SCES in the Quantum Information era:
New challenges and paradigms.

Piers Coleman

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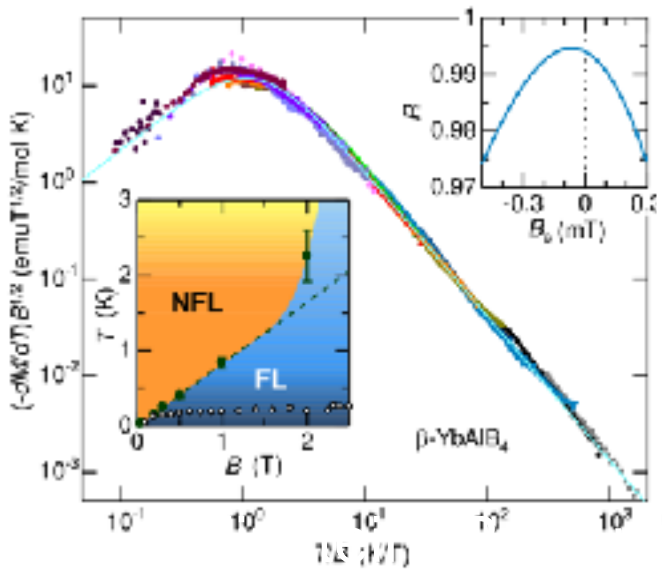
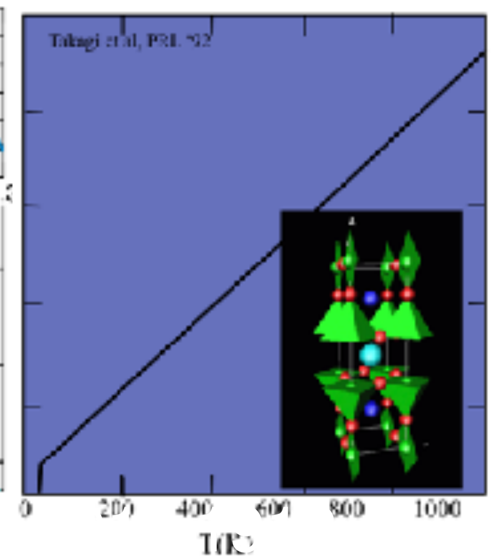
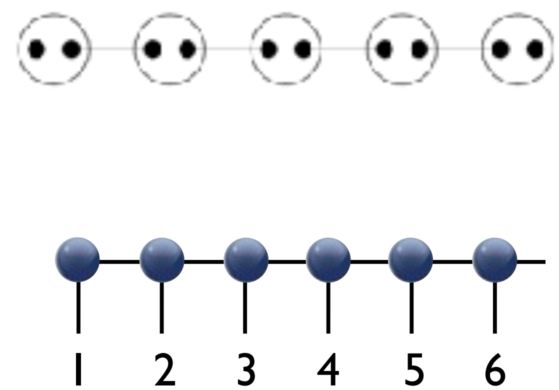
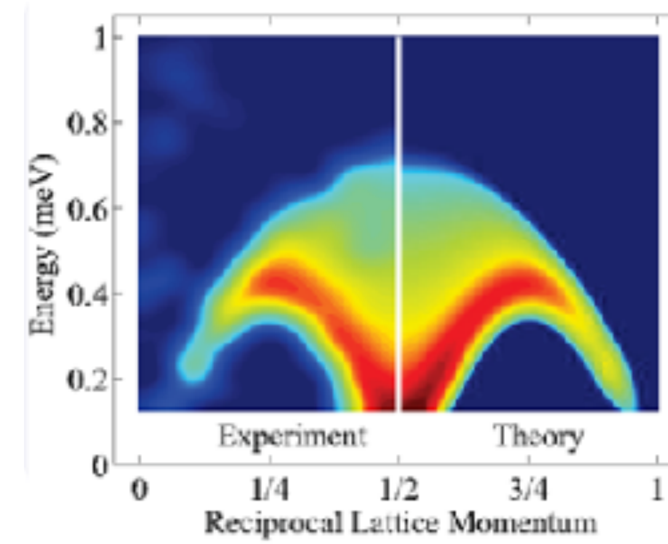
Hubbard Theory Consortium, Royal Holloway, U. London









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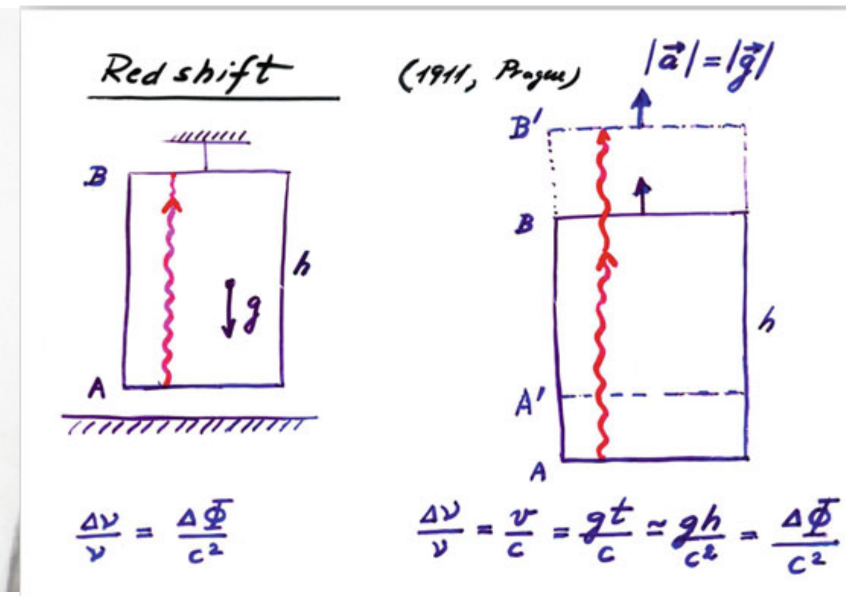

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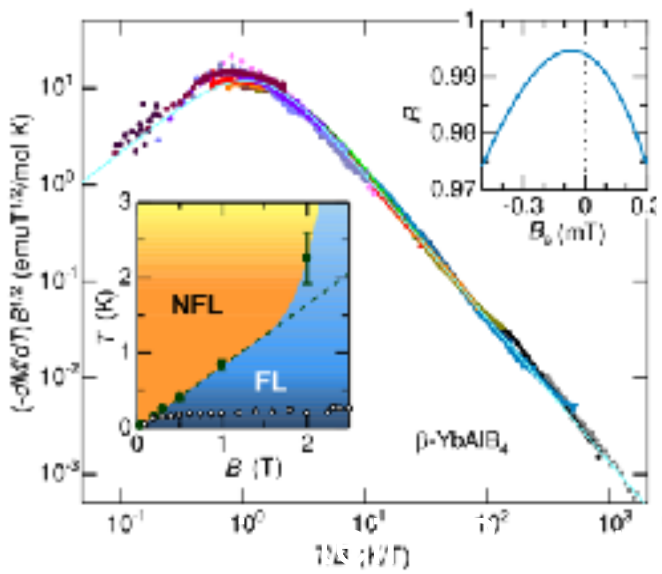

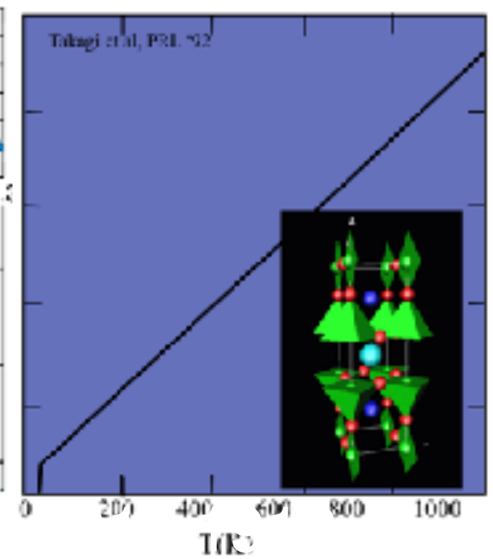

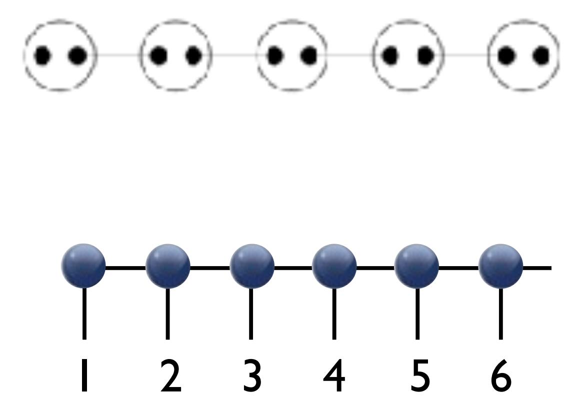

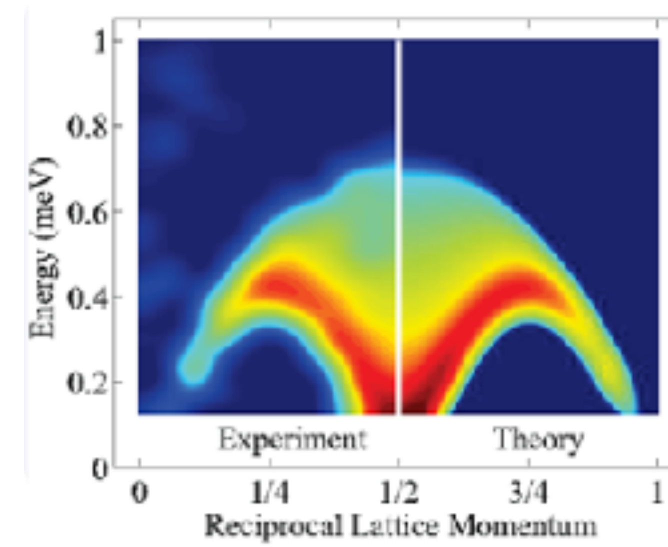

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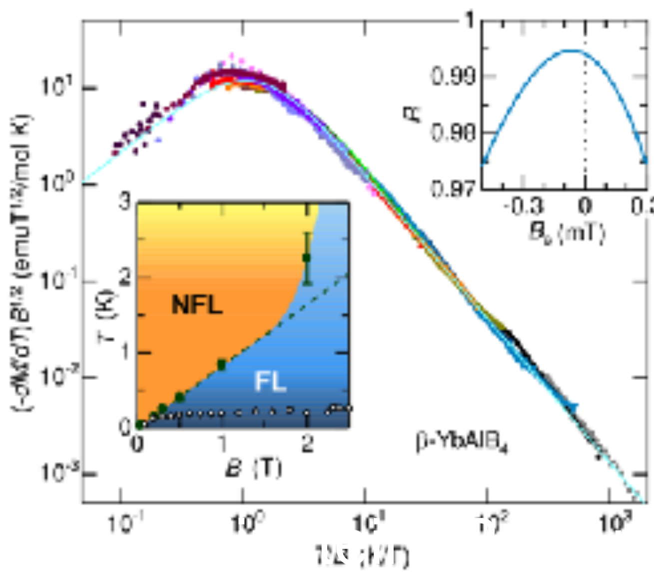

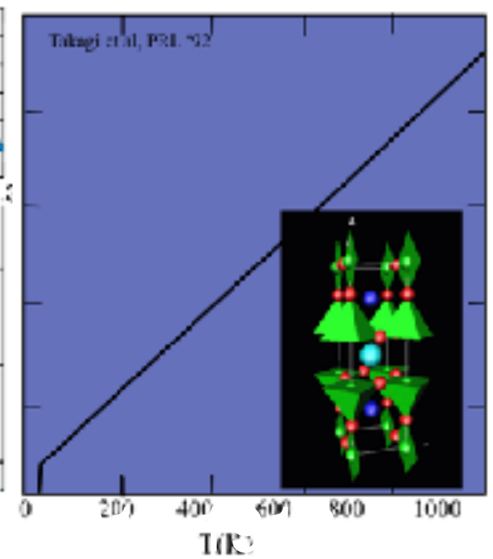

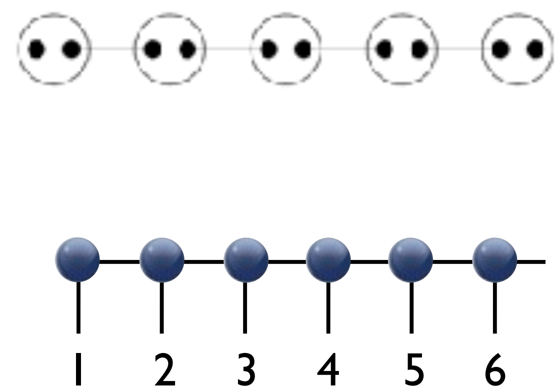

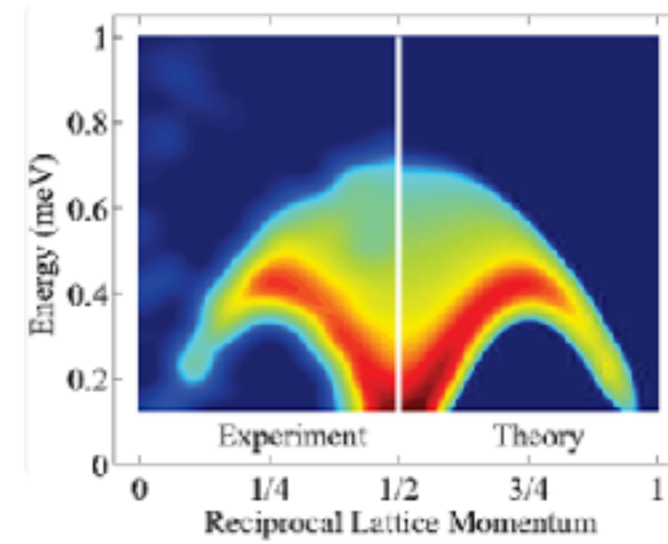

An era of extraordinary opportunity for our field.

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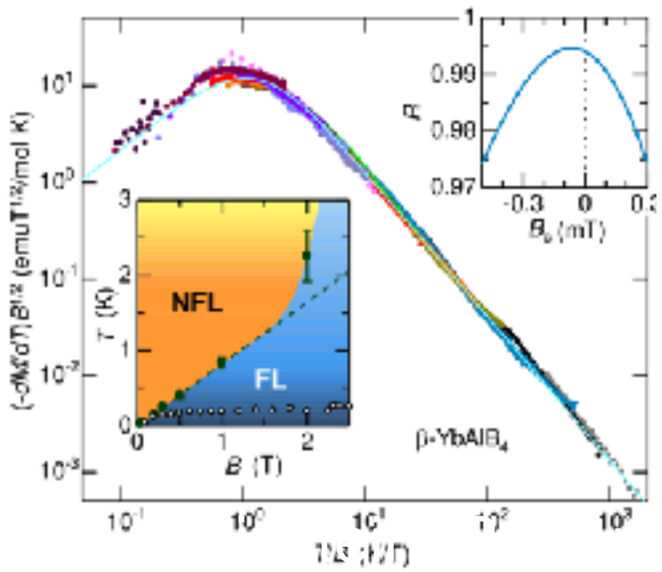

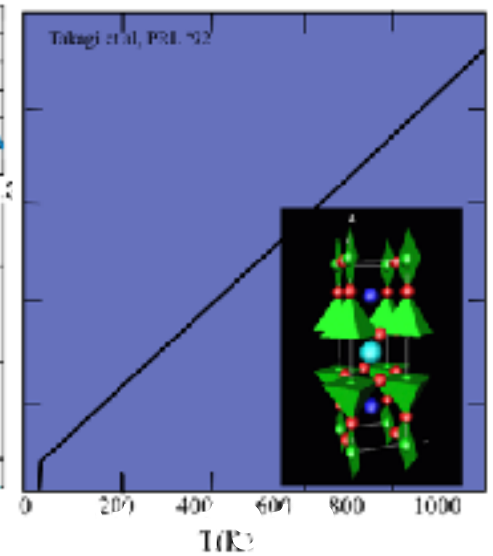

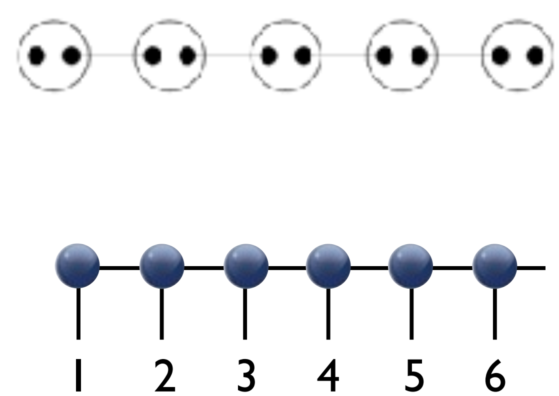

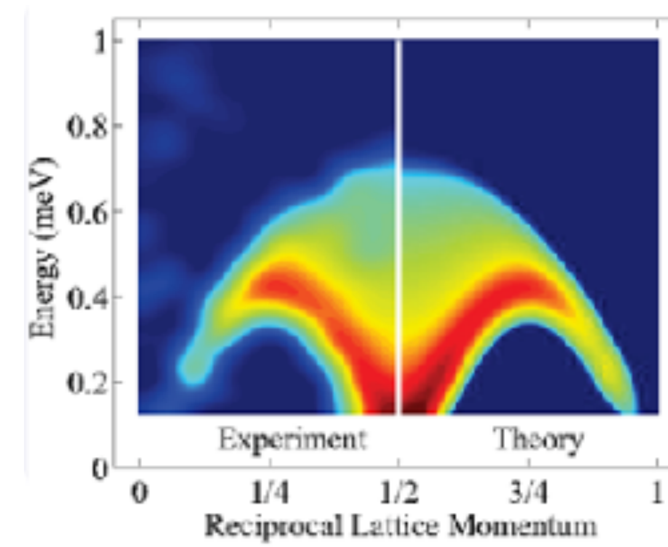

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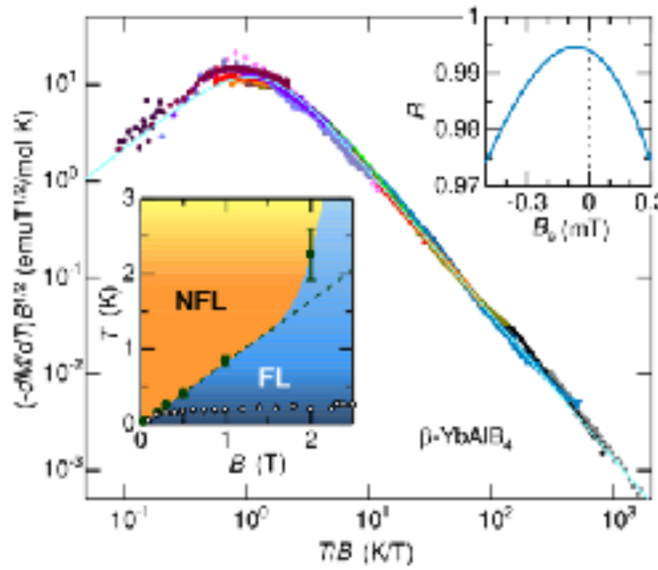

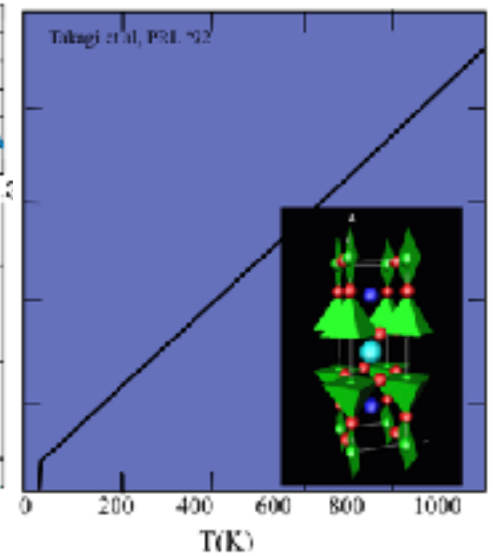

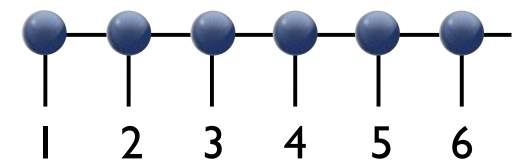

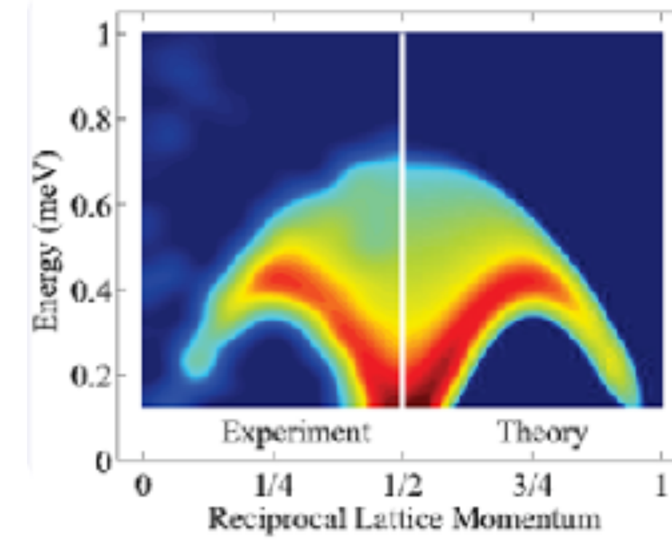

Thanks to:

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Gilbert Lonzarich
Frank Pollmann
Filip Ronning
Patricia Rosa
Suchitra Sebastian
Todadri Senthil
Toshio Takabatake

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Po Yao Chang	Rutgers
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Alexei Tsvelik	Brookhaven NL
Premi Chandra	Rutgers
Yashar Komijani	Rutgers
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Silke Paschen	TU Wien
Andriy Nevidomskyy	Rice U
Rebecca Flint	Iowa St.
Maxim Dzero	Kent U.
Victor Galitski	U. Maryland
Kai Sun	U. Michigan

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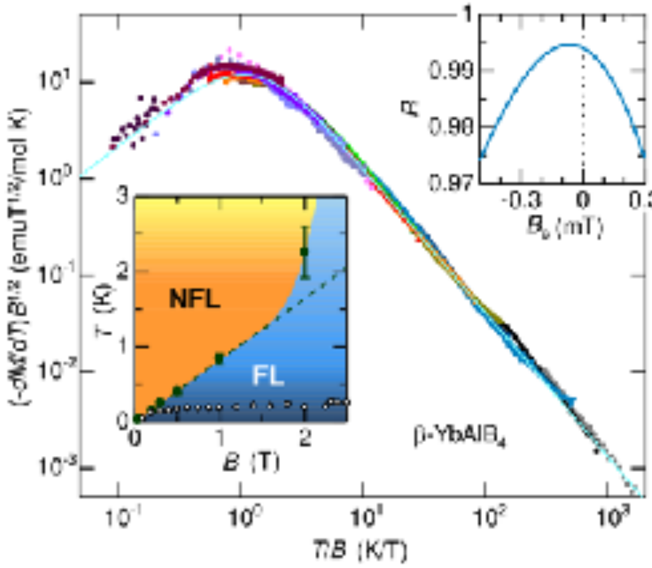

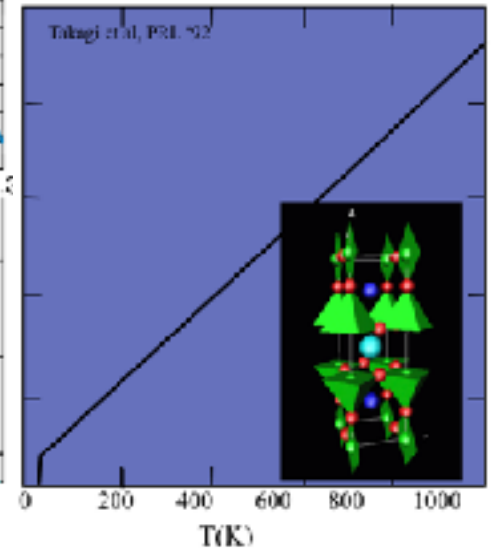

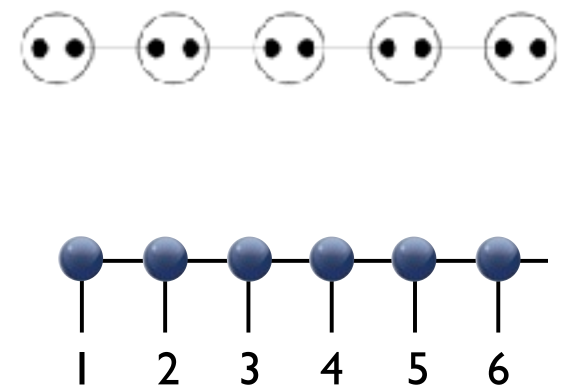

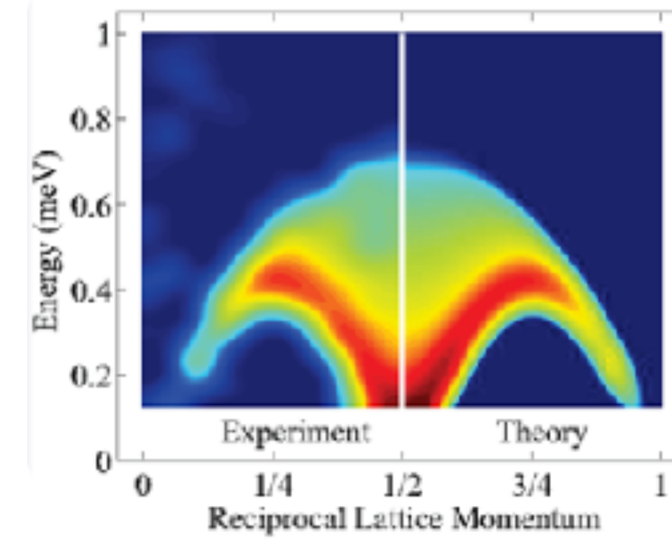

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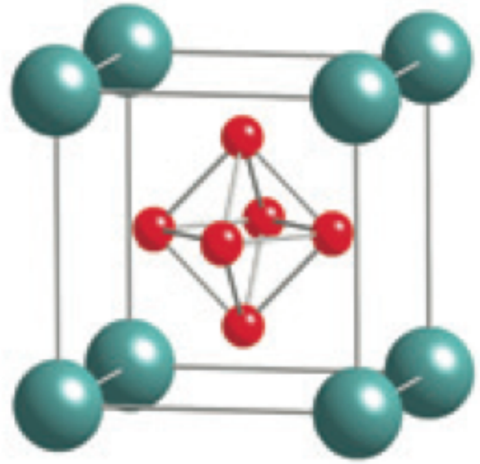
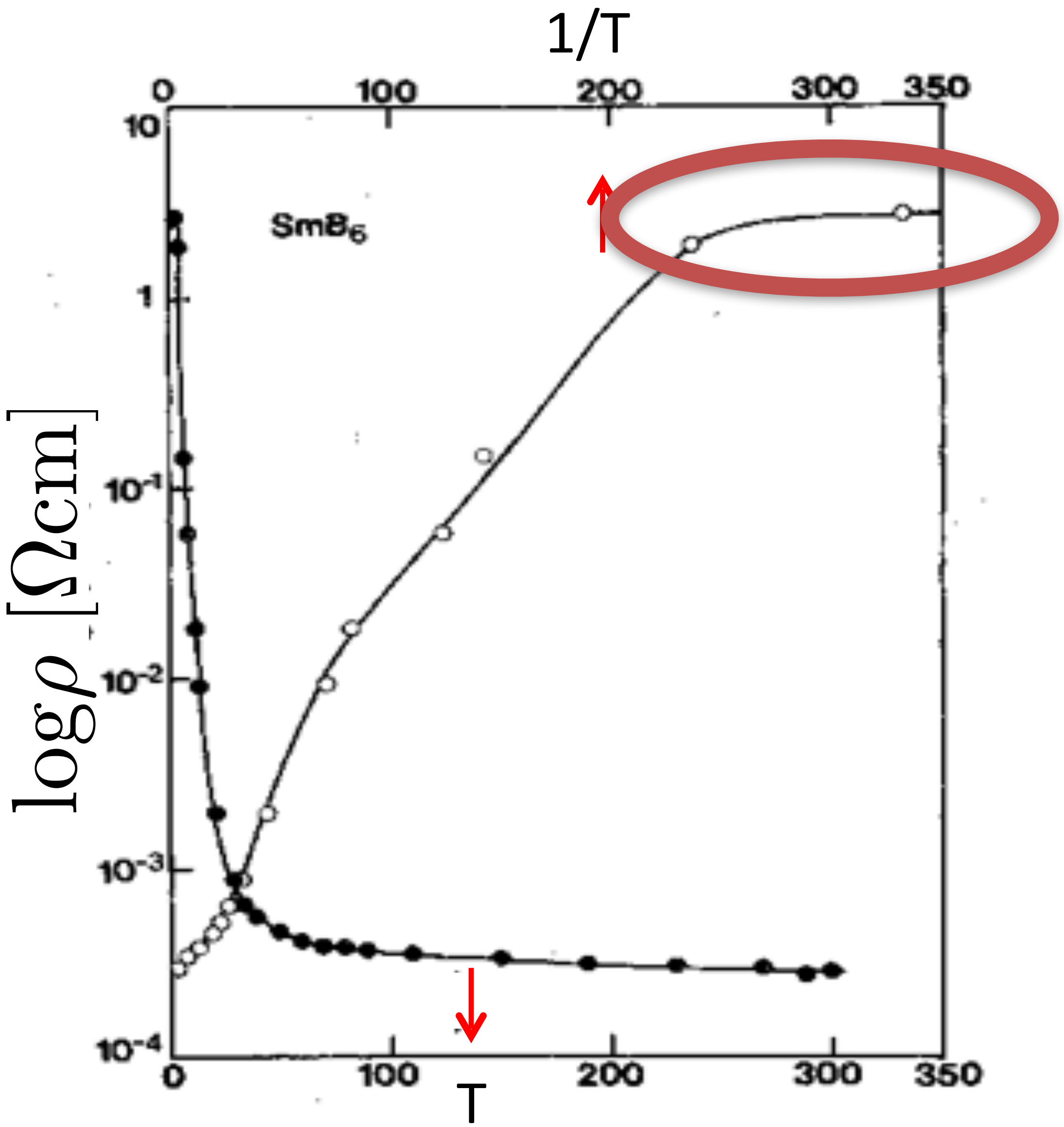
Fifty Years of Novel Phases.

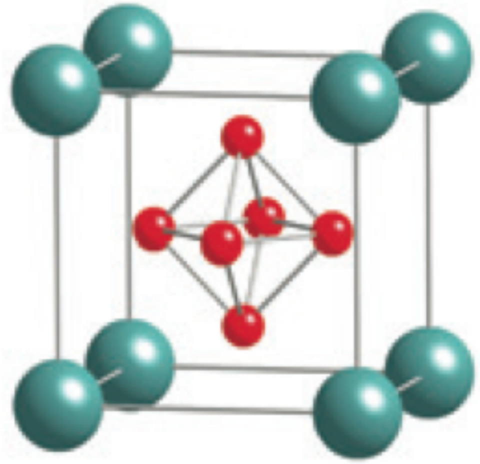
SmB_6 1969

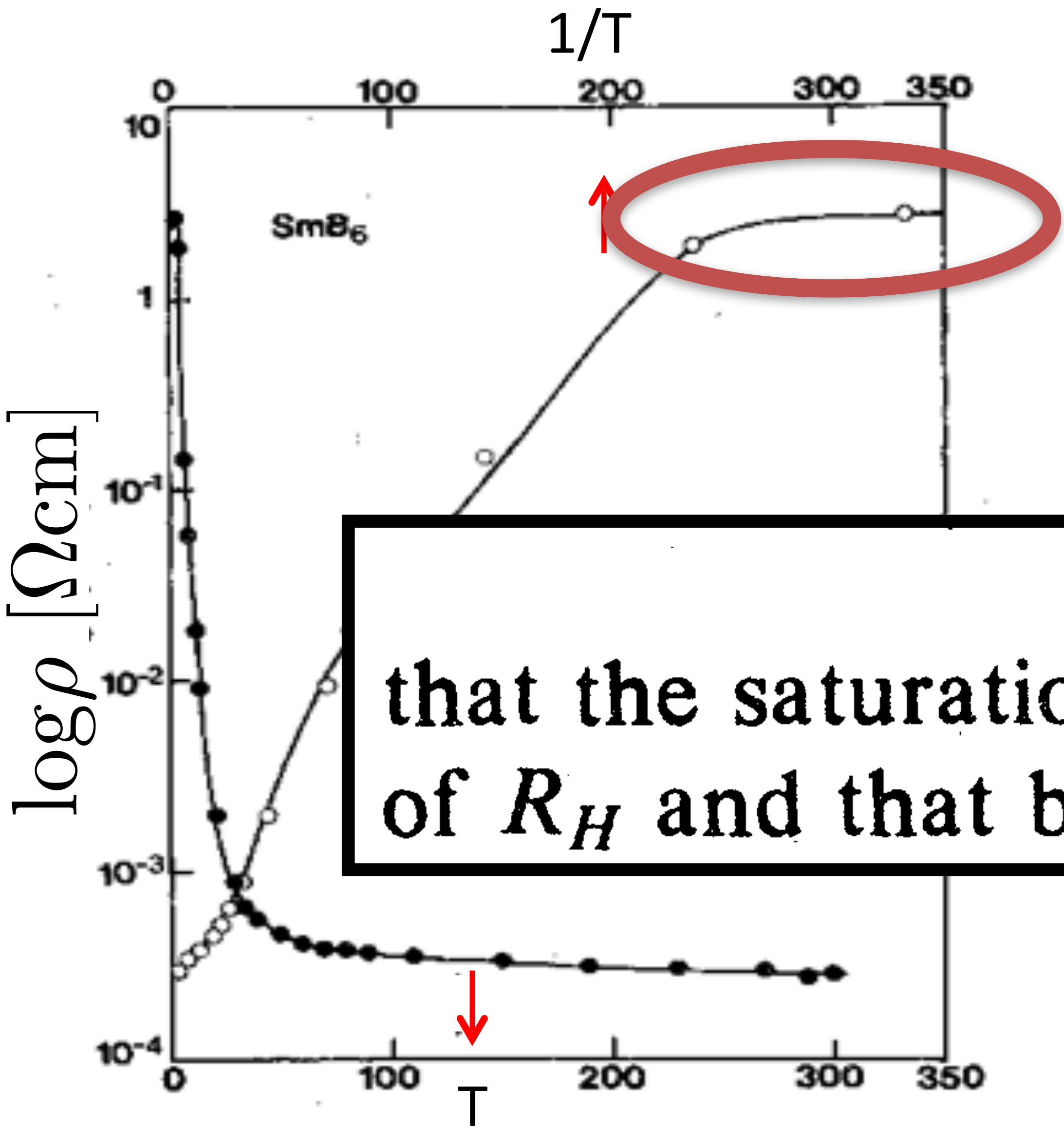




Menth, Buehler, Geballe PRL **22**, 295 (1969)
Allen, Batlogg, Watchter PRB **20** 4807 (1979)

SmB_6
1969





This strongly suggests that the saturation of ρ is correlated with the peaking of R_H and that both are extrinsic.

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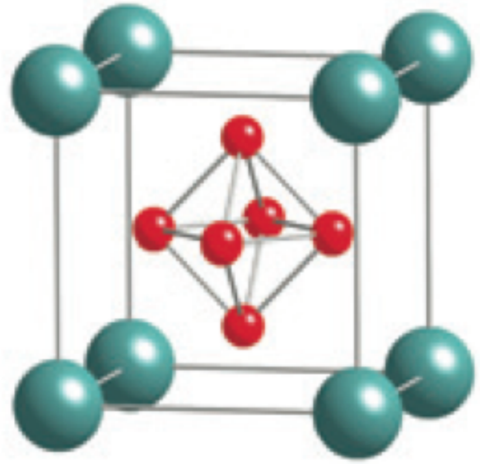
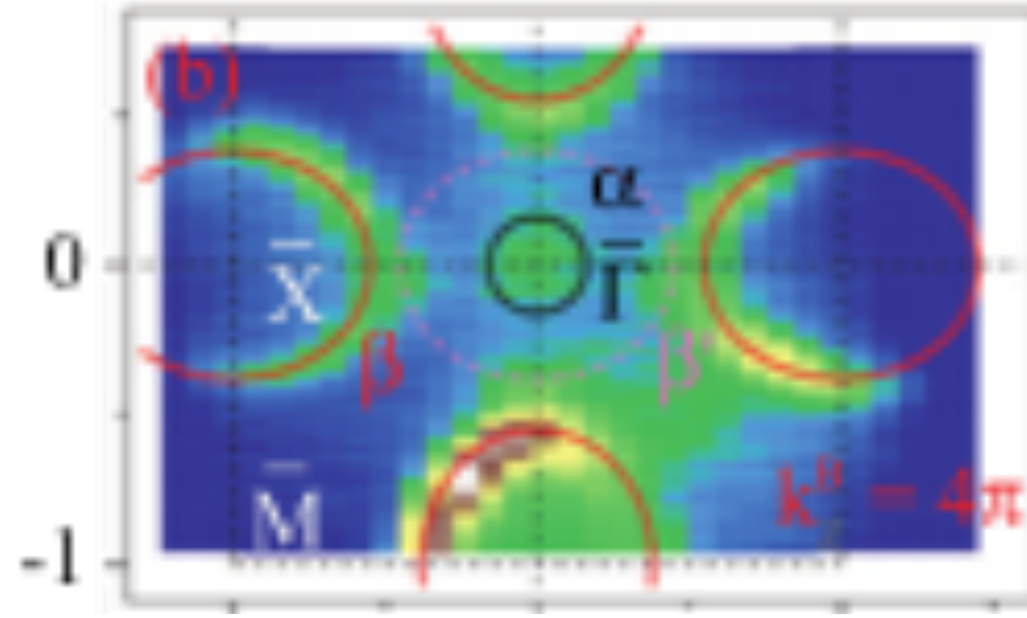
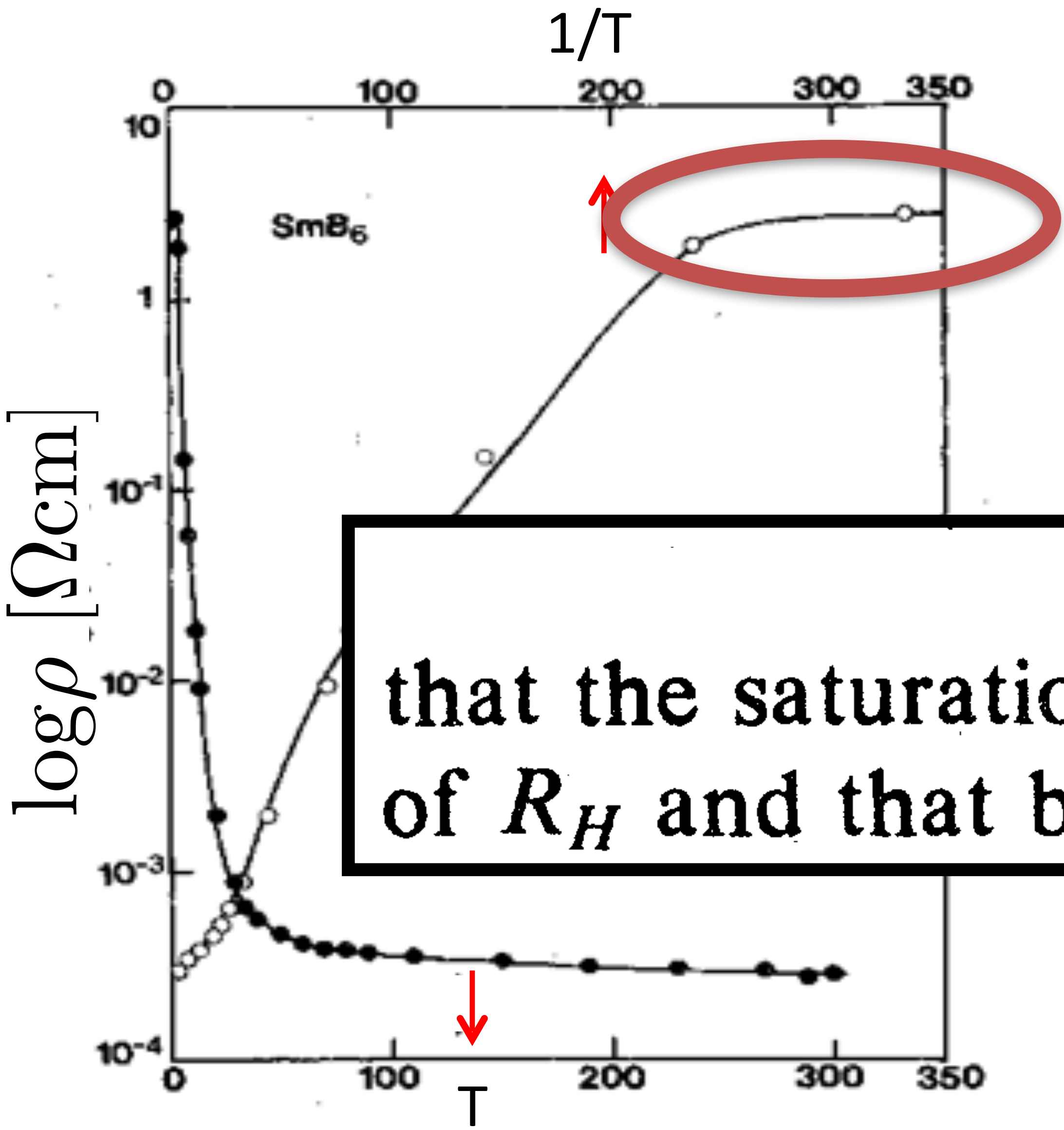


ARPES → Surface states



Xu et. al PRB **88**, 121102(R) (2013)



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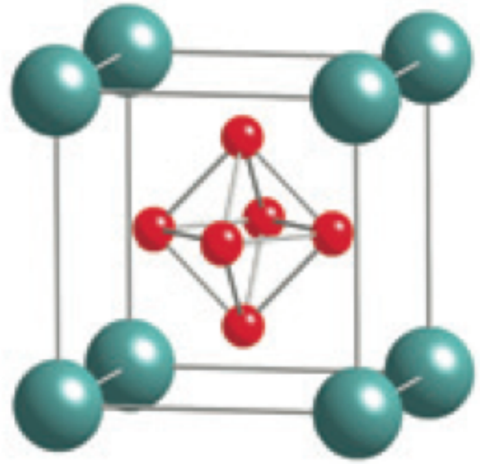
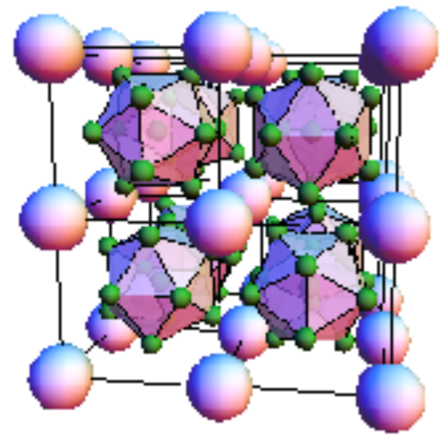
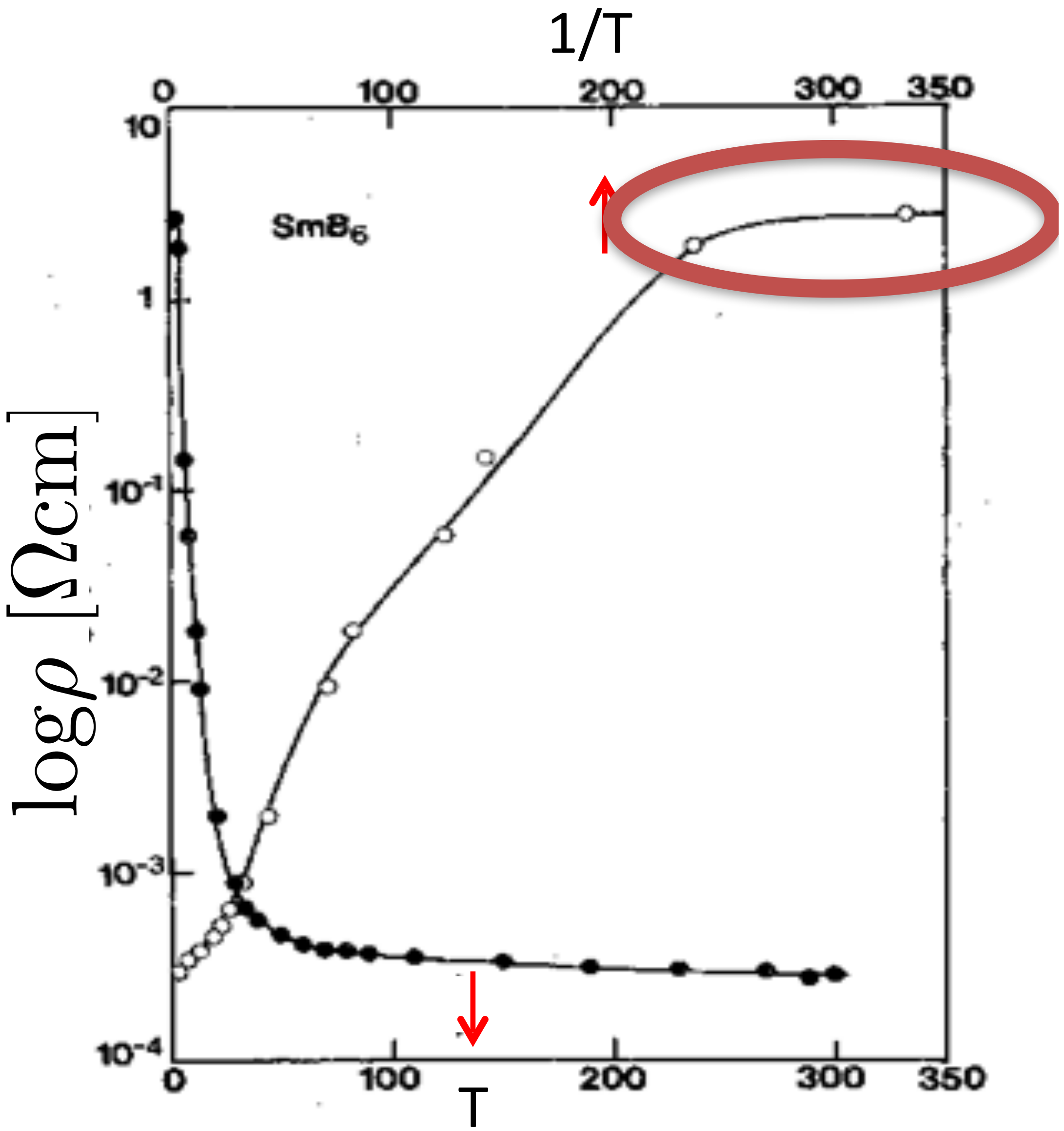




UBe_{13}
1974



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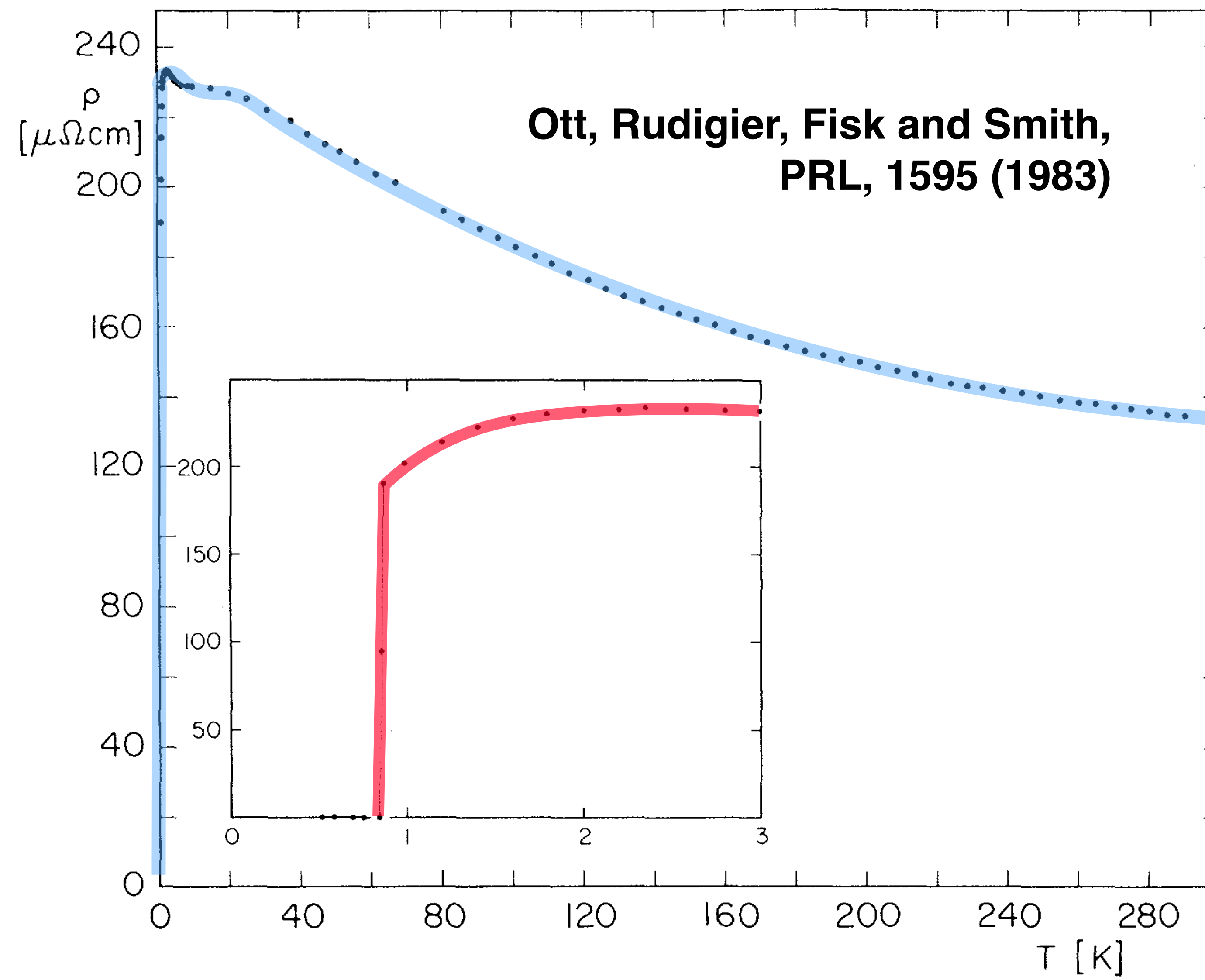

UBe_{13} 1974

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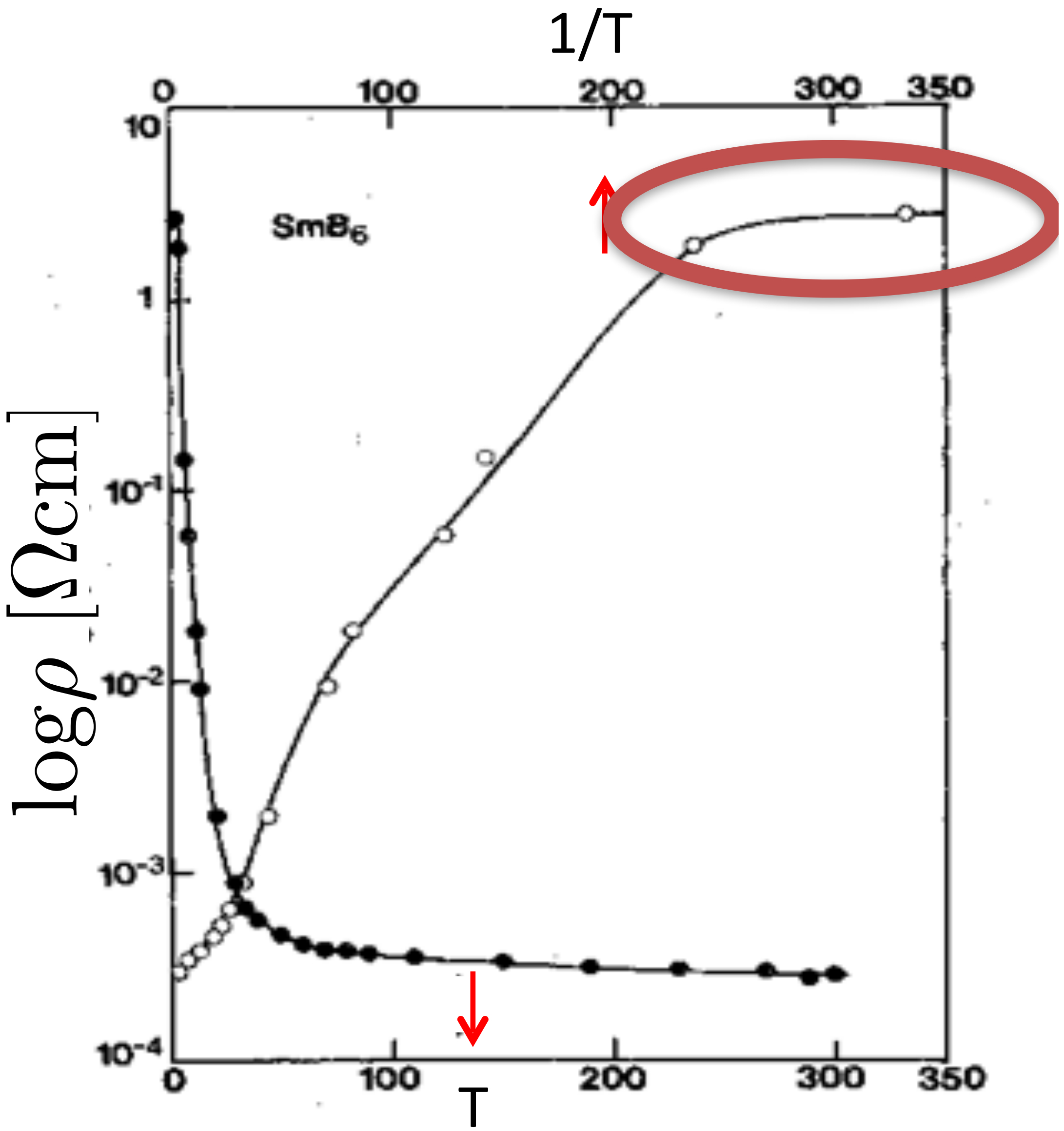

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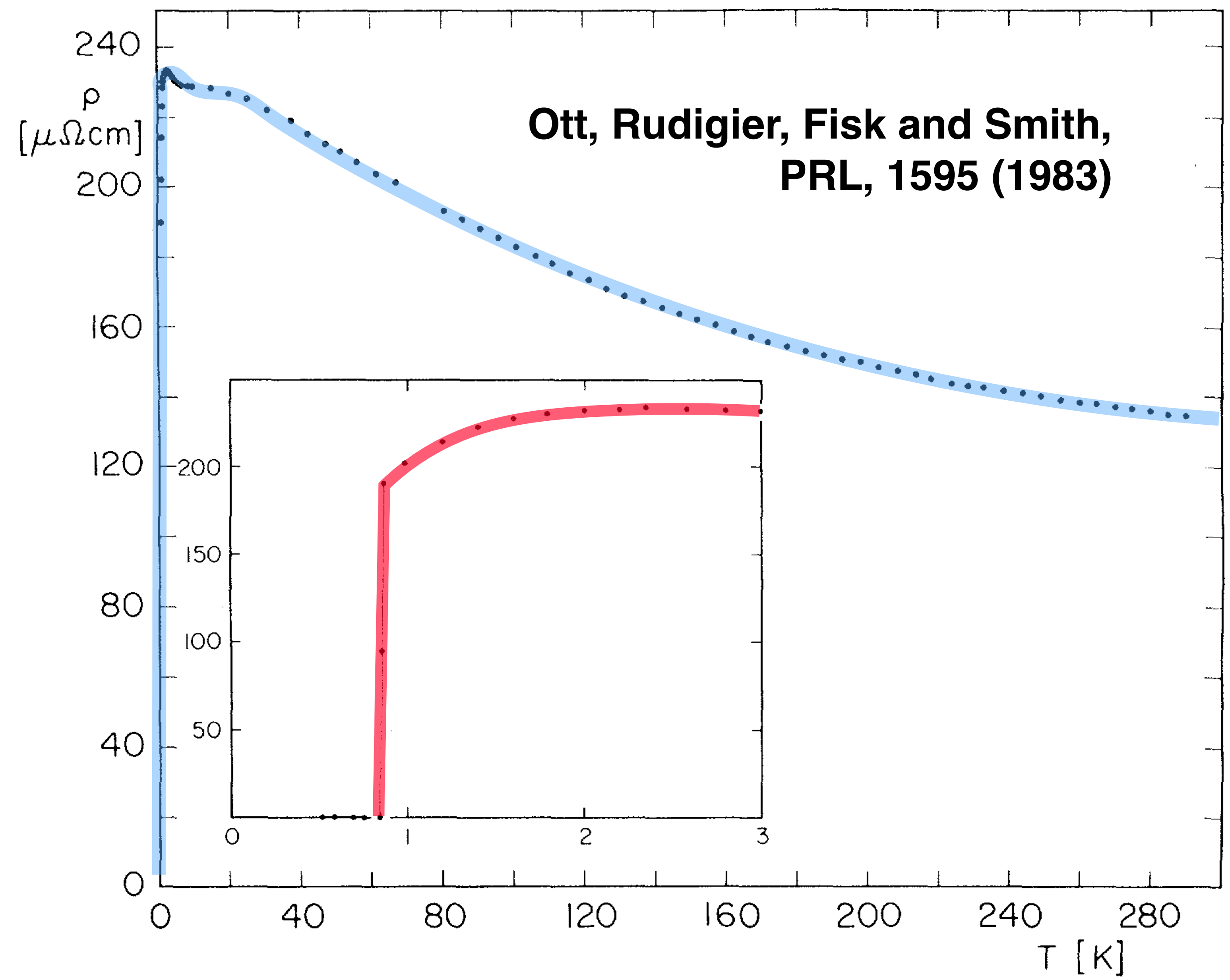

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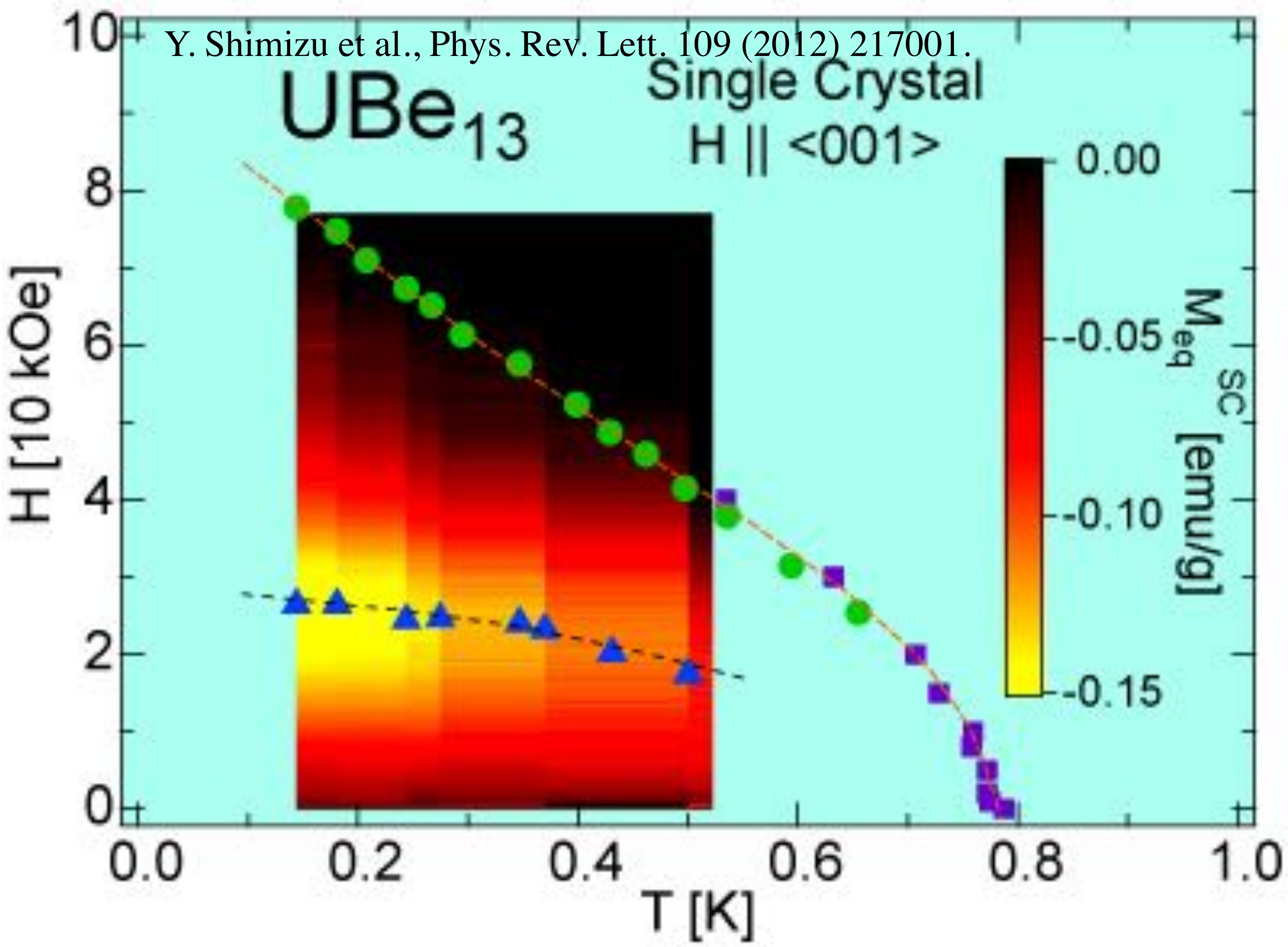

