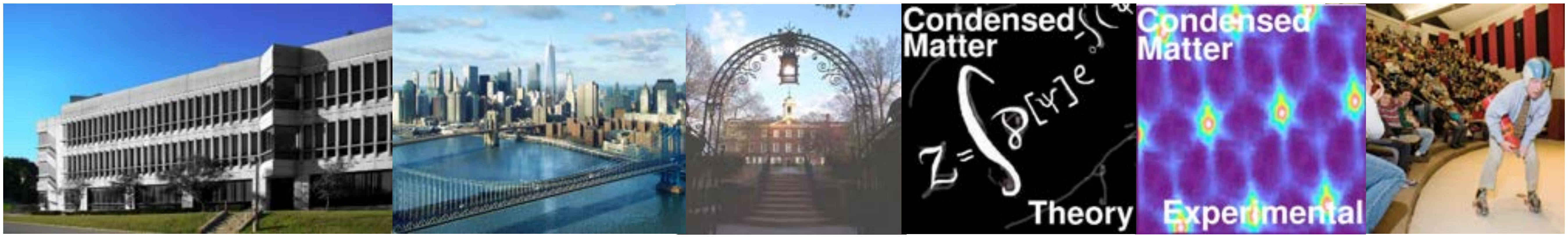
Piers Coleman

Center for Materials Theory, Rutgers.

Royal Holloway University of London

The Physics of Heavy Fermion Superconductivity

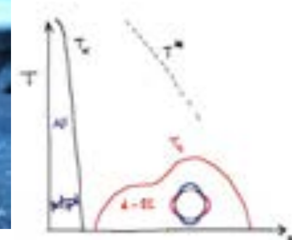


Piers Coleman

Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30-July 25, 2014

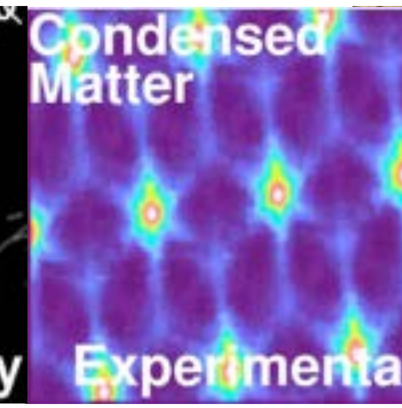


14-17 July 2014

Royal Holloway University of London

The Physics of Heavy Fermion Superconductivity

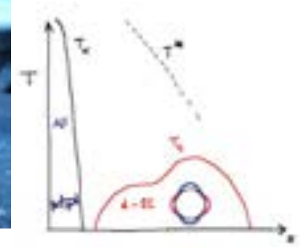


Piers Coleman
Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30–July 25, 2014

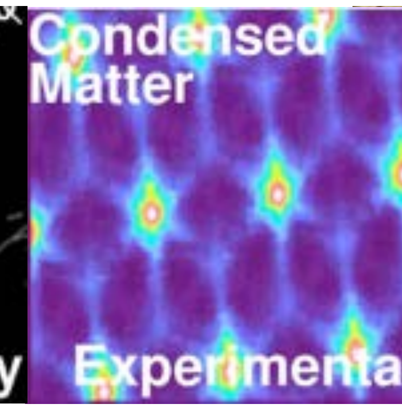
$PuCoGa_5$: 20 K Superconductor

14-17 July 2014

The Physics of Heavy Fermion Superconductivity

Lecture I. Introduction: Heavy Fermions and the Kondo Lattice.



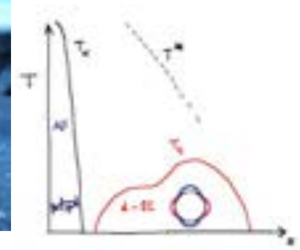



Piers Coleman

Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30-July 25, 2014

14-17 July 2014

NSF

Royal Holloway University of London

Rutgers The State University of New Jersey

The Physics of Heavy Fermion Superconductivity

1. Introduction: Heavy Fermions and the Kondo Lattice.
2. BCS meets Kondo: mean-field approach to the Kondo Lattice.
3. Glue vs Fabric: Good, Bad and Ugly Heavy Fermion Superconductors.
4. Composite vs AFM induced pairing.

Rutgers
Center for Materials Theory

Notes:

"Many Body Physics: an introduction", Ch 8,15-16", PC, CUP to be published (2014).
http://www.physics.rutgers.edu/~coleman. Password on request.
"Heavy Fermions: electrons at the edge of magnetism." Wiley encyclopedia of magnetism. PC. cond-mat/0612006.
"I2CAM-FAPERJ Lectures on Heavy Fermion Physics", (X=I, II, III)
http://physics.rutgers.edu/~coleman/talks/RIO13_X.pdf

General reading:

A. Hewson, "Kondo effect to heavy fermions", CUP, (1993).
"The Theory of Quantum Liquids", Nozieres and Pines (Perseus 1999).

P. Coleman and N. Andrei, J. Phys. Cond. Matt C1, 4057-4080, (1989).
P. Coleman, A. M. Tsvelik, N. Andrei and H. Y. Kee, PRB 60, 3605 (1999).
R. Flint and P. Coleman, Nature Physics 4, 643 (2008).
R. Flint and P. Coleman PRL, 105, 246404 (2010)
R. Flint, A. Nevidomskyy and P. Coleman PRB 84, 064514 (2011).

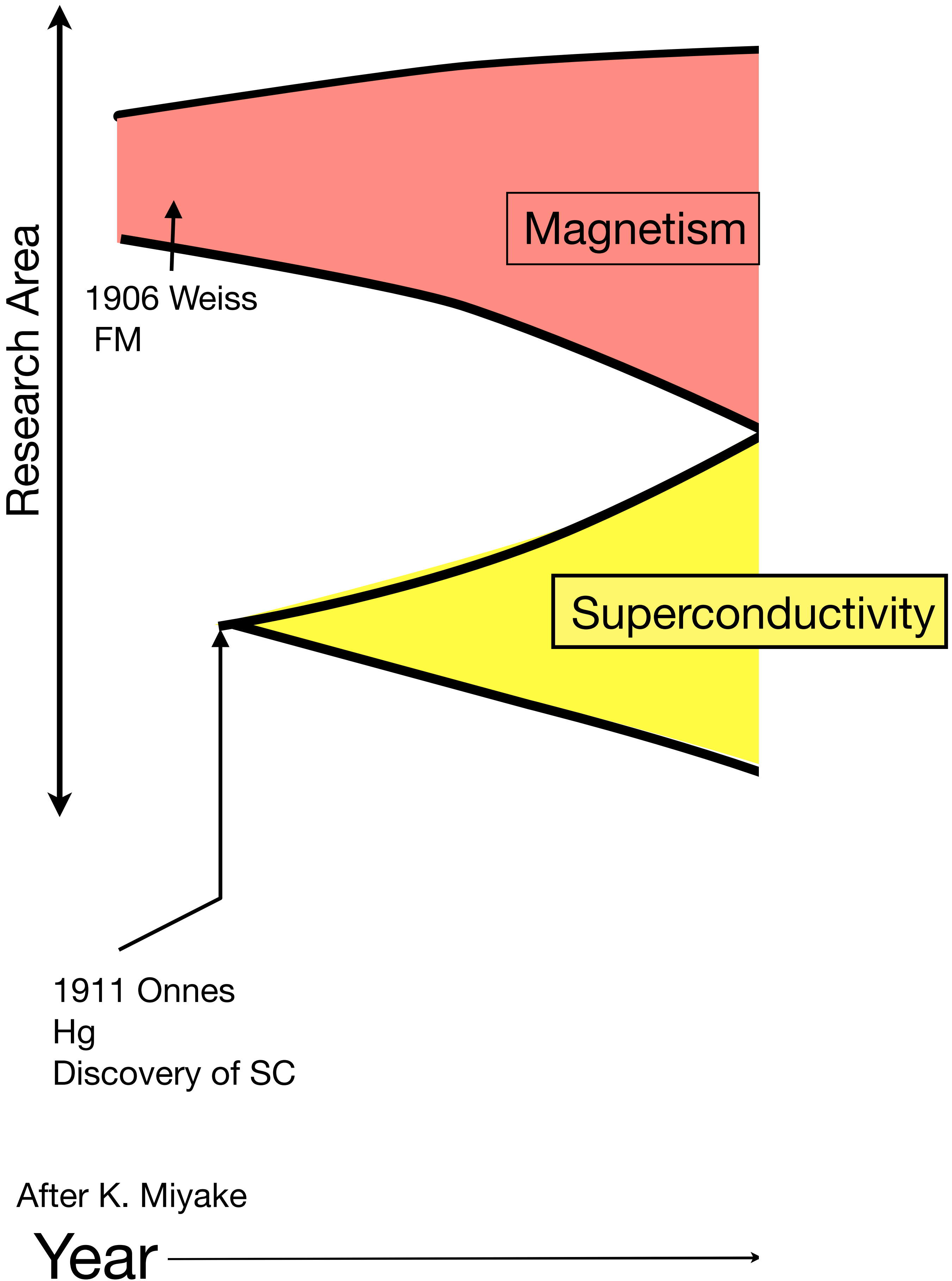
Rutgers Center for Materials Theory

Lecture 1 Introduction to Heavy Fermions and the Kondo Lattice.

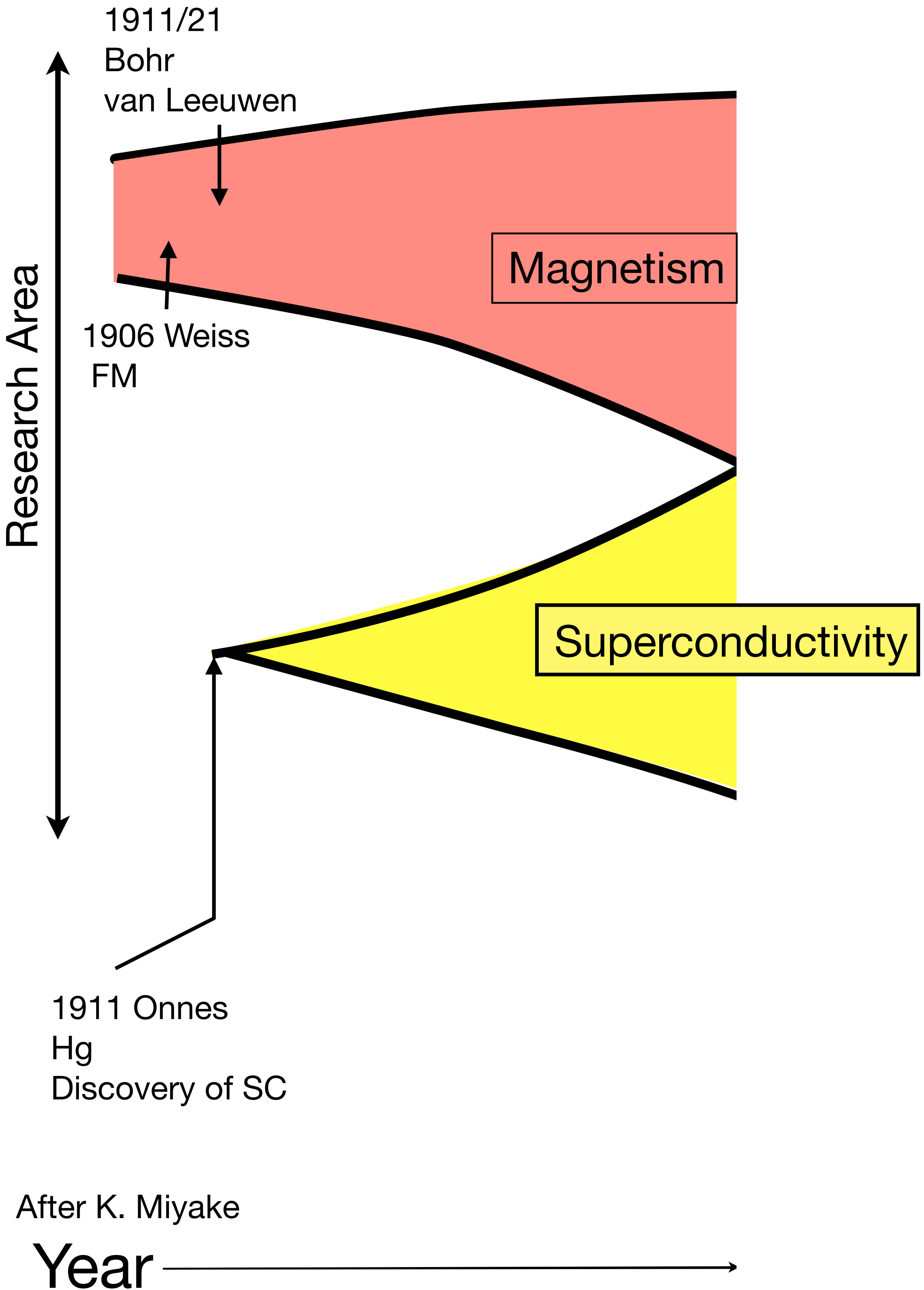
1. Magnetism and SC: a remarkable converegence.
2. Electrons on the Brink of Localization.
3. Cartoon introduction to Heavy Fermions.
4. Lev Landau versus Ken Wilson: Criticality as a driver of Superconductivity.
5. Anderson, Kondo and Doniach.

Magnetism and Superconductivity: A remarkable convergence

Magnetism and Superconductivity

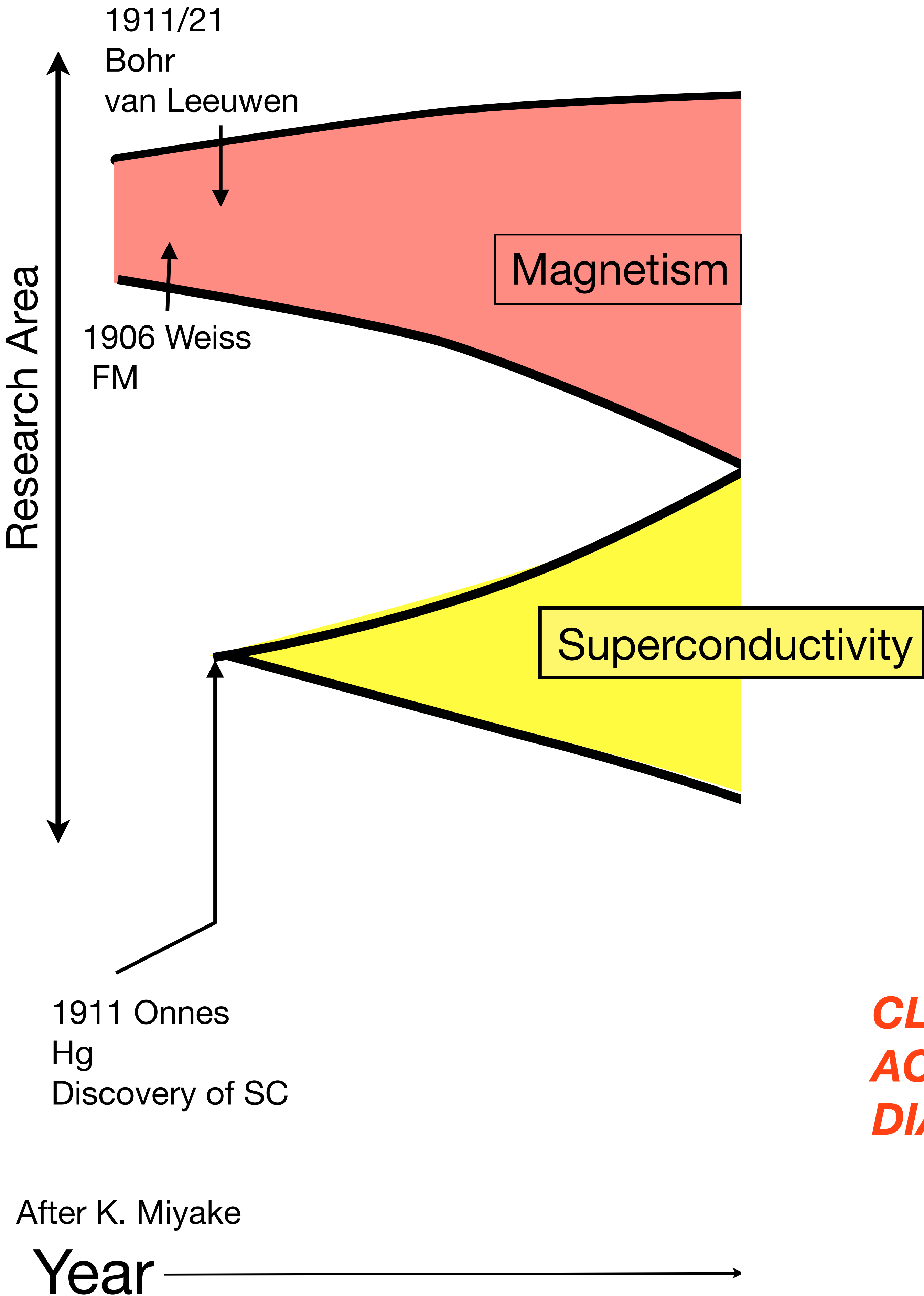


Magnetism and Superconductivity



Bohr-van Leeuwen Theorem (1911,1921)

Magnetism and Superconductivity



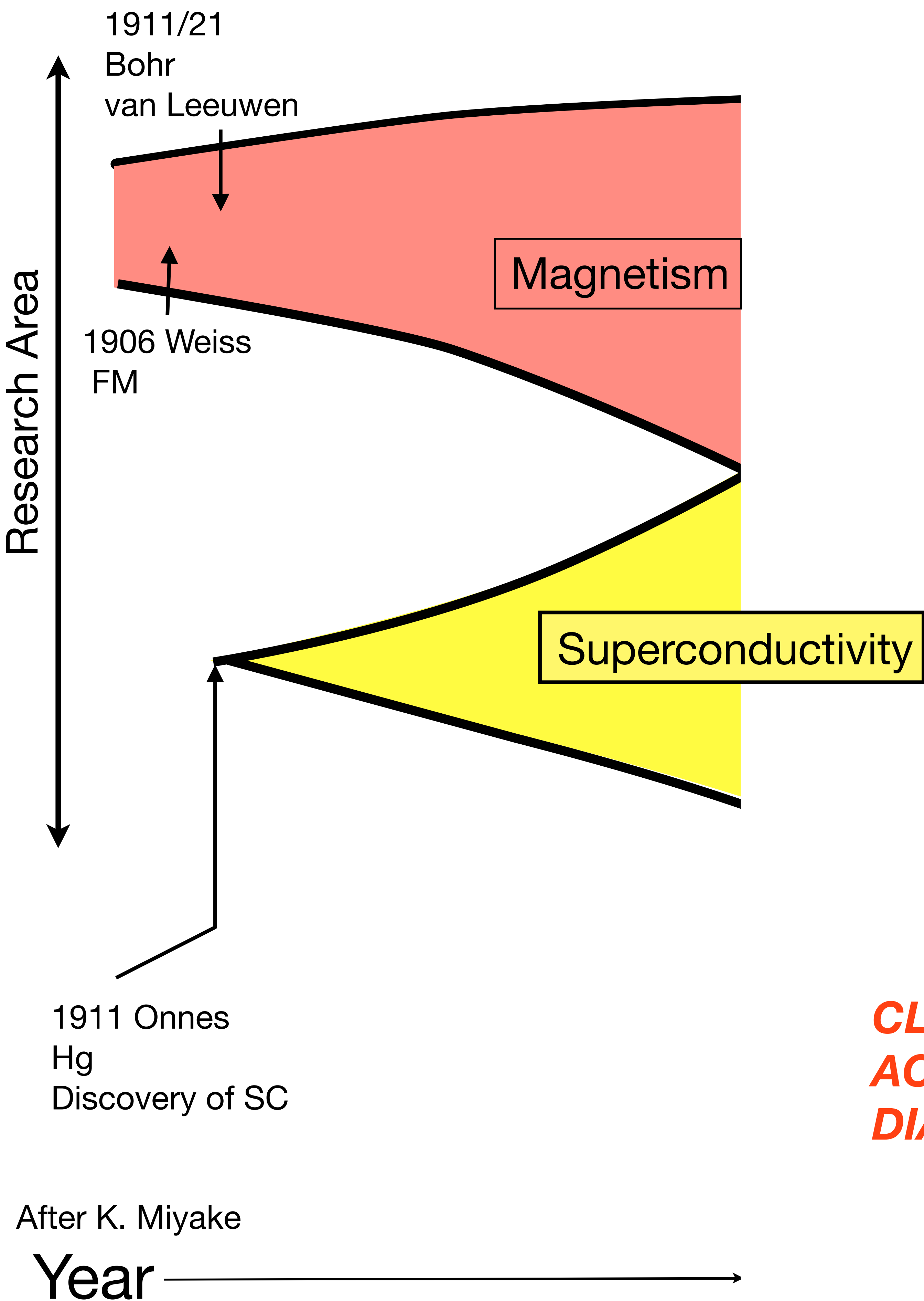
Bohr-van Leeuwen Theorem (1911,1921)

$$p' = p - eA$$

$$H[p, A] = H[p', A = 0]$$

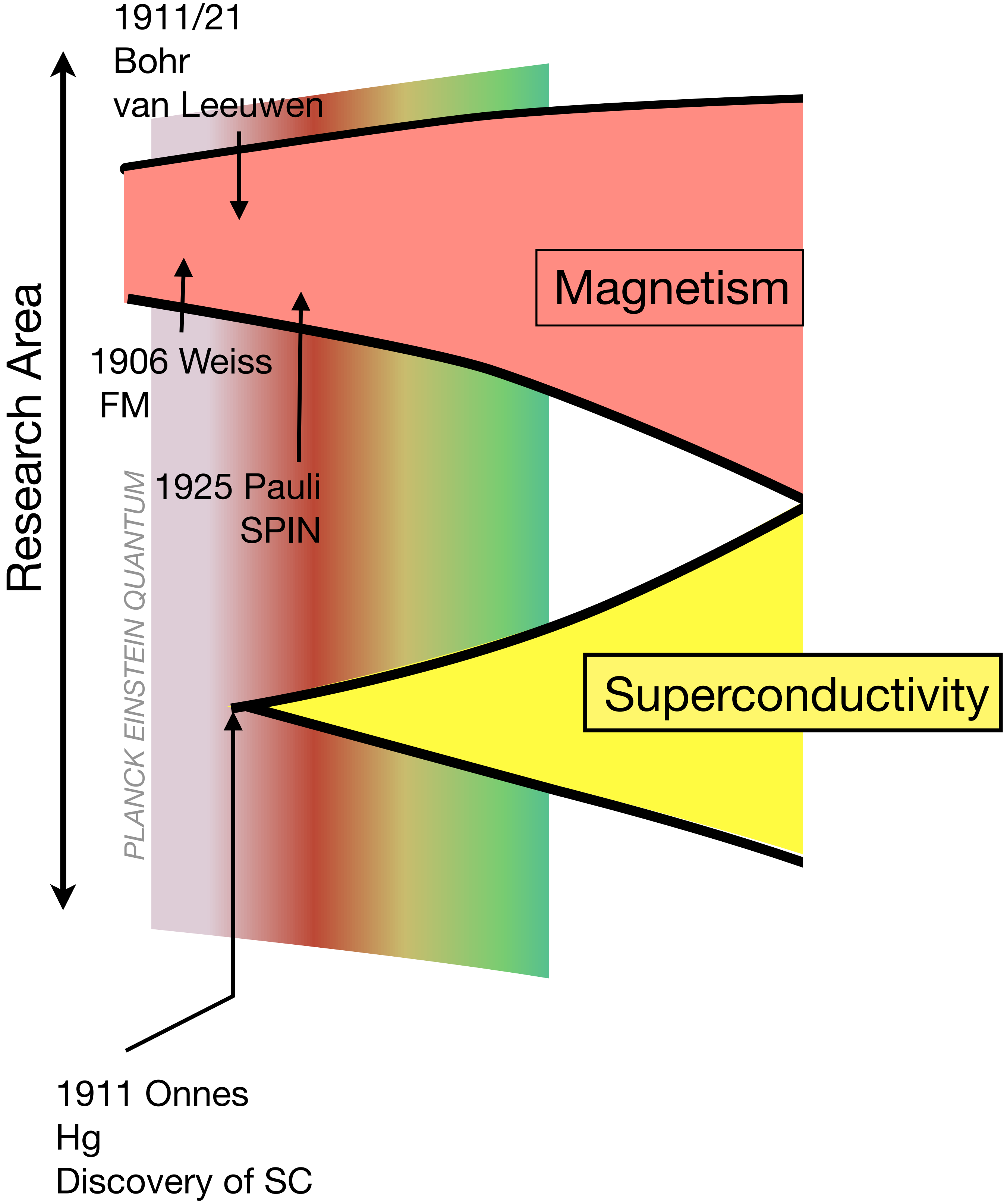
CLASSICAL PHYSICS IS UNABLE TO ACCOUNT FOR <u>ANY</u> FORM OF MAGNETISM DIA- FERRO- OR PARA- MAGNETISM.

Magnetism and Superconductivity



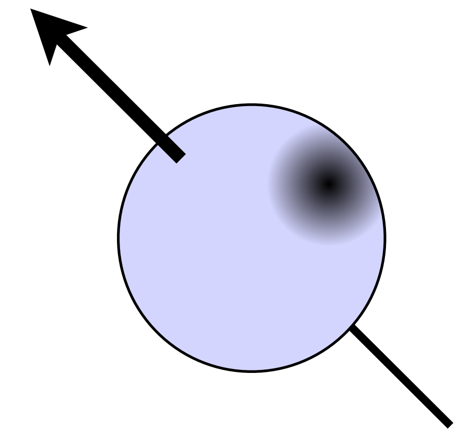
CLASSICAL PHYSICS IS UNABLE TO ACCOUNT FOR ANY FORM OF MAGNETISM DIA- FERRO- OR PARA- MAGNETISM.

Magnetism and Superconductivity

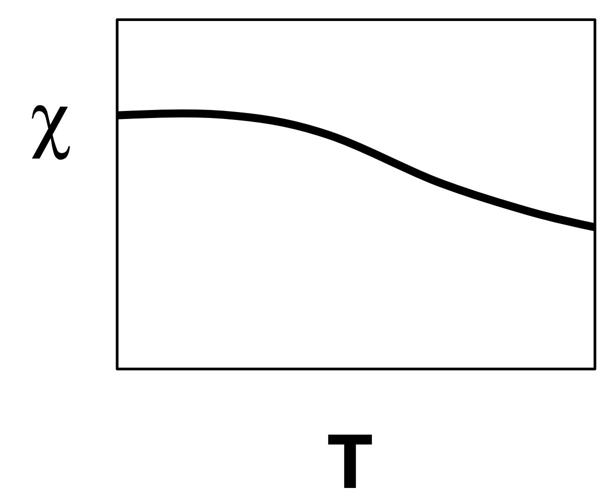


After K. Miyake

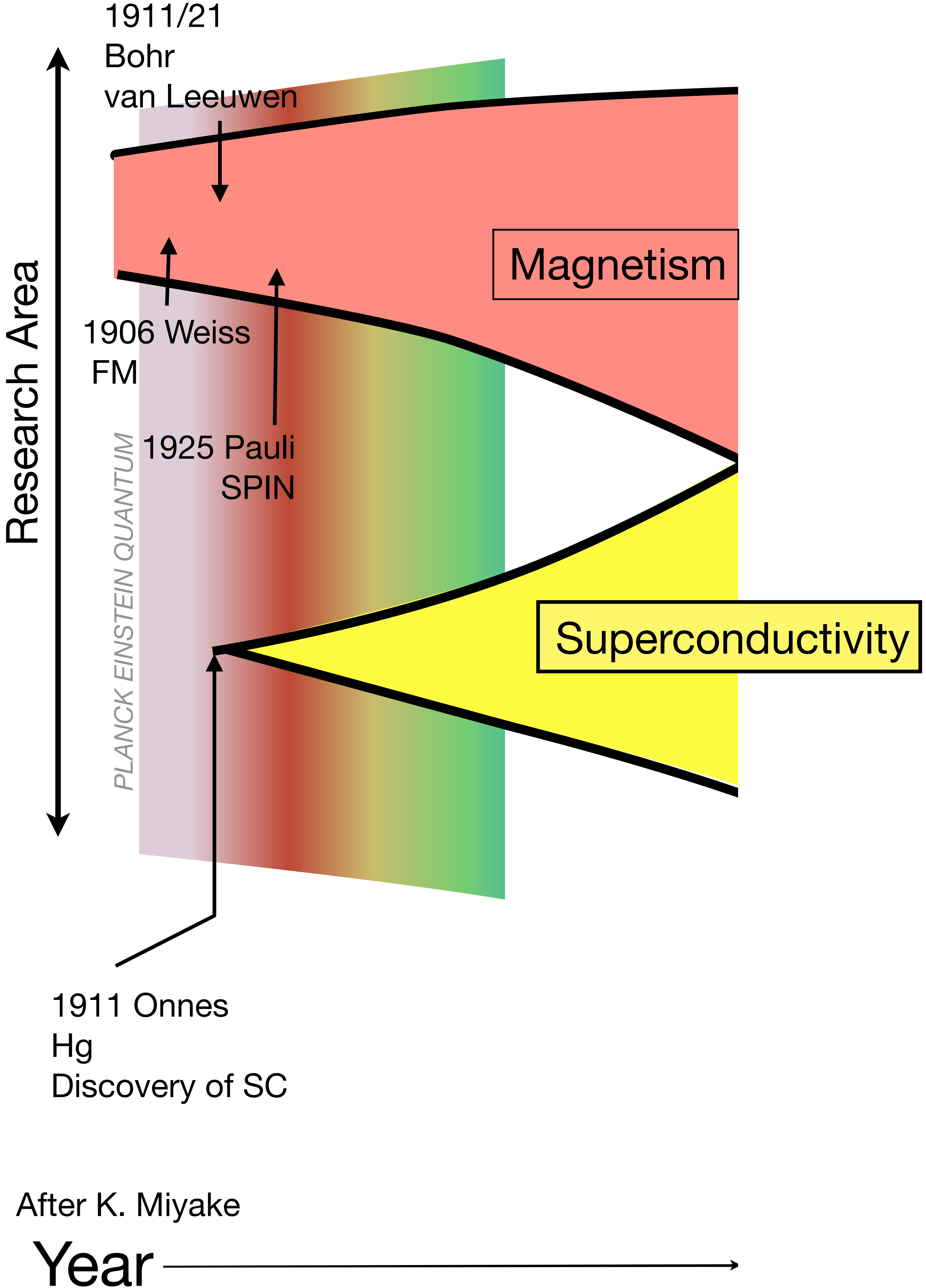
Pauli



spin

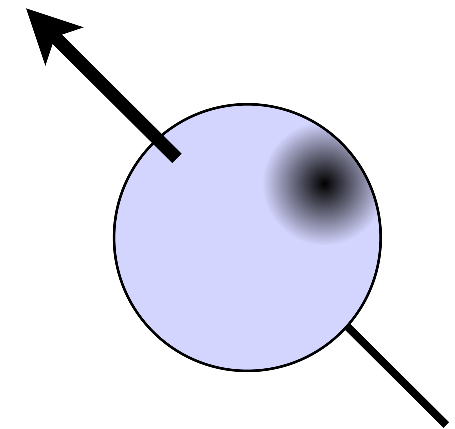


Magnetism and Superconductivity

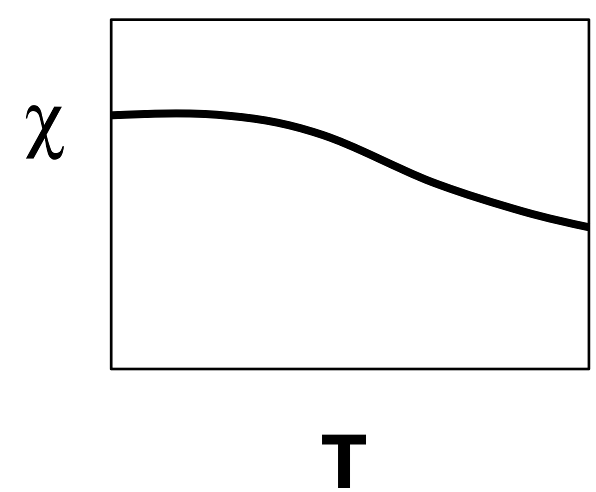


After K. Miyake

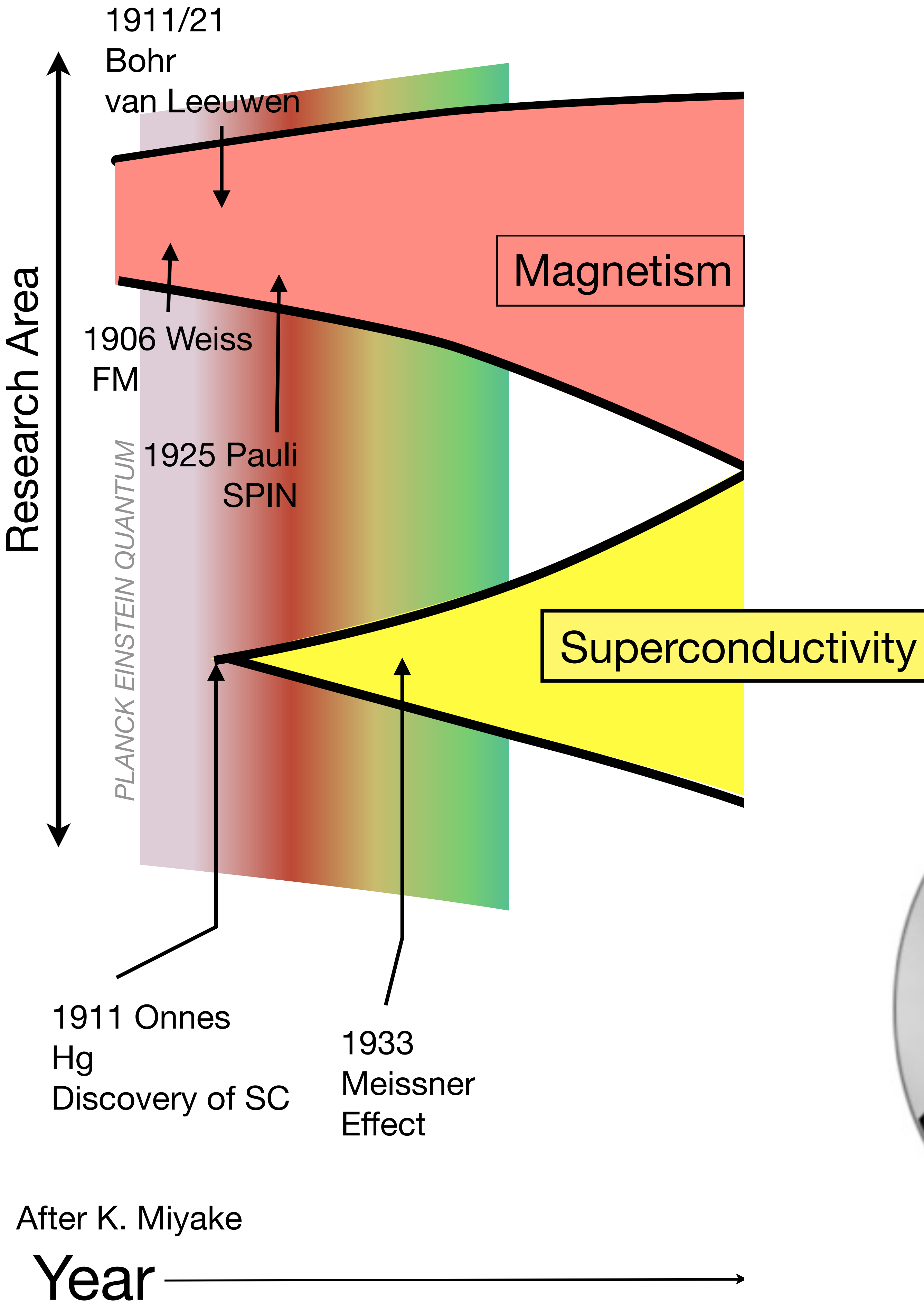
Pauli



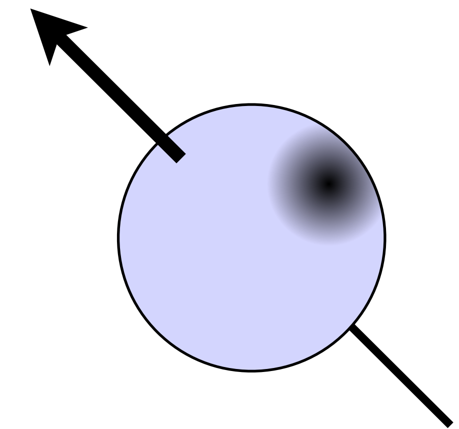
spin



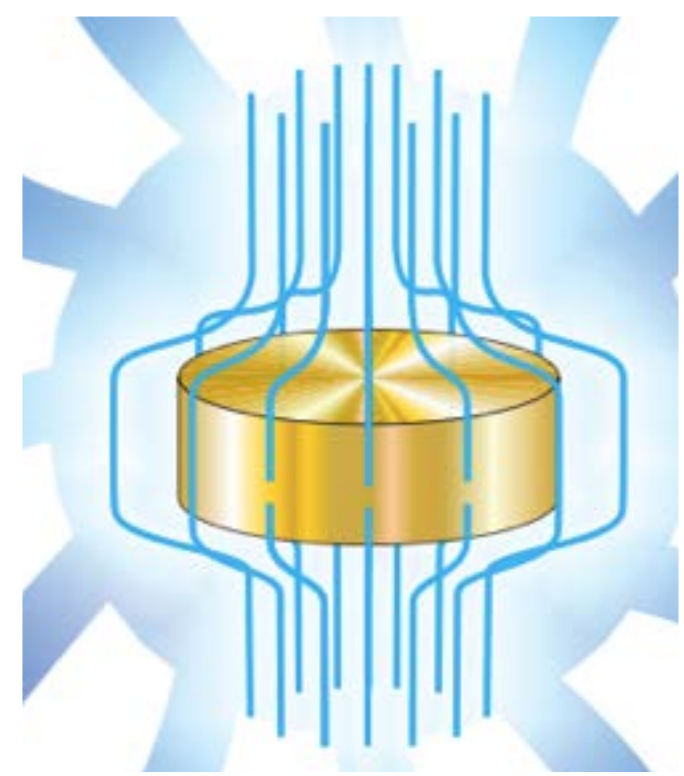
Magnetism and Superconductivity



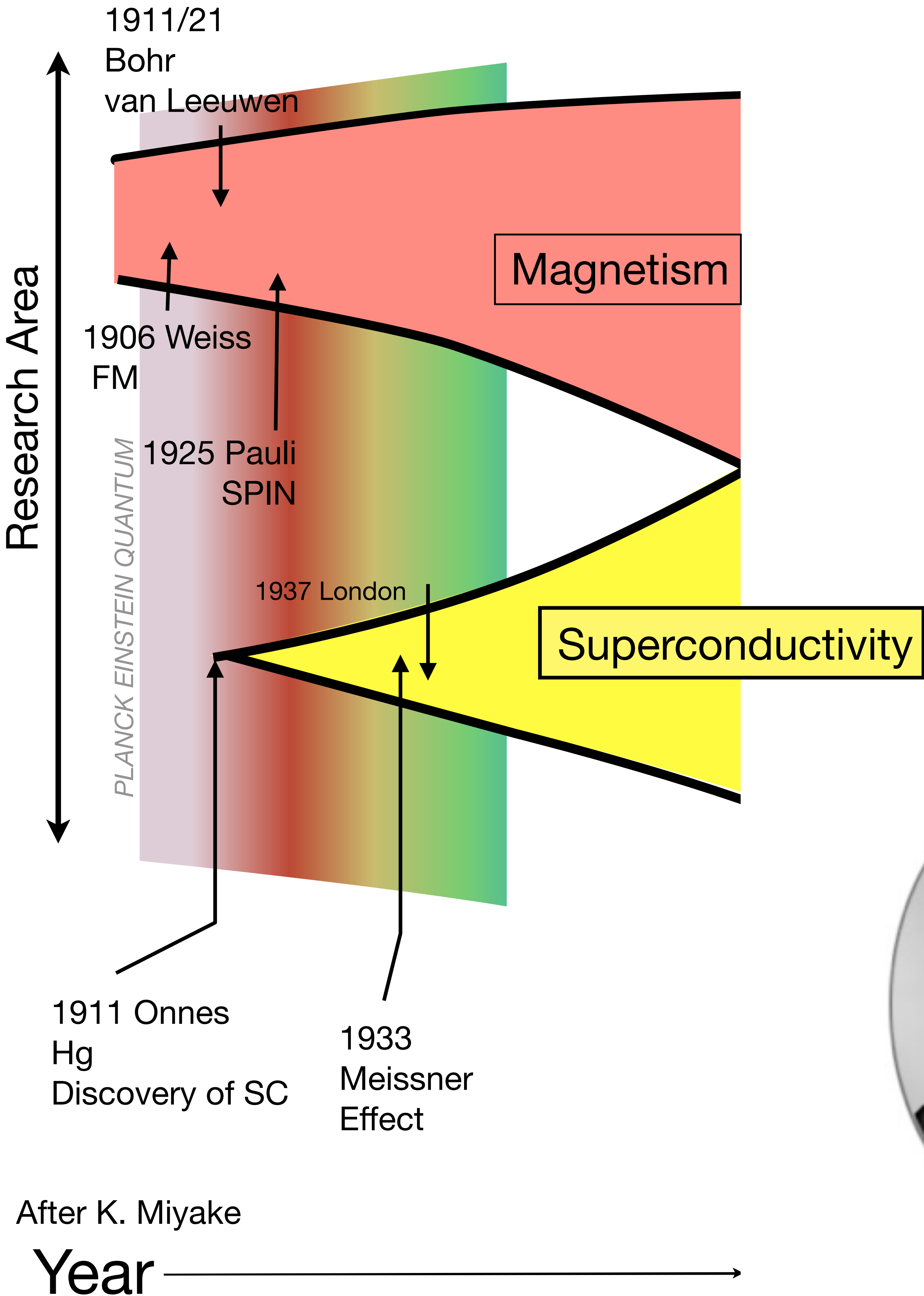
Pauli

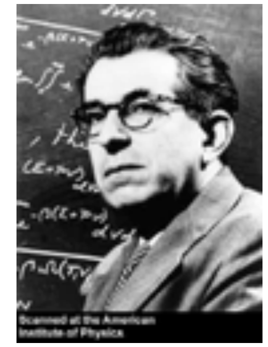


spin



Magnetism and Superconductivity

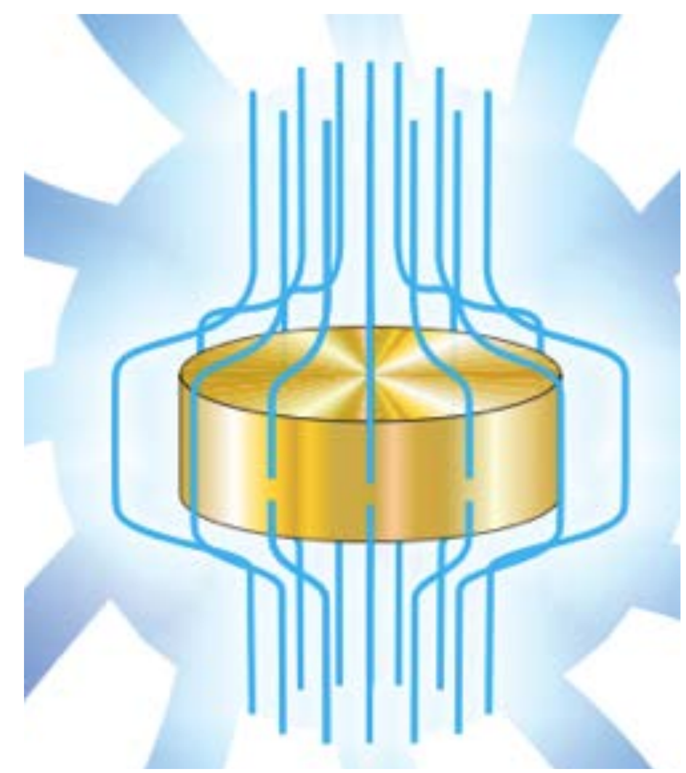




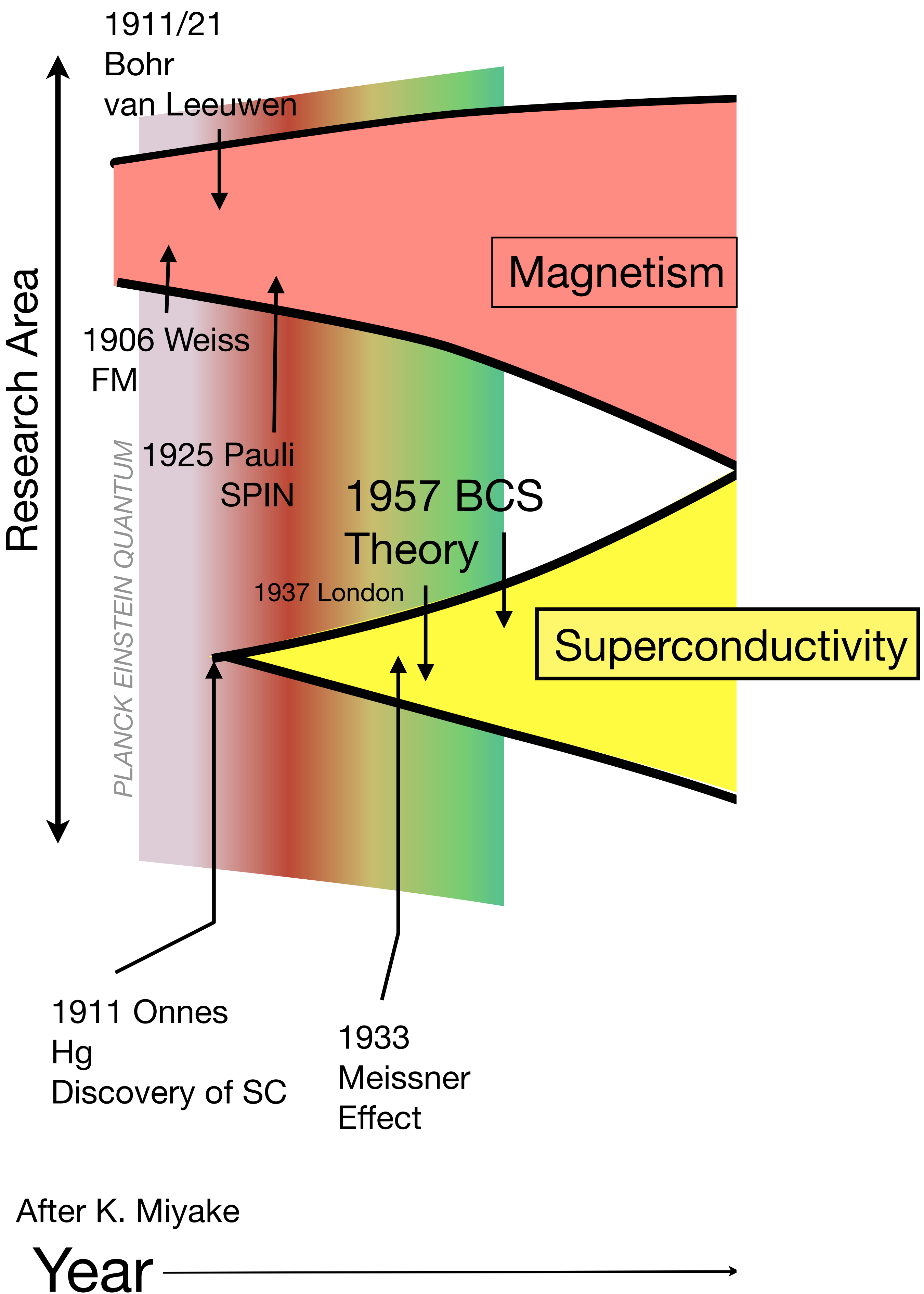
London 1937

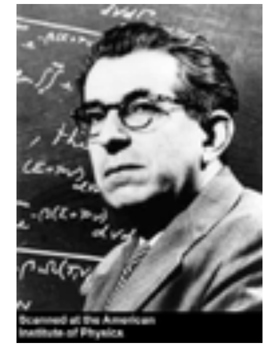
Rigidity of wavefunction
-> DIAMAGNETISM

Walther Meissner
(1882-1974)



Magnetism and Superconductivity



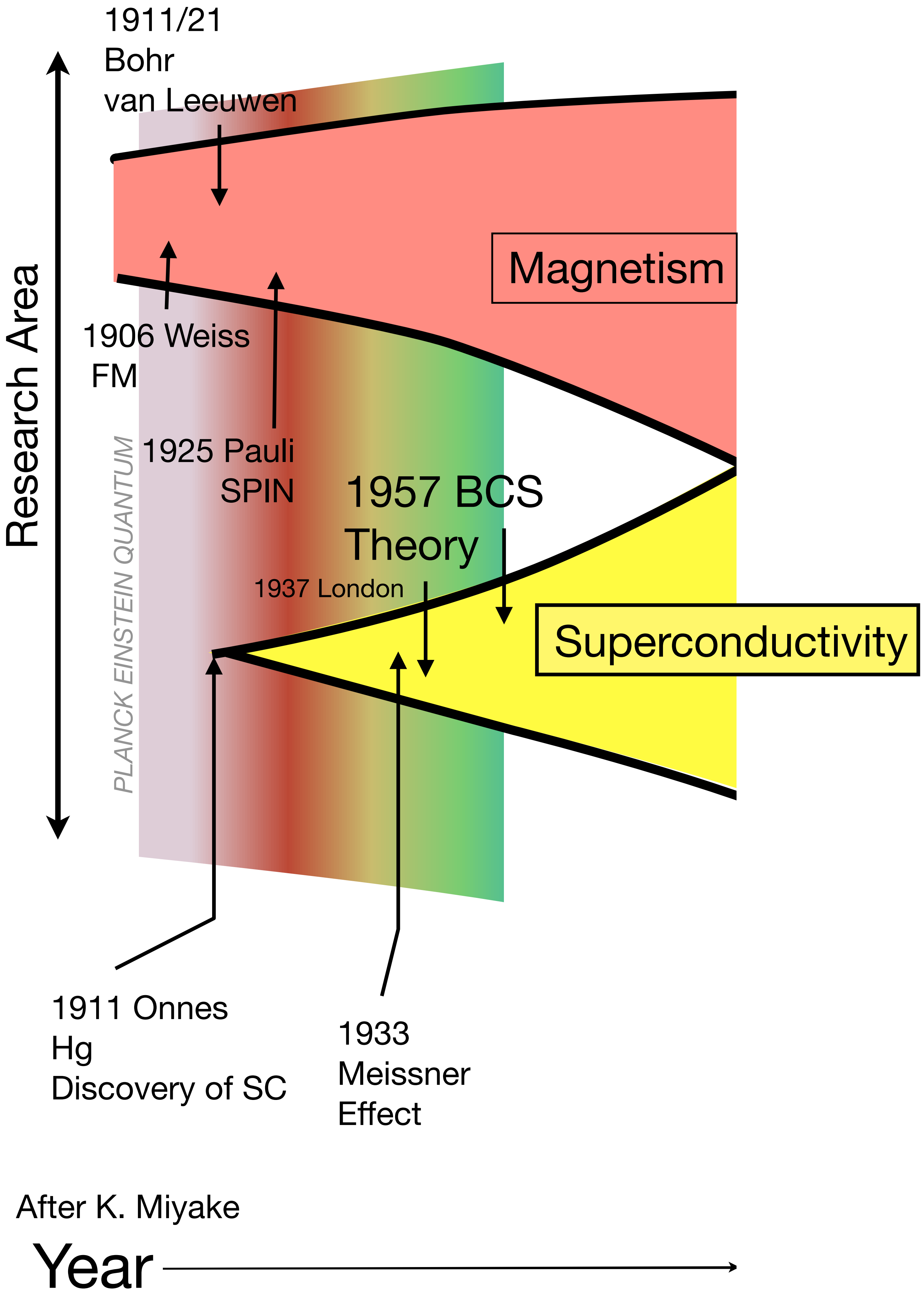


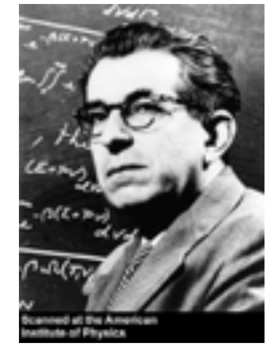
London 1937

Rigidity of wavefunction
-> DIAMAGNETISM

$$|\Psi\rangle = \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} c^\dagger_{-\mathbf{k}\downarrow} c^\dagger_{\mathbf{k}\uparrow})|0\rangle$$

Magnetism and Superconductivity



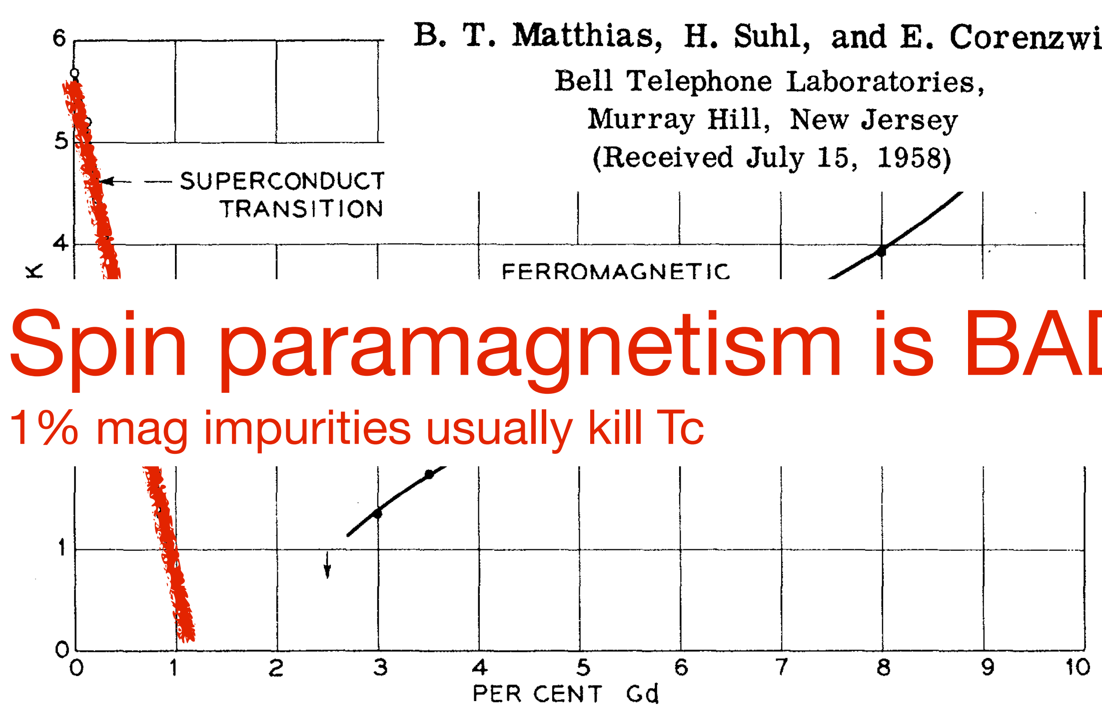


London 1937

Rigidity of wavefunction

-> DIAMAGNETISM

$$|\Psi\rangle = \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} c^{\dagger}_{-\mathbf{k}\downarrow} c^{\dagger}_{\mathbf{k}\uparrow})|0\rangle$$

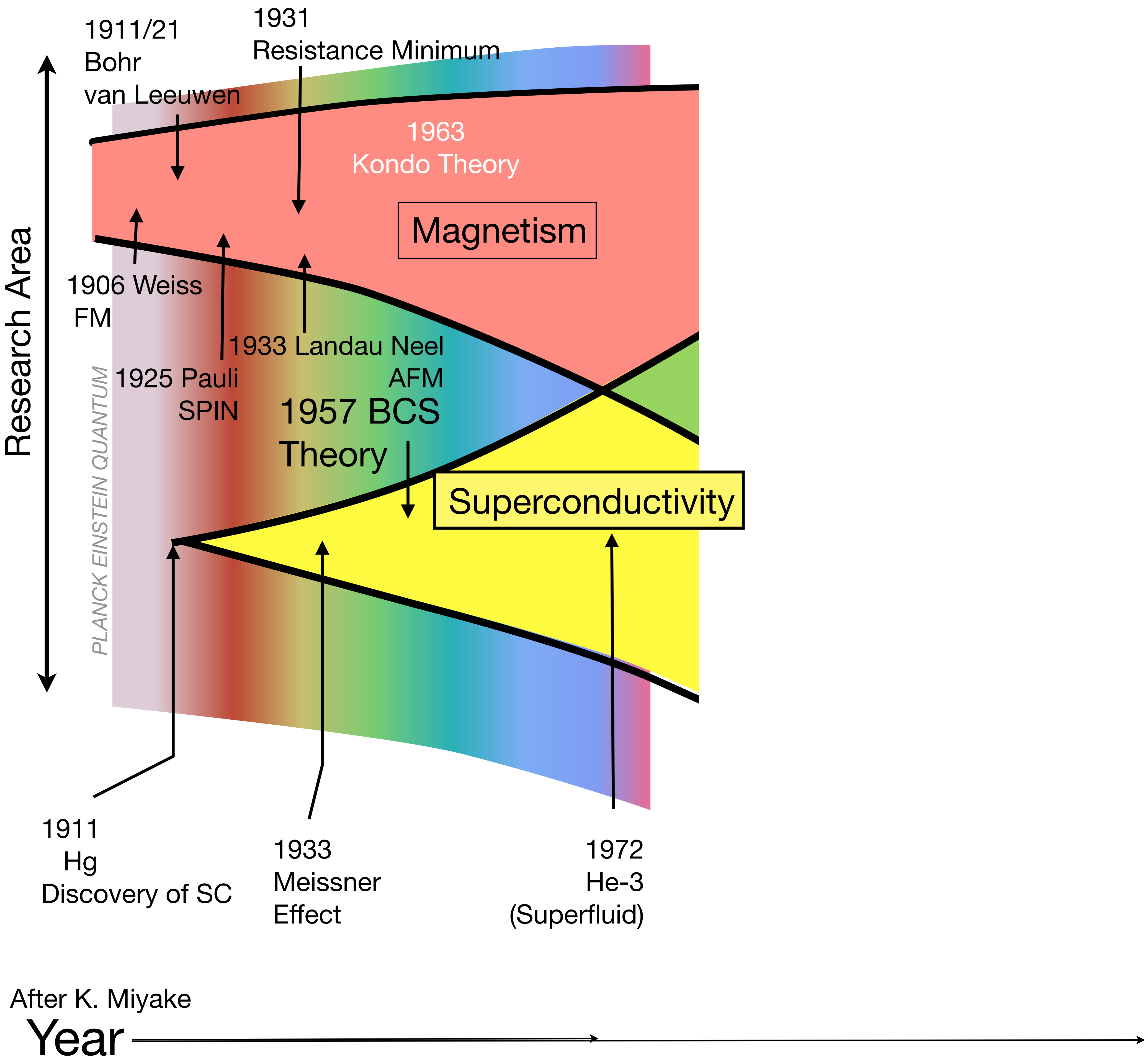


Spin paramagnetism is BAD!

1% mag impurities usually kill Tc

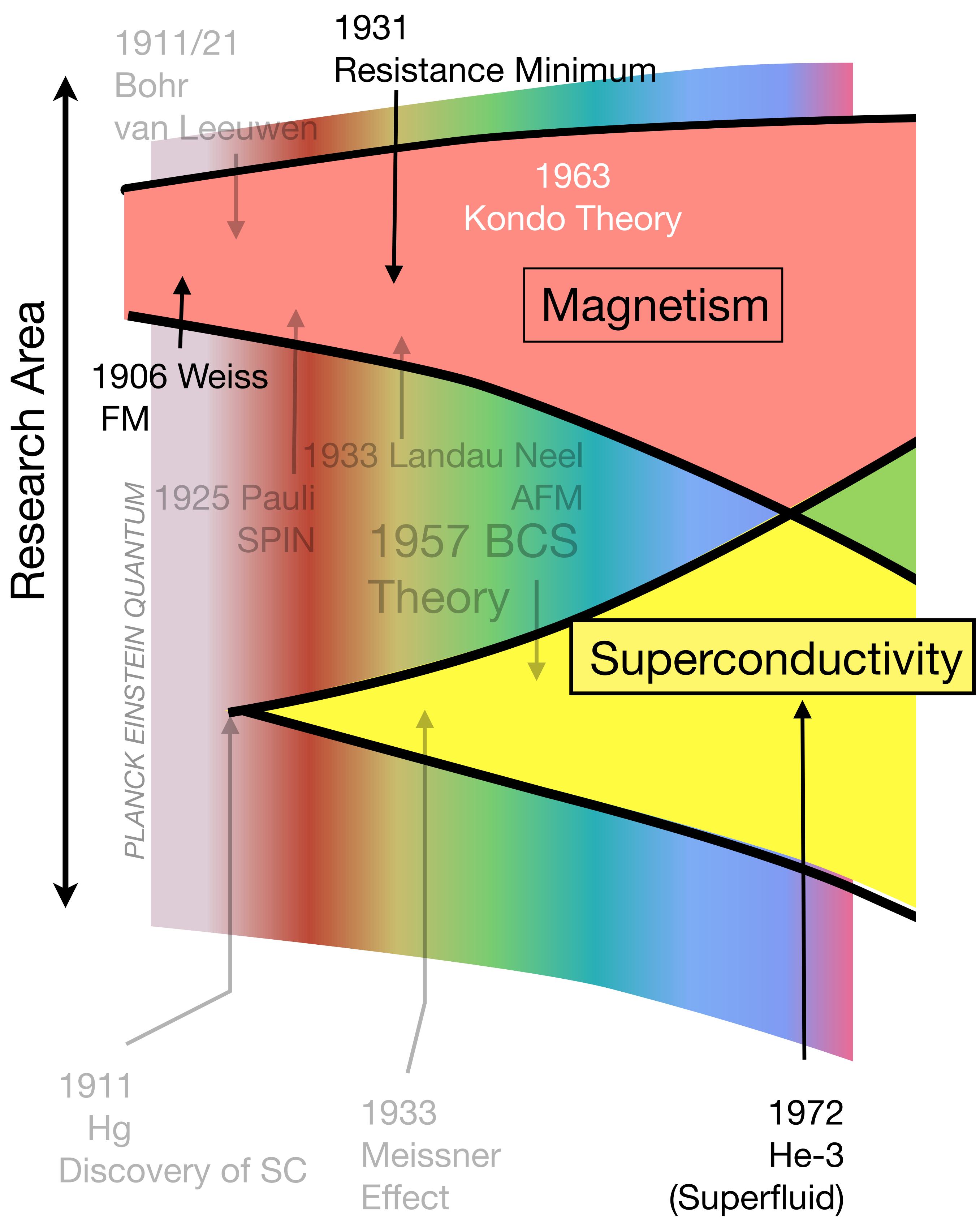
FIG. 3. Ferromagnetic and superconducting transition temperatures of solid solutions of gadolinium in lanthanum.

Magnetism and Superconductivity



After K. Miyake

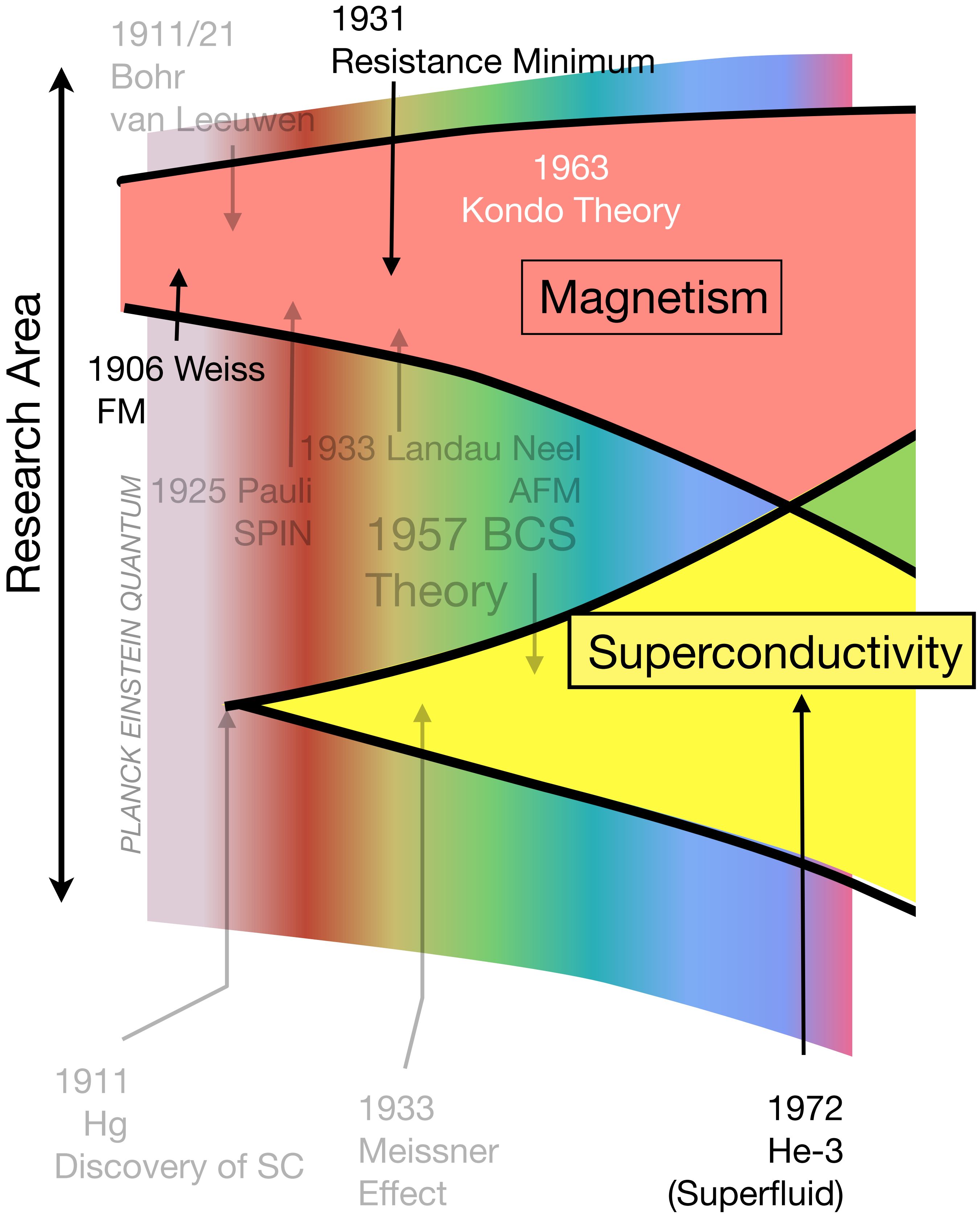
Magnetism and Superconductivity

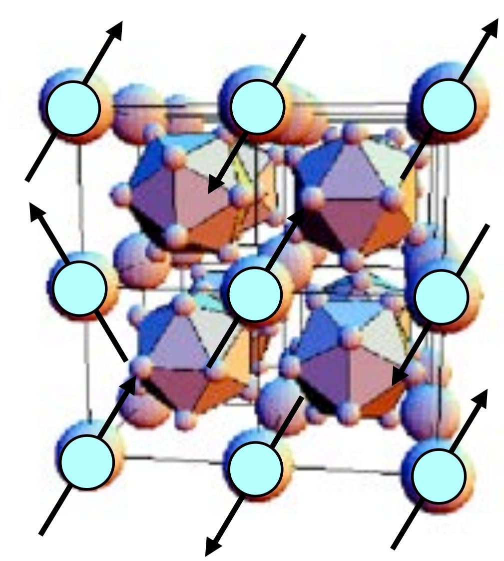


After K. Miyake

Year

Magnetism and Superconductivity





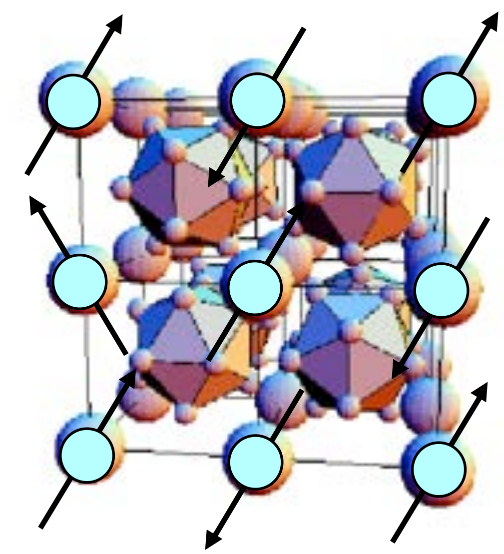
UBe_{13}

After K. Miyake

Year

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe.

Bell Labs, NJ 1973



UBe_{13}

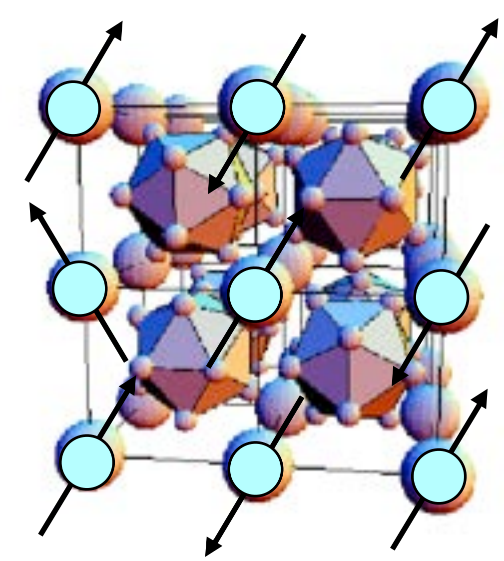
PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13.

Bell Labs, NJ 1973



UBe_{13}

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

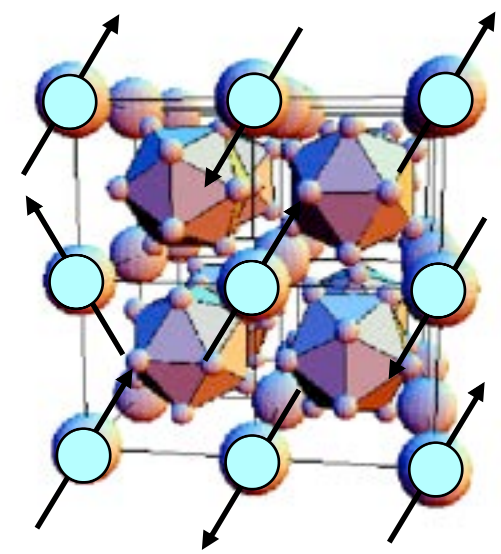
E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 14 March 1974)

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13.

Bell Labs, NJ 1973

Steglich
1979



UBe_{13}

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)

Volume 43, Number 25 PHYSICAL REVIEW LETTERS 17 December 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

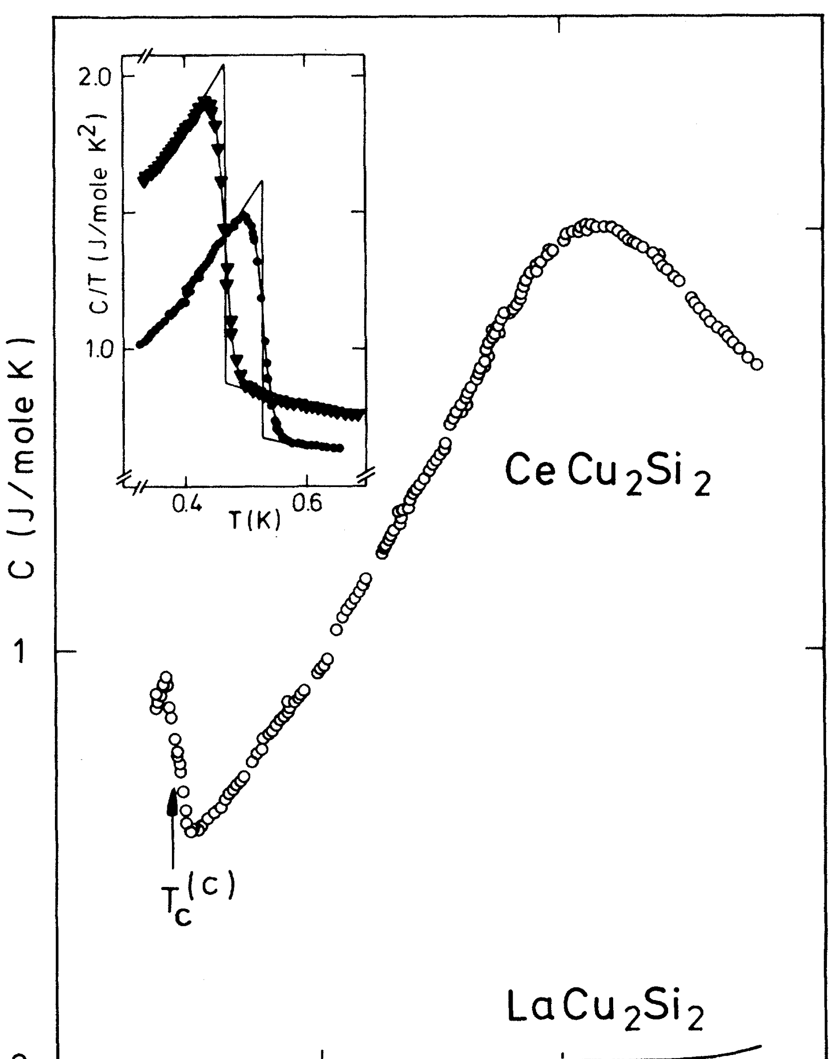
J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

and

H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 10 August 1979; revised manuscript received 7 November 1979)

Steglich
1979



VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

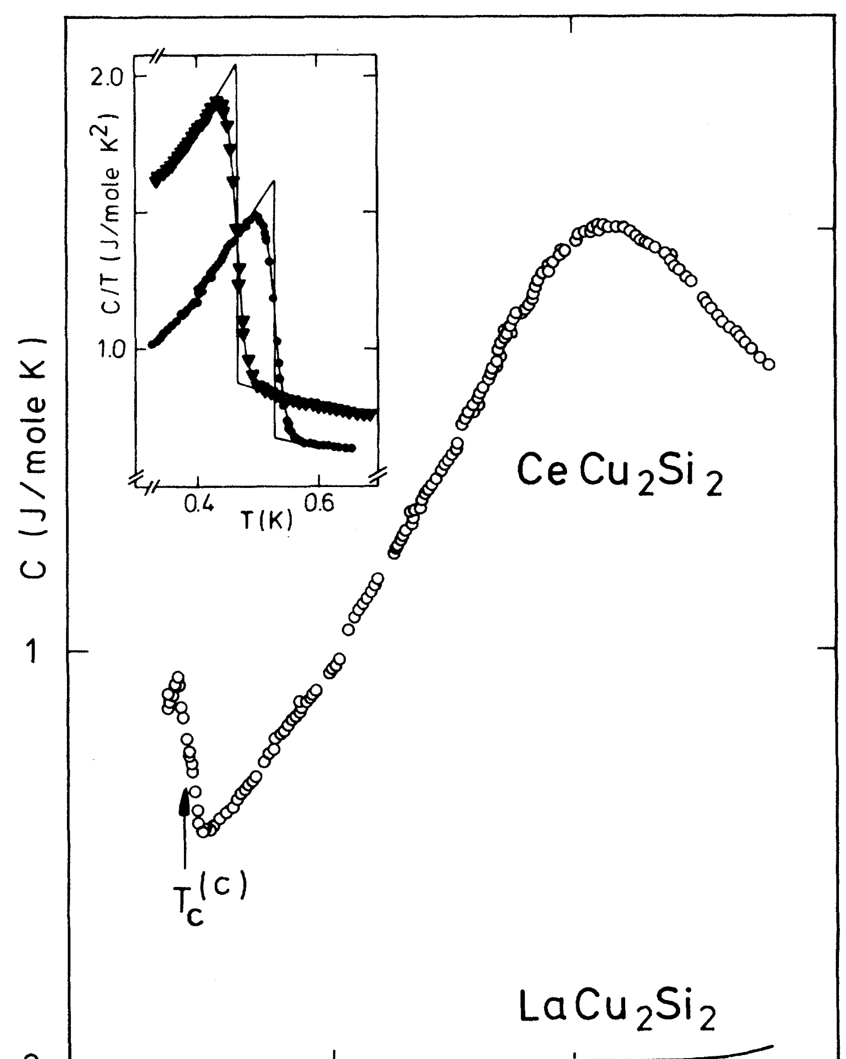
and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

and

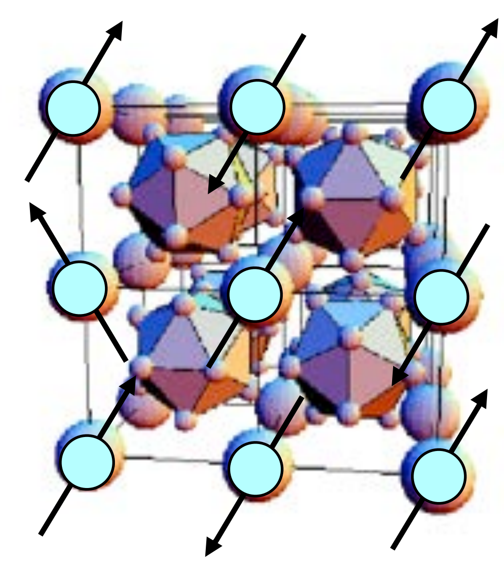
H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany
(Received 10 August 1979; revised manuscript received 7 November 1979)

Steglich
1979



Since the Debye temperature, Θ, is of the order of 200 K,[5] we find $T_c < T_F < \Theta$ with $T_c/T_F \simeq T_F/\Theta \simeq 0.05$. This suggests that $CeCu_2Si$ (i) behaves as a "high-temperature superconductor" and (ii) cannot be described by conventional theory of superconductivity which assumes a typical phonon frequency $k_B\Theta/h \ll k_B T_F/h$, the characteristic frequency of the fermions.

