Hong Kong Forum 2007, Dec 14-16, 2007

Conference in honor of Yu Lu and Su Zhao bin

Heavy Fermions and symplectic symmetry

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M. Dzero[1,2]

P. Coleman[1]

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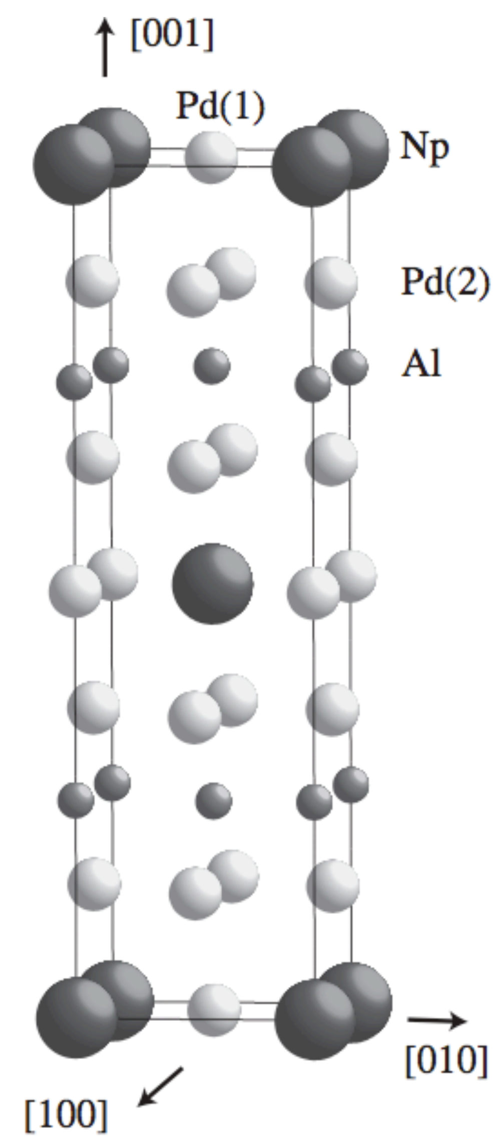
arXiv:0710.1126



$NpAl_2Pd_5$

Rutgers Center for Materials Theory

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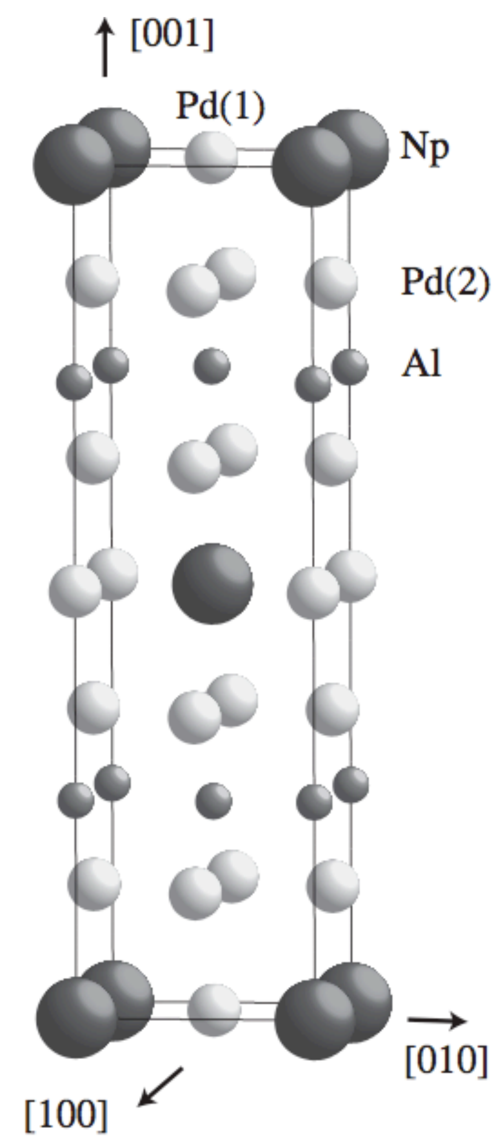
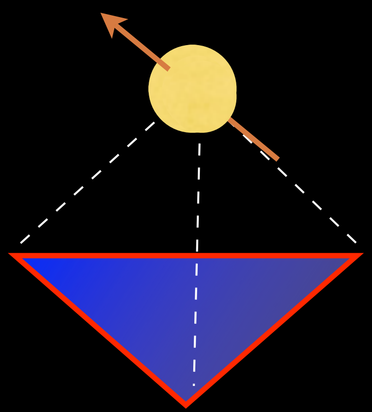


$NpAl_2Pd_5$

- Collision of ideas
- New Superconductors
- Time reversal and Symplectic spins
- Super-coherent Kondo
- Predictions

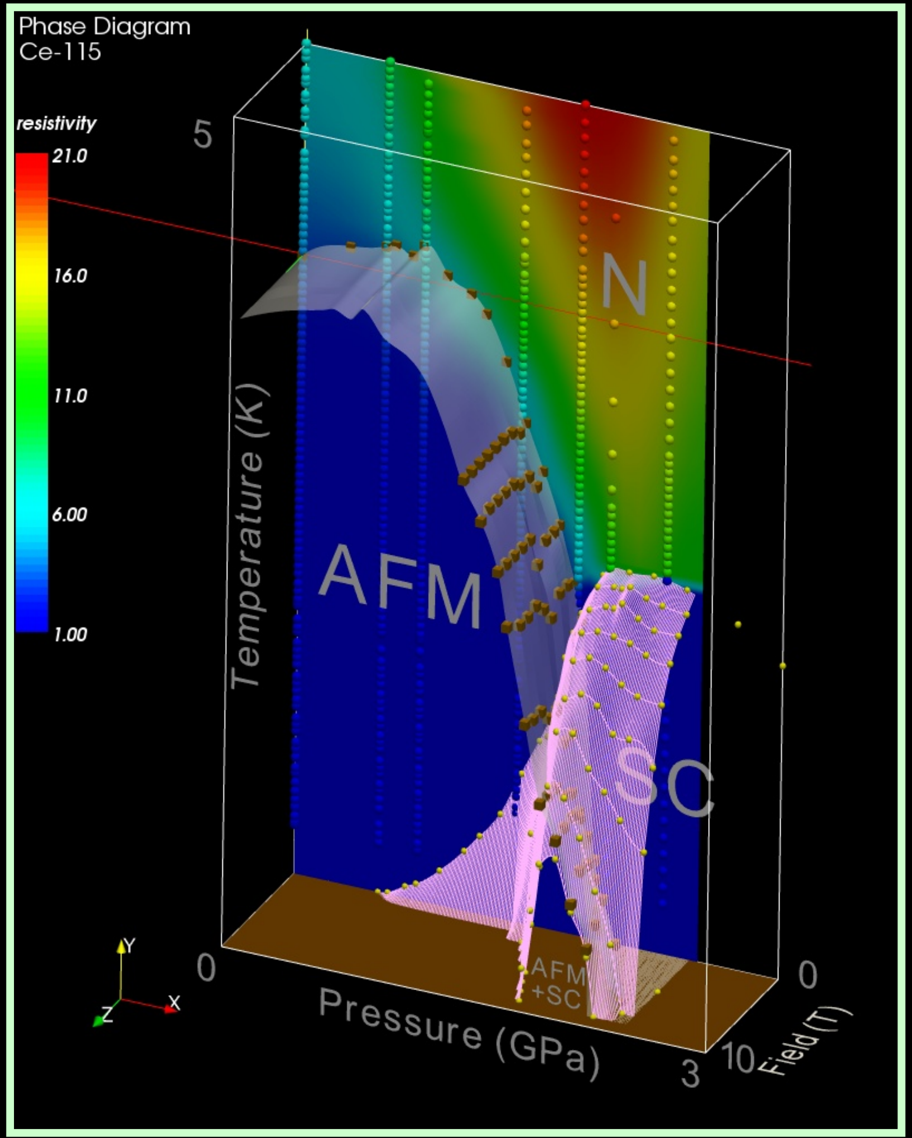
Rutgers Center for Materials Theory

Heavy Fermions: Collision of ideas



Tuson Park, (2007).

CeRhIn5



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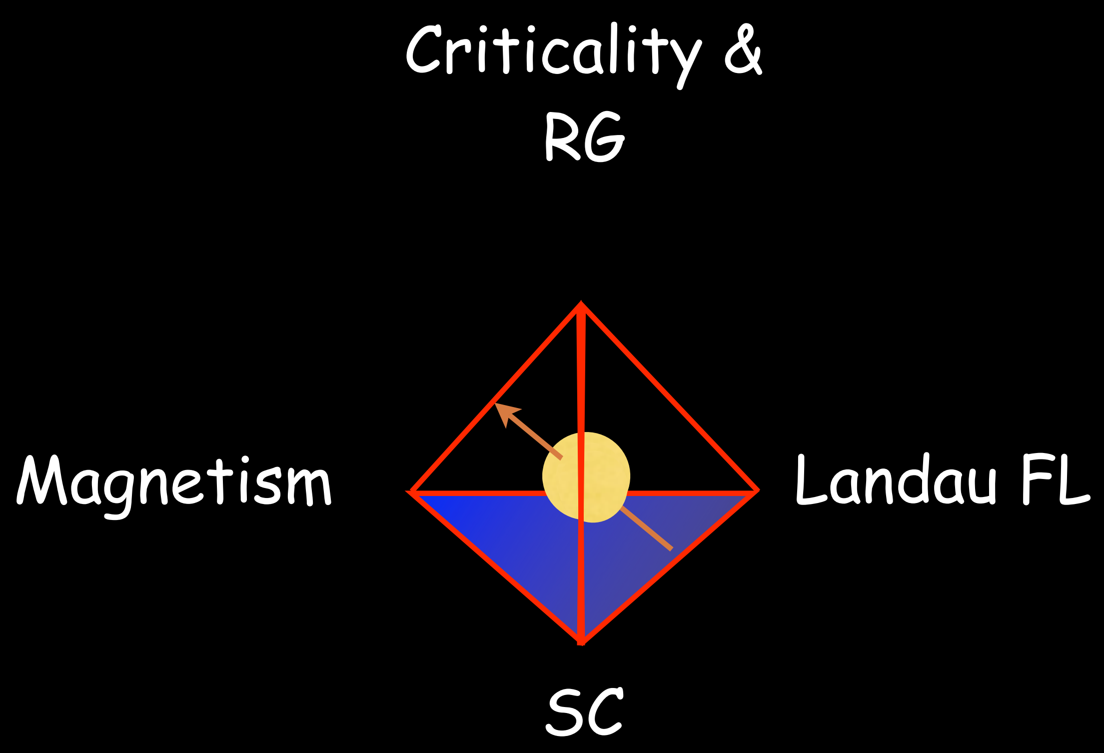

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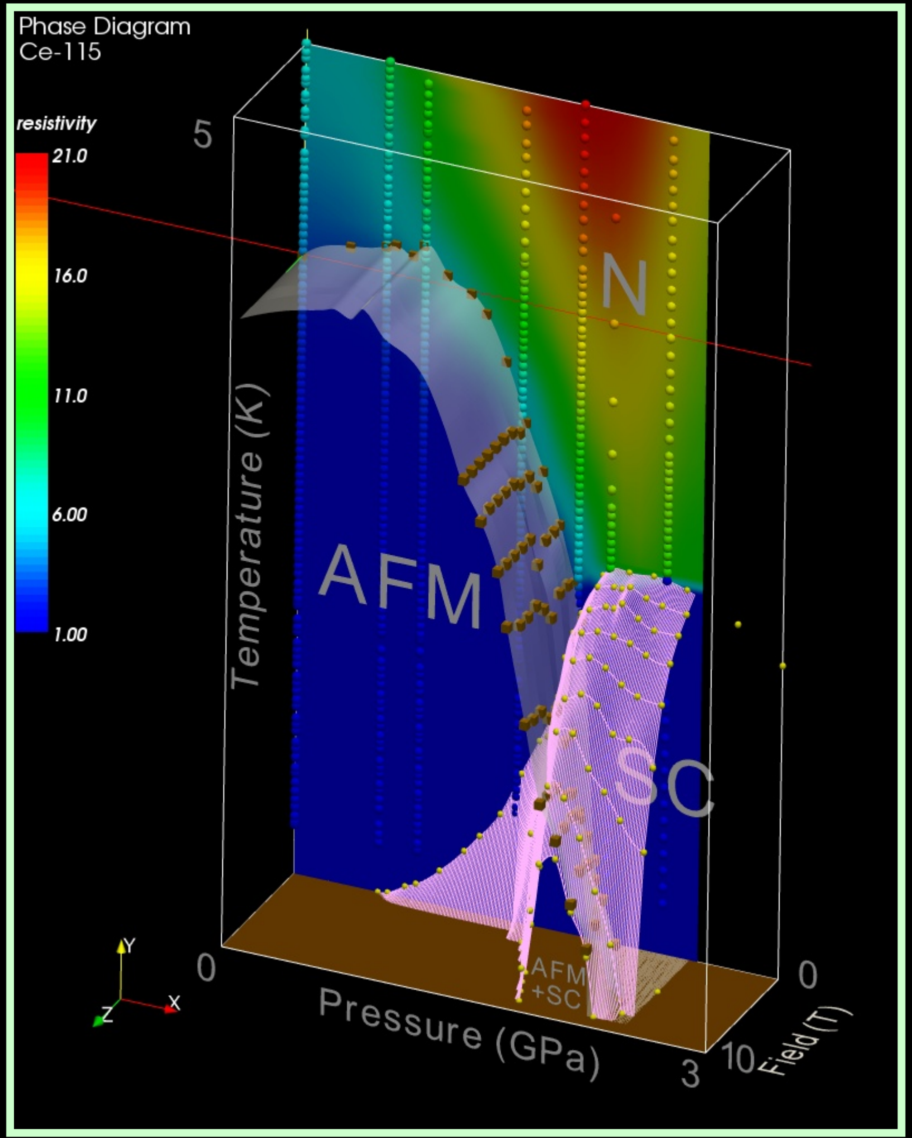

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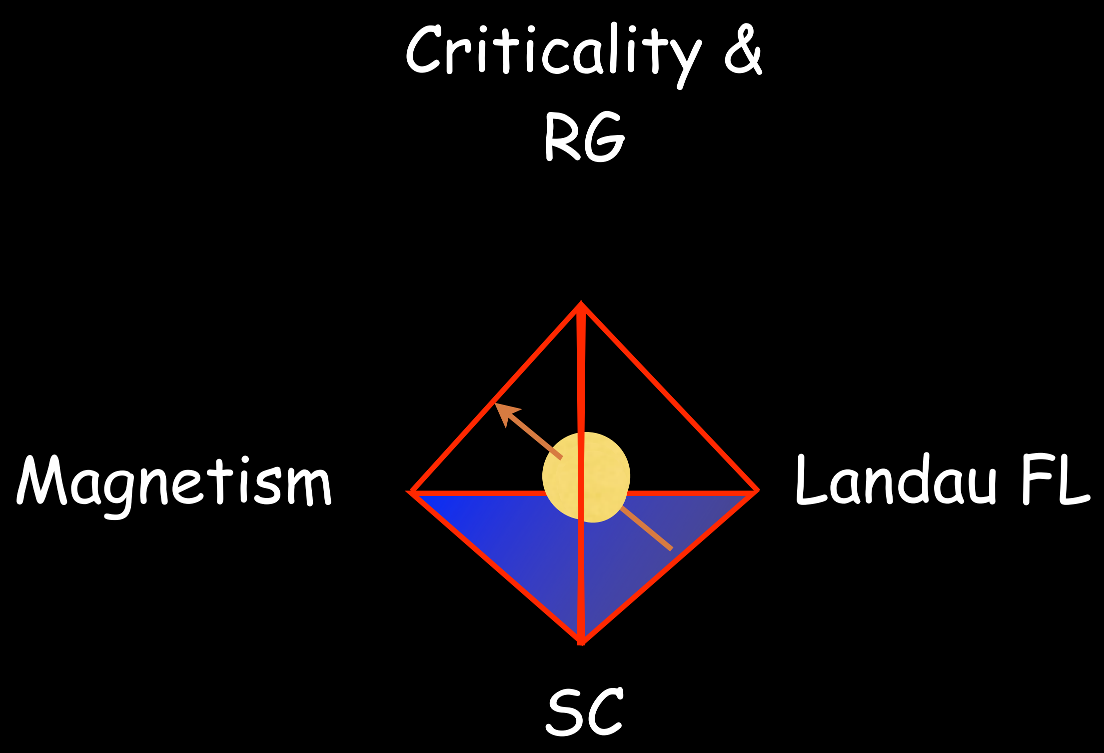
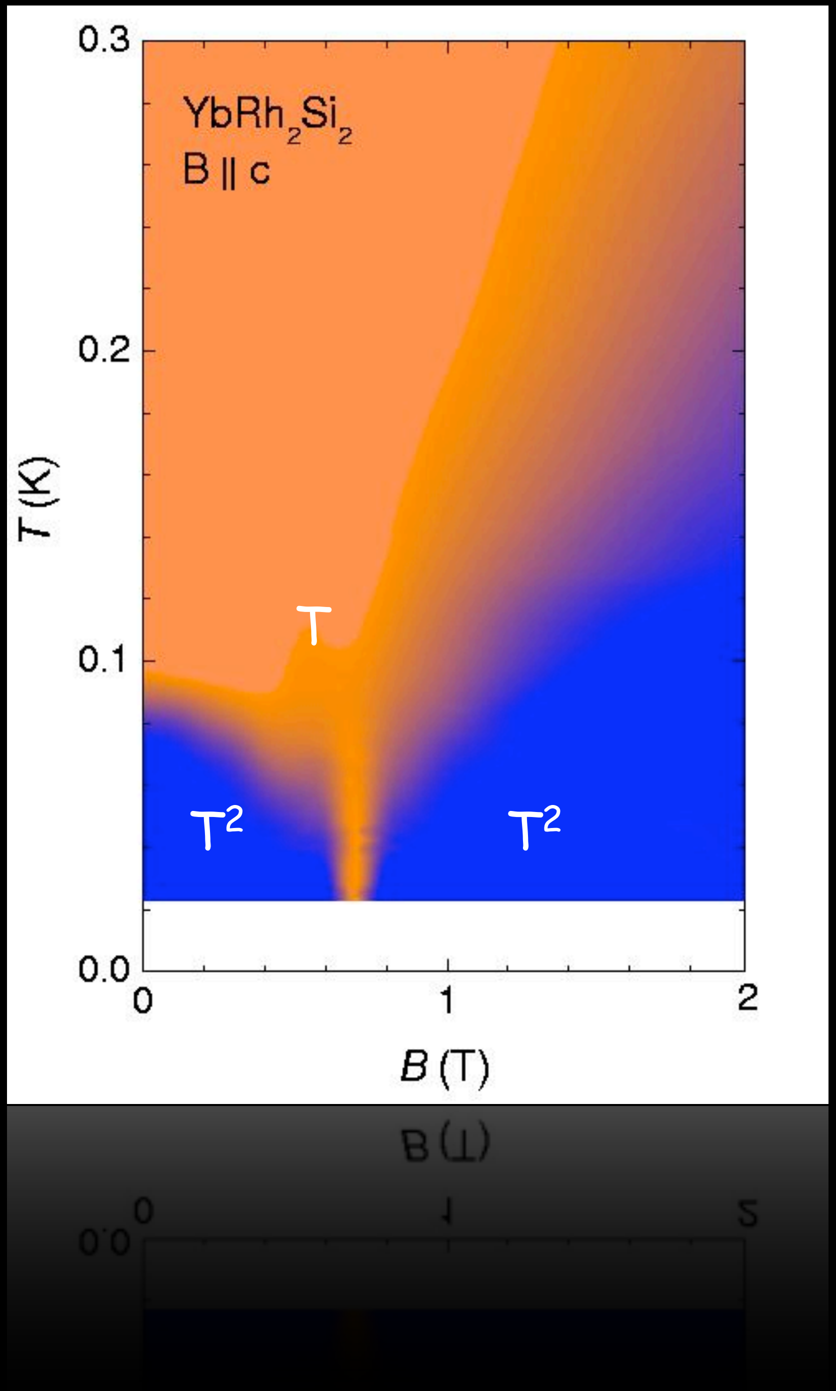


Custers et al (2003)



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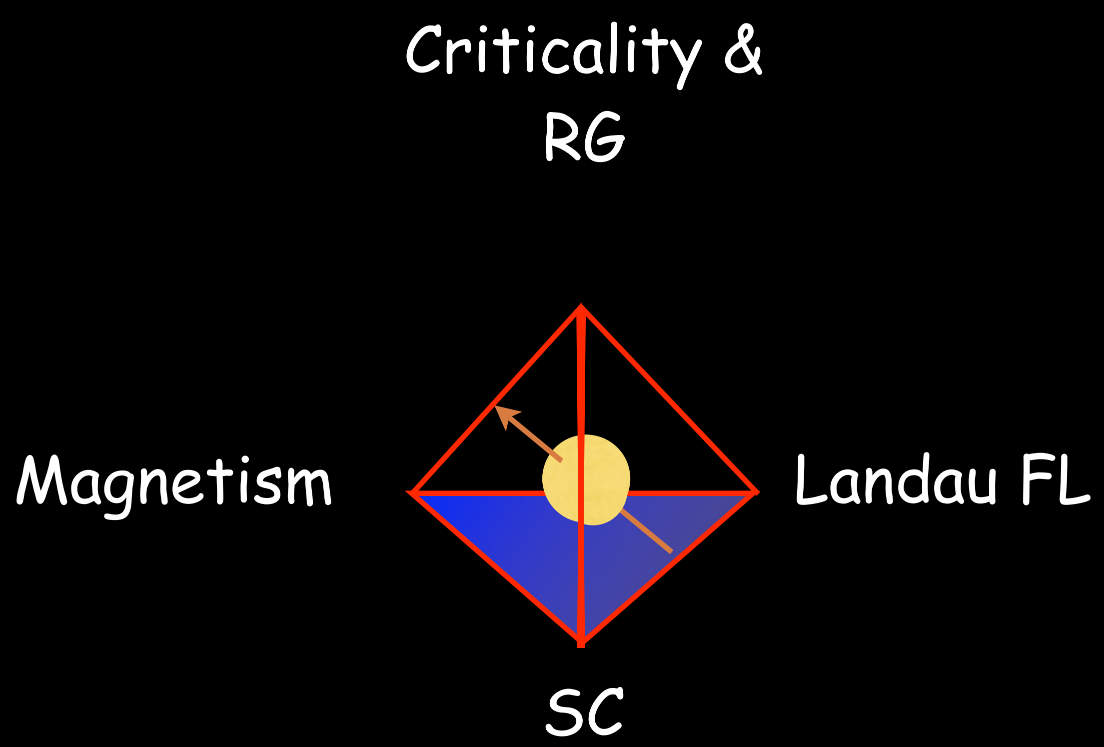


Heavy Fermions: Collision of ideas

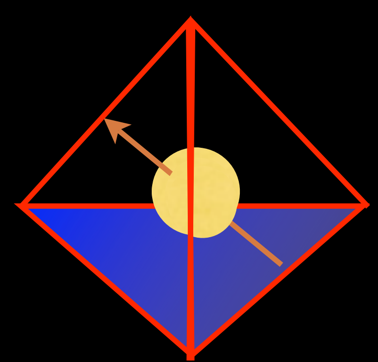
Oxides

Criticality &
RG

T_c

?

Magnetism



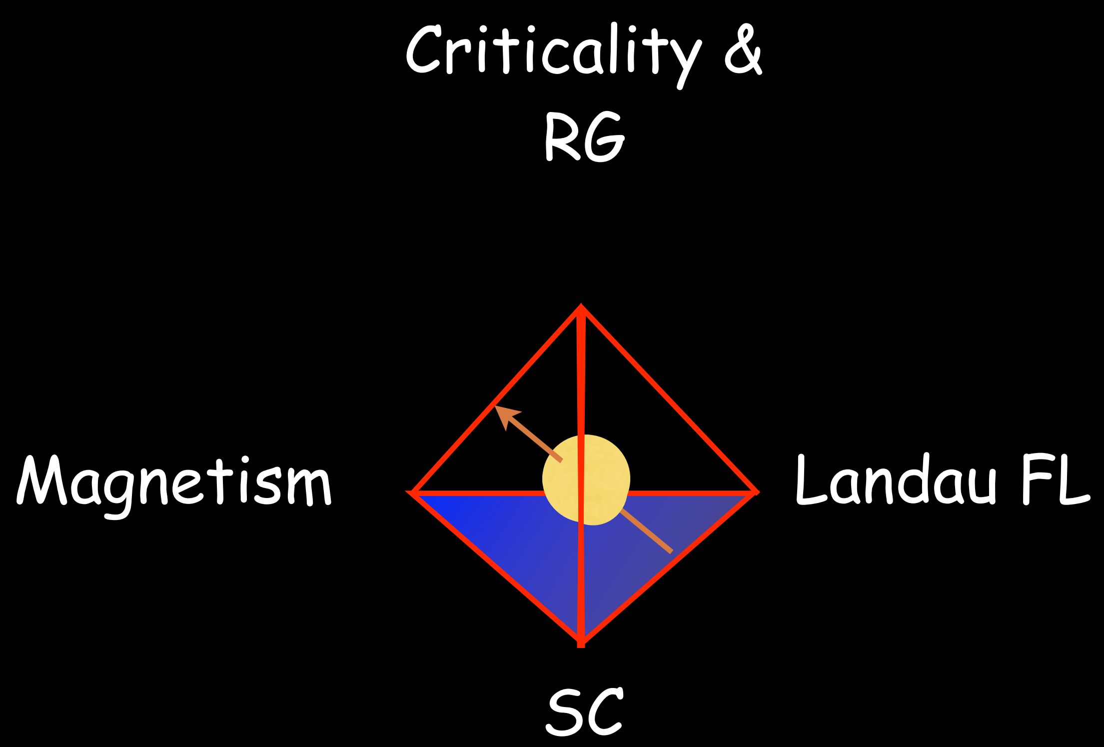
Landau FL

SC

$YBa_2Cu_3O_7$ 92K

Ba2212 12K

Heavy Fermions: Collision of ideas



Oxides	T_c	T_c	Intermetallics	
?		18.5K	$PuCoGa_5$	'02
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2212	12K	0.2K	$CeIn_3$	'96

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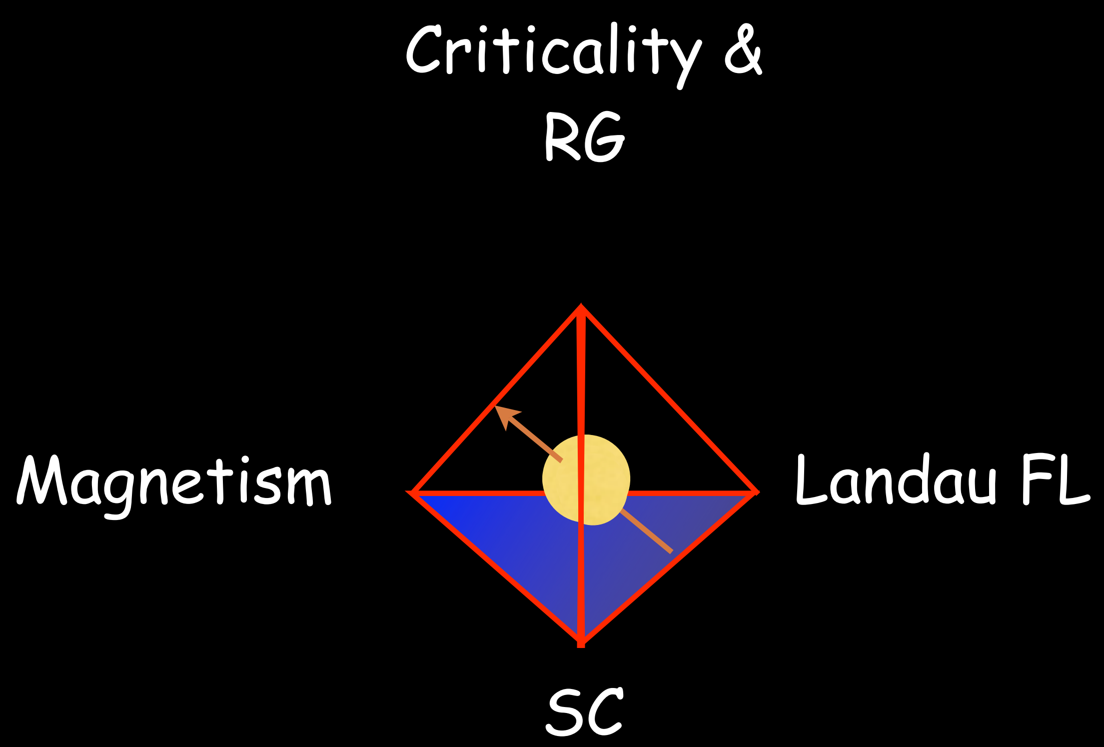

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“Fruit fly” for correlated materials

Heavy Fermions: Collision of ideas

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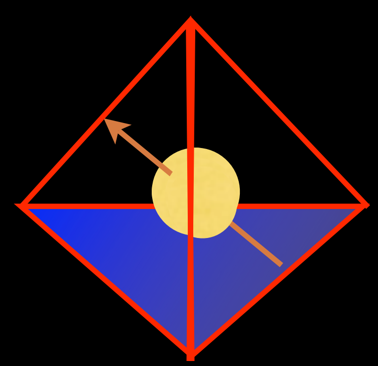


