Detection of novel electronic order in Fe-based superconducting (and related) materials with point contact spectroscopy

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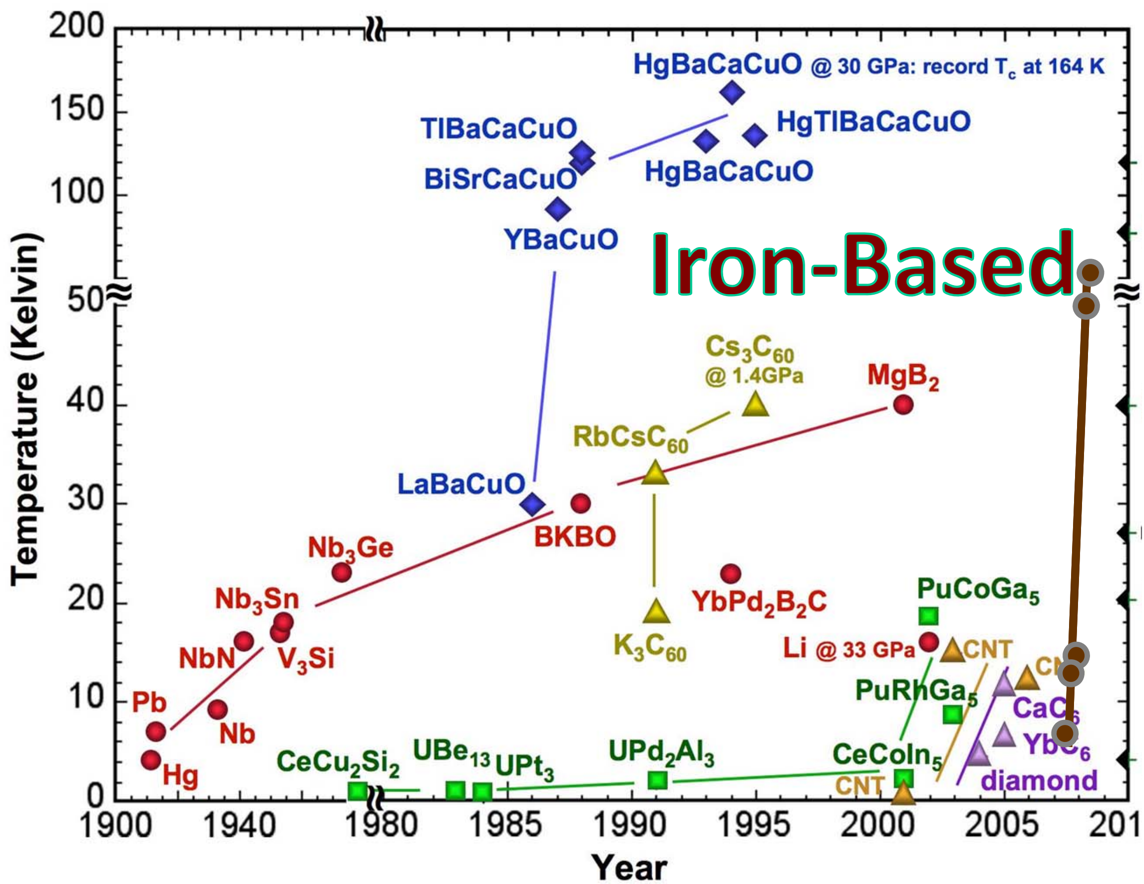
Center for Emergent Superconductivity

ICMT Conference on Disordered Materials — May 17, 2011

After a couple of decades…

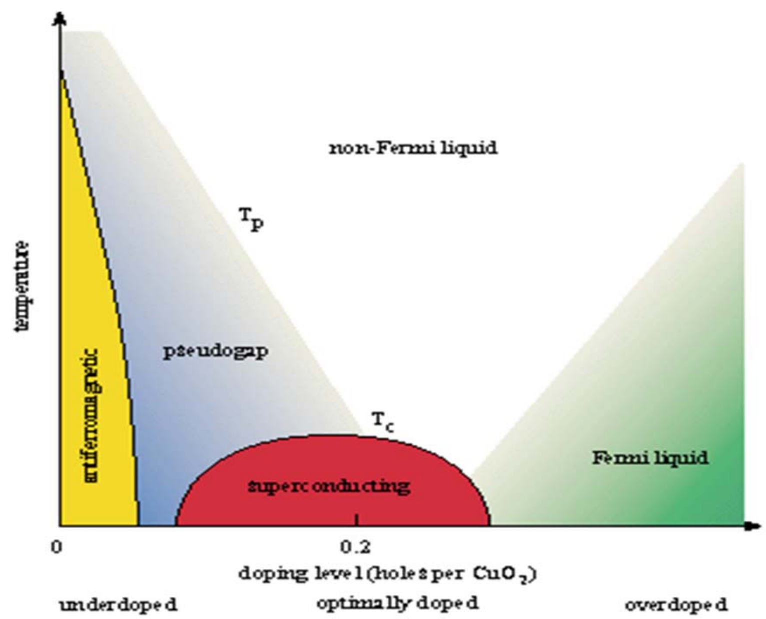
HTS is NOT UNIQUE to Cuprates!!!



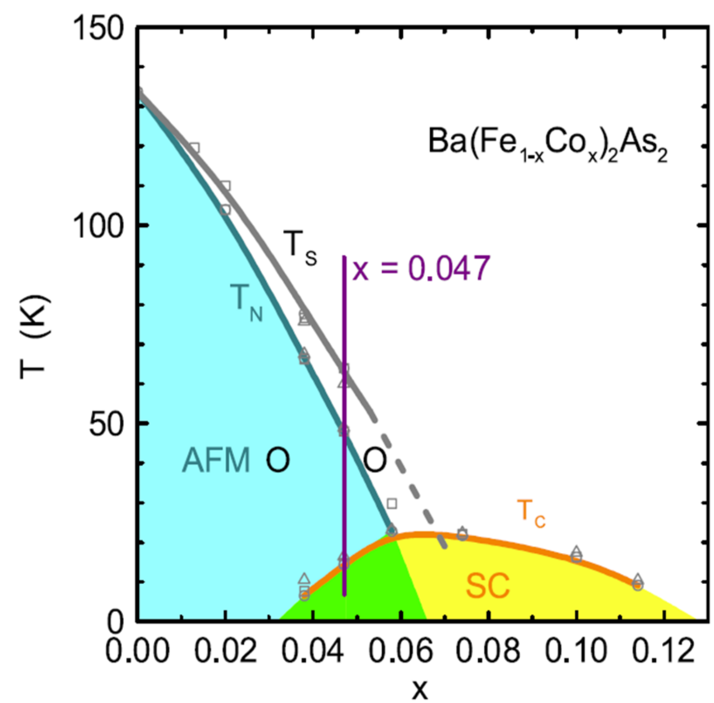
And we still do not understand the mechanism of SC in any of the HTS and related novel superconductors!

Generic HTS phase diagrams
Pressure and doping tuning

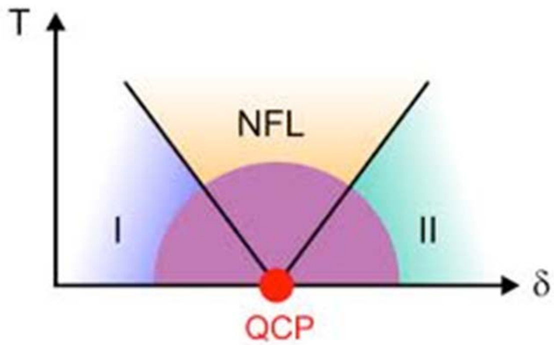
Cuprates

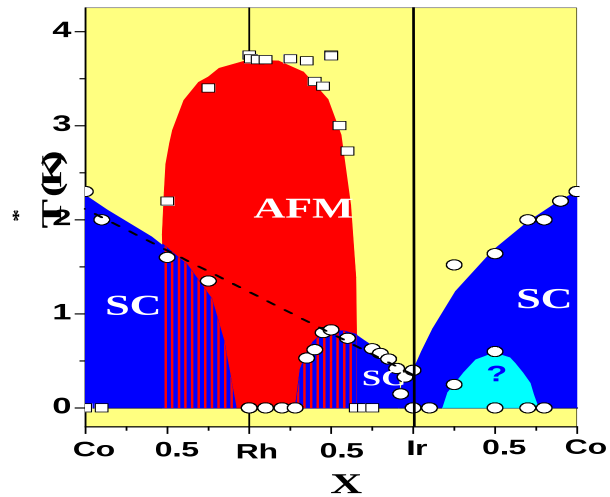


Fe-Based



Similar phase diagrams of related materials organic and heavy-Fermion SCs





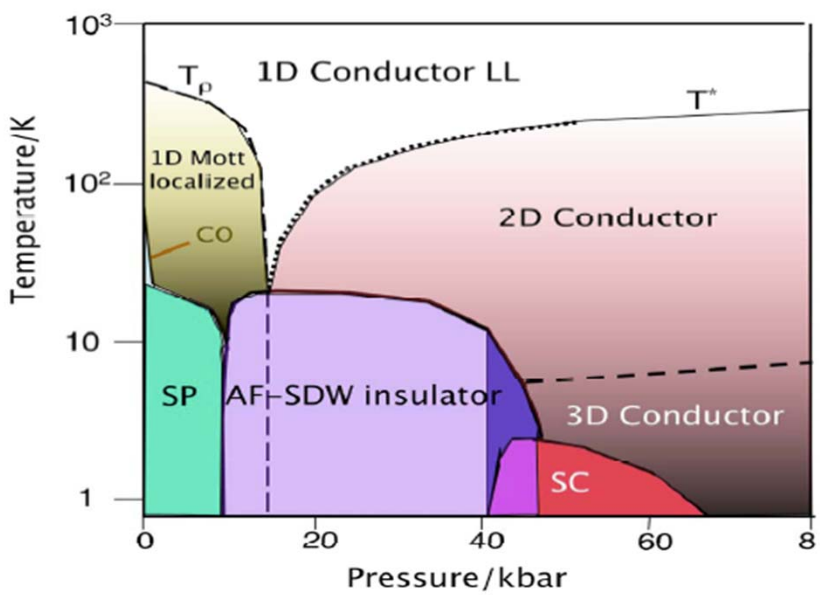
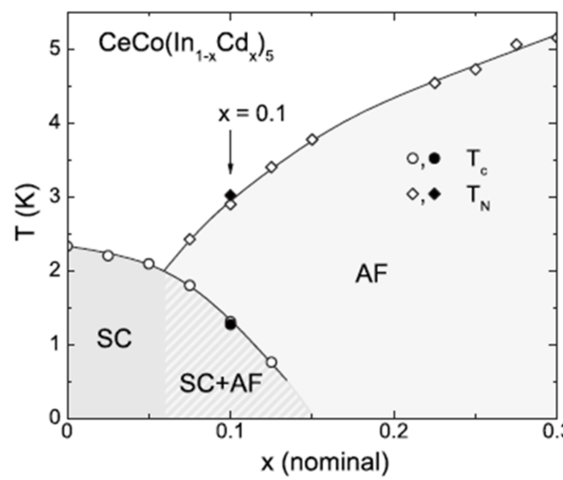


Figure 1: Generic temperature-pressure phase diagram of the $(TM)_2X$ family of organic conductors. The diagram is drawn for the compound



Outline

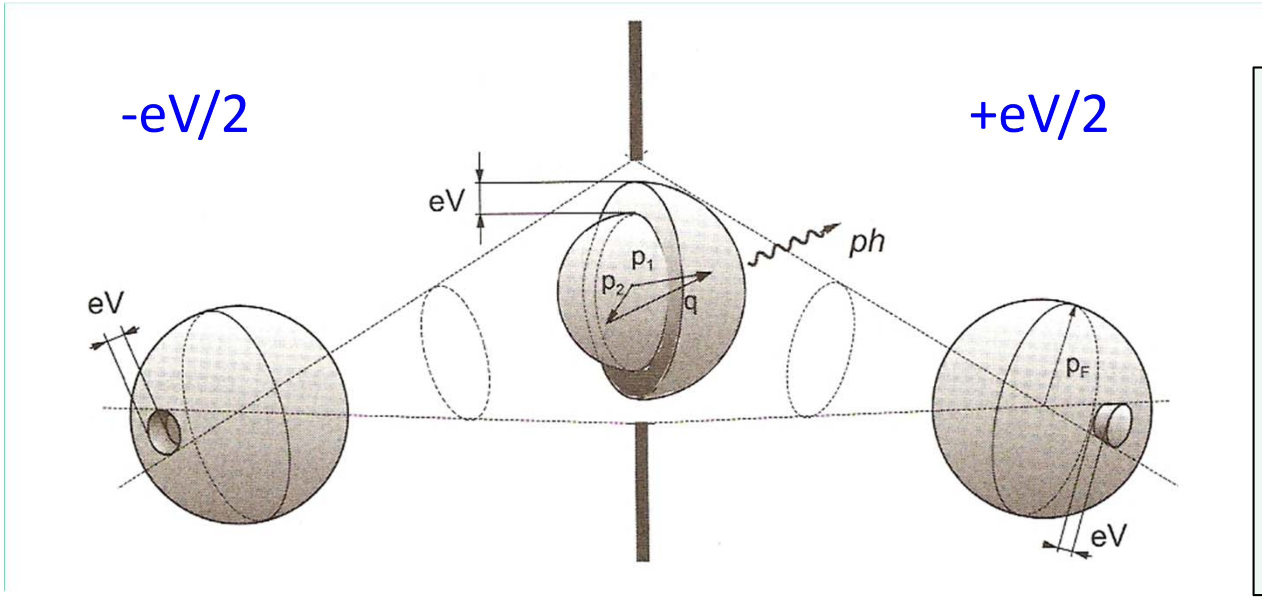
- Quasiparticle Scattering Spectroscopy
  [Point-Contact Spectroscopy]

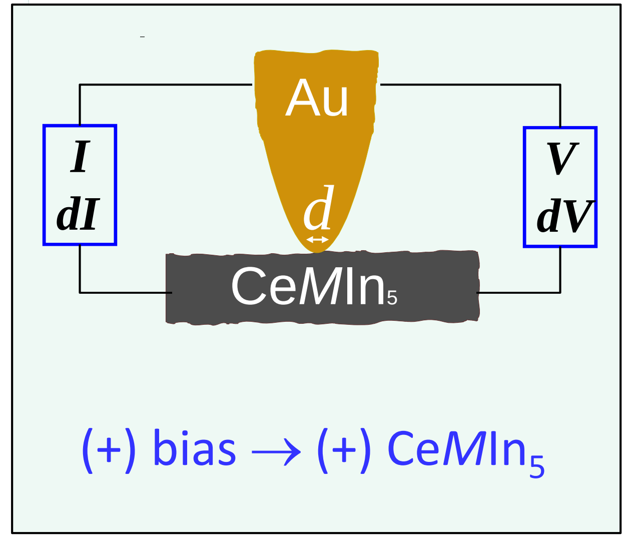
- Heavy Fermion $CeCoIn_5$
  Detecting phase orderings and broken symmetries

- Heavy Fermion URu_2Si_2
  Detecting the Hybridization Gap

- $Ba(Fe_{1-x}Co_x)_2As_2$ and $Fe_{1+y}Te$
  Detecting orbital ordering?

Quasiparticle Scattering Spectroscopy (Point Contact Spectroscopy "PCS")





Point-Contact Spectroscopy, Naidyuk & Yanson (2005)

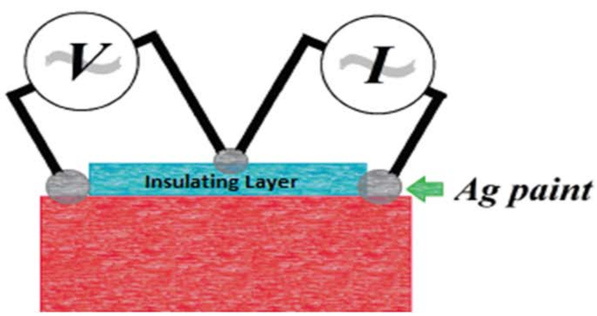
- If two bulk metals are in contact with each other and the contact size is smaller than electronic mean free paths, quasiparticle energy gain/loss mostly occurs at the constriction.

- Nolinearities in current-voltage characteristics reflect energy-dependent quasiparticle scatterings in the contact region.

Quasiparticle Scattering Spectroscopy (Point Contact Spectroscopy "PCS")

- Transparent Contact between two materials (***not tunneling***).
- ***Contact area less than elastic mean free path***.
- Measure dI/dV vs. V bias.

