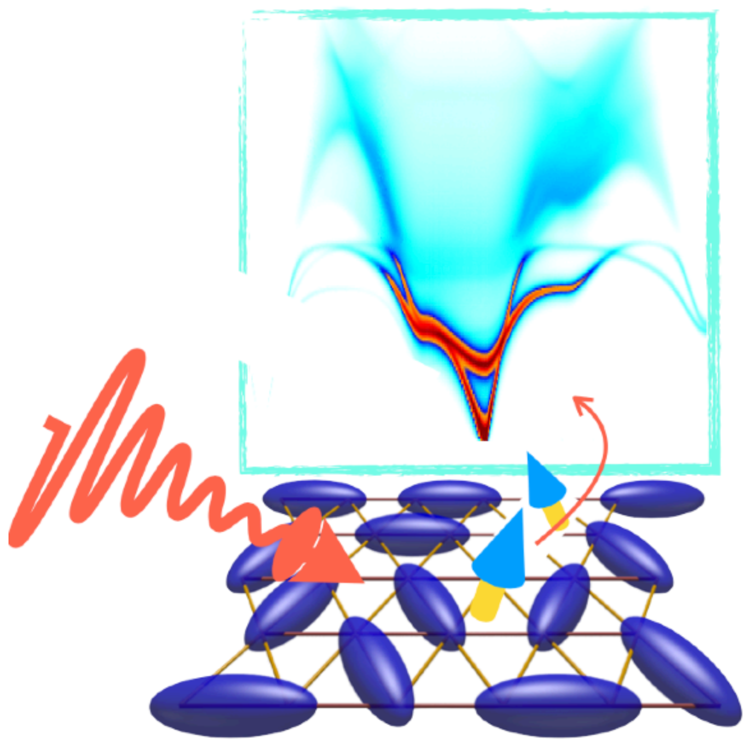
Dynamical response of magnetized spin liquids



Oleg Starykh, University of Utah

ICTP, December 2023, Trieste

Probing fractionalized excitations *and* their interactions

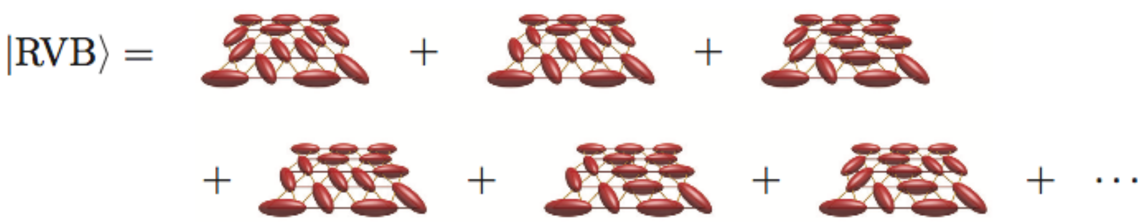


Figure 1. A 'resonating valence bond' (RVB) state. Ellipsoids indicate spin-zero singlet states of two $S = 1/2$ spins.

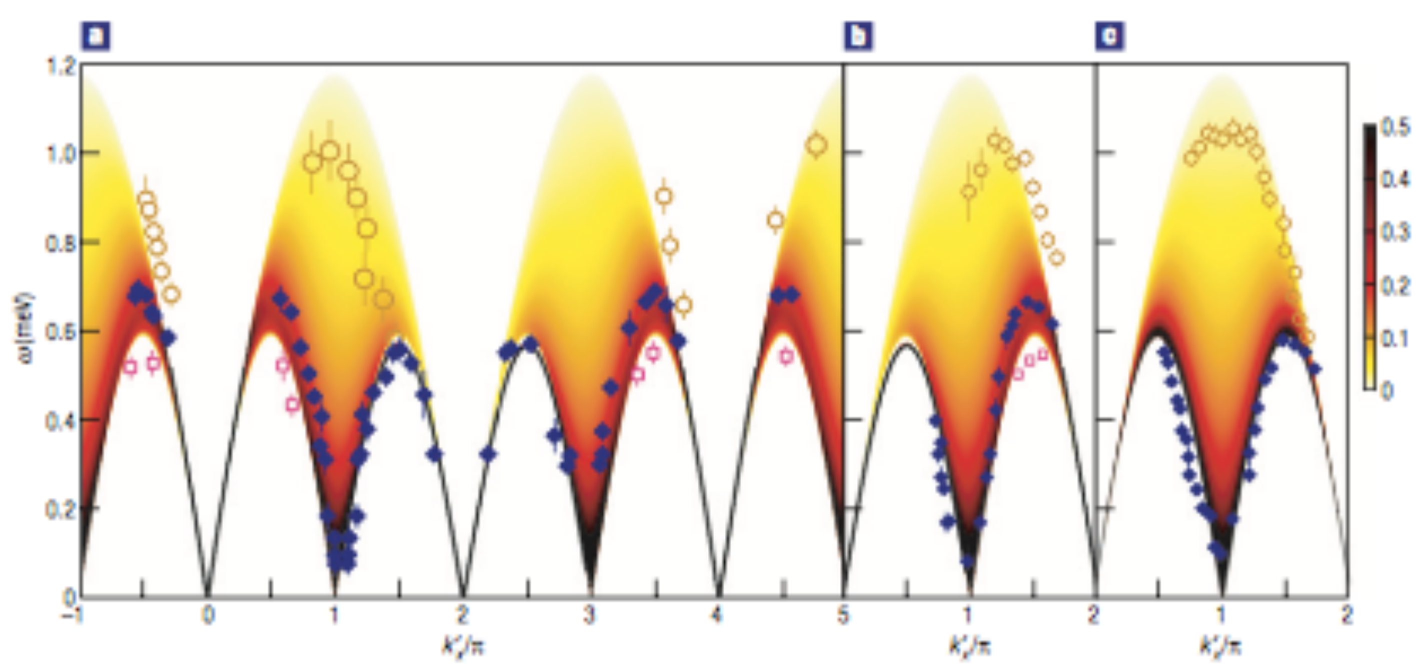
Savary, Balents 2017

No broken symmetries.
Quantum entangled state:
fractionalized excitations = spinons
+ emergent gauge fields

How to detect/observe it?

Neutrons, RIXS, NMR, thermal transport, terahertz optics, ESR, quantum spintronics

Dynamics in magnetic field!



Outline

Probing fractionalized excitations *and* their collective modes.

Spinon Fermi surface spin liquid in magnetic field. Spinon spin wave.

New take on the magnetized Heisenberg spin chain.

Interacting Dirac fermions in magnetic field.

Spin liquid (?) in magnetic field

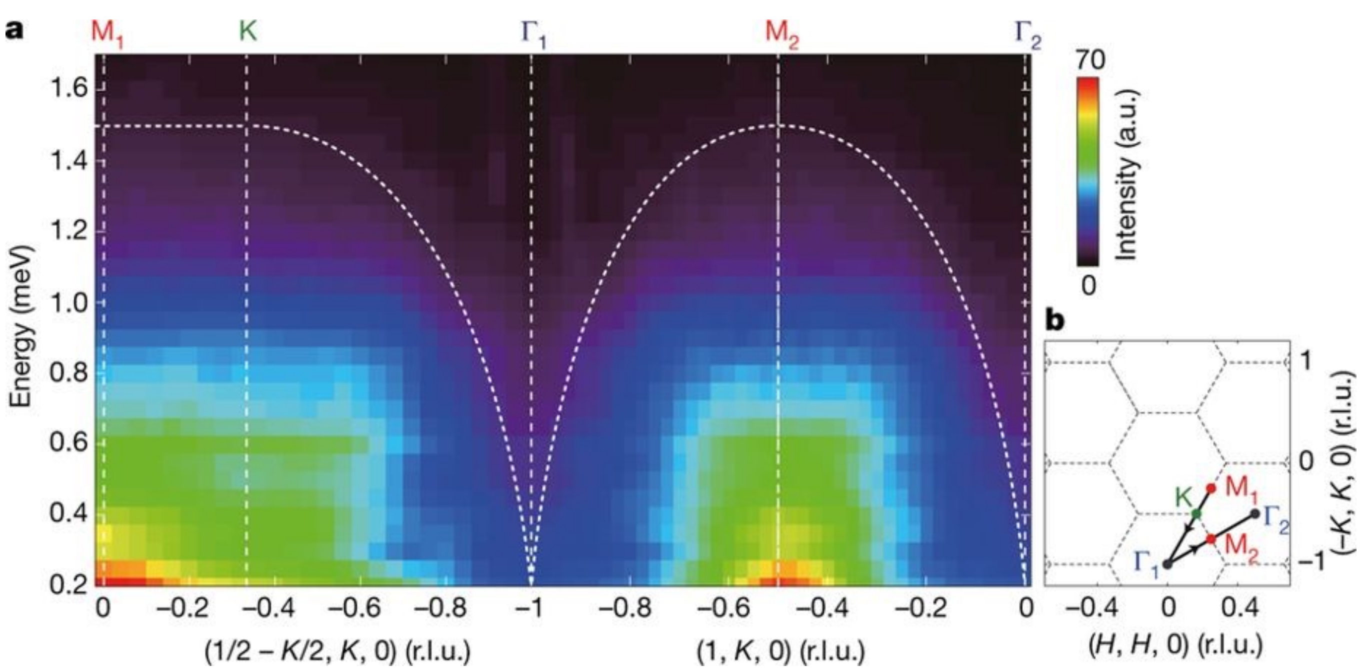
What is S(k,w) for a spinon FS QSL?

Letter | Published: 05 December 2016

Evidence for a spinon Fermi surface in a triangular-lattice quantum-spin-liquid candidate

Yao Shen, Yao-Dong Li, Hongliang Wo, Yuesheng Li, Shoudong Shen, Bingying Pan, Qisi Wang, H. C. Walker, P. Steffens, M. Boehm, Yiqing Hao, D. L. Quintero-Castro, L. W. Harriger, M. D. Frontzek, Lijie Hao, Siqin Meng, Qingming Zhang, Gang Chen & Jun Zhao

Nature **540**, 559–562 (22 December 2016) | Download Citation



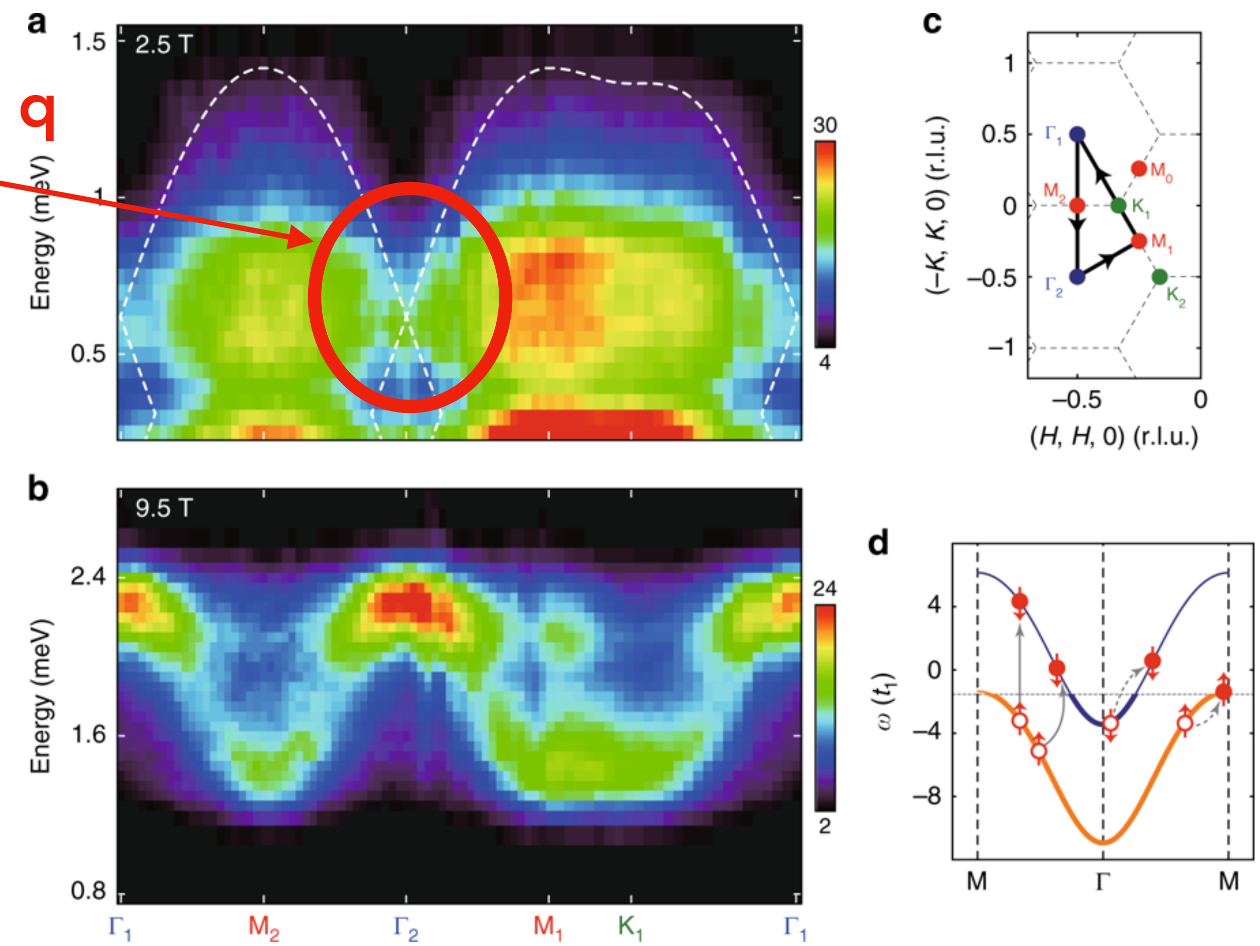
Article | OPEN | Published: 08 October 2018

Fractionalized excitations in the partially magnetized spin liquid candidate $YbMgGaO_4$

Yao Shen, Yao-Dong Li, H. C. Walker, P. Steffens, M. Boehm, Xiaowen Zhang, Shoudong Shen, Hongliang Wo, Gang Chen & Jun Zhao

Nature Communications **9**, Article number: 4138 (2018) | Download Citation

Small momentum **q** structure



Sketch of U(1) gauge theory

1) $S^a_{\mathbf{r}} = \frac{1}{2}\psi^\dagger_{\mathbf{r},\alpha}\sigma^a_{\alpha\beta}\psi_{\mathbf{r},\beta}$ provided $\sum_\alpha \psi^\dagger_{\mathbf{r},\alpha}\psi_{\mathbf{r},\alpha} = 1$ enforced by $\mathbf{A_0}$

2) $\vec{S}_{\mathbf{r}} \cdot \vec{S}_{\mathbf{r}'} \to |\Delta_{\mathbf{r}\mathbf{r}'}| e^{iA_{\mathbf{r}\mathbf{r}'}} \psi^\dagger_{\mathbf{r}\alpha}\psi_{\mathbf{r}'\alpha}$ → $A_{\mathbf{r}\mathbf{r}'} \to (\mathbf{r}-\mathbf{r}') \cdot \mathbf{A}\left(\frac{\mathbf{r}+\mathbf{r}'}{2}\right)$

3) $S_\psi = \int d\tau d^2\mathbf{r}\, \psi^\dagger_\alpha \Big([\partial_\tau - iA_0 - \mu - \frac{(\nabla_{\mathbf{r}} - i\mathbf{A})^2}{2m}]\delta_{\alpha\beta} - \omega_B \sigma^3_{\alpha\beta} \Big) \psi_\beta.$

Spinon

External magnetic field

Gauge field

Gauge theory of high-temperature superconductors and strongly correlated Fermi systems

G. Baskaran and P. W. Anderson

Gapless fermions and gauge fields in dielectrics

L. B. Ioffe and A. I. Larkin

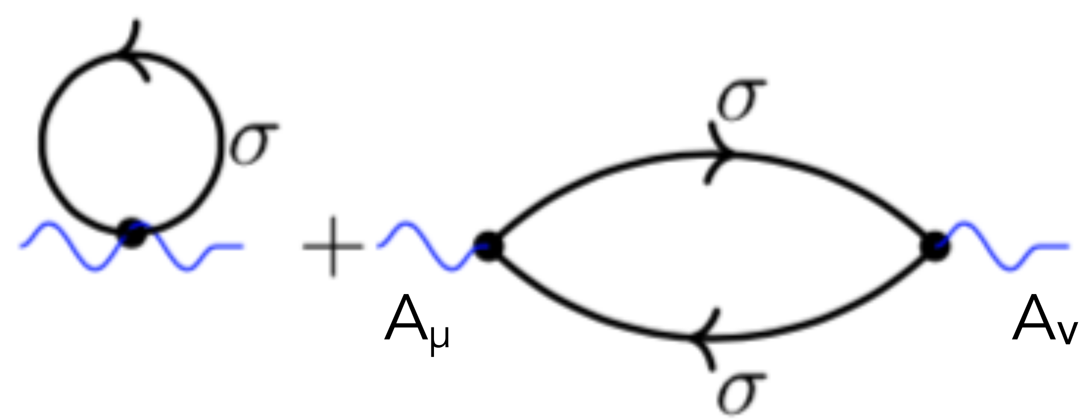
Phys. Rev. B **39**, 8988 – Published 1 May 1989

Gauge theory of the normal state of high-T_c superconductors

Patrick A. Lee and Naoto Nagaosa

Phys. Rev. B **46**, 5621 – Published 1 September 1992

4) Gauge dynamics generated by spinons



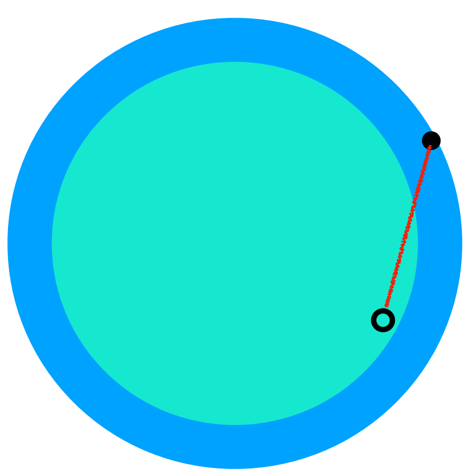
Interactions

- Longitudinal

$$A_0\psi^\dagger\psi \rightarrow u\psi^\dagger_\uparrow\psi_\uparrow\psi^\dagger_\downarrow\psi_\downarrow$$

screened Coulomb interaction

Short-ranged

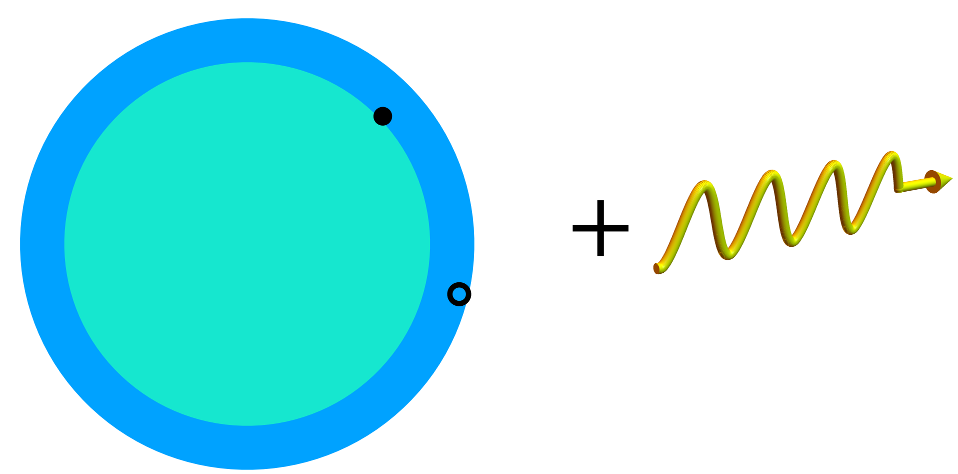


- Transverse

$$i\boldsymbol{A}\cdot\left(\psi^\dagger\boldsymbol{\nabla}\psi - \boldsymbol{\nabla}\psi^\dagger\psi\right)$$

coupling to dynamical photons

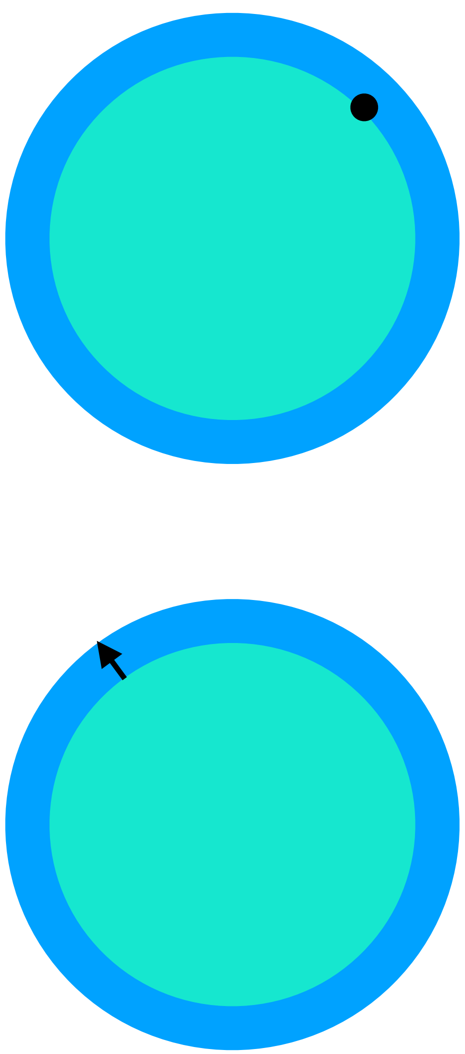
Source of non-analytical behaviors $\omega^{2/3}$, etc



