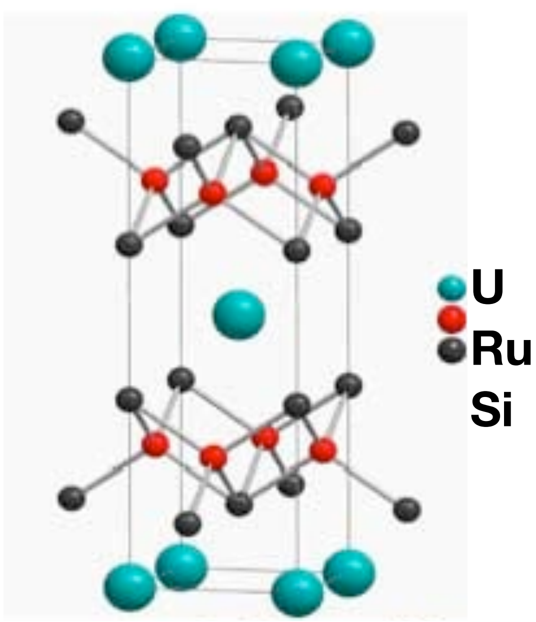
Spin, charge and energy transport in novel materials

Hvar, Croatia, October 1 - 7, 2017

Challenges and Implications of Hidden Order in URu_2Si_2

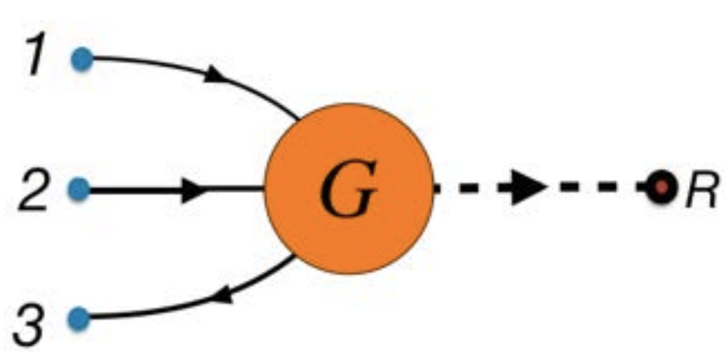


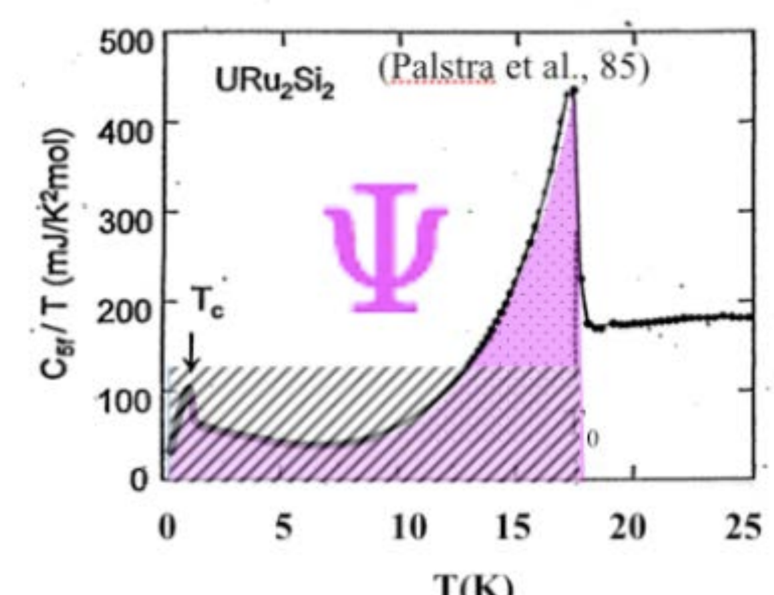
I. The Mystery

II. The Story So Far

III. A New Type of Order Parameter?

P. Chandra
Rutgers





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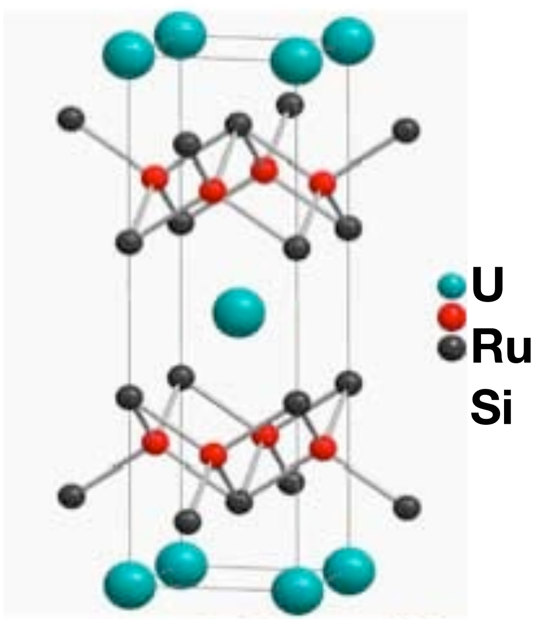
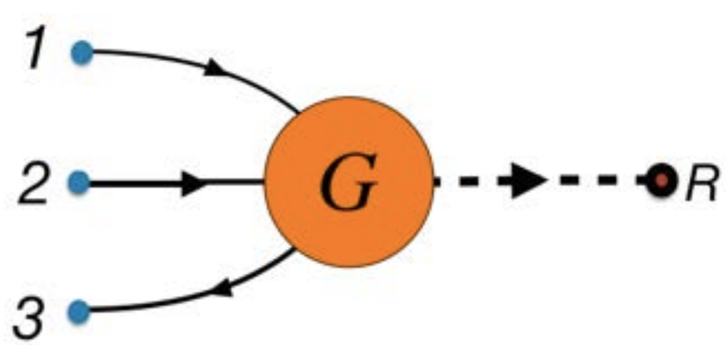


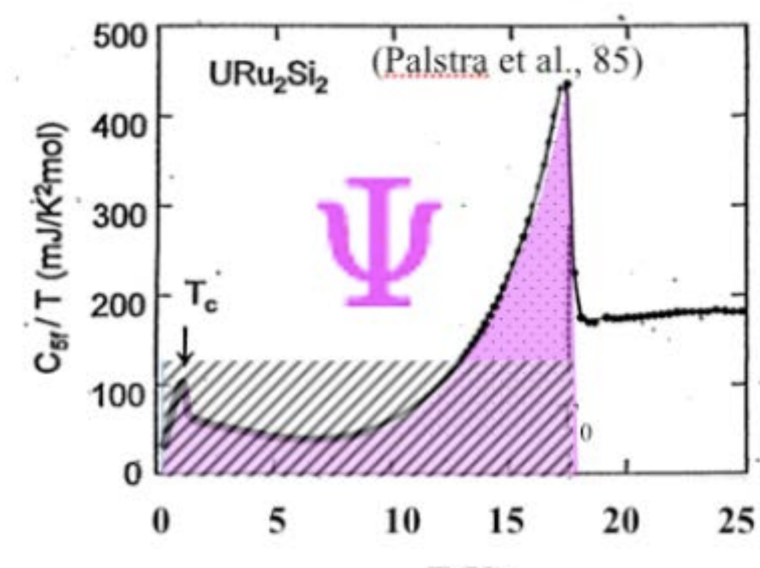
Jennifer Trinh (UC Santa Cruz)
Arthur P. Ramirez (UC Santa Cruz)

Rebecca Flint (Iowa State)
Piers Coleman (Rutgers)

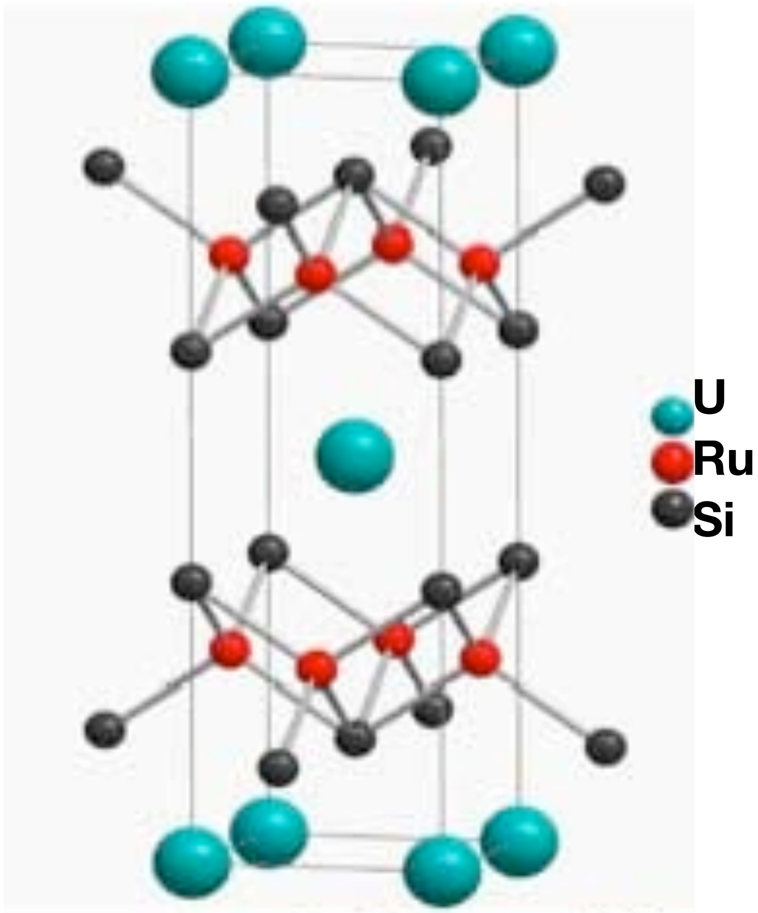
P. Chandra
Rutgers

arXiv.1708.02604
PRL (2016)





The Mystery of URu_2Si_2



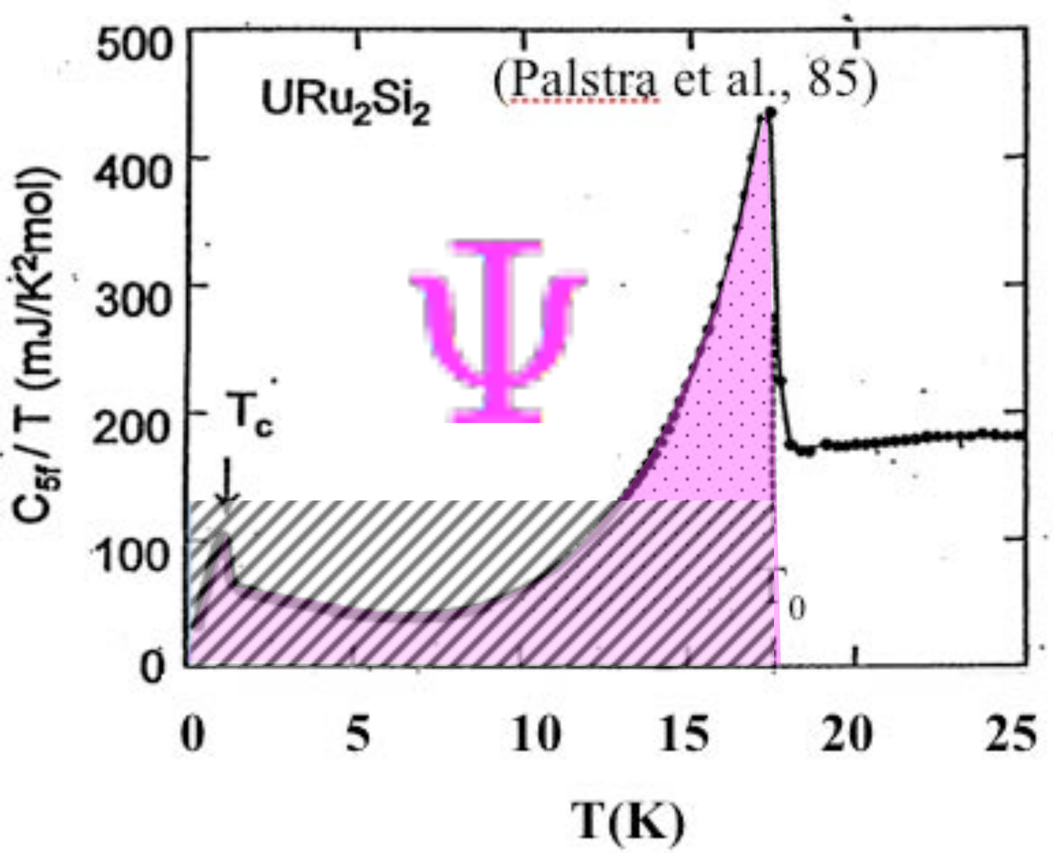
$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

=0.14 x 17.5 K
=2.45 J/mol/K
=0.42 R ln 2

Large Order Parameter Expected

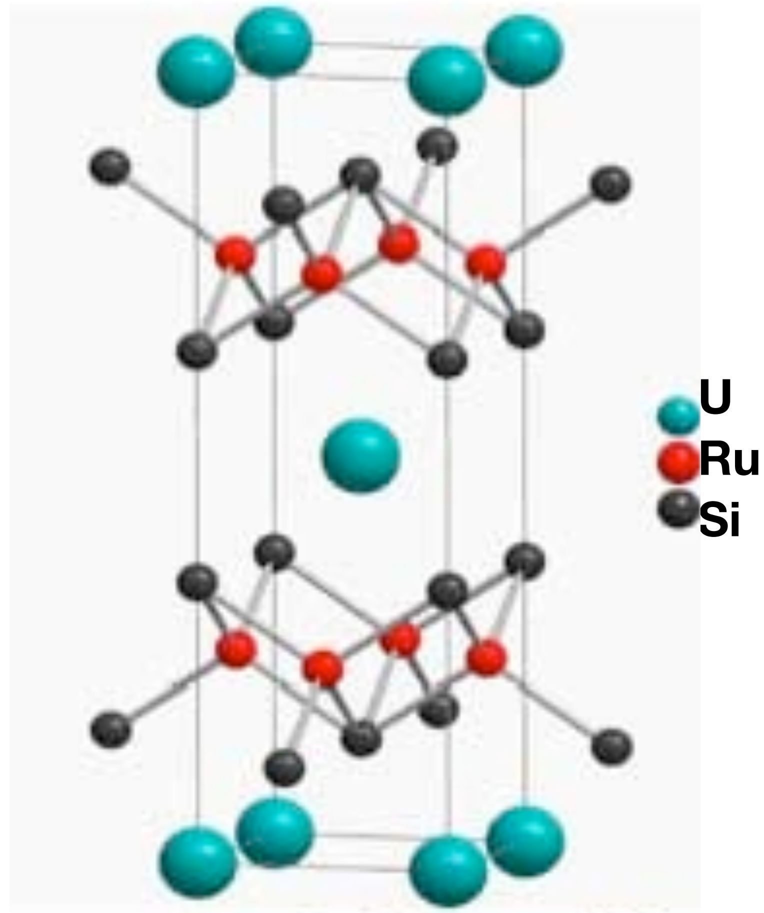
"Textbook" Ordering Transition at T = 17.5 K

Precursor to Superconductivity at T = 1.2 K



Yet....

Order parameter undetected after more than 25 years of research.



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$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

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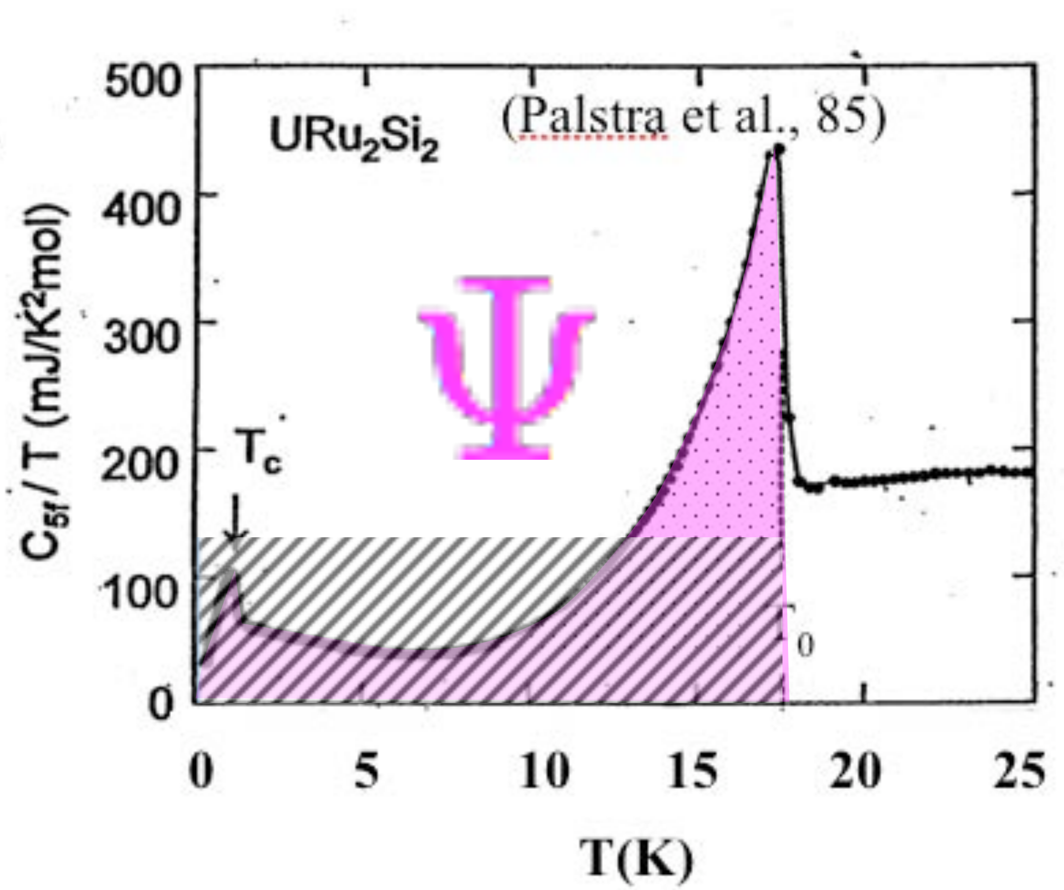
What is the nature of the quasiparticle excitations

and

the Broken Symmetries

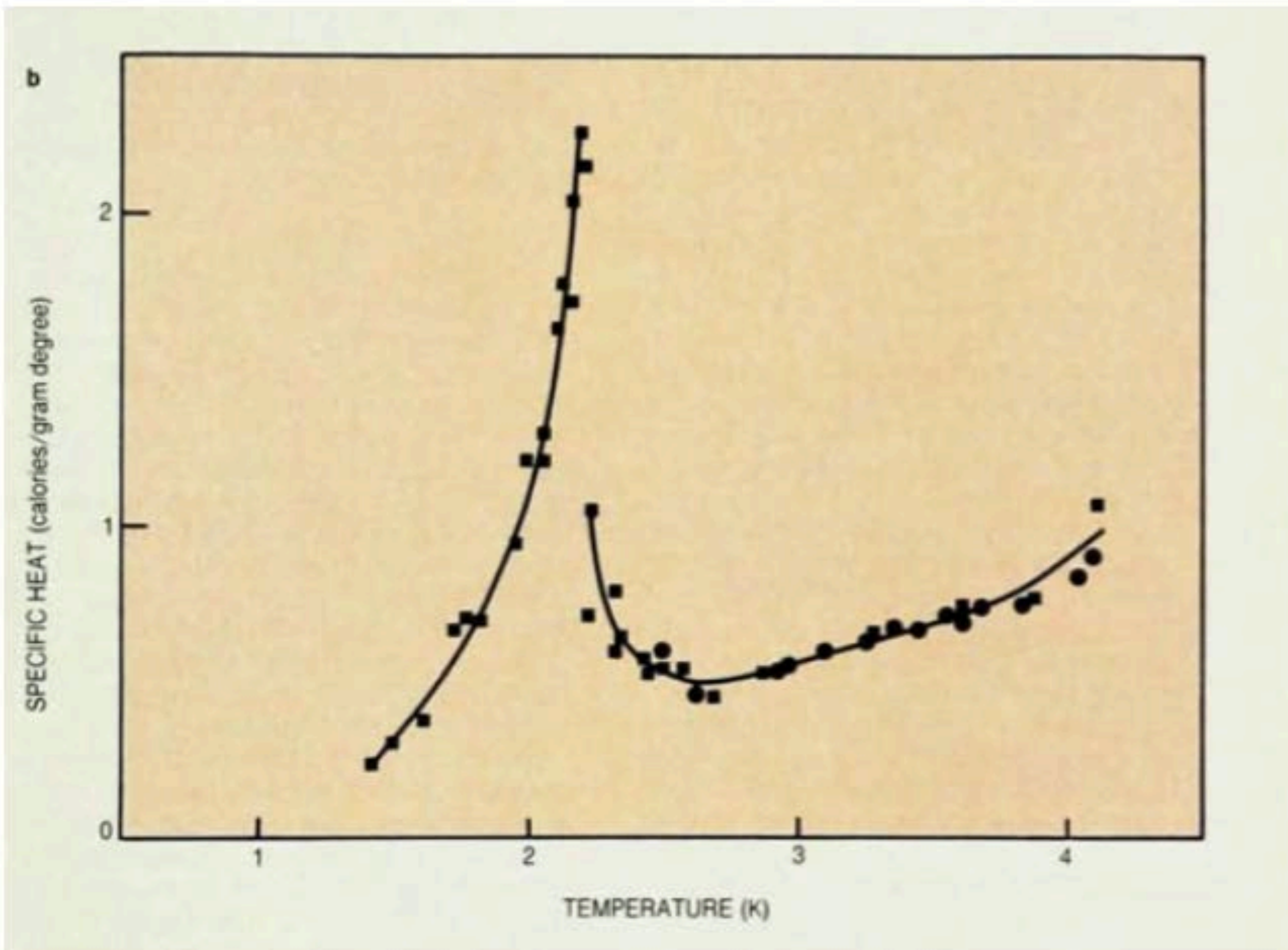
associated with this

Hidden Order Phase ??



Hidden Order: State of Matter where the Correlations Cannot be Identified

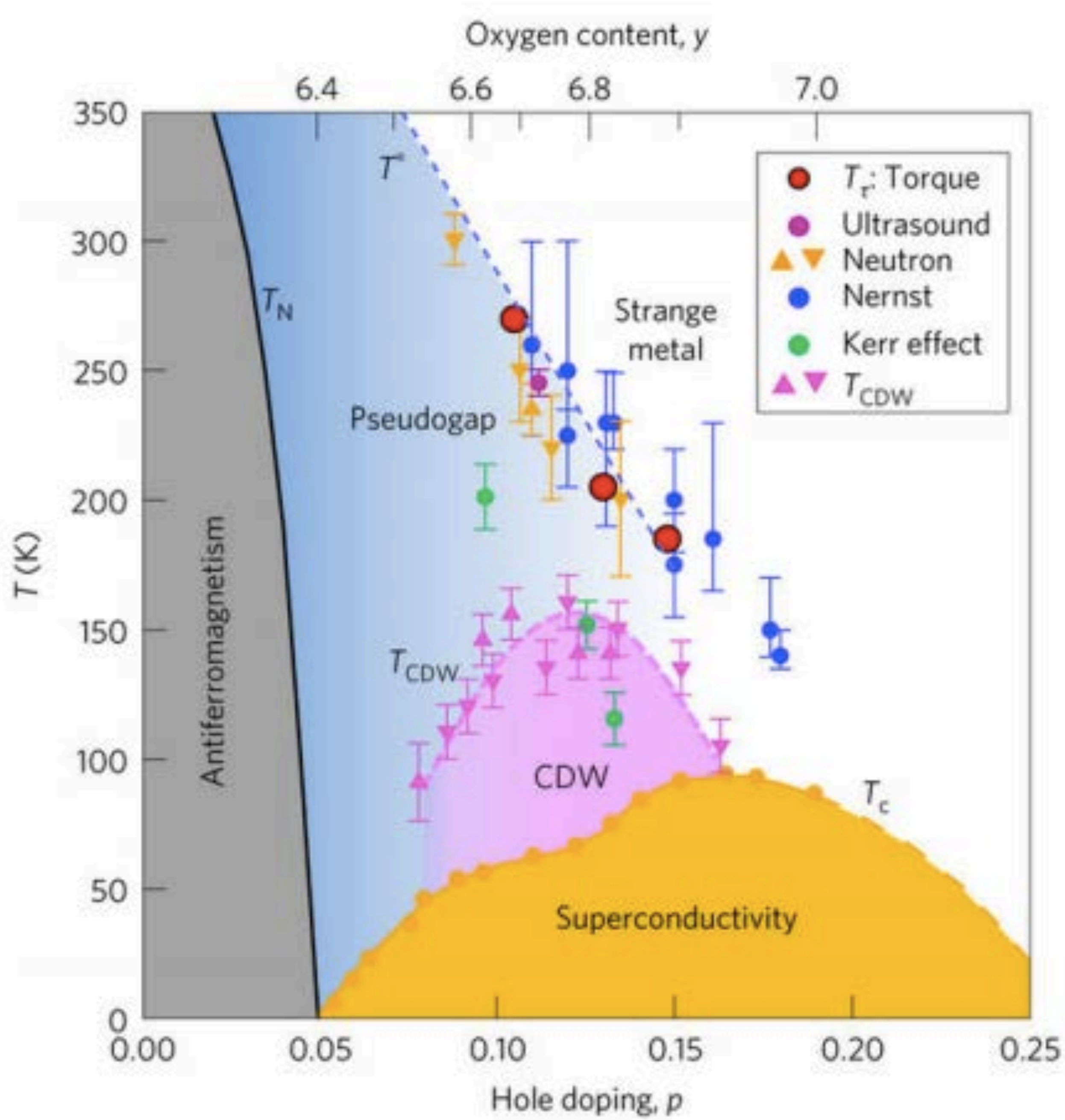
New Forms of Order



Dana and Omnes (1923)

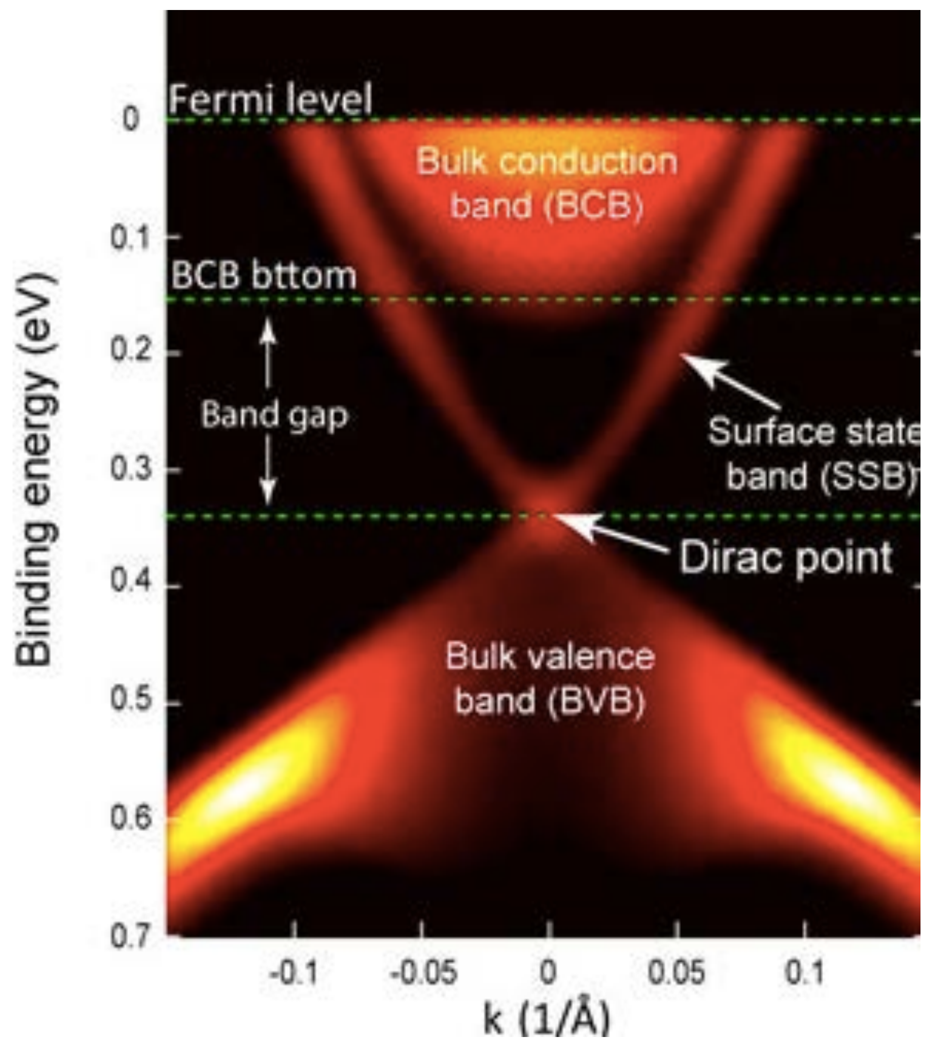
Hidden Order: State of Matter where the Correlations Cannot be Identified

Competing/Intertwined Order



Forms of Order Beyond the Landau Classification ??

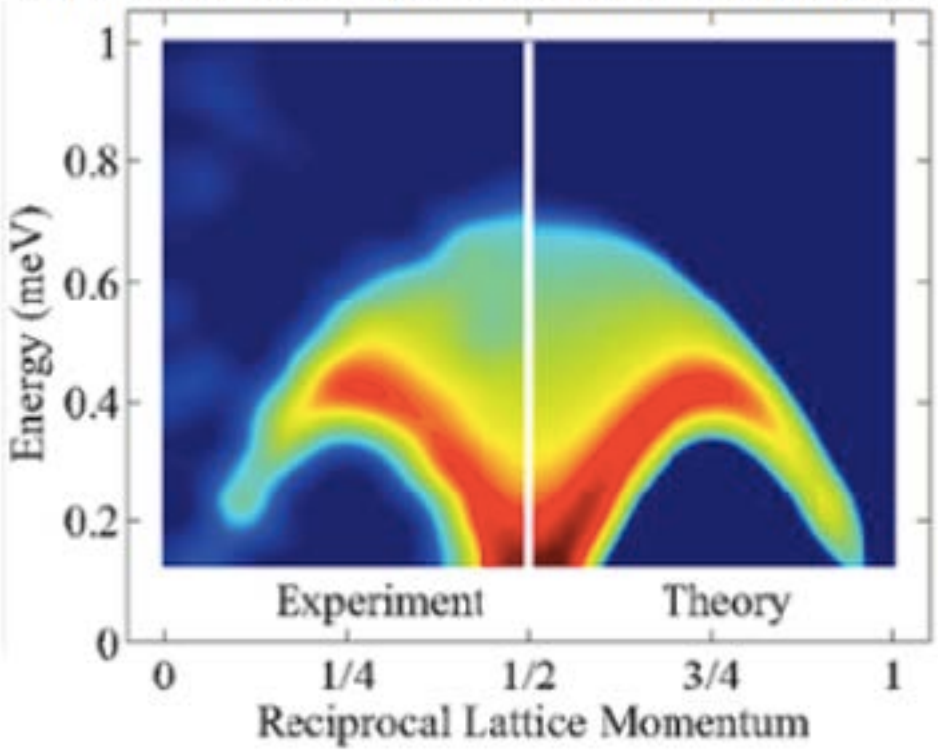
Topological Order



Forms of Order Beyond the Landau Classification ??

New Types of Symmetry-Breaking Order Parameters ??

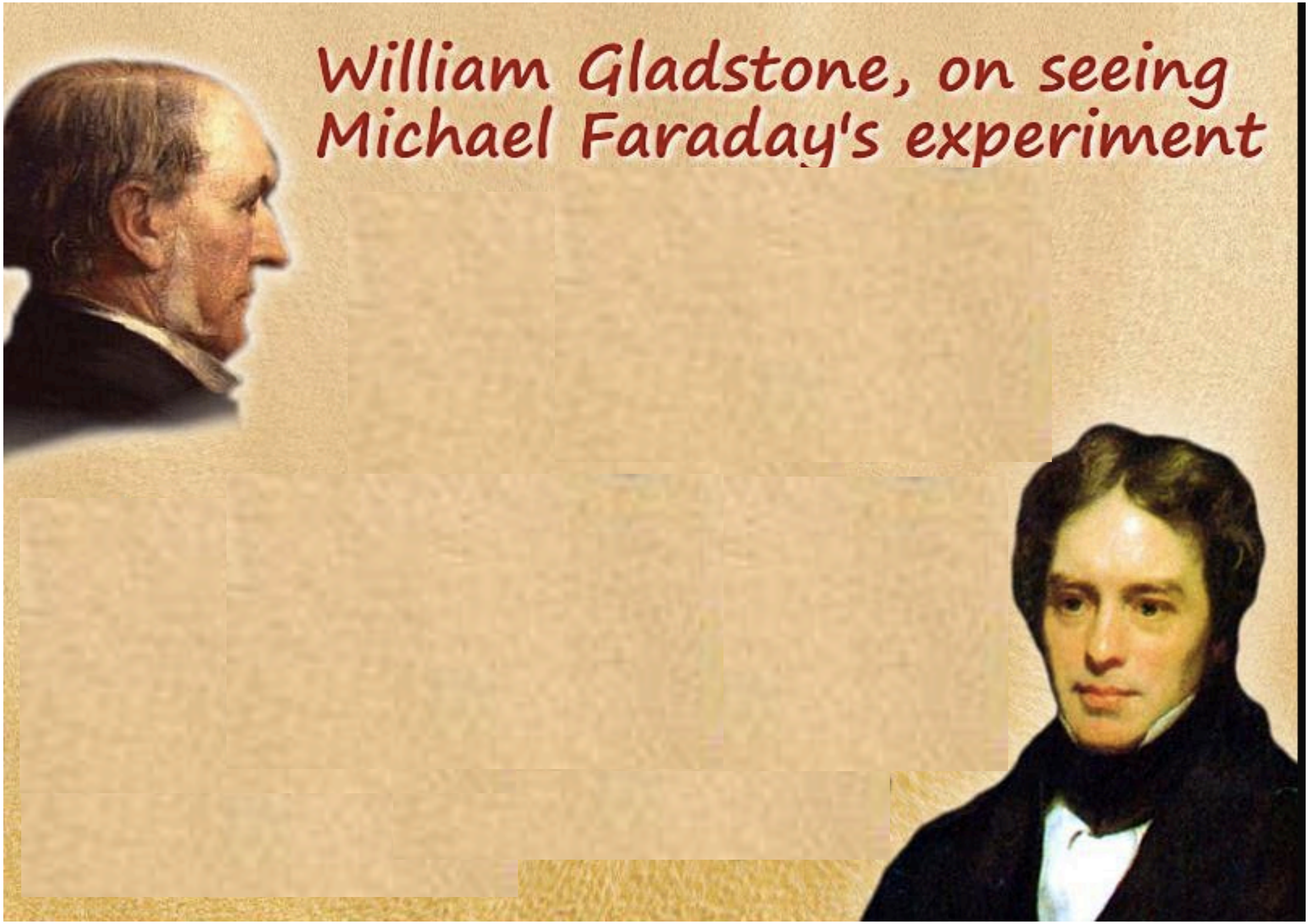
Spinons: Mourigal et al, Nat Phys (2013)

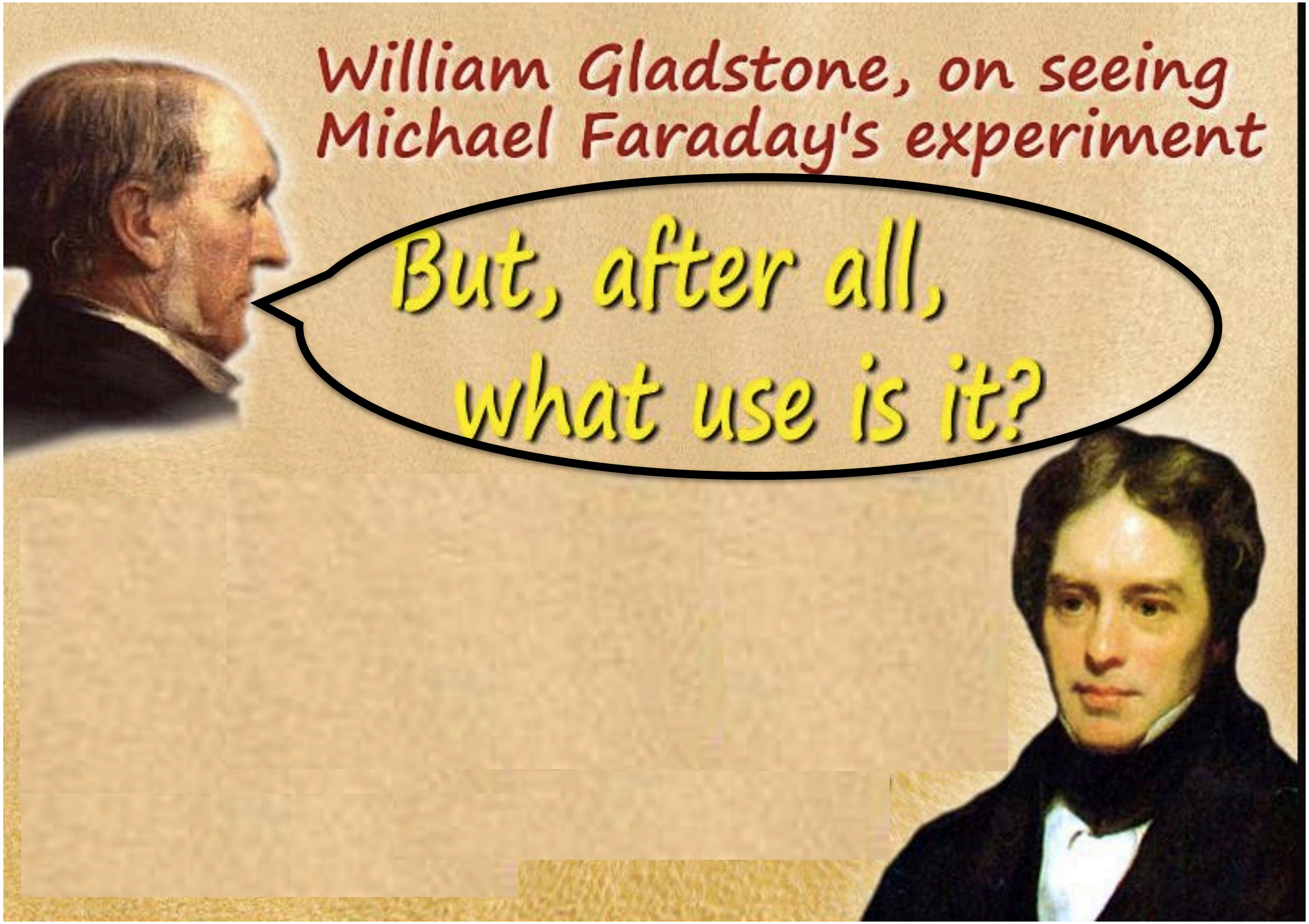


Can order parameters, like excitations, fractionalize ??

$$\psi = \sqrt{\text{Multipole}} = \text{Spinorial OP}$$

PC, P. Coleman, R. Flint (2013).