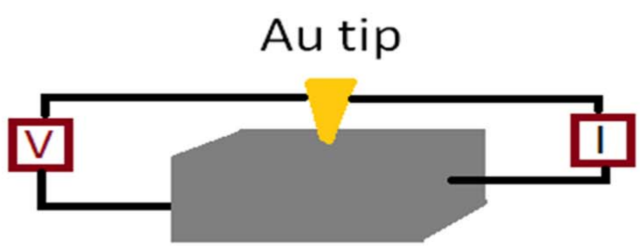
Soft PCS



Microshorts through insulating layer

- ✓ Thermally stable
- X Little control over junction resistance

Needle-anvil PCS



Electrochemically etched nanoscale gold

- ✓ Tunable junction resistance (piezoelectric bimorphs / screw)
- X Thermally less stable

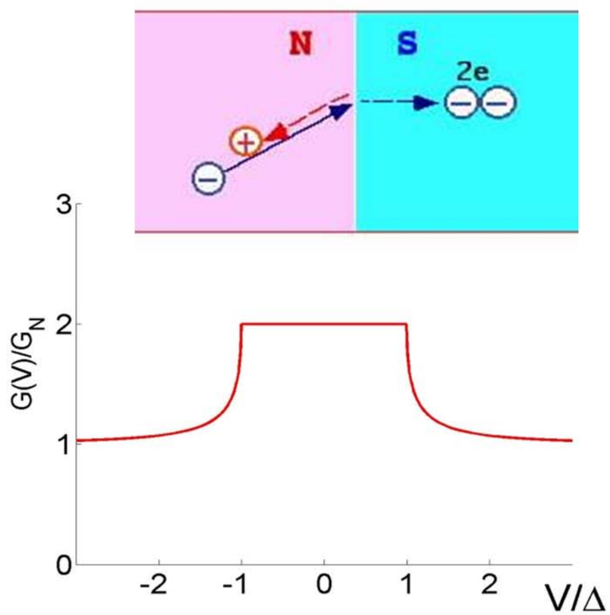
Quasiparticle scattering (PCS): What we detect

1. Superconductivity (intro):
   Gap, order parameter symmetry, density of state, … this is well understood in the framework of BTK and Andreev reflection.
2. Kondo Impurity / Kondo Lattice effects (intro):
   Fano lineshape consistent with the growth of the Kondo liquid (starts at T*, and grows until T_c): microscopic explanation?
3. Antiferromagnetic ordering (intro):
   Conductance enhancement at T_N in some AF systems (not all)
4. **The hybridization gap & Fano resonance in a heavy fermions**
5. **Orbital ordering?**
   This talk: Enhancement at high-T in Co:$BaFe_2As_2$and FeTe.

Superconductivity: PCS to Tunneling - BTK model

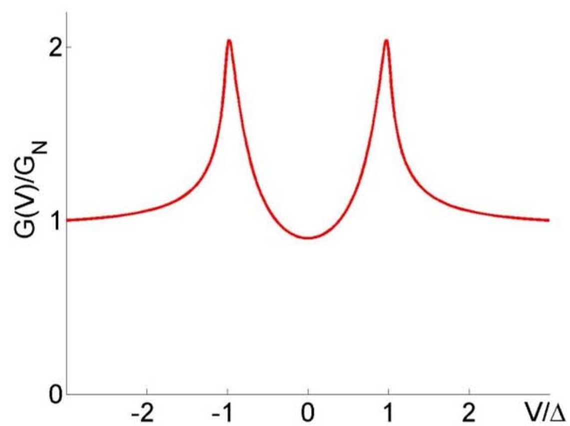
Three fitting parameters

- Δ = superconducting gap
- Γ = Dynes broadening factor (qp scattering rate)
- Z_{eff} = barrier strength at the N/S interface

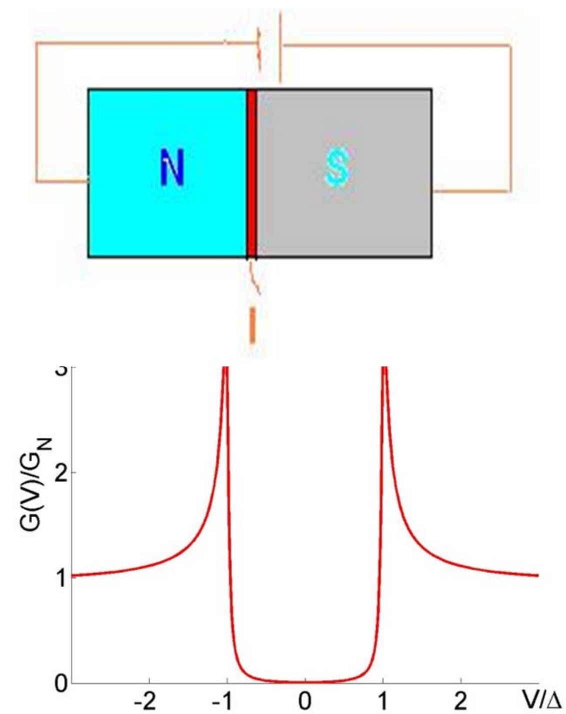


Z = 0
Andreev Reflection

Assuming $\Gamma = 0$ and $\Delta = 1$



Z = 0.5

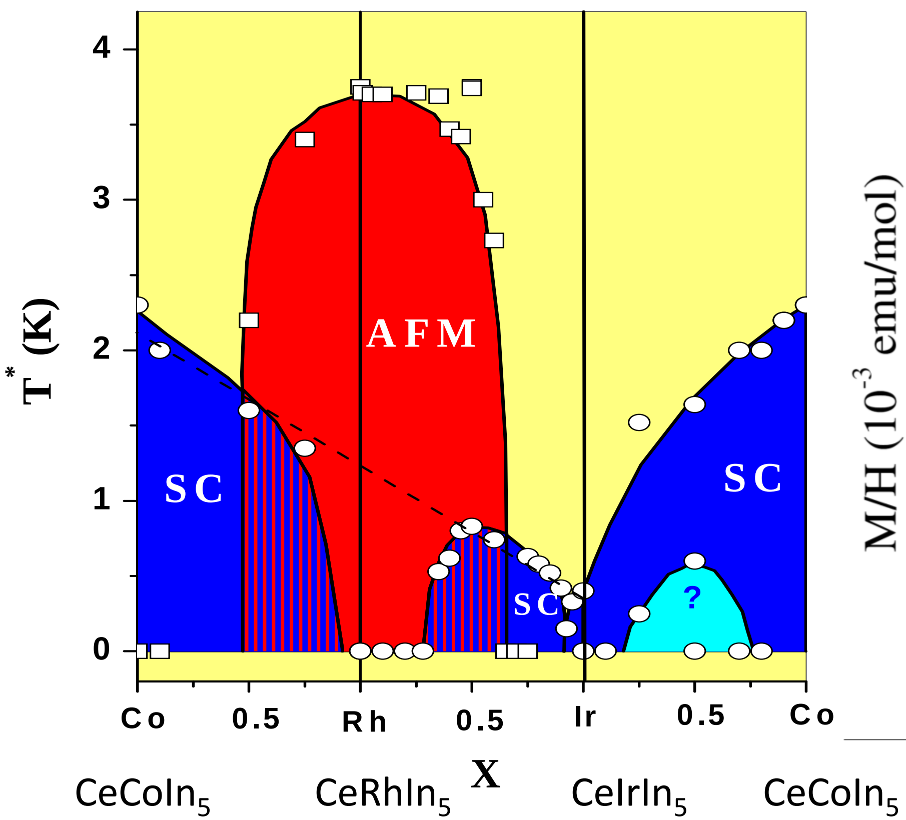


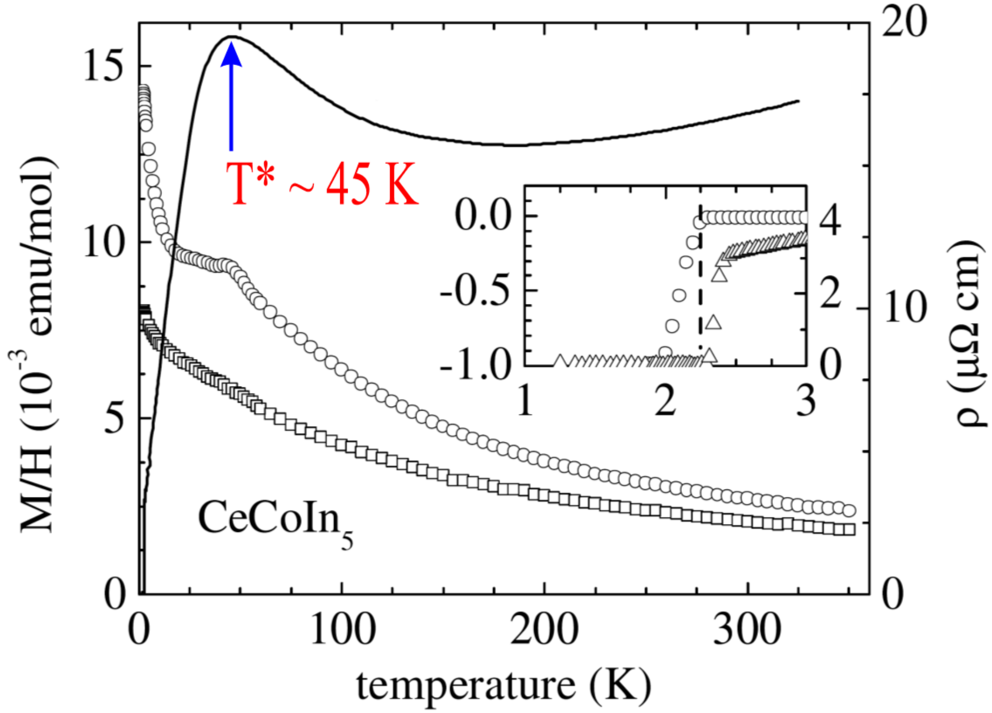
Z = 5.0
Tunneling

The Heavy Fermion Superconductor $CeCoIn_5$:

Phase diagram of series Ce M In_5 (M = Co, Rh, In) & transport

- T_c = 2.3 K (high for many HFS)
- Superconductivity in clean limit (*mfp* = 810Å >> ξ_0)

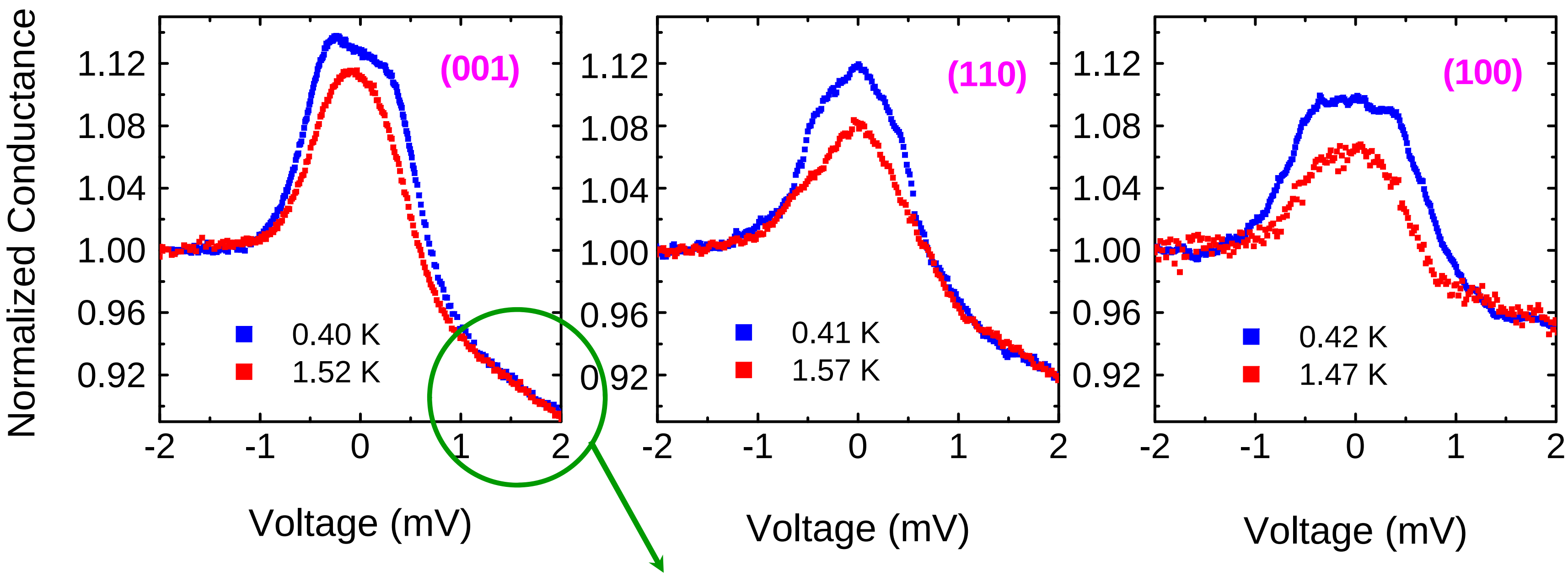




Pagliuso et al., Phys. Rev. B 64 (2001) 100503(R)

Superconductivity: Gap and OP Symmetry

Data: Consistency Along Three Orientations

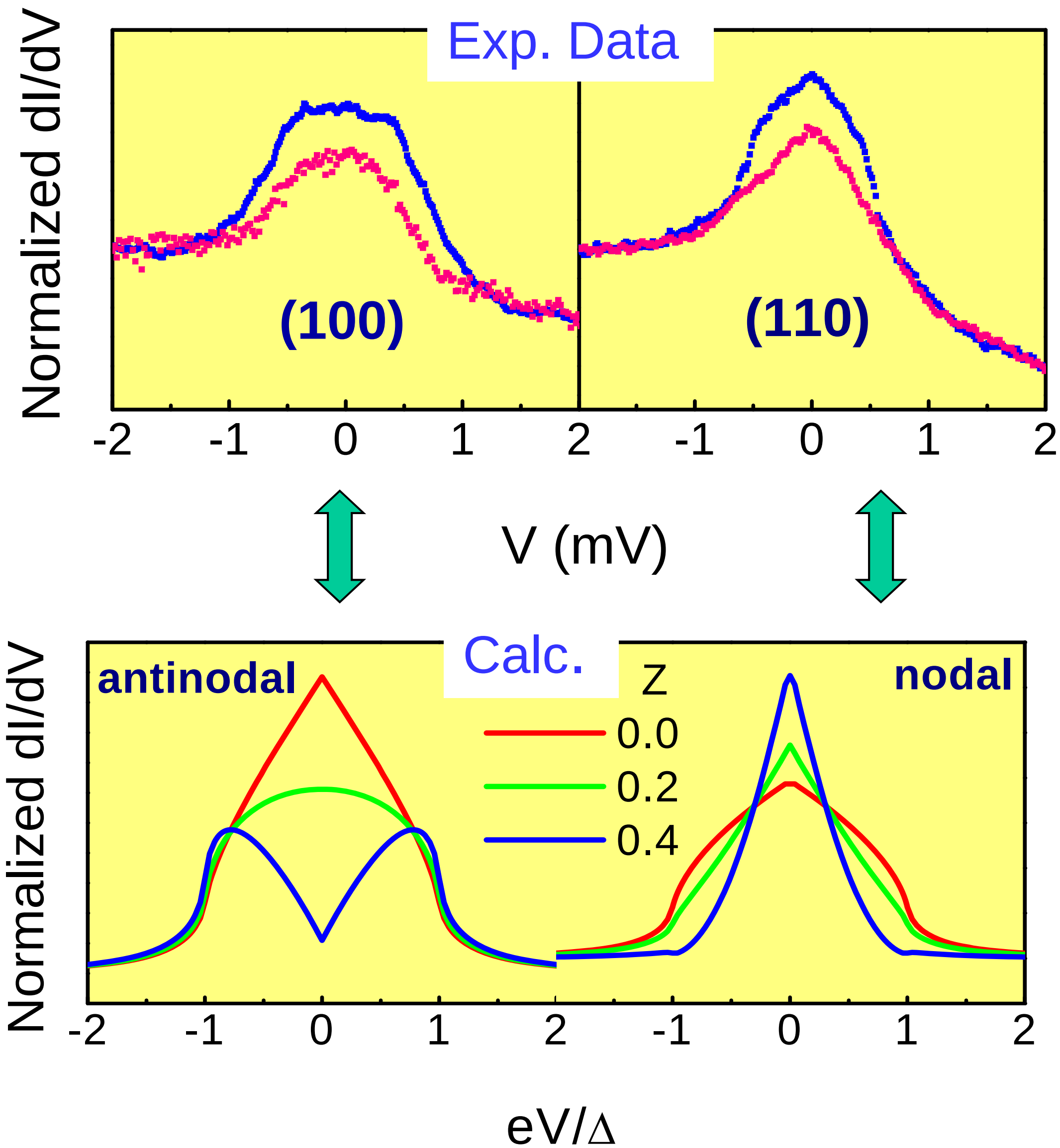


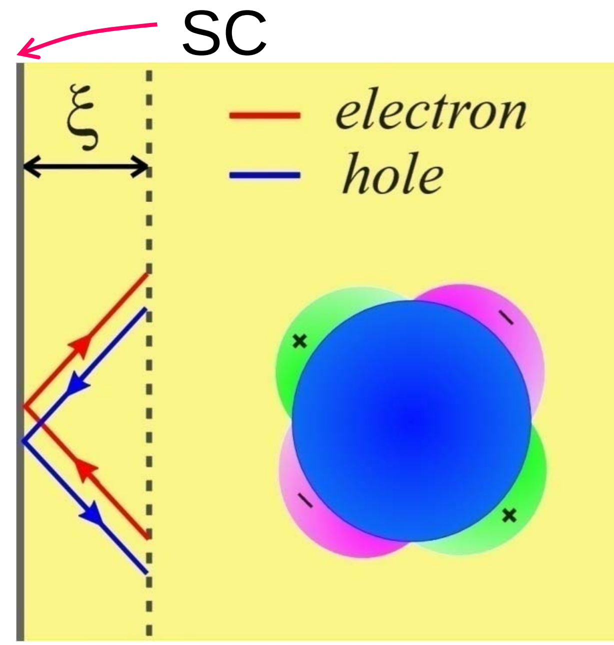
(+) $CeCoIn_5$; (–) Au

=> Adding electrons to $CeCoIn_5$ above the Fermi energy is more difficult than removing them

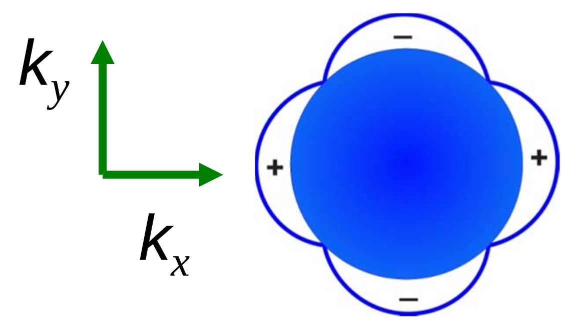
Note the shapes of the conductance curves