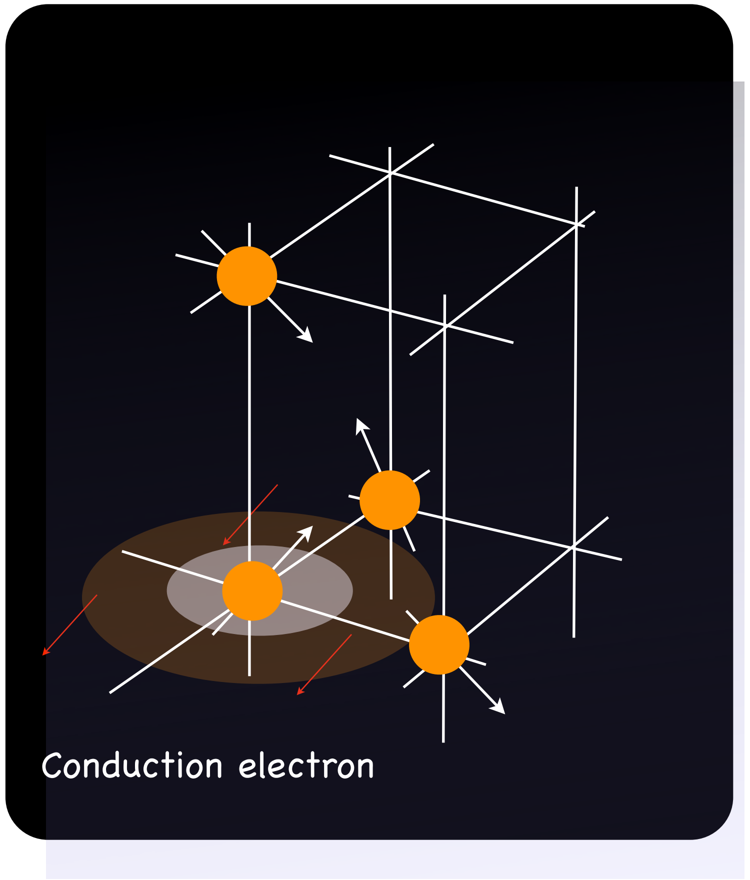
SC

Oxides	T_c	T_c	Intermetallics	
?		18.5K	$PuCoGa_5$	'02
		4.5K	$NpPd_2Al_5$	'07
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2212	12K	0.2K	$CeIn_3$	'96

"Fruit fly" for correlated materials

New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$

J. Sarrao et al., Nature 420, (2002)



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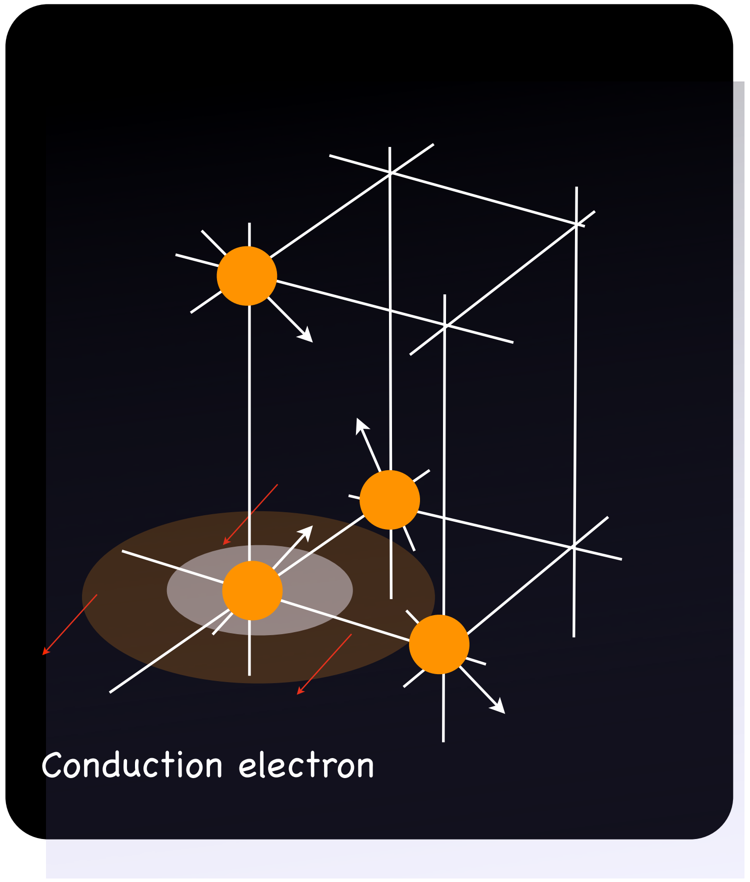

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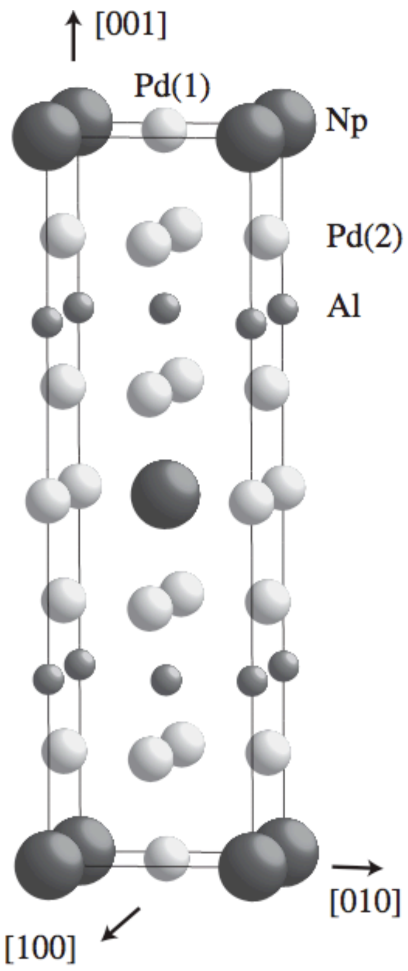

4.5K Heavy Fermion S.C
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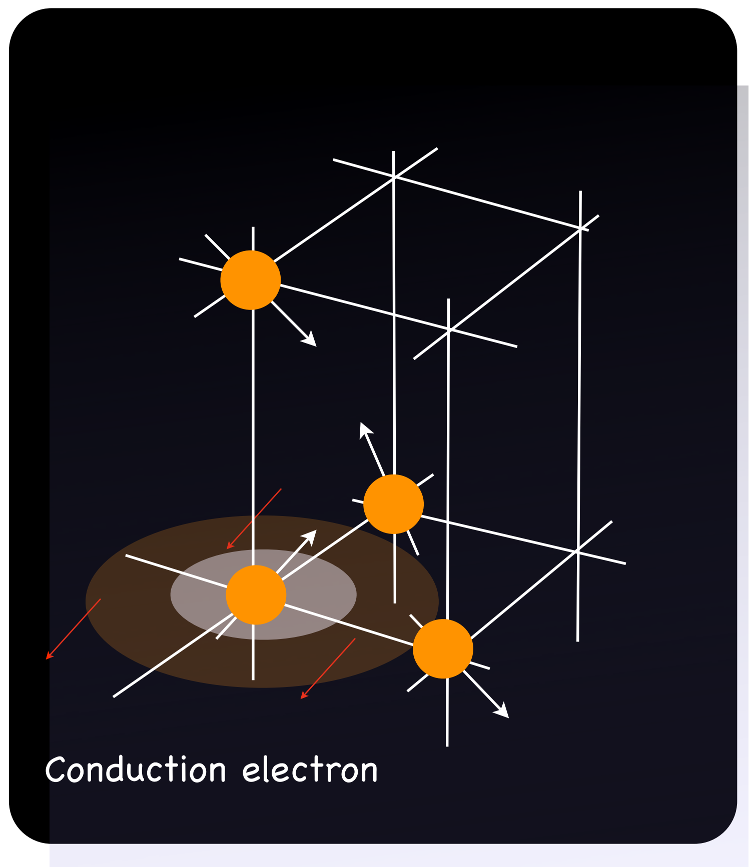

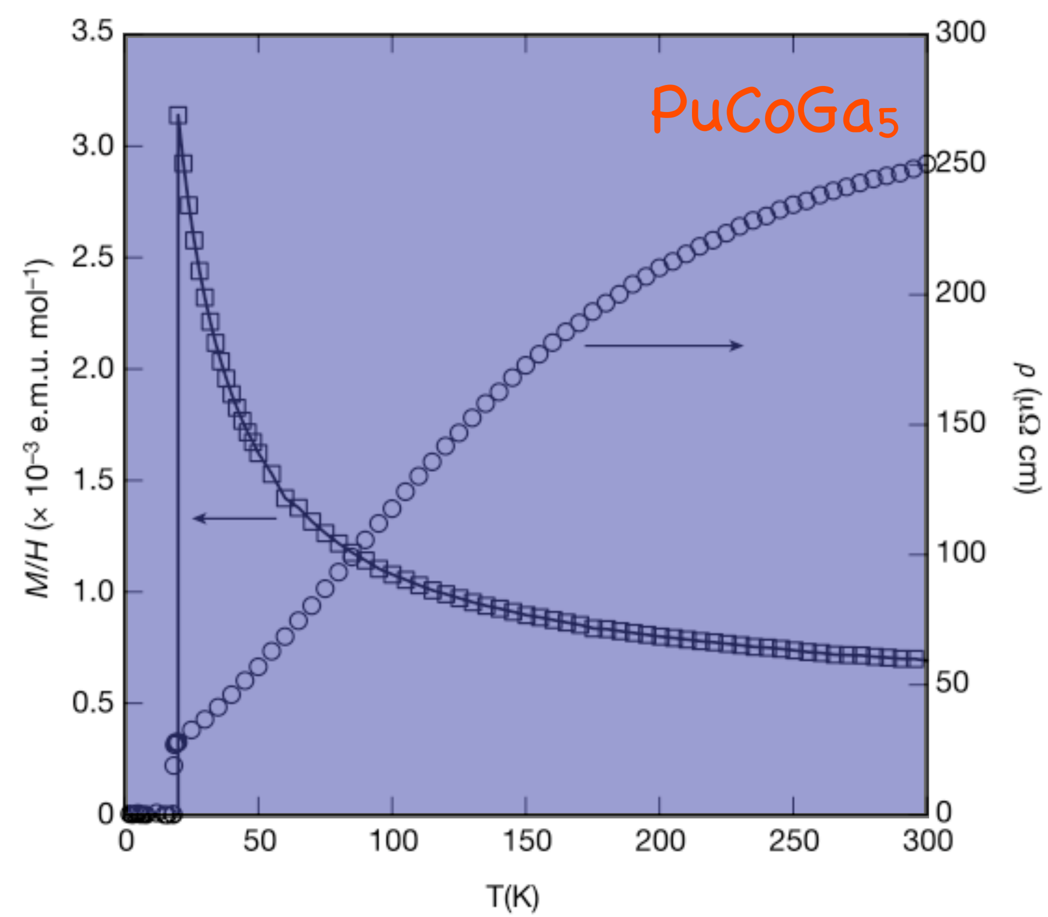

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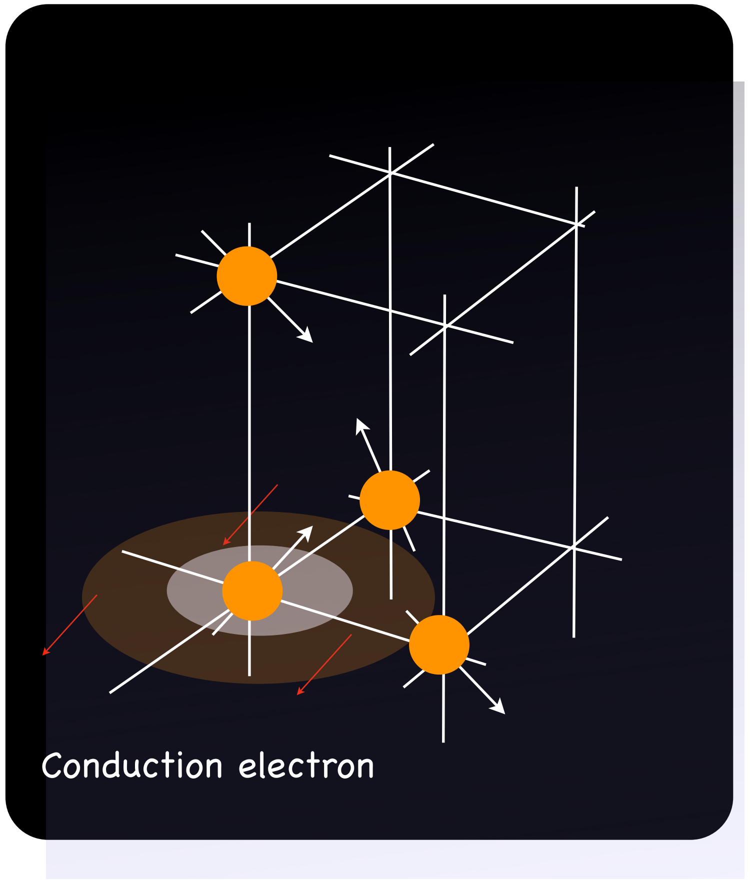

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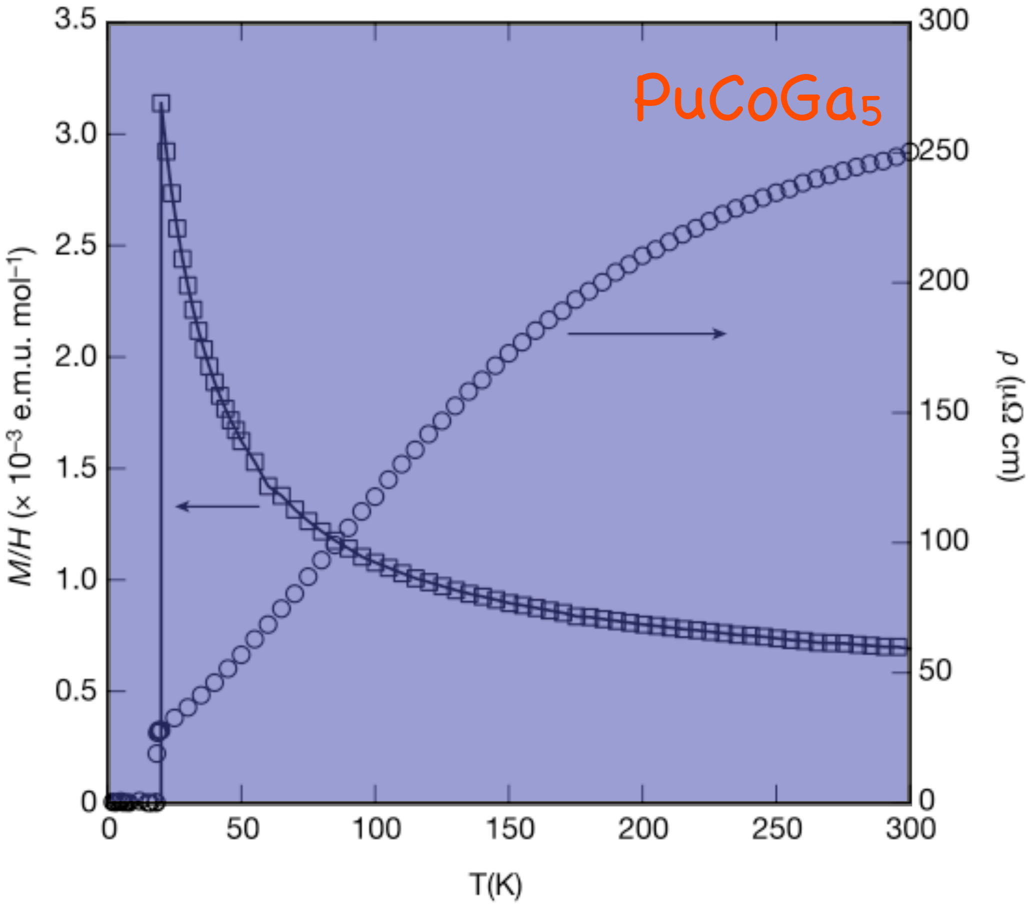

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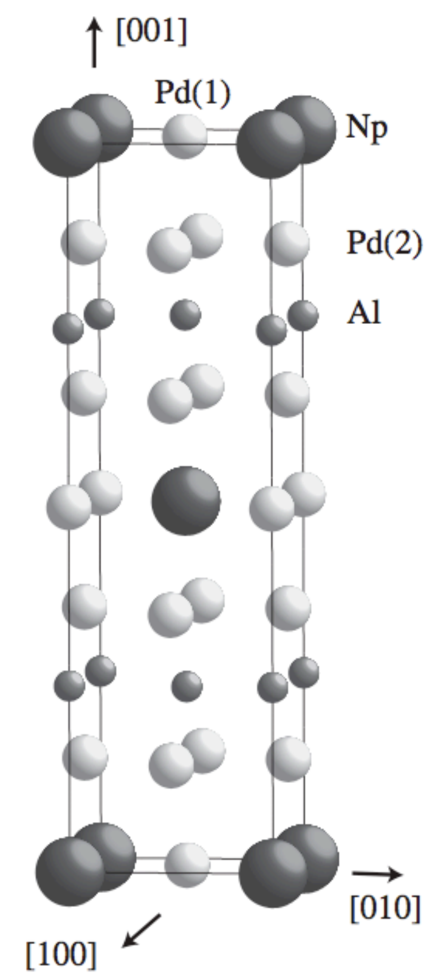

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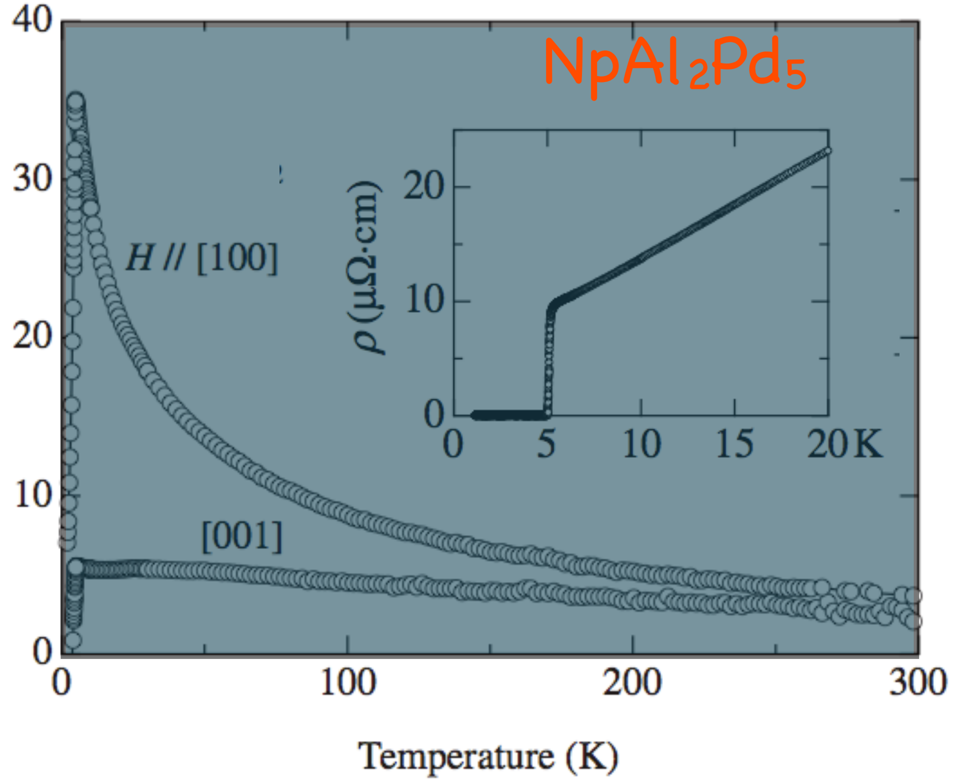

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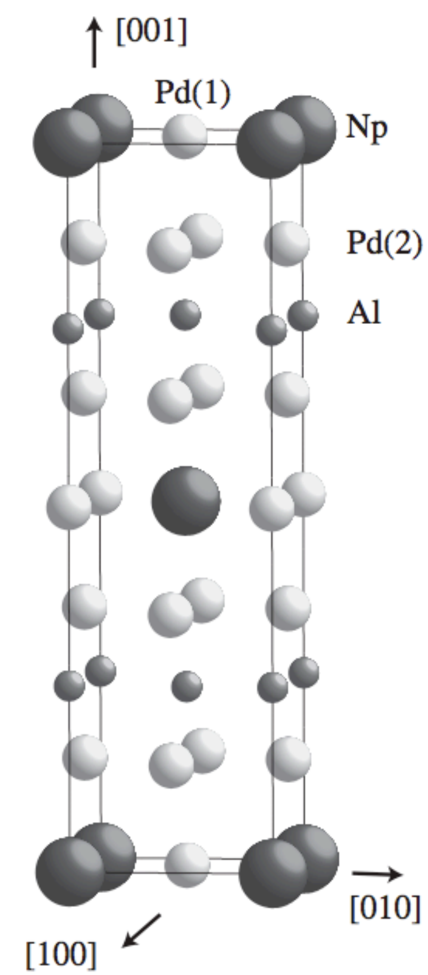

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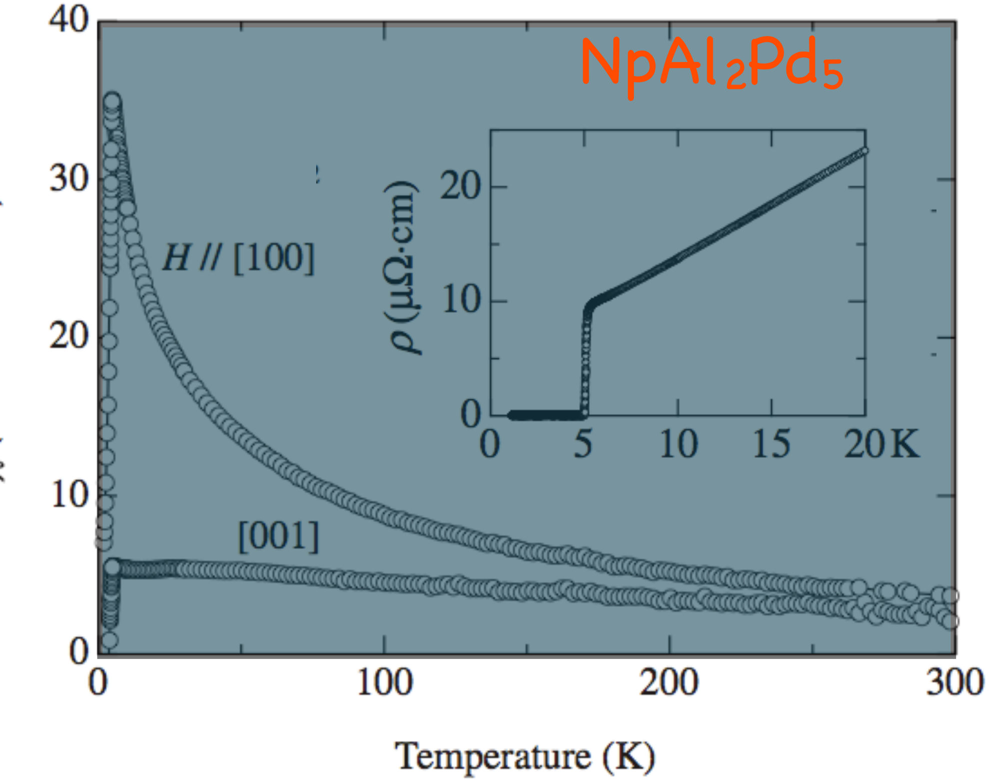

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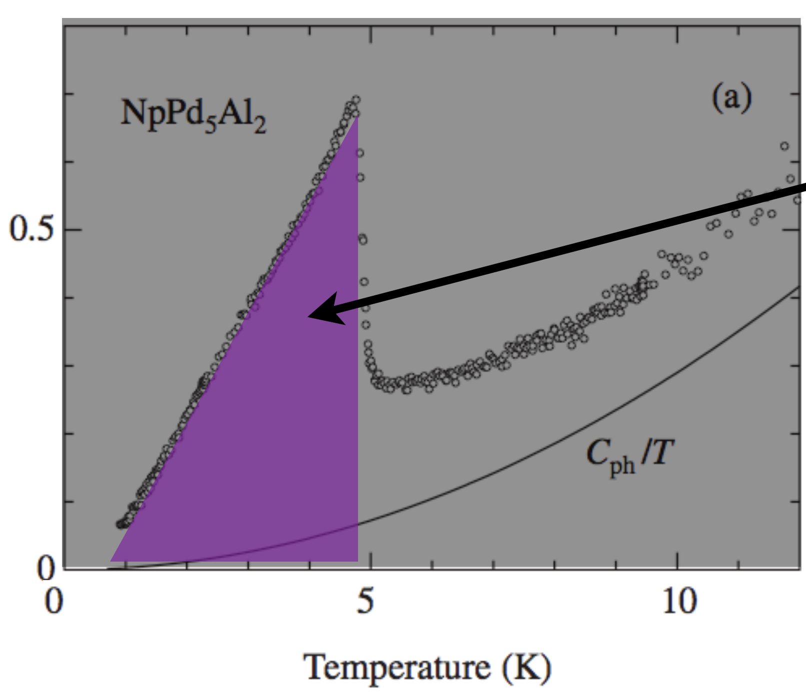

Substantial fraction of
spin entropy.
1/3 R ln 2

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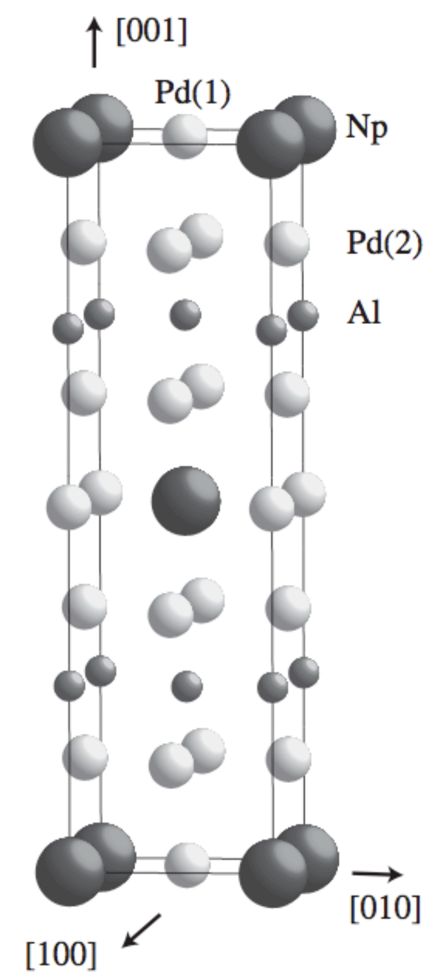

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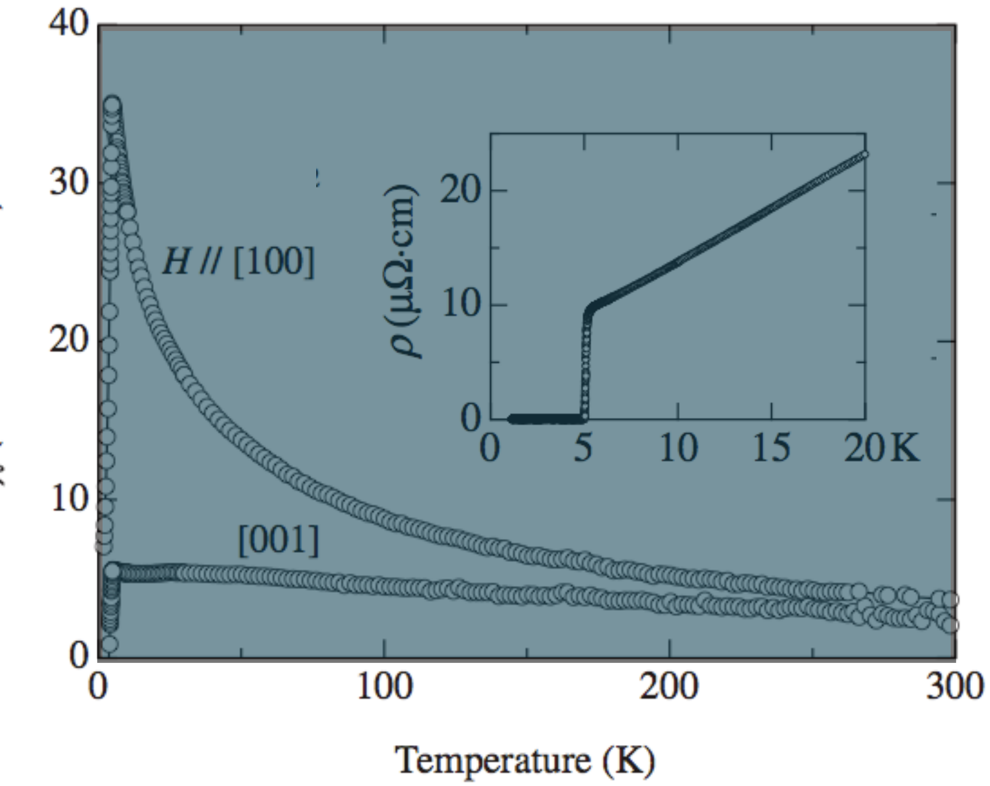