William Gladstone, on seeing
Michael Faraday's experiment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But, after all,
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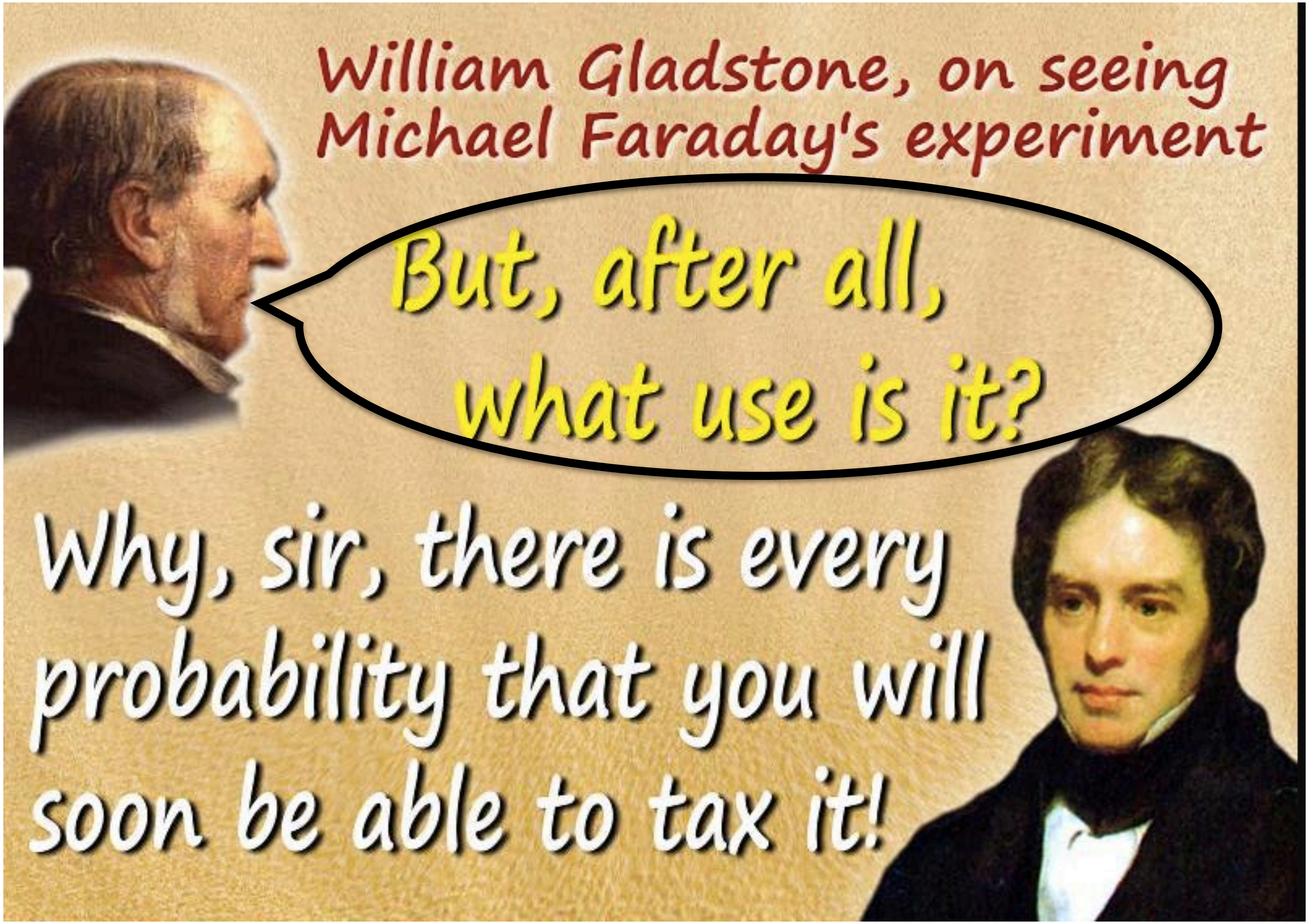
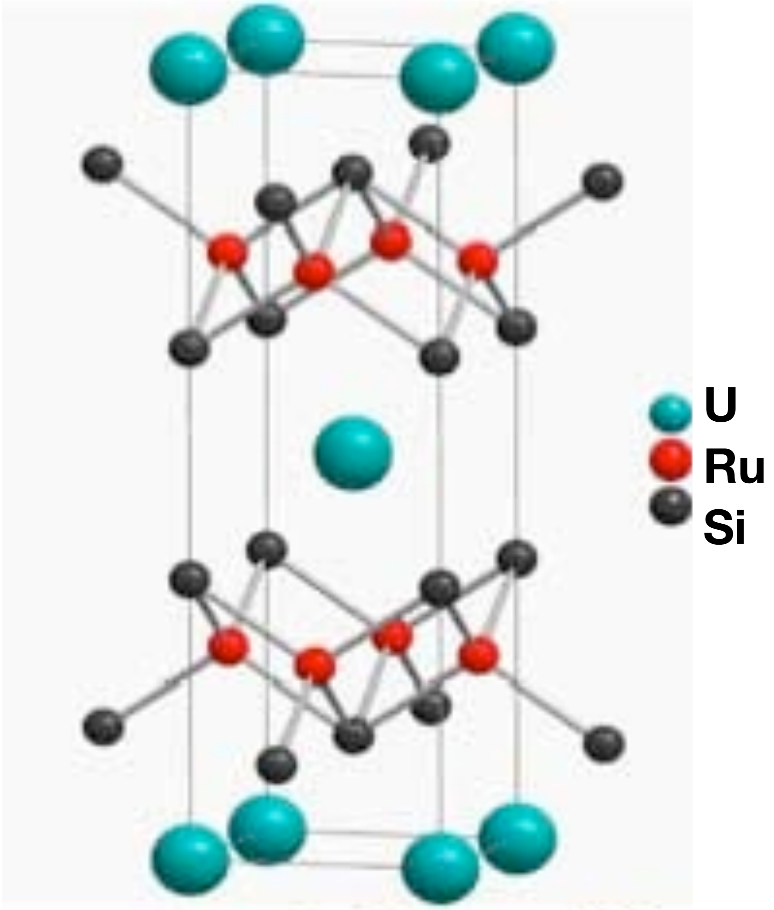

William Gladstone, on seeing
Michael Faraday's experiment
But, after all,
what use is it?
Why, sir, there is every
probability that you will
soon be able to tax it!



The Mystery of URu_2Si_2

$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

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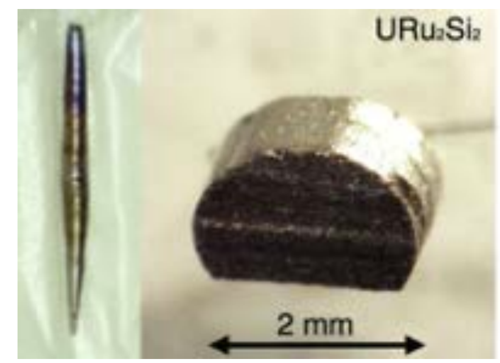
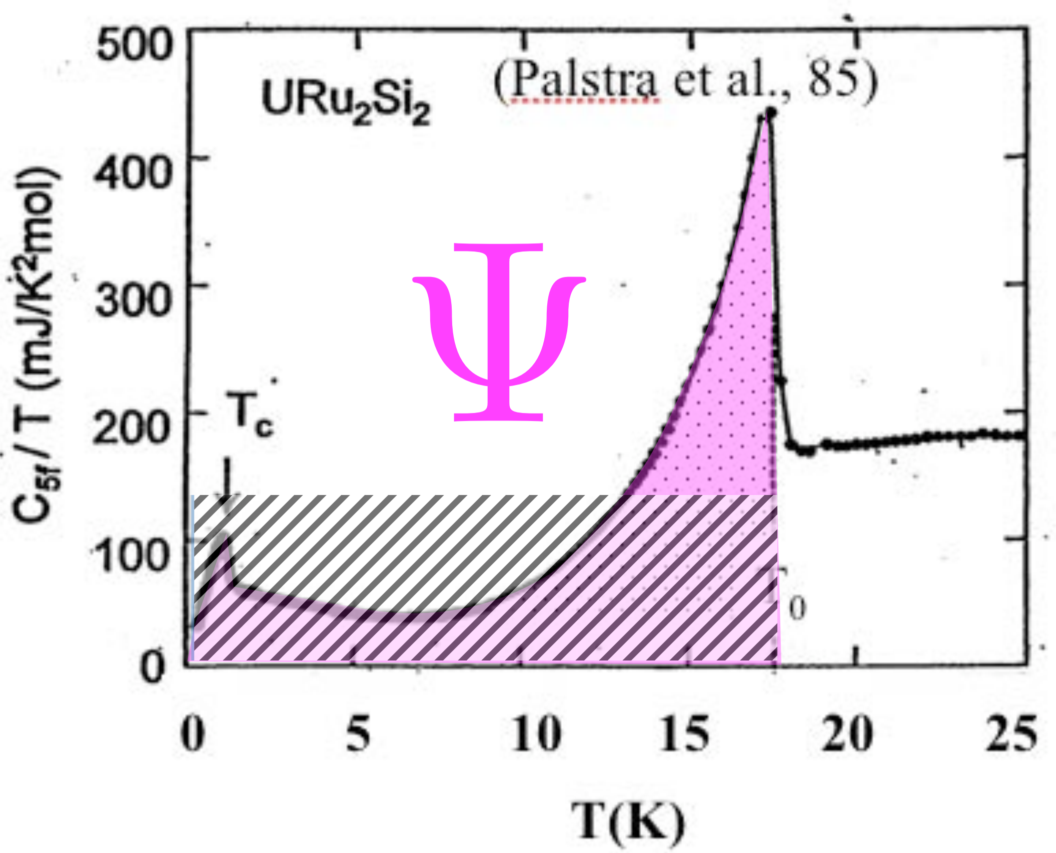
Large entropy of condensation.



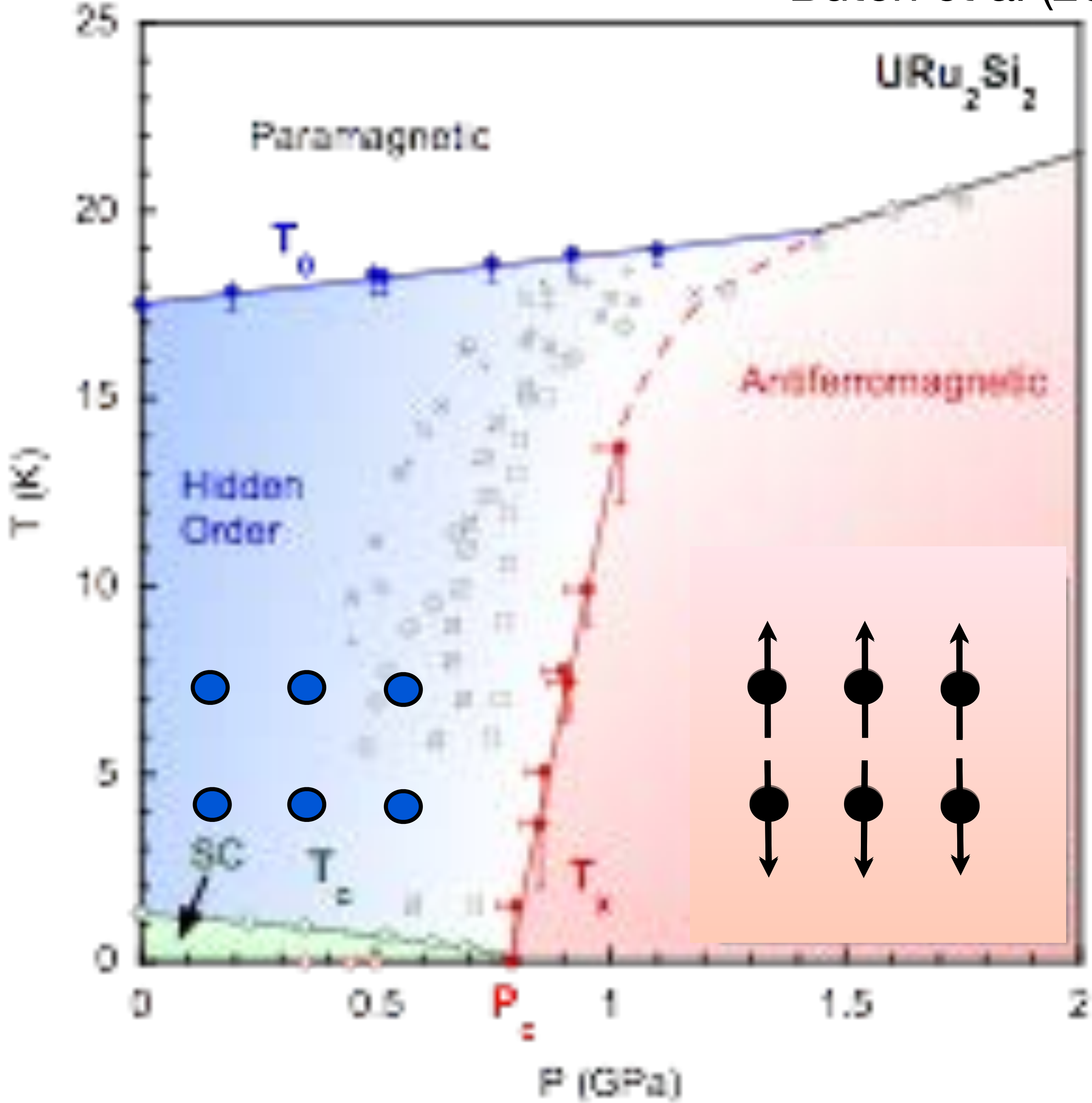


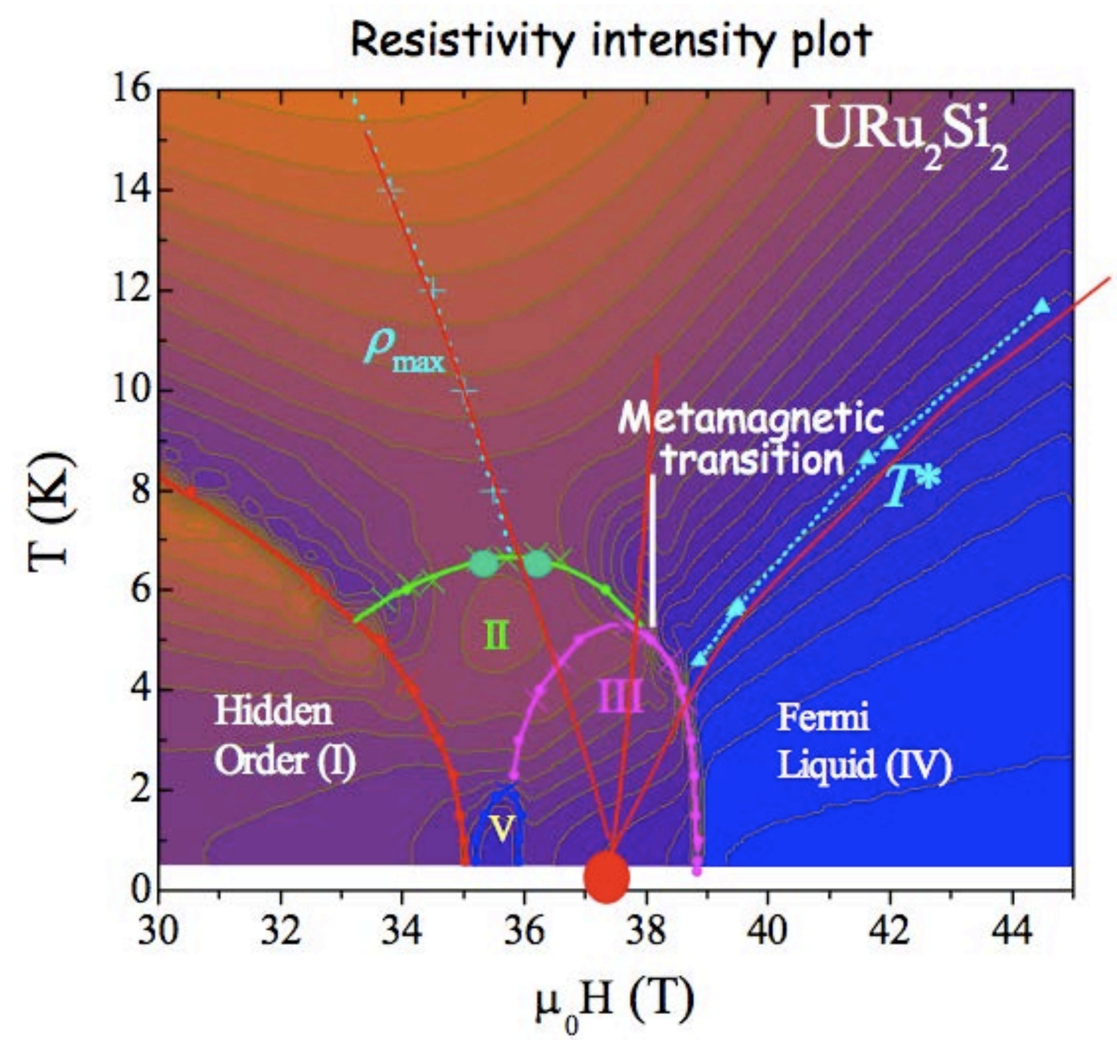
Broken Symmetry: ??
Order Parameter : ??

What is the nature of the hidden order?

High pressures, high fields

Butch et al (2011)



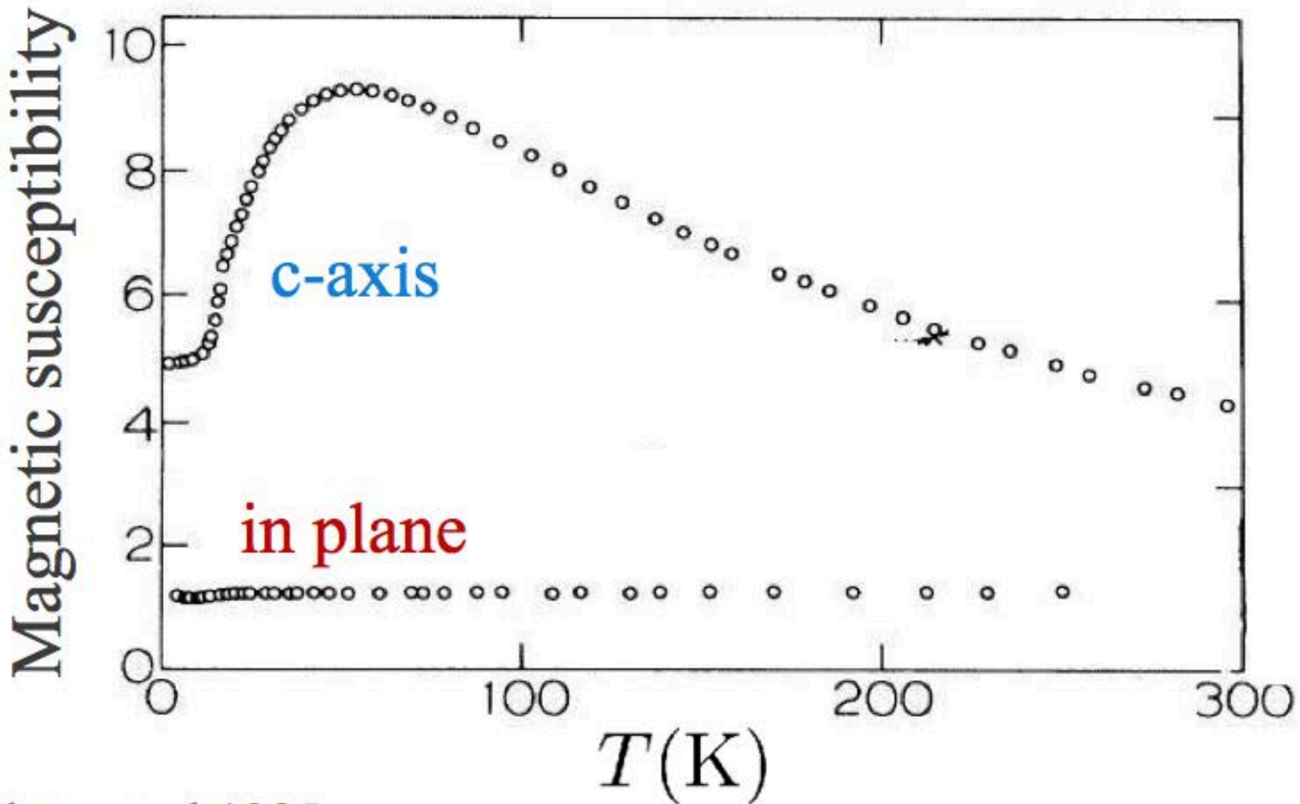


What is the nature of the hidden order?

25 Years of Theoretical Proposals

Landau Theory	Shah et al. ('00) "Hidden Order"
Itinerant	Ramirez et al, '92 (Quadrupolar SDW)
	Ikeda and Ohashi '98 (d-density wave)
	Okuno and Miyake '98 (composite)
	Tripathi, Coleman, Mydosh and PC, '02 (orbital afm)
	Dori and Maki, '03 (Unconventional SDW)
	Mineev and Zhitomirsky, '04 (SDW)
	Varma and Zhu, '05 (Spin-nematic)
	Ezgar et al '06 (Dynamic symmetry breaking)
	Fujimoto, '11 (Spin-nematic)
	Ikeda et al '12 (Rank 5 nematic)
	Tanmoy Das '12 (Topological Spin-nematic)
Local	Barzykin & Gorkov, '93 (three-spin correlation)
	Santini & Amoretti, '94, Santini ('98) (Quadrupole order)
	Amitsuka & Sakihabara (Γ_5, Quadrupolar doublet, '94)
	Kasuya, '97 (U dimerization)
	Kiss and Fazekas '04, (Rank 3 octupolar order)
	Haule and Kotliar '09 (Rank 4 hexa-decapolar)
	Rau and Kee '12 (Rank 5 pseudo-spin vector)
	Pepin et al '10 (Spin liquid/Kondo Lattice)
Kondo Lattice	Dubi and Balatsky, '10 (Hybridization density wave)

Importance of Ising Anisotropy to HO Problem



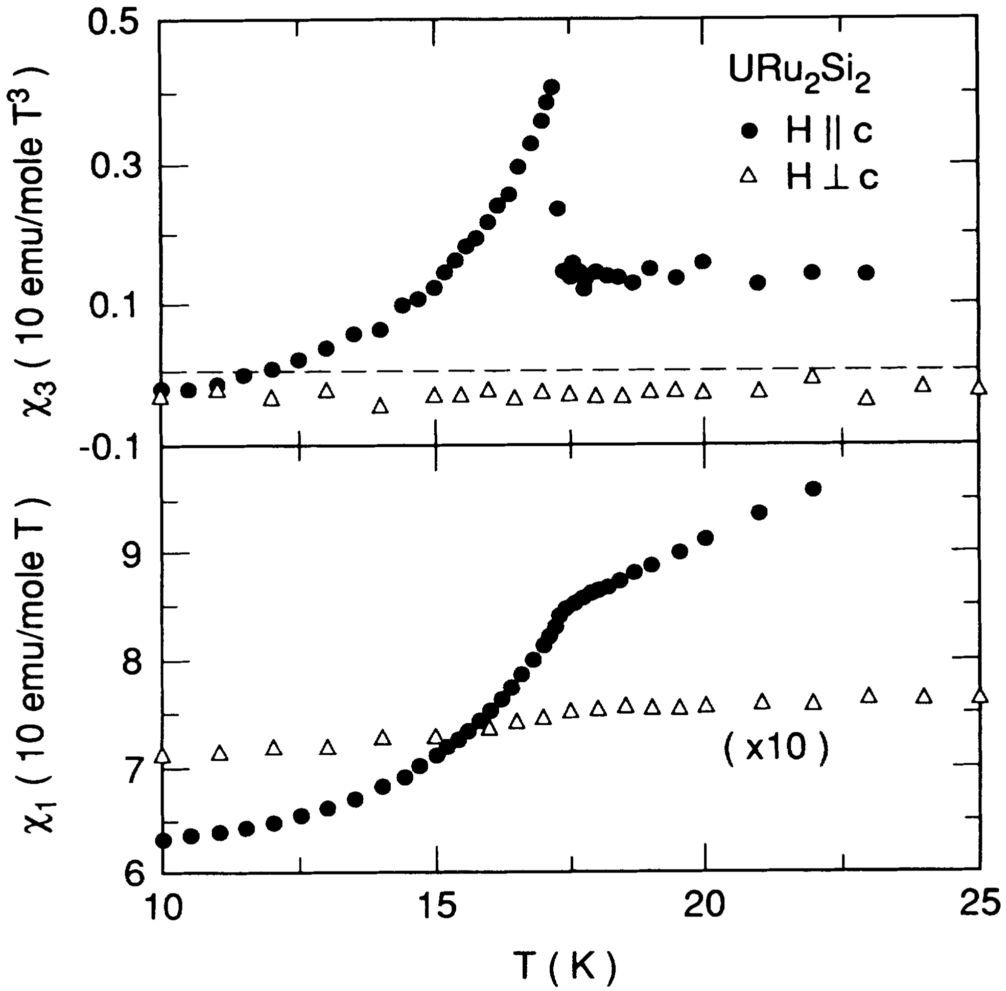
Palstra et al 1985

U moments are Ising $\langle + | J_{\pm} | - \rangle = 0$

Integer S ($5f^2$)

Importance of Ising Anisotropy to HO Problem

Ramirez et al '92



Absence of Local Moments !!

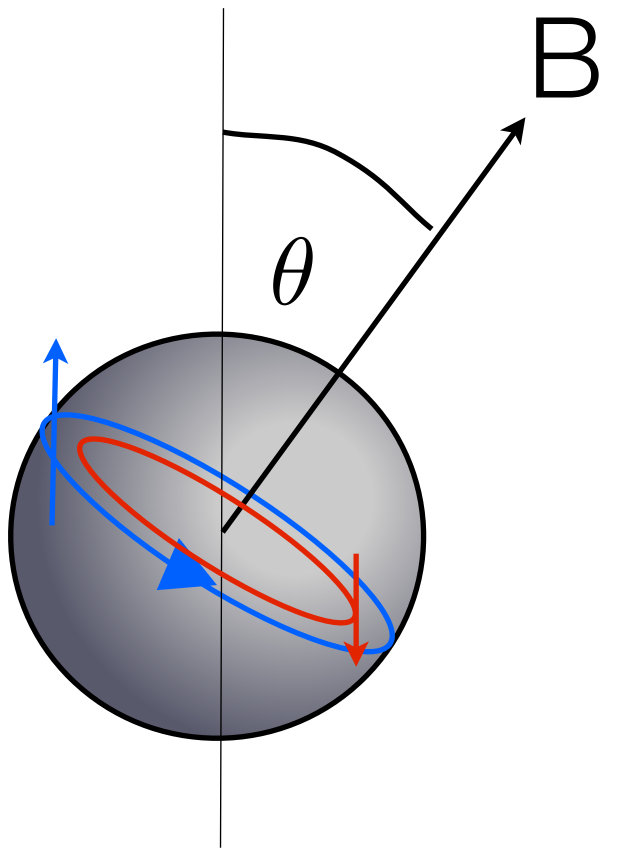
What about the quasiparticle excitations ??

Non-spinflip $(\Delta J_z = 0)$ magnetic excitations also have Ising character !!

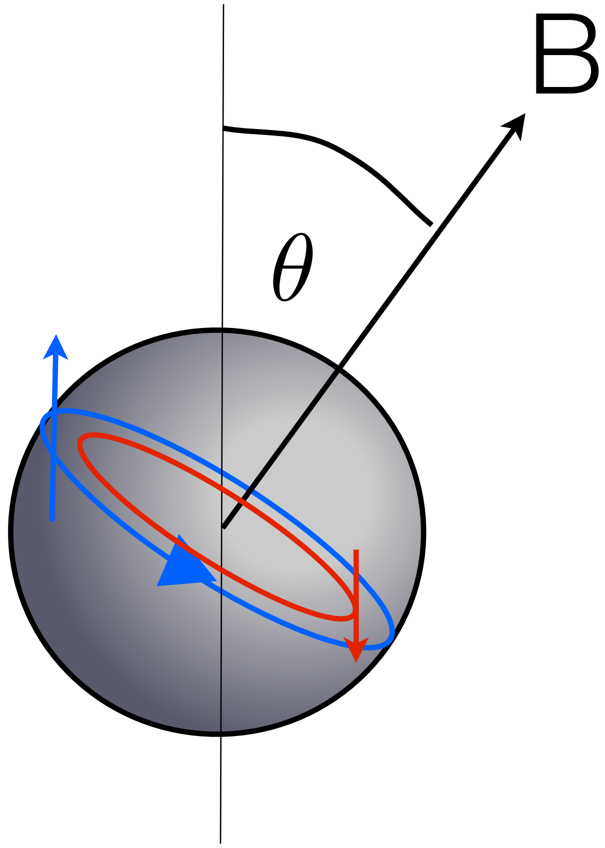
Inelastic Neutrons (Broholm et al, 91)
Raman (Buhot et al, Kung et al., 15)

Fermi Surface Magnetization in a Field

Fermi Surface Magnetization in a Field



Fermi Surface Magnetization in a Field



$$M \propto \cos\left[2\pi \frac{\text{Zeeman}}{\text{cyclotron}}\right]$$

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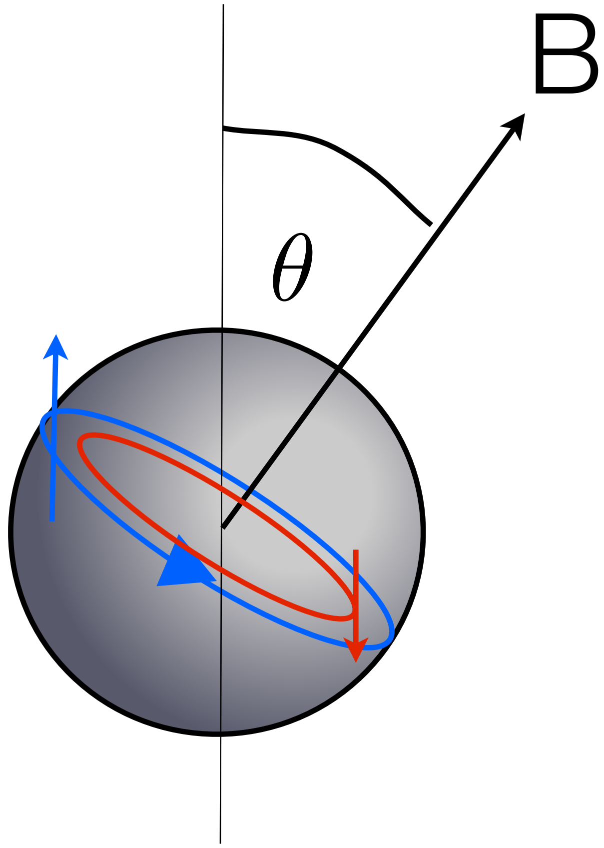

$$\frac{g}{2}\frac{eB}{2m_e}$$

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$$\omega_c = \frac{eB}{m^*}$$

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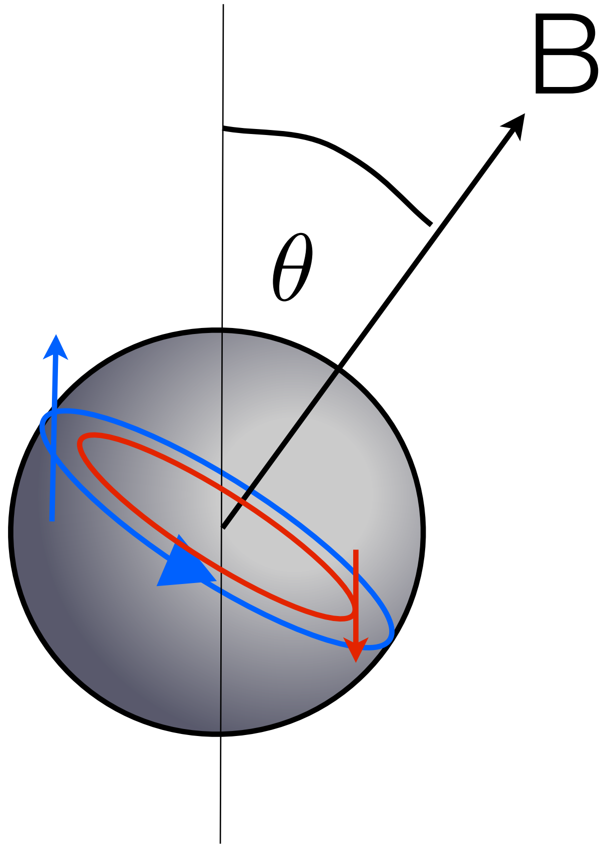

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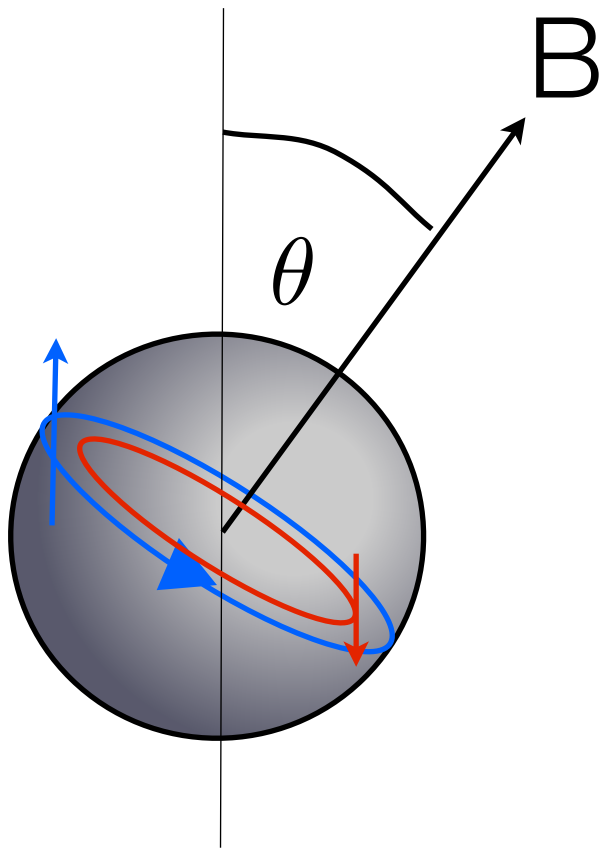

