Kondo effect in layered heavy-fermion systems

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Collaborators

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(RIKEN)

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(Tokyo)

"Kondo lattice model"

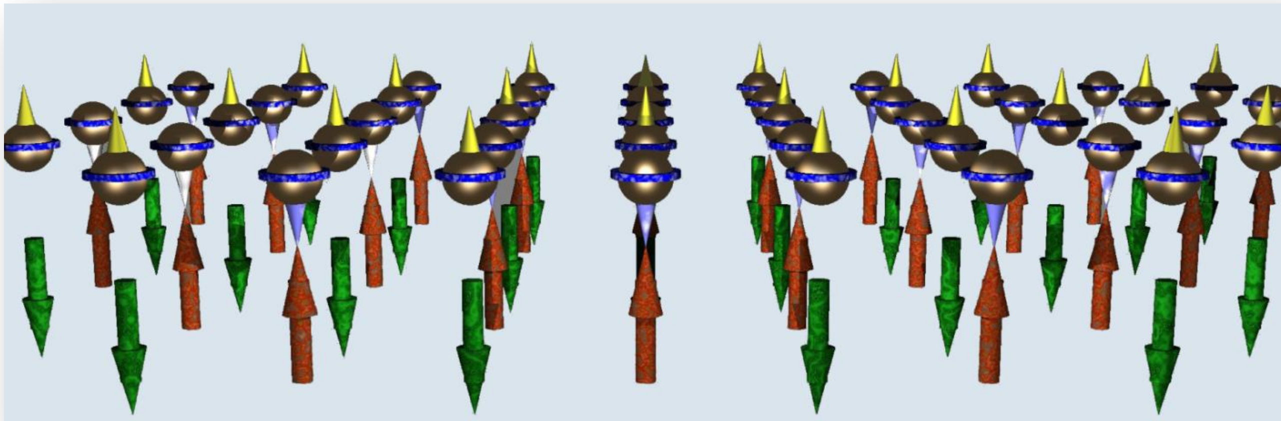
Heavy fermions

Correlated metal
Kondo insulators
Exotic superconductors
Antiferromagnetism
Ferromagnetism

Kondo screening vs RKKY

$$H = t \sum_{<i,j>,\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + J \sum_{i} \vec{s}_i \vec{S}_i$$

RKKY and Kondo effect



Local Kondo coupling

favoring a singlet state:

➡ **Kondo insulator at half filling**

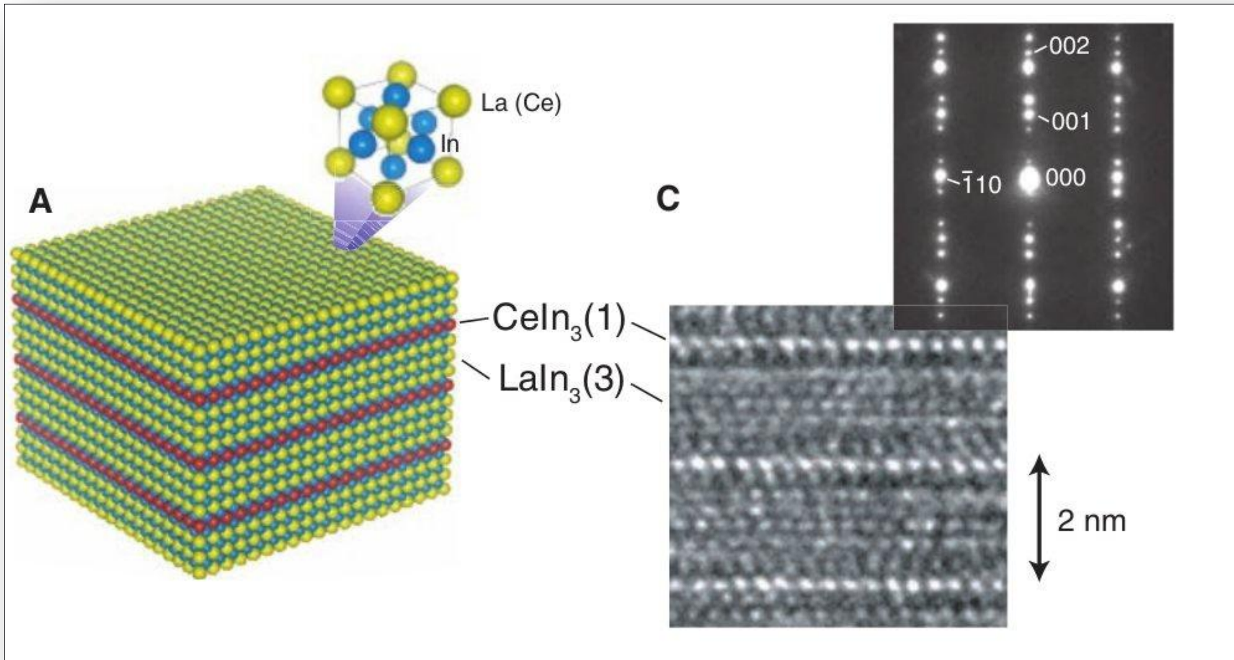
Magnetic long-range interaction

favoring a magnetic state: $E_{RKKY} \sim J^2$

➡ **Neel state at half filling**
Superconductor away from half filling
etc

f-electron superlattices

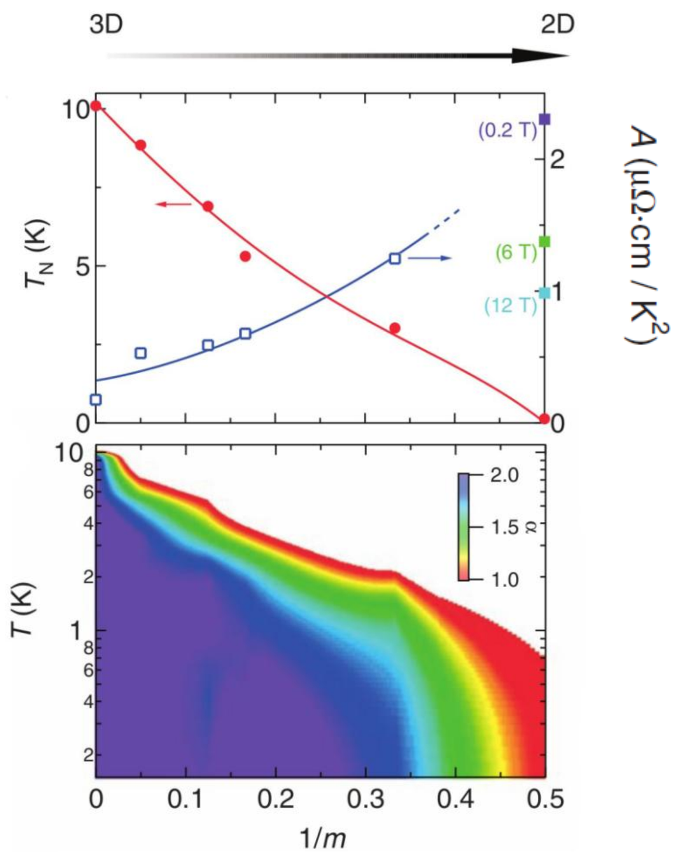
Tuning the Dimensionality of the Heavy Fermion Compound $CeIn_3$
H. Shishido *et al.*
Science **327**, 980 (2010);
DOI: 10.1126/science.1183376



Shishido et al. Science 327, 980 (2010)
Mizukami et al. Nature Phys. 7, 849 (2011)
Goh et al. Phys. Rev. Lett. 109, 157006 (2012)

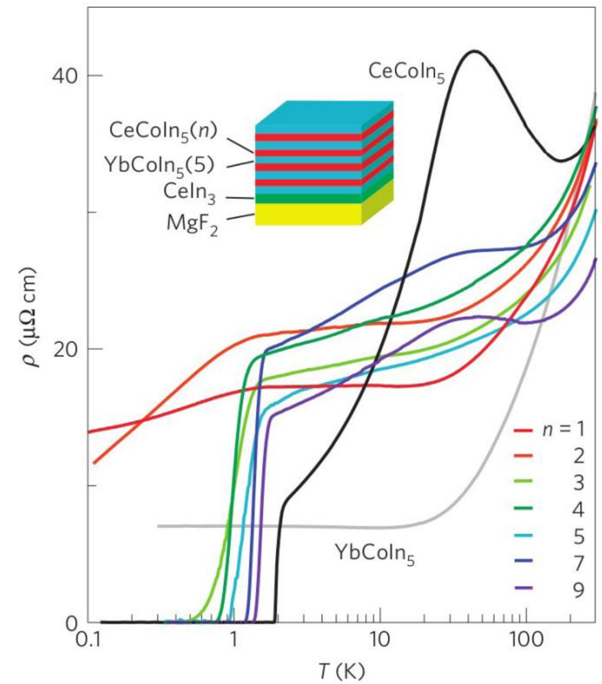
f-electron superlattices

Antiferromagnetism



$CeIn_3(m)/LaIn_3(4)$

Superconductivity



$CeCoIn_5(n)/YbCoIn_5(5)$

Shishido et al. Science 327, 980 (2010)
Mizukami et al. Nature Phys. 7, 849 (2011)
Goh et al. Phys. Rev. Lett. 109, 157006 (2012)

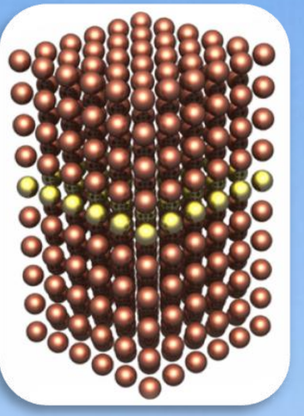
Outline

How heavy fermions behave
in the superlattice ?

