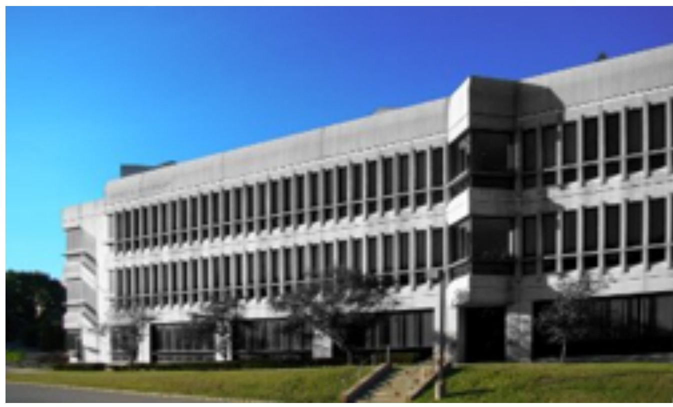
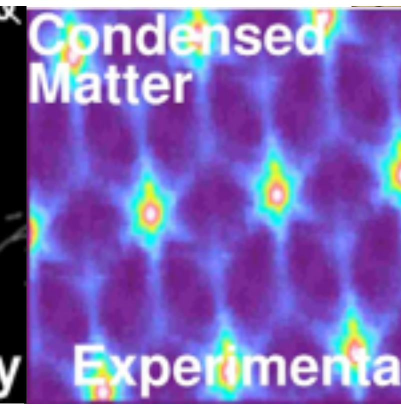
The Physics of Heavy Fermion Superconductivity

Lecture IV. Composite Pairing Hypothesis. Hastatic Order.

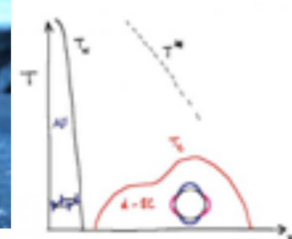


Piers Coleman   Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30-July 25, 2014

14-17 July 2014

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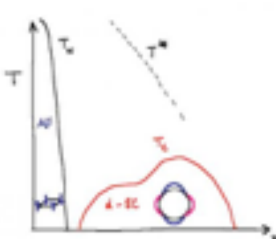


14-17 July 2014

A solvable model of composite pairing.

PC, Tsvelik, Kee, Andrei PRB 60, 3605 (1999).

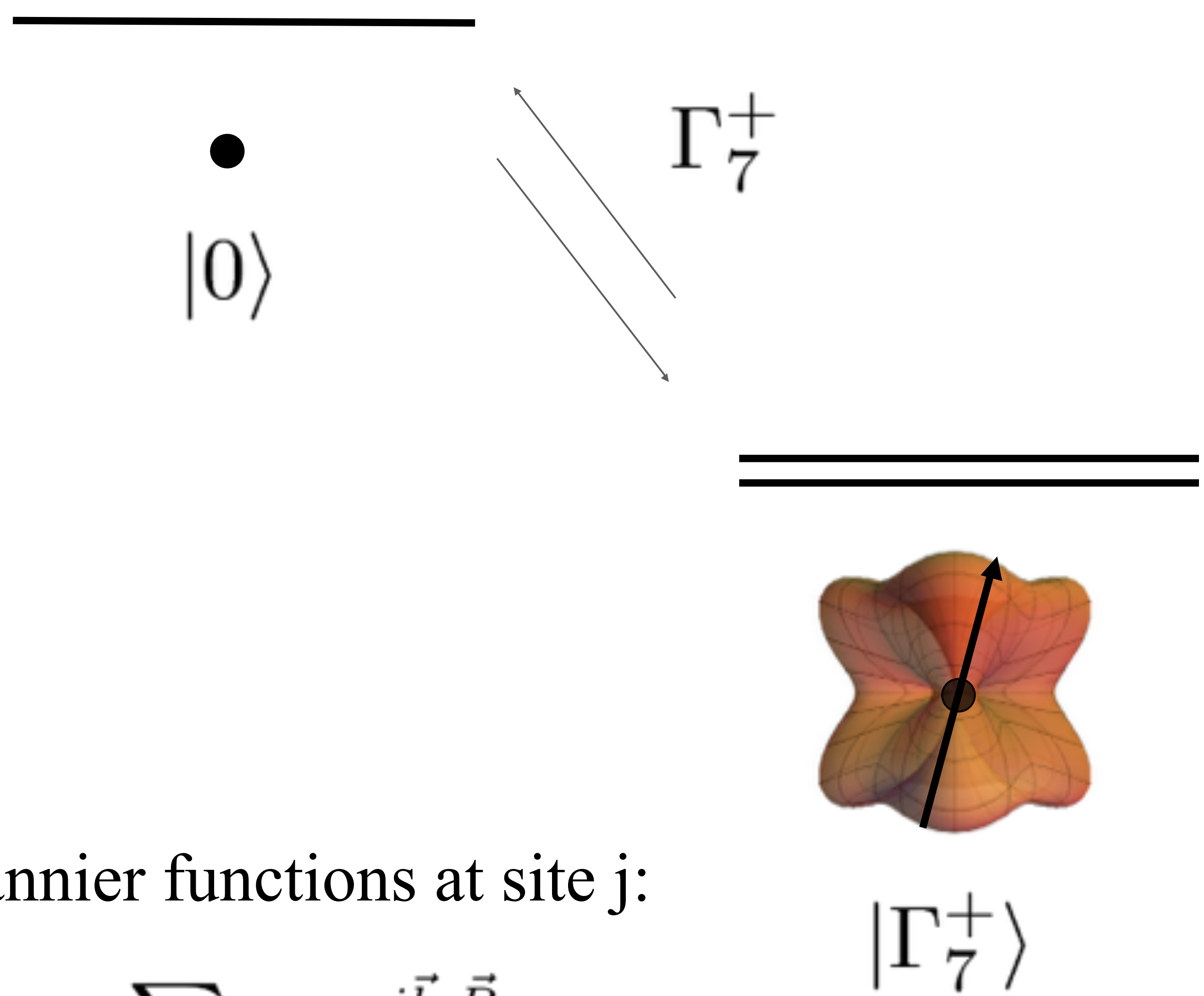
Flint, Dzero, PC, Nature Physics 4, 643 (2008).

Flint, PC, PRL, 105, 246404 (2010).

Flint, Nevidomskyy, PC, PRB 84, 064514 (2011).

The Two Channel Kondo Model

$$H = \sum_k \epsilon_k c_k^\dagger c_k + J_1 \sum_j \psi^\dagger_{1j\alpha} \vec{\sigma}_{\alpha\beta} \psi_{1k\beta} \cdot \vec{S}_j$$



Wannier functions at site j:

$$\psi^\dagger_{\Gamma j} = \sum_k \Phi_{\Gamma k} e^{i\vec{k}\cdot\vec{R}_j} c_k$$

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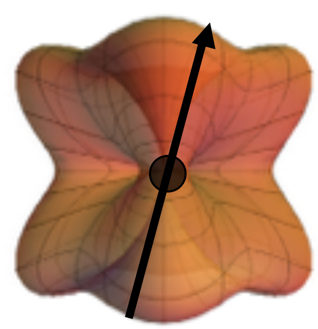
$|0\rangle$

Γ_7^+



$|\Gamma_7^+\rangle$

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- Both $\left\{ \begin{array}{l} f^0 + e^- \rightleftharpoons f^1 \\ f^1 \rightleftharpoons f^2 + h^+ \end{array} \right.$

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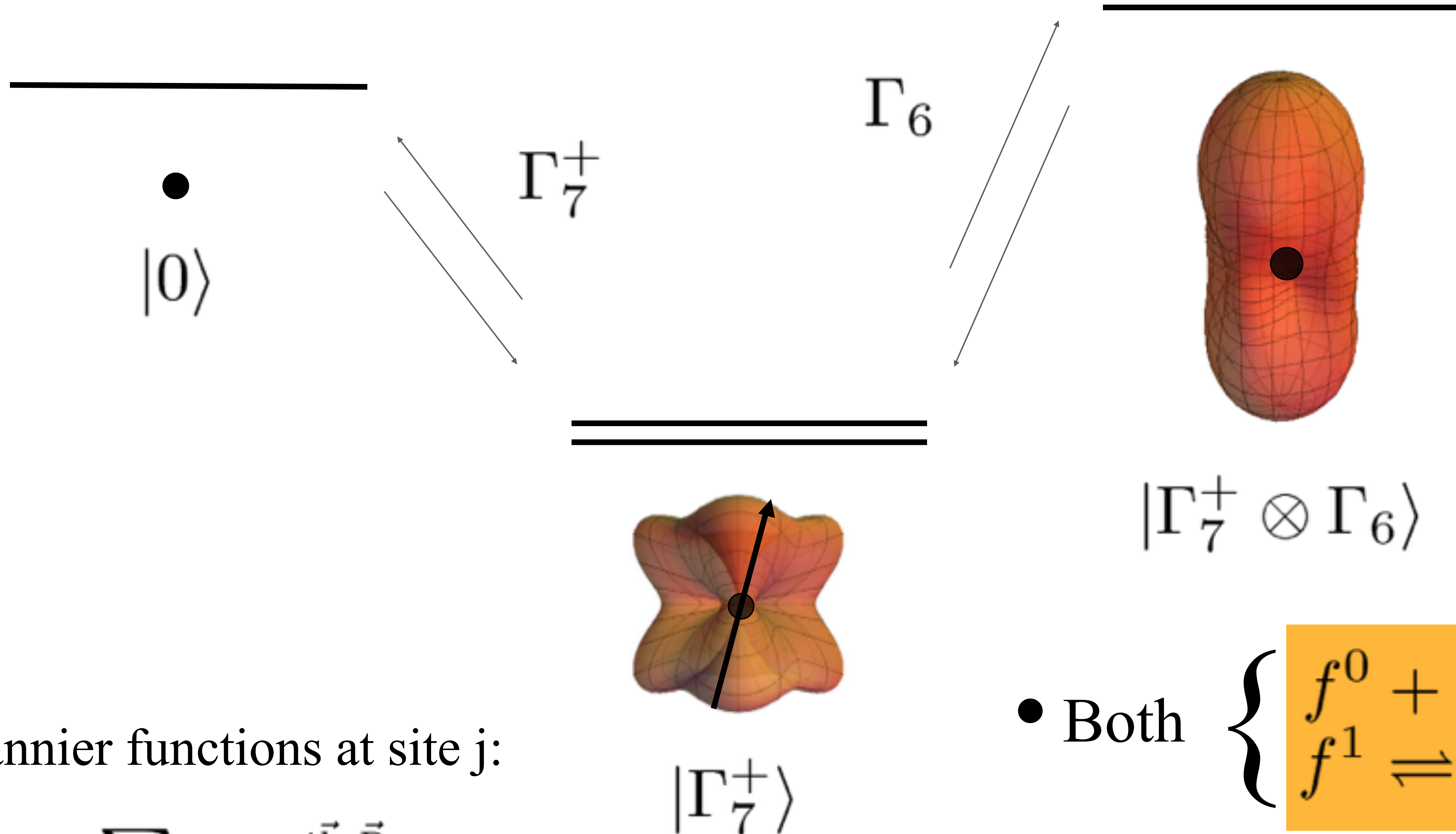

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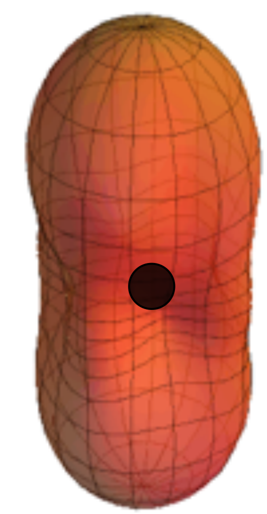
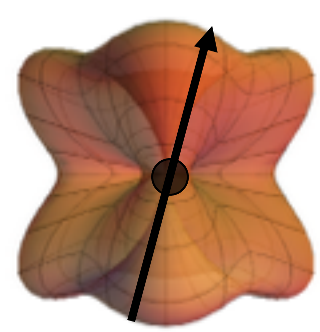
$|0\rangle$

Γ_7^+

Γ_6



$|\Gamma_7^+ \otimes \Gamma_6\rangle$



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Single FS, two channels.

$$\psi_\Gamma(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \gamma_{\Gamma\mathbf{k}} \; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)
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$$Z = \int_{\text{history}} \mathcal{D}[\psi] e^{-S[\psi_\sigma]}$$

Feynman

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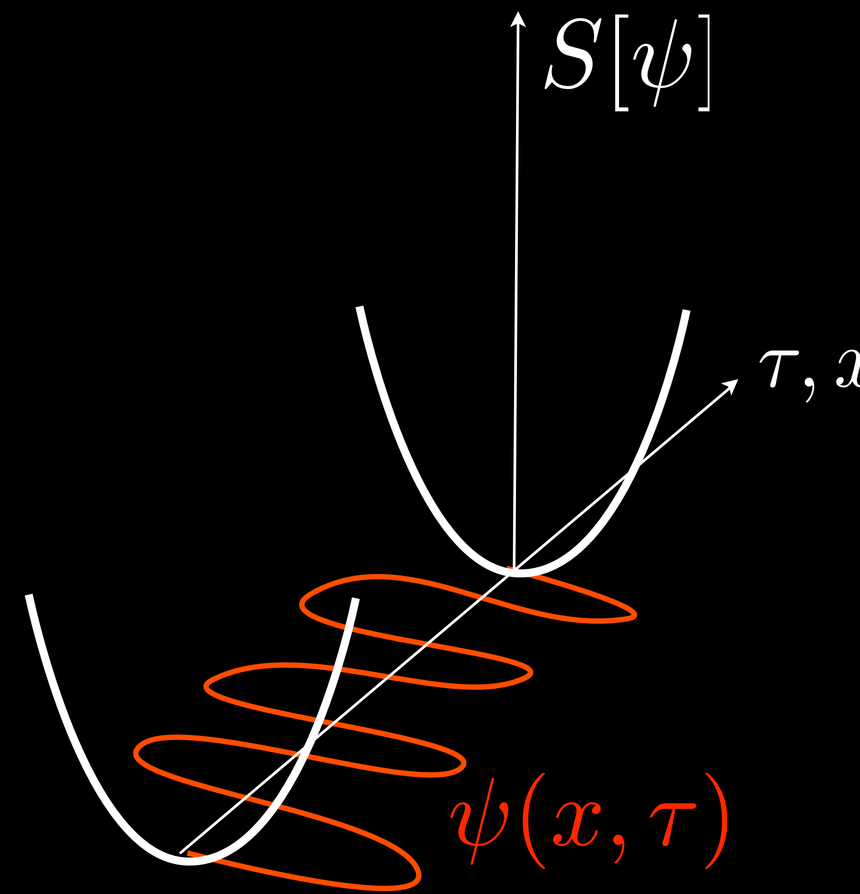

Wild quantum fluctuations!

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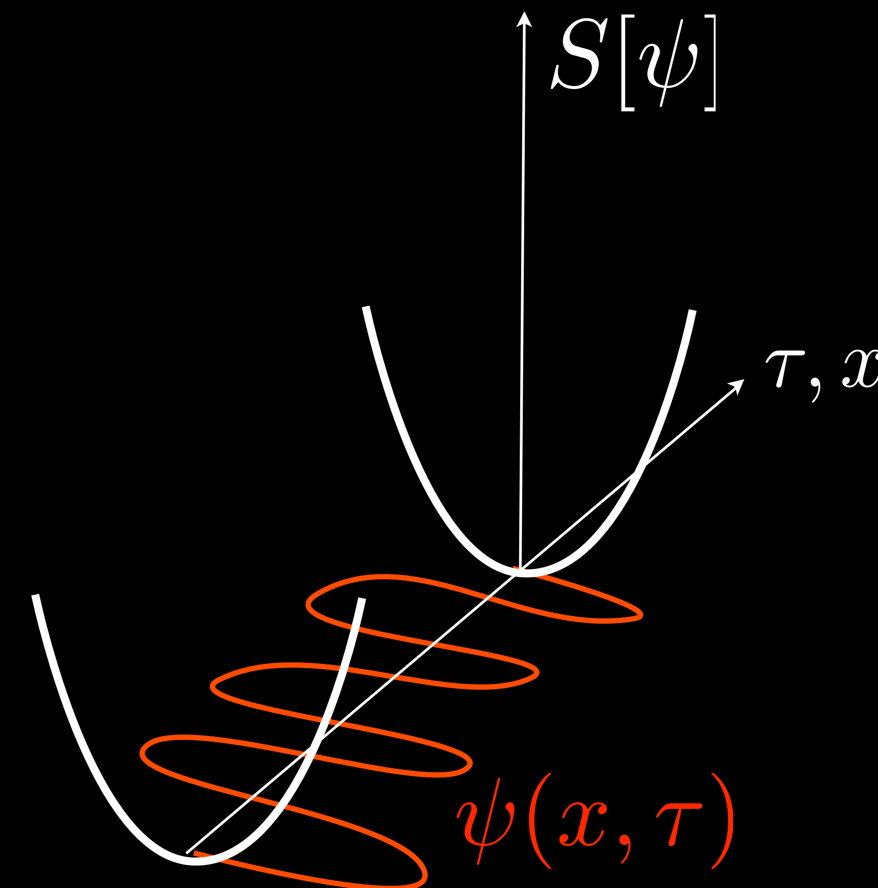

So how can we solve this model?

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Method: large N

Flint, Dzero Coleman Nature Physics '08
PRB 79, 014424(2009)

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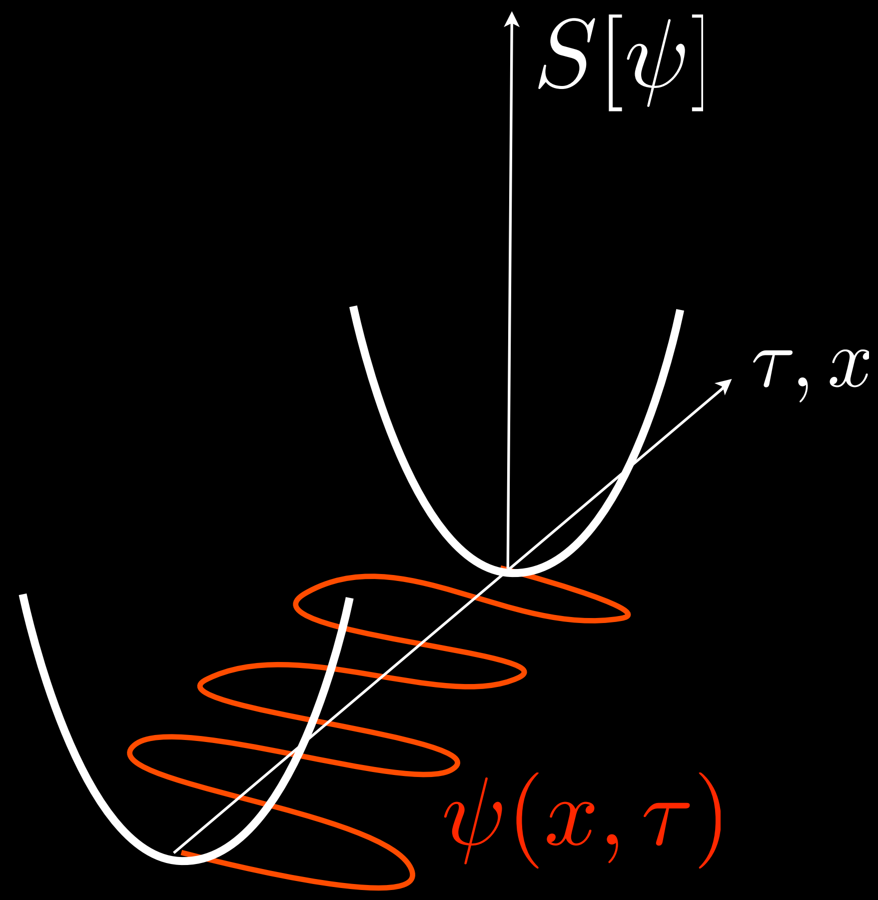

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$$\sigma \in (-\tfrac{1}{2}, \tfrac{1}{2}) \longrightarrow$$

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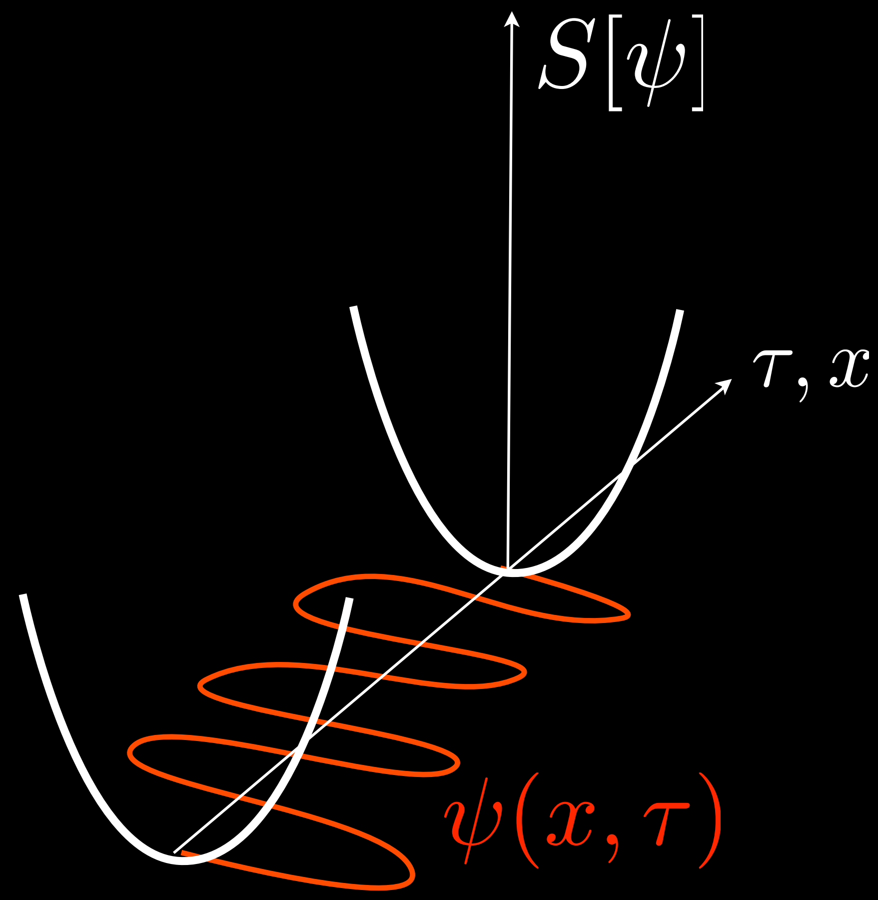

Feynman

$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

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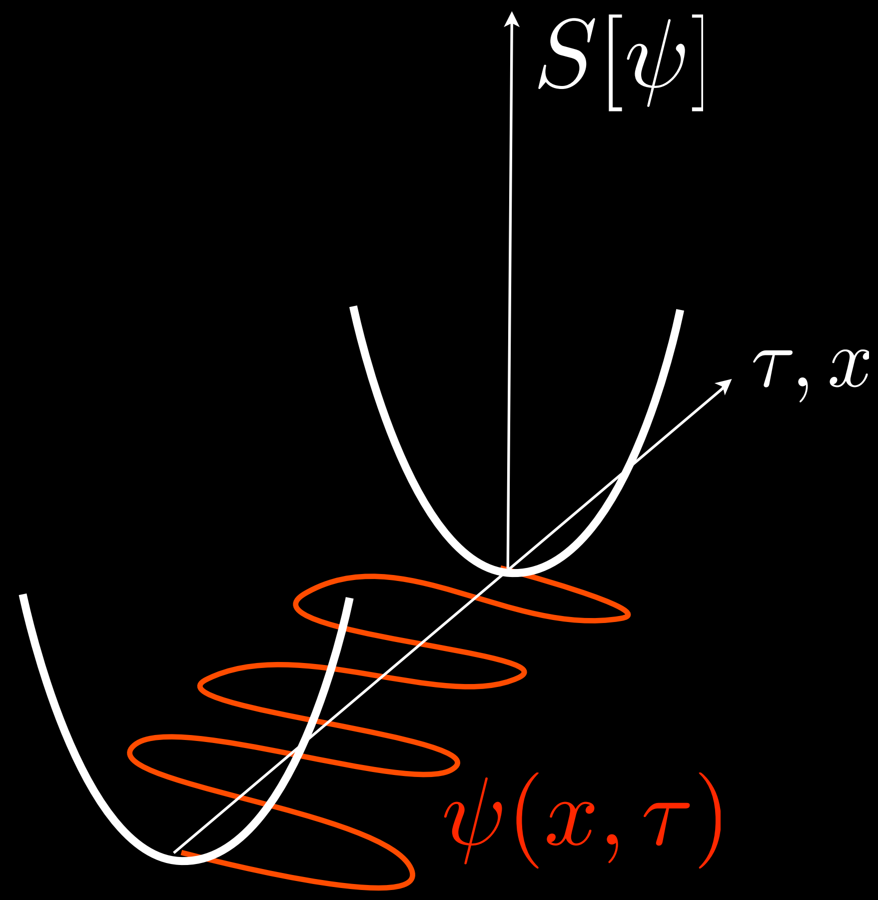

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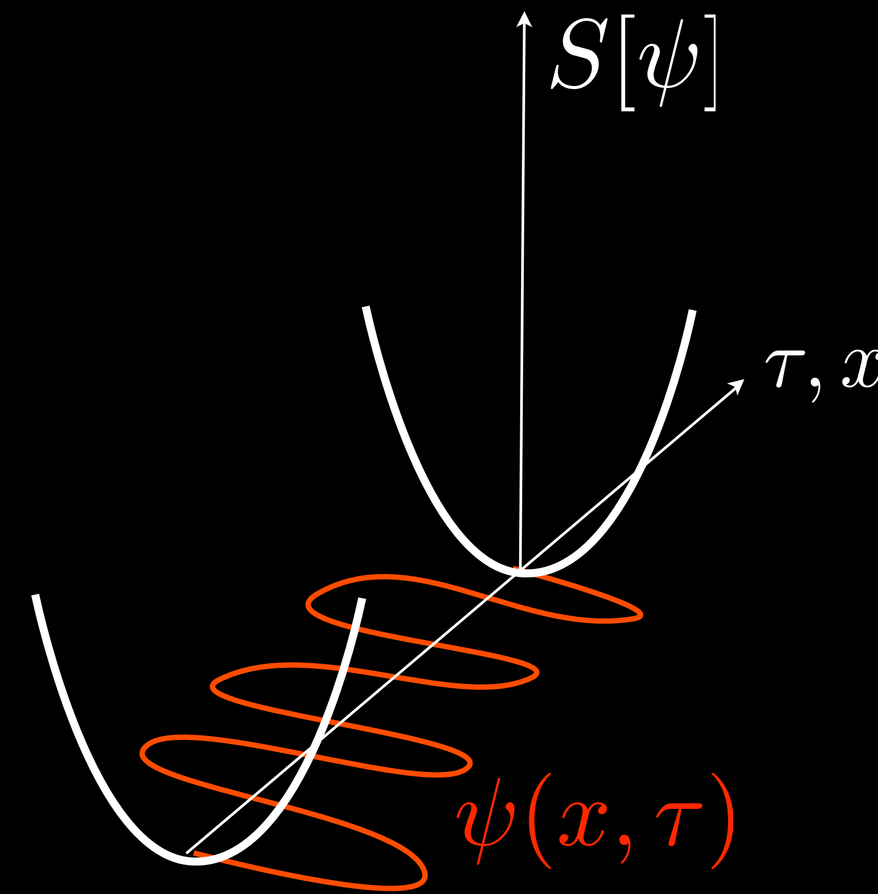

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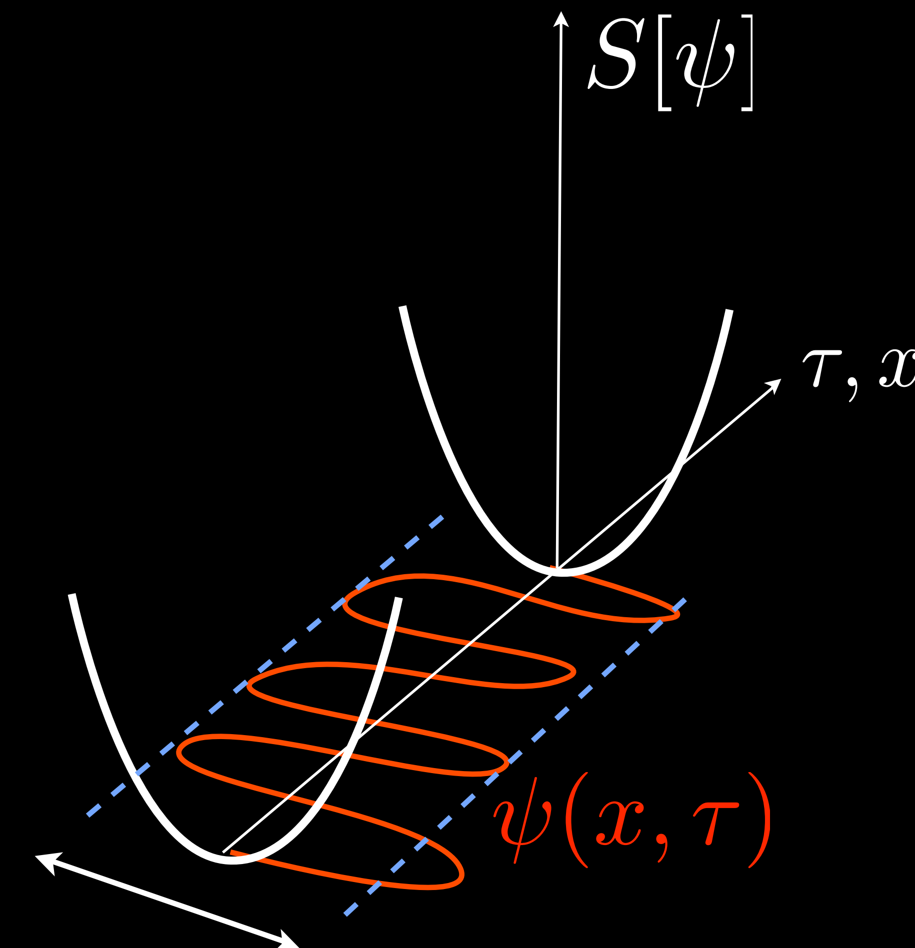

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Large N

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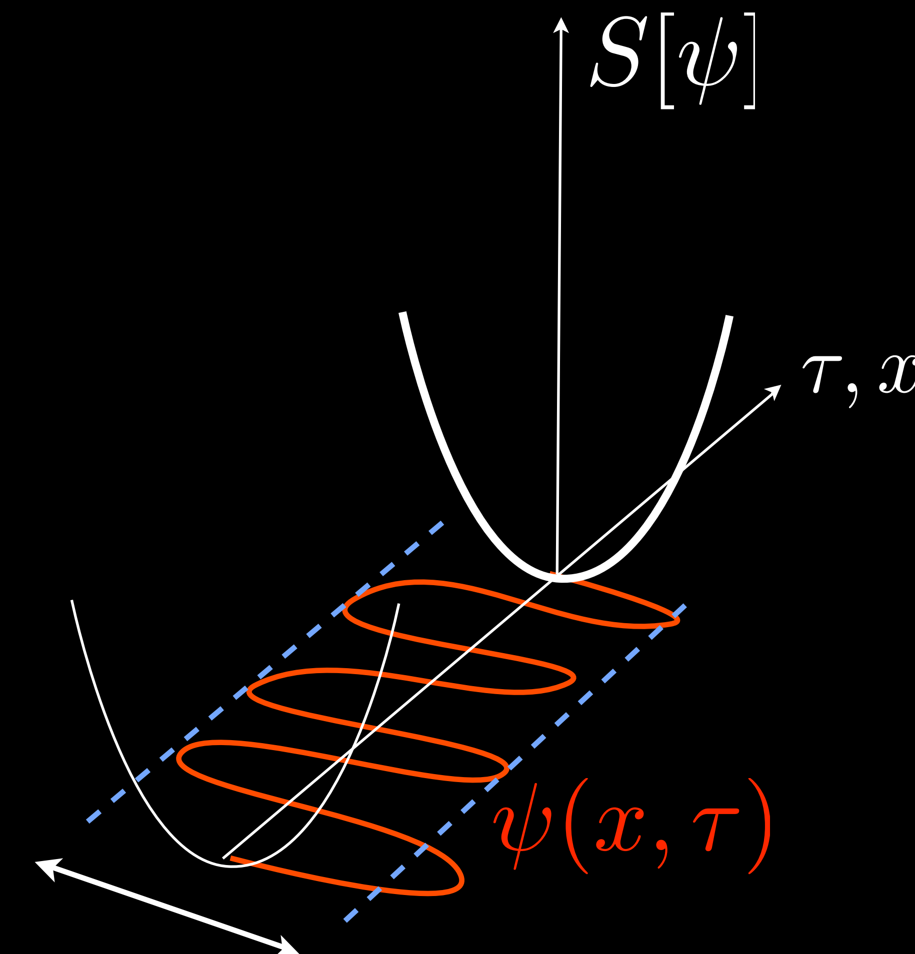

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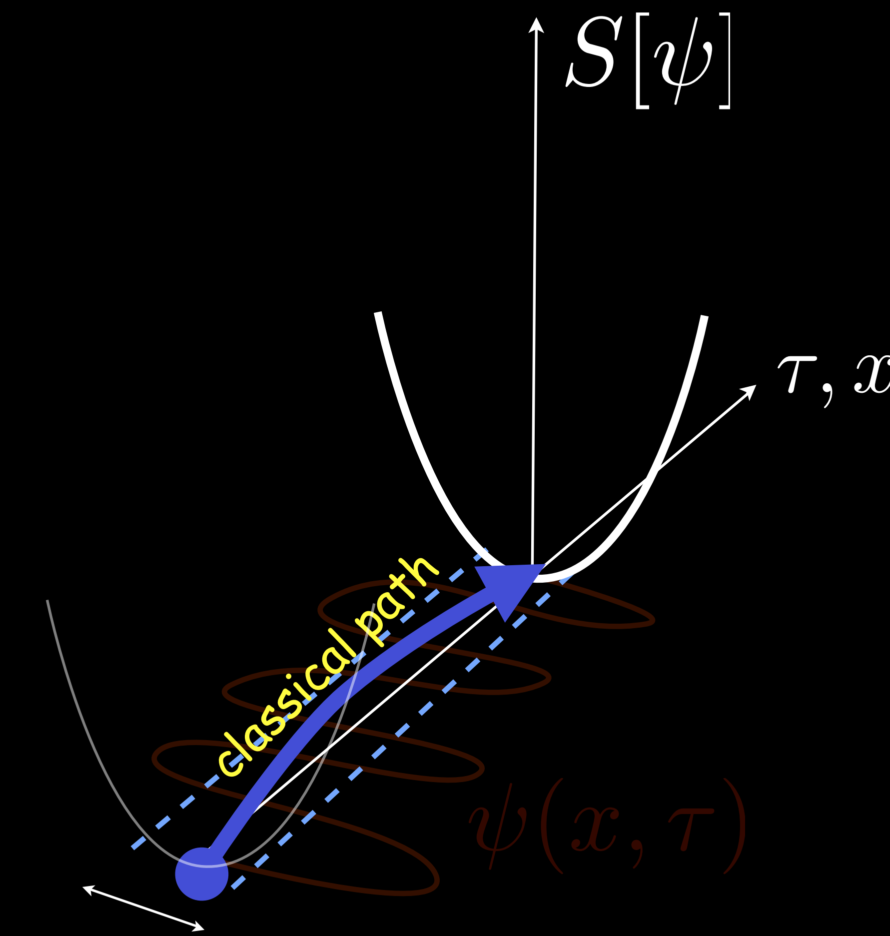

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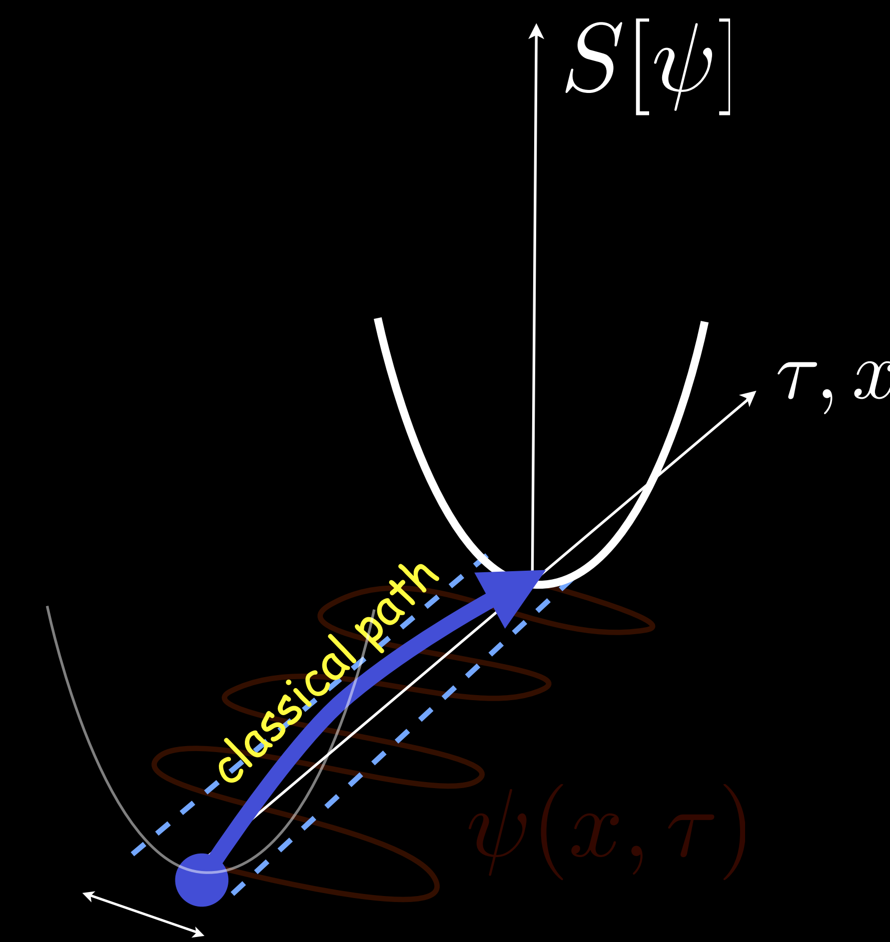

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?

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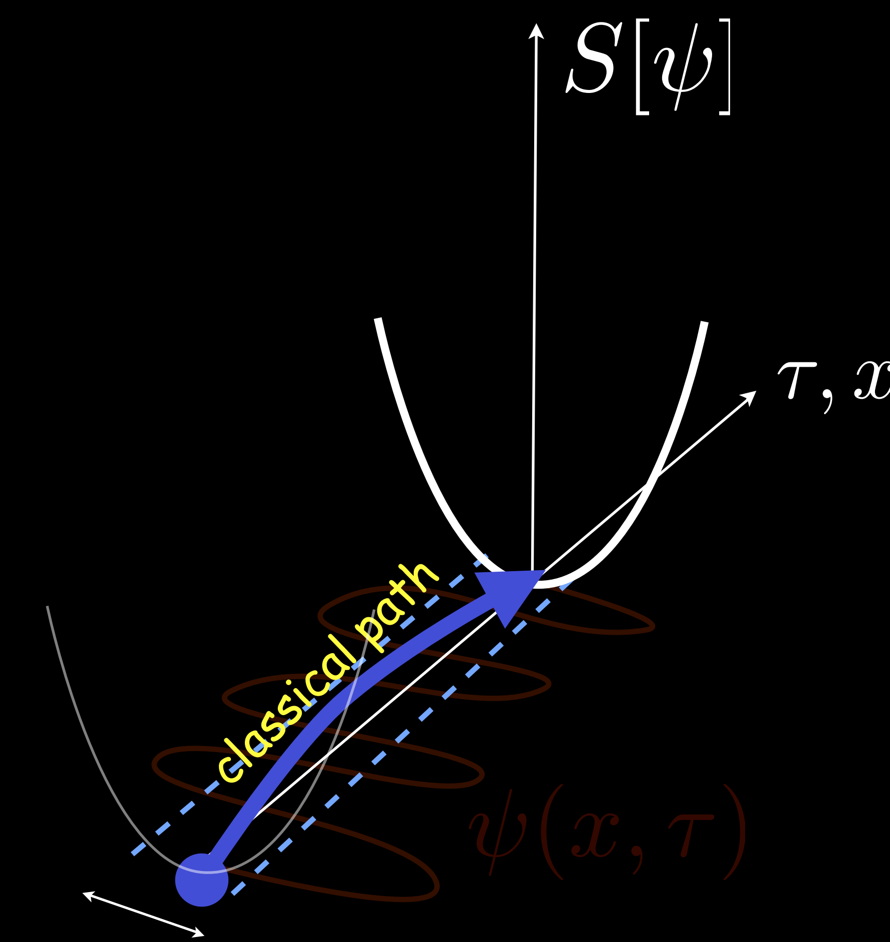

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?

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"Symplectic N" *(large N + time reversal symmetry)*

$N \to \infty$

R. Flint, Dzero and PC '08

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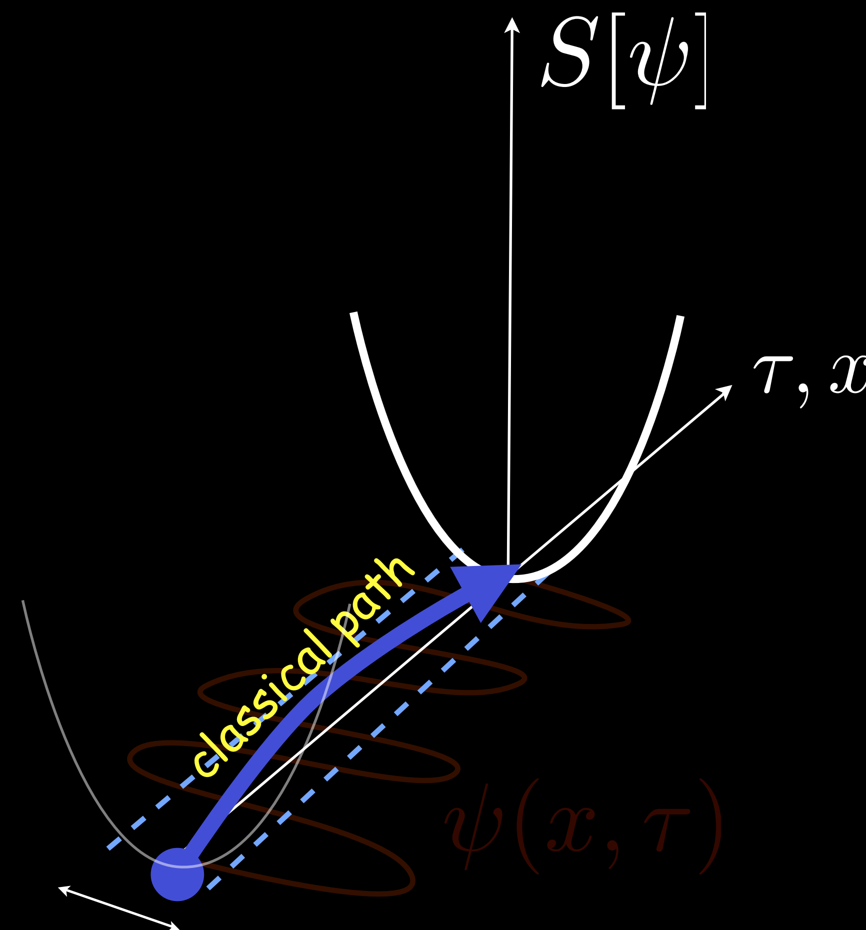

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$$S_{\alpha\beta} = f^{\dagger}_{\alpha} f_{\beta} + \mathrm{sgn}(\alpha\beta) f_{-\alpha} f^{\dagger}_{-\beta}$$

$$S_{\alpha\beta} = f_\alpha^\dagger f_\beta + \mathrm{sgn}(\alpha\beta) f_{-\alpha} f_{-\beta}^\dagger$$

$$H = \sum \epsilon_k c_{\vec{k}\alpha}^\dagger c_{\vec{k}\alpha} + \sum_{j,\Gamma=1,2} J_\Gamma c_{j\Gamma\alpha}^\dagger c_{j\Gamma\beta} S_{\beta\alpha}(j)$$

$$c_{j\Gamma\alpha}^\dagger = \frac{1}{\sqrt{N}} \sum c_{\vec{k}\alpha}^\dagger \; \underset{\text{Form factor}}{\underset{\uparrow}{\Phi_{\gamma\alpha\alpha'}(\vec{k})}} \; e^{-i\vec{k}\cdot\vec{R}_j}$$

$$S_{\alpha\beta} = f^\dagger_\alpha f_\beta + \mathrm{sgn}(\alpha\beta) f_{-\alpha} f^\dagger_{-\beta}$$

$$H = \sum \epsilon_k c^\dagger_{\vec{k}\alpha} c_{\vec{k}\alpha} + \sum_{j,\Gamma=1,2} J_\Gamma c^\dagger_{j\Gamma\alpha} c_{j\Gamma\beta} \; S_{\beta\alpha}(j)$$

$$c^\dagger_{j\Gamma\alpha} = \frac{1}{\sqrt{N}} \sum c^\dagger_{k\alpha} \; \Phi_{\Gamma\alpha\alpha'}(\vec{k}) \; e^{-i\vec{k}\cdot\vec{R}_j}$$

Form factor

e.g without spin orbit

$$\Phi_1(\vec{k}) = 1$$ s

$$\Phi_2(\vec{k}) = \cos k_x - \cos k_y$$ d

more realistic with s.o. c.

$$\Phi_\Gamma(\vec{k})_{\sigma\alpha} = \sum_m Y^3_{m-\sigma}(\vec{k}) \langle \ell\, m-\sigma\ \tfrac{1}{2}\, \sigma \,|\, \tfrac{5}{2}\, m \rangle \langle m | \alpha \rangle$$

$\Gamma = \Gamma_6, \Gamma_7$

more realistic with s.o. c.

$$\Phi_\Gamma(\vec{k})_{\sigma\alpha} = \sum_m Y^3_{m-\sigma}(\vec{k}) \langle \ell\, m-\sigma\, \tfrac{1}{2}\, \sigma | \tfrac{5}{2}\, m \rangle \langle m | \alpha \rangle$$

$\Gamma = \Gamma_6, \Gamma_7$

Γ_7^- ═══ $\beta|5/2\rangle - \alpha|-3/2\rangle$

Γ_6 ═══ $|\pm 1/2\rangle$

Γ_7^+ ═══ $\alpha|5/2\rangle + \beta|-3/2\rangle$

$$\frac{J}{2N} \quad c^{+}_{j\alpha} \; c_{j\beta} \left(f^{+}_{j\beta} f_{j\alpha} + \tilde{\alpha}\tilde{\beta} f_{j-\beta} f_{j-\alpha} \right)$$

$$\frac{J}{2N} \quad c^{+}_{j\alpha} \; c_{j\beta} \left(f^{+}_{j\beta} f_{j\alpha} + \tilde{\alpha}\tilde{\beta} f_{j-\beta} f_{j-\alpha} \right)$$

$$= \quad -\frac{J}{2N} \left[\left(c^{+}_{j\alpha} \; f_{j\alpha} \right) \left(f^{+}_{j\beta} \; c_{j\beta} \right) + \left(\tilde{\alpha} c^{+}_{j\alpha} f^{+}_{j-\alpha} \right) \left(\tilde{\beta} f_{j-\beta} c_{j\beta} \right) \right]$$

$$\frac{J}{2N} c^{\dagger}_{j\alpha} c_{j\beta} \left(f^{\dagger}_{j\beta} f_{j\alpha} + \tilde{\alpha}\tilde{\beta} f_{j-\beta} f_{j-\alpha} \right)$$

$$= -\frac{J}{2N} \left[\left(c^{\dagger}_{j\alpha} f_{j\alpha} \right) \left(f^{\dagger}_{j\beta} c_{j\beta} \right) + \left(\tilde{\alpha} c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha} \right) \left(\tilde{\beta} f_{j-\beta} c_{j\beta} \right) \right]$$

$$\longrightarrow \quad \sum_{\sigma} \left(\bar{V} c^{\dagger}_{j\alpha} f_{\alpha} + \text{H.c} \right) + \left(\Delta\, c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha} \tilde{\alpha} + \text{h.c} \right)$$

$$+ 2N \left(\frac{\bar{V} V}{J} + \frac{\bar{\Delta} \Delta}{J} \right)$$

$$\frac{J}{2N} c^{\dagger}_{j\alpha} c_{j\beta} \left(f^{\dagger}_{j\beta} f_{j\alpha} + \tilde{\alpha}\tilde{\beta} f_{j-\beta} f_{j-\alpha} \right)$$

$$= -\frac{J}{2N} \left[\left(c^{\dagger}_{j\alpha} f_{j\alpha} \right) \left(f^{\dagger}_{j\beta} c_{j\beta} \right) + \left(\tilde{\alpha} c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha} \right) \left(\tilde{\beta} f_{j-\beta} c_{j\beta} \right) \right]$$

$$\longrightarrow \sum_{\sigma} \left(\bar{V} c^{\dagger}_{j\alpha} f_{\alpha} + \text{H.c} \right) + \left(\Delta c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha} \tilde{\alpha} + \text{h.c} \right)$$

$$+ 2N \left(\frac{\bar{V} V}{J} + \frac{\bar{\Delta}\Delta}{J} \right)$$

$$= \sum_{\sigma > 0} \left[\left(f^{\dagger}_{j\alpha}, f_{j-\alpha} \right) \begin{pmatrix} V & \Delta \\ \bar{\Delta} & -\bar{V} \end{pmatrix} \begin{pmatrix} c_{j\alpha} \\ c^{\dagger}_{j-\alpha} \end{pmatrix} + \text{h.c} \right]$$

$$+ \operatorname{Tr} \left[\begin{pmatrix} \bar{V} & \bar{\Delta} \\ \Delta & -V \end{pmatrix} \begin{pmatrix} V & \Delta \\ \bar{\Delta} & -\bar{V} \end{pmatrix} \right] \left(\frac{N}{J} \right)$$

$$\frac{J}{2N}\, c^{\dagger}_{j\alpha}\, c_{j\beta}\left(f^{\dagger}_{j\beta} f_{j\alpha} + \tilde{\alpha}\tilde{\beta} f_{j-\beta} f_{j-\alpha}\right)$$

$$\equiv -\frac{J}{2N}\left[\left(c^{\dagger}_{j\alpha} f_{j\alpha}\right)\left(f^{\dagger}_{j\beta} c_{j\beta}\right) + \left(\tilde{\alpha} c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha}\right)\left(\tilde{\beta} f_{j-\beta} c_{j\beta}\right)\right]$$

$$\longrightarrow \sum_{\sigma}\left(\bar{V} c^{\dagger}_{j\alpha} f_{\alpha} + \text{H.c}\right) + \left(\Delta\, c^{\dagger}_{j\alpha} f^{\dagger}_{j-\alpha}\tilde{\alpha} + \text{h.c}\right)$$

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$$= \sum_{\sigma>0} \left[\left(f^{+}_{j\alpha},\, f_{j-\alpha} \right) \begin{pmatrix} V & \Delta \\ \bar{\Delta} & -\bar{V} \end{pmatrix} \begin{pmatrix} c_{j\alpha} \\ c^{+}_{j-\alpha} \end{pmatrix} + \text{h.c} \right]$$

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$$= \left[\tilde{f}^{+}_{j} \mathcal{V} c_j + c^{+}_{j} \bar{\mathcal{V}} f_j \right] + \mathrm{Tr}\left(\frac{\bar{\mathcal{V}} \mathcal{V}}{J} \right) \left(\frac{N}{J} \right)$$

$$\mathcal{V} = \begin{pmatrix} V & \Delta \\ +\bar{\Delta} & -\bar{V} \end{pmatrix}$$

$$= \sum_{\sigma>0} \left[\left(f^{+}_{j\alpha},\, f_{j-\alpha} \right) \begin{pmatrix} V & \Delta \\ \bar{\Delta} & -\bar{V} \end{pmatrix} \begin{pmatrix} c_{j\alpha} \\ c^{+}_{j-\alpha} \end{pmatrix} + h.c \right]$$

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$$\mathcal{V} = \begin{pmatrix} V & \Delta \\ +\bar{\Delta} & -\bar{V} \end{pmatrix}$$

$$\Longrightarrow \quad \sum_{r,j} \left(f^{+}_{j} \mathcal{V}_r\, c_{rj} + h.c + \frac{N}{J_r} \mathrm{Tr}\left(\mathcal{V}^{+}_{r} \mathcal{V}_r \right) \right)$$

$$H = \sum_{k} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^{\dagger}_{1a}(j) \psi_{1b}(j) + J_2 \psi^{\dagger}_{2a}(j) \psi_{2b}(j) \right) S^{ba}(j)$$

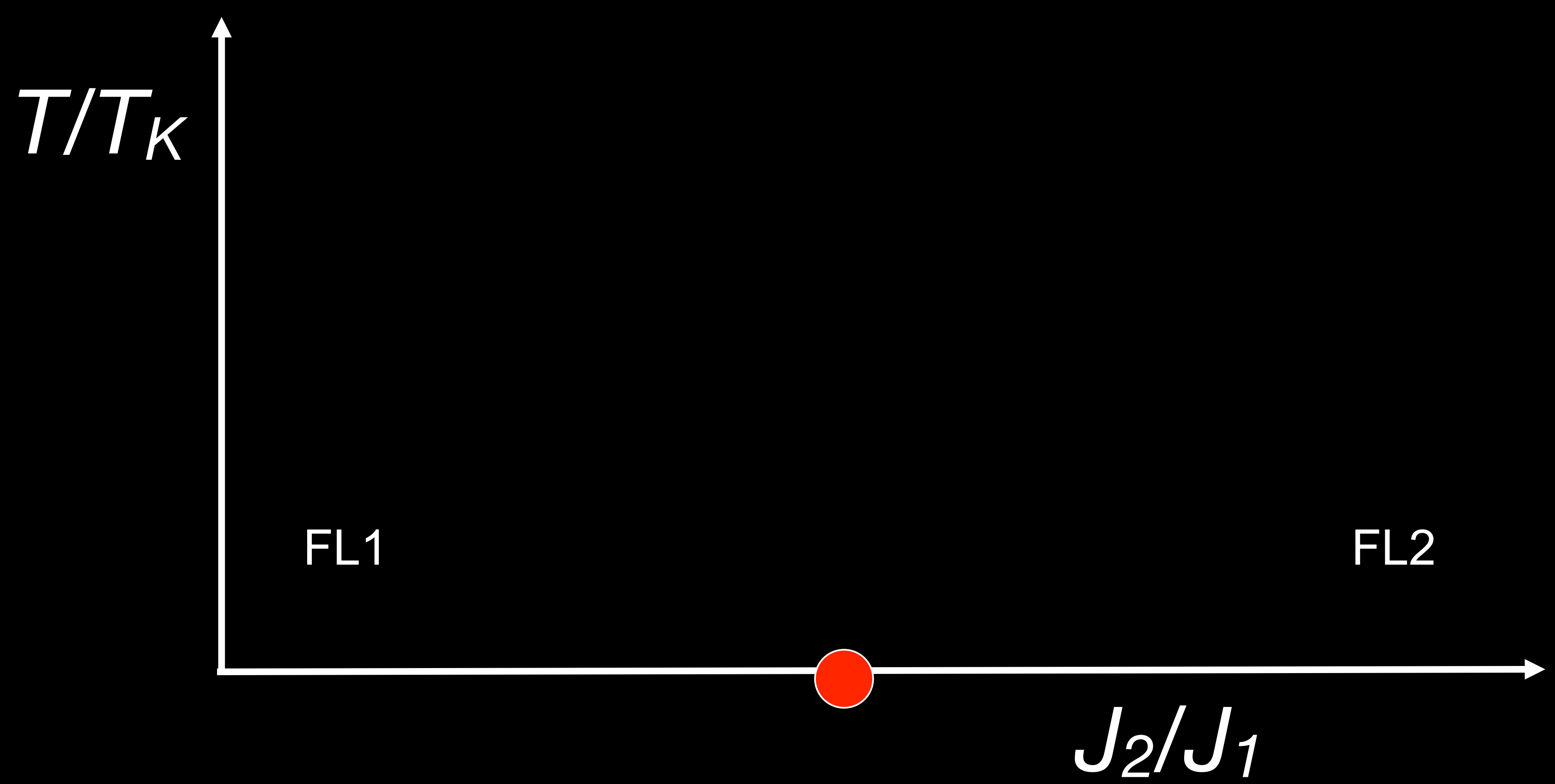
Single FS, two channels.

$$\psi_{\Gamma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \gamma_{\Gamma \mathbf{k}} \; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)
PC, Kee, Andrei, Tsvelik (98)

Impurity: quantum critical point for $J_1 = J_2$

Nozieres and Blandin 1980



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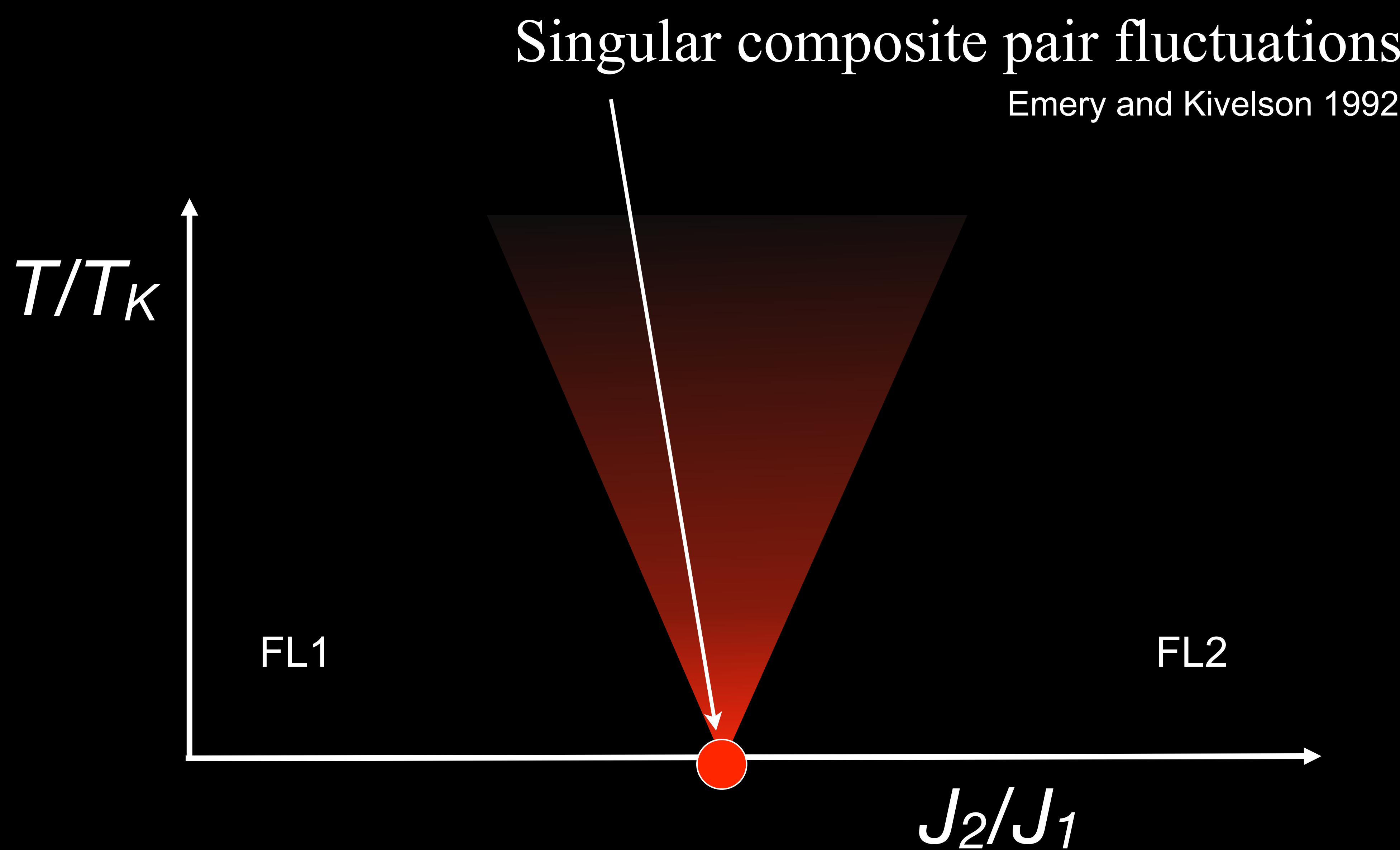

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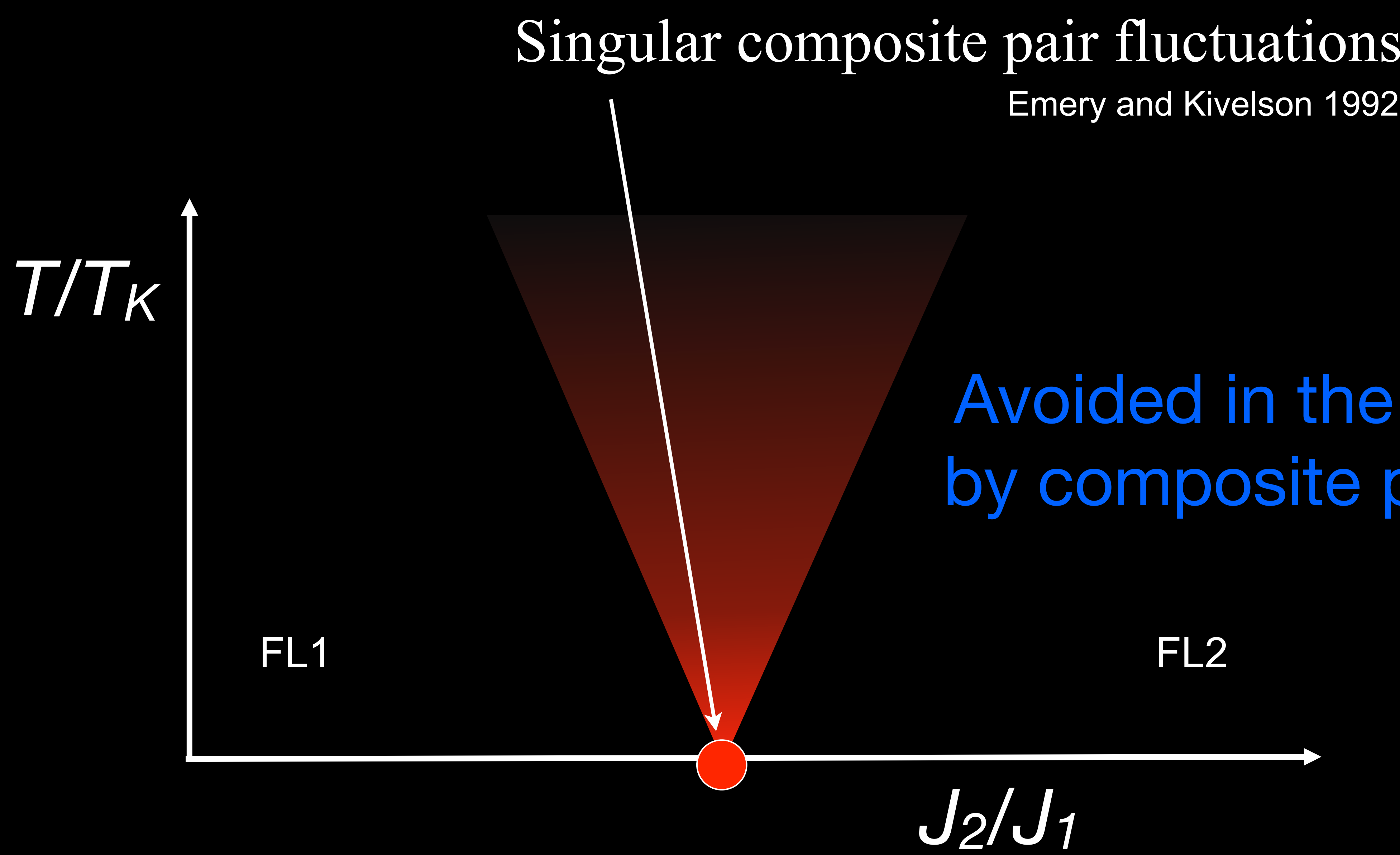

Avoided in the lattice by composite pairing.

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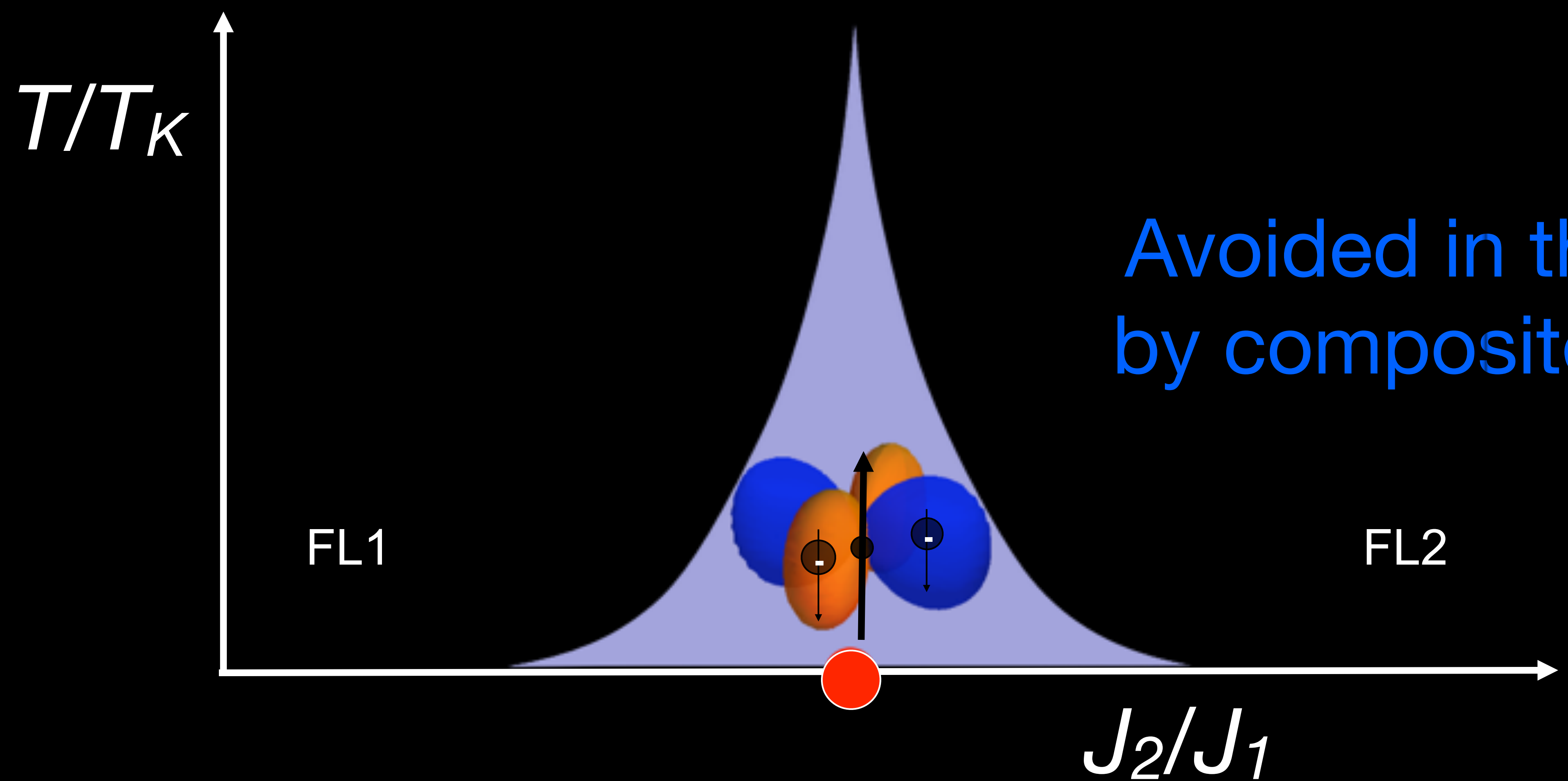
Nozieres and Blandin 1980

Singular composite pair fluctuations

Emery and Kivelson 1992



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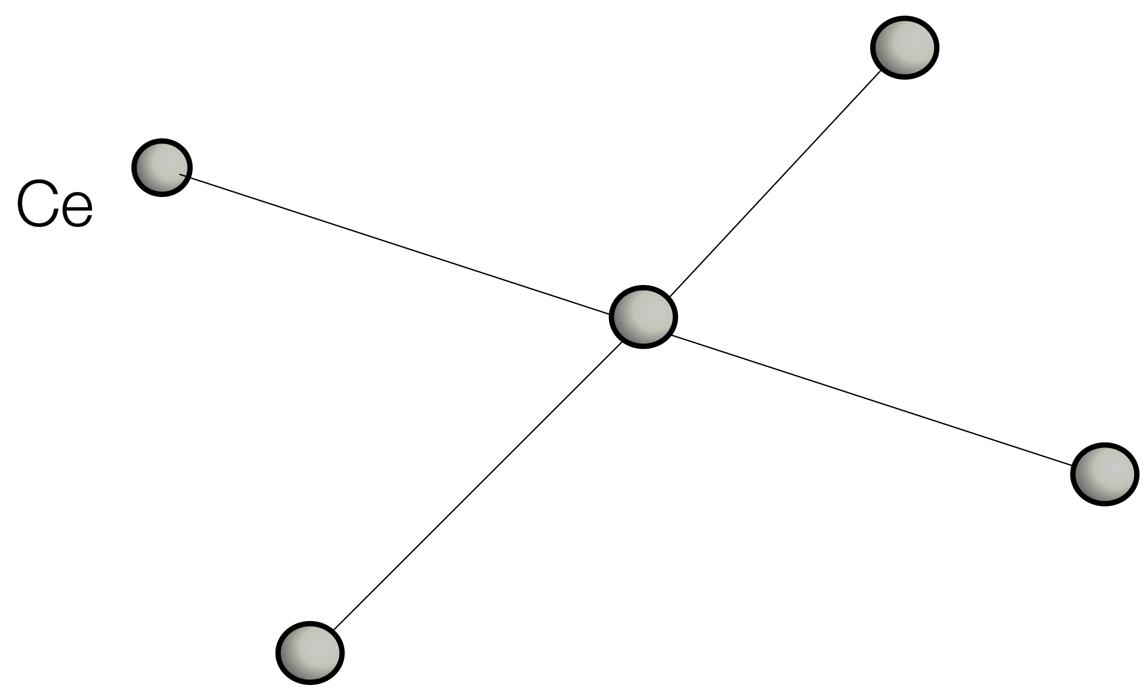
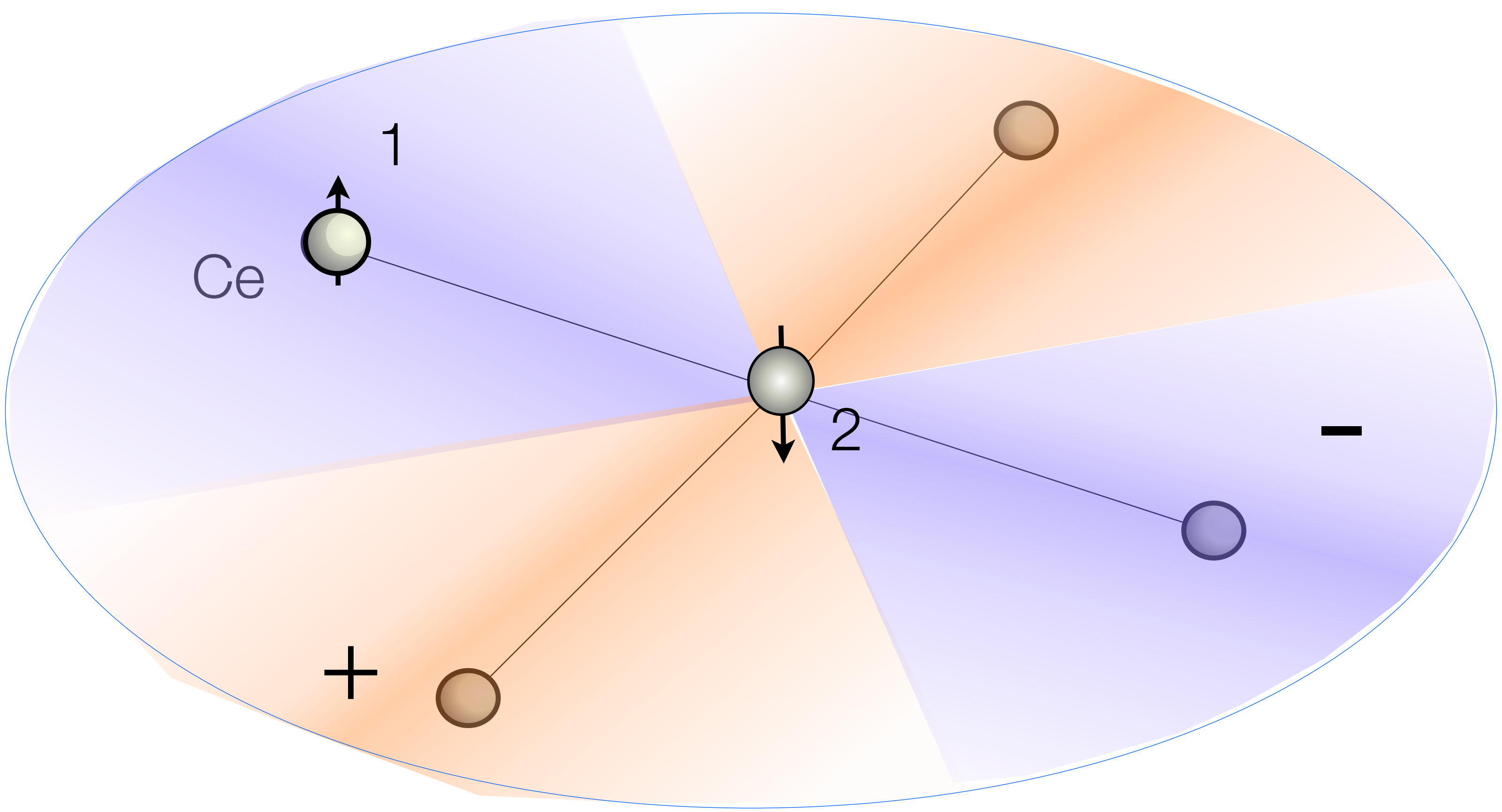
Real-space structure of pair



Real-space structure of pair

Magnetic pair: intercell

$$\Psi_M^\dagger = \Delta_d(1-2) f_\uparrow^\dagger(1) f_\downarrow^\dagger(2)$$



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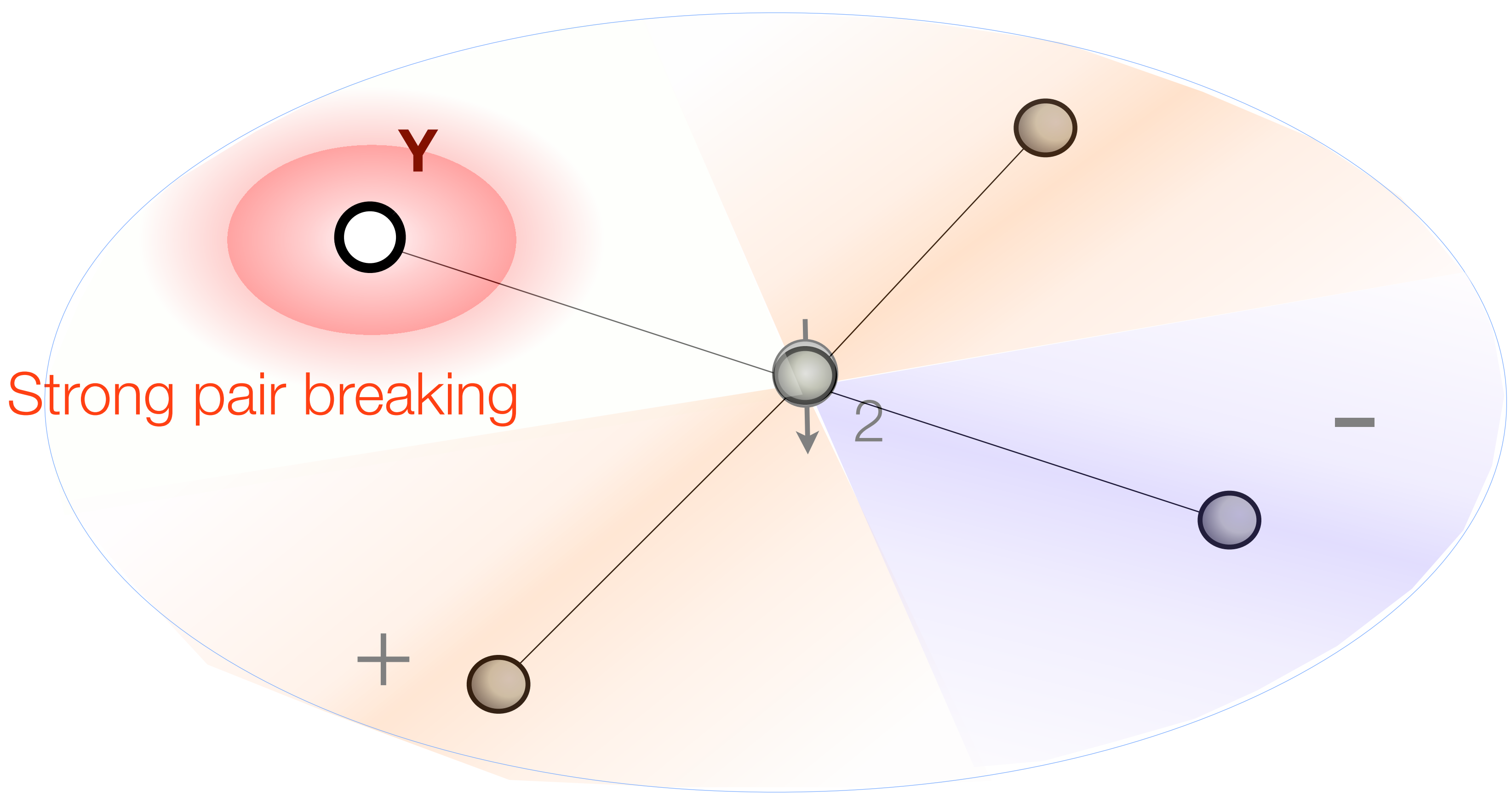

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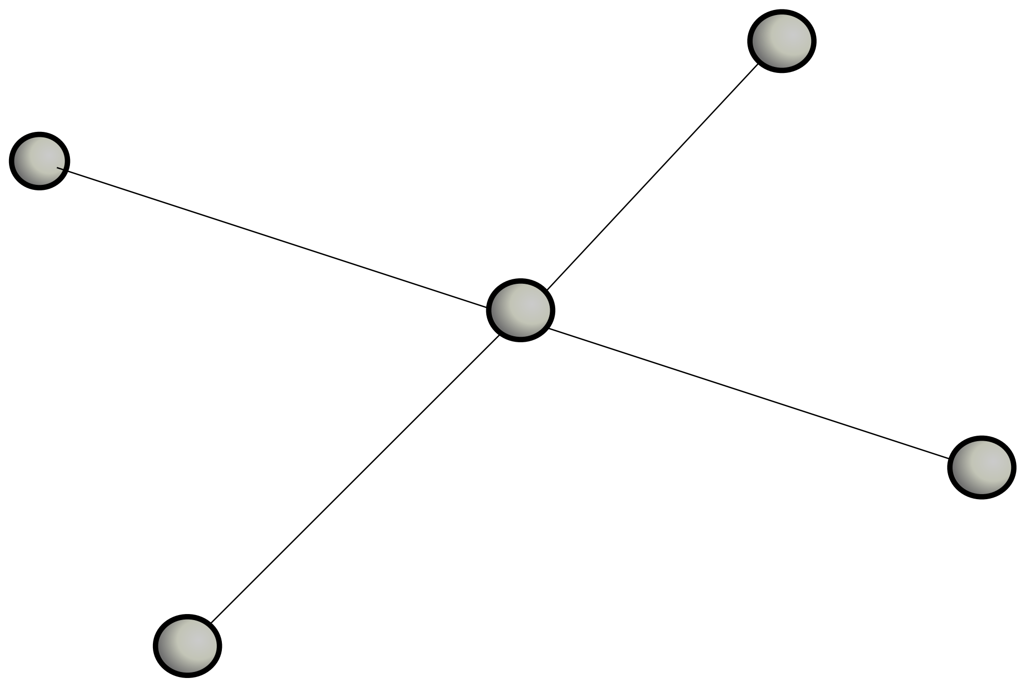