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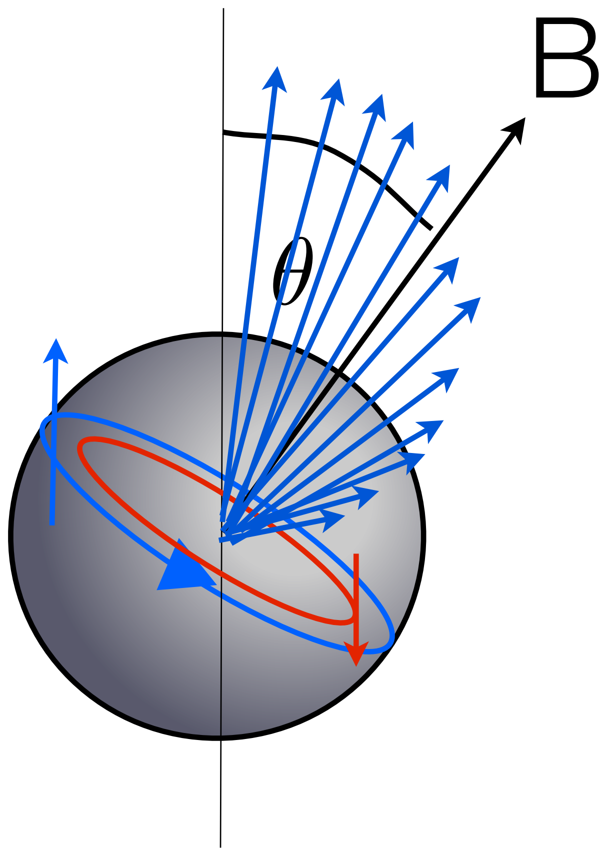
Spin Zero condition

Fermi Surface Magnetization in a Field



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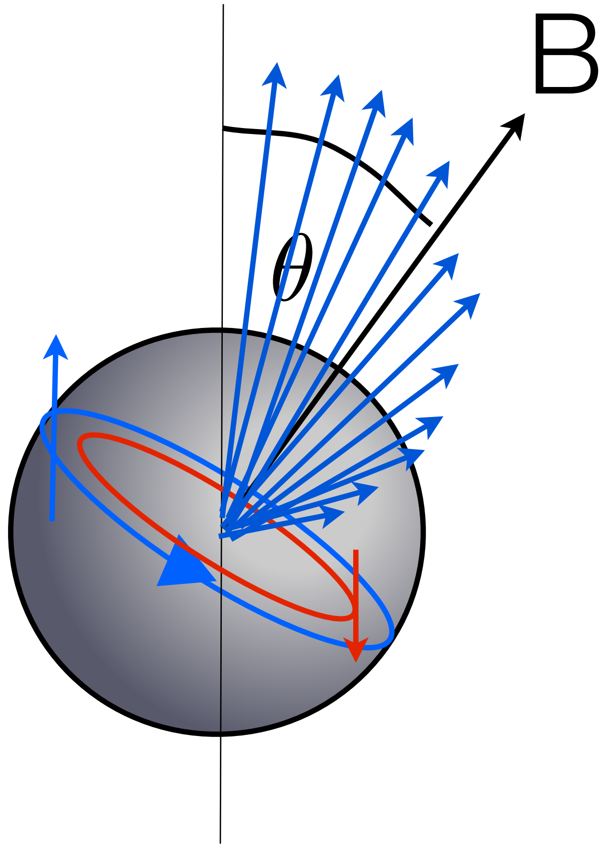

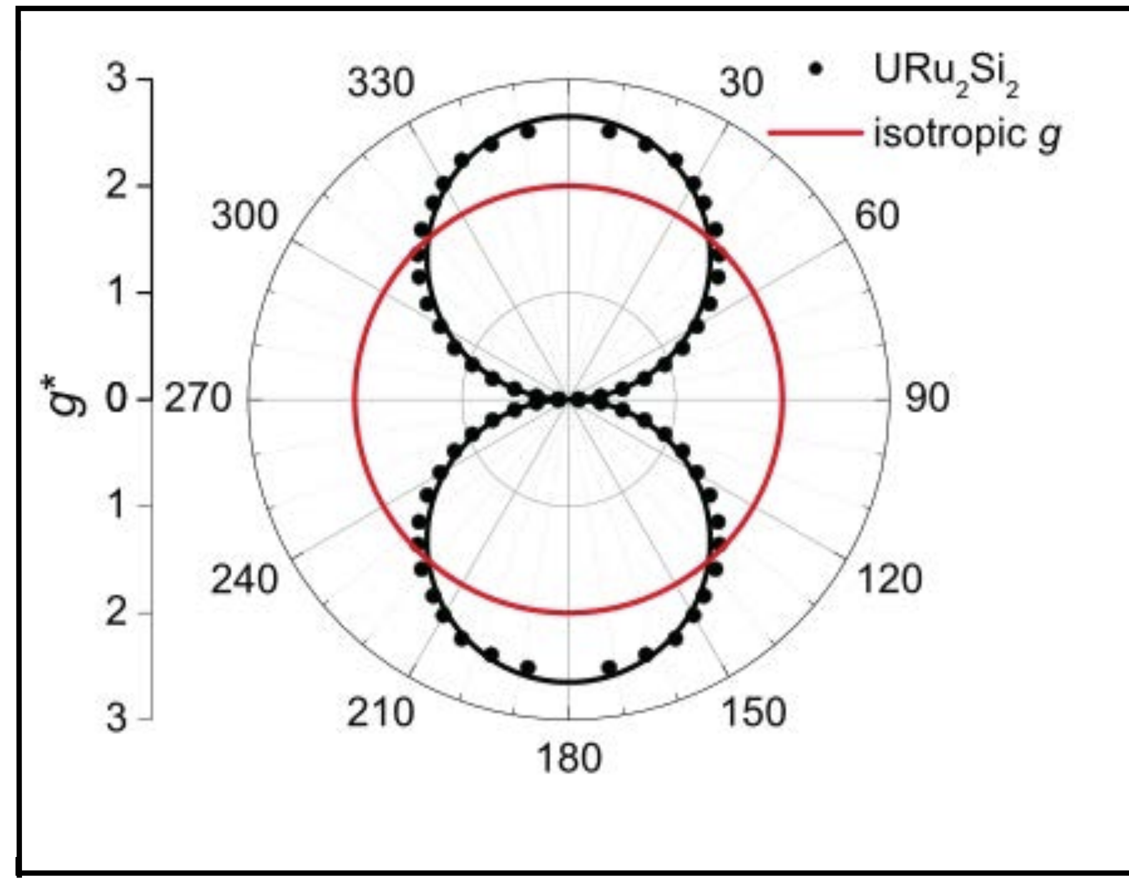

M. M. Altarawneh, N. Harrison, S. E. Sebastian, et al., PRL (2011).
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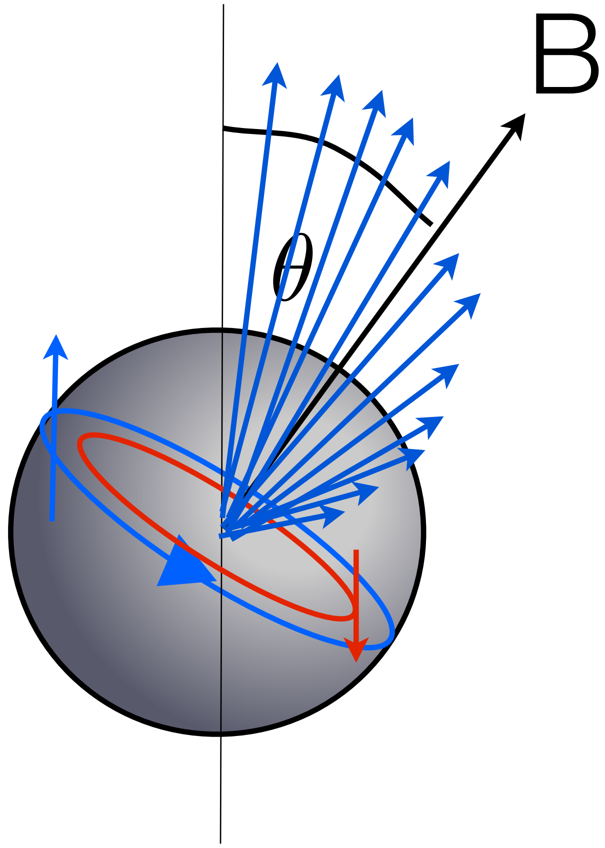

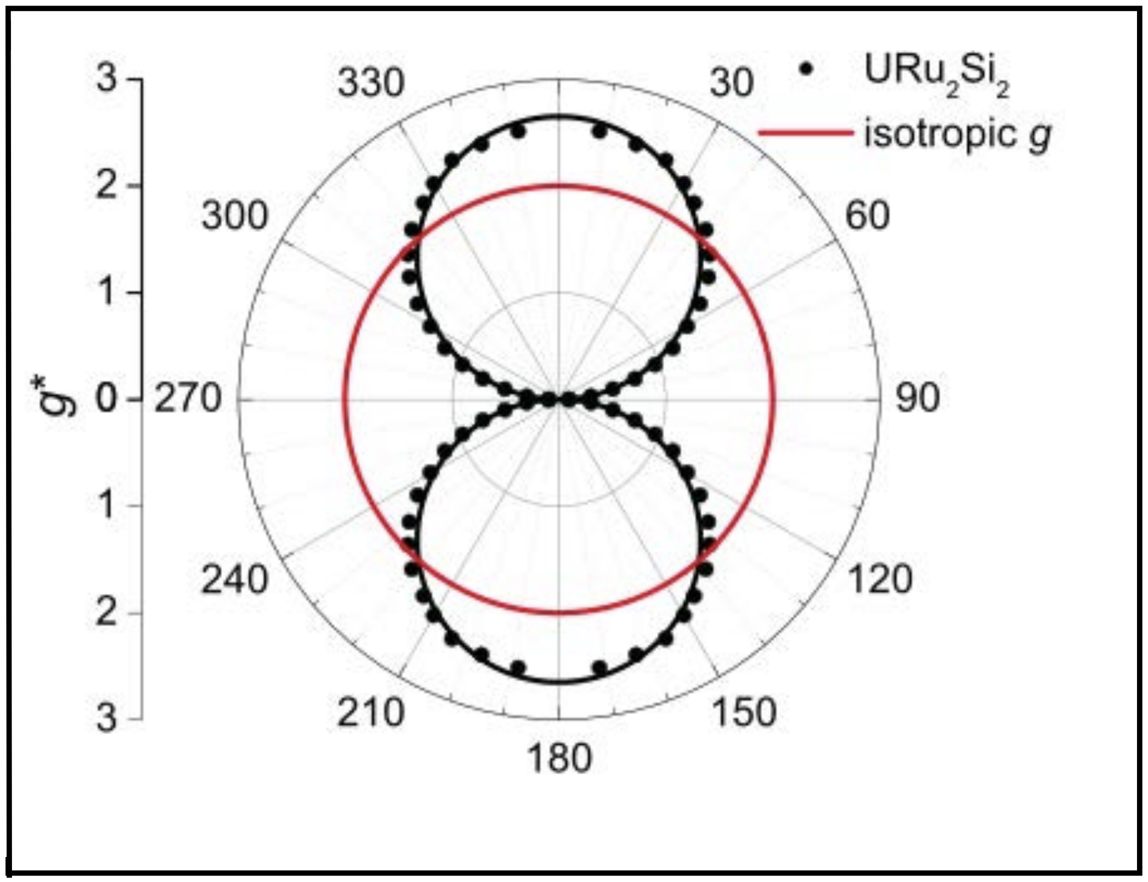

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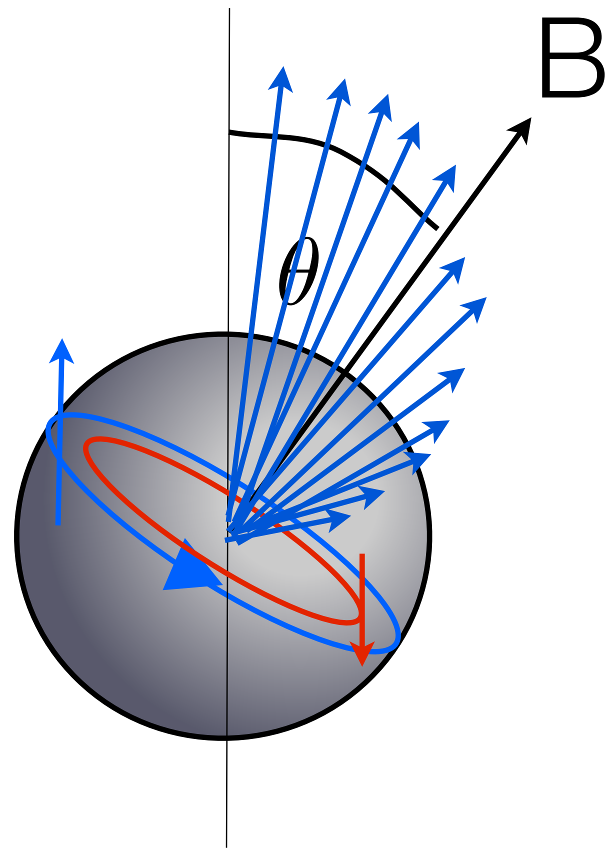

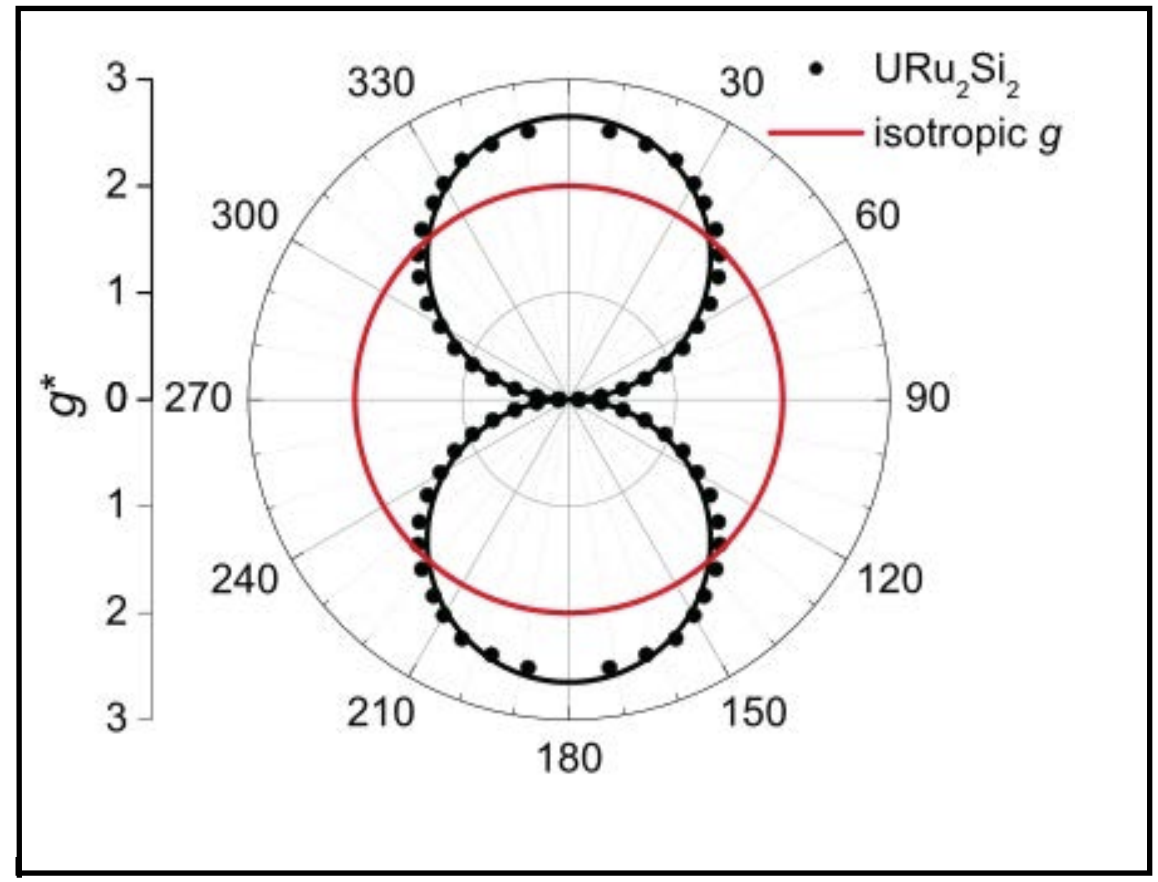

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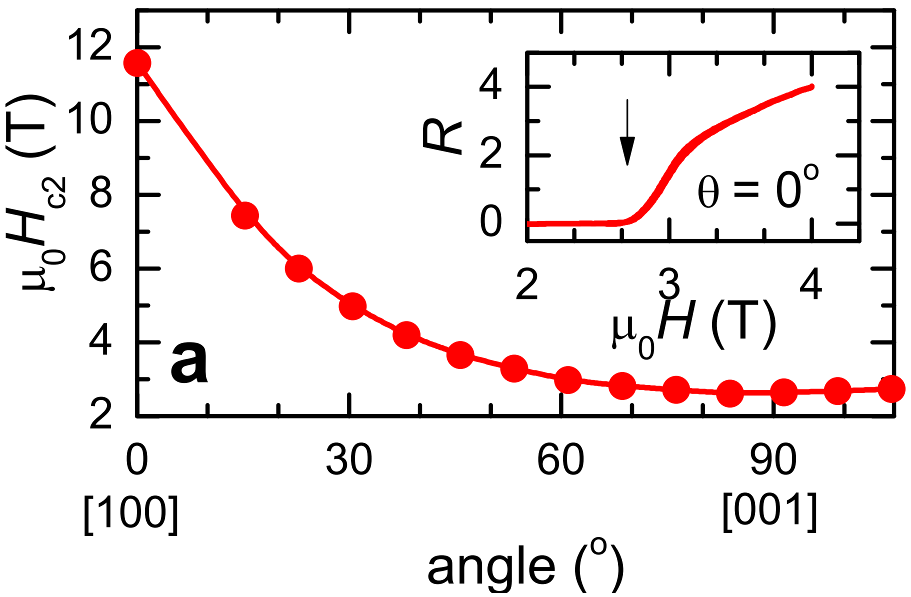
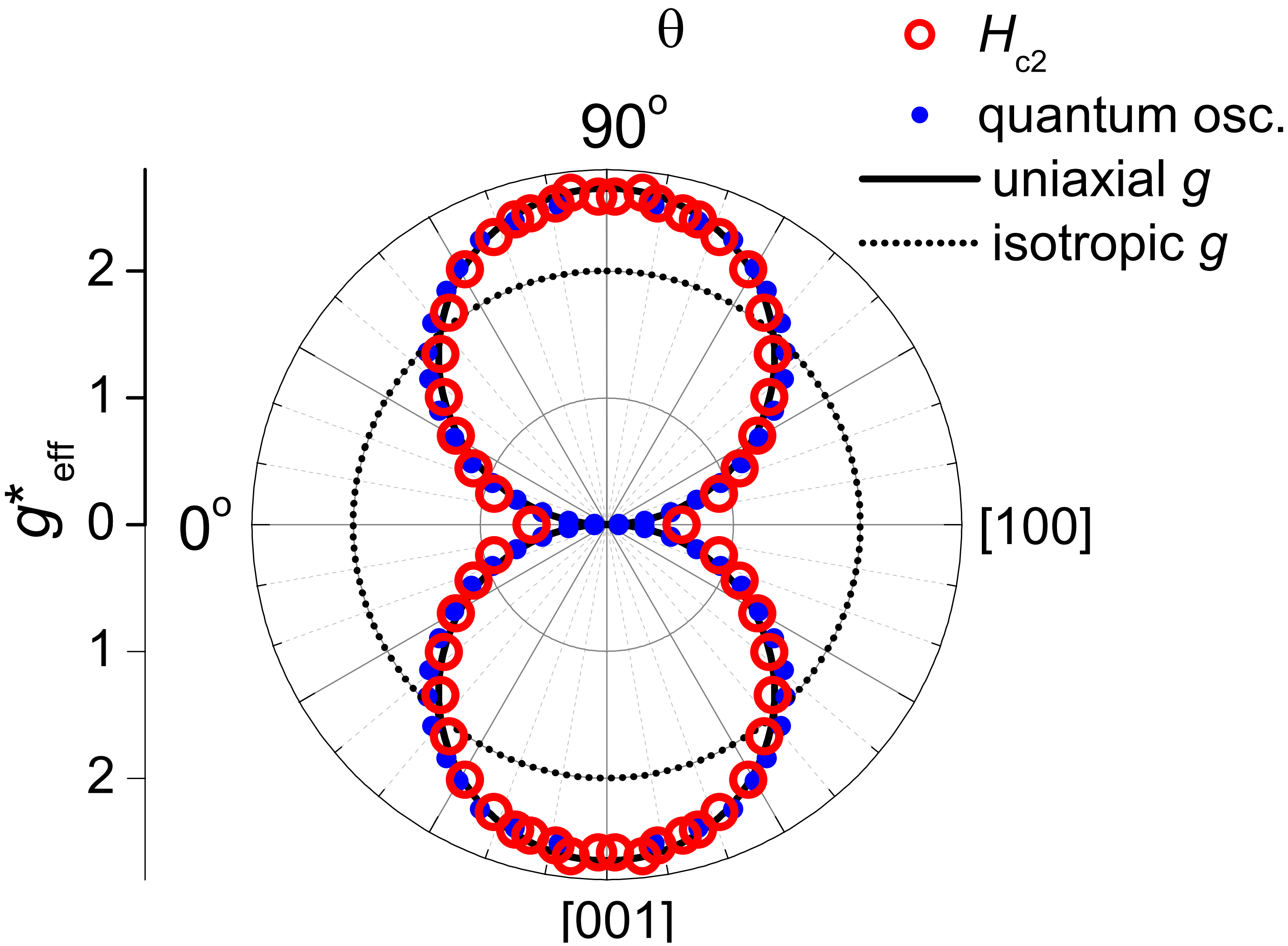
Heavy Quasiparticles with Ising Anisotropy

Superconductivity: Giant Ising Anisotropy

Altarawneh et al., PRL 108, 066407 (2012)





Ising 5f doublet degenerate to within
$$2\Delta \sim 5K$$

Quasiparticle with giant Ising anisotropy > 30.
Pauli susceptibility anisotropy > 900

$$\langle \mathbf{k}\sigma | J_{\pm} | \mathbf{k}\sigma' \rangle = 0$$

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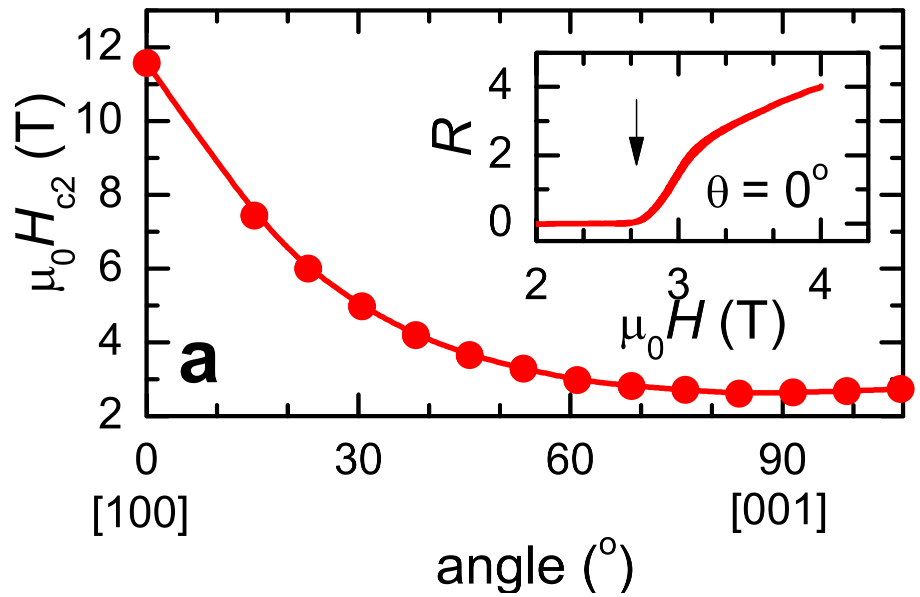

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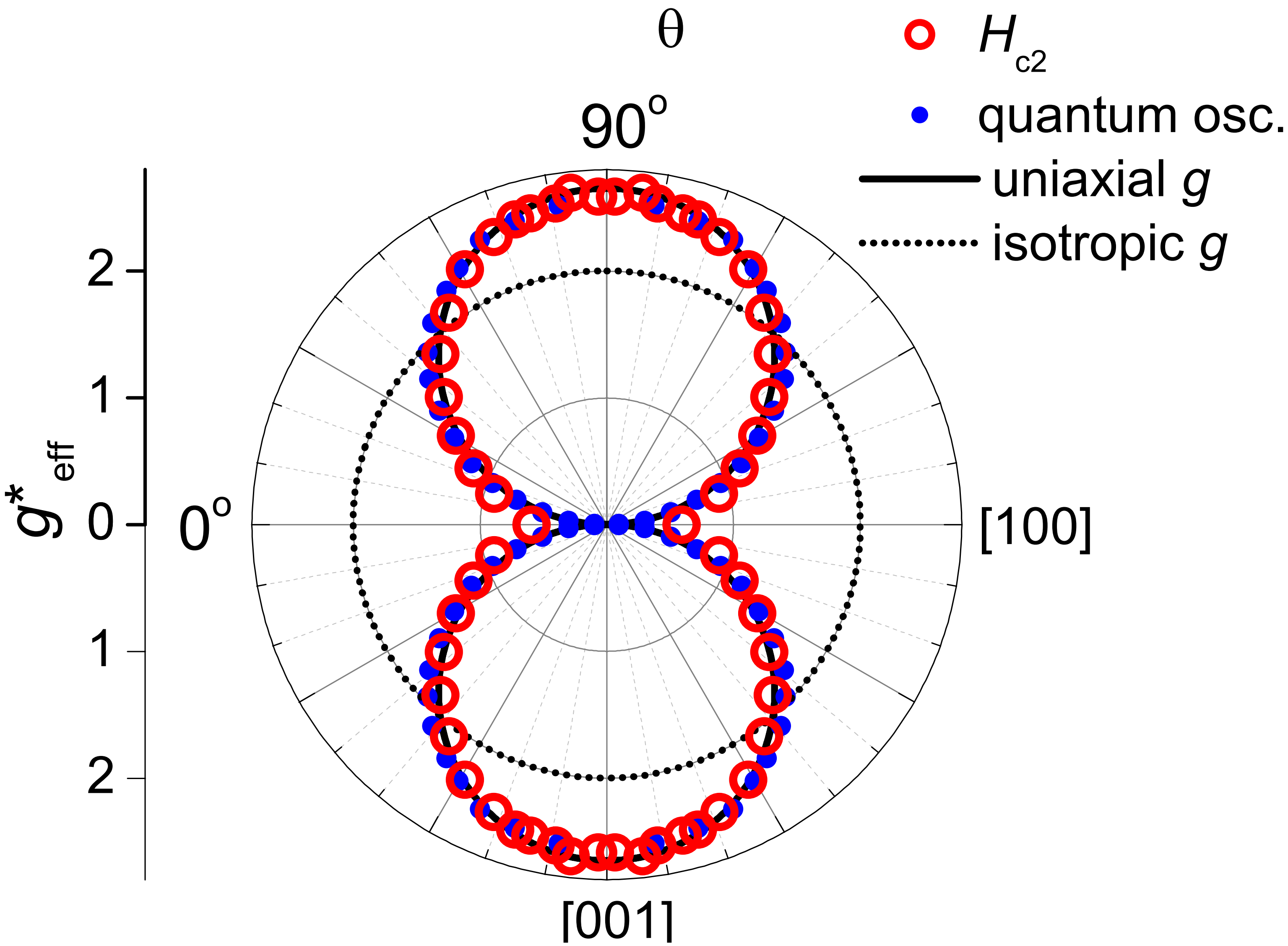

<u>Ising QP's pair condense.</u>

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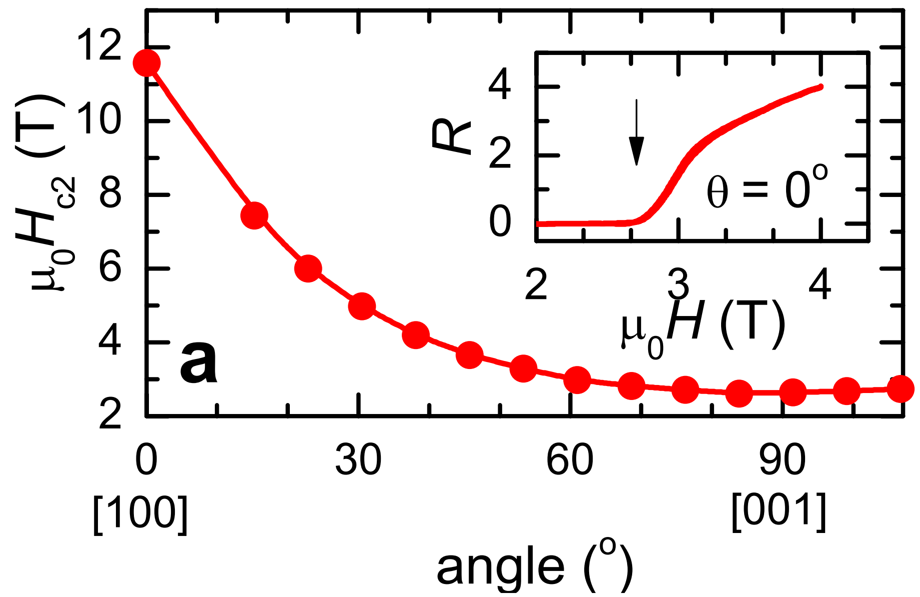

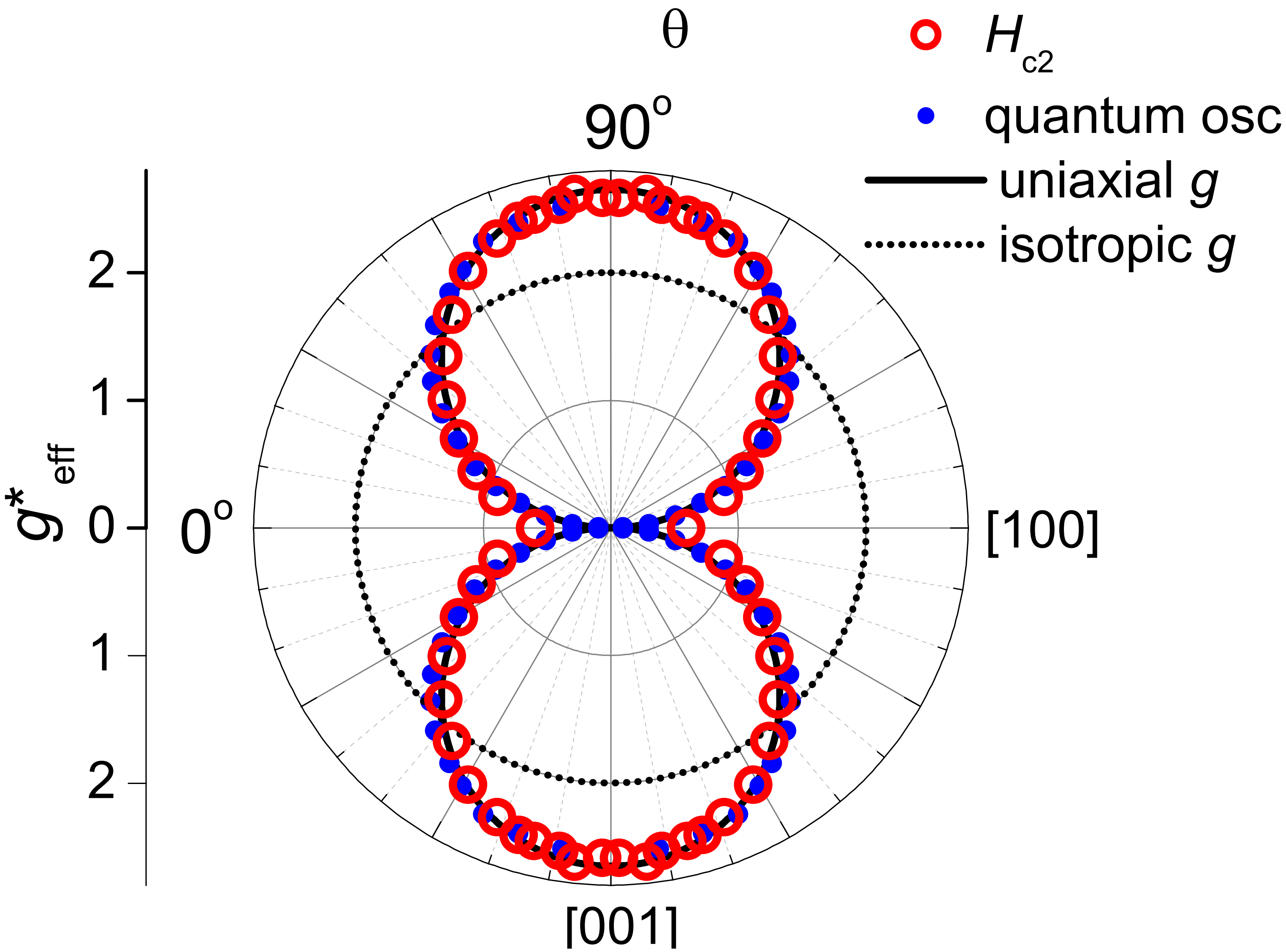

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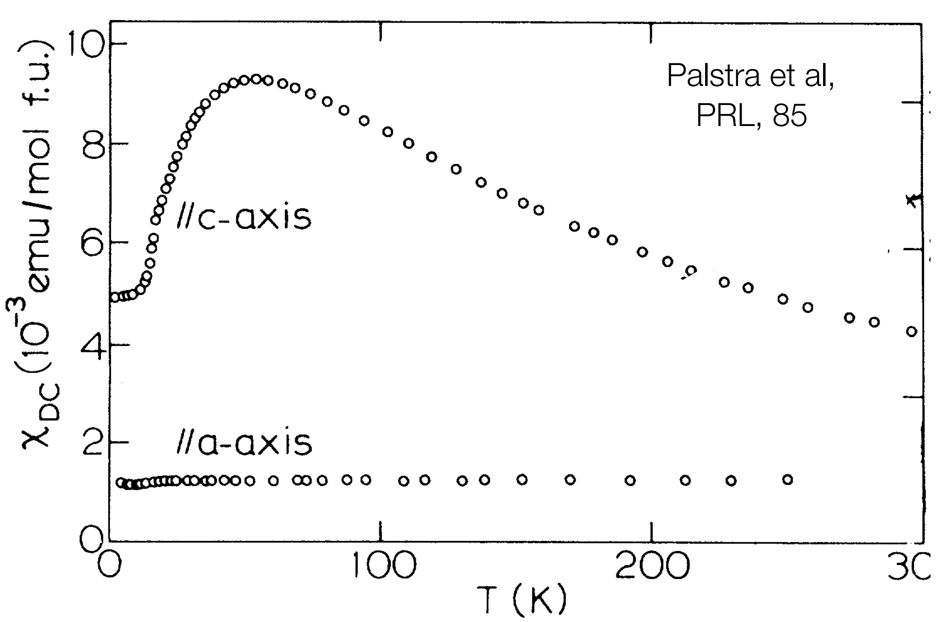

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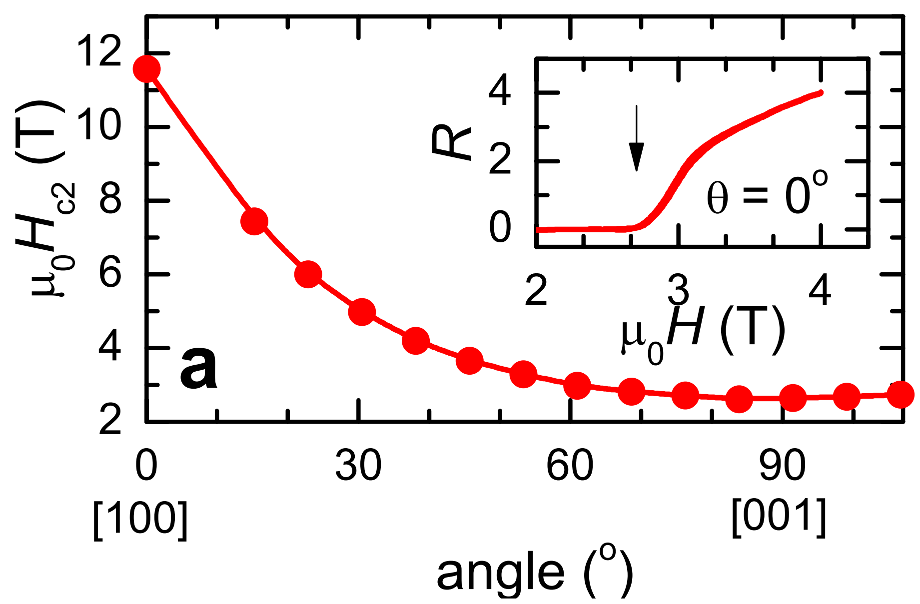

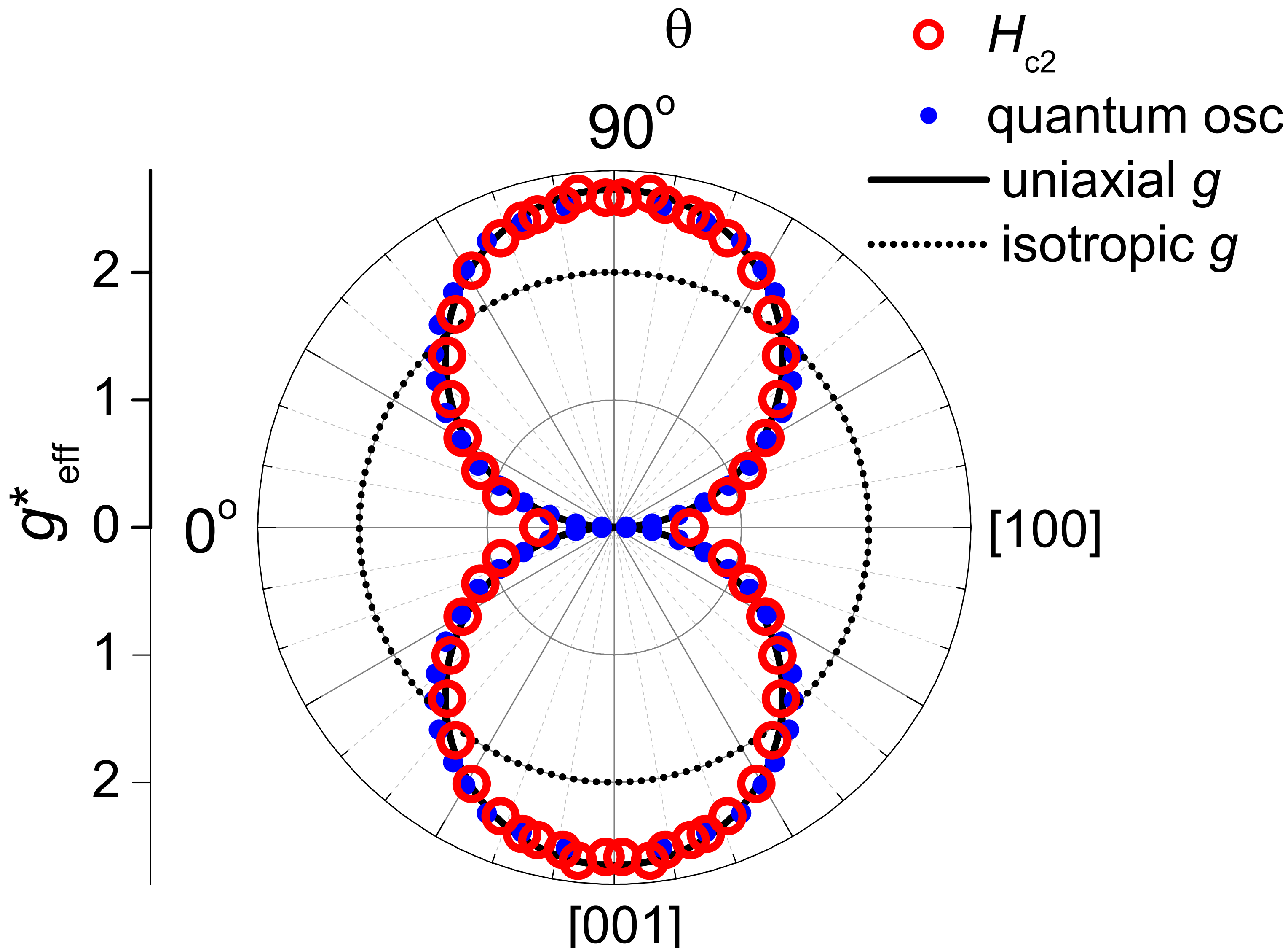

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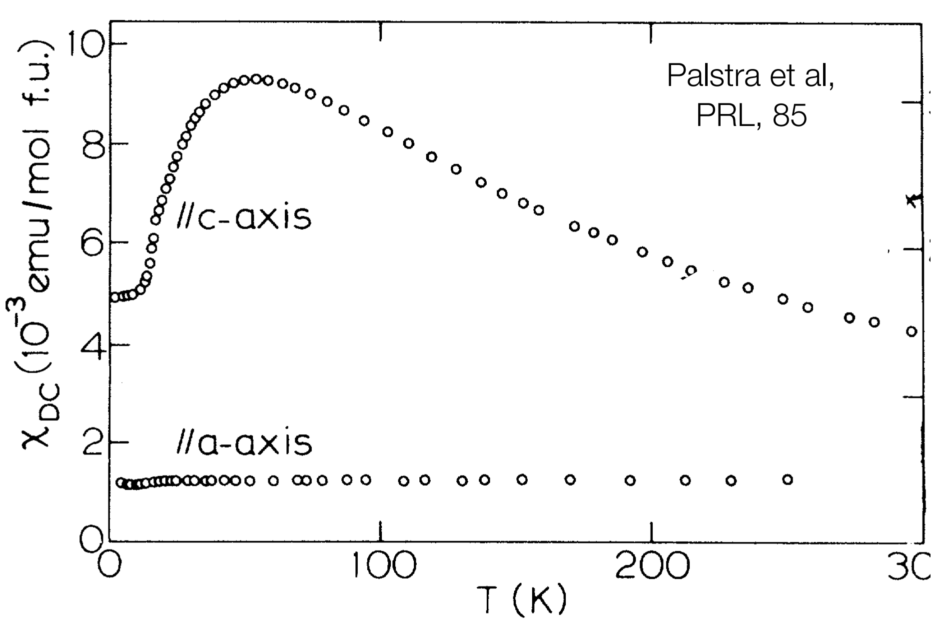


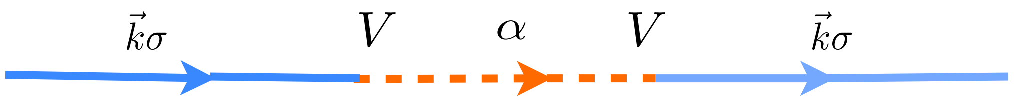
Quasiparticle with giant Ising anisotropy > 30.