Proximity of the Kondo effect

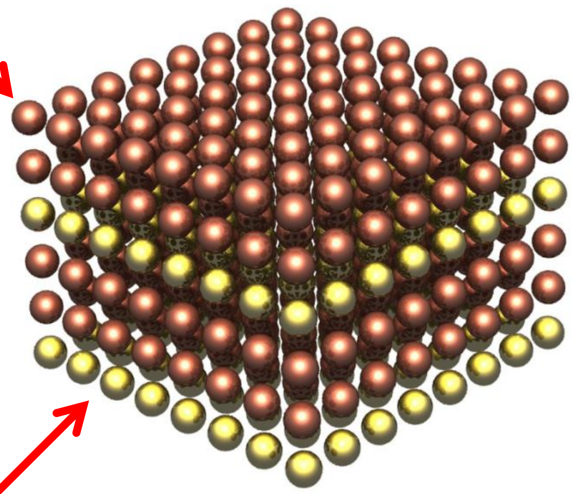
(1) Heavy fermions
(2) Magnetism
(3) Application to experiments

Model and Method



Model and Method

non-interacting layer



f-electron layer
(Kondo-lattice)

Superlattice:
Kondo lattice layers (*f*- layers)
noninteracting layers.

n Kondo lattice layers (KLL)
m non-interacting layers (NIL)
(n;m) KLL(n)/NIL(m)

Heavy f-electron layers

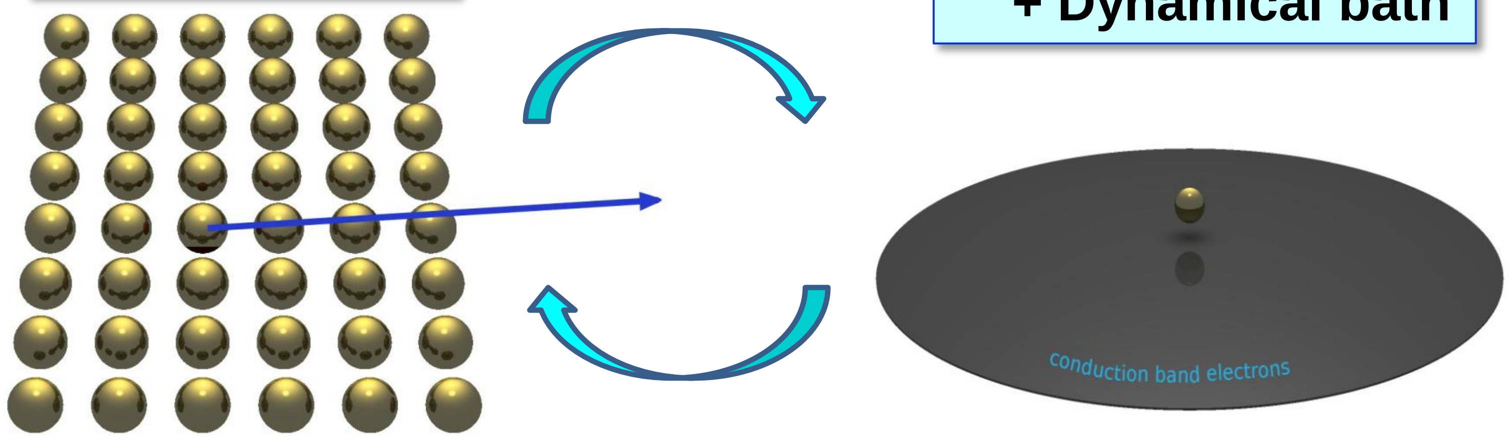
⇨ **Kondo lattice model**

Model and Method

Dynamical mean field theory (DMFT)

Original Lattice

Impurity system
+ Dynamical bath



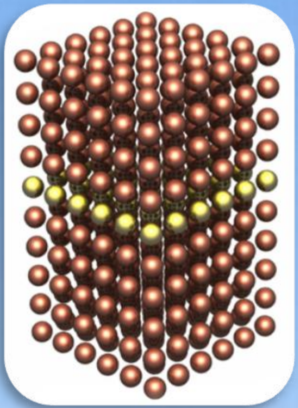
DMFT maps the lattice model
⇨ self-consistent impurity problem

DMFT: Metzner - Vollhardt (1989); A. Georges et al.(1996)

Warm up!

Single *f*-electron layer

embedded in a 3D metal

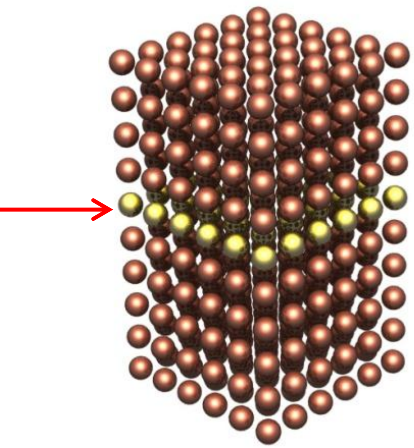


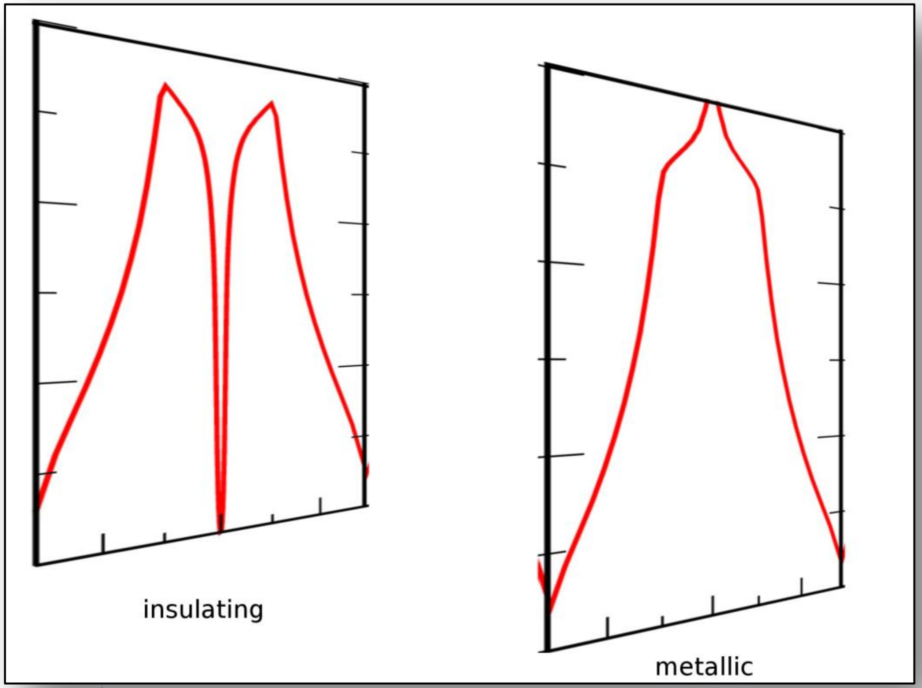
A single *f*-layer in 3D

What happens,

if a single Kondo lattice is inserted into a 3D metal ?