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13. Bell Labs, NJ 1973



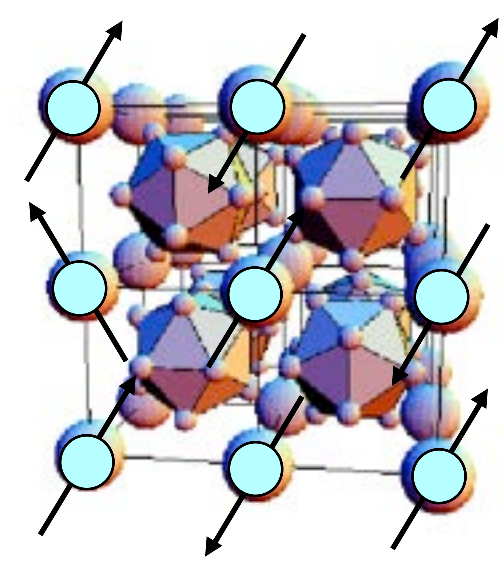
UBe_{13}

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)

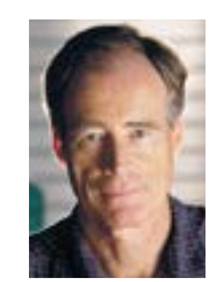
We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13. Bell Labs, NJ 1973



UBe_{13}

Ott 1976

Steglich 1979

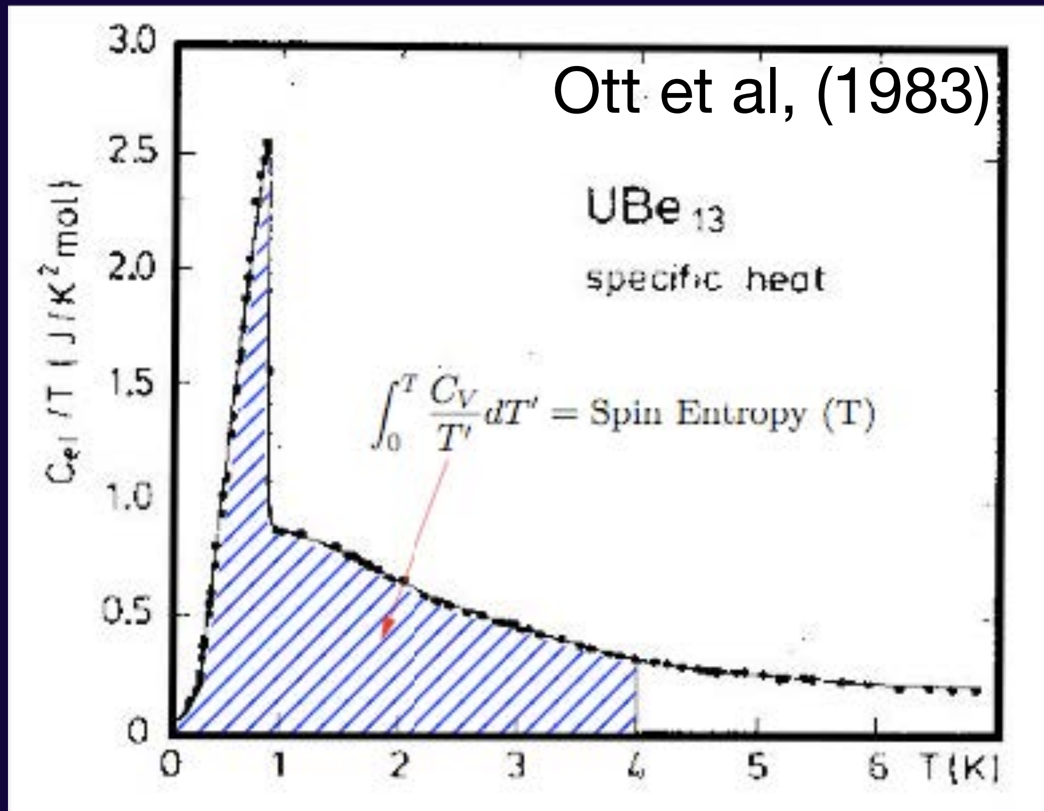


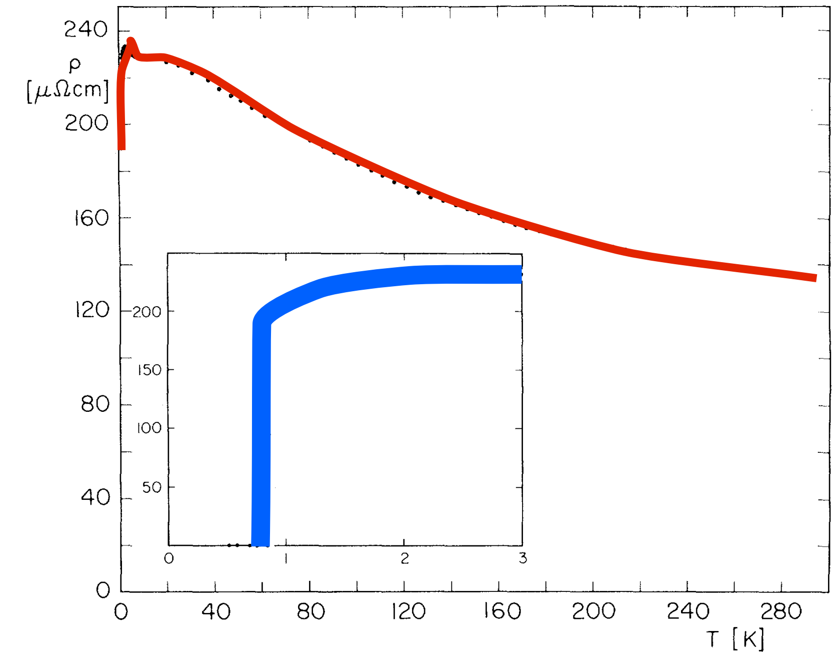
Fisk 1983

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

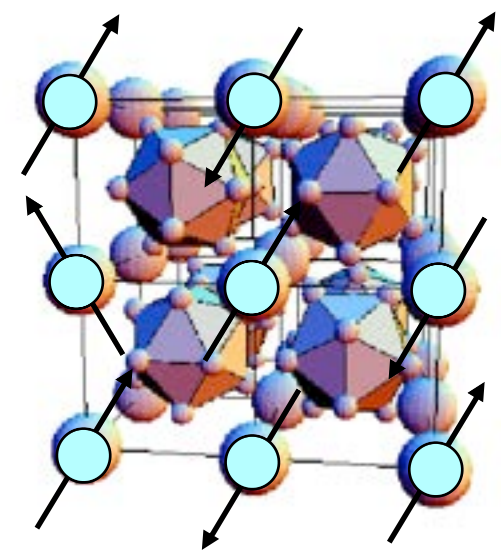
Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)





We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13. Bell Labs, NJ 1973



UBe_{13}



Ott 1976

Steglich 1979

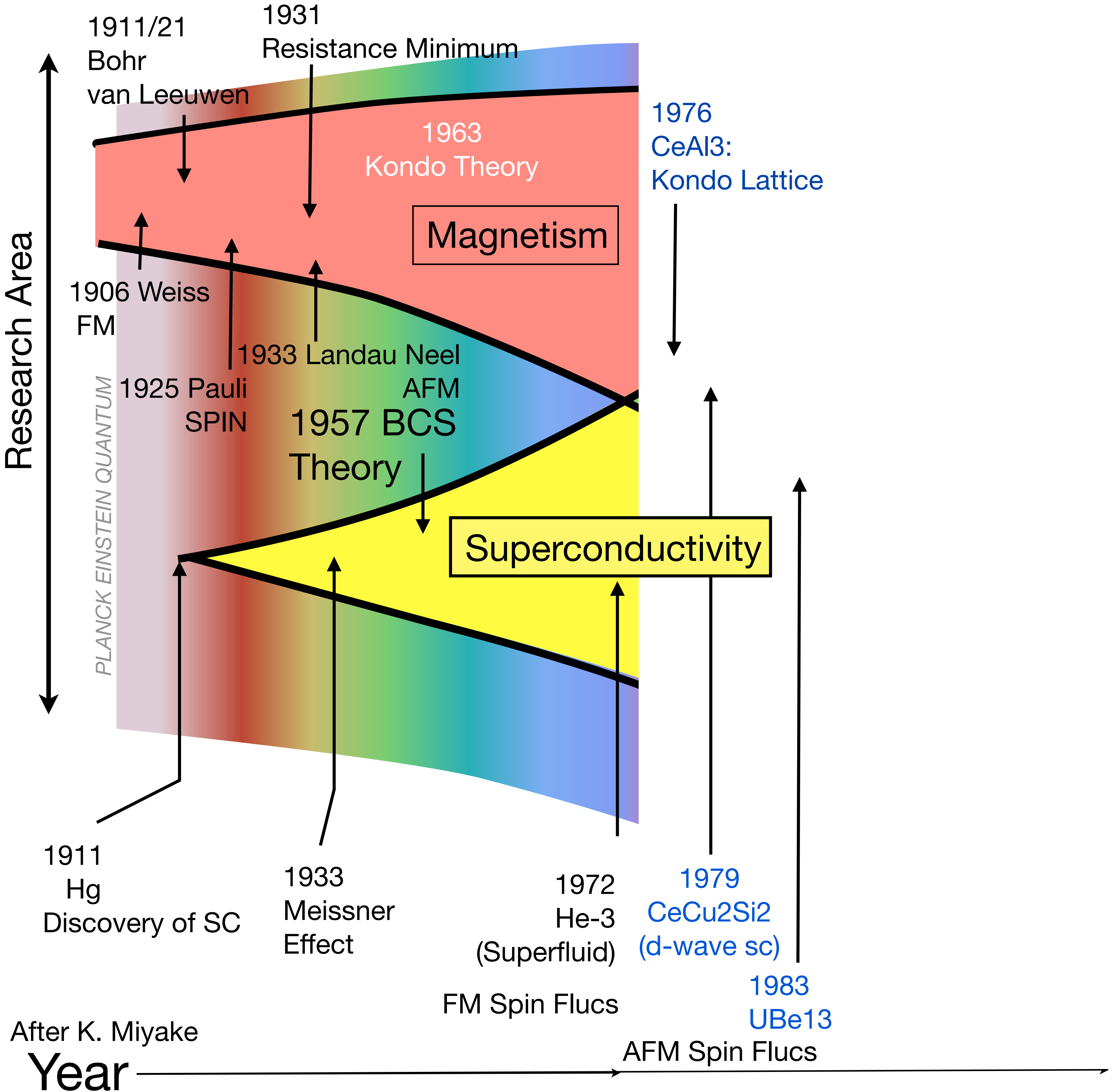
Fisk 1983

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)

Magnetism and Supercond

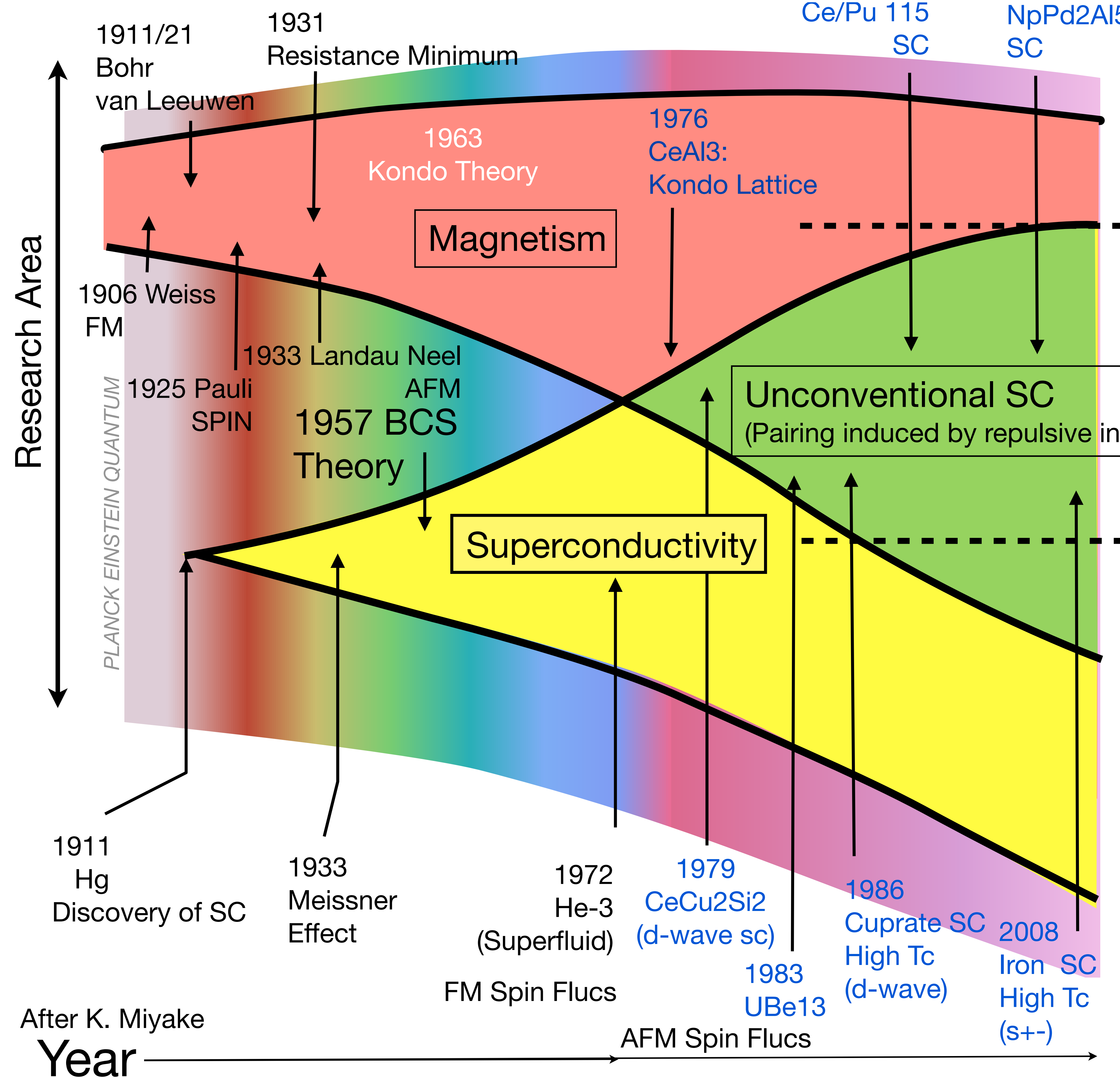


Ott
1976

Steglich
1979

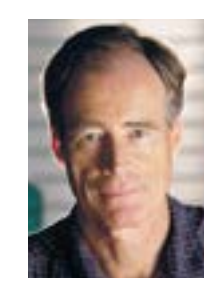
Fisk
1983

A remarkable convergence of two fields.

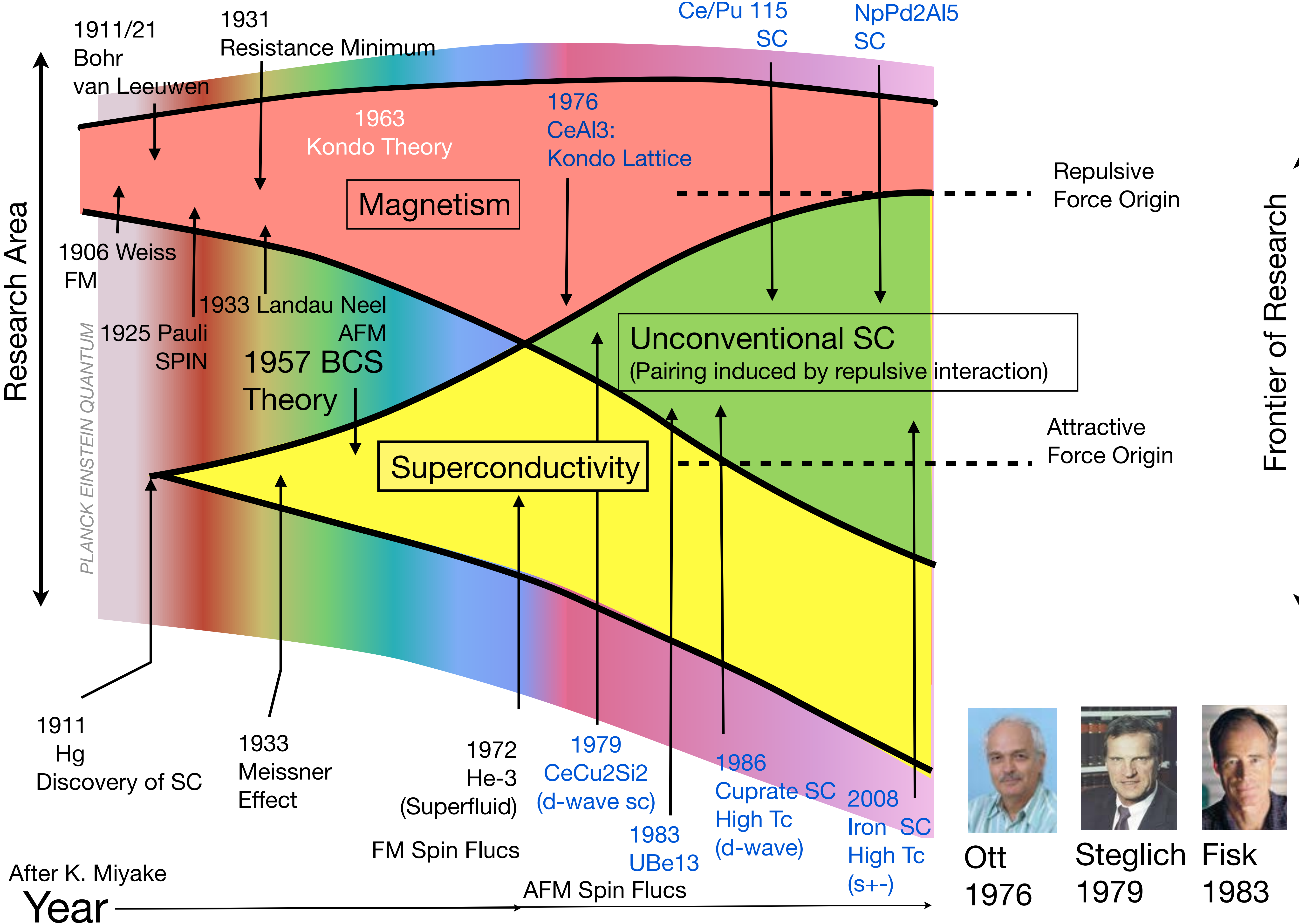



Ott
1976

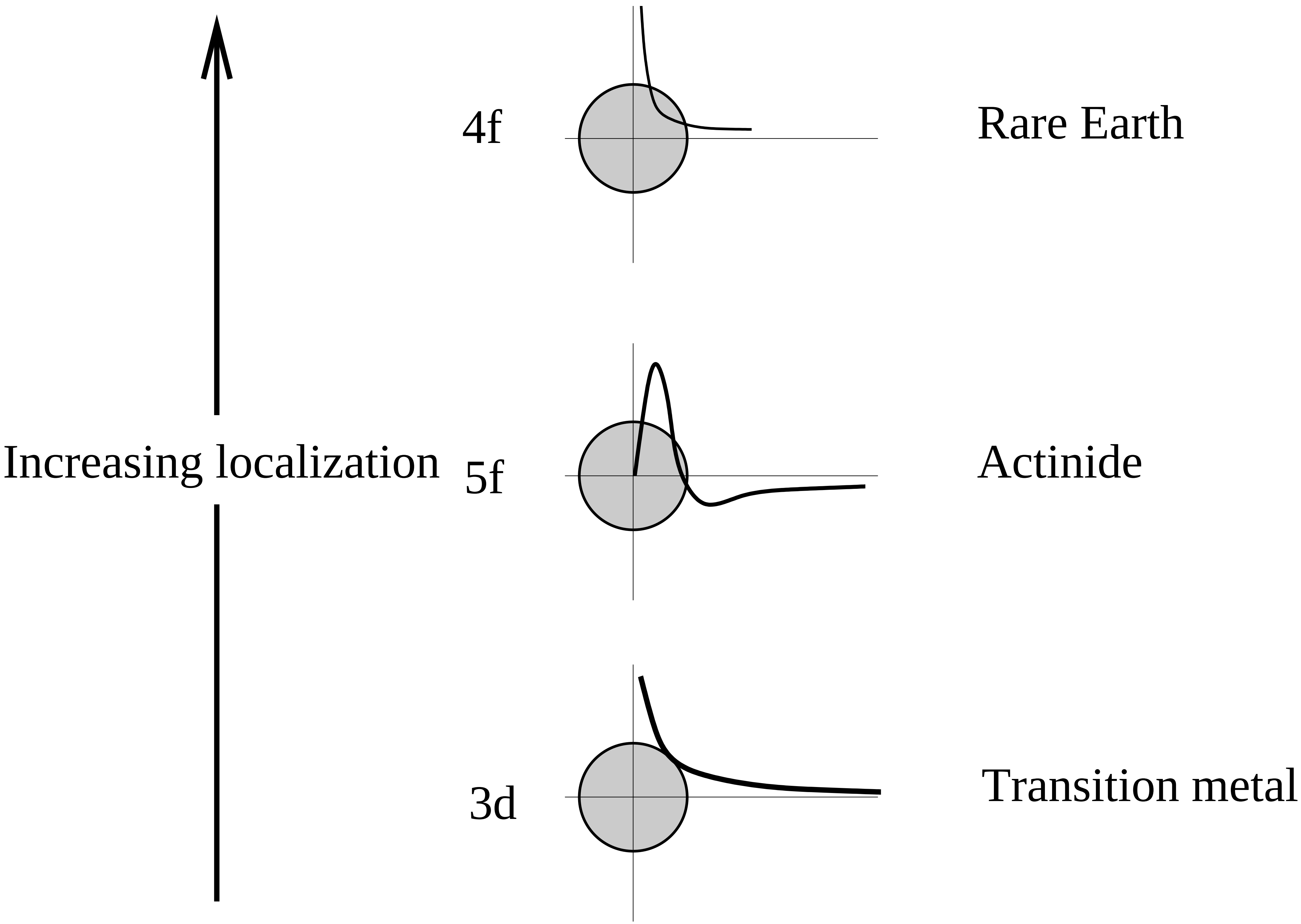

Steglich
1979


Fisk
1983

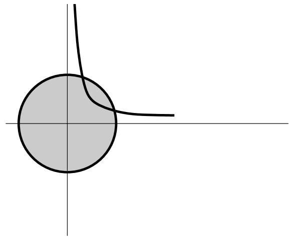
A remarkable convergence of two fields.

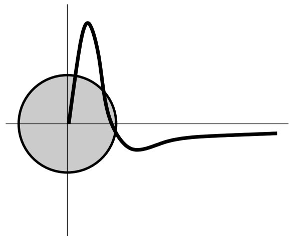


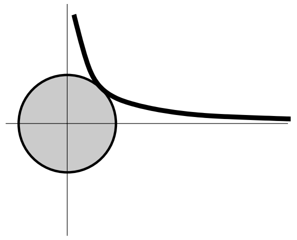
Electrons on the brink of localization

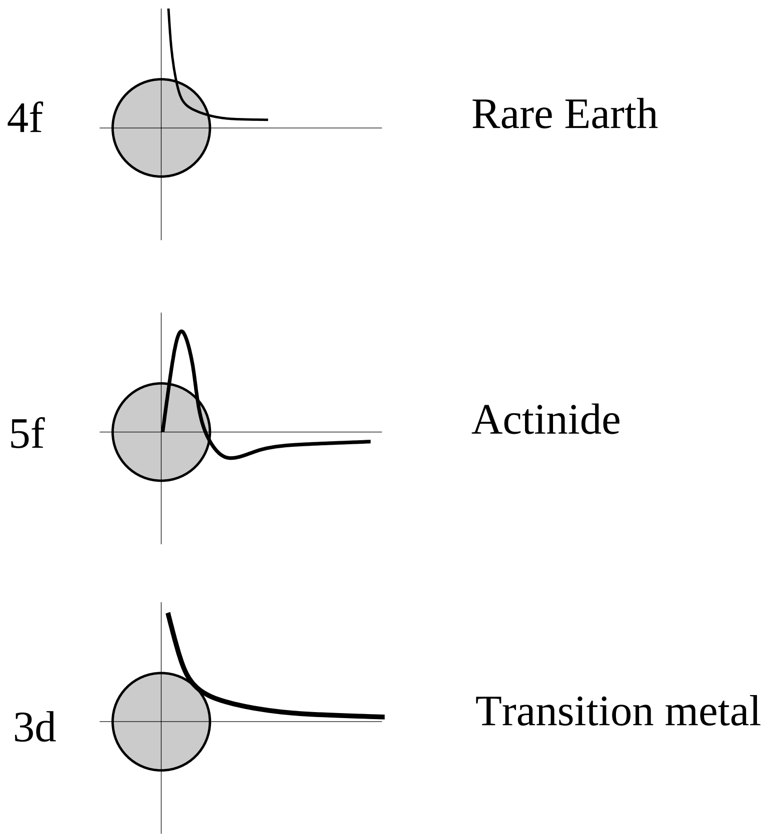


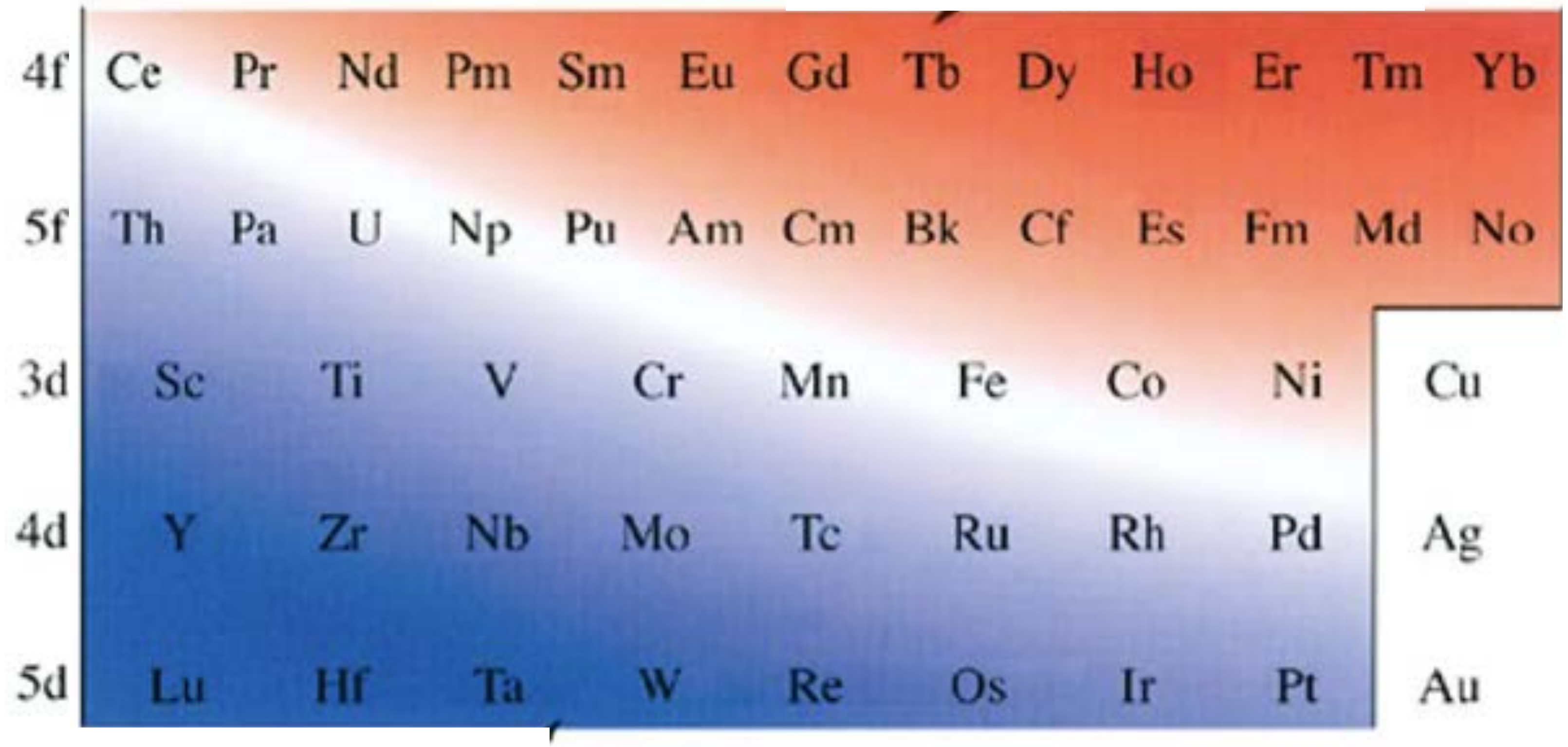
Increasing localization
4f
Rare Earth
5f
Actinide
3d
Transition metal

4f

Rare Earth

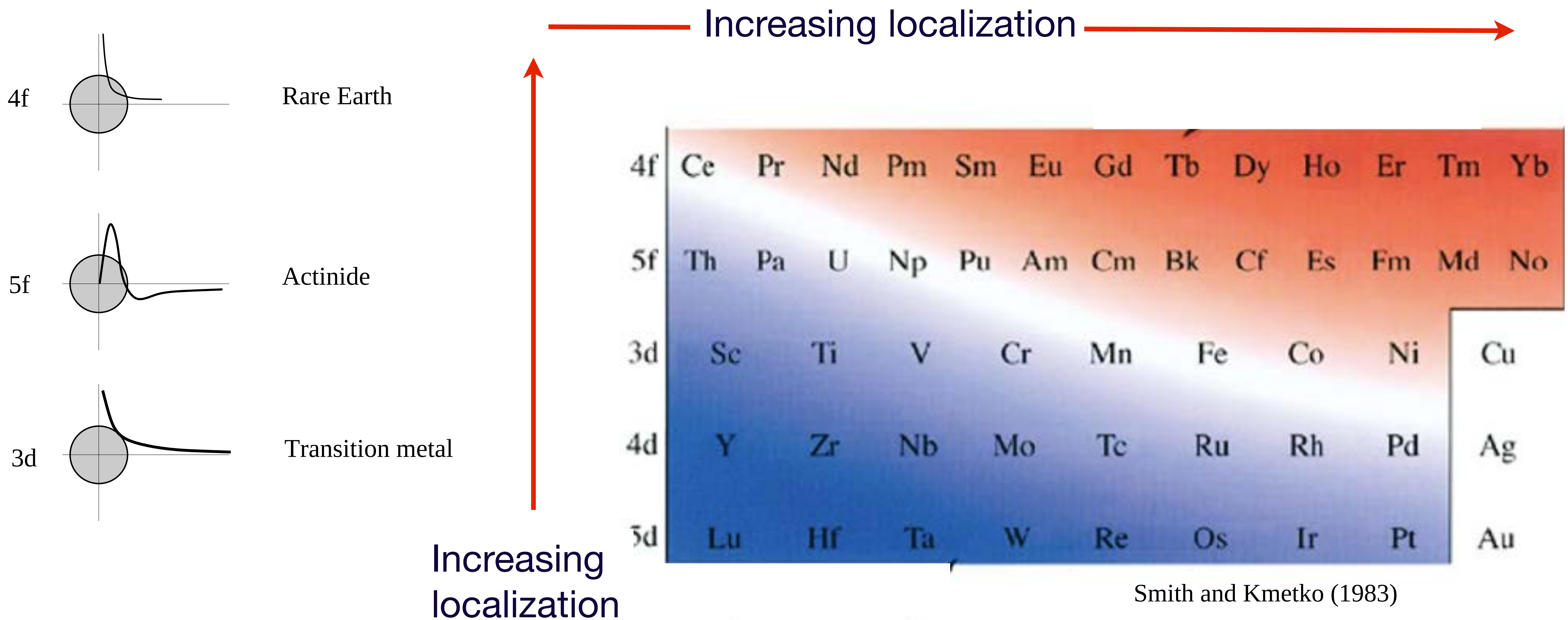
5f

Actinide

3d

Transition metal

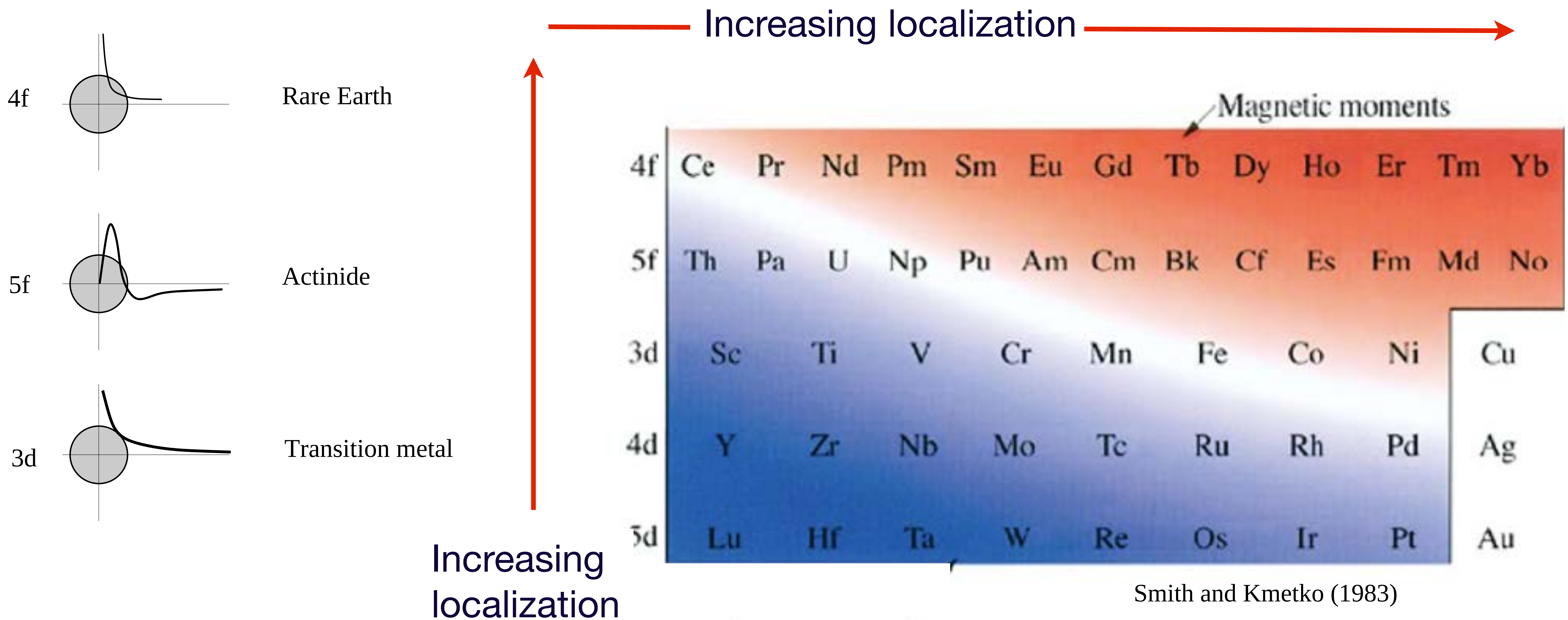




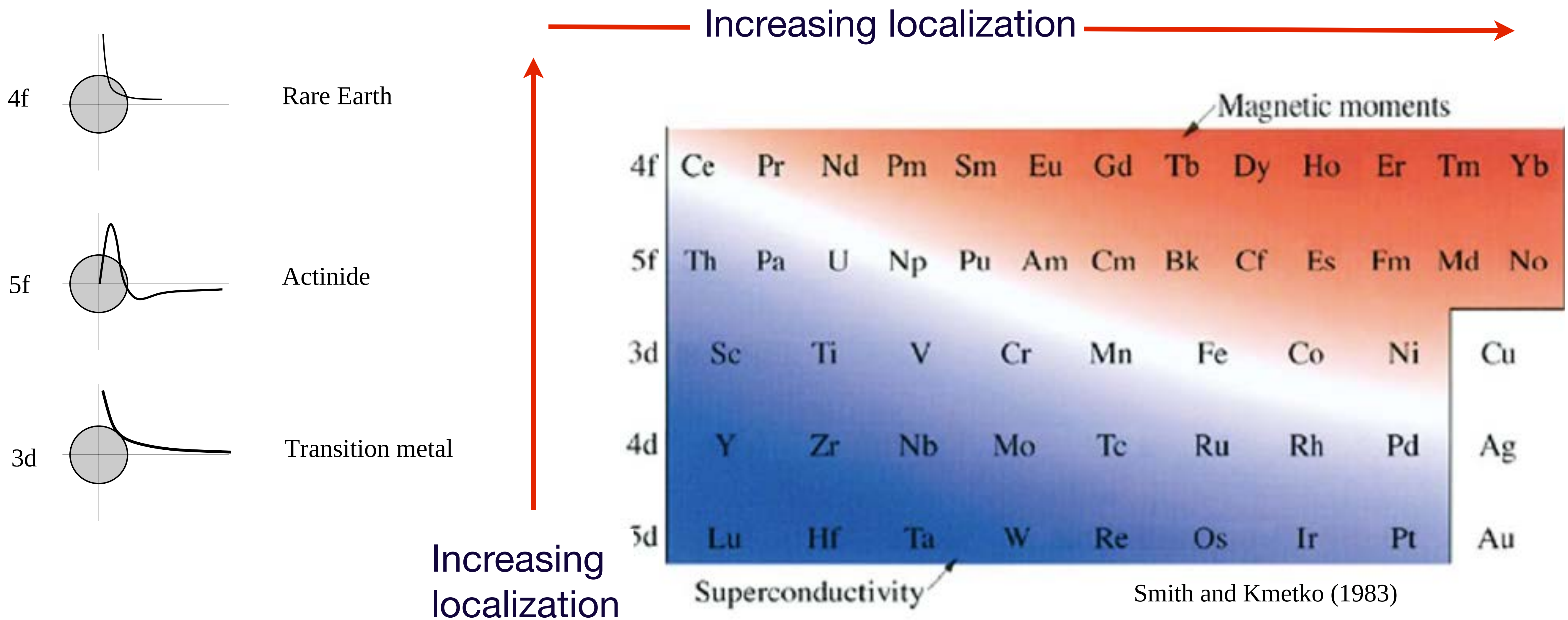
Smith and Kmetko (1983)



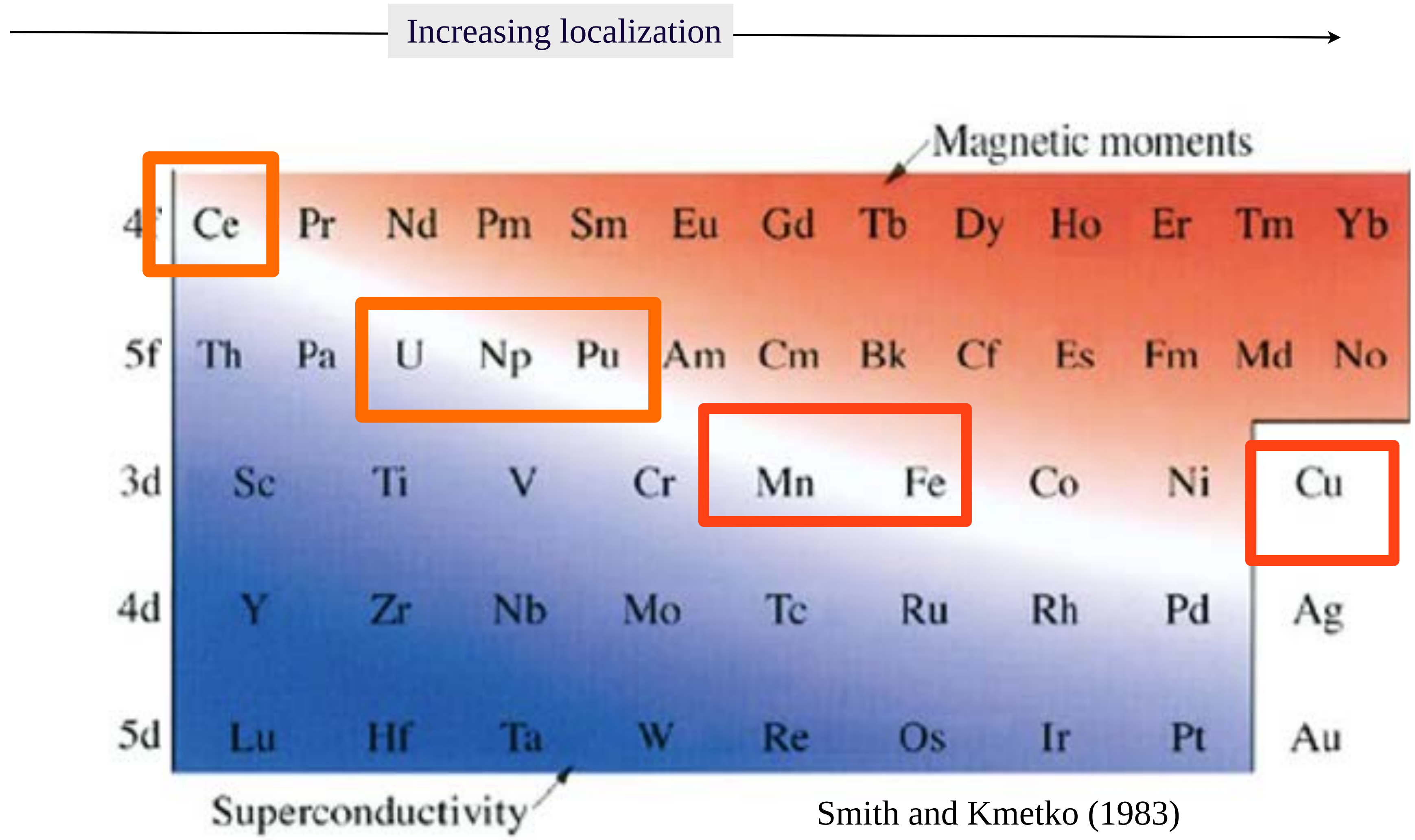
Smith and Kmetko (1983)



Smith and Kmetko (1983)

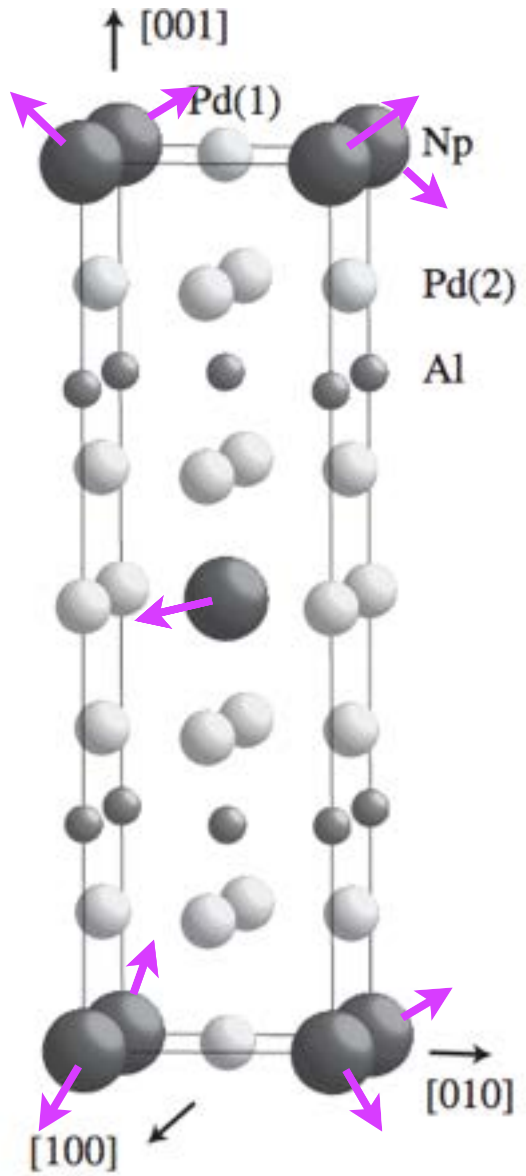


Smith and Kmetko (1983)

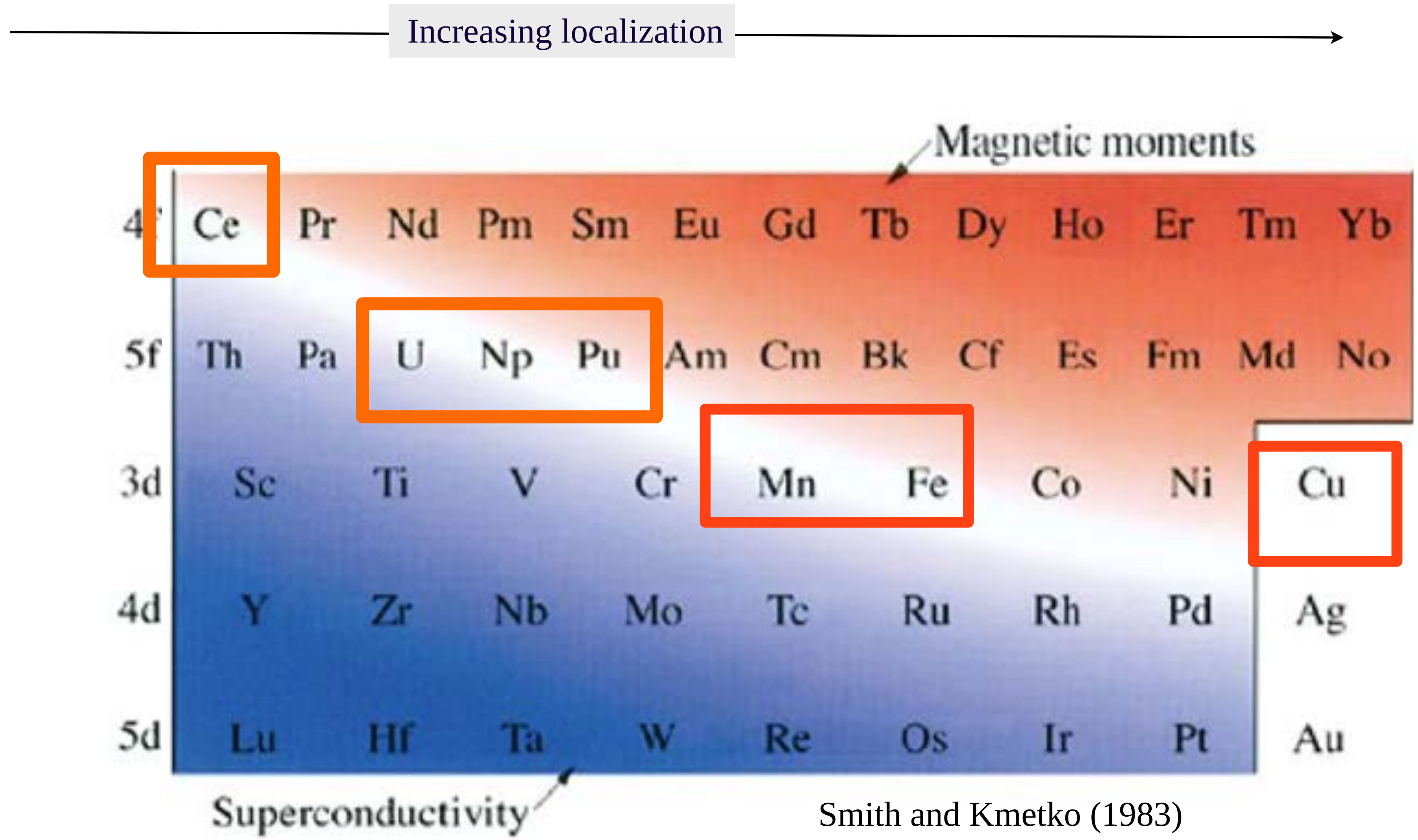


Smith and Kmetko (1983)

Diversity of new ground-states on the brink of localization.



$NpAl_2Pd_5$



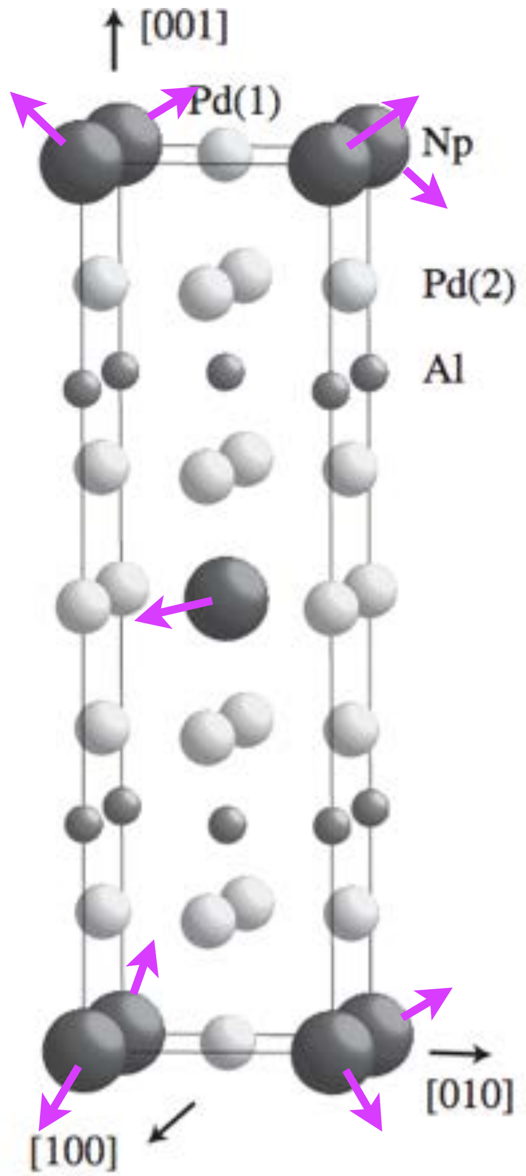
Smith and Kmetko (1983)

HF 115s

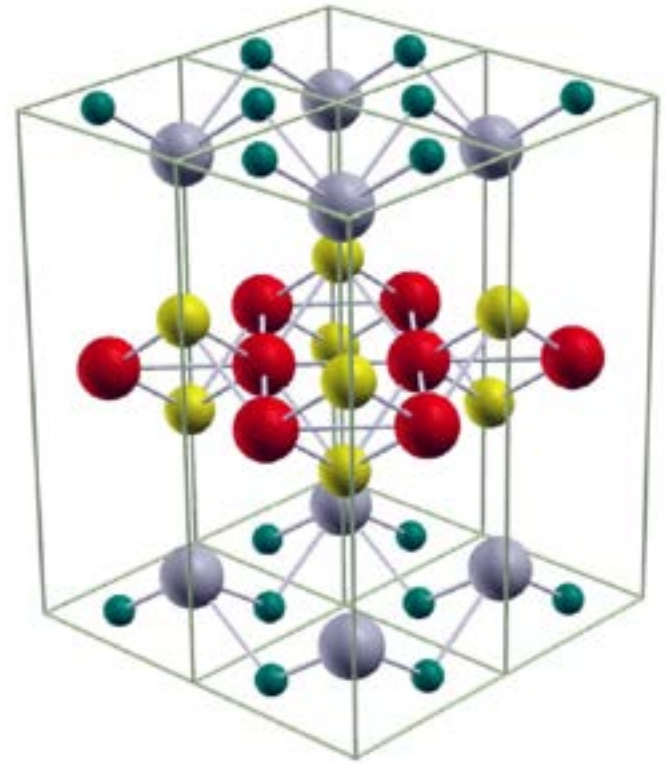
Tc=0.2 -18.5 K

Diversity of new ground-states on the brink of localization.

f-electron systems: 4f Ce, Yb systems 5f U, Np, Pu systems.

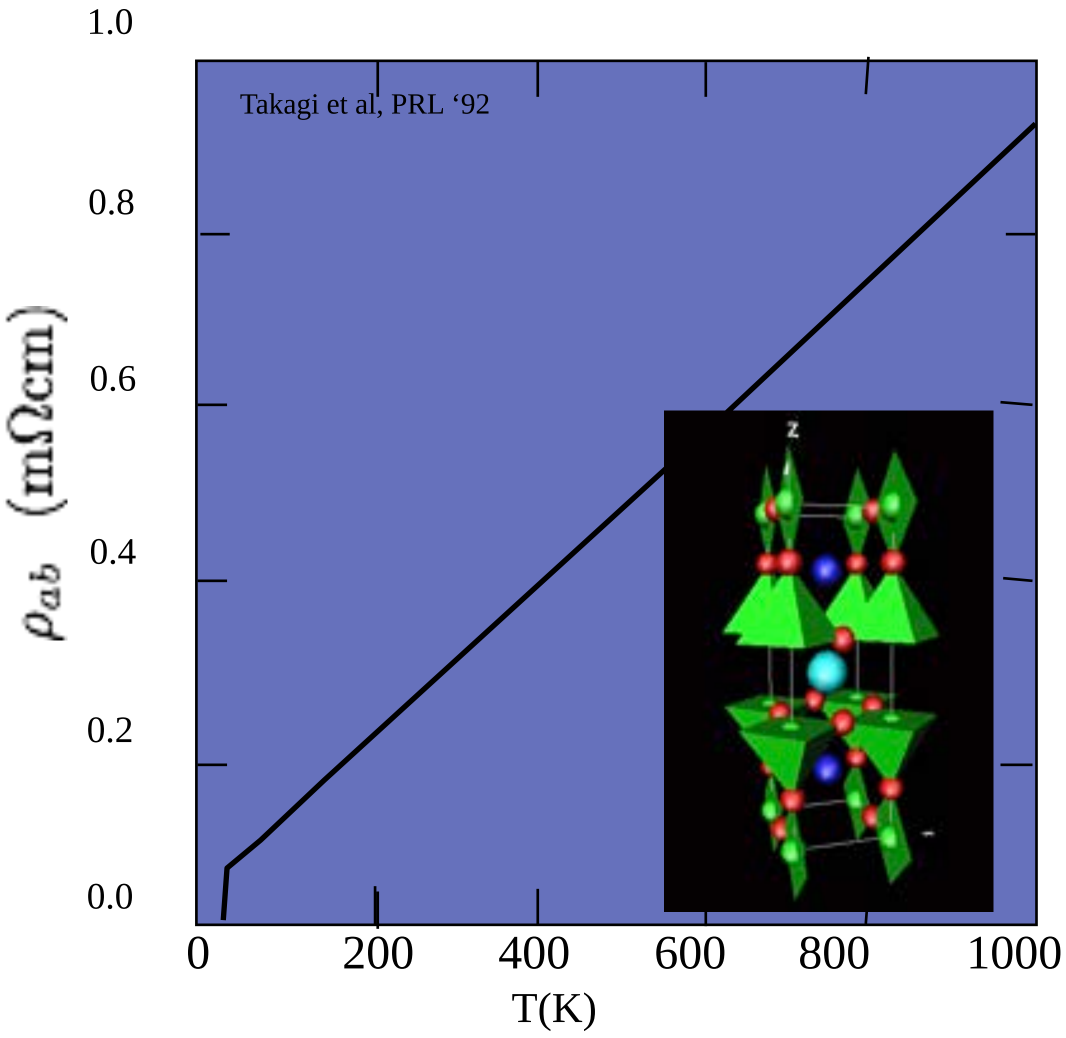


$NpAl_2Pd_5$



Pr

Z.A. Ren et.al, Beijing, (08)



HF 115s
T_c=0.2 -18.5 K

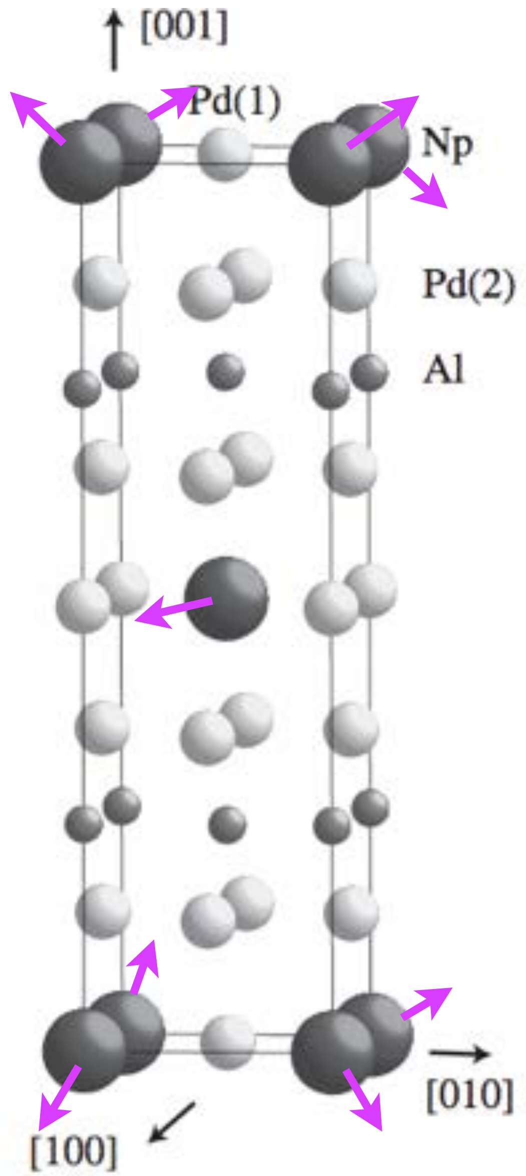
Iron based sc
T_c= 6 - 53 ++ ? K

Cuprates T_c=11-92K

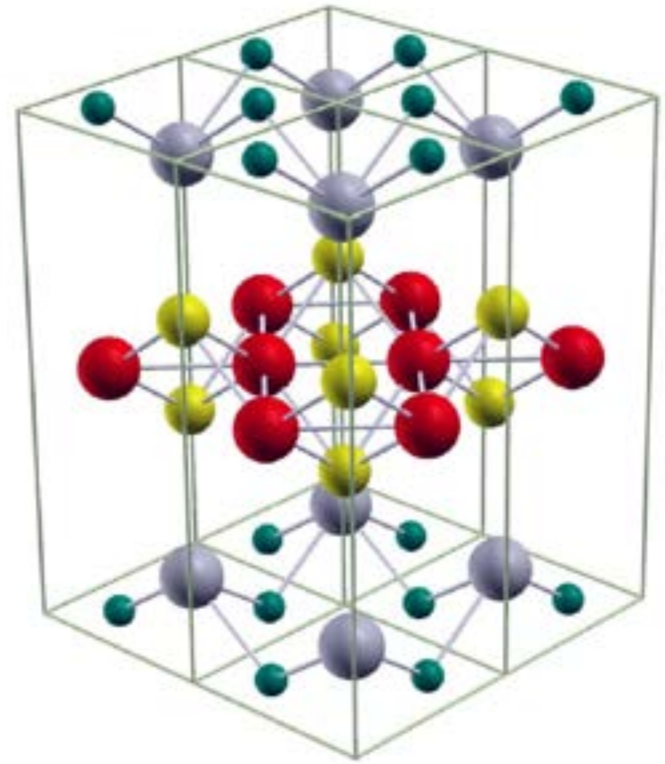
Diversity of new ground-states on the brink of localization.

f-electron systems: 4f Ce, Yb systems 5f U, Np, Pu systems.

d-electron systems: e.g Pnictides, Cuprate SC.

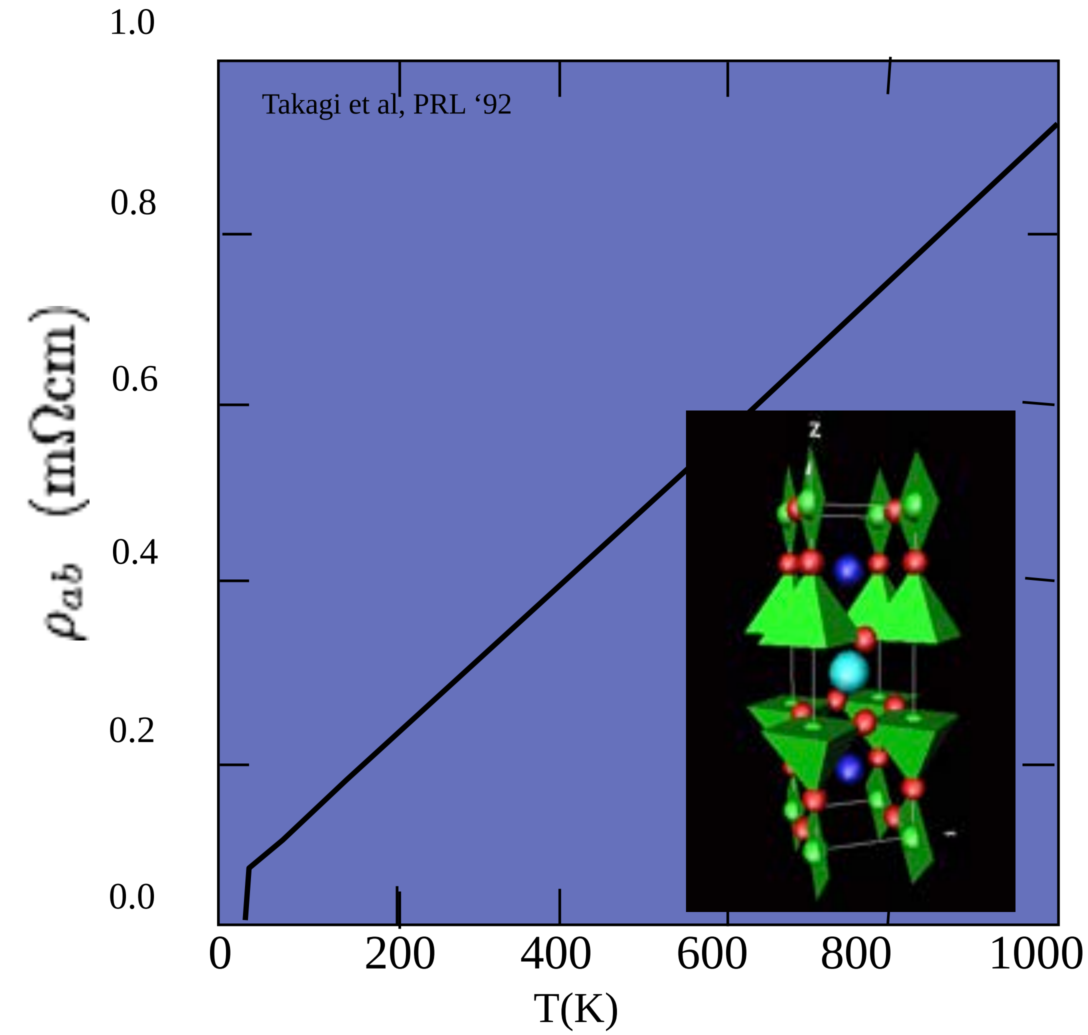


$NpAl_2Pd_5$



Pr

Z.A. Ren et.al, Beijing, (08)



HF 115s

T_c=0.2 -18.5 K

Iron based sc

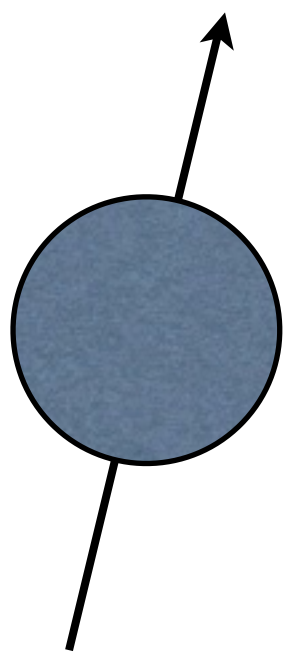
T_c= 6 - 53 ++ ? K

Cuprates T_c=11-92K

A new era of mysteries

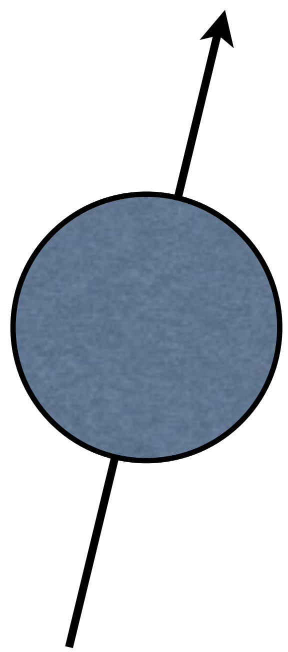
Cartoon Introduction to Heavy Fermions

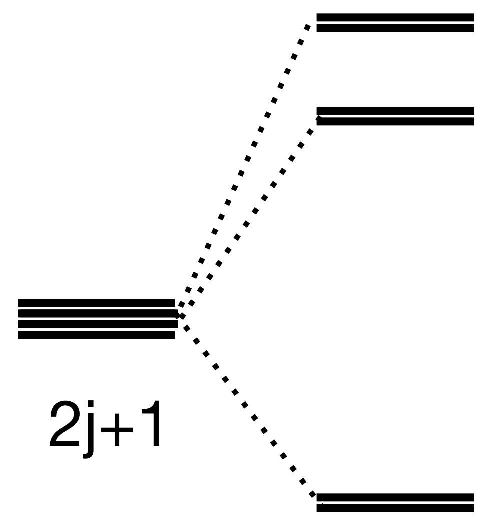
Heavy Fermions + Kondo



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

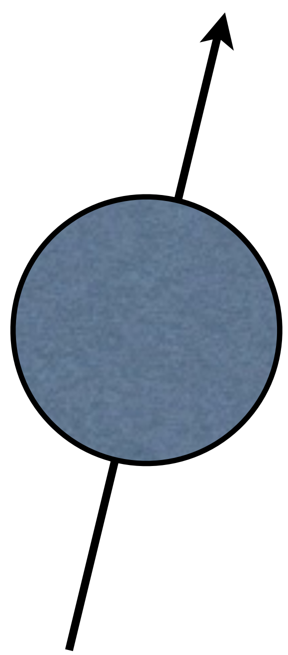
Heavy Fermions + Kondo

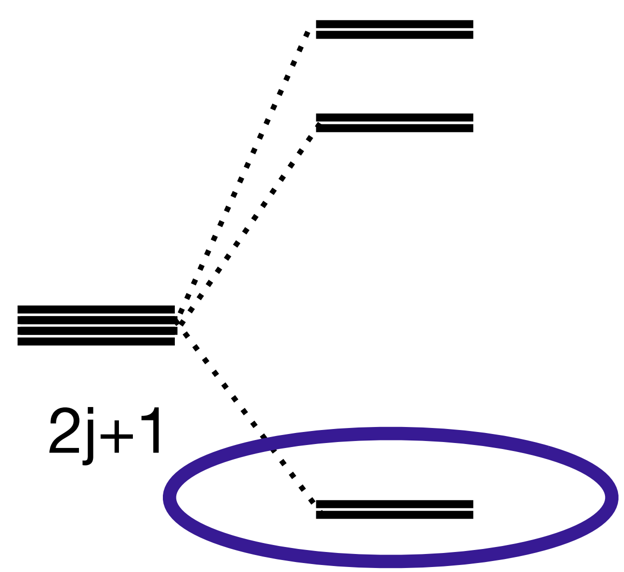




Spin (4f,5f): basic
fabric of heavy
electron physics.

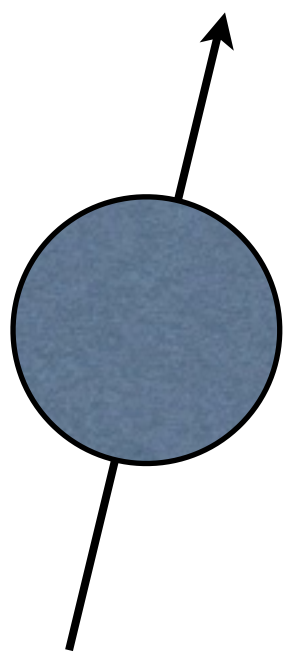
Heavy Fermions + Kondo

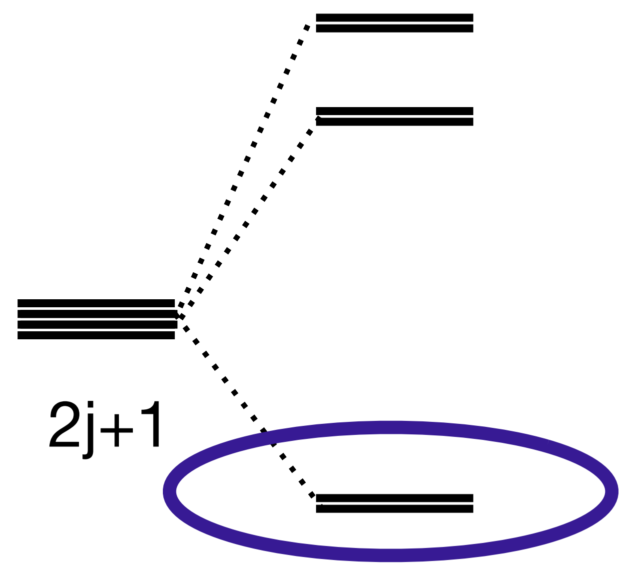


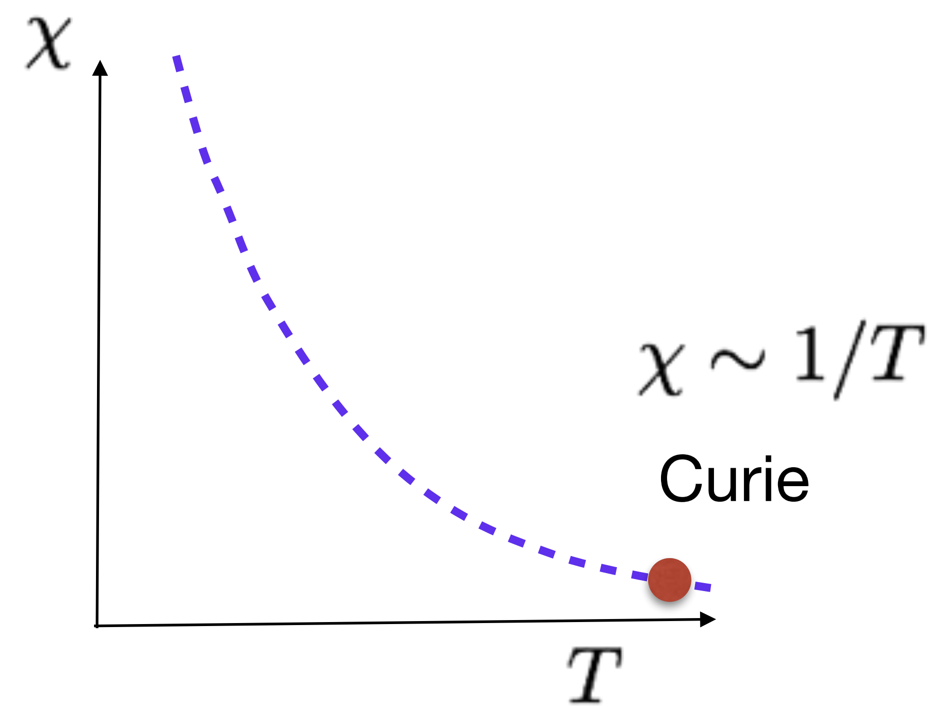


Spin (4f,5f): basic fabric of heavy electron physics.

Heavy Fermions + Kondo

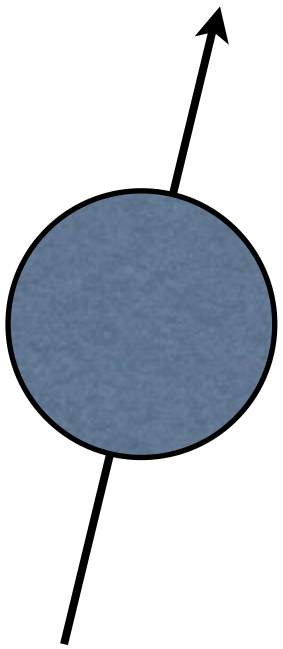


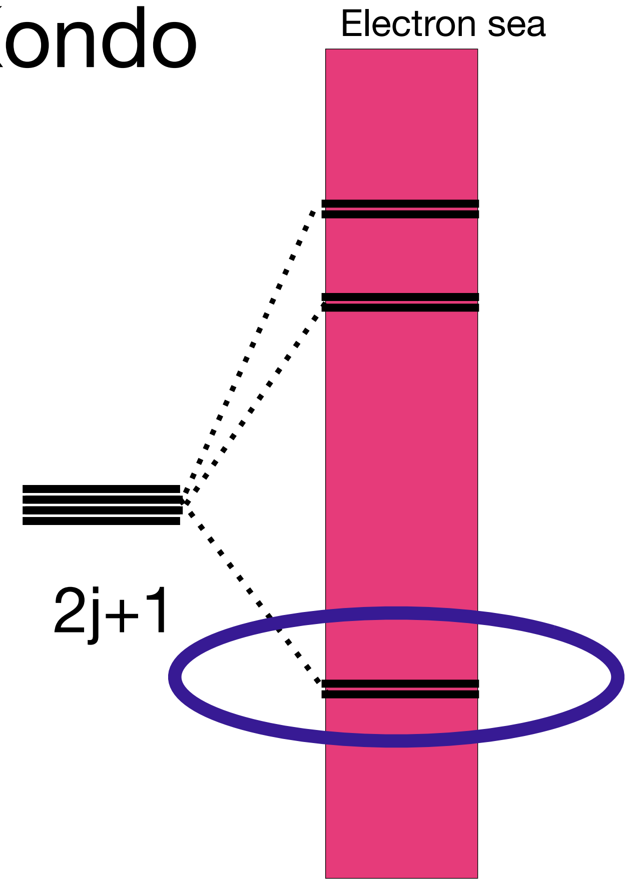


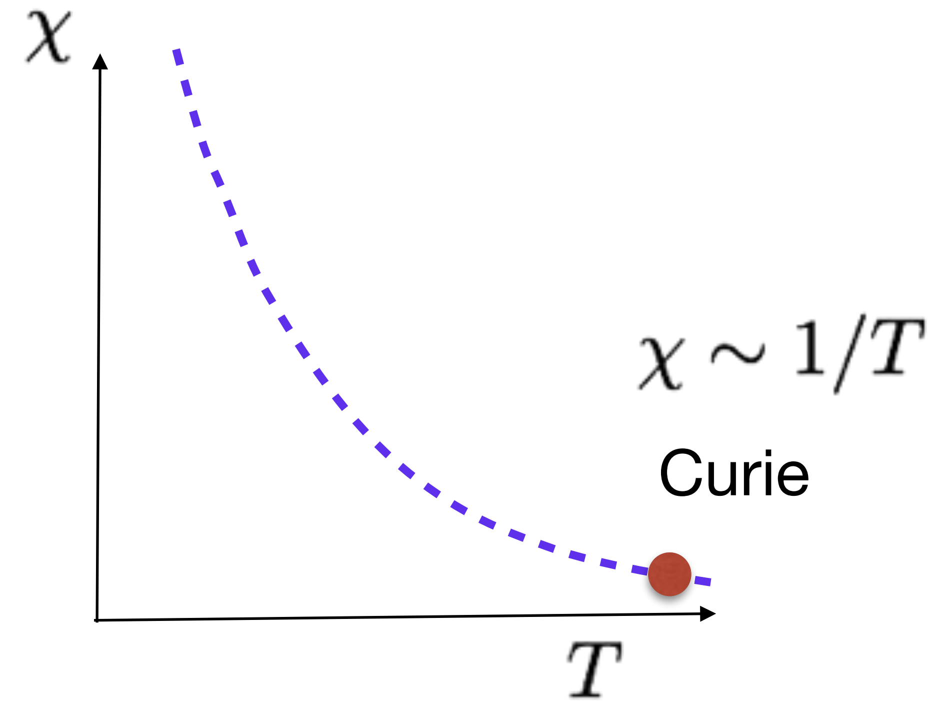


Spin (4f,5f): basic fabric of heavy electron physics.

Heavy Fermions + Kondo







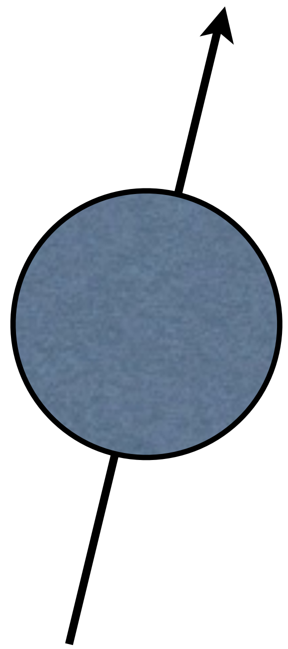
Spin (4f,5f): basic fabric of heavy electron physics.

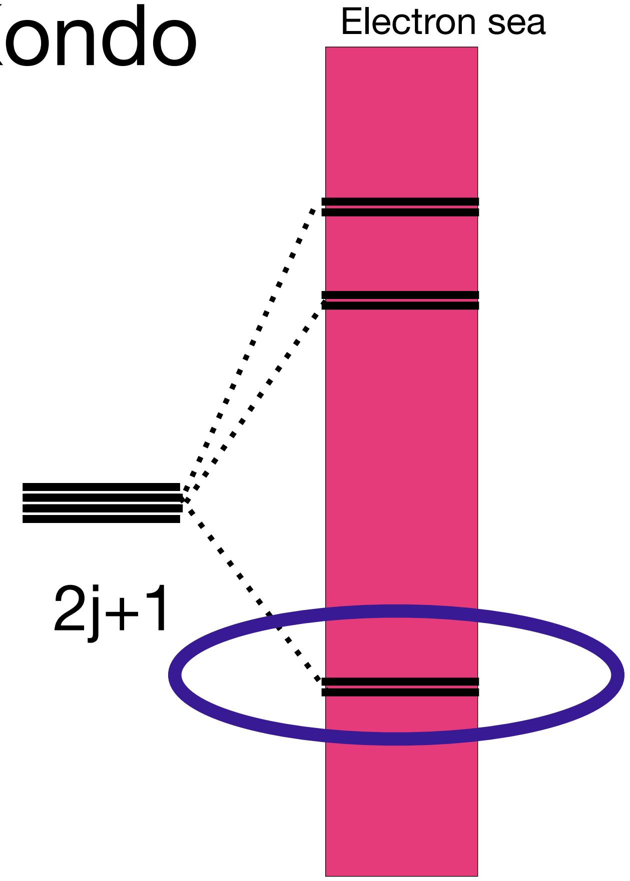
Scales to
Strong Coupling

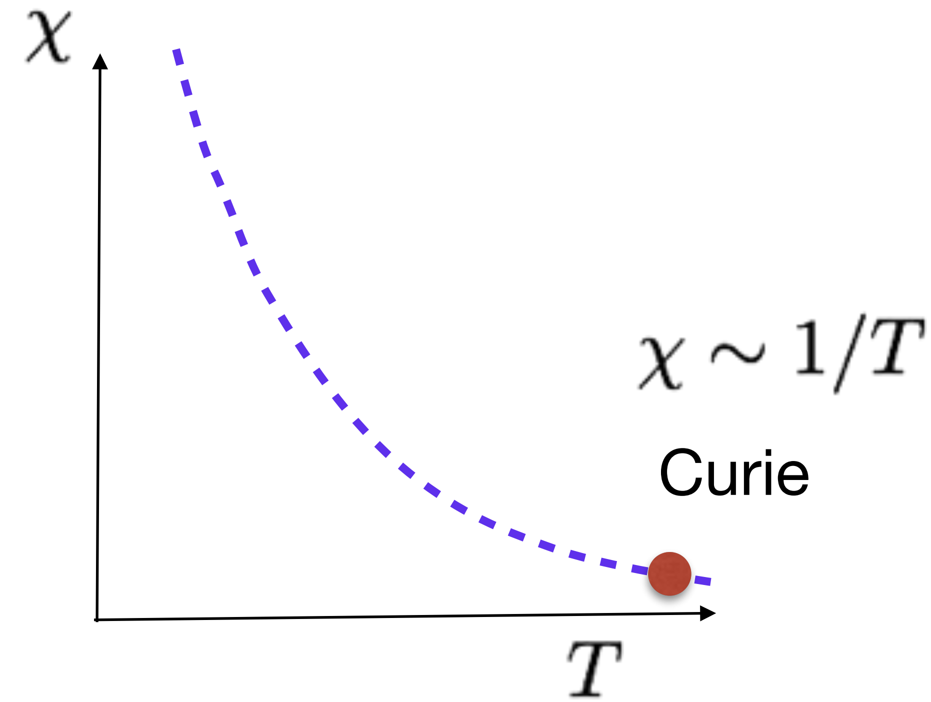
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \vec{S} \cdot \vec{\sigma}(0)$$

J. Kondo, 1962

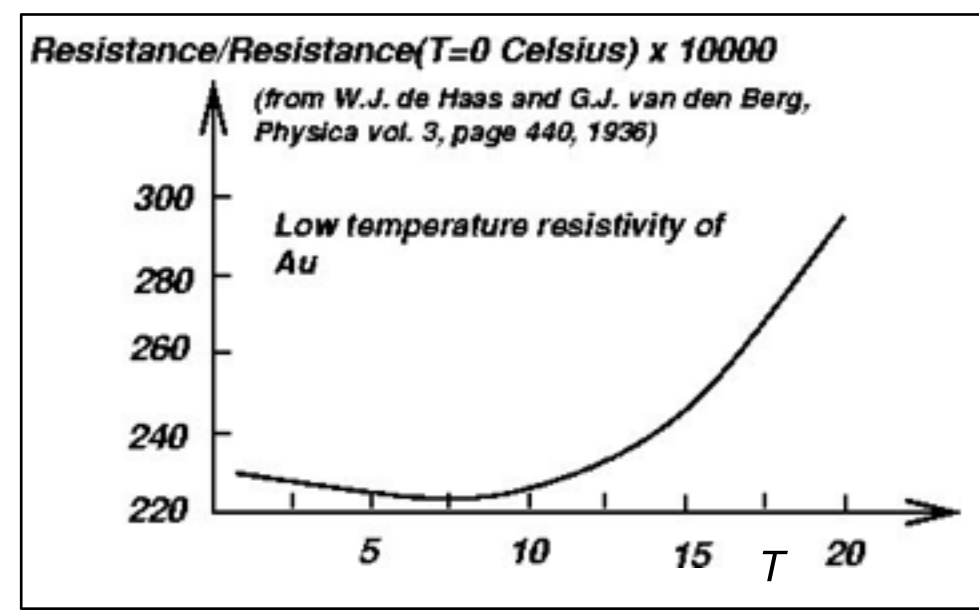
Heavy Fermions + Kondo







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

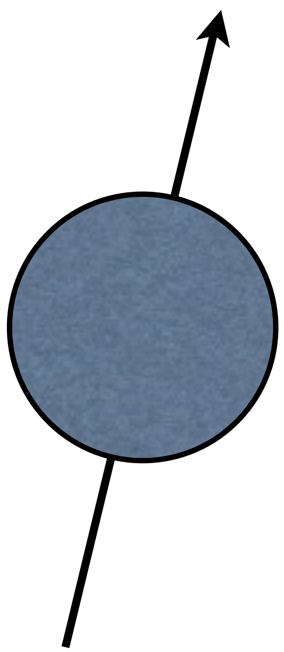


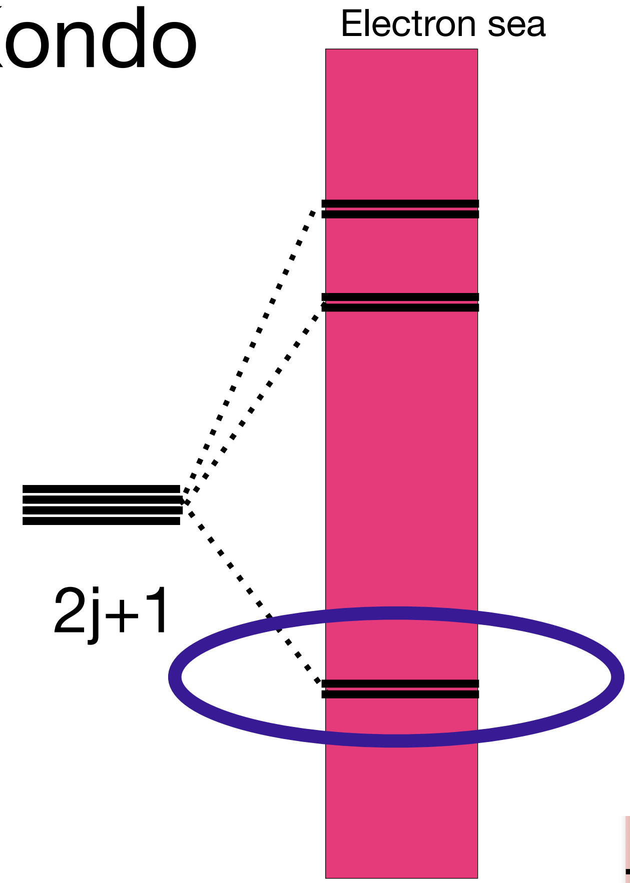
Scales to
Strong Coupling

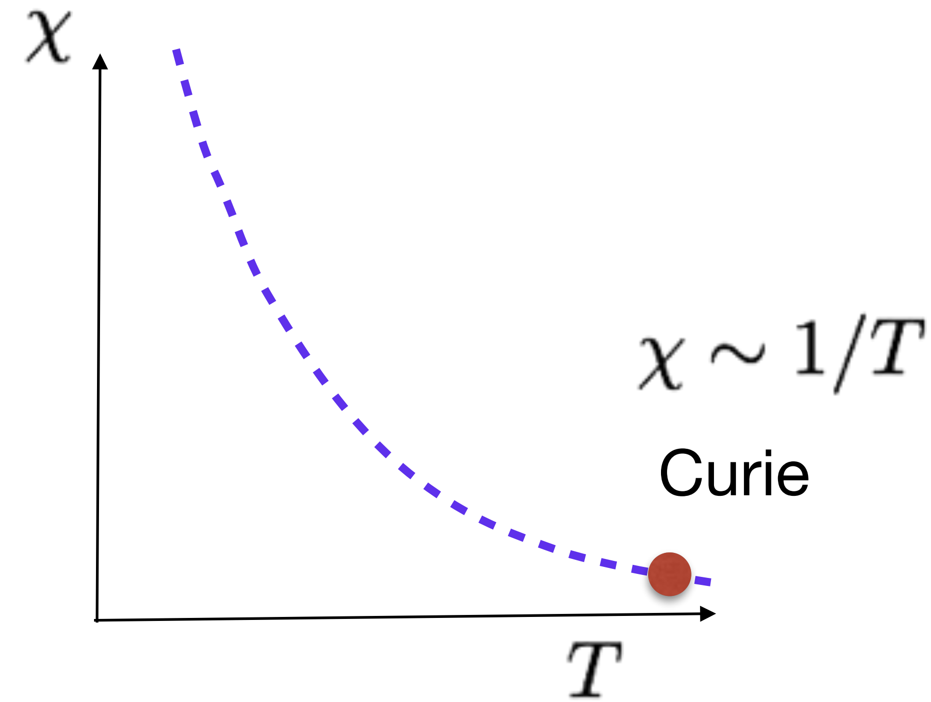
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \vec{S} \cdot \vec{\sigma}(0)$$

J. Kondo, 1962

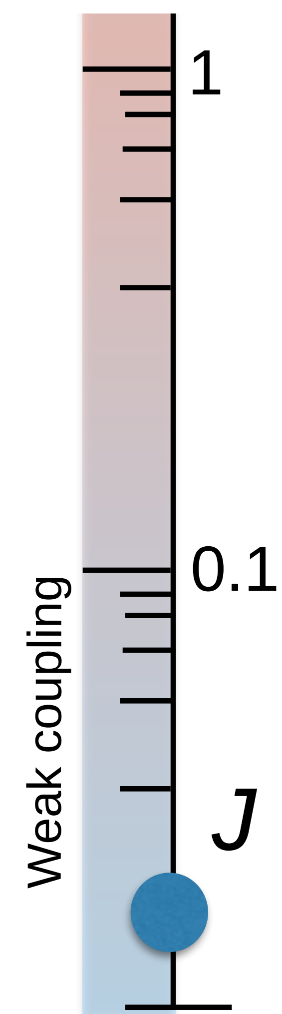
Heavy Fermions + Kondo

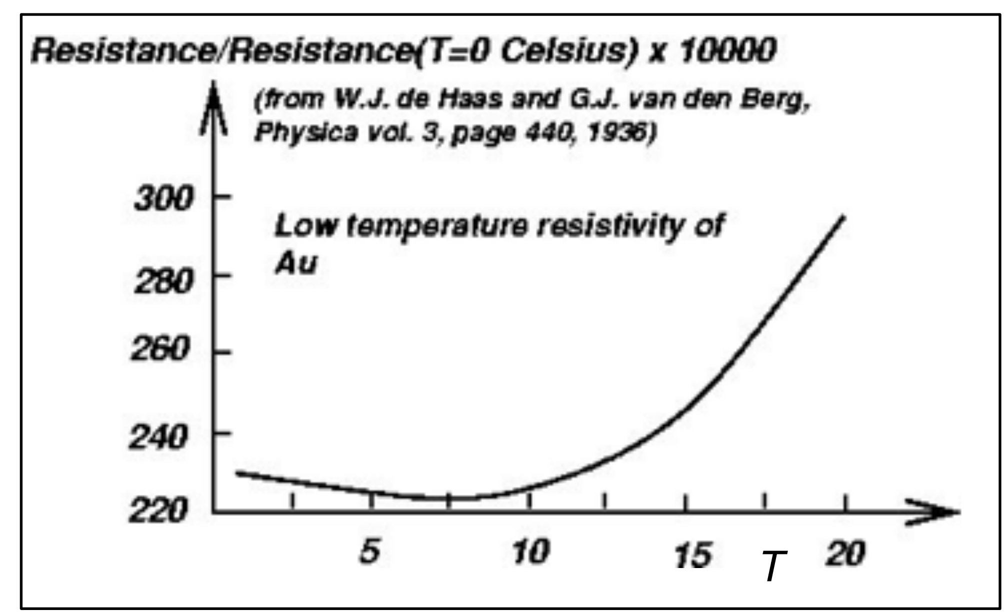






Spin (4f,5f): basic fabric of heavy electron physics.