Pauli susceptibility anisotropy > 900

Electrons hybridize with Ising 5f state to form Landau quasiparticles.

$$\langle \mathbf{k}\sigma | J_\pm | \mathbf{k}\sigma' \rangle = 0$$

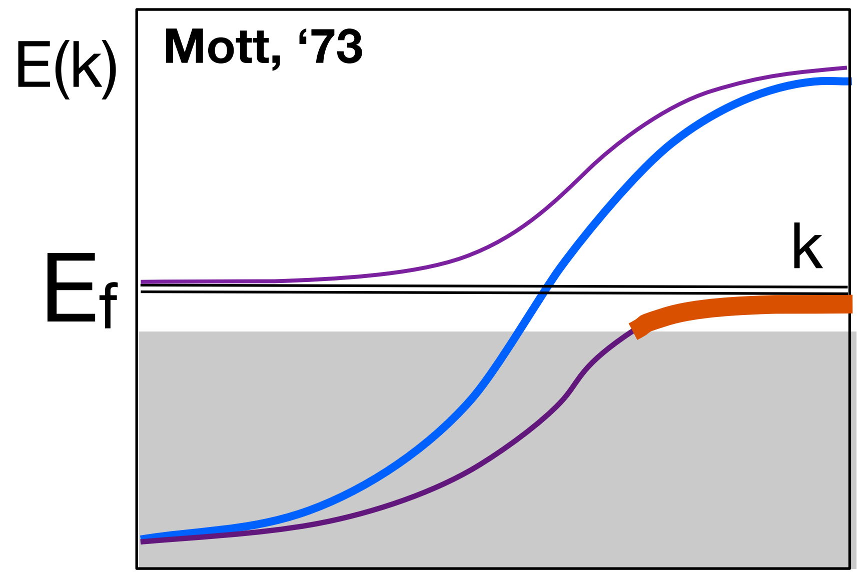
Symmetry Implications of giant Ising anisotropy

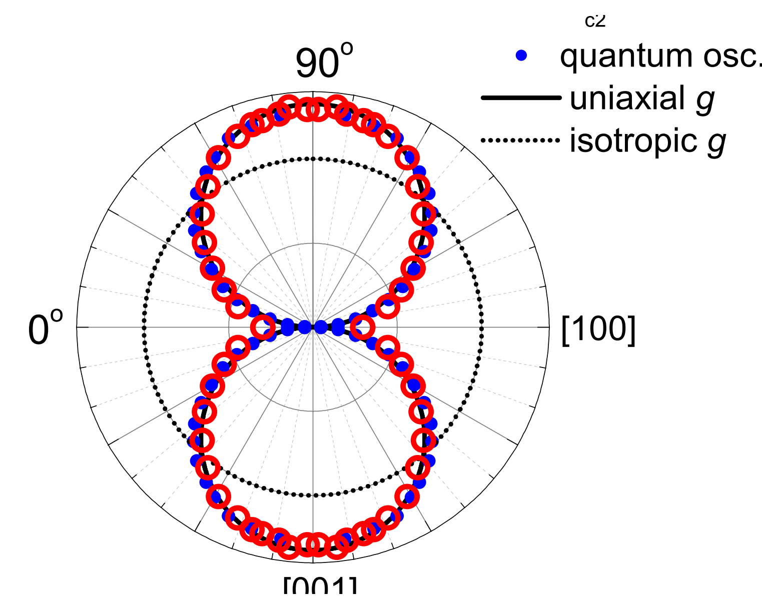


$$\langle + | J_{\pm} | - \rangle = 0$$

$$|\alpha\rangle \equiv |\pm\rangle$$

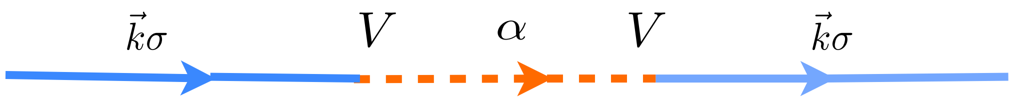
$$\mathcal{H} = (|\mathbf{k}\sigma\rangle V_{\sigma\alpha}(\mathbf{k})\langle\alpha| + \mathrm{H.c})$$





∴ Integer spin M

Symmetry Implications of giant Ising anisotropy



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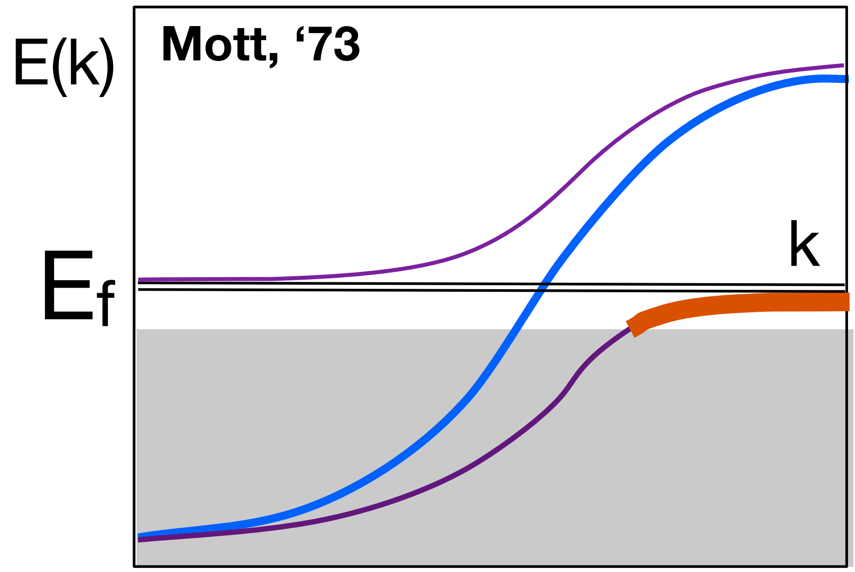
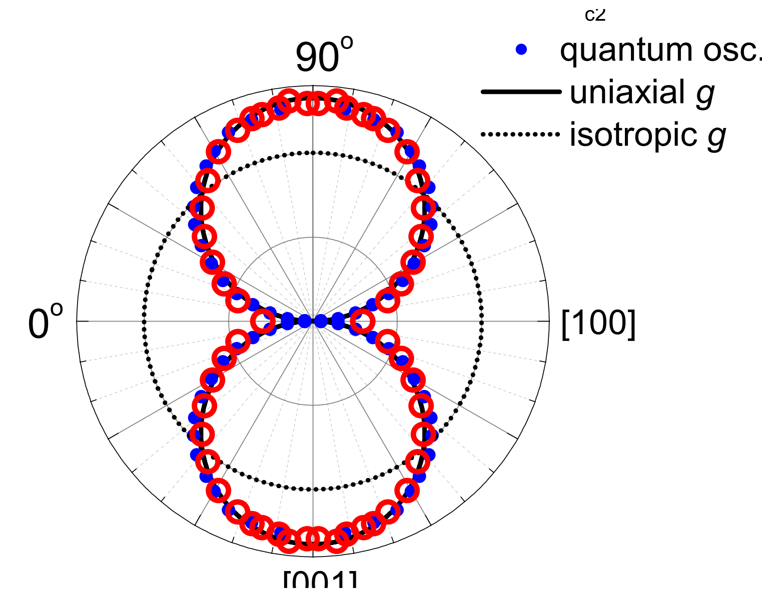


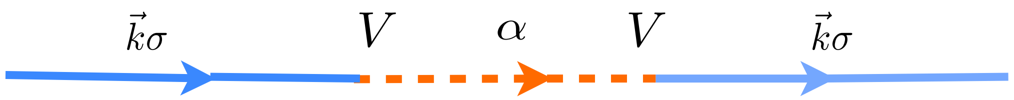


$$|\Gamma, \pm\rangle = a|\pm 3\rangle + b|\mp 1\rangle$$

"Γ_5" non-Kramers doublet $5f^2$

∴ Integer spin M

Symmetry Implications of giant Ising anisotropy



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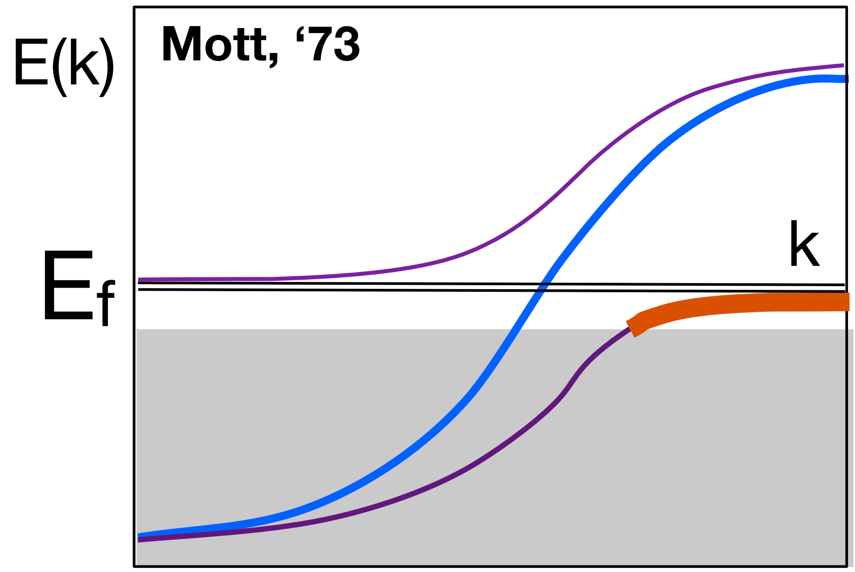

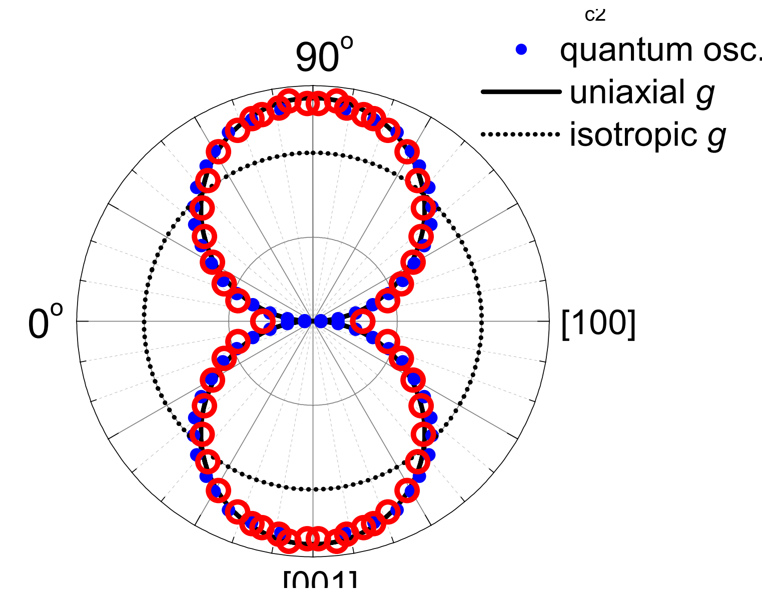

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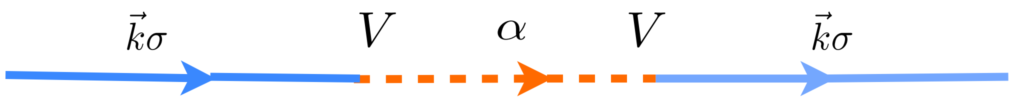

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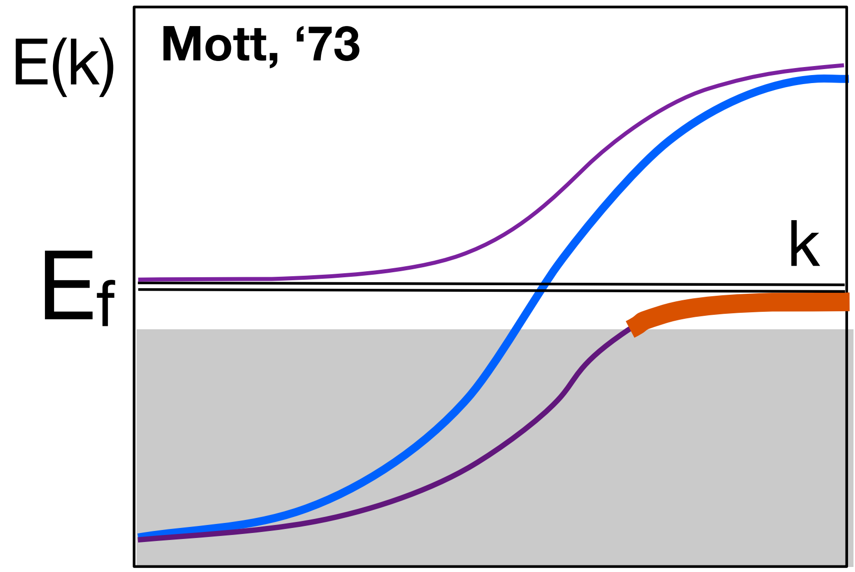

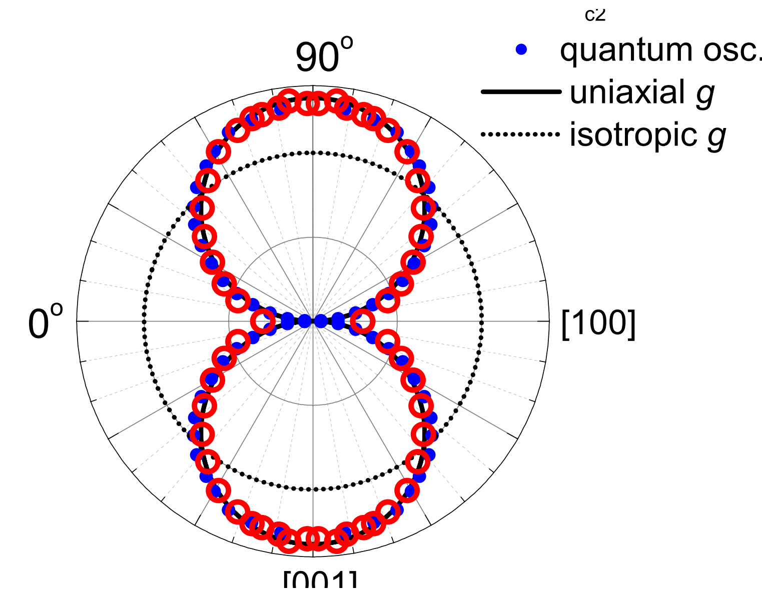

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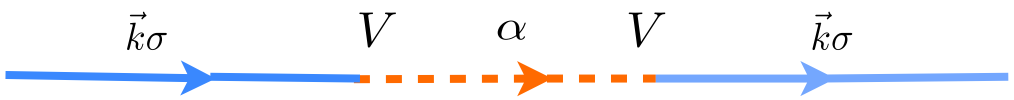

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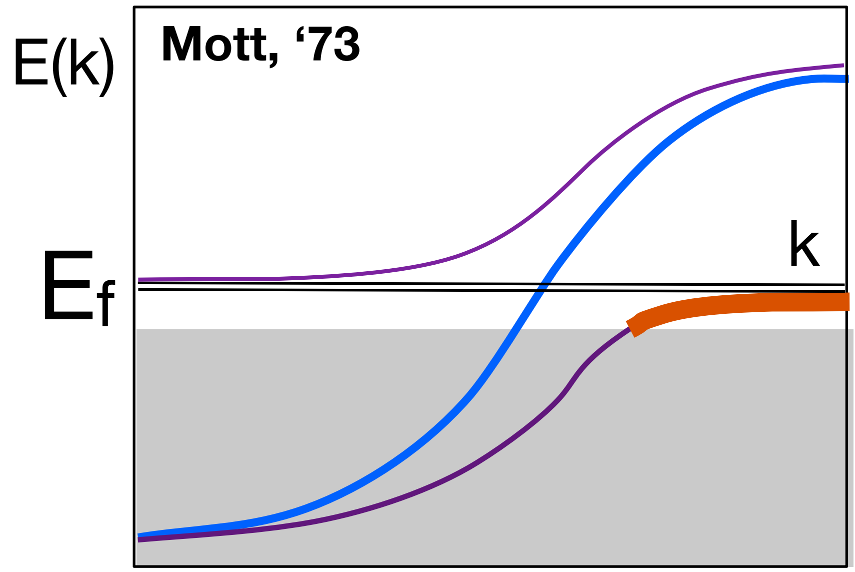

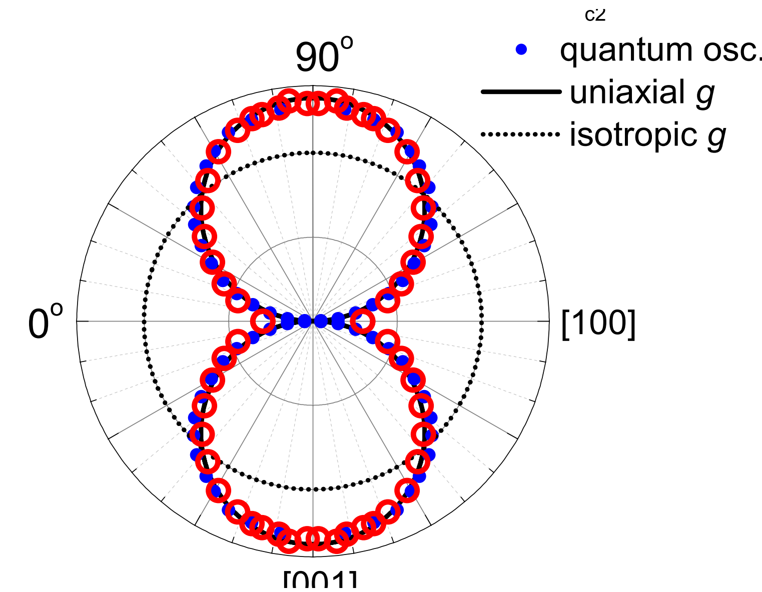

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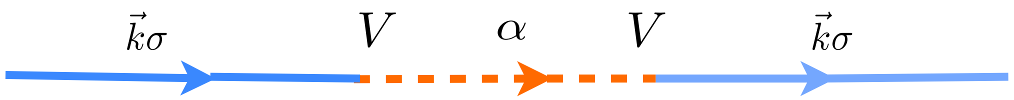

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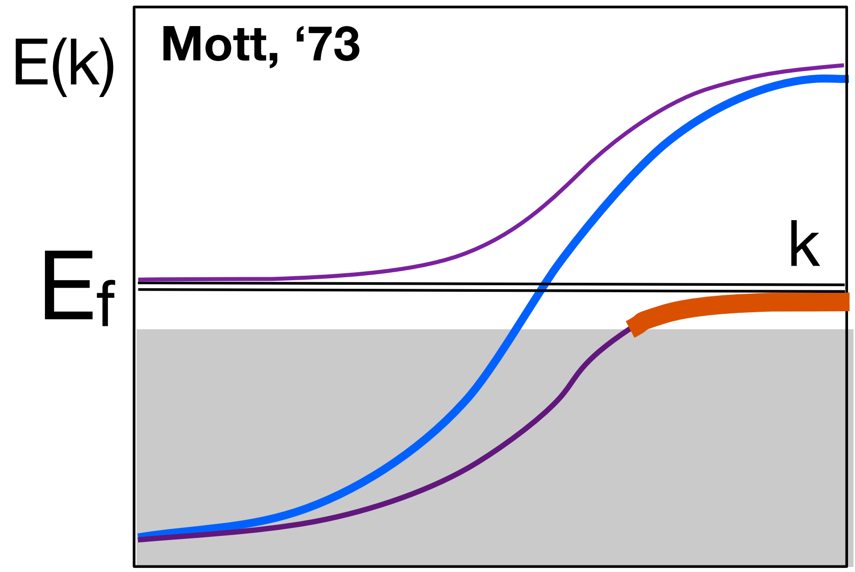

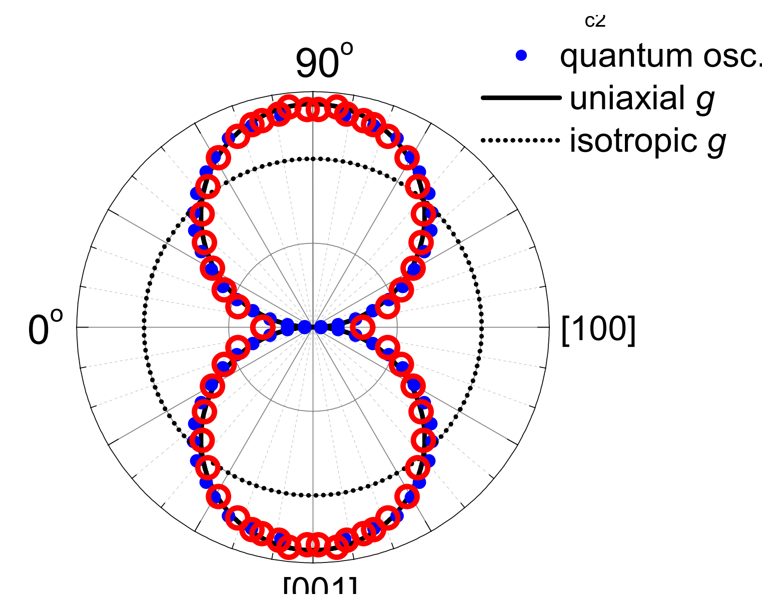

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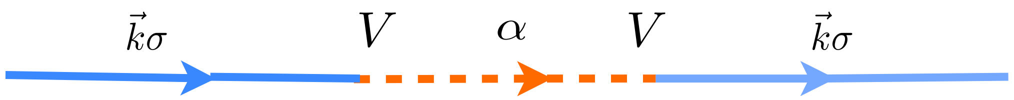

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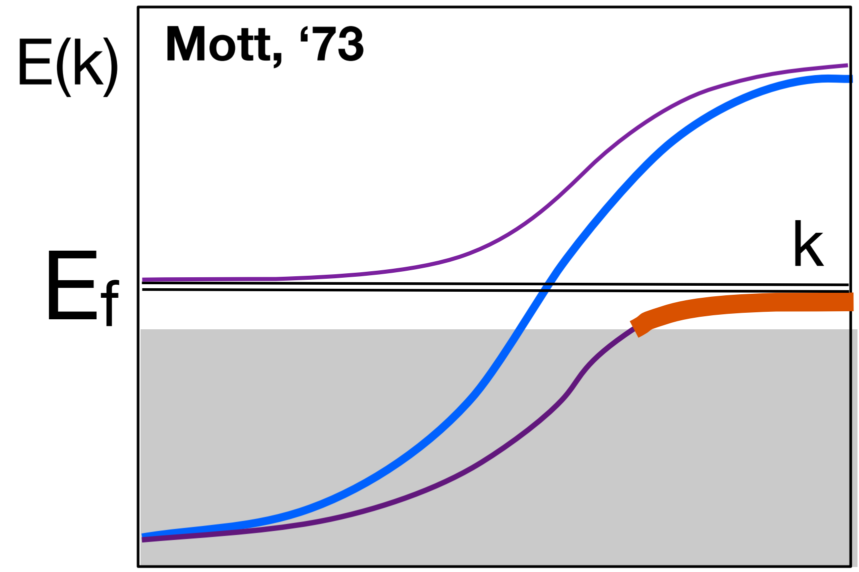

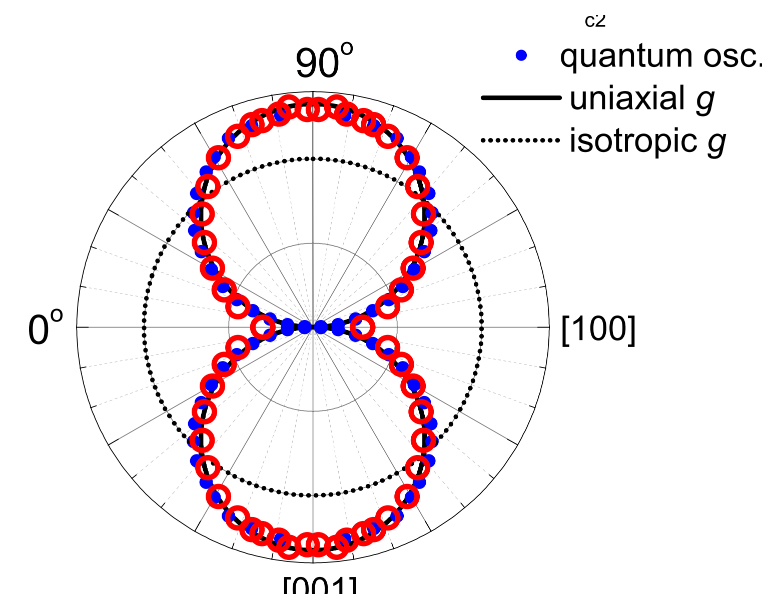

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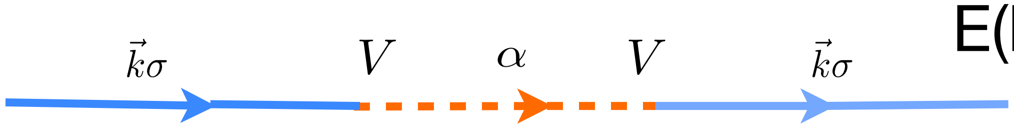

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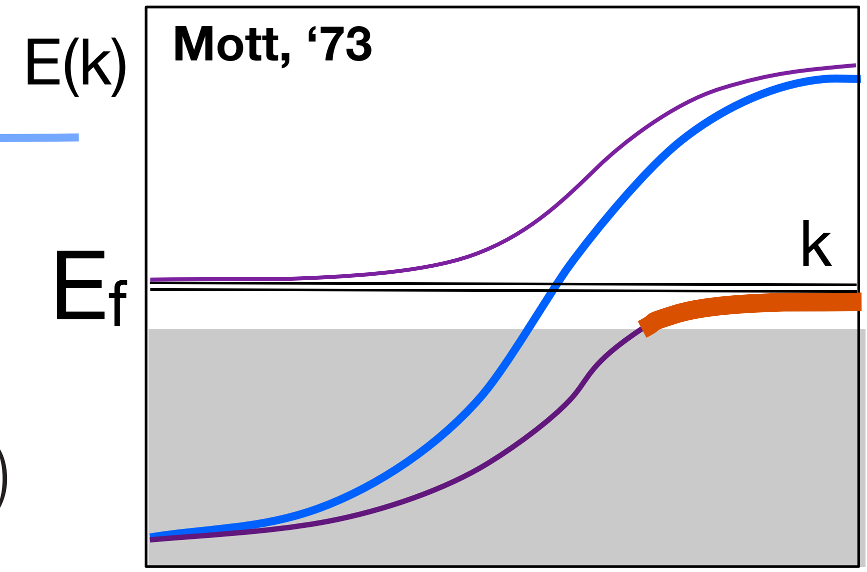

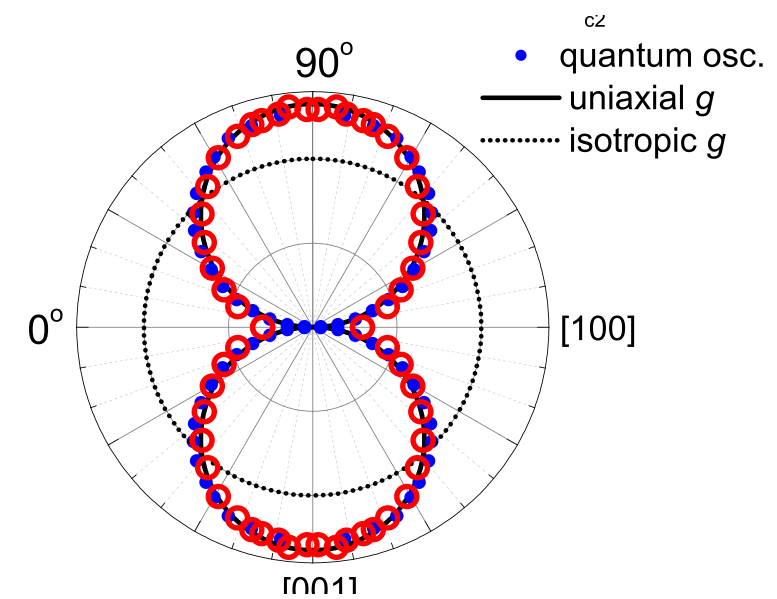

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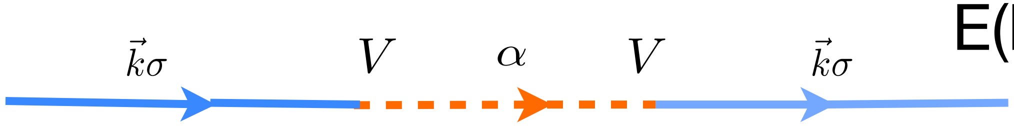

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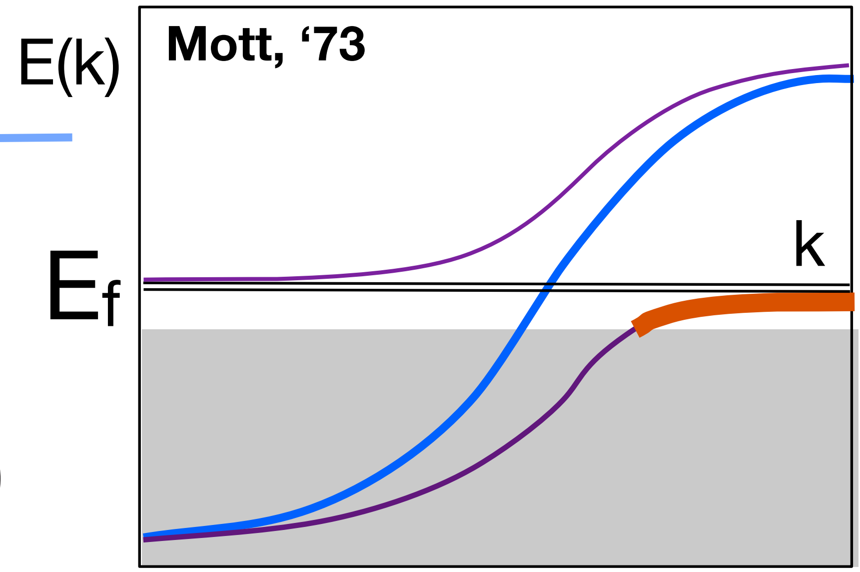

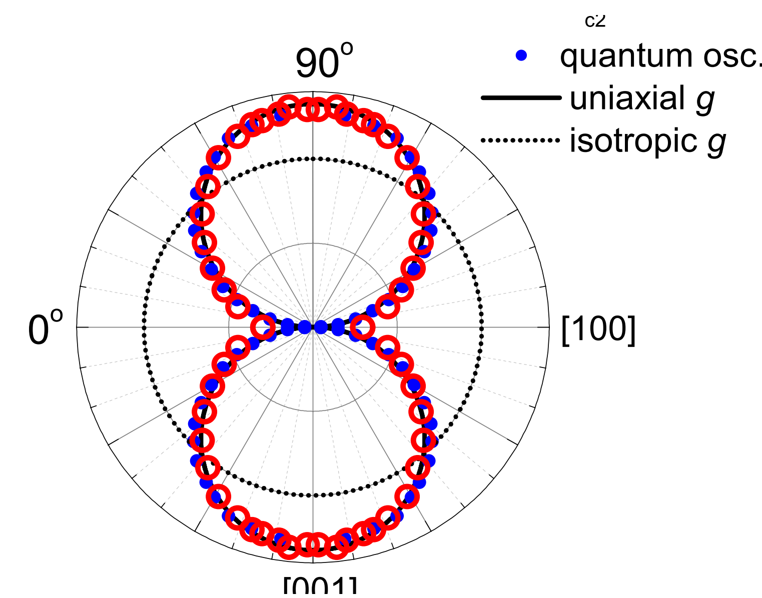

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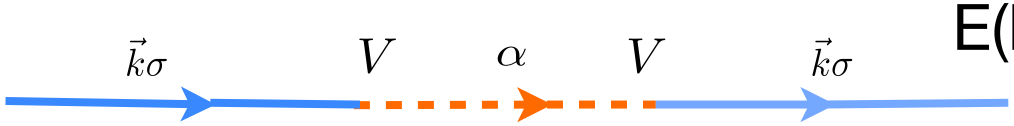