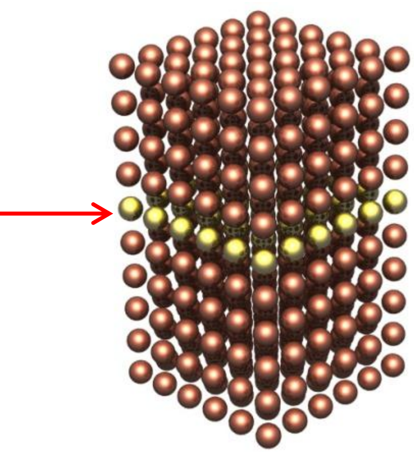
Mixed dimensions





A single *f*-layer in 3D

Mixed dimensions

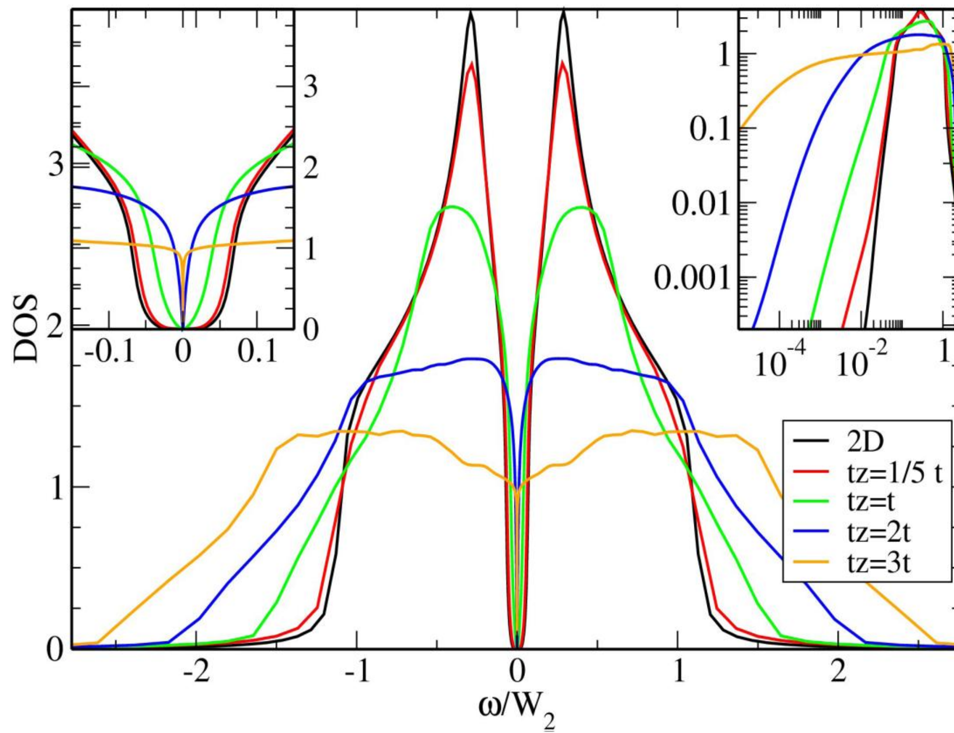


Density of States

***f*-layer**

T=0

J/W=0.5



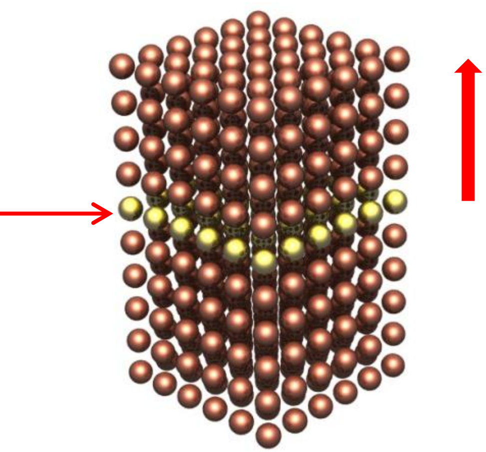
Inter-layer Hopping t_z

Kondo lattice gap changes

Inter-layer hopping
⇨ Gap size decreases

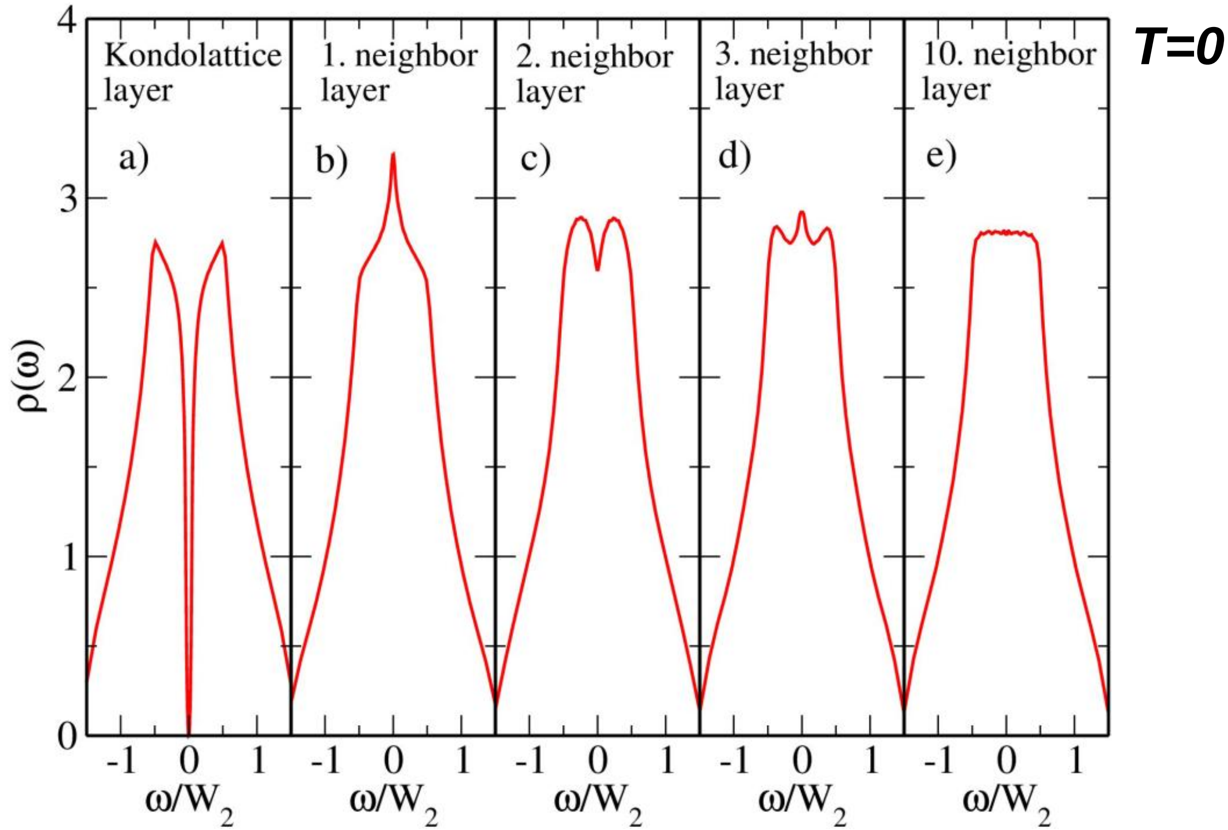
Gap shows a power-law
$\rho(\omega) \sim \omega^2$