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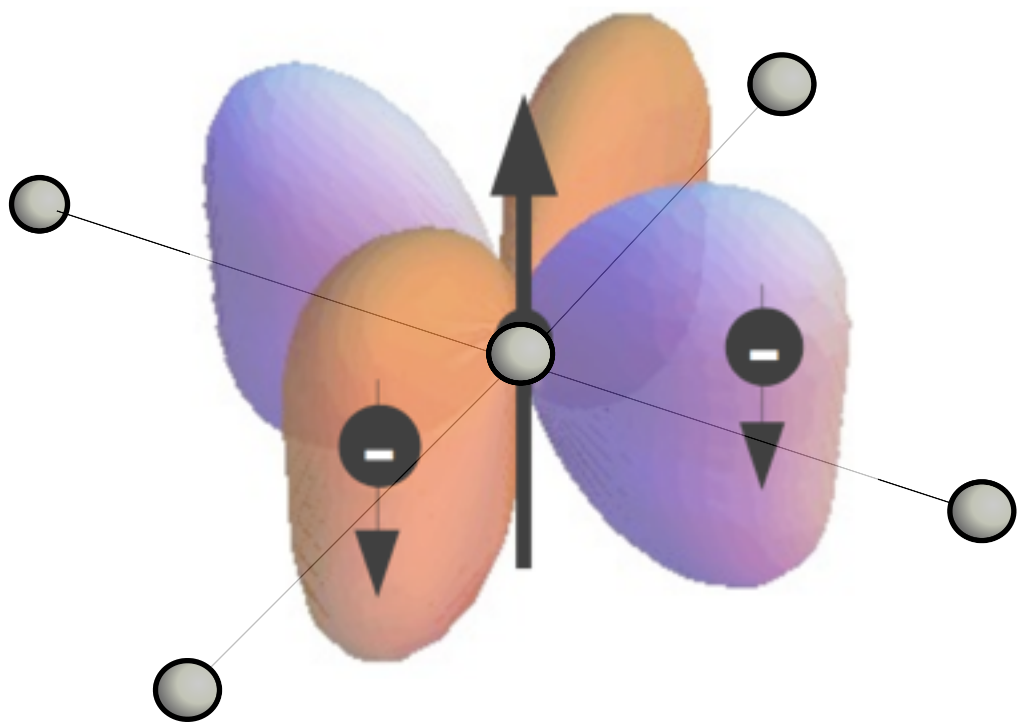

Composite pair

$$\Psi_C^\dagger = c_{1\downarrow}^\dagger c_{2\downarrow}^\dagger S_+$$

Abrahams, Balatsky, Scalapino, Schrieffer 1995

Andrei, Coleman, Kee & Tsvelik PRB (1998)
Flint, Dzero, Coleman , Nat. Phys, (2008)

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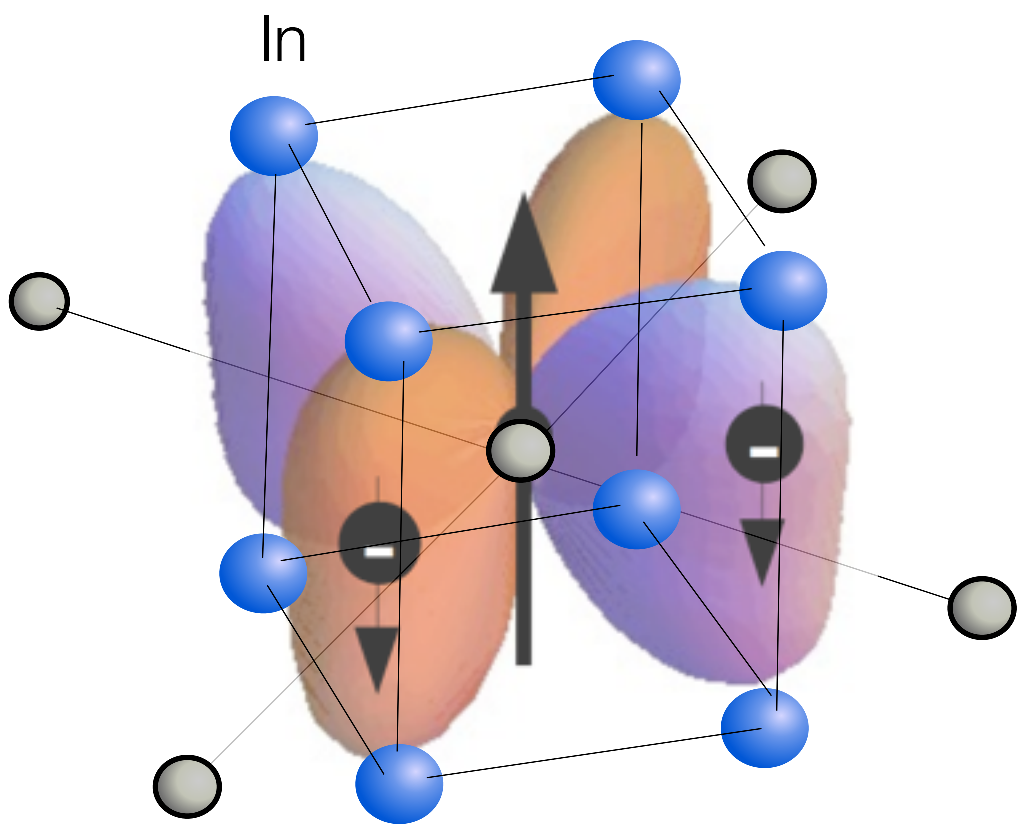

Composite pair**: intra-cell boson**

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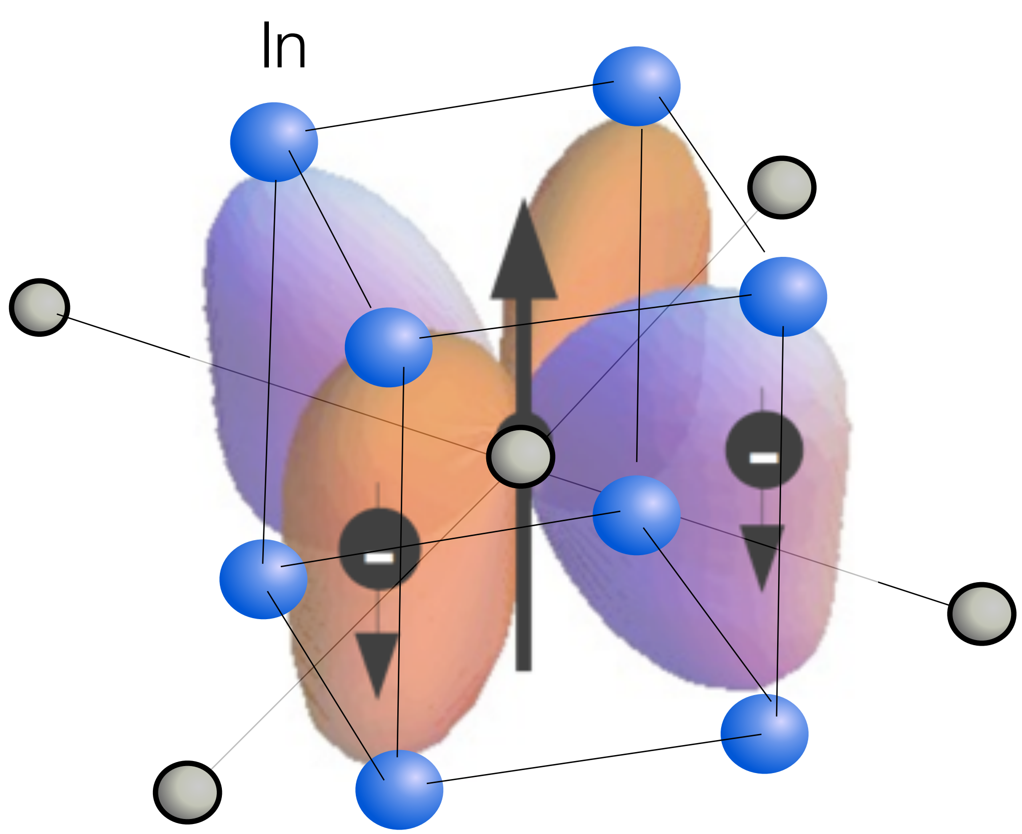

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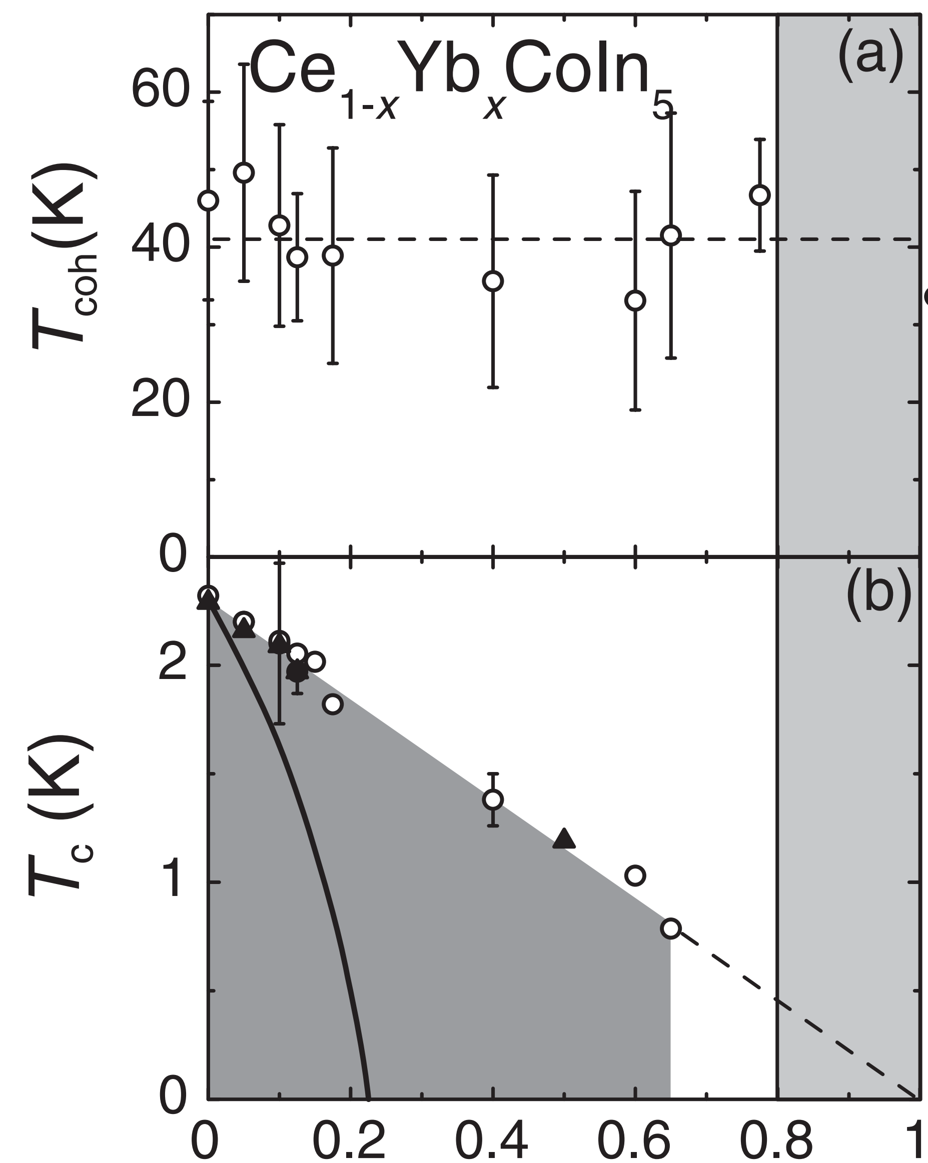
Extreme Resilience to doping on Ce site.



Lei Shu et al, PRL, (2011)

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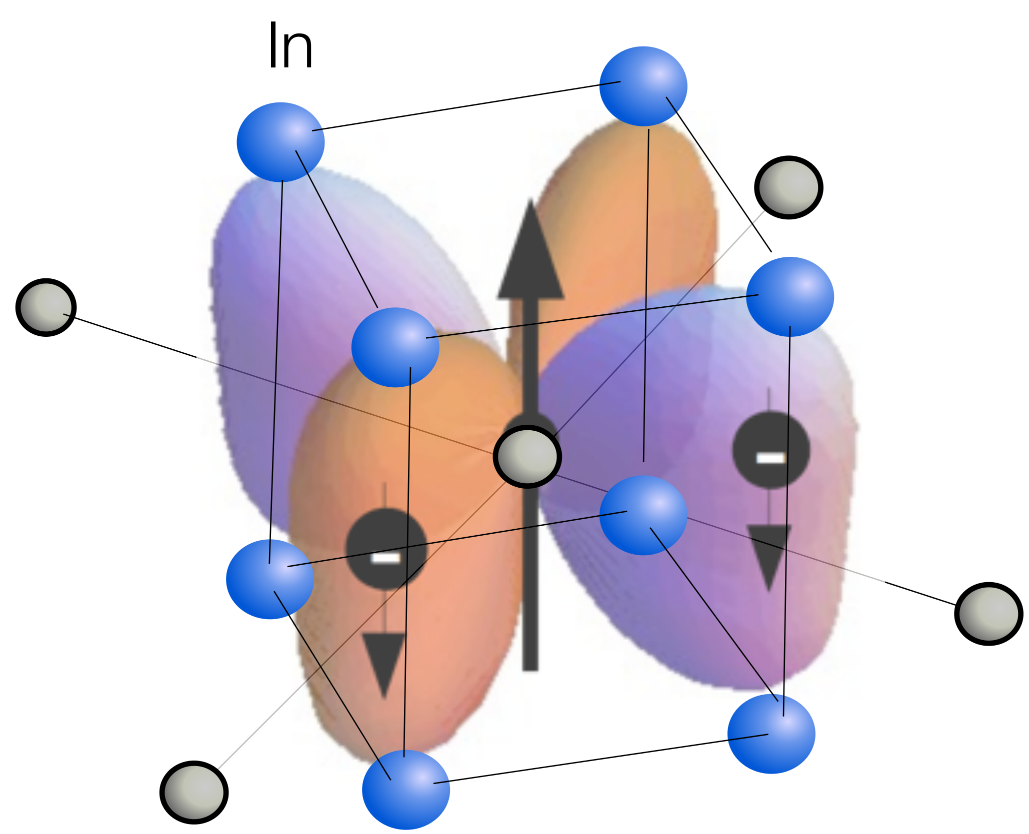

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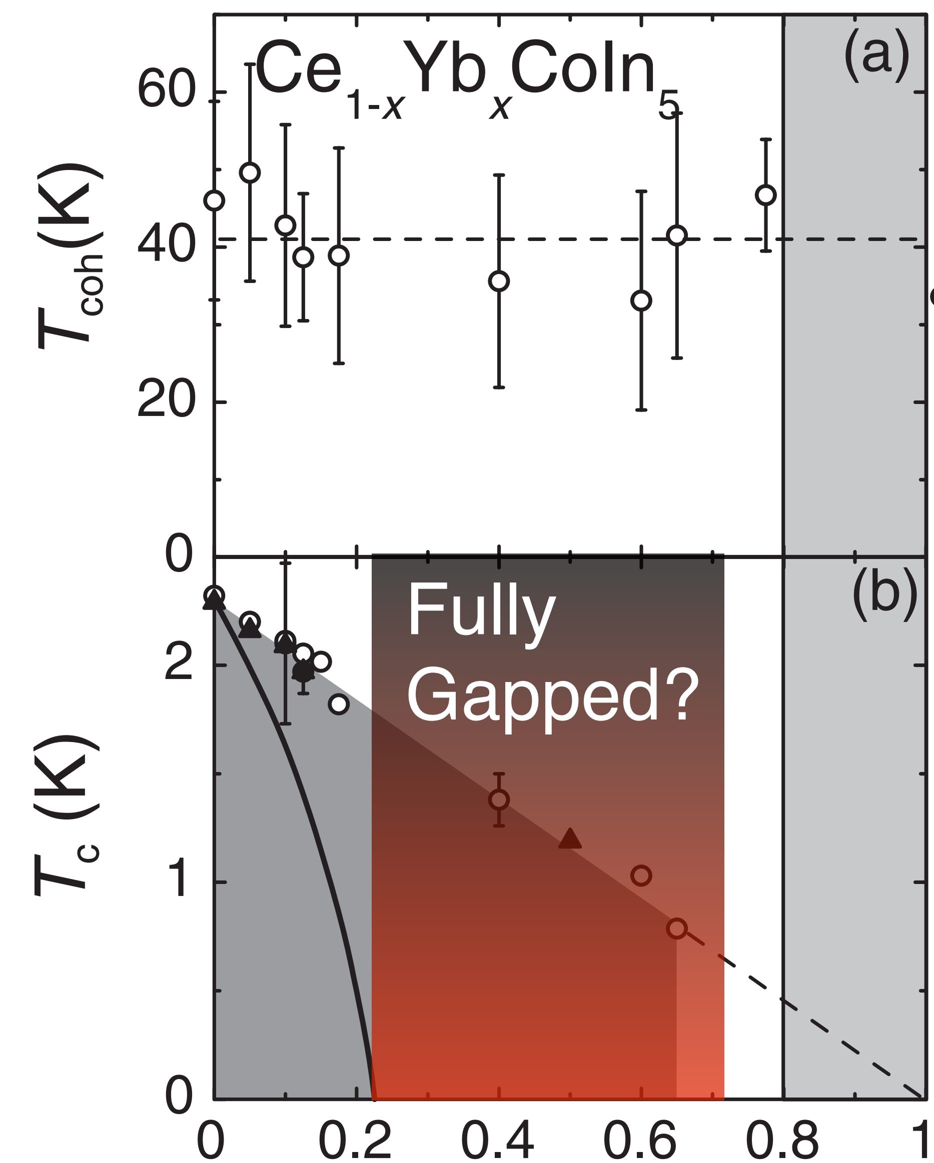
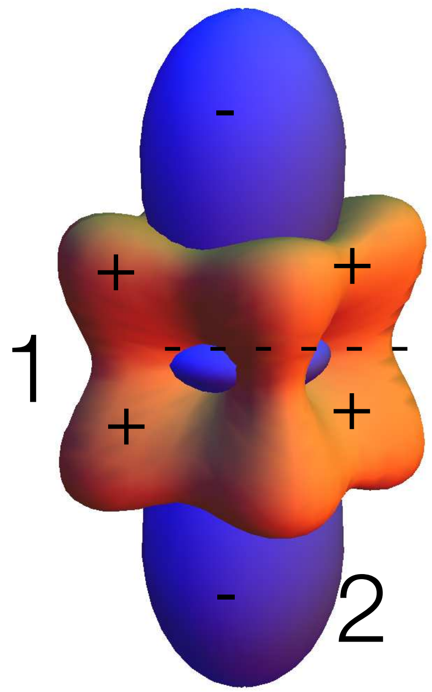


Lei Shu et al, PRL, (2011)

M. Tanatar et al (unpublished)
Erten and PC arXiv1402.7361

4f/5f superconductors



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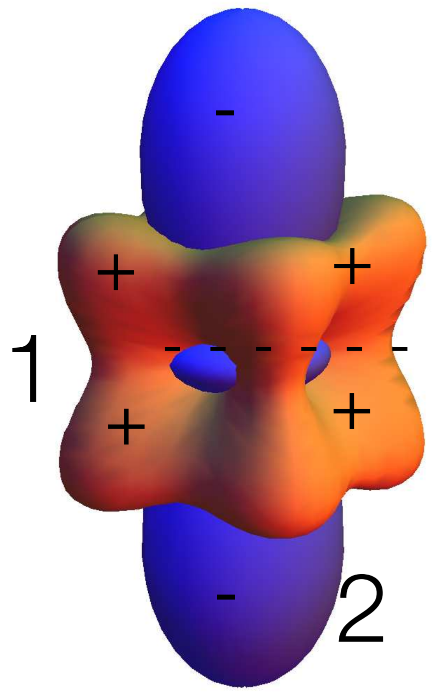

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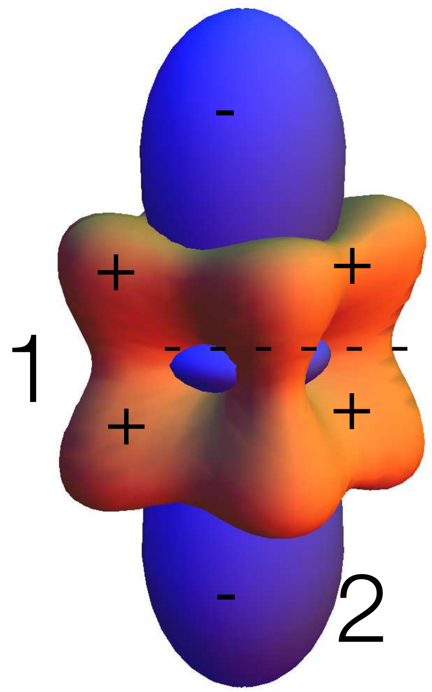
$$Q_{zz} \propto \Psi_C^2$$

4f/5f superconductors



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$$\Delta F \propto -Q_{zz} u_{tet}$$

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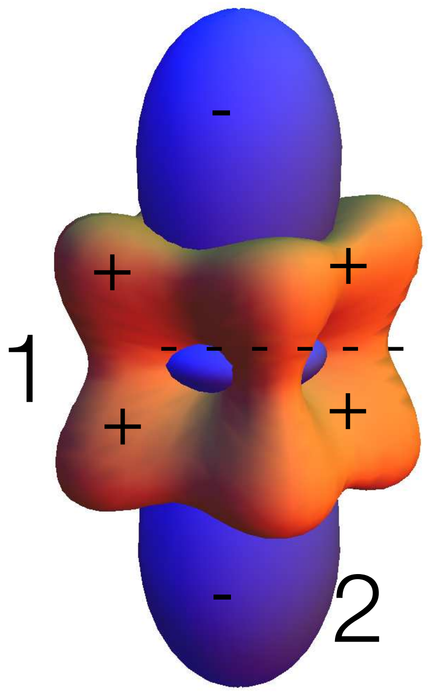

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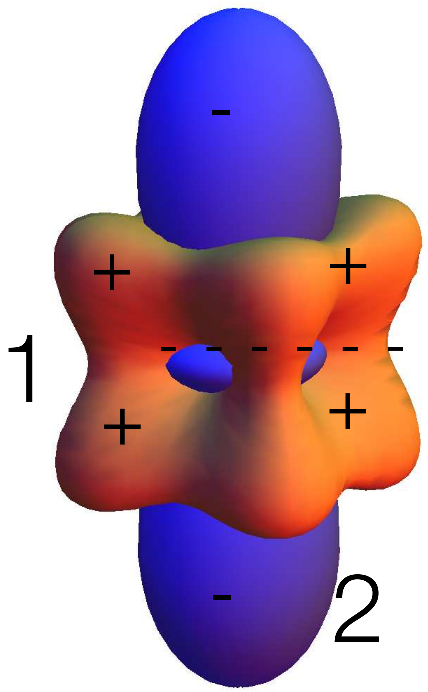

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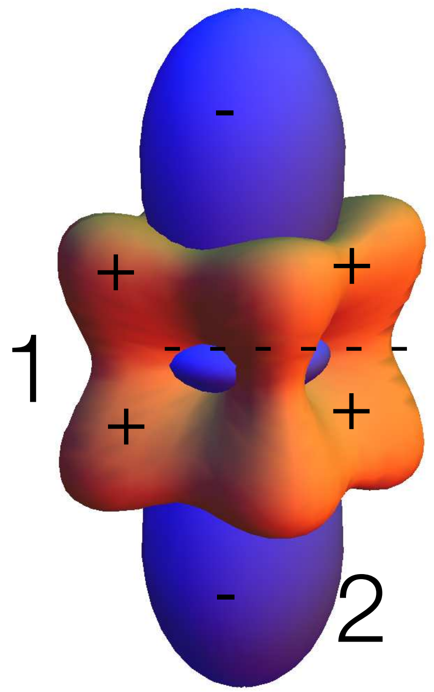

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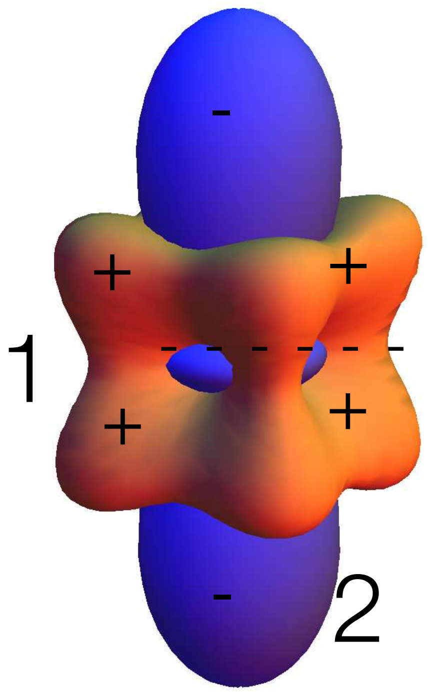
Strain expected to enhance Tc

4f/5f superconductors



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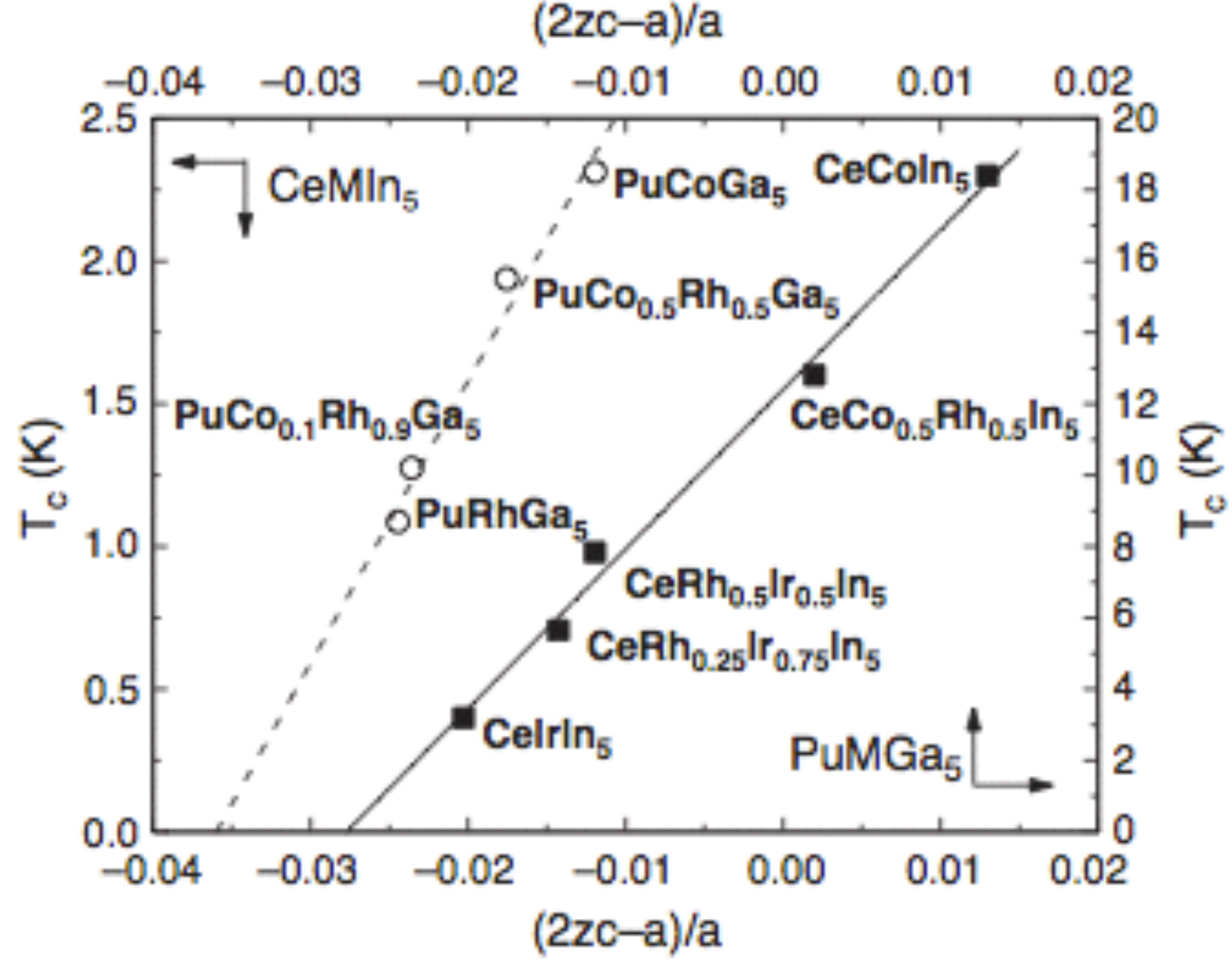
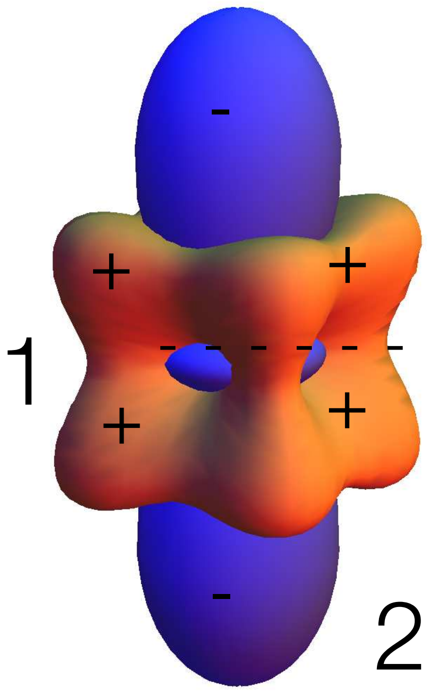


J.L. Sarrao et al. / Physica B 359– 361 (2005) 1144–1146



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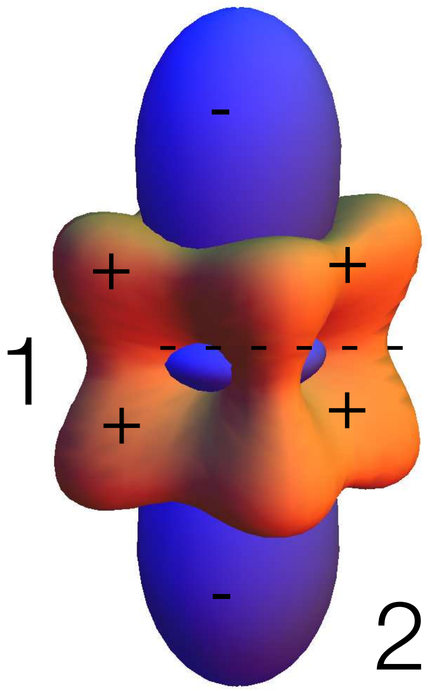

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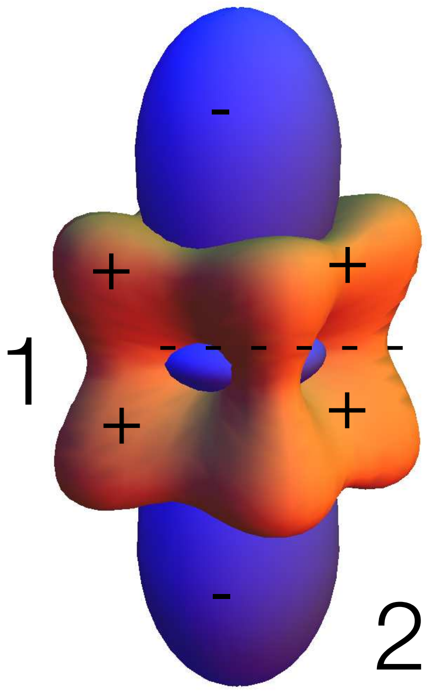

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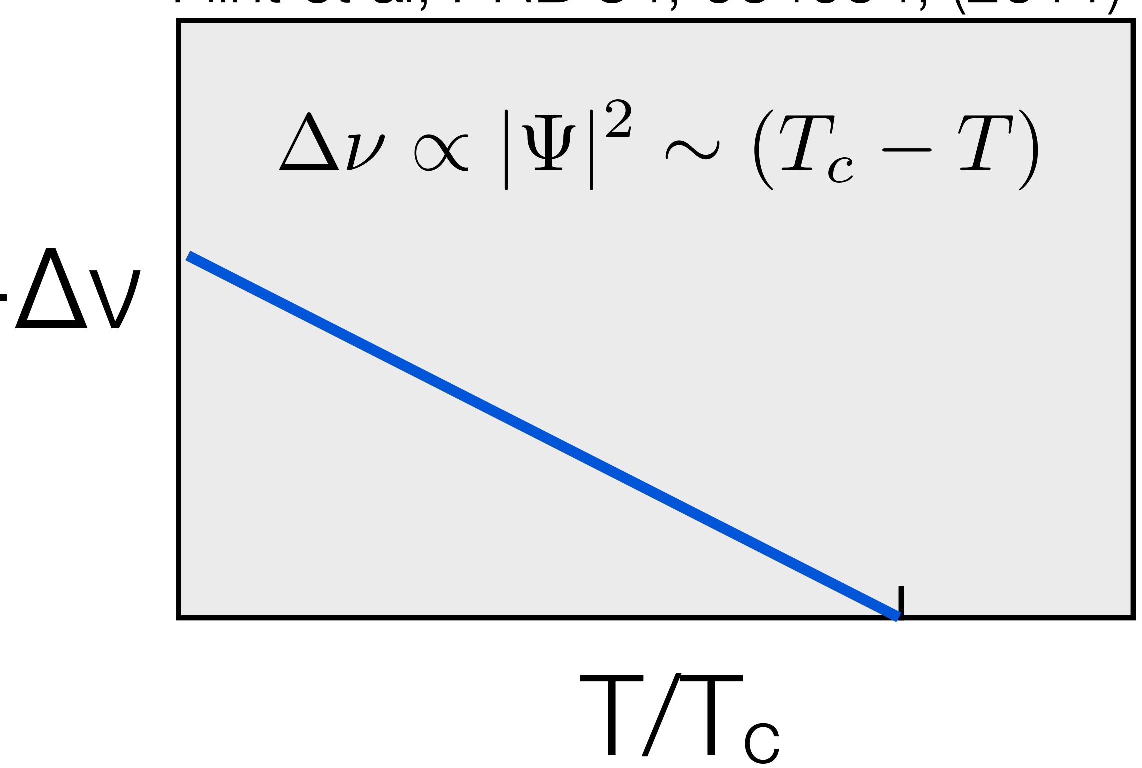
Flint et al, PRB 84, 064054, (2011)



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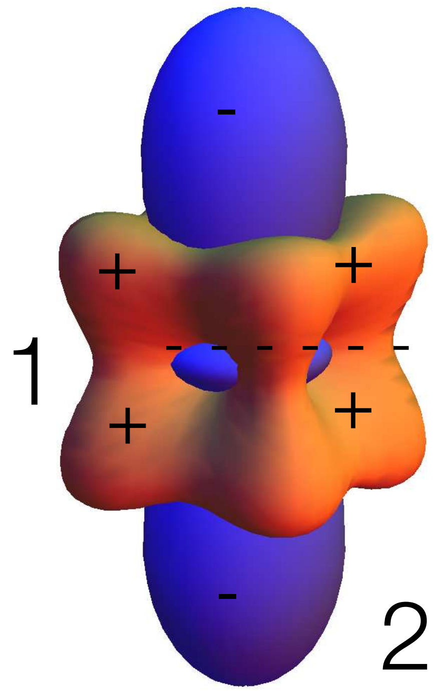

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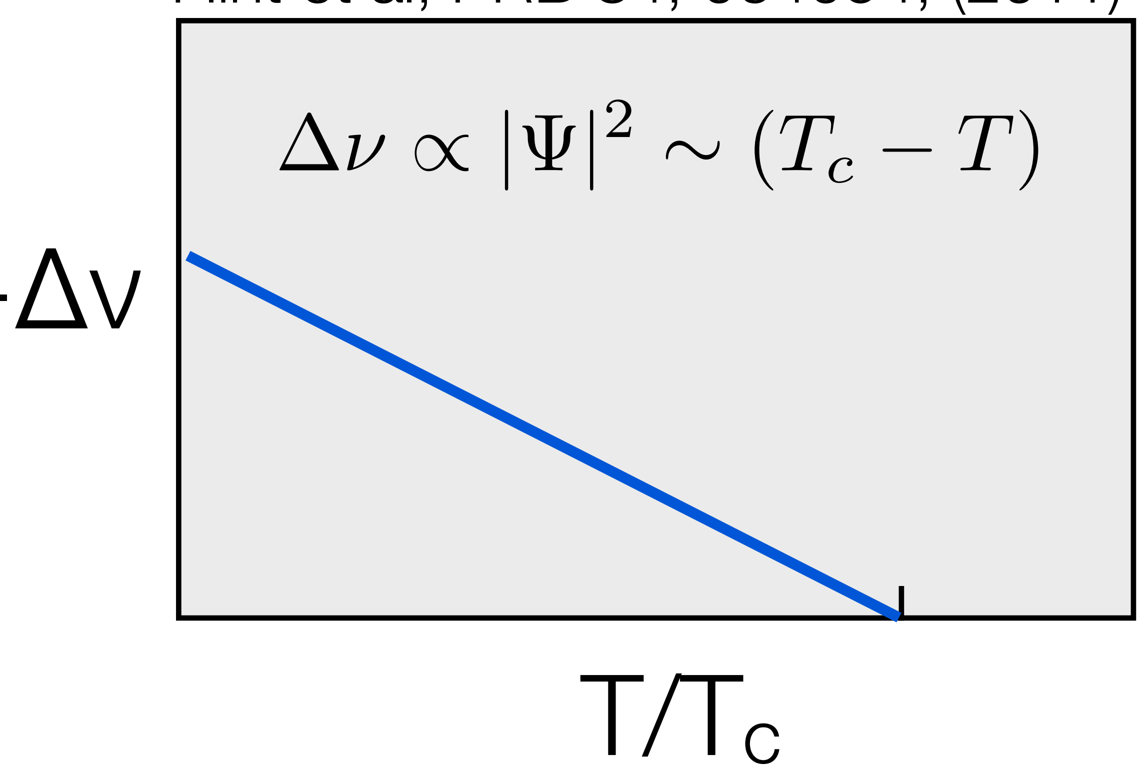
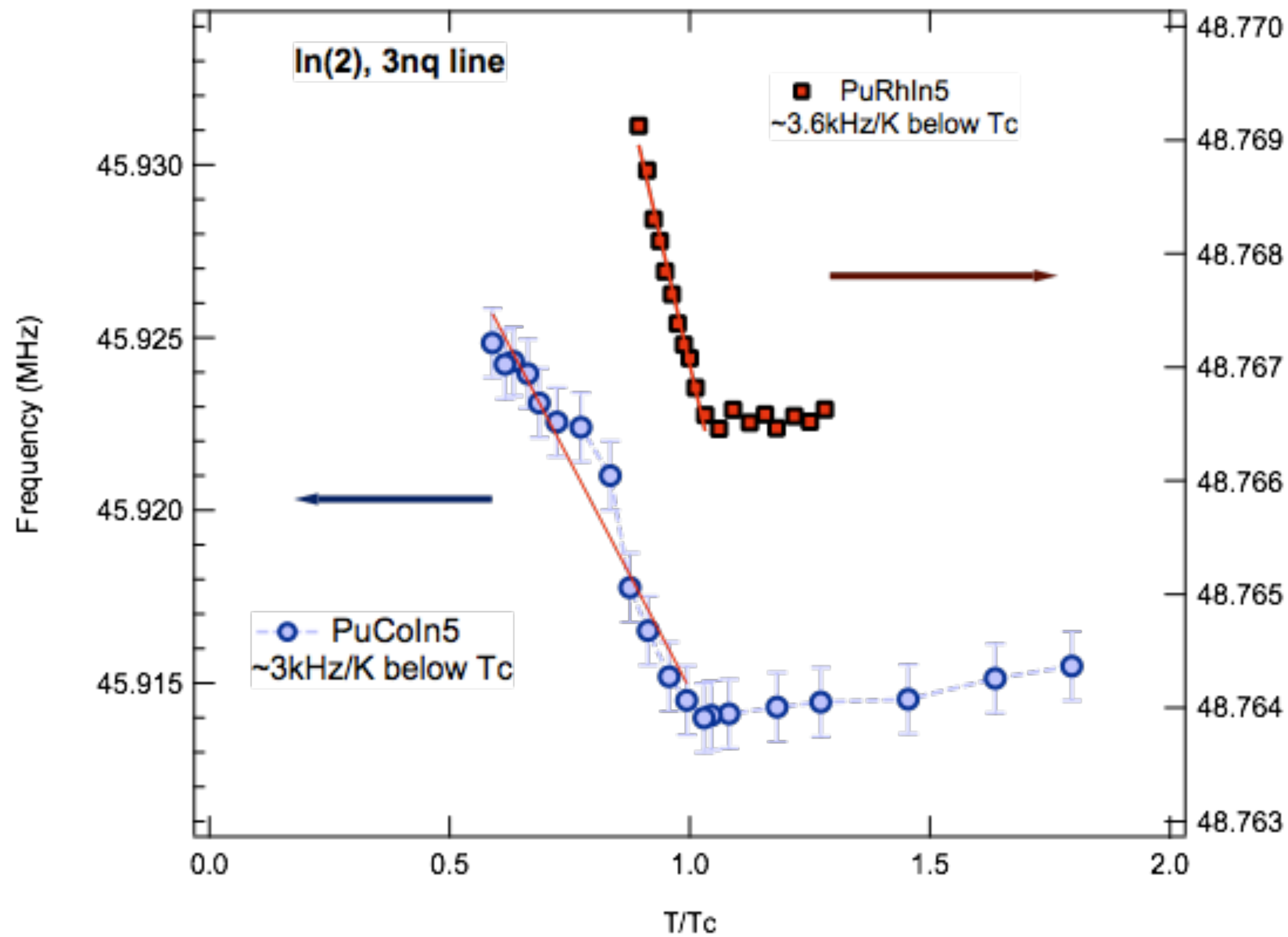
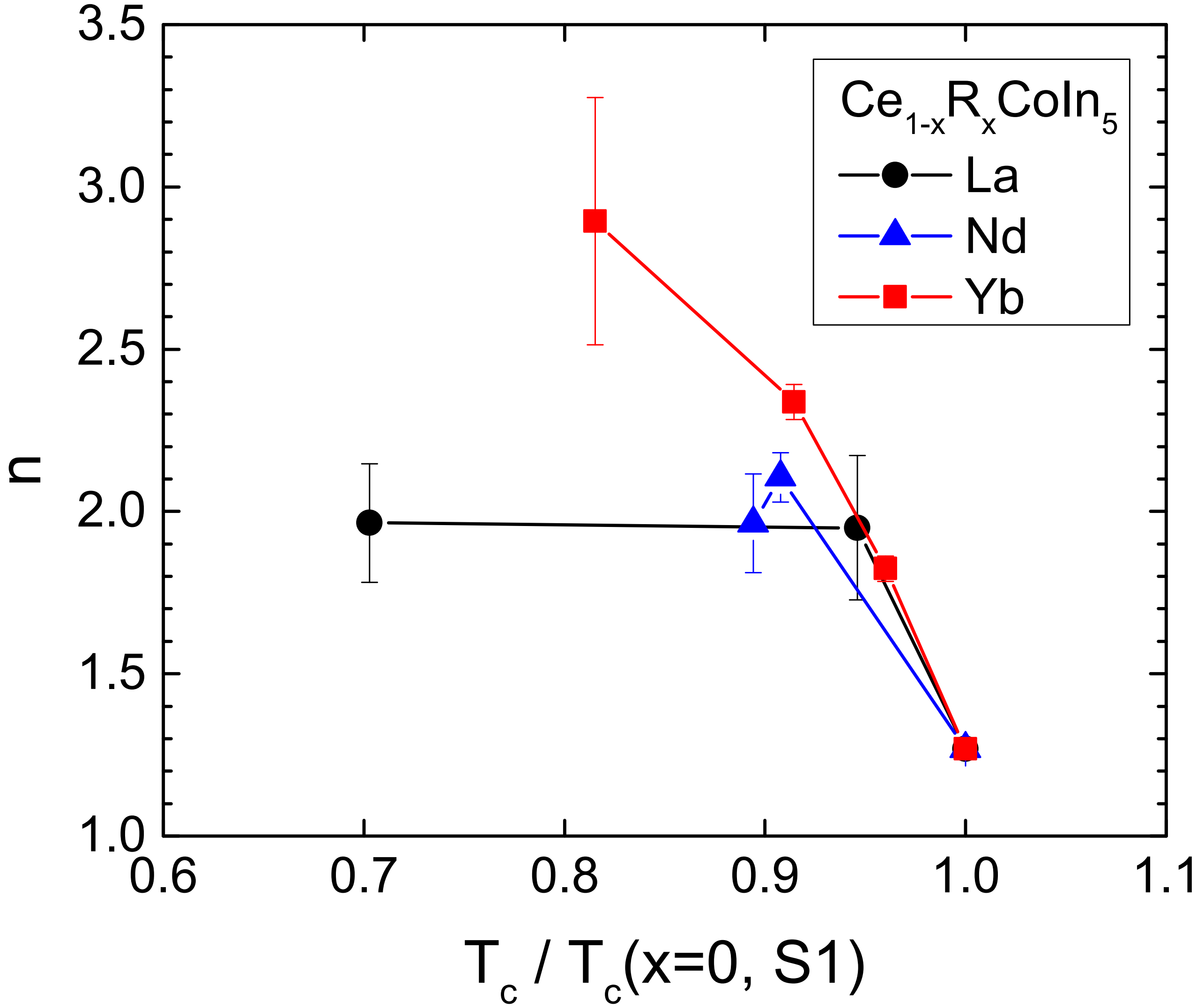
Flint et al, PRB 84, 064054, (2011)

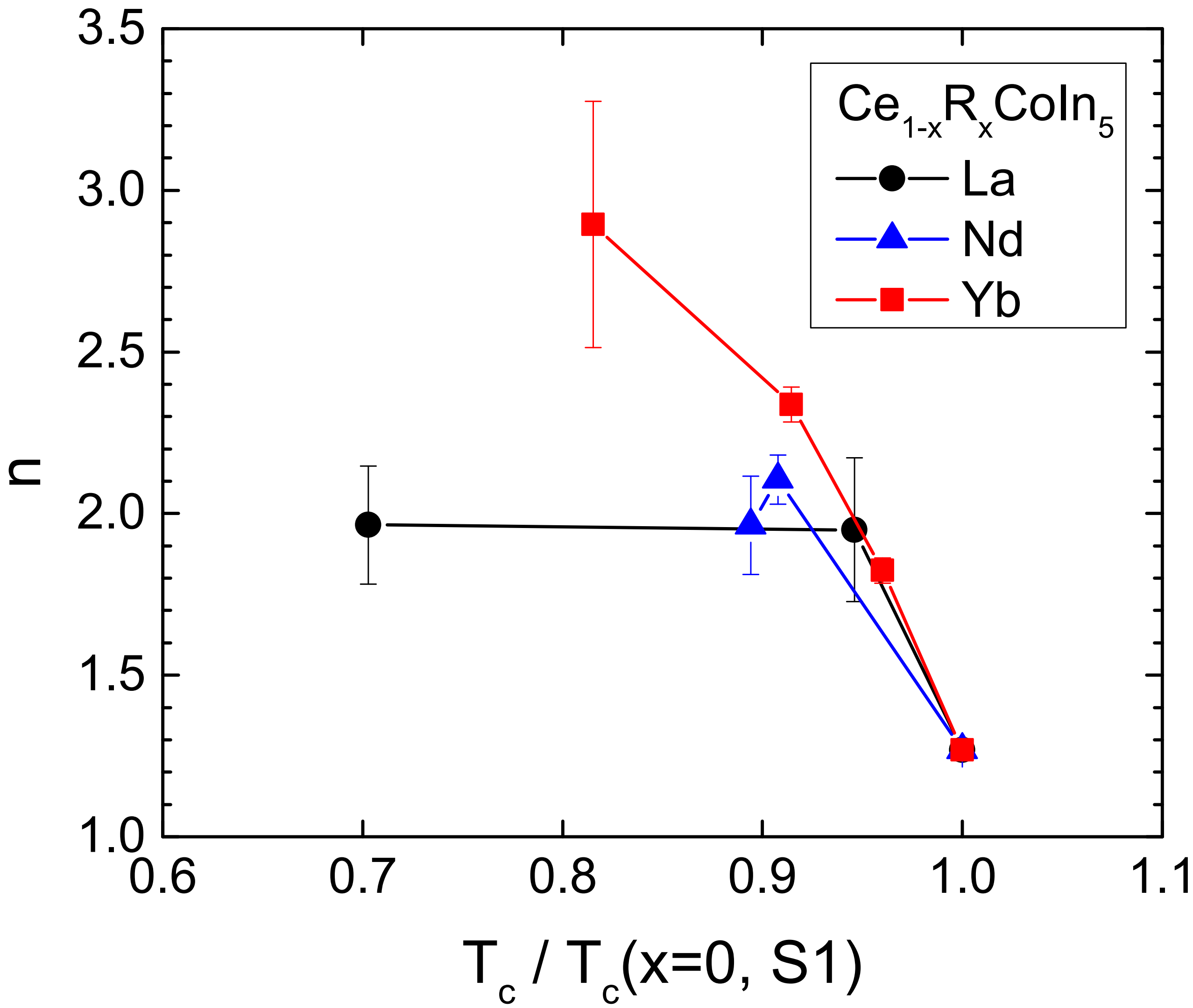


Bauer, G. Koutroulakis Yasuoko,(2014)





$$\lambda_L(T) = \lambda_L(0) + aT^n$$



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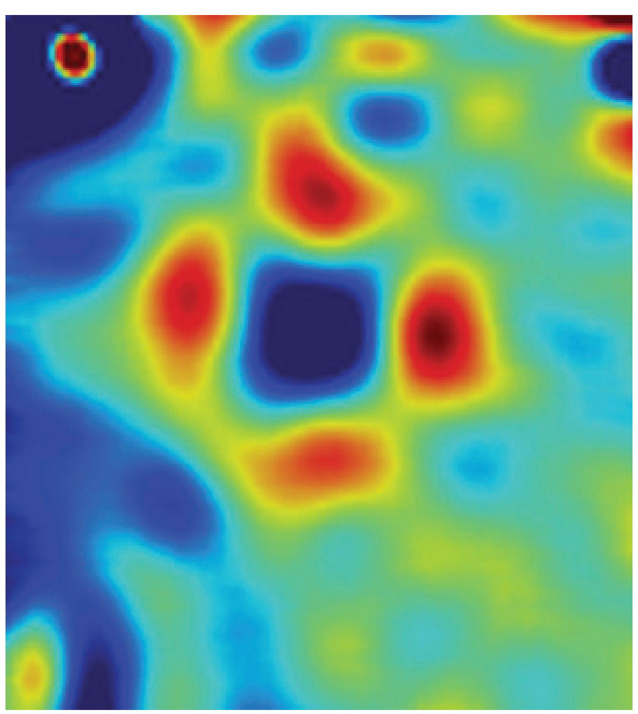
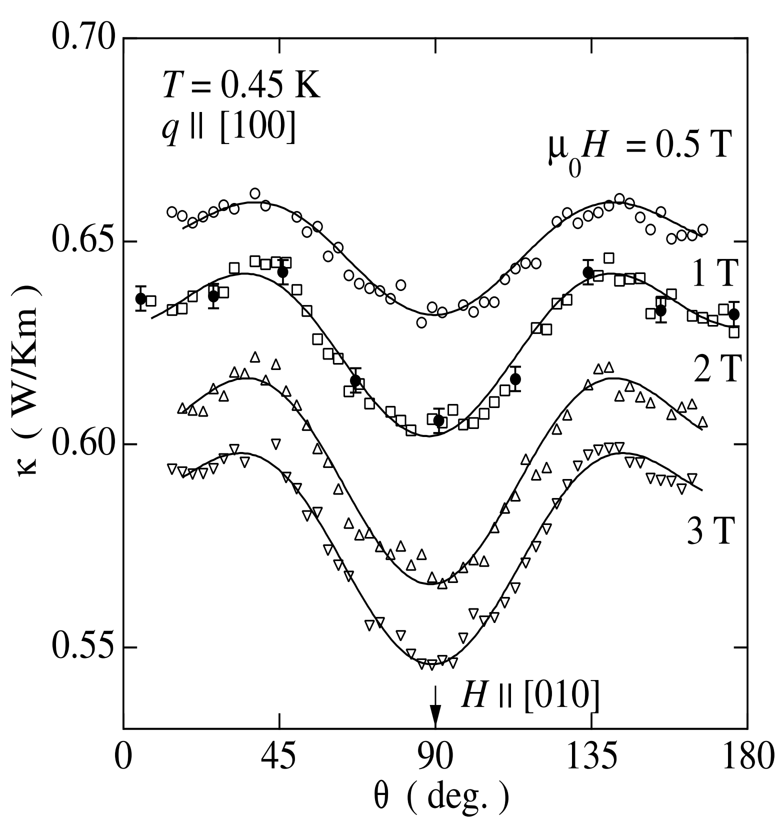
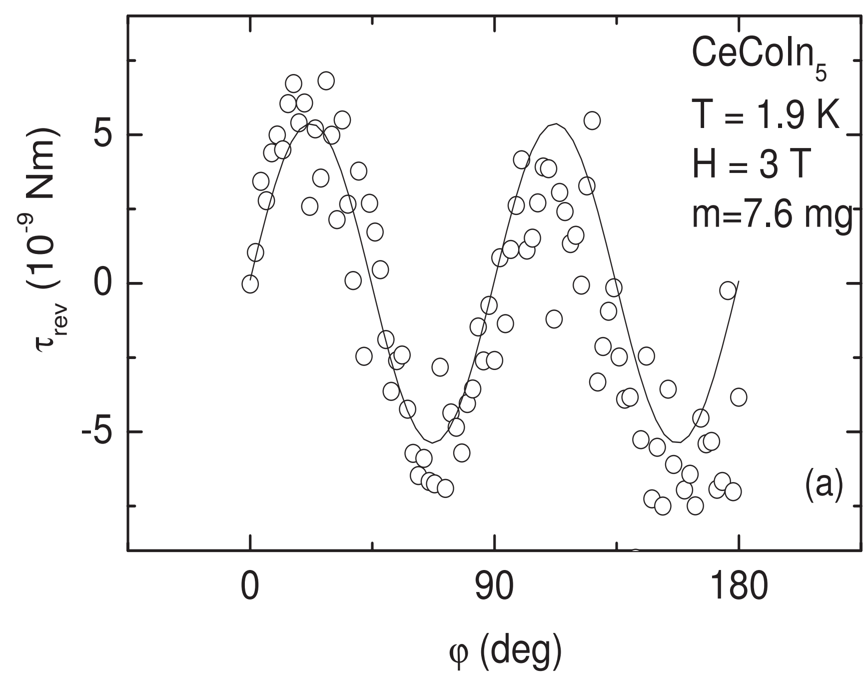


STM: B. Zhou *et al.*
Nature Phys. 9, 474 (2013)



Thermal cond:
K. Izawa *et al.* PRL 87,



Torque magnetometry:
H. Xiao *et al.* PRB 78,
014510 (2008)

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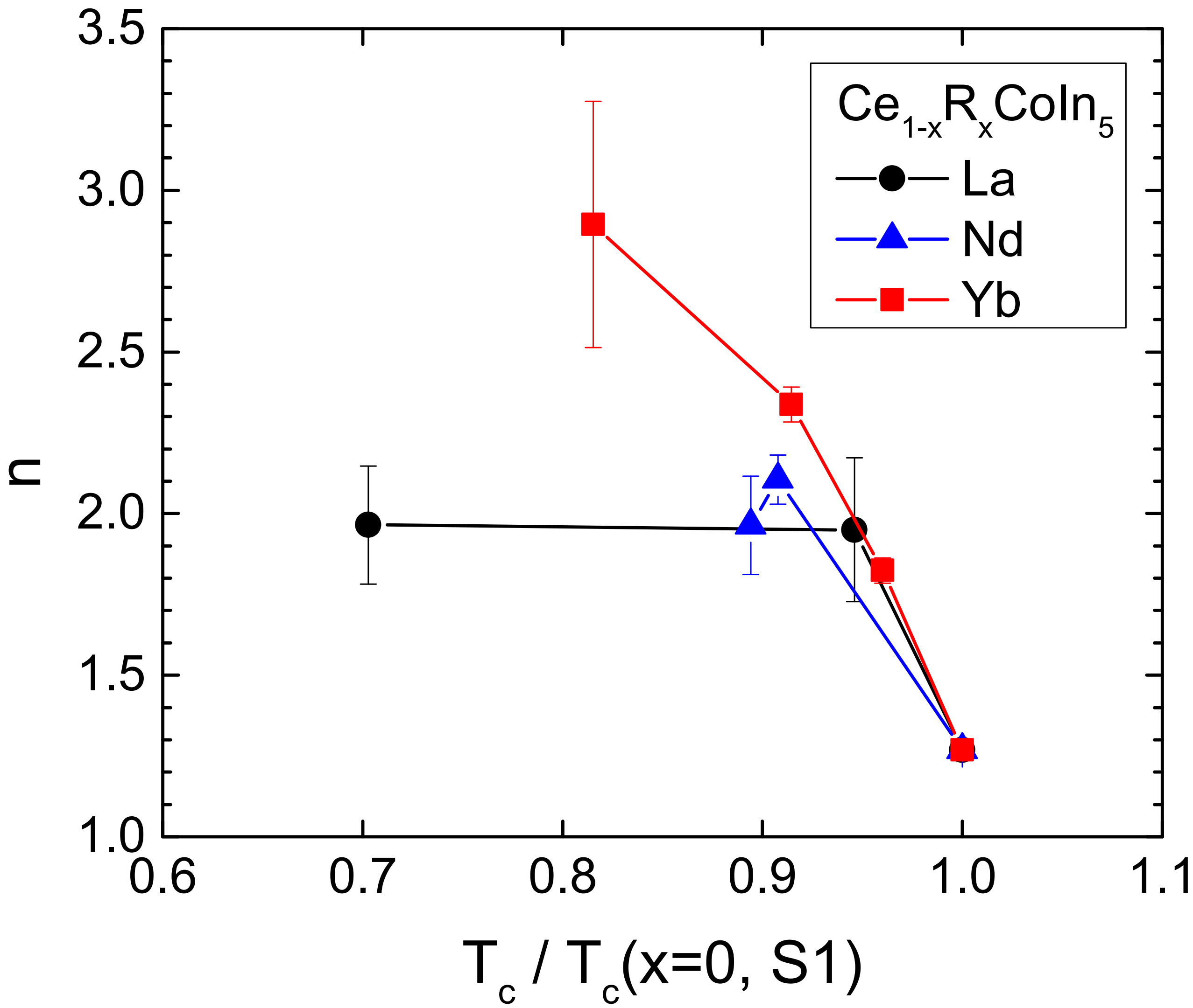

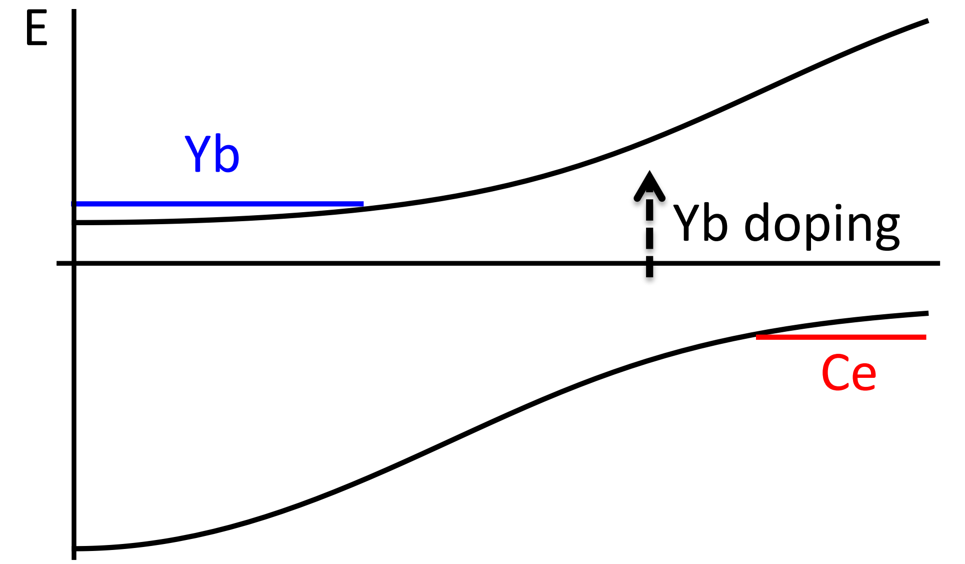

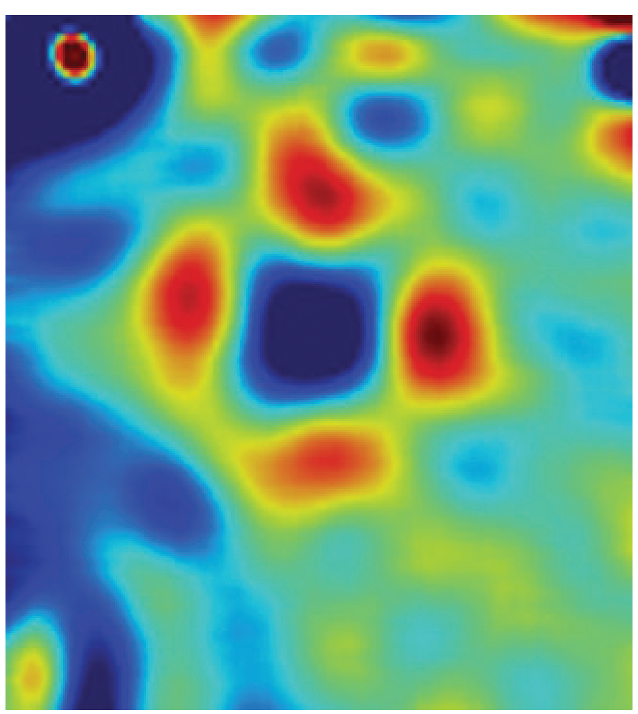

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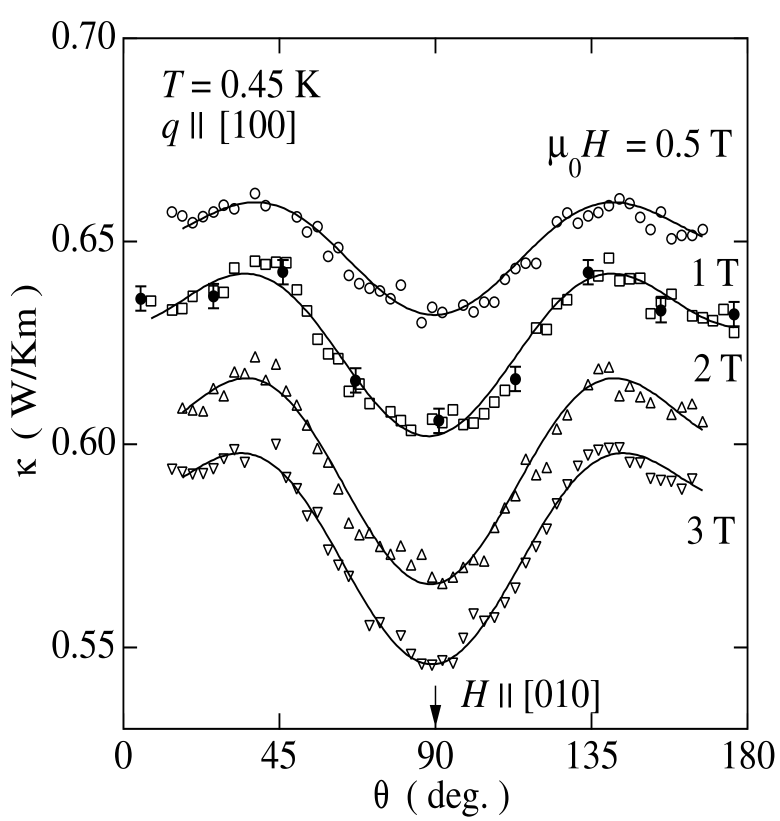

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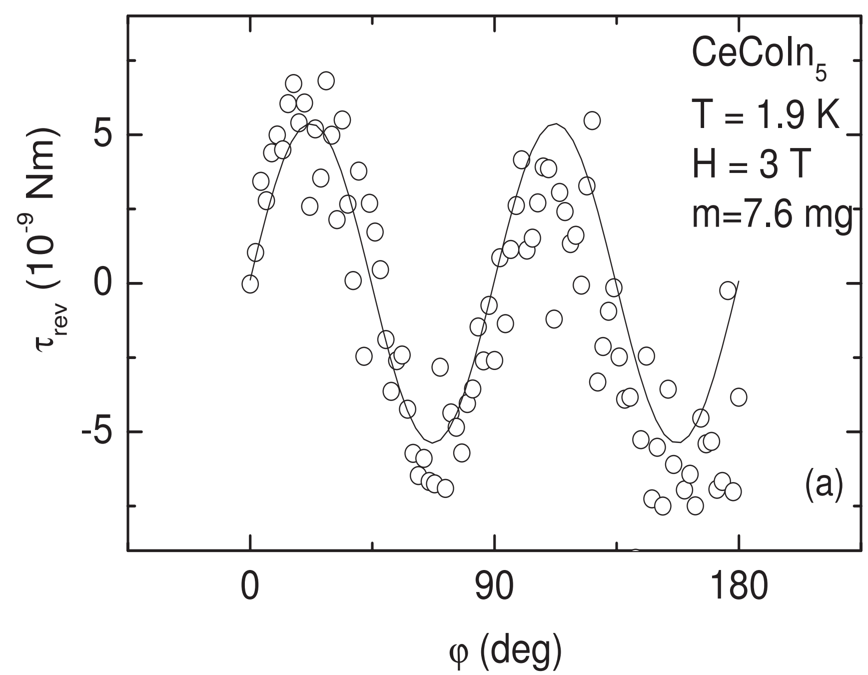

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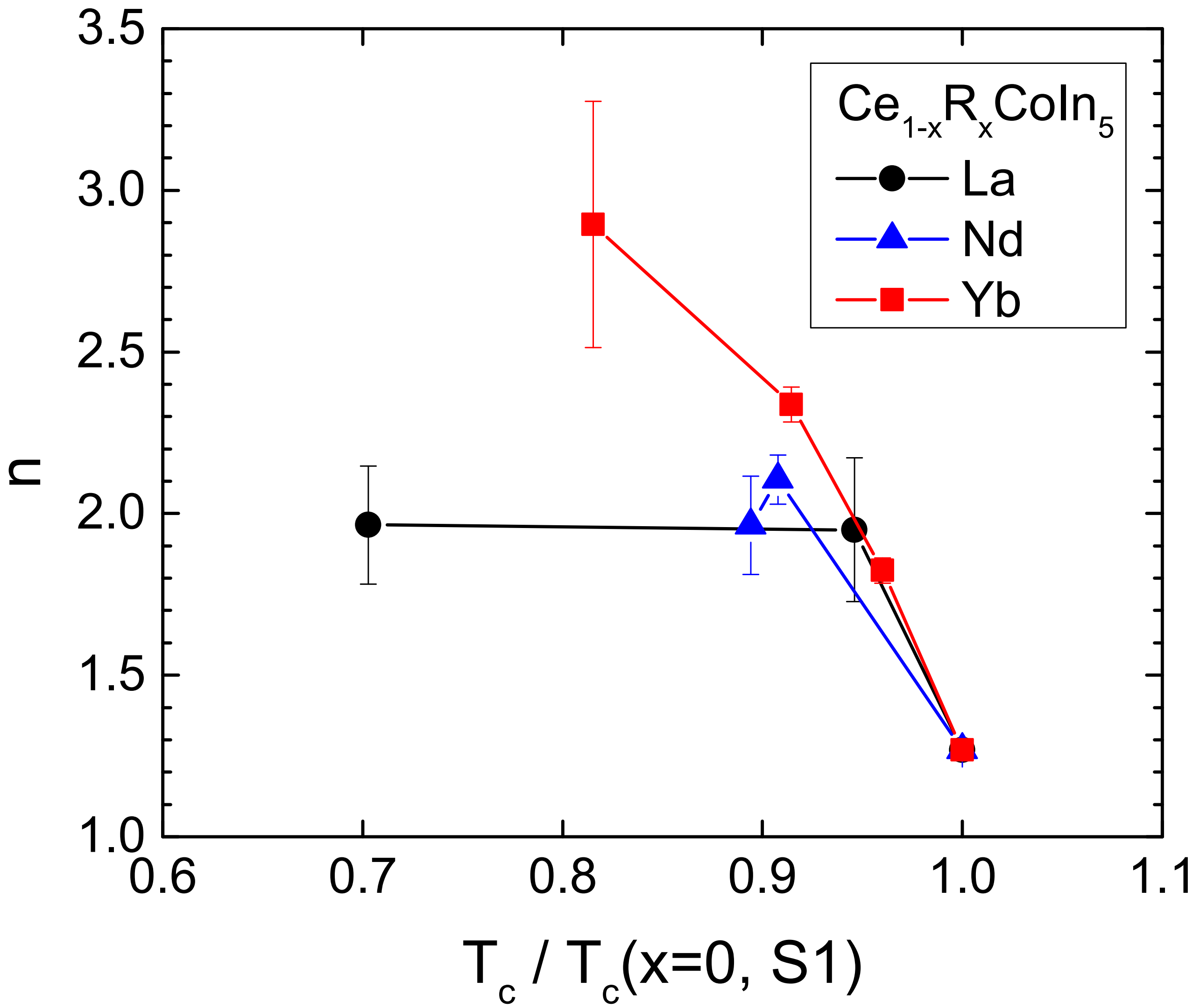

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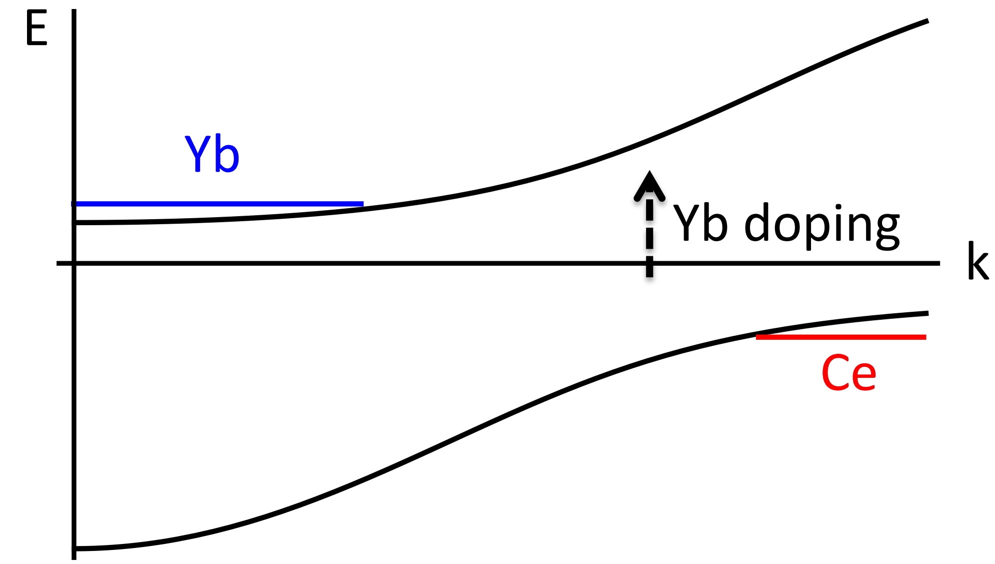
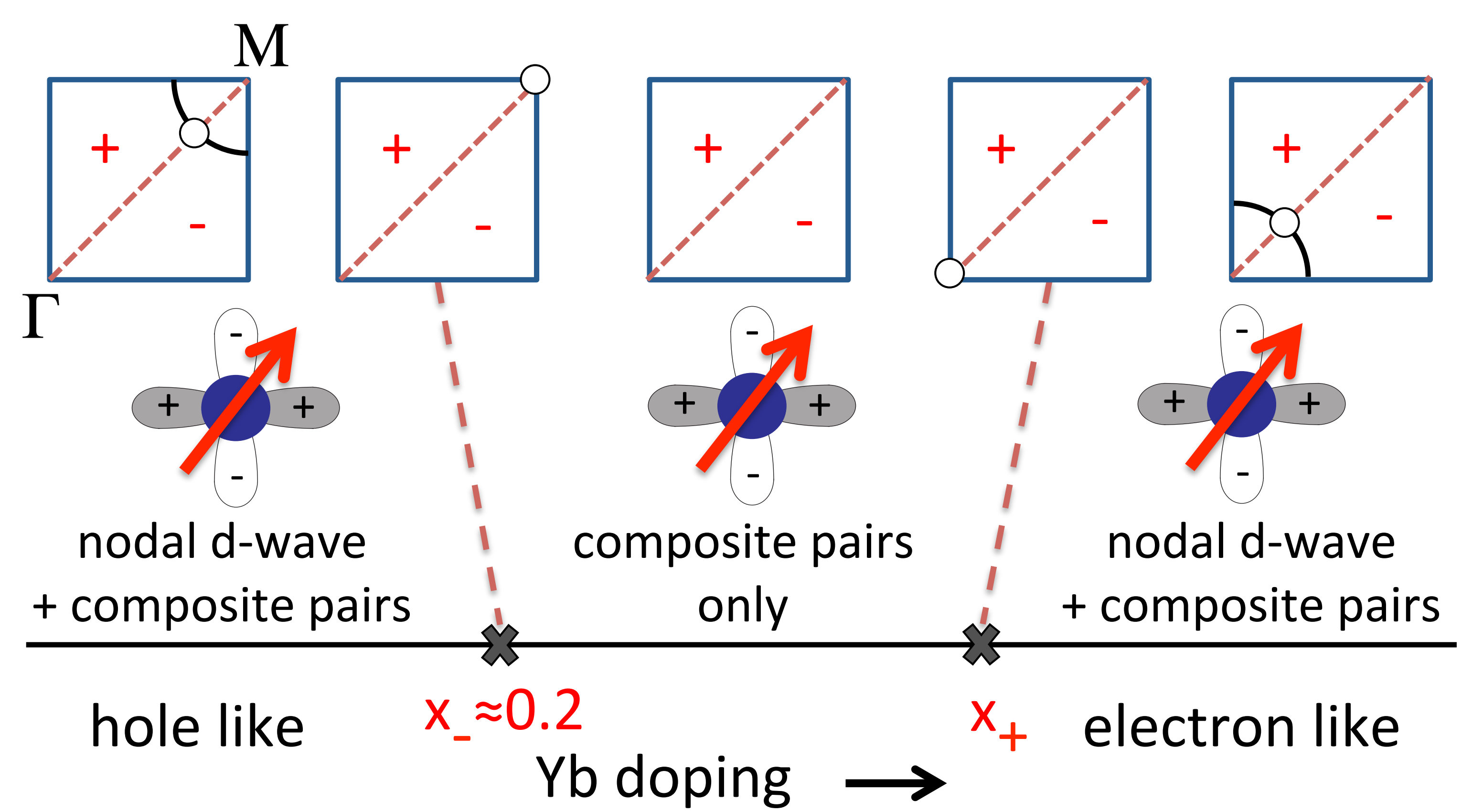




$\rho_s = \rho_0 - \alpha T^{(1-2)}$ $\rho_s = \rho_0 - \beta T^{(3-4)}$ $\rho_s = \rho_0 - \alpha T^{(1-2)}$

Erten, Flint et al, 2014

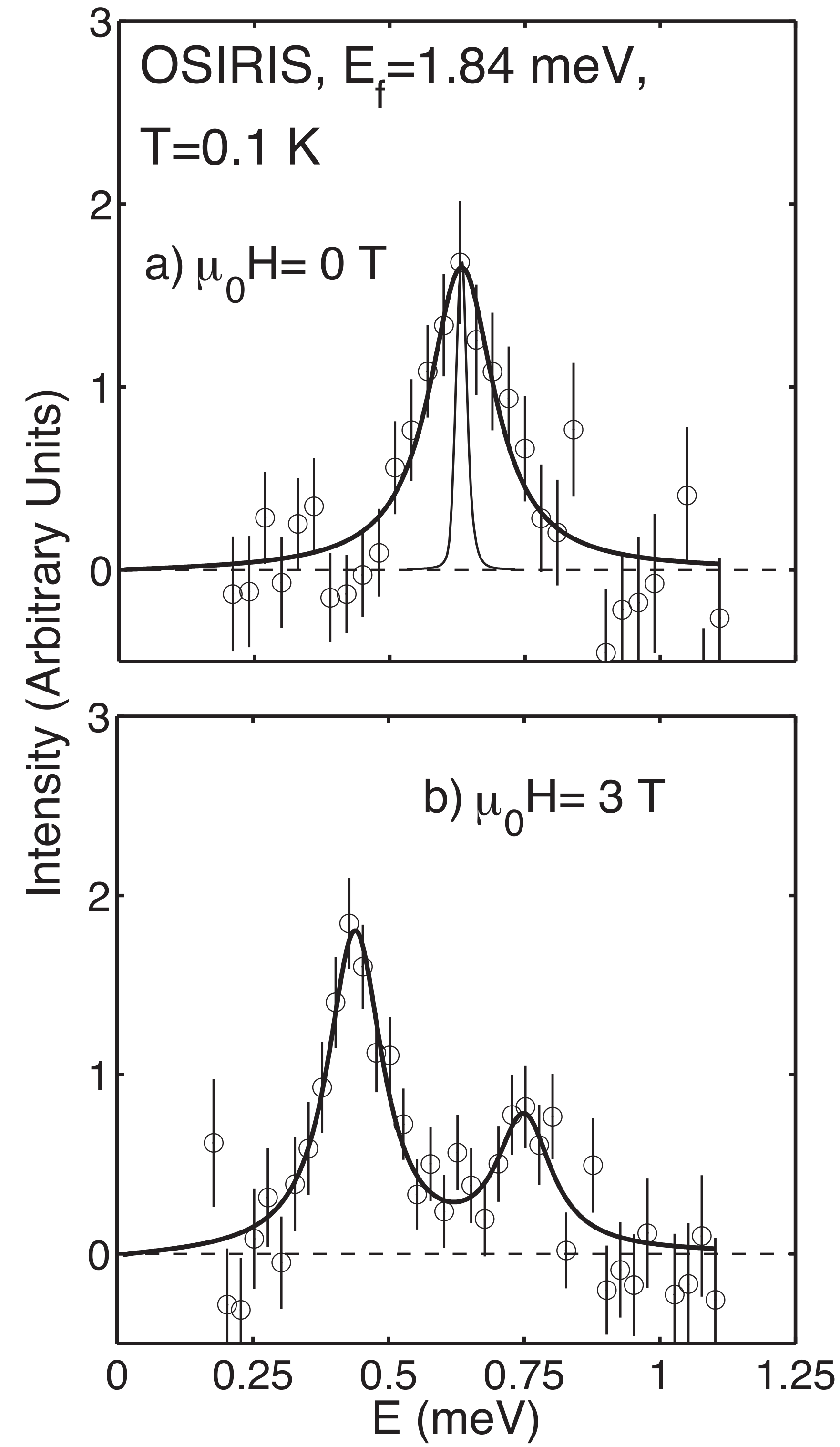
2. arXiv:1203.2189 [pdf, ps, other]

Magnetic field splitting of the spin-resonance in CeCoIn5

C. Stock, C. Broholm, Y. Zhao, F. Demmel, H.J. Kang, K. C. Rule, C. Petrovic

Comments: 5 pages, 4 figures

Subjects: **Superconductivity (cond-mat.supr-con)**



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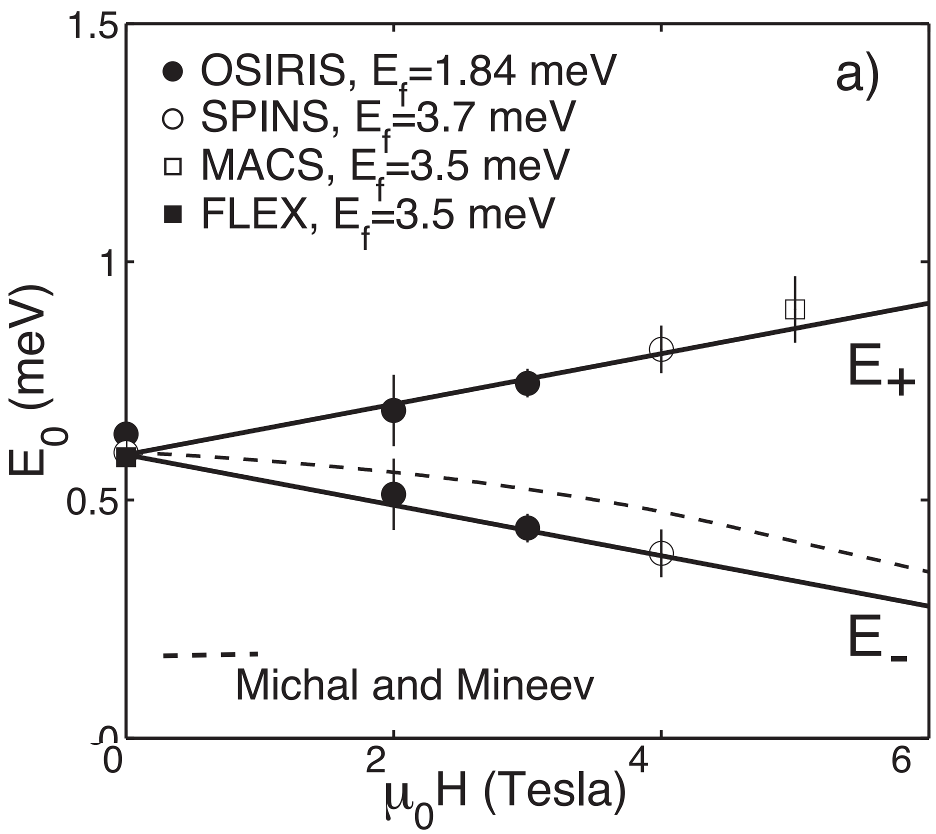
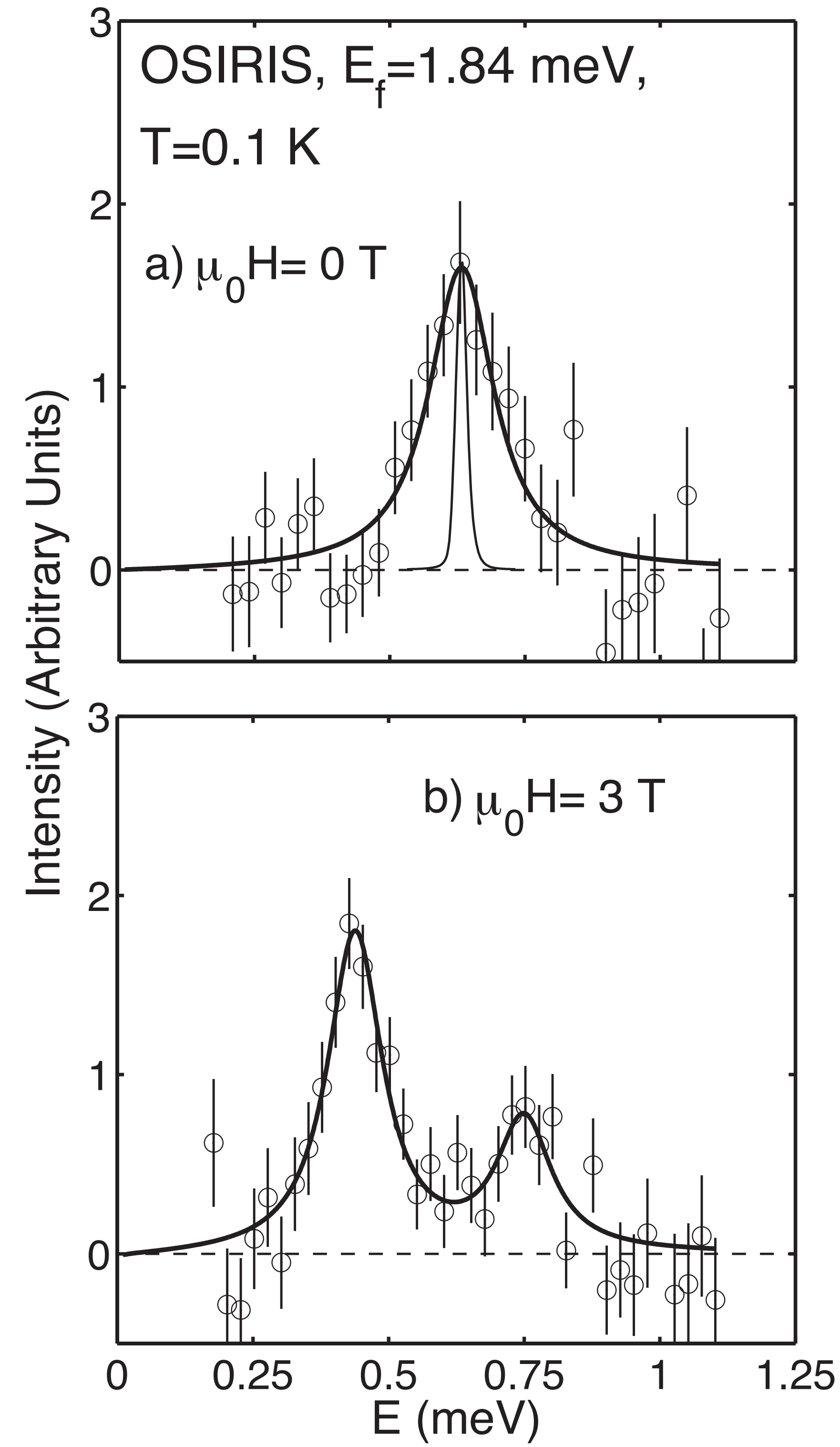


$g\mu_B H$



$g\mu_B H$

g=0.96 crystal fields give
g=0.81

Conclusions

- Convergence of magnetism and superconductivity: require new concepts over and beyond spin fluctuation theory. TREMENDOUS POTENTIAL FOR DISCOVERY.