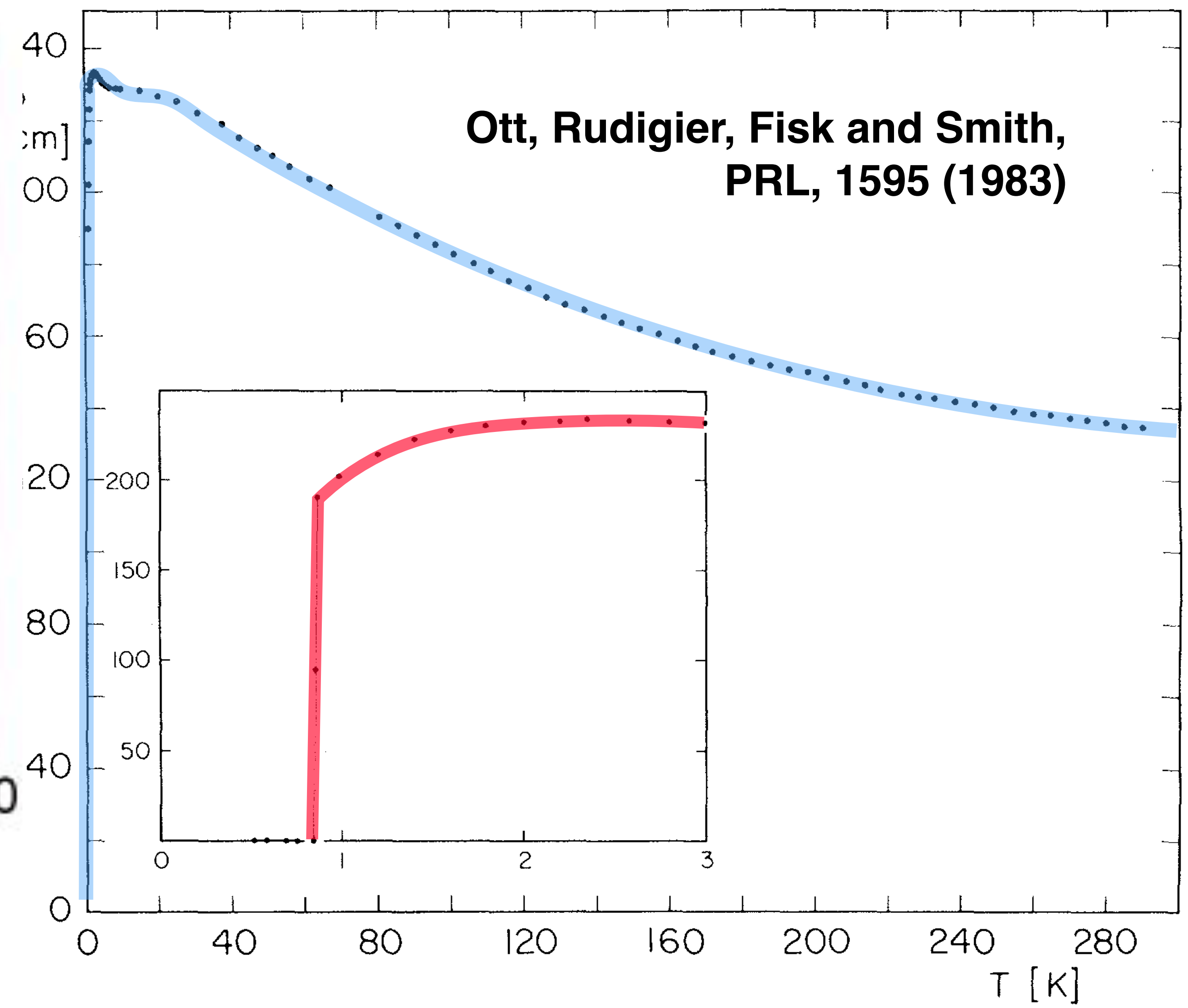

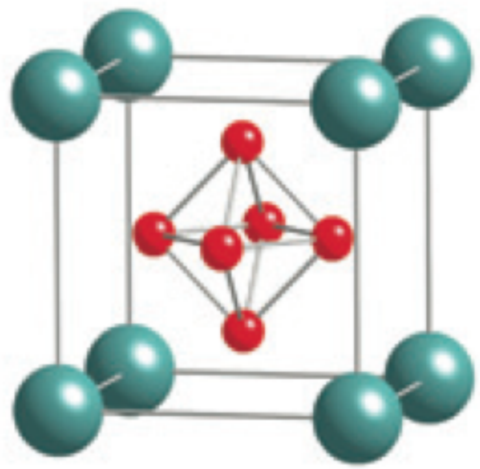

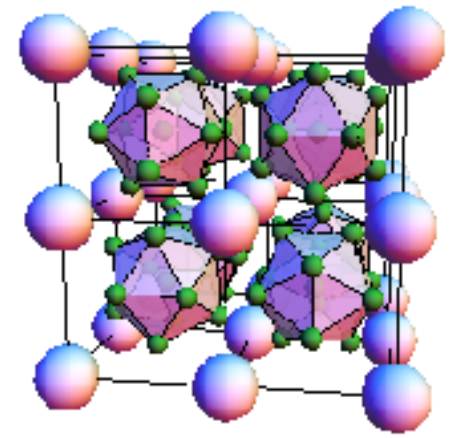

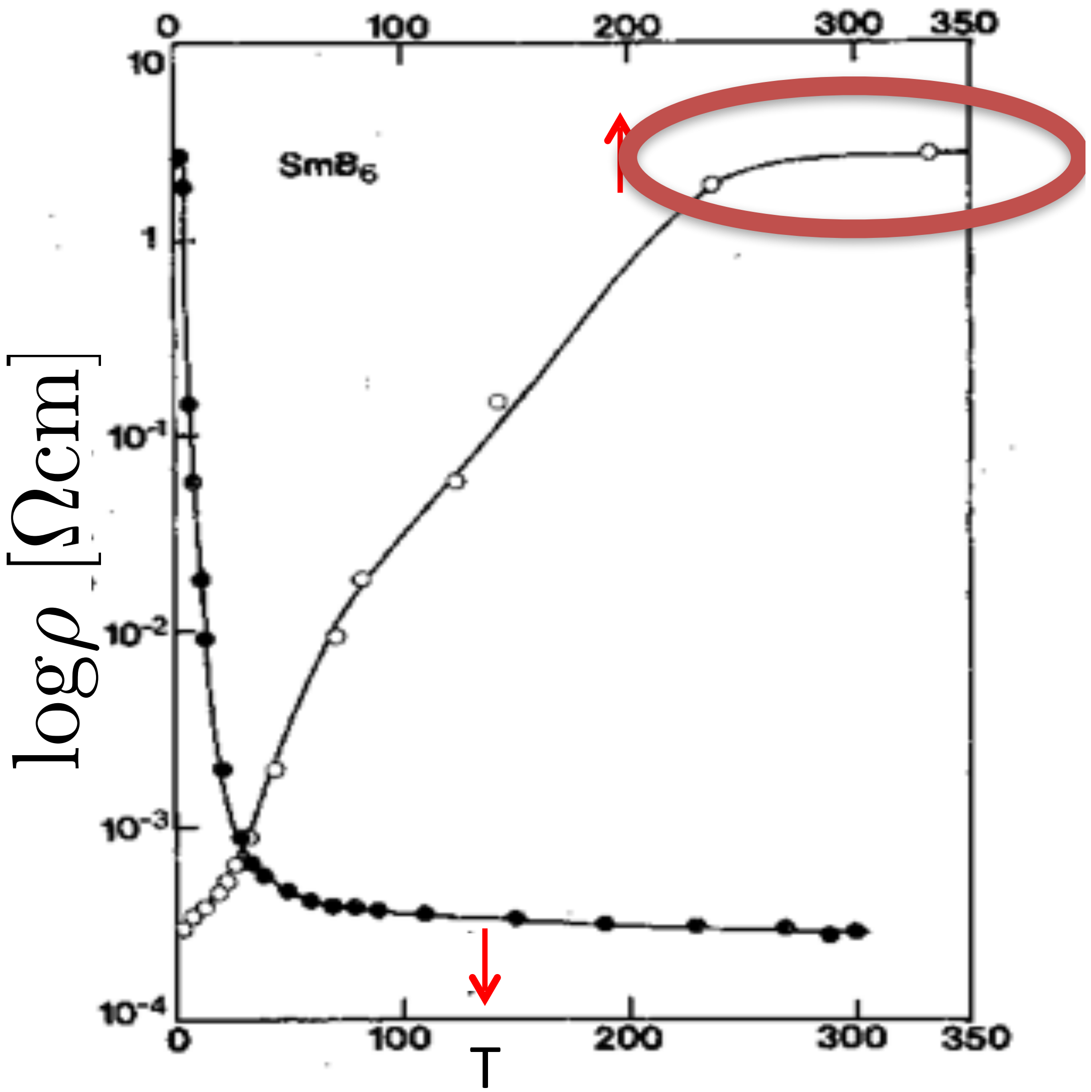

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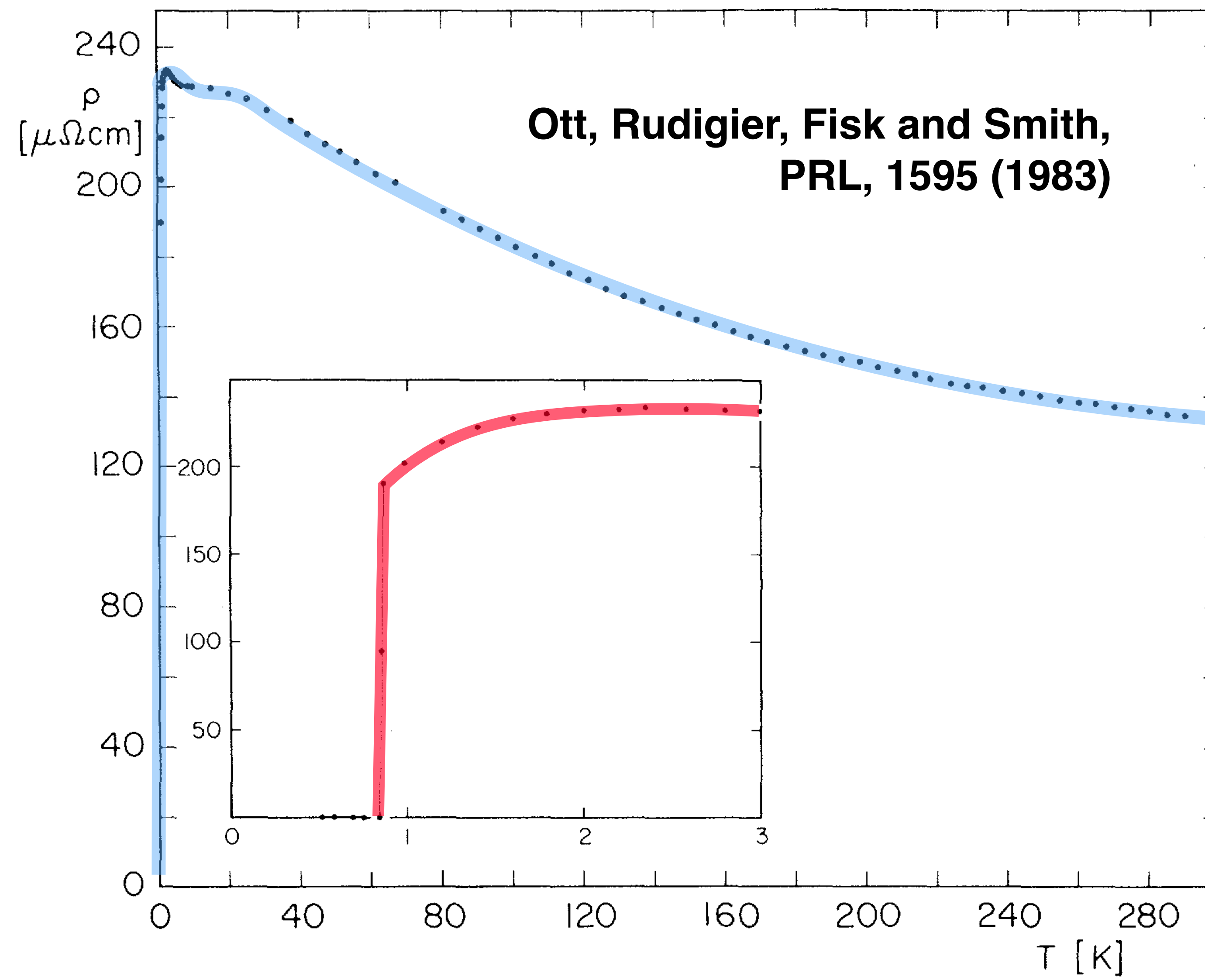
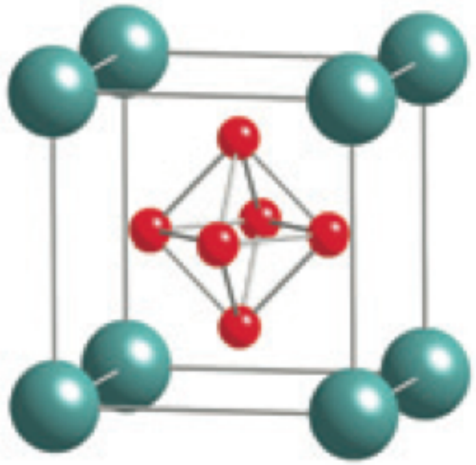
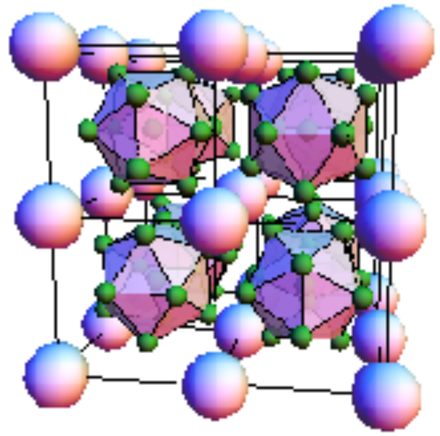


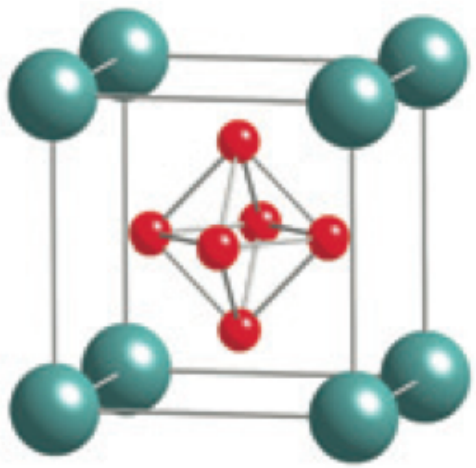


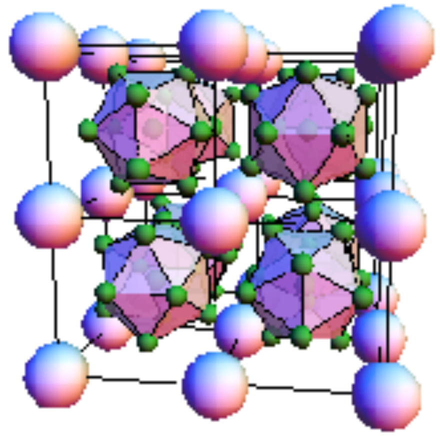
SmB_6 1969



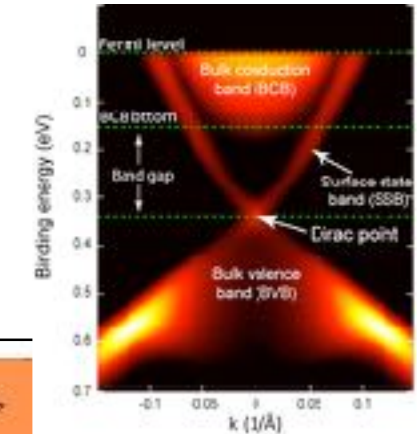
UBe_{13} 1974

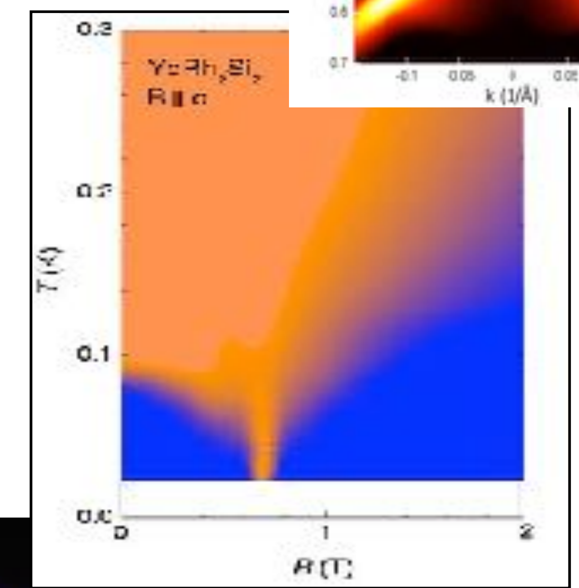
Discovery often awaits new concepts, new consensus





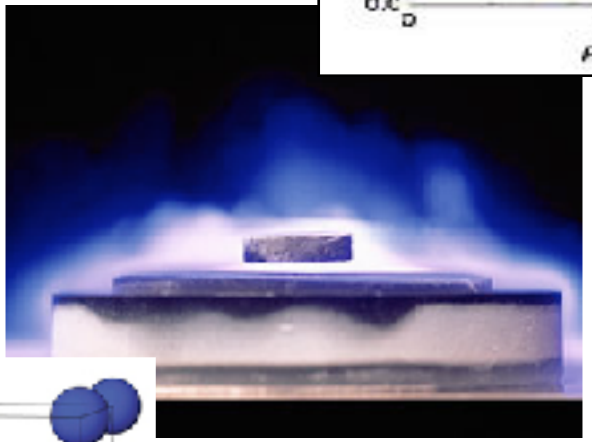
SmB$_6$ 1969 UBe$_{13}$ 1974

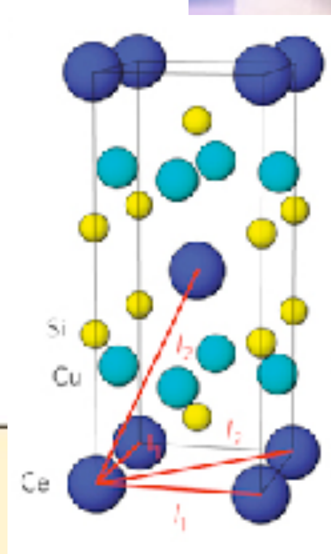




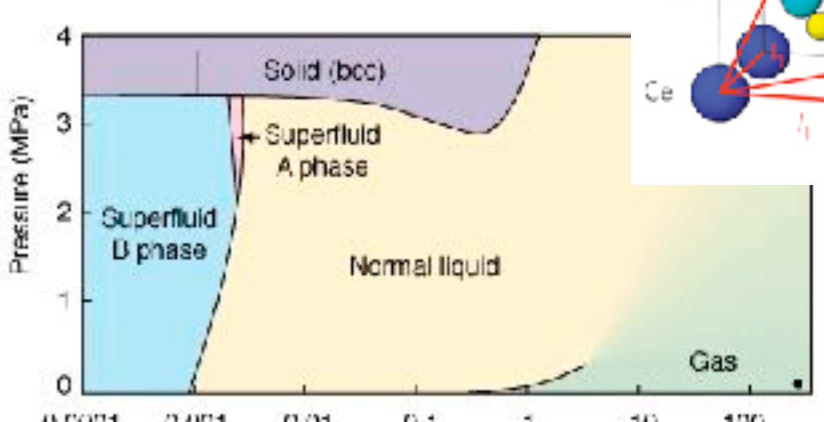
Fifty Years of Novel Phases.

Discovery often awaits new concepts, new consensus

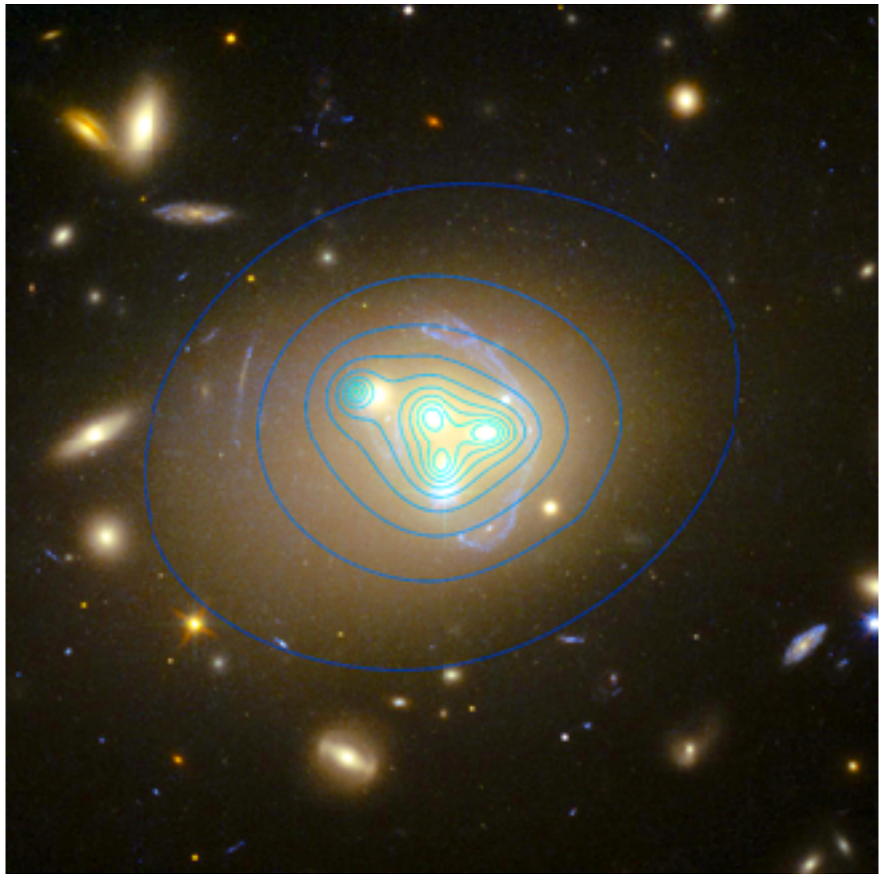




~5 yrs before **Superfluid He-3**
10 yrs before **Heavy Fermion SC**
20 yrs before **High Temperature SC**
30 yrs before **Quantum criticality**
40 yrs before **Topological insulators, Fe based SC**



Dark Matter Challenges of the Solid State.

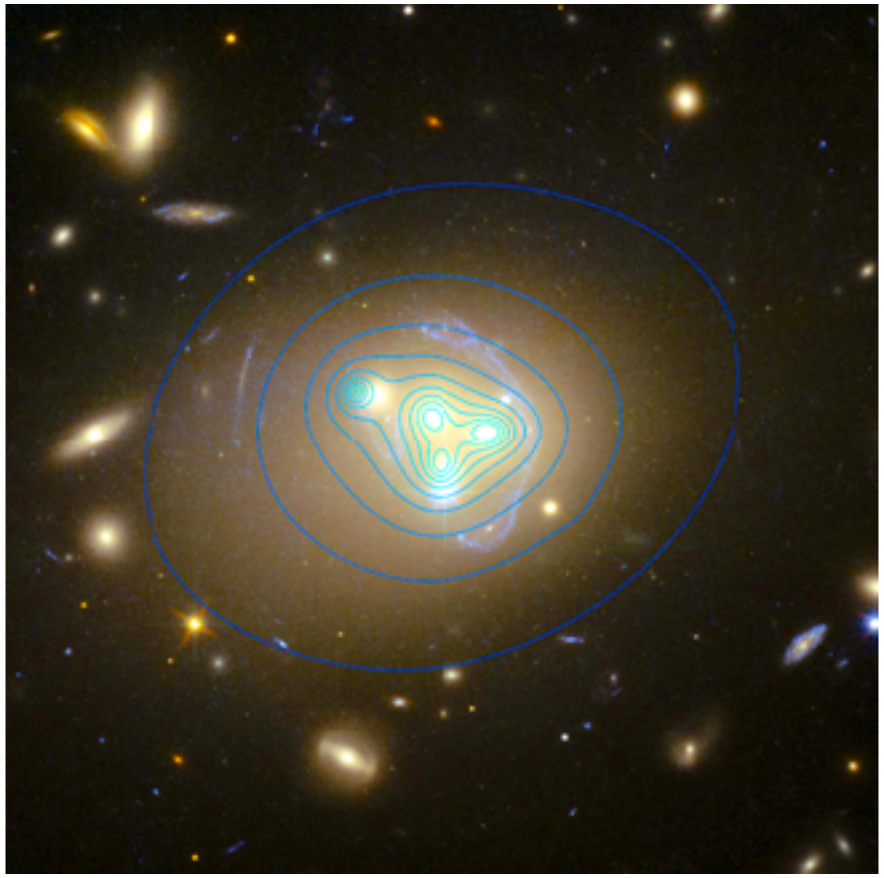


Abell Cluster 3827 (ESO/R Massey)

Dark Matter Challenges of the Solid State.

- Linear resistivity in strange metals
- Strange Insulator SmB_6

- Pairing Mechanism of Cu/Fe/HFSC
- Quantum Criticality in Metals
- Nature of the pseudogap
- Sign Problem in QMC
- Topology in SCES
- Uemura Scaling $\rho_s \sim T_c$ (overdoped) cuprates
- Ground-state of Spin Liquids



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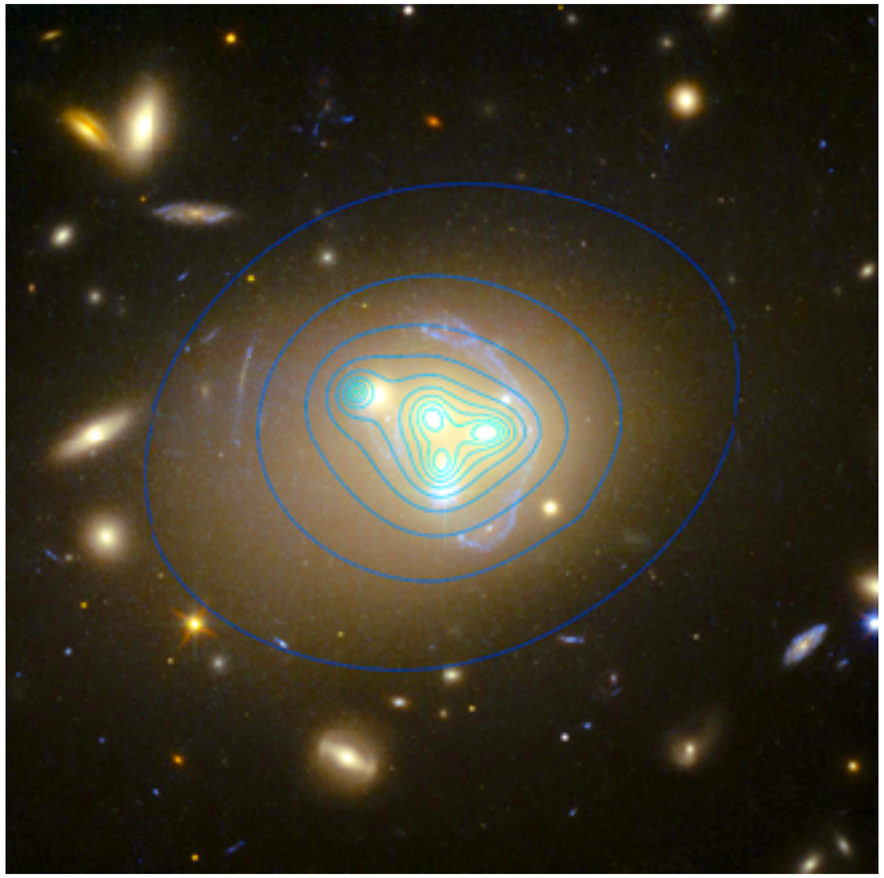

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These, and many other examples suggest the potential for qualitatively new advances in our understanding of quantum matter.

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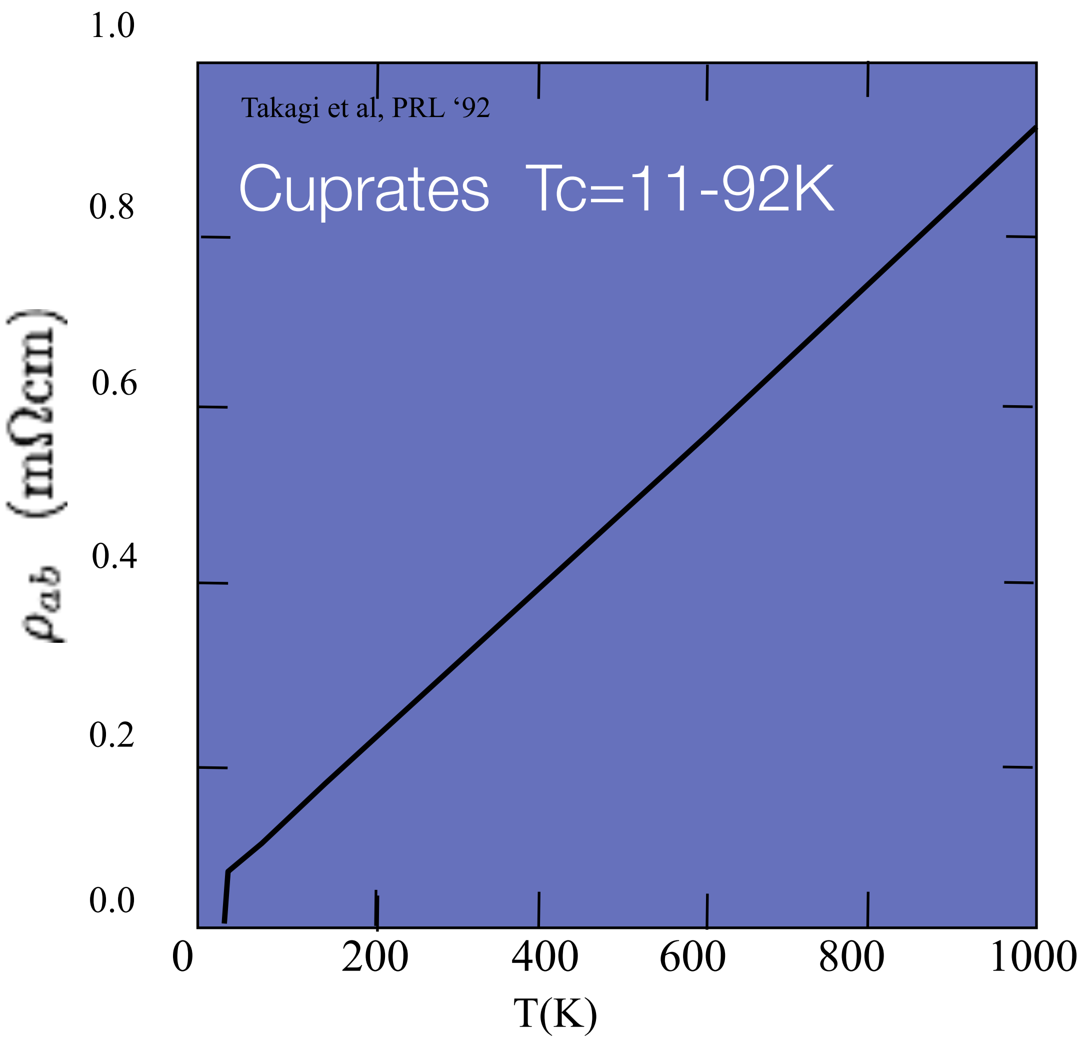

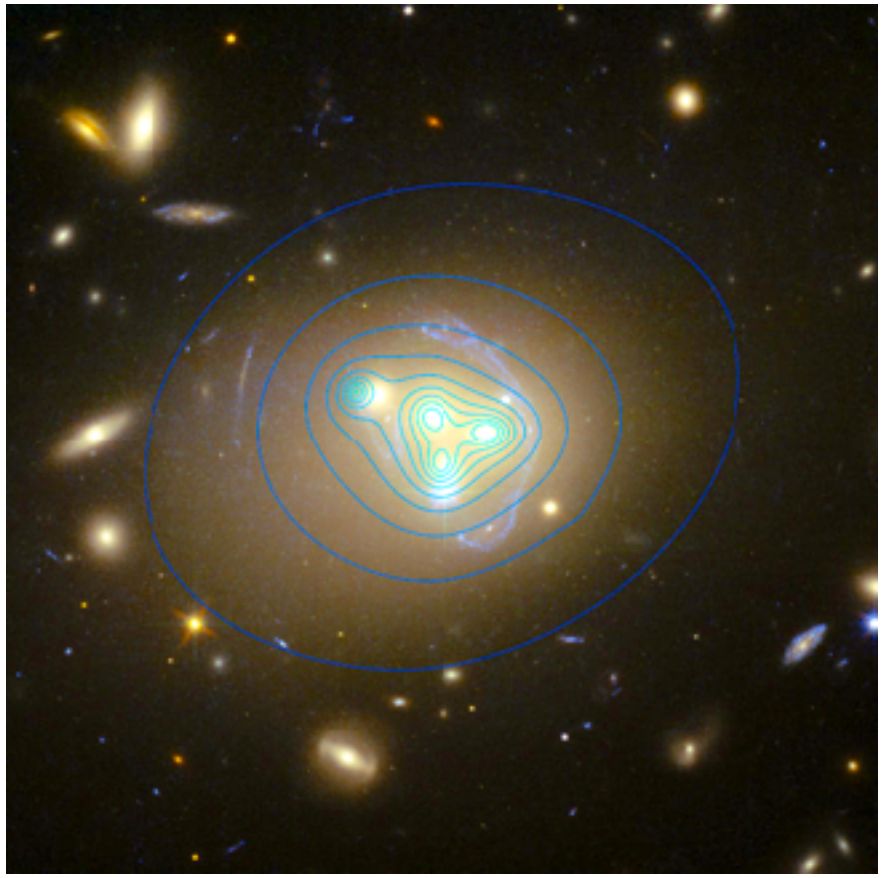

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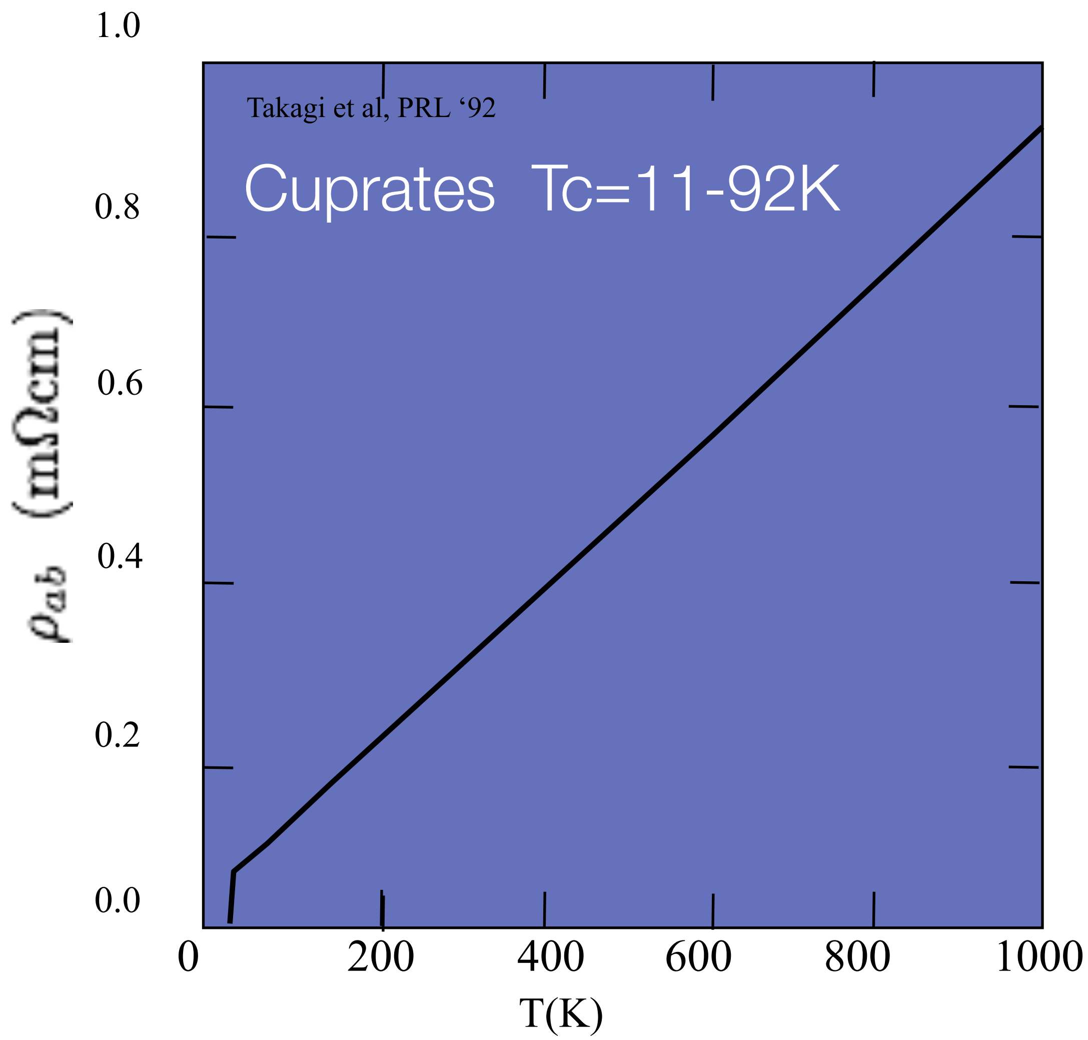
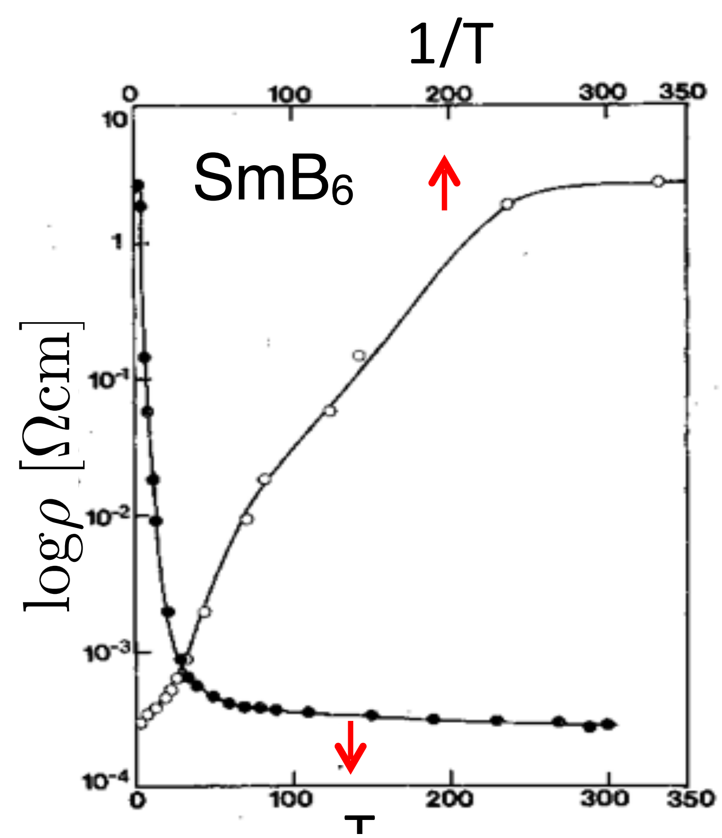


- Strange Insulator

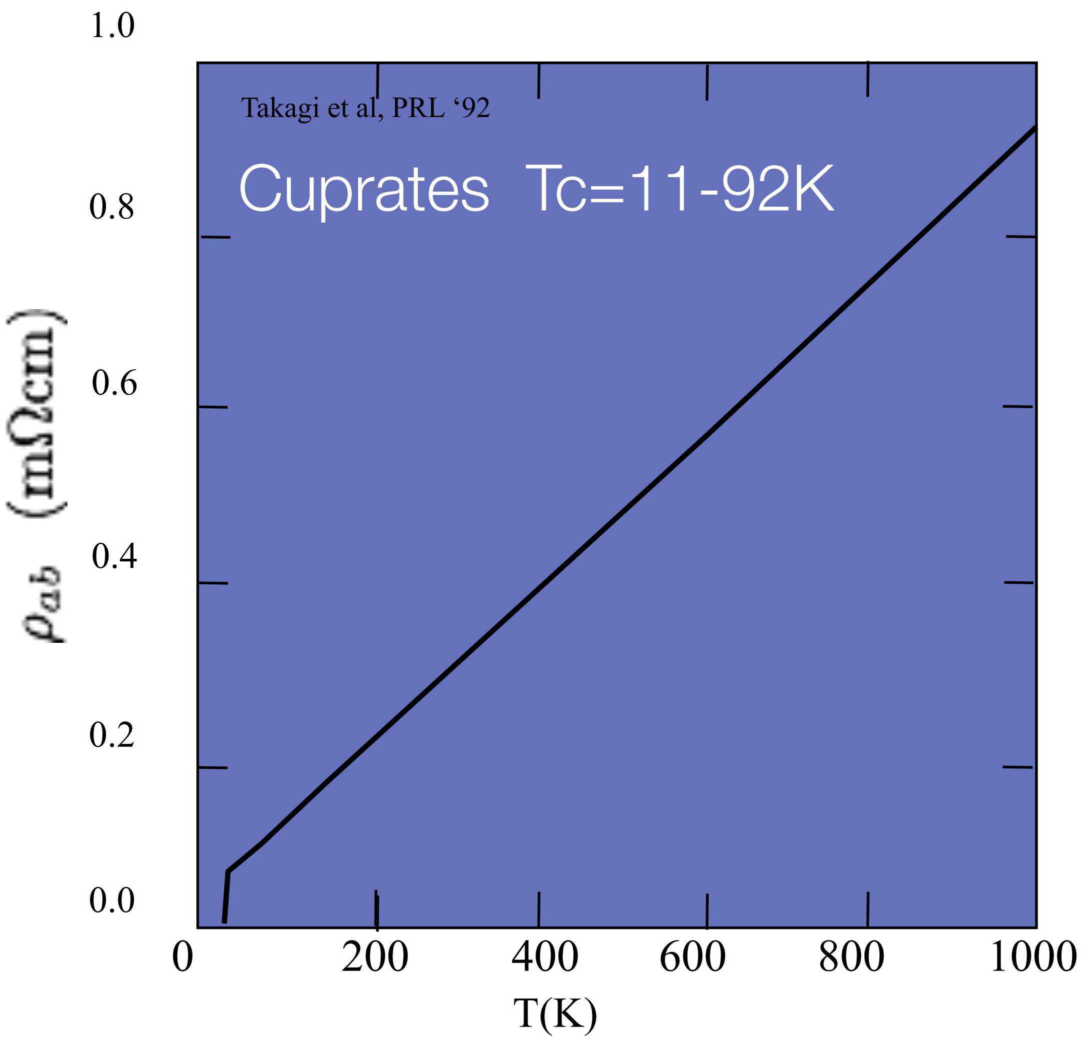


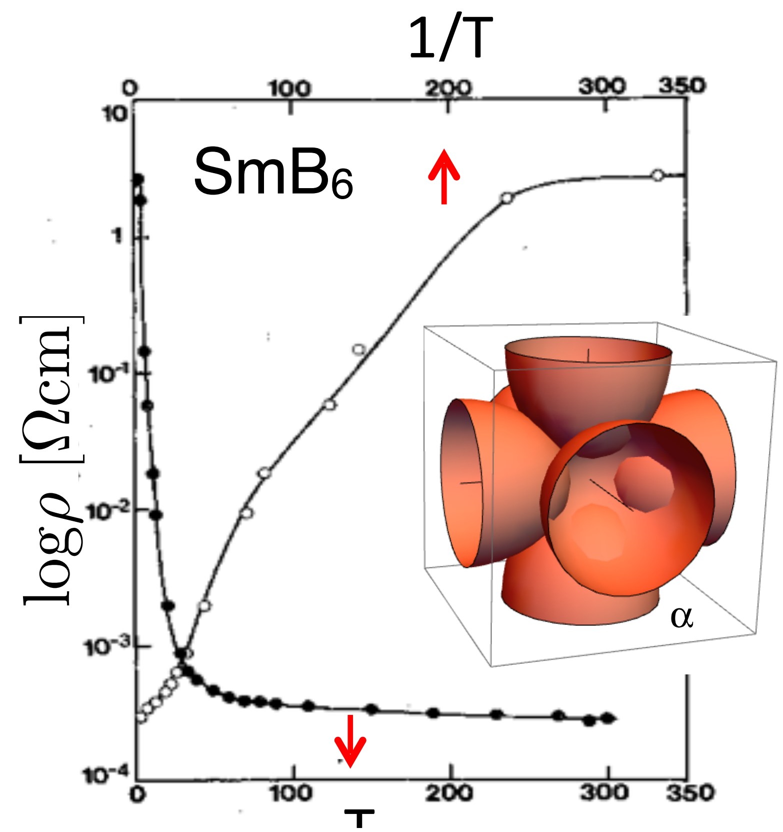
These, and many other examples suggest the potential for qualitatively new advances in our understanding of quantum matter.

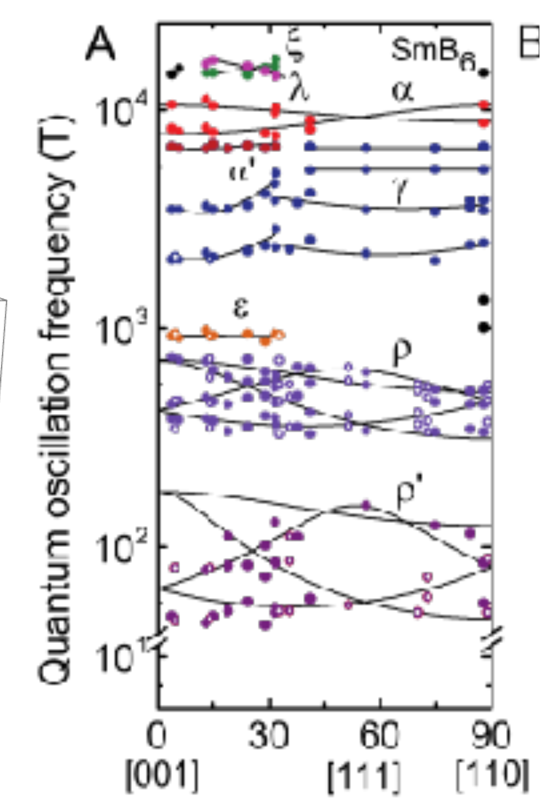
Dark Matter Challenges of the Solid State.

- Linear resistivity in strange metals
- Strange Insulator

Bulk Fermi Surface in a robust insulator ?







Tan *et al.* Science 349, 287 (2015)

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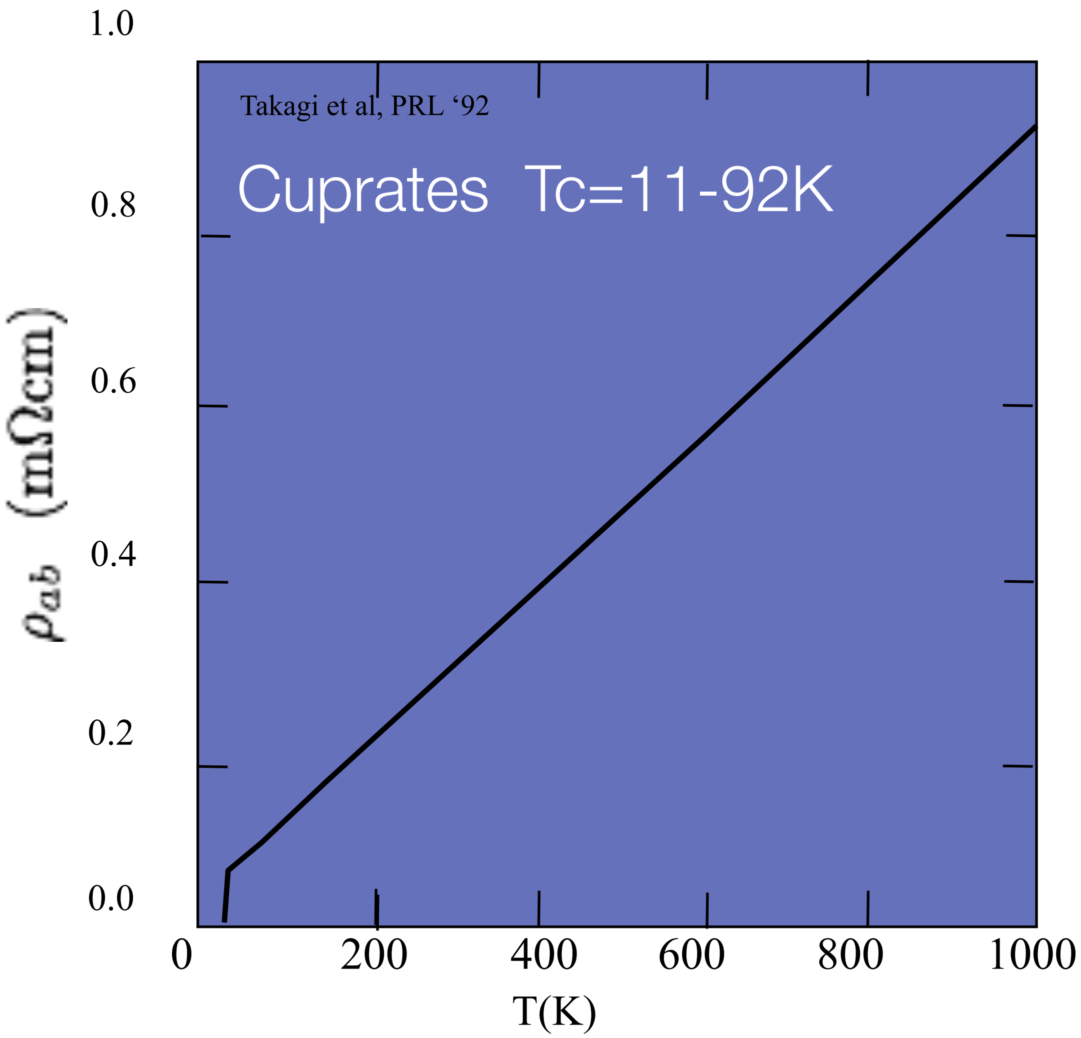

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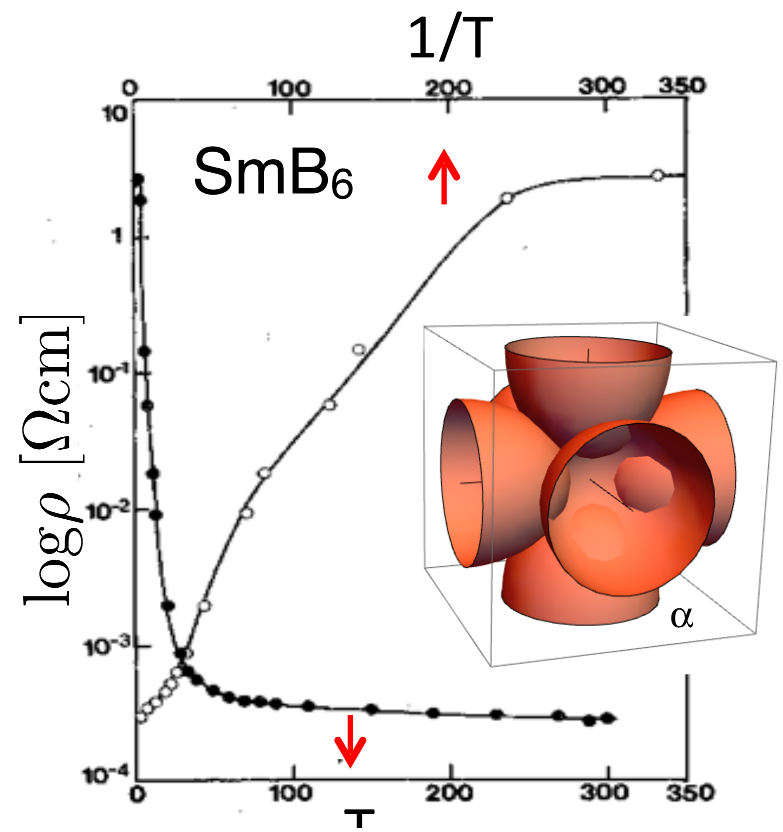

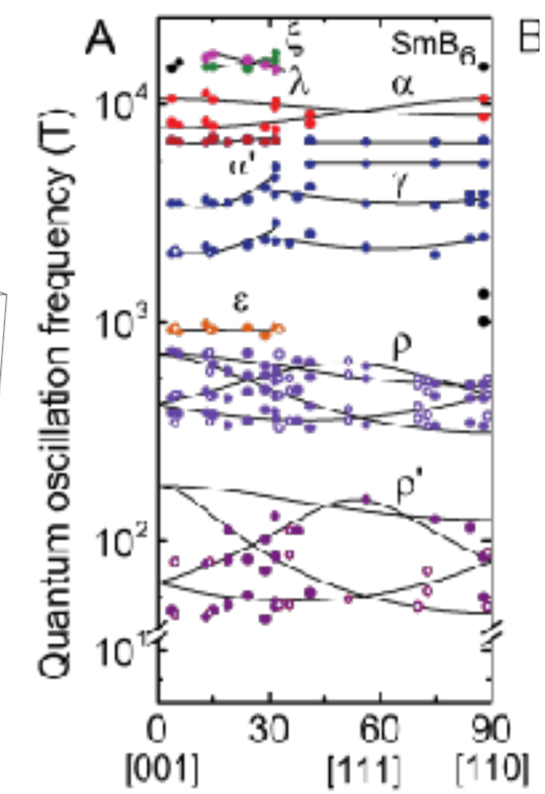

Tan *et al.* Science 349, 287 (2015)

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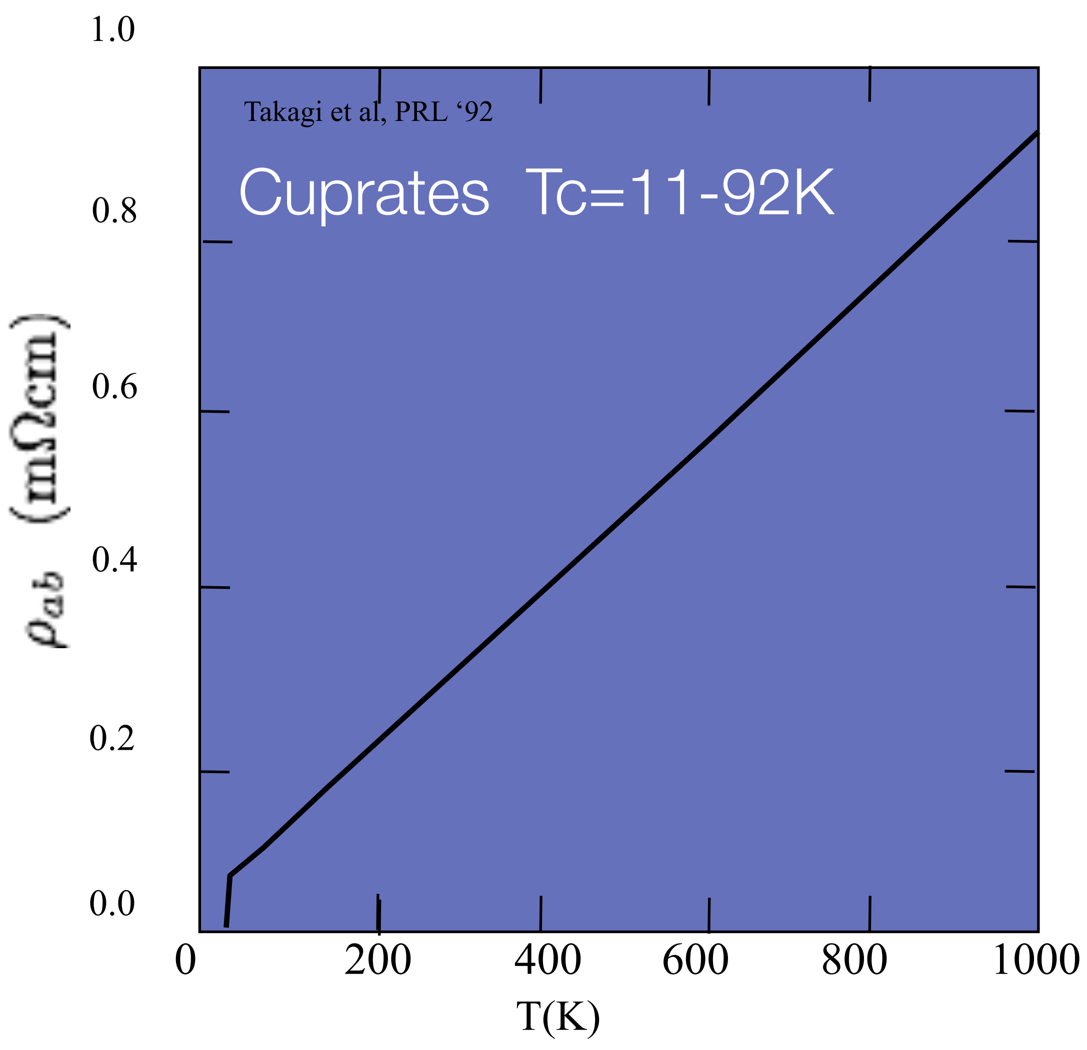

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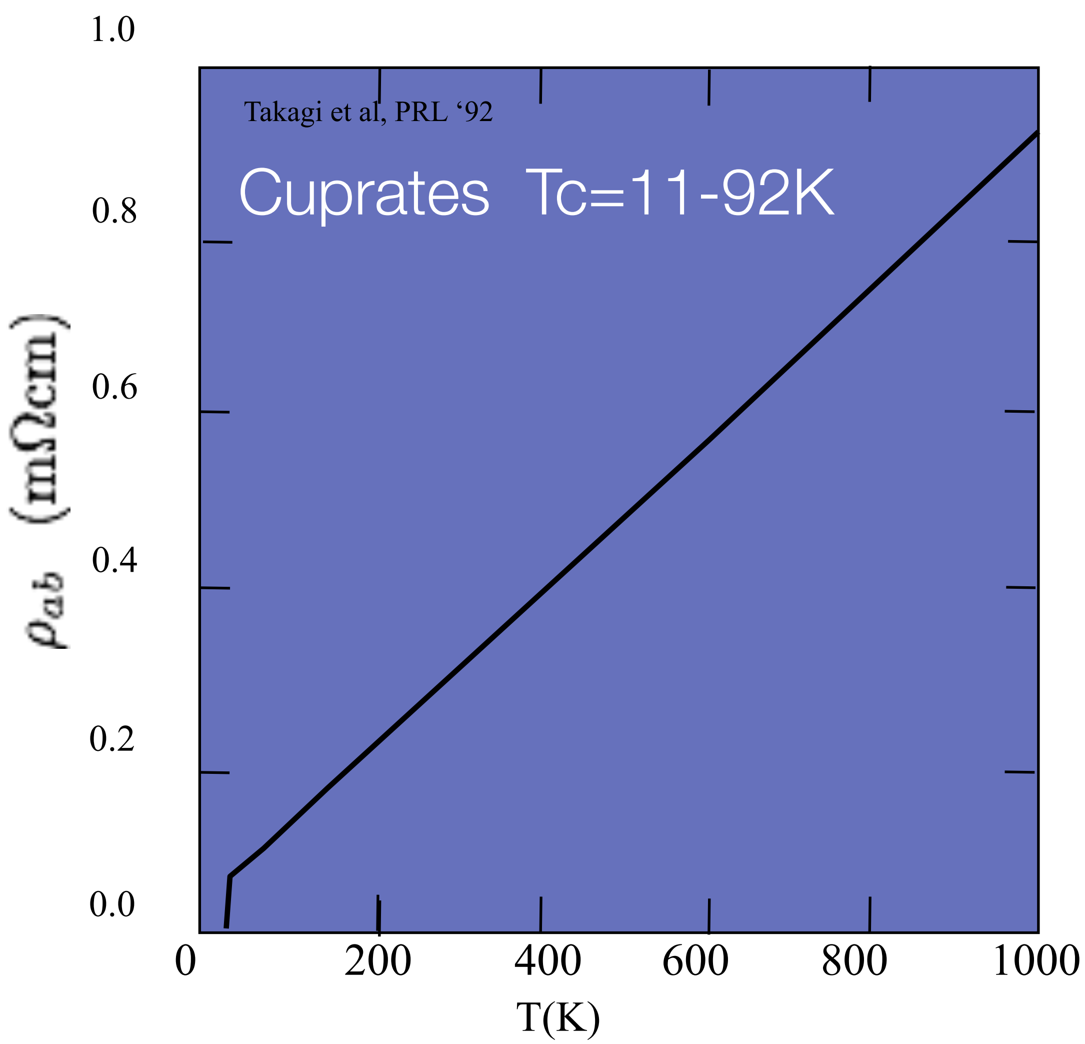

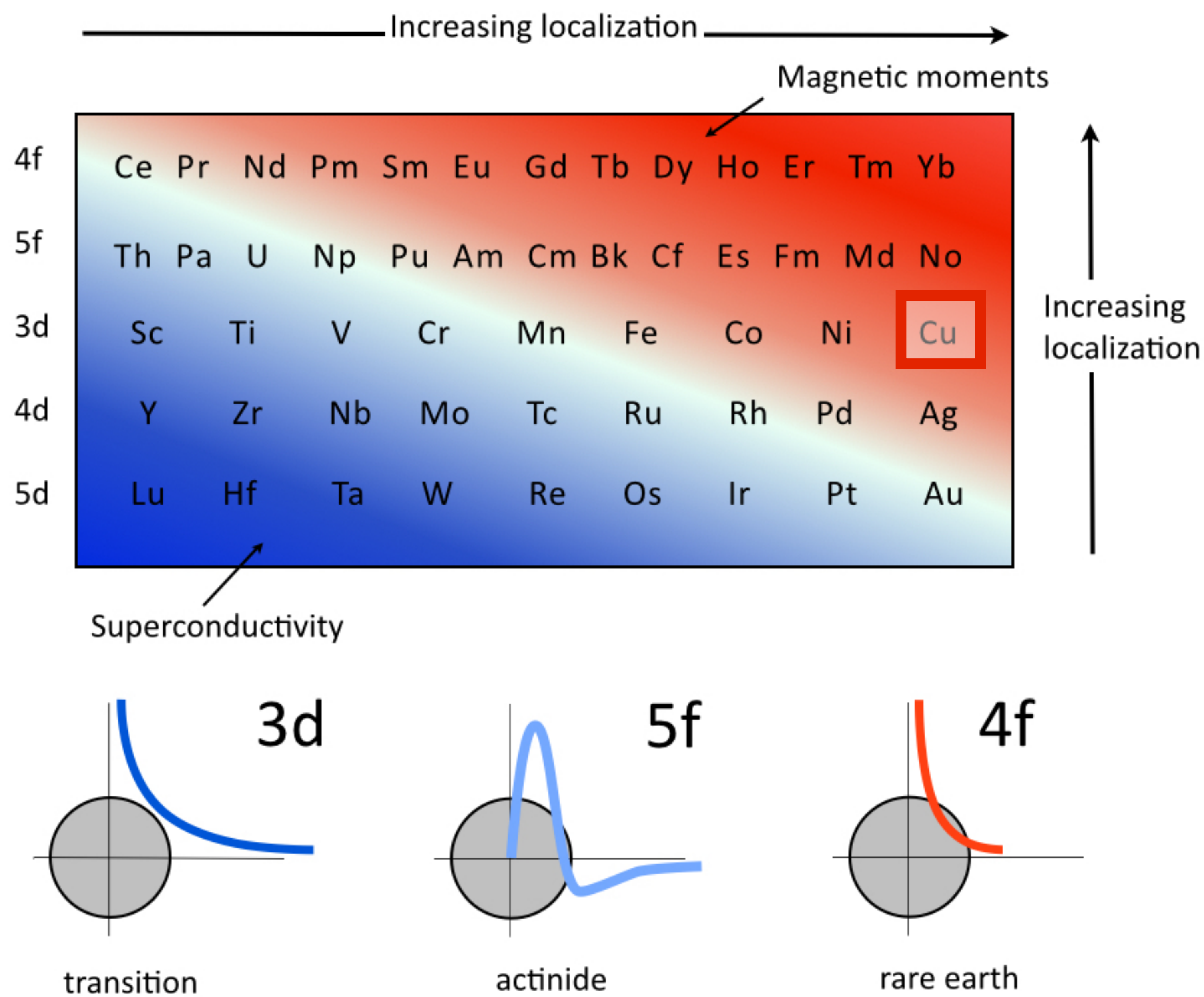

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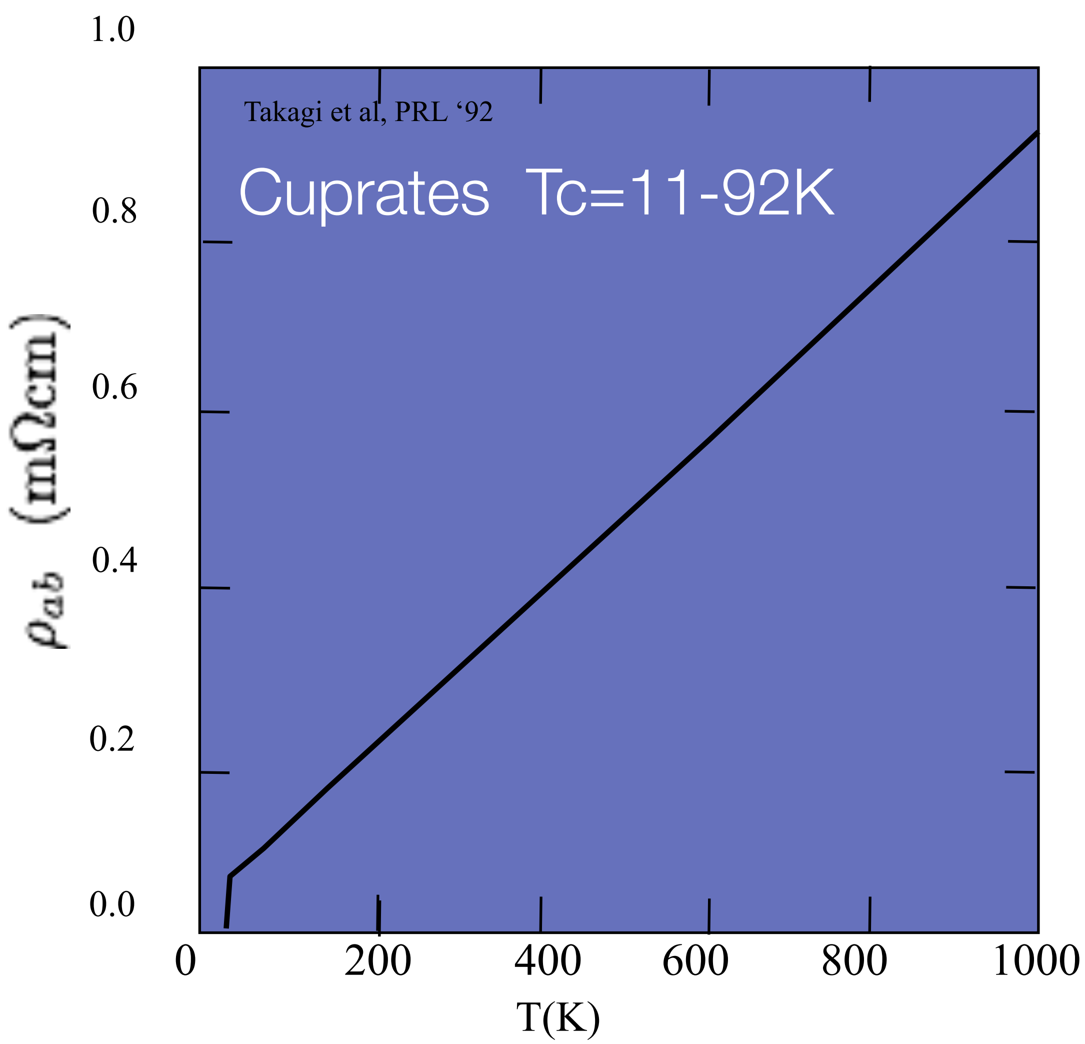