A single *f*-layer in 3D



Proximity of Kondo effect

Layer-dependent DOS

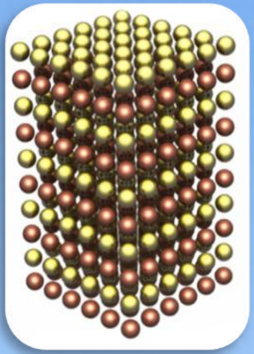


◇ *f*-electron layer forms the Kondo gap

◇ 2k_F oscillation of the resonance

Heavy electron superlattice

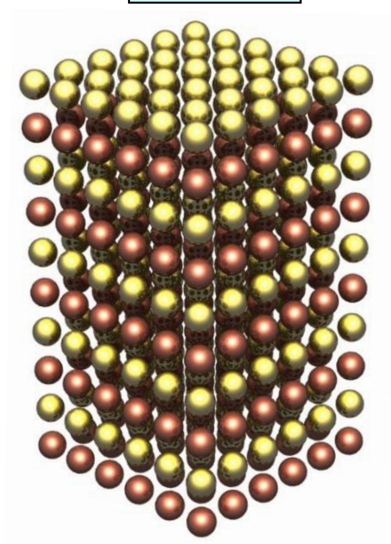
Paramagnetic state



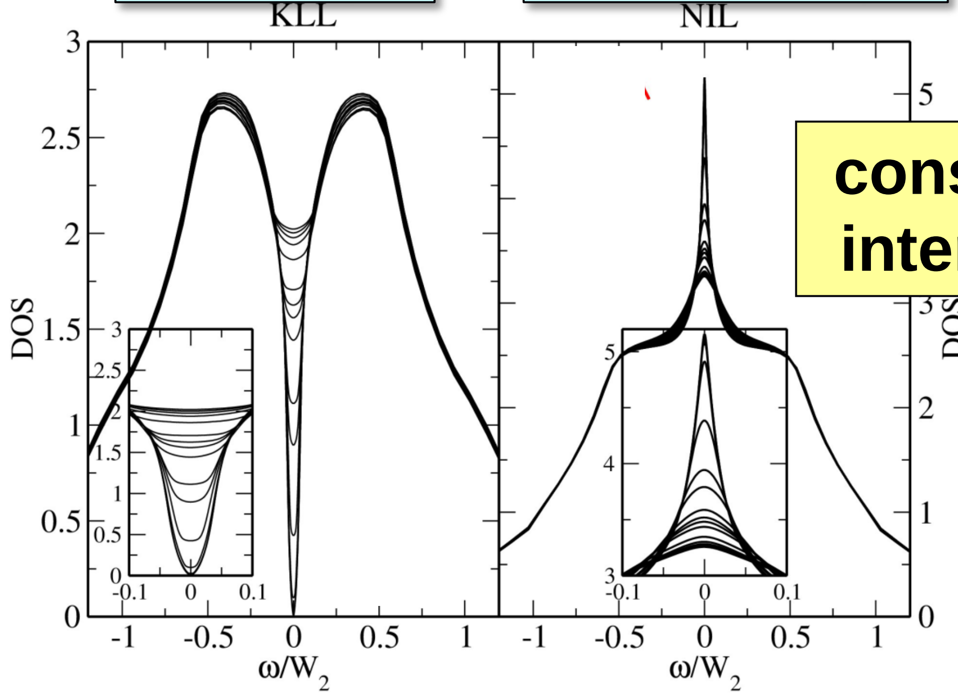
Paramagnetic state in *f*-electron superlattice

1 Kondo lattice layer　1 non-interacting layer

(1,1)



Kondo layer　　non-Kondo layer　　$t = t_z$



constructive interference

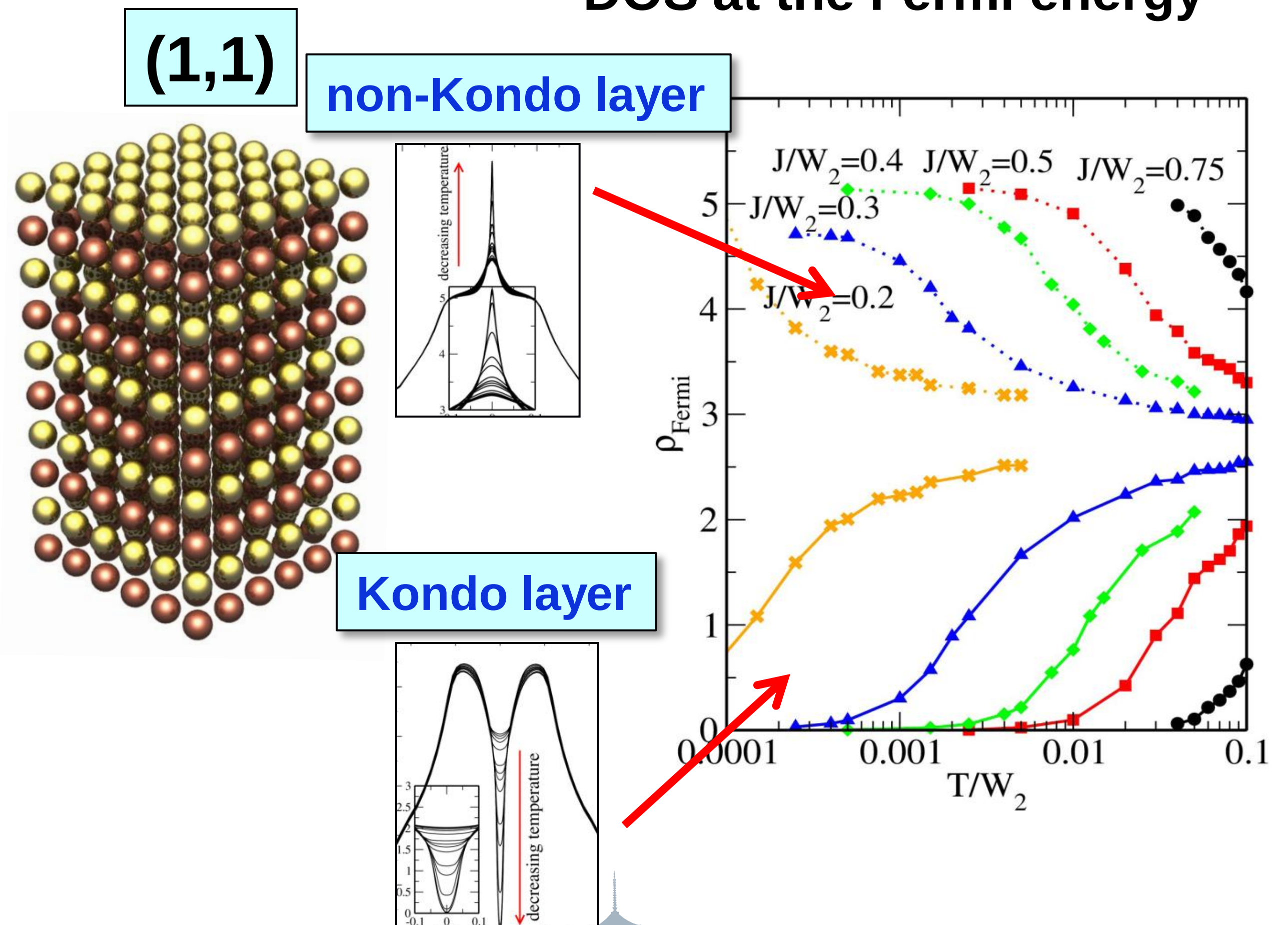
◇ f-electron layer forms the Kondo gap

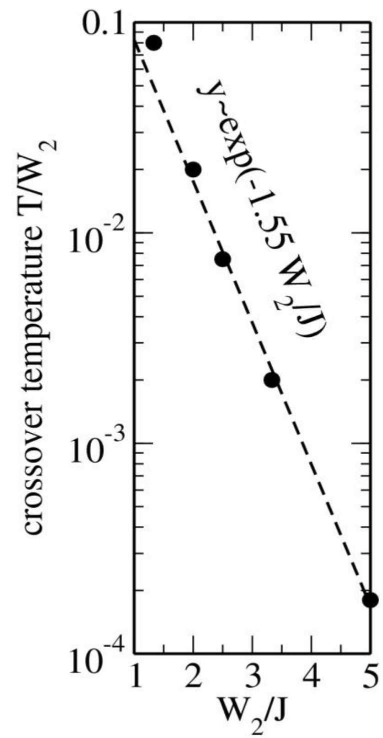
◇ Kondo peak in the NIL is strongly enhanced