Spectroscopic Evidence for $d_{x^2-y^2}$ Symmetry



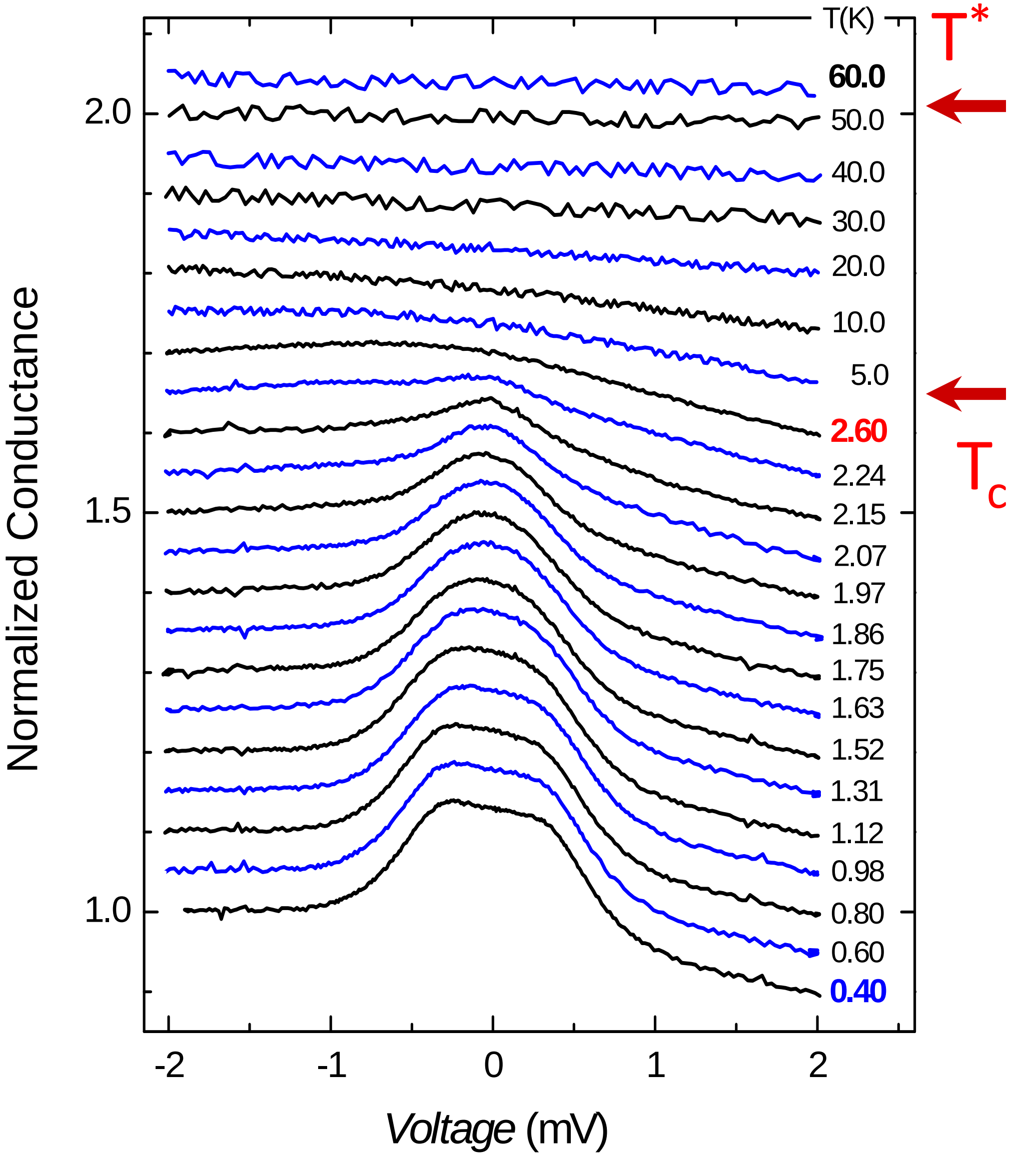


Andreev Bound States (ABS)



WK Park et al., PRL **100**, 177001

Kondo: Background Conductance Asymmetry of $CeCoIn_5$

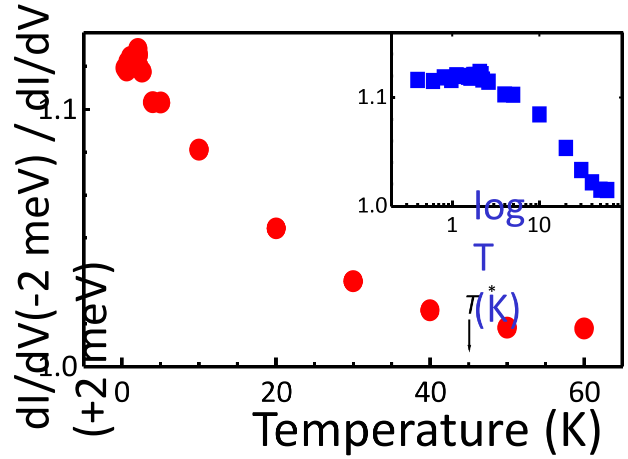


Background develops an asymmetry* at the heavy-fermion liquid coherence temperature,

$T^* \sim 45$ K.

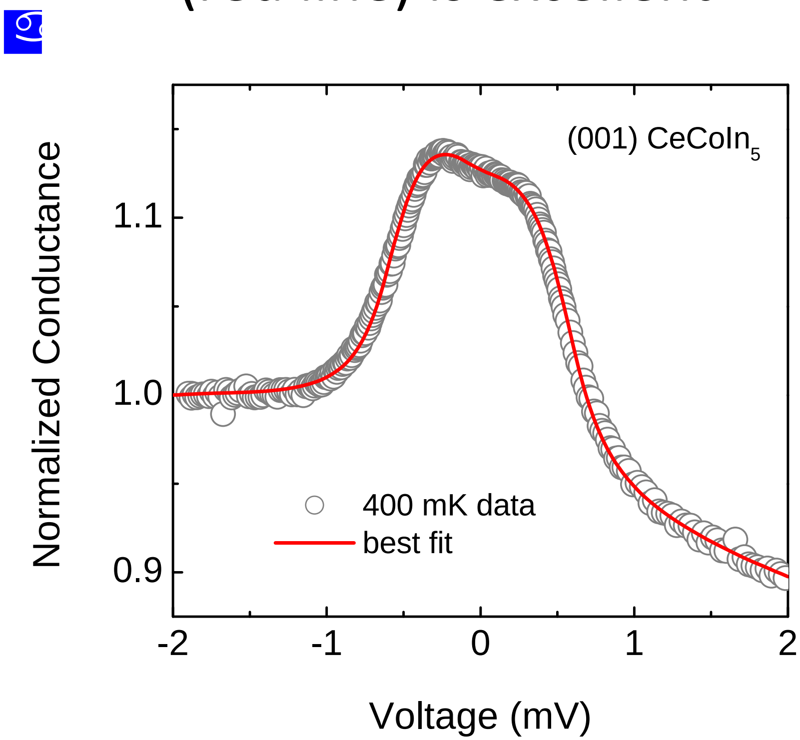
This asymmetry gradually increases with decreasing temperature until the onset of superconducting coherence,

$T_c = 2.3$ K.

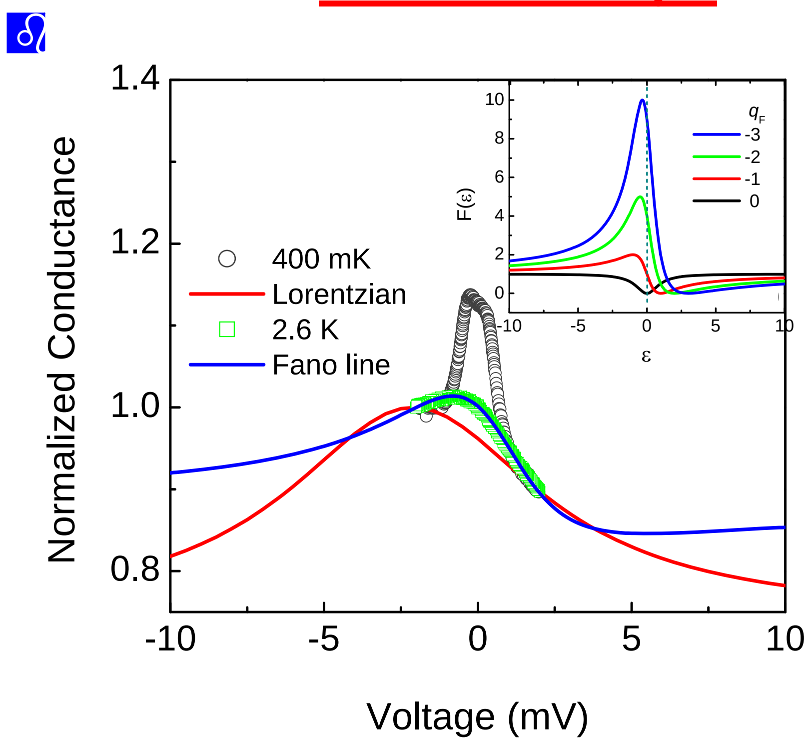


Model fits magnitude of AR, asymmetry and T-dep !

Data (circles) and fit (red line) is excellent



Best fit over wide T-range with a **Fano lineshape**

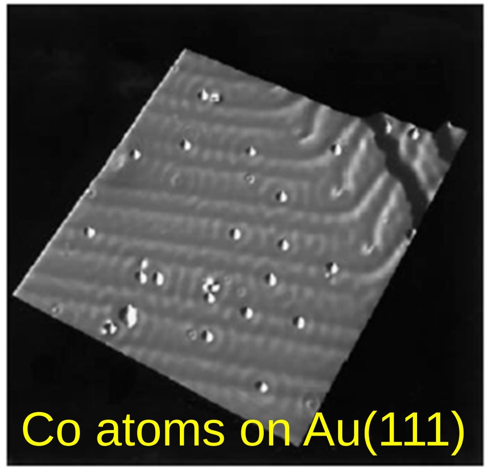


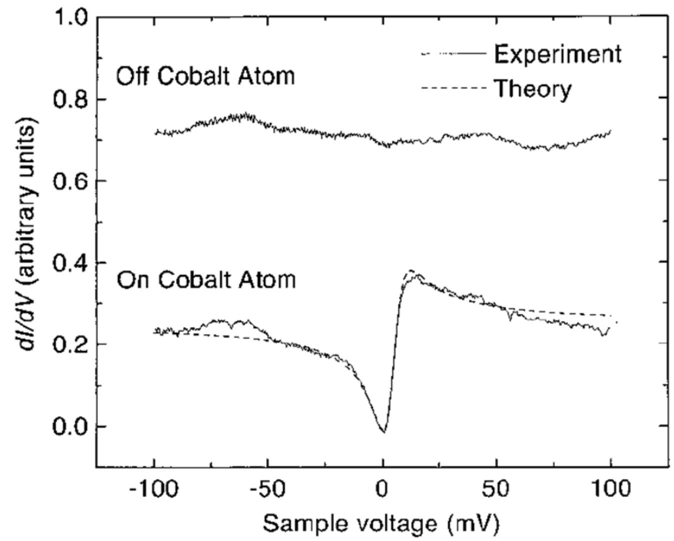
Fano may be explained by interference between f-electrons and conduction electrons via spin-flip (Kondo) scattering.

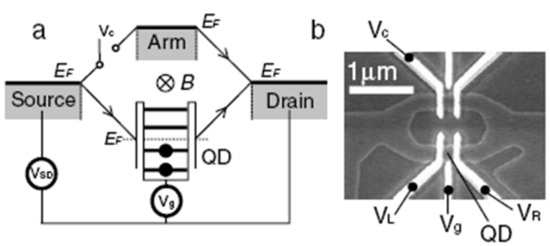
W. K. Park et al., PRL 08 and Y.-F. Yang et al., PRL 08

Fano Resonance in Single Impurity and Quantum Dot

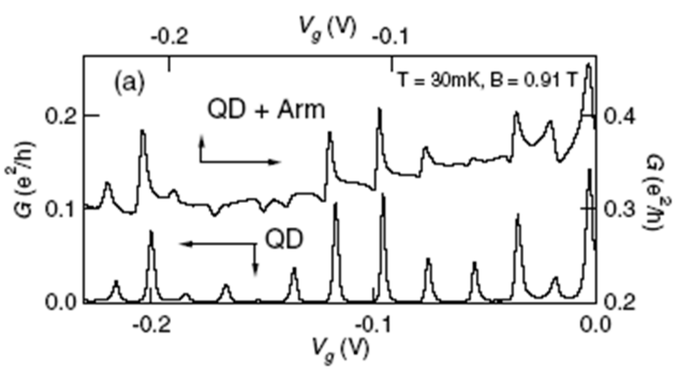
V. Madhavan et al., Science 280, 567 (1998)



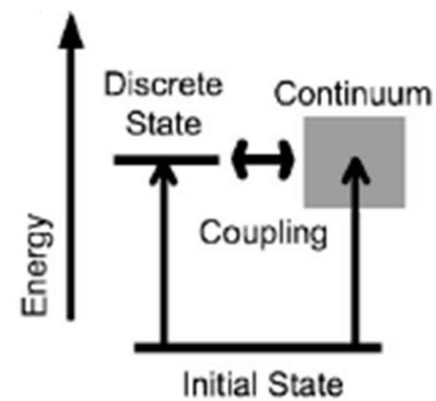




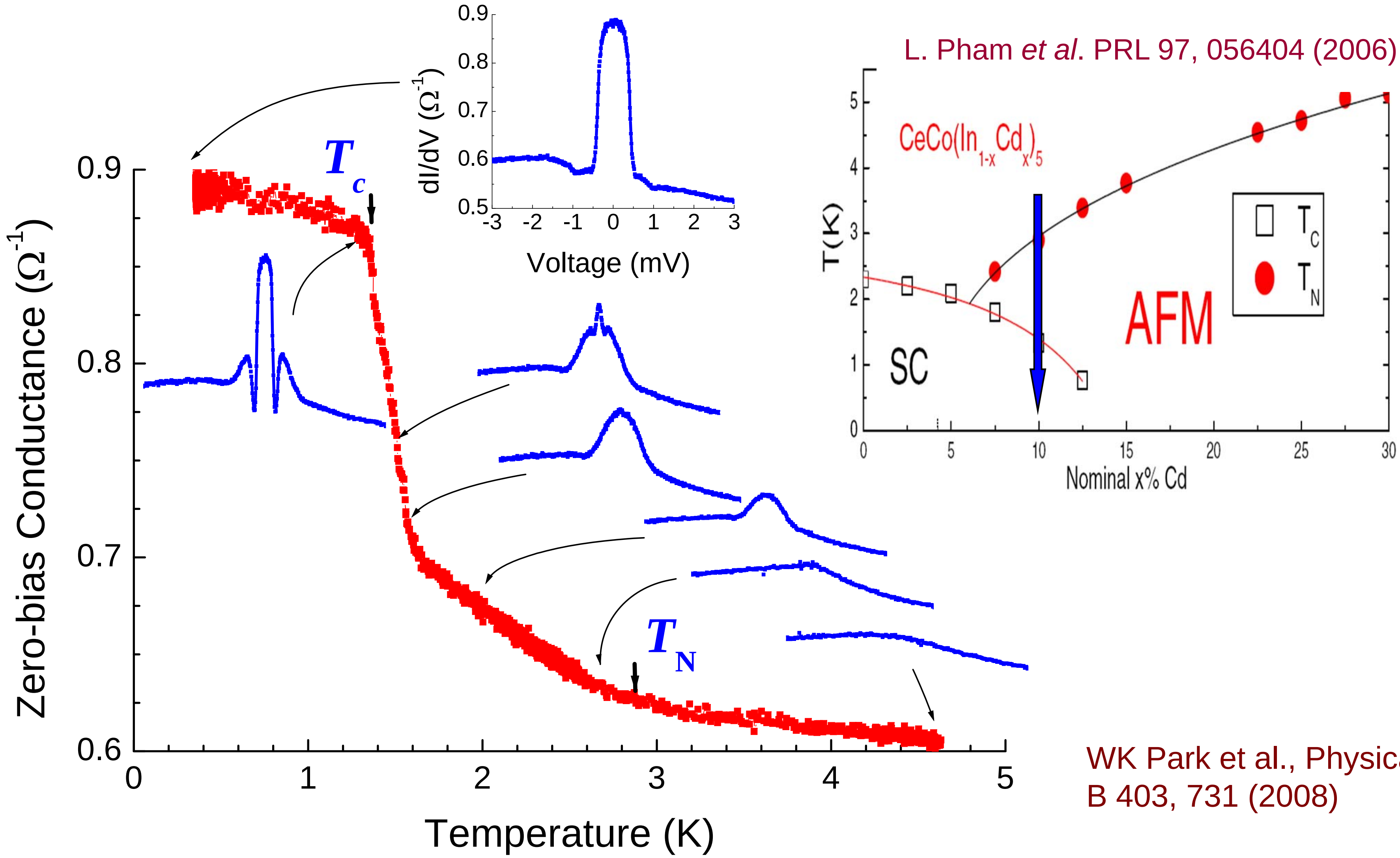
K. Kobayashi et al., PRL 88, 256806 (2002)



"The Fano effect is essentially a single-impurity problem describing how a localized state embedded in the continuum acquires itinerancy over the system."