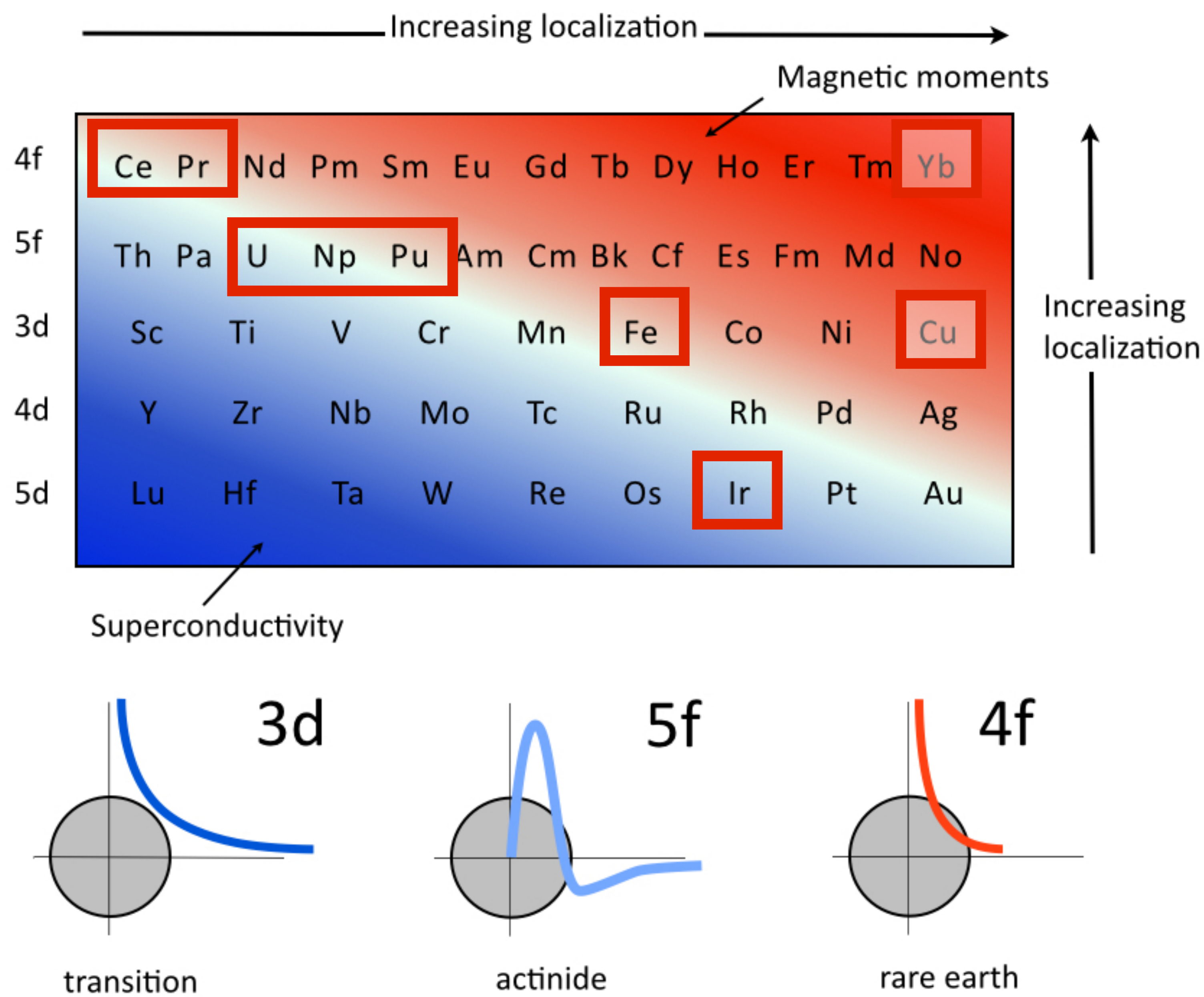

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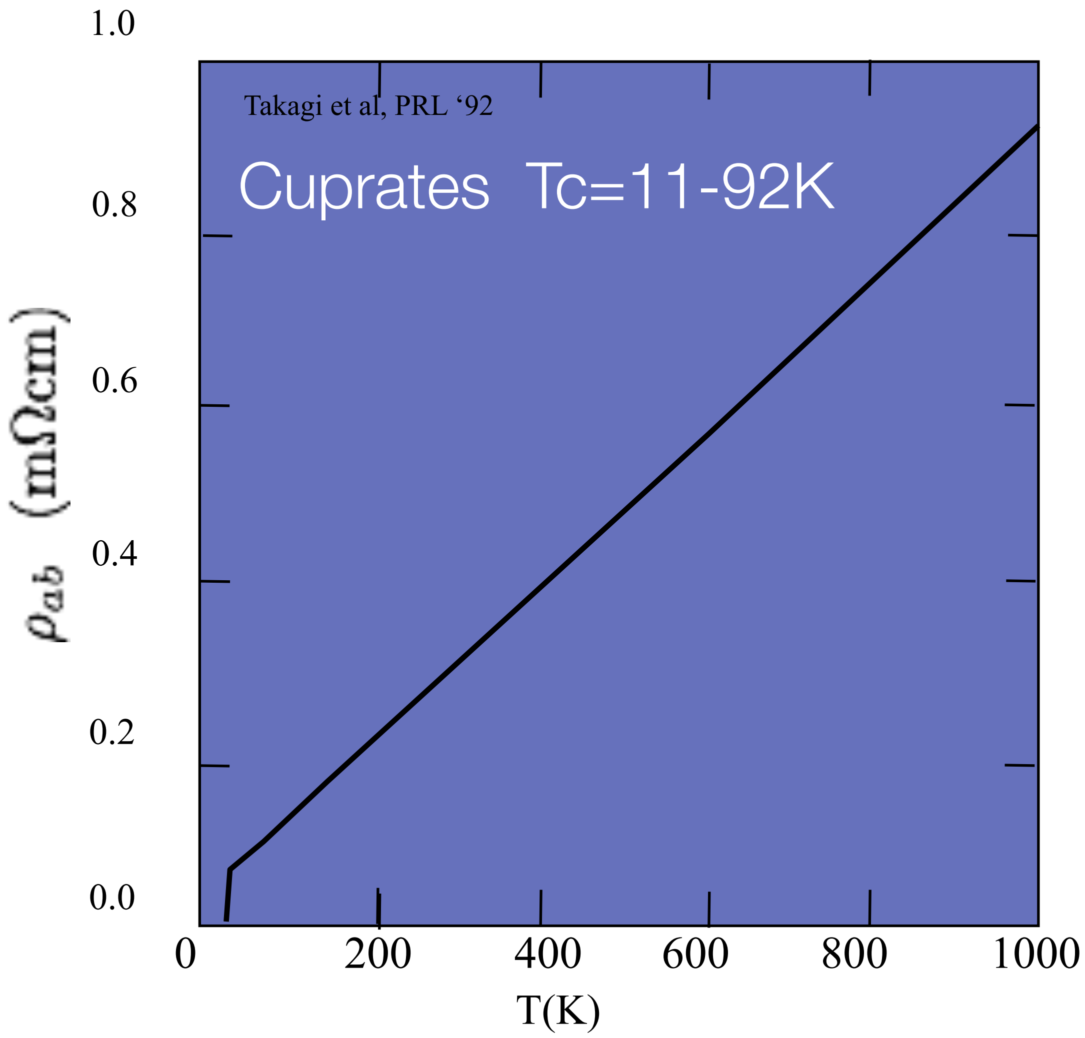

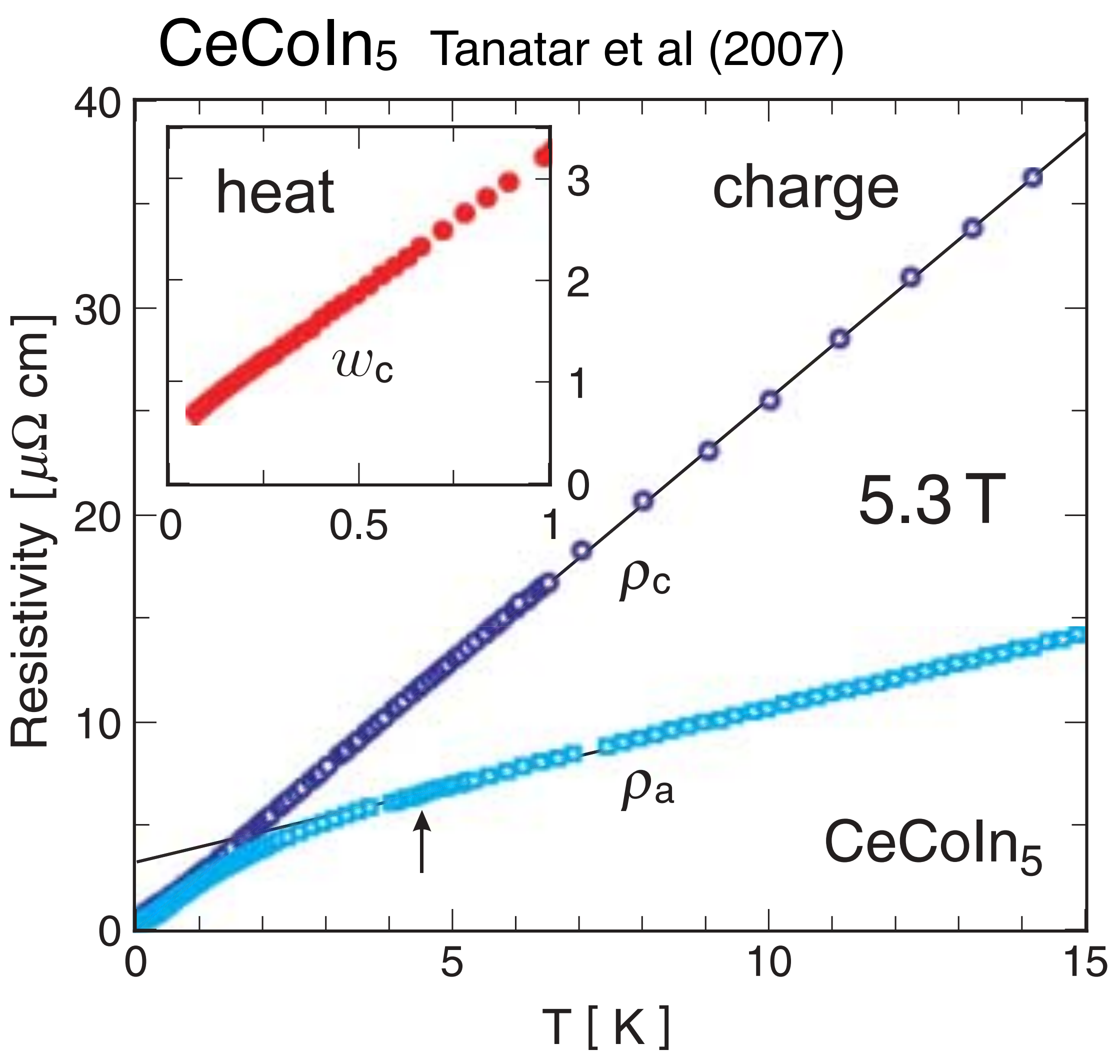

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- Linear resistivity in strange metals
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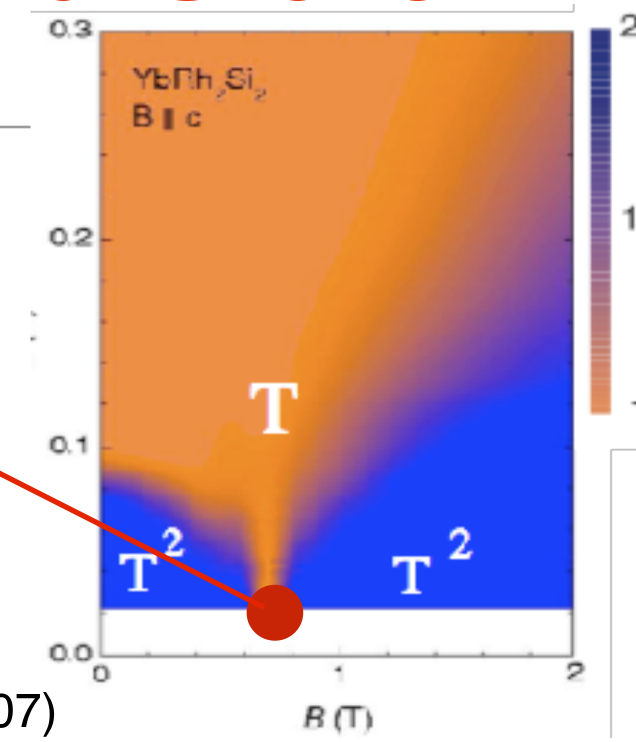
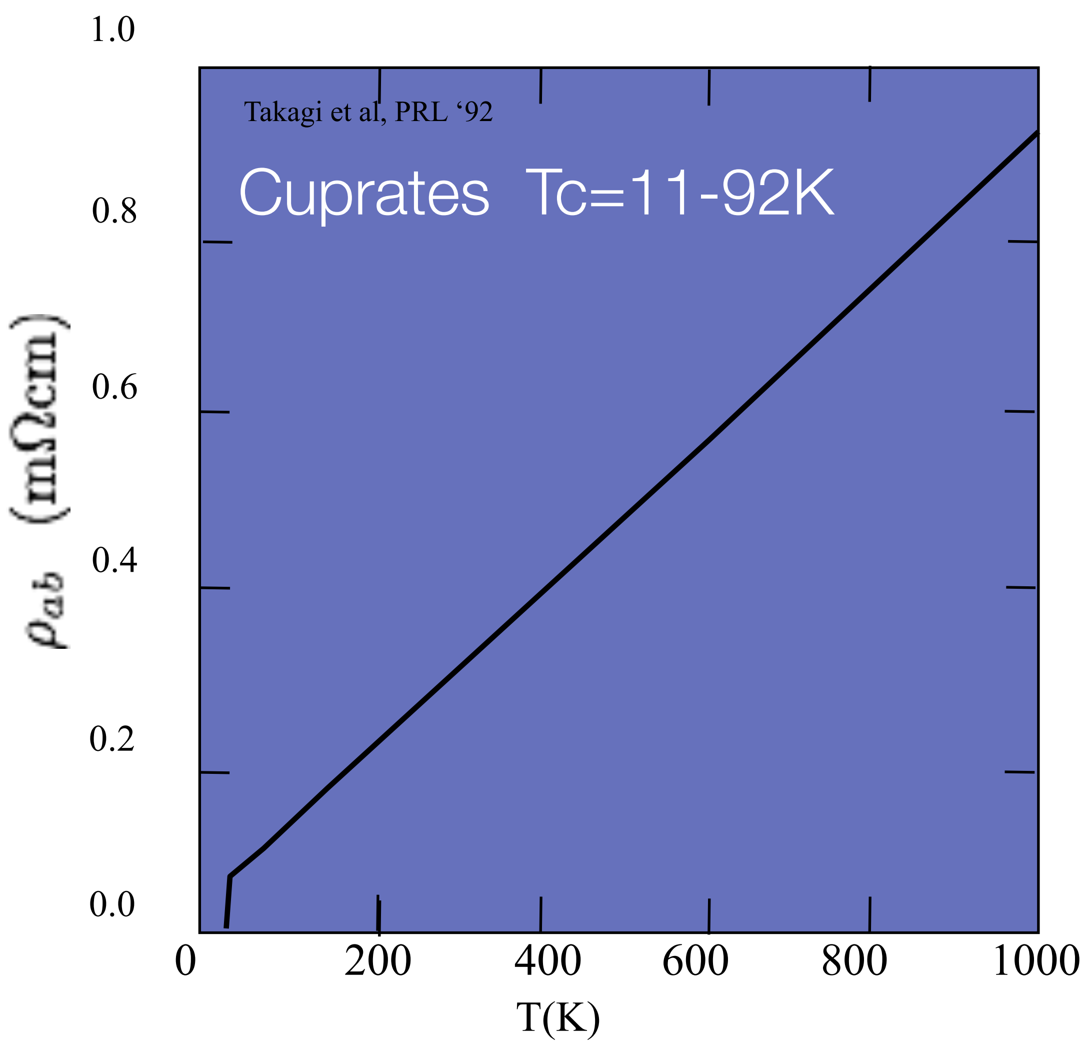
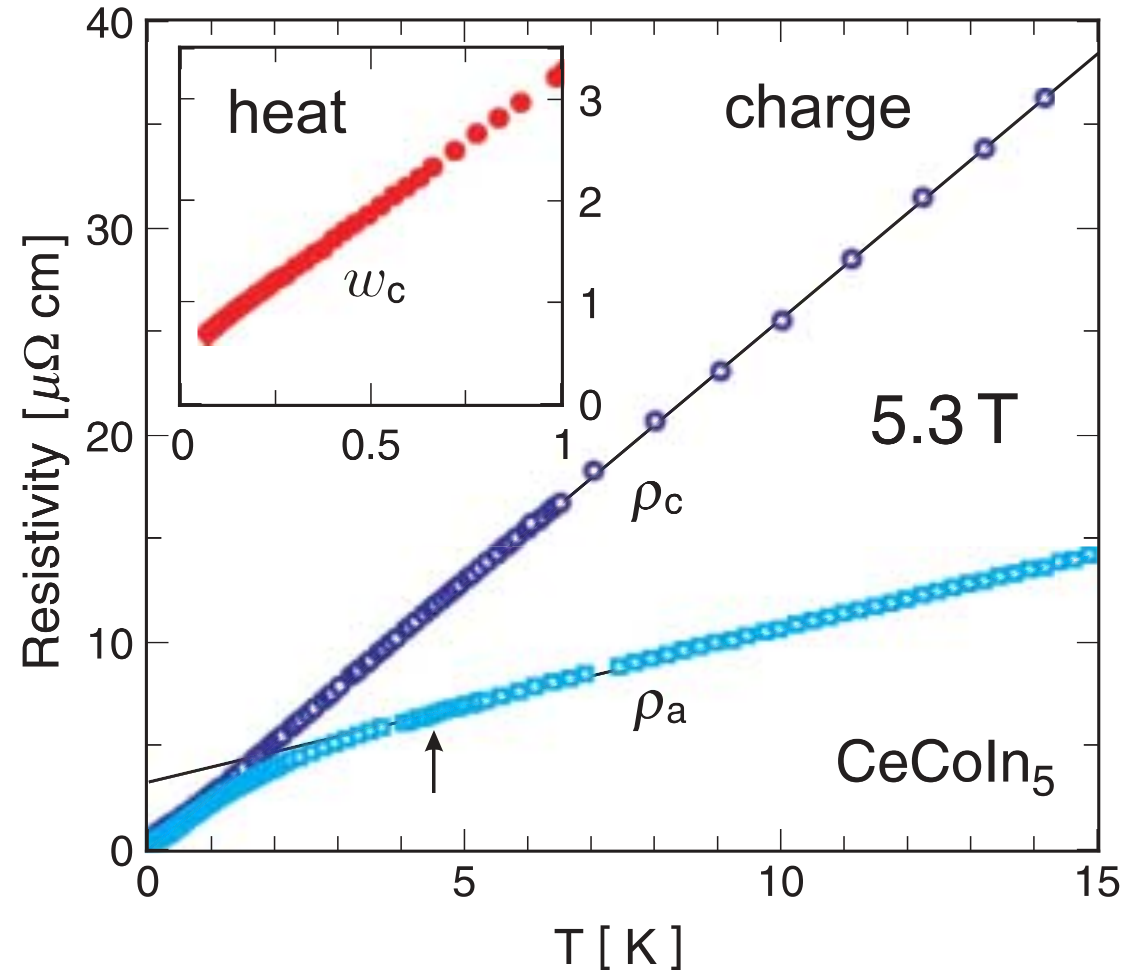




$CeCoIn_5$ Tanatar et al (2007)



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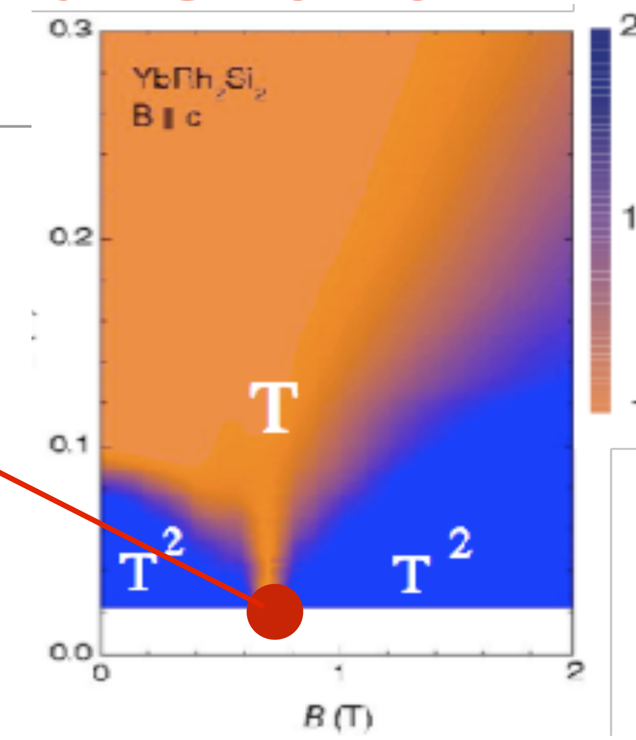

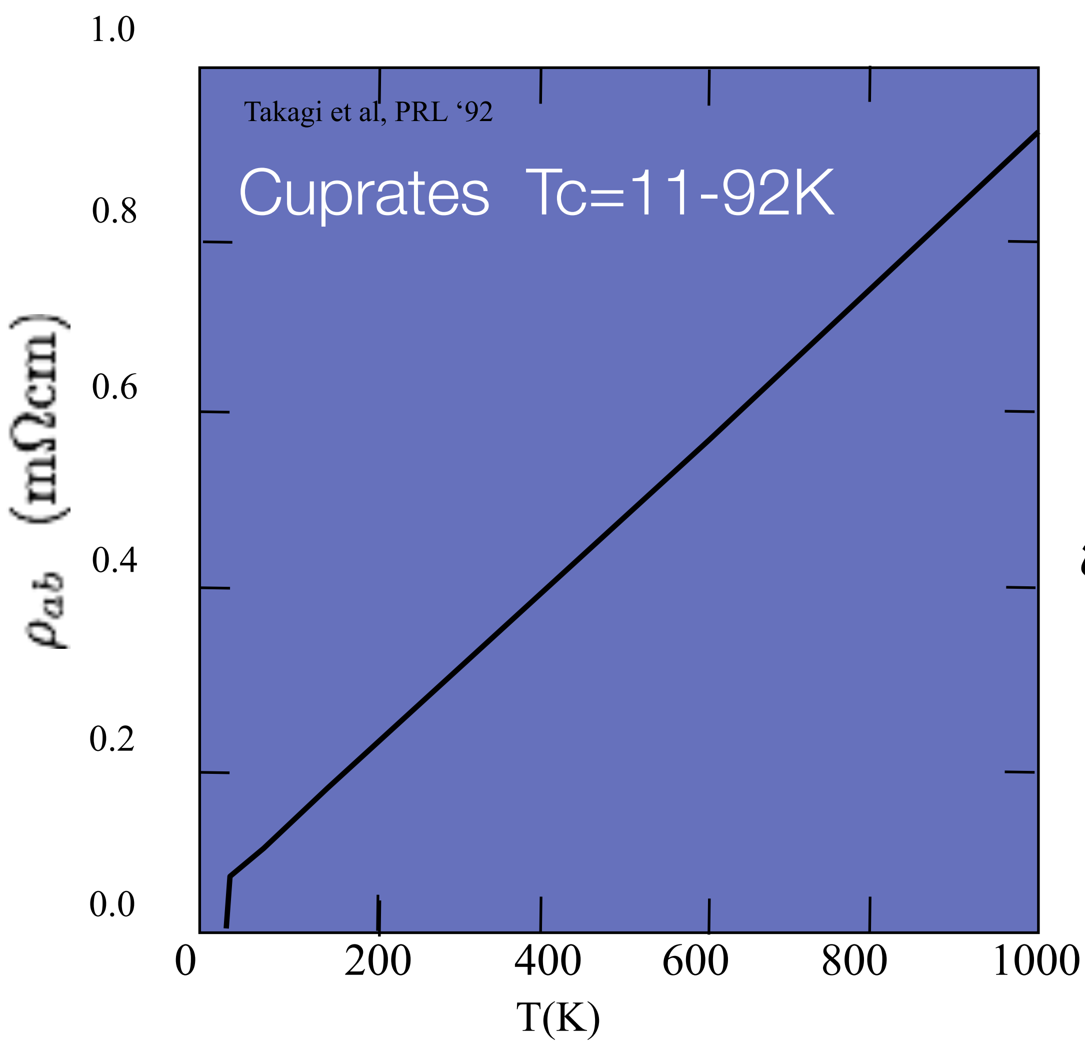

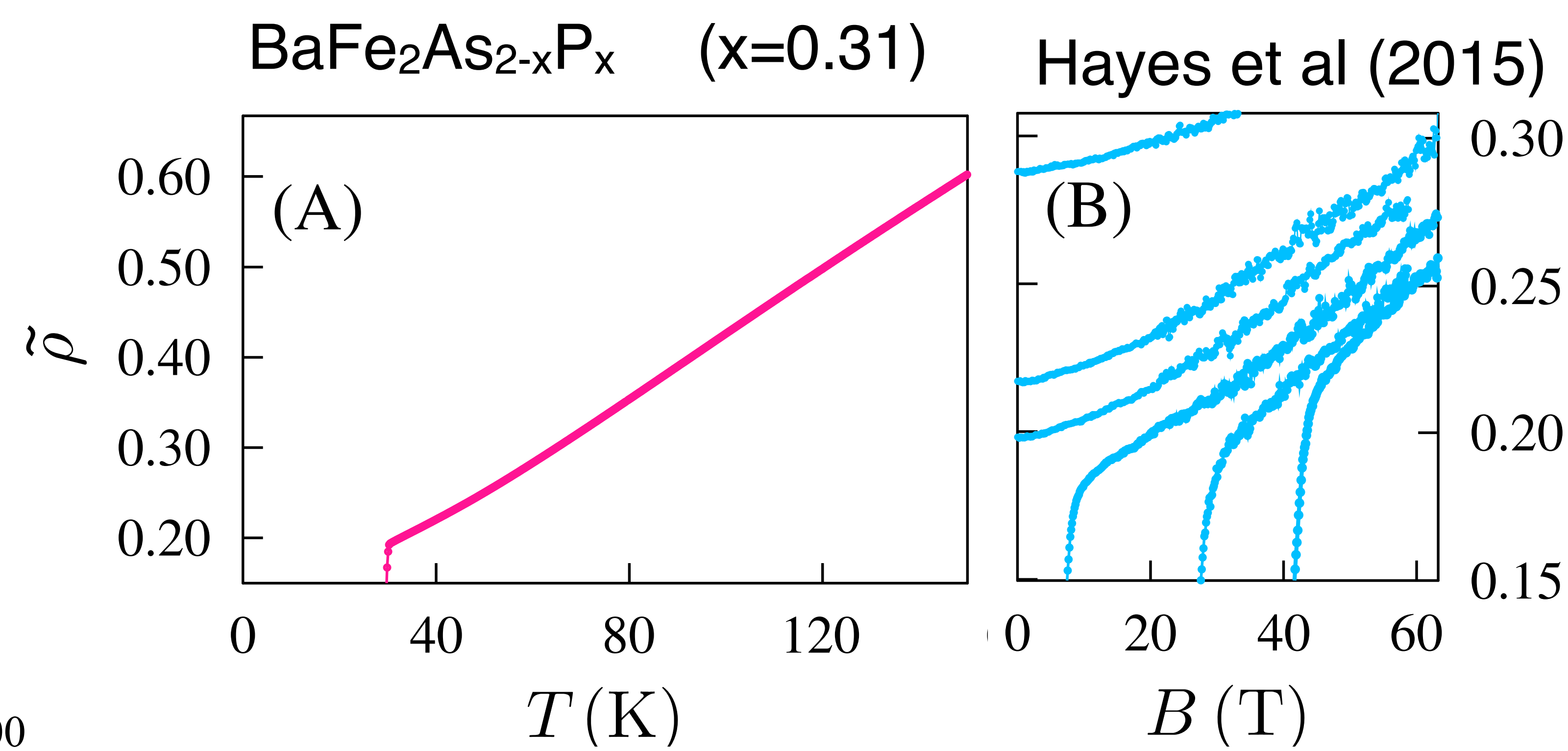

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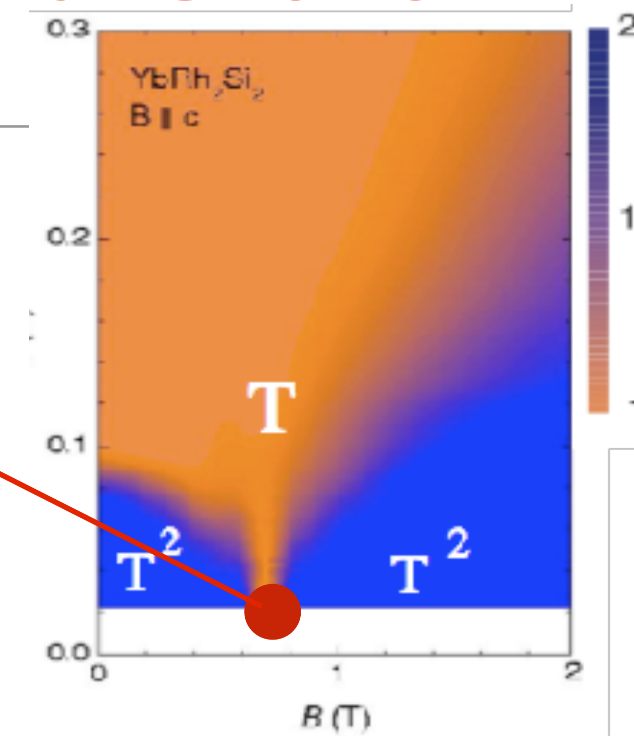
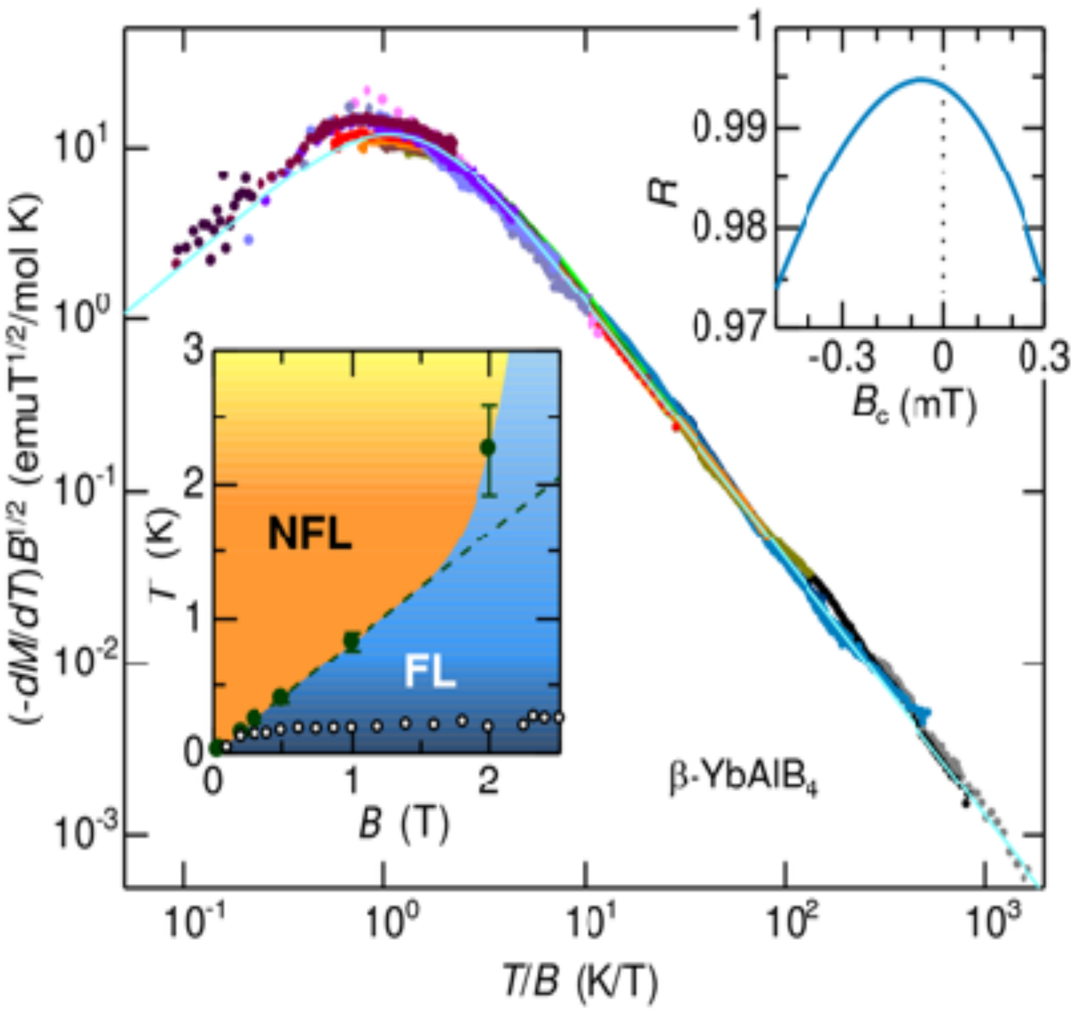
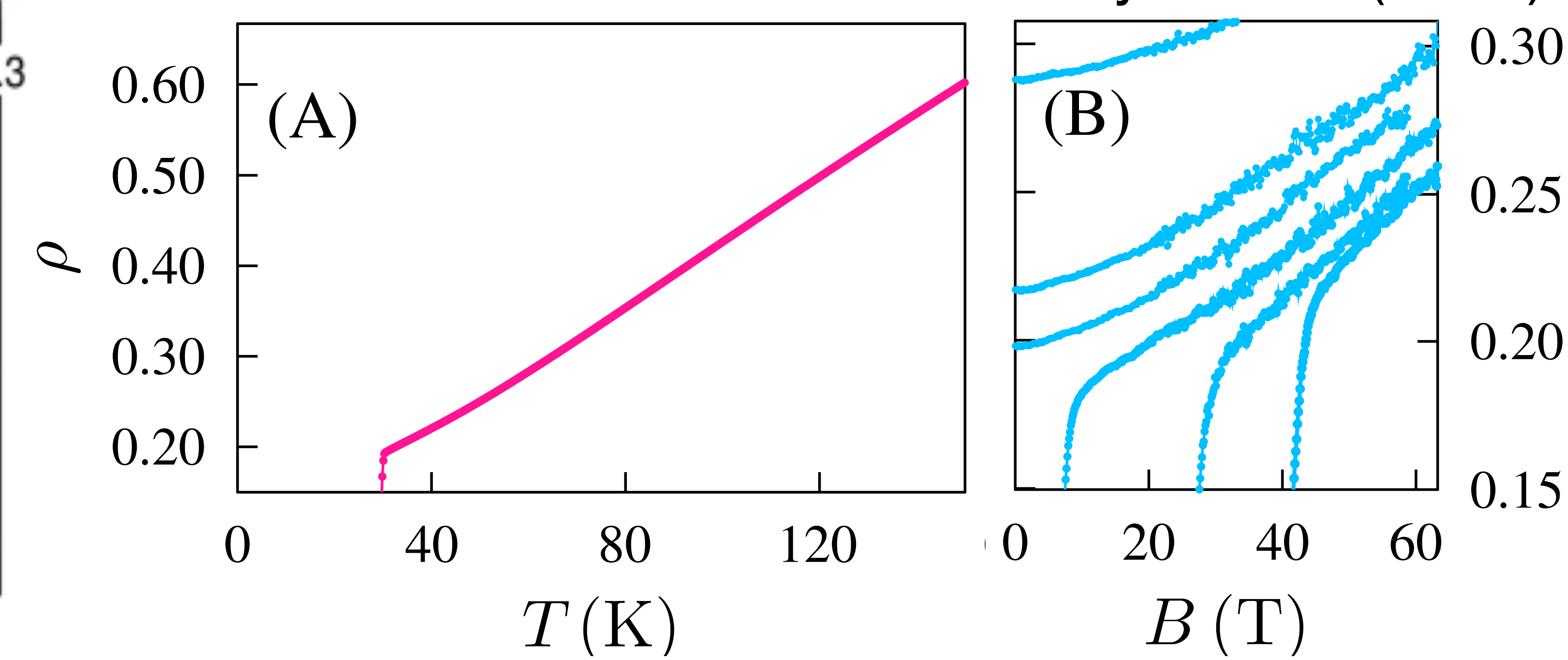




$BaFe_2As_{2-x}P_x$ (x=0.31)

Hayes et al (2015)



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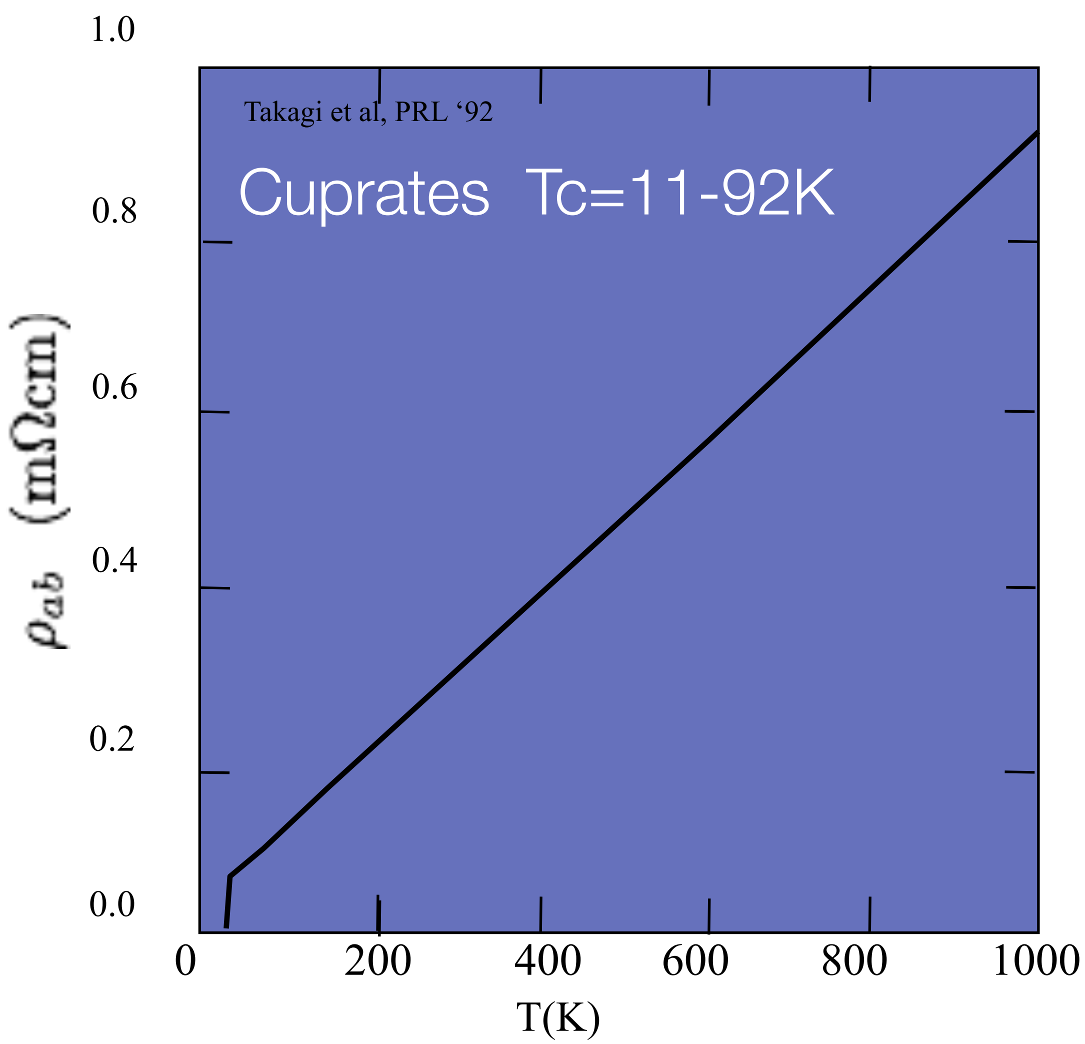

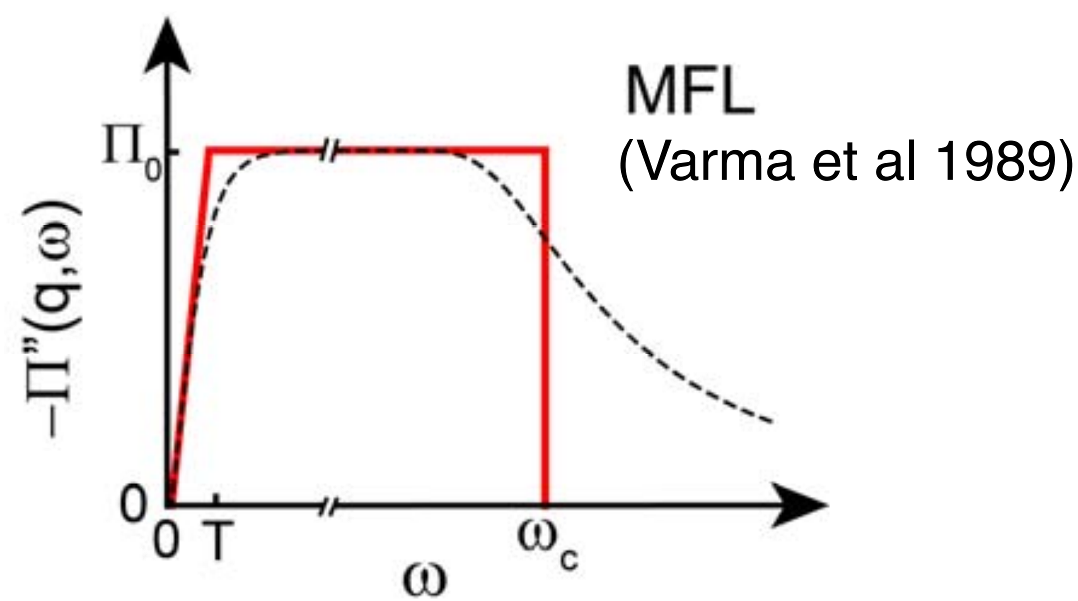

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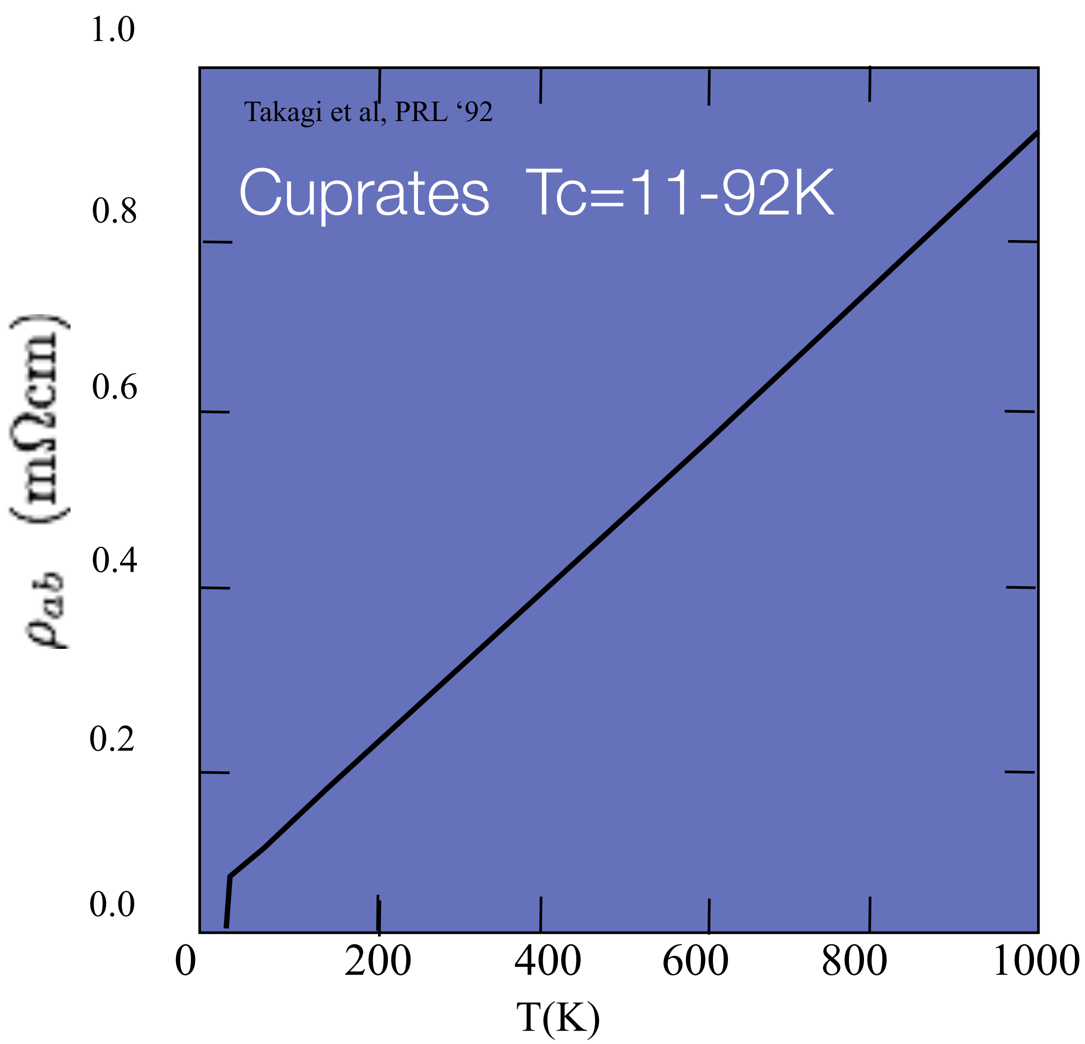
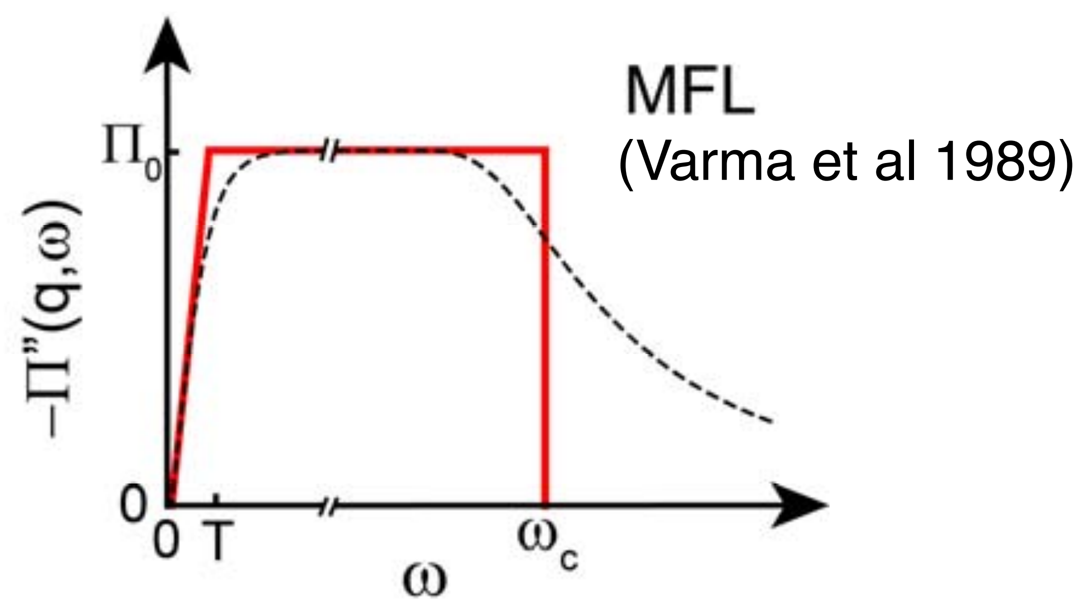
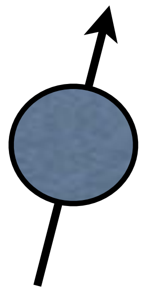




Unidentified (local) critical scattering.

Abbamonte: EELS

Kondo effect: Iconic example of Entanglement



$\xi = v_F / T_K$

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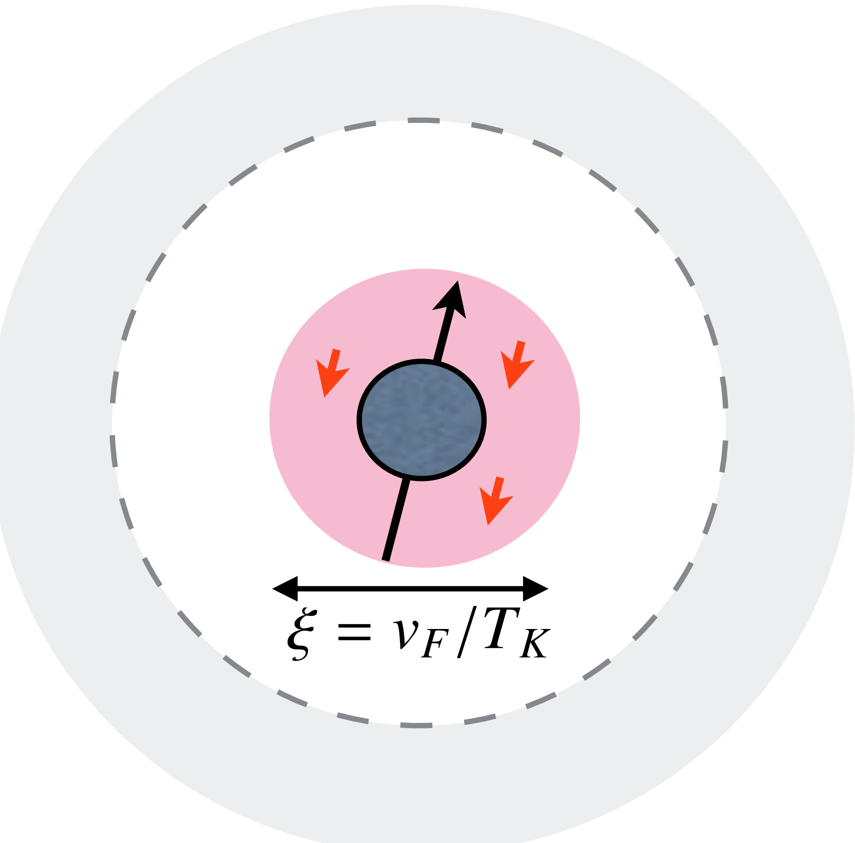

Spin screened by conduction electrons: entangled

$\uparrow \downarrow - \downarrow \uparrow$

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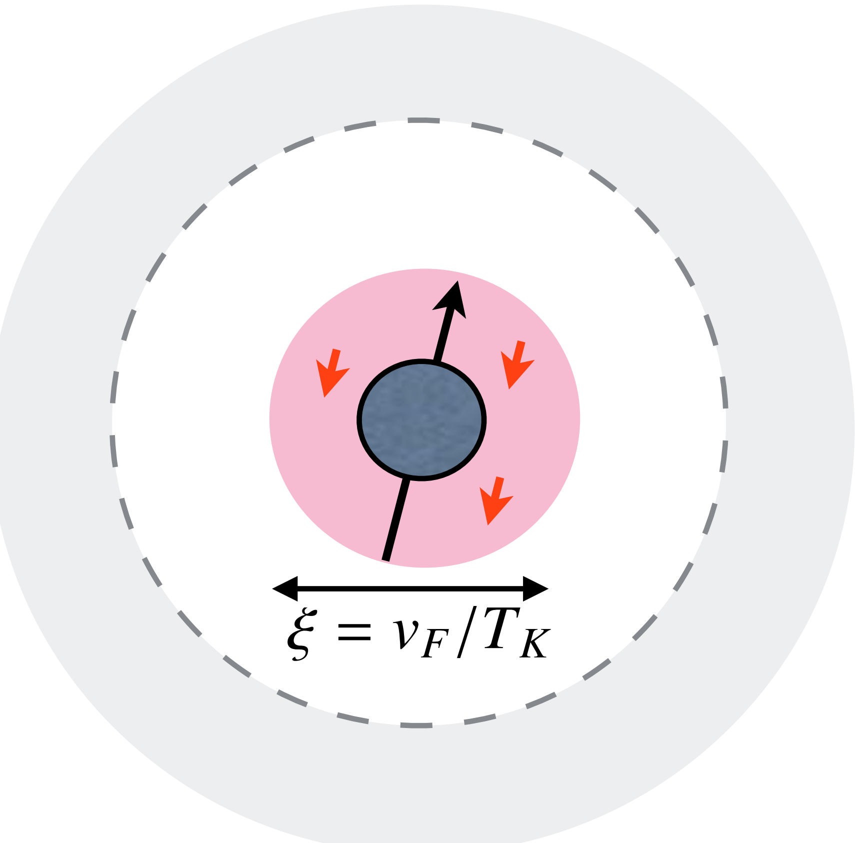

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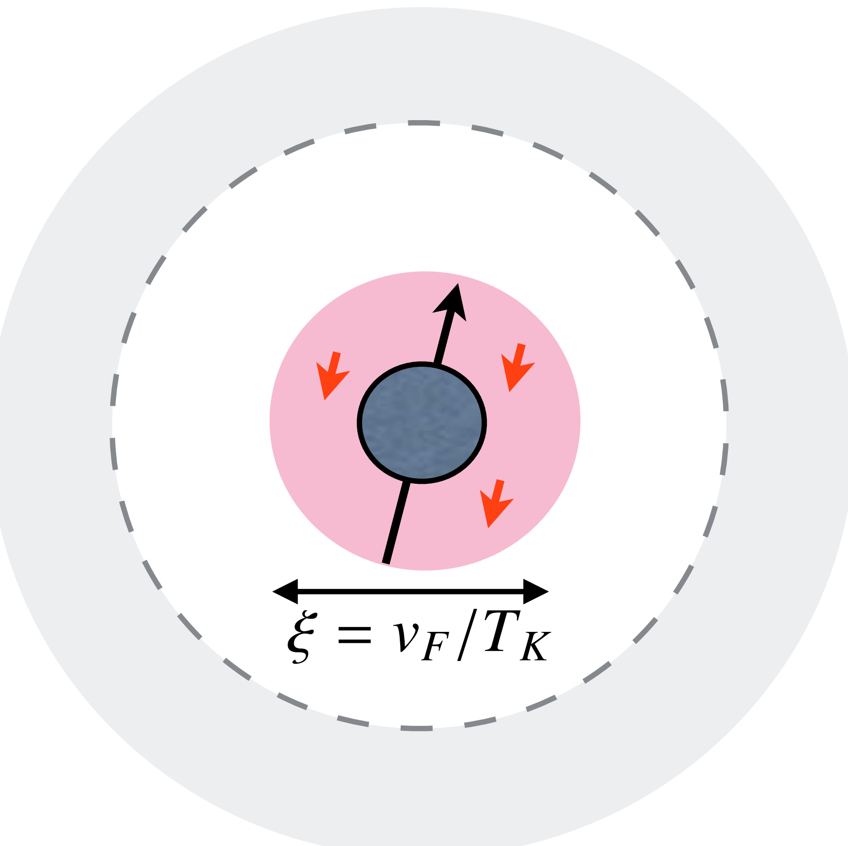

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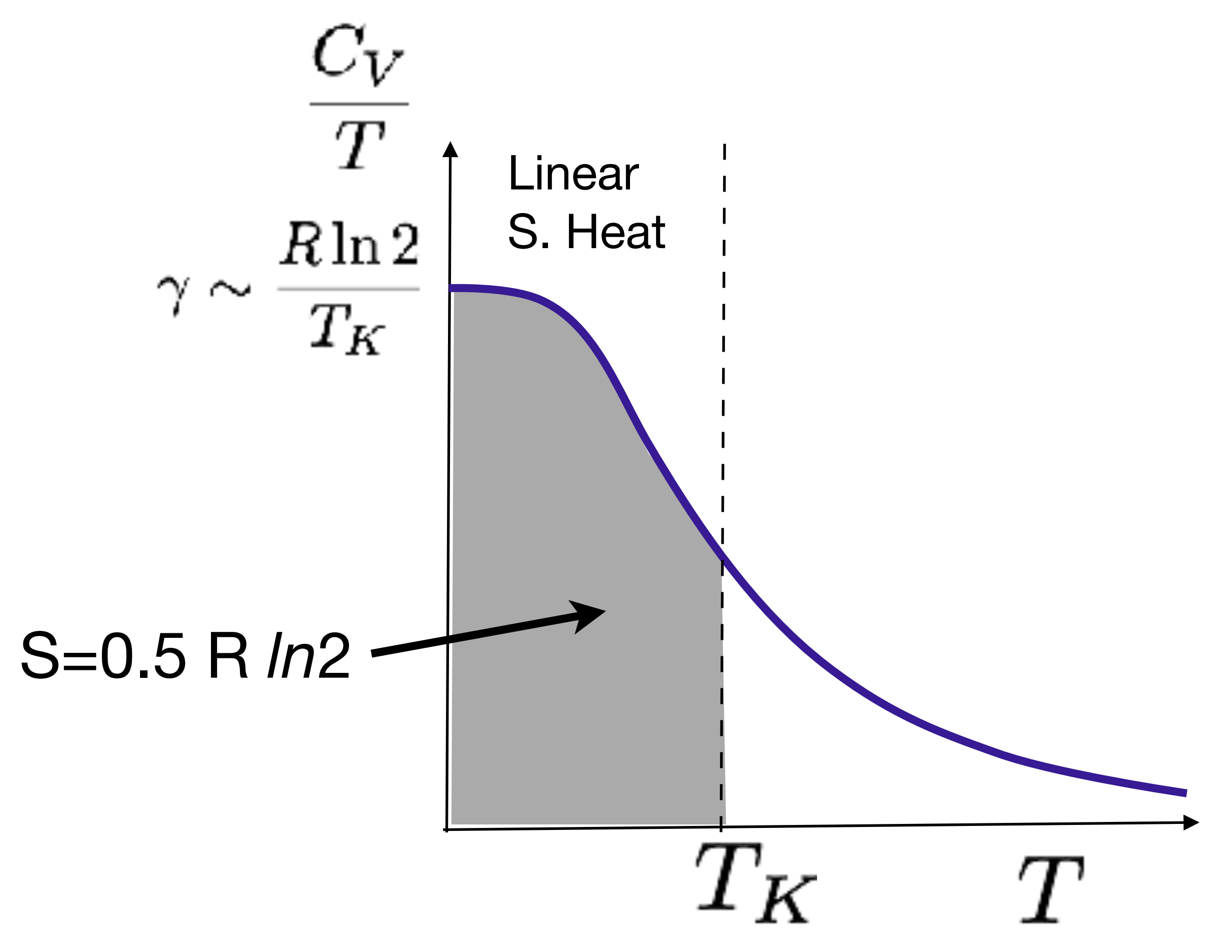
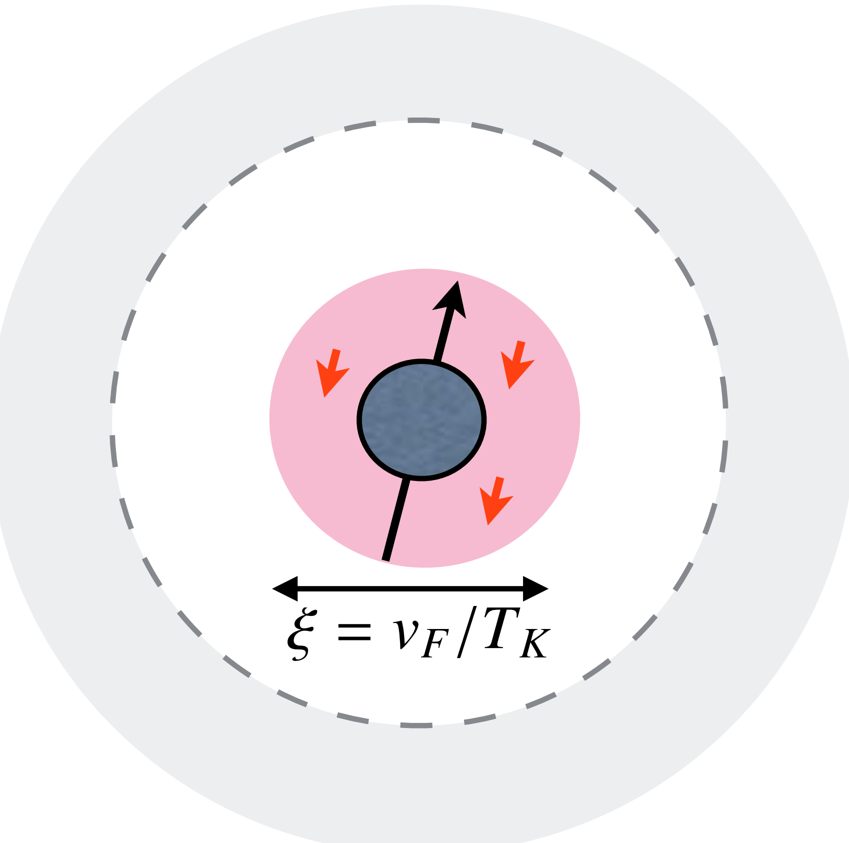


Kondo effect: l



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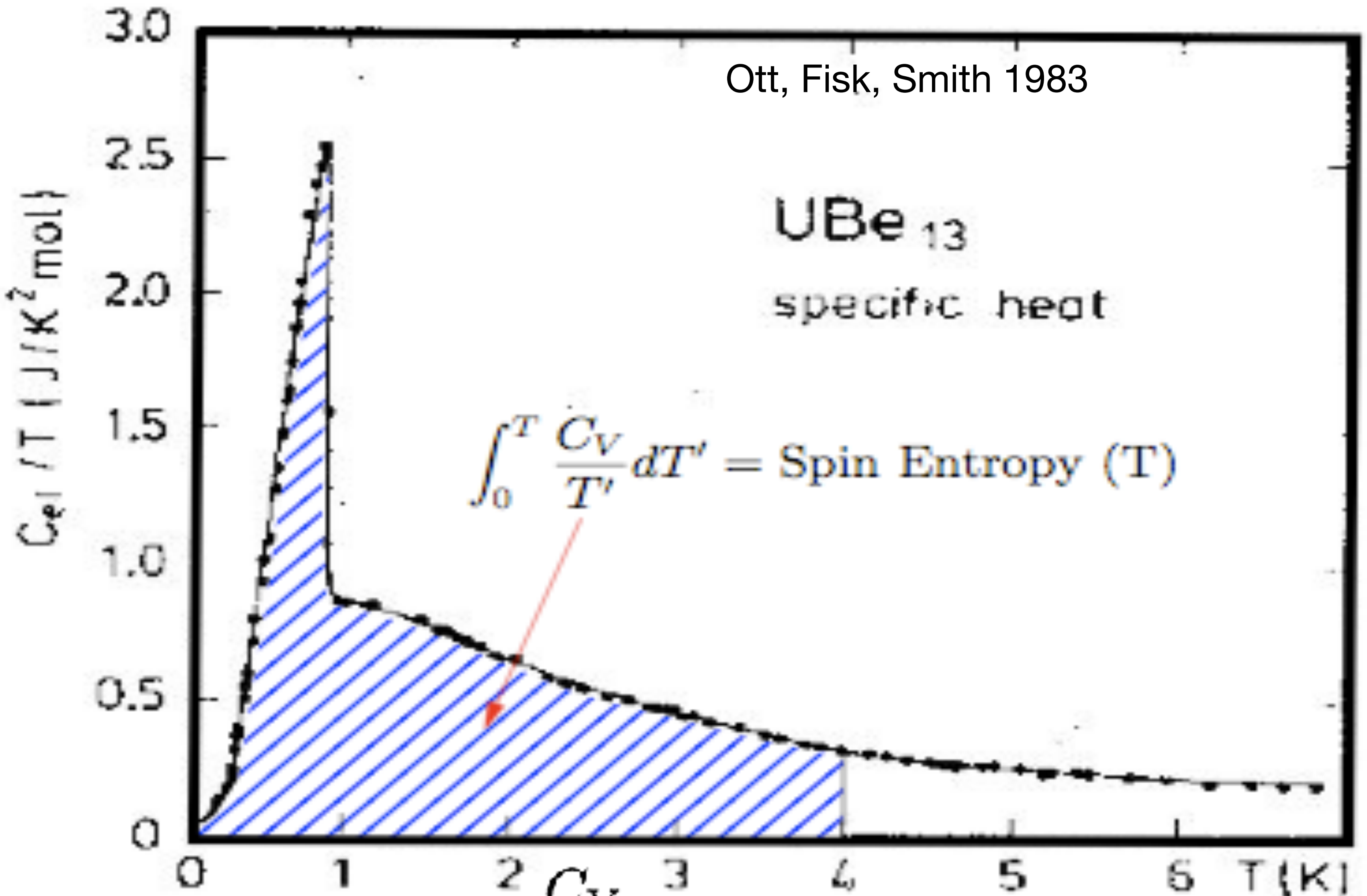

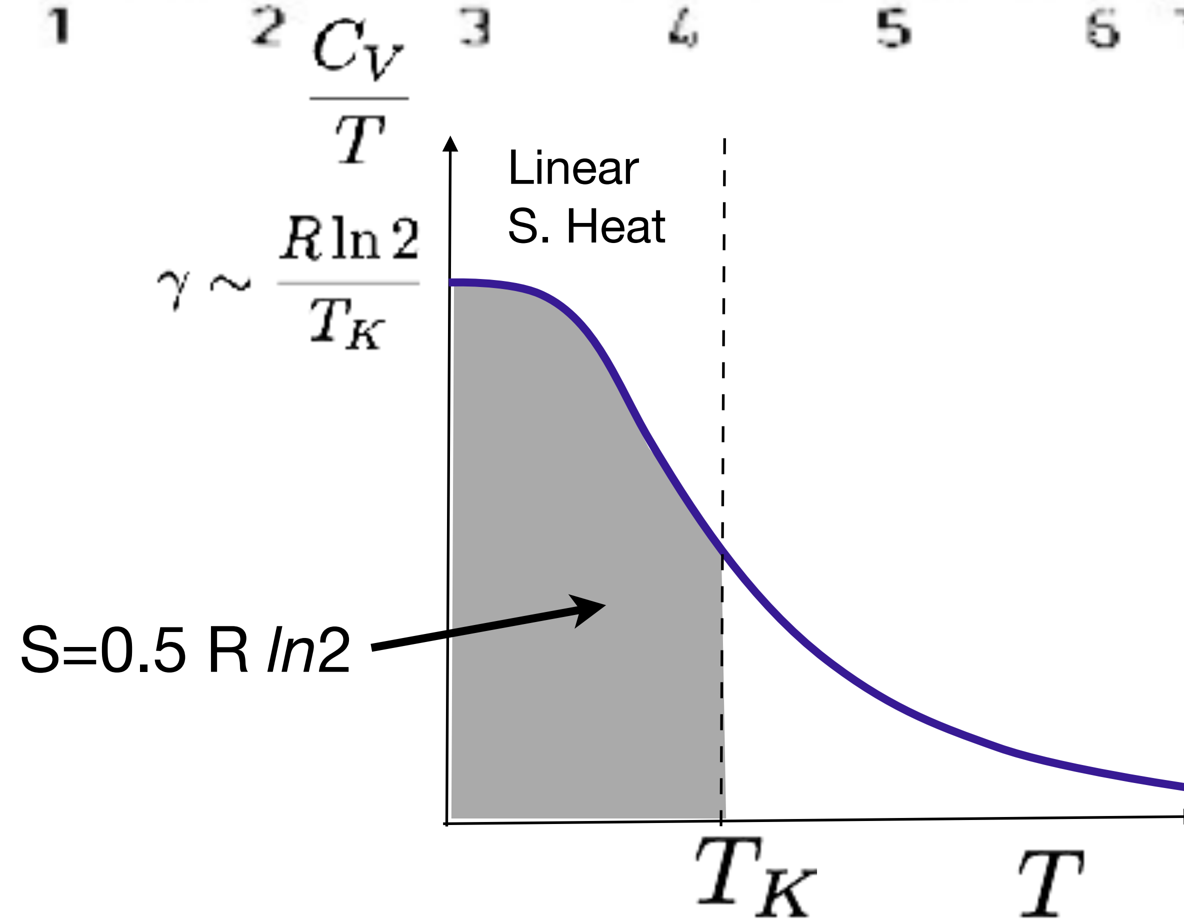

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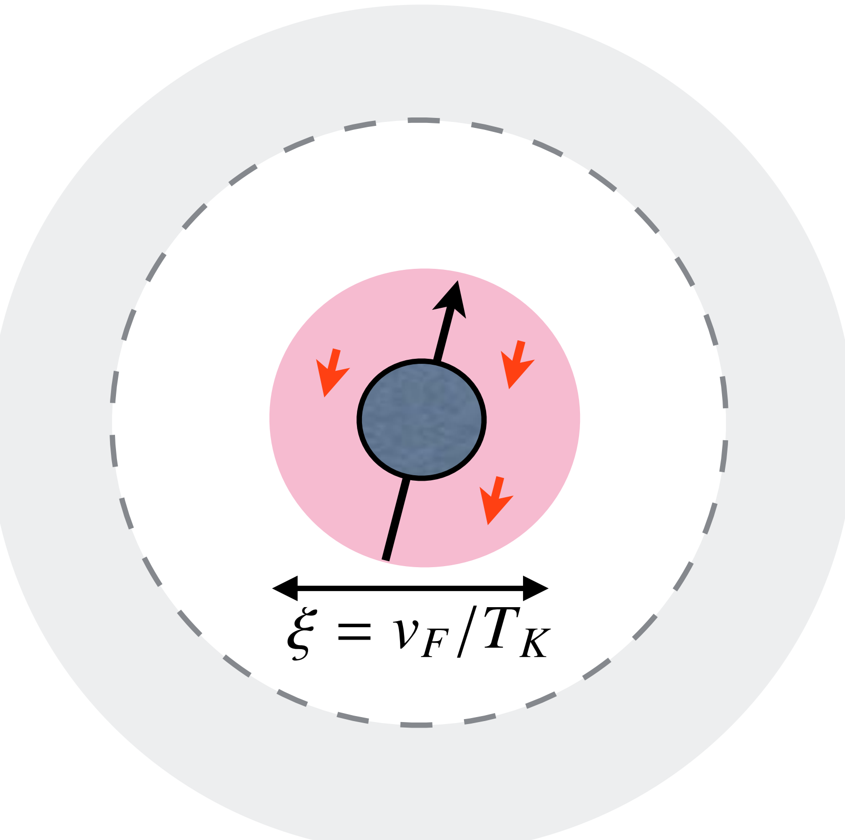

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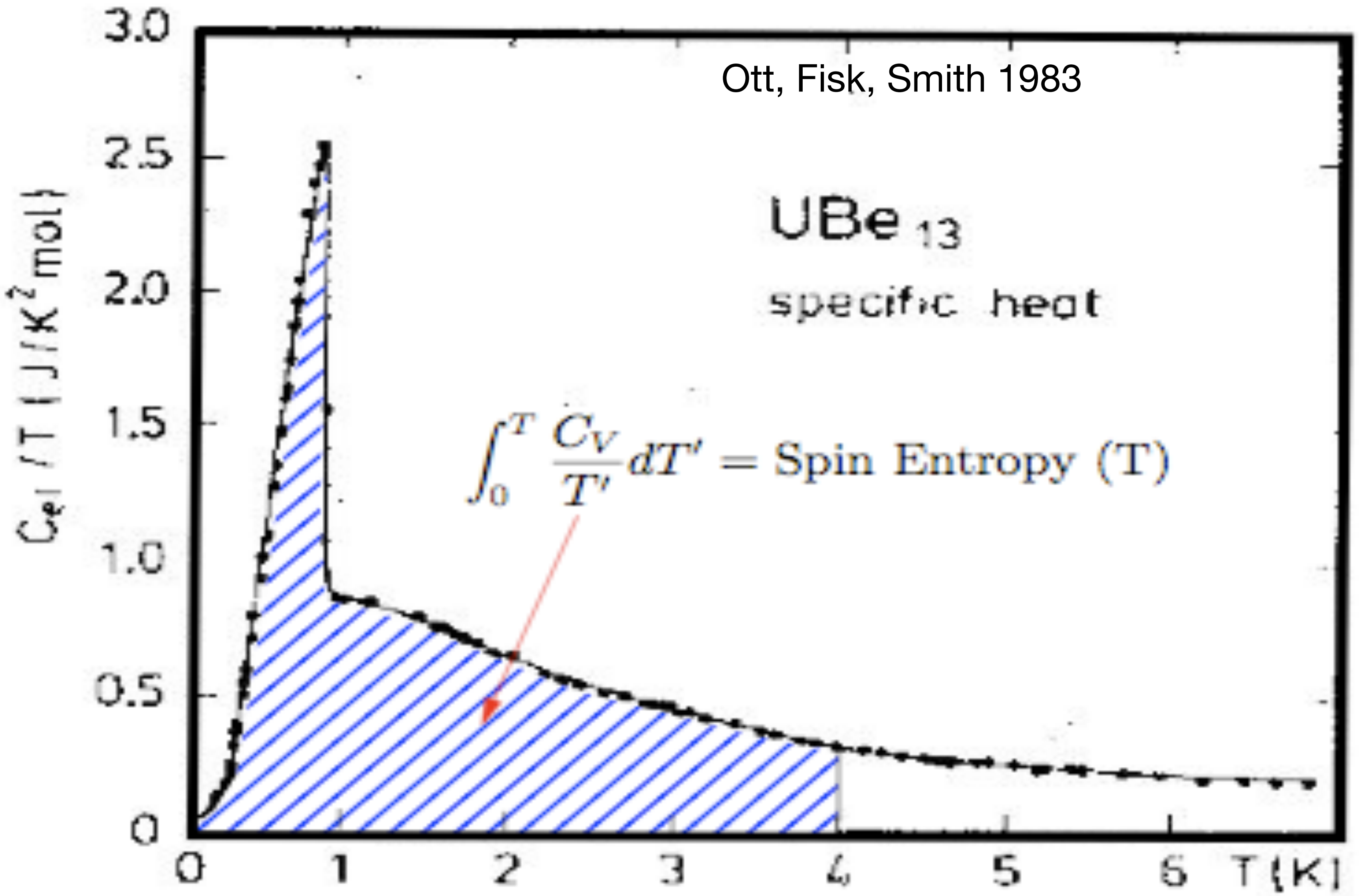
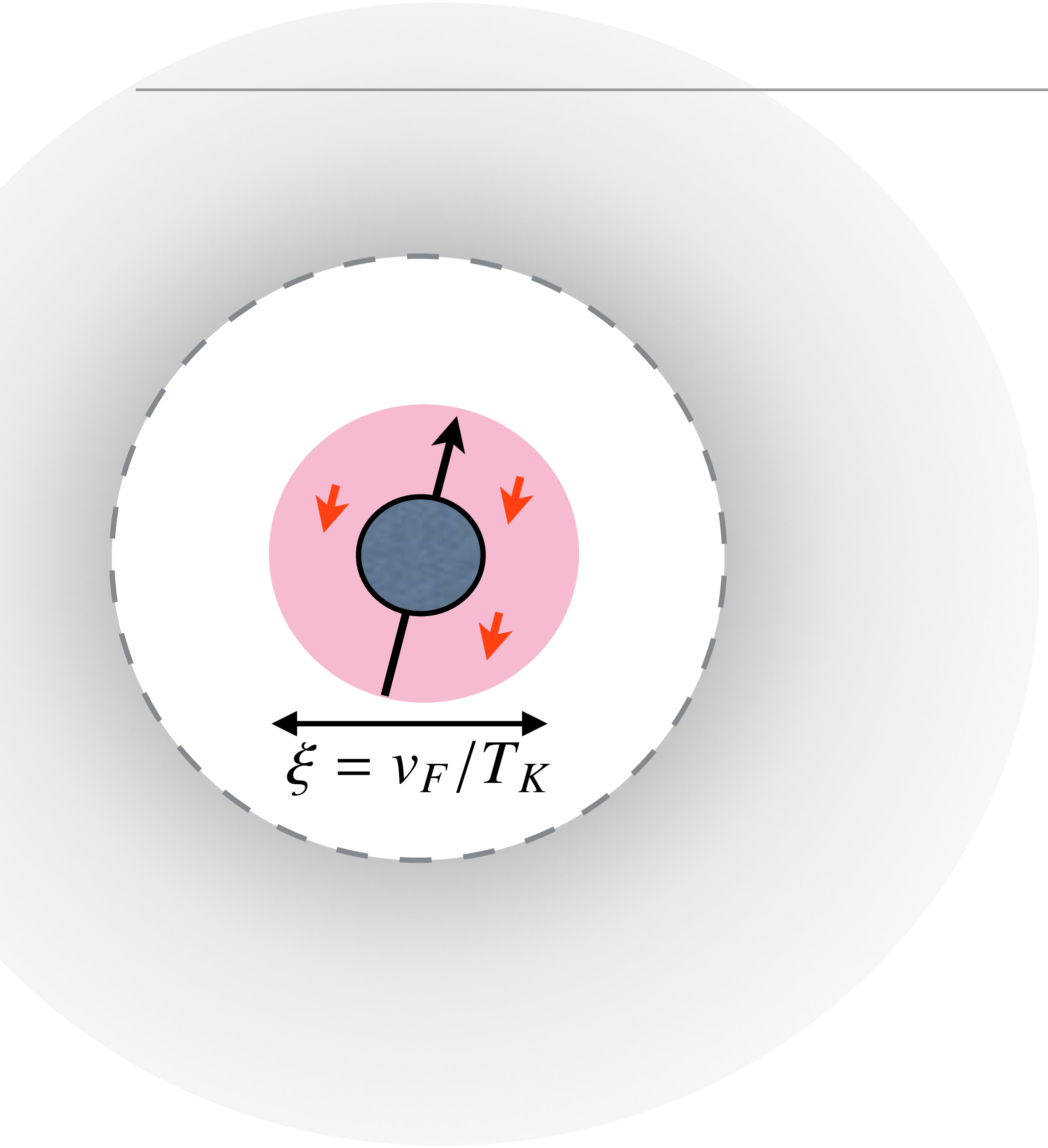


SCES: What new forms of entanglement are possible?