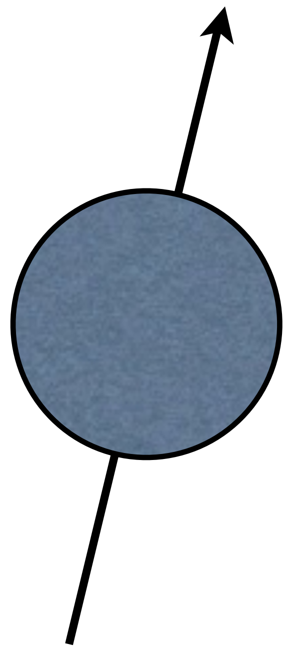


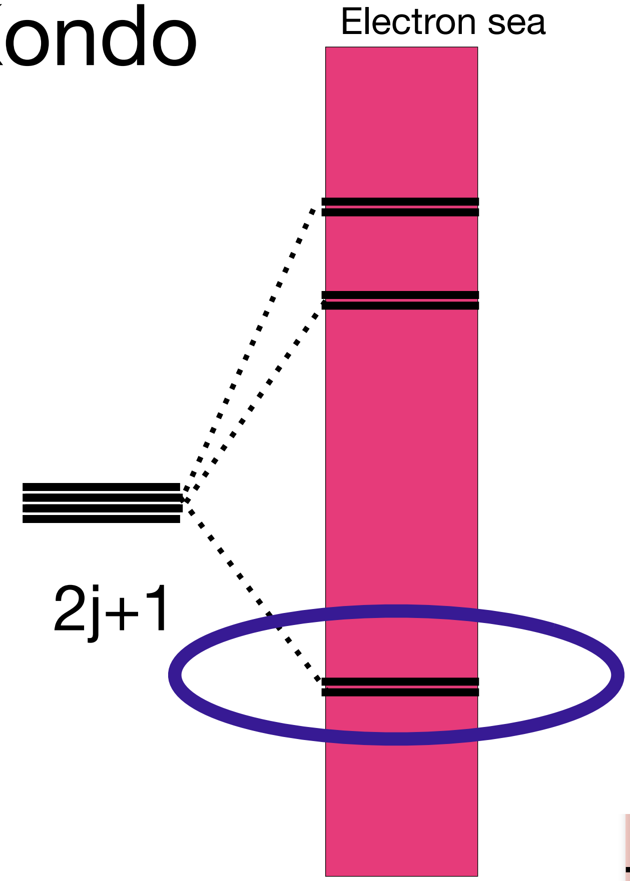
Scales to
Strong Coupling

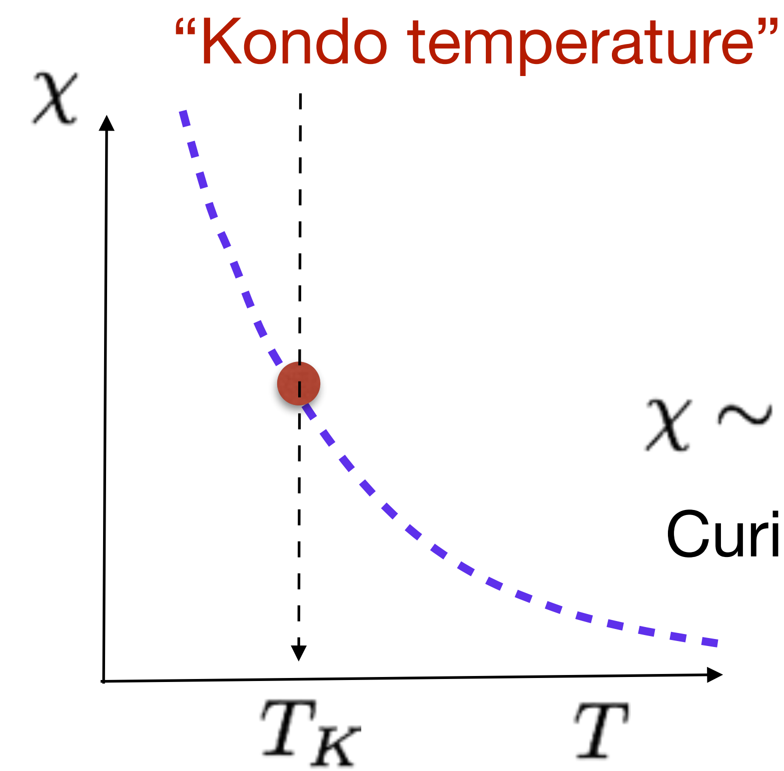
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \vec{S} \cdot \vec{\sigma}(0)$$

J. Kondo, 1962

Heavy Fermions + Kondo





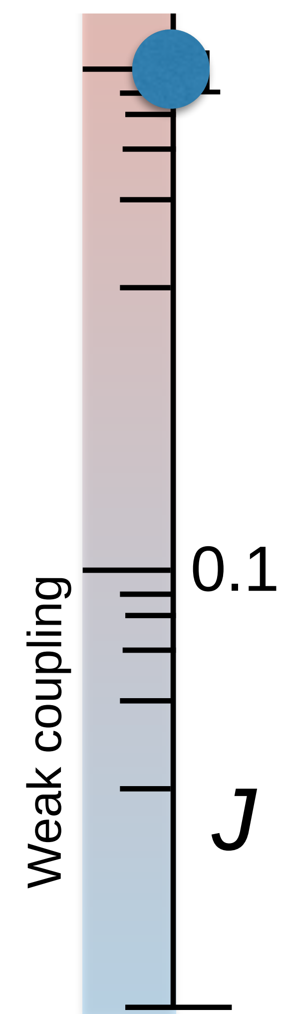


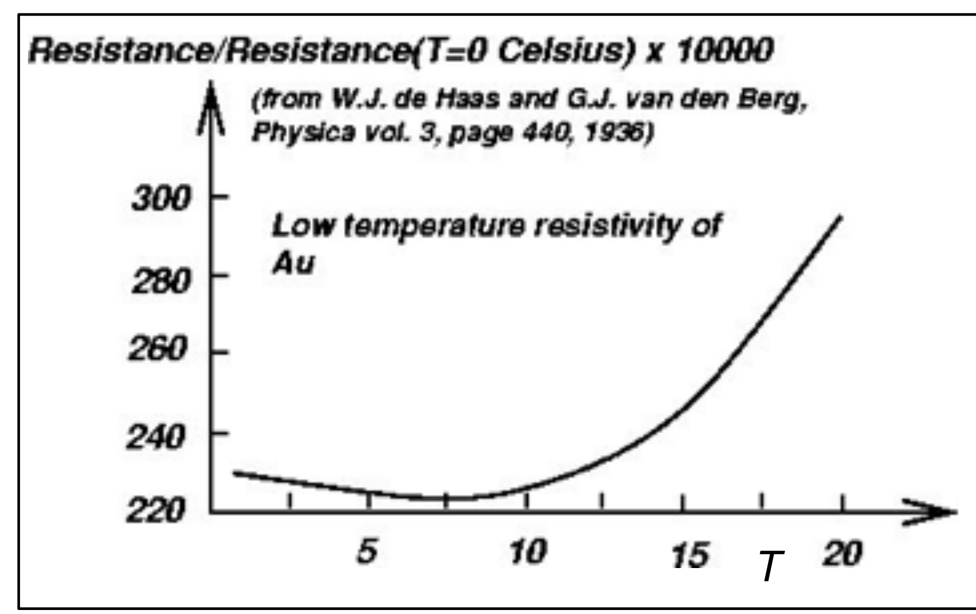
$\chi \sim 1/T$

Curie

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

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



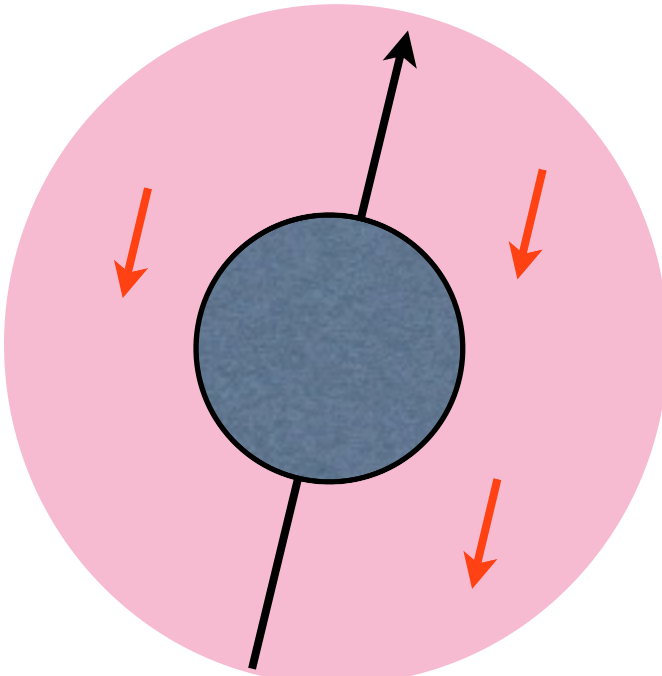


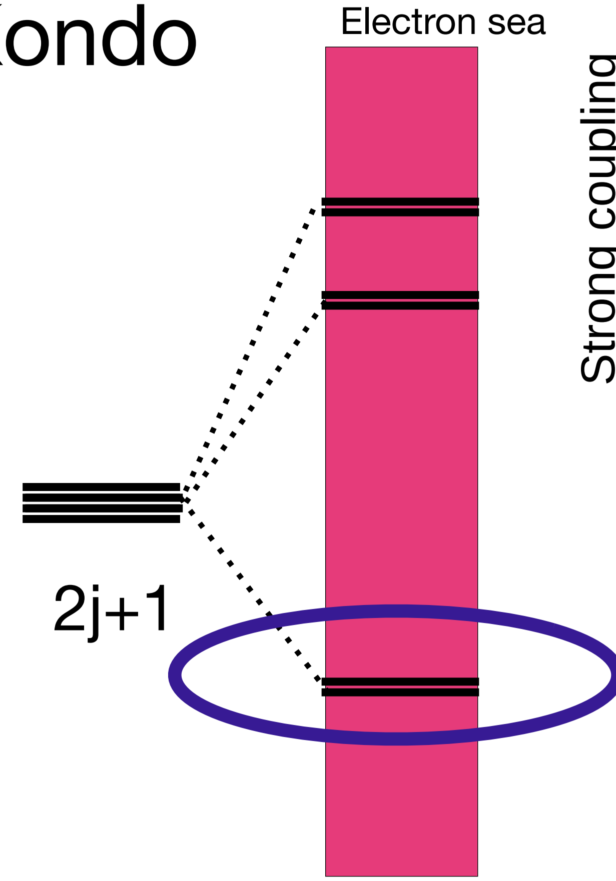
Scales to Strong Coupling

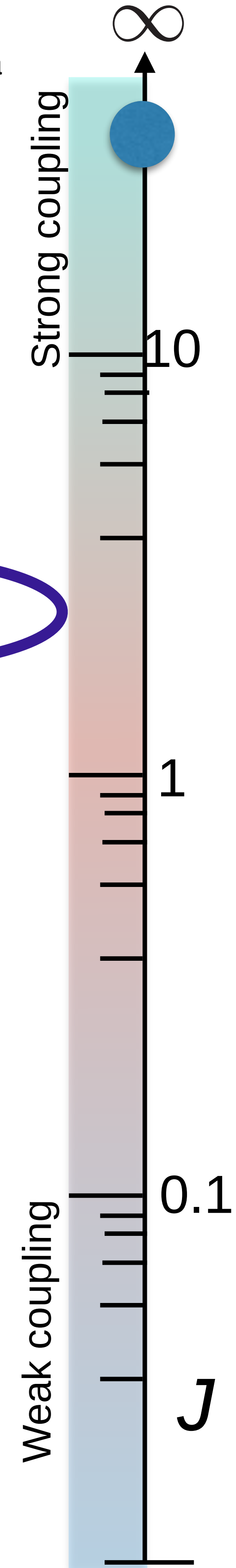
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J\,\vec{S}\cdot\vec{\sigma}(0)$$

J. Kondo, 1962

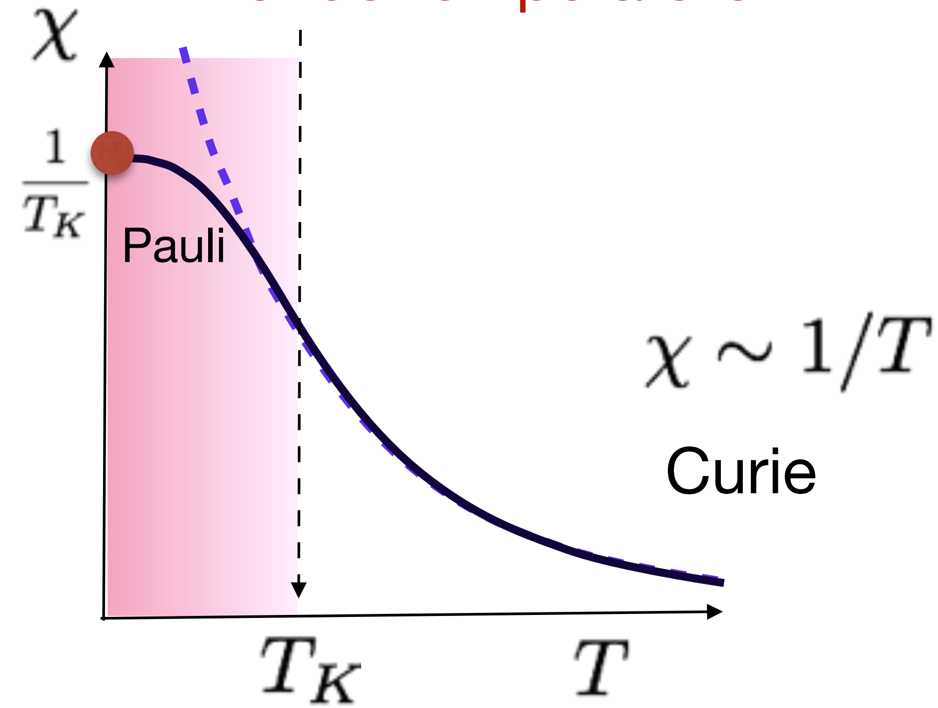
Heavy Fermions + Kondo







“Kondo temperature”



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

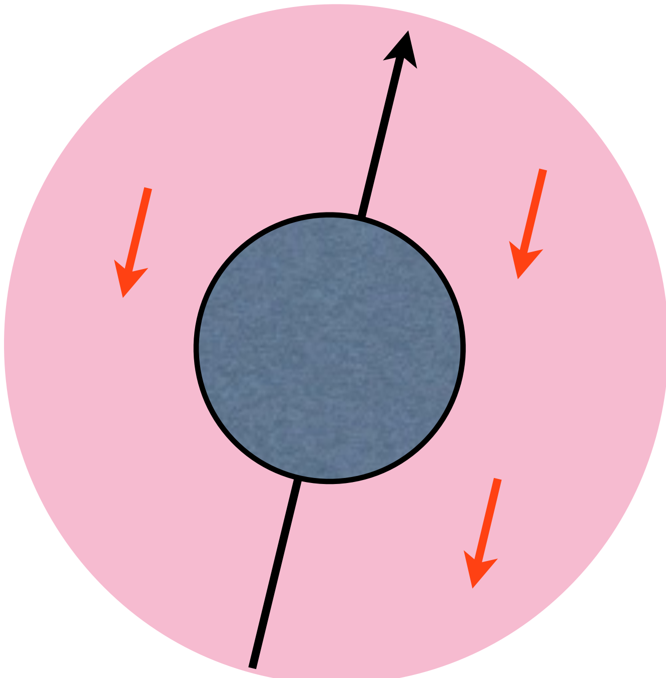
Spin screened by conduction electrons: entangled

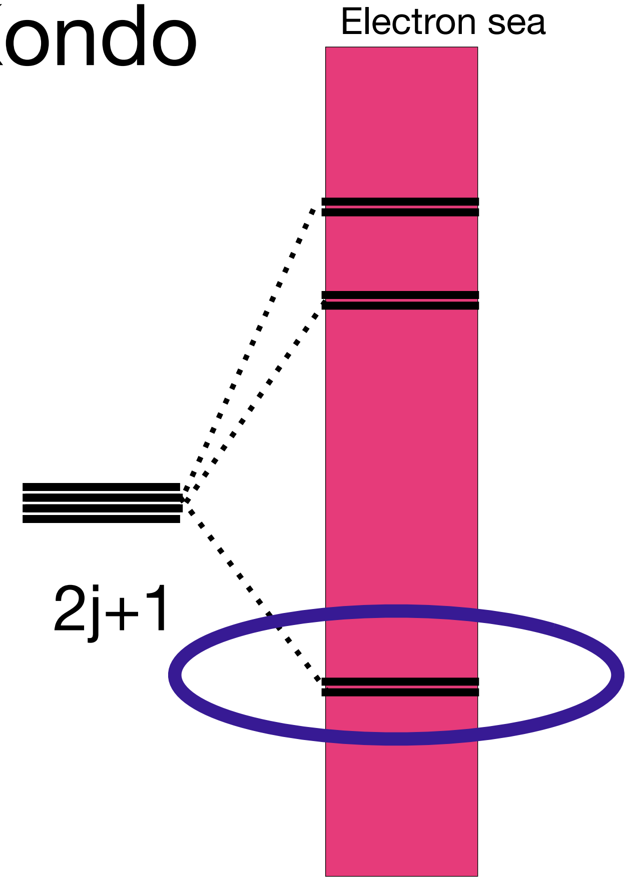
$$\uparrow\downarrow - \downarrow\uparrow$$

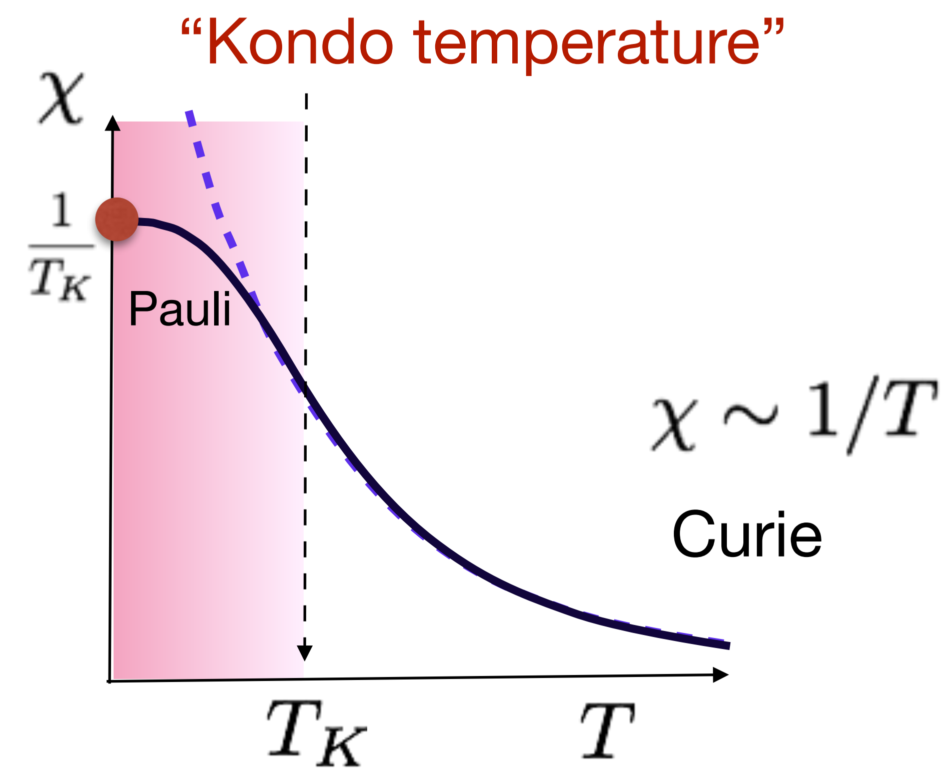
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \quad \vec{S}\cdot\vec{\sigma}(0)$$

J. Kondo, 1962

Heavy Fermions + Kondo





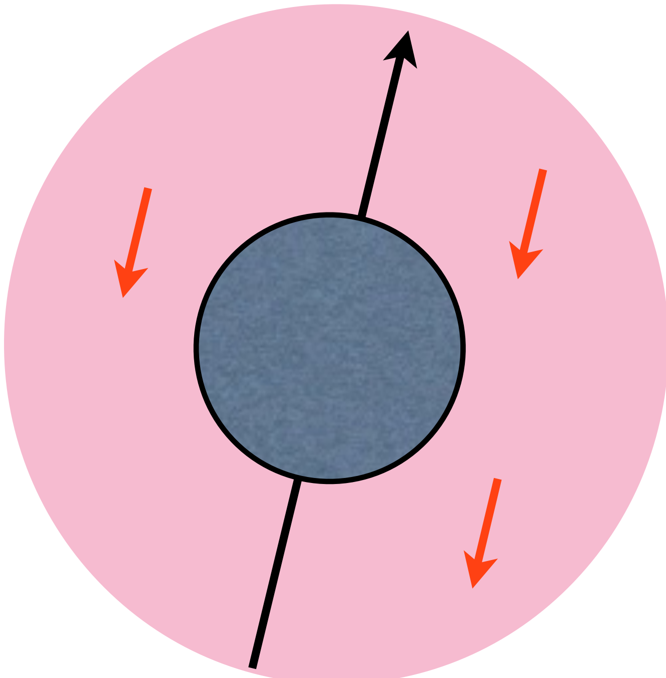


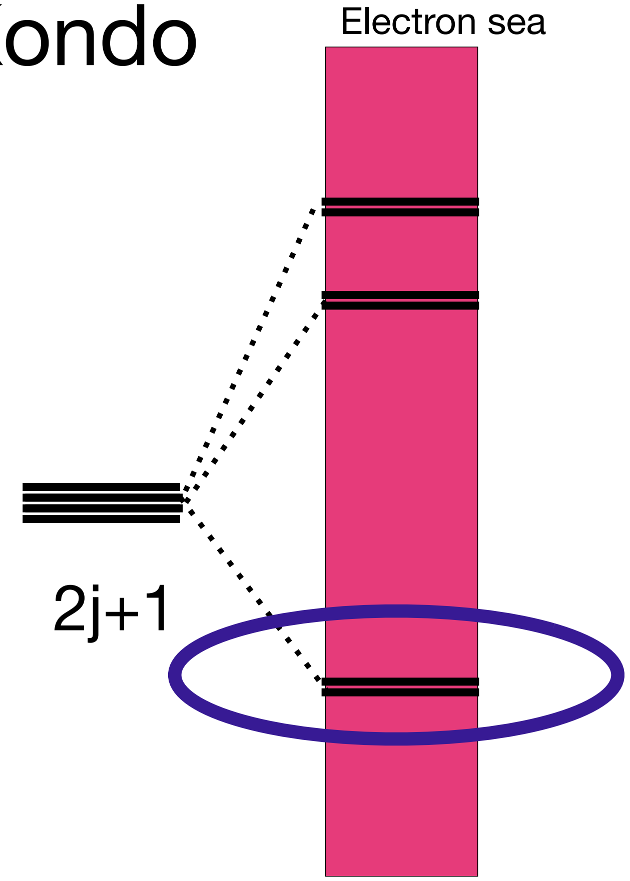
$$T_K = W\sqrt{J\rho}\,e^{-\frac{1}{2J\rho}}$$

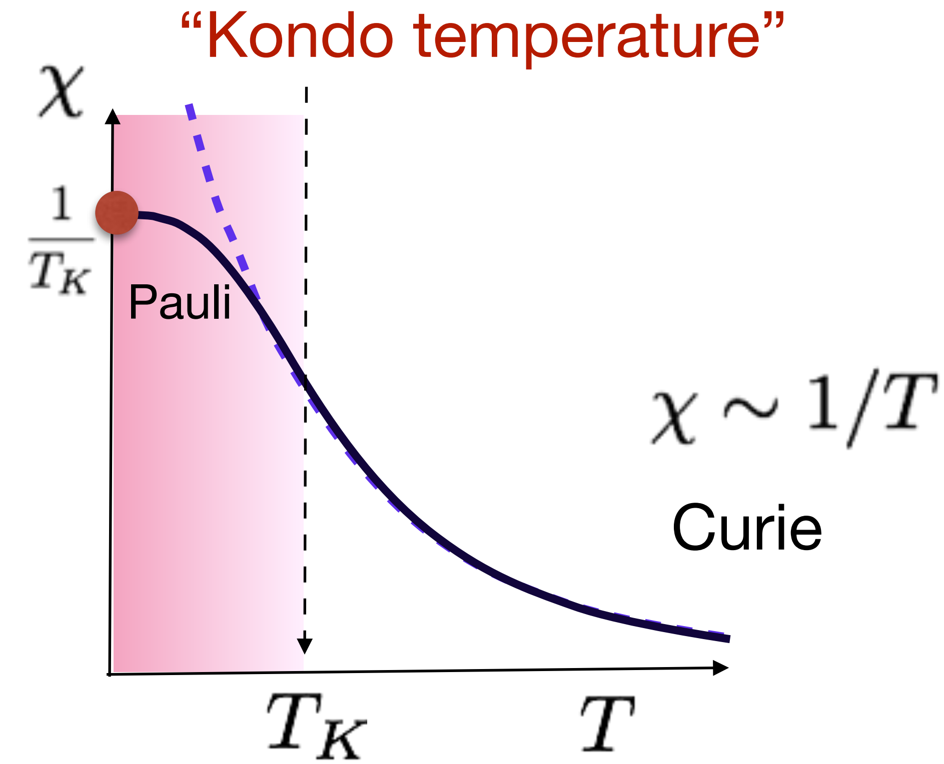
Spin screened by conduction electrons: <u>entangled</u>

$\uparrow\downarrow - \downarrow\uparrow$

Heavy Fermions + Kondo







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

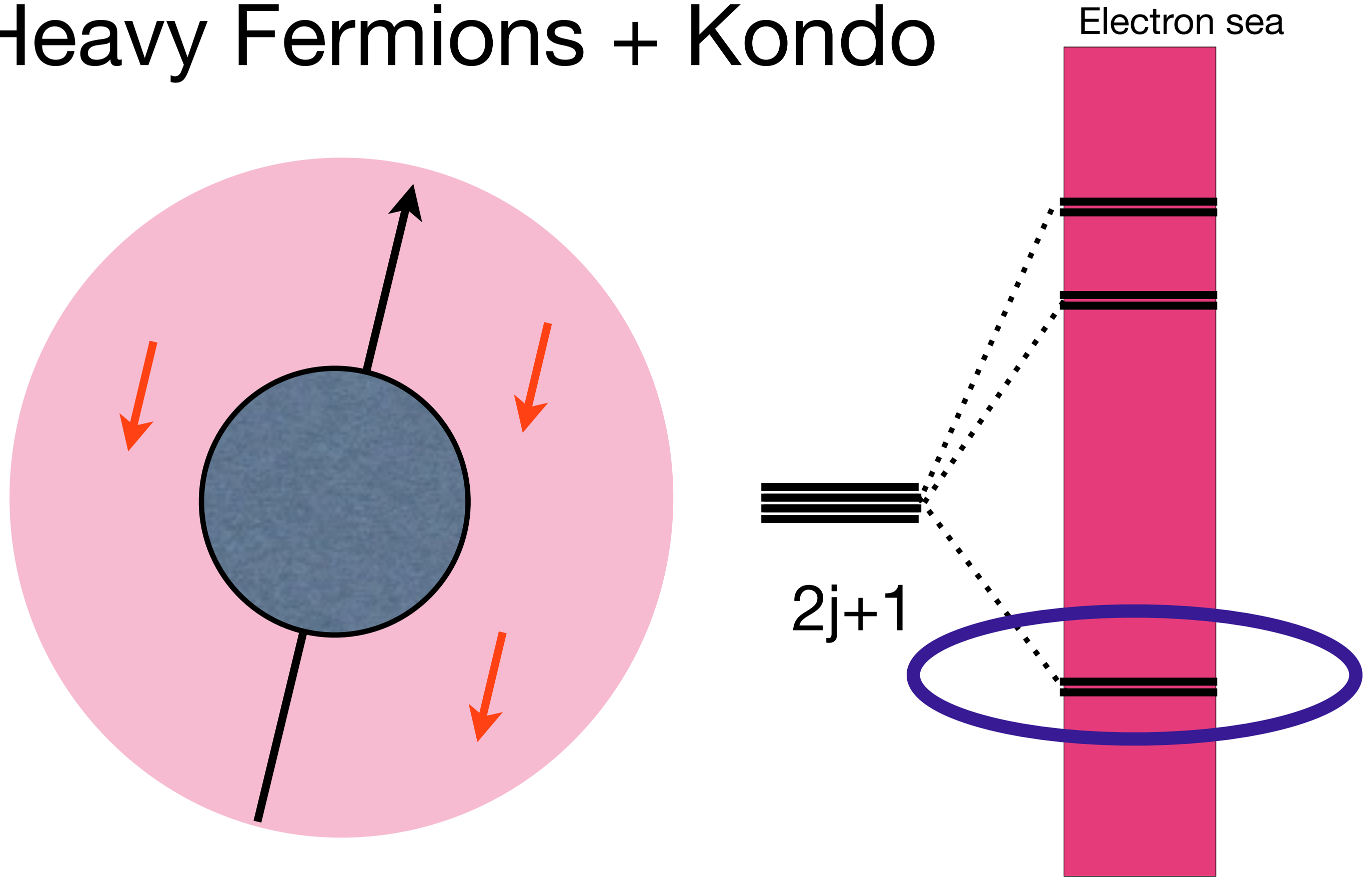
Spin screened by conduction electrons: entangled

$$\uparrow{\color{red}\downarrow} - \downarrow{\color{red}\uparrow}$$

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

Spin entanglement entropy

Heavy Fermions + Kondo

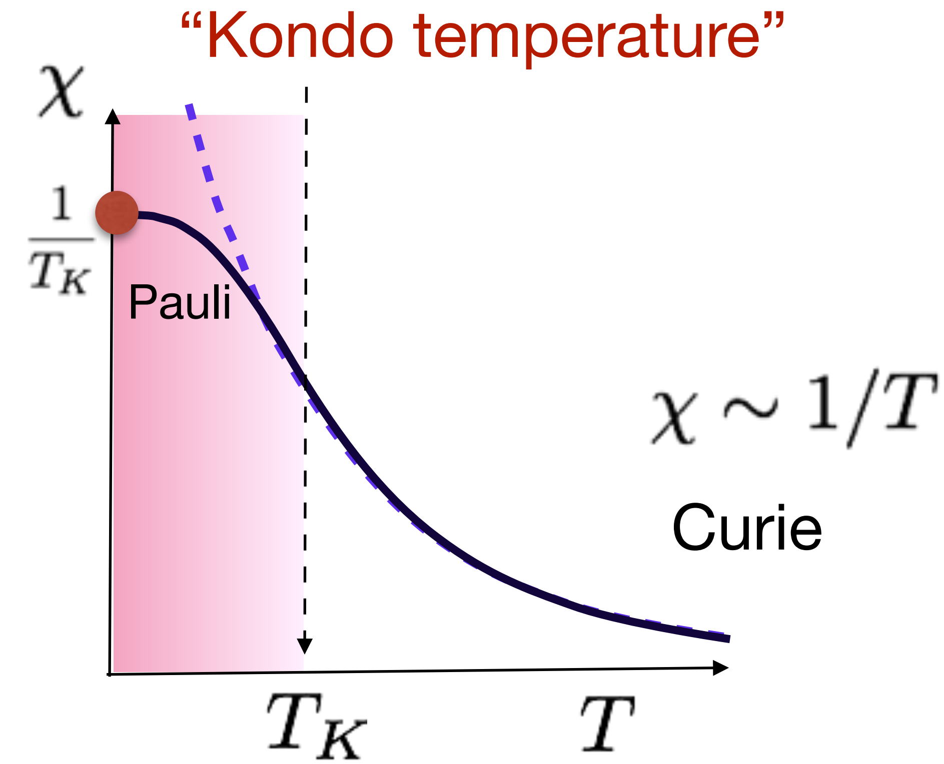


Spin screened by conduction electrons: entangled

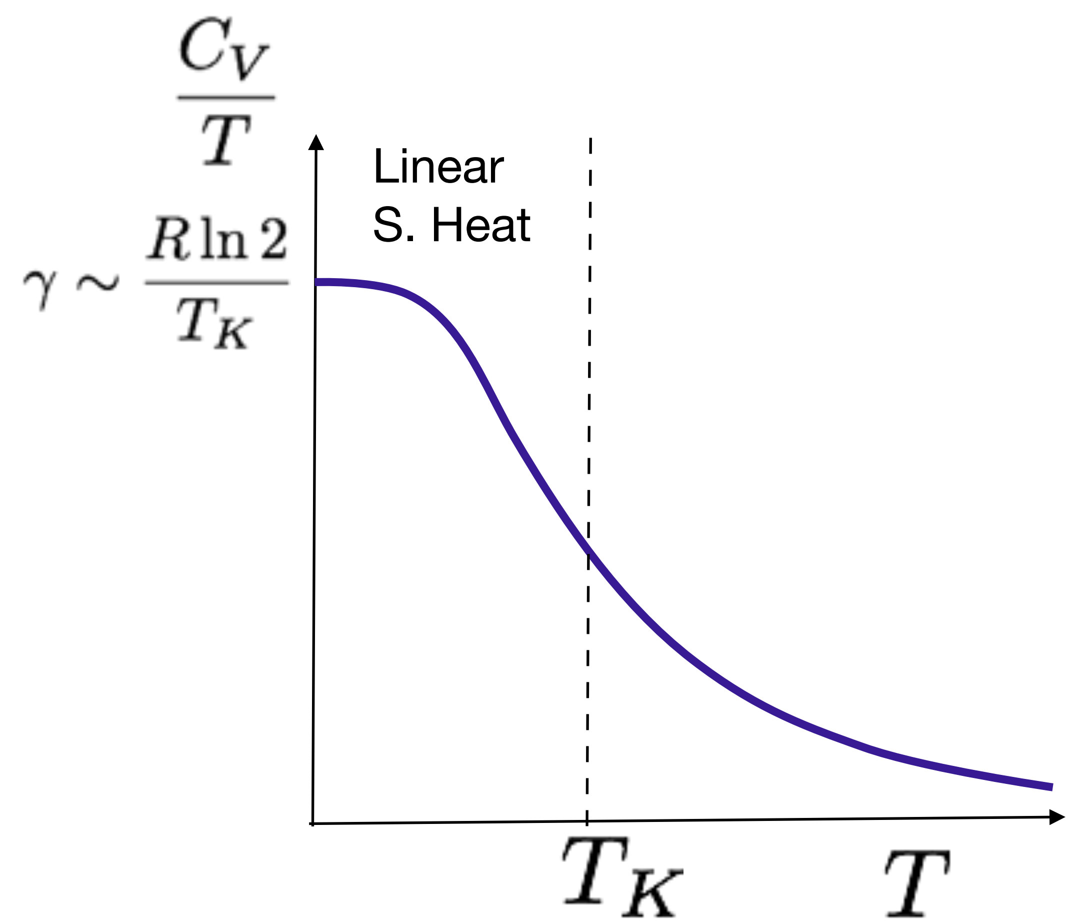
$$\uparrow\downarrow - \downarrow\uparrow$$

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

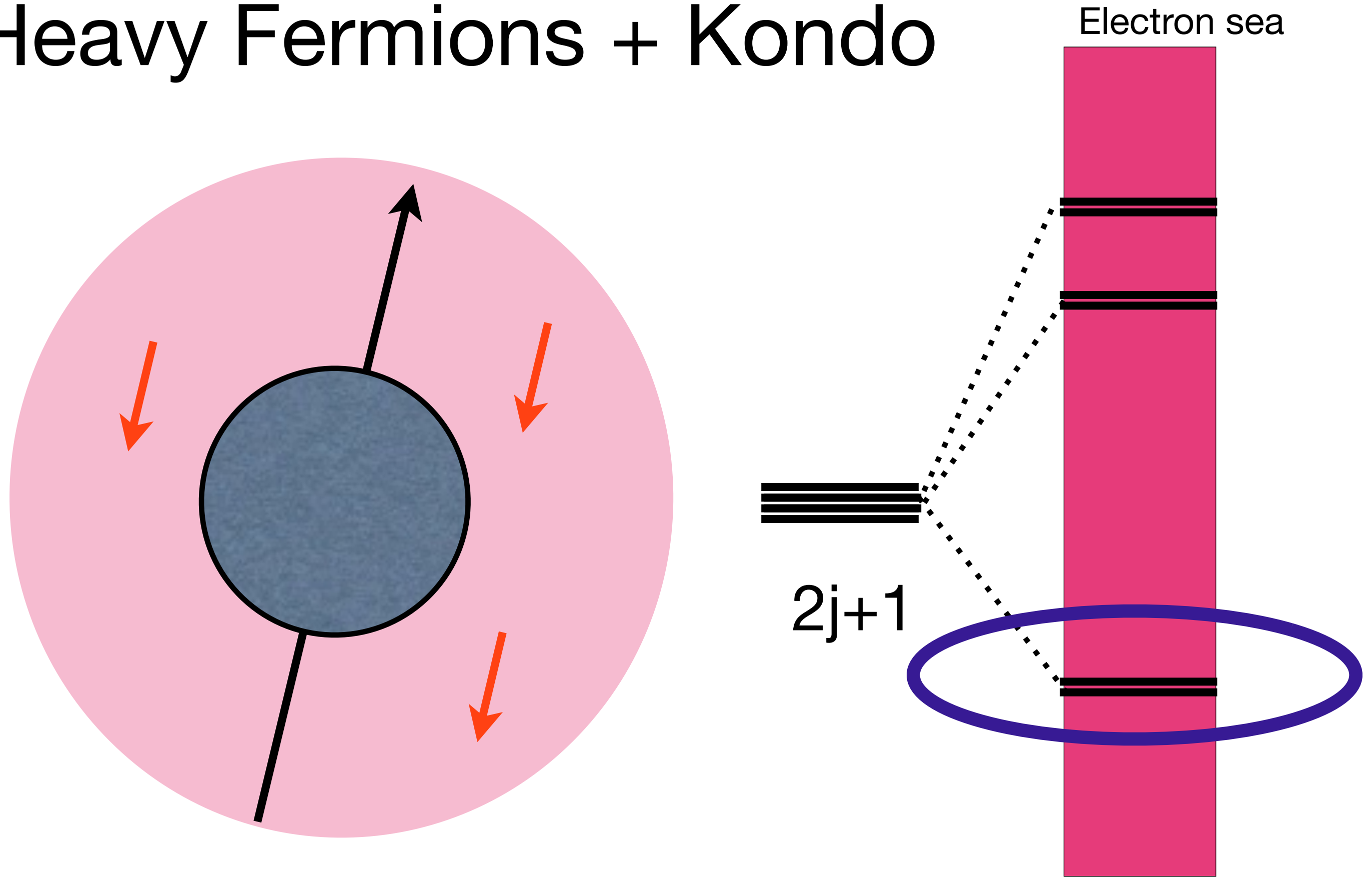
Spin entanglement entropy



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

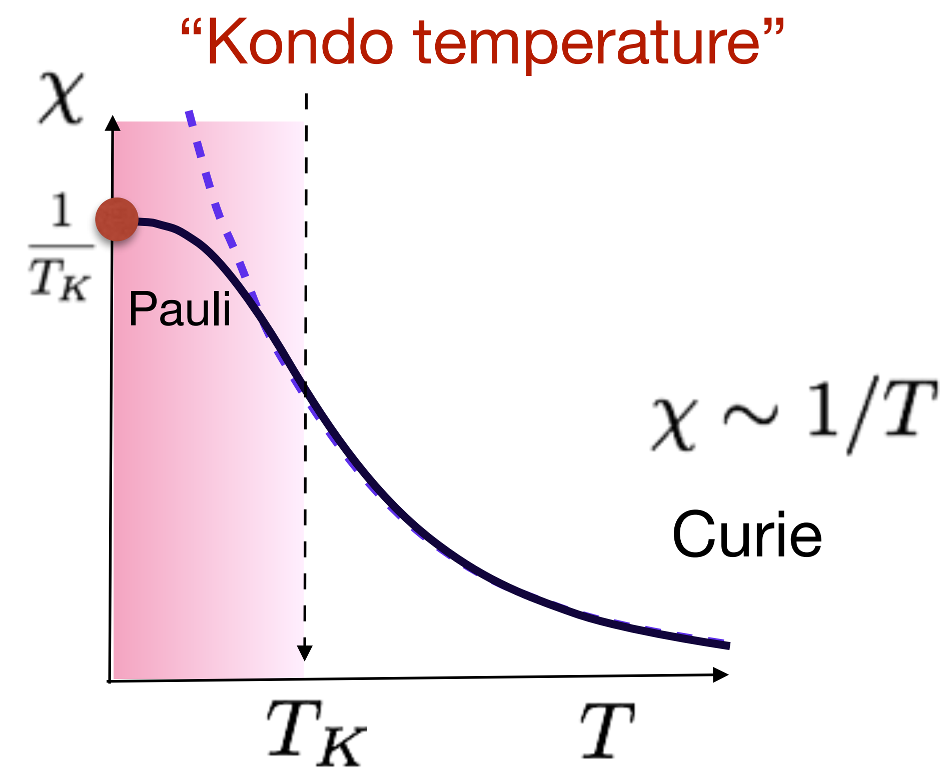


Heavy Fermions + Kondo

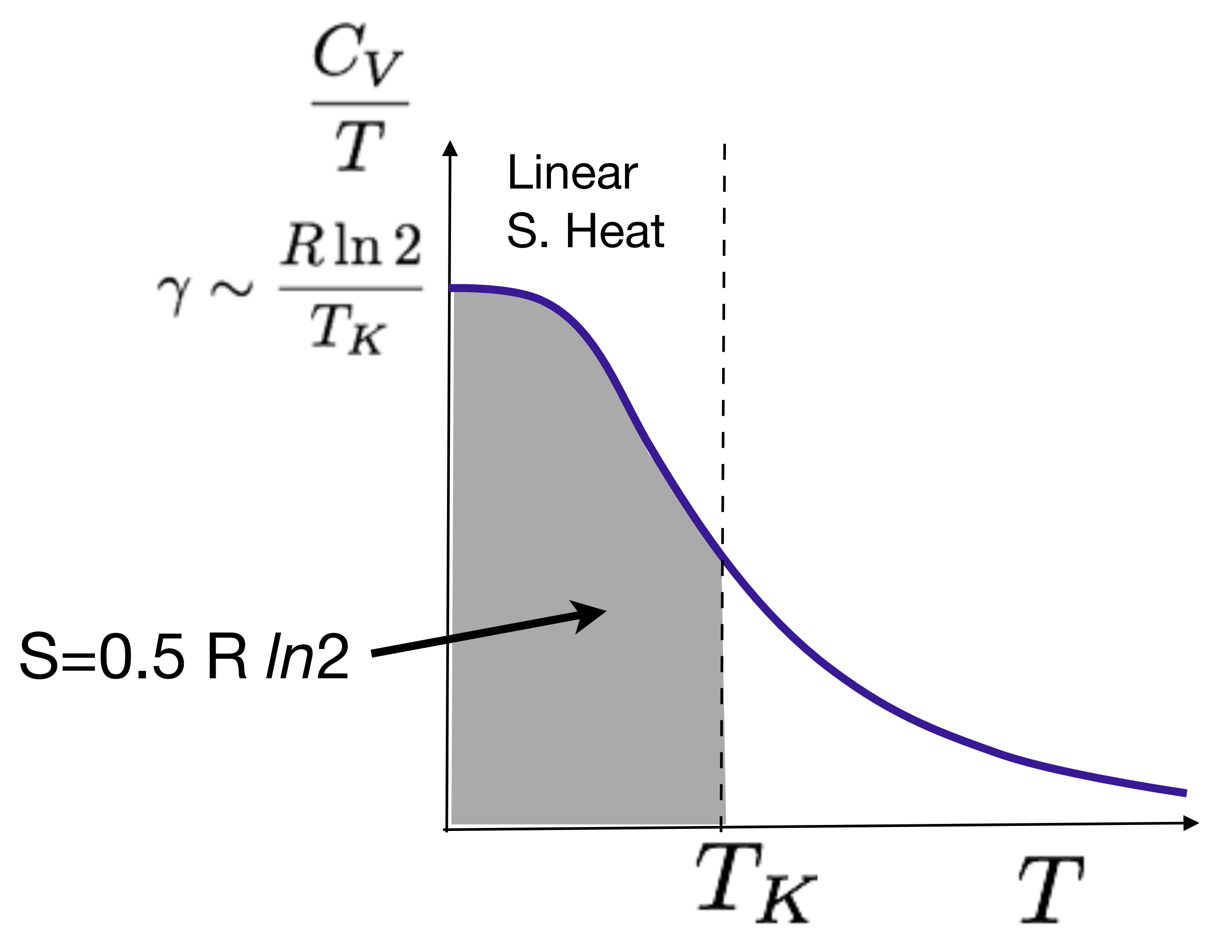


Spin screened by conduction electrons: entangled

$$\uparrow \downarrow - \downarrow \uparrow$$



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



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

Spin entanglement entropy

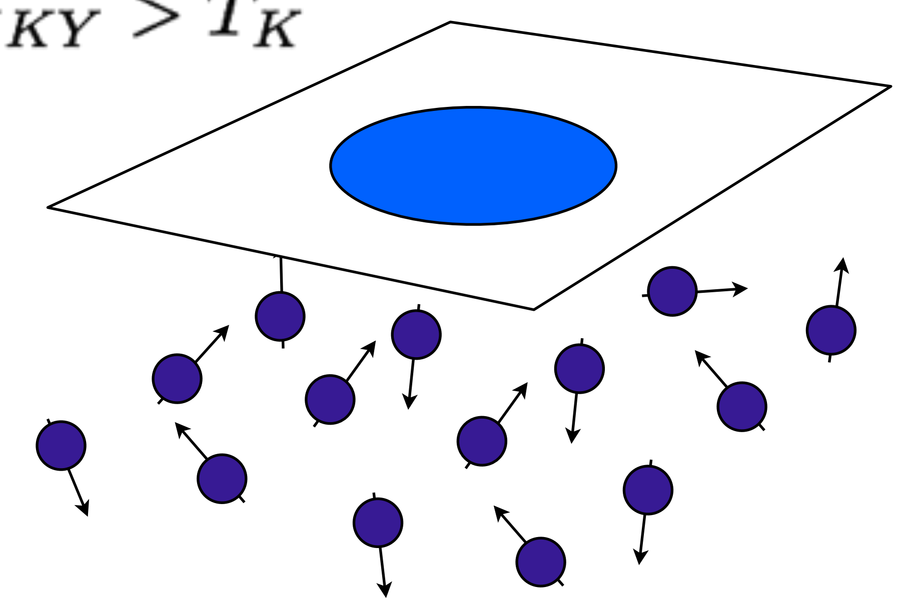
DONIACH'S
Hypothesis.
Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

DONIACH'S
Hypothesis.
Doniach (1977)

$T_{RKKY} > T_K$



$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

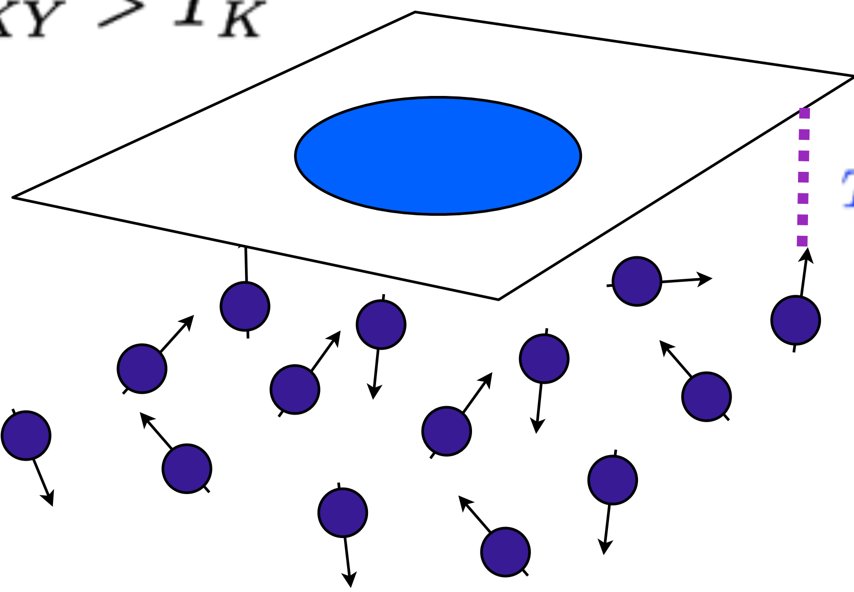
Kondo Lattice Model
(Kasuya, 1951)

DONIACH'S
Hypothesis.
Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

$$T_{RKKY} > T_K$$



$$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$$

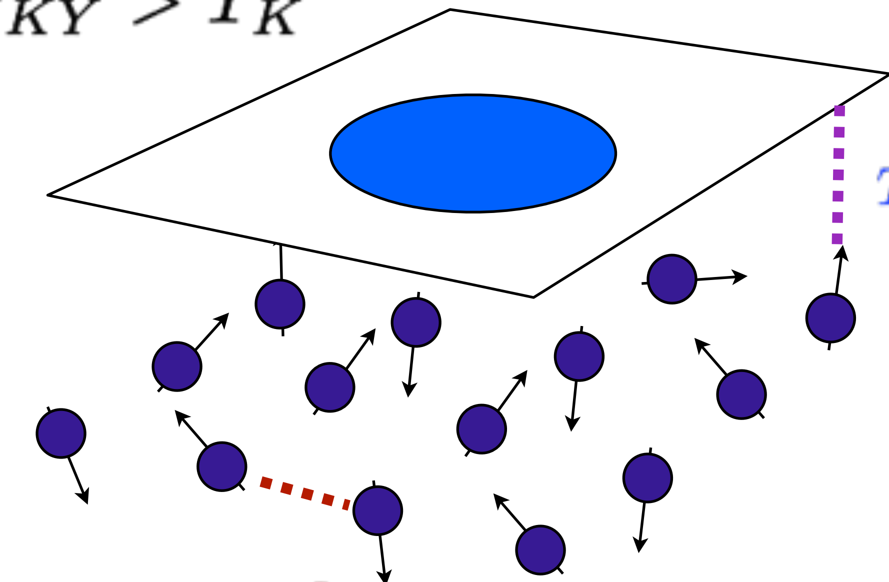
DONIACH'S Hypothesis.

Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

$T_{RKKY} > T_K$



$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2 \rho$

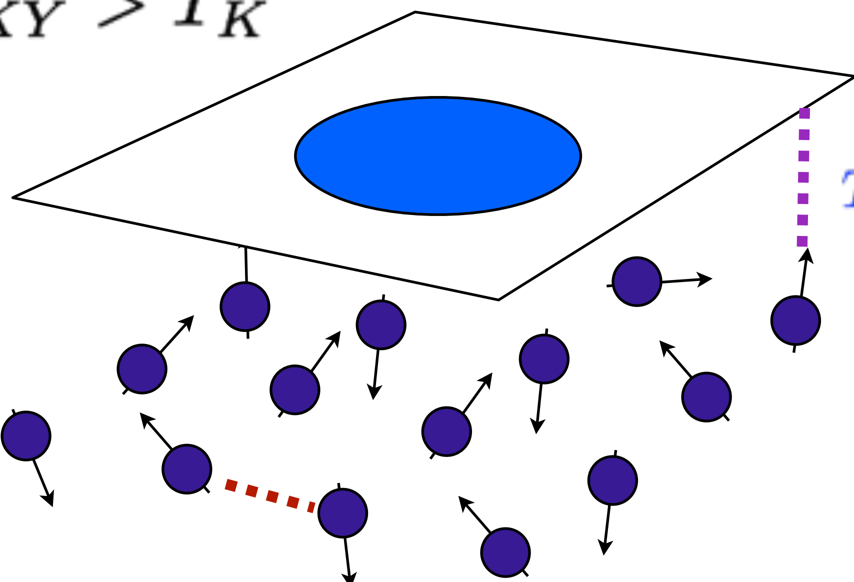
DONIACH'S
Hypothesis.

Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}{}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

$T_{RKKY} > T_K$



$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2 \rho$

$T_{RKKY} < T_K$

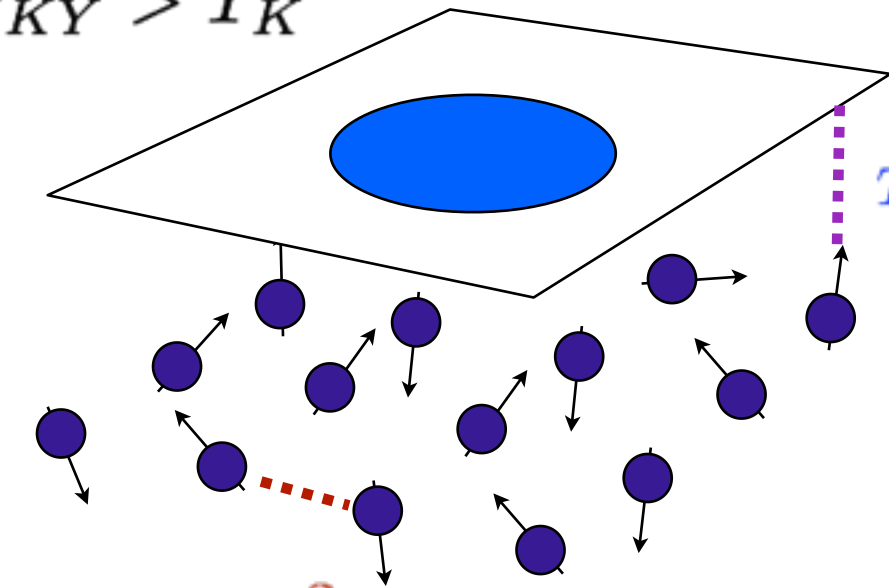
DONIACH'S Hypothesis.

Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J\sum_j (\psi^{\dagger}_j \vec{\sigma}\, \psi_j)\cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

$T_{RKKY} > T_K$

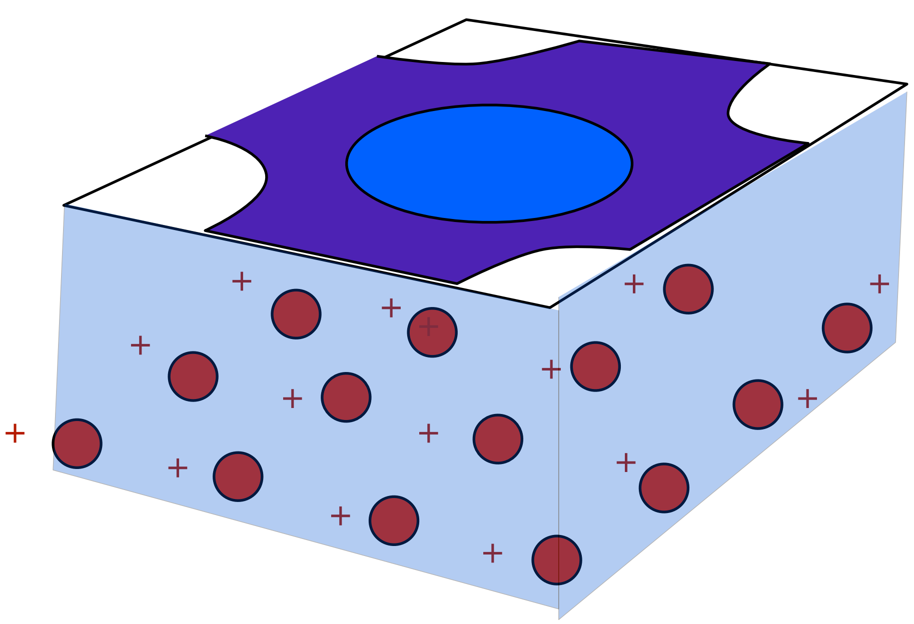


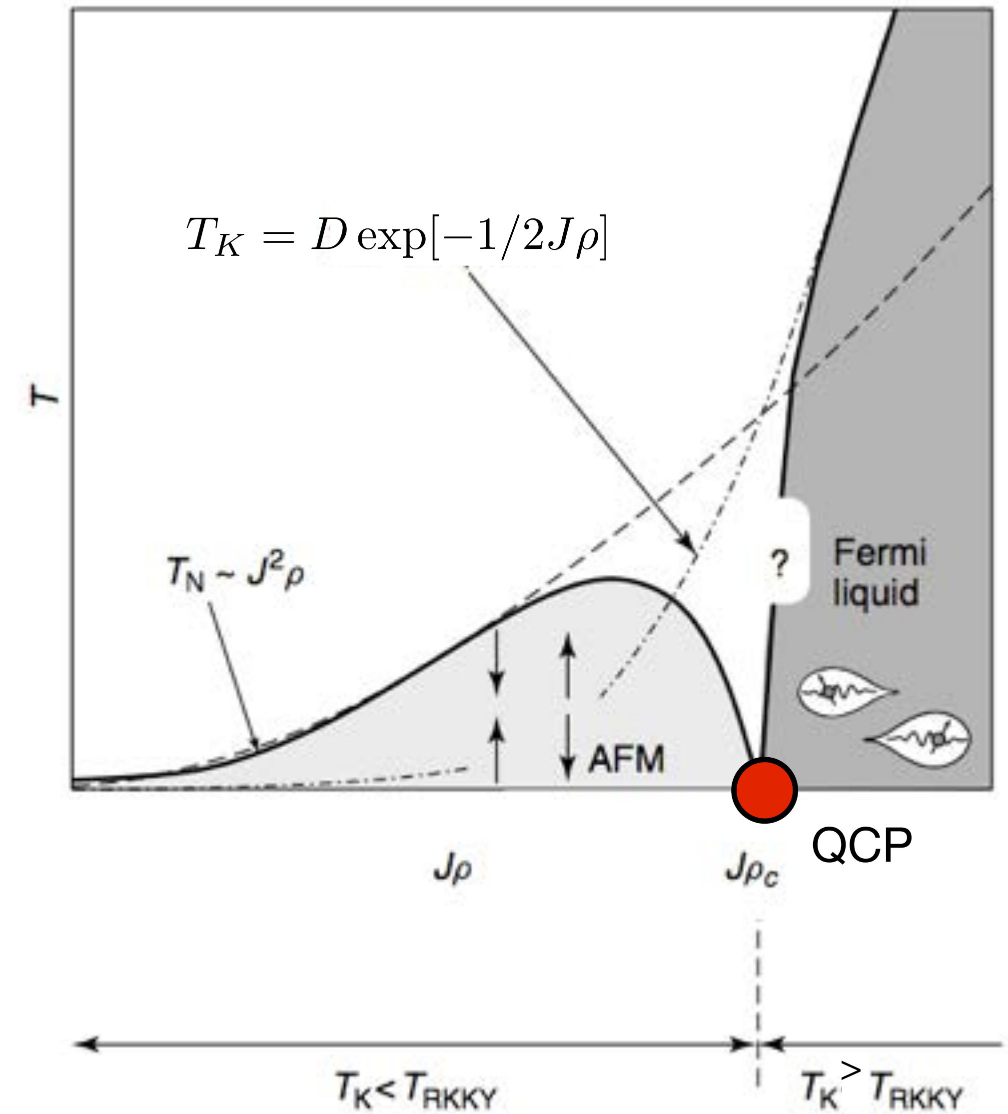
$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2 \rho$

$T_{RKKY} < T_K$

Large Fermi surface of composite Fermions



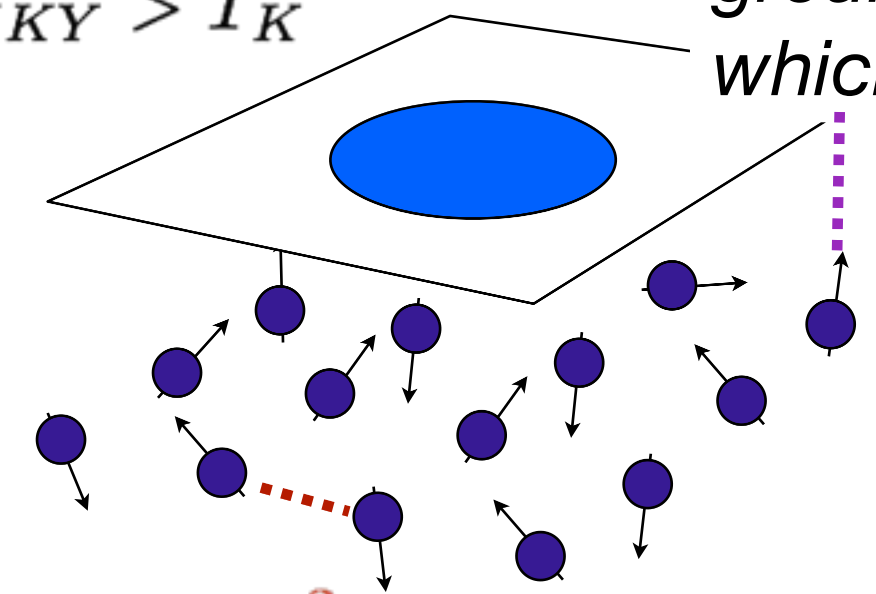


DONIACH'S Hypothesis.

Doniach (1977)

The main result ... is that there should be a second-order transition at zero temperature, as the exchange is varied, between an antiferromagnetic ground state for weak J and a Kondo-like state in which the local moments are quenched.

$T_{RKKY} > T_K$

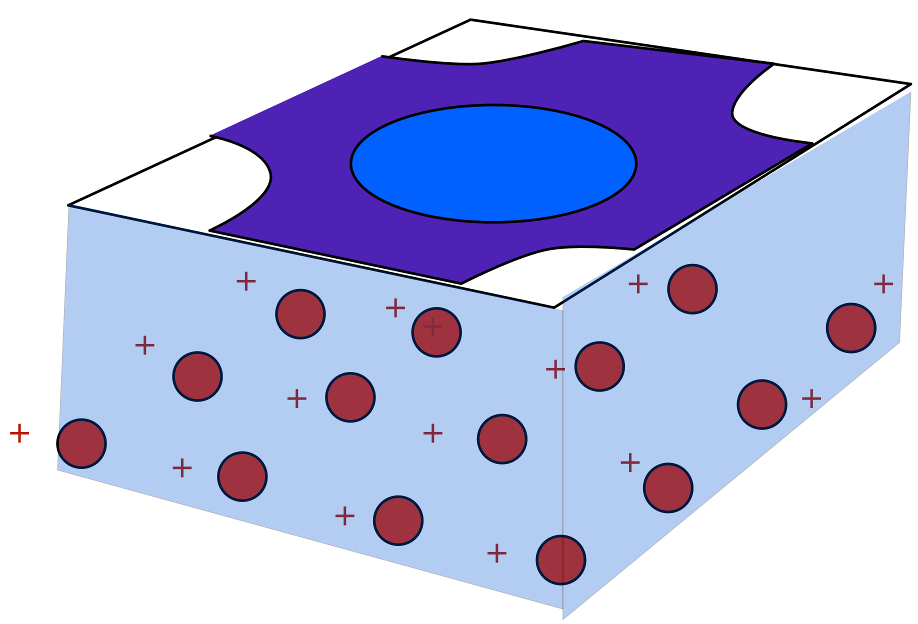


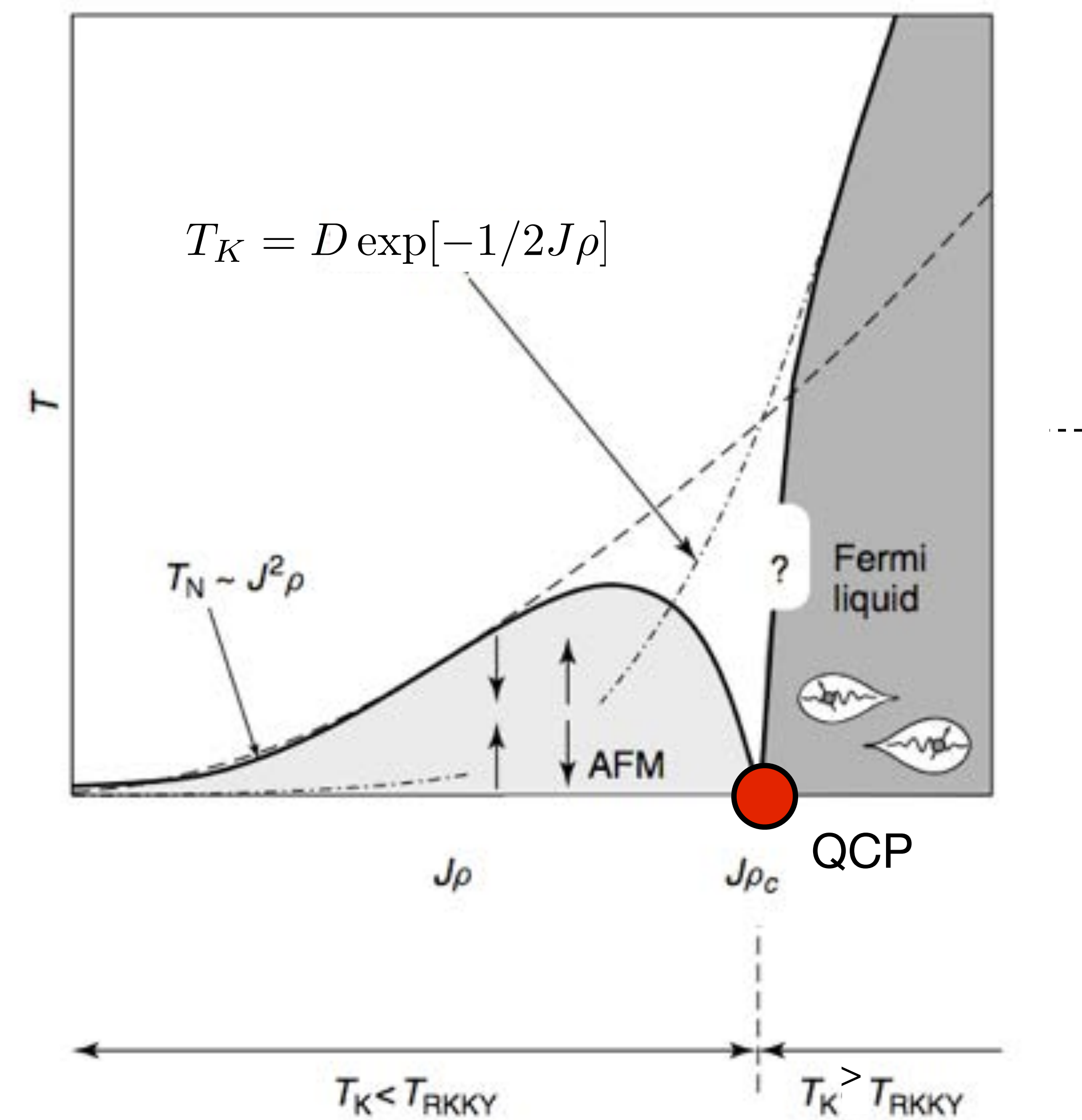
$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2\rho$

$T_{RKKY} < T_K$

Large Fermi surface of composite Fermions



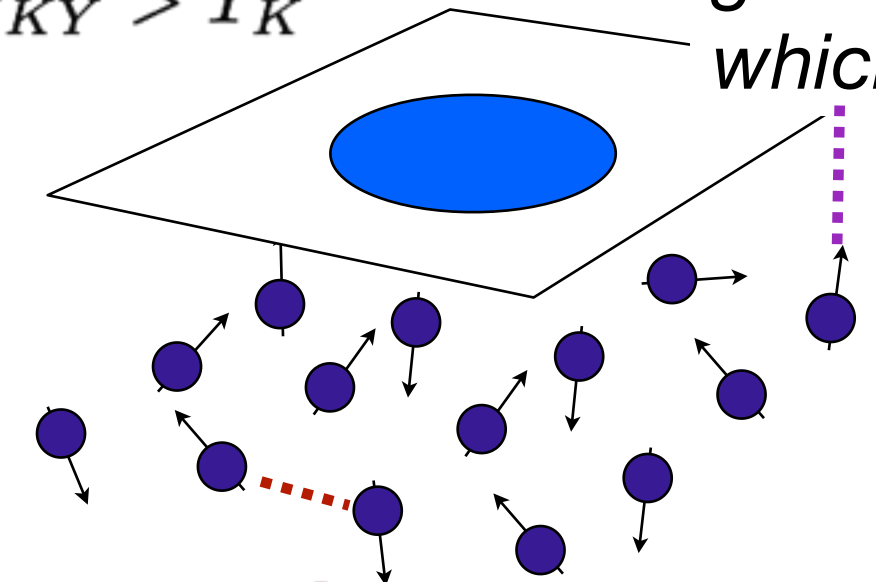


DONIACH'S Hypothesis.

Doniach (1977)

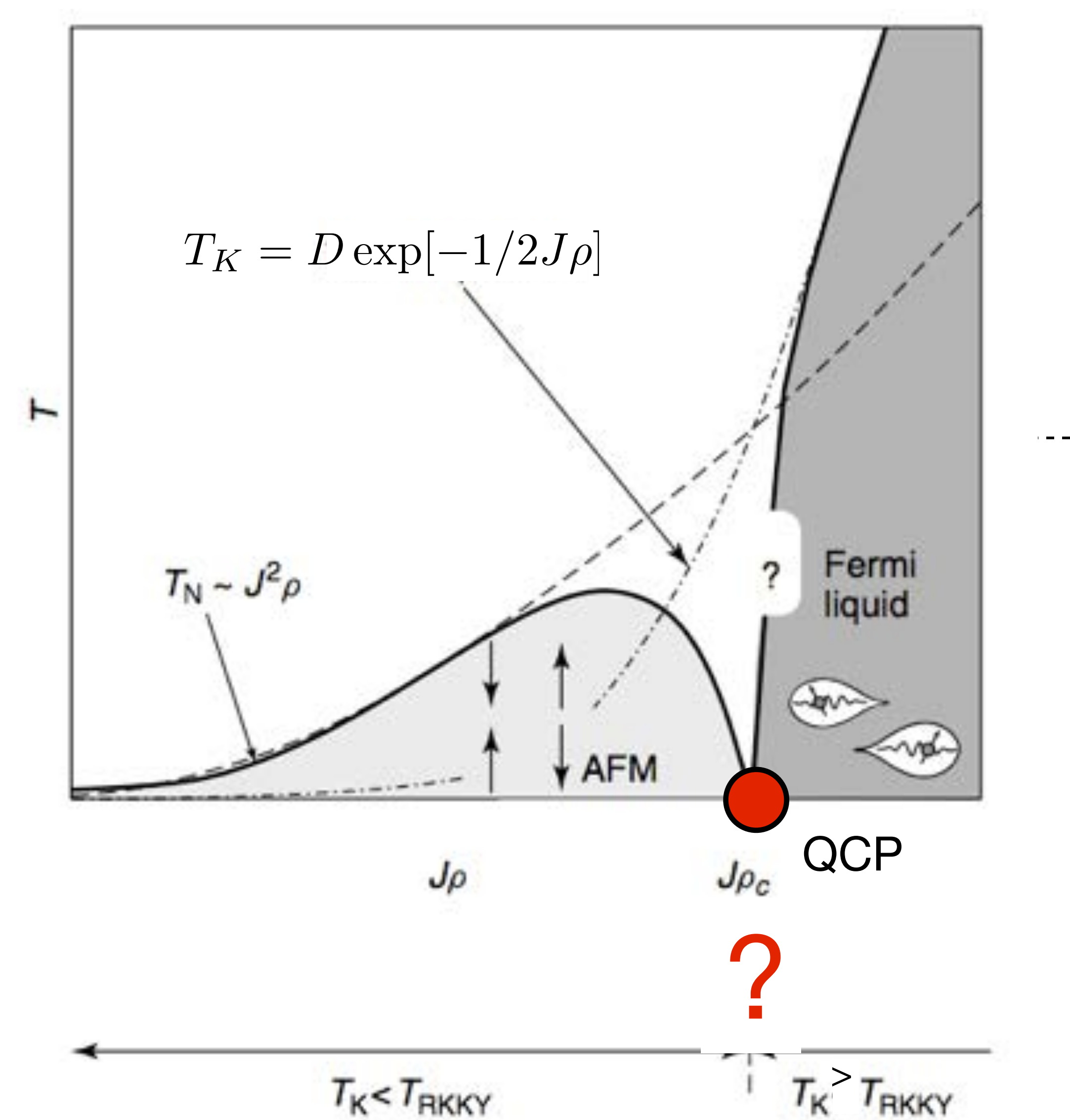
The main result ... is that there should be a second-order transition at zero temperature, as the exchange is varied, between an antiferromagnetic ground state for weak J and a Kondo-like state in which the local moments are quenched.