- 115 heavy fermion superconductors suggest a new kind of pairing: composite pairing, robust against disorder on magnetic site.

- Could the same phenomenon occur in d-electron materials, at much higher temperatures?

Hastatic Order in URu_2Si_2

Hasta: Spear (Latin). A new kind of spinor order.

Piers Coleman
Center for Materials Theory
Rutgers, USA
Royal Holloway University of London

Rebecca Flint (MIT)

Premi Chandra (Rutgers)

P.Chandra, R. Flint and P.C
arXiv:1404.5920, *PRB 86*, 155155 (2012).
doi:10.1038/nature11820

Wills Lab, Bristol U
19 Jun 2014

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- Motivation/Overview
- Hidden order in URu_2Si_2
- Giant Ising Anisotropy and implications
- Hastatic Order.

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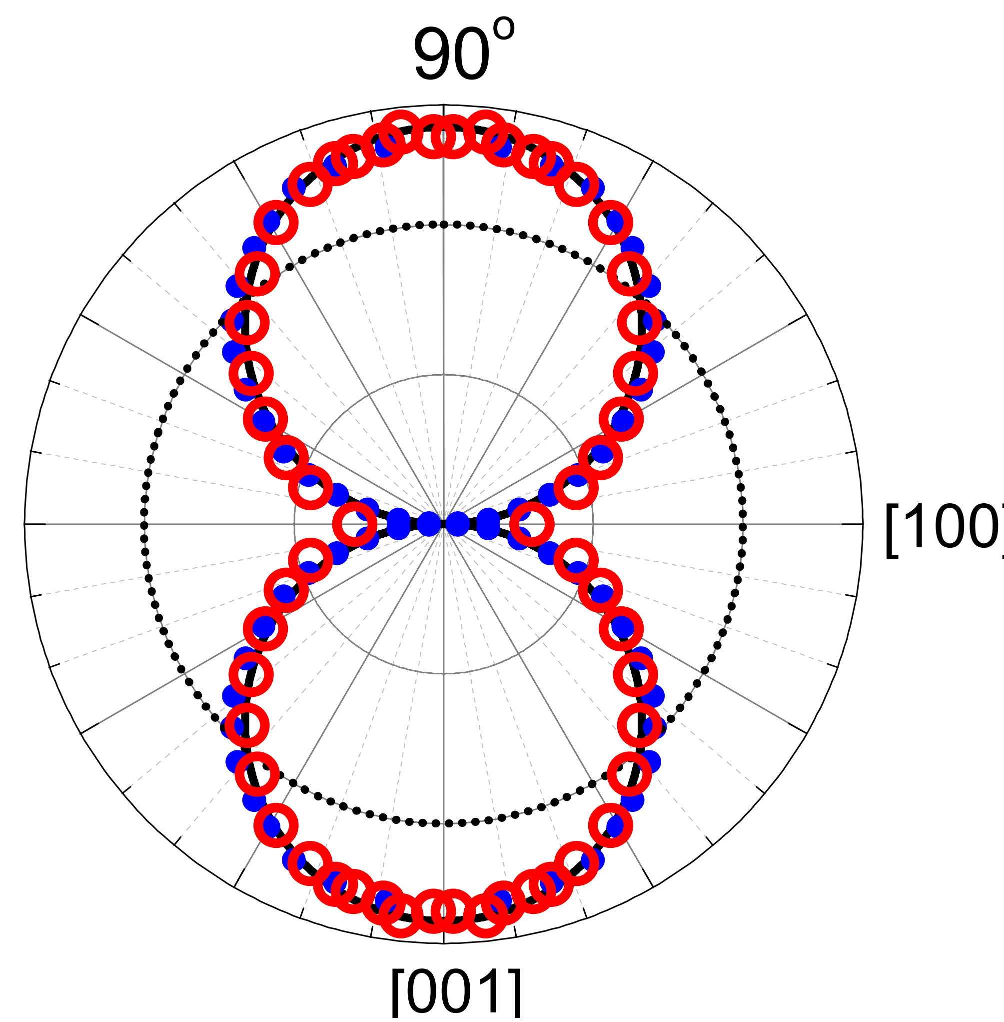

Altarawneh et al., PRL 108, 066407 (2012)

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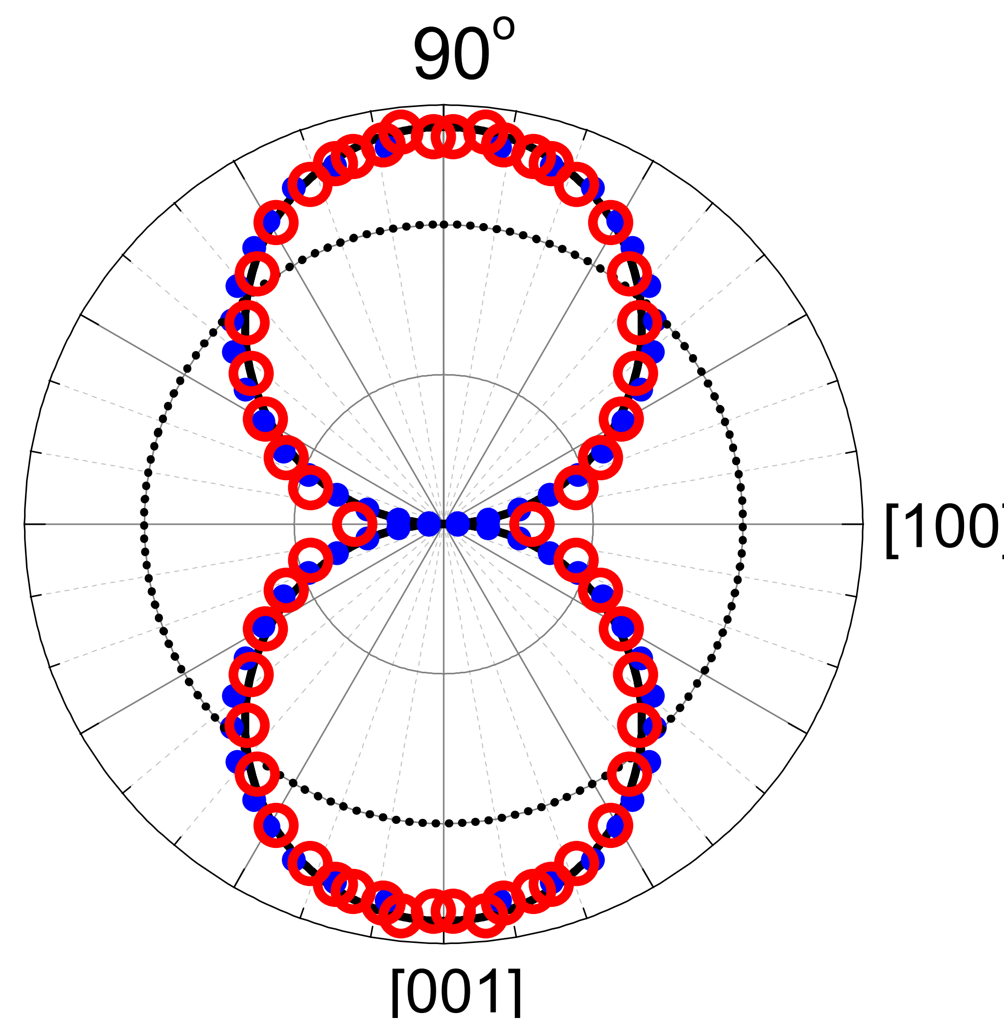

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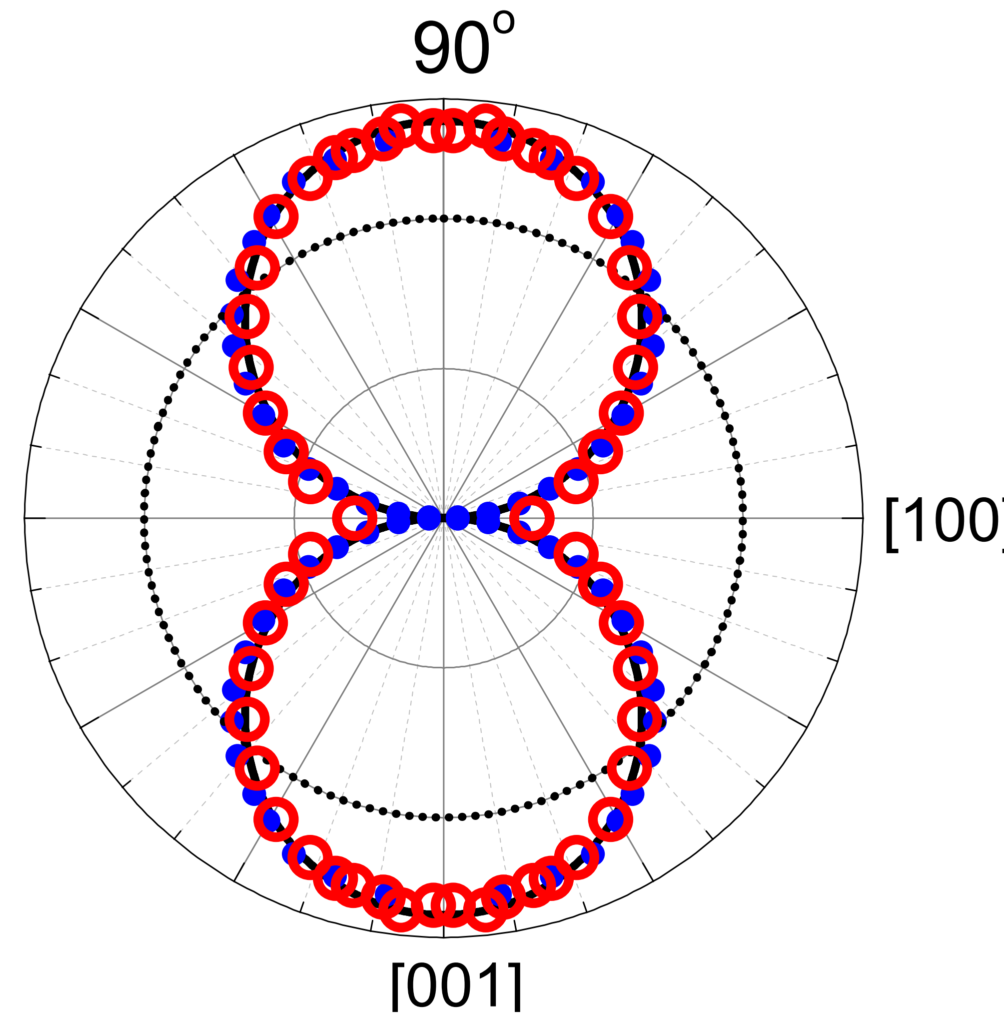
Take-home:
Observation of (Perfect) Ising Quasiparticles



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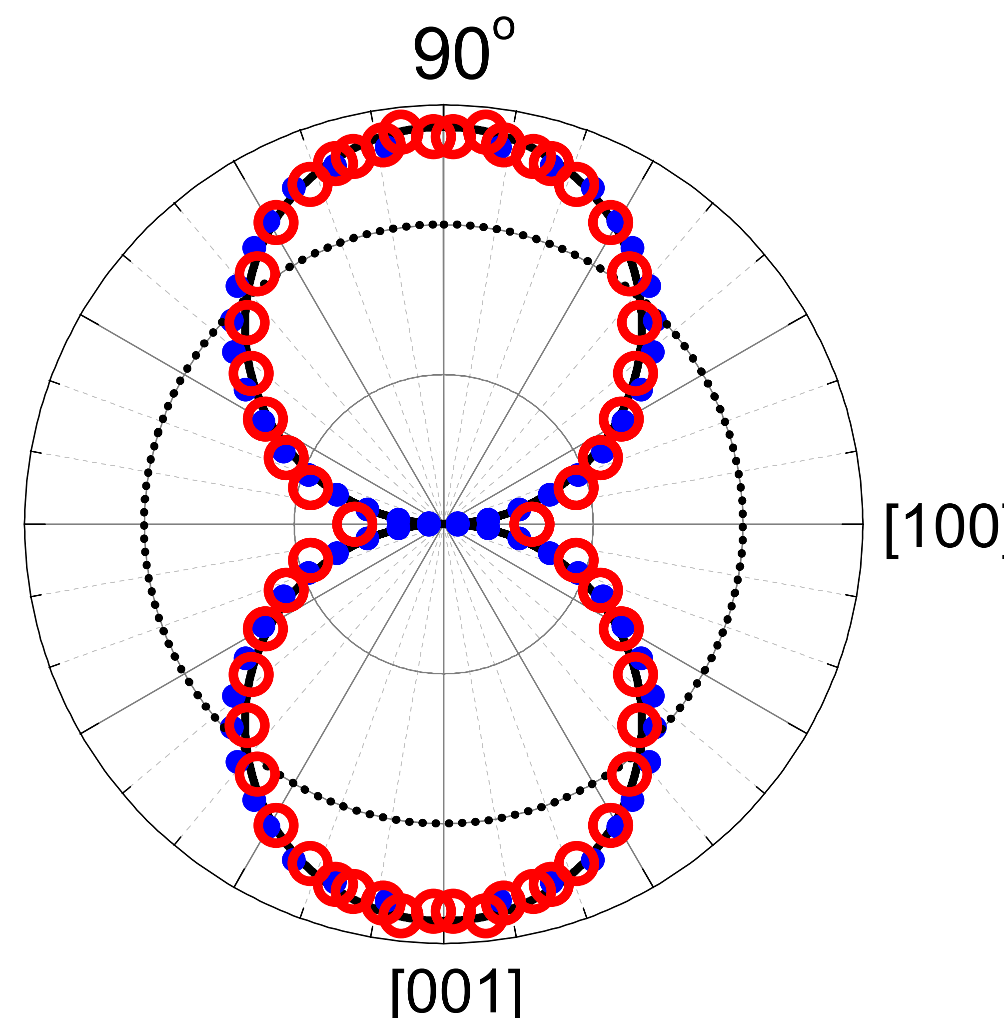
Take-home:
Observation of (Perfect) Ising Quasiparticles

$\downarrow$

Many body hybridization

Spin 1/2 e $\rightleftharpoons$ <u>Integer spin</u> (J_z=±1) Doublets



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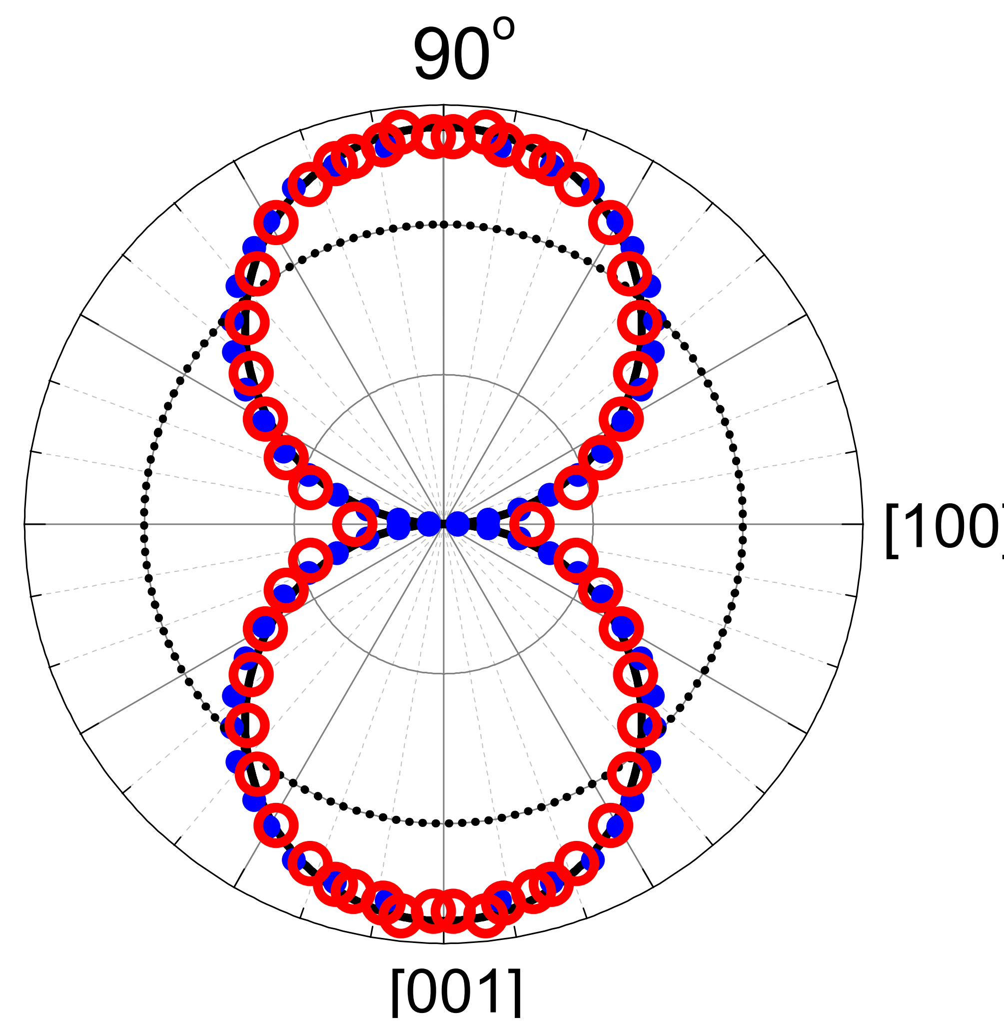
Take-home:
Observation of (Perfect) Ising Quasiparticles

↓

Many body hybridization
Spin 1/2 e ⇄ <u>Integer spin</u> ($J_z=\pm1$) Doublets

↓

Proposal: Order parameter is a <u>spinor</u>



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Take-home:
Observation of (Perfect) Ising Quasiparticles

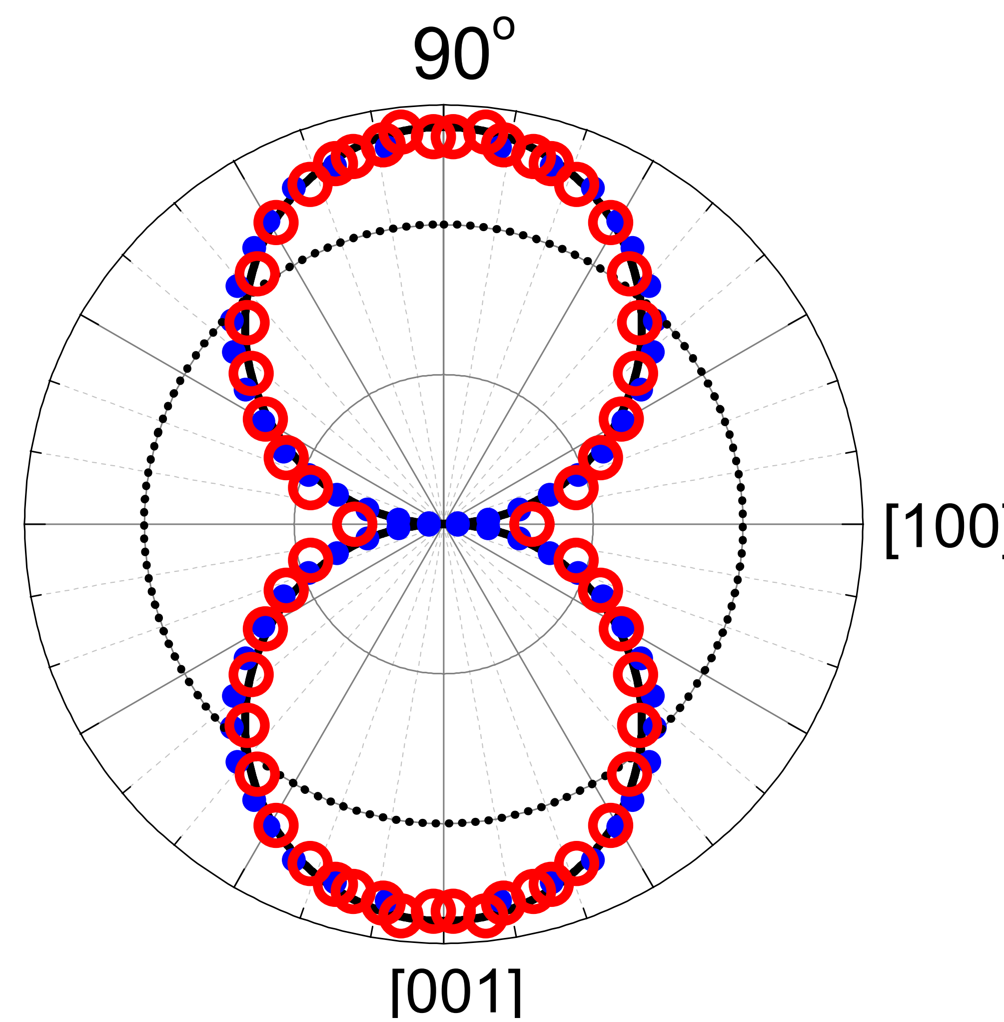
↓

Many body hybridization
Spin 1/2 e ⇌ Integer spin (J_z=±1) Doublets

↓

Proposal: Order parameter is a spinor
(mixing J & J+1/2, breaking double time reversal)

$$\Theta^2 = (-1)^{2J}$$



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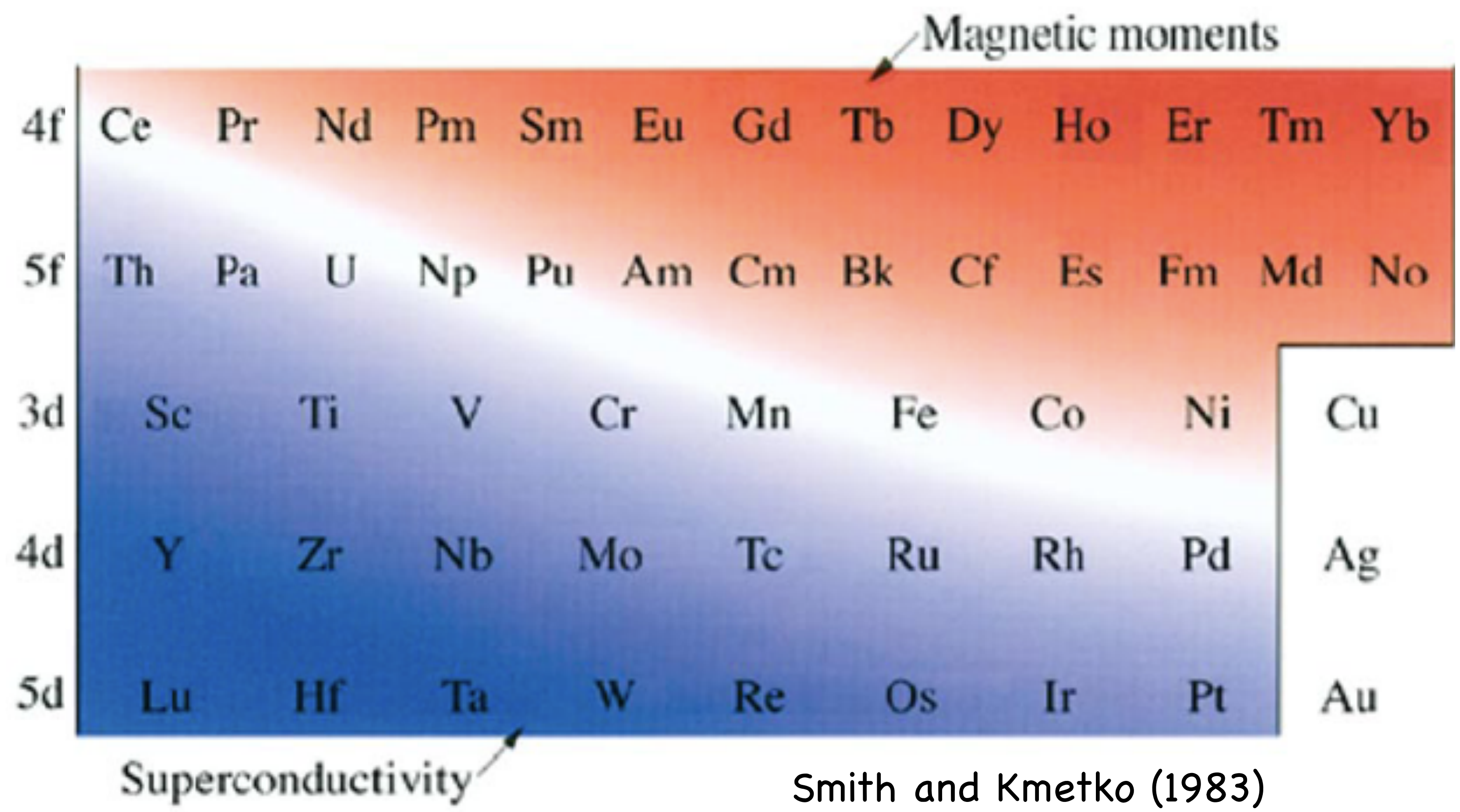
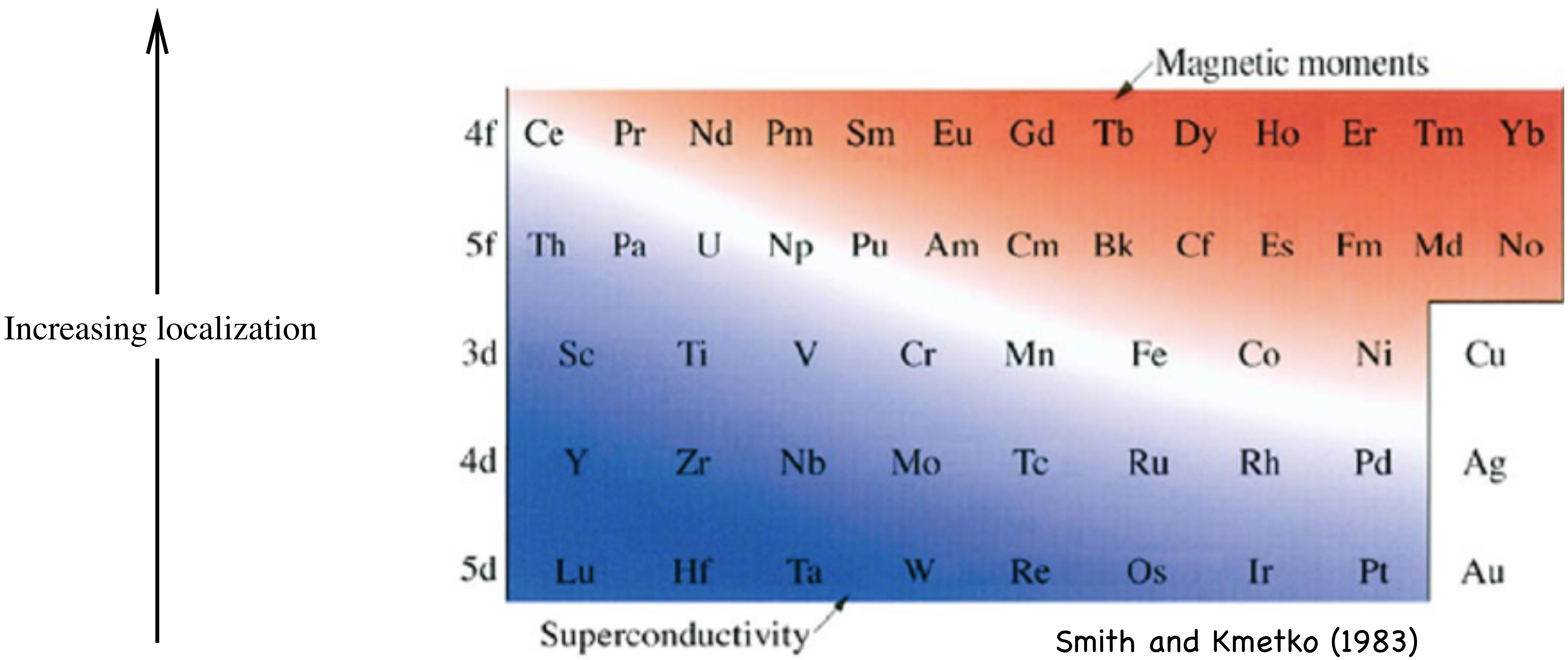
URu_2Si_2: The Hidden Order Mystery

Kmetko-Smith Phase Diagram



Smith and Kmetko (1983)

Kmetko-Smith Phase Diagram



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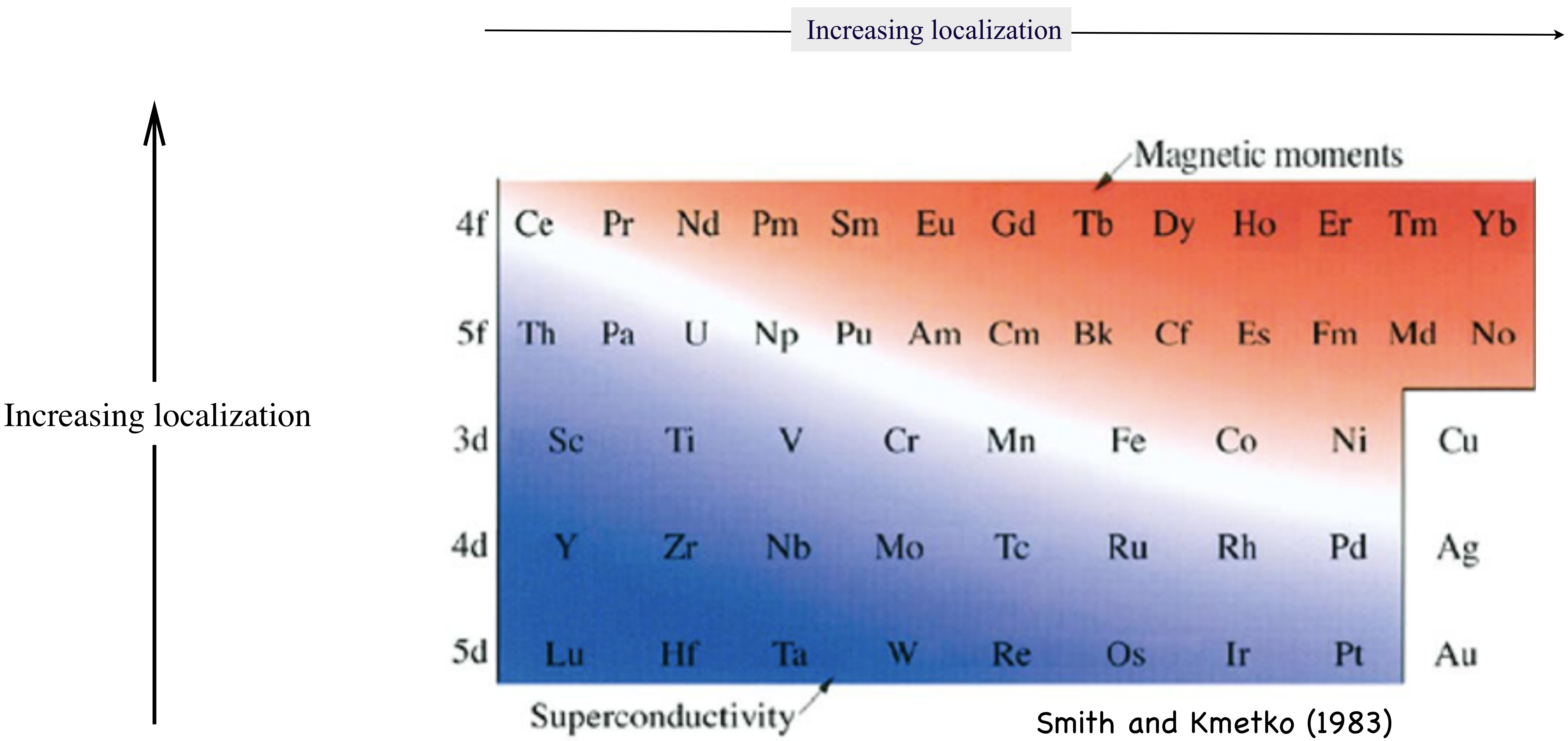

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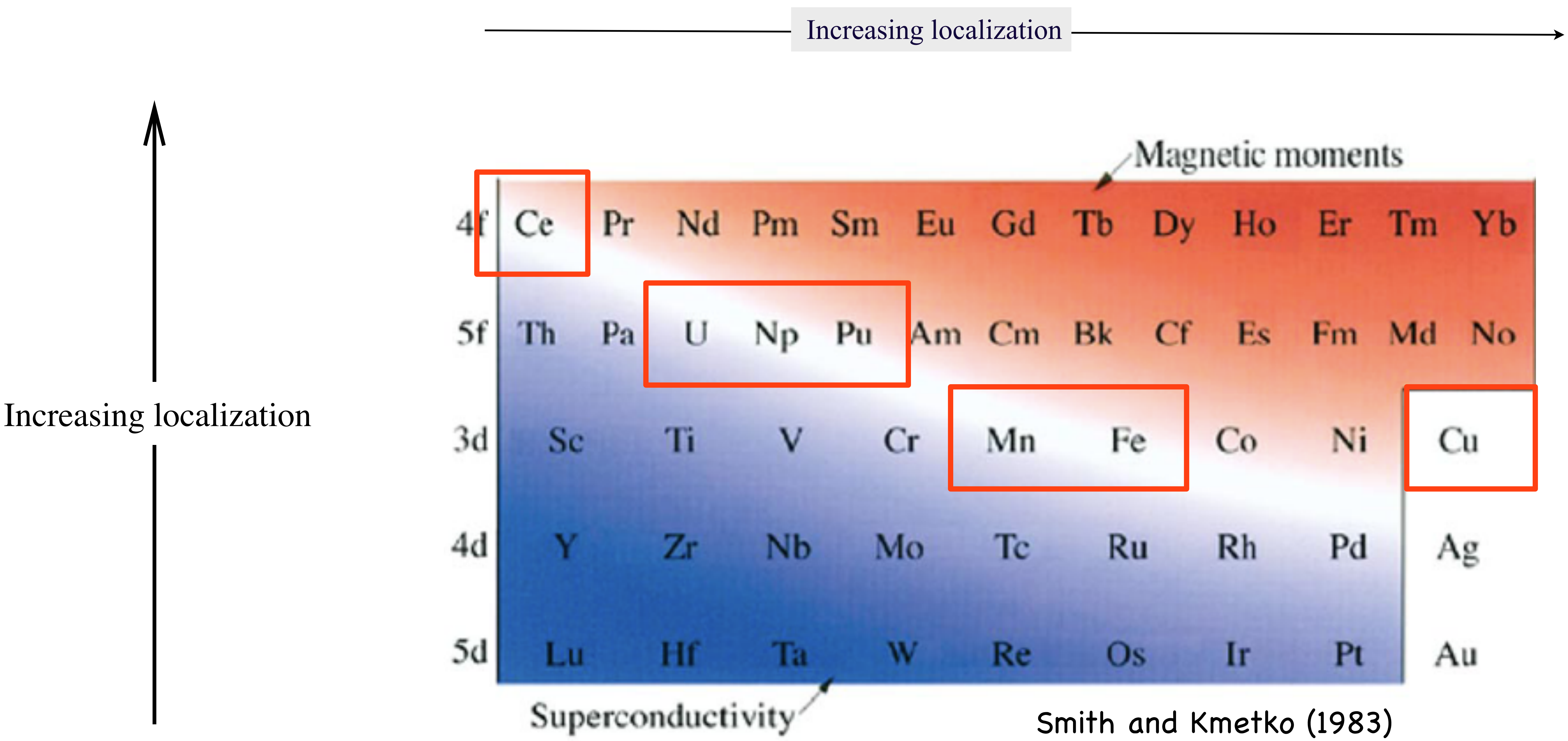

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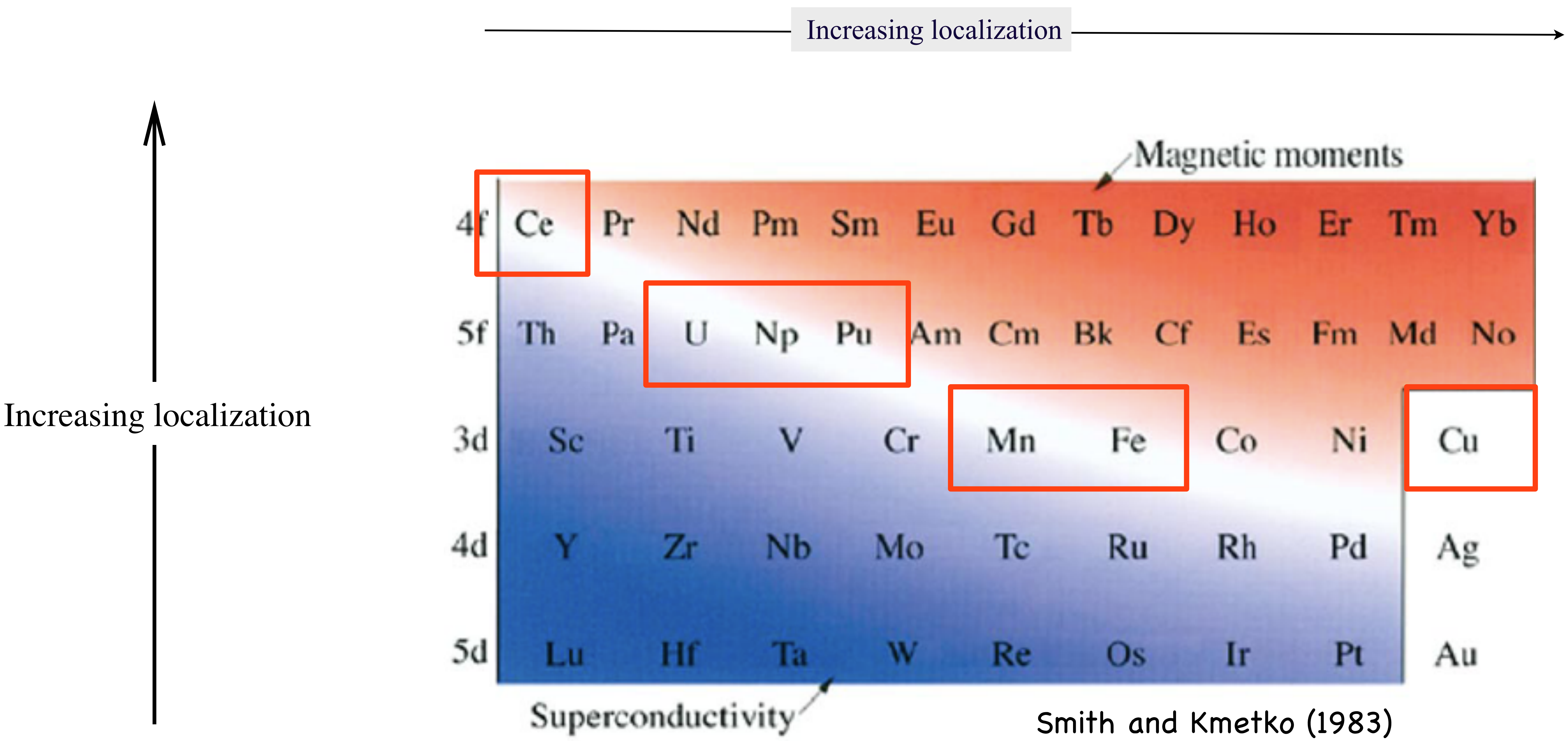
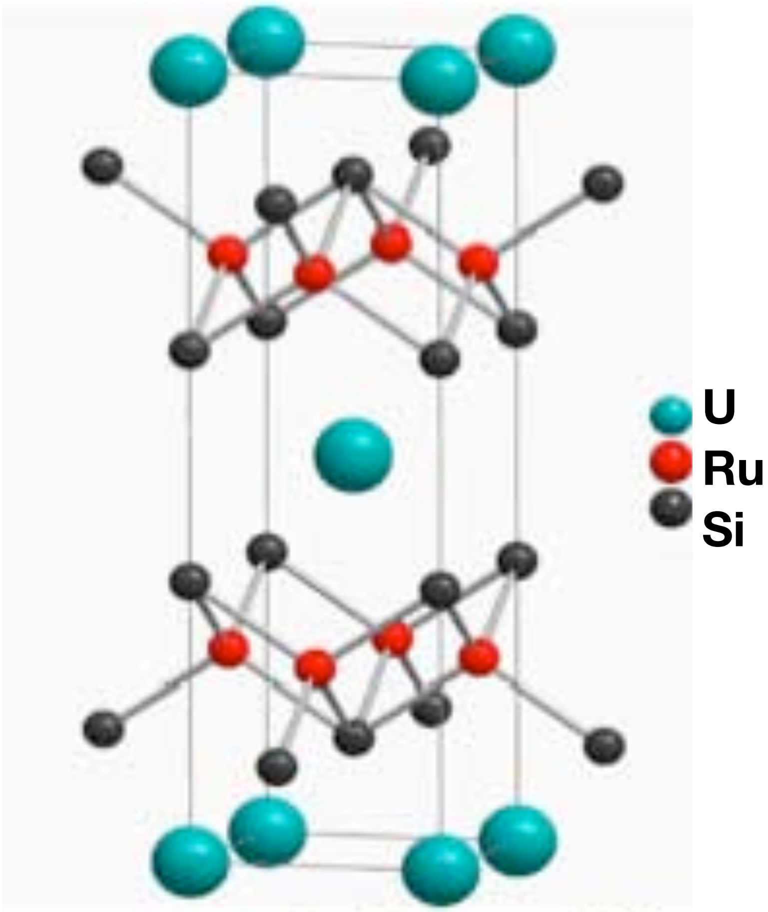


Smith and Kmetko (1983)

A lot of action at the brink of localization.

Hidden Order in URu_2Si_2



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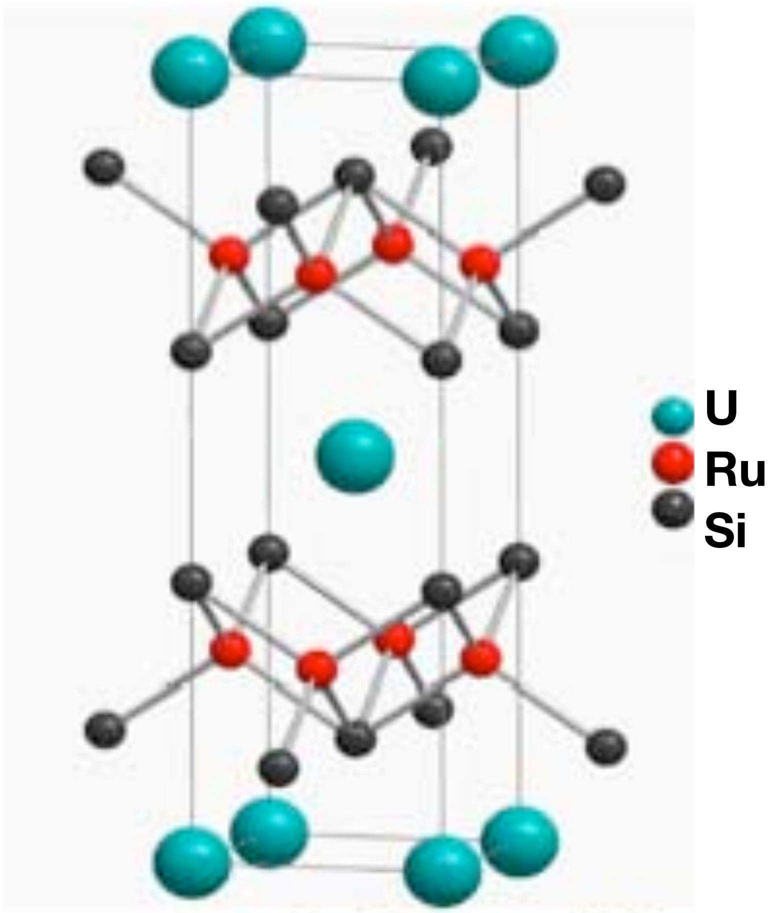

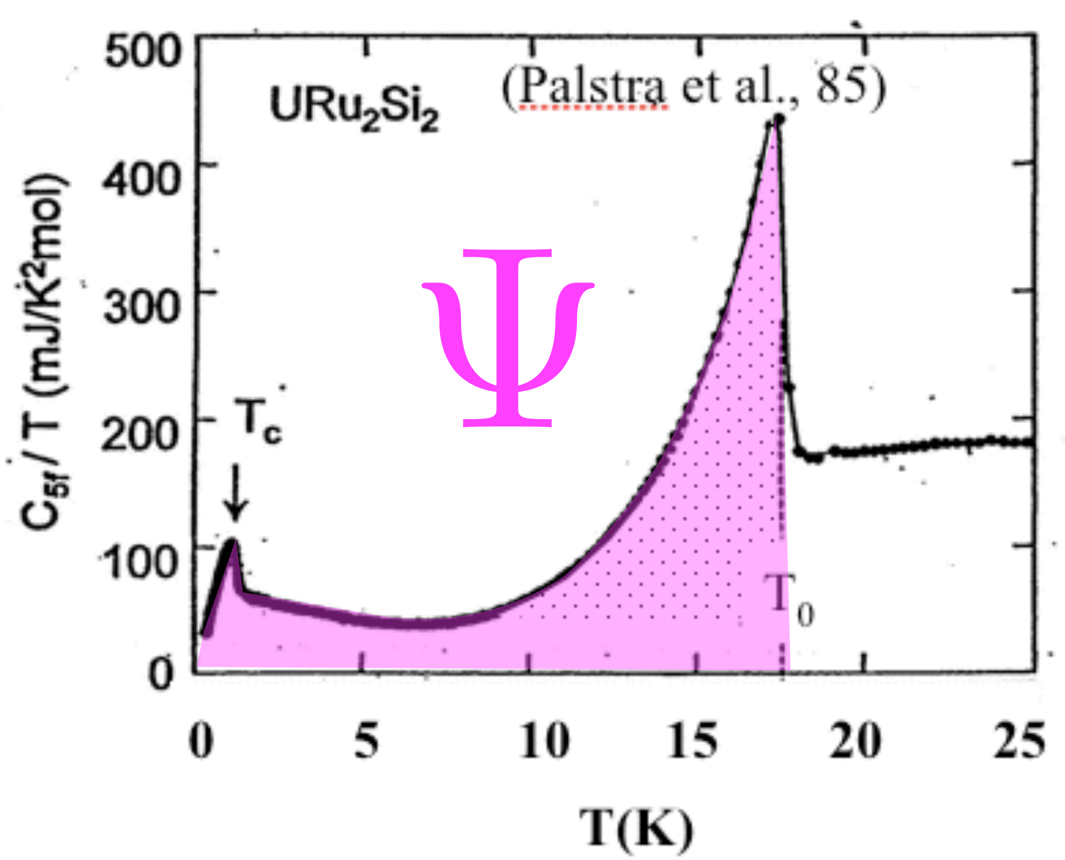

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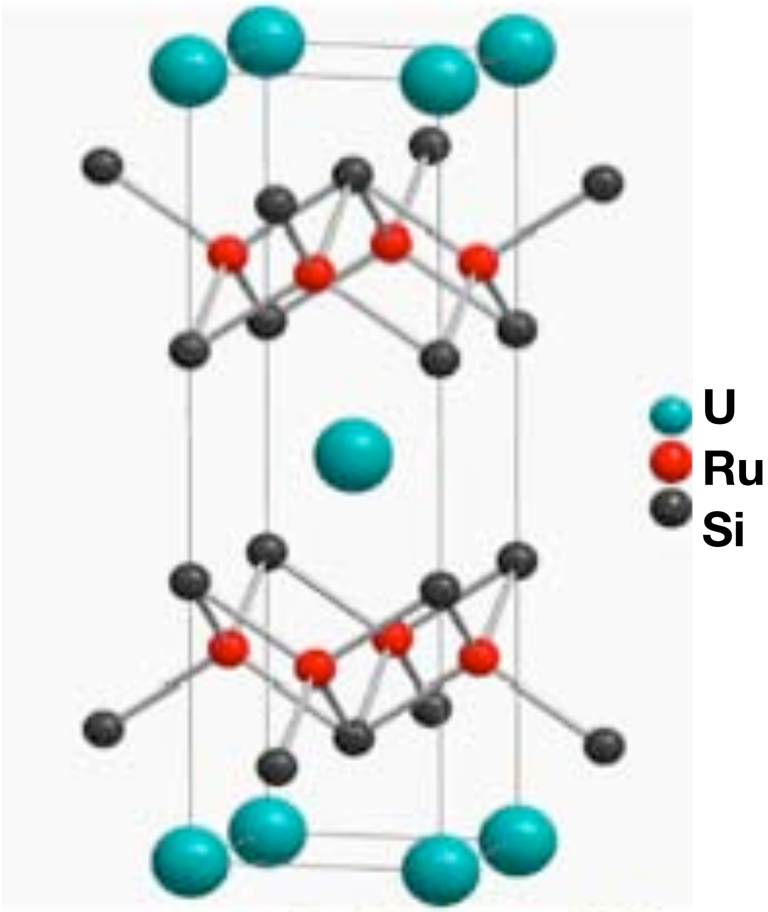
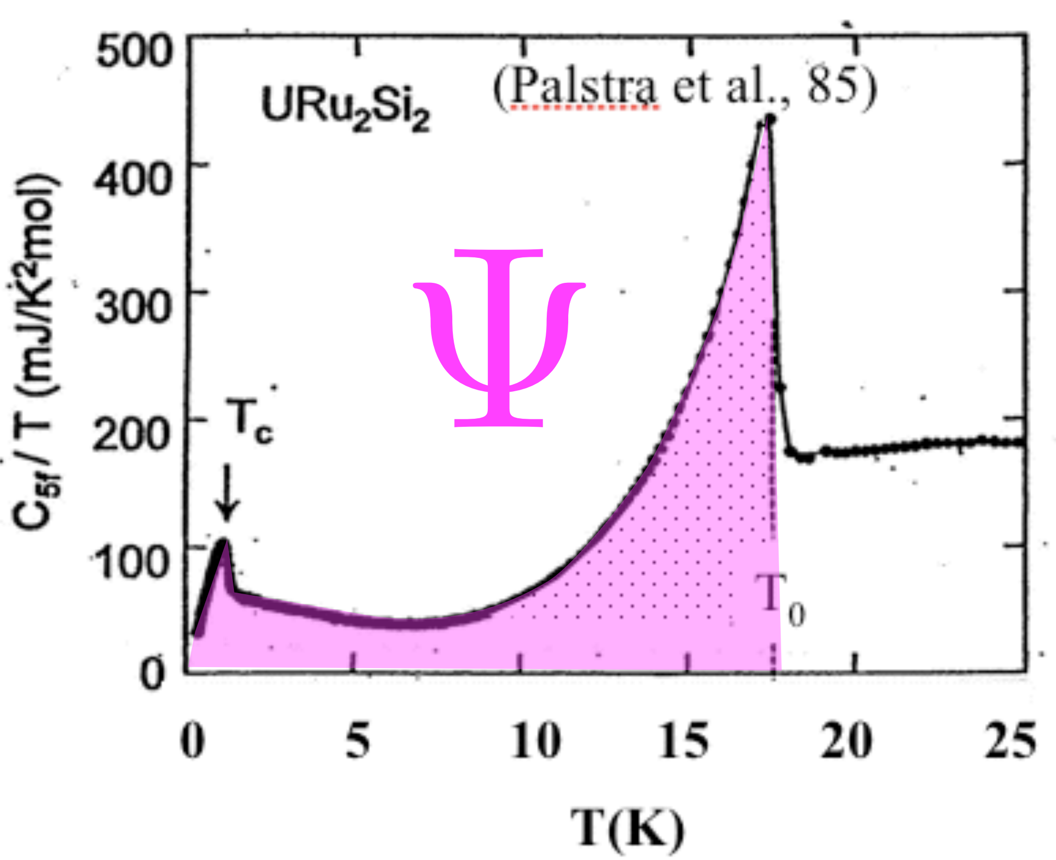


$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$



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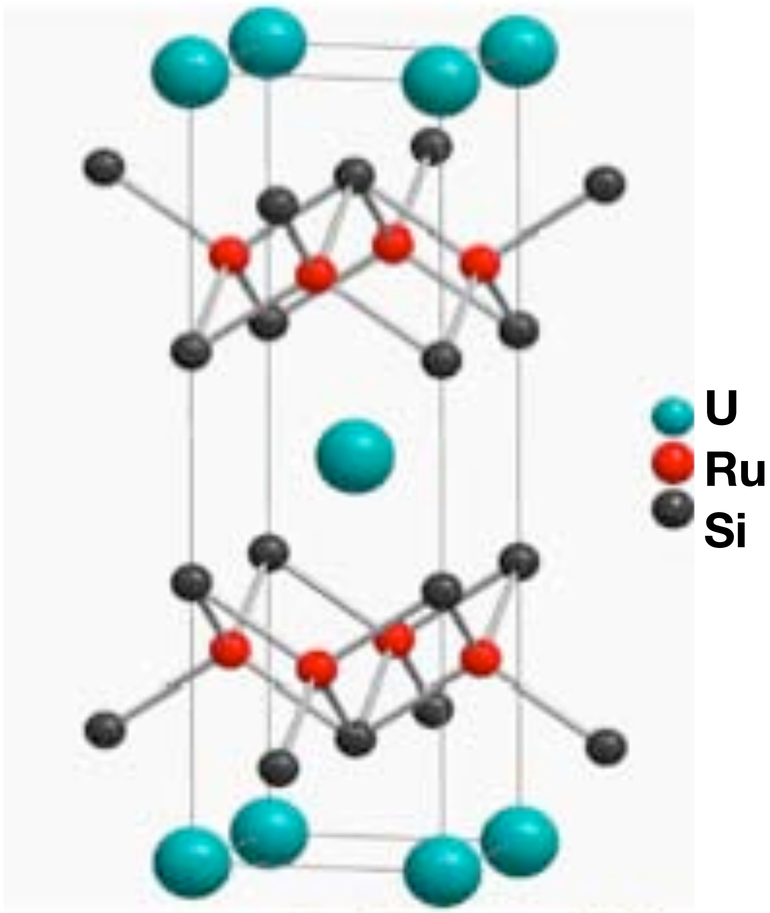

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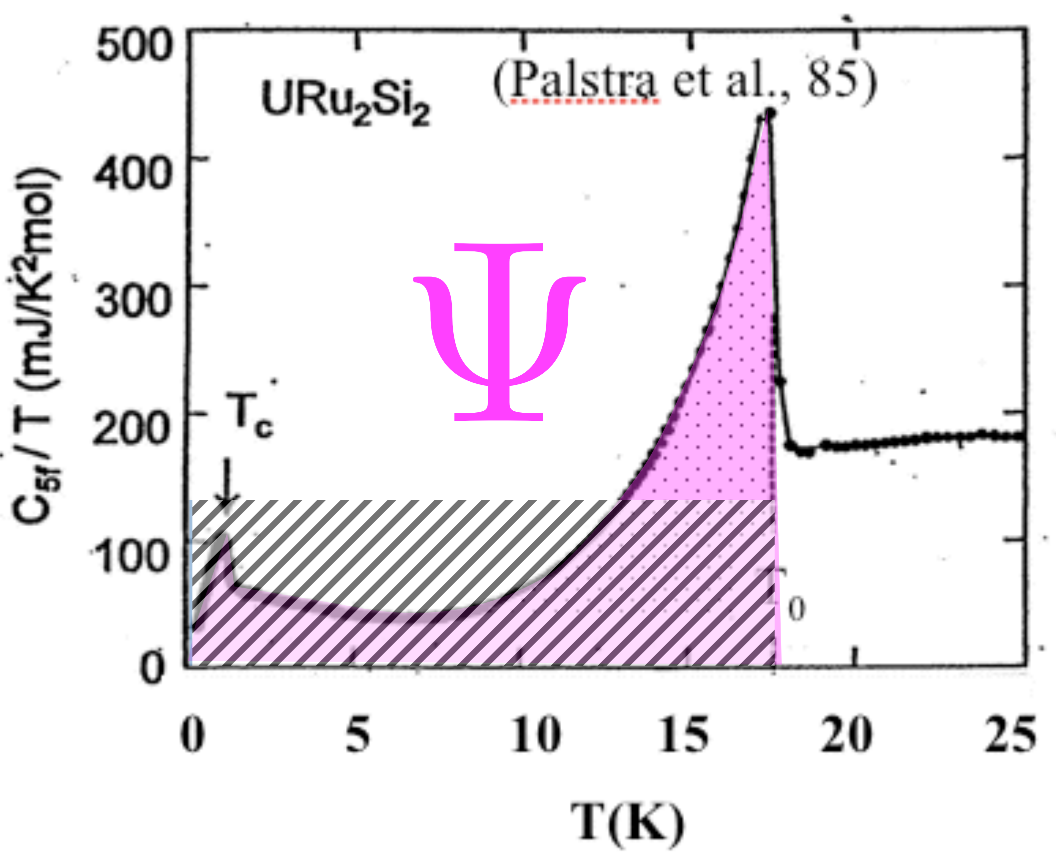

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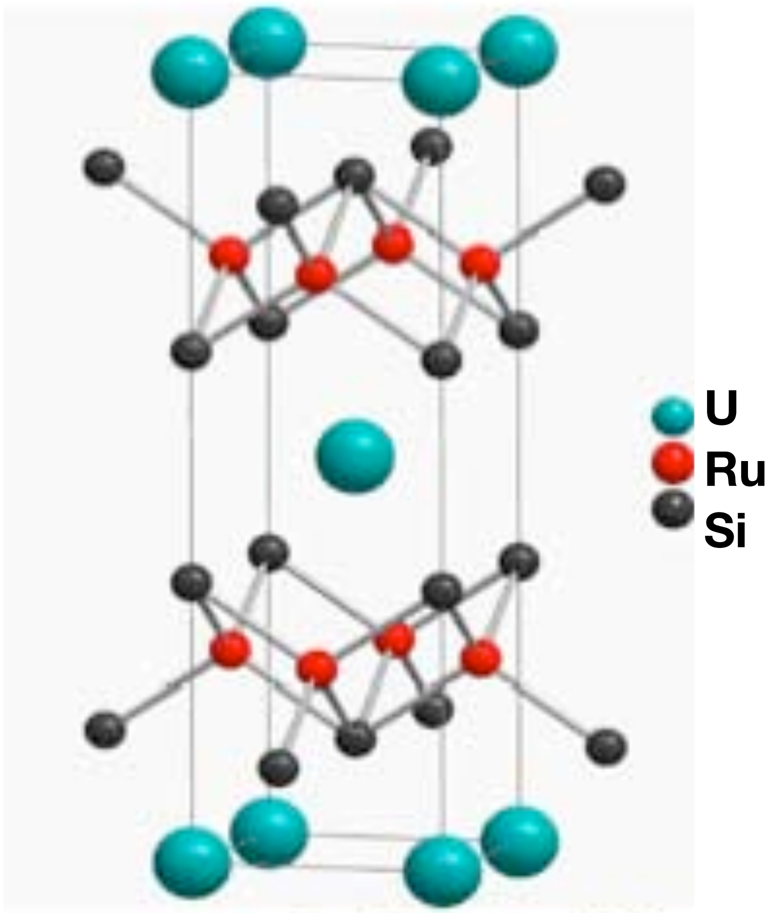
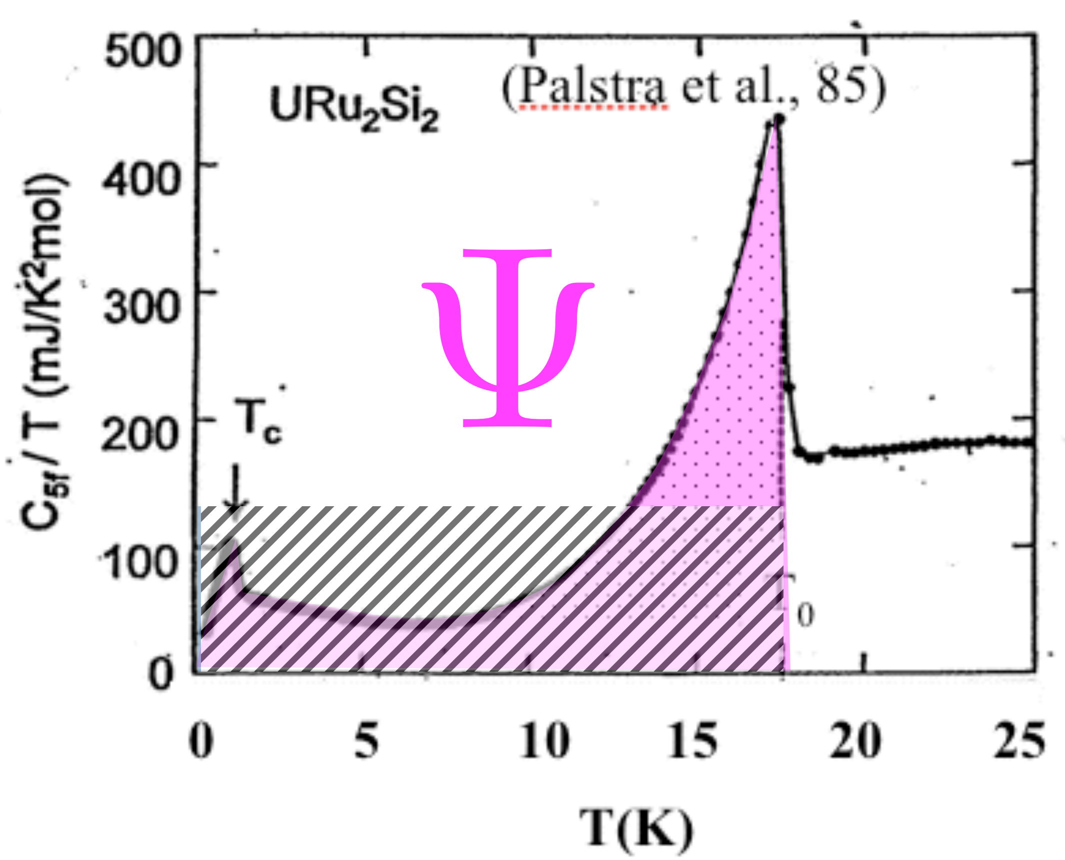


$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

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



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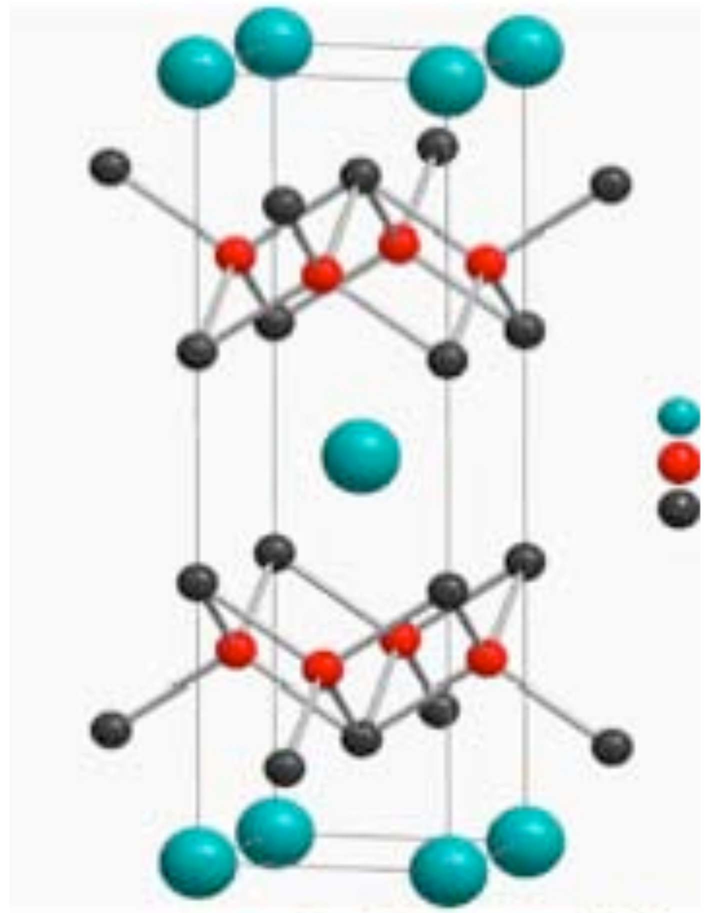

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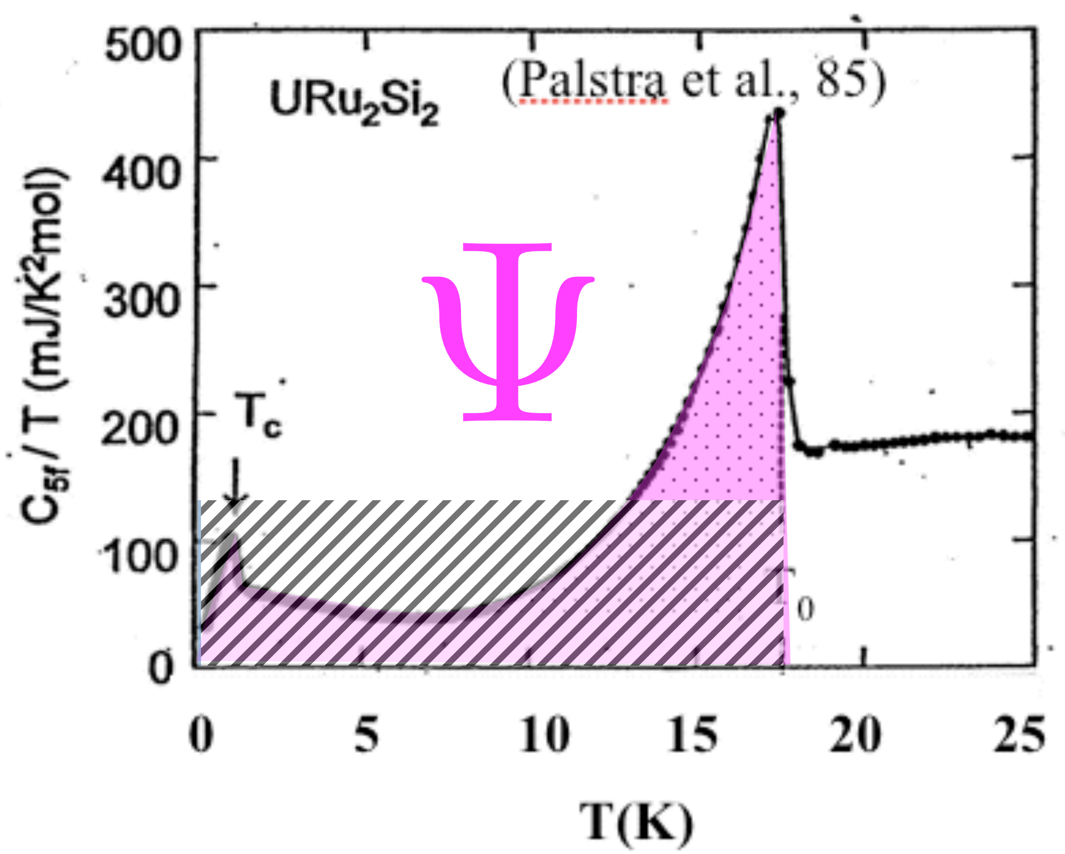
Large entanglement entropy.



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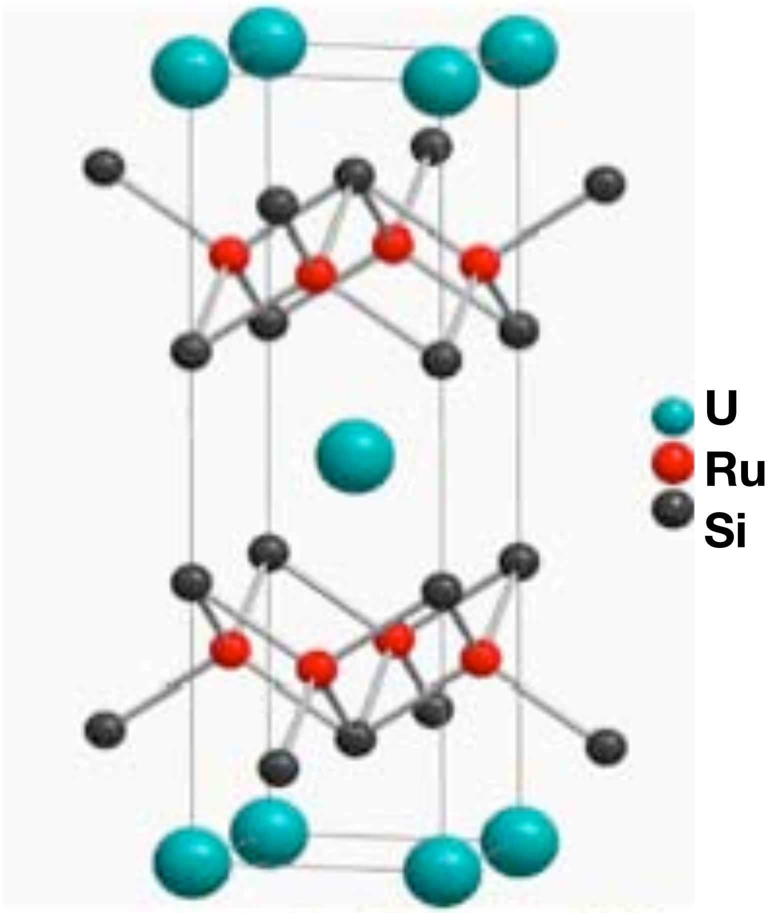

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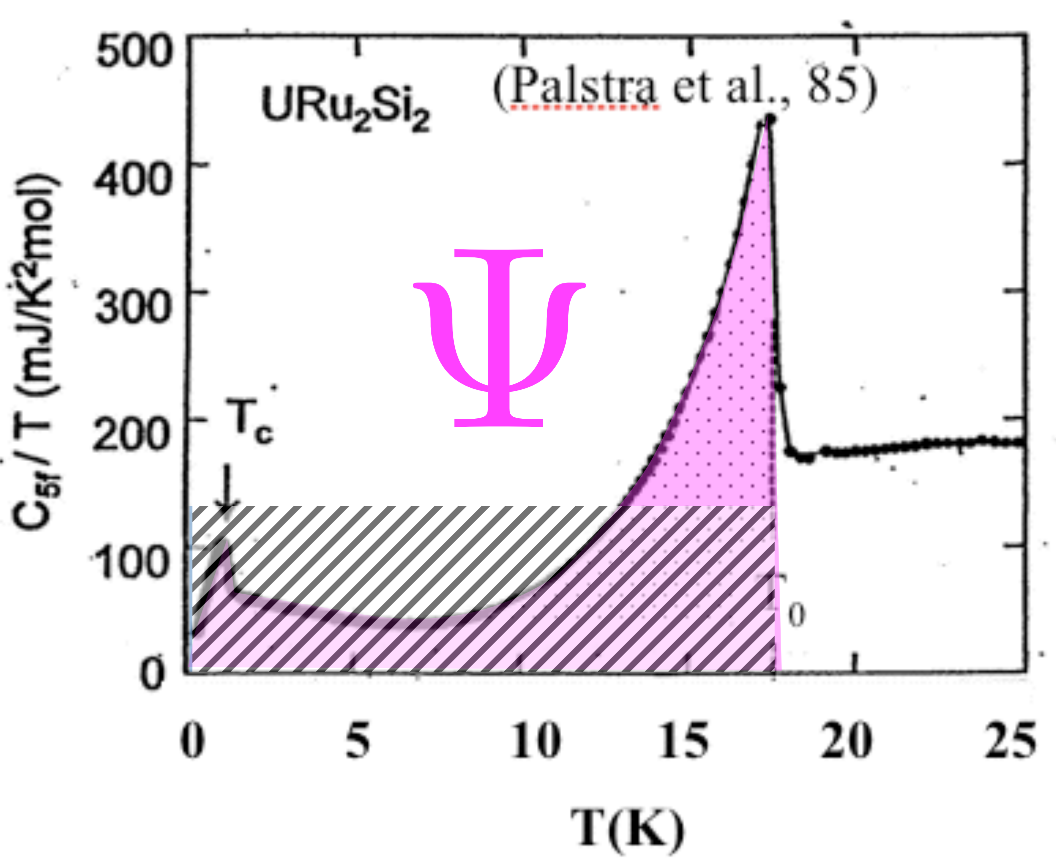
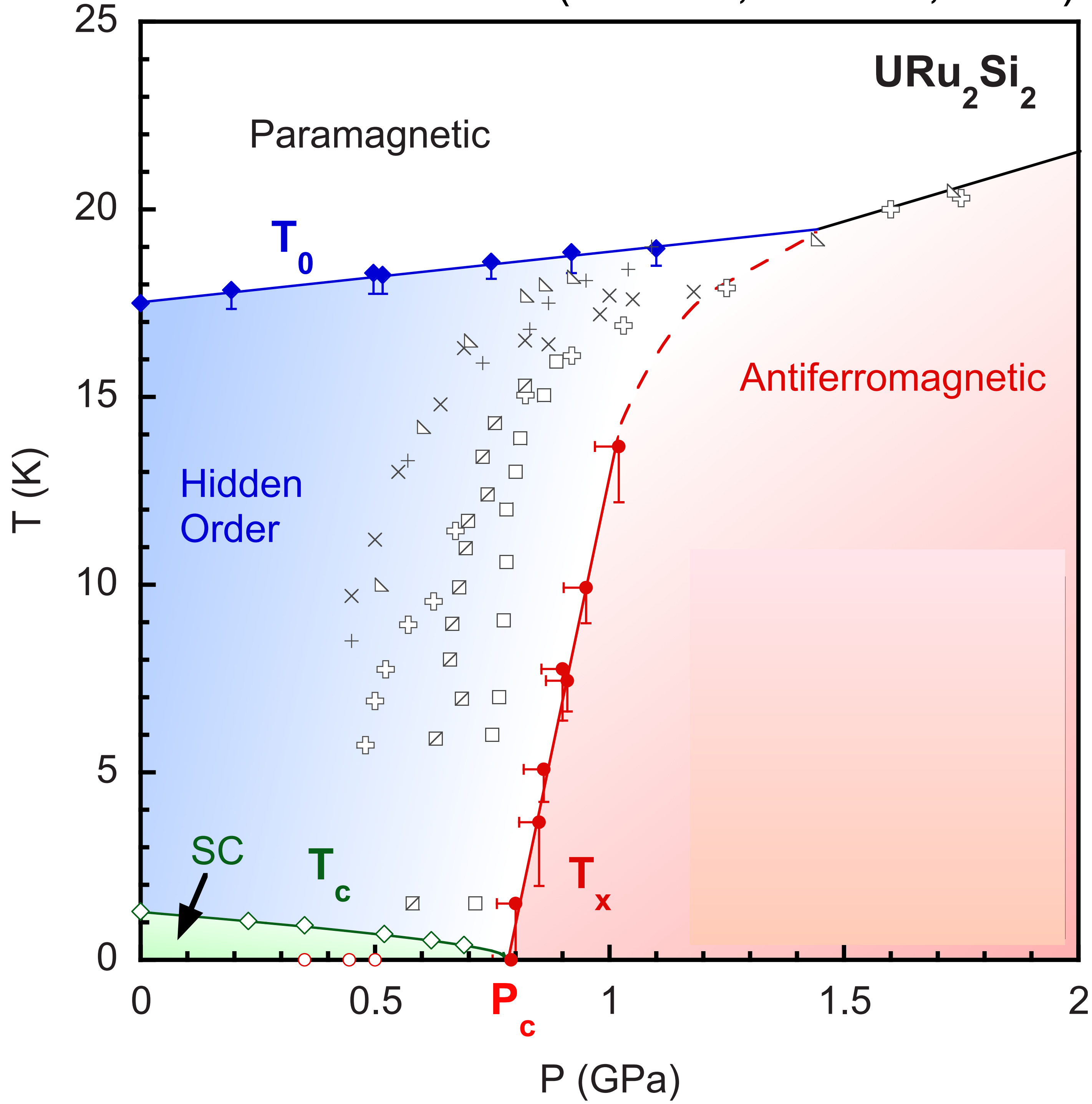


What is the nature of the hidden order?

