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TOPNES Meeting, Higgs Centre
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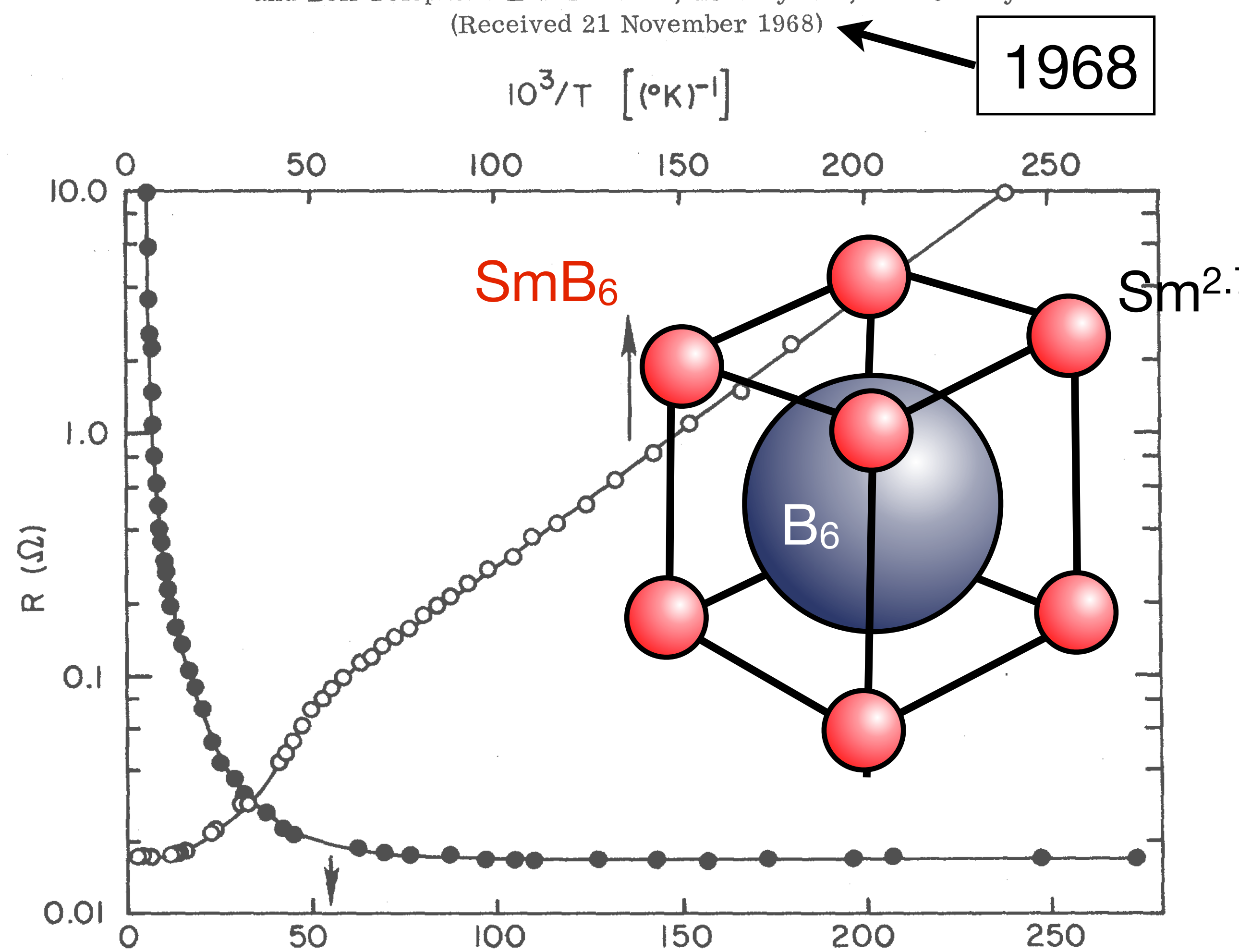

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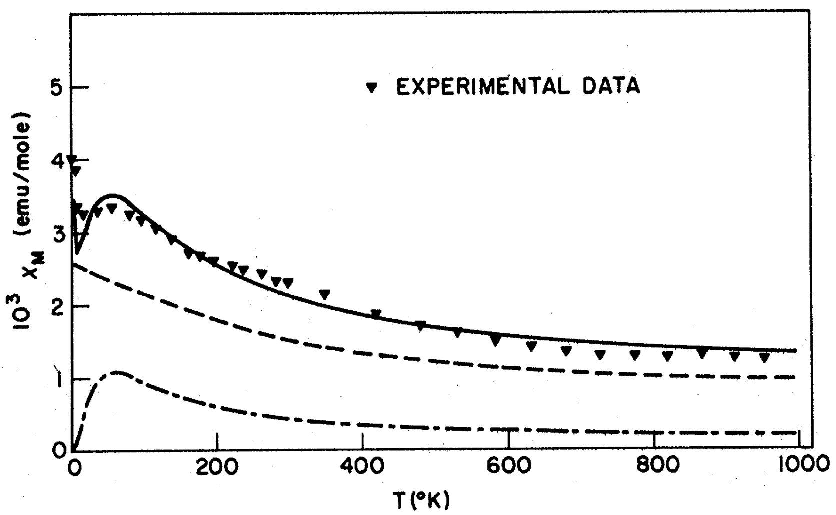

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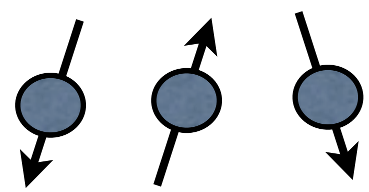

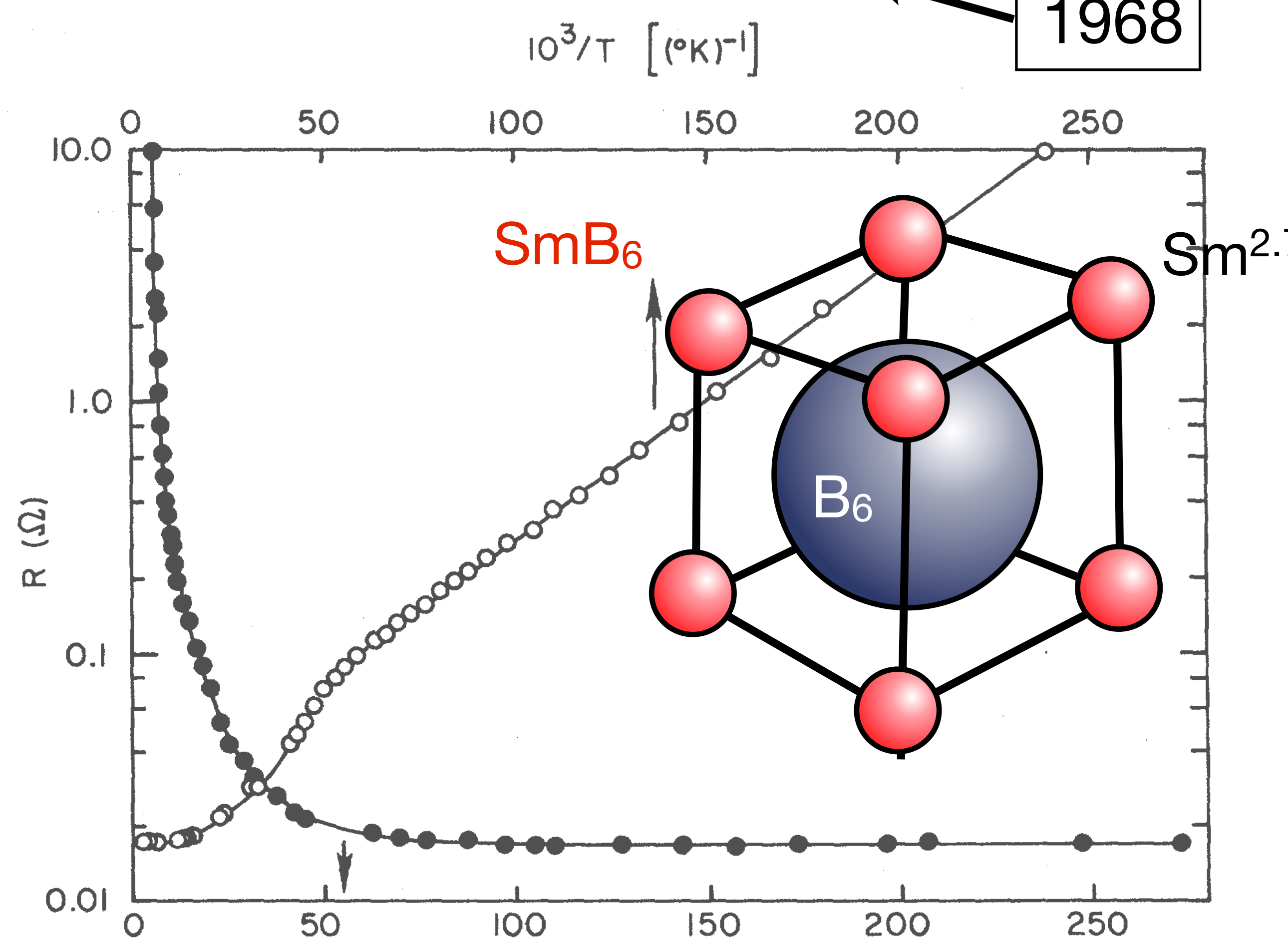

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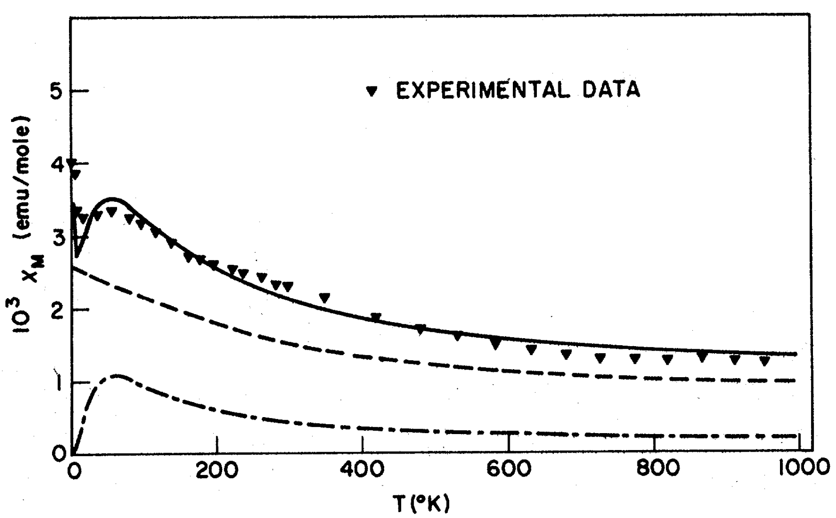
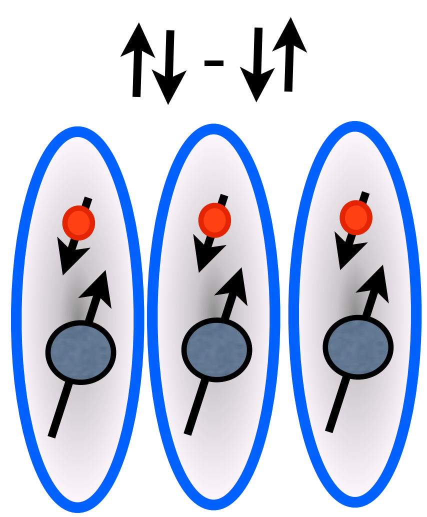
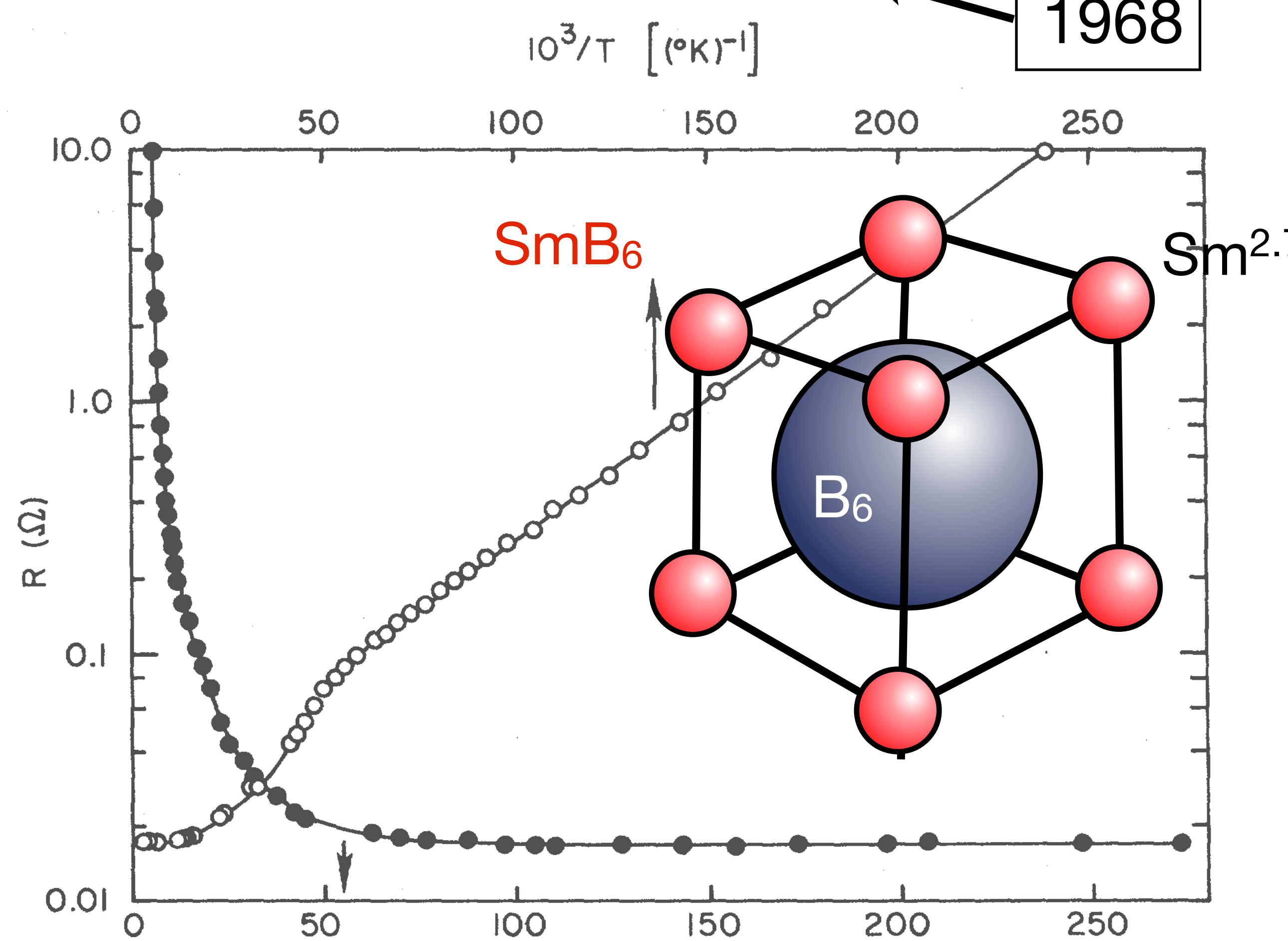




"Kondo Insulator"



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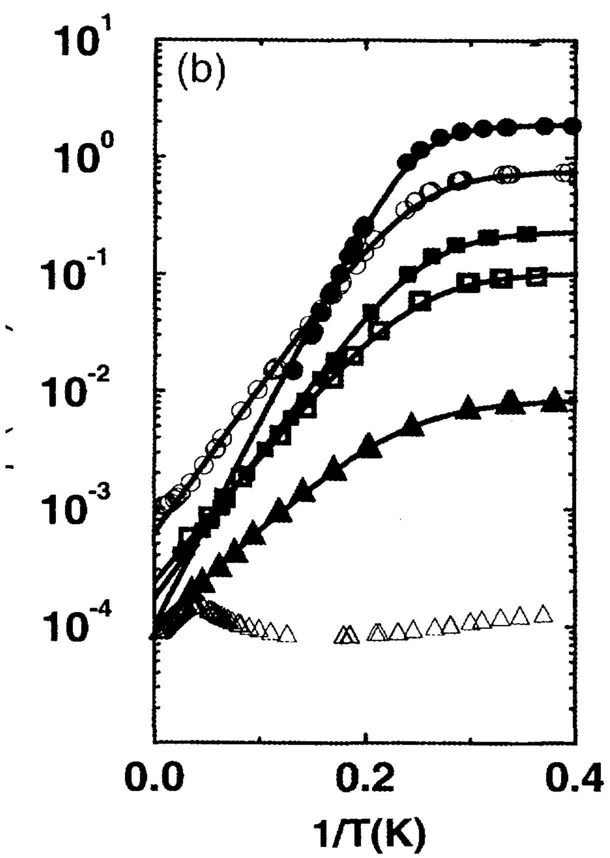
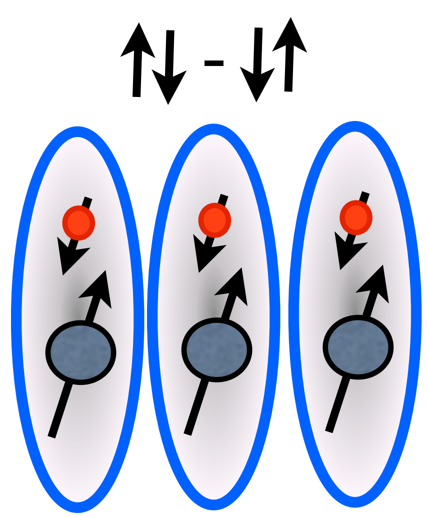
Persistent conductivity

Cooleyet al (1995)





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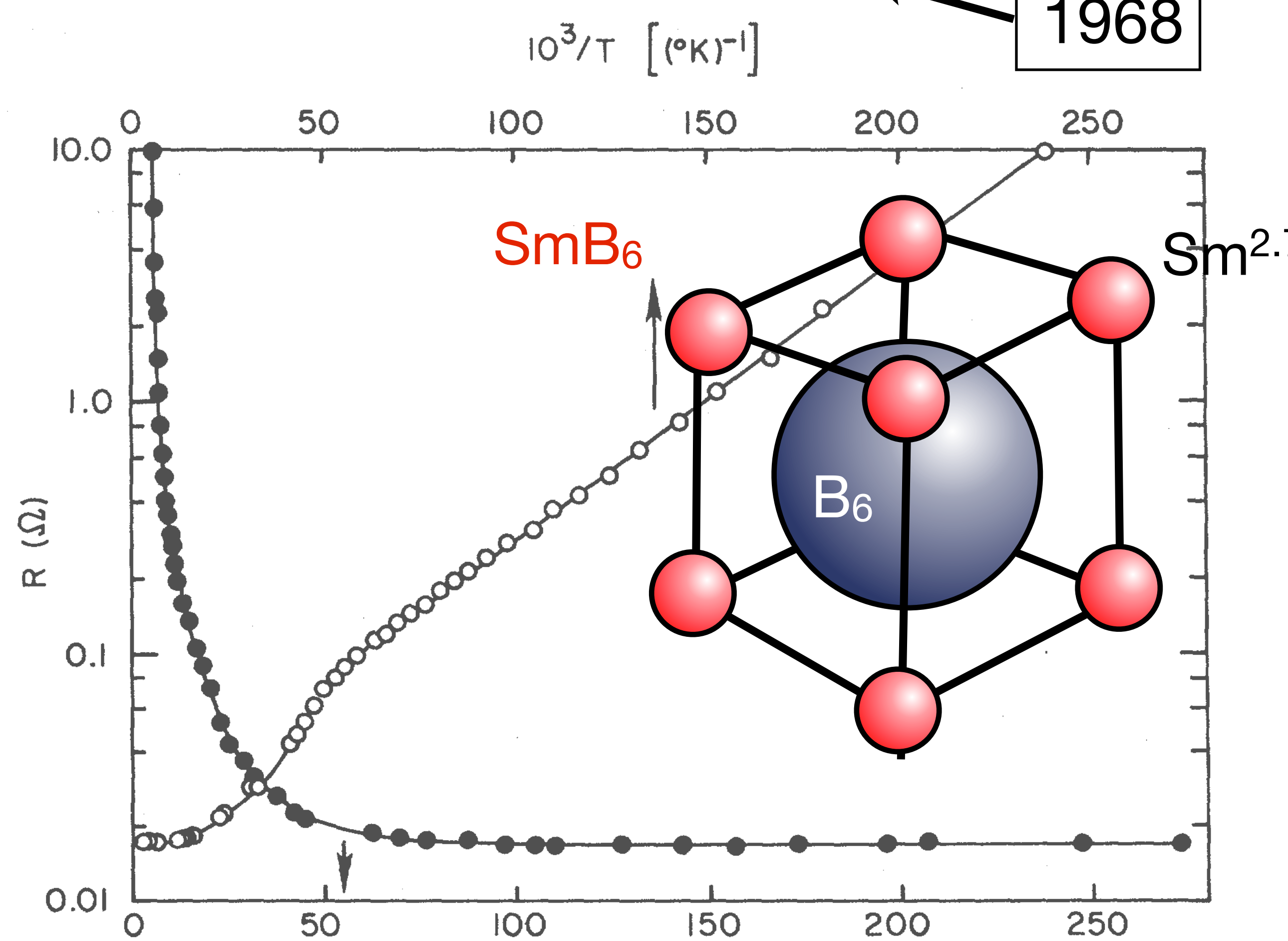

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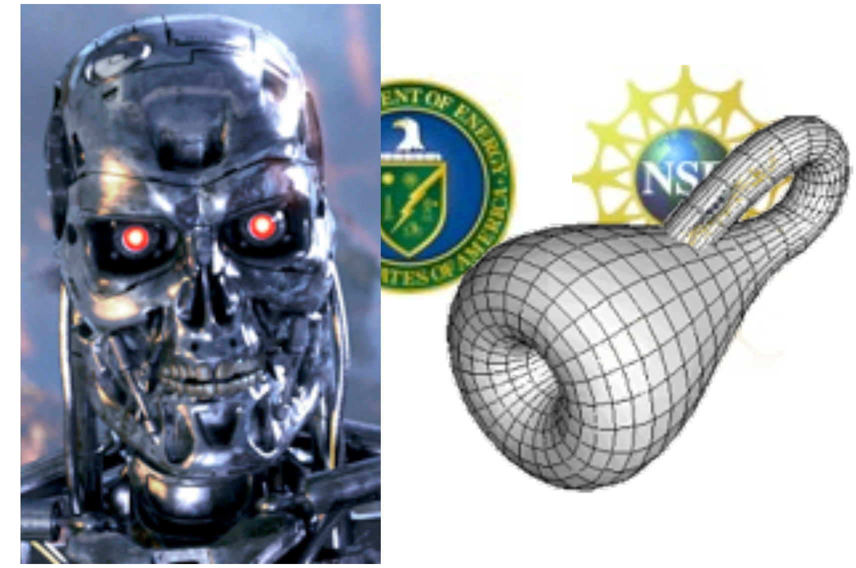

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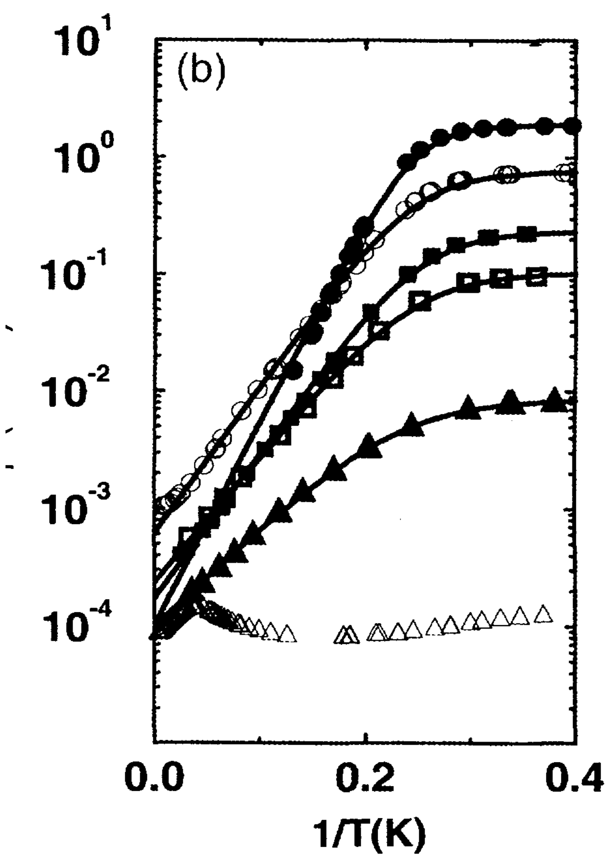

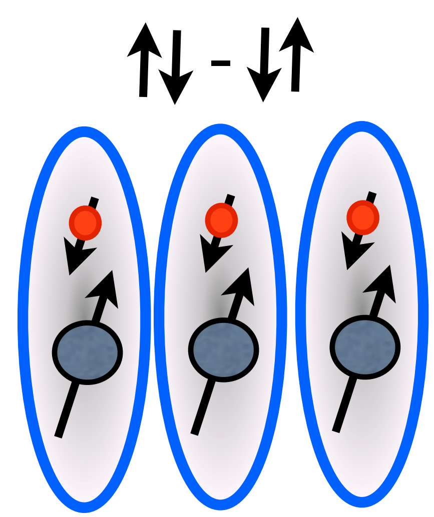

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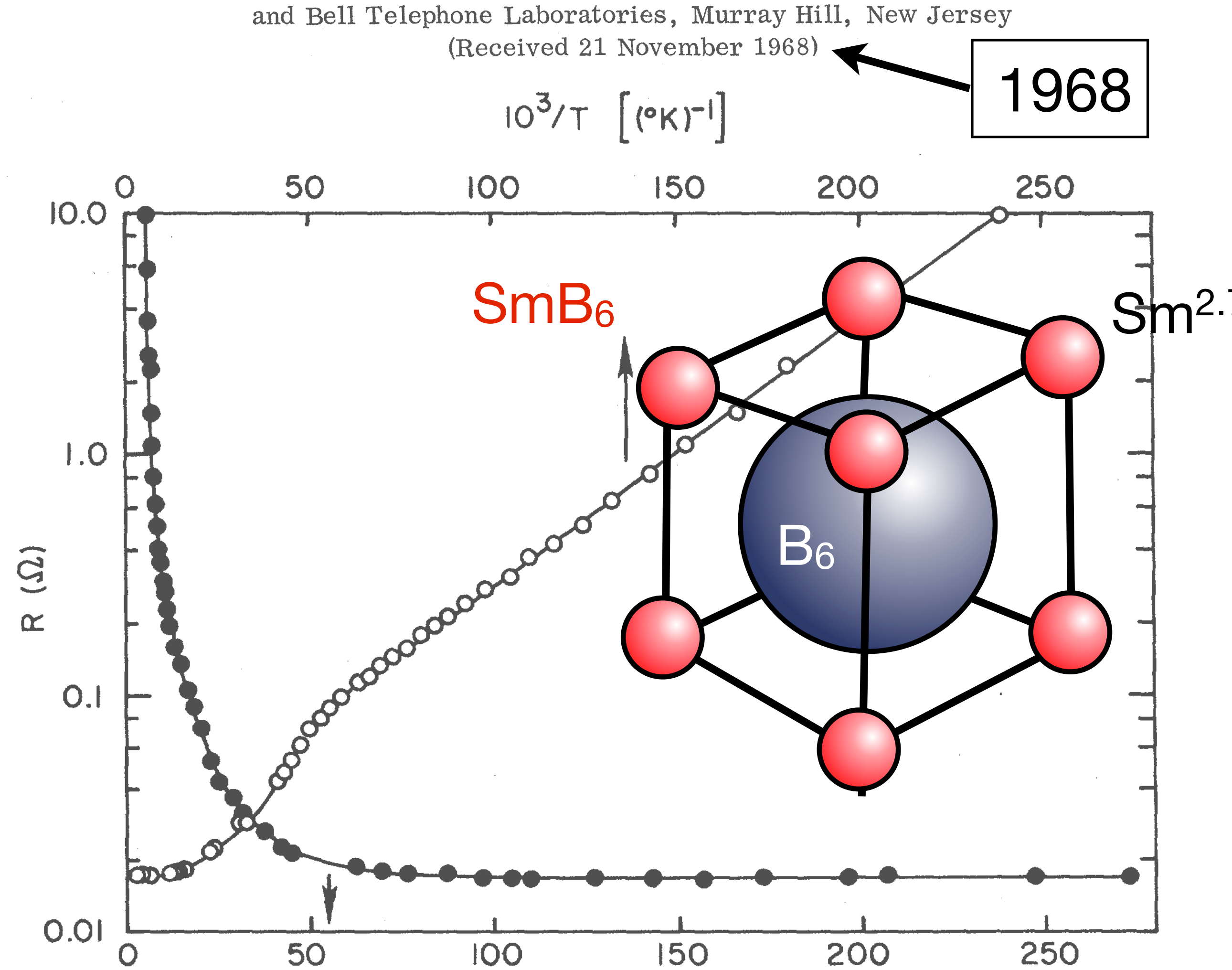

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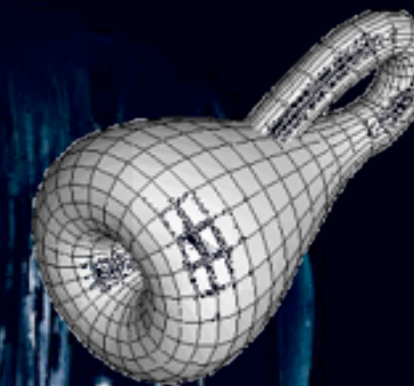

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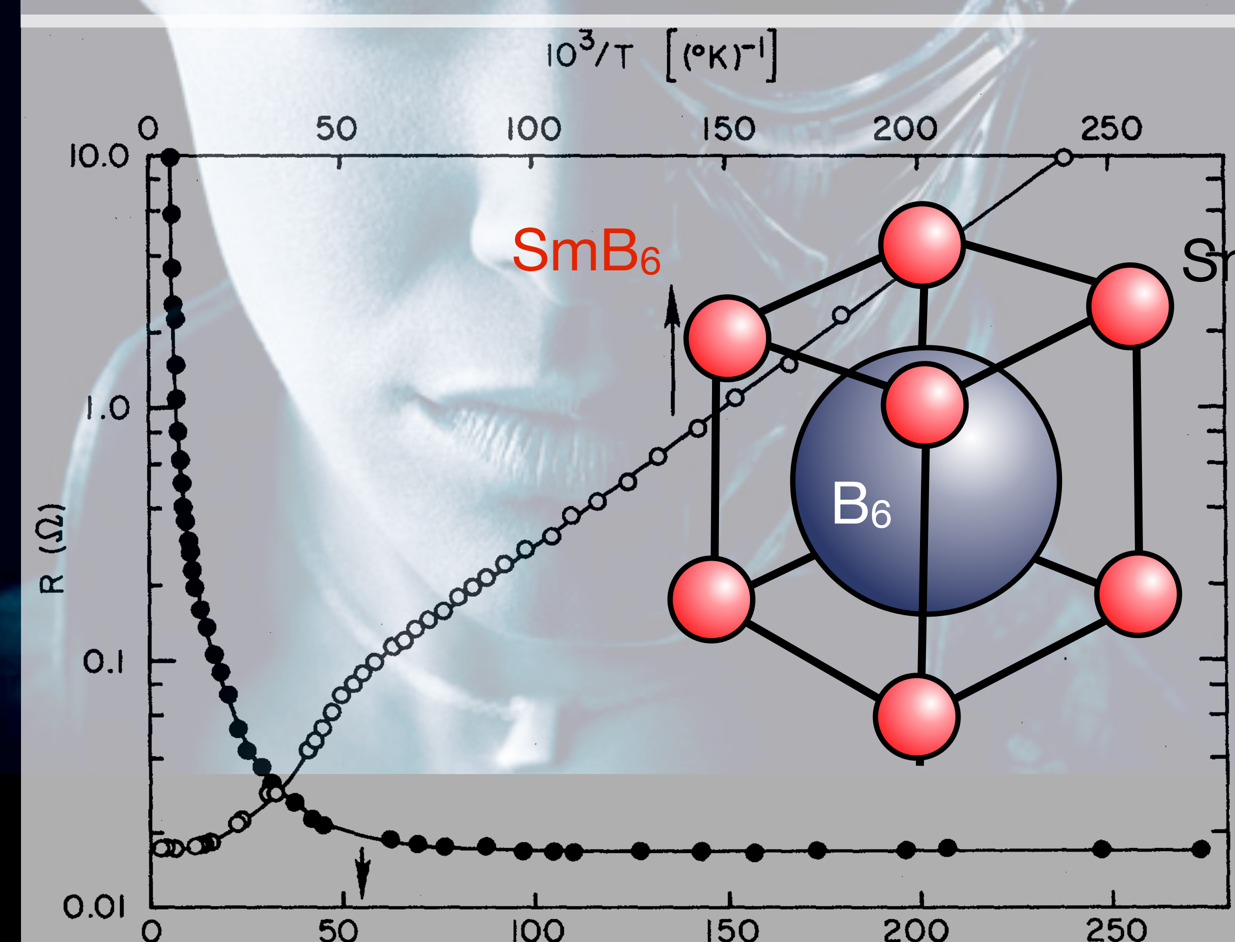

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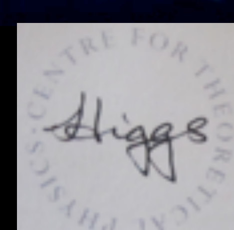

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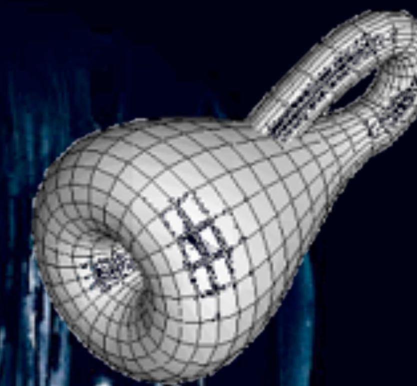

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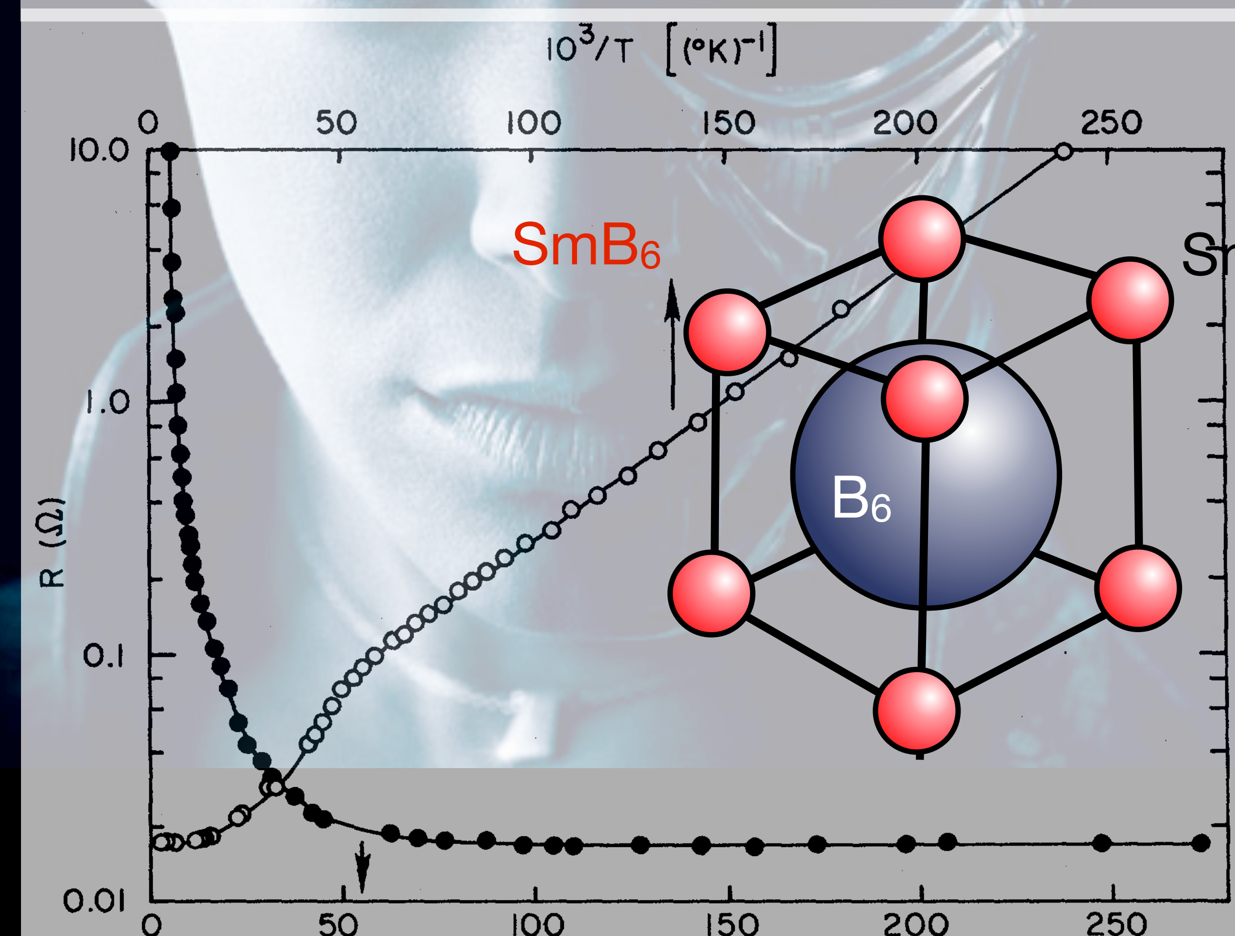

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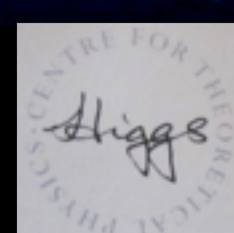

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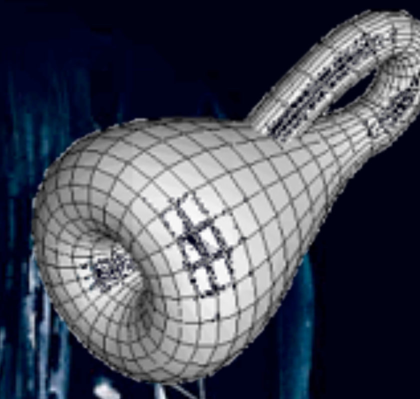

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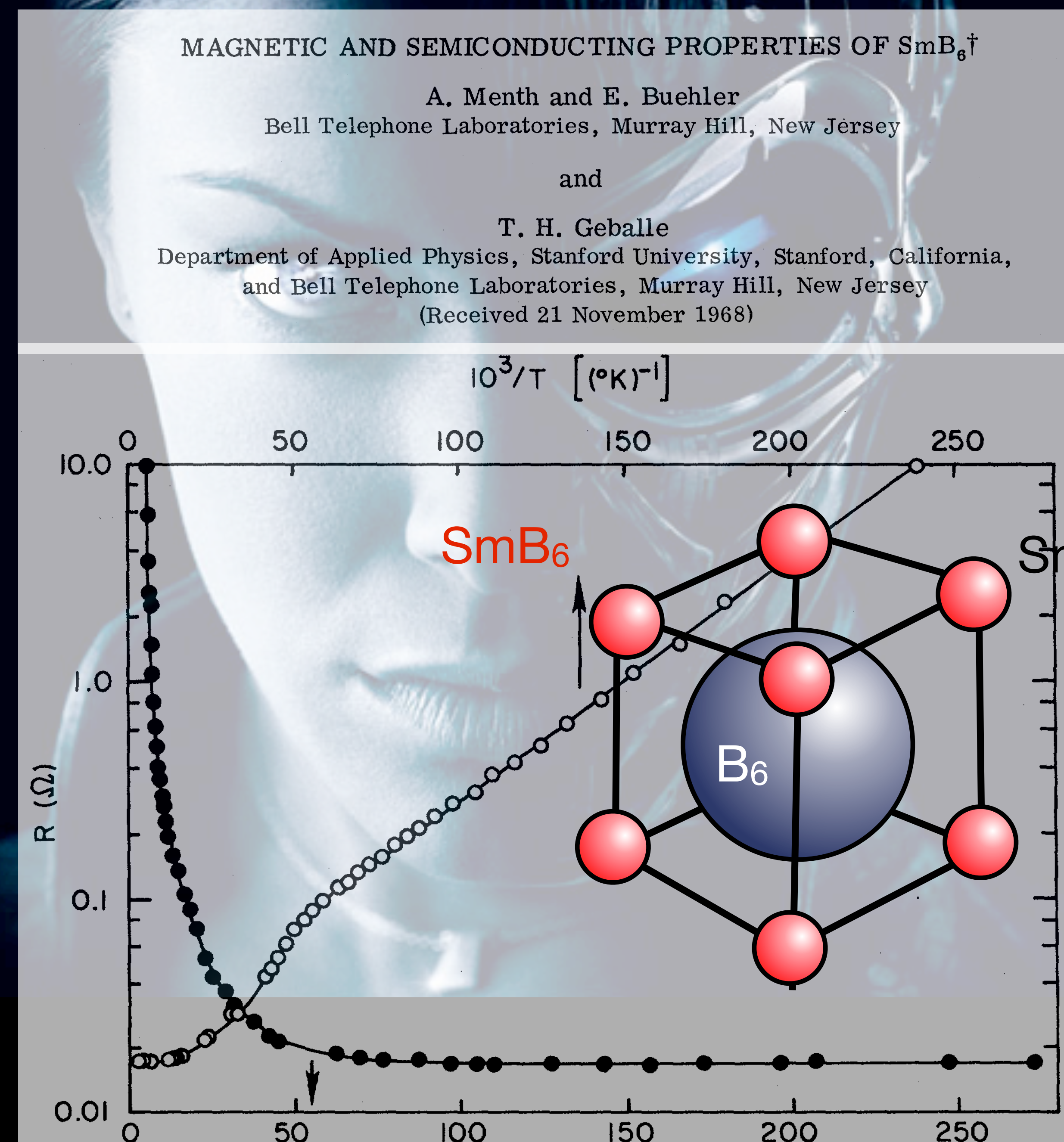
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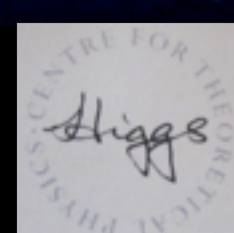

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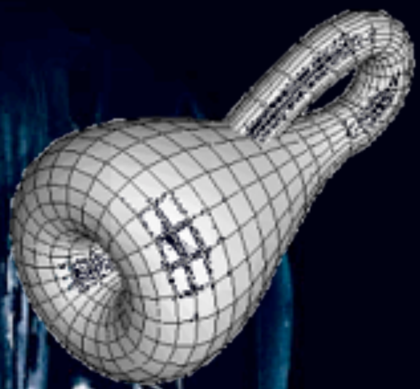

- Kondo insulators.
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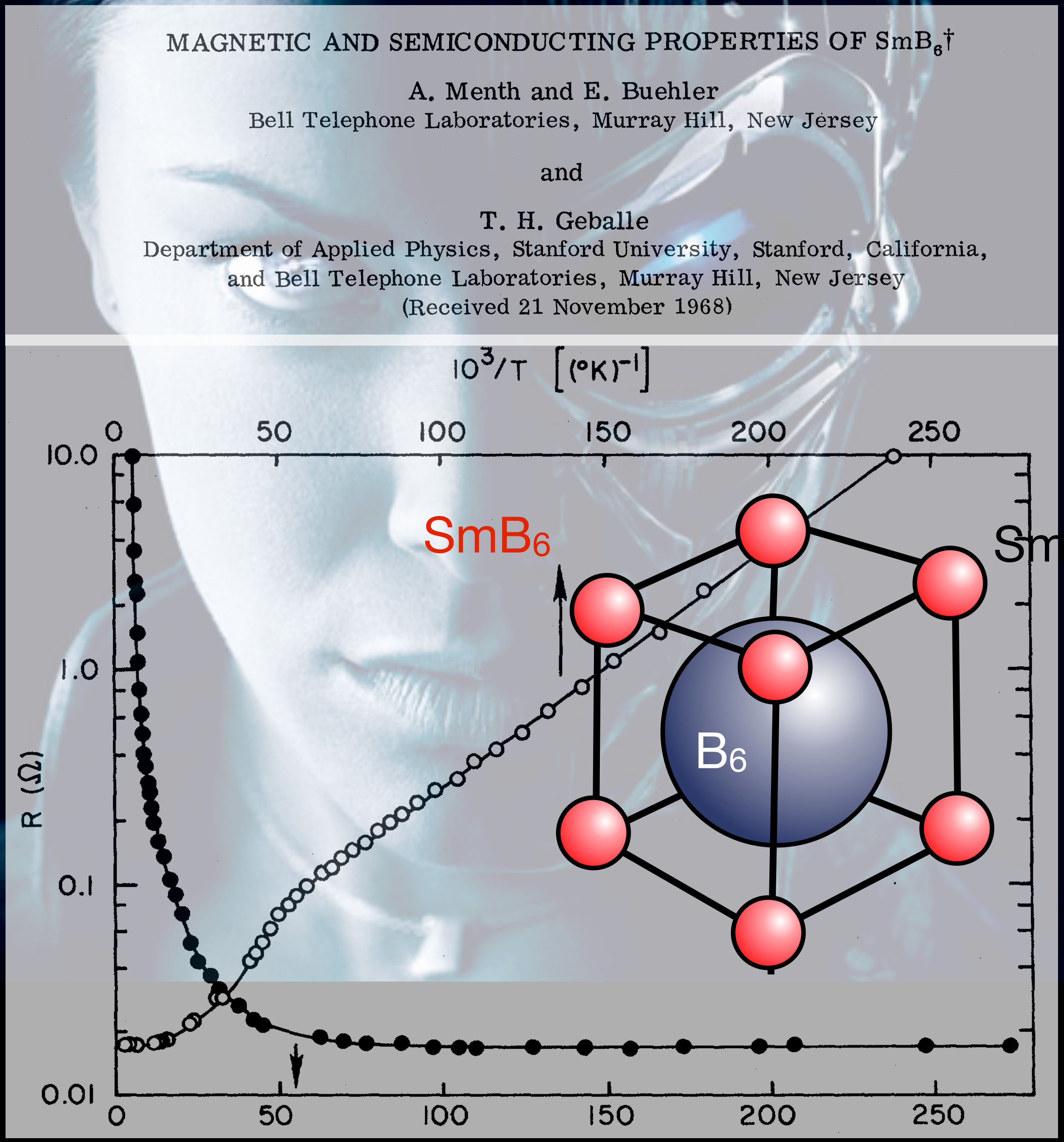
- β-$YbAlB_4$: intrinsic QC metal.
- YbAuAl: Kondo Quasicrystal.



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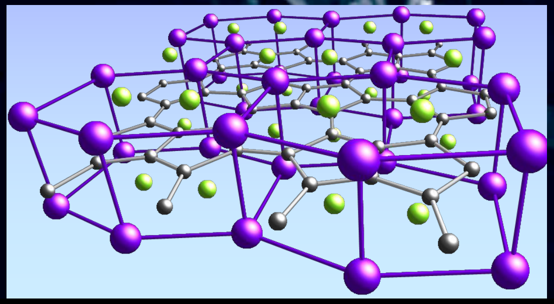

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Victor Galitski	Maryland
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Condensed Matter > Strongly Correlated Electrons

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(Submitted on 21 Nov 2012 (v1), last revised 27 Nov 2012 (this version, v2))

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Alexei Tsvelik	Brookhaven NL
Satoru Nakatsuji	ISSP Tokyo
Yosuke Matsumoto	ISSP Tokyo
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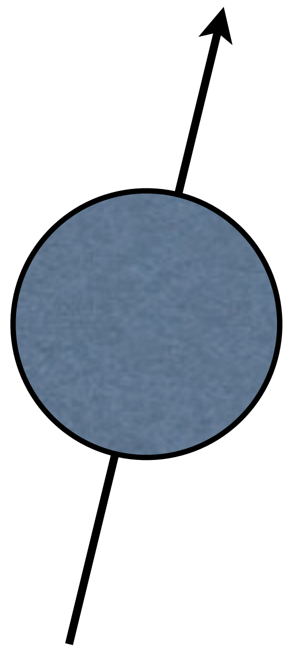
Heavy Fermion Primer



Spin (4f,5f): basic fabric of heavy electron physics.

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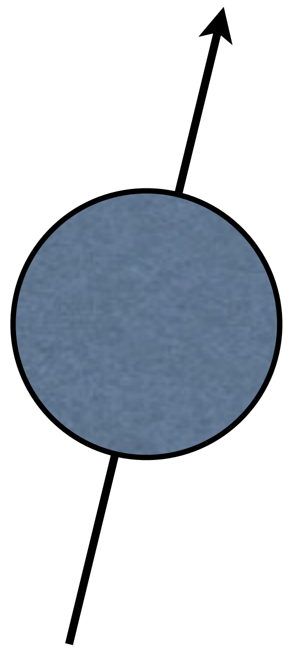

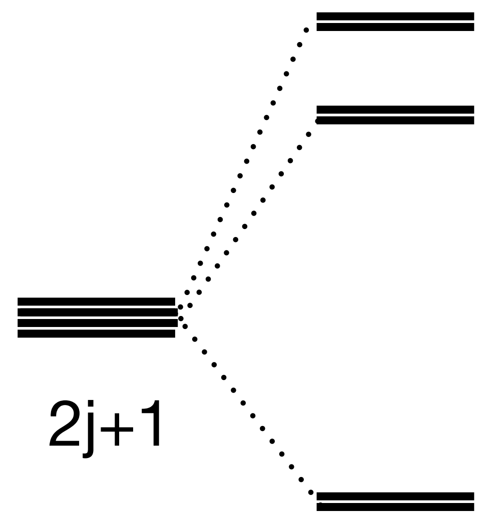

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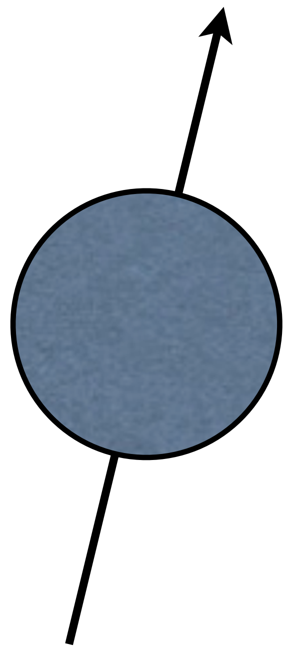

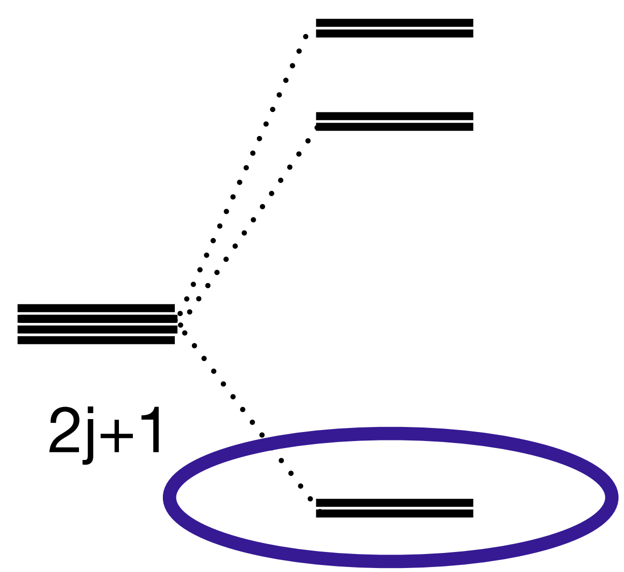

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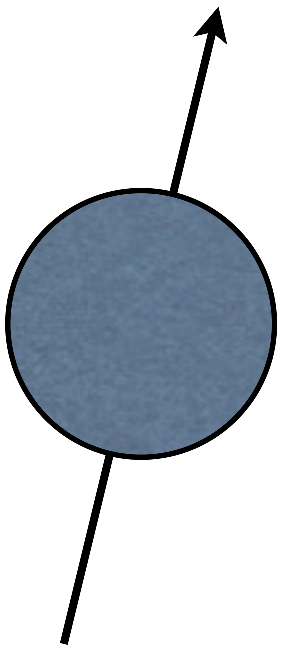

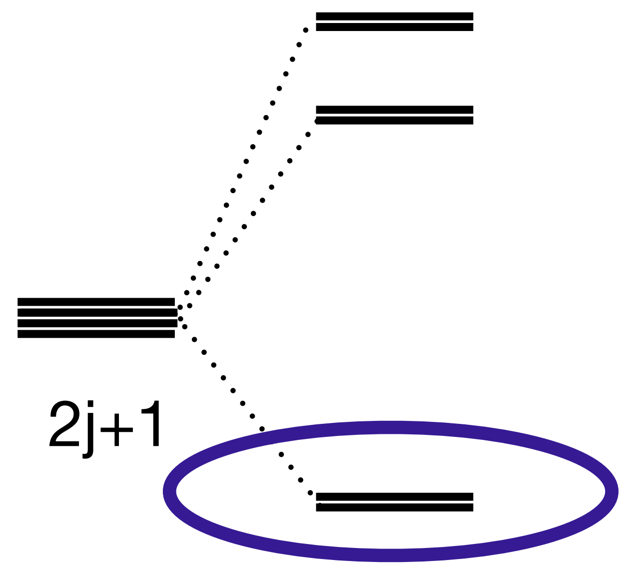

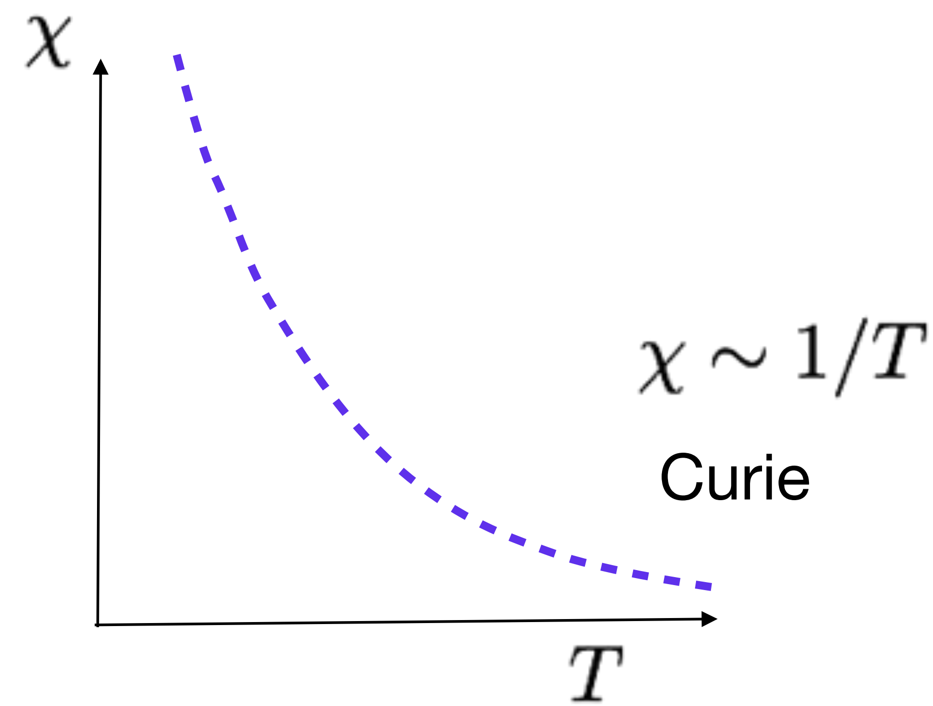

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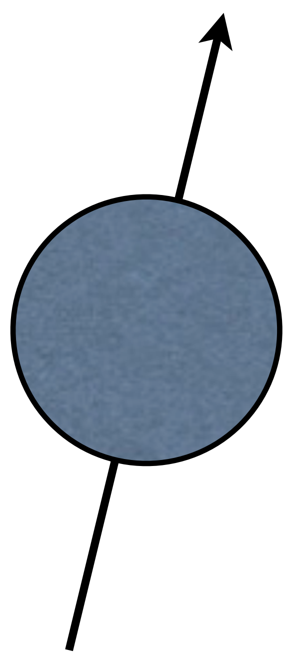

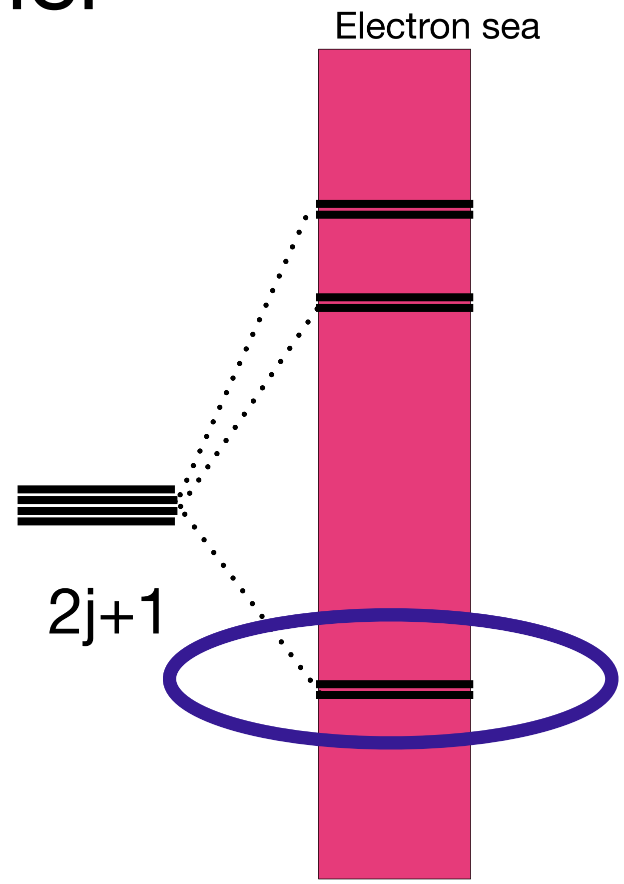

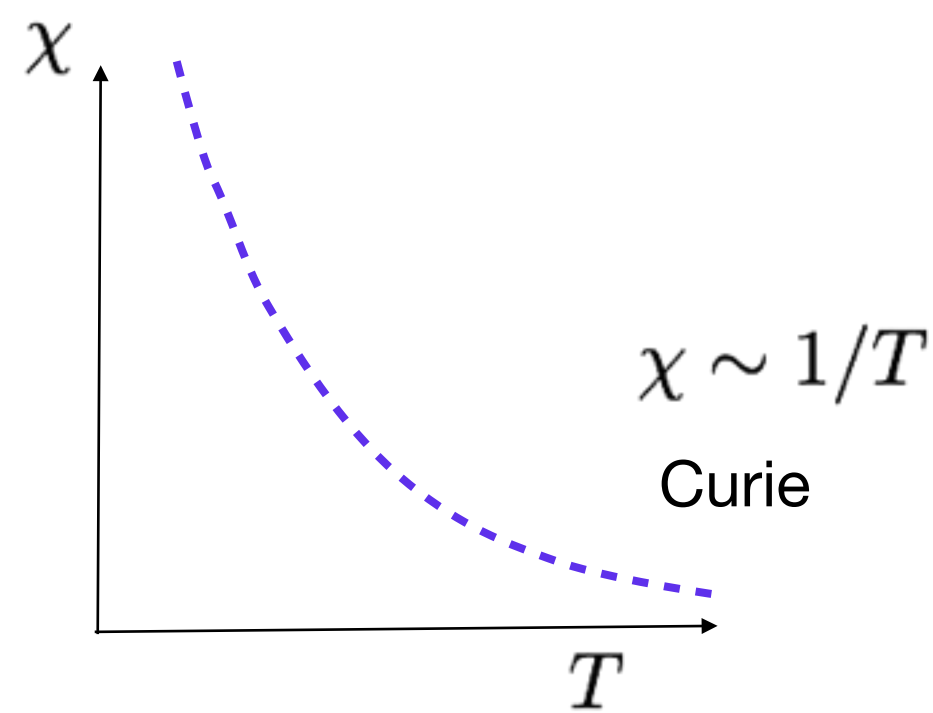

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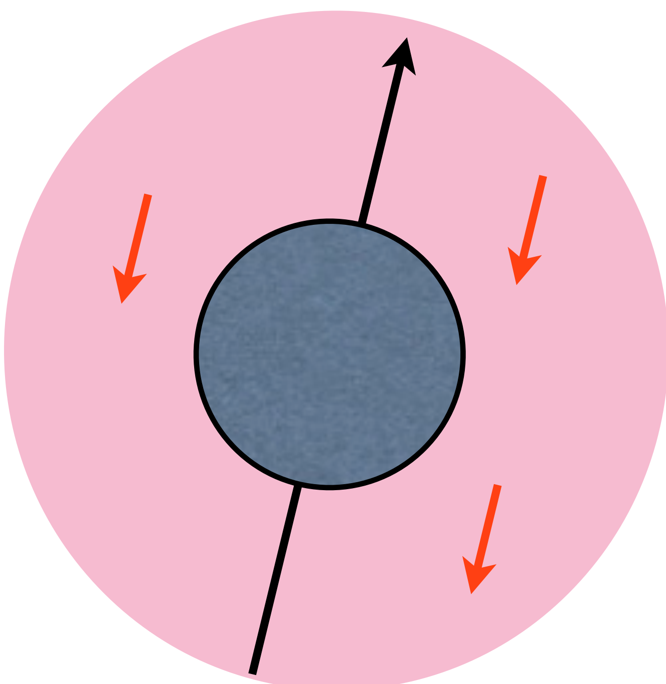
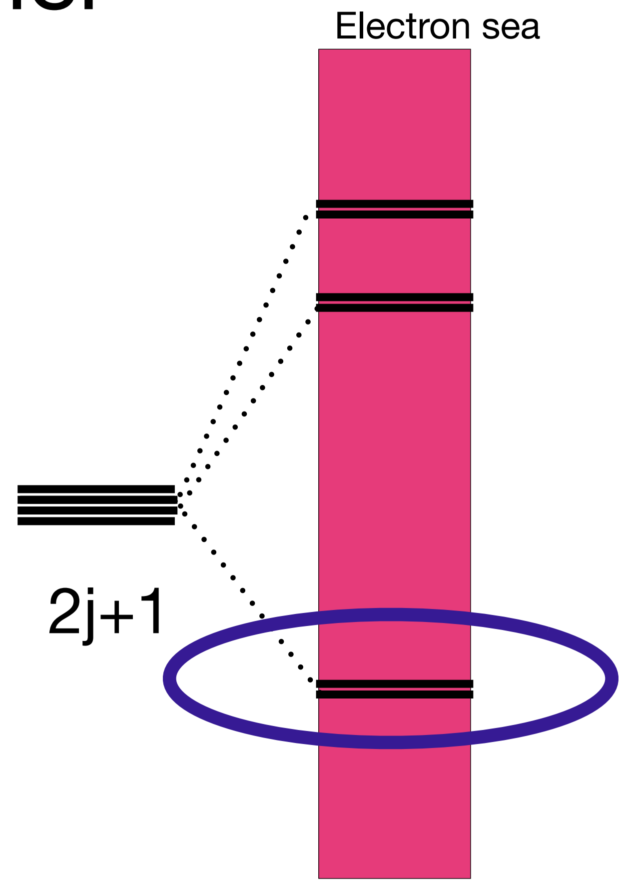
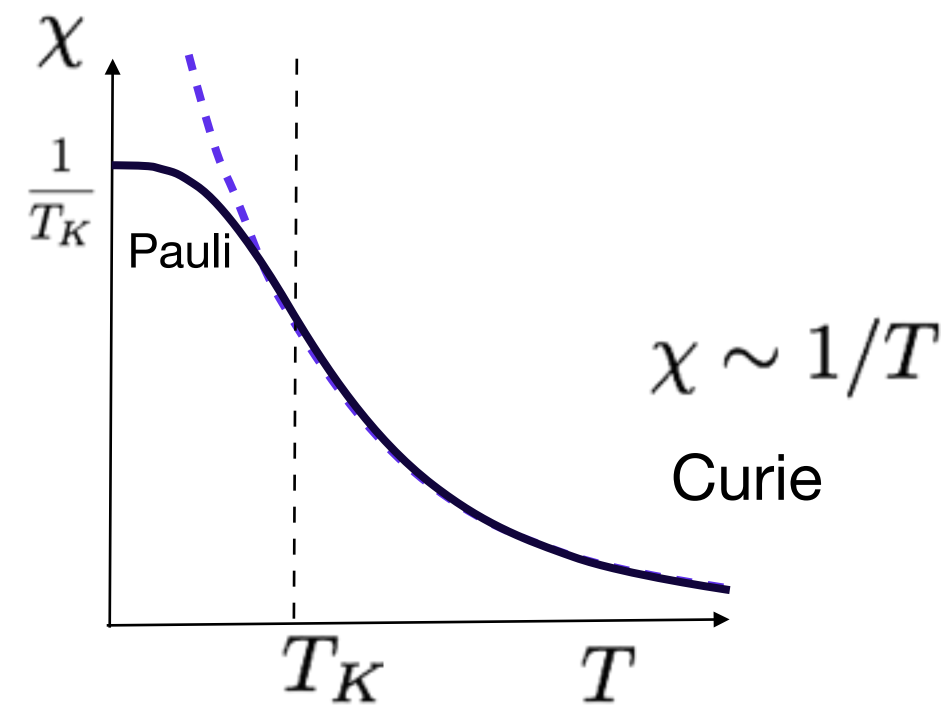


Spin screened by conduction electrons





"Kondo temperature"

$$T_K = W\sqrt{J\rho}e^{-\frac{1}{2J\rho}}$$

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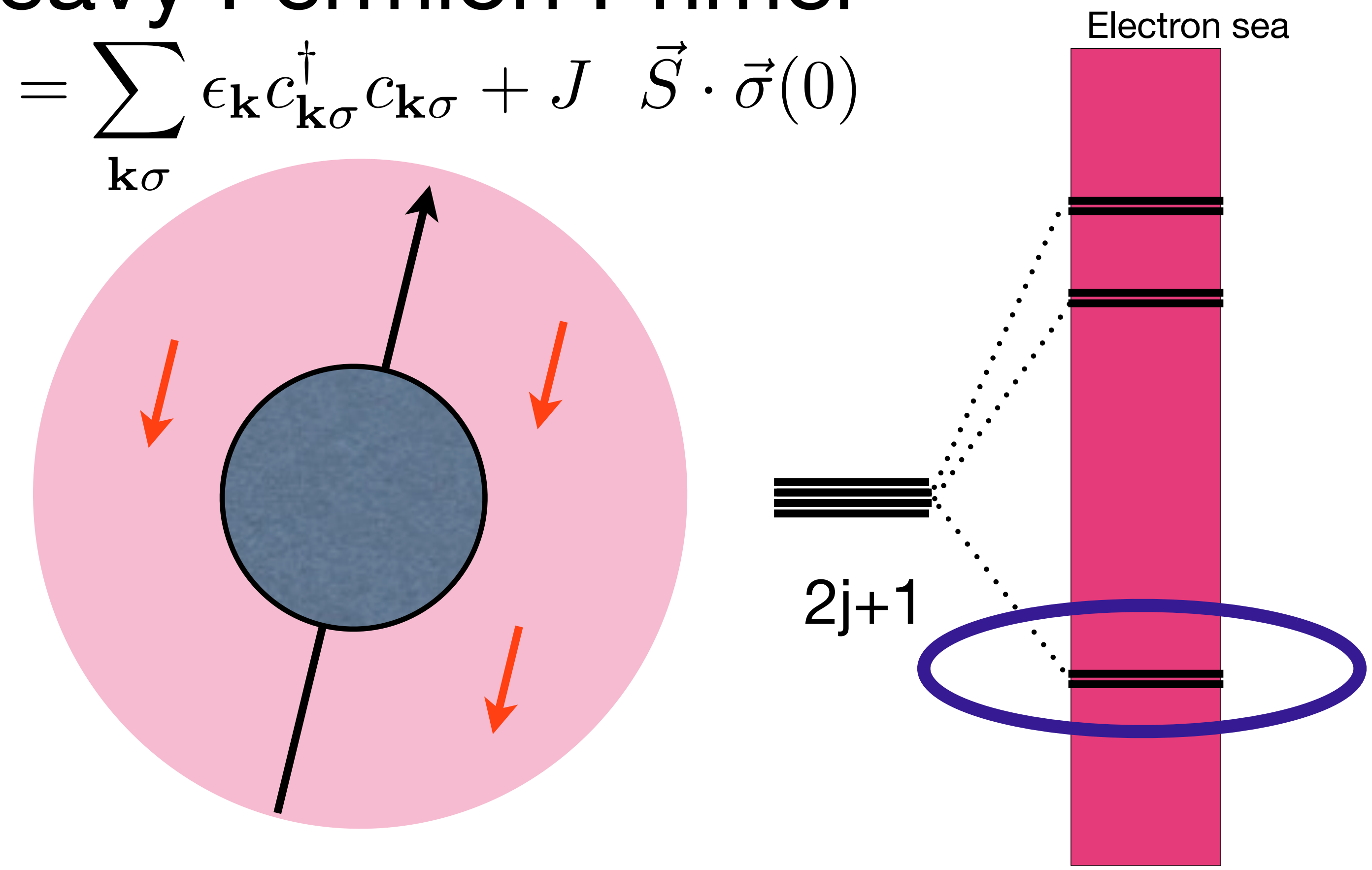

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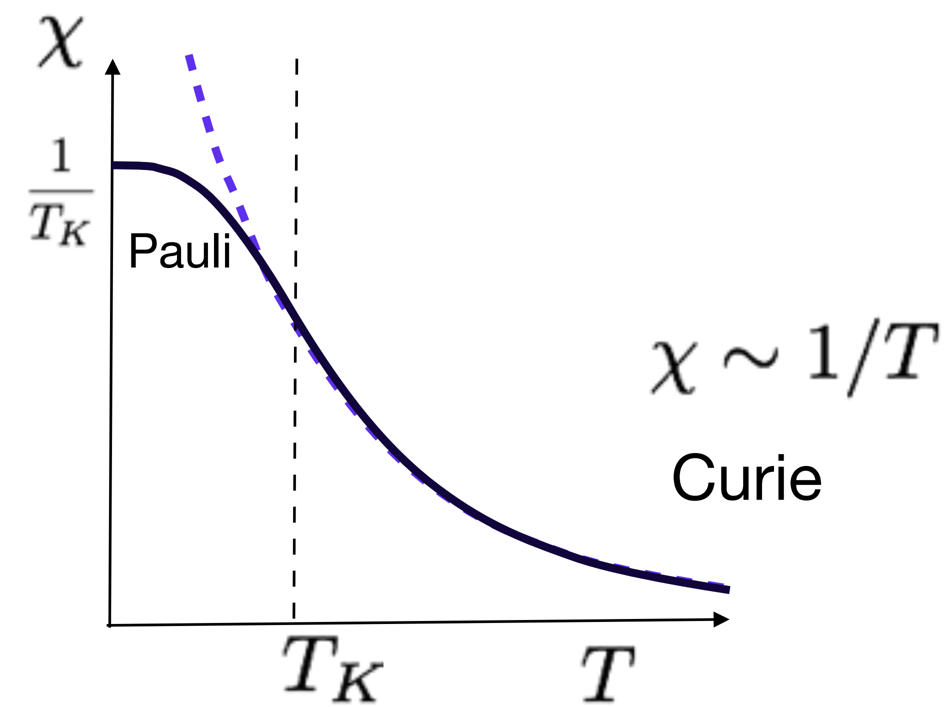

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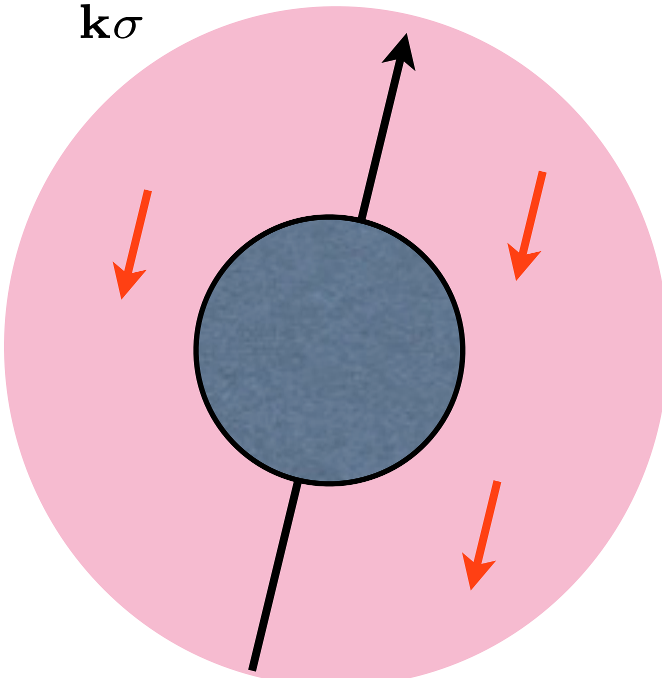

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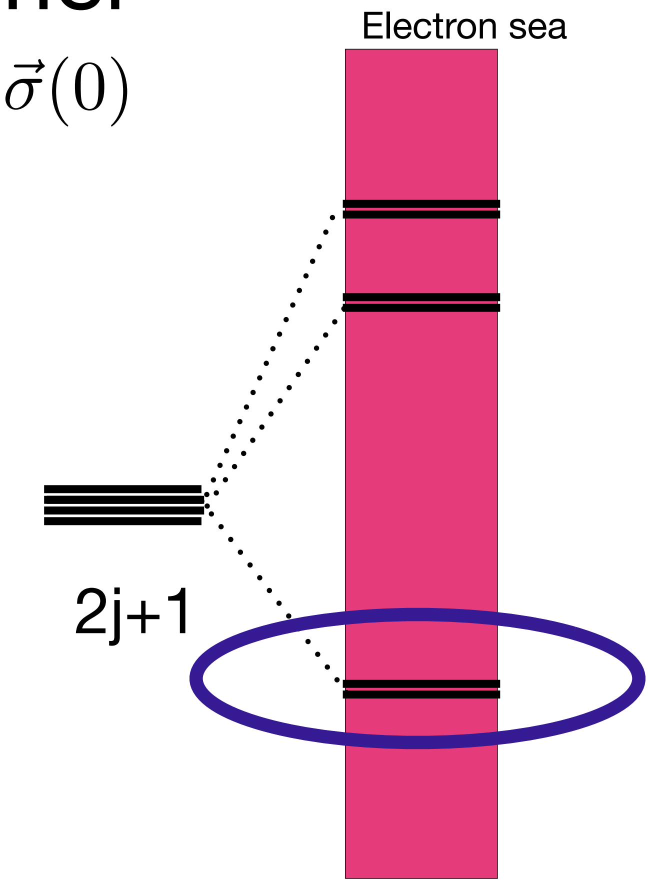

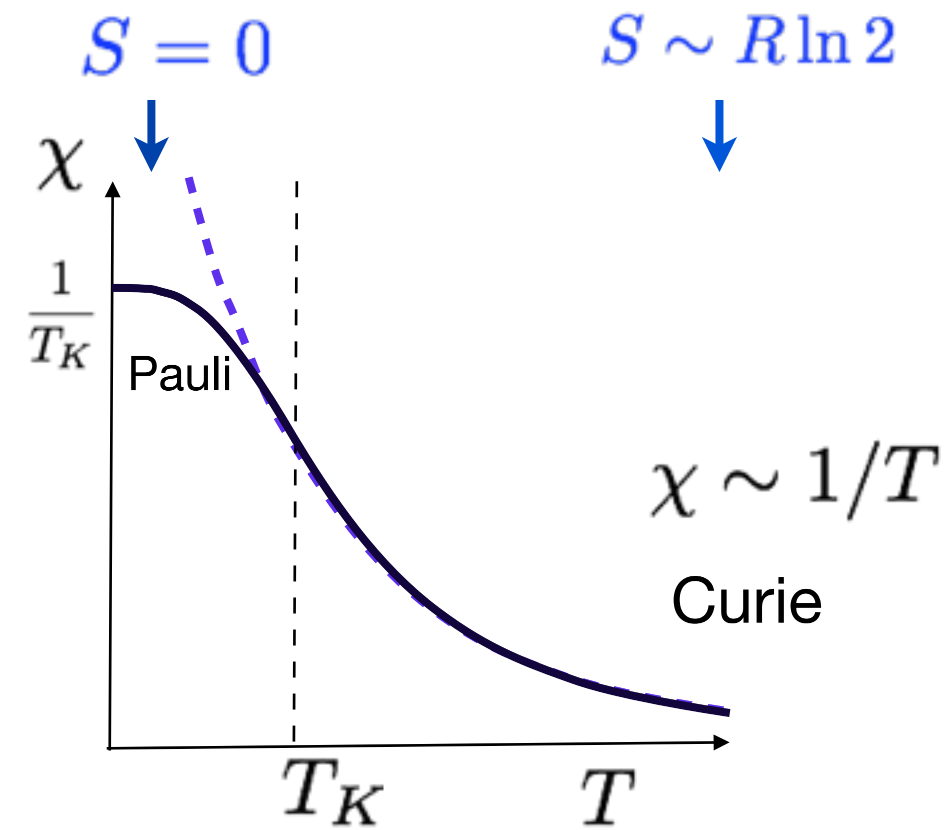

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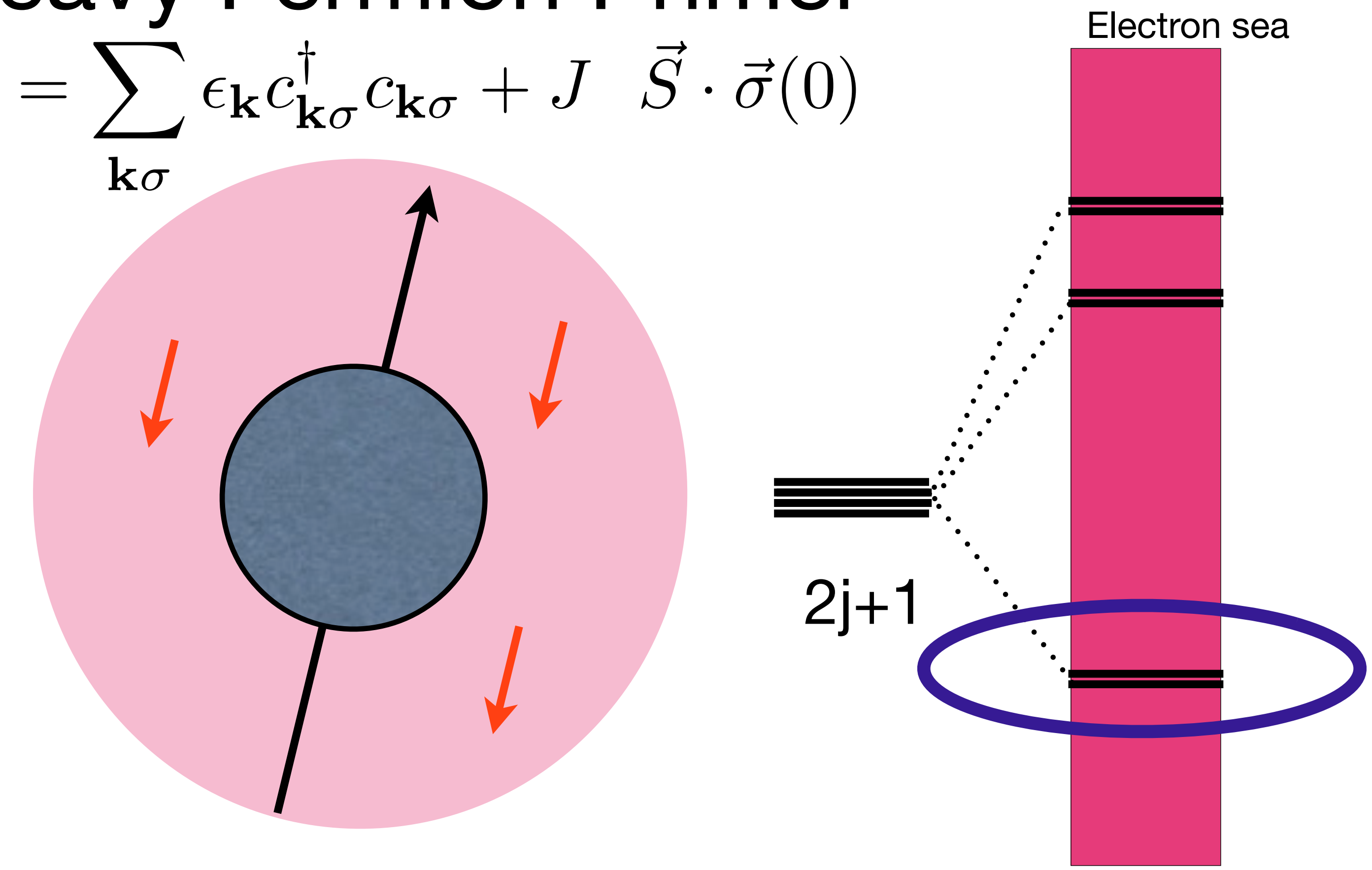

