Collective modes of magnetized spin liquids

Oleg Starykh, Univ of Utah

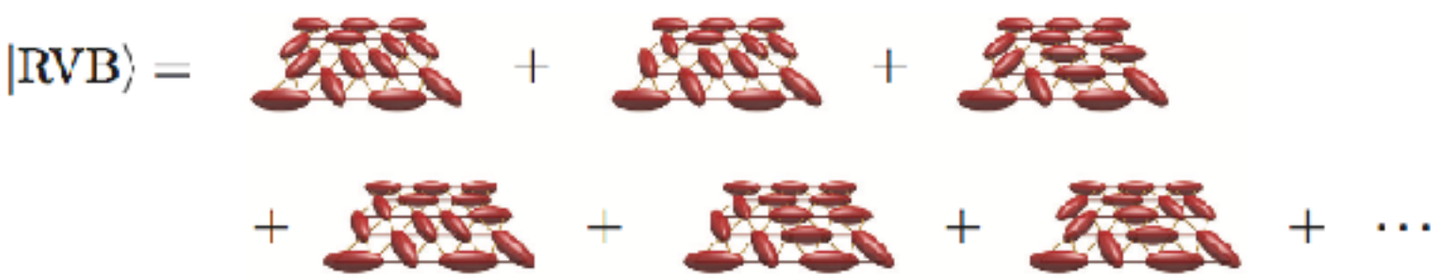


in collaboration with Leon Balents, KITP UCSB

Low-dimensional emergent phenomena in correlated systems and topological quantum matter, Tbilisi, June 4, 2019

The big question(s)

What is quantum spin liquid?



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

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

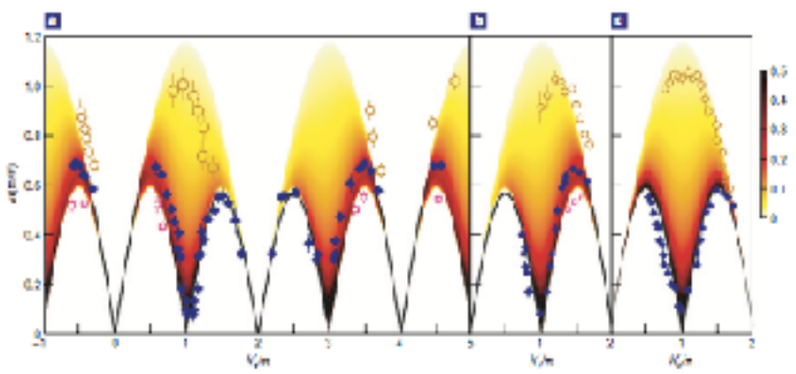
Savary, Balents 2017

Which materials realize it?

Past candidates: Cs2CuCl4, kagome volborthite…
Current candidates: kagome herbertsmithite, α-RuCl3, YbMgGaO4, organic Mott insulators

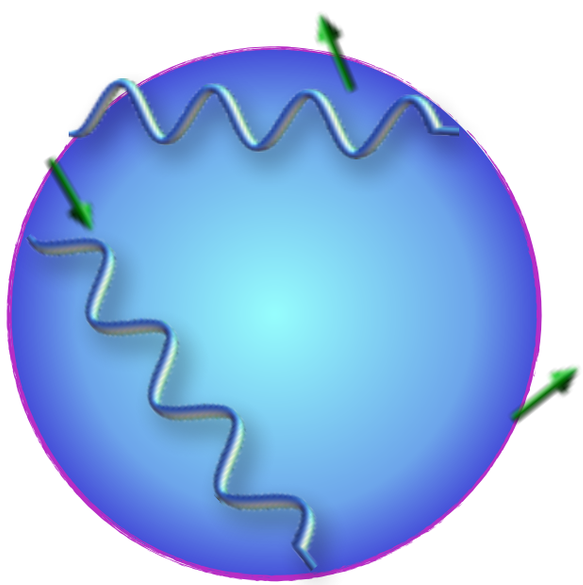
How to detect/observe it?

Neutrons (if good single crystals are available), RIXS, NMR, thermal transport, terahertz optics, ESR



Spinon Fermi surface

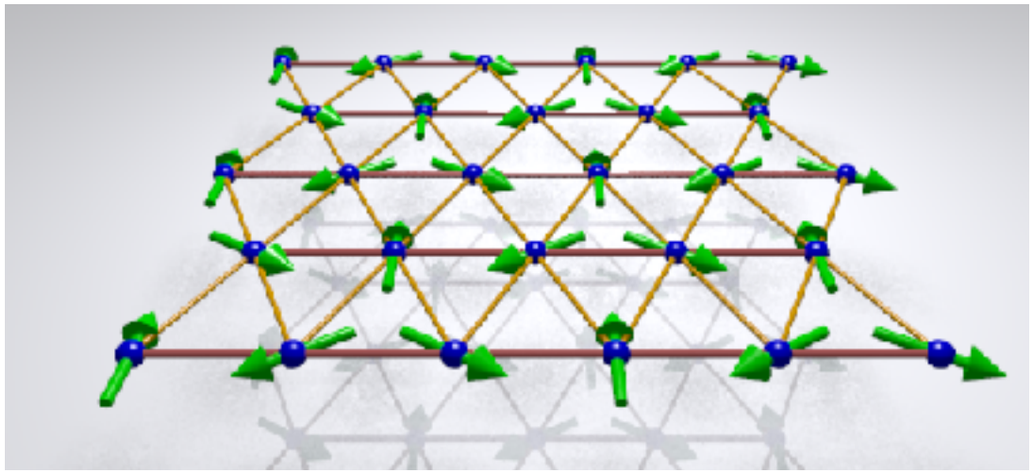
$$|\Psi\rangle = \prod_i \hat{n}_i(2-\hat{n}_i) \prod_{k<k_F} c^\dagger_{k\uparrow} c^\dagger_{k\downarrow}|0\rangle$$

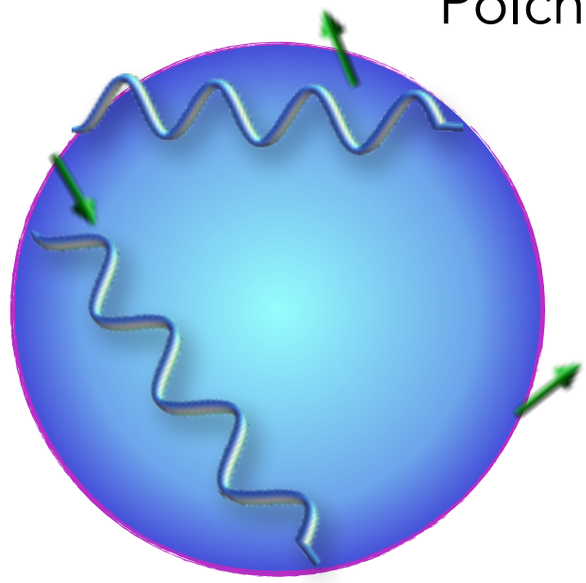


- The most gapless/highly entangled QSL state
- Like a “metal” of neutral fermions w/ a U(1) gauge field
- Prototype “non-Fermi liquid” state of great theoretical interest