$T_{RKKY} > T_K$



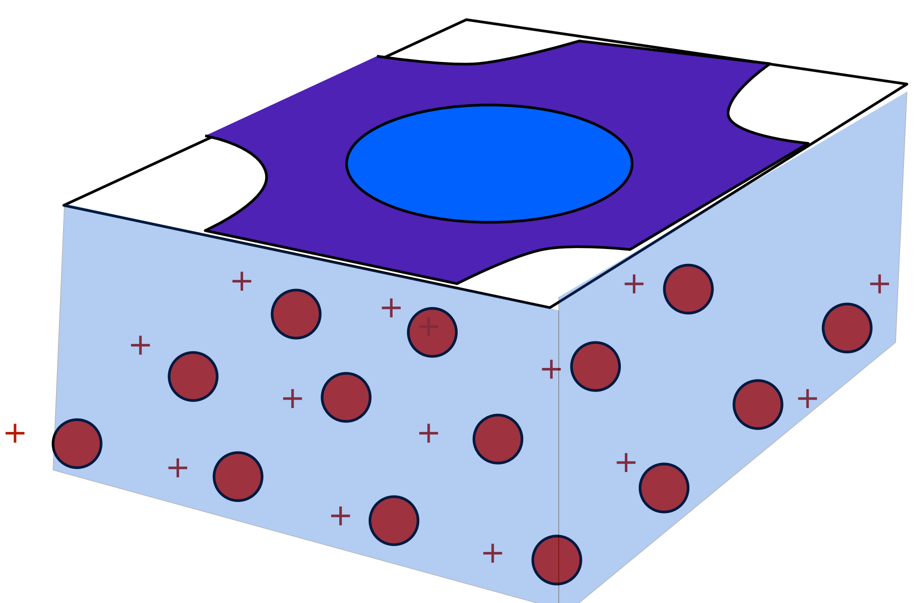
$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2\rho$

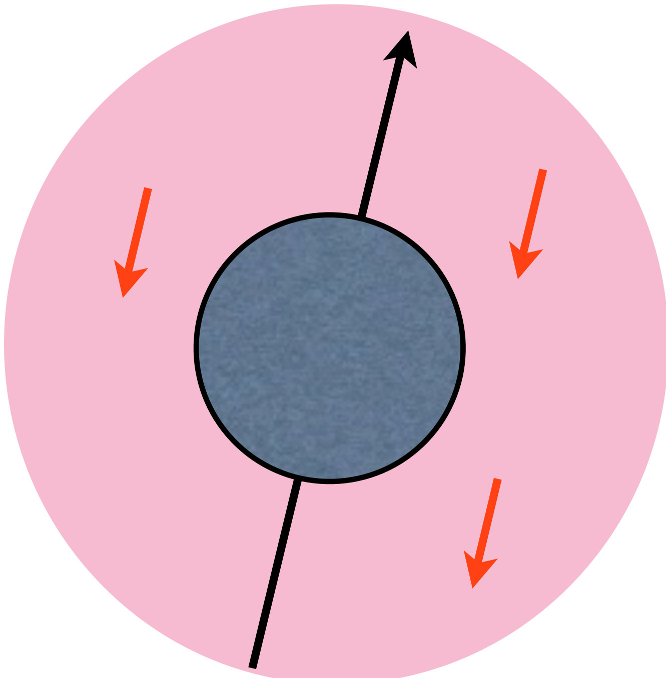


$T_{RKKY} < T_K$

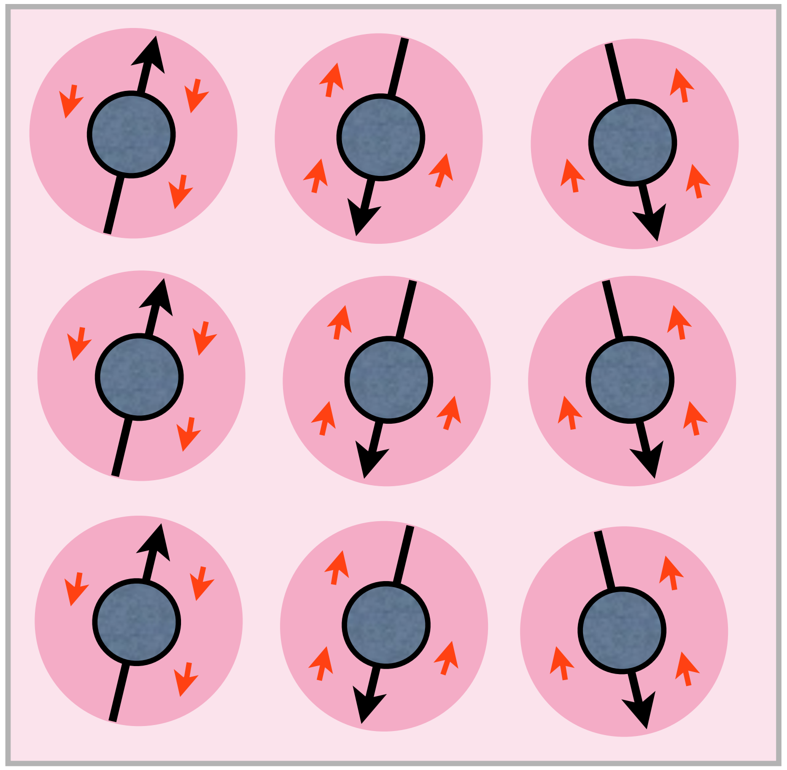
Large Fermi surface of composite Fermions



Heavy Fermion Primer

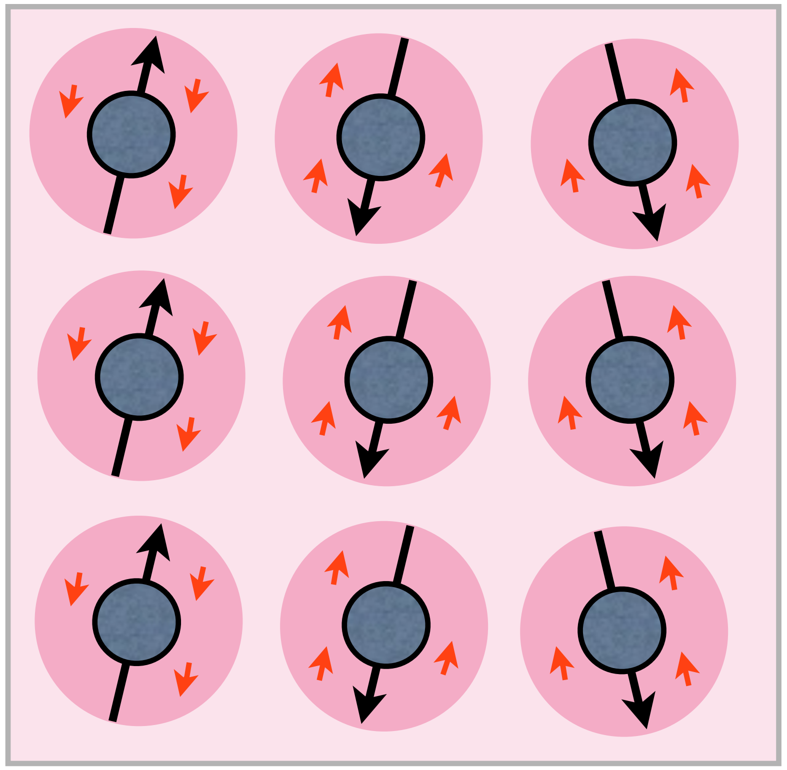


$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} \vec{S}_j \cdot \vec{\sigma}(j)$$



"Kondo Lattice"

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

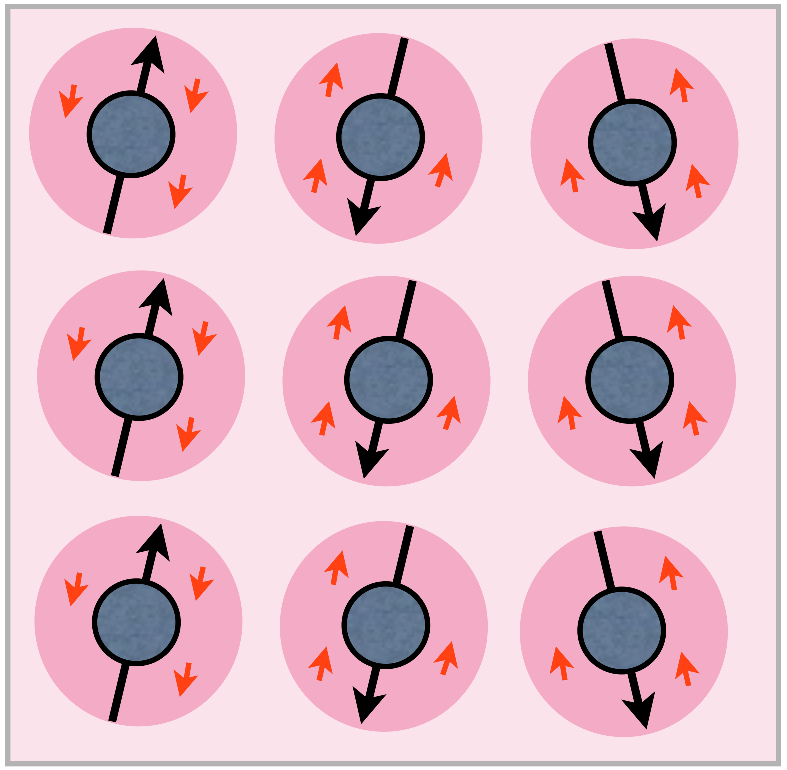


“Kondo Lattice”

Entangled spins and electrons

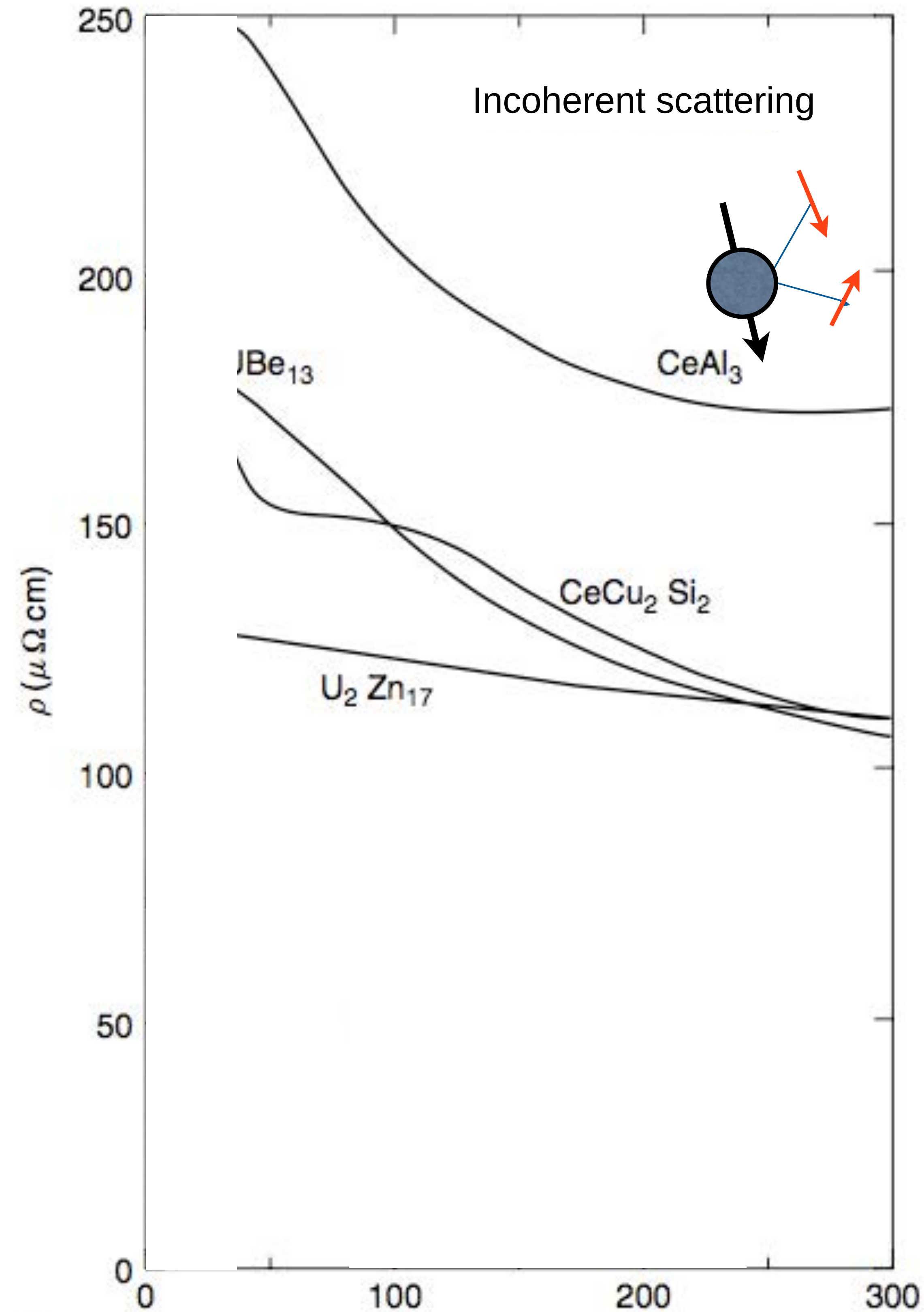
→ **Heavy Fermion Metals**

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

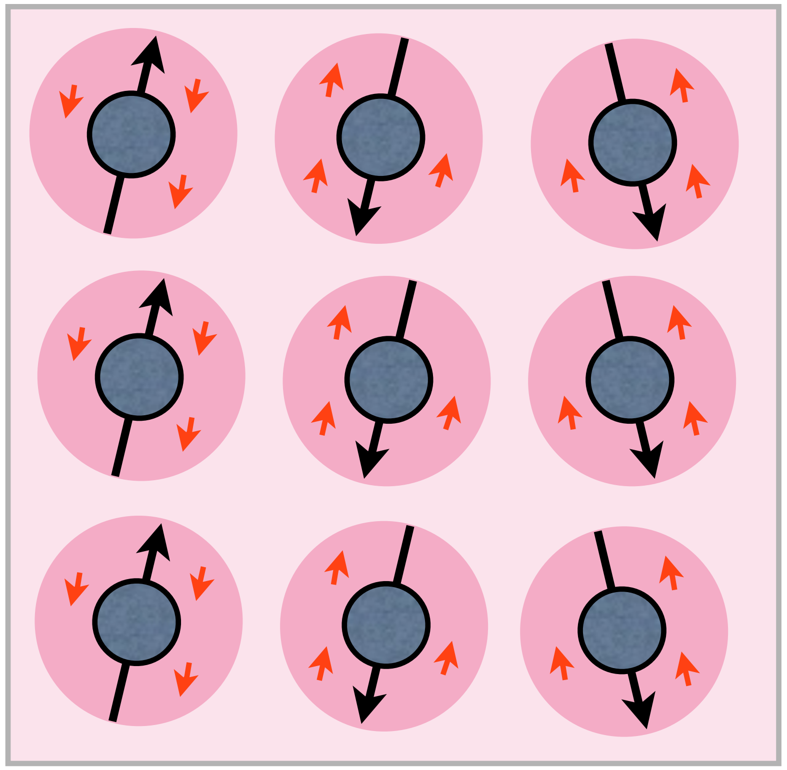


"Kondo Lattice"

Entangled spins and electrons
→ **Heavy Fermion Metals**

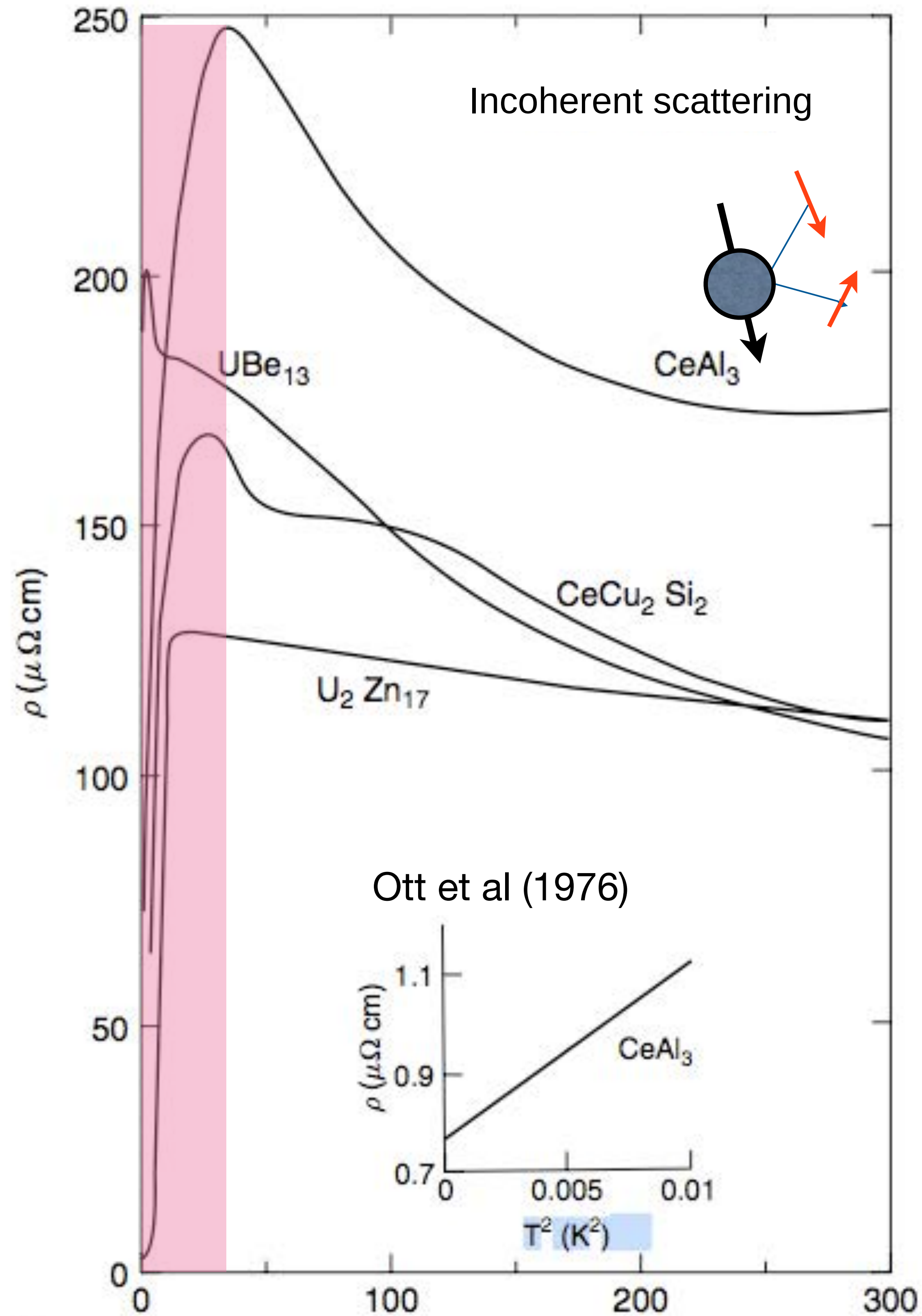


$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} \vec{S}_j \cdot \vec{\sigma}(j)$$



"Kondo Lattice"

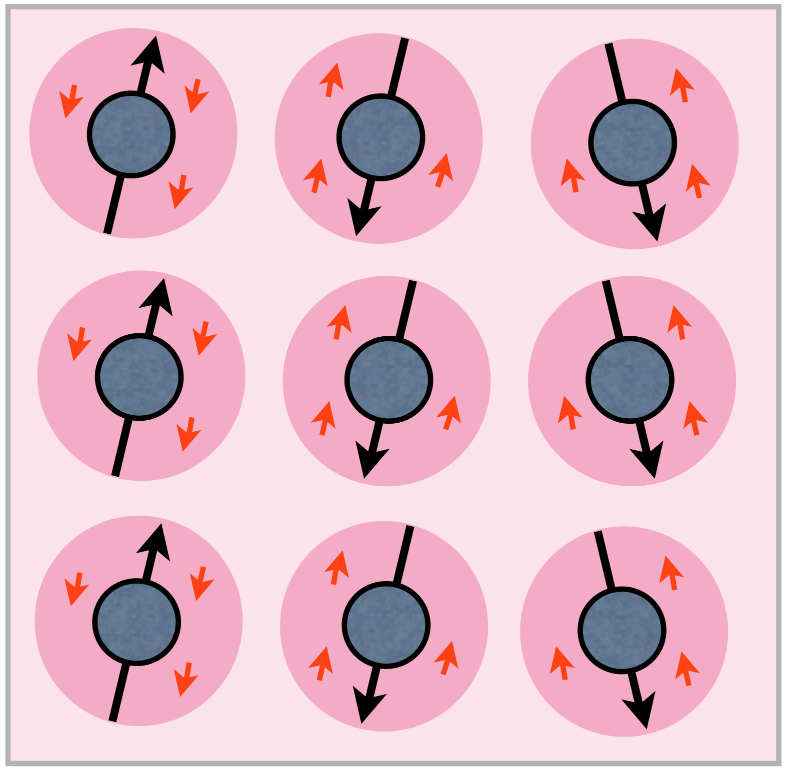
Entangled spins and electrons
→ **Heavy Fermion Metals**



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

Coherent Heavy Fermions

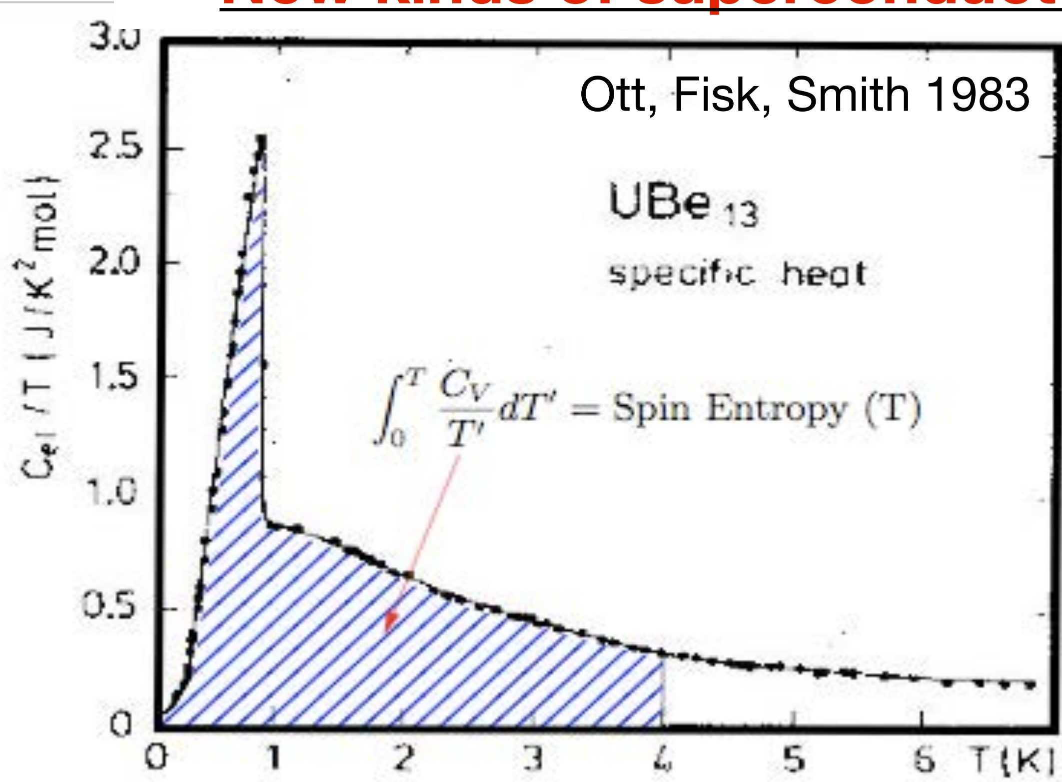
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} \vec{S}_j \cdot \vec{\sigma}(j)$$

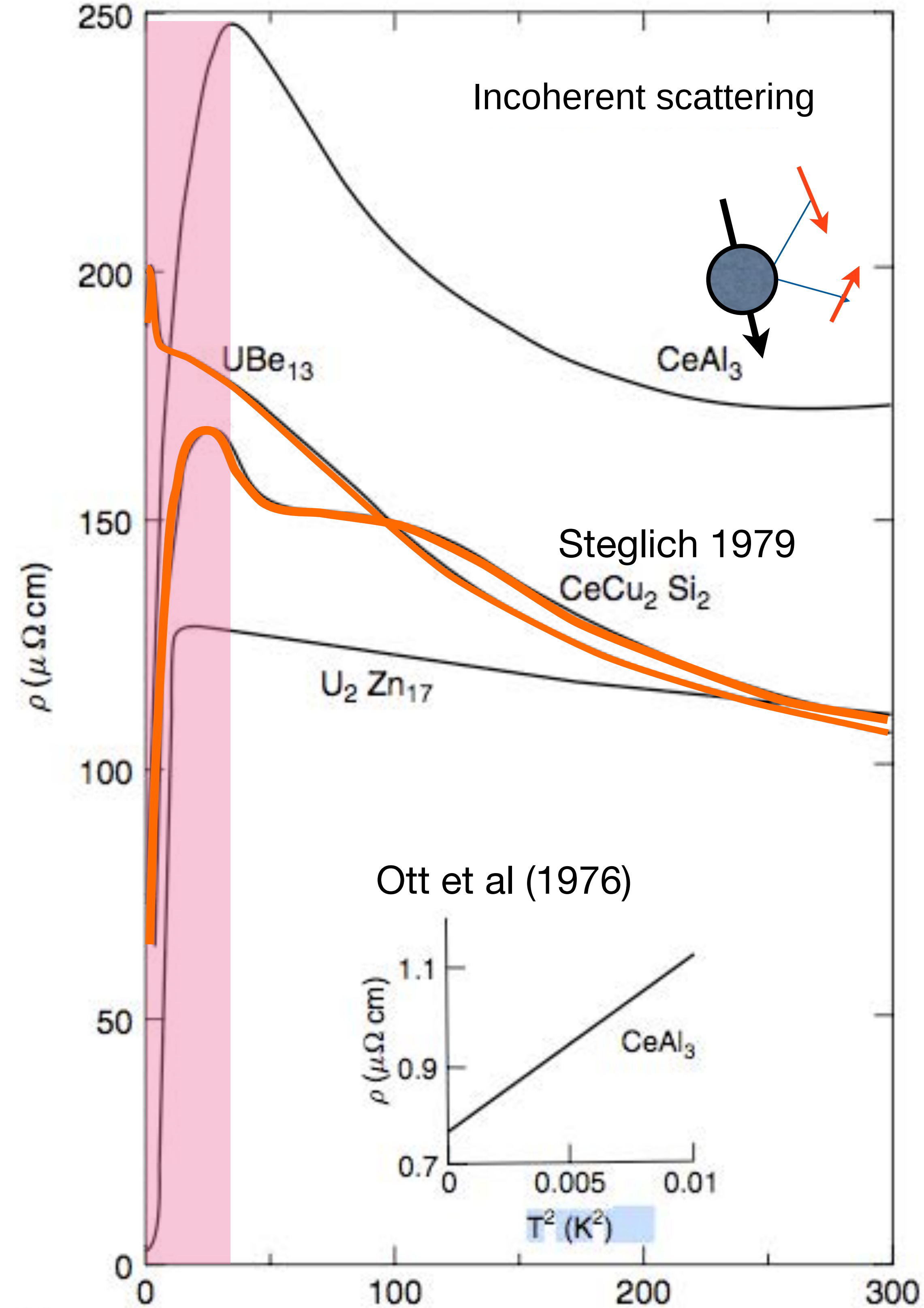


"Kondo Lattice"

Entangled spins and electrons

→ **New kinds of superconductor**



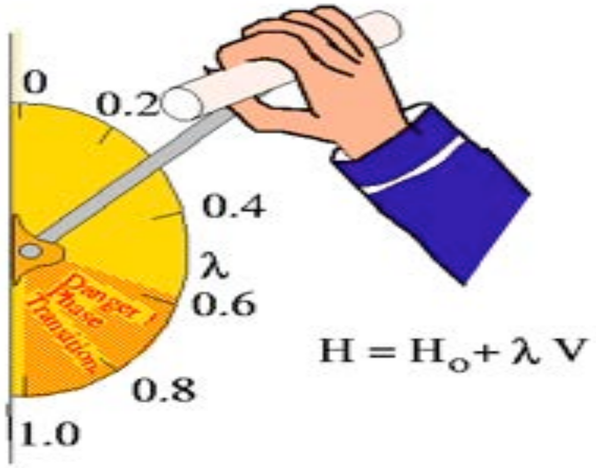


$$\rho(T) = \rho_0 + AT^2$$

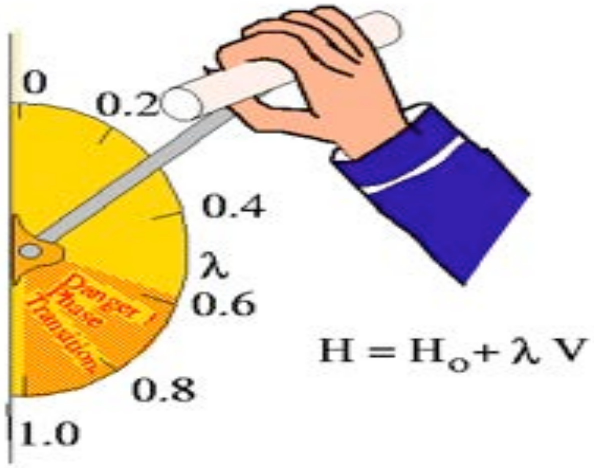
Coherent Heavy Fermions

Lev Landau vs Ken Wilson:

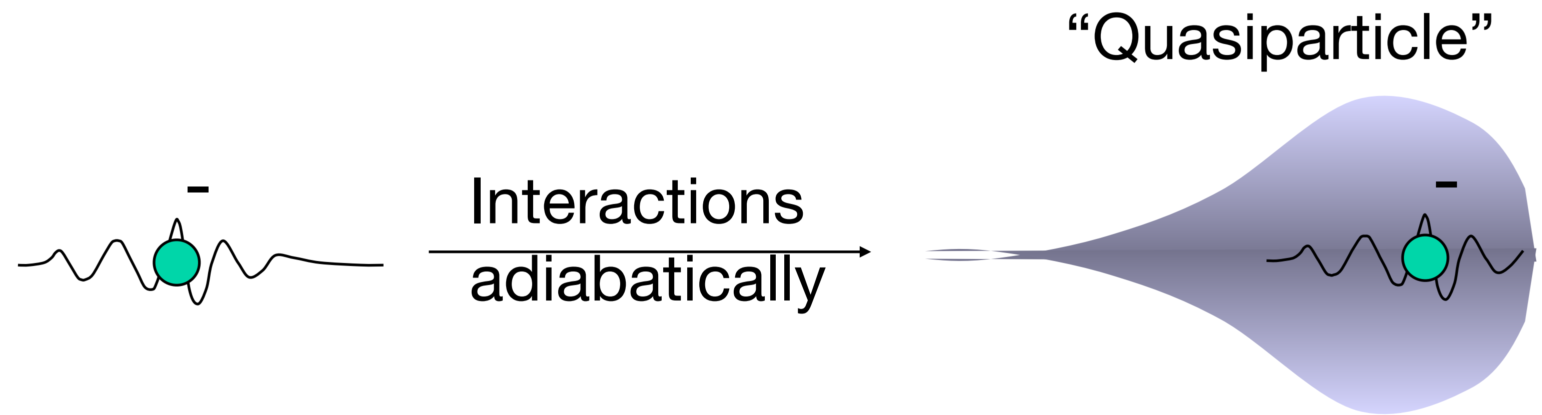
Criticality as a driver of new States of Matter



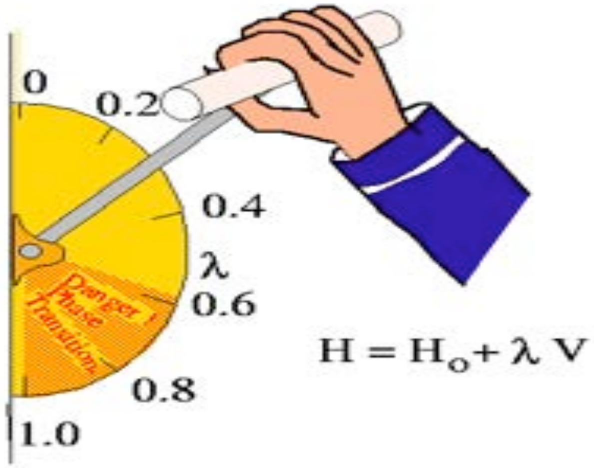
Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.



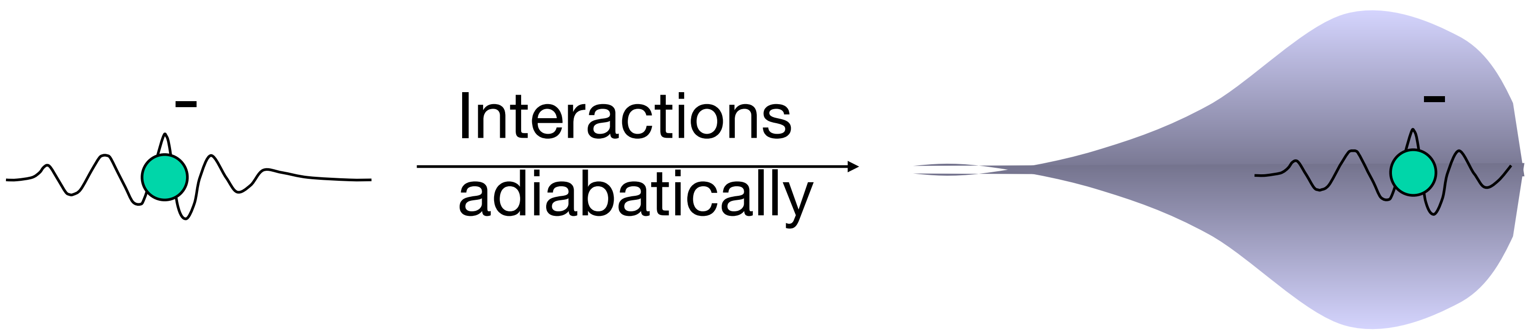
Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.



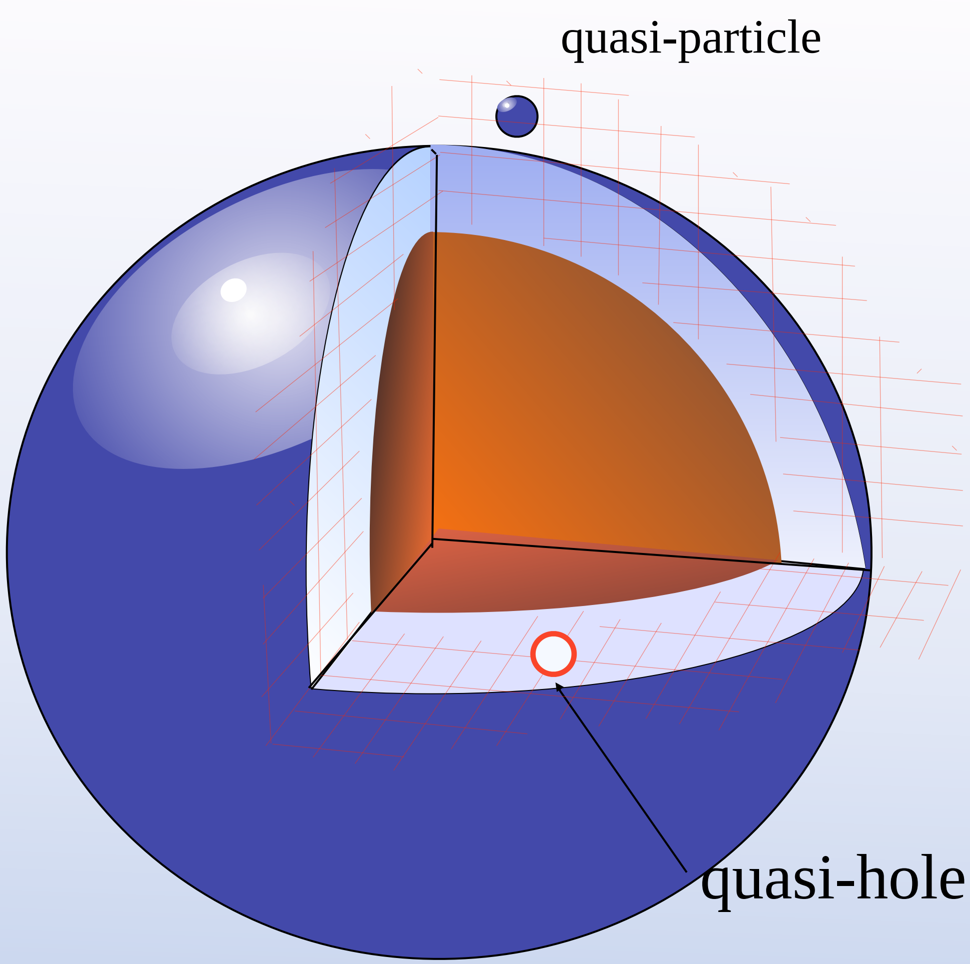
$$\left|e^-\right\rangle \qquad\qquad \left|qp^-\right\rangle$$

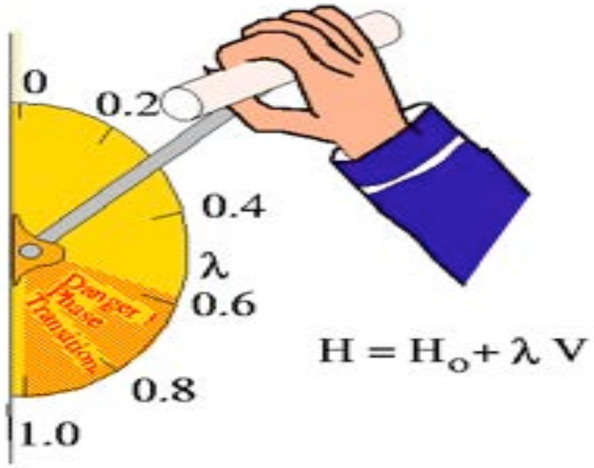


Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.

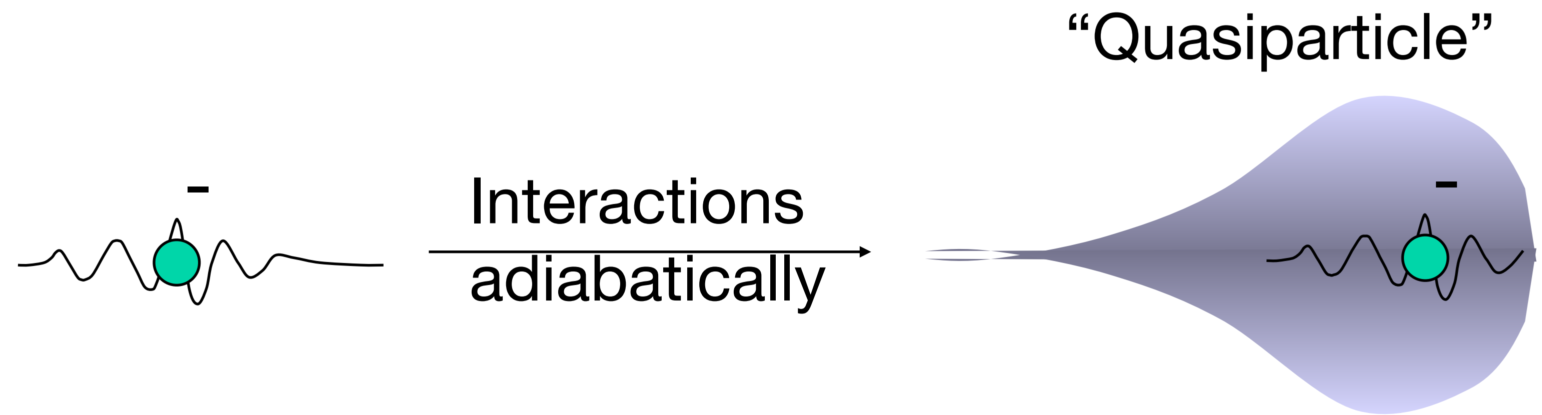


$$|e^-\rangle \qquad\qquad |qp^-\rangle$$

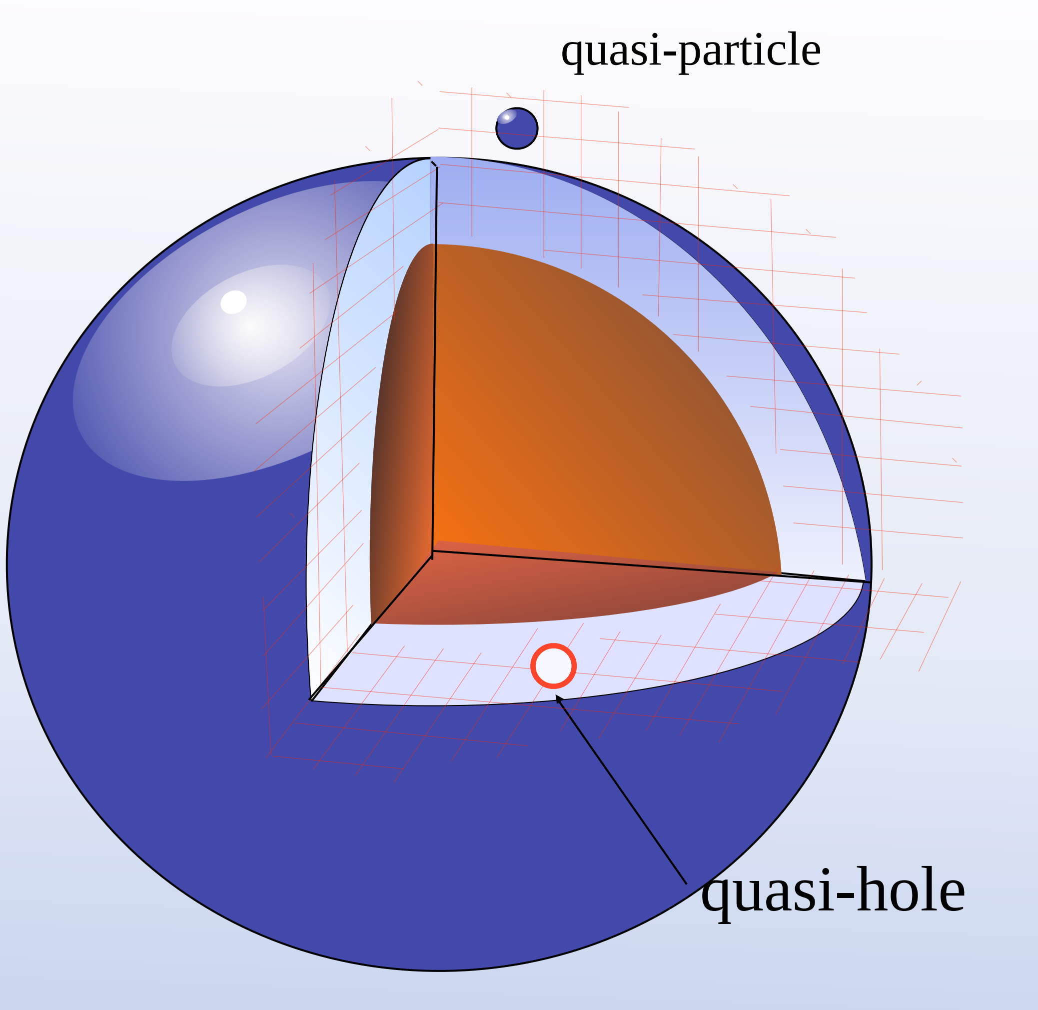




Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.



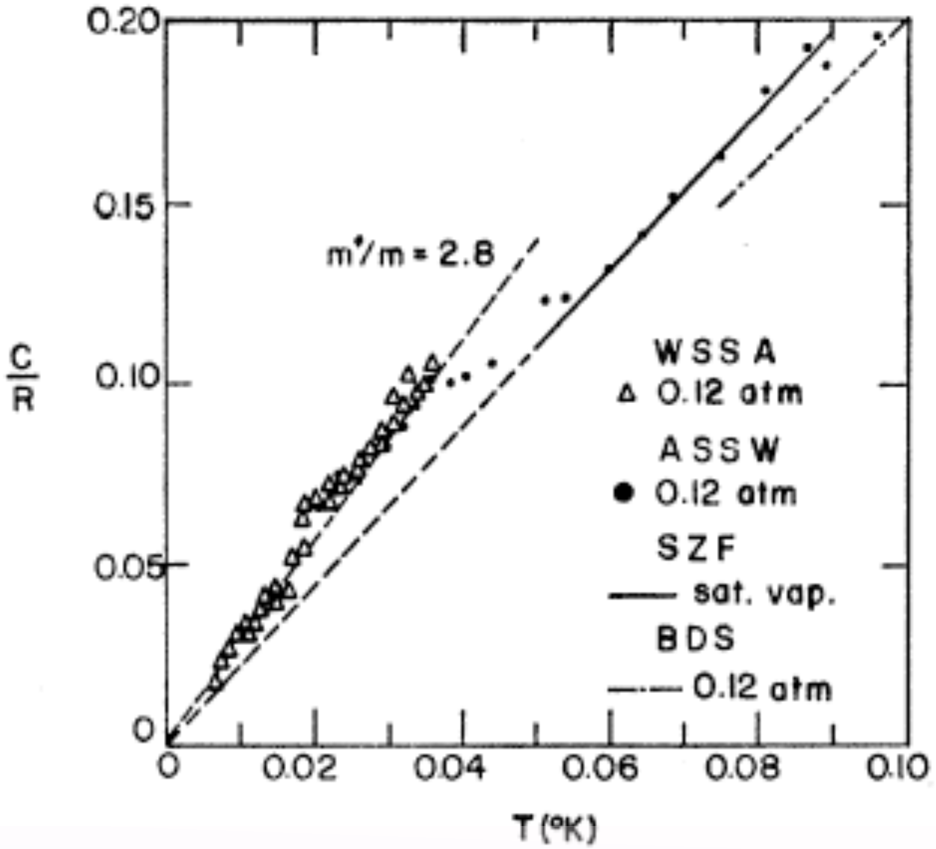
$$|e^-\rangle \qquad\qquad |qp^-\rangle$$

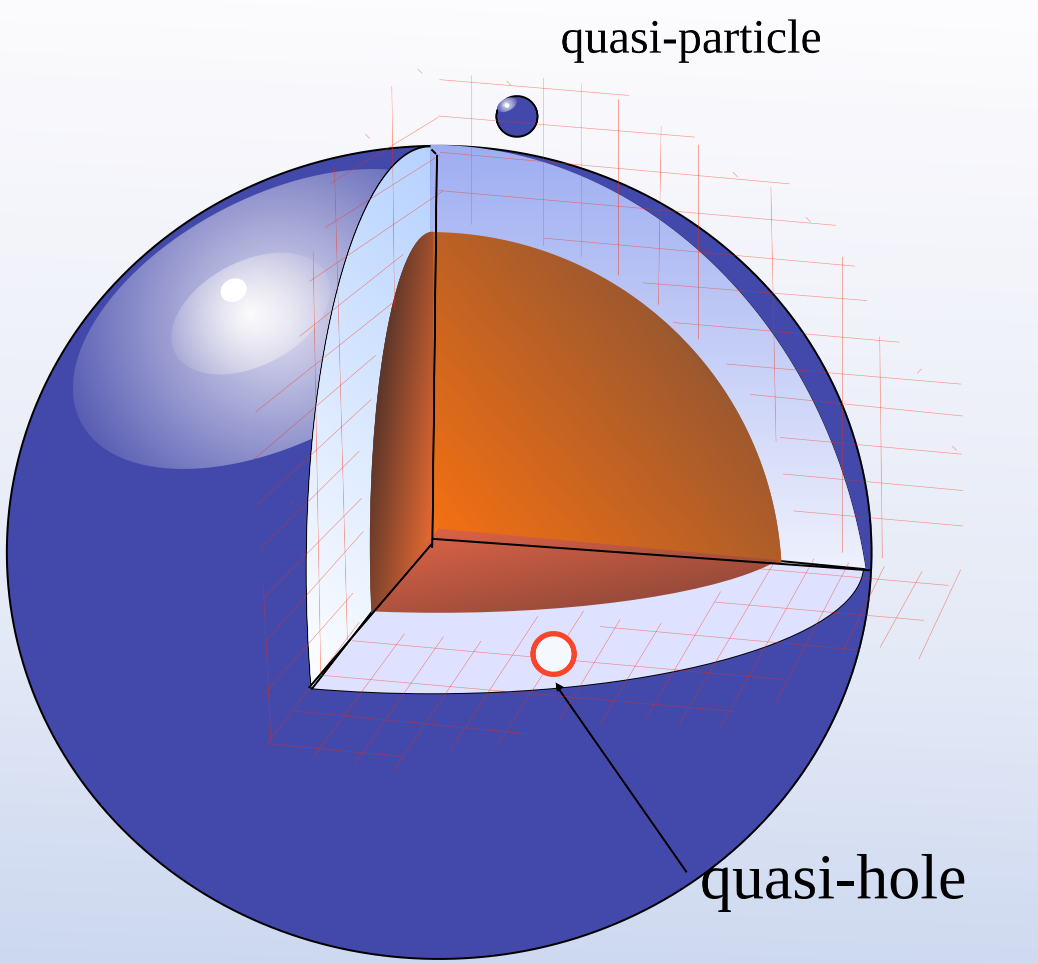


$$\frac{m^*}{m} = \frac{N(0)^*}{N(0)} = 1 + \frac{F_1^s}{3}$$

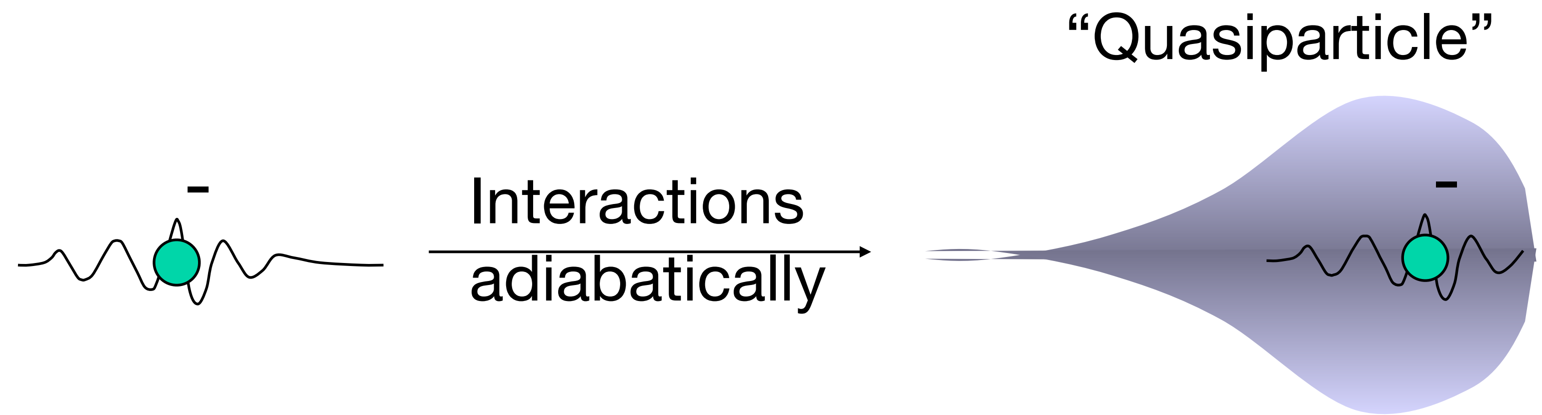
Landau, JETP 3, 920 (1957)

He-3 (1950/60s)
(Fairbanks, many others)





Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.



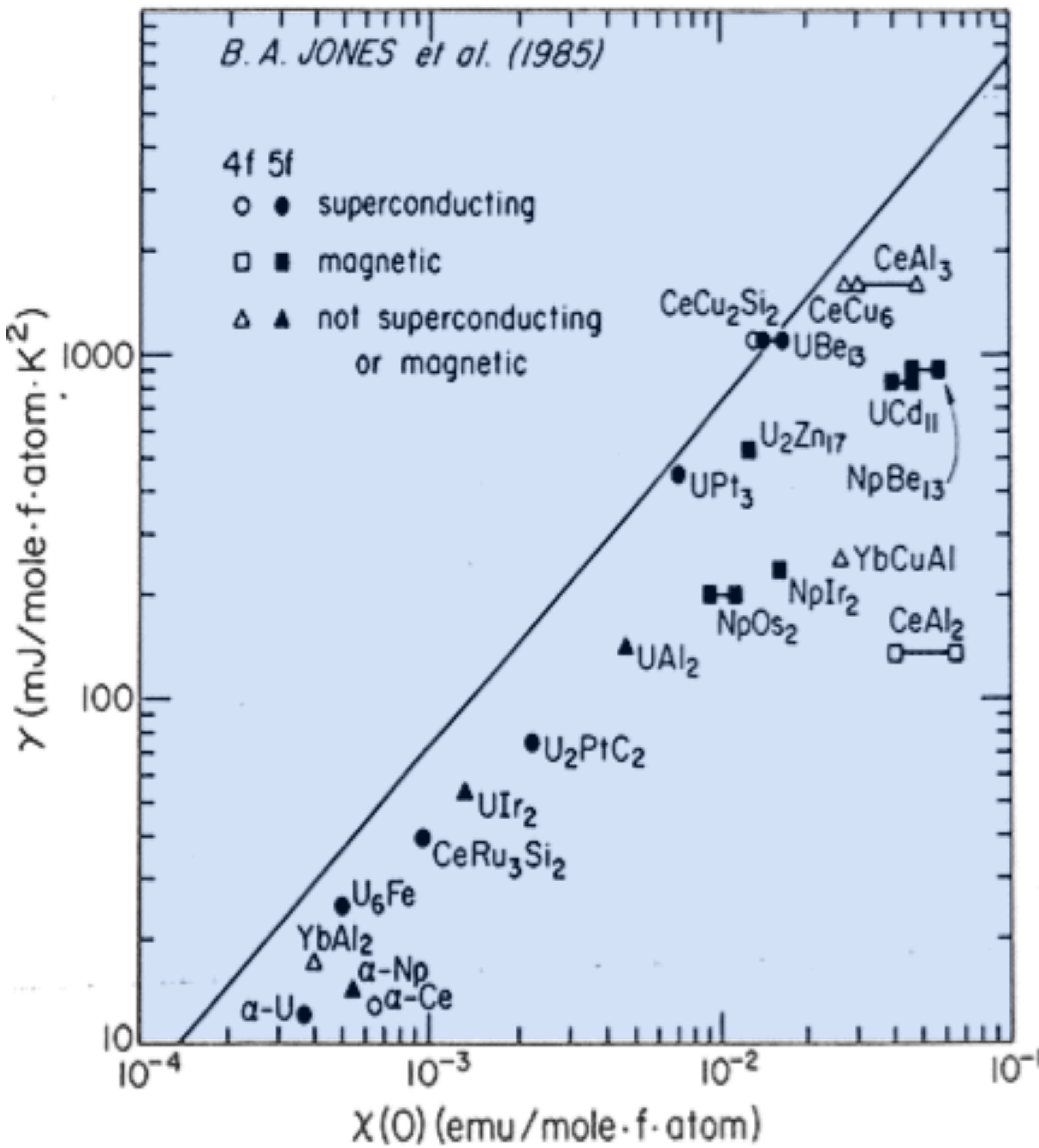
$$|e^-\rangle \qquad\qquad |qp^-\rangle$$

$$\frac{m^*}{m} = \frac{N(0)^*}{N(0)} = 1 + \frac{F_1^s}{3}$$

Landau, JETP 3, 920 (1957)

Heavy Fermions: magnetically polarizable Landau Fermi liquids.

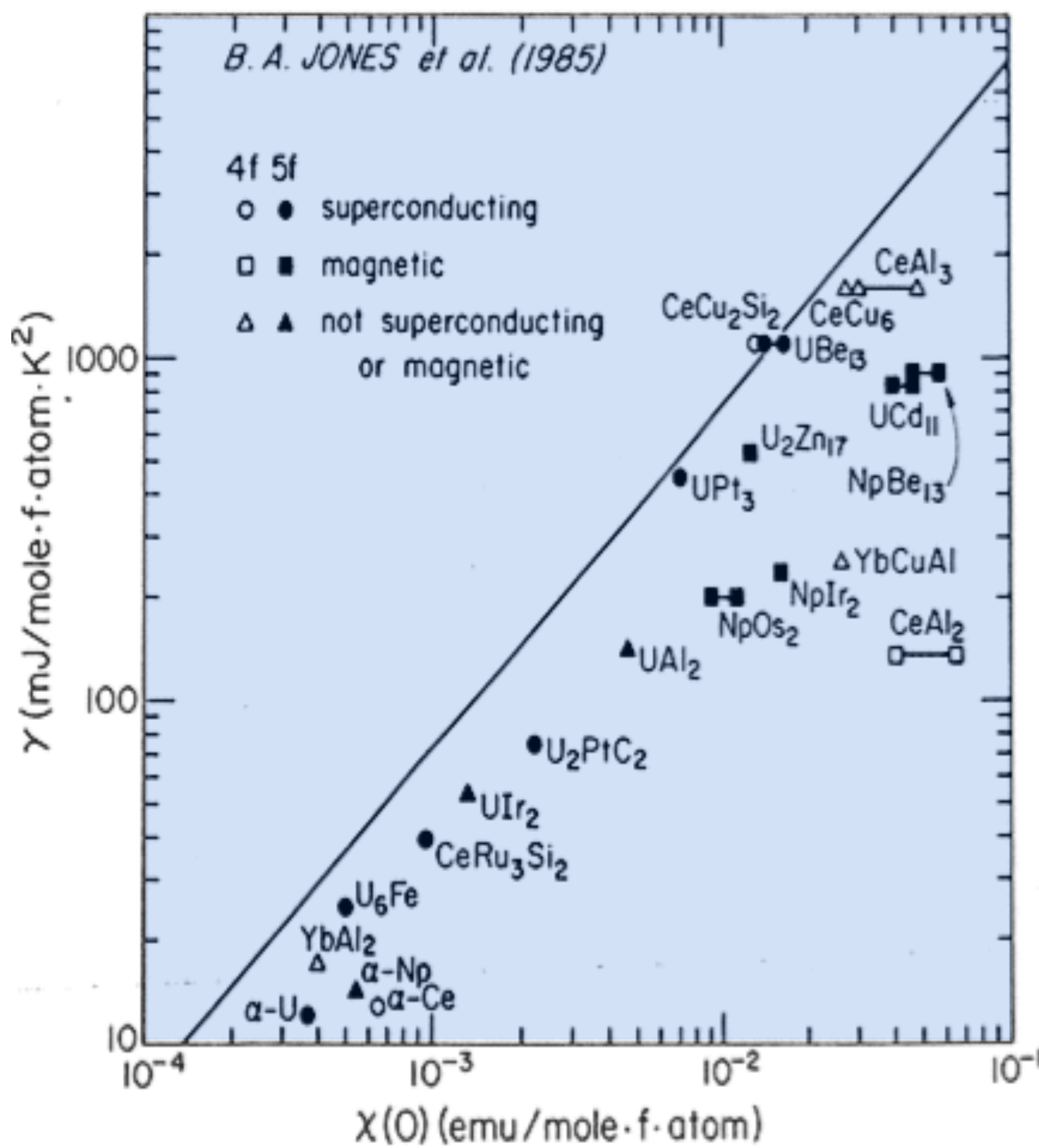
$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$



Heavy Fermions: magnetically polarizable Landau Fermi liquids.

$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

$$\gamma = \mathrm{Lim}_{T\to 0}\left(\frac{C_V}{T}\right) = \frac{\pi^2 k_B^2}{3} N(0)^*.$$

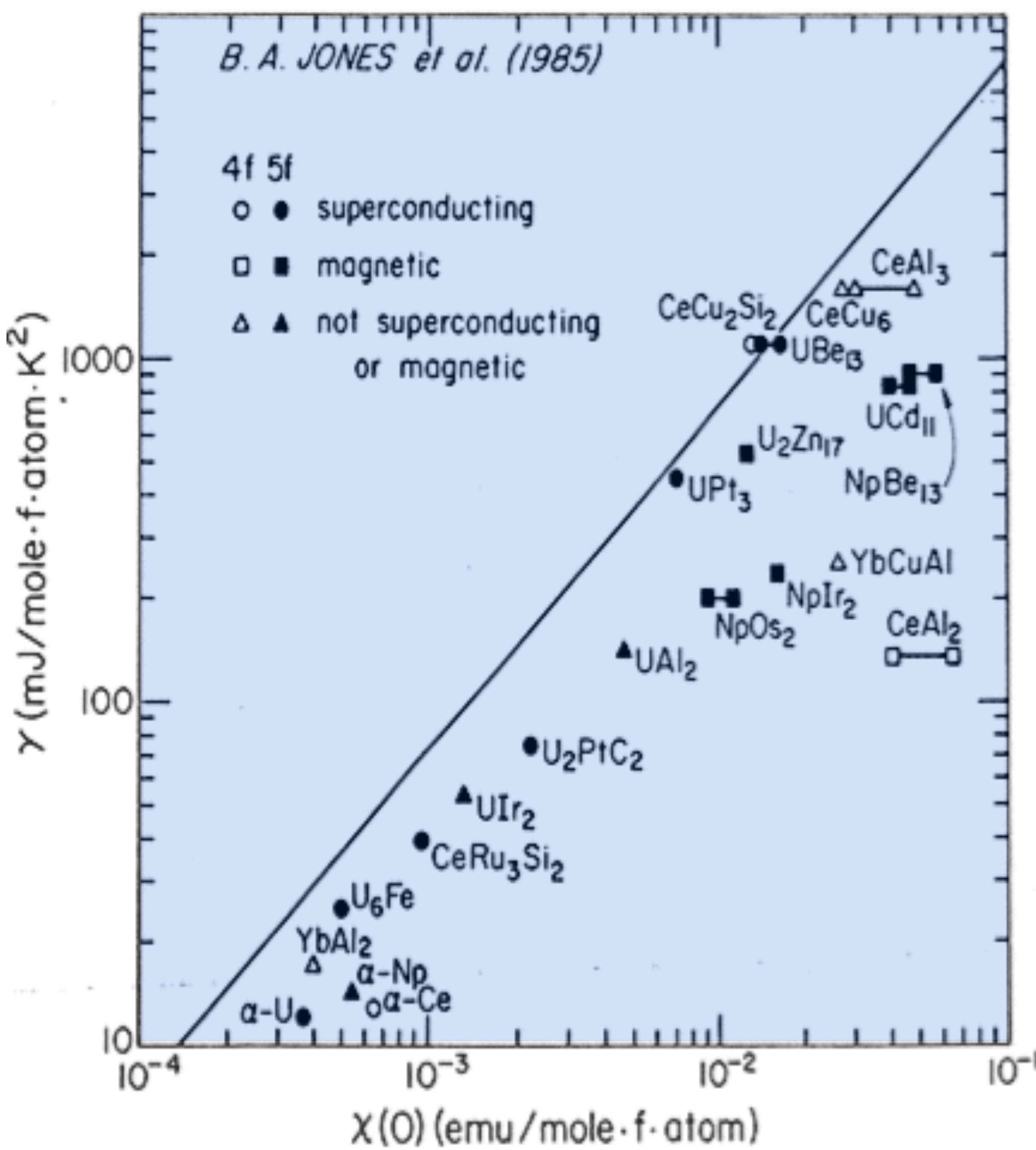


Heavy Fermions: magnetically polarizable Landau Fermi liquids.

$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

$$\gamma = \mathrm{Lim}_{T\to 0}\left(\frac{C_V}{T}\right) = \frac{\pi^2 k_B^2}{3} N(0)^*.$$

$$\chi = \frac{\mu_B^2 N^*(0)}{1 + F_0^a}$$



Heavy Fermions: magnetically polarizable Landau Fermi liquids.

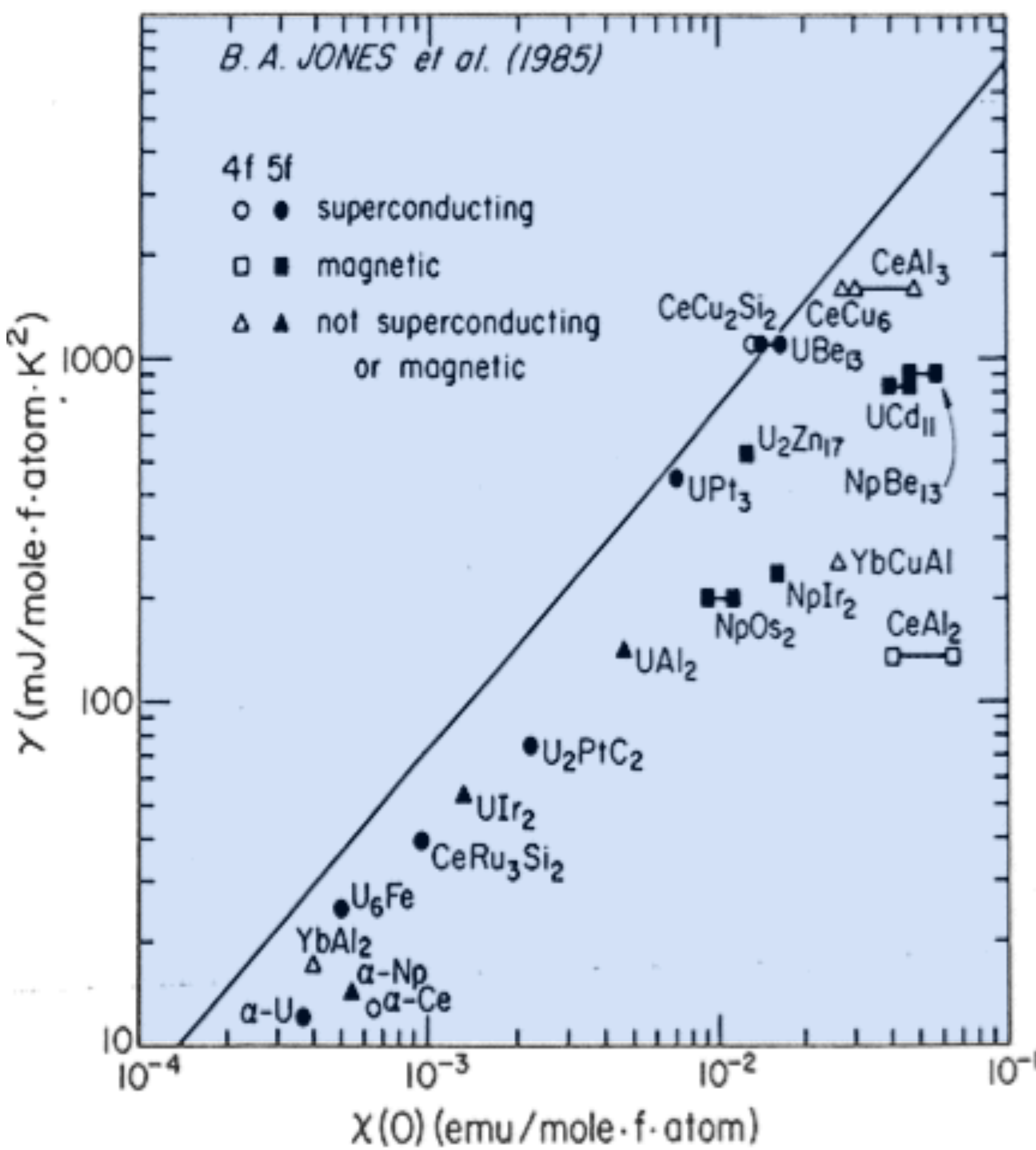
$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

$$\gamma = \mathrm{Lim}_{T\to 0}\left(\frac{C_V}{T}\right) = \frac{\pi^2 k_B^2}{3} N(0)^*.$$

$$\chi = \frac{\mu_B^2 N^*(0)}{1+F_0^a}$$

$$W = \frac{\chi}{\gamma} = 3\left(\frac{\mu_{\mathrm{B}}}{2\pi k_B}\right)^2 \frac{1}{1+F_0^a}$$

"Wilson" or "Sommerfeld" ratio.



Heavy Fermions: magnetically polarizable Landau Fermi liquids.

$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

$$\gamma = \mathrm{Lim}_{T\to 0}\left(\frac{C_V}{T}\right) = \frac{\pi^2 k_B^2}{3} N(0)^*.$$

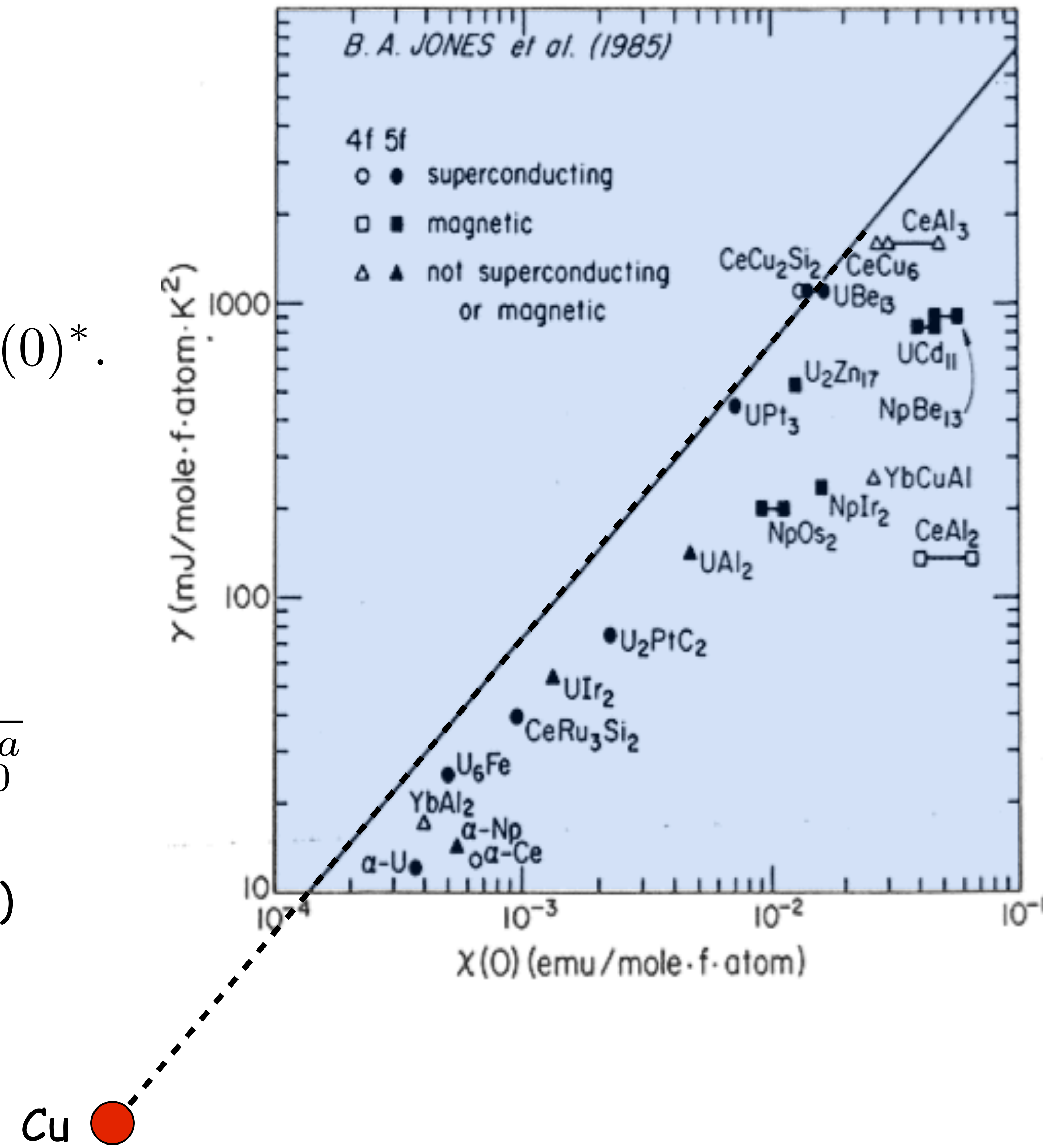
$$\chi = \frac{\mu_B^2 N^*(0)}{1+F_0^a}$$

$$W = \frac{\chi}{\gamma} = 3\left(\frac{\mu_\mathrm{B}}{2\pi k_B}\right)^2 \frac{1}{1+F_0^a}$$

"Wilson" or "Sommerfeld" ratio.

eg Cu vs $CeCu_6$ (copper, spin doped)

γCu ~ 1 mJ/mol/K^2,



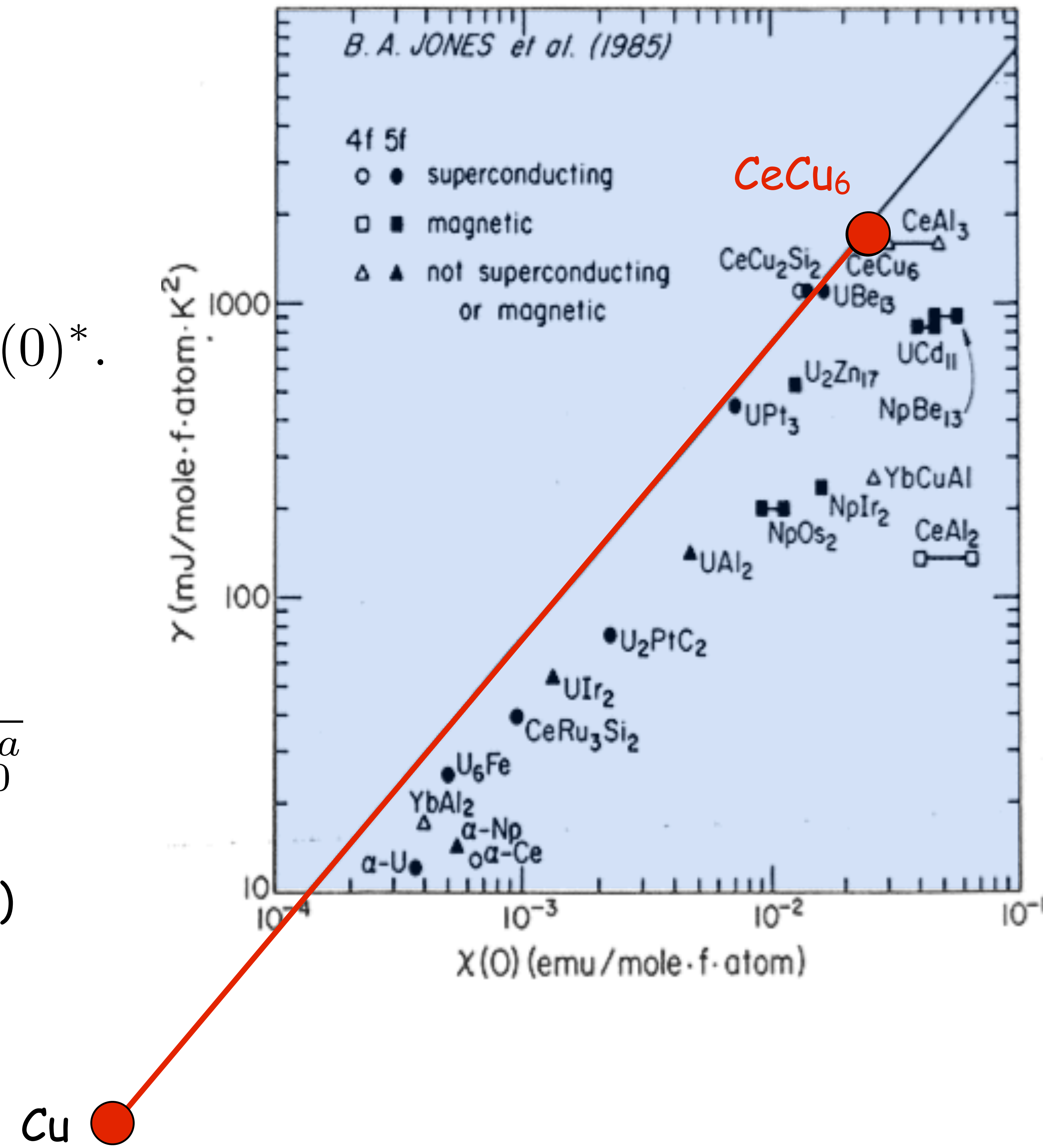
Heavy Fermions: magnetically polarizable Landau Fermi liquids.

$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

$$\gamma = \mathrm{Lim}_{T\to 0}\left(\frac{C_V}{T}\right) = \frac{\pi^2 k_B^2}{3} N(0)^*.$$

$$\chi = \frac{\mu_B^2 N^*(0)}{1 + F_0^a}$$

$$W = \frac{\chi}{\gamma} = 3\left(\frac{\mu_{\rm B}}{2\pi k_B}\right)^2 \frac{1}{1+F_0^a}$$

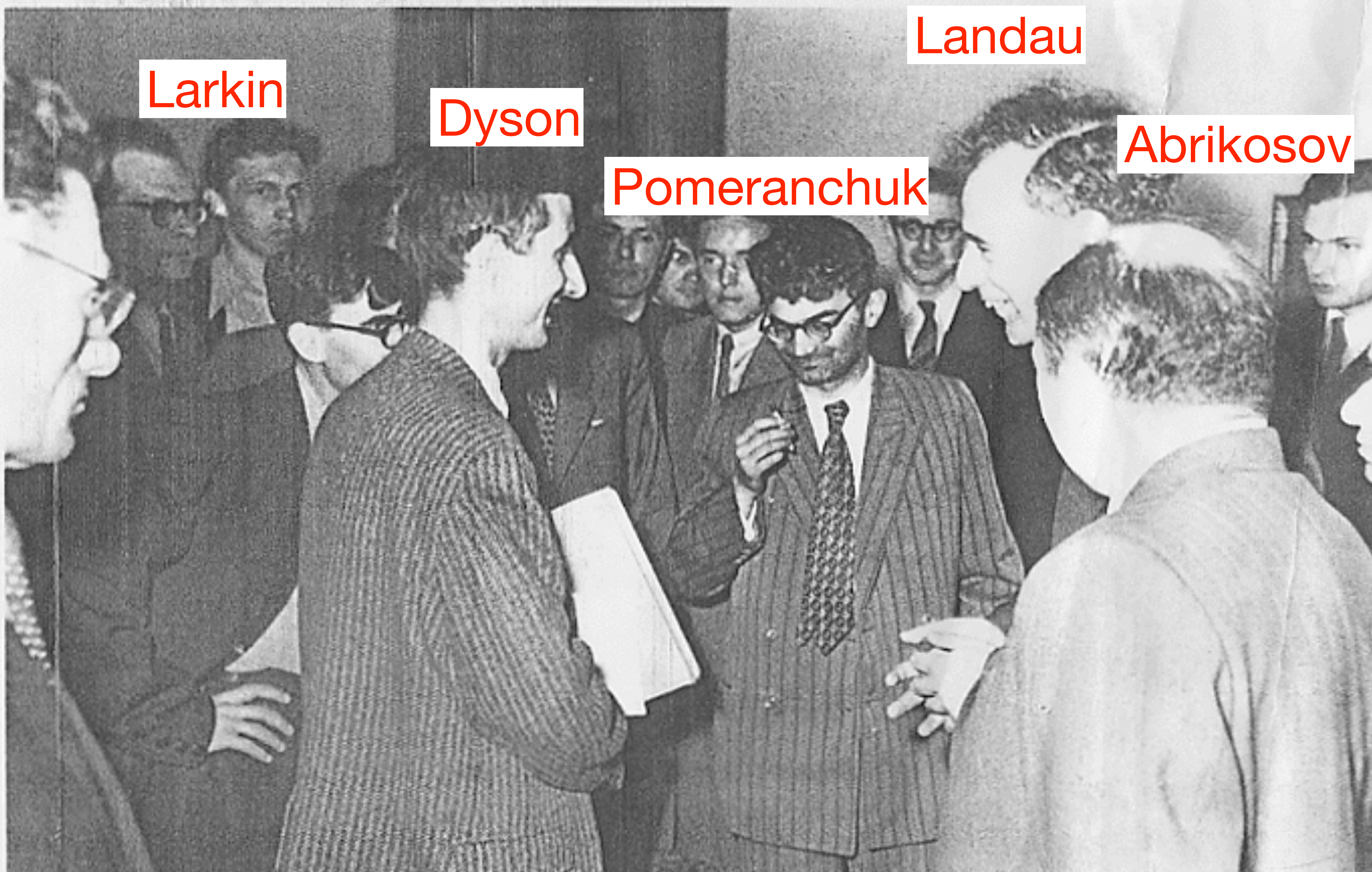


eg Cu vs $CeCu_6$ (copper, spin doped)
γCu ~ 1 mJ/mol/K^2,
$\Upsilon[CeCu_6]$ ~ 1000 mJ/mol/K^2,

m^*/m_e ~ 1000

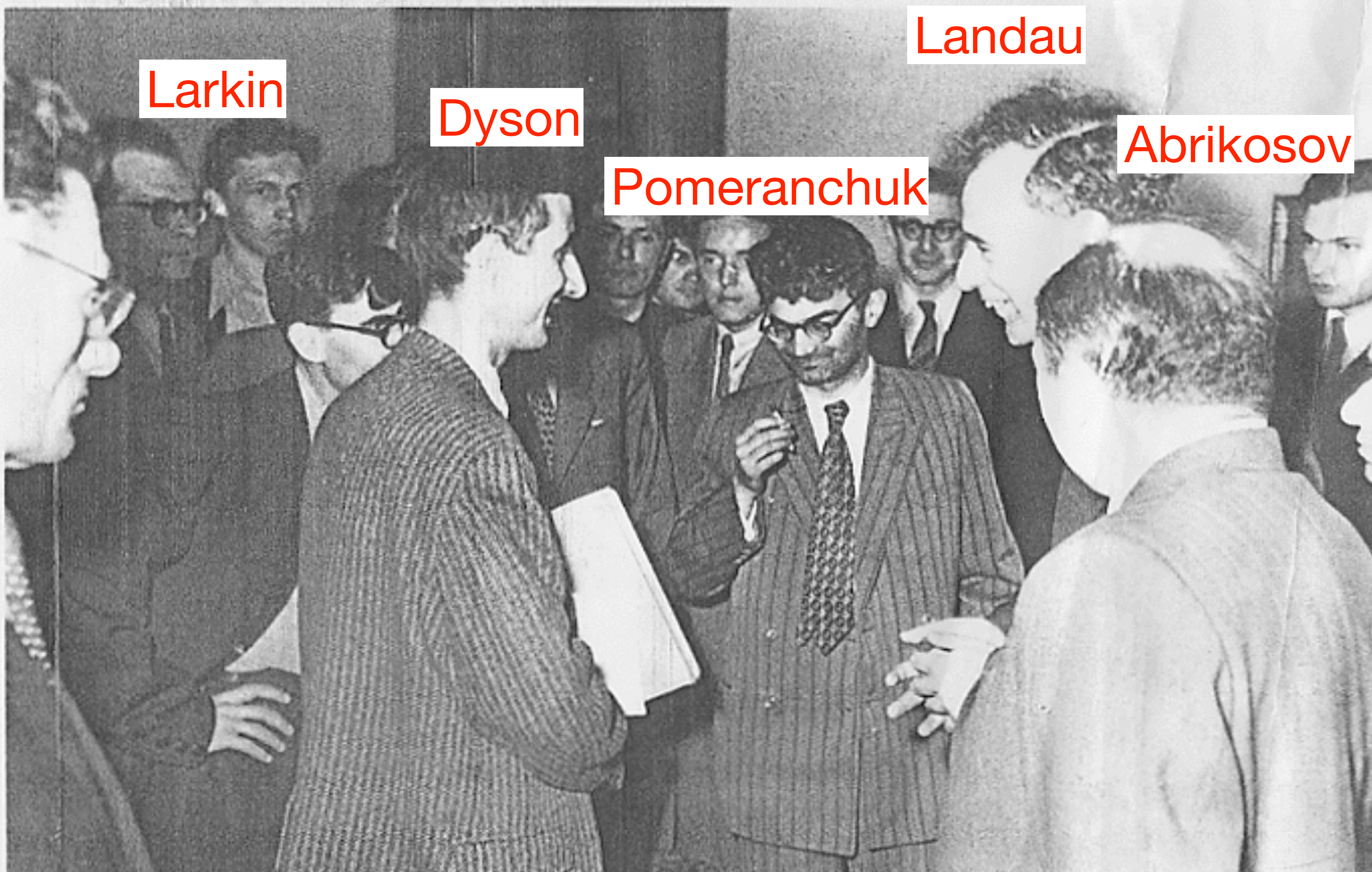
20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.

20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.



20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.