Kondo effect: QI perspective



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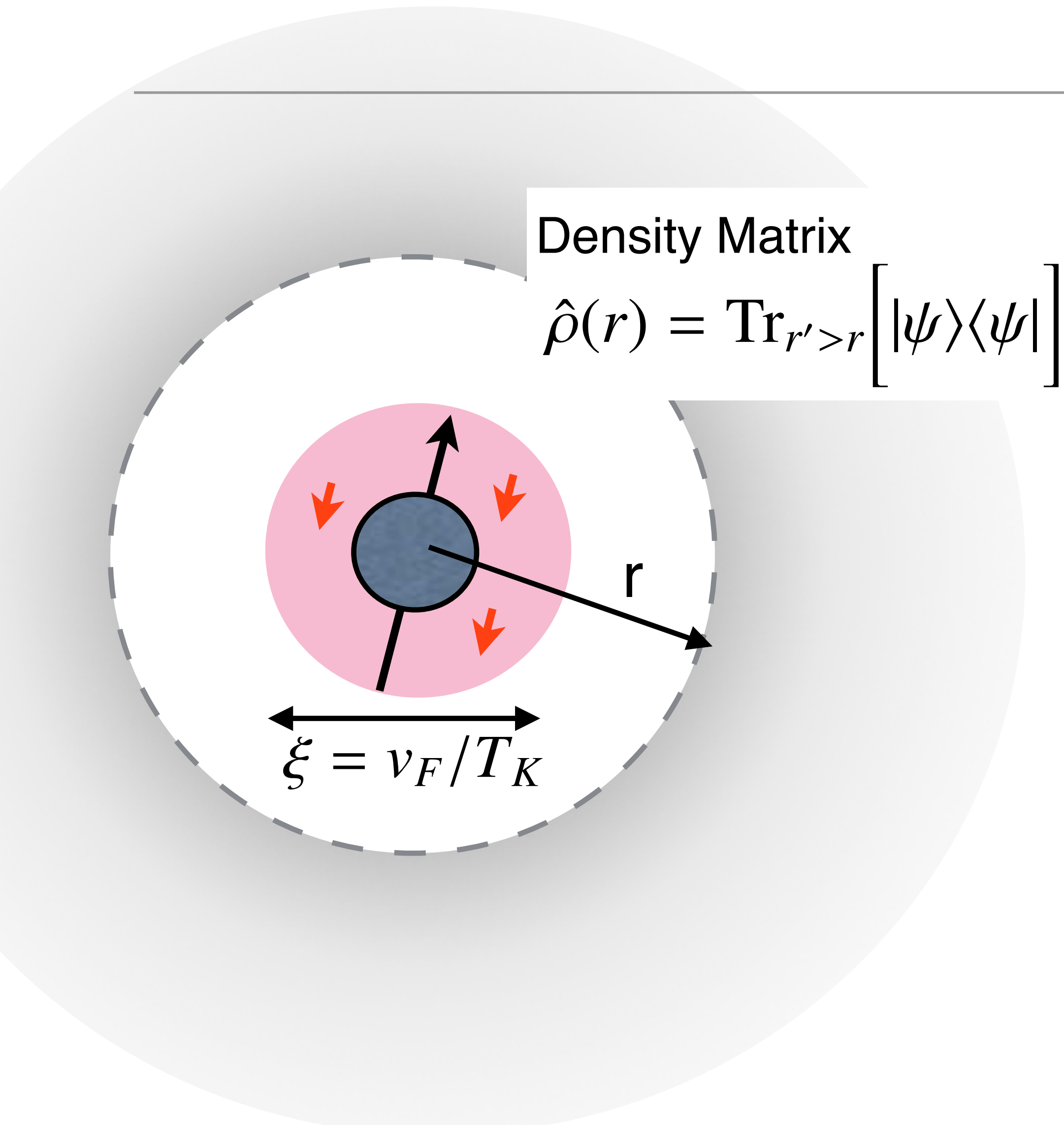

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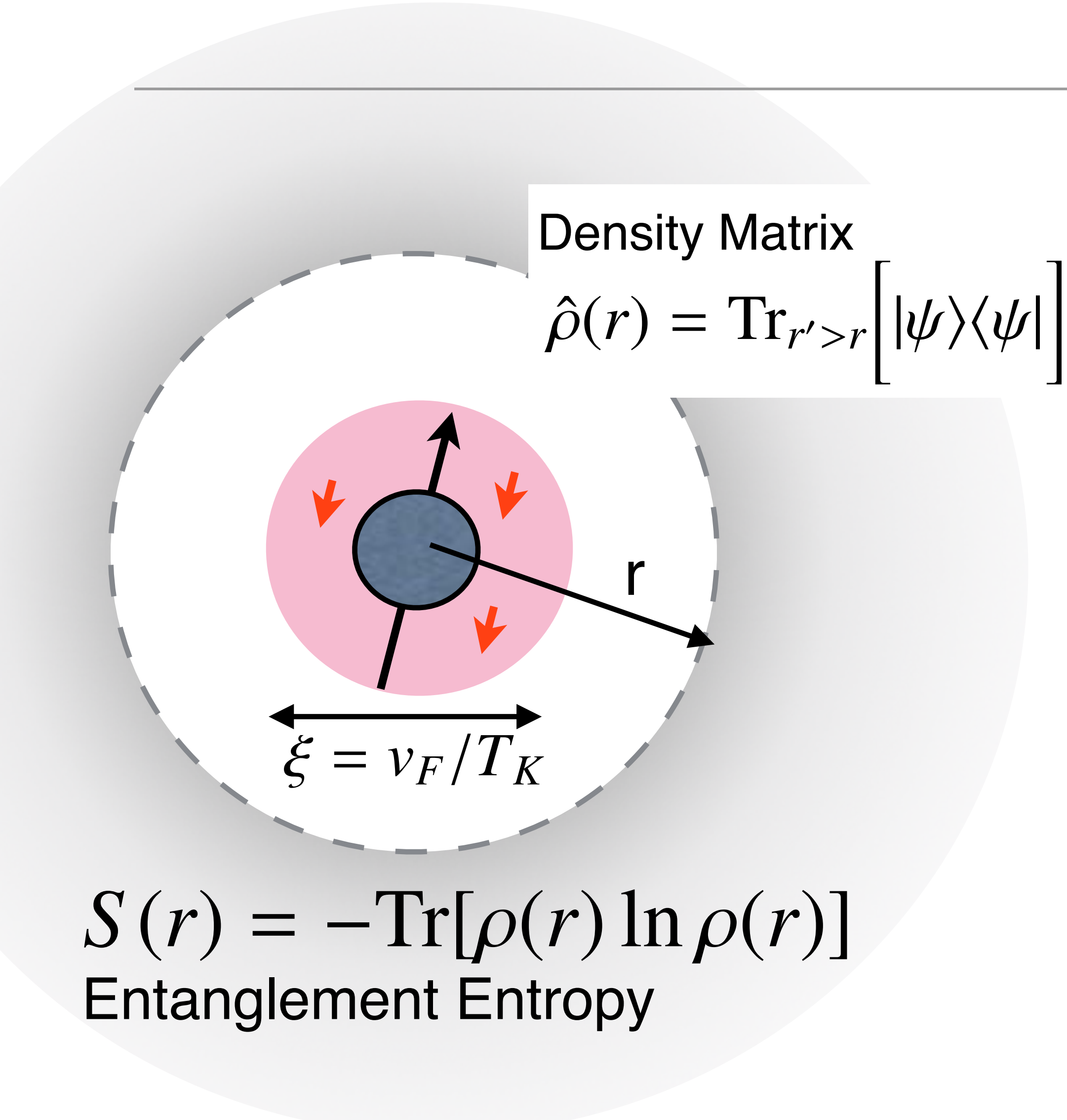
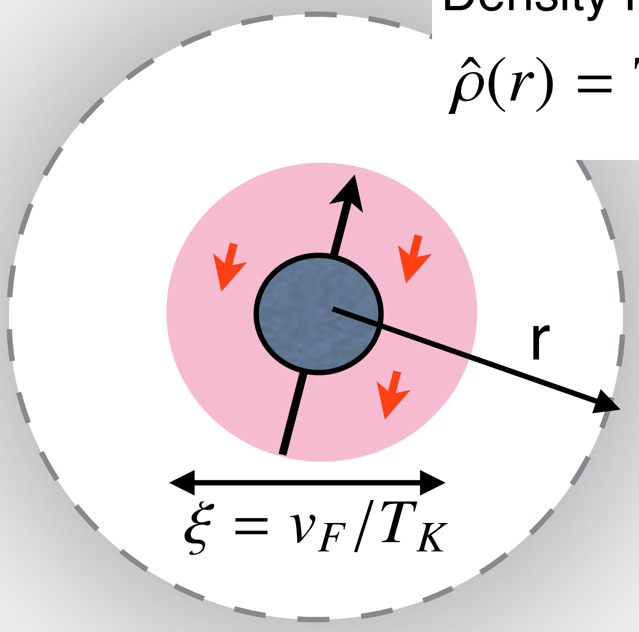


Kondo effect: QI perspective

Density Matrix

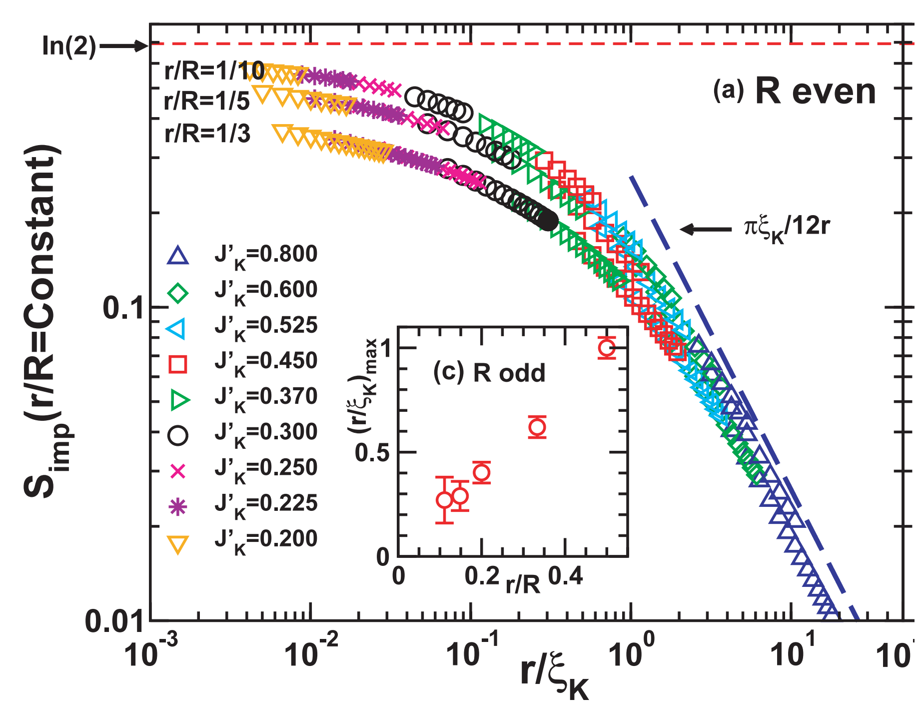
$$\hat{\rho}(r) = \mathrm{Tr}_{r'>r}\Big[|\psi\rangle\langle\psi|\Big]$$



$$S(r) = -\mathrm{Tr}[\rho(r)\ln\rho(r)]$$

Entanglement Entropy

$$S_i(r) = S(r) - S_{BULK}(r)$$



Sorenson, Chang, LaFlorencie & Affleck, JSM (2007)

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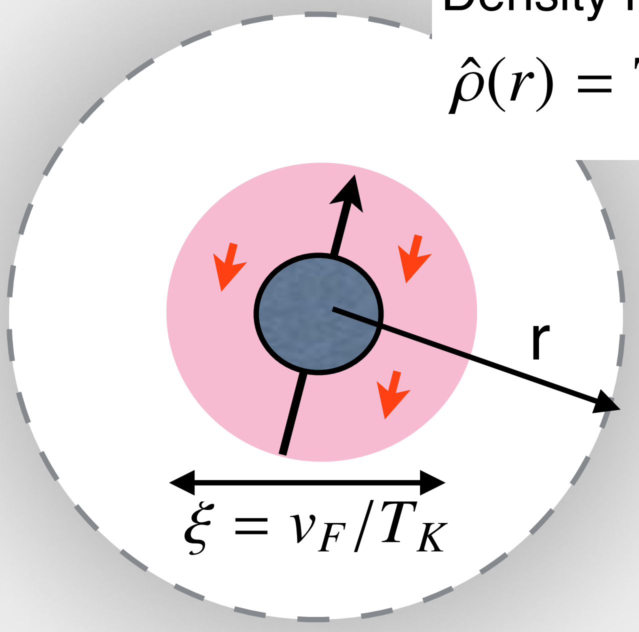

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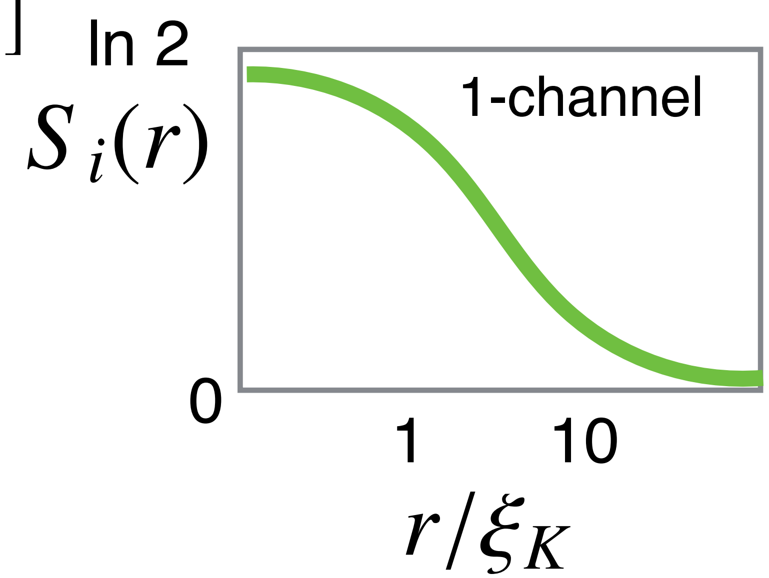

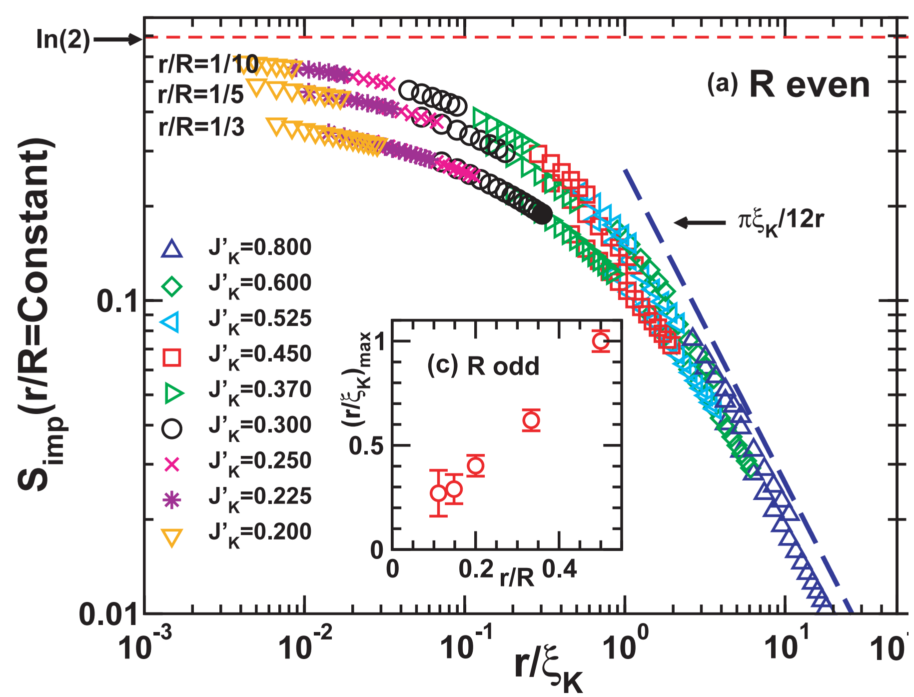

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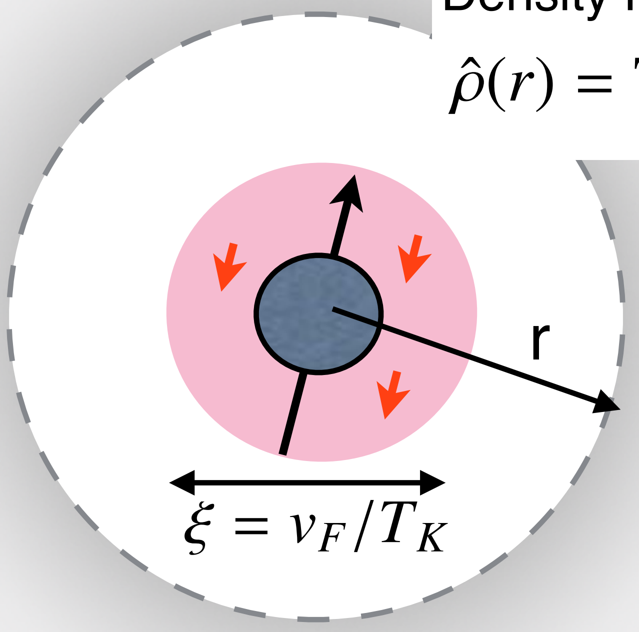

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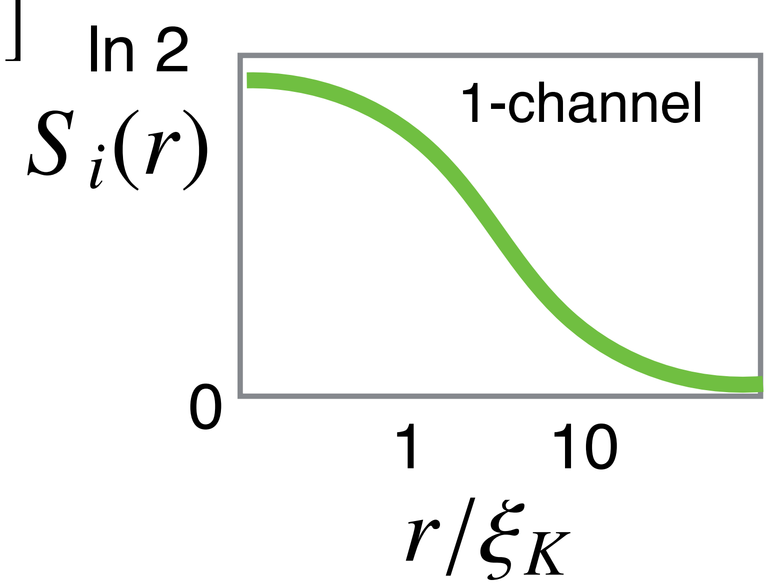

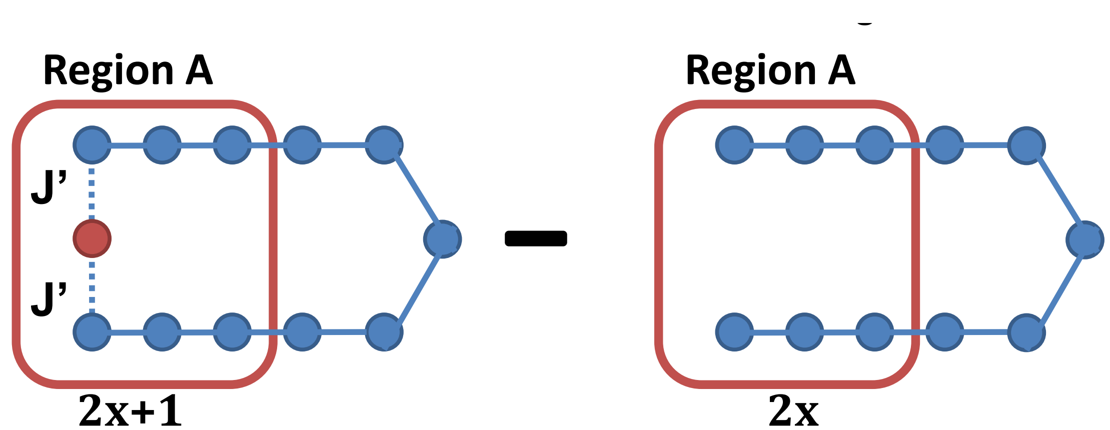

2-channel: Quantum Critical

Kondo effect: QI perspective

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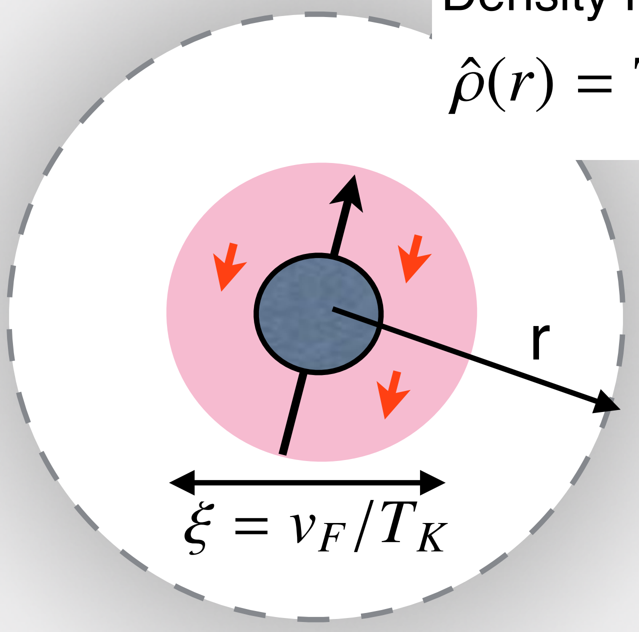

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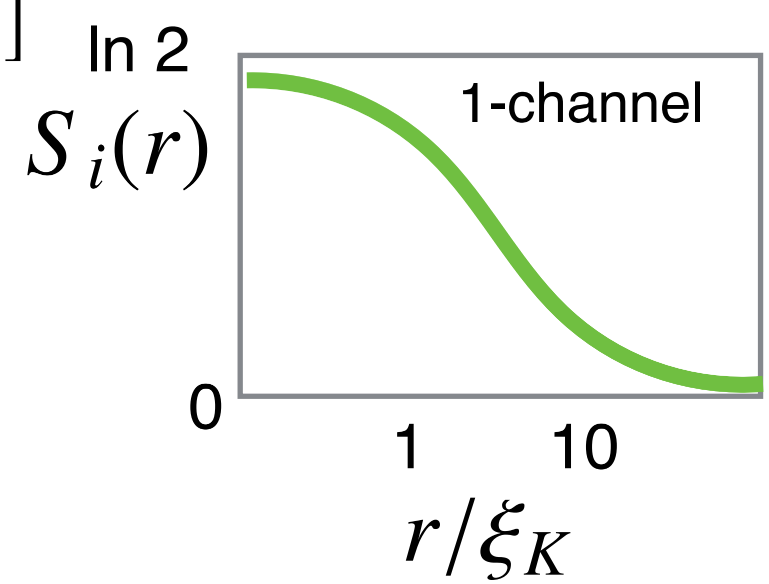
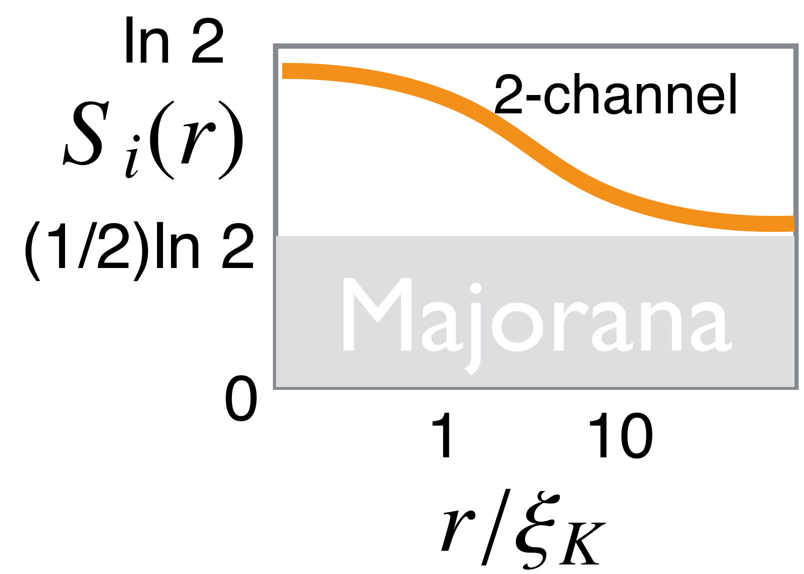
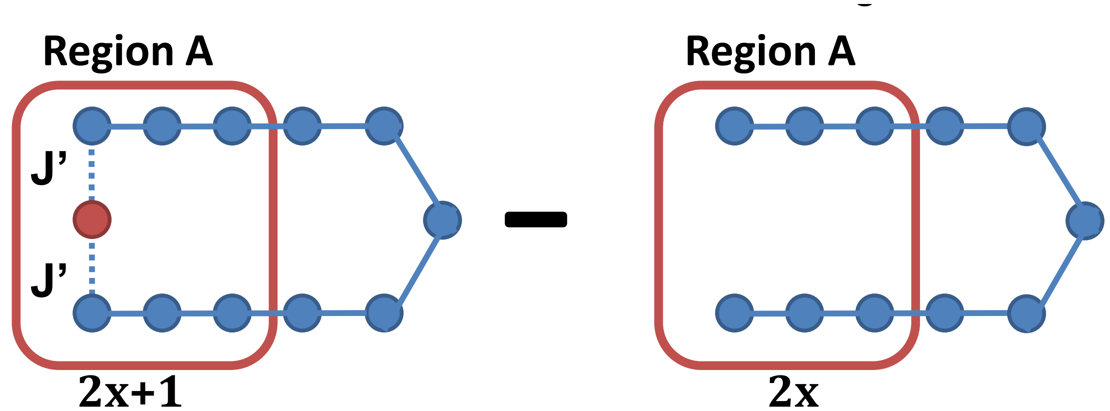




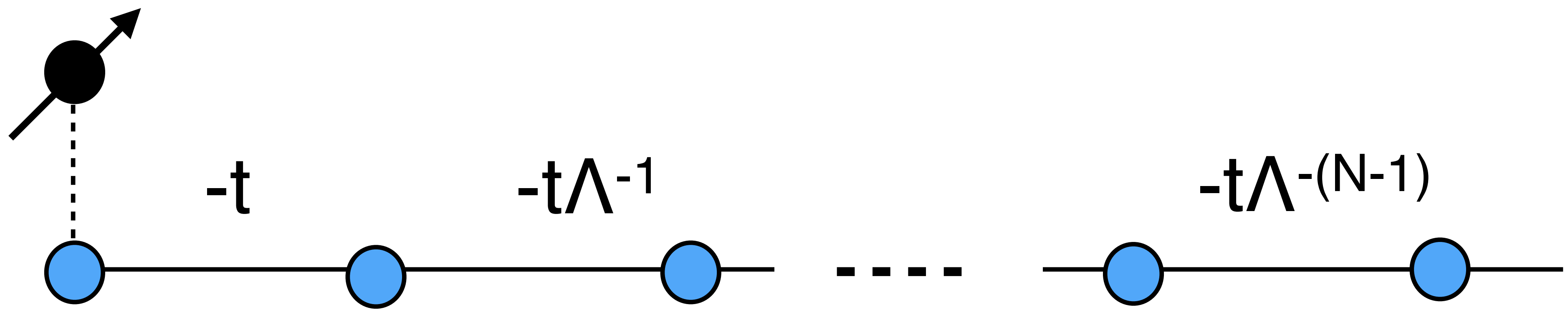
Alkurtass et al, PRB 93,081106R (2016)

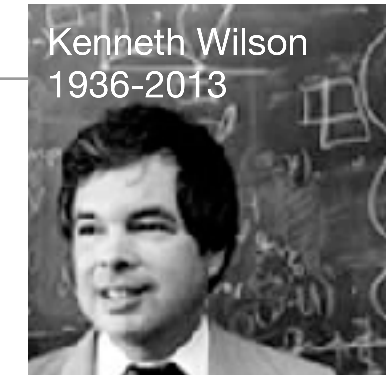
Screening cloud of 2-channel Kondo model is infinitely large



2-channel: Quantum Critical

From Wilsonian NRG to Tensor Networks





NRG Wilson 1973
DMRG White 1992

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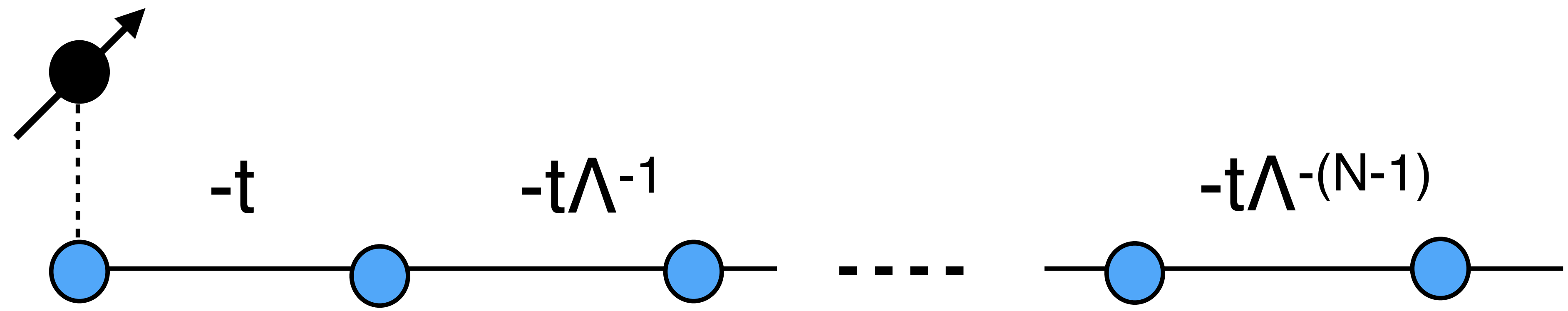

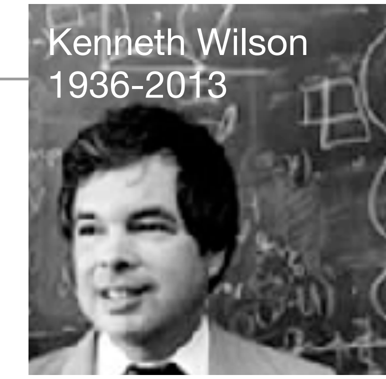

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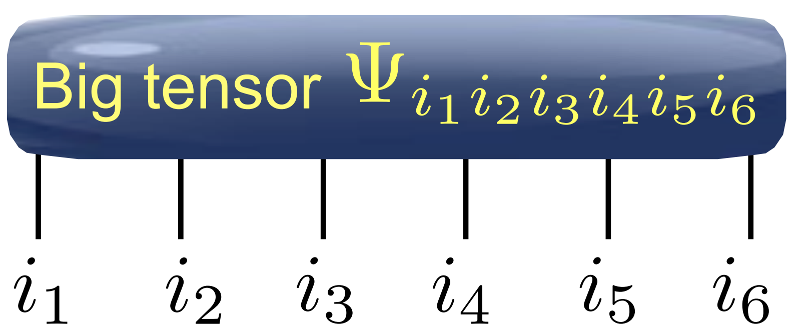
Wavefunction



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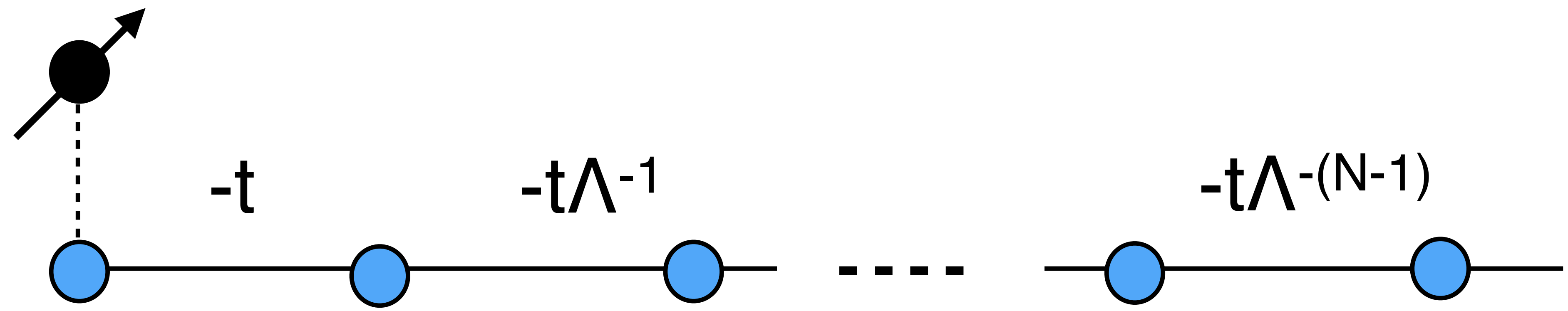

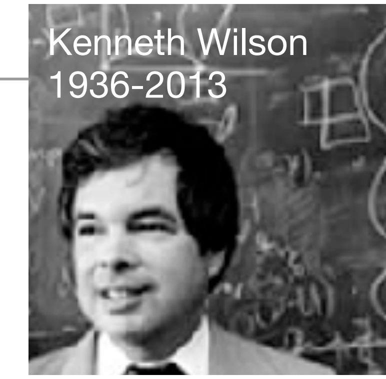

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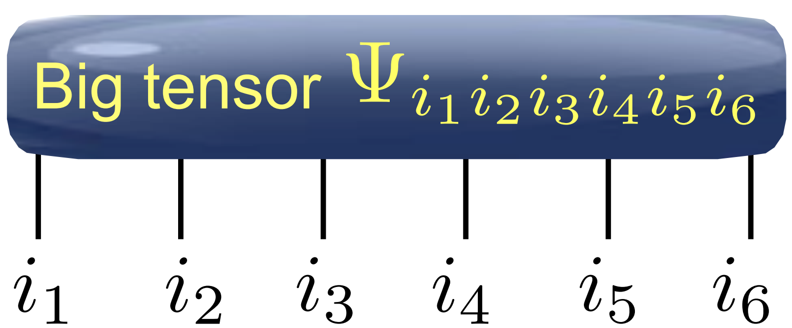
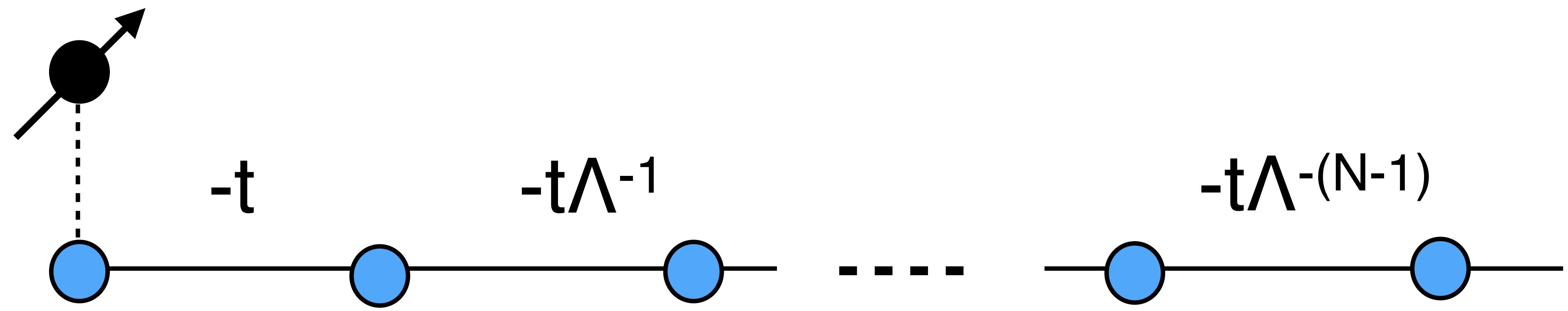
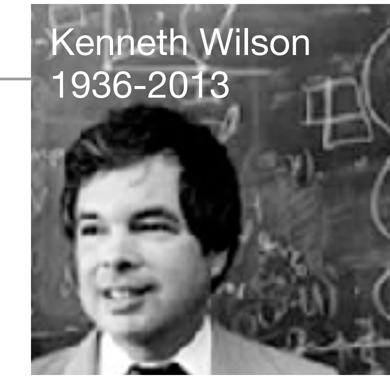


$\sim e^N$

From Wilsonian NRG to Tensor Networks





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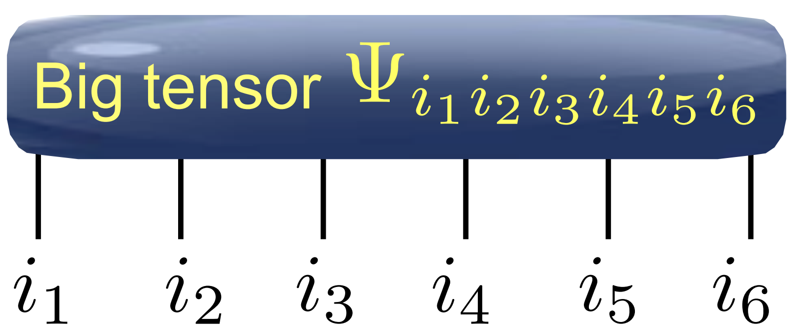
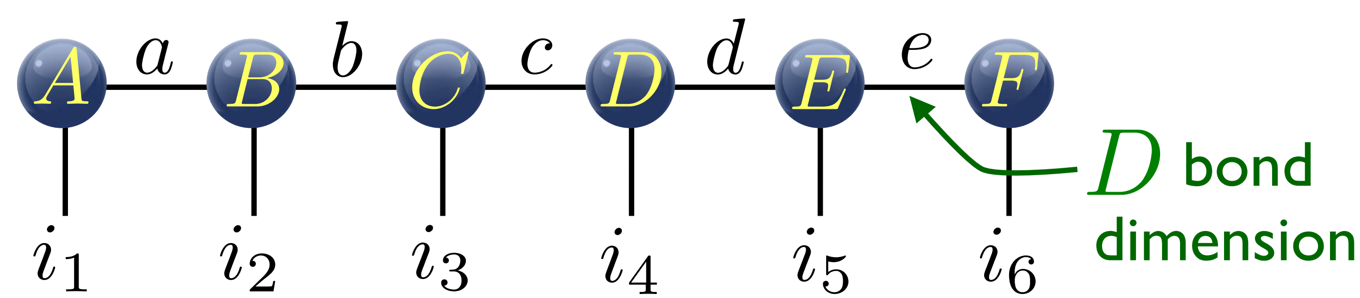
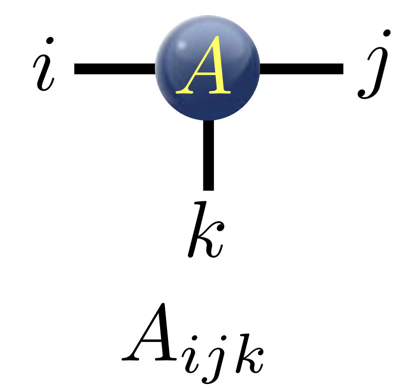


$\sim e^N$

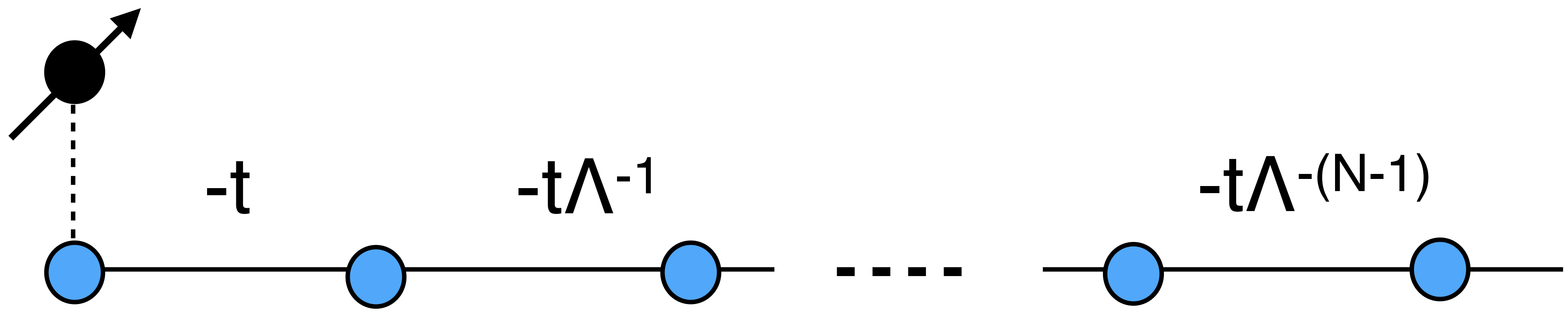
Tensor network: matrix product state (**MPS**)

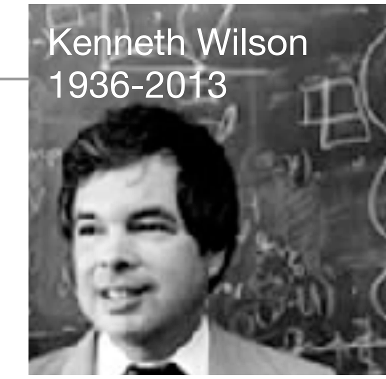




rank-3 tensor

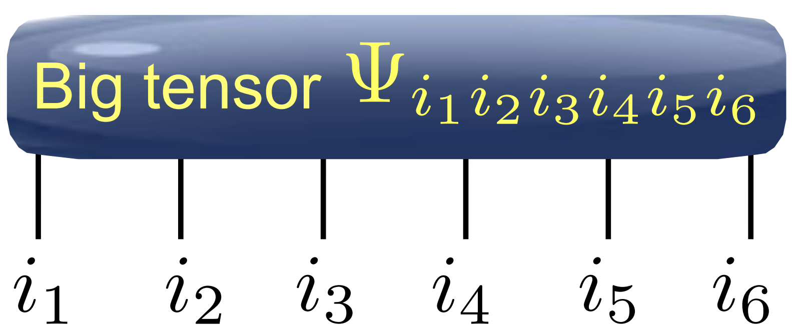
From Wilsonian NRG to Tensor Networks





NRG Wilson 1973
DMRG White 1992

Wavefunction



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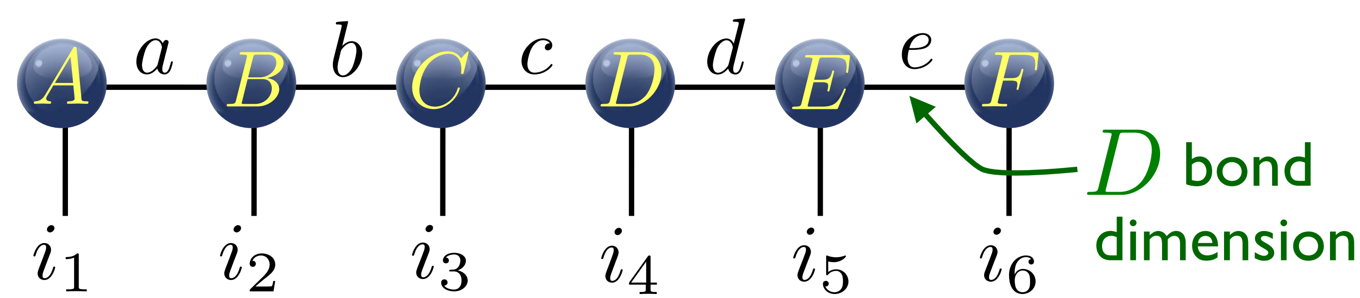
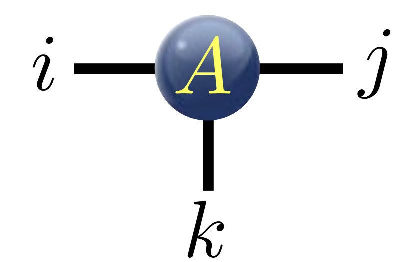


$\sim e^N$

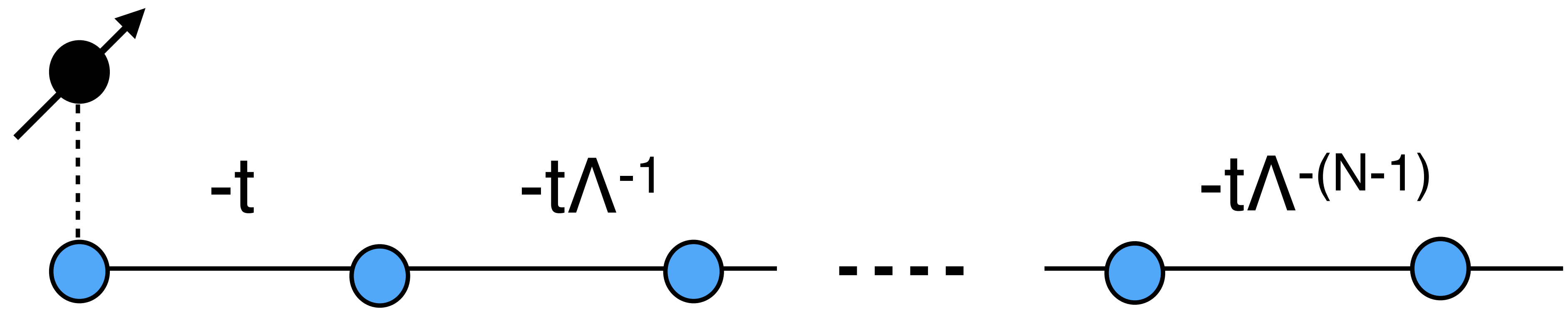
Polynomial in N

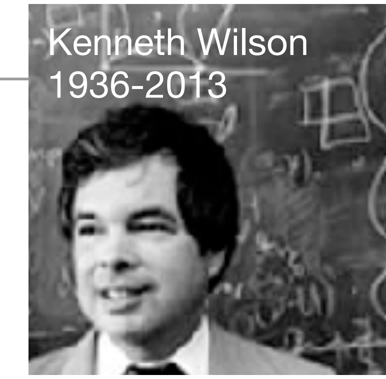


A_{ijk}

rank-3 tensor

From Wilsonian NRG to Tensor Networks





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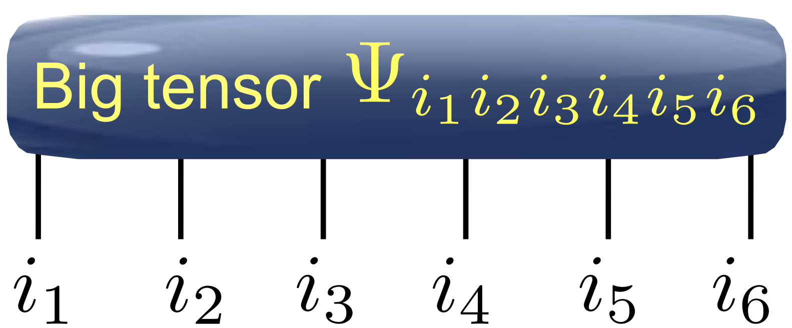

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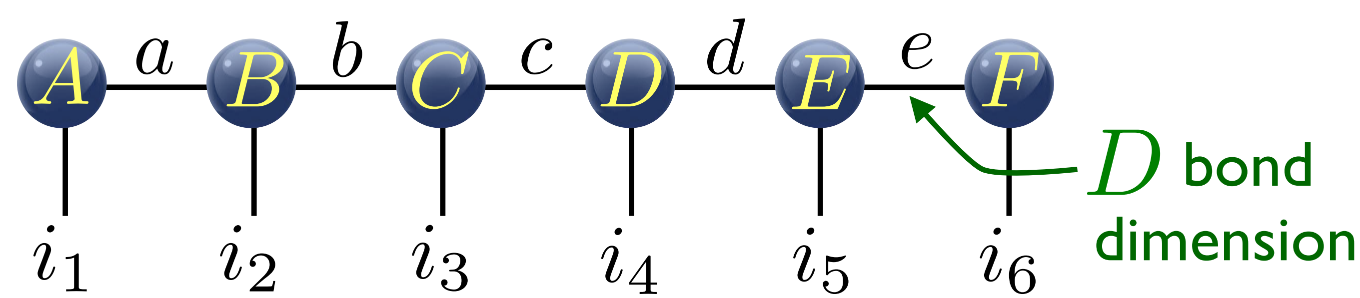
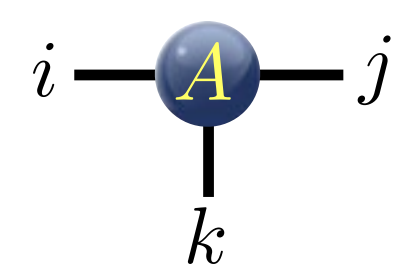




$\sim e^N$

Polynomial in N

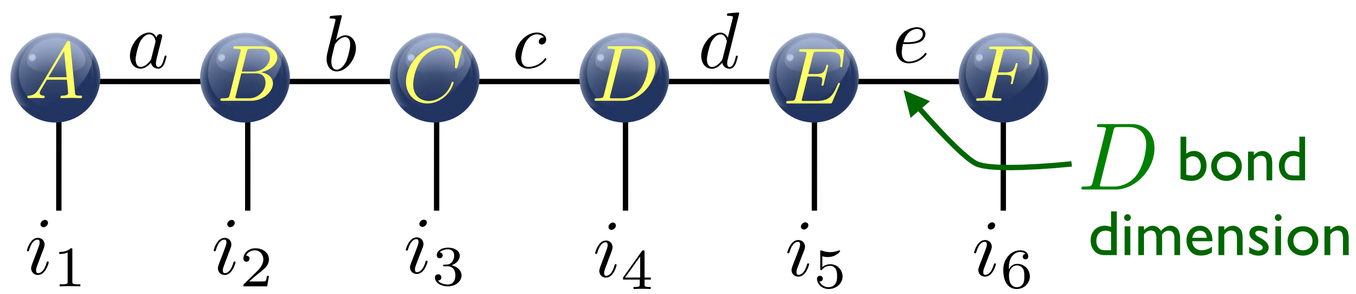
A_{ijk}

Variational MPS is equivalent to Density Matrix Renormalization Group

rank-3 tensor

From Wilsonian NRG to Tensor Networks

Tensor network: matrix product state (**MPS**)



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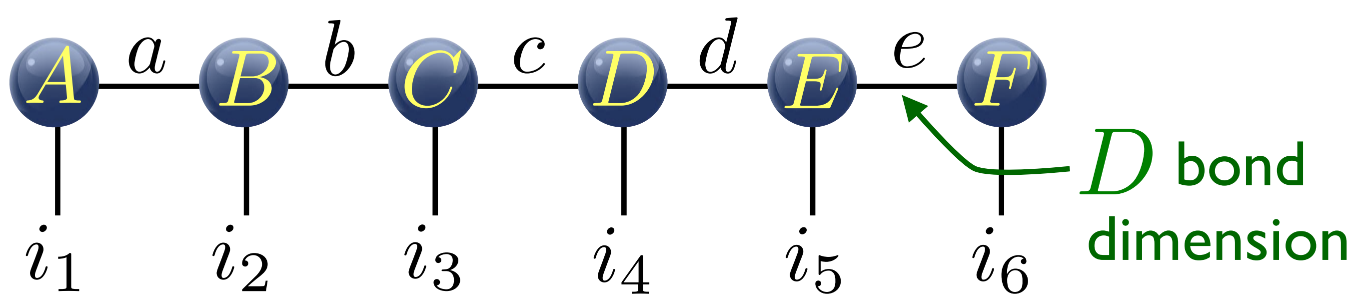

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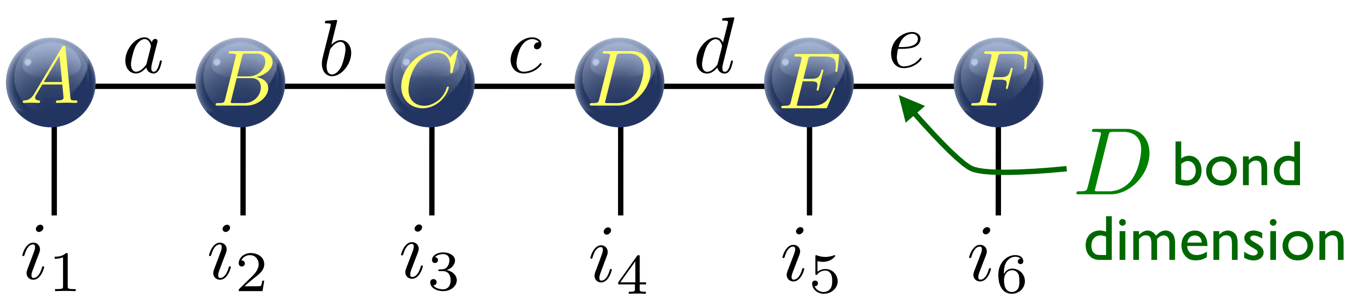
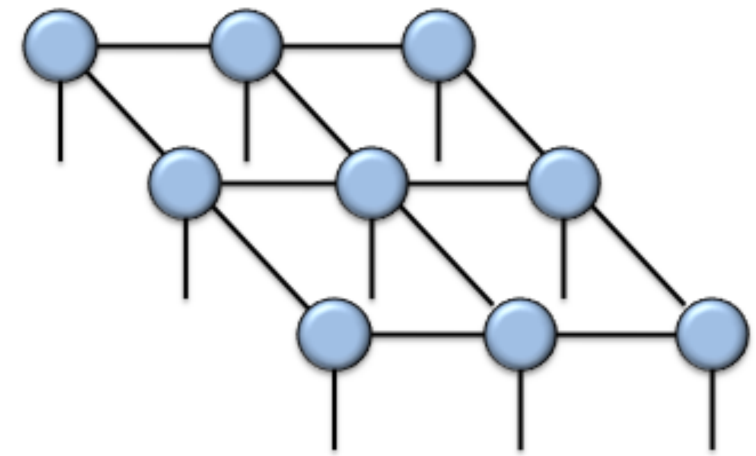


PEPS (2D)

projected entangled-pair state



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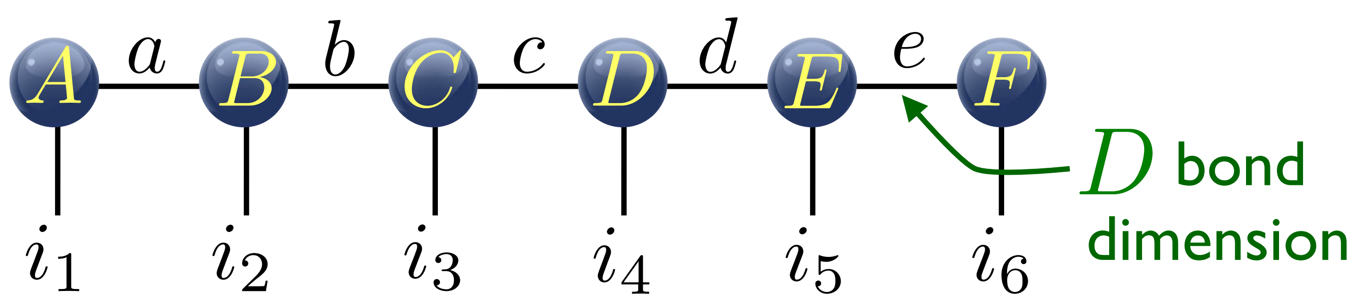

Capability for detailed study of spectral functions in impurity, 1 & 2D.