Triangular lattice w/ ring exchange

Ioffe, Larkin 1989
Lee, Nagaosa 1992
Polchinsky 1994…

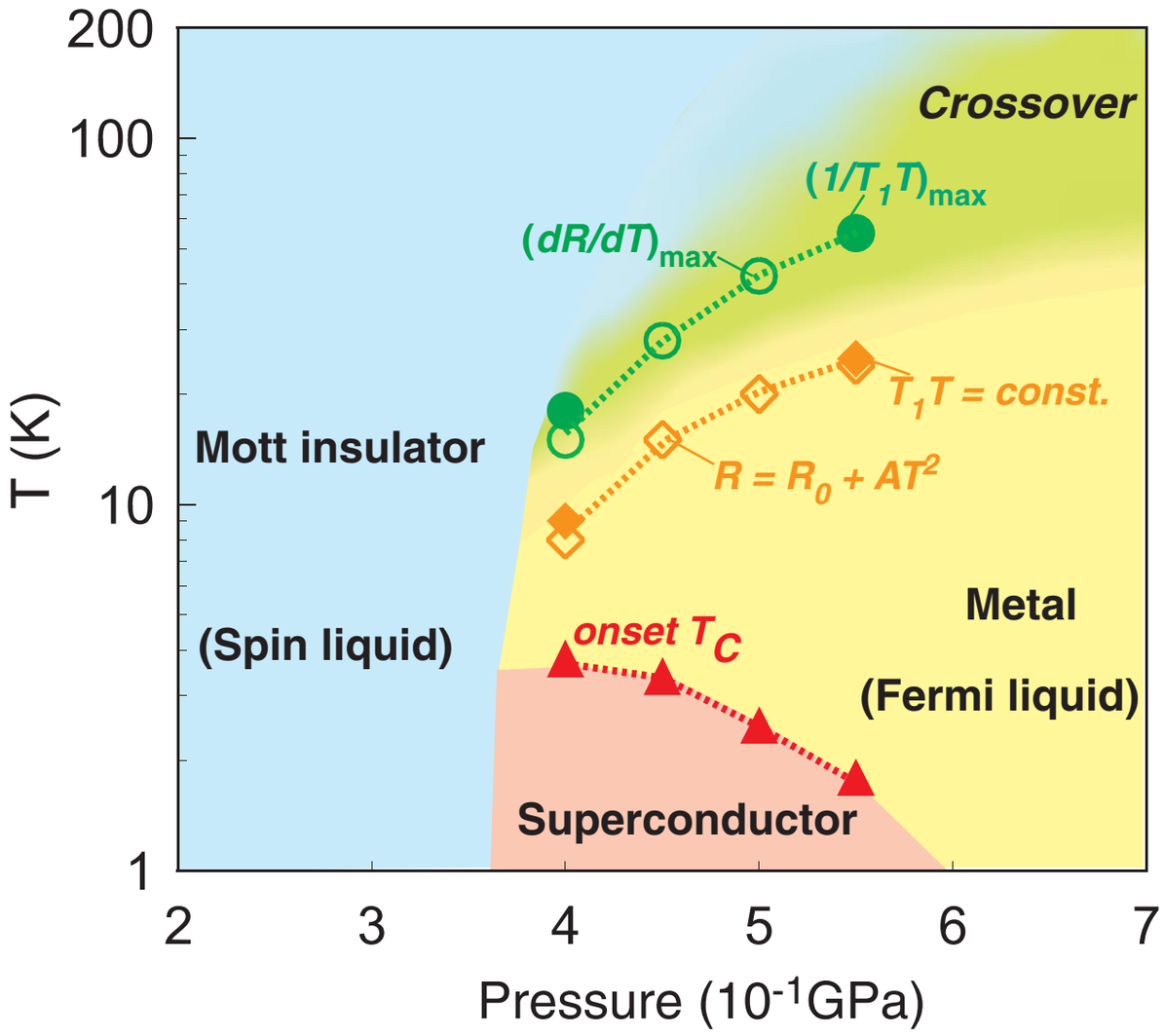




- Motrunich (2005): ring exchange stabilizes a spin liquid

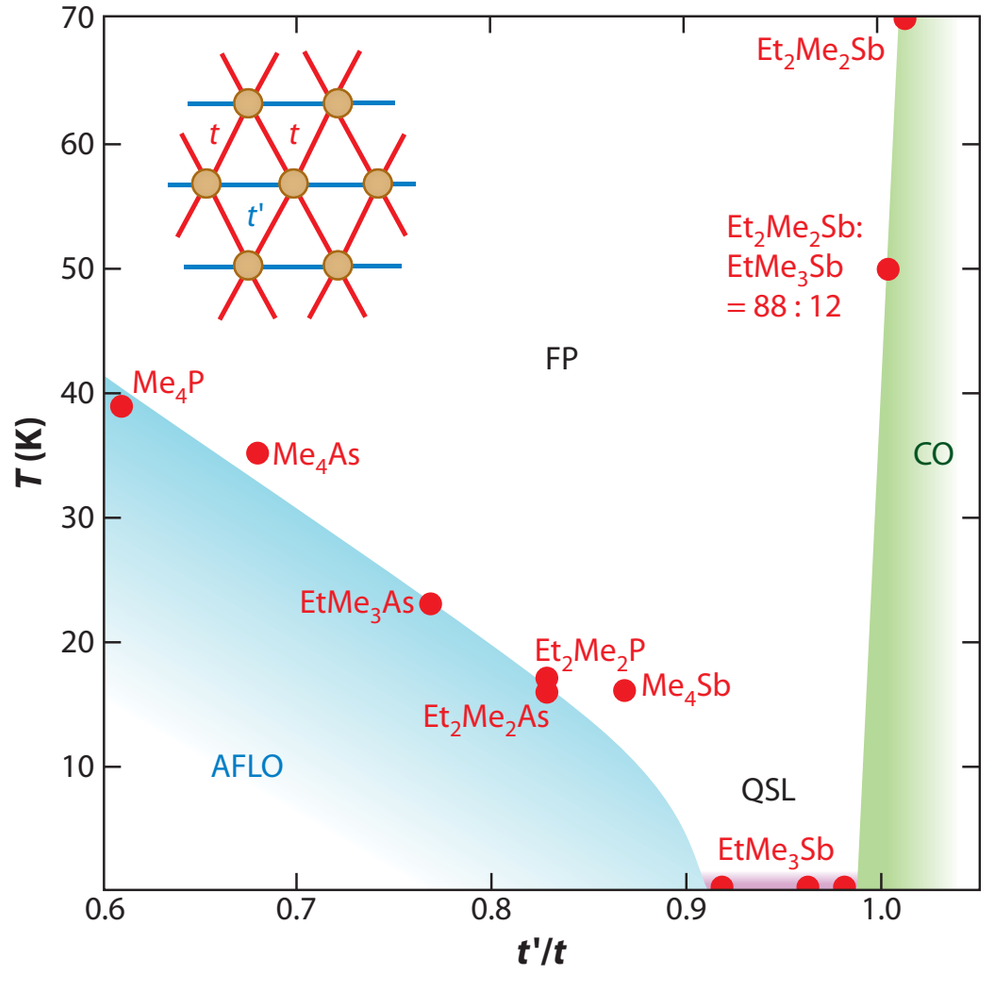
- Motrunich, Lee/Lee: spin liquid state favored by ring exchange is the "spinon Fermi sea" state

Exps: triangular organics



κ-$(ET)_2Cu_2(CN)_3$

K. Kanoda group (2003-)

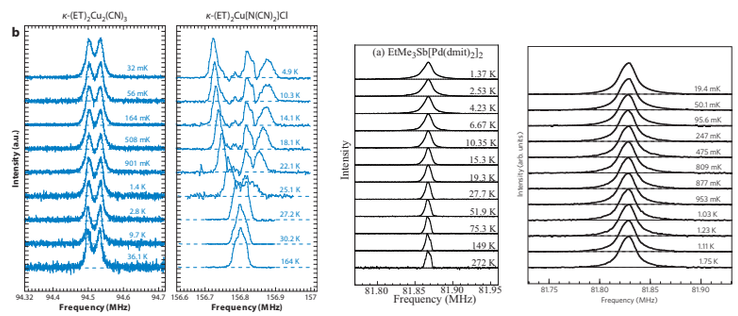


β′-$Pd(dmit)_2$

R. Kato group (2008-)

Experimental Evidence

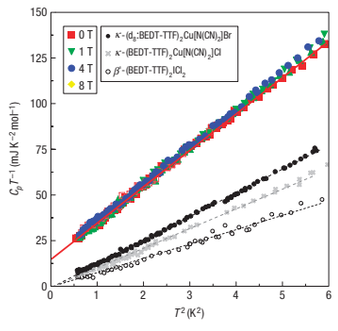
- NMR

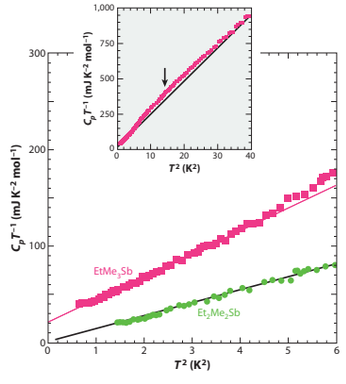


Y. Shimizu *et al*, 2003 T. Itou *et al*, 2008,2010

no magnetic order

- Specific heat

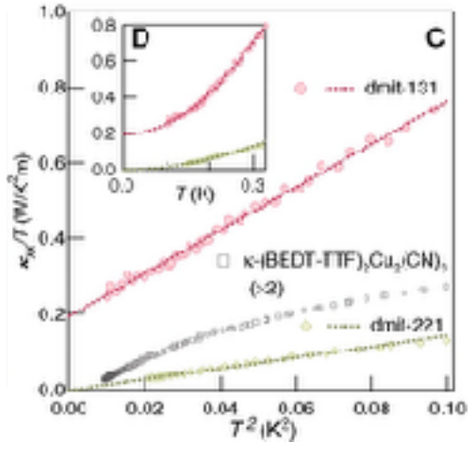




S. Yamashita *et al*, 2008

Sommerfeld law

- Thermal conductivity

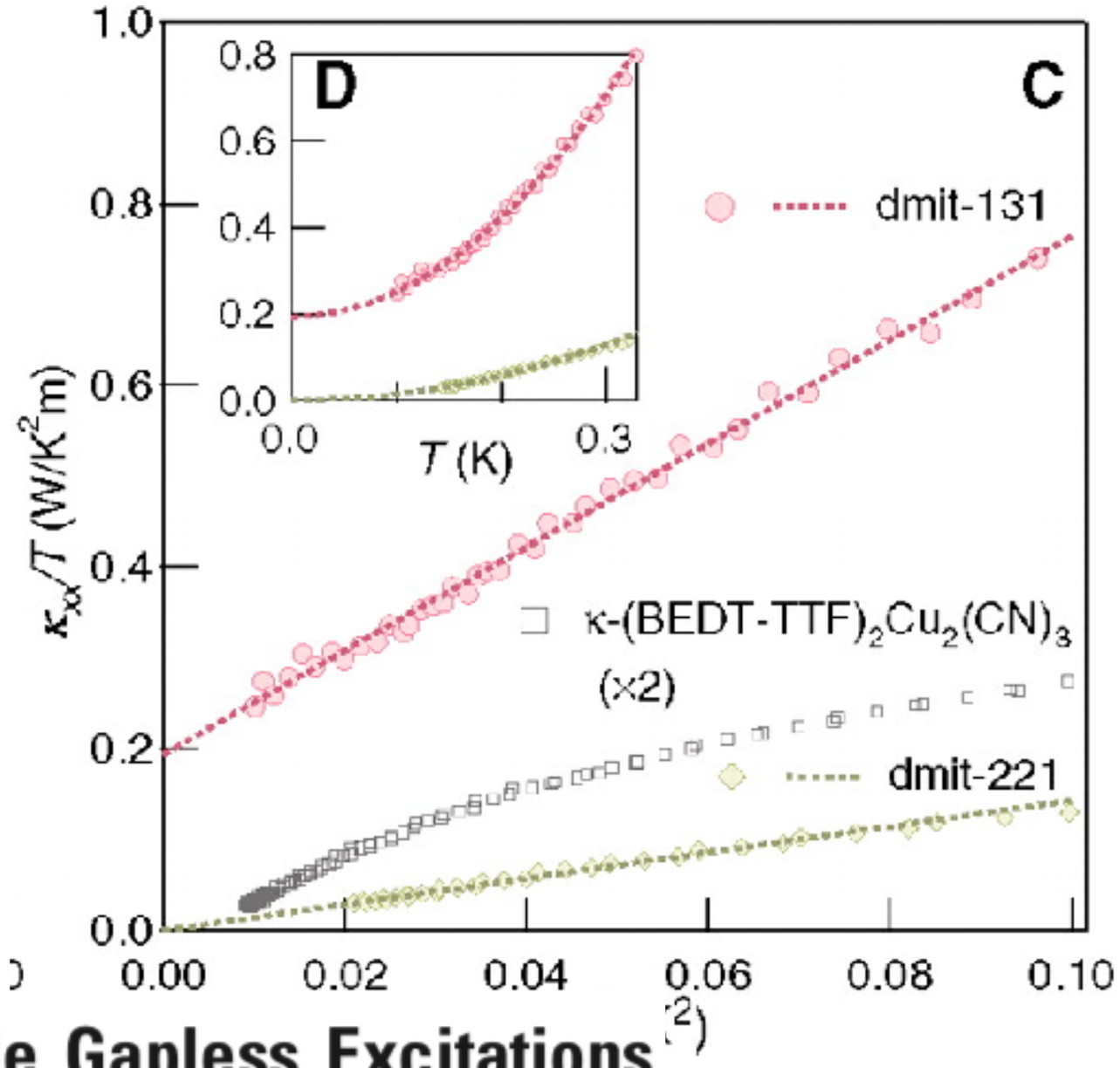


M. Yamashita *et al*, 2010

itinerant fermions?

Organic Mott insulators: Spin liquid with spinon Fermi surface?

THERMAL TRANSPORT



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

Spin liquid?