0 Fermi Liquid Adiabaticity Landau Fermi Liquid $X \sim U/t$

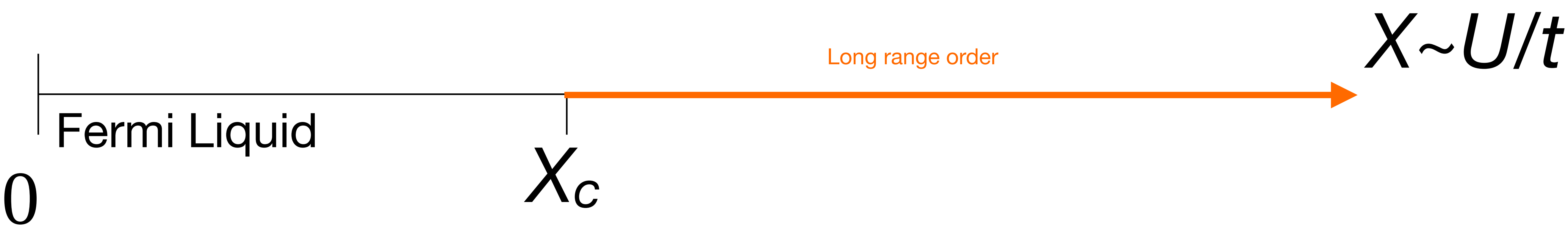


20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.

0 Fermi Liquid — Adiabaticity — Landau Fermi Liquid $X \sim U/t$

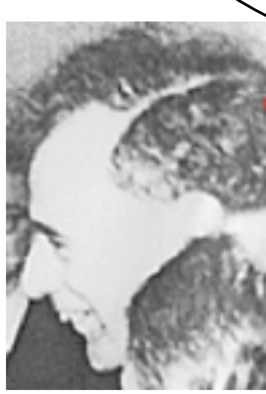
20. Moscow, 1956. Freeman Dyson (front, left), chuk and Lev Landau.

What happens when the interaction becomes too large?



What happens when the interaction becomes too large?

Wigner/ Landau 1934/36



"Electrons order"

$X \sim U/t$

Long range order

Fermi Liquid

0 X_c

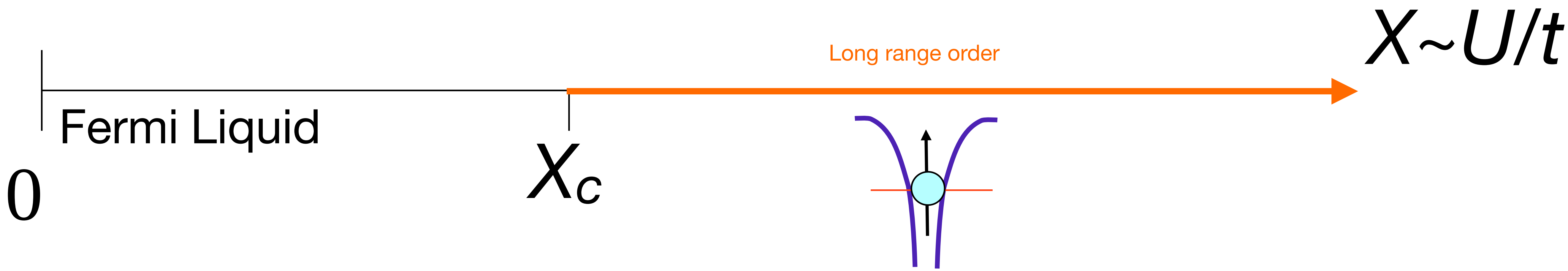
What happens when the interaction becomes too large?

Wigner/ Landau 1934/36

Peierls/Mott 1939

“Electrons order”

“Electrons localize”



What happens when the interaction becomes too large?

Wigner/ Landau 1934/36

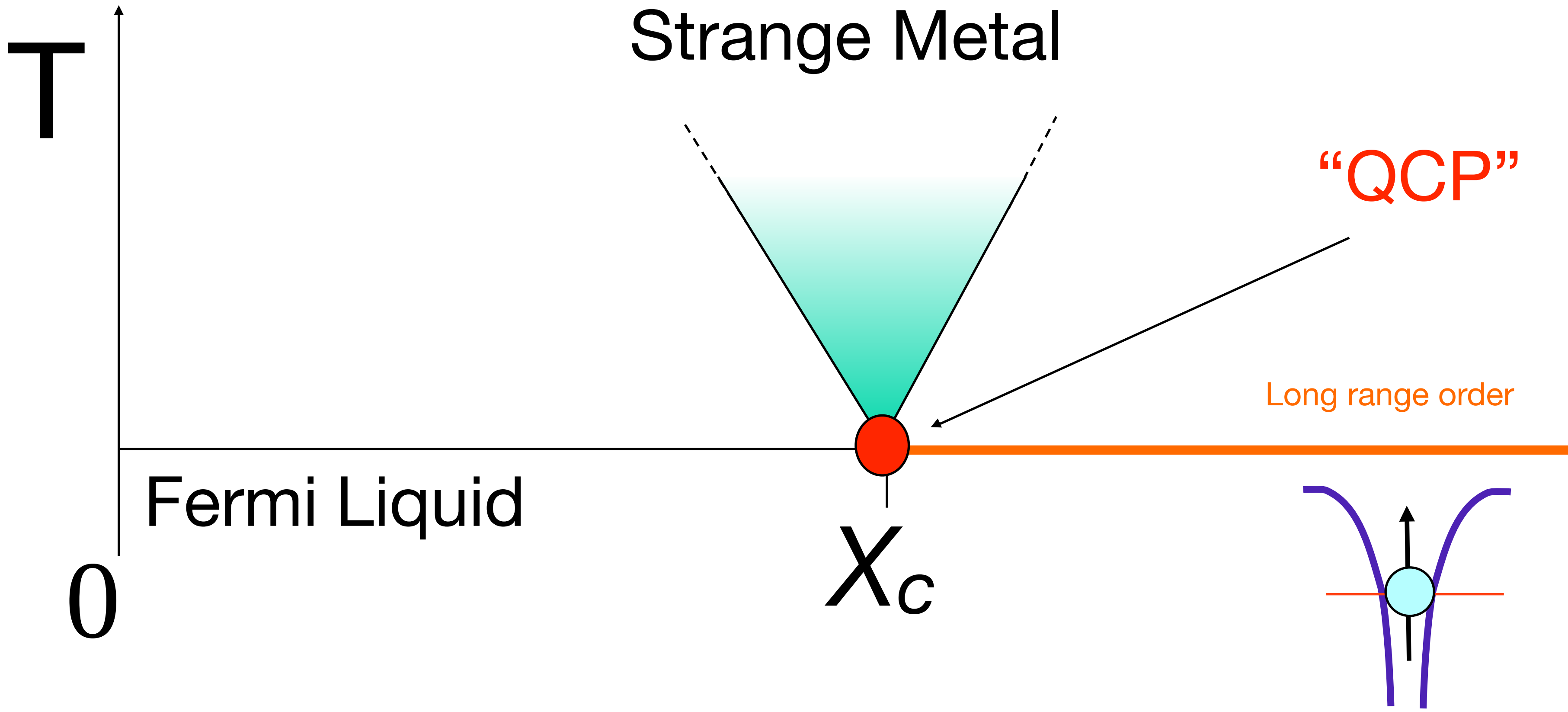
Peierls/Mott 1939

Anderson 1961

"Electrons order"

"Electrons localize"

"Moments form"



Hertz, 1976, Doniach, 1977

What happens when
the interaction
becomes too large?

Wigner/ Landau 1934/36

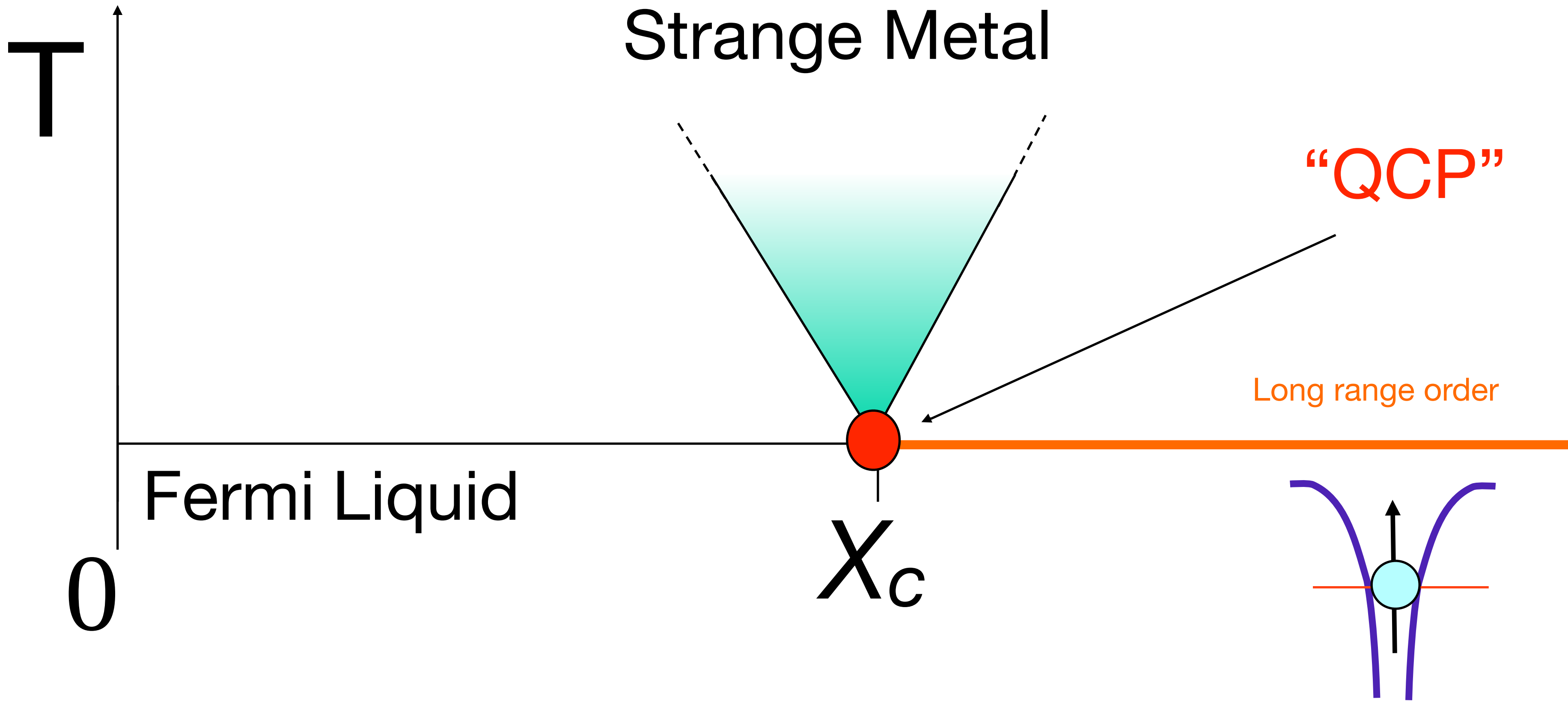
"Electrons order"

Peierls/Mott 1939

"Electrons localize"

Anderson 1961

"Moments form"



Hertz, 1976, Doniach, 1977

What happens when
the interaction
becomes too large?

Wigner/ Landau 1934/36

"Electrons order"

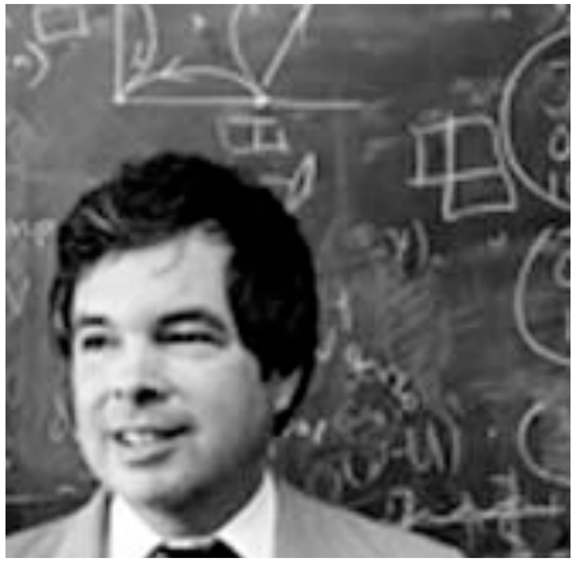
Peierls/Mott 1939

"Electrons localize"

Anderson 1961

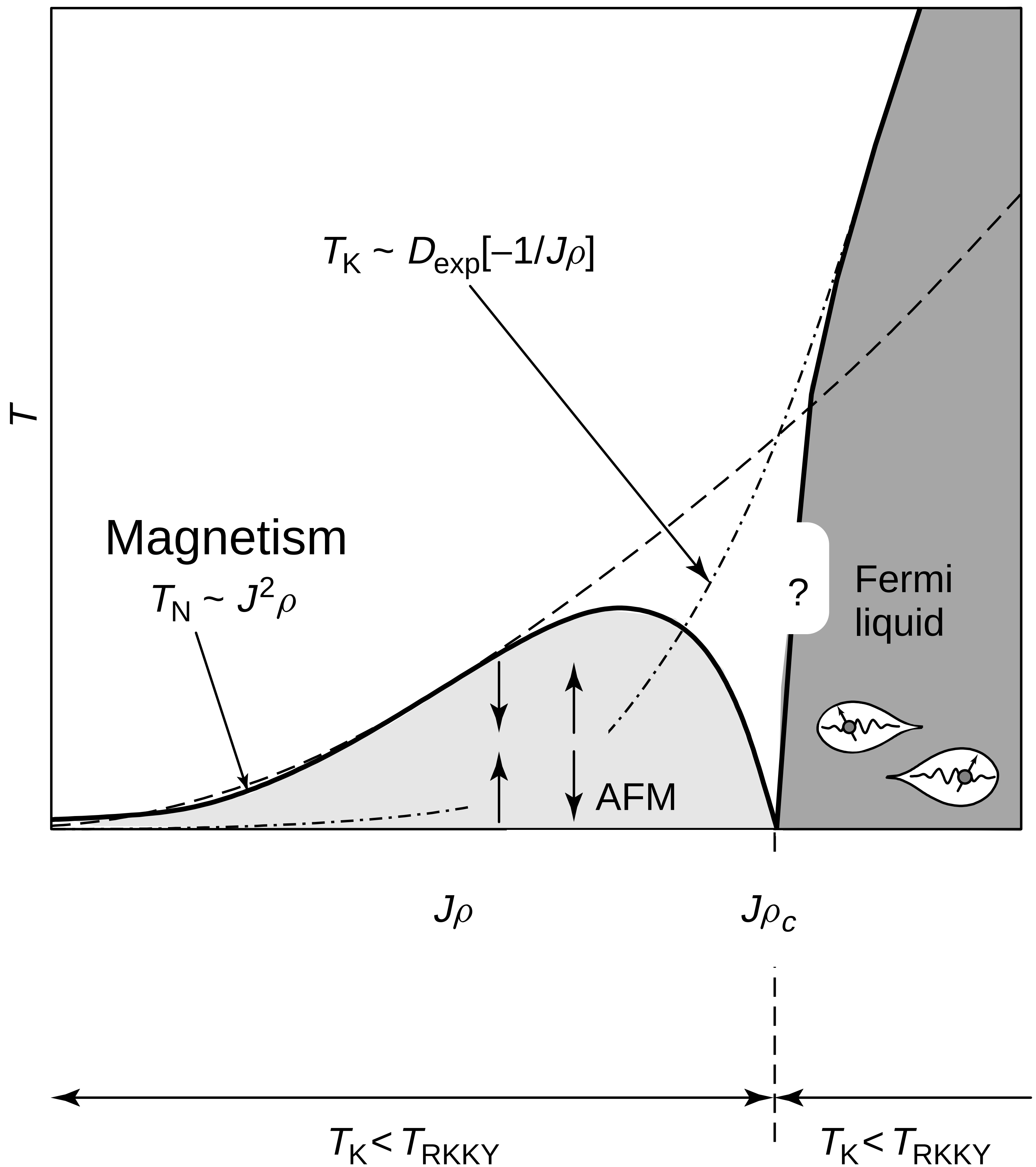
"Moments form"

Kenneth Wilson 1936-2013

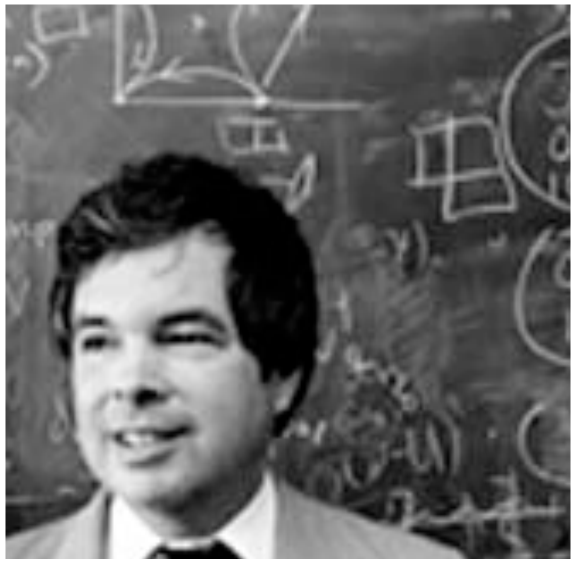


New Fixed Points

Mott, 1973
Doniach 1976

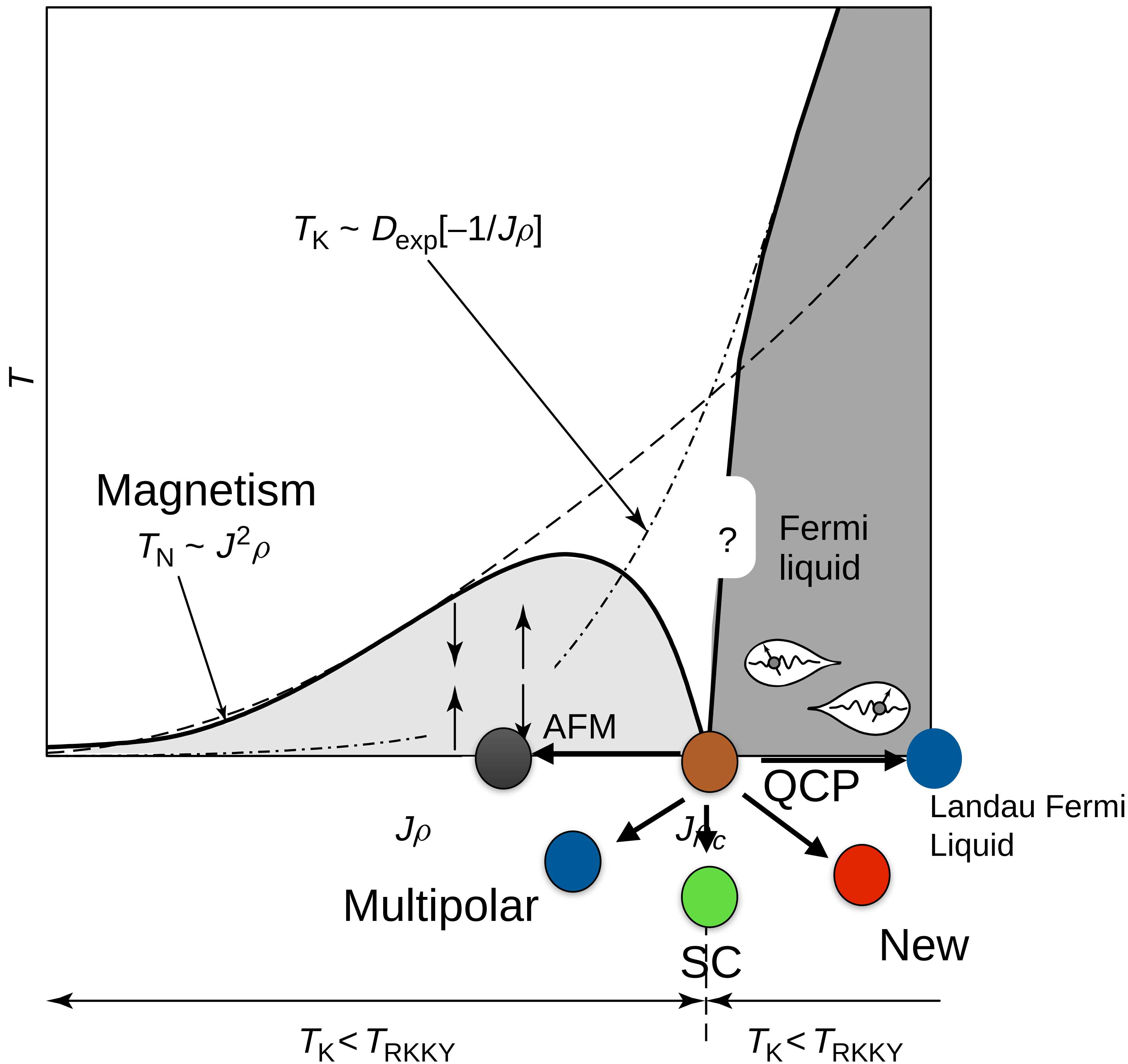


Wilson 1975

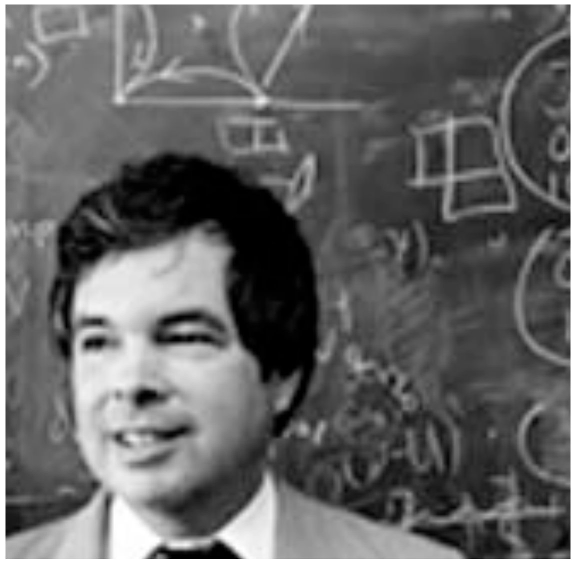


New Fixed Points

Mott, 1973
Doniach 1976

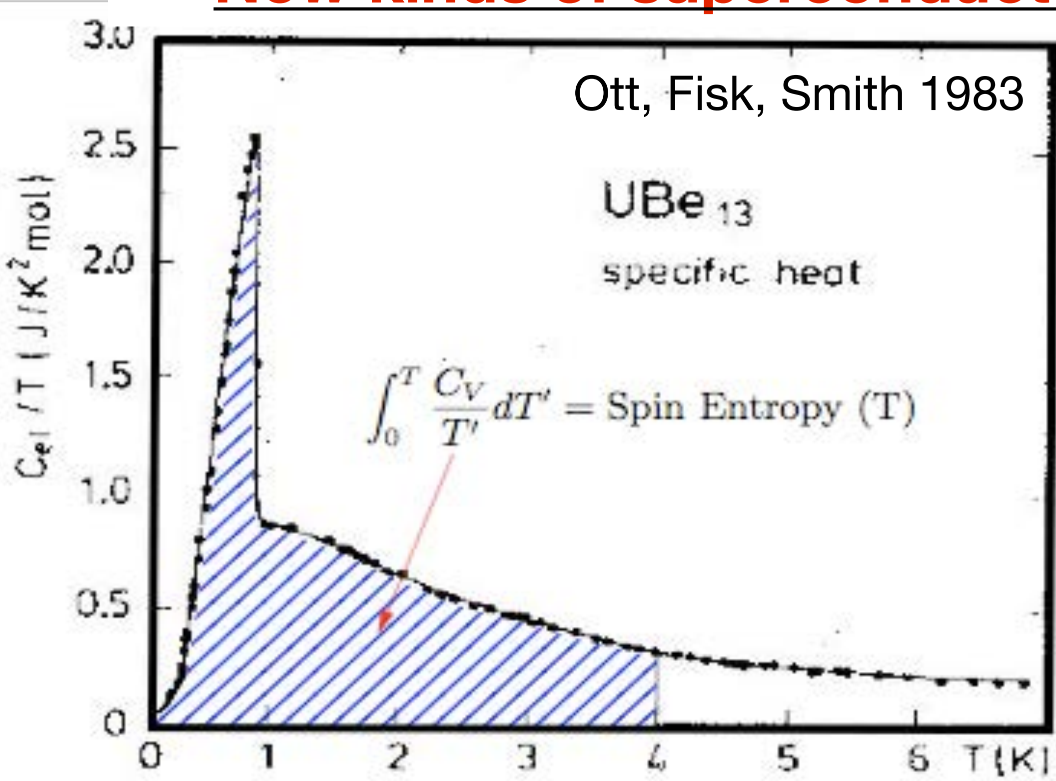


Wilson 1975



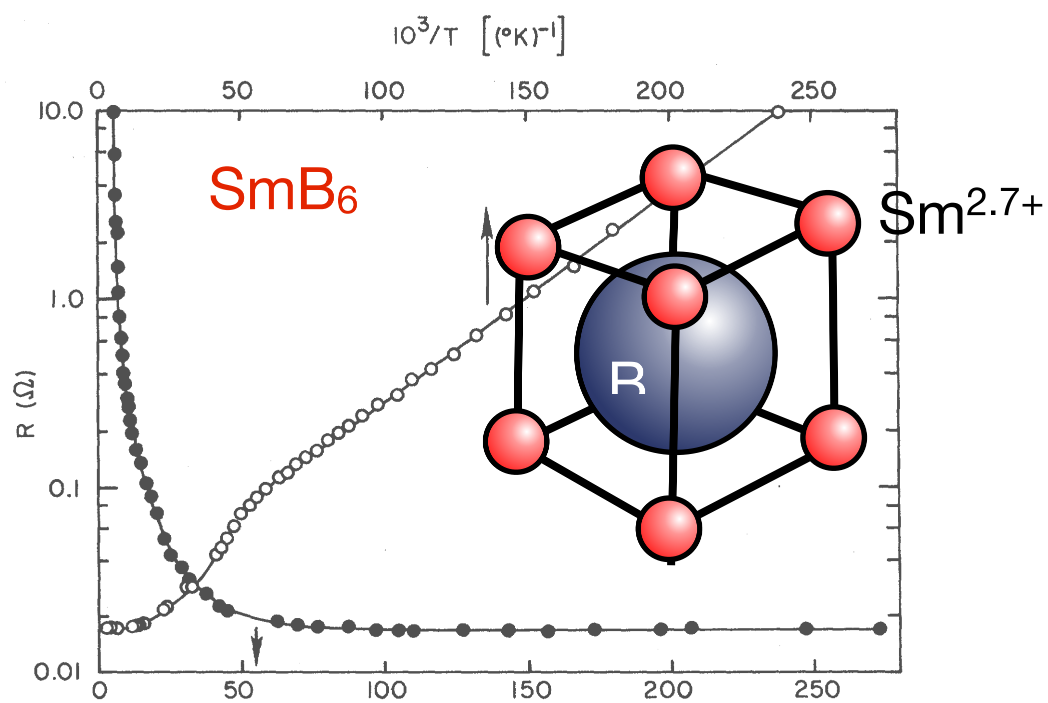
New Fixed Points

→ **New kinds of superconductor**

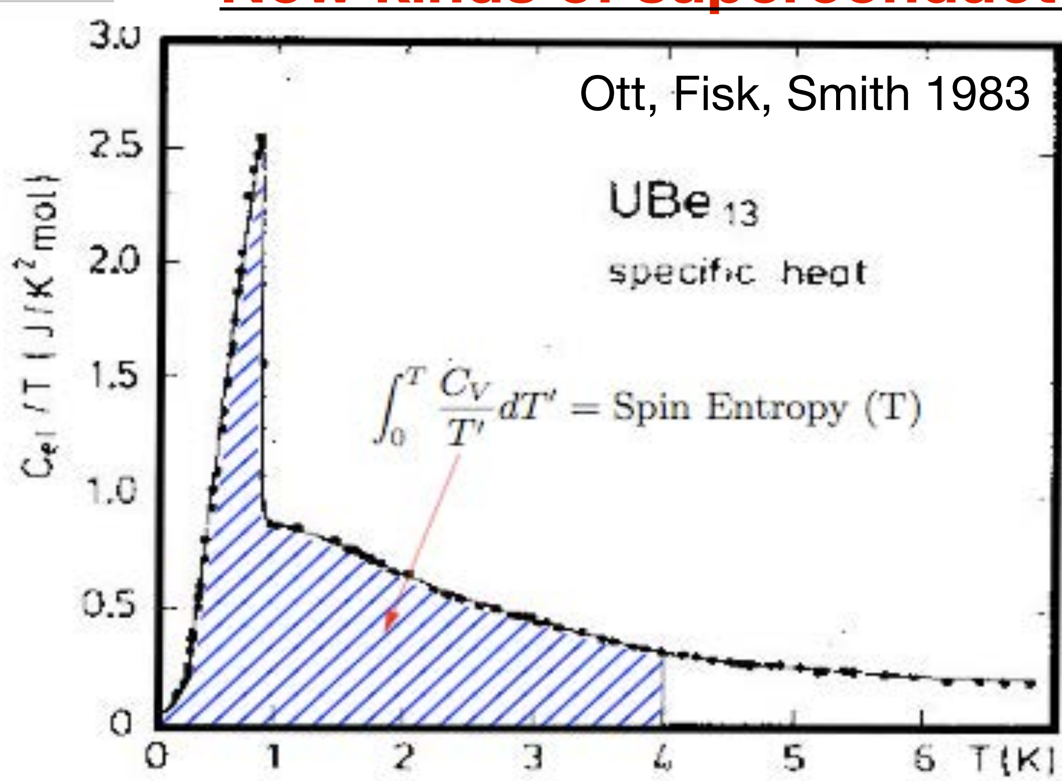


→ New kinds of insulator

Kondo Insulators

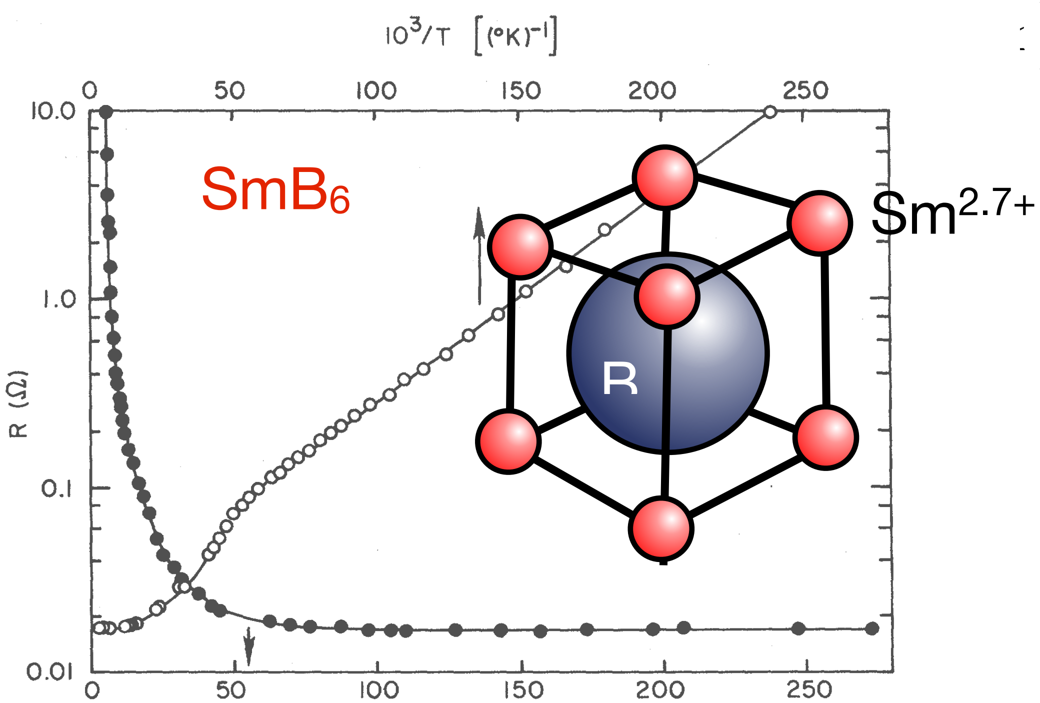


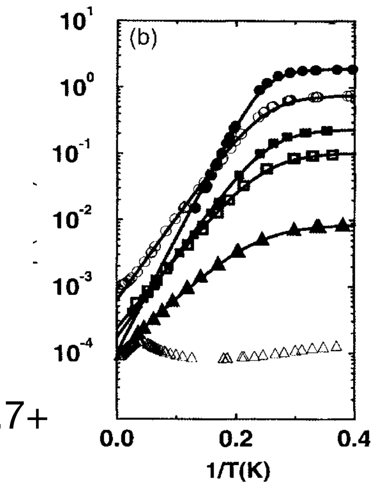
→ New kinds of superconductor



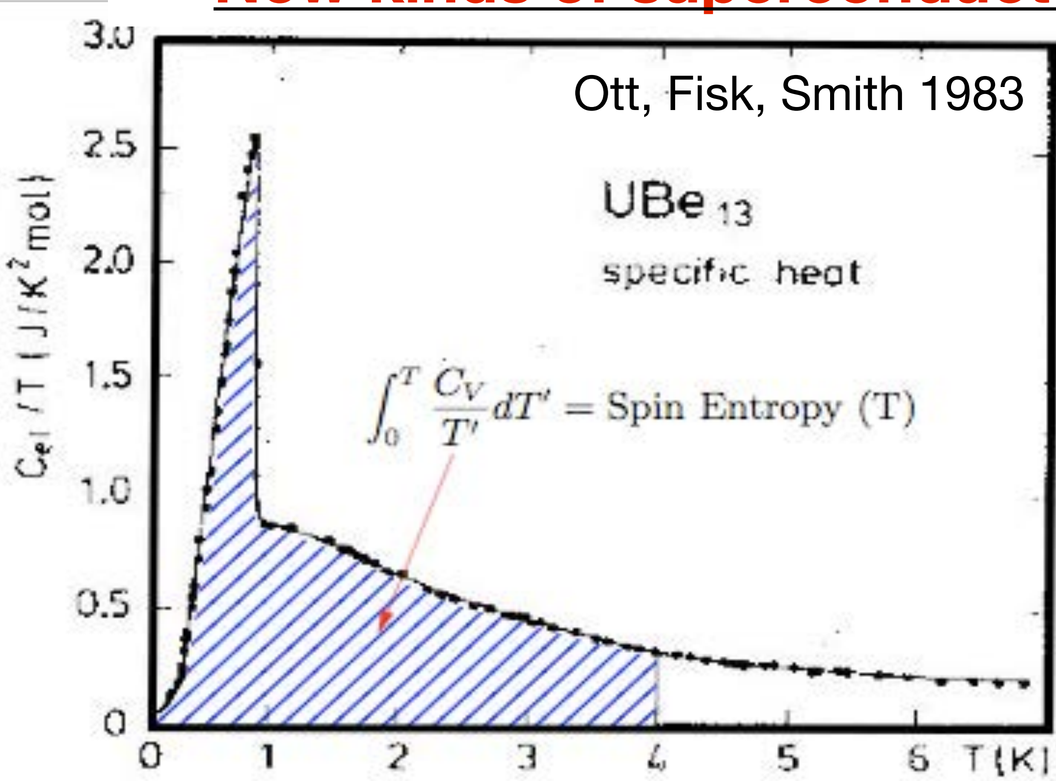
→ New kinds of insulator

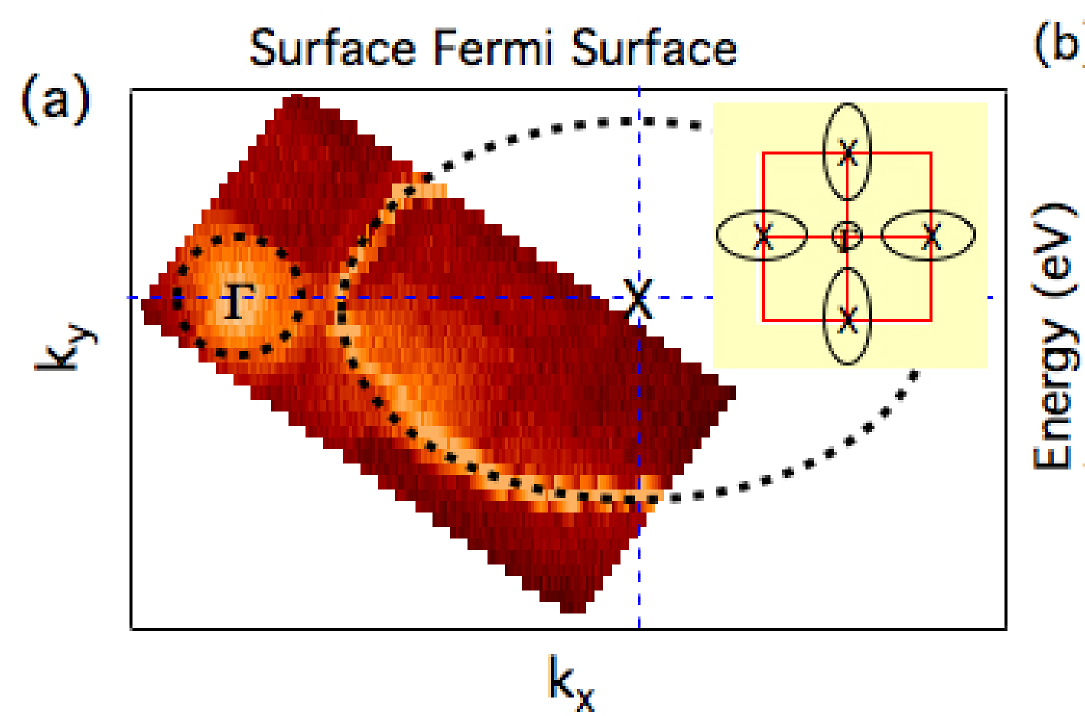
Topological Kondo Insulators





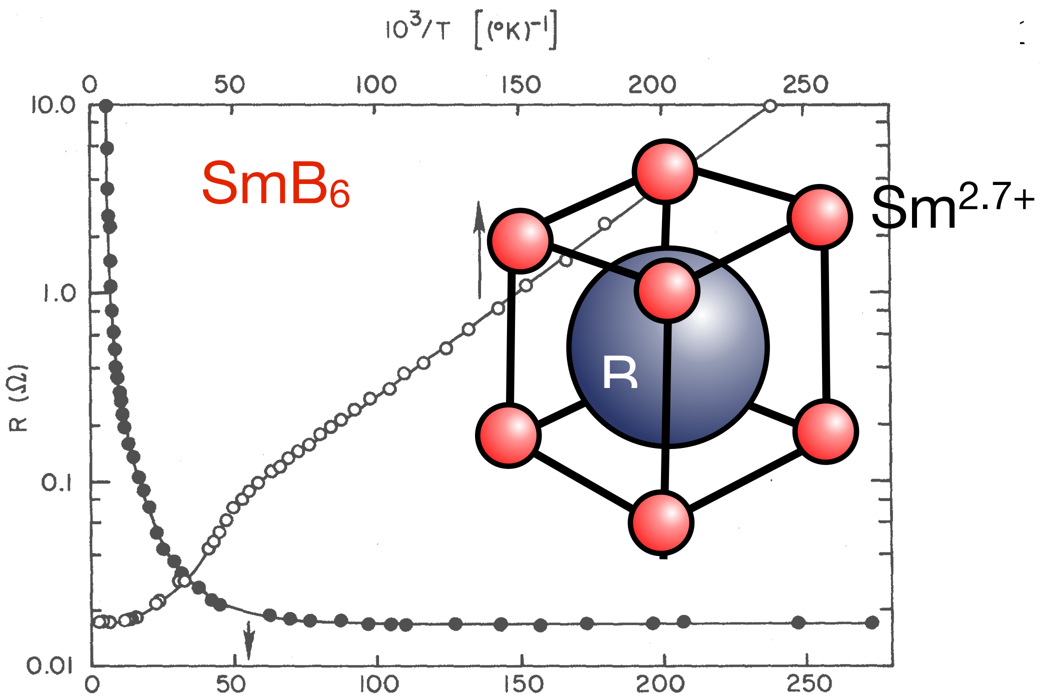
→ New kinds of superconductor

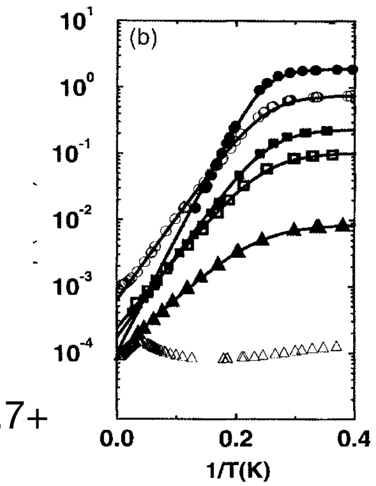




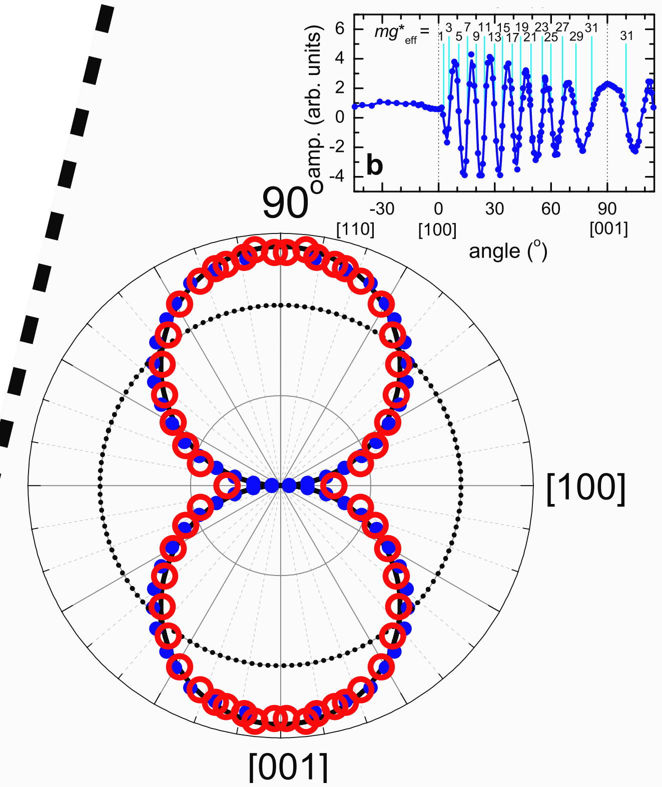
→ New kinds of insulator

Topological Kondo Insulators



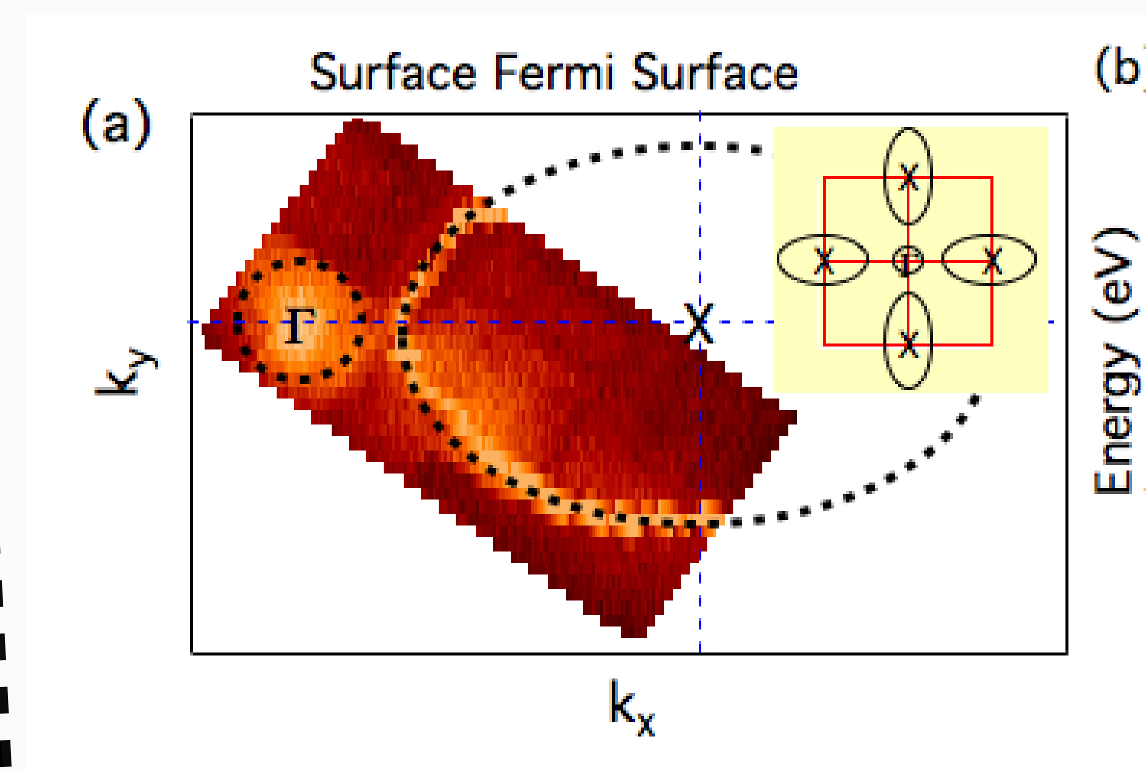


Altarawneh et al., (2012)

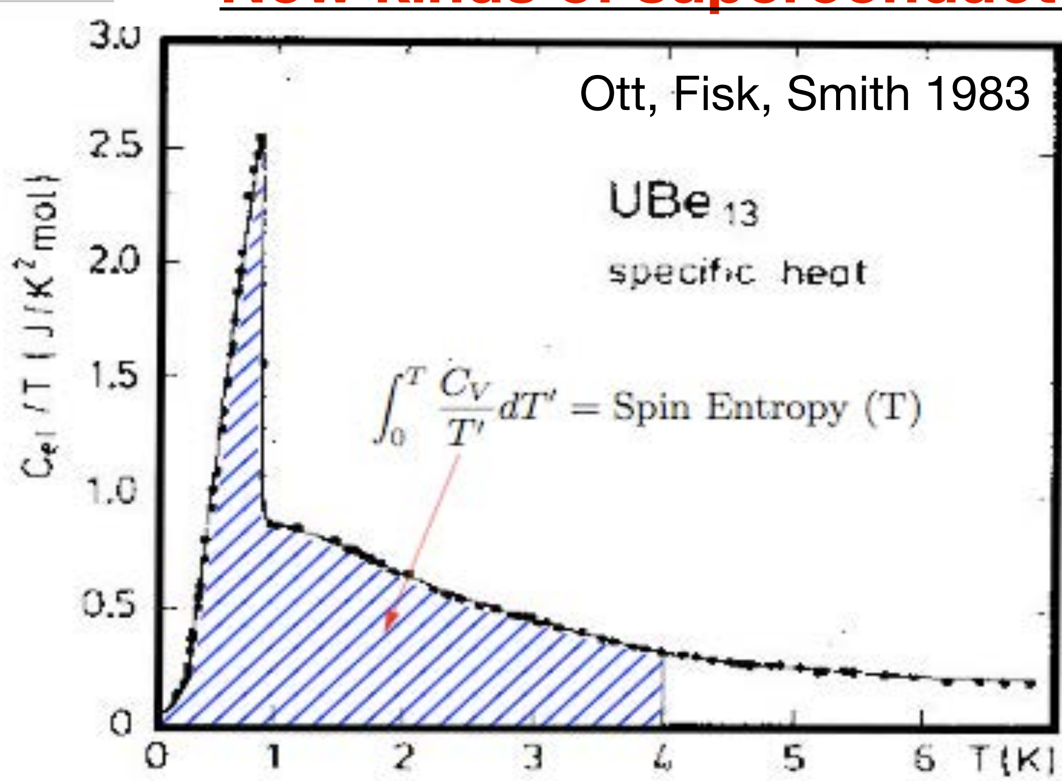


URu$_2$Si$_2$

→ New kinds of Electron Order

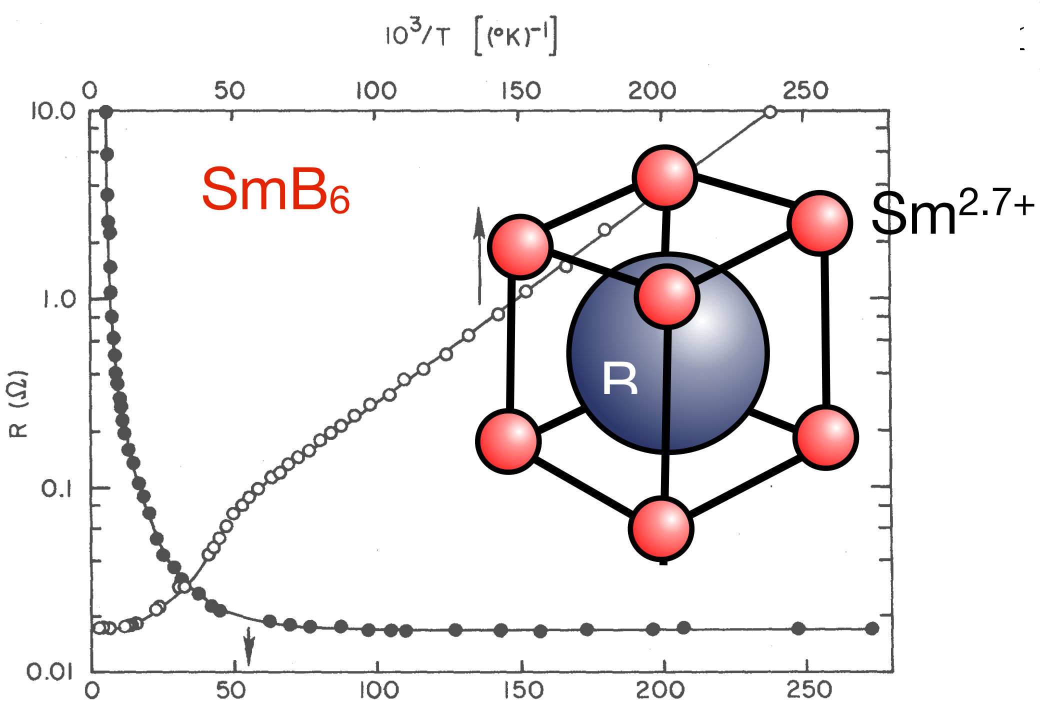


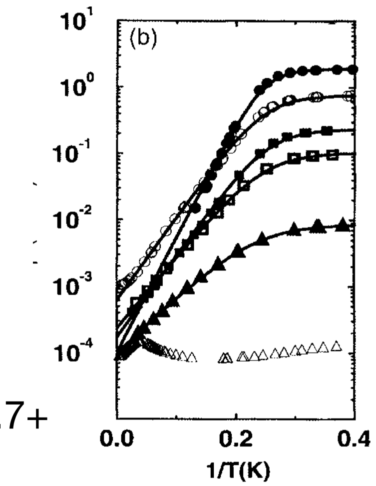
→ New kinds of superconductor



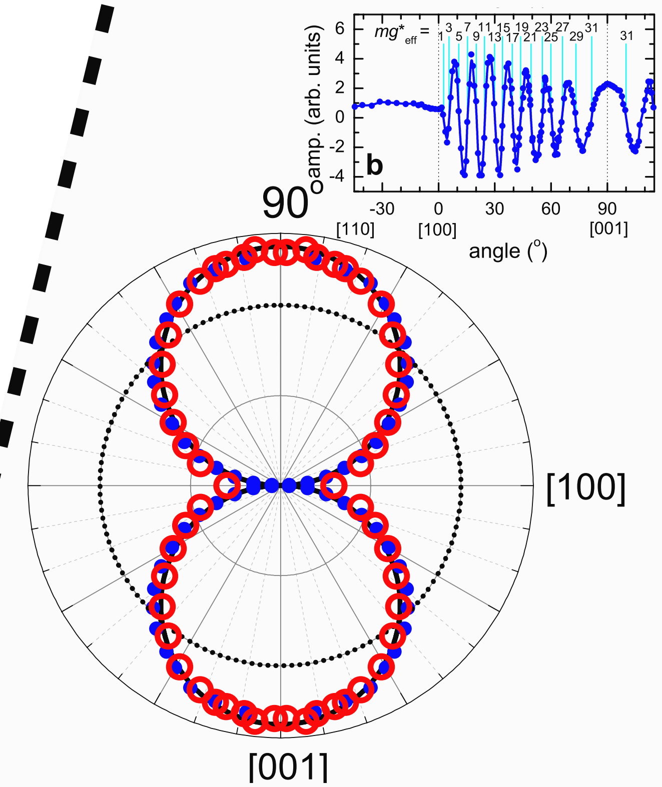
→ New kinds of insulator

Topological Kondo Insulators





Altarawneh et al., (2012)

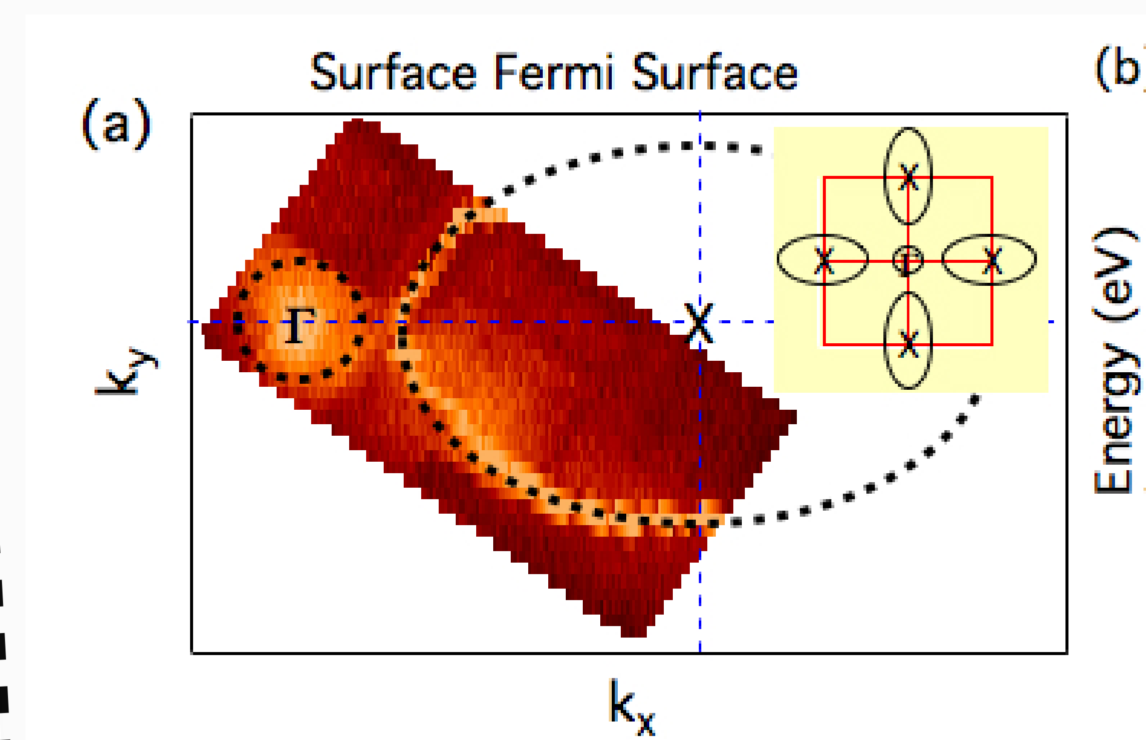


URu$_2$Si$_2$

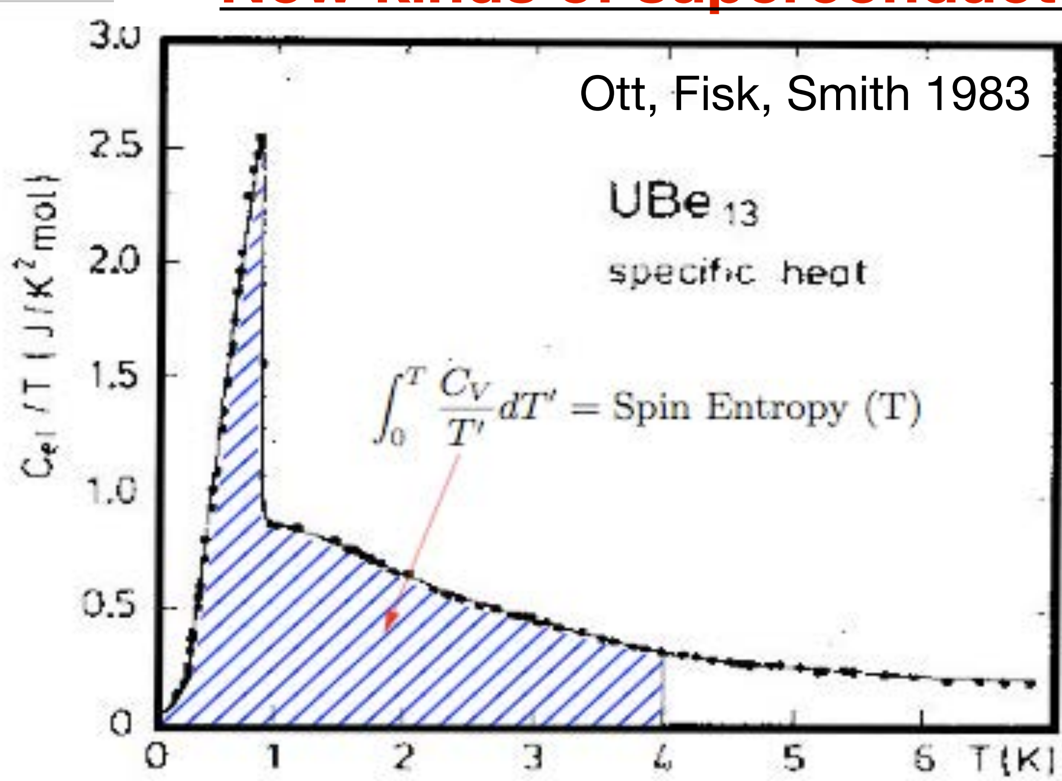
$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

Ising Electrons: *Hastatic order ?*

→ New kinds of Electron Order

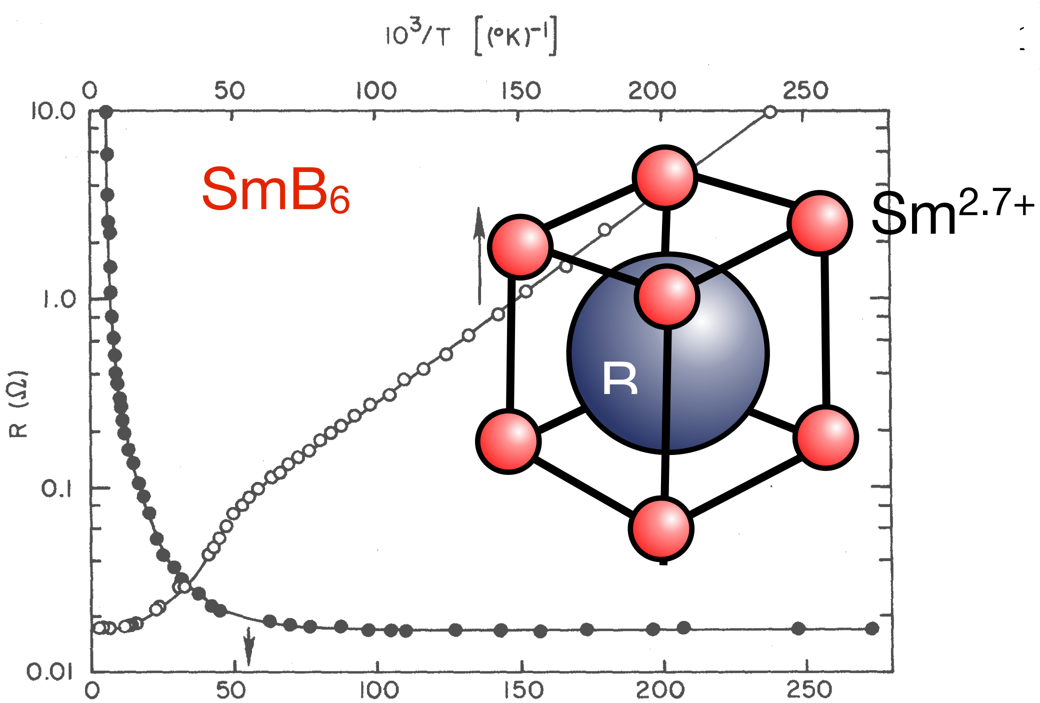


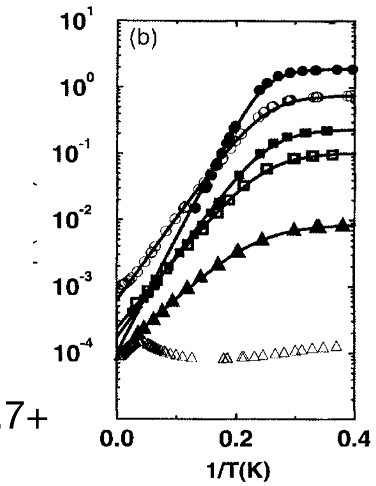
→ New kinds of superconductor



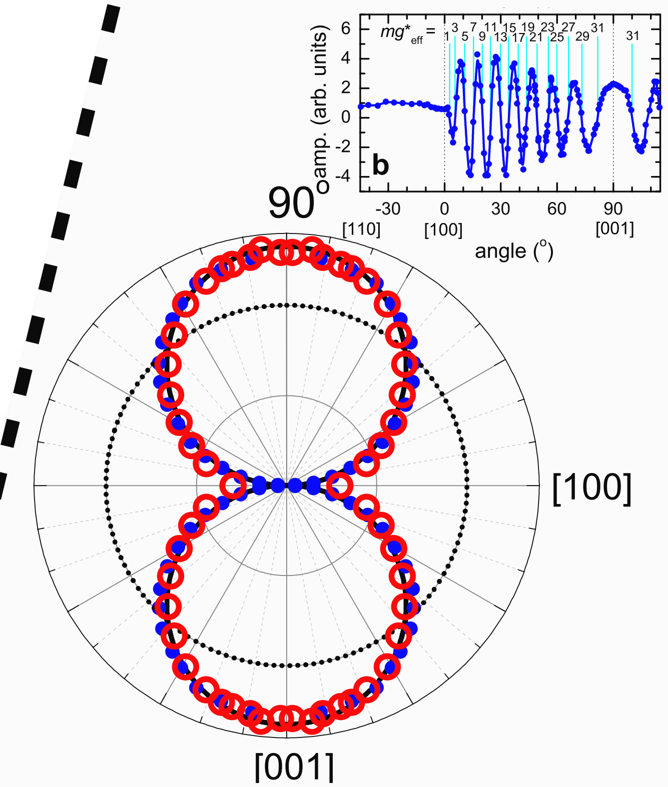
→ New kinds of insulator

Topological Kondo Insulators





Altarawneh et al., (2012)



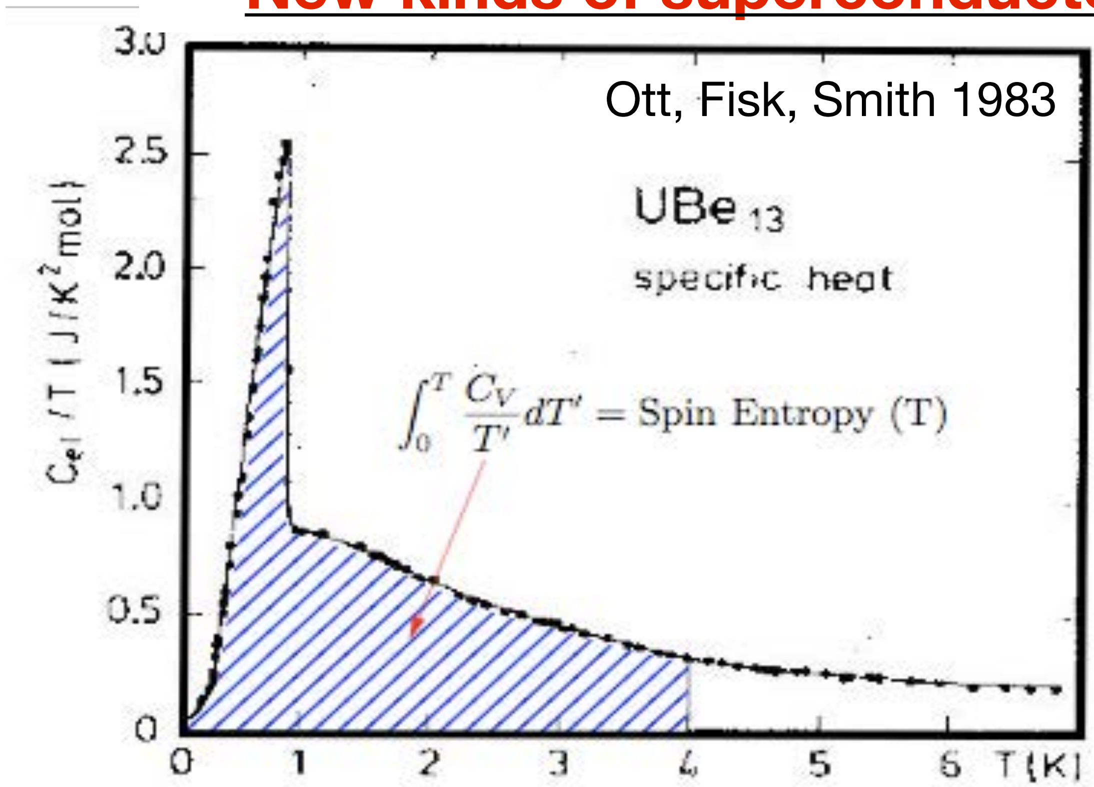
URu_2Si_2

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

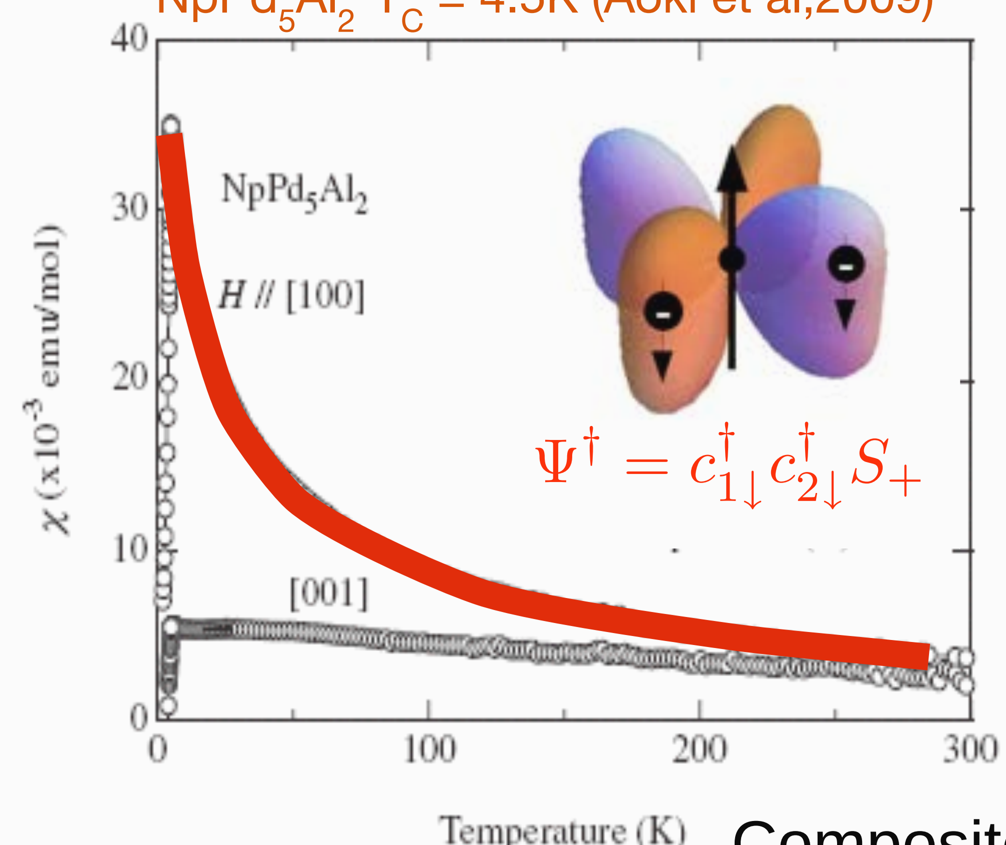
Ising Electrons: *Hastatic order ?*

→ New kinds of Electron Order

→ New kinds of superconductor



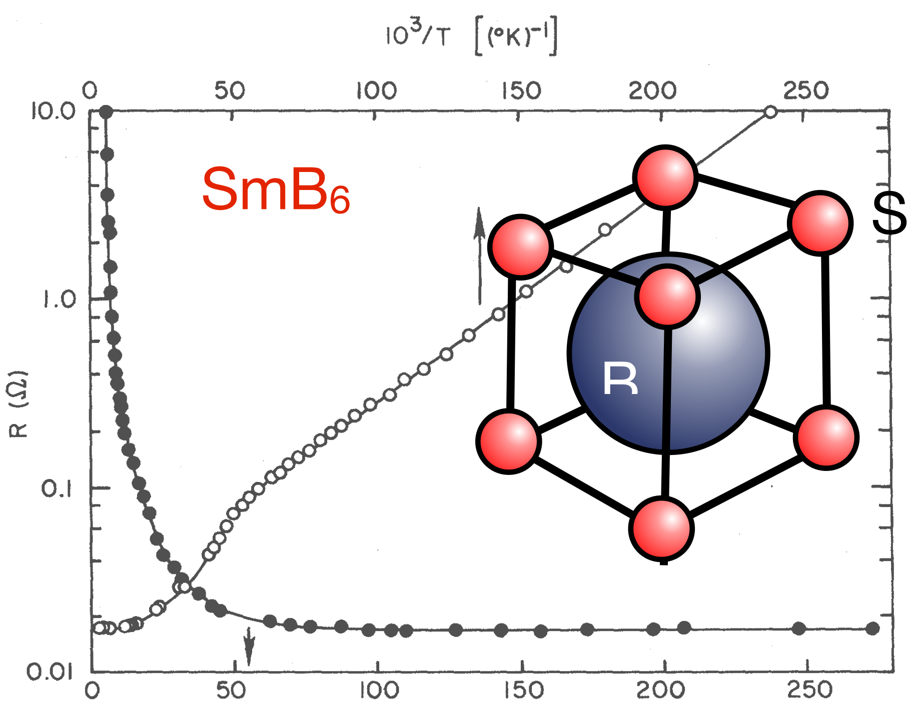
$NpPd_5Al_2$ T_C = 4.5K (Aoki et al,2009)

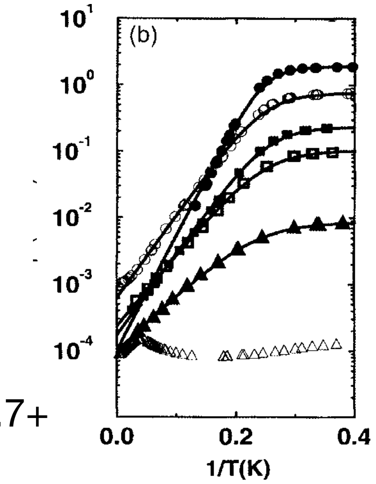


Composite Pairing

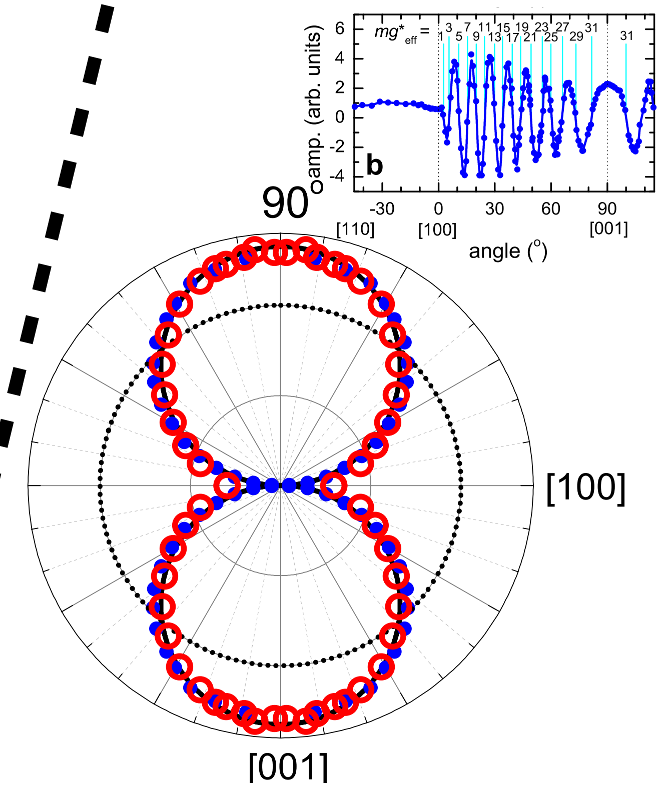
→ New kinds of insulator

Topological Kondo Insulators





Altarawneh et al., (2012)



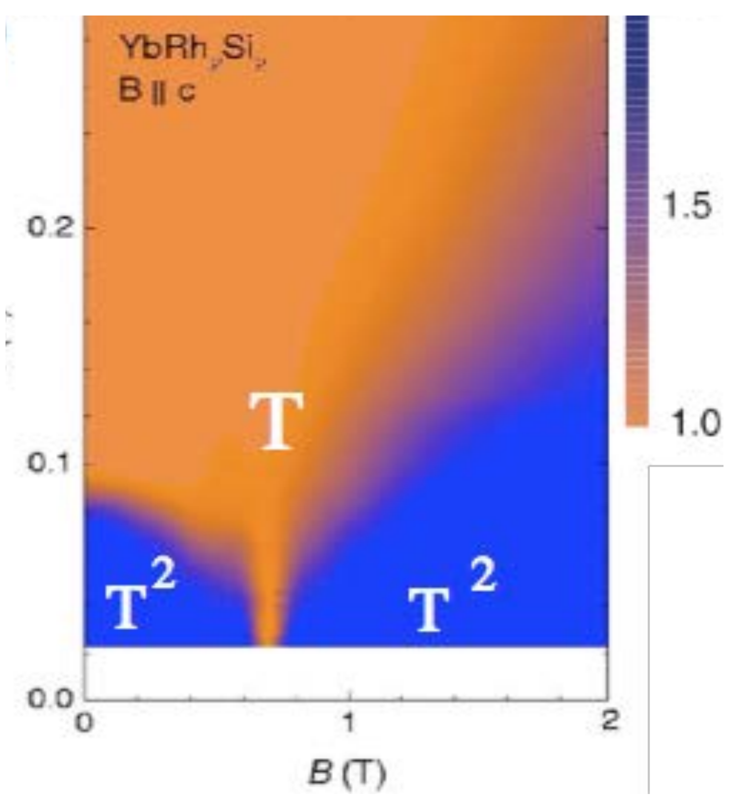
URu$_2$Si$_2$

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

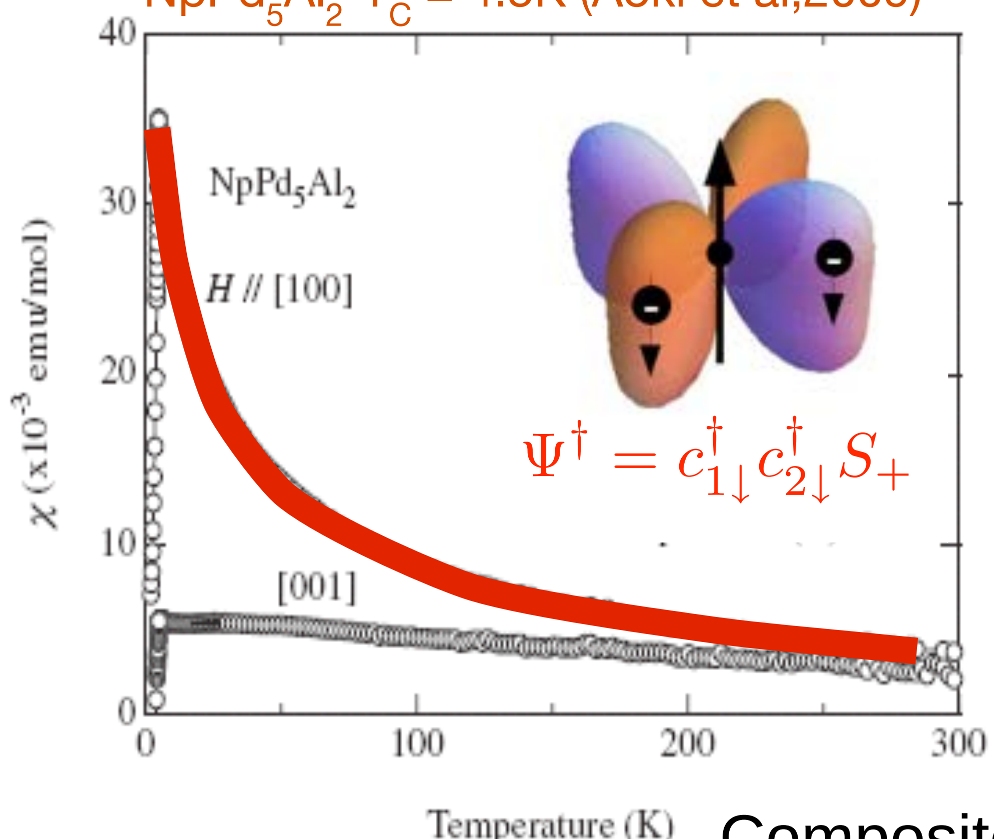
Ising Electrons: *Hastatic order*

→ New kinds of Electron Order

→ New kinds of Phase Transition



NpPd$_5$Al$_2$ T$_C$ = 4.5K (Aoki et al,2009)

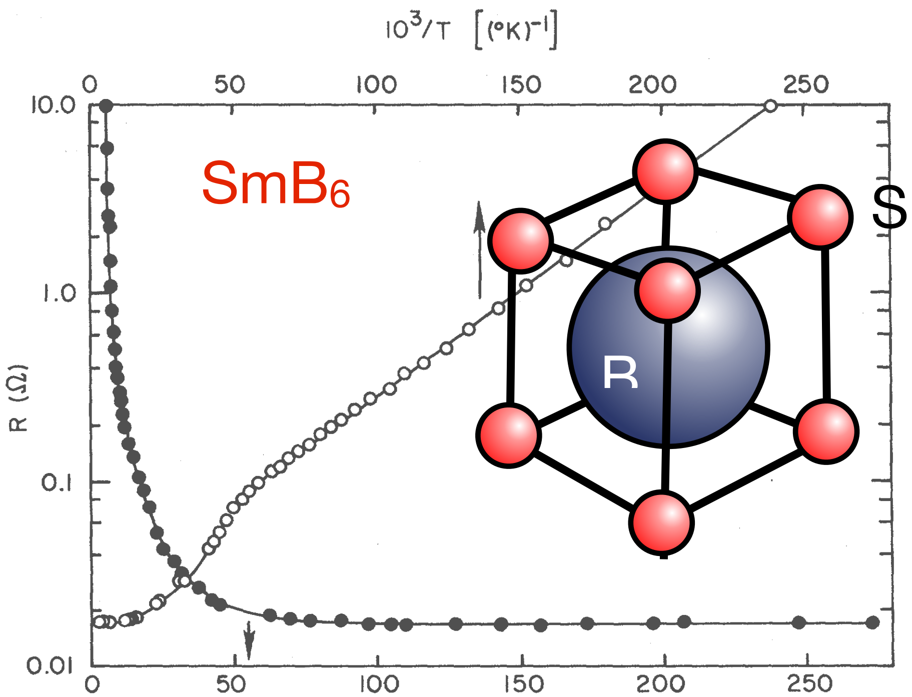


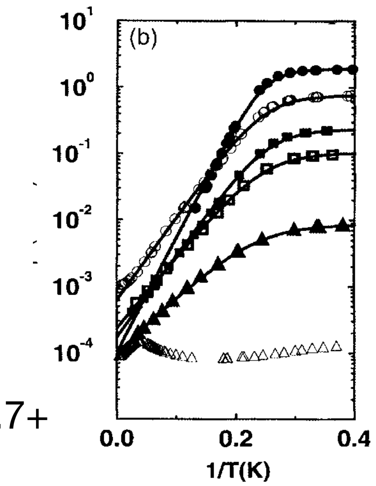
$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Composite Pairing

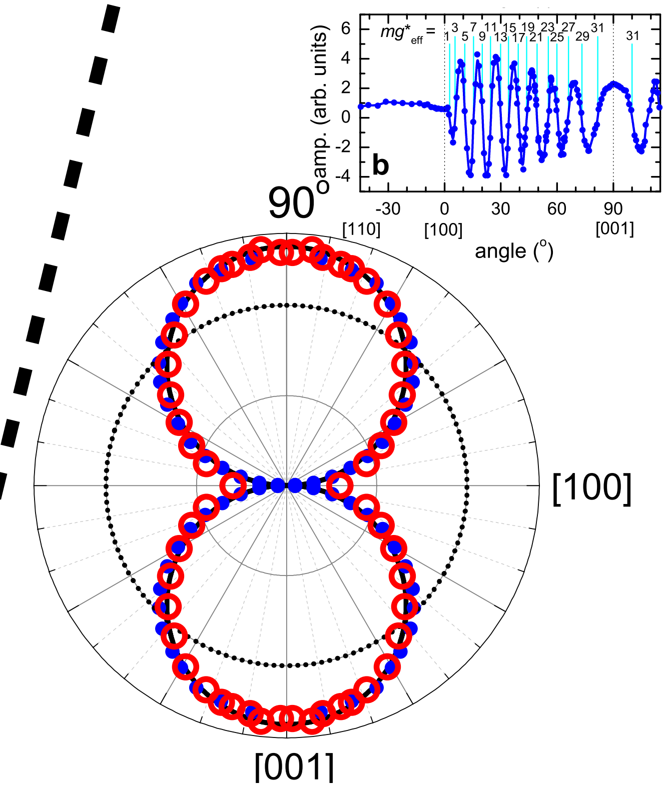
→ New kinds of insulator

Topological Kondo Insulators





Altarawneh et al., (2012)