Paramagnetic state in *f*-electron superlattice

1 Kondo lattice layer 1 non-interacting layer

DOS at the Fermi energy Kondo temperature

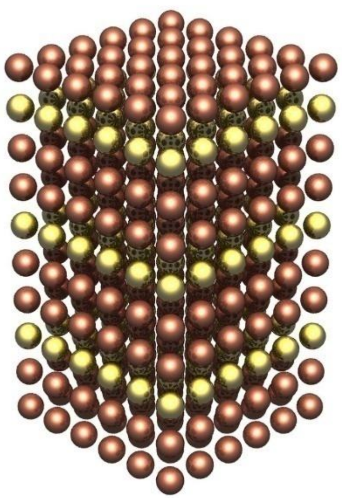




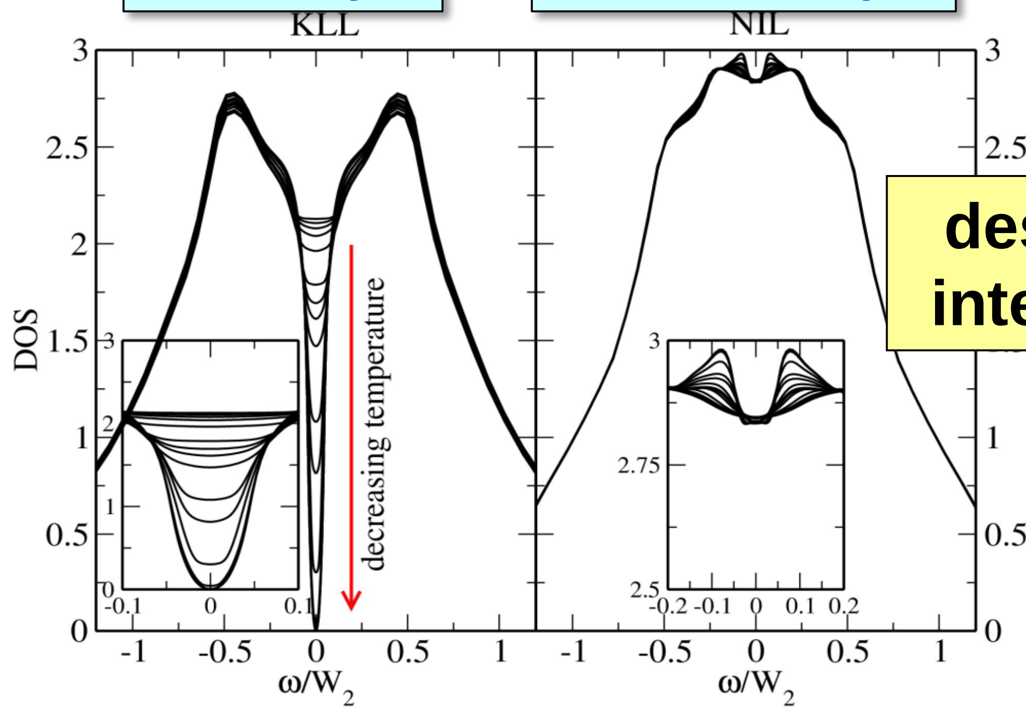
Paramagnetic state in *f*-electron superlattice

1 Kondo lattice layer   2 non-interacting layers

(1,2)



Kondo layer   **non-Kondo layer**



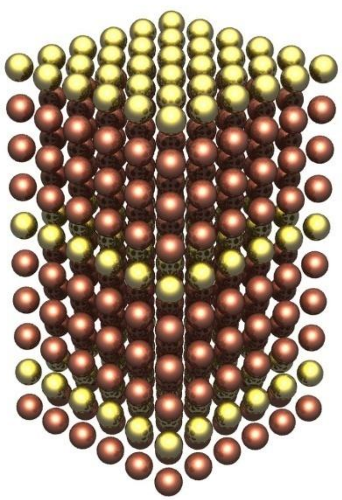
destructive interference

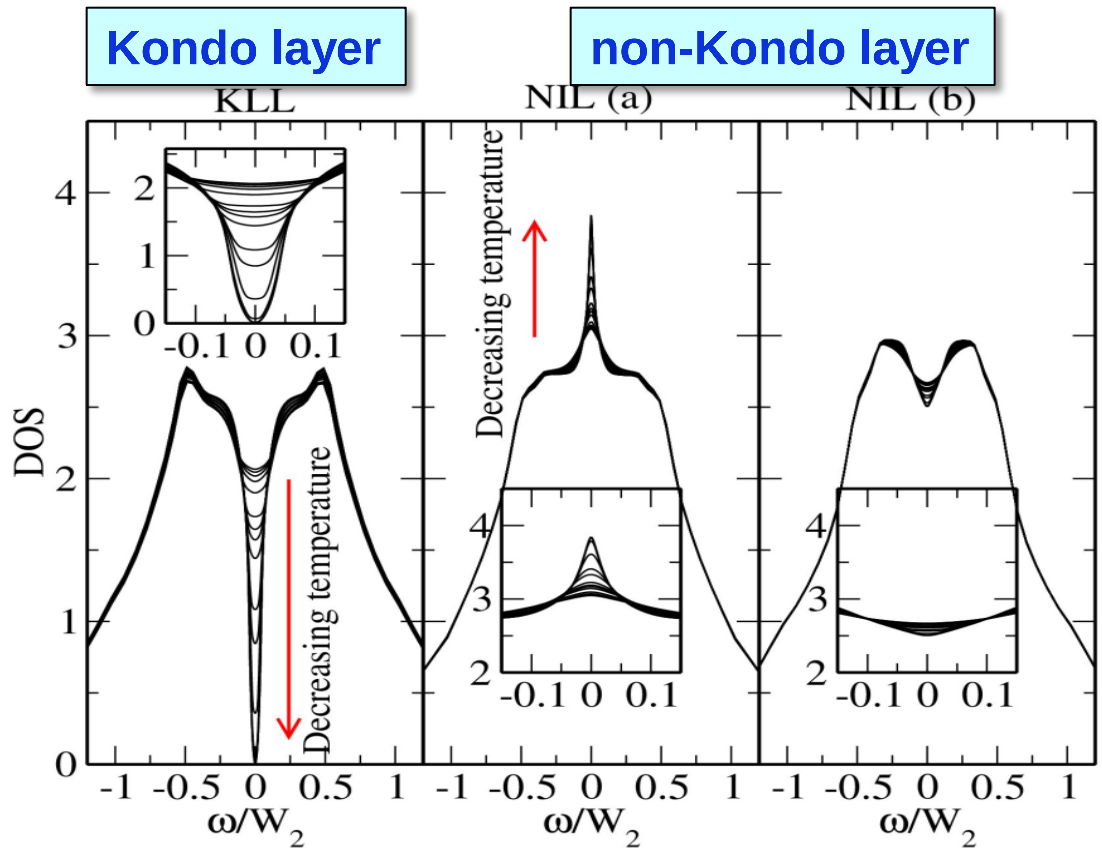
Kondo peak in the NIL is completely suppressed

Paramagnetic state in *f*-electron superlattice

1 Kondo lattice layer   3 non-interacting layers

(1,3)





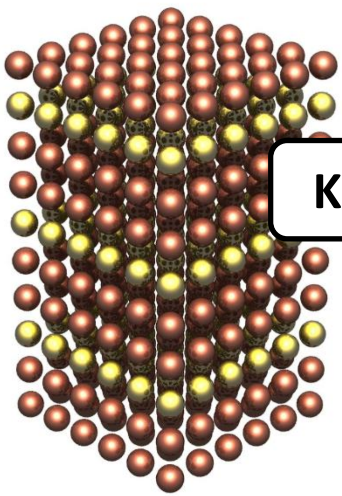
(1,3)-superlattice
resonances at the Fermi energy

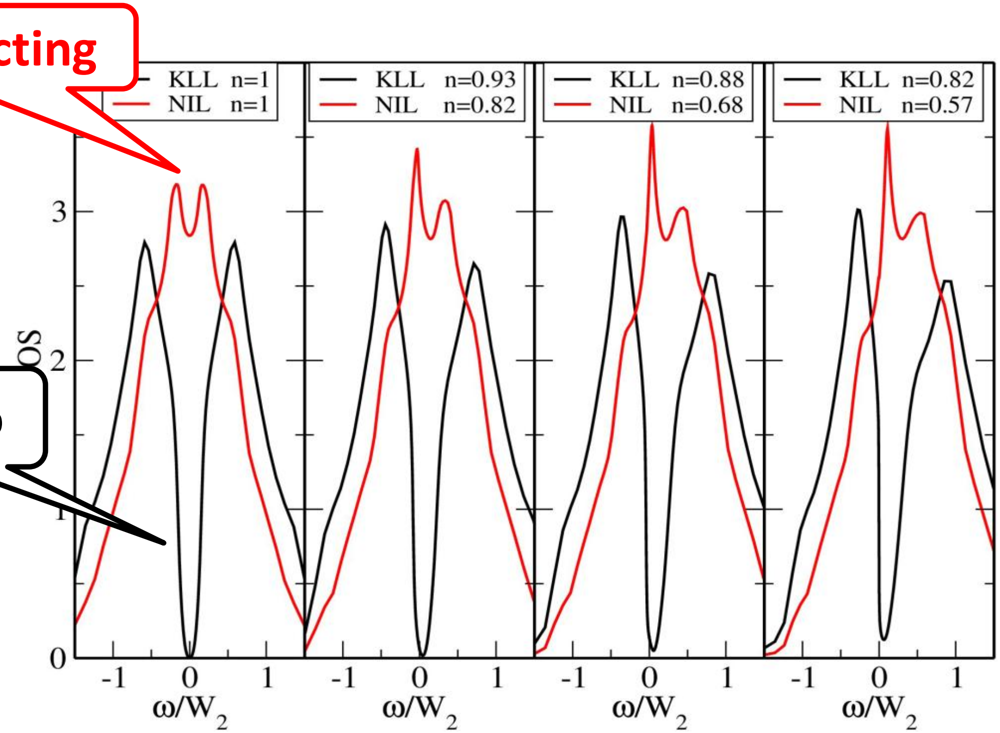
Paramagnetic state in *f*-electron superlattice

doping away from half filling

***T*=0**

(1,2)