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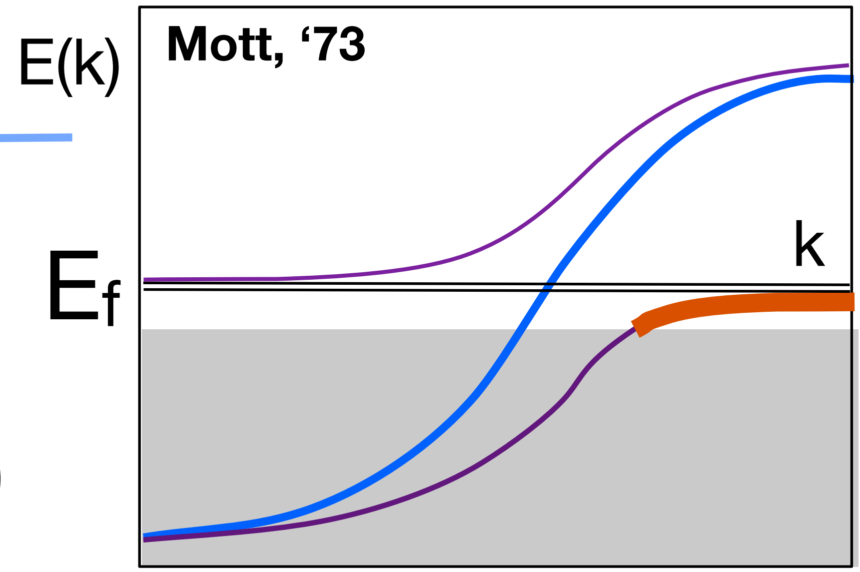

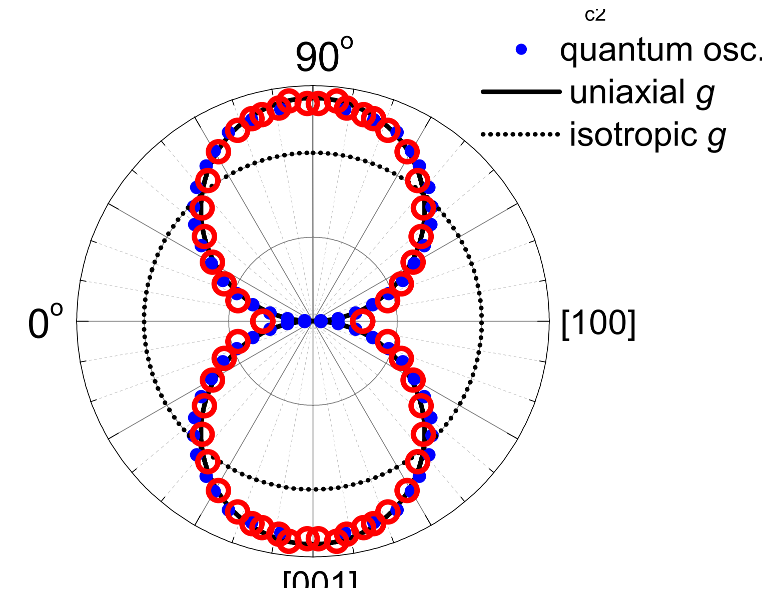

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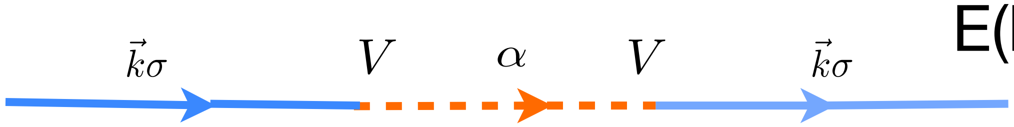

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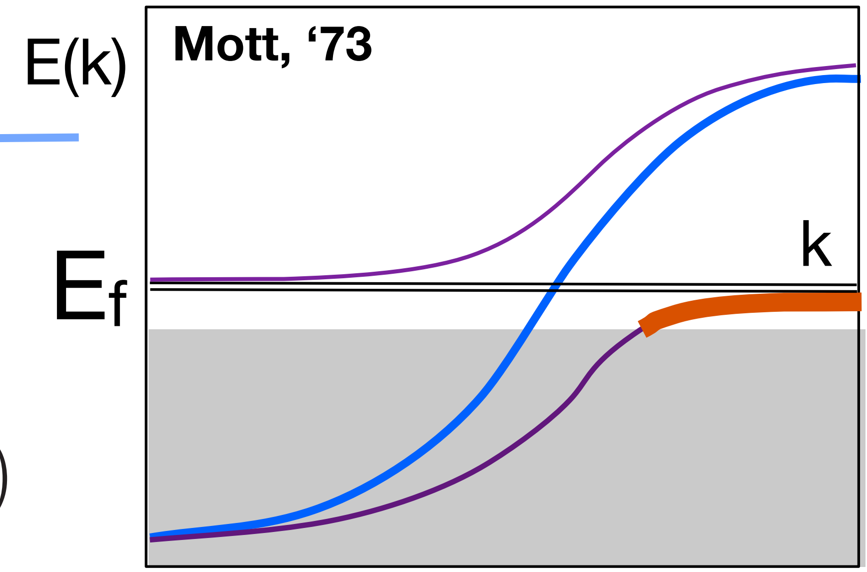

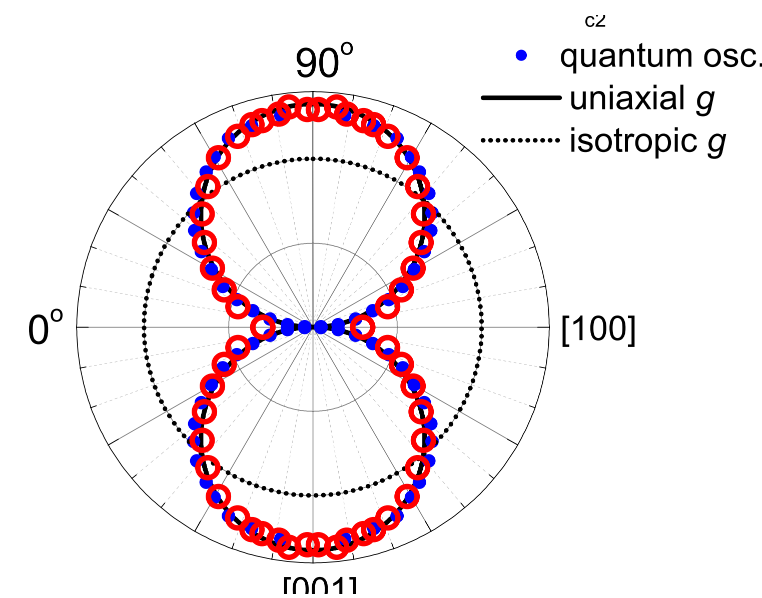

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Half-integer spins change sign, integer spins do not.

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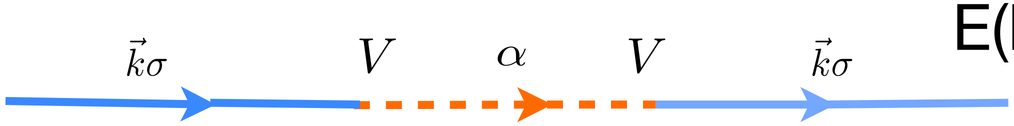

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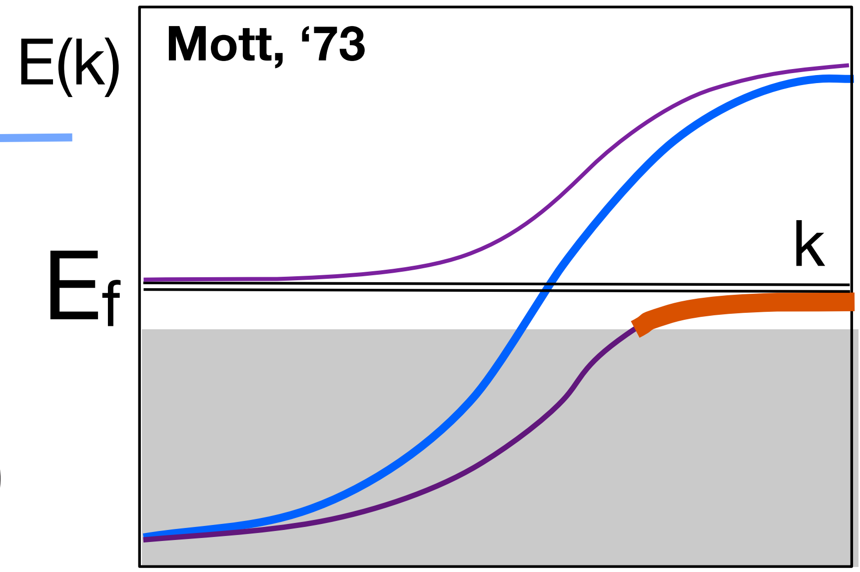
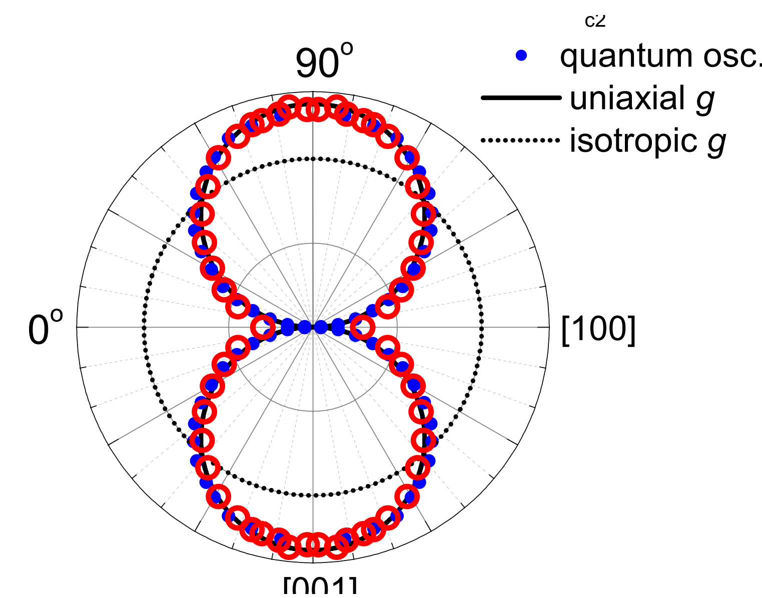
-1





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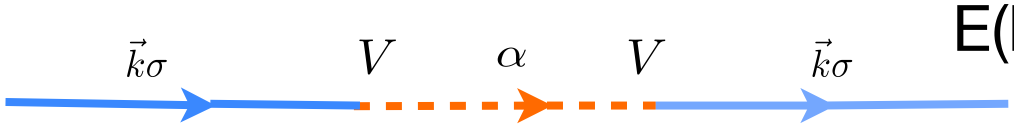

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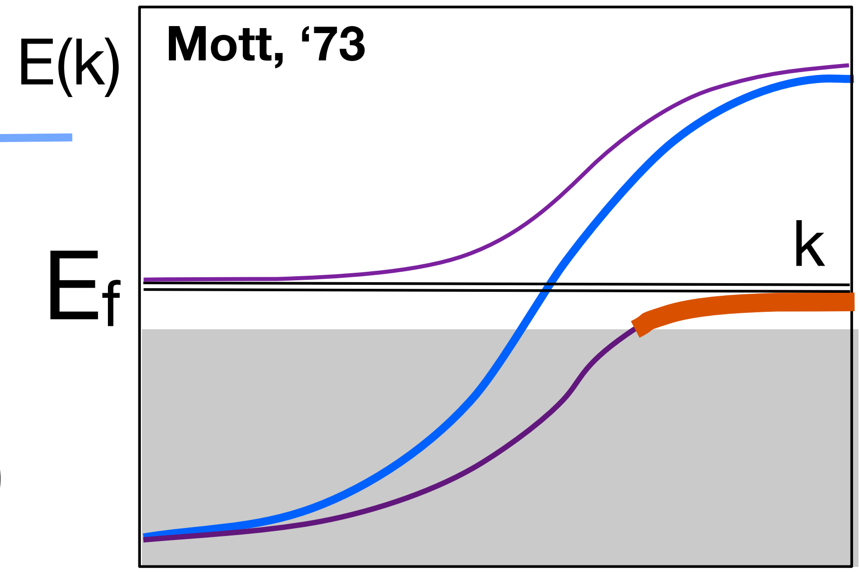

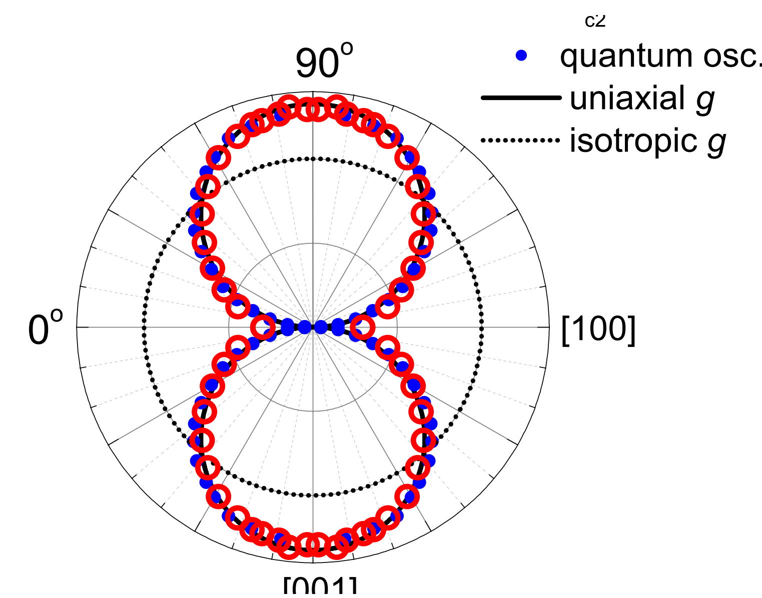

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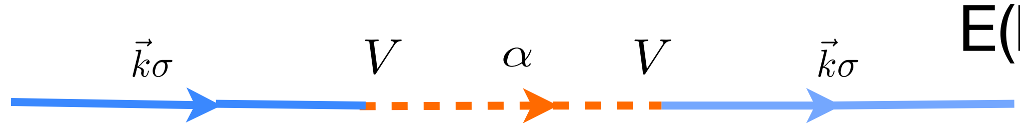

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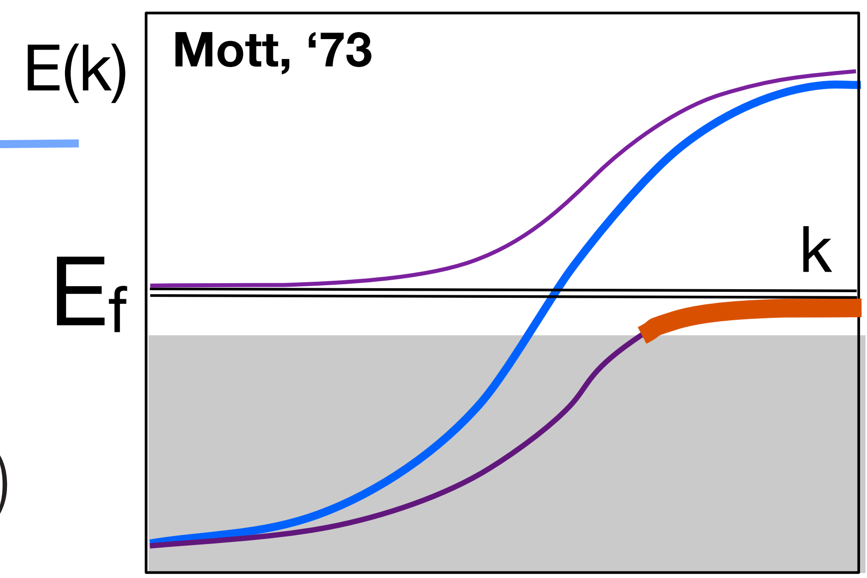

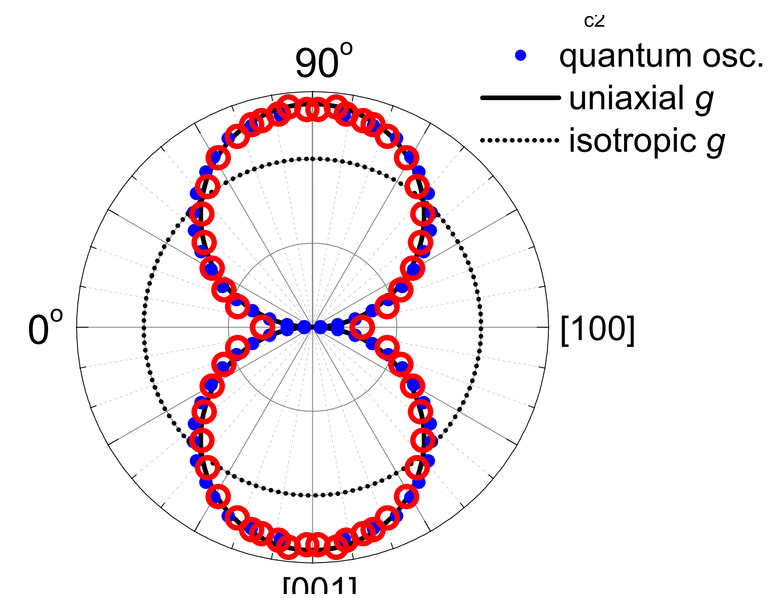

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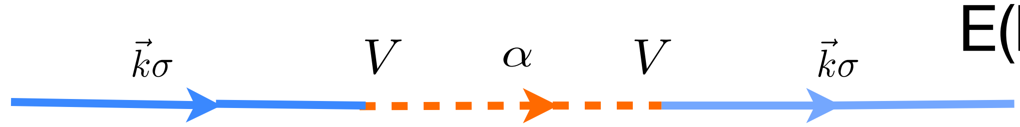

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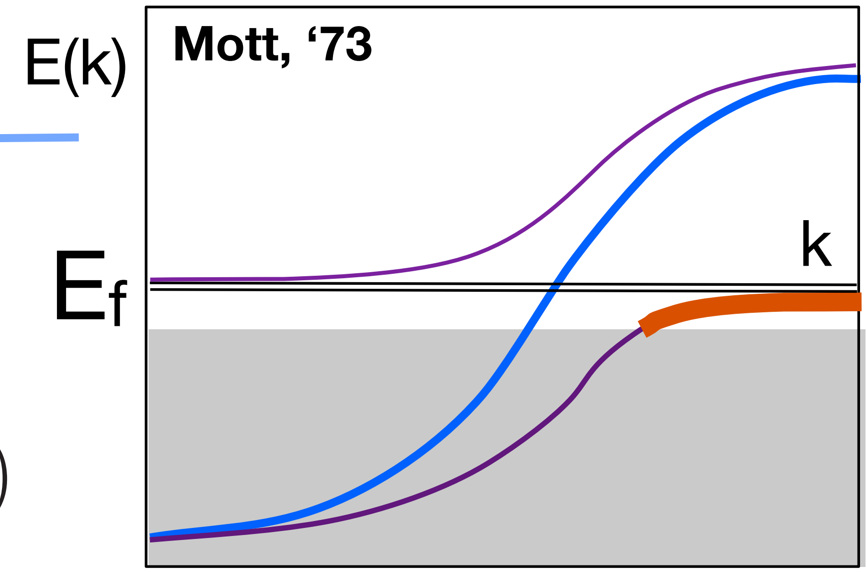

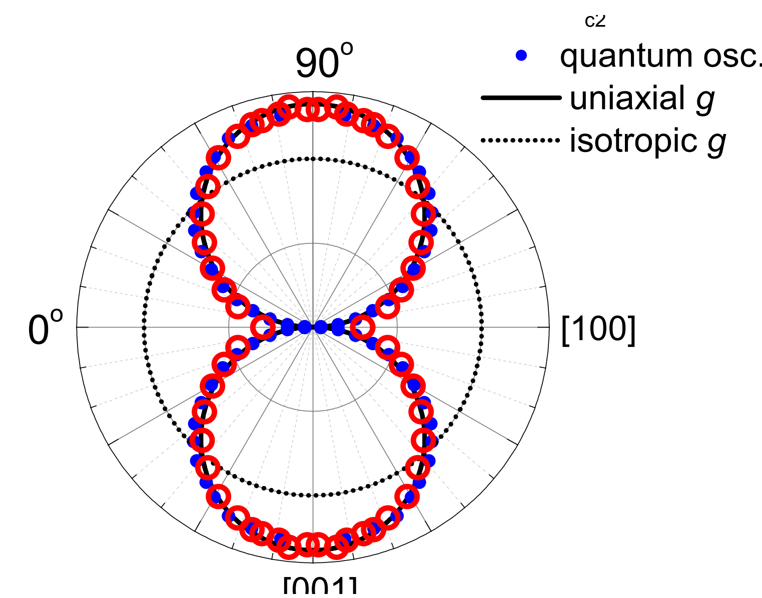

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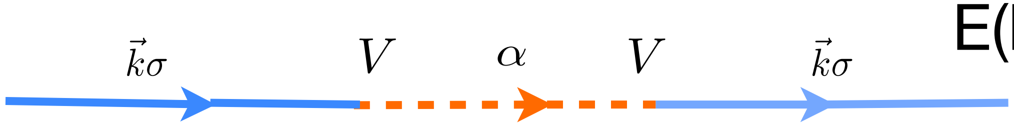

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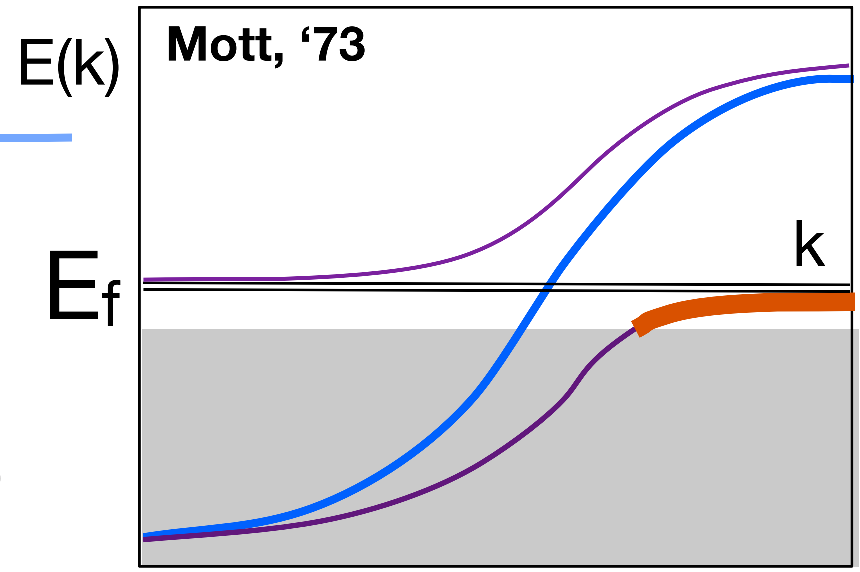

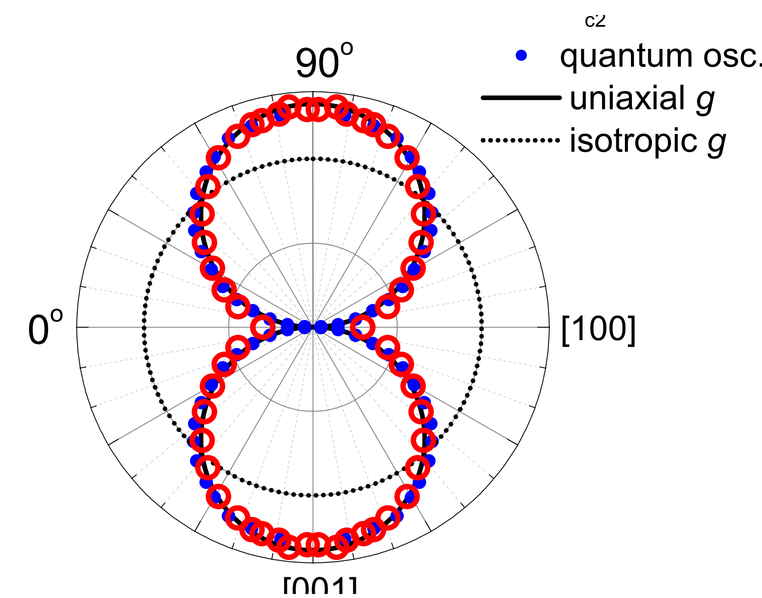

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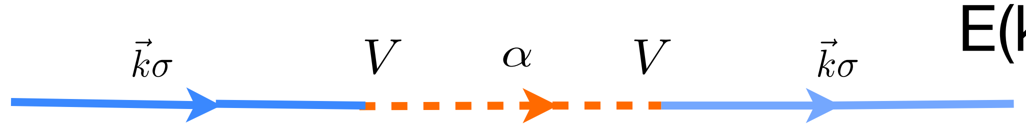

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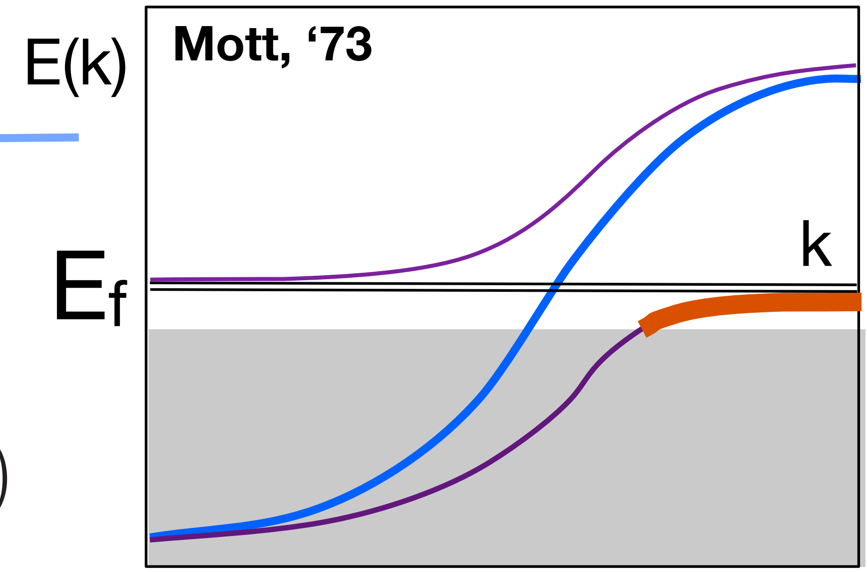

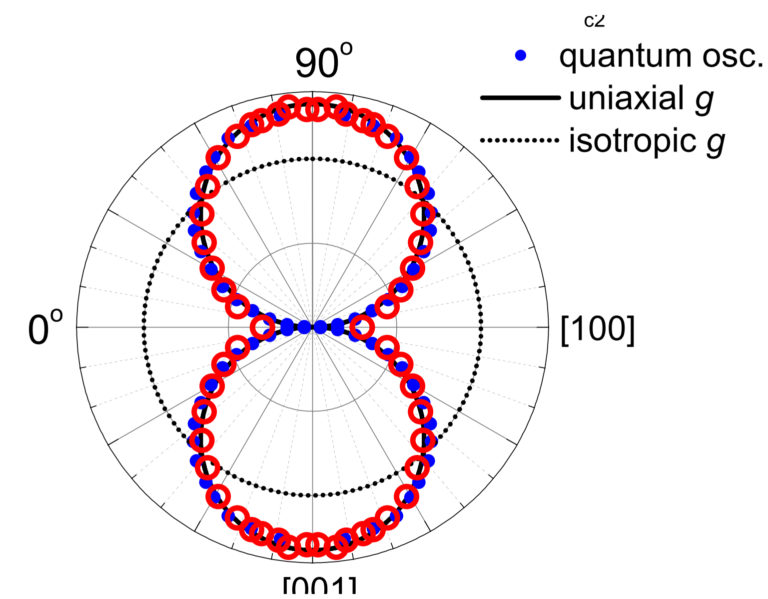

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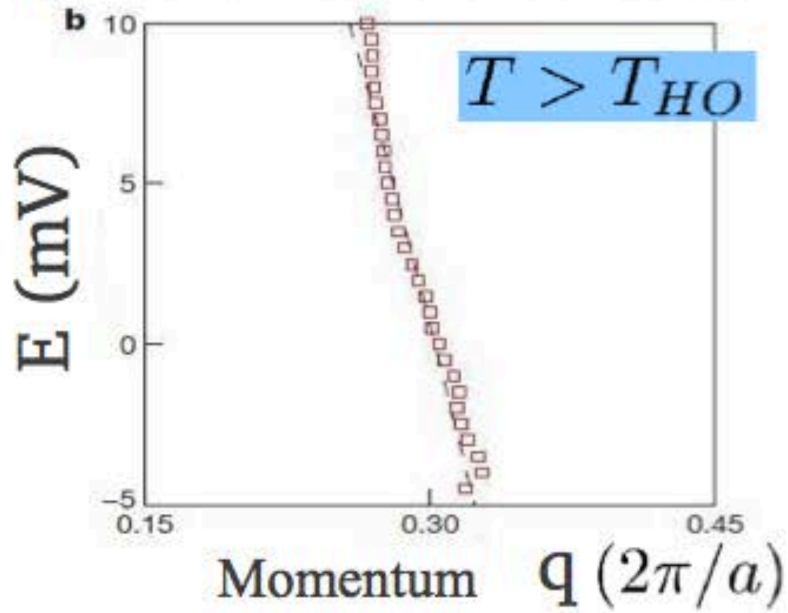
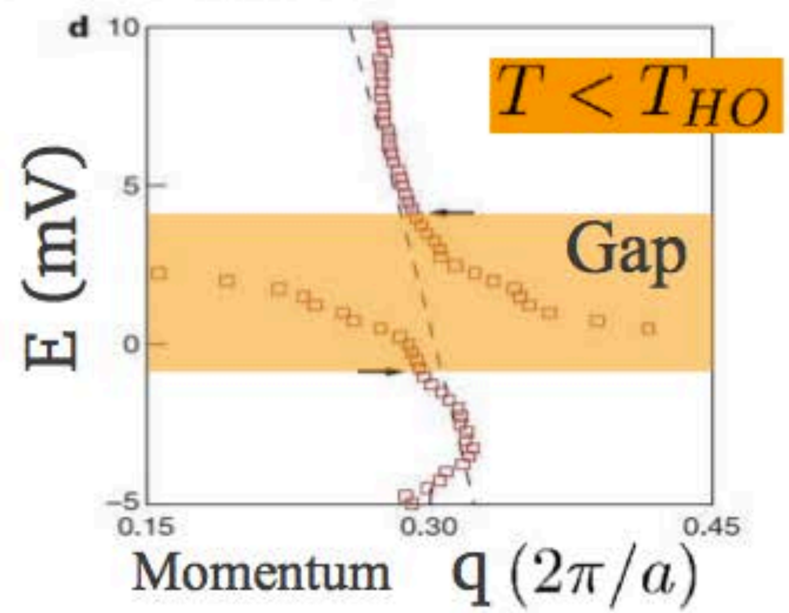
Hybridization transforms as a 1/2 integer spin.
Unlike magnetism, it breaks **double time reversal.**
A new kind of order parameter.

Measuring the hybridization gap

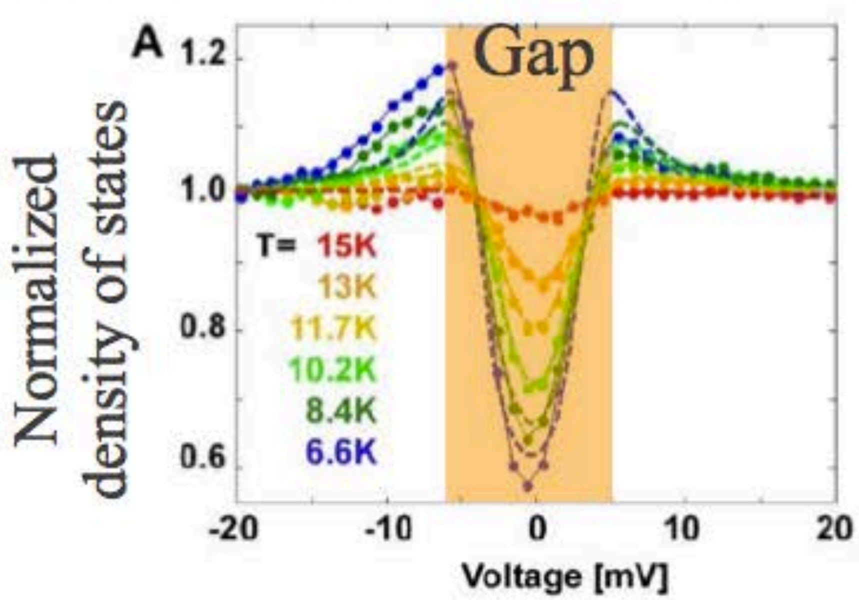
new insights from spectroscopy

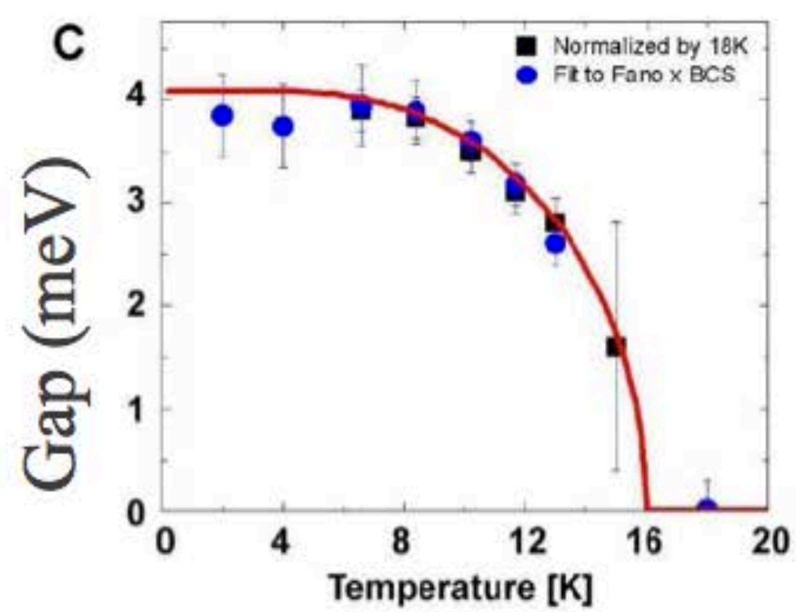
Quasiparticle interference reveals band structure



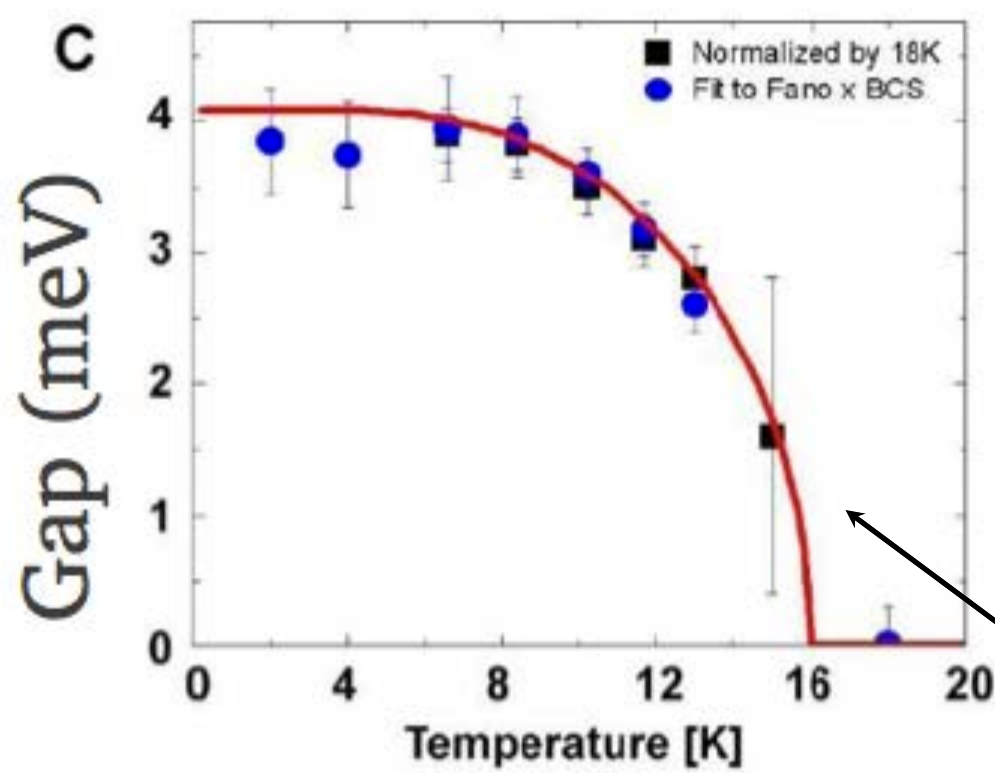


Density of states reveals order parameter-like gap – matches heat capacity





Schmidt et al 2010
Aynajian et al 2010



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$$\Psi_H \sim \left(1 - \frac{T}{T_c}\right)^{\frac{1}{2}}$$

Hybridization develops at T_{HO}

Hybridization is the Order Parameter !!??!!