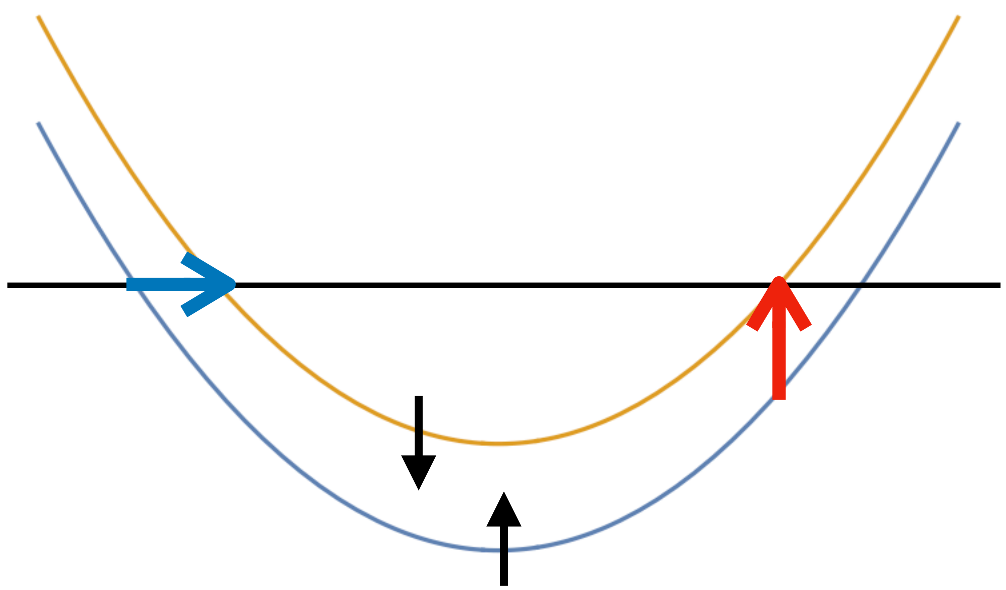
Spinon particle-hole continuum

+ Zeeman field

$$\chi_{\pm}(\boldsymbol{q},\omega) = i\int_0^{\infty} dt \langle [S^{\dagger}_{\mathbf{q}}(t), S^{-}_{-\mathbf{q}}(0)]\rangle e^{i\omega t}$$

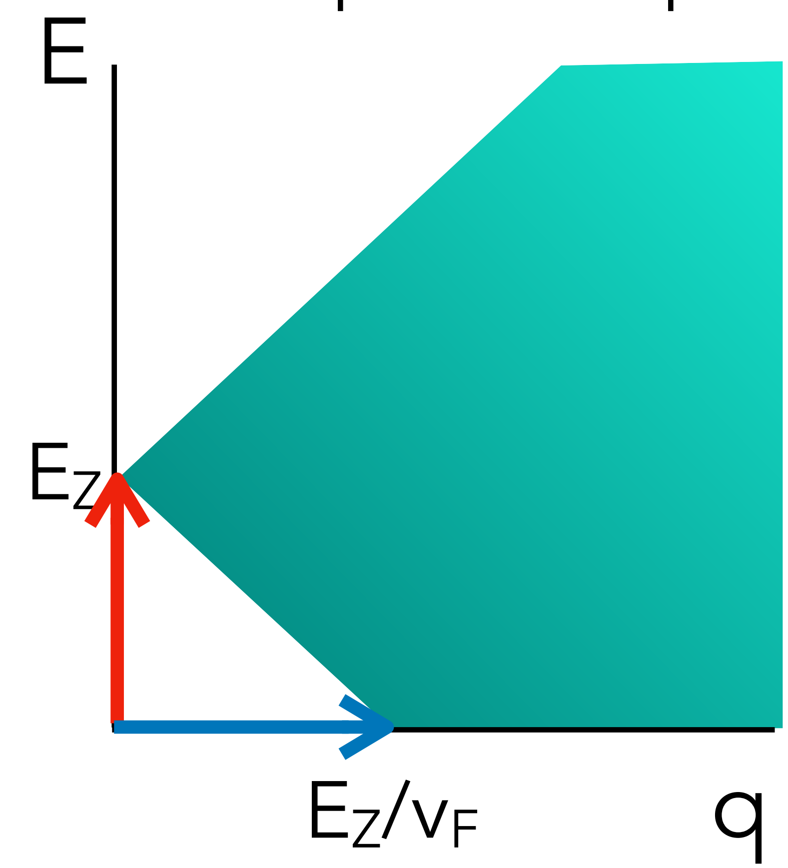


q=0 costs Zeeman energy



zero energy when $v_F q$
= Zeeman

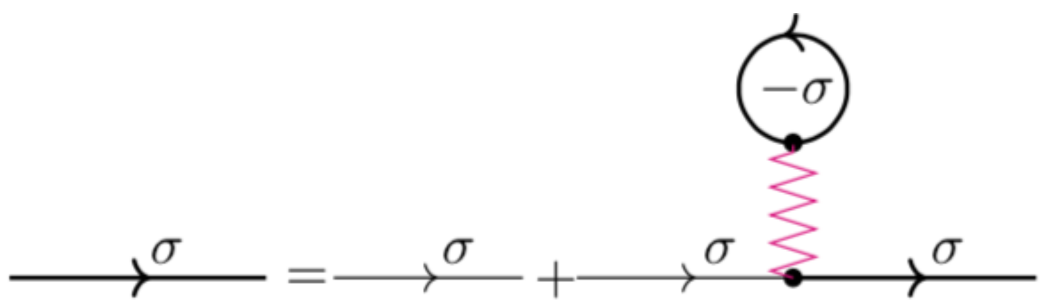
Transverse spin susceptibility



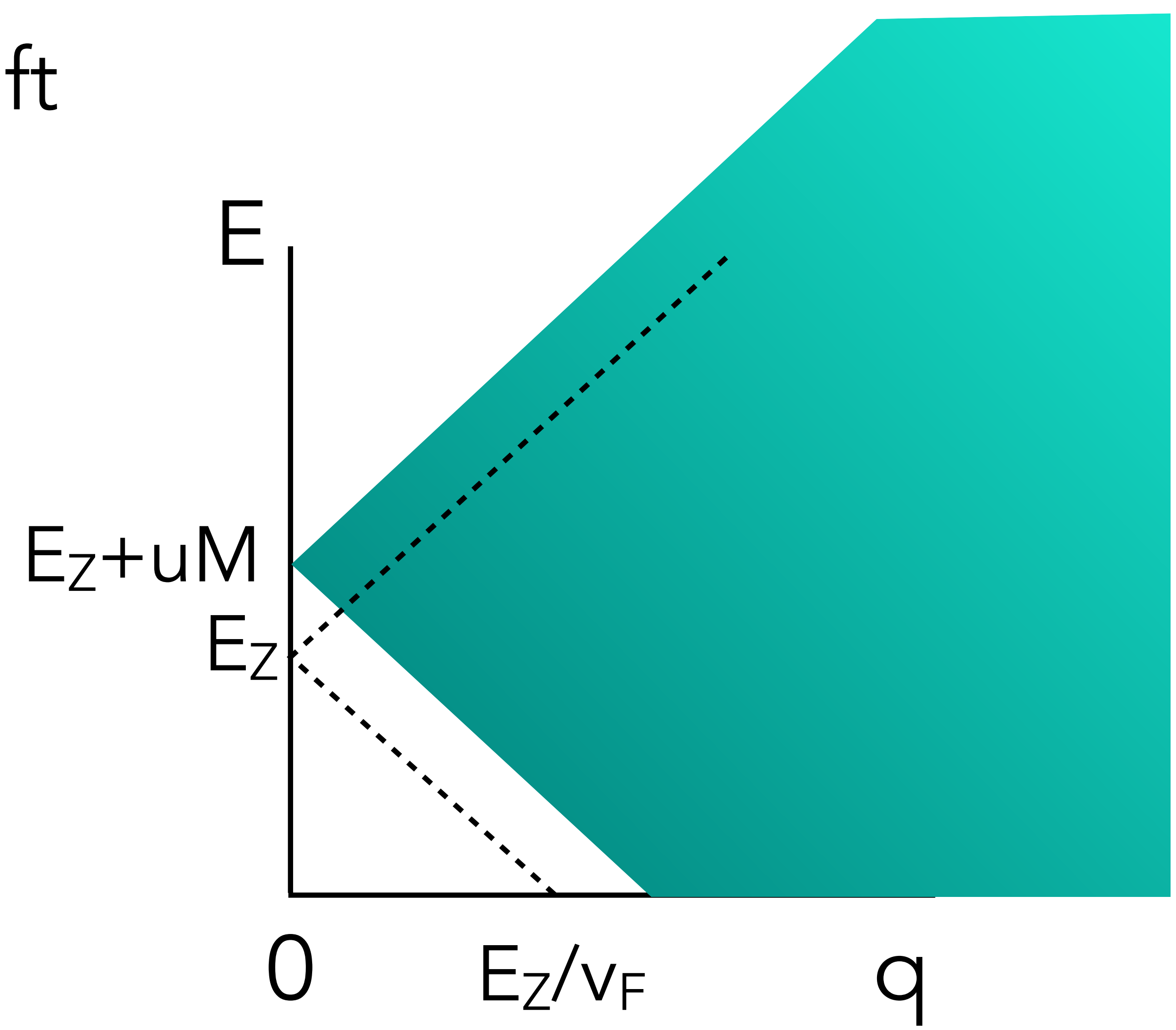
Short-range interaction + Zeeman magnetic field

$$u\psi_\uparrow^\dagger\psi_\uparrow\psi_\downarrow^\dagger\psi_\downarrow \rightarrow = -\frac{1}{2}uM(\psi_\uparrow^\dagger\psi_\uparrow - \psi_\downarrow^\dagger\psi_\downarrow)$$

Self-energy = mean field shift



PH continuum shifts *up* in energy by **uM**



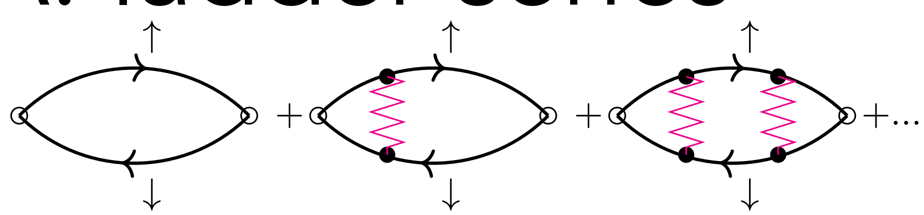
$$E_Z = 2\omega_B$$

Silin spin wave

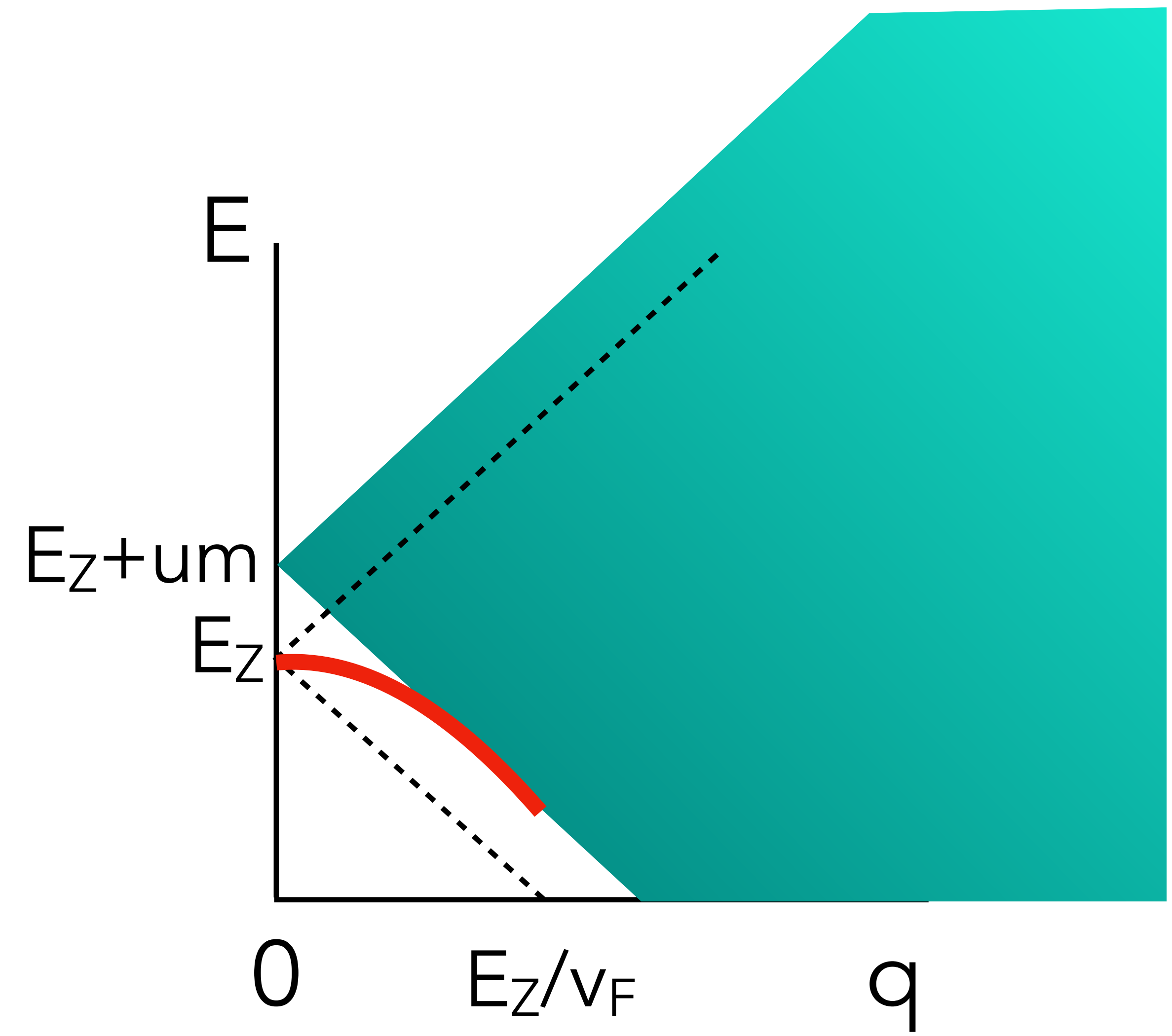
<u>Larmor theorem</u>: **q**=0 excitation *must* be at E_Z

$$\frac{dS^+_{\mathrm{tot}}}{dt} = -iBS^+_{\mathrm{tot}}$$

RPA: ladder series



$$\chi(\boldsymbol{q}, i\omega_n) = \frac{\chi^0(\boldsymbol{q}, i\omega_n)}{1 + u\chi^0(\boldsymbol{q}, i\omega_n)}$$



"Silin spin wave"

pole: collective mode

$$\omega = E_Z + um - \sqrt{u^2m^2 + v_F^2 q^2}$$

<u>Theory:</u> V.P. Silin, JETP 6, 945 (1958); Platzman, Wolf, PRL 18, 280 (1967);
<u>Exp:</u> Schultz, Dunifer, PRL 18, 283 (1967).

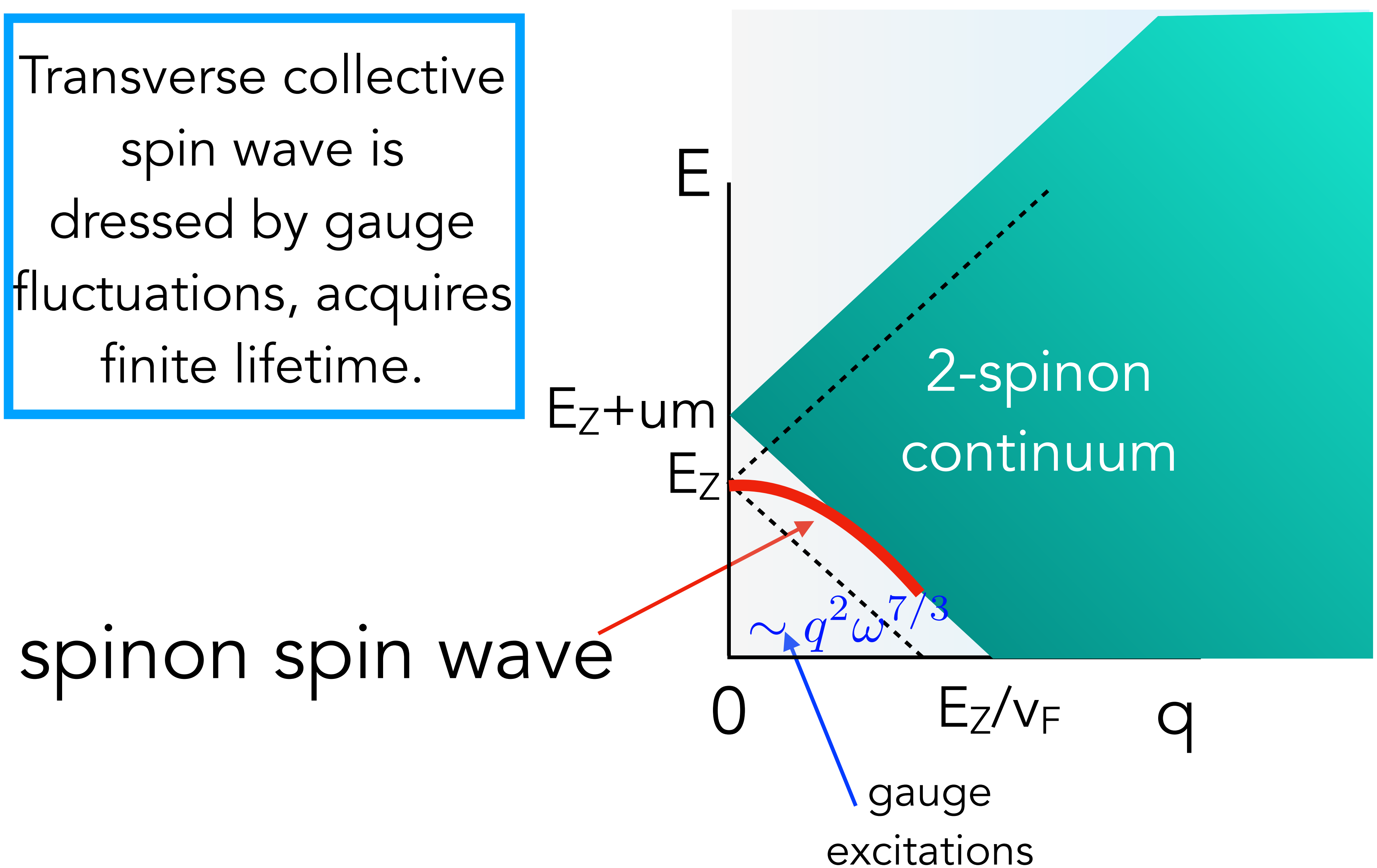
Rapid Communication

Collective spinon spin wave in a magnetized U(1) spin liquid

Leon Balents and Oleg A. Starykh
Phys. Rev. B **101**, 020401(R)