High pressures, high fields

Butch et al (PRB 82, 060402, 2011)



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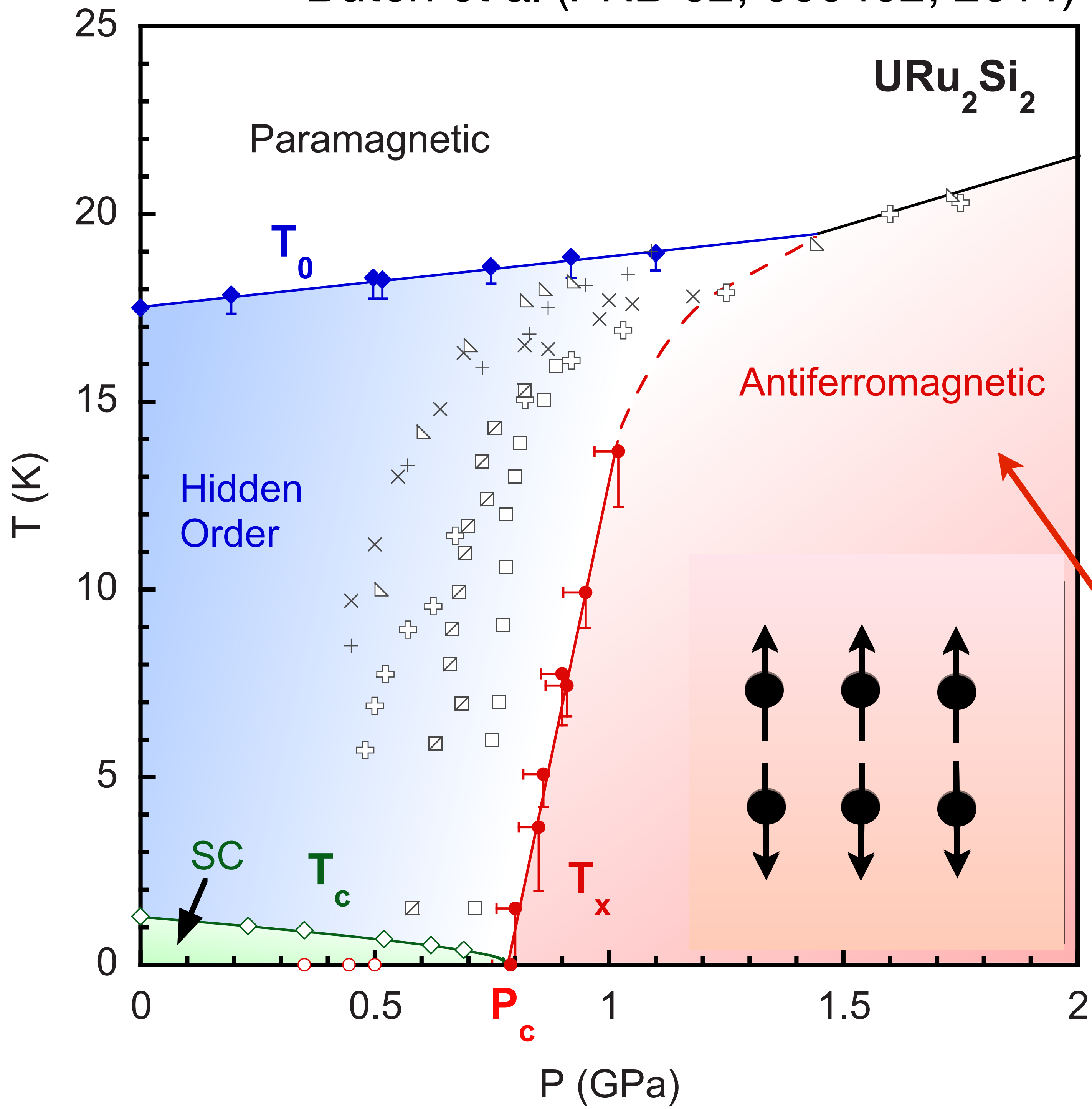
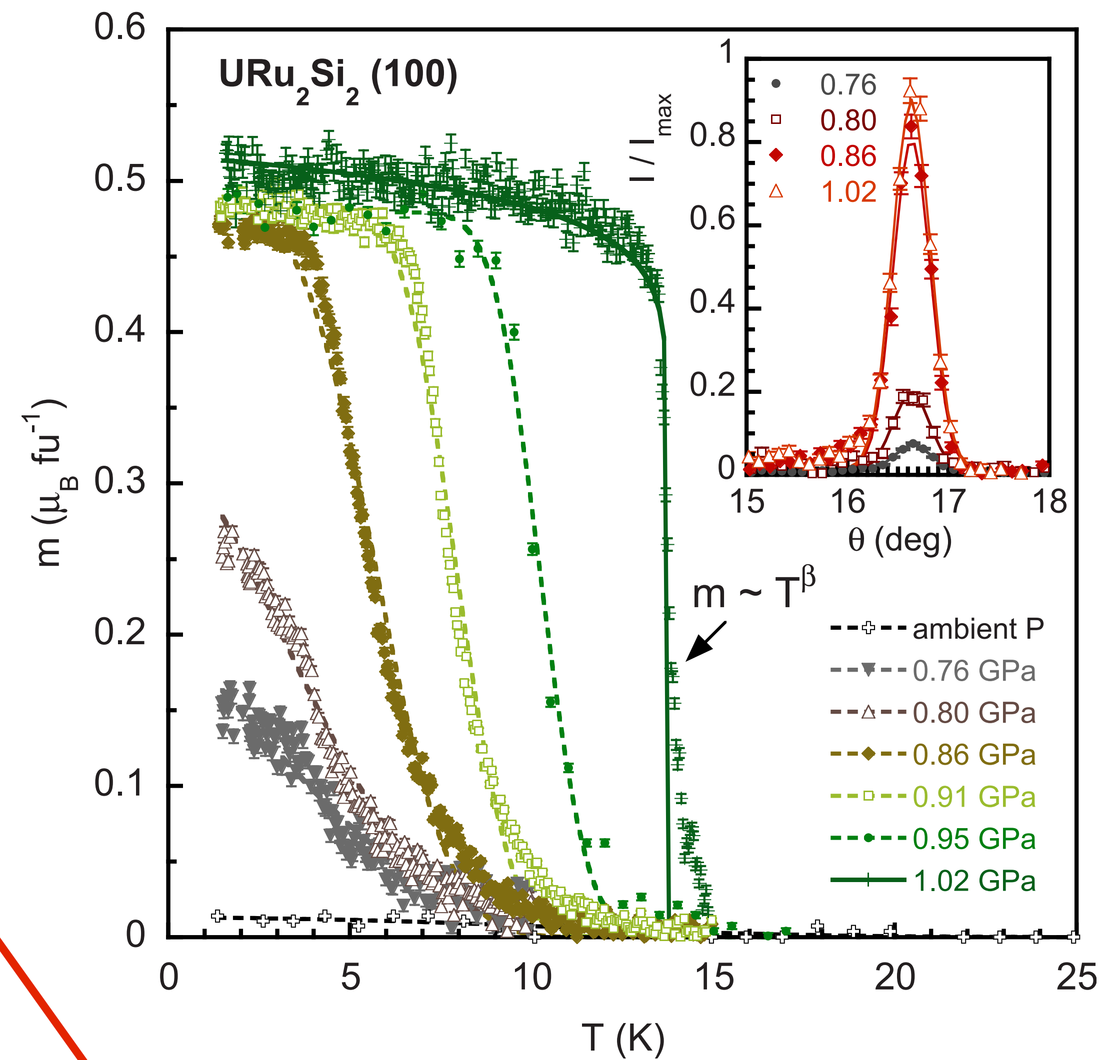
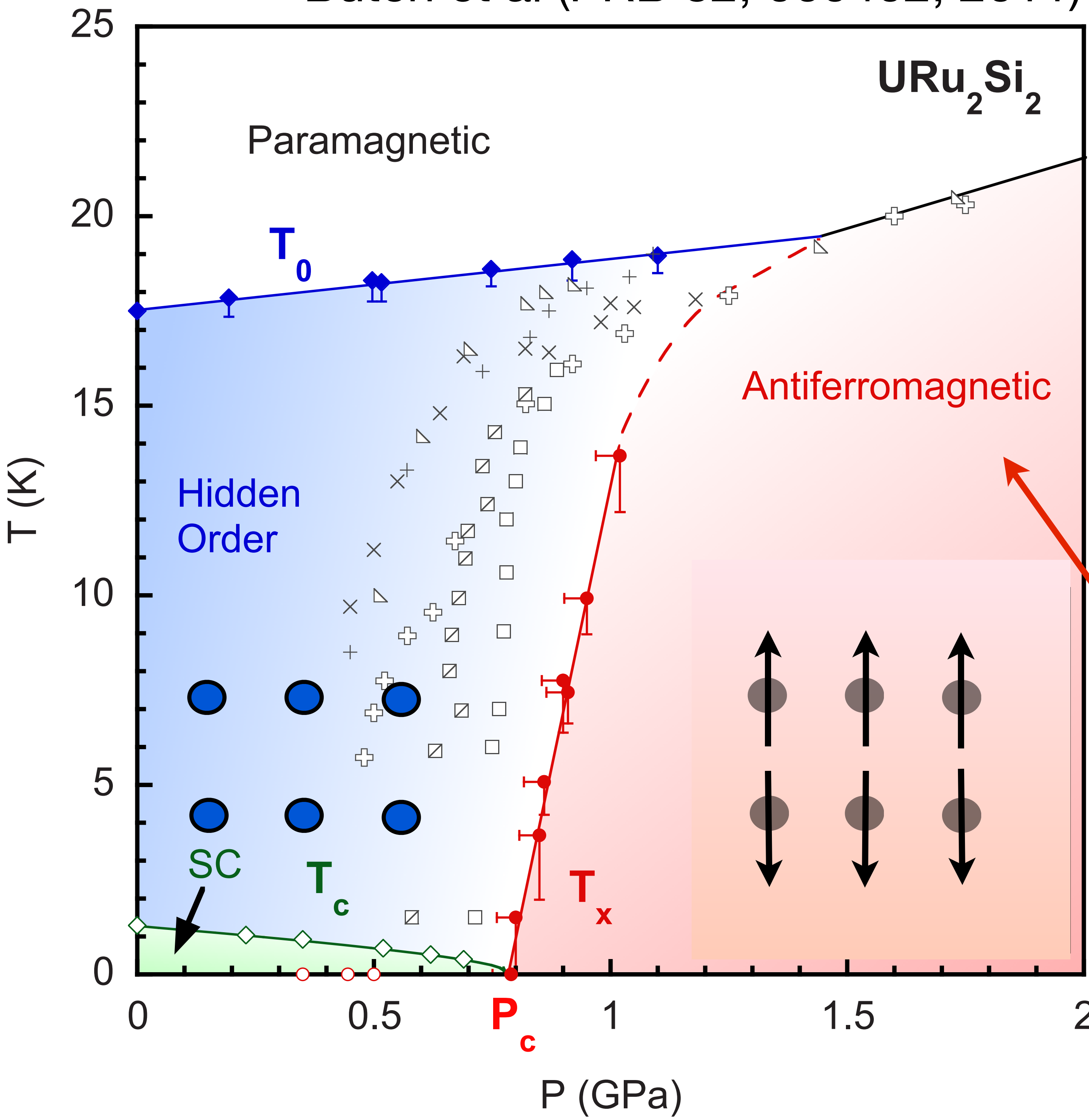


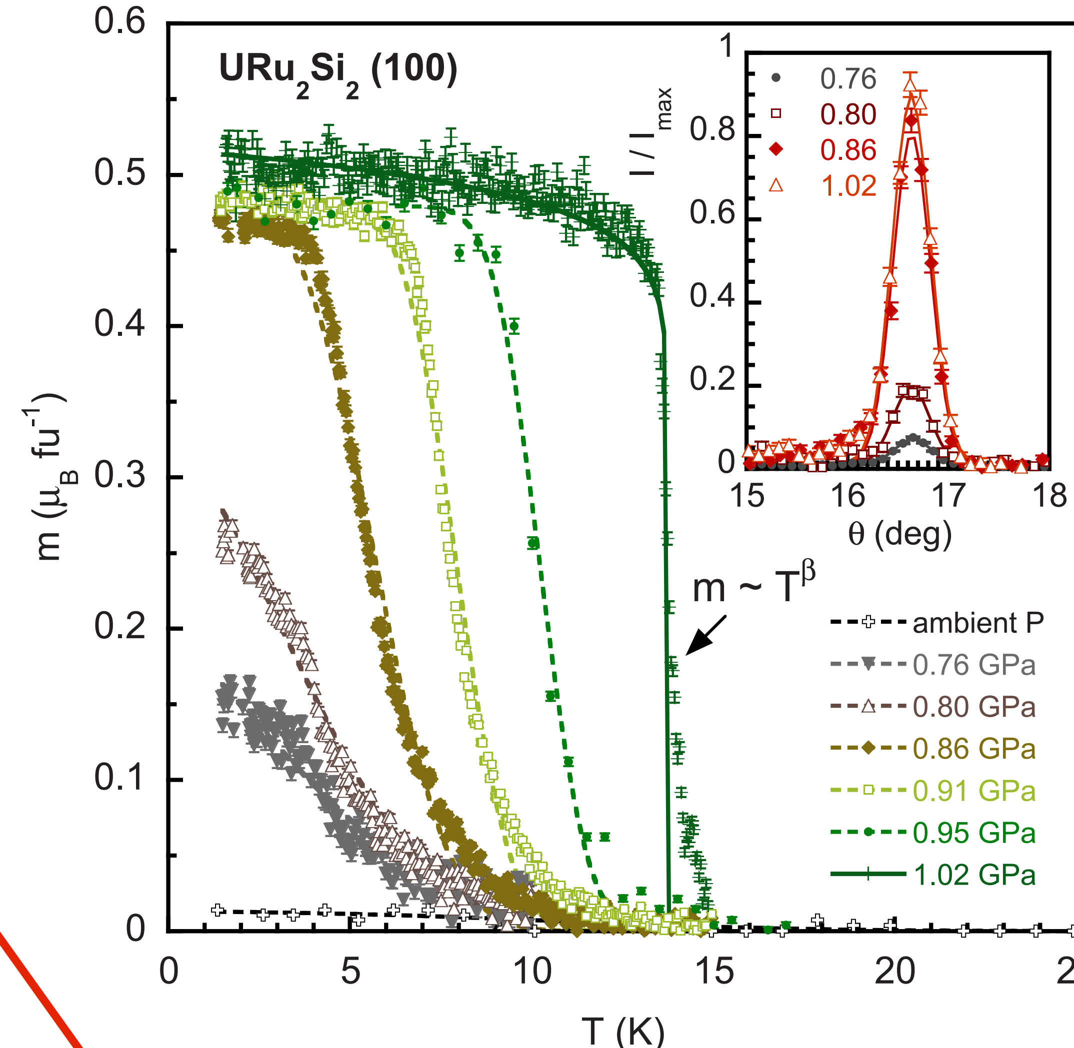


Ising order, present in LMAF,

High pressures, high fields

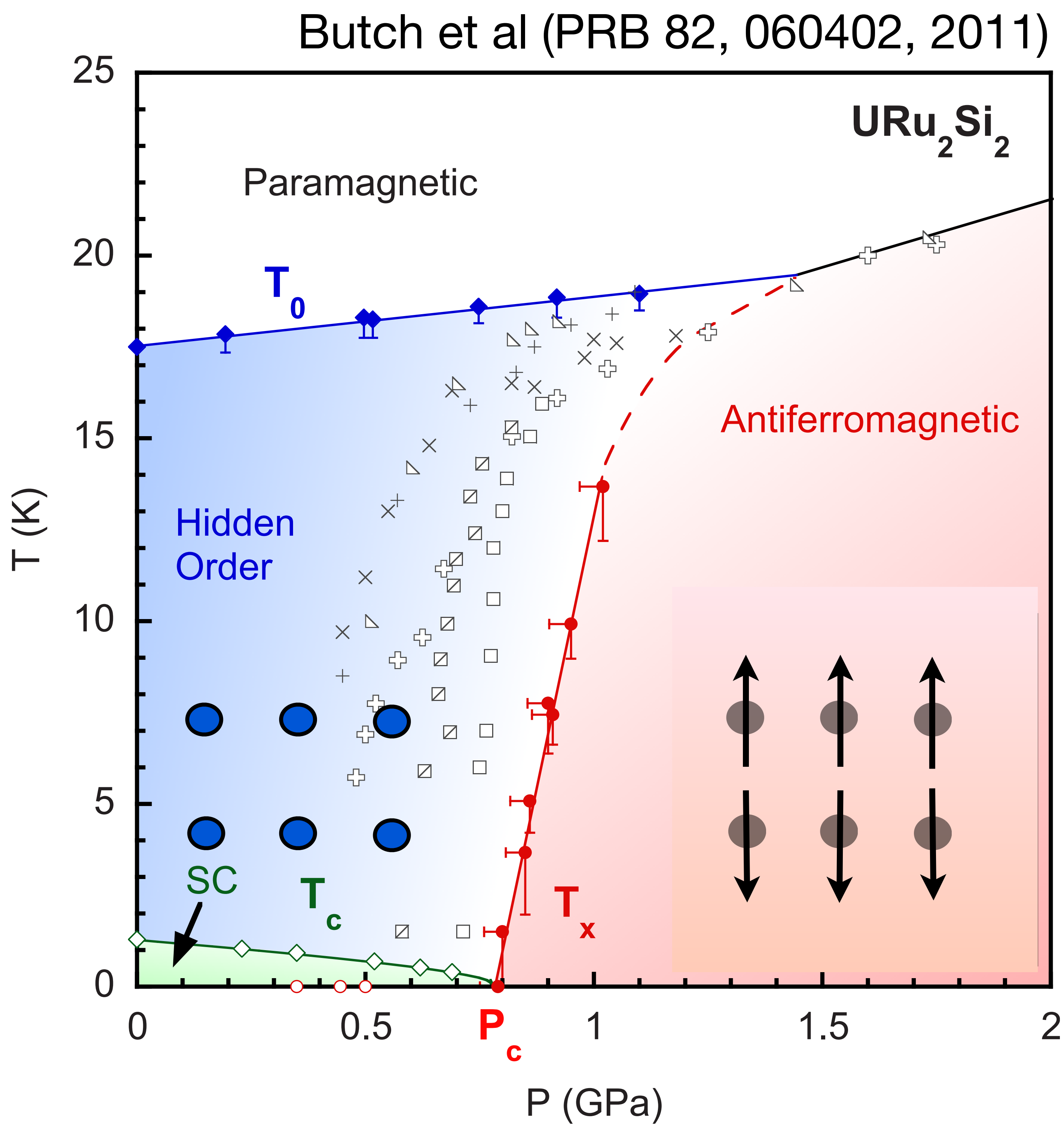
Butch et al (PRB 82, 060402, 2011)



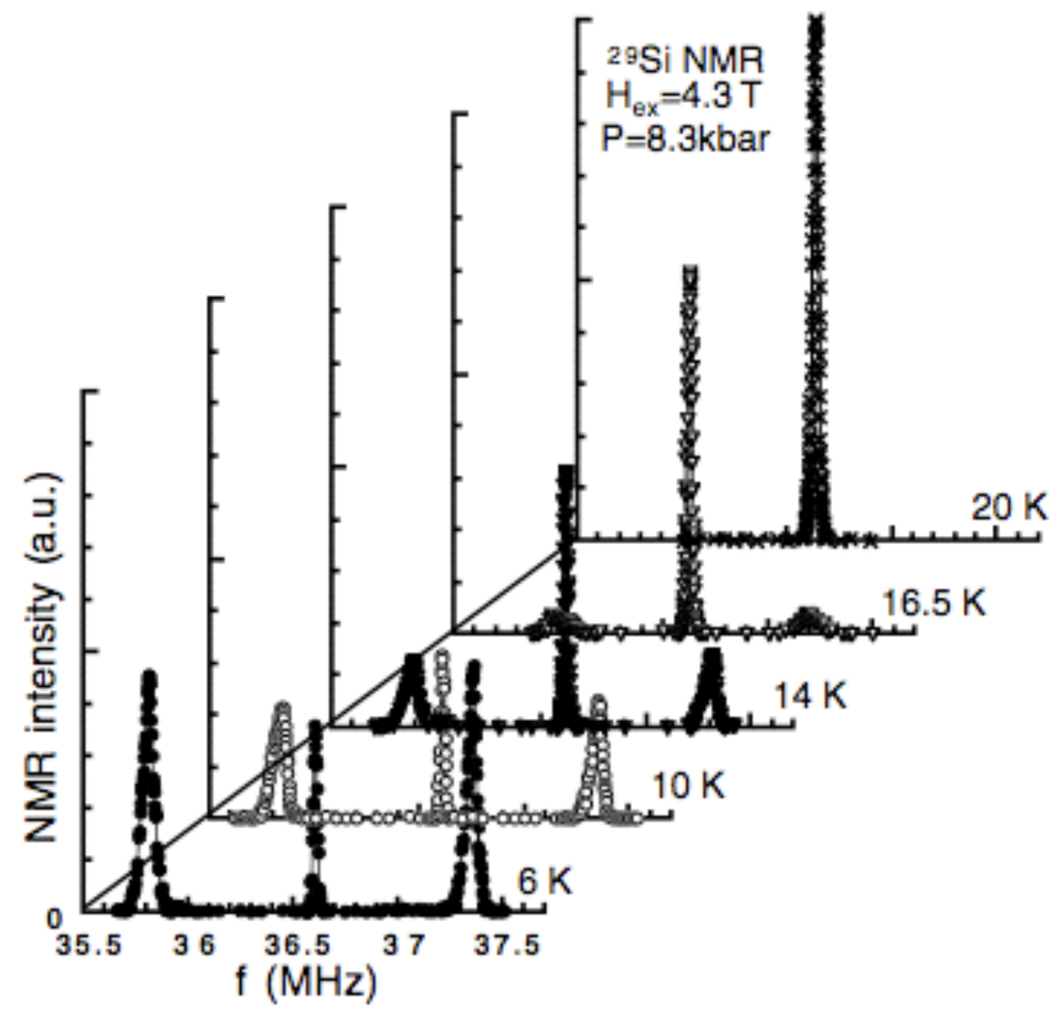


Ising order, present in LMAF,
vanishes in the hidden order state.
(NMR,MuSR).

High pressures, high fields



McElfresh et al. (87), Fisher et al (90), Luke et al (94), Amitsuka et al. (99)



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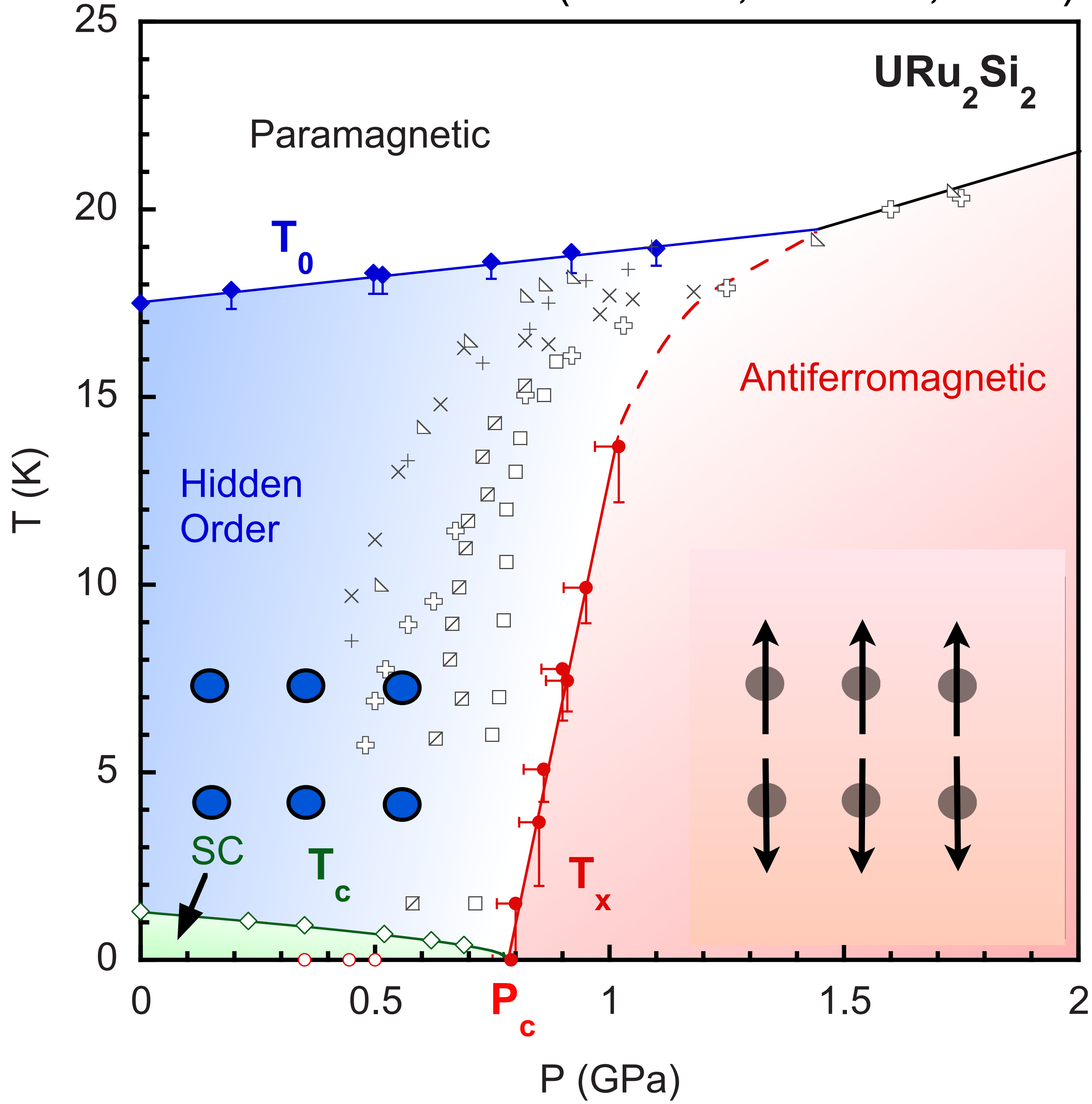
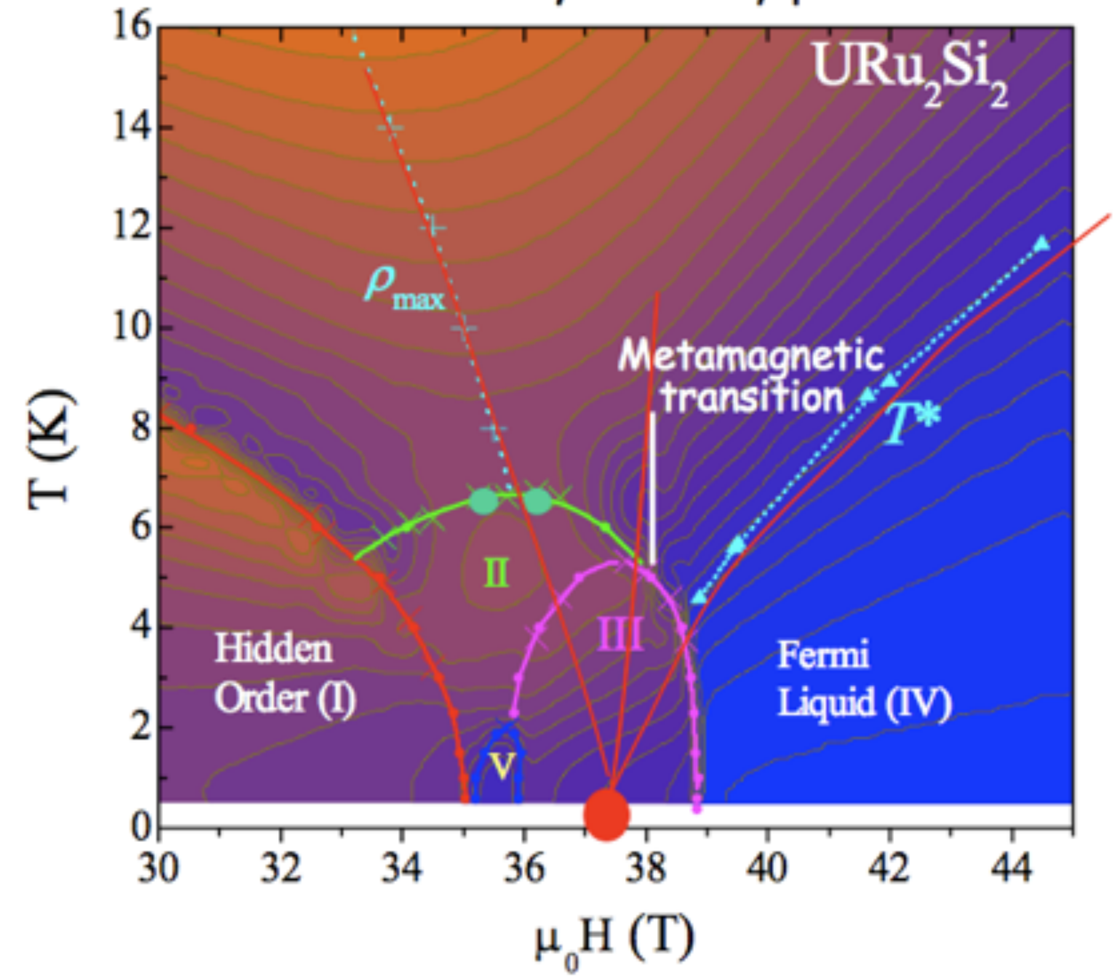


Resistivity intensity plot



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25 Years of Theoretical Proposals

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	Ezgar et al '06 (Dynamic symmetry breaking)
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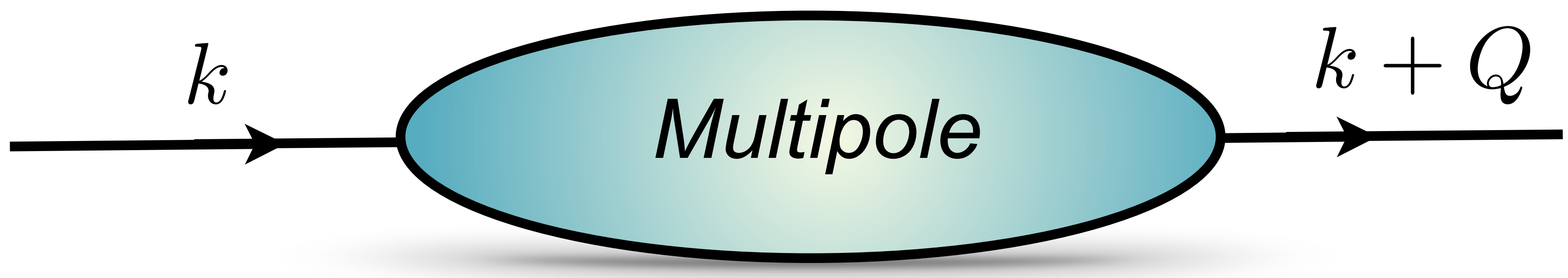
Kondo Lattice	Dubi and Balatsky, '10 (Hybridization density wave)

a)



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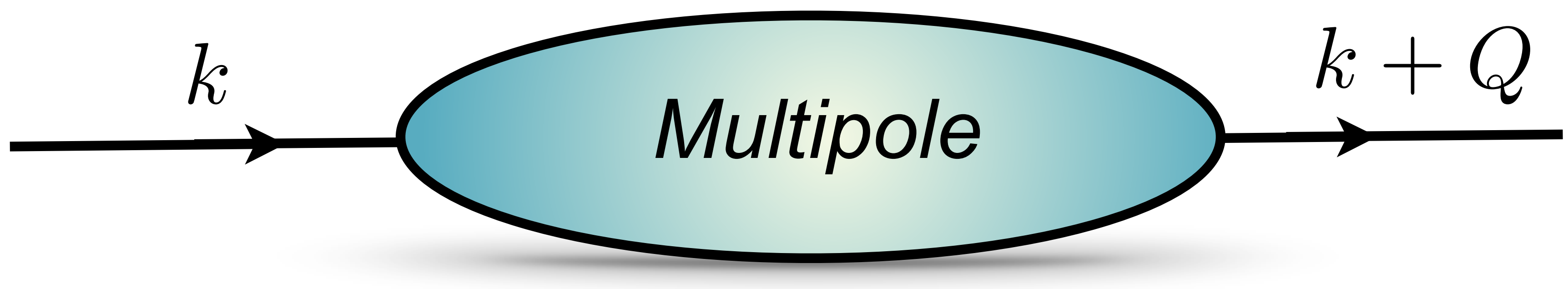

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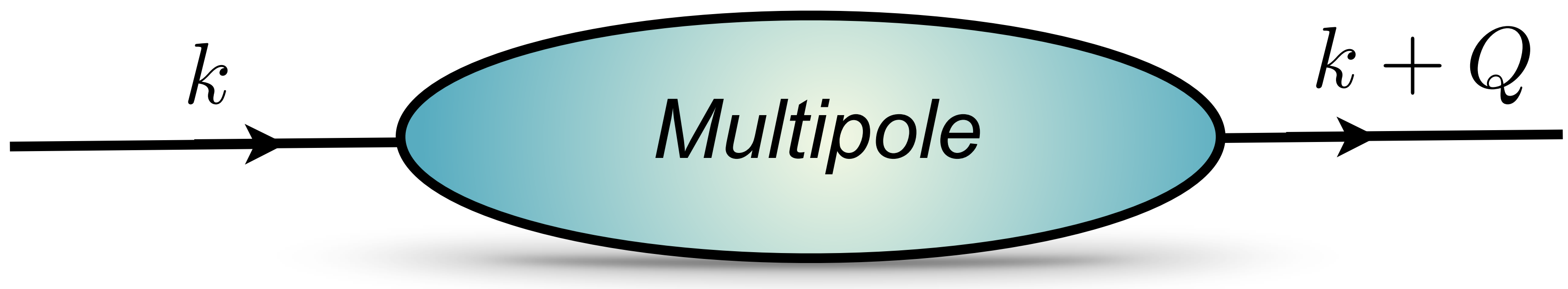

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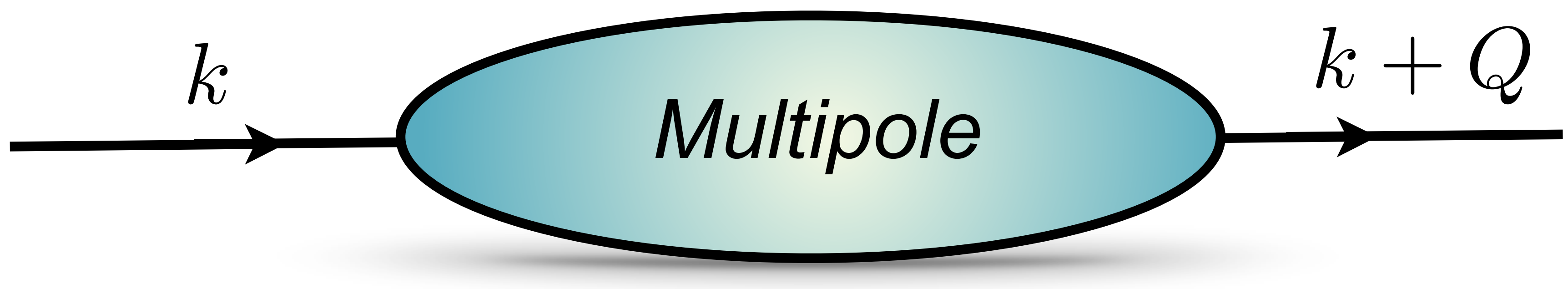

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OP	L	S	Name

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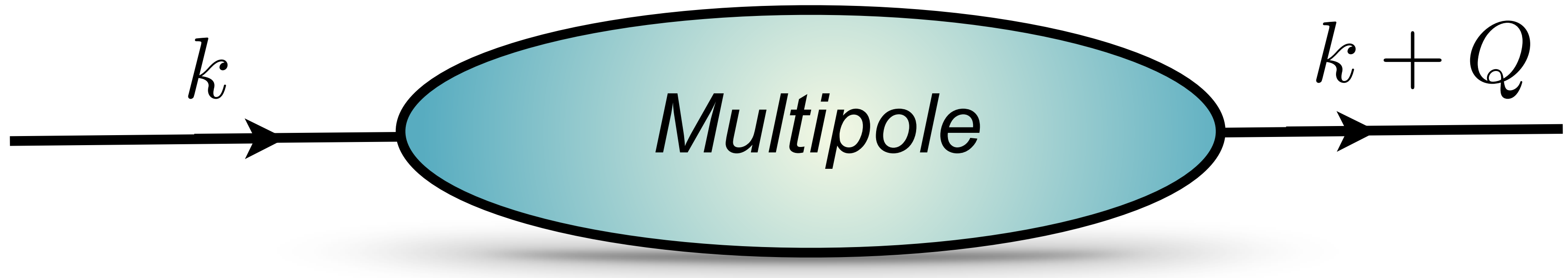

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OP	L	S	Name
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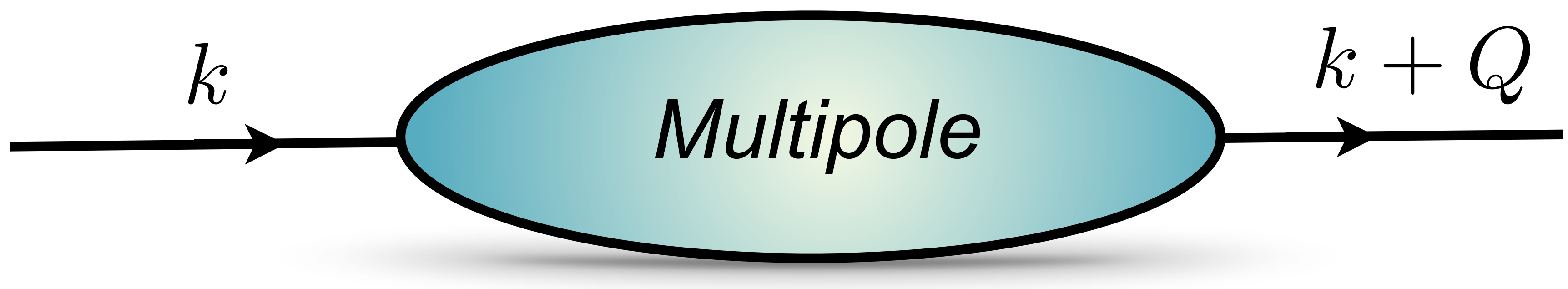

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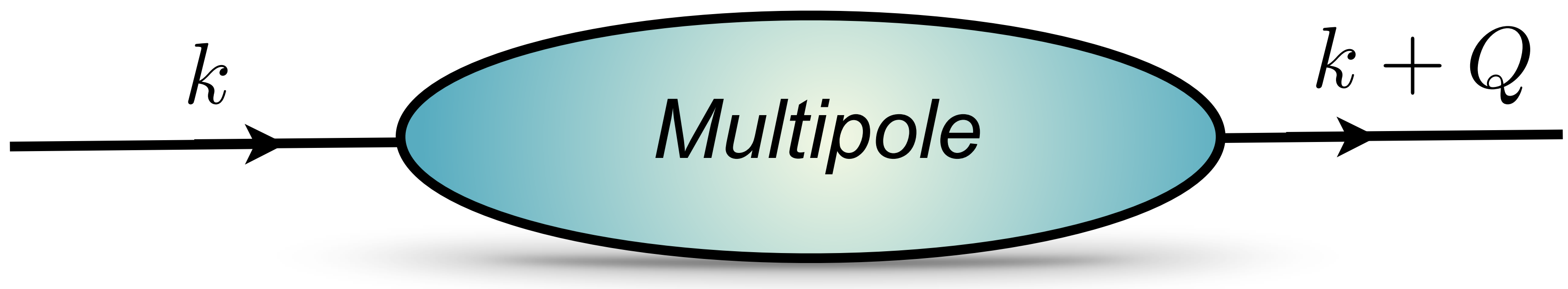

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k_x	1		Vector (c.f nematic)

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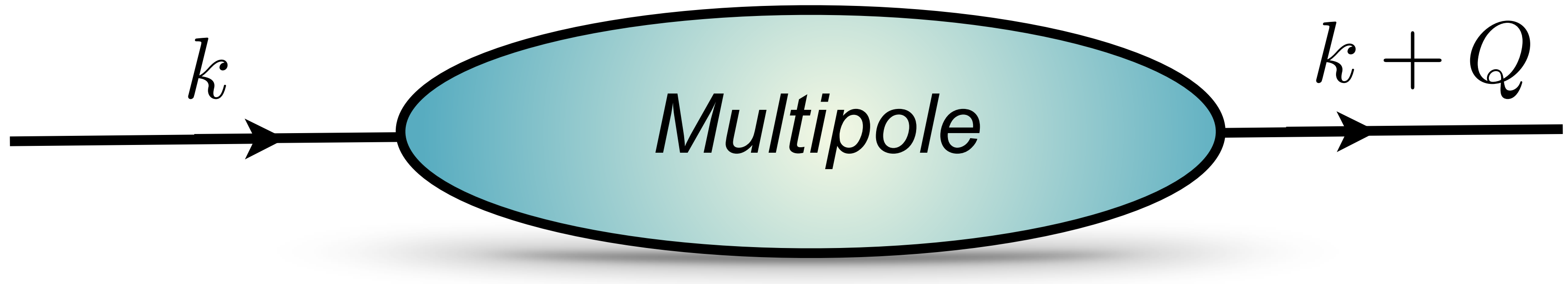

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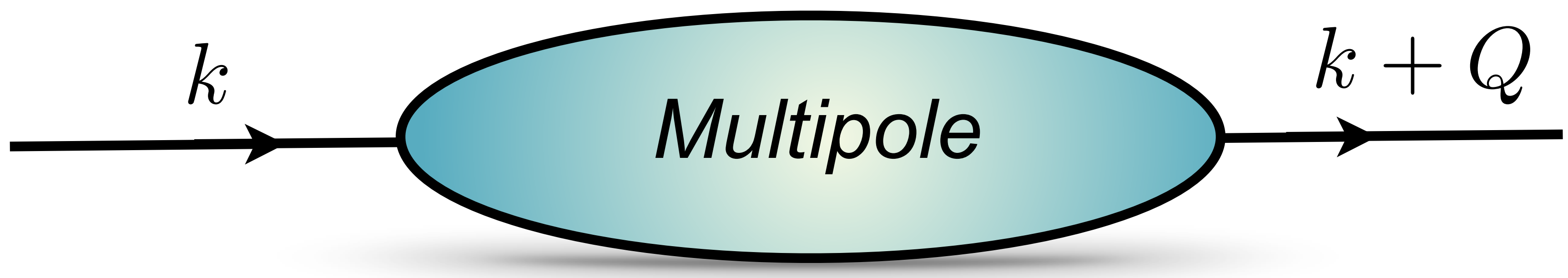

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$k_x k_y (k_x^2 - k_y^2)$	4		Hexdecapole.

Can Electron Order Parameters carry 1/2 integer Spin?

$$f_L[\psi] = \frac{1}{V}F[\psi] = \frac{r}{2}\psi^2 + \frac{u}{4}\psi^4.$$

Landau Theory

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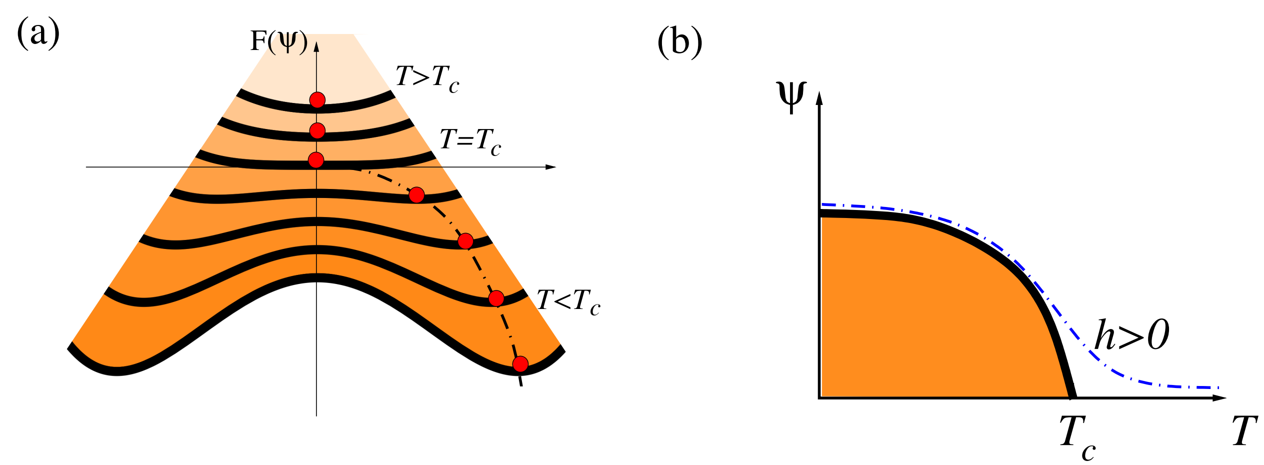

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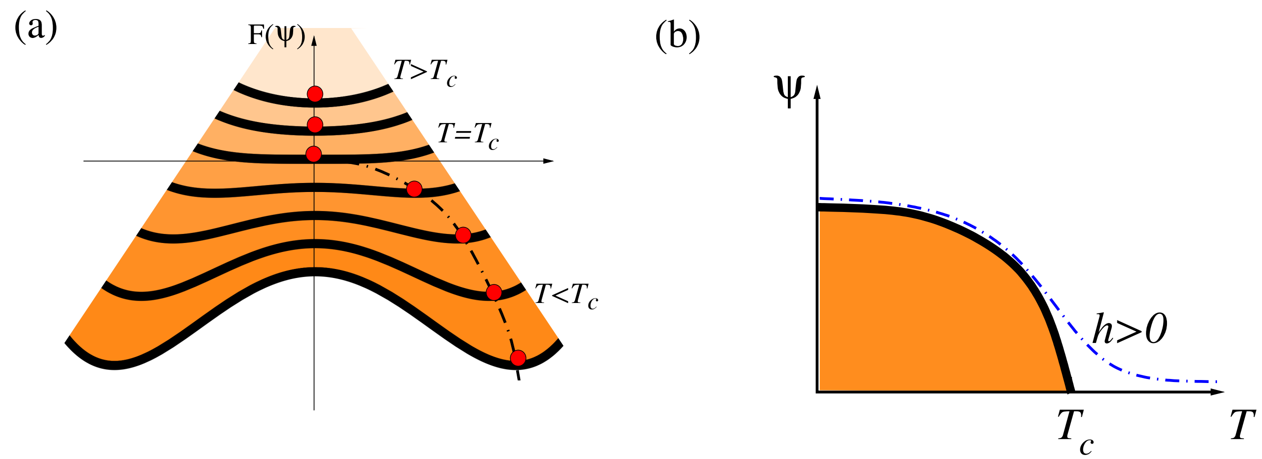

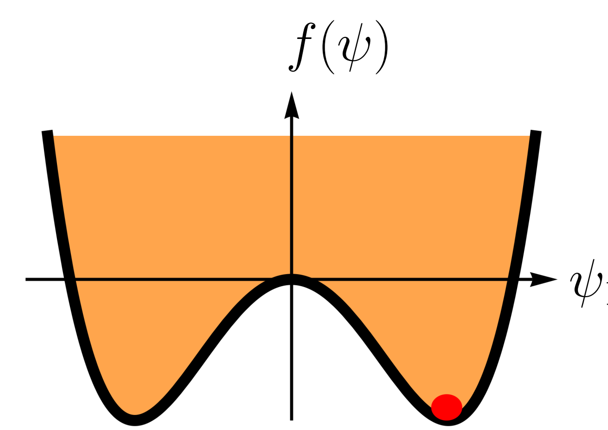

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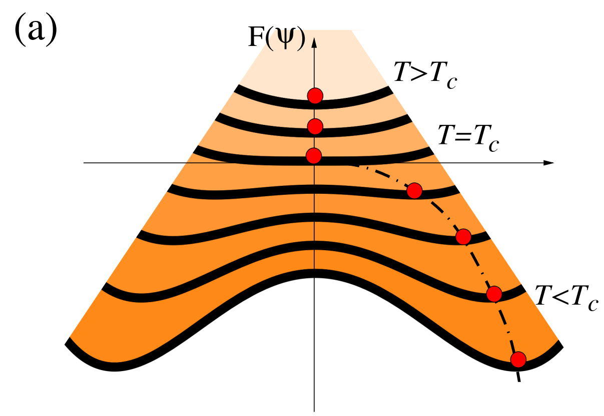

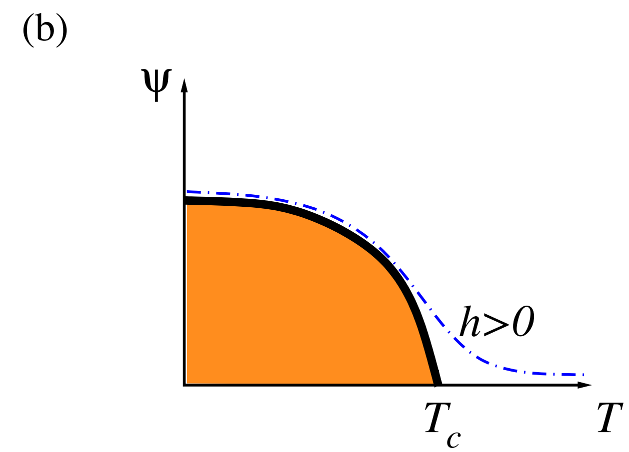

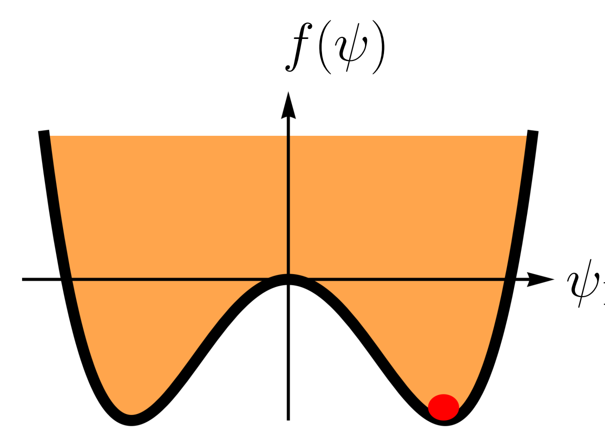

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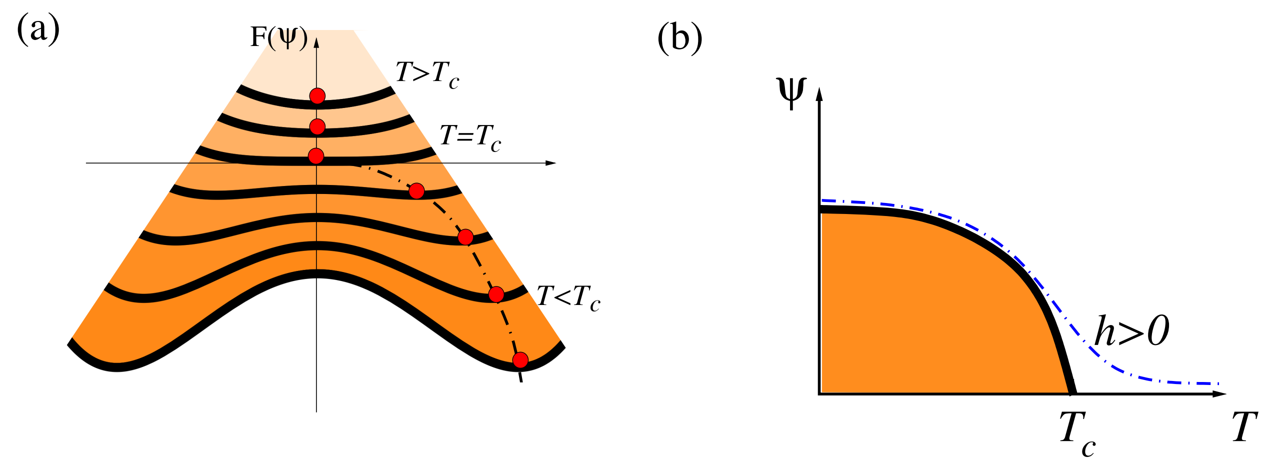

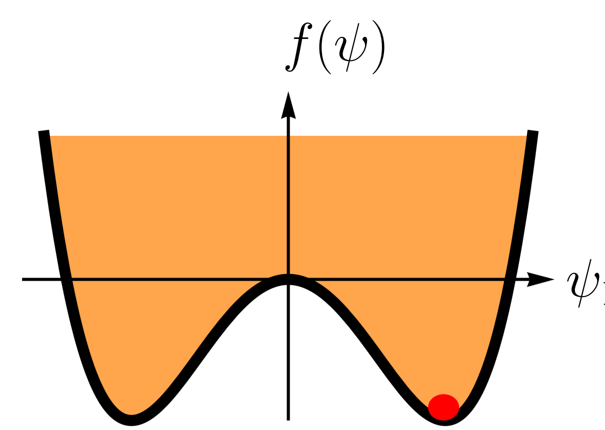

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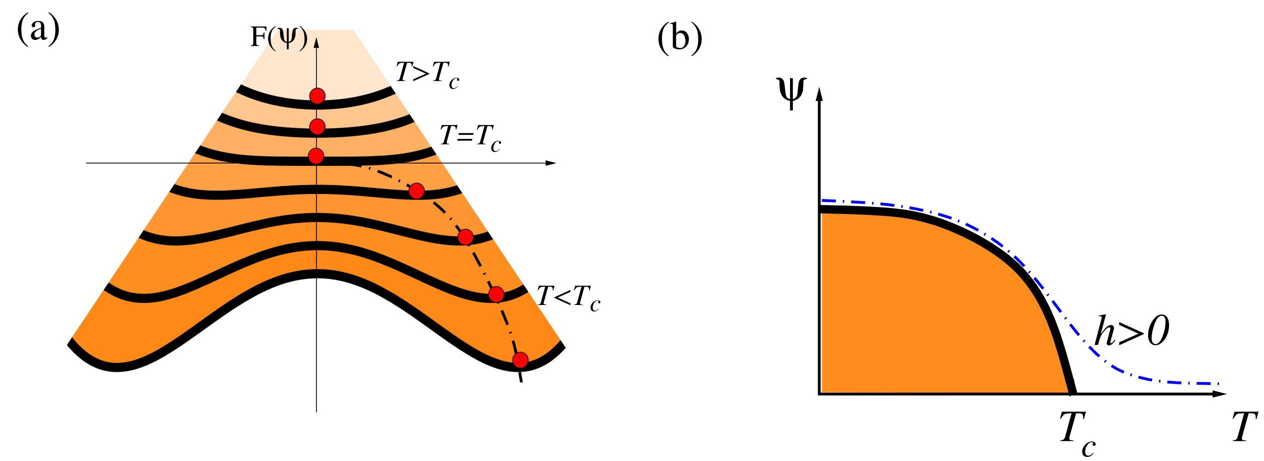

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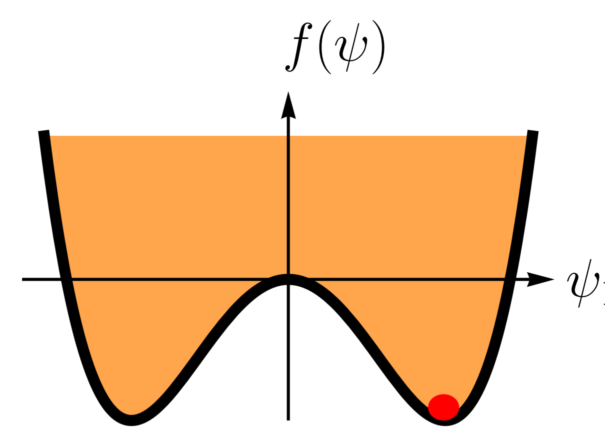

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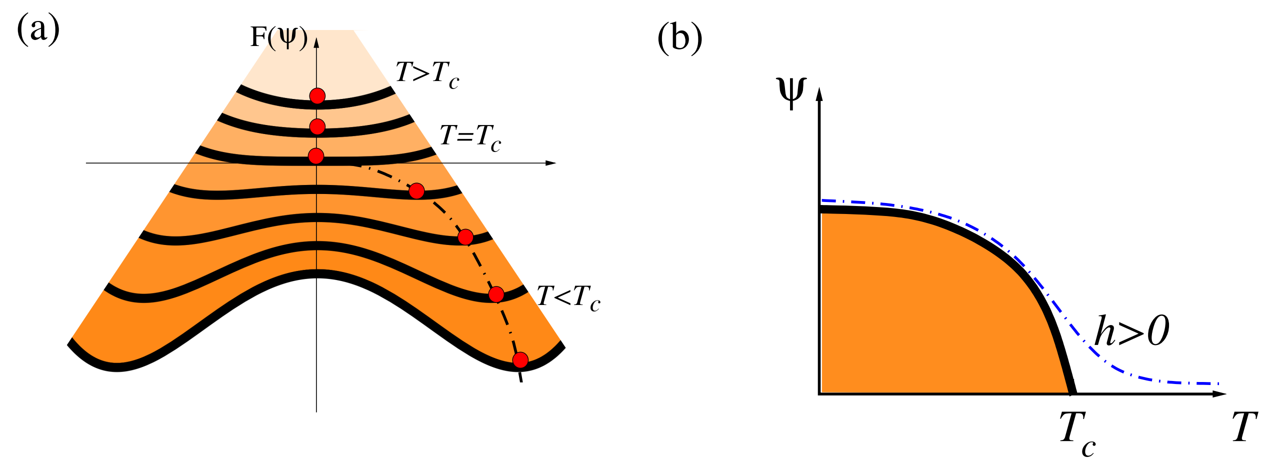

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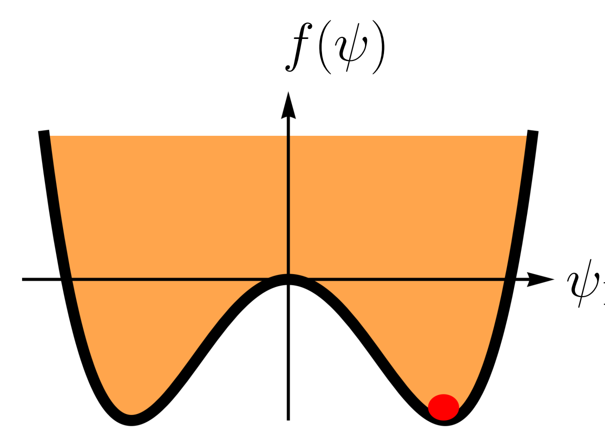

Broken Symmetry

Can an electron OP- ever transform like a spinor, or 1/2 integer particle?

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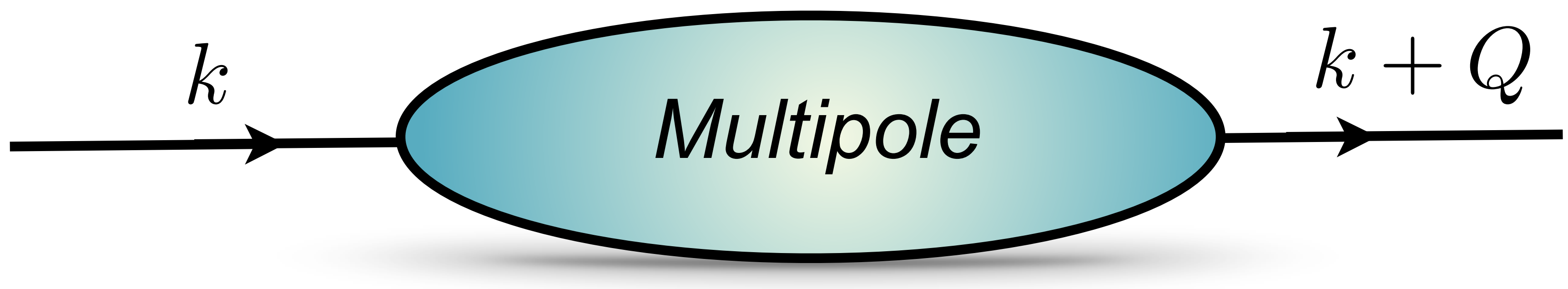

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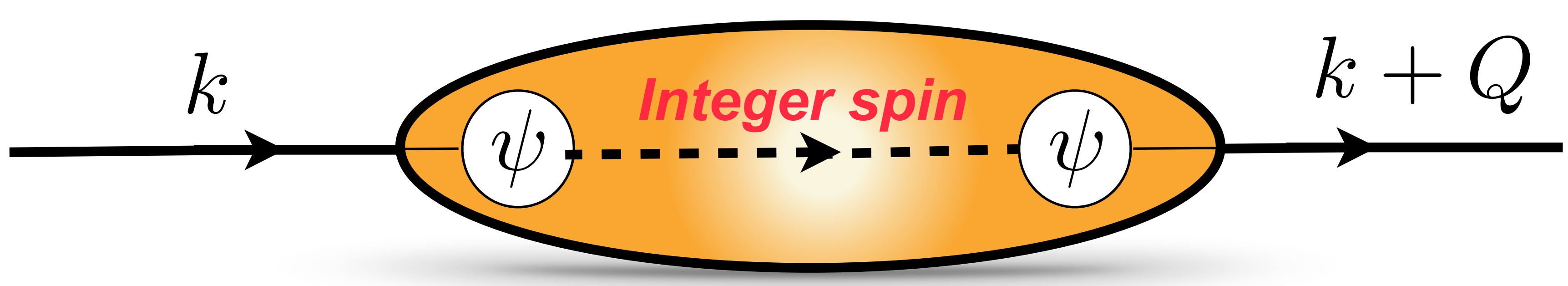

$$\psi = \sqrt{\mathrm{Multipole}} = \mathrm{Spinorial\ OP}$$

The Giant Ising Anisotropy.

Quantum Oscillations and Spin Zeros

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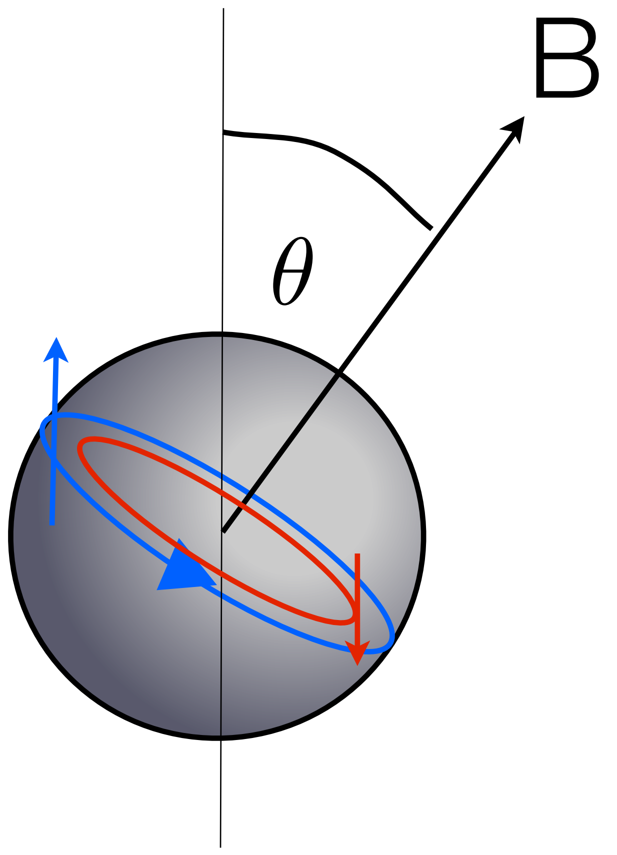

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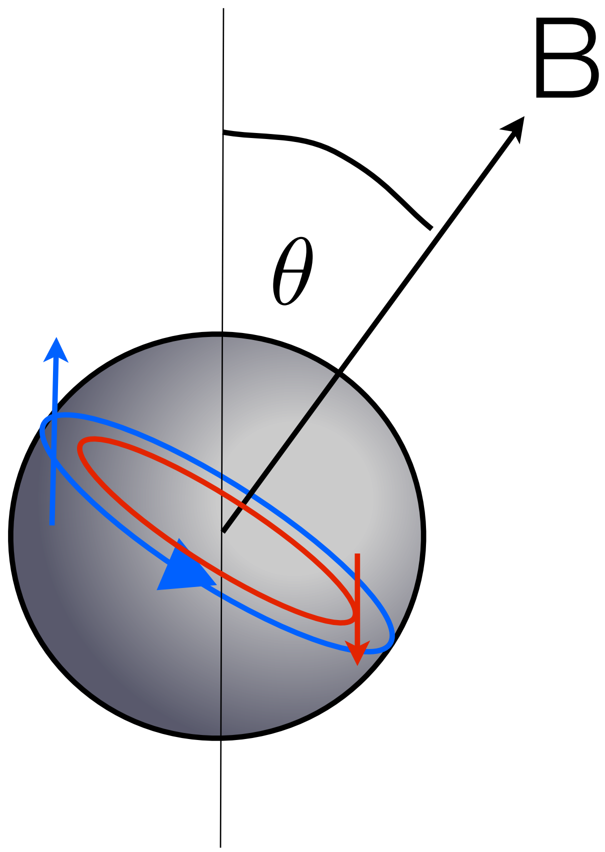

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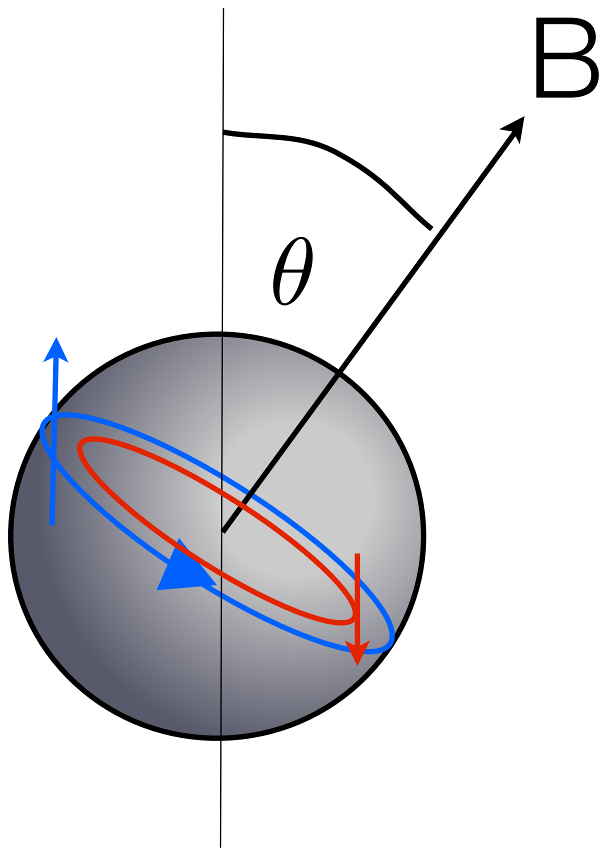
Quantum Oscillations and Spin Zeros



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

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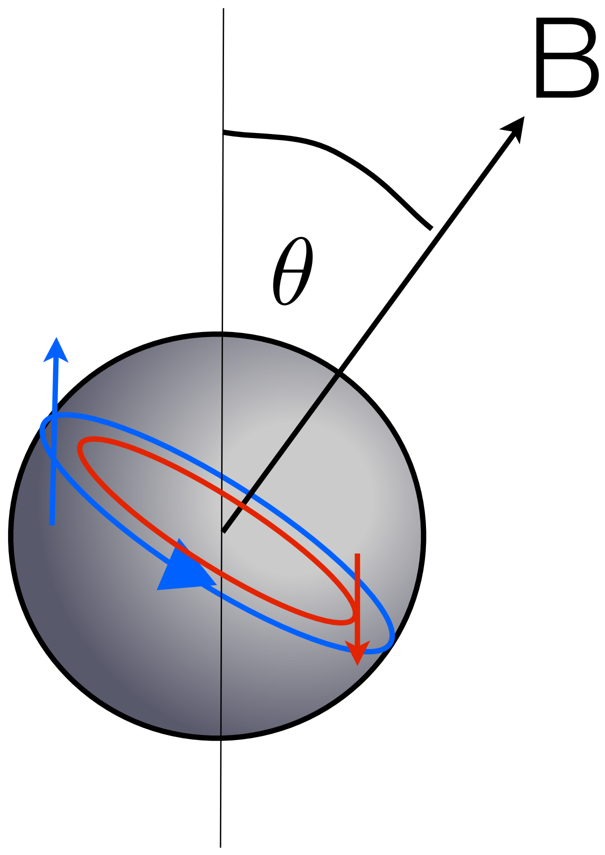

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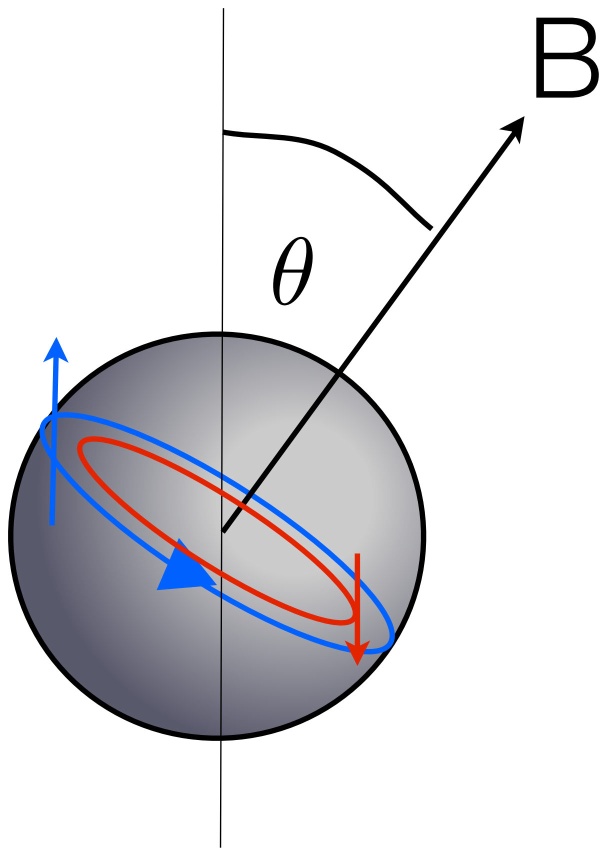

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Spin Zero condition

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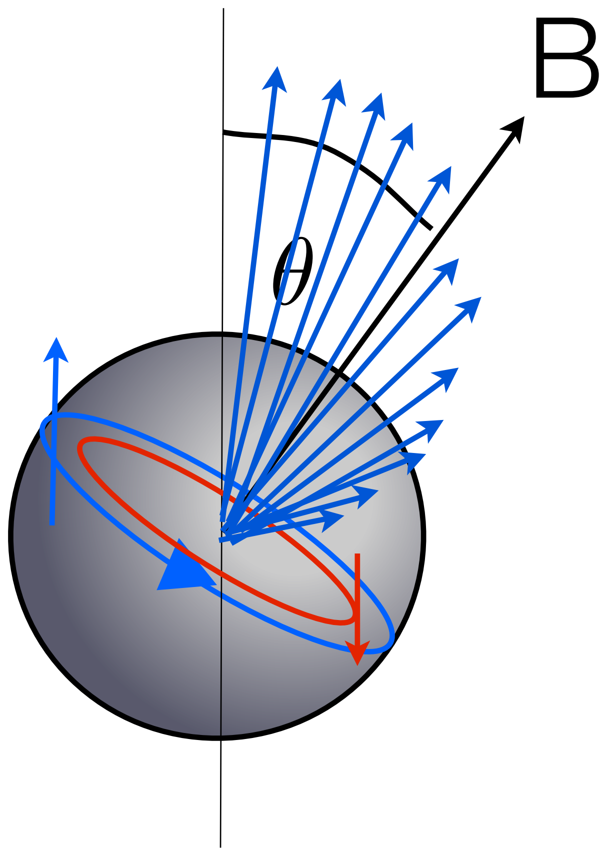

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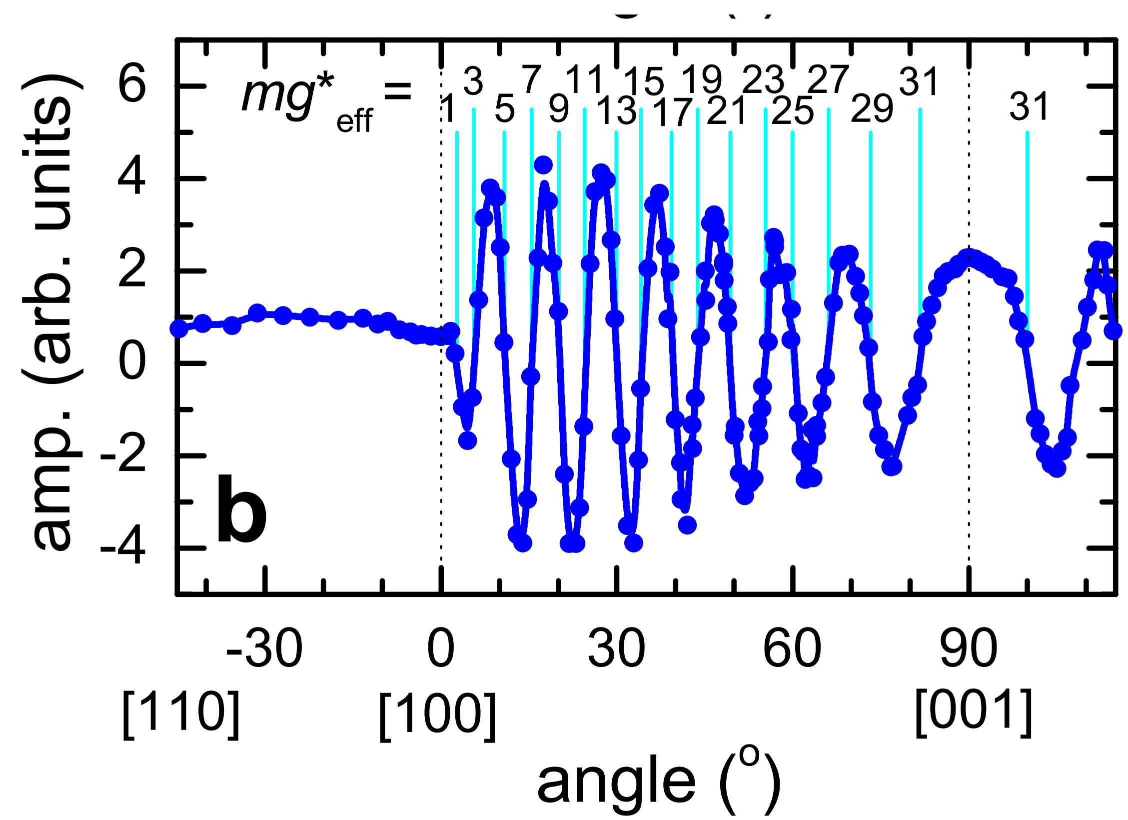

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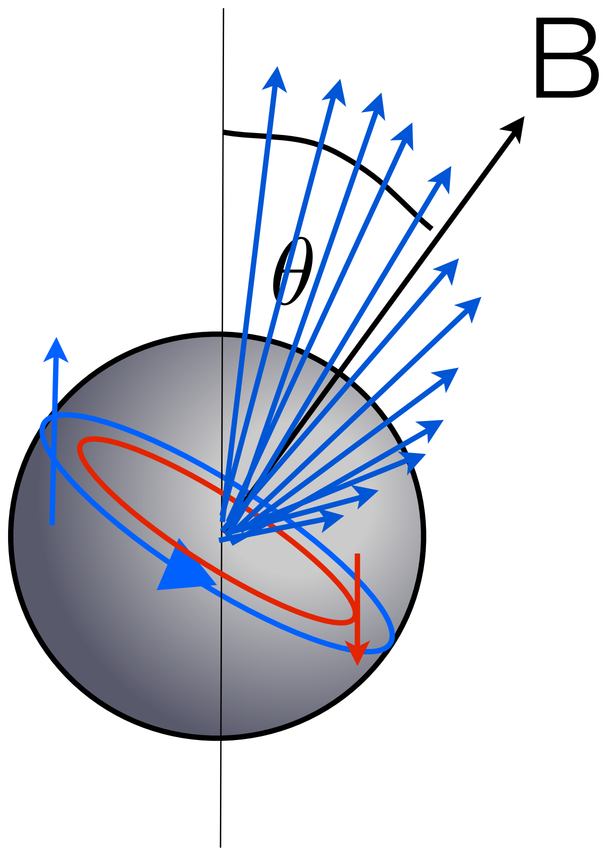