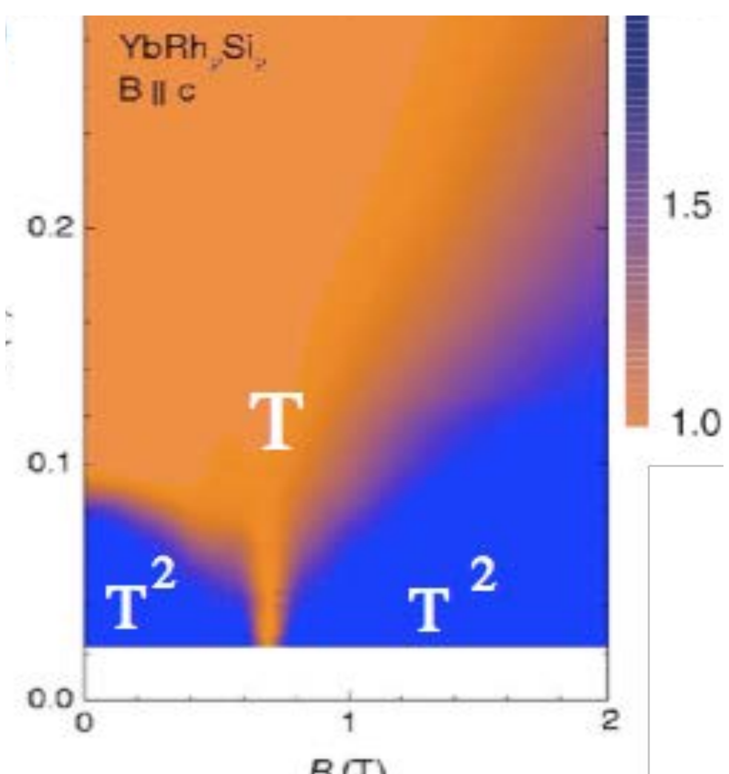
URu_2Si_2

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

Ising Electrons: *Hastatic order*

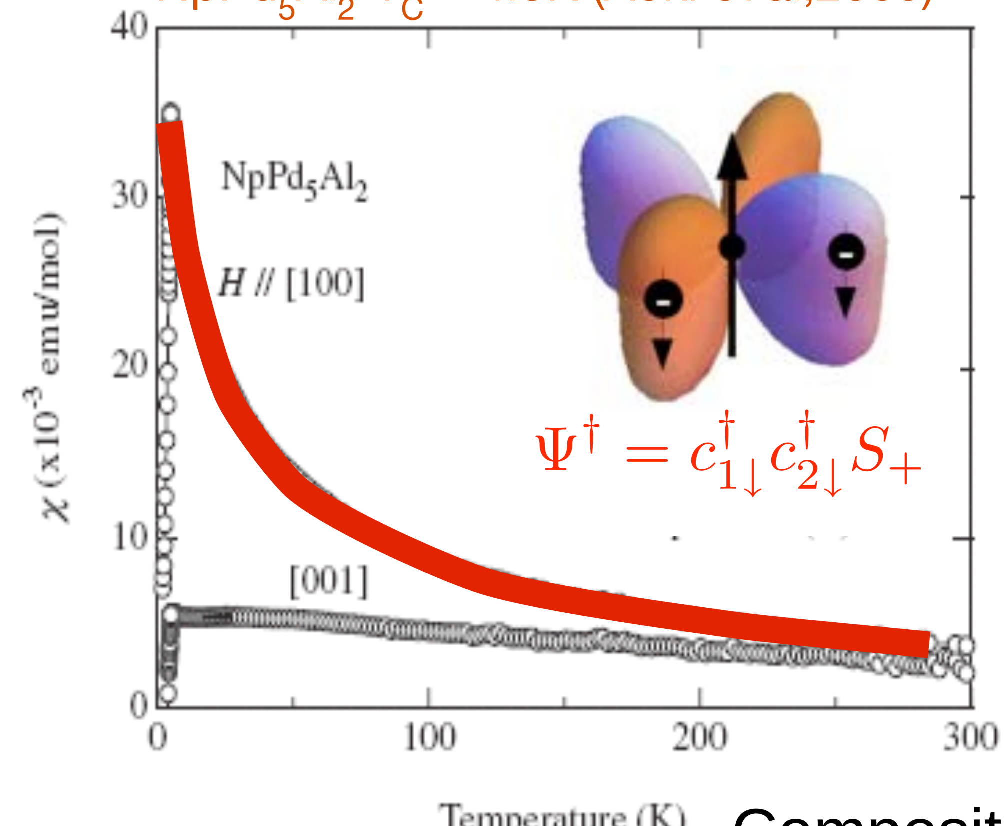
→ New kinds of Electron Order

→ New kinds of Phase Transition



→ Quantum Criticality

$NpPd_5Al_2$ T_C = 4.5K (Aoki et al,2009)

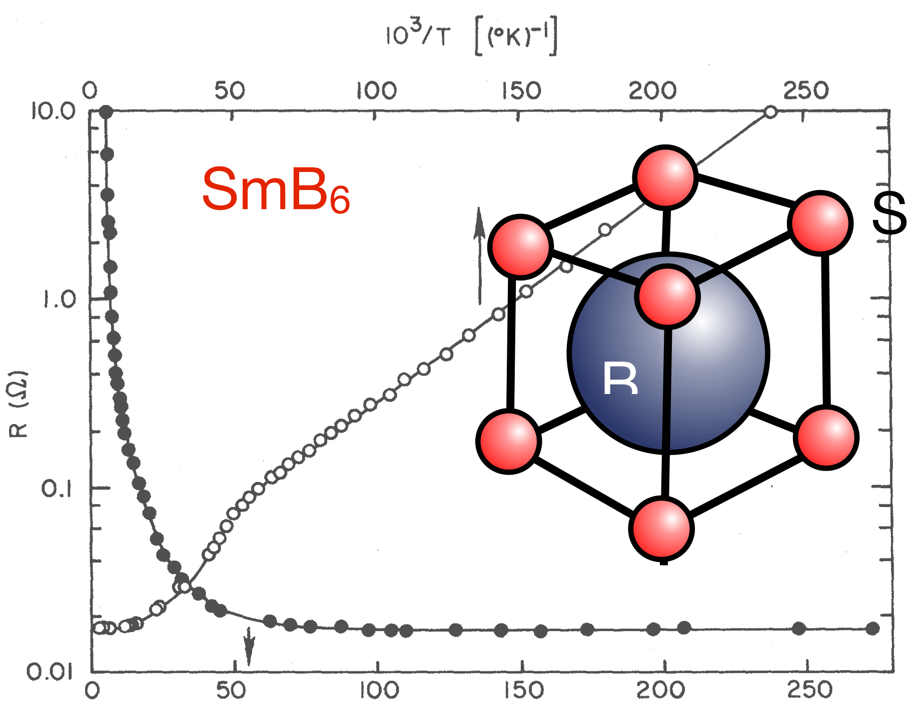


$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

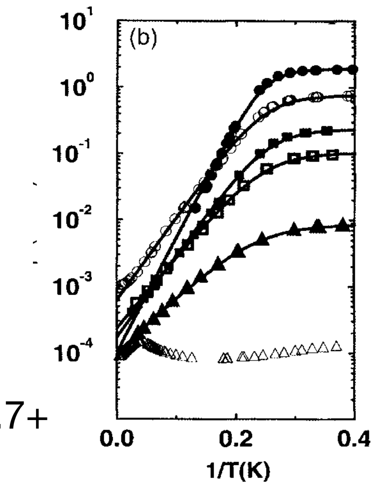
Composite Pairing

→ **New kinds of insulator**

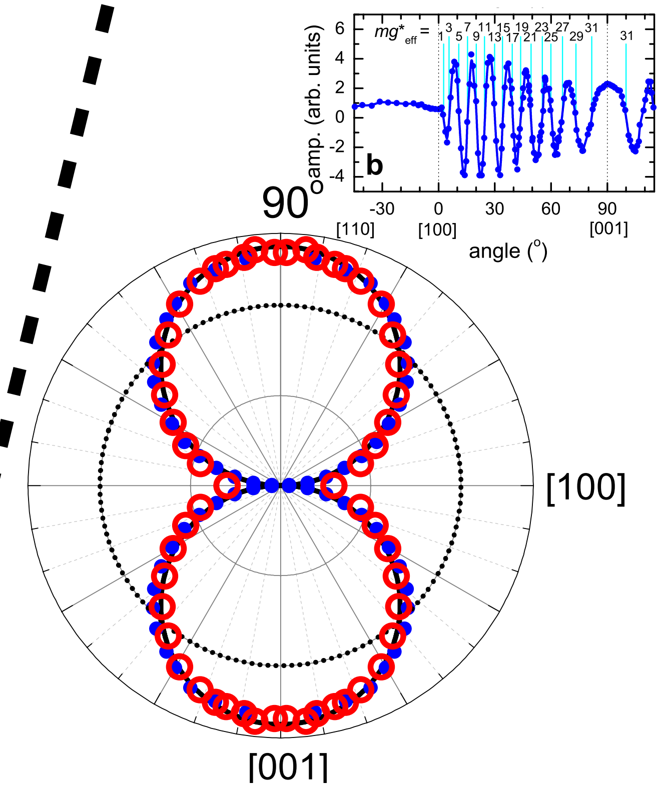
Topological Kondo Insulators



Sm$^{2.7+}$



Altarawneh et al., (2012)

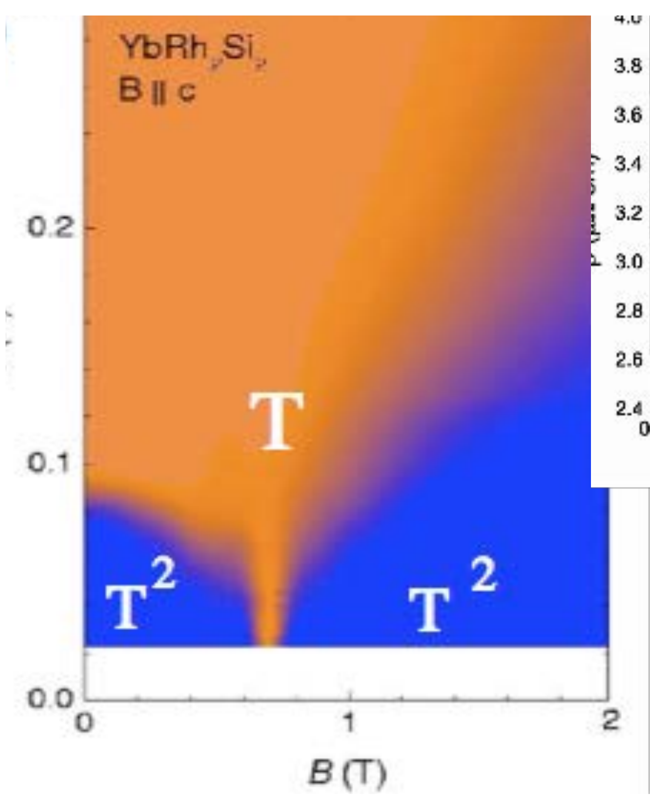


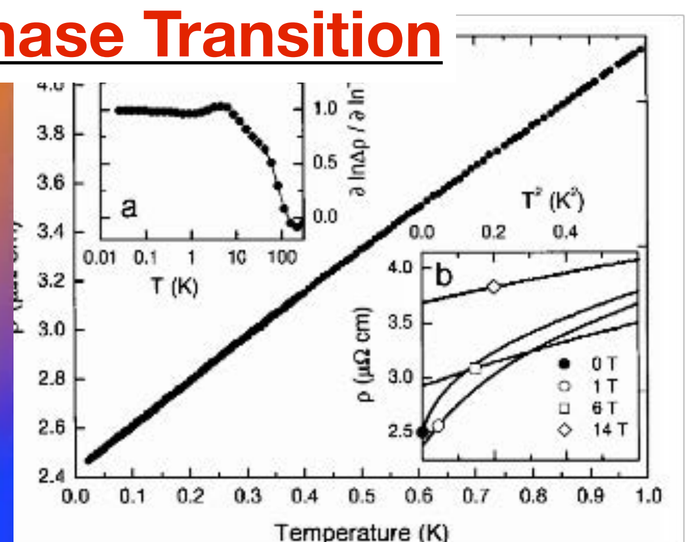
URu_2Si_2

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

Ising Electrons: *Hastatic order*

→ **New kinds of Phase Transition**



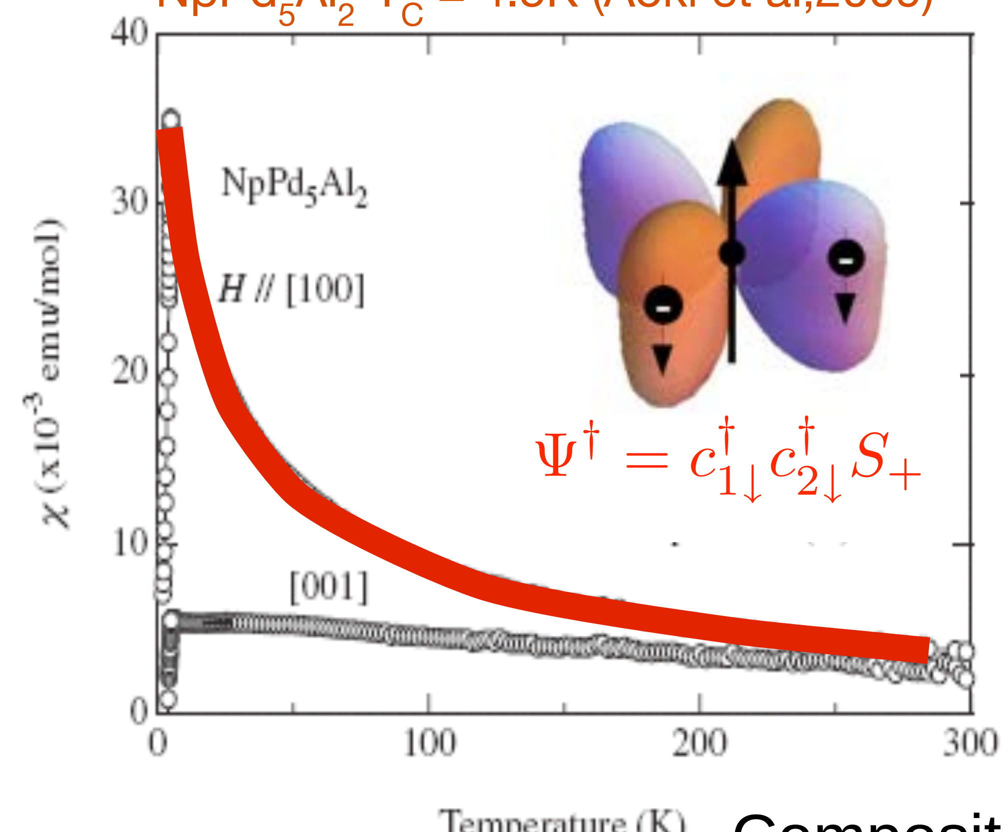


→ **Strange Metals**

→ **Quantum Criticality**

→ **New kinds of Electron Order**

$NpPd_5Al_2$ T_C = 4.5K (Aoki et al,2009)



$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

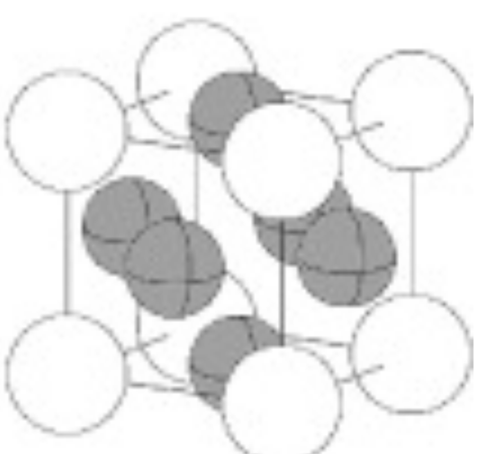
Composite Pairing

To whet your appetite.

"115" Family

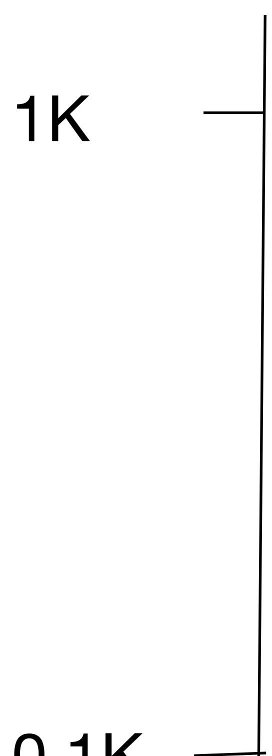
1K

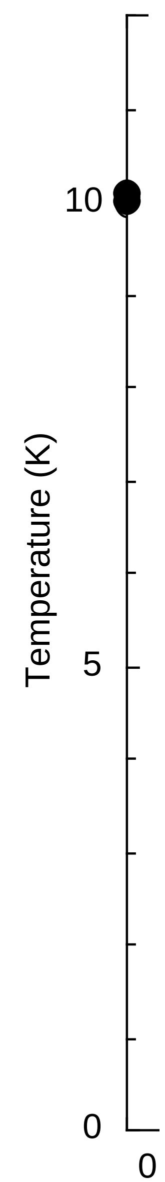
CeIn3



0.1K

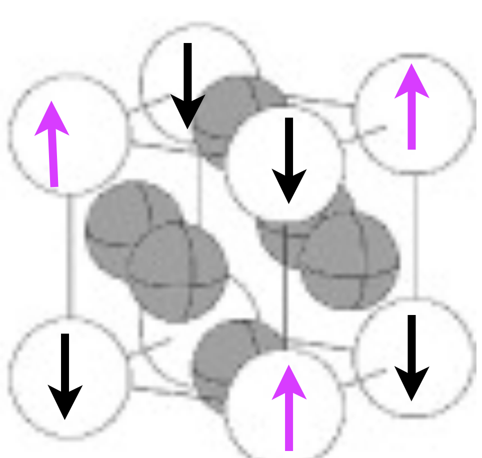
“115” Family





CeIn3

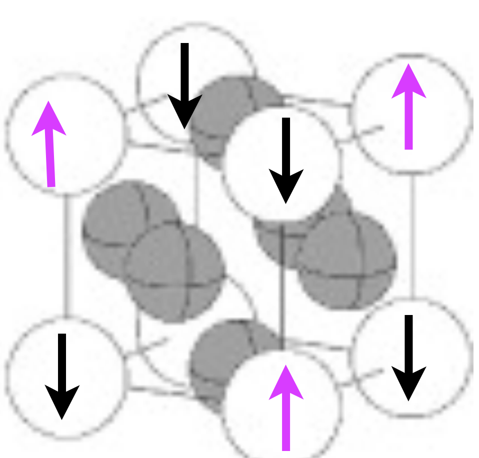
10K AFM

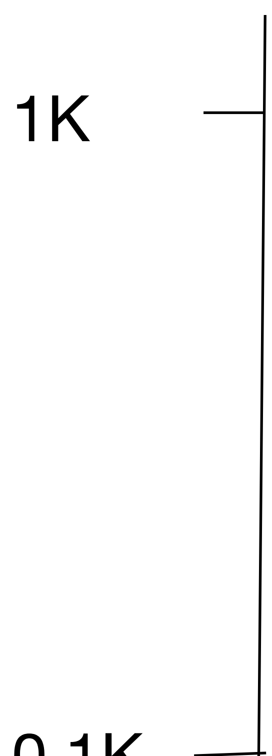


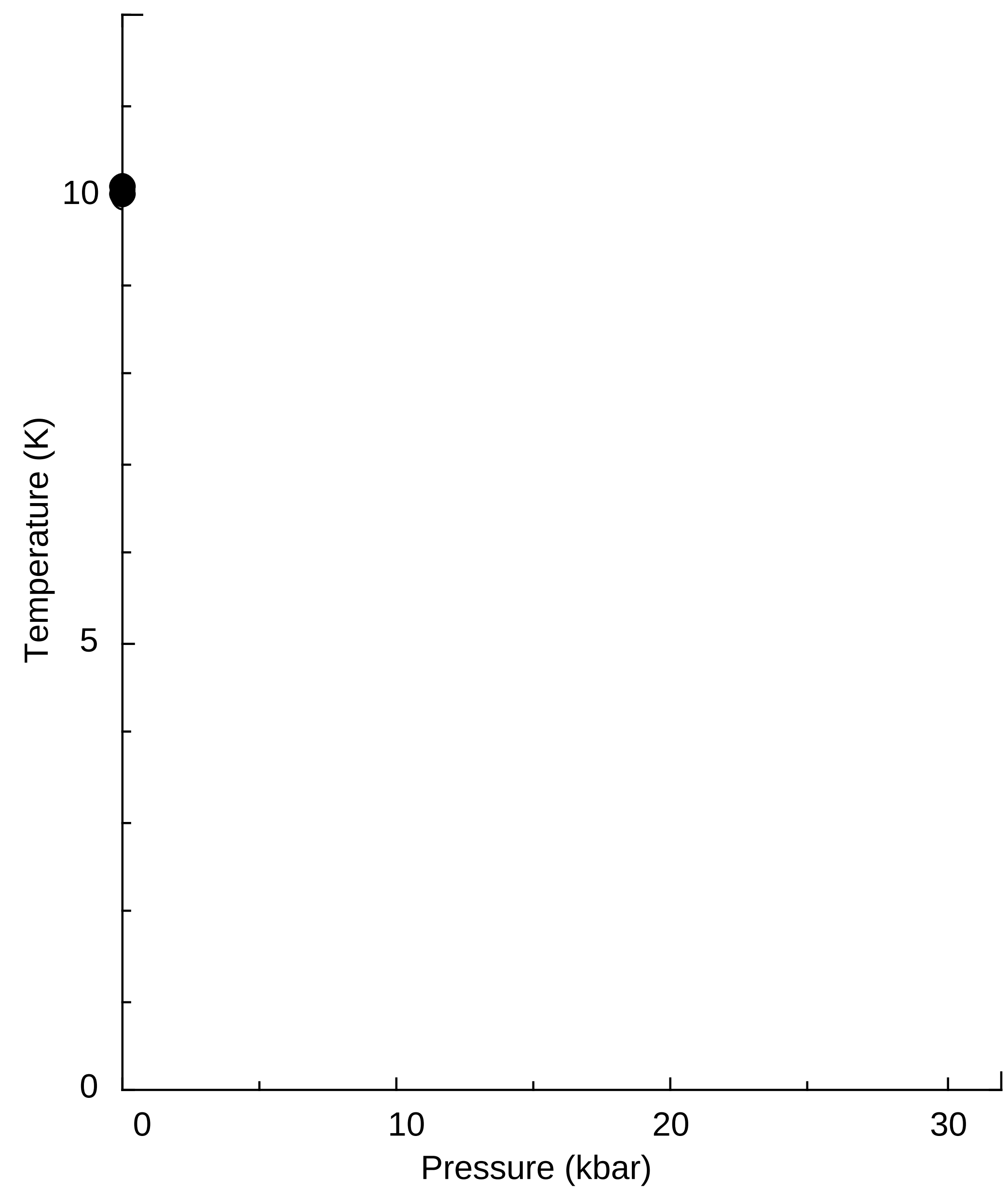
“115” Family

CeIn3

10K AFM







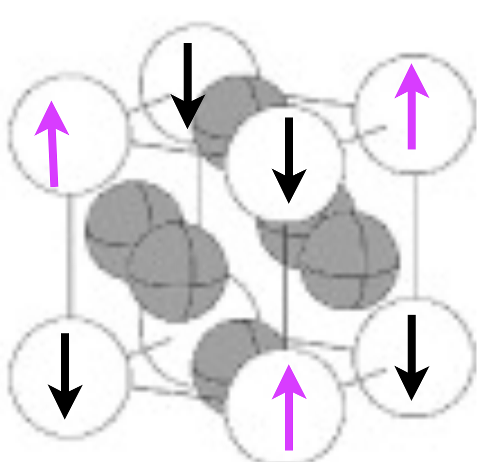
“115” Family

1K

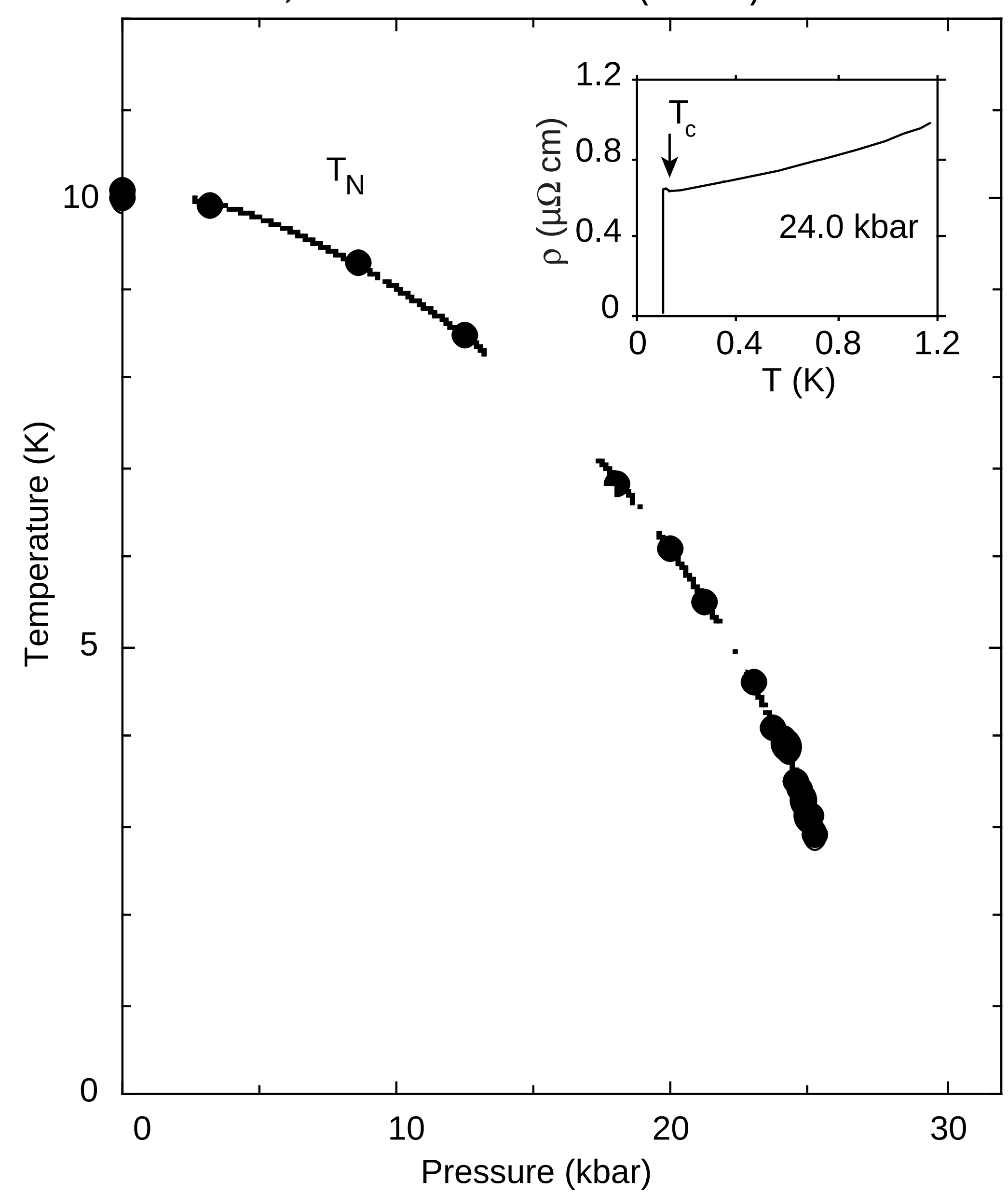
0.1K

CeIn3

10K AFM



Mathur, Lonzarich et al (1998)



“115” Family

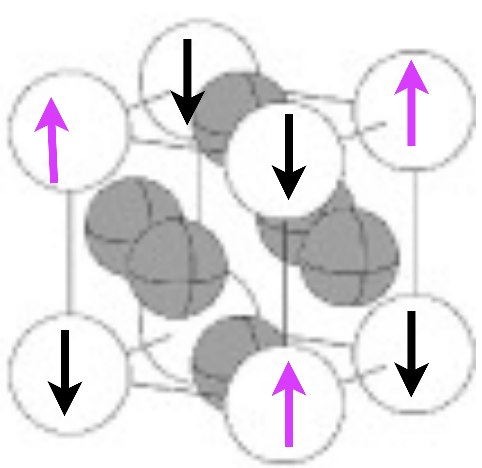
1K

CeIn3

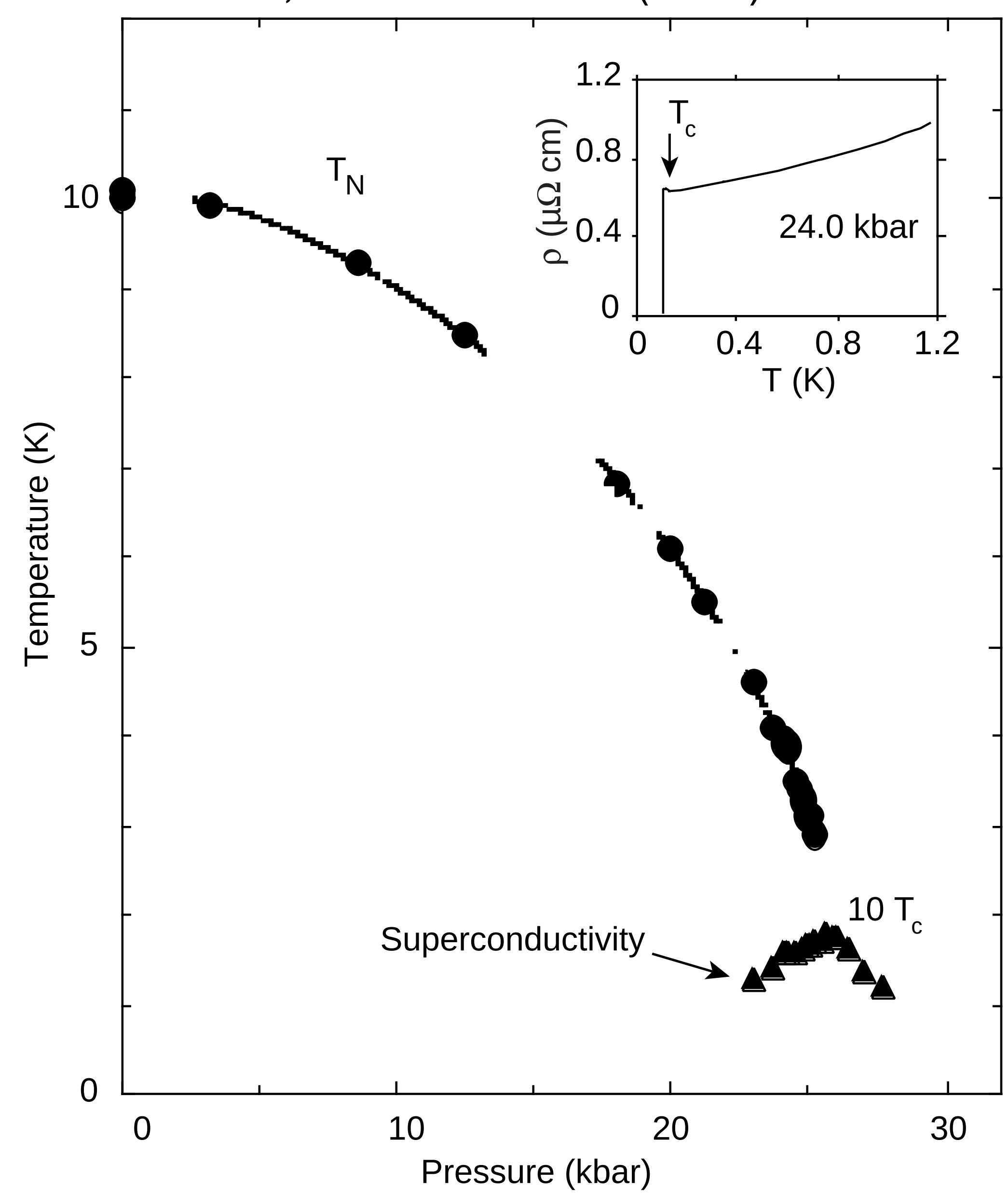
10K AFM

CeIn3 (0.2K)

0.1K



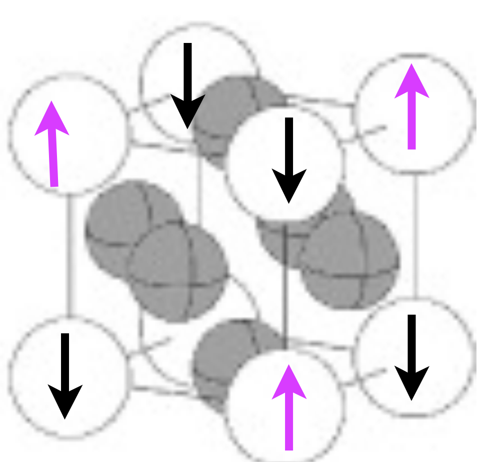
Mathur, Lonzarich et al (1998)

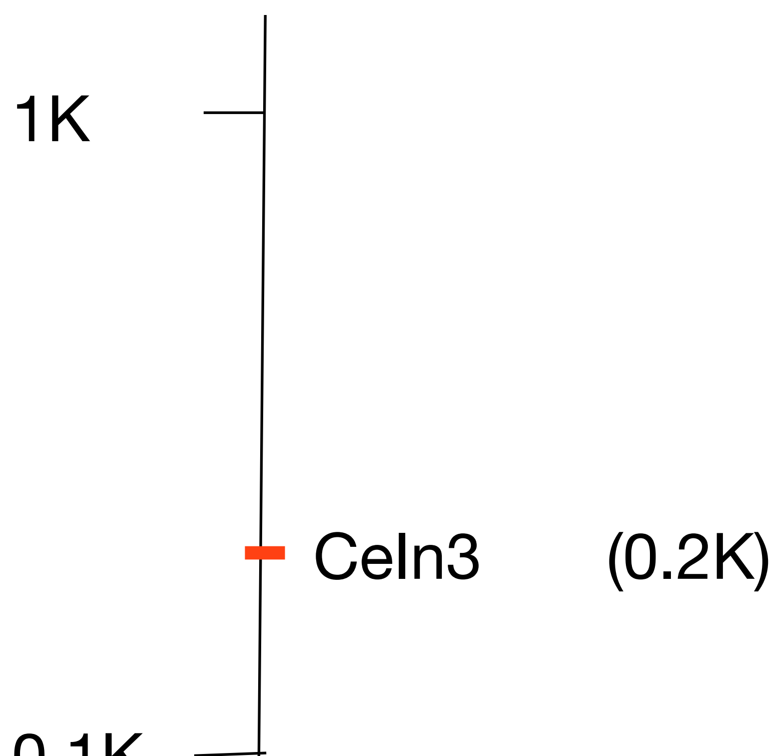


“115” Family

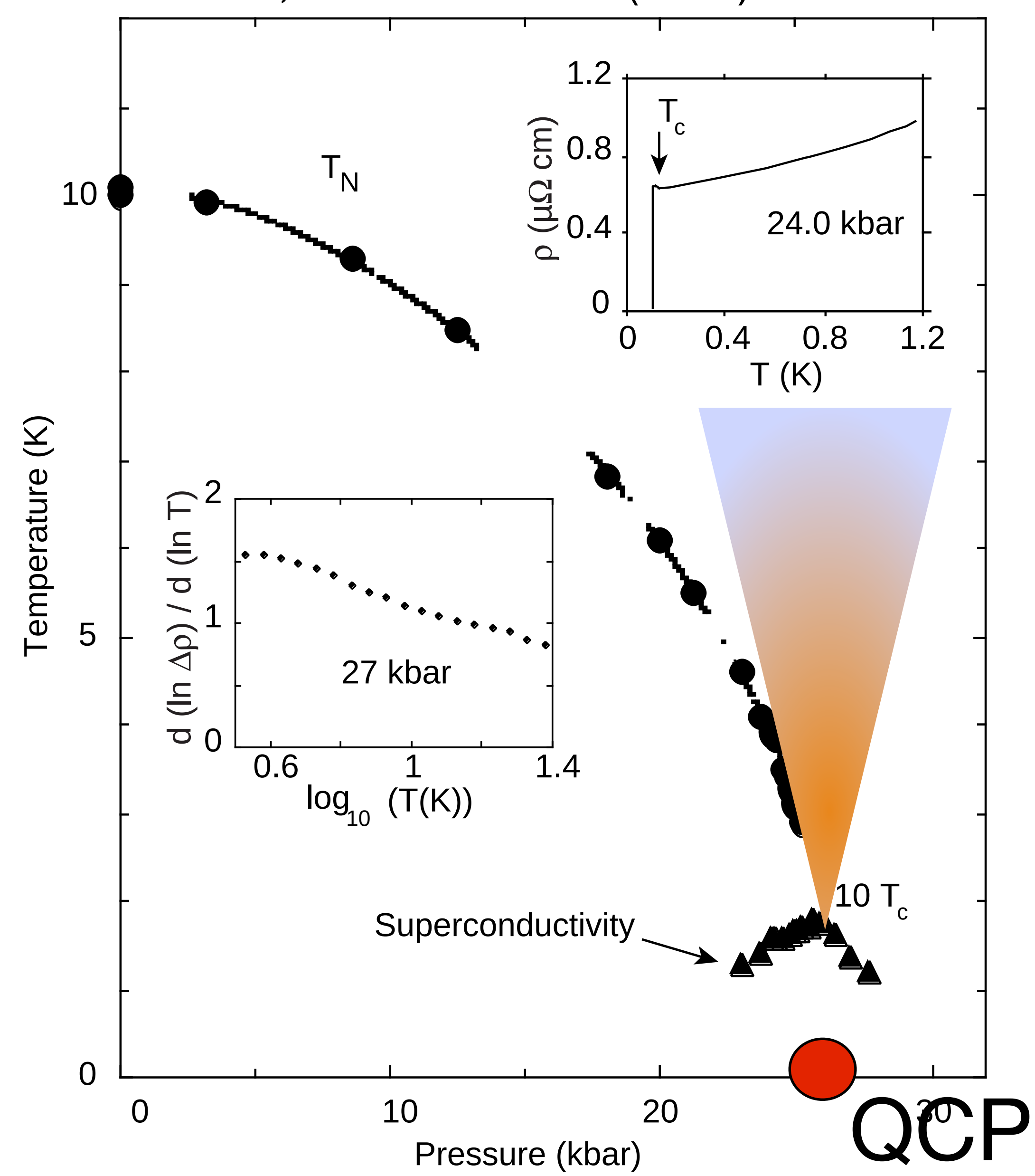
CeIn3

10K AFM





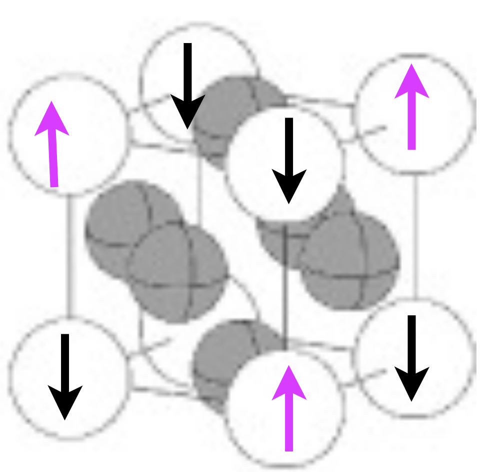
Mathur, Lonzarich et al (1998)

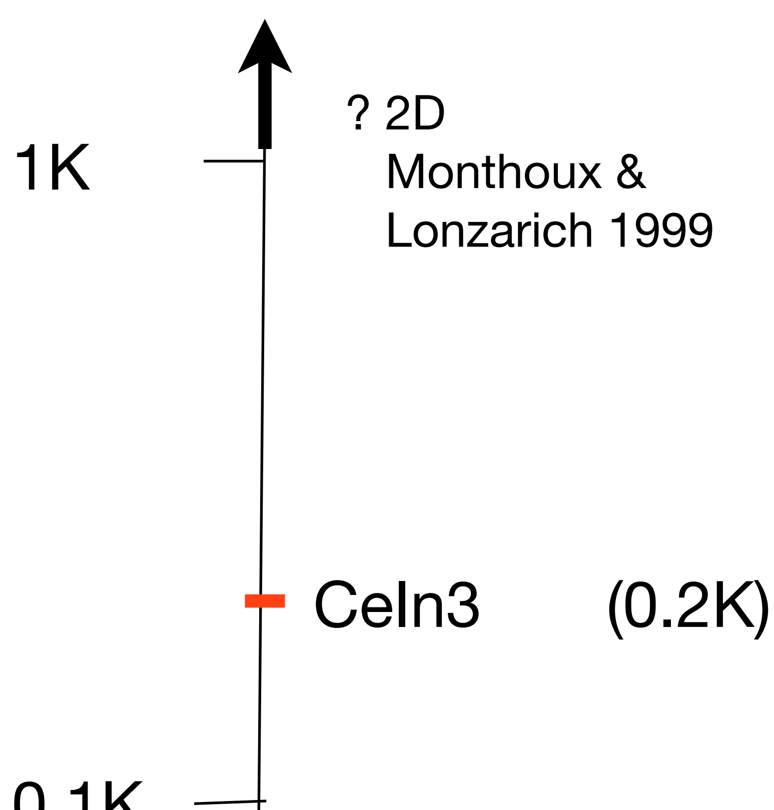


“115” Family

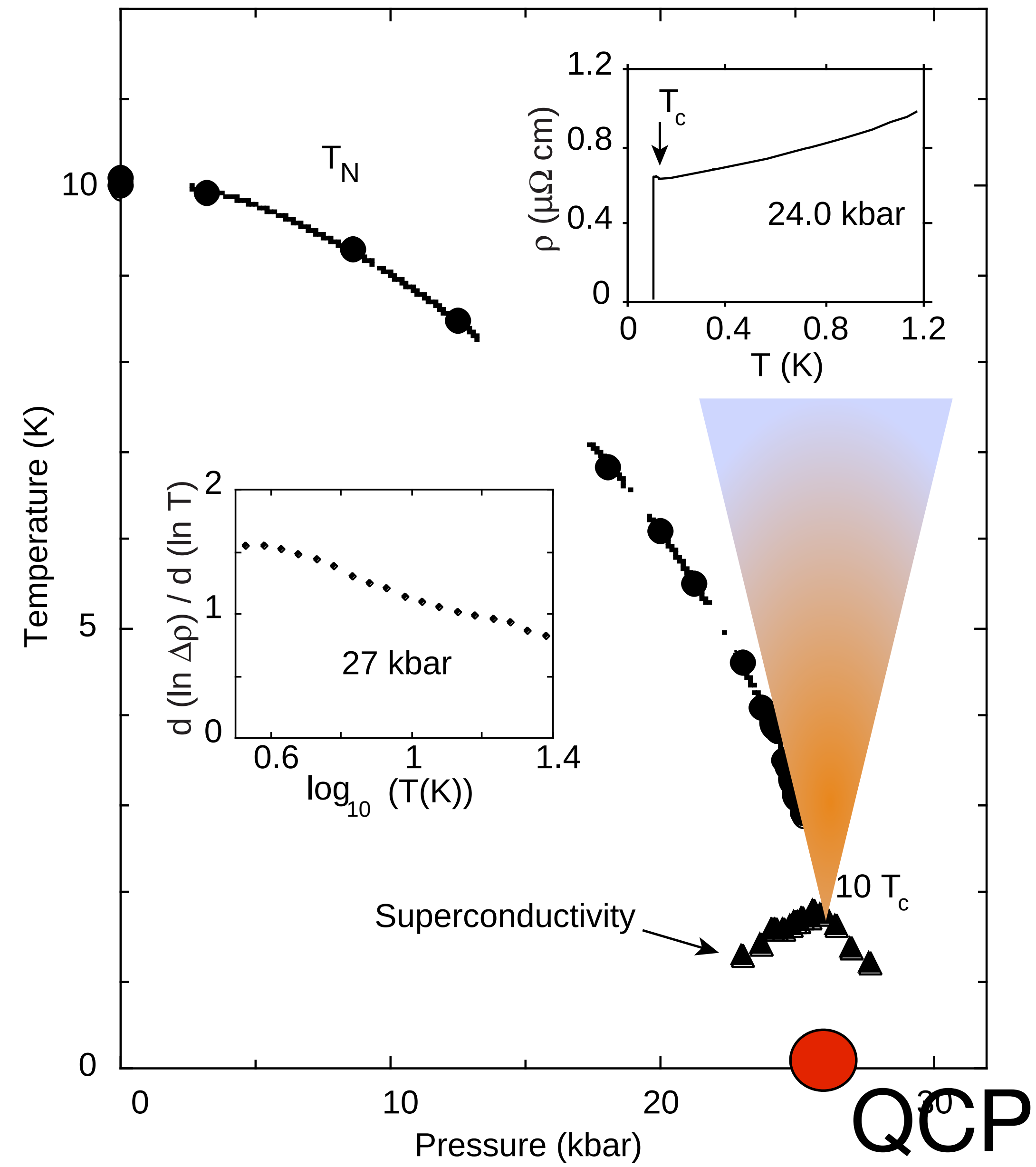
CeIn3

10K AFM

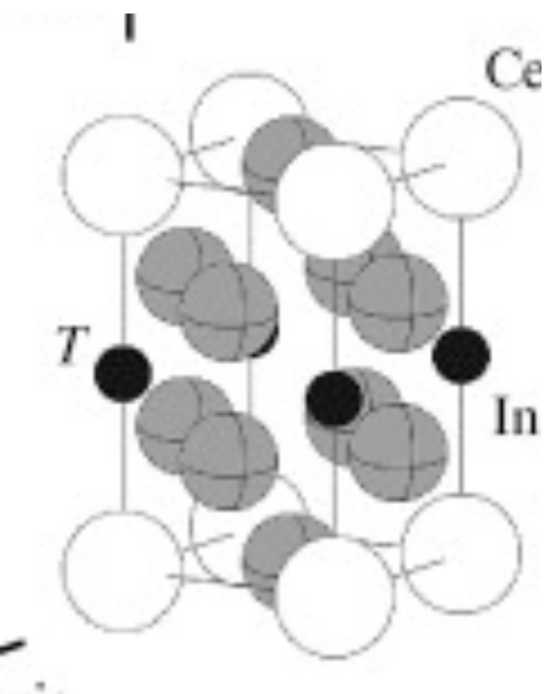


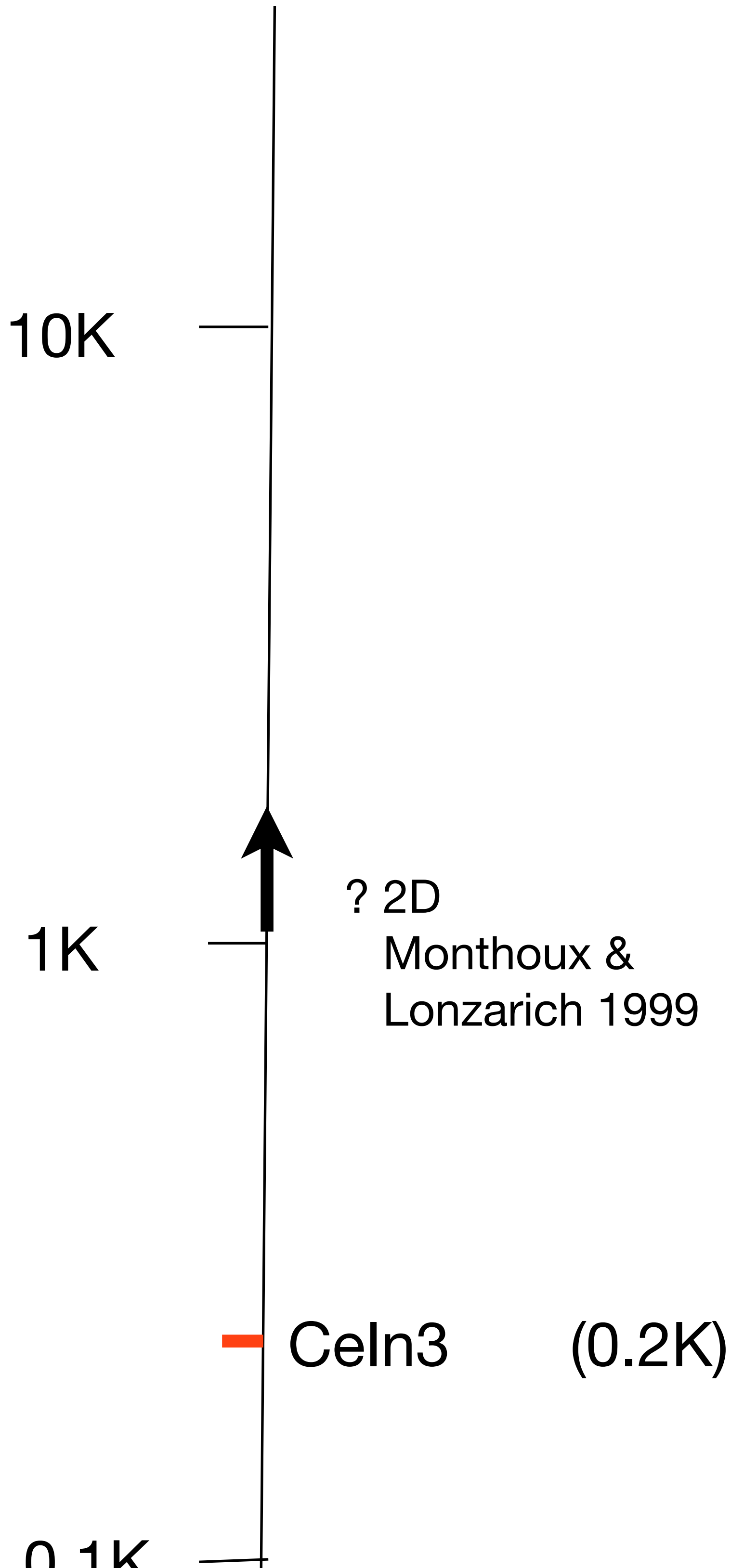


Mathur, Lonzarich et al (1998)

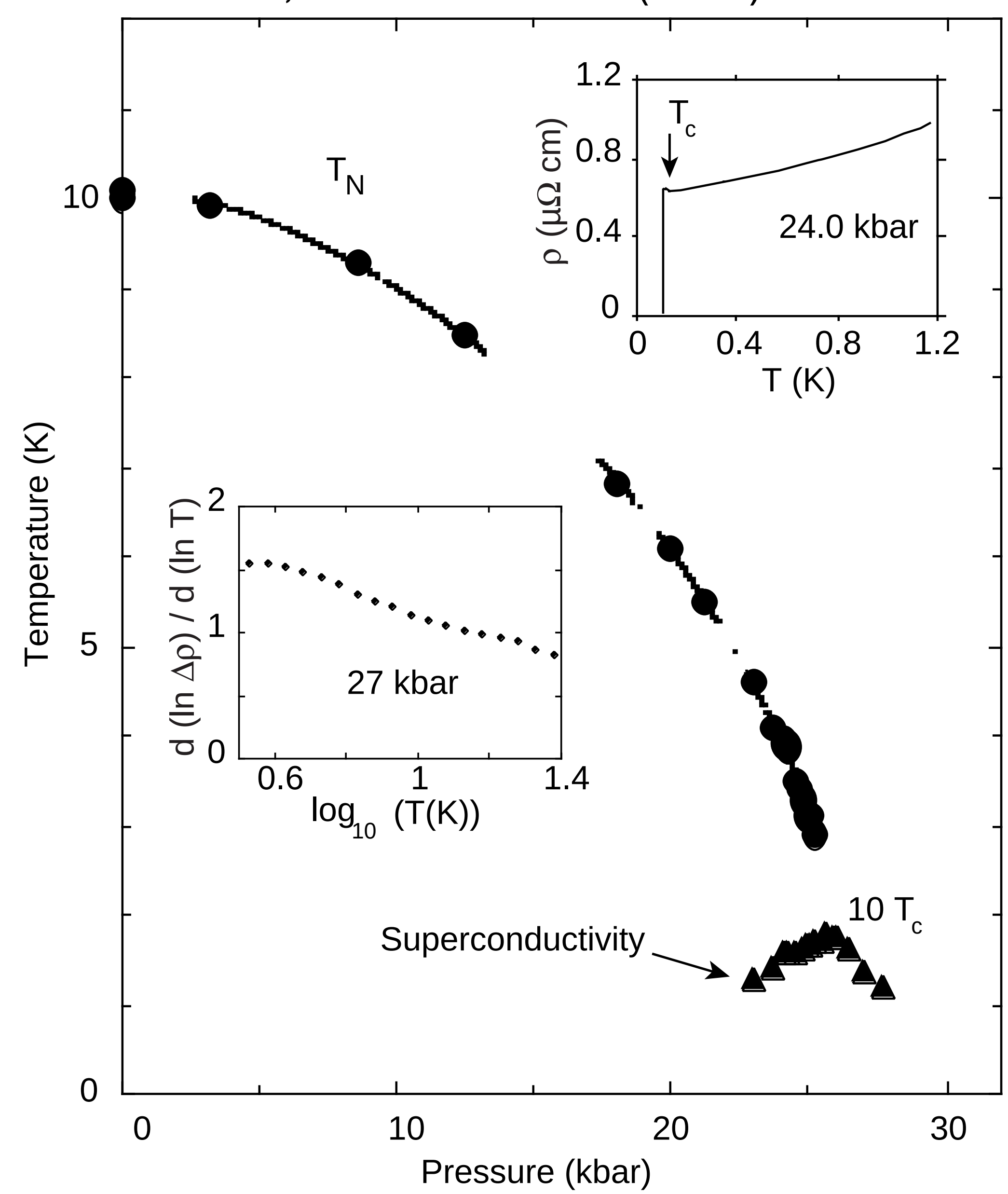


“115” Family

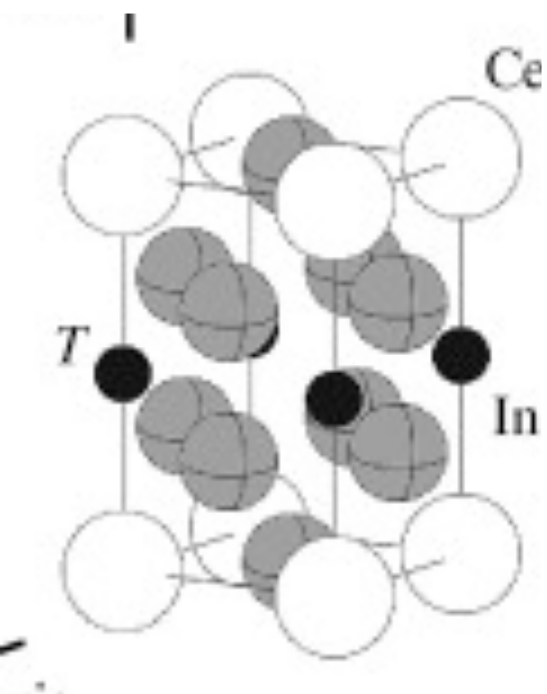


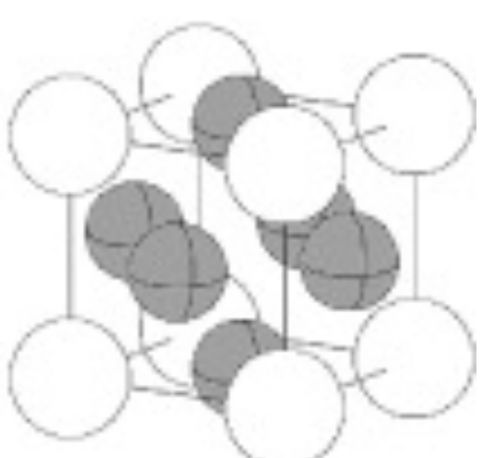


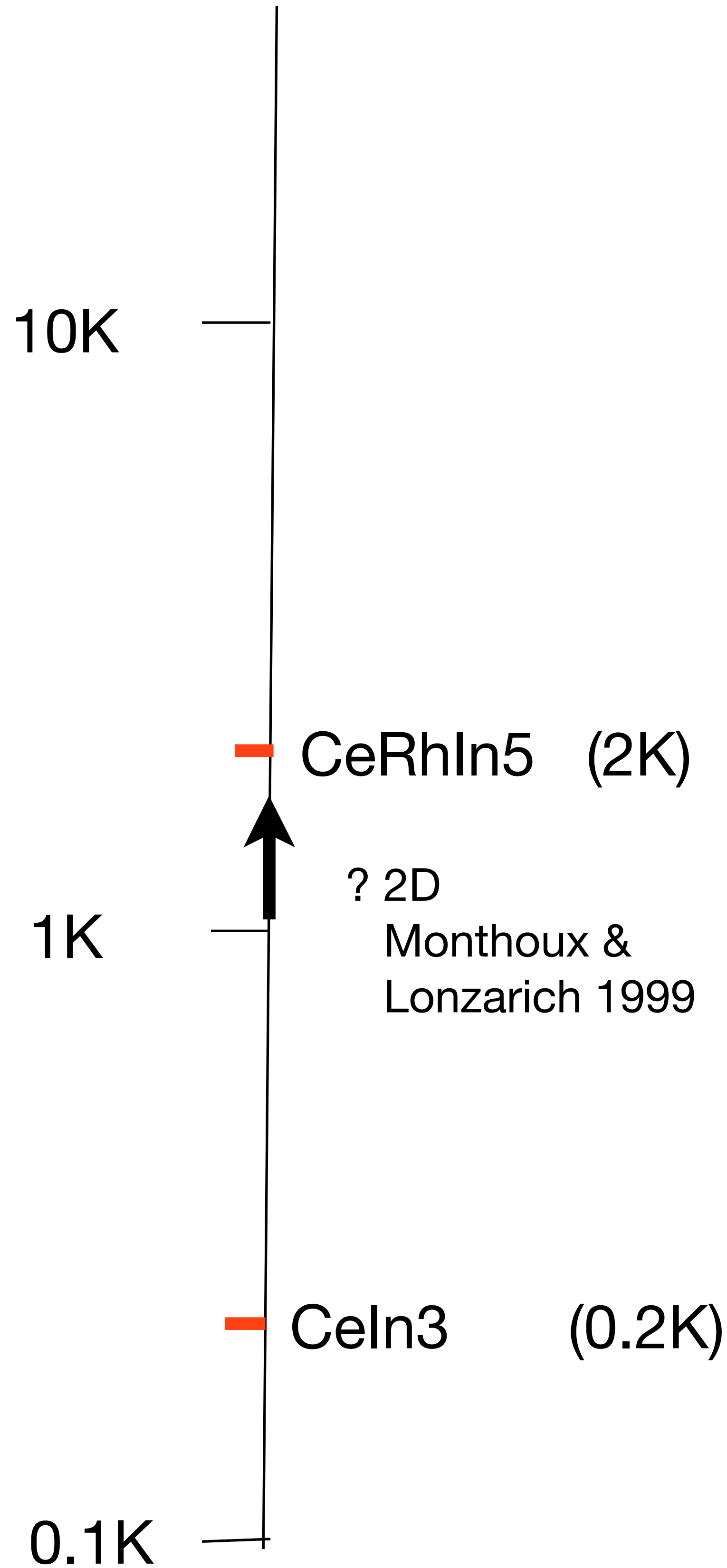
Mathur, Lonzarich et al (1998)

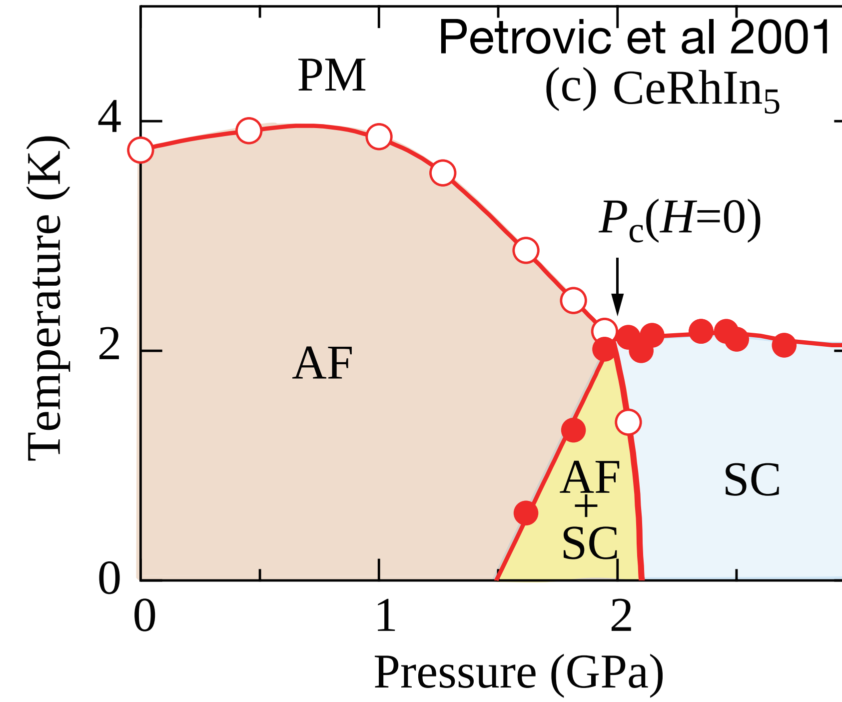


“115” Family

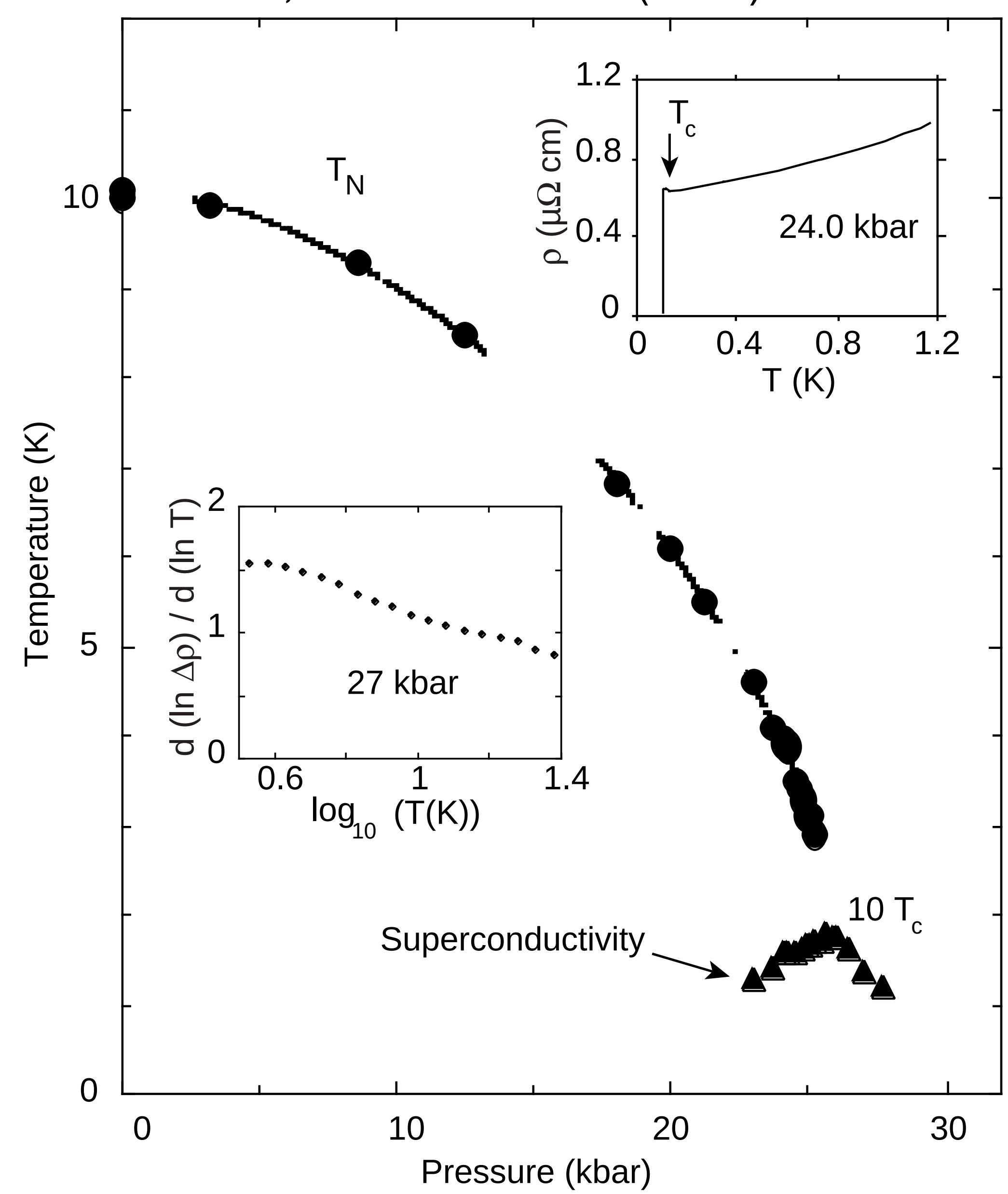




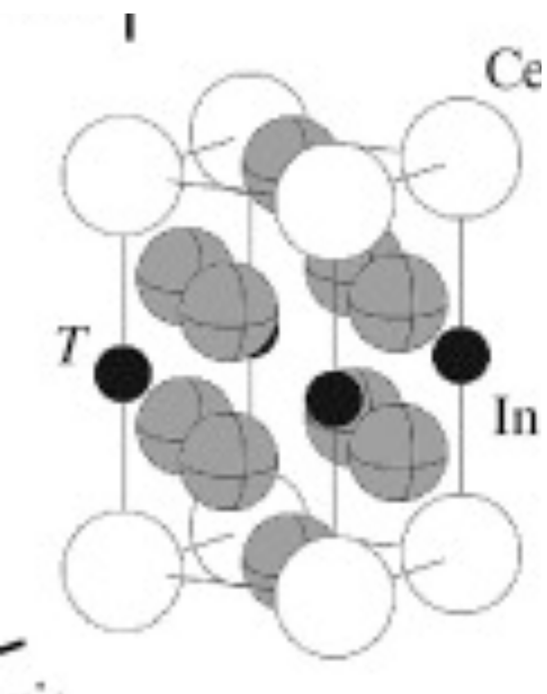


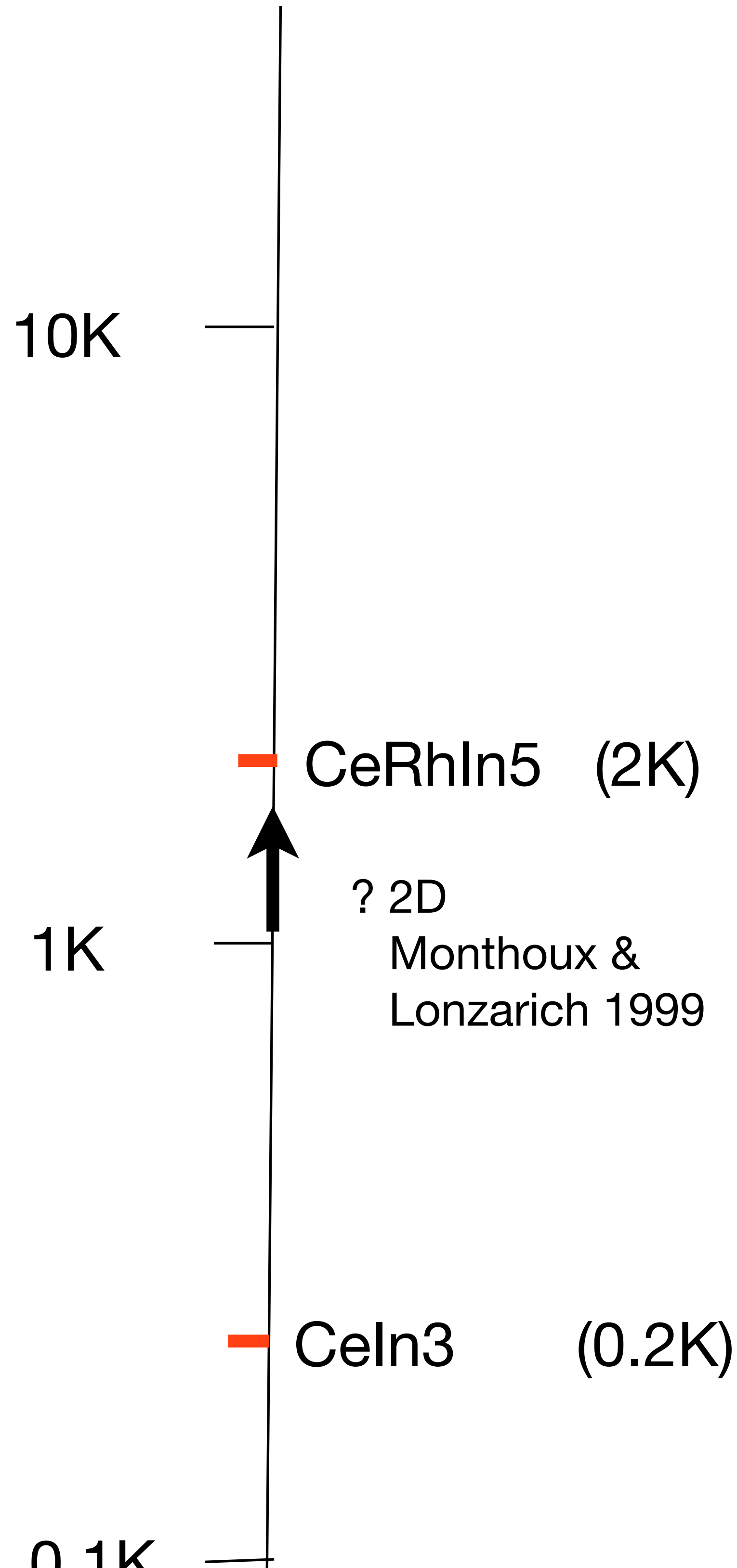


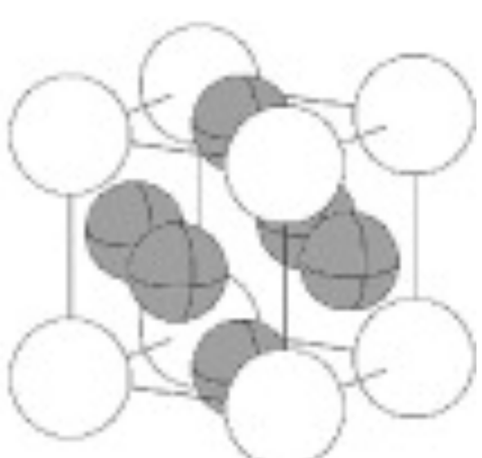
Mathur, Lonzarich et al (1998)

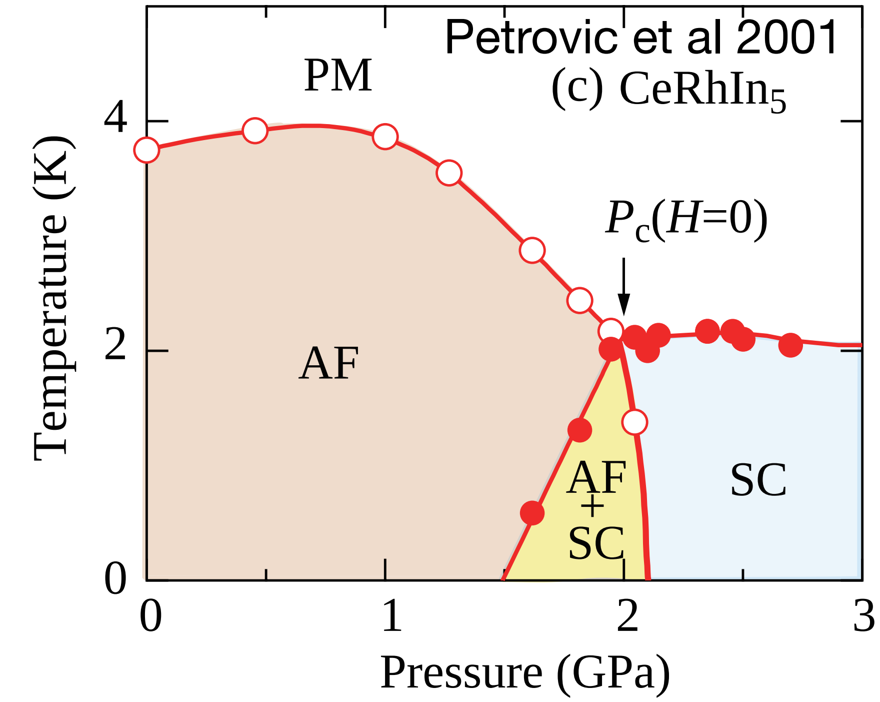


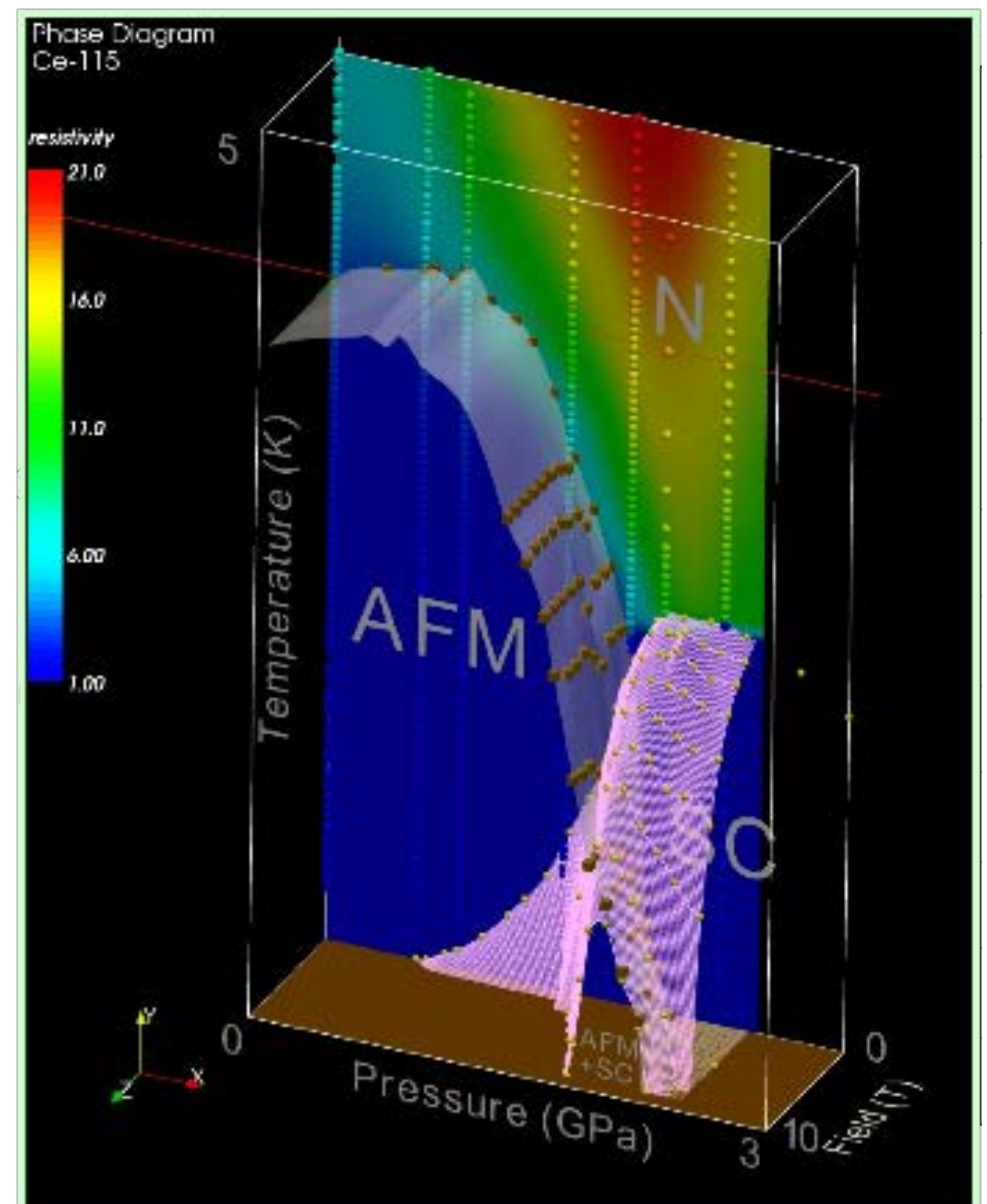
"115" Family


Ce
T
In

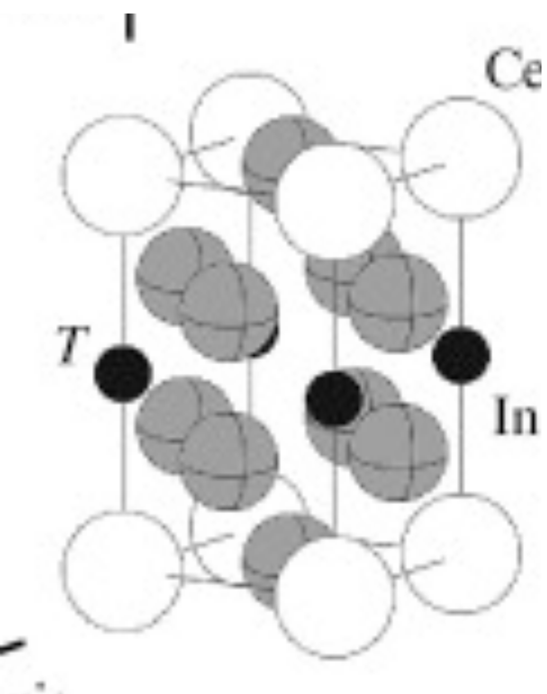

10K
CeRhIn5 (2K)
? 2D
Monthoux &
Lonzarich 1999
1K
CeIn3 (0.2K)
0.1K




Petrovic et al 2001
(c) $CeRhIn_5$
PM
$P_c(H=0)$
AF
AF + SC
SC
Temperature (K)
Pressure (GPa)
0
1
2
3
0
2
4


Phase Diagram
Ce-115
resistivity
21.0
16.0
11.0
6.00
1.00
5
Temperature (K)
N
AFM
SC
AFM +SC
0
Pressure (GPa)
3
0
10
Field (T)