Morr et al. (10)
Dubi and Balatsky (10)

"Hastatic" order.

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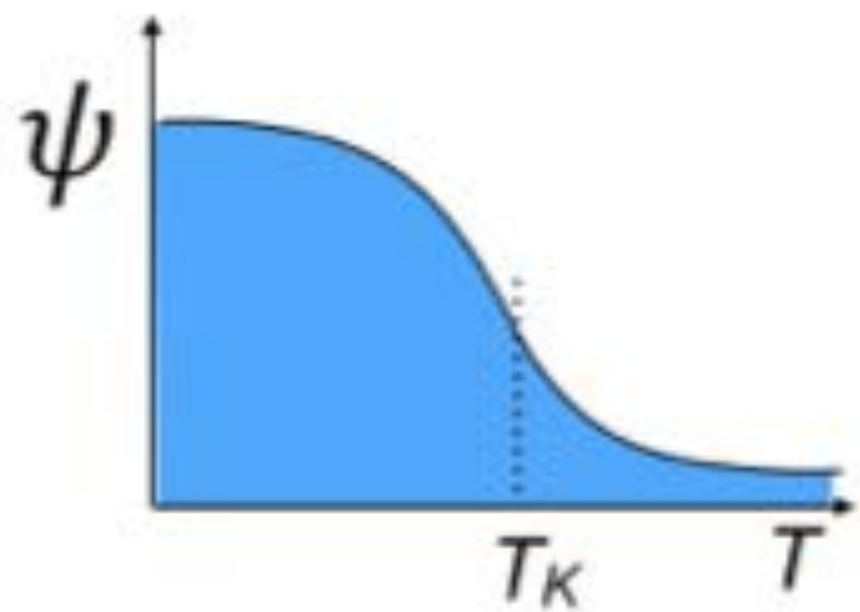

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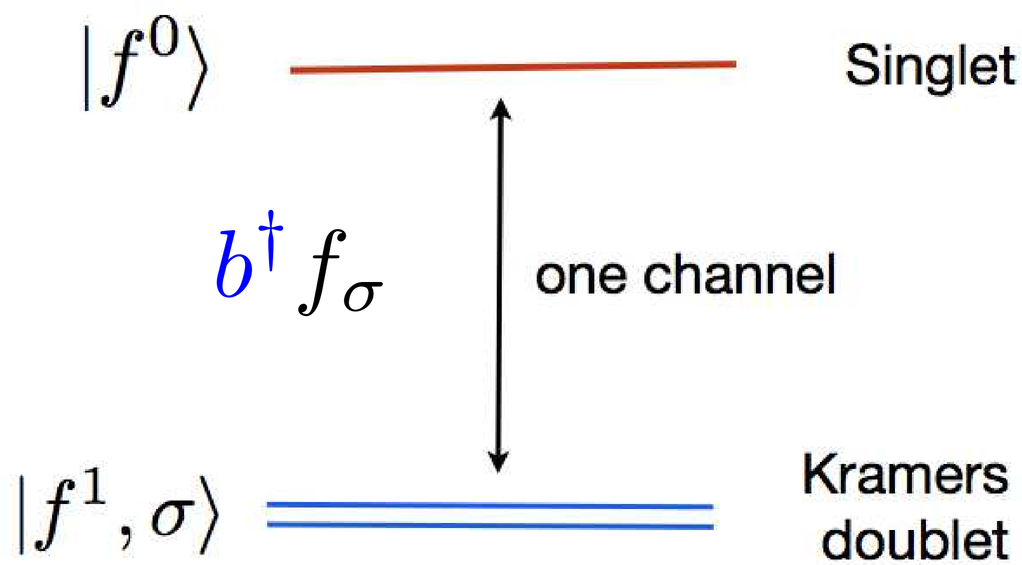

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H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

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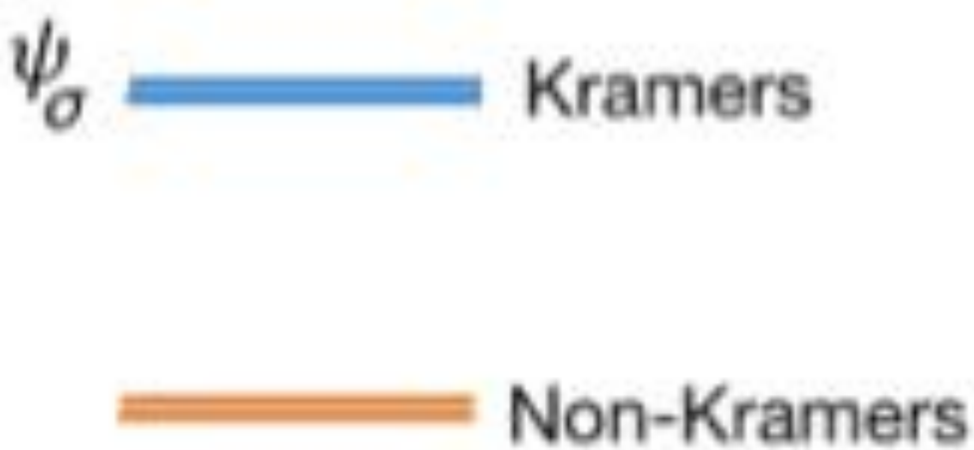

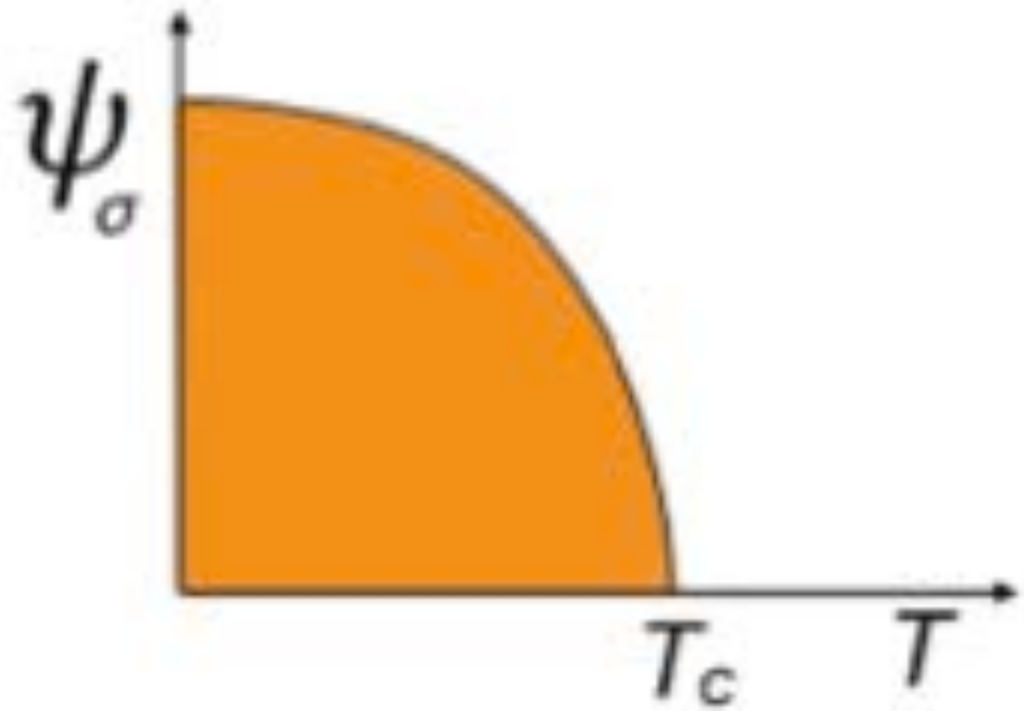

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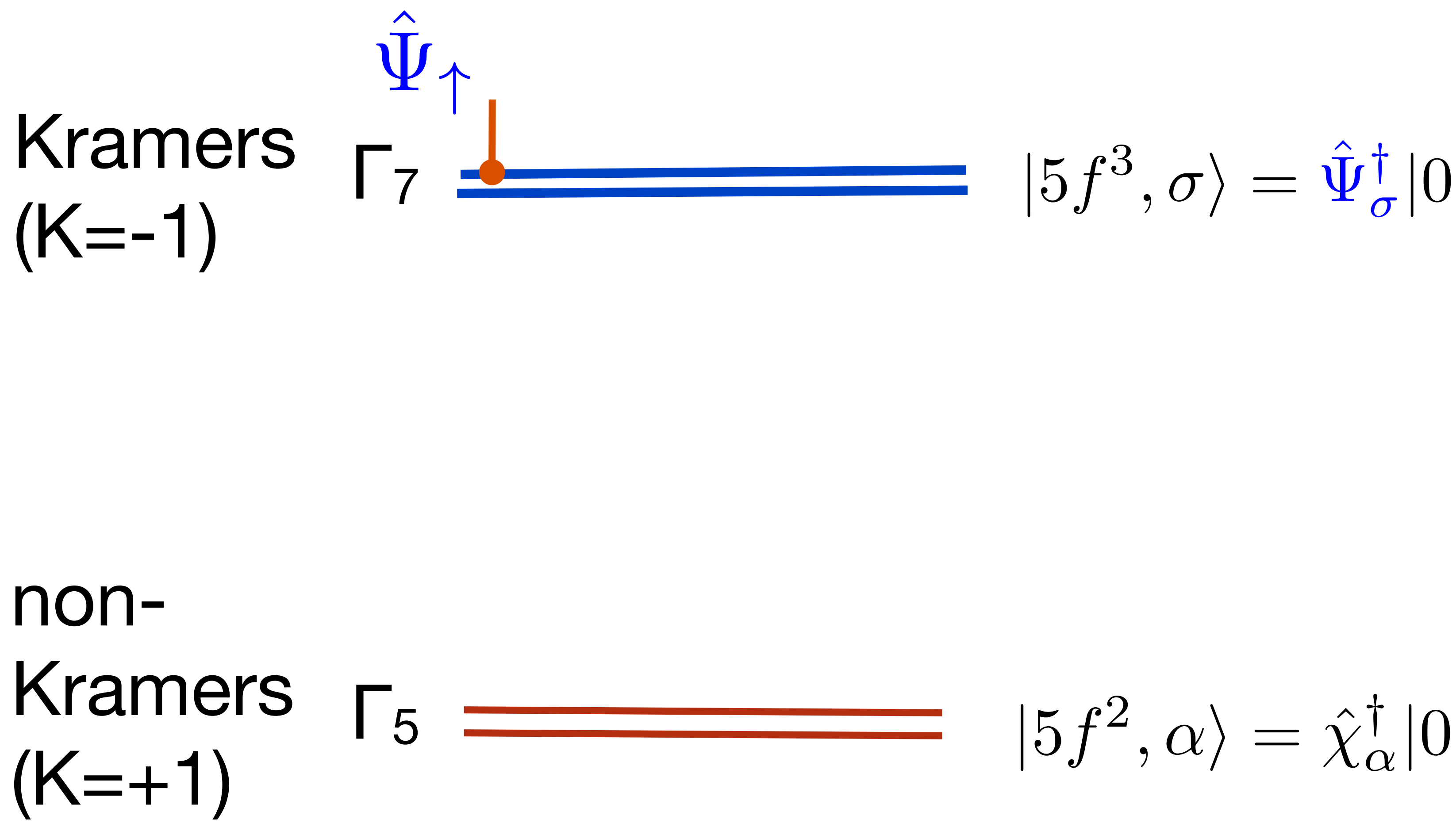

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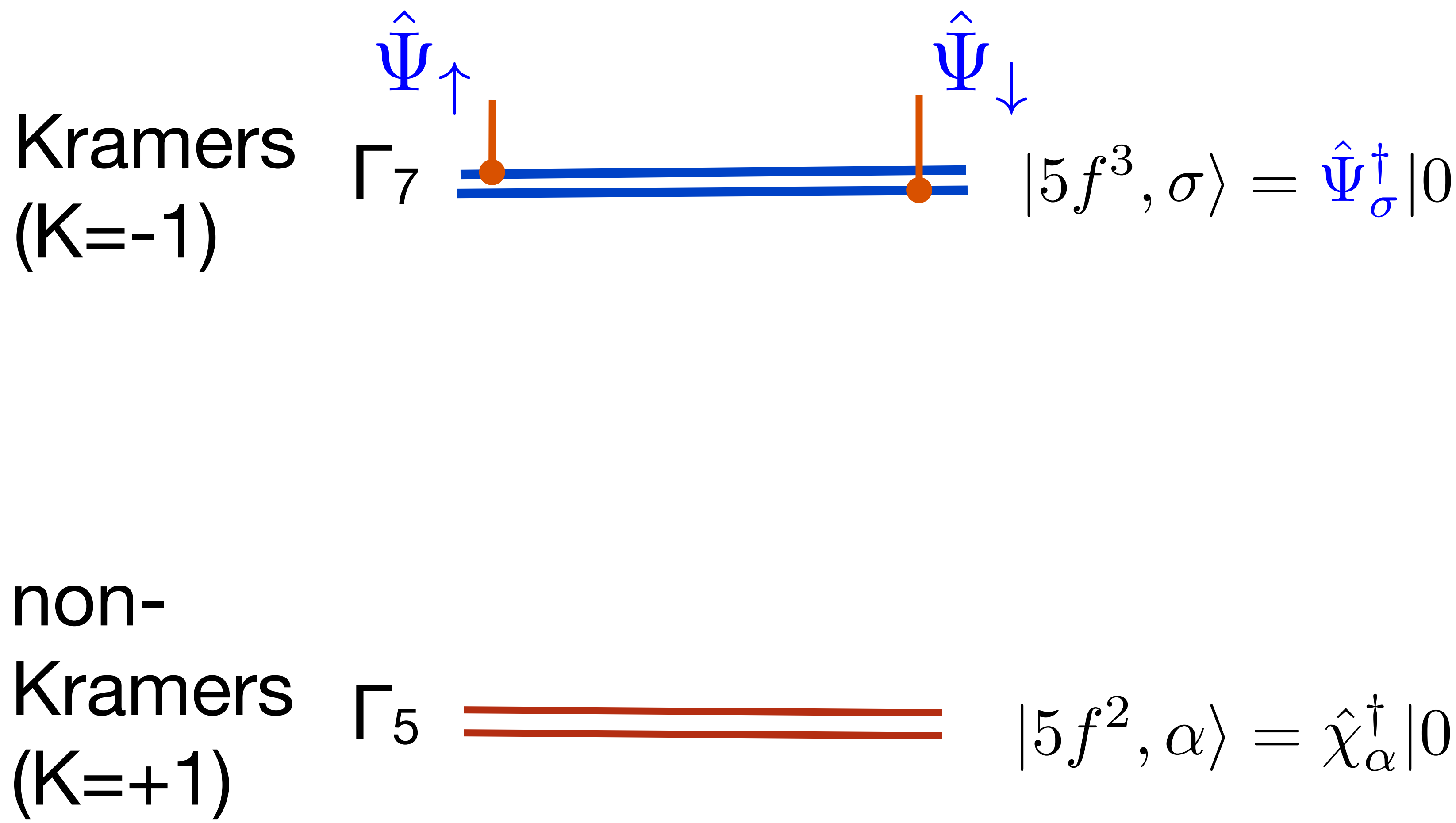

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$\hat{\Psi}_{\uparrow}$ $\hat{\Psi}_{\downarrow}$

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$$|5f^3,\sigma\rangle\langle 5f^2,\alpha| = \hat{\Psi}^{\dagger}_{\sigma}\hat{\chi}_{\alpha}$$

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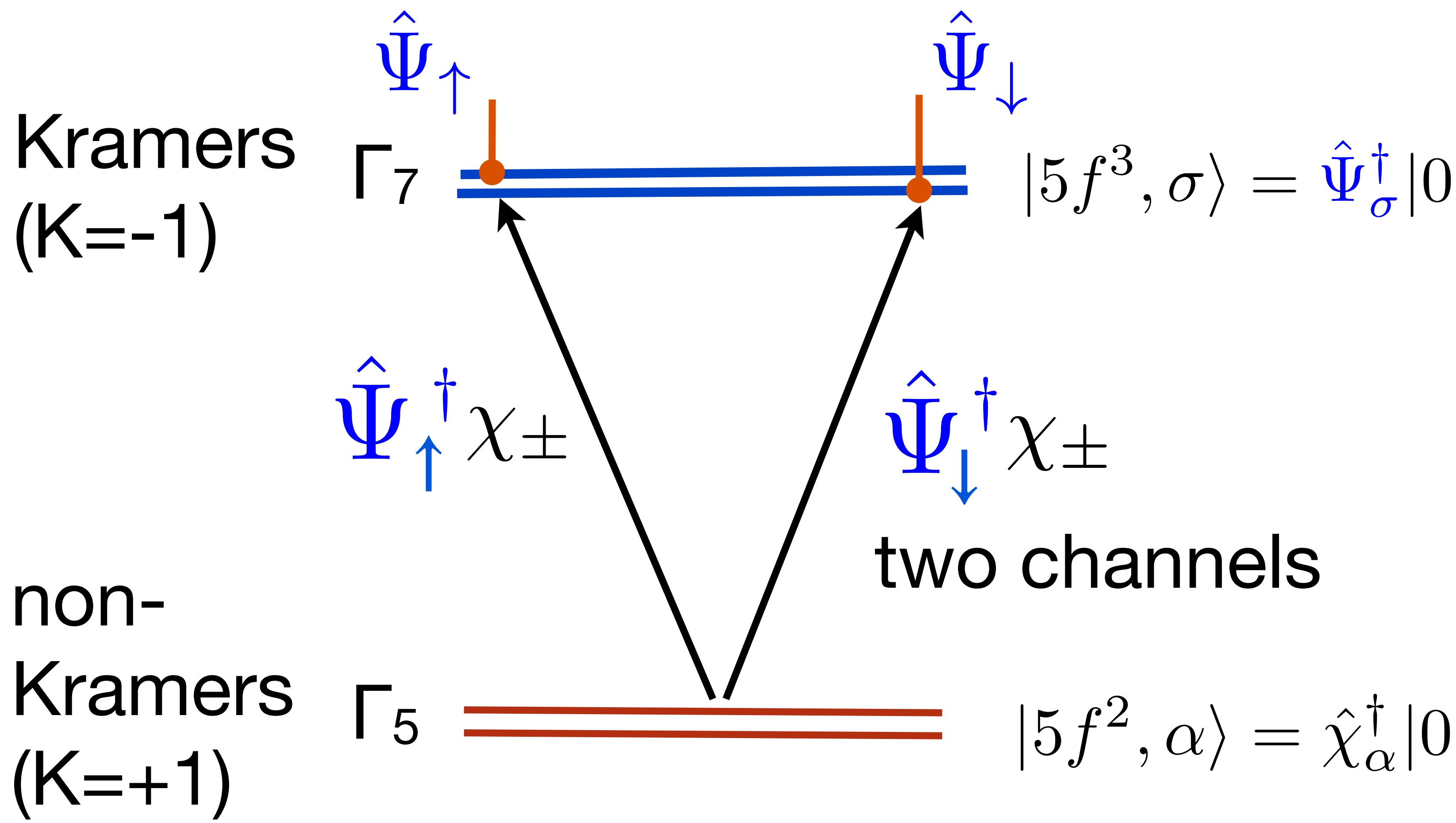

$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| = \hat{\Psi}^\dagger_\sigma \hat{\chi}_\alpha$$

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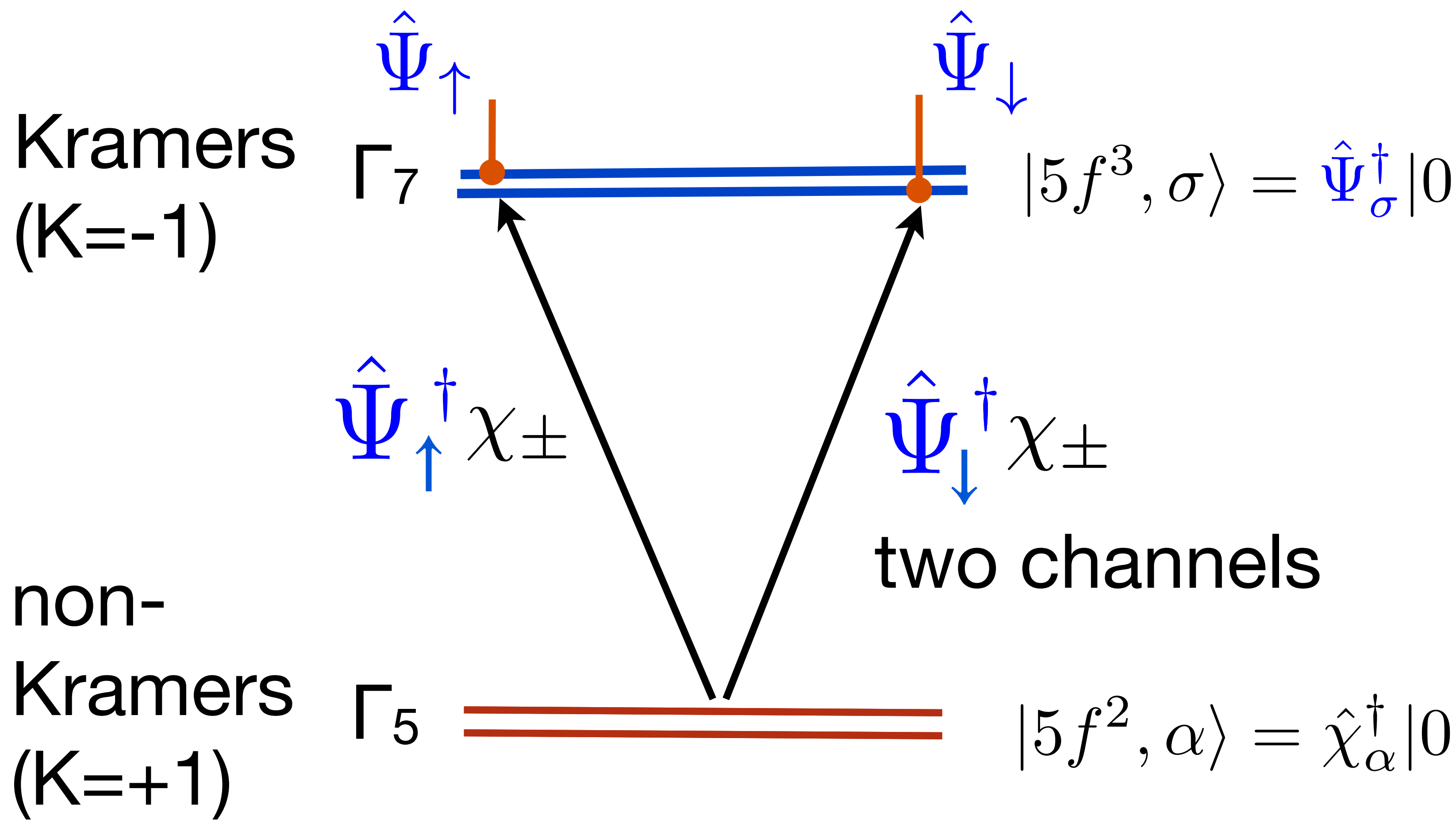

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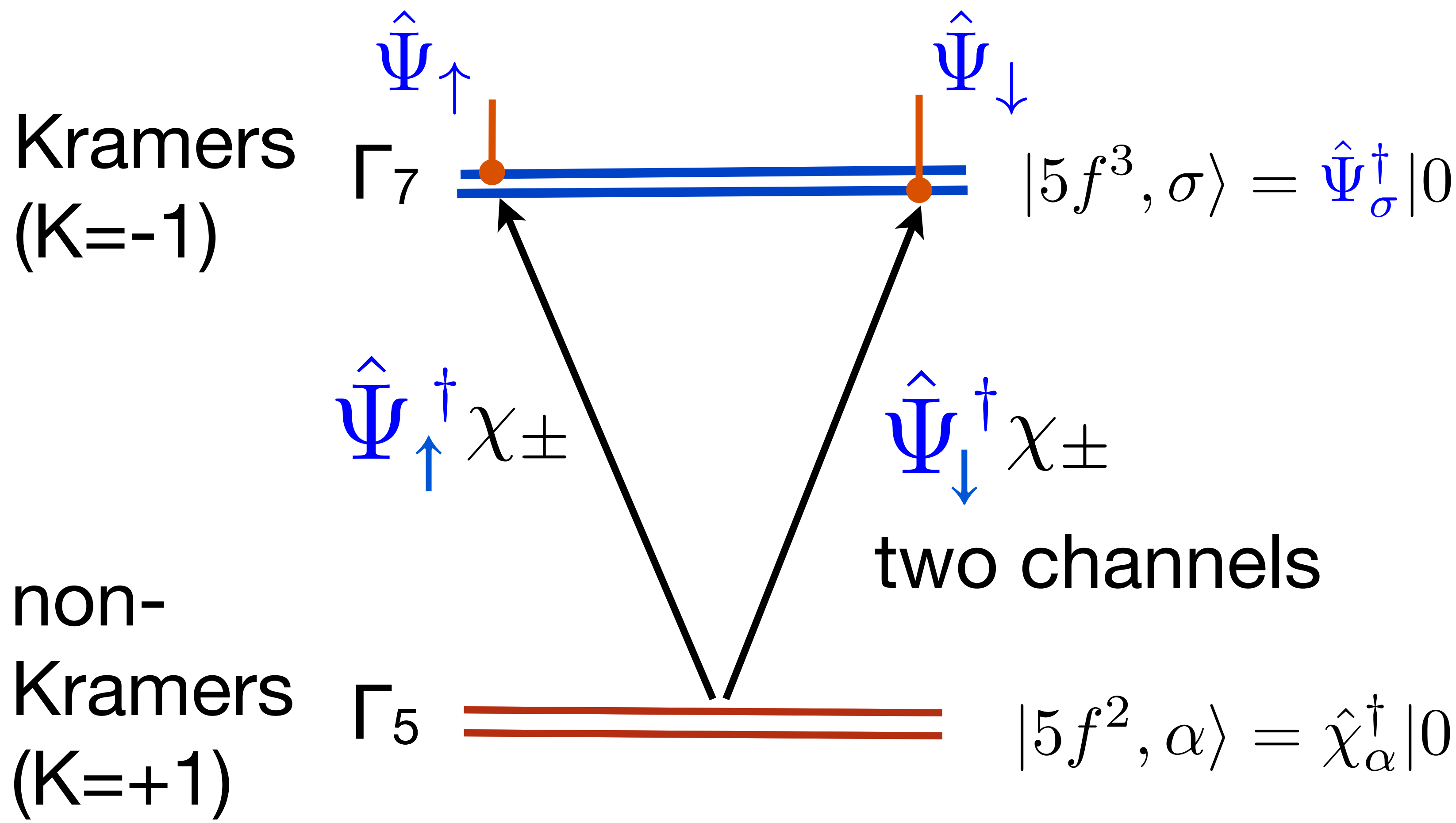

$$|5f^3,\sigma\rangle\langle 5f^2,\alpha| \longrightarrow \langle\hat{\Psi}^\dagger_\sigma\rangle\hat{\chi}_\alpha$$

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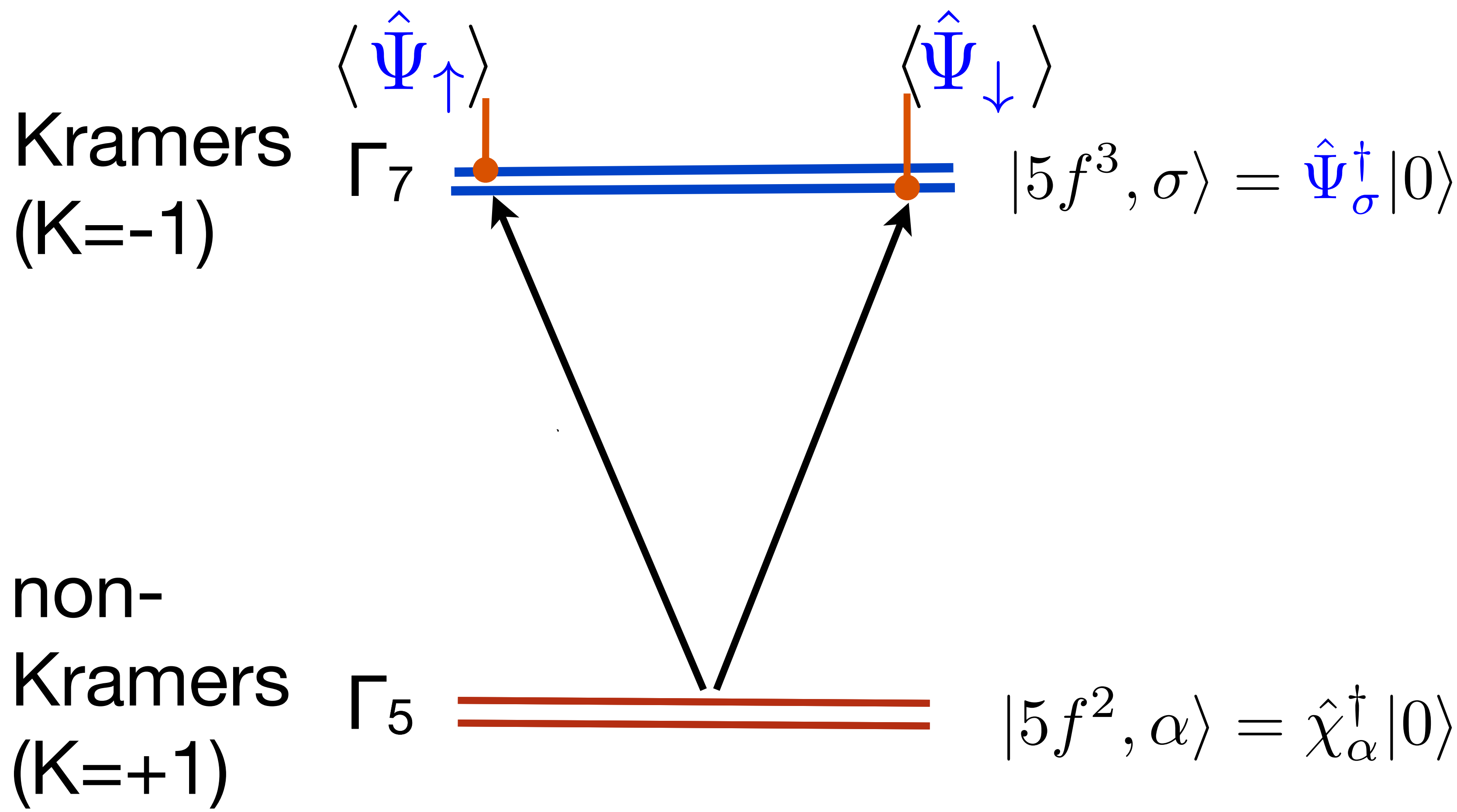
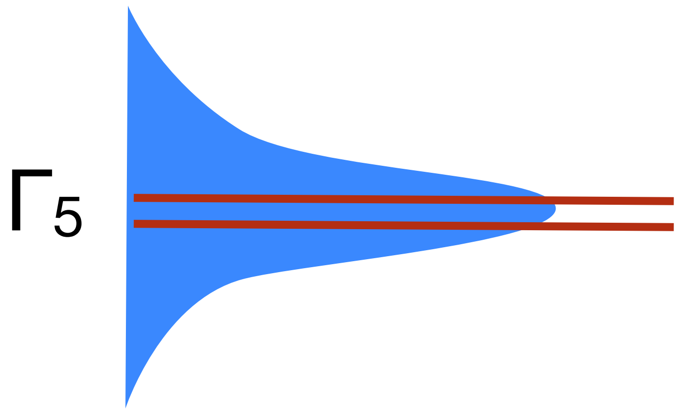


(“Magnetic Higgs Boson”)

$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| \longrightarrow \langle \hat{\Psi}^\dagger_\sigma \rangle \hat{\chi}_\alpha$$

"Hastatic" order.



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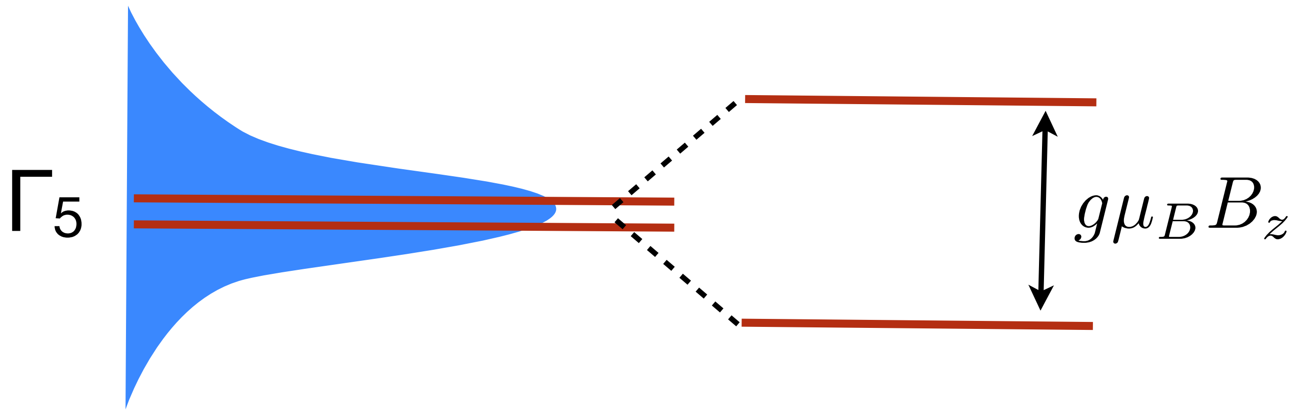
"Hastatic" order.

Quasiparticles acquire the Ising anisotropy of the non-Kramers doublet.