Antiferromagnetism: Cd:$CeCoIn_5$: Anomalous Conductance



WK Park et al., Physica B 403, 731 (2008)

non-monotonic; enhancement below T_N, competition below T_{c0}

Quasiparticle scattering (PCS): What we detect

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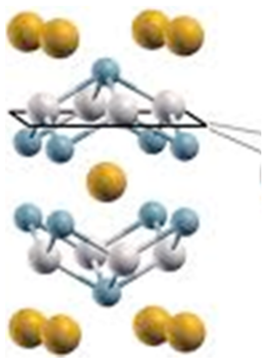
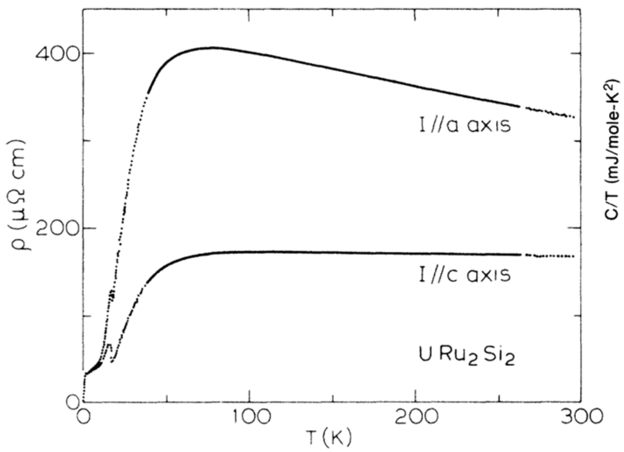
   Gap, order parameter symmetry, density of state, … this is well understood in the framework of BTK and Andreev reflection.
2. Kondo Impurity / Kondo Lattice effects (intro):
   Fano lineshape consistent with the growth of the Kondo liquid (starts at T*, and grows until Tc): microscopic explanation?
3. Antiferromagnetic ordering (intro):
   Conductance enhancement at T_N in some AF systems (not all

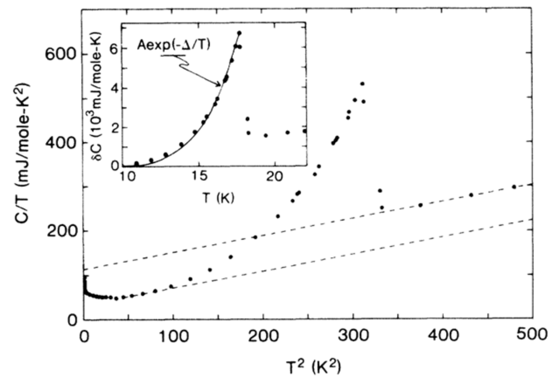
NOW:

1. **The hybridization gap & Fano resonance in a heavy fermion This talk**: Helps explain #2.
2. **Orbital ordering?**
   This talk: Enhancement at high-T in Co:$BaFe_2$As2and FeTeSe.

The Heavy Fermion / Kondo Lattice URu_2Si_2





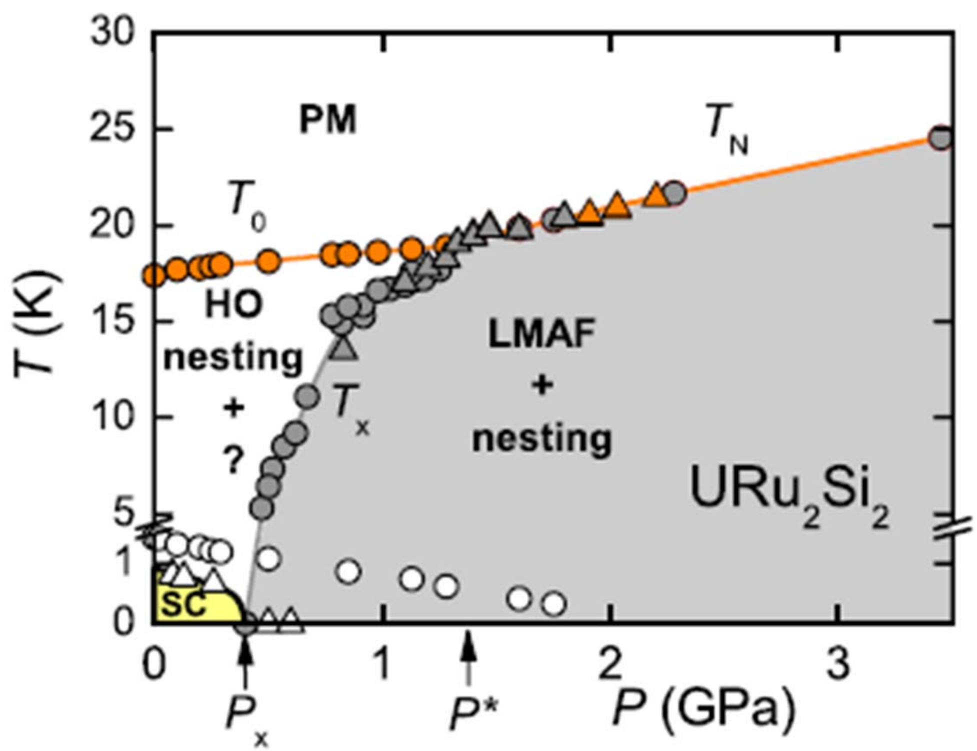


Δ = 115 K (9.9 meV)

Palstra et al., PRL (86); PRB (87)

A Phase Diagram

Hassinger et al., PRB 77, 115117 (2008)



Hybridization Picture of a Kondo Lattice

Periodic Anderson model

e.g., Newns & Read, Adv. Phys. (1987)

$$H_{\mathrm{PAM}} = \sum_{\mathrm{k}\sigma} (\varepsilon_{\mathrm{k}} - \mu) c^{\dagger}_{\mathrm{k}\sigma} c_{\mathrm{k}\sigma} + \sum_{\mathrm{k}\sigma} (\varepsilon_f - \mu) f^{\dagger}_{\mathrm{k}\sigma} f_{\mathrm{k}\sigma} + \sum_{\mathrm{k}\sigma} V_{\mathrm{k}} \left(f^{\dagger}_{\mathrm{k}\sigma} c_{\mathrm{k}\sigma} + c^{\dagger}_{\mathrm{k}\sigma} f_{\mathrm{k}\sigma} \right) + U \sum_i n_{f,i\uparrow} n_{f,i\downarrow}$$

Mean field solution

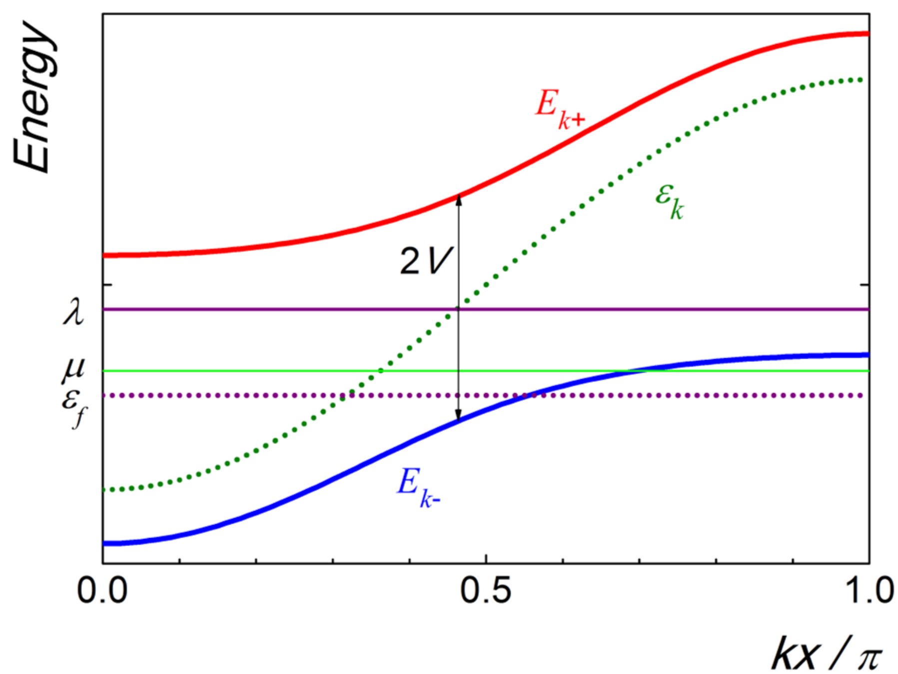
$$E_{\mathrm{k}\pm} = \frac{1}{2}\left\{ \varepsilon_{\mathrm{k}} + \lambda \pm \sqrt{(\varepsilon_{\mathrm{k}} - \lambda)^2 + 4V^2} \right\}, \quad V = z^{1/2} V_0$$

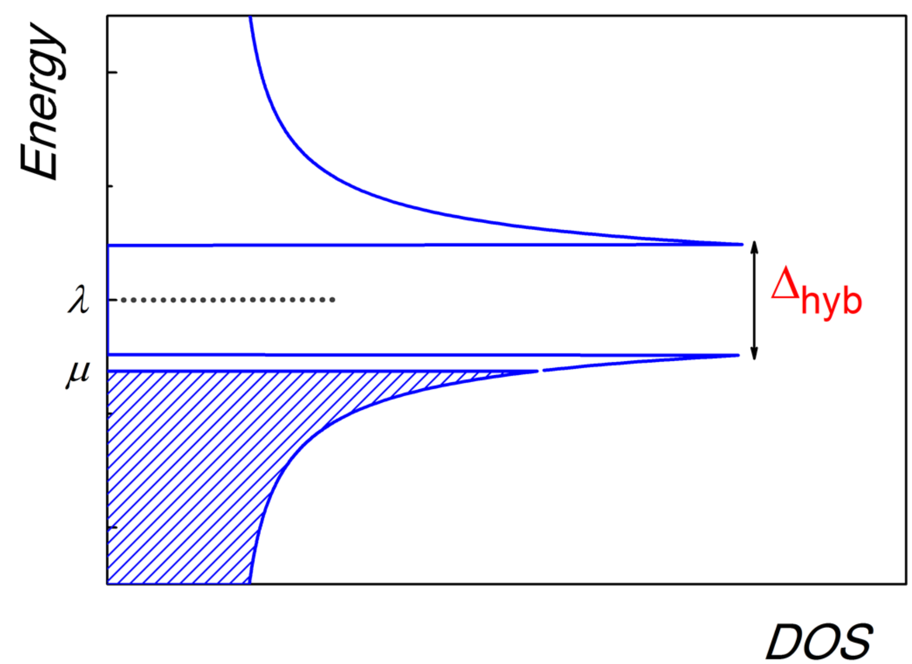
μ: chemical potential

λ : renormalized f-level

V: renormalized hybridization amplitude

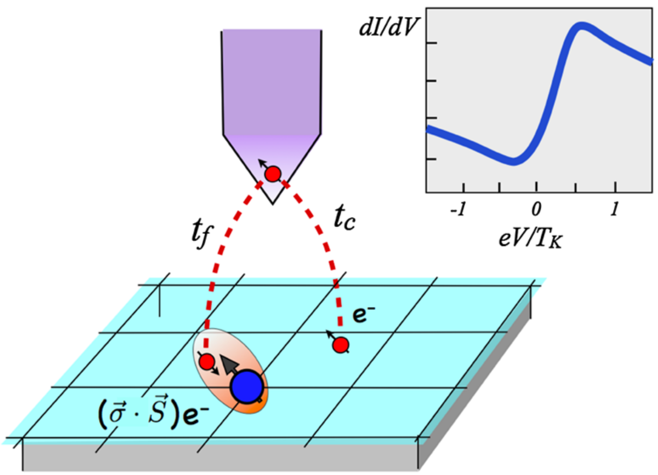
z = 1- n_f (n_f: occupancy)

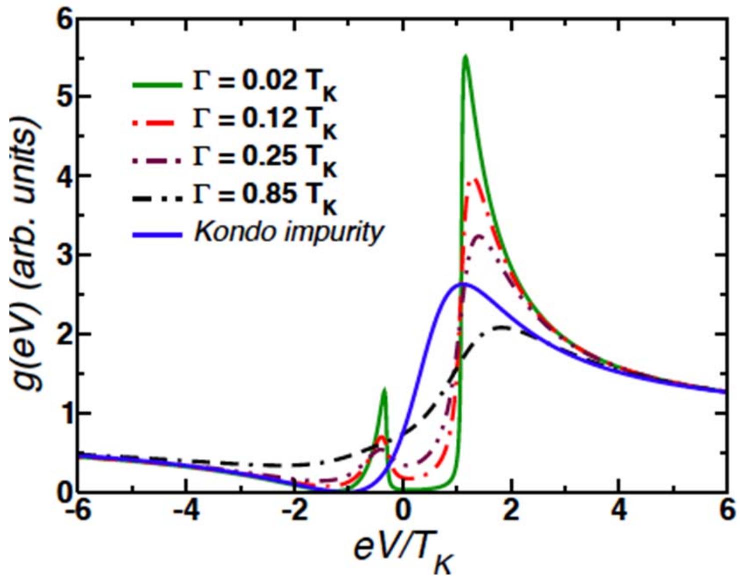




Electron co-tunneling in a Kondo Lattice

Provides a model to account for transport / tunneling – taking itinerant and re-normalized f-electron band



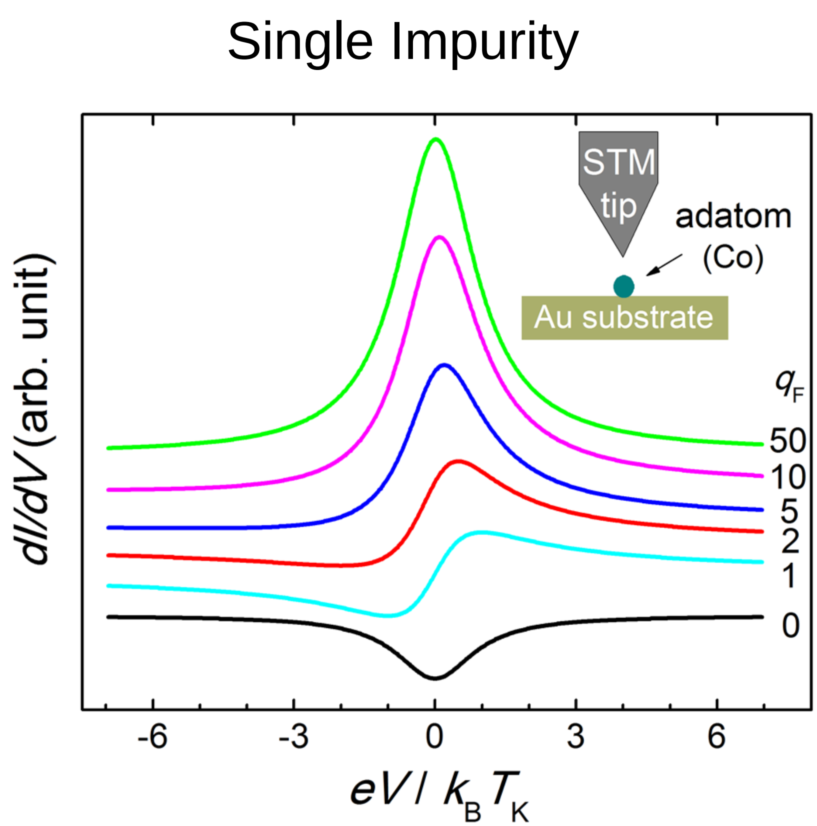


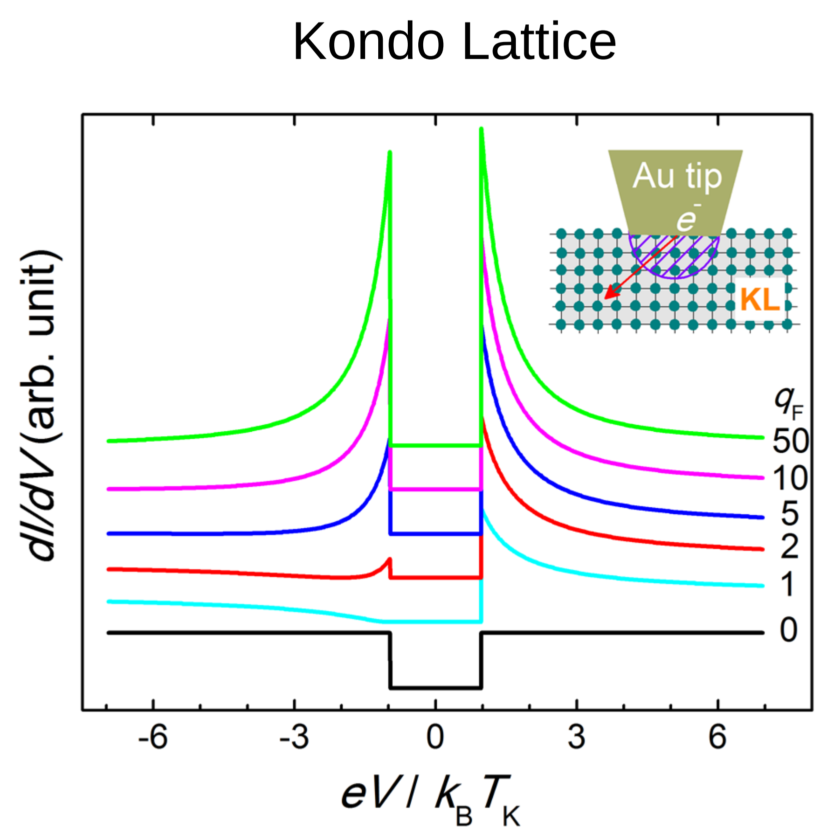
Single-impurity:
Fano ineshape

Kondo lattice hybridization gap:
Double peak

Maltseva, Dzero, Coleman, PRL (09)