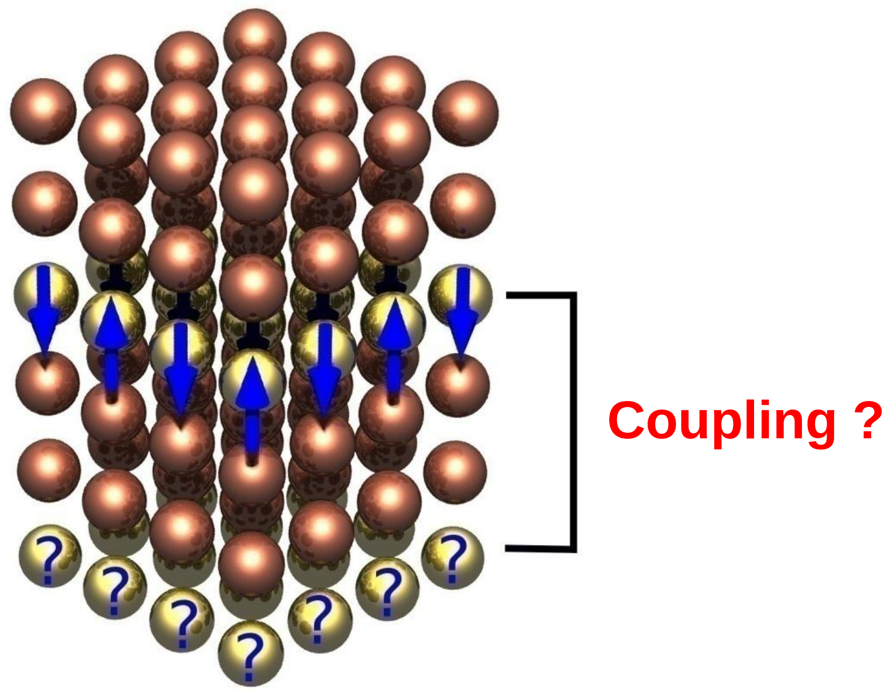
Hole doped systems:

Kondo effects are visible: Dip-Peak structure

Asymmetric shape

Magnetism

Magnetism in the superlattice



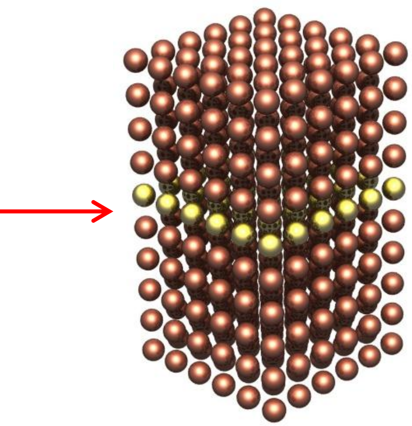
How are different layers in the superlattice magnetically coupled ?

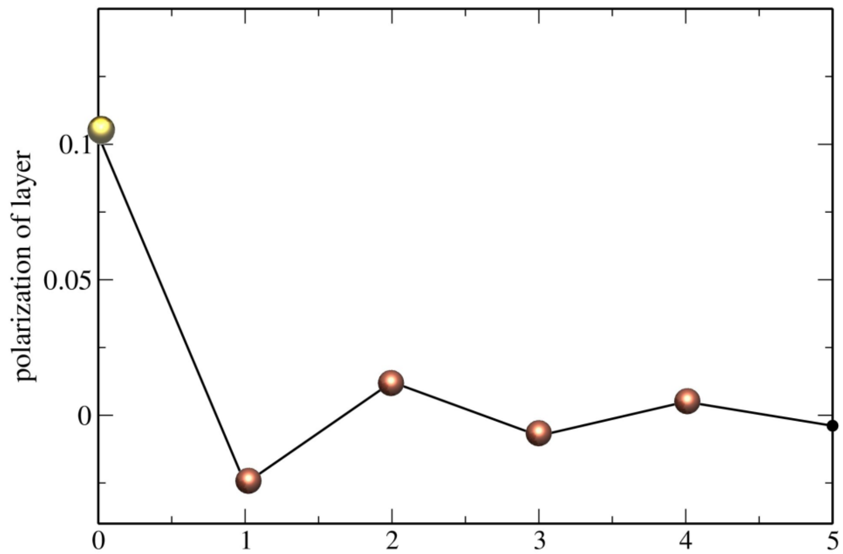
How strong is this coupling ?

Magnetism in the superlattice

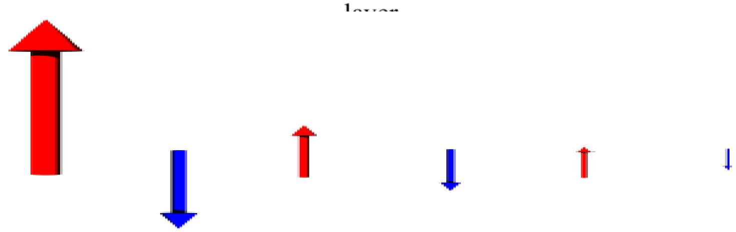
a single layer in 3D, polarization at T = 0

Mixed dimensions





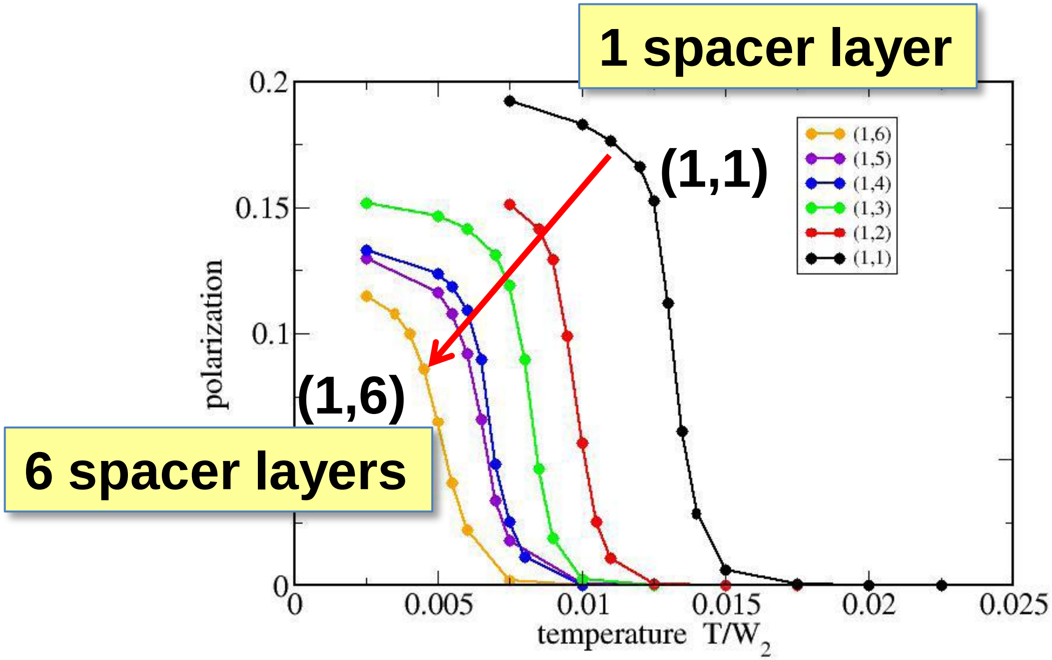
AF order



The single KLL polarizes surrounding layers.

Magnetism in the superlattice

Temperature-dependent polarization



J = 0.4 W_2

(W_2=4t)

With increasing the spacer-layers (e.g. La-layers)