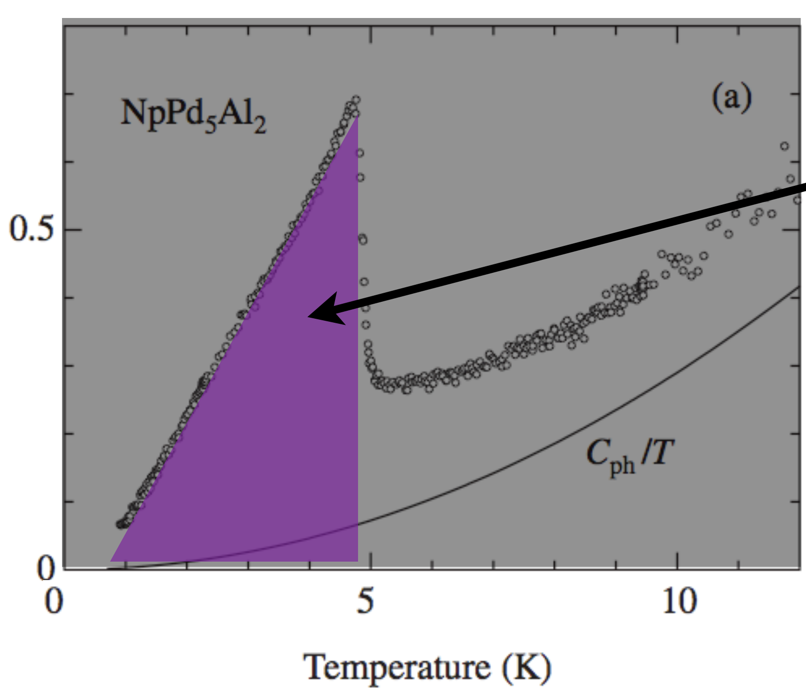

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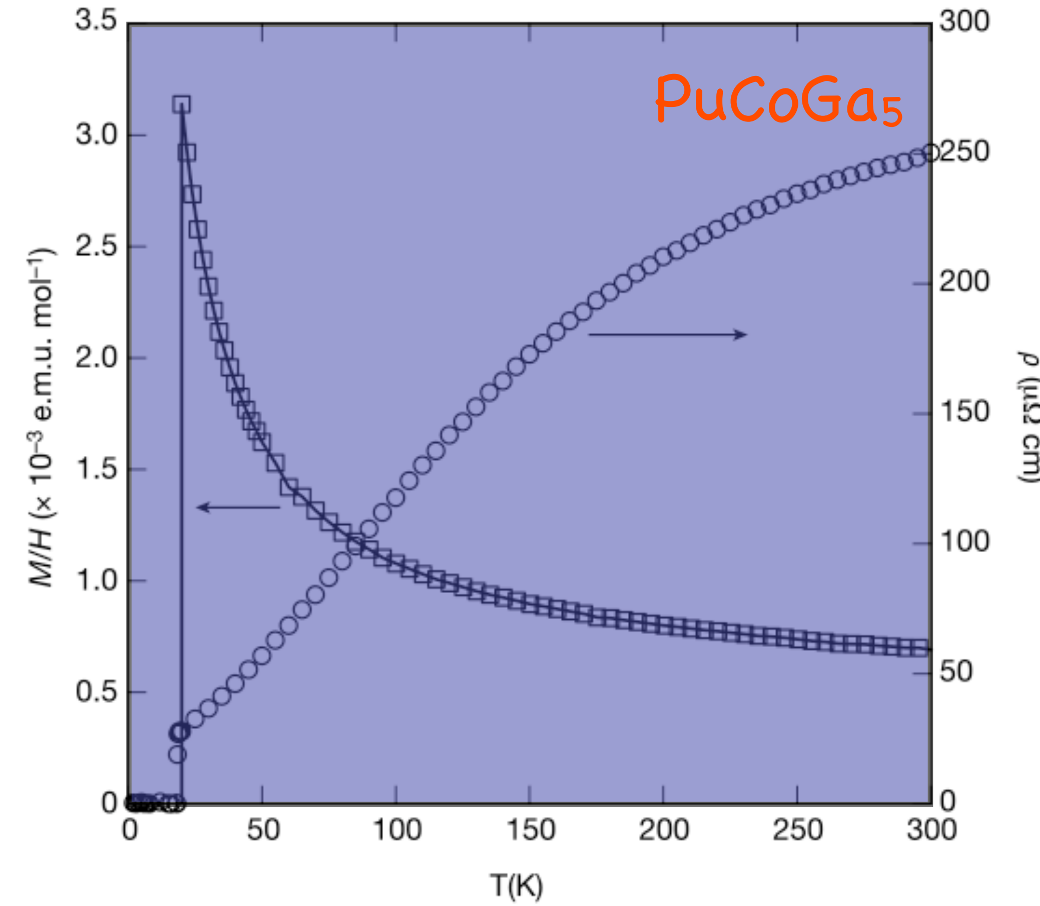

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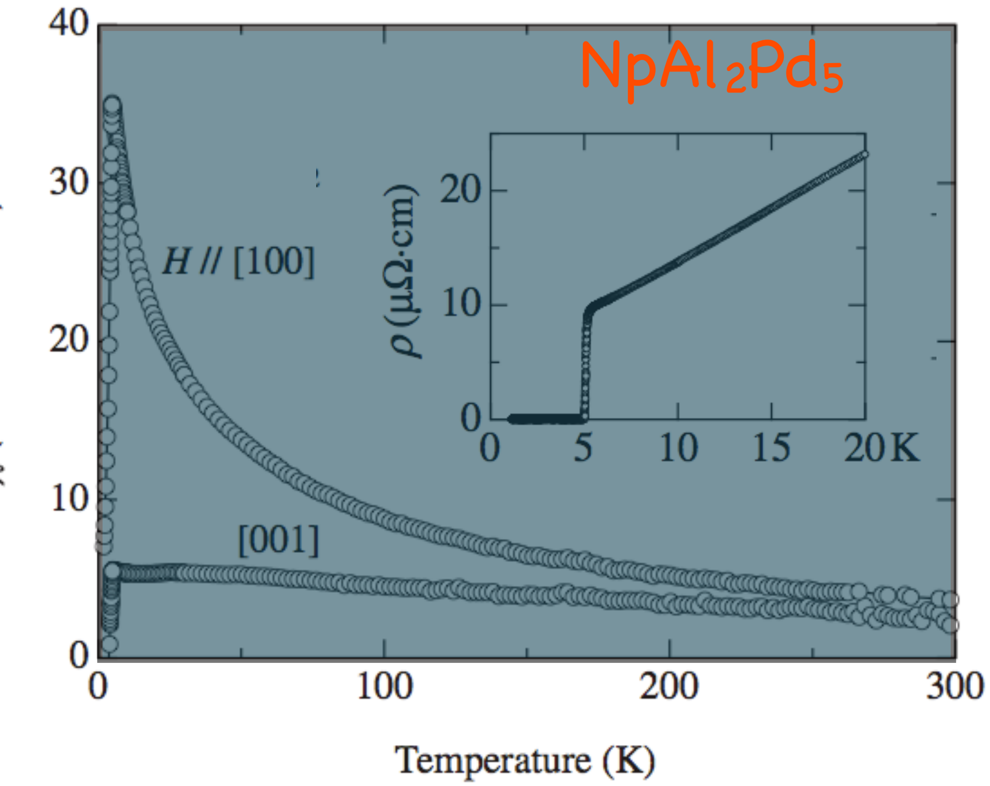

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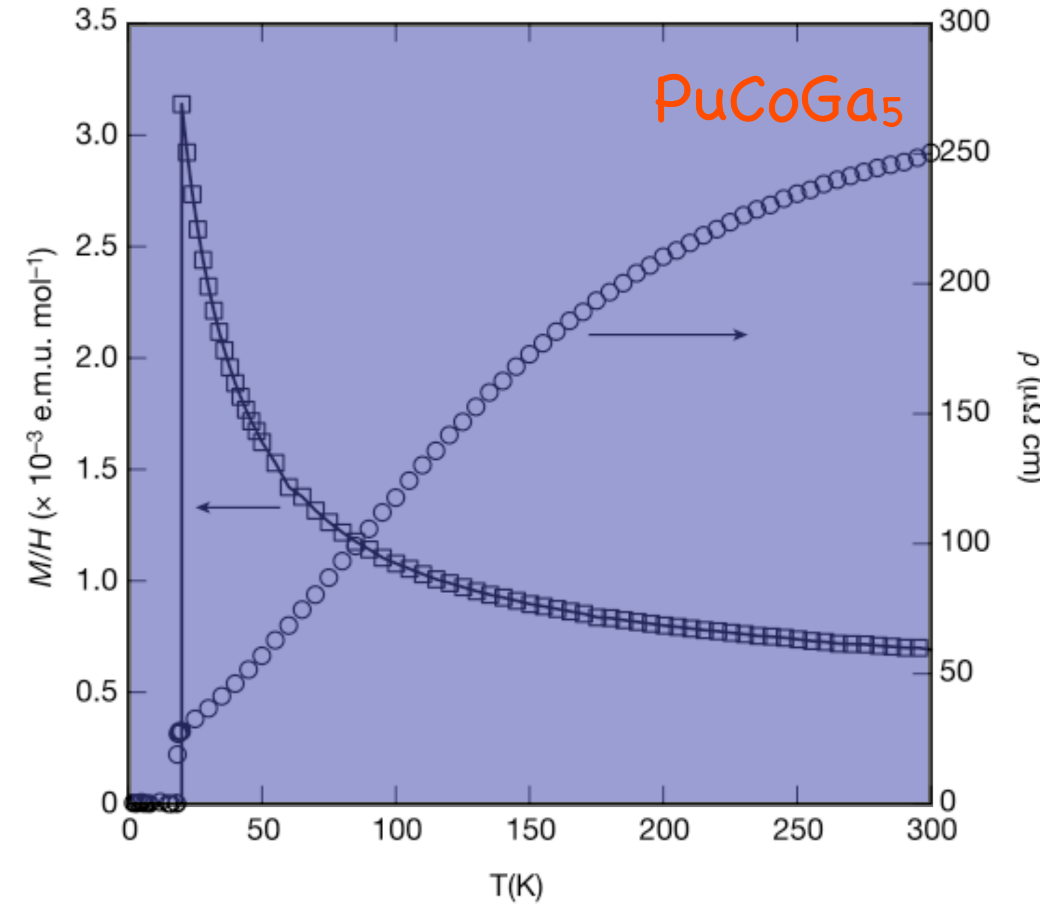

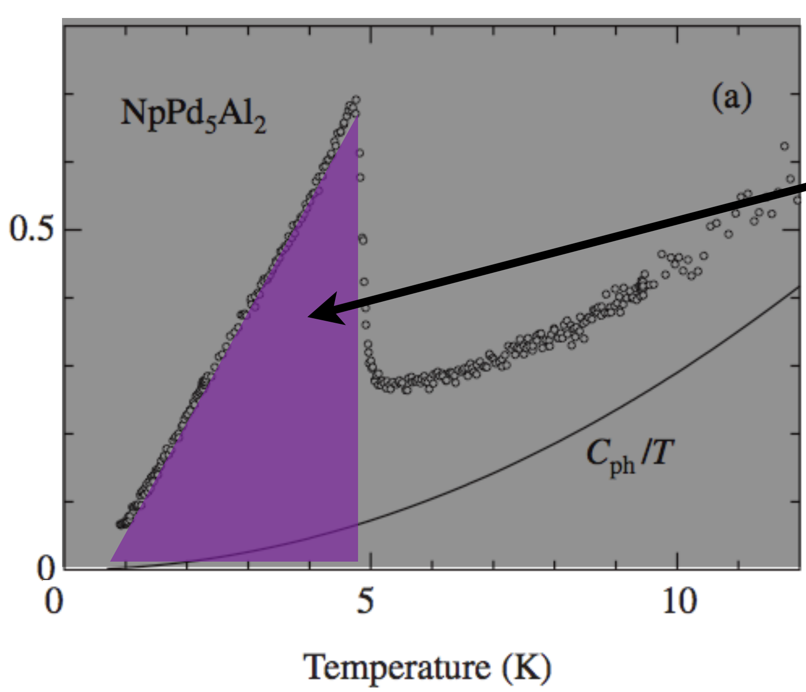

Substantial fraction of spin entropy.
1/3 R ln 2

•Suggests Kondo spin quenching and superconductivity develop <u>simultaneously.</u>

•Spin is not the glue, but the *<u>fabric</u>*

Symplectic Spins and Large N Expansions

Strongly correlated electron physics: no small parameter

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Large N : family of models which retain the key physics and can be solved in the large N limit.

$$Z = \sum_{configs} e^{-N \times S[\psi]}$$

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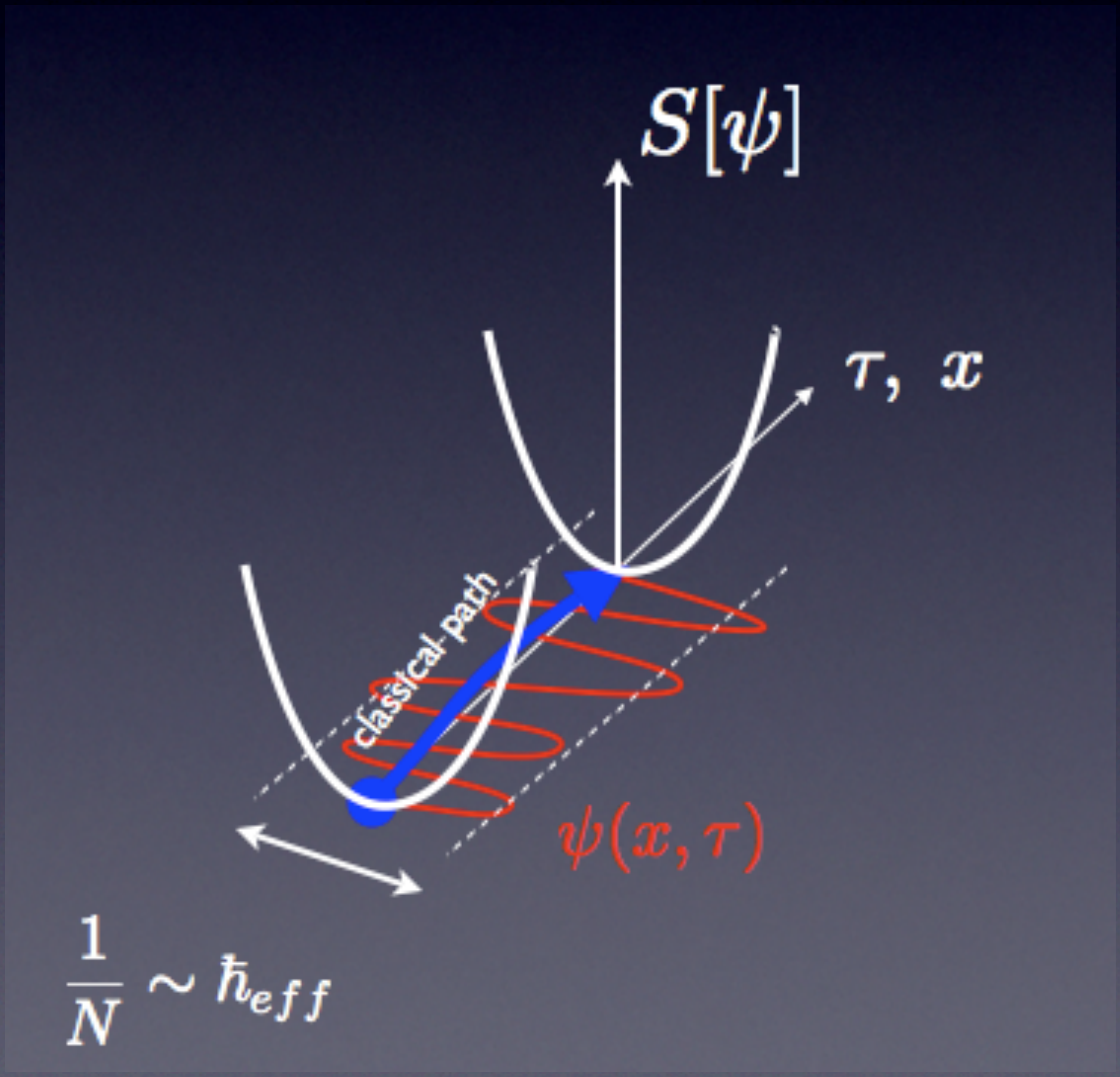

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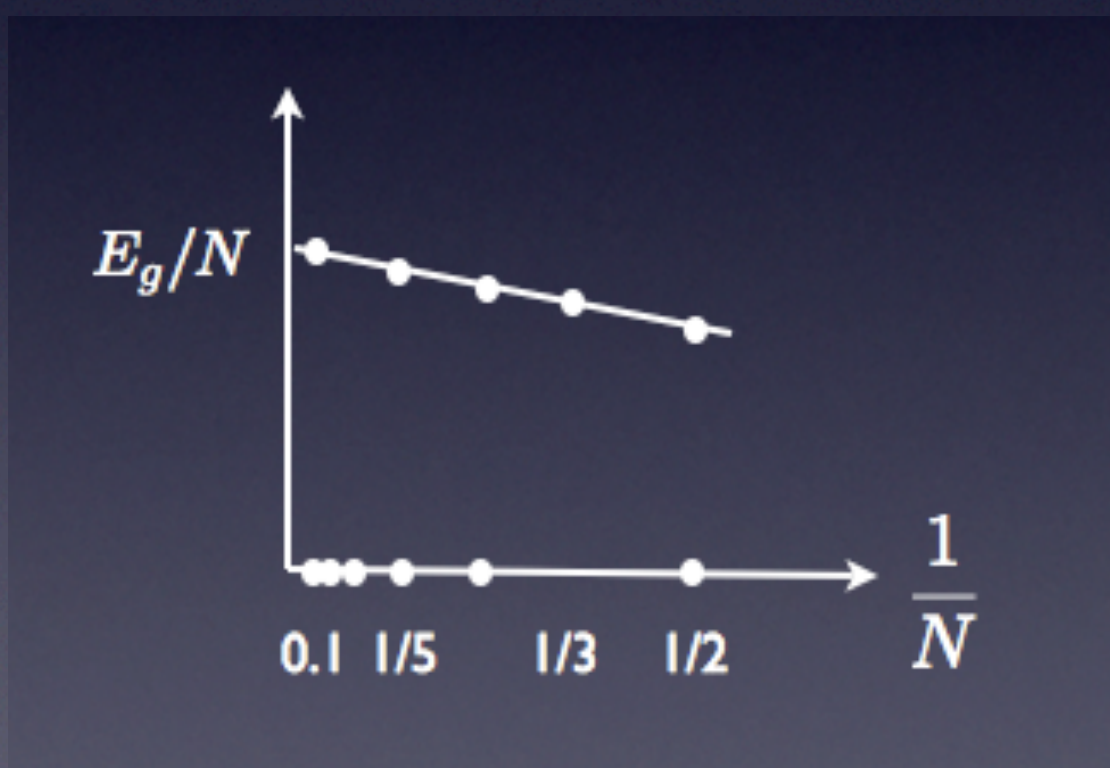

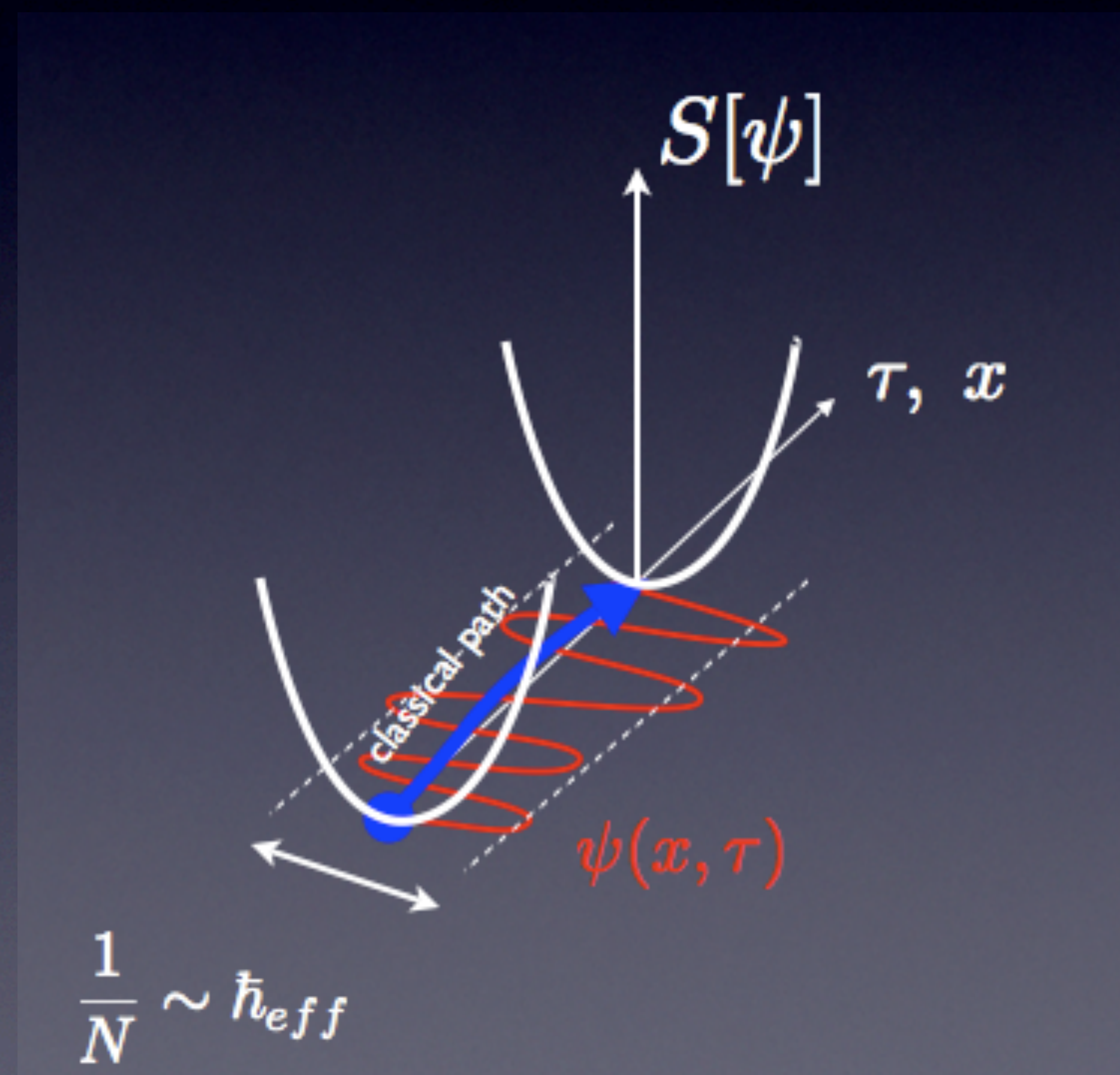

The magnetism and neutrality of the electron spin are manifested two discrete parities:

odd *under time reversal,*
even *under charge conjugation*

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$$S \xrightarrow{\theta} -S \quad \text{Magnetism}$$
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These discrete parities are lost in conventional large N expansions.

Time reversal = antiunitary operator = U K

$$\theta = i\sigma_2 K \qquad (Ka|\psi\rangle = a^* K|\psi\rangle)$$

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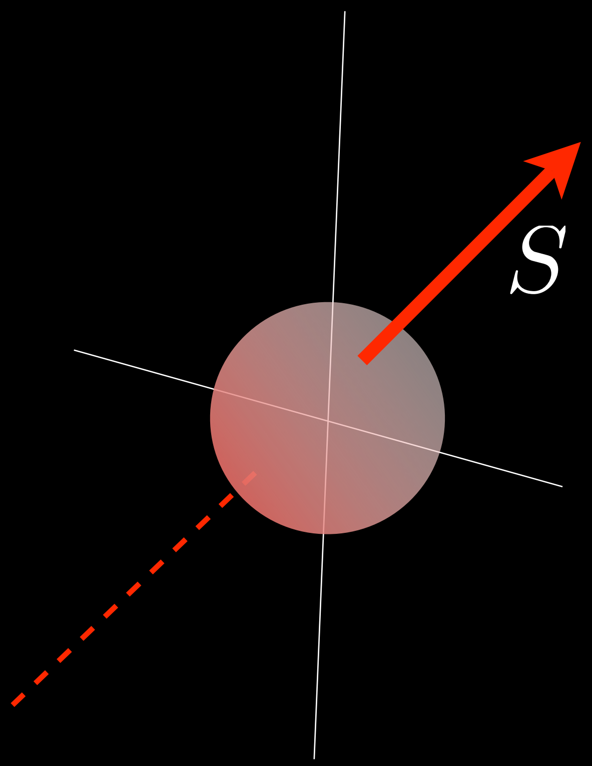

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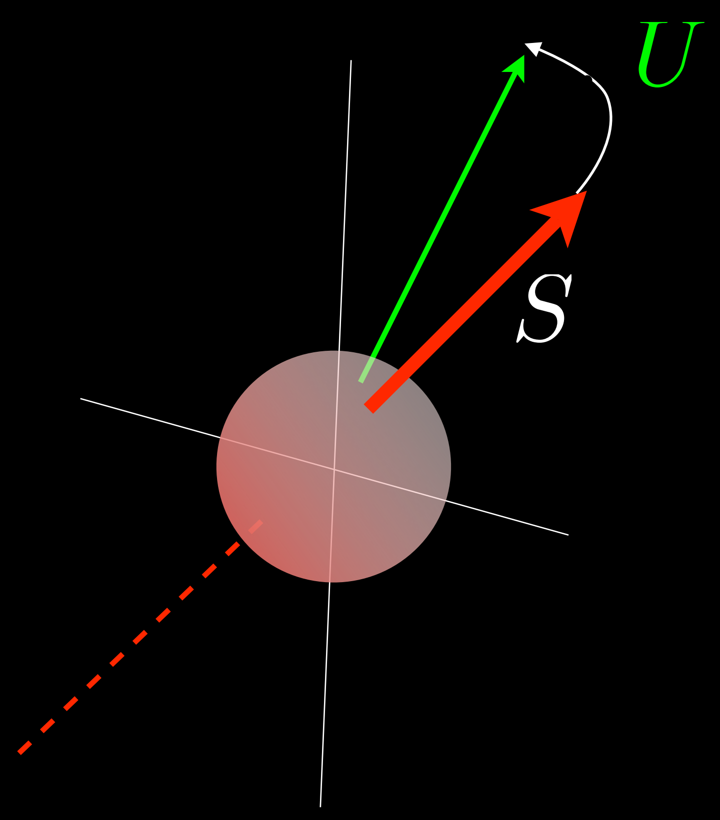

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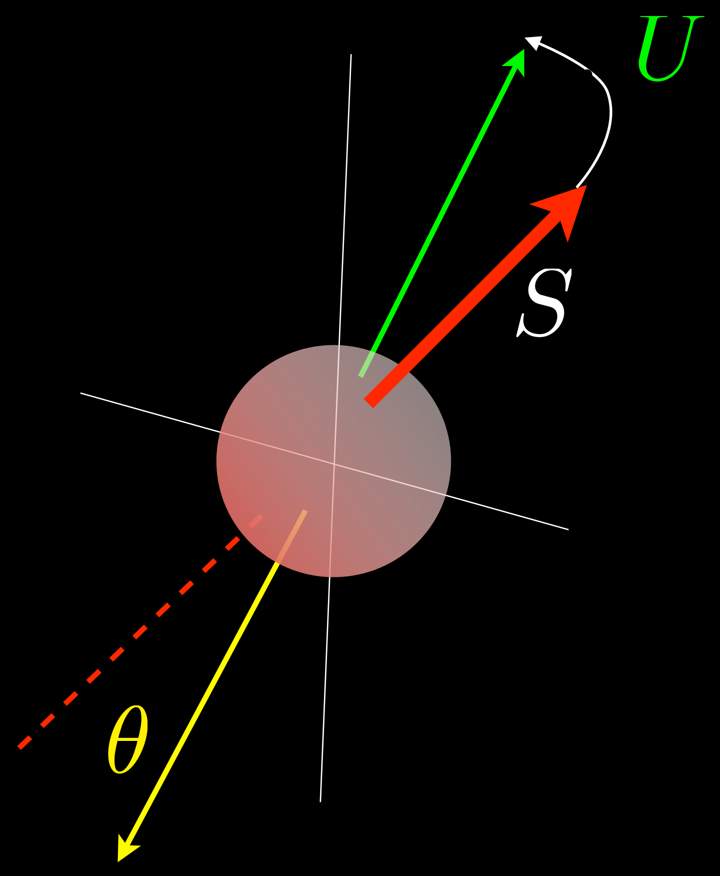