Distinct signature of spinons, interactions, and gauge fields

Transverse collective spin wave is dressed by gauge fluctuations, acquires finite lifetime.



$$\frac{E_Z}{v_F} \sim \sqrt{mE_Z}\sqrt{\frac{E_Z}{E_F}}$$

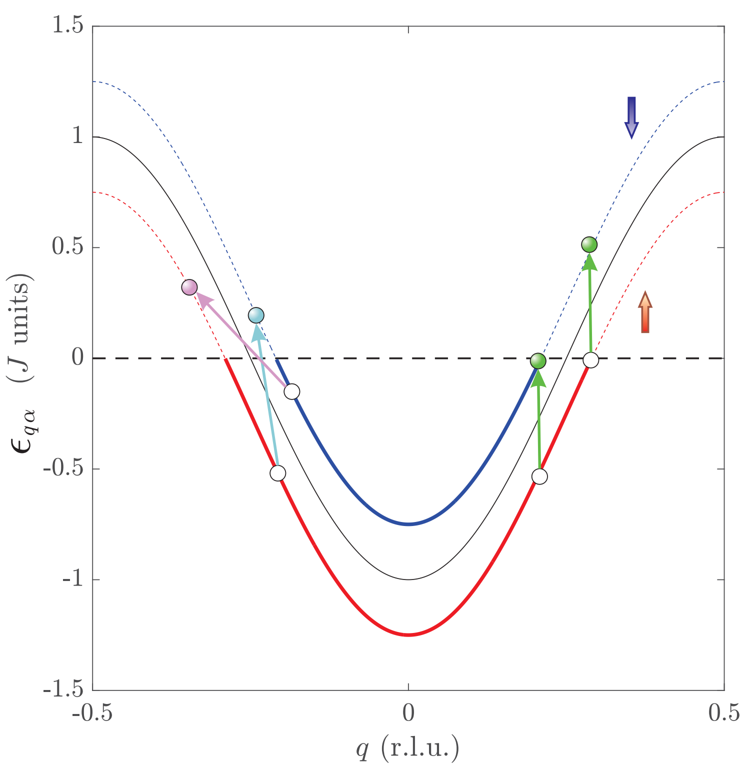
conductors $\frac{E_Z}{E_F} \to 0$

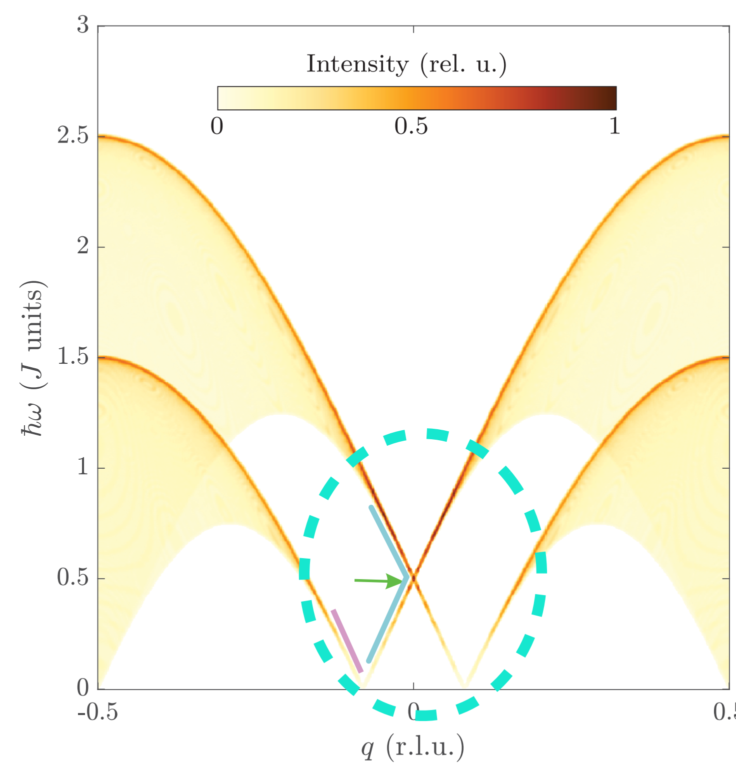
QSL $\frac{E_Z}{E_F} \sim 1$

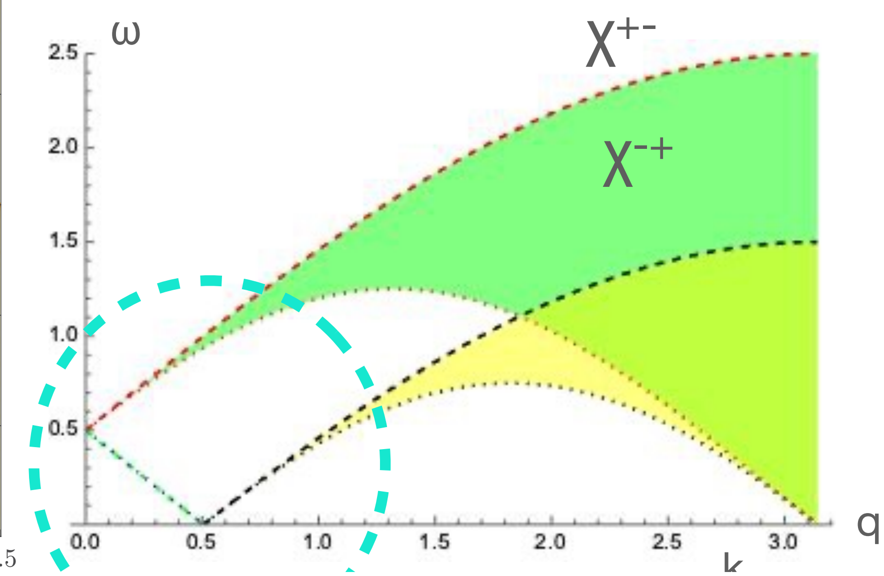
Check the best-known spin liquid: spin-1/2 chain in a magnetic field

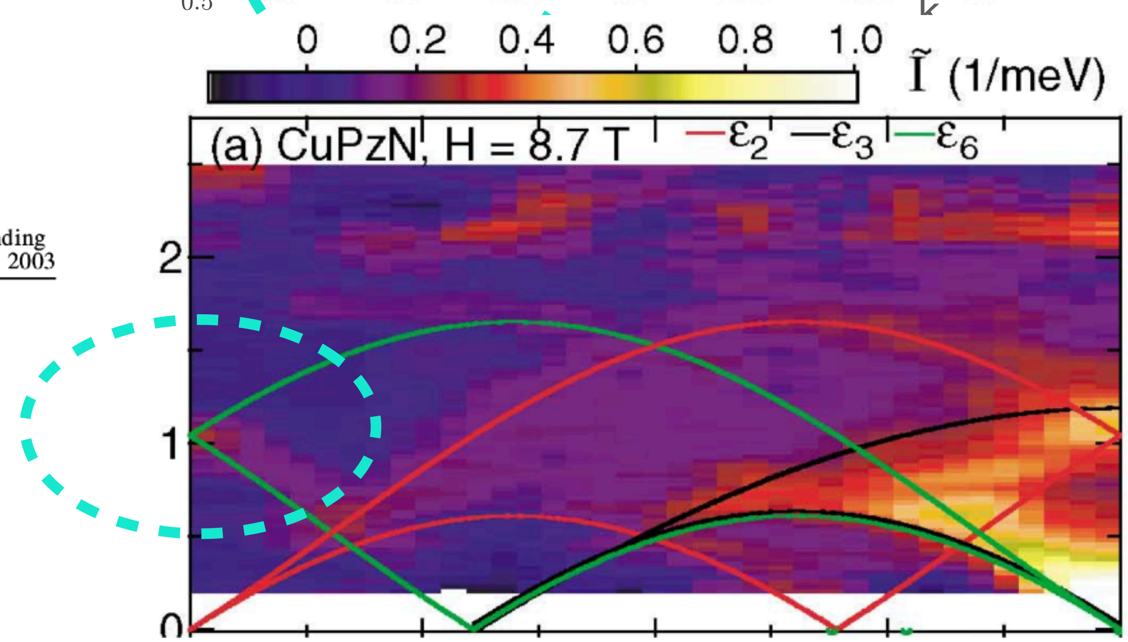
Non-interacting limit (g=0) - field splits spin up/down bands

$$H = H_0 - B\int dx \left[\underbrace{J_R^z(x) + J_L^z(x)}_{\text{Magnetization}}\right]$$









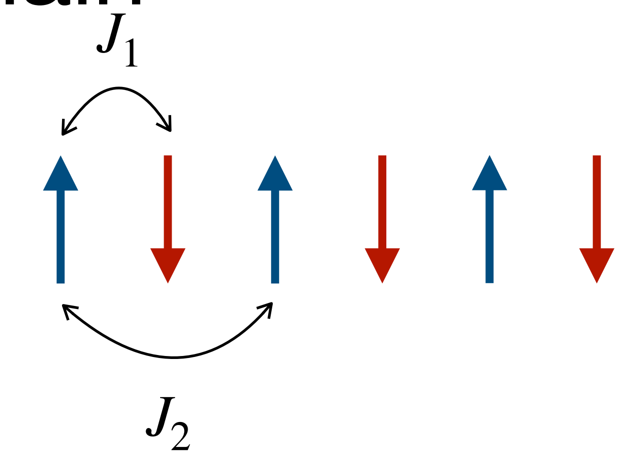
VOLUME 91, NUMBER 3 PHYSICAL REVIEW LETTERS week ending 18 JULY 2003

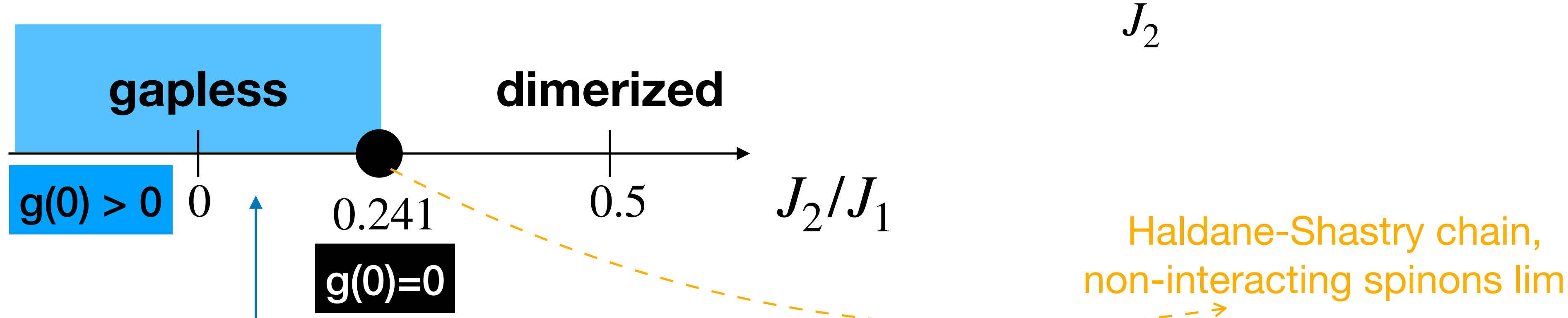
Extended Quantum Critical Phase in a Magnetized Spin-$\frac{1}{2}$ Antiferromagnetic Chain

M. B. Stone,[1,*] D. H. Reich,[1] C. Broholm,[1,2] K. Lefmann,[3] C. Rischel,[4] C. P. Landee,[5] and M. M. Turnbull[5]

Spin-1/2 antiferromagnetic chain

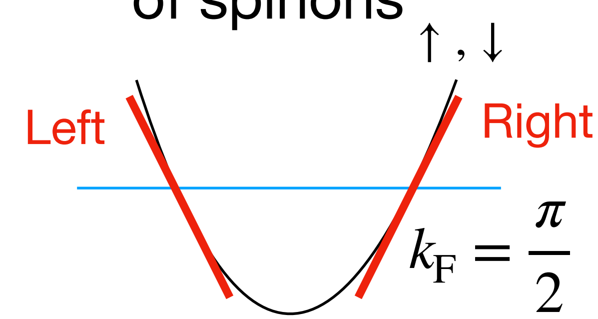
$$H = \sum_n J_1 \vec{S}_n \cdot \vec{S}_{n+1} + J_2 \vec{S}_n \cdot \vec{S}_{n+2} - B S_n^z$$





backscattering is
marginally irrelevant!

half-filled band
of spinons

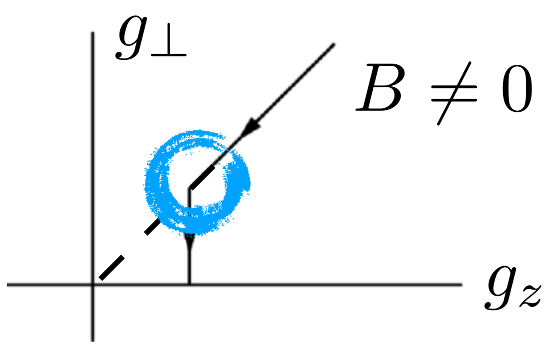


$$H = \int dx \Big(\underbrace{\psi_R^\dagger (-i v_F \partial_x) \psi_R + \psi_L^\dagger (i v_F \partial_x) \psi_L}_{H_0} \Big) \underbrace{- g \vec{J}_R \cdot \vec{J}_L}_{H_{\rm int}}$$

Free fermions

Spin current $\vec{J}_{R/L} = \frac{1}{2} \psi_{R/L}^\dagger \vec{\sigma} \psi_{R/L}$

$$\vec{S}(x_i) \to \vec{J}_R + \vec{J}_L + \frac{(-1)^{x_i}}{2} \left(\psi_R^\dagger \vec{\sigma} \psi_L + \psi_L^\dagger \vec{\sigma} \psi_R \right)$$



g>0: marginally irrelevant interaction of spin currents (spin backscattering ~ $g \cos[\sqrt{8\pi}\varphi_\sigma]$)

$$g(\ell) = \frac{g(0)}{1 + g(0)\ell}, \ \ell = \ln(J/E) \longrightarrow g(E \to 0) \to 1/\ln(J/E)$$

Spin-1/2 Heisenberg chain in magnetic field

PHYSICAL REVIEW B, VOLUME 65, 134410

Electron spin resonance in $S=\frac{1}{2}$ antiferromagnetic chains

Masaki Oshikawa[1] and Ian Affleck[2,*]
[1]*Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan*
[2]*Department of Physics, Boston University, Boston, Massachusetts 02215*
(Received 13 August 2001; published 19 March 2002)

Dynamically Dominant Excitations of String Solutions in the Spin-1/2 Antiferromagnetic Heisenberg Chain in a Magnetic Field

Masanori Kohno
Phys. Rev. Lett. **102**, 037203 – Published 22 January 2009

Non-interacting spinon continuum

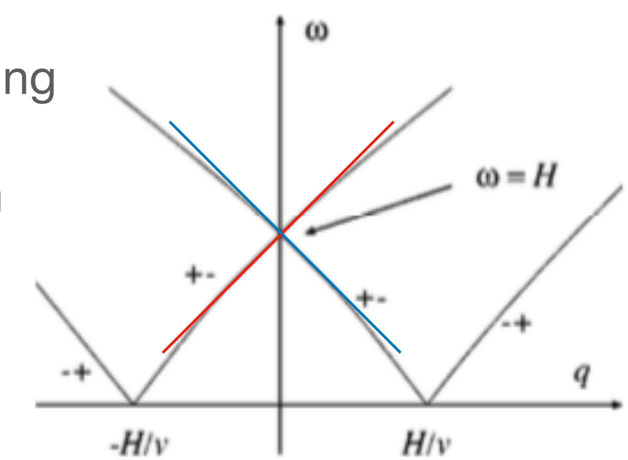


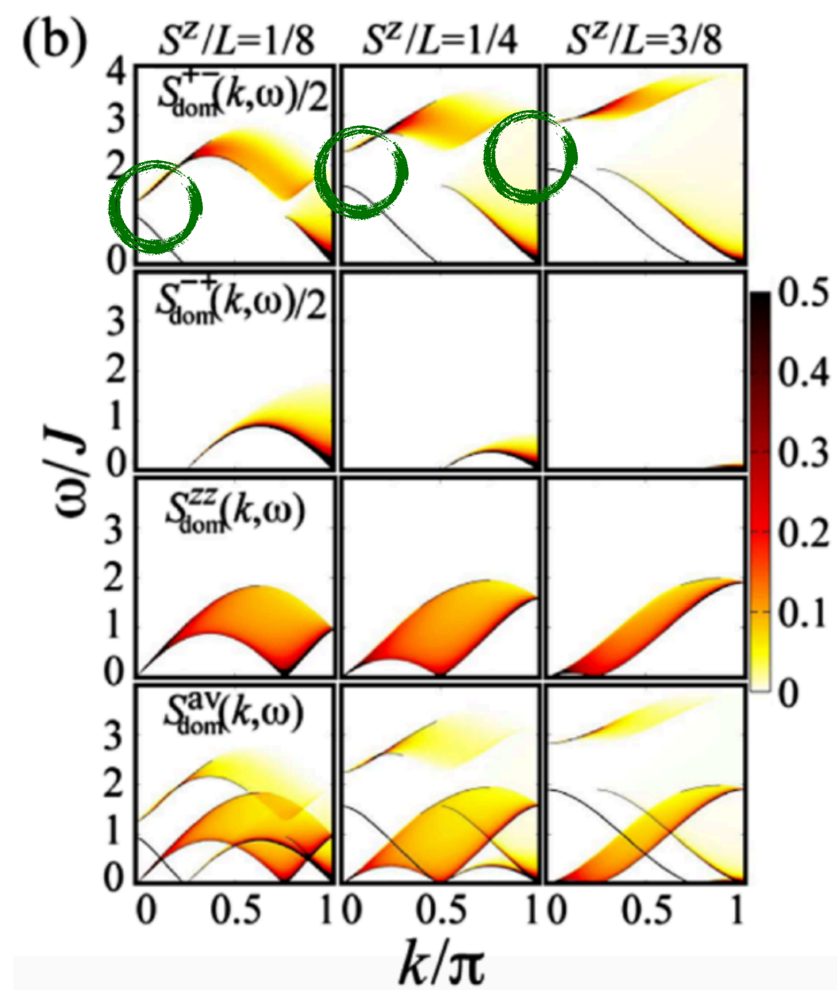
FIG. 2. The zero temperature transverse spin structure factor $S_{xx}(\omega,q)=S_{yy}(\omega,q)$ of the $S=1/2$ Heisenberg antiferromagnetic chain under an applied field H, near $q=0$. It is approximately proportional to $\omega[\delta(\omega-|q-H|)+\delta(\omega-|q+H|)]$, giving the resonance at $q=0$, $\omega=H$. This consists of two branches coming from S_{+-} and S_{-+}, which are marked by $+-$ and $-+$ in the graph. In fact, there is a small spreading of the spectrum and the structure factor is generally not a perfect delta function. However, it is exactly the delta function $\delta(\omega-H)$ at $q=0$, as explained in the text.

$$S_{xx}(\omega,q)=S_{yy}(\omega,q)\propto\omega[\delta(\omega-|q+H|)+\delta(\omega-|q-H|)].$$

BUT

???