M. Yamashita et al, Science 2010

$Et_2Me_2Sb[Pd(dmit)_2]_2$ (dmit-221)

Non-magnetic
charge-ordered

theory: O. Motrunich 2005,
S.-S. Lee and P. A. Lee 2005

Highly Mobile Gapless Excitations in a Two-Dimensional Candidate Quantum Spin Liquid

Minoru Yamashita,[1*] Norihito Nakata,[1] Yoshinori Senshu,[1] Masaki Nagata,[1] Hiroshi M. Yamamoto,[2,3] Reizo Kato,[2] Takasada Shibauchi,[1] Yuji Matsuda[1*]

4 JUNE 2010 VOL 328 SCIENCE

electrical insulator,
but metal-like thermal conductor

A month-old surprise

Absence of magnetic thermal conductivity in the quantum spin li
$EtMe_3Sb[Pd(dmit)_2]_2$ – revisited

J. M. Ni,[1] B. L. Pan,[1] Y. Y. Huang,[1] J. Y. Zeng,[1] Y. J. Yu,[1] E. J. Cheng,[1] L. S. Wang,[1] R.
[1] *State Key Laboratory of Surface Physics, Department of Physics, and Laboratory of Advanced Materials, Fudan University, Shanghai 200438,*
[2] *RIKEN, Condensed Molecular Materials Laboratory, Wako 351-0198, Jap*
[3] *Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, China*
(Dated: April 25, 2019)

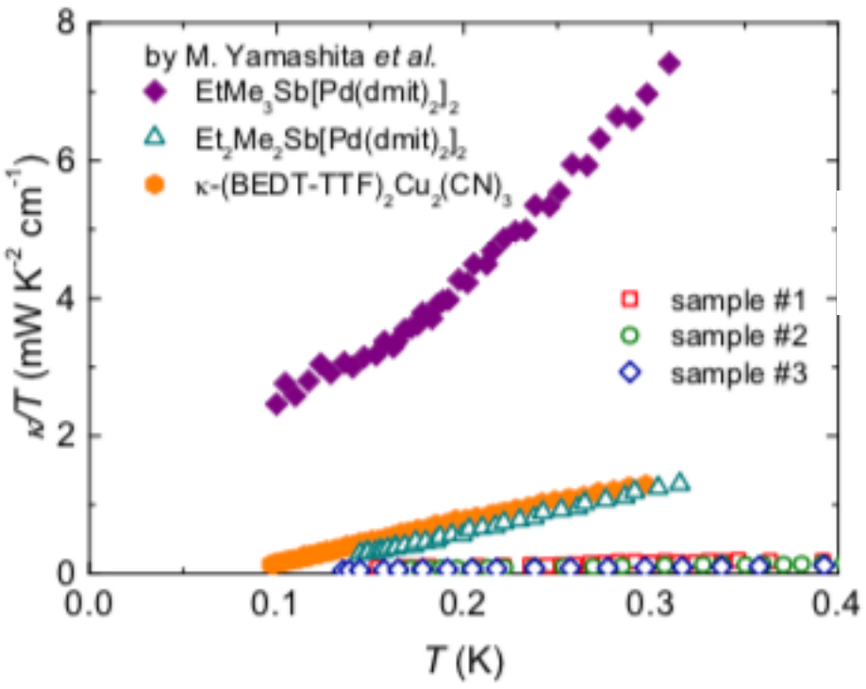


FIG. 4. Comparison of our thermal conductivity data with the data of $EtMe_3Sb[Pd(dmit)_2]_2$ and $Et_2Me_2Sb[Pd(dmit)_2]_2$ in Ref. [12] and κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$ in Ref. [9]. The absolute value of our data are much smaller than that in Ref. [12], even 10 times smaller than the nonmagnetic reference compound $Et_2Me_2Sb[Pd(dmit)_2]_2$, indicating phonons being strongly scattered in our samples.



Thermal conductivity of the quantum spin liquid candidate $EtMe_3Sb[Pd(dmit)_2]_2$: No evidence of mobile gapless excitations

P. Bourgeois-Hope,[1] F. Laliberté,[1] E. Lefrançois,[1] G. Grissonnanche,[1] S. René de Cotret,[1] R. Gordon,[1] R. Kato,[2] L. Taillefer,[1,3,*] and N. Doiron-Leyraud[1,†]
[1] *Institut Quantique, Département de physique & RQMP, Université de Sherbrooke, Sherbrooke, Québec, Canada*
[2] *RIKEN, Wako-shi, Saitama 351-0198, Japan*
[3] *Canadian Institute for Advanced Research, Toronto, Ontario, Canada*
(Dated: April 25, 2019)

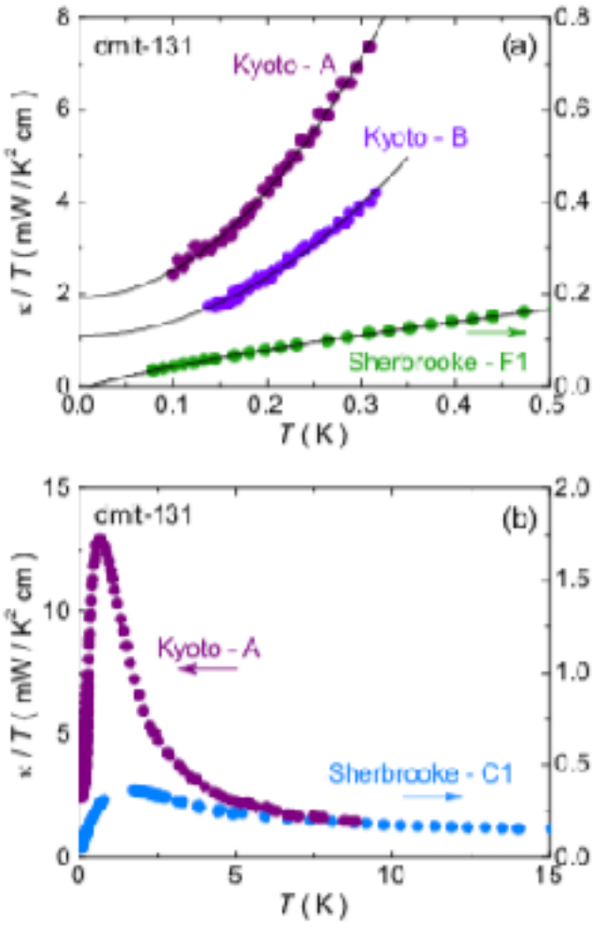


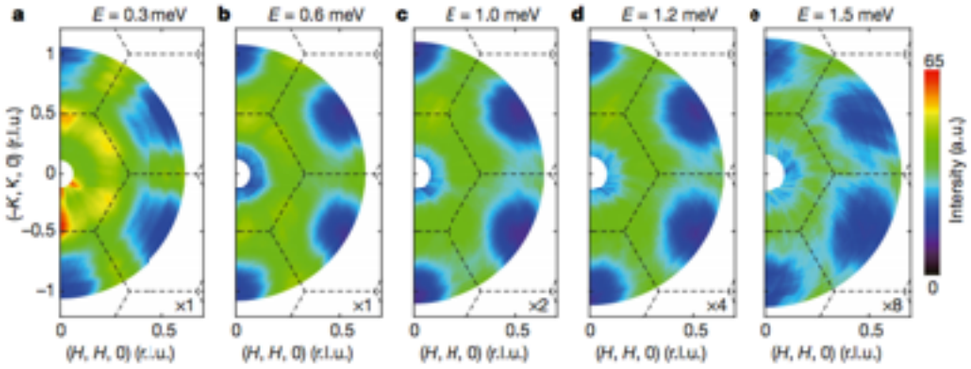
FIG. 4. (a) κ/T vs T for our sample F1 (green, right scale) and for samples A (purple) and B (violet) of ref. [10] (left scale). Note that the left and right vertical scales differ by a factor 10. The three samples were grown in identical conditions, using the same starting material. For our data, the black line is the free power law fit below 0.55 K shown in Fig. 6(b). For the Kyoto data, the lines are quadratic fits reproduced from Ref. [10]. (b) κ/T vs T up to 15 K for our sample C1 (blue, right scale) and for sample A of ref. [10] (purple, left scale). Note that the left and right vertical scales differ by a factor 7.5.

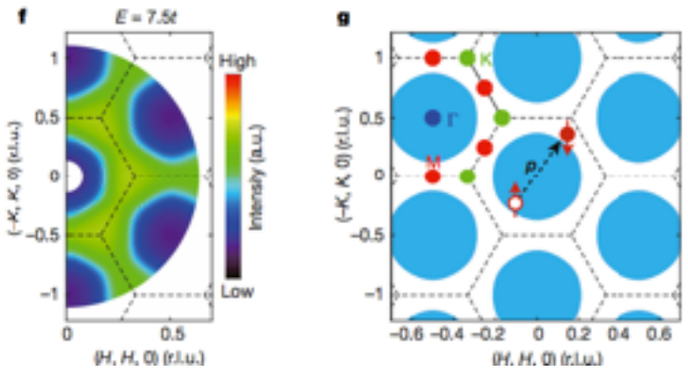
LETTER Experimentally observed?!

nature physics LETTERS
PUBLISHED ONLINE: 5 DECEMBER 2016 | DOI: 10.1038/NPHYS3971

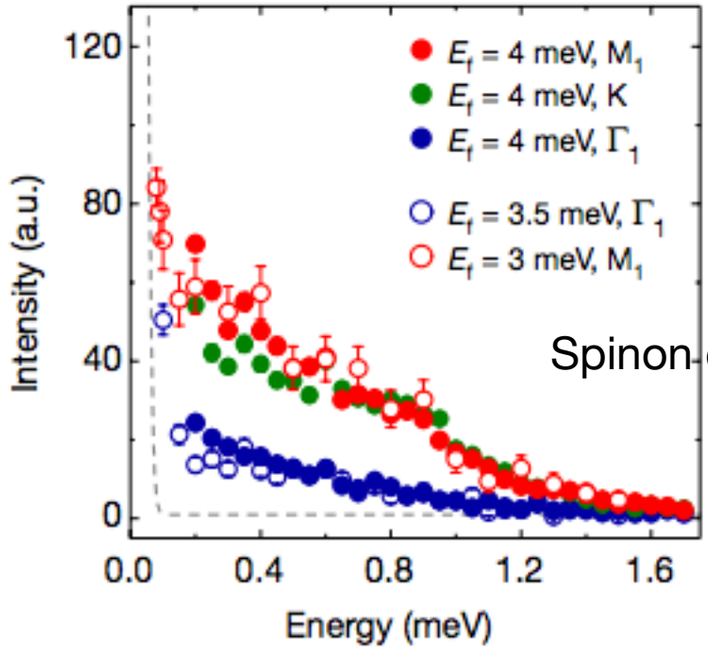
Evidence for a spinon Fermi surface in a triangular-lattice quantum-spin-liquid candidate

Yao Shen[1], Yao-Dong Li[2], Hongliang Wo[1], Yuesheng Li[1], Shoudong Shen[1], Bingying Pan[1], Qisi Wang[1], H. C. Walker[4], P. Steffens[5], M. Boehm[5], Yiqing Hao[1], D. L. Quintero-Castro[6], L. W. Harriger[7], M. D. Frontzek[8], Lijie Hao[9], Siqin Meng[9], Qingming Zhang[9,10,11], Gang Chen[1,11,12] & Jun Zhao[1,11]





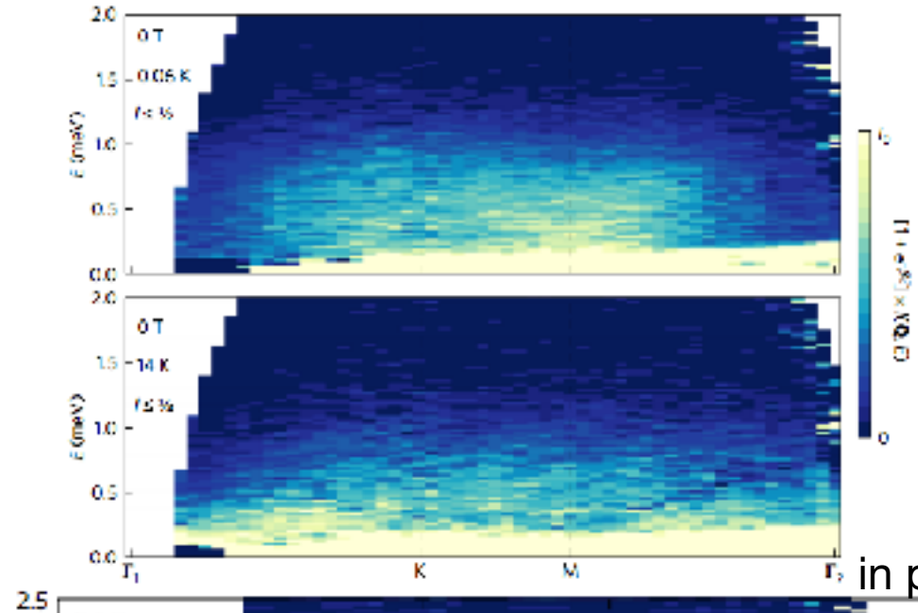
Sign of spinon Fermi surface?