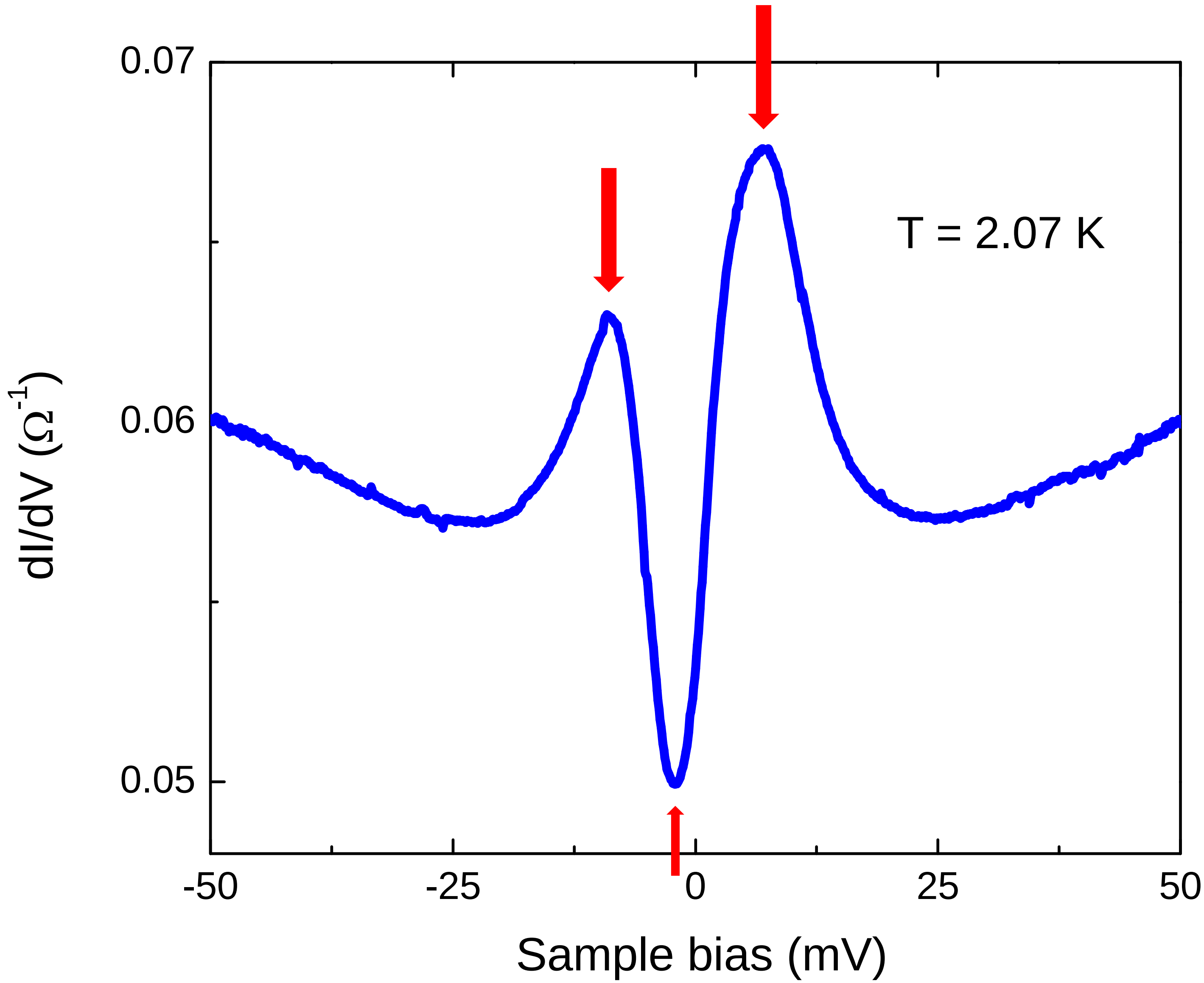
Fano Resonance: Single Impurity vs. Kondo Lattice



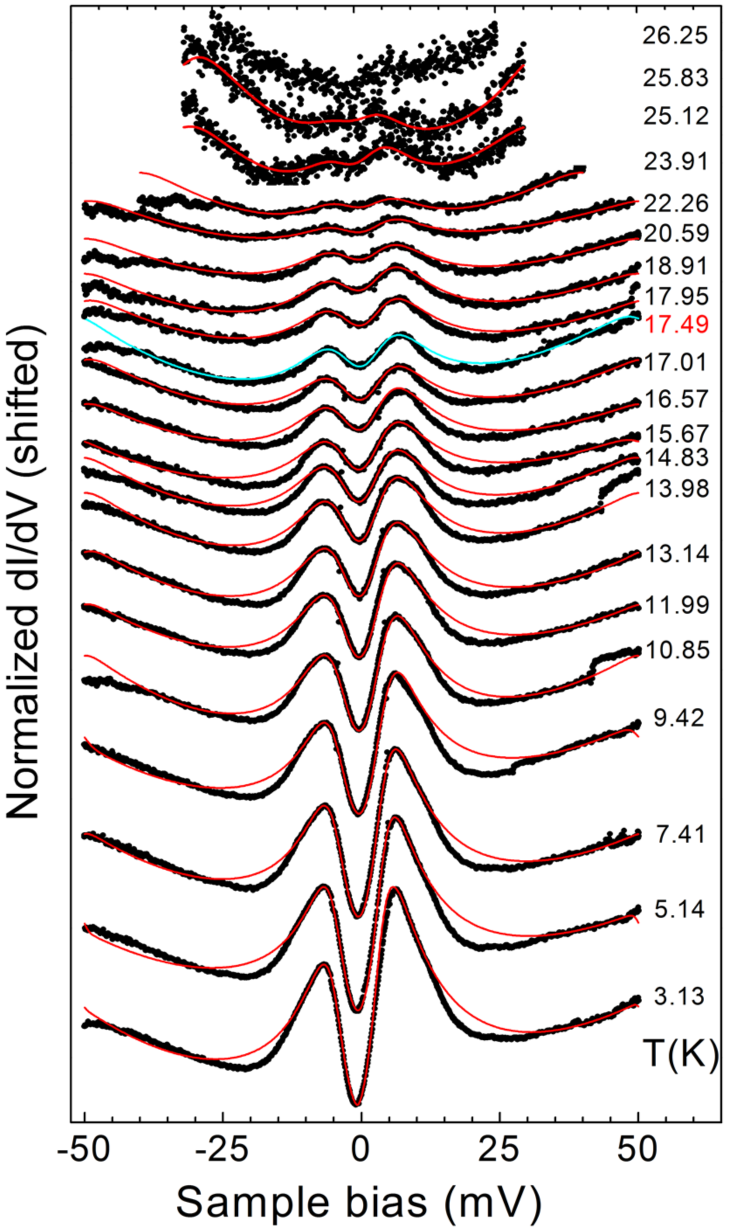


- A distinct double-peak structure in a Kondo lattice: signature of a hybridization gap, distinguishable from a single impurity Fano resonance.
- Asymmetry due to interference between renormalized heavy bands and conduction band.

Typical Conductance Data



Temperature Dependence



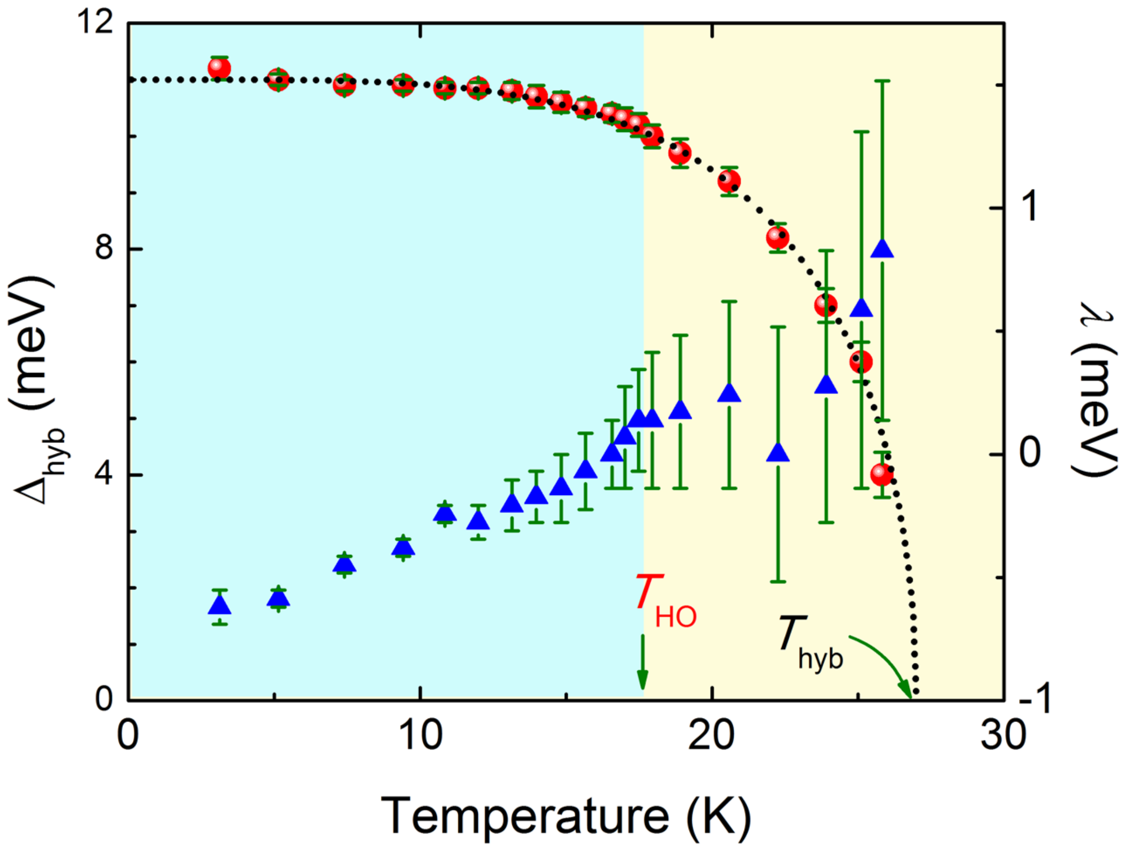
- Is this hybridization gap the long-thought hidden order parameter?

→ The answer lies in the temperature dependence.

T_{HO}

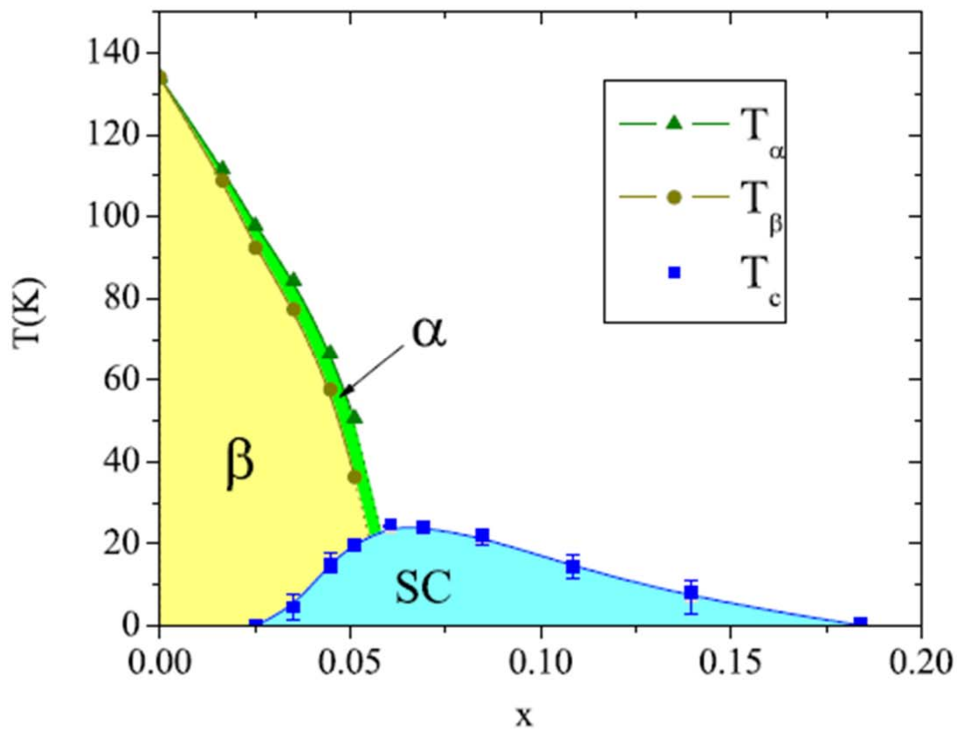
- Conductance spectra (filled circles) along with fitted curves (solid lines). Top three curves on a magnified vertical scale.
- The double-peak structure persists well above T_{HO}.

Hybridization Gap

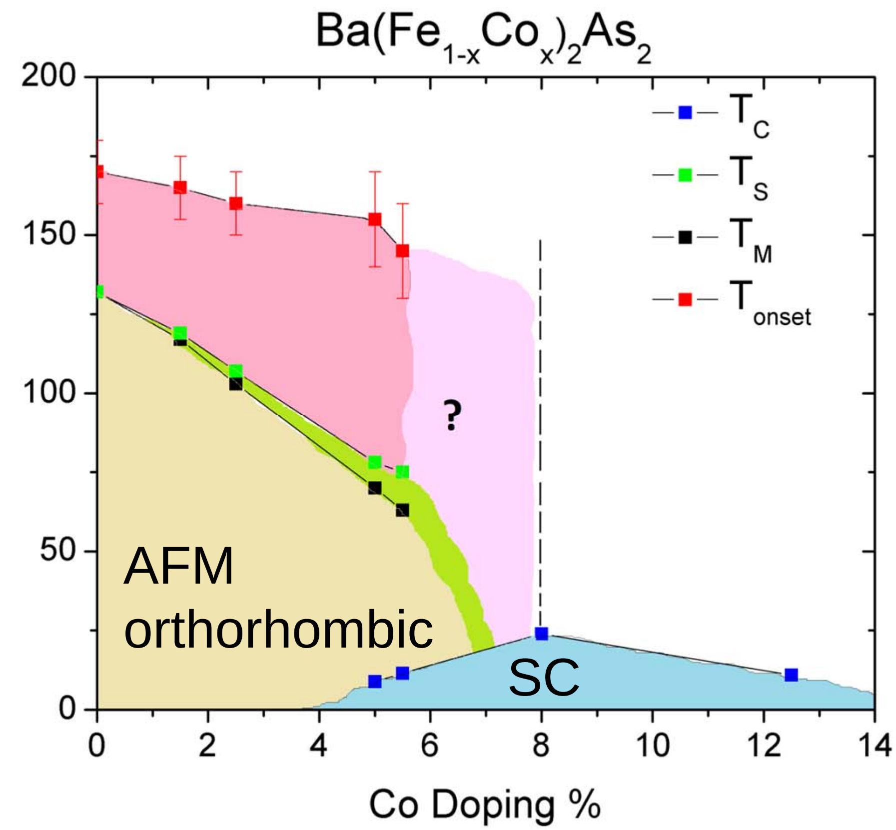


- Hybridization gap opening temperature T_{hyb} = 27 K >> T_{HO}.
- Δ_{hyb} is unlikely to be the hidden order parameter, as opposed to recent theoretical claims.
- Renormalized *f*-level shows characteristic temperature dependence. Crossing the chemical potential at T_{HO}?