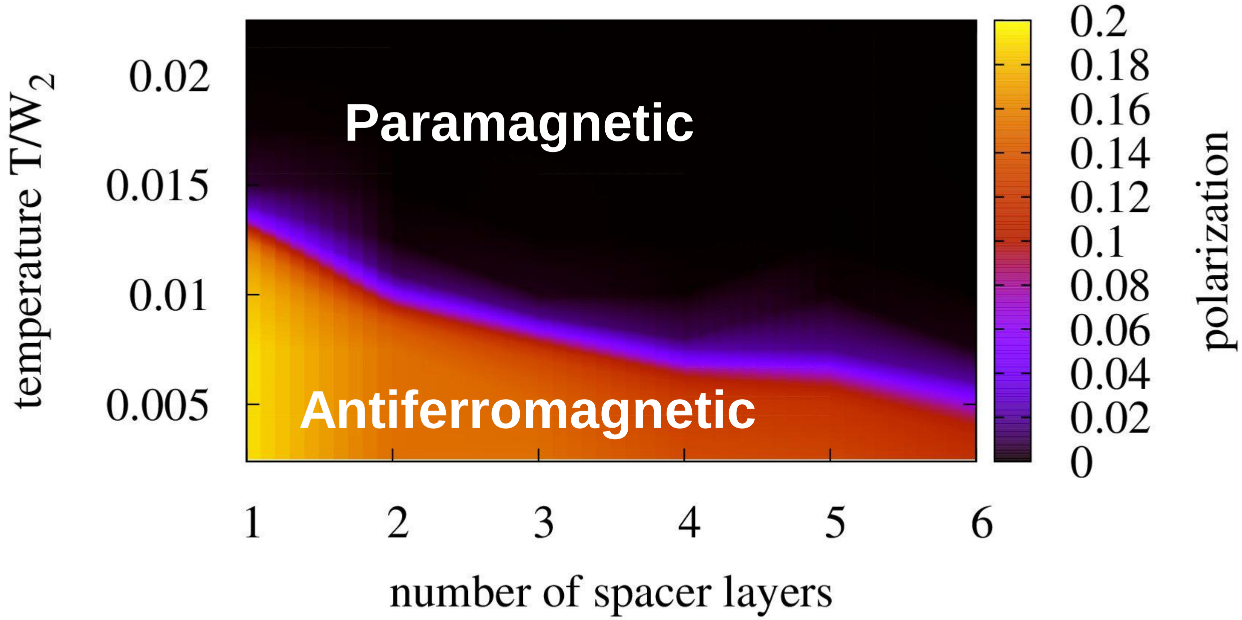
Polarization

Transition temperature

decrease in accordance with the experiments.

Magnetism in the superlattice

Transition temperature

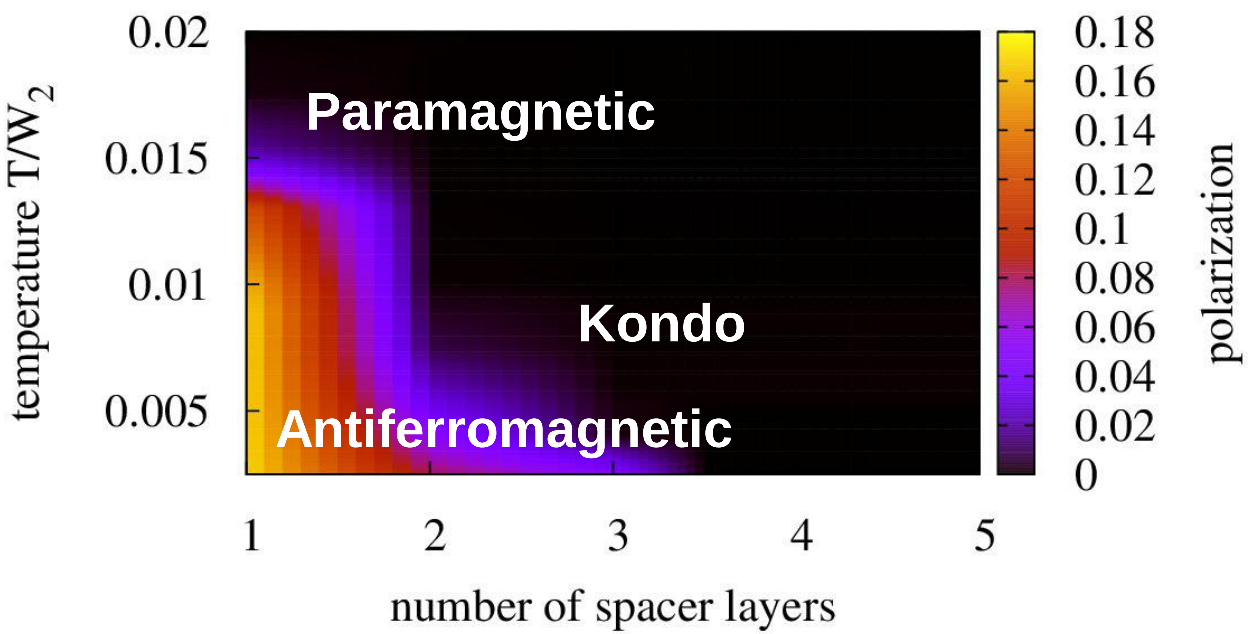


J=1.5 t (J_c=2.2 t for 3D)

Away from the mag-nonmag transition

Magnetism in the superlattice

Transition temperature



J=2.2 t (J_c=2.2 t for 3D)

close to the mag-nonmag transition

Applications

STM experiments

$CeCoIn_5$

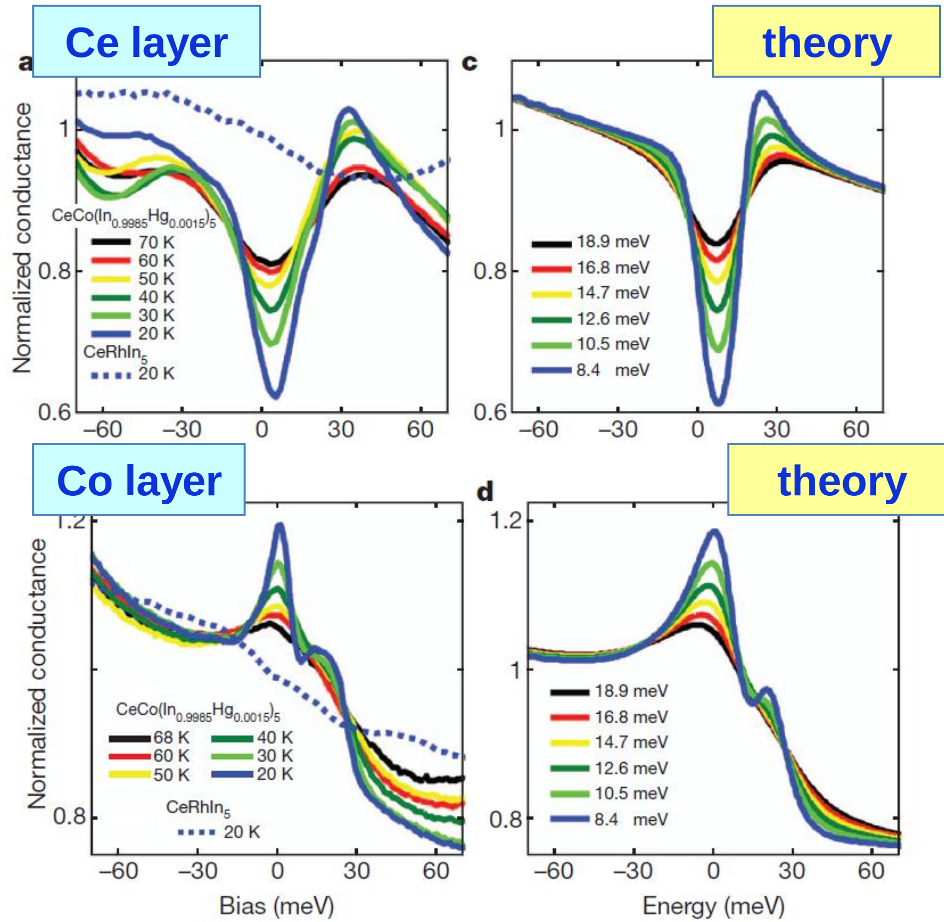
Natural superlattice

STM Experiments

Visualizing heavy fermions emerging in a quantum critical Kondo lattice

P Aynajian et al.

NATURE 286, 201(2012)