Splitting between two branches; increases with M



Numerical simulations

Spin backscattering is finite at energy E = B

$$H = H_0 - g\int dx\left[J_R^z J_L^z + \frac{1}{2}J_R^+ J_L^- + \frac{1}{2}J_R^- J_L^+\right] - B\int dx\left[J_R^z(x) + J_L^z(x)\right]$$

Transverse interaction must restore Larmor Th

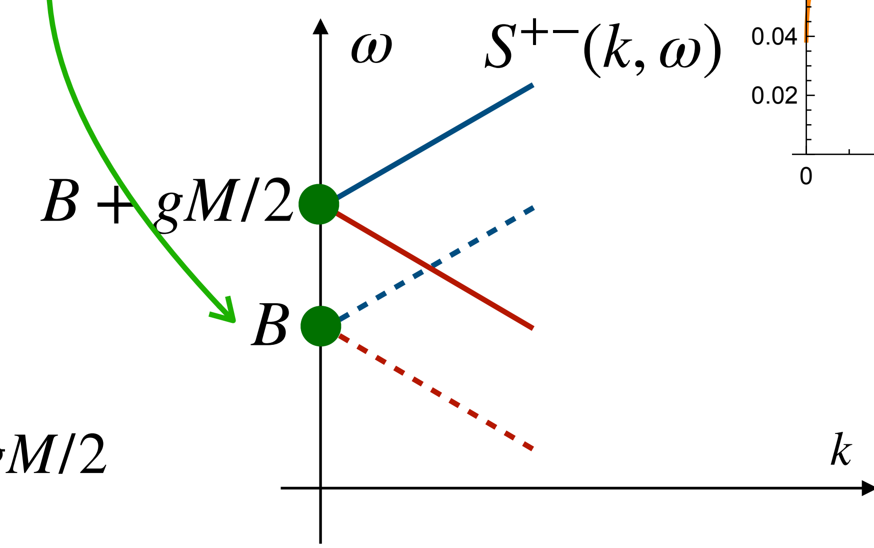
Self energy

$$-g\int dx\left[\langle J_L^z\rangle J_R^z + J_L^z\langle J_R^z\rangle\right]$$

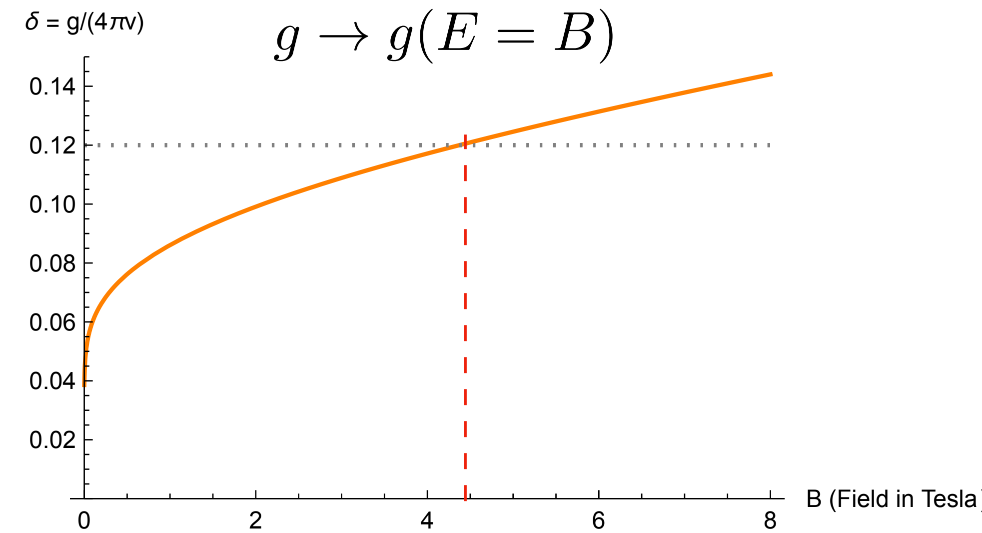
$$\langle J_{L,R}^z\rangle = M/2 \longrightarrow B + gM/2$$

(magnetization)

shifts the mode at k=0: $B \to B + gM/2$



$g \to g(E = B)$



$$g \approx \frac{\pi^2 J}{\ln\left(\frac{\sqrt{2\pi^3}e^{\gamma}J}{B}\right)}$$

Theoretical problem: need to calculate dynamical spin susceptibility with the finite backscattering interaction between spinons

ELSEVIER
Nuclear Physics B 522 [FS] (1998) 533–549
NUCLEAR PHYSICS B

Low energy effective Hamiltonian for the XXZ spin chain

Sergei Lukyanov[1]
Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08855-0849, USA
L.D. Landau Institute for Theoretical Physics, Kosygina 2, Moscow, Russia

(approximate) hydrodynamics: Dynamical susceptibility of interacting spinon liquid

Spin currents obey (level 1) Kac-Moody algebra: $[\hat{J}^a_{R/L}(x), \hat{J}^b_{R/L}(x')] = \frac{\mp i}{4\pi}\delta^{ab}\partial_x\delta(x-x') + i\epsilon^{abc}\hat{J}^c_{R/L}(x)\delta(x-x')$

Equations of motion for right/left spin currents lead to the **hydrodynamic** description of the small-**k** response: $\mathbf{M} = \mathbf{J}_R + \mathbf{J}_L, \mathbf{L} = \mathbf{J}_R - \mathbf{J}_L$

$$\partial_t \mathbf{M} = -v(1+\delta)\partial_x \mathbf{L} - \mathbf{B}\times\mathbf{M}$$

$$\partial_t \mathbf{L} = -v(1-\delta)\partial_x \mathbf{M} - \mathbf{B}\times\mathbf{L} - \boxed{g\mathbf{M}\times\mathbf{L}} \dashrightarrow \boxed{\mathbf{M}\to\langle\mathbf{M}\rangle = \frac{\chi_0}{1-\delta}\mathbf{B}} \to \partial_t\mathbf{L} = -v(1-\delta)\partial_x\mathbf{M} - \frac{1+\delta}{1-\delta}\mathbf{B}\times\mathbf{L}$$

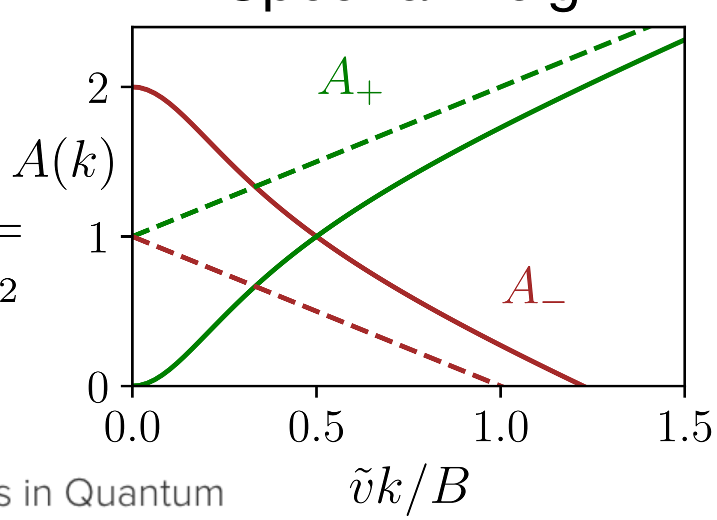
interaction ! approximation

The result: $$\chi^{\pm}(k,\omega) = M\left(\frac{A_+(k)}{\omega-\omega_+(k)} + \frac{A_-(k)}{\omega-\omega_-(k)}\right) \qquad \omega_\pm(k) = B + \frac{\delta B}{1-\delta} \pm \sqrt{\left(\frac{\delta B}{1-\delta}\right)^2 + v^2(1-\delta^2)k^2}$$

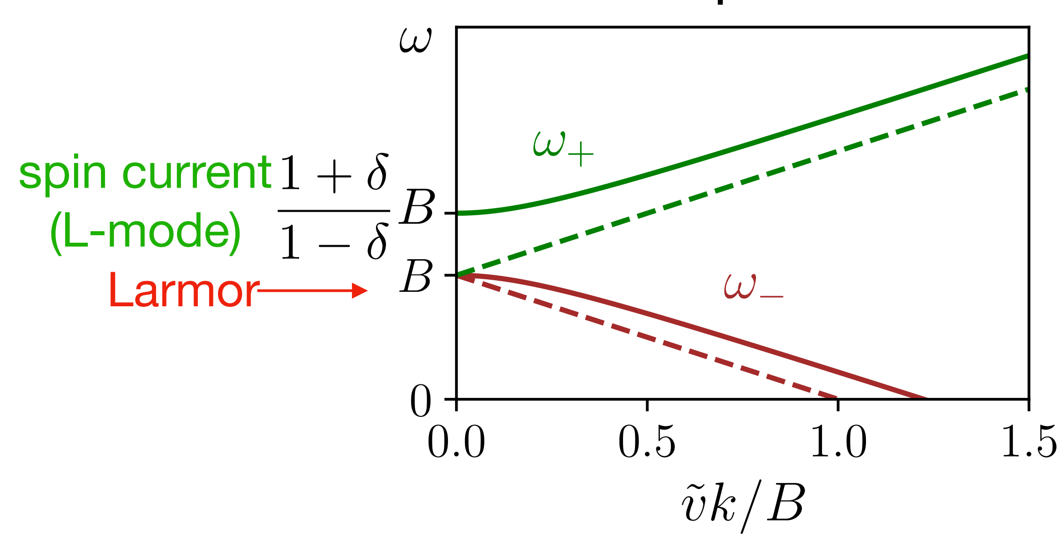
$$\delta = \frac{g}{4\pi v} = \frac{g}{2\pi^2 J}$$

$$A_\pm(k) = 1 \pm \frac{v^2(1-\delta^2)k^2 - \frac{\delta}{1-\delta}B^2}{B\sqrt{\left(\frac{\delta B}{1-\delta}\right)^2 + v^2(1-\delta^2)k^2}}$$

Spectral weight



Dispersion



Dashed lines: free spinon gas (g=0)

$\tilde{v} = v\sqrt{1-\delta^2}$

Dynamical Signatures of Quasiparticle Interactions in Quantum Spin Chains

Anna Keselman, Leon Balents, and Oleg A. Starykh
Phys. Rev. Lett. **125**, 187201 – Published 27 October 2020

Hydrodynamics of interacting spinons in the magnetized spin-$\frac{1}{2}$ chain with a uniform Dzyaloshinskii-Moriya interaction

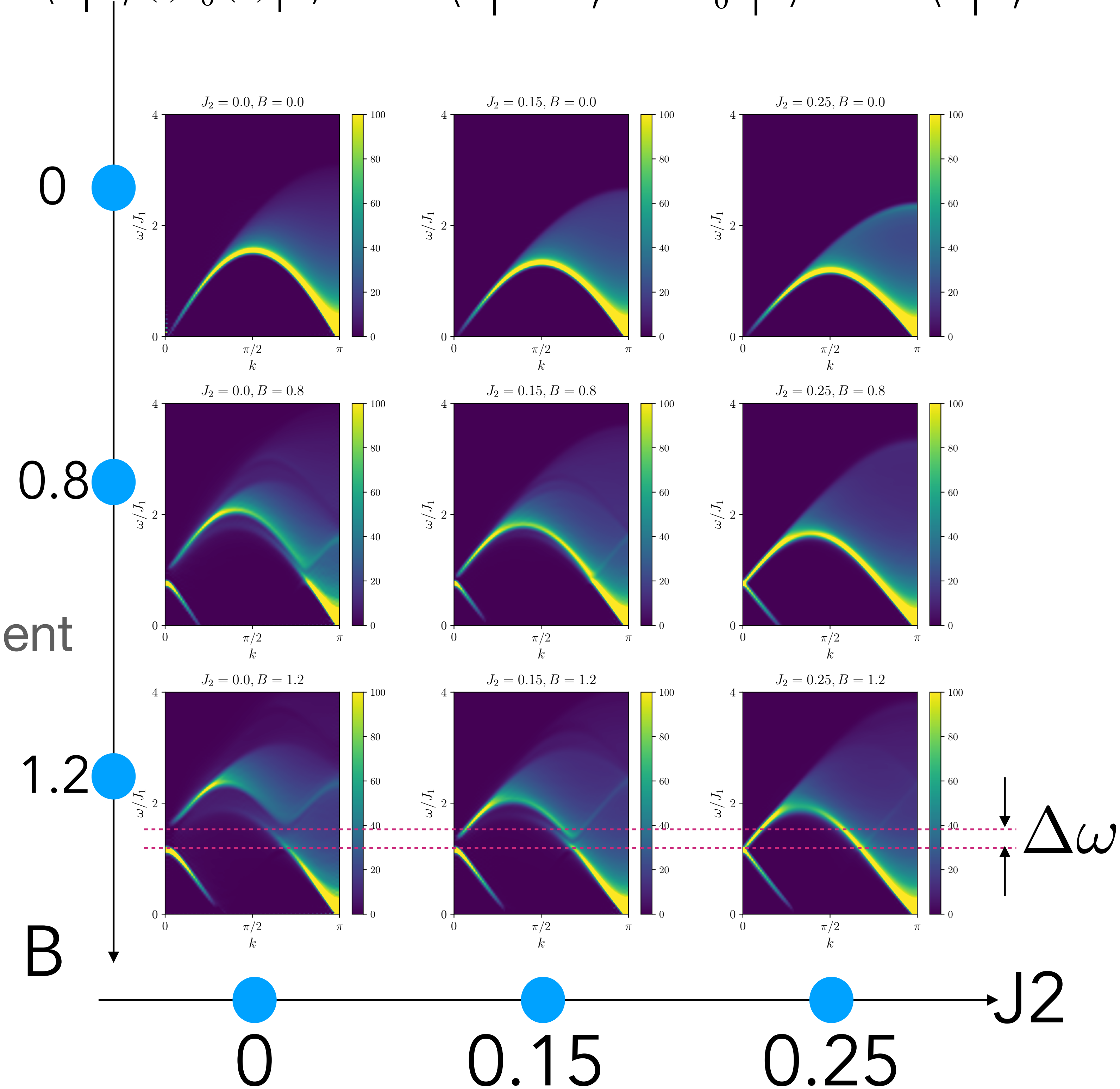
Ren-Bo Wang, Anna Keselman, and Oleg A. Starykh
Phys. Rev. B **105**, 184429 – Published 27 May 2022

Numerical confirmation

$$S^{+-}(\vec{k},\omega) = \int_{-\infty}^{\infty} dt e^{i\omega t} \int d\vec{r} e^{-i\vec{k}\cdot\vec{r}} \langle 0 | S_r^+(t) S_0^-(0) | 0 \rangle \longrightarrow \langle 0 | e^{iHt} S_r^+ e^{-iHt} S_0^- | 0 \rangle = e^{iE_0 t} \langle 0 | S_r^+ e^{-iHt} S_0^- | 0 \rangle$$

It works!

Explains ESR experiment in $K_2CuSO_4Br_2$



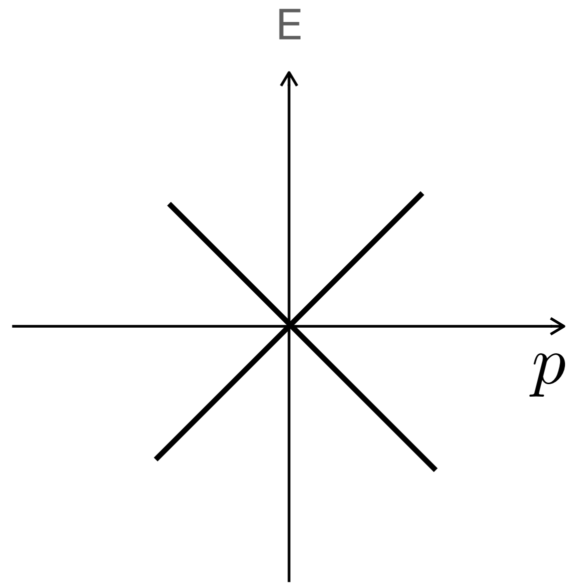
Heisenberg chain

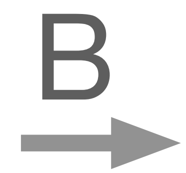
interacting spinon liquid

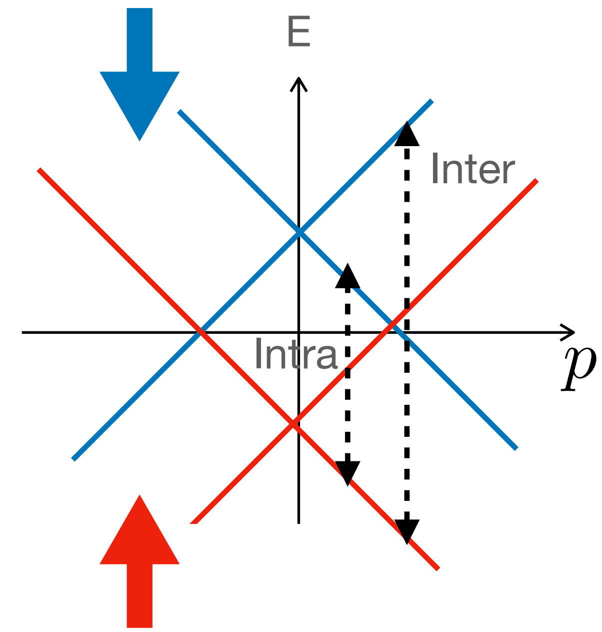
Haldane-Shastry chain

spinon gas

Dirac fermions -> Graphene



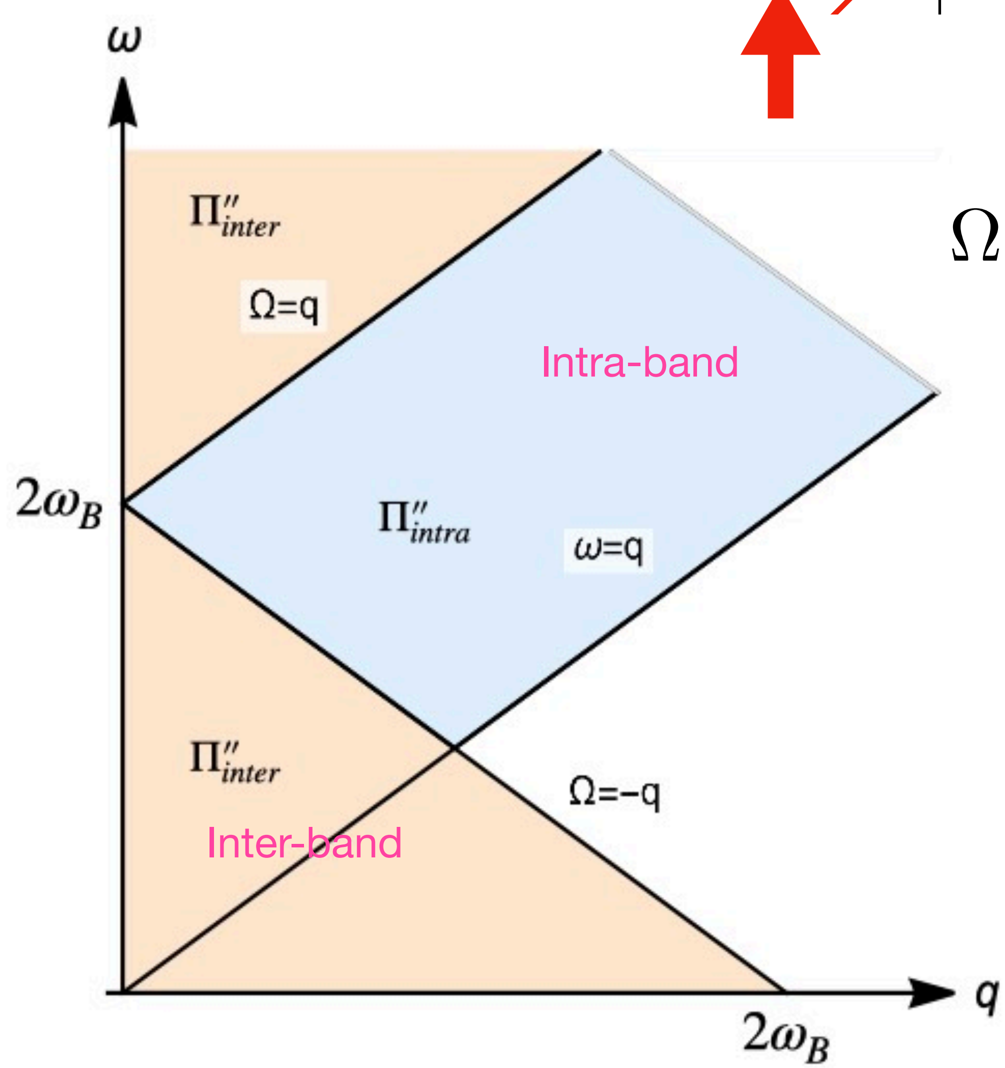




Non-interacting fermions

$$H = H_0 + H_{\text{zeeman}}$$

$$H_0 = \sum_{\mathbf{p}} \Psi^\dagger \vec{\sigma} \cdot \vec{p}\, \Psi$$



$$\Omega = \omega - 2\omega_B$$

Megha Agarwal, D. Pesin, E. Mishchenko, OS (to appear)