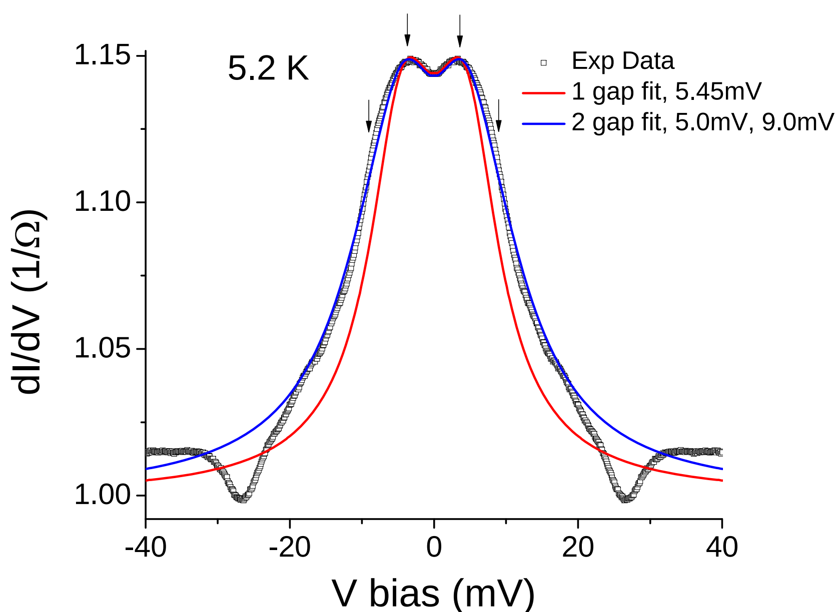
FINALLY: Measurement of ordering in the normal state of underdoped $Ba(Fe_{1-x}Co_x)_2As_2$ and $Fe_{1+y}Te$

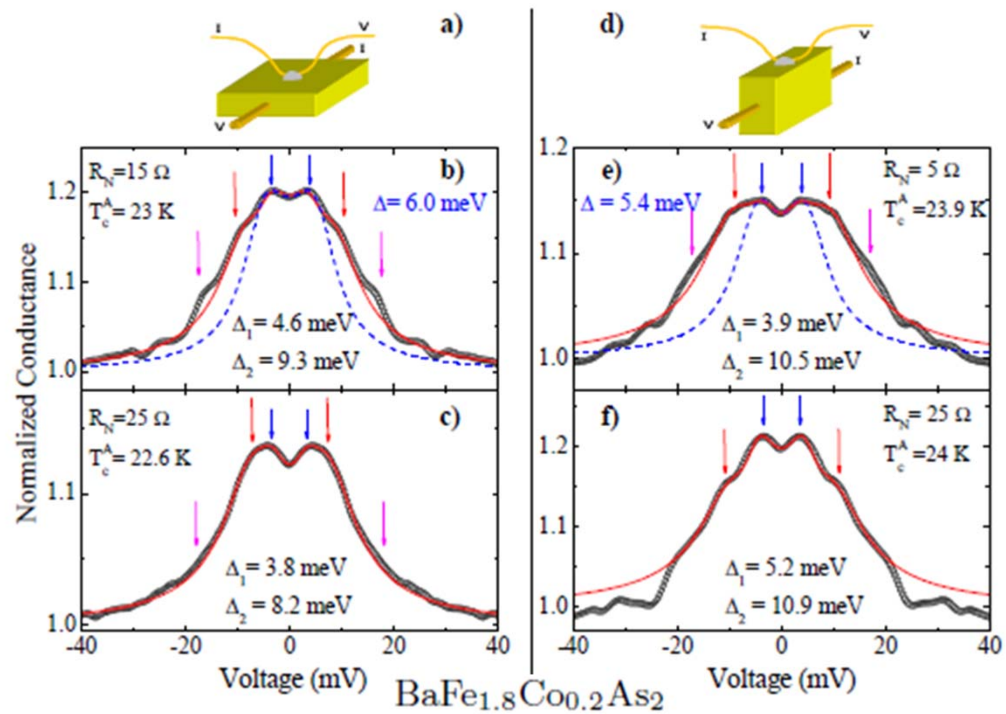


Chu *et al.* PRB **79**, 014506 (2009)



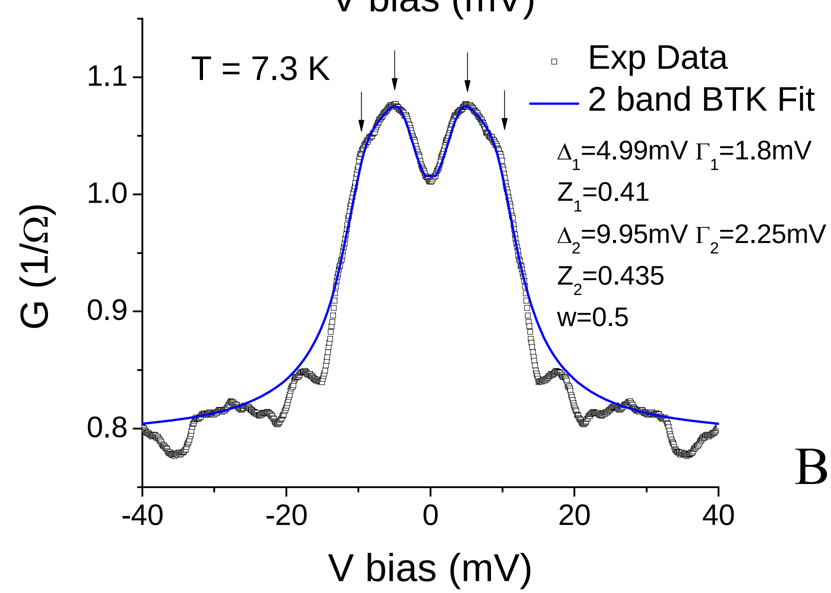
Agreement with published data for $T<T_c$





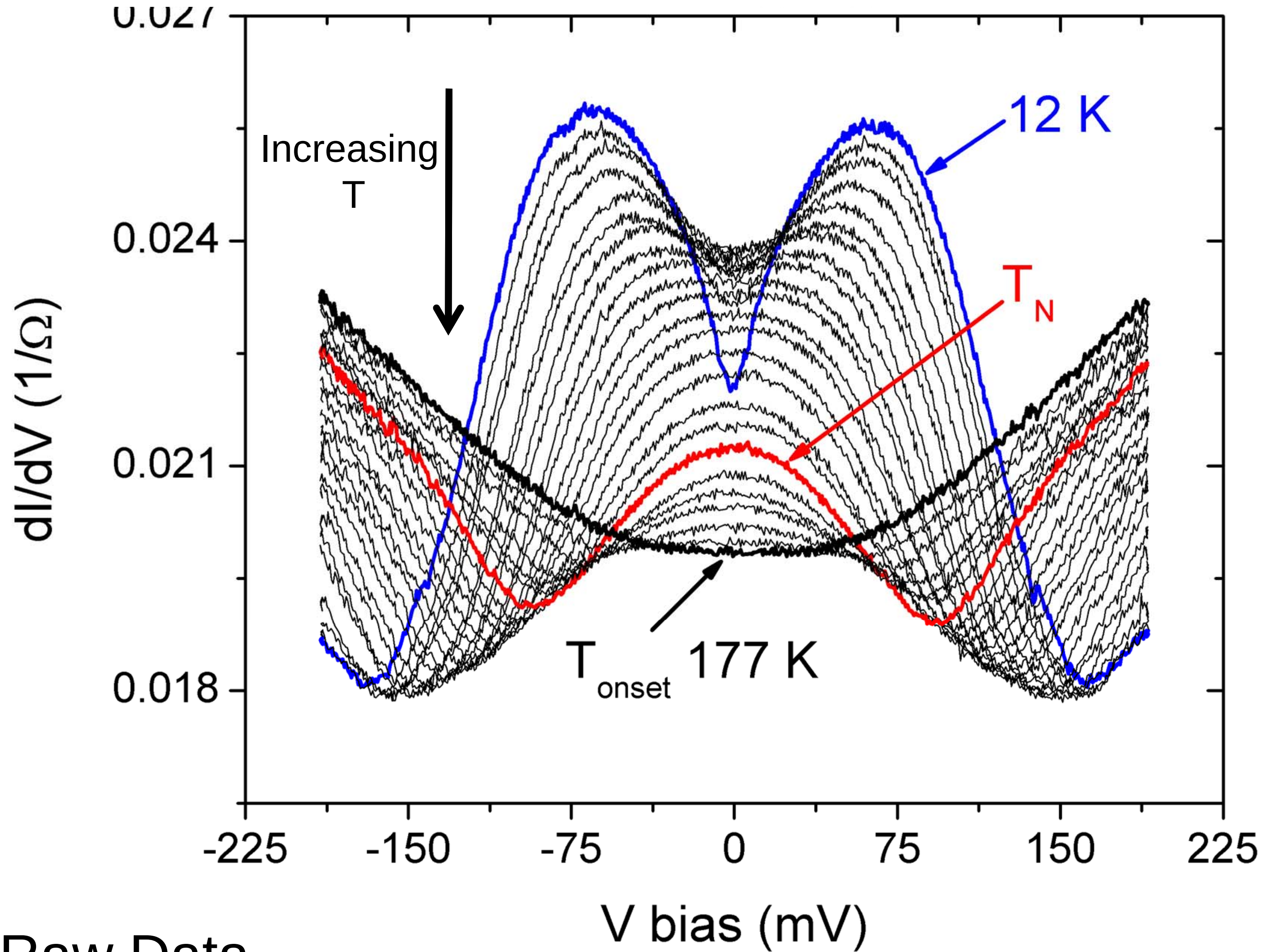
Normalized conductance curves at 4.2 K

Tortello *et al.* PRL **105**, 237002 (2010)

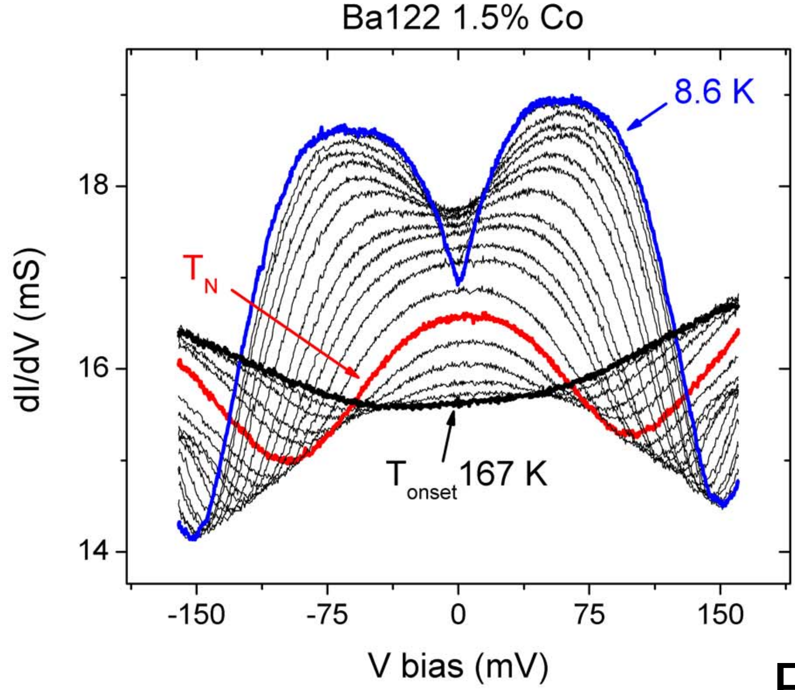


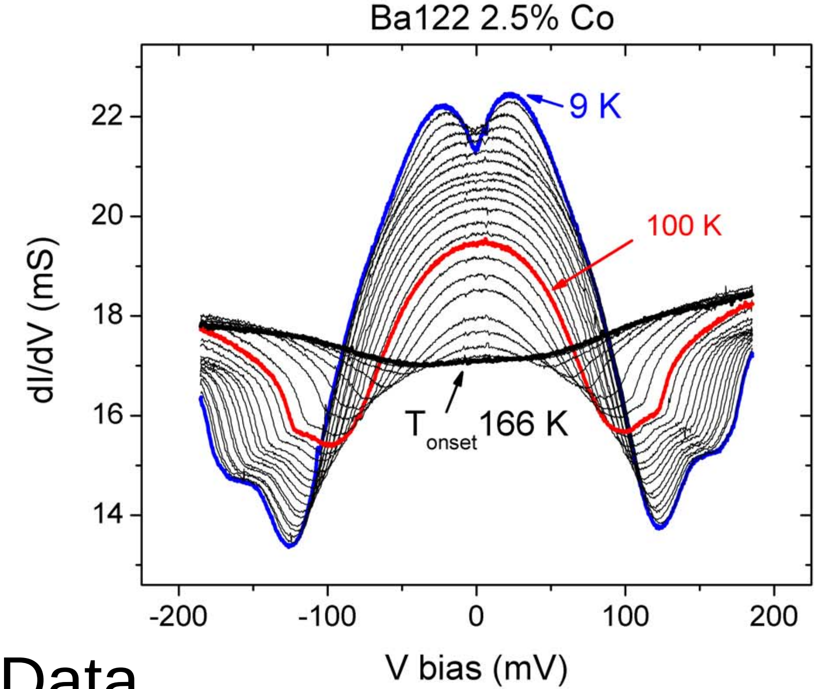
$Bα(Φε_{0.92}Χο_{0.08})_2Ασ_2$

PCS on Parent Compound: $BaFe_2As_2$

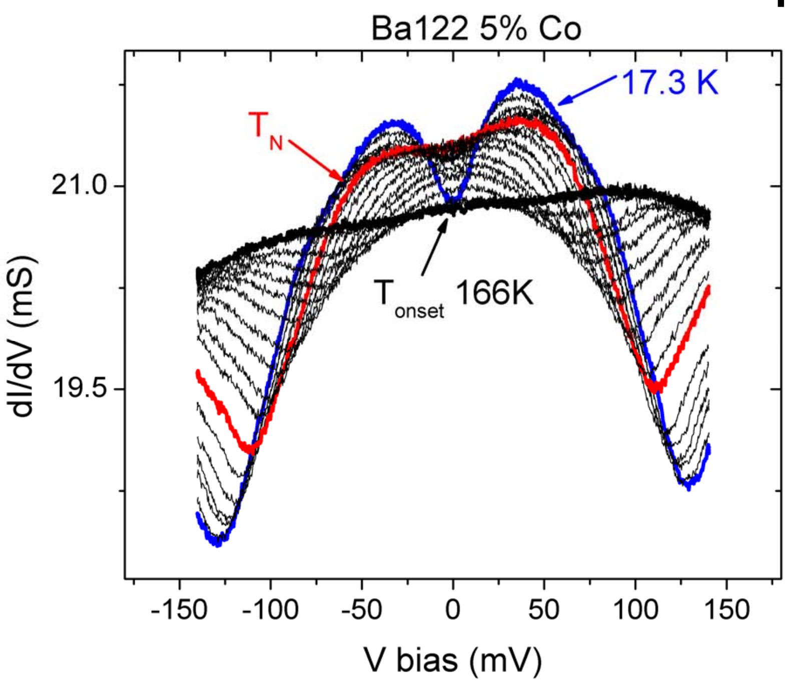


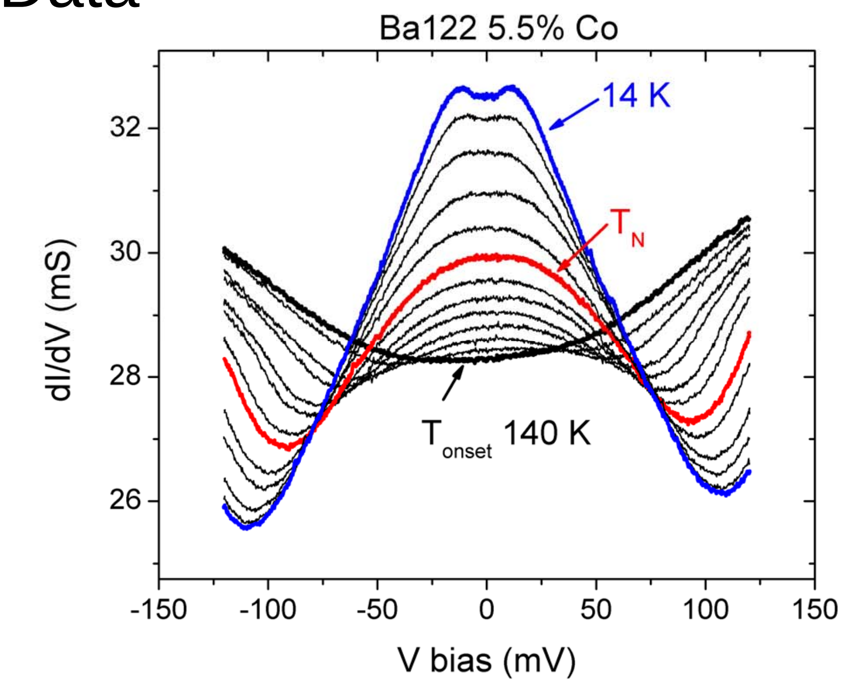
Raw Data


Ba122 1.5% Co
8.6 K
T_N
T_onset 167 K
dI/dV (mS)
V bias (mV)
14
16
18
-150
-75
0
75
150

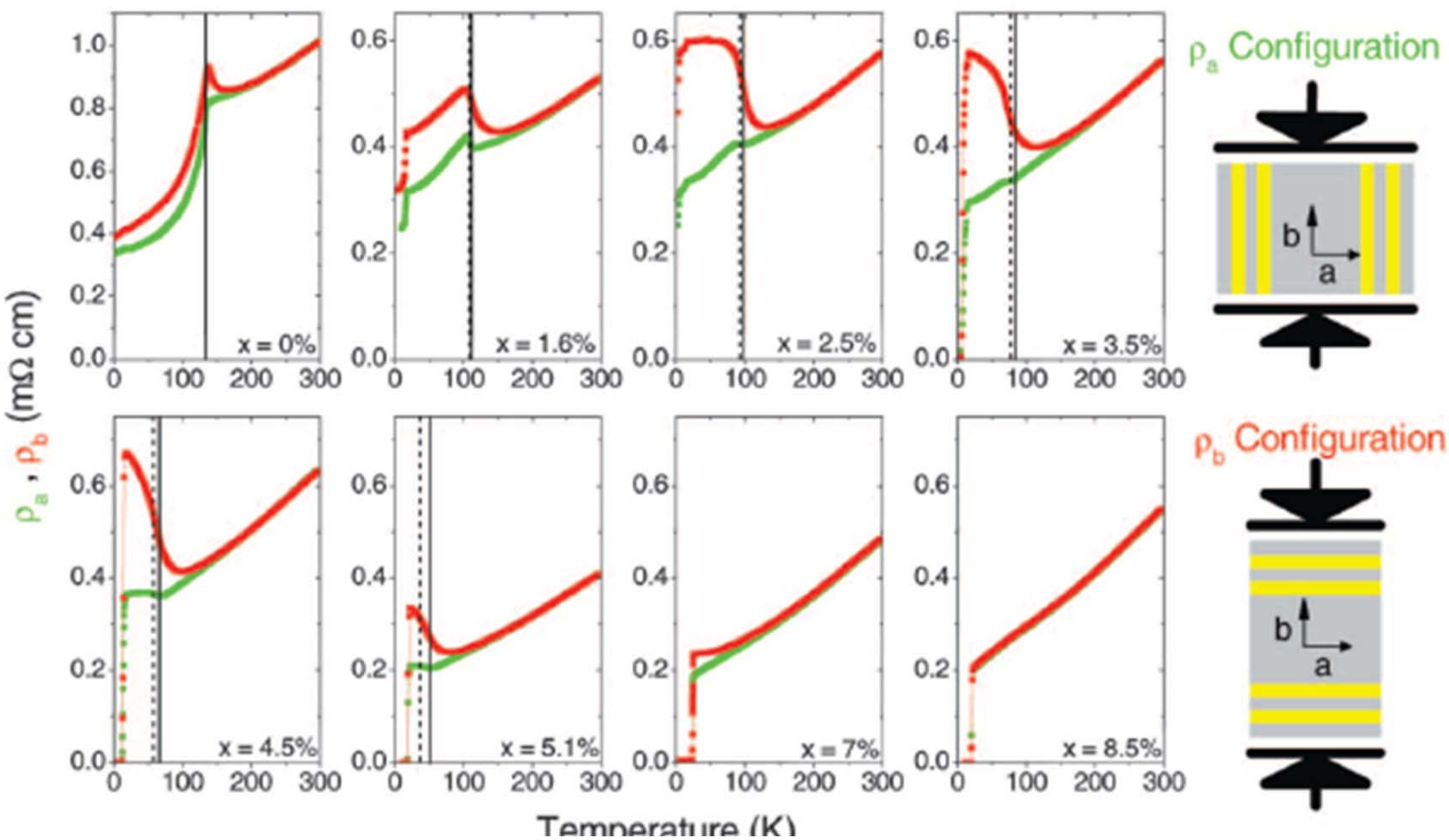

Ba122 2.5% Co
9 K
100 K
T_onset 166 K
dI/dV (mS)
V bias (mV)
14
16
18
20
22
-200
-100
0
100
200