PEPS (2D)

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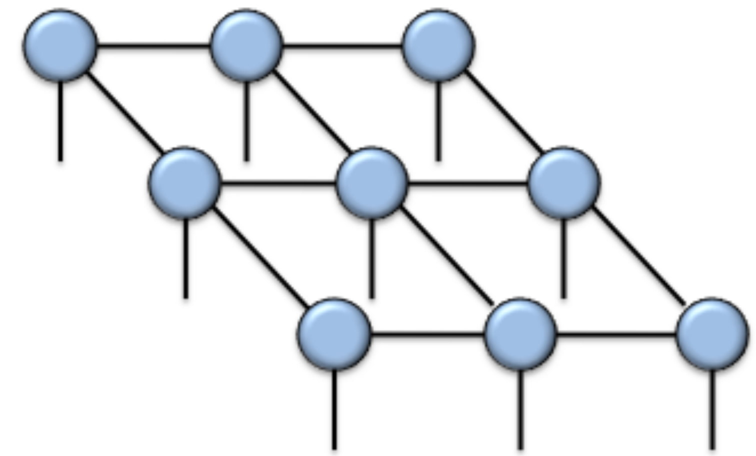

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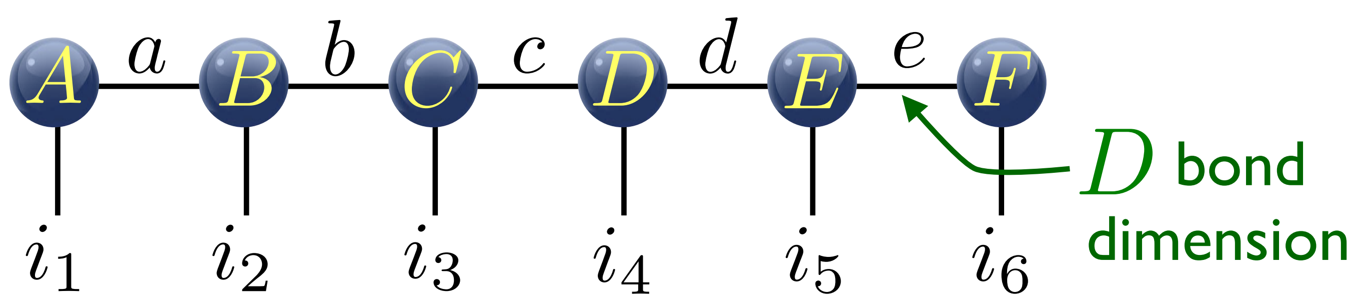

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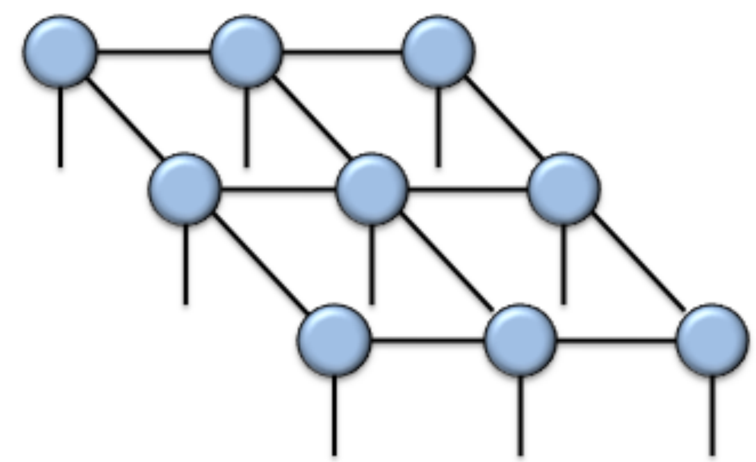

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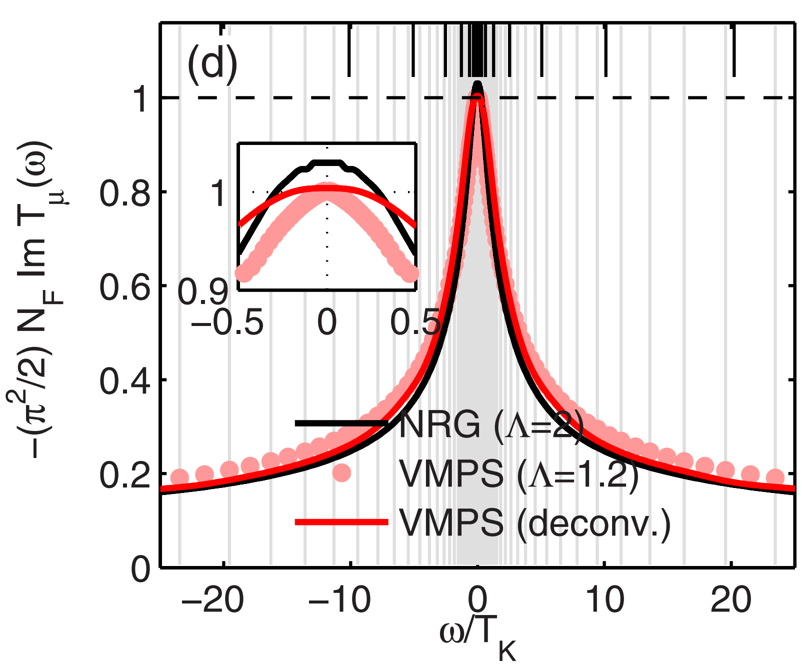
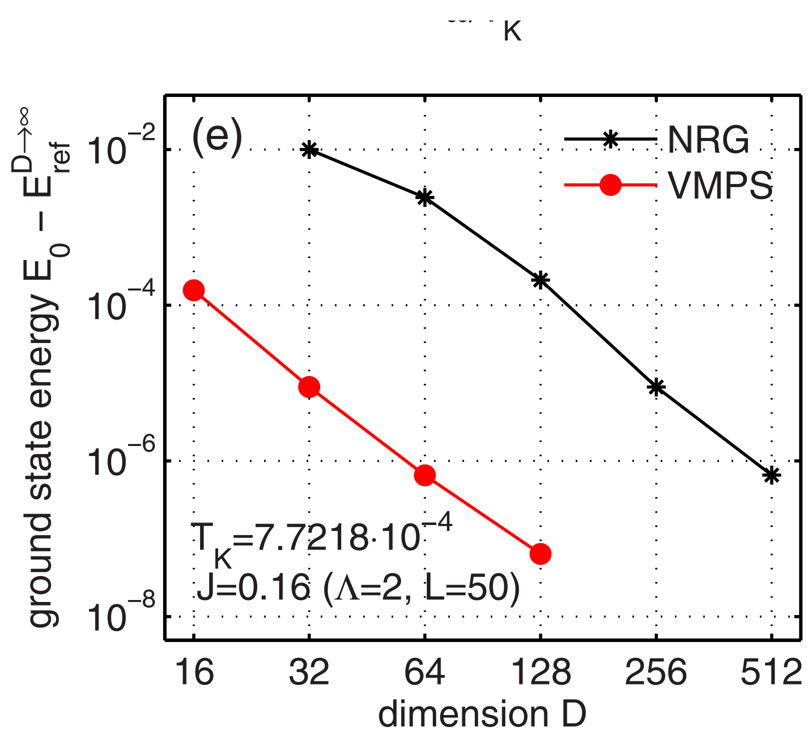
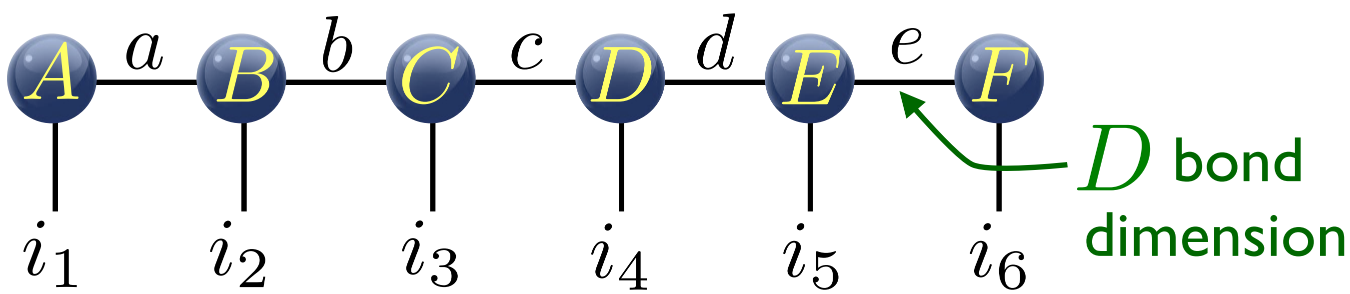




Weichelsbaum et al (2009)

From Wilsonian NRG to Tensor Networks

Tensor network: matrix product state (**MPS**)



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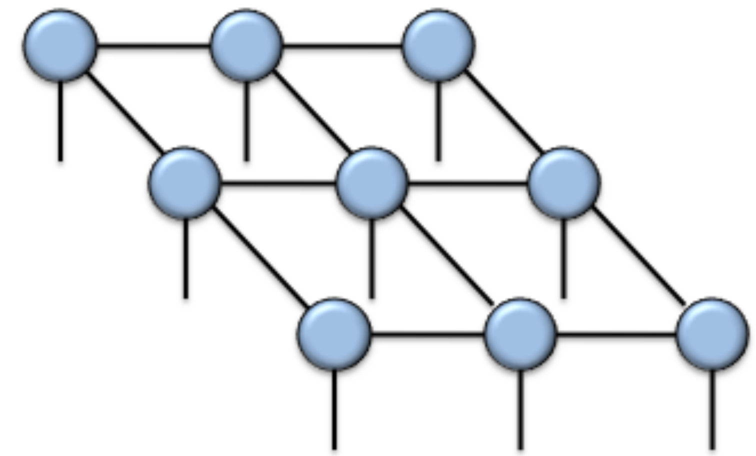
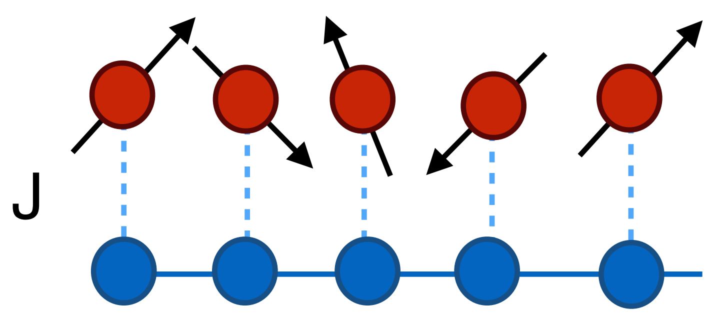
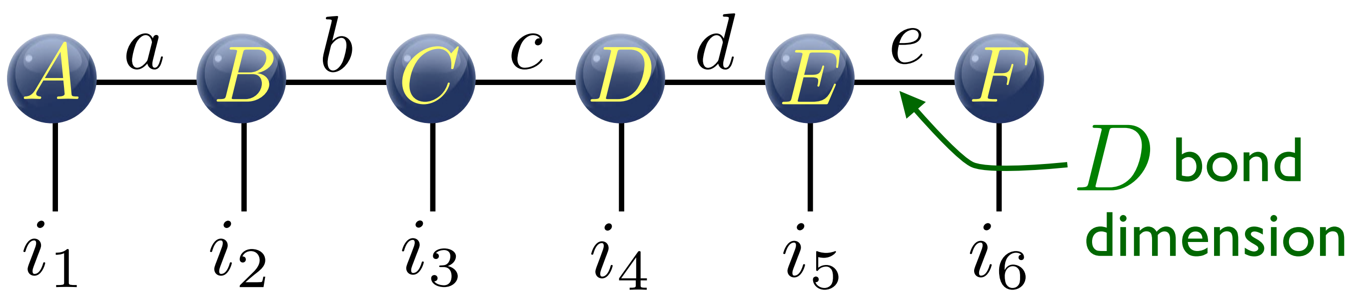




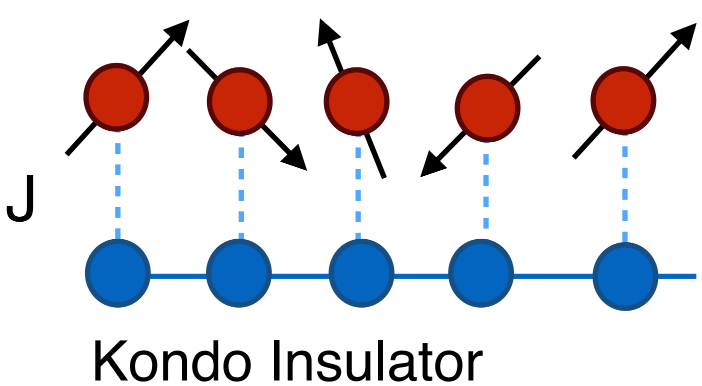
Kondo Insulator

From Wilsonian NRG to Tensor Networks

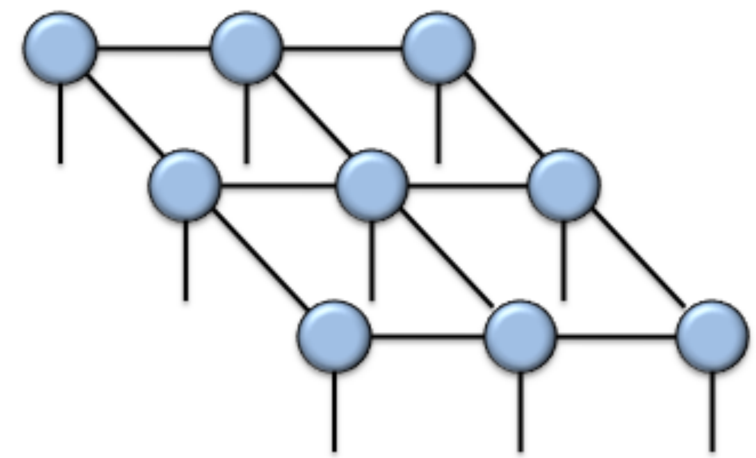
Tensor network: matrix product state (**MPS**)

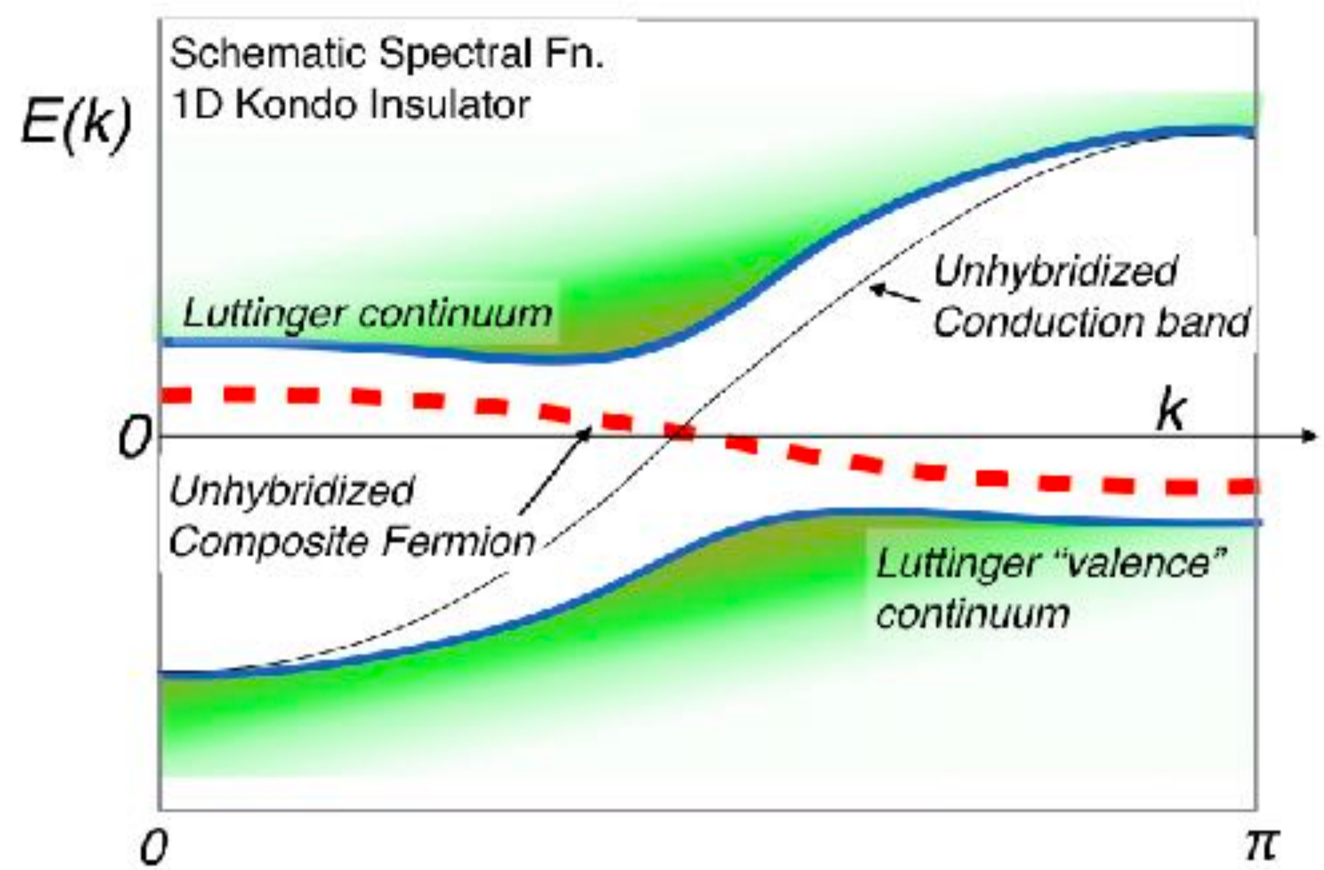


Capability for detailed study of spectral functions in impurity, 1 & 2D.



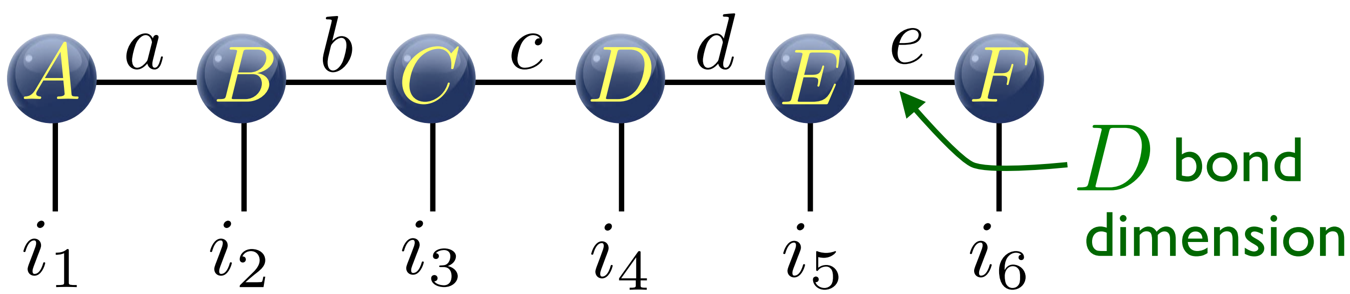
PEPS (2D)
projected entangled-pair state



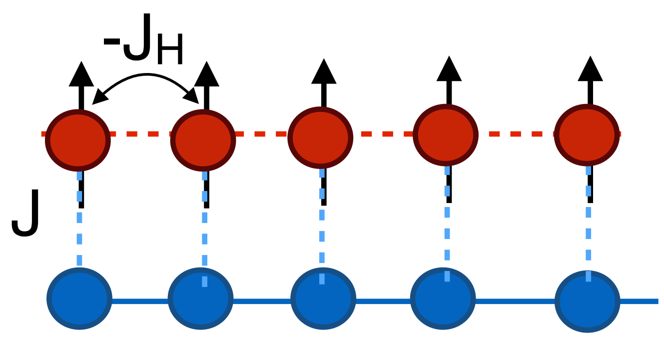


From Wilsonian NRG to Tensor Networks

Tensor network: matrix product state (**MPS**)



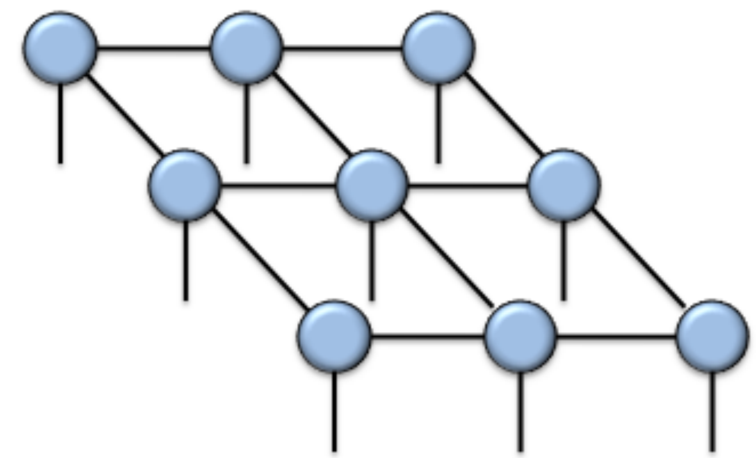
Capability for detailed study of spectral functions in impurity, 1D & 2D



FM Kondo-Heisenberg

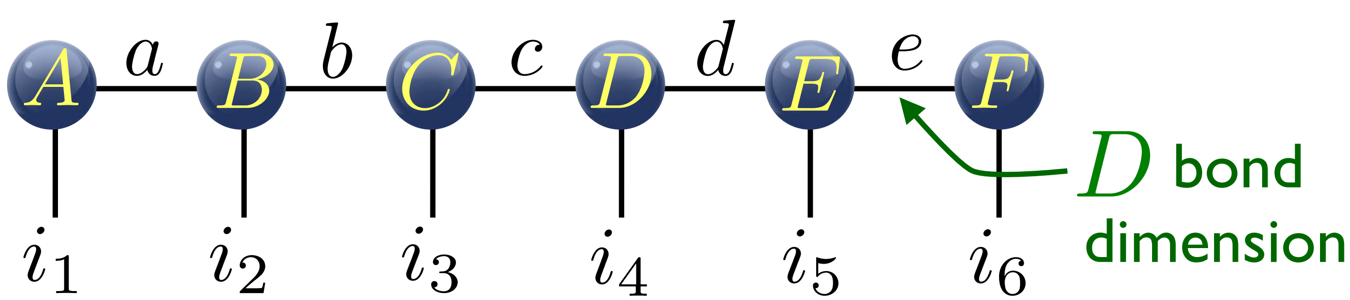
PEPS (2D)

projected entangled-pair state



From Wilsonian NRG to Tensor Networks

Tensor network: matrix product state (**MPS**)



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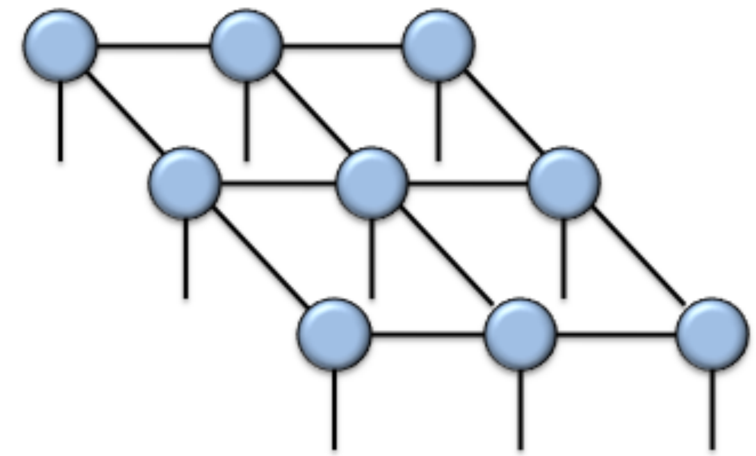

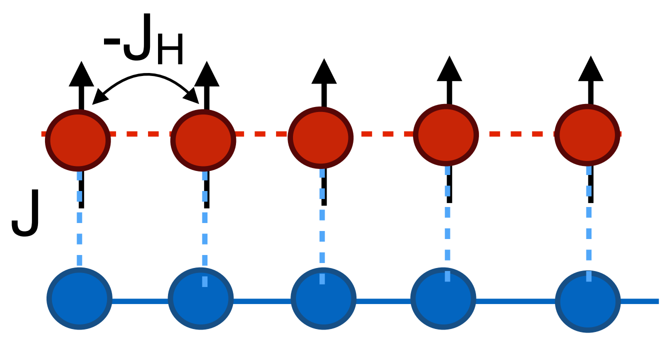

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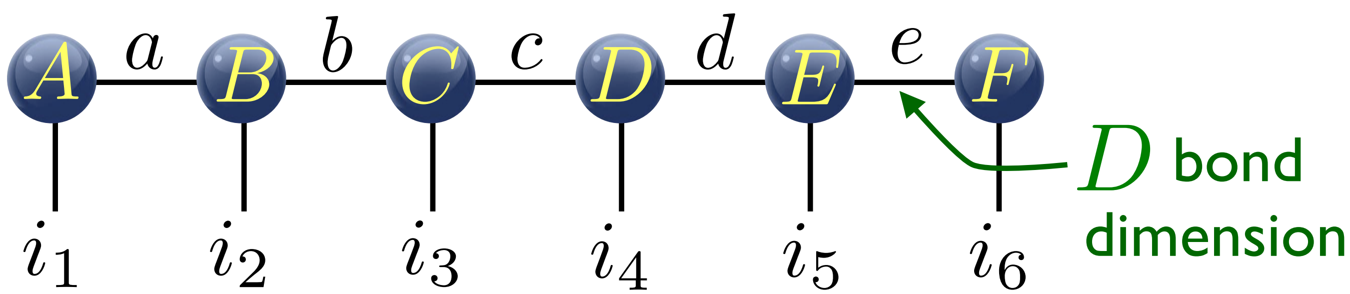

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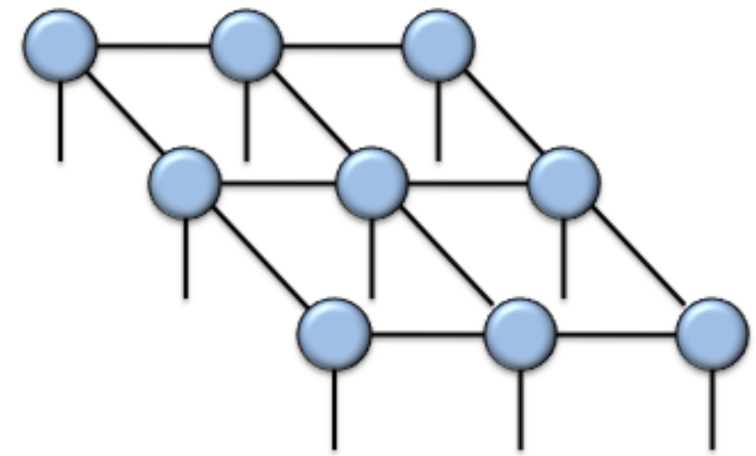

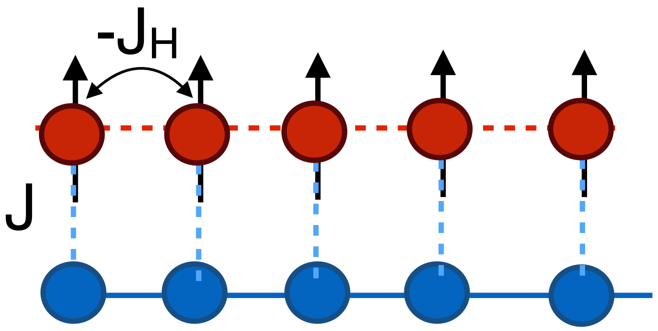

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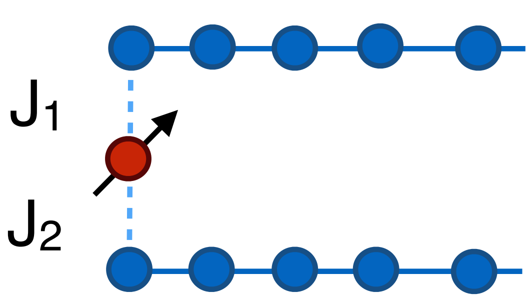
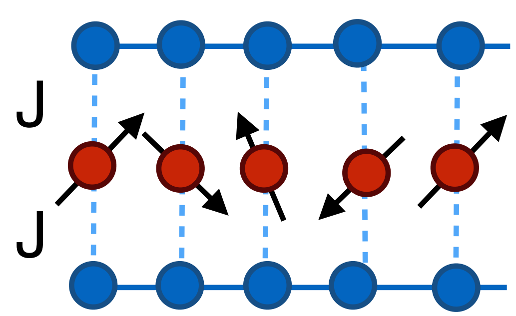
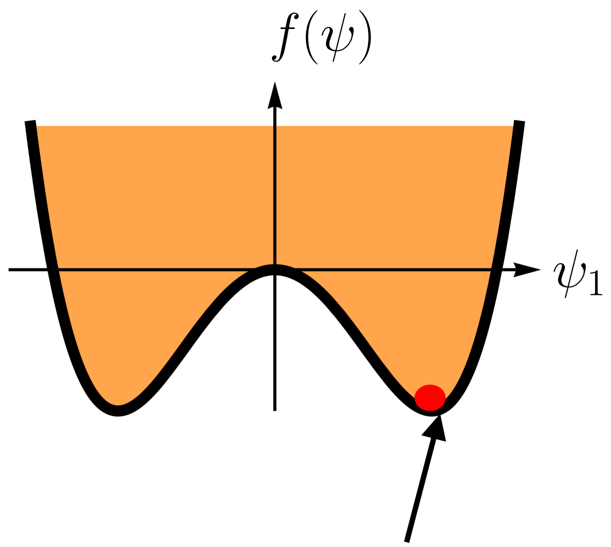


2-channel Kondo



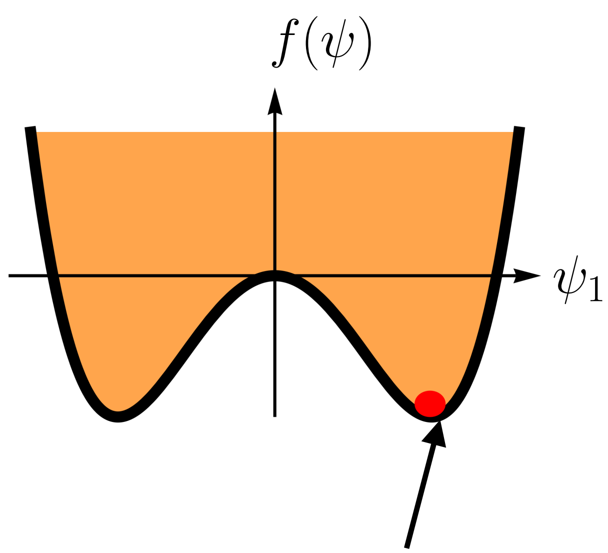
2-channel Kondo Lattice

Beyond Hartree Fock/BCS



Order parameter ψ

Beyond Hartree Fock/BCS



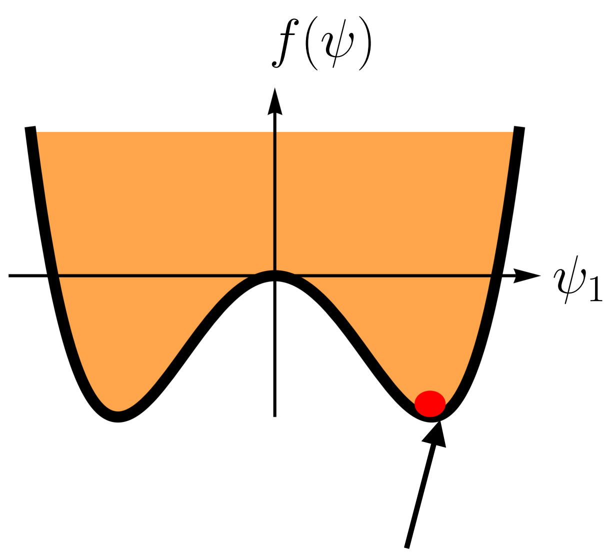
Order parameter ψ

- Order Parameters are bosons, and must contain an even number of fermions: even charge, integer spin.

$$\Psi = \langle \hat{\psi}_\uparrow \hat{\psi}_\downarrow \rangle \qquad \vec{M} = \langle \psi^\dagger \vec{\sigma} \psi \rangle$$

cf BCS theory, Stoner Magnetism.

Beyond Hartree Fock/BCS



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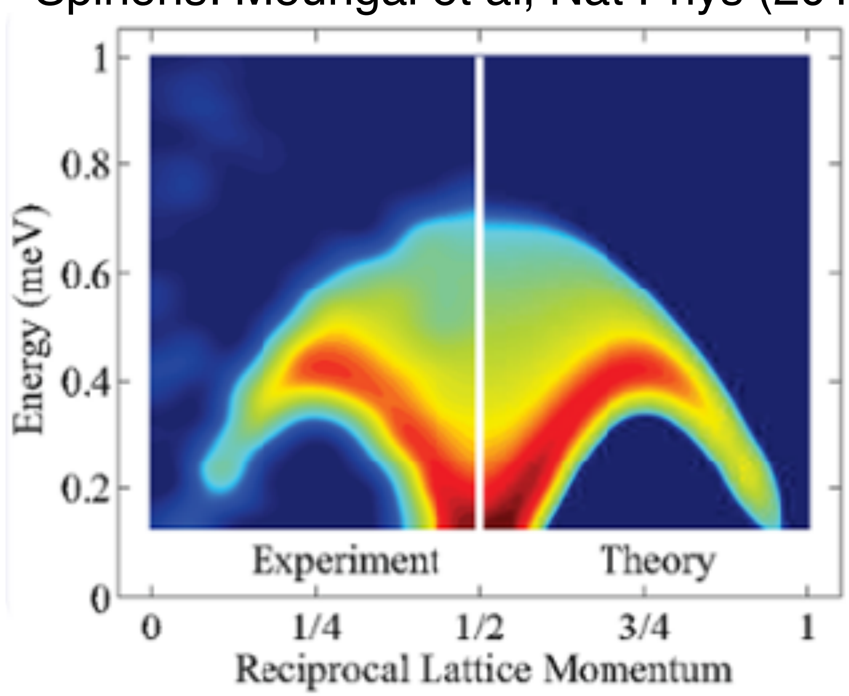
Spinons: Mourigal et al, Nat Phys (2013)



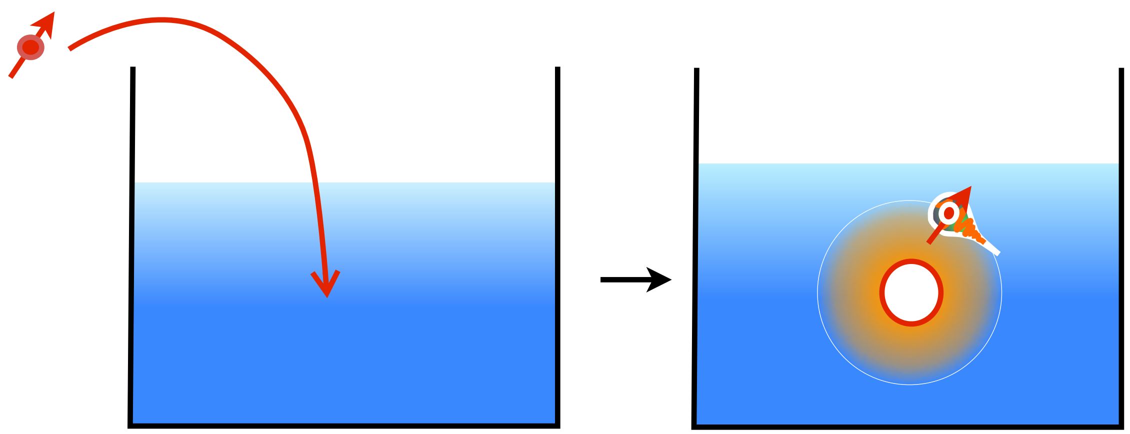
- But can order parameters, like excitations, fractionalize?

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

P. Chandra, P. Coleman, R. Flint, Nature (2013)

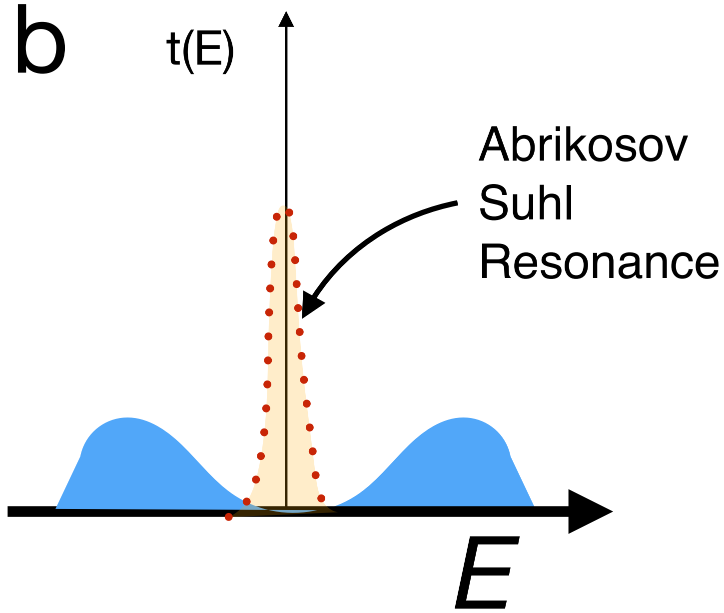
Beyond Hartree Fock/BCS: 3 body Bound States

a



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

b



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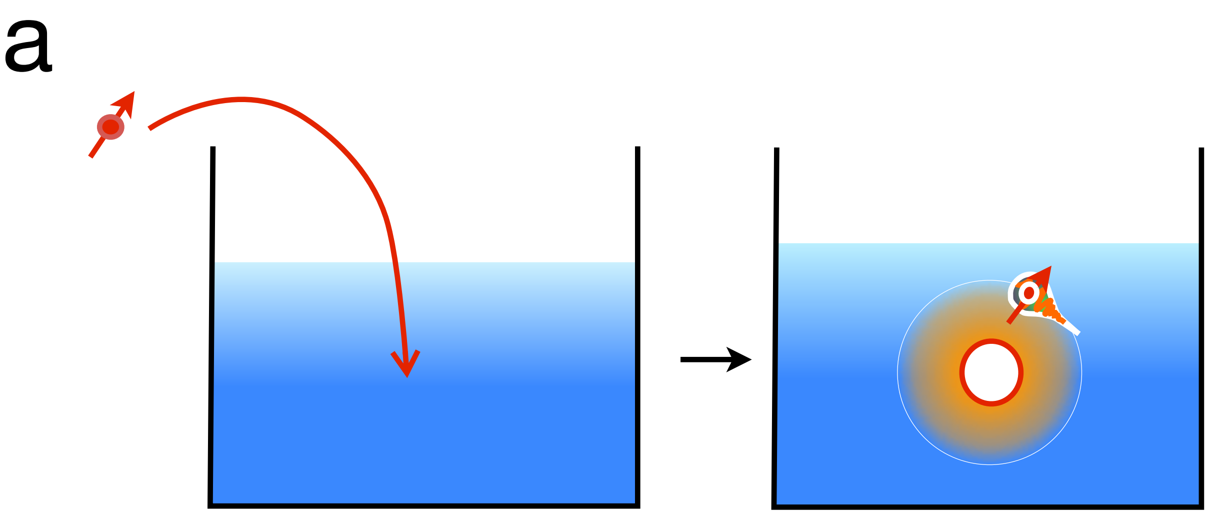

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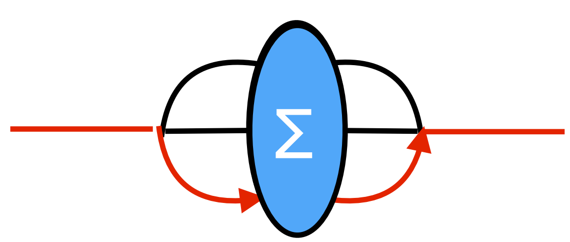
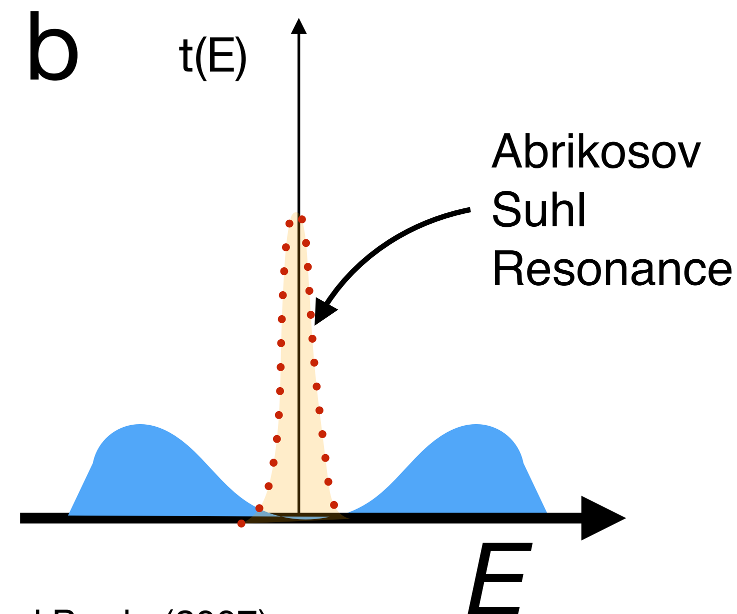
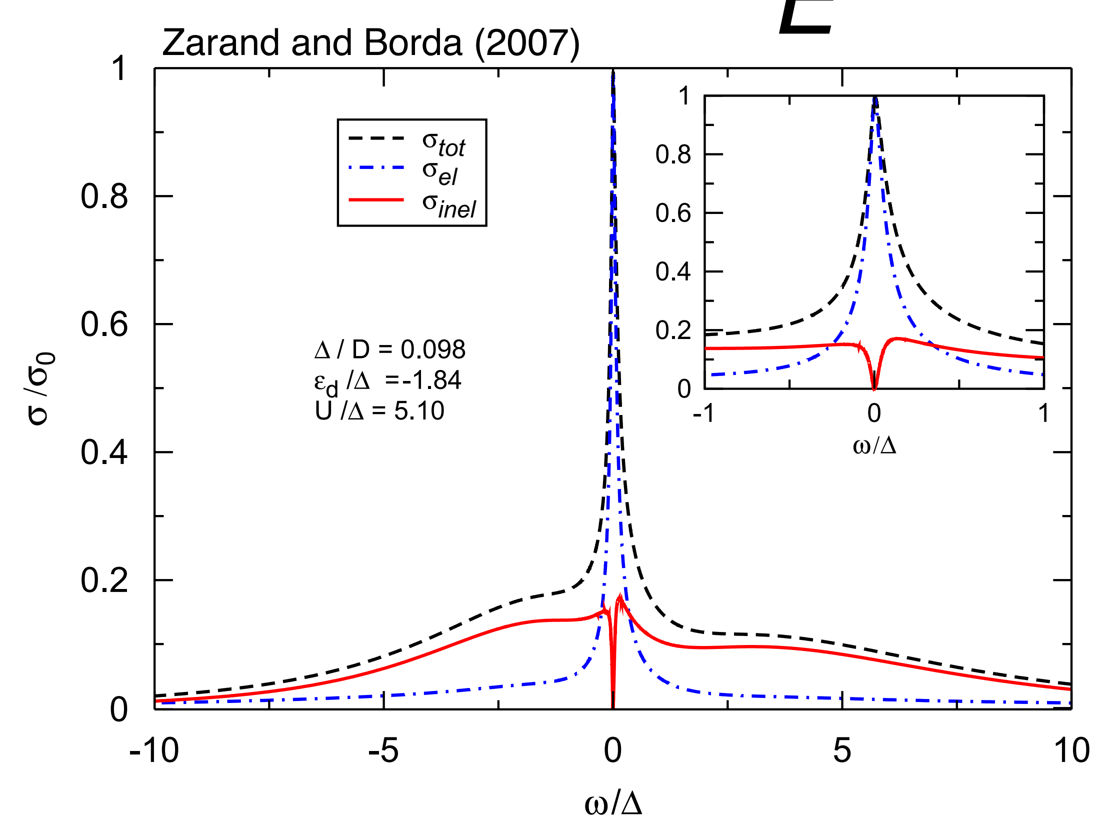


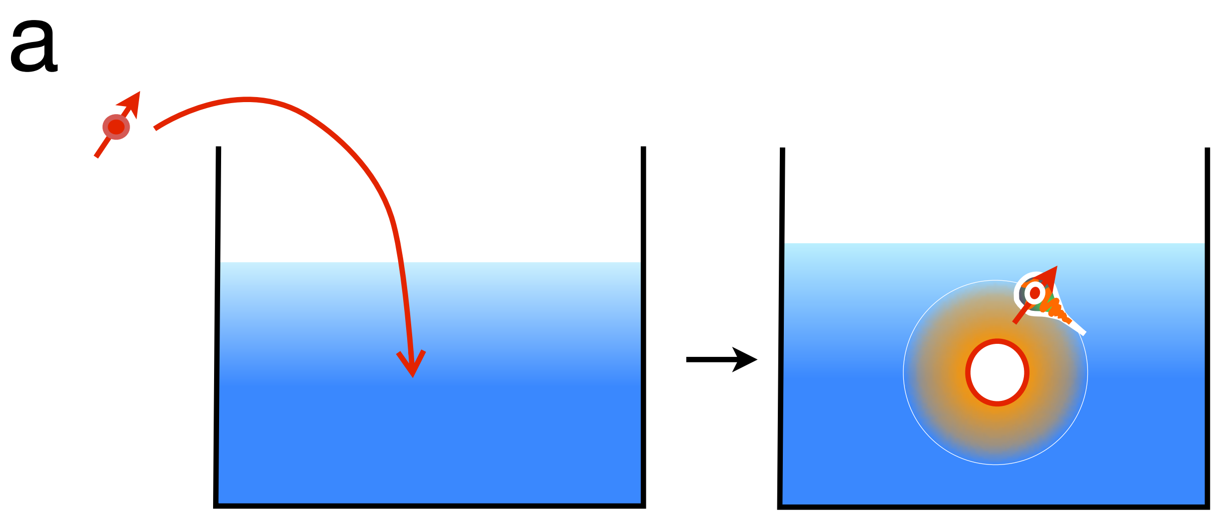
Irreducible t-matrix

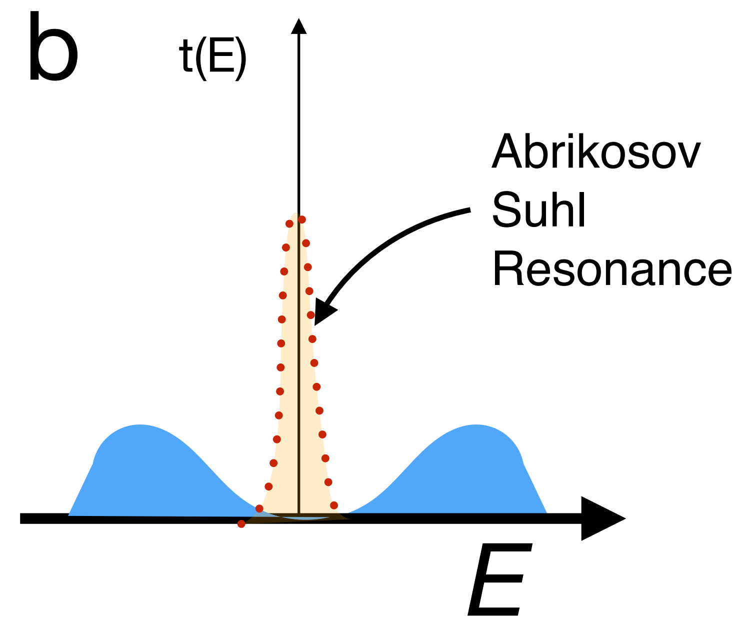
$t(E)=\Sigma(E)+t(E)G_0(E)\Sigma(E)$





Beyond Hartree Fock/BCS: 3 body Bound States





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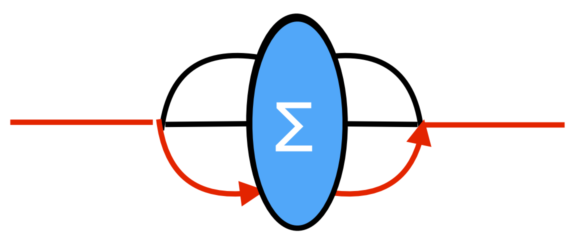
$$\Sigma(\omega) \sim \frac{V^2}{\omega}$$



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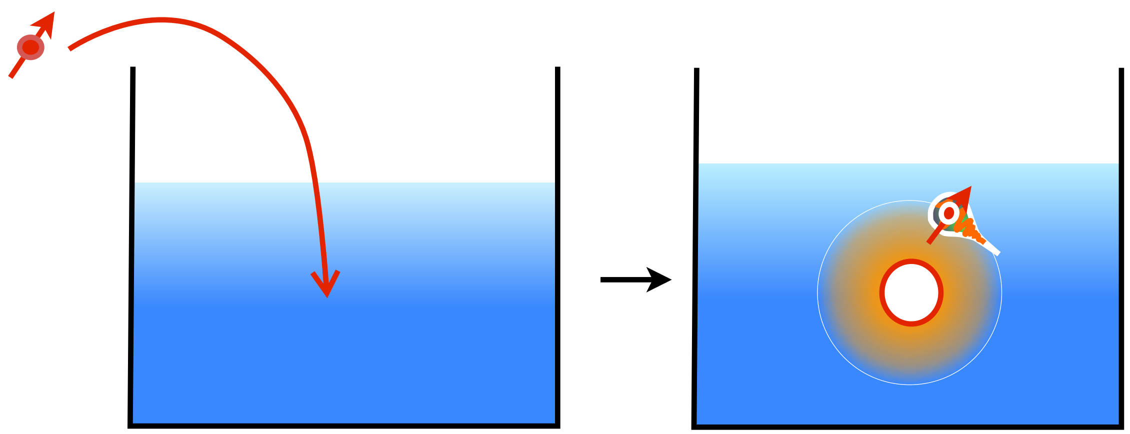
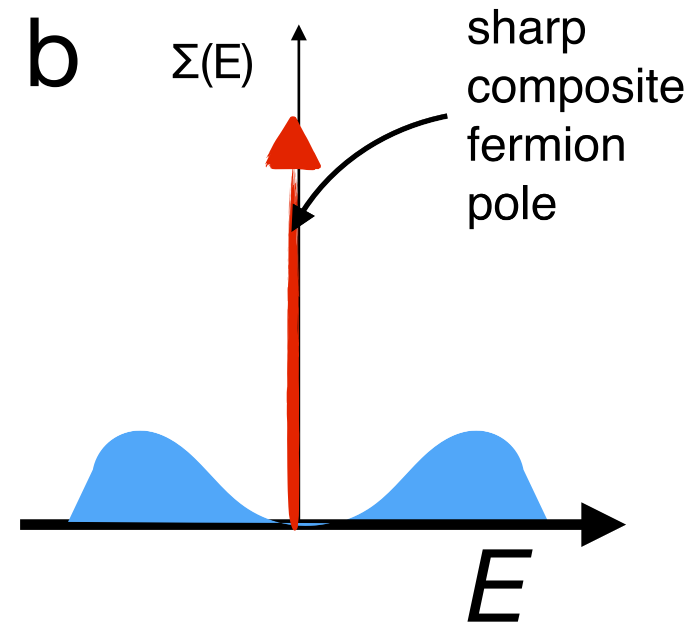
$t(E)=\Sigma(E)+t(E)G_0(E)\Sigma(E)$

Beyond Hartree Fock/BCS: 3 body Bound States

a



b



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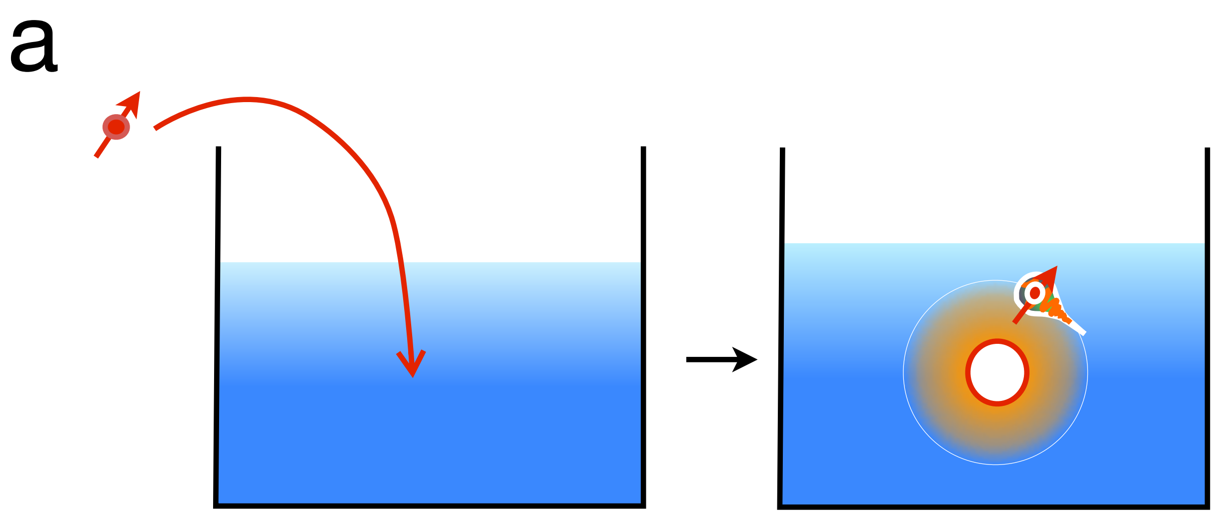

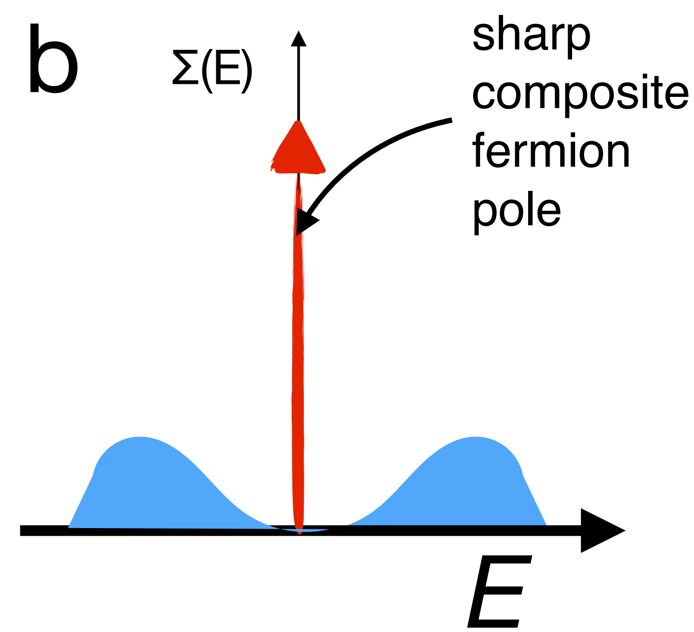

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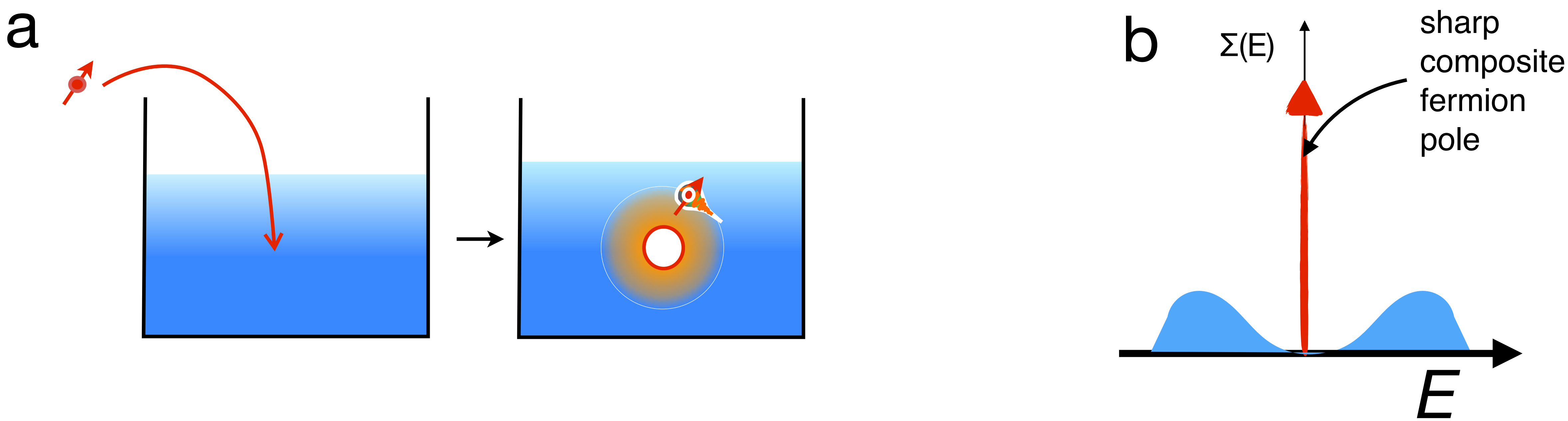

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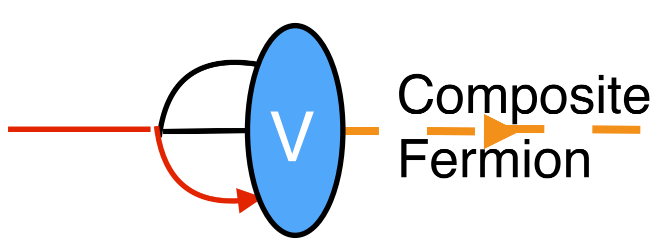
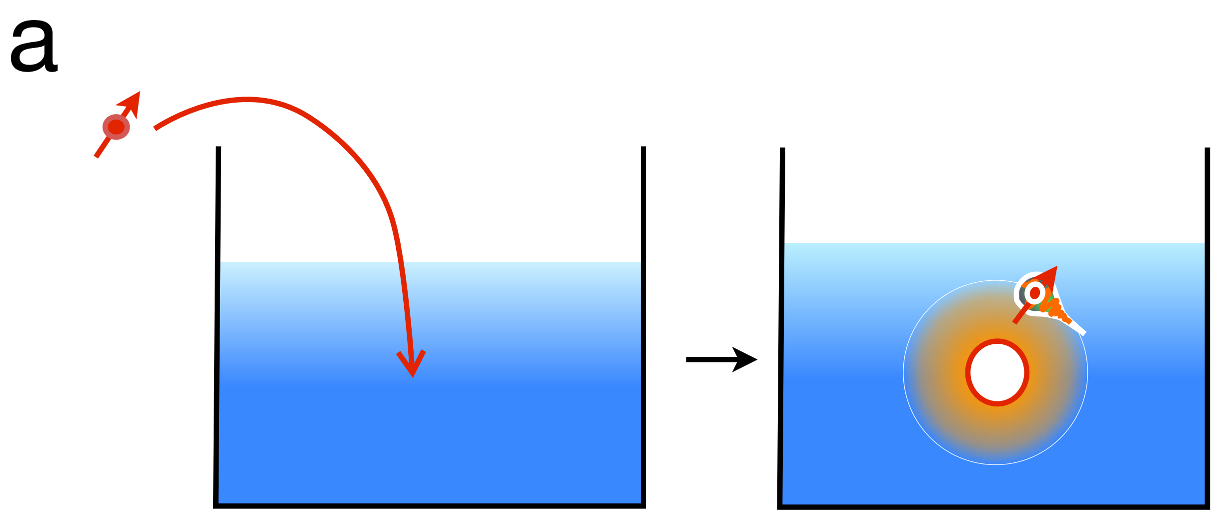
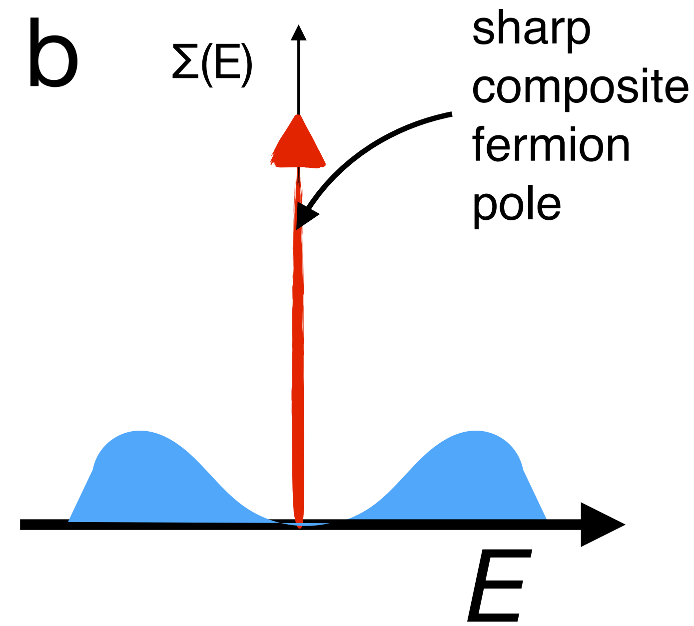


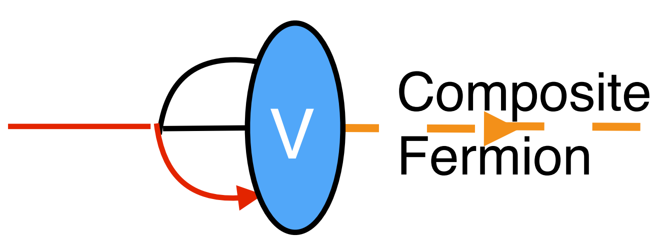
Beyond Hartree Fock/BCS: 3 body Bound States





$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \psi^{\dagger}_{0} \vec{\sigma} \psi_0 \cdot \vec{S}_0$$

$$\Sigma(\omega) \sim \frac{V^2}{\omega}$$



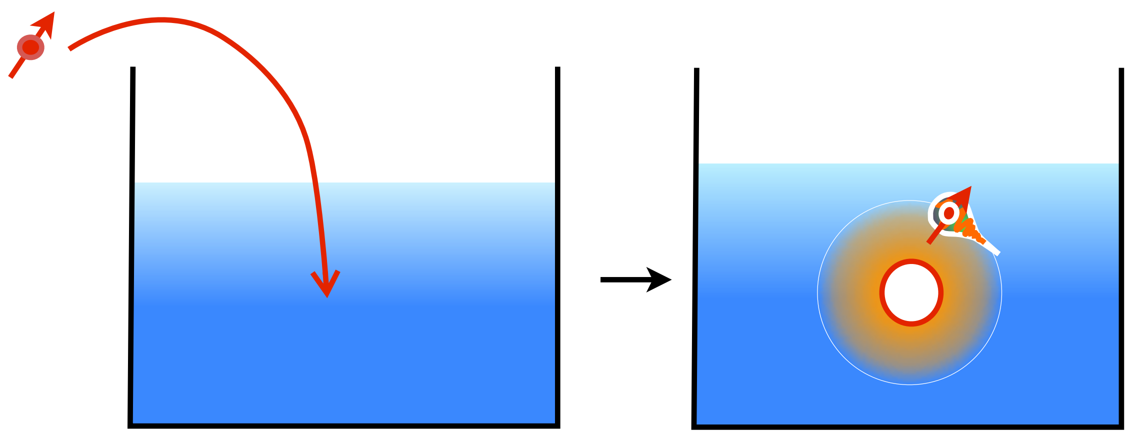
$$\mathcal{F}_{\alpha} = J(\vec{\sigma} \cdot \vec{S}_0)\psi_{0\alpha} \rightarrow V f_{\alpha}(0)$$

Read and Newns, 1983

Three-body Bound State

Beyond Hartree Fock/BCS: 3 body Bound States

a



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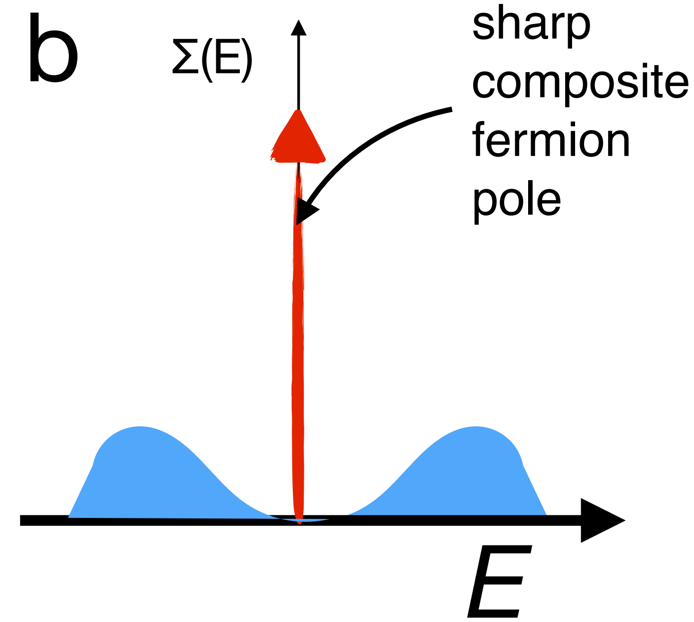
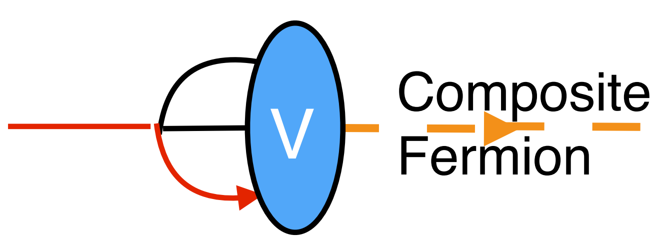


$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + V(\psi^{\dagger}_{j} f_{j} + \mathrm{H.c})$$

$$\Sigma(\omega) \sim \frac{V^2}{\omega}$$

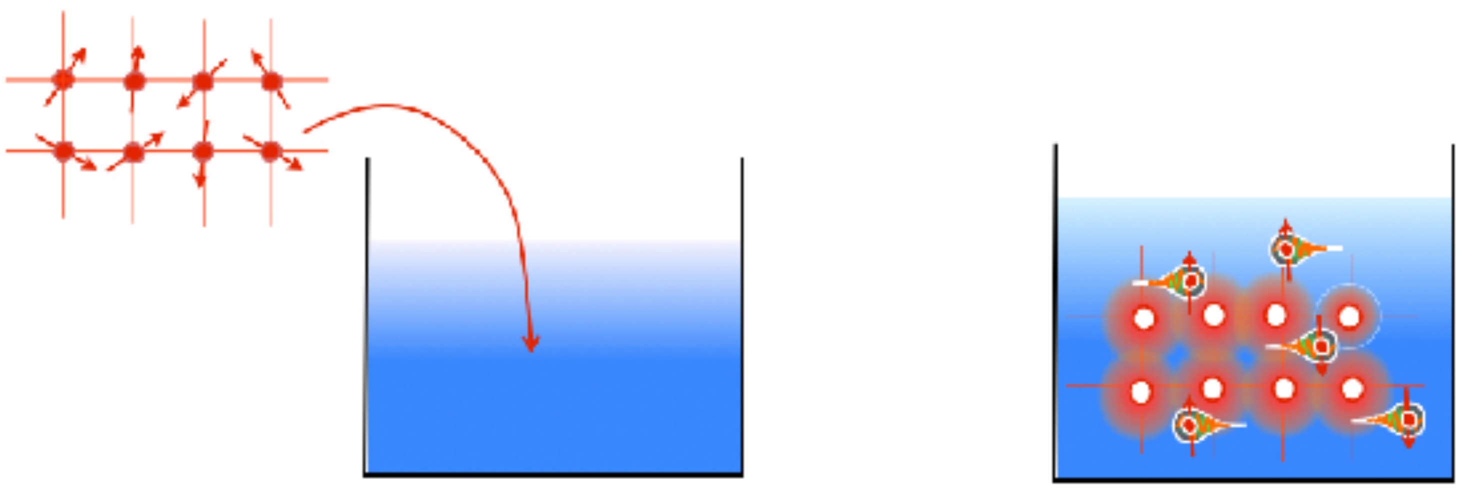


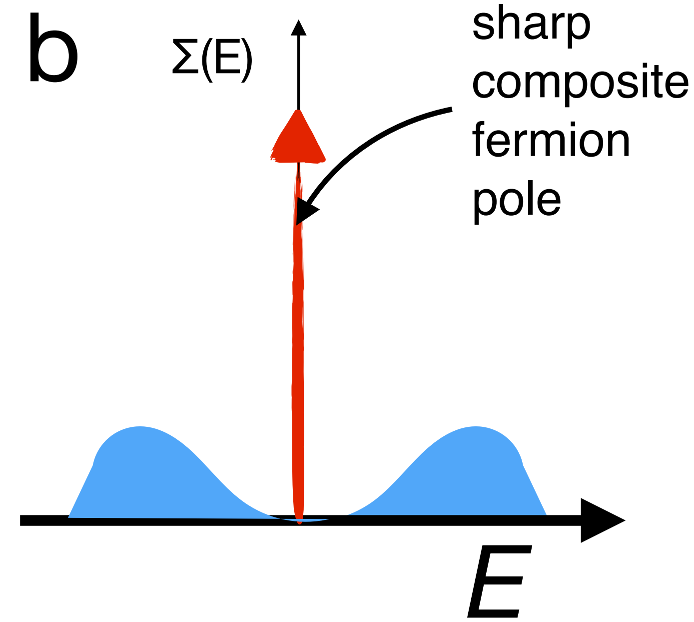
$$\mathcal{F}_{\alpha} = J(\vec{\sigma} \cdot \vec{S}_0)\psi_{0\alpha} \rightarrow V f_{\alpha}(0)$$

Read and Newns, 1983

Three-body Bound State

Beyond Hartree Fock/BCS: 3 body Bound States





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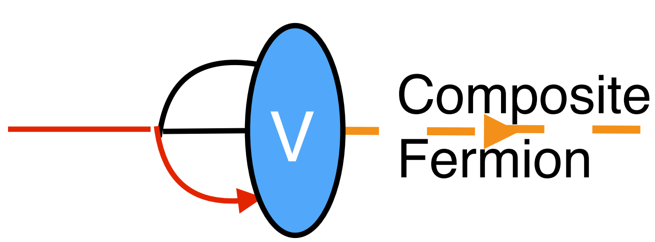