$CeCoIn_5$

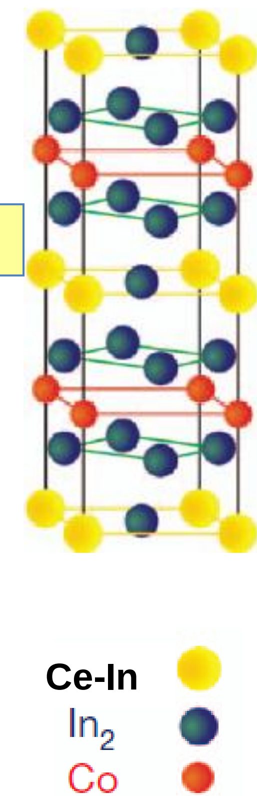
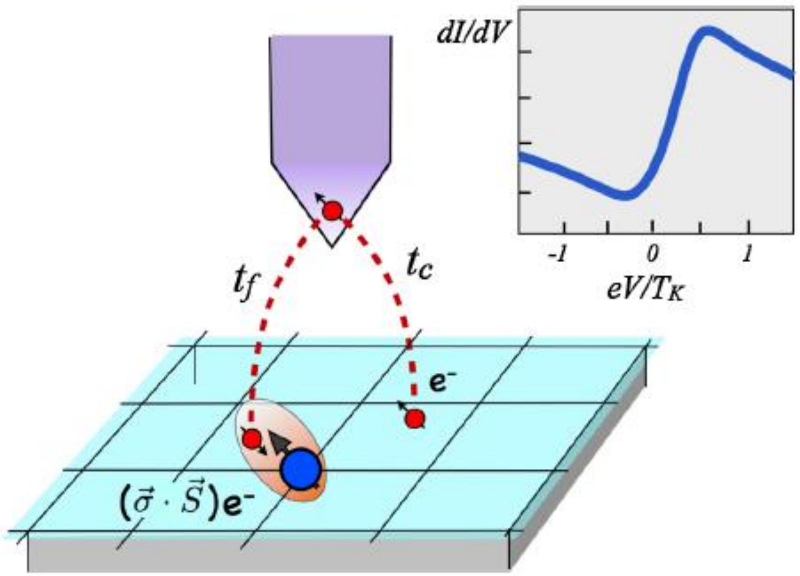
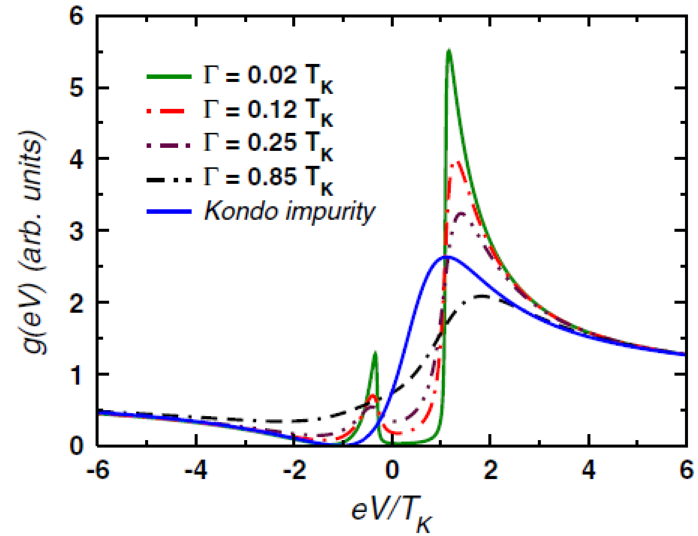


Figure 3 | Composite nature of heavy-fermion excitations. a, Averaged tunnelling spectra (−150 mV, 200 pA) measured on surface A of $CeCo(In_{0.9985}Hg_{0.0015})_5$ for different temperatures (T, in K; solid lines) and on the corresponding surface A of $CeRhIn_5$ at 20 K (dashed line). **b**, Averaged tunnelling spectra (−150 mV, 200 pA) measured on surface B of $CeCo(In_{0.9985}Hg_{0.0015})_5$ for different temperatures (T, in K; solid lines) and on corresponding surface B of $CeRhIn_5$ at 20 K (dashed line). **c**, **d**, Tunnelling spectra computed for $t_f/t_c = -0.01$ (**c**) and $t_f/t_c = -0.20$ (**d**) for selected values of γ_f (in meV; solid lines). See Supplementary Information section I for details of the model.

Two-channel Cotunneling Model

M.Maltseva, M. Dzero, and P. Coleman PRL 103, 206402 (2009).





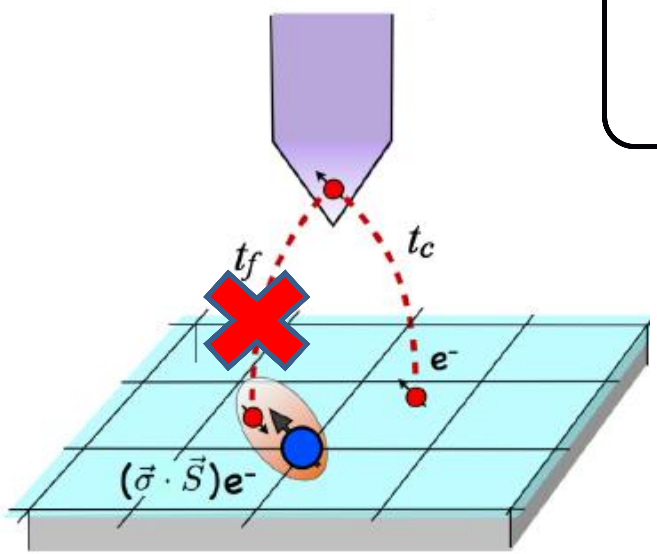
Interference between two tunneling processes

⇨ **Fano-type asymmetric resonance** **Extrinsic effect**

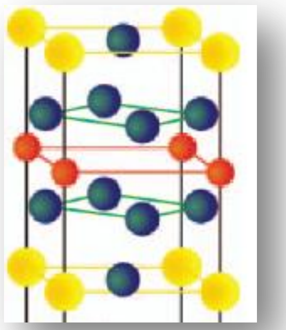
$CeCoIn_5$ **Serious drawback**
- $t_f > t_c$
- large t_f at Co site

Our Model

R. Peters and NK (2014)



Tunneling t_c into conduction electrons
(t_f should be small)



Superlattice structure

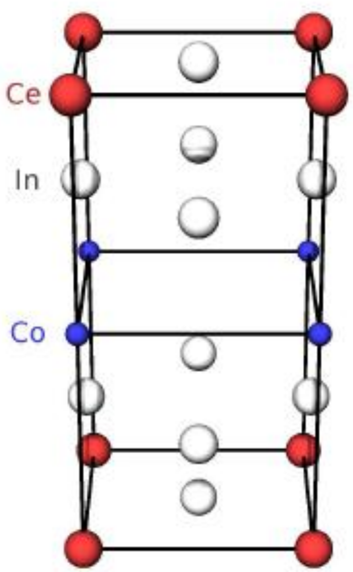
⇨ Proximity of Kondo effect

Intrinsic effect !

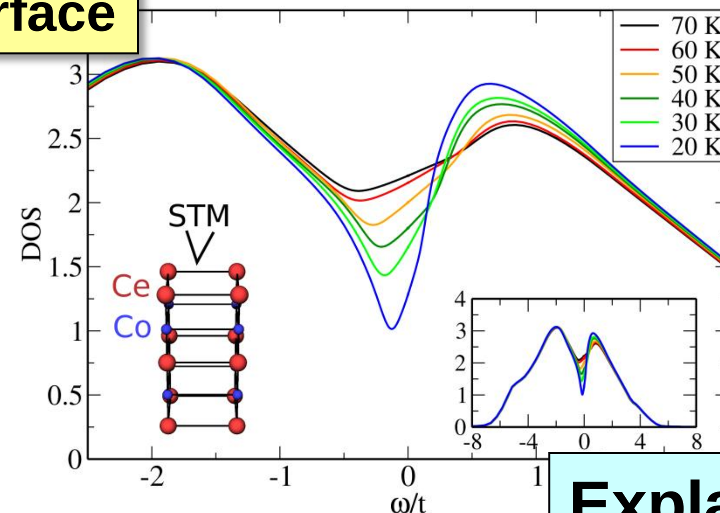
Temperature dependent LDOS

Peters-NK, 2014

CeCoIn5



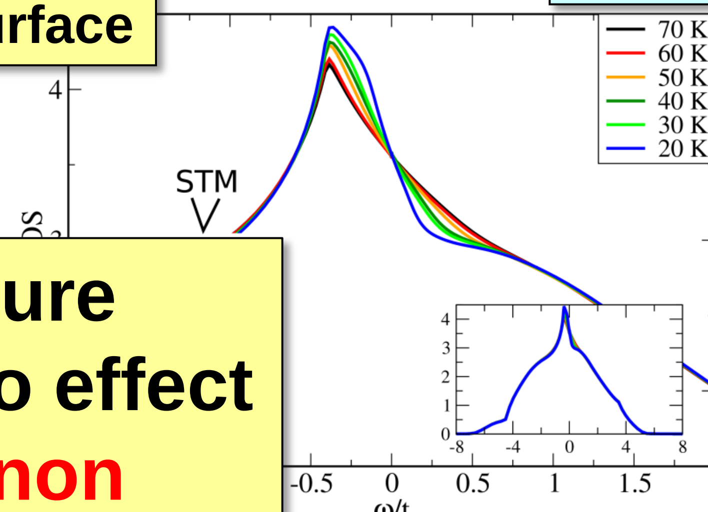
Ce surface



T_K=50K

Explain STM of $CeCoIn_5$

Co surface



Superlattice structure

Proximity of Kondo effect

Intrinsic phenomenon

Summary

How heavy fermions behave in the superlattice ?

Proximity of the Kondo effect

(1) Heavy fermions

constructive/destructive

(2) Magnetism

(3) Application to experiments

$CeCoIn_5$

STM: new mechanism: intrinsic