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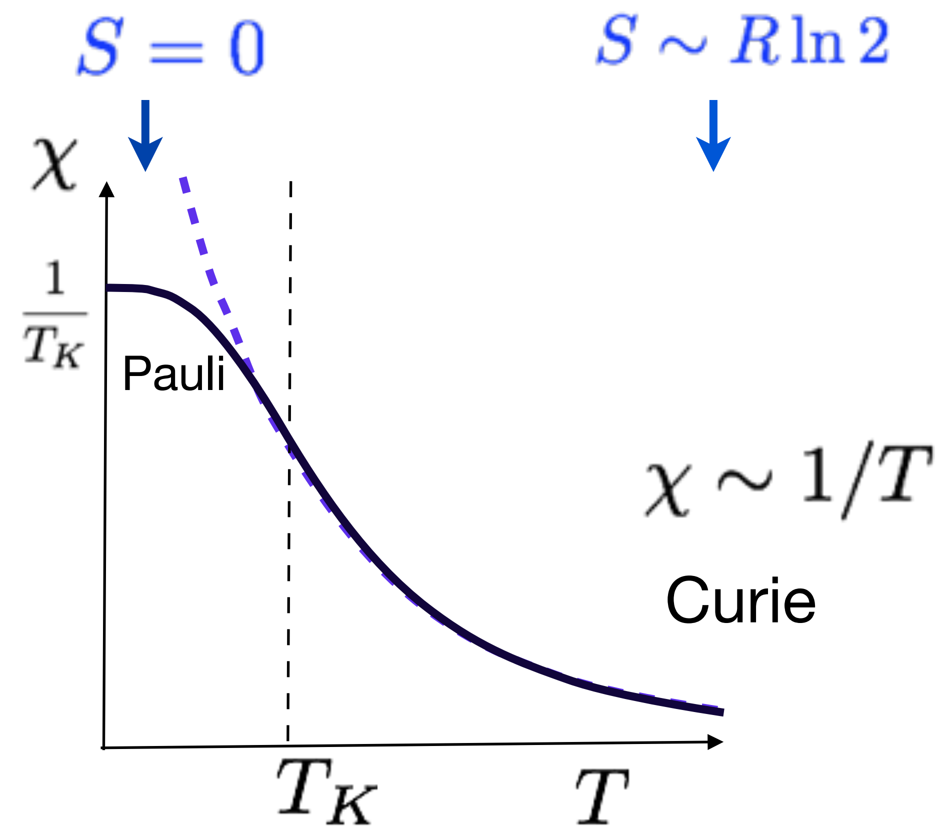

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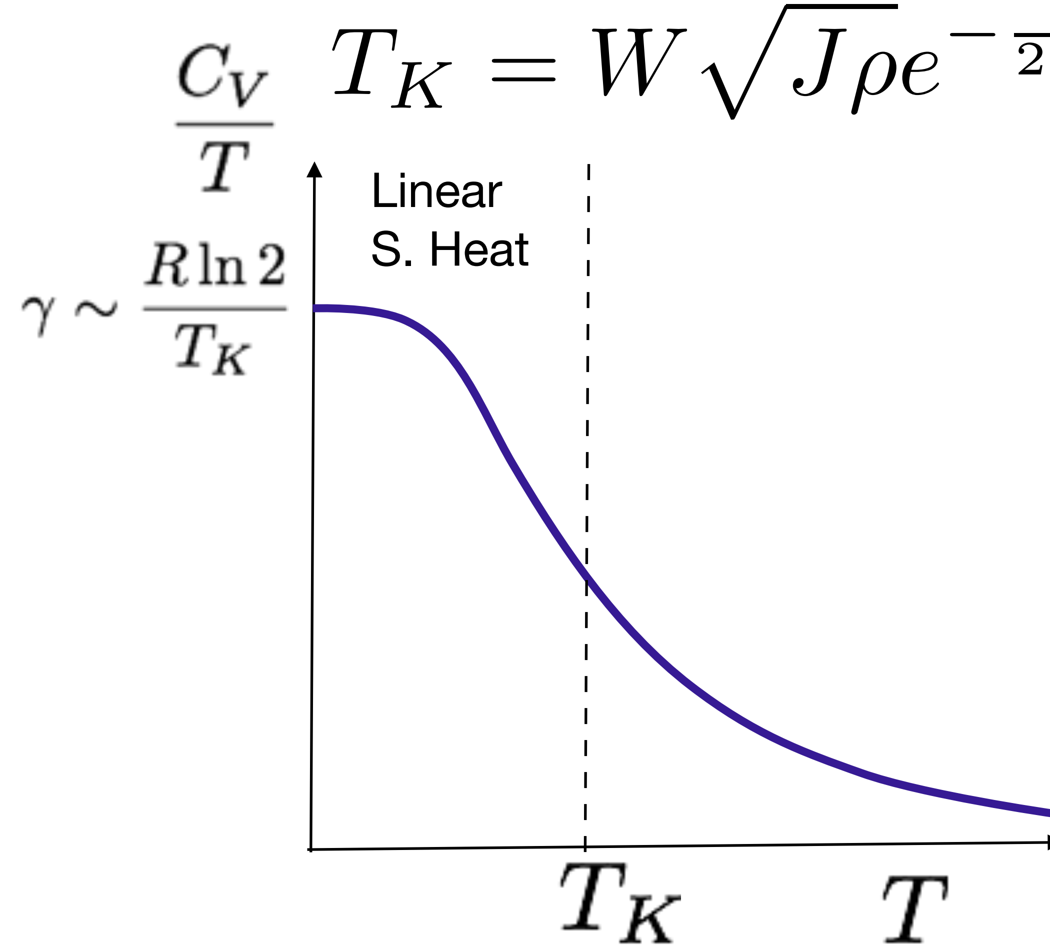

$$S(T) = \int_0^T \frac{C_V}{T'} dT'$$

Spin entropy

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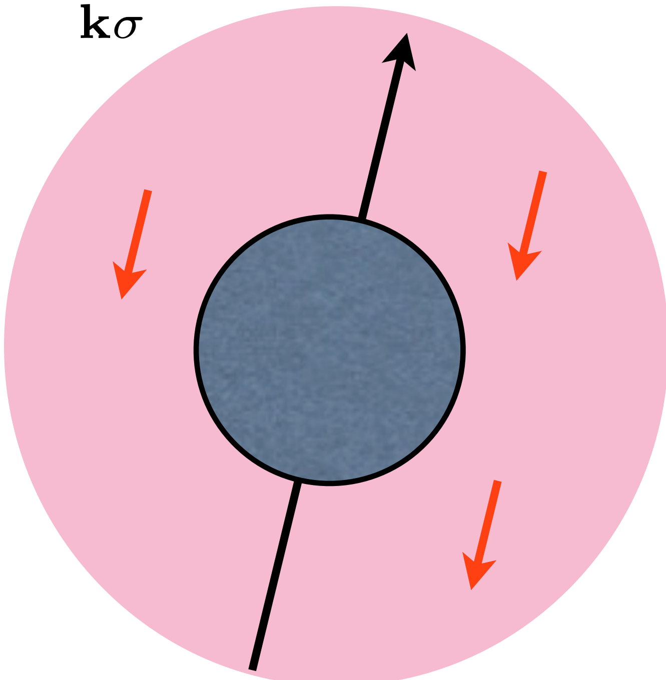
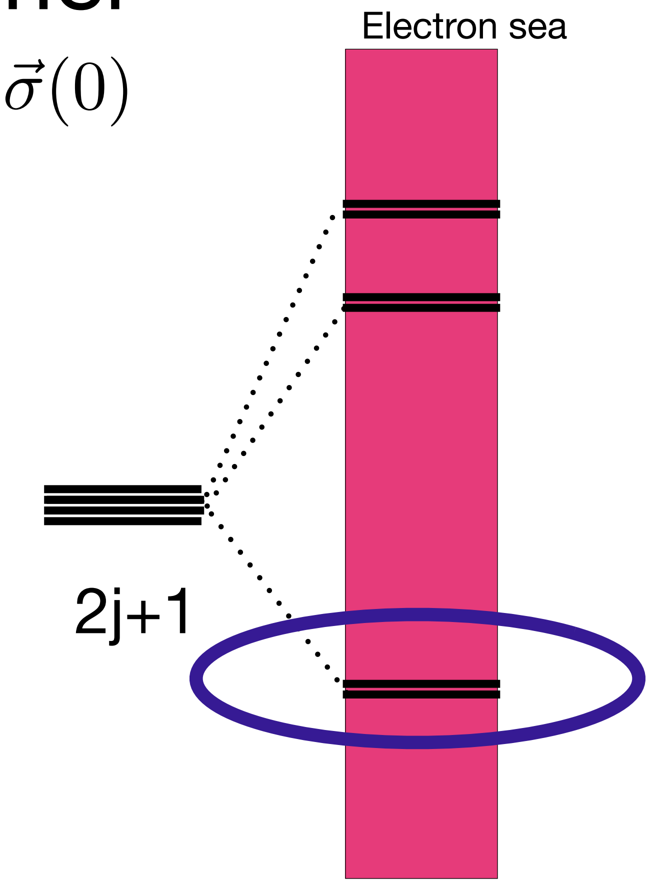
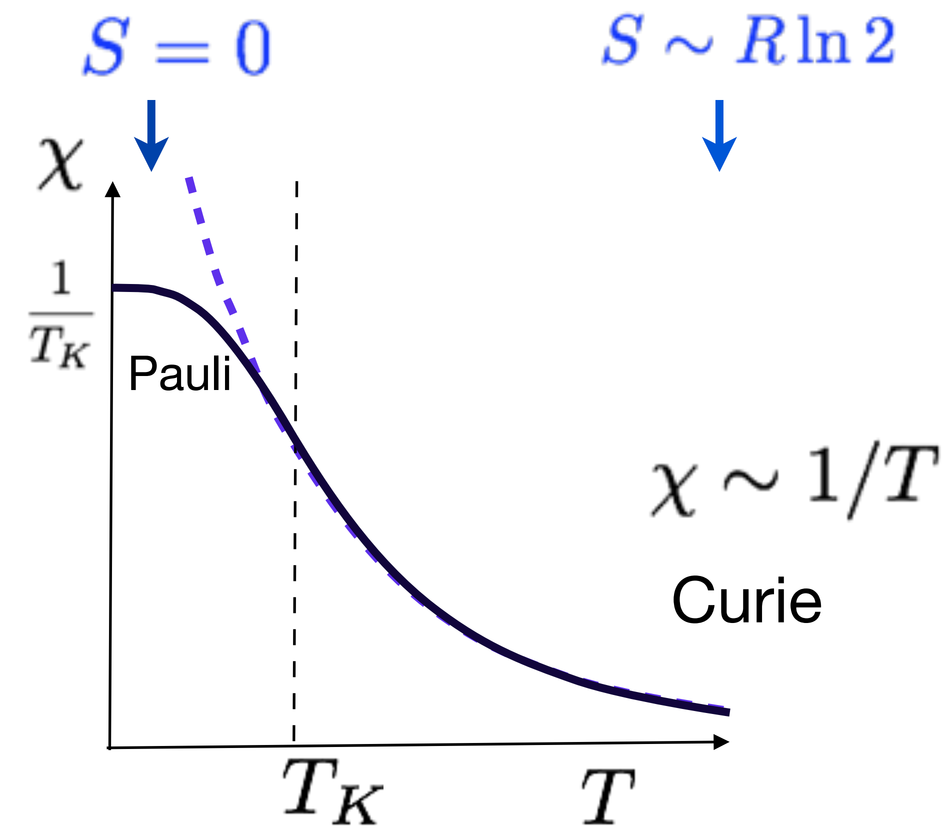
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \ \vec{S} \cdot \vec{\sigma}(0)$$



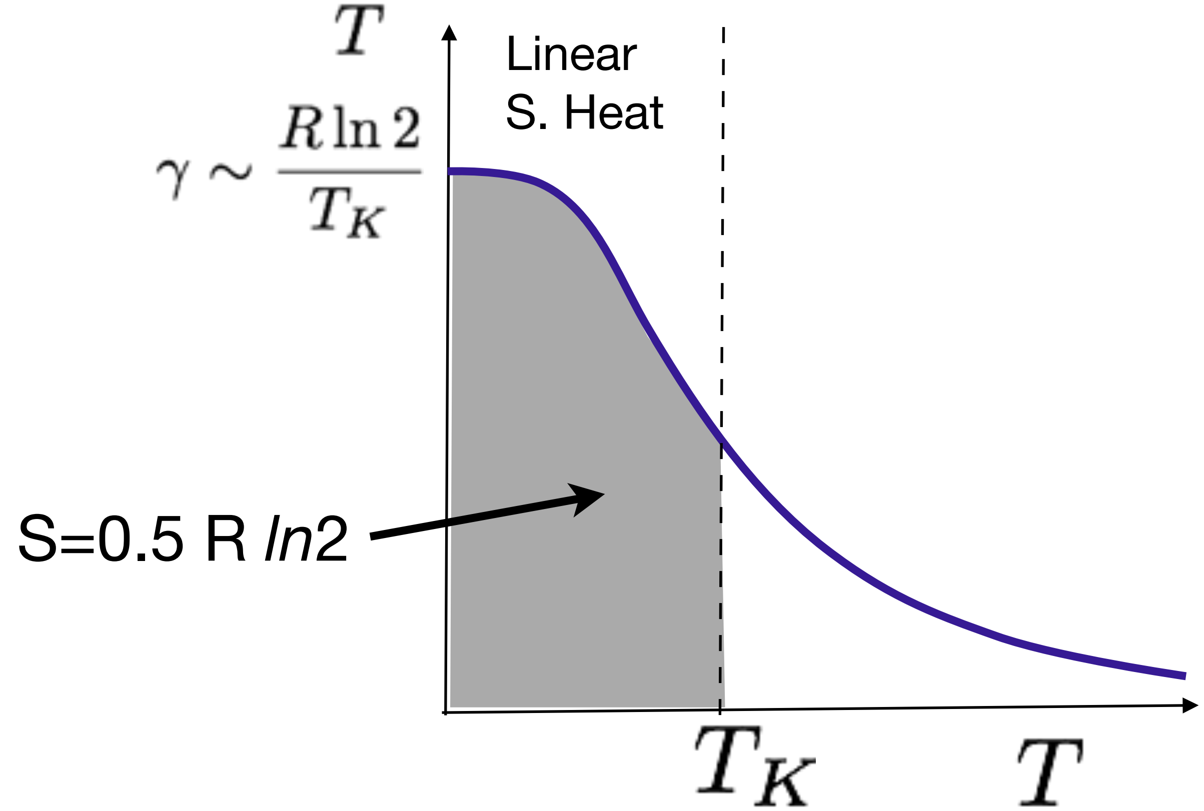


Spin screened by conduction electrons



“Kondo temperature”

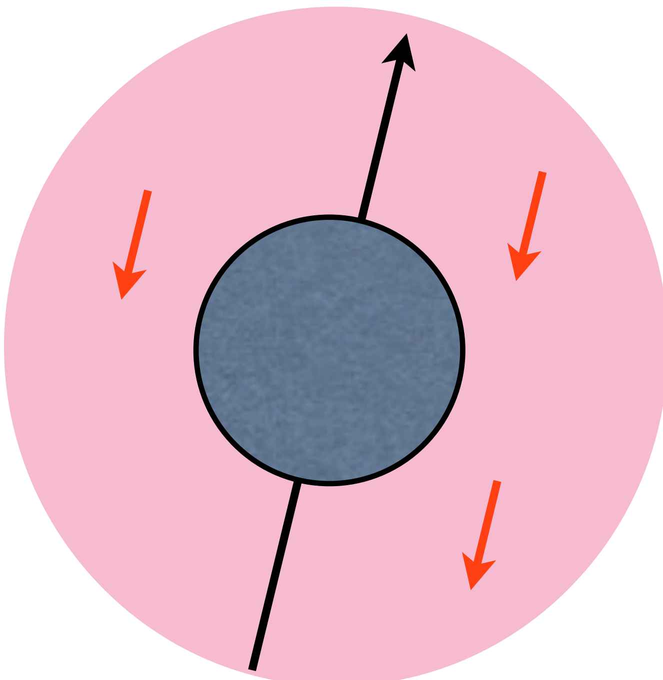
$$T_K = W \sqrt{J\rho}\, e^{-\frac{1}{2J\rho}}$$

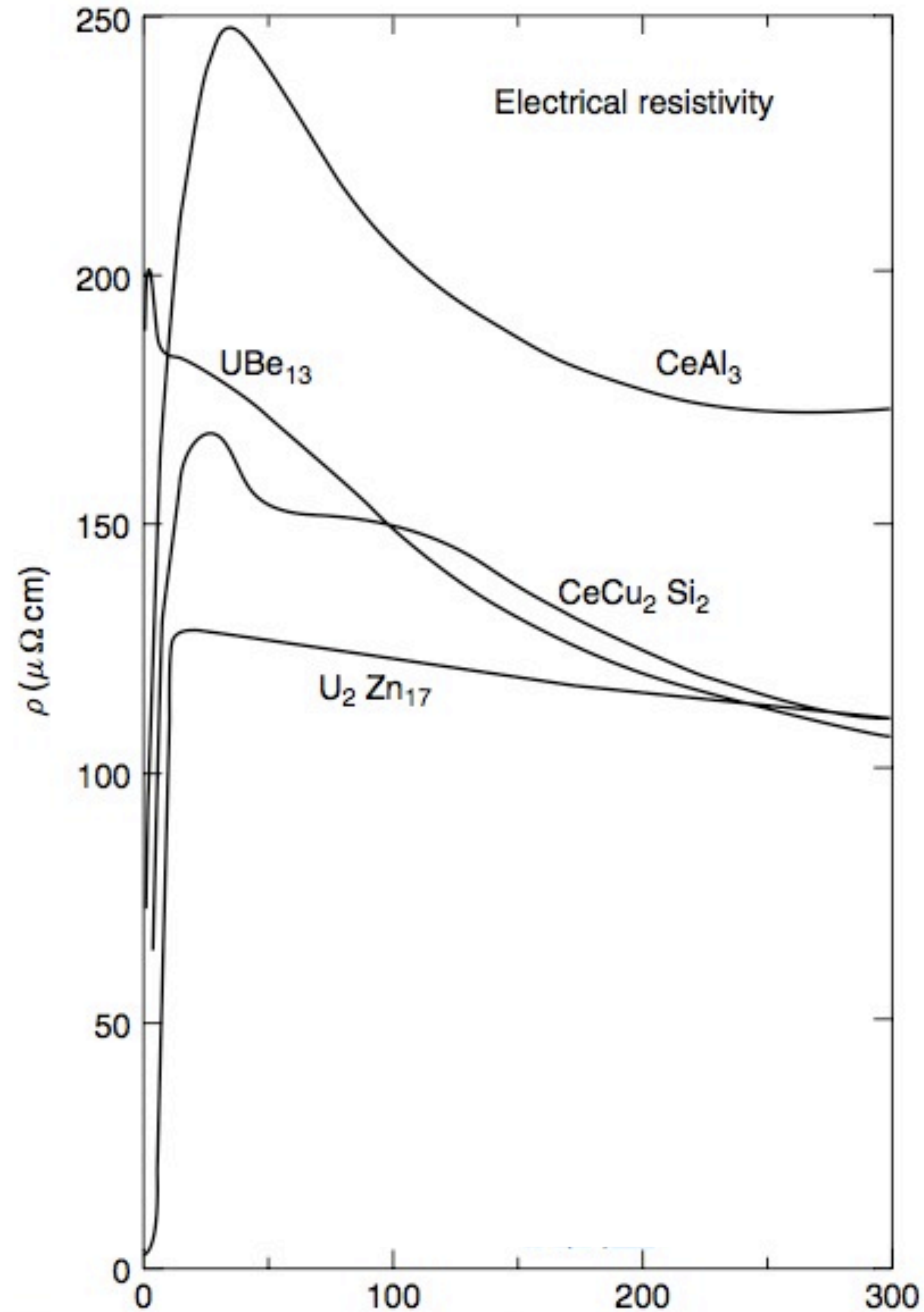


$$S(T) = \int_0^T \frac{C_V}{T'} dT'$$

Spin entropy

Heavy Fermion Primer





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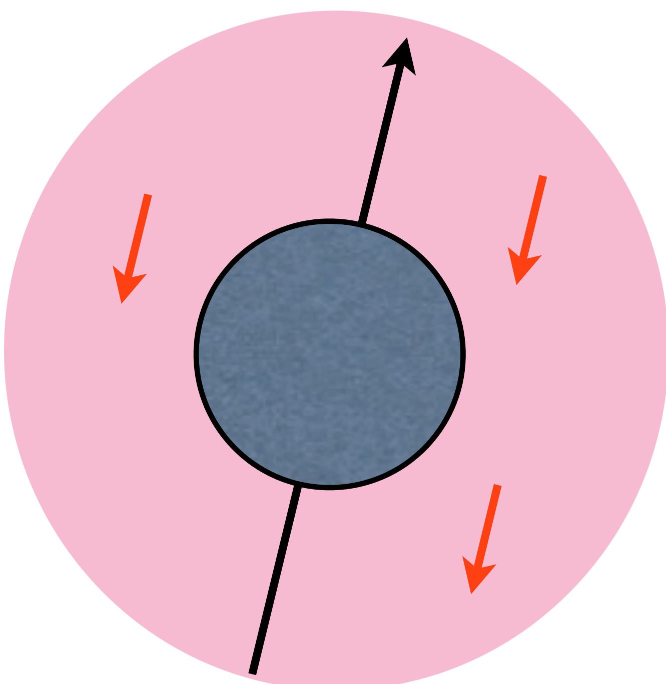
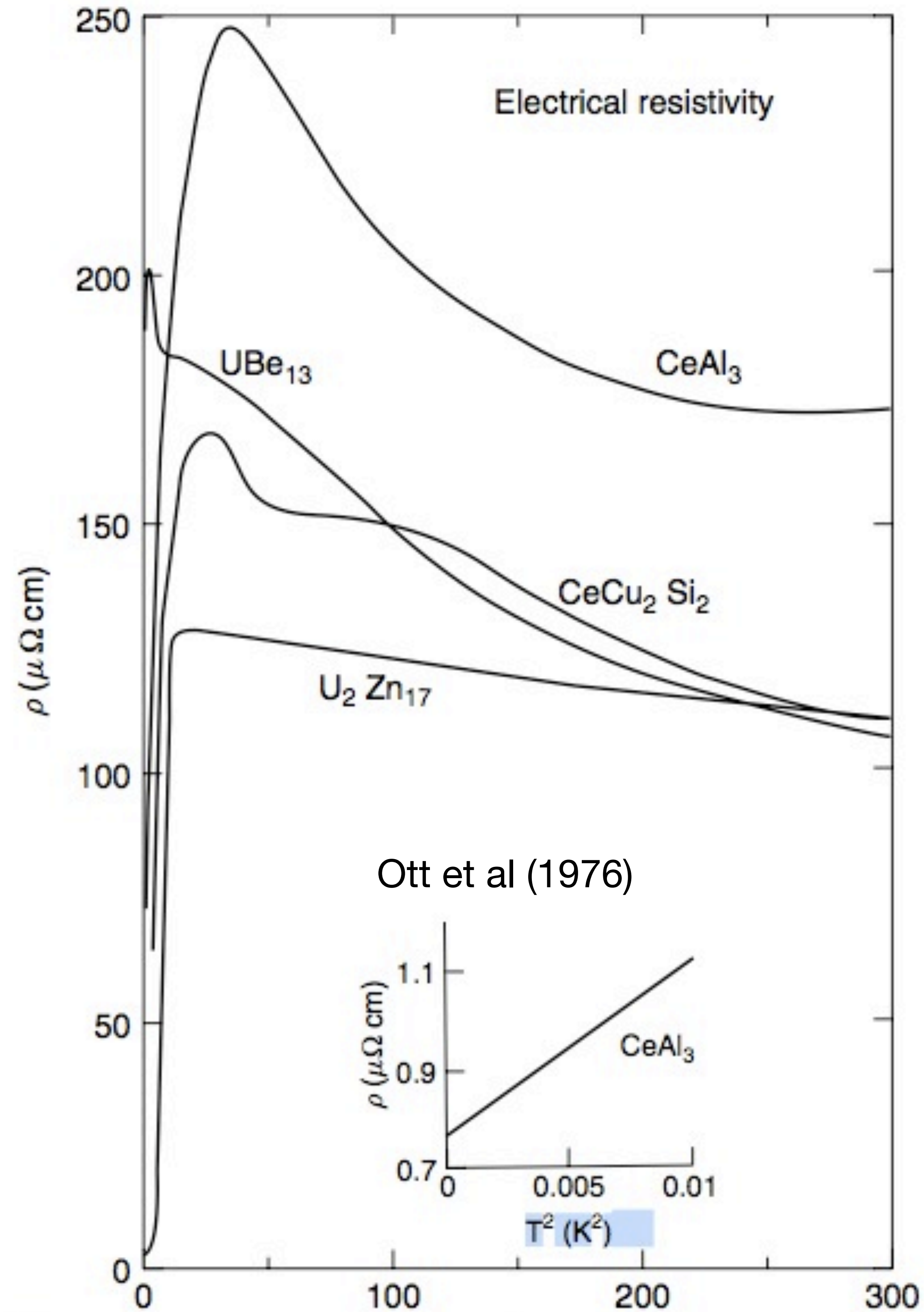
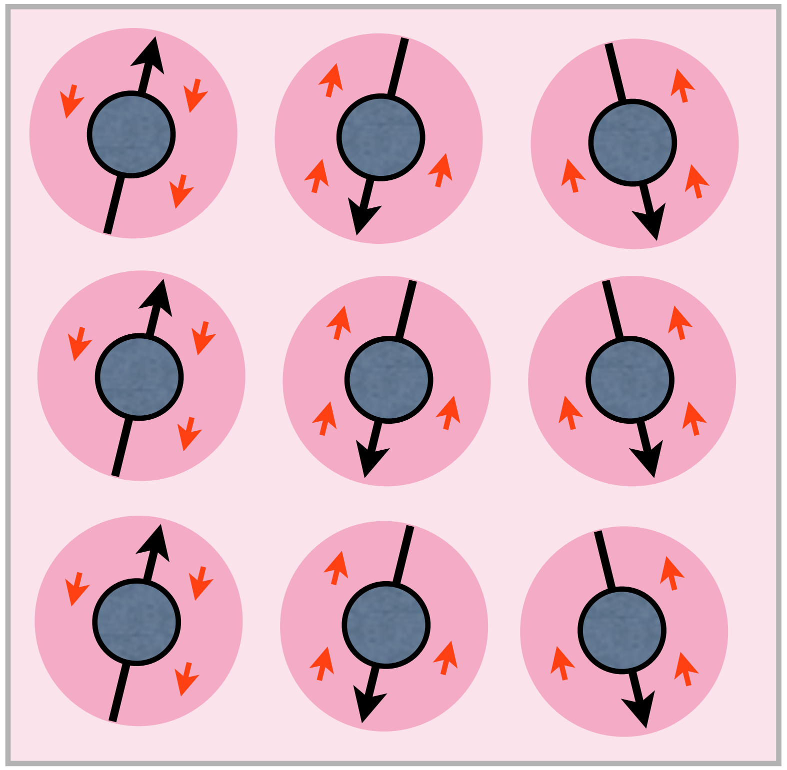




$$\rho(T) = \rho_0 + AT^2$$

Coherent Heavy Fermions

Heavy Fermion Primer



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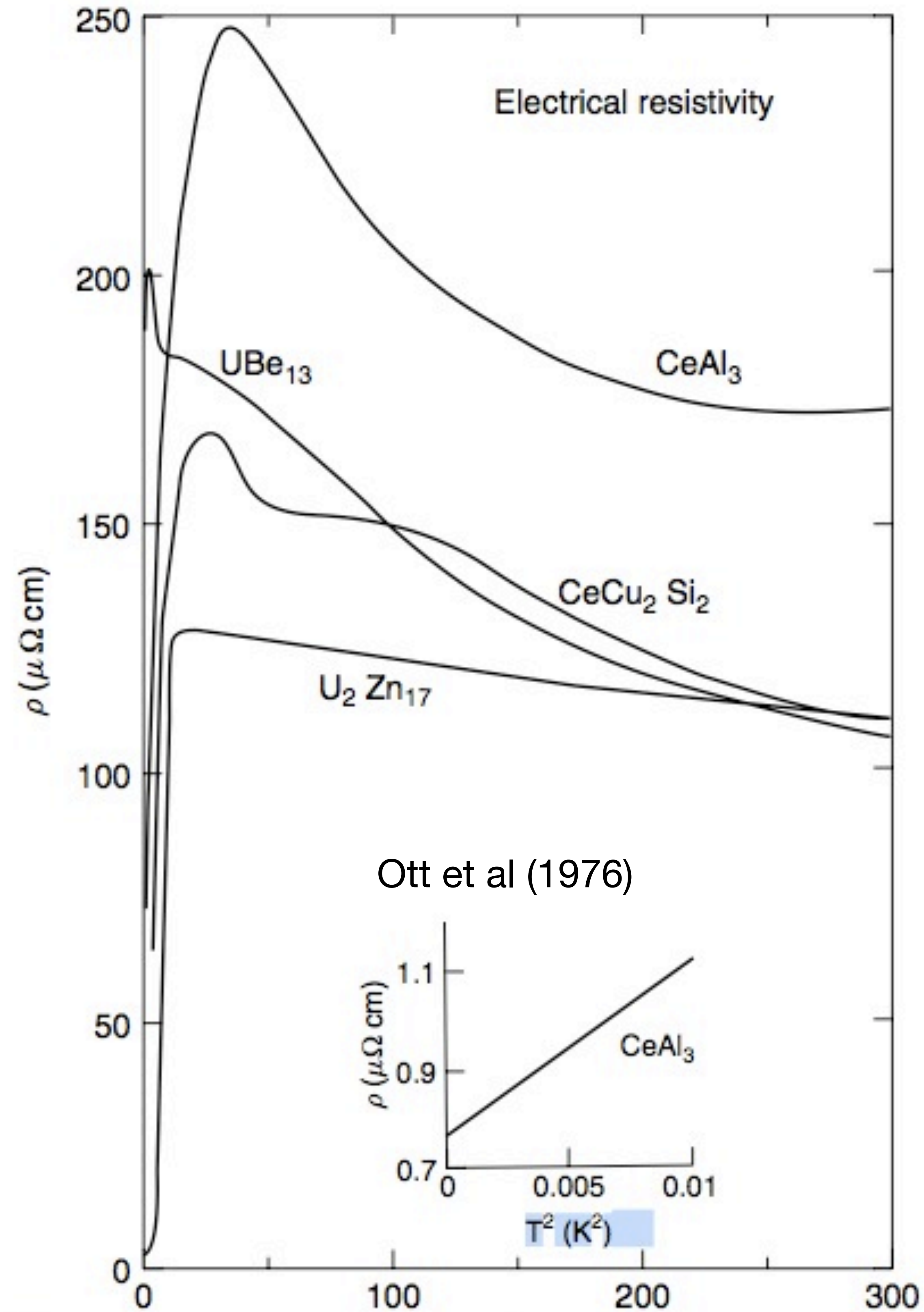

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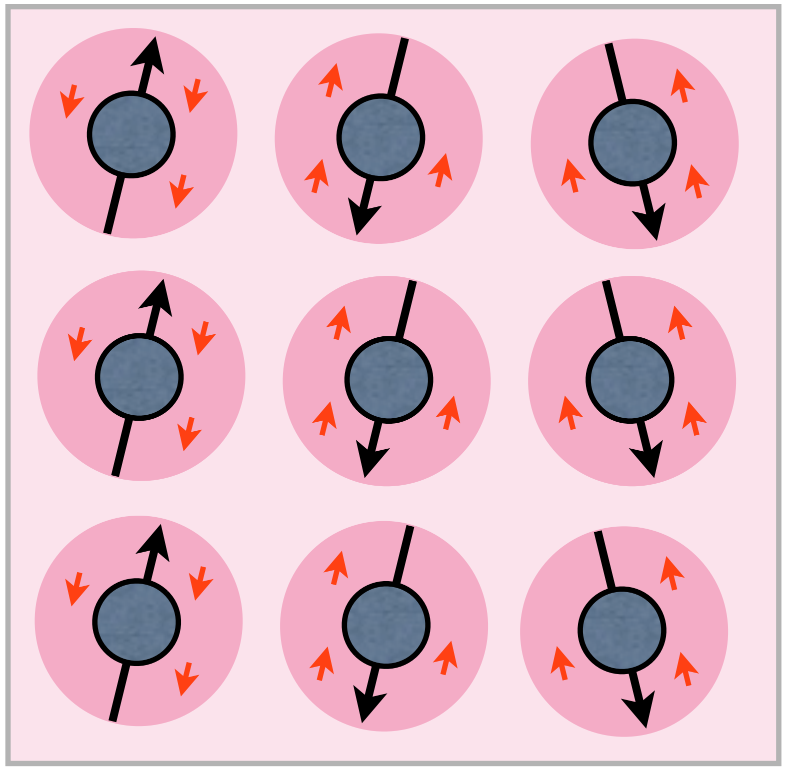

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Entangled many body state of spins
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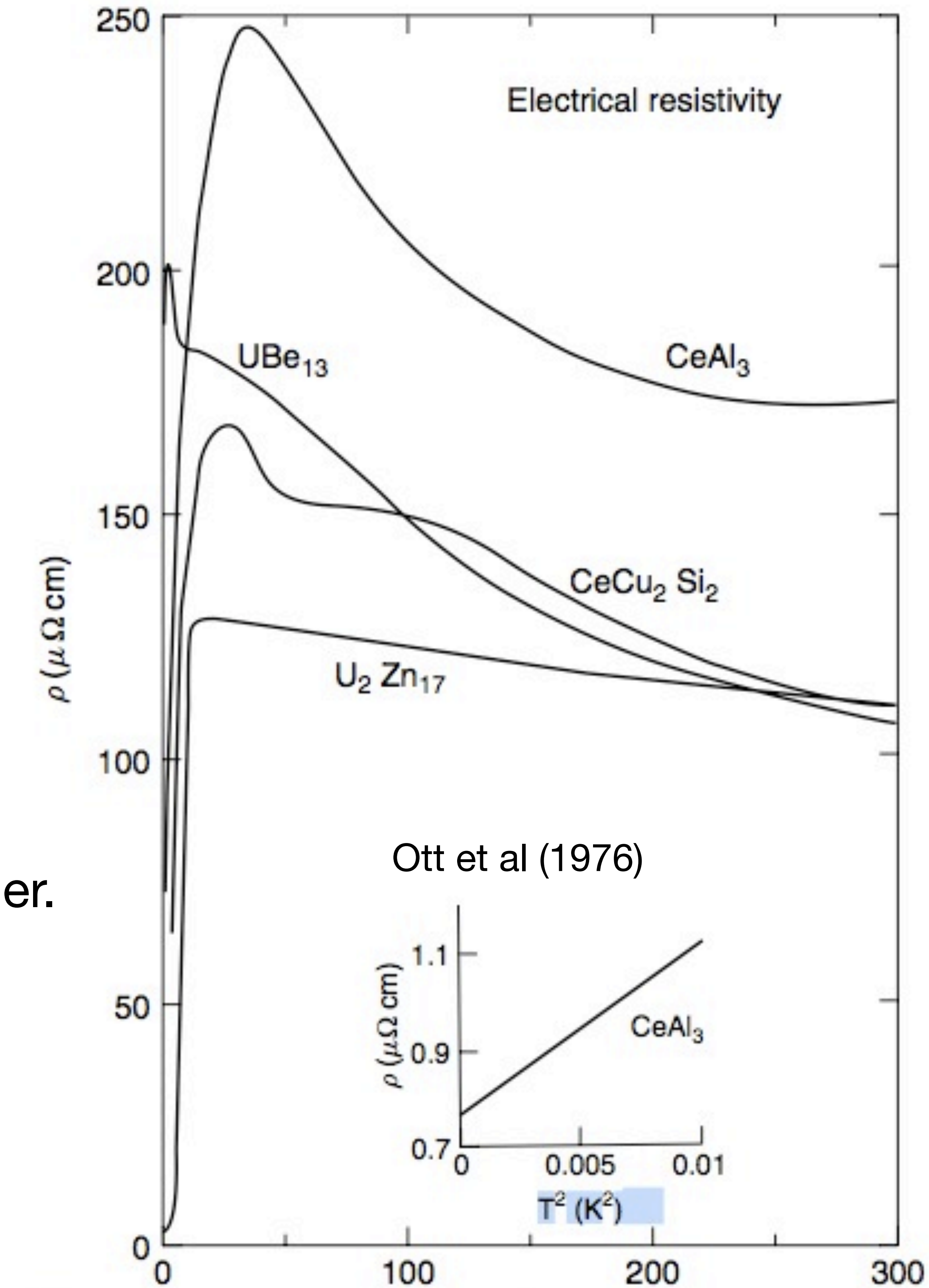

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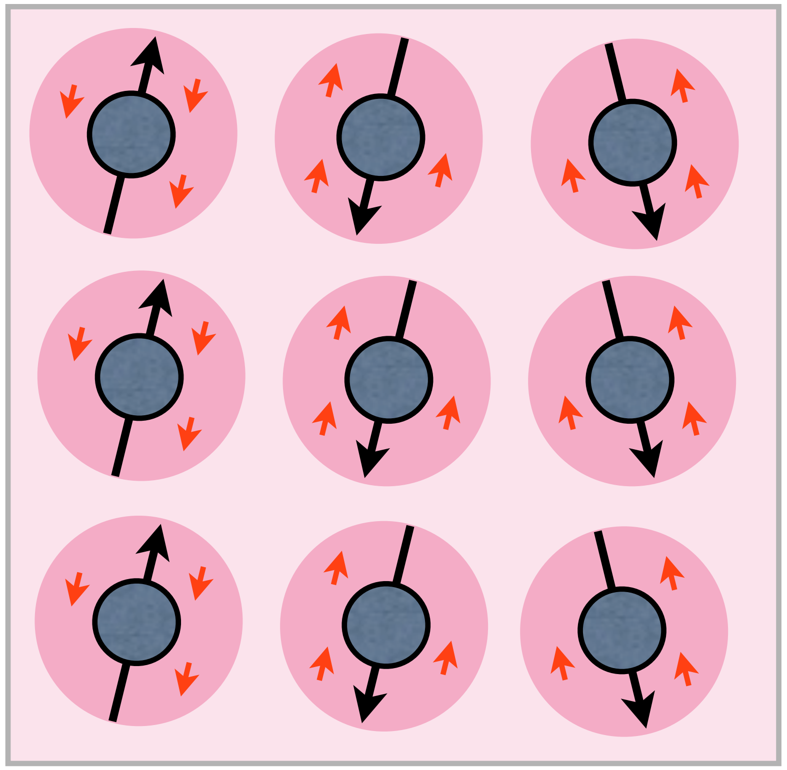

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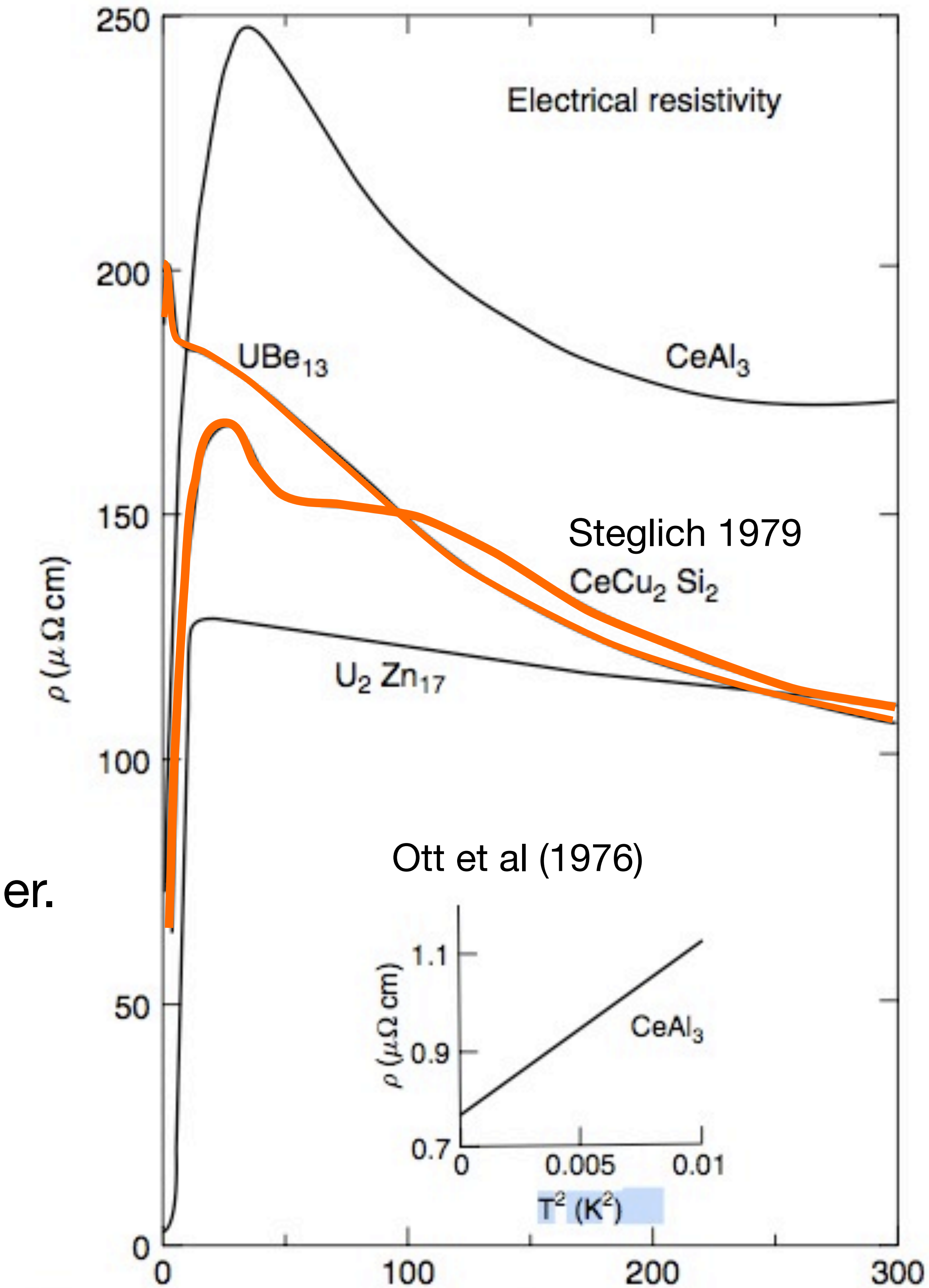

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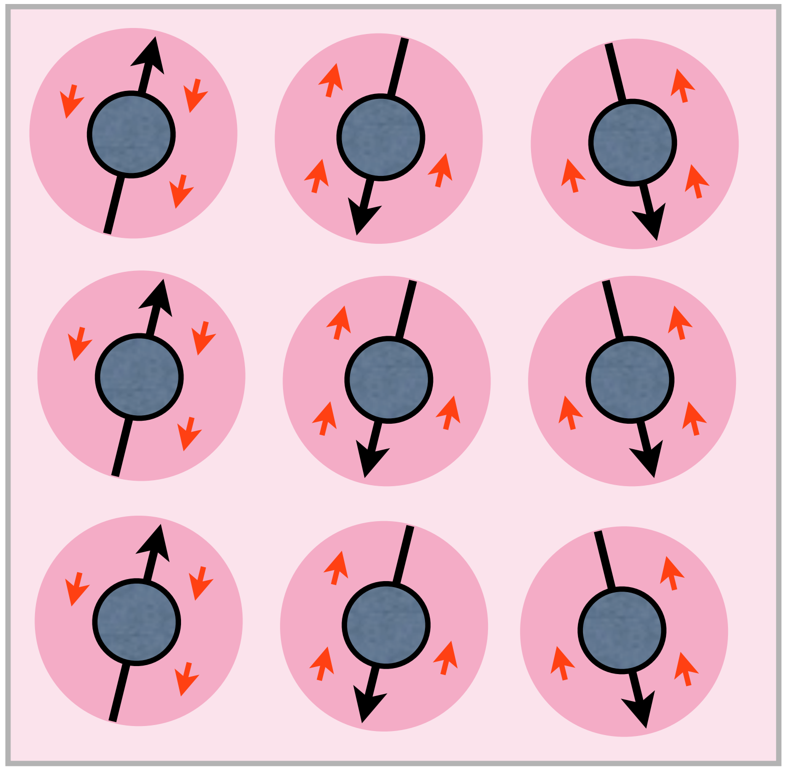

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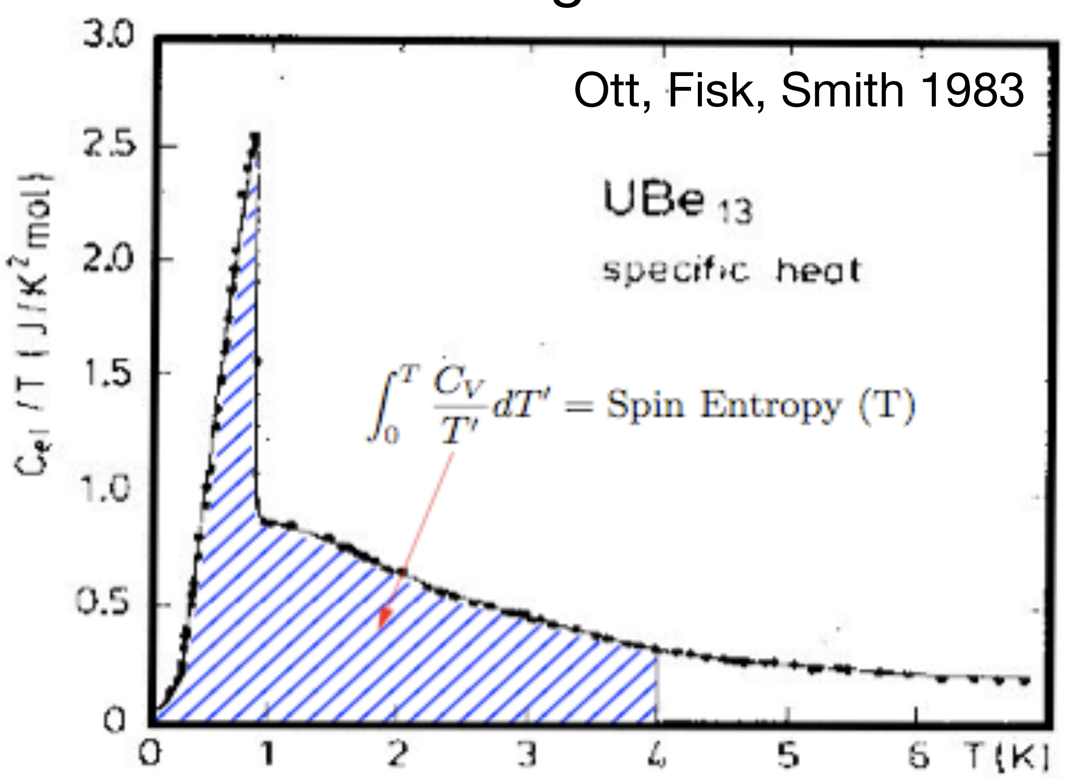

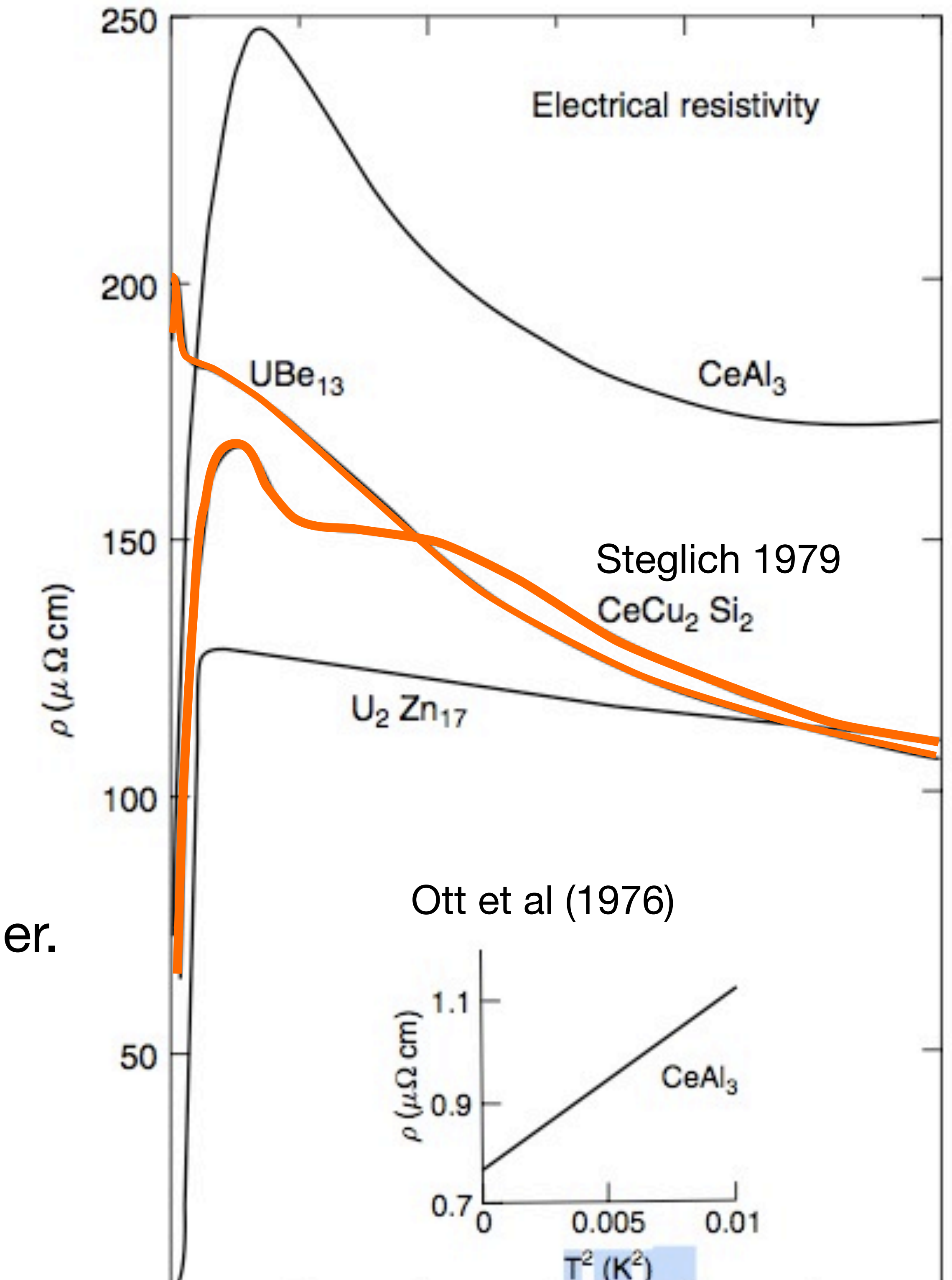

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Coherent Heavy Fermions

Kondo insulators

Menth, Bueller and Geballe (PRL 22,295, 1969)
Aeppli and Fisk (Comments CMP 16, 155, 1992)

Simplest Kondo Lattice

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MAGNETIC AND SEMICONDUCTING PROPERTIES OF SmB_6†

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(Received 21 November 1968)

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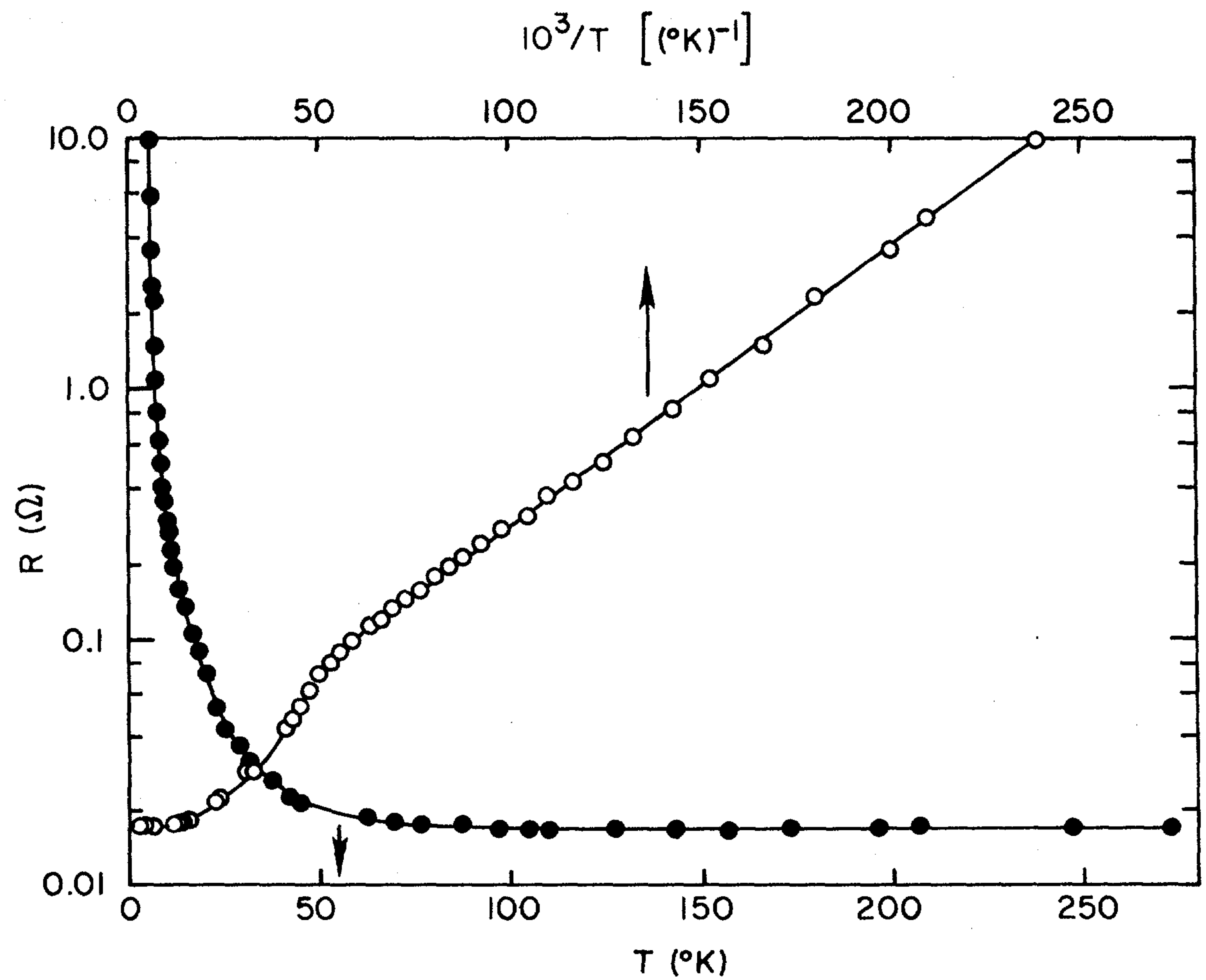

FIG. 1. Resistance of SmB_6 as a function of temperature. Closed circles: resistance versus T; open circles: resistance versus $10^3/T$.

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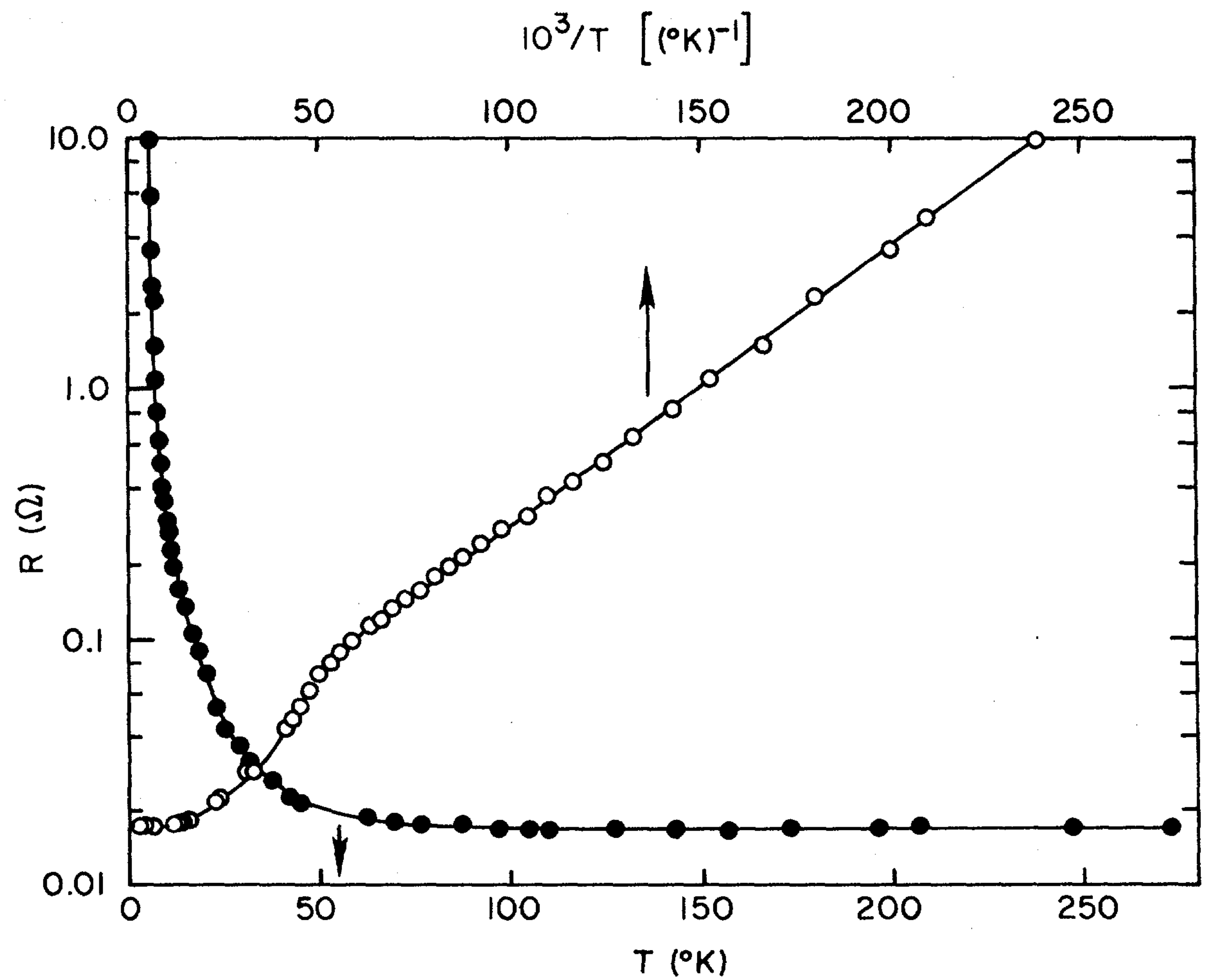

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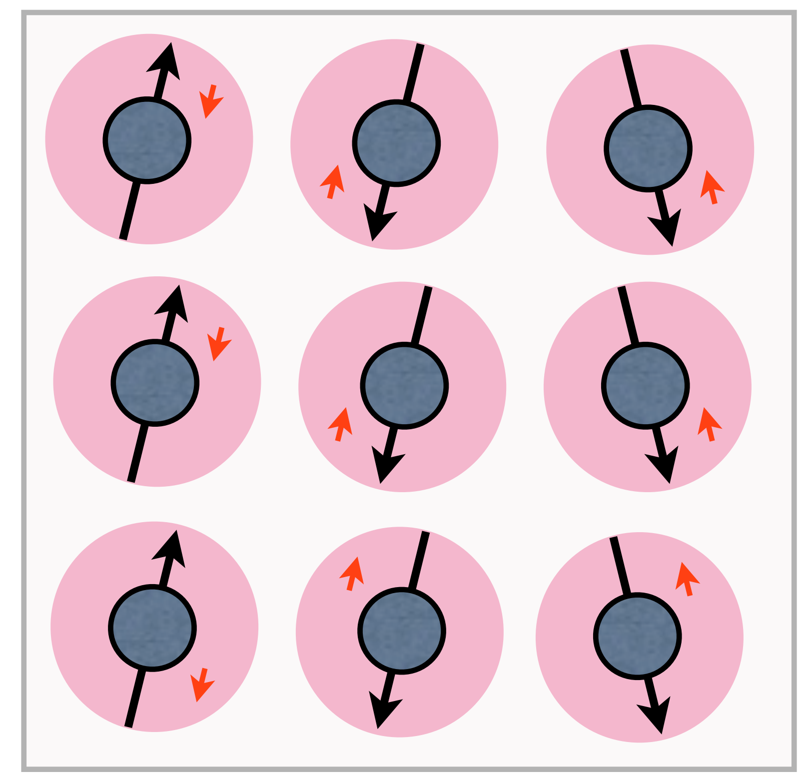

Mott's Hybridization picture. Mott Phil Mag, 30,403,1974

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Formation of Heavy f-bands: quasiparticle hybridization
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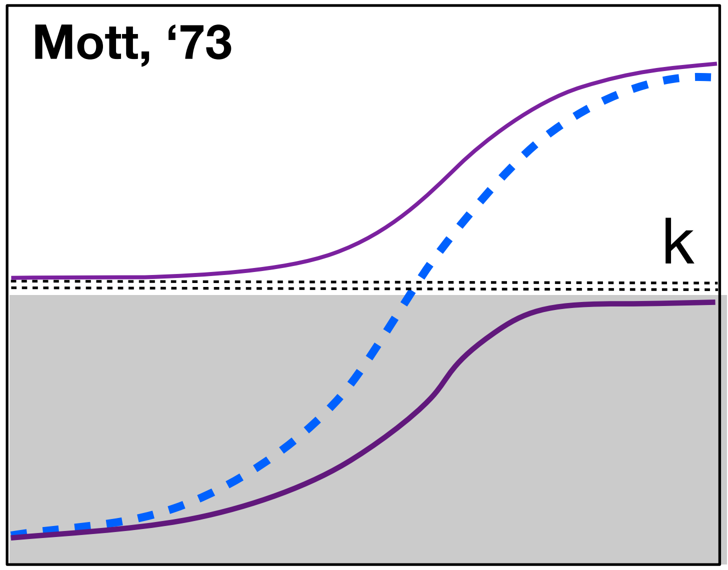

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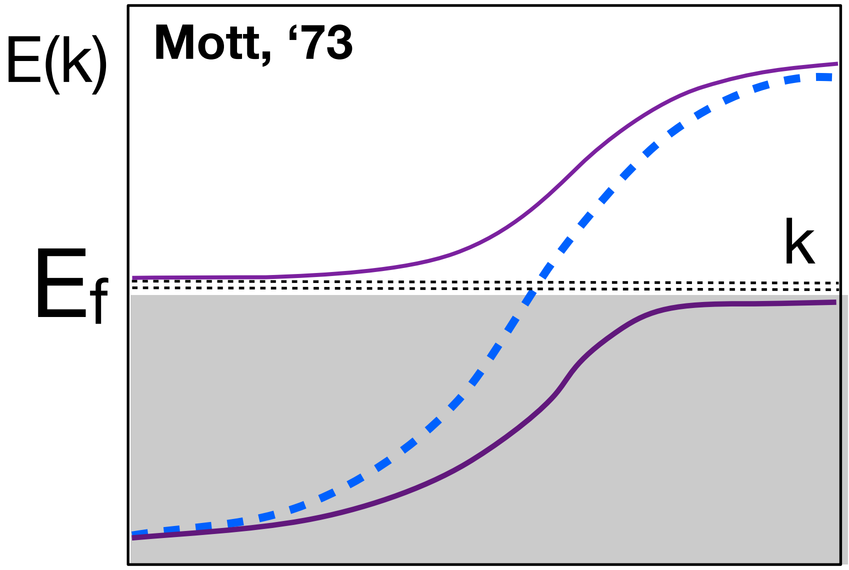

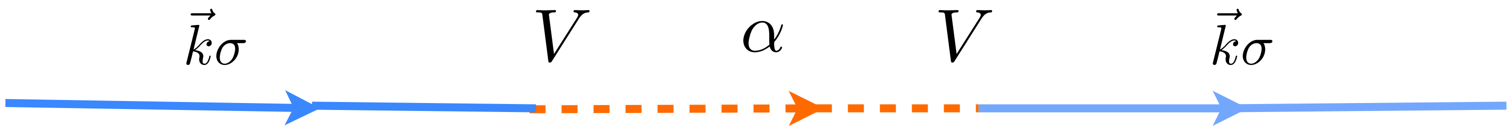

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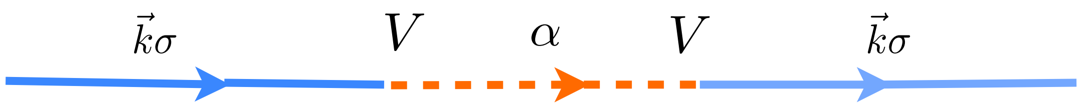

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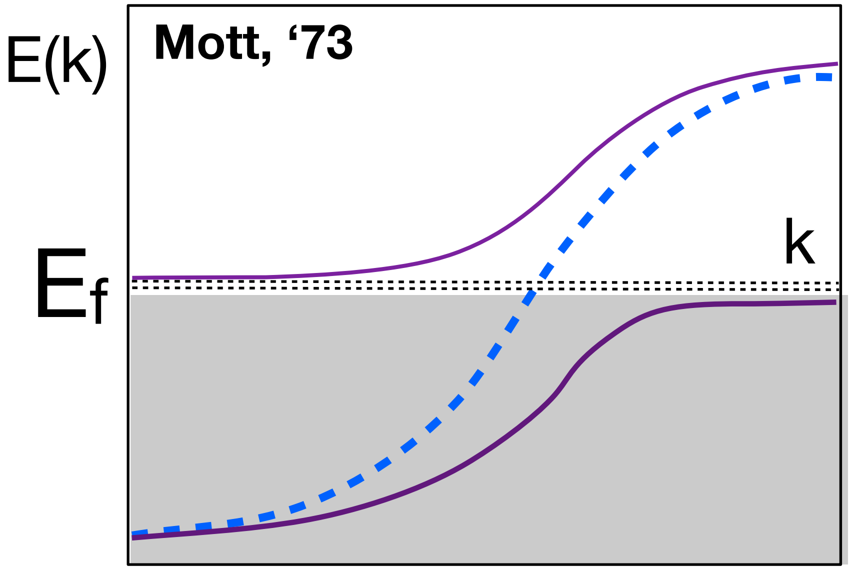

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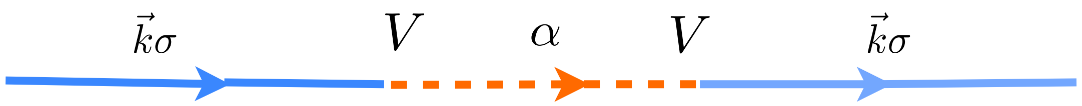

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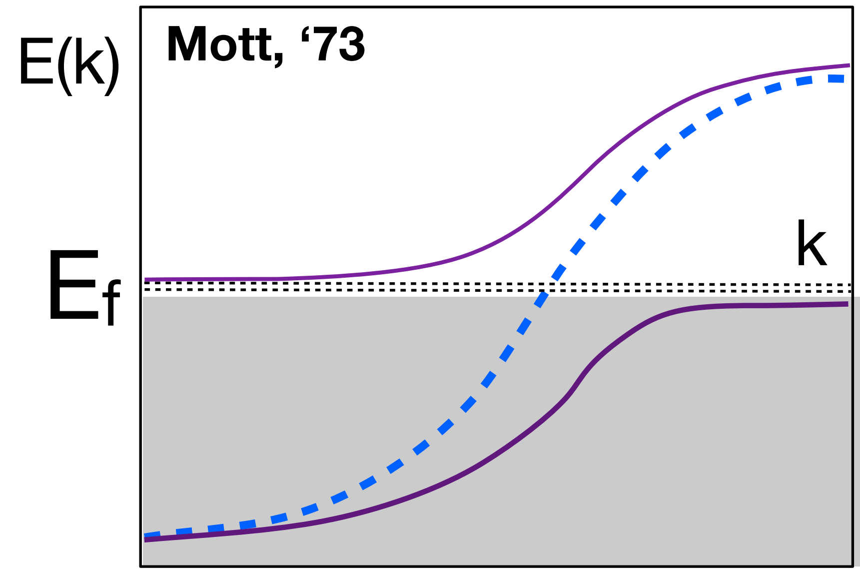

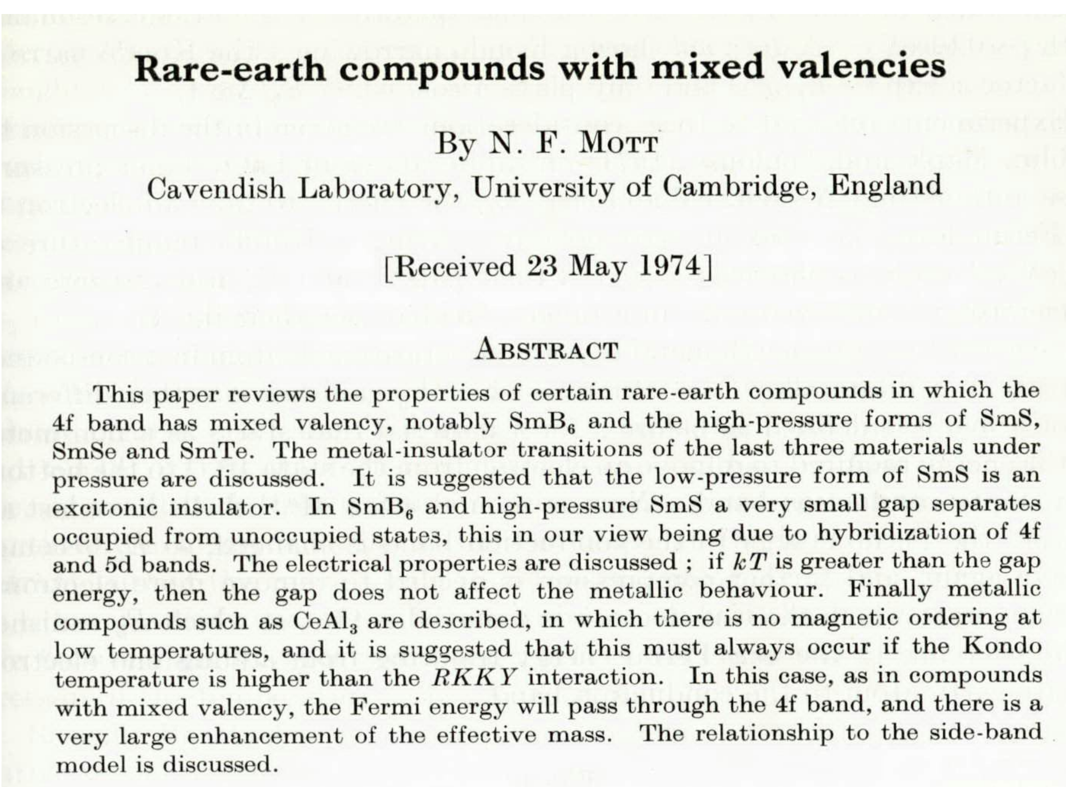

Rare-earth compounds with mixed valencies

By N. F. Mott
Cavendish Laboratory, University of Cambridge, England

[Received 23 May 1974]

Abstract

This paper reviews the properties of certain rare-earth compounds in which the 4f band has mixed valency, notably SmB_6 and the high-pressure forms of SmS, SmSe and SmTe. The metal-insulator transitions of the last three materials under pressure are discussed. It is suggested that the low-pressure form of SmS is an excitonic insulator. In SmB_6 and high-pressure SmS a very small gap separates occupied from unoccupied states, this in our view being due to hybridization of 4f and 5d bands. The electrical properties are discussed; if kT is greater than the gap energy, then the gap does not affect the metallic behaviour. Finally metallic compounds such as $CeAl_3$ are described, in which there is no magnetic ordering at low temperatures, and it is suggested that this must always occur if the Kondo temperature is higher than the $RKKY$ interaction. In this case, as in compounds with mixed valency, the Fermi energy will pass through the 4f band, and there is a very large enhancement of the effective mass. The relationship to the side-band model is discussed.