Interacting (short-ranged) Dirac fermions

$$H = H_0 + H_{\mathrm{zeeman}} + H_{\mathrm{int}}$$

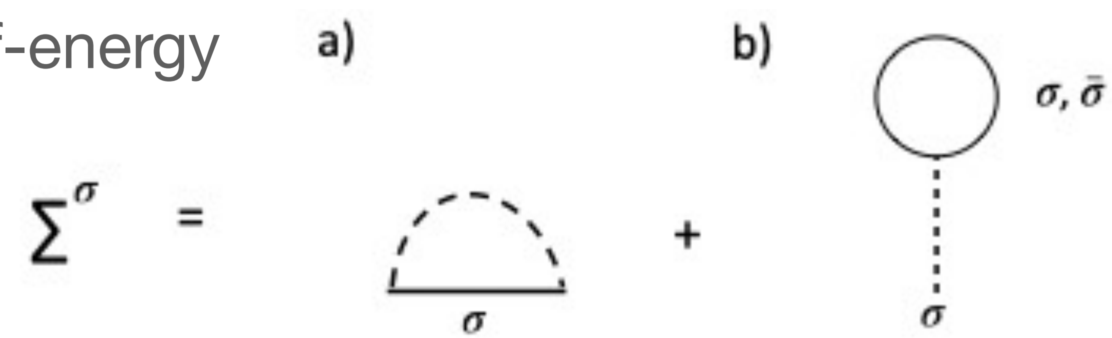
1) Collisionless kinetic equation for the single-particle density matrix

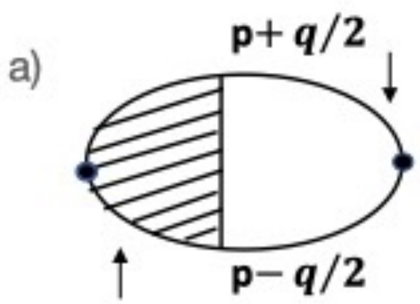
$$\partial_t f^{\downarrow\uparrow}(\mathbf{p},\mathbf{x},t) + \frac{1}{2}\{\nabla^a_{\mathbf{x}} f^{\downarrow\uparrow}(\mathbf{p},\mathbf{x},t), \partial_{p_a} H\} - i[f^{\downarrow\uparrow}(\mathbf{p},\mathbf{x},t), H + \epsilon^{\mathrm{HF}}] - \frac{1}{2}\{\nabla^a_{\mathbf{x}}\epsilon^{\mathrm{HF}}, \partial_{p_a} f^{\downarrow\uparrow}(\mathbf{p},\mathbf{x},t)\} = 0$$

1) = 2)

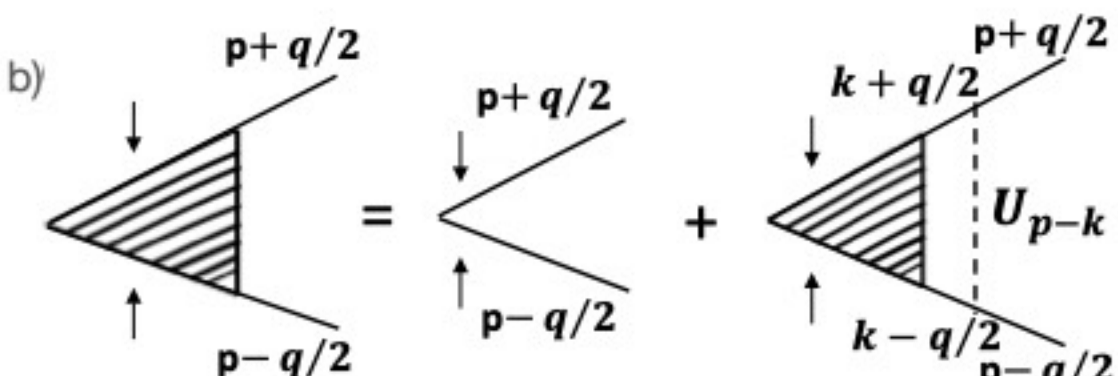
2) Diagrammatic calculation

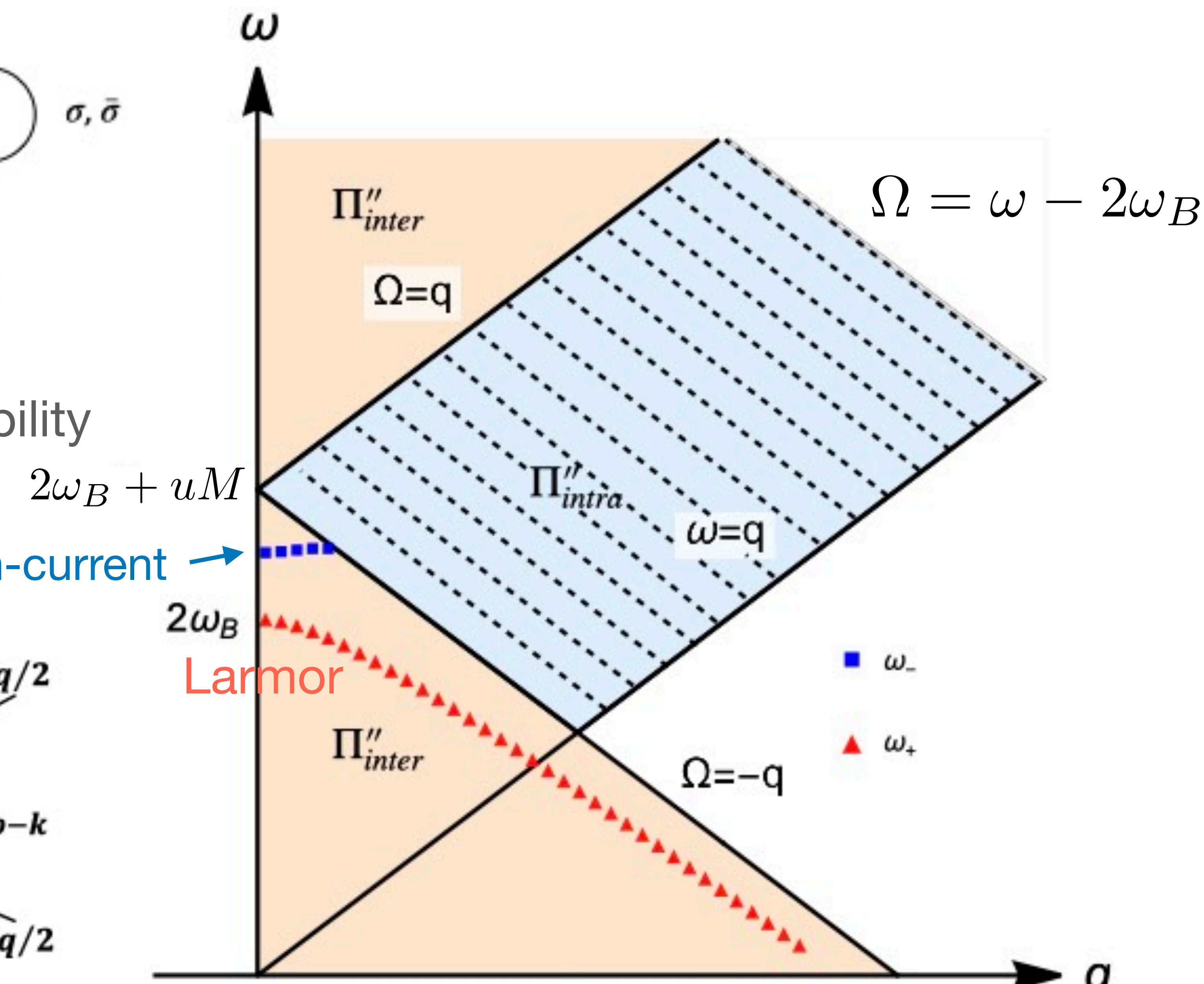
Self-energy





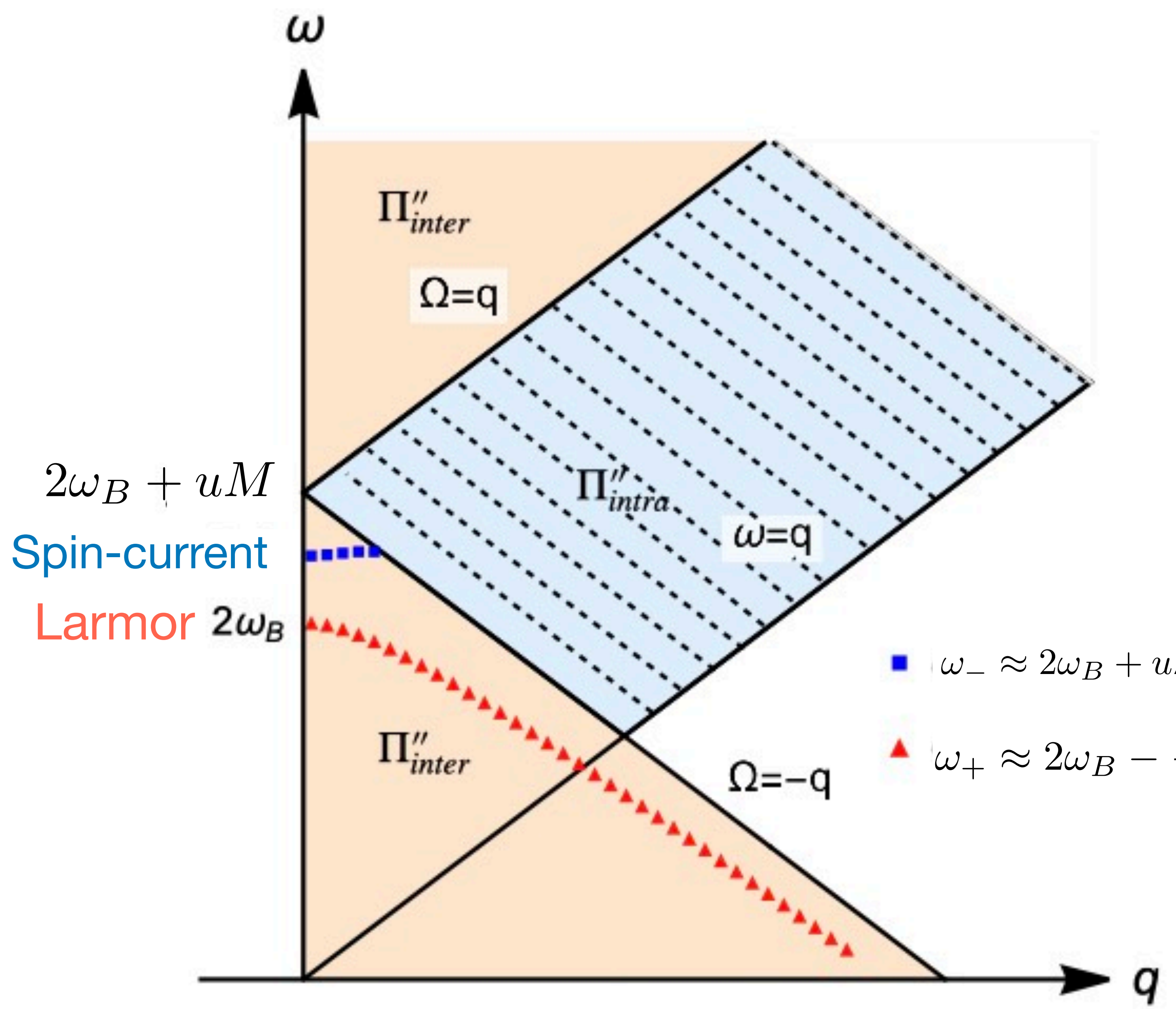
Transverse susceptibility





$$\Pi_{\uparrow\downarrow}(\omega,q) = \frac{2\Delta n}{\omega - \omega_+ + i\frac{u\alpha^2 q^2}{4(2\alpha-1)^2}} + \frac{2(3-2\alpha)\alpha^2 q^2}{u^2\Delta n(2\alpha-1)^2[\omega - \omega_- + i\frac{u^3\Delta n^2(1-2\alpha)^2}{64\alpha^3}]}.$$

$$\alpha = 1 - u\Lambda$$



$$\omega_- \approx 2\omega_B + u\Delta n\frac{2\alpha-1}{2\alpha} + \frac{\alpha(3-2\alpha)}{2u\Delta n(2\alpha-1)}q^2$$

$$\omega_+ \approx 2\omega_B - \frac{\alpha\ q^2}{(2\alpha-1)u\Delta n},$$

Conclusions

Probing fractionalized excitations *and* their collective modes.

Spinon Fermi surface spin liquid in magnetic field. Spinon spin wave.

New take on the magnetized Heisenberg spin chain.

Interacting Dirac fermions in magnetic field.

Dynamical response of the quantum spin liquid in magnetic field is very informative!

ESR: Spin chain with **uniform** Dzyaloshinskii - Moriya (DM) interaction

PHYSICAL REVIEW LETTERS **128**, 187202 (2022)

Editors' Suggestion | Featured in Physics

Electron Spin Resonance of the Interacting Spinon Liquid

Kirill Yu. Povarov,[1,*] Timofei A. Soldatov,[2] Ren-Bo Wang,[3] Andrey Zheludev,[1] Alexander I. Smirnov,[2,†] and Oleg A. Starykh[3,‡]

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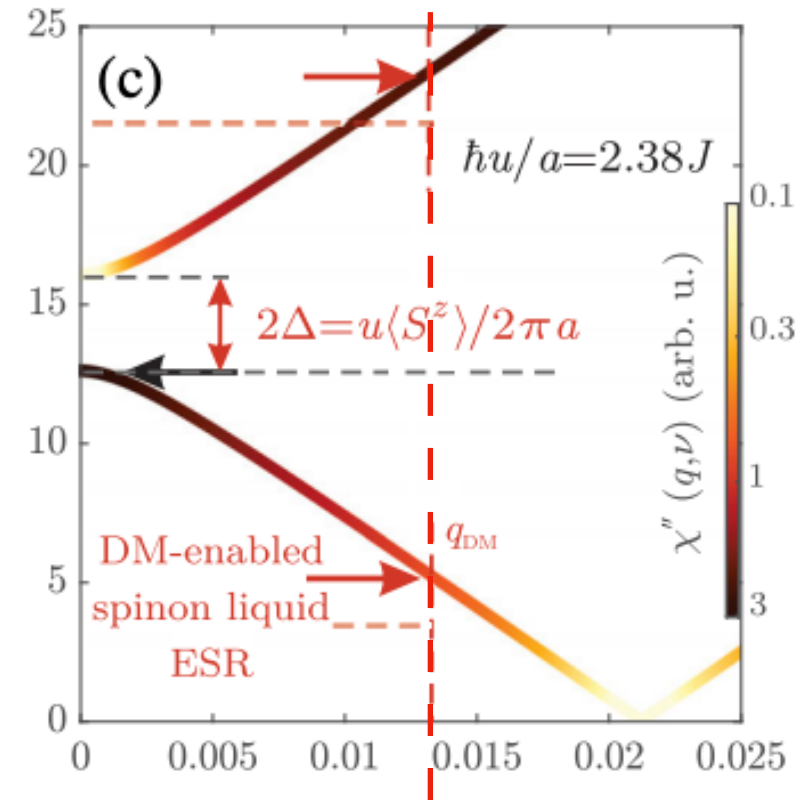
(Received 17 January 2022; accepted 25 March 2022; published 6 May 2022)

We report experimental verification of the recently predicted collective modes of spinons, stabilized by backscattering interaction, in a model quantum spin chain material. We exploit the unique geometry of uniform Dzyaloshinskii-Moriya interactions in $K_2CuSO_4Br_2$ to measure the interaction-induced splitting between the two components of the electron spin resonance (ESR) response doublet. From that we directly determine the magnitude of the "marginally irrelevant" backscattering interaction between spinons for the first time.

B II D



D/J

Heisenberg chain with **uniform** DM

$$\mathcal{H} = \sum_n J\vec{S}_n \cdot \vec{S}_{n+1} - \vec{D}\cdot\vec{S}_n \times \vec{S}_{n+1} - BS^z_n$$

Unitary rotation for B II D $S^+_n = \tilde{S}^+_n e^{iQn},\ Q = \tan^{-1}(D/J),\ S^z_n = \tilde{S}^z_n$ maps onto

$$\tilde{\mathcal{H}} = \sum_n \sqrt{J^2+D^2}(\tilde{S}^x_n\tilde{S}^x_{n+1} + \tilde{S}^y_n\tilde{S}^y_{n+1}) + J\tilde{S}^z_n\tilde{S}^z_{n+1} - B\tilde{S}^z_n \approx \sum_n J\tilde{S}^a_n\tilde{S}^a_{n+1} - B\tilde{S}^z_n$$

Momentum boost $k \to k + D/J$

Structure factor $\mathcal{S}(k=0,\omega)|_{\rm DM} = \tilde{\mathcal{S}}(D/J,\omega)|_{\rm no\ DM}$

DM allows ESR to probe upper (forbidden) branch at Q = D/J.

- Similar materials: $Na_2CuSO_4Cl_2$ [Ohta et al. PRB 105, 144410 (2022)] and $Ca_3ReO_5Cl_2$ [Nawa et al. PR Research 2, 043121 (2020)]

Electron Spin Resonance in $K_2CuSO_4Br_2$

PHYSICAL REVIEW B **90**, 174413 (2014)

Quantum spin chains with frustration due to Dzyaloshinskii-Moriya interactions

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(Received 25 August 2014; revised manuscript received 22 October 2014; published 12 November 2014)

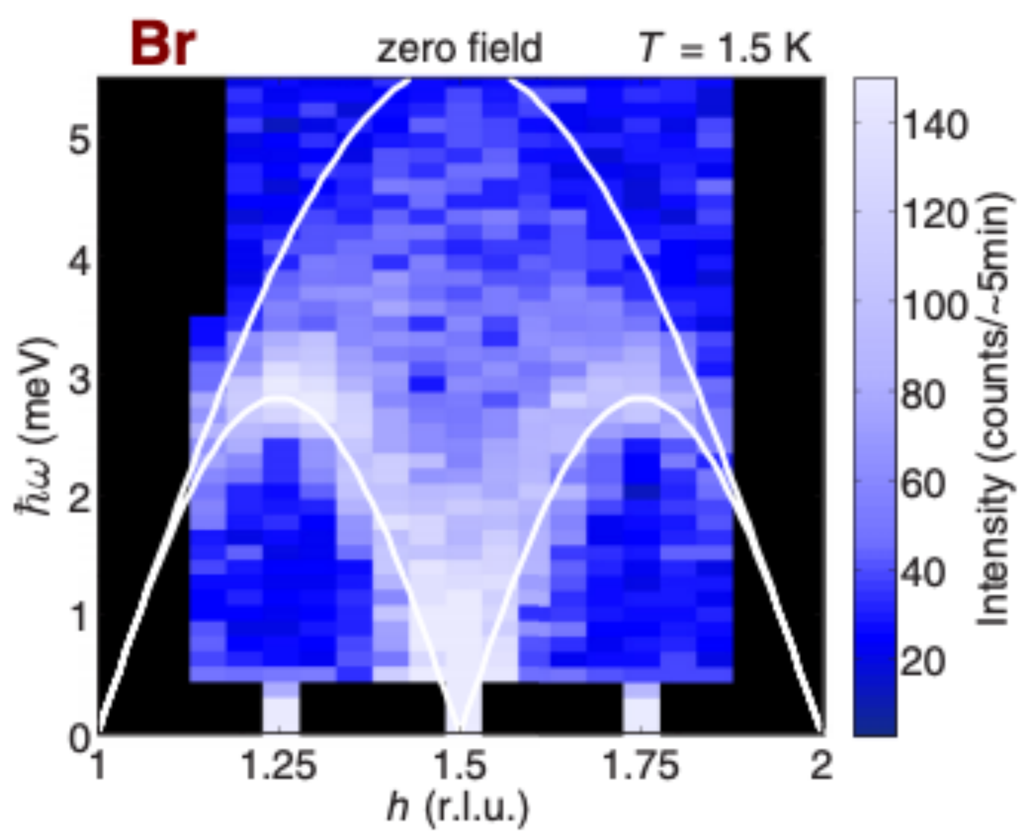

FIG. 7. (Color online) Neutron scattering intensity map of the two-spinon continuum along the a^* axis [$\mathbf{q} = (h,0,0)$] for $K_2CuSO_4Br_2$ in zero magnetic field. Raw data are shown in Fig. 8. The white line indicates the lower and upper boundary of the continuum following Eqs. (4) and (5) with $J_{\mathrm{Br},a} = 20.7$ K.