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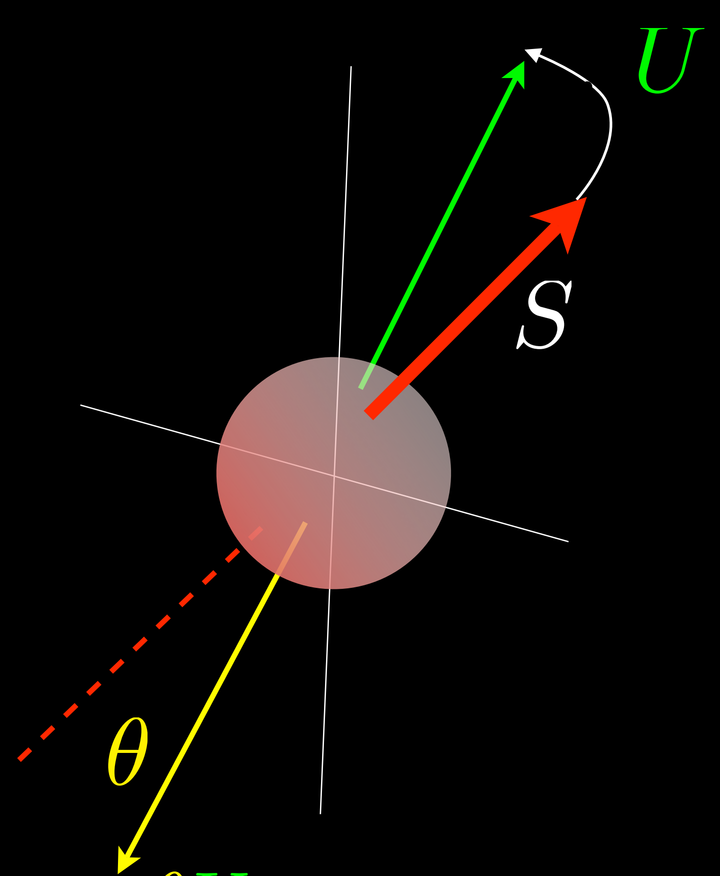

$$S \xrightarrow{\theta U} -(\underline{R}S)$$

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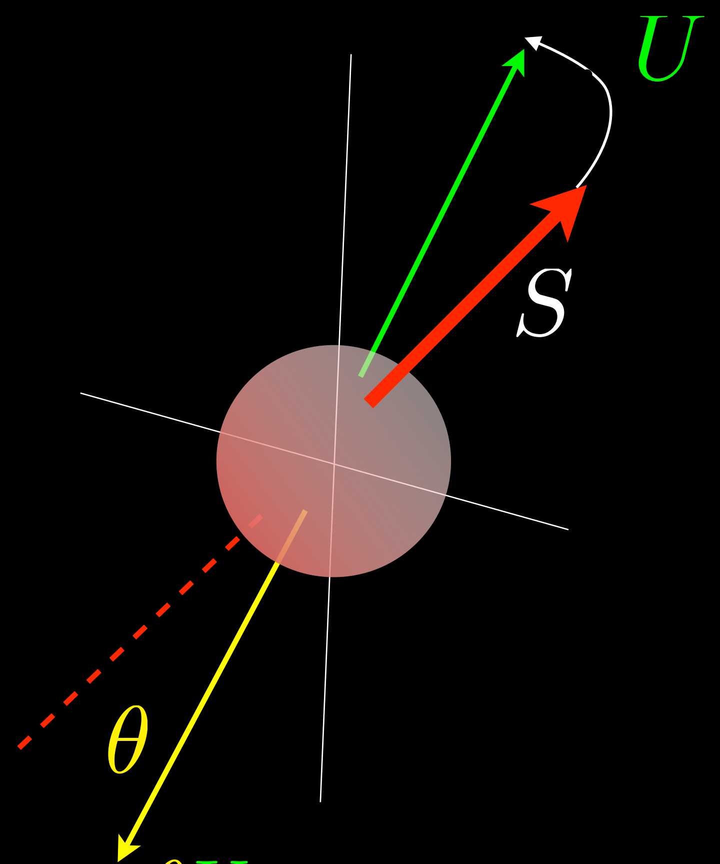

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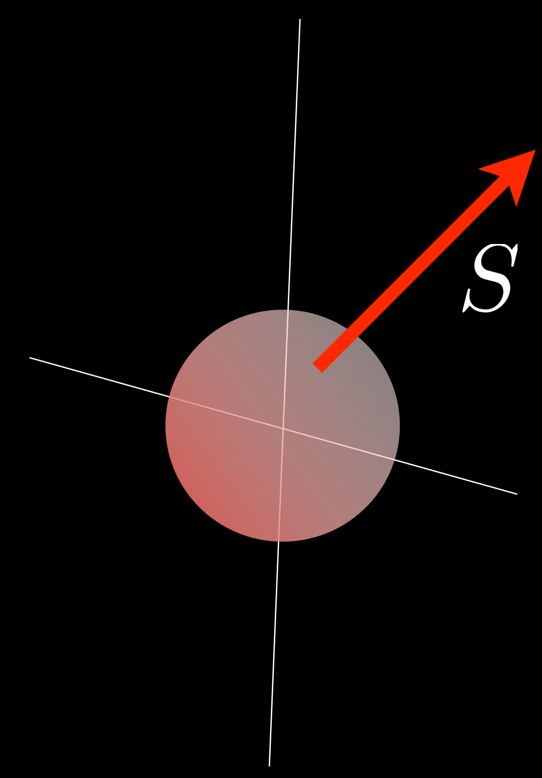

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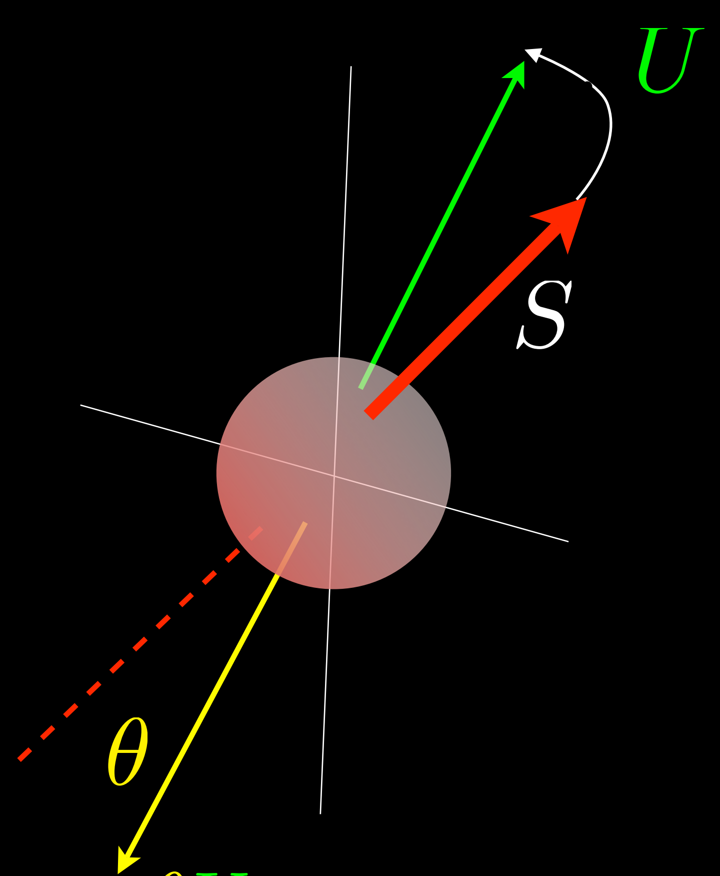

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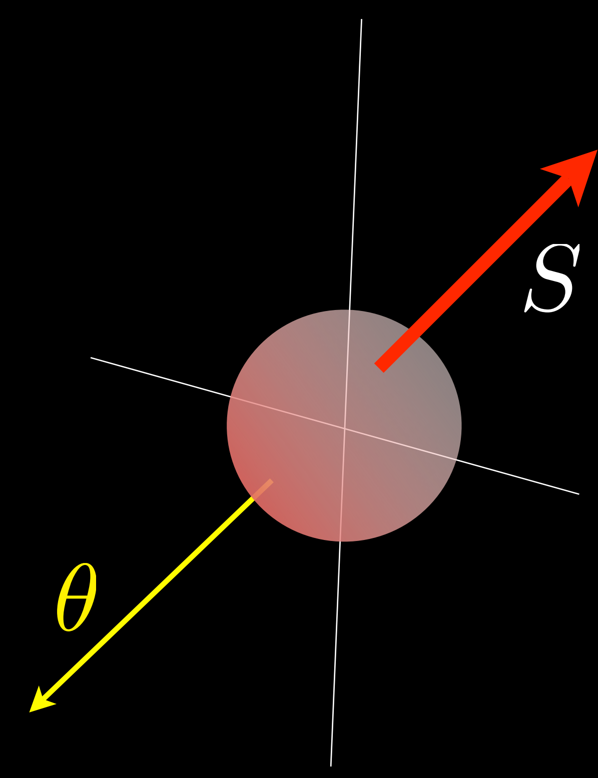

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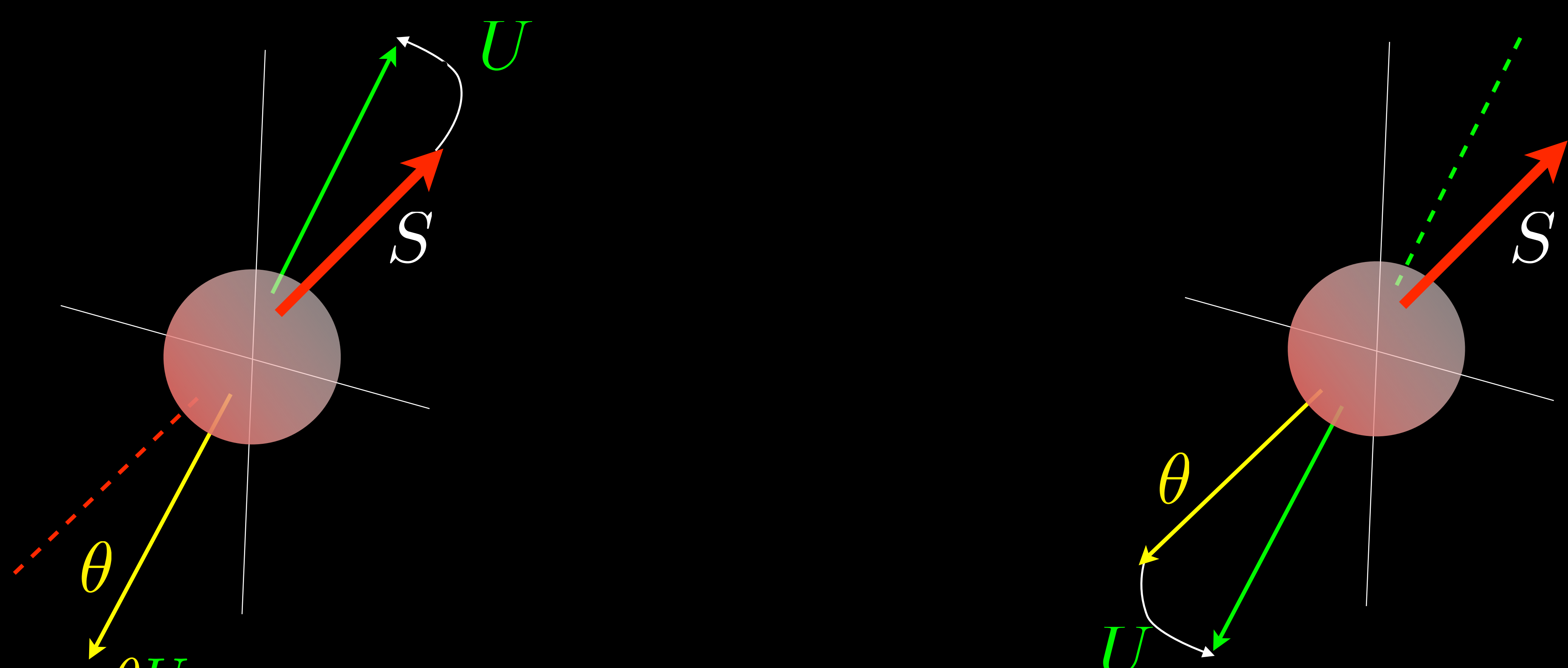

$$S \xrightarrow{\theta U} -(\underline{R}S) \qquad\qquad S \xrightarrow{U\theta} \underline{R}(-S)$$

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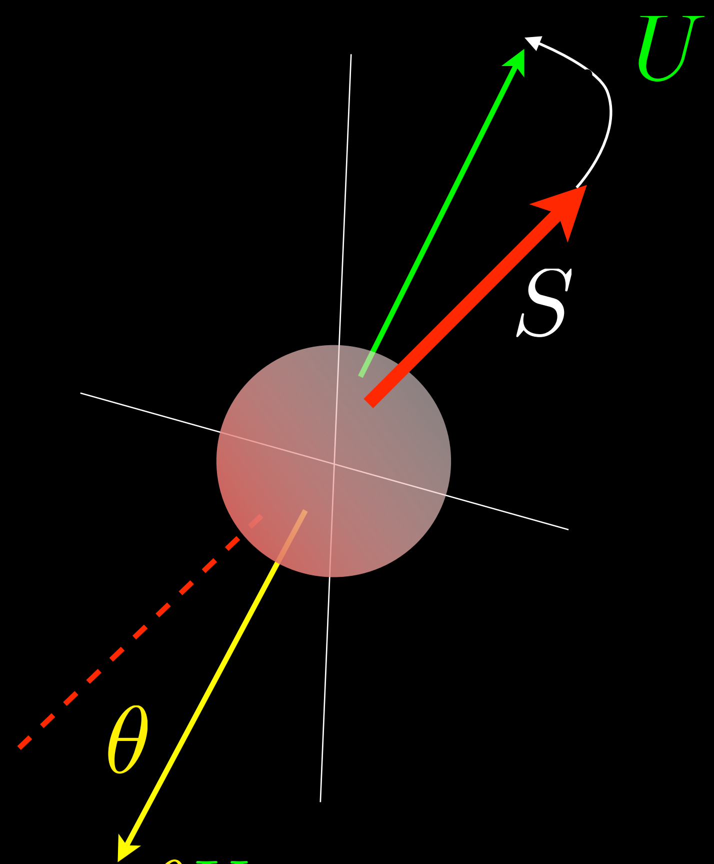
Invariance of time reversal under rotations U:

$$U\theta = \theta U \qquad (U = e^{i\frac{\vec{\alpha}}{2}\cdot\vec{\sigma}})$$



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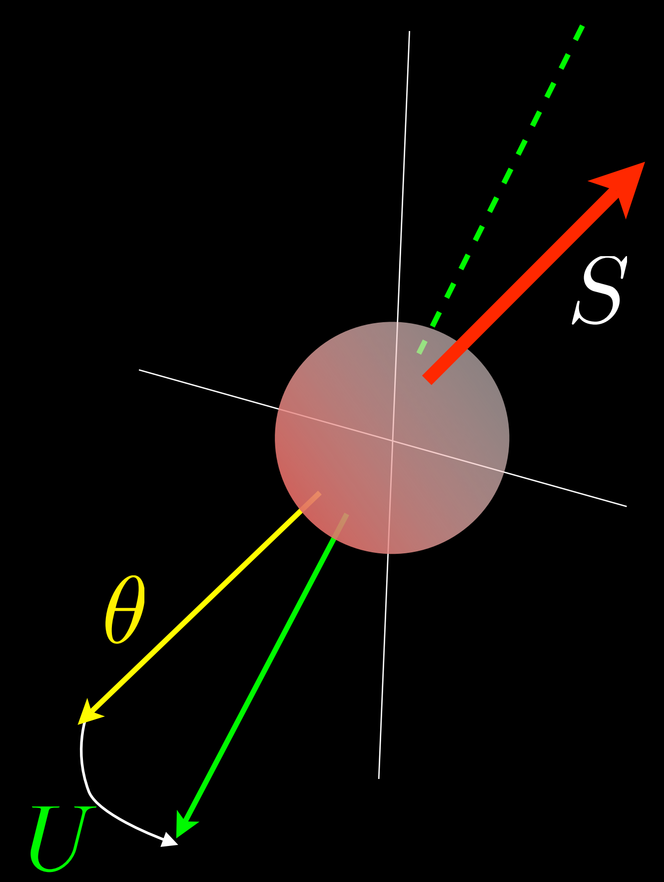

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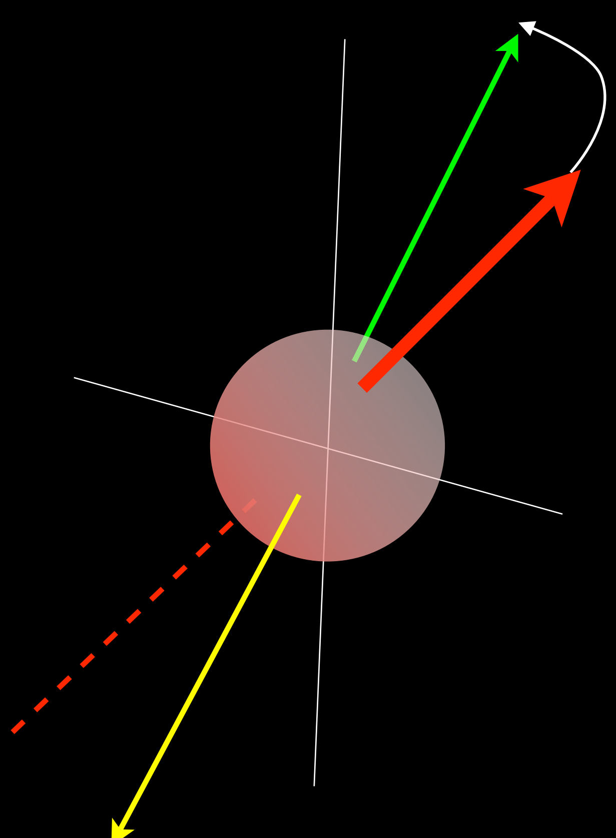

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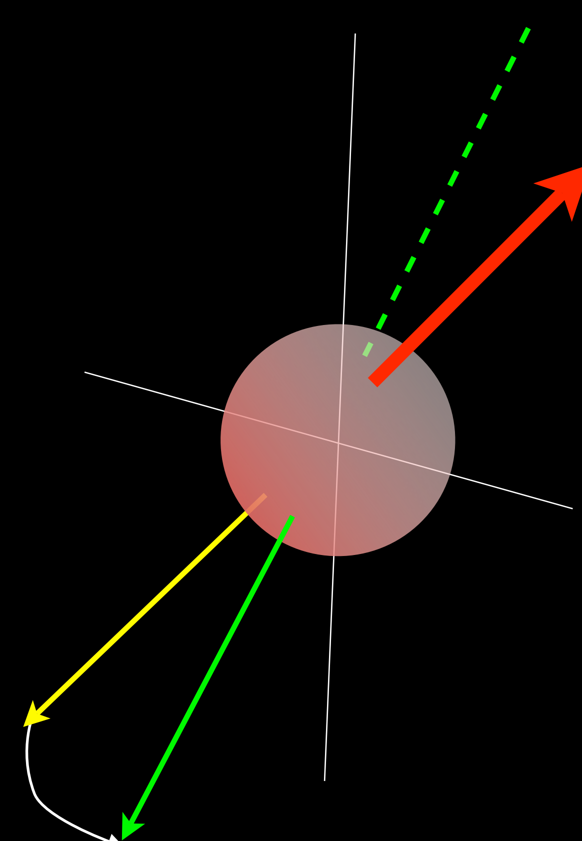

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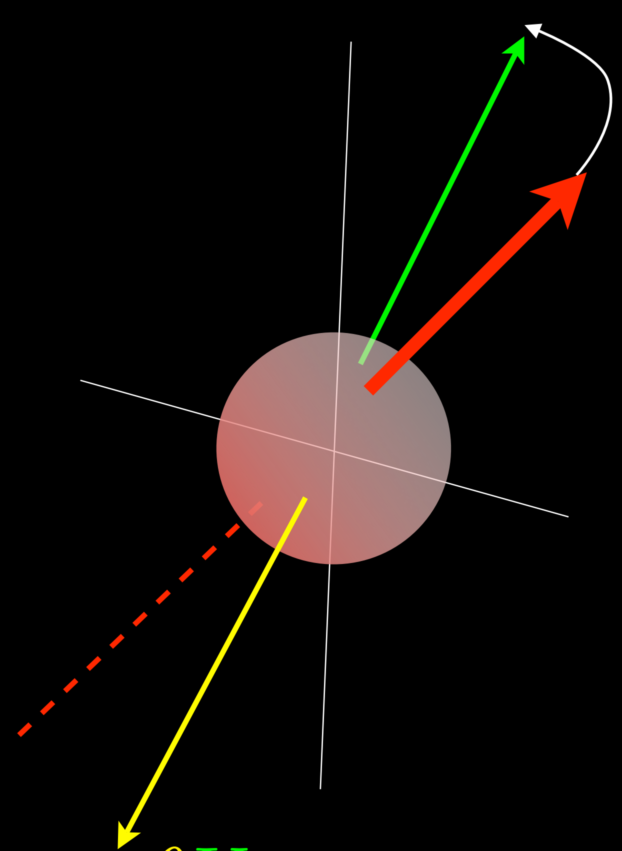

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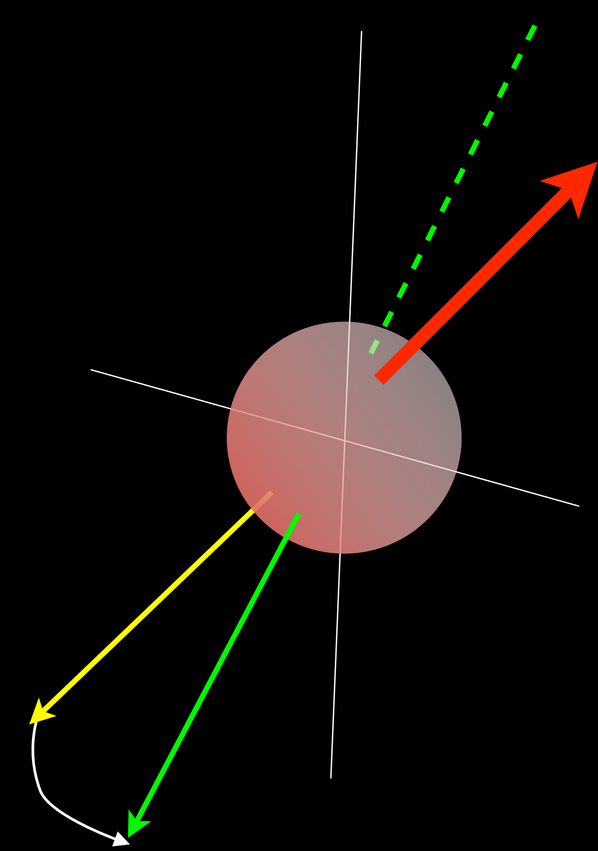

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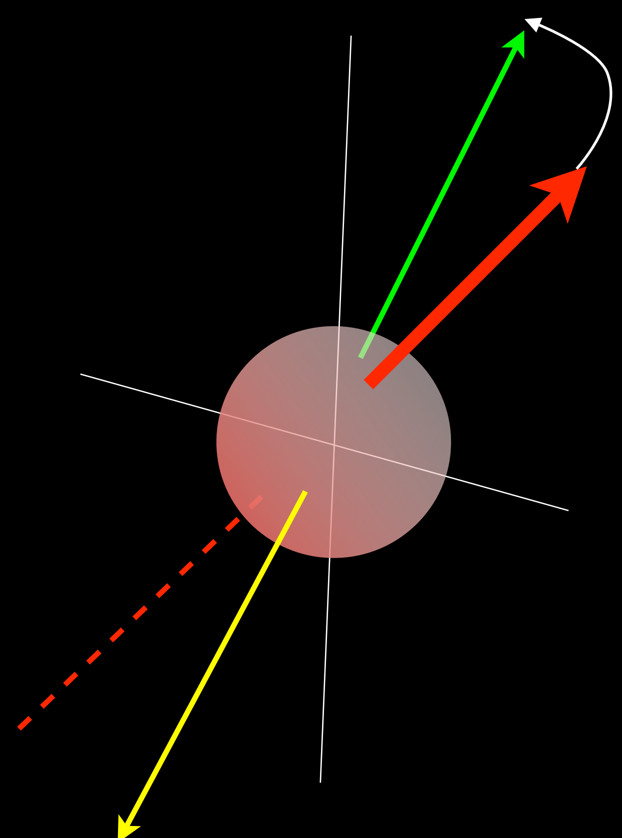
$$\boxed{U i\sigma_2 U^T = i\sigma_2 \qquad \text{SYMPLECTIC CONDITION}}$$



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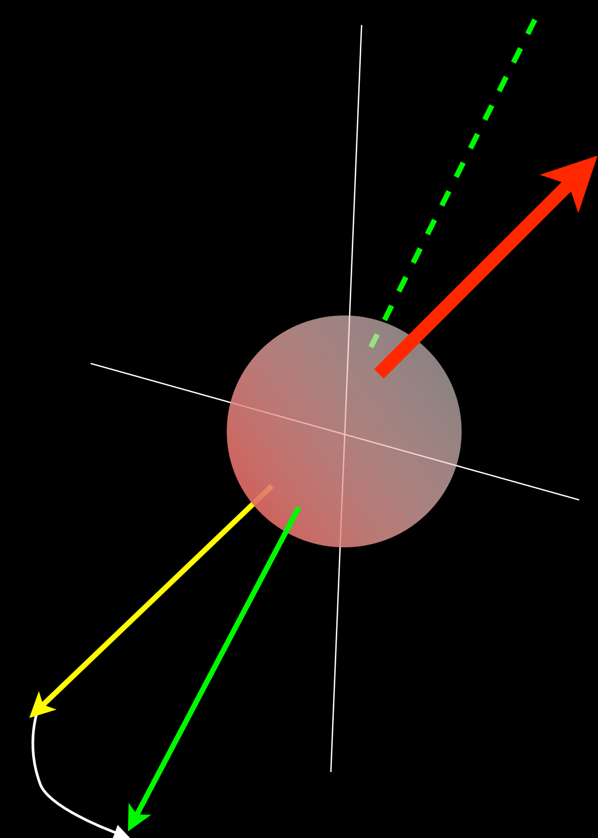

$$S \xrightarrow{U\theta} \underline{R}(-S)$$

SU(N) spin:

$$M_{\alpha\beta} = f^\dagger_\alpha f_\beta$$

$(\tilde{\alpha} \equiv \mathrm{sgn}(\alpha))$

SU(N) spin:

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$$\xrightarrow{\theta} \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}$$

$$\xrightarrow{\mathcal{C}} \tilde{\alpha}\tilde{\beta} f_{-\beta} f^\dagger_{-\alpha} = -\tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}$$

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$\mathcal{C}\theta = -1$, but $\mathcal{C}$ and θ ill-defined.

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$\mathcal{C}\theta = -1$, but $\mathcal{C}$ and θ ill-defined.

"magnetic" moments $\quad S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}, \quad (\theta, \mathcal{C}) = (-, +)$

"electric" dipoles $\quad \mathcal{P}_{\alpha\beta} = f^\dagger_\alpha f_\beta + \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}, \quad (\theta, \mathcal{C}) = (+, -)$

$S_{\alpha\beta} \equiv$ generators of the SP(N) group

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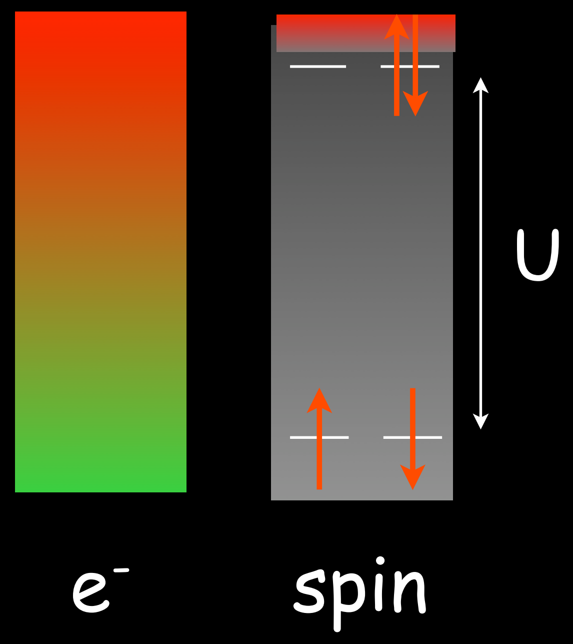
$S_{\alpha\beta} \equiv$ generators of the SP(N) group

$$[S, \tilde{\alpha} f_\alpha f_{-\alpha}] = 0$$

$\boxed{\text{Singlet pair commutes with symplectic spin} \longrightarrow \text{Local SU(2) gauge symmetry.}}$

Application to the Kondo Lattice

SPIN NEUTRALITY (Flint, Dzero,PC).