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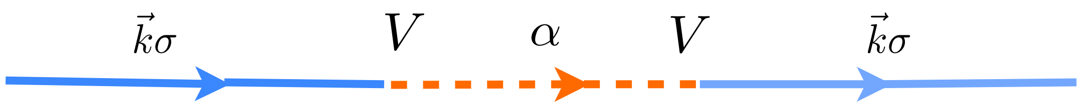

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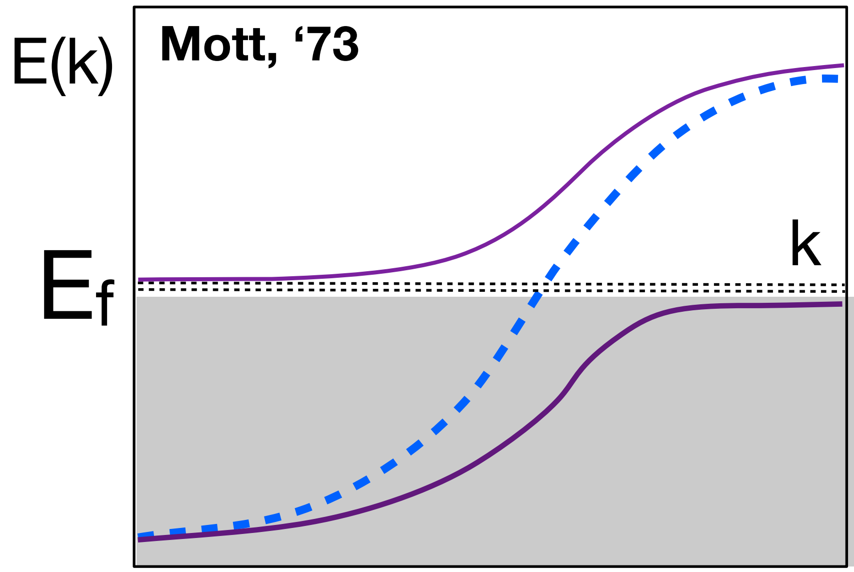

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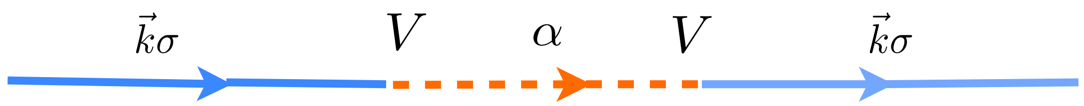

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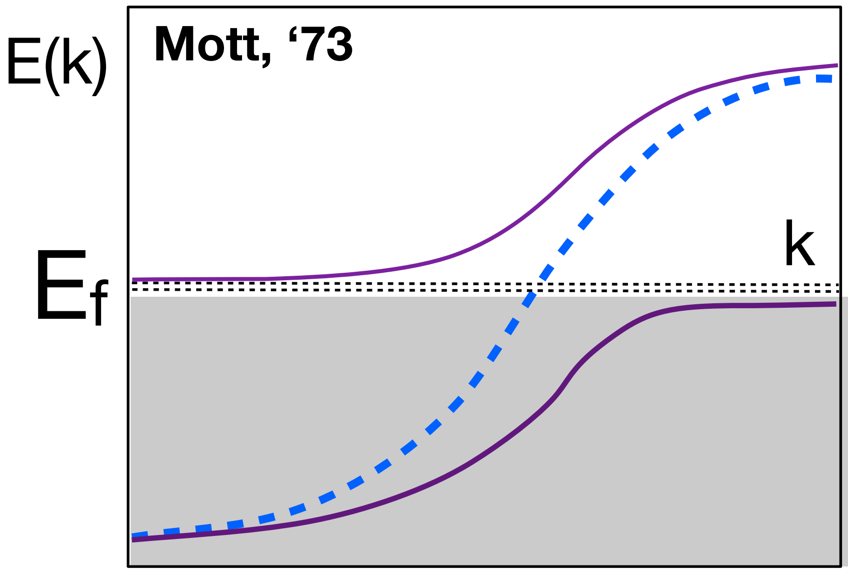

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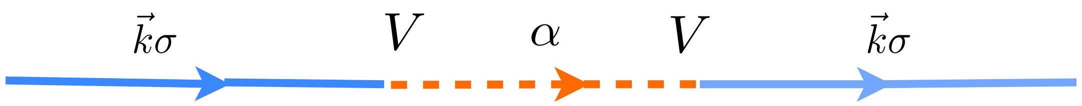

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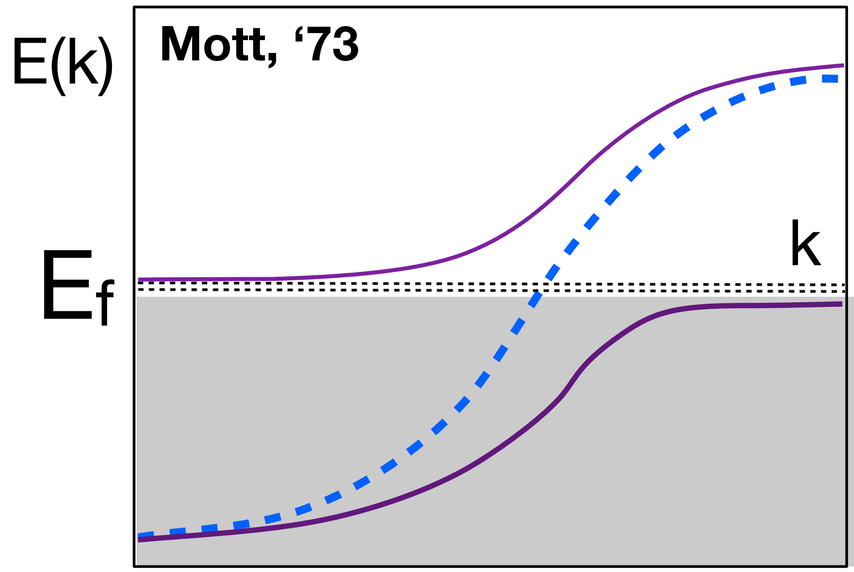

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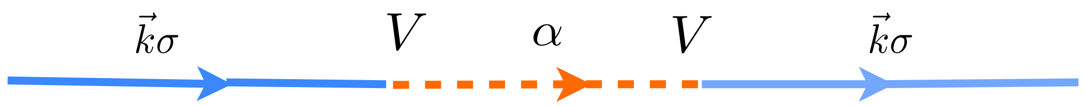

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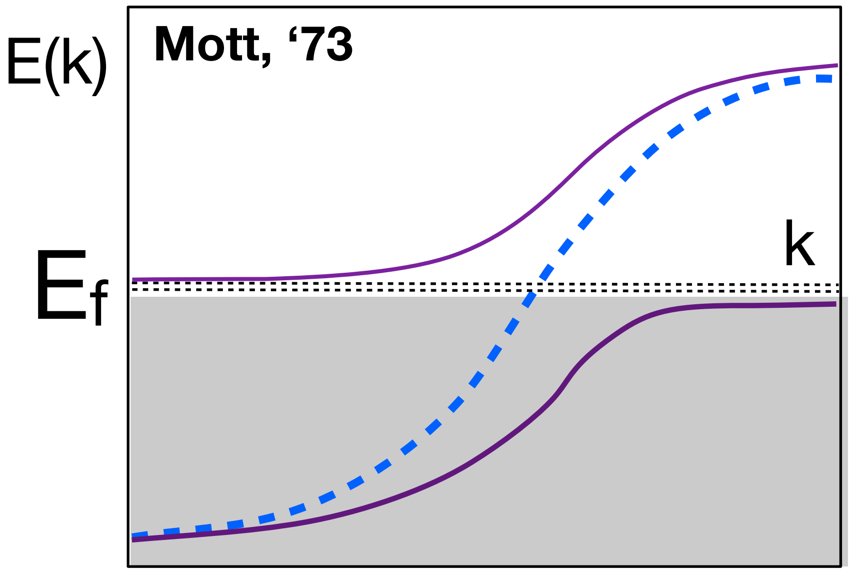

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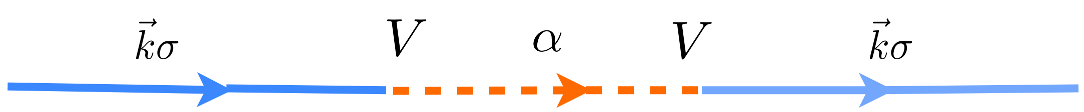

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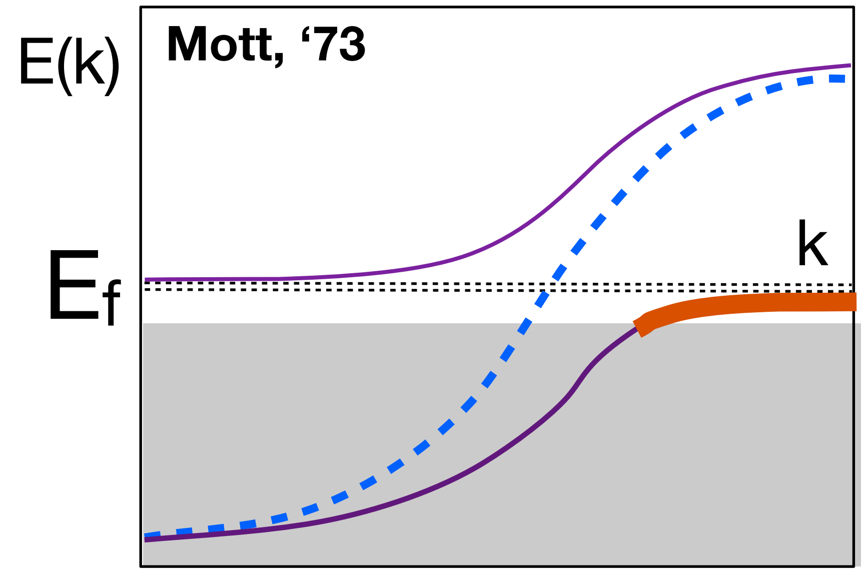

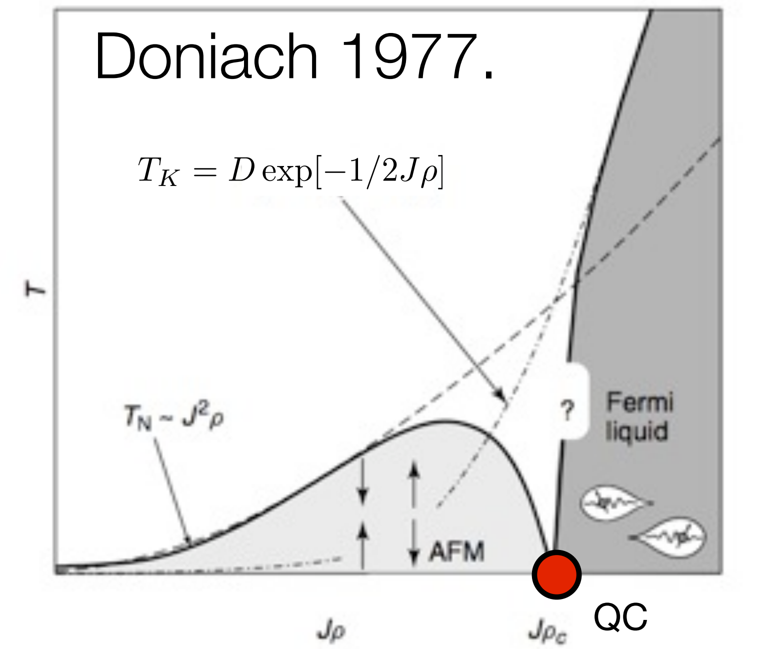

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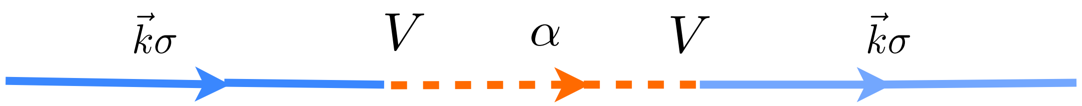

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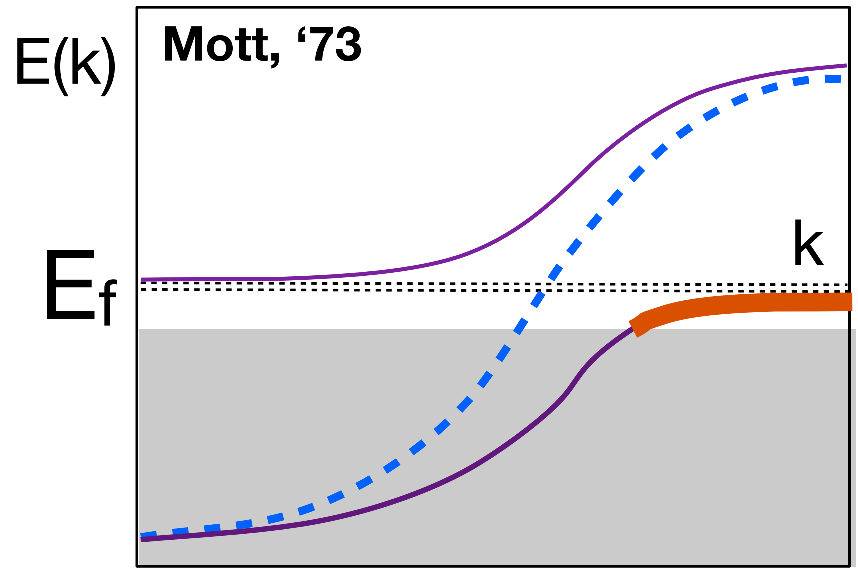
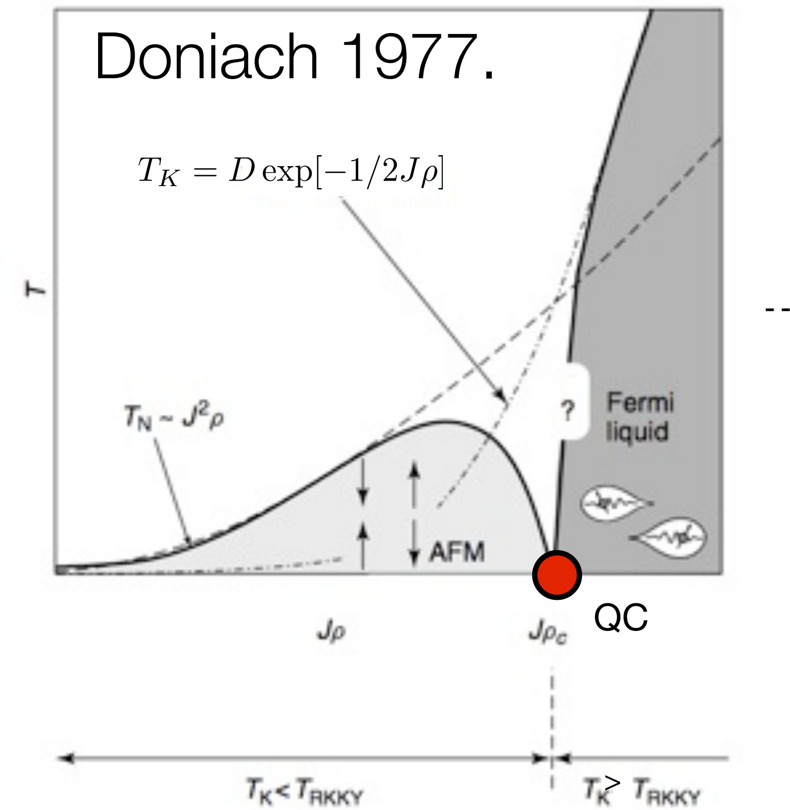
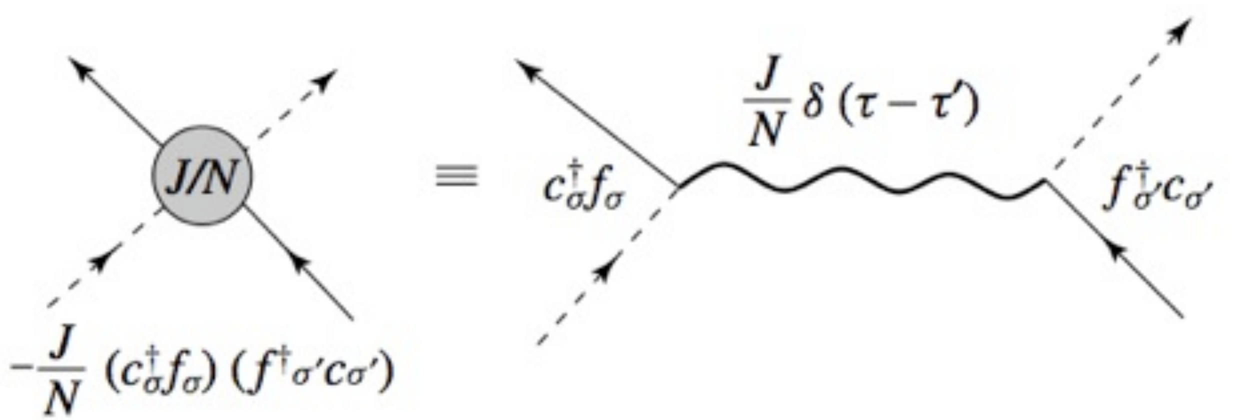




- The large N approach to the Kondo lattice.

Spin x conduction = composite fermion

$$H_I(j) = \frac{J}{N}(c^{\dagger}_{j\beta}c_{j\alpha})S_{\alpha\beta} \rightarrow \left(\bar{V}_j c^{\dagger}_{j\beta} f_{j\beta} + \text{H.c}\right)$$



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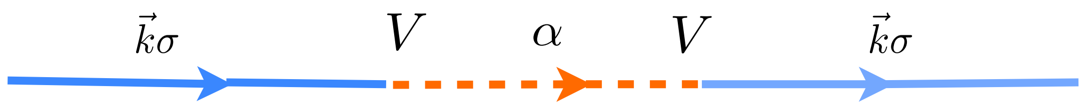

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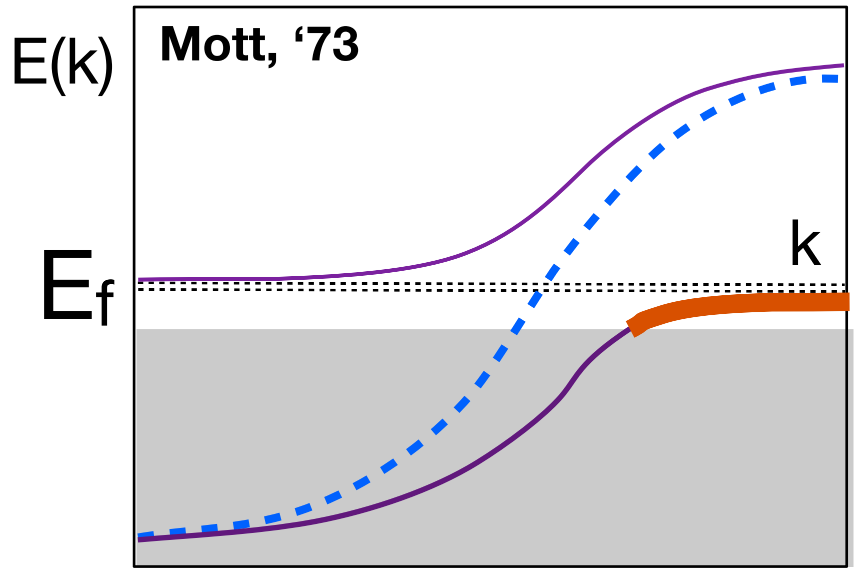

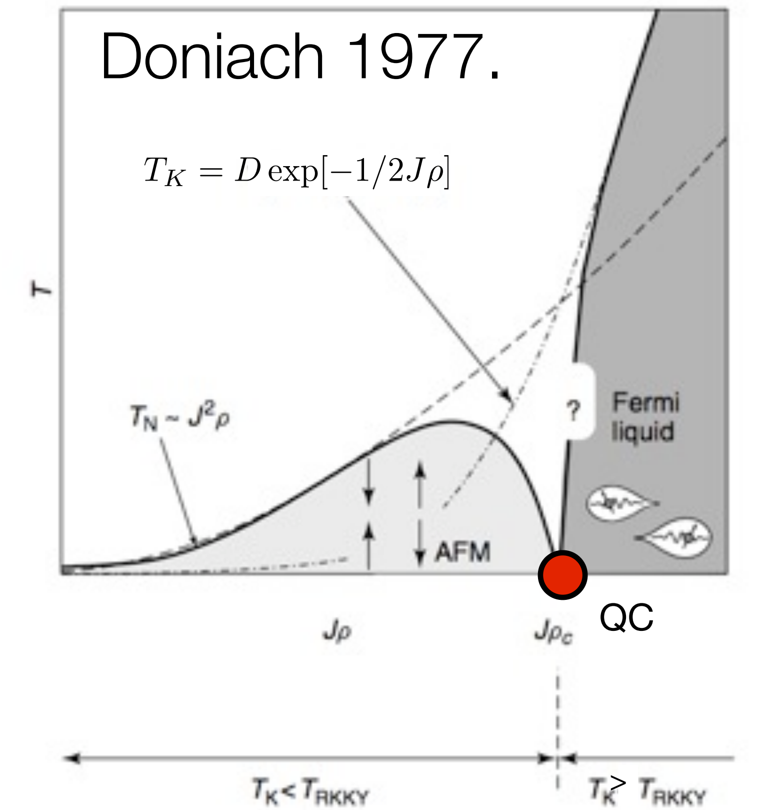

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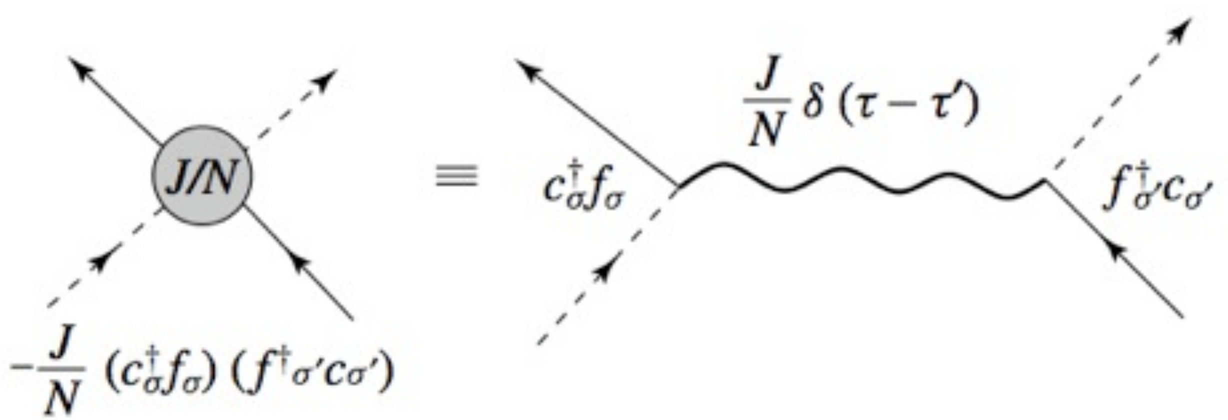

$$\frac{J}{N} c_{j\alpha} S_{\alpha\beta} \equiv \bar{V}_j f_{j\beta}$$

Composite Fermion

Read & Newns 1983, PC 1983.

MAGNETIC AND SEMICONDUCTING PROPERTIES OF SmB_6†

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Bell Telephone Laboratories, Murray Hill, New Jersey

and

T. H. Geballe
Department of Applied Physics, Stanford University, Stanford, California,
and Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 21 November 1968)

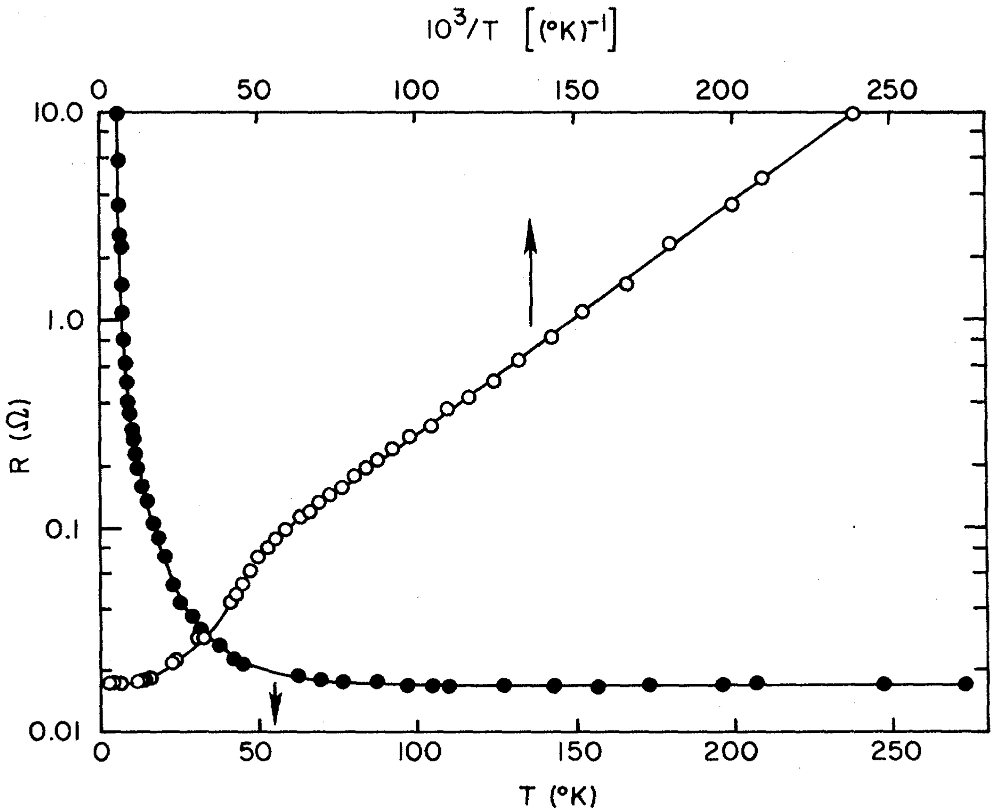

FIG. 1. Resistance of SmB_6 as a function of temperature. Closed circles: resistance versus T; open circles: resistance versus $10^3/T$.

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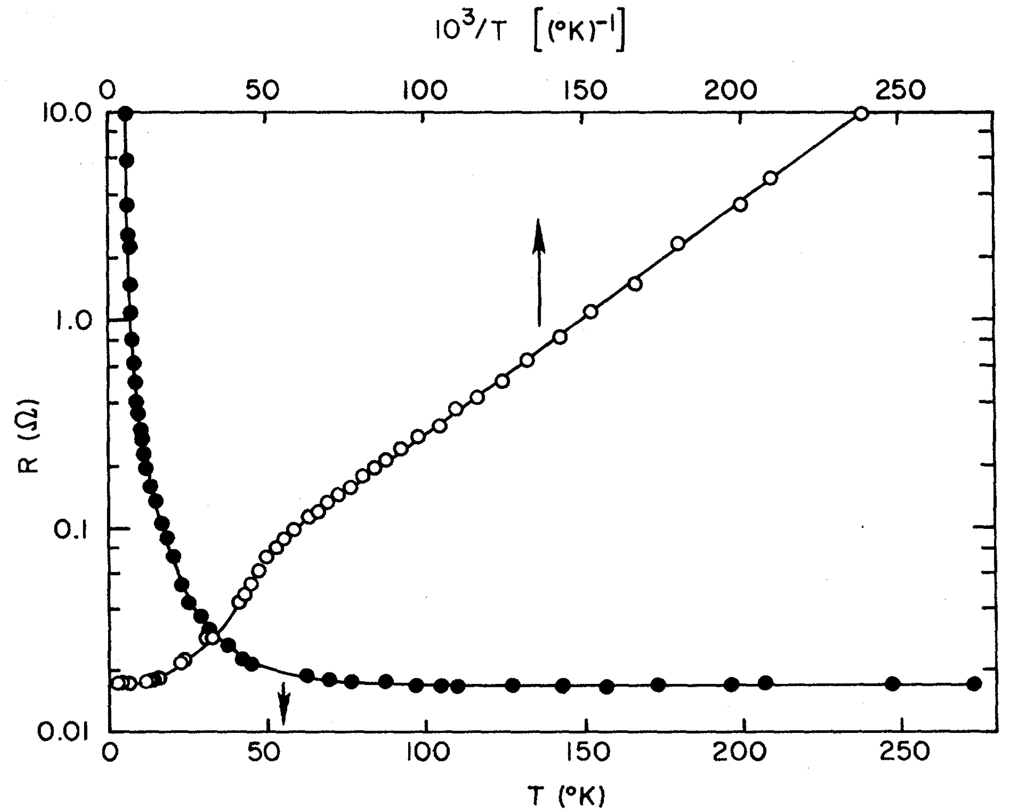

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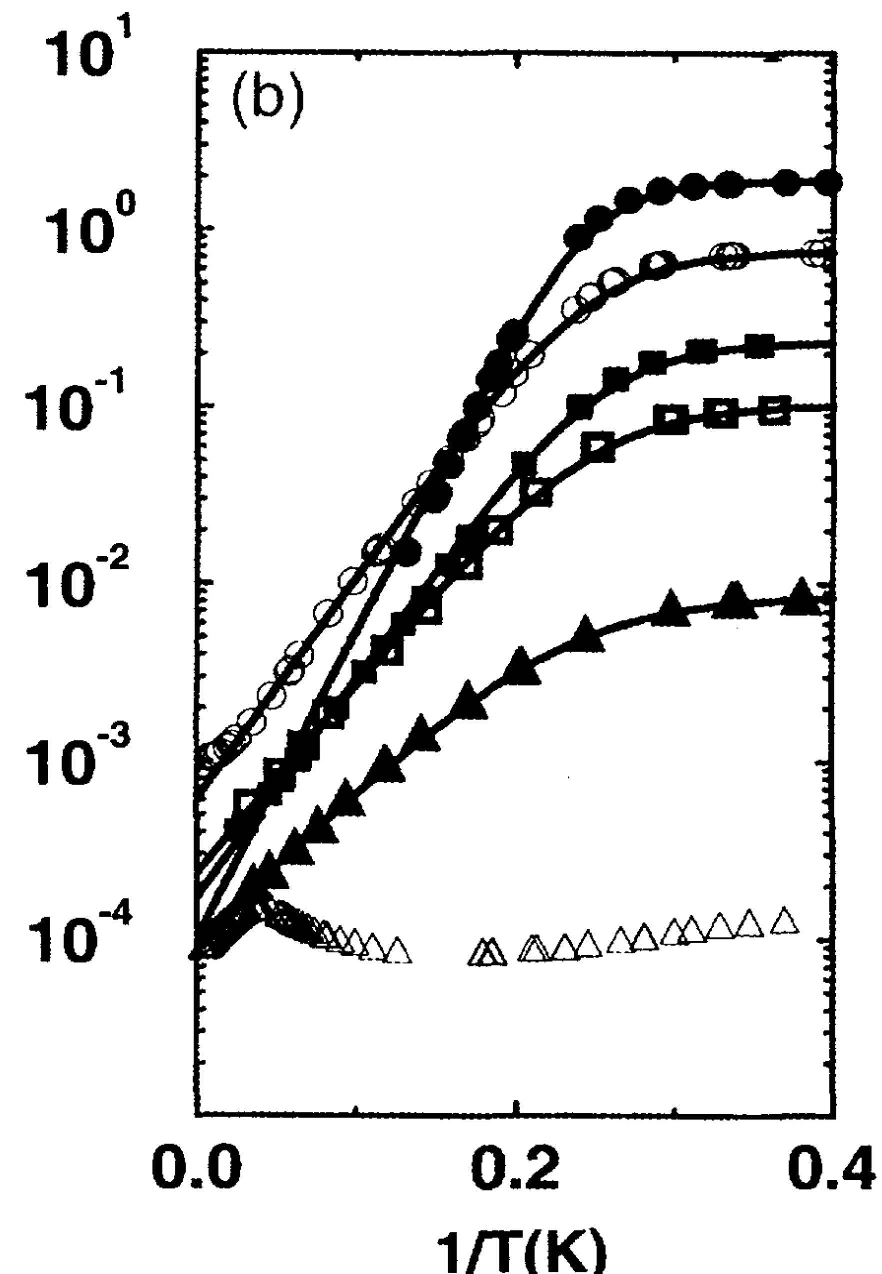
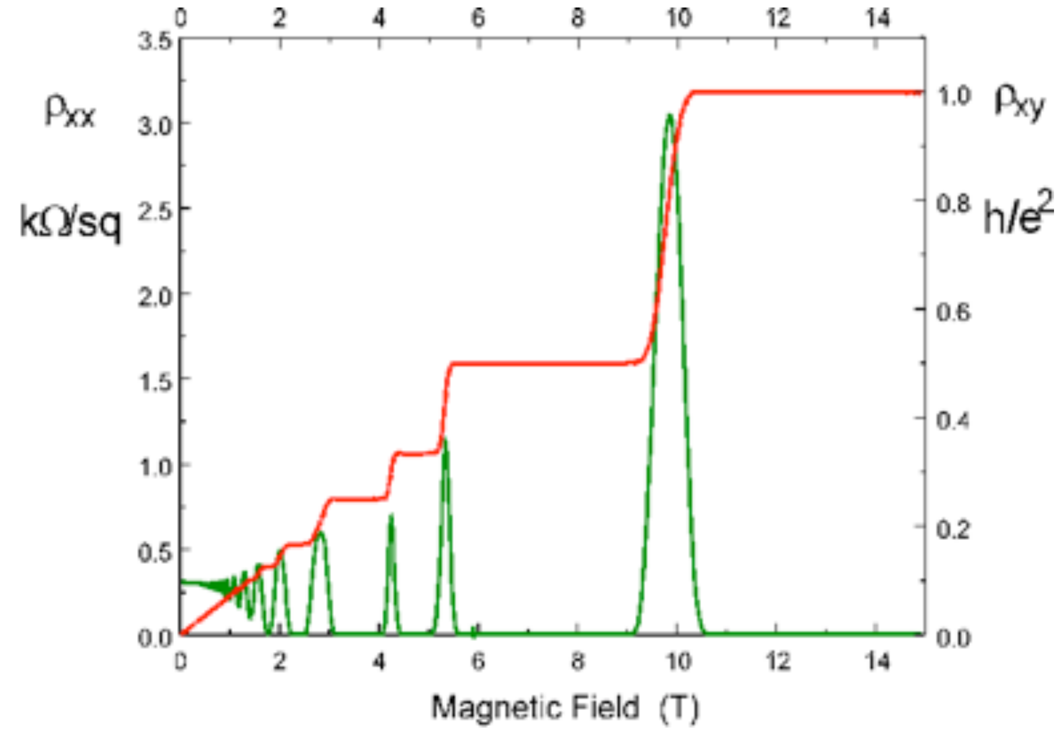
Persistent conductivity Plateau Cooley et al (1995)



Topological insulators.

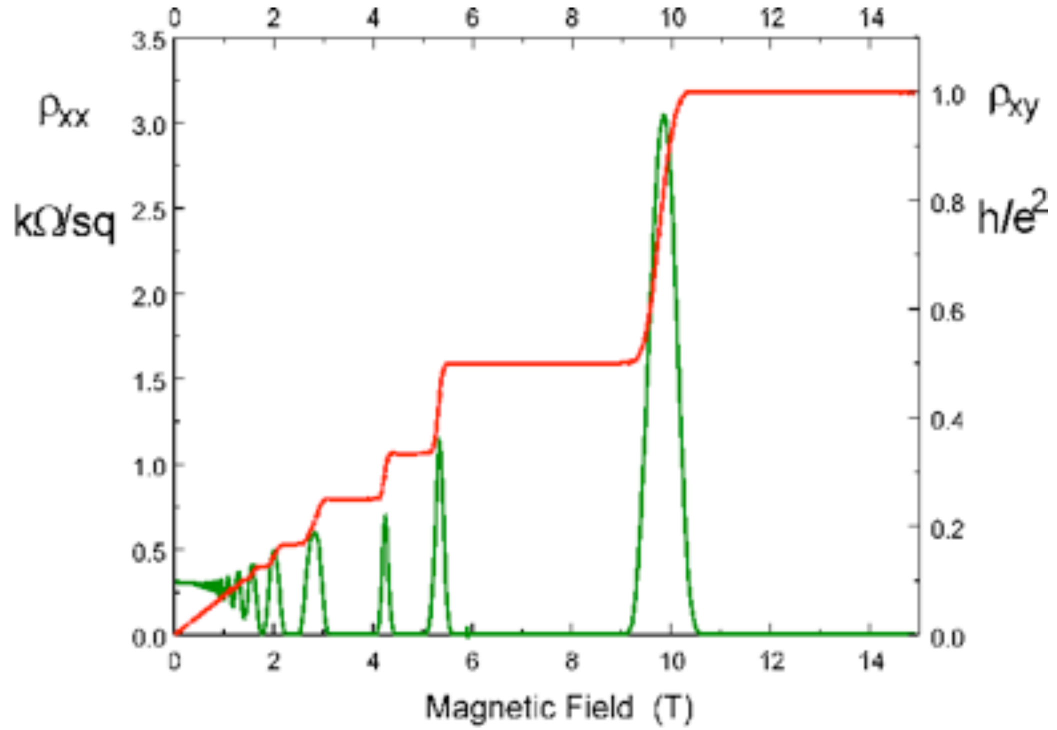
Hasan and Kane (RMP 2009)
Qi and Zhang (RMP 2010)

Differential Geometry of the wavefunction ⟷ Topological states of matter



von Klitzing, Dorda & Pepper (1980)

Differential Geometry of the wavefunction ⟷ Topological states of matter



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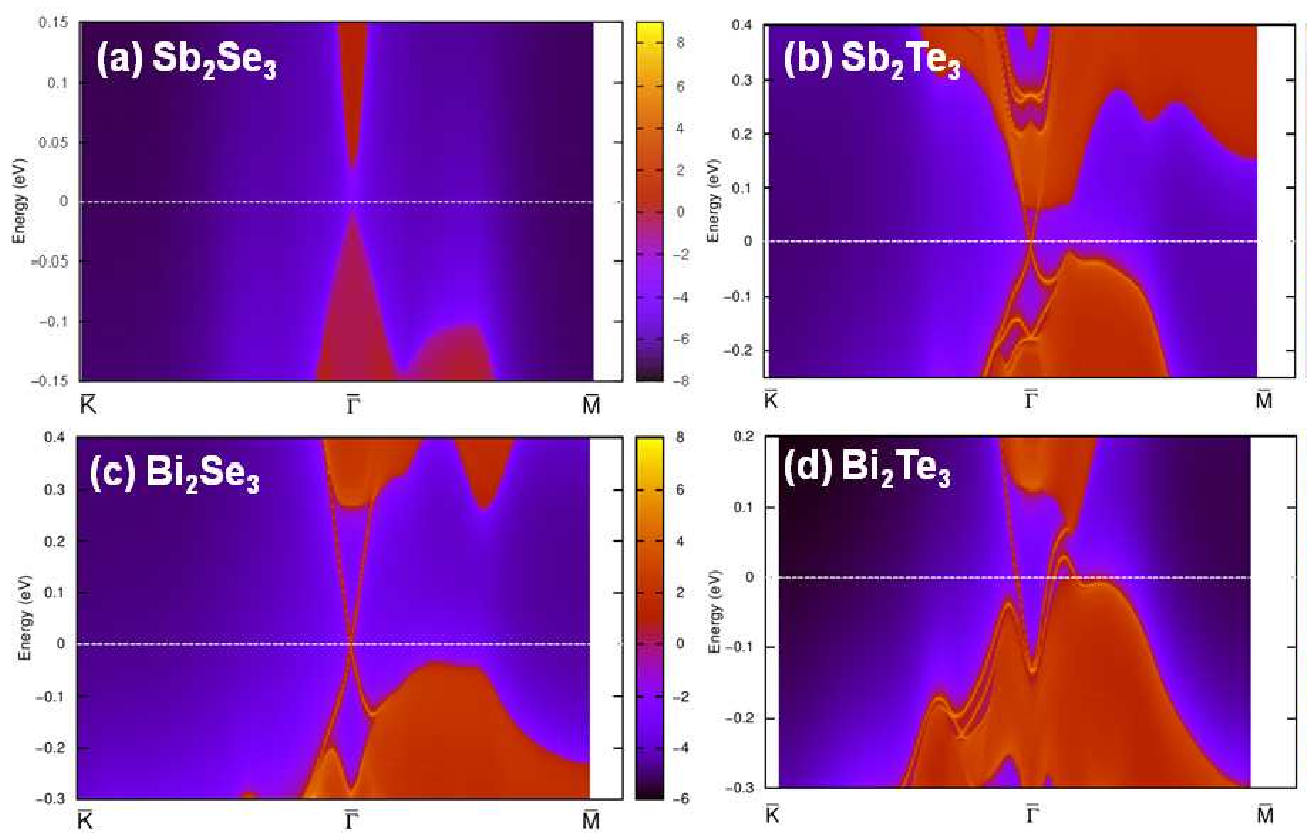
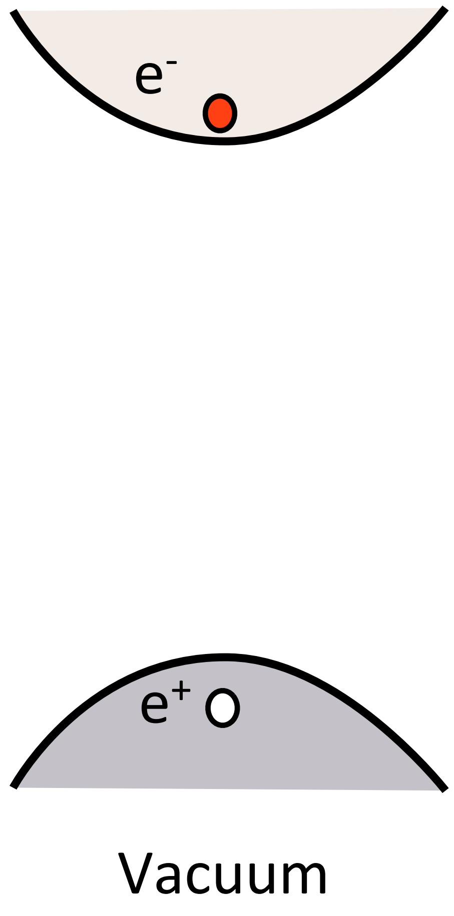
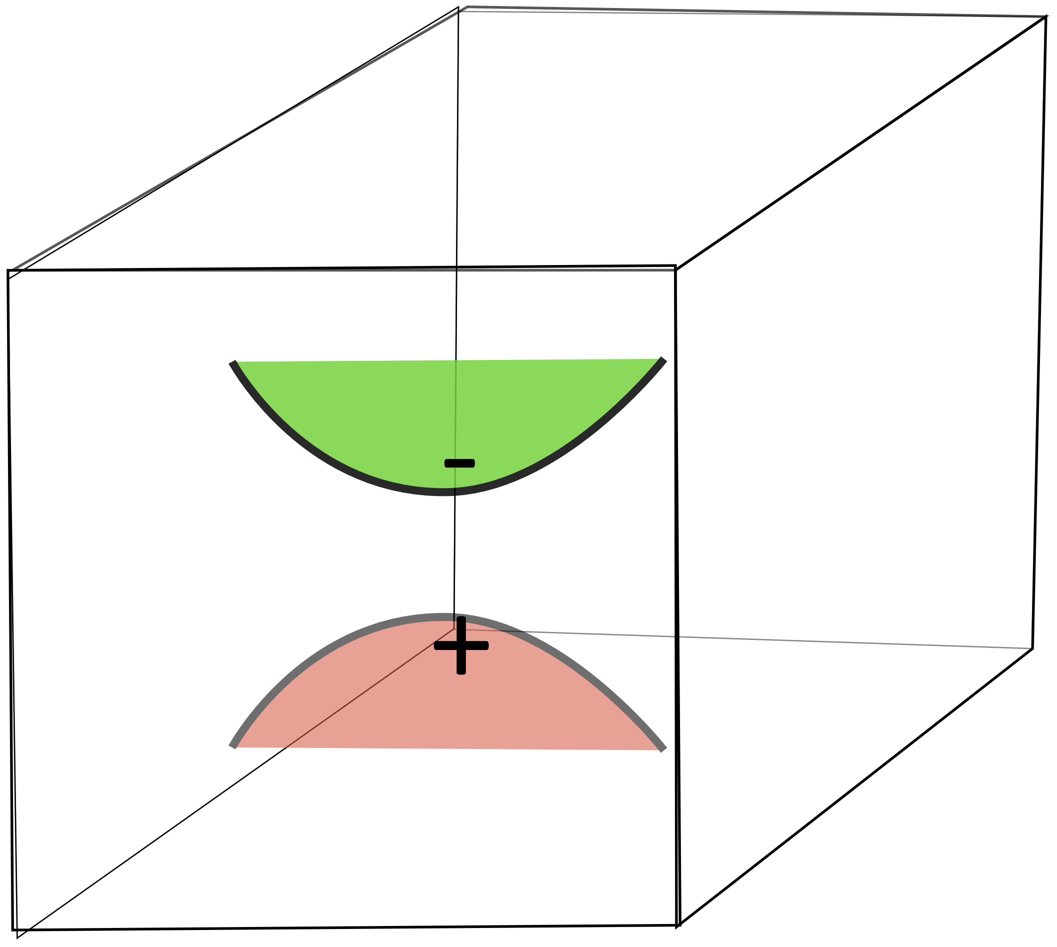
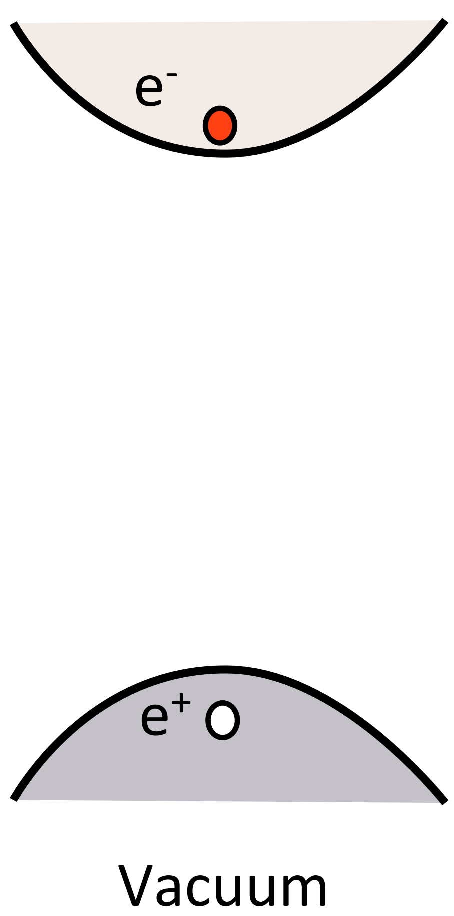


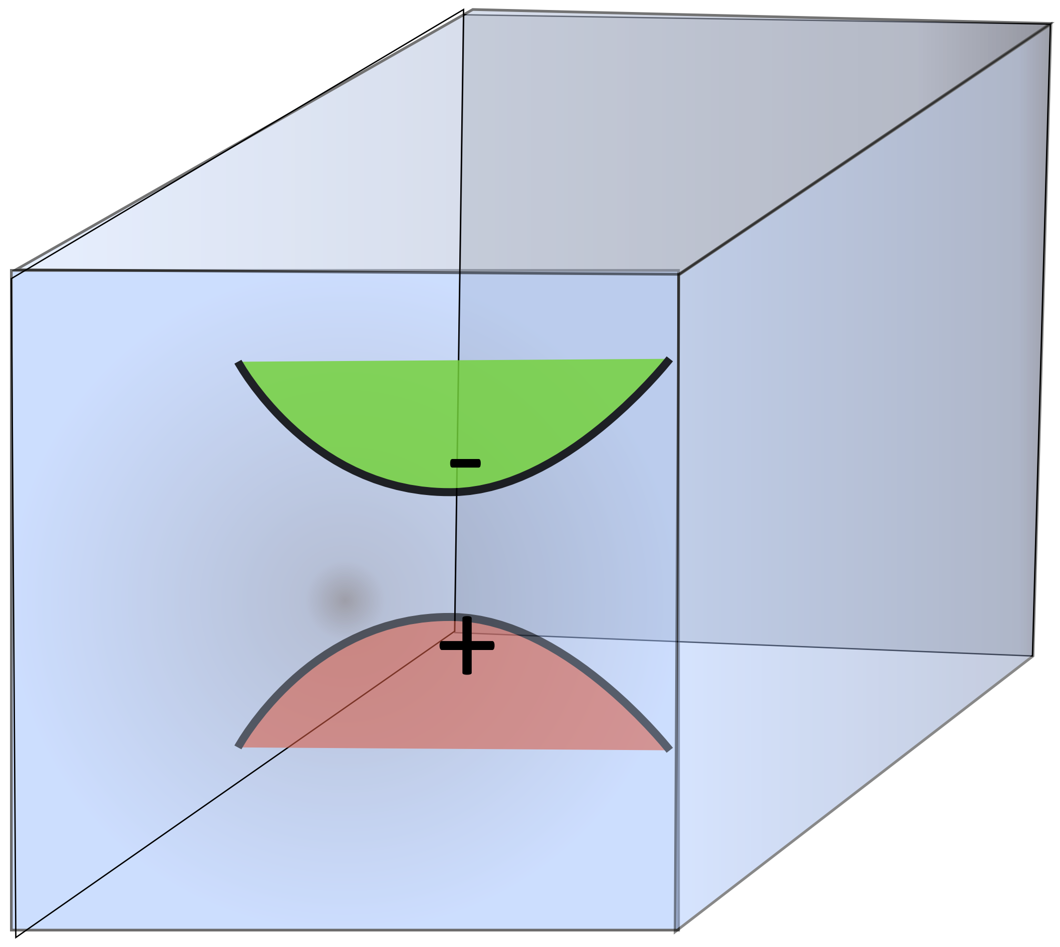
Qi and Zhang, Rev. Mod Phys (2010).


e-
e+
Vacuum

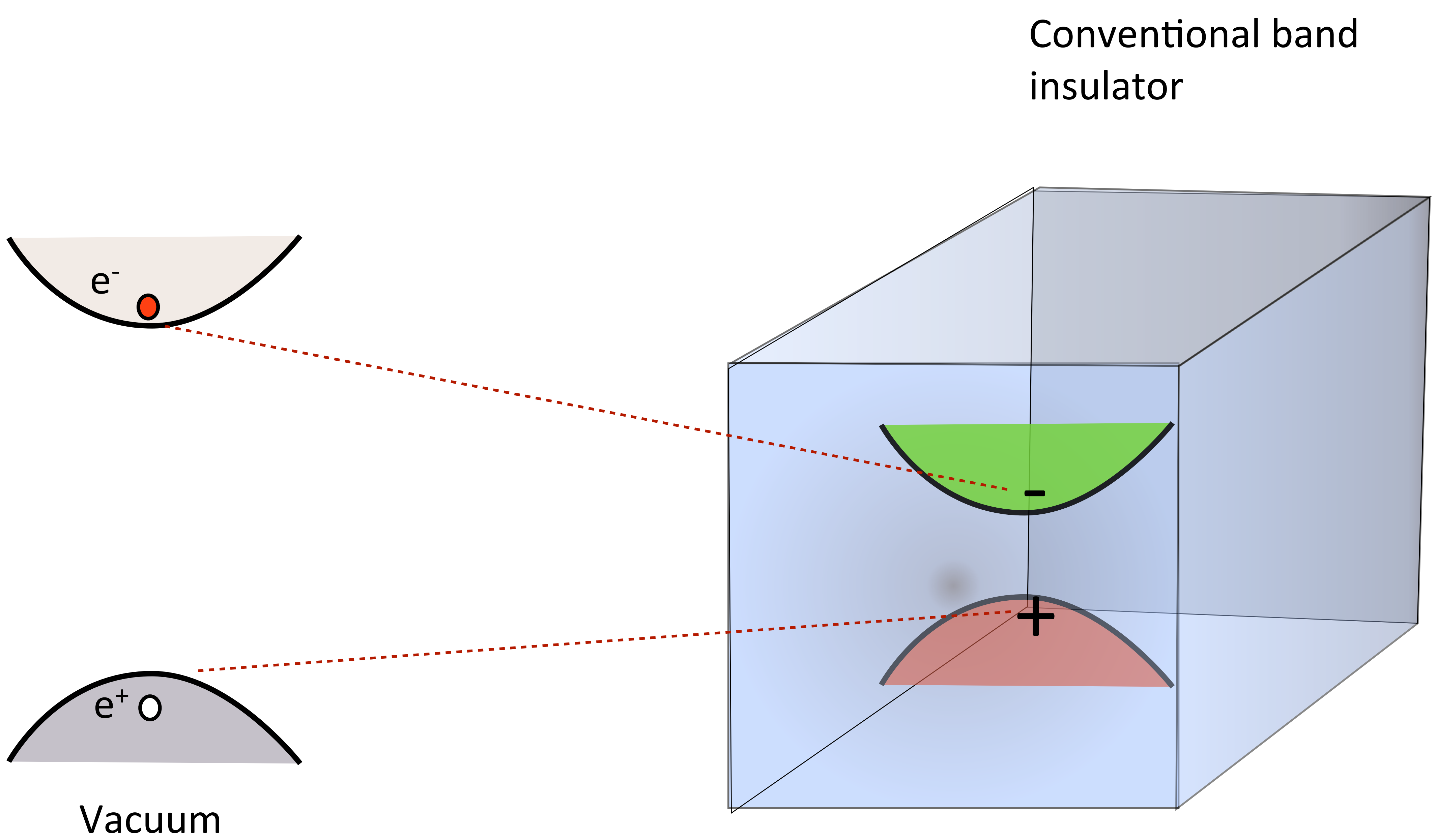

-
+



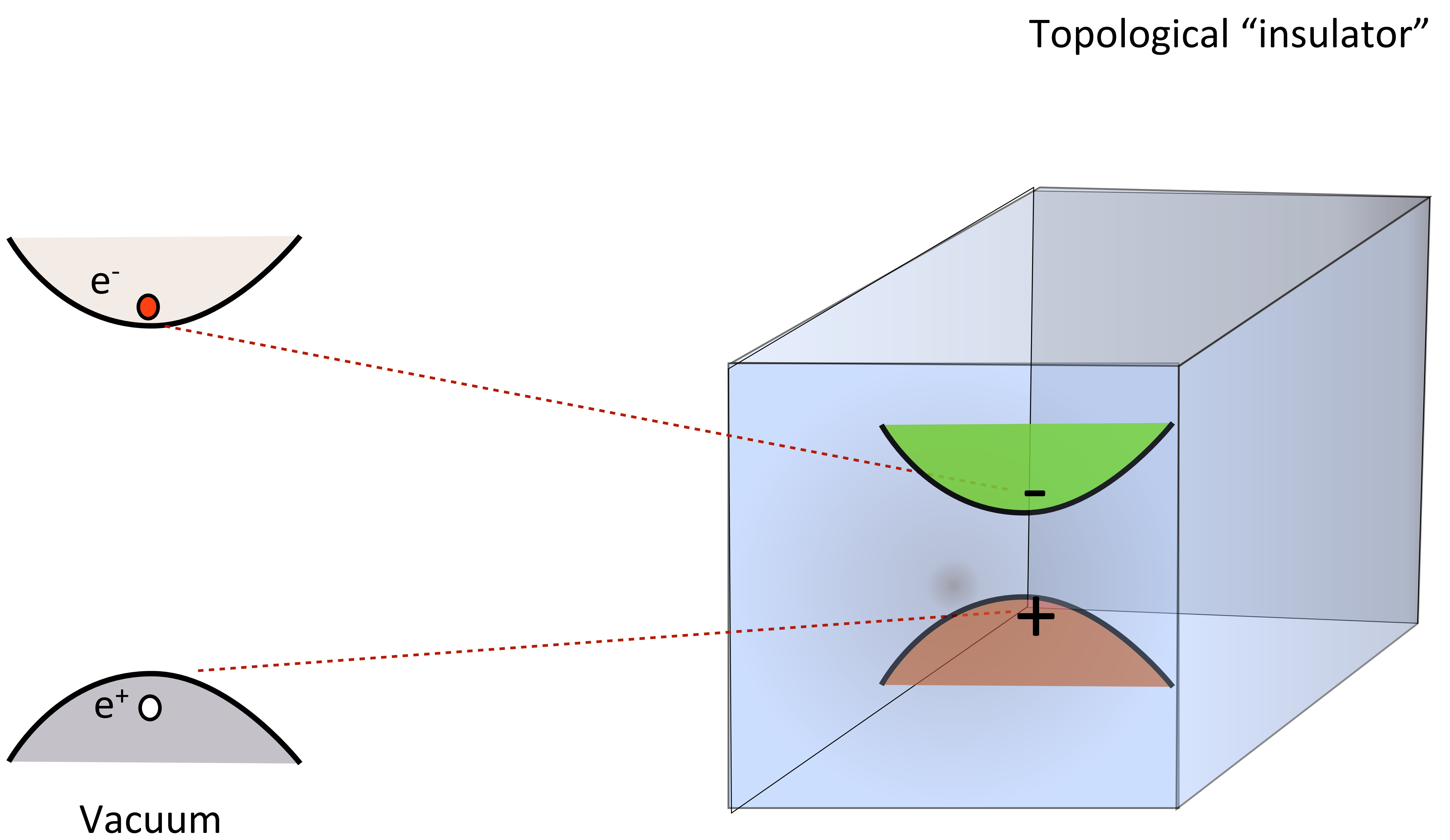
Conventional band insulator



Conventional band insulator:
adiabatic continuation of the vacuum.



Topological insulator: adiabatically disconnected to vacuum.



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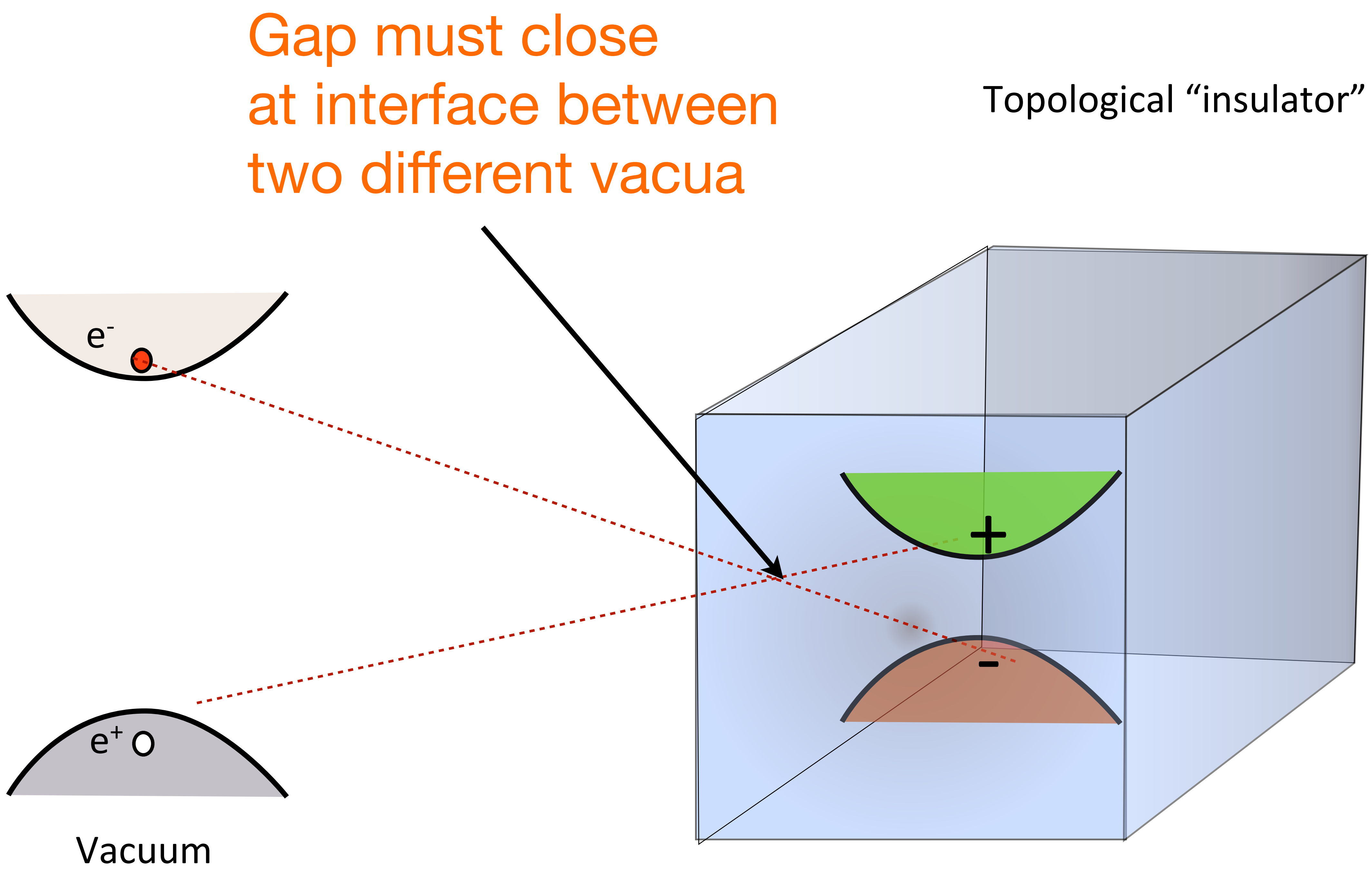

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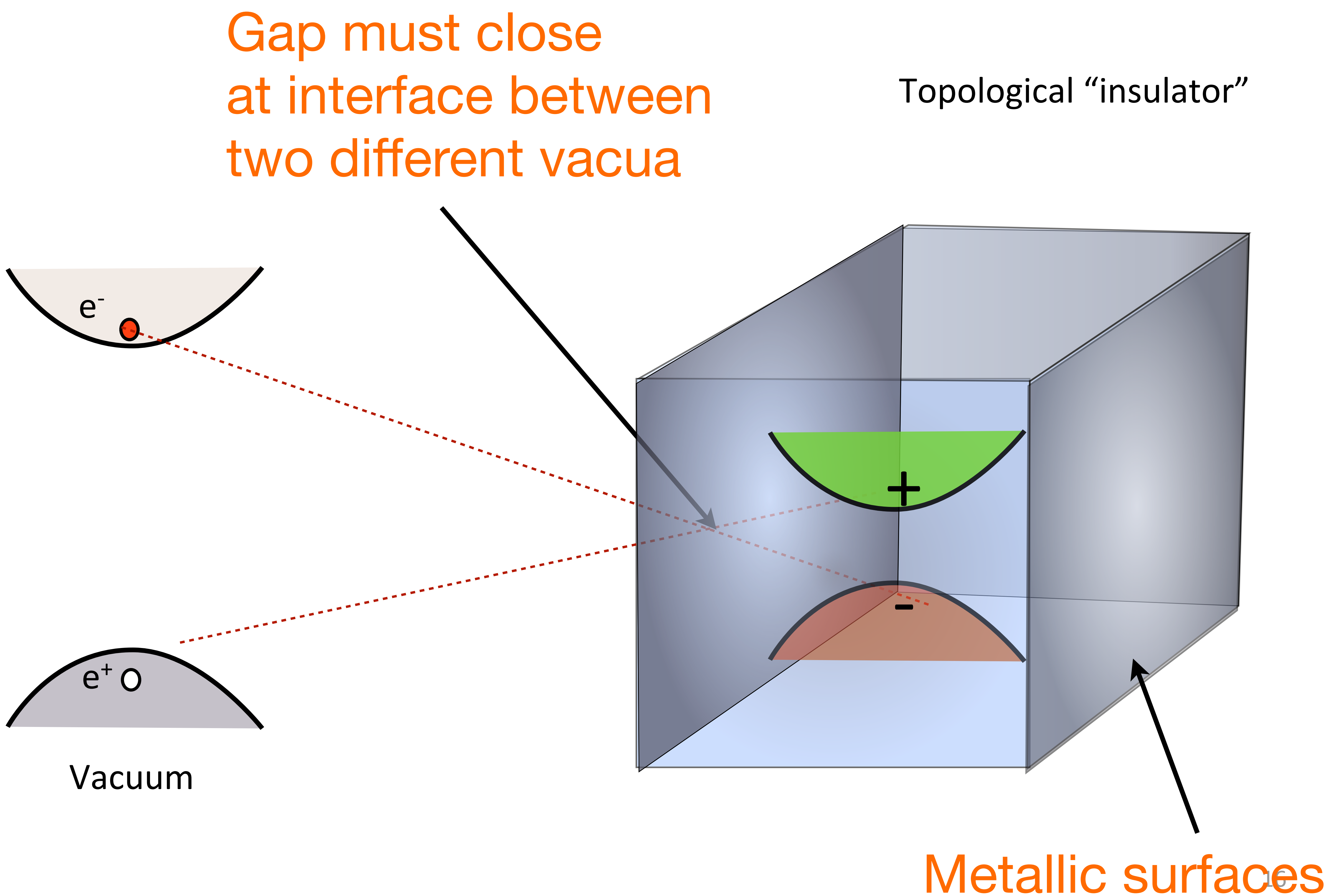


So are Kondo insulators topological?

Topological Kondo Insulators, Dzero, Sun, Galitski, PC Phys. Rev. Lett. **104**, 106408 (2010)

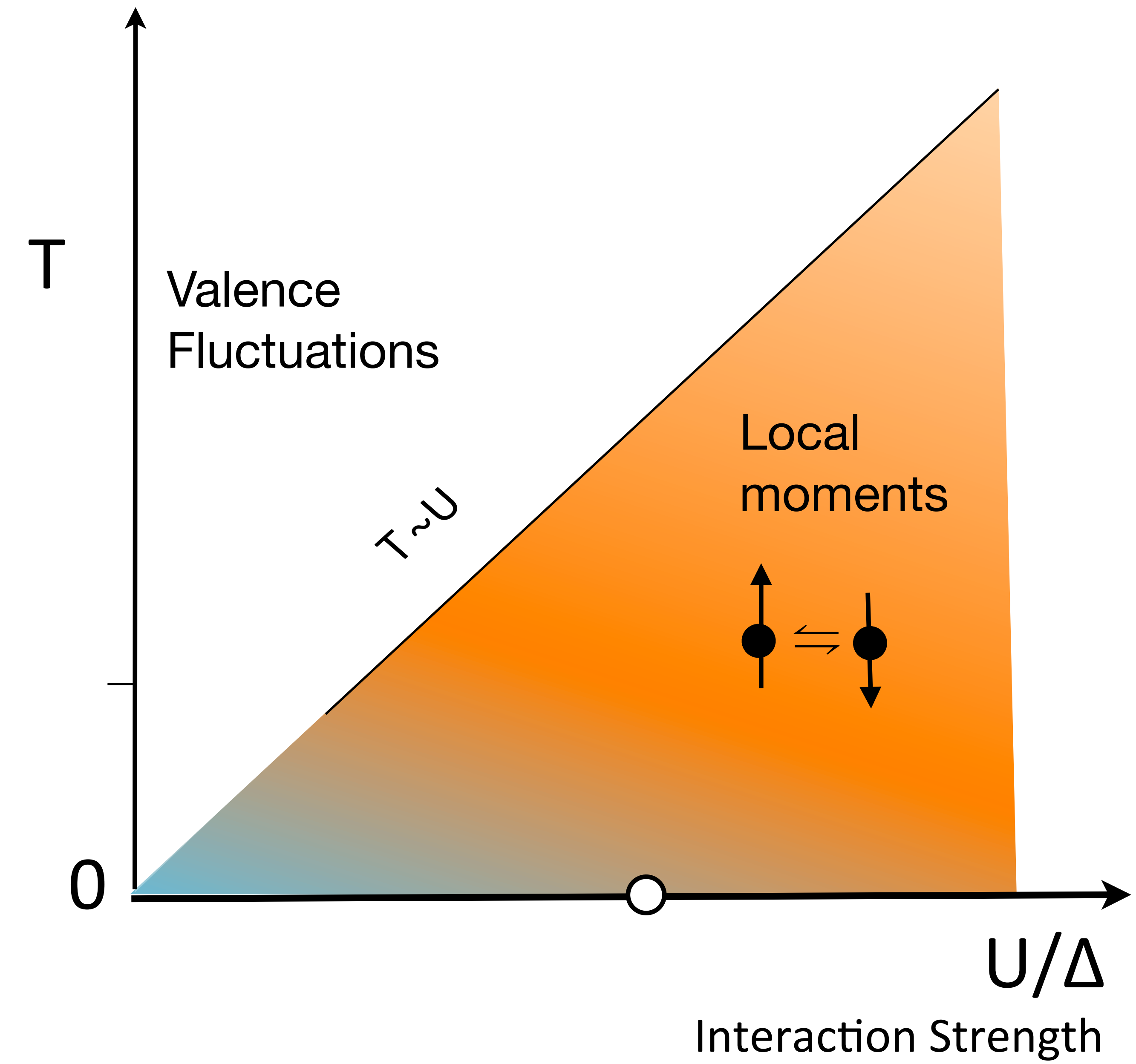
Maxim Dzero, Kai Sun, Piers Coleman and Victor Galitski, Phys. Rev. B 85 , 045130-045140 (2012).

Victor Alexandrov, Maxim Dzero and Piers Coleman preprint (2013).

Band Theory: T. Takimoto, J. Phys. Soc. Jpn. 80, 123710 (2011).

Gutzwiller + Band Theory F. Lu, J. Zhao, H. Weng, Z. Fang and X. Dai, Phys. Rev. Lett. 110, 096401 (2013).

Adiabatic Considerations about KI's



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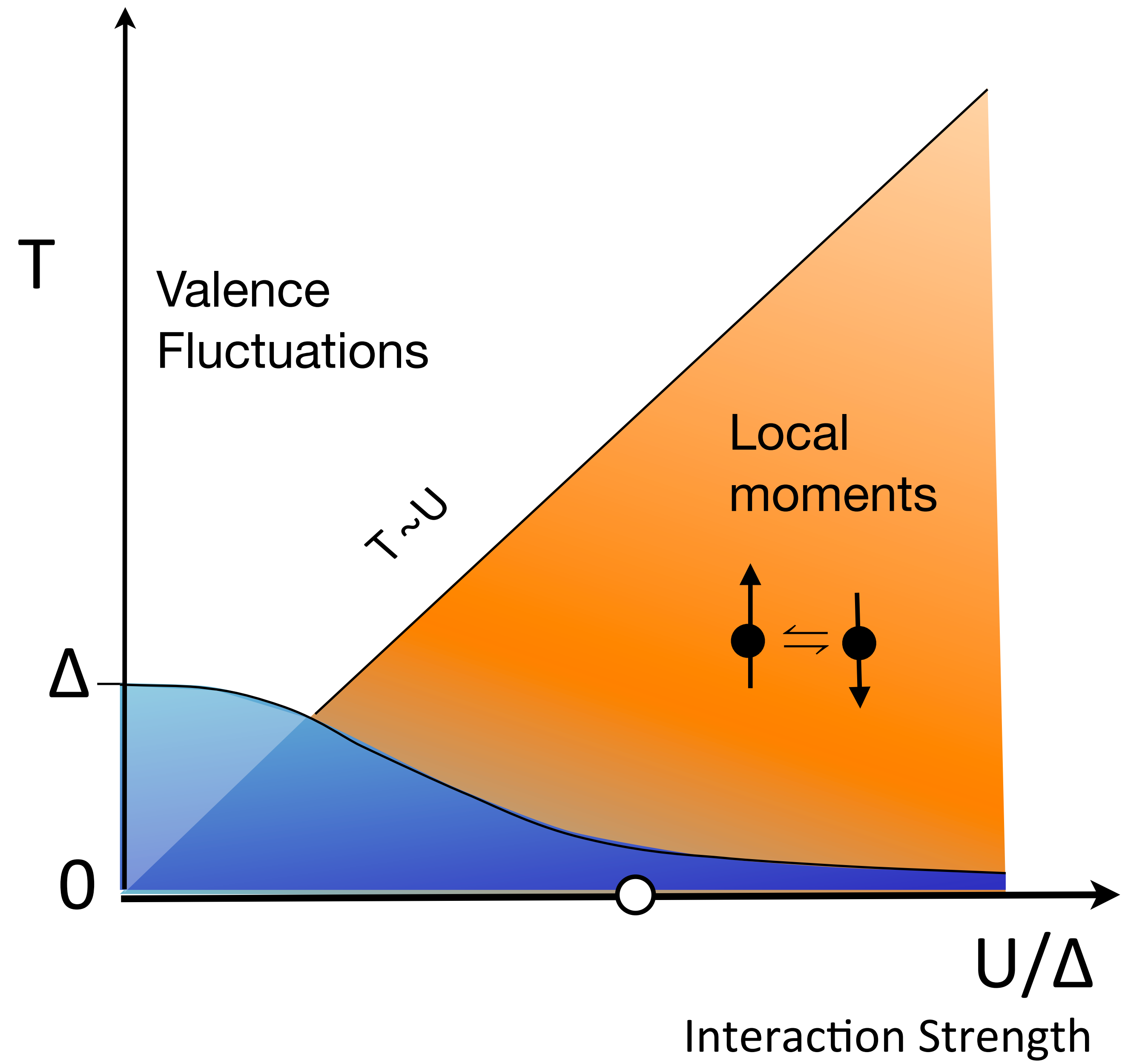

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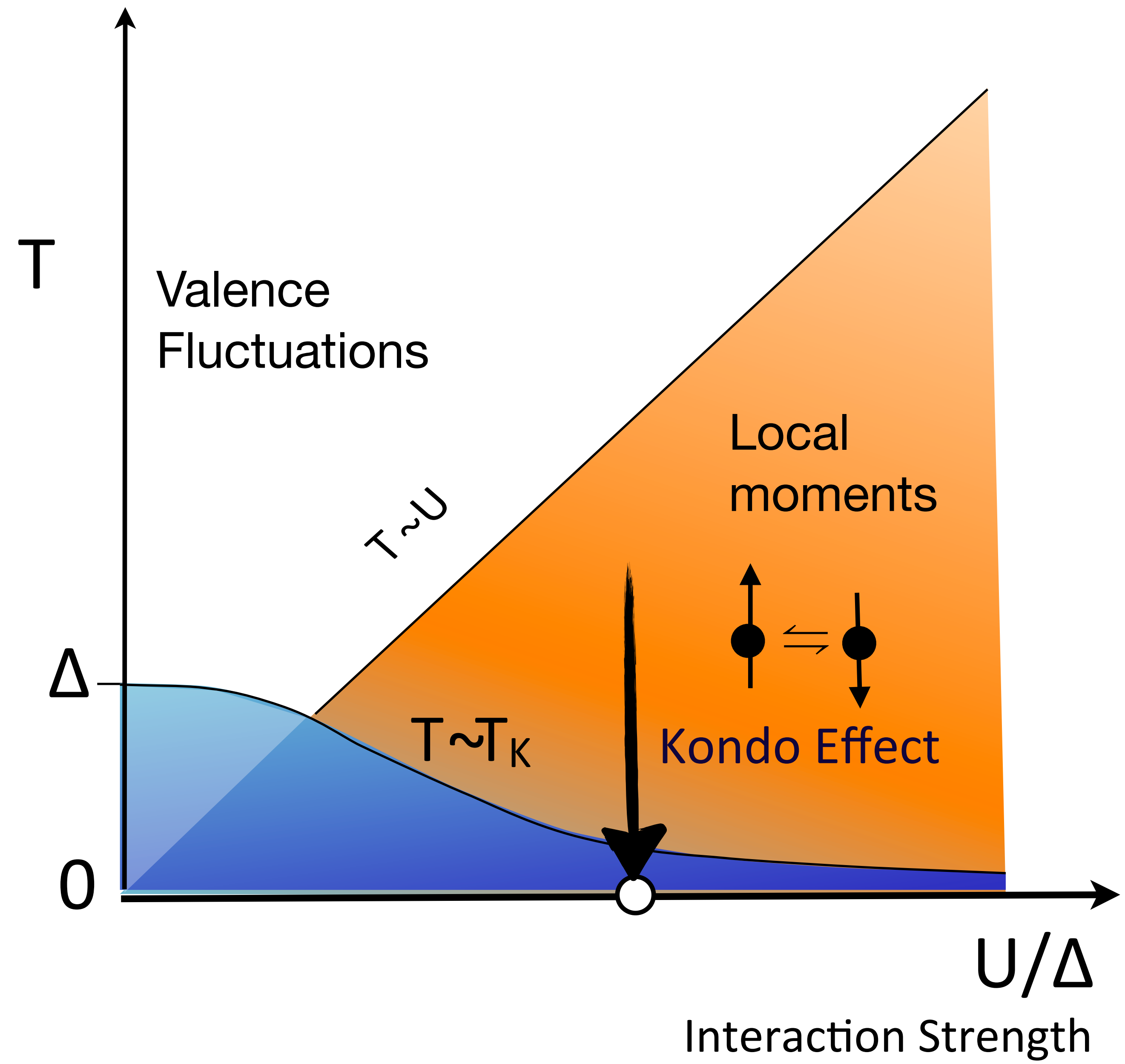

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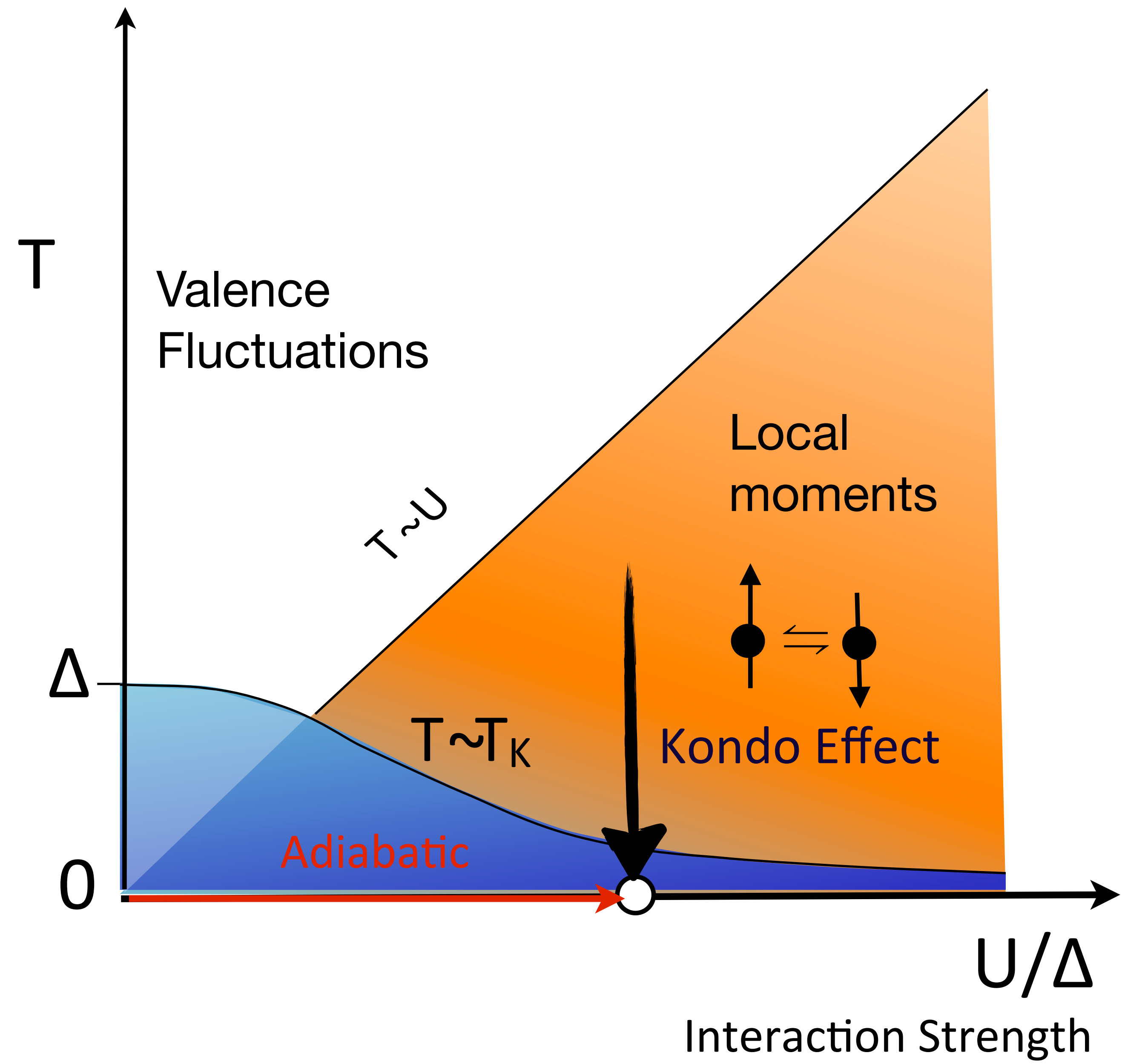

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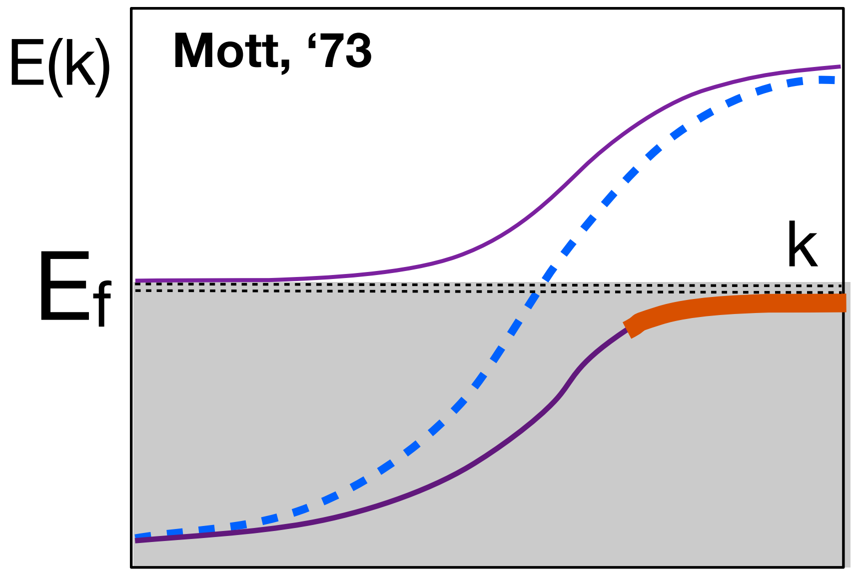