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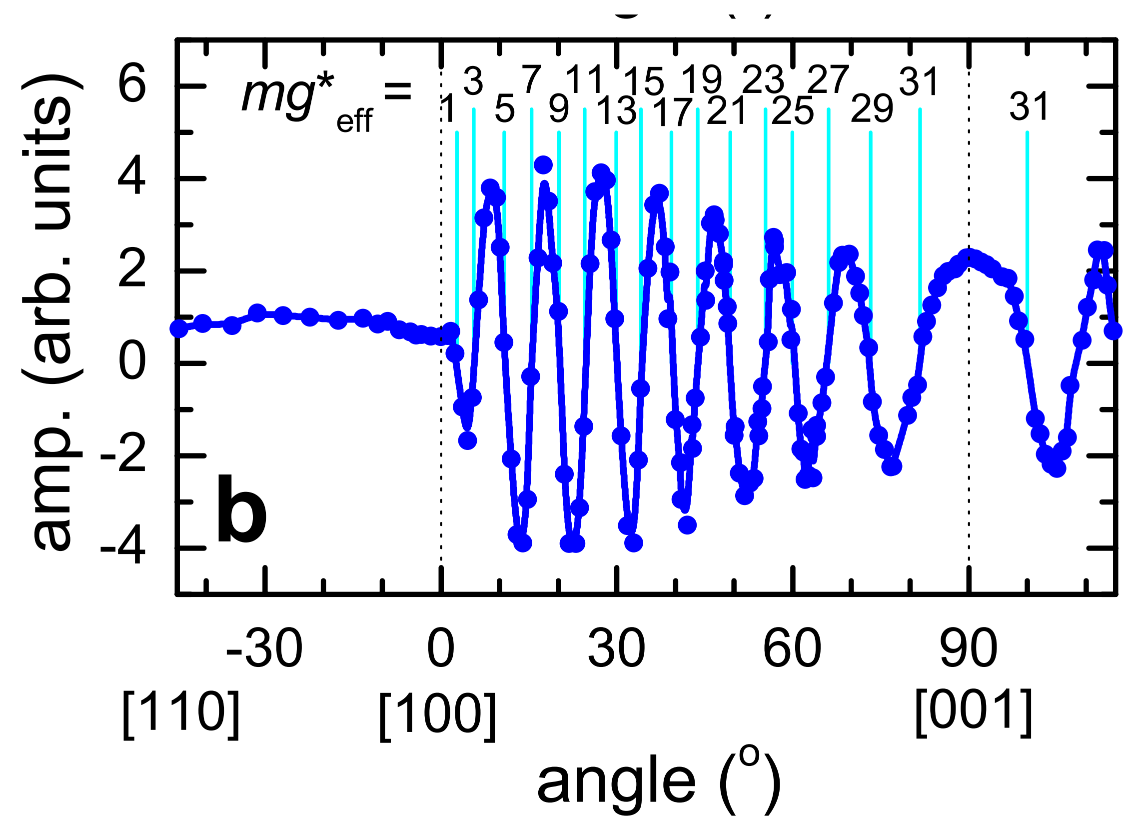

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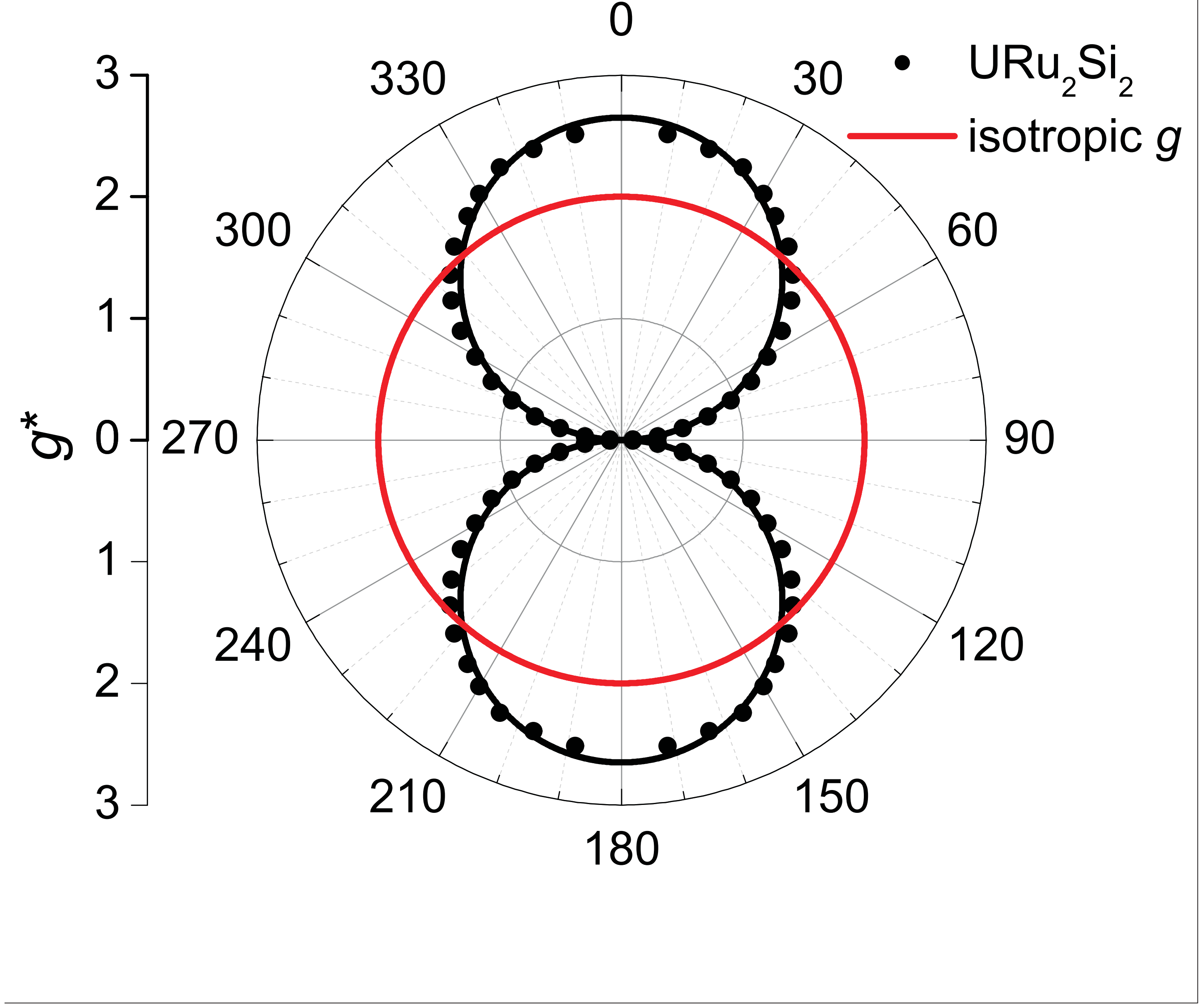

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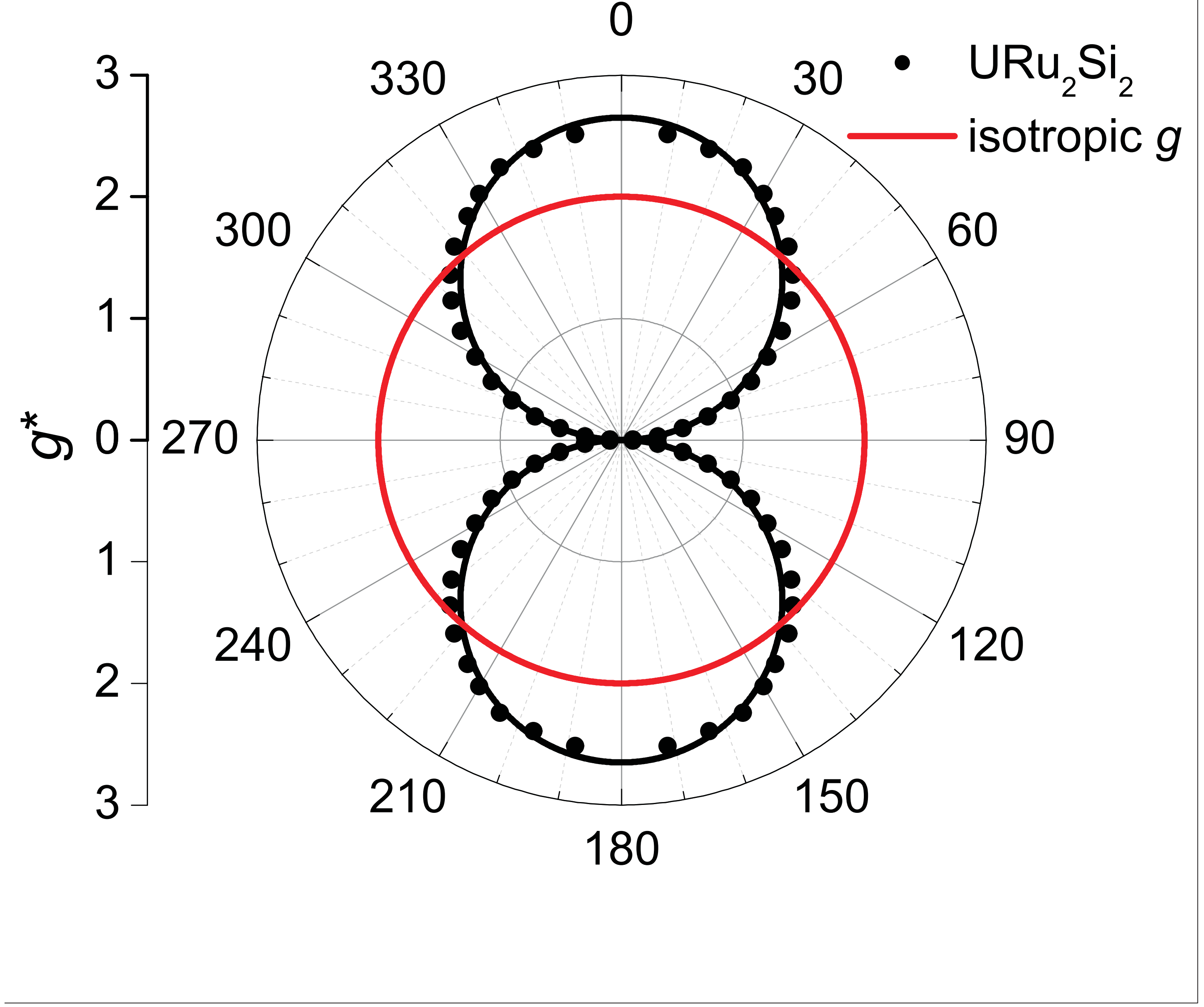

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Quasiparticle with giant Ising anisotropy > 30.
Pauli susceptibility anisotropy > 900

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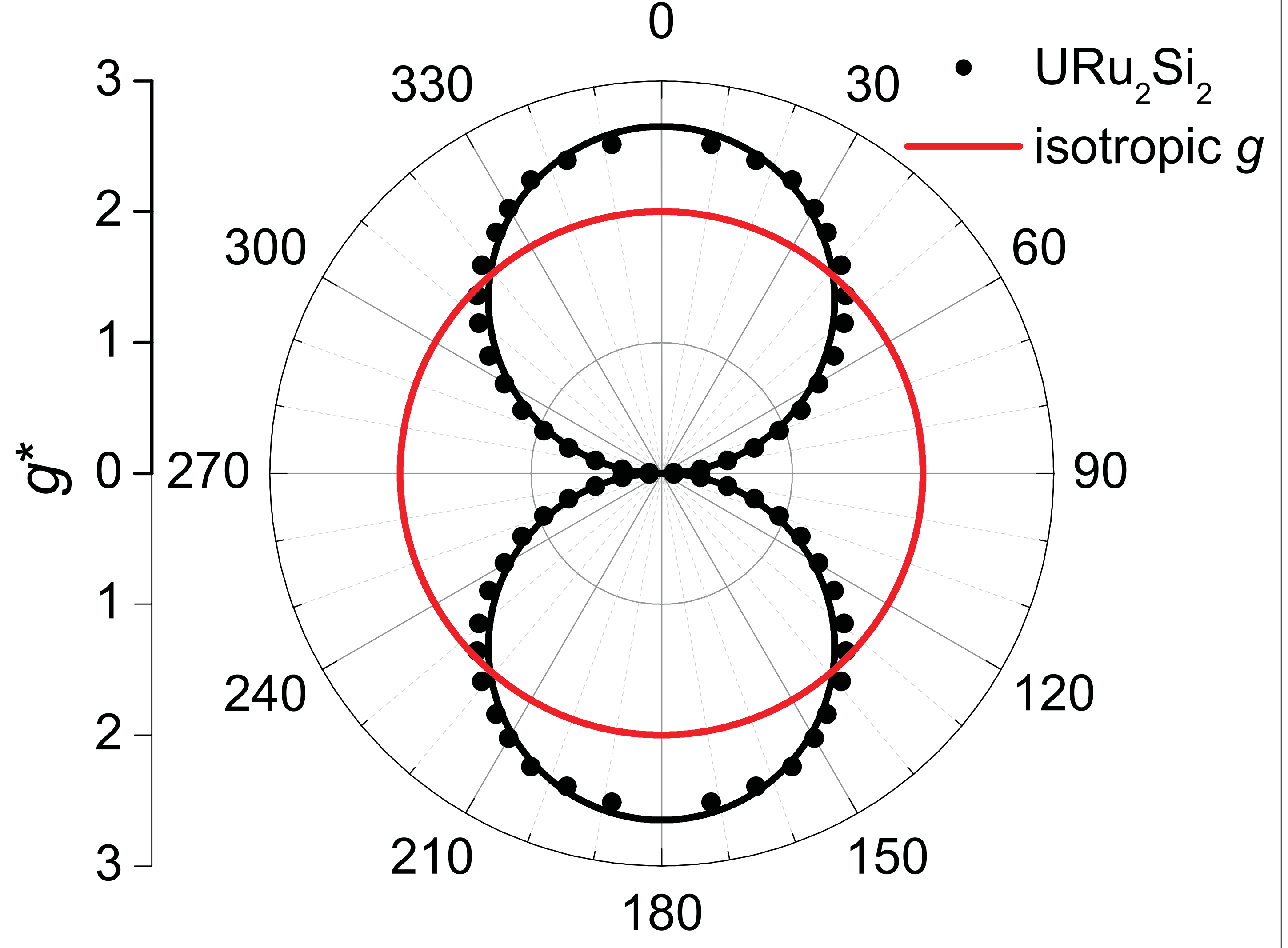

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Superconductivity: Giant Ising Anisotropy

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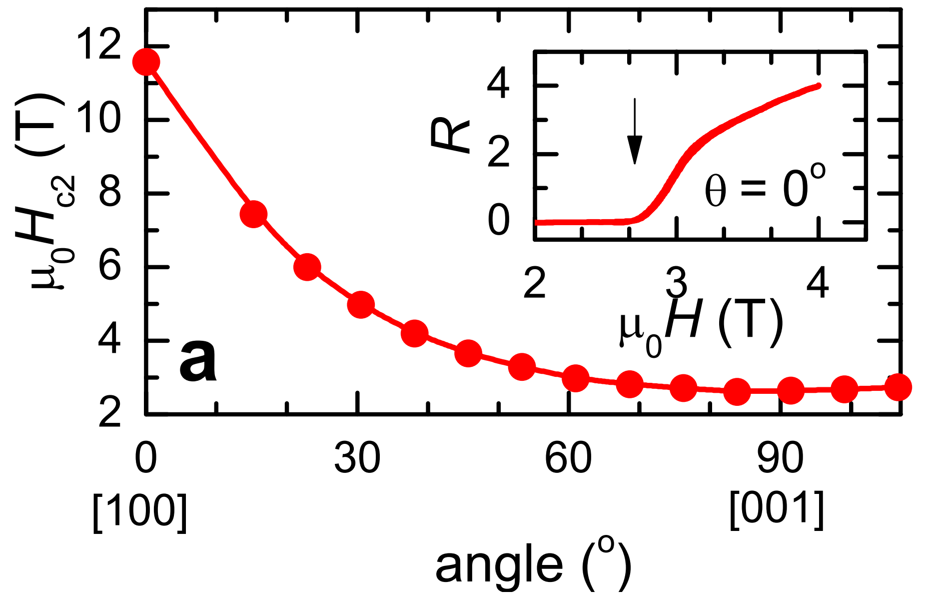
Altarawneh et al., PRL 108, 066407 (2012)



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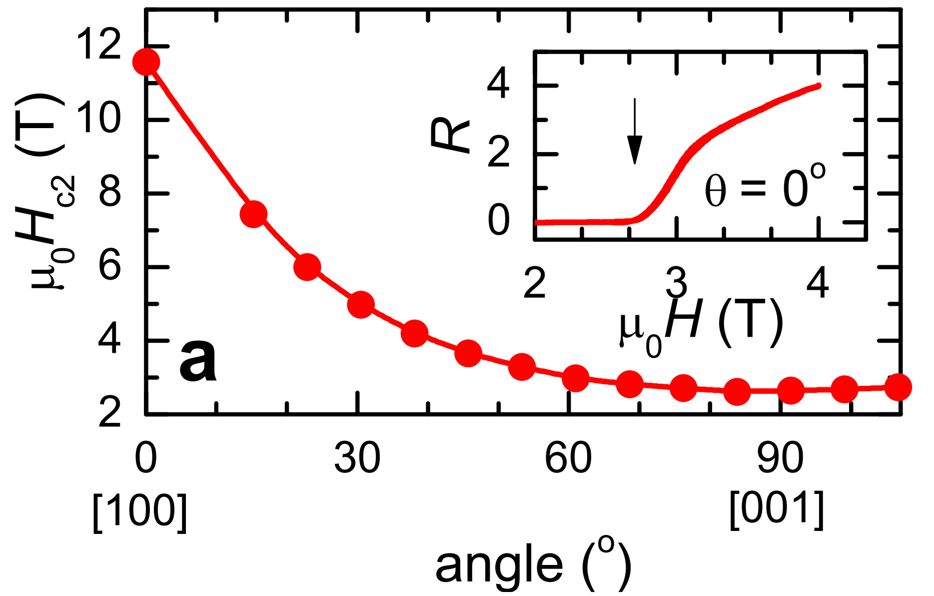

$$\mu_0 H_{\mathrm{p}} = \frac{2\Delta}{\sqrt{2}\ \mu_{\mathrm{B}} g^{*}_{\mathrm{eff}}}$$

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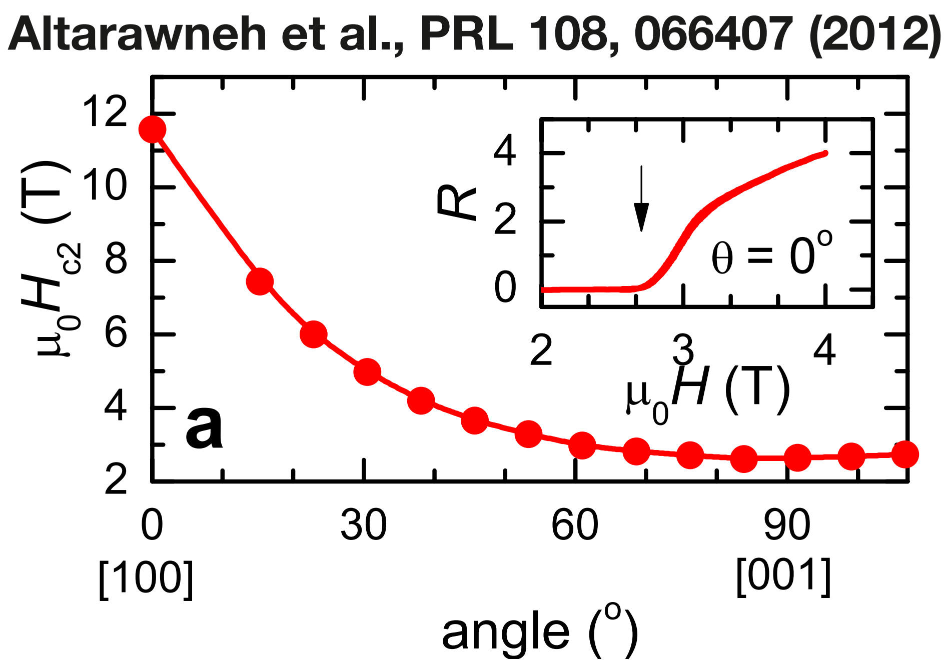

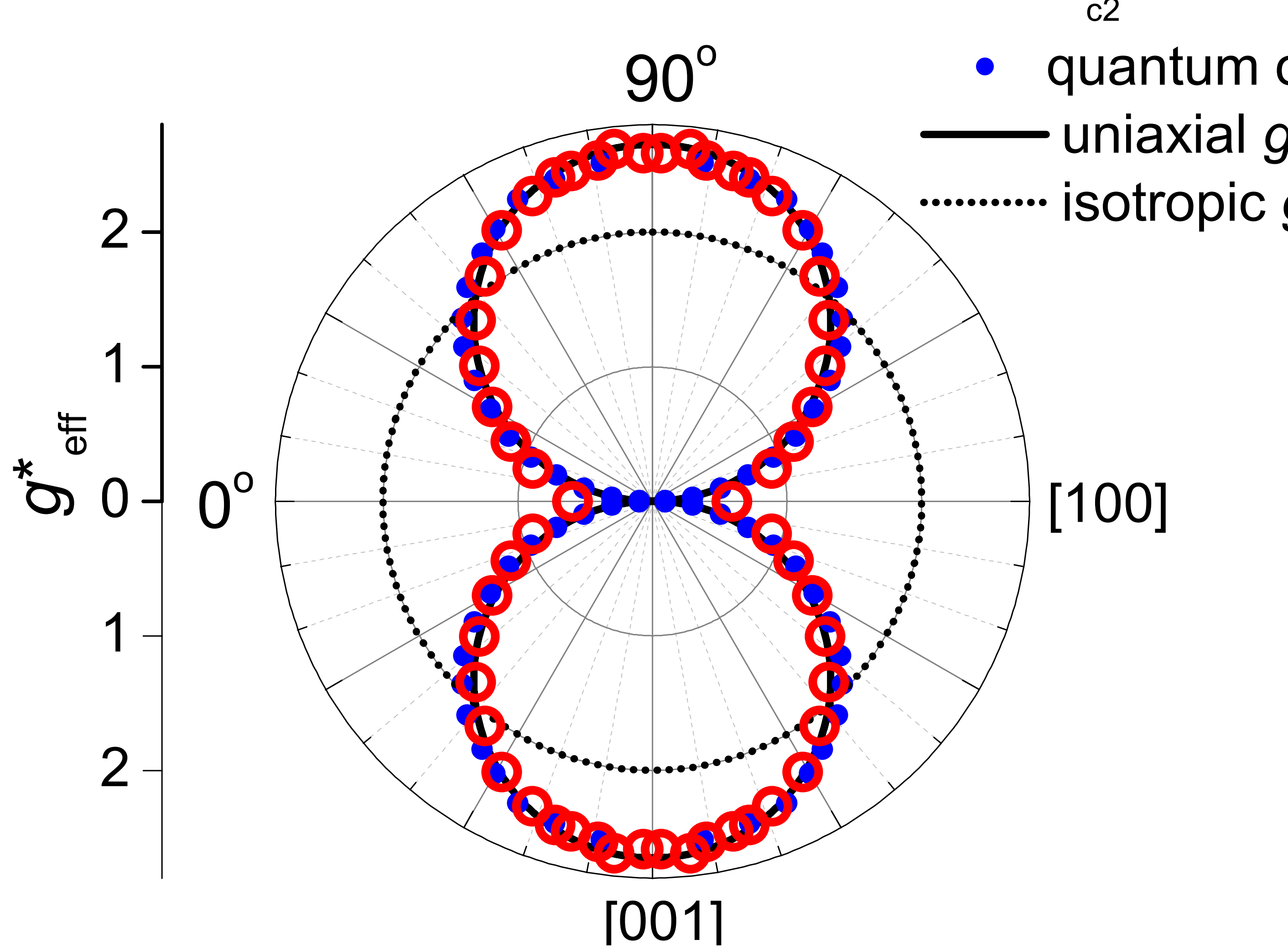

$$\mu_0 H_{\rm p} = \frac{2\Delta}{\sqrt{2}\ \mu_{\rm B} g^*_{\rm eff}}$$

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

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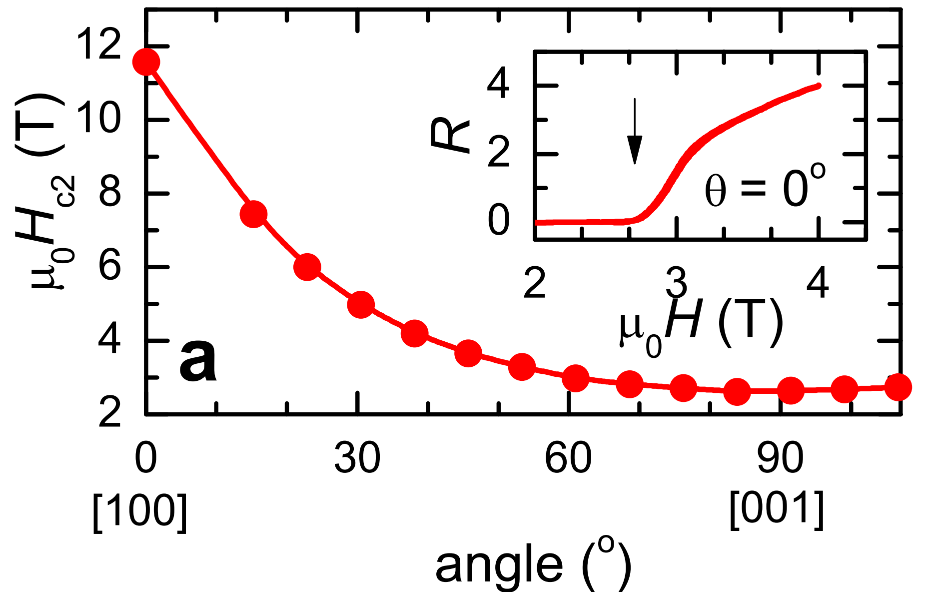
Superconductivity: Giant Ising Anisotropy

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



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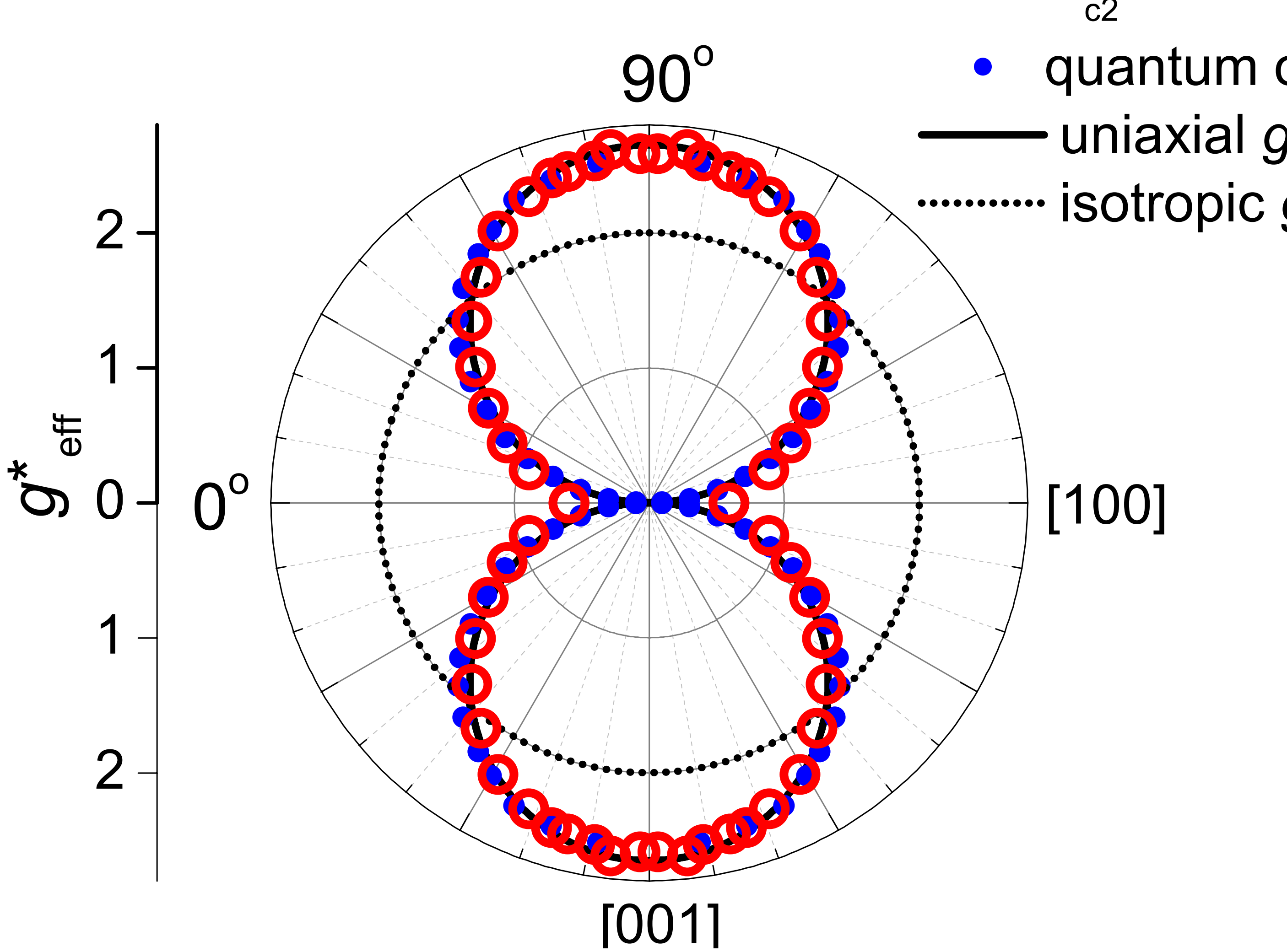

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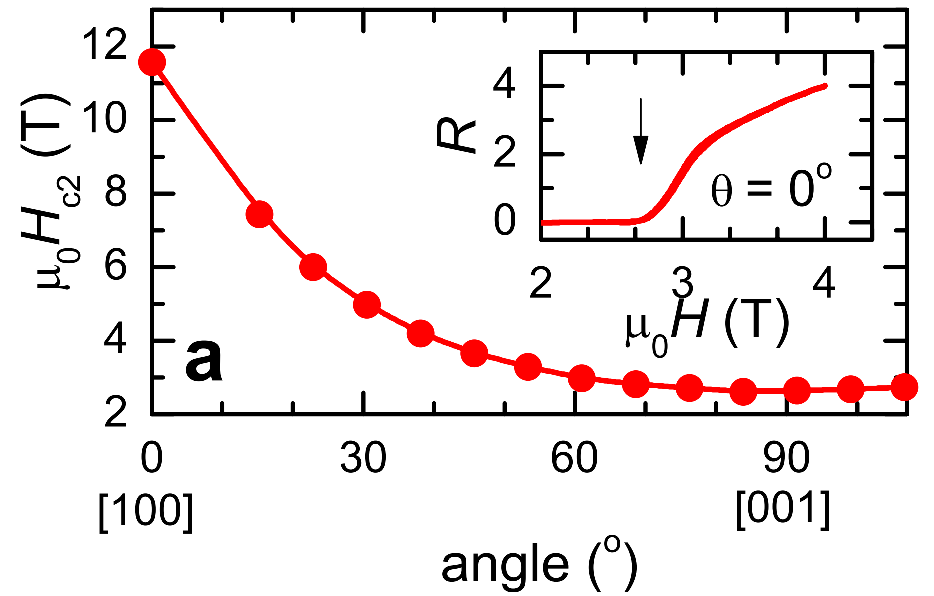

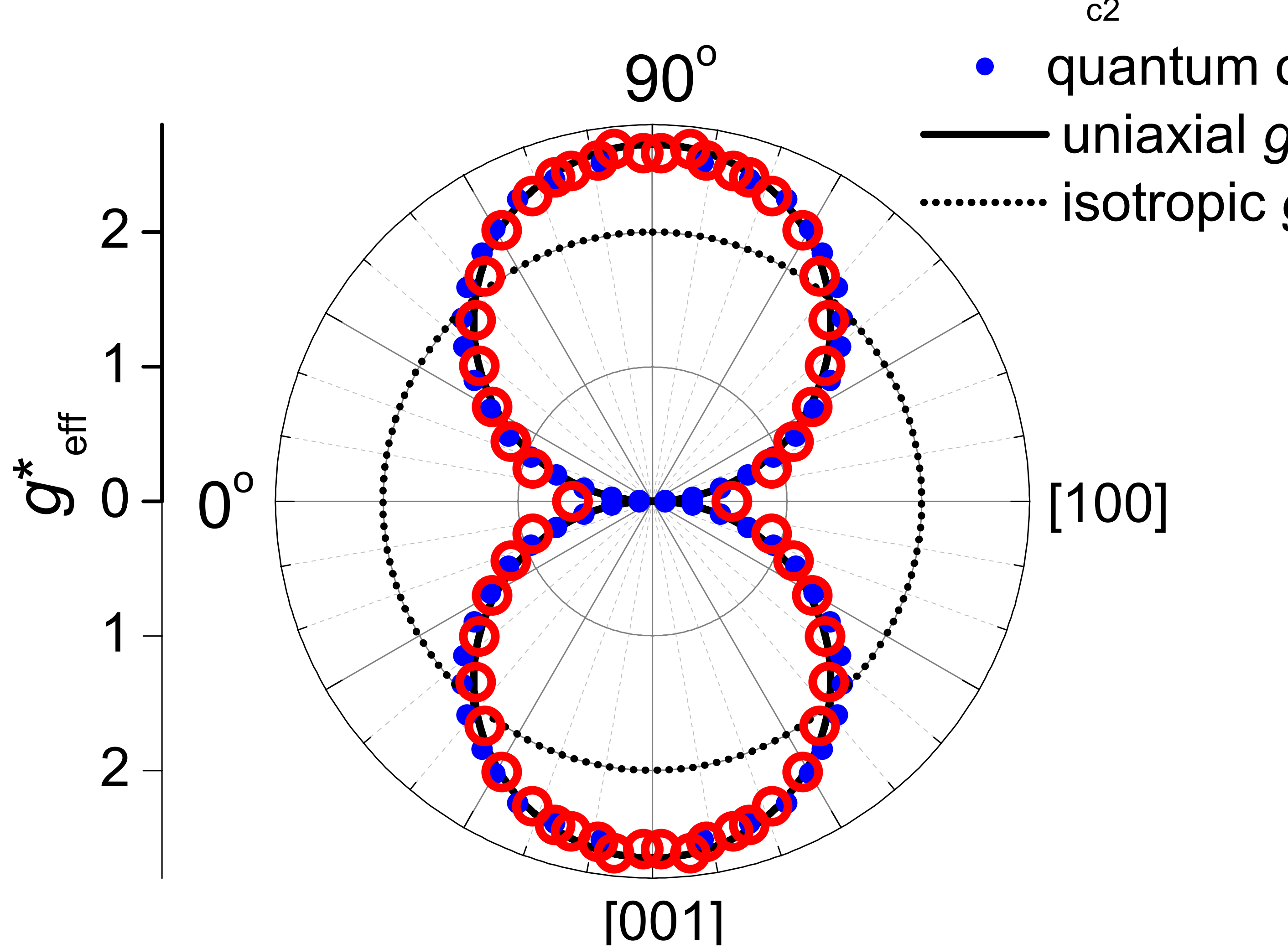

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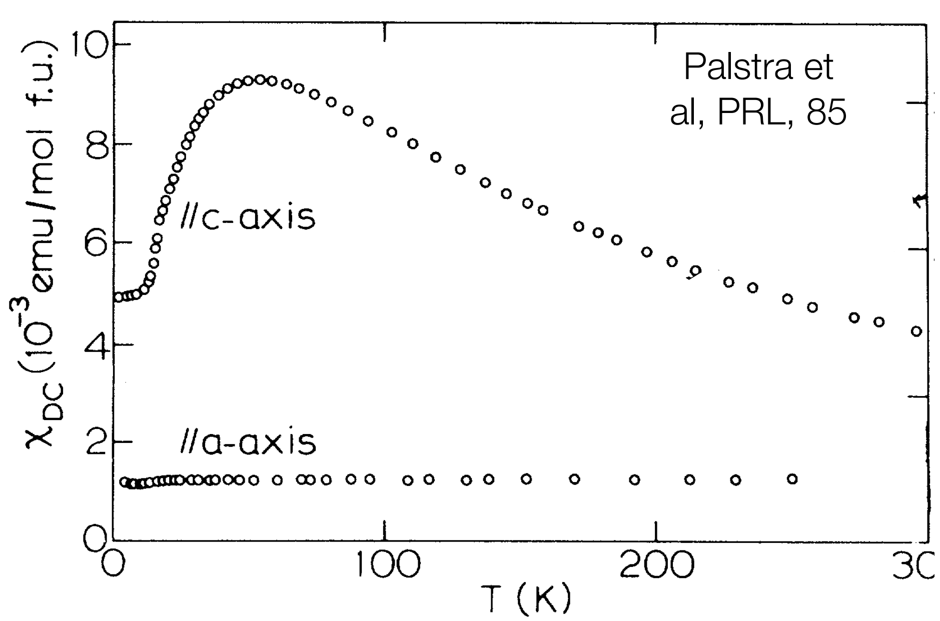

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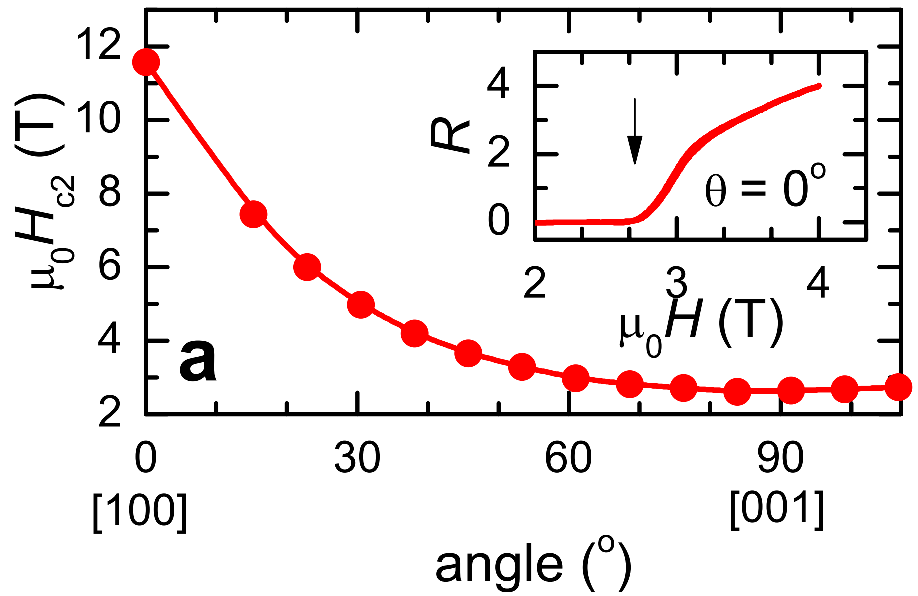

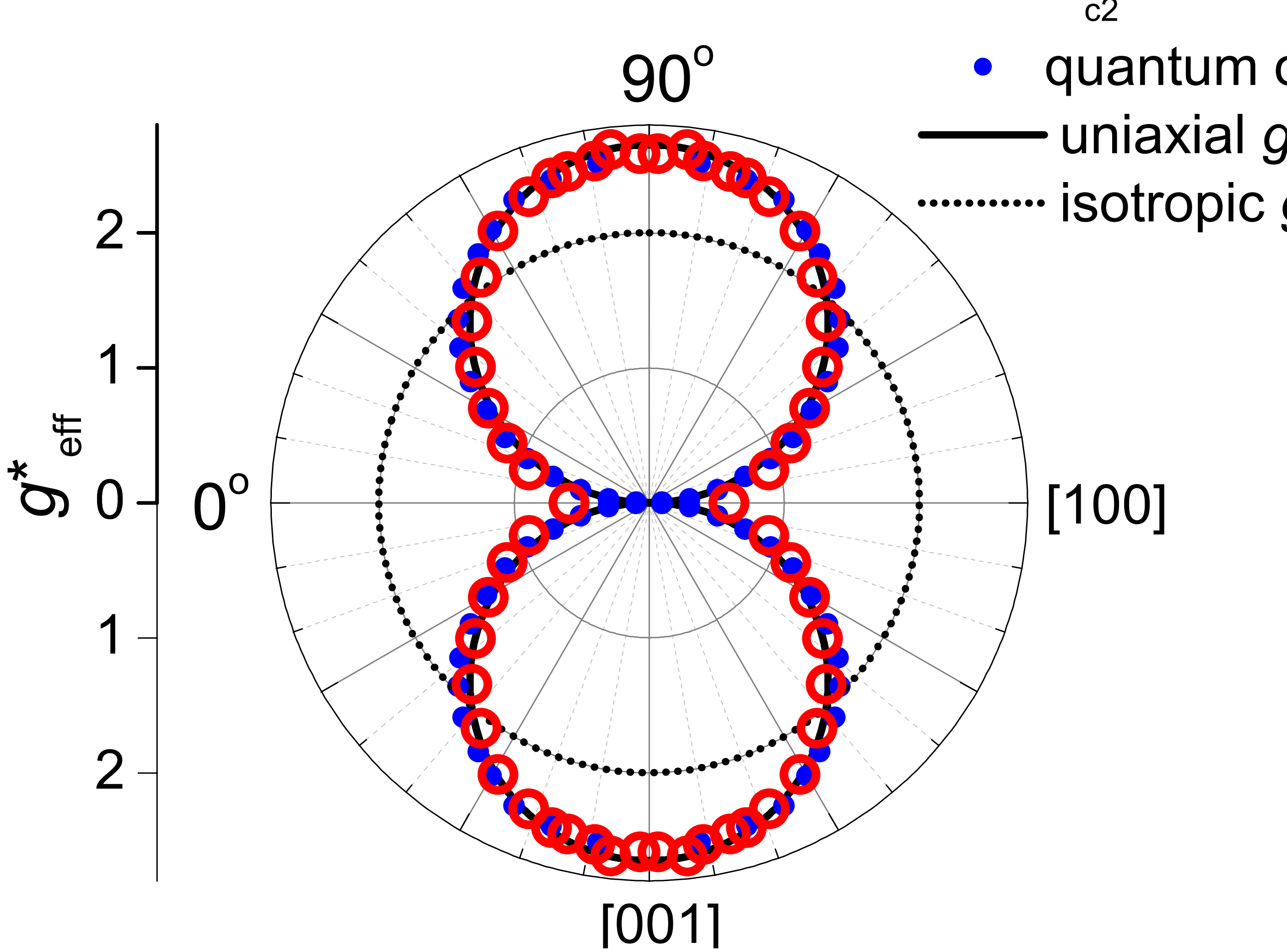

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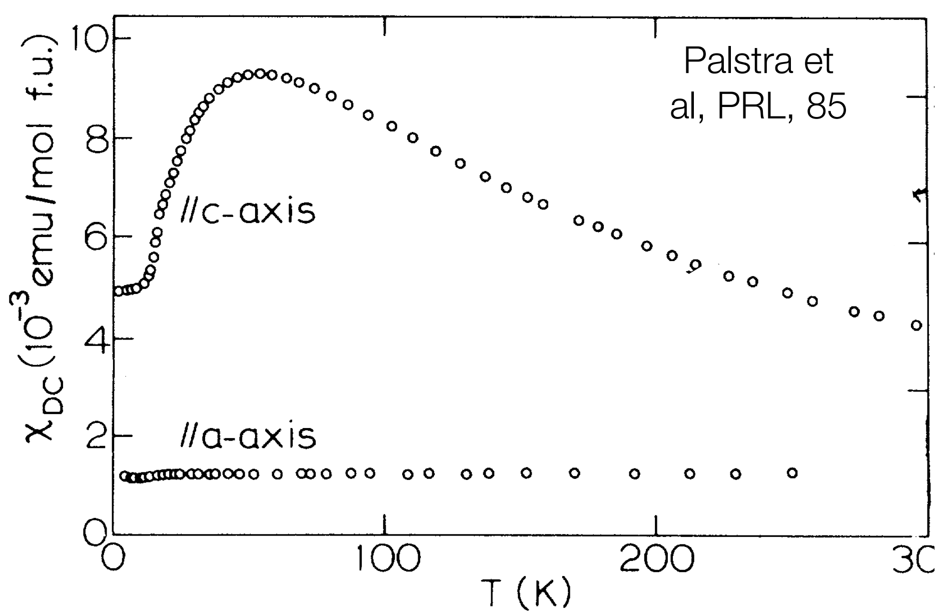

<u>Ising QP's pair condense.</u>

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

Electrons hybridize with Ising 5f state to form Landau quasiparticles. $\langle \mathbf{k}\sigma | J_\pm | \mathbf{k}\sigma' \rangle = 0$

“Ising Order: detailed analysis.”

Symmetry Implications of giant Ising anisotropy

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Giant Ising anisotropy indicates quasiparticle hybridization of electrons $|\mathbf{k}\sigma\rangle$ and **Ising 5f** doublet

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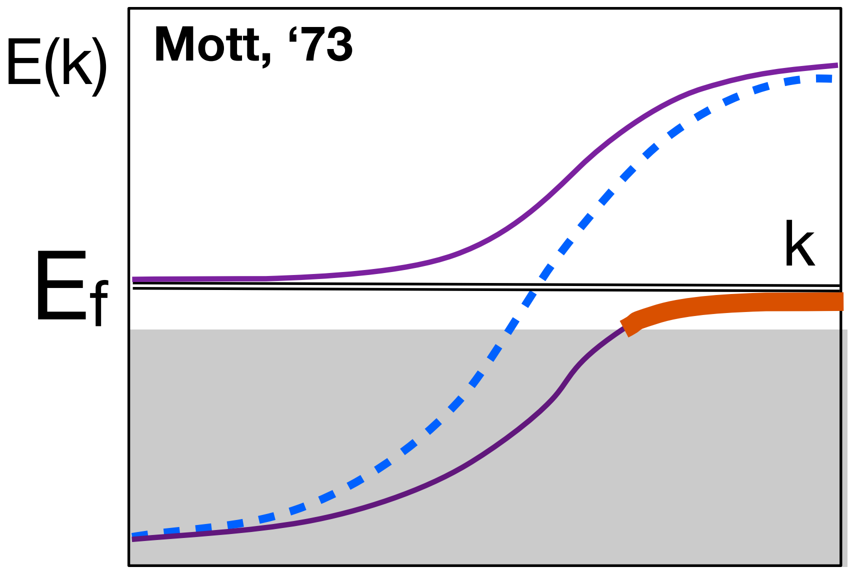

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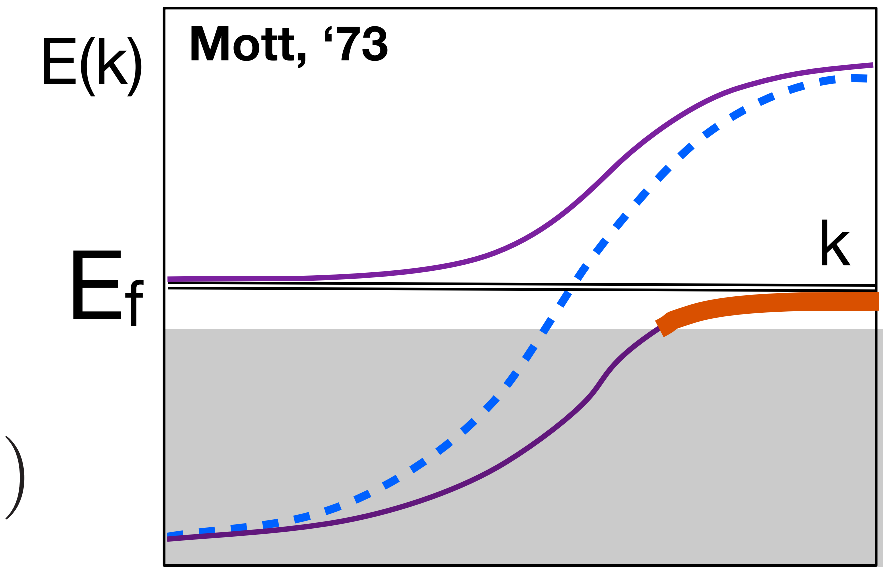

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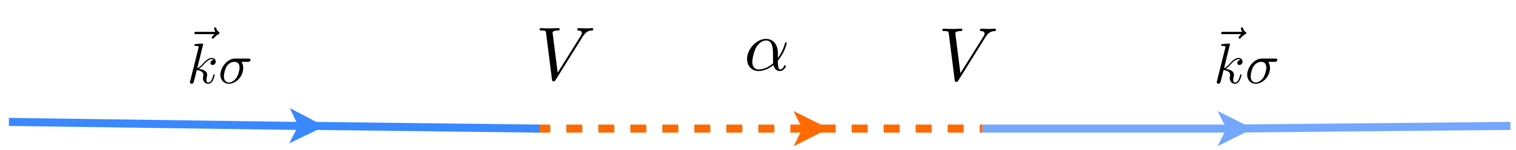

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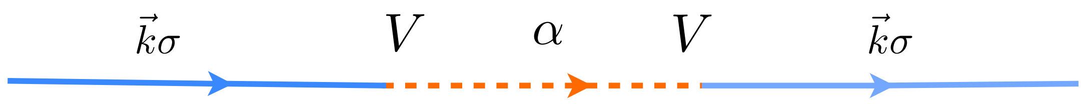

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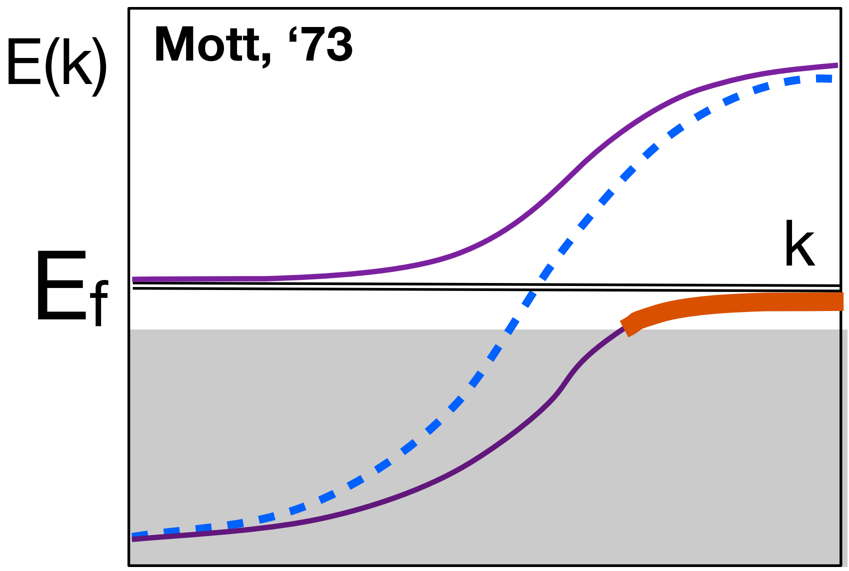

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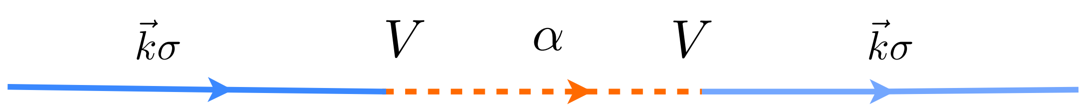

$$\langle +|J_\pm|-\rangle = 0$$

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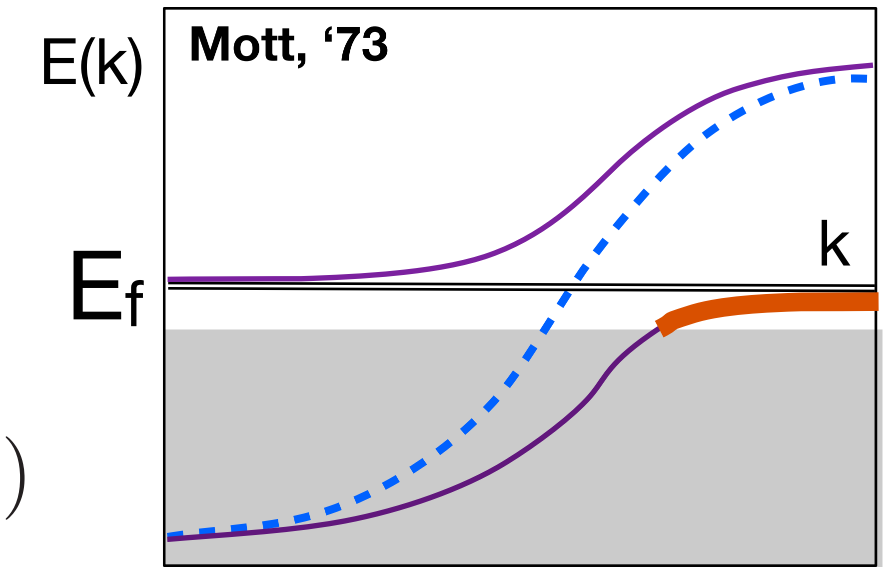

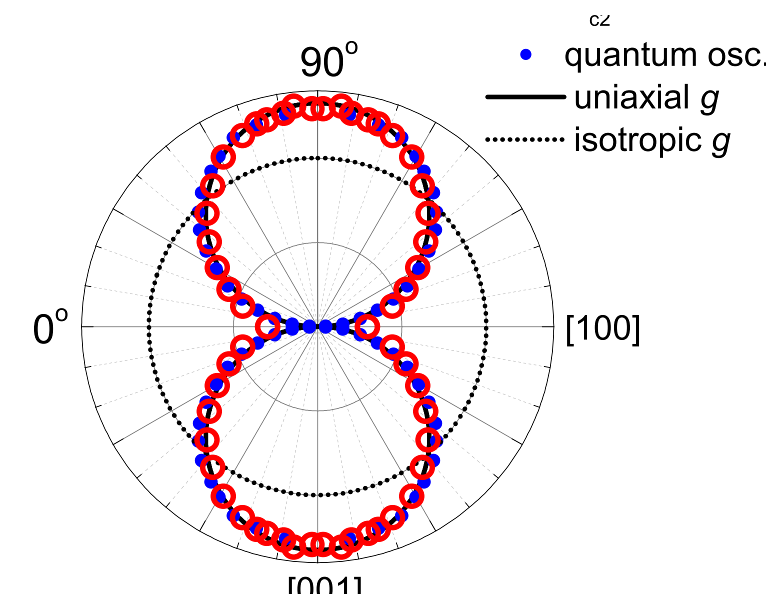

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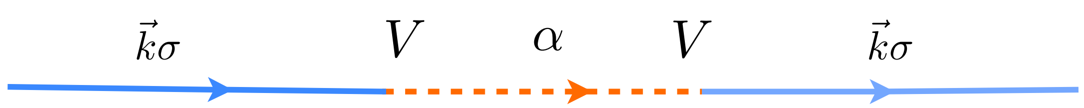

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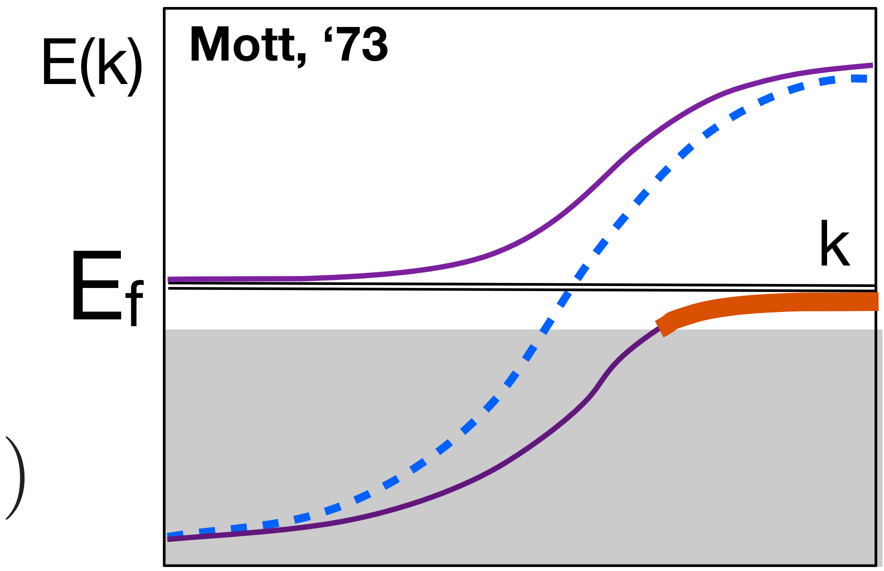

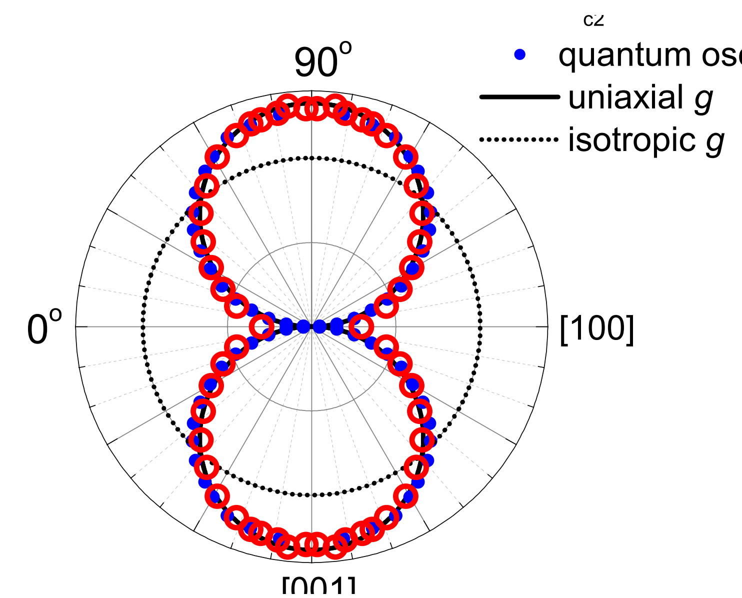

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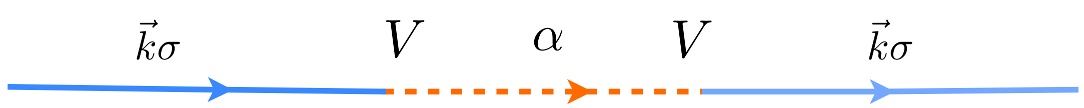

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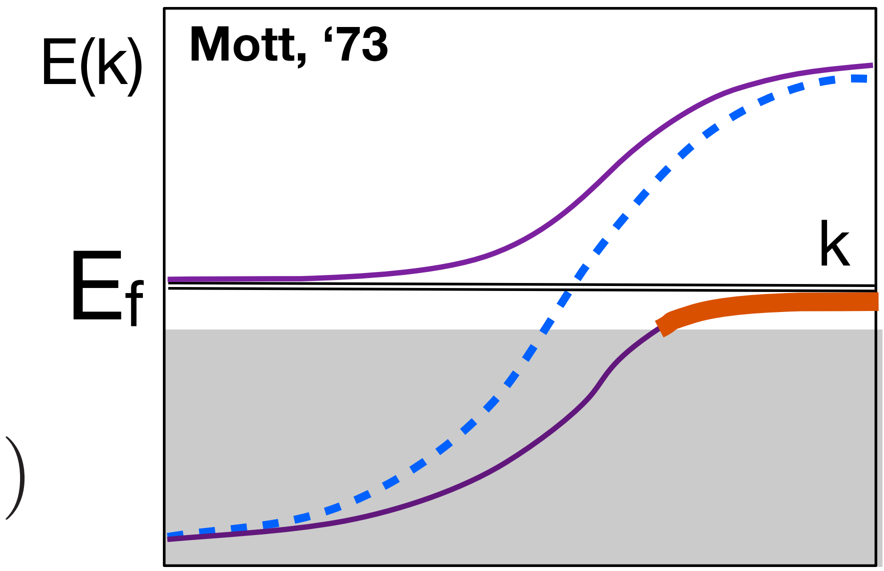

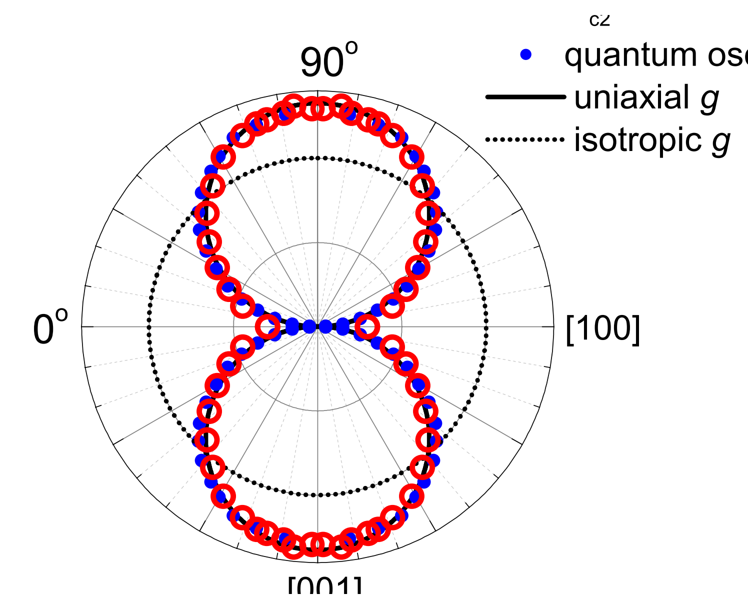

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4 fold symmetry
mixes states differing by $4\hbar$

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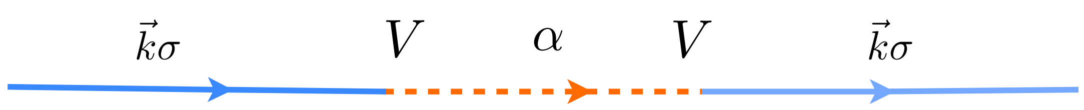

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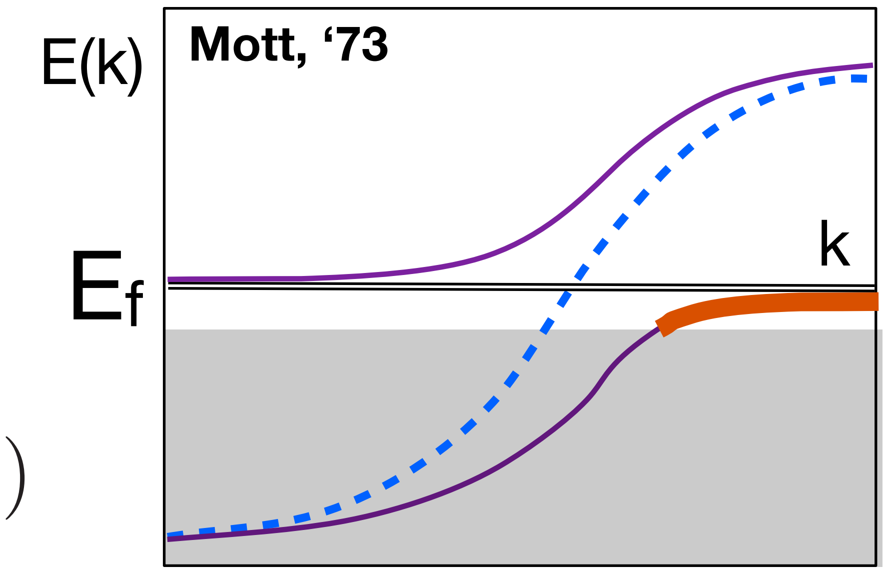

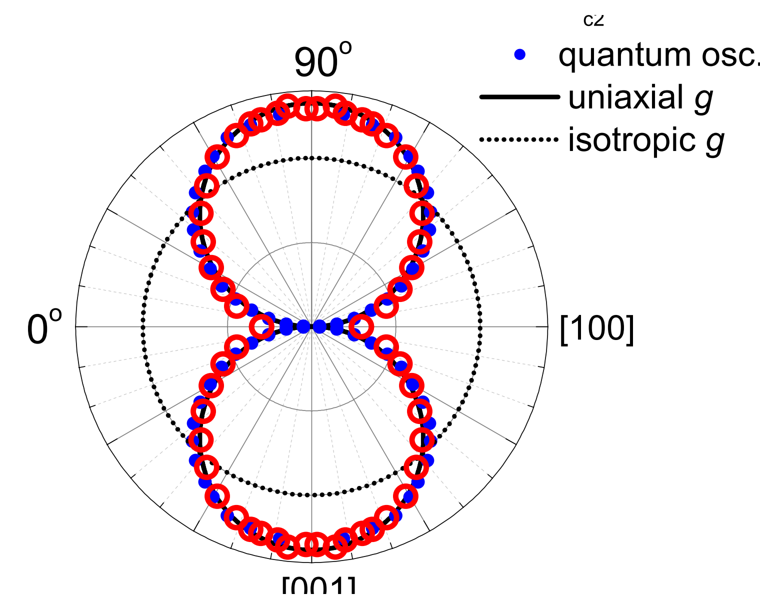

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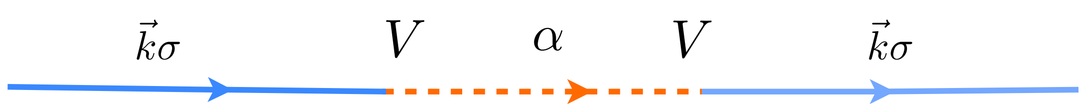

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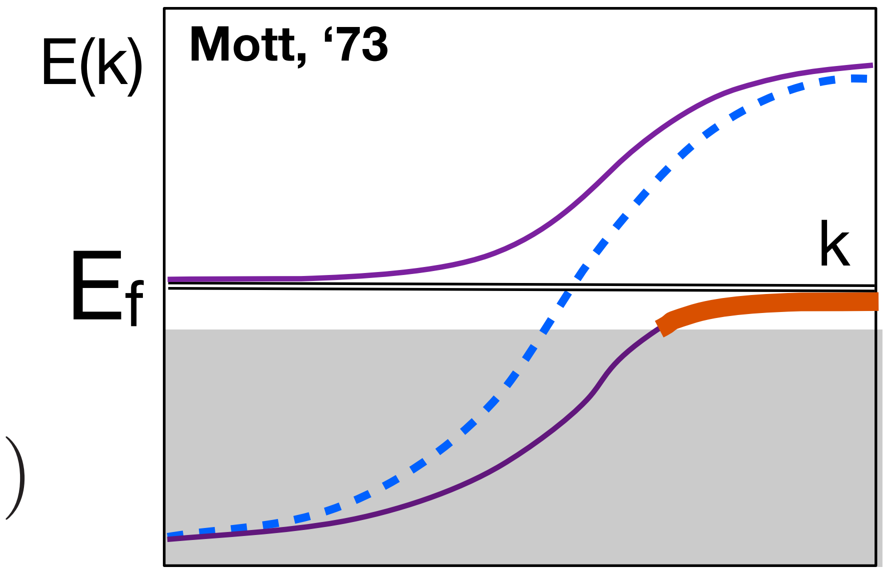

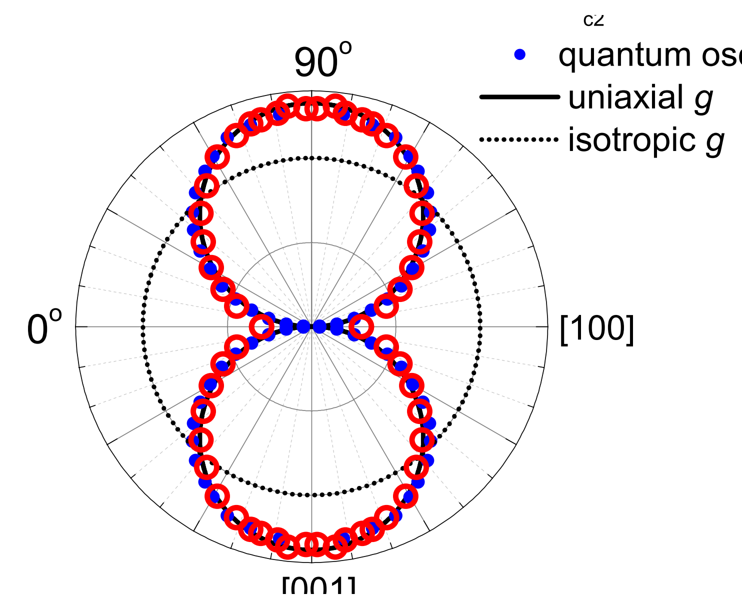

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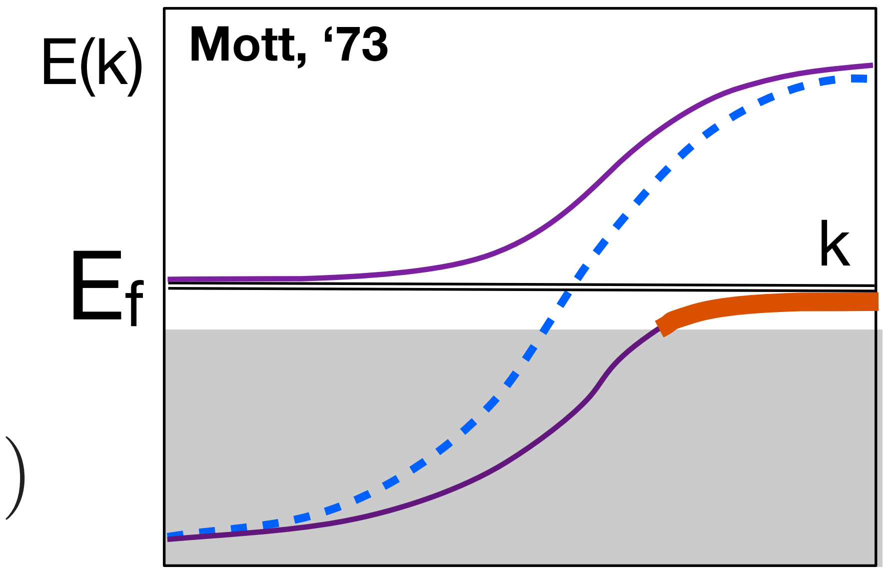

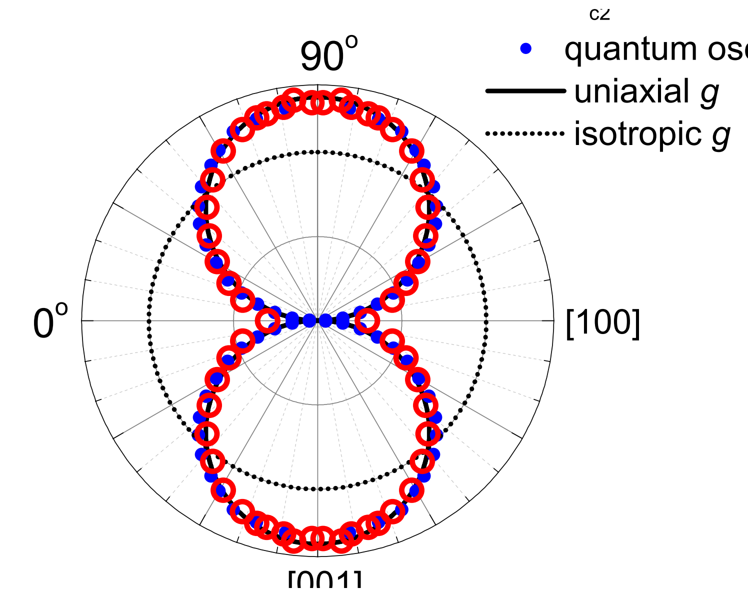

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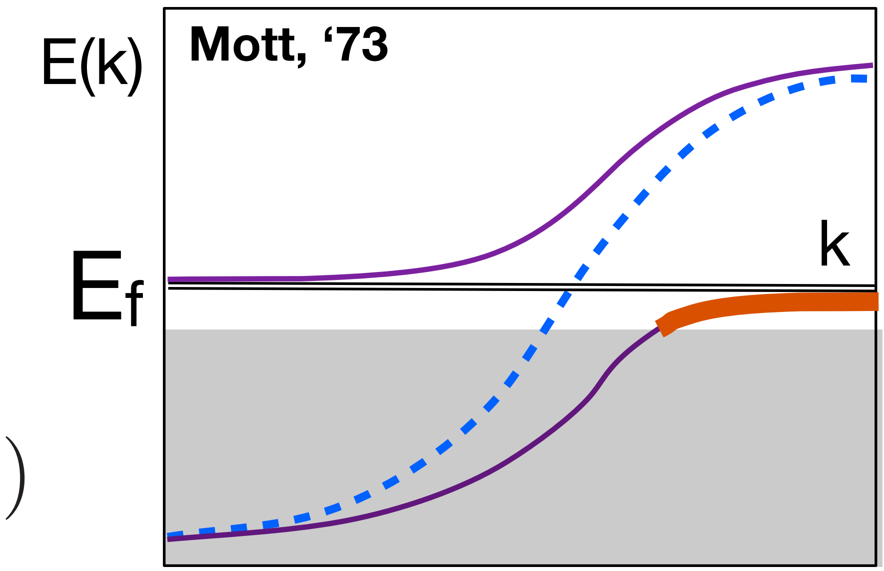

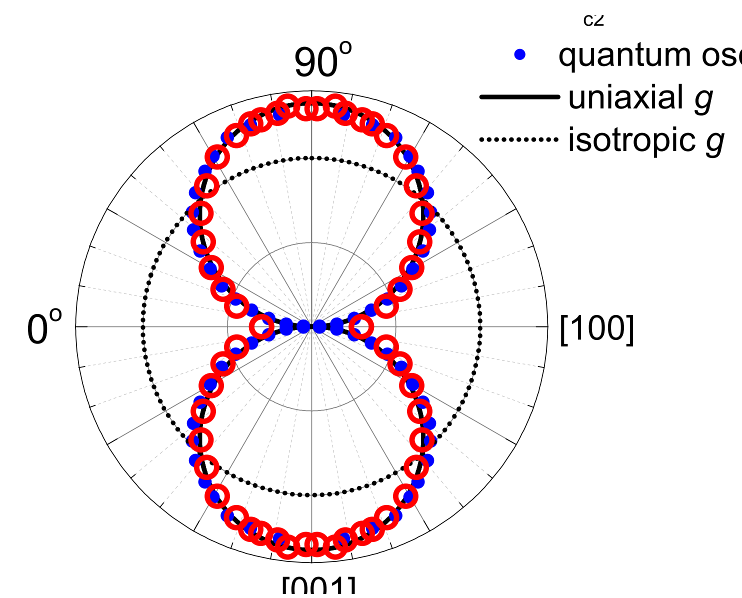

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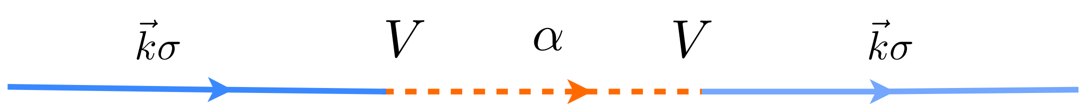
Symmetry Implications of giant Ising anisotropy



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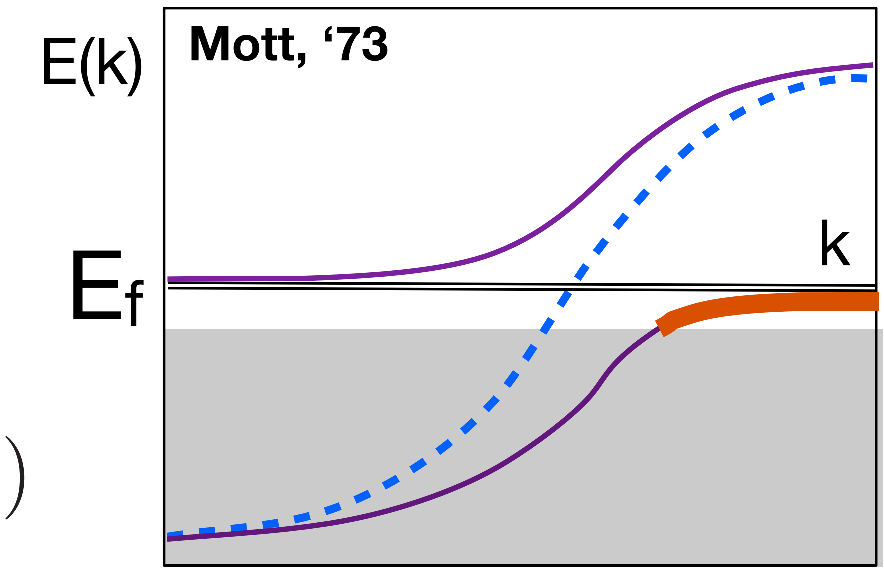

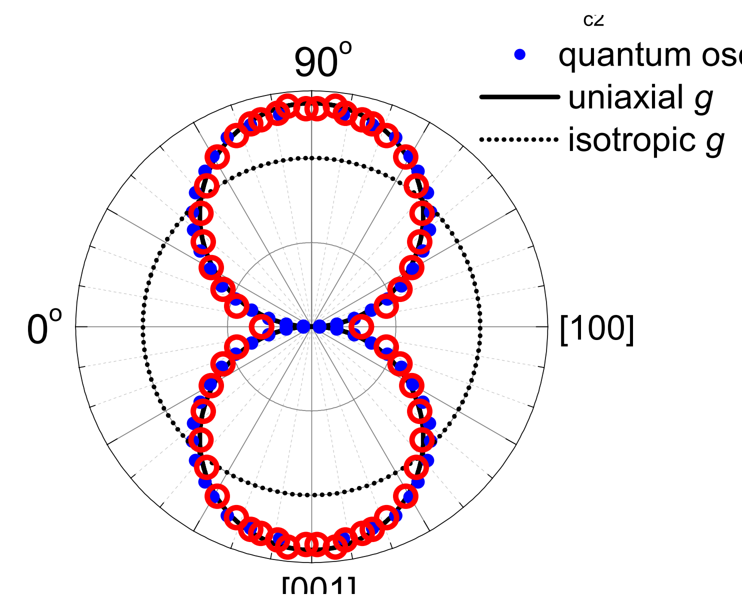

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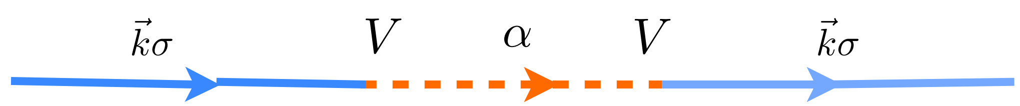
$\therefore$ Integer spin M