PHYSICAL REVIEW B **92**, 134417 (2015)

Electron spin resonance in a model $S = \frac{1}{2}$ chain antiferromagnet with a uniform Dzyaloshinskii-Moriya interaction

A. I. Smirnov,[1] T. A. Soldatov,[1,2] K. Yu. Povarov,[3,*] M. Hälg,[3] W. E. A. Lorenz,[3] and A. Zheludev[3]
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(Received 27 July 2015; revised manuscript received 6 October 2015; published 22 October 2015)

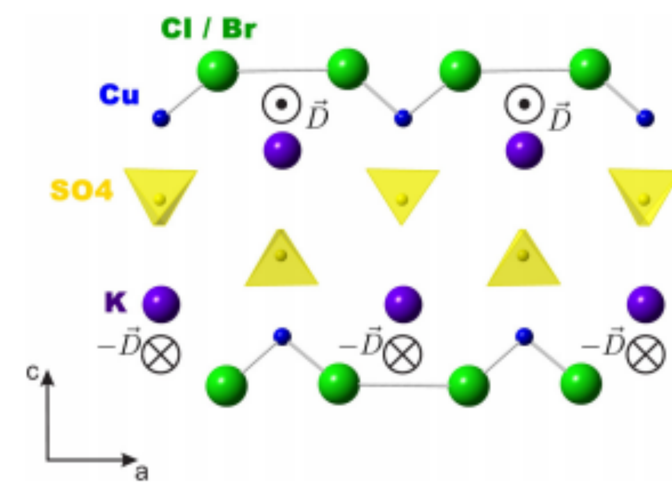


FIG. 9. (Color online) The antisymmetric contribution $\mathbf{D}$ to J_a points along the b axis, is uniform along the chain, and antiparallel in adjacent chains.

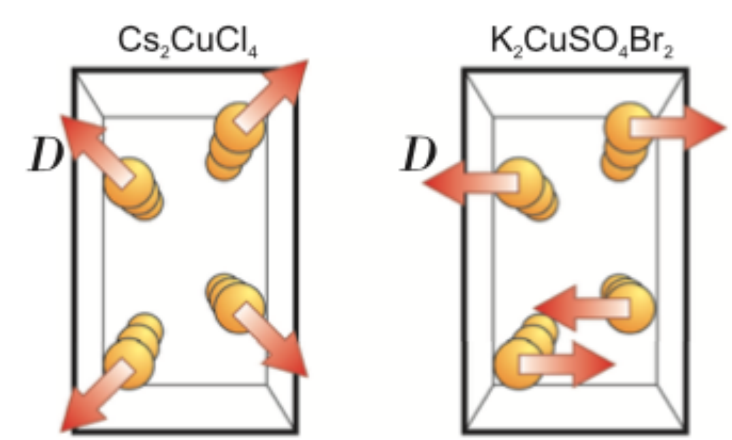
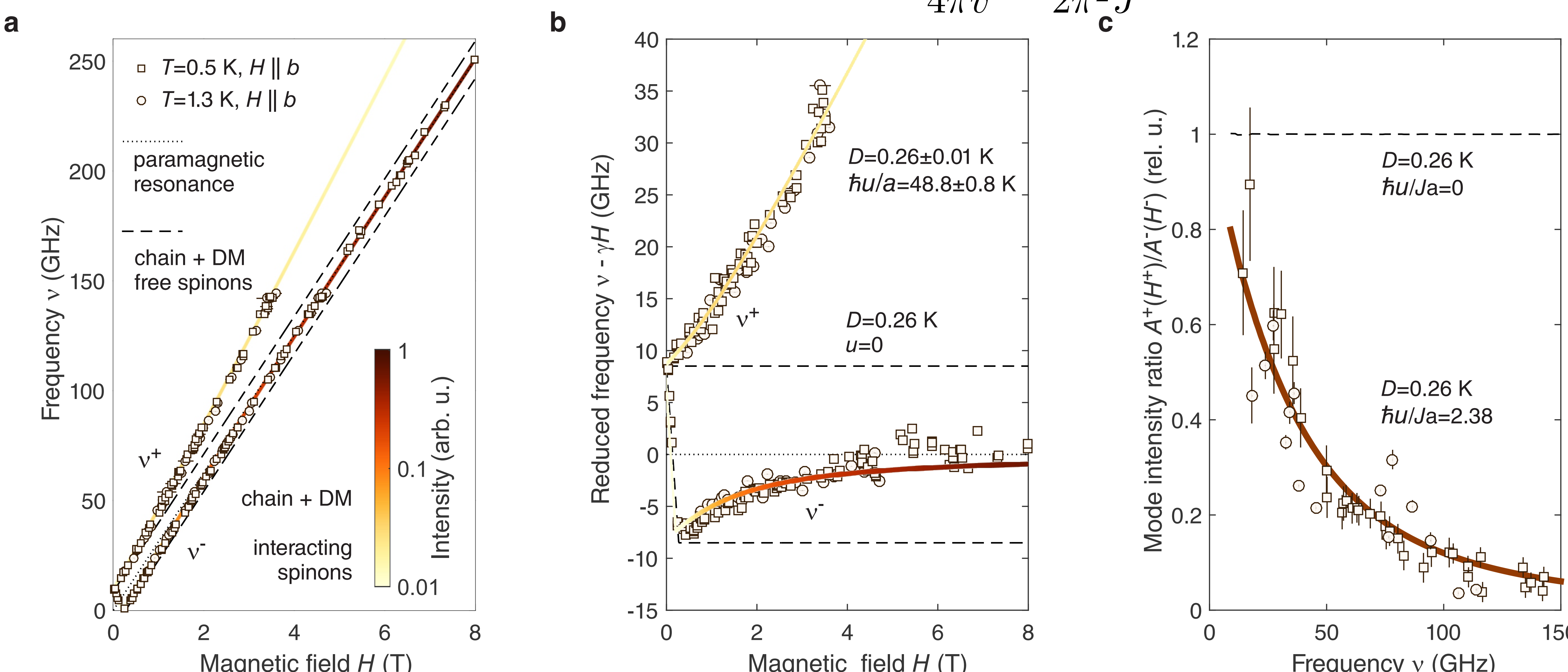
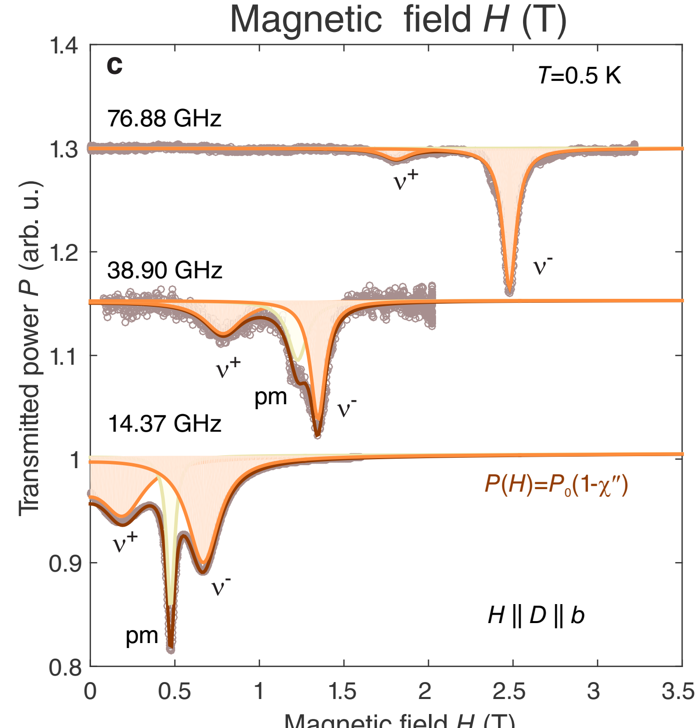


FIG. 2. (Color online) Comparison of the Dzyaloshinskii-Moriya vectors in Cs_2CuCl_4 and $K_2CuSO_4Br_2$. Perspective view along the spin chains.

Qualitative difference between (strongly) interacting spinons and the non-interacting approximation!

Notation change: g = u $\longrightarrow$ $\delta = \frac{u}{4\pi v} = \frac{u}{2\pi^2 J} = 0.12$





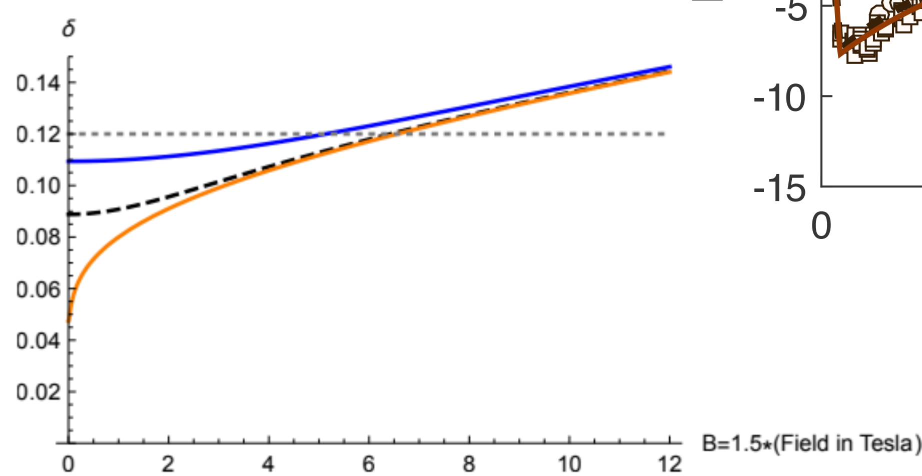
- - - - - - non-interacting spinon gas

interacting spinon liquid

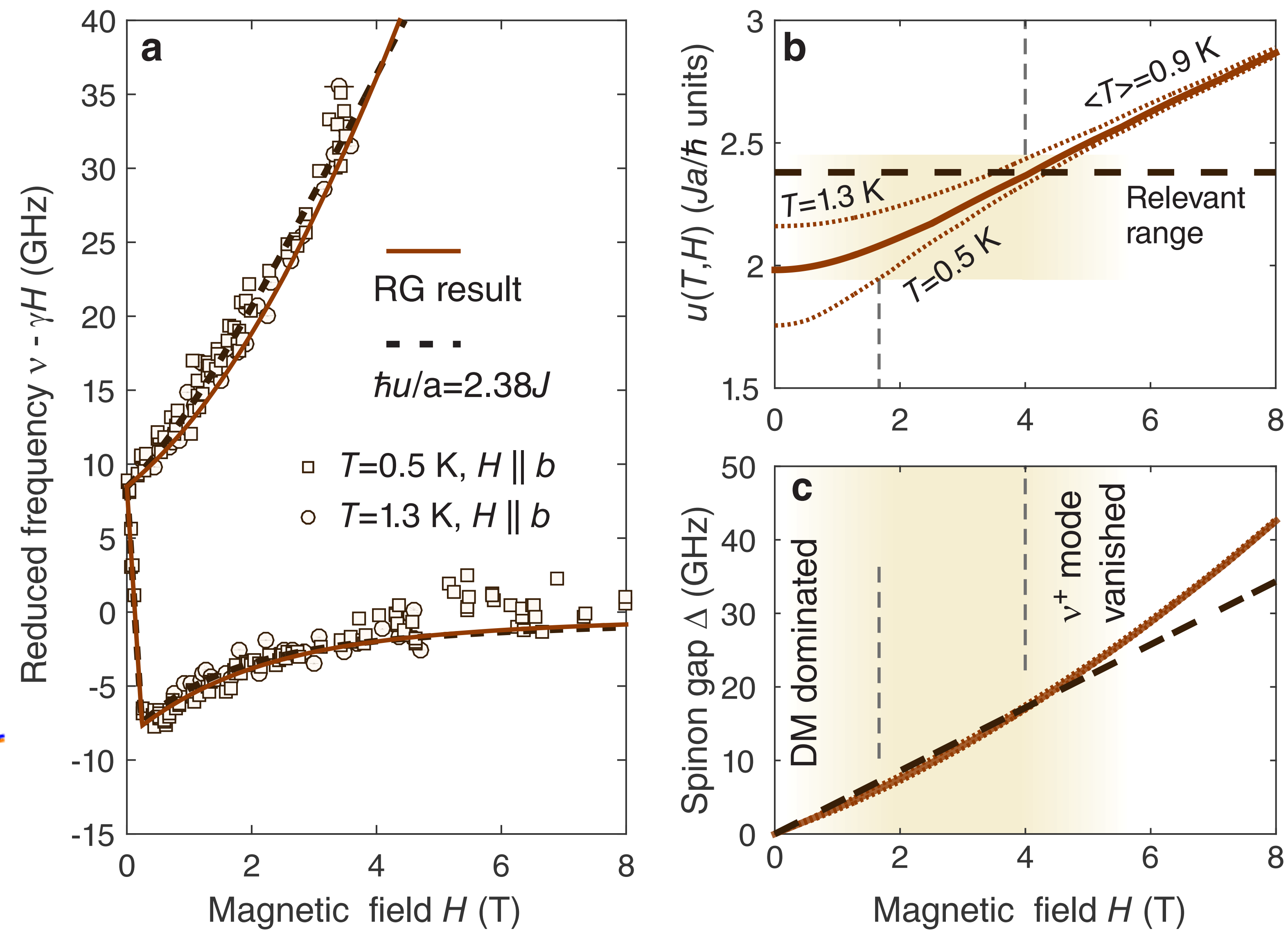
Comparison with the Renormalization Group approach

$$\frac{1}{2\delta} + \frac{\ln 2\delta}{2} = \ln\left(\sqrt{\frac{\pi}{2}} e^{1/4} \frac{J}{T}\right) - \mathrm{Re}\left[\psi\left(1 + i\frac{g\mu_B H}{2\pi T}\right)\right]$$

$$\delta = \frac{u}{4\pi v}$$

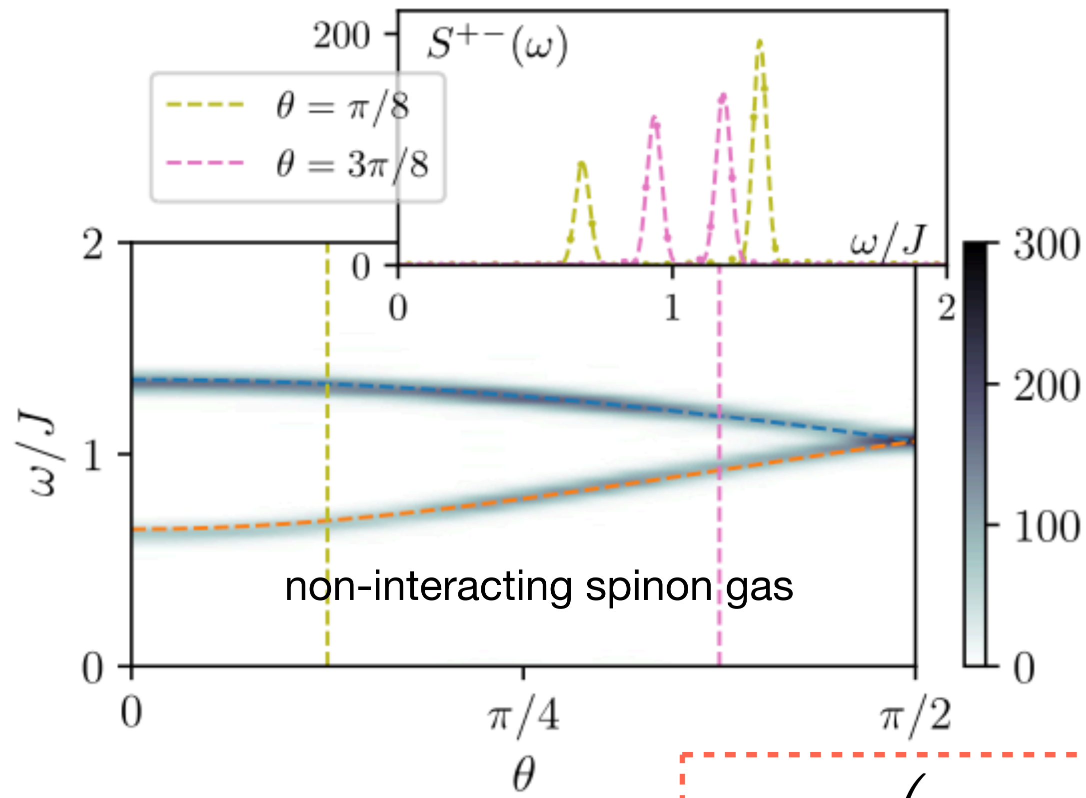


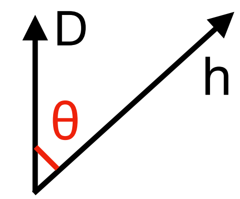
SUPP. FIG. 3. Solution of Eq.(S.65) for $T = 1.3$K (solid blue line), $T = 0.5$K (dashed black line) and $T = 0.0005$K (solid orange line) as a function of field B from 0 to 8 T. The field is converted into Kelvins by $B = 1.5 \times$ (field in Tesla)K. Dotted gray line shows $\delta = 0.12$.