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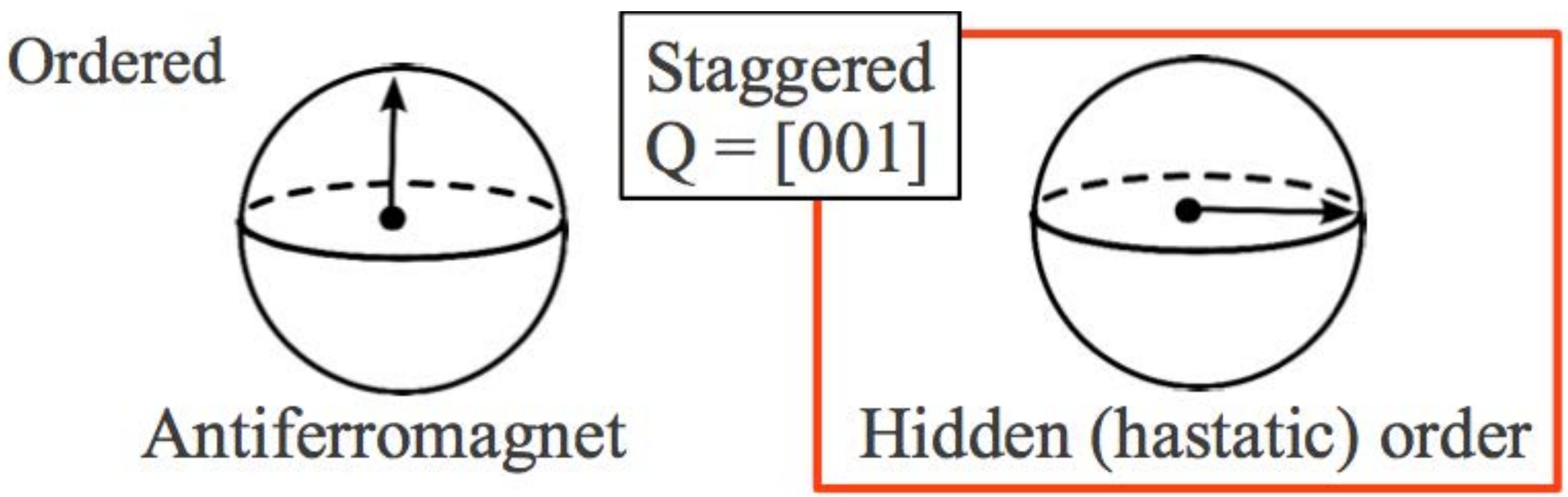
$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| \longrightarrow \langle \hat{\Psi}^\dagger_\sigma \rangle \hat{\chi}_\alpha$$

Landau Theory of Hastatic Order

$$\Psi = \begin{pmatrix} \Psi_\uparrow \\ \Psi_\downarrow \end{pmatrix}$$

$$f[T,P] = \alpha(T_c - T)|\Psi|^2 + \beta|\Psi|^4 - \gamma(\Psi^\dagger \sigma_z \Psi)^2$$

$$\gamma = \delta(P - P_c)$$



AFM: $P>P_c$

$$\Psi_A \sim \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \Psi_B \sim \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Large f-moment

HO: $P<P_c$

$$\Psi_A \sim \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-i\phi/2} \\ e^{i\phi/2} \end{pmatrix}, \Psi_B \sim \frac{1}{\sqrt{2}} \begin{pmatrix} -e^{-i\phi/2} \\ e^{i\phi/2} \end{pmatrix}$$

No f-moment: large Ising fluctuations

Landau Theory of Hastatic Order

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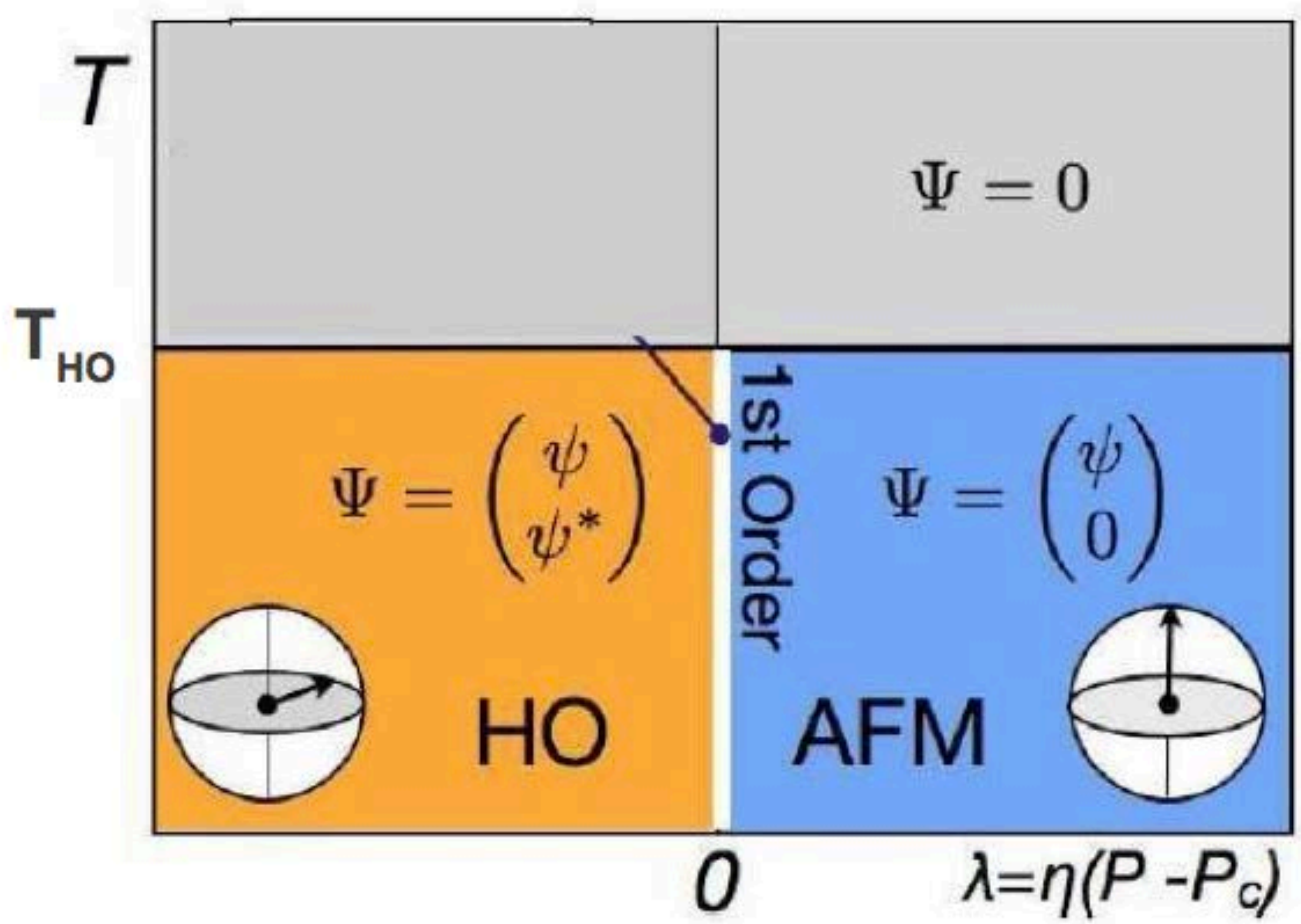

Spin Flop-like Transition between HO and AFM

Hastatic 1.0
(Needs Serious Revision)

$$|\Gamma_7^+, \sigma\rangle \equiv \Psi^\dagger_\sigma|0\rangle$$

E_b

$$|\pm\rangle \equiv \chi^\dagger_\pm|0\rangle$$

$$5f^2 \rightleftharpoons 5f^1 + e^- \qquad \psi^\dagger_{\Gamma\sigma}(j) = \sum_{\mathbf{k}} \left[\Phi^\dagger_\Gamma(\mathbf{k})\right]_{\sigma\tau} c^\dagger_{\mathbf{k}\tau} \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{R}_j}$$

$$H_{VF}(j) = V_6 \psi^\dagger_{\Gamma_6\pm}(j)|\Gamma_7^+ \pm\rangle\langle\Gamma_5 \pm| + V_7 \psi^\dagger_{\Gamma_7\mp}(j)|\Gamma_7^+ \mp\rangle\langle\Gamma_5 \pm| + \mathrm{H.c.}$$

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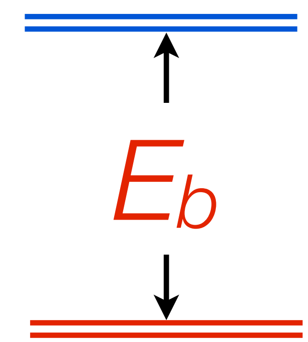
$$|\Gamma_7^+,\sigma\rangle \equiv \Psi_\sigma^\dagger|0\rangle$$



$$|\pm\rangle \equiv \chi_\pm^\dagger|0\rangle$$

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$$H_{VF}(j) = V_6\psi_{\Gamma_6\pm}^\dagger(j)\Psi_{j\pm}^\dagger\chi_{j\pm} + V_7\psi_{\Gamma_7\mp}^\dagger(j)\Psi_{j\mp}^\dagger\chi_{j\pm} + \mathrm{H.c.}$$

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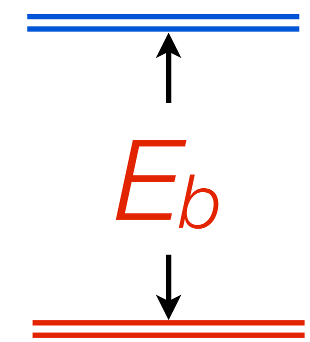

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$$\langle\Psi_j^\dagger\rangle = |\Psi| \begin{pmatrix} \mathrm{e}^{i(\mathbf{Q}\cdot\mathbf{R}_j+\phi)/2} \\ \mathrm{e}^{-i(\mathbf{Q}\cdot\mathbf{R}_j+\phi)/2} \end{pmatrix}, \qquad (\phi = \pi/4).$$

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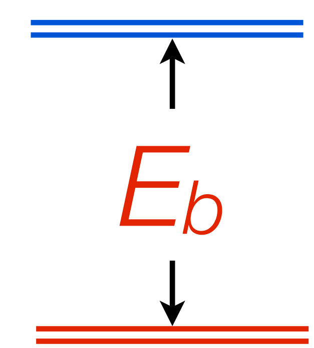

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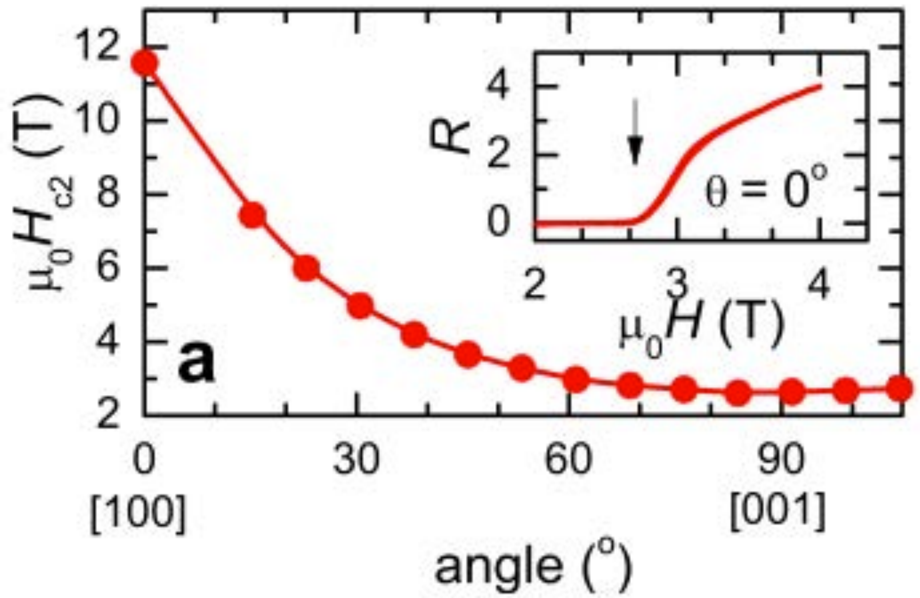
$$H_{VF} = \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}} \mathcal{V}_6(\mathbf{k})\chi_{\mathbf{k}} + c^\dagger_{\mathbf{k}}\mathcal{V}_7(\mathbf{k})\chi_{\mathbf{k}+\mathbf{Q}} + \mathrm{h.c.}$$

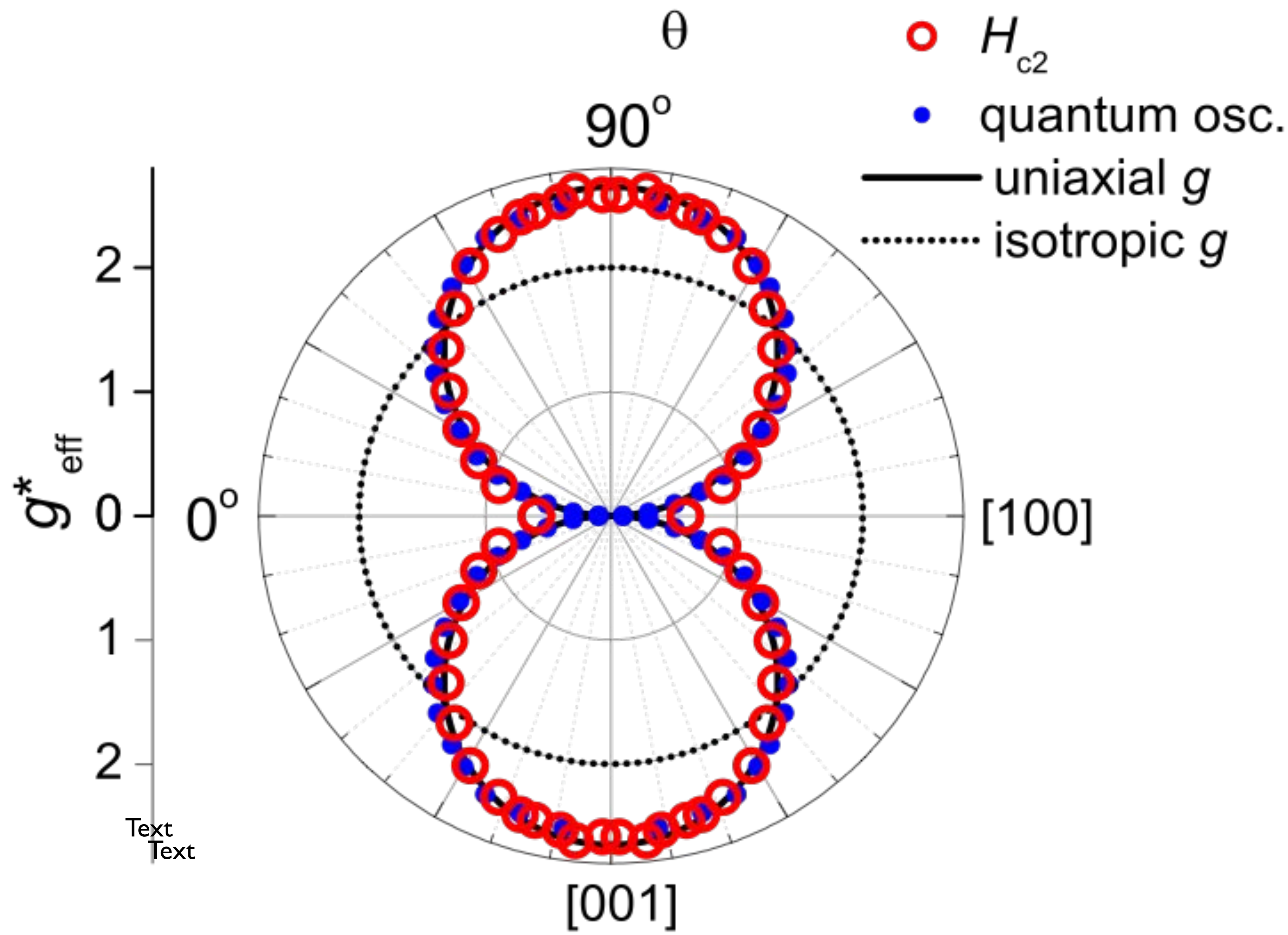
Superconductivity: Giant Ising Anisotropy

Altarawneh et al PRL 108, 066407 (2012); Brison et al Physica C 250 128 (1995).



Ising degeneracy to within

$$2\Delta \sim 5K$$



Ising QP's pair condense.

$$g(\theta) \propto \cos(\theta)$$

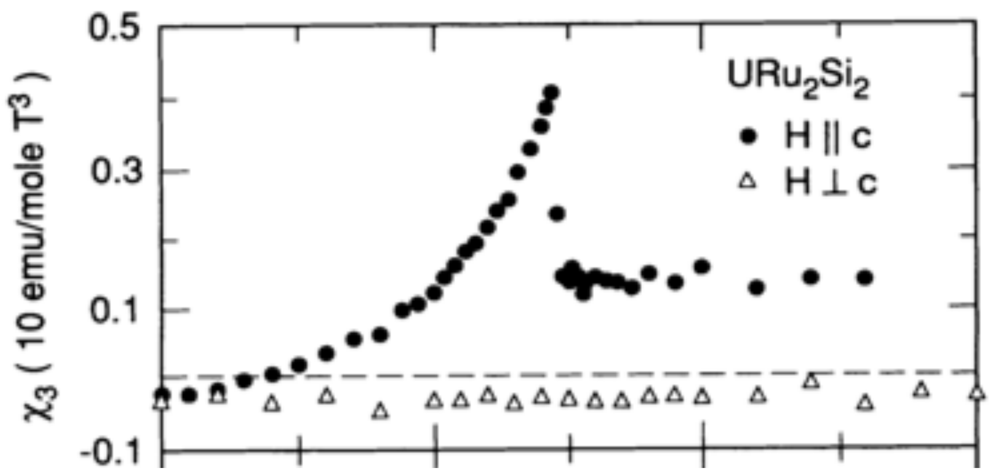
Does this behavior survive to higher temperatures in the Hidden Order phase ??

The Nonlinear Susceptibility in a Tetragonal Environment

Field-Dependent Part of Free Energy

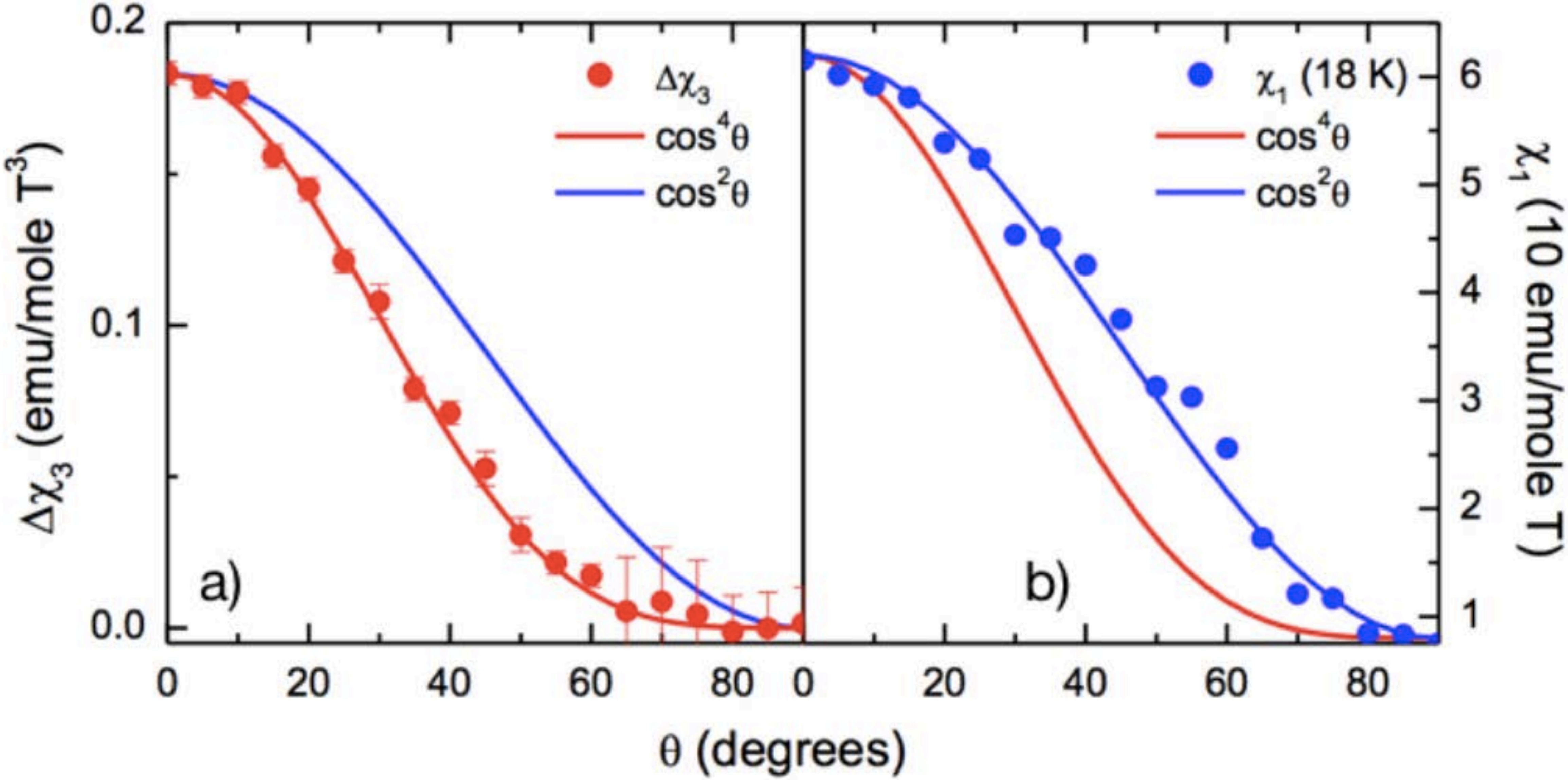
$$F = -\chi_1(\theta)\frac{H^2}{2} - \chi_3(\theta,\phi)\frac{H^4}{4}$$

Ramirez et al '92

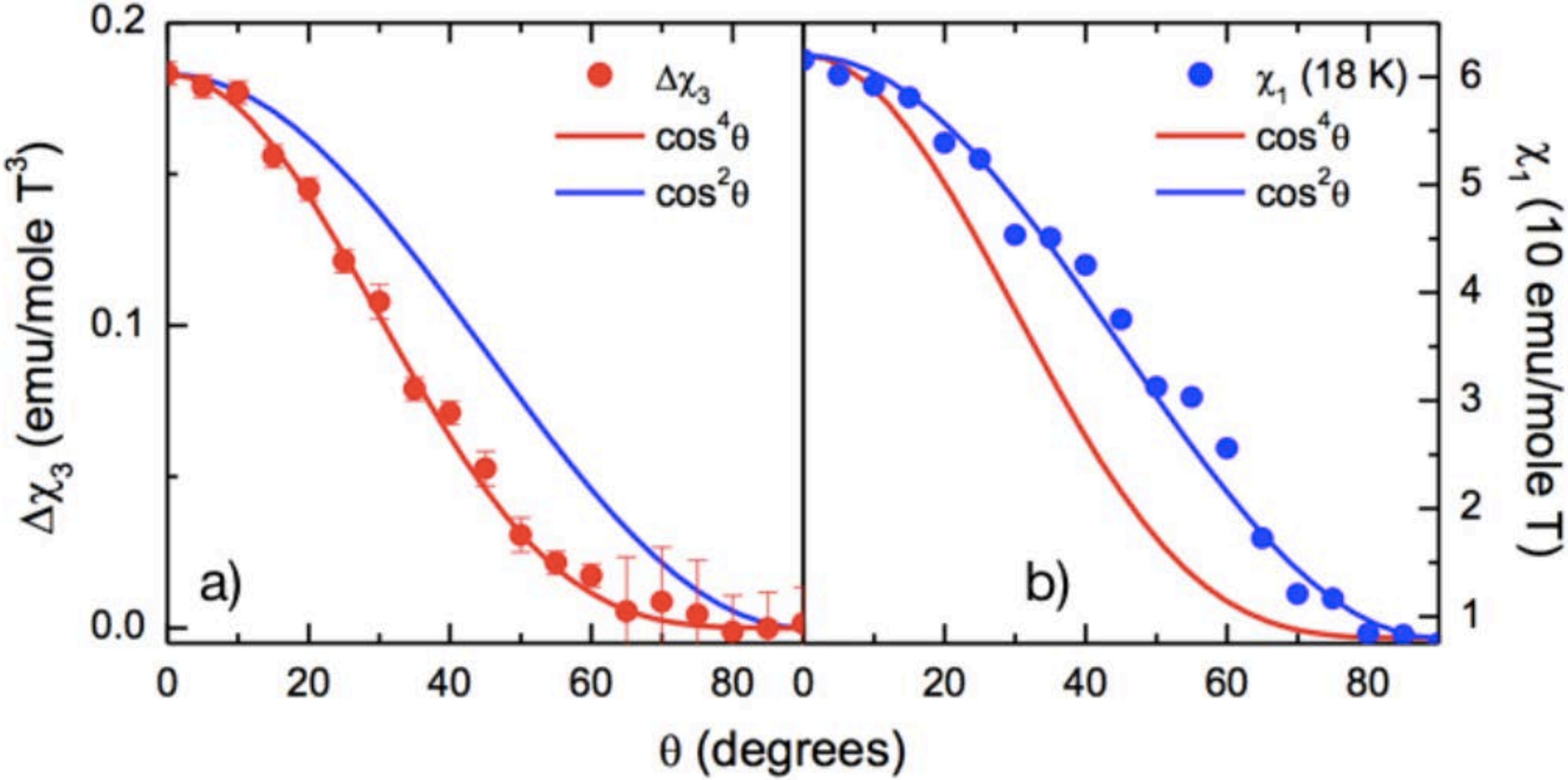


$\Delta\chi_3(\theta)$ is a direct thermodynamic probe of $g(\theta)$

at the Hidden Order transition !!

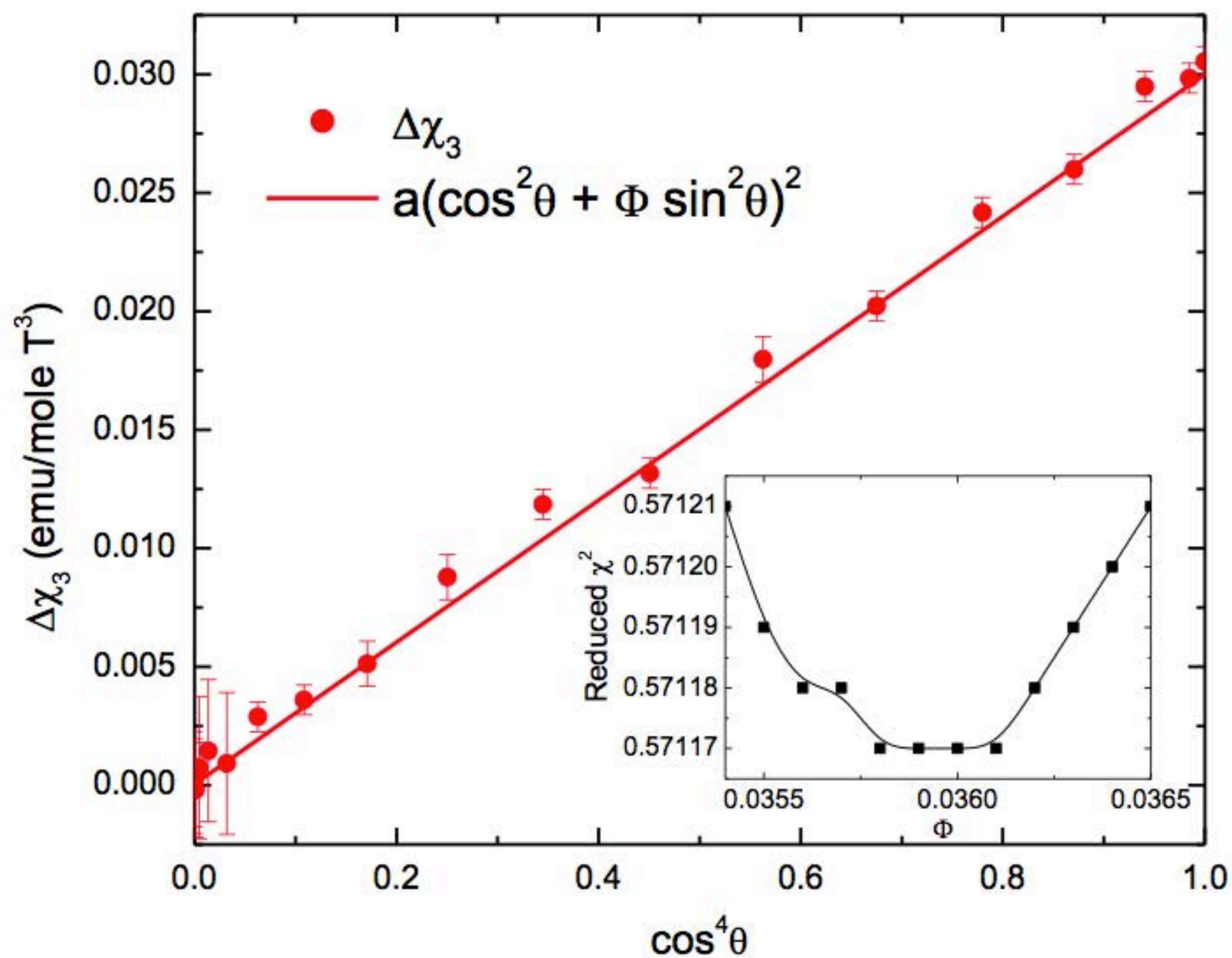


$$\chi_1(\theta, T) = \chi_1^{(0)} + \chi_1^{Ising}(T)\cos^2\theta$$



$$\Delta\chi_3(\theta) = \Delta\chi_3^{Ising}(T)\cos^4\theta$$

Robustness of Ising Anisotropy



J. Trinh et al (2016)

$$\Delta\chi_3(\theta) \propto (\cos^2\theta + \Phi\sin^2\theta)^2$$

Ising Quasiparticles at the Hidden Order Transition !!

$$F[\vec{H}] = F[H_z] \rightarrow H_{Zeeman} \propto -J_z B_z$$

Single-Ion Physics

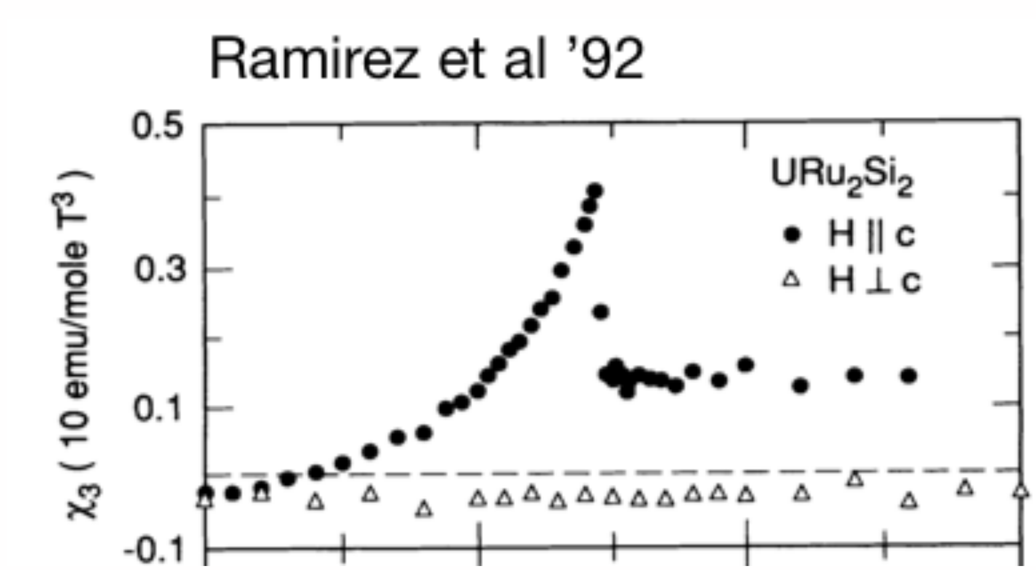
U moments are Ising $\langle + | J_{\pm} | - \rangle = 0$

Integer S ($5f^2$)

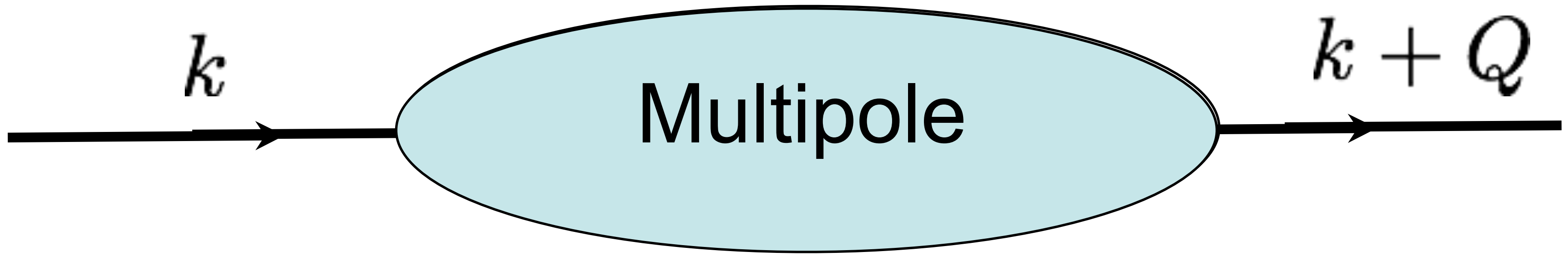
Confirmed by DMFT and high-resolution RIXS

(Haule, Kotliar 09) (Wray et al. 15)

Also underlying itinerant ordering process (with Ising anisotropy!)



How to reconcile single-ion and itinerant perspectives ??



P. Coleman, R. Flint and PC, Nature 493, 611 (2013)
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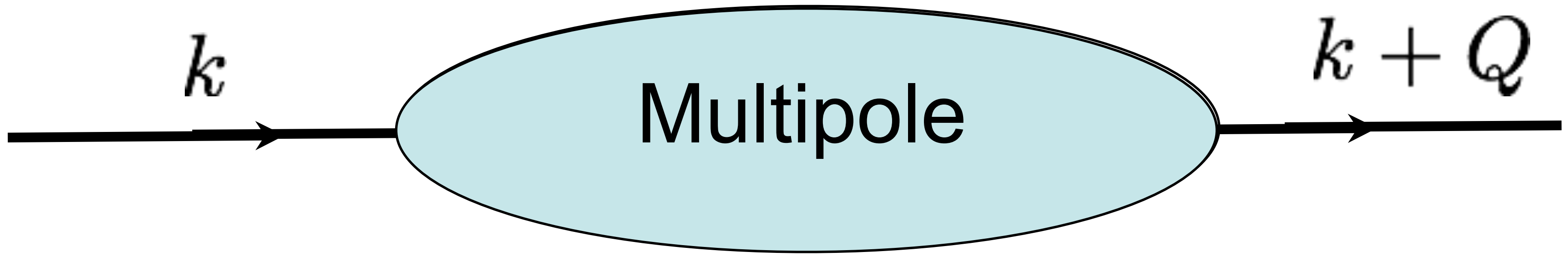

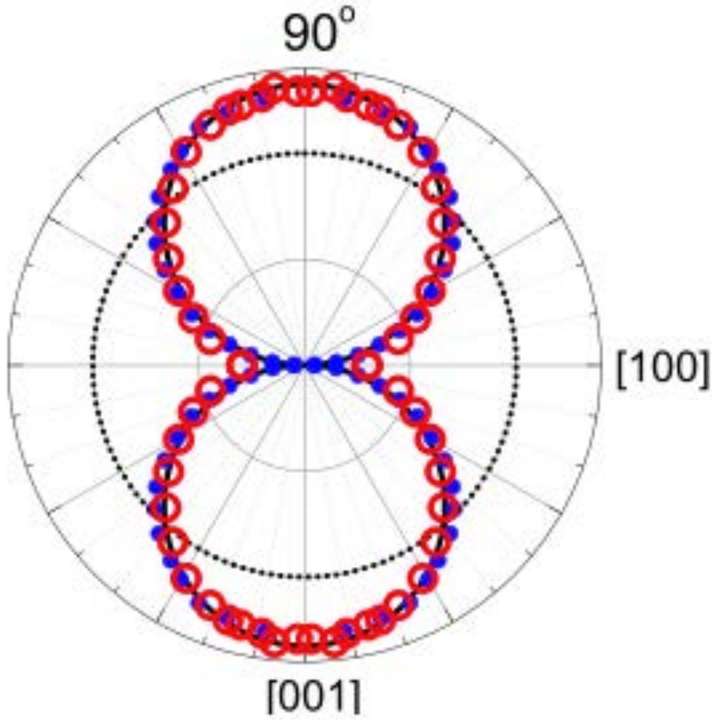

Observation of Anisotropic Conduction Fluid

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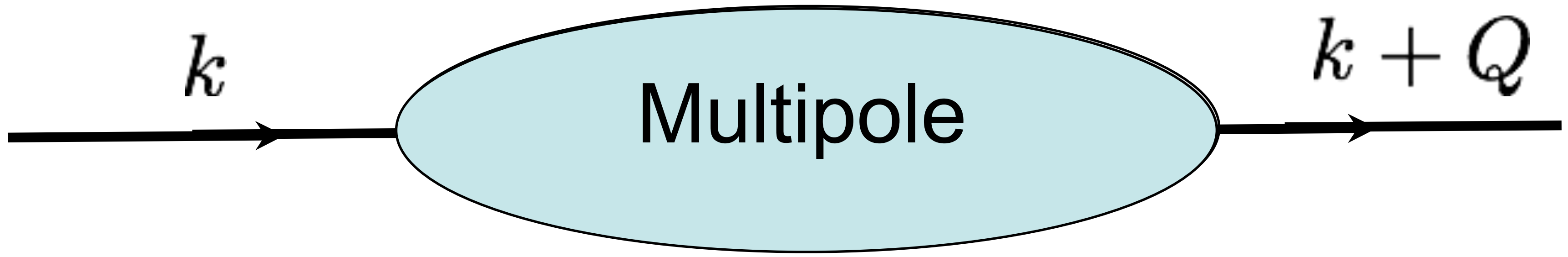

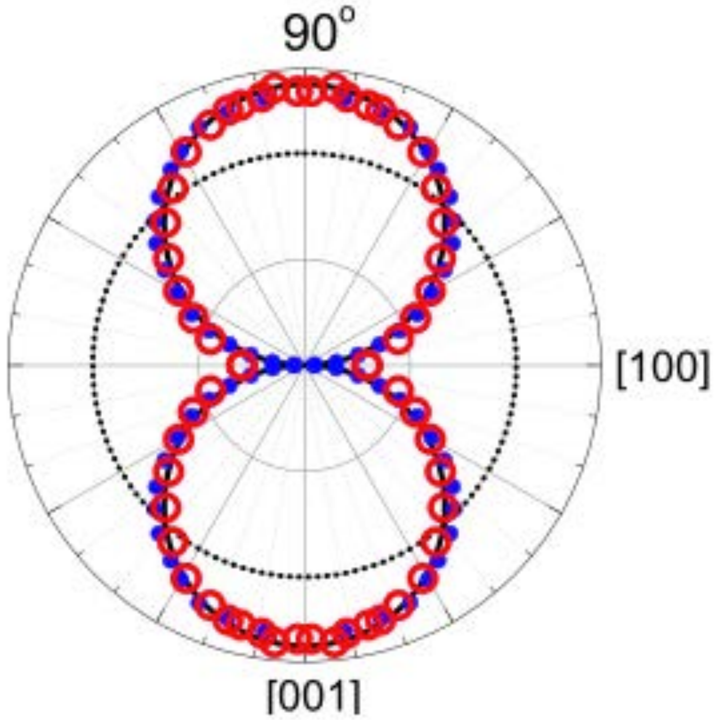

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Coherent Admixture of Spin 1/2 Conduction Electrons with Integer Spin f-states.