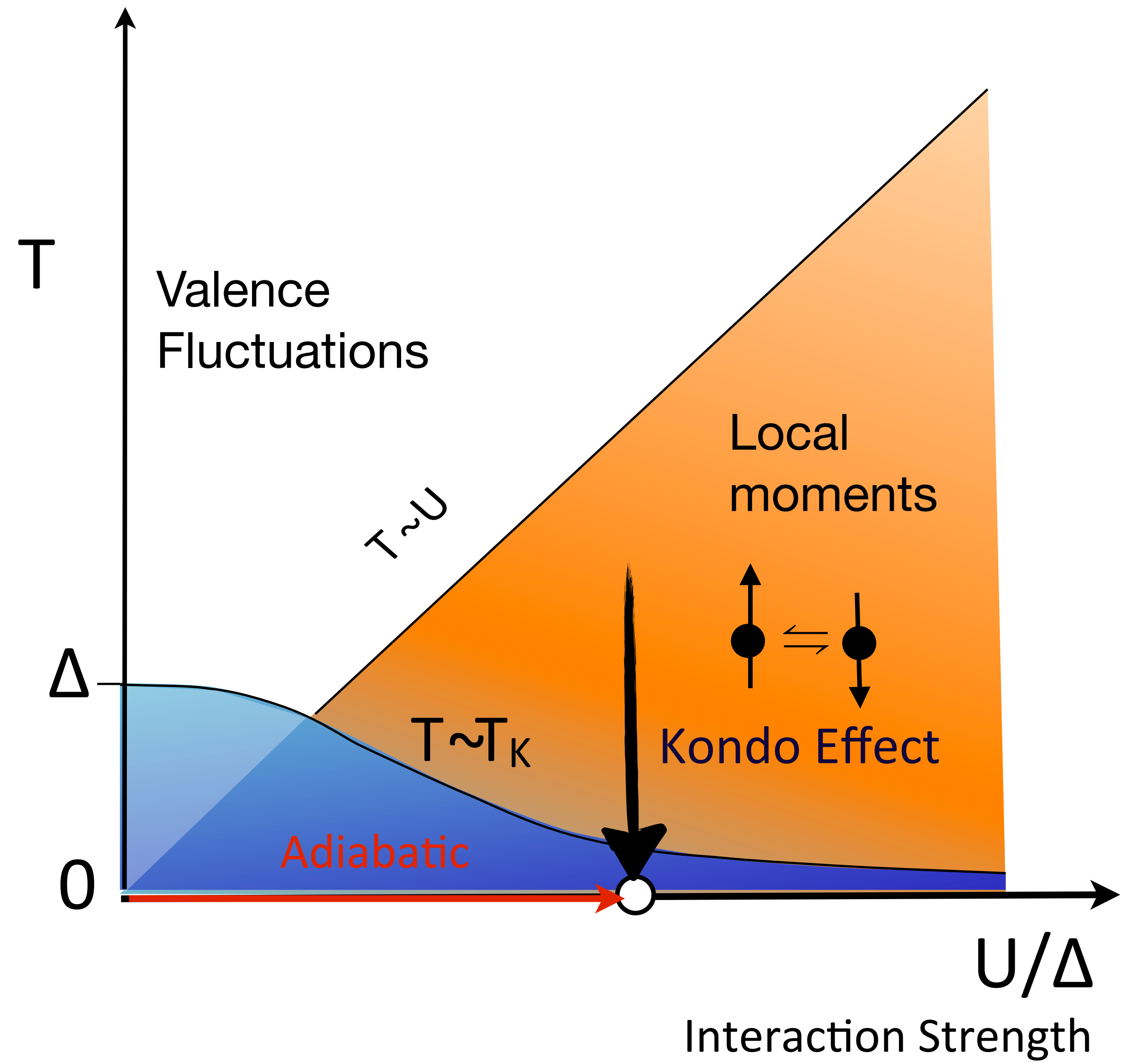

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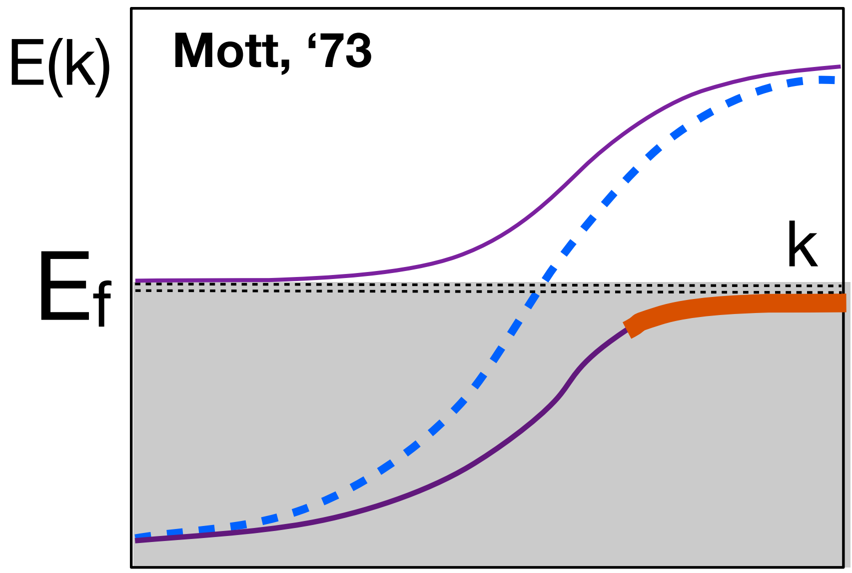

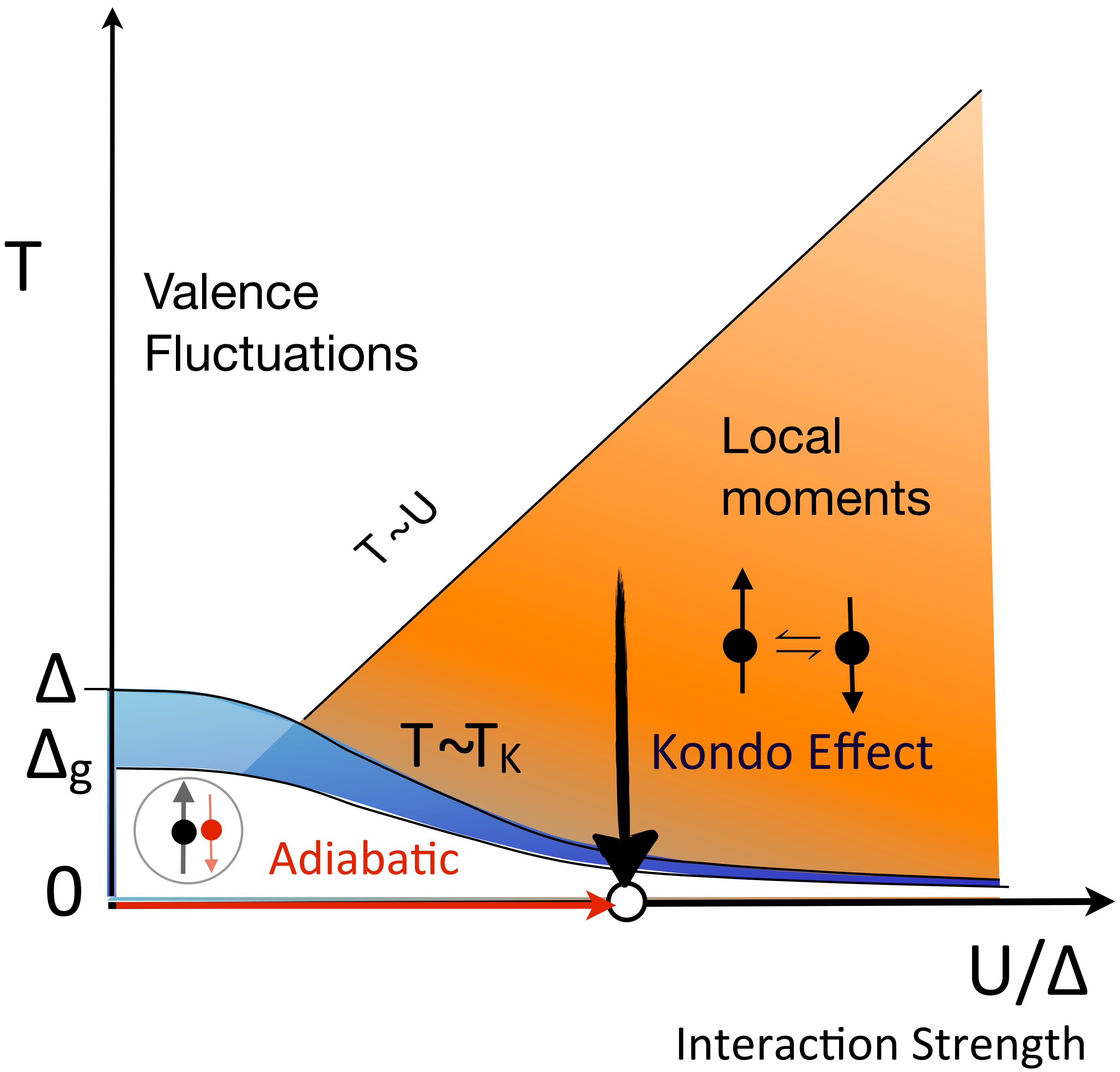

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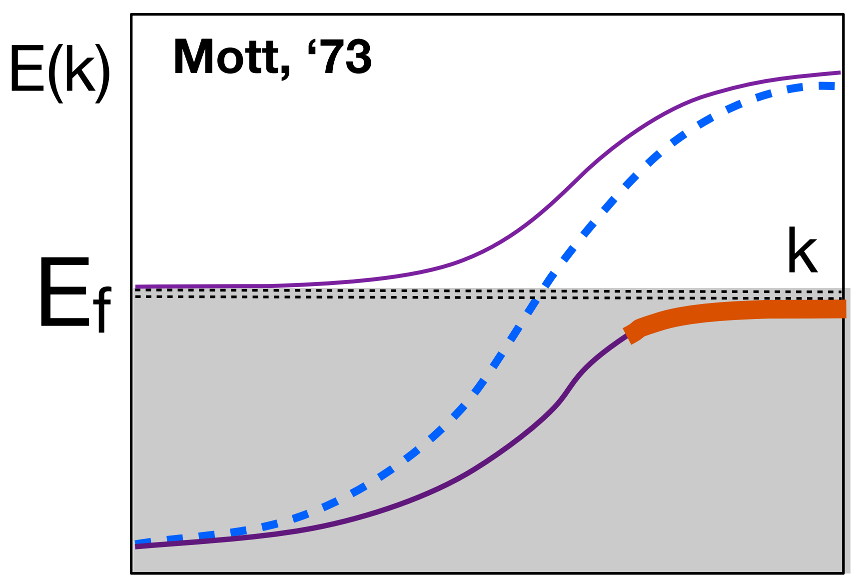
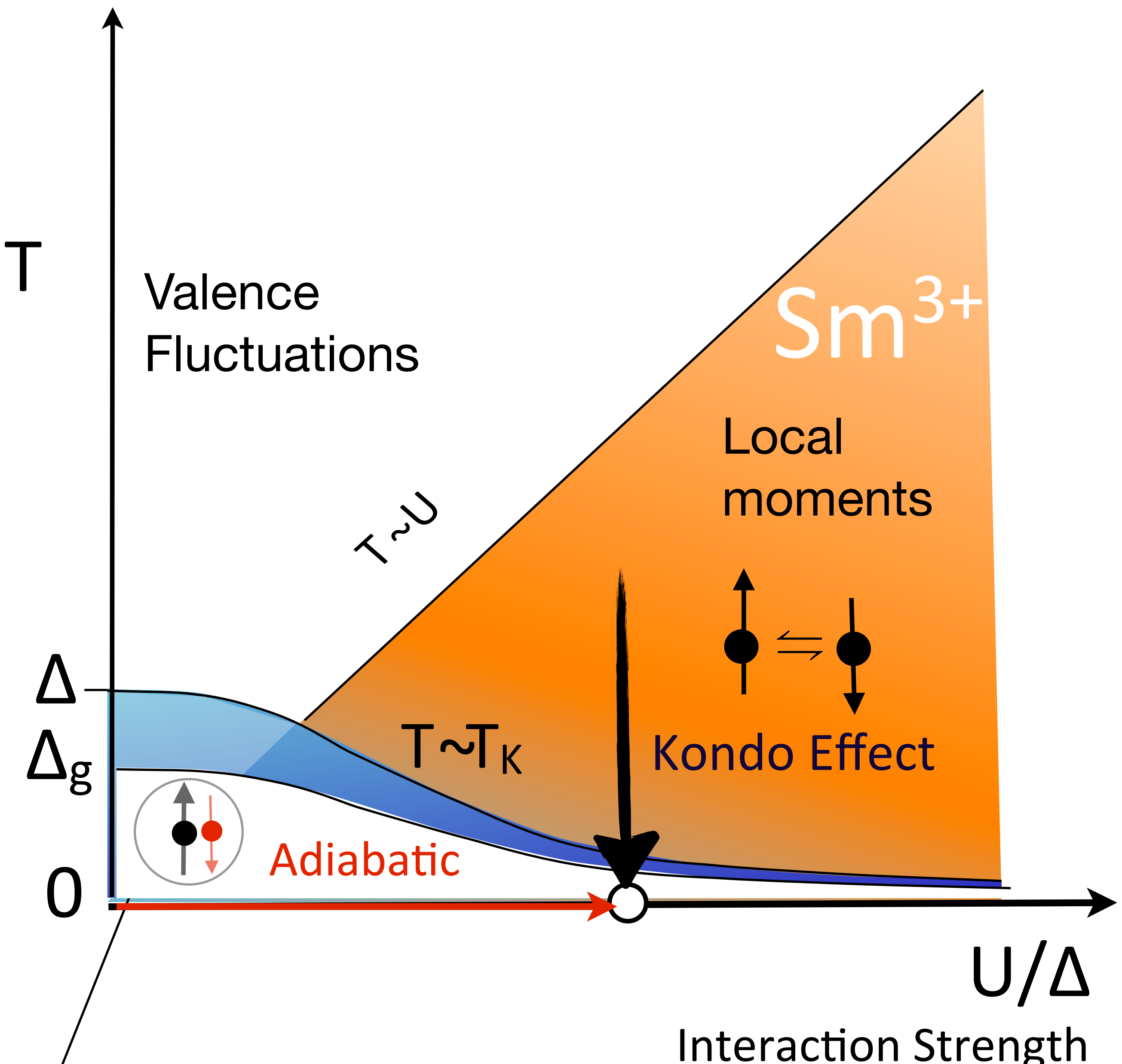
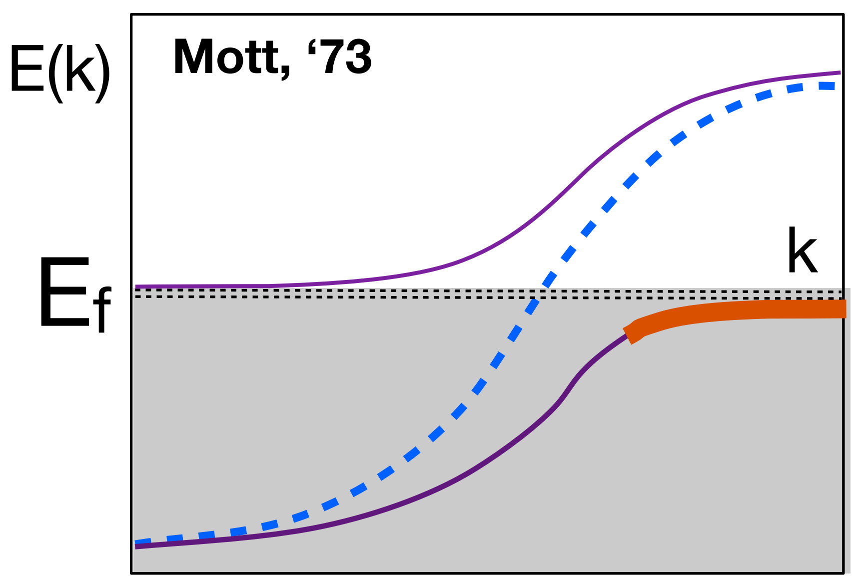
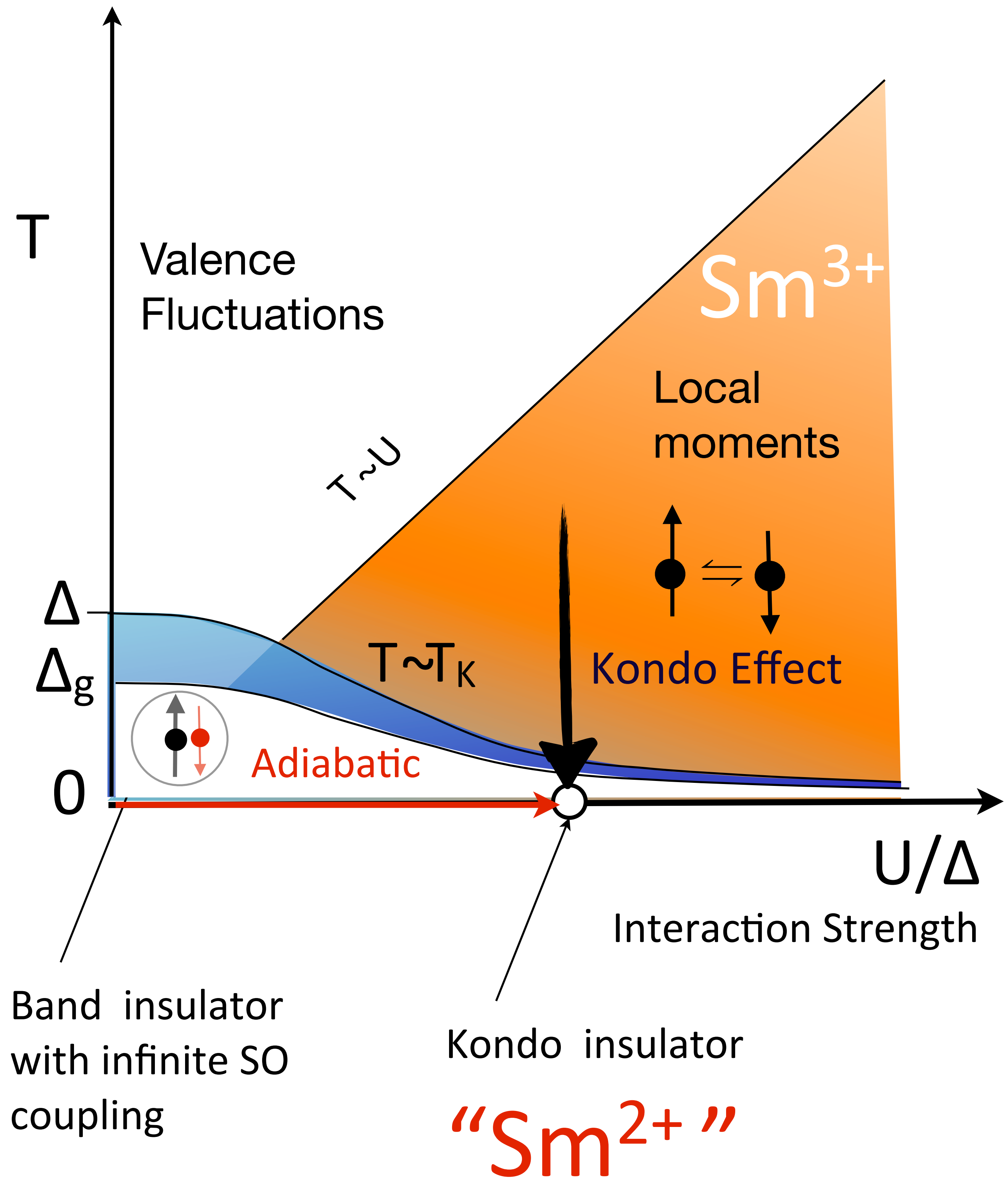




Band insulator with infinite SO coupling

Adiabatic Considerations about KI's





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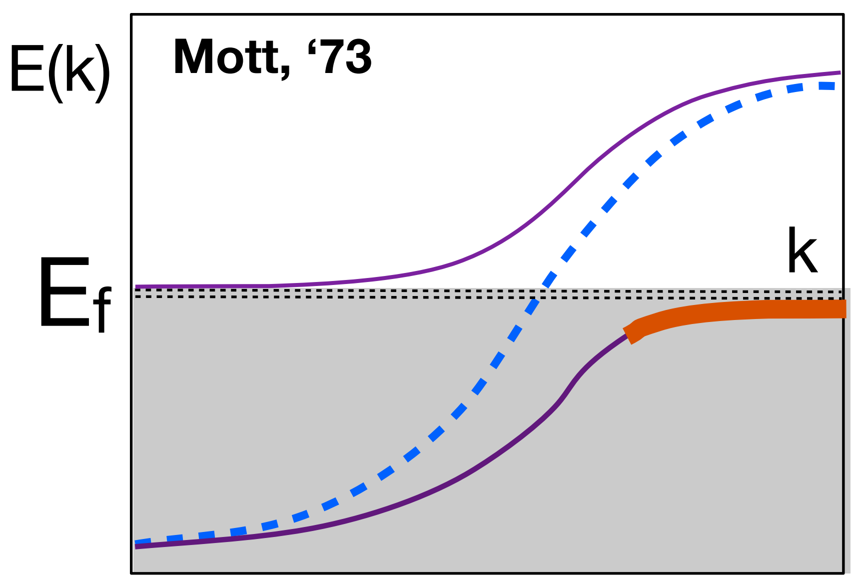

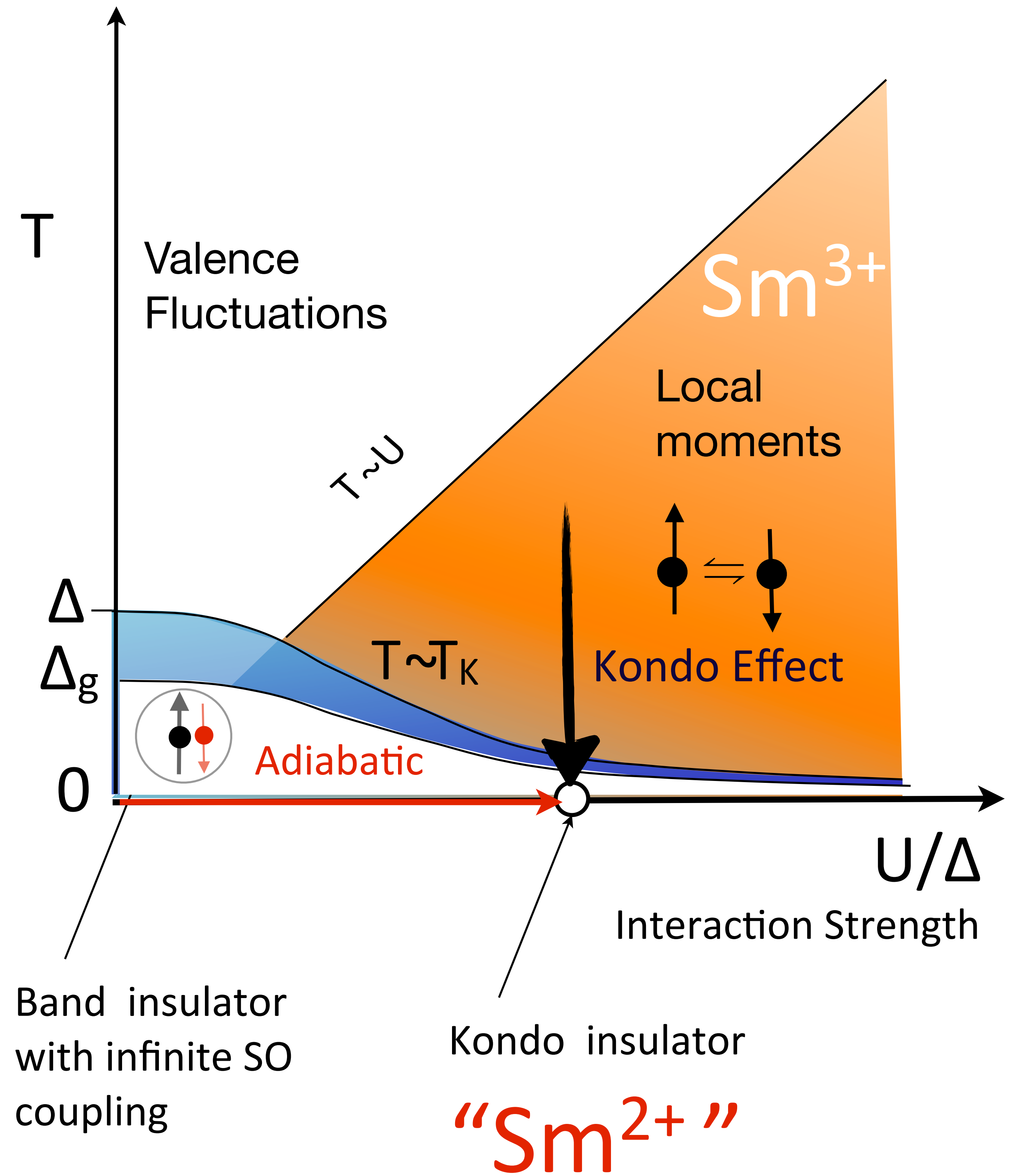

If f-states "sink" beneath the Fermi sea, does the Insulator become topological?

Kondo insulators: theory

- Anderson model:

$$\hat{H} = \sum_{\mathbf{k},\alpha} \xi_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + \sum_{j\alpha} \left[V \psi^\dagger_{j\alpha} f_\alpha + \text{h.c} \right] + \sum_{j\alpha} \left[E_f^{(0)} n_{f\alpha} + \frac{U_f}{2} n_{f,j\alpha} n_{f,j\bar{\alpha}} \right]$$

$$\psi_{j\alpha} = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \underbrace{\Phi_{\alpha\sigma}(\hat{\mathbf{k}})}_{\text{f-electron form factor}} e^{-i\mathbf{k}\cdot\mathbf{x}_j} c_{\mathbf{k}\sigma}$$

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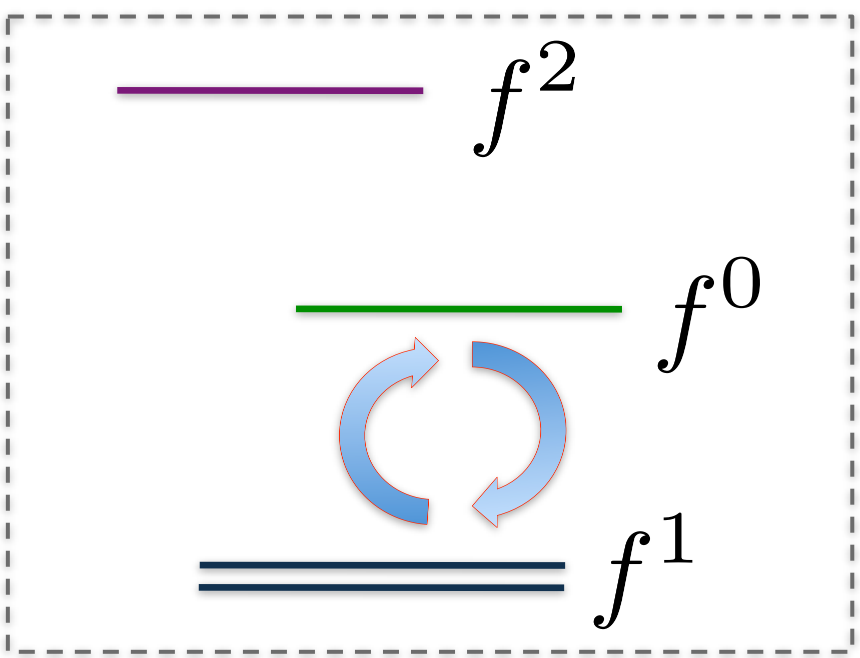
- Hybridization



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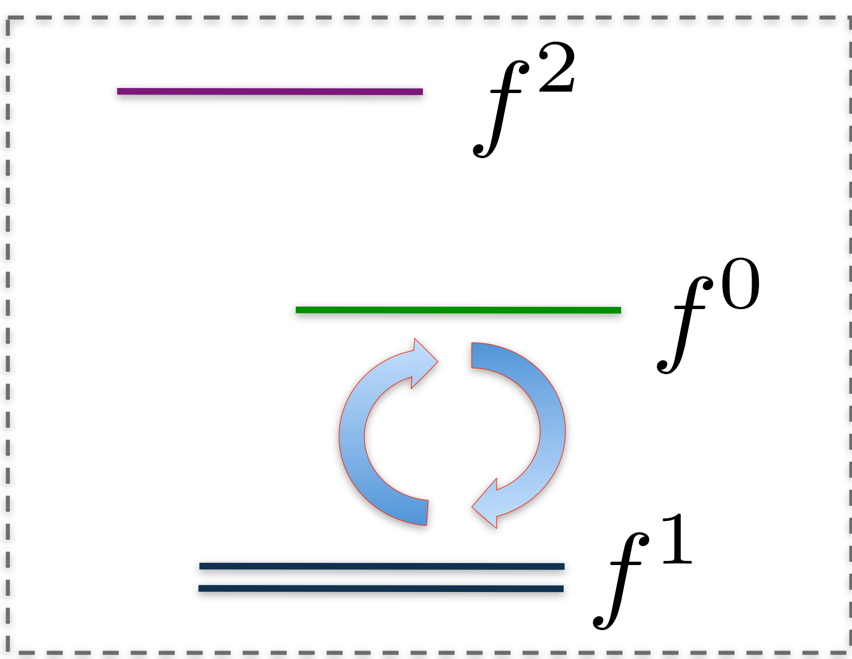

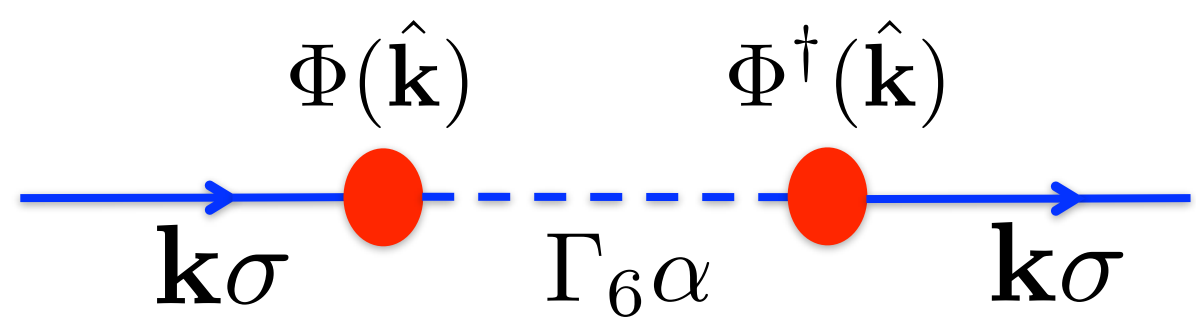

Strong spin-orbit coupling is encoded in the hybridization.

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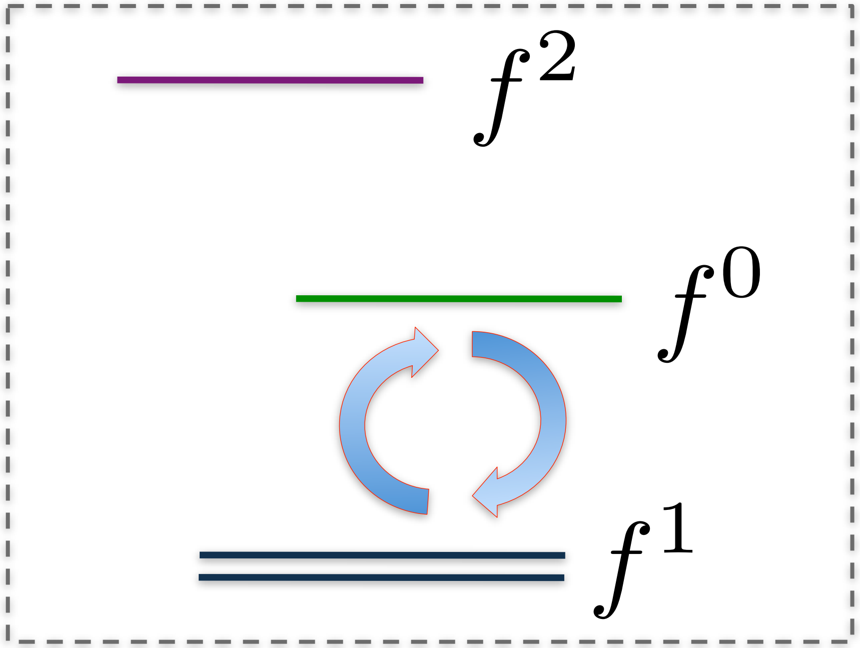

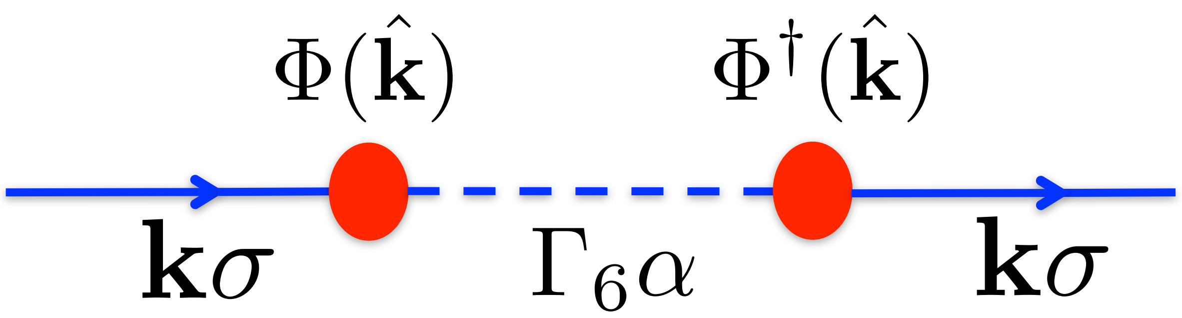

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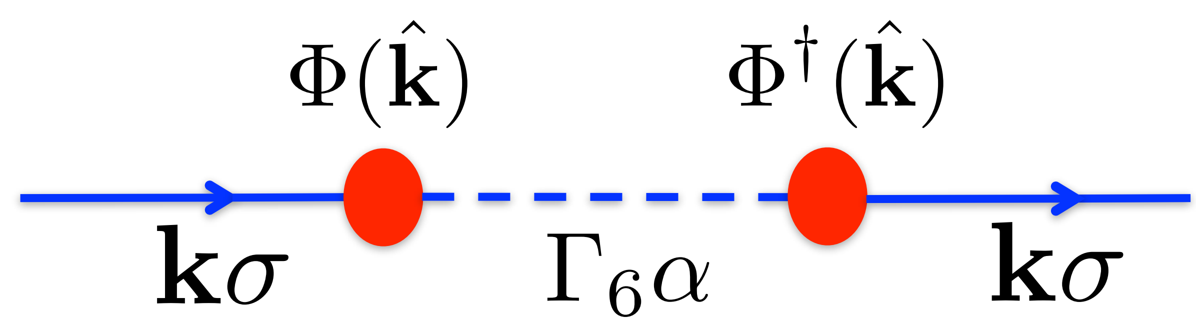
f-electron
form factor

form factors:

$$[\Phi_{\Gamma\mathbf{k}}]_{\alpha\sigma} = \sum_{m} \langle \Gamma\alpha | jm \rangle \underbrace{\langle jm | \mathbf{k}\sigma \rangle}_{\text{Matrix element between Bloch and Wannier states}}$$

Matrix element between
Bloch and Wannier states



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Matrix element between Bloch and Wannier states

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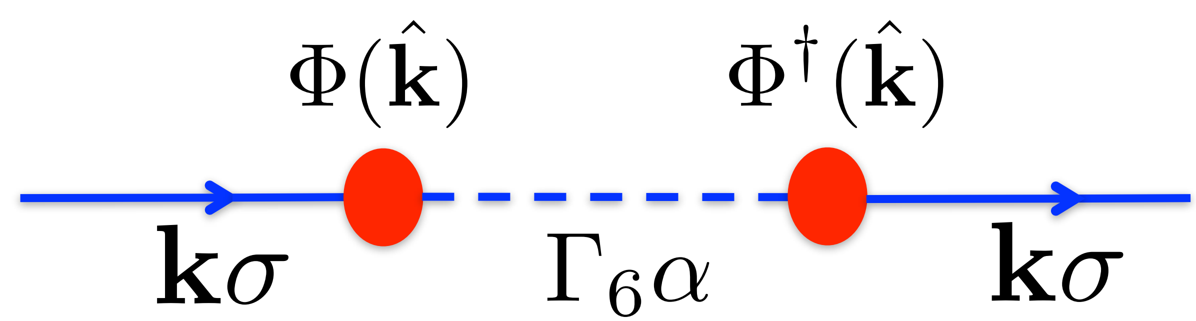

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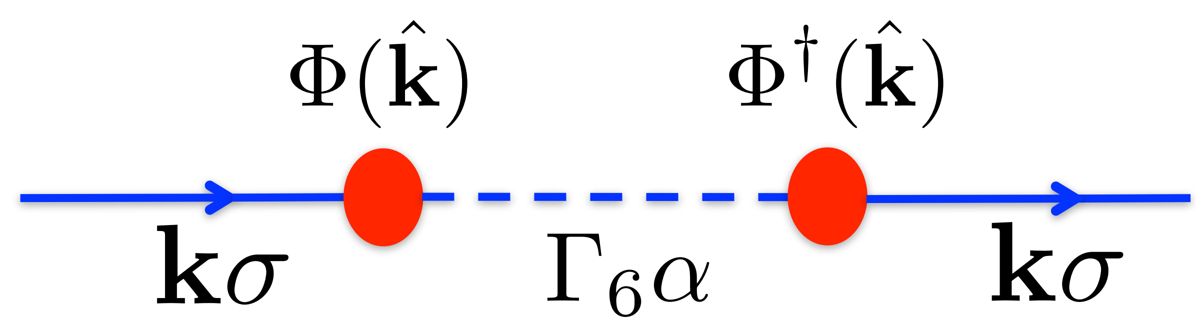

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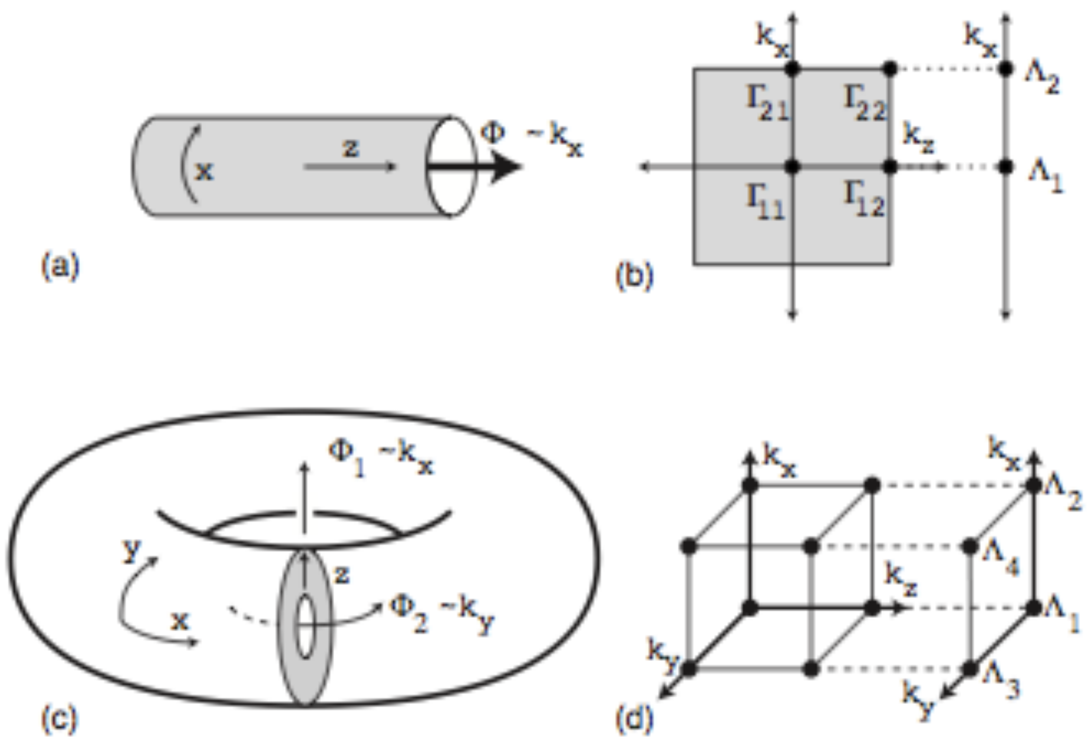
ODD PARITY!

Topological insulators

L. Fu & C. Kane, “Topological Insulators with Inversion Symmetry”, PRB 76, 45302 (2007).

Response to a fictitious applied flux



- 2D: Flux plays the role of the edge crystal momentum k_x

- 3D: two fluxes corresponding to two components of the surface crystal momentum

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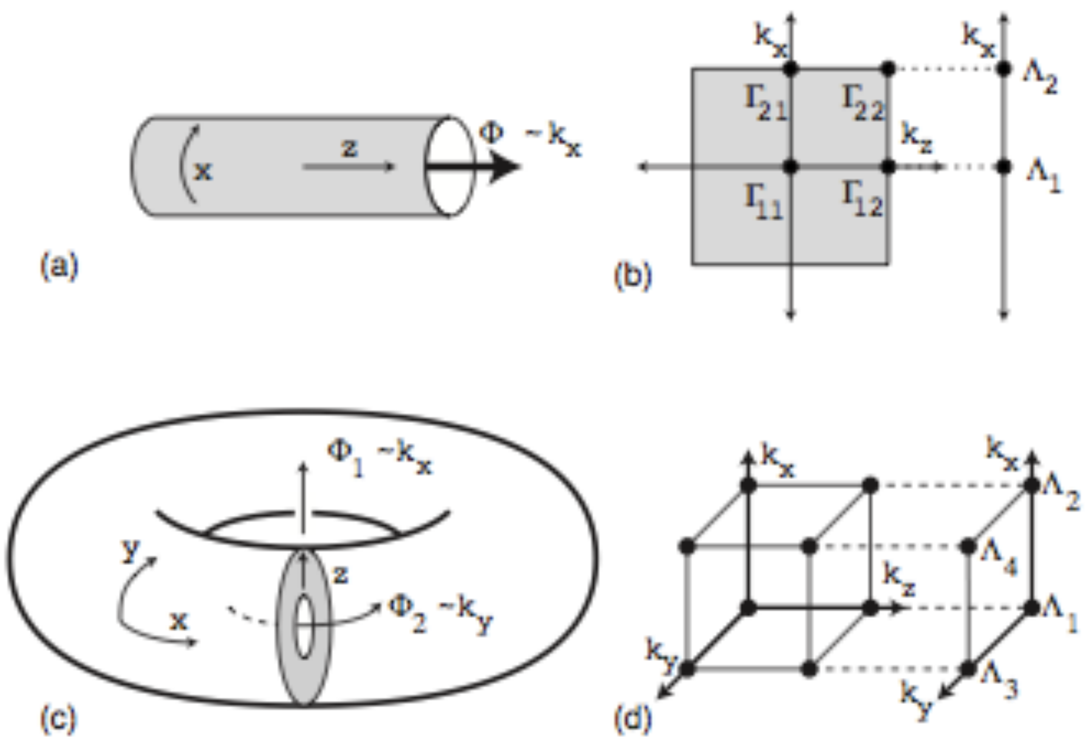

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Z_2 invariants computed from the **parity** of the occupied bands at high SPs.
Change in time reversal polarization due to changes in bulk Hamiltonian

$$Z_2 = \prod_i \delta(\Gamma_i)$$

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$$V_{\alpha\sigma}(\mathbf{k_m}) = V_{\alpha\sigma}(\mathbf{k_m} + \mathbf{G}) = -V_{\alpha\sigma}(-\mathbf{k_m}) = -V_{\alpha\sigma}(\mathbf{k_m}) = 0$$

Vanishes at high symmetry points

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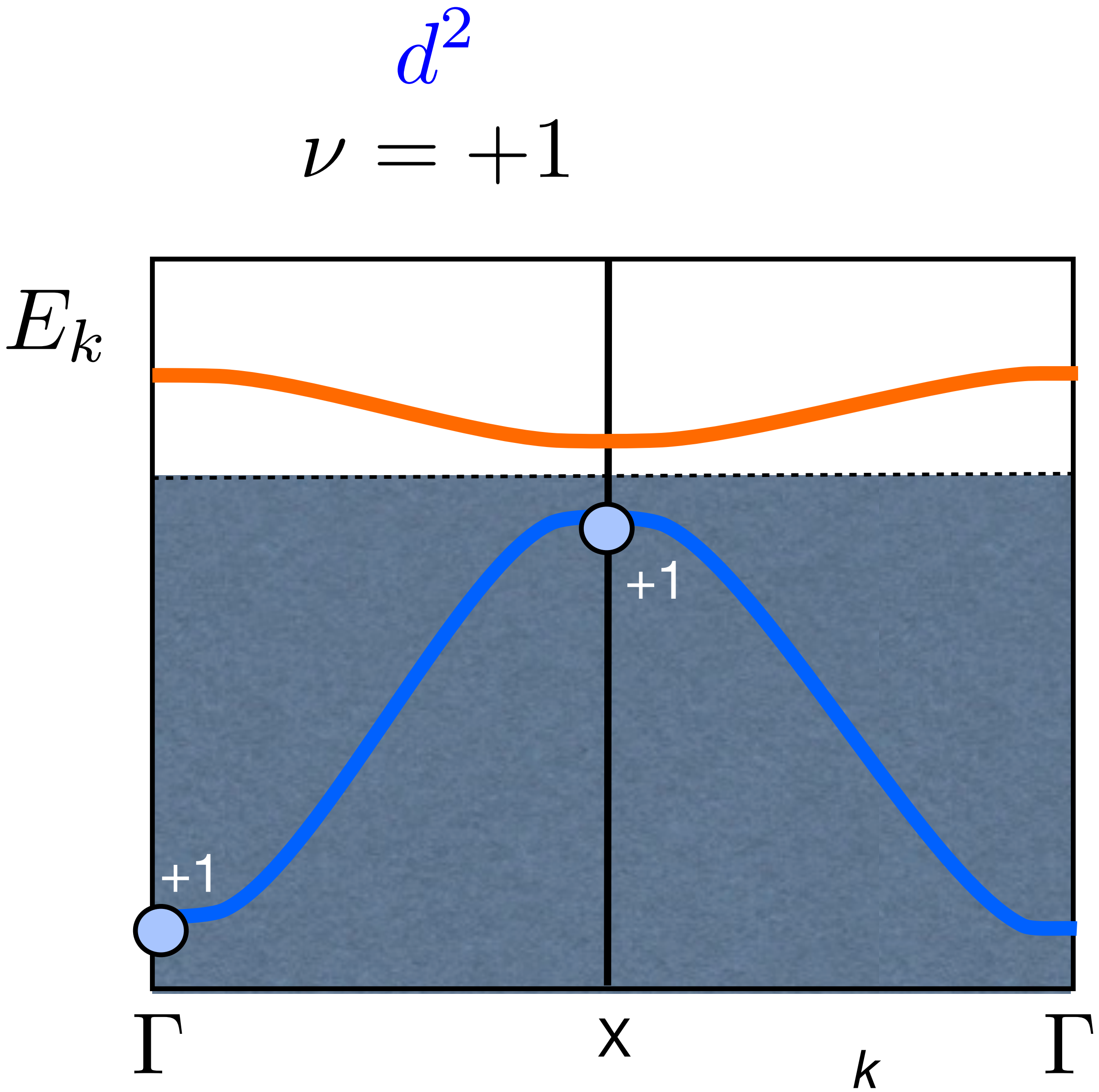
- Z_2 invariants are characterized by the parity eigenvalues:

$$\delta(\Gamma_m) = \mathrm{sgn}(E_f^* - \xi_{\mathbf{k_m}})$$

1D Kondo Insulator



Alexandrov, Dzero and PC (2013)

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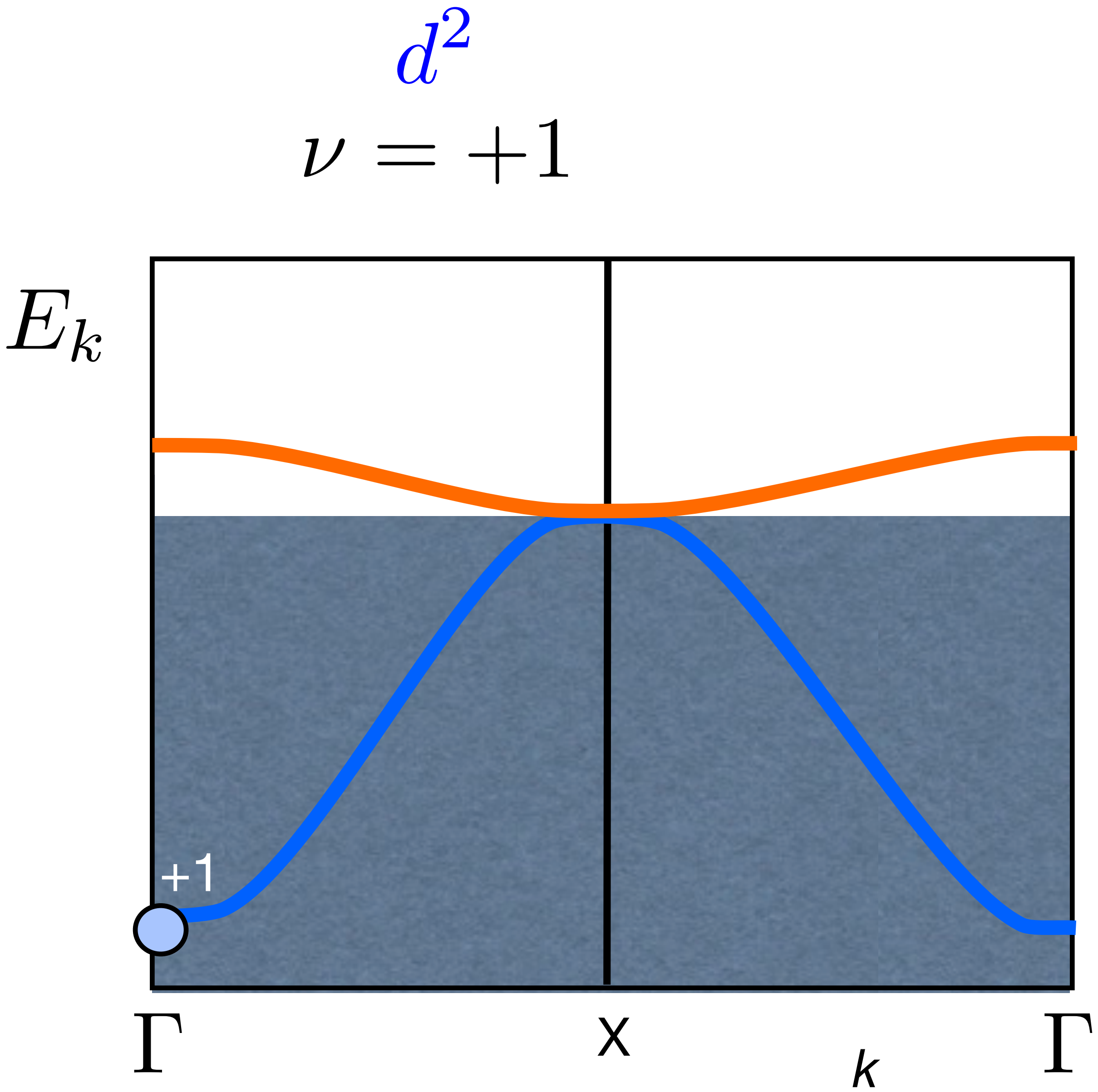

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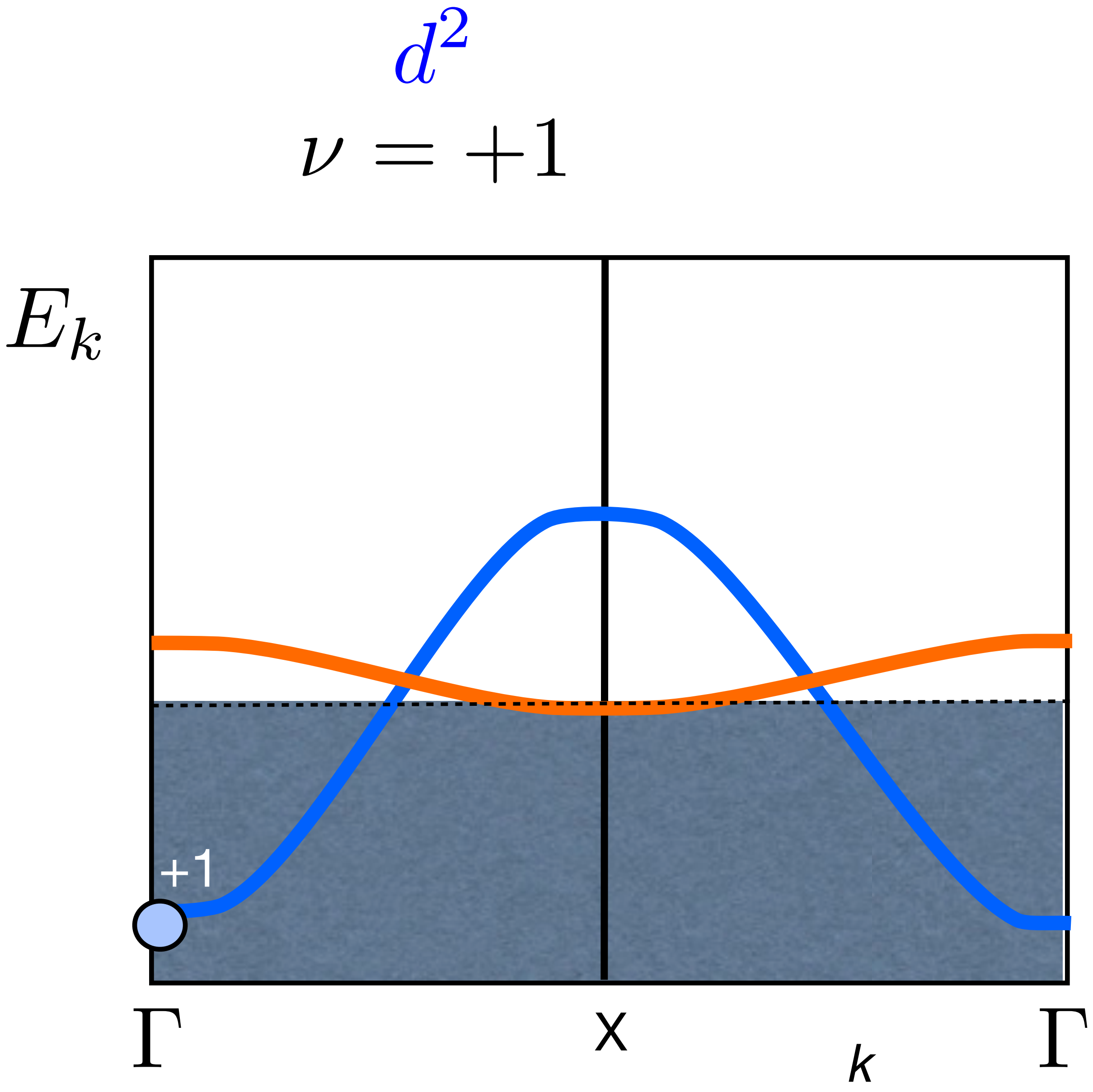

Alexandrov, Dzero and PC (2013)

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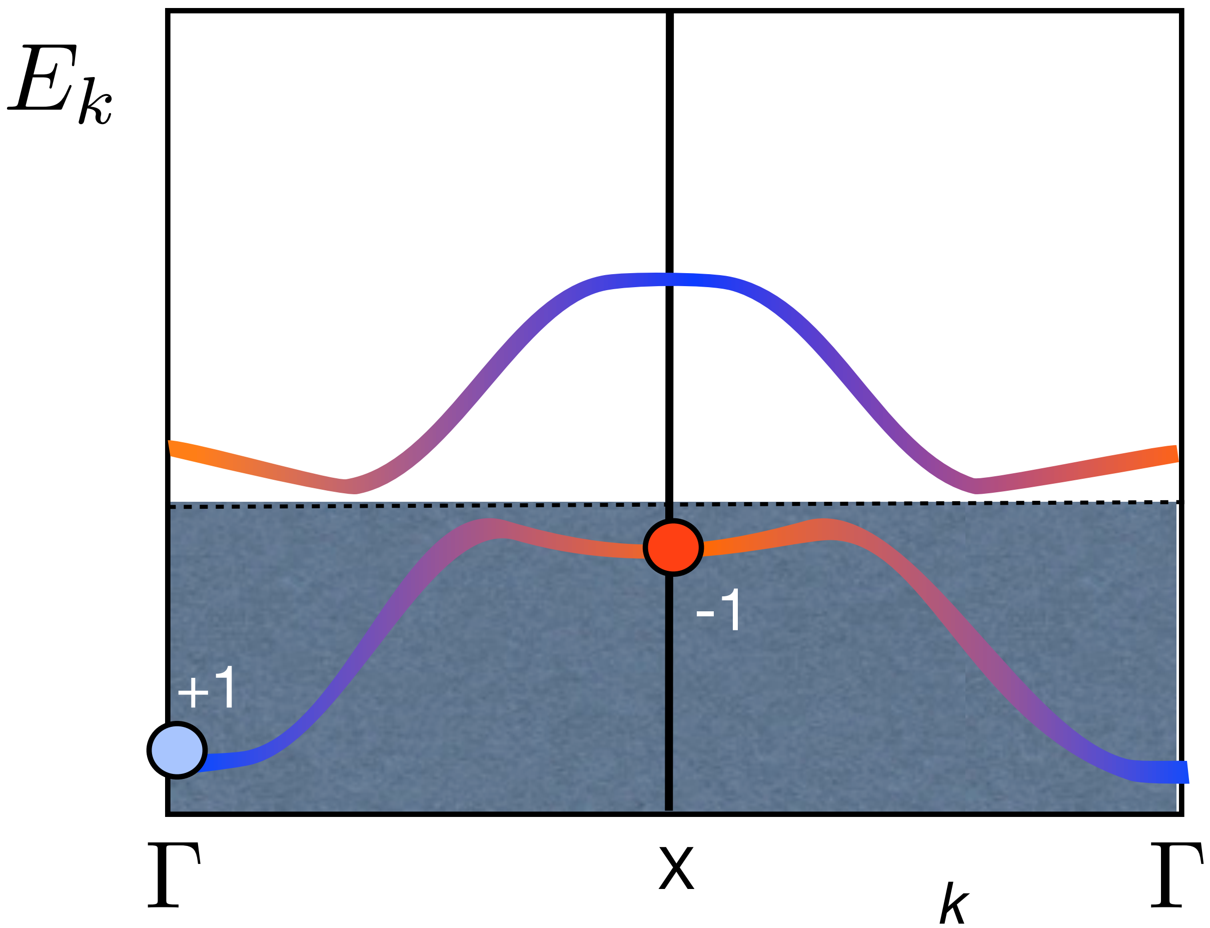
$$\nu = +1 \quad \nu = -1$$



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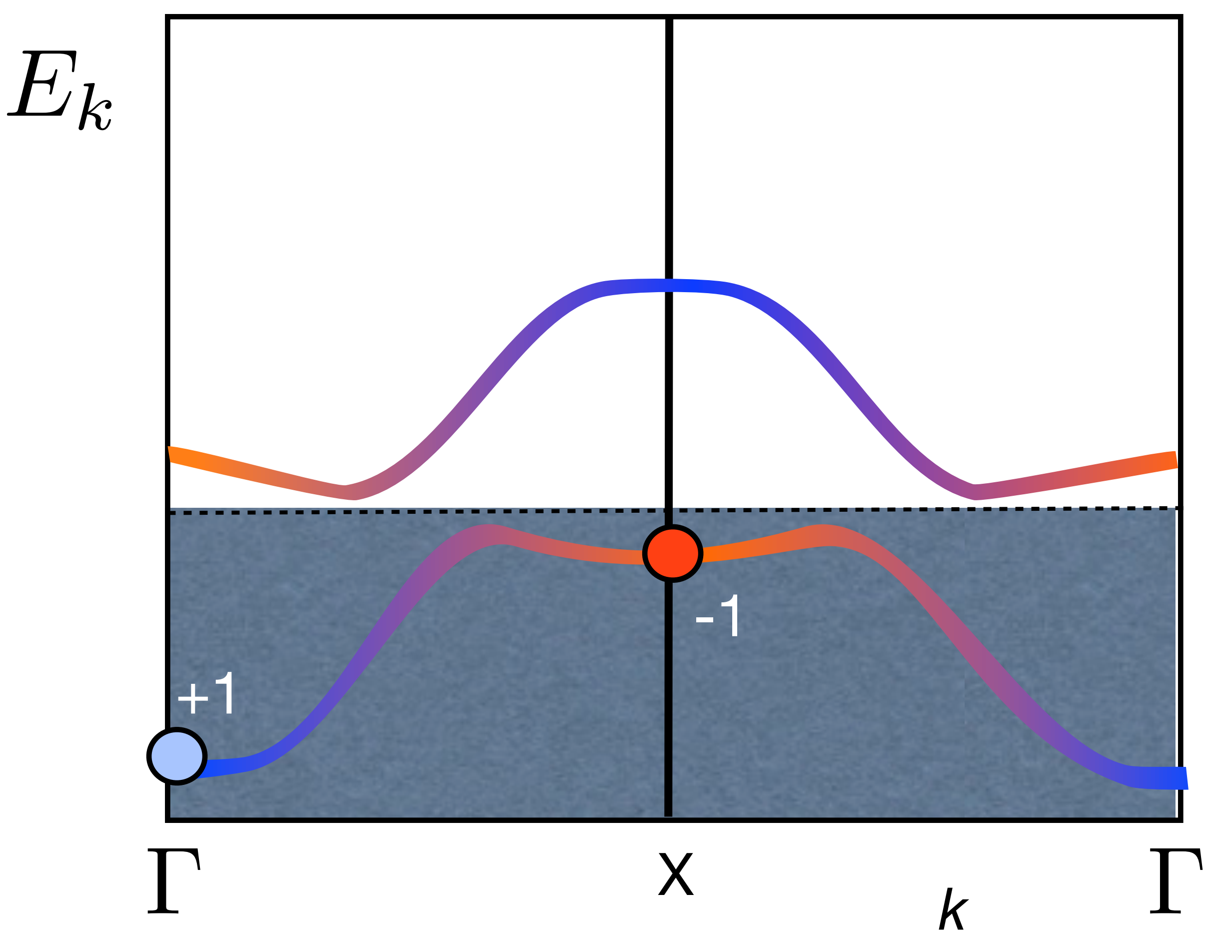
$$d^2 \rightarrow f^1 d^1$$

$$\nu = +1 \quad \nu = -1$$



Alexandrov, Dzero and PC (2013)

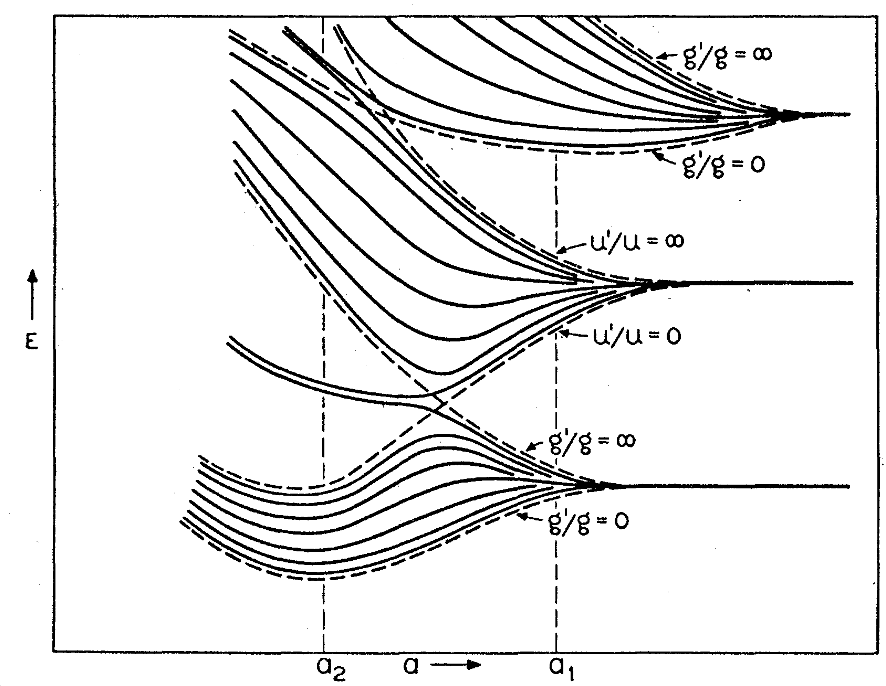
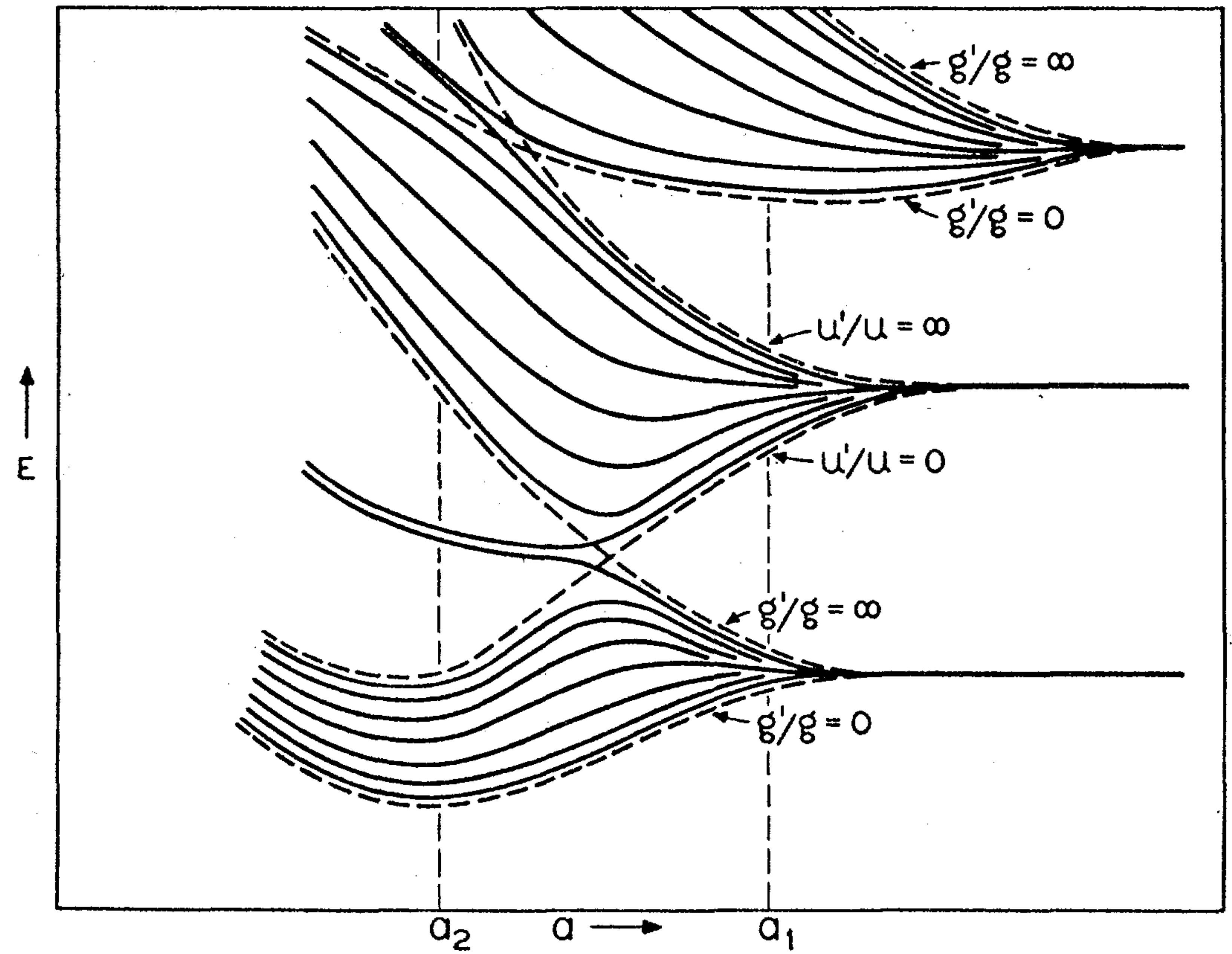


FIG. 2. Energy spectrum for a one-dimensional lattice with eight atoms.

Schockley, Phys Rev, 56, 317 (1939).



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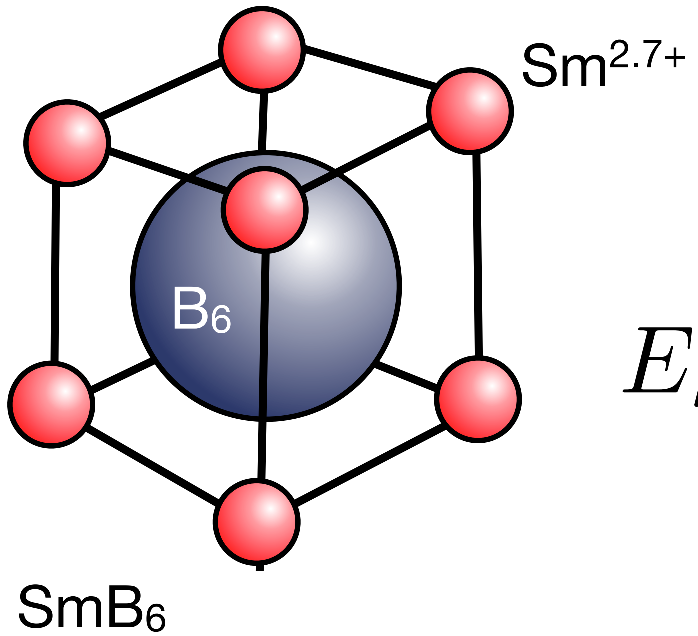
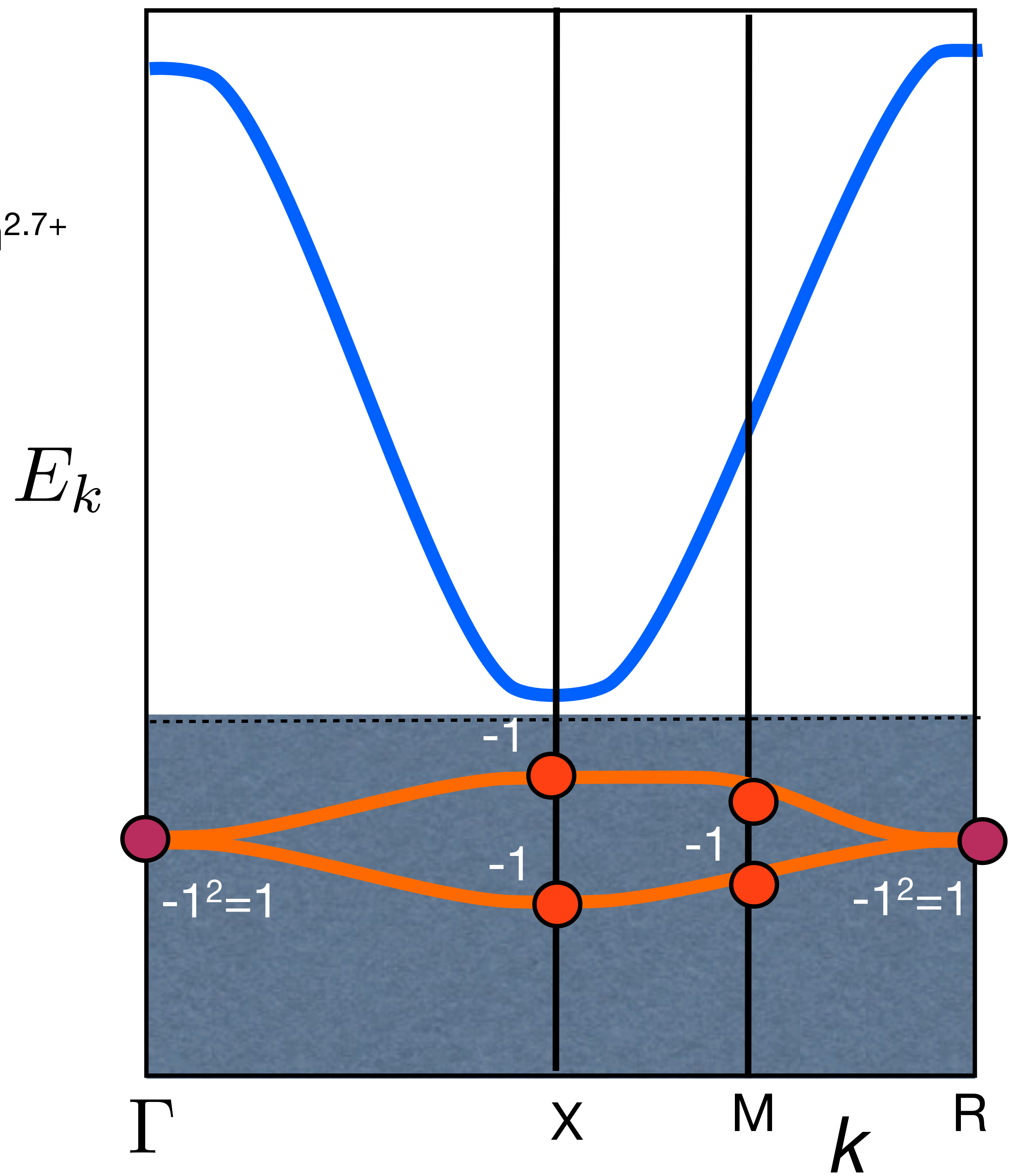
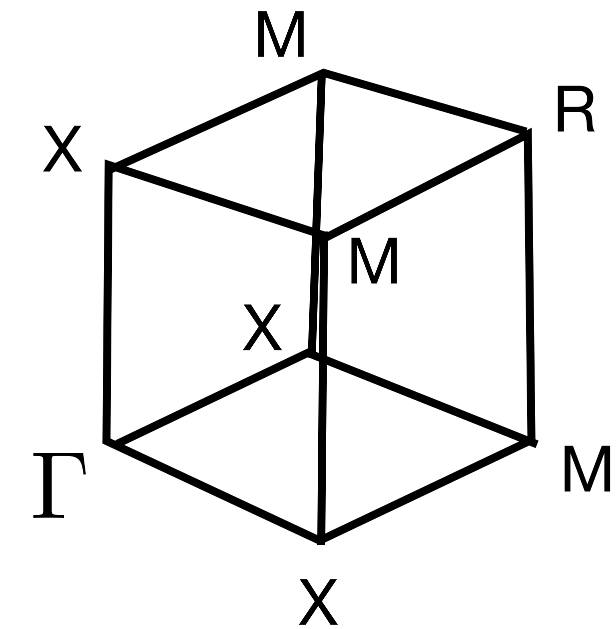
3D Cubic Kondo Insulator







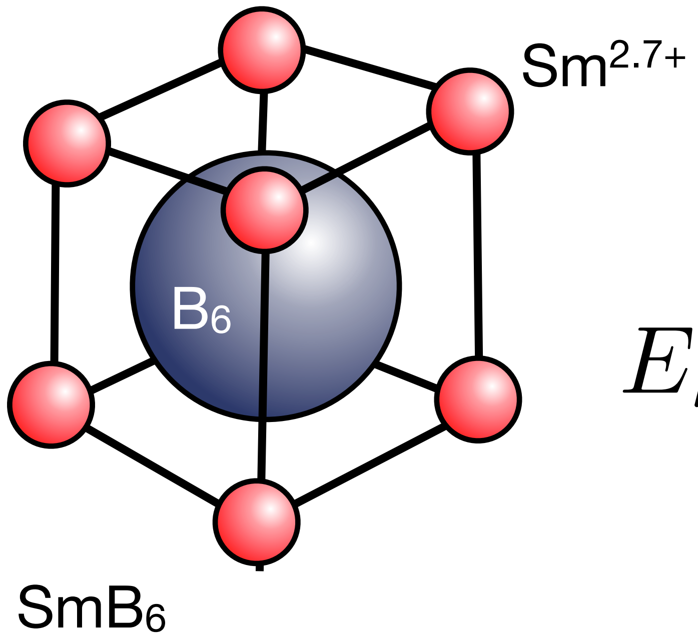
$d^0 f^6$

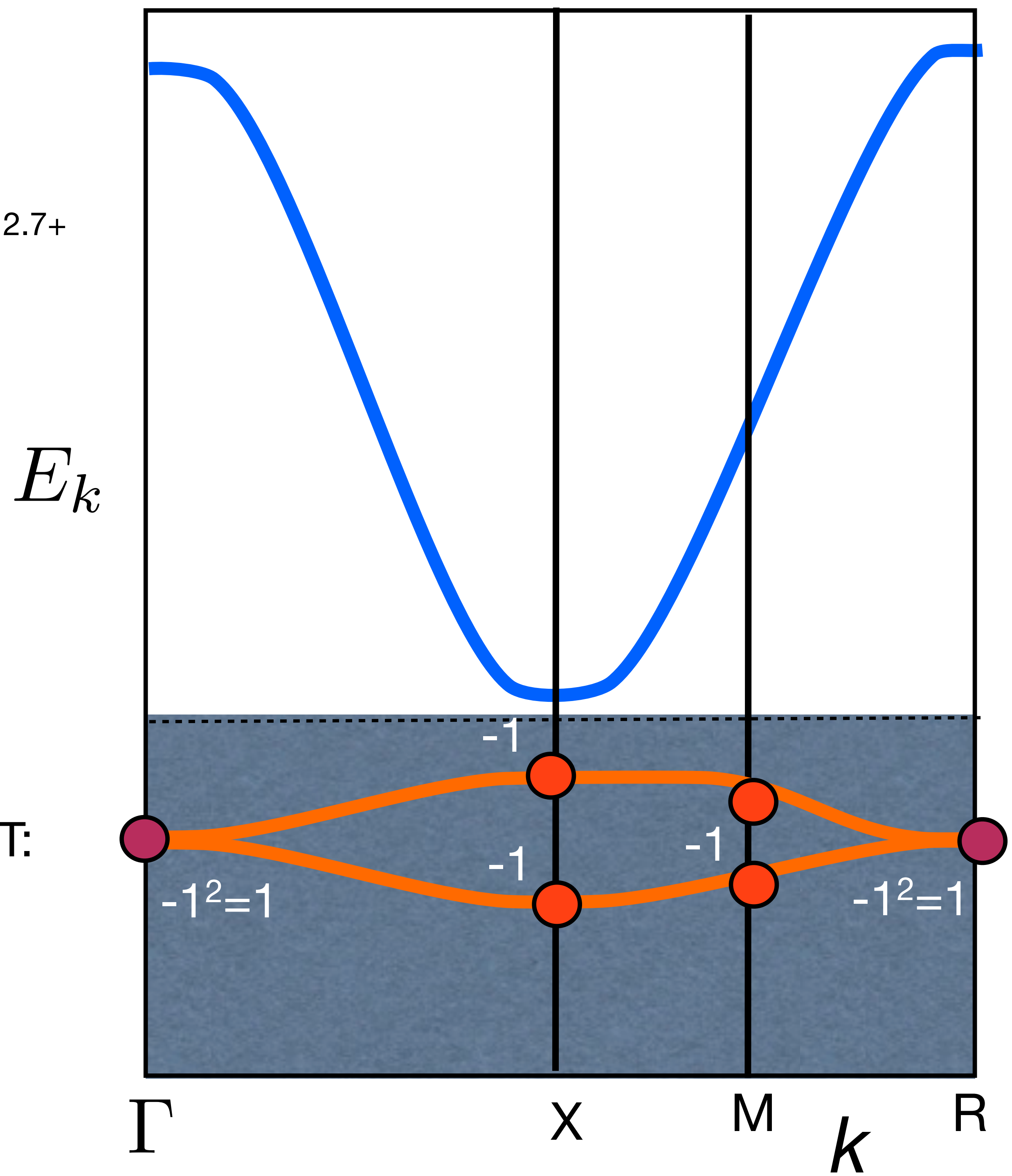
$\nu = +1$

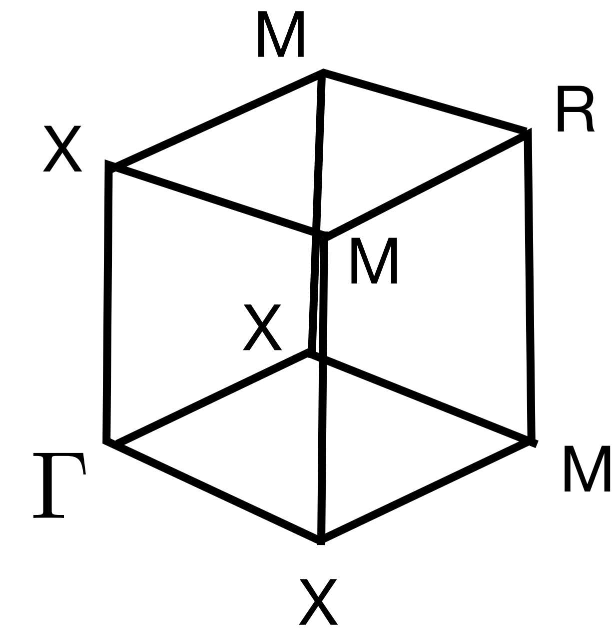
THREE DIRAC CONES ON SURFACE.