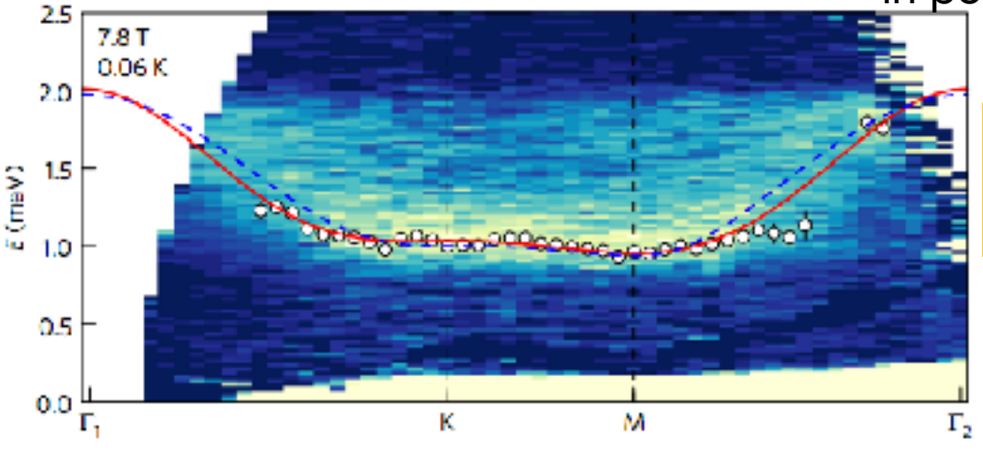
Spinon continuum?

Continuous excitations of the triangular-lattice quantum spin liquid $YbMgGaO_4$

Joseph A. M. Paddison[1], Marcus Daum[1†], Zhiling Dun[2†], Georg Ehlers[3], Yaohua Liu[3], Matthew B. Stone[3], Haidong Zhou[2] and Martin Mourigal[1*]



Broad signal in polarized phase?



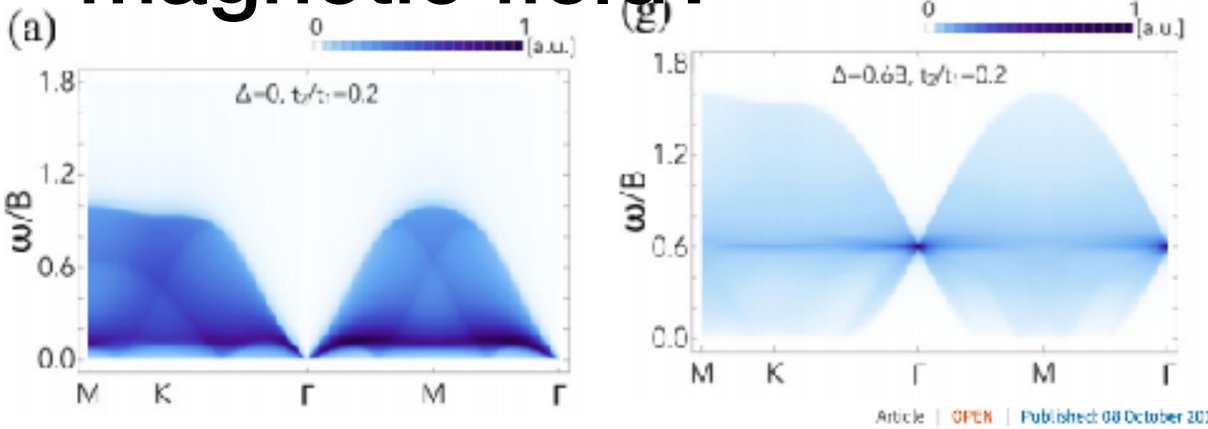
very disordered

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[J_1^{zz} S_i^z S_j^z + J_1^{\pm} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) + J_1^{\pm\pm} \left(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^- \right) \right]$$

$$+ \sum_{\langle\langle ij \rangle\rangle} \left[J_2^{zz} S_i^z S_j^z + J_2^{\pm} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) \right]$$

$$- \mu_0 \mu_B \sum_i \left[g_\perp \left(H^x S_i^x + H^y S_i^y \right) + g_\parallel H^z S_i^z \right] \qquad (1)$$

Expected spinon Fermi surface behavior in applied magnetic field?



PHYSICAL REVIEW B 96, 075105 (2017)

Detecting spin fractionalization in a spinon Fermi surface spin liquid

Yao-Dong Li[1] and Gang Chen[1,2,*]

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

$YbMgGaO_4$

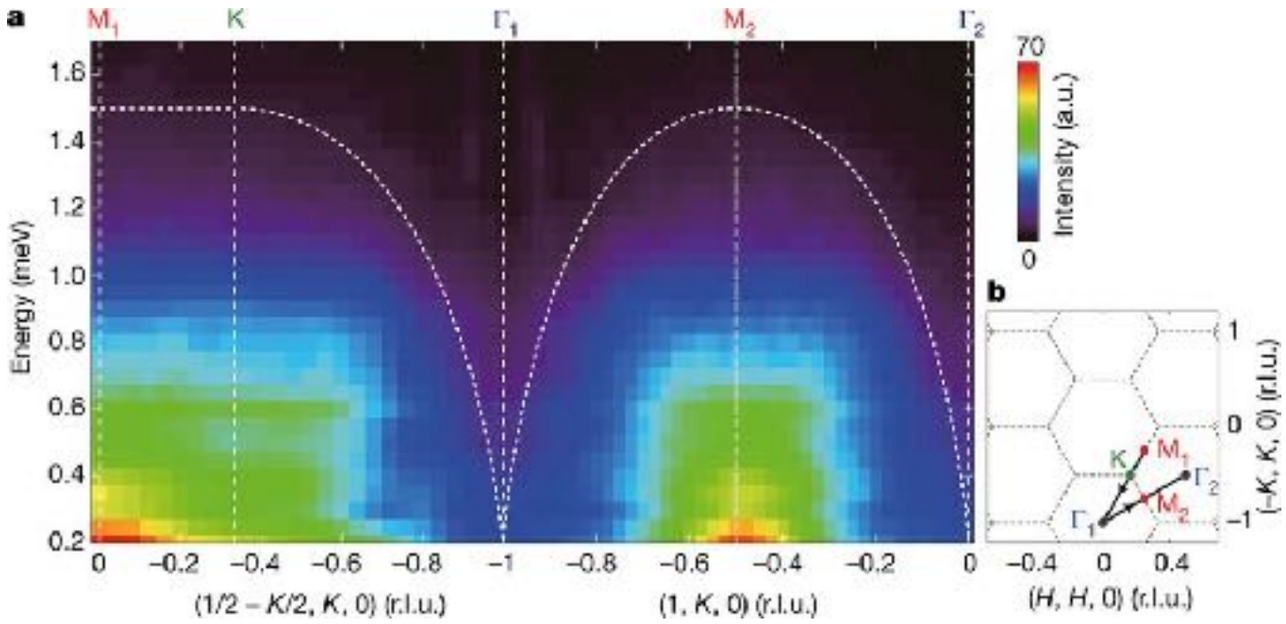
Small momentum **q** structure

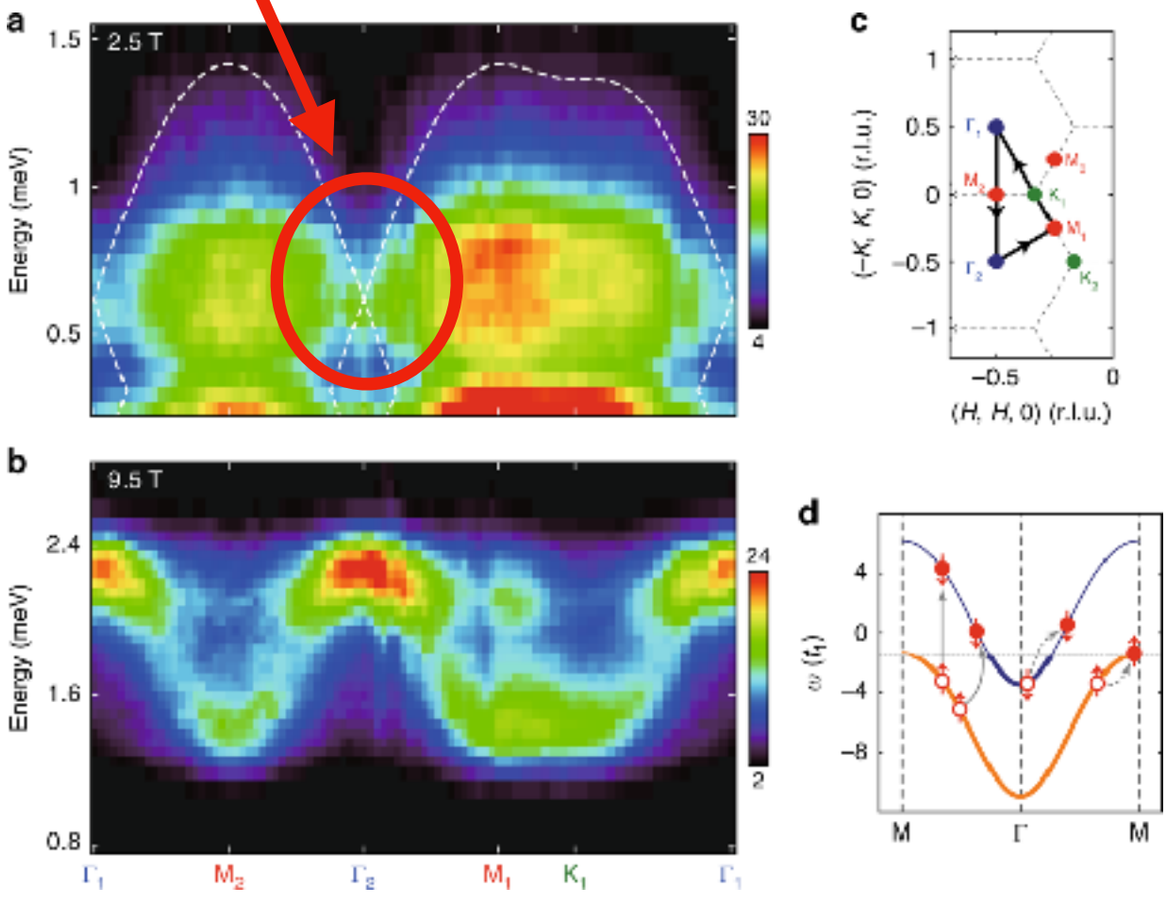
Letter | Published: 05 December 2016

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

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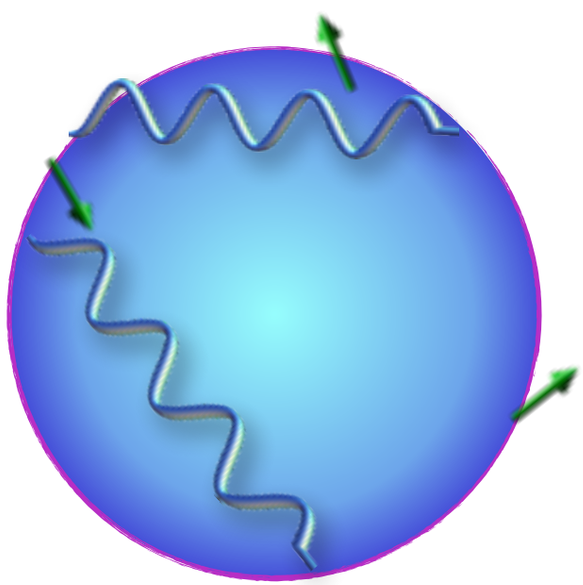
Nature 540, 559–562 (22 December 2016) | Download Citation