Symmetry Implications of giant Ising anisotropy



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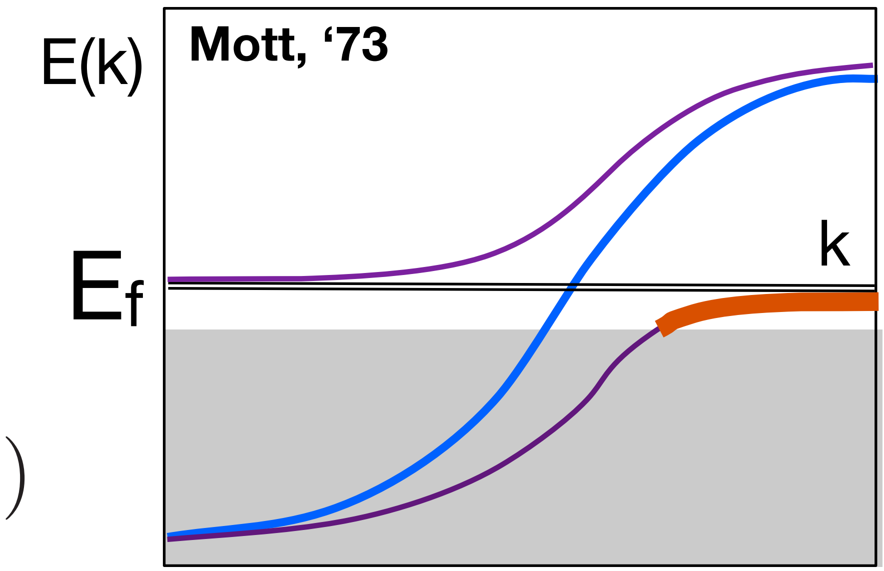

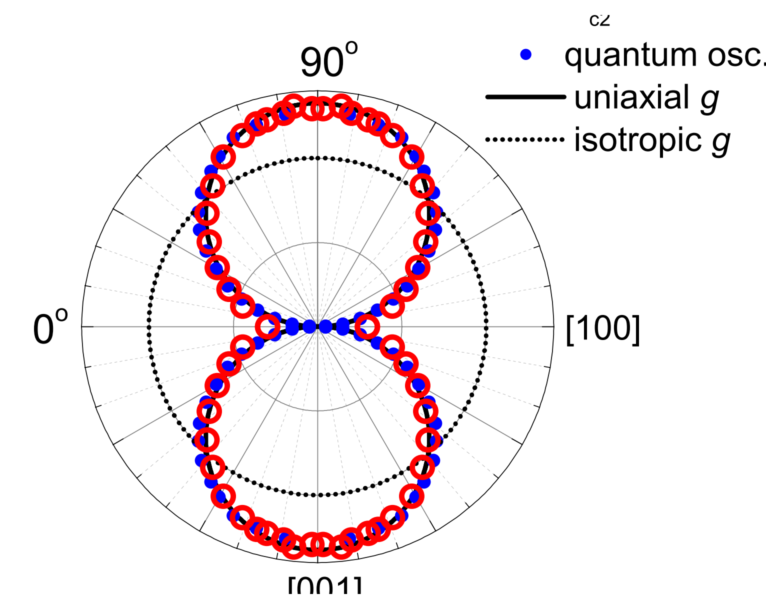

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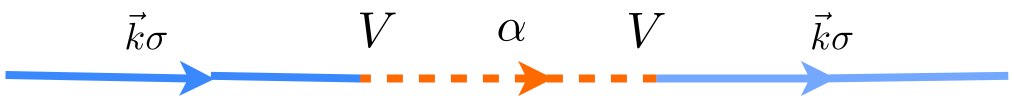

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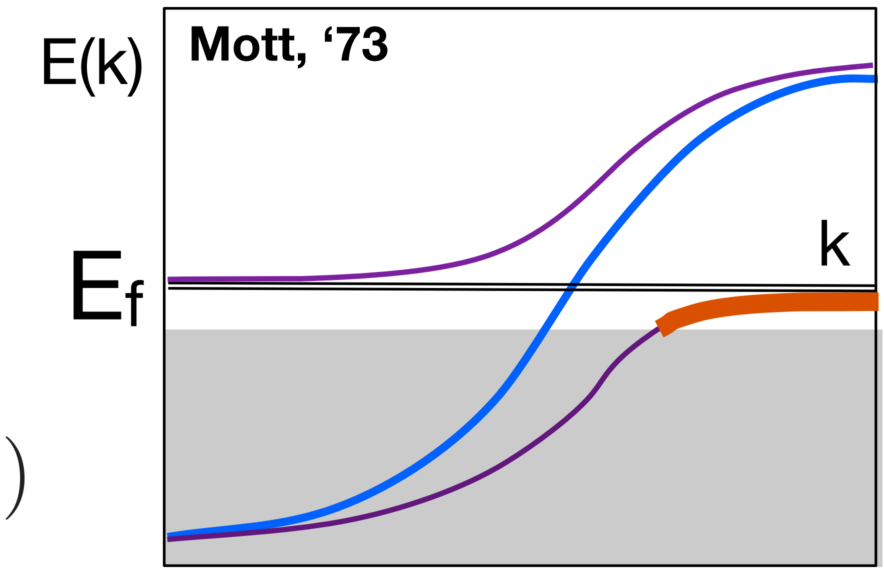

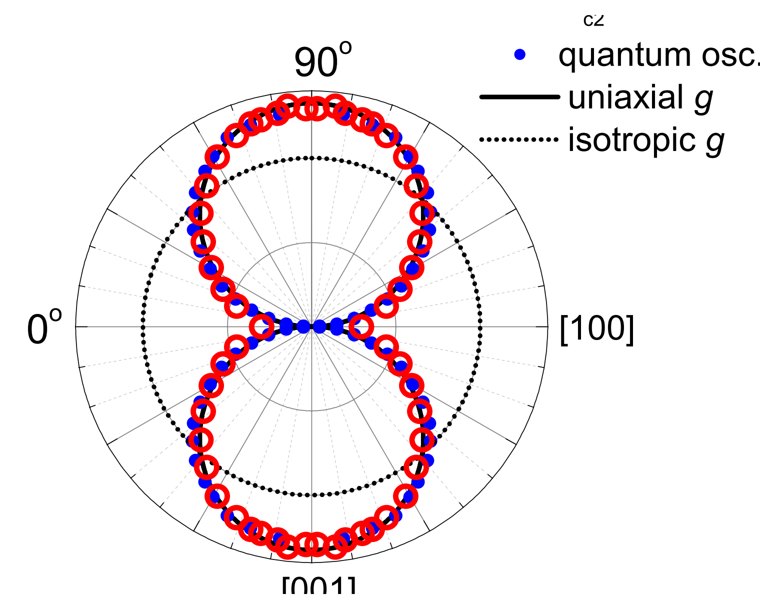

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$$|\Gamma, \pm\rangle = a|\pm 3\rangle + b|\mp 1\rangle$$

"Γ_5" non-Kramers doublet $5f^2$

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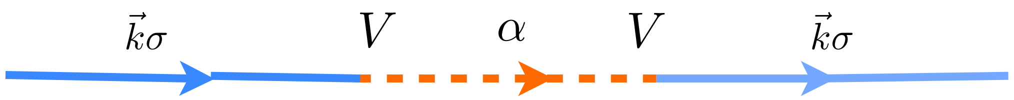
Symmetry Implications of giant Ising anisotropy



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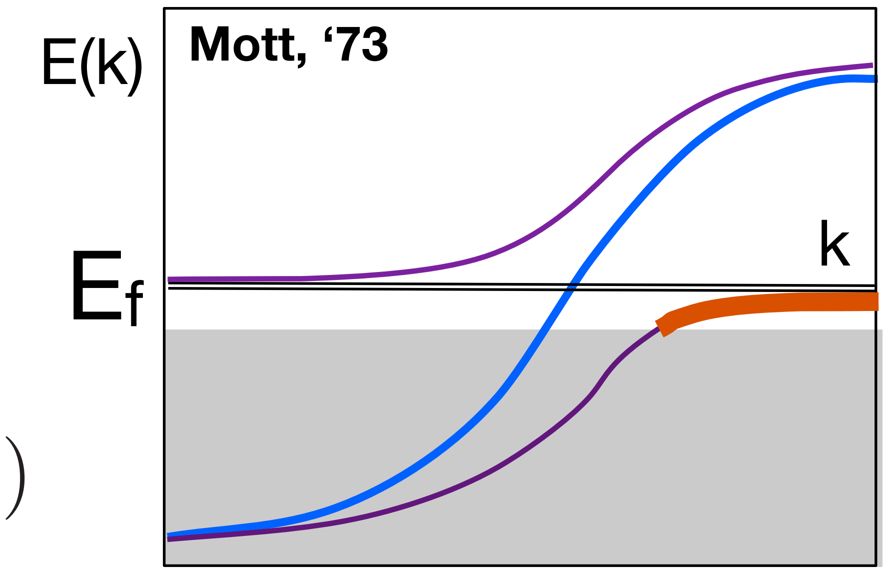

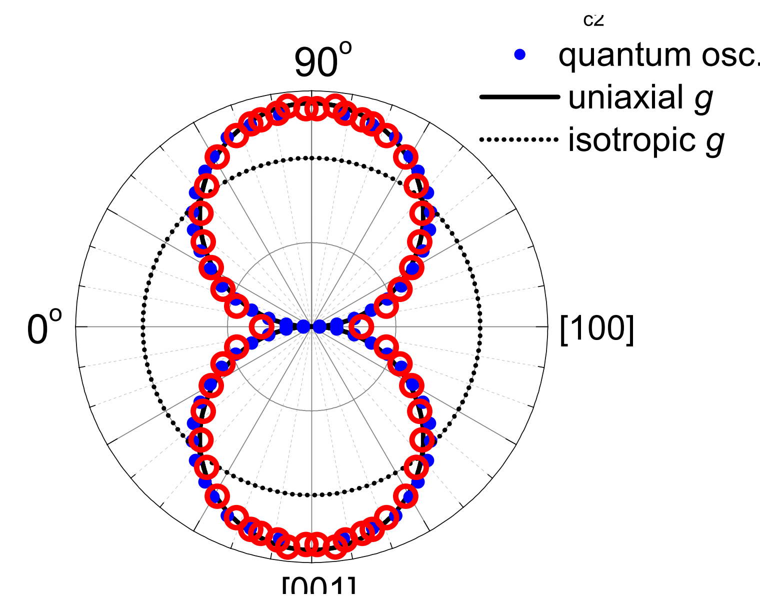

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Integer

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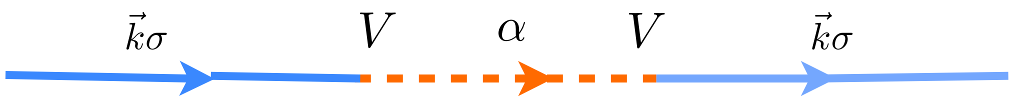

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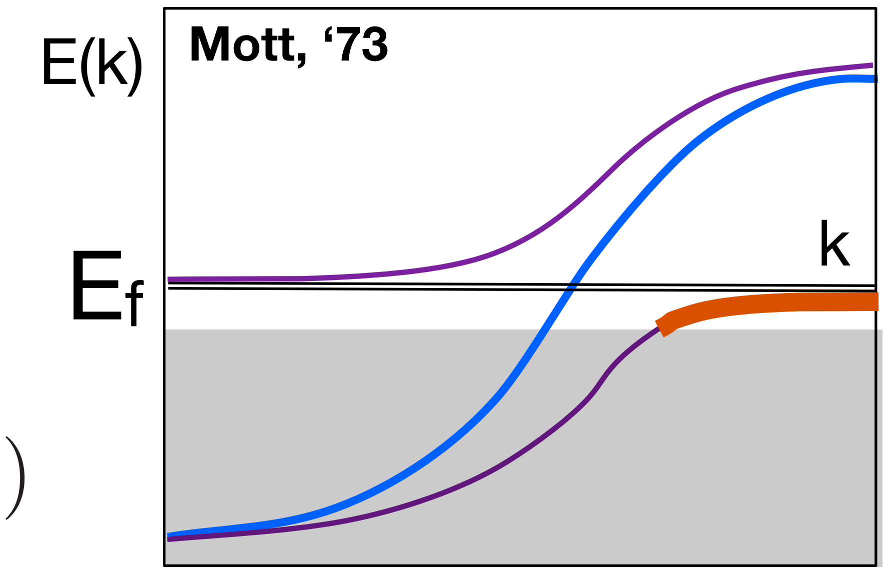

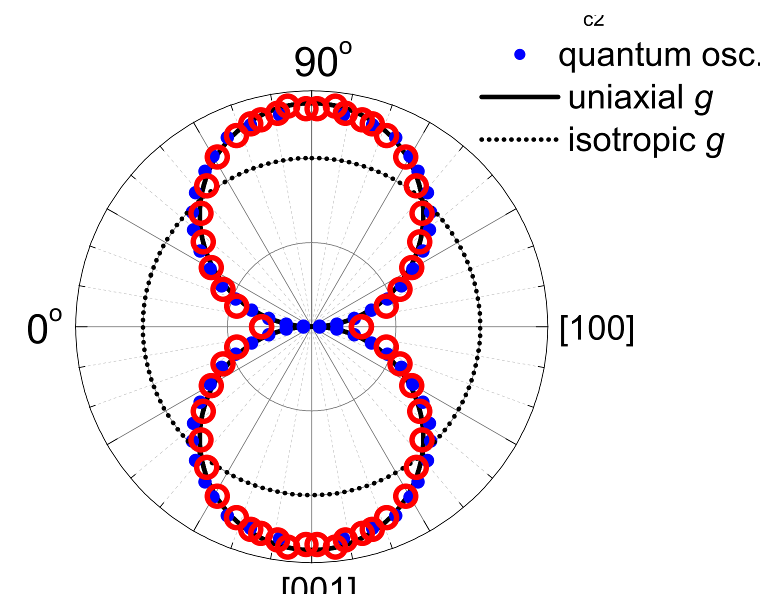

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Integer

1/2 integer

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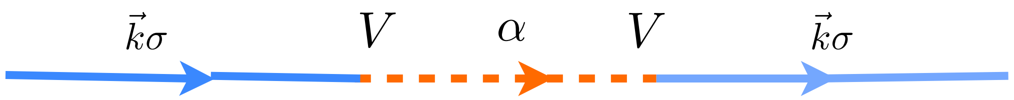

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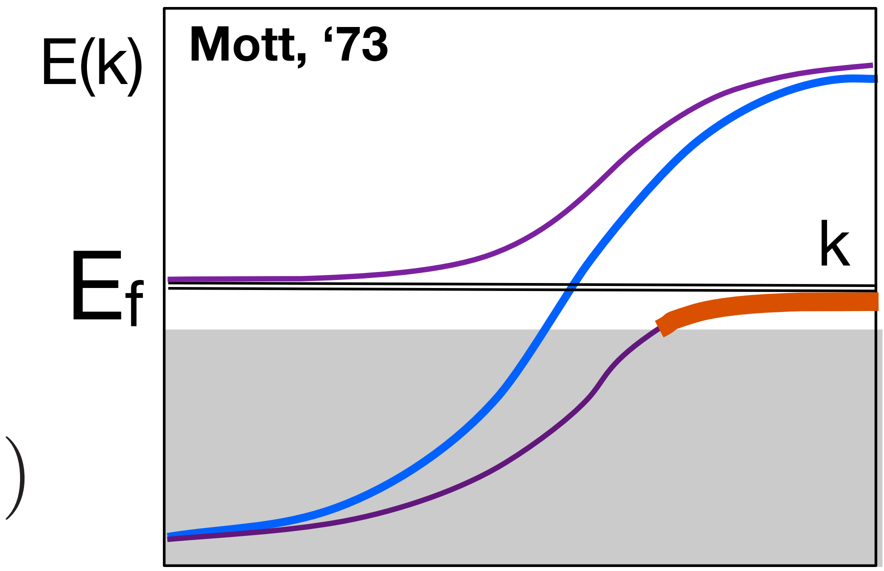
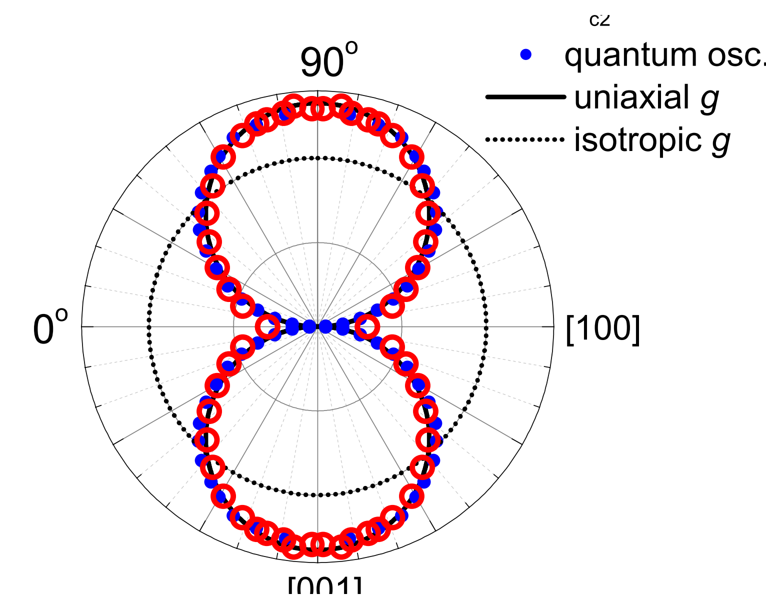




$$\mathcal{H} = (|\mathbf{k}\sigma\rangle V_{\sigma\alpha}(\mathbf{k})\langle\alpha| + \mathrm{H.c})$$

Integer

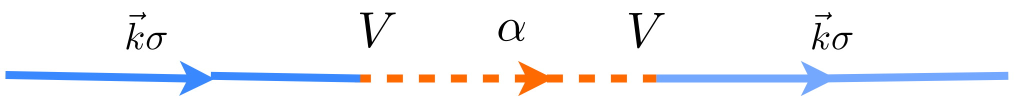
1/2 integer

1/2 integer

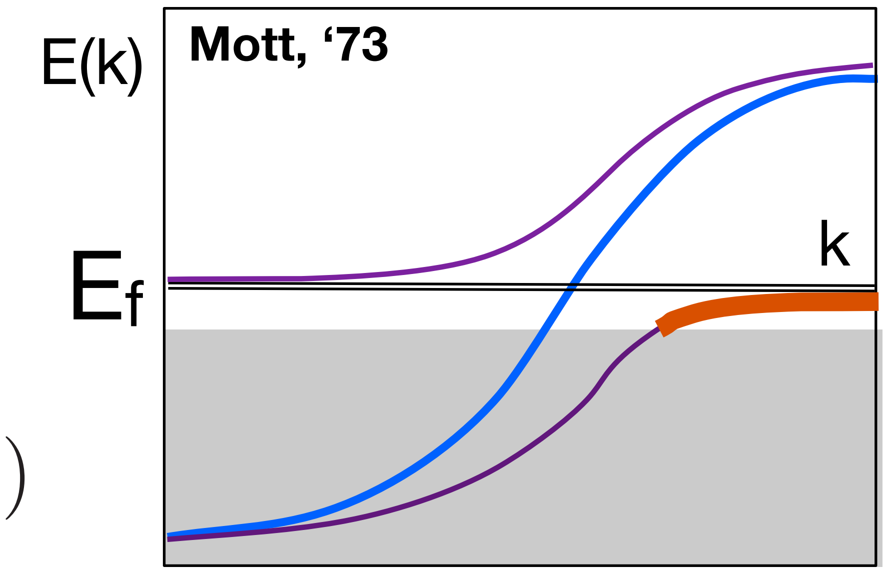
$$|\Gamma, \pm\rangle = a|\pm 3\rangle + b|\mp 1\rangle$$

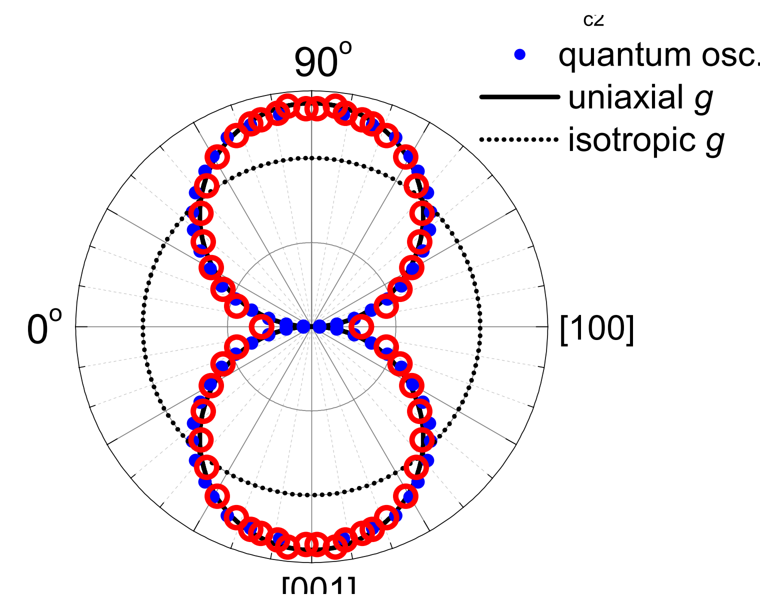
"Γ_5" non-Kramers doublet $5f^2$

Symmetry Implications of giant Ising anisotropy



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





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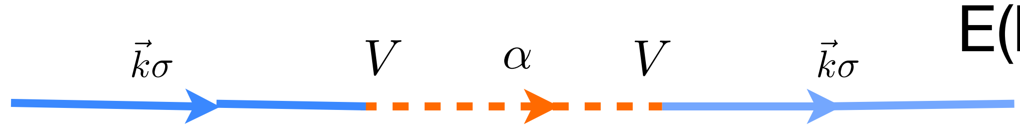

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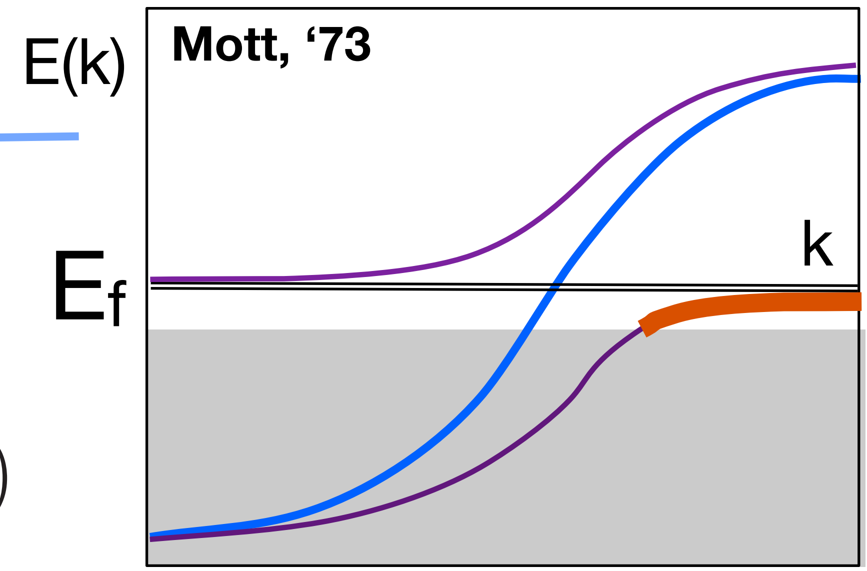

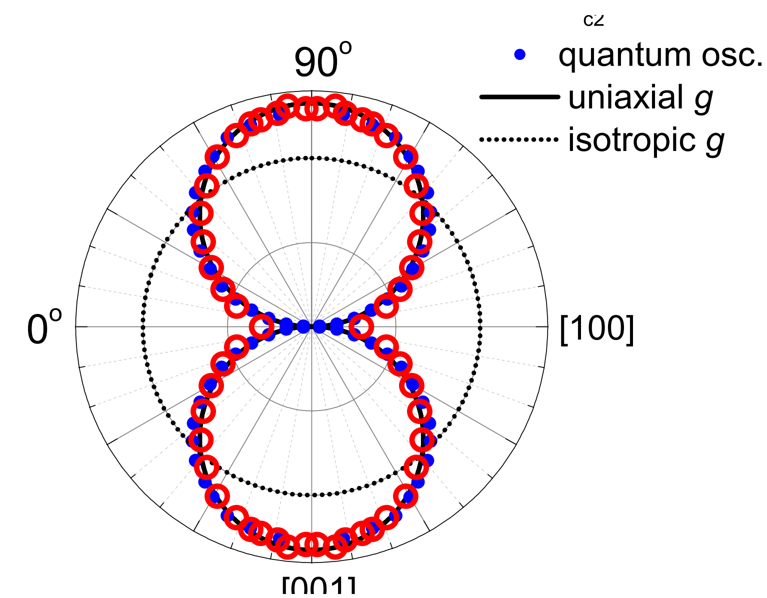

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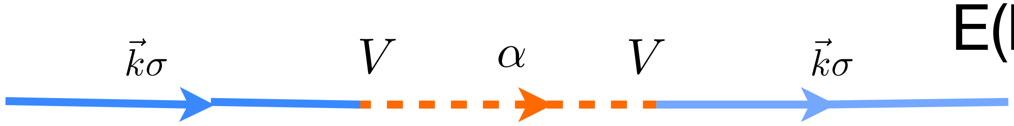

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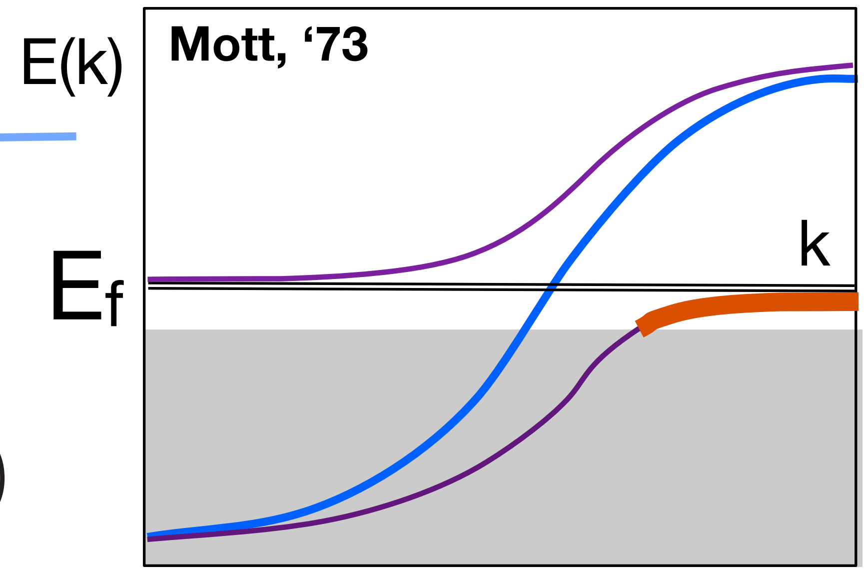

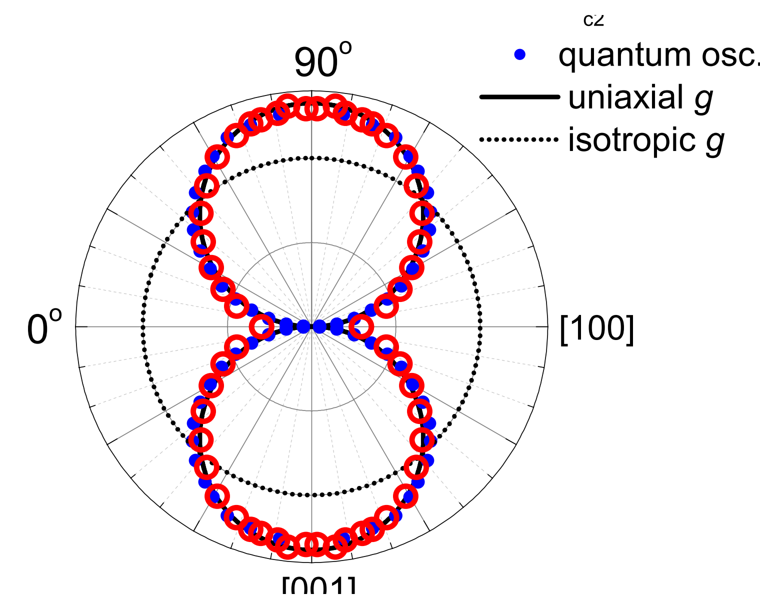

Kramers index K: quantum no of ***double*** time reversal θxθ = θ^2.

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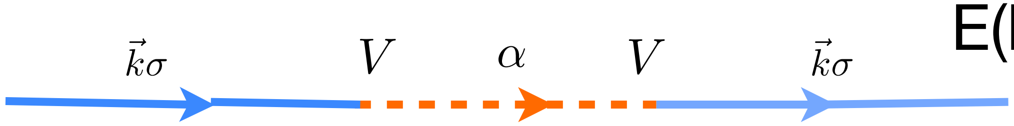

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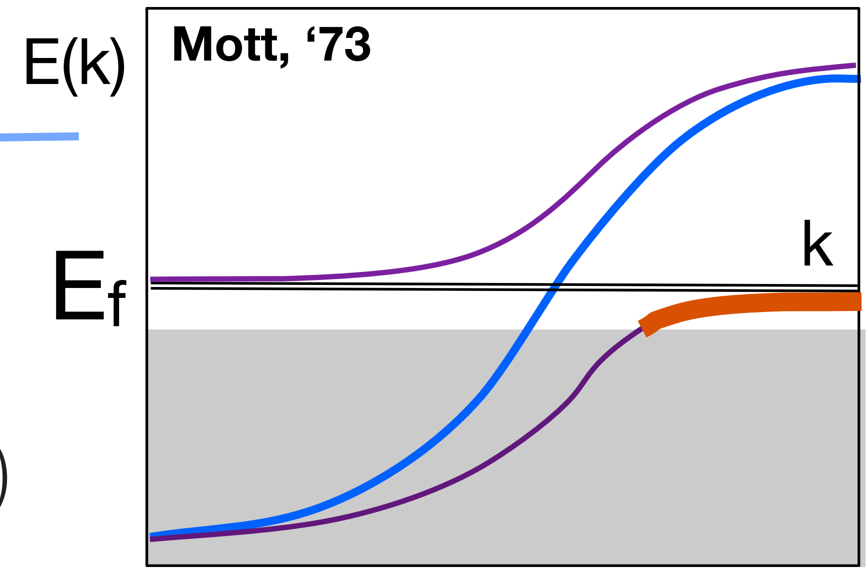

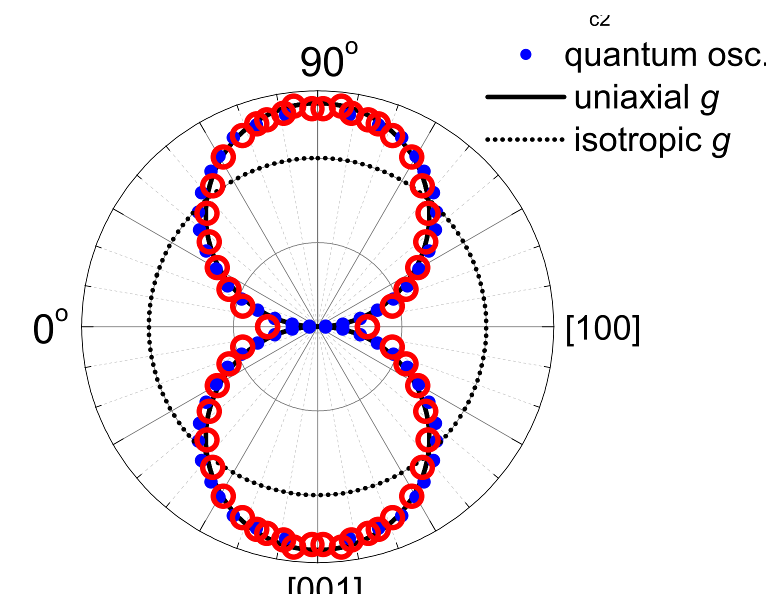

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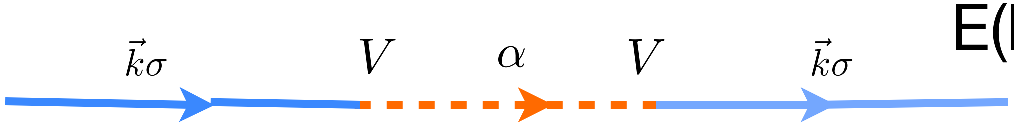

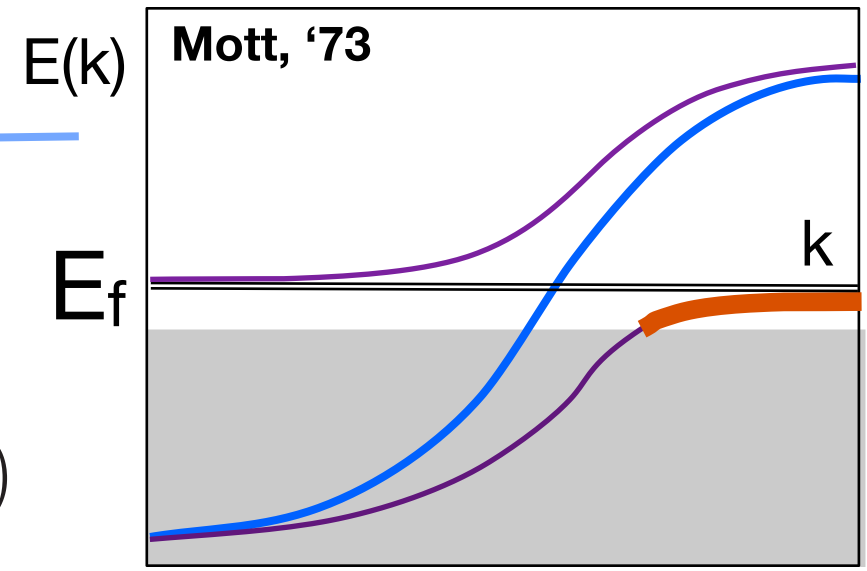

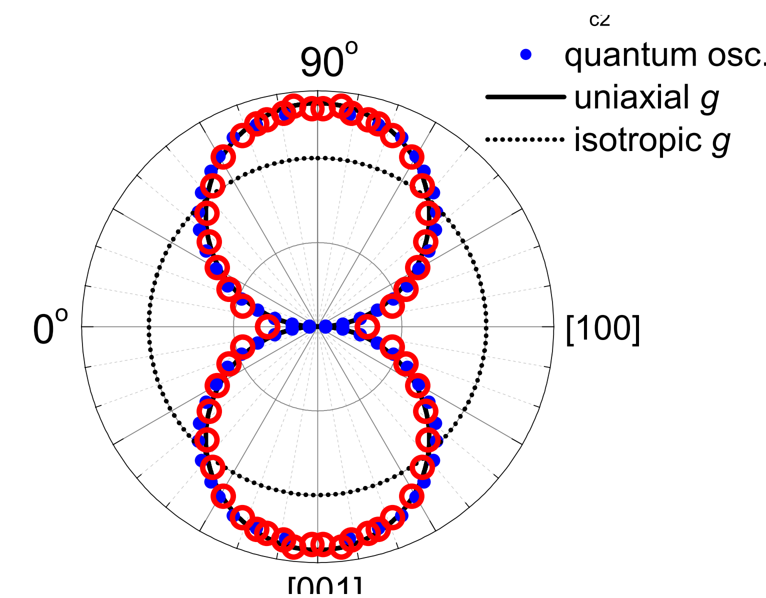

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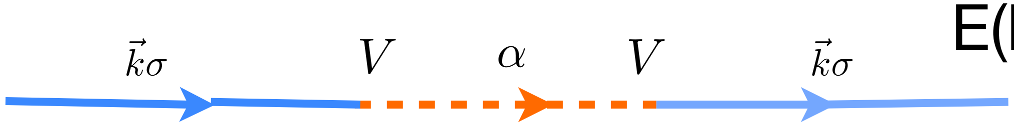

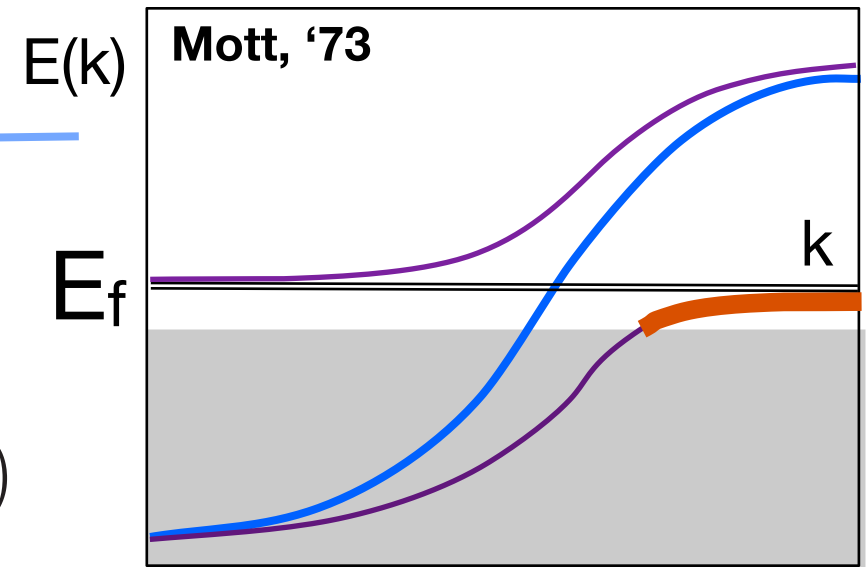

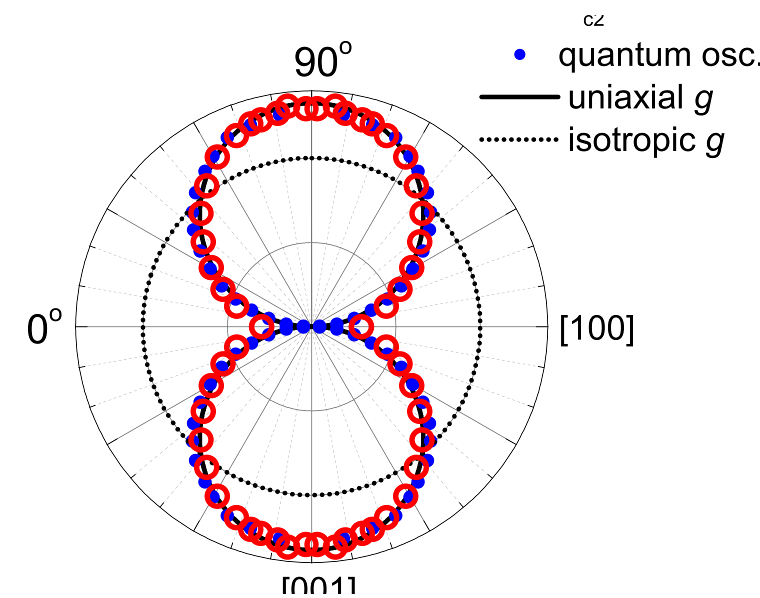

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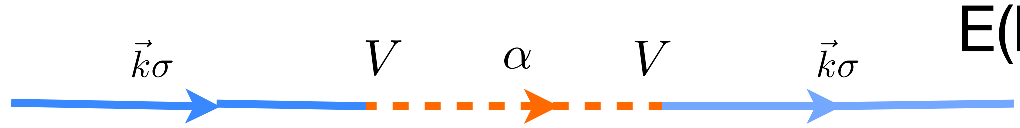

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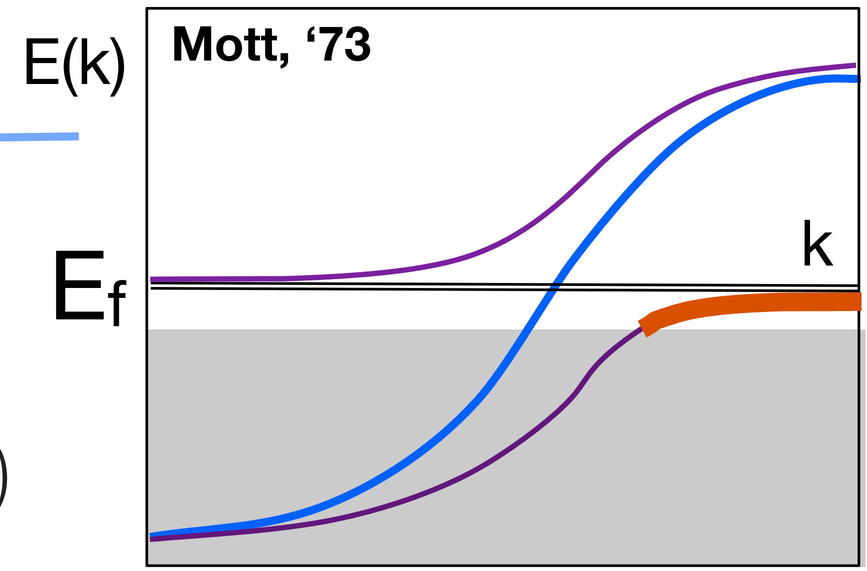

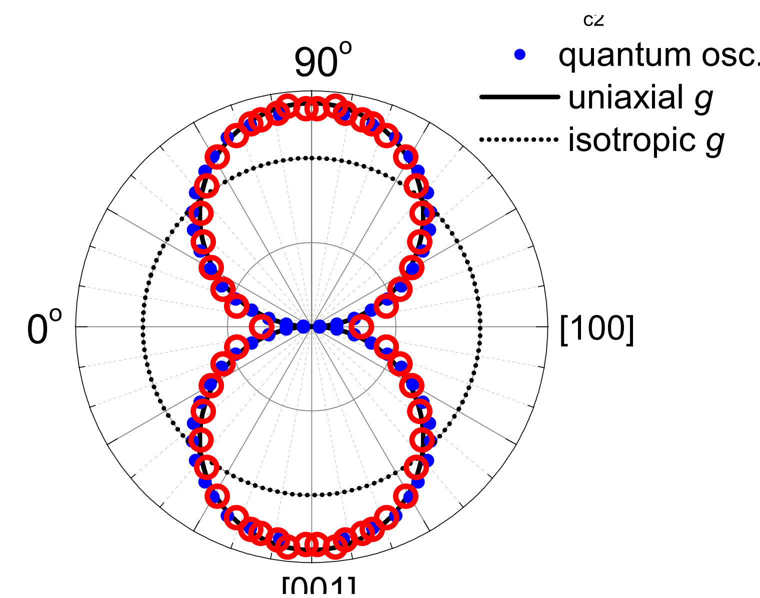

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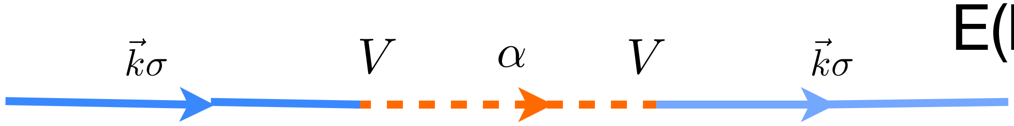

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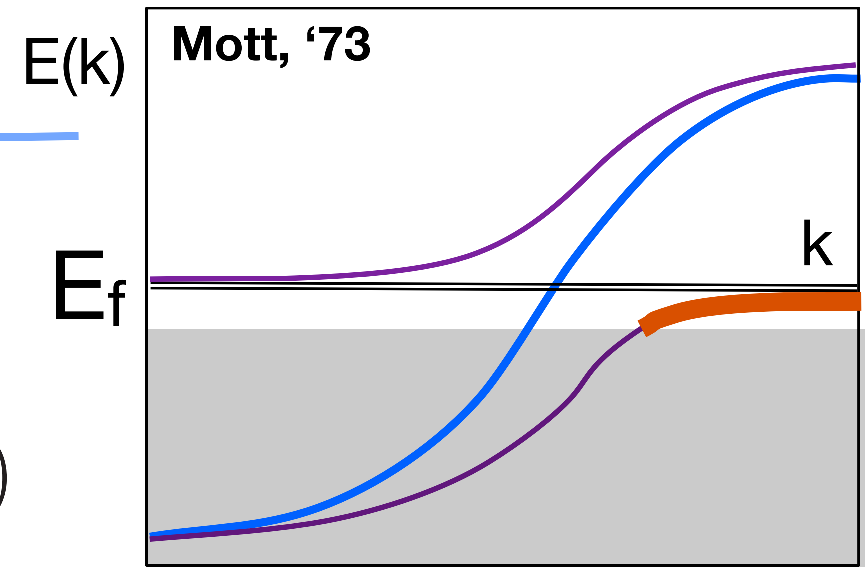

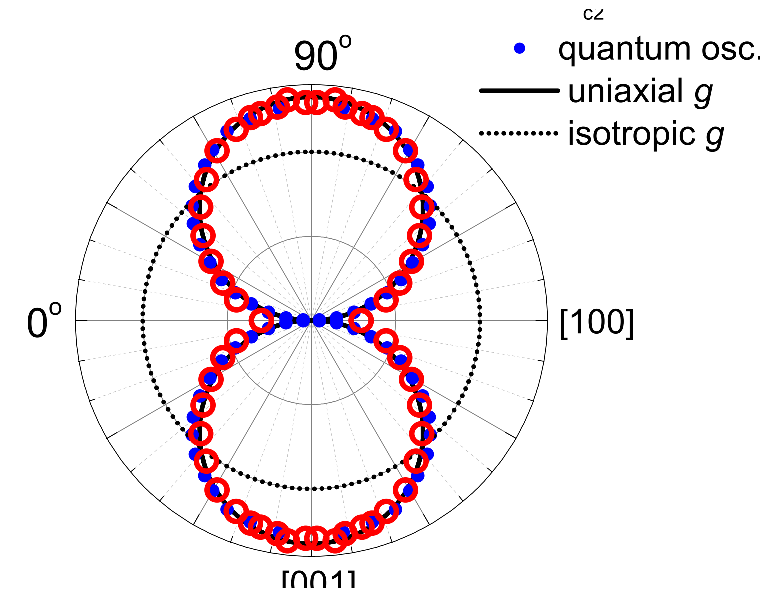

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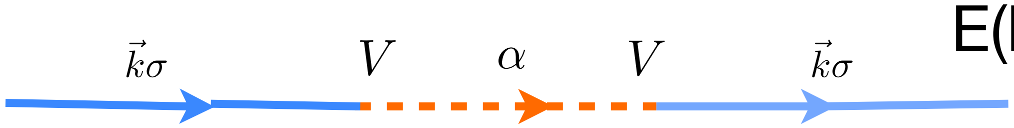

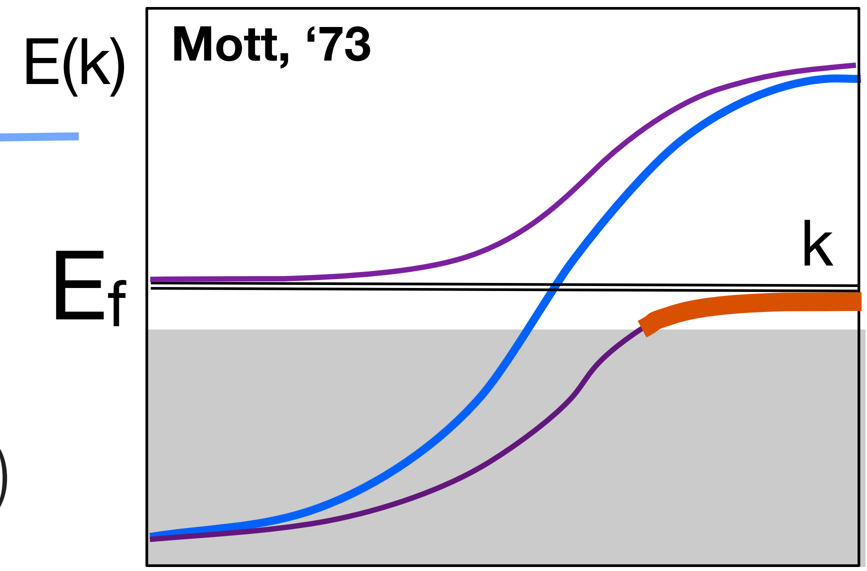

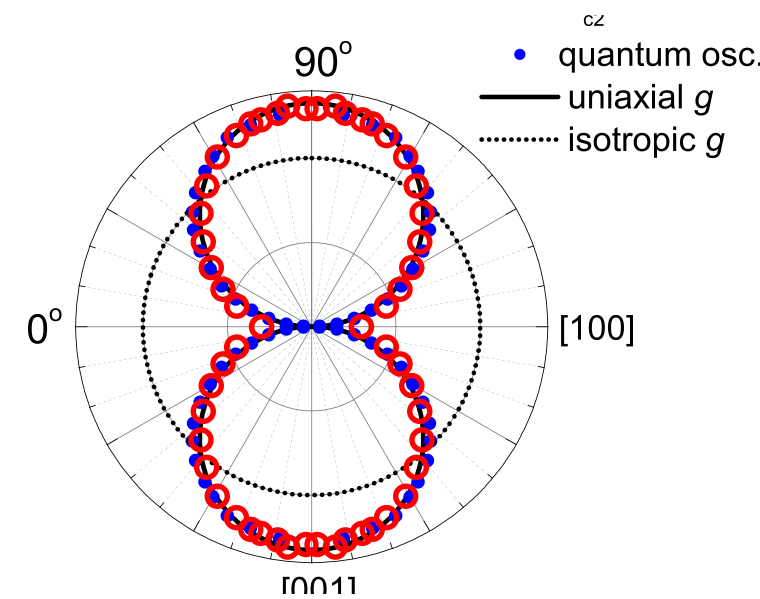

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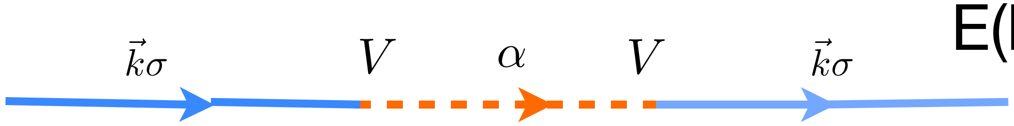

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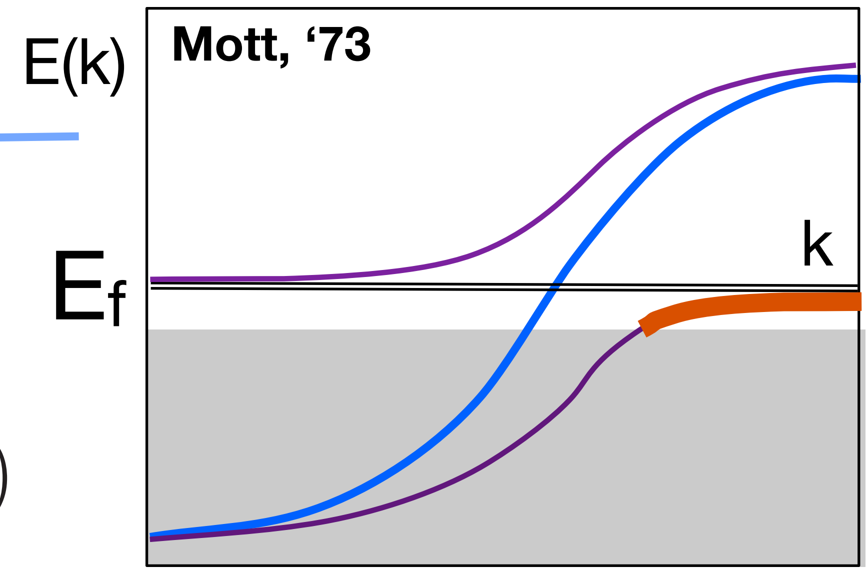

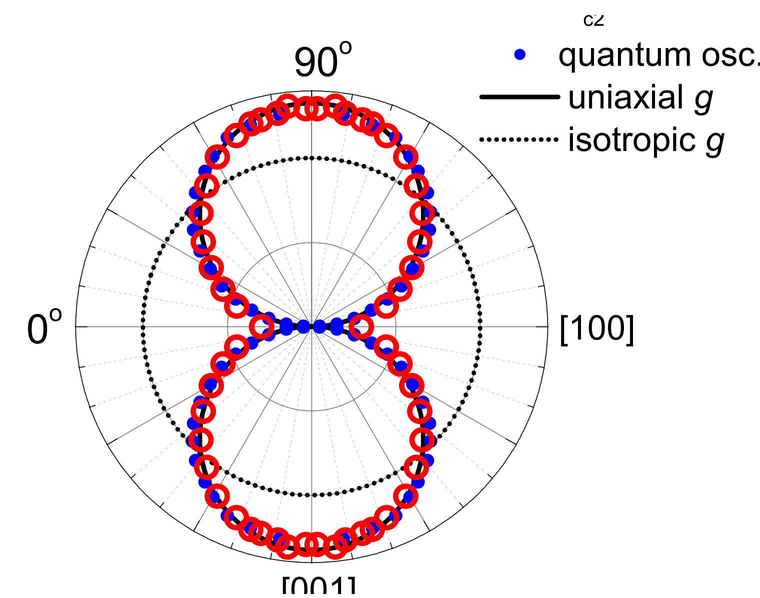

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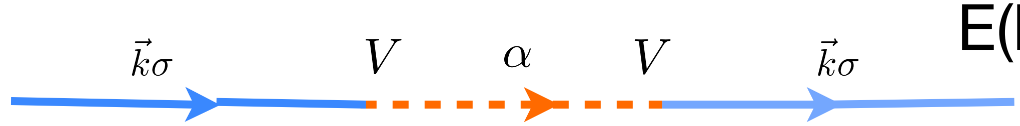

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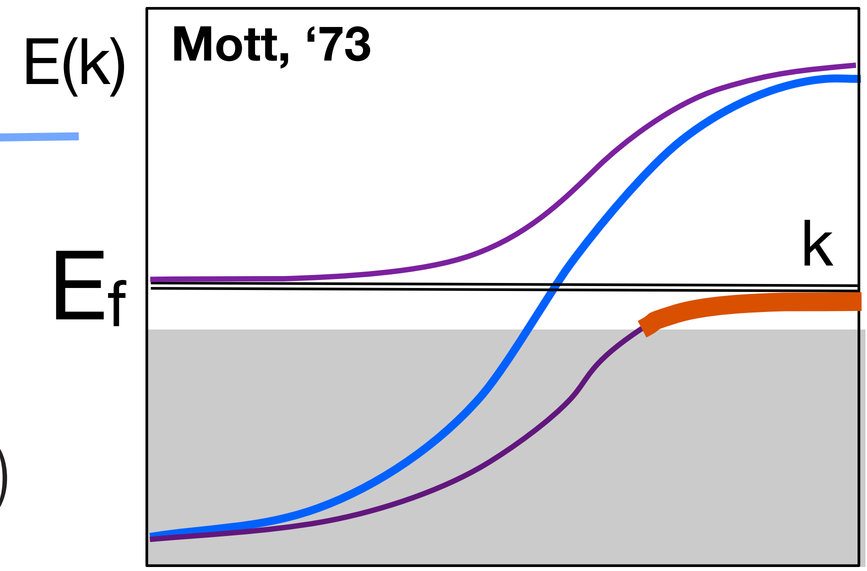

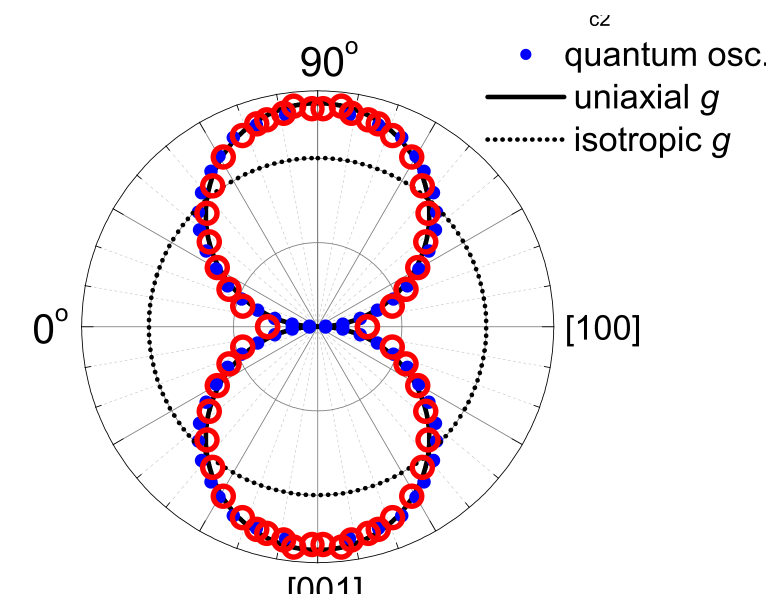

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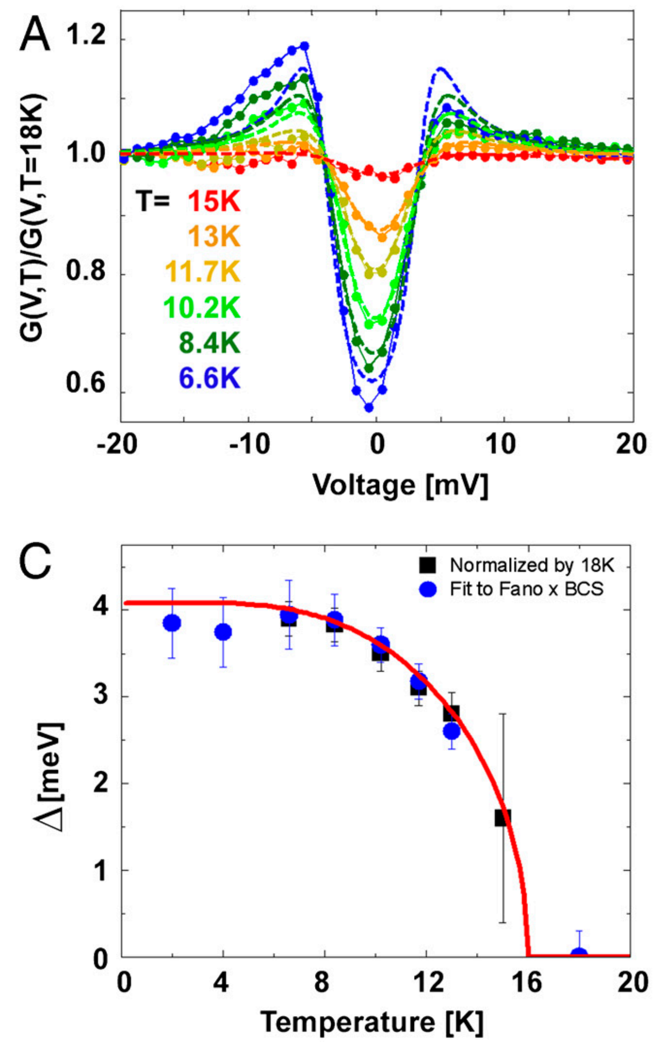
Hybridization is a spinor.

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

Support for hybridization as the order parameter.

Spectroscopy:
H-gap in STM/Optics

Aynajian* et al, PNAS (2010)



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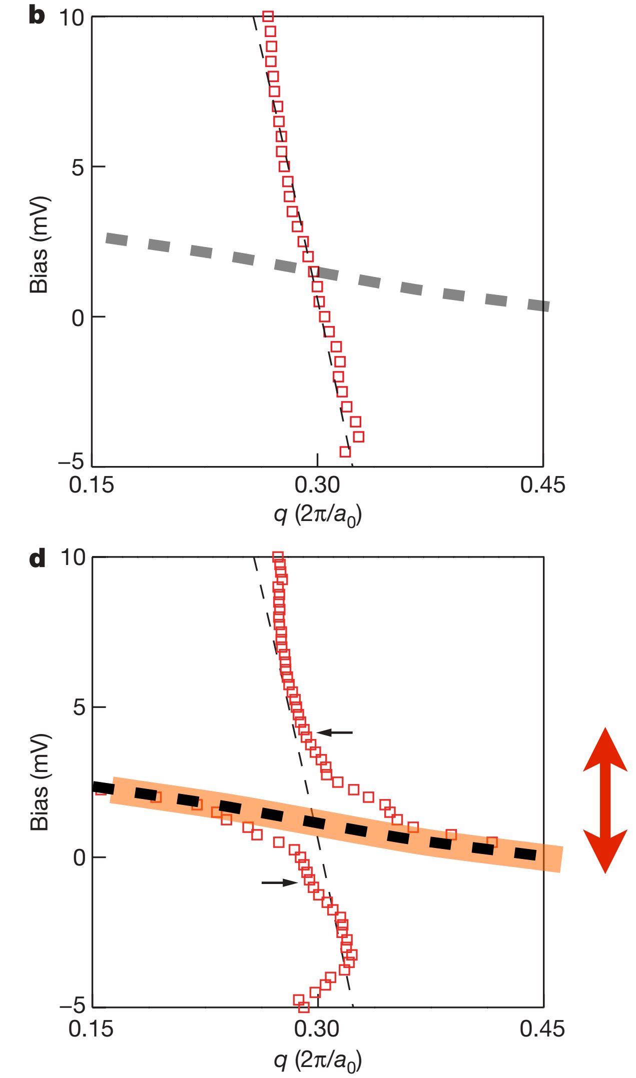

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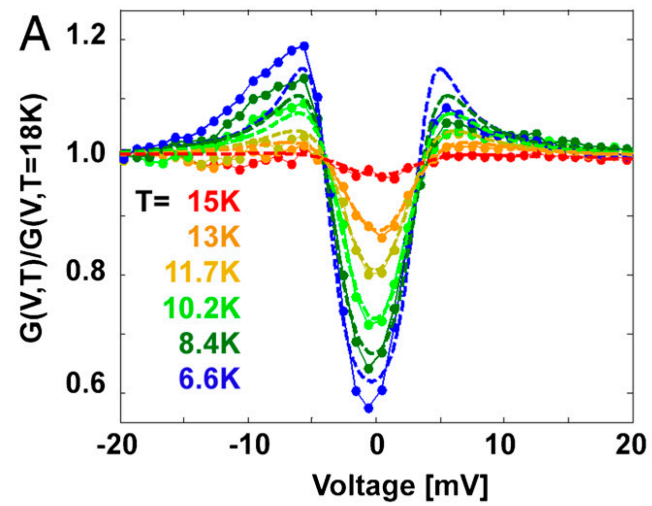

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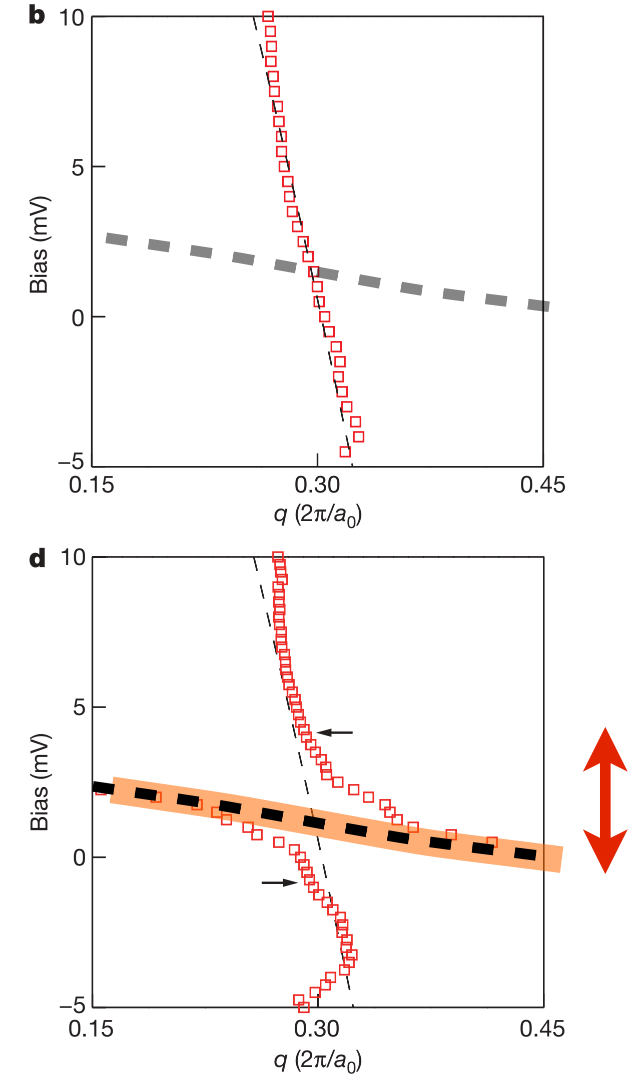

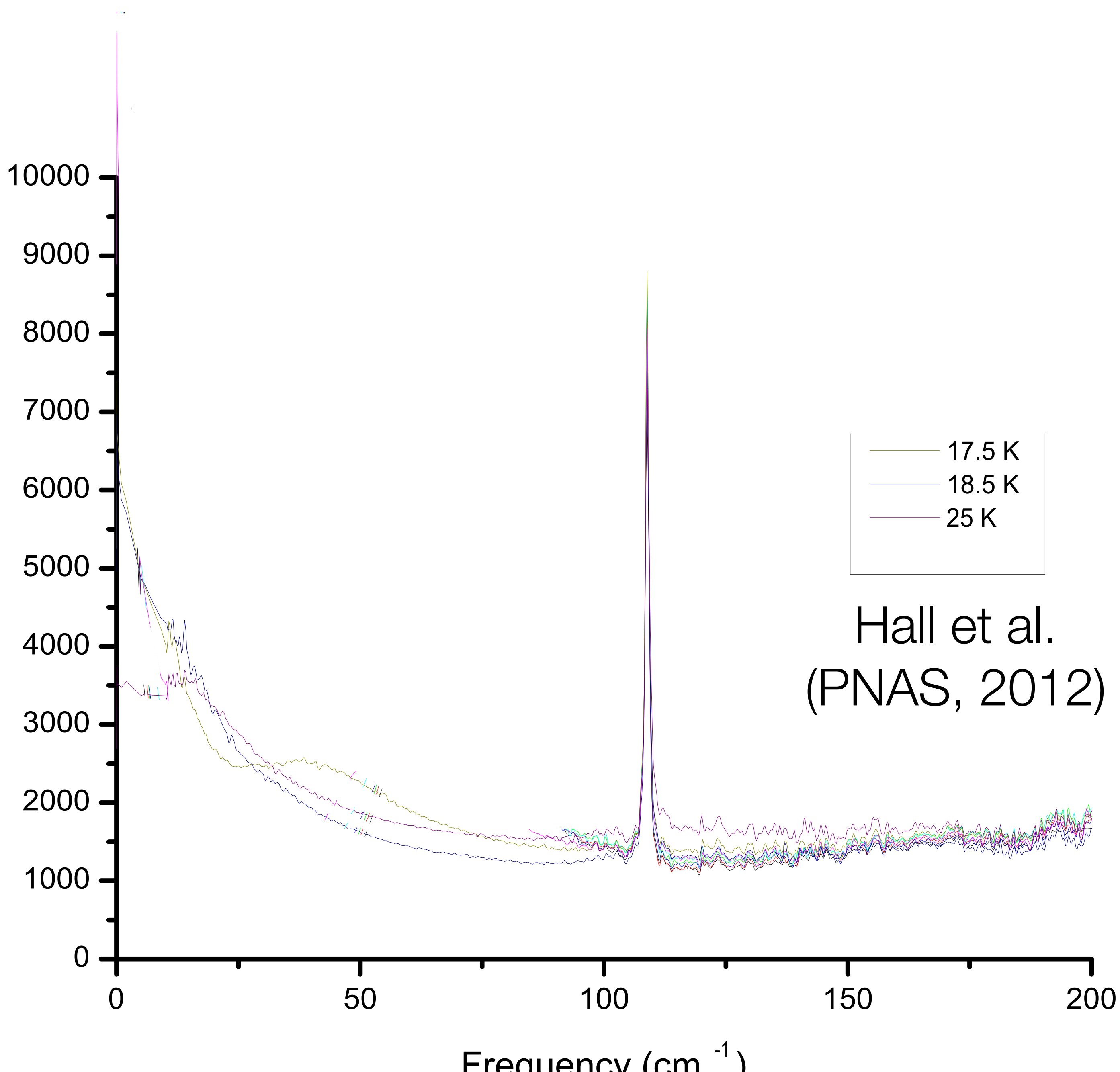

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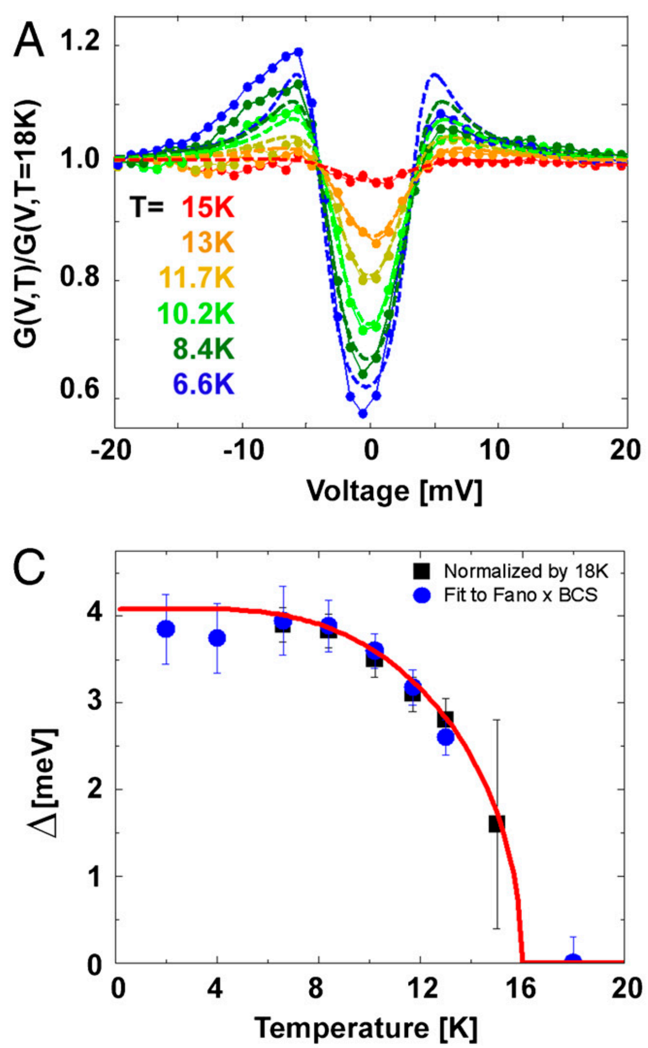

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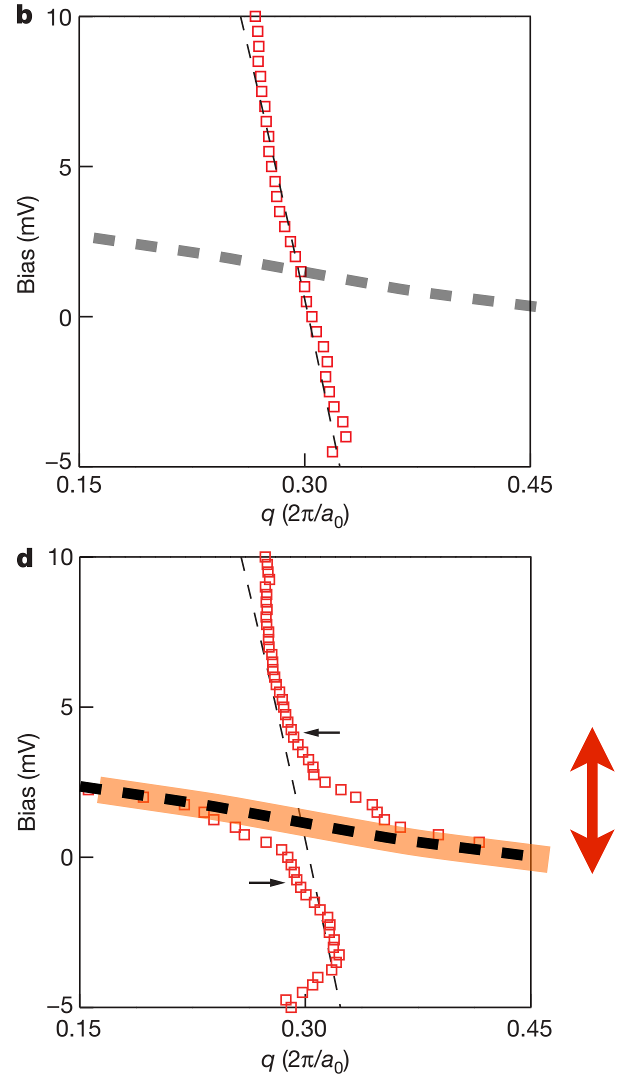

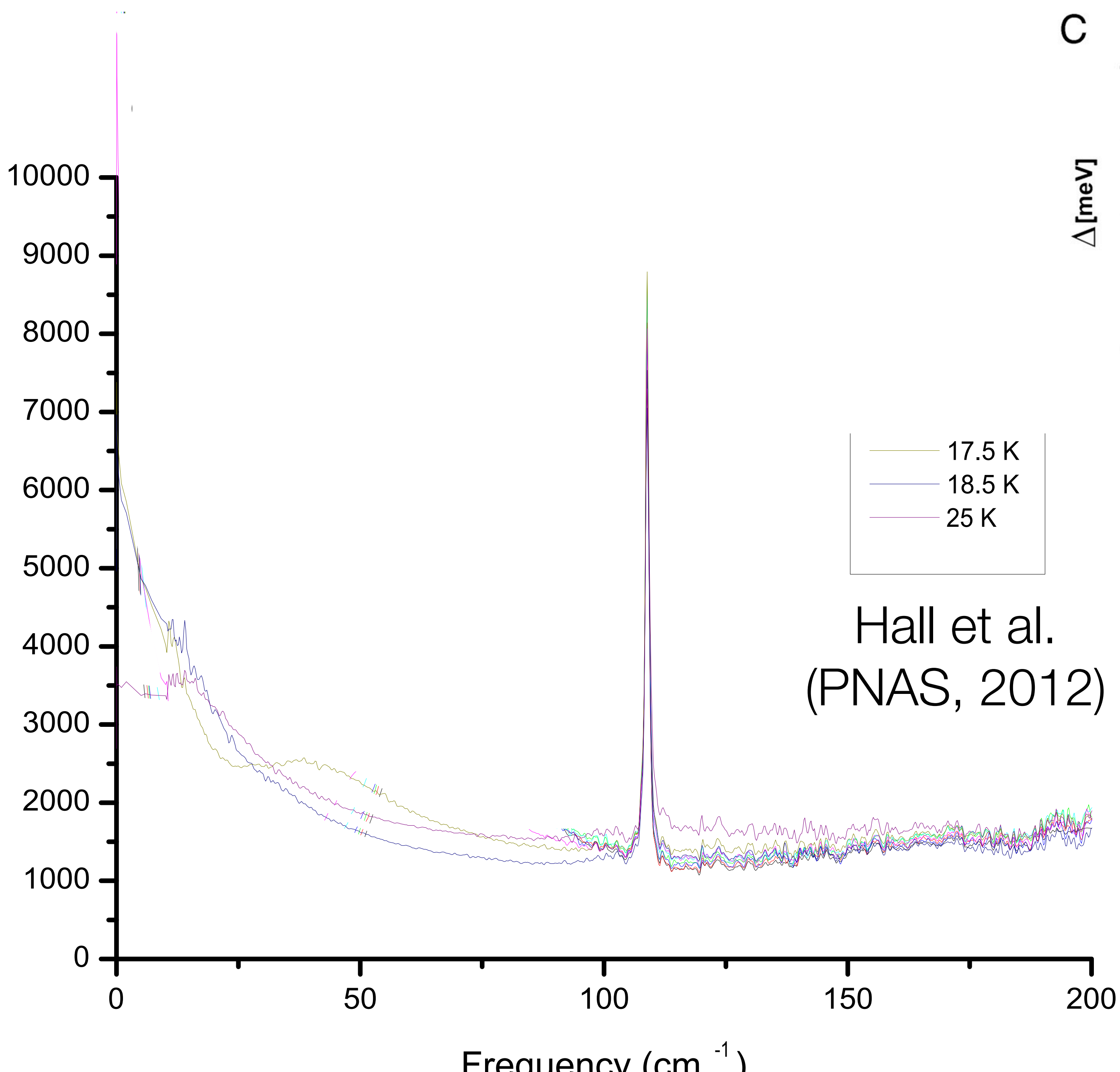

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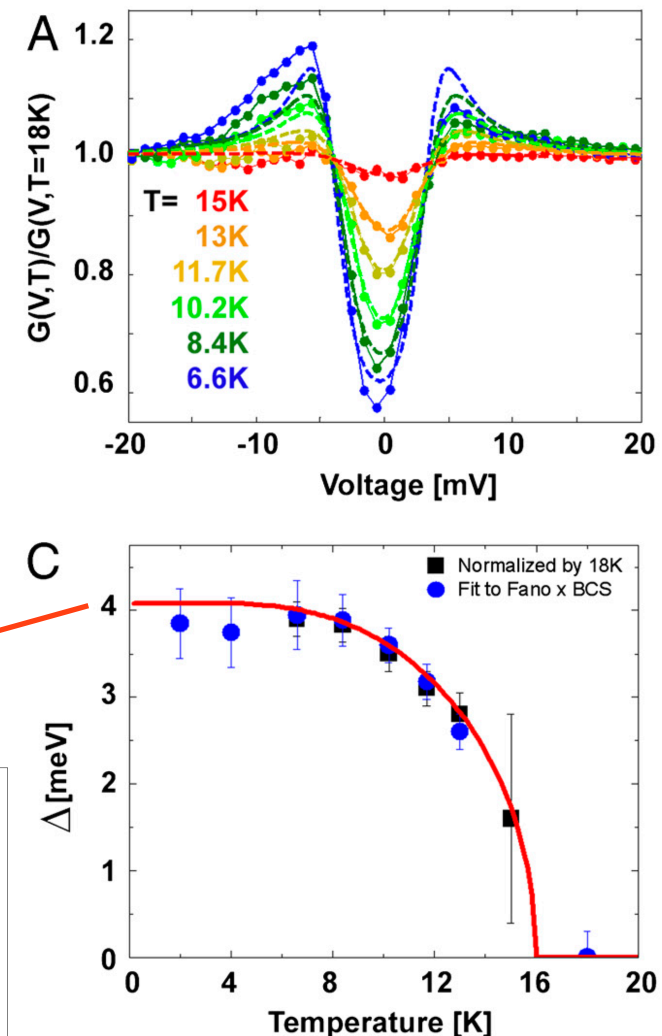