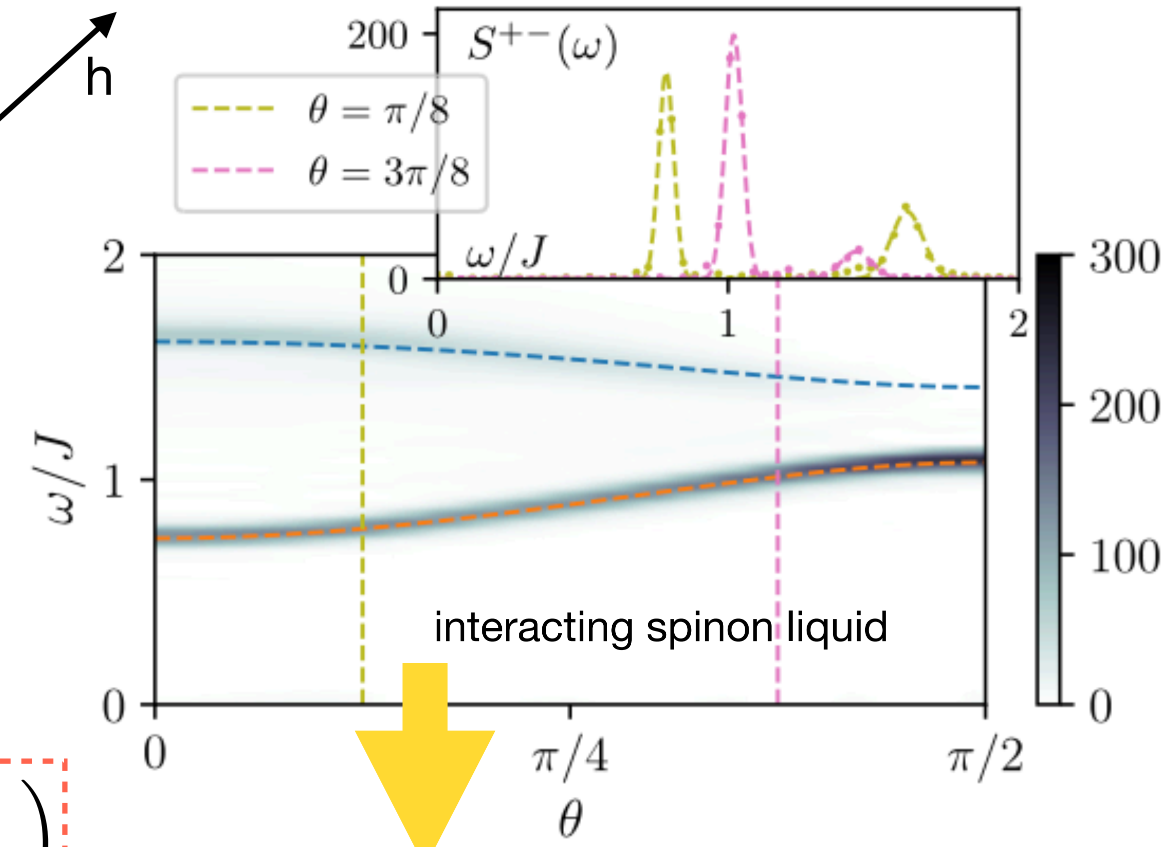


First ever spectroscopic measurement
of the backscattering spinon interaction **u** (=**g**)

Angular dependence of the ESR response

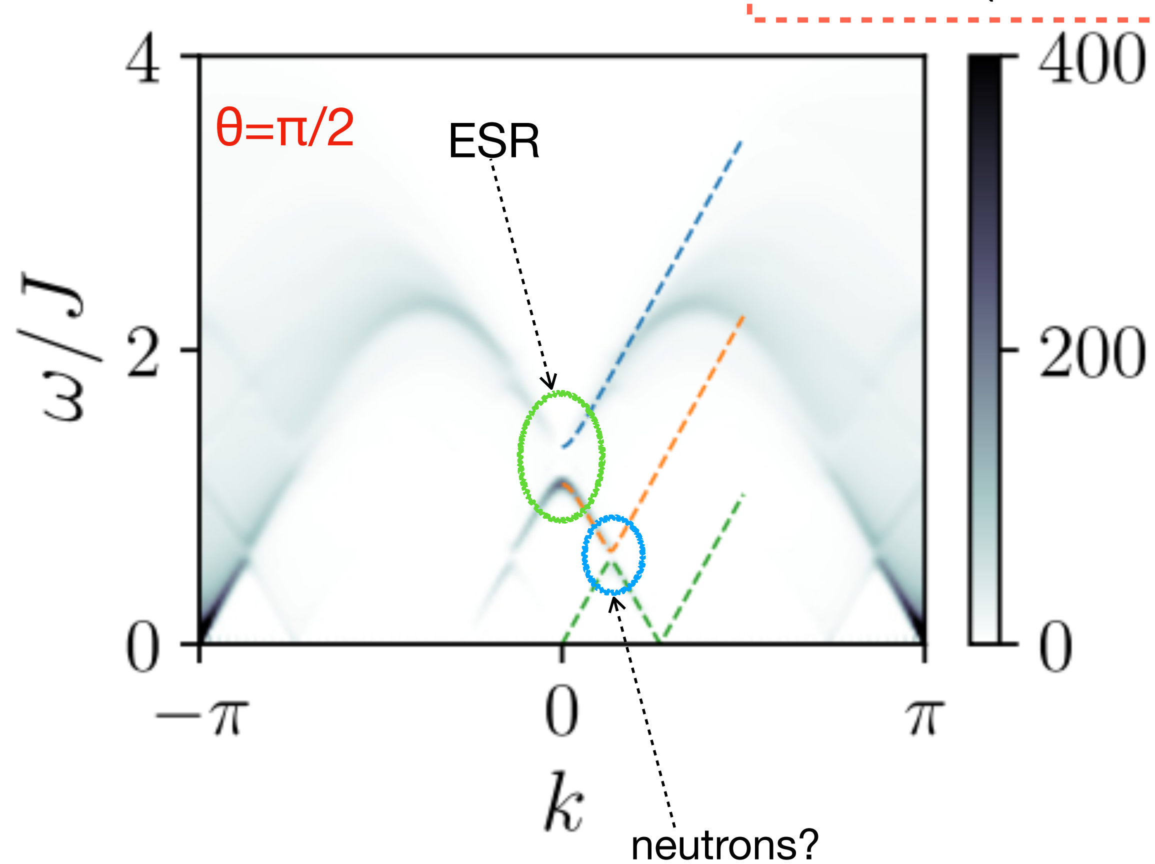


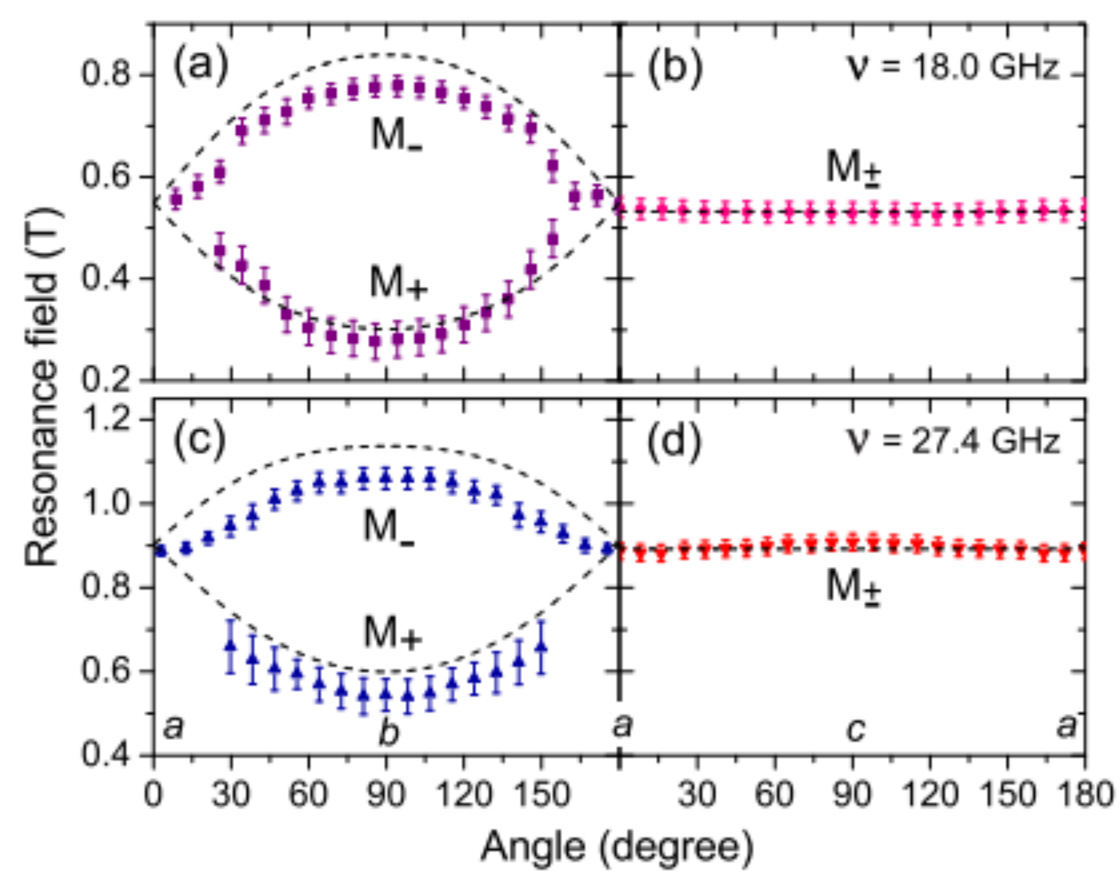




$$\partial_x \to \left(\partial_x + \mathbf{D} \times\right)$$

Smirnov et al PHYSICAL REVIEW B **92**, 134417 (2015)





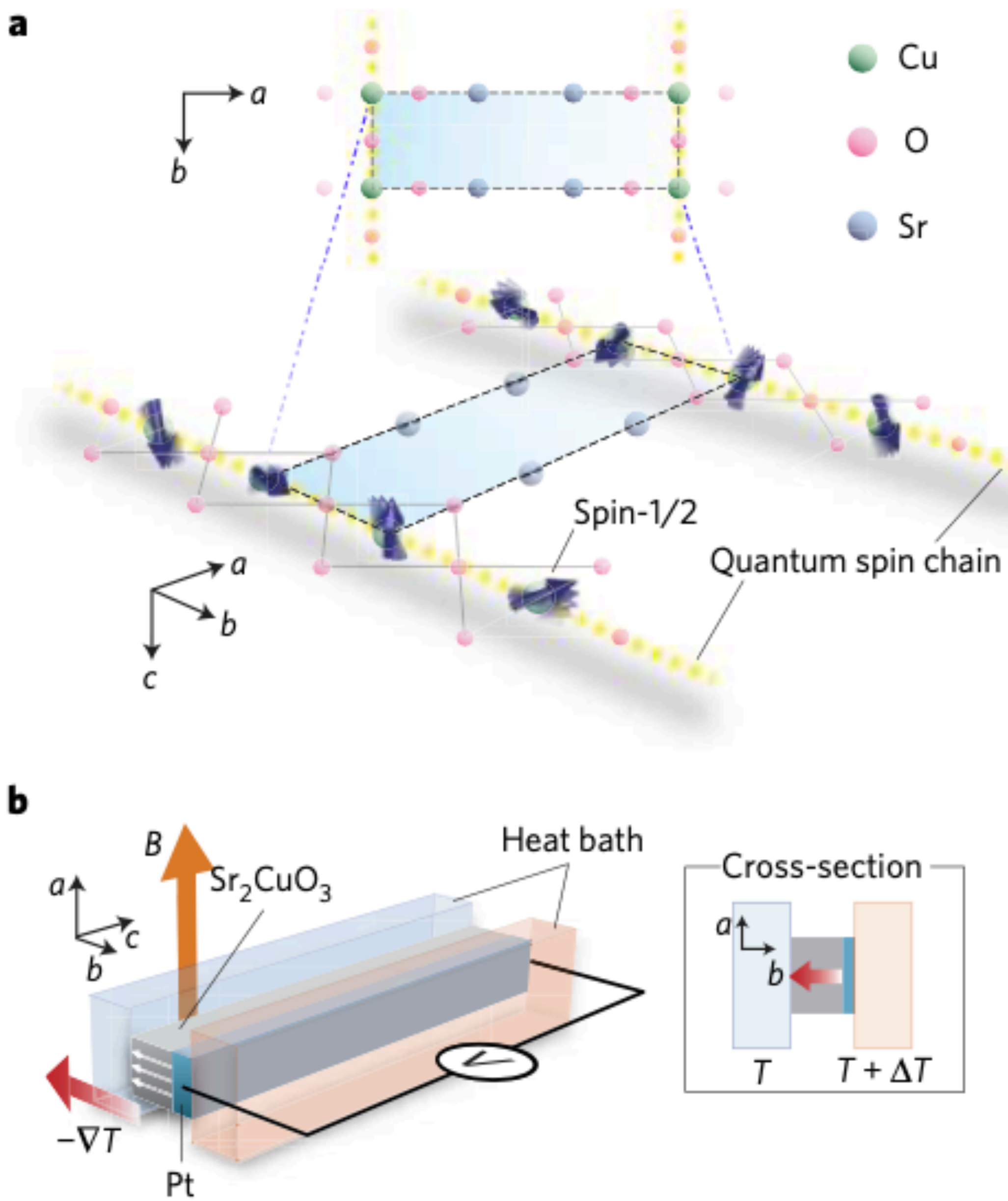
Quantum spintronics

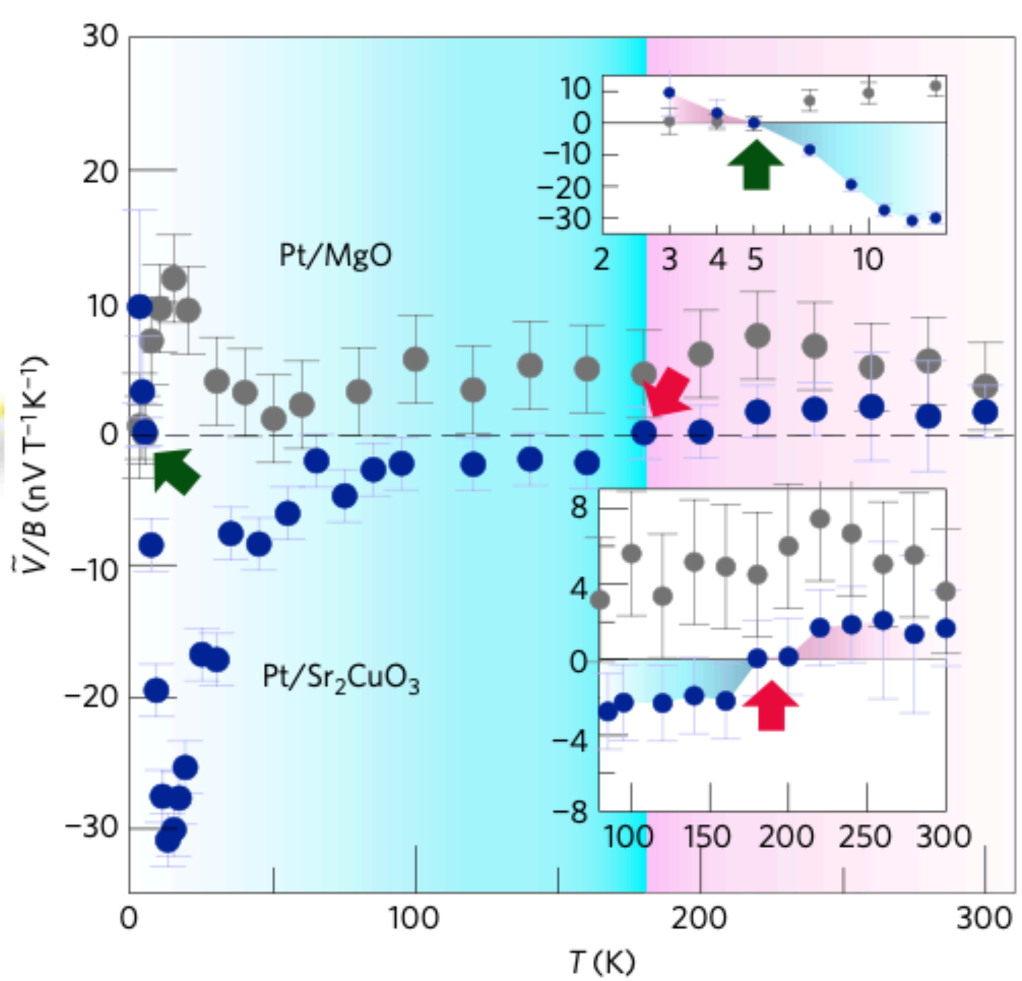
LETTERS
PUBLISHED ONLINE: 26 SEPTEMBER 2016 | DOI: 10.1038/NPHYS3895
nature physics

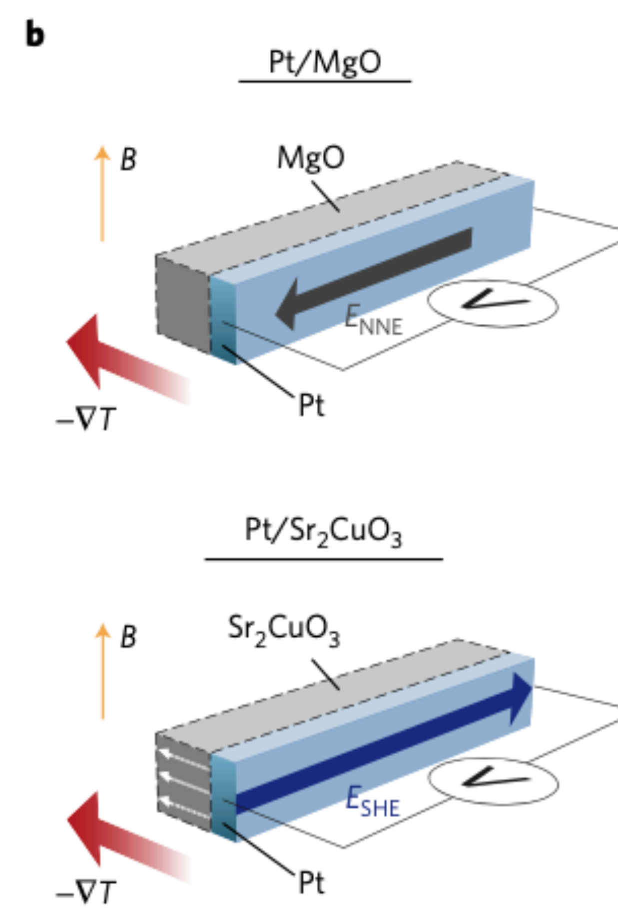
The essence: spin current across the tunneling barrier between different magnetic materials due to the finite temperature gradient δT

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]*







Quantum spintronics

The essence: spin current across the tunneling barrier between different magnetic materials due to the finite temperature gradient δT

1. $$\vec{S}(x_i) \to \vec{J}_R + \vec{J}_L + \frac{(-1)^{x_i}}{2}\left(\psi_R^\dagger \vec{\sigma} \psi_L + \psi_L^\dagger \vec{\sigma} \psi_R\right)$$

Interface = tunneling contact = open boundary condition for the spin chain

$$\psi(x=0,t) = 0 \to \psi_L(x=0,t) = -\psi_R(x=0,t)$$

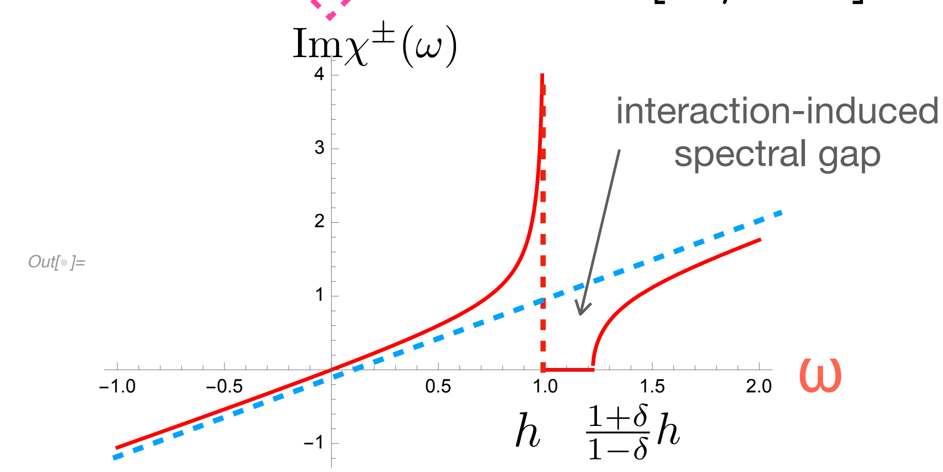
$$\to \vec{S}(x=0,t) = 0 \text{ and } \vec{S}(x=1,t) \approx 2\left(\vec{J}_R + \vec{J}_L\right)$$

local susceptibility

2. $$I_{\text{spin}} \propto \frac{J^2_{\text{interface}}}{T^2} \int_{-\infty}^{+\infty} d\omega\, \mathrm{Im}\chi^{\pm}_{\text{Pt}}(\omega)\, \mathrm{Im}\chi^{\pm}_{\text{chain}}(\omega)\, \frac{\omega\, \delta T}{\sinh^2[\omega/2T]}$$

ω

$$\to I_{\text{spin}} = 0 \text{ if } \mathrm{Im}\chi^{\pm}_{\text{chain}}(\omega) \text{ is odd.}$$



Non-interacting spinon gas: $\mathrm{Im}\chi^{\pm}_{\text{chain}}(\omega) \propto \omega$

Interacting spinon liquid: finite spin current for δ > 0, $I_{\text{spin}} \neq 0$

$$\mathrm{Im}\chi^{\pm}_{\text{chain}}(\omega) \propto \omega \sqrt{\frac{\omega-(1+\delta)h/(1-\delta)}{\omega-h}}\left[\Theta(h-\omega) + \Theta(\omega-(1+\delta)h/(1-\delta))\right]$$

Experiment

VOLUME 91, NUMBER 3 PHYSICAL REVIEW LETTERS week ending 18 JULY 2003

Extended Quantum Critical Phase in a Magnetized Spin-$\frac{1}{2}$ Antiferromagnetic Chain

M. B. Stone,[1,*] D. H. Reich,[1] C. Broholm,[1,2] K. Lefmann,[3] C. Rischel,[4] C. P. Landee,[5] and M. M. Turnbull[5]

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(Received 18 March 2003; published 17 July 2003)

Measurements are reported of the magnetic field dependence of excitations in the quantum critical state of the spin $S = 1/2$ linear chain Heisenberg antiferromagnet copper pyrazine dinitrate (CuPzN). The complete spectrum was measured at $k_BT/J \leq 0.025$ for $H = 0$ and $H = 8.7$ T, where the system is ~30% magnetized. At $H = 0$, the results are in agreement with exact calculations of the dynamic spin correlation function for a two-spinon continuum. At $H = 8.7$ T, there are multiple overlapping continua with incommensurate soft modes. The boundaries of these continua confirm long-standing predictions, and the intensities are consistent with exact diagonalization and Bethe ansatz calculations.