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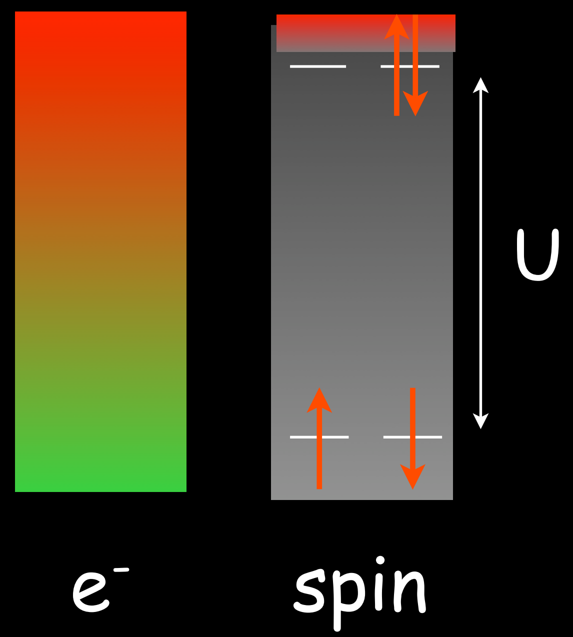

$$H = \sum \epsilon_k c^{\dagger}_{k\sigma} c_{k\sigma} + \frac{J}{N} \sum_j c^{\dagger}_{j\alpha} c_{j\beta} S_{\beta\alpha}(j) + H_g$$

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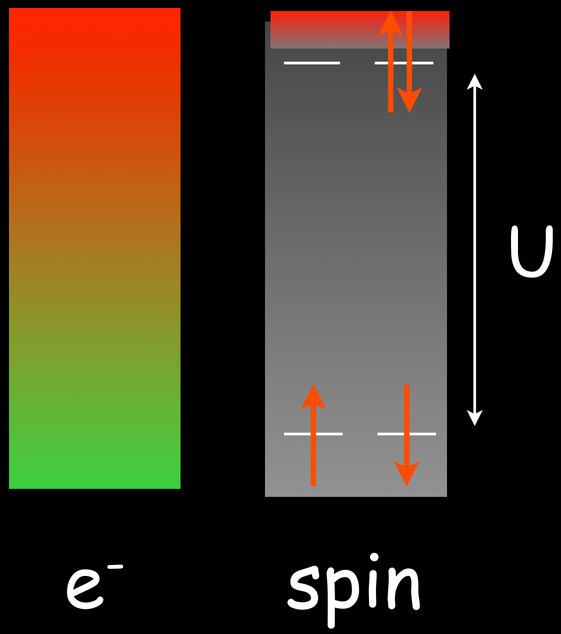

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What is the gauge field of the constraint?

(Read Newns, PC, Millis Lee... 80's)

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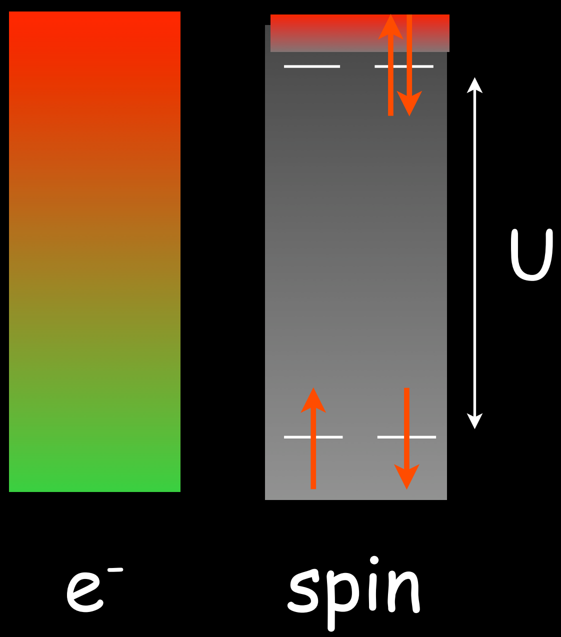

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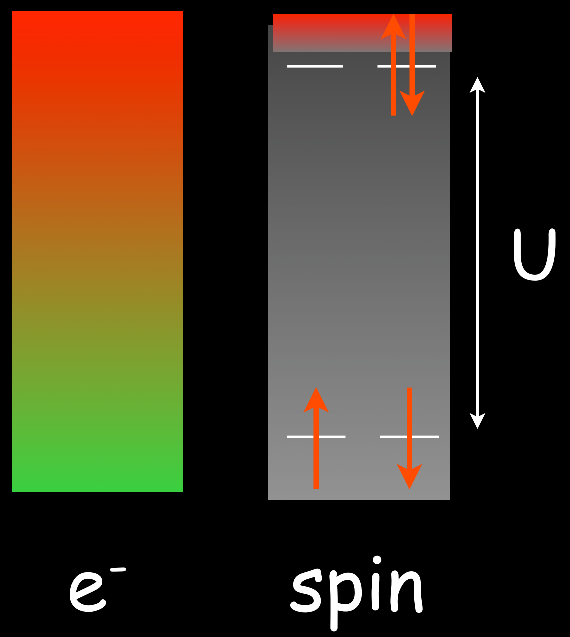

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"Symplectic spin" (Flint,Dzero,PC)

$$f_\alpha \to e^{i\theta} f_\alpha$$
$$f_\alpha \to \cos\phi\, f_\alpha + \sin\phi\ \mathrm{sgn}(\alpha) f^\dagger_{-\alpha}$$

SU(2) gauge symmetry (Affleck et al '89)

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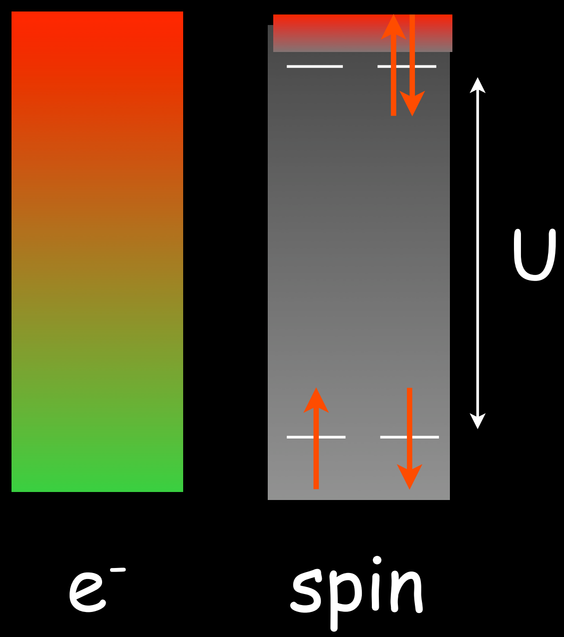

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$$\begin{aligned} H_g &= (\Phi - \mu) c^{\dagger}_j c_j \\ &+ W_+(f^{\dagger} f^{\dagger}) + W_0(f^{\dagger} f) + W_-(f f) \end{aligned}$$

$U(1)_{\text{global}} \times SU(2)_{\text{local}}$

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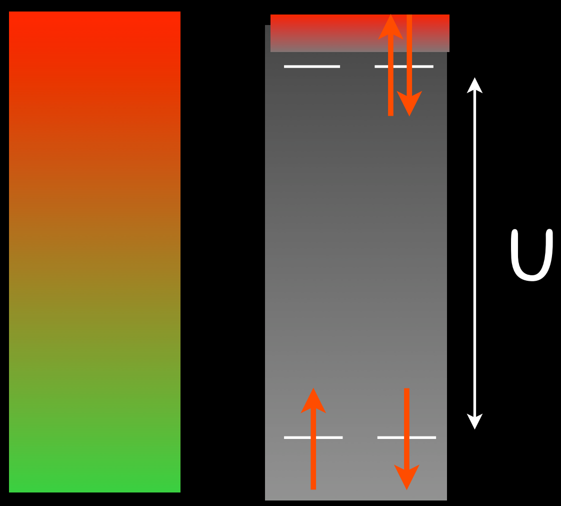

e^- spin

Φ W

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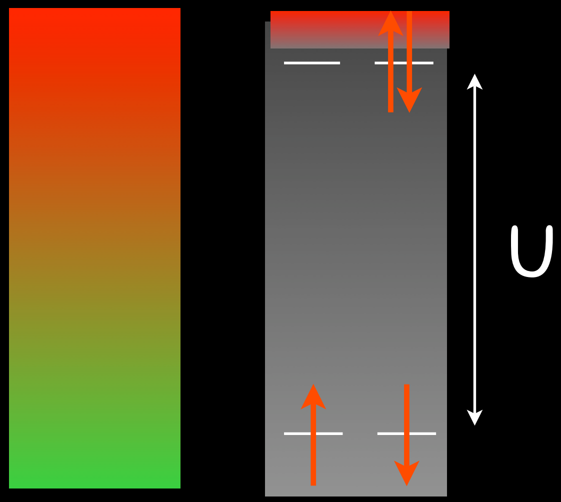

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Φ

W^- W^0 W^+

cf Weinberg Salem

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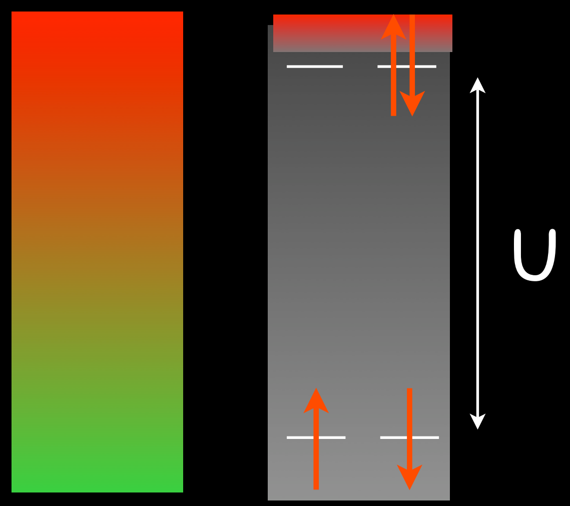

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$\boxed{\begin{array}{c} \Phi \\ W^0 \end{array}}$

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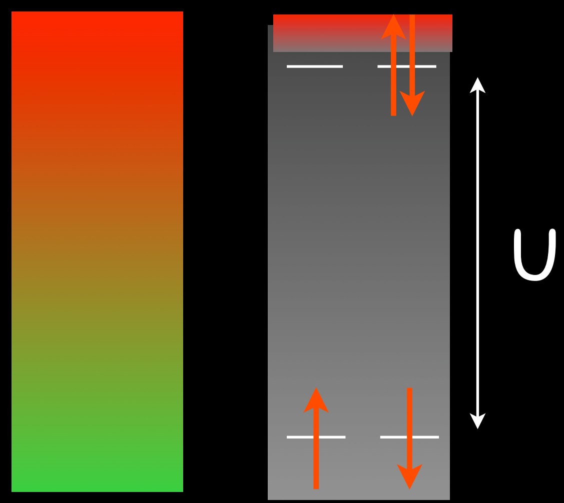

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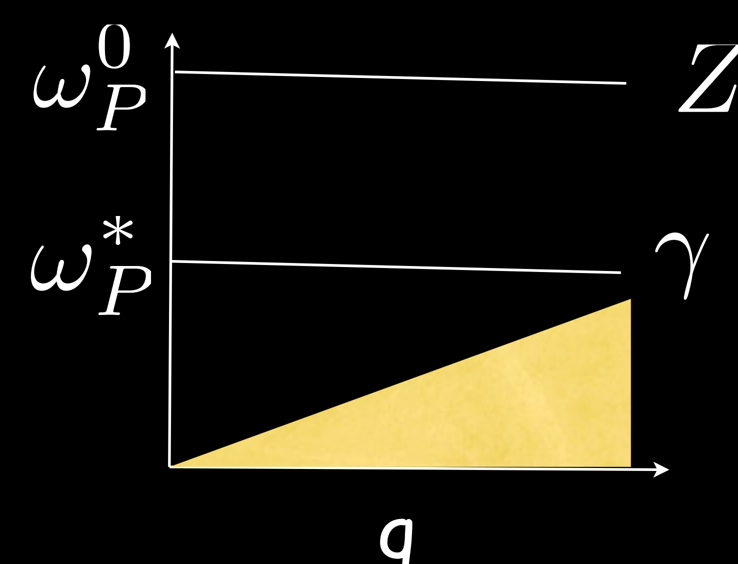
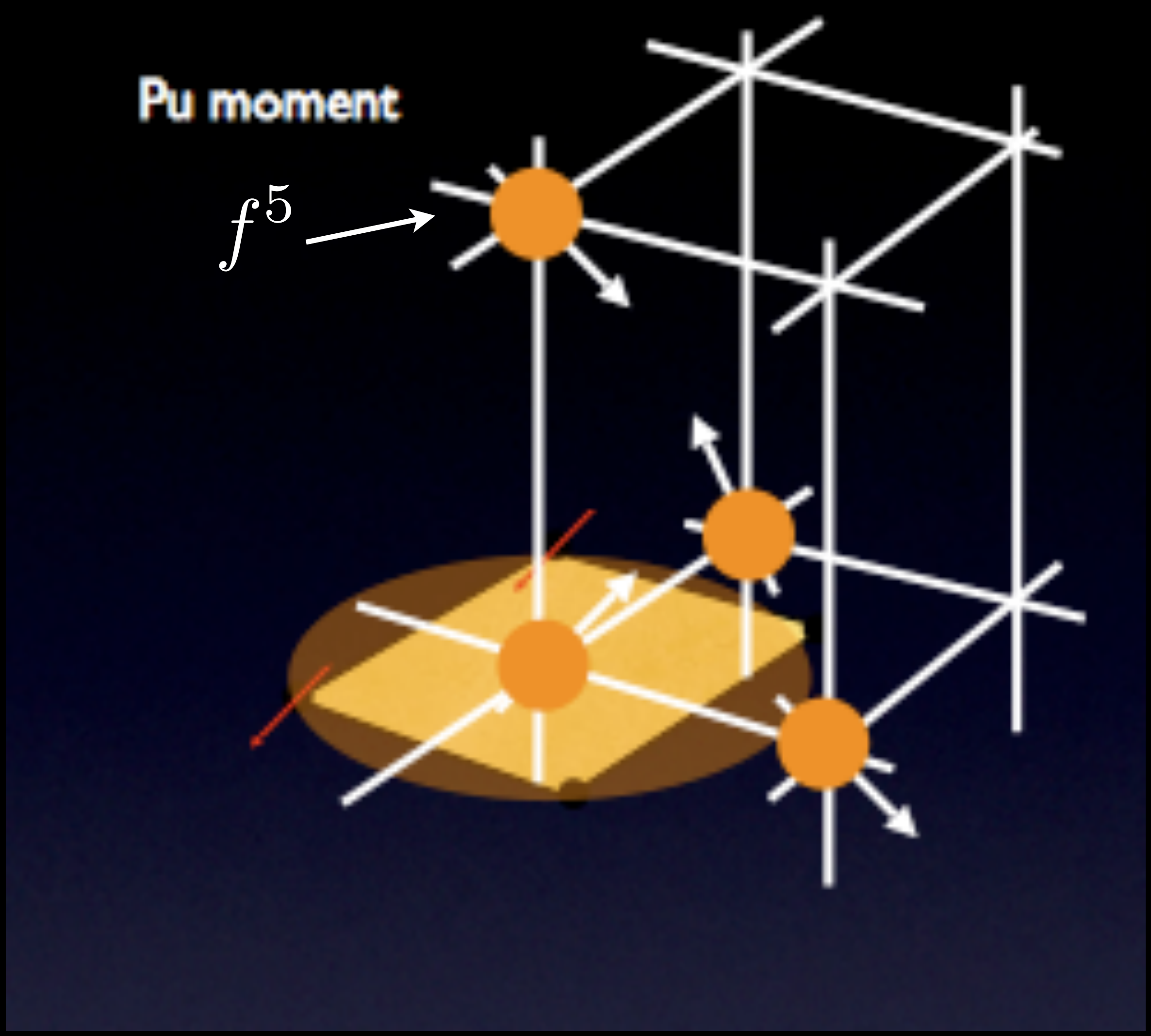
$$\begin{array}{ccc} & \Phi & \\ W^- & W^0 & W^+ \end{array}$$

cf Weinberg Salem

$$\text{photon} = (\Phi + W_0)/2$$
$$Z = (\Phi - W_0)/2$$



Model for $PuCoGa_5$ & $NpPd_2Al_5$



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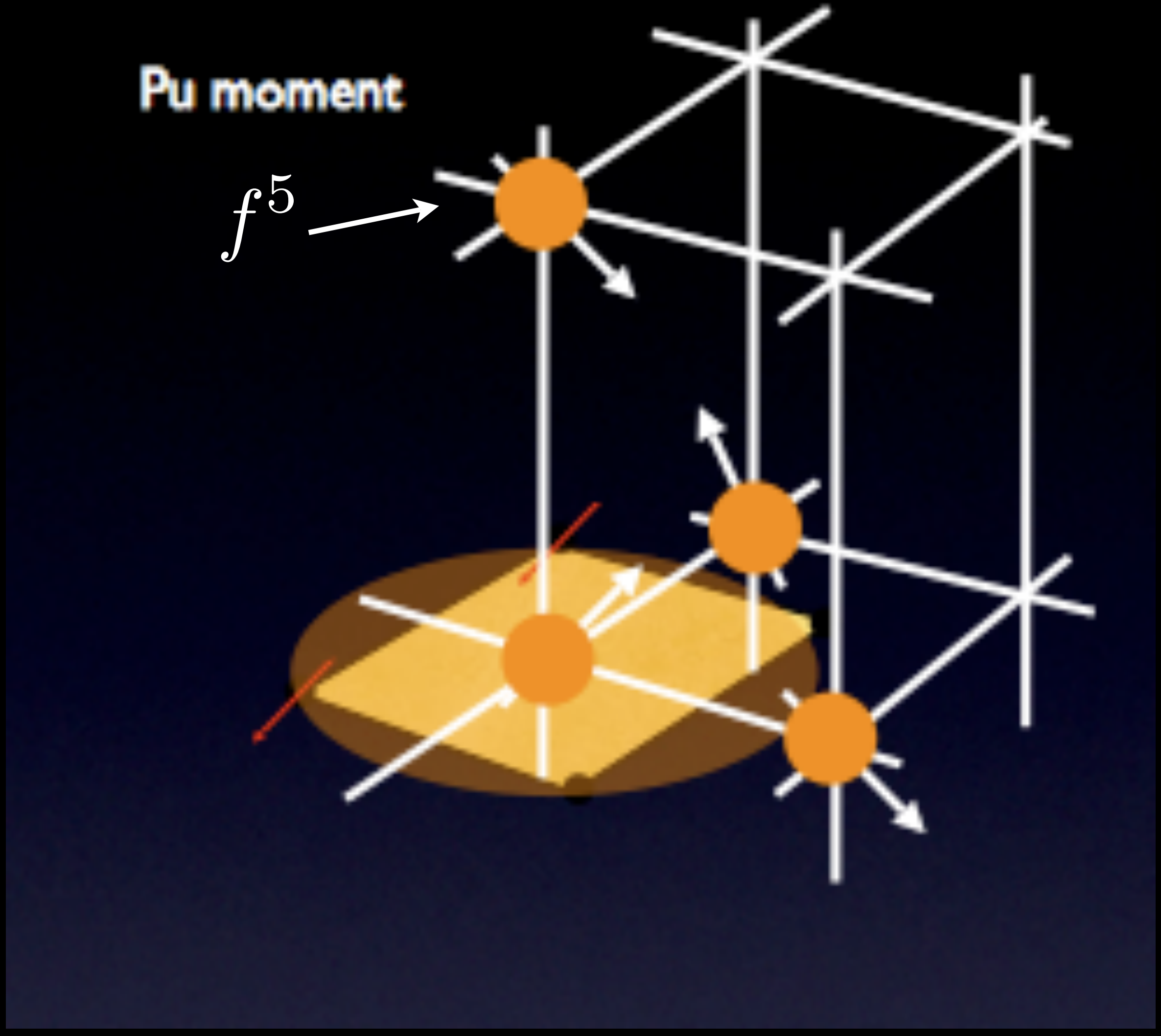

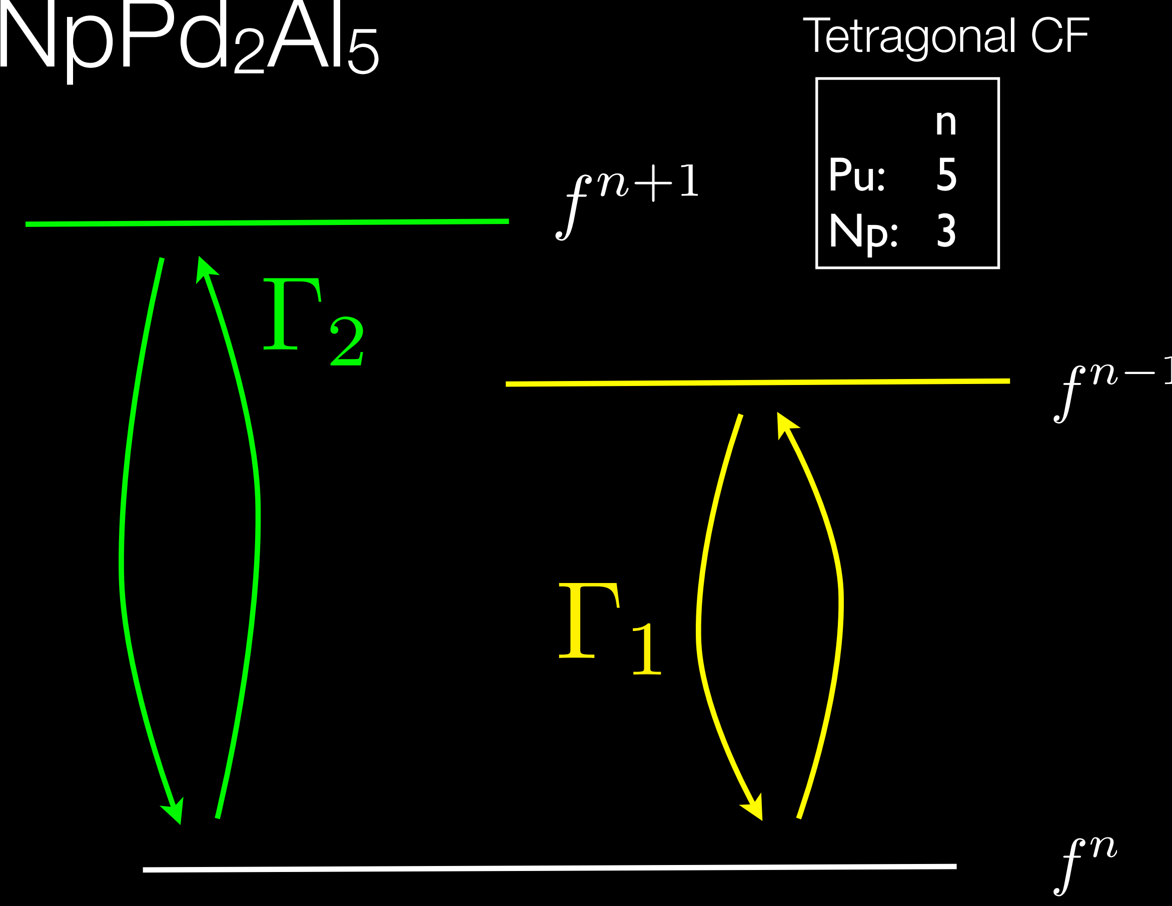

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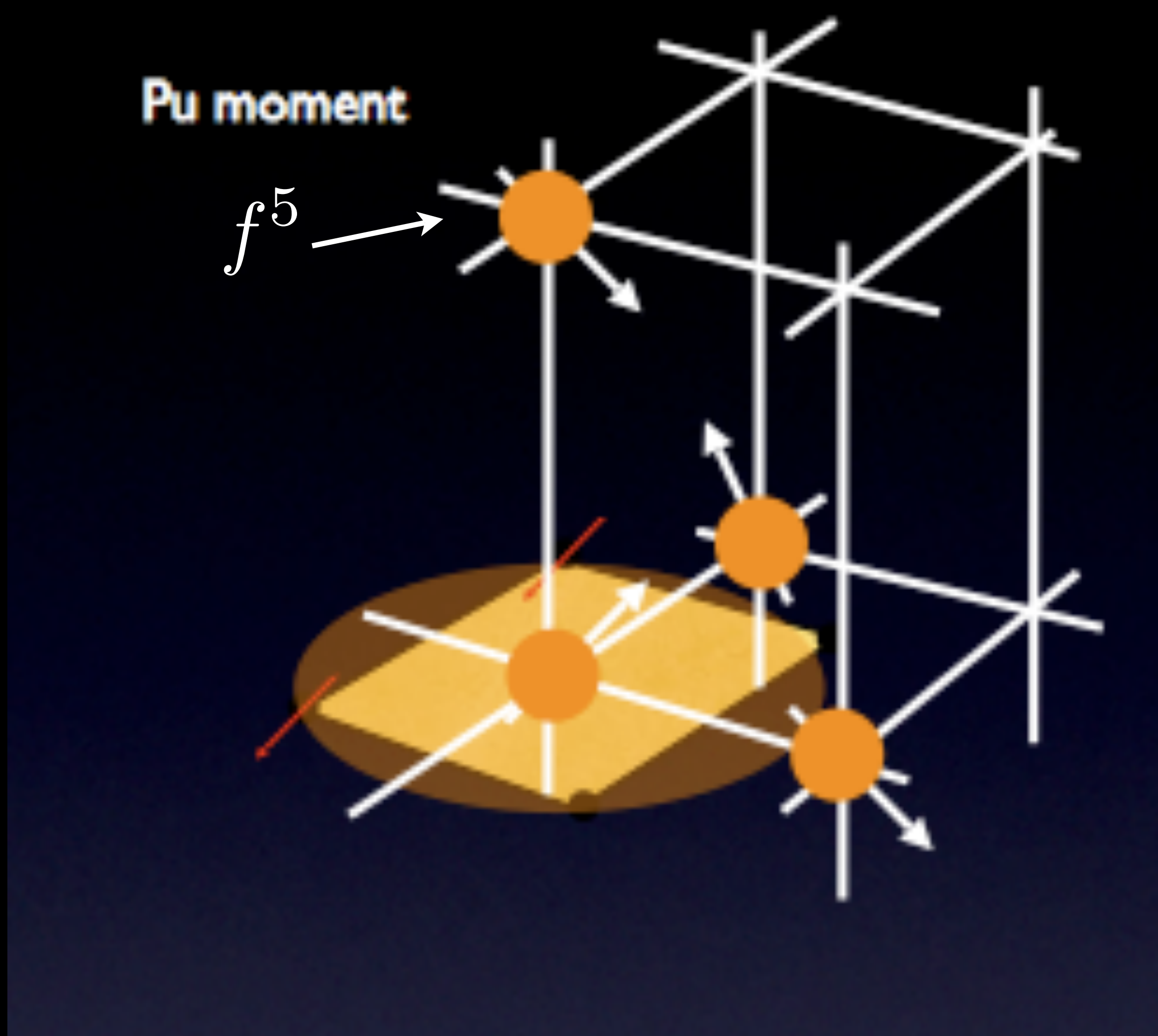

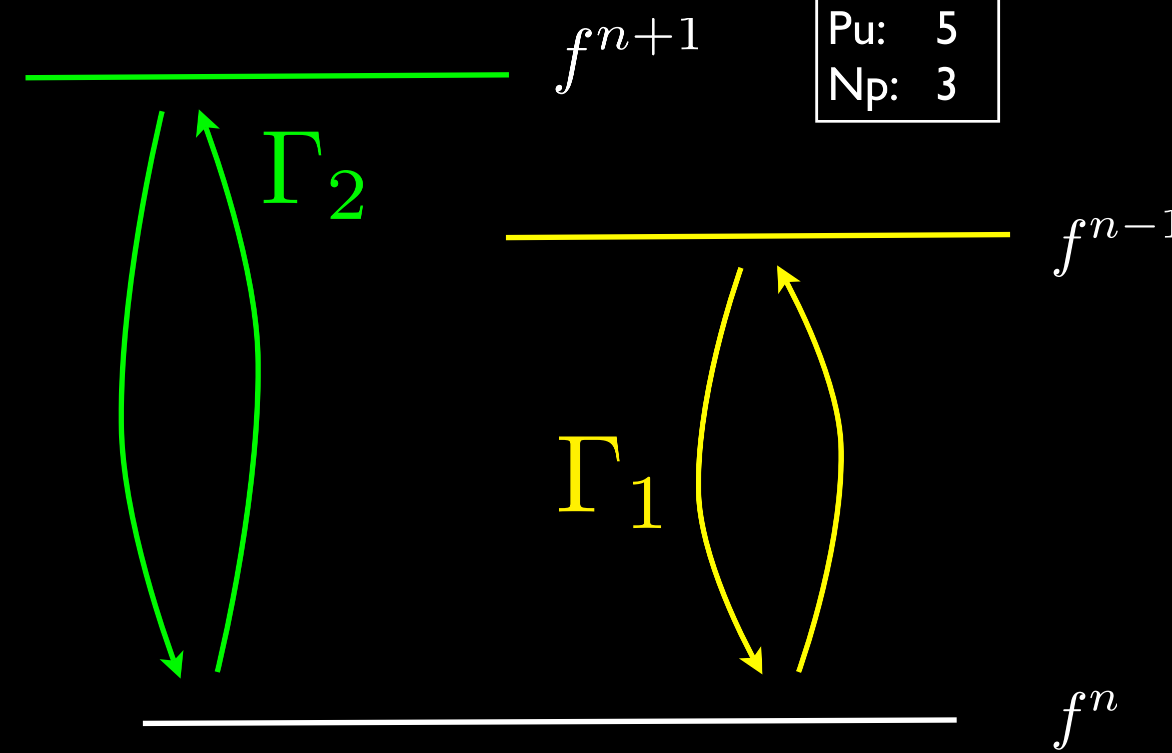

Tetragonal CF

	n
Pu:	5
Np:	3

Virtual valence fluctuations mediate Kondo-spin exchange in two channels with different symmetry (Cox, 89).