"115" Family



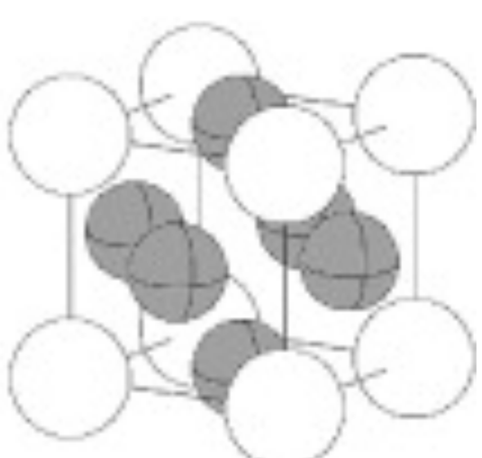
10K

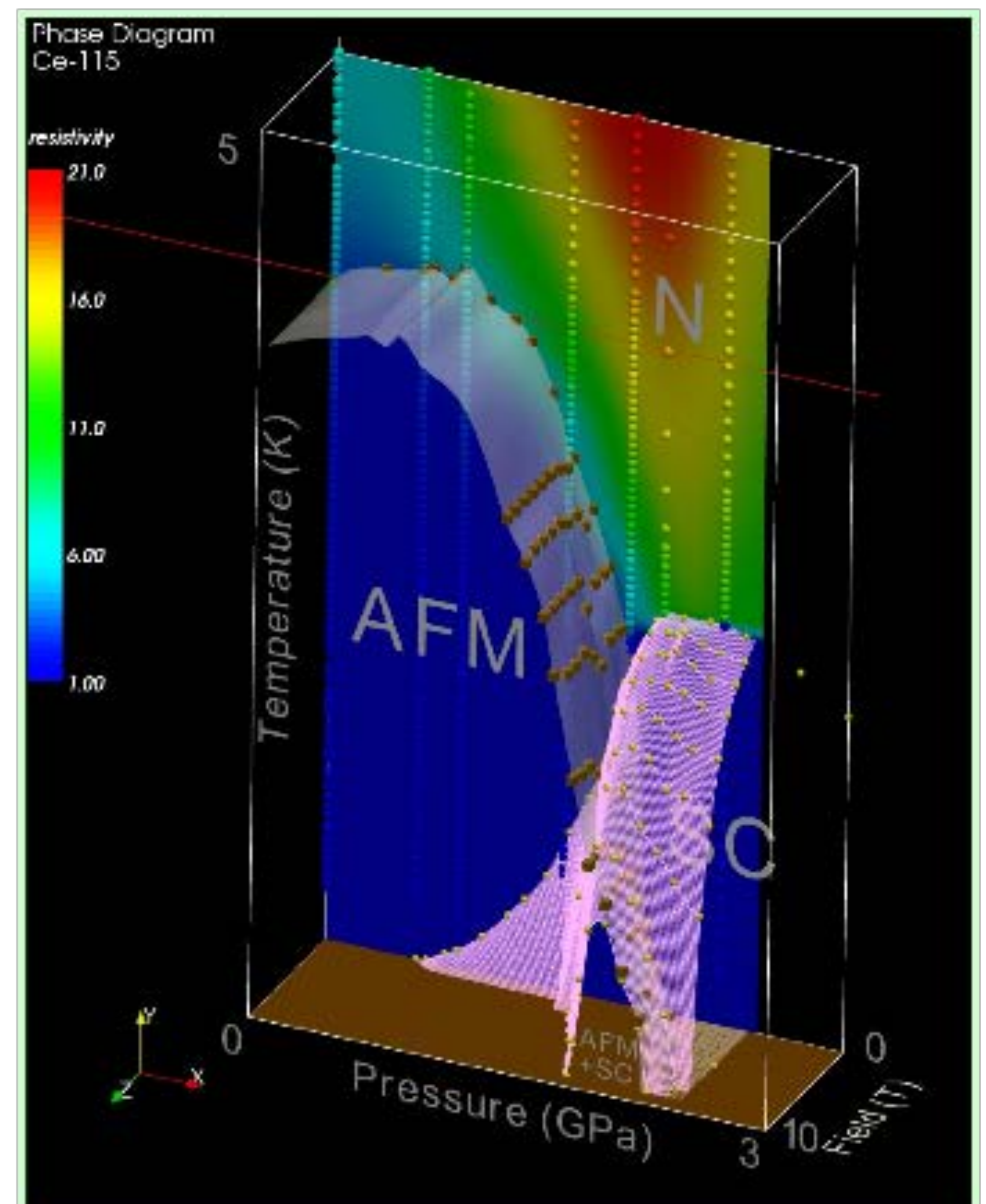
CeRhIn5 (2K)

1K

CeIn3 (0.2K)

0.1K





“115” Family

PuCoGa5 (18.5K)

10K

PuRhGa5 (9K)

NpAl2Pd5 (4.5K)

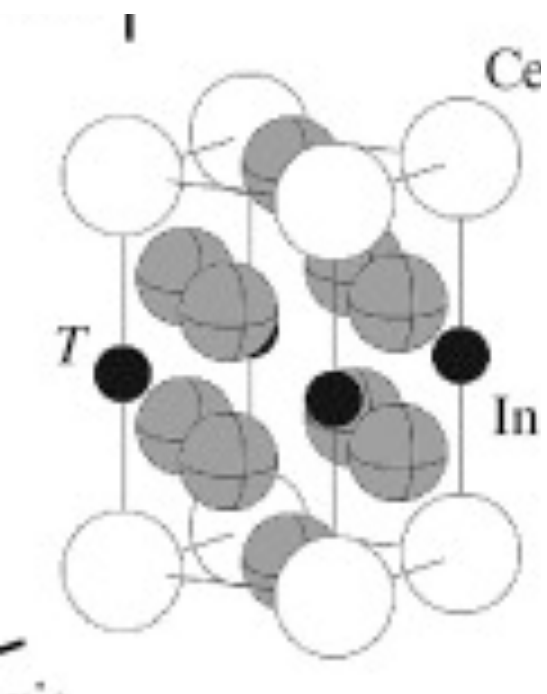
CeCoIn5 (2.5K)

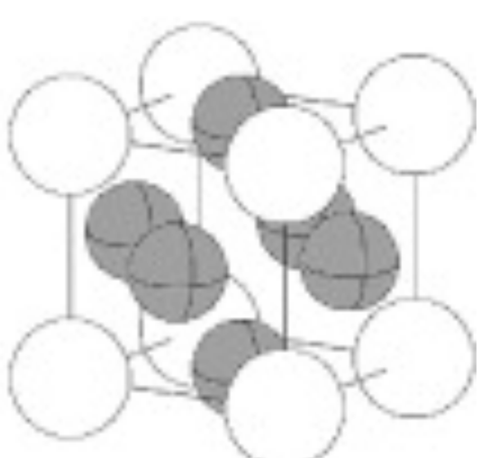
CeRhIn5 (2K)

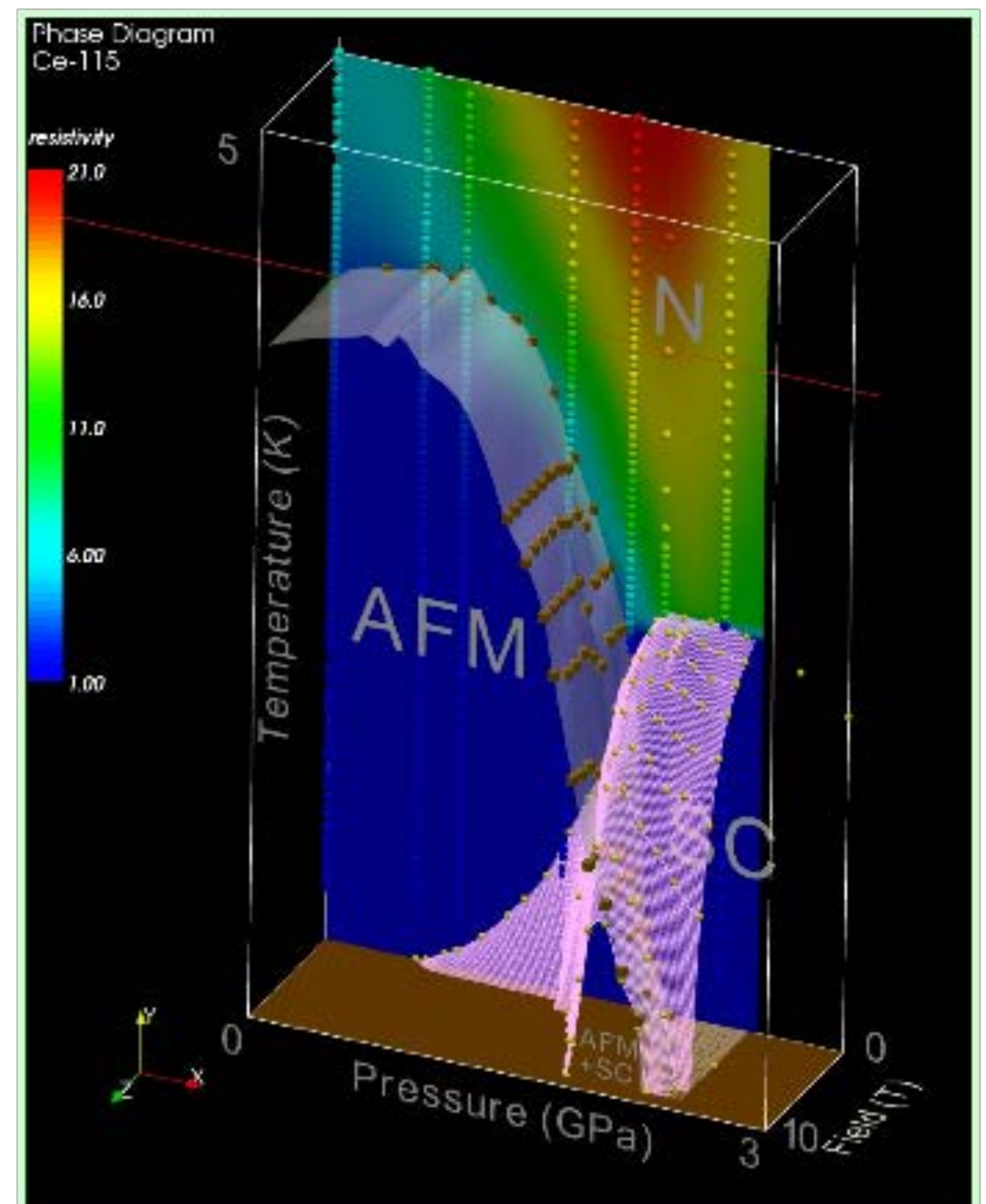
1K

CeIn3 (0.2K)

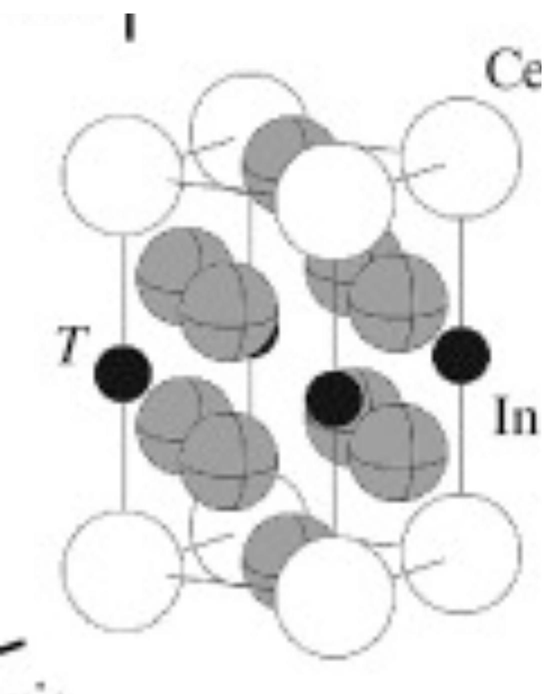
0.1K



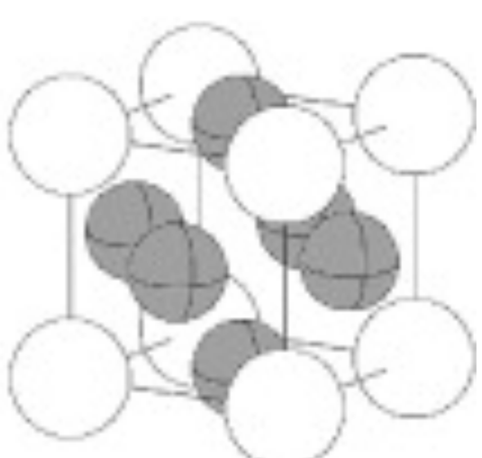


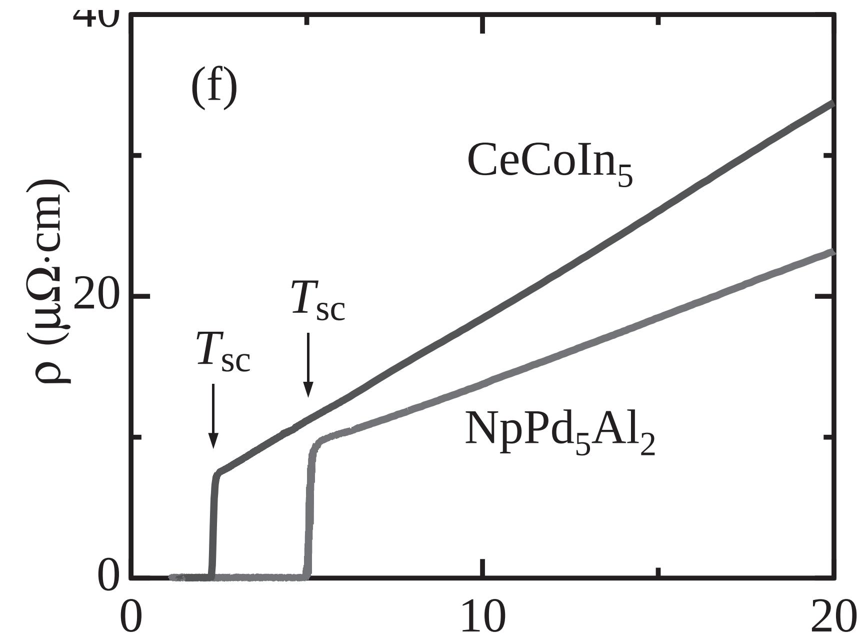


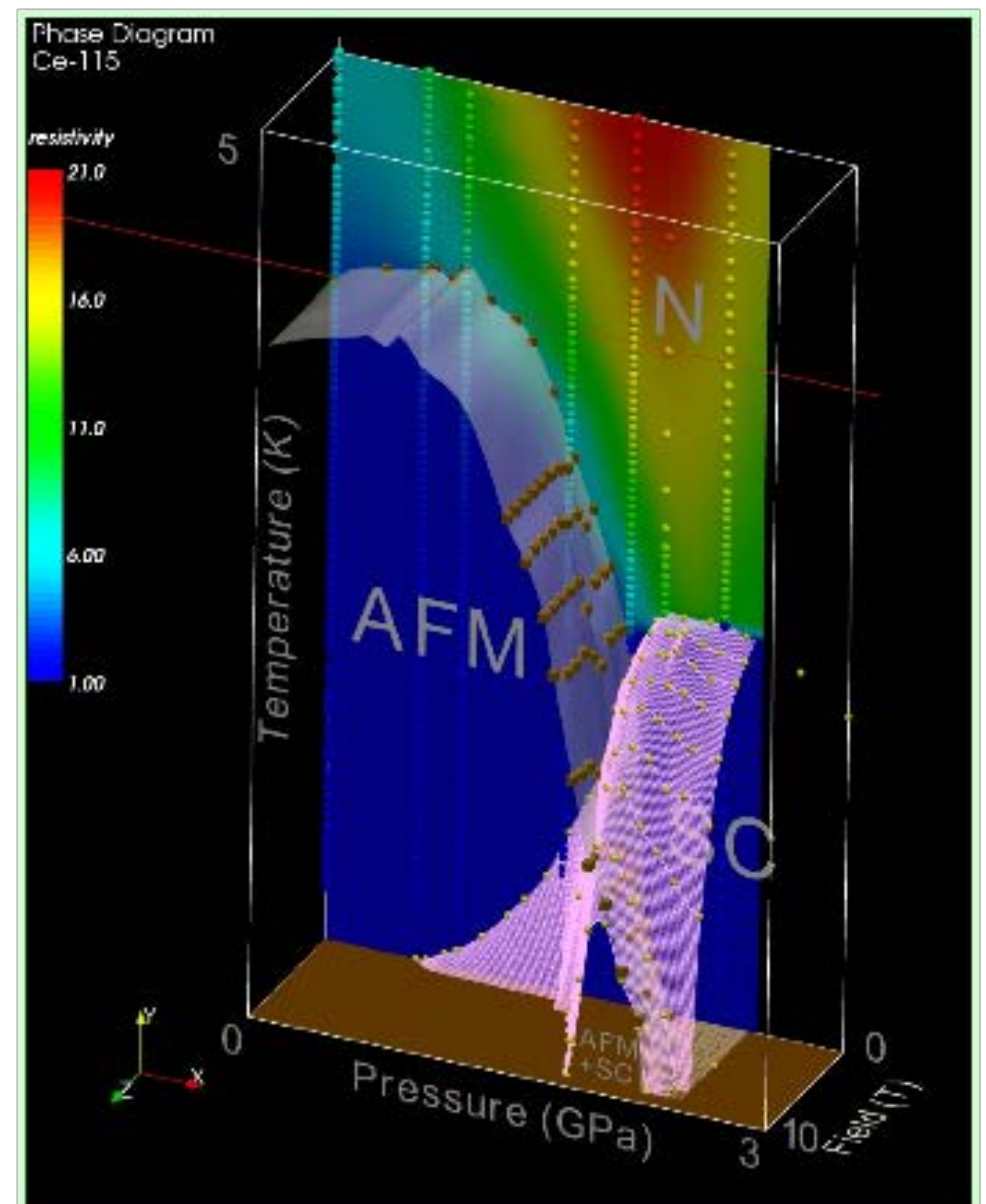
“115” Family



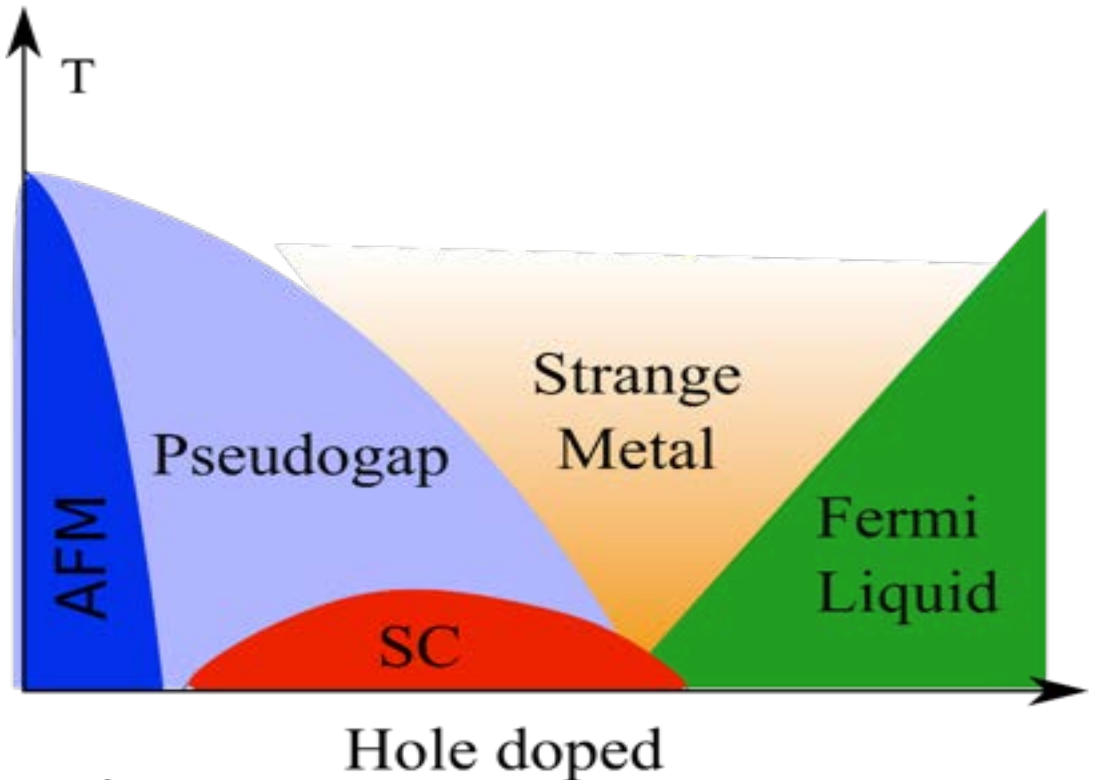
- PuCoGa5 (18.5K)
- 10K
- PuRhGa5 (9K)
- NpAl2Pd5 (4.5K)
- CeCoIn5 (2.5K)
- CeRhIn5 (2K)
- 1K
- CeIn3 (0.2K)
- 0.1K



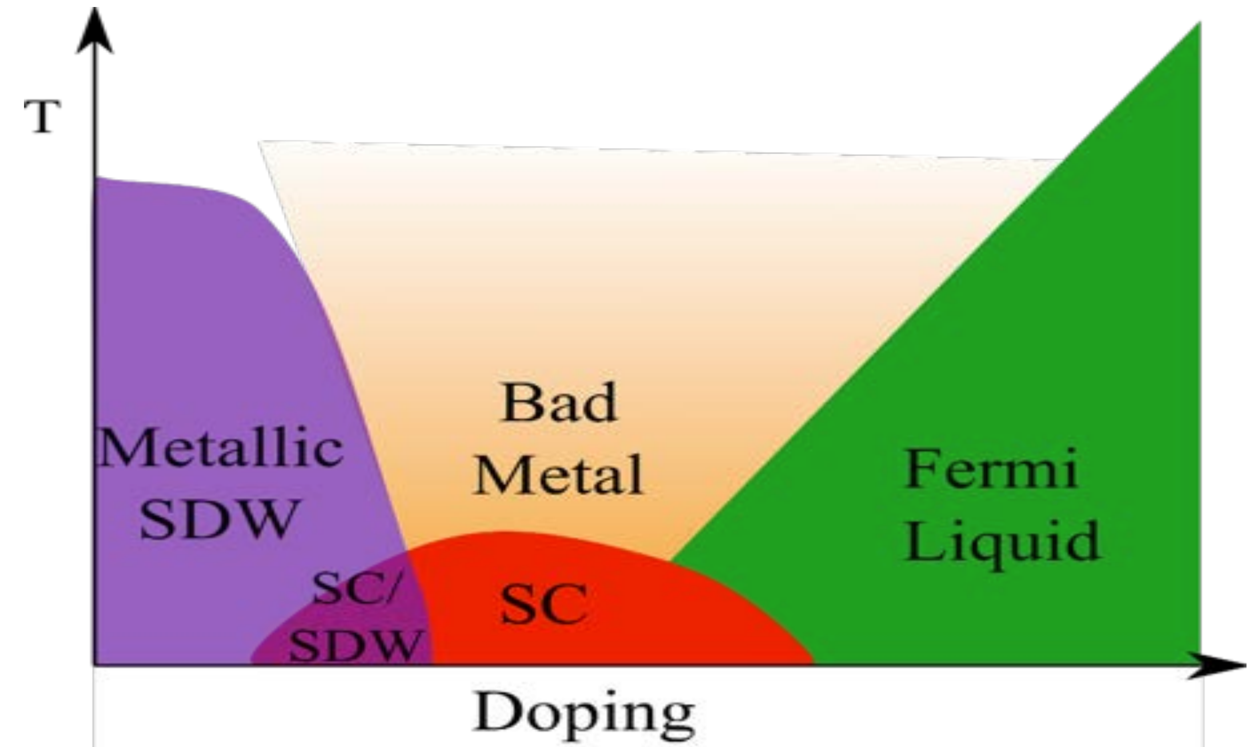




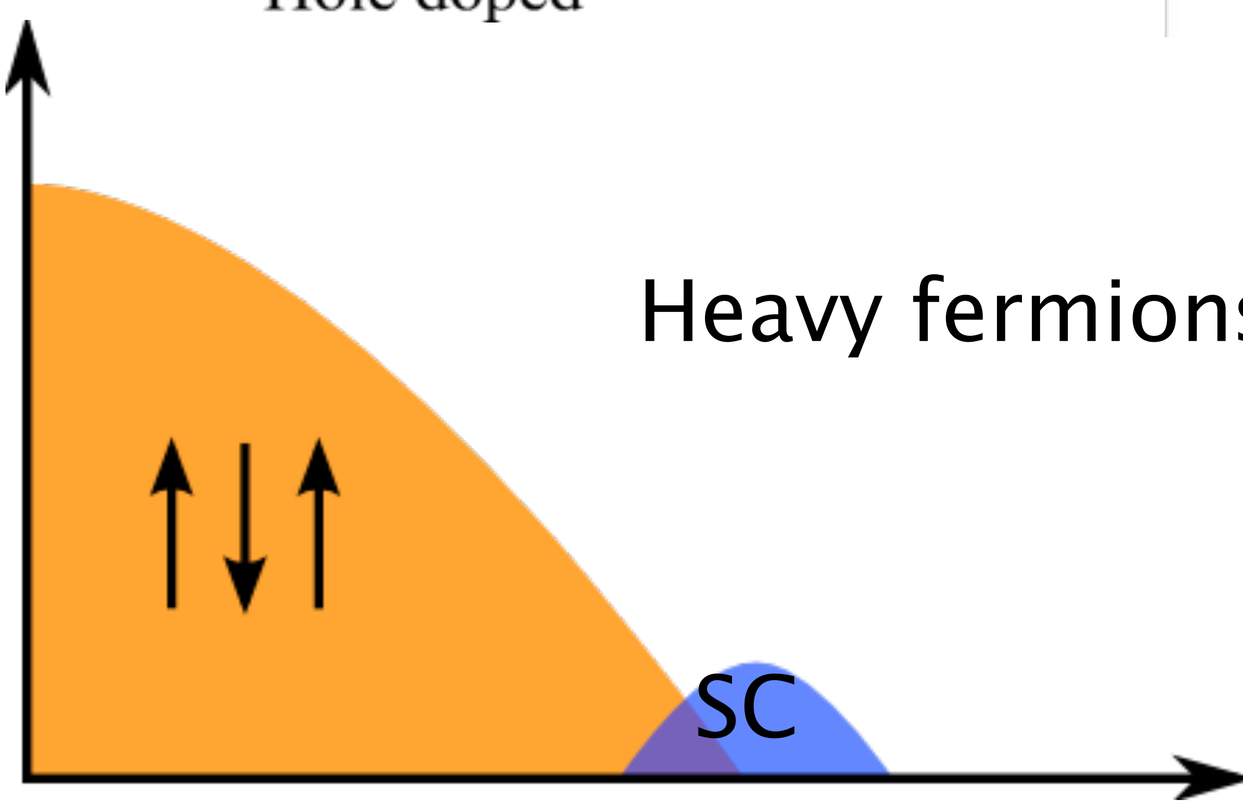
Cuprates

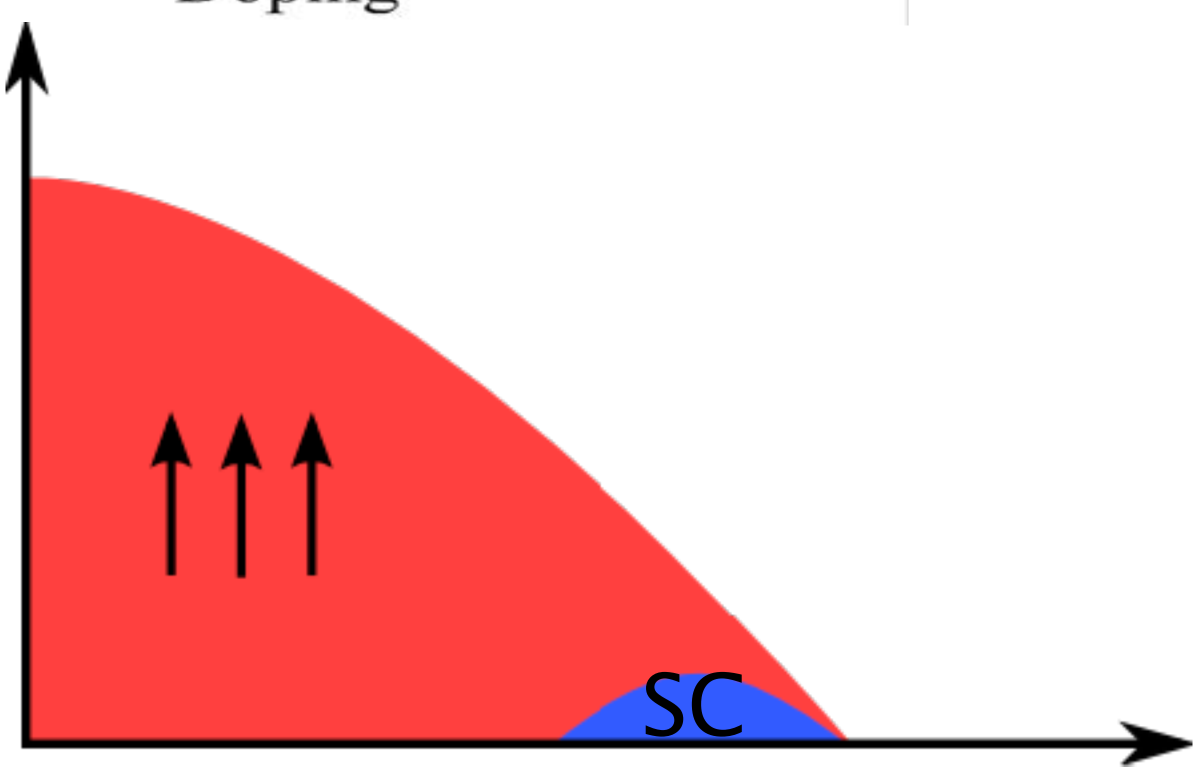


Iron-based superconductors



Heavy fermions





Important Points about HF Materials

Important Points about HF Materials

- Classic strongly correlated materials.

Important Points about HF Materials

- Classic strongly correlated materials.

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.

Important Points about HF Materials

- Classic strongly correlated materials.

- Birth of many ideas - gauge theory approach, d-wave driven by AFM.

- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)

Important Points about HF Materials

- Classic strongly correlated materials.

- Birth of many ideas - gauge theory approach, d-wave driven by AFM.

- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).

- Highly tunable (“Fruit Fly” of correlated e systems)

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)
- Share common behavior with high T_c materials (eg strange metals with linear resistivity)

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable (“Fruit Fly” of correlated e systems)
- Share common behavior with high T_C materials (eg strange metals with linear resistivity)

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)
- Share common behavior with high T_c materials (eg strange metals with linear resistivity)
- Clean separation between conduction and spin degrees of freedom

Important Points about HF Materials

- Classic strongly correlated materials.

- Birth of many ideas - gauge theory approach, d-wave driven by AFM.

- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).

- Highly tunable (“Fruit Fly” of correlated e systems)

- Share common behavior with high T_c materials (eg strange metals with linear resistivity)

- Clean separation between conduction and spin degrees of freedom

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)
- Share common behavior with high T_C materials (eg strange metals with linear resistivity)
- Clean separation between conduction and spin degrees of freedom
- System where gauge theory approach to strongly correlated electrons is reasonably well established.

Important Points about HF Materials

- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)
- Share common behavior with high T_C materials (eg strange metals with linear resistivity)
- Clean separation between conduction and spin degrees of freedom
- System where gauge theory approach to strongly correlated electrons is reasonably well established.

Important Points about HF Materials

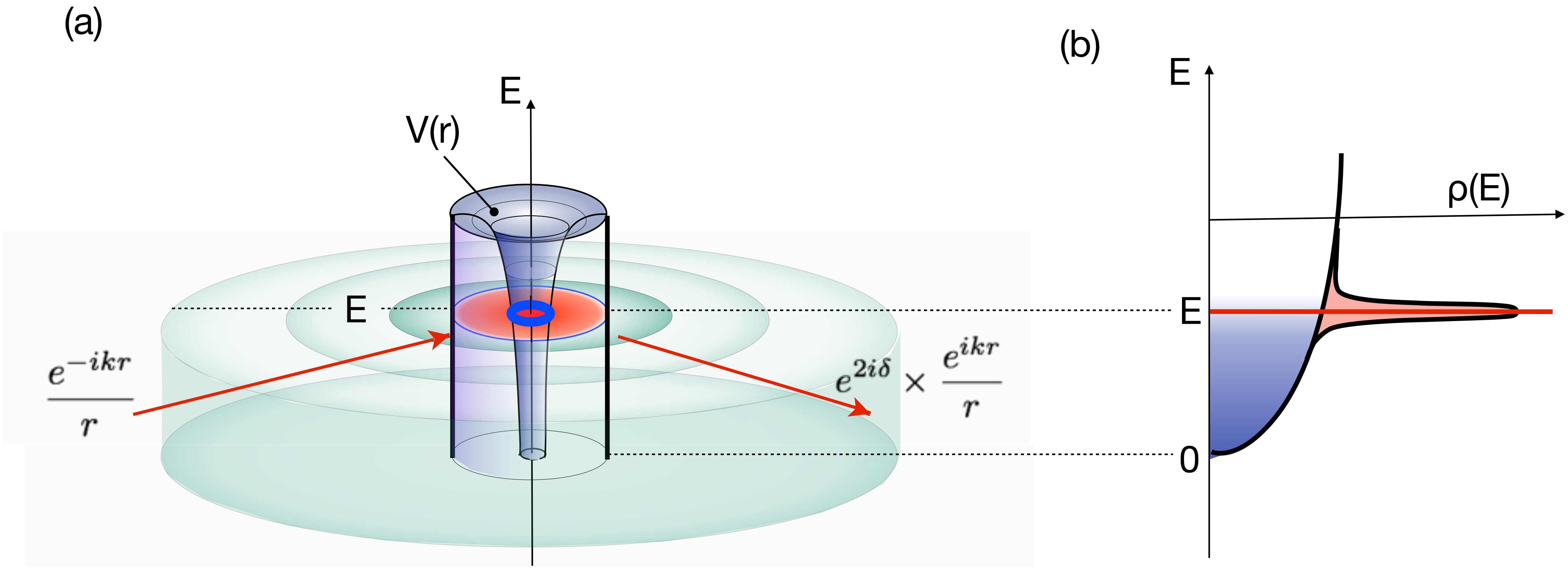
- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable (“Fruit Fly” of correlated e systems)
- Share common behavior with high T_C materials (eg strange metals with linear resistivity)
- Clean separation between conduction and spin degrees of freedom
- System where gauge theory approach to strongly correlated electrons is reasonably well established.

Important Points about HF Materials

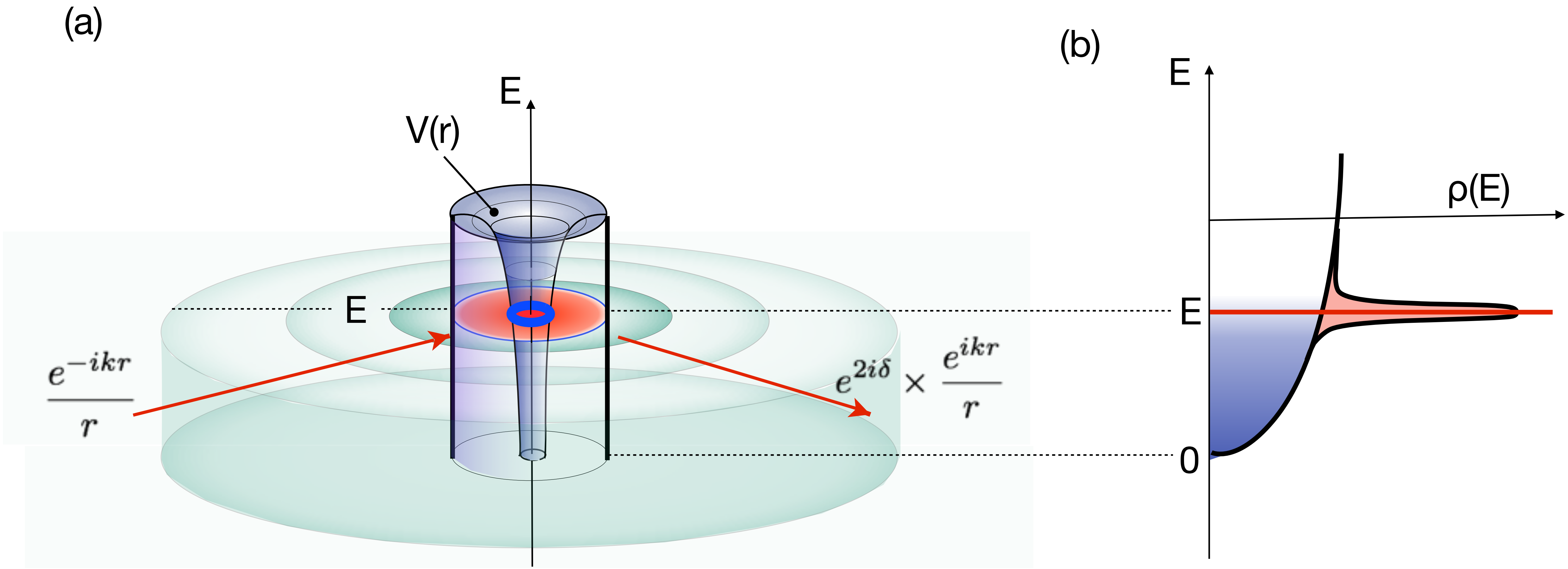
- Classic strongly correlated materials.
- Birth of many ideas - gauge theory approach, d-wave driven by AFM.
- Many families of materials, intermetallics easily synthesized, continue to provide major surprises (eg Topological Kondo insulators).
- Highly tunable ("Fruit Fly" of correlated e systems)
- Share common behavior with high T_C materials (eg strange metals with linear resistivity)
- Clean separation between conduction and spin degrees of freedom
- System where gauge theory approach to strongly correlated electrons is reasonably well established.

Anderson, Kondo and Doniach.

The Anderson Model.

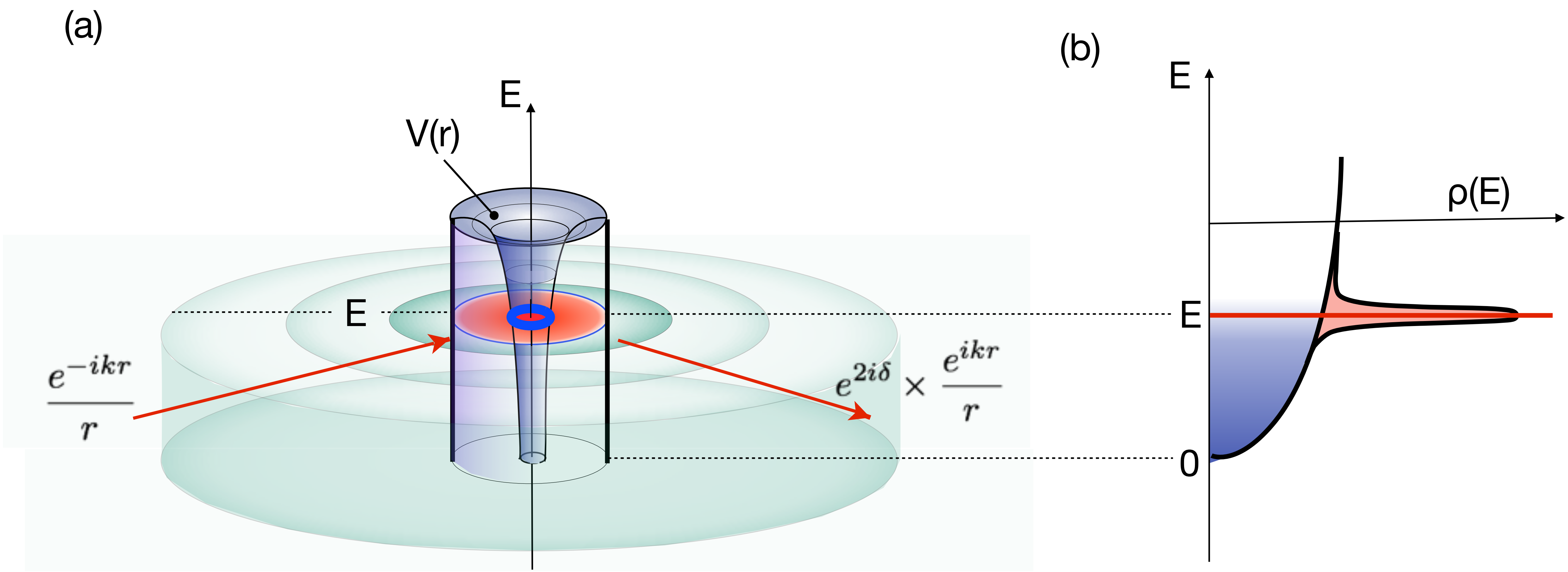


The Anderson Model.



$$H = \overbrace{\sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\sigma} \left[V(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} f_{\sigma} + V^{*}(\mathbf{k}) f^{\dagger}_{\sigma} c_{\mathbf{k}\sigma} \right]}^{H_{resonance}} + \underbrace{E_f n_f + U n_{f\uparrow} n_{f\downarrow}}_{H_{atomic}},$$

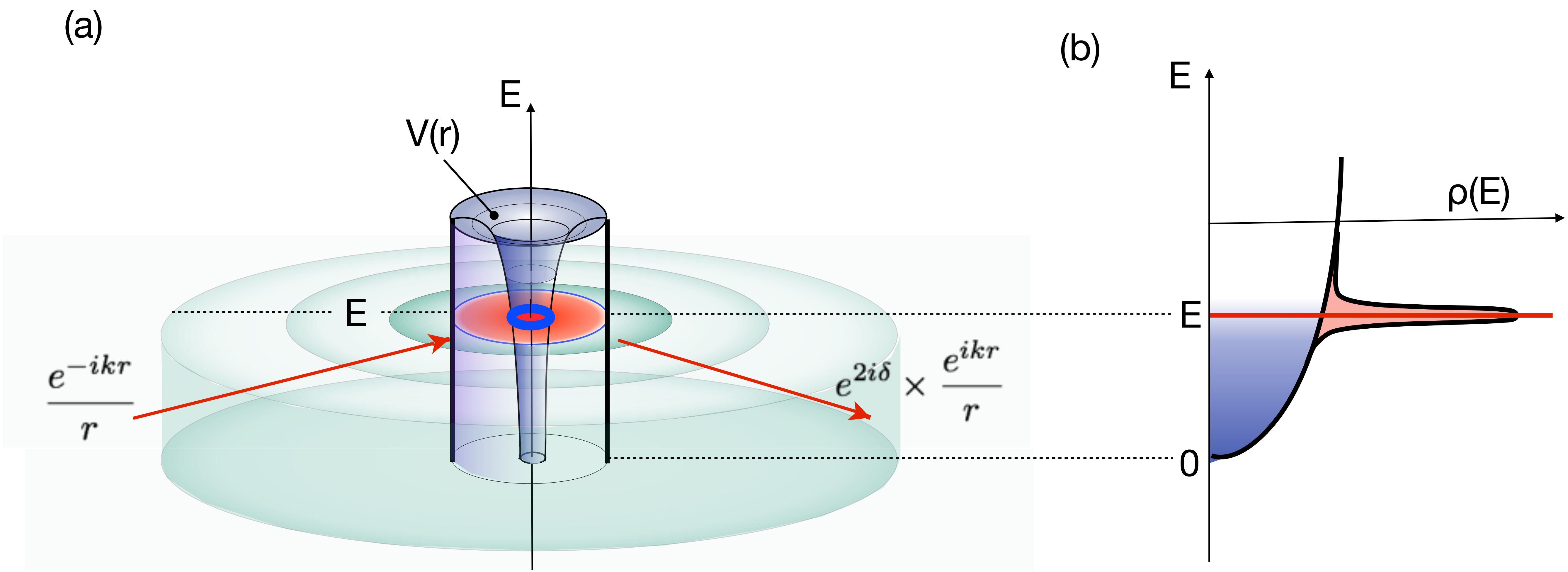
The Anderson Model.



$$H = \overbrace{\sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\sigma} \left[V(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} f_{\sigma} + V^{*}(\mathbf{k}) f^{\dagger}_{\sigma} c_{\mathbf{k}\sigma} \right]}^{H_{resonance}} + \underbrace{E_f n_f + U n_{f\uparrow} n_{f\downarrow}}_{H_{atomic}},$$

$$f^{\dagger}{}_{\sigma} = \int_{\mathbf{r}} \Psi_f(\mathbf{r}) \hat{\psi}^{\dagger}{}_{\sigma}(r),$$

The Anderson Model.



$$H = \overbrace{\sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\sigma} \left[V(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} f_{\sigma} + V^{*}(\mathbf{k}) f^{\dagger}_{\sigma} c_{\mathbf{k}\sigma} \right]}^{H_{resonance}} + \underbrace{E_f n_f + U n_{f\uparrow} n_{f\downarrow}}_{H_{atomic}},$$

$$f^{\dagger}{}_{\sigma} = \int_{\mathbf{r}} \Psi_f(\mathbf{r}) \hat{\psi}^{\dagger}{}_{\sigma}(r),$$

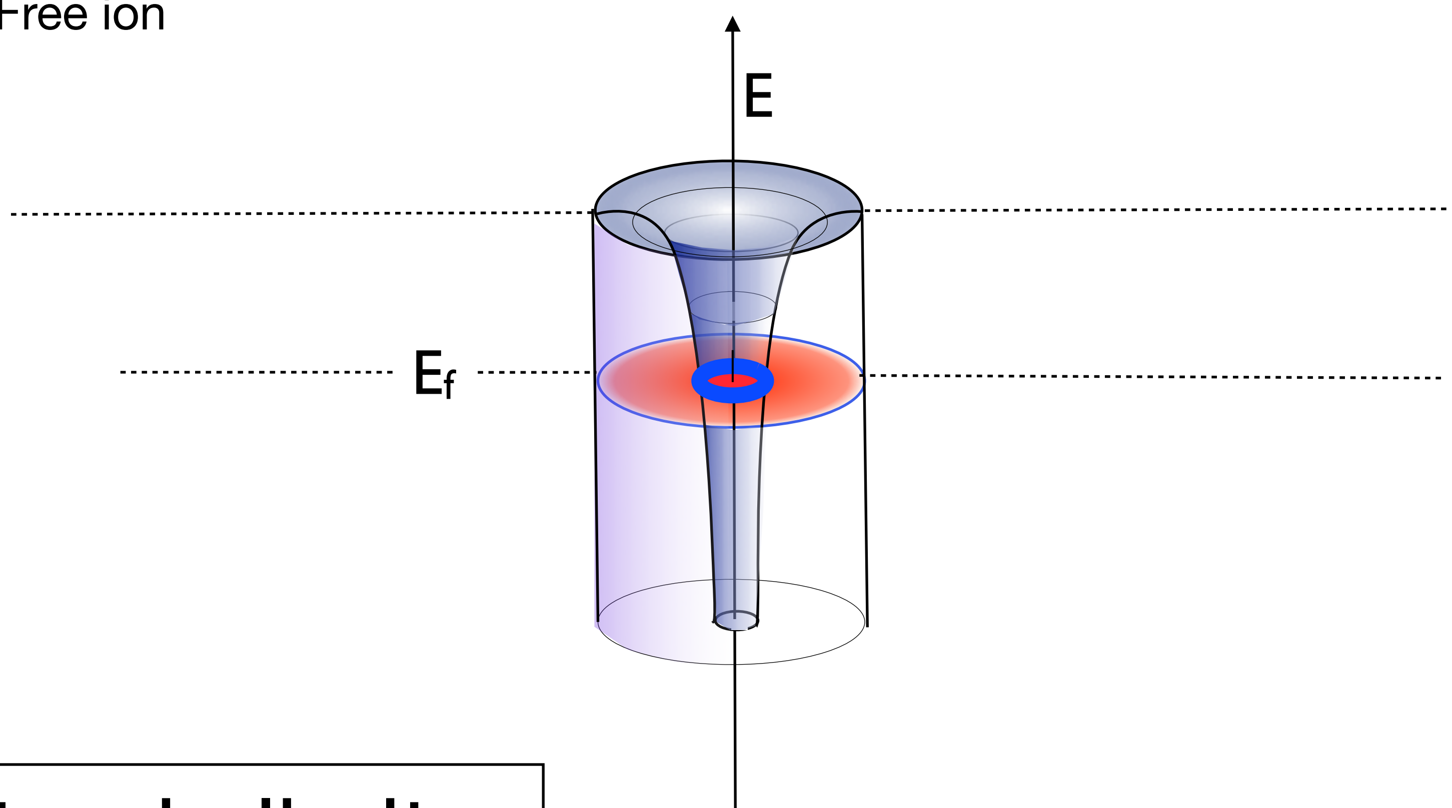
$$U = \frac{e^2}{4\pi\epsilon_0} \int_{\mathbf{r},\mathbf{r}'} \frac{1}{|\mathbf{r}-\mathbf{r}'|} \rho_f(\mathbf{r}) \rho_f(\mathbf{r}')$$

Atomic limit
(V=0)

$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

Free ion

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

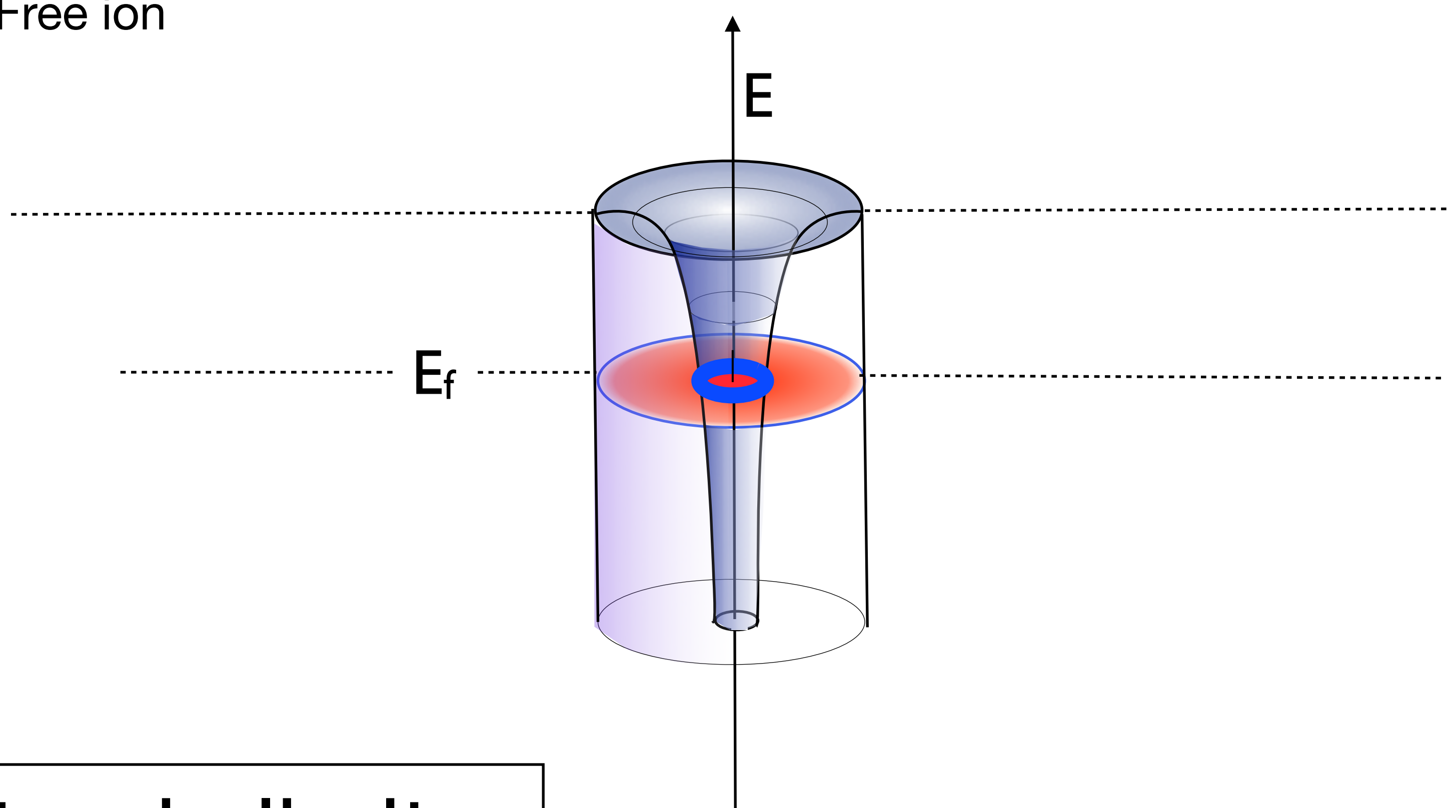


Atomic limit
(V=0)

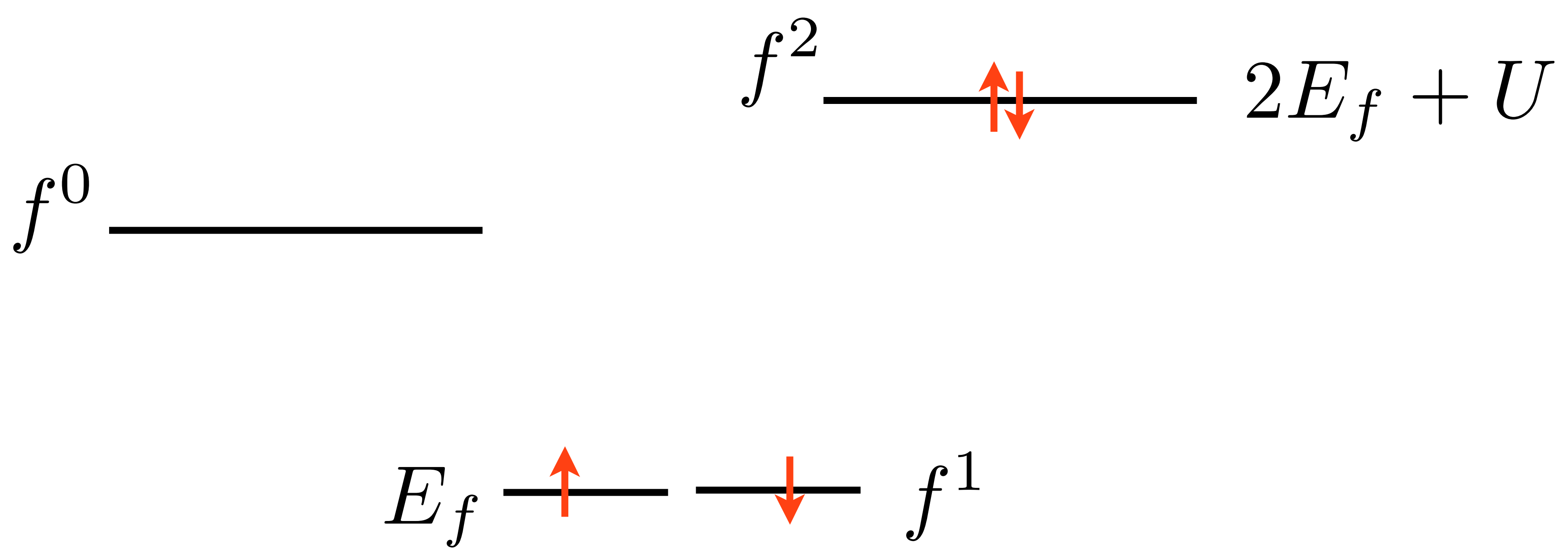
$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion

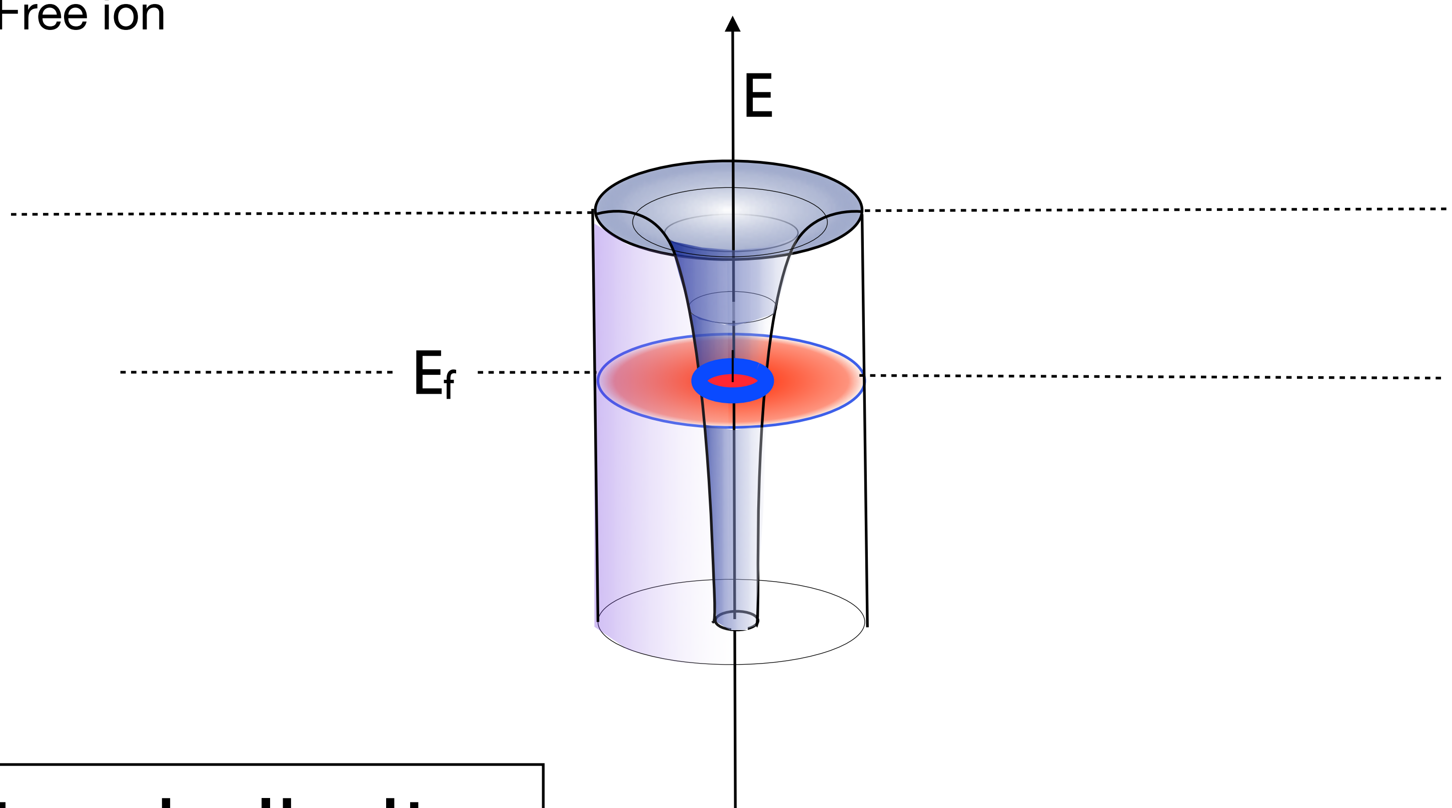


Atomic limit
(V=0)



$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle, \qquad H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion



Atomic limit (V=0)

f^2 — $2E_f + U$

f^0

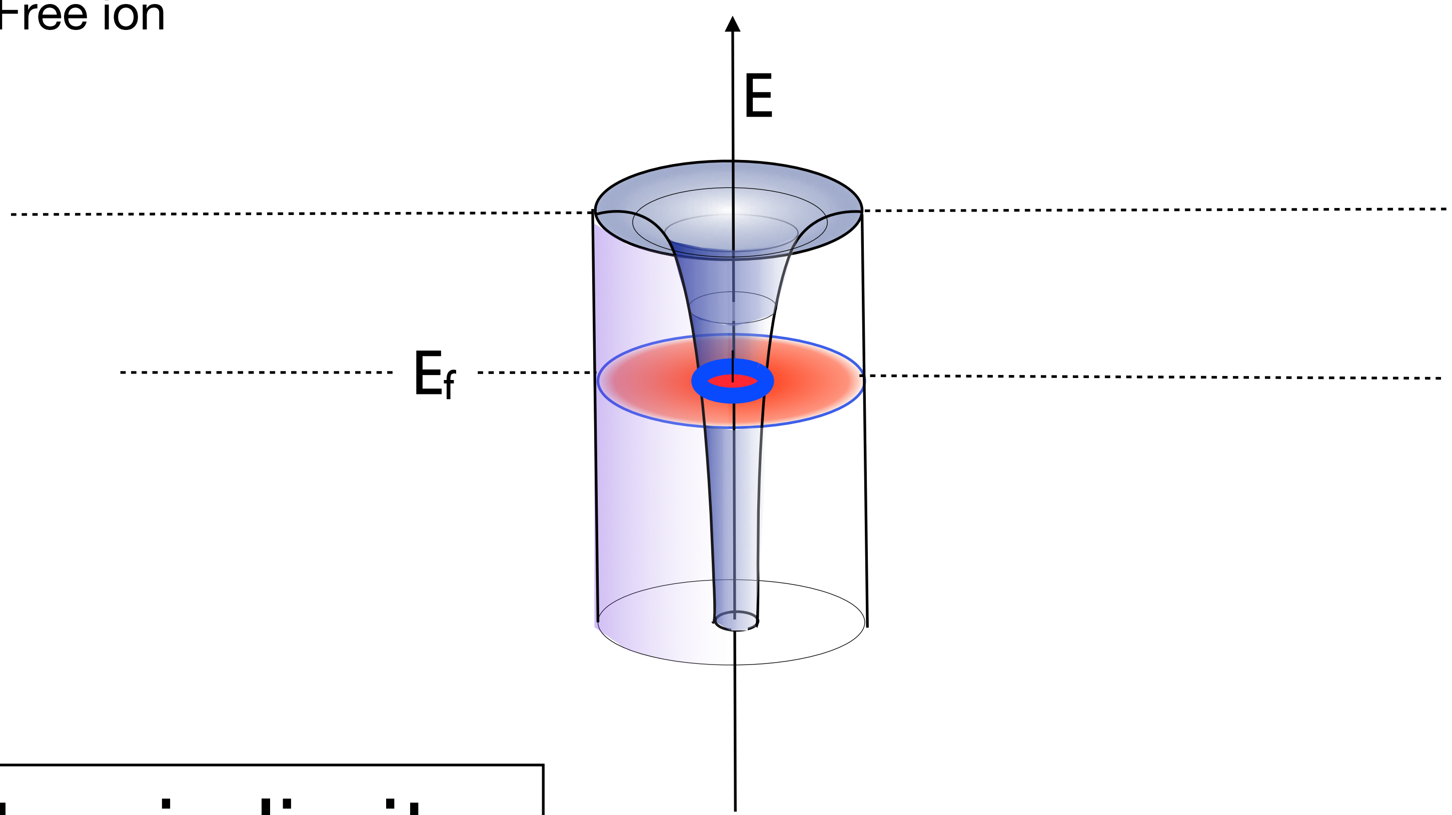
E_f — f^1

$$\left.\begin{array}{rcl} E_f & < & 0 \\ U + E_f & > & 0 \end{array}\right\}$$

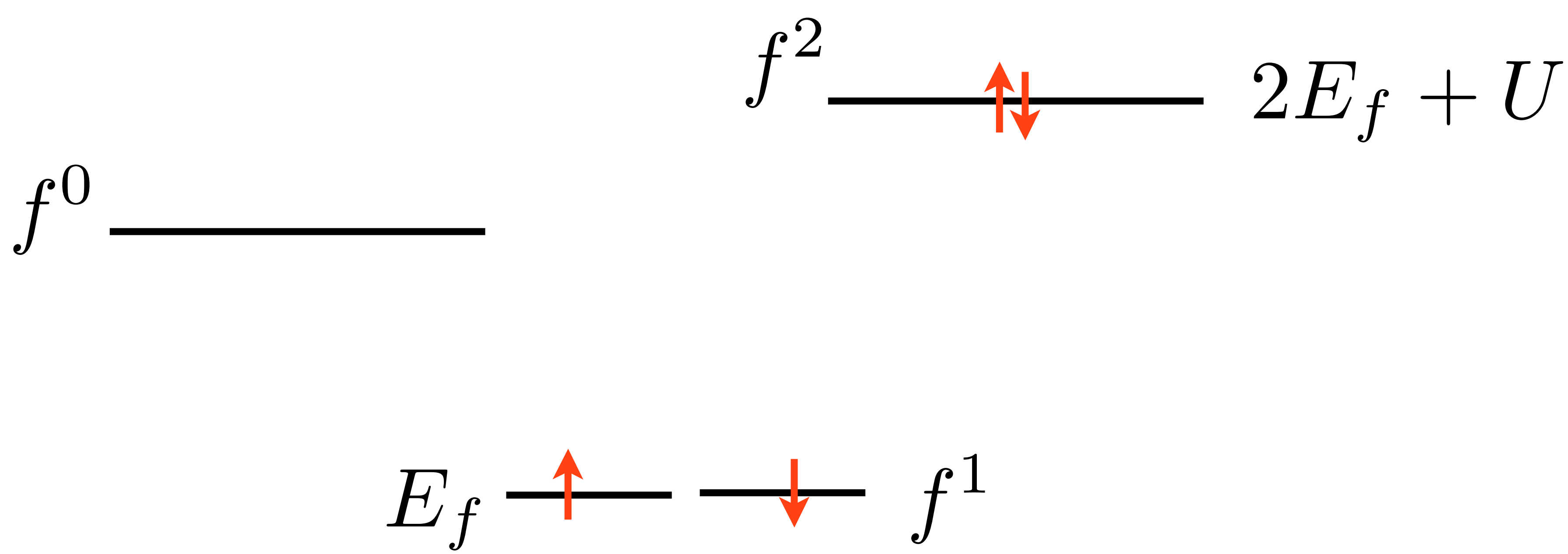
$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion



Atomic limit
(V=0)

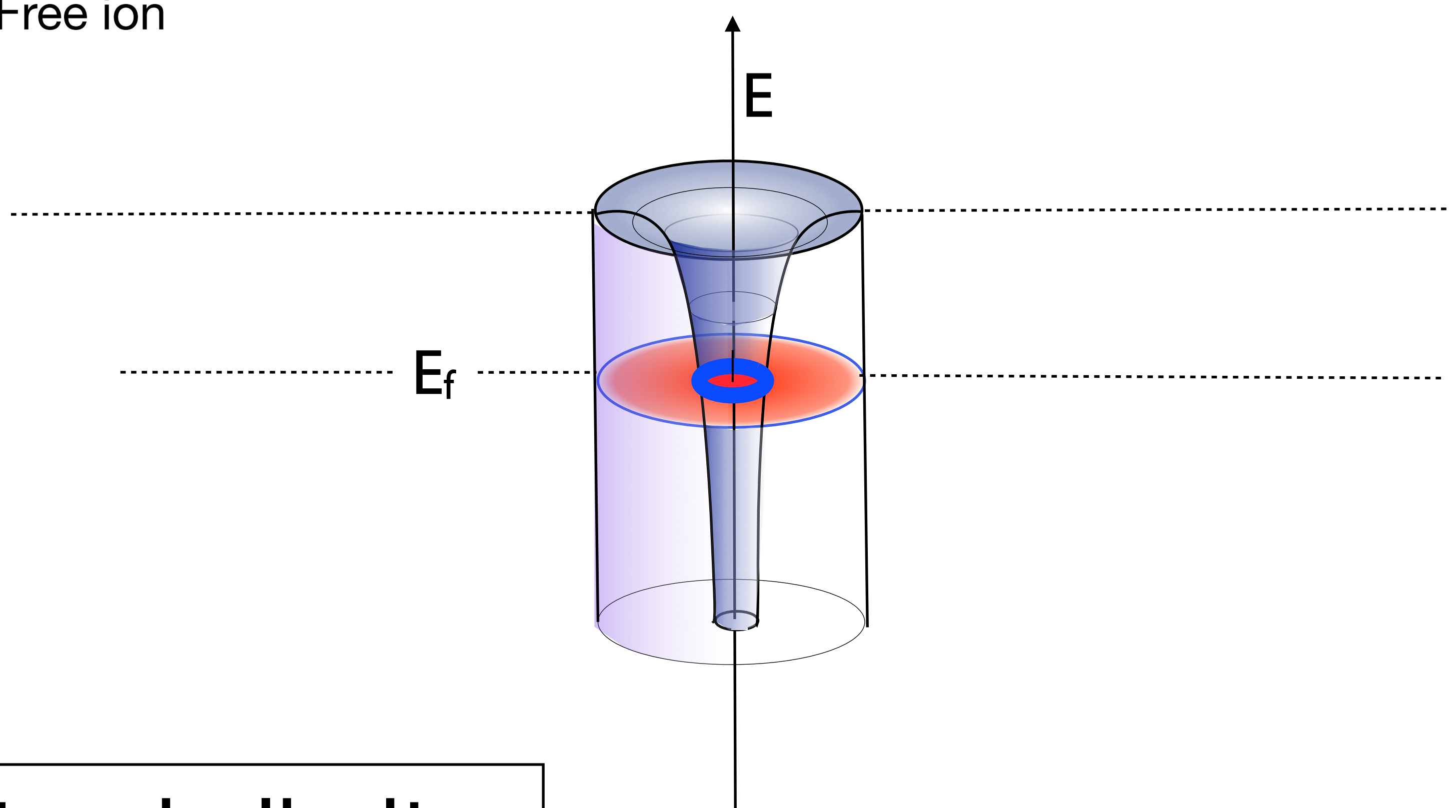


$$\left.\begin{array}{rcl} E_f & < & 0 \\ U + E_f & > & 0 \end{array}\right\} \Rightarrow \left\{\begin{array}{rcl} E_f + U/2 & < & U/2 \\ U/2 & > & -(E_f + U/2) \end{array}\right.$$

$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion



Atomic limit
(V=0)

f^2 ↑↓ $2E_f + U$

f^0

E_f ↑ ↓ f^1

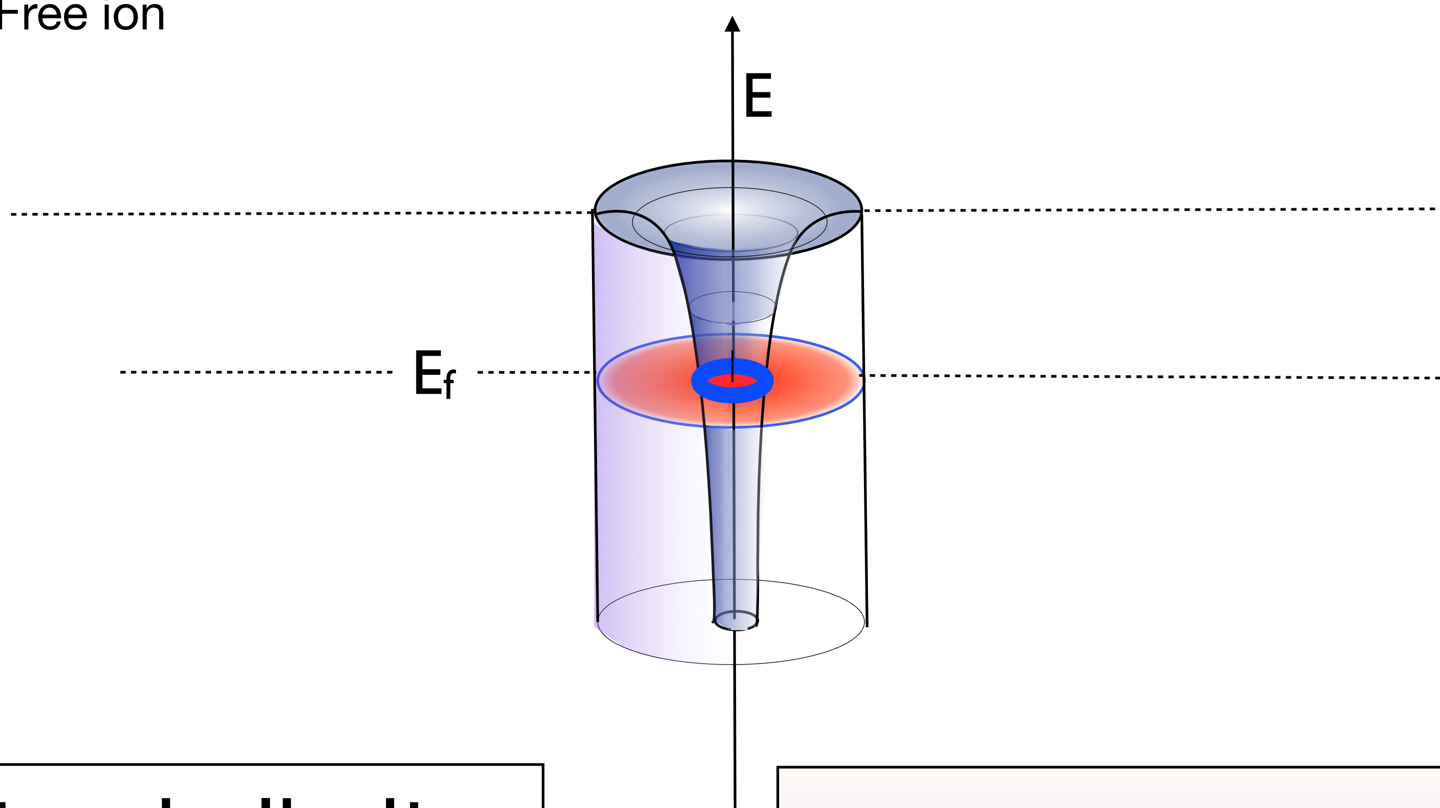
$U/2 > |E_f + U/2|$

Magnetic GS

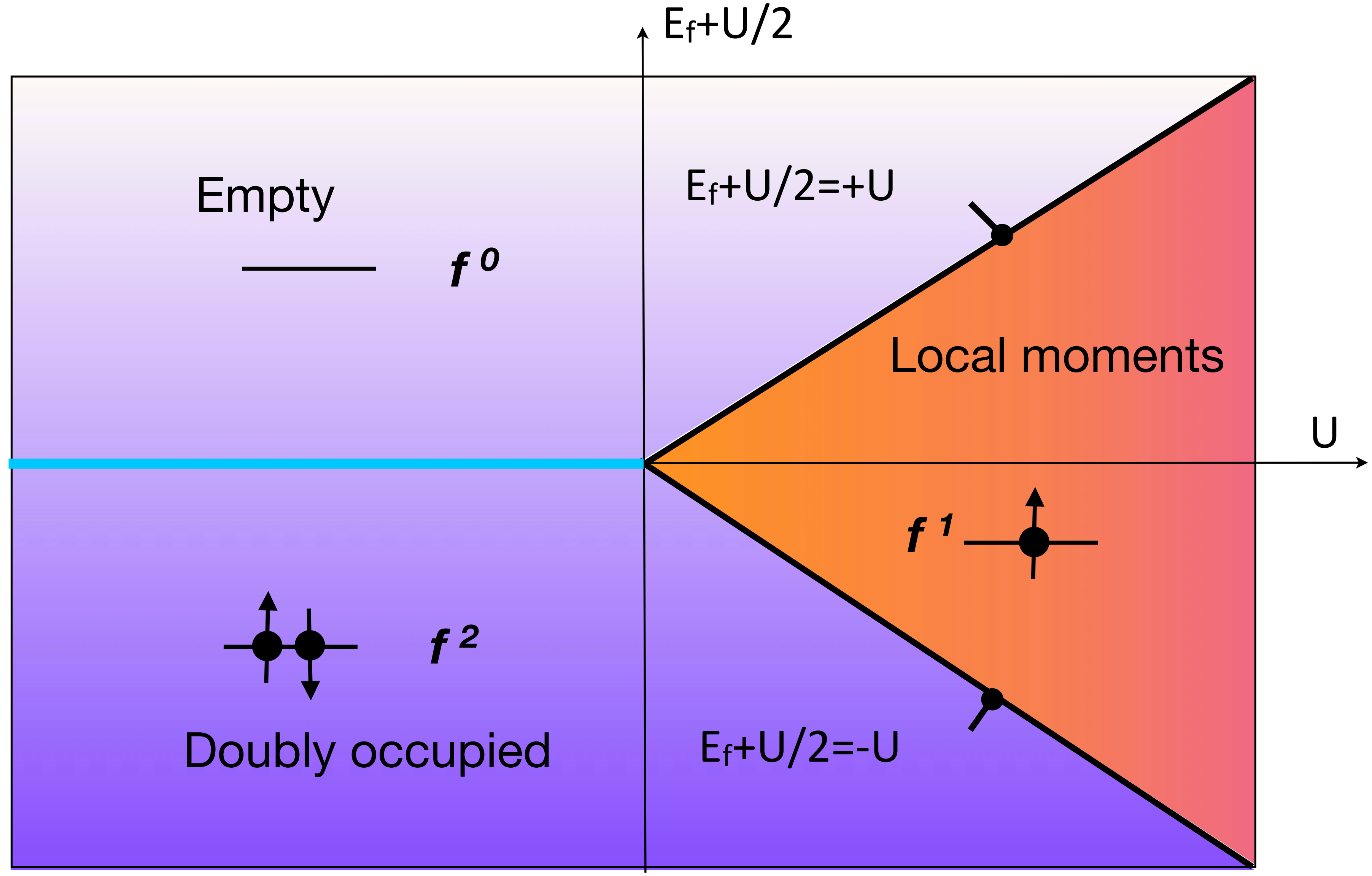
$$\left.\begin{array}{rcl} E_f & < & 0 \\ U + E_f & > & 0 \end{array}\right\} \Rightarrow \left\{\begin{array}{rcl} E_f + U/2 & < & U/2 \\ U/2 & > & -(E_f + U/2) \end{array}\right.$$

$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle, \qquad H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion



Atomic limit
(V=0)

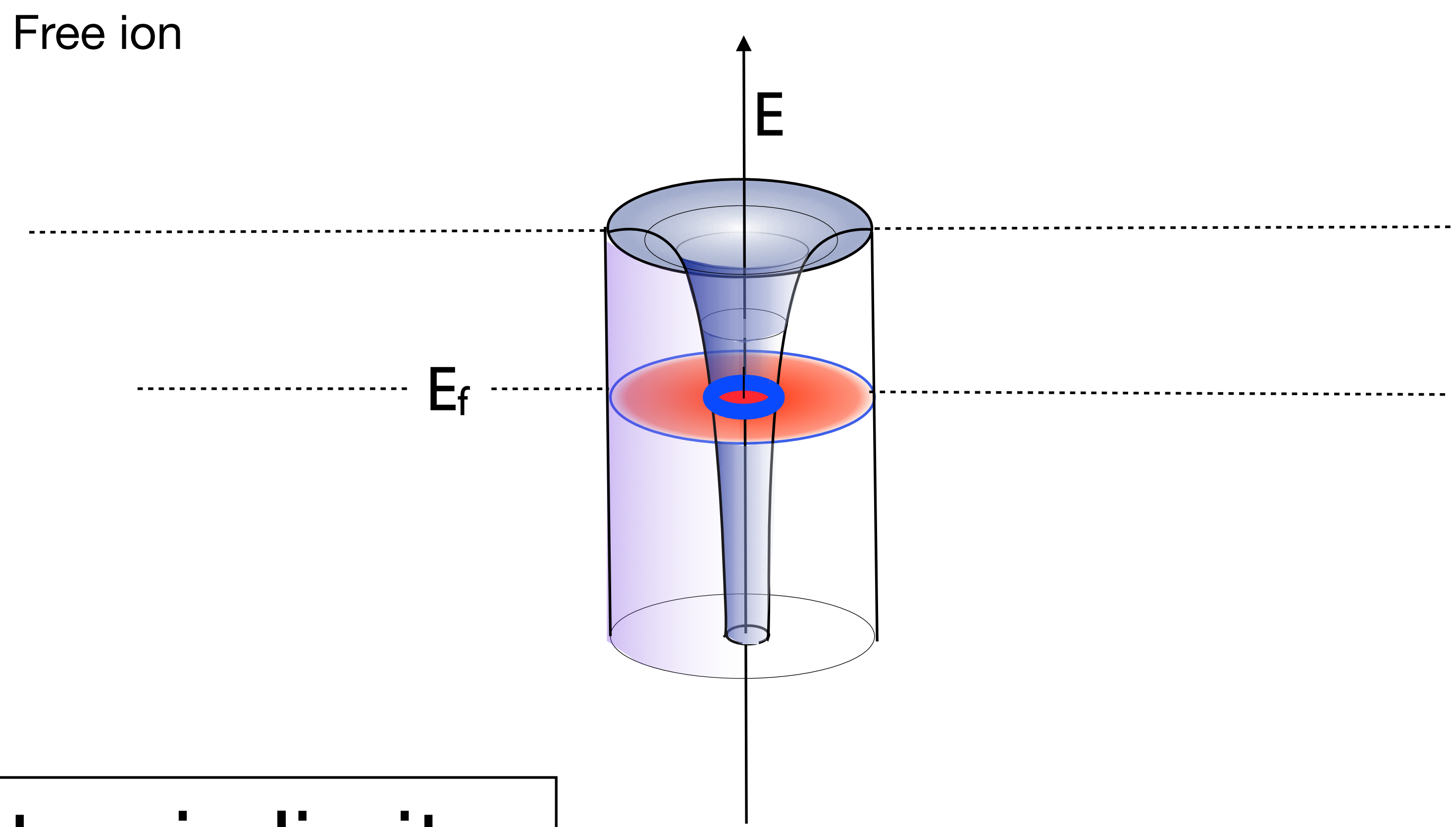


$U/2 > |E_f + U/2|$

Magnetic GS

$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$



Atomic limit
(V=0)

f^2 ——↑↓—— $2E_f + U$

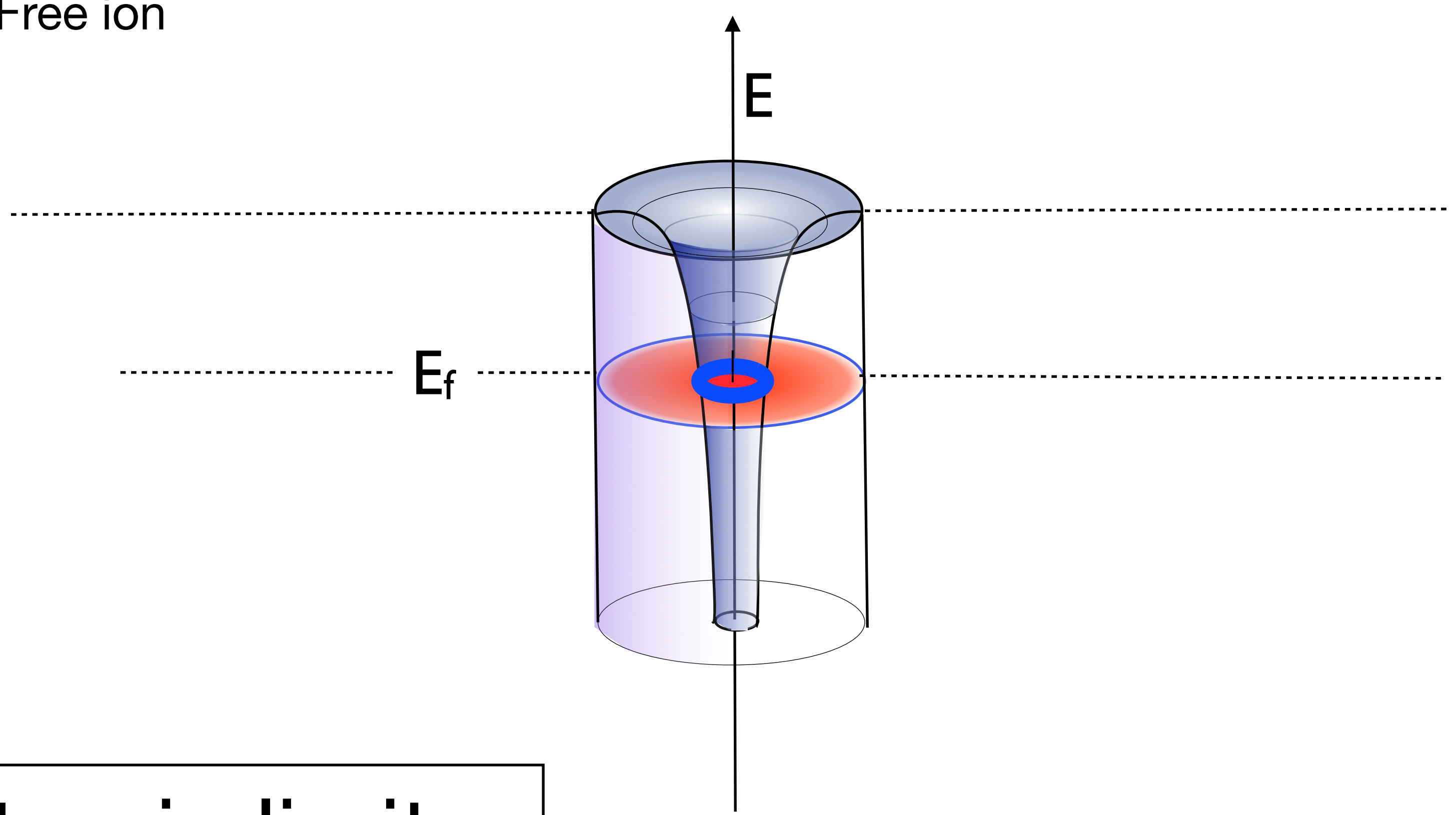
f^0 ————

E_f —↑— —↓— f^1

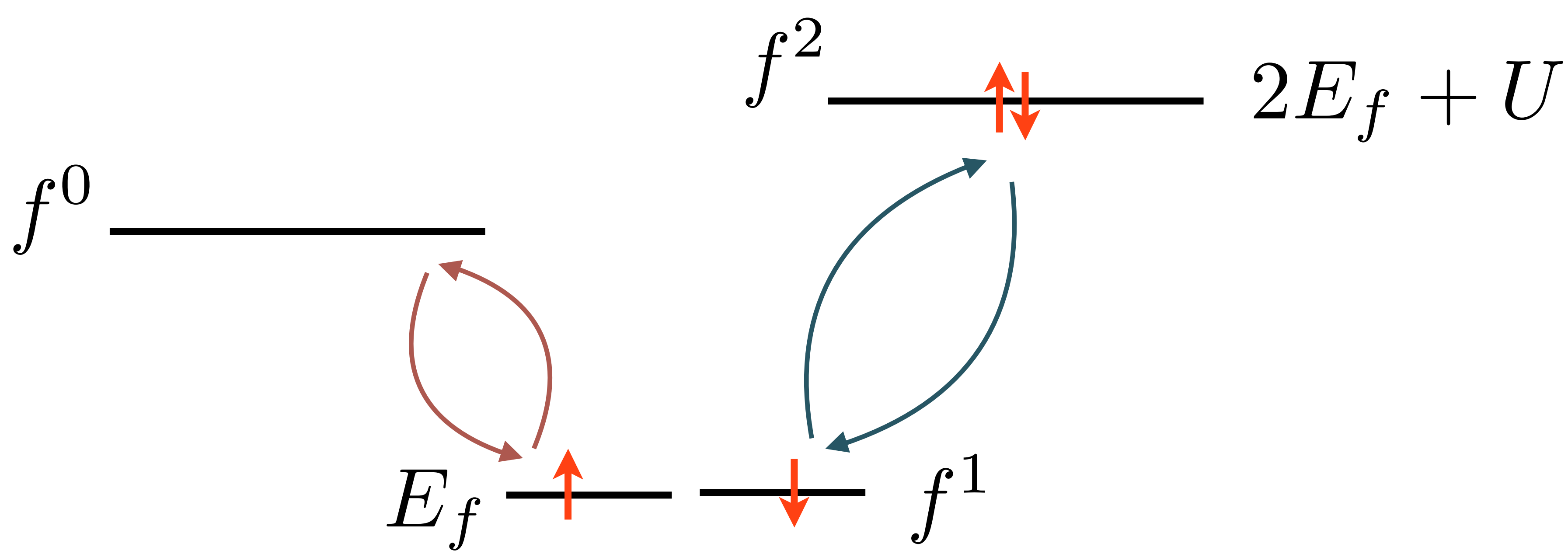
$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion

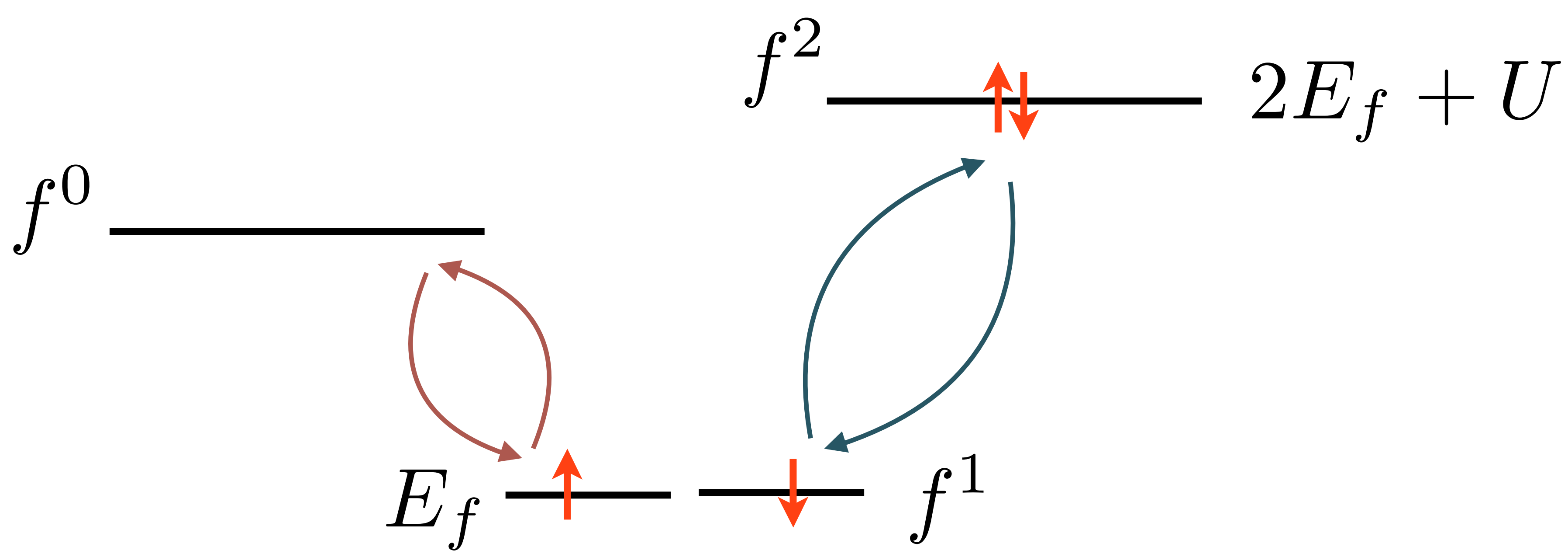


Atomic limit
(V=0)



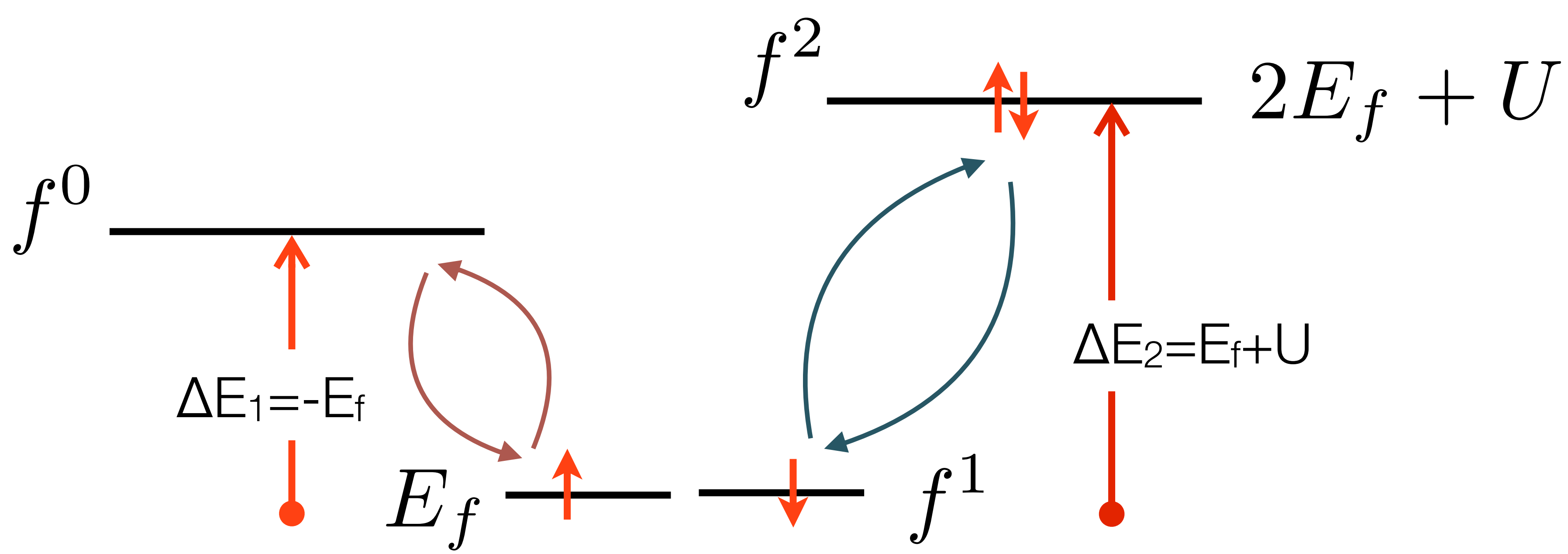
Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.