DOI: 10.1103/PhysRevLett.91.037205 PACS numbers: 75.10.Jm, 75.40.Gb, 75.50.Ee

Finally, we note that Fig. 4(a) shows some evidence of weak scattering intensity for $\hbar\omega > 2$ meV. This could be due to the presence of short chains resulting from impurities, or to higher-order processes not included in the spinon/psinon picture. However, we note that our error bars are much larger here than at lower energy due to shorter counting times (see Fig. 2), and so a definitive statement on the existence of excitations in this energy range cannot be made at this time.

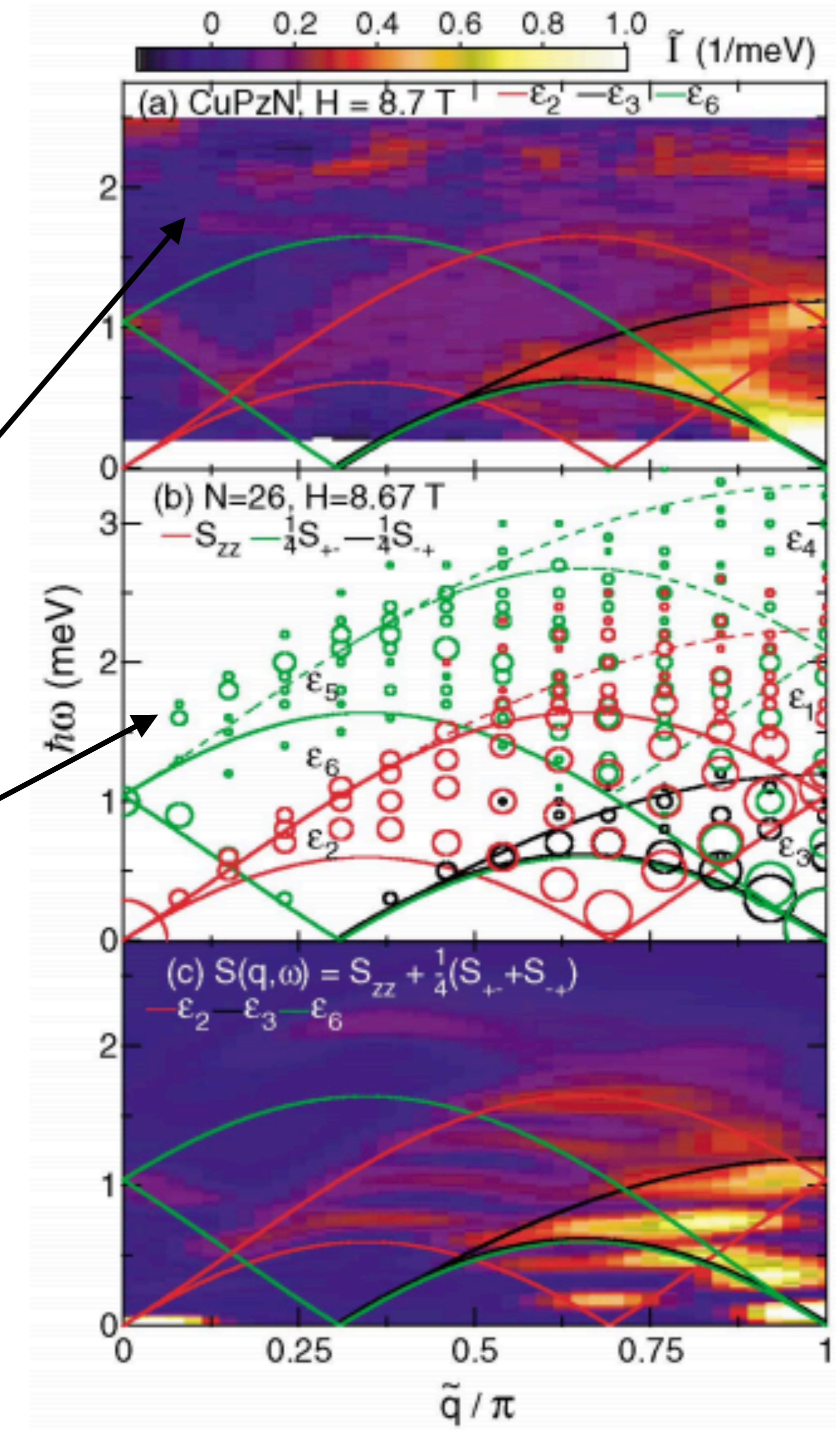

FIG. 4 (color). (a) Inelastic neutron scattering intensity $\tilde{I}_m(\tilde{q}, \omega)$ for CuPzN at $T = 0.25$ K and $H = 8.7$ T. (b) Calculations of the different components of $S(\tilde{q}, \omega)$ for $N = 26$ spins and $m = 2/13$. The area of each circle is proportional to $S(\tilde{q}, \omega)$. (c) $\tilde{I}_m(\tilde{q}, \omega)$ calculated for ensemble of chains with $N = 24$, 26, and 28. The curves in (a)–(c) show the bounds of the excitation continua $\mathcal{E}_1$–$\mathcal{E}_6$. Solid lines: Continua predicted to predominate as $N \to \infty$. In (b), $\mathcal{E}_2$(upper) = $\mathcal{E}_1$(lower).

PHYSICAL REVIEW B VOLUME 54, NUMBER 9 1 SEPTEMBER 1996-I

Dynamical correlation functions of the $S=1/2$ nearest-neighbor and Haldane-Shastry Heisenberg antiferromagnetic chains in zero and applied fields

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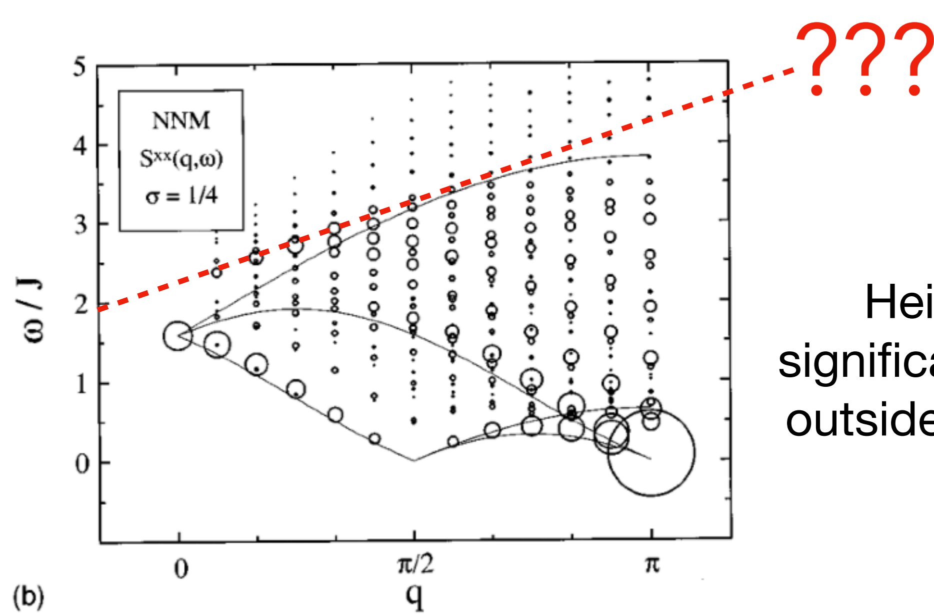
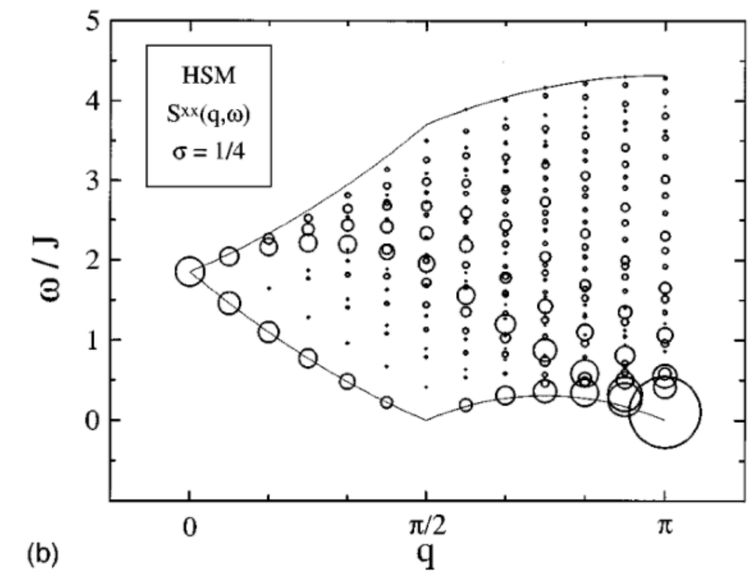
Christian Rischel†
Ørsted Laboratory, Niels Bohr Institute, University of Copenhagen, DK-2100 København Ø, Denmark

(Received 12 February 1996)

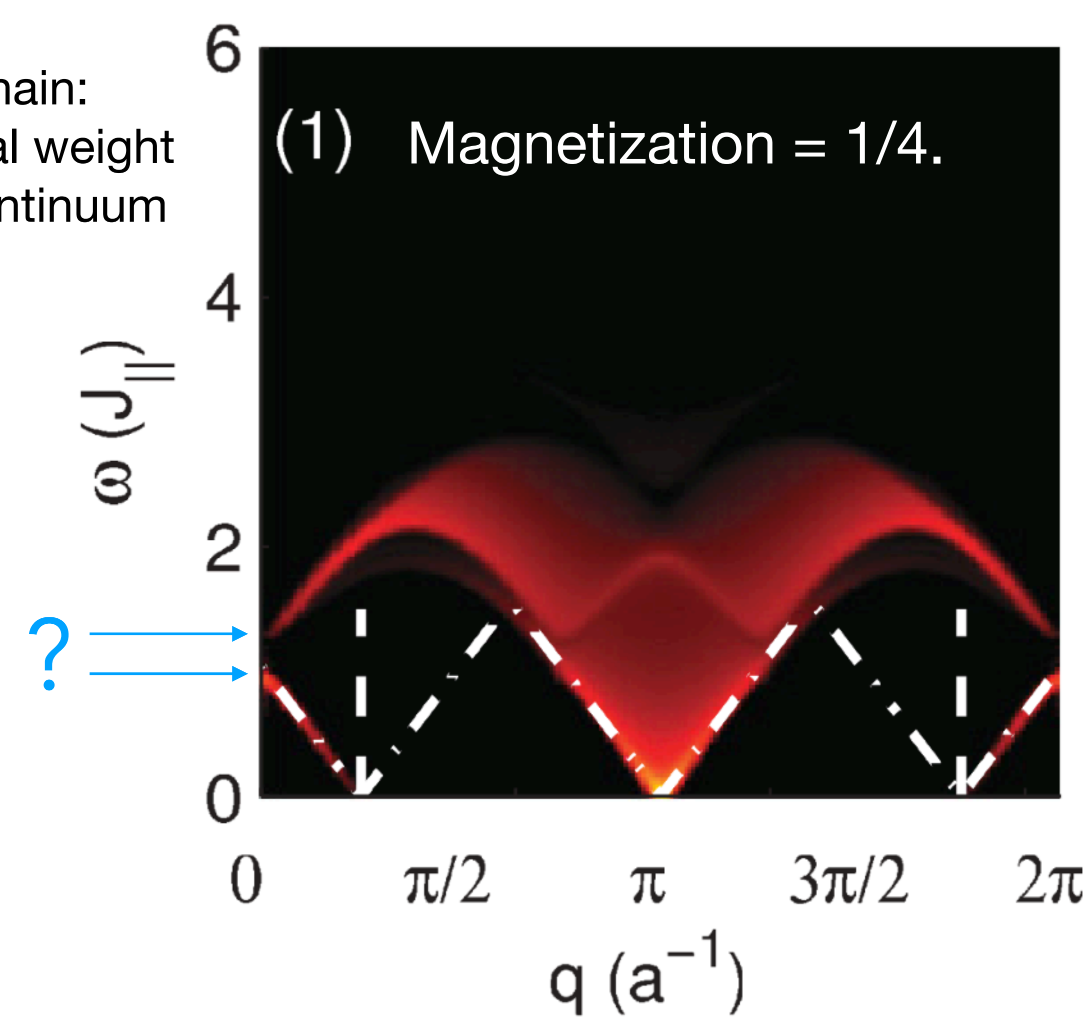
We present a numerical diagonalization study of two one-dimensional $S=1/2$ antiferromagnetic Heisenberg chains, having nearest-neighbor and Haldane-Shastry ($1/r^2$) interactions, respectively. We have obtained the $T=0$ dynamical correlation function, $S^{aa}(q,\omega)$, for chains of length $N=8-28$. We have studied $S^{zz}(q,\omega)$ for the Heisenberg chain in zero field, and from finite-size scaling we have obtained a limiting behavior that for large ω deviates from the conjecture proposed earlier by Müller *et al.* For both chains we describe the behavior of $S^{zz}(q,\omega)$ and $S^{xx}(q,\omega)$ for selected values of the applied field, and compare with previous work by Müller *et al.* and Talstra and Haldane. Suggestions for future finite-field neutron scattering experiments are made. [S0163-1829(96)00733-3]





Haldane-Shastry chain: non-interacting 2-spinon continuum

Heisenberg chain: significant spectral weight outside Muller continuum



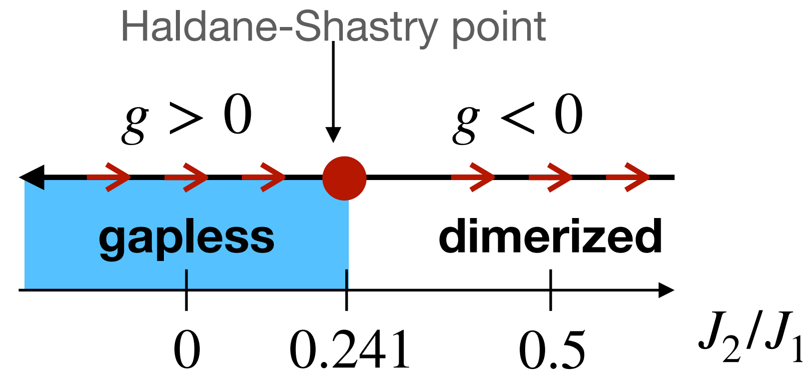
Clearly, looks more like an interacting Fermi liquid than a non-interacting Fermi gas…

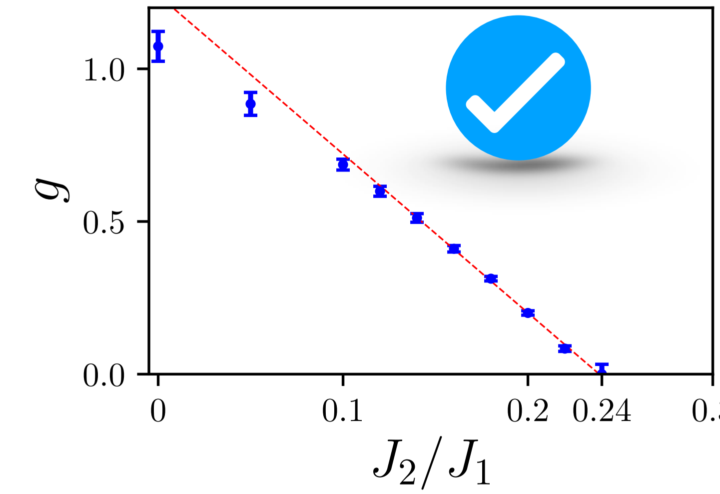
Statics and dynamics of weakly coupled antiferromagnetic spin-$\frac{1}{2}$ ladders in a magnetic field

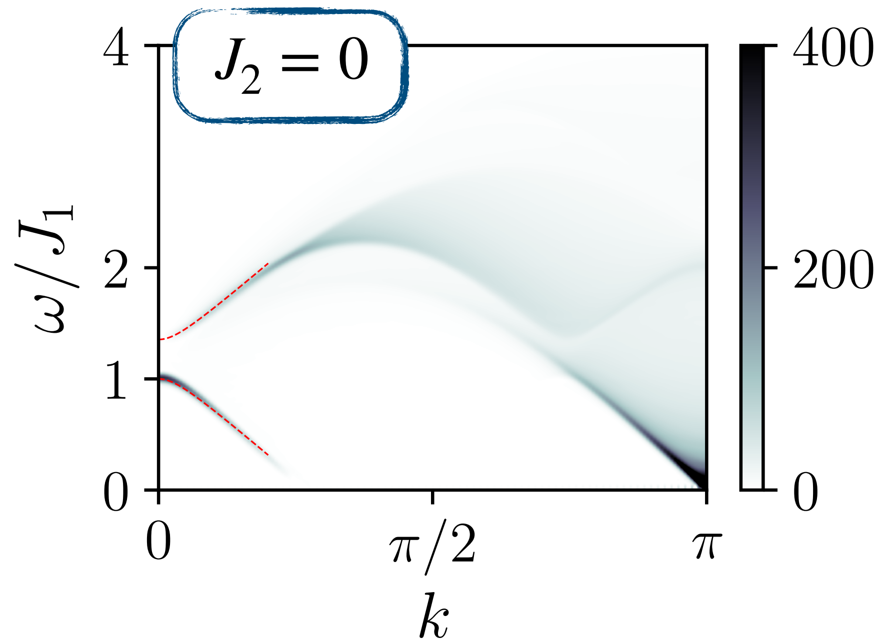
Pierre Bouillot, Corinna Kollath, Andreas M. Läuchli, Mikhail Zvonarev, Benedikt Thielemann, Christian Rüegg, Edmond Orignac, Roberta Citro, Martin Klanjšek, Claude Berthier, Mladen Horvatić, and Thierry Giamarchi
Phys. Rev. B **83**, 054407 – Published 9 February 2011

Numerical results

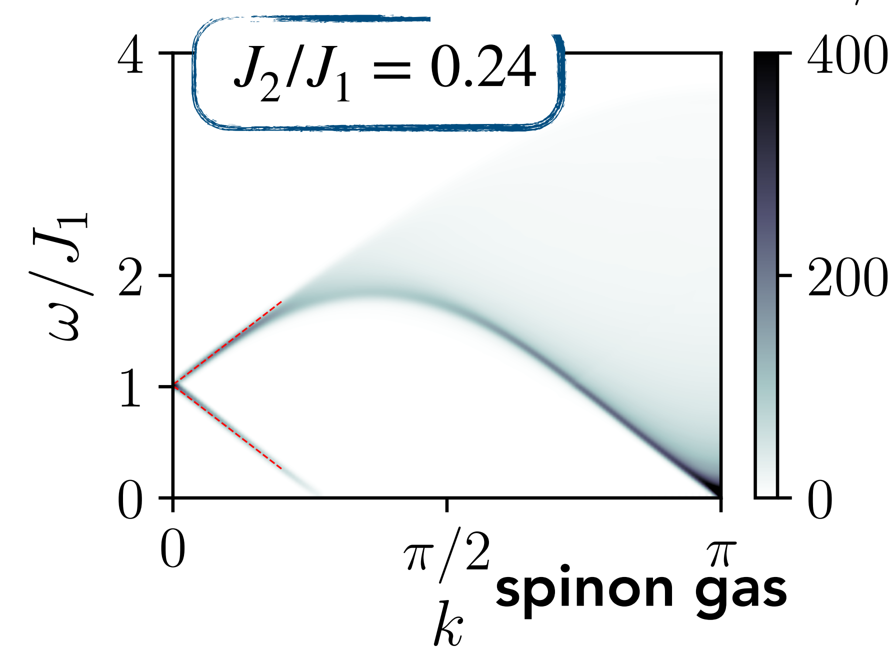
$B/J_1 = 1$







interacting spinon liquid



spinon gas