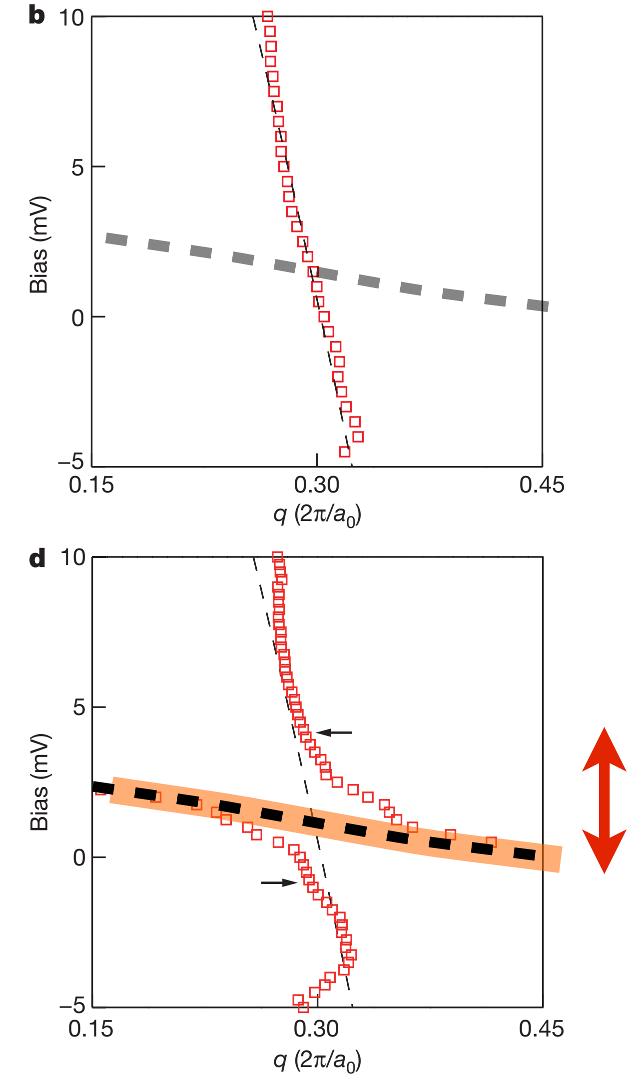

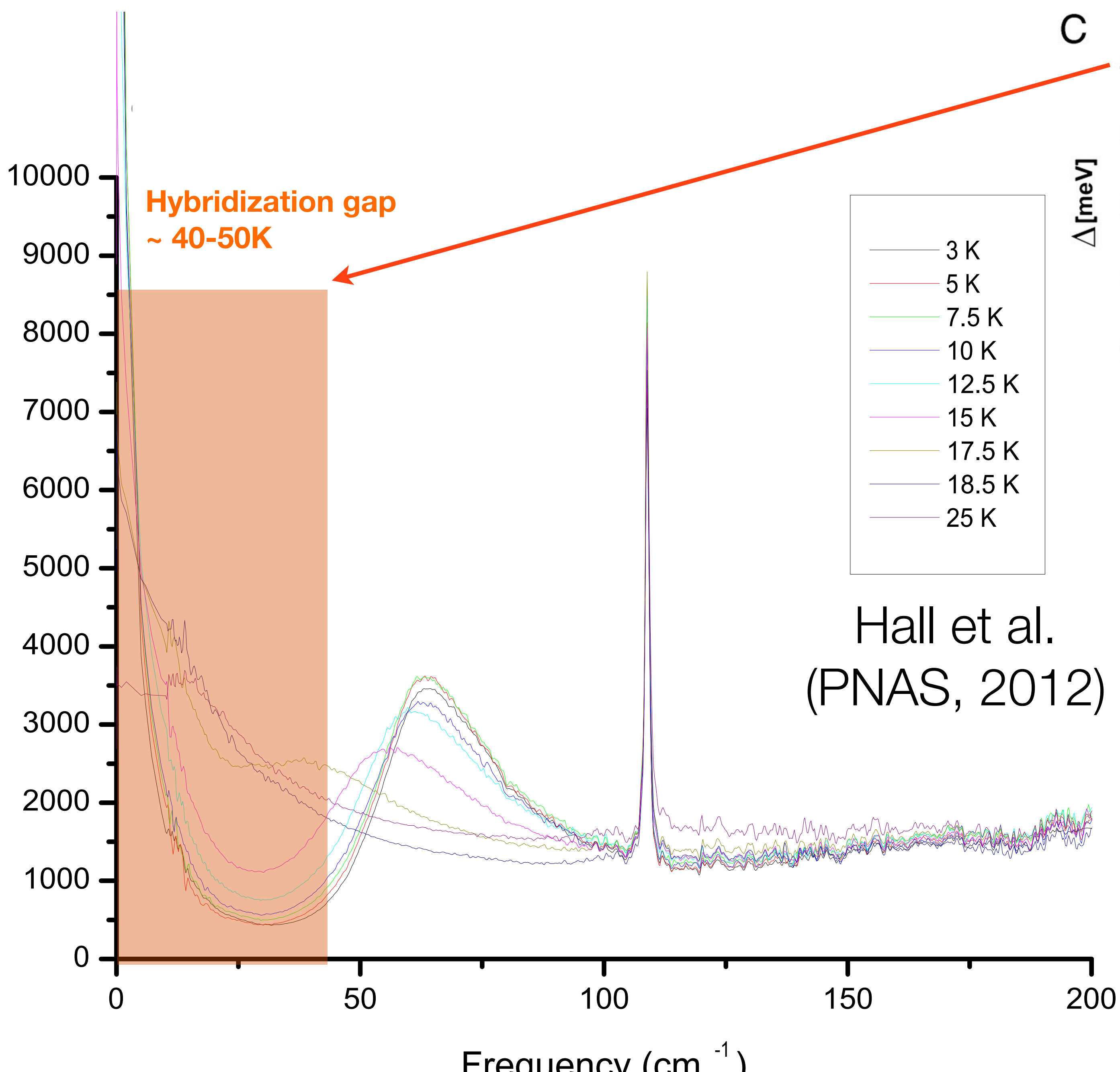

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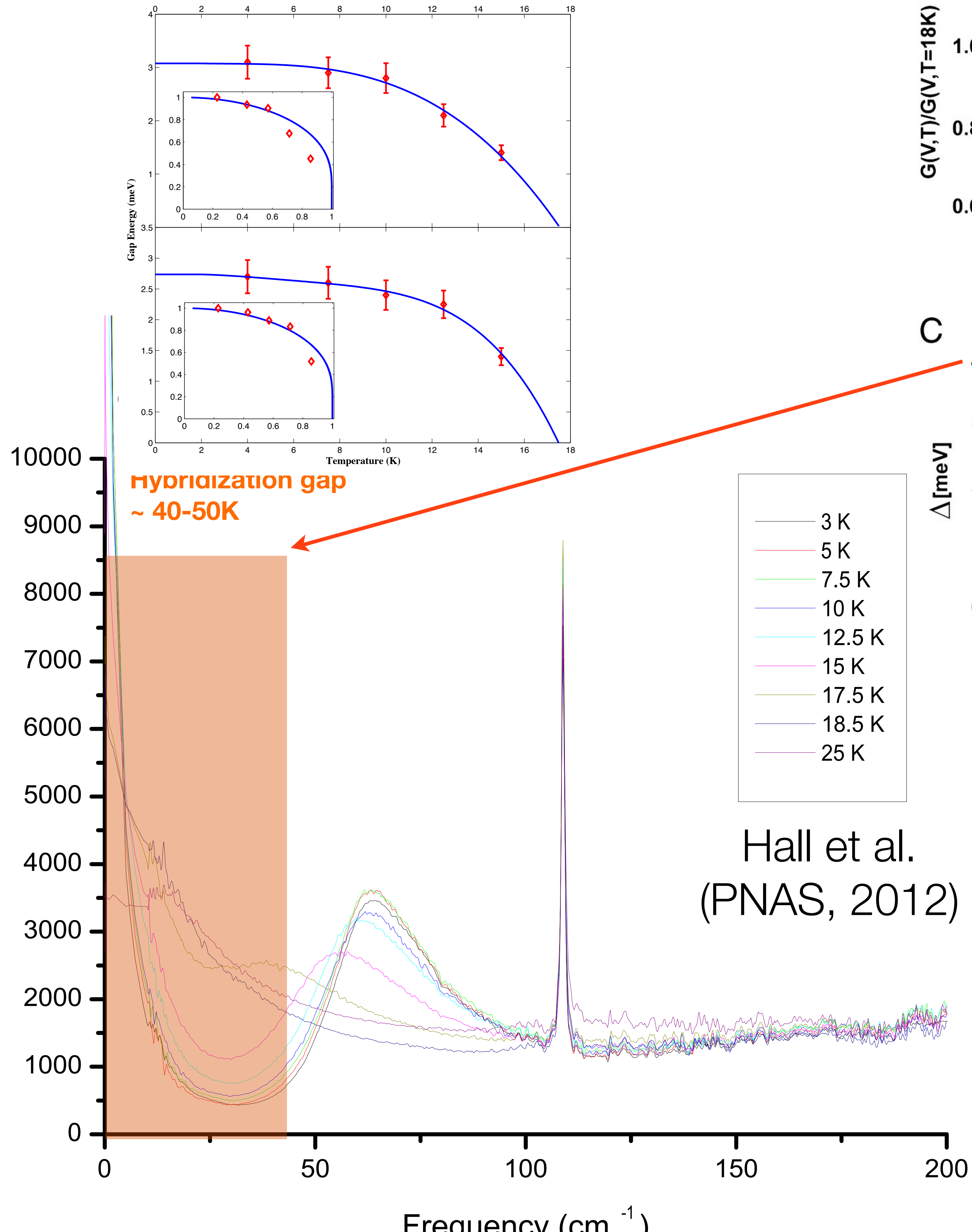

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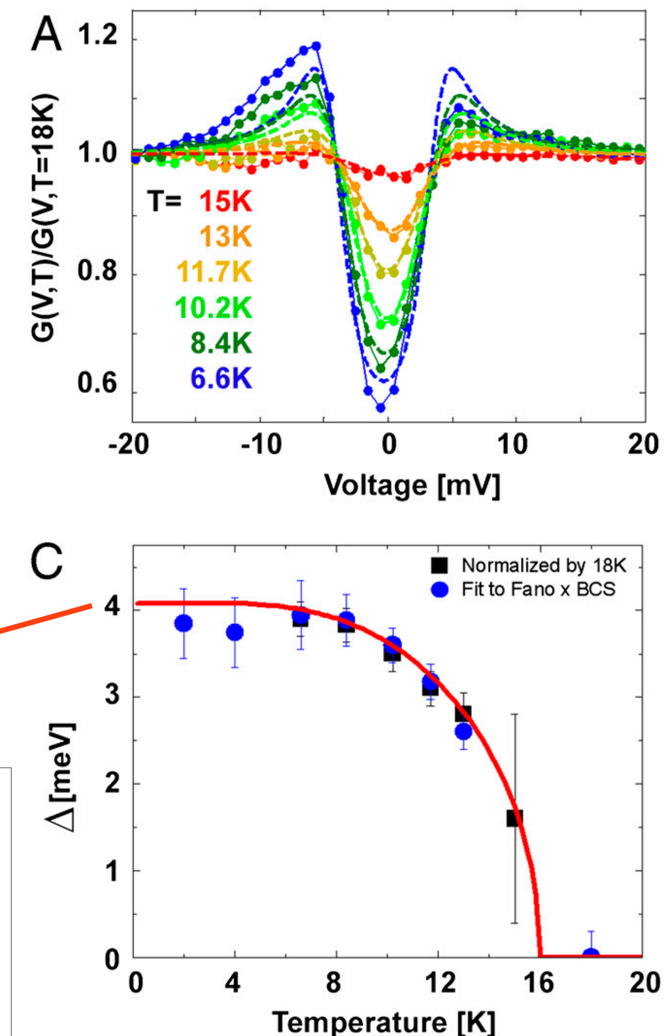

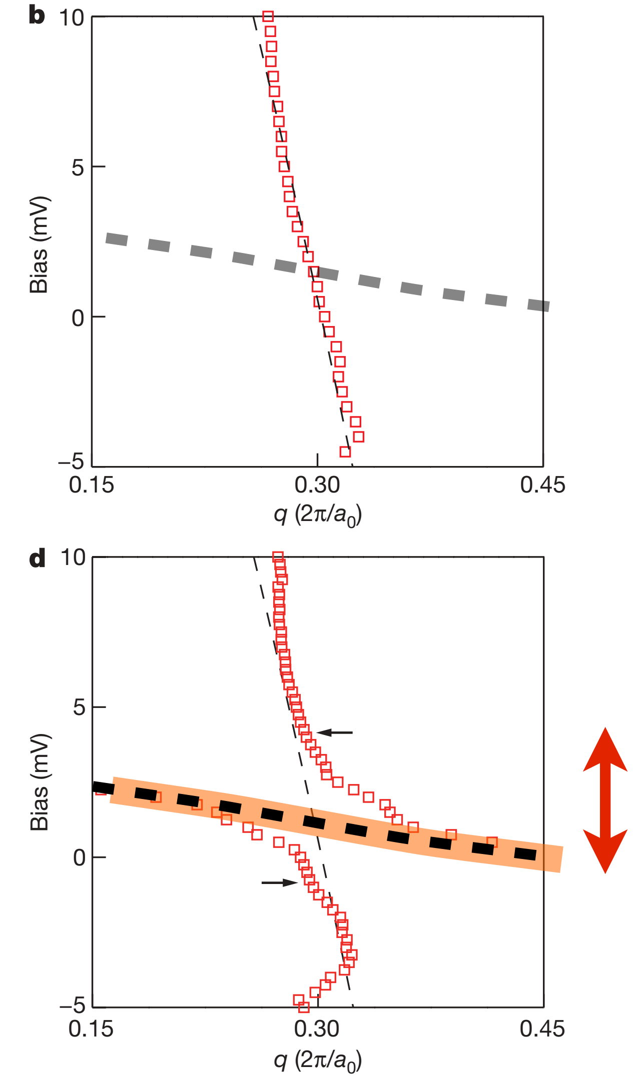

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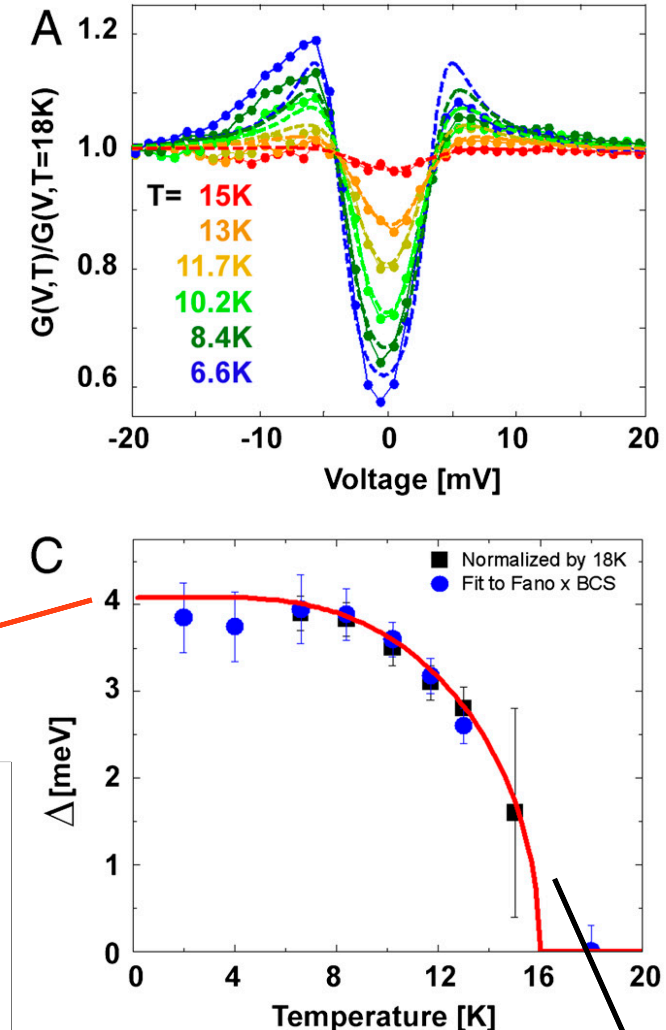

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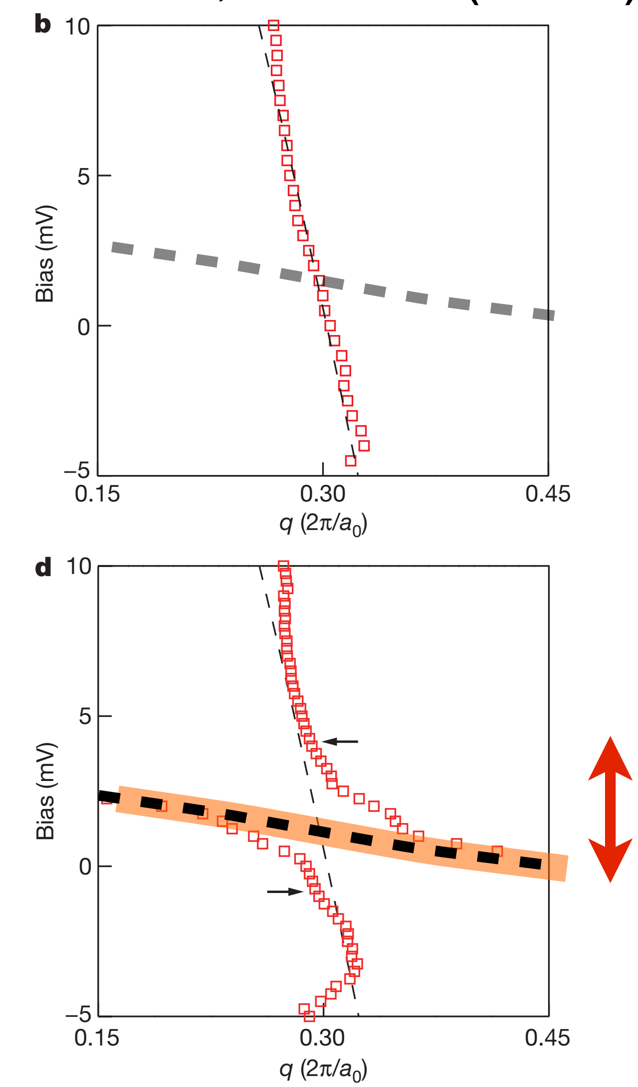

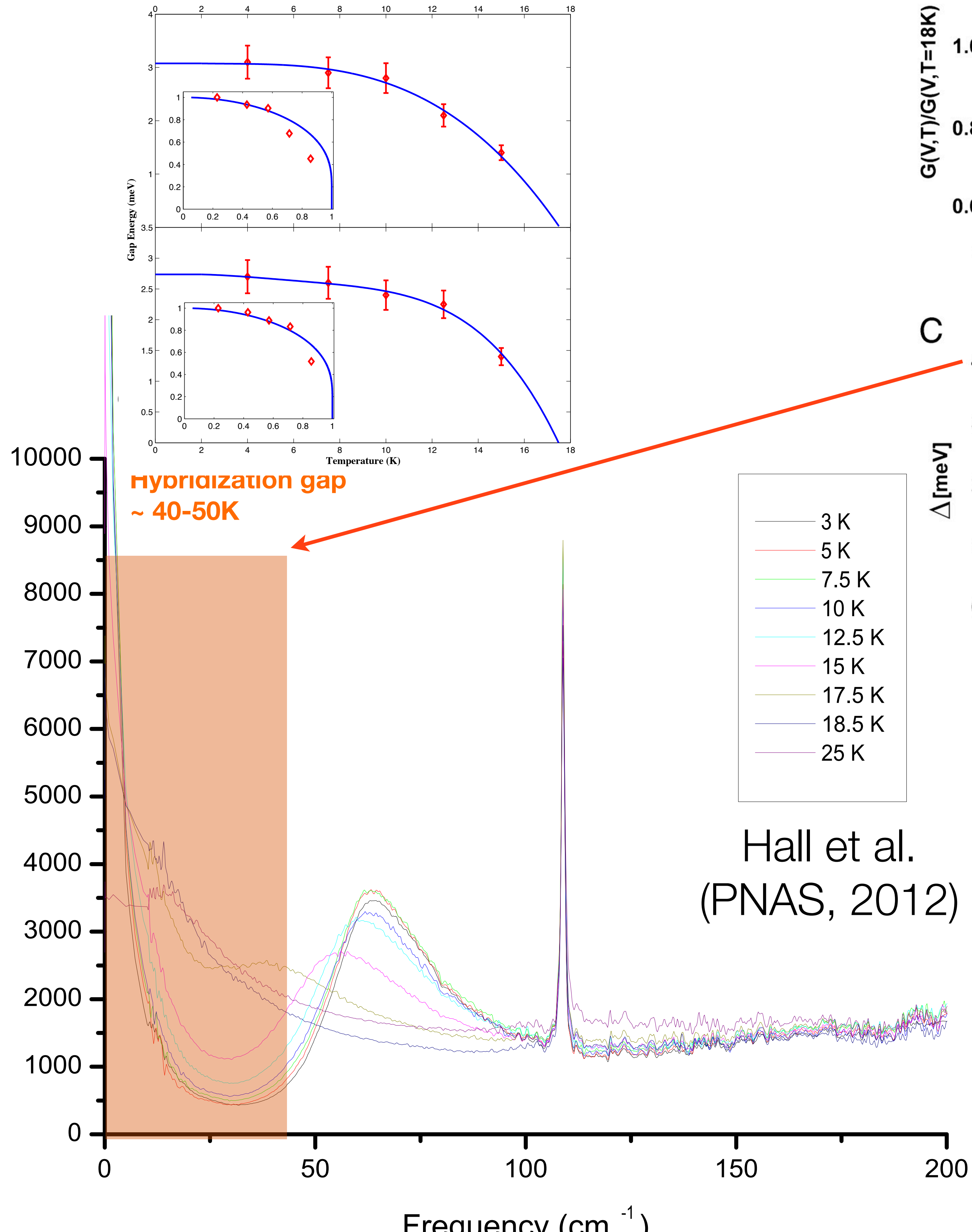

Hall et al. (PNAS, 2012)

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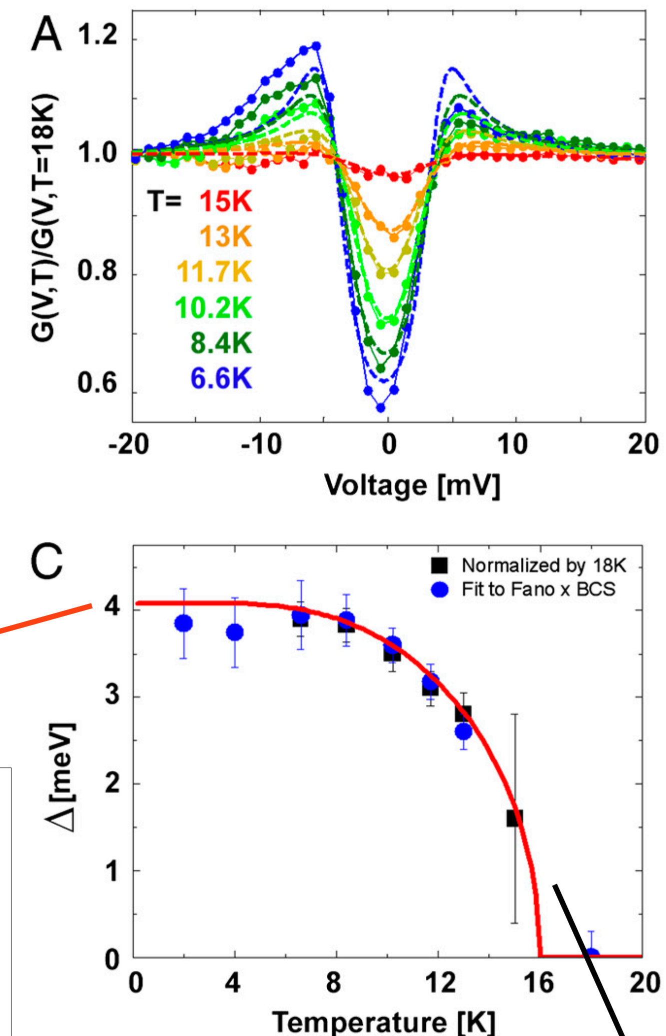

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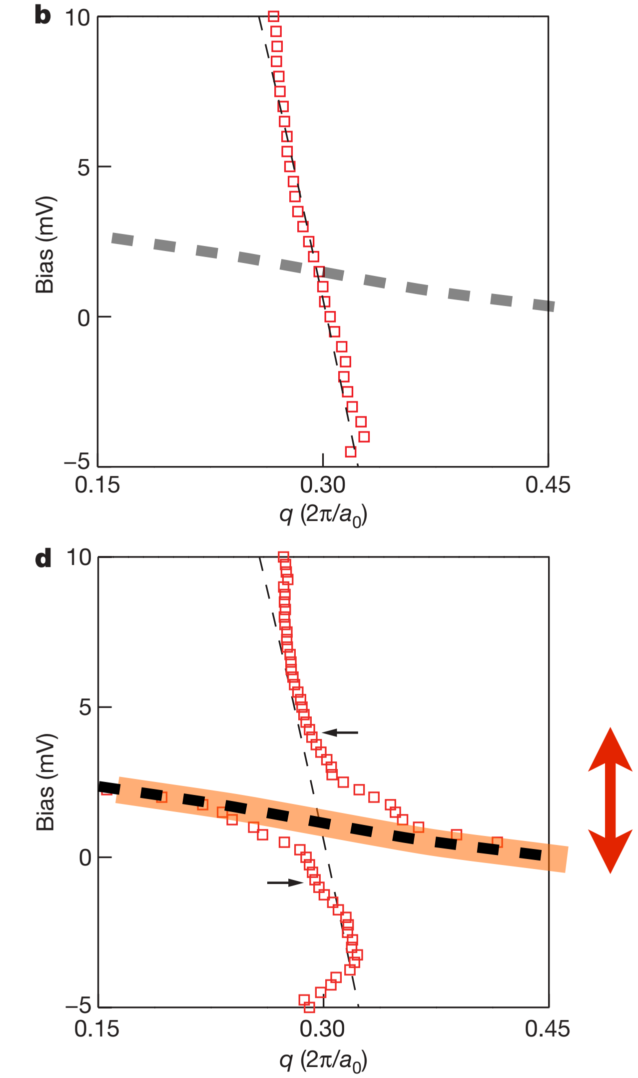

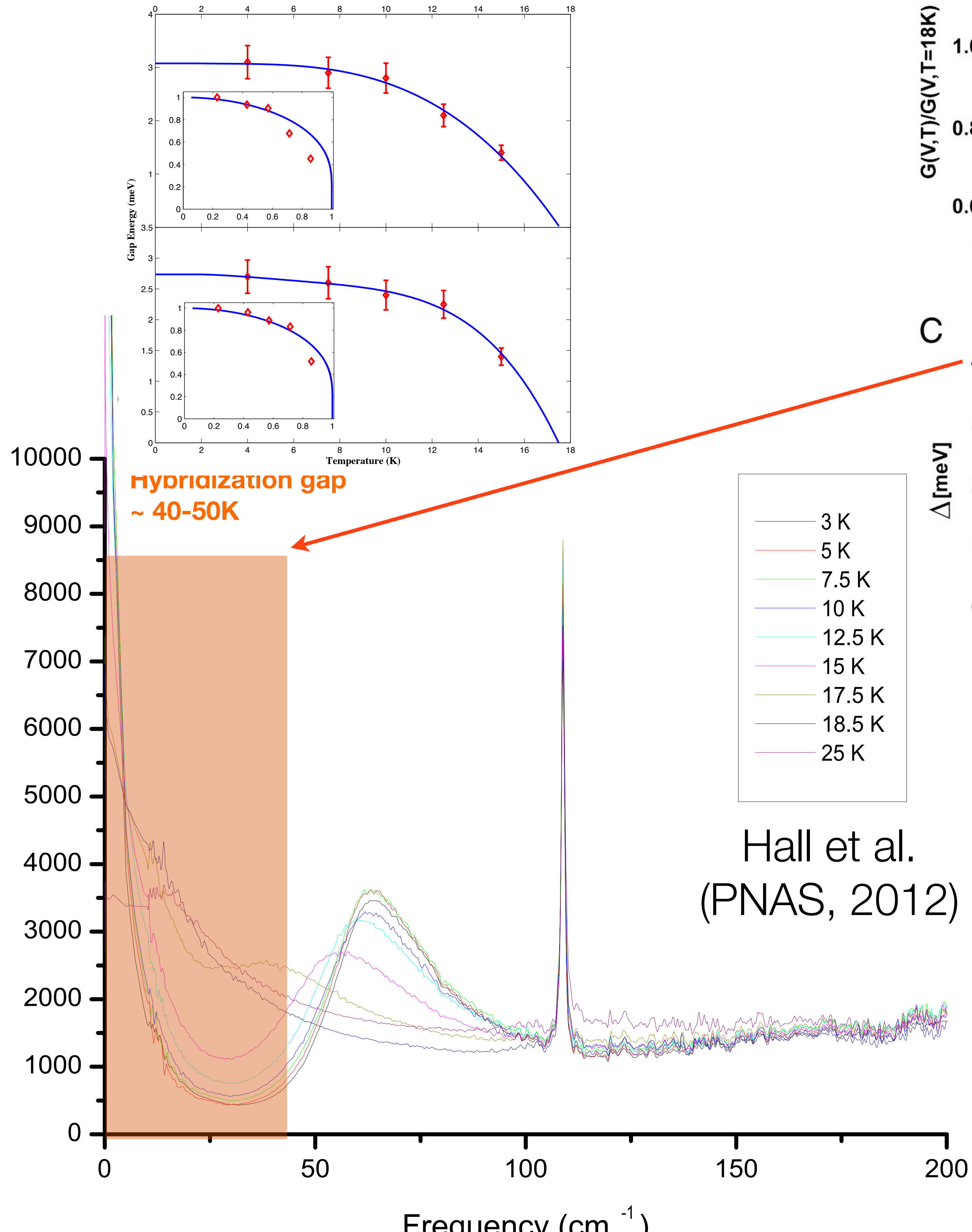

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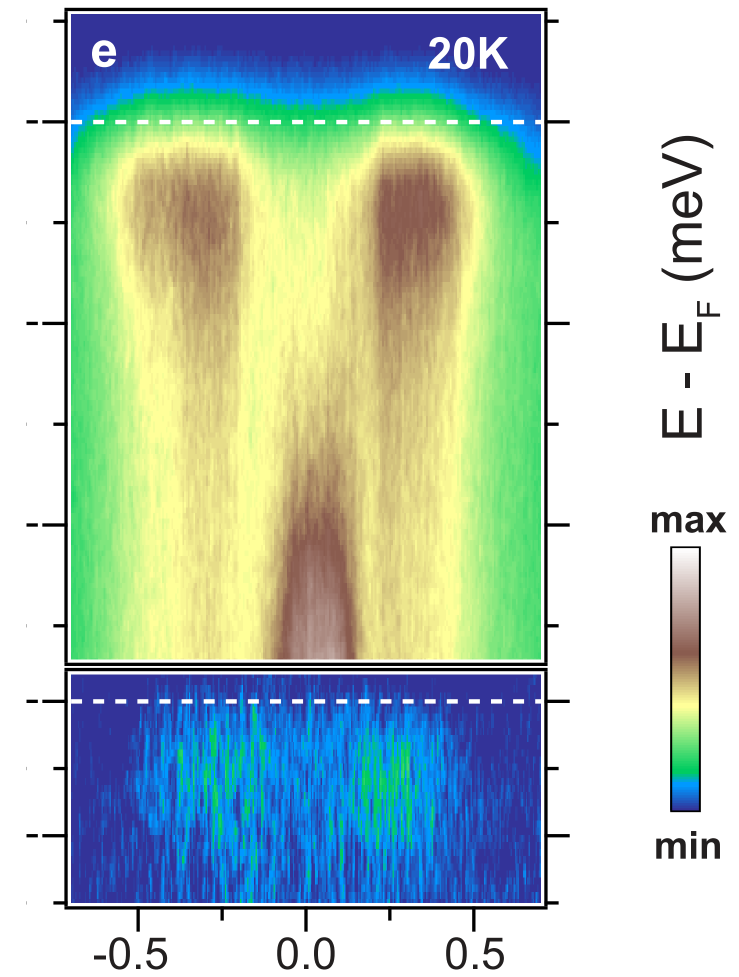
Hybridization

develops at T_{HO}

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

High Resolution ARPES

Chaterjee et al, arXiv 1211.5312



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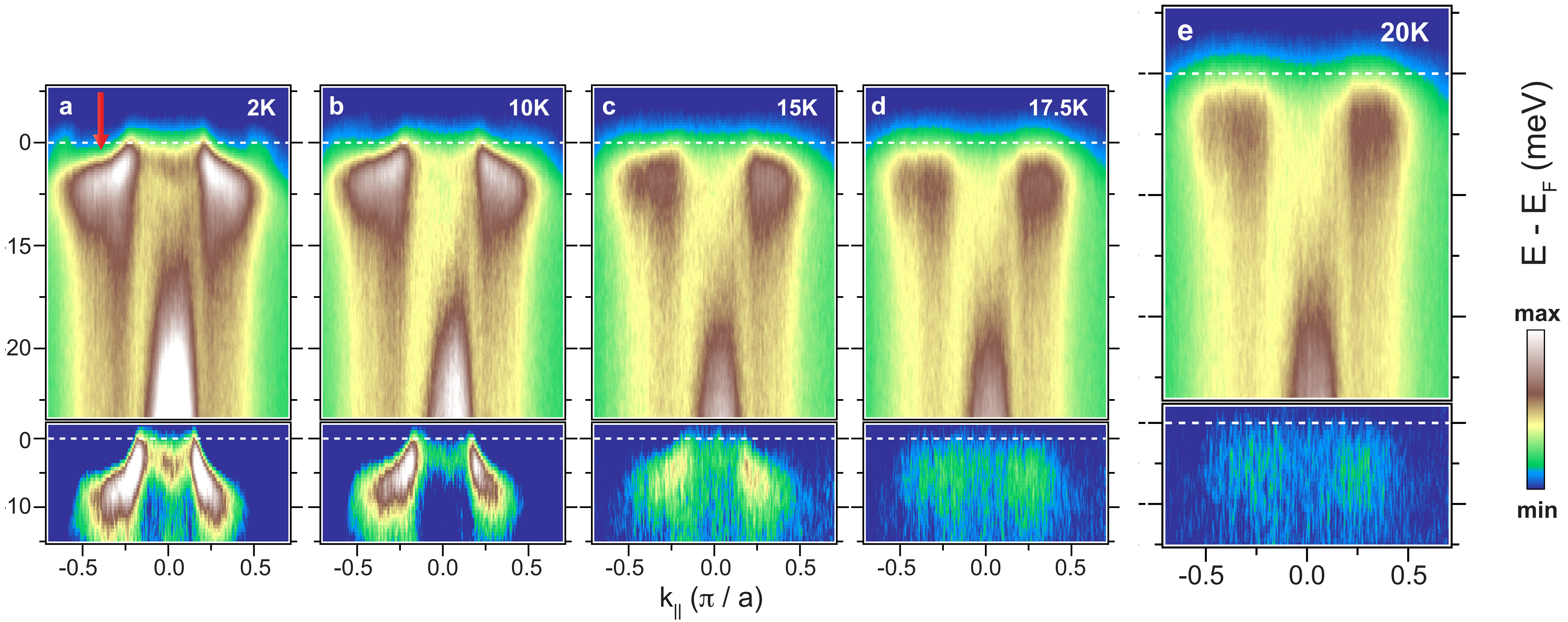

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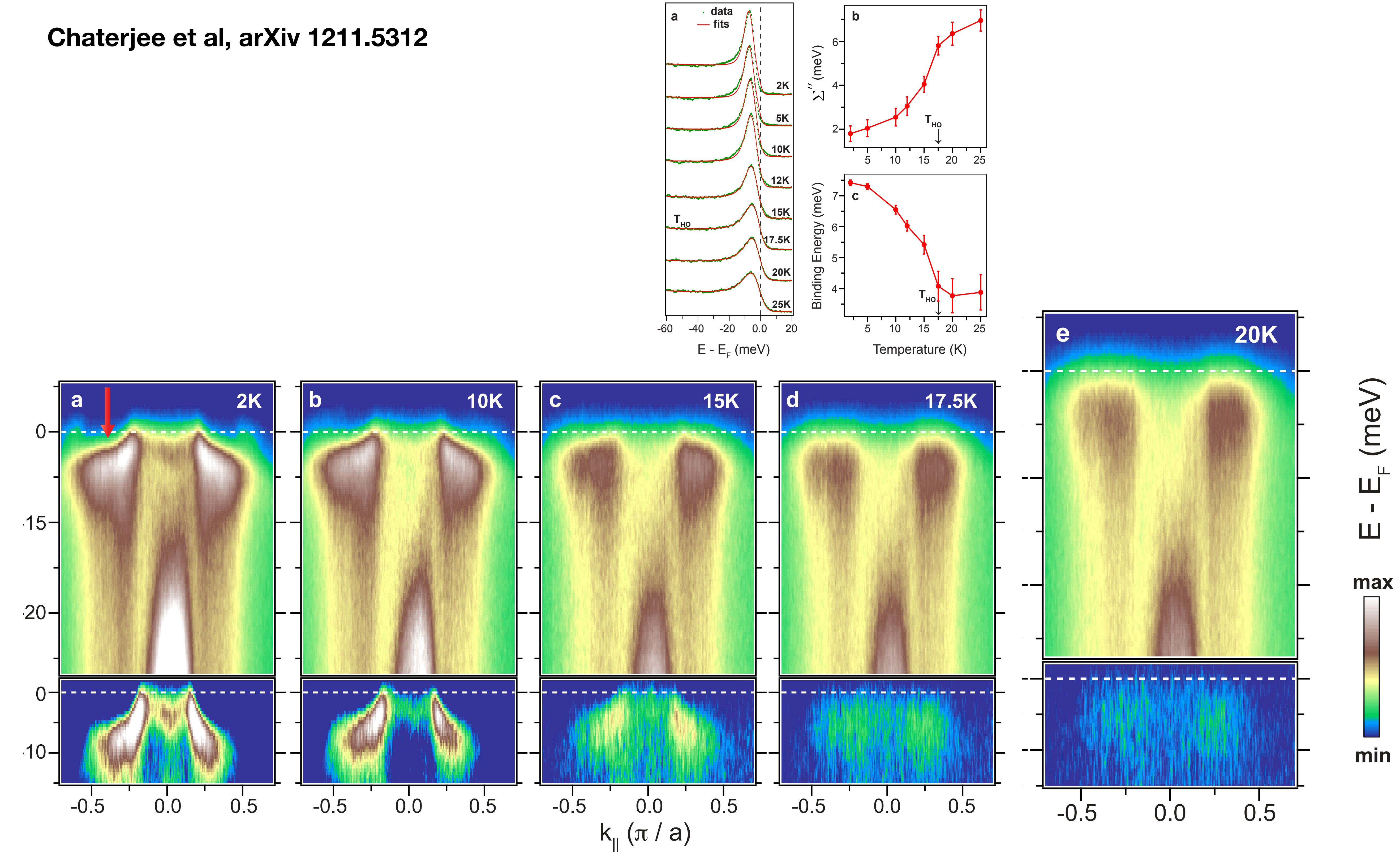

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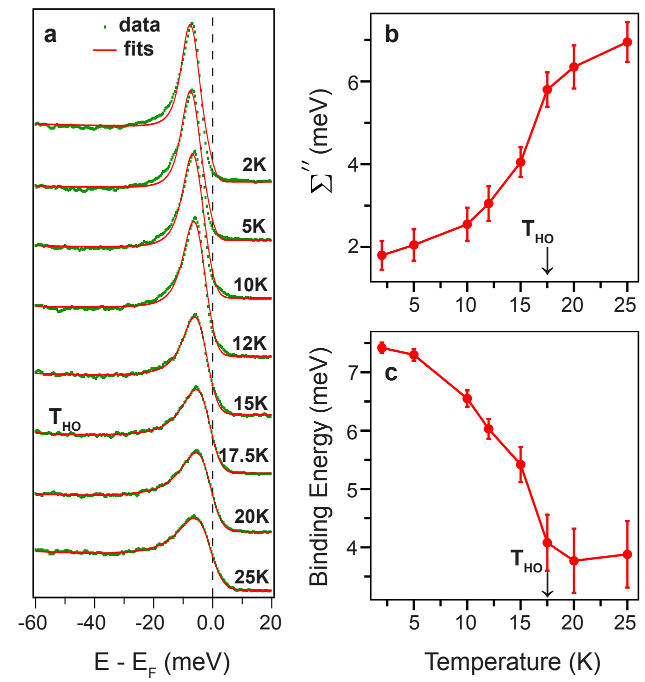

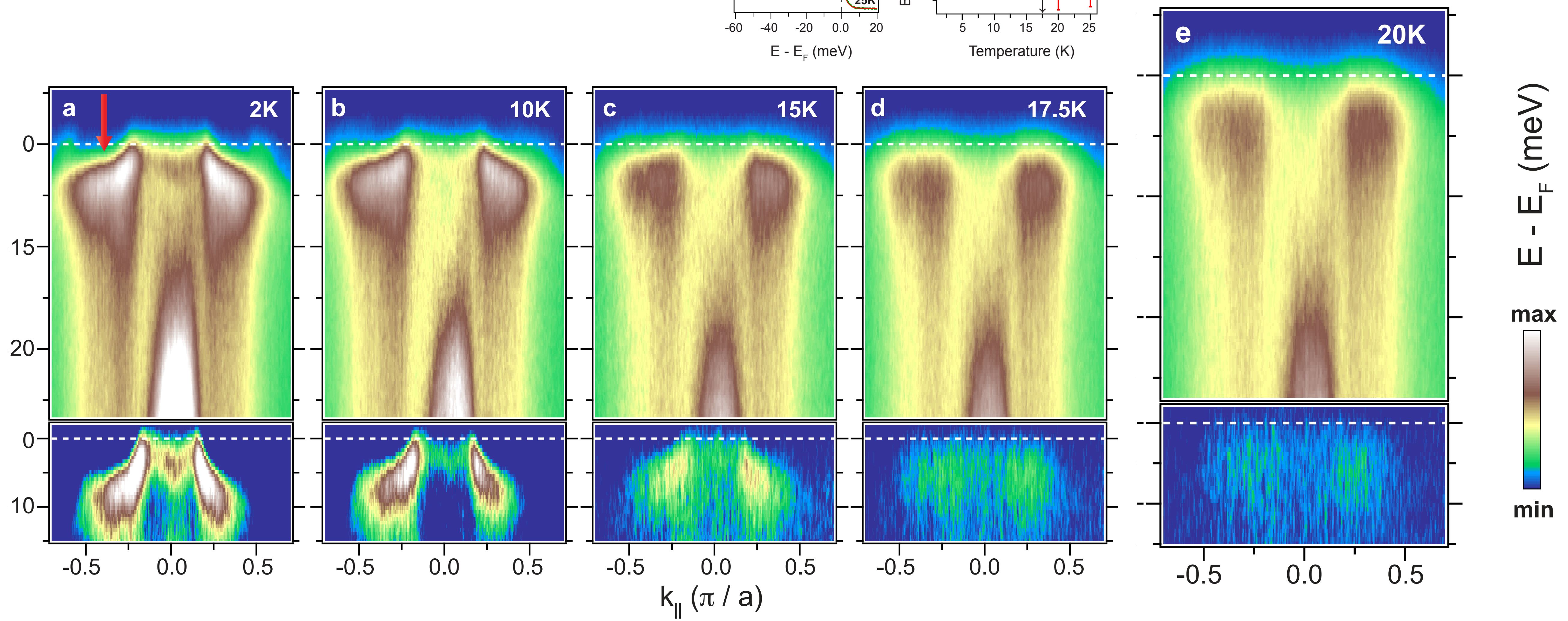

Heavy fermion bands come into focus at T_{HO}

“Hastatic Order”

Landau Theory:

Conventional Landau theory of electron fluids involves the formation of two body bound-states. When the two body bound-state carries a quantum number, the corresponding two body wavefunction transforms non-trivially under the symmetries of the vacuum, and is promoted to an order parameter. Landau order parameters involve even numbers of electrons and carry integer spin.

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e.g. $$\psi^\dagger_\alpha(x)\psi_\beta(x) = \vec{M}(x)\cdot\vec{\sigma}_{\alpha\beta}$$ Ferromagnetism=2 body BS

Transforms as vector (S=1)

Hastatic order generalizes Landau’s concept to half integer order parameters (bosons) which violate the spin-statistic theorem.

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$$\psi^\dagger_{\sigma_1}(1)\psi^\dagger_{\sigma_2}(2)\psi_{\bar\sigma_3}(3) = \Gamma^\alpha_{\sigma_1\sigma_2\bar\sigma_3}(1,2,3;x)\chi^\dagger_\alpha(x)$$

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“Hastatic” order.

hasta: spear (latin)

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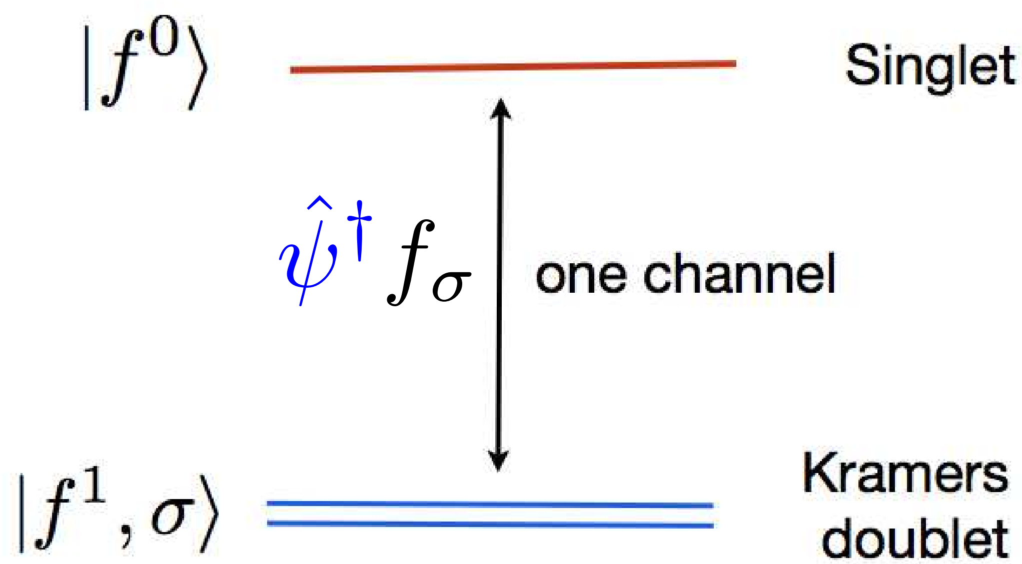

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In conventional heavy fermion materials a hybridization derives from virtual excitations between a Kramers doublet and an excited singlet. A uniform hybridization breaks no symmetry and develops as a cross-over.

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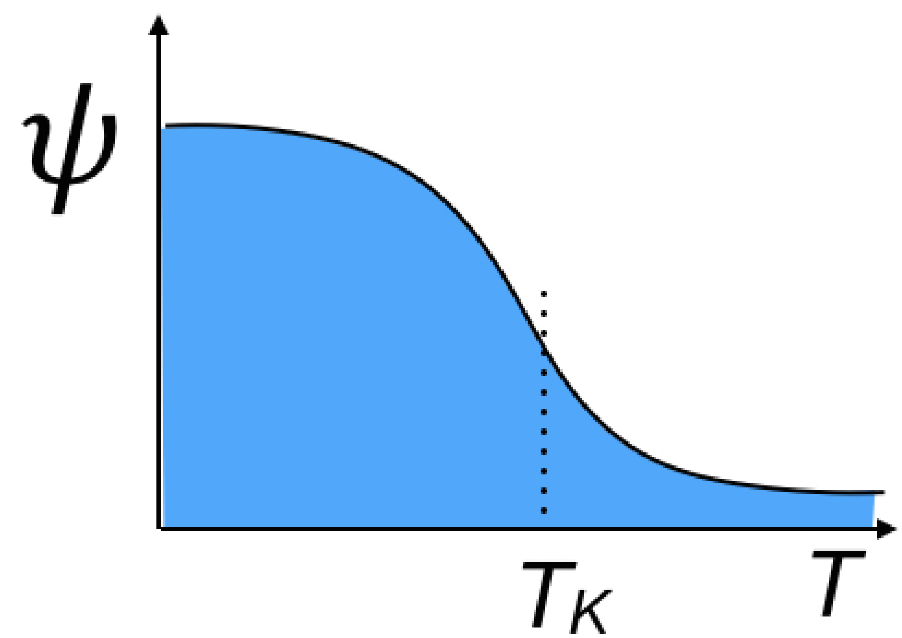

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H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

But if the ground-state is a non-Kramer's doublet, the Kondo effect occurs via an *excited Kramer's doublet*.

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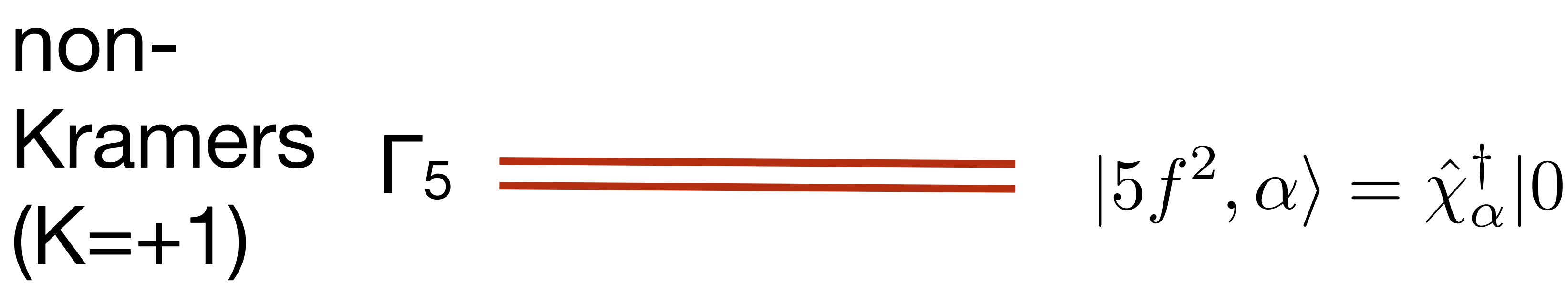

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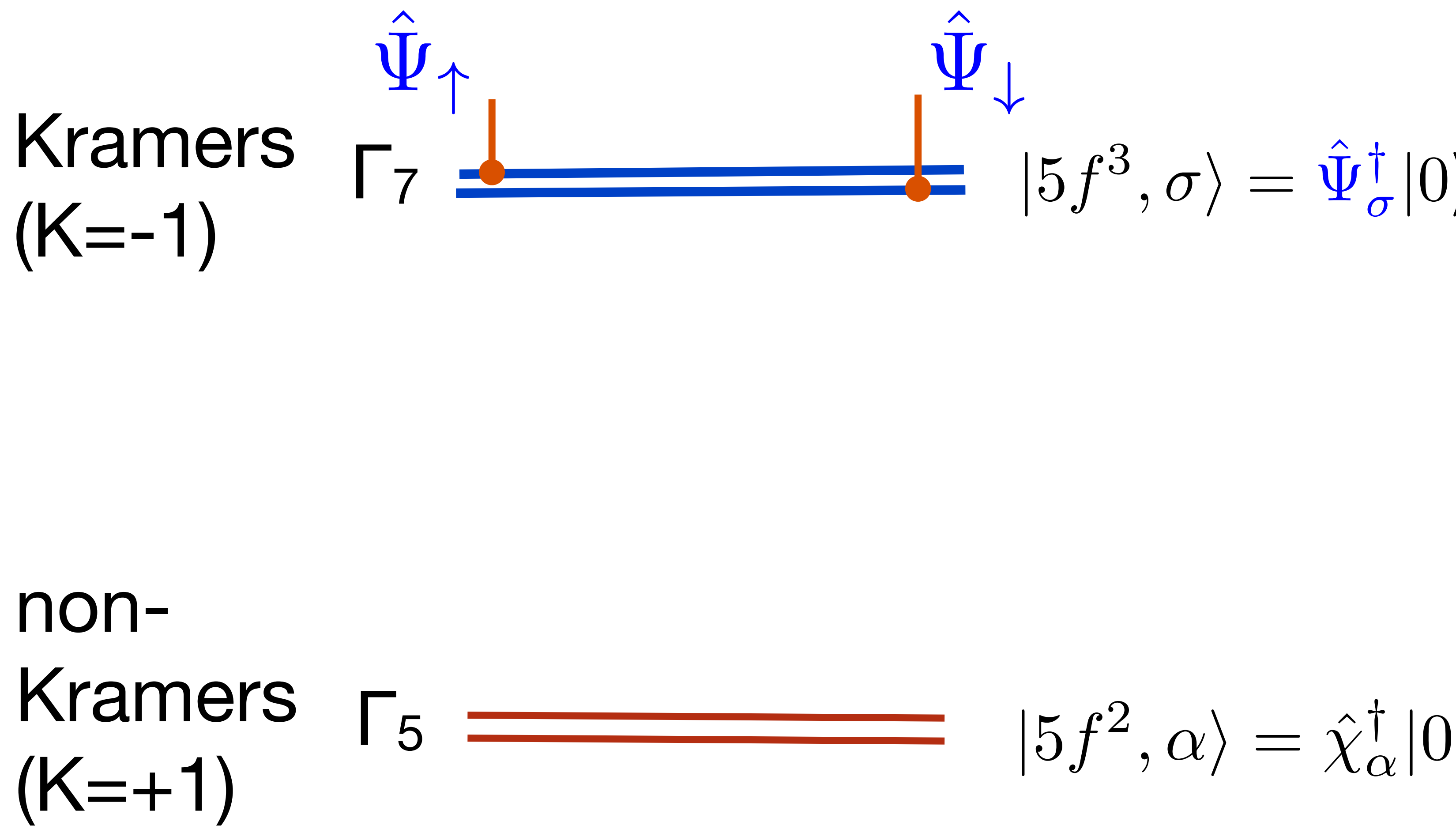

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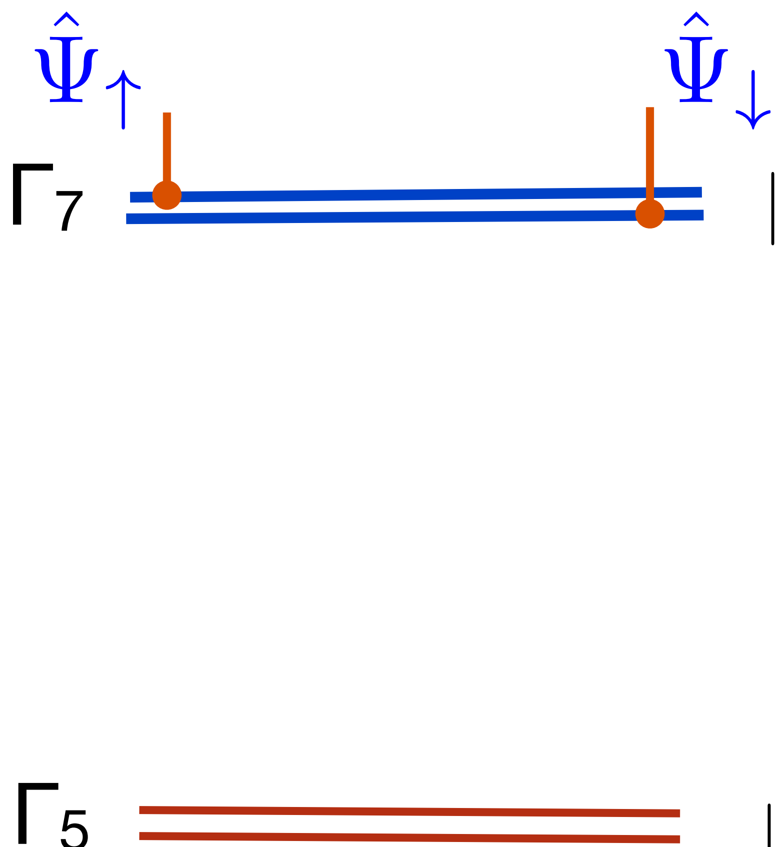

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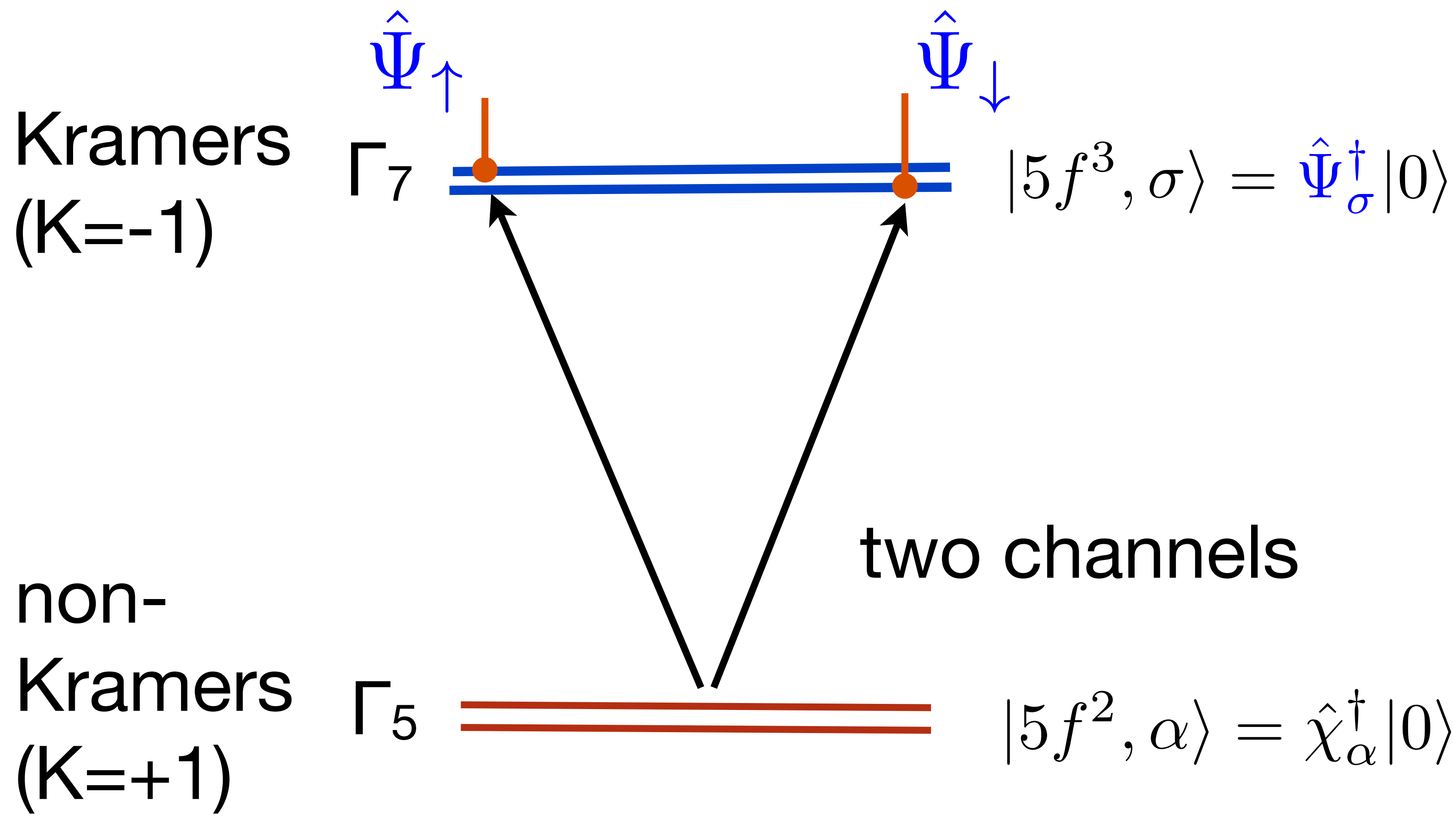

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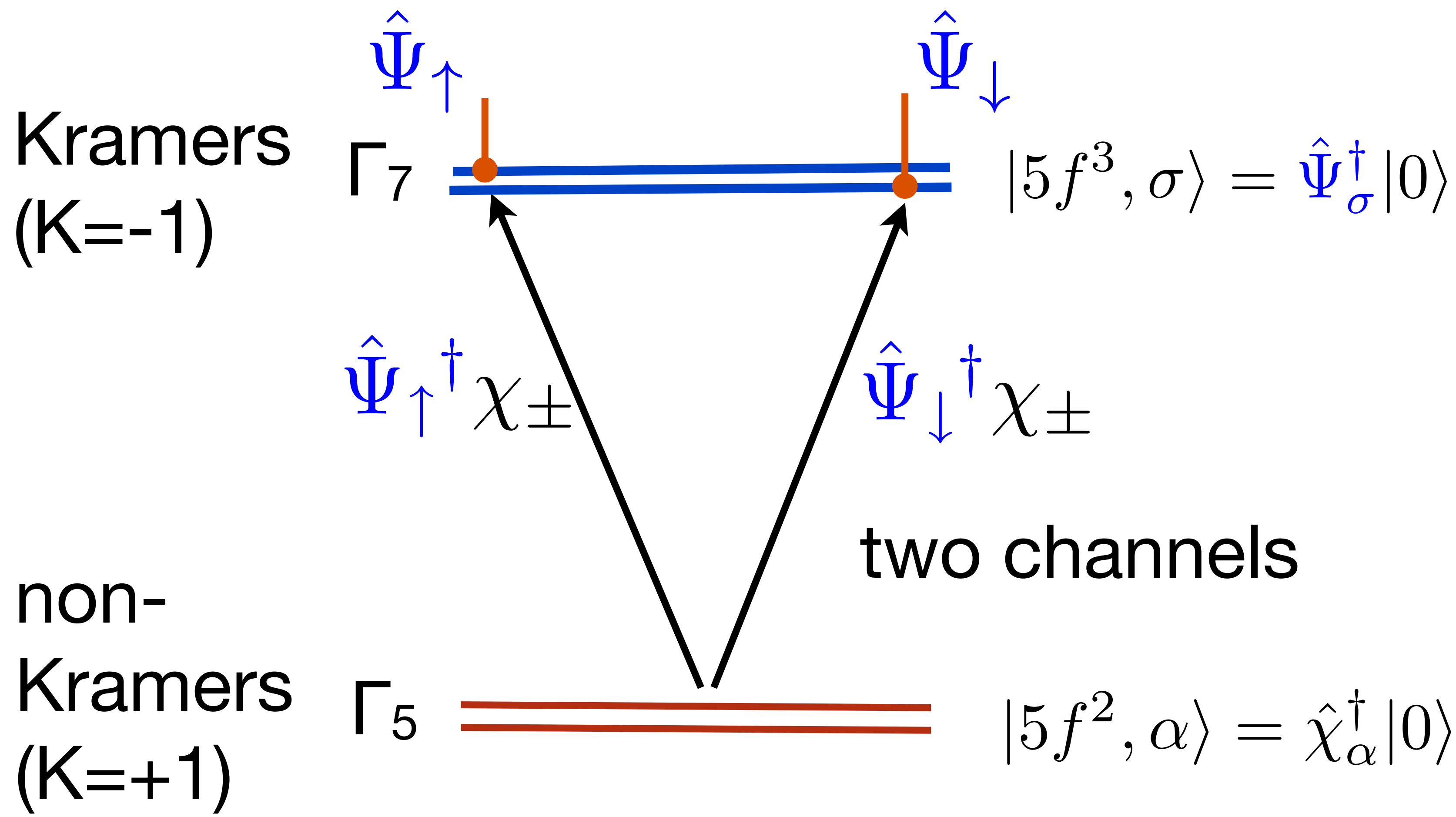

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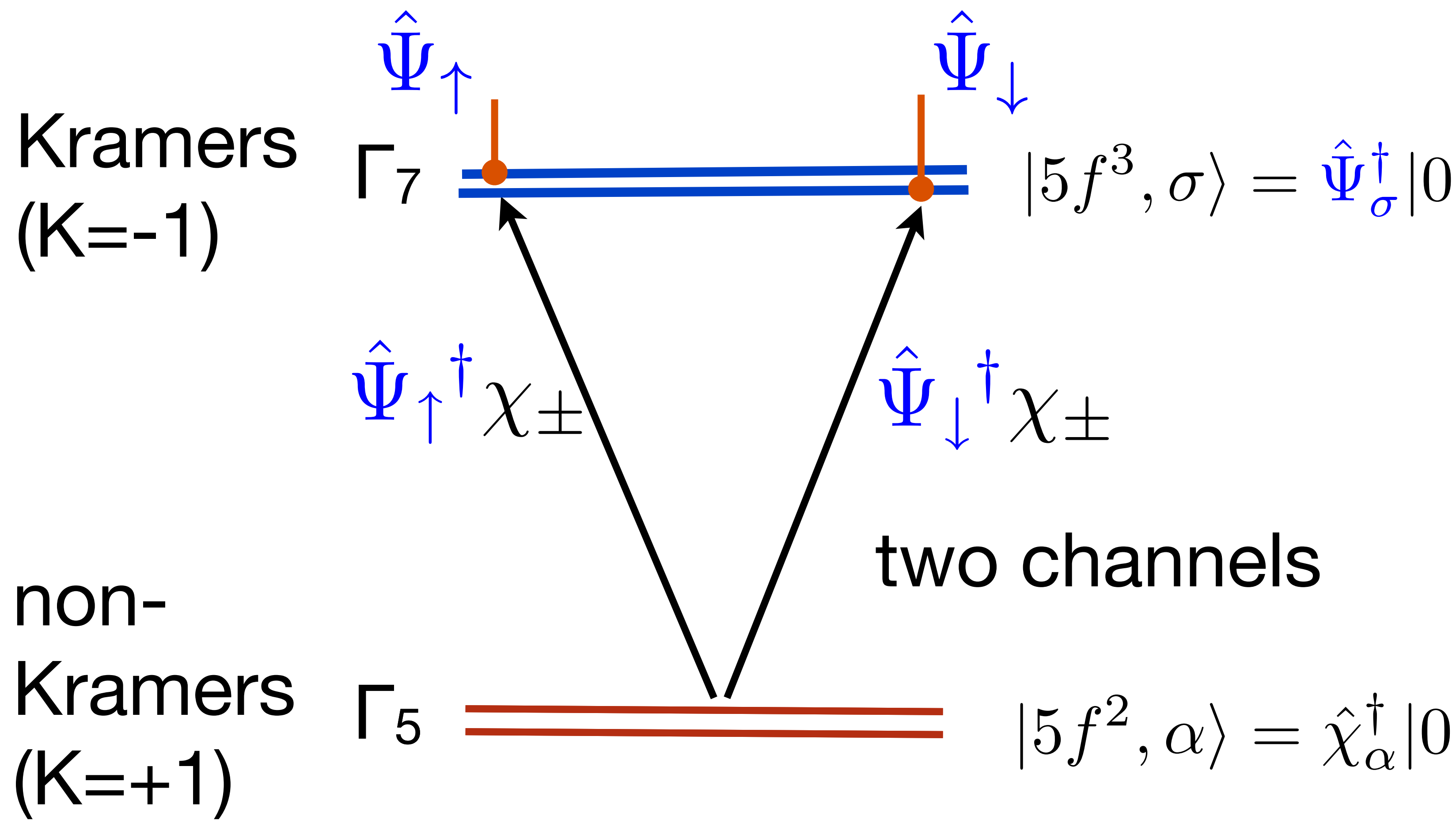

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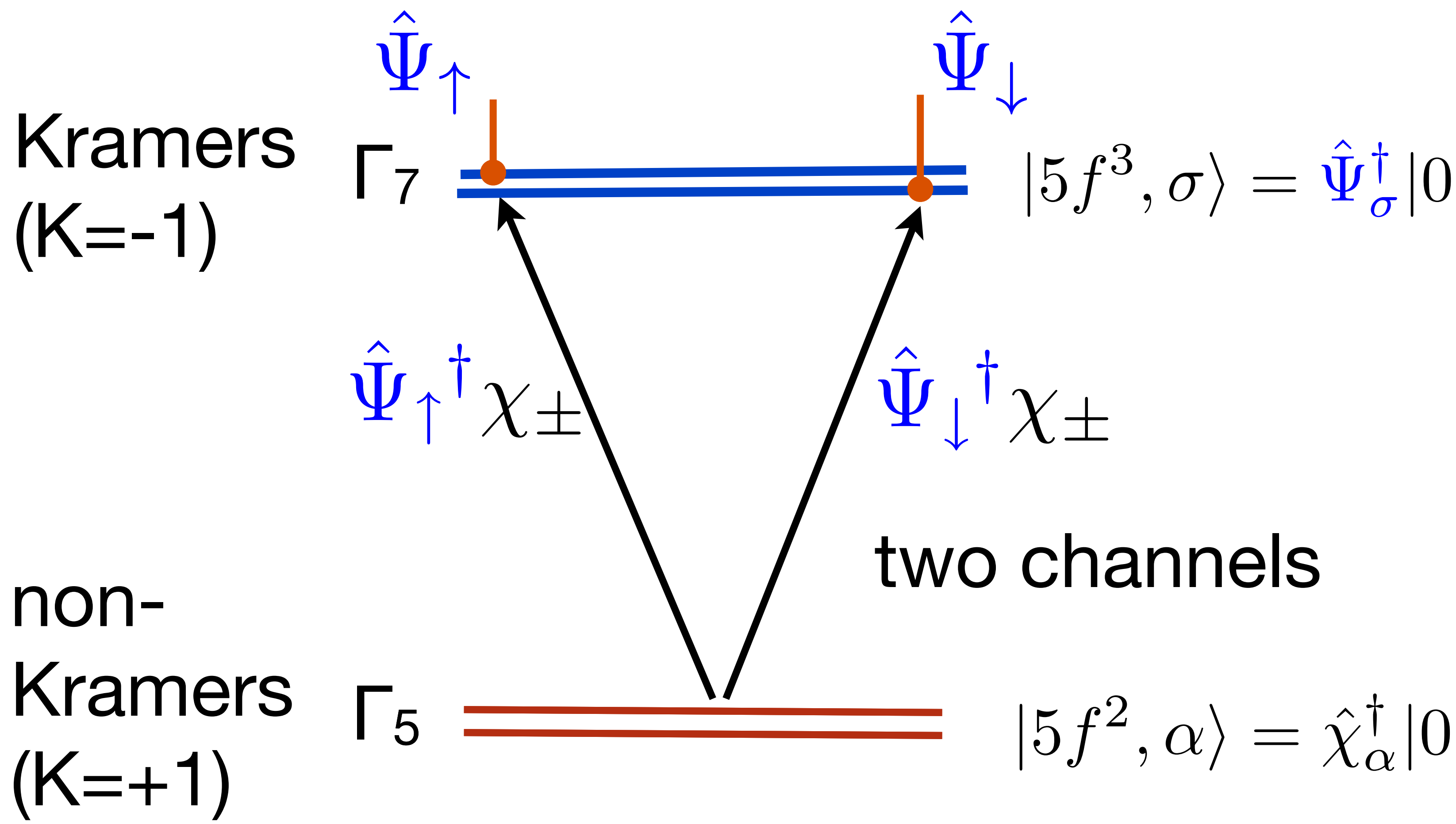

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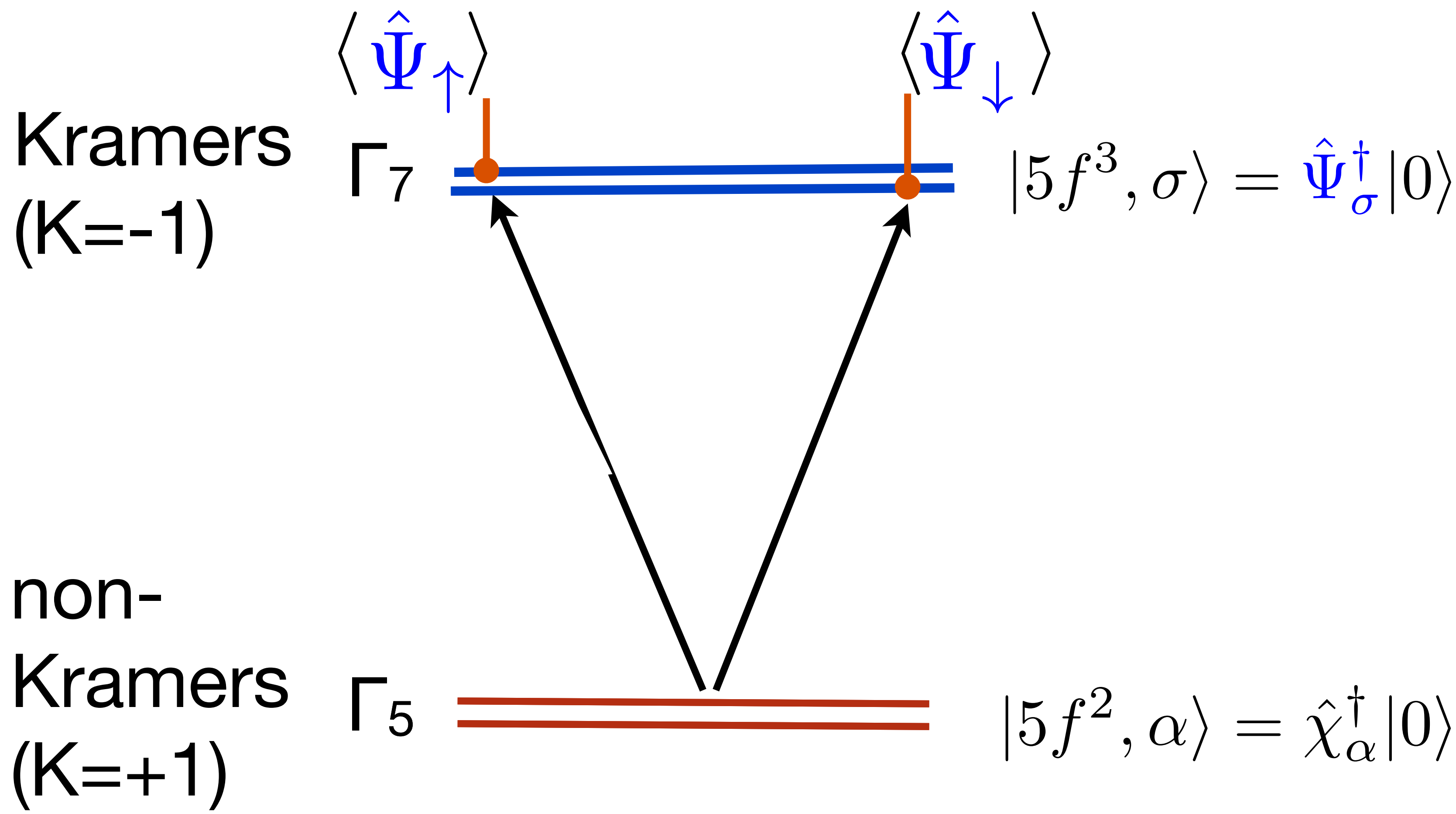

(“Magnetic Higgs Boson”)

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

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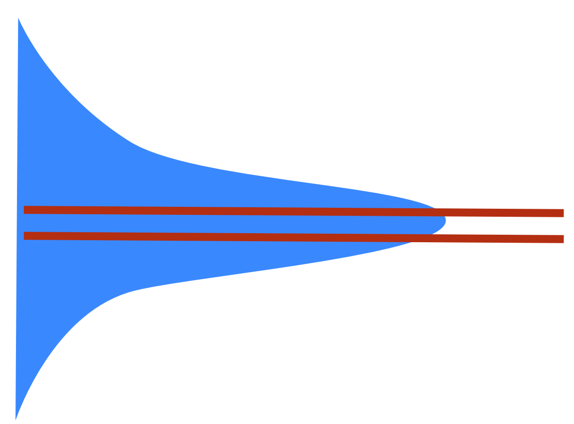

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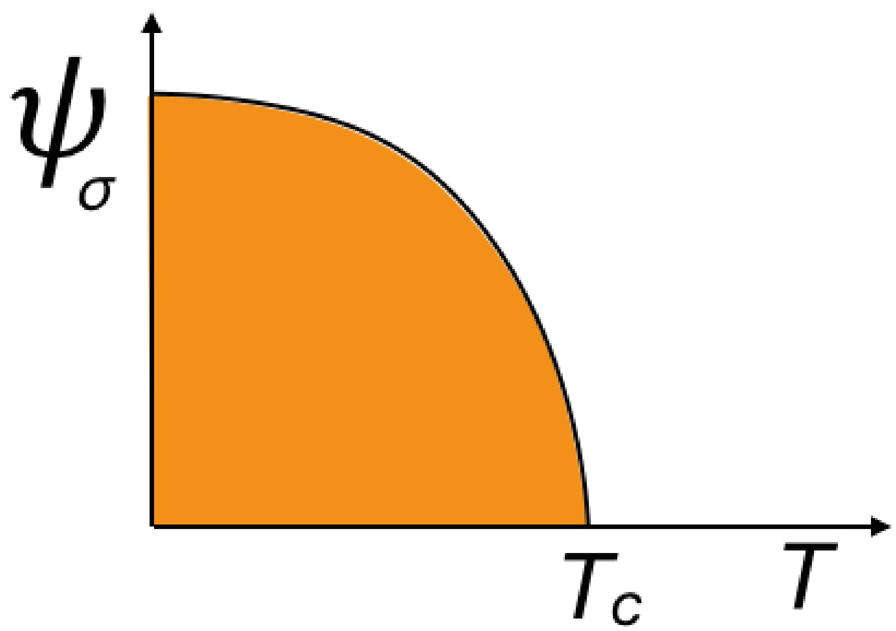
Quasiparticles acquire the Ising anisotropy of the non-Kramers doublet.



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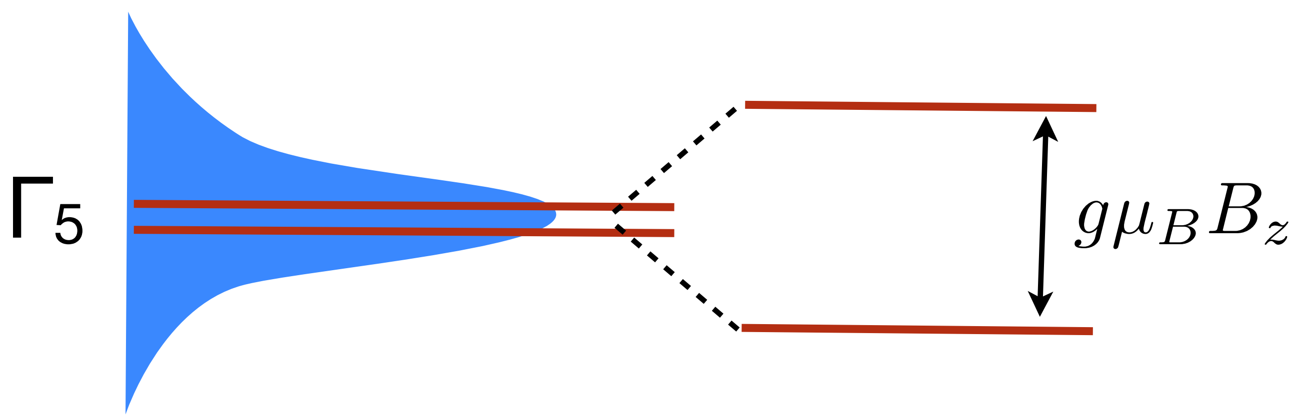

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The origin of the anisotropy in the non-linear susceptibility.