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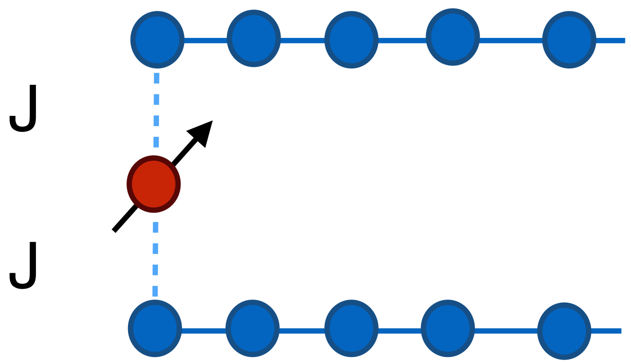
Read and Newns, 1983

Three-body Bound State

Order Parameter Fractionalization Hypothesis

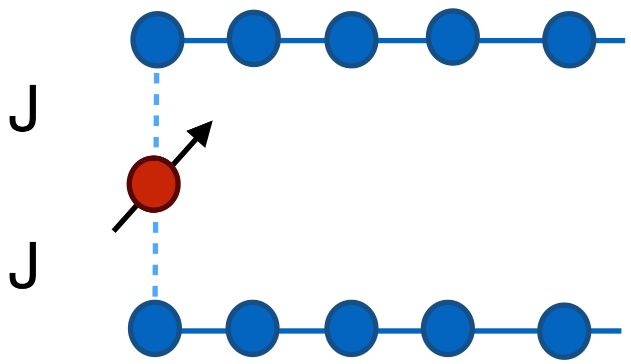
P. Chandra, P. Coleman, Y. Komijani



2-channel Kondo

Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani



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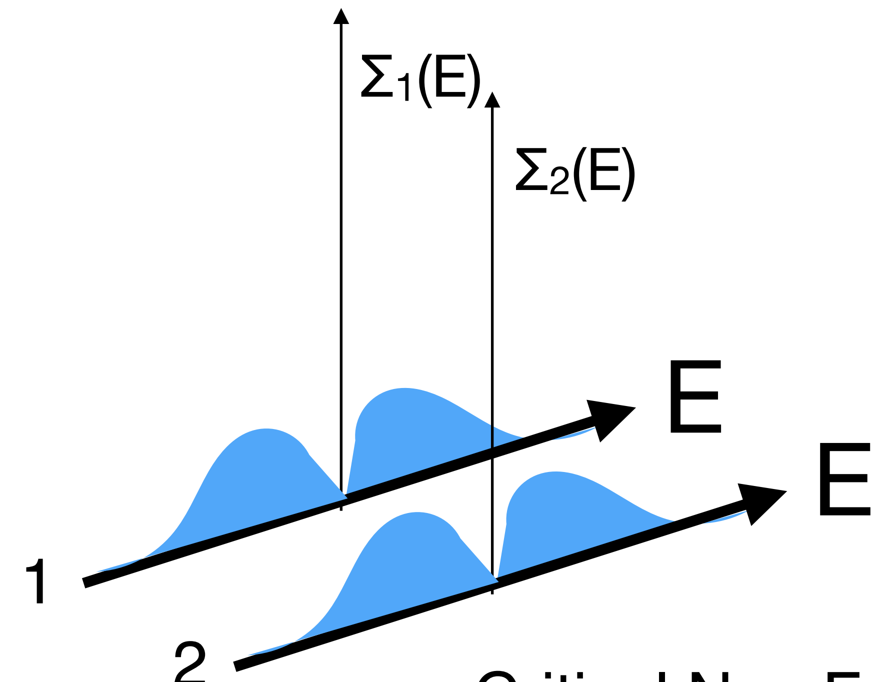
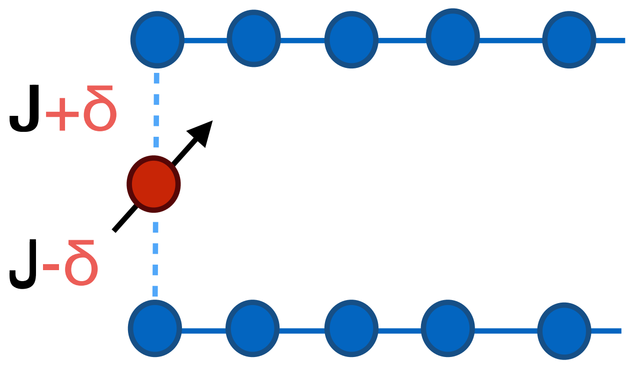


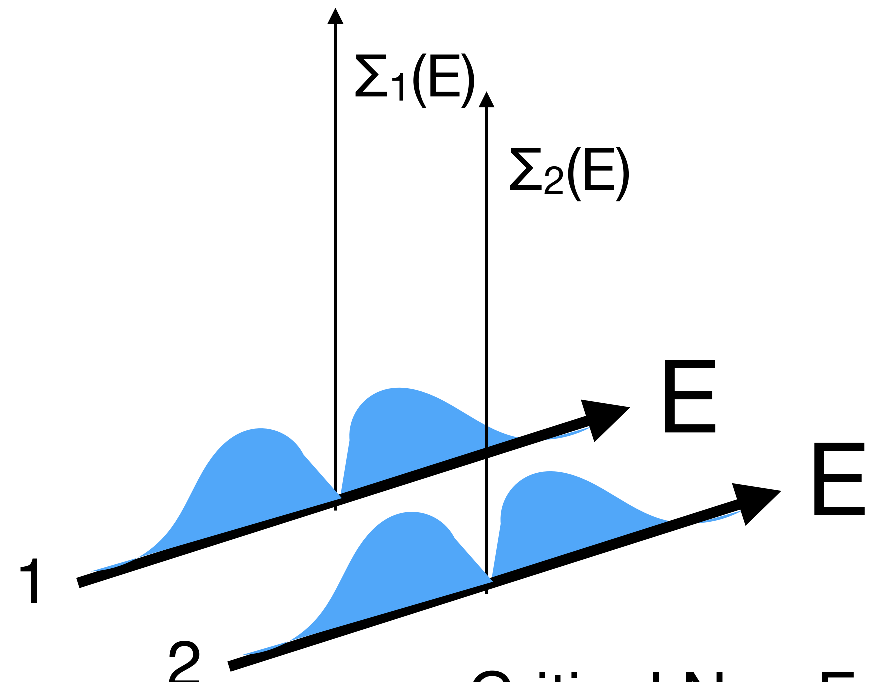
Critical Non Fermi LIquid

Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani



2-channel Kondo



Critical Non Fermi LIquid

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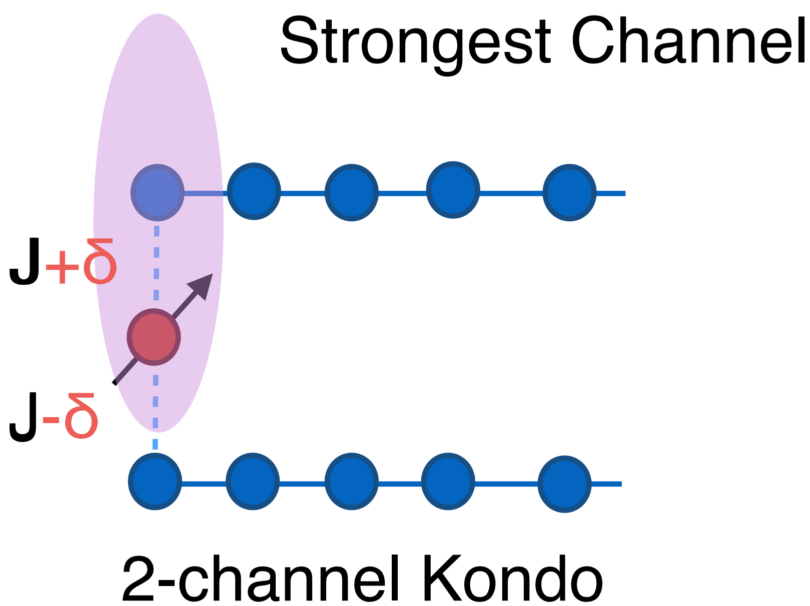
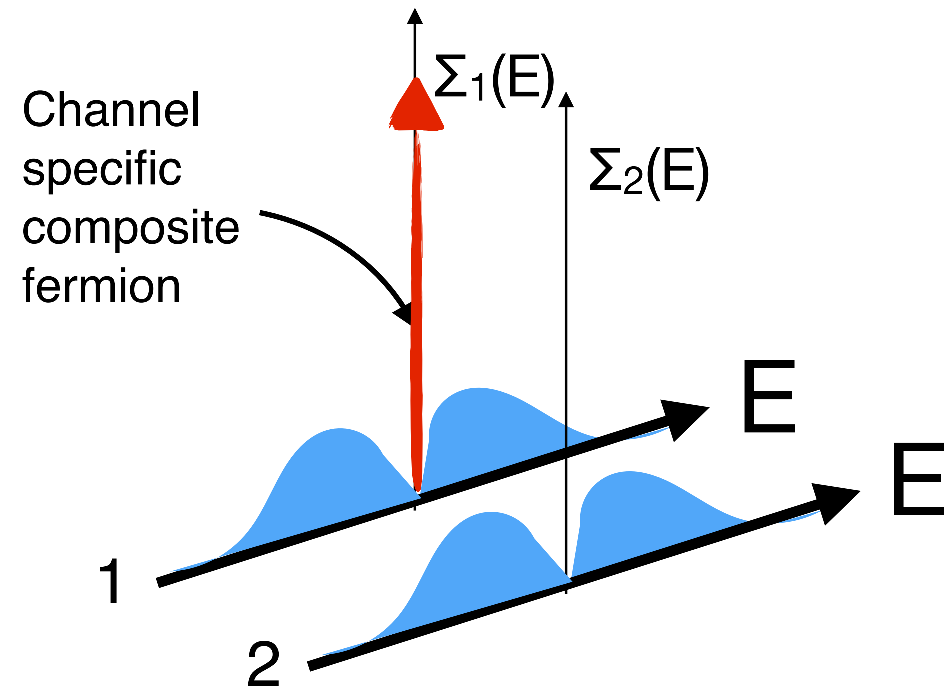
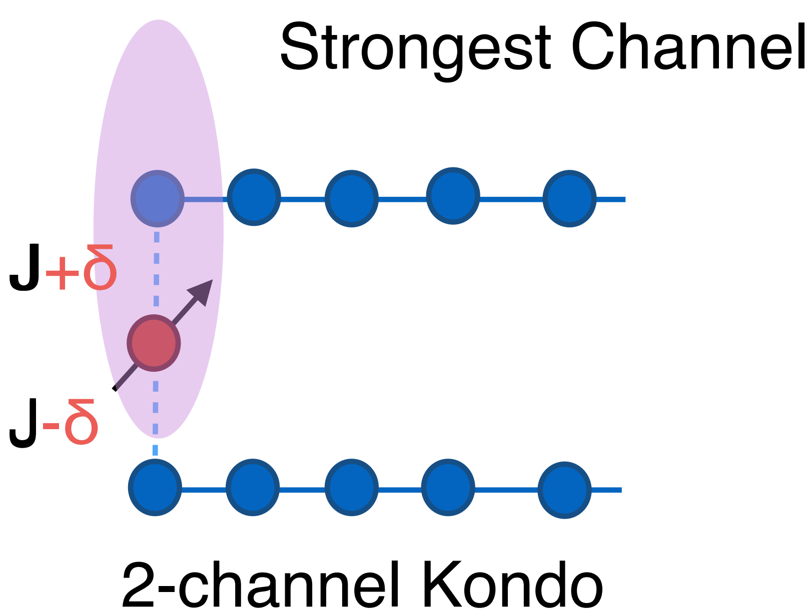
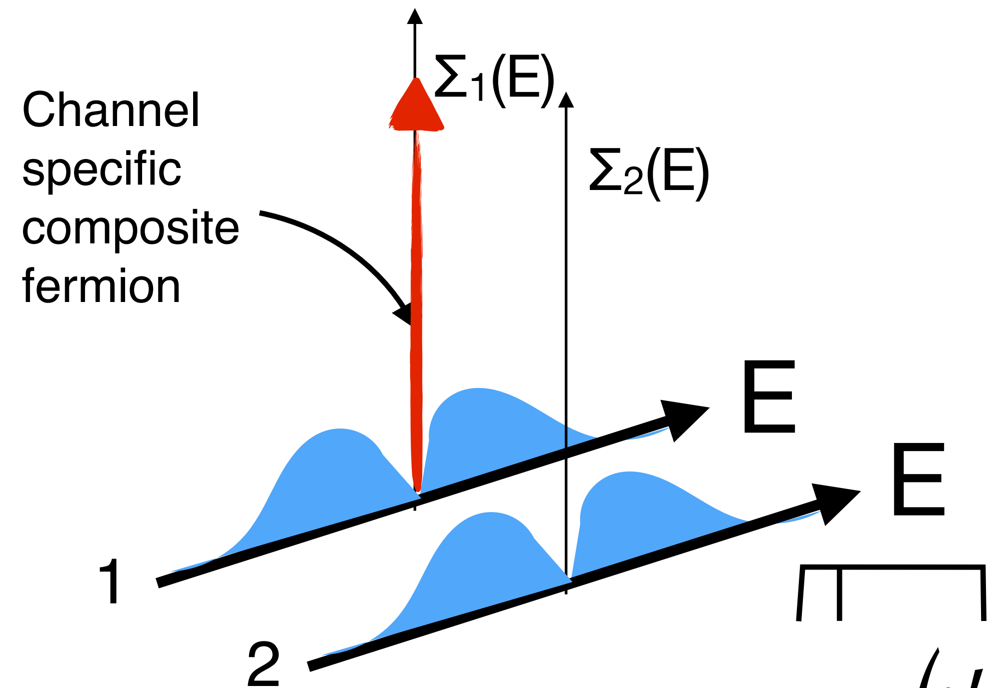




Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani

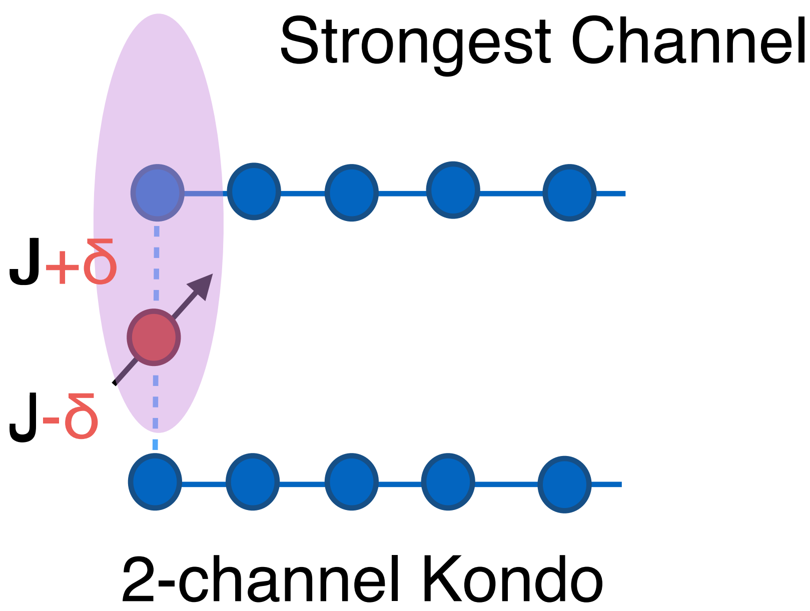


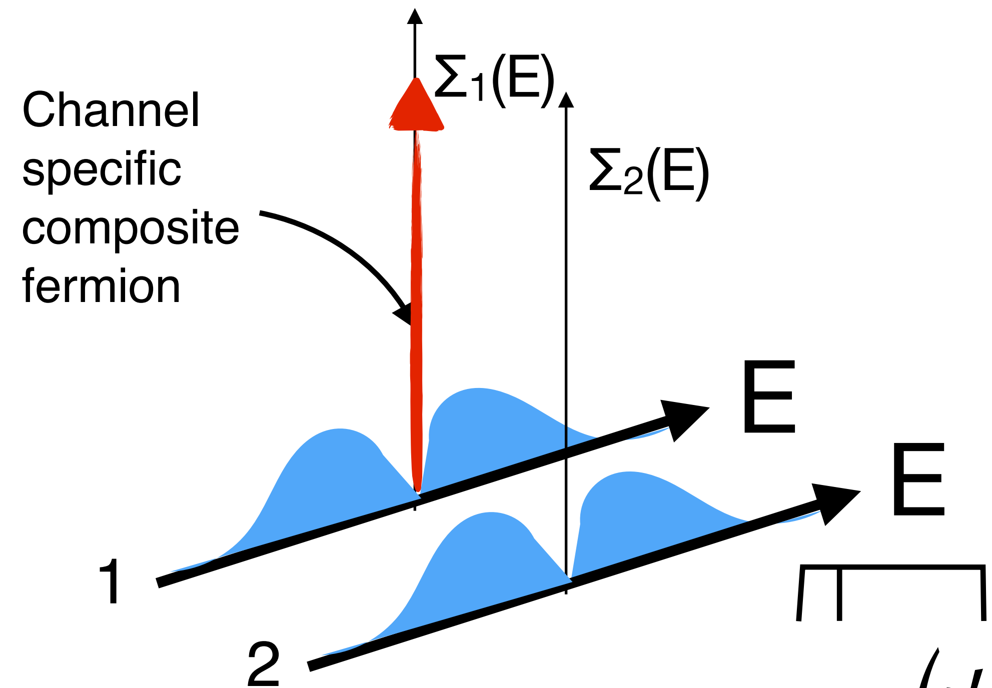


$$(\vec{\sigma}_{\alpha\beta} \cdot \vec{S}_0) \begin{pmatrix} \psi_{1\beta} \\ \psi_{2\beta} \end{pmatrix} \rightarrow \begin{pmatrix} V \\ 0 \end{pmatrix} f_\beta$$

Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani



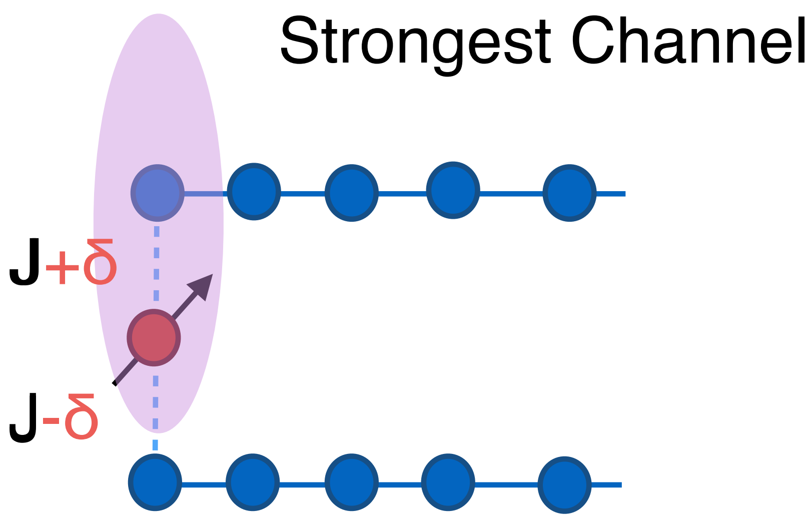


$$(\vec{\sigma}_{\alpha\beta}\cdot\vec{S}_0)\begin{pmatrix}\psi_{1\beta}\\ \psi_{2\beta}\end{pmatrix}\rightarrow\begin{pmatrix}V\\ 0\end{pmatrix}f_\beta$$

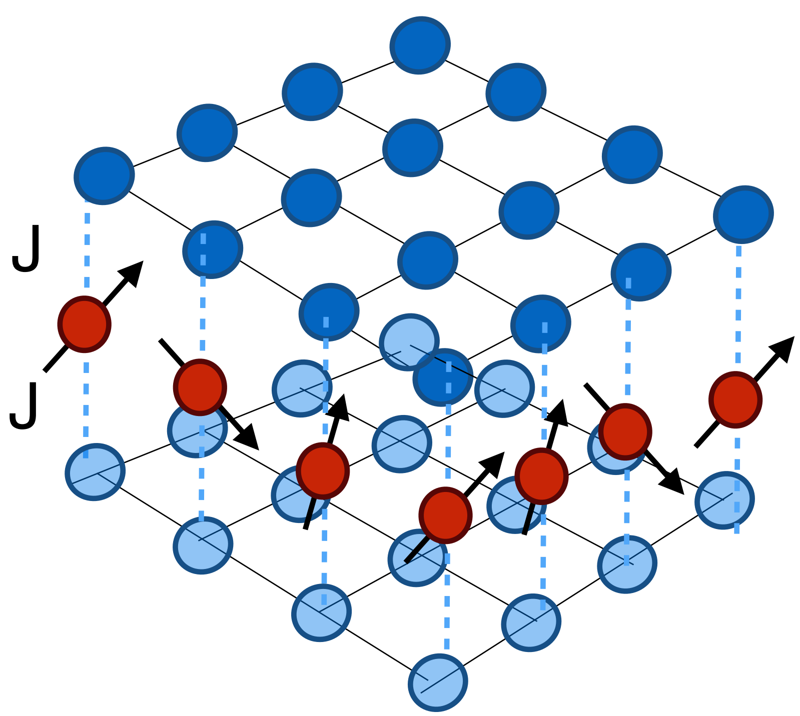
Hybridization Weiss Field

Order Parameter Fractionalization Hypothesis

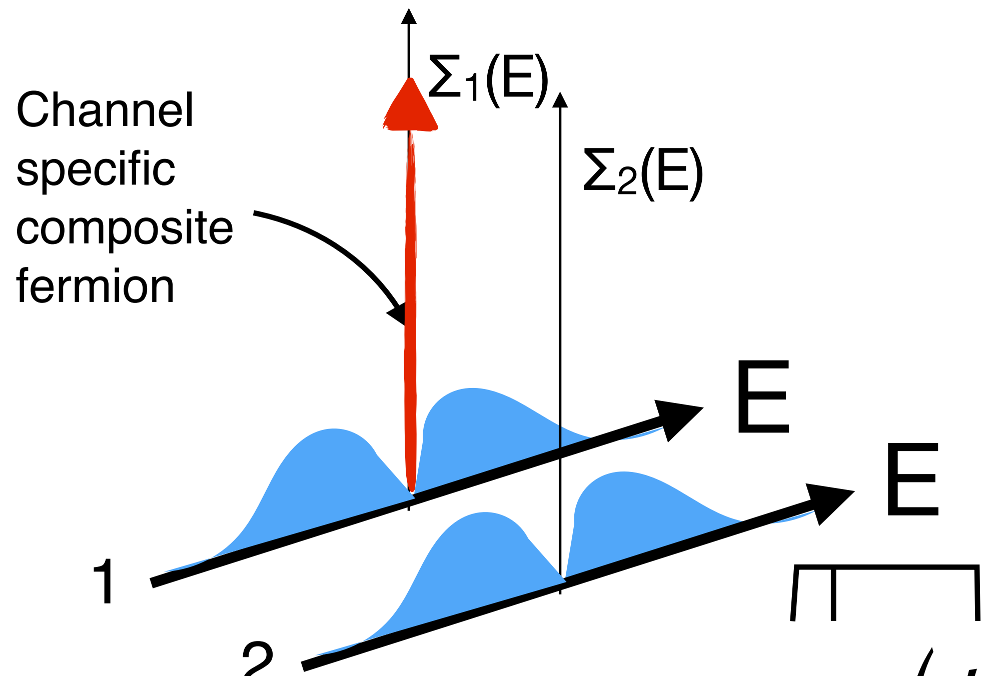
P. Chandra, P. Coleman, Y. Komijani



2-channel Kondo



2-channel Kondo Lattice



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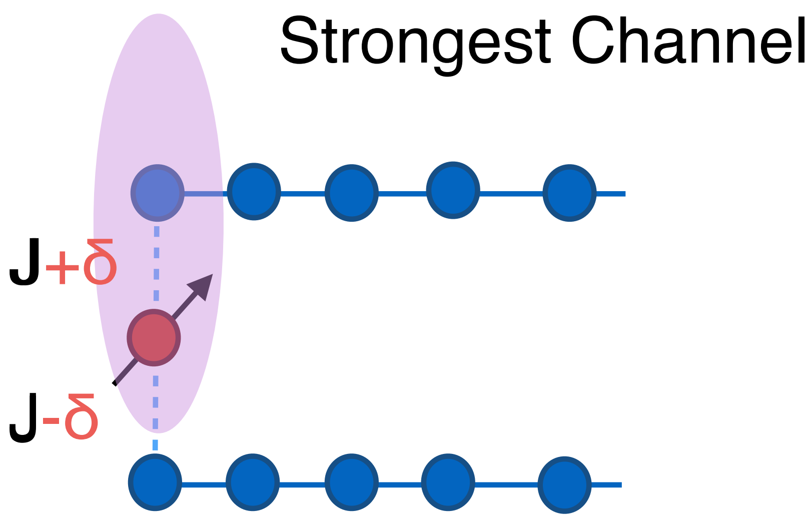
Hybridization Weiss Field

Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani



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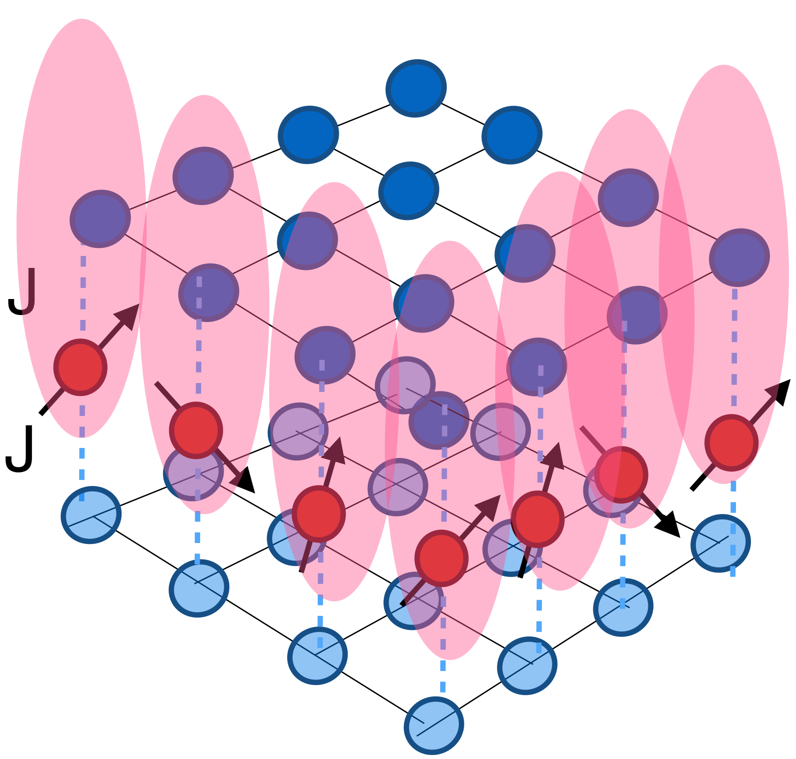

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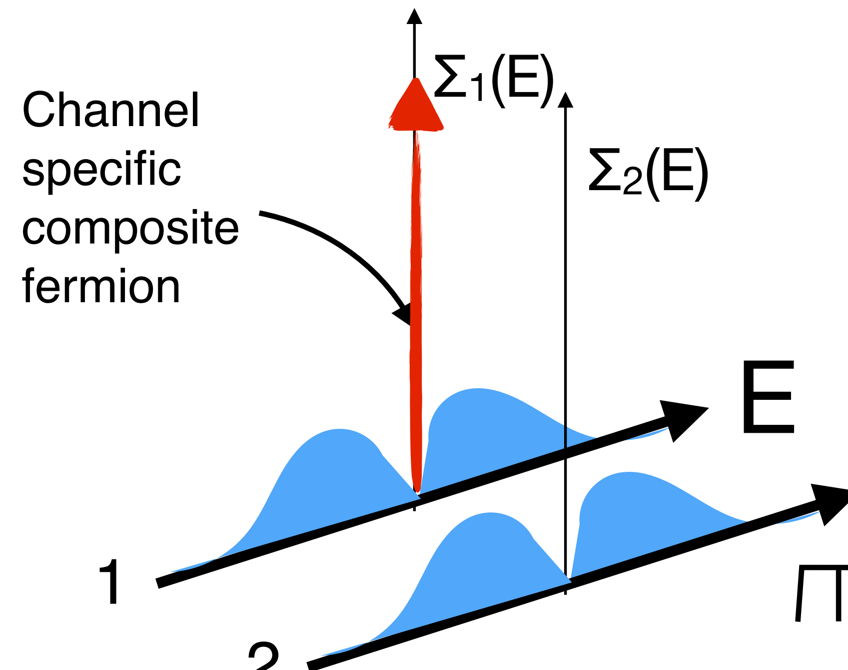

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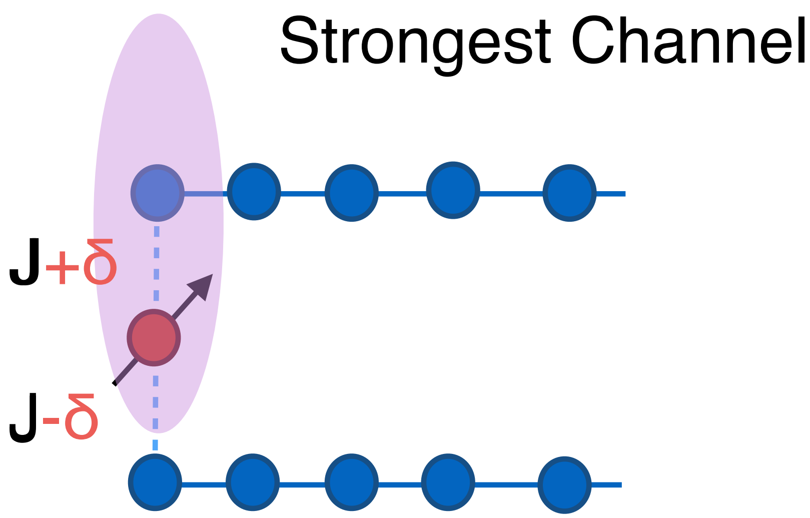
Hybridization Weiss Field

$$(\vec{\sigma}_{\alpha\beta}\cdot\vec{S}_j)\psi_{\lambda\beta}\rightarrow V_\lambda f_\alpha(0)$$

Spinor OP Forms Spontaneously

Order Parameter Fractionalization Hypothesis

P. Chandra, P. Coleman, Y. Komijani



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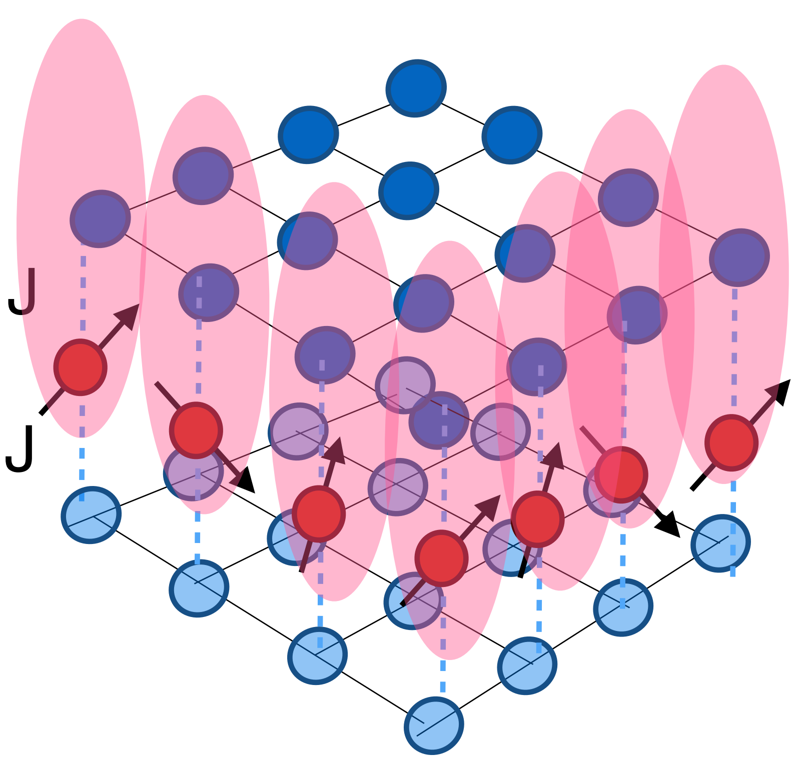
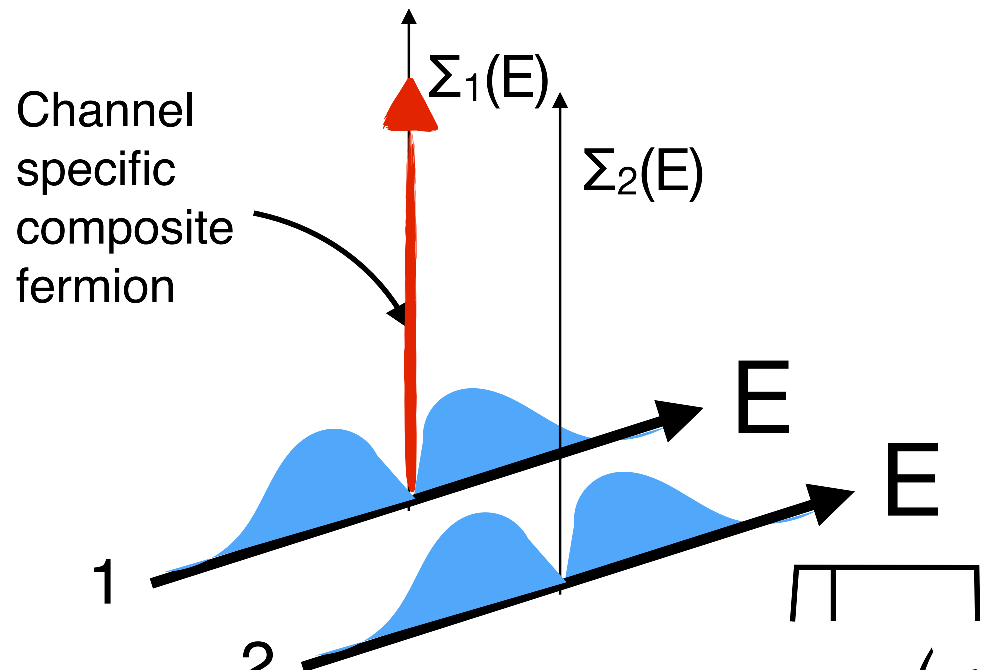


2-channel Kondo Lattice



$$(\vec{\sigma}_{\alpha\beta} \cdot \vec{S}_0) \begin{pmatrix} \psi_{1\beta} \\ \psi_{2\beta} \end{pmatrix} \rightarrow \begin{pmatrix} V \\ 0 \end{pmatrix} f_\beta$$

Hybridization Weiss Field

$$(\vec{\sigma}_{\alpha\beta} \cdot \vec{S}_j)\psi_{\lambda\beta} \rightarrow V_\lambda f_\alpha(0)$$

Spinor OP Forms Spontaneously

Fractionalization of Bound-State into Fermion+OP

Order Parameter Fractionalization Hypothesis

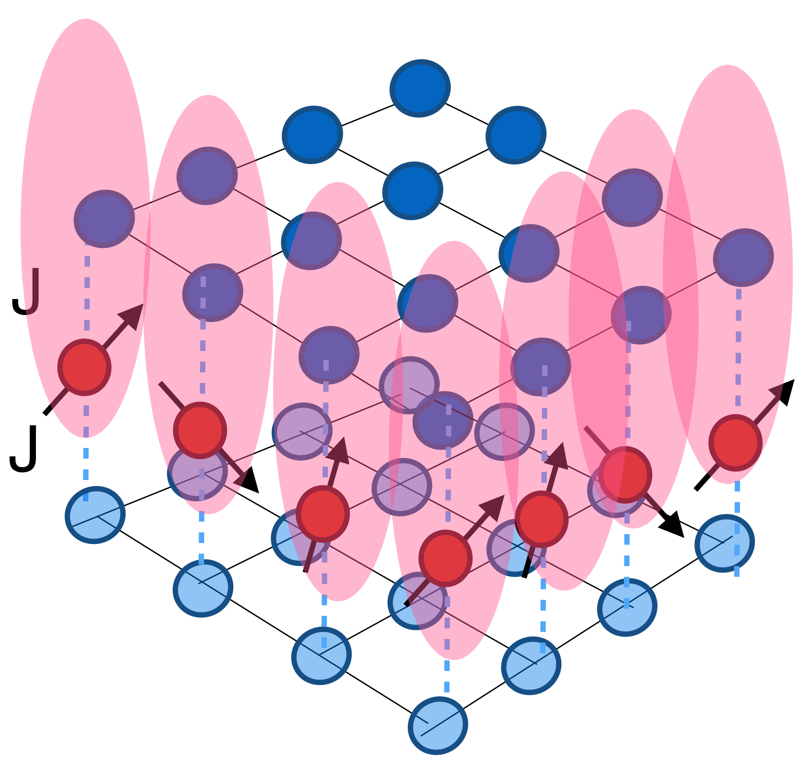
P. Chandra, P. Coleman, Y. Komijani

Composite order

$$\Psi = \langle \left(\psi_1^\dagger \vec{\sigma} \psi_1 - \psi_2^\dagger \vec{\sigma} \psi_2 \right) \cdot \vec{S} \rangle$$

$$\propto |V_1|^2 - |V_2|^2$$

Emery and Kivelson 1993



2-channel Kondo Lattice

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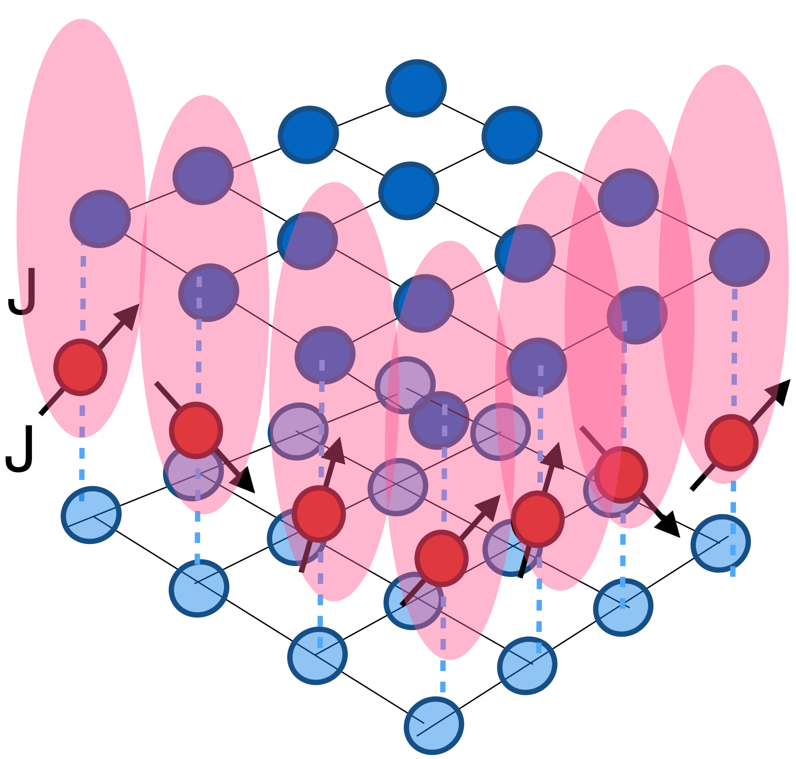

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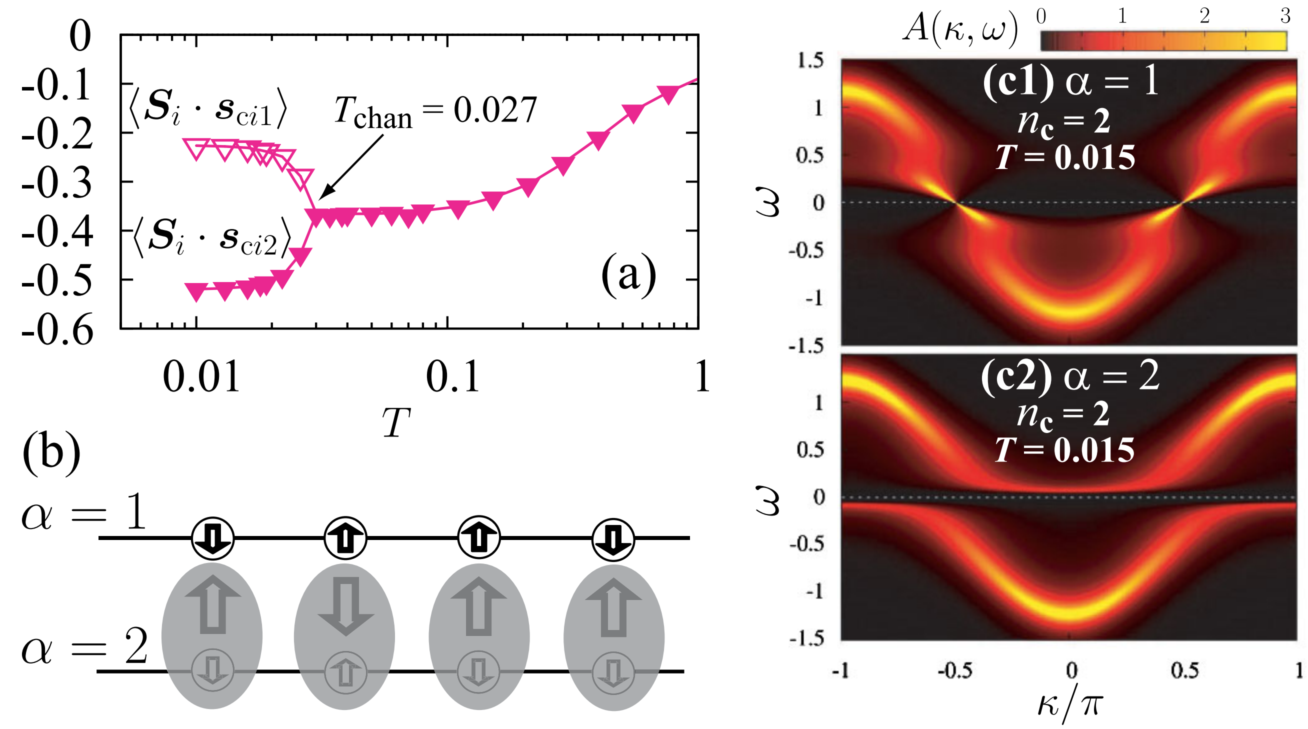


Hisono, Otsuki & Kuromoto, PRL 107, 247202 (2011)

$$(\vec{\sigma}_{\alpha\beta}\cdot\vec{S}_j)\psi_{\lambda\beta} \rightarrow V_\lambda f_\alpha(0)$$

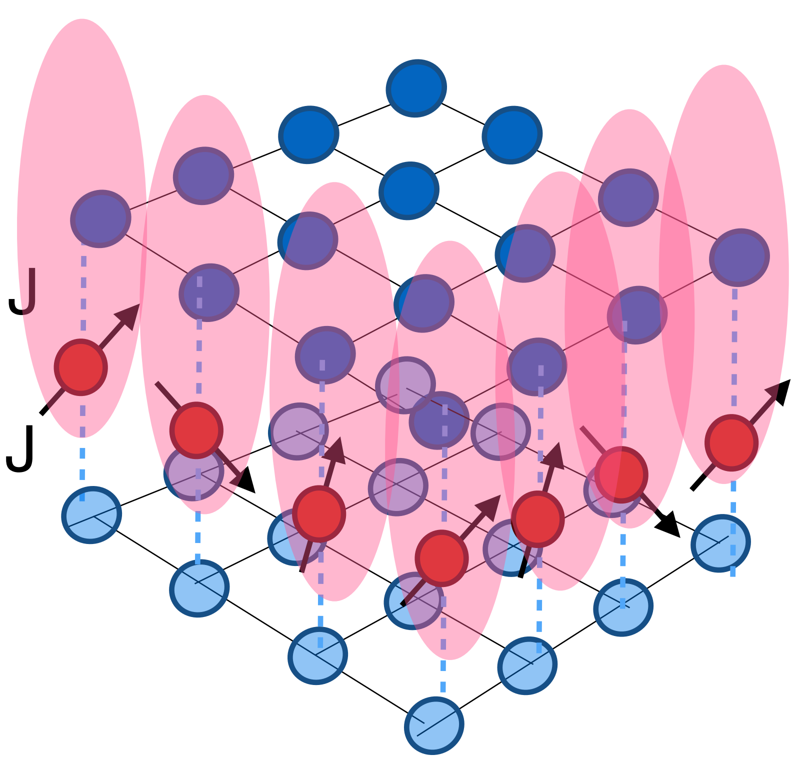
Spinor OP Forms Spontaneously

Fractionalization of Bound-State into Fermion+OP

Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

				Composite Order
Kondo	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_\beta$	$V f_\alpha$	HF	$\langle \psi^\dagger(\vec{\sigma}\cdot\vec{S})\psi\rangle \propto \vert V\vert^2$
Majorana		$(\vec{\sigma}\cdot\vec{\eta})_{\alpha\beta}\mathcal{V}_\beta$	Odd-w triplet/ Skyrme Insulator	$\langle \psi_\uparrow\psi_\downarrow\vec{S}\rangle \propto \mathcal{V}^T\vec{\sigma}\sigma_2\mathcal{V}$
2-channel	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_{\lambda\beta}$	$V_\lambda f_\alpha$	Composite Multipole	$\langle\left(\psi_1^\dagger\vec{\sigma}\psi_1 - \psi_2^\dagger\vec{\sigma}\psi_2\right)\cdot\vec{S}\rangle$
		$V_\lambda f_\alpha + \Delta_\lambda \bar{\alpha} f^\dagger_{-\alpha}$	Composite Pair	$\langle(\psi_1\vec{\sigma}\sigma_2\psi_2)\cdot\vec{S}\rangle$
		$\Psi_\alpha\hat{\chi}_\lambda$	Hastatic	$\langle c^\dagger\vec{\sigma}\left(\vec{I}\cdot\vec{\tau}\right)c\rangle \propto \Psi^\dagger\vec{\sigma}\,\Psi$



2-channel Kondo Lattice

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$$(\vec{\sigma}_{\alpha\beta}\cdot\vec{S}_j)\psi_{\lambda\beta} \rightarrow V_\lambda f_\alpha(0)$$

Spinor OP Forms Spontaneously

Fractionalization of Bound-State into Fermion+OP

Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

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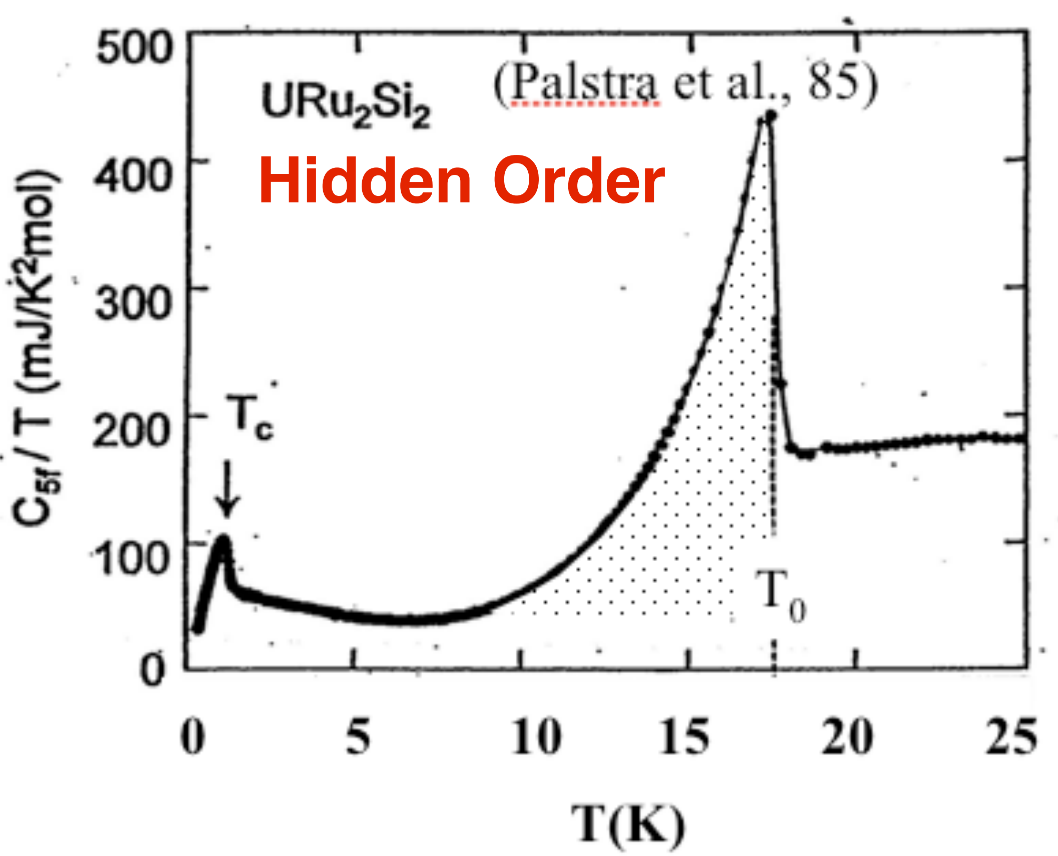
		$\Psi_\alpha\hat{\chi}_\lambda$	Hastatic	$\langle c^\dagger\vec{\sigma}\left(\vec{I}\cdot\vec{\tau}\right)c\rangle \propto \Psi^\dagger\vec{\sigma}\,\Psi$



Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

				Composite Order
Kondo	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_\beta$	$V f_\alpha$	HF	$\langle\psi^\dagger(\vec{\sigma}\cdot\vec{S})\psi\rangle \propto \|V\|^2$
Majorana		$(\vec{\sigma}\cdot\vec{\eta})_{\alpha\beta}\mathcal{V}_\beta$	Odd-w triplet/ Skyrme Insulator	$\langle\psi_\uparrow\psi_\downarrow\vec{S}\rangle \propto \mathcal{V}^T\vec{\sigma}\sigma_2\mathcal{V}$
2-channel	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_{\lambda\beta}$	$V_\lambda f_\alpha$	Composite Multipole	$\langle\left(\psi_1^\dagger\vec{\sigma}\psi_1 - \psi_2^\dagger\vec{\sigma}\psi_2\right)\cdot\vec{S}\rangle$
		$V_\lambda f_\alpha + \Delta_\lambda\bar{\alpha} f^\dagger_{-\alpha}$	Composite Pair	$\langle(\psi_1\vec{\sigma}\sigma_2\psi_2)\cdot\vec{S}\rangle$
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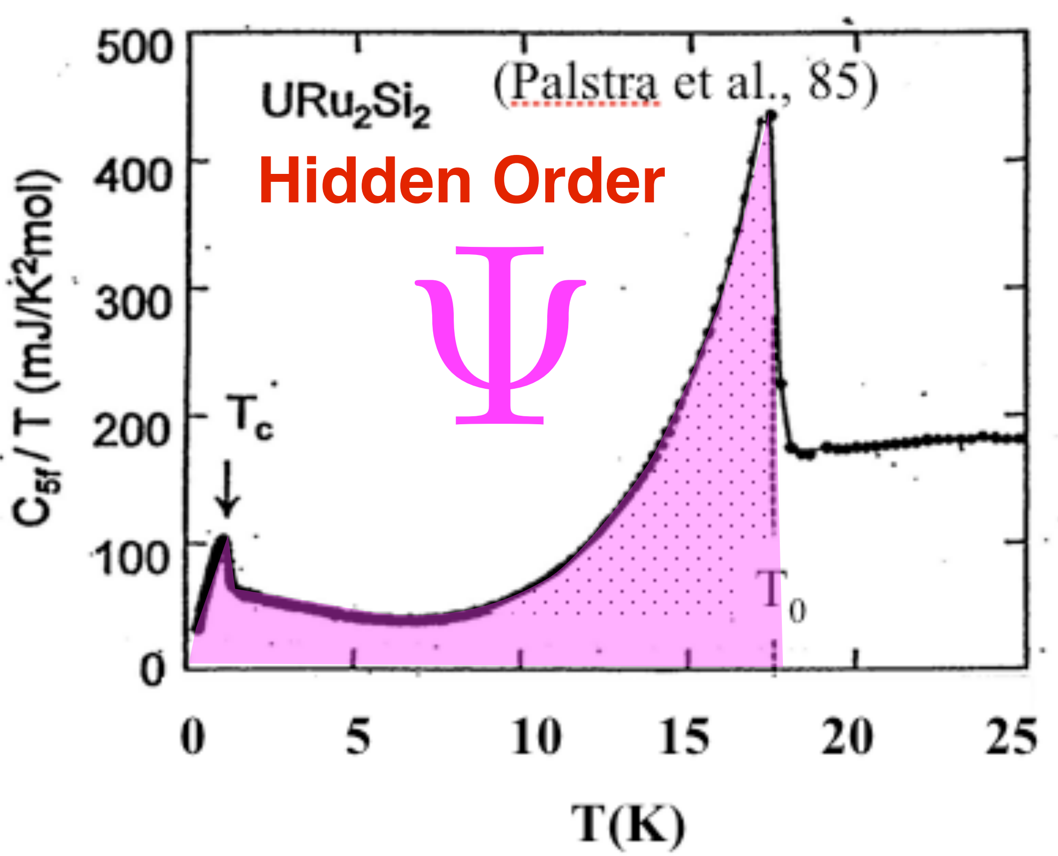

Order Parameter Fractionalization Hypothesis

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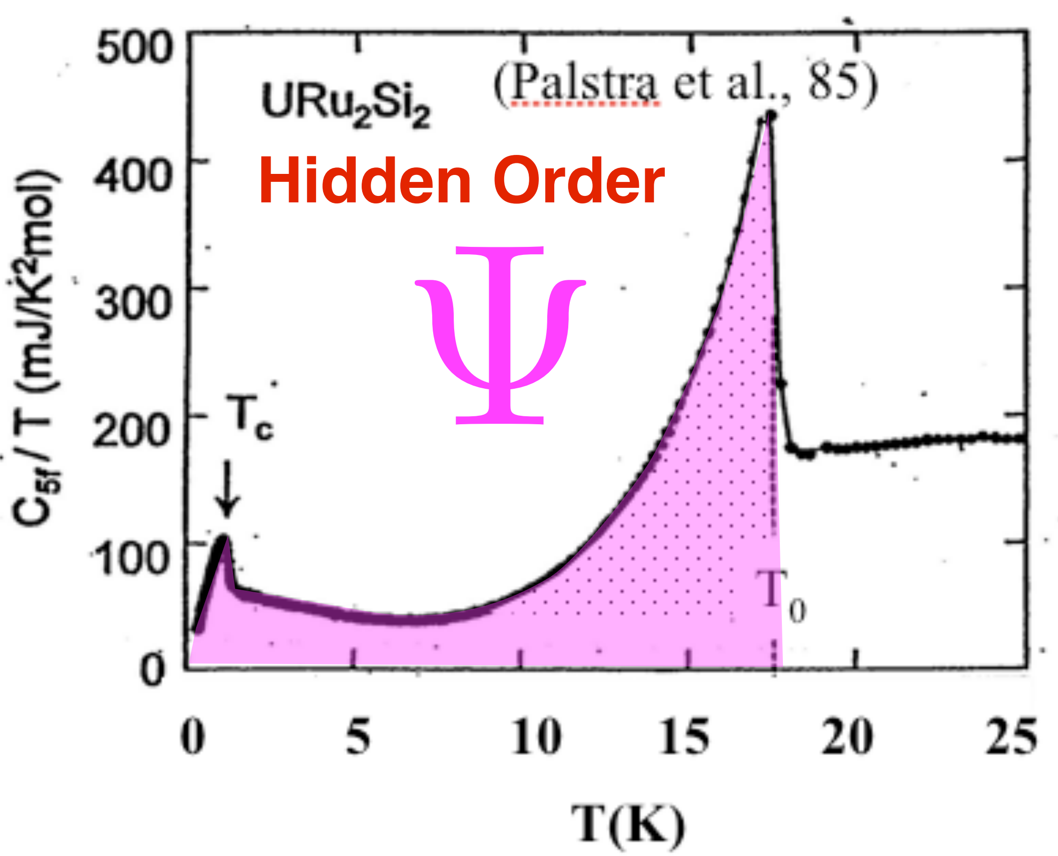
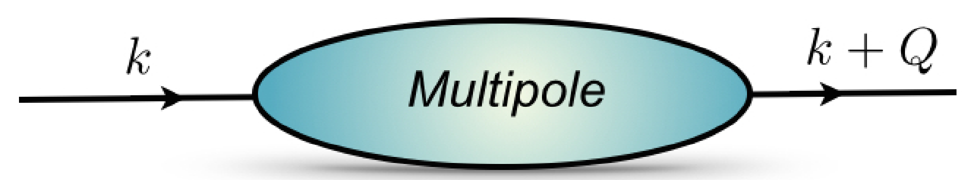
2-channel	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_{\lambda\beta}$	$V_\lambda f_\alpha$	Composite Multipole	$\langle\left(\psi_1^\dagger\vec{\sigma}\psi_1-\psi_2^\dagger\vec{\sigma}\psi_2\right)\cdot\vec{S}\rangle$
		$V_\lambda f_\alpha + \Delta_\lambda\bar{\alpha}f^\dagger_{-\alpha}$	Composite Pair	$\langle\left(\psi_1\vec{\sigma}\sigma_2\psi_2\right)\cdot\vec{S}\rangle$
		$\Psi_\alpha\hat{\chi}_\lambda$	Hastatic	$\langle c^\dagger\vec{\sigma}\left(\vec{I}\cdot\vec{\tau}\right)c\rangle \propto \Psi^\dagger\vec{\sigma}\,\Psi$





See eg:

J=3 Kiss & Fazekas, Phys Rev B, (2005)
J=4 Kotliar & Haule, Nat Phys, (2009)
J=5 Ikeda et al, Nat. Phys (2012)

Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

Composite Order

Kondo	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_\beta$	$V f_\alpha$	HF	$\langle\psi^\dagger(\vec{\sigma}\cdot\vec{S})\psi\rangle \propto \lvert V\rvert^2$
Majorana		$(\vec{\sigma}\cdot\vec{\eta})_{\alpha\beta}\mathcal{V}_\beta$	Odd-w triplet/ Skyrme Insulator	$\langle\psi_\uparrow\psi_\downarrow\vec{S}\rangle \propto \mathcal{V}^T\vec{\sigma}\sigma_2\mathcal{V}$
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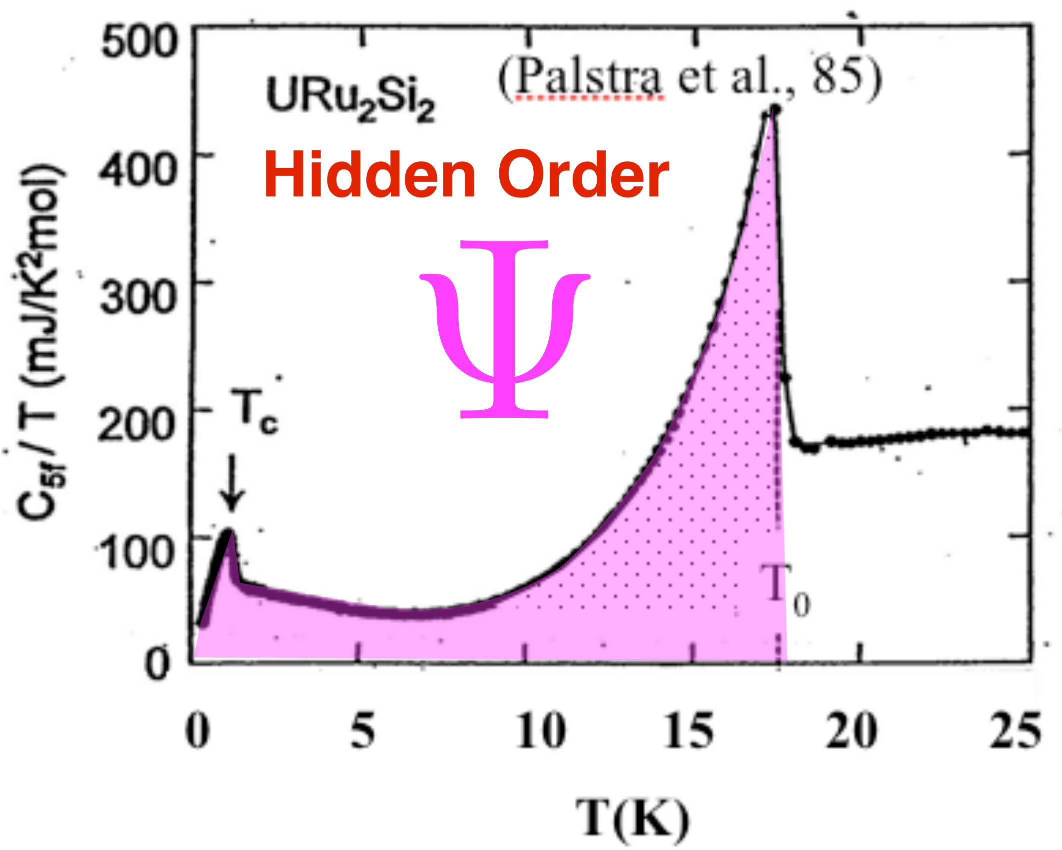
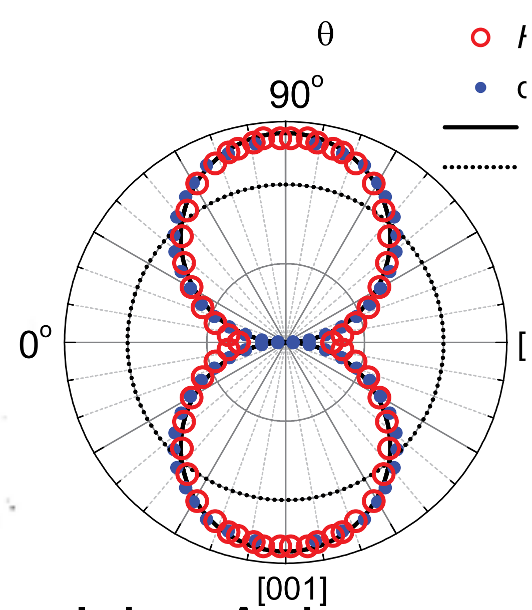
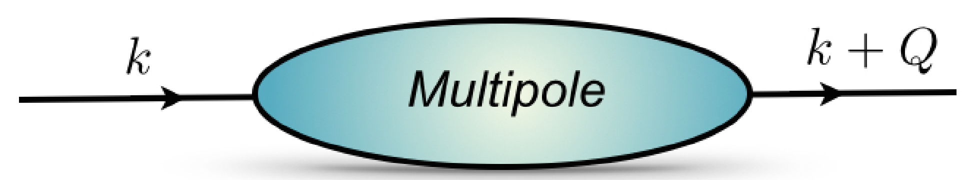
		$V_\lambda f_\alpha + \Delta_\lambda\bar{\alpha}f^\dagger_{-\alpha}$	Composite Pair	$\langle(\psi_1\vec{\sigma}\sigma_2\psi_2)\cdot\vec{S}\rangle$
		$\Psi_\alpha\hat{\chi}_\lambda$	Hastatic	$\langle c^\dagger\vec{\sigma}\left(\vec{I}\cdot\vec{\tau}\right)c\rangle \propto \Psi^\dagger\vec{\sigma}\,\Psi$





Ising Anisotropy



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Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

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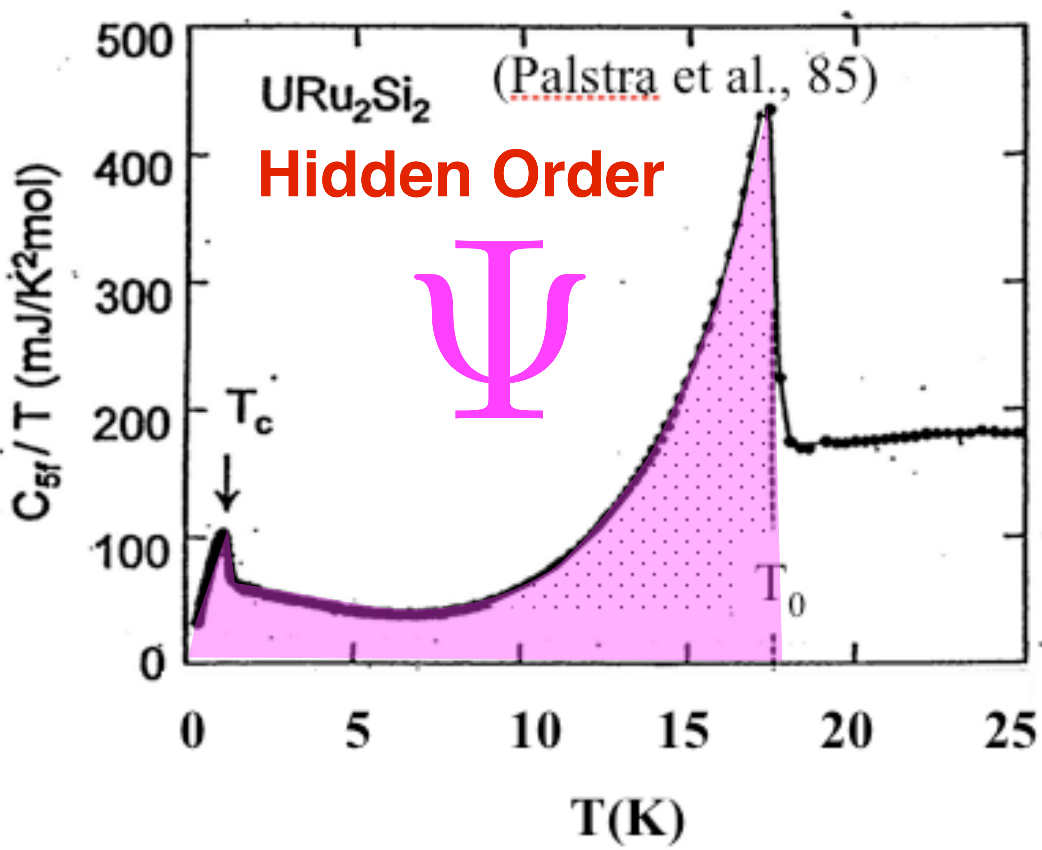
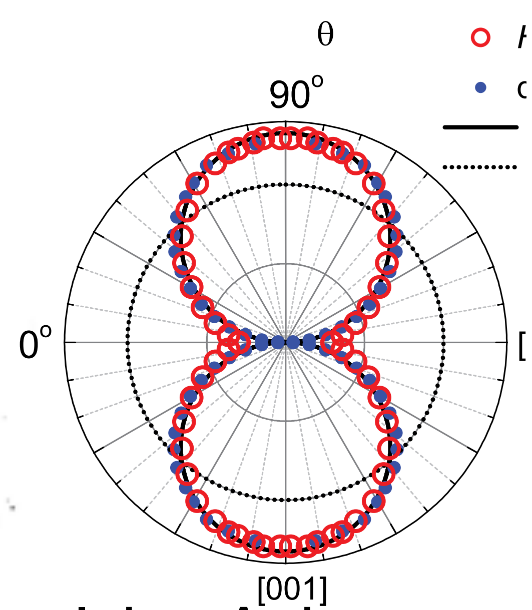
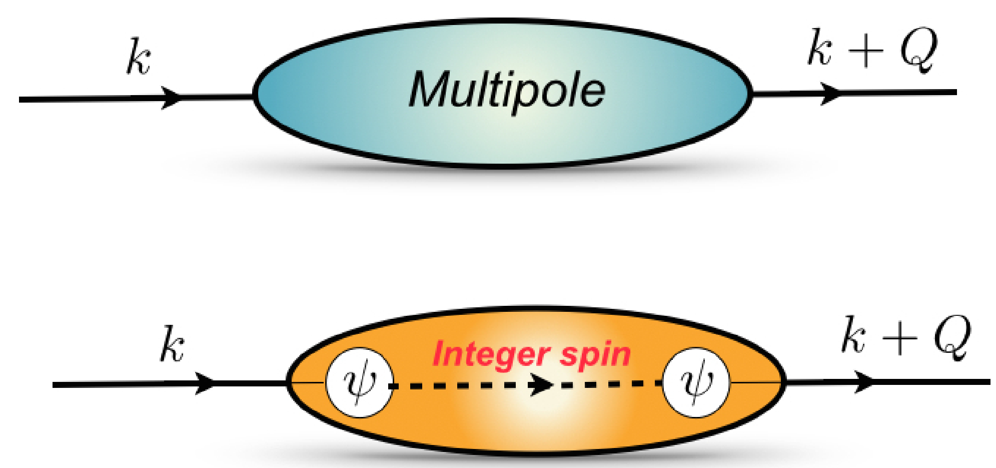
2-channel	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_{\lambda\beta}$	$V_\lambda f_\alpha$	Composite Multipole	$\langle\left(\psi_1^\dagger\vec{\sigma}\psi_1 - \psi_2^\dagger\vec{\sigma}\psi_2\right)\cdot\vec{S}\rangle$
		$V_\lambda f_\alpha + \Delta_\lambda\bar{\alpha}f^\dagger_{-\alpha}$	Composite Pair	$\langle(\psi_1\vec{\sigma}\sigma_2\psi_2)\cdot\vec{S}\rangle$
		$\Psi_\alpha\hat{\chi}_\lambda$	Hastatic	$\langle c^\dagger\vec{\sigma}\left(\vec{I}\cdot\vec{\tau}\right)c\rangle \propto \Psi^\dagger\vec{\sigma}\,\Psi$