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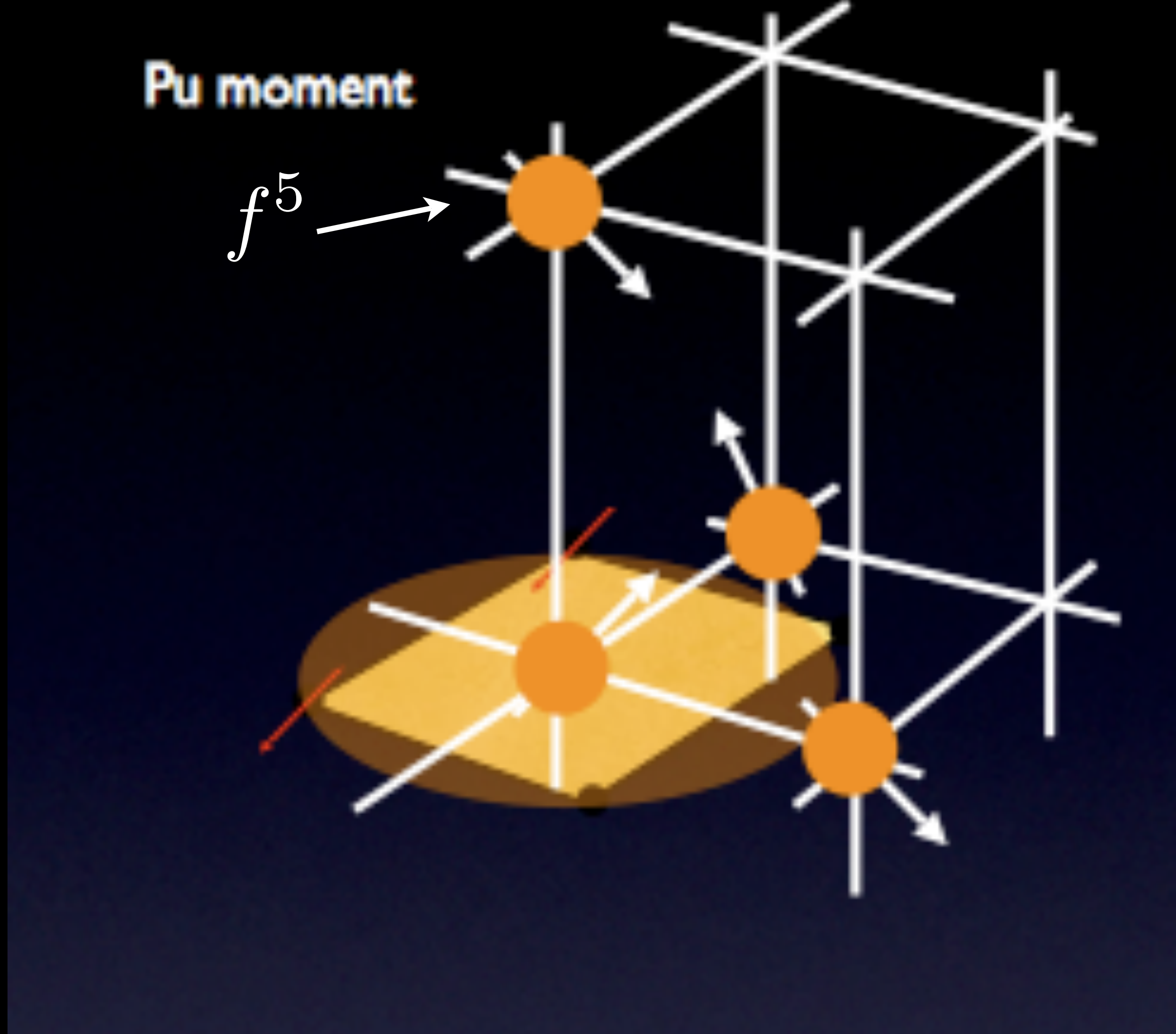

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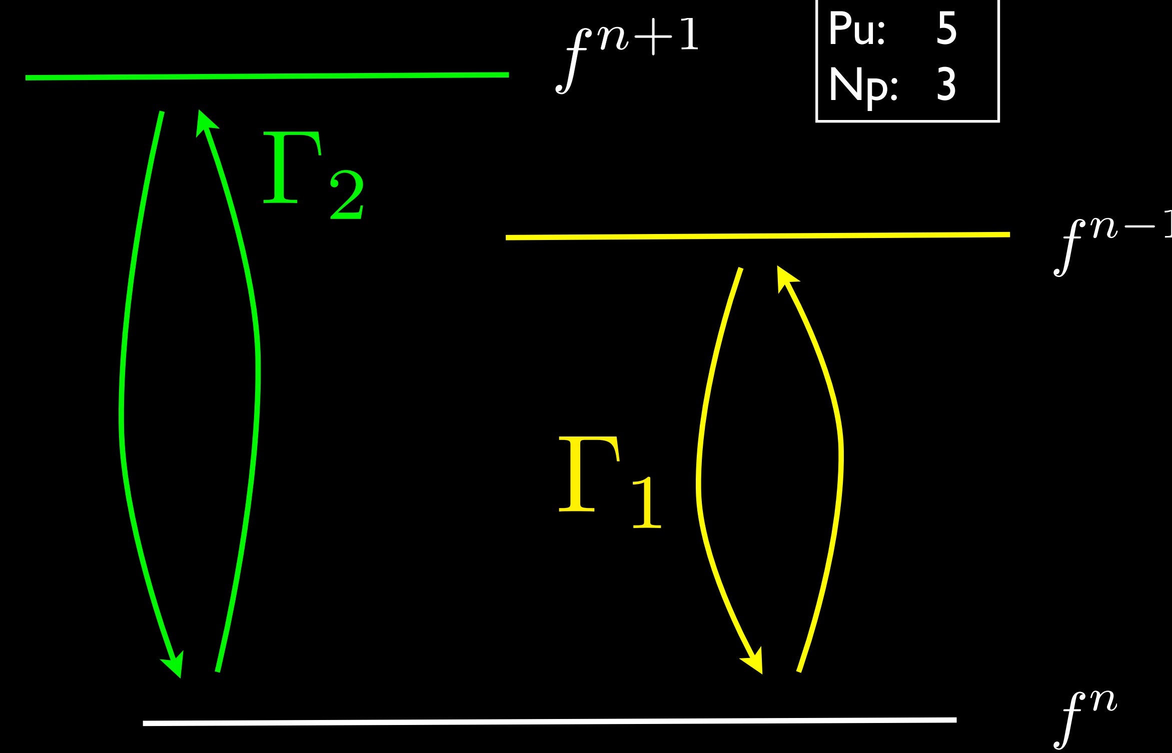

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$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \right) S^{ba}(j)$$

Single FS, two channels.

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

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

Decoupling the interactions

$$
\begin{aligned}
H_I &= \frac{J_K}{N}\sum \psi_a^\dagger \psi_b \overbrace{\left(f_b^\dagger f_a - \tilde{a}\tilde{b} f^\dagger_{-a} f_{-b}\right)}^{S_{ba}} \\
&= -\frac{J_K}{N}\sum \Big[(\psi^\dagger f)(f^\dagger \psi) + (\psi^\dagger \sigma_2 f^\dagger)(f\sigma_2\psi) \Big].
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$$

$$
H_I \rightarrow \left[\underbrace{[V f^\dagger + (\Delta f \sigma_2)]}_{=\tilde{f}^\dagger \sqrt{|V|^2+|\Delta|^2} = \tilde{f}^\dagger \tilde{V}} \psi + \mathrm{H.c} \right] + N\left(\frac{\bar{V}V + \bar{\Delta}\Delta}{J_K}\right).
$$

- "Pairing" can be gauged away for 1 channel.

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\end{aligned}
$$

$$
H_I \to \Big[[\tilde{V}\tilde{f}^\dagger]\psi \qquad\qquad\qquad + \mathrm{H.c} \Big] + N\left(\frac{\tilde{V}^2}{J_K}\right).
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Decoupling the interactions

- Two channels:

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\begin{aligned}
H_I \quad &\rightarrow \quad \left[[V_1 f^\dagger + (\Delta_1 f \sigma_2)]\psi_1 + \mathrm{H.c} \right] + N \left(\frac{V_1 V_1 + \Delta_1 \Delta_1}{J_1} \right) \\
&+ \quad \left[[V_2 f^\dagger + (\Delta_2 f \sigma_2)]\psi_2 + \mathrm{H.c} \right] + N \left(\frac{\bar{V}_2 V_2 + \bar{\Delta}_2 \Delta_2}{J_2} \right)
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Gauge fixing does not remove the pairing

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The gauge-invariant cross term $V_1\Delta_2 - V_2\Delta_1$ describe the overscreened formation of composite pairs

$$
\langle \vec{S} \cdot \psi_1 \sigma_2 \vec{\sigma} \psi_1 \rangle \propto V_1\Delta_2 - V_2\Delta_1
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PC, Kee, Andrei & Tsvelik. (97)

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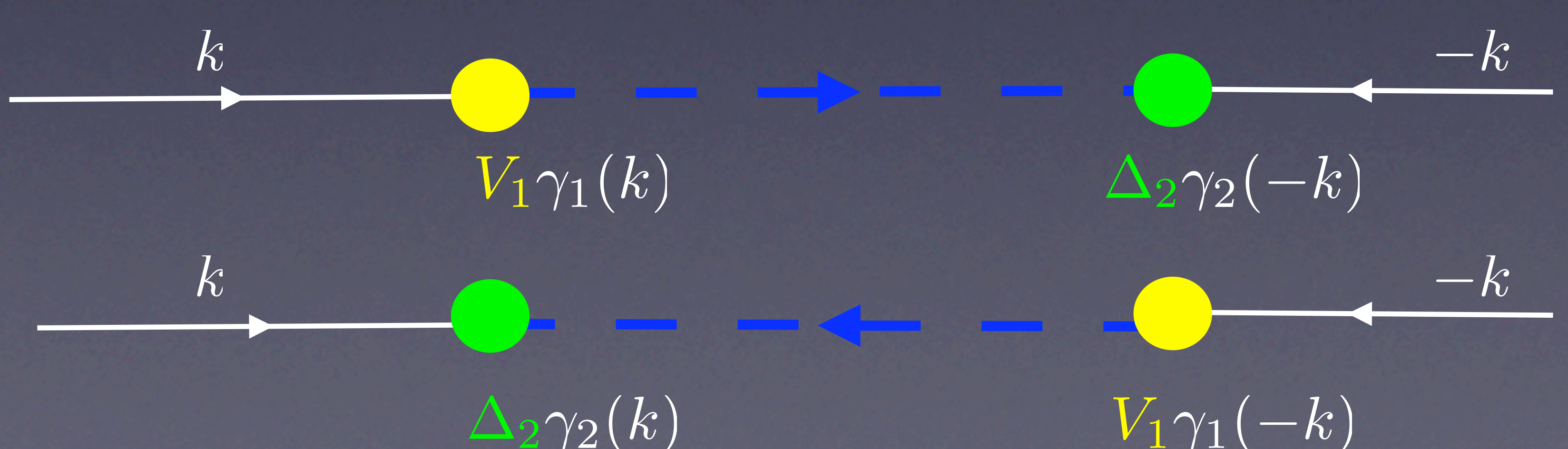

$$\Delta_{eff}(k) \sim V_1 \Delta_2 \gamma_1(k)\gamma_2(k)$$

"resonant Andreev scattering."

Crystal Fields determine the gap symmetry

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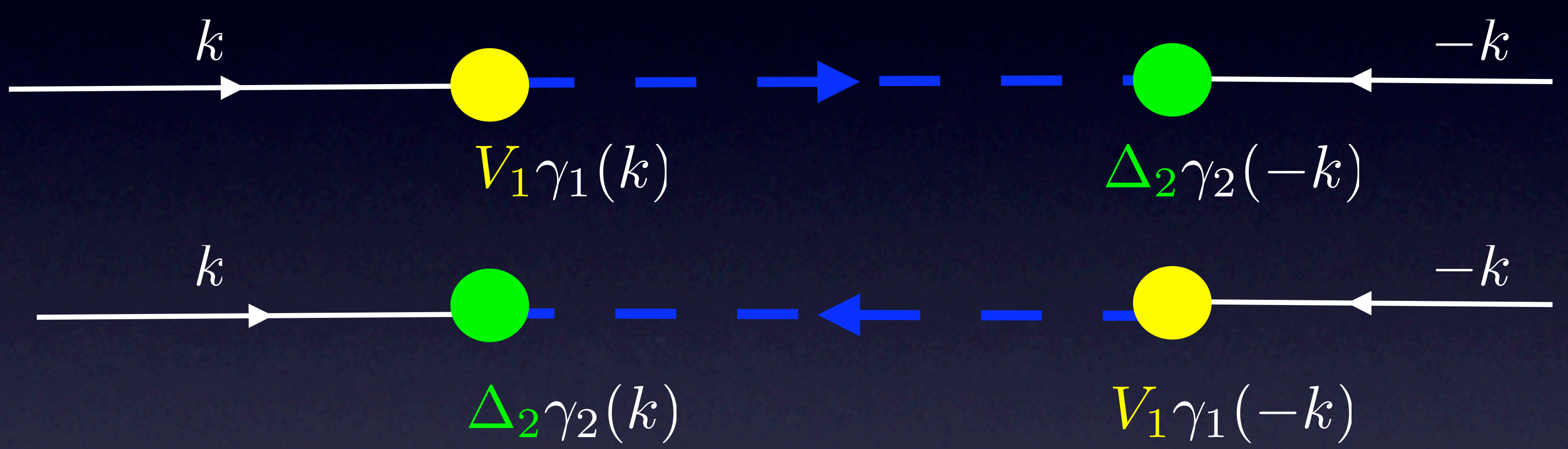

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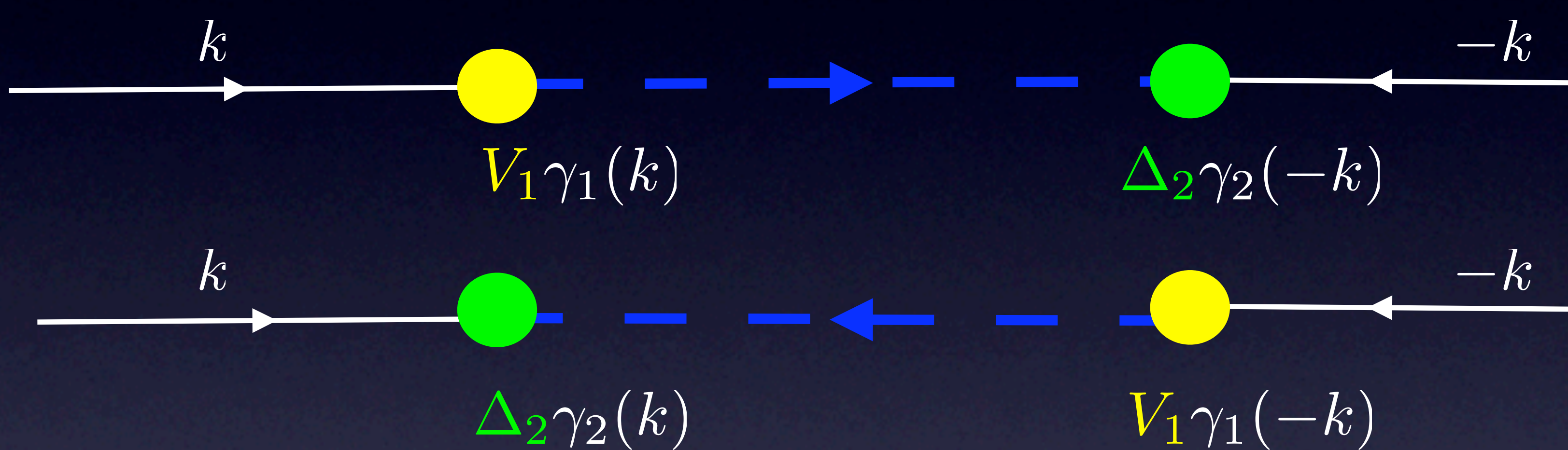

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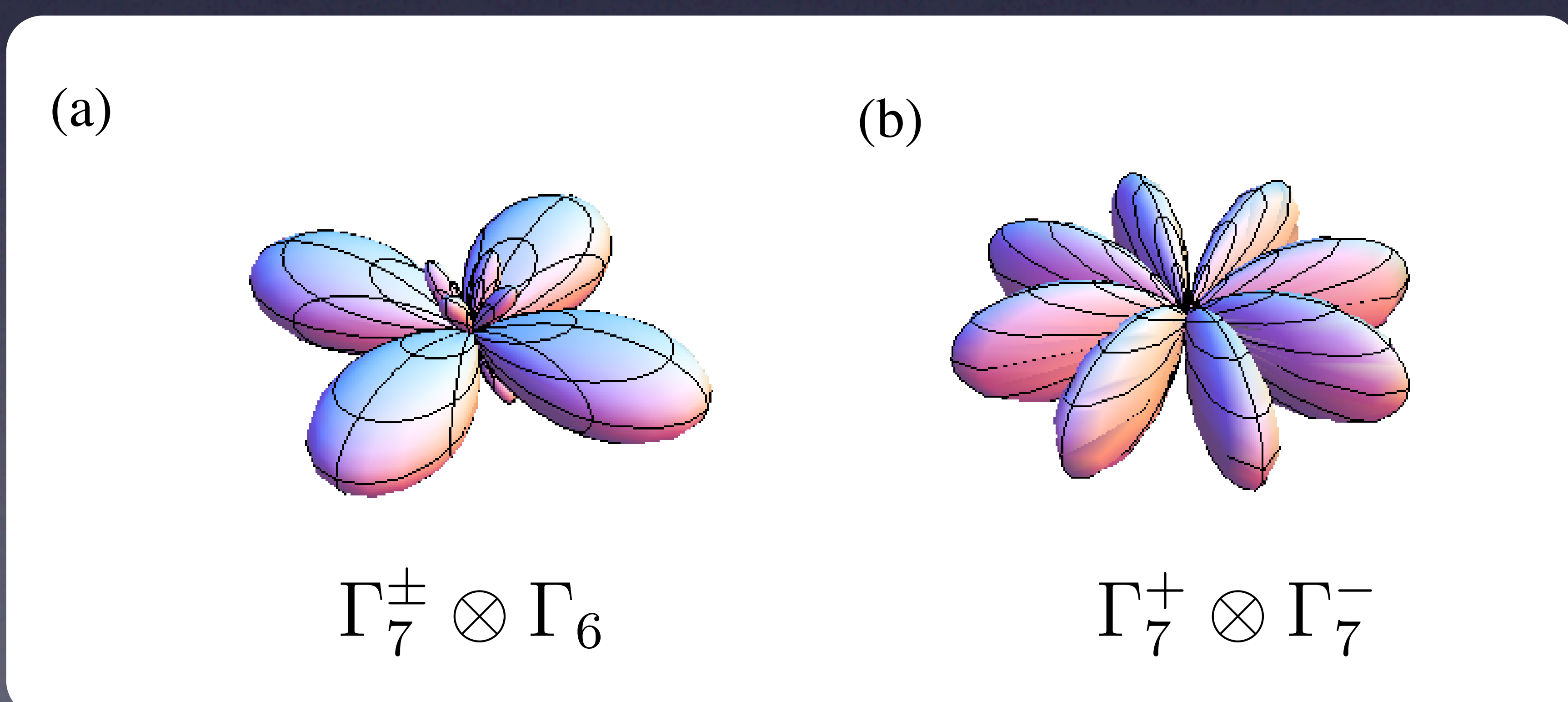

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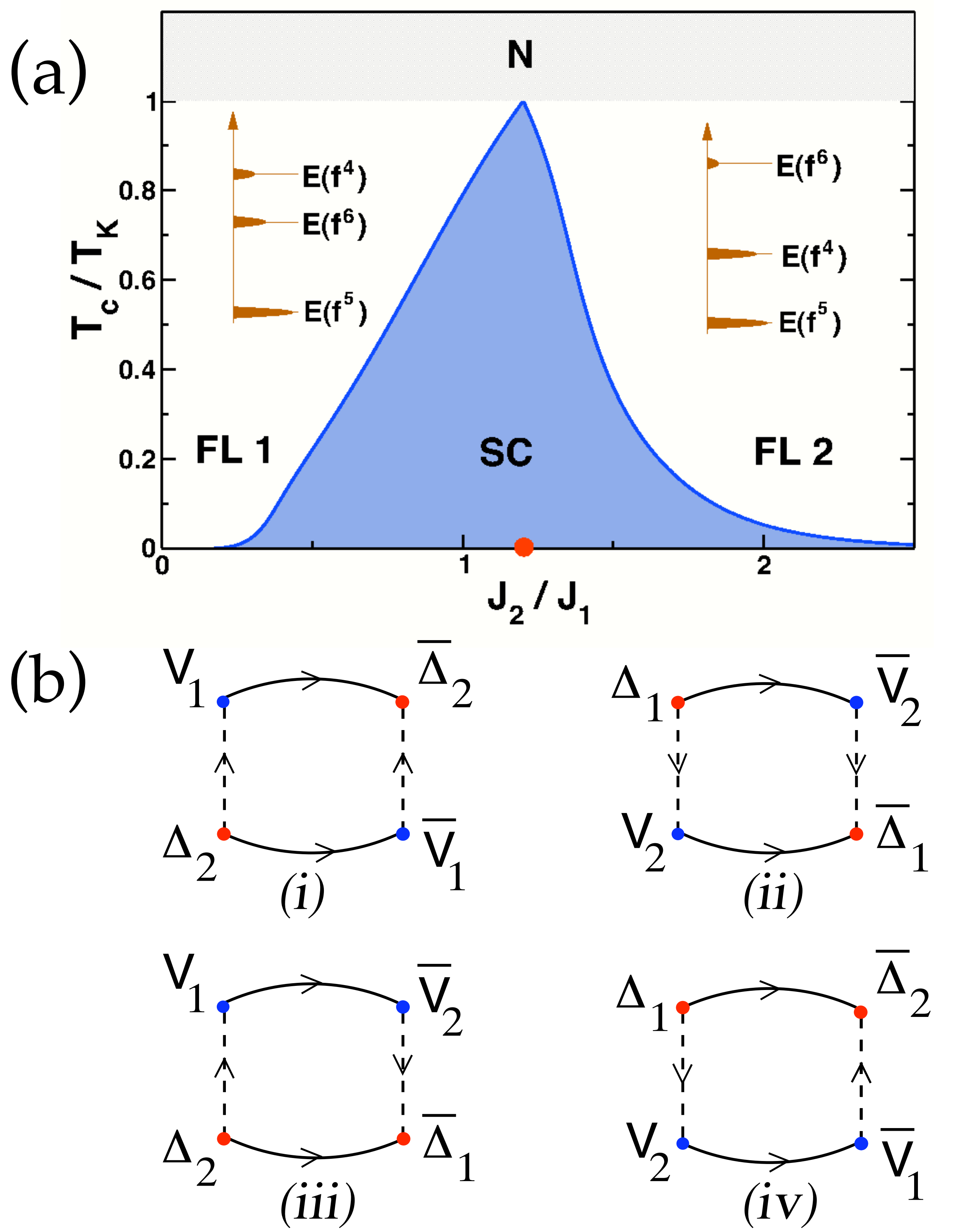
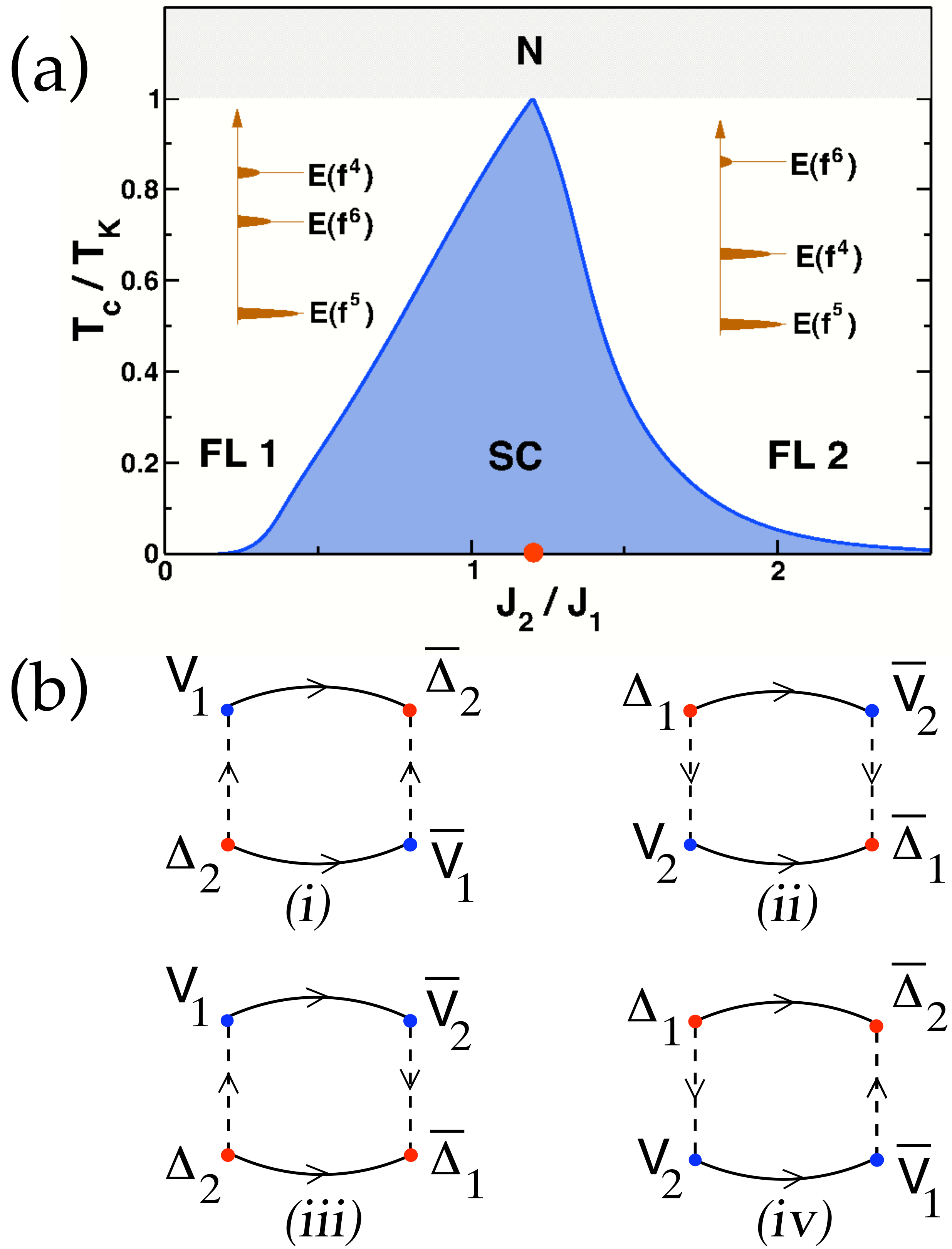
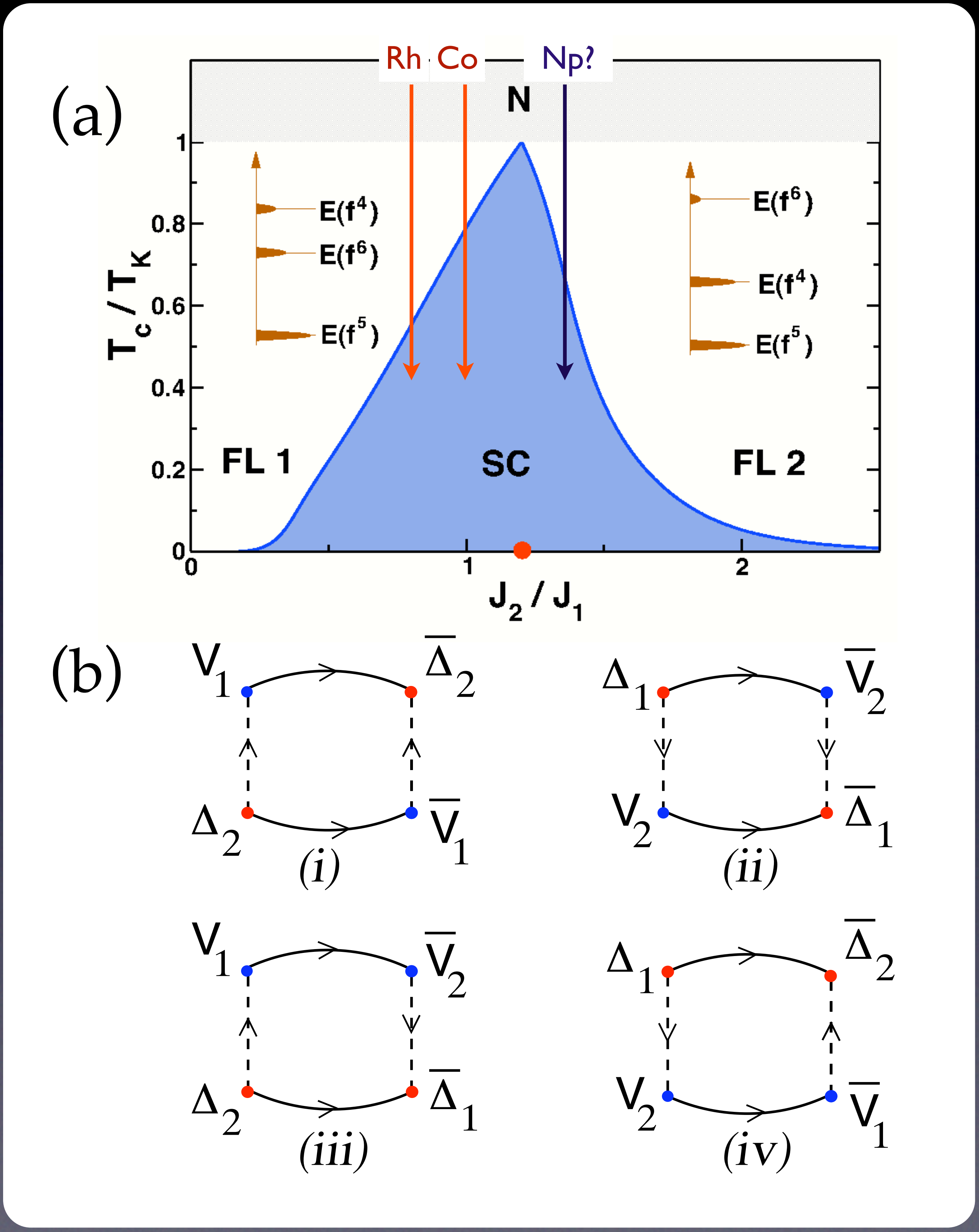

(a)
N
1
0.8
0.6
0.4
0.2
0
T_c / T_K
E(f⁴)
E(f⁶)
E(f⁵)
FL 1
SC
FL 2
0
1
2
J_2 / J_1
(b)
V_1
$\bar{\Delta}_2$
Δ_2
$\bar{V}_1$
(i)
Δ_1
$\bar{V}_2$
V_2
$\bar{\Delta}_1$
(ii)
V_1
$\bar{V}_2$
Δ_2
$\bar{\Delta}_1$
(iii)
Δ_1
$\bar{\Delta}_2$
V_2
$\bar{V}_1$
(iv)



Large N Kondo lattice:

overscreening drives pairing.