Alexandrov, Dzero and PC (2013)

3D Cubic Kondo Insulator







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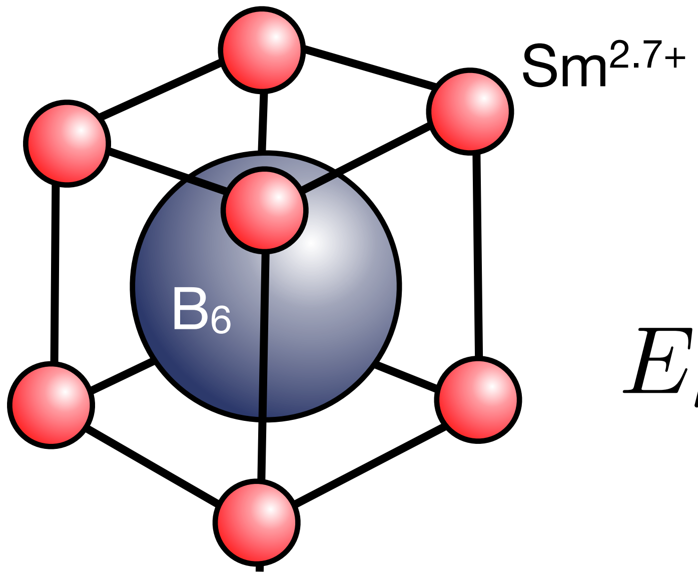
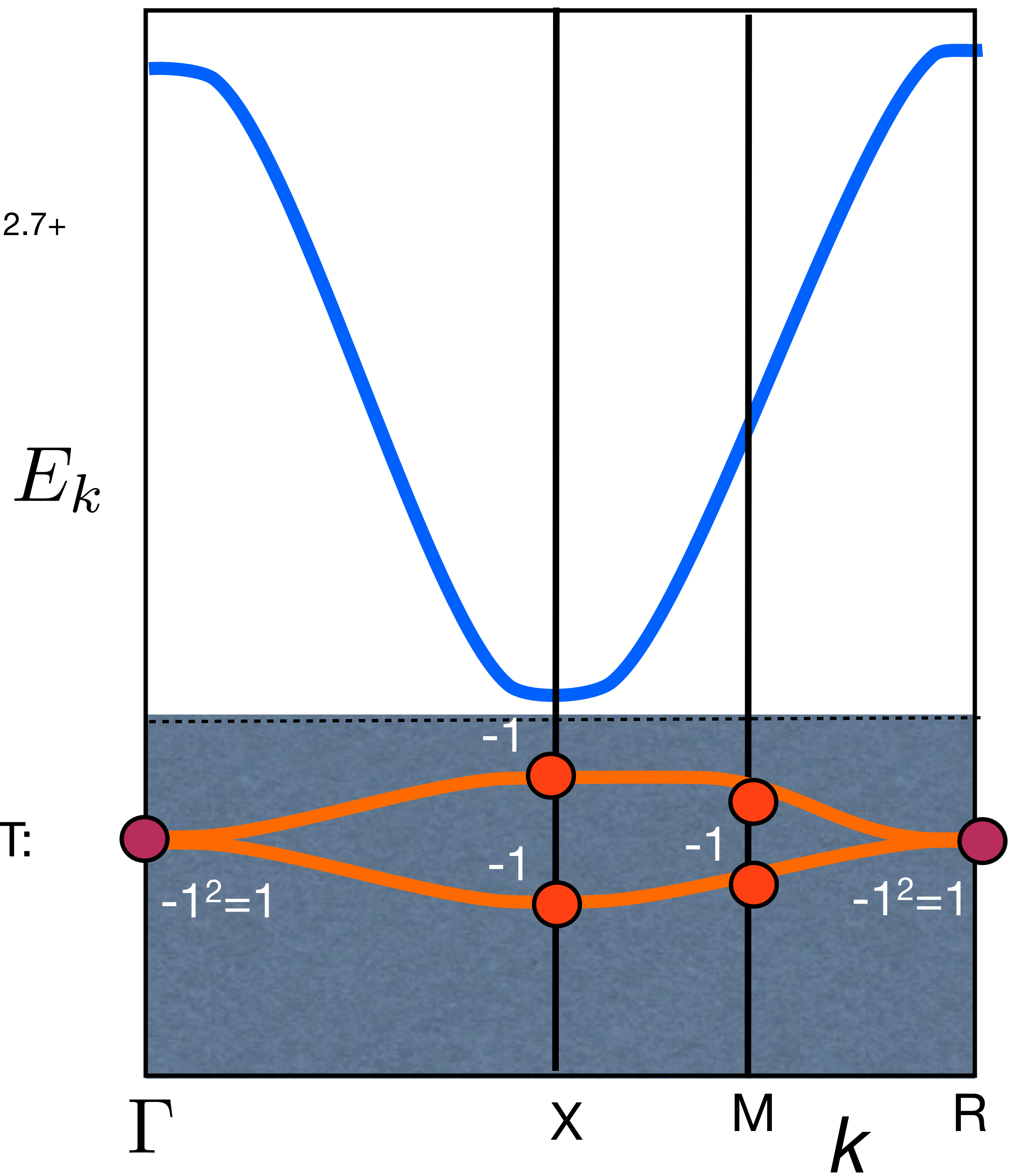
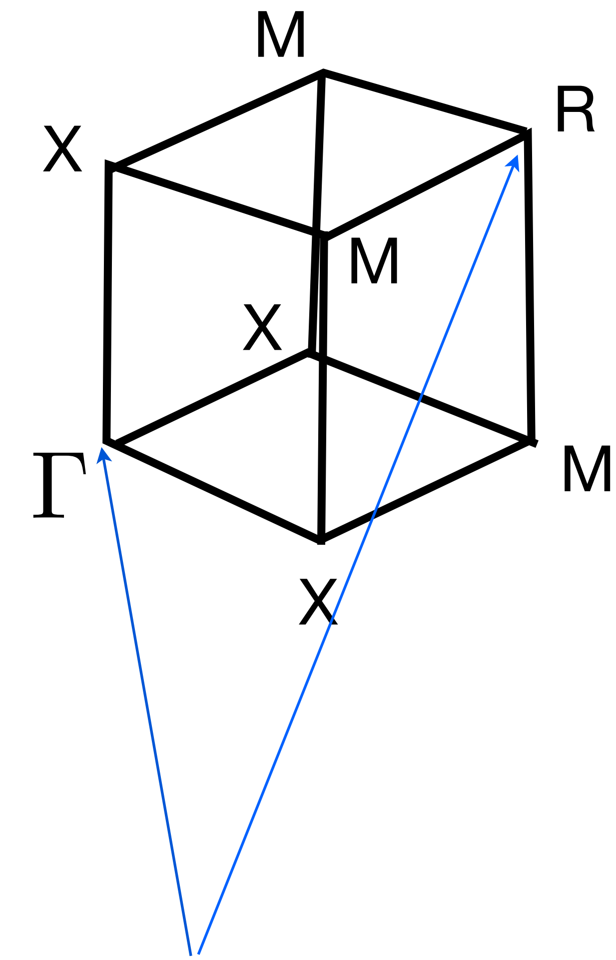
3D Cubic Kondo Insulator



SmB_6

QUARTET:





QUARTET:
topologically inert

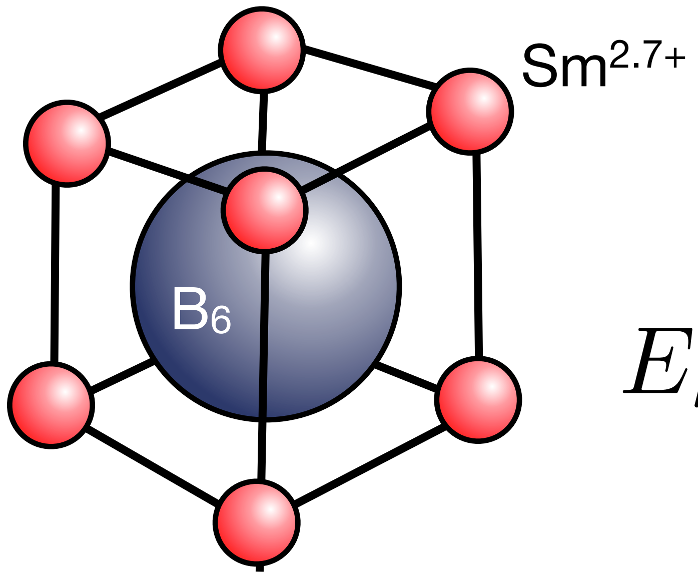
$d^0 f^6$

$\nu = +1$

THREE DIRAC CONES
ON SURFACE.

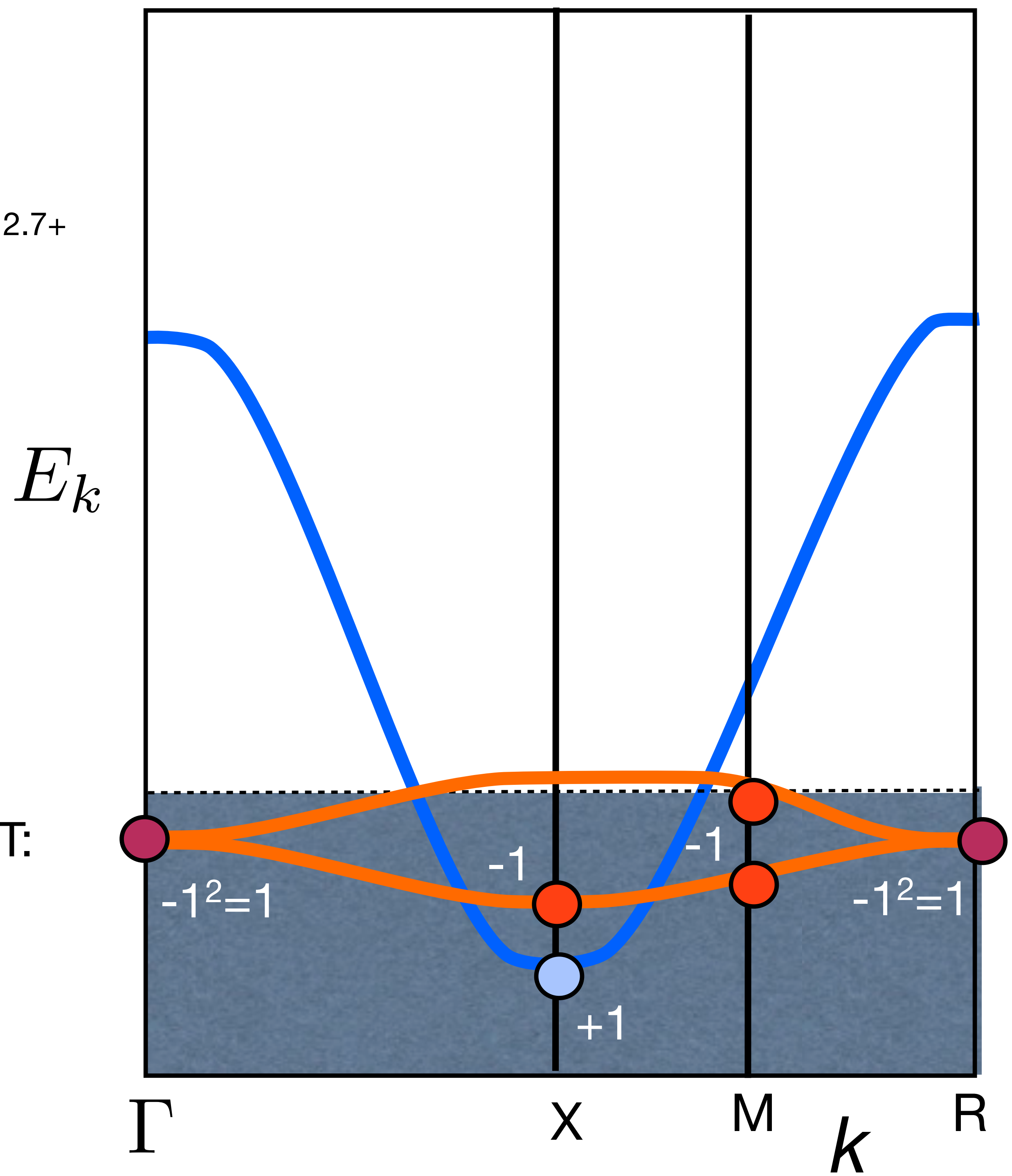
Alexandrov, Dzero and PC (2013)

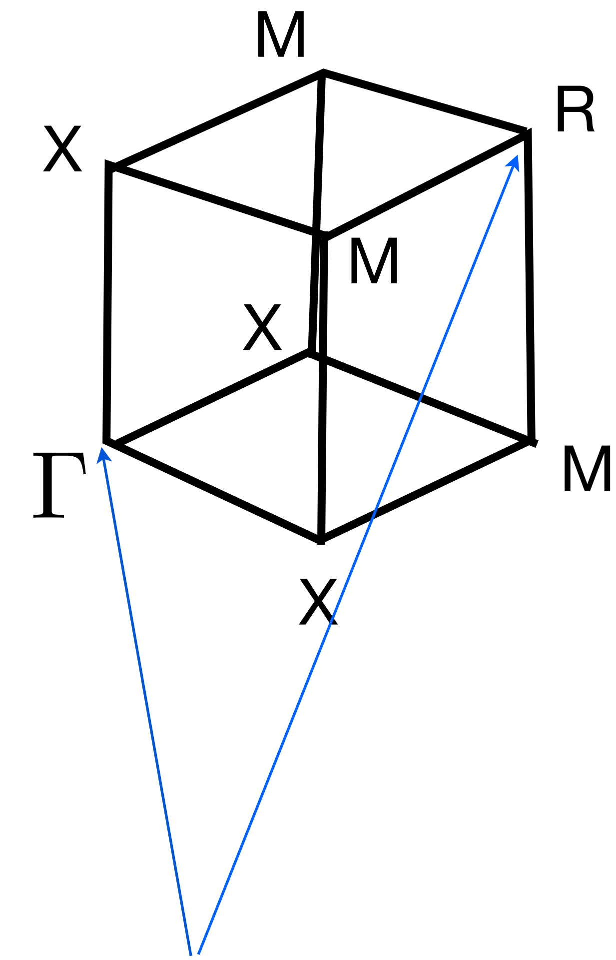
3D Cubic Kondo Insulator



SmB$_6$

QUARTET:





QUARTET:
topologically inert

$$d^0\, f^6$$

$$\nu = +1$$

THREE DIRAC CONES
ON SURFACE.

Alexandrov, Dzero and PC (2013)

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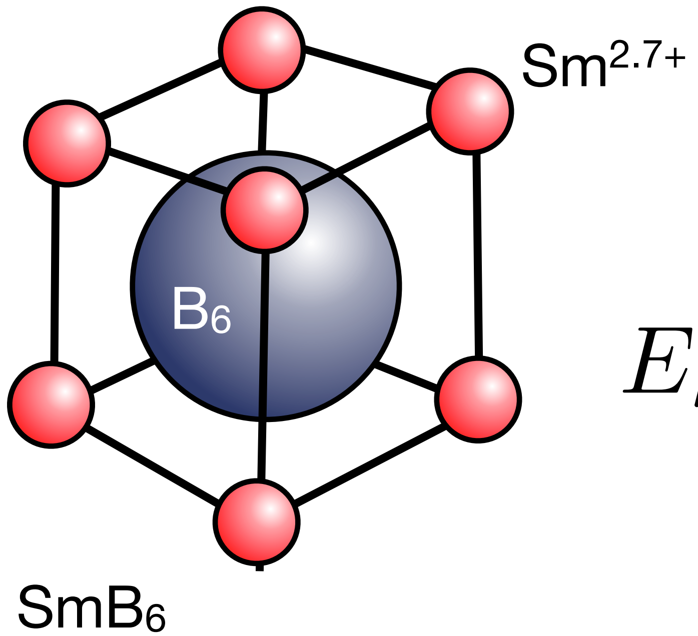
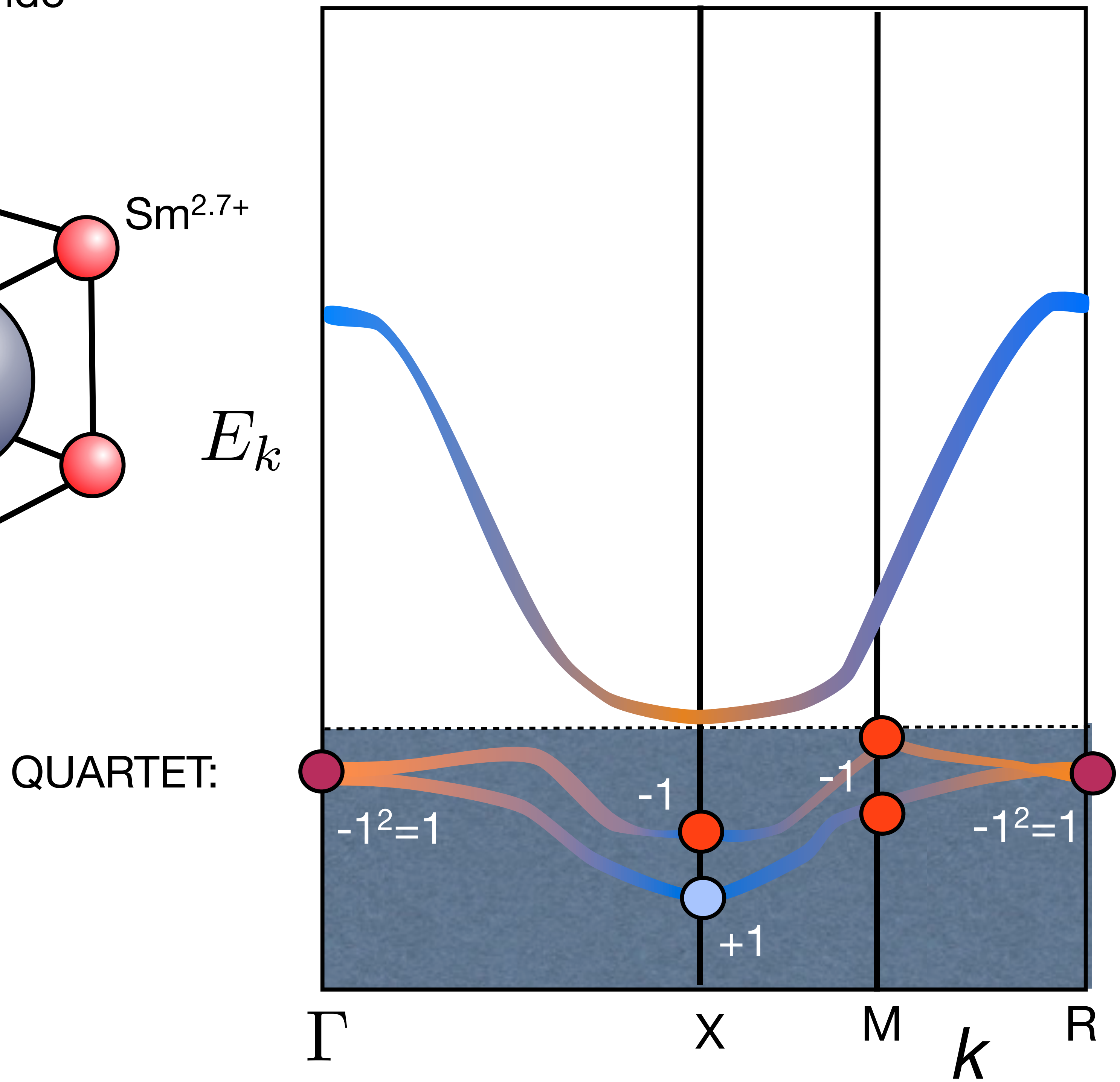
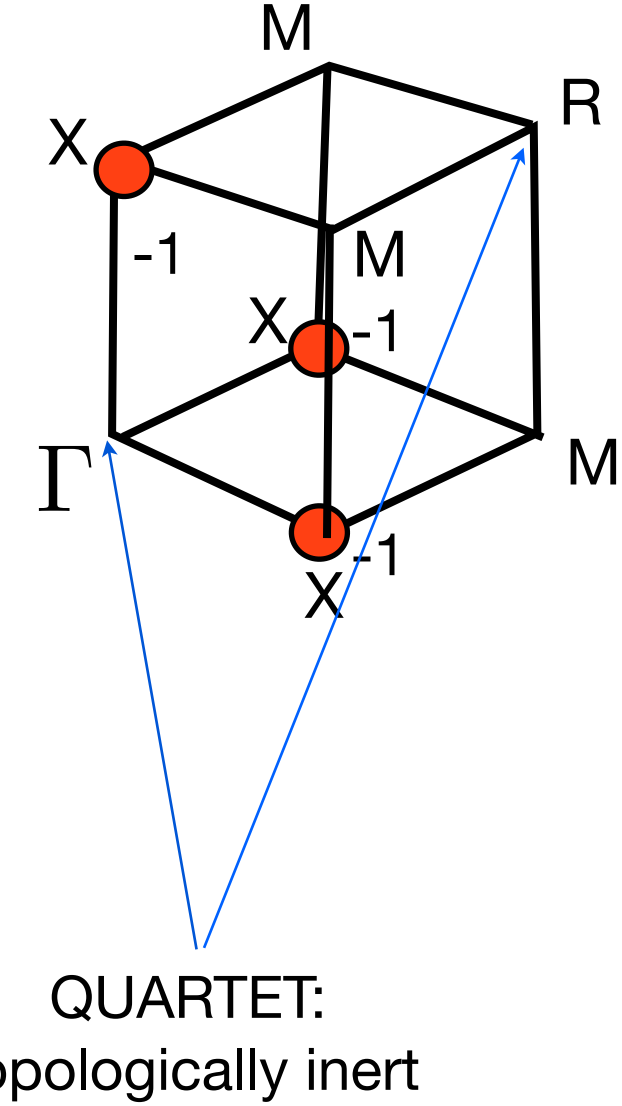






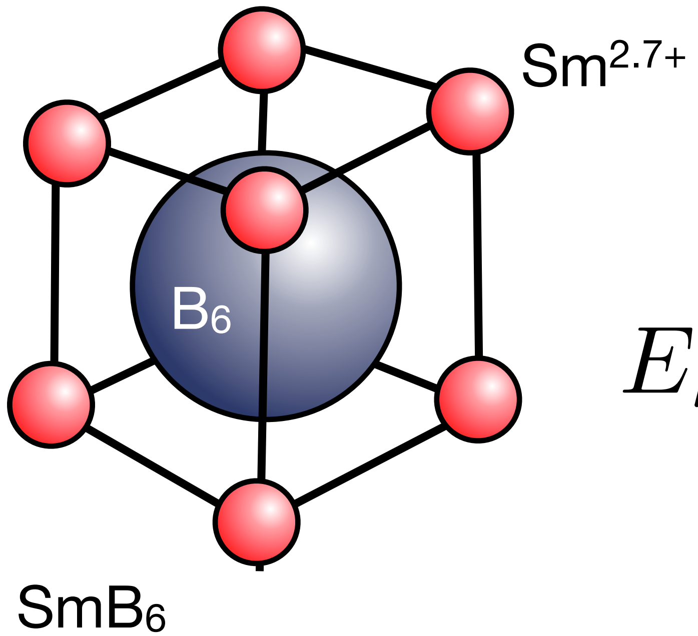
$d^0 f^6$

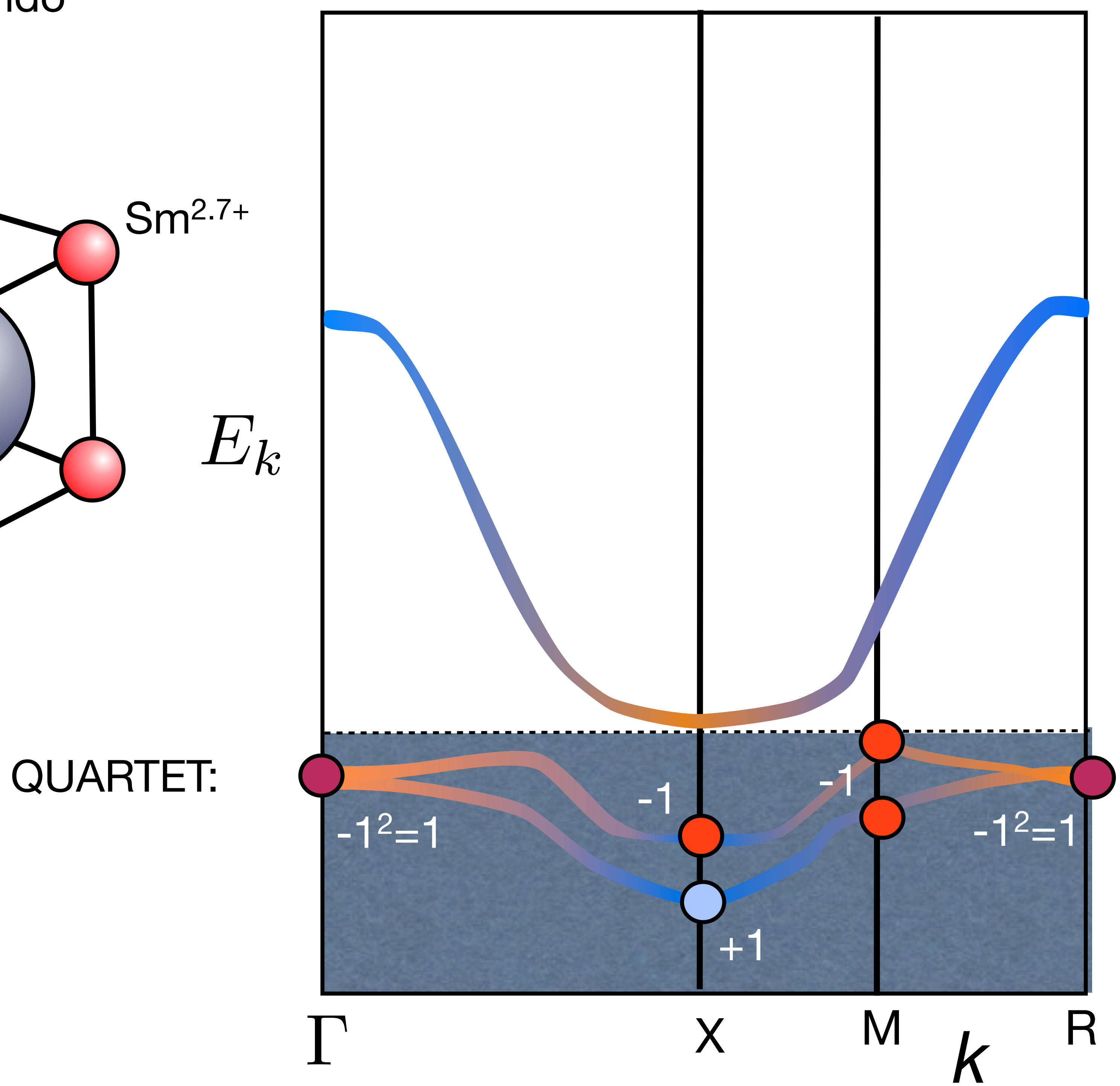
$\nu = +1$

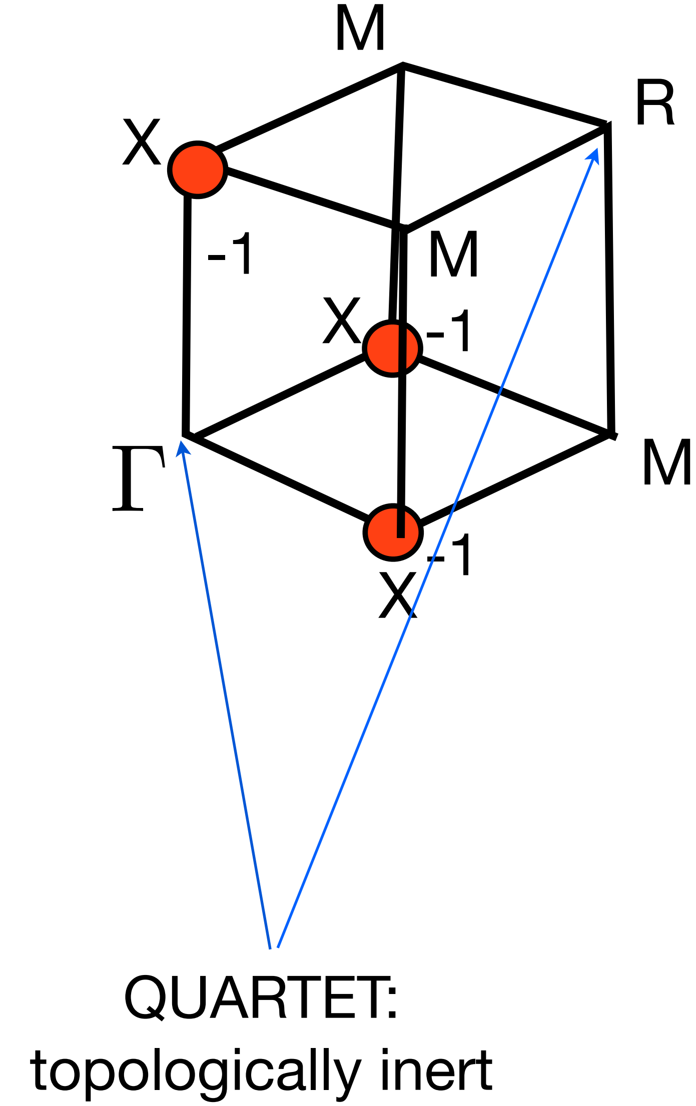
THREE DIRAC CONES
ON SURFACE.

Alexandrov, Dzero and PC (2013)

3D Cubic Kondo Insulator







$$d^0 f^6 \longrightarrow d^1 f^5$$

$$\nu = +1 \qquad \nu = -1$$

THREE DIRAC CONES
ON SURFACE.

Alexandrov, Dzero and PC (2013)

Experiments:

- Non-local conductivity
- Arpes
- dHvA
- Weak Antilocalization

arXiv.org > cond-mat > arXiv:1211.5104

Condensed Matter > Strongly Correlated Electrons

Discovery of the First Topological Kondo Insulator: Samarium Hexaboride

Steven Wolgast, Cagliyan Kurdak, Kai Sun, J. W. Allen, Dae-Jeong Kim, Zachary Fisk

(Submitted on 21 Nov 2012 (v1), last revised 27 Nov 2012 (this version, v2))

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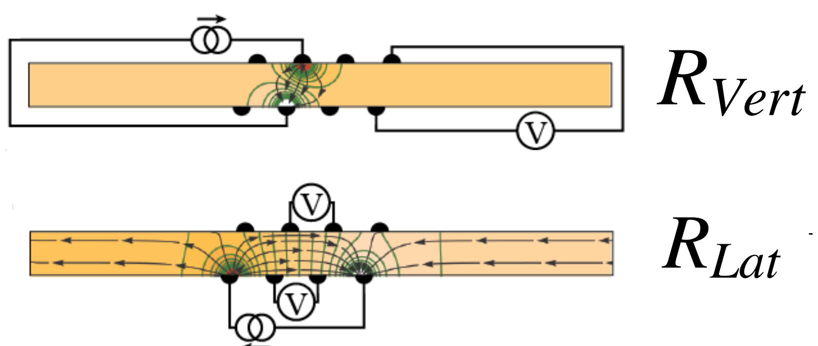

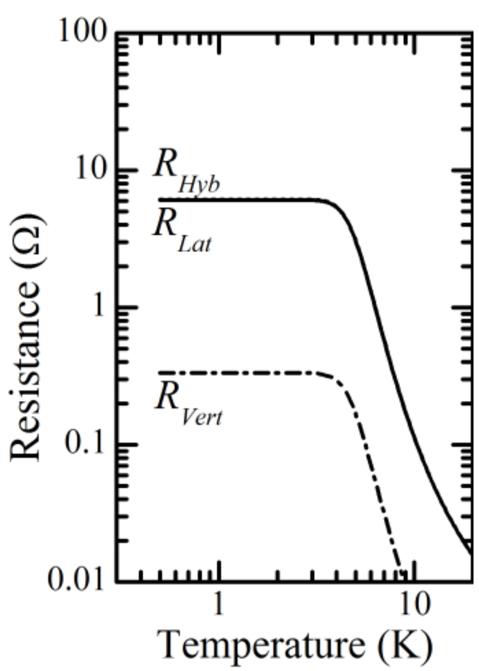

Simulation-bulk scenario

arXiv.org > cond-mat > arXiv:1211.5104

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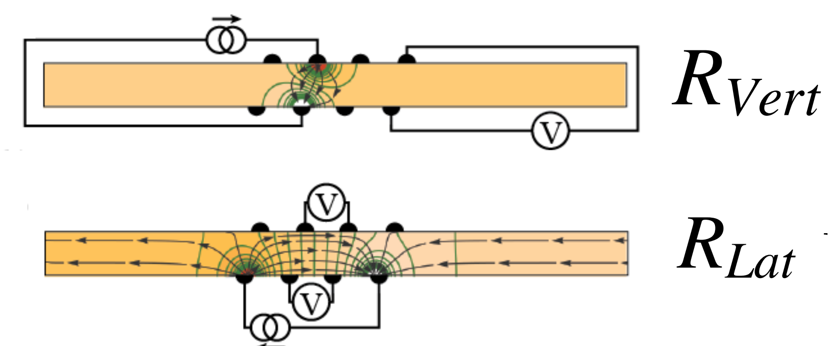

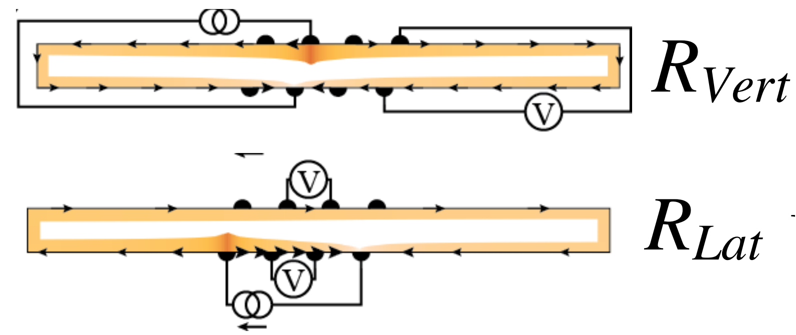

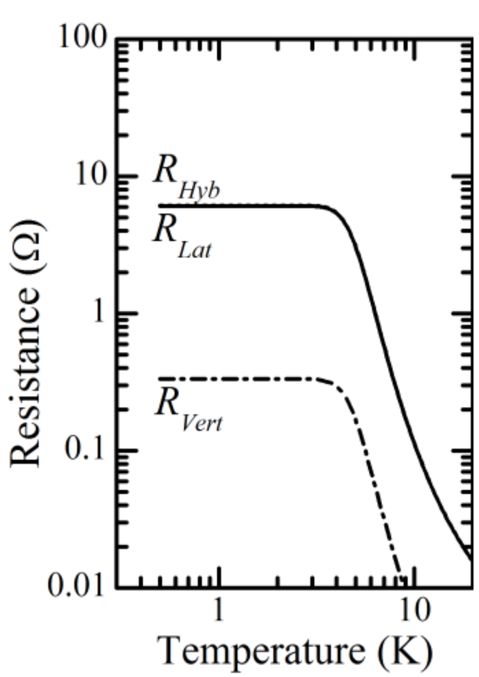

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Condensed Matter > Strongly Correlated Electrons

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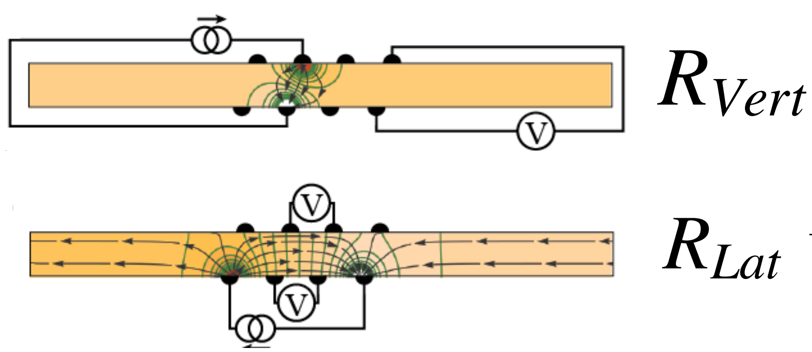
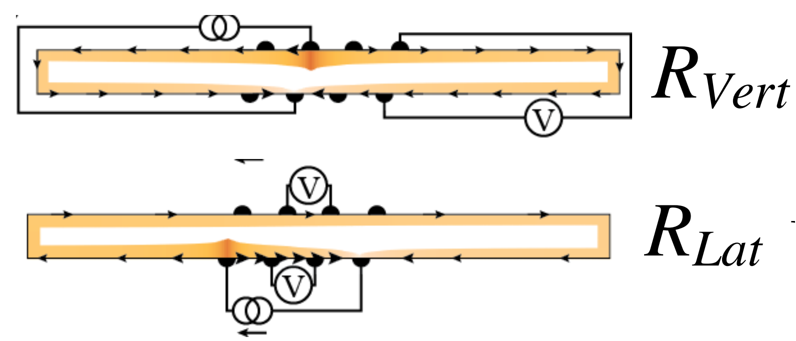
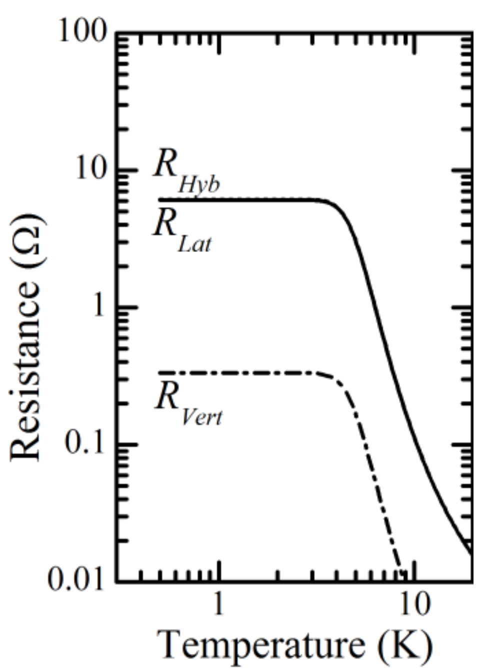
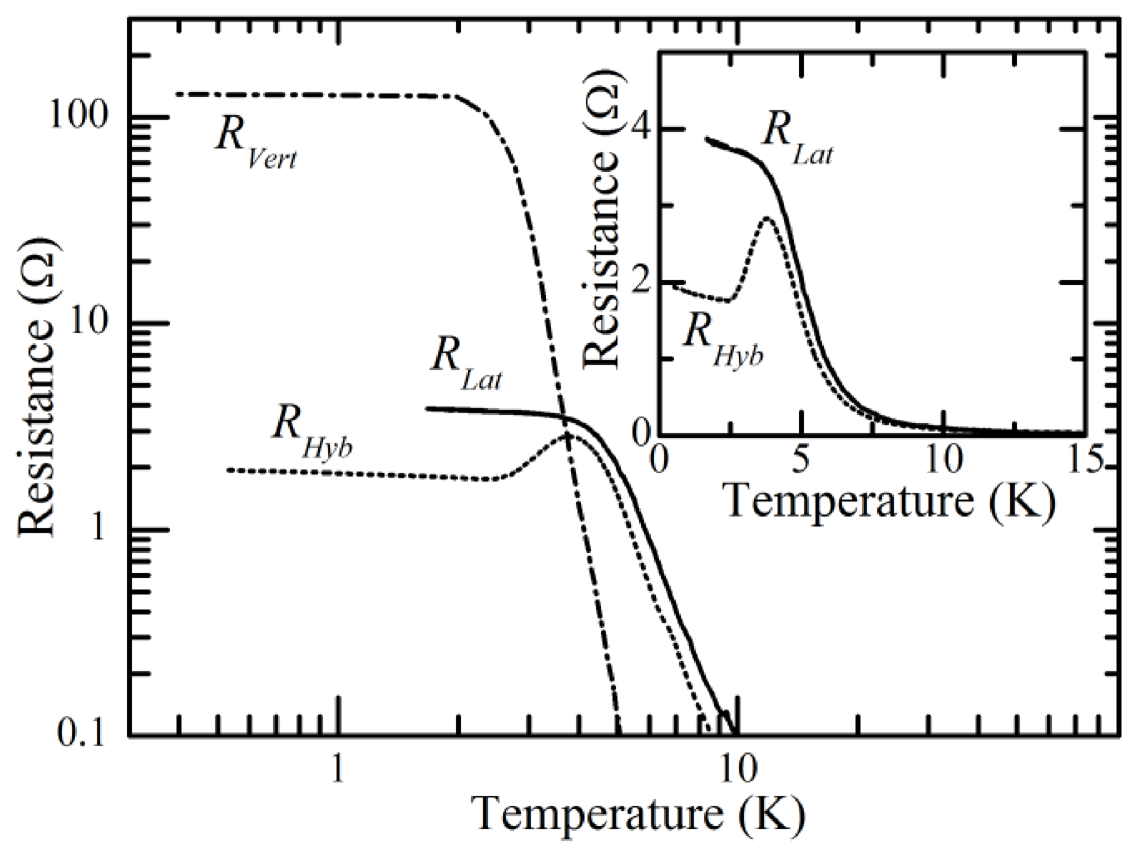




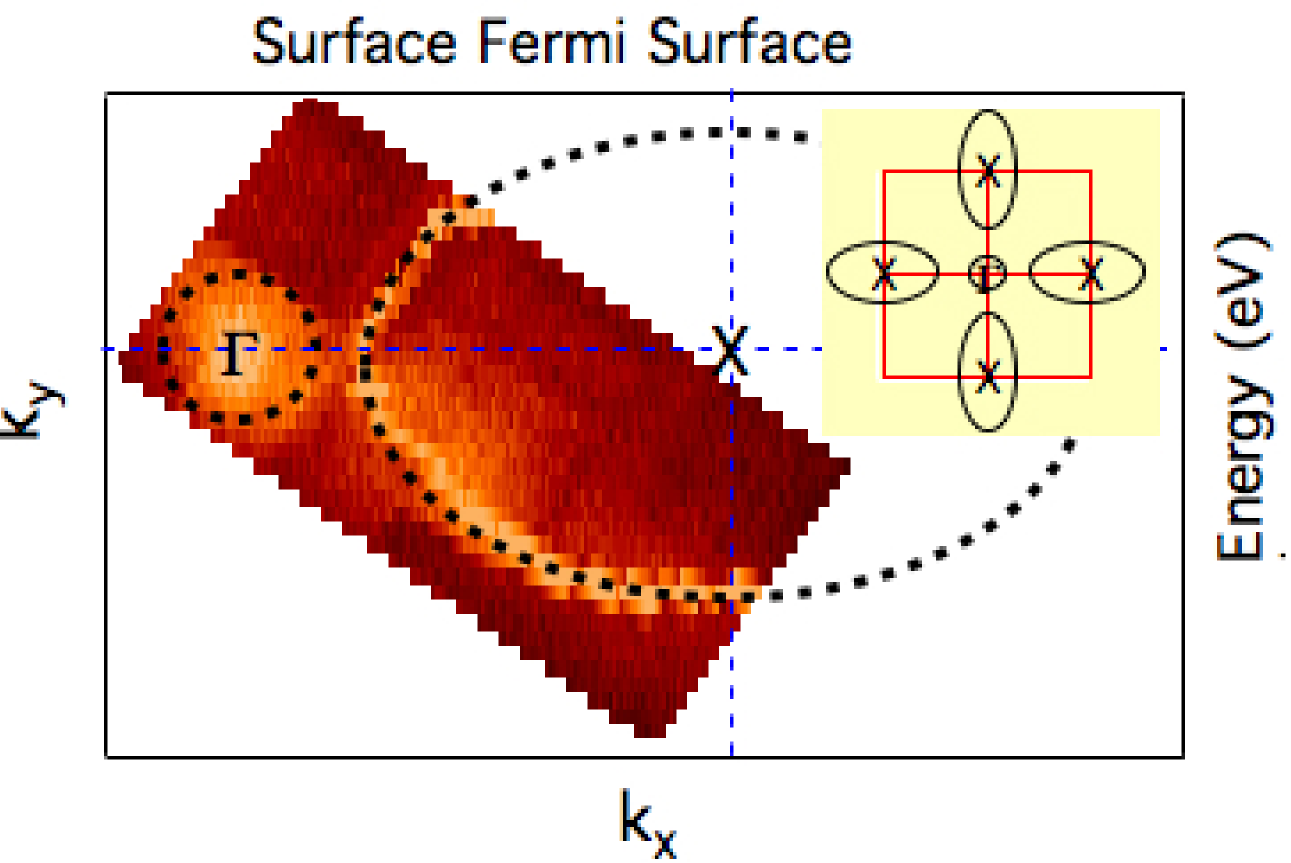


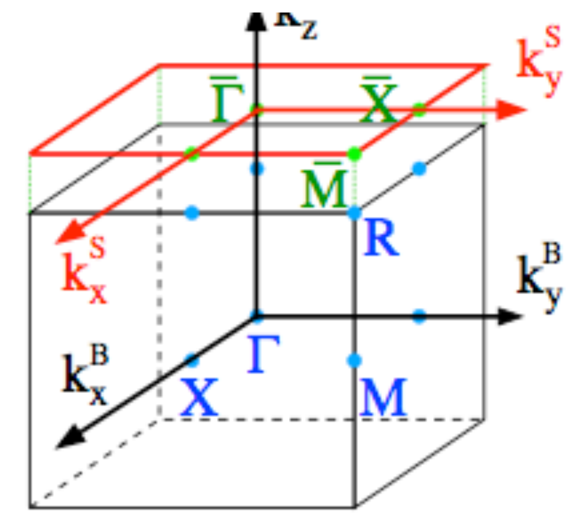


Simulation-bulk scenario

Surface electronic structure of topological Kondo insulator candidate SmB_6: A view from high-resolution Laser-ARPES

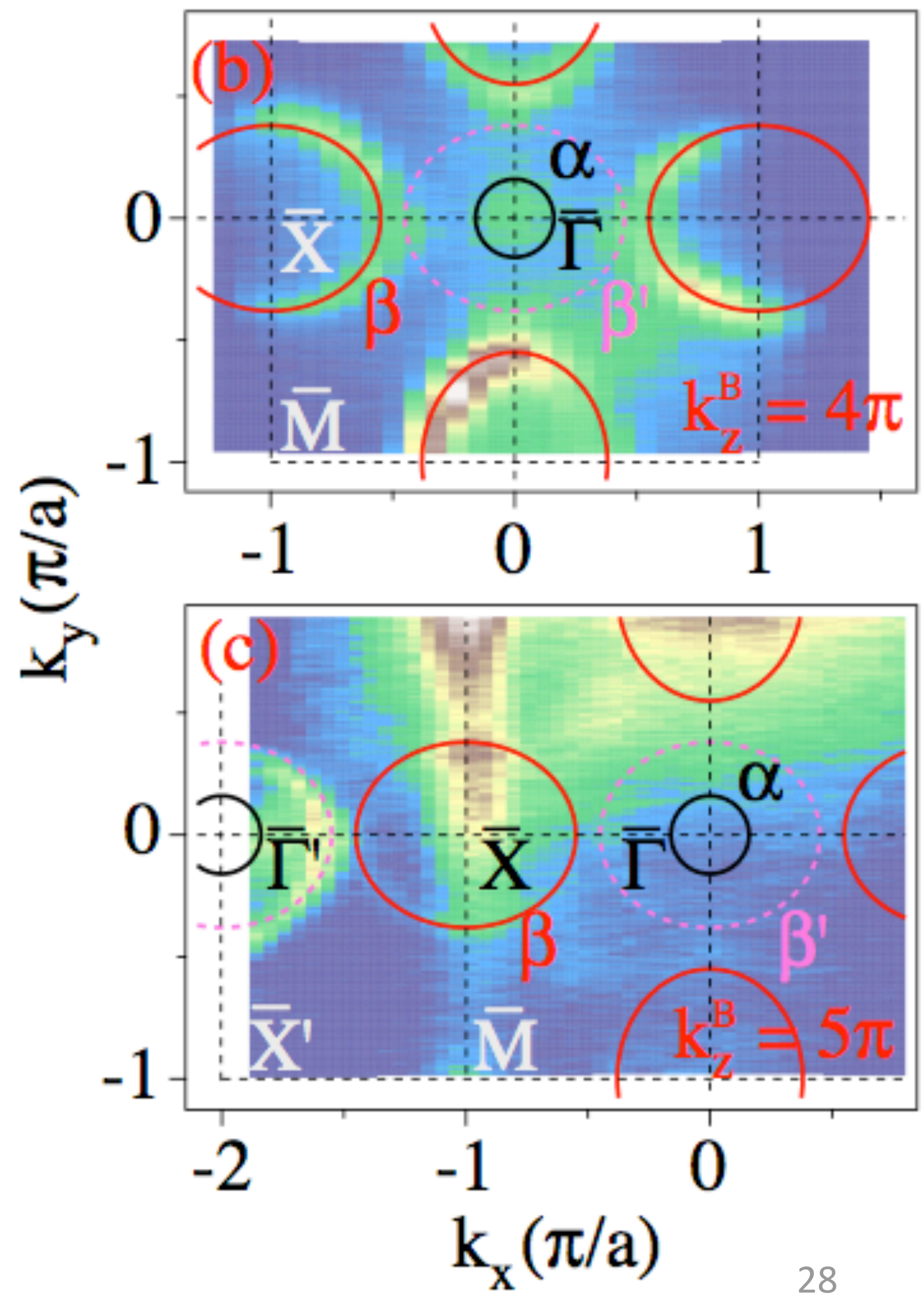
M. Neupane,[1] N. Alidoust,[1] S.-Y. Xu,[1] T. Kondo,[2] Dae-Jeong Kim,[3] Chang Liu,[1] I. Belopolski,[1] T.-R. Chang,[4] H.-T. Jeng,[4,5] T. Durakiewicz,[6] L. Balicas,[7] H. Lin,[8] A. Bansil,[8] S. Shin,[2] Z. Fisk,[3] and M. Z. Hasan[1]

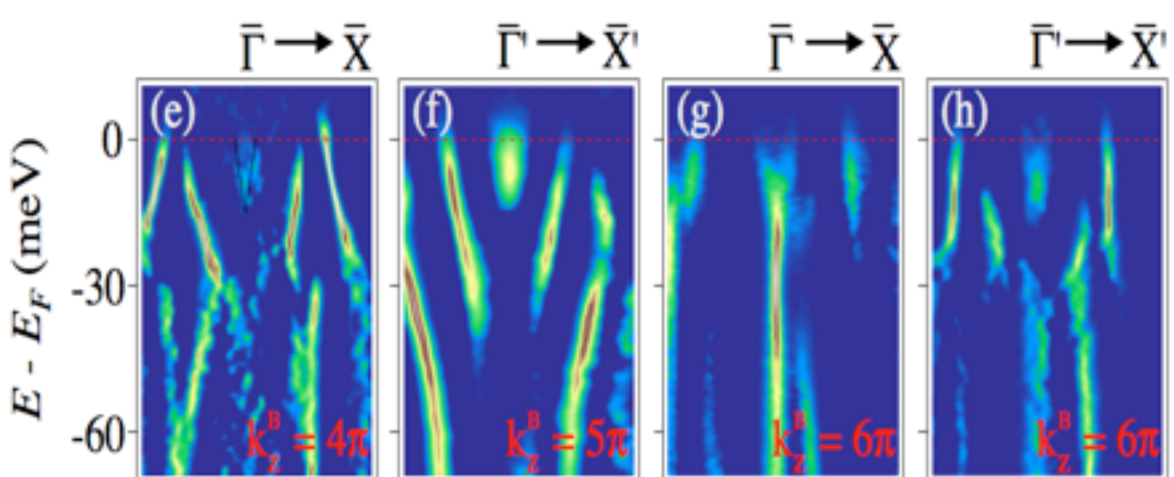




Surface and Bulk Electronic Structure of the Strongly Correlated System SmB_6 and Implications for a Topological Kondo Insulator

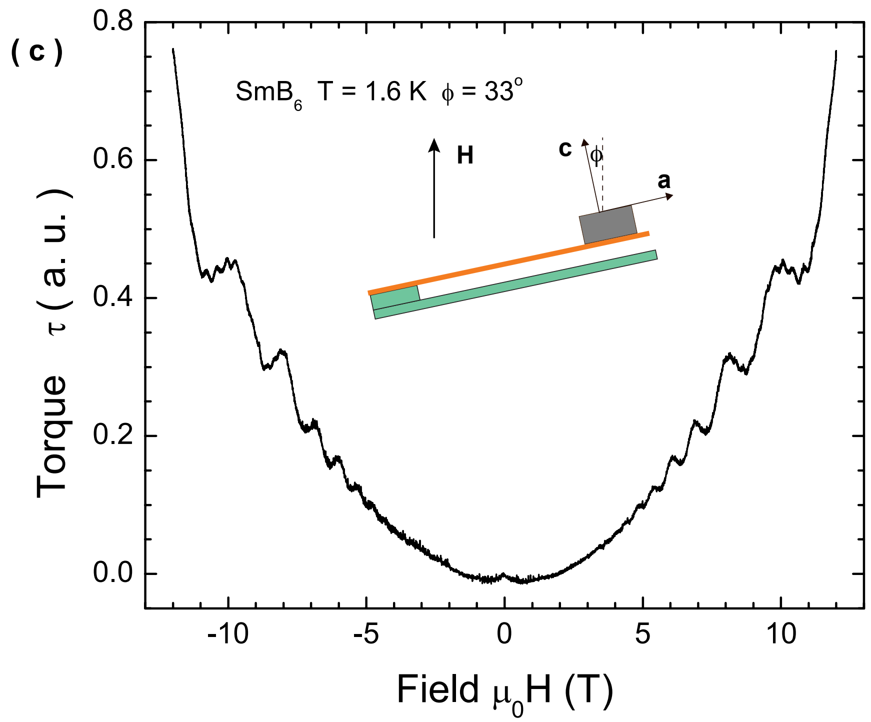
N. Xu,[1,*] X. Shi,[1,2] P. K. Biswas,[3] C. E. Matt,[1,4] R. S. Dhaka,[1] Y. Huang,[1] N. C. Plumb,[1] M. Radovic,[1,5] J. H. Dil,[6,1] E. Pomjakushina,[7] A. Amato,[3] Z. Salman,[3] D. McK. Paul,[8] J. Mesot,[1,9] H. Ding,[2] and M. Shi[1,†]





Quantum oscillations in Kondo Insulator SmB_6

G. Li[1], Z. Xiang[1,2], F. Yu[1], T. Asaba[1], B. Lawson[1], P. Cai[1,3], C. Tinsman[1], A. Berkley[1], S. Walgast[1], Y. S. Eo[1], Dae-Jeong Kim[4], C. Kurdak[1], J. W. Allen[1], K. Sun[1], X. H. Chen[2], Y. Y. Wang[3], Z. Fisk[4], Lu Li[1]



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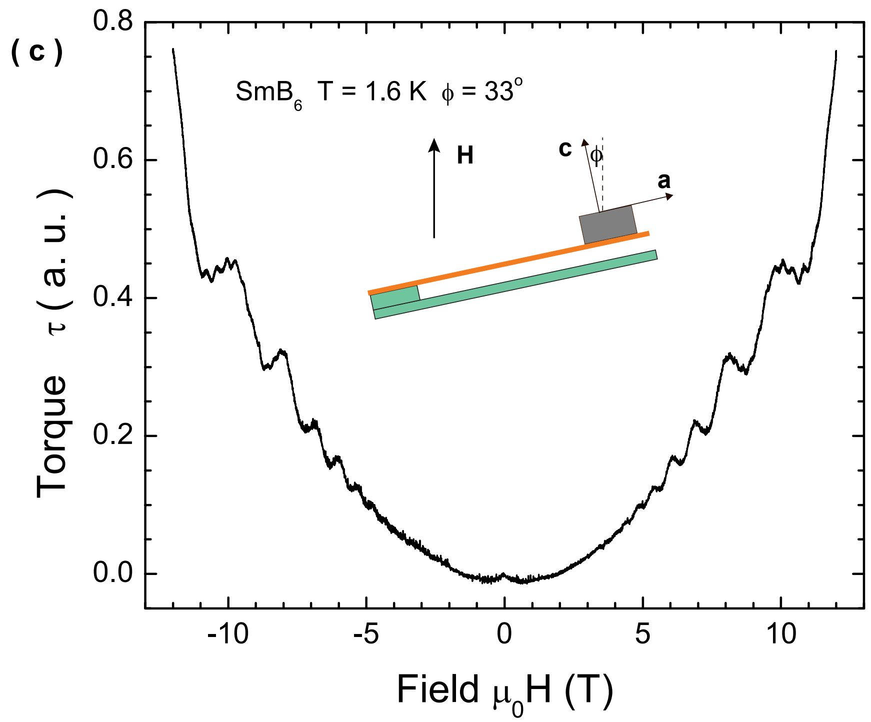

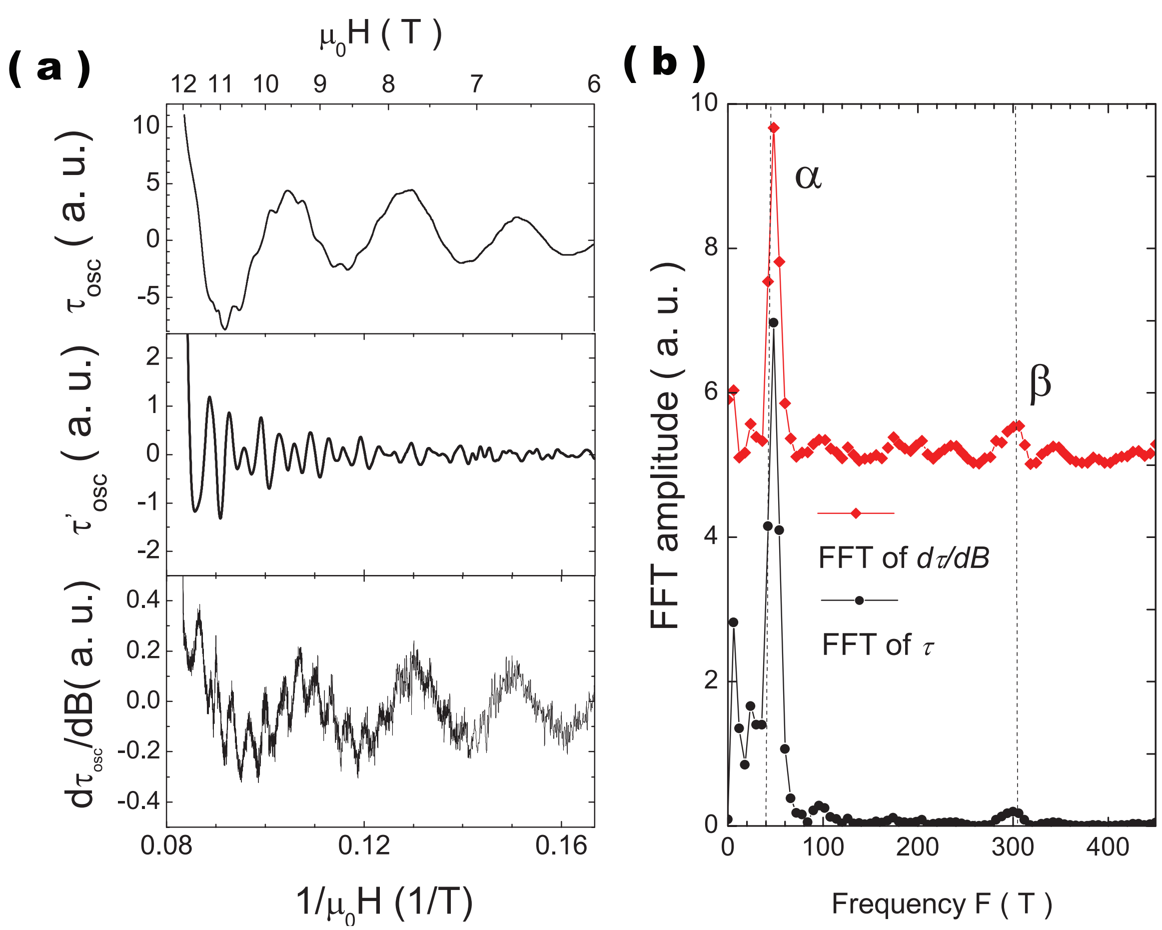

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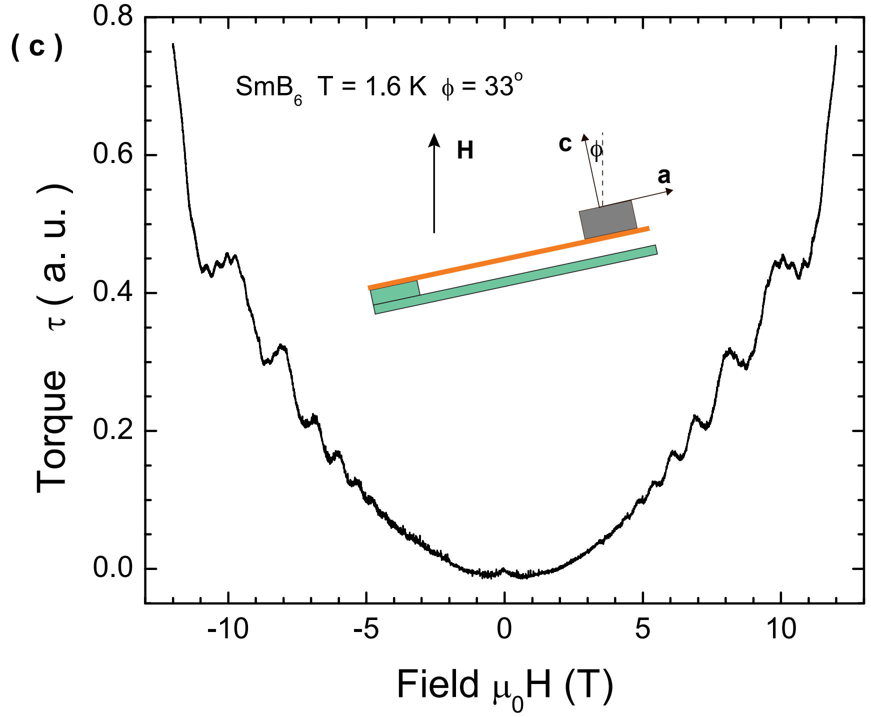

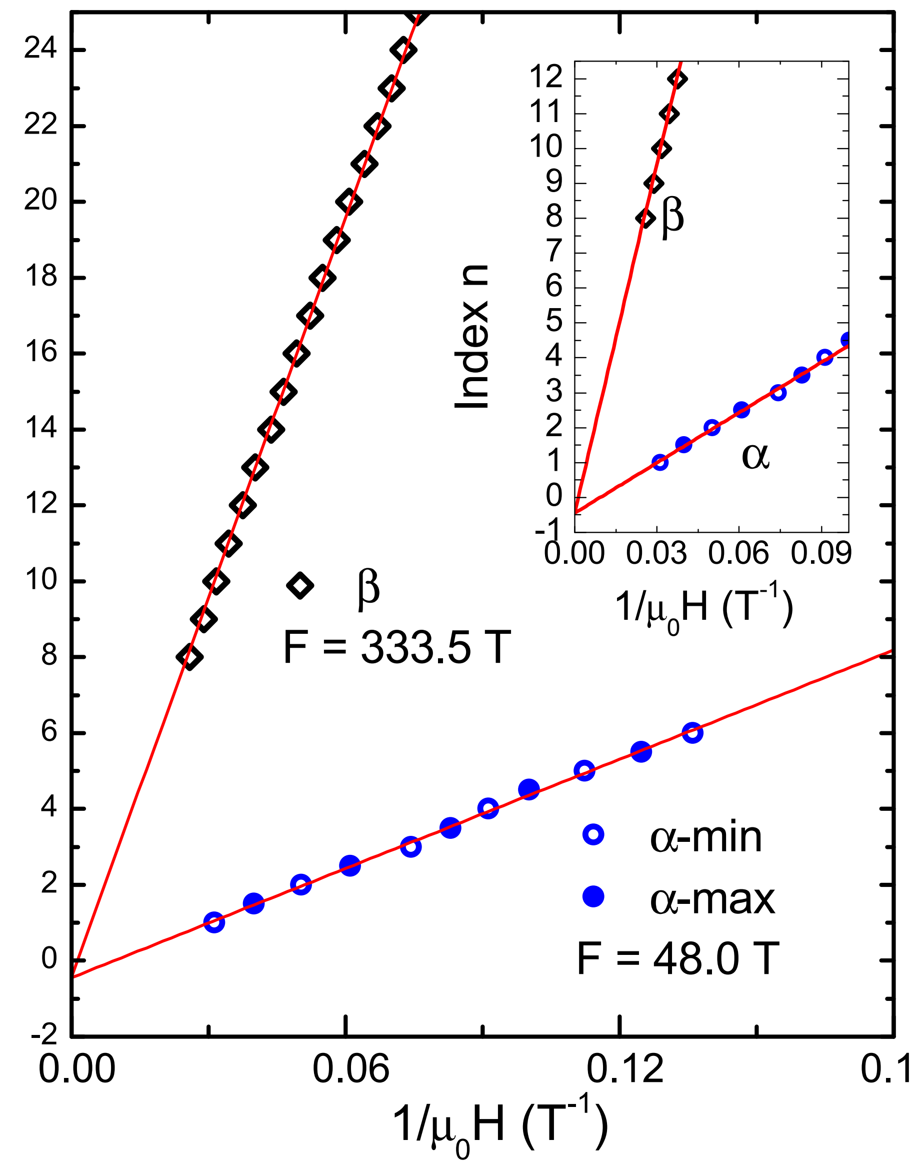

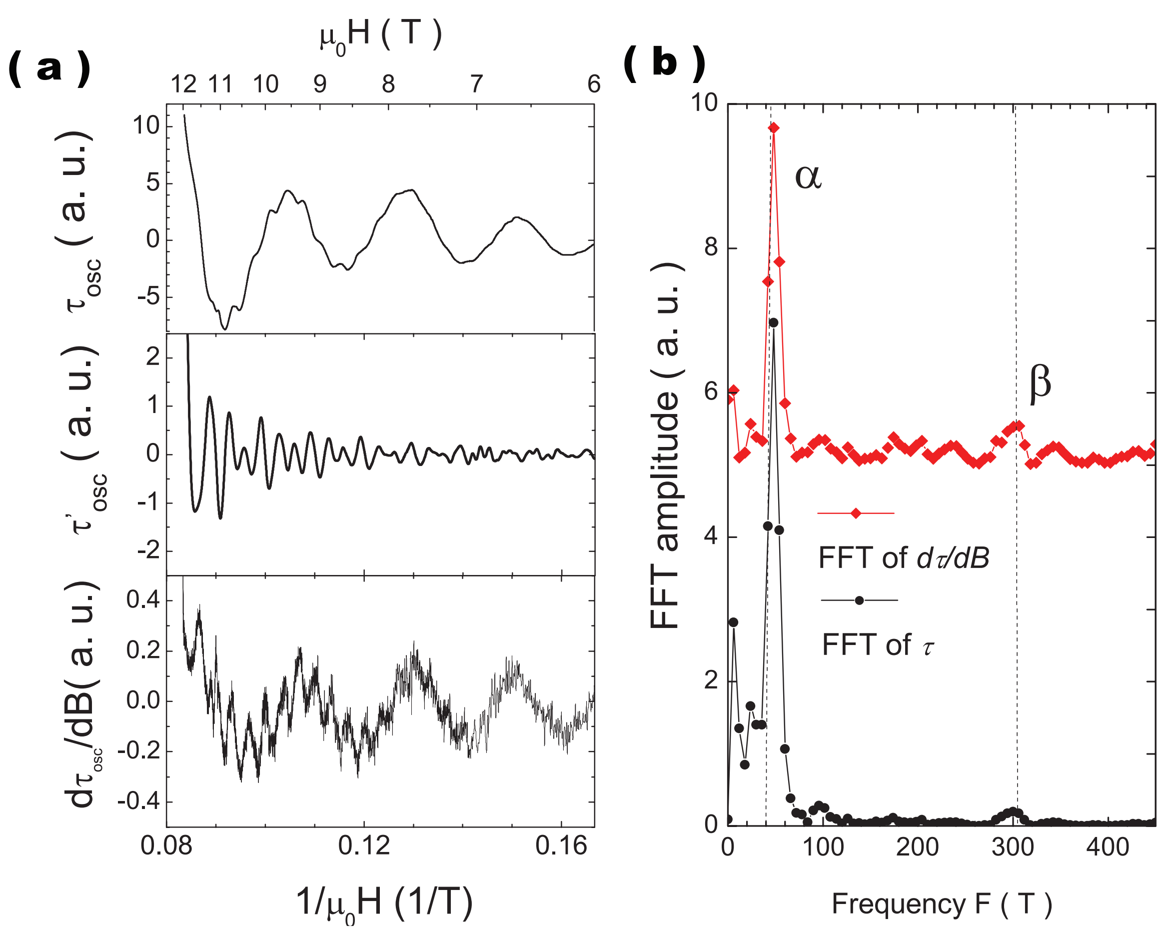

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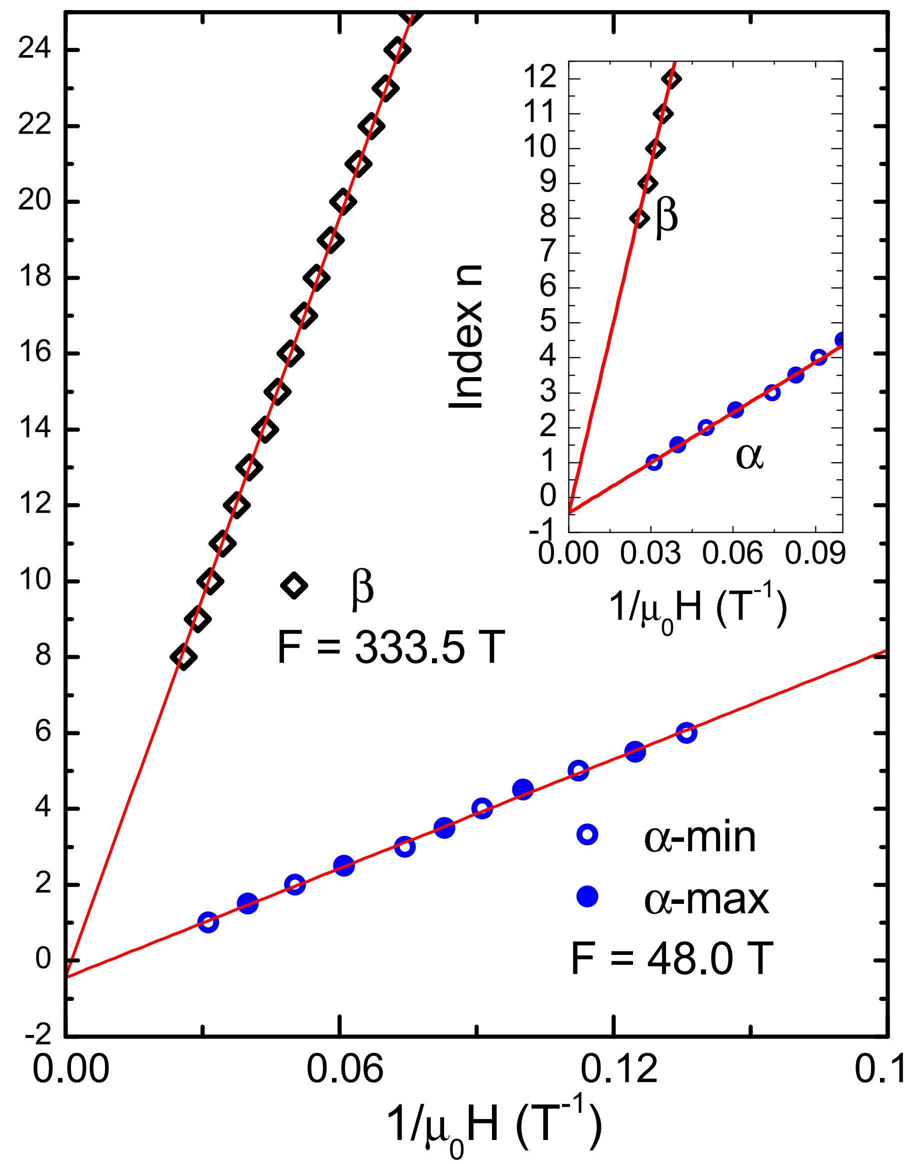
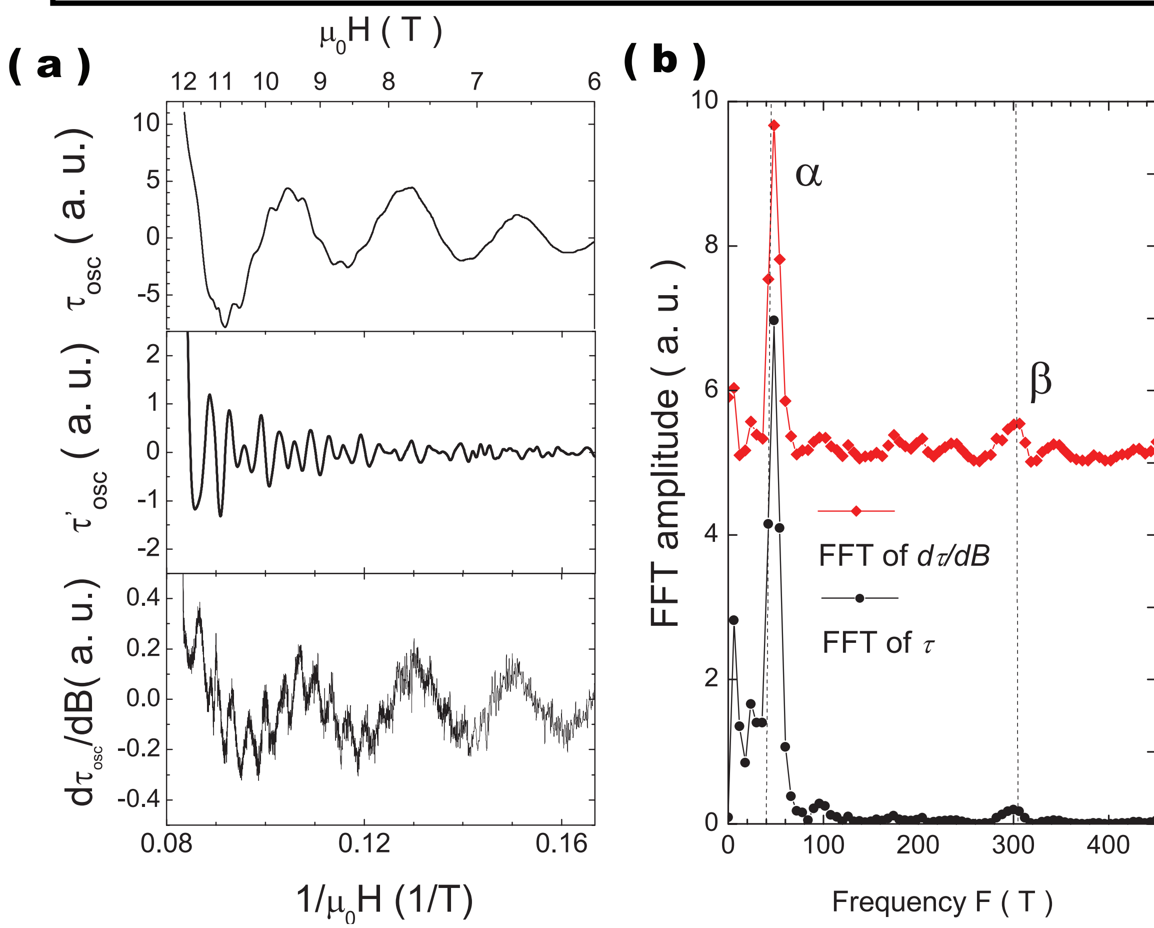
	α	β
F (T)	48.3 ±1.8	300.5 ± 1.3
k_F (nm^{-1})	0.383 ± 0.007	0.955 ± 0.002
$\frac{m}{m_e}$	0.074 ± 0.004	0.101± 0.012
v_F (10^5 m s^{-1})	6.0 ± 0.4	10.9± 1.3
l (nm)	33 ± 7	55 ± 16
μ ($\times 10^3 cm^2$/V s)	1.3 ± 0.3	0.86 ± 0.26
$k_F l$	13 ± 3	53 ± 15
γ	-0.45 ± 0.07	-0.44 ± 0.06