Ising Anisotropy



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

Chandra, Coleman, Flint, Nature (2013)

Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

				Composite Order
Kondo	$(\vec{S}\cdot\vec{\sigma})_{\alpha\beta}\psi_\beta$	$V f_\alpha$	HF	$\langle\psi^\dagger(\vec{\sigma}\cdot\vec{S})\psi\rangle \propto \lvert V\rvert^2$
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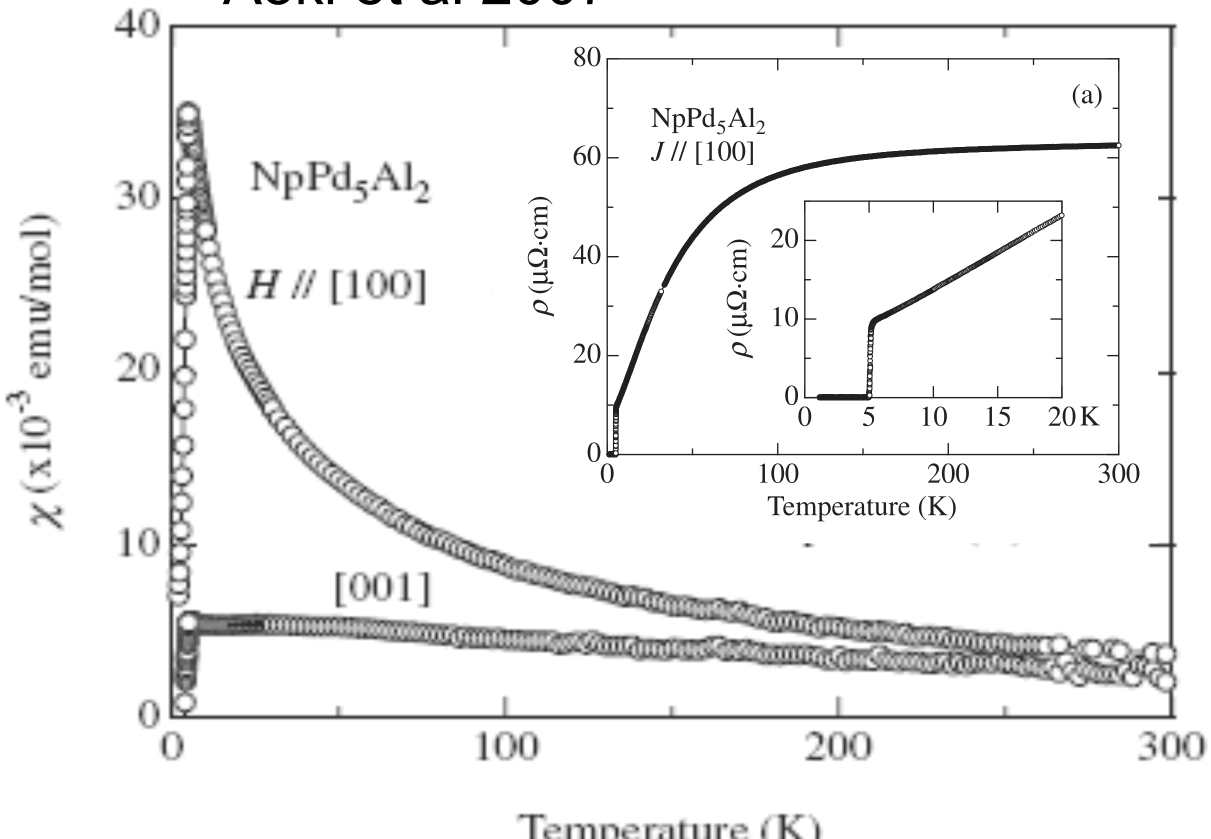
Aoki et al 2007



See: Flint, Dzero, PC, Nat Phys. (2008)

$NpPd_5Al_2$ T_C = 4.5K

Curie Law SC

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P. Chandra, PC, Y. Komijani

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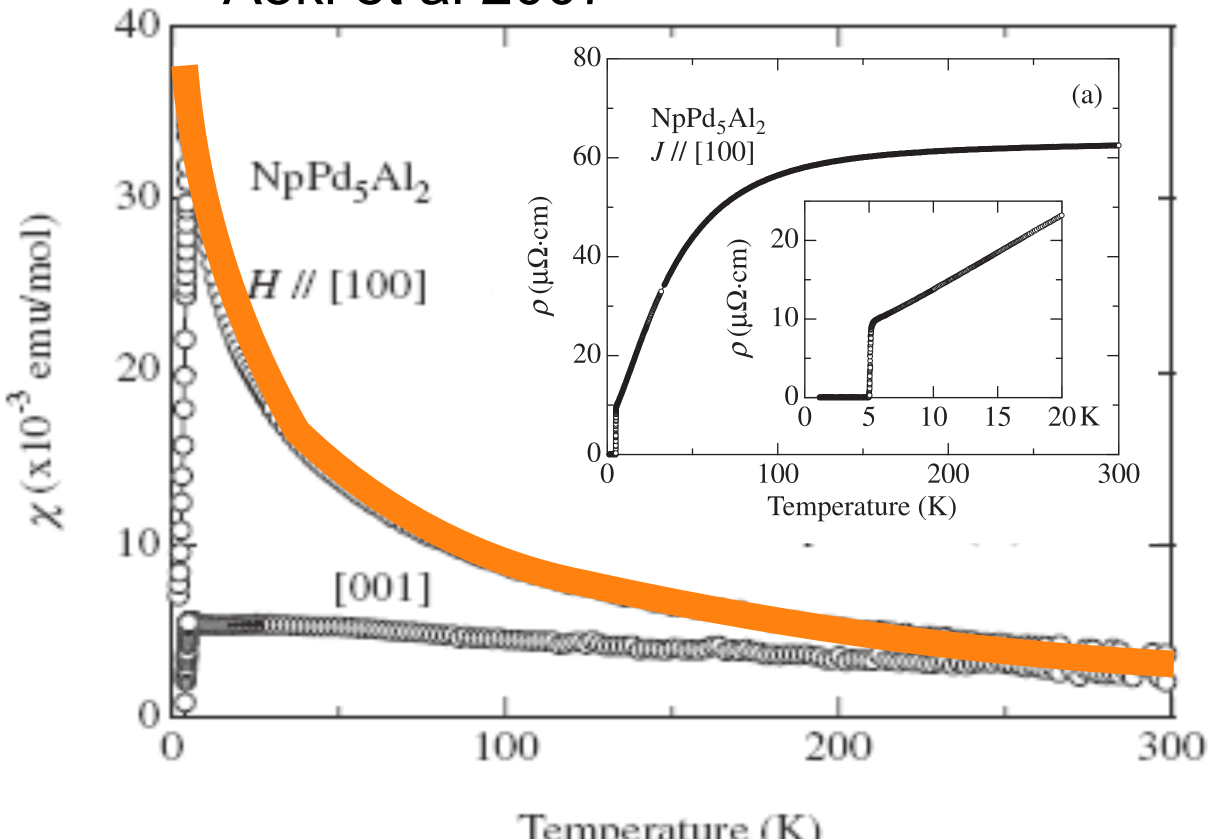
Aoki et al 2007



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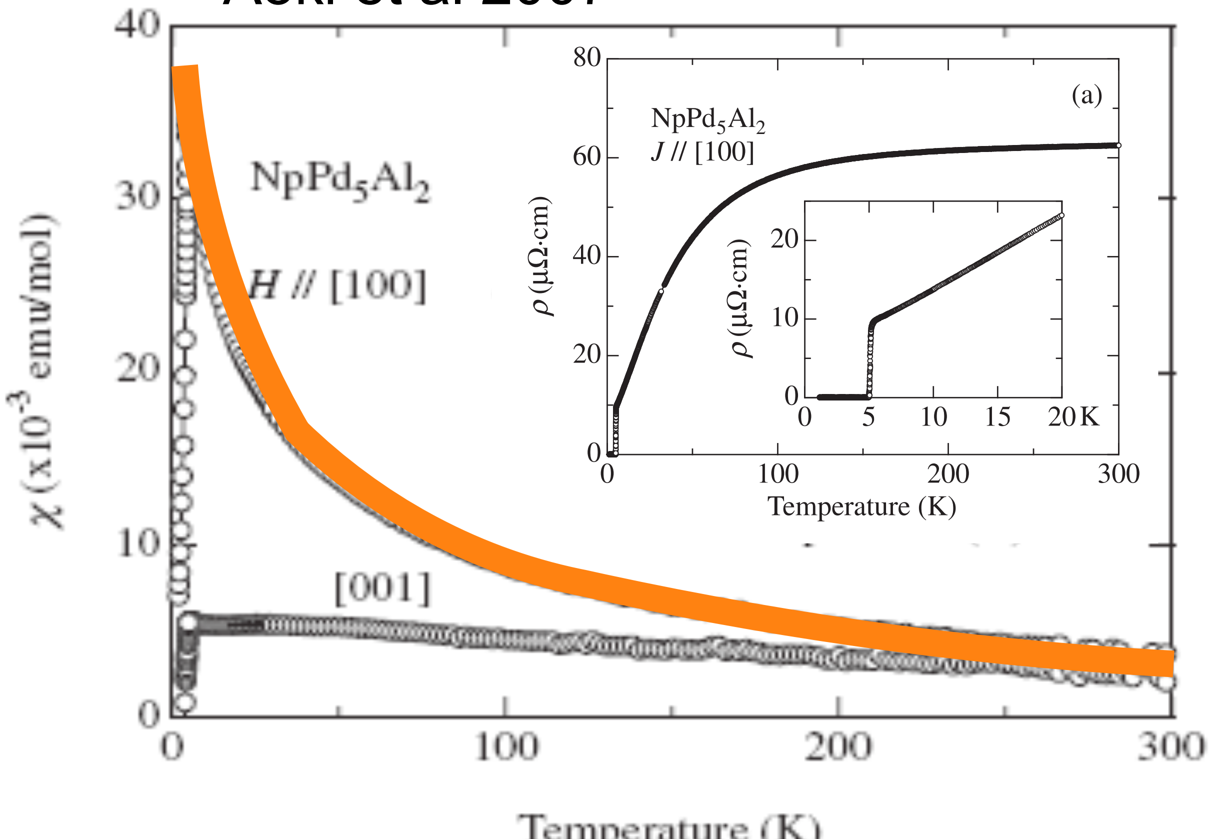
Aoki et al 2007



Composite order

$$\langle(\psi_1\vec{\sigma}\sigma_2\psi_2)\cdot\vec{S}\rangle \propto (V_1\Delta_2 - V_2\Delta_1)$$

See: Flint, Dzero, PC, Nat Phys. (2008)

$NpPd_5Al_2$ $T_C = 4.5K$

Curie Law SC

Order Parameter Fractionalization Hypothesis

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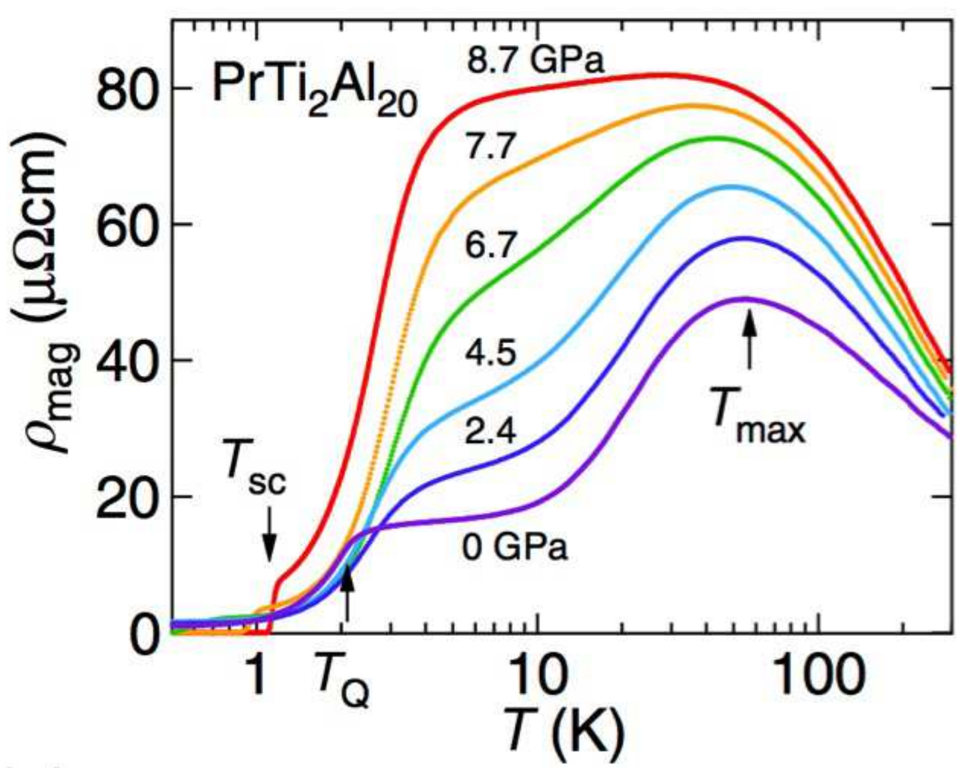
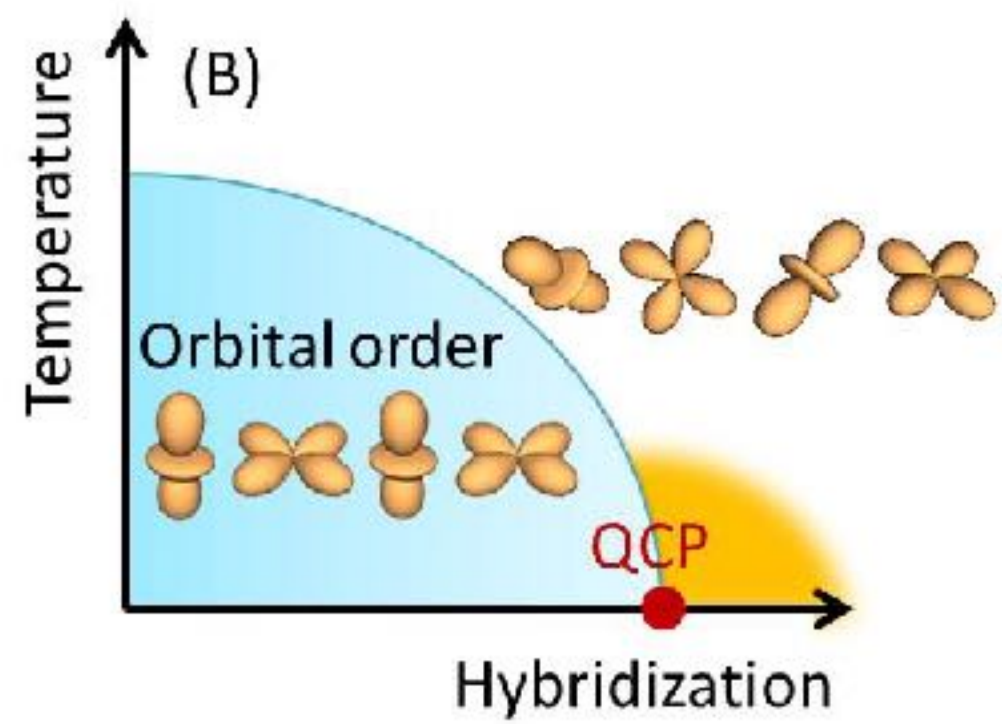
A. Sakai, K. Kuga, and S. Nakatsuji, J. Phys. Soc. Jpn. **81**, 083702 (2012).





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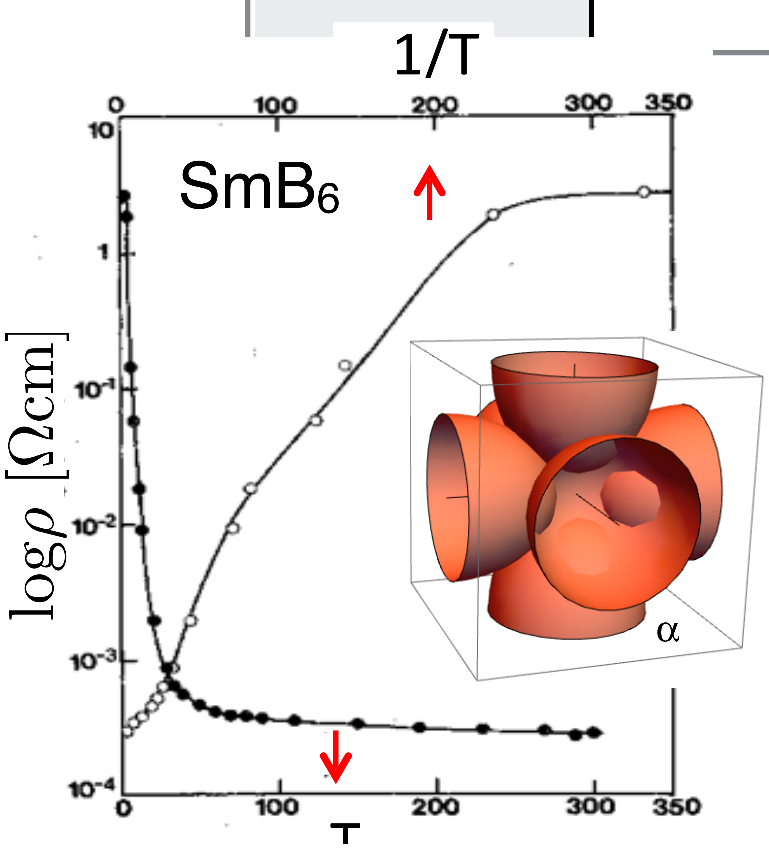

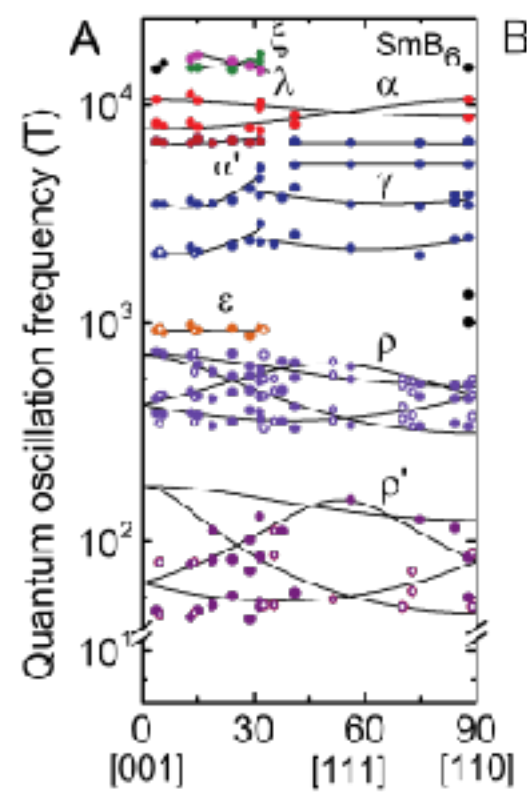

Tan *et al.* Science 349, 287 (2015)

Order Parameter Fractionalization Hypothesis

P. Chandra, PC, Y. Komijani

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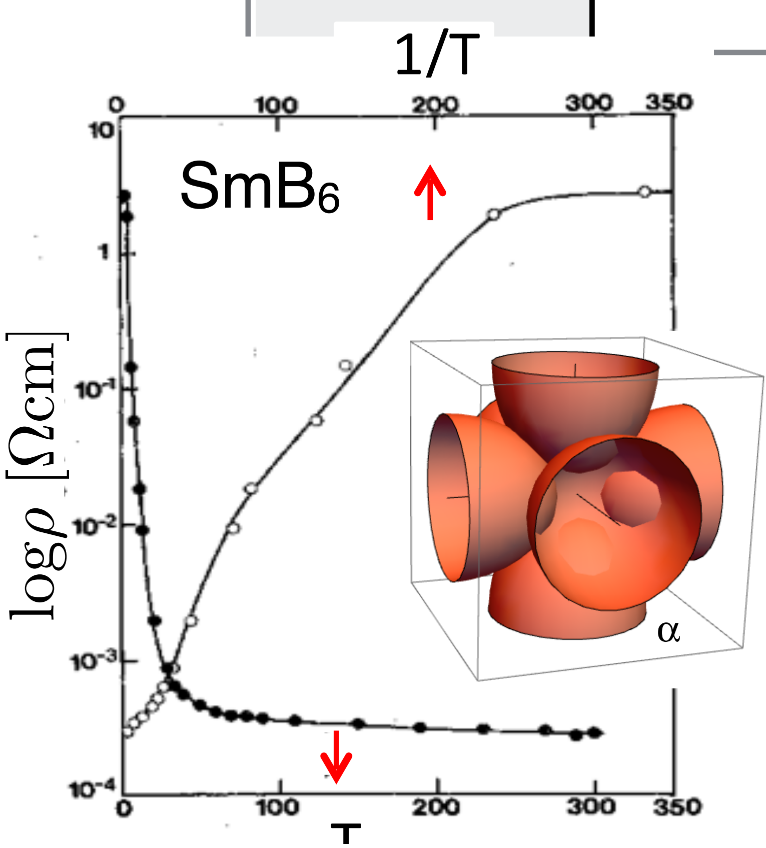
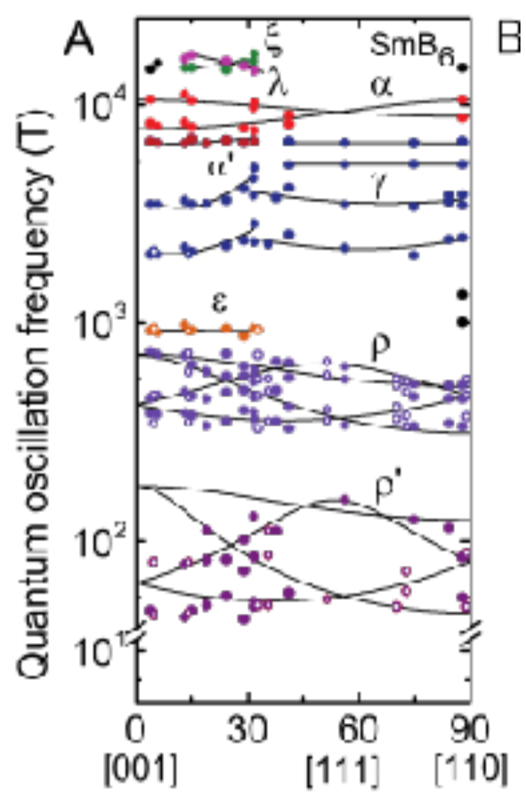
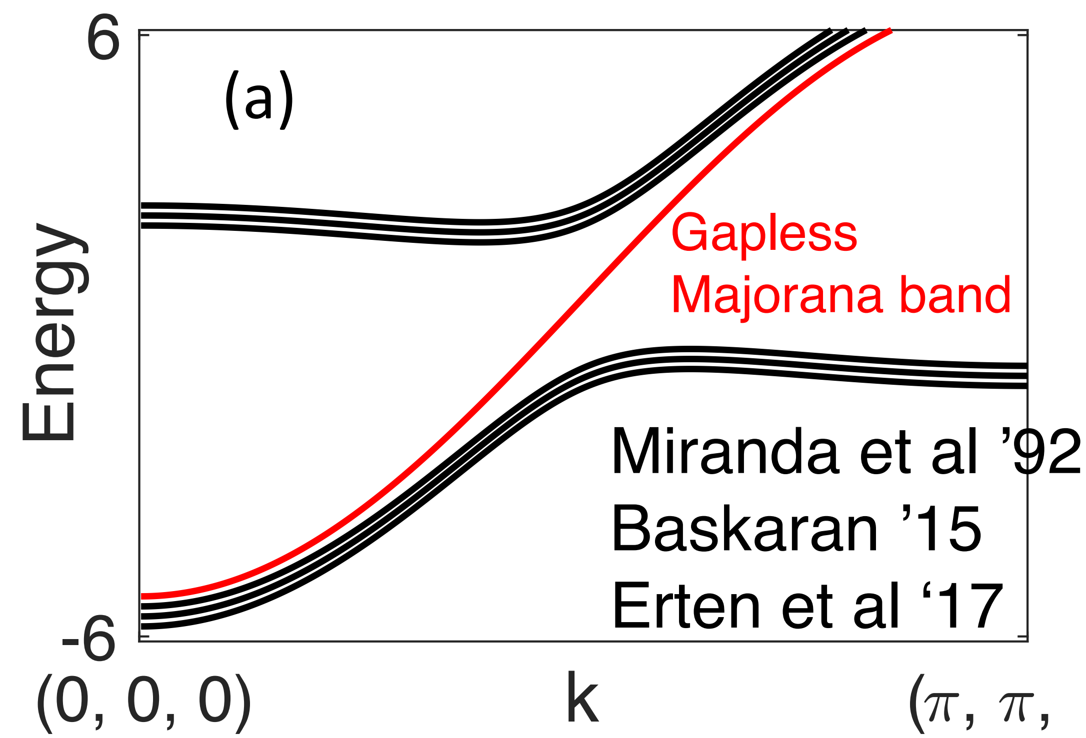






Tan *et al.* Science 349, 287 (2015)

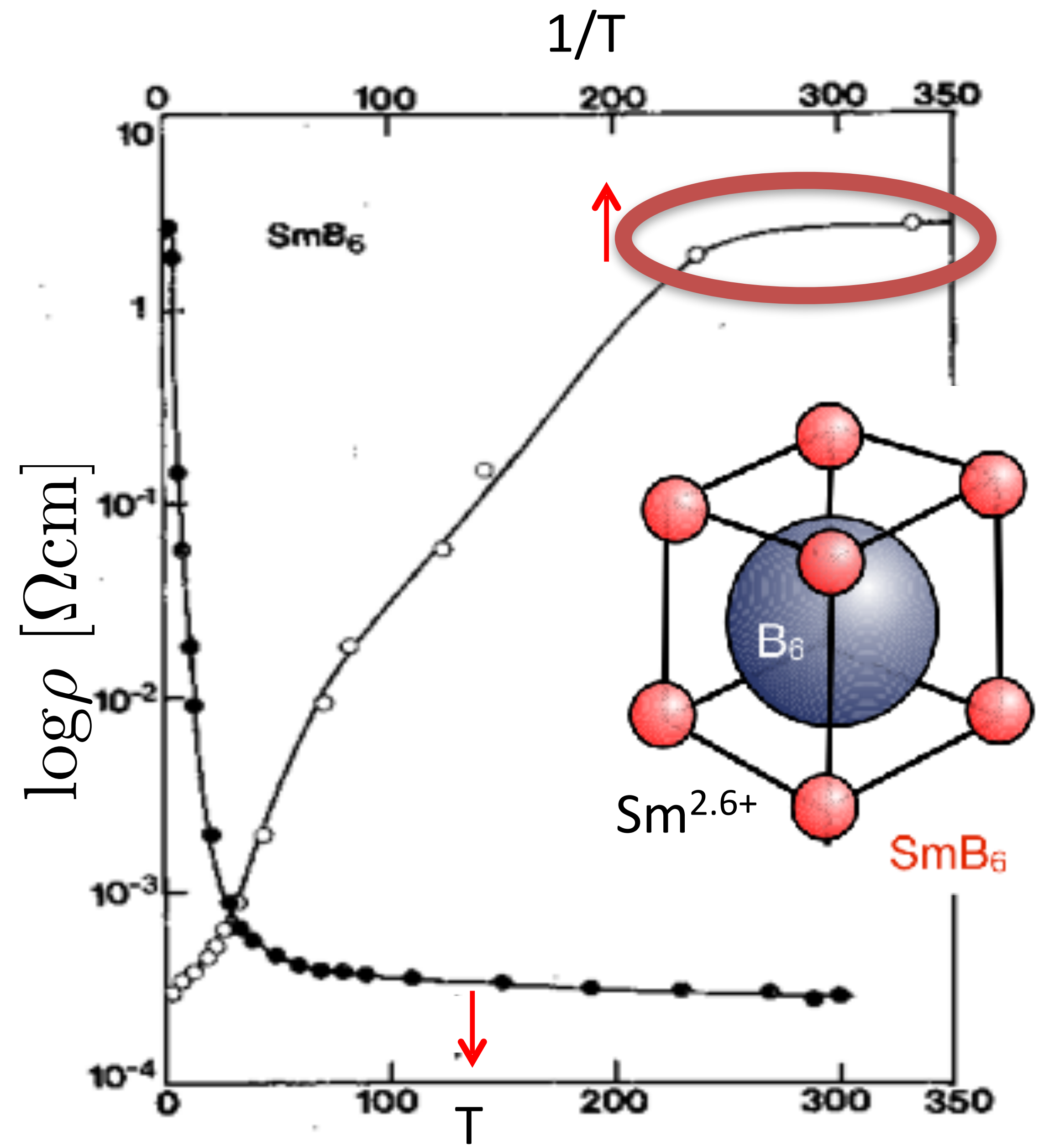
SmB_6 : Strange Insulator

A possible Topological Insulator?

- Insulating gap opens at T_K ~ 50K
- Resistivity plateau below T ~ 3K

  Topological surface states?

Dzero, Sun, Galitski, Coleman, PRL **104**, 106408 (2010)
Takimoto, J. Phys. Soc. Jpn. **80**, 123710 (2011)



Menth, Buehler, Geballe PRL **22**, 295 (1969)
Allen, Batlogg, Watchter PRB **20** 4807 (1979)

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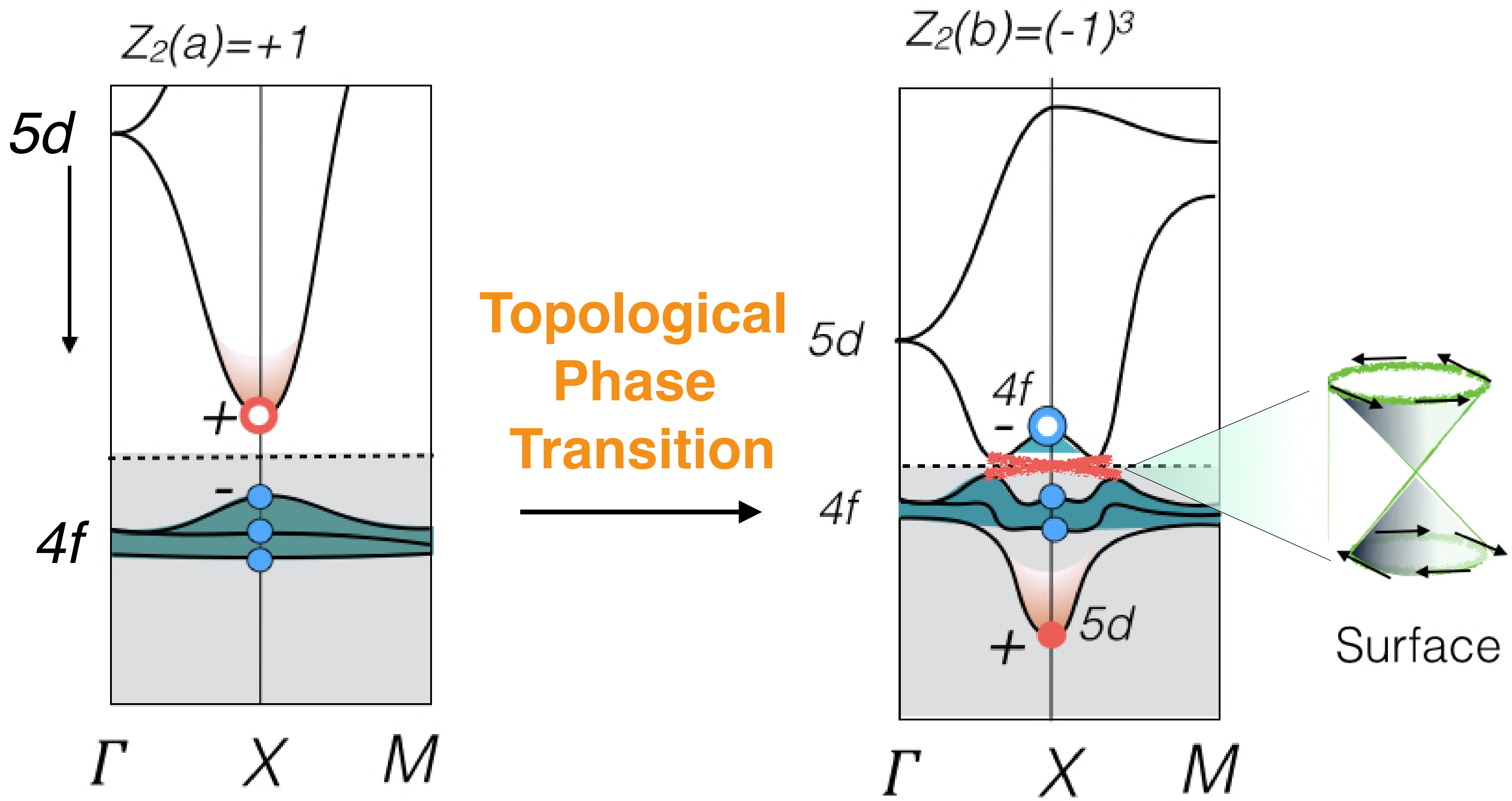

- d-f band inversion at the X point
- 3 Dirac cones on the surface

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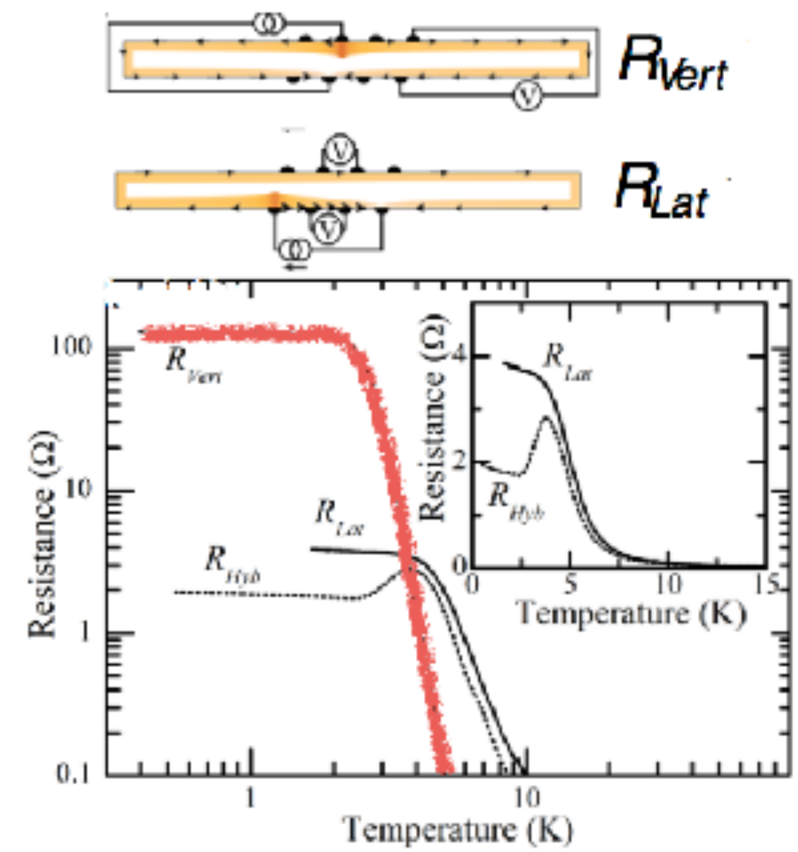
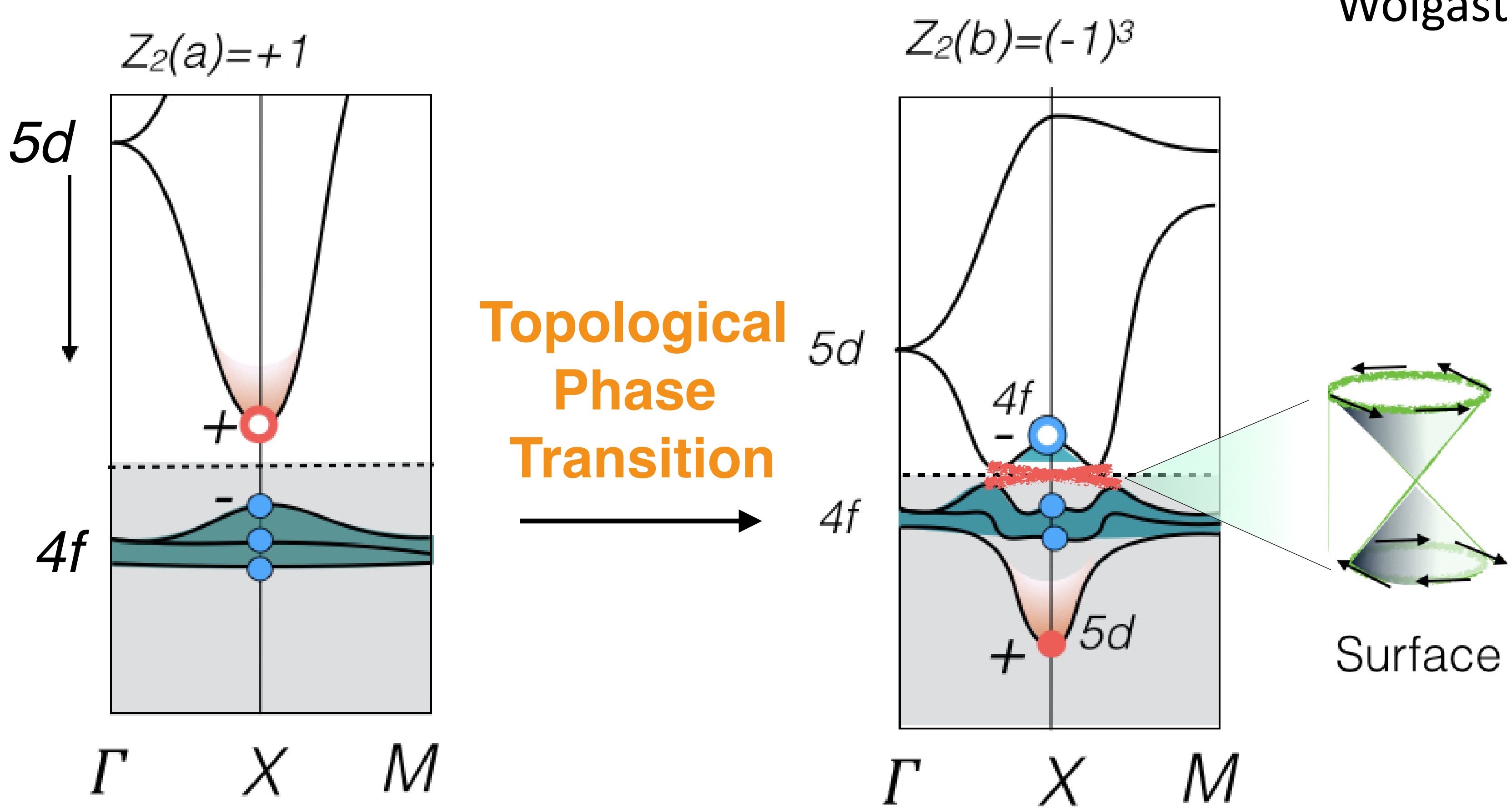
Nonlocal transport→ surface cond.



Wolgast et al, Phys Rev B, 88, 180405 (2013)



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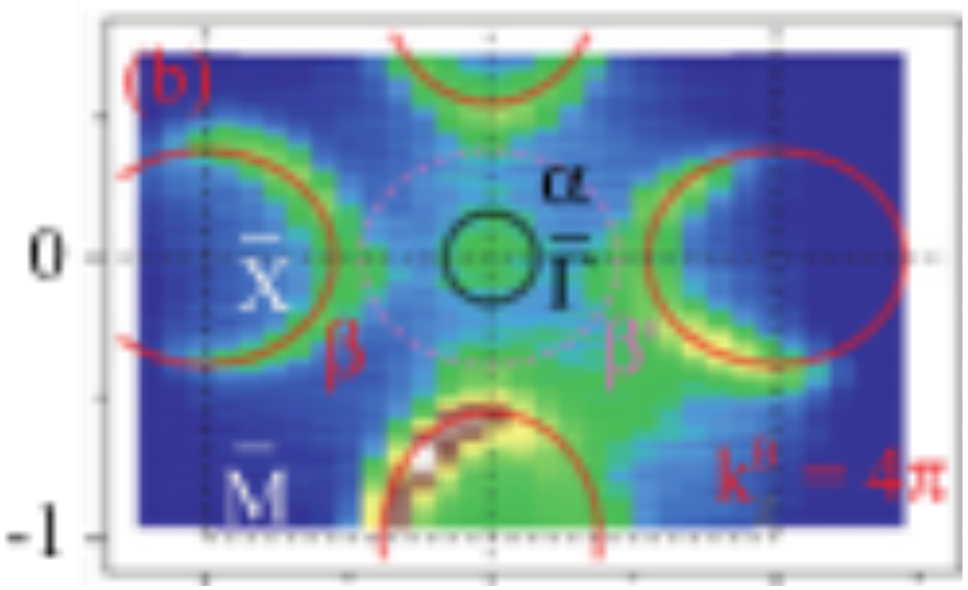
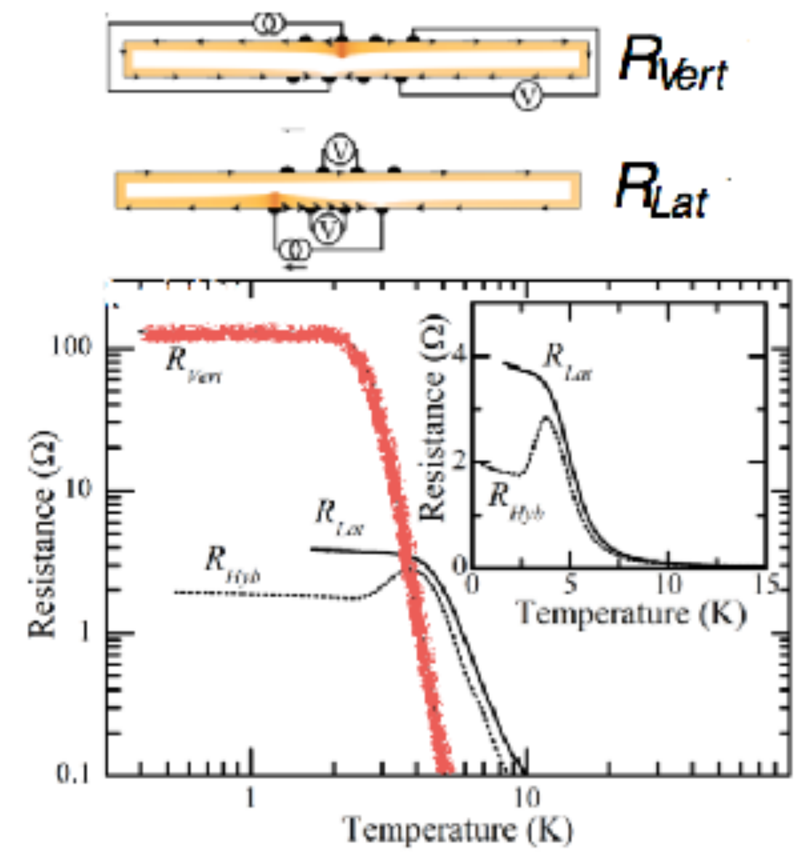
A possible Topological Insulator?

ARPES → Surface states

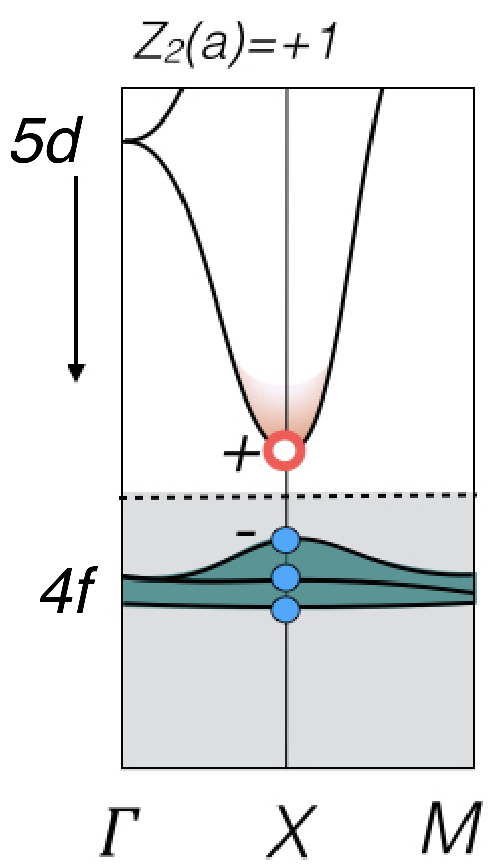


Xu et. al PRB **88**, 121102(R) (2013)

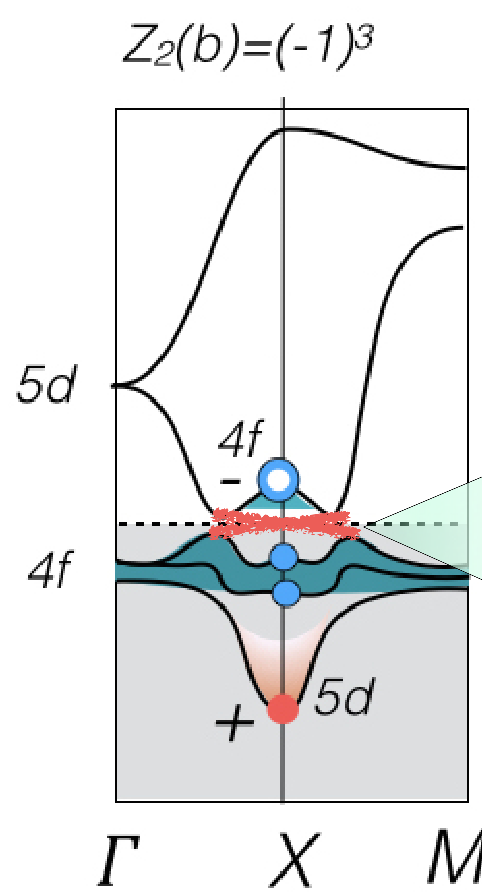
Nonlocal transport→ surface cond.

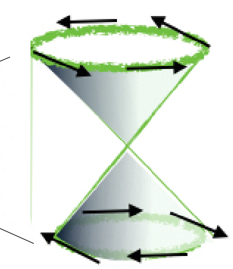


Wolgast et al, Phys Rev B, 88, 180405 (2013)



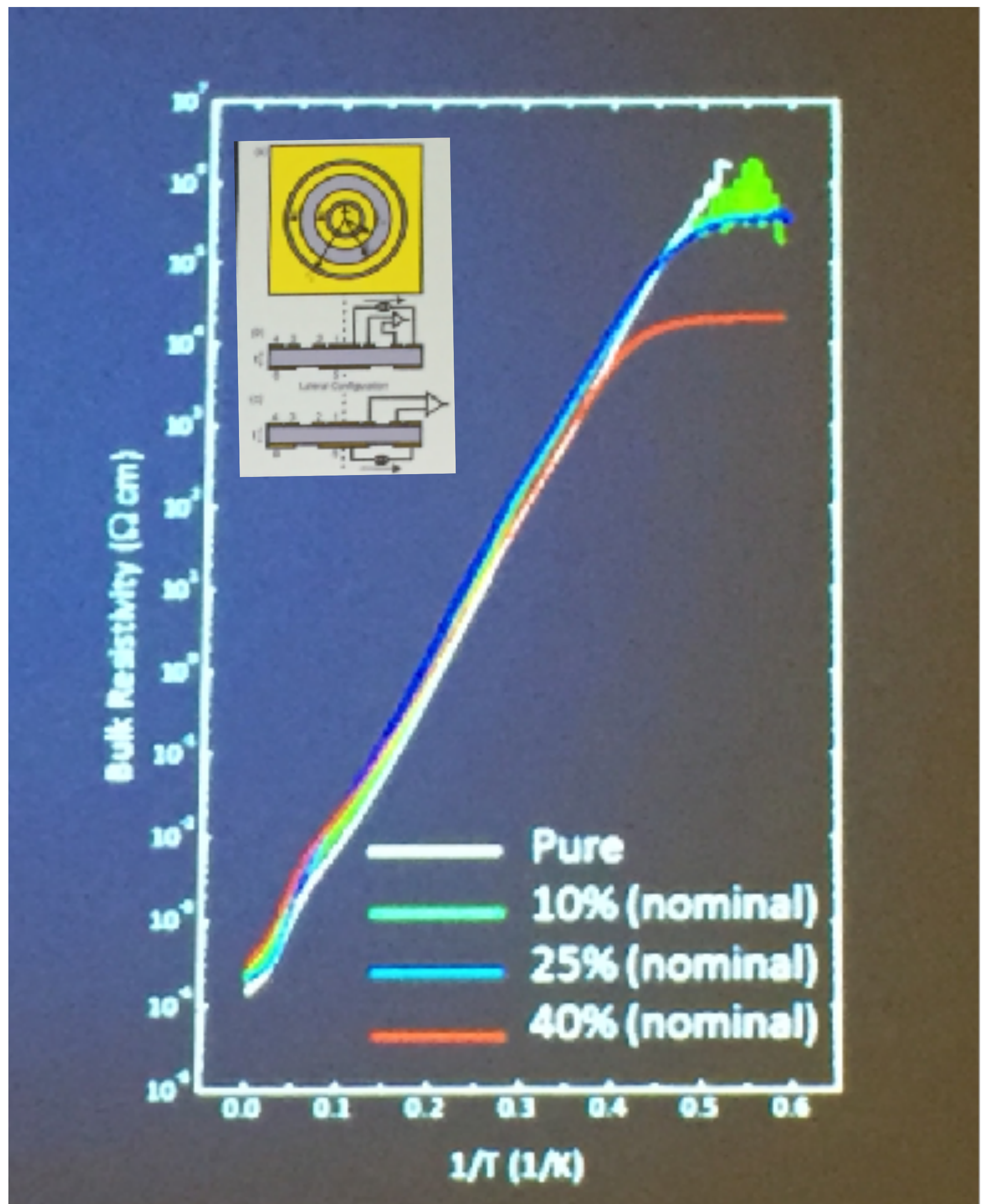
Topological Phase Transition



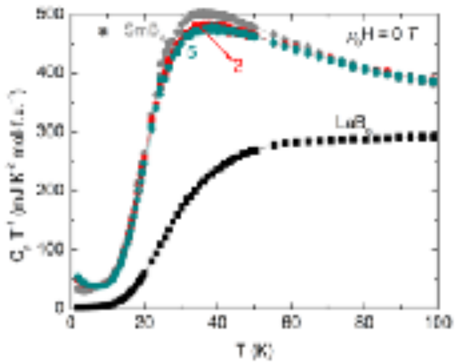


Surface

- d-f band inversion at the X point
- 3 Dirac cones on the surface

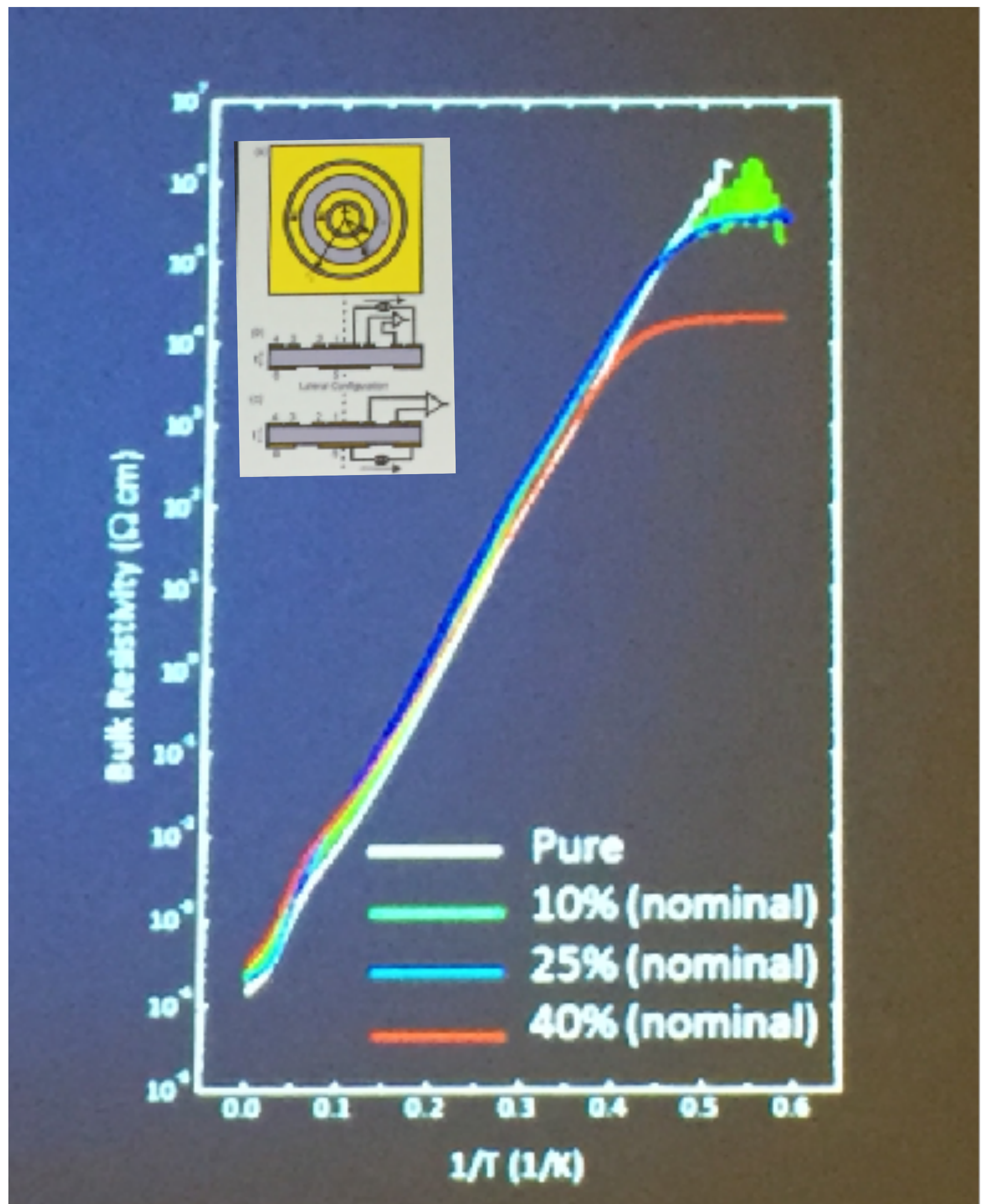


Robust bulk insulator
(Kurdak et al, APS 2017)
Seemingly Topological, yet



Linear Sheat

Phalen, PRX **4** 031012 (2014)



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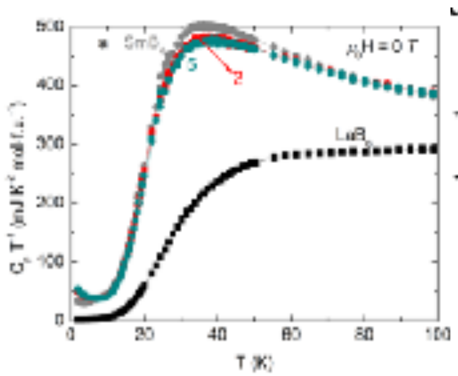

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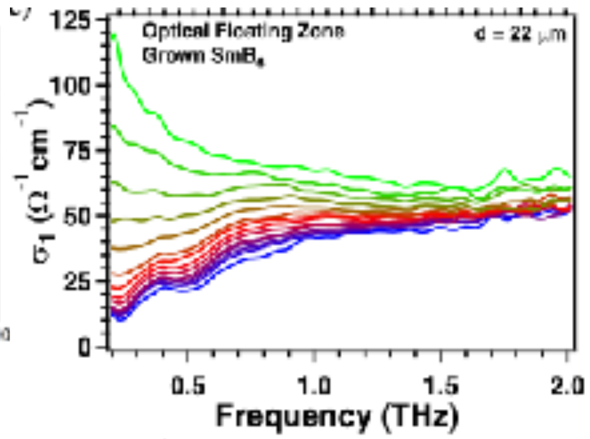
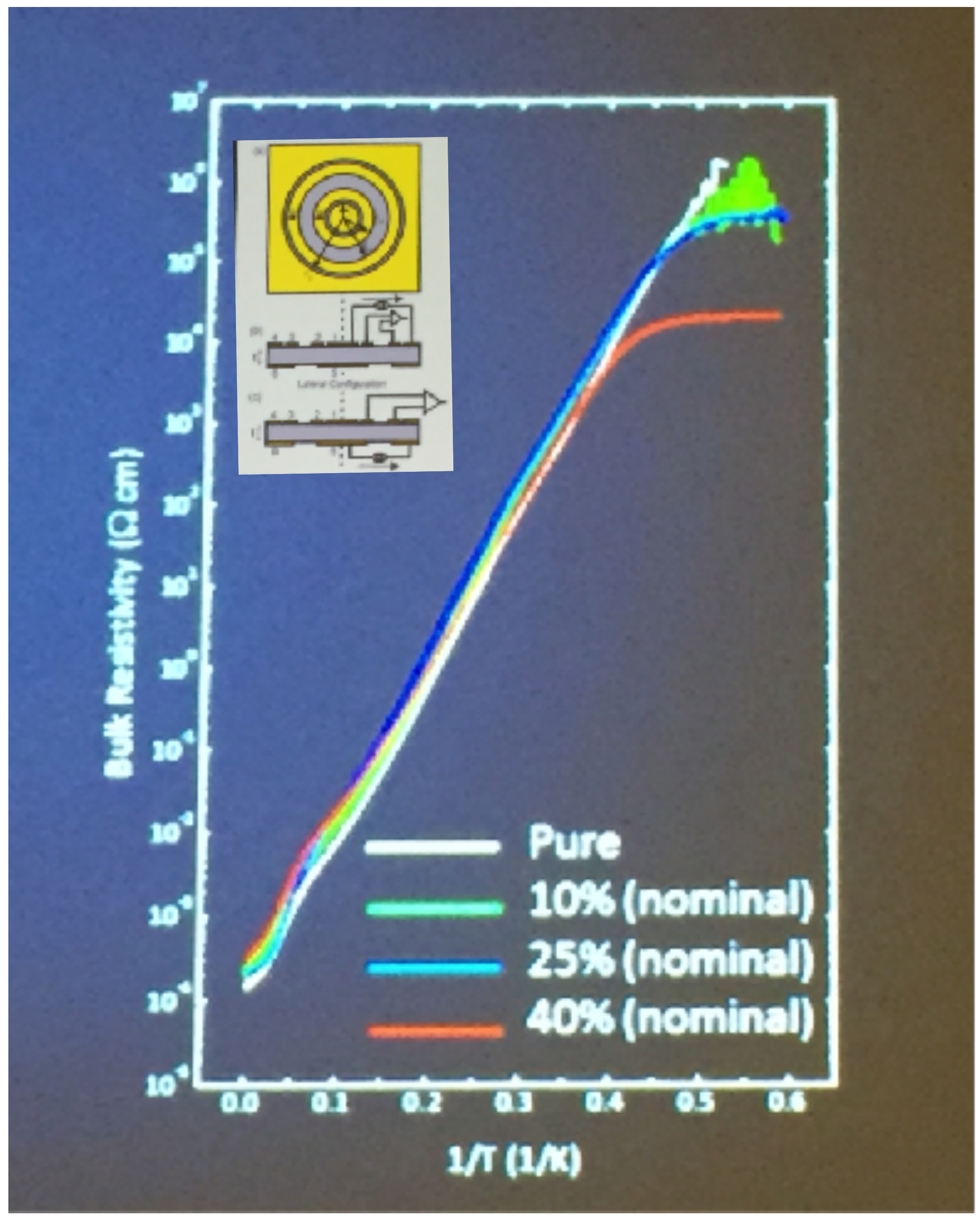


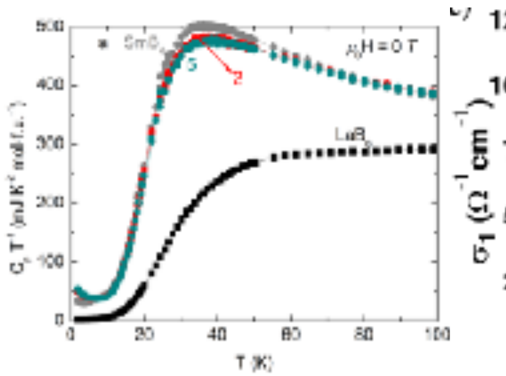
AC Metal

Laurita, *et al.* PRB 94, 165154 (2016).