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



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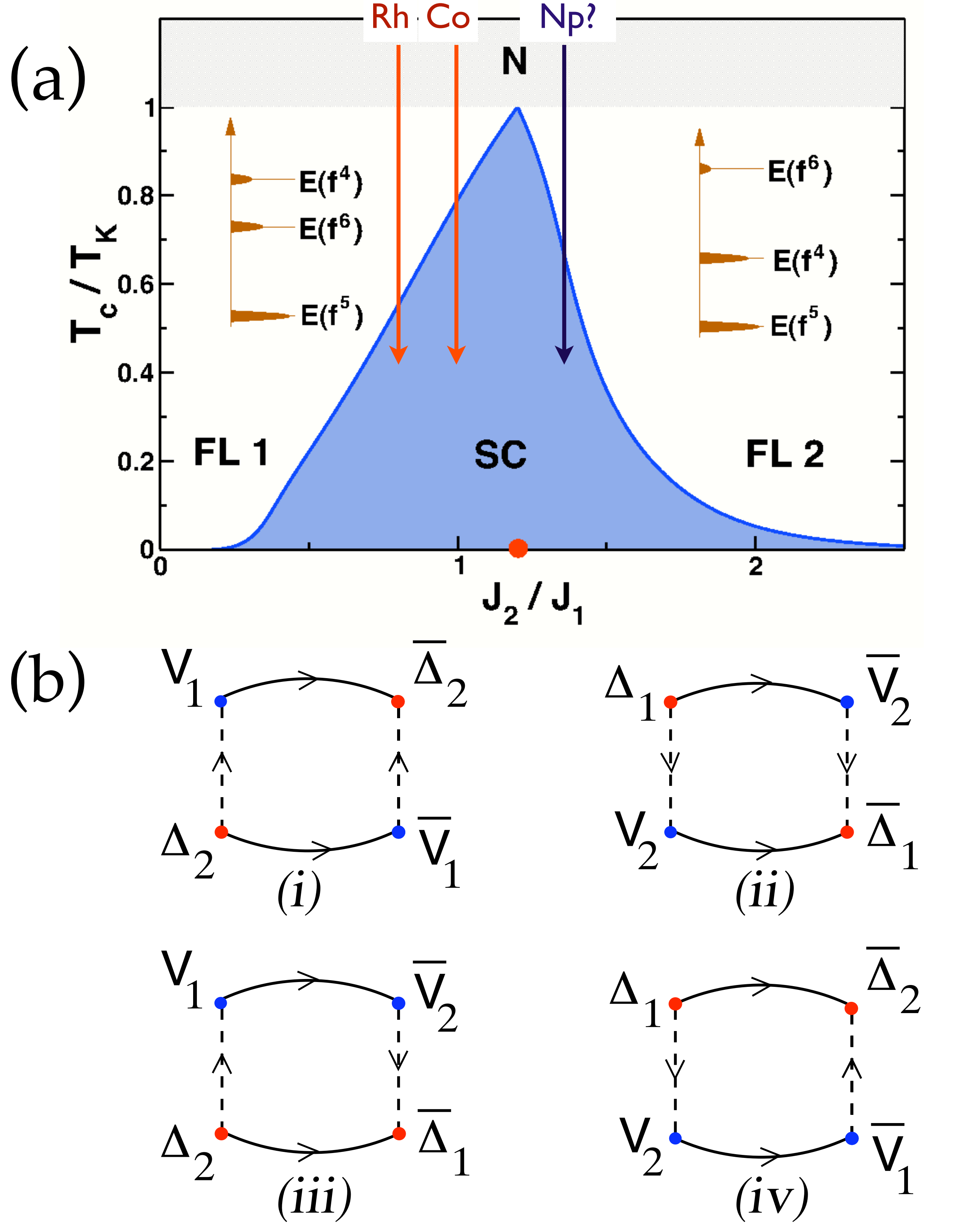
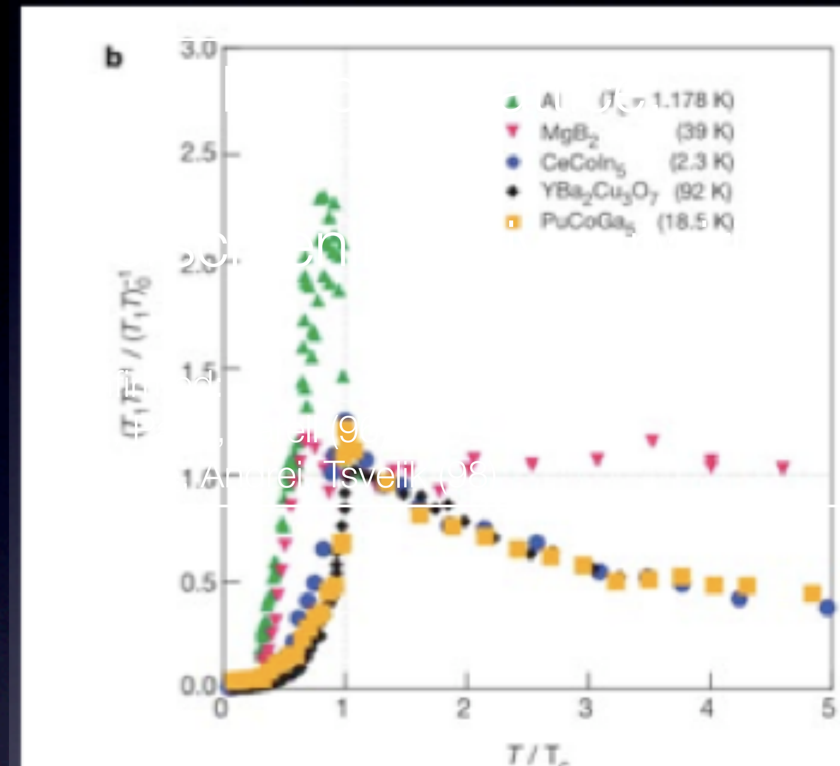
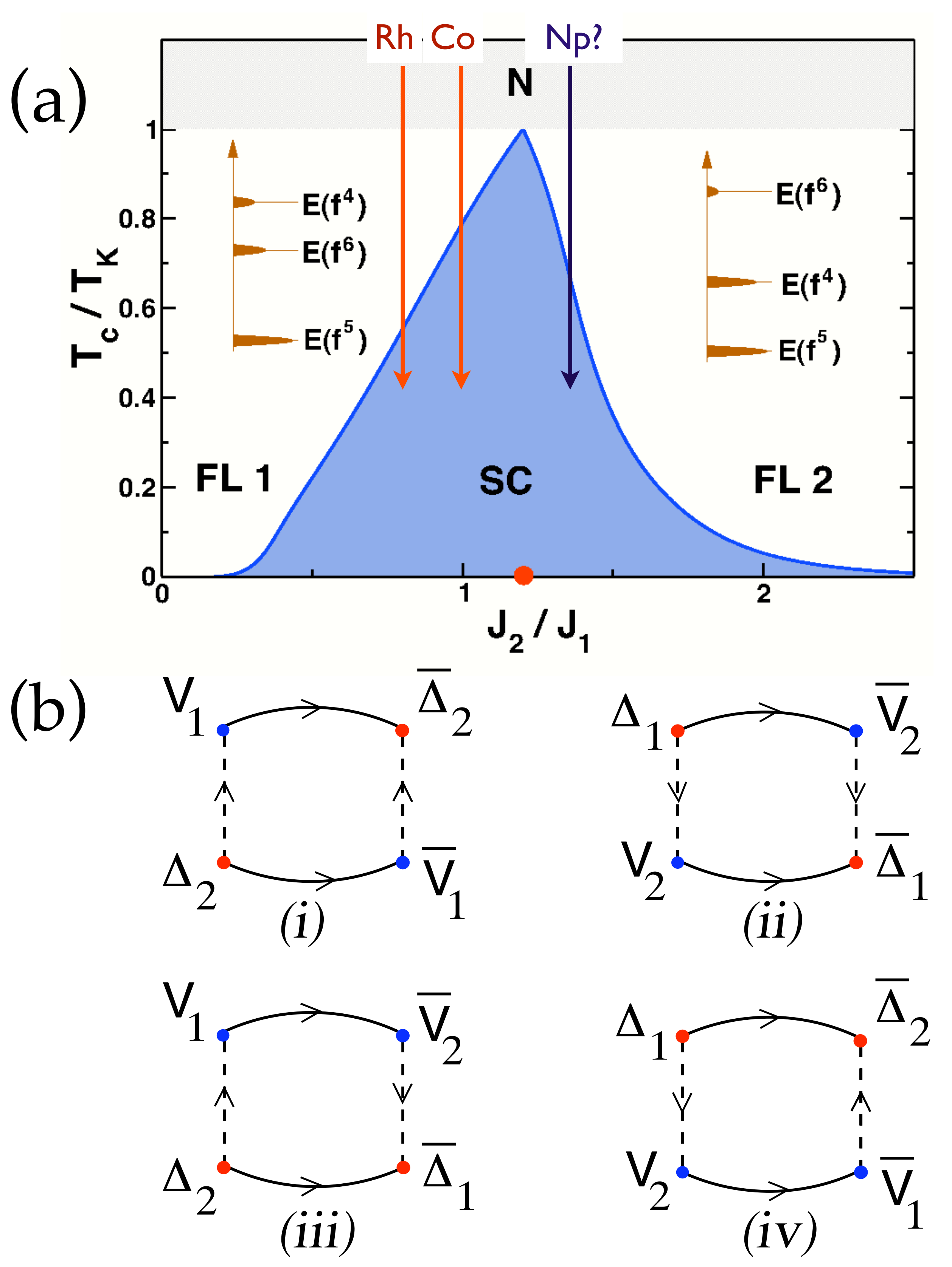
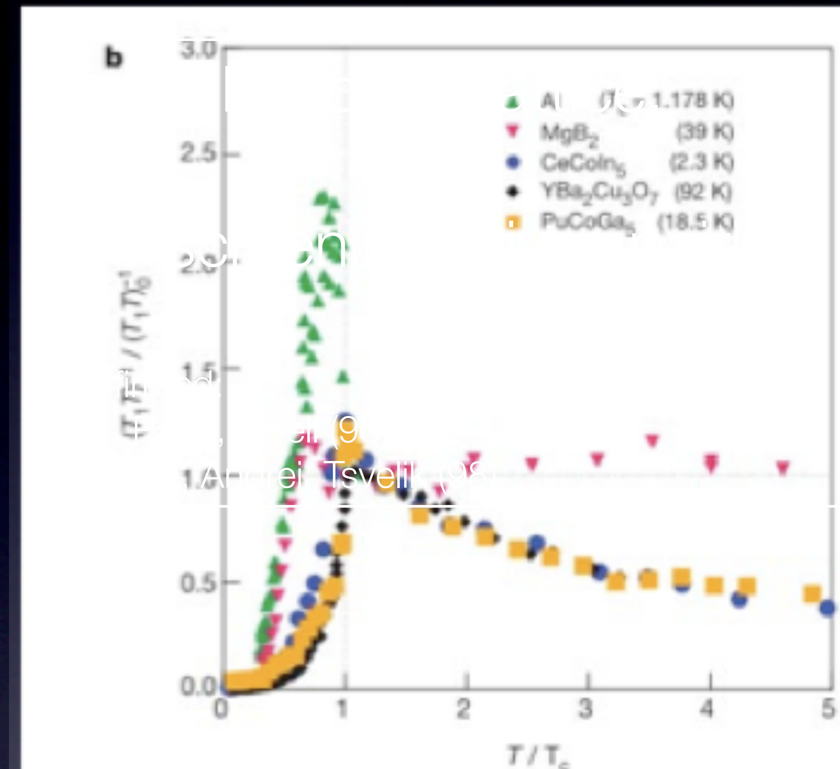




Curro et al, Nature, 434,622 (2005).





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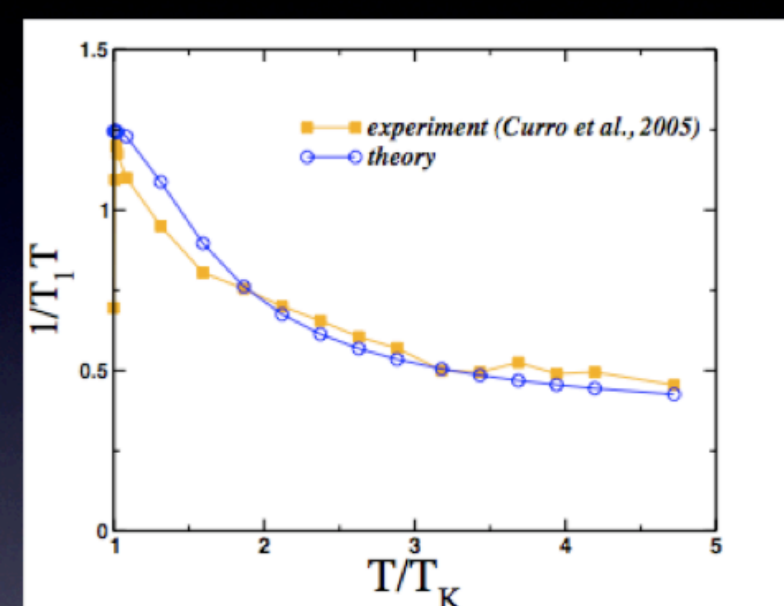

Conclusions

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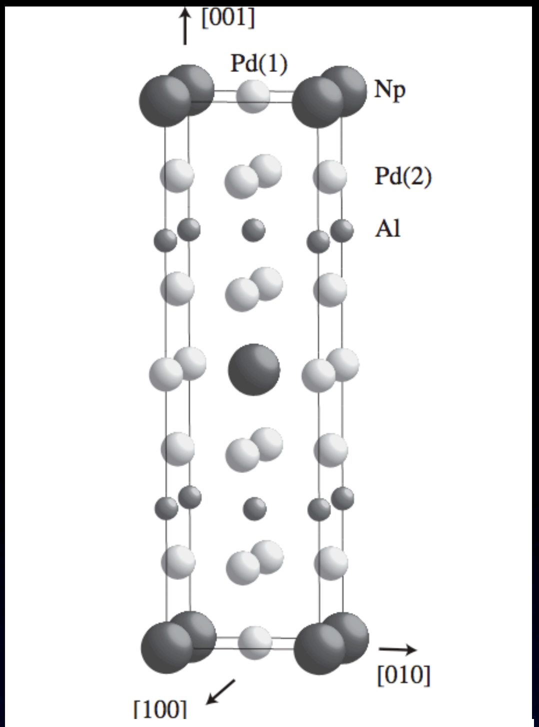
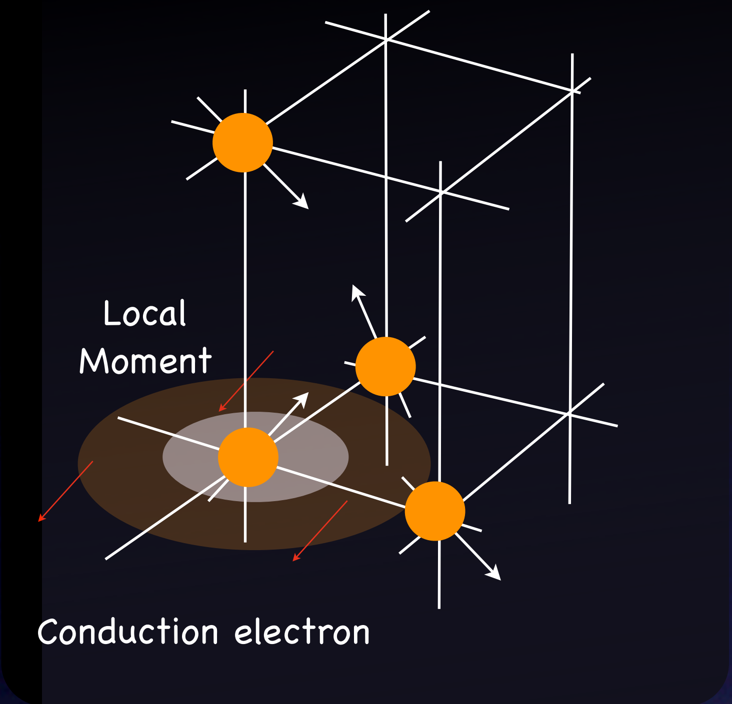
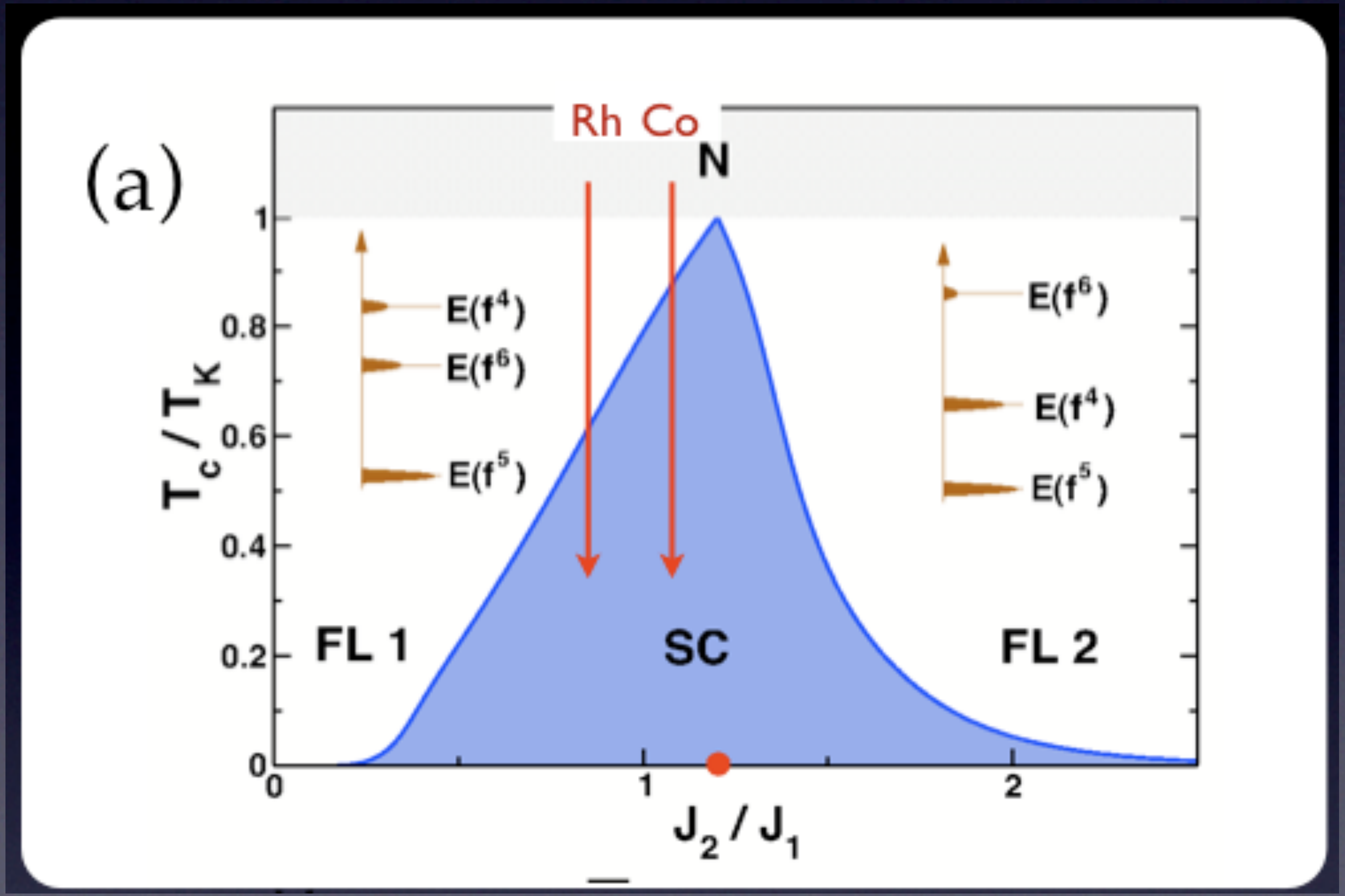


4.5K Heavy Fermion
S.C $NpAl_2Pd_5$

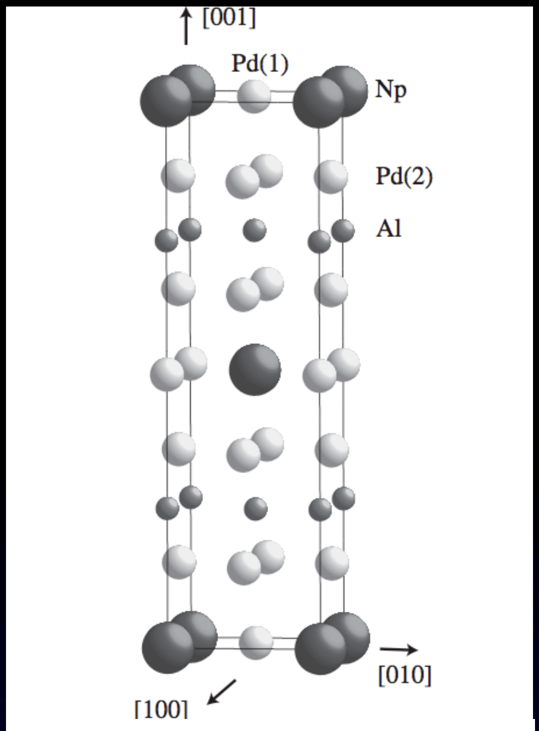
18.5 K Heavy Fermion
SC $PuCoGa_5$





Conclusions

- Motivated by new superconductors, new method for preserving symplectic symmetry of spin in 1/N expansions.



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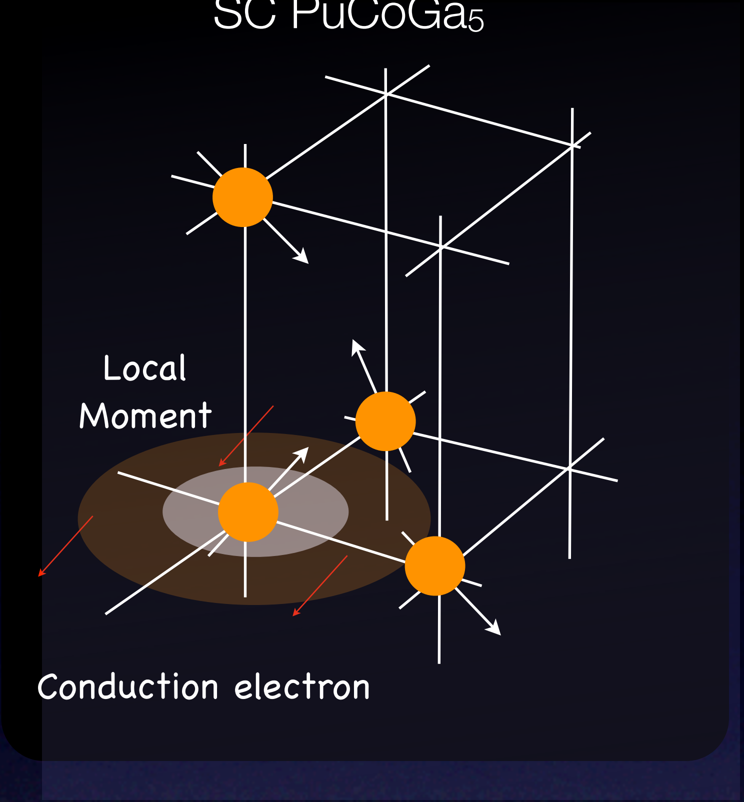

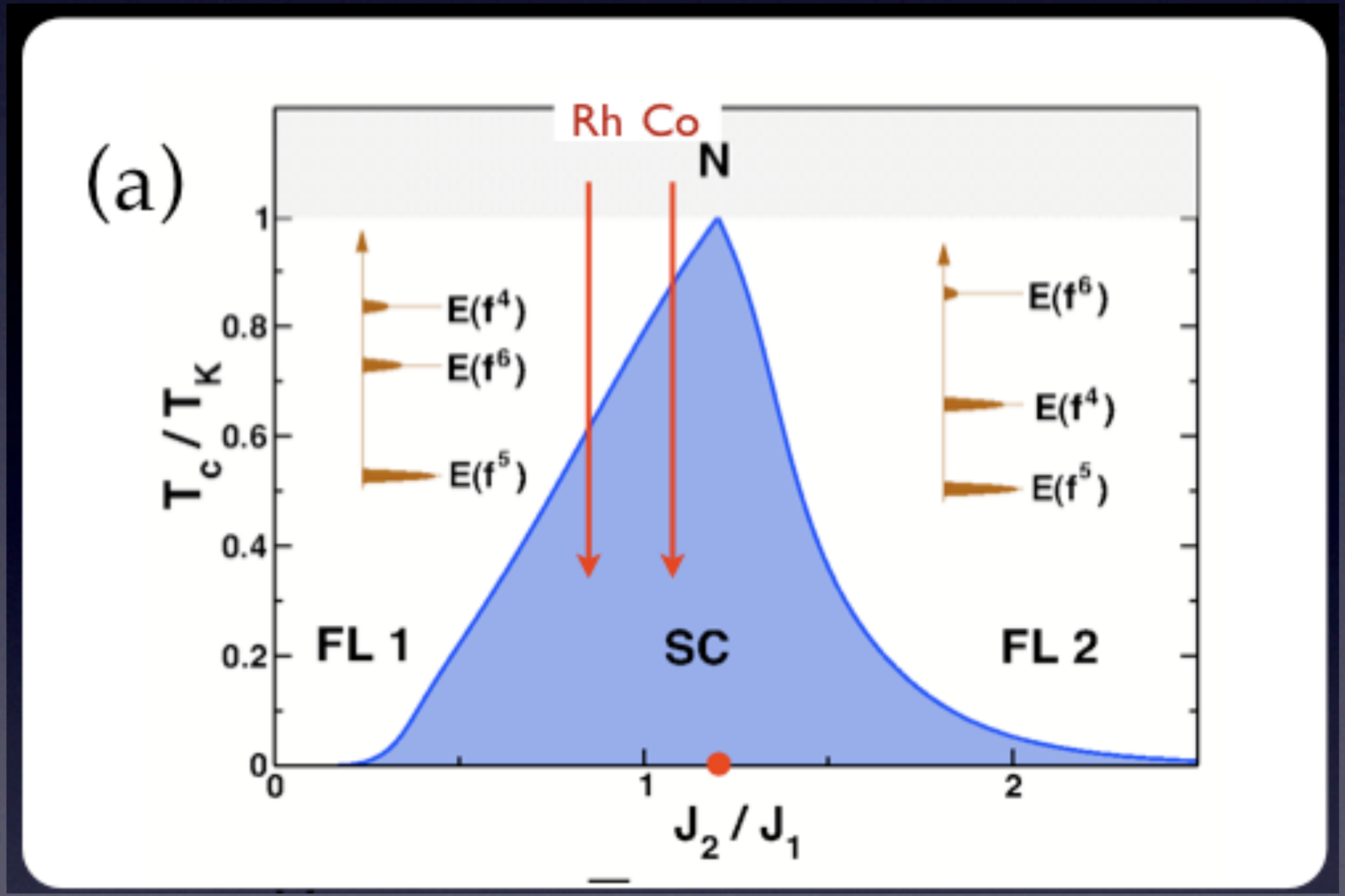

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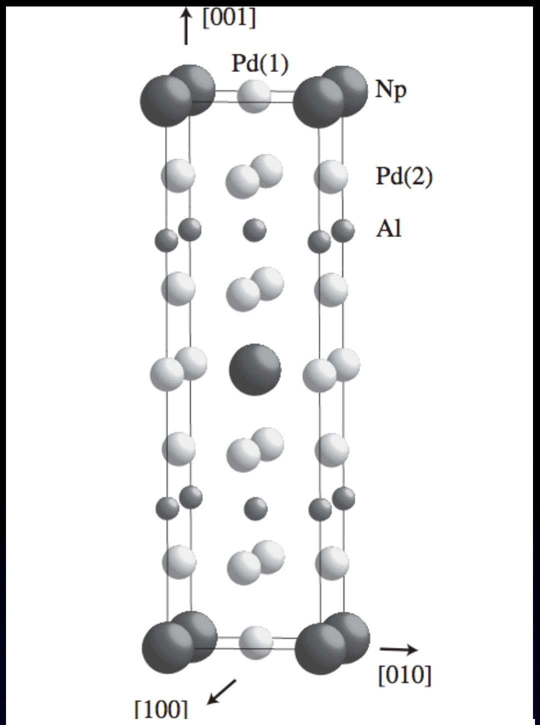