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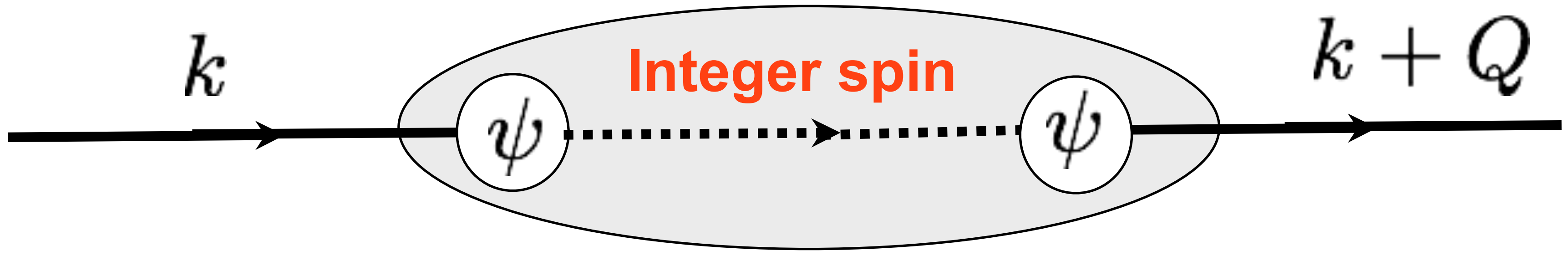

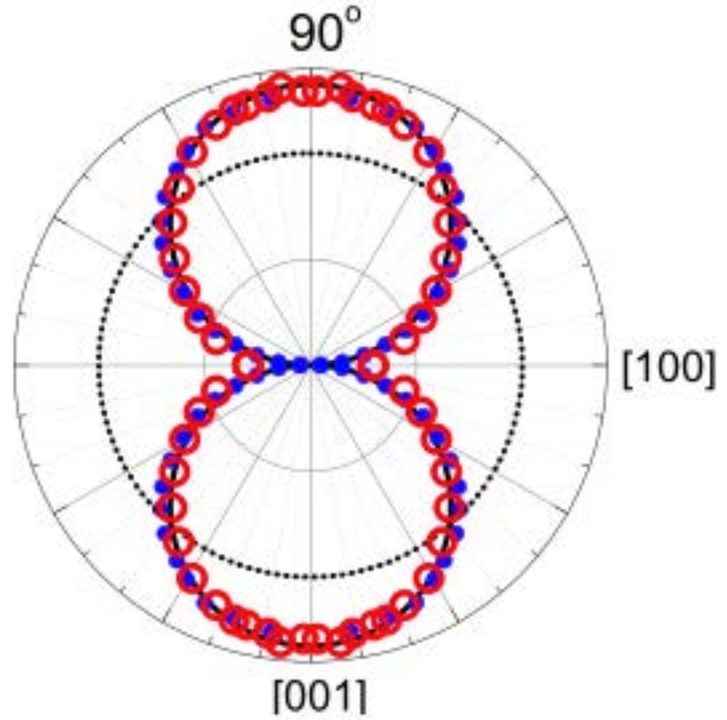

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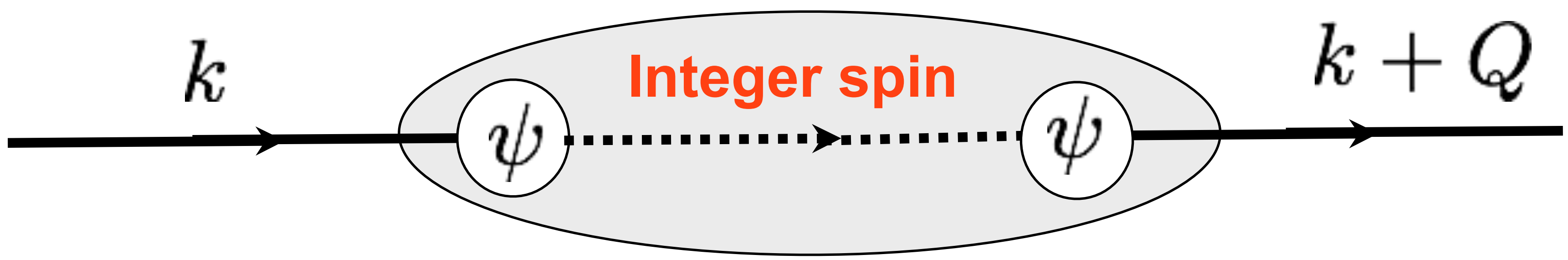
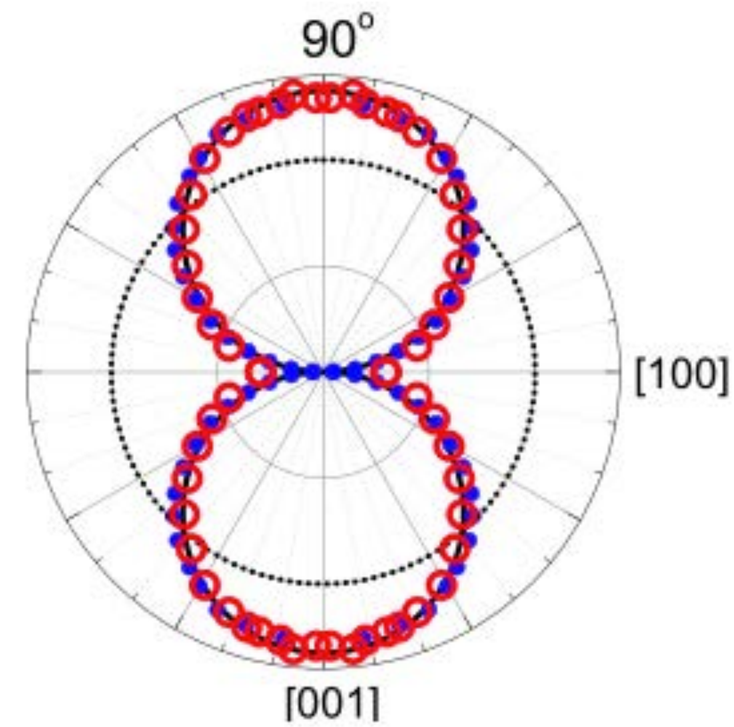
Hastatic Order in URu_2Si_2

Hasta: Spear (Latin)





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Proposal: Order Parameter is half-integer.

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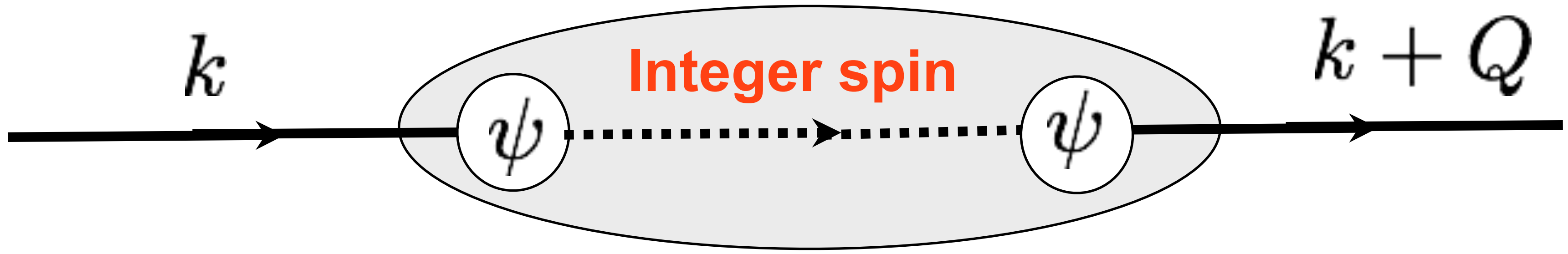

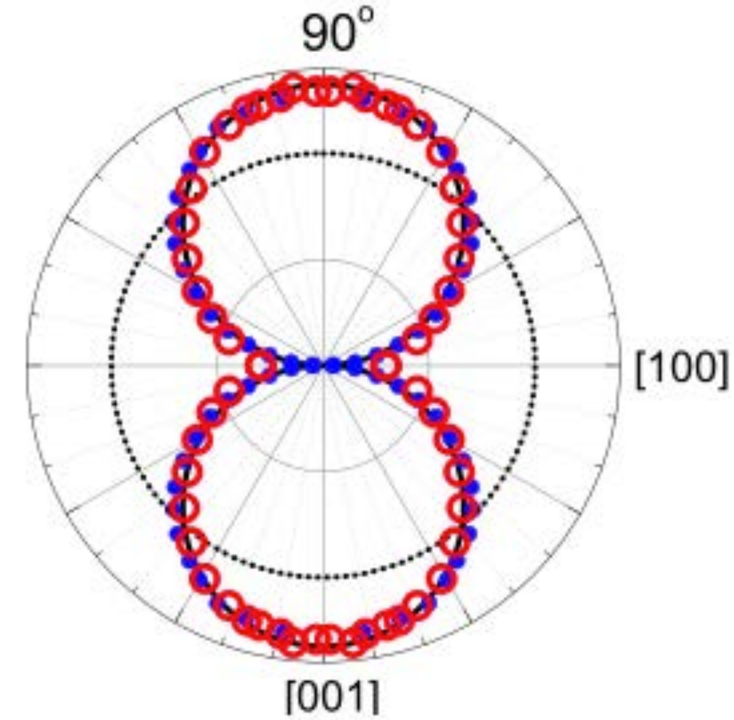

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$$\psi = \sqrt{\text{Multipole}} = \text{Spinorial OP}$$

(Fractionalization of the OP)

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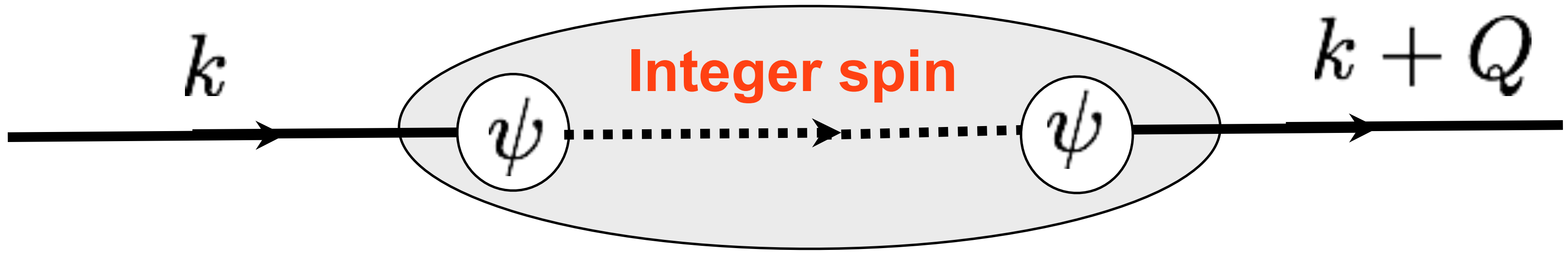

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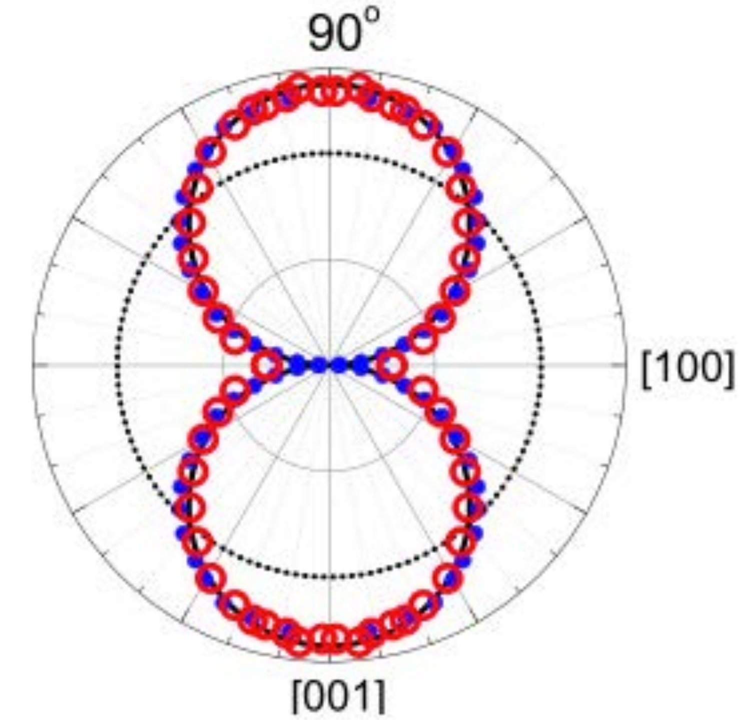
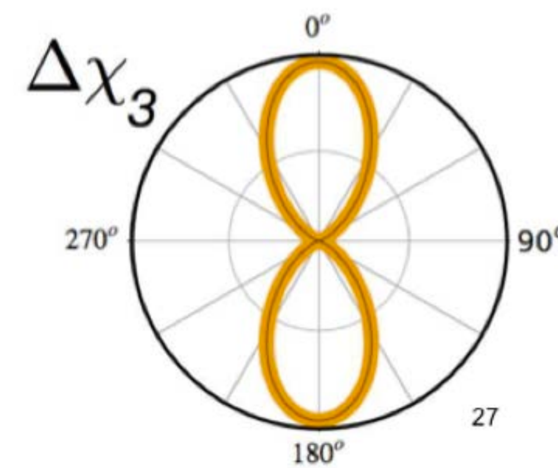


$$\Delta\chi_3 \propto \cos^4\theta$$



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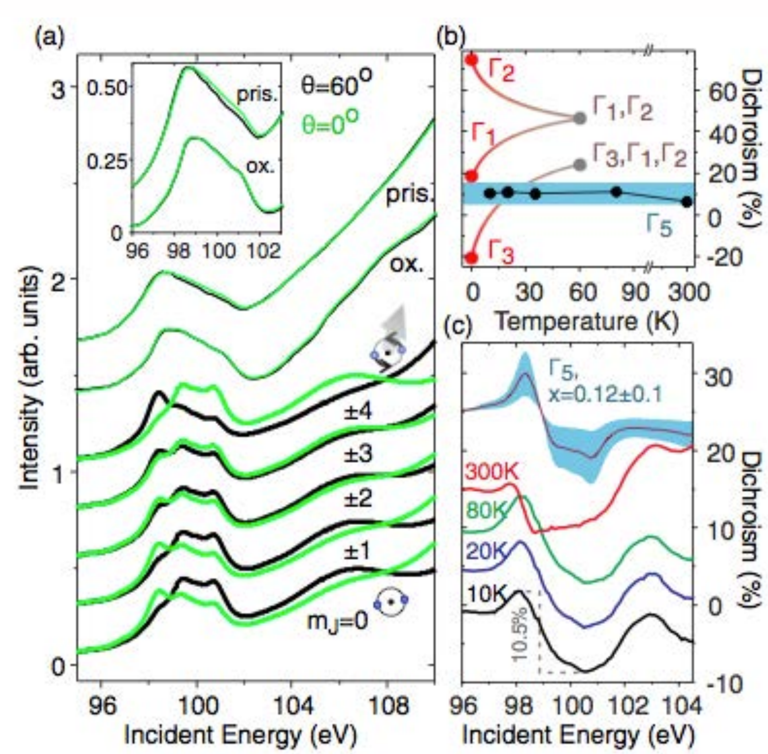
PRL **114,** 236401 (2015) PHYSICAL REVIEW LETTERS week ending 12 JUNE 2015

Spectroscopic Determination of the Atomic *f*-Electron Symmetry Underlying Hidden Order in URu_2Si_2

L. Andrew Wray,[1,2,3,*] Jonathan Denlinger,[3] Shih-Wen Huang,[3] Haowei He,[1] Nicholas P. Butch,[4,5] M. Brian Maple,[6] Zahid Hussain,[3] and Yi-De Chuang[3]

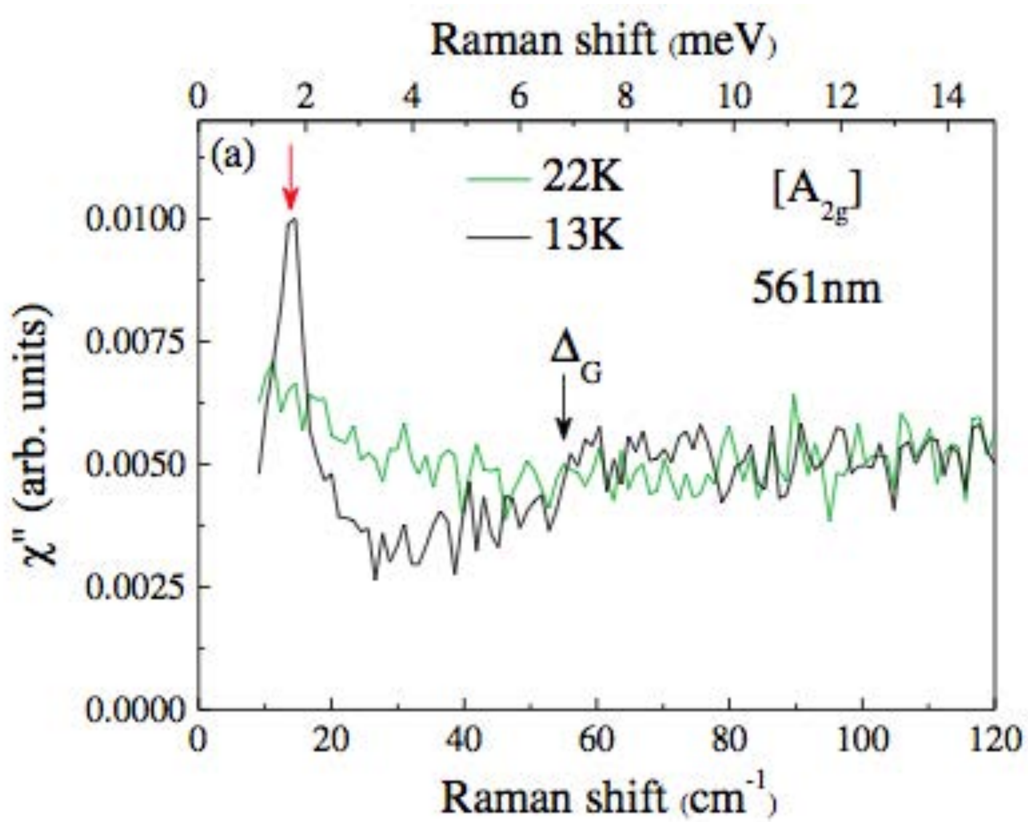
The low-temperature hidden-order state of URu_2Si_2 has long been a subject of intense speculation, and is thought to represent an as-yet-undetermined many-body quantum state not realized by other known materials. Here, x-ray absorption spectroscopy and high-resolution resonant inelastic x-ray scattering are used to observe electronic excitation spectra of URu_2Si_2, as a means to identify the degrees of freedom available to constitute the hidden-order wave function. Excitations are shown to have symmetries that derive from a correlated $5f^2$ atomic multiplet basis that is modified by itinerancy. The features, amplitude, and temperature dependence of linear dichroism are in agreement with ground states that closely resemble the doublet Γ_5 crystal field state of uranium.



Raman

Buhot et al., PRL (2014)
Kung et al., Science (2015)

Most significant T-dependence at the HO transition is in the A_{2g} channel

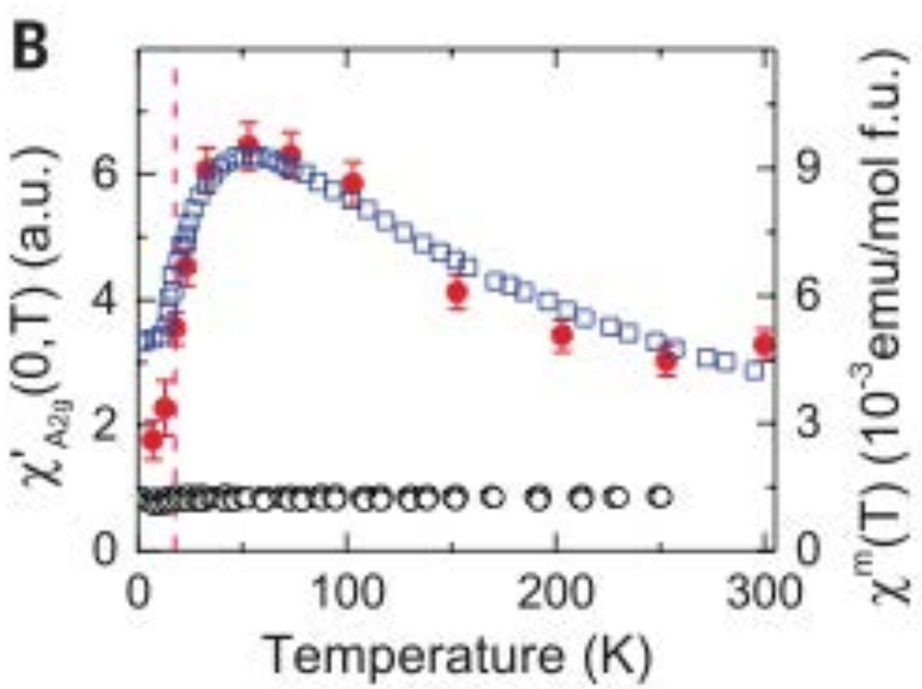


Constraints on theory?

Raman

Buhot et al., PRL (2014)
Kung et al., Science (2015)

$$\chi'_{A_{2G}}(0,T) = \frac{2}{\pi}\int_0^{25meV} \frac{\chi''_{A_{2g}}(\omega,T)}{\omega}d\omega$$



Scales nicely with c-axis magnetic susceptibility !!

J_z transforms under A_{2g} !!

Beautiful spectroscopy of $\chi''(q=0,\omega)$ consistent with previous neutron results at finite wavevector (analogous to SANS)

Raman

Buhot et al., PRL (2014)
Kung et al., Science (2015)

Crystal-field Hamiltonian expanded to linear order in the electromagnetic stress tensor (in tetragonal environment)

$$H = \hat{H}_0 + \hat{O}_{A2g}(A_x A'_y - A_y A'_x)$$

where

$$\hat{O}_{A_{2g}} = \left[a(\omega)(J_z^2 - J_y^2)J_x J_y + b(\omega) J_z\right]$$

$a(\omega)$: oscillatory field components of stress-energy tensor

$b(\omega)$: Poynting vector

More work to be done to determine which term is larger (particularly in the presence of large spin-orbit coupling)

Nernst Effect

Colossal thermomagnetic response in the exotic superconductor URu_2Si_2

nature physics
LETTERS
PUBLISHED ONLINE: 1 DECEMBER 2014 | DOI: 10.1038/NPHYS3170

T. Yamashita[1], Y. Shimoyama[1], Y. Haga[2], T. D. Matsuda[3], E. Yamamoto[2], Y. Onuki[2,4], H. Sumiyoshi[1], S. Fujimoto[5], A. Levchenko[6], T. Shibauchi[1,7] and Y. Matsuda[1*]

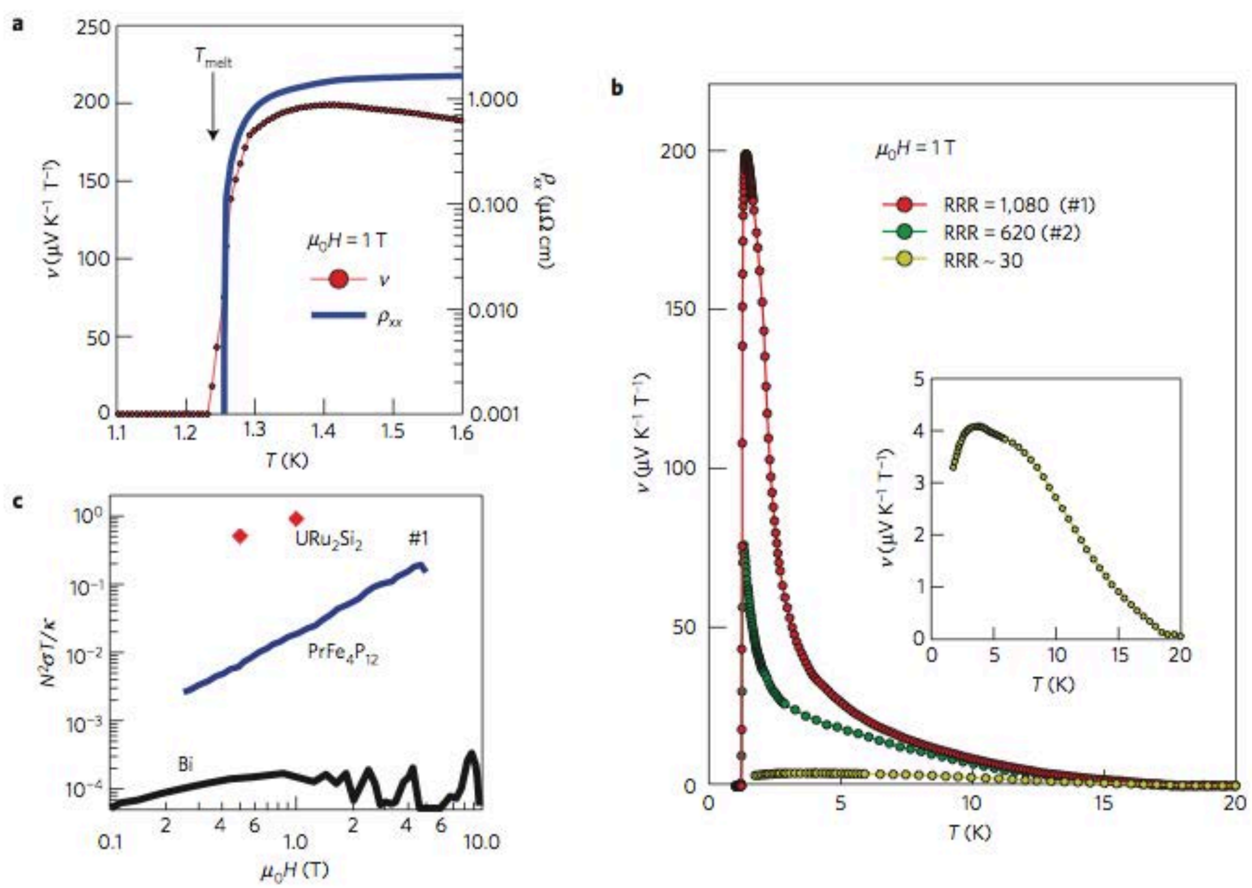


Figure 2 | Anomalously large Nernst signal and thermomagnetic figure of merit. a, The T-dependence of ν (left scale) and ρ_{xx} (right scale) measured at $\mu_0 H = 1$ T near the superconducting transition. Both ν and ρ_{xx} vanish at the vortex lattice melting transition temperature T_{melt}. **b**, Comparison of the $\nu(T)$ data at $\mu_0 H = 1$ T between samples with different scattering rates (RRR=1,080, 620 and 30). The data for RRR~30 (expanded in the inset) is taken from ref. 23. **c**, Thermomagnetic figure of merit $ZT_\epsilon = N^2\sigma T/\kappa$ at 1.5 K as a function of field in crystal #1 of URu_2Si_2 (red diamonds), compared with previous data in the semimetals $PrFe_4P_{12}$ (blue line) and Bi (black line) at 1.2 K taken from ref. 24.

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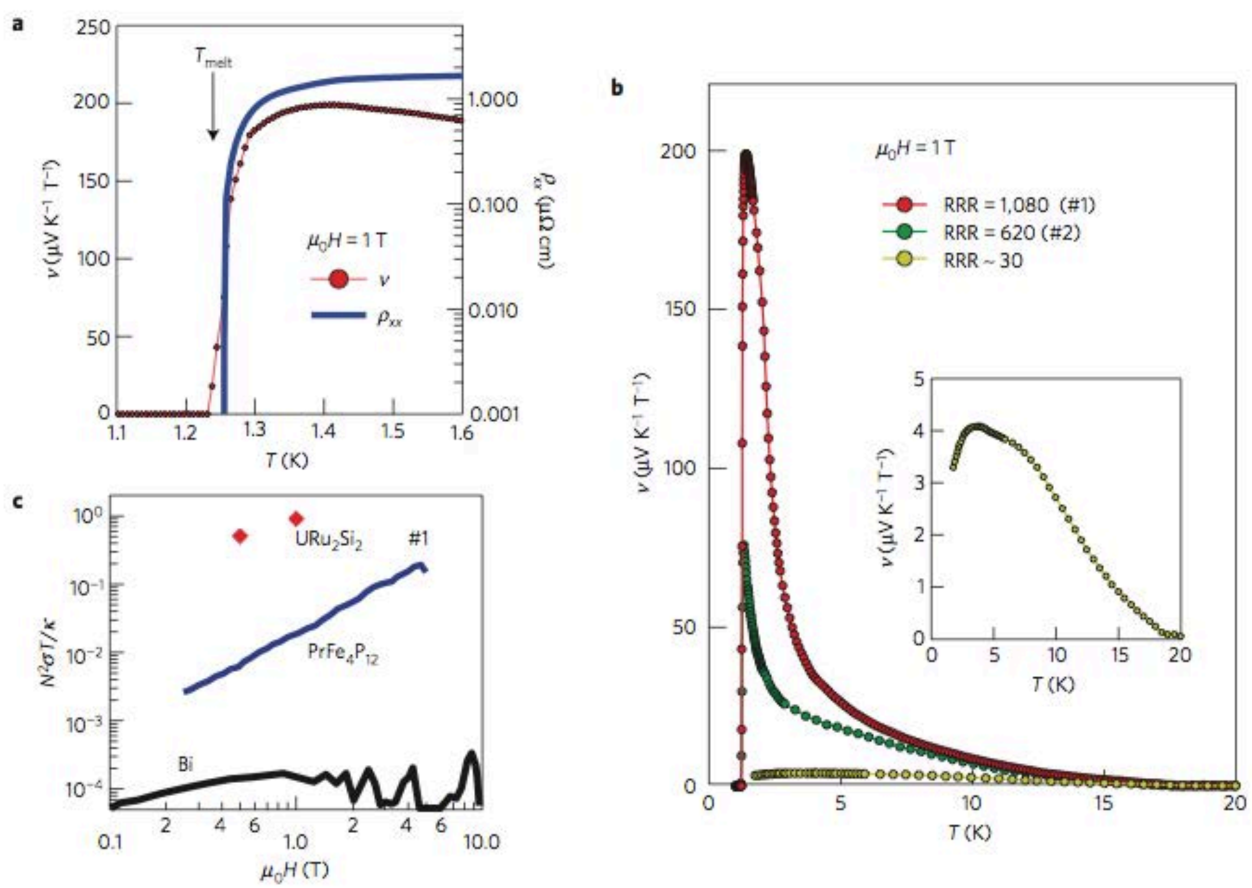

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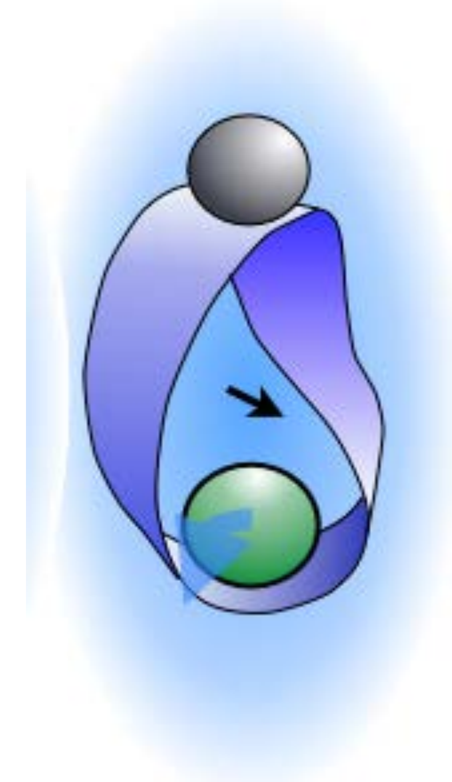
Is this giant Nernst effect a signature of exotic superconductivity or is it telling us something crucial about the Hidden Order phase?

Conclusions (for now)



- Recent Raman, elastoresistivity and RIXS measurements emphasize the importance of the Ising response, the multicomponent nature of Hidden Order parameter and the Gamma_5 U ground-state.....this all combined with the previous observation of Ising quasiparticles continues to suggest a spinor order parameter. Hidden order parameter has Ising anisotropy.

- Previous microscopics (Hastatic 1.0) must be revised to improve band structure (details of conduction electrons) and modelling of AFM phase (f-f hopping)

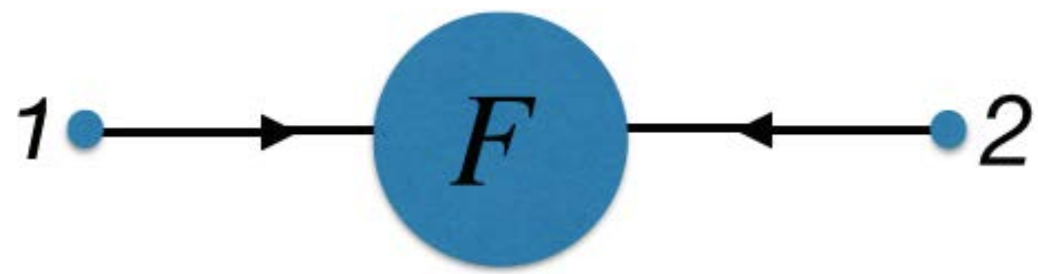
- Experiments we'd love to see:

  Knight shift as a function of angle
  dHvA on all the heavy fermi-surface pockets
  Spin zeroes in the AFM phase (finite pressure)
  Low temperature probes of the 5f valence

P. Coleman, R. Flint and PC, Nature 493, 611 (2013)
Phil. Mag. 94, 32-33 (2014)
PRB 91, 205103 (2015)

Broader Implications of Hastatic Order : A New Kind of Landau Order Parameter ?

Conventionally Landau theory in electronic systems based on formation and condensation of two-body bound states



e.g. s-wave superconductivity

$$\psi_\uparrow(1)\psi_\downarrow(2) = -F(1-2)$$

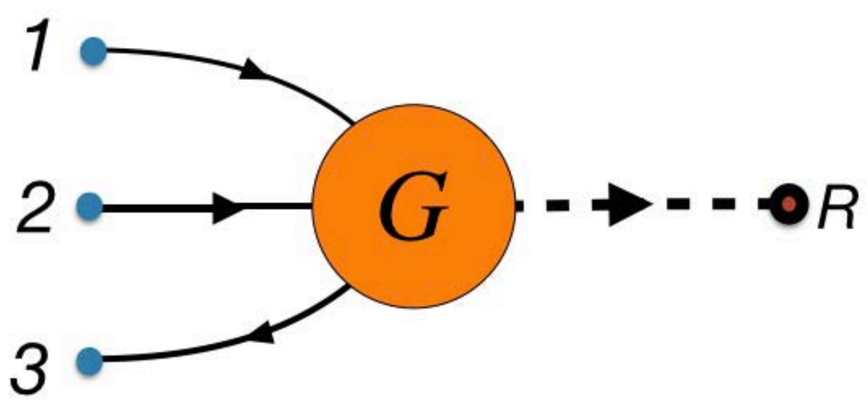
When two-body bound-state wavefunction carries quantum number (spin, charge..), symmetry broken

All order parameters are bosons with integer spin !!

A new column in the classification of order parameters ??

Hastatic order generalizes Landau's concept to three-body bound-states

(Natural in heavy fermions, for the conventional Kondo effect is the formation of a three-body bound-state between a spin flip and conduction electron. However, in the conventional Kondo effect, the three body wavefunction carries no quantum number and is not an order parameter.)



$$\psi^\dagger(1)\psi^\dagger(2)\psi(3) = G(1,2,3;R)\langle\Psi^\dagger(R)\rangle\chi(R)$$

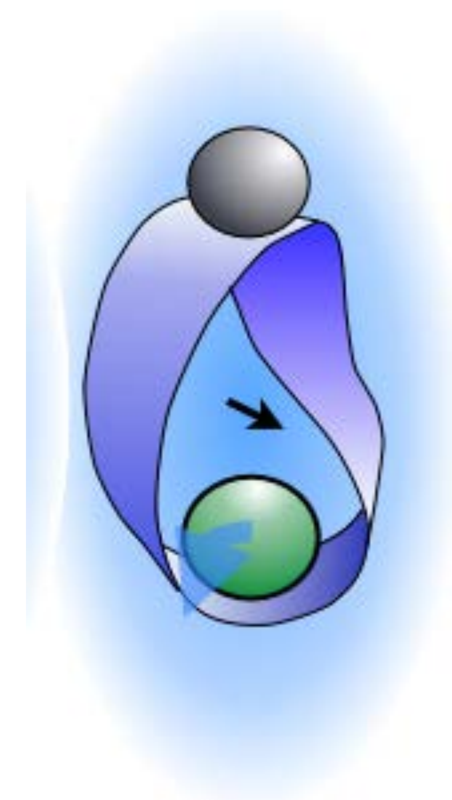
Half integer OP

Bound state of three fermions
where the resulting fermionic bound-state
carries integer spin while its 3-body
wavefunction has 1/2 integer spin

(non-relativistic)

Hastatic order transforms under a double-group representation of the underlying symmetry group......order parameter fractionalization !!

Open Questions



- For Hastatic Order of URS

  Development of Hastatic 2.0....new predictions ??

- Emergence of Superconductivity from the HO State?

- Other examples of Hastatic Order?
  (non-Kramers doublets in Pr and U materials)

- Direct Experimental Probe of Double-Time Reversal?

- Broader Implications: a new kind of broken symmetry where the order parameter transforms under a DOUBLE GROUP (S = 1/2) representation
  (symmetry analysis and Landau theory ??)

Thank you !!!