Raw Data


Ba122 5% Co
17.3 K
T_N
T_onset 166K
dI/dV (mS)
V bias (mV)
19.5
21.0
-150
-100
-50
0
50
100
150

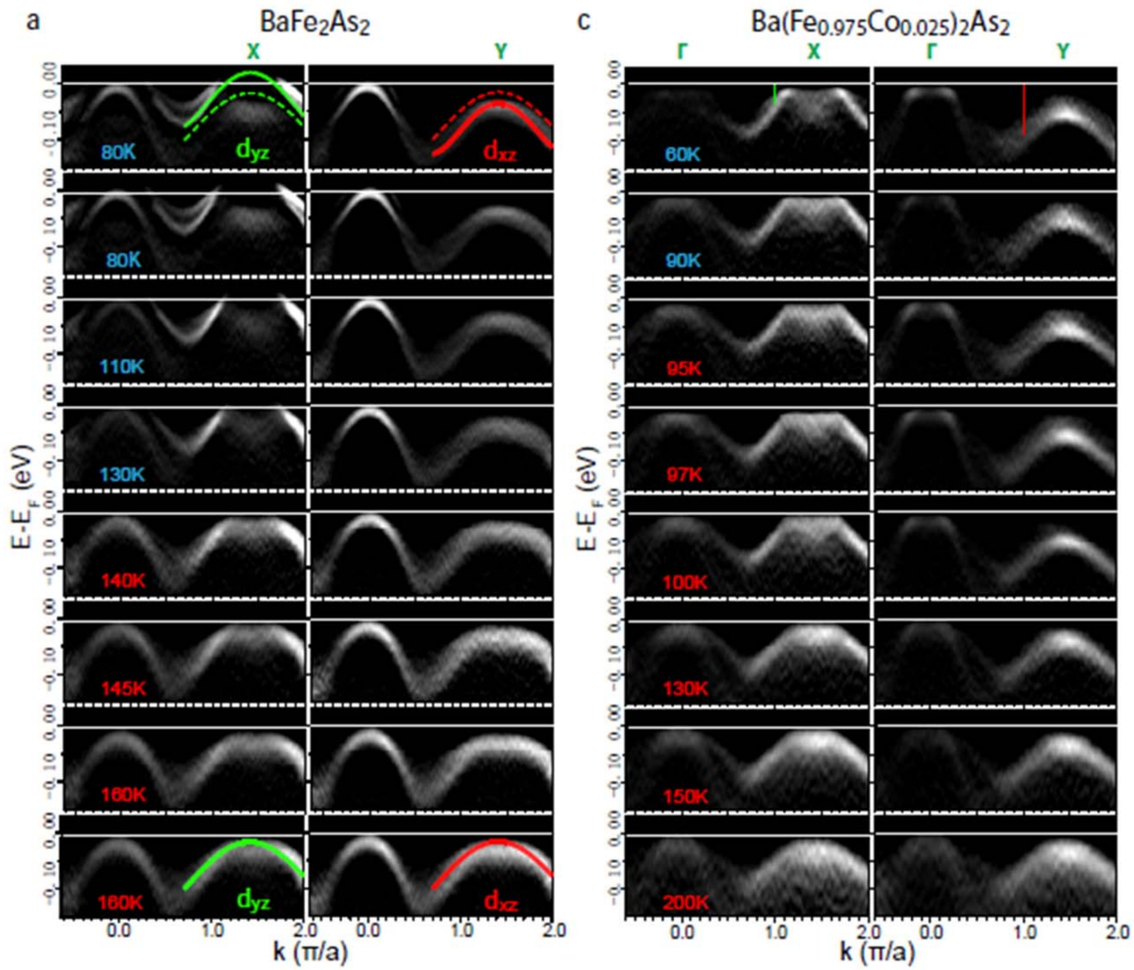

Ba122 5.5% Co
14 K
T_N
T_onset 140 K
dI/dV (mS)
V bias (mV)
26
28
30
32
-150
-100
-50
0
50
100
150

Electronic Orthorhombicity



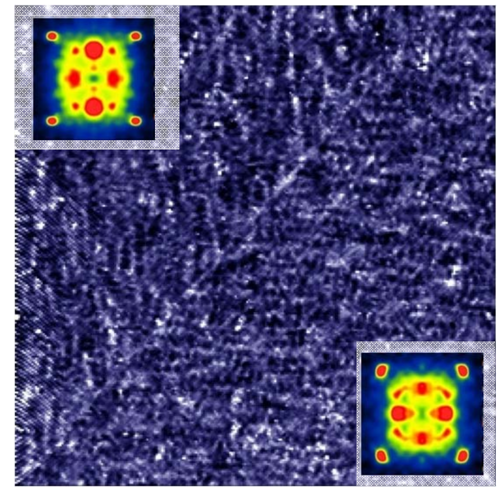
Fisher Group: Science **329**, 824 (2010).

ARPES



Shen Group:
arXiv:1011.0050v1

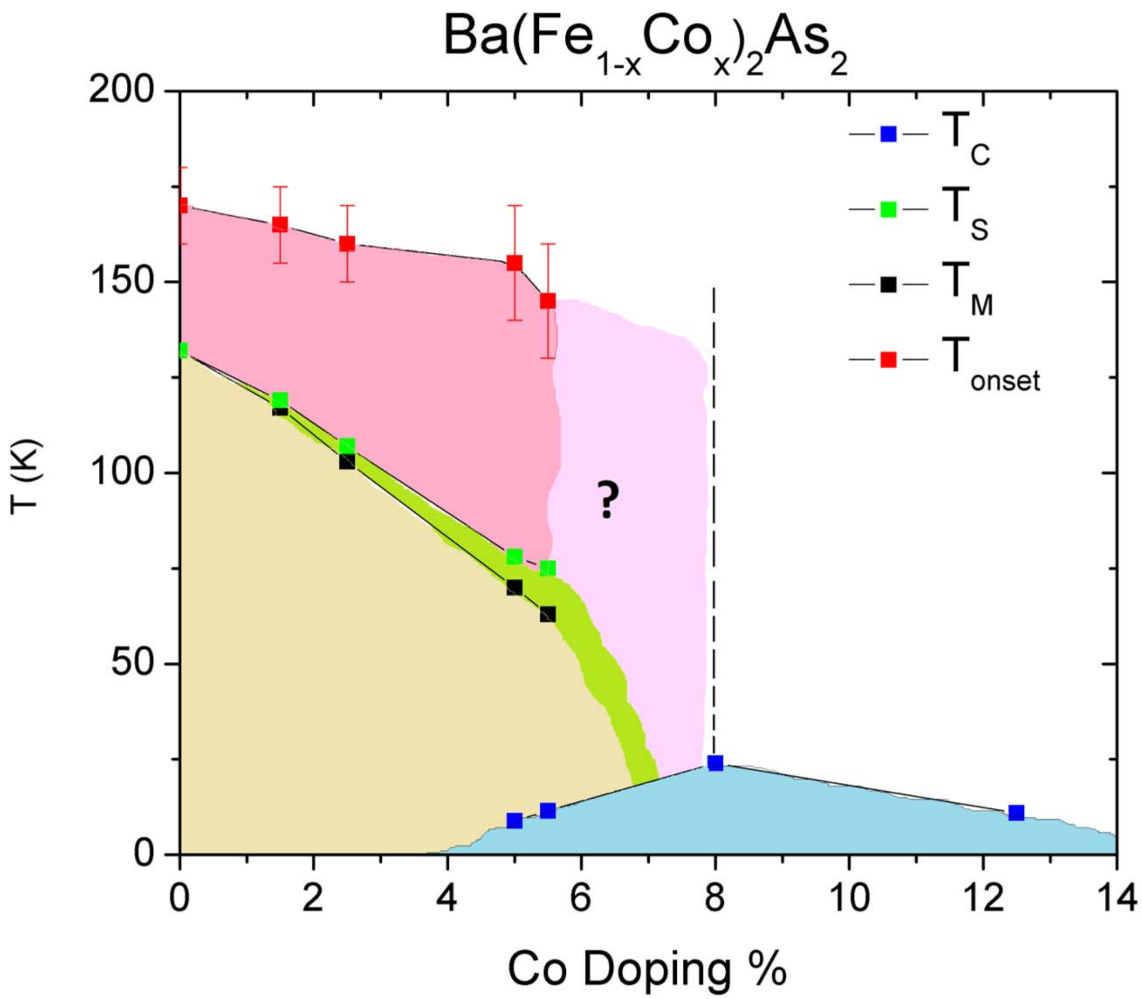
STM



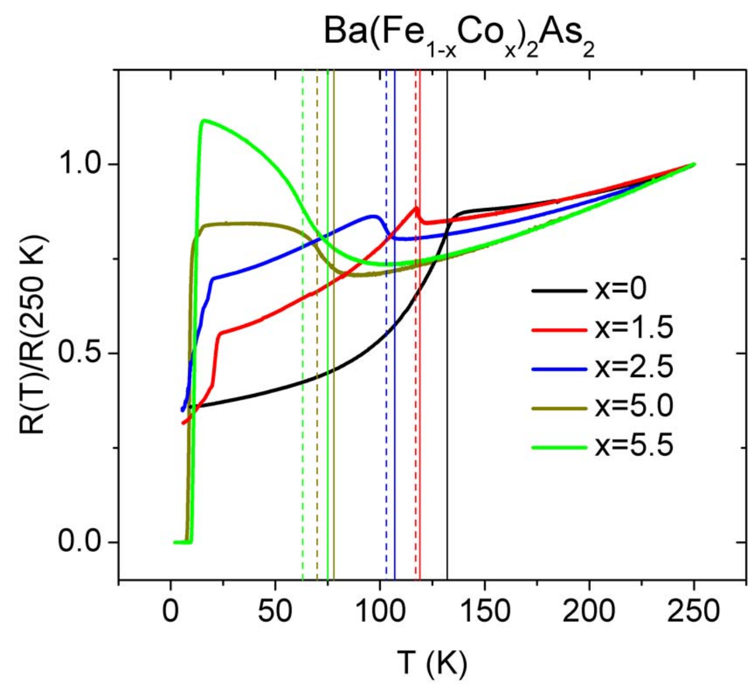
Davis Group: Science 327, 181 (2010)

PCS
sensitive to orbital ordering?

New line in the Phase Diagram



T_S, T_M determined from peaks in –dR/dT



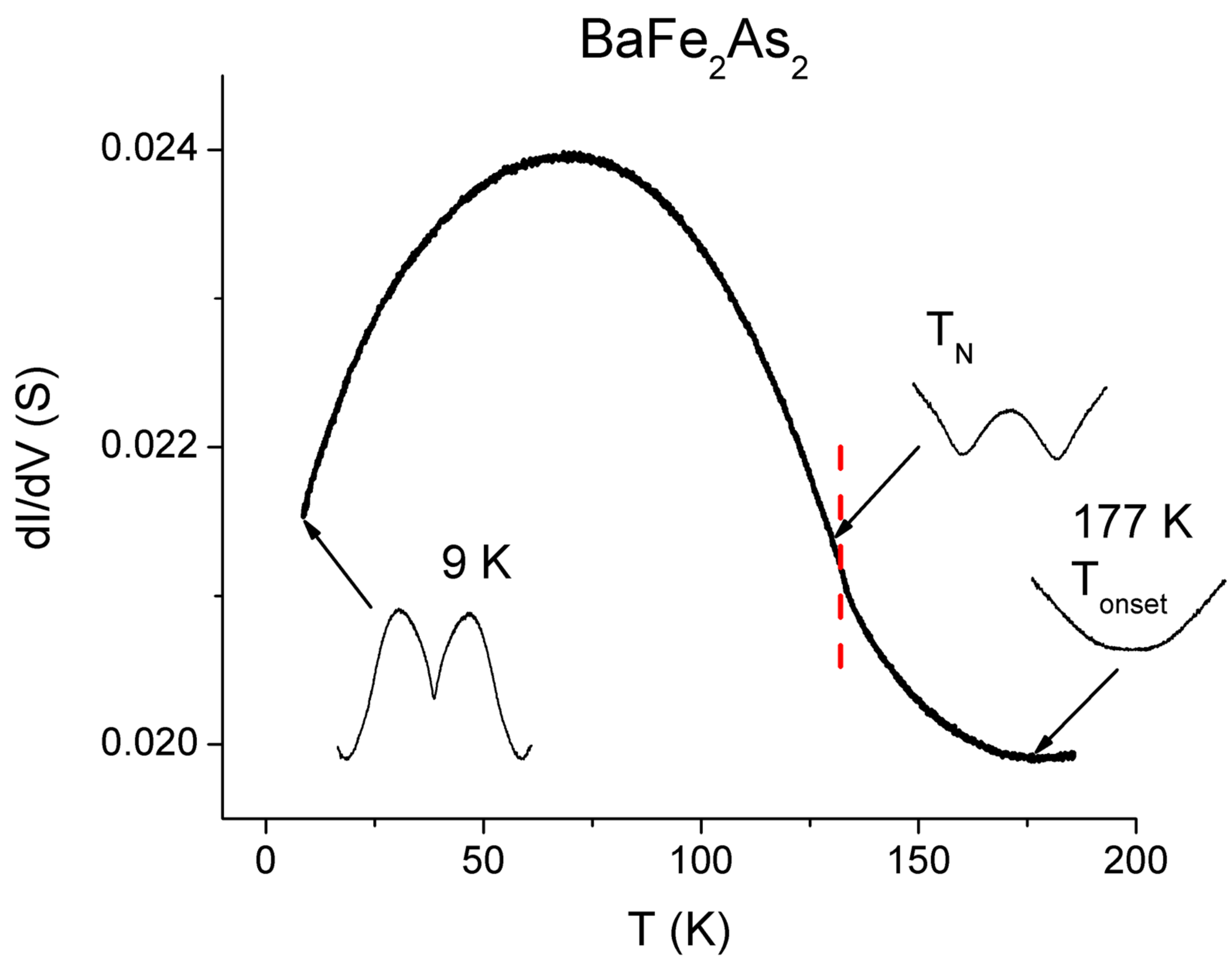
Quasiparticle scattering / Point Contact Spectroscopy

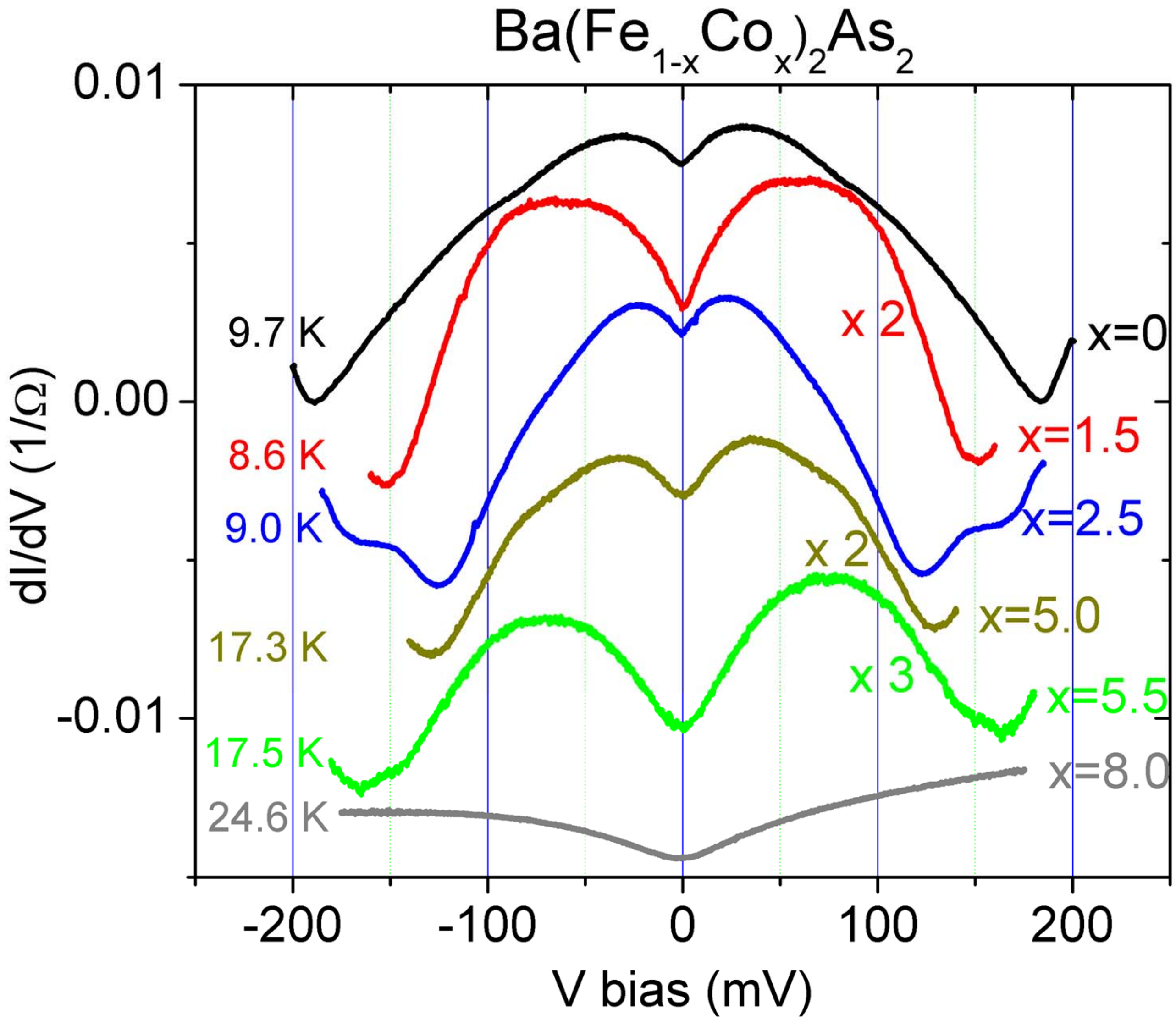
1. Superconductivity (intro):
   Gap, order parameter symmetry, density of state, … this is well understood in the framework of BTK and Andreev reflection.
2. Kondo Impurity / Kondo Lattice effects (intro):
   Fano lineshape consistent with the growth of the Kondo liquid (starts at T*, and grows until Tc): microscopic explanation?
3. Antiferromagnetic ordering (intro):
   Conductance enhancement at T_N in some AF systems (not all)

4. **The hybridization gap & Fano resonance in a heavy fermion This talk**: Helps explain #2.
5. **Orbital ordering?**
   This talk: Enhancement at high-T in Co:$BaFe_2$As2and FeTeSe.