Spinon Fermi surface

$$|\Psi\rangle = \prod_i \hat{n}_i(2-\hat{n}_i) \prod_{k<k_F} c^\dagger_{k\uparrow} c^\dagger_{k\downarrow}|0\rangle$$



- The most gapless/highly entangled QSL state
- Like a “metal” of neutral fermions w/ a U(1) gauge field
- Prototype “non-Fermi liquid” state of great theoretical interest

U(1) gauge theory: main technical steps

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

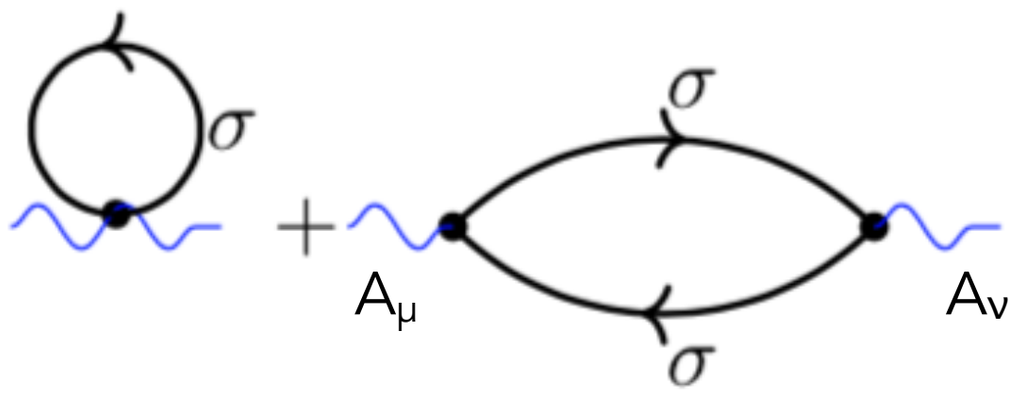
3) $S_\psi = \int d\tau d^2\mathbf{r}\,\psi^\dagger_\alpha\Big([\partial_\tau - iA_0 - \mu - \frac{(\boldsymbol{\nabla}_{\mathbf{r}} - i\mathbf{A})^2}{2m}]\delta_{\alpha\beta} - \omega_B\sigma^3_{\alpha\beta}\Big)\psi_\beta.$

Spinon

External magnetic field

Gauge field

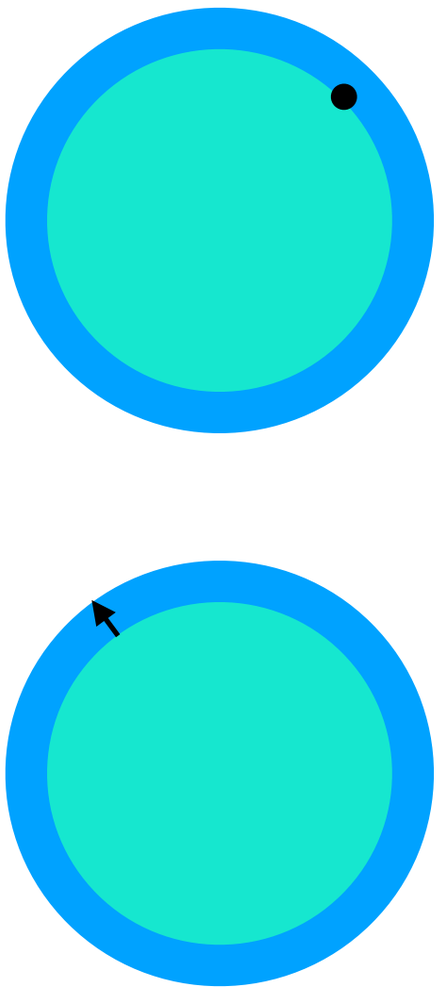
4) Gauge dynamics generated by spinons

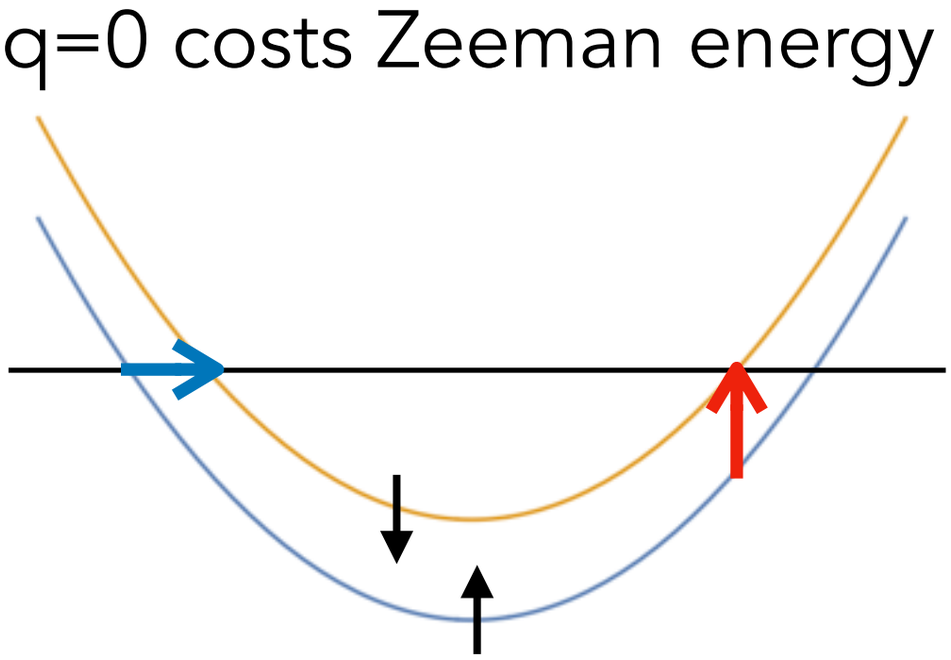


Spinon particle-hole continuum

+ Zeeman field

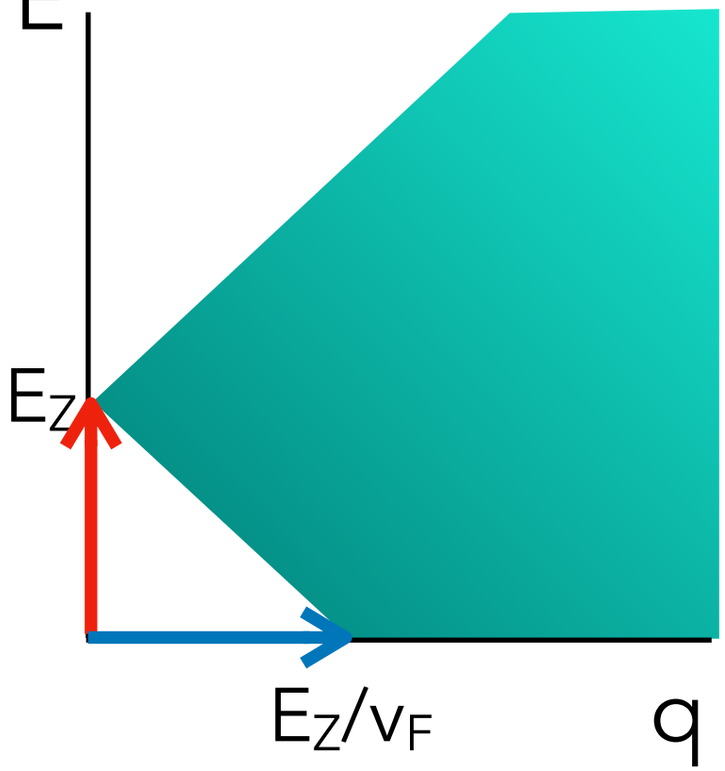
$$\chi_{\pm}(\boldsymbol{q},\omega) = i\int_0^\infty dt \langle [S^\dagger_{\mathbf{q}}(t), S^-_{-\mathbf{q}}(0)]\rangle e^{i\omega t}$$





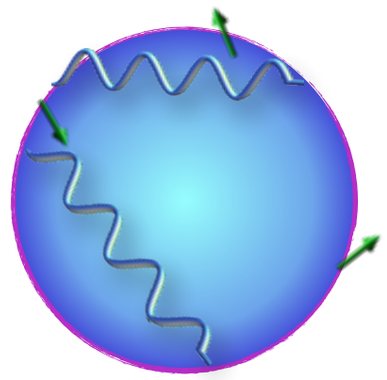
zero energy when $v_F q$
= Zeeman

Transverse spin susceptibility



U(1) gauge theory

Claim: spin susceptibility at small **q** is strongly affected by gauge fluctuations **in the presence of external magnetic field**



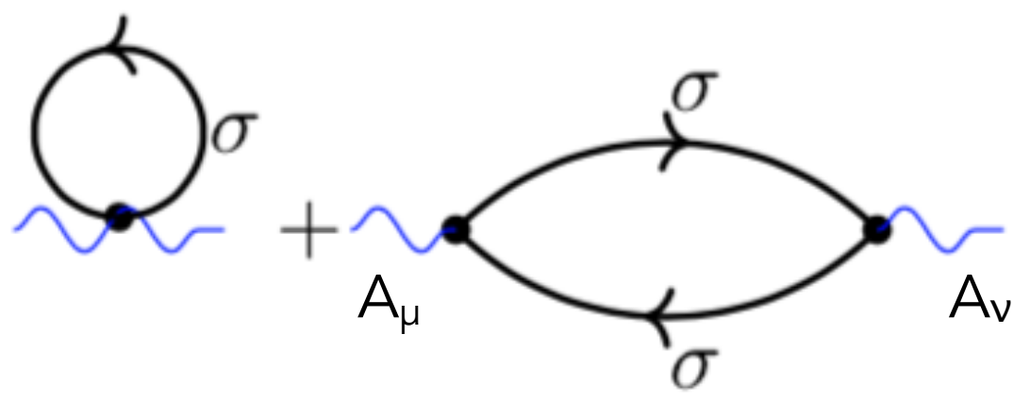
magnetic field

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

Gauge field

Spinon

Gauge dynamics generated by spinons



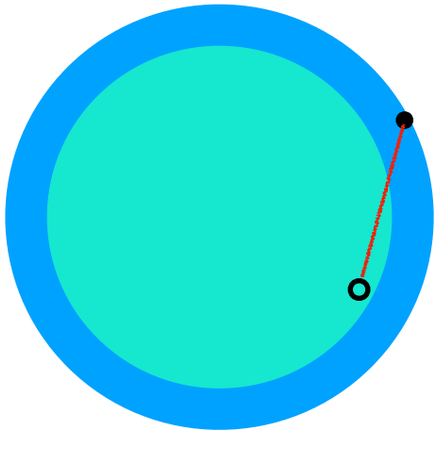
Interactions

- Longitudinal

$$A_0\psi^\dagger\psi$$

screened Coulomb interaction

boring!?