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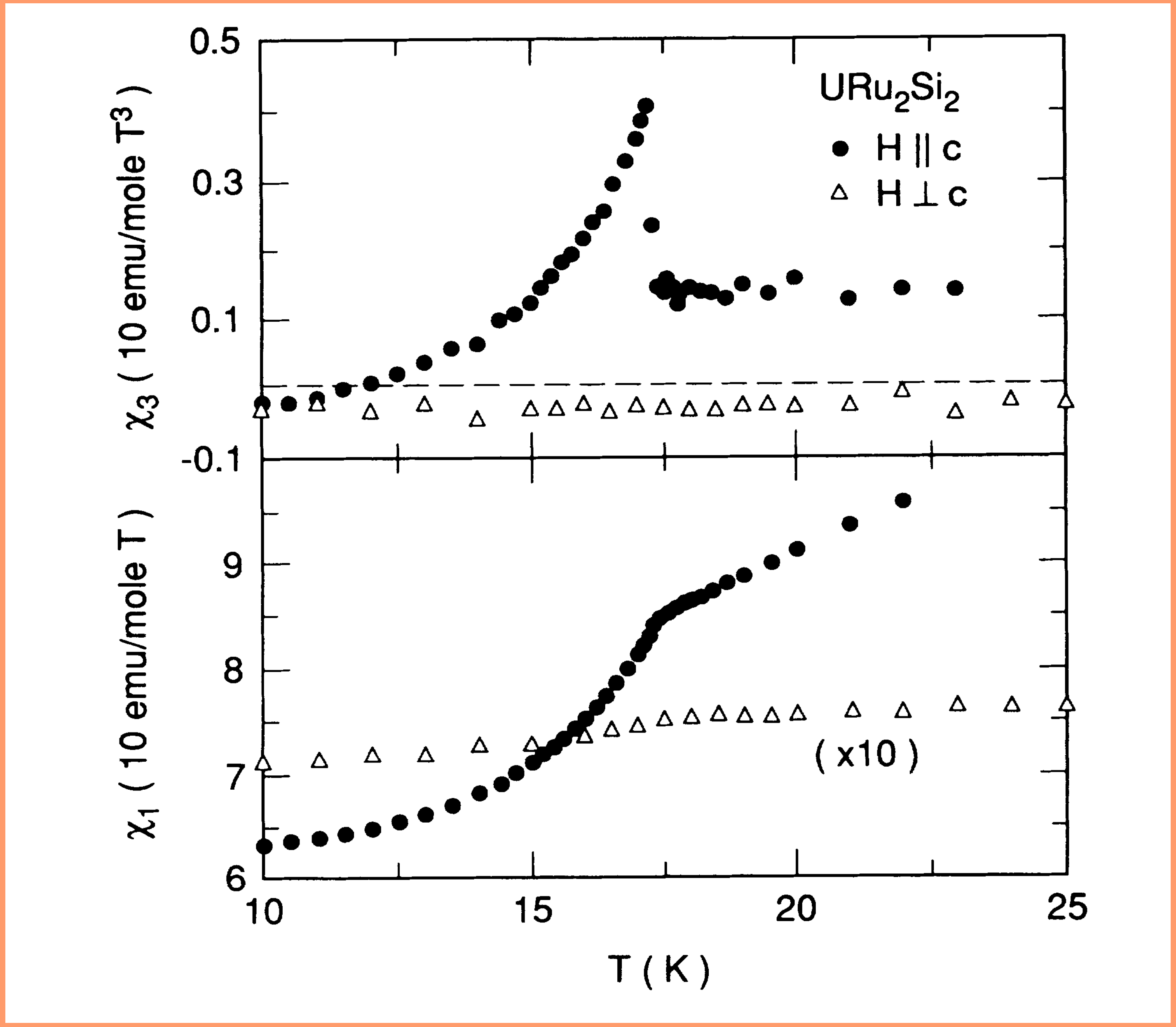
A. Ramirez, P. Coleman, P. Chandra, A. Menovsky, E. Bruck, Z. Fisk and E. Bucher, Physical Review Letters, 68, 2680, (1992).



Landau Theory of Hastatic Order.   I.

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

Large f-moment

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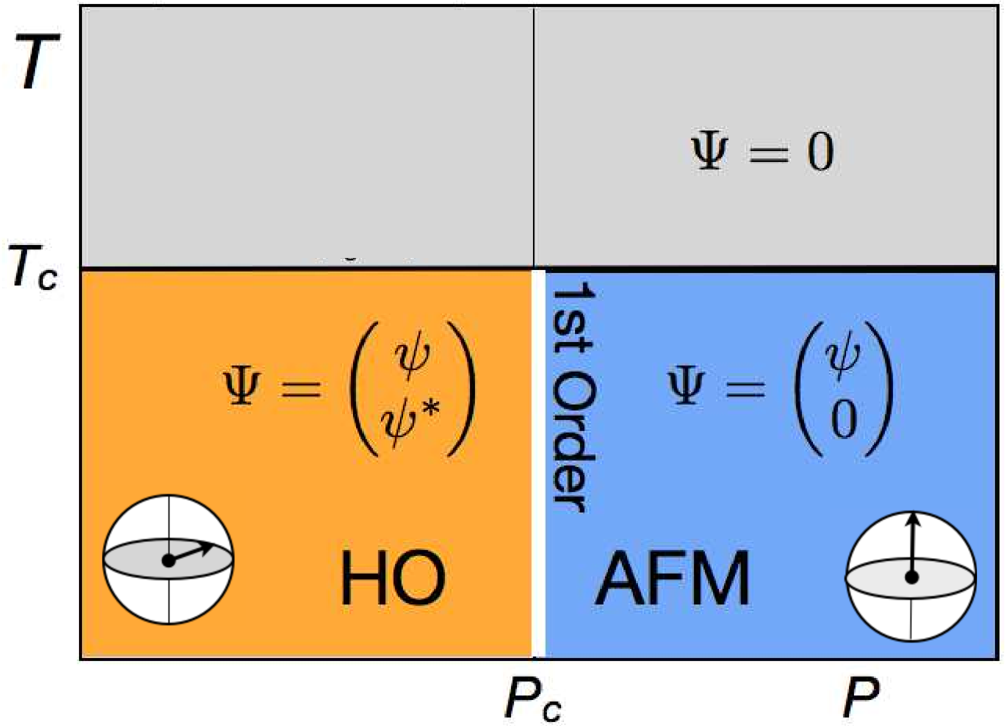

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Landau Theory of Hastatic Order. II. Origin of the non-linear susceptibility

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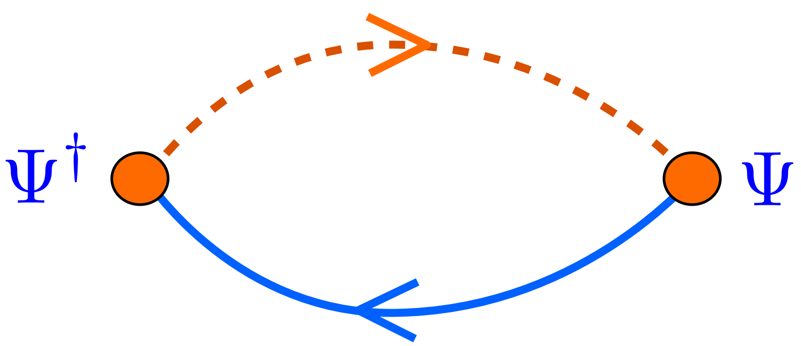

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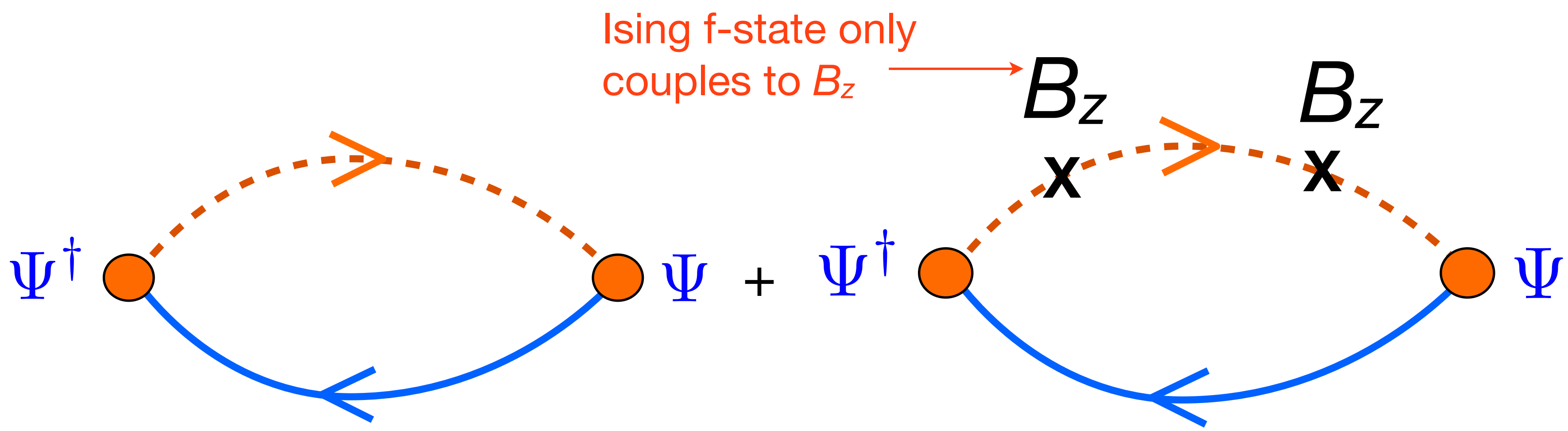

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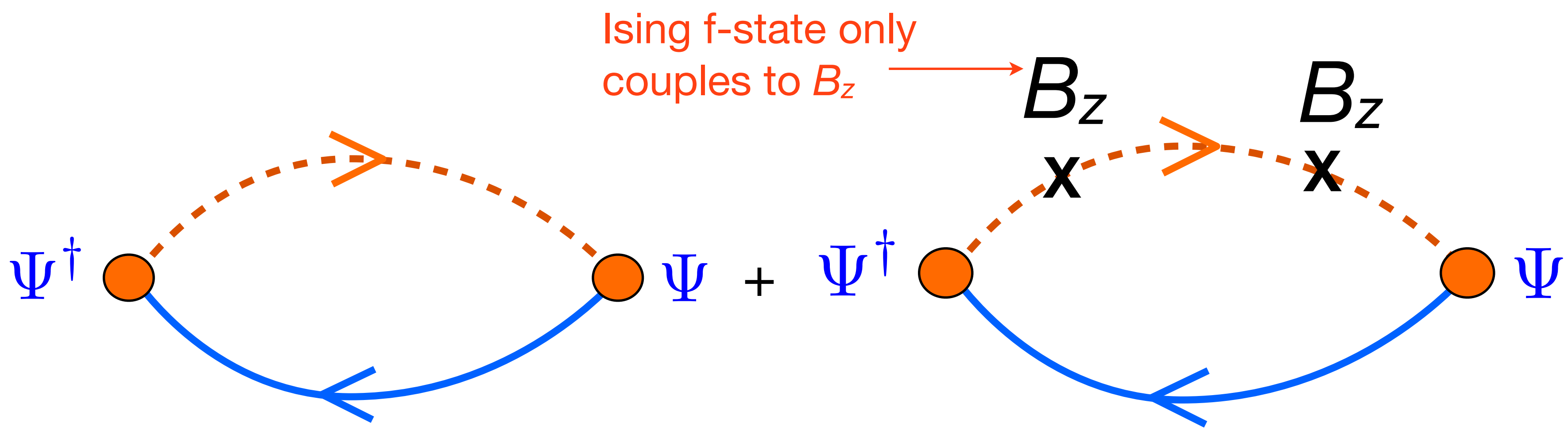

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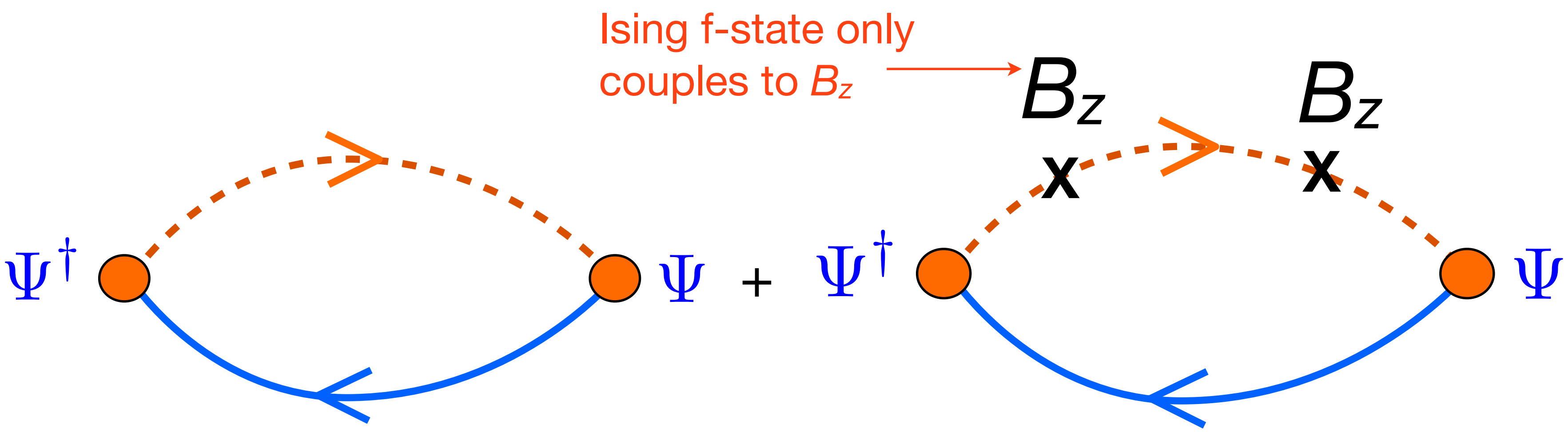

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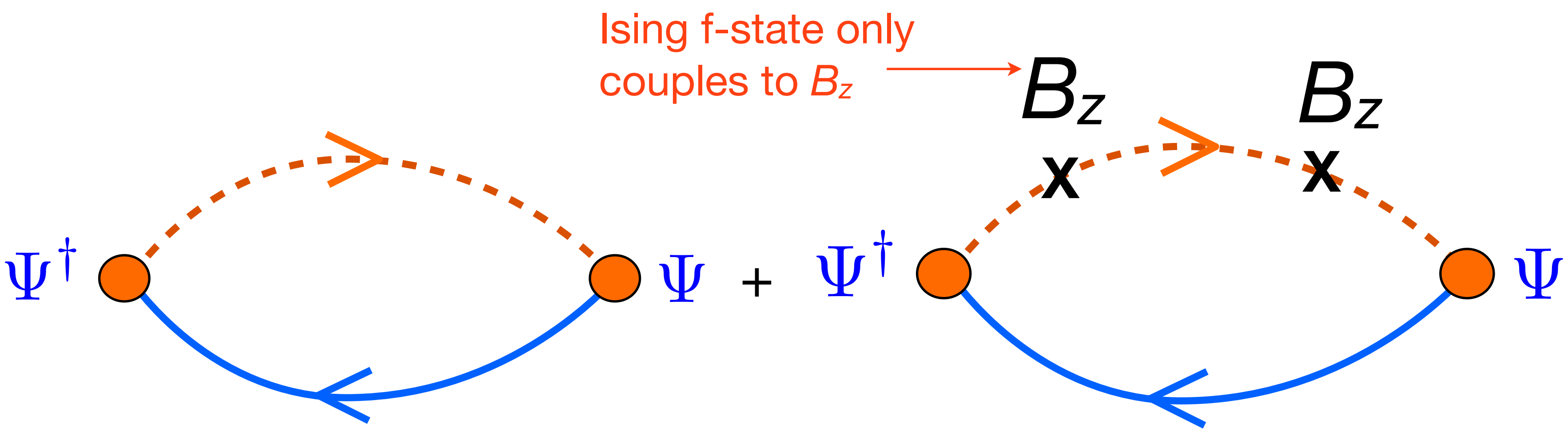

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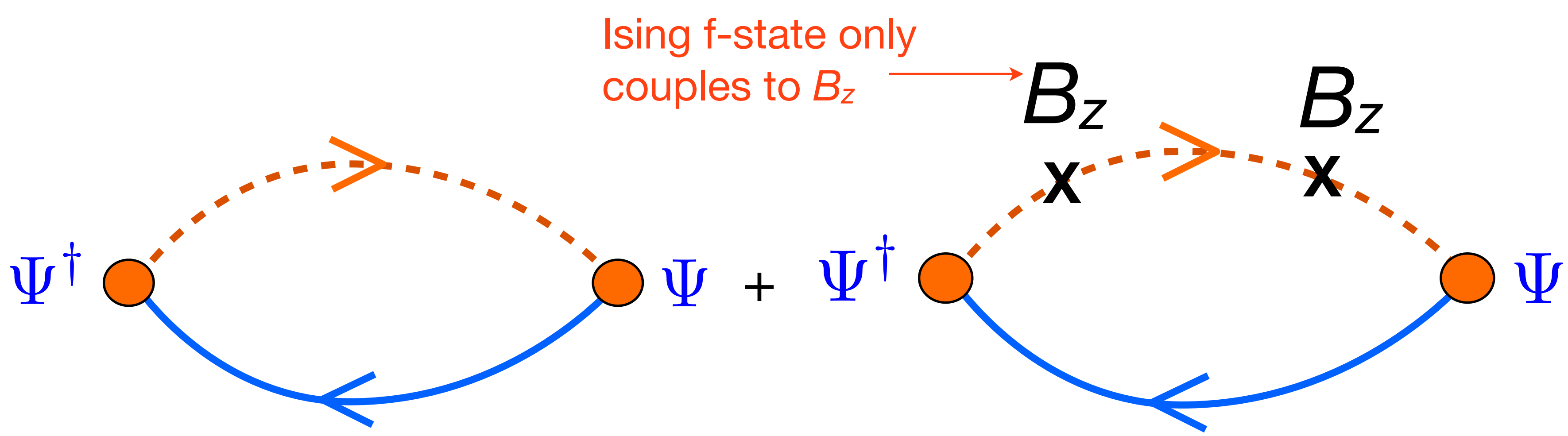

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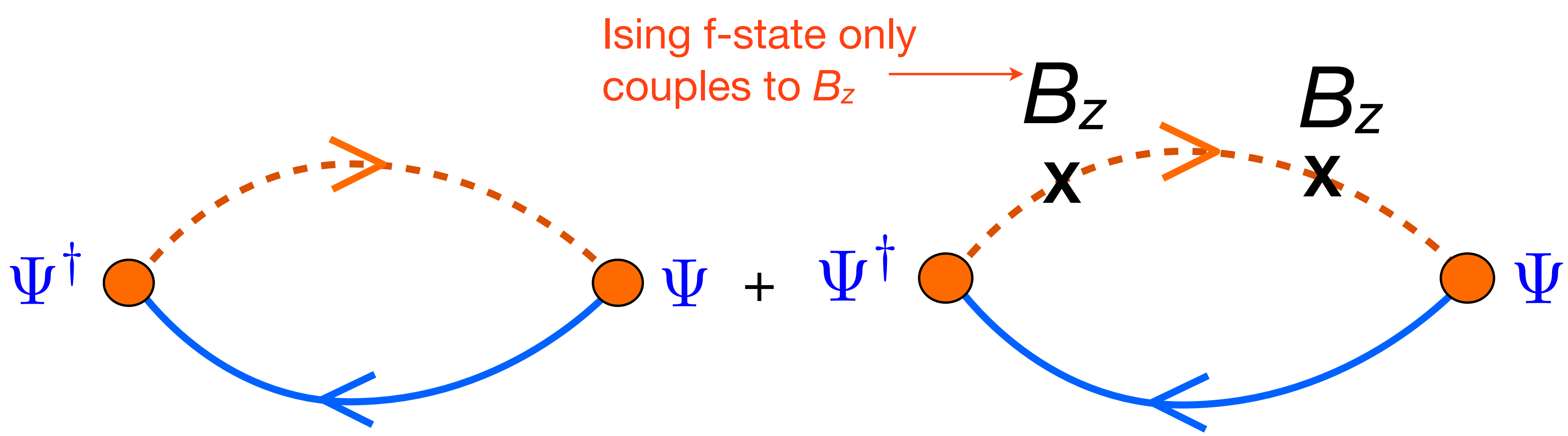

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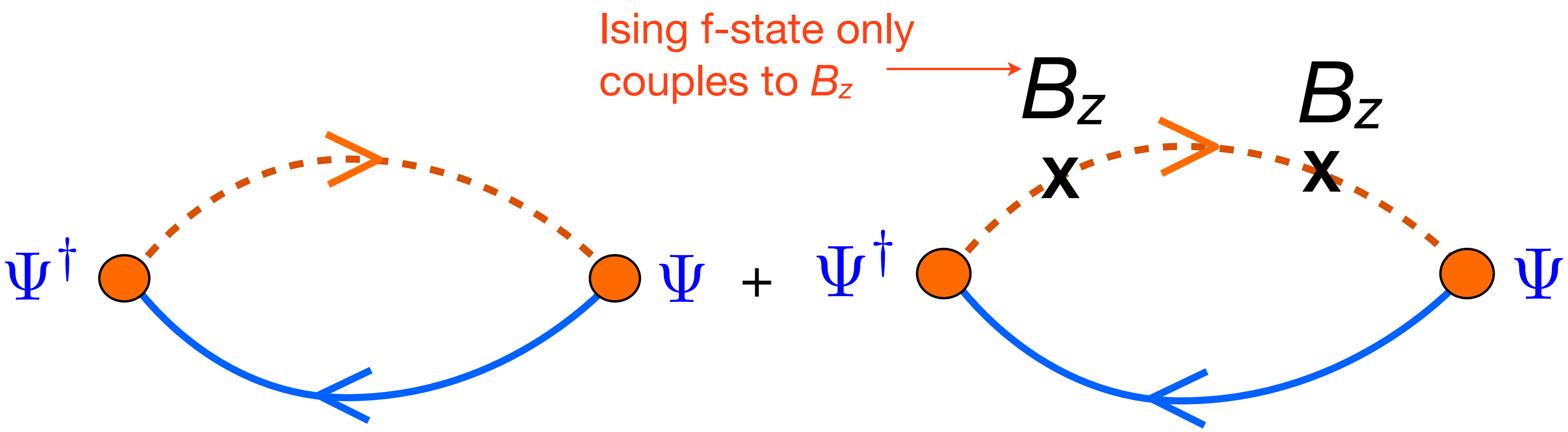

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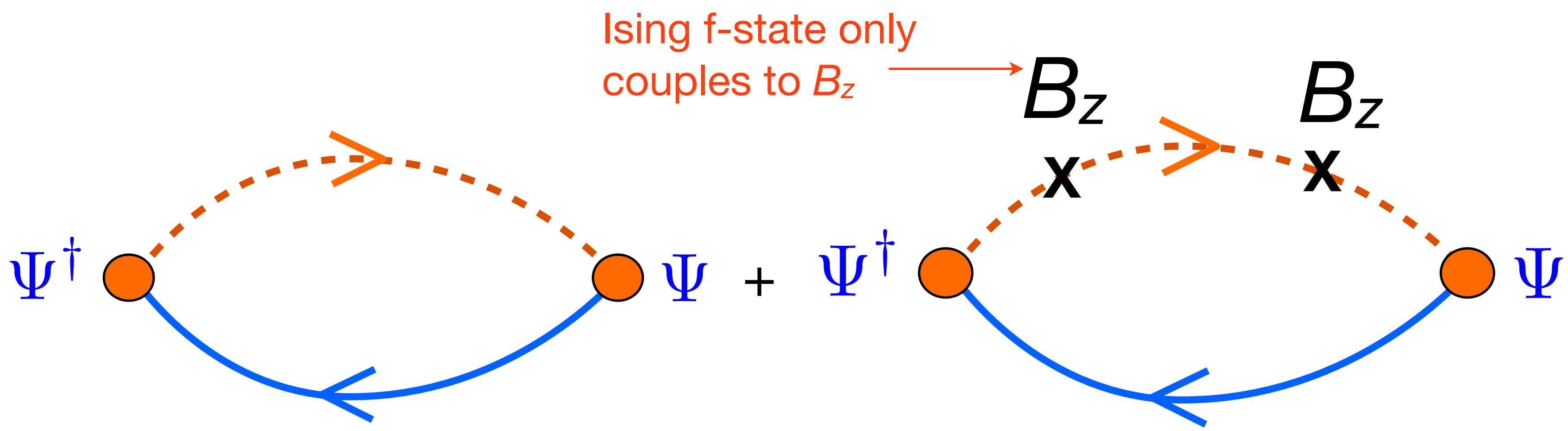

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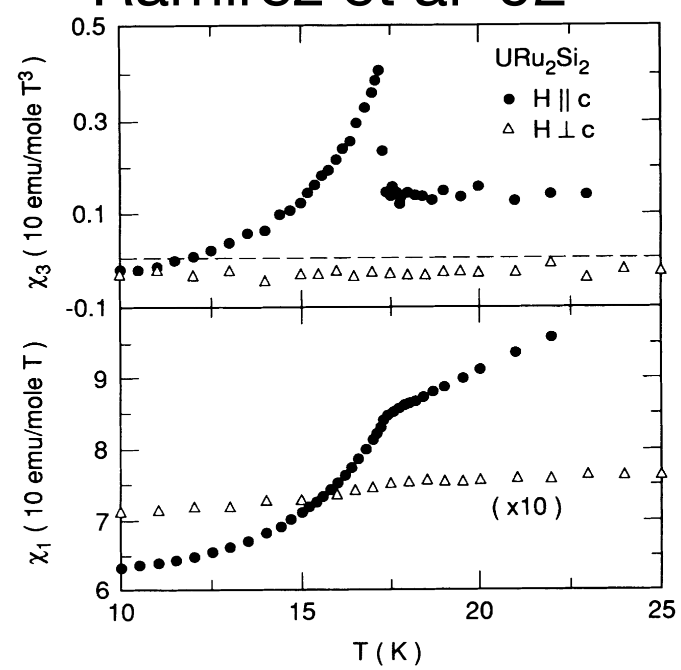
Ramirez et al '92



Landau Theory of Hastatic Order. II. Origin of the non-linear susceptibility

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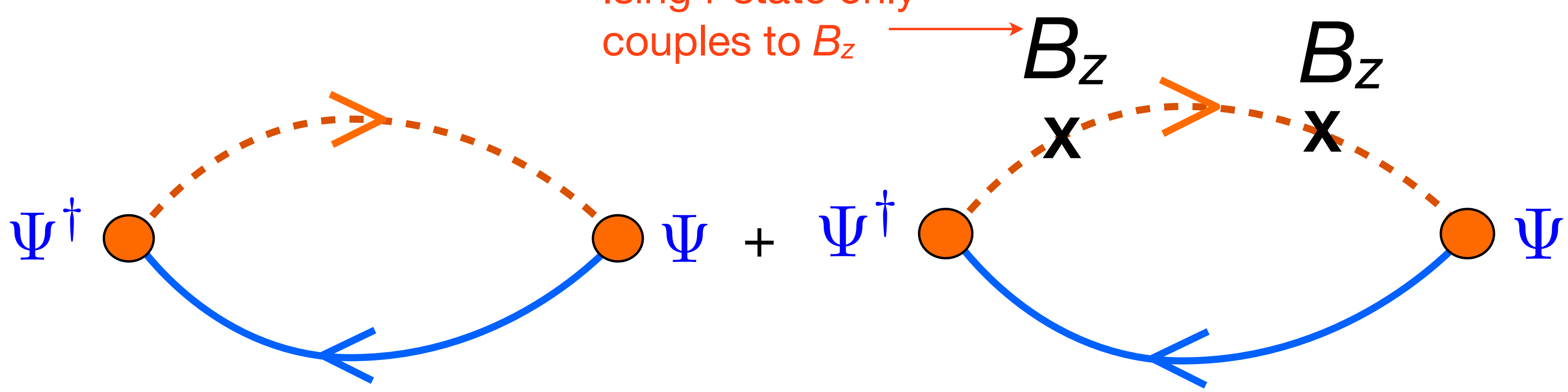
$$f[T, P, B_z] = [\alpha(T_c - T) - \eta_z B_z^2]|\Psi|^2 + \beta|\Psi|^4 - \gamma(\Psi^\dagger \sigma_z \Psi)^2$$

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

Ising f-state only couples to B_z



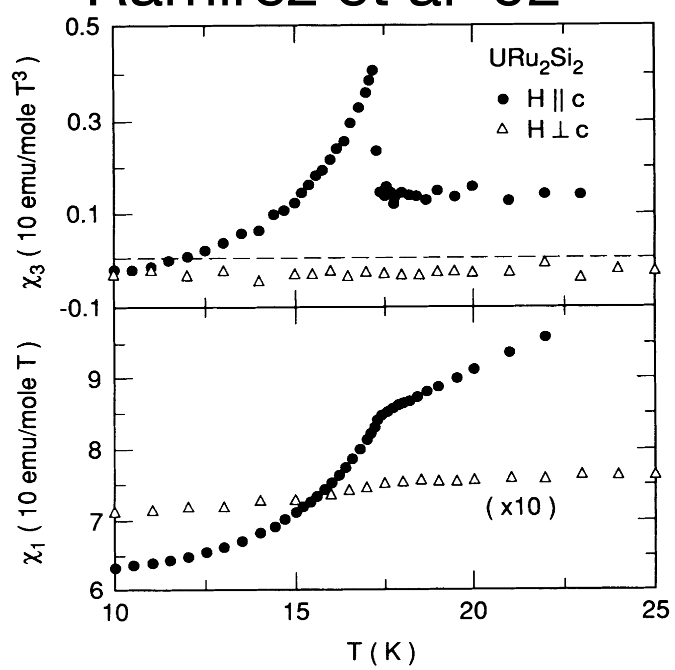
$$= [\alpha(T_c - T) - \eta_z B_z^2]|\Psi|^2$$

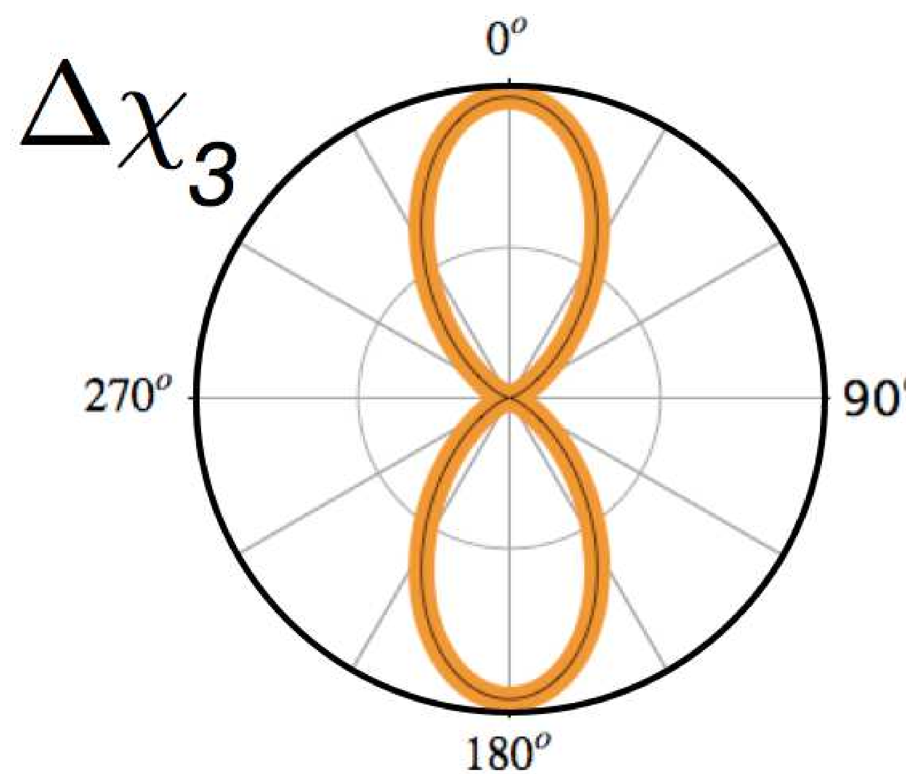
$$f = -\frac{1}{4\beta}\left[\alpha(T_c - T) - \eta_z (B\cos\theta)^2\right]^2$$

$$M = \chi_1 B + \frac{\chi_3}{3!} B^3$$

$$\Delta\chi_3 = -\frac{d^4 f}{dB^4} = \frac{6}{\beta}(\eta_z \cos\theta)^4$$

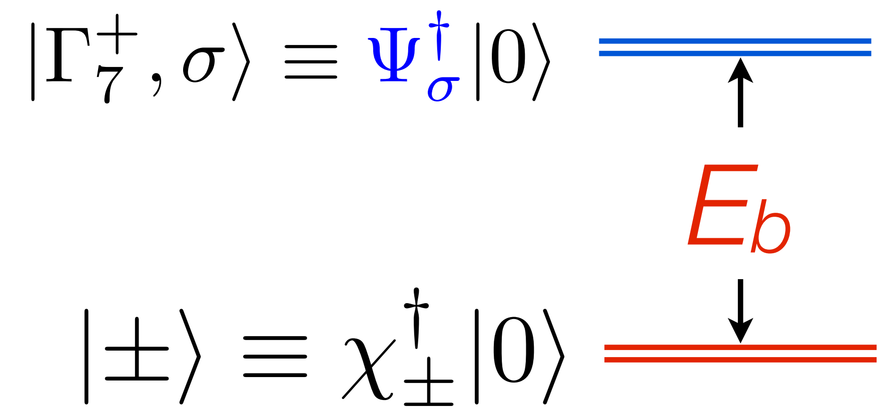
Ramirez et al '92





Anisotropy in excess of 1000 predicted.

Microscopic theory of Hastatic Order



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

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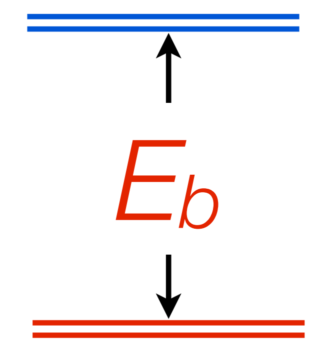

$$5f^2 \rightleftharpoons 5f^1 + e^- \qquad \psi_{\Gamma\sigma}^\dagger(j) = \sum_{\mathbf{k}} \left[\Phi_\Gamma^\dagger(\mathbf{k})\right]_{\sigma\tau} c_{\mathbf{k}\tau}^\dagger \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{R}_j}$$

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

Schwinger/Slave boson

$$|\Gamma_7^+\sigma\rangle\langle\Gamma_5\alpha| = \hat{\Psi}^\dagger_\sigma \chi_\alpha$$

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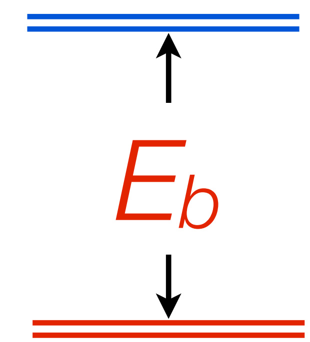

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$$H = \sum_{\mathbf{k}} \left(c^\dagger_{\mathbf{k}}, c^\dagger_{\mathbf{k}+\mathbf{Q}}, \chi^\dagger_{\mathbf{k}}, \chi^\dagger_{\mathbf{k}+\mathbf{Q}}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & 0 & \mathcal{V}_6(\mathbf{k}) & \mathcal{V}_7(\mathbf{k}) \\ 0 & \epsilon_{\mathbf{k}+\mathbf{Q}} & -\mathcal{V}_7(\mathbf{k}) & -\mathcal{V}_6(\mathbf{k}) \\ \mathcal{V}^\dagger_6(\mathbf{k}) & -\mathcal{V}^\dagger_7(\mathbf{k}) & \lambda_{\mathbf{k}} & 0 \\ \mathcal{V}^\dagger_7(\mathbf{k}) & -\mathcal{V}^\dagger_6(\mathbf{k}) & 0 & \lambda_{\mathbf{k}+\mathbf{Q}} \end{pmatrix}}^{\mathcal{H}_{\alpha\beta}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}} \\ c_{\mathbf{k}+\mathbf{Q}} \\ \chi_{\mathbf{k}} \\ \chi_{\mathbf{k}+\mathbf{Q}} \end{pmatrix}$$

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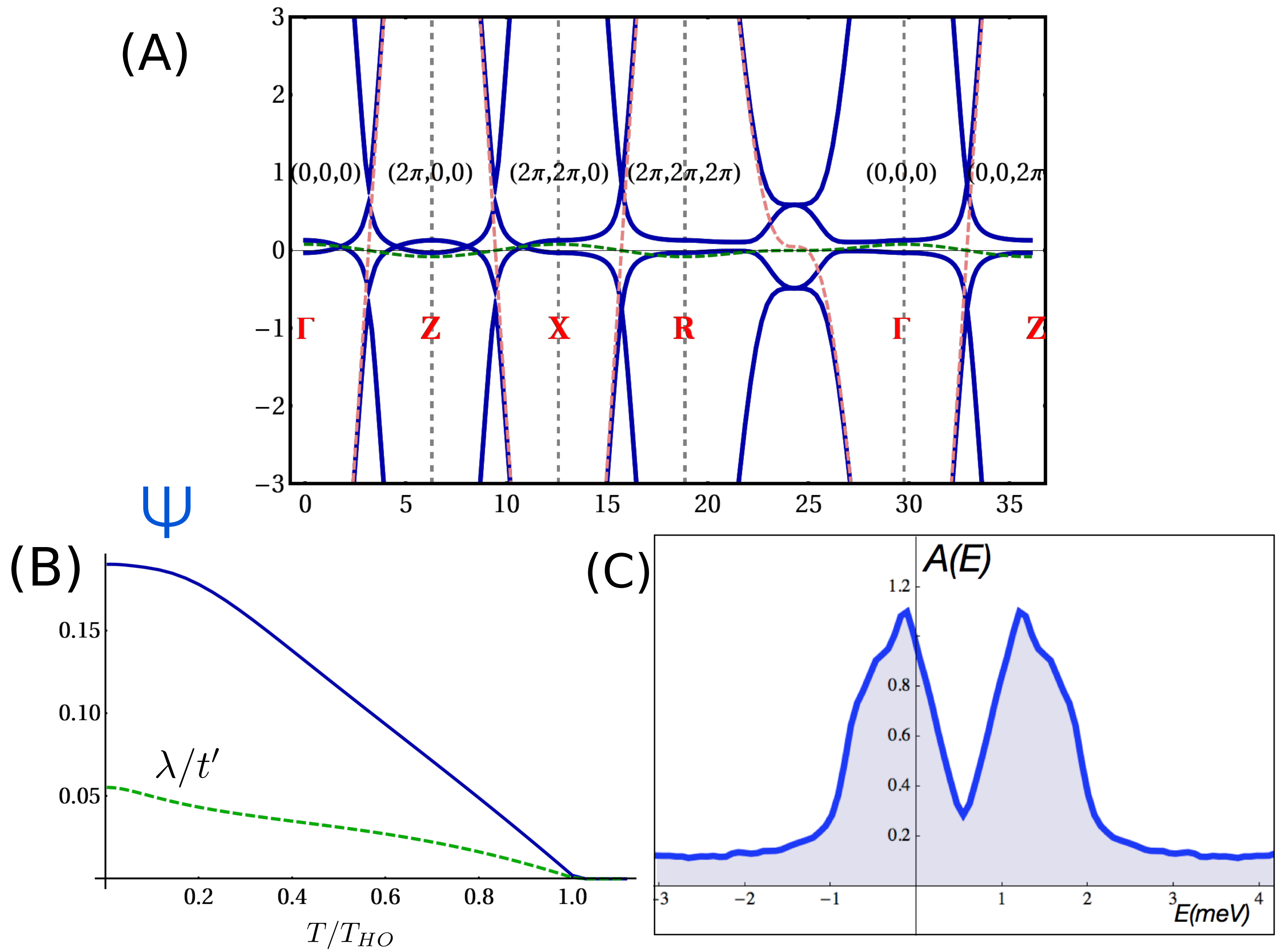
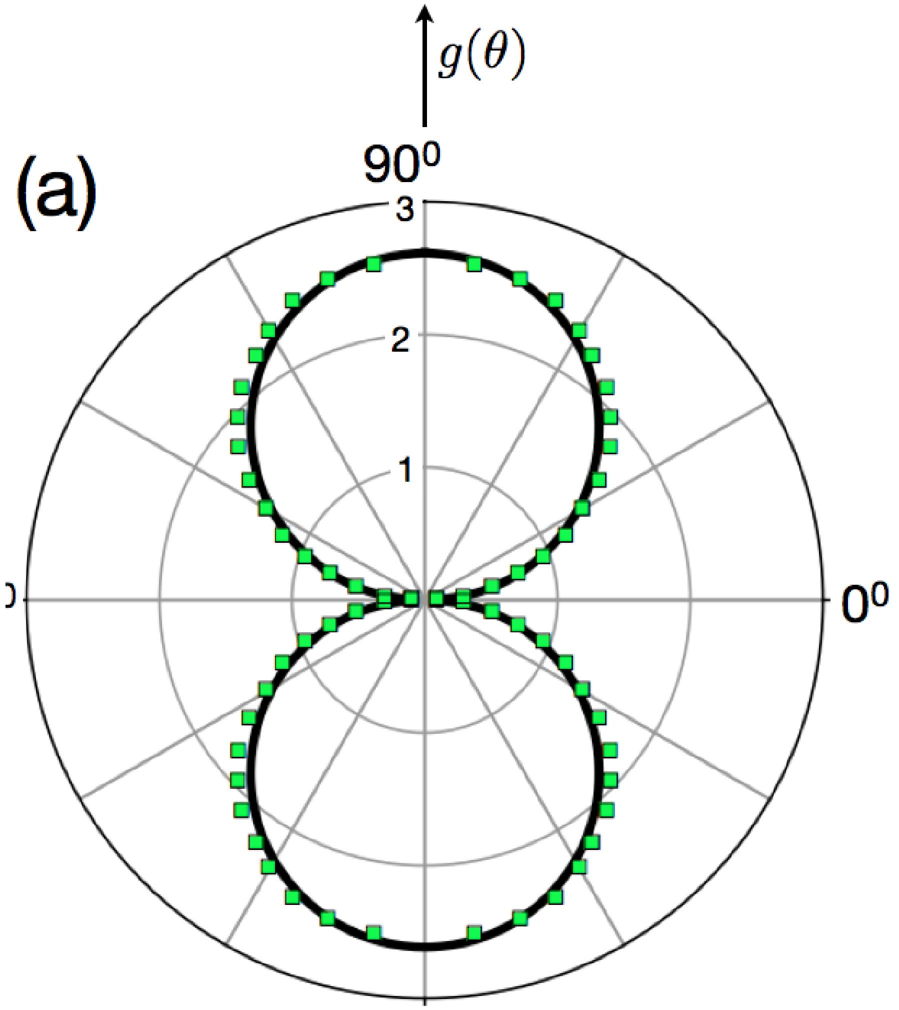
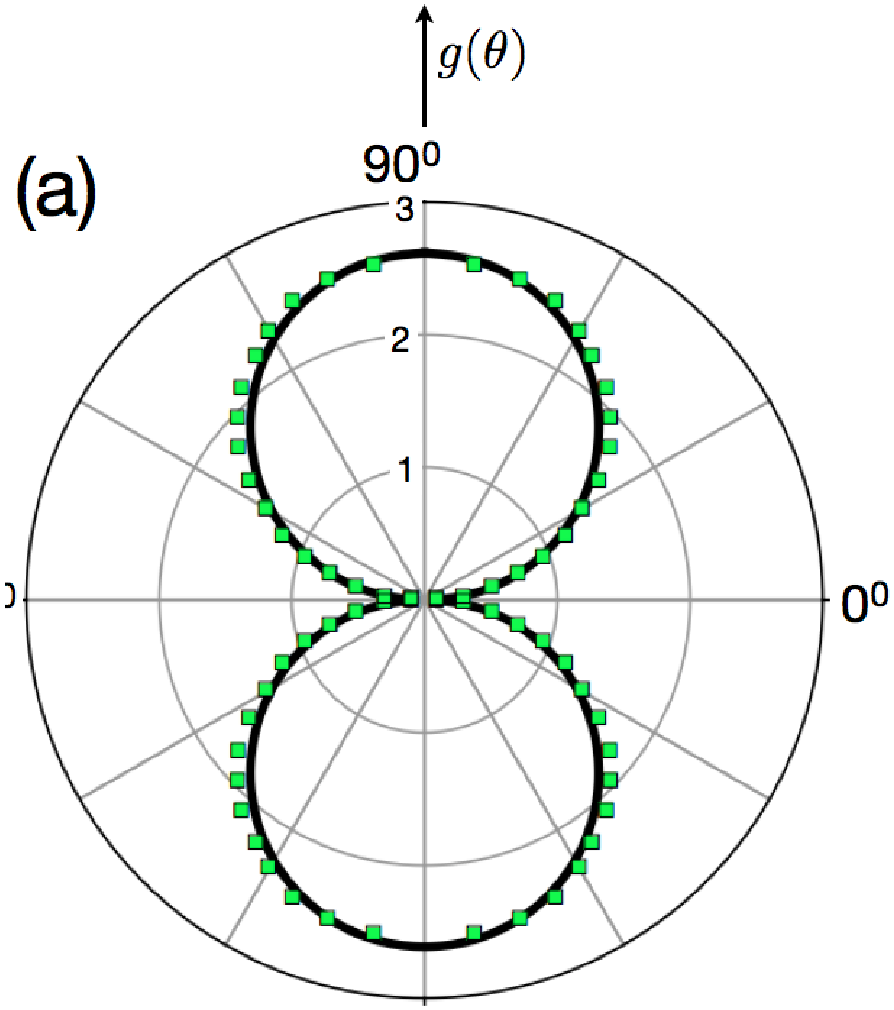


Consistency with experiment.



Computed g-factor Anisotropy



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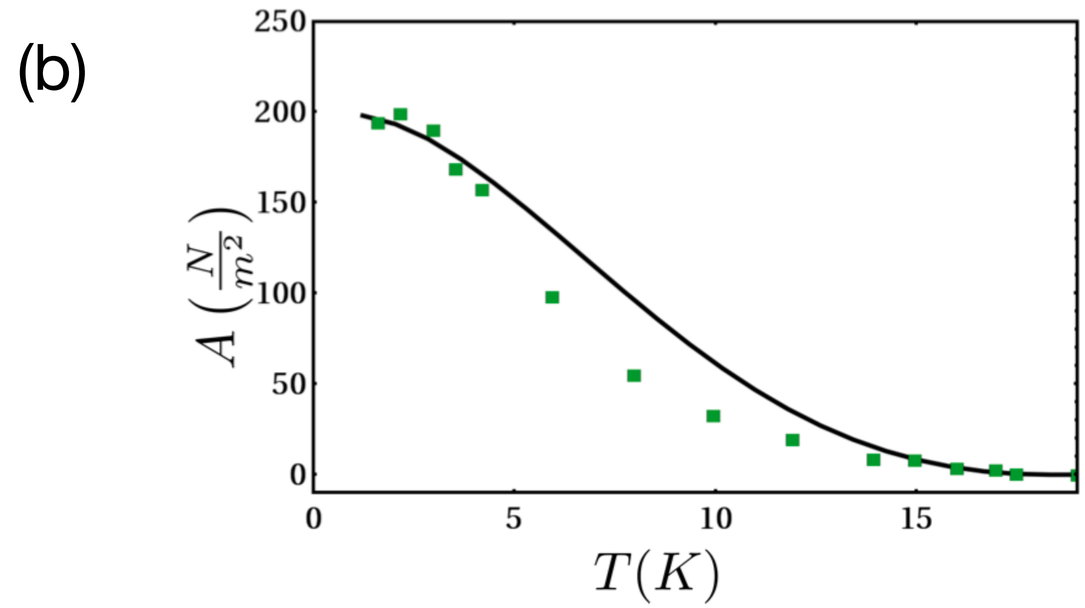
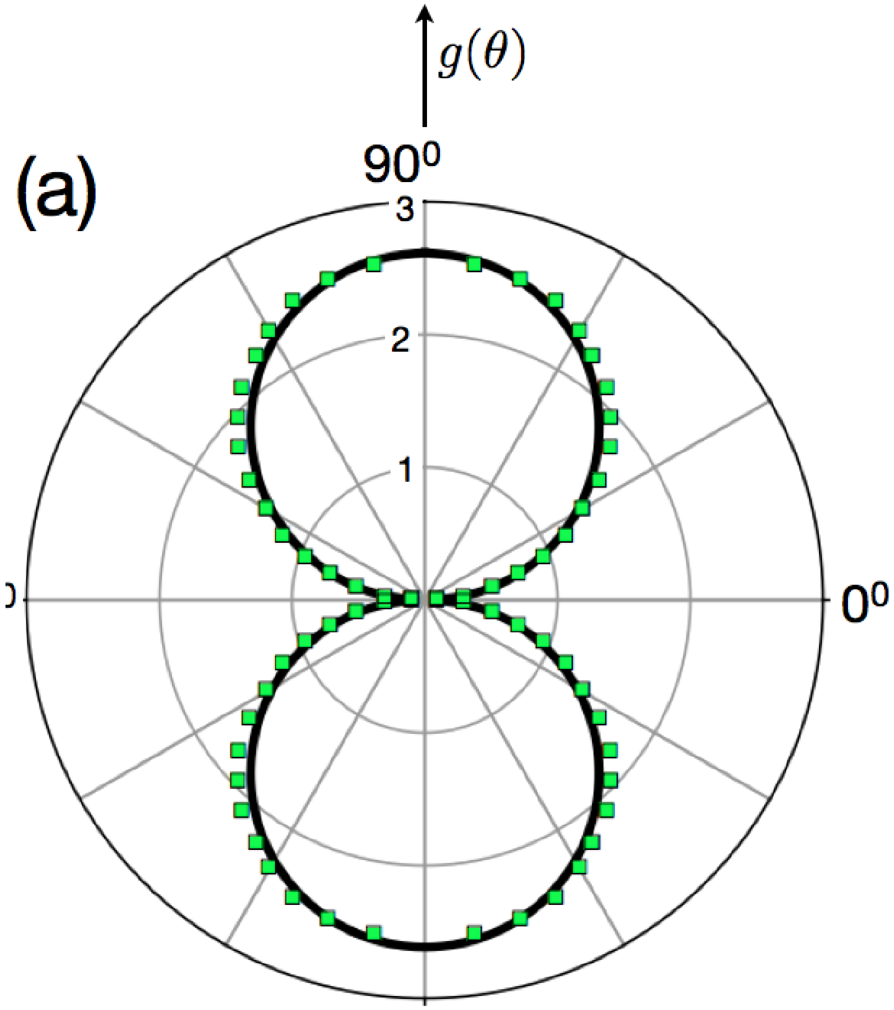


Nematicity: anisotropic X_{xy} consistent with observed susceptibility anomaly.



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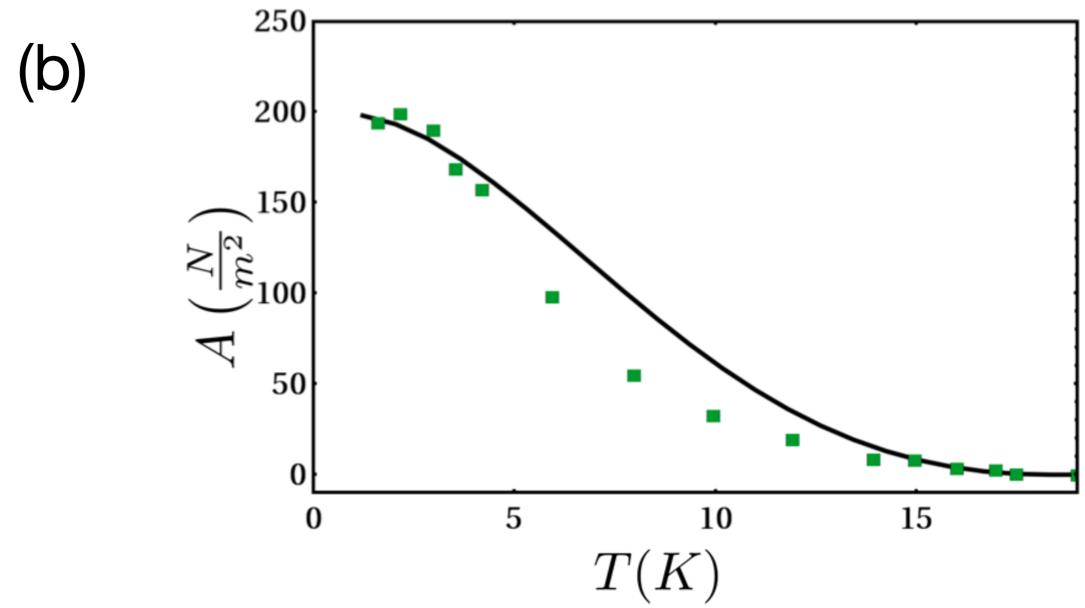

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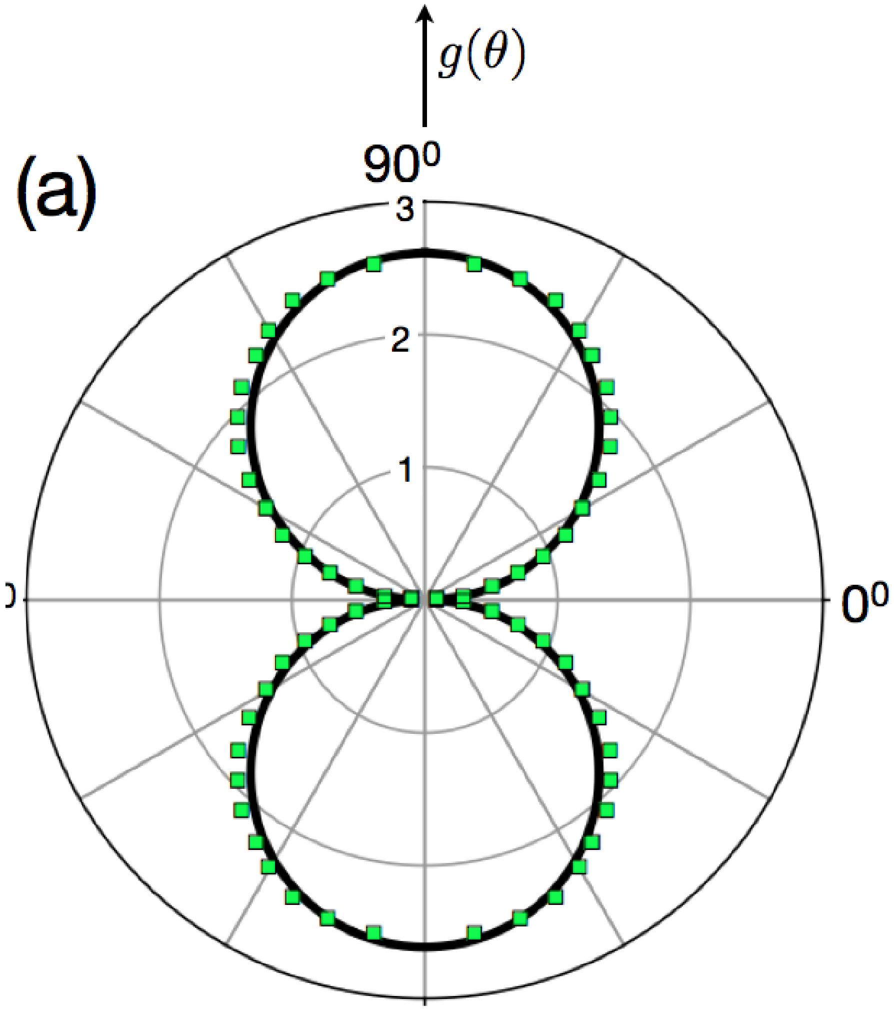
(c) S ~ 1/2 ln (2) natural consequence of Majorana zero mode in two channel Kondo physics.



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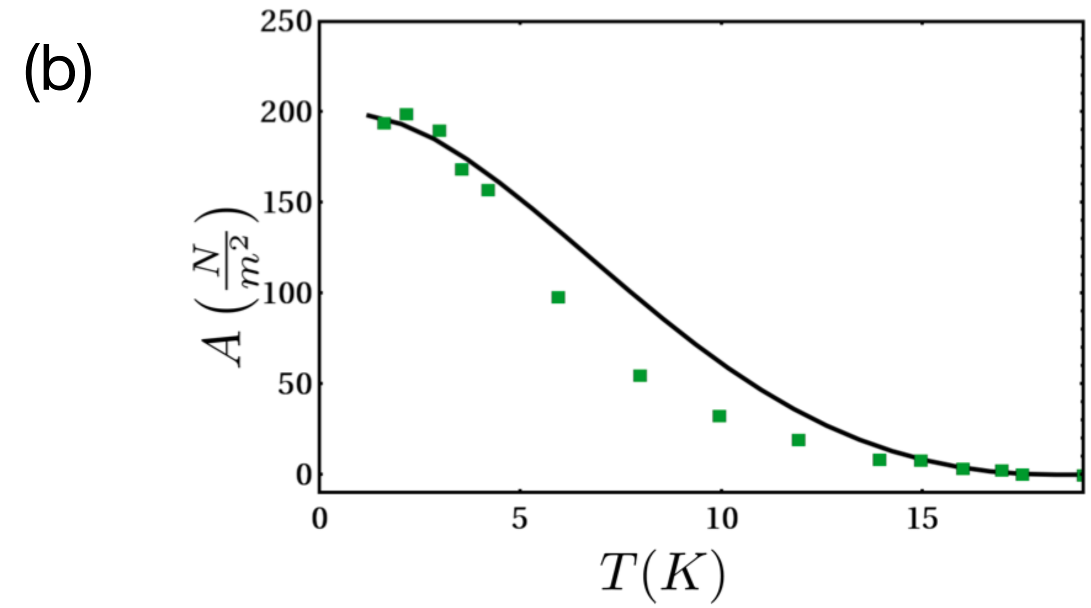

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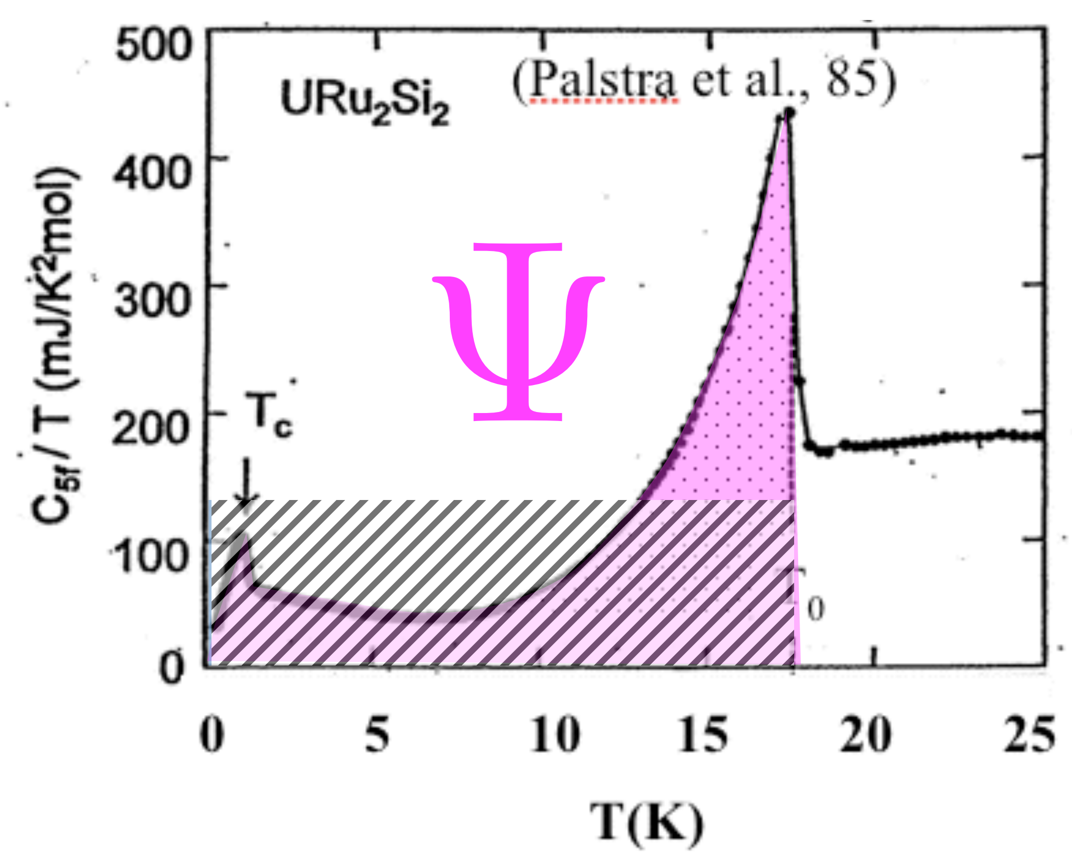
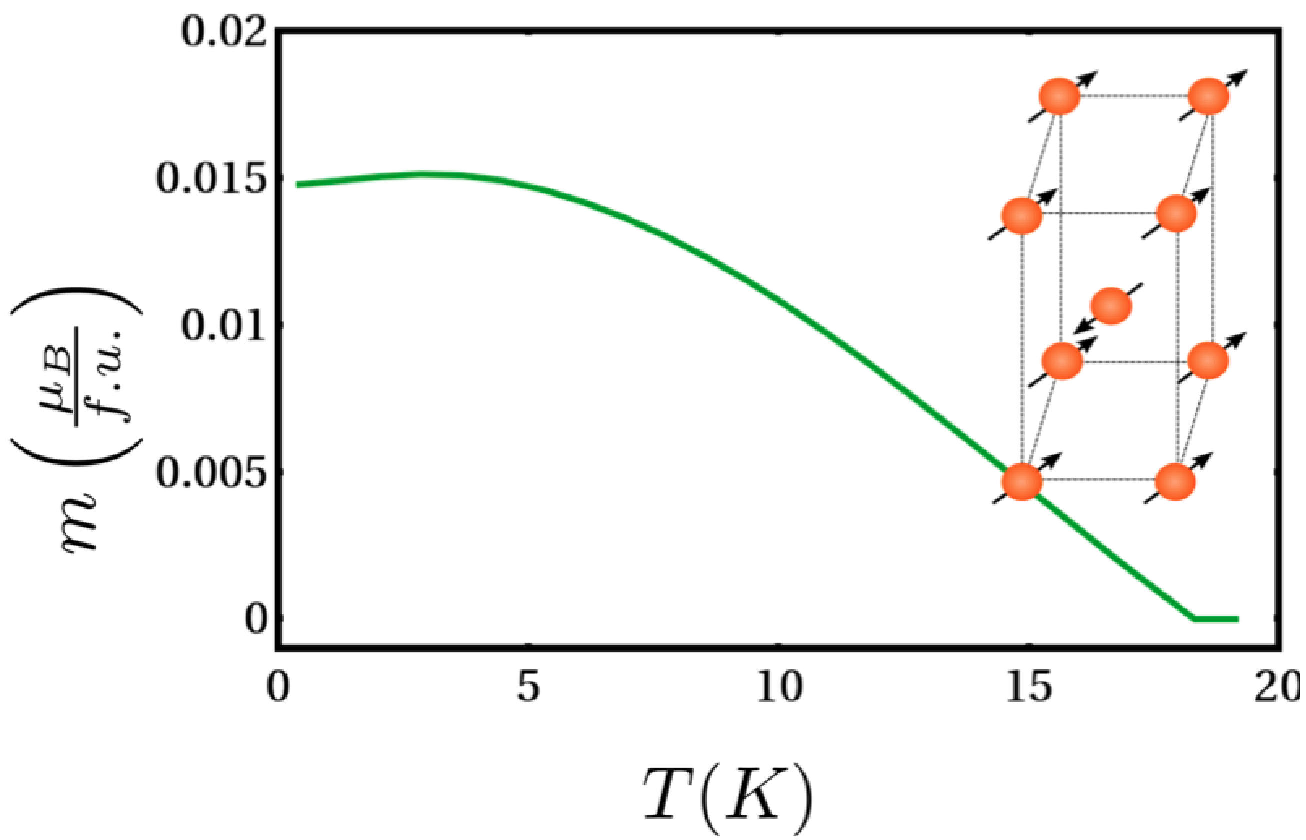


Predictions.

(a) Transverse moment in conduction sea
m~ O(TK/D)~ 0.01$\mu\mu_B$



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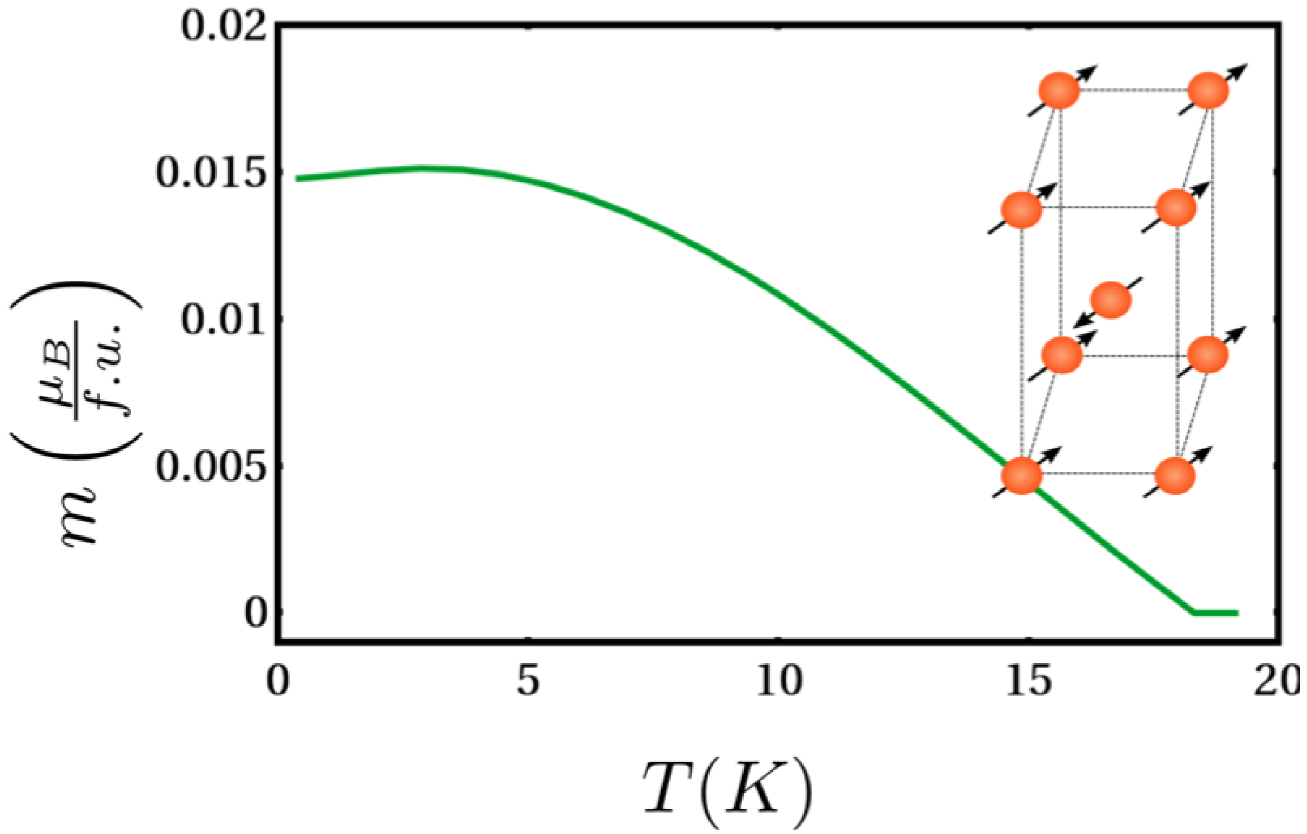
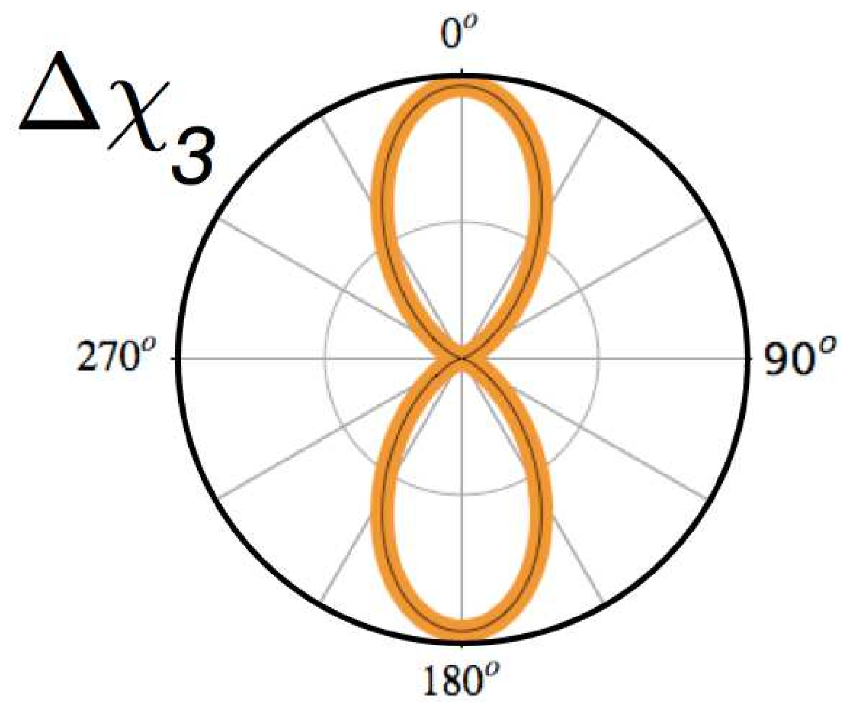


(b) Giant non-linear susceptibility anomaly.



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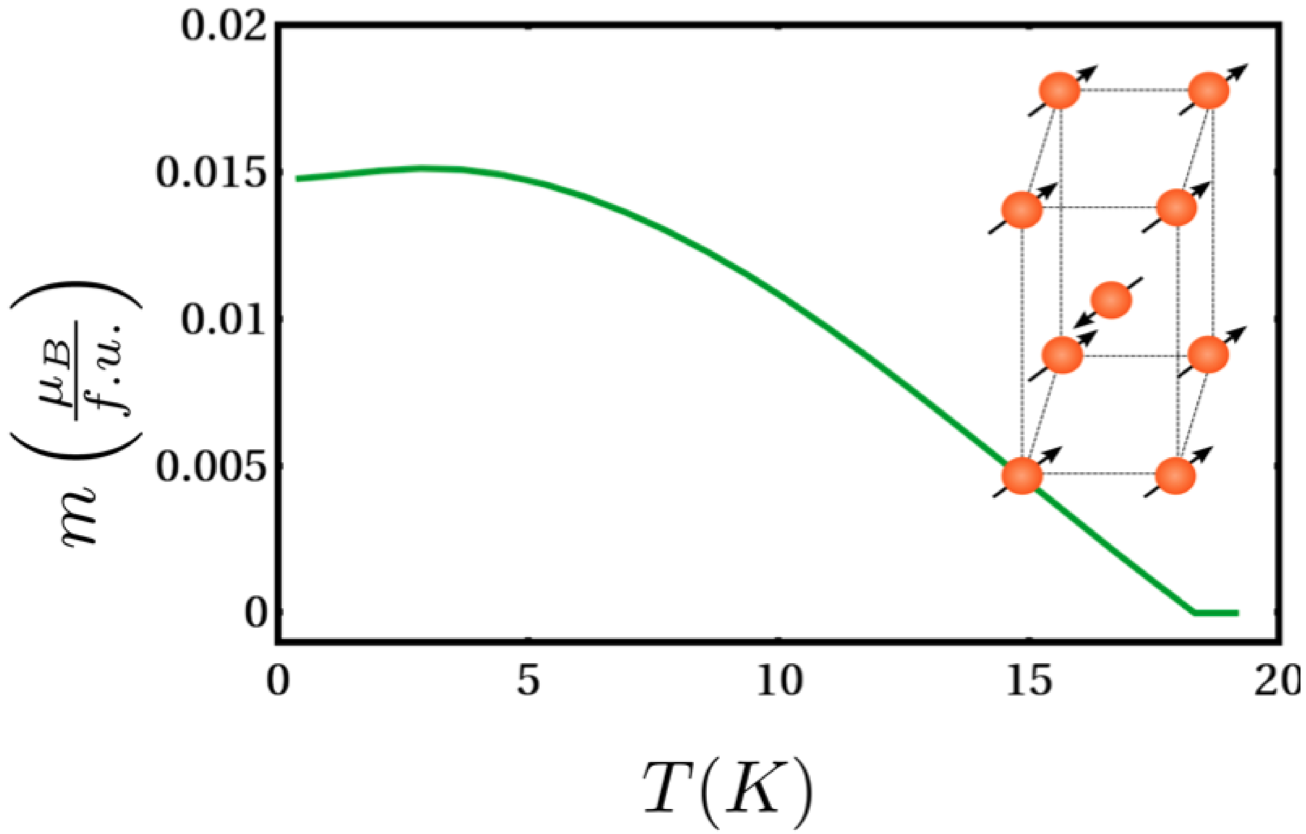

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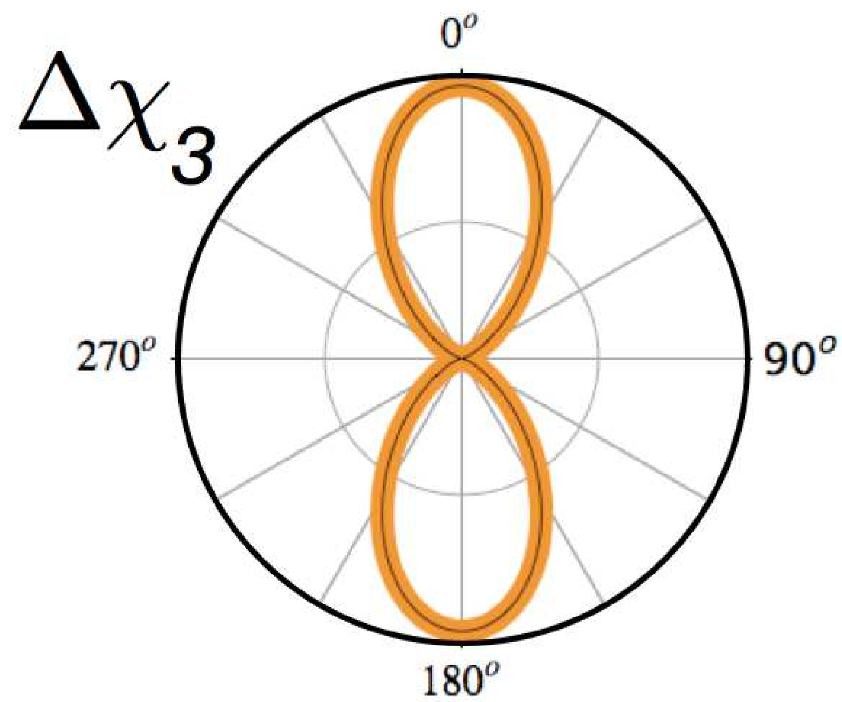
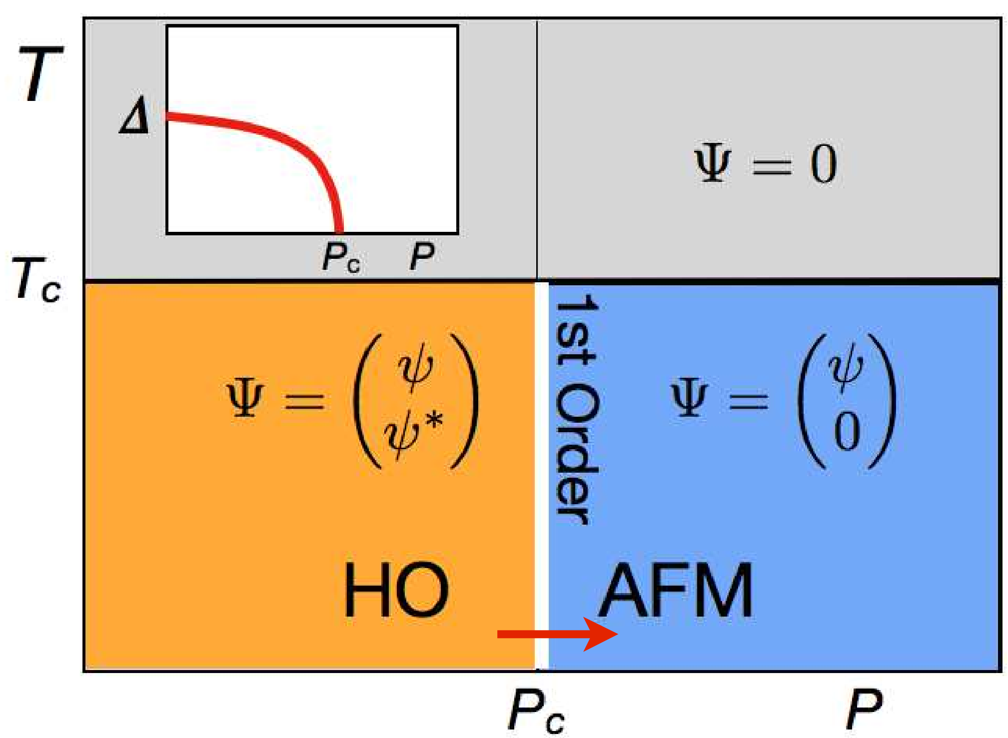
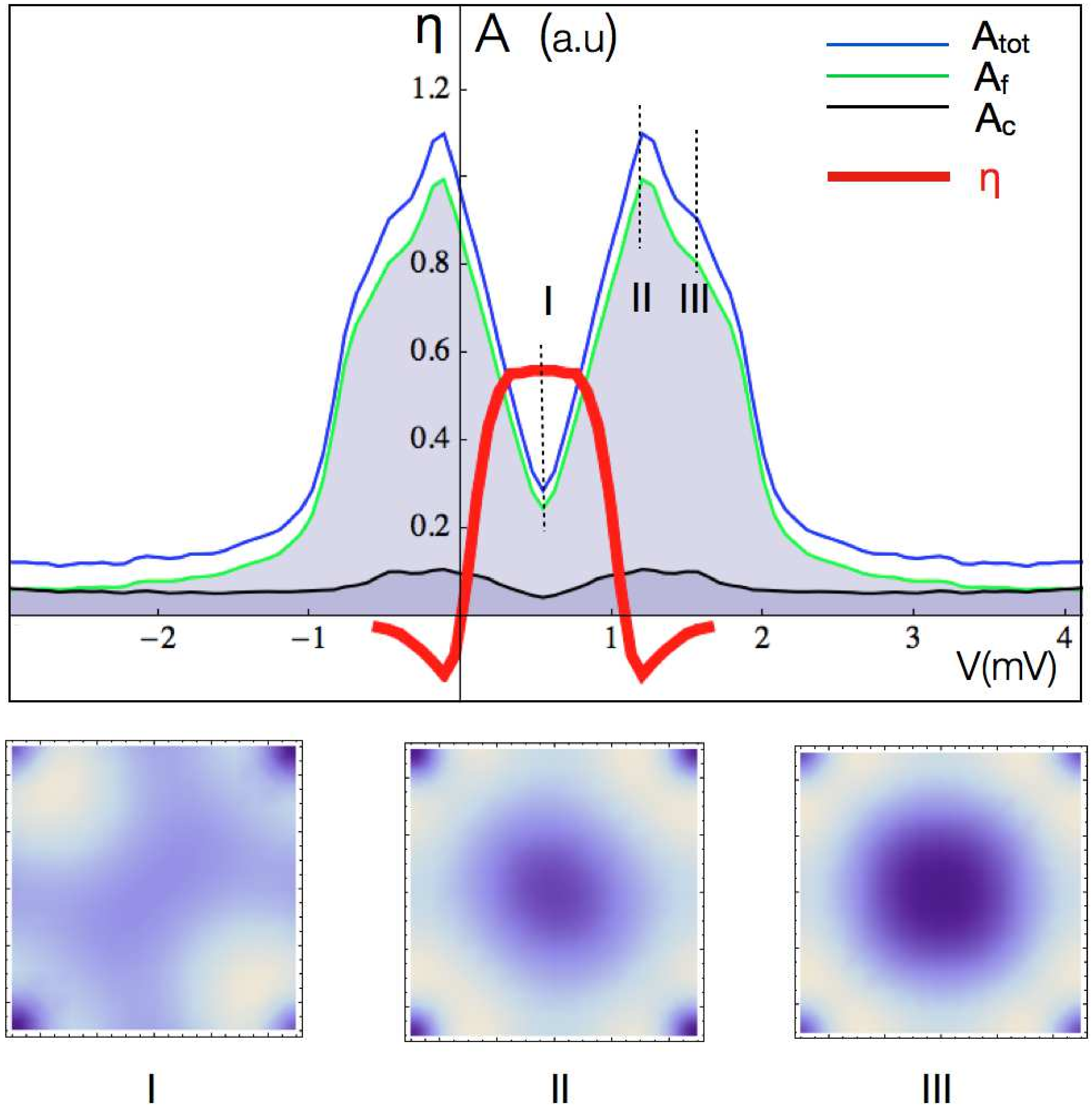




(c) Collapse of gap to Ising fluctuations at 1st order transition line.

(d) Resonant Nematicity in STM



Conclusions about Hidden Order in URu2Si2.

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