Virtual Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

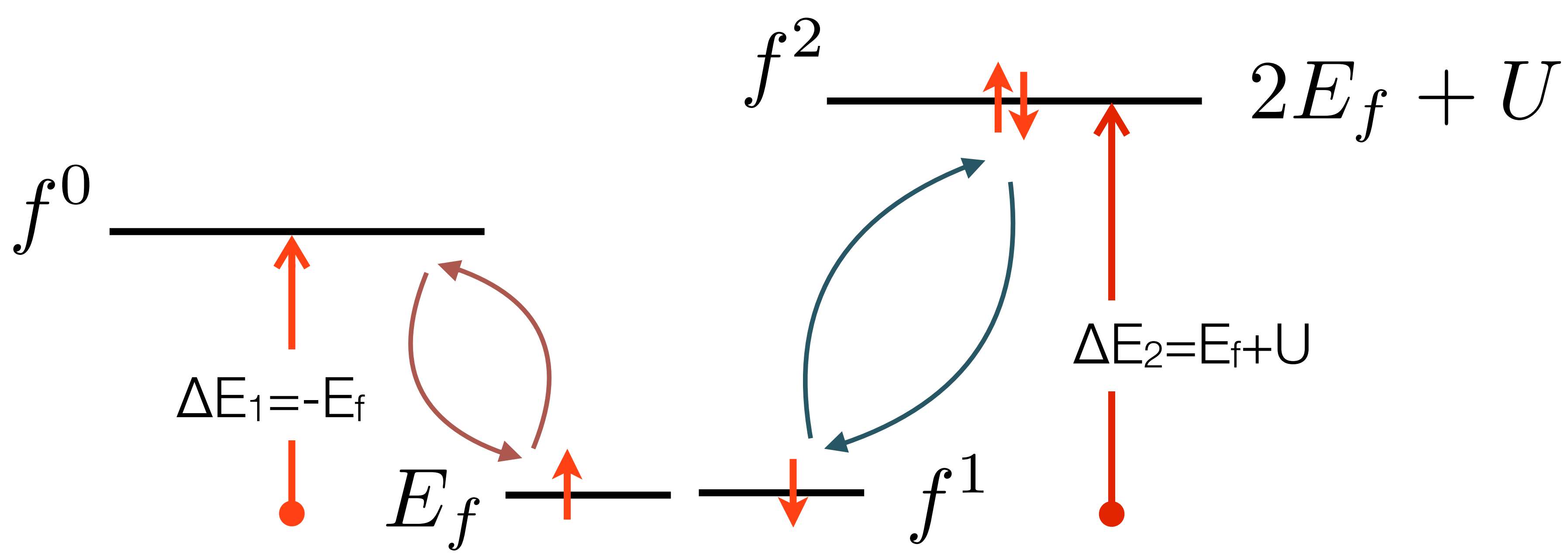


Virtual Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

Virtual Valence fluctuations in the singlet channel, induced by hybridization

$$e^-_\uparrow + f^1_\downarrow \leftrightarrow f^2 \leftrightarrow e^-_\downarrow + f^1_\uparrow \qquad \Delta E_I \sim U + E_f$$
$$h^+_\uparrow + f^1_\downarrow \leftrightarrow f^0 \leftrightarrow h^+_\downarrow + f^1_\uparrow \qquad \Delta E_{II} \sim -E_f$$



Virtual Valence Fluctuations

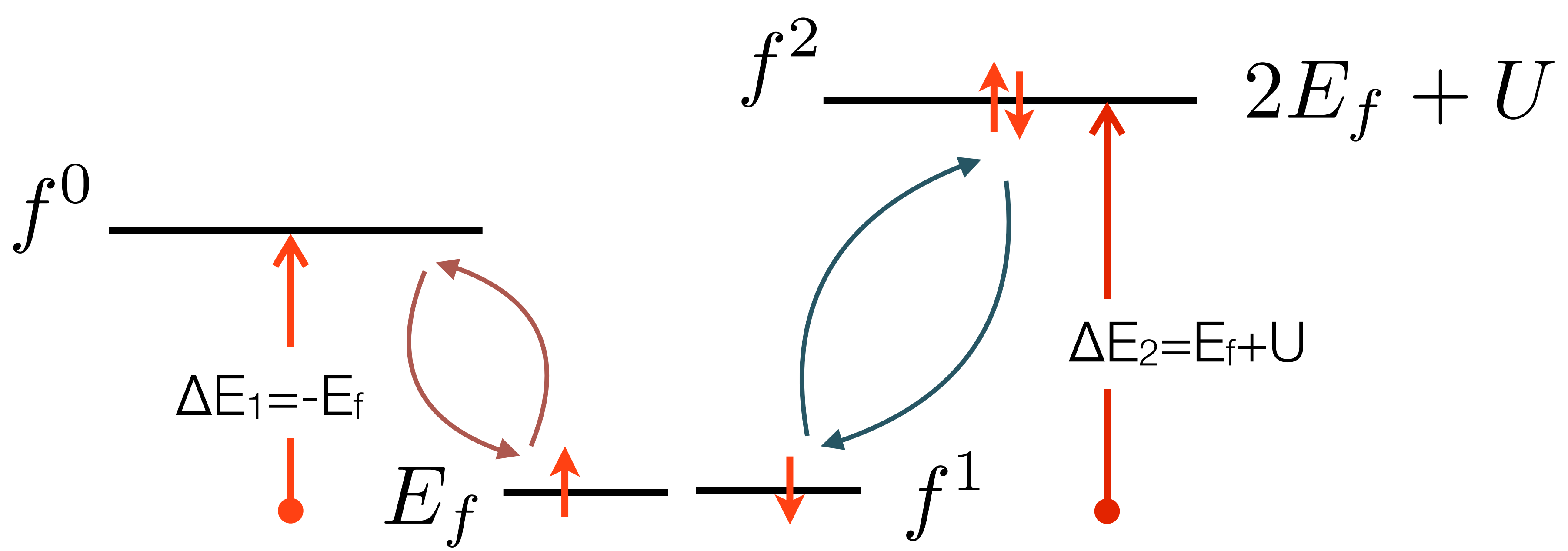
Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

Virtual Valence fluctuations in the singlet channel, induced by hybridization

$$e^-_\uparrow + f^1_\downarrow \leftrightarrow f^2 \leftrightarrow e^-_\downarrow + f^1_\uparrow \qquad \Delta E_I \sim U + E_f$$
$$h^+_\uparrow + f^1_\downarrow \leftrightarrow f^0 \leftrightarrow h^+_\downarrow + f^1_\uparrow \qquad \Delta E_{II} \sim -E_f$$

From second order perturbation theory, the energy of c-f singlets reduces by an amount 2J, where

$$J = V^2\left[\frac{1}{\Delta E_1} + \frac{1}{\Delta E_2}\right]$$



Virtual Valence Fluctuations

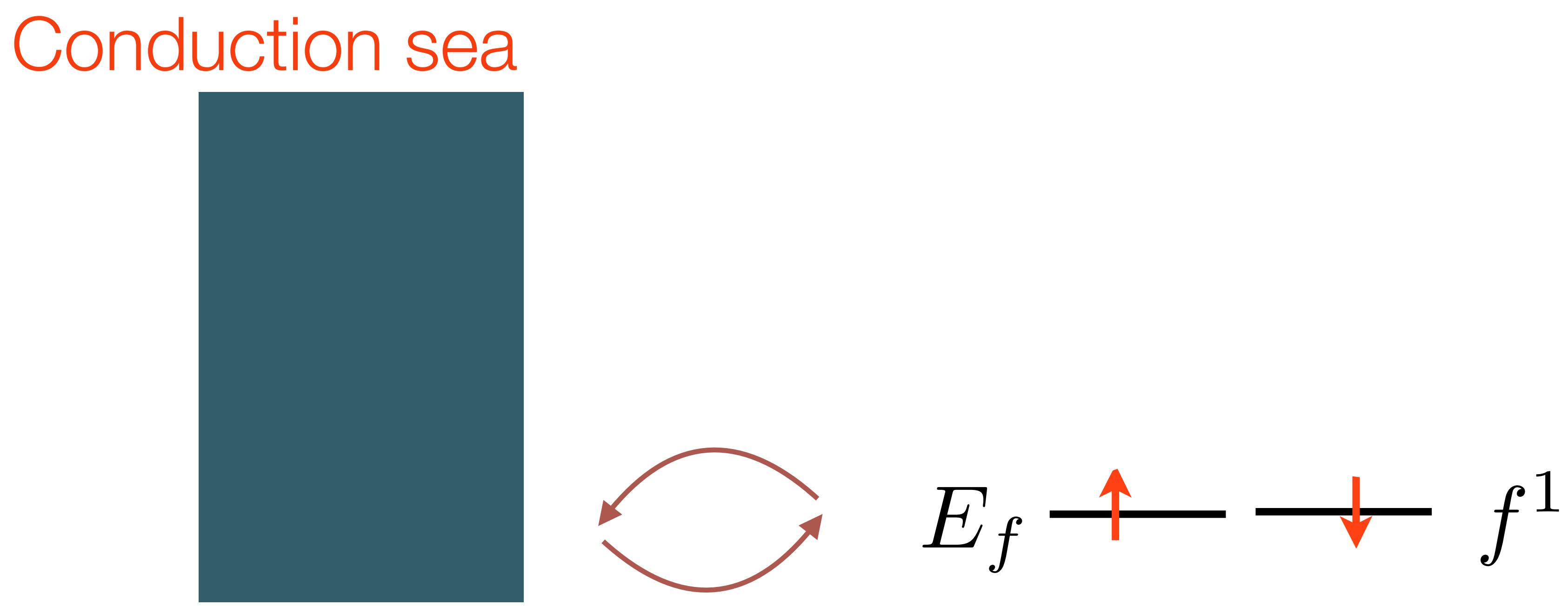
Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

Virtual Valence fluctuations in the singlet channel, induced by hybridization

$$e^-_\uparrow + f^1_\downarrow \leftrightarrow f^2 \leftrightarrow e^-_\downarrow + f^1_\uparrow \qquad \Delta E_I \sim U + E_f$$
$$h^+_\uparrow + f^1_\downarrow \leftrightarrow f^0 \leftrightarrow h^+_\downarrow + f^1_\uparrow \qquad \Delta E_{II} \sim -E_f$$

From second order perturbation theory, the energy of c-f singlets reduces by an amount 2J, where

$$J = V^2 \left[\frac{1}{\Delta E_1} + \frac{1}{\Delta E_2} \right]$$

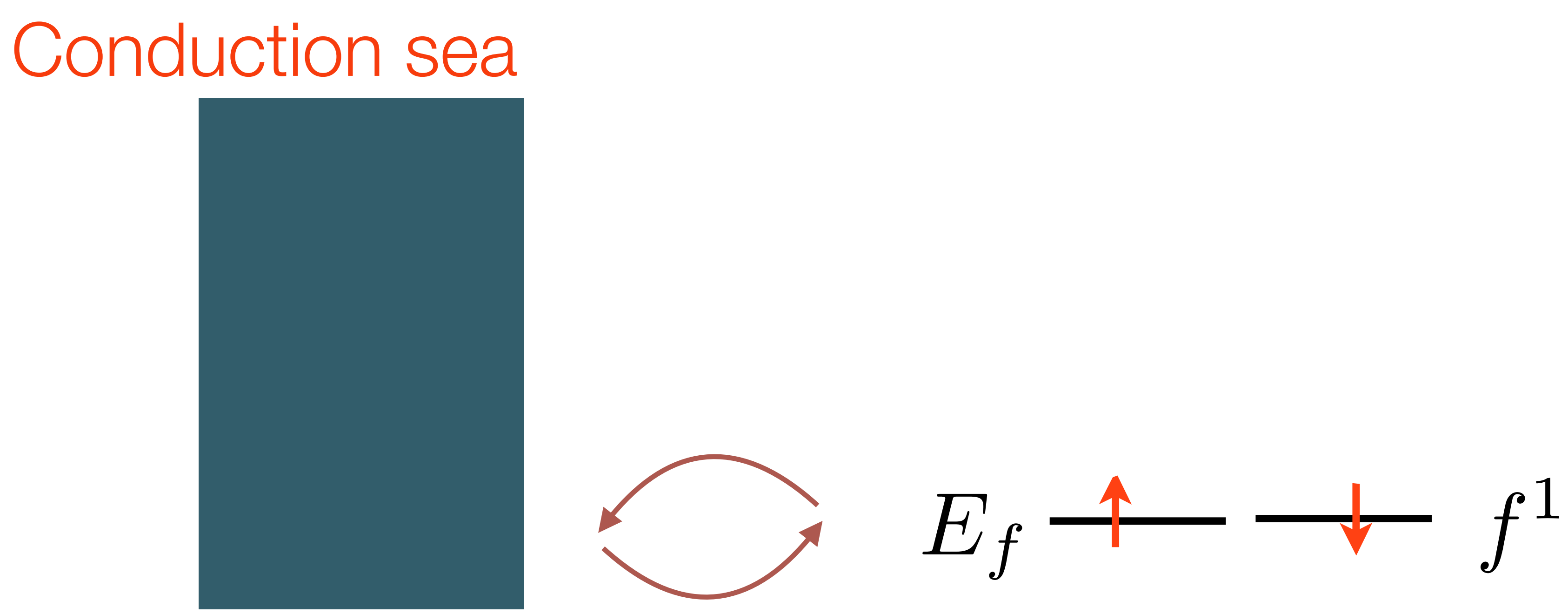


$$H_K = -2JP_{S=0} = -2J\left[\frac{1}{4} - \frac{1}{2}\vec{\sigma}_c(0)\cdot\vec{S}_f\right] \to J\vec{\sigma}_c(0)\cdot\vec{S}_f$$

Antiferromagnetic Kondo interaction

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{\mathcal{N}} \sum_{j} \vec{S}_j \cdot c^{\dagger}_{\mathbf{k}\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}'\beta} e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$



$$H_K = -2JP_{S=0} = -2J\left[\frac{1}{4} - \frac{1}{2}\vec{\sigma}_c(0)\cdot\vec{S}_f\right] \rightarrow J\vec{\sigma}_c(0)\cdot\vec{S}_f$$

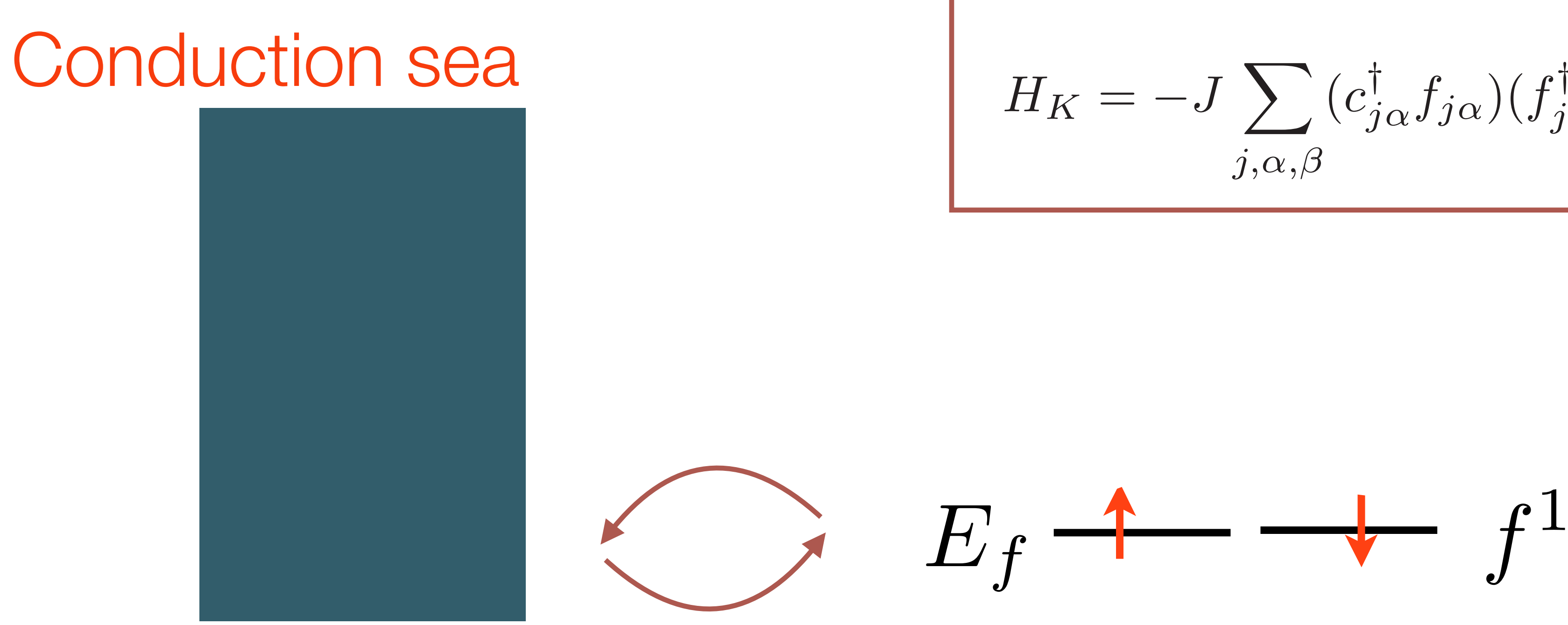
Antiferromagnetic Kondo interaction

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

$$H=\sum_{\mathbf{k}\sigma}\epsilon_{\mathbf{k}}c^{\dagger}_{\mathbf{k}\sigma}c_{\mathbf{k}\sigma}+\frac{J}{\mathcal{N}}\sum_{j}\vec{S}_j\cdot c^{\dagger}_{\mathbf{k}\alpha}\vec{\sigma}_{\alpha\beta}c_{\mathbf{k}'\beta}e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$

Note: can also write Kondo interaction in the “Coqblin Schrieffer” form

$$H_K=-J\sum_{j,\alpha,\beta}(c^{\dagger}_{j\alpha}f_{j\alpha})(f^{\dagger}_{j\beta}c_{j\beta})$$



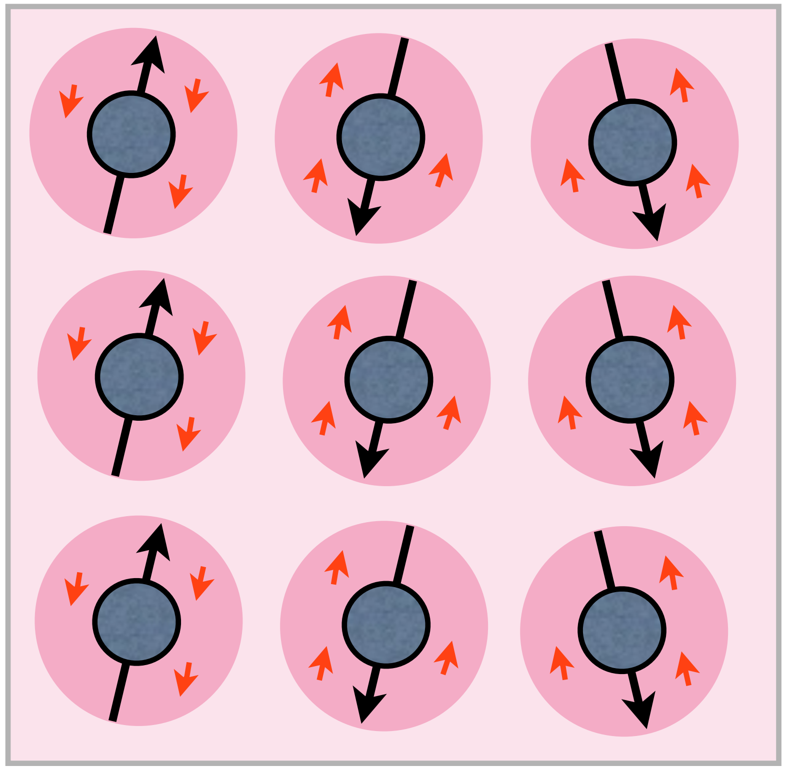
$$H_K=-2JP_{S=0}=-2J\left[\frac{1}{4}-\frac{1}{2}\vec{\sigma}_c(0)\cdot\vec{S}_f\right]\rightarrow J\vec{\sigma}_c(0)\cdot\vec{S}_f$$

Antiferromagnetic Kondo interaction

THE KONDO LATTICE

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{\mathcal{N}} \sum_{j} \vec{S}_j \cdot c^{\dagger}_{\mathbf{k}\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}'\beta} e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$

T. Kasuya (1951)



“Kondo Lattice”

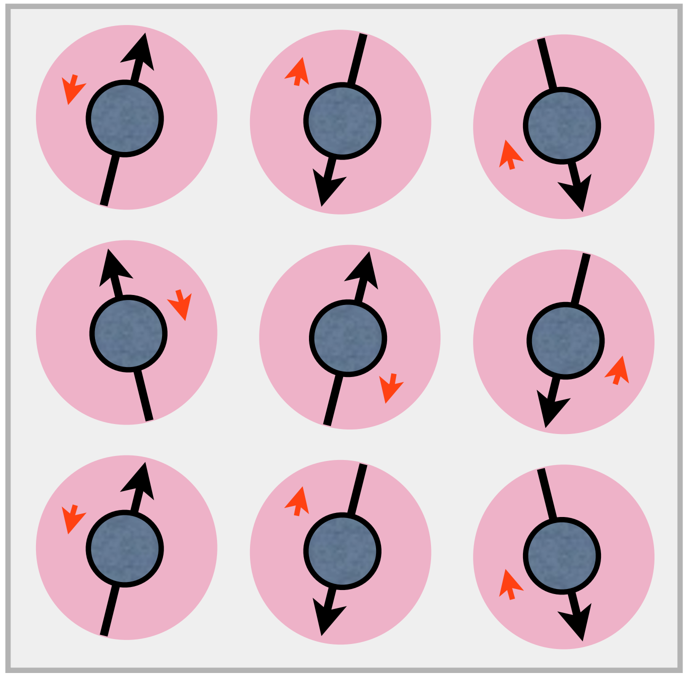
Doniach Hypothesis.

Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$

Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \text{H.c})$$

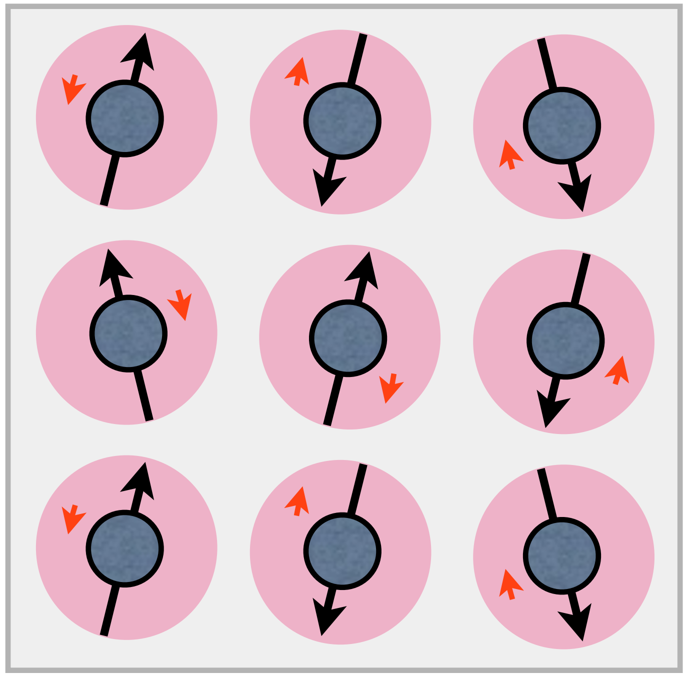


$n_e = n_{\text{spins}}$

Kondo insulator

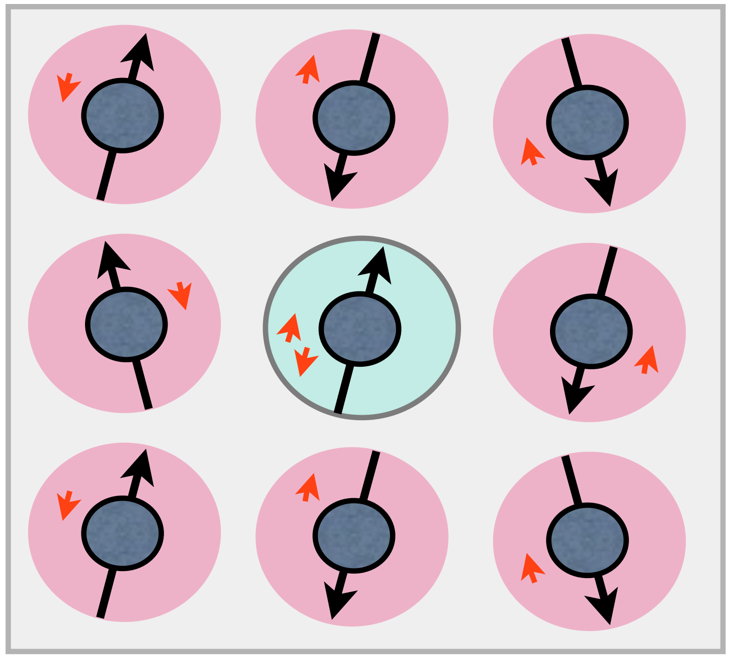
Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$



$n_e = n_{\rm spins}$

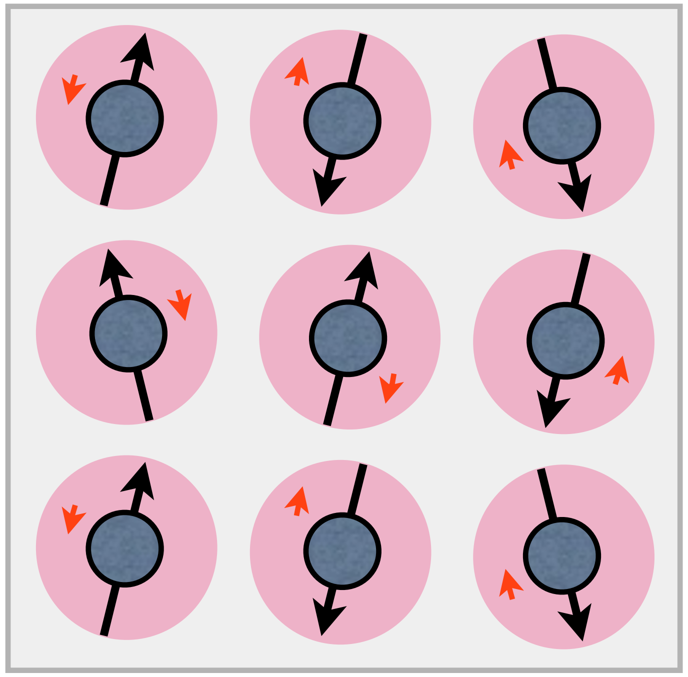
Kondo insulator



Electron doping

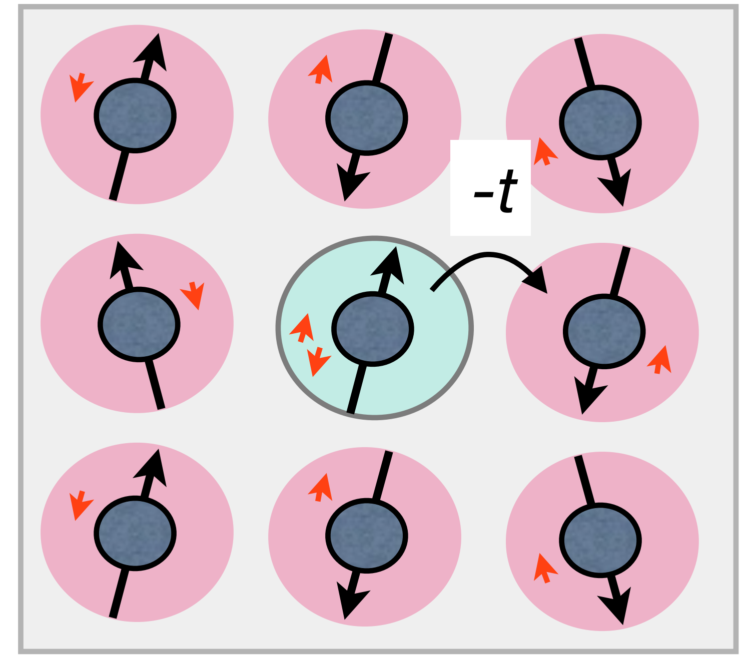
Strong coupling Kondo Lattice $J >> t$

$$H = J\sum \vec{\sigma}(j)\cdot\vec{S}_j - t\sum_{(i,j)}(c^{\dagger}_{i\sigma}c_{j\sigma} + \mathrm{H.c})$$



$n_e = n_{\text{spins}}$

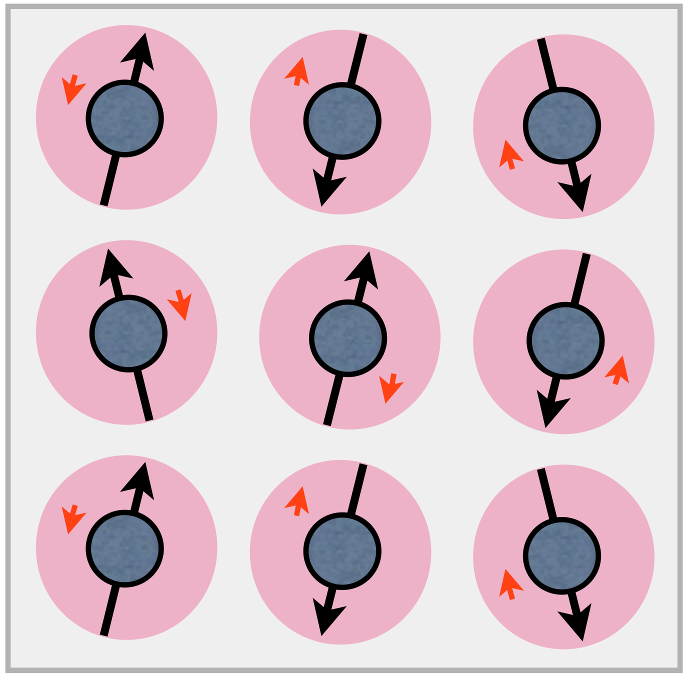
Kondo insulator



Electron doping

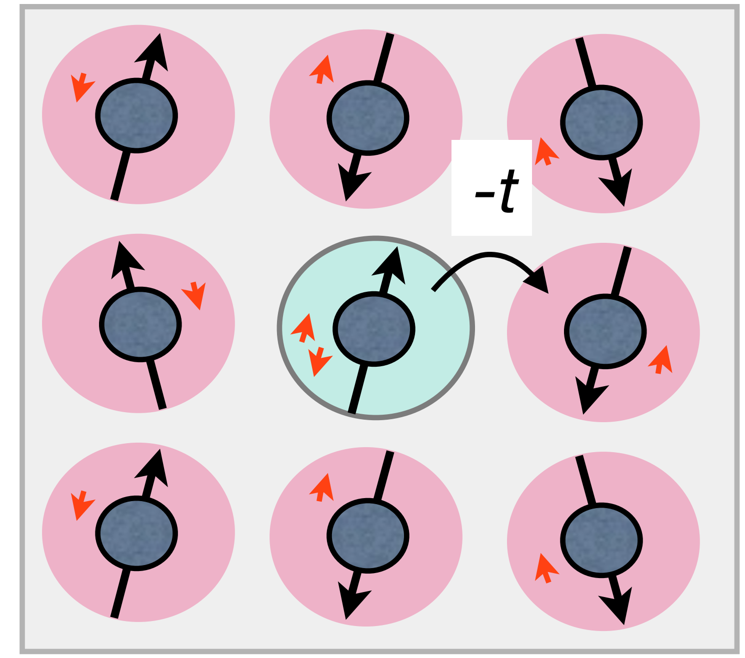
Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^\dagger_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$



$n_e = n_{\mathrm{spins}}$

Kondo insulator



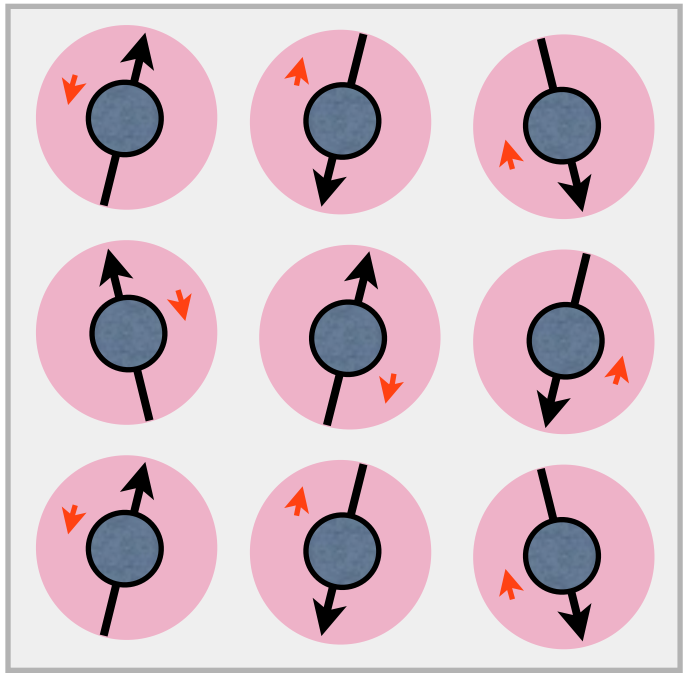
Electron doping

Mobile

“Heavy Electrons”

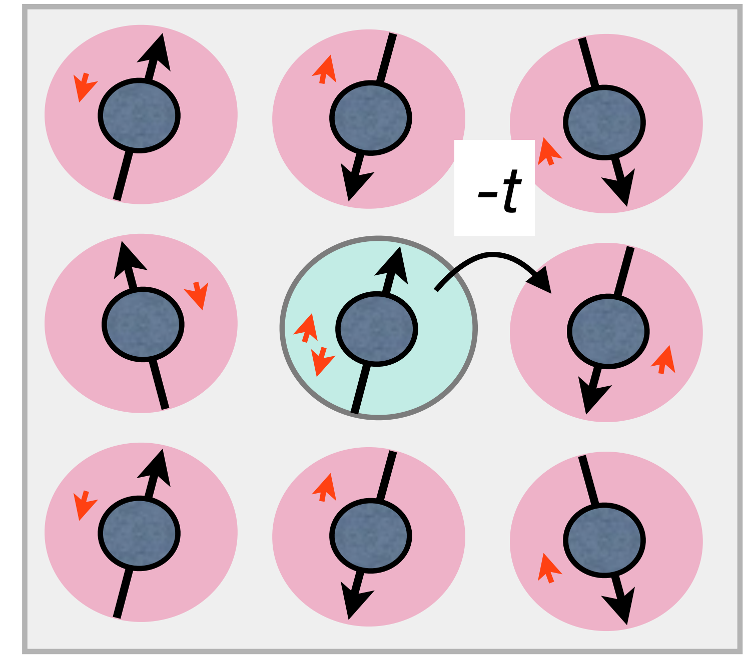
Strong coupling Kondo Lattice $J >> t$

$$H = J\sum \vec{\sigma}(j)\cdot\vec{S}_j - t\sum_{(i,j)}(c^{\dagger}_{i\sigma}c_{j\sigma} + \text{H.c})$$

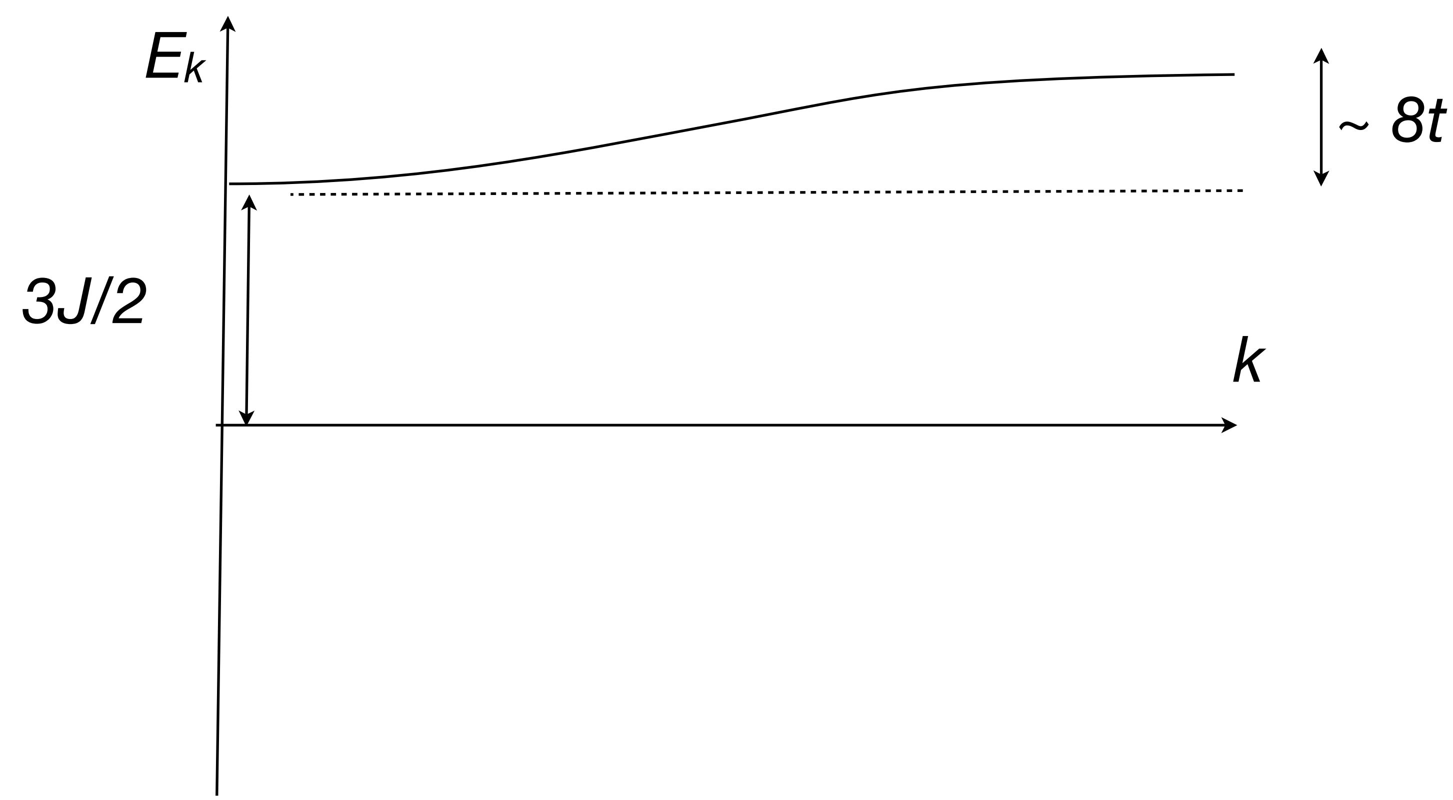


$$n_e = n_{\text{spins}}$$

Kondo insulator

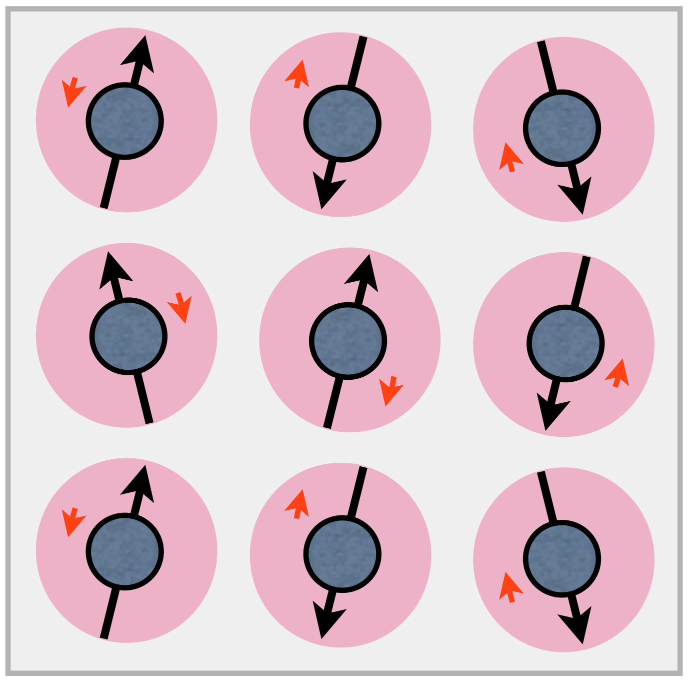


Electron doping
Mobile
"Heavy Electrons"



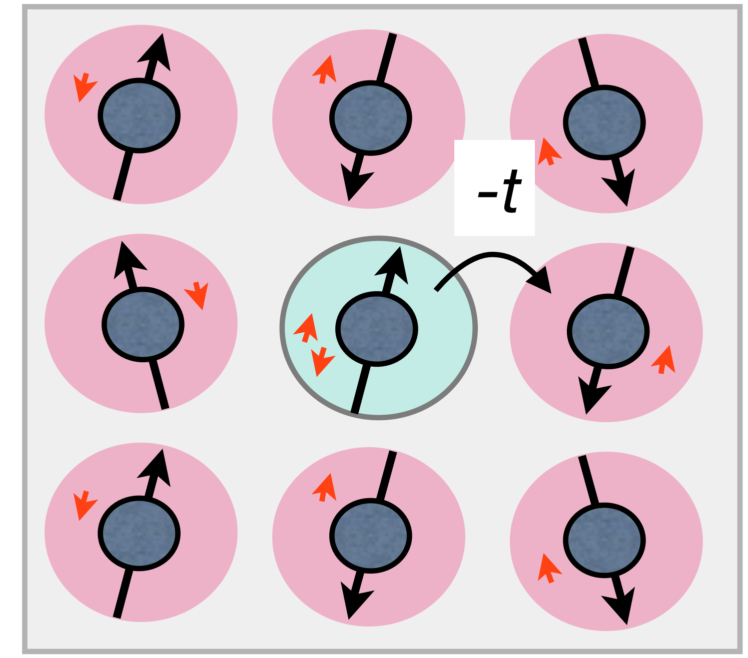
Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$



$n_e = n_{\text{spins}}$

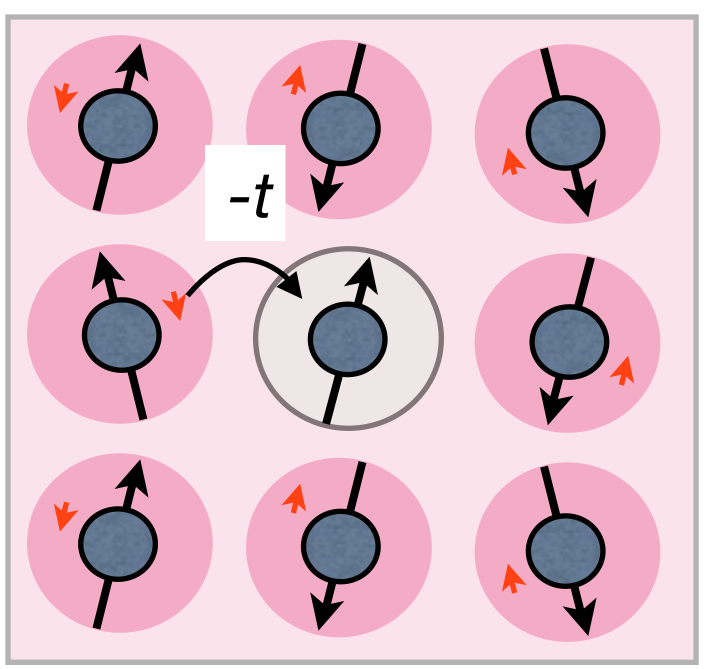
Kondo insulator



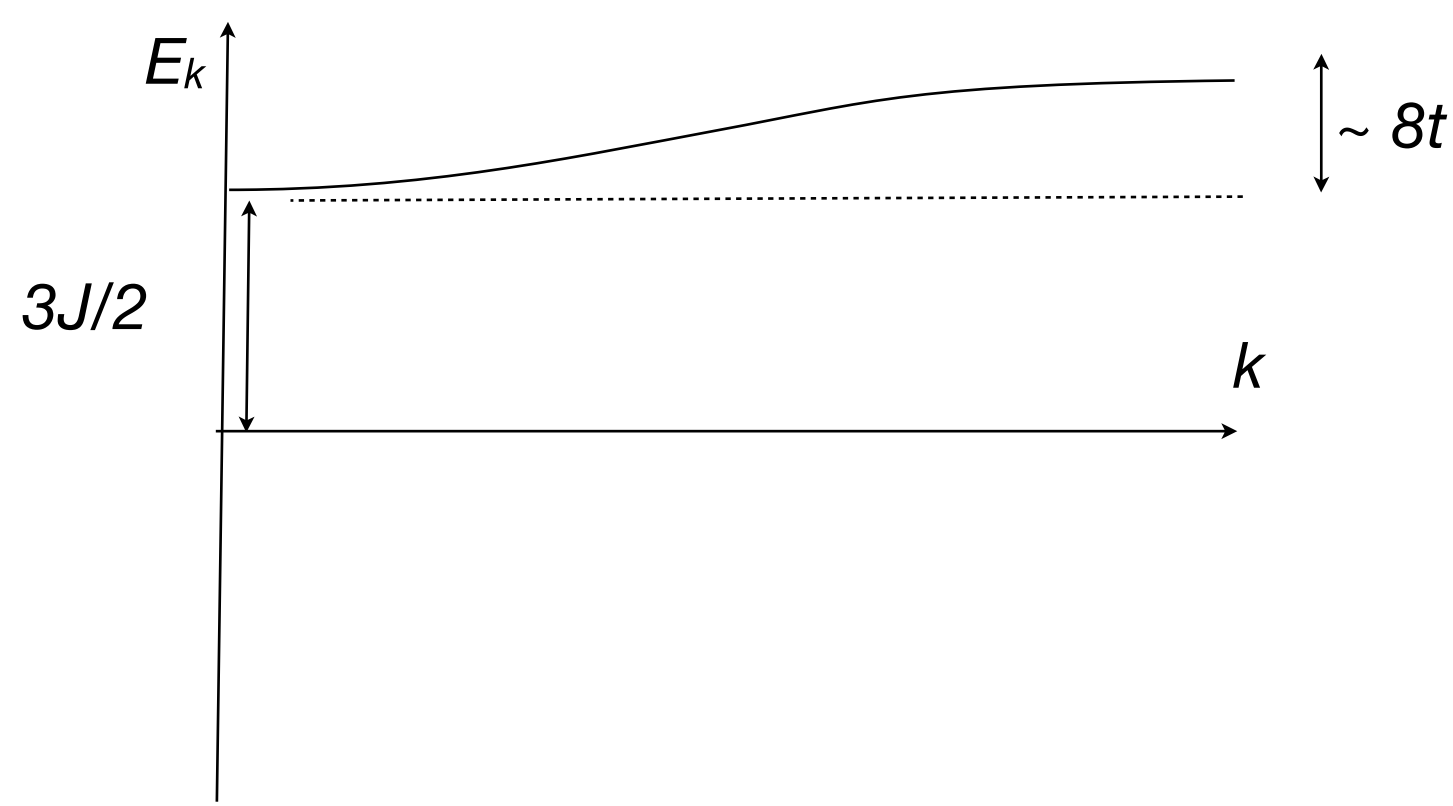
Electron doping

Mobile

"Heavy Electrons"

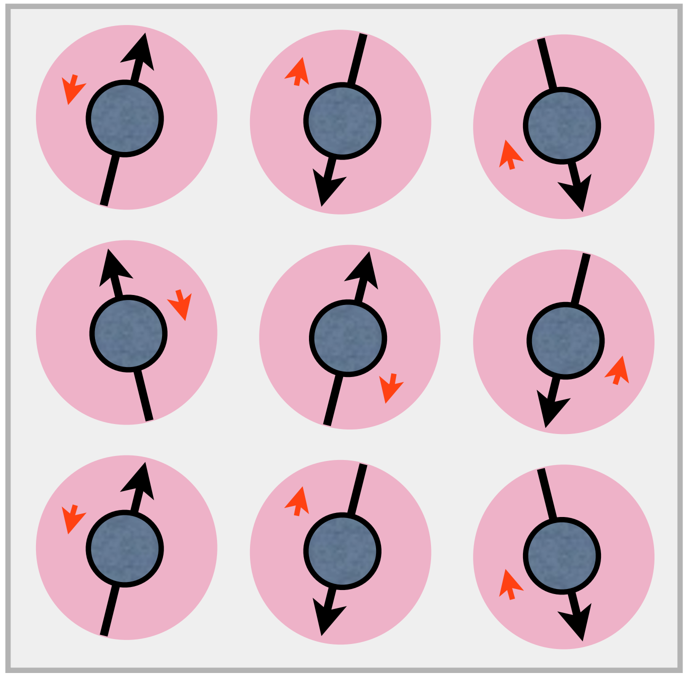


Hole doping: mobile heavy holes $n_e = n_{\text{spins}} - \delta$



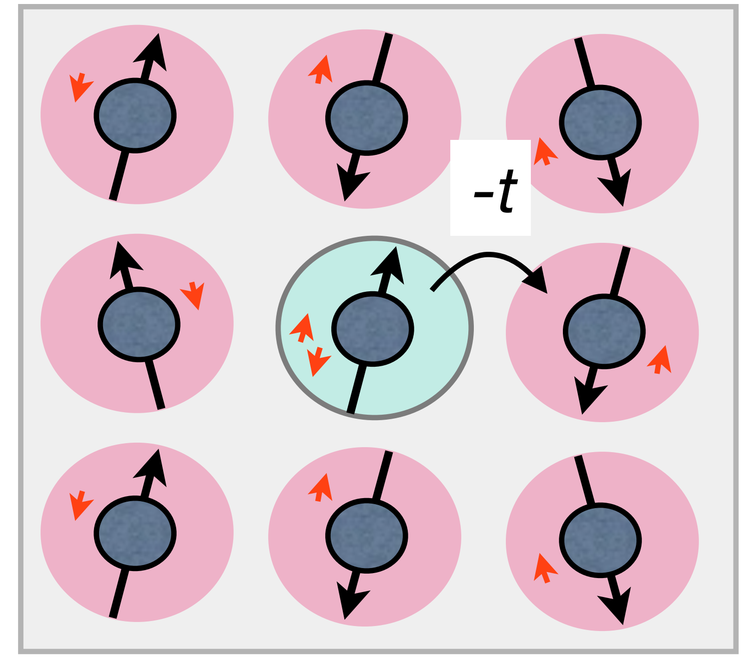
Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$

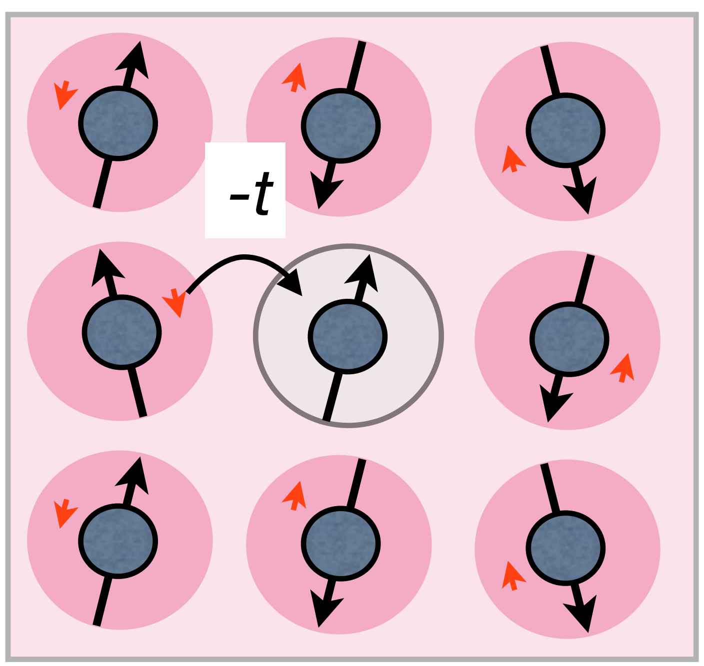


$n_e = n_{\rm spins}$

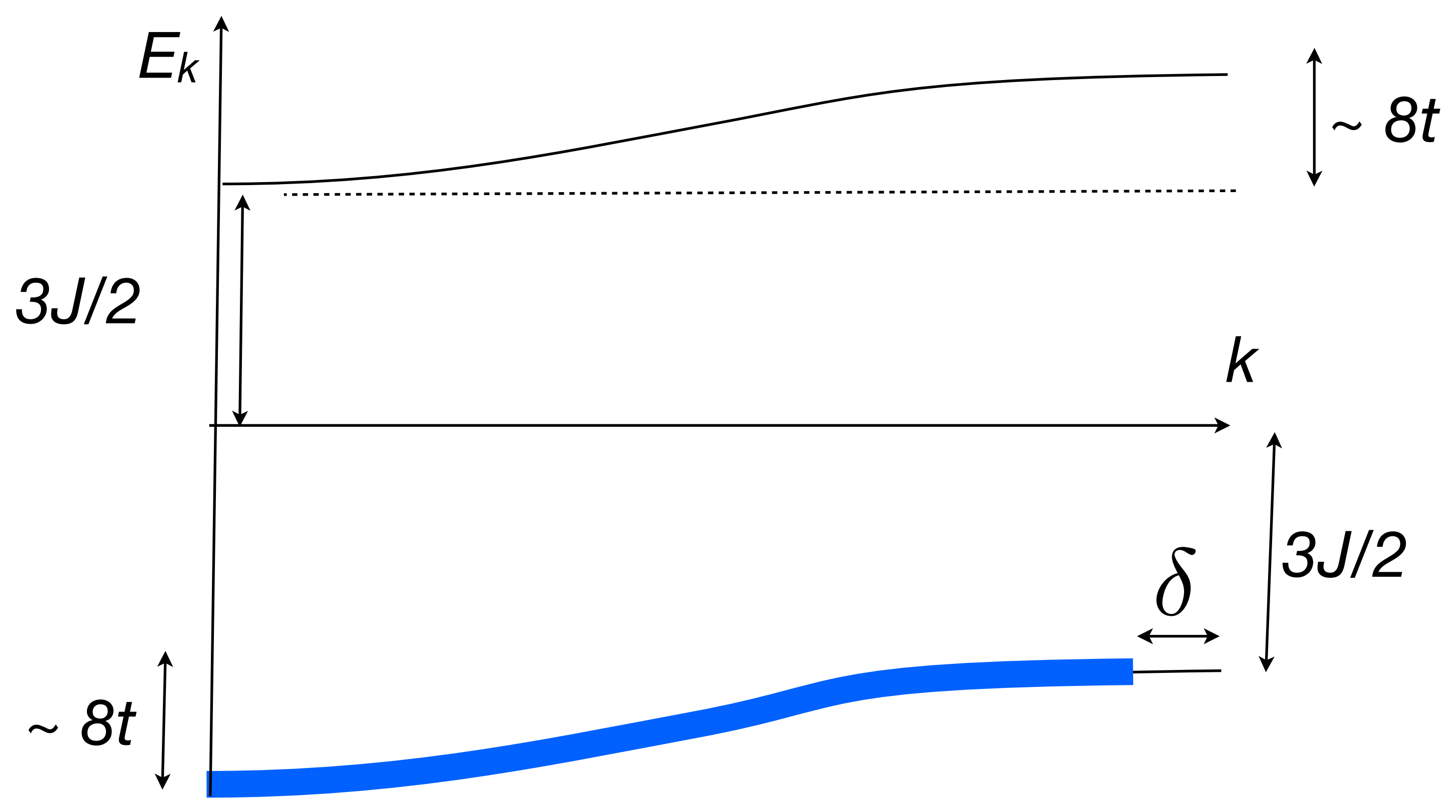
Kondo insulator



Electron doping
Mobile
“Heavy Electrons”

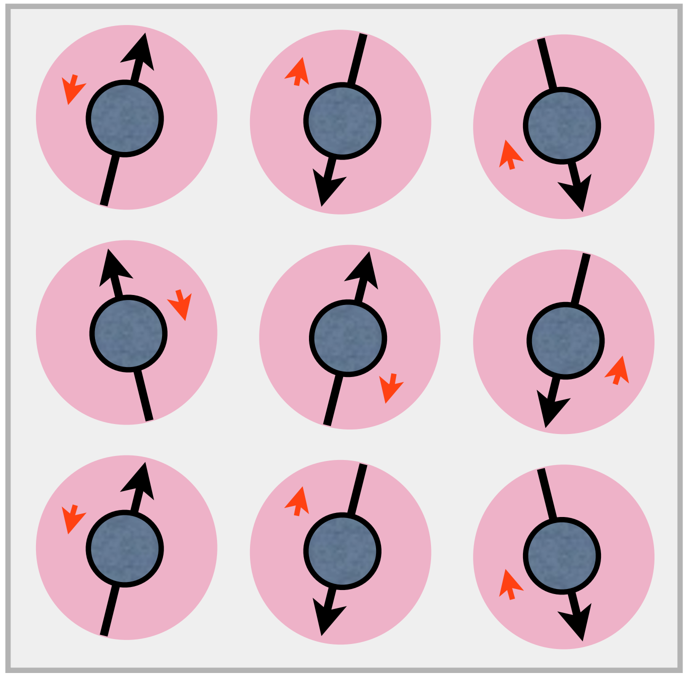


Hole doping: mobile heavy holes $n_e = n_{\rm spins} - \delta$



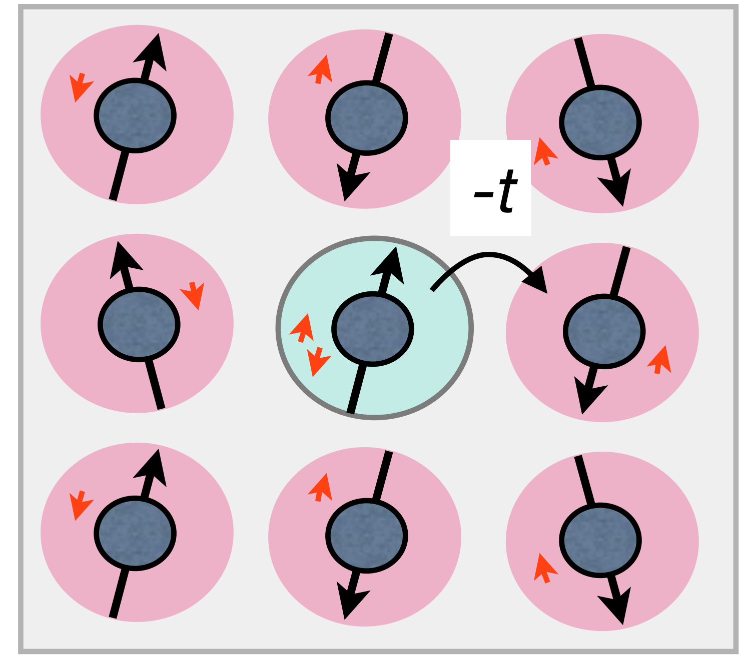
Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$

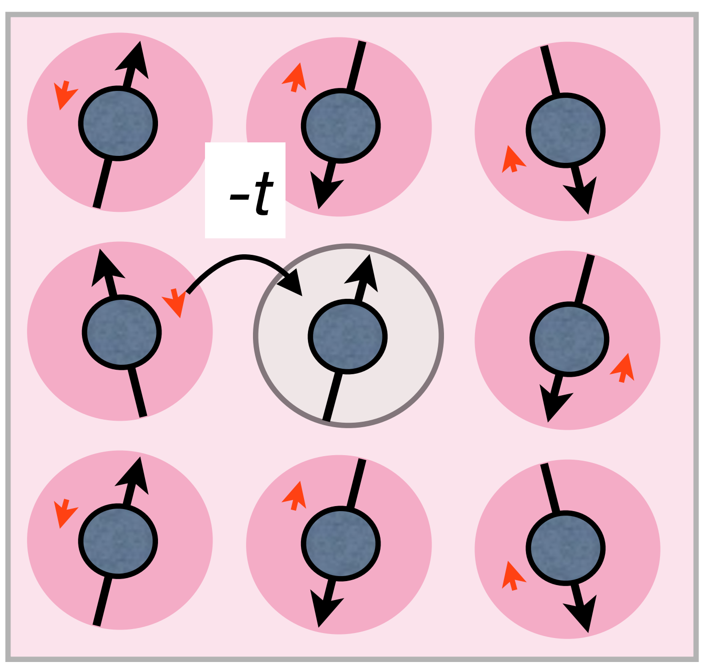


$n_e = n_{\mathrm{spins}}$

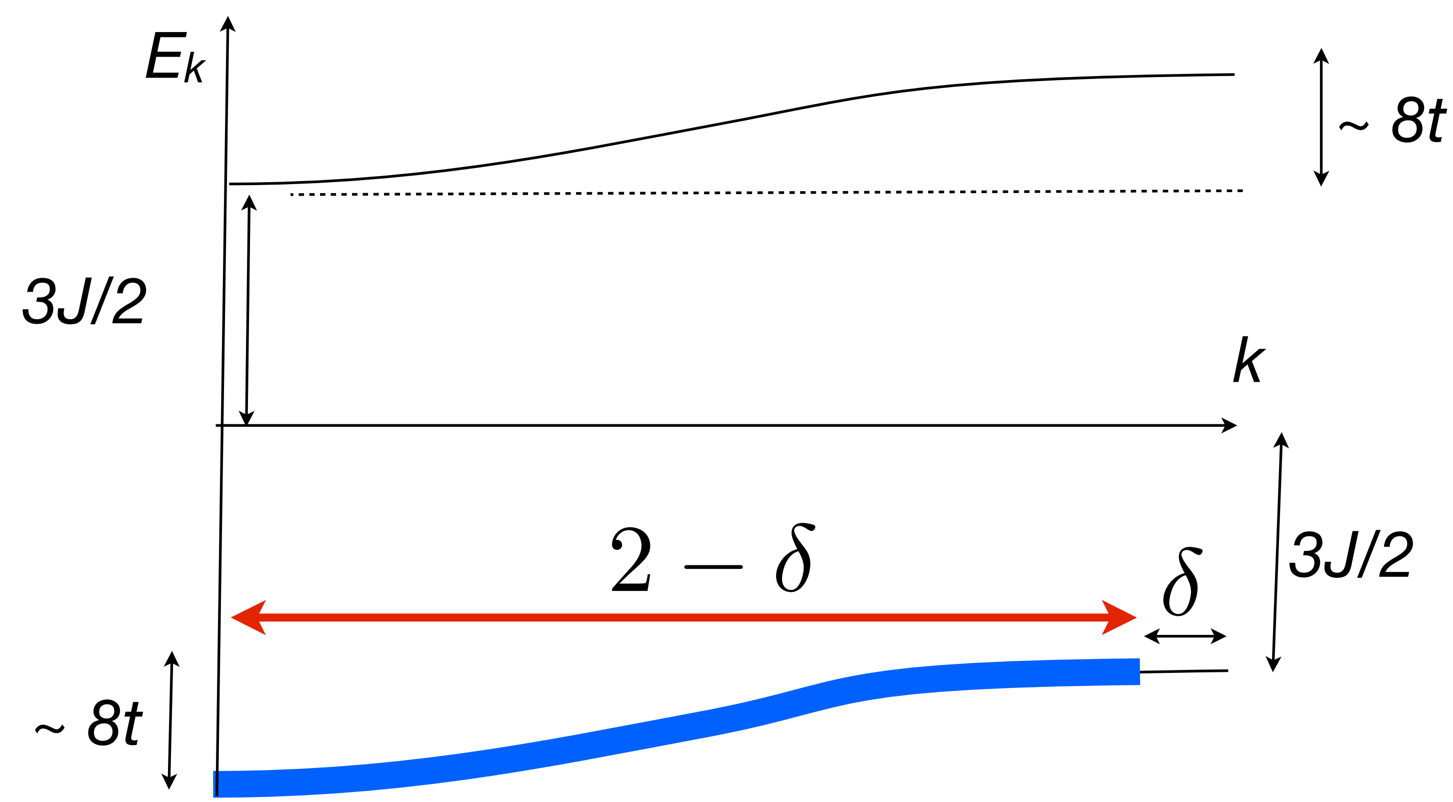
Kondo insulator



Electron doping
Mobile
"Heavy Electrons"

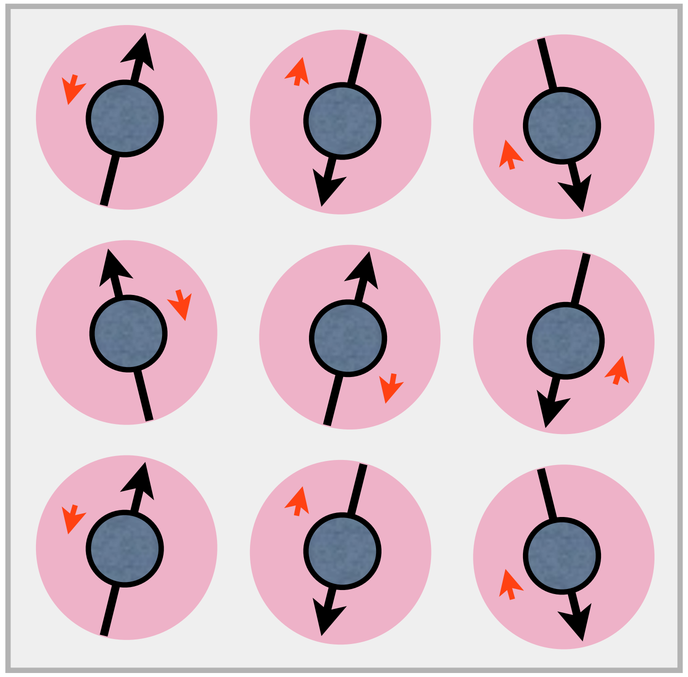


Hole doping: mobile heavy holes $n_e = n_{\mathrm{spins}} - \delta$



Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$

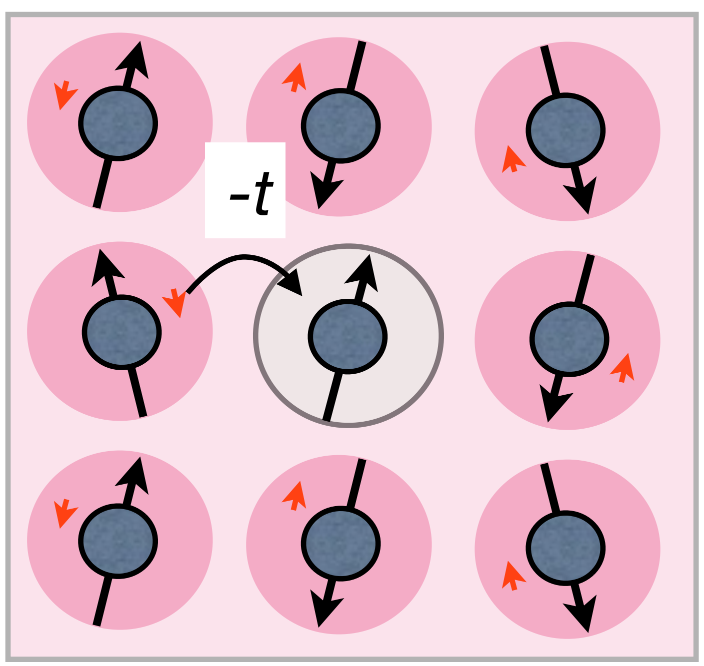


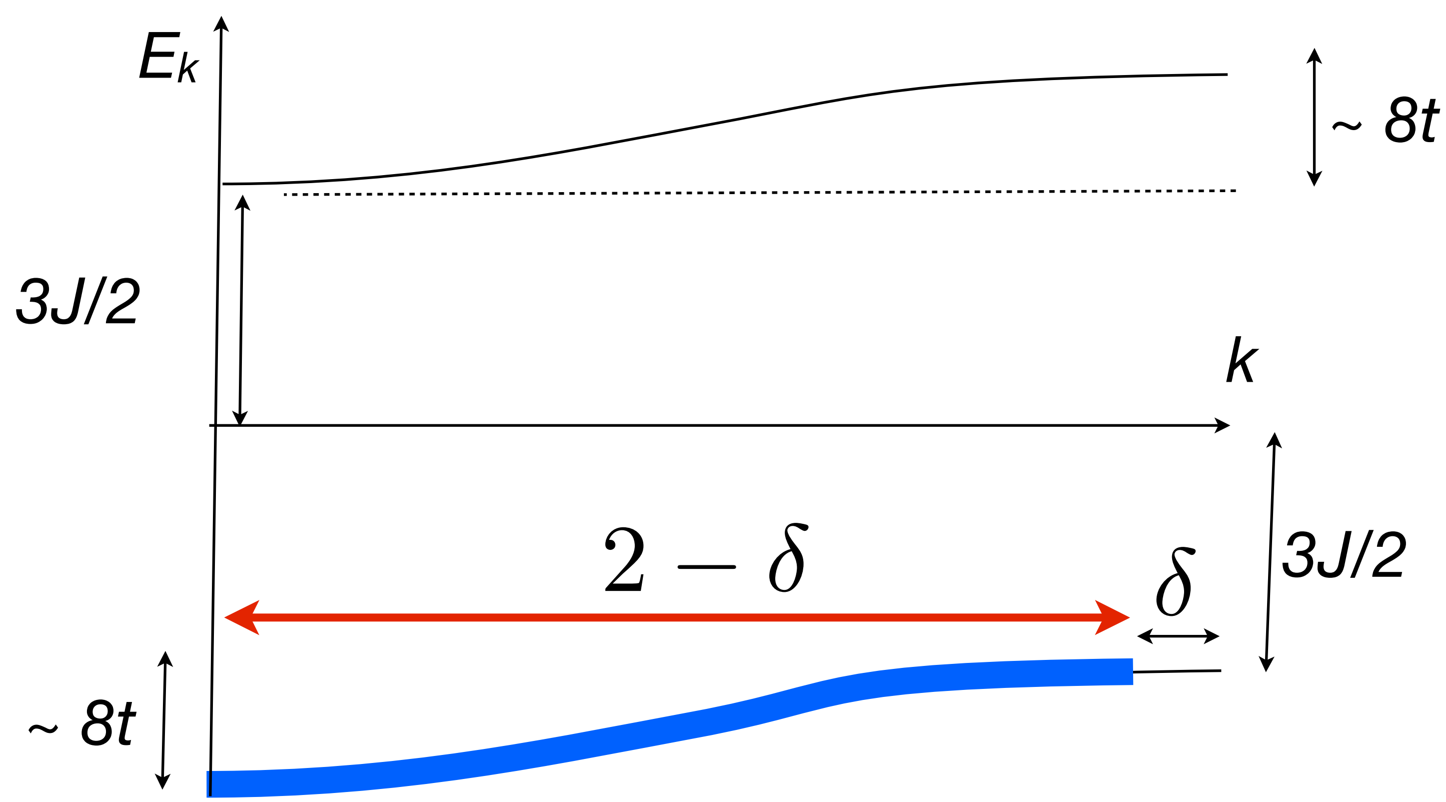
$n_e = n_{\mathrm{spins}}$

Kondo insulator

$$2 \left(\frac{v_{\mathrm{FS}}}{(2\pi)^D} \right) = 2 - \delta = n_{\mathrm{spins}} + n_e$$

FS sum rule counts spins as charged qp.





Hole doping: mobile heavy holes $n_e = n_{\mathrm{spins}} - \delta$

Large Fermi surface and the charge of the f-electron