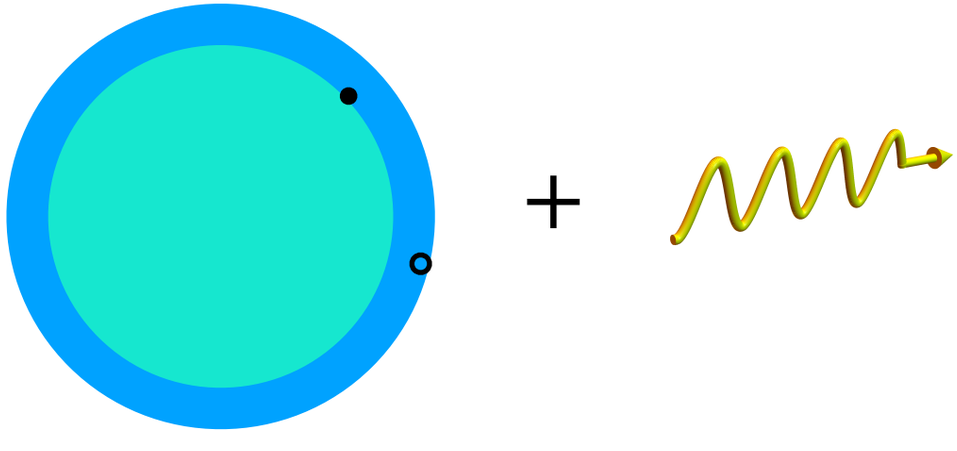


- Transverse

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

coupling to dynamical photons

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



Equivalent formulation of U(1) gauge theory

Finite spinon density of states on the Fermi surface leads to the screening of longitudinal gauge field

$$S_{A_0} \approx \frac{-m}{4\pi} \int \frac{d\omega_n d^2\mathbf{q}}{(2\pi)^3} |A_0(\mathbf{q}, \omega_n)|^2$$

Integrate out $iA_0\psi_\alpha^\dagger\psi_\alpha$

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

$$S_A = \frac{1}{2} \int \frac{d\omega_n d^2\mathbf{q}}{(2\pi)^3} A_\mu(\mathbf{q}, \omega_n) \Big(\gamma \frac{|\omega_n|}{q} + \chi q^2 \Big) A_\nu(-\mathbf{q}, -\omega_n),$$

$$S_u = \int d\tau d^2\mathbf{r}\, u\, \psi_\uparrow^\dagger(\mathbf{r}, \tau)\psi_\uparrow(\mathbf{r}, \tau)\psi_\downarrow^\dagger(\mathbf{r}, \tau)\psi_\downarrow(\mathbf{r}, \tau).$$

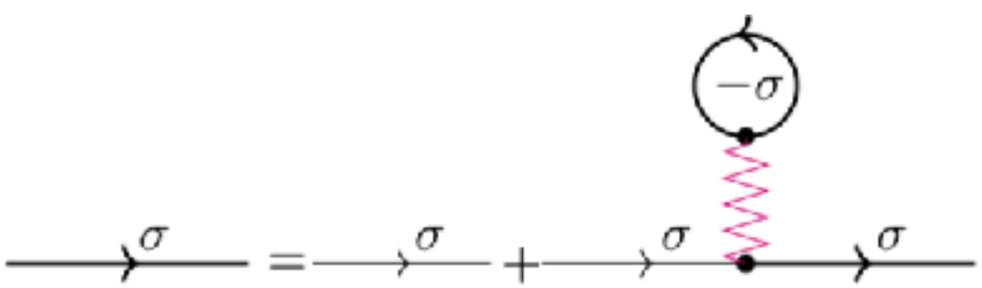
Short-ranged repulsion

Spinon self energy

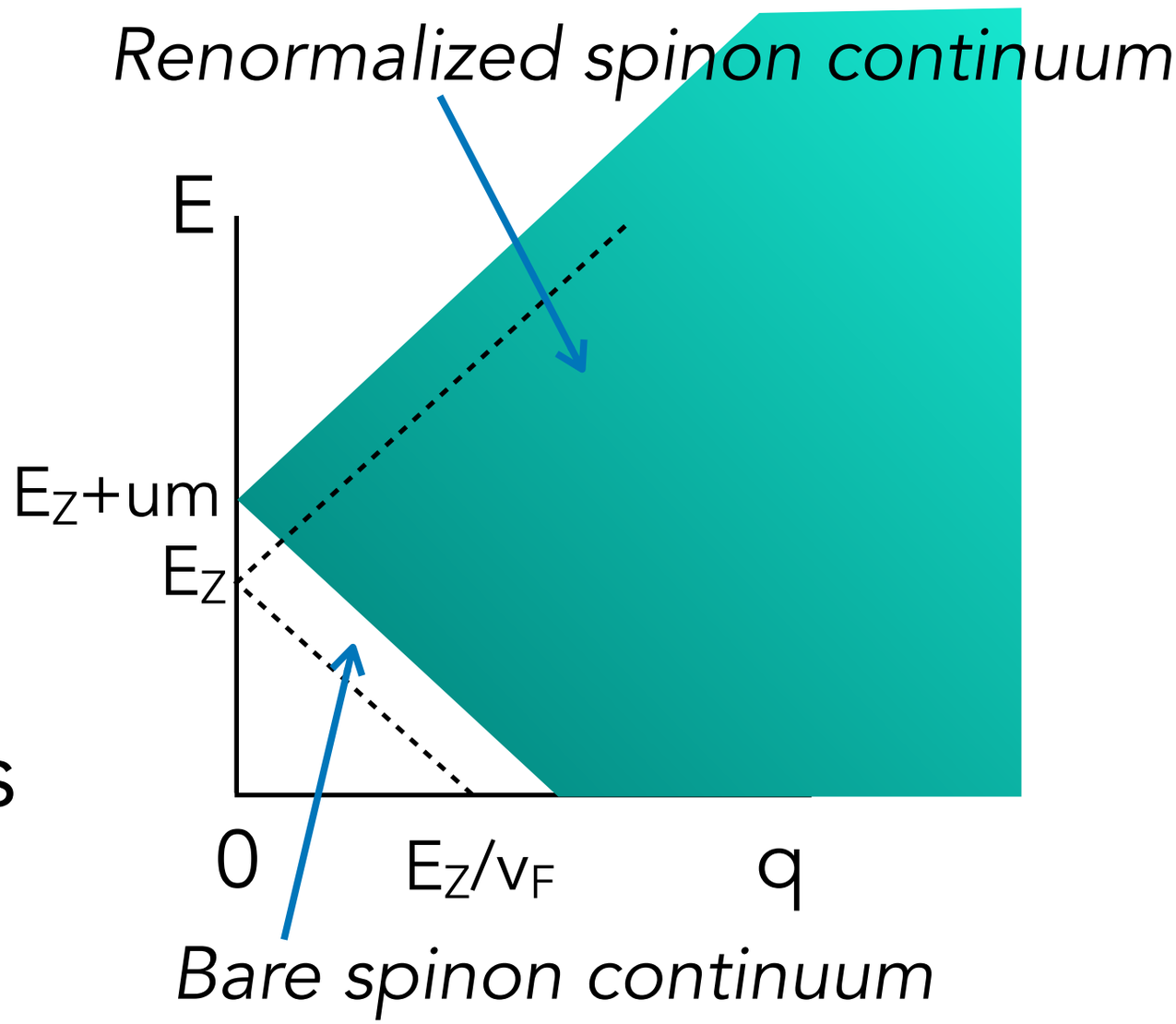
- Longitudinal $a_0\psi^\dagger\psi$ → $u\psi^\dagger_\uparrow\psi_\uparrow\psi^\dagger_\downarrow\psi_\downarrow$

$$= -um\left(\psi^\dagger_\uparrow\psi_\uparrow - \psi^\dagger_\downarrow\psi_\downarrow\right)$$

mean field shift



Spinon continuum shifts **up** in energy

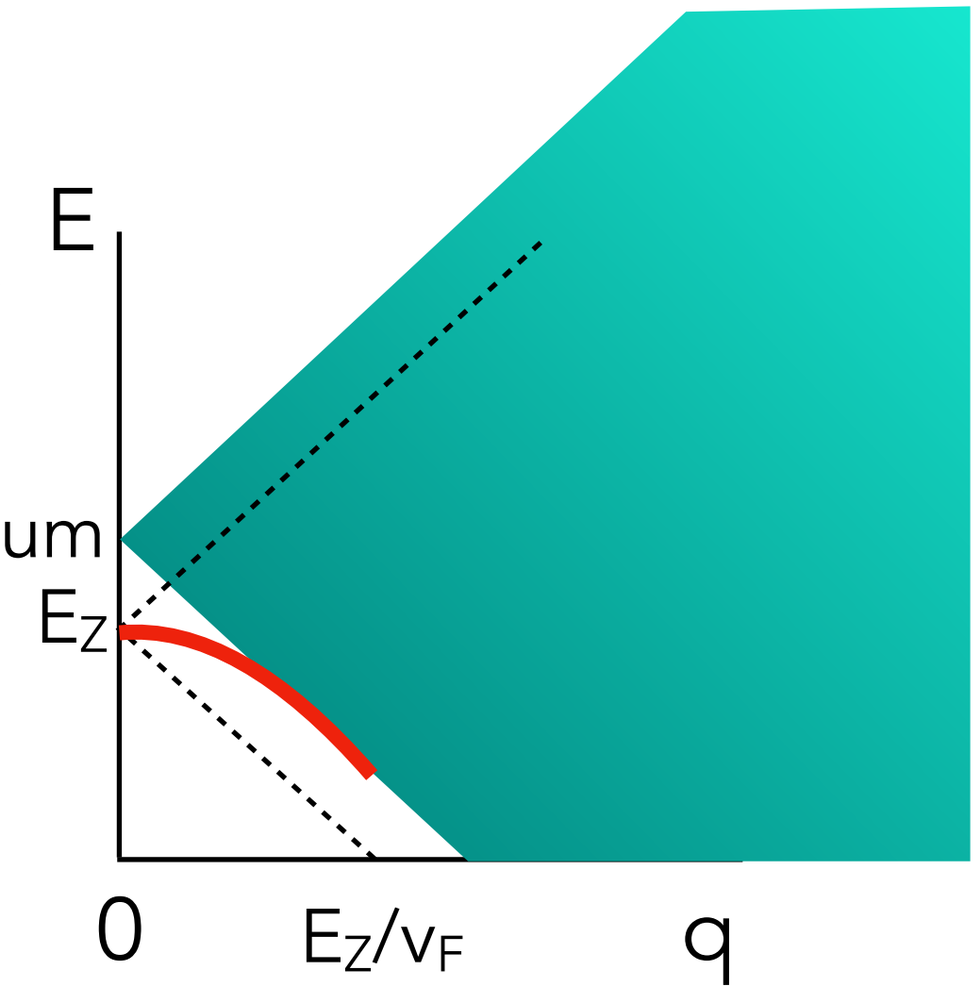


Silin spin wave

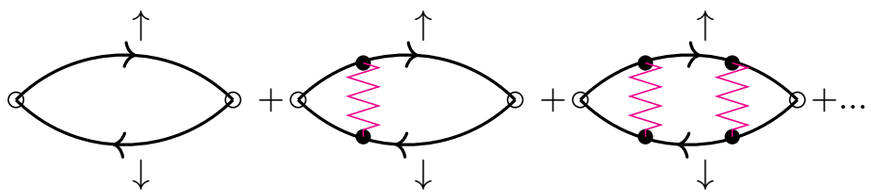
Larmor theorem: **q**=0

excitation *must* be at $E_{\mathrm{Z}} = 2\omega_{\mathrm{B}}$

$$\frac{dS^{+}_{\mathrm{total}}}{dt} = -ihS^{+}_{\mathrm{total}} \rightarrow \chi(\mathbf{q}=0,\omega) = \frac{2m}{\omega - E_z + i0}$$



RPA



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

"Silin spin wave"

pole: collective mode

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

[1]V. P. Silin, Zh. Eksperim. i Teor. Fiz. 35, 1243 (1958) [Sov. Phys. JETP 8, 870 (1959)].