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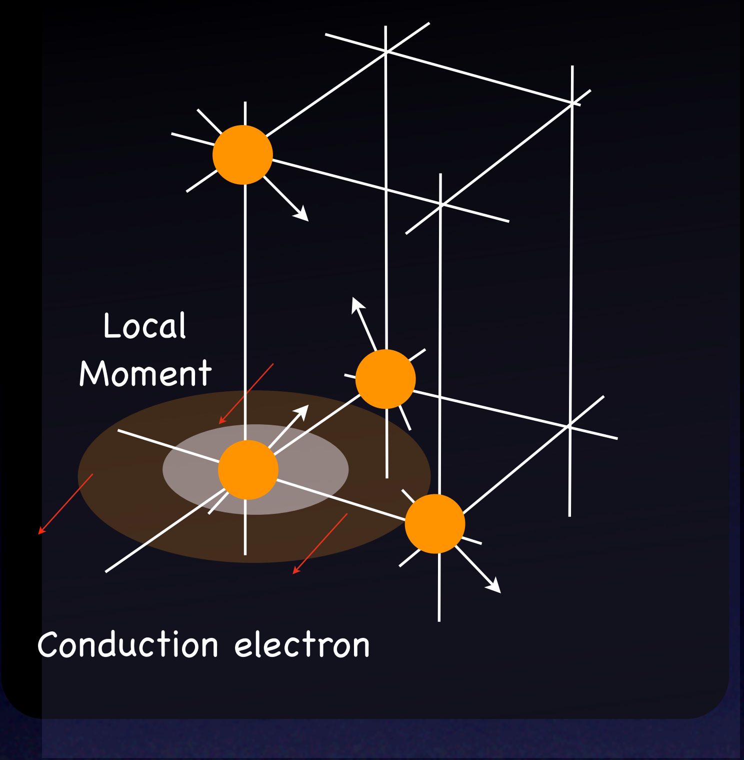

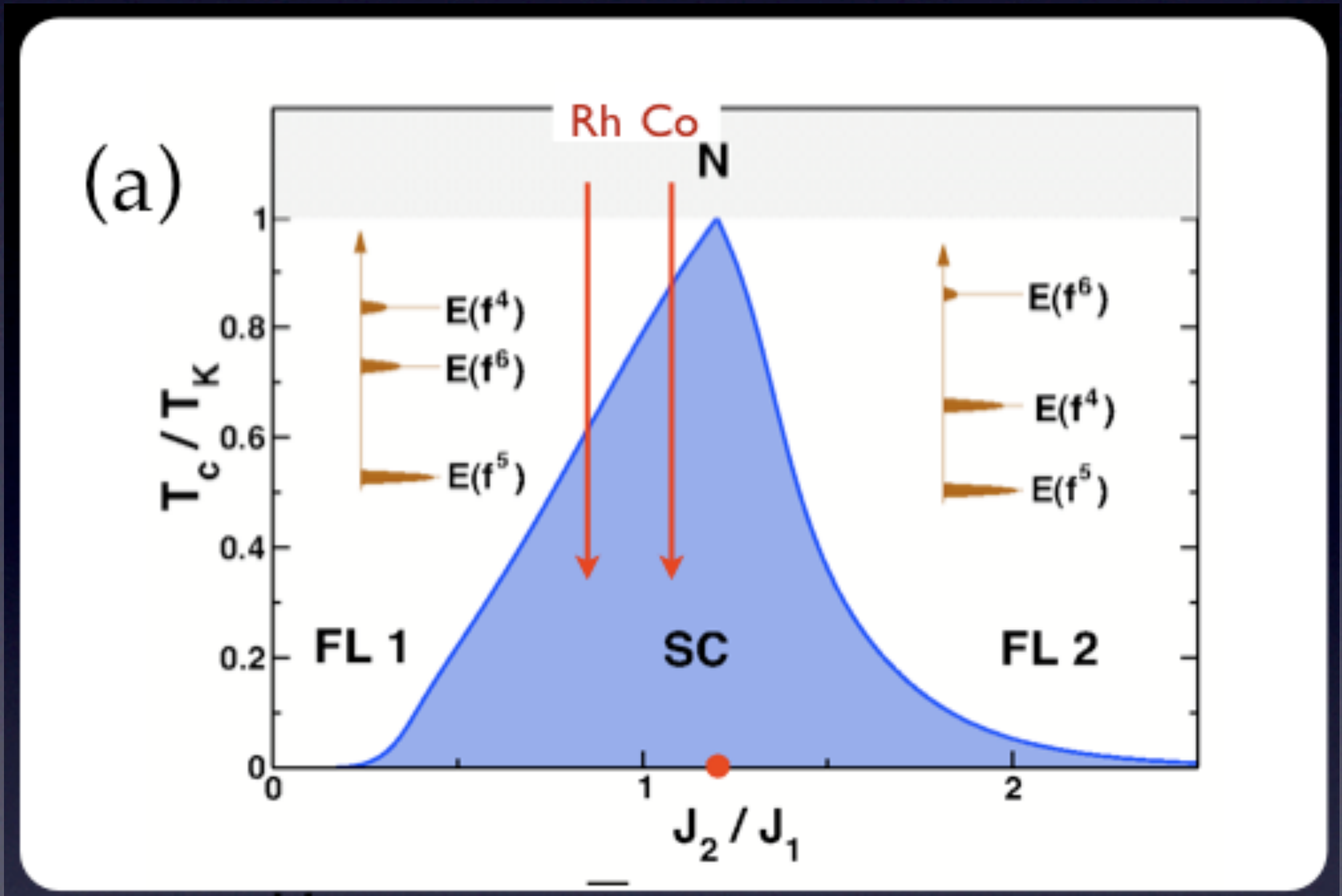

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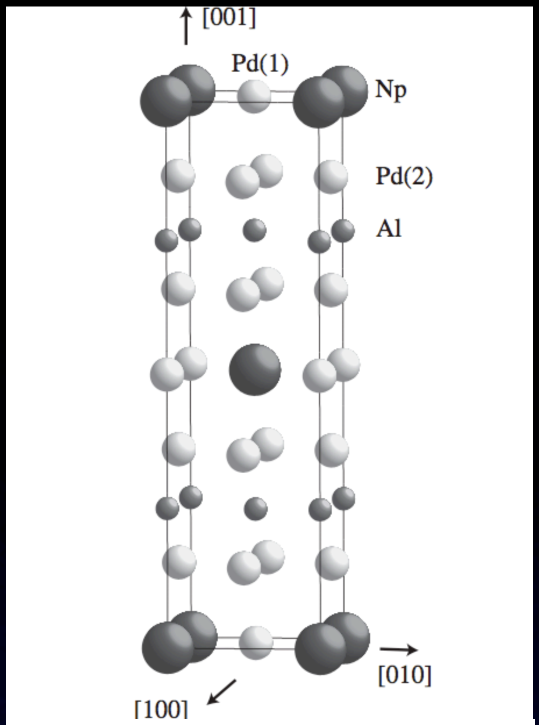
- 1/N expansion for heavy fermion superconductivity
- Predicts overscreening will lead to composite pairing and a new type of Andreev scattering.



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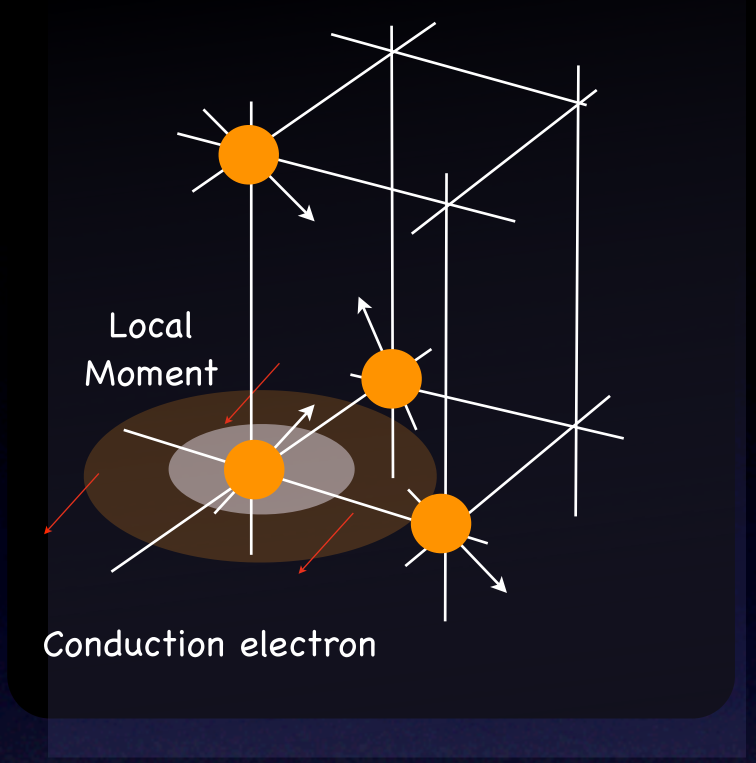

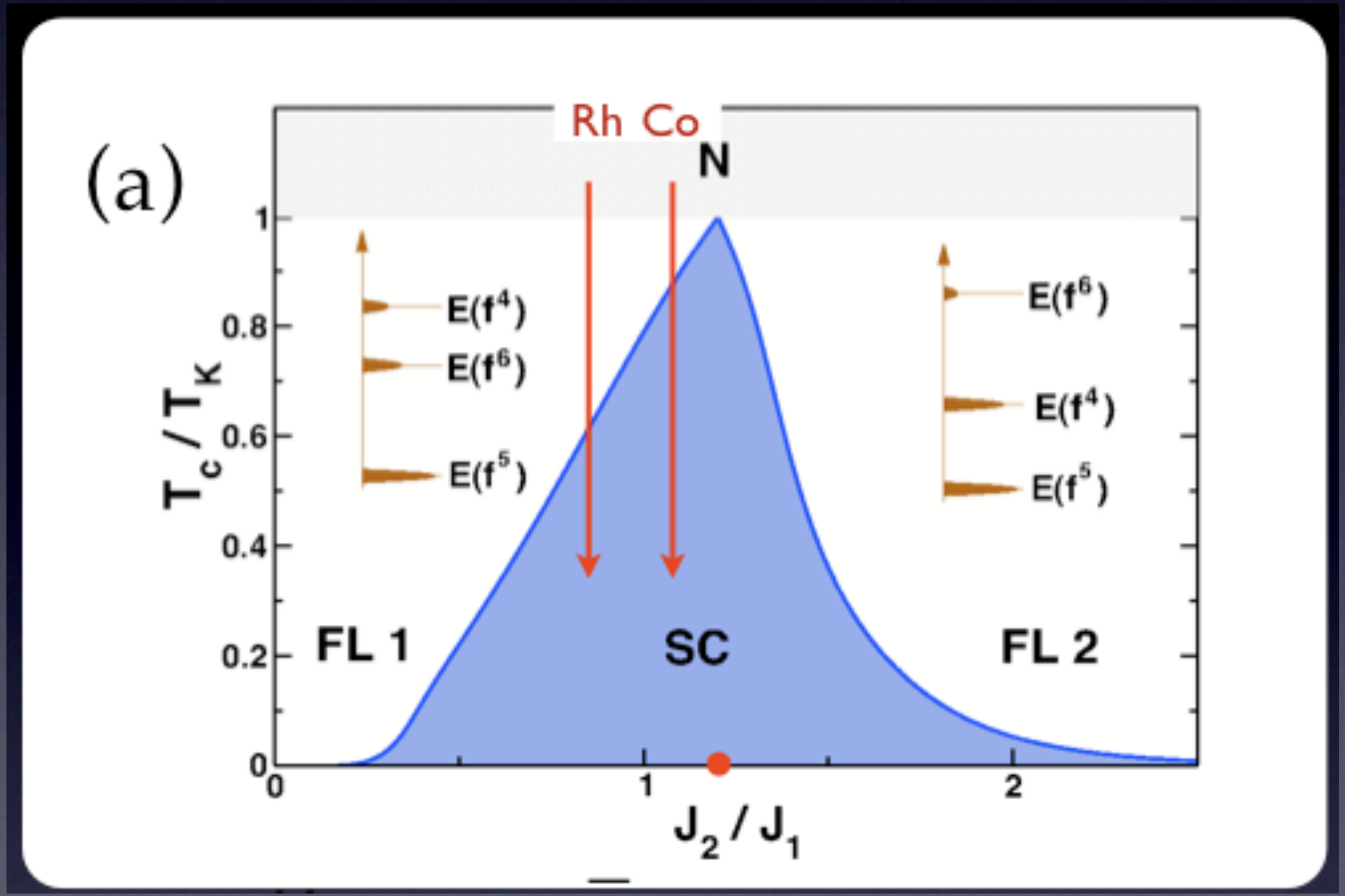

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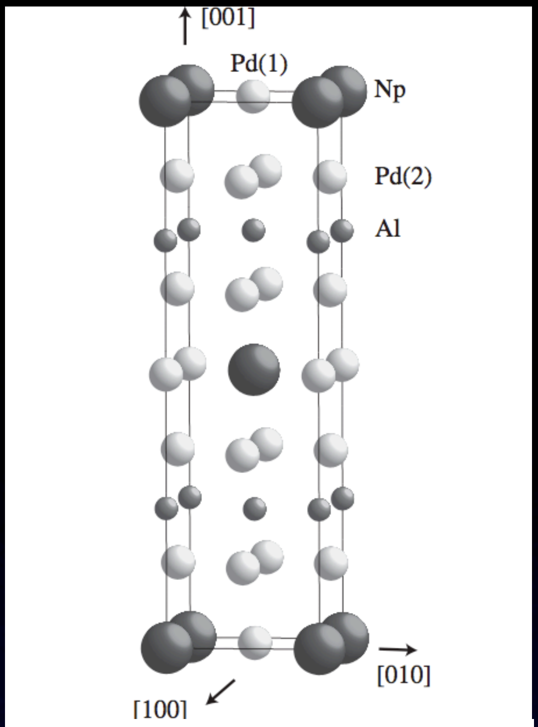

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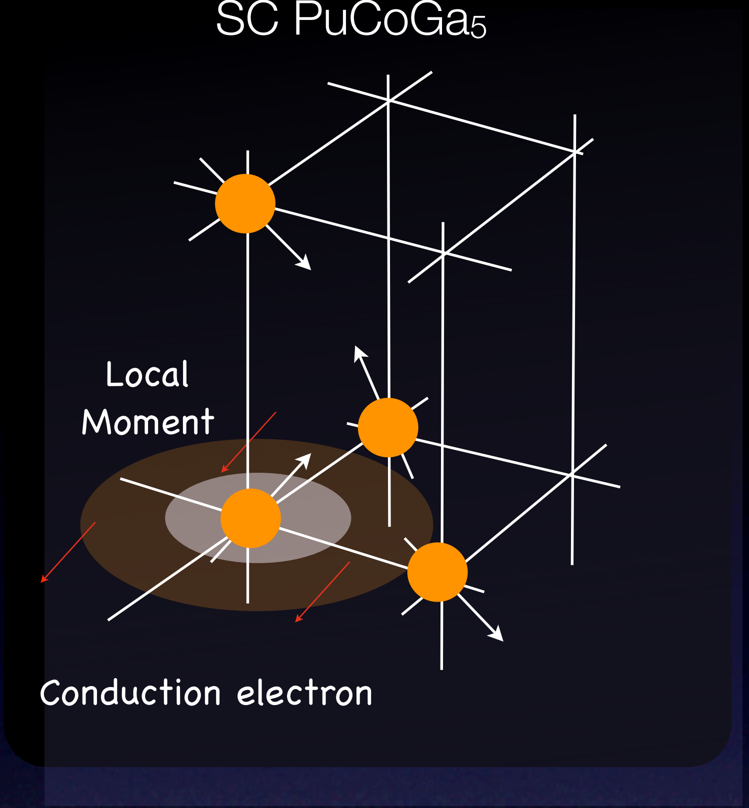

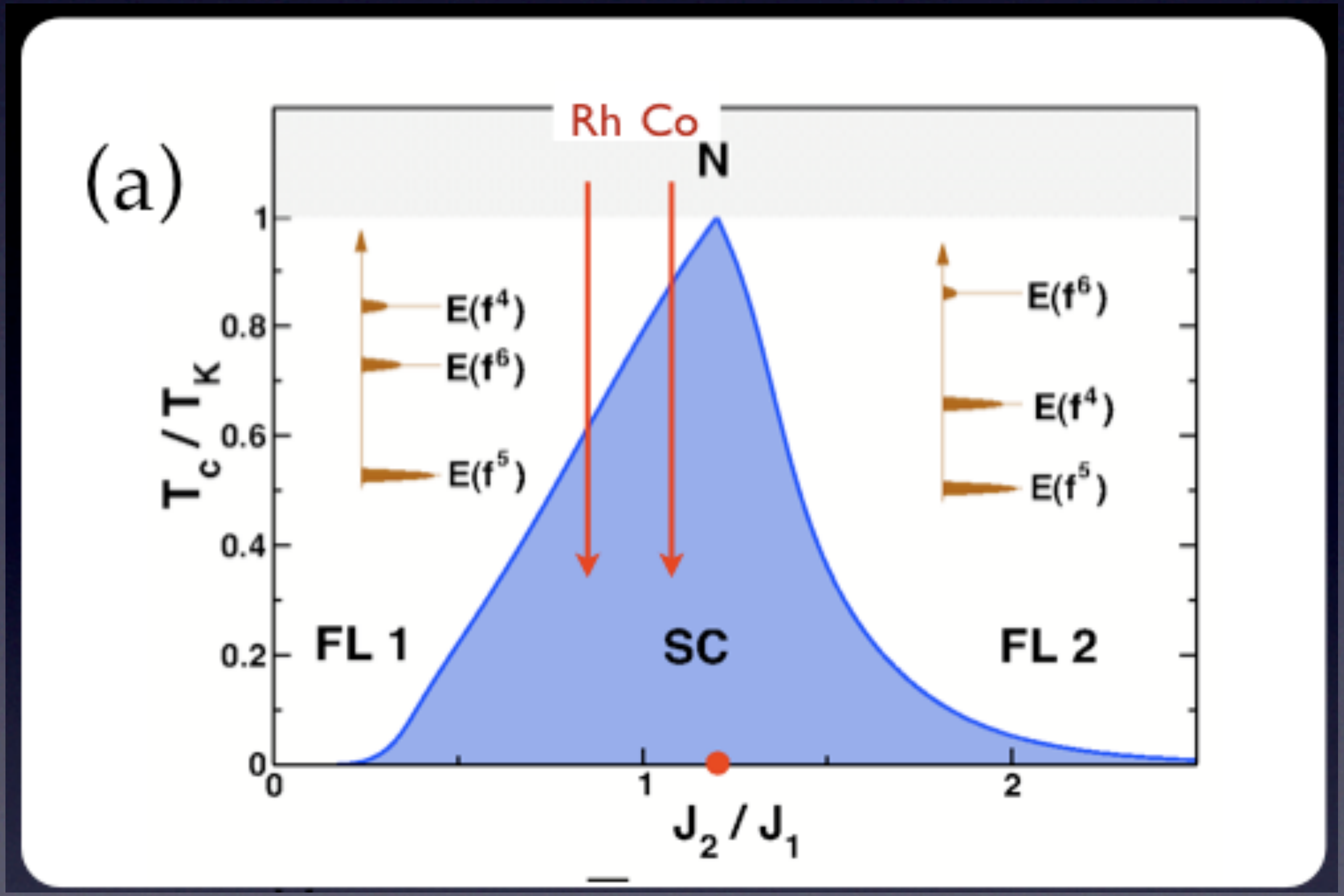

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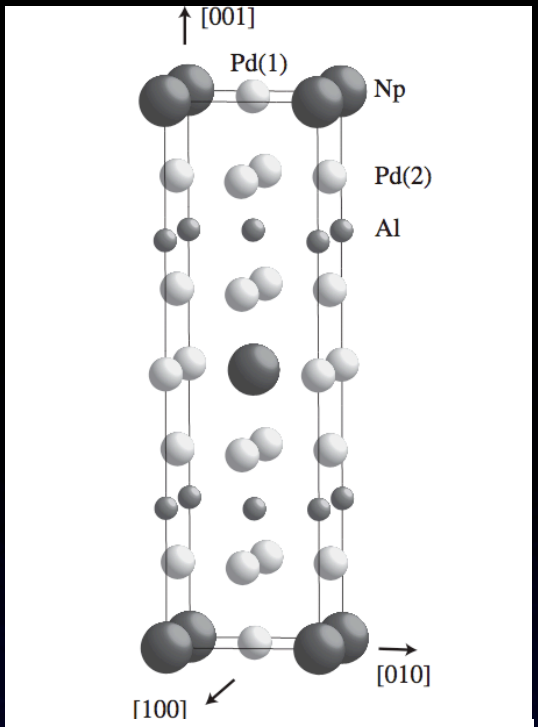

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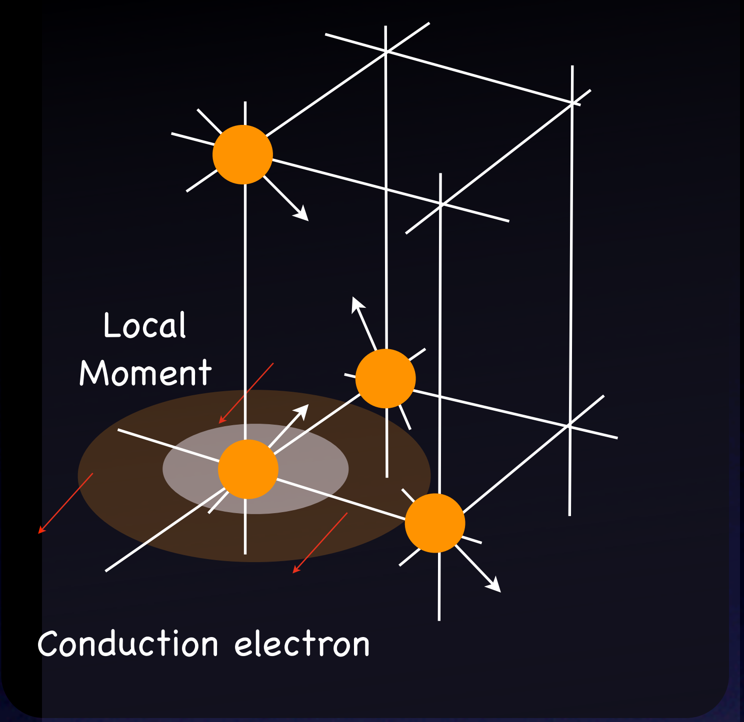

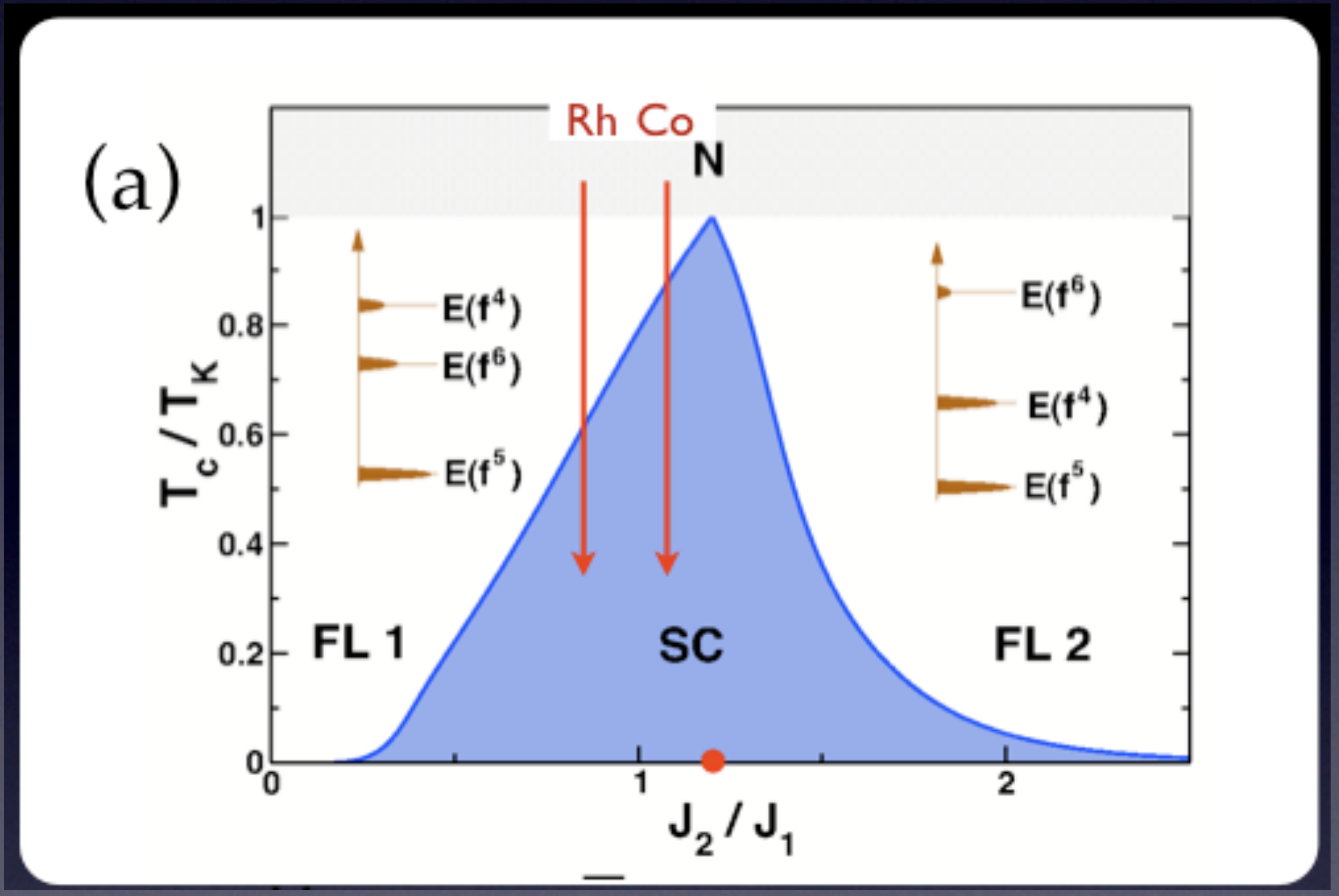

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- Predicts overscreening will lead to composite pairing and a new type of Andreev scattering.
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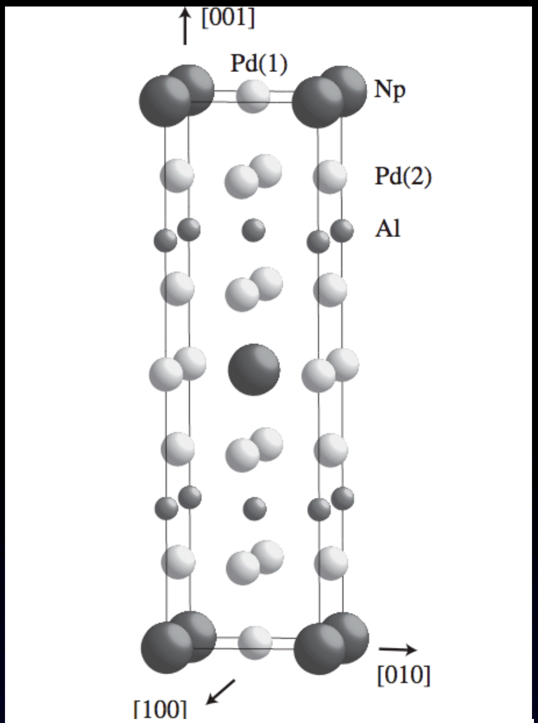
- Enhancement of Andreev scattering above predictions of BTK
- $NpAl_2Pd_5$ and $PuCoGa_5$ have identical crystal symmetry. Possibility that Pu doping will enhance Tc in $NpPd_2Al_5$.



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