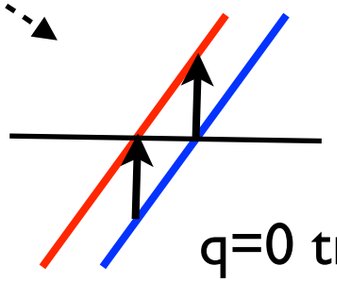
Estimates for 2d spinon gas using Rashba model as an example

no DM

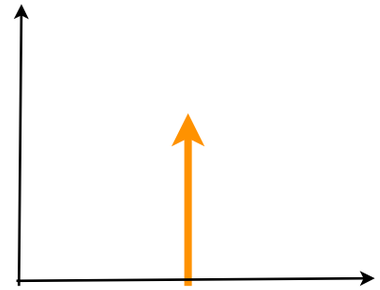


in-plane ***H***





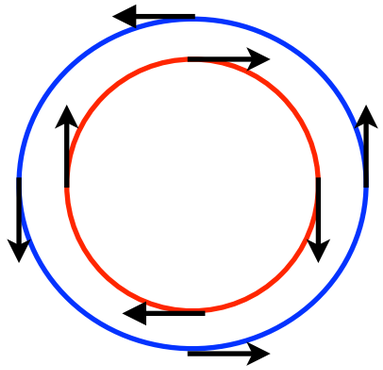
ESR signal



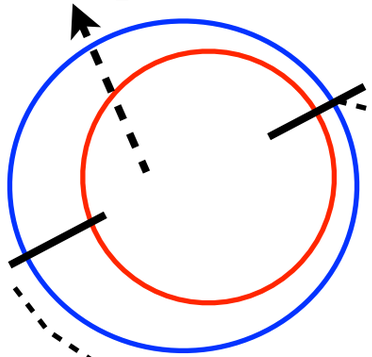
q=0 transitions at single ω = gμh

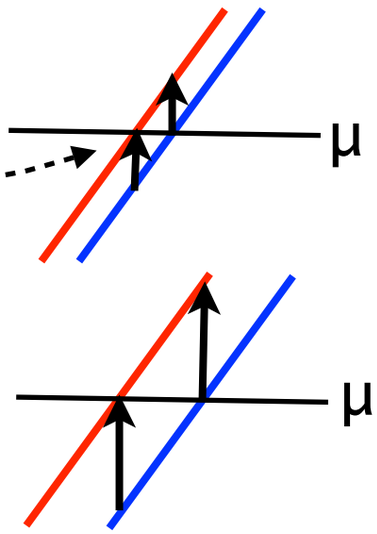
ω = gμH

DM $\alpha_R(p_x\sigma_y - p_y\sigma_x)$



in-plane ***H***





ω_{min}

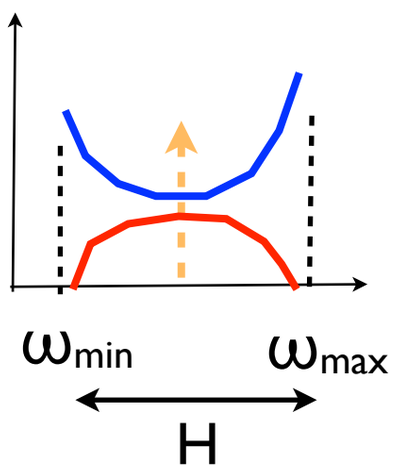
ω_{max}

splitting of Fermi surfaces $\sqrt{\Delta_{so}^2 + \Delta_Z^2 + 2\Delta_{so}\Delta_Z \sin\phi}$

Energy absorption due to microwave h(t)

ESR signal

χ”



the width of the line ~ min(H, α_R k_F)
line shape is strongly polarization-dependent:

$[\omega - \omega_{min/max}]^{-1/2}$ for h(t) perpendicular to H

$[\omega - \omega_{min/max}]^{1/2}$ for h(t) parallel to H

Glenn, Raikh, OS, 2012

Conclusions

- Spinons *vs.* spin waves. Seen in neutrons, thermal transport.
- ESR as a novel probe of critical spinons (neutral fermions)
  - measurements at small momentum ~ D/J
  - allows to extract parameters of DM (spin-orbit) interaction
- Higher-dimensional extensions?!

"old" ESR probe
can access "new"
deconfined spinons
with a help from
DM interactions