[2]S. Schultz and G. Dunifer, Phys. Rev. Letters 18, 283 (1967).

[3]P. M. Platzman and P. A. Wolff, Phys. Rev. Letters 18, 280 (1967).

STATISTICAL PHYSICS

Part 2

Theory of the Condensed State

by

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Volume 9 of *Course of Theoretical Physics*

Translated from the Russian by
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§3 magnetic field. In calculating the magnetic susceptibility, we must therefore write the quasi-particle energy change operator as

$$\delta\hat{\varepsilon} = -\beta\boldsymbol{\sigma}.\mathbf{H} + \mathrm{tr}' \int f\, \delta\hat{n}'\, d\tau'. \tag{3.1}$$

The change in the distribution function is given in terms of $\delta\hat{\varepsilon}$ by $\delta\hat{n} = (\partial n/\partial\varepsilon)\,\delta\hat{\varepsilon}$;† we thus have

$$\delta\hat{\varepsilon}(\mathbf{p}) = -\beta\boldsymbol{\sigma}.\mathbf{H} + \mathrm{tr}' \int f(\mathbf{p}, \mathbf{p}')\,(dn'/d\varepsilon')\,\delta\hat{\varepsilon}(\mathbf{p}')\, d\tau'. \tag{3.2}$$

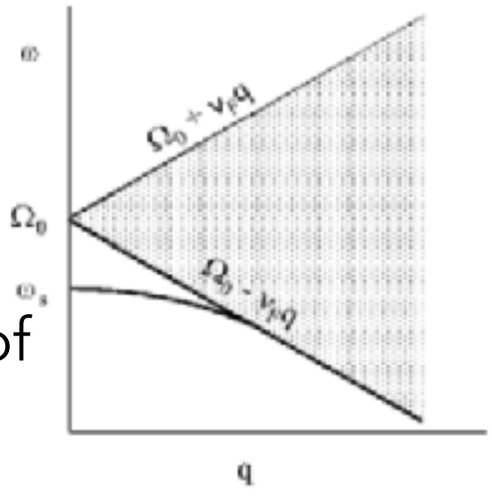
Authoritative Opinion

$$\chi = \frac{\beta^2 p_F m^*}{\pi^2\hbar^3(1+\bar{G})} = \frac{3\gamma\beta^2}{\pi^2(1+\bar{G})}, \tag{3.5}$$

where γ is the coefficient in the linear specific heat law (1.15). The expression $\chi = 3\gamma\beta^2/\pi^2$ gives the susceptibility of a denegerate Fermi gas of particles with magnetic moment β; see Part 1, (59.5). The factor $1/(1+\bar{G})$ represents the difference between a Fermi liquid and a Fermi gas.†

† For He^3, $\bar{G} \approx -2/3$.

§5 Spin waves of another kind can be propagated in a Fermi liquid when a magnetic field is present (V. P. Silin 1958). Here we shall consider only vibrations with $\mathbf{k} = 0$, in which $\delta\hat{n}$ is independent of the coordinates.



The first frequency ω_{00} corresponds to vibrations with μ = constant; then $\rho = \mu(1+\bar{G})$, and (5.6) becomes

$$i\omega_{00}\mu = (2\beta/\hbar)\mathbf{H}\times\mu;$$

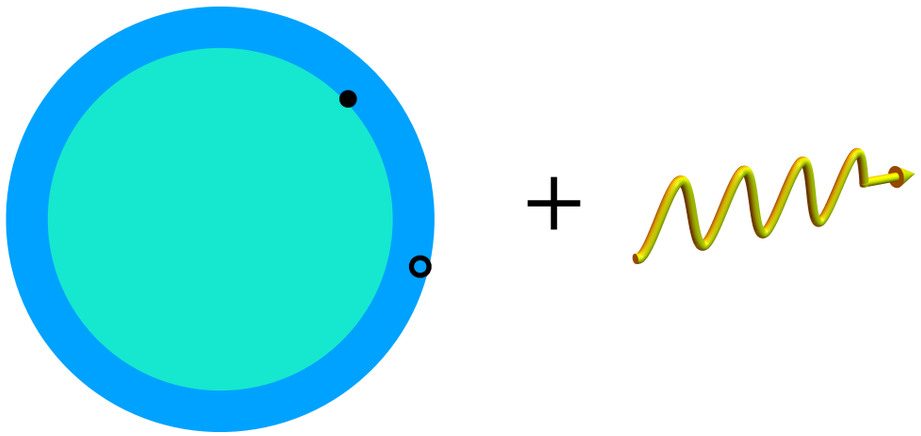
the vibrations are transverse to the field ($\mu \perp \mathbf{H}$). Writing the equation in components in the plane perpendicular to **H** and taking the determinant, we find the frequency

$$\omega_{00} = 2\beta H/\hbar. \tag{5.8}$$

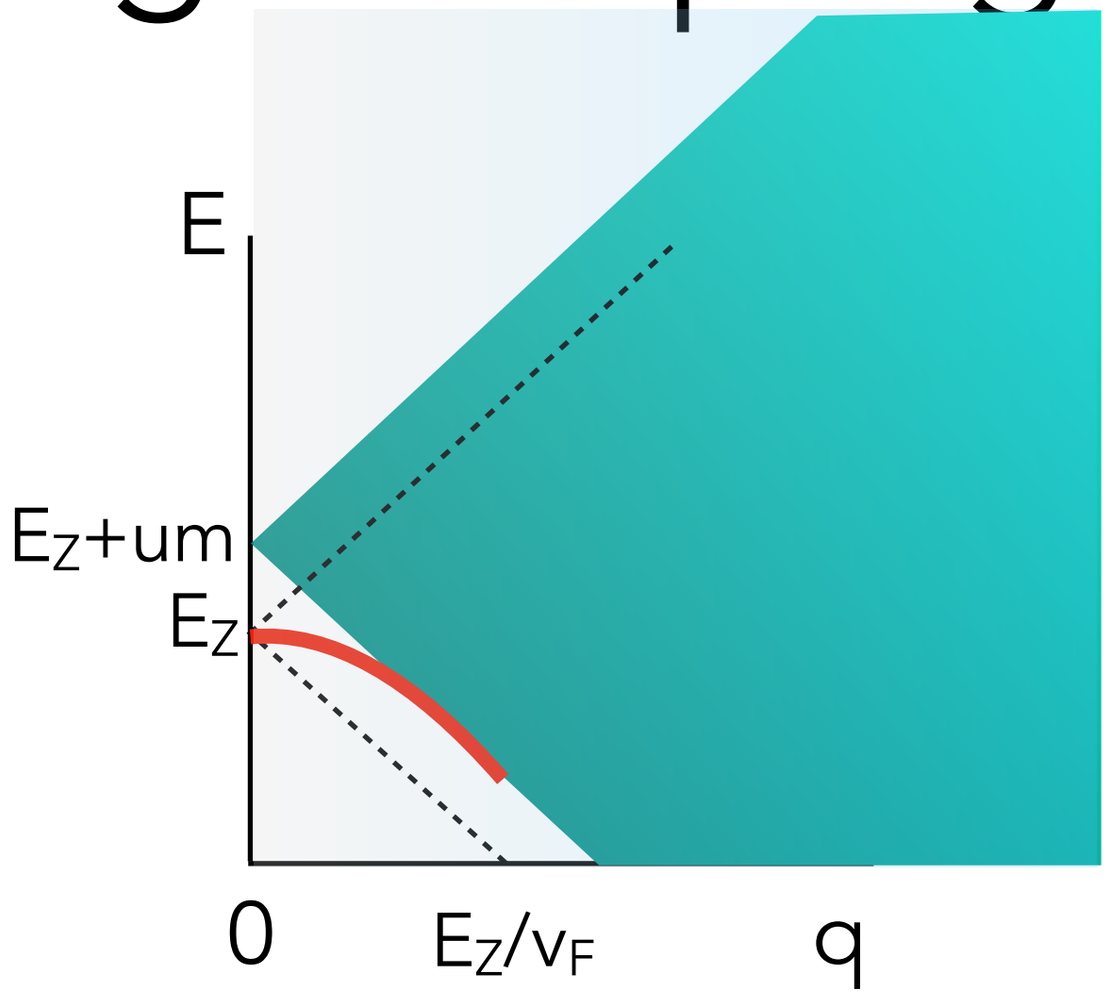
Here β is the magnetic moment of a particle (actual) in the liquid. Thus ω_{00} is independent of the specific properties of the liquid. The values of all the other frequencies ω_{lm}, however, depend on the specific form of the function $G(\theta)$.

\+ R. M. White, Quantum theory of Magnetism

Transverse gauge coupling



+



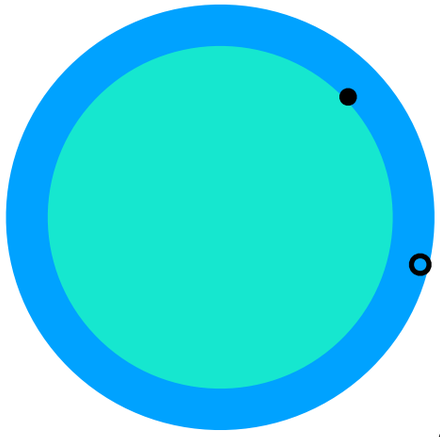
Simple picture:

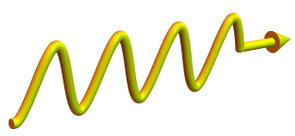
3-particle process:

$$E = E_{\mathrm{p/h}}(q-k) + E_{\mathrm{photon}}(k)$$
$$\sim c\,k^3$$

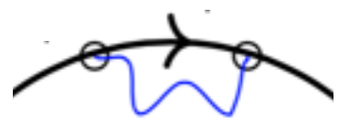
Does this smear out all the Fermi liquid structure?