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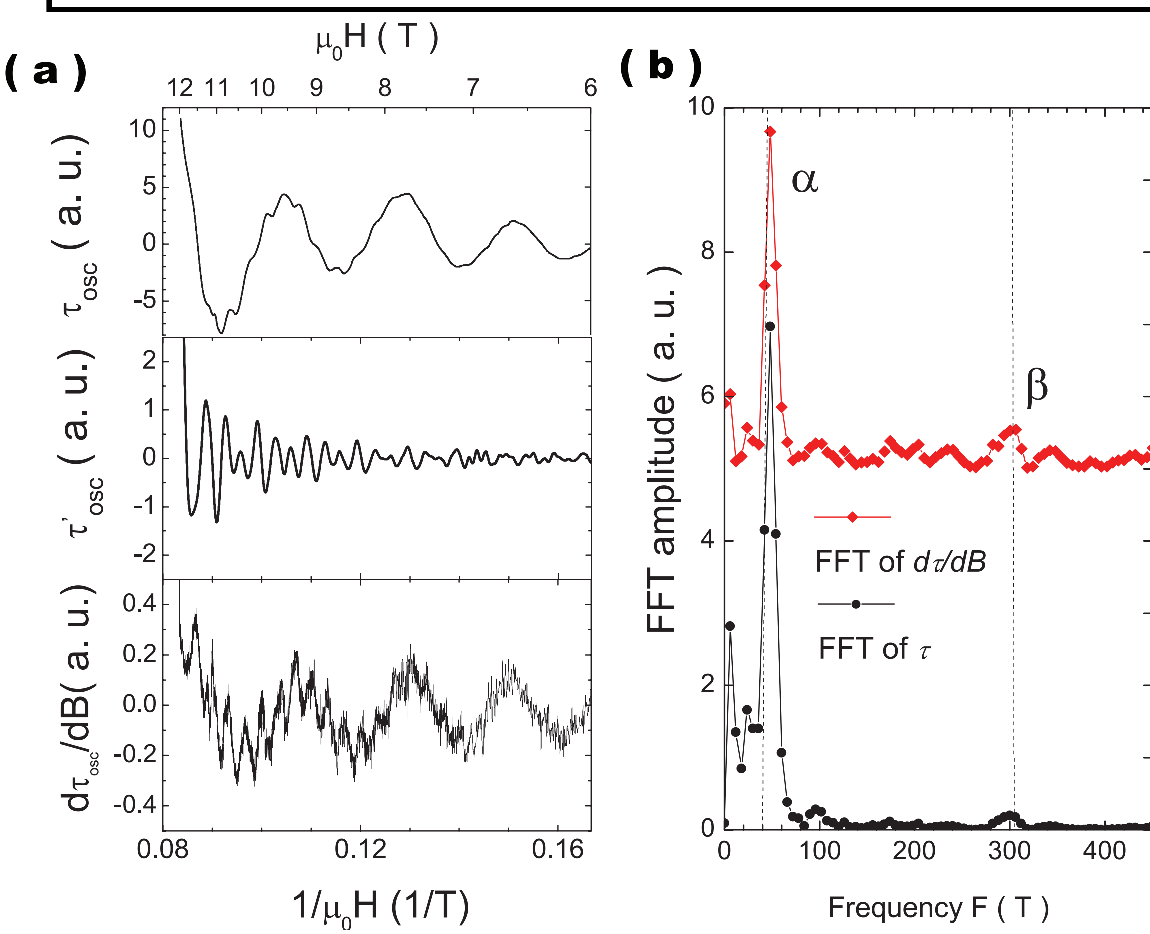

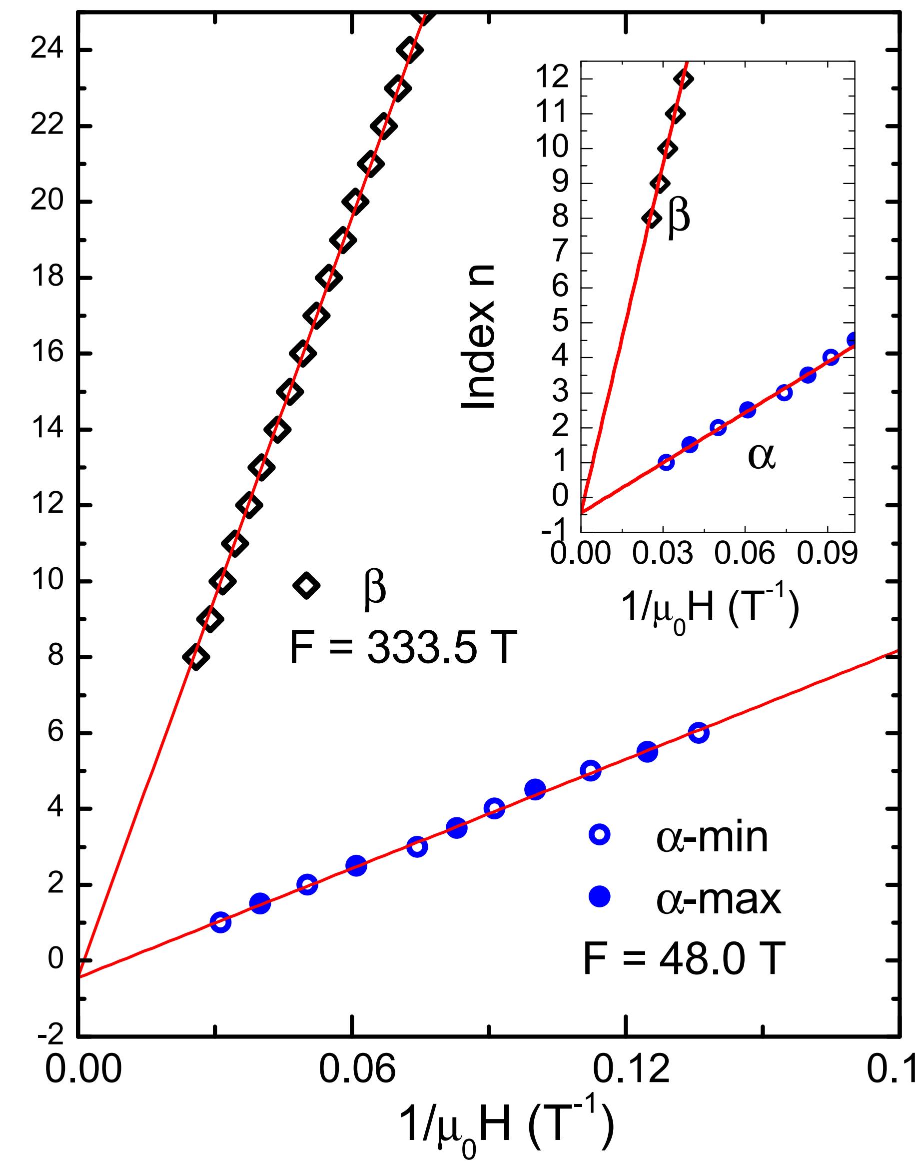

- Two Dirac Cones
- Light quasiparticles

Weak Antilocalization and Linear Magnetoresistance in The Surface State of SmB_6

S. Thomas[1]*, D.J. Kim[1]*, S. B. Chung[2], T. Grant[1], Z. Fisk[1] and Jing Xia[1]

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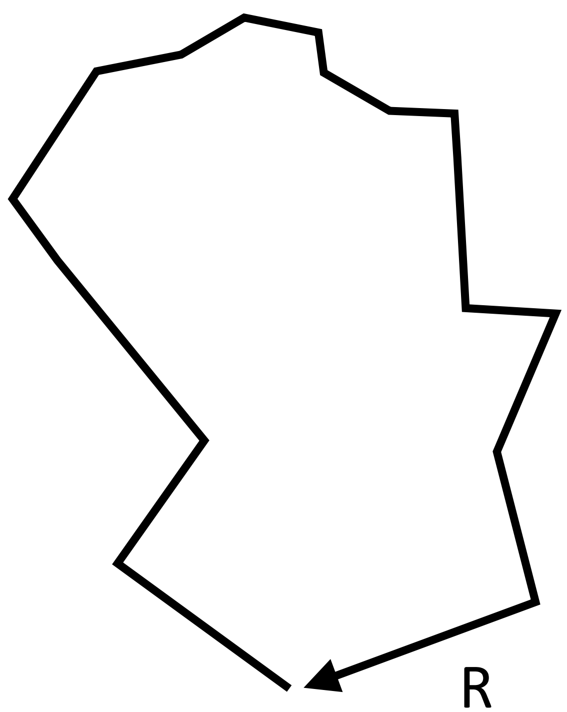

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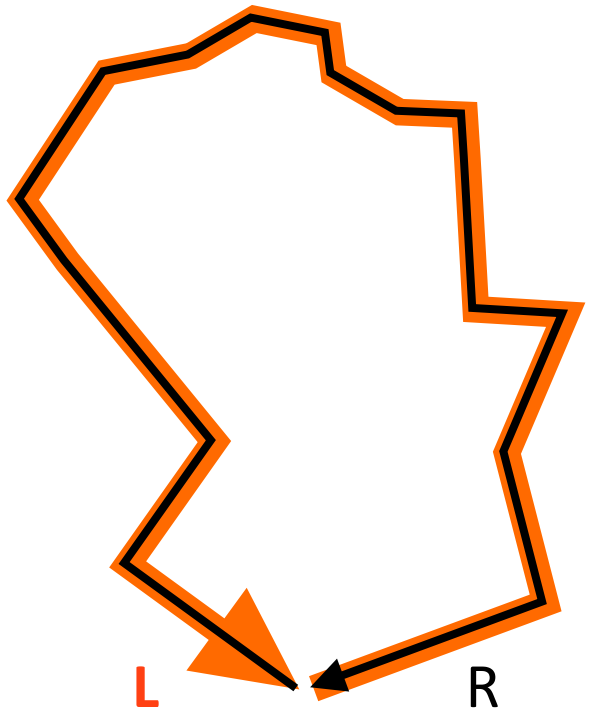

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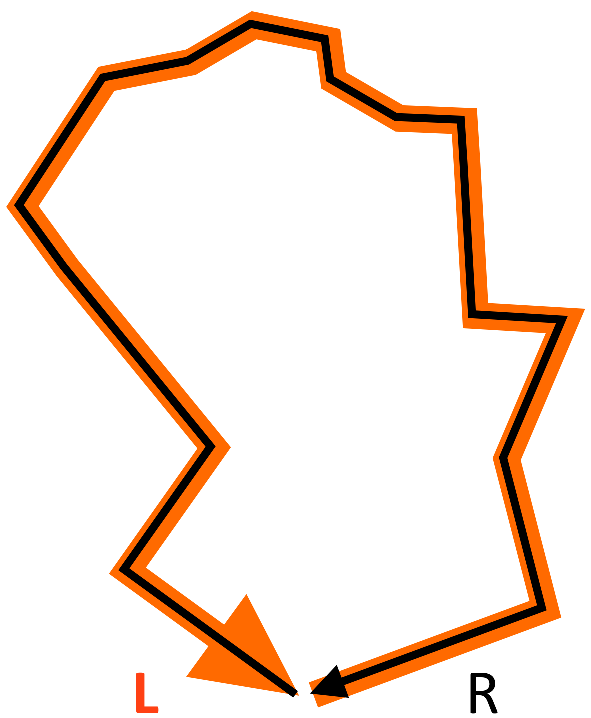

Localization

$$\psi_L = \psi_R$$

$$p = |\psi_L + \psi_R|^2 = |\psi_L|^2 + |\psi_R|^2 + 2|\psi_L||\psi_R|$$

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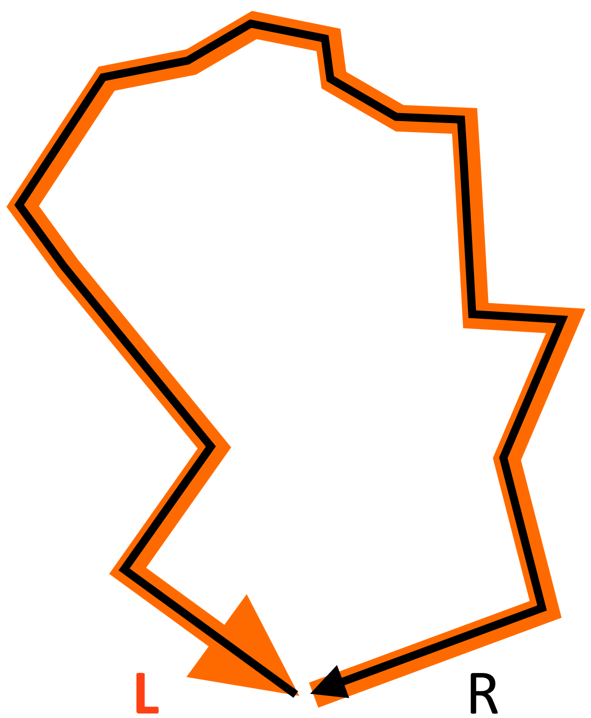

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Anti Localization:
spin rotates with p.

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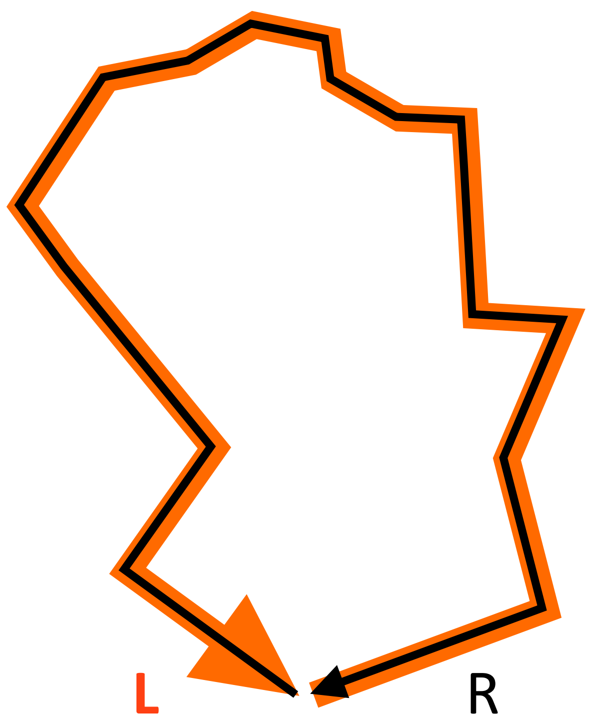

Localization

$$\psi_L = \psi_R$$

$$p = |\psi_L + \psi_R|^2 = |\psi_L|^2 + |\psi_R|^2 + 2|\psi_L||\psi_R|$$

Anti Localization:
spin rotates with p.

$$\psi_L = -\psi_R$$

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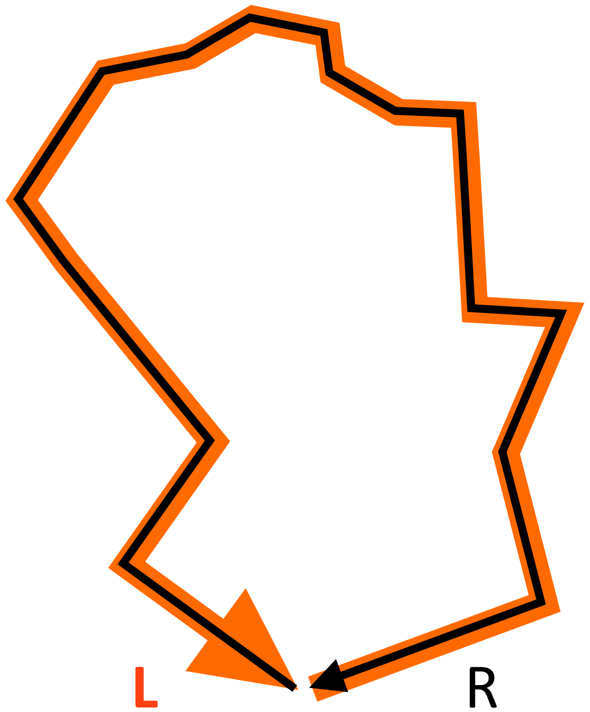
Weak Antilocalization and Linear Magnetoresistance in The Surface State of SmB_6

S. Thomas[1]*, D.J. Kim[1]*, S. B. Chung[2], T. Grant[1], Z. Fisk[1] and Jing Xia[1]



Localization

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Hikami, Larkin & Nagaosa, Prof. Th. Physics, 63, 707 (1980)

$$\Delta\sigma = \sigma(H) - \sigma(0)$$

$$= -\frac{\alpha e^2}{2\pi^2\hbar}\left[\ln\frac{1}{\tau_\varepsilon a} - \psi\left(\frac{1}{2} + \frac{1}{\tau_\varepsilon a}\right)\right].$$

where $a = 4DeH/\hbar c$,

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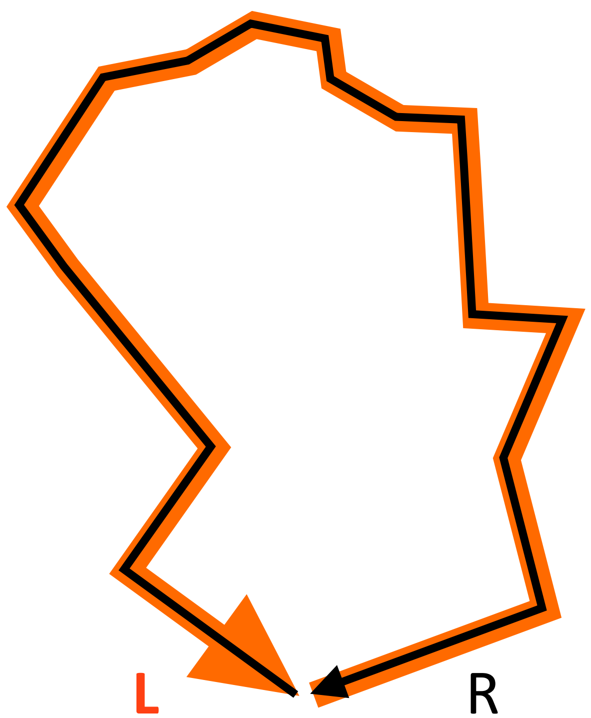

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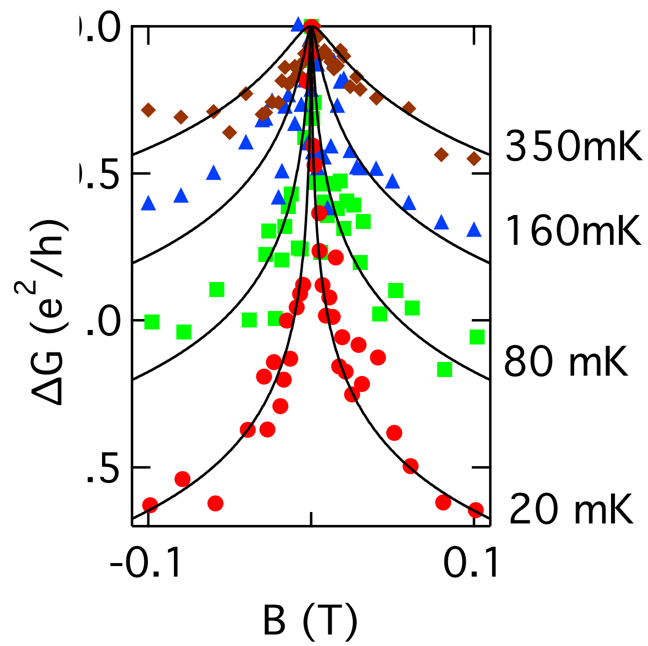

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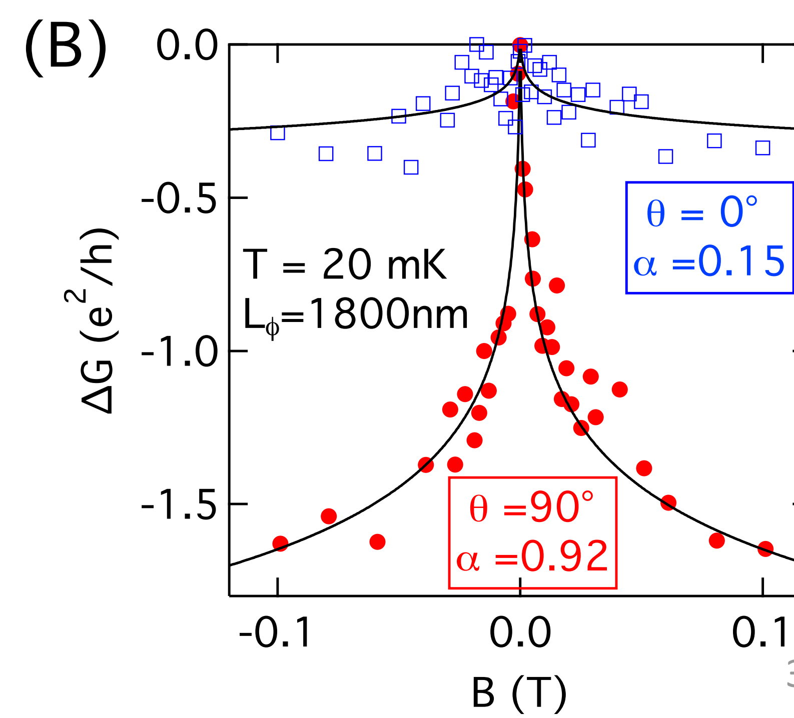

SmB_6 : Summary & Questions

- Weak localization, dHvA, surface conductance and Arpes, taken together, indicate that this is a topological insulator - moreoever, a TKI.

- The multiplicity of Dirac cones supports the idea that this system derives from a quartet state of SmB_6.

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SmB_6: Summary & Questions

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- The multiplicity of Dirac cones supports the idea that this system derives from a quartet state of SmB_6.

- The high bulk resistivity may make this the best practical candidate for 3D TI's discovered to date.

- But! Why are the surface states light in dHvA and Arpes?

- Can the surface states undergo phase transitions? eg Paired surface states.

- Is topology important for other strongly correlated systems - metals, superconductors?

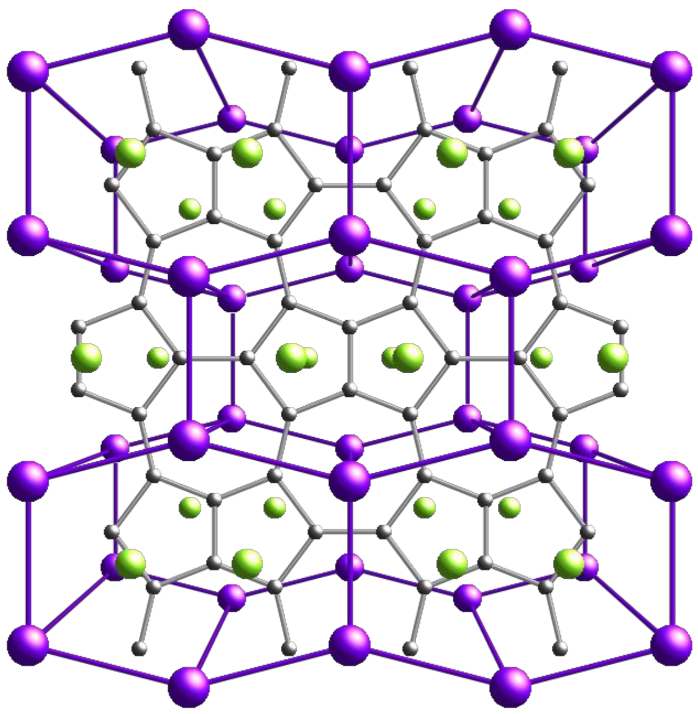
Topological Kondo insulators ?

Hasan and Kane (RMP 2009)
Qi and Zhang (RMP 2010)

β-$YbAlB_4$: Intrinsically Quantum Critical Heavy Fermion Superconductor

β-$YbAlB_4$:

Intrinsically Quantum Critical Heavy Fermion SC.



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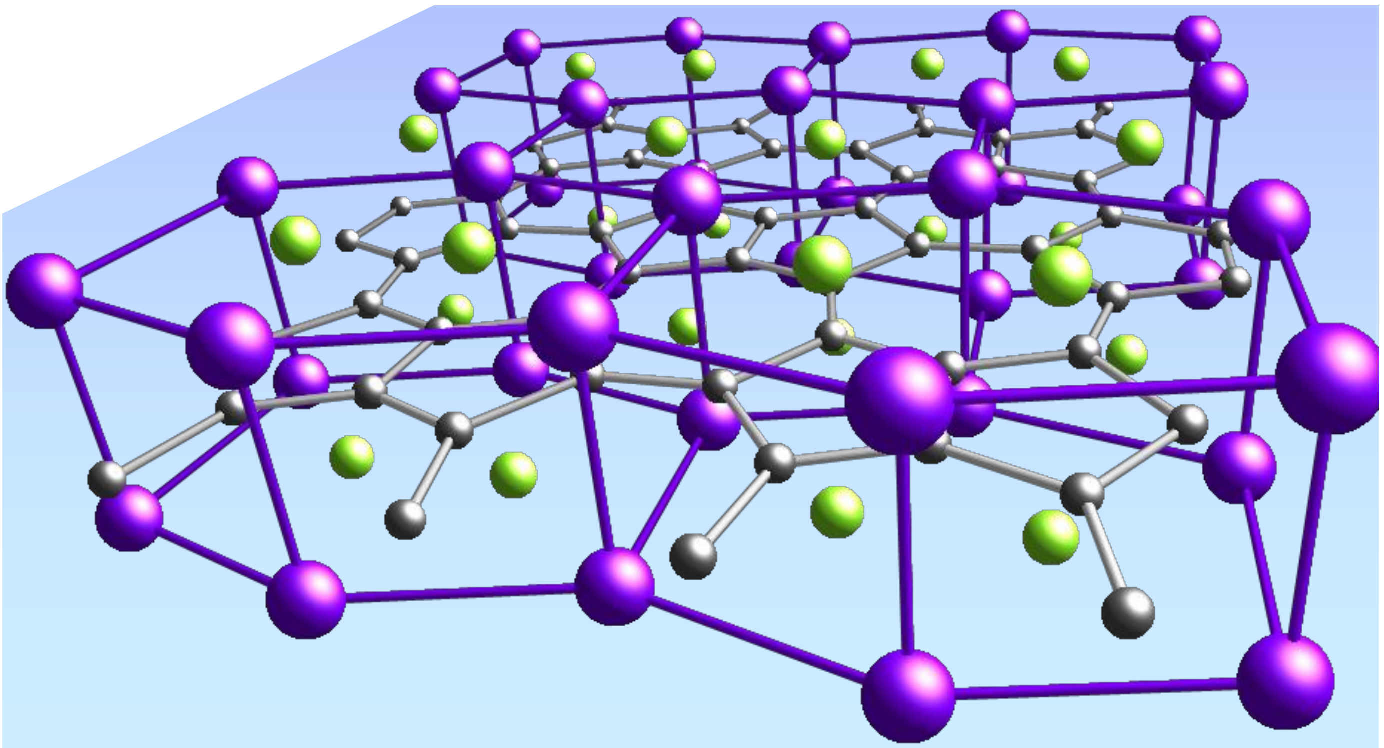

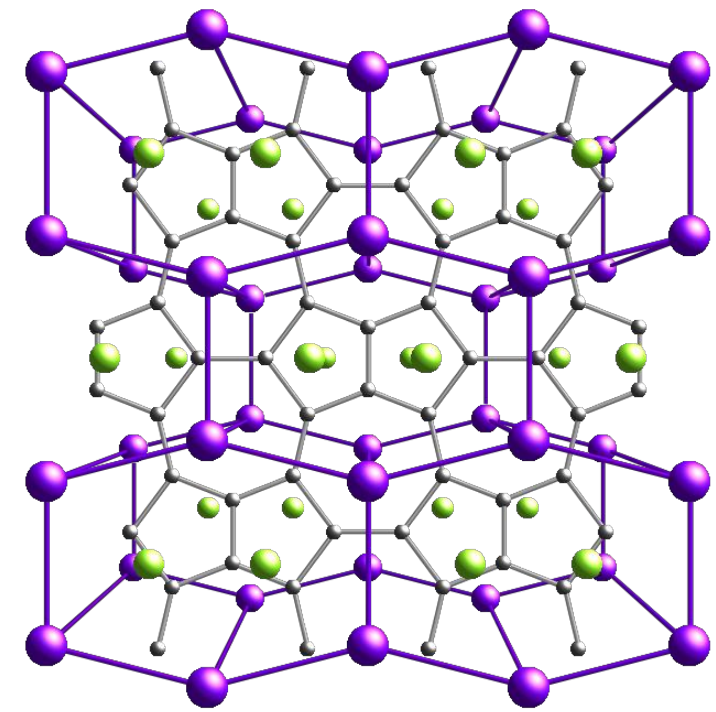

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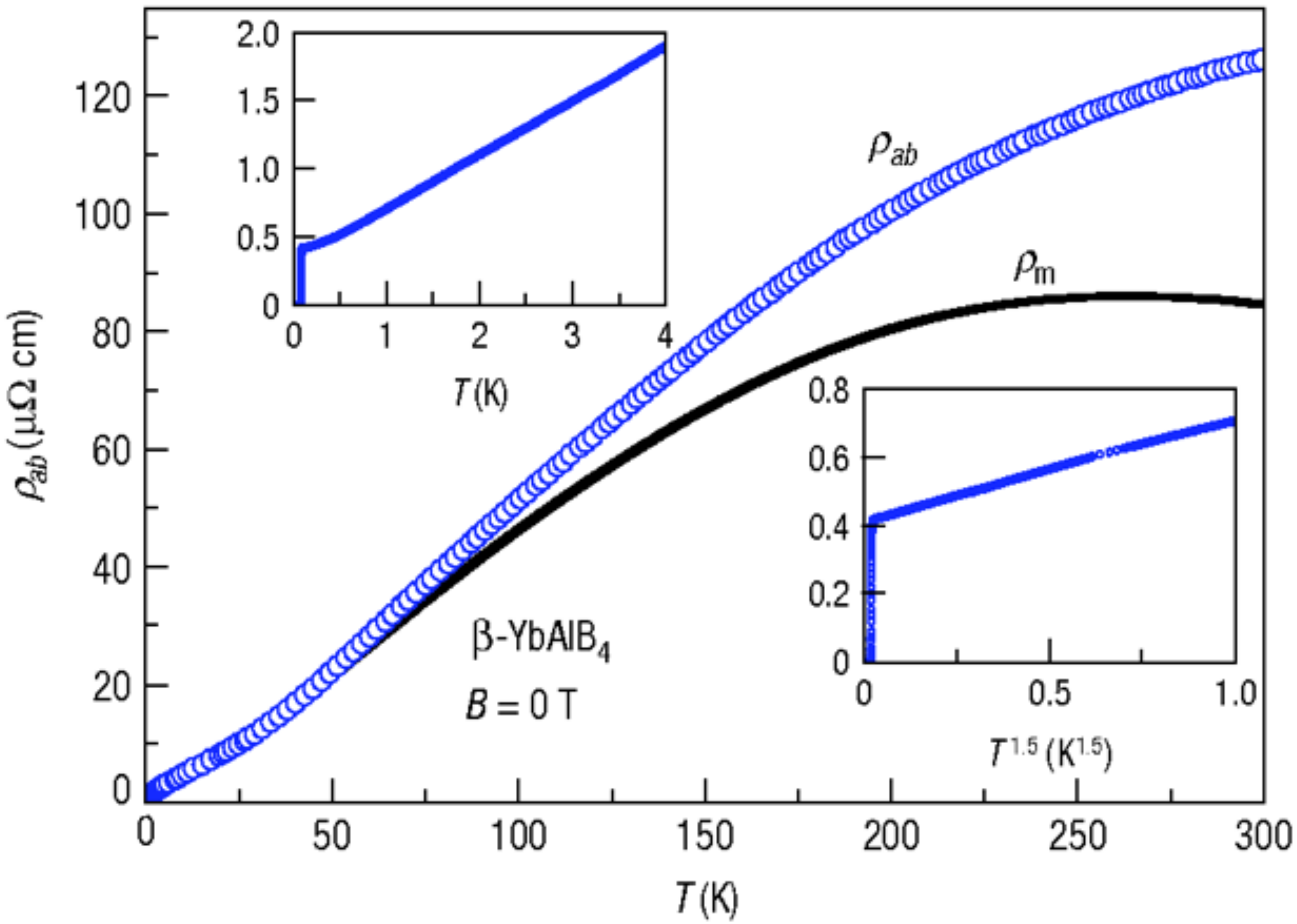

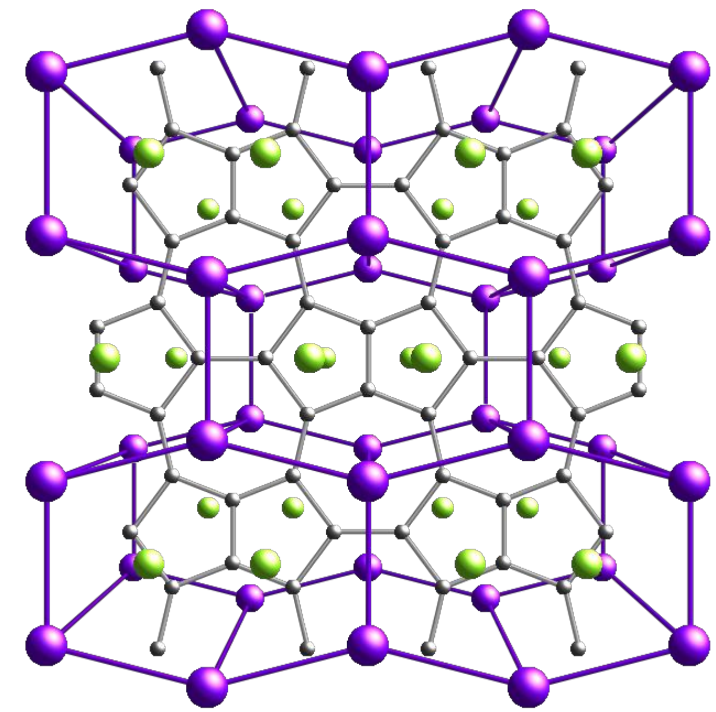

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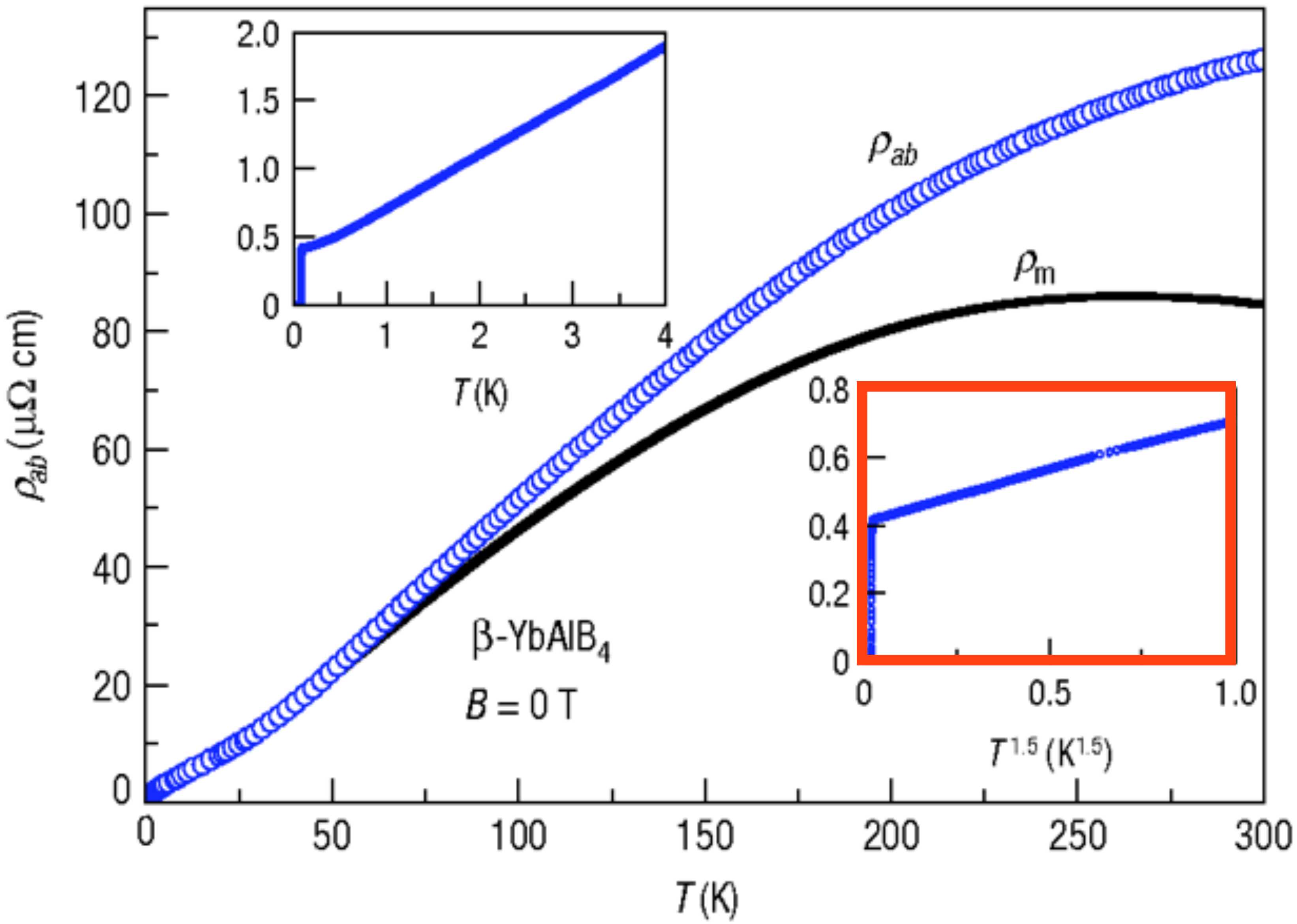

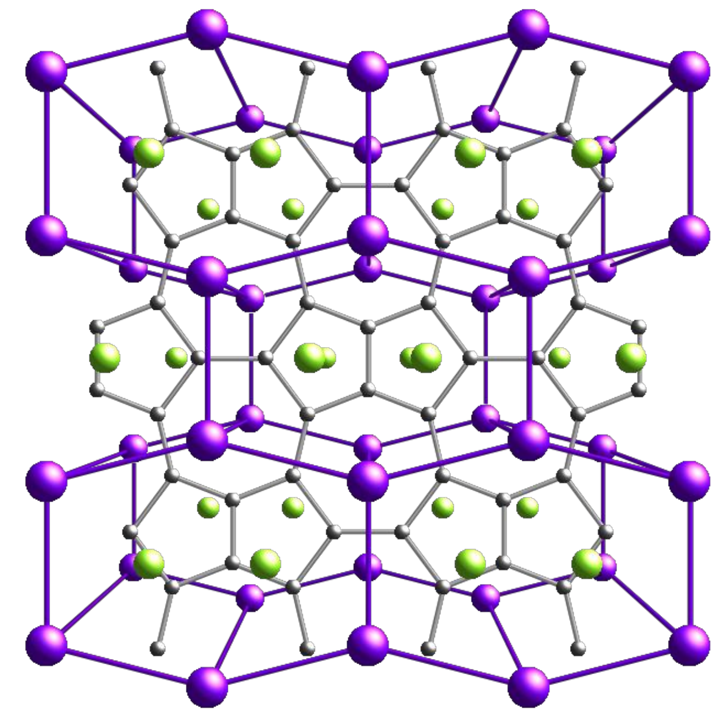

β-YbAlB$_4$

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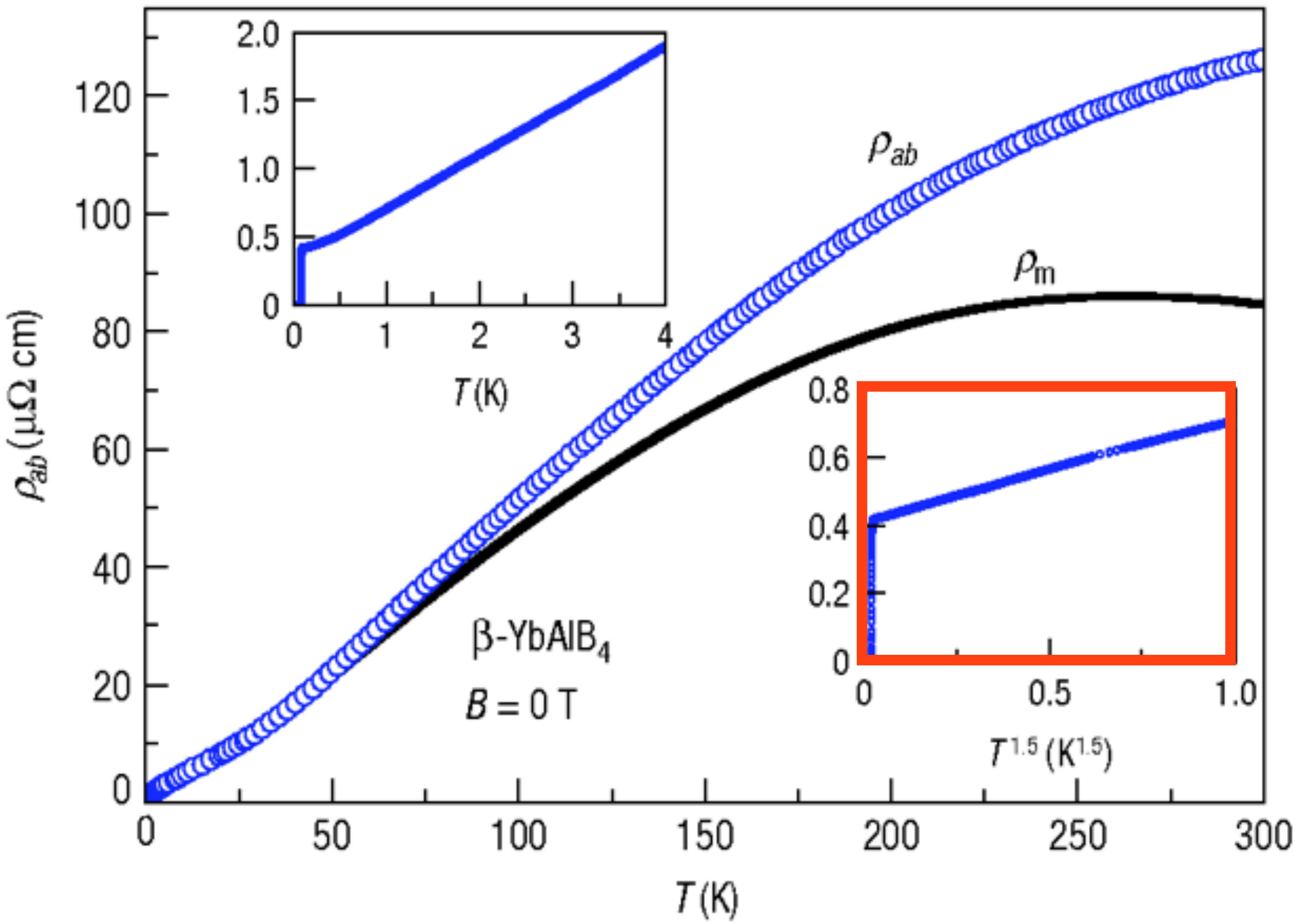

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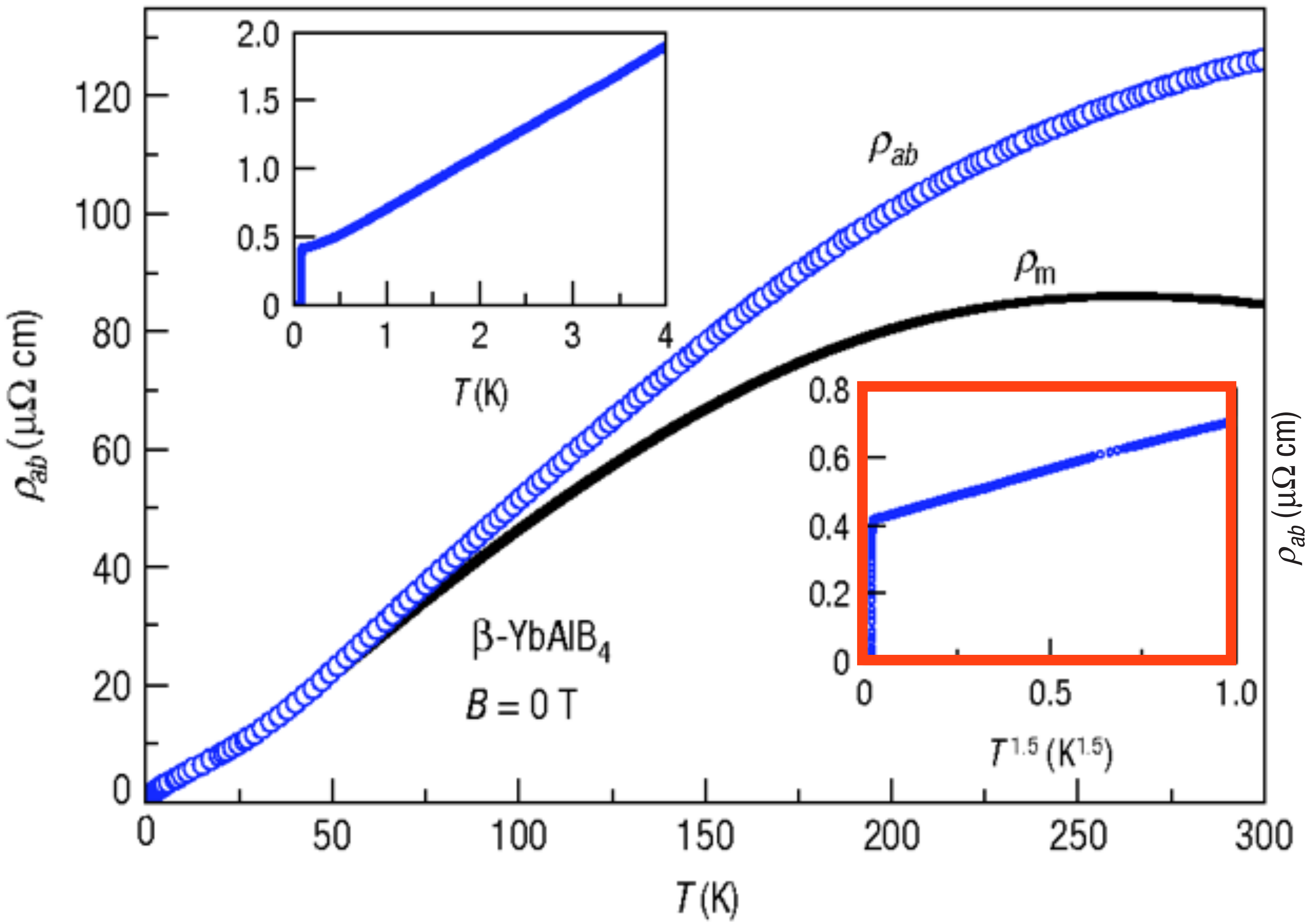

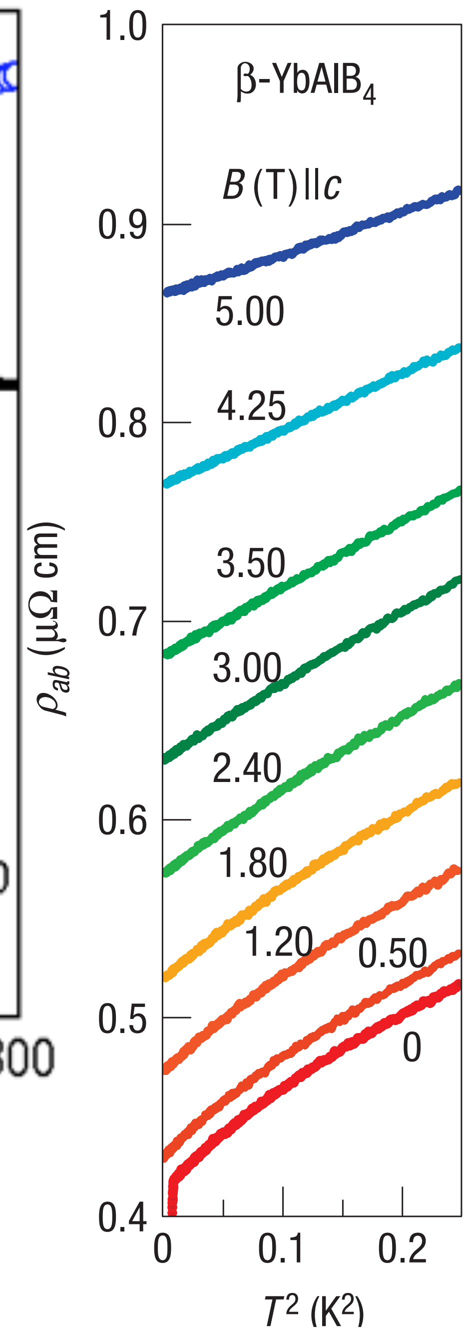

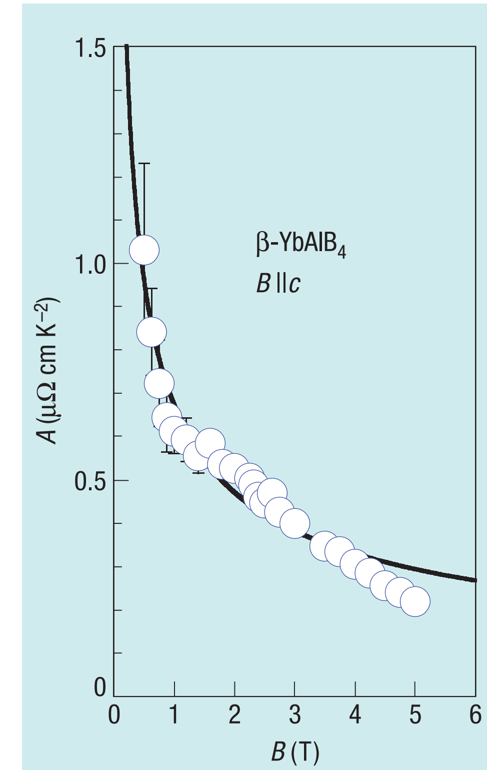

$$\rho(T) = \rho_0 + A(B)T^2$$

$$B \to 0 : A(B) \to \infty$$

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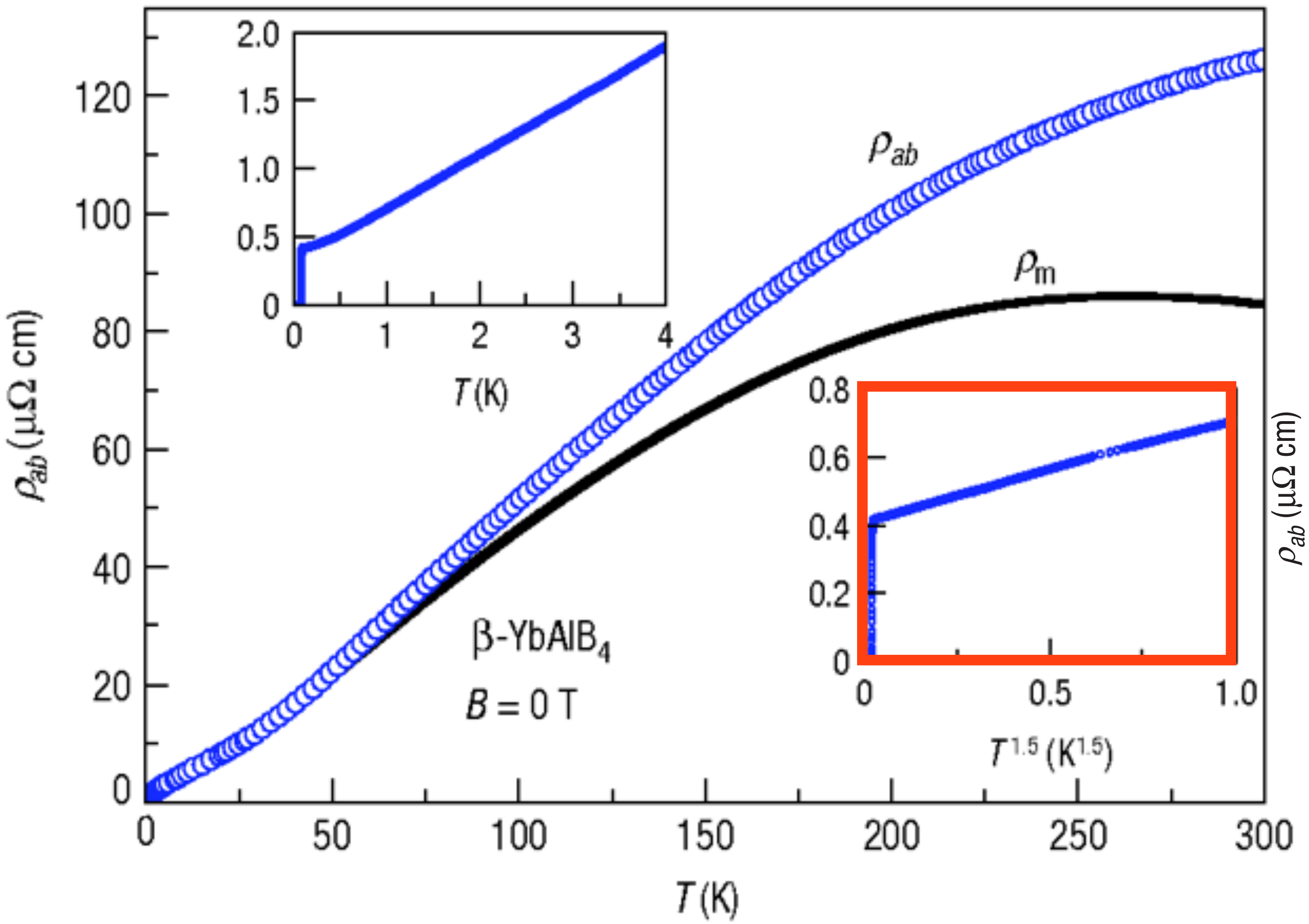

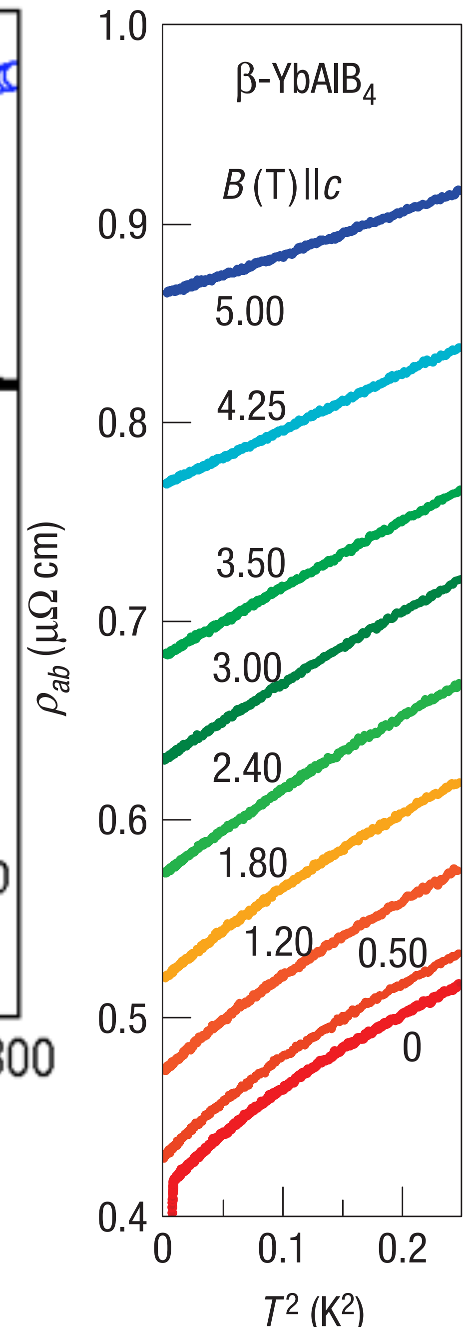

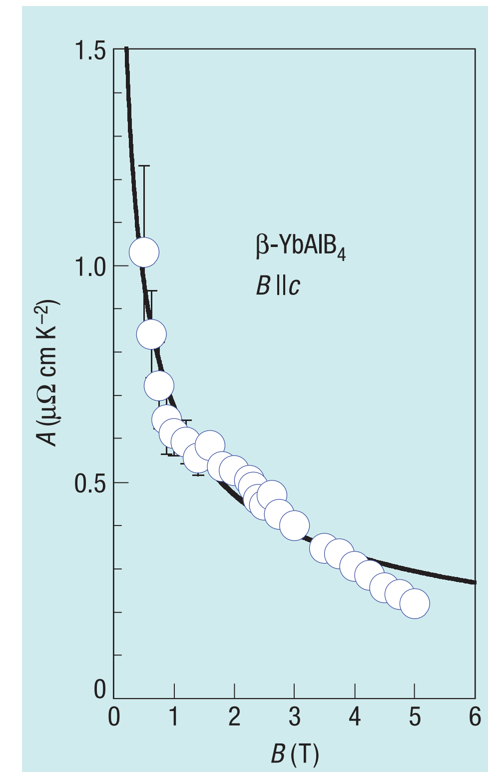

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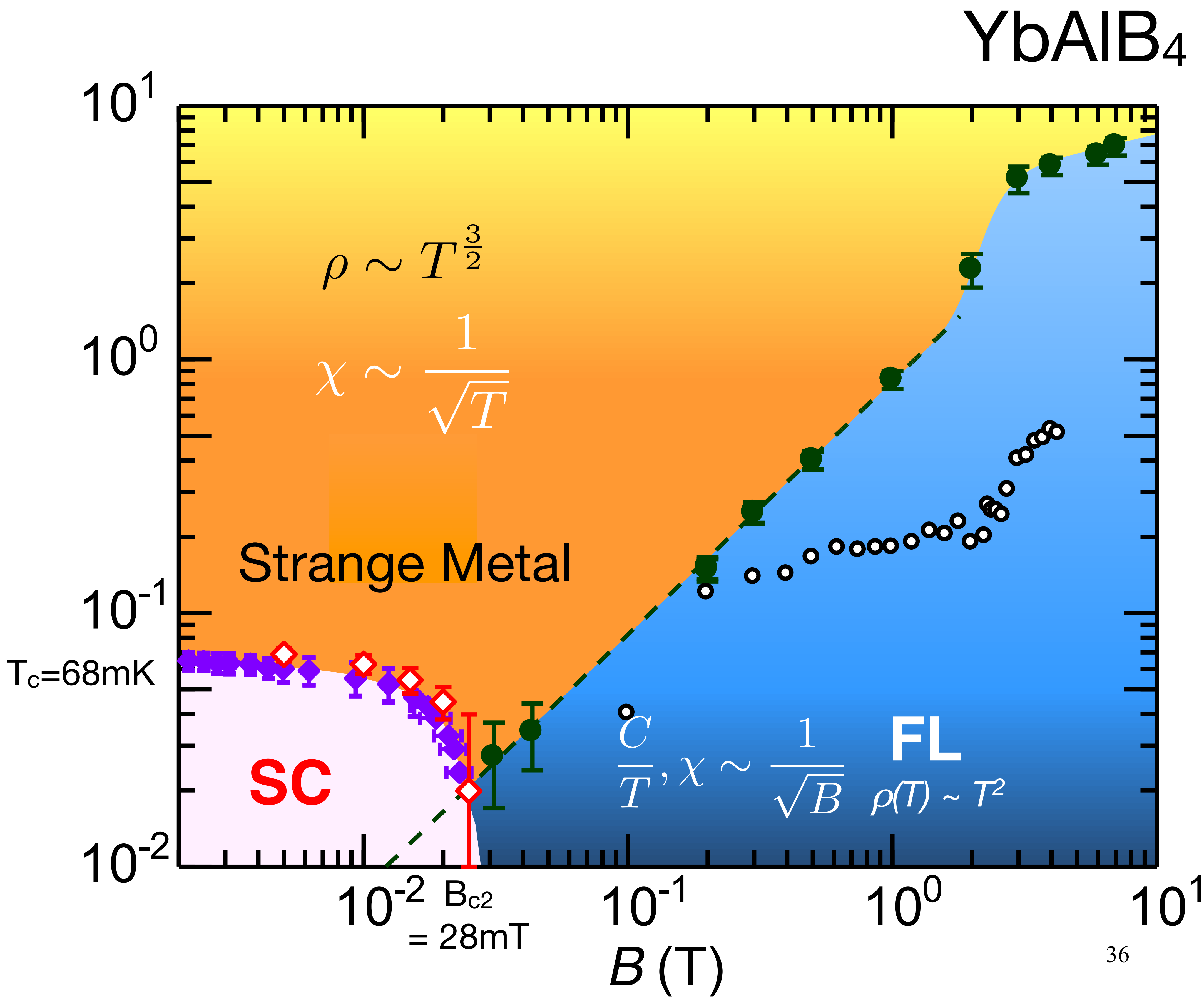
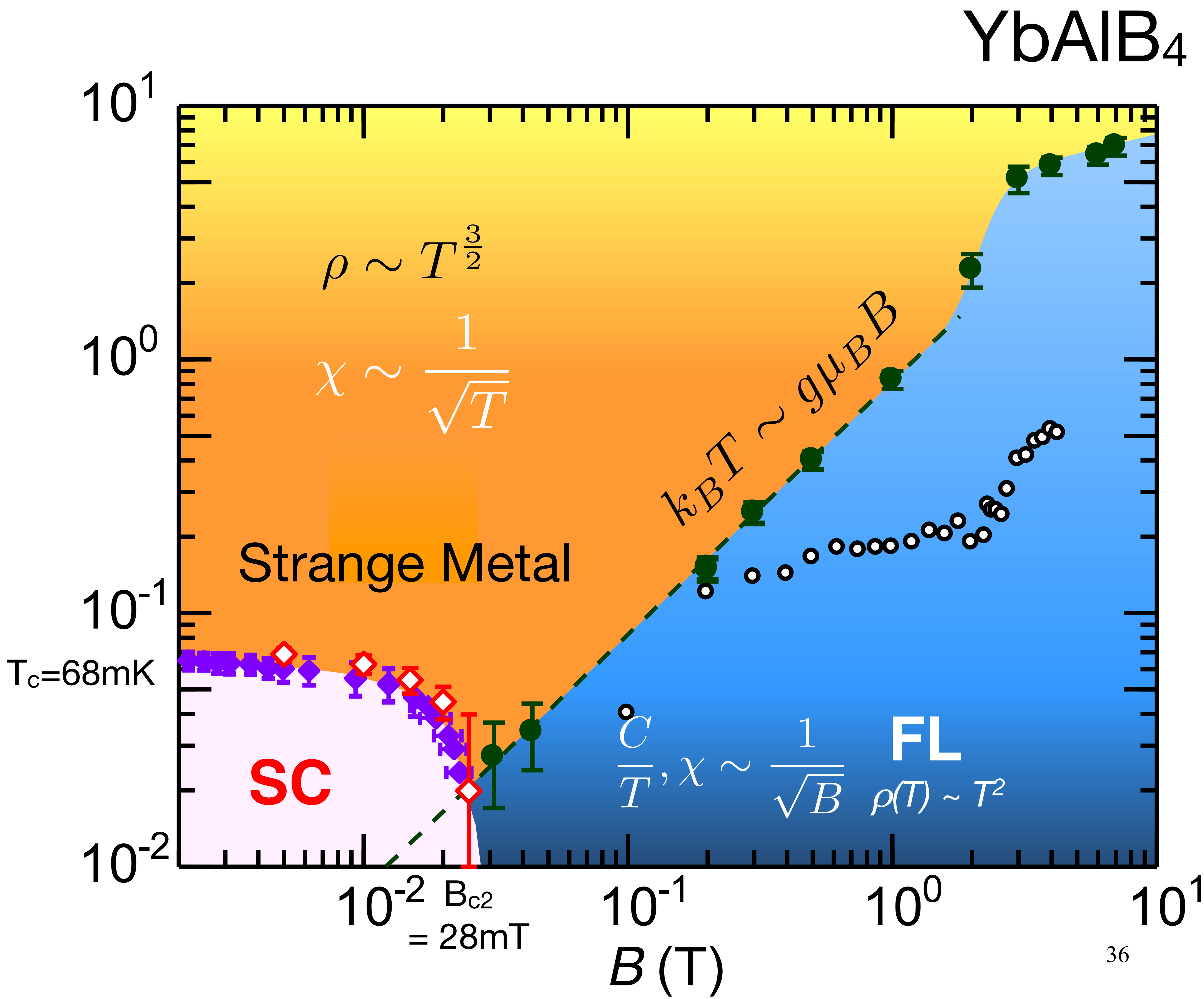
$$B \to 0 : A(B) \to \infty \qquad T_F(B^+) \to 0$$

Releasing the field reveals the strange metal.



YbAlB$_4$
$\rho \sim T^{\frac{3}{2}}$
$\chi \sim \frac{1}{\sqrt{T}}$
Strange Metal
T_c=68mK
SC
$\frac{C}{T}, \chi \sim \frac{1}{\sqrt{B}}$
FL
$\rho(T) \sim T^2$
10^1
10^0
10^{-1}
10^{-2}
B_{c2}
= 28mT
B (T)



YbAlB$_4$
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Strange Metal
$k_B T \sim g\mu_B B$
T_c=68mK
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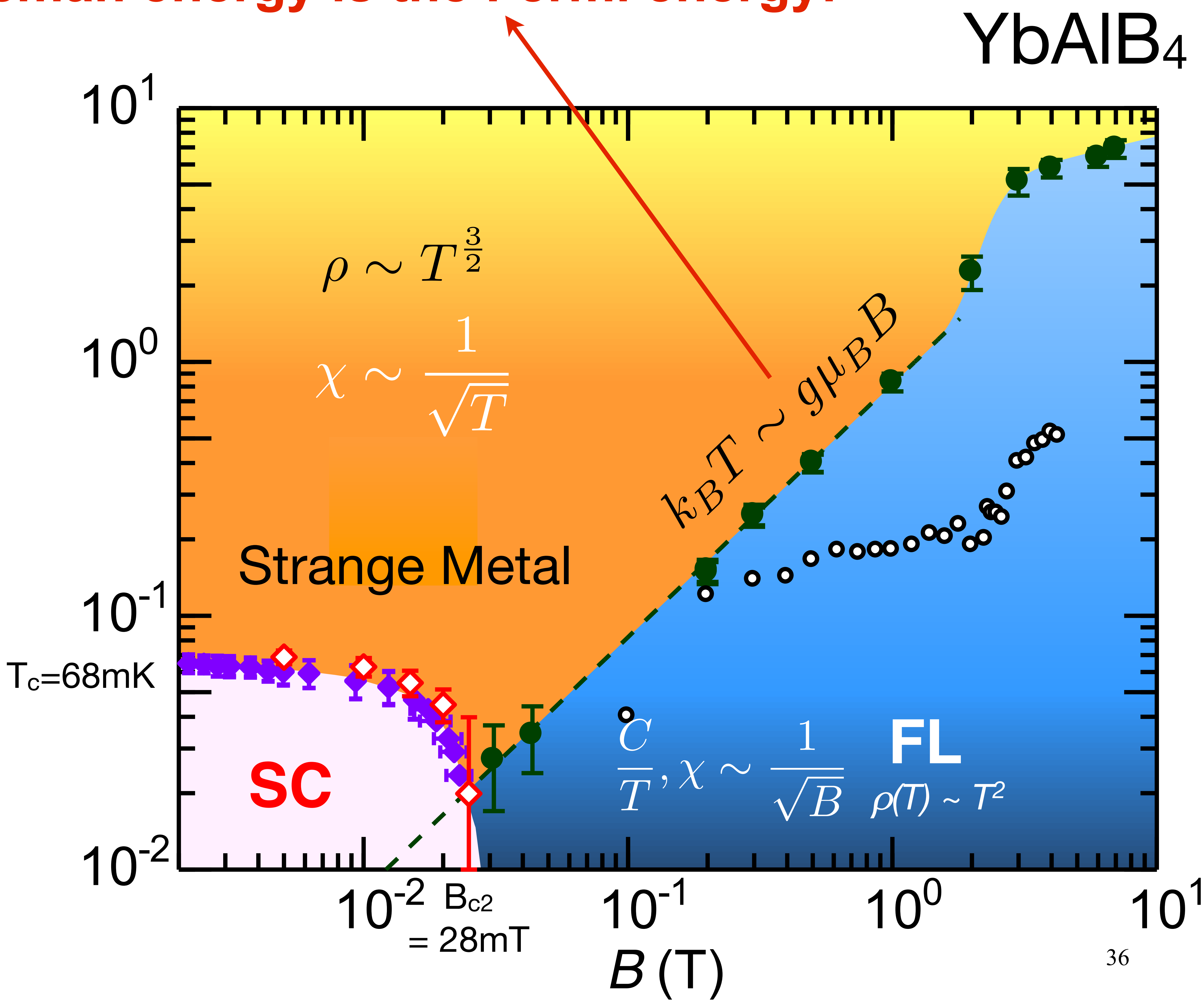
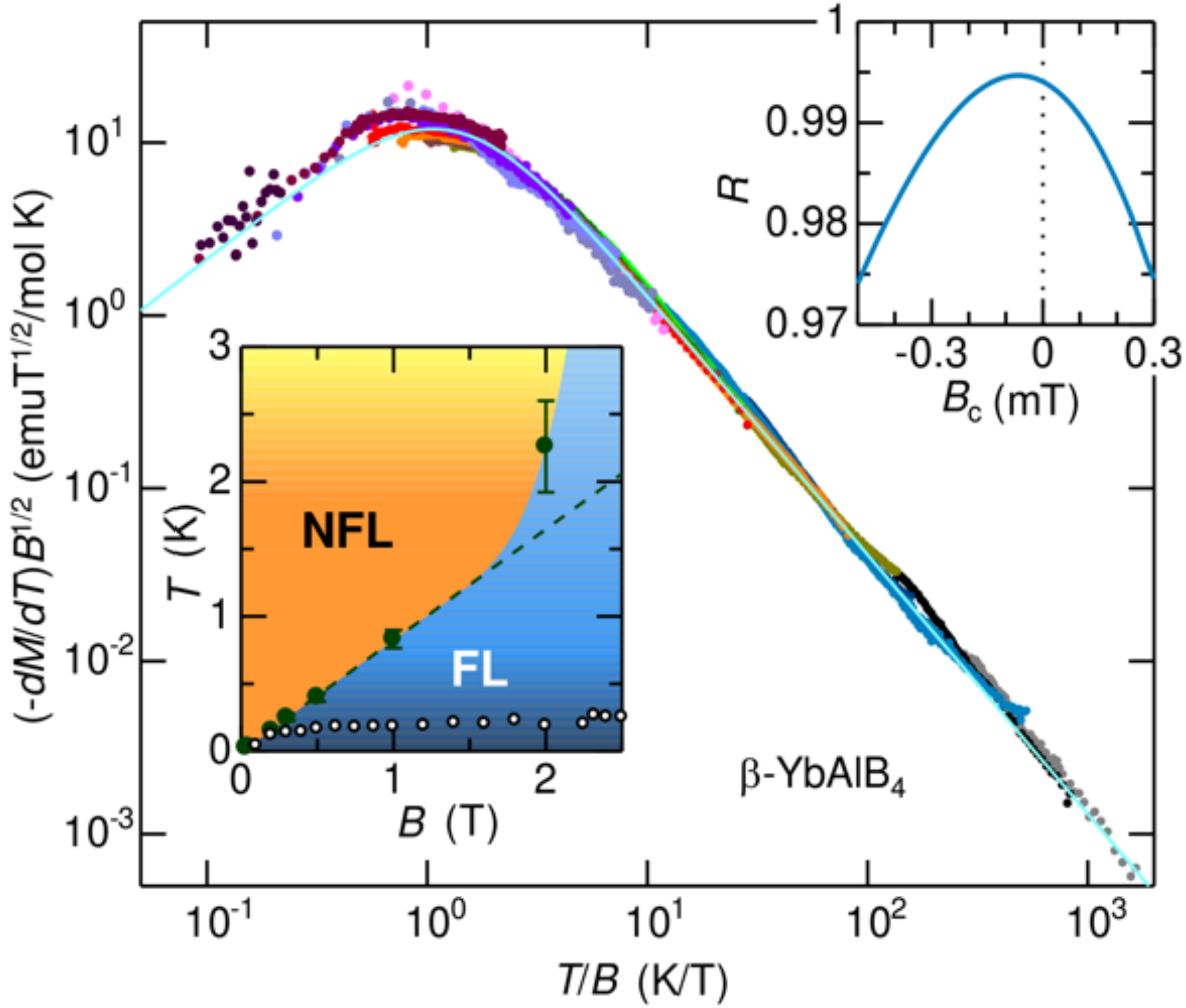
10^1
10^0
10^{-1}
10^{-2}
B_{c2}
= 28mT
B (T)

Zeeman energy is the Fermi energy!