Robust bulk insulator
(Kurdak et al, APS 2017)
Seemingly Topological, yet

- Bulk Linear SHeat 10x LaB_6
- Optical conductor, DC insulator



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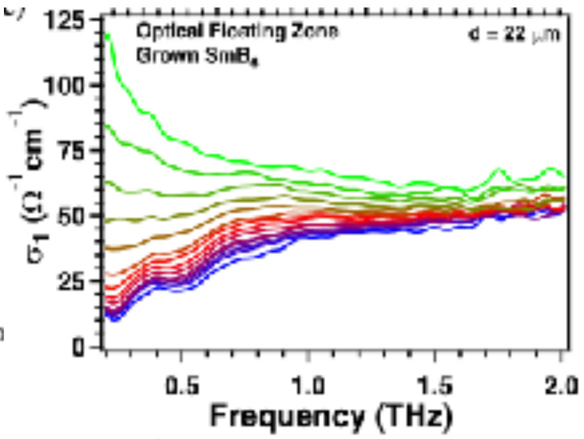

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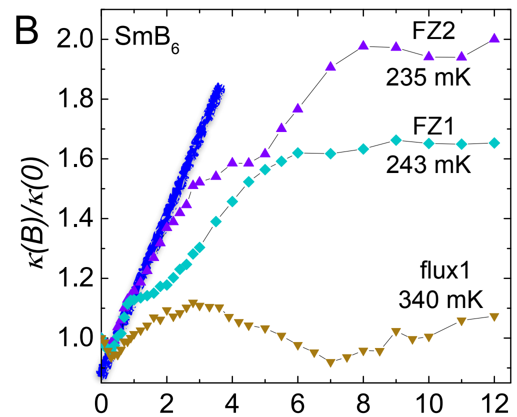
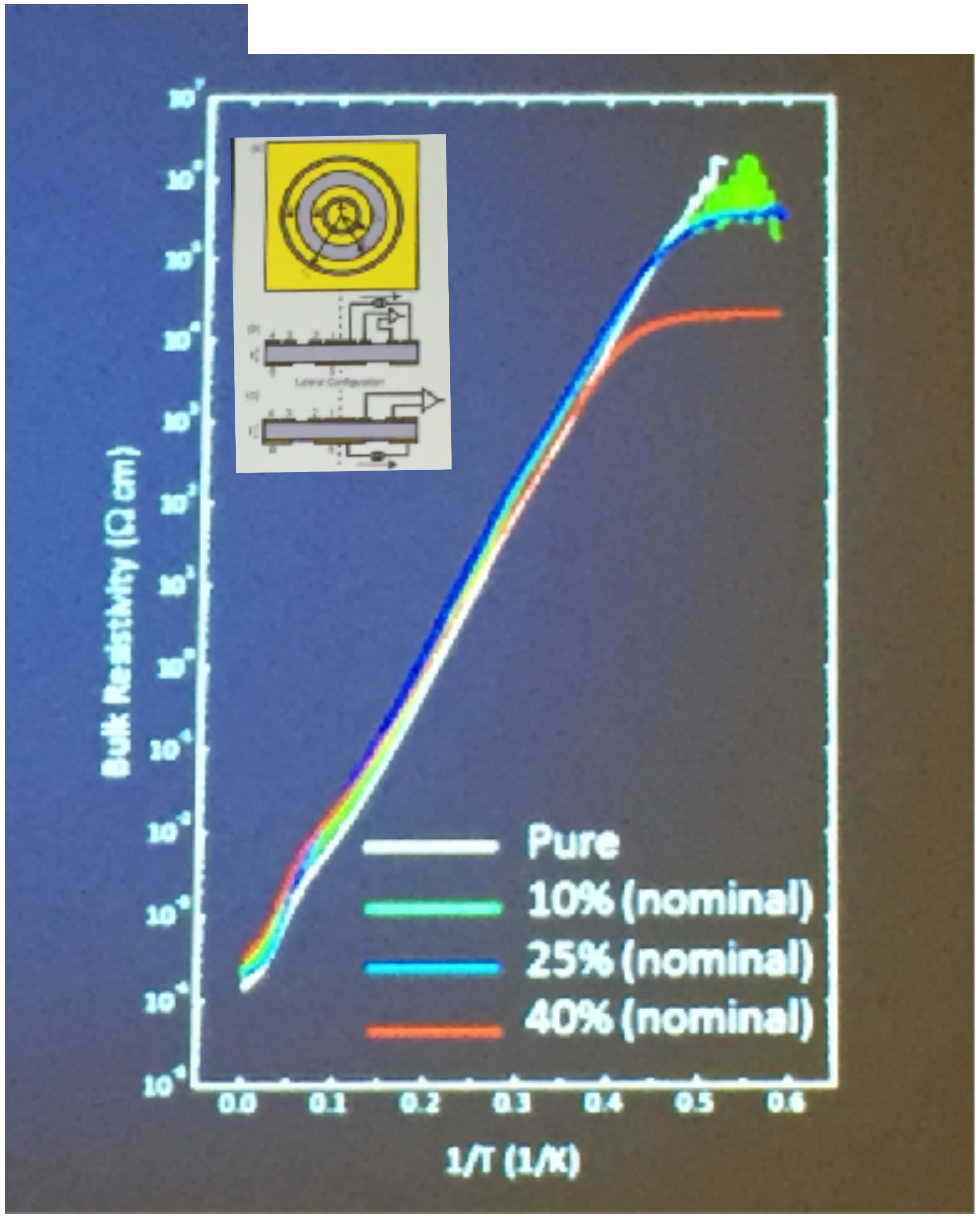


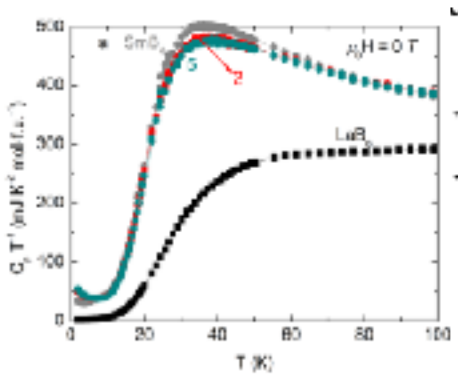
κ/T~ B

M. Hartstein, M Sutherland
S. Sebastian et al. (Preprint)



Robust bulk insulator
(Kurdak et al, APS 2017)
Seemingly Topological, yet

- Bulk Linear SHeat 10x LaB_6
- Optical conductor, DC insulator
- B-dependent Thermal Conductivity



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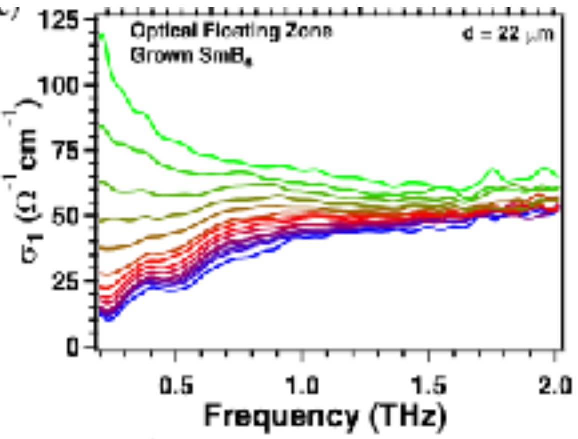

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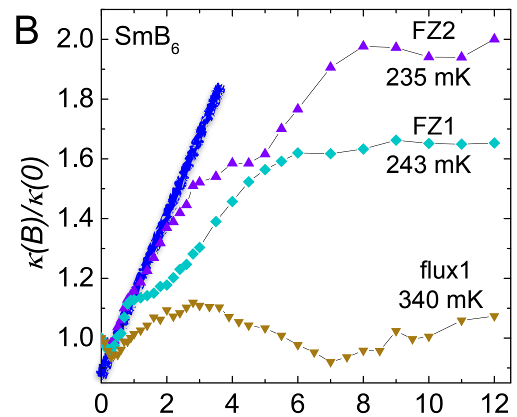

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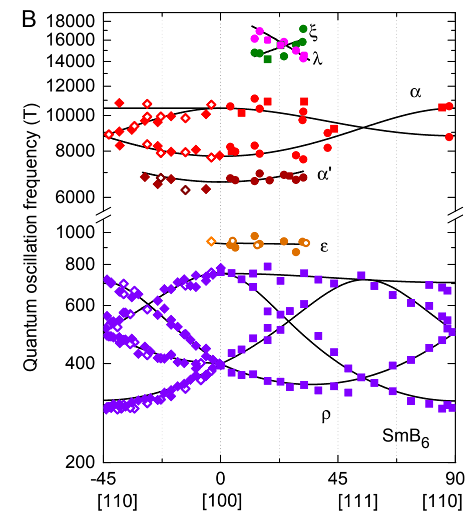
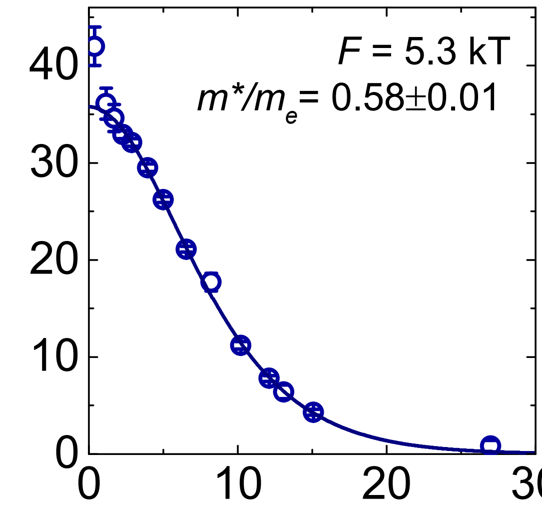
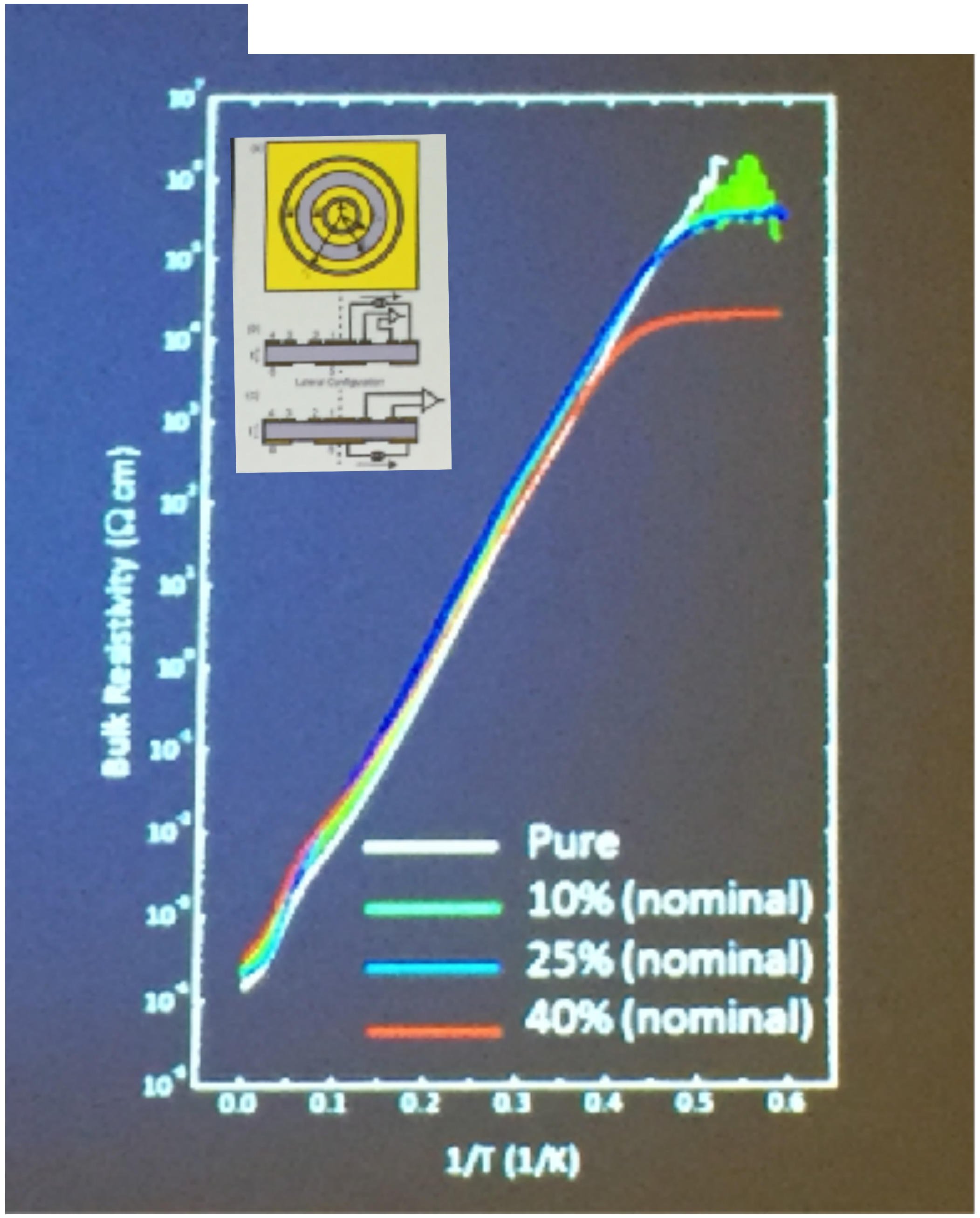


Bulk dHvA



Lifschitz Kosevich=
FT of Fermi Function.

The SmB_6 Conundrum



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(Kurdak et al, APS 2017)
Seemingly Topological, yet

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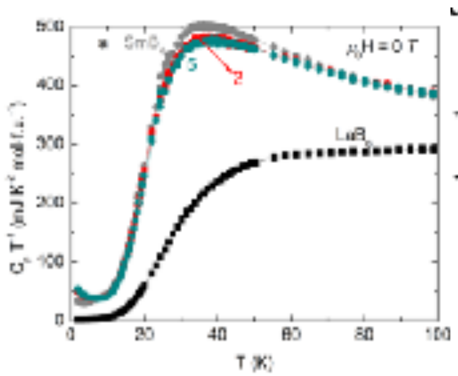
- Optical conductor, DC insulator
- B-dependent Thermal Conductivity
- Bulk dHvA + Lifschitz Kosevitch



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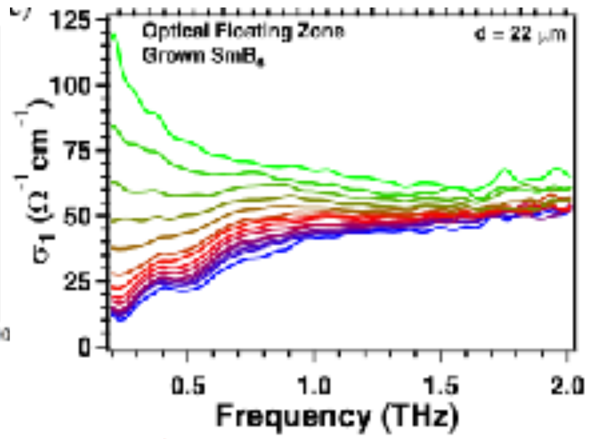

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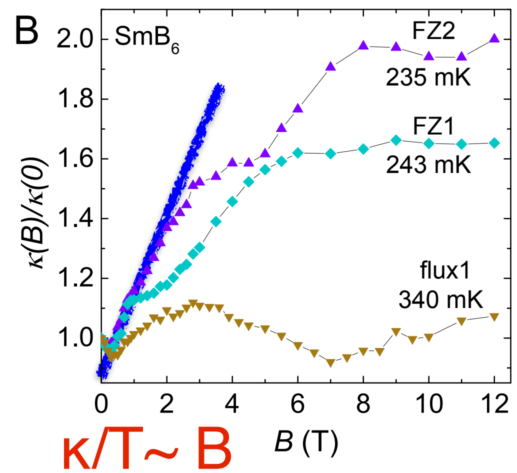

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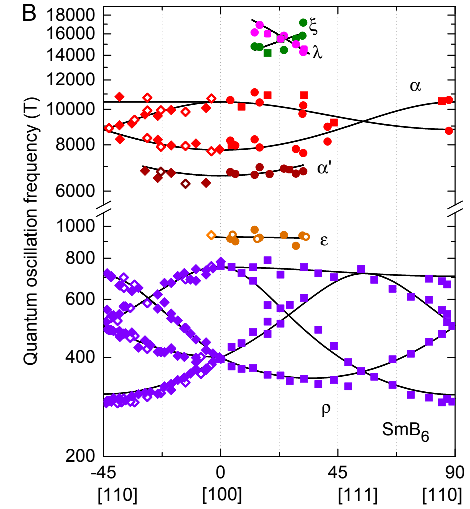

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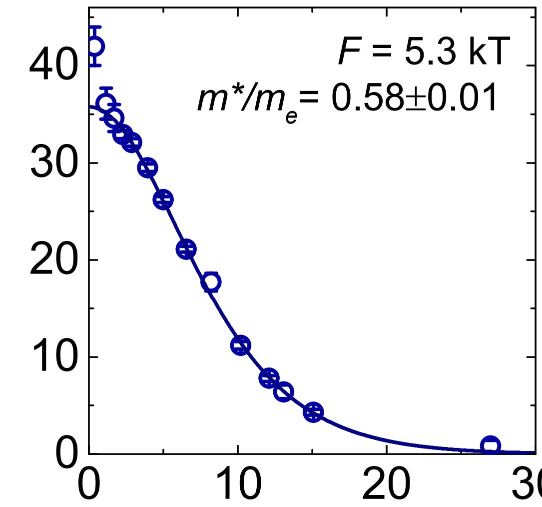

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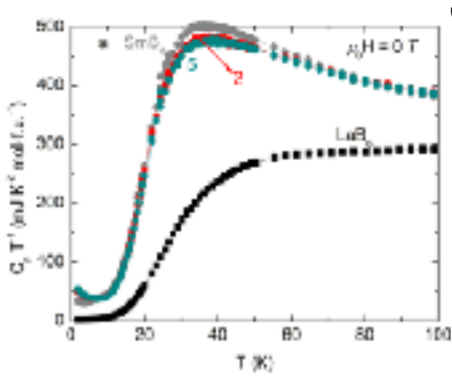

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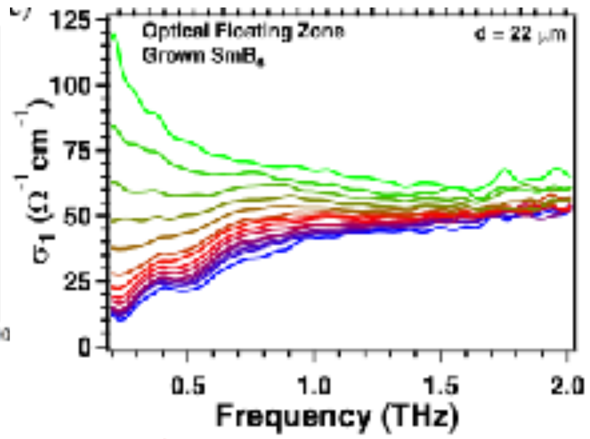
Phalen, PRX **4** 031012 (2014)



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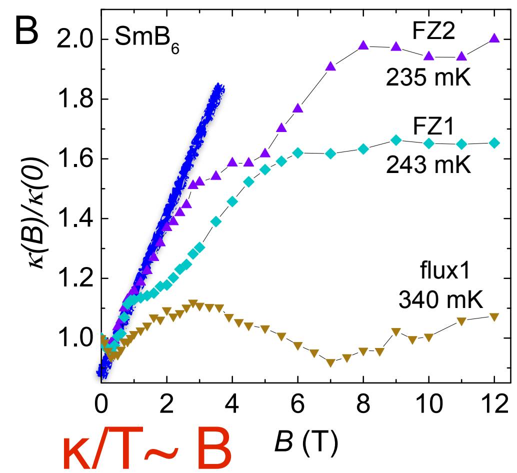

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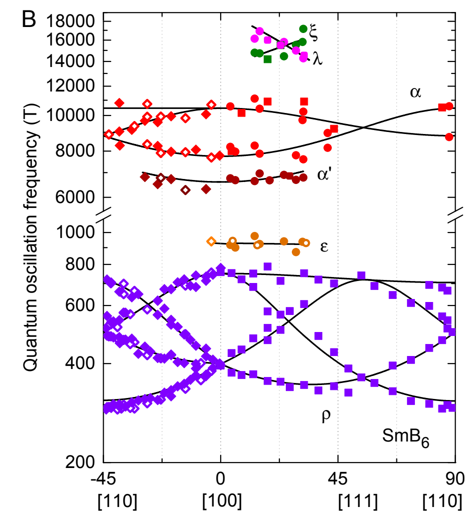

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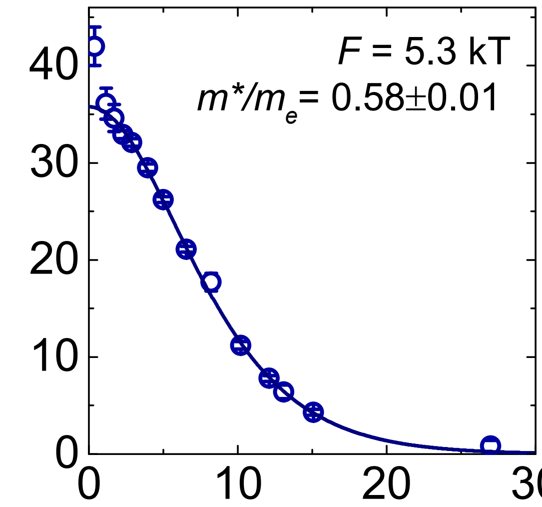

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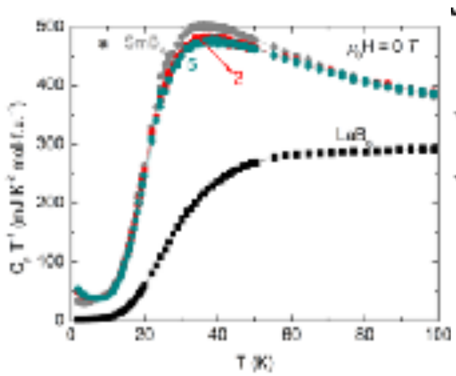
Excitonic/Breakdown Theory

J. Knolle and N. Cooper PRL 118, 096604 (2017)

Fractionalization

P. Coleman, E. Miranda, and A. Tsvelik, Physica B: Condensed Matter 186-188, 362 (1993).
G. Baskaran, ArXiv e-prints (2015), arXiv:1507.03477.
T. Senthil et al, arXiv:1707
O. Erten, P-Y Chang, Coleman and A. Tsvelik, arXiv:1701.06582, PRL in press.



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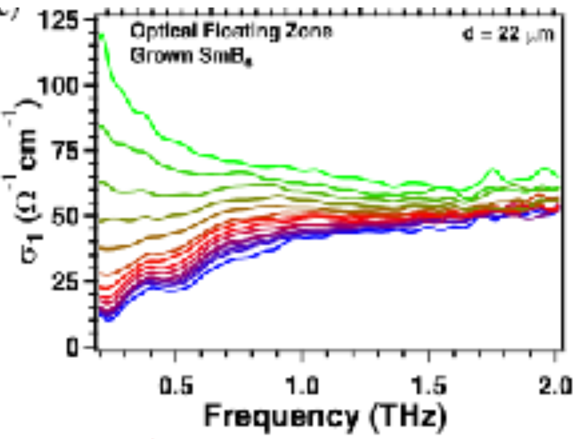

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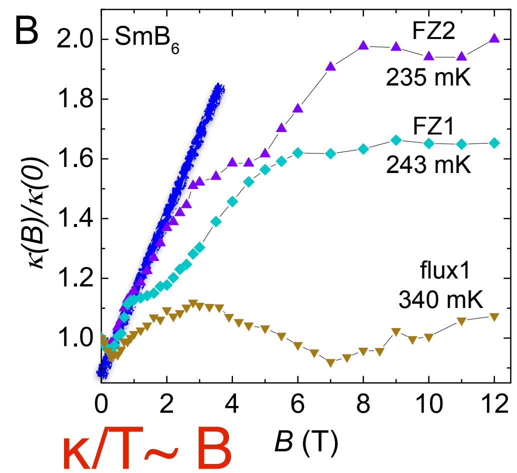

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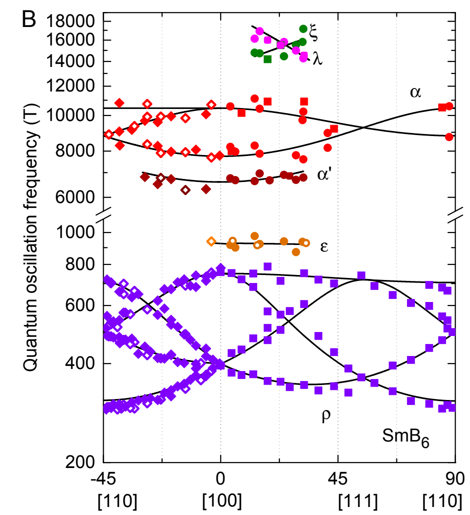

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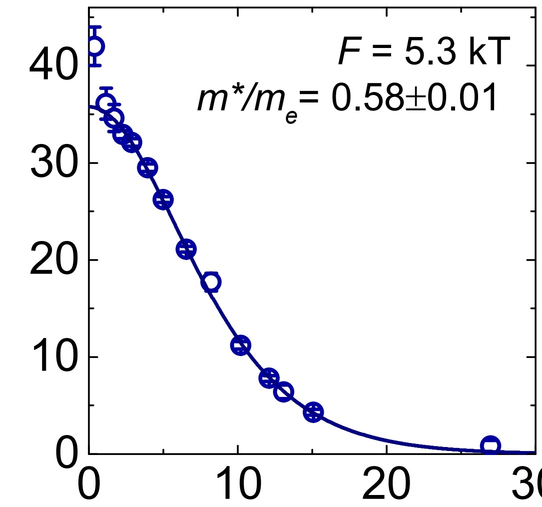

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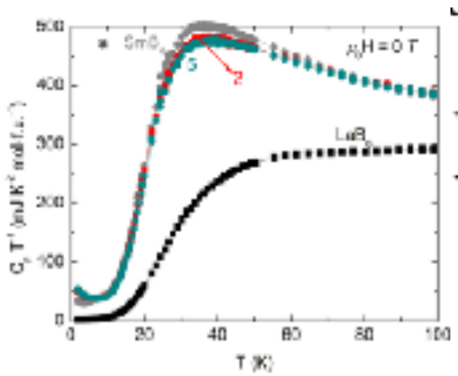

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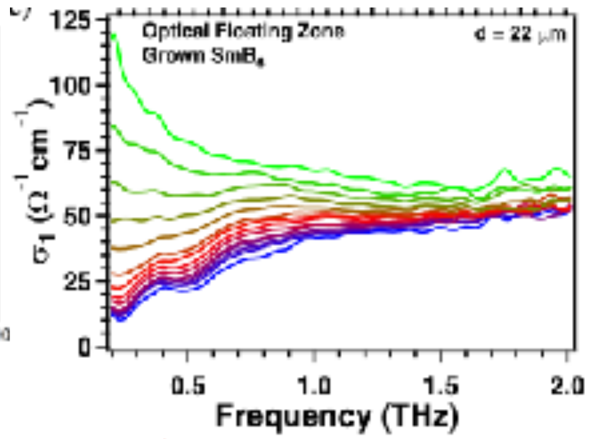

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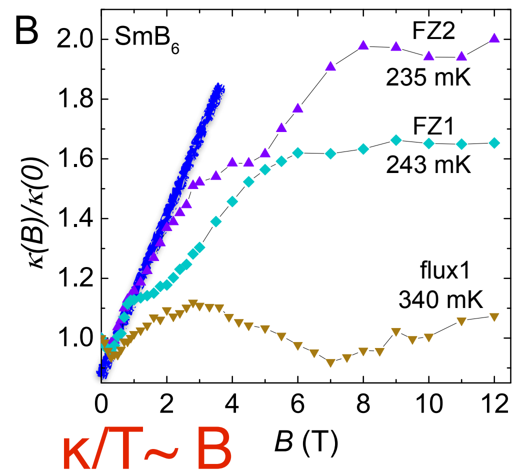

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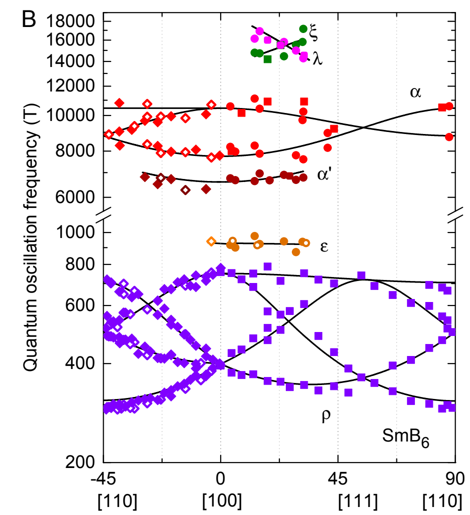

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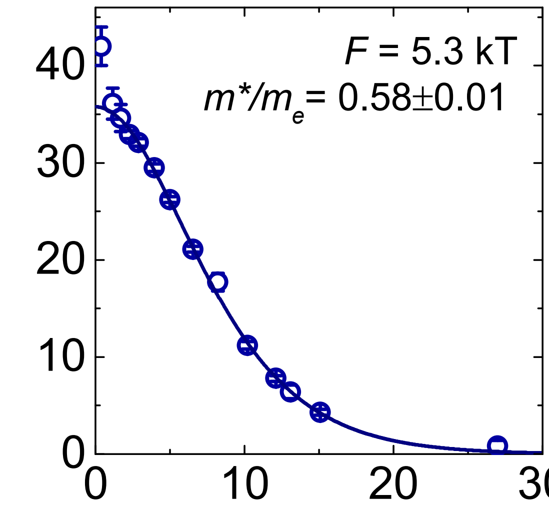

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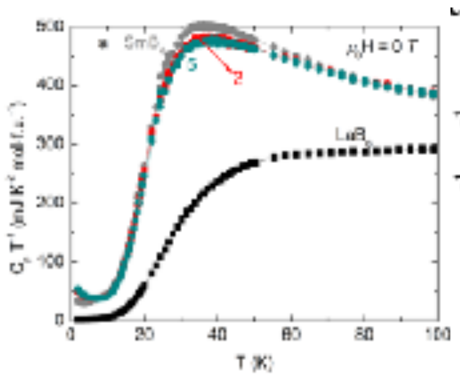

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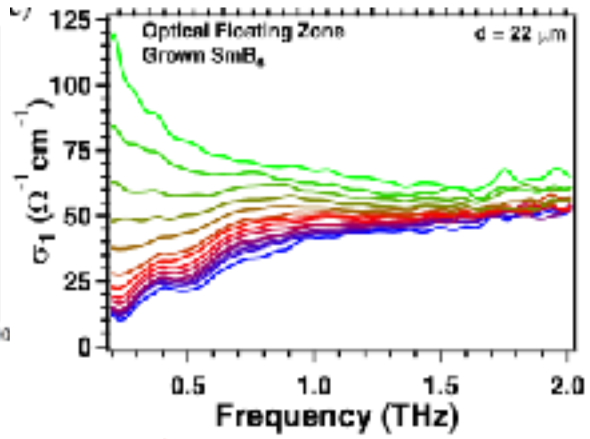

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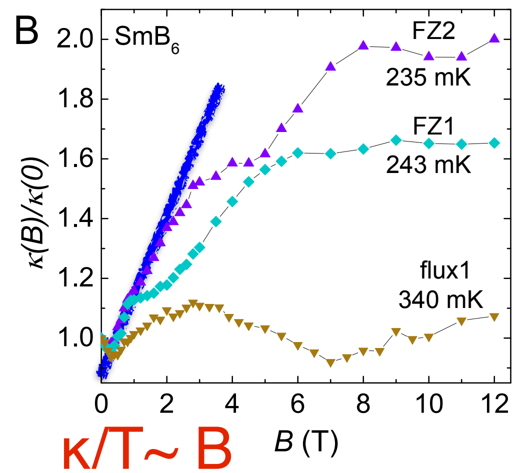

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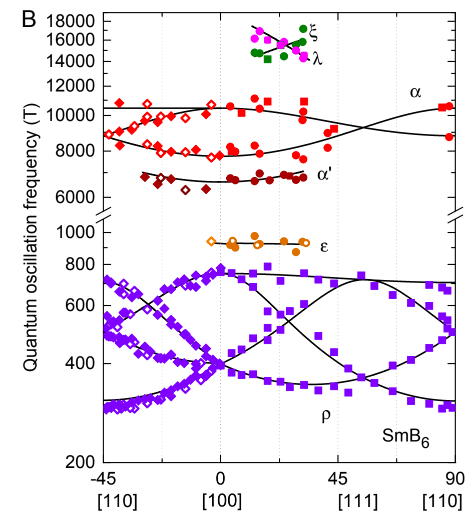

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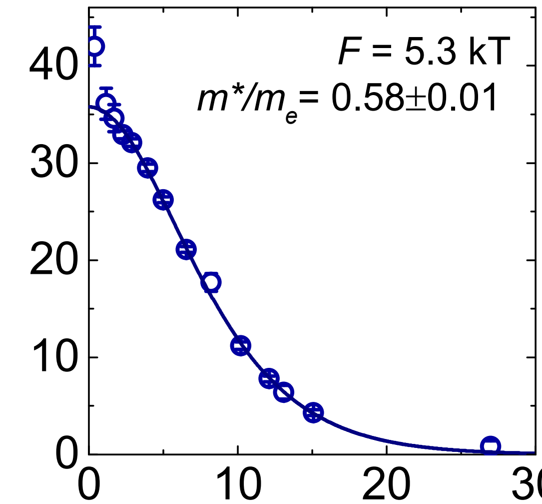

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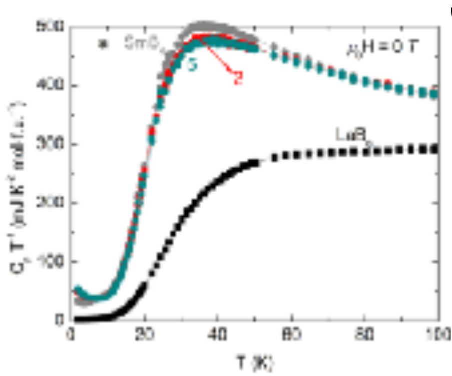

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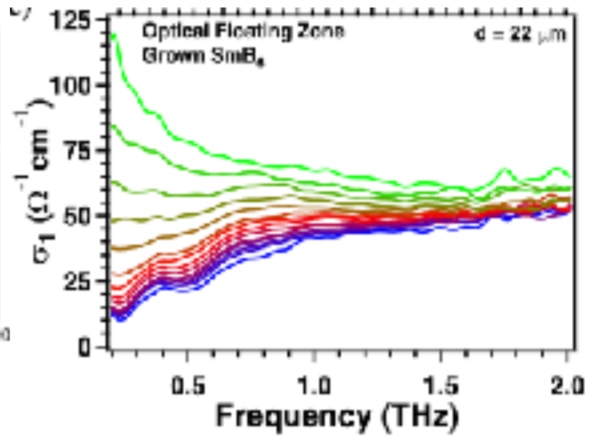

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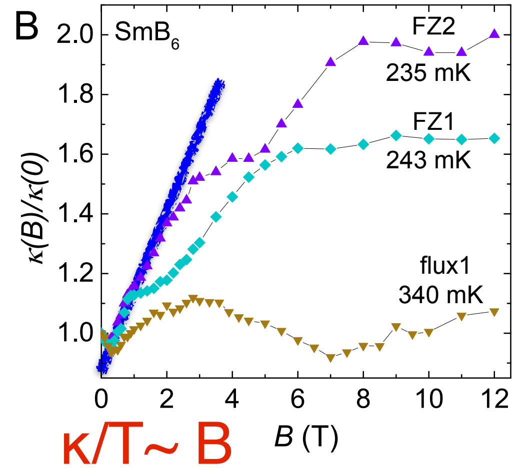

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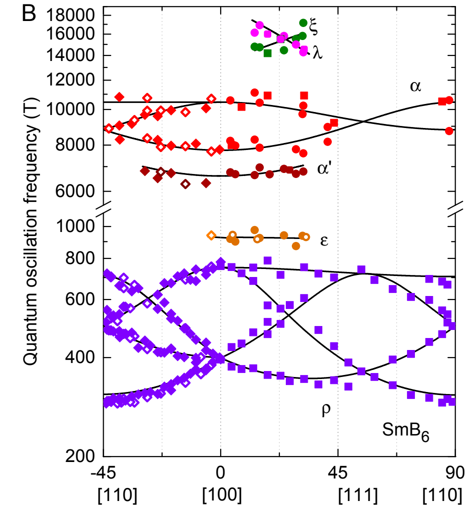

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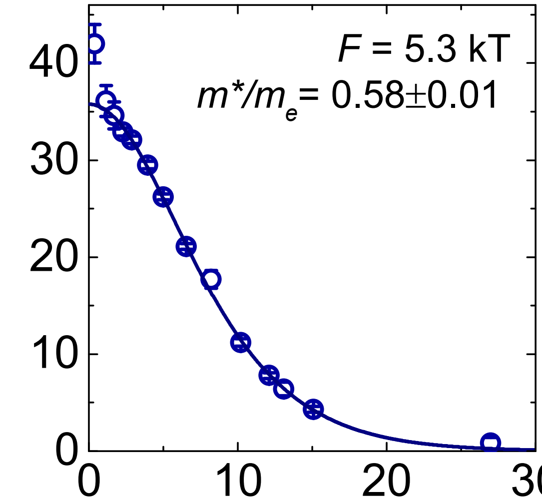

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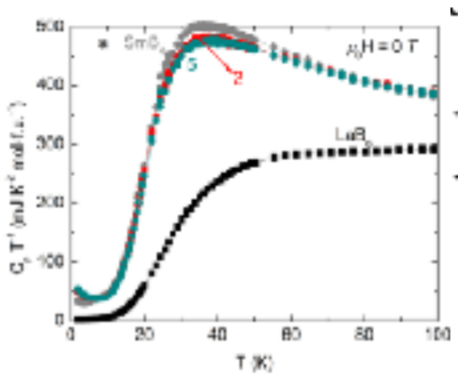

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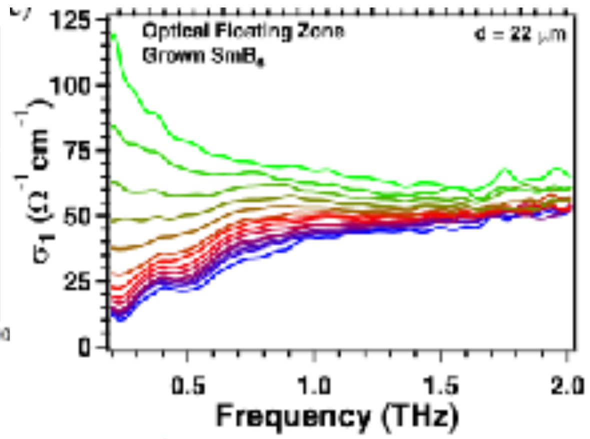

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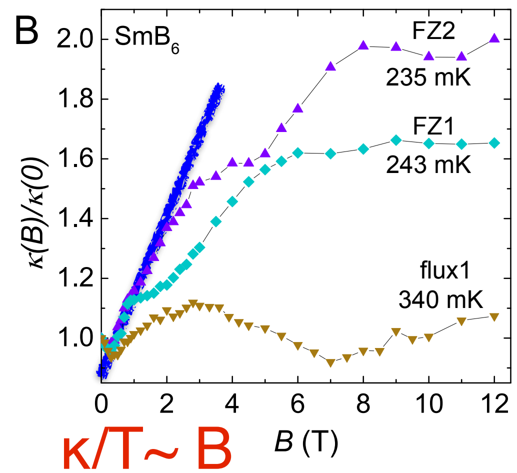

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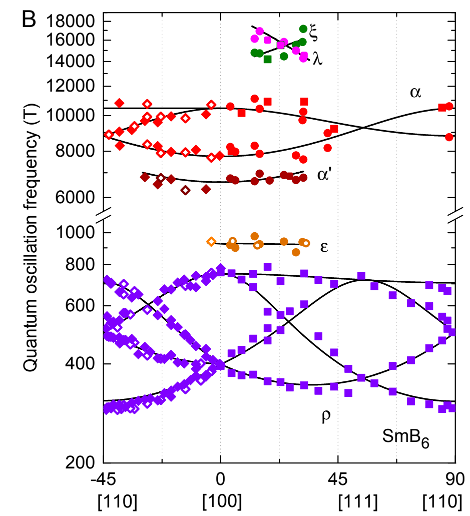

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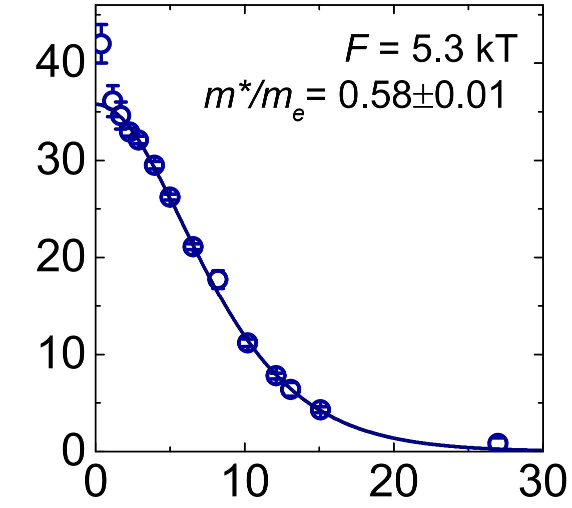

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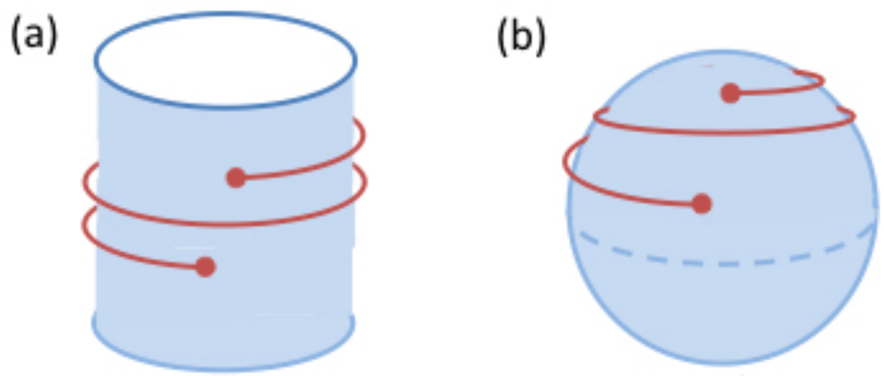

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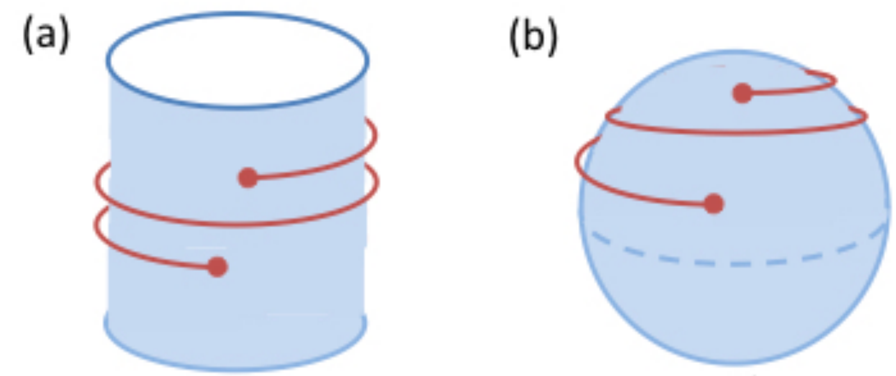

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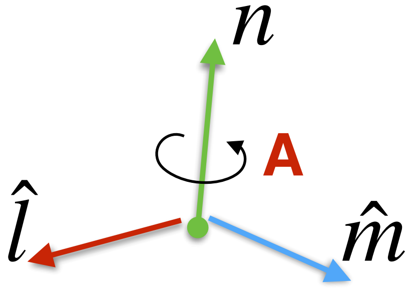

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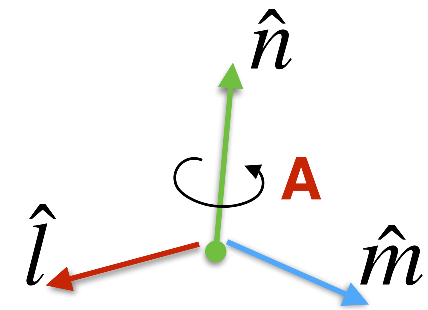
London equation

$$\boldsymbol{\rho}(x) = \mathbf{B}/\phi_0$$

Skyrmion density



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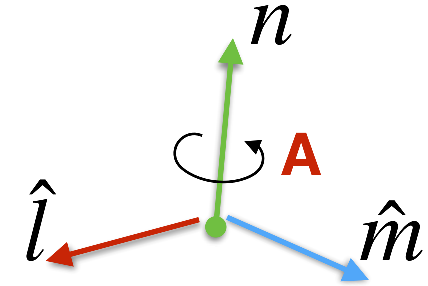

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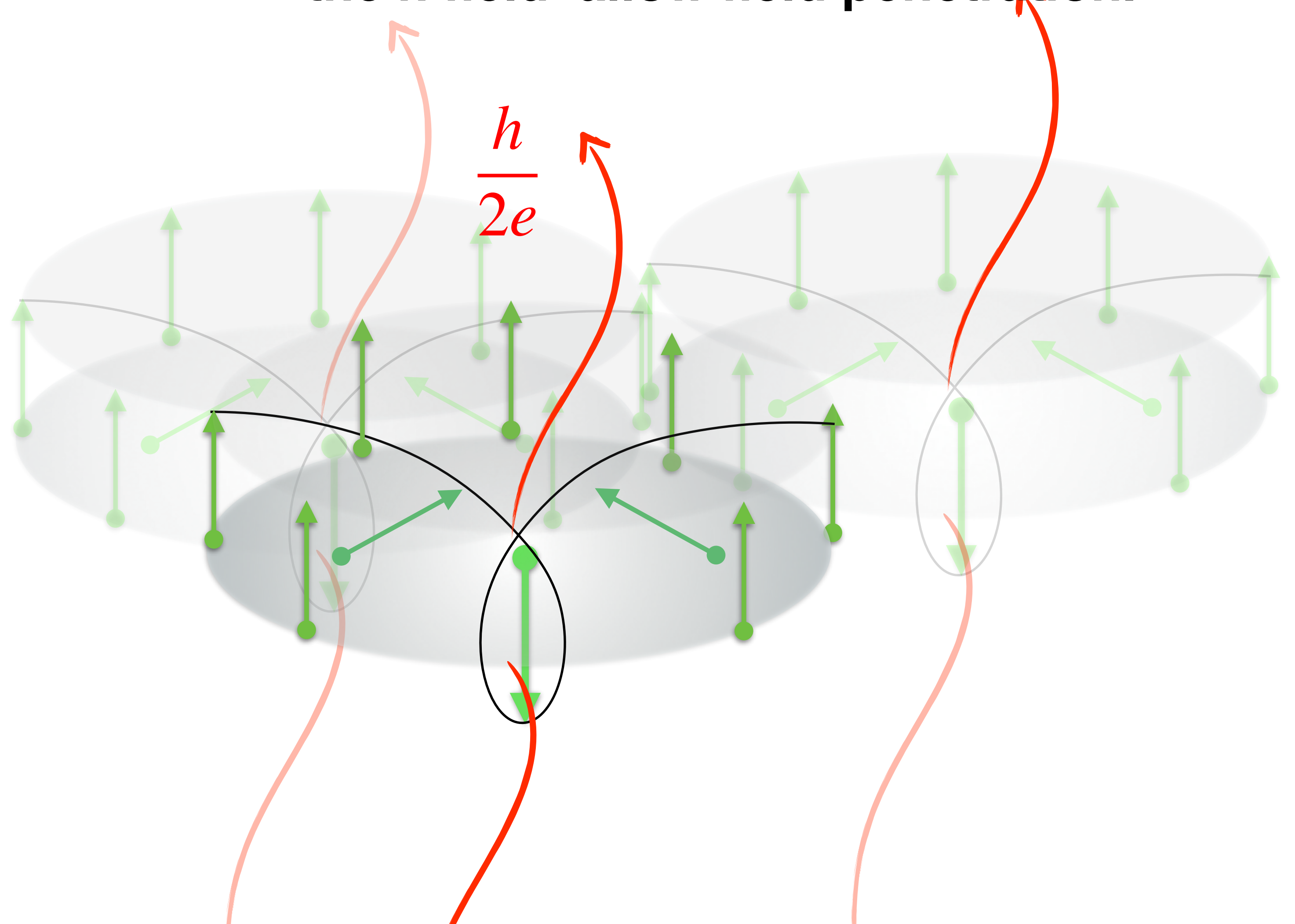

$$\kappa \sim B$$

Skyrmion fluid
coreless, mobile
$n_S \sim B \rightarrow \kappa \sim B$

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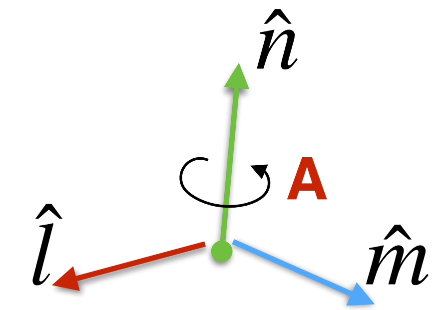

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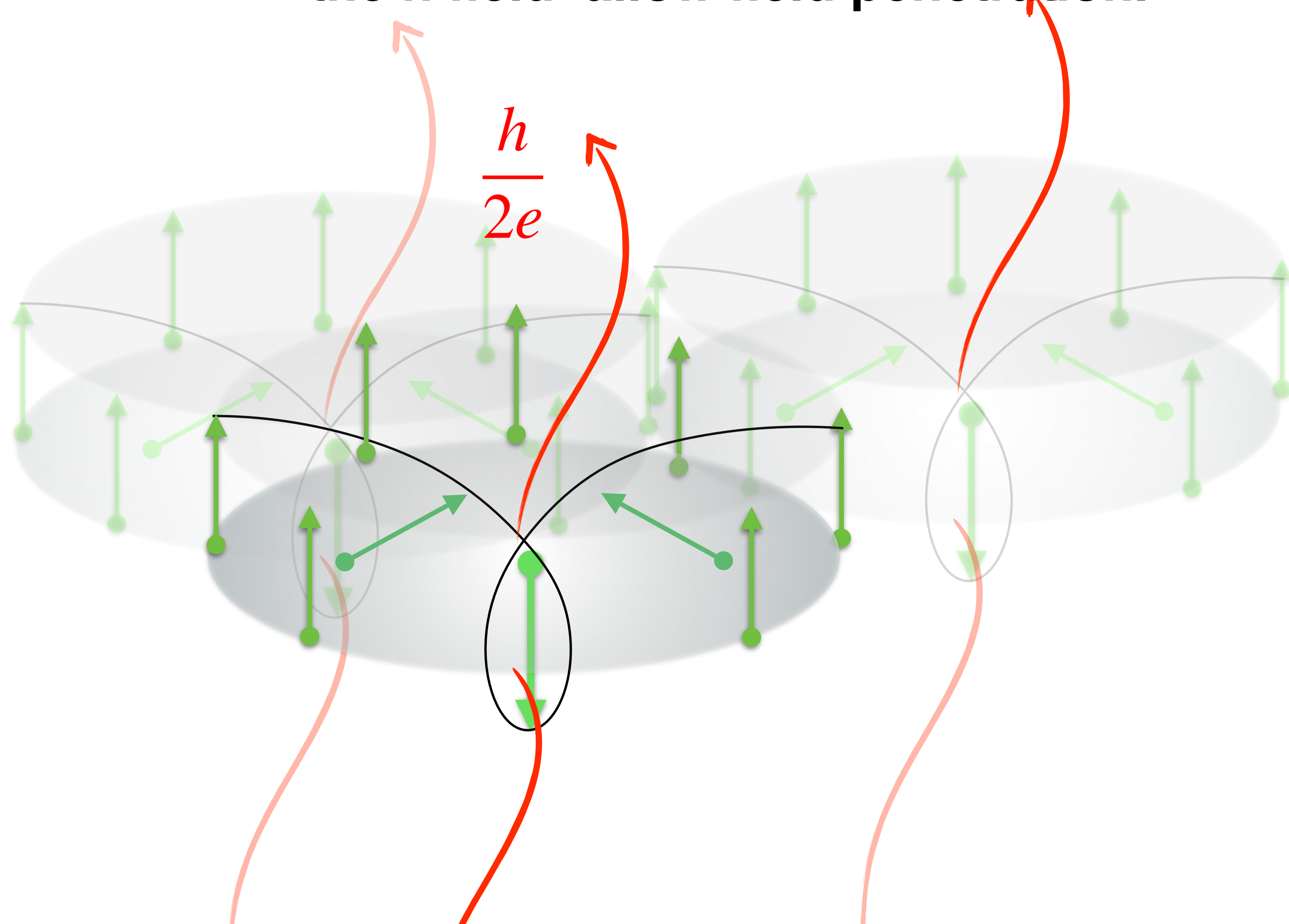

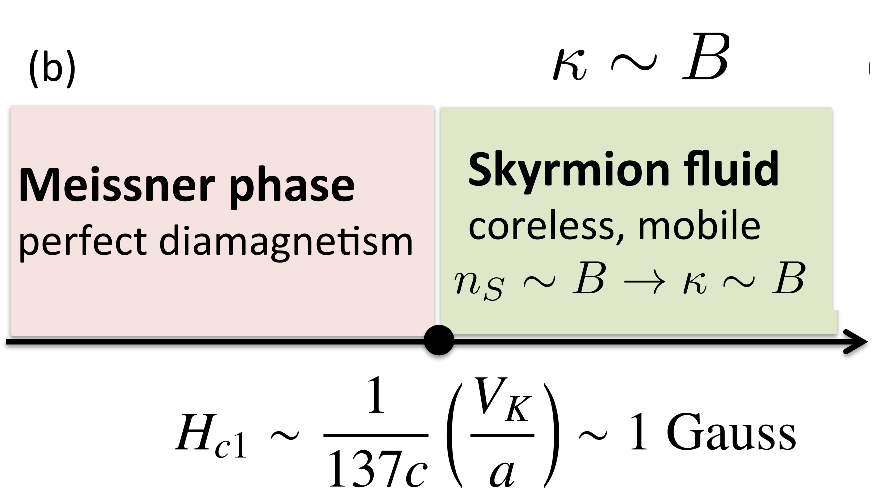

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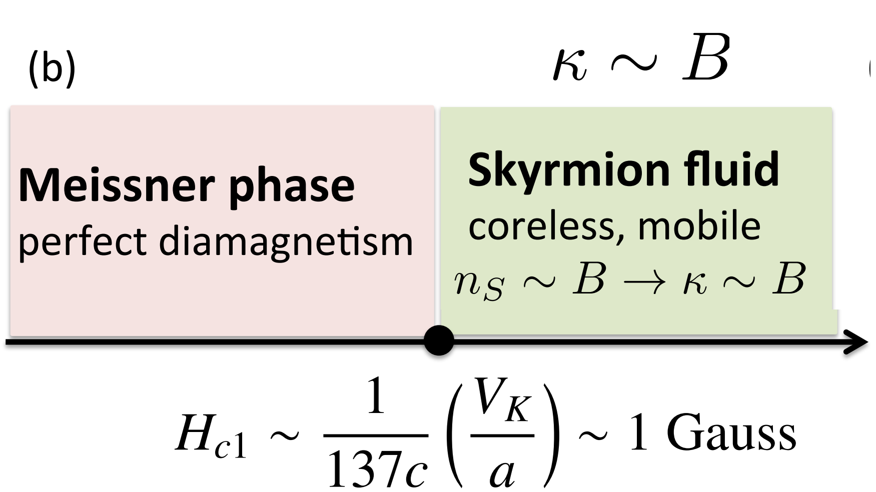
Majorana spin representation



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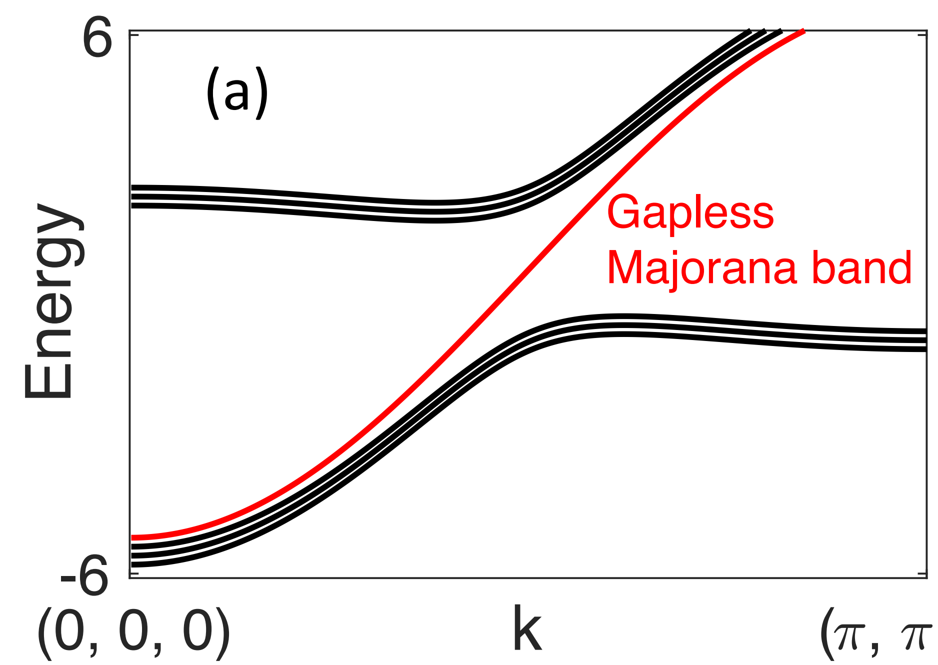
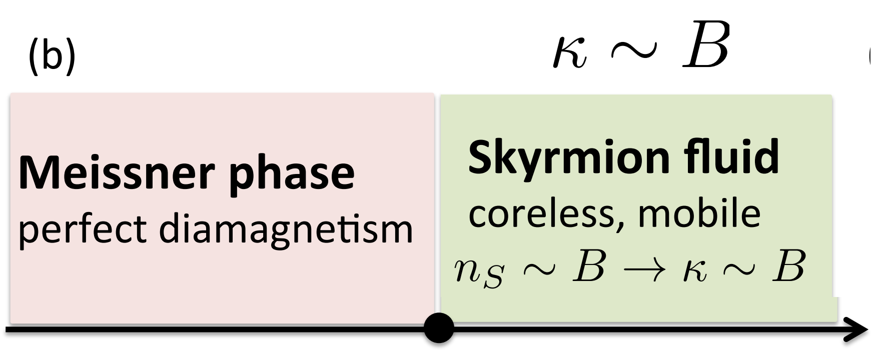


$$\vec{S}_j=-\left(\frac{i}{2}\right)\vec{\eta}_j\times\vec{\eta}_j$$

Majorana spin representation



$$H_{c1}\sim\frac{1}{137c}\left(\frac{V_K}{a}\right)\sim 1\ \text{Gauss}$$

SmB_6: a Skyrme Dielectric?

Coleman, Miranda, Tsvelik, 1993, Baskaran 2015
Onur Erten, Po-Yao Chang, Piers Coleman and Alexei Tsvelik **arXiv:1701.06582**

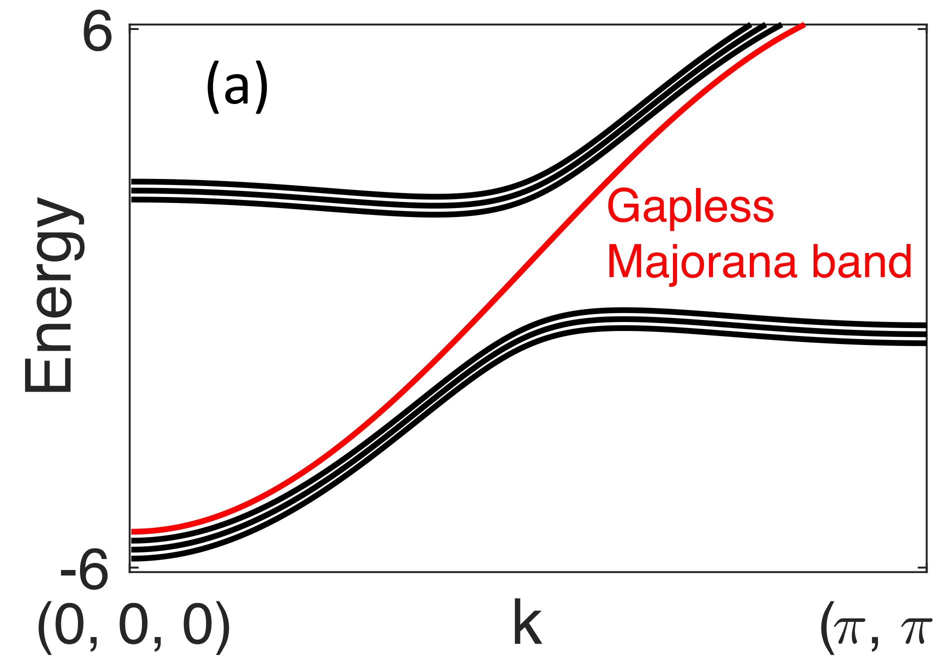
Superconductivity: requires Meissner *and* topological rigidity.

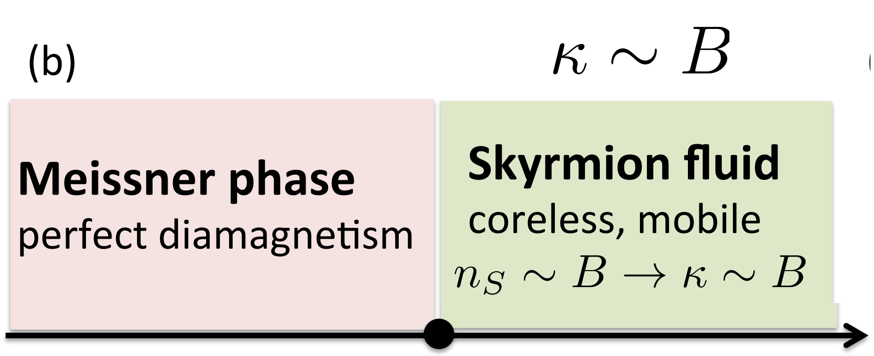
s-wave *odd-frequency triplet.*

$$(-1)^{i+j+k}\langle\psi_\uparrow\psi_\downarrow\mathbf{S}(\mathbf{x})\rangle \propto \hat{\mathbf{l}}(\mathbf{x}) + i\hat{\mathbf{m}}(\mathbf{x}),$$

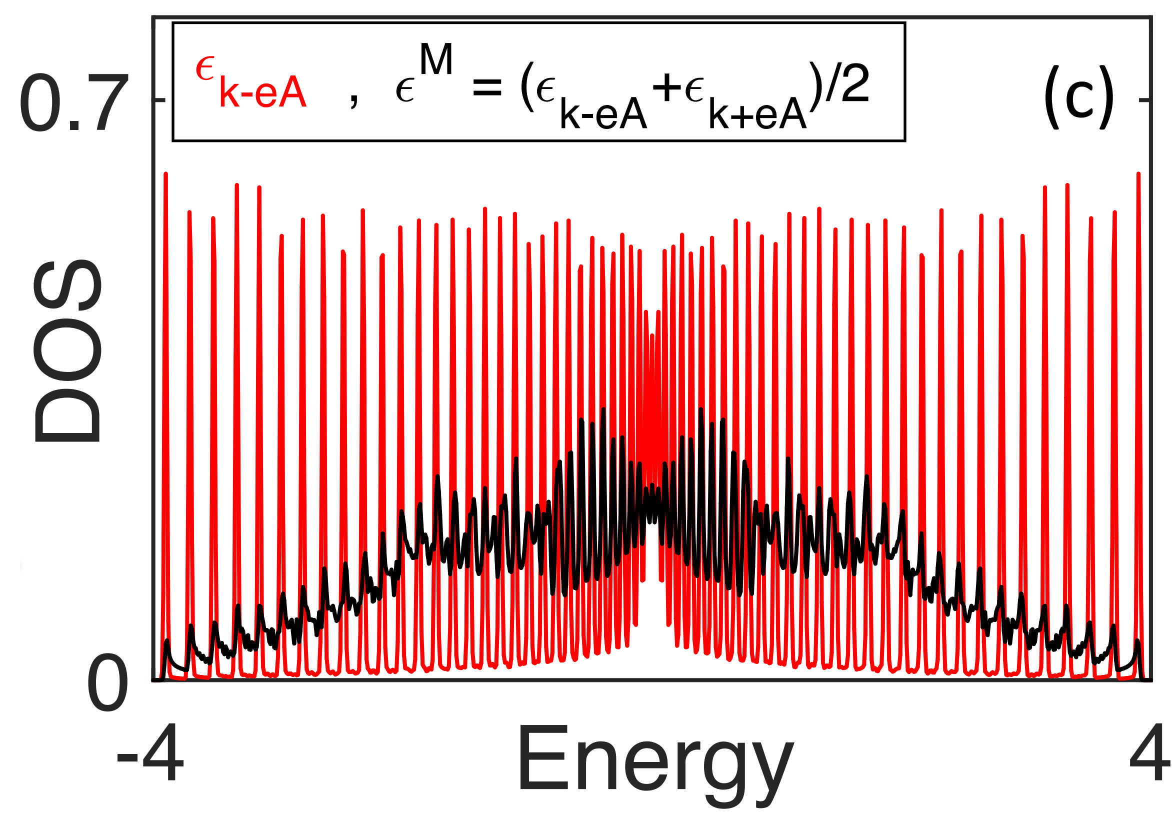
$$\vec{S}_j = -\left(\frac{i}{2}\right)\vec{\eta}_j \times \vec{\eta}_j$$

Majorana spin representation



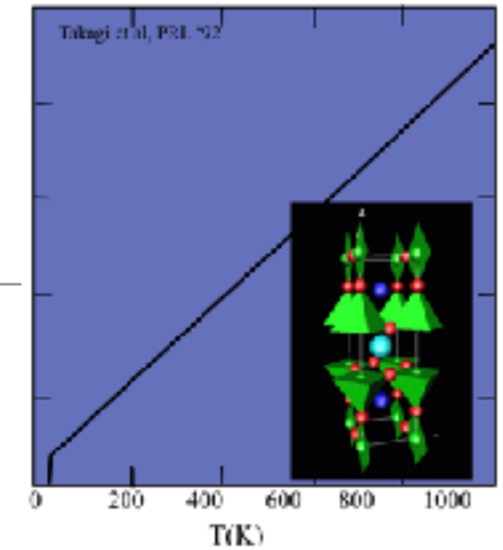


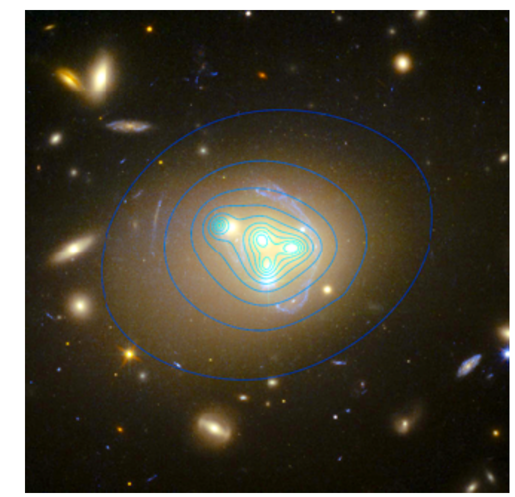
$$H_{c1} \sim \frac{1}{137c}\left(\frac{V_K}{a}\right) \sim 1\ \text{Gauss}$$

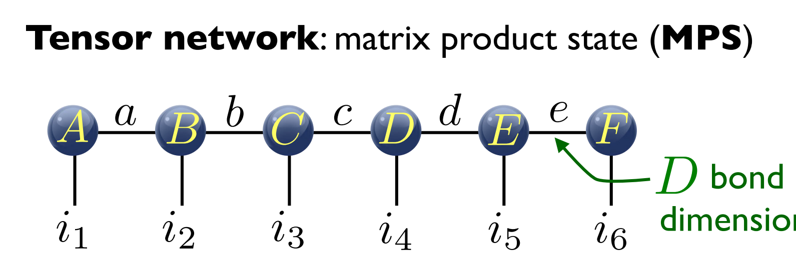


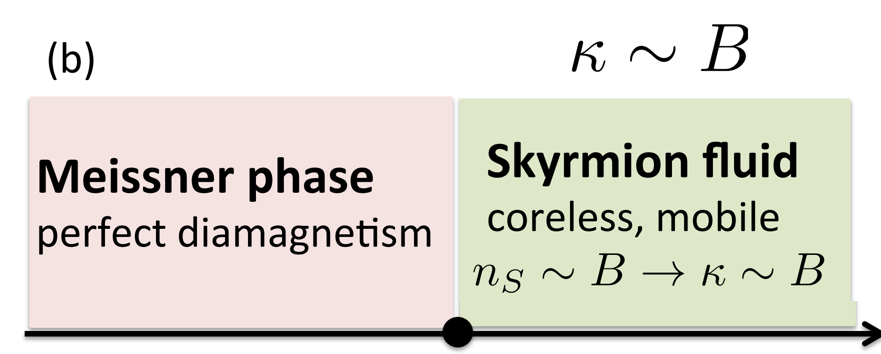
Conclusions

- 50 Years of Novel Phases.
  Discovery often awaits new concepts.
- Dark Matter Challenges of the Solid State.
  Potential for qualitatively new advances in our understanding of quantum matter.
- Quantum I: MPS, PEPS. Tools to manipulate and explore new mechanisms of entanglement.
- Beyond Hartree Fock/BCS: Order parameter fractionalization hypothesis.
- Fermi surface in an insulator. Skyrme Dielectric?









$$H_{c1} \sim \frac{1}{137c}\left(\frac{V_K}{a}\right) \sim 1 \text{ Gauss}$$

Thank you!