Transverse gauge coupling



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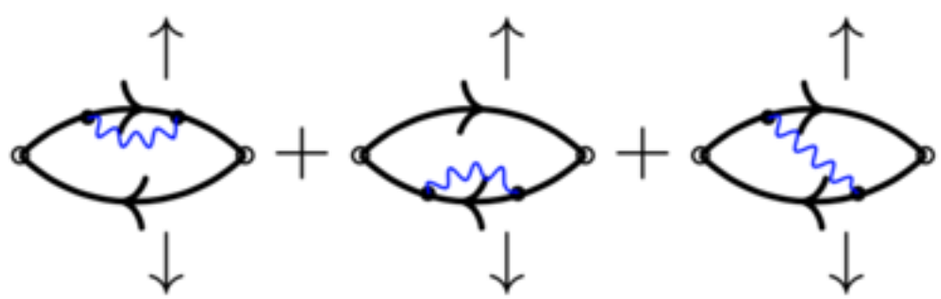
$$D_{\mu\nu}(\boldsymbol{p}, p_n) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) \frac{1}{\gamma |p_n|/p + \chi p^2}.$$

Spinon self-energy 

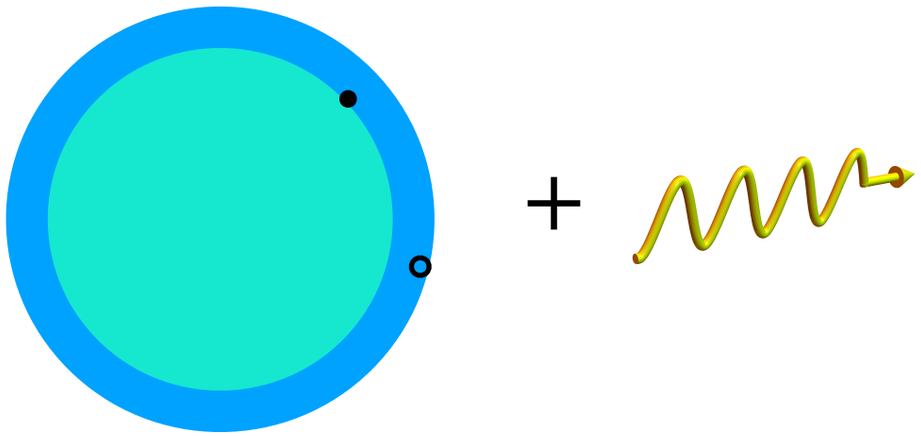
$$\Sigma_\alpha(\boldsymbol{k}, k_n) = \frac{-iv_F}{2\sqrt{3}\pi} \frac{\mathrm{sign}(k_n)|k_n|^{2/3}}{\gamma^{1/3}\chi^{2/3}}.$$

(Not a gauge-invariant object)

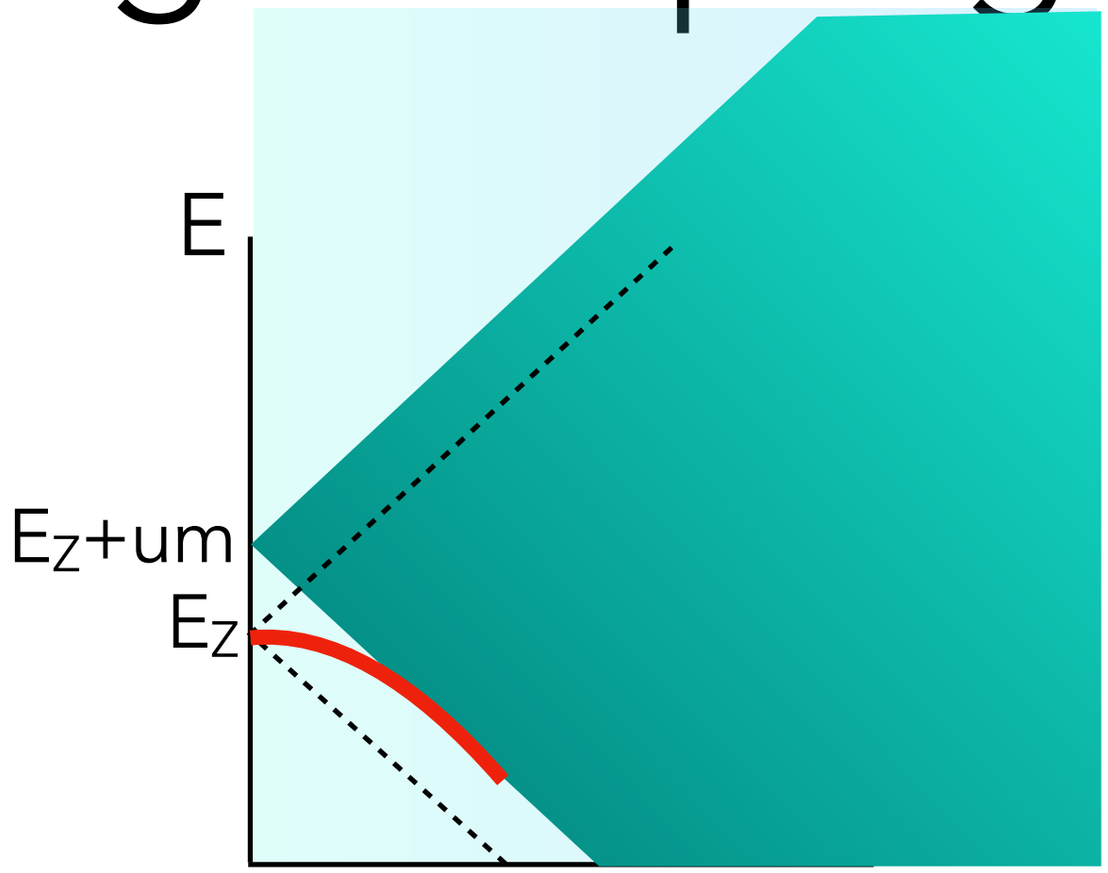
Gauge correction to the transverse spin susceptibility

$$\chi^1_\pm(\boldsymbol{q}, i\omega_n) =$$ 

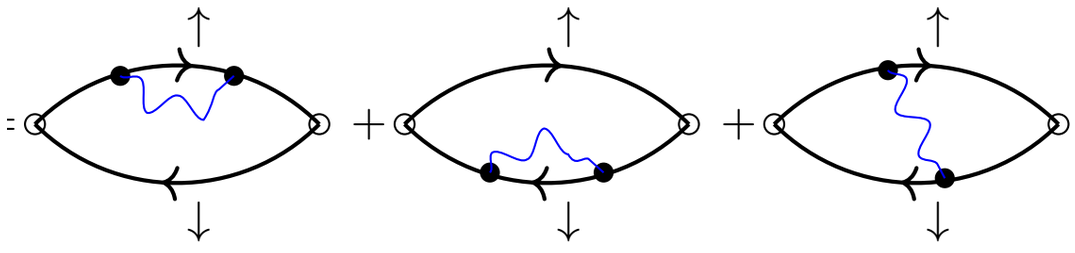
Transverse gauge coupling



+



Actual calculation:



c.f. Y. B. Kim, A. Furusaki, X.-G. Wen, and P. A. Lee, Phys Rev. B **50**, 17917 (1994).

$$\chi = \frac{\chi^0 + \chi^1}{1 + u(\chi^0 + \chi^1)}$$

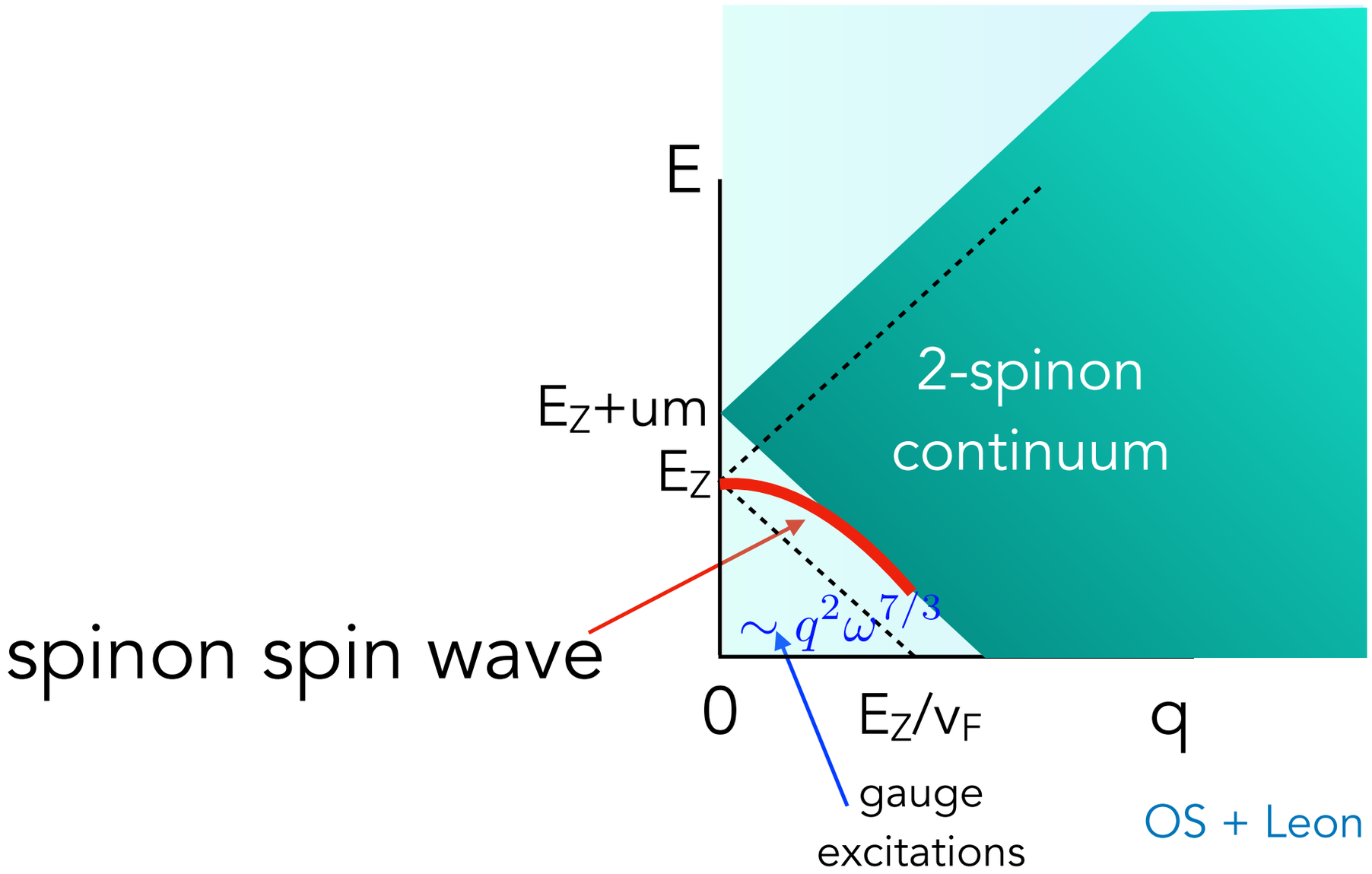
$$\chi_1''(\mathbf{q},\omega) \propto \omega^{7/3} v_F^2 q^2 / [(v_F k_F)^{1/3} (uM)^4]$$

weight at all $\mathbf{q} \neq 0$

but weak enough to preserve structure

Summary

Distinct signature of spinons, interactions, and gauge fields



OS + Leon Balents, arxiv:1904.02117

Thank you!