Scaling in β-$YbAlB_4$



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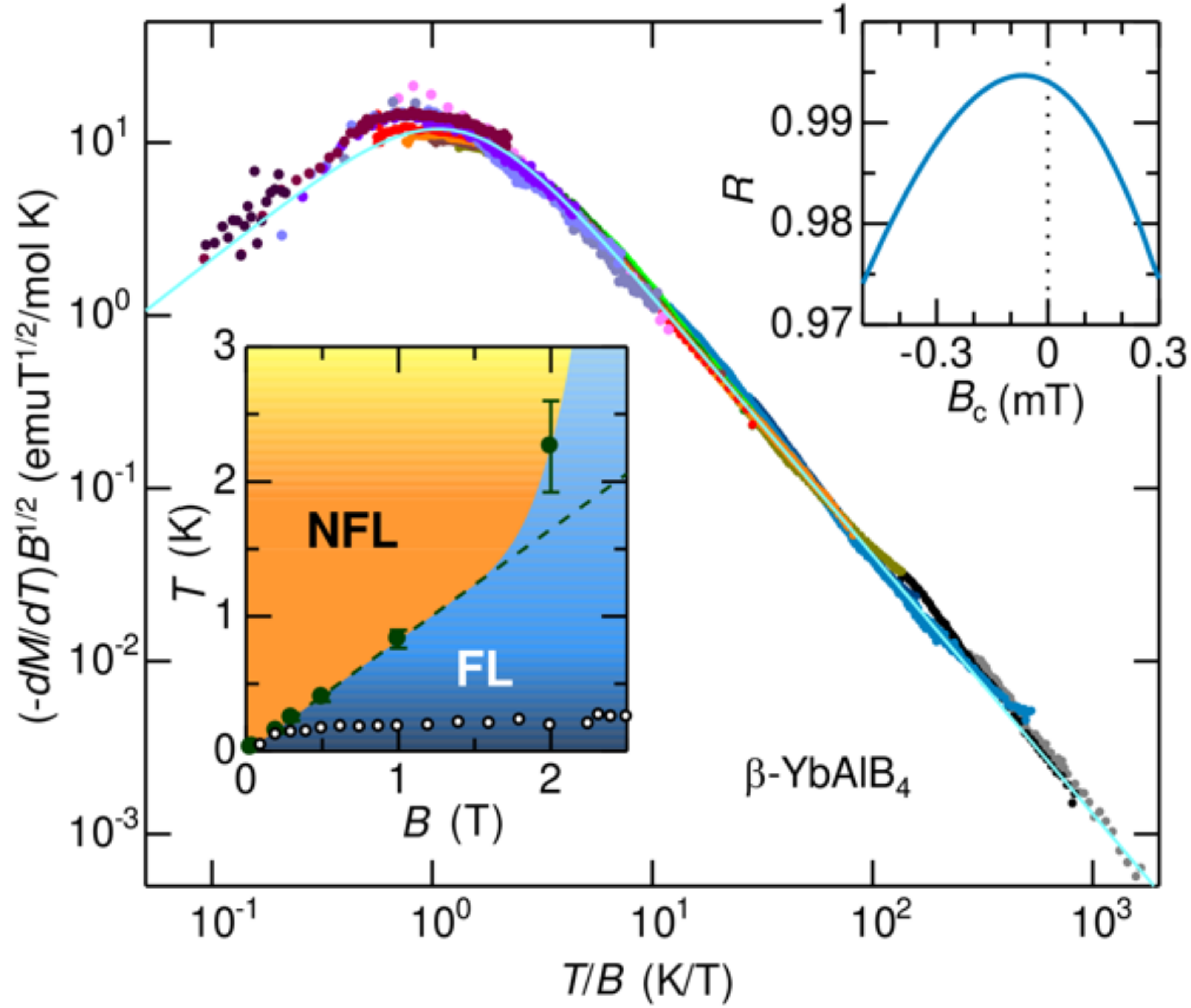
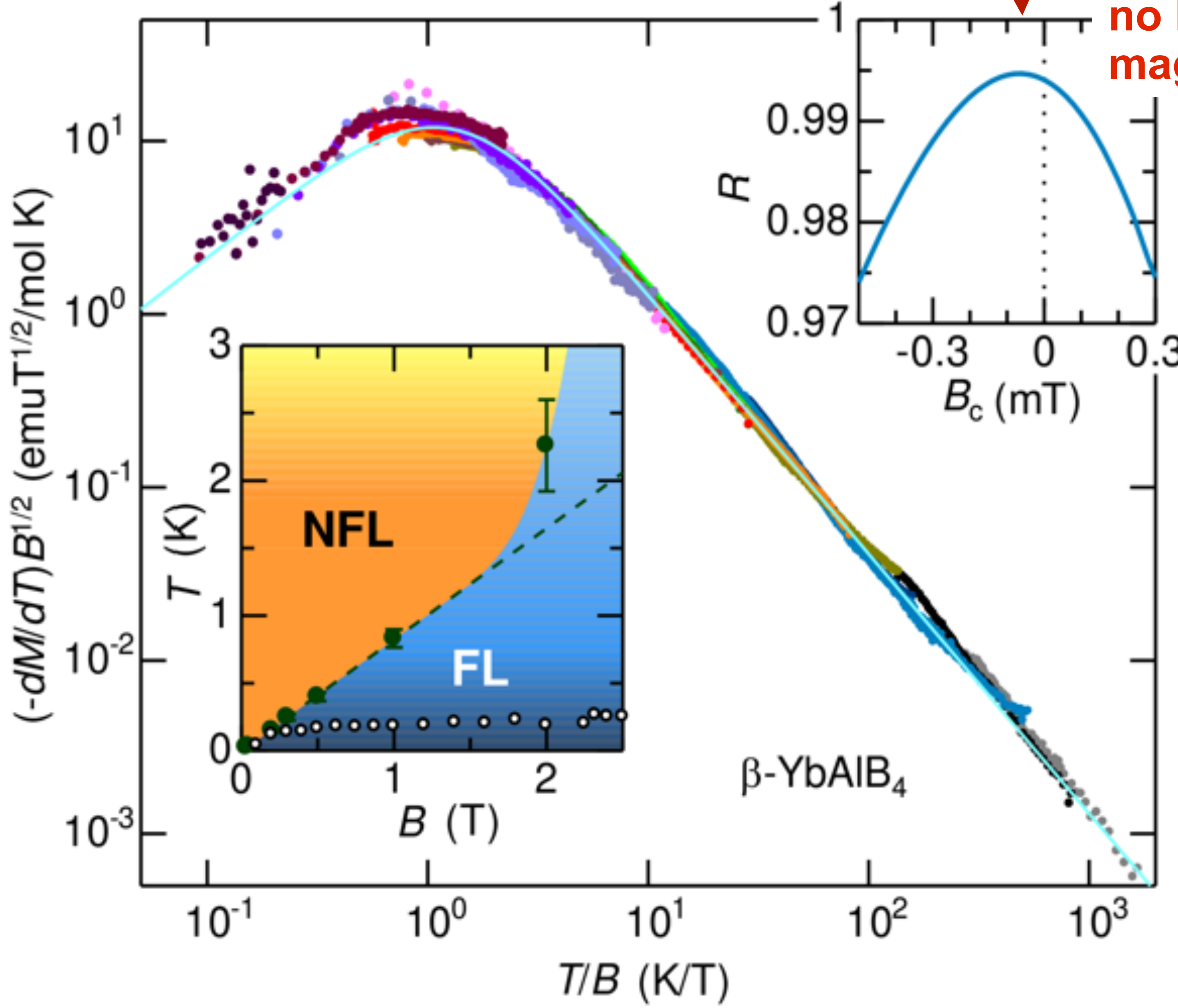


$$-\frac{\mathrm{d}M}{\mathrm{d}T} = B^{-1/2} f\left(\frac{T}{B}\right), \quad T \gg B$$

Scaling in β-YbAlB$_4$

Bc < 0.1mT

Critical field, if it exists, is no bigger than the earth's magnetic field (0.06mT)



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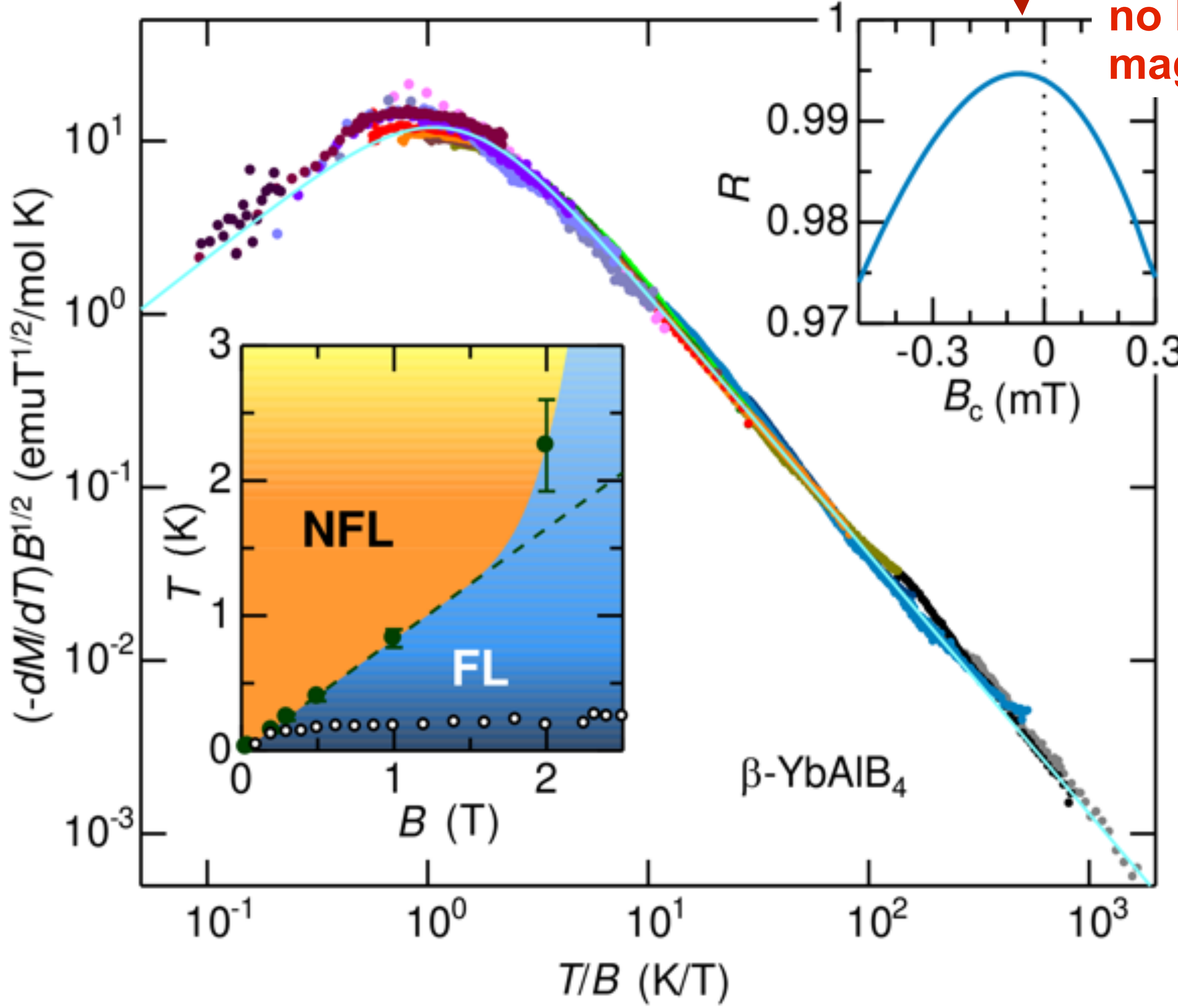

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$$F_{QC} = -\frac{1}{(k_B\tilde{T})^{1/2}}\left[(g\mu_B B)^2 + (k_B T)^2\right]^{3/4}$$

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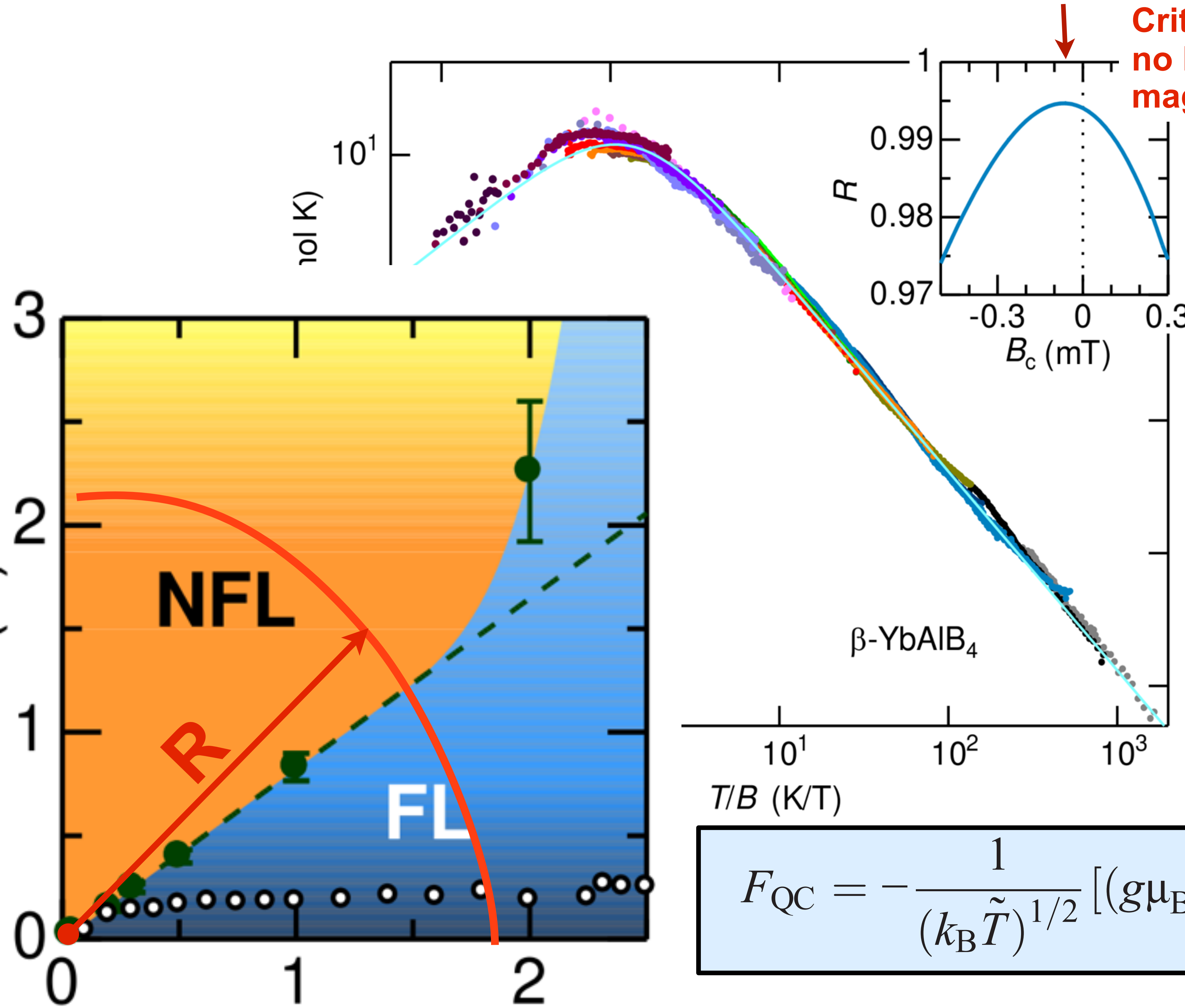

F~ $R^{3/2}$

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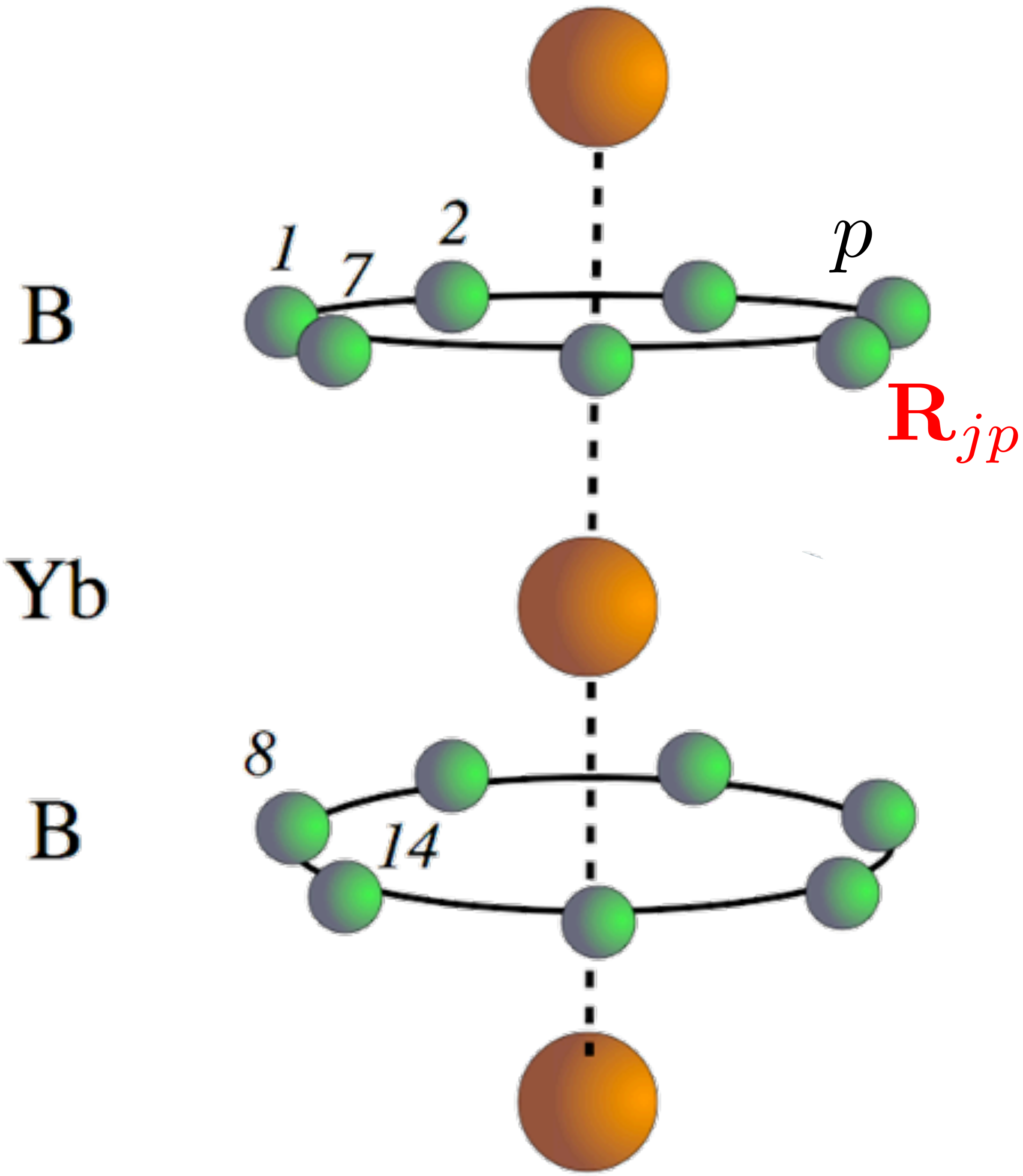
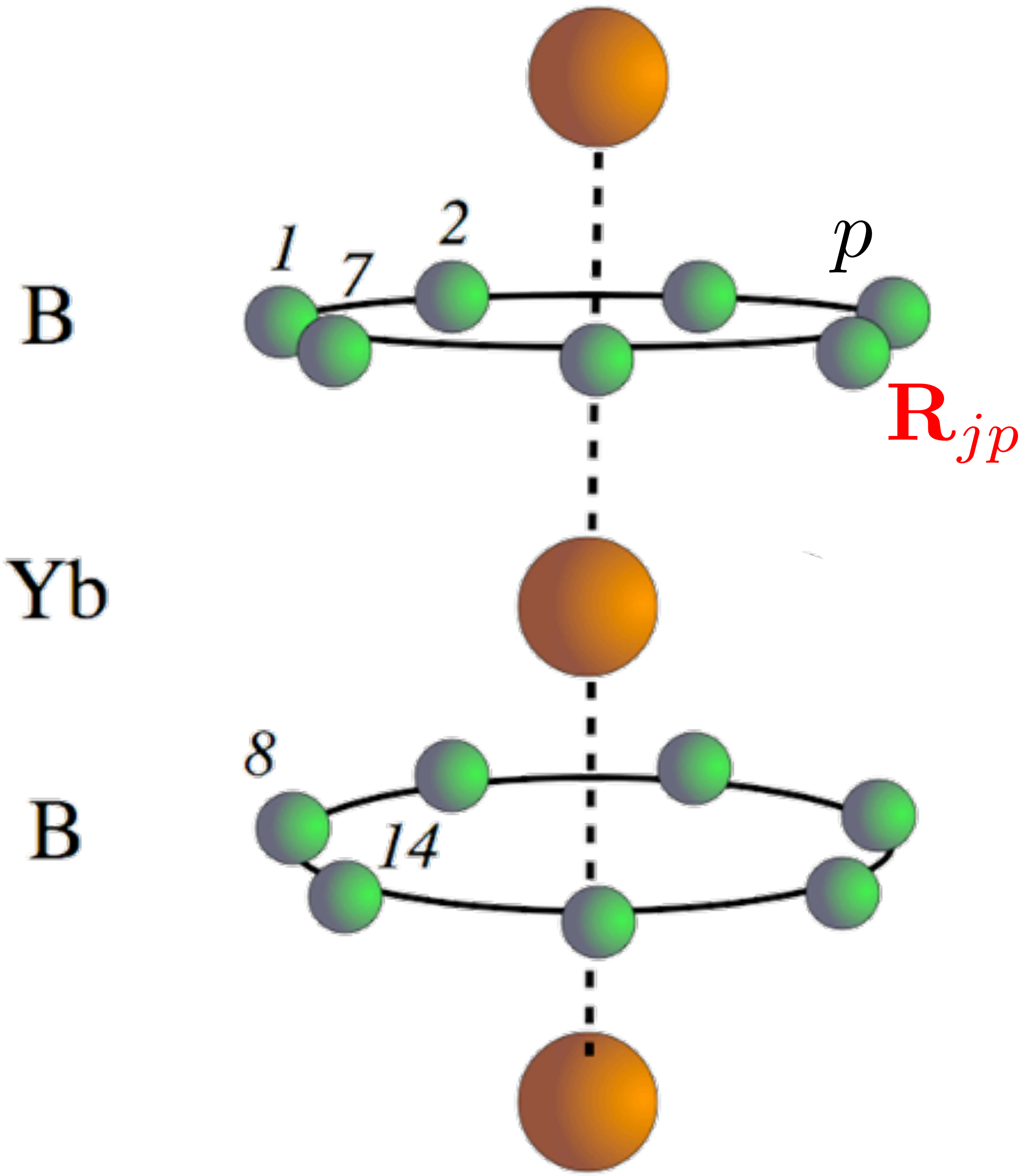
β-$YbAlB_4$: Vortex Metal.

β-$YbAlB_4$: A Critical Nodal Metal

Aline Ramires, PC, Andriy H. Nevidomskyy and A. M. Tsvelik, Phys. Rev. Lett. 109, 176404 (2012).



B
Yb
B
1
7
2
p
$\mathbf{R}_{jp}$
8
14


B
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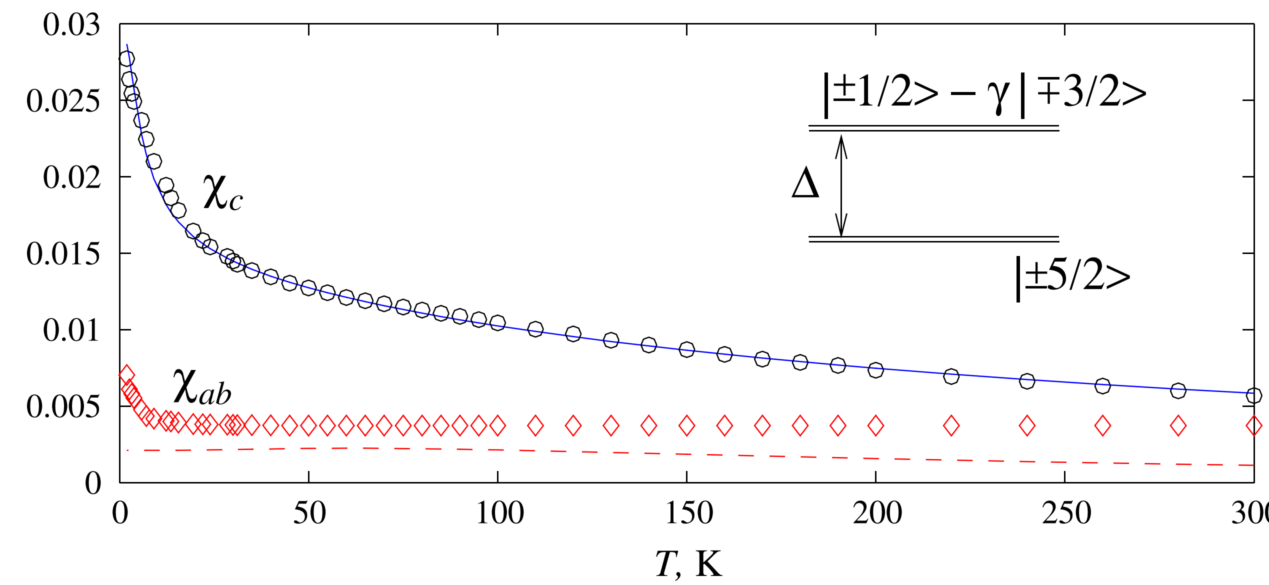
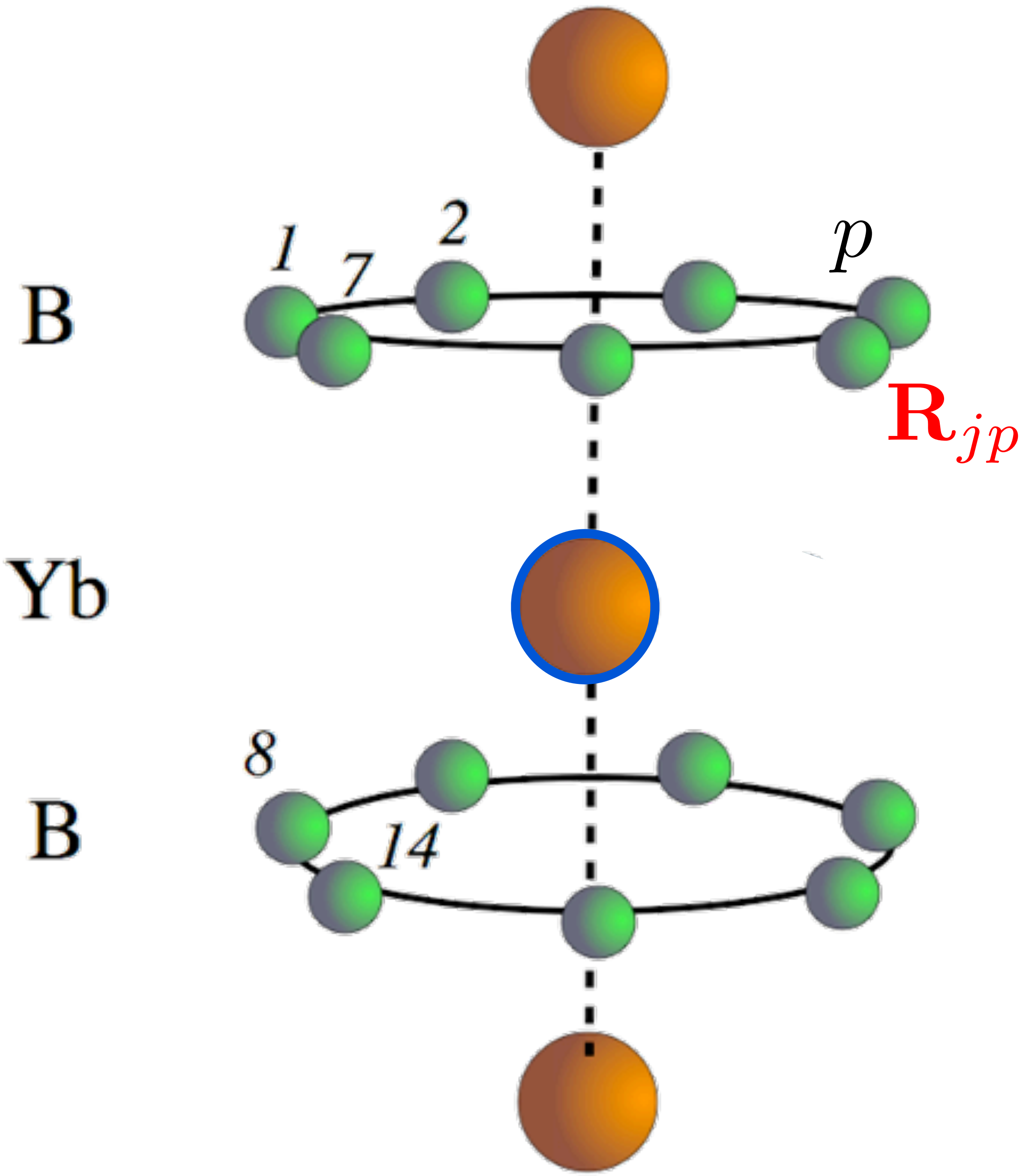
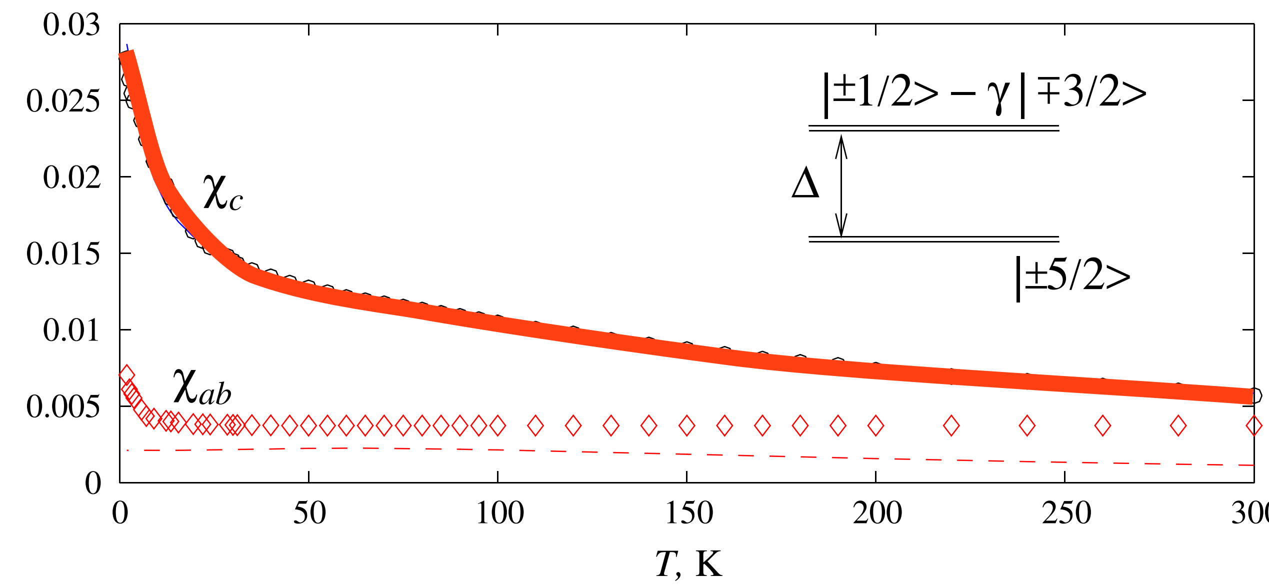
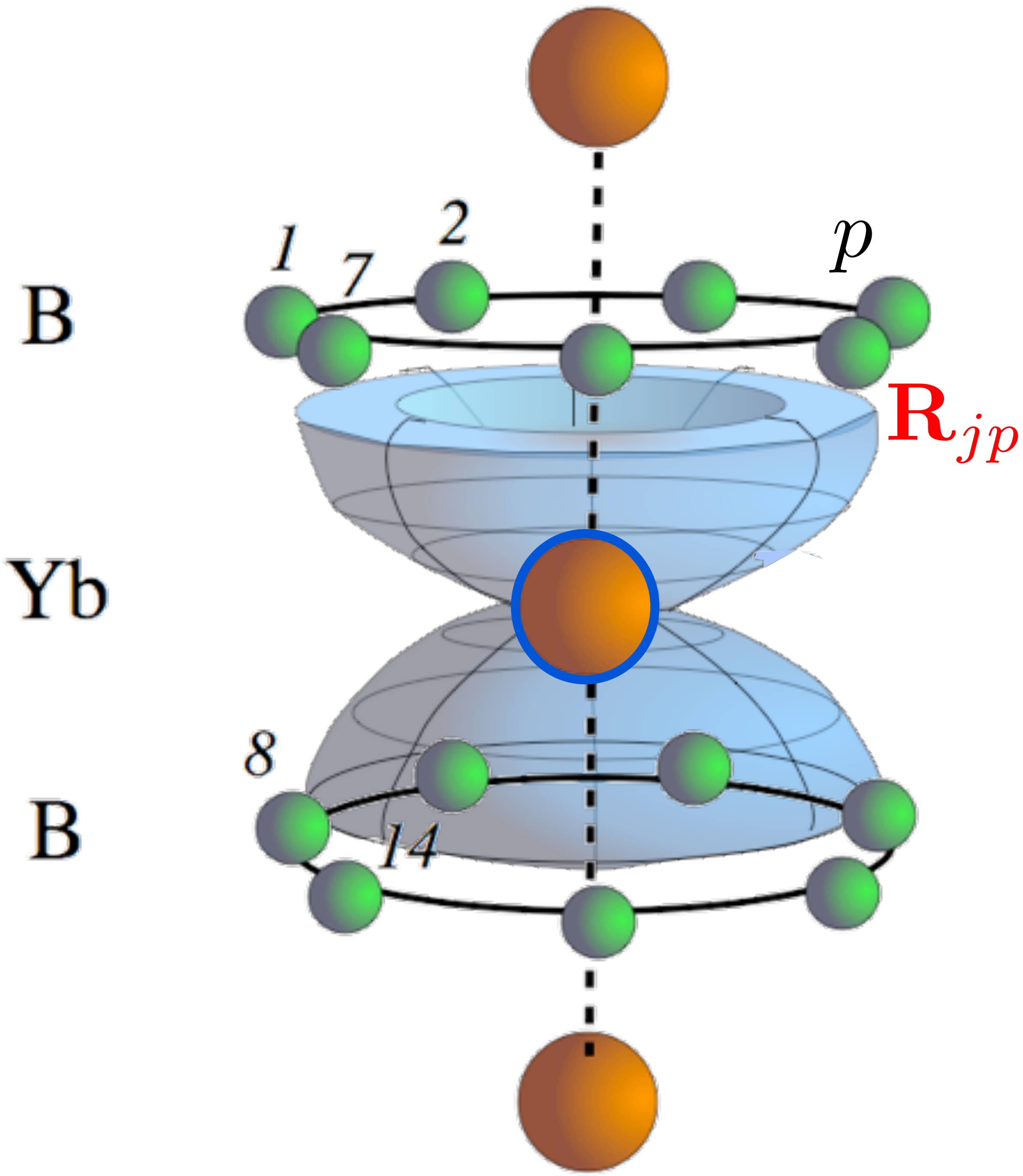

0.03
0.025
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
T, K
χc
χab
|±1/2> – γ|∓3/2>
Δ
|±5/2>



$|m_J = \pm 5/2\rangle$





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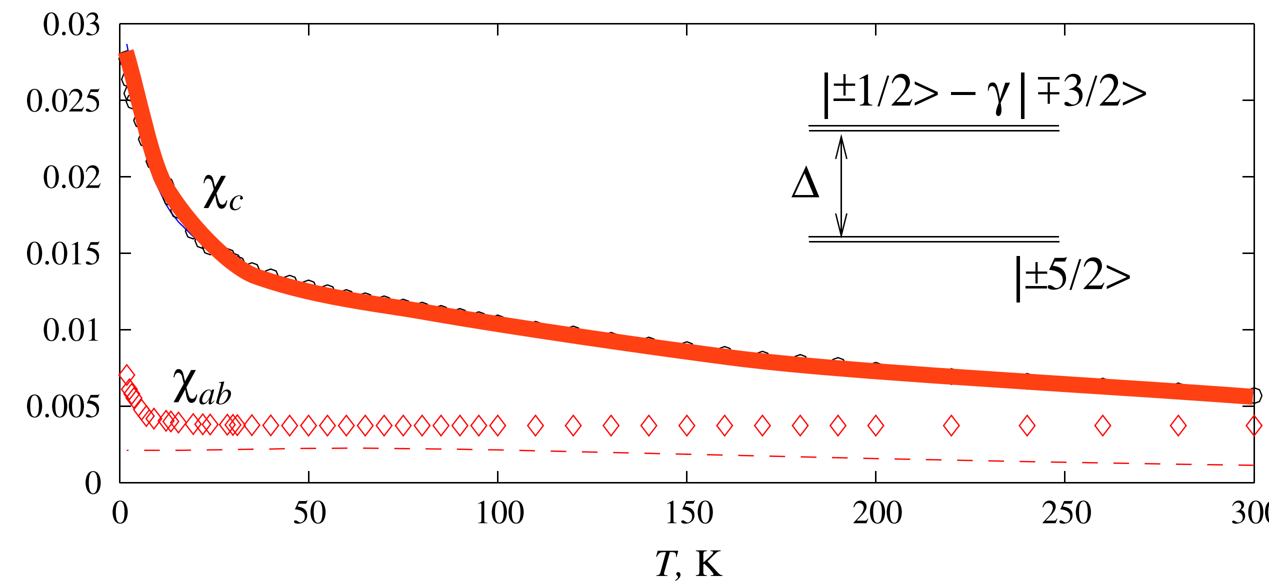

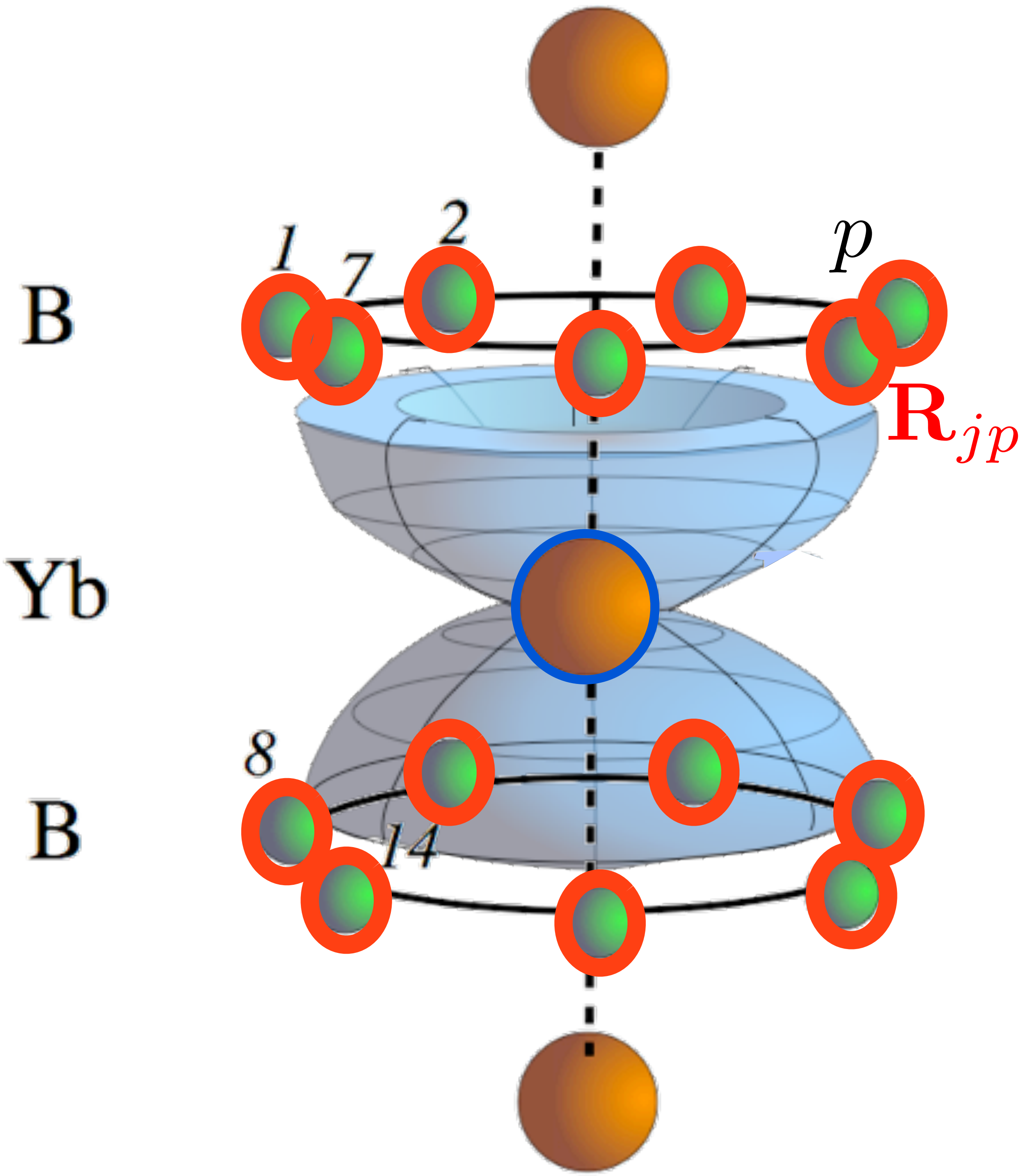

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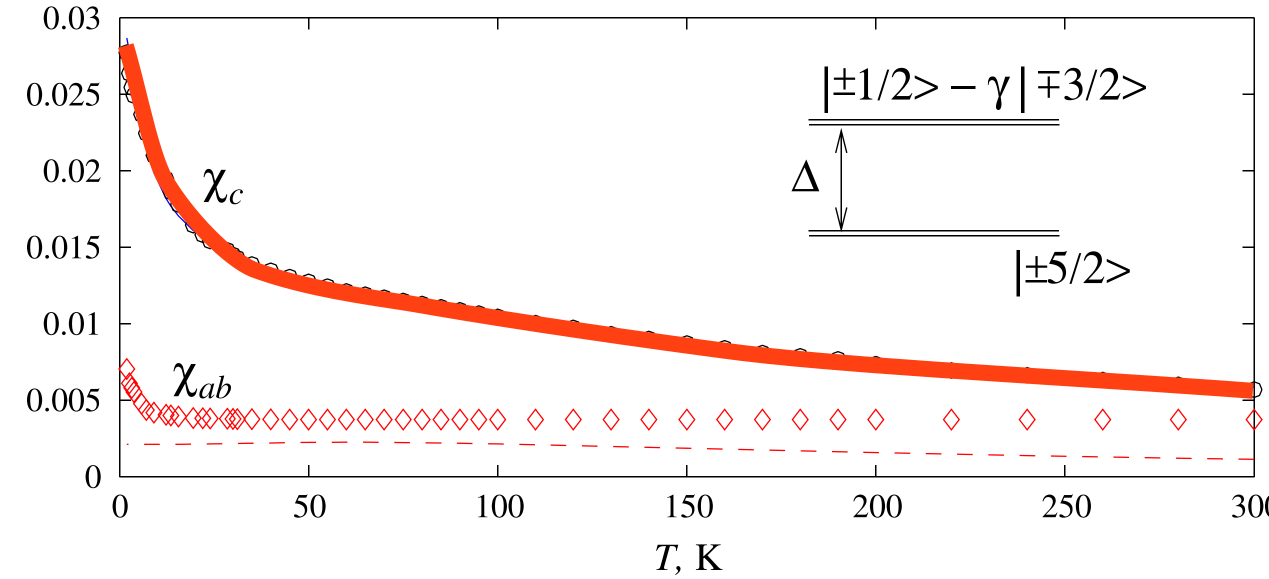
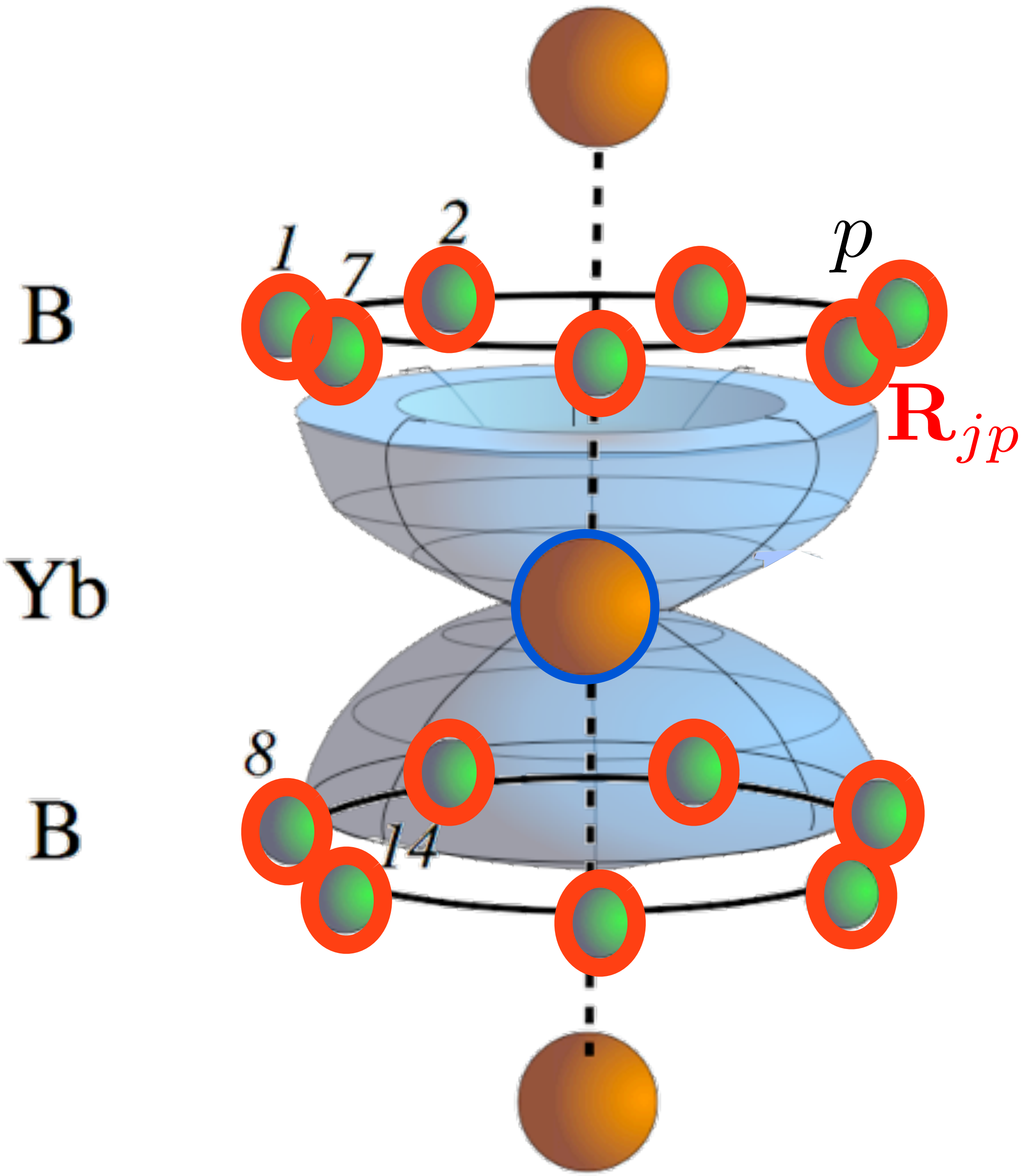


$$c^{\dagger}_{j\alpha} = \sum_{p\in(1,14),\sigma} c^{\dagger}_{\sigma}(\mathbf{R}_{jp})\ \mathcal{Y}_{\sigma\alpha}(\mathbf{r}_p)$$

Conduction Wannier state with j=7/2, m_J=±5/2



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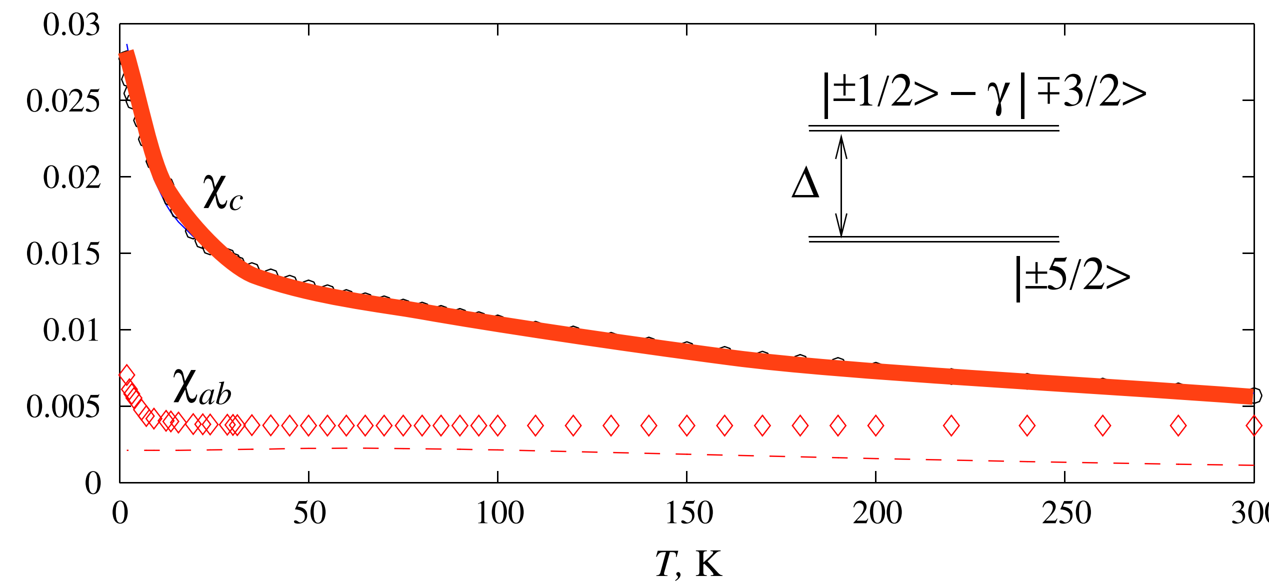

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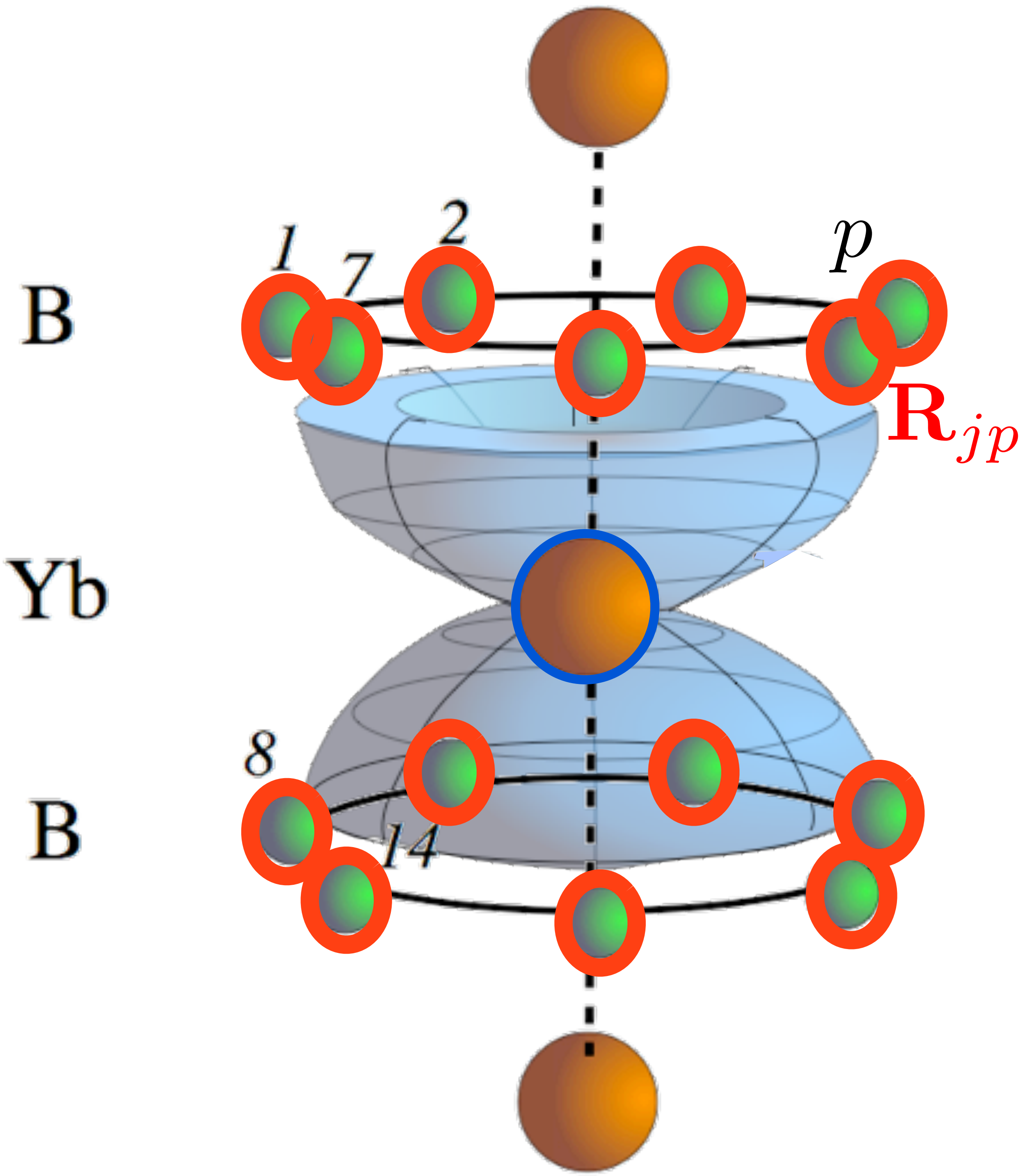
$$H = \sum_{n,k,\sigma} \epsilon_{\mathbf{k}n} c^\dagger_{\mathbf{k}n\sigma} c_{\mathbf{k}n\sigma} + \sum_j H_m(j)$$



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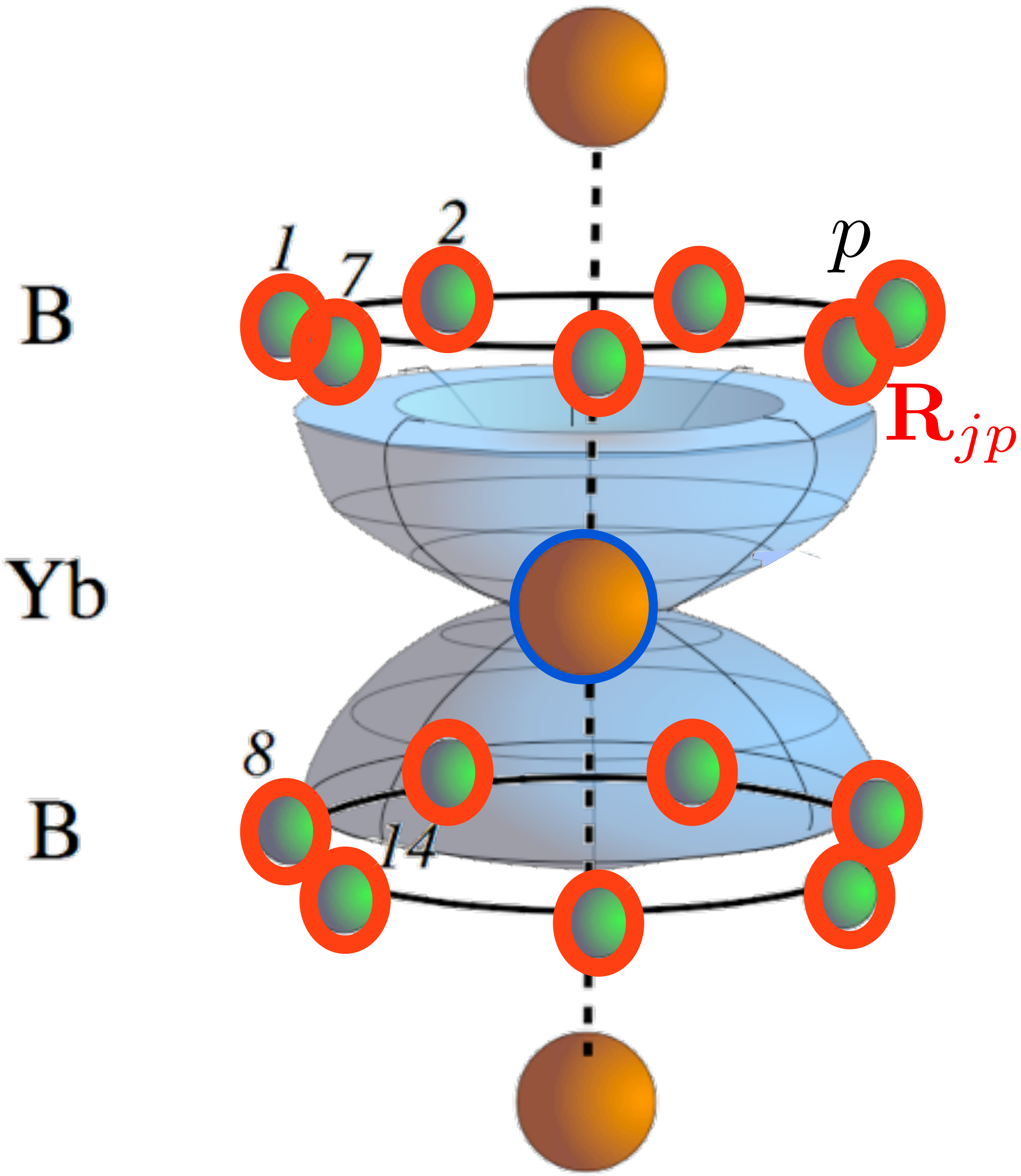
$$H_m(j) = V_0 (c^\dagger_{j\alpha} X_{0\alpha}(j) + \text{h.c.}) + E_f X_{\alpha\alpha}(j),$$



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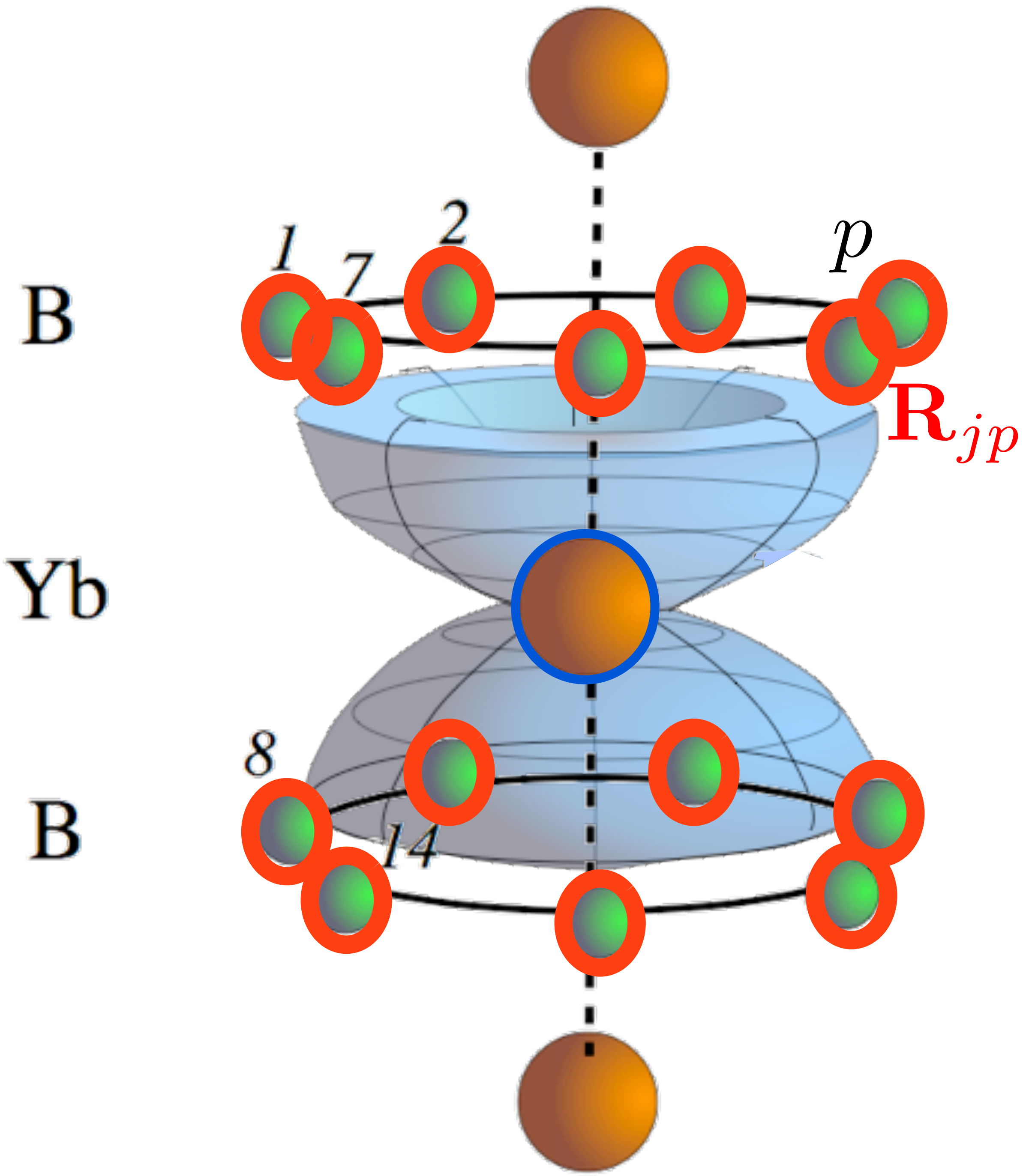

$$H_{eff} = \sum_{\mathbf{k}} (c^\dagger_{\mathbf{k}}, f^\dagger_{\mathbf{k}}) \begin{pmatrix} \epsilon_{\mathbf{k}} \mathbb{I} & \underline{V}(\mathbf{k}) \\ \underline{V}^\dagger(\mathbf{k}) & \tilde{E}_f \mathbb{I} \end{pmatrix} \begin{pmatrix} c_{\mathbf{k}} \\ f_{\mathbf{k}} \end{pmatrix}$$

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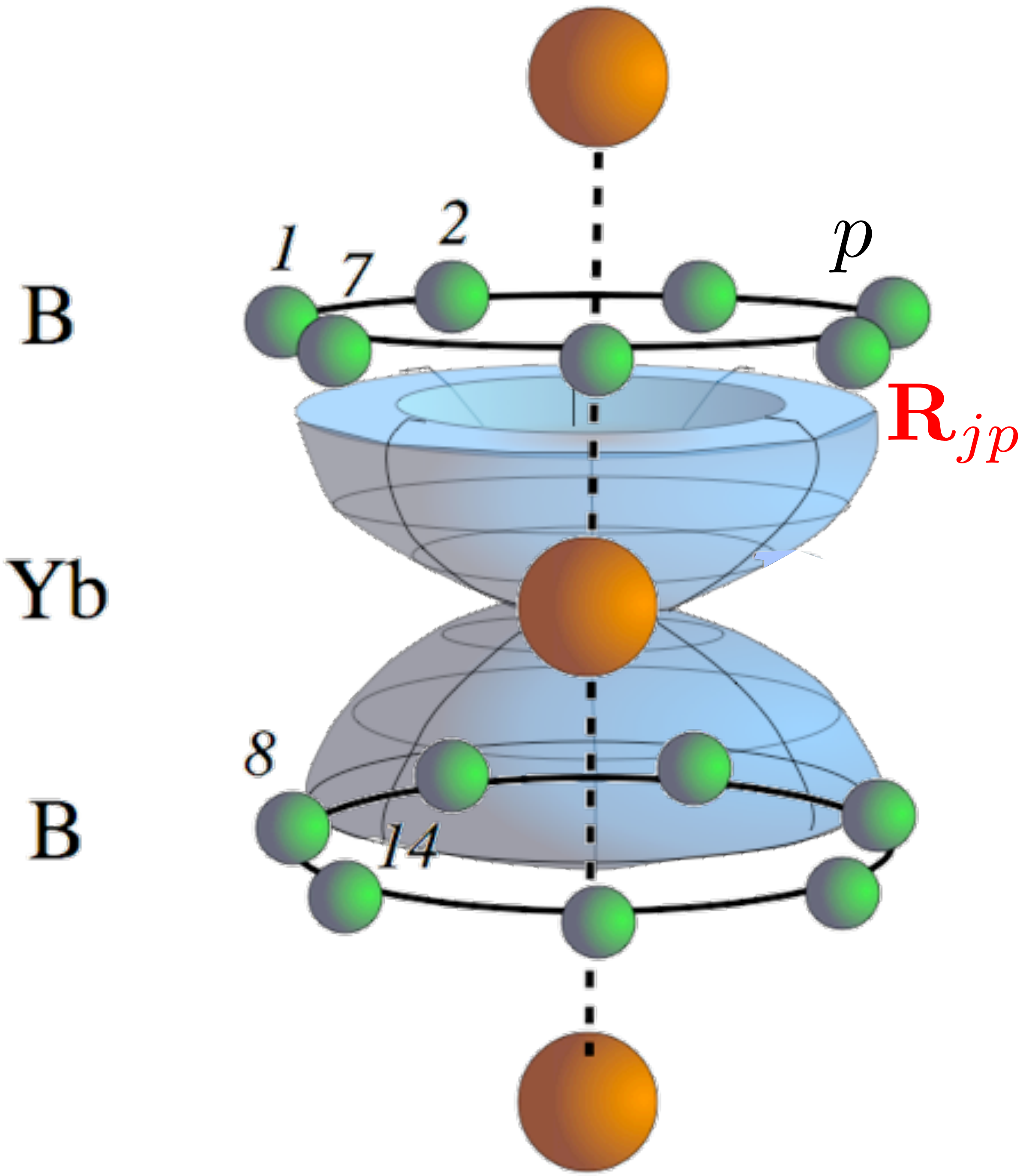

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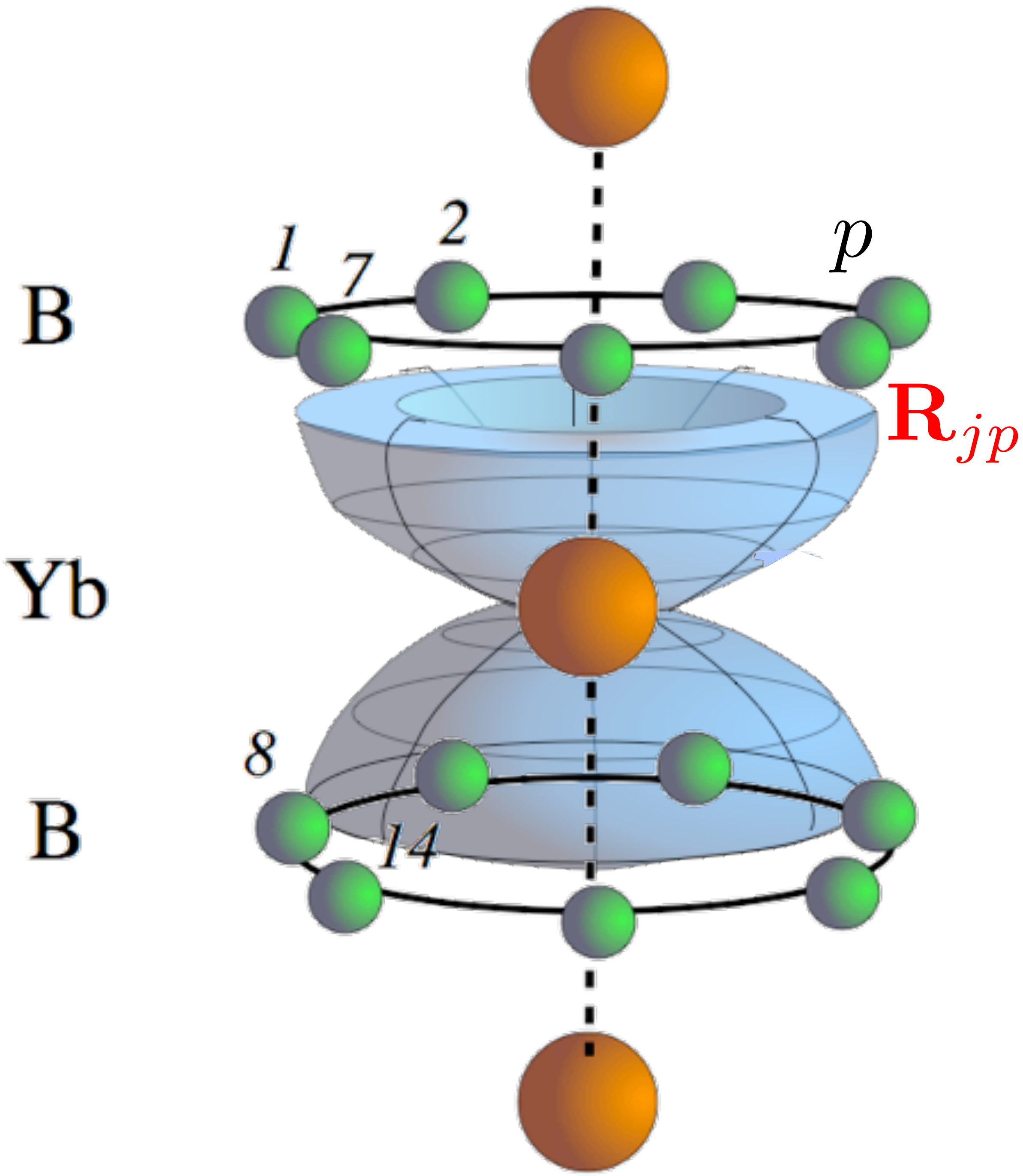
$$\underline{V}(\mathbf{k}) = V_0^{*} \underline{\gamma}(\mathbf{k})$$

$$[\underline{\gamma}(\mathbf{k})]_{\sigma\alpha} = \sum_{p=1,14} \mathcal{Y}_{\sigma\alpha}(\mathbf{r}_p) e^{-i\mathbf{k}\cdot\mathbf{r}_p}.$$



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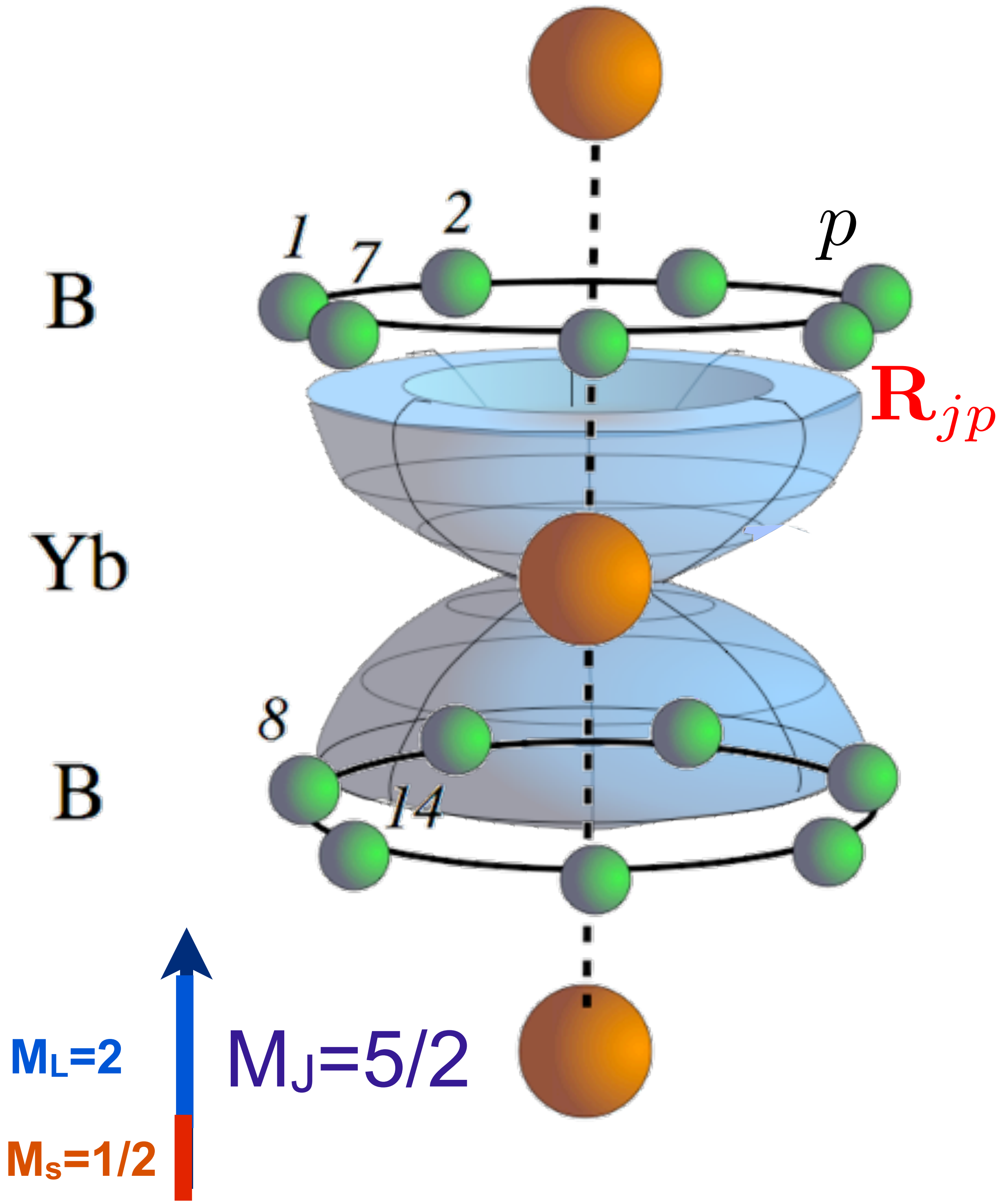

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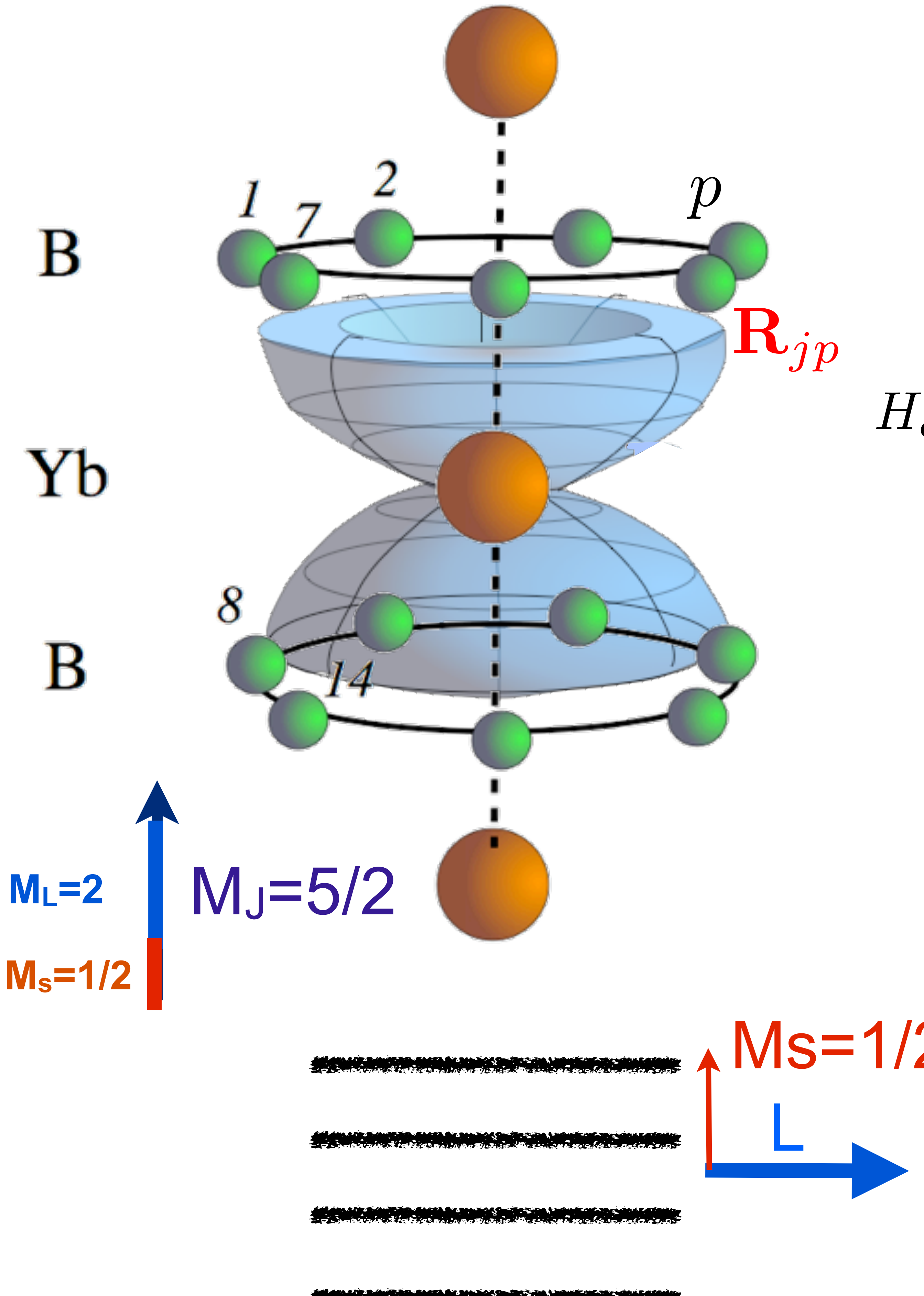

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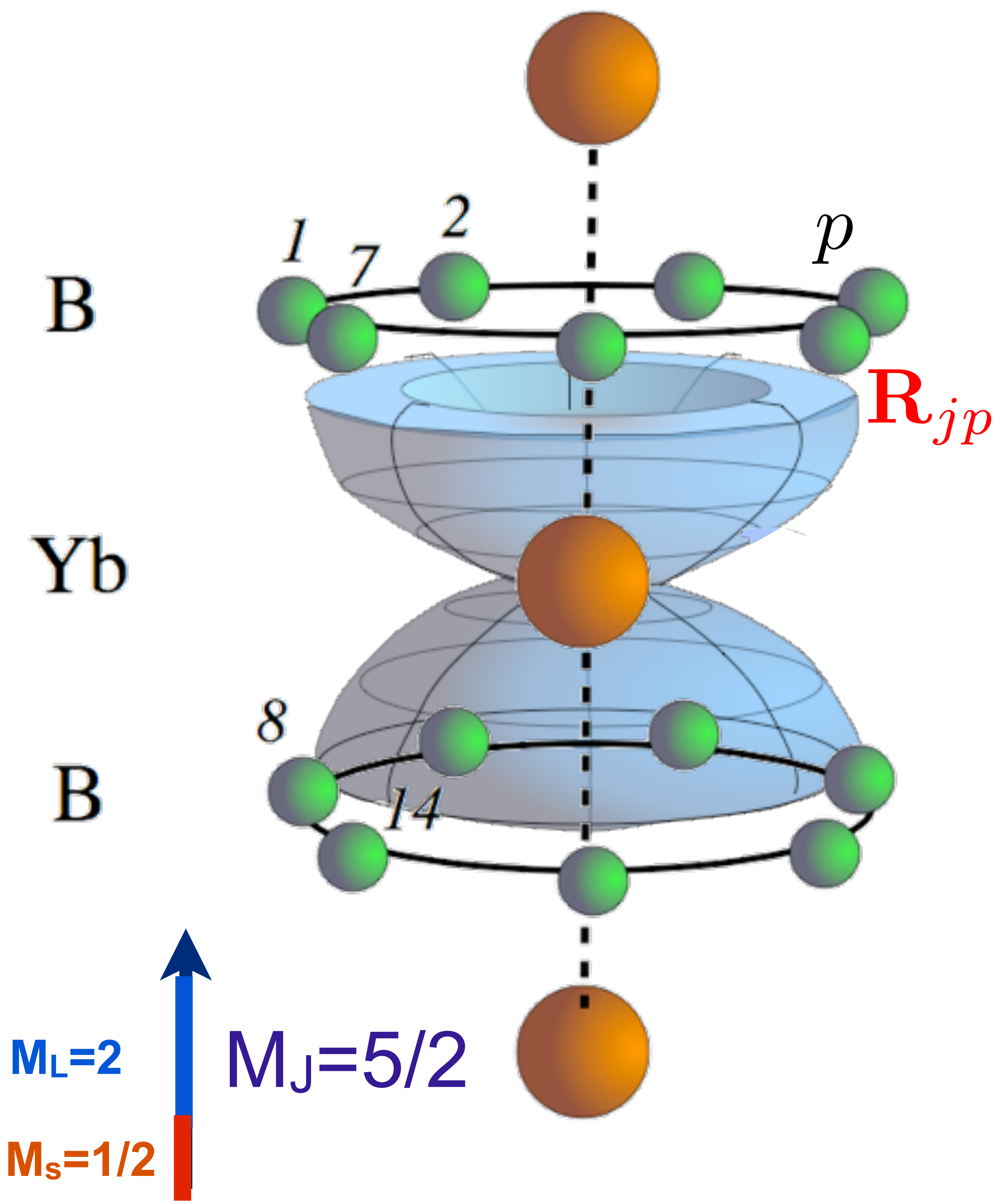

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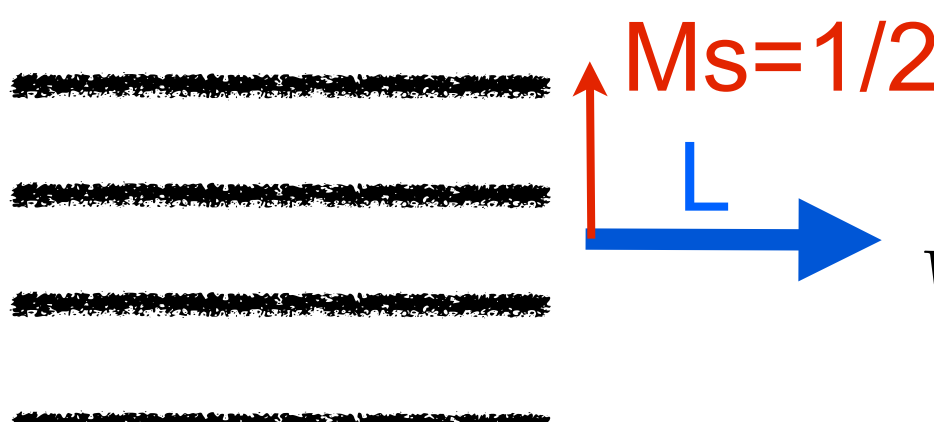
"Spin Blockade"
(Ikeda and Miyake, JPSJ, 65,1769, **1997**, Maignan, Caignaert, Raveau, Khomskii & Sawatzky, PRL 93, 026401, **2004**)



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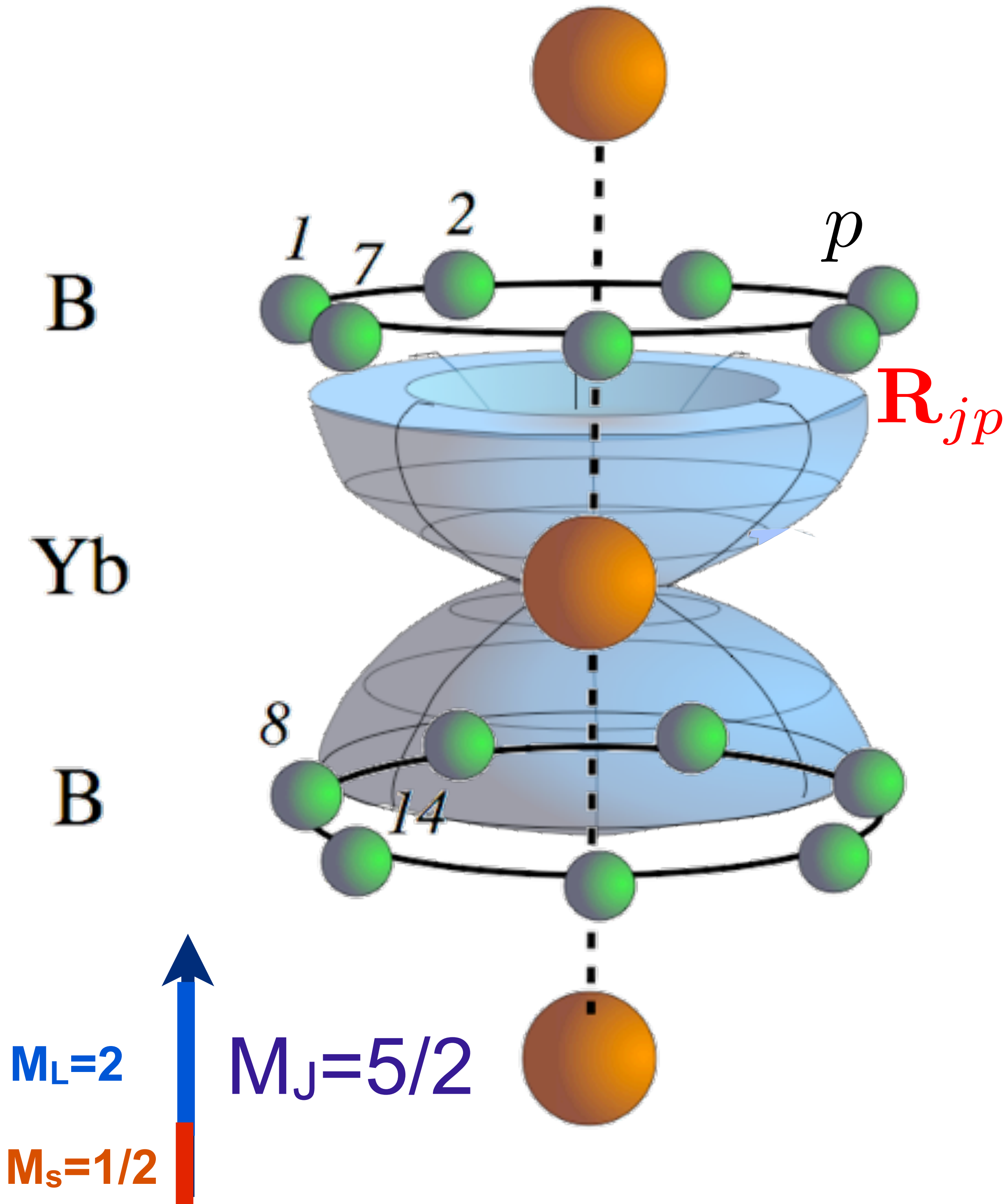

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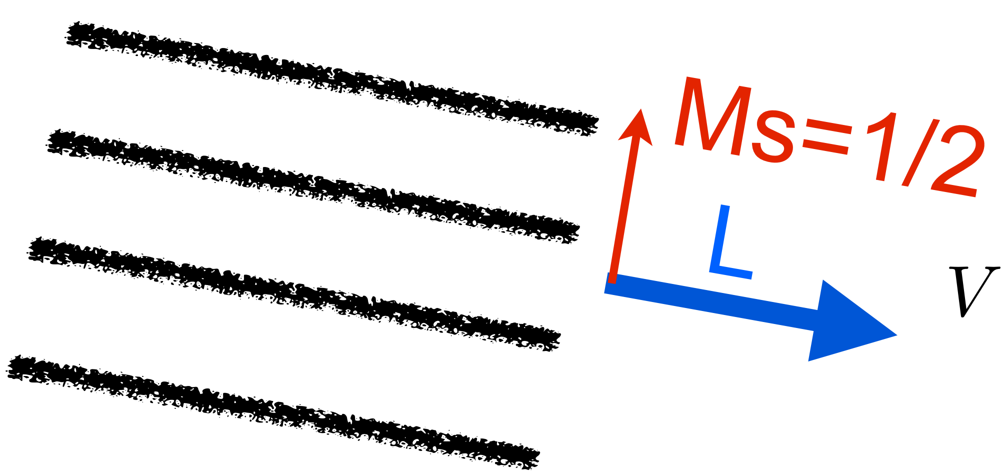

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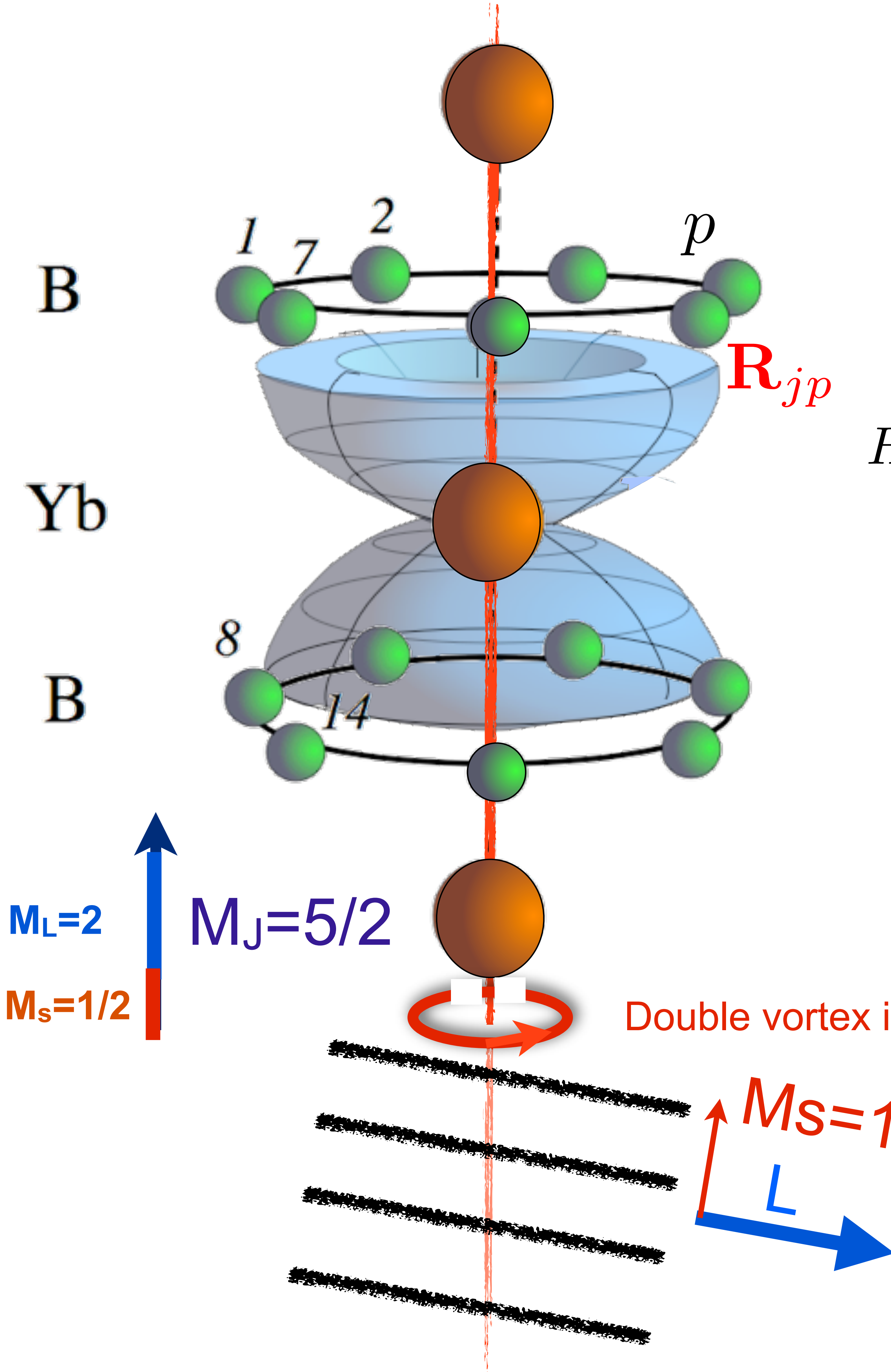

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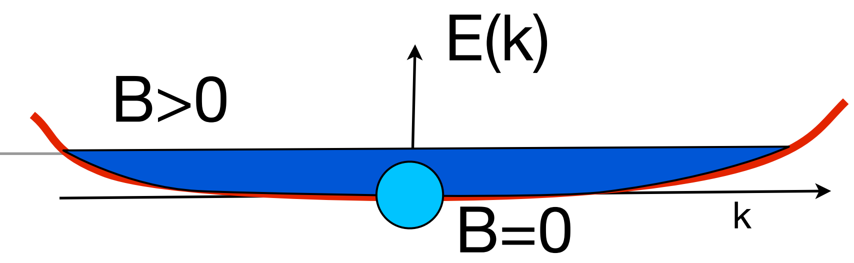
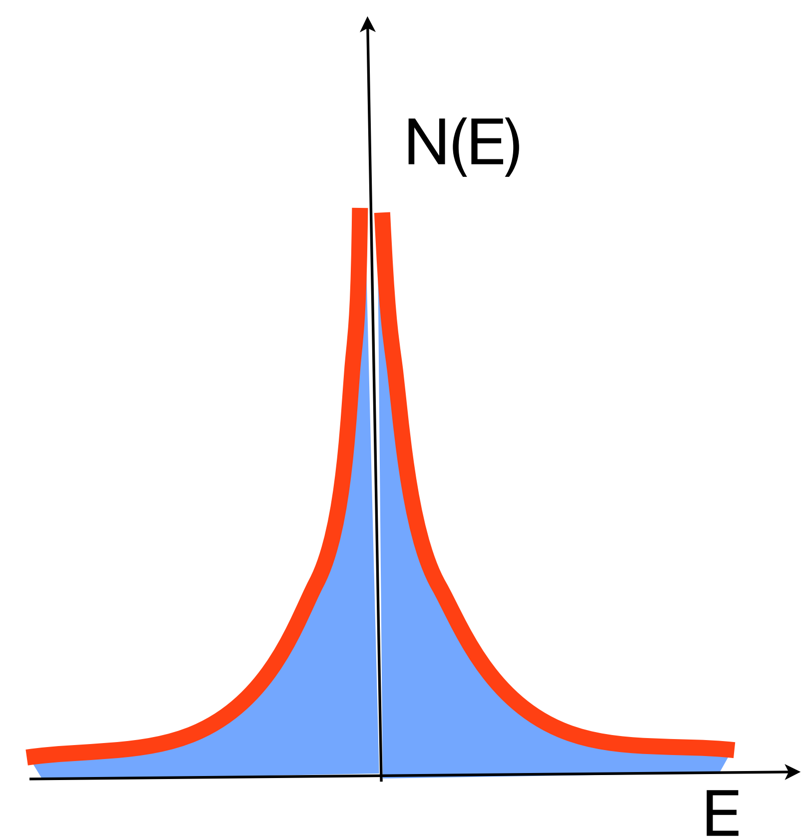
T/B scaling



"Vortex" Transition.

Zeeman energy is the Fermi Energy



$$N^*_{\pm}(E) = 2\int k_{\perp}\frac{dk_{\perp}}{dE_{\pm}}\frac{dk_z}{(2\pi)^2} = \frac{1}{\sqrt{|E|T_0^{\pm}}}$$

$$\frac{1}{\sqrt{T_0^{\pm}}} = \frac{1}{8\pi^2}\int\frac{dk_z}{\sqrt{|\eta(k_z)|}}\theta[\mp\epsilon(k_z)$$

T/B scaling

$$F[B,T] = -T \sum_{\alpha=\pm 5/2} \int_{-\infty}^{\infty} dE N(E) \ln[1 + e^{-\beta(E - g\mu_B B\alpha)}]$$

$$= T^{3/2}\Phi\left(\frac{g\mu_B B}{T}\right)$$

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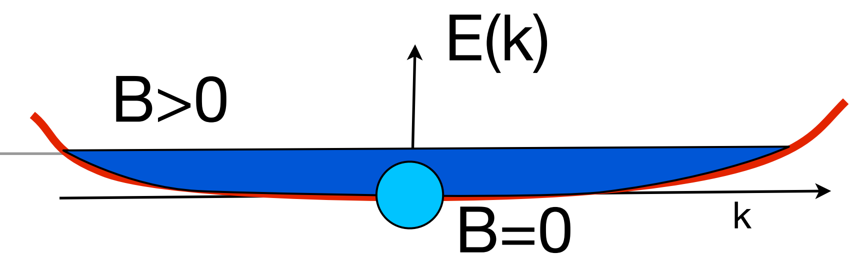

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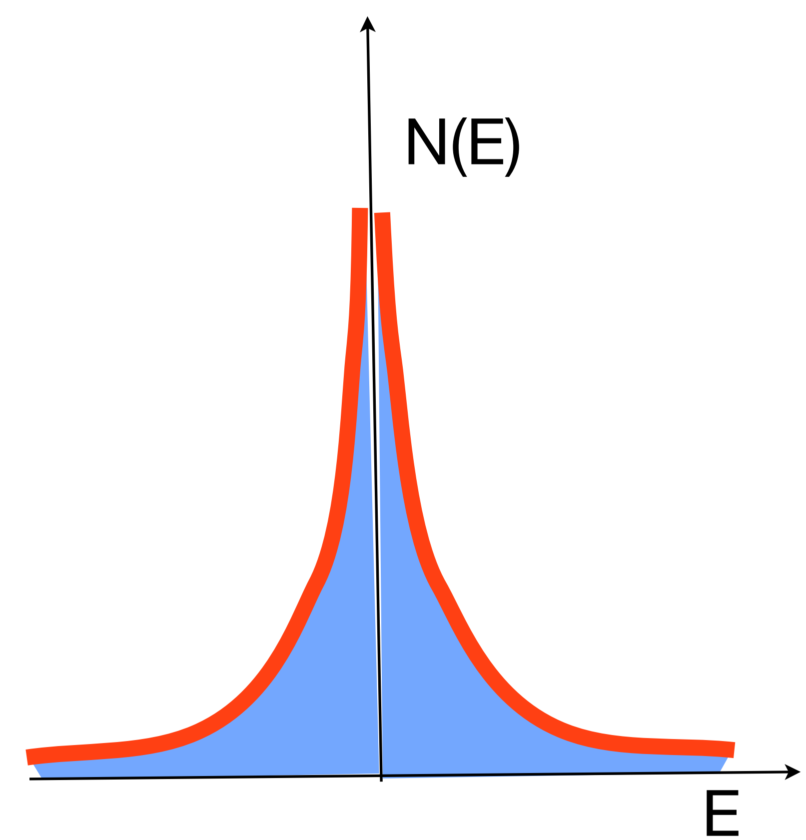

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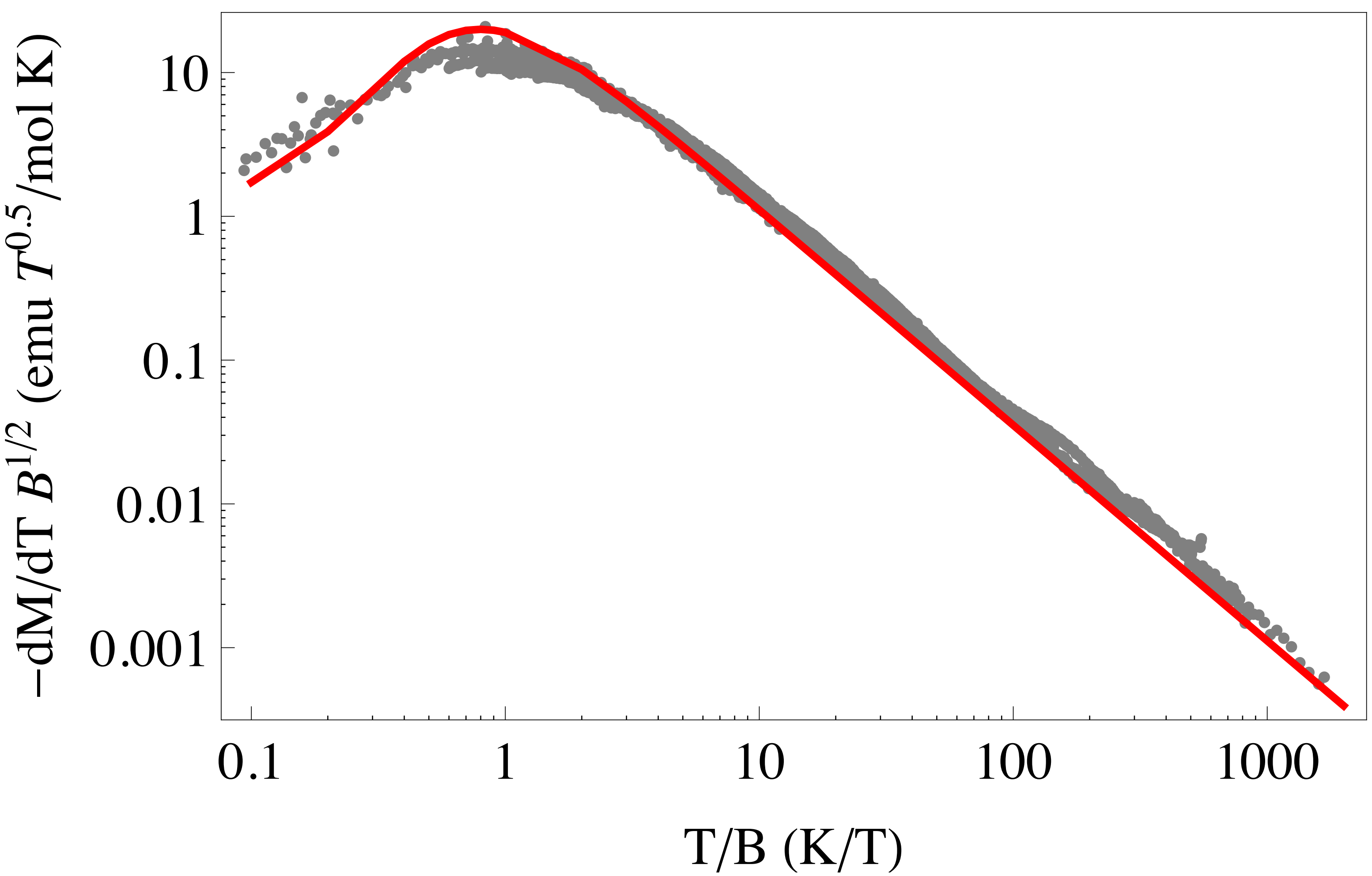

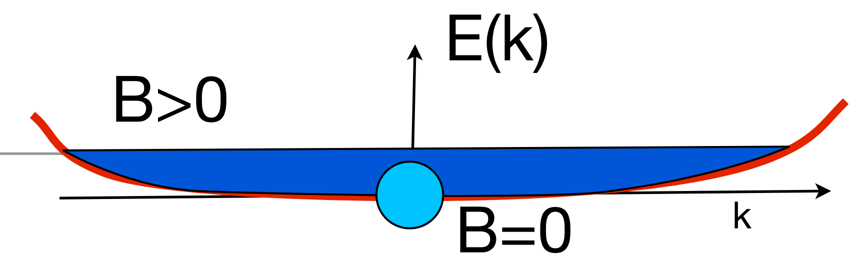

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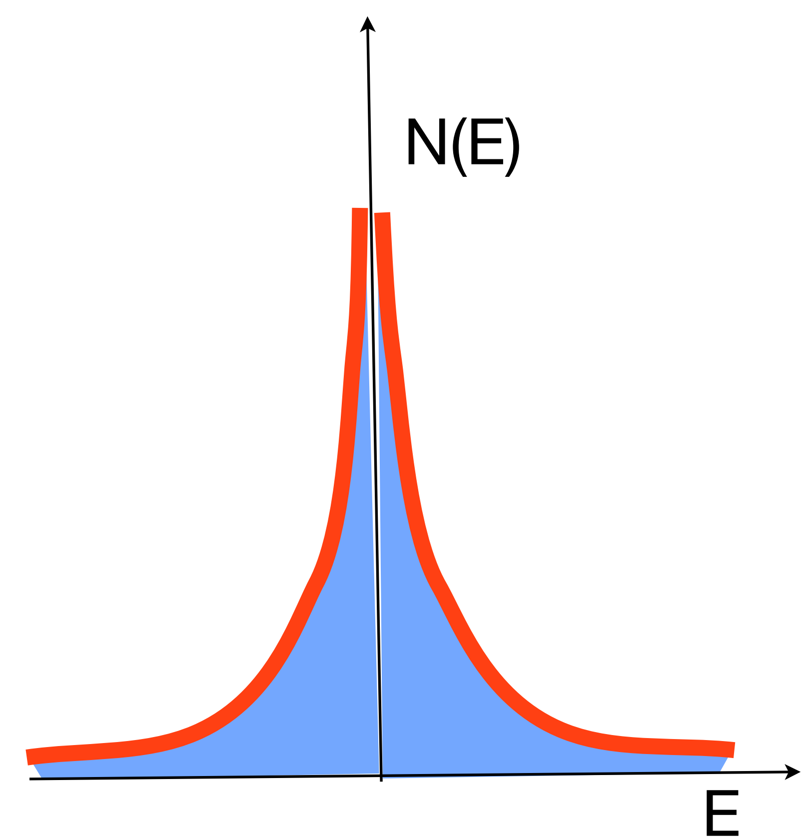

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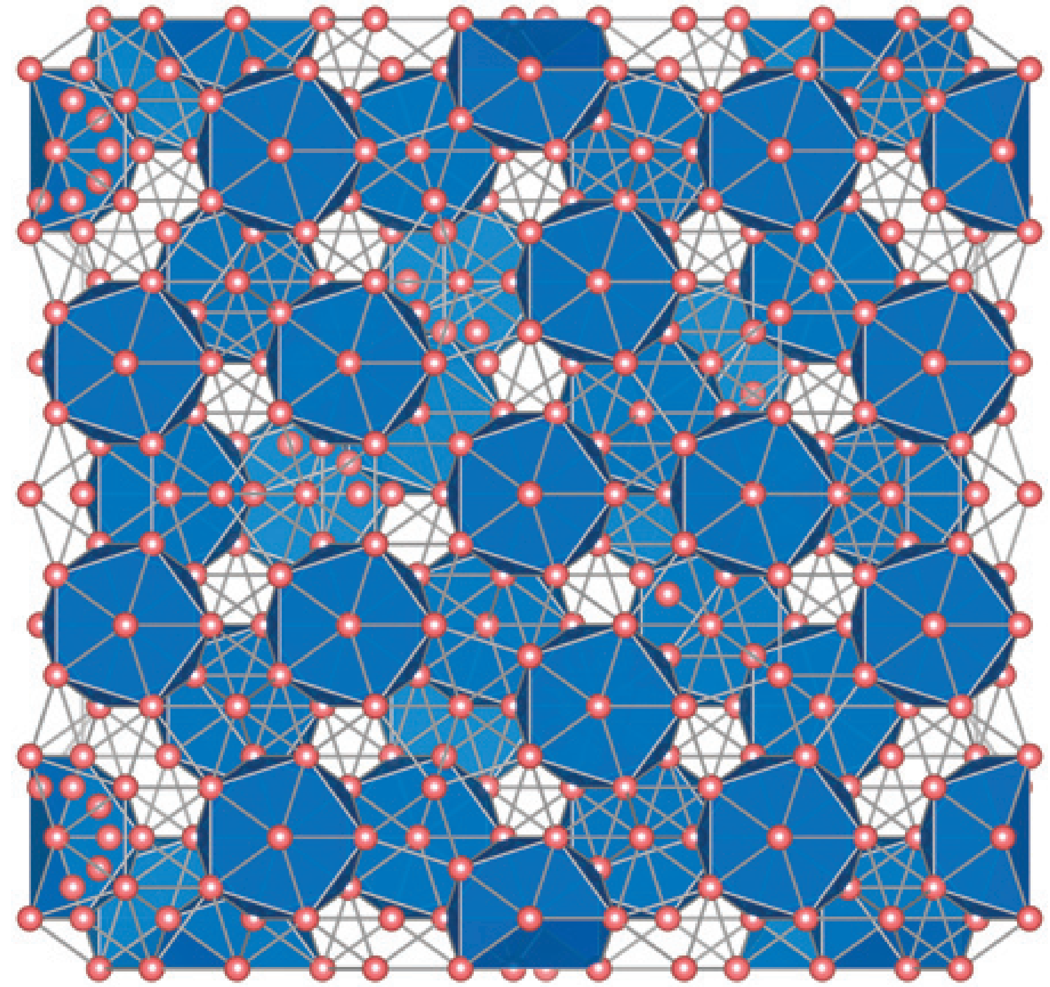
Kondo Quasicrystal.

b



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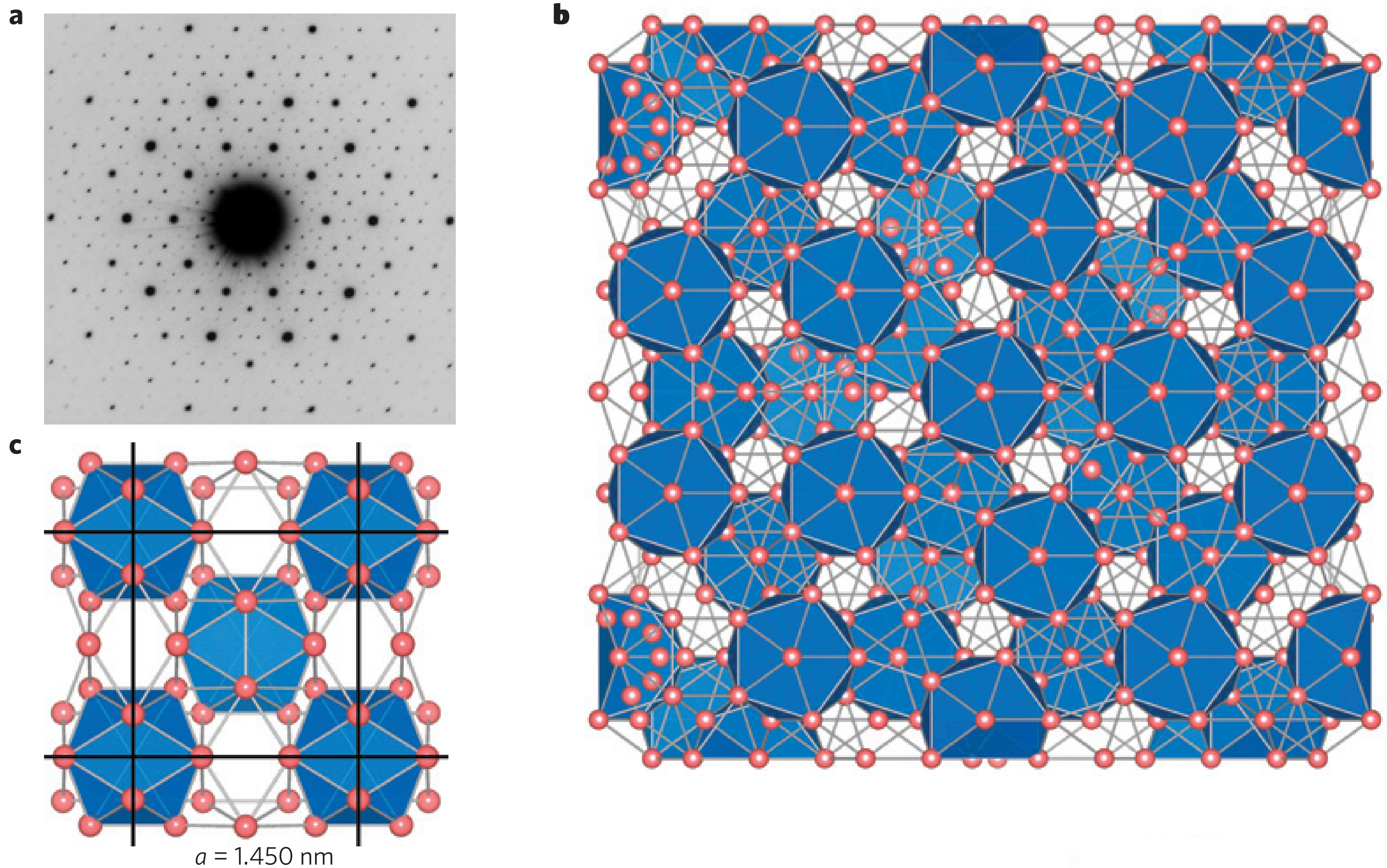

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Kazuhiko Deguchi[1]*, Shuya Matsukawa[1], Noriaki K. Sato[1], Taisuke Hattori[2], Kenji Ishida[2], Hiroyuki Takakura[3] and Tsutomu Ishimasa[3]

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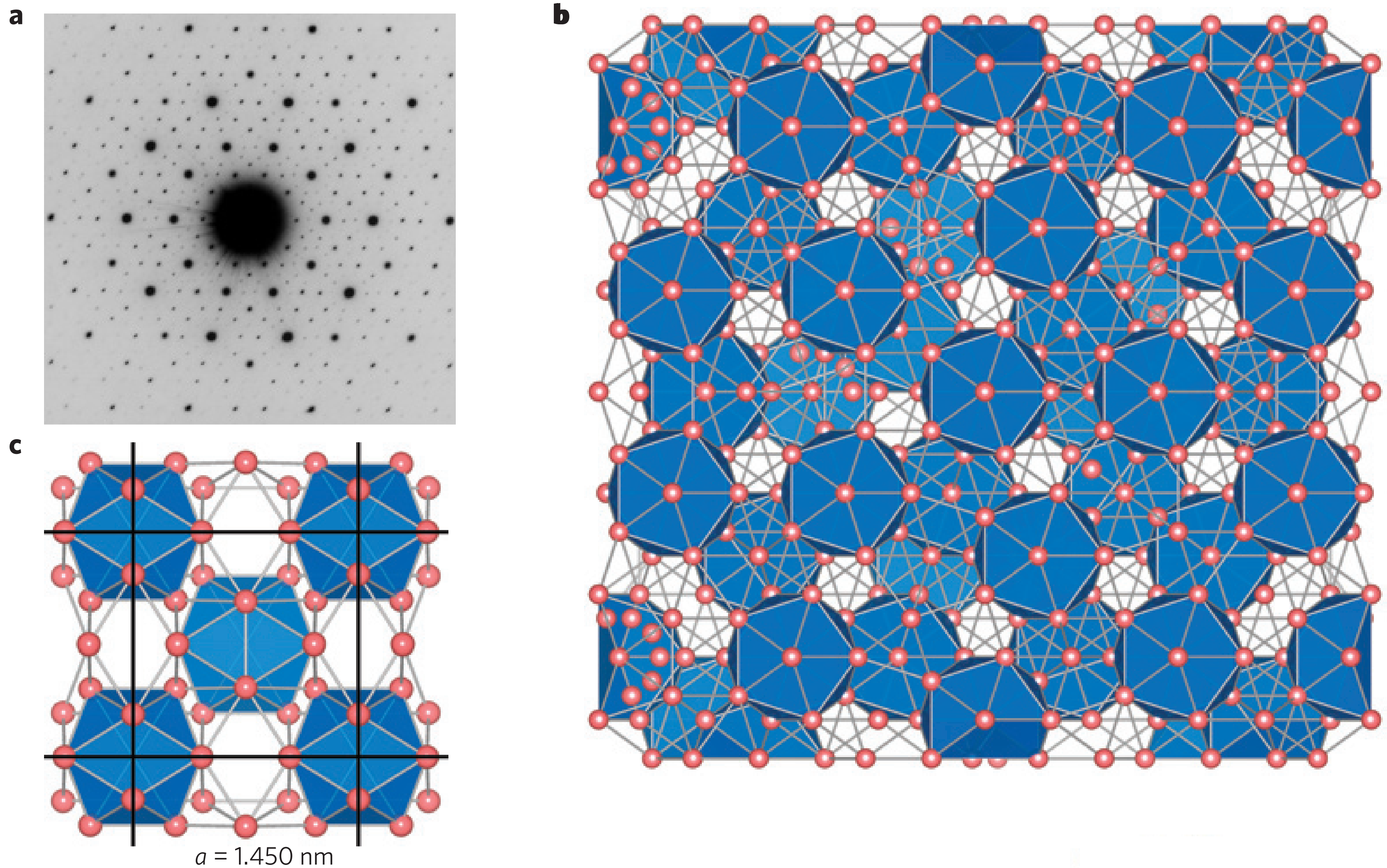

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Approximant:

$Au_{51}\ Al_{35}\ Yb_{14}$

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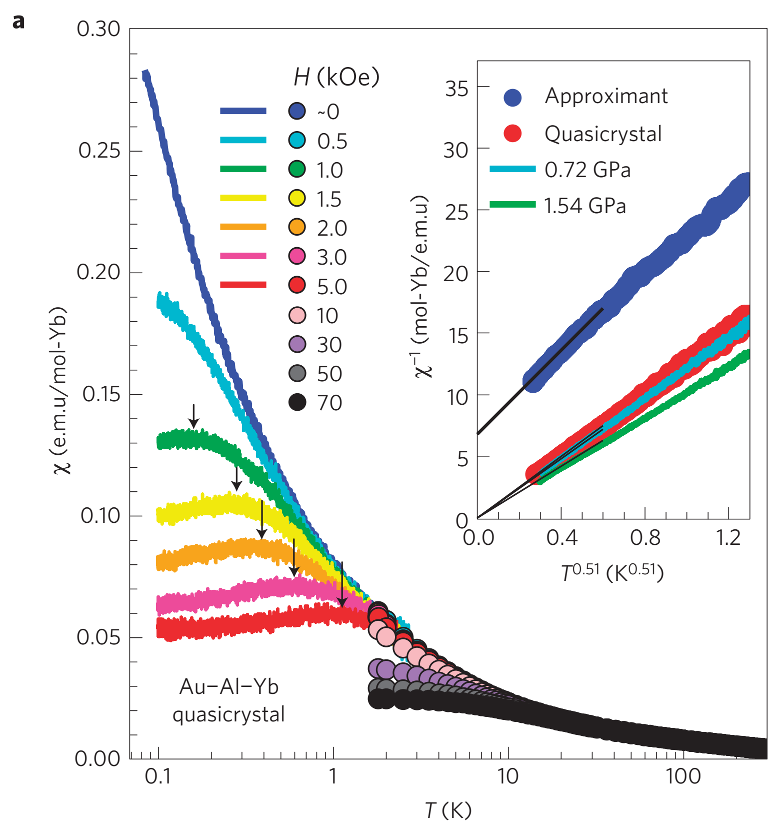

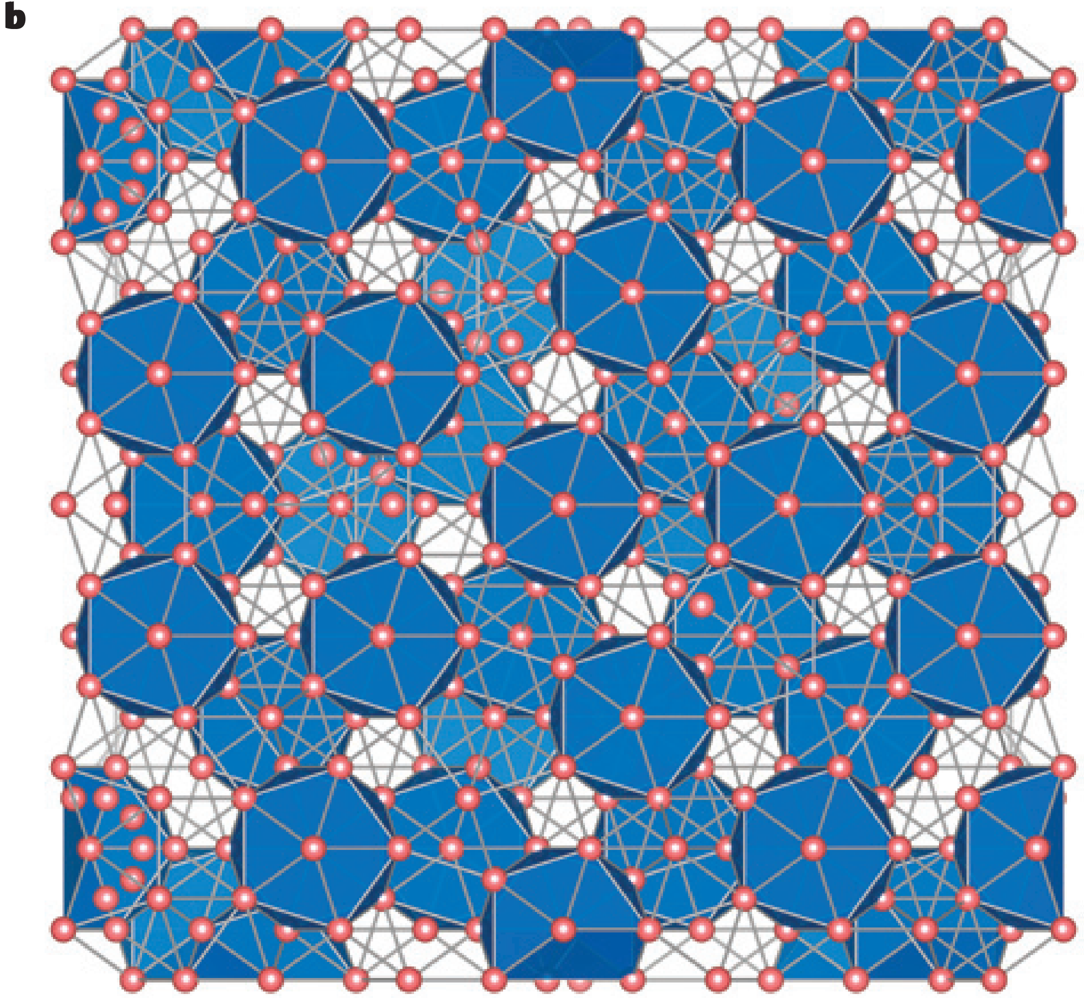

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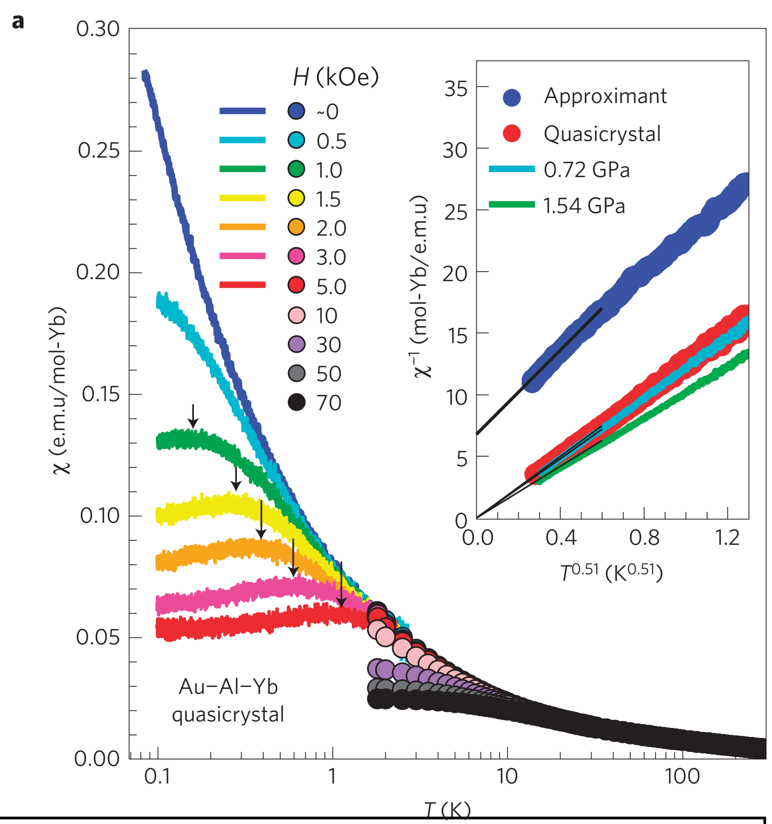
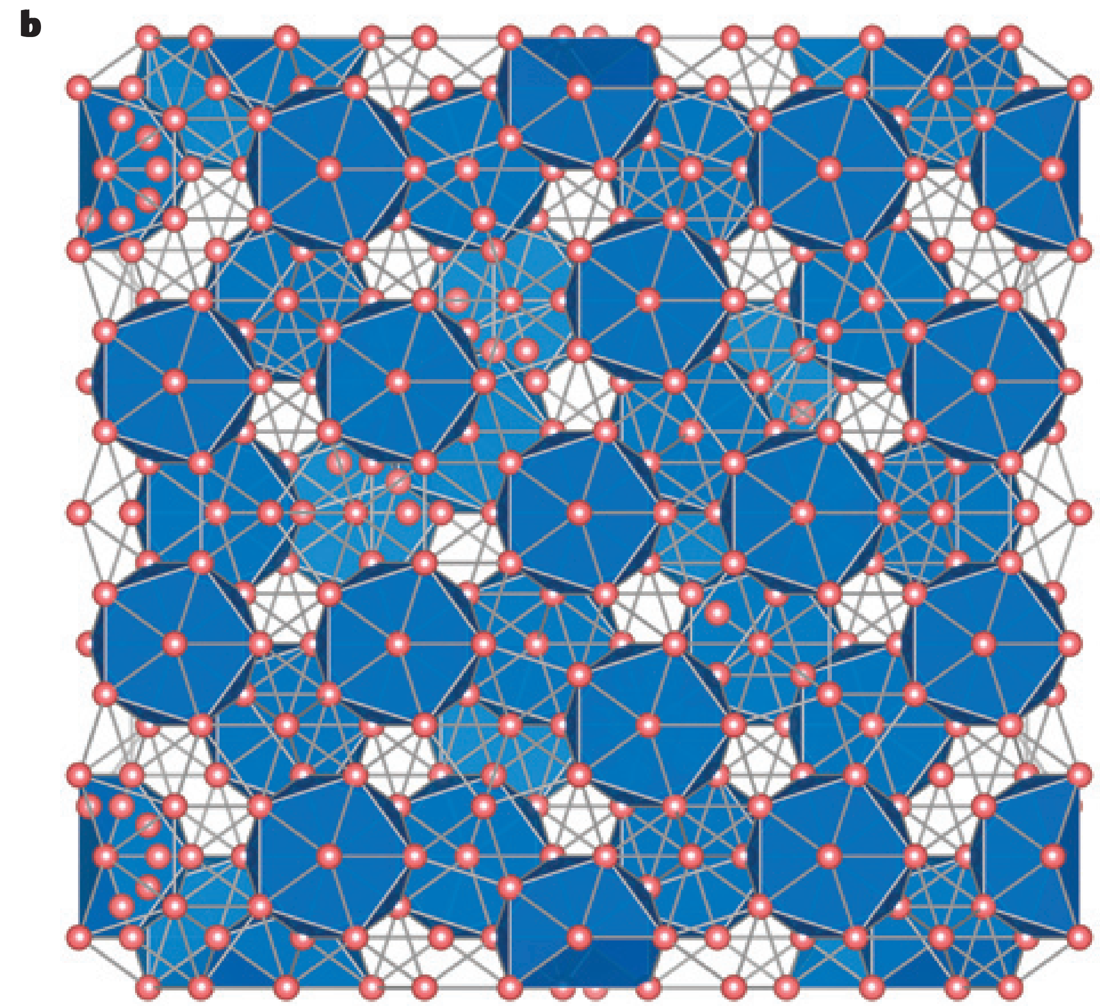


Strange metal like $YbAlB_4$!



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Quasicrystals as “surfaces” (with irrational Miller indices) of hypercrystals.
(H. Bohr, 1925, de Brujin 1981)

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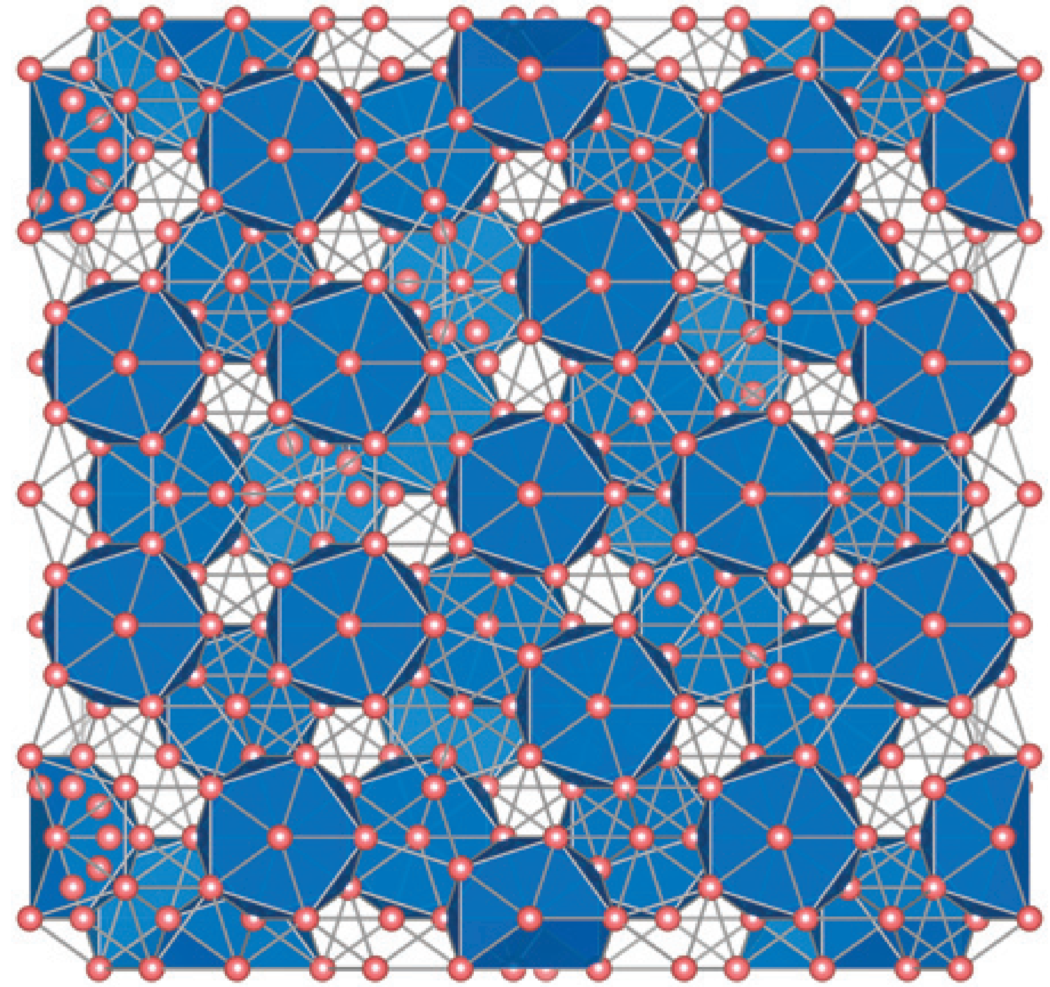

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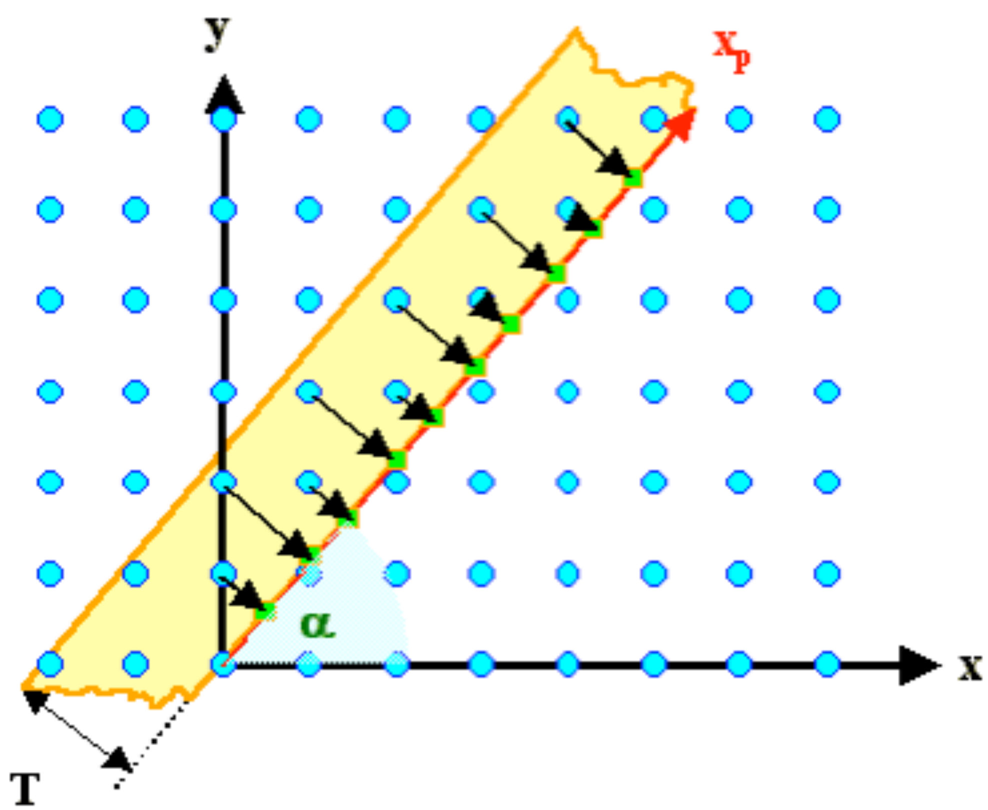

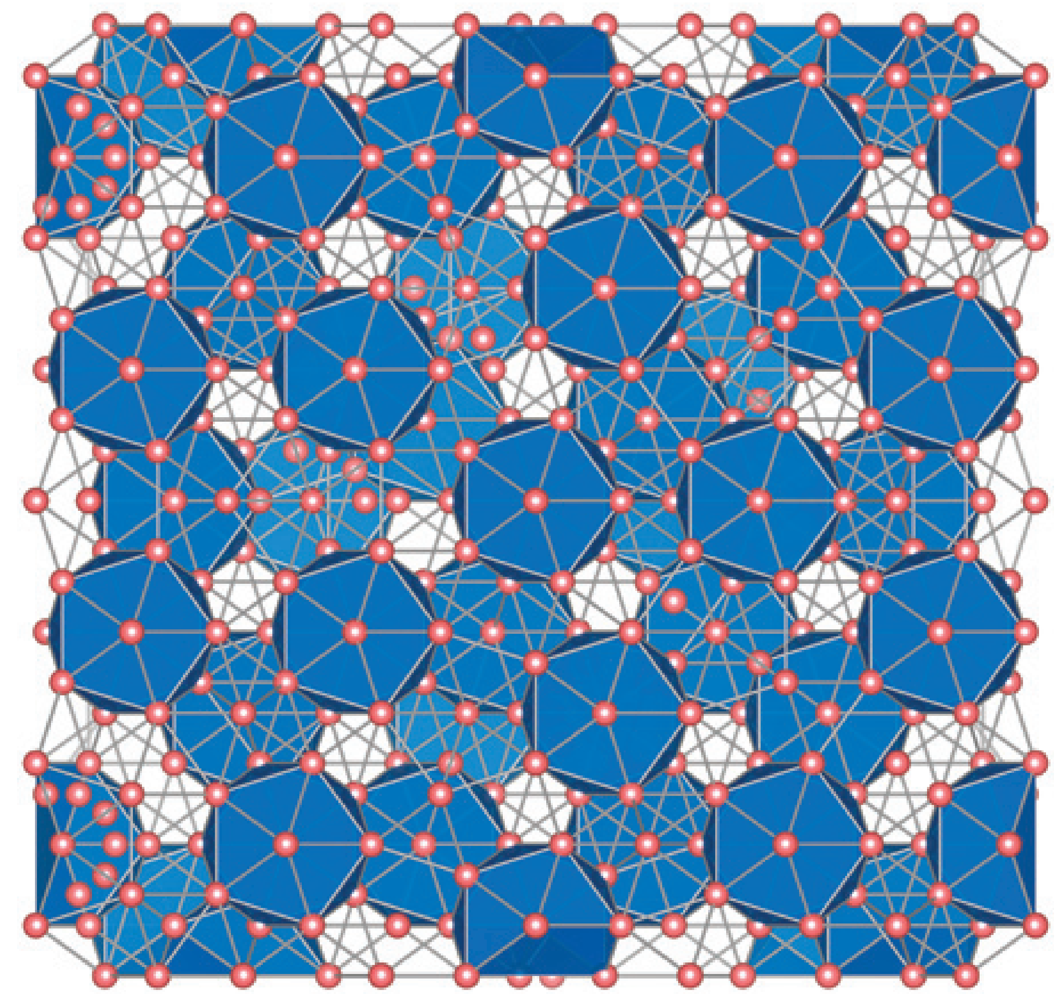

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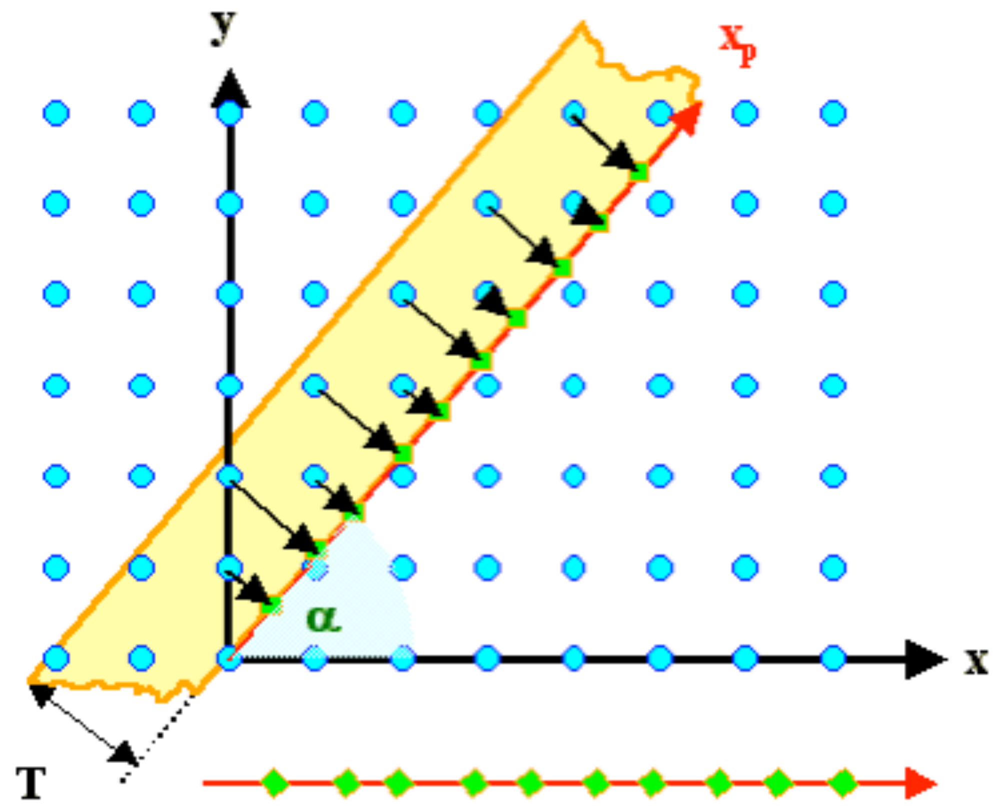

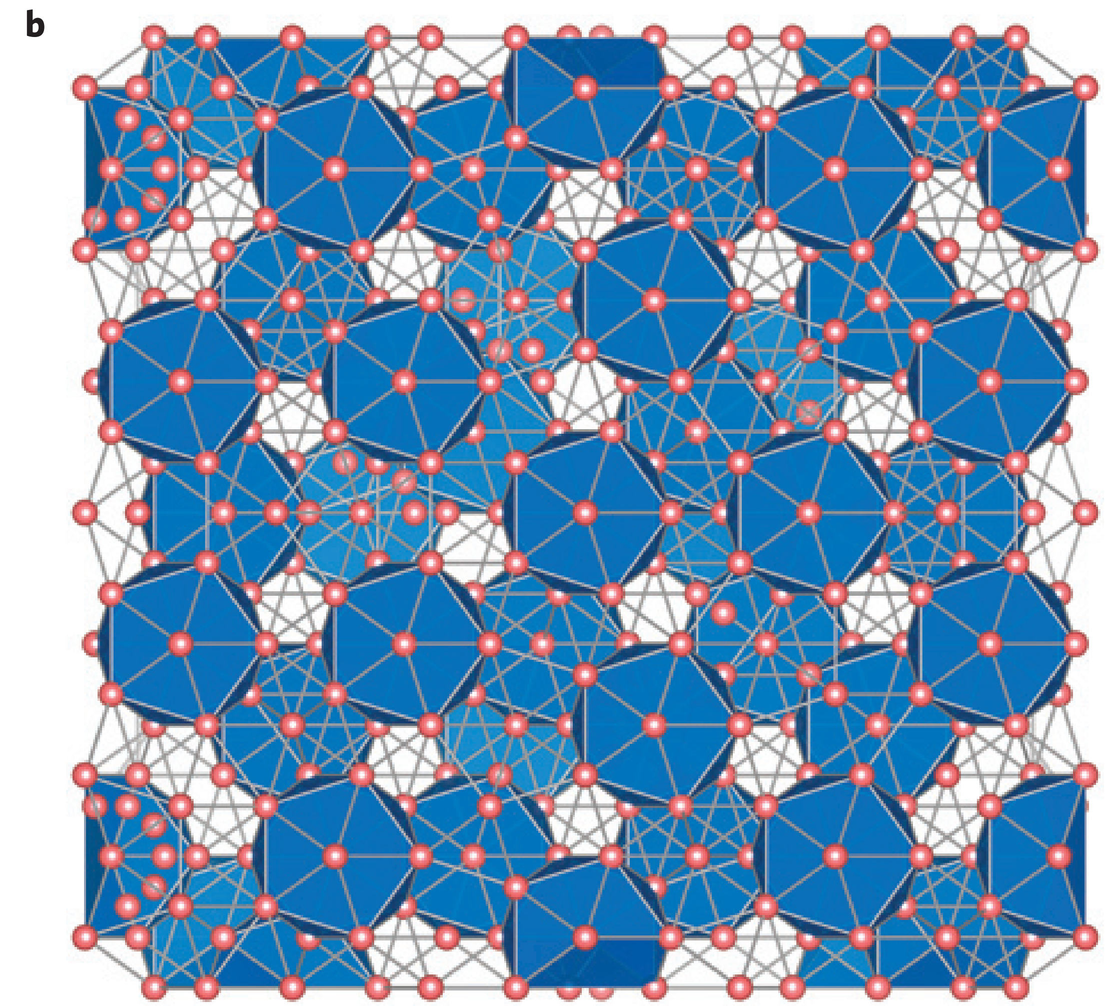

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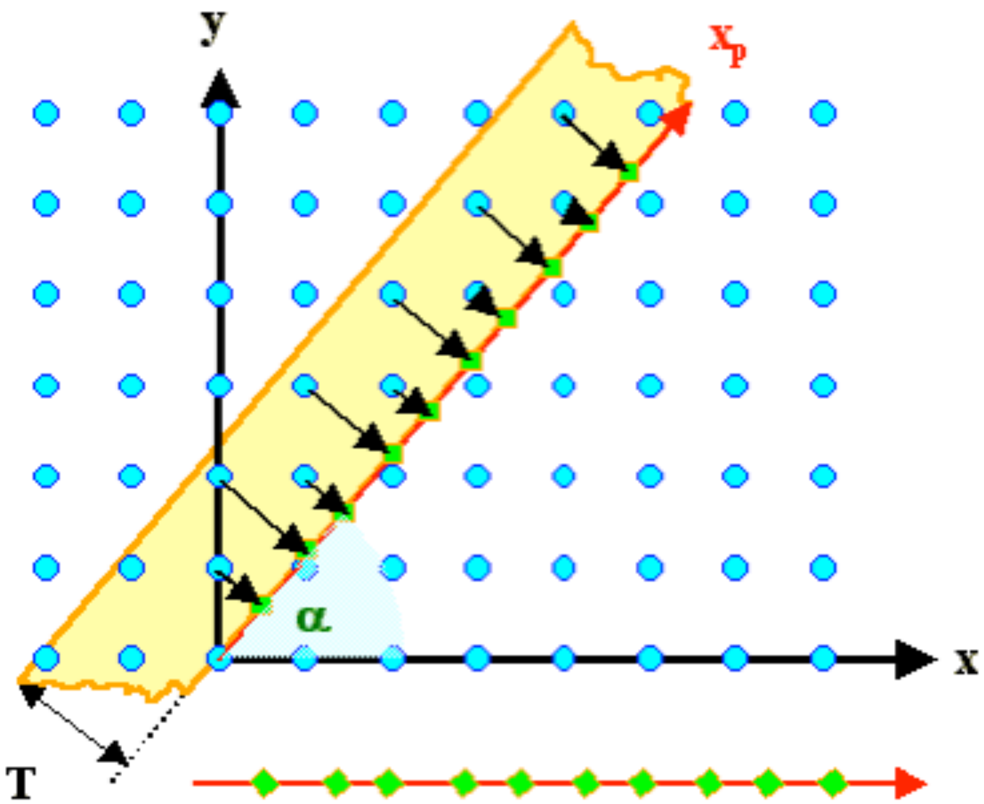

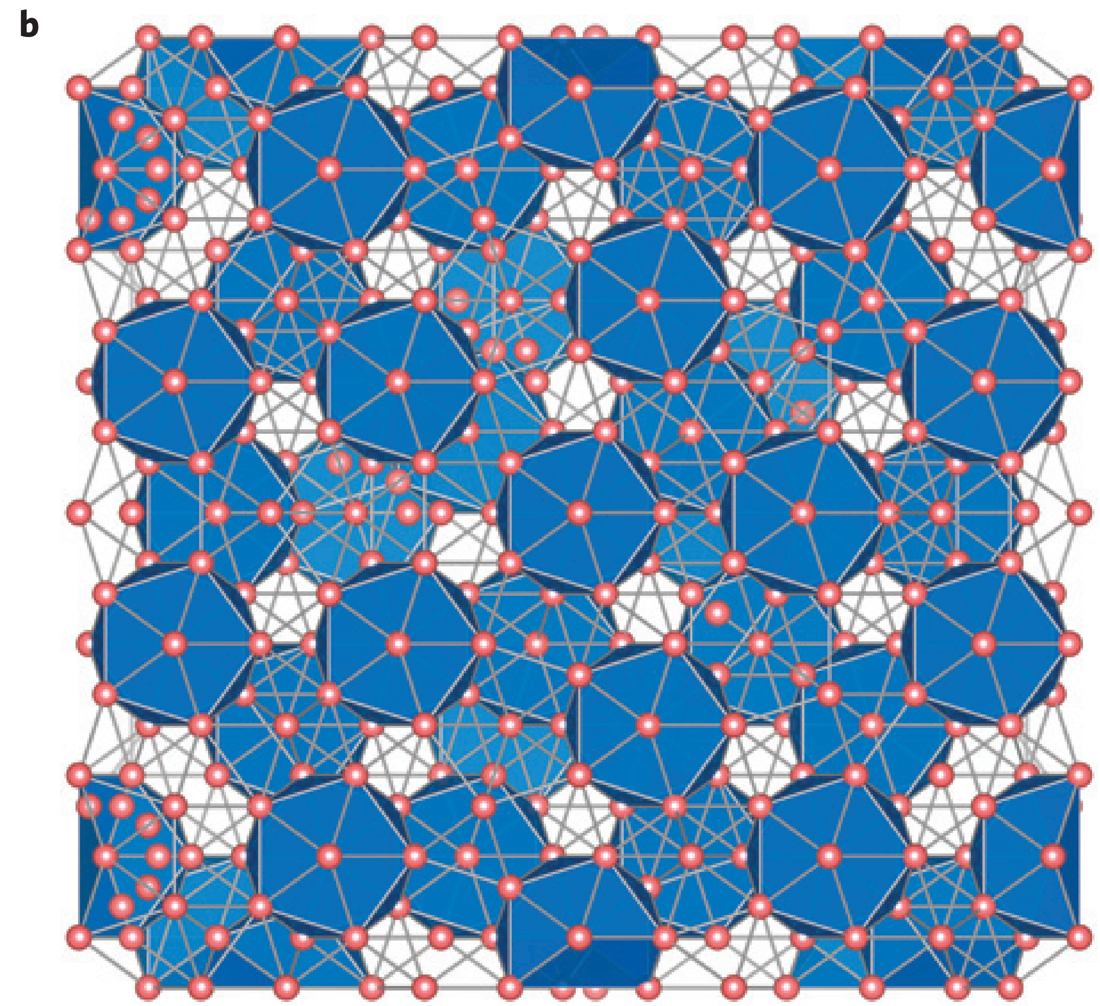

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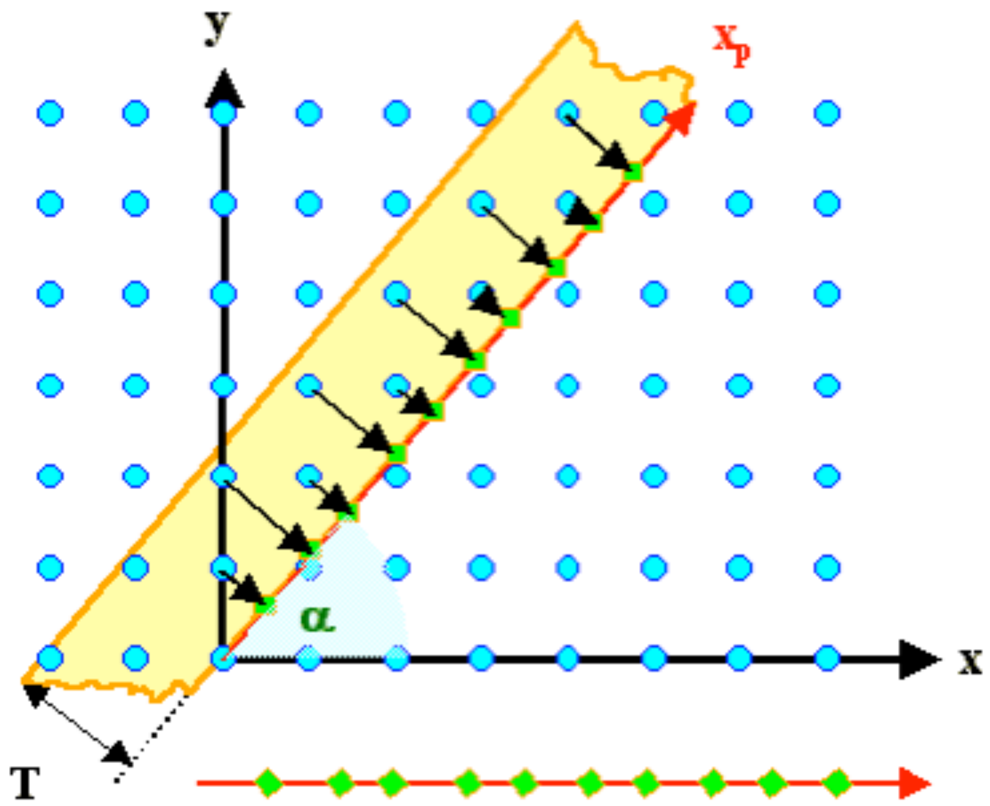

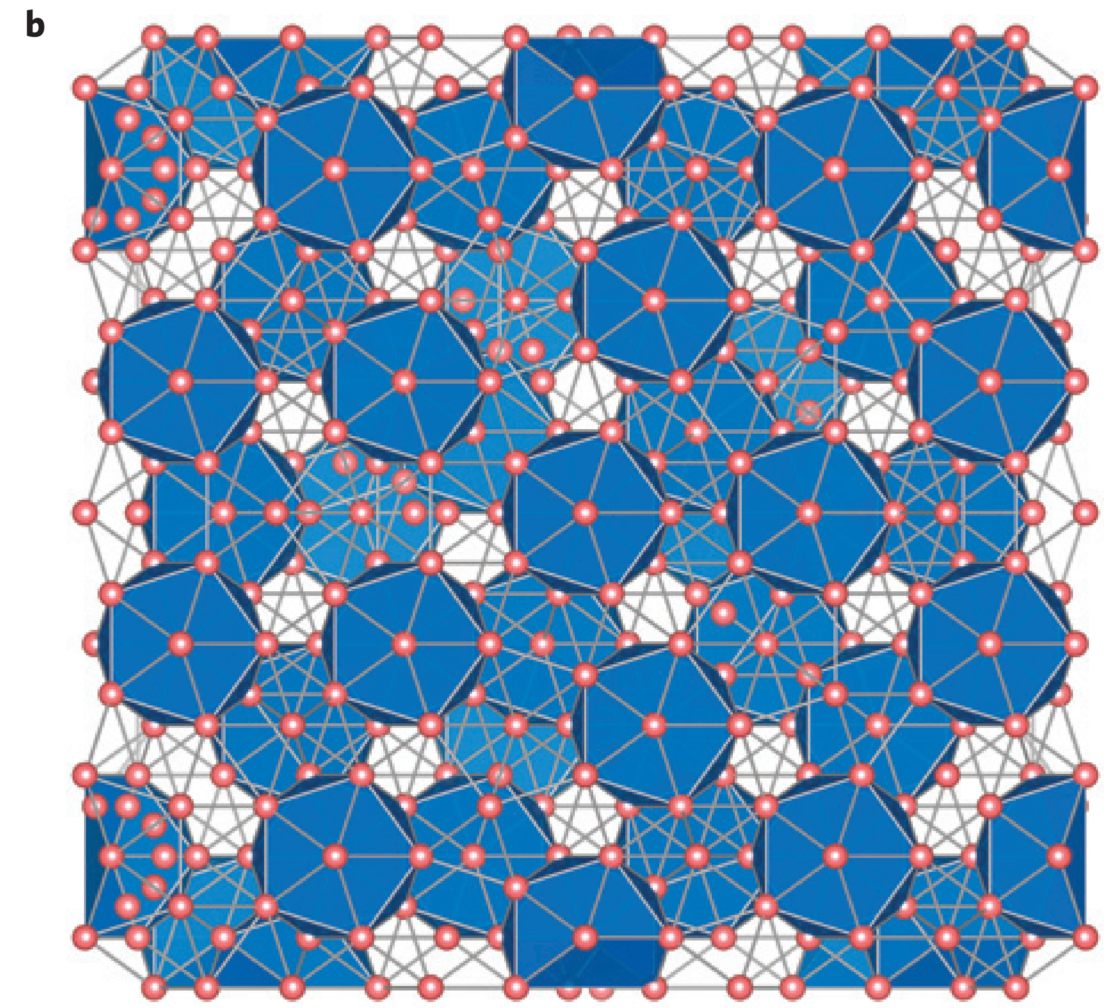

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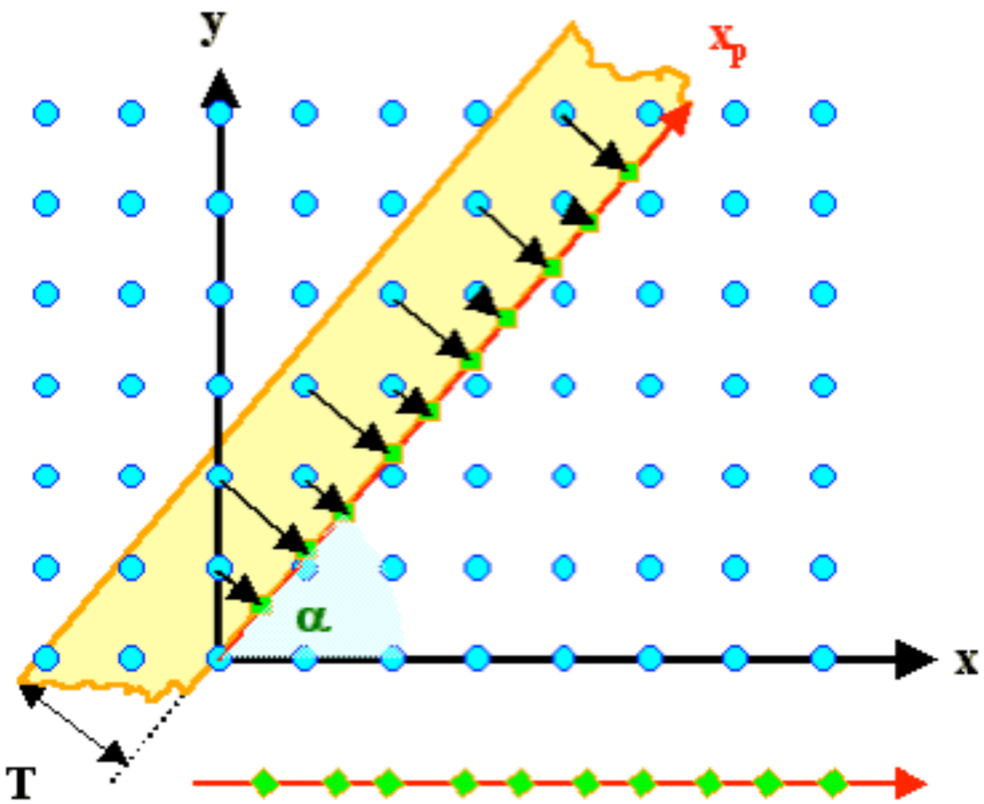

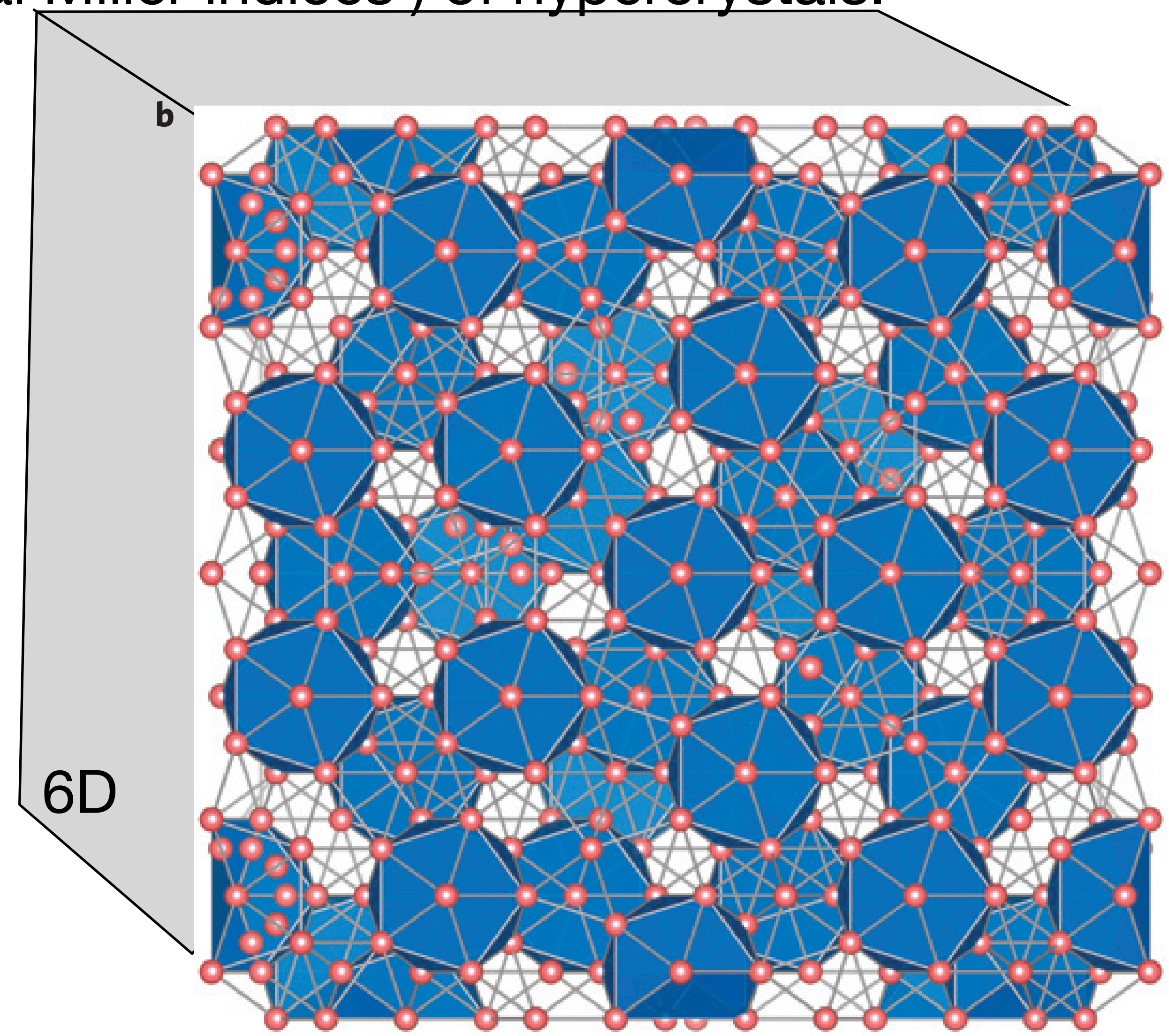

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Summary & Questions

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