Thank You !

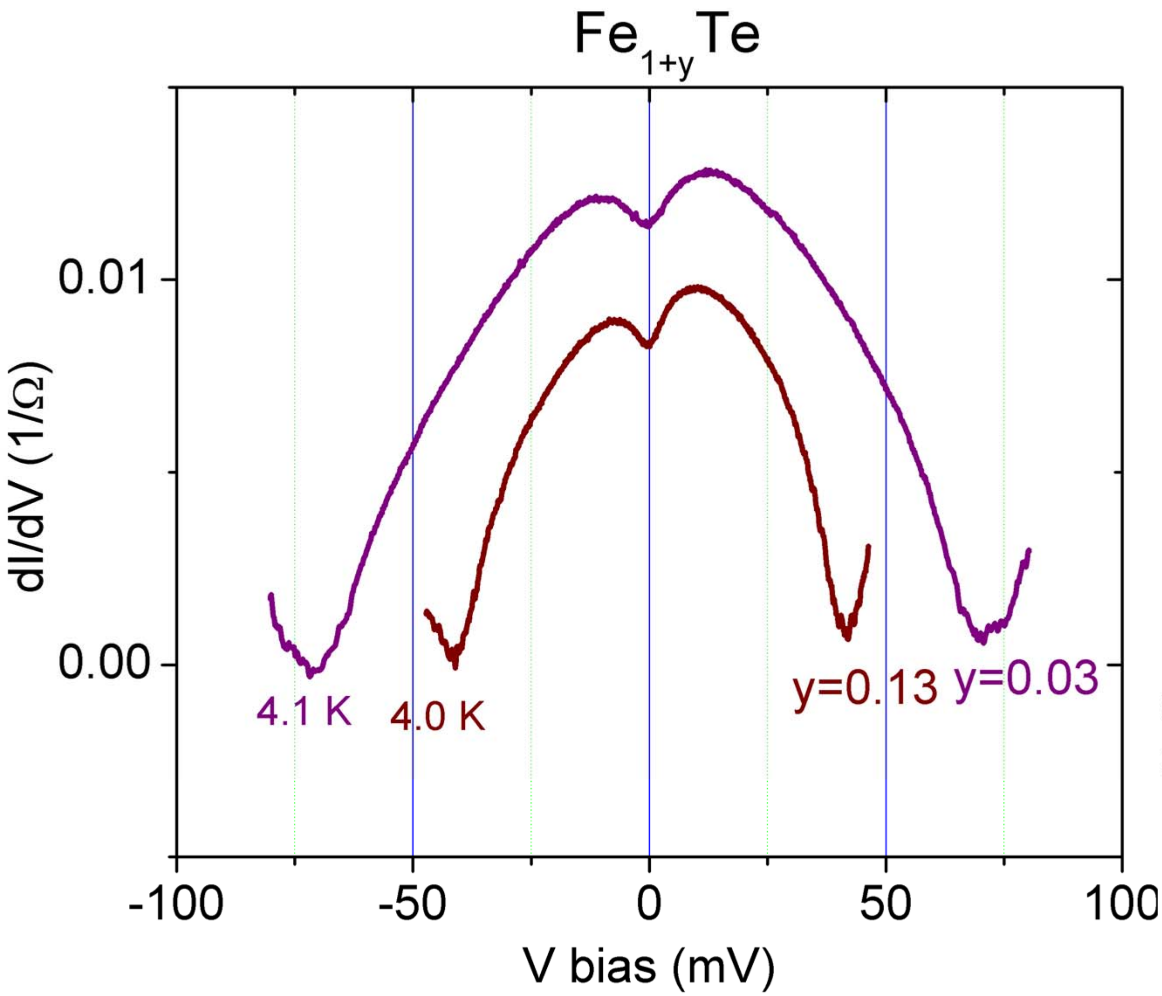
T_{onset} reflected in zero bias conductance

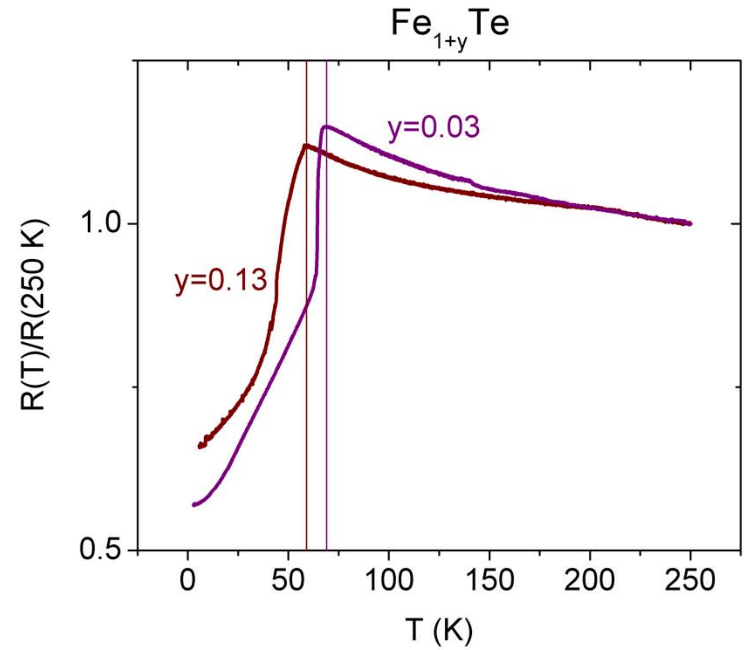


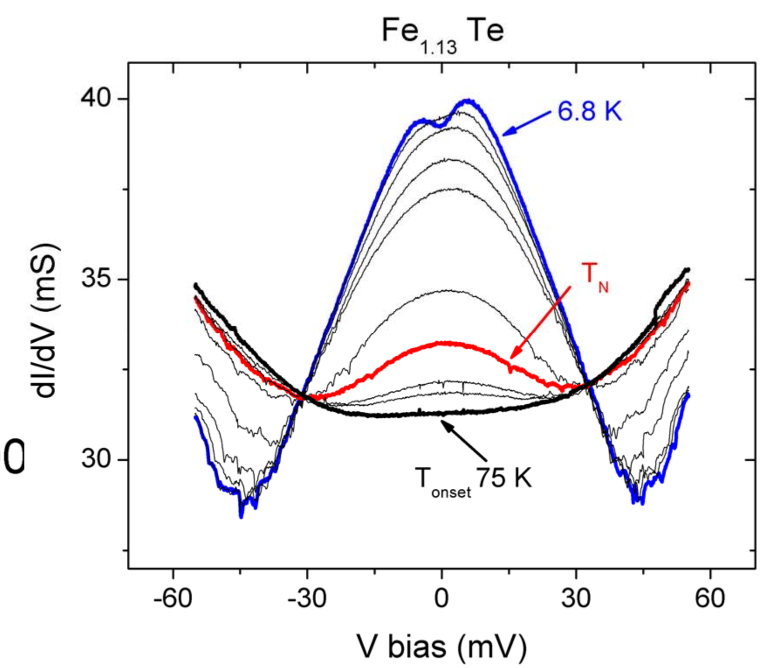


Similar spectra observed when Co doping is low enough for magnetic order to exist (underdoped regime)

$Fe_{1+y}Te$ shows similar curves







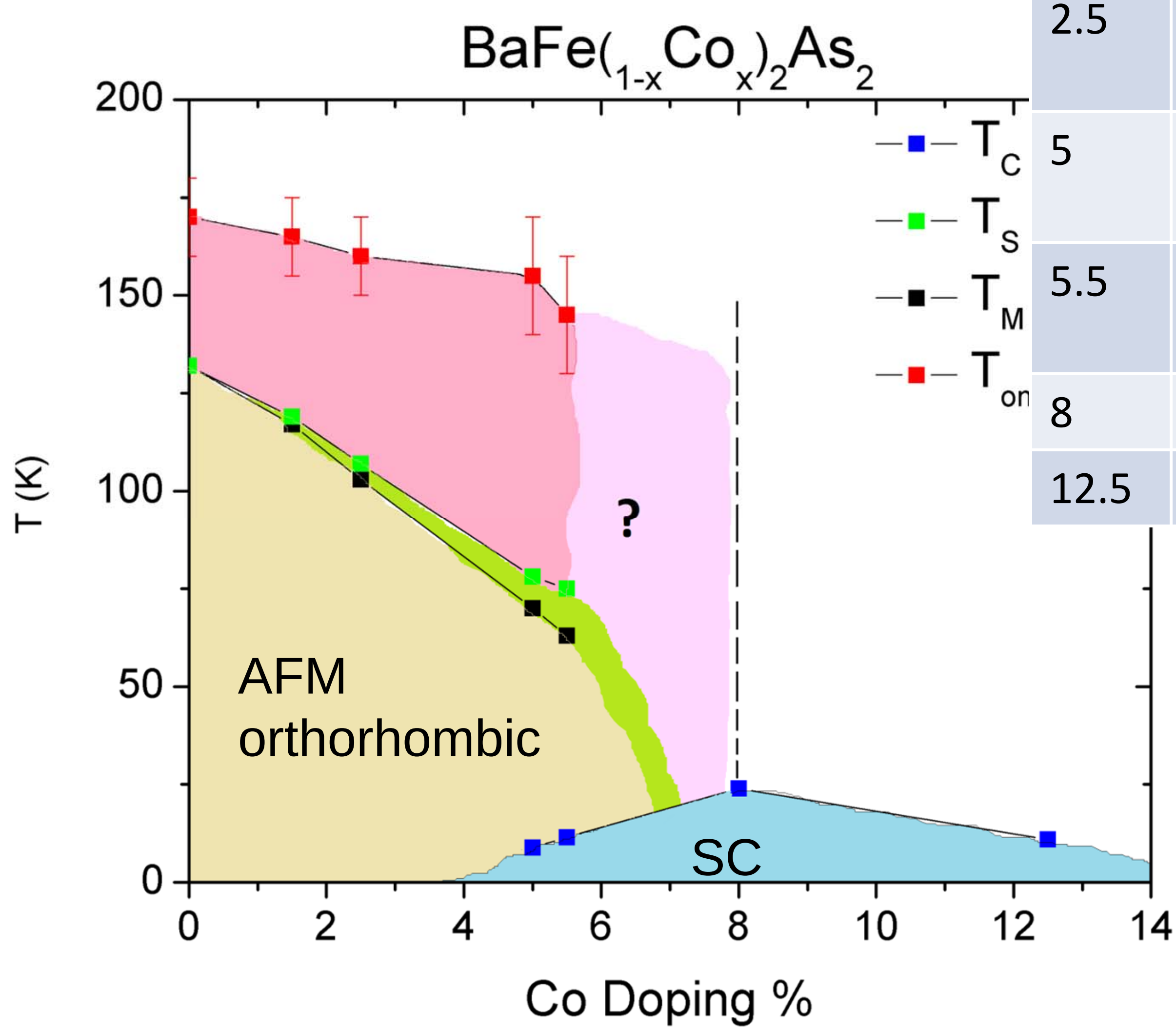
Other experimental techniques that have observed signals above T_S:

- **ARPES:** Splitting between the d_{xz} and d_{yz} bands that develops above the magnetic transition temperature. Yi et al. arXiv:1011.0050v1 (to be published PNAS)
- **Inelastic Neutron Scattering:** Anisotropic high energy spin excitations in the paramagnetic phase. Harriger et al. arXiv:1011.3771v1
- **Resistivity:** In-plane resistive anisotropy above T_S. *Chu et al.* Science 329, 824 (2010);
- **Optical Conductivity:** Anisotropic charge dynamics above T_S. Dusza et al. arXiv:1007.2543v1

These signals are attributed to unequal occupation of the d_{xz} and d_{yz} bands, leading to orbital ordering above T_M. The unequal occupation is speculated to occur due to spin excitations or some sort of instability preferring one band over the other.

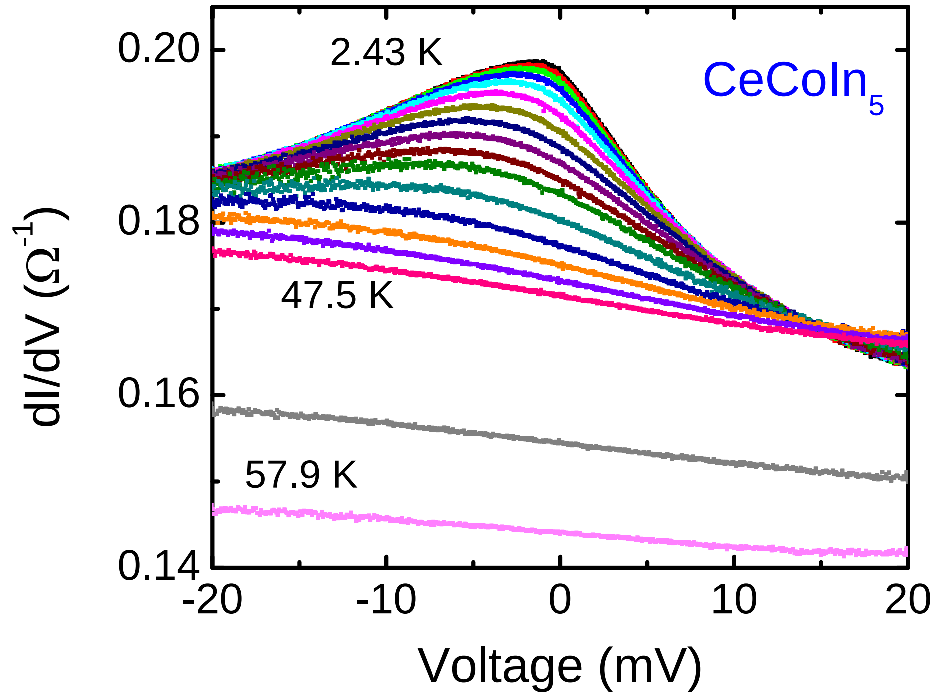
Modified Phase Diagram & Conclusion

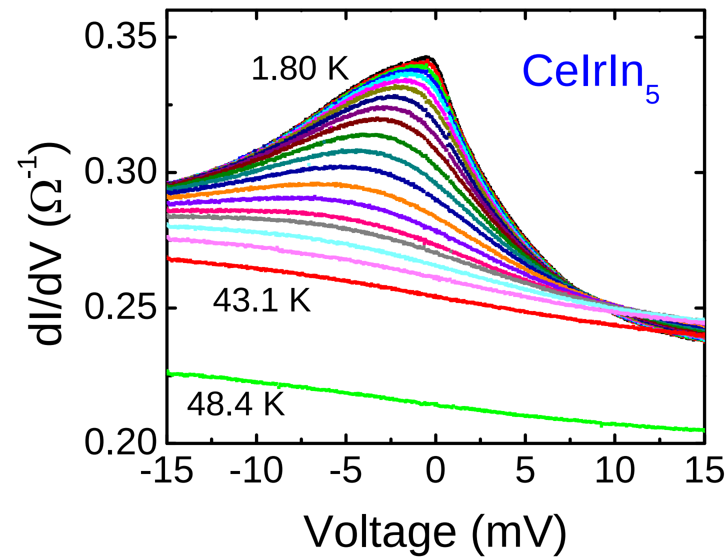
% Co	T_N	T_S	T_{onset}	T_{c_mid}
0	132 K	132 K	170±10 K	-
1.5	117 K	119 K	165±10 K	-
2.5	103 K	107 K	160±10 K	-
5	70 K	78 K	155±15 K	8.9 K
5.5	63 K	75 K	145±15 K	11.5 K
8	-	-		24 K
12.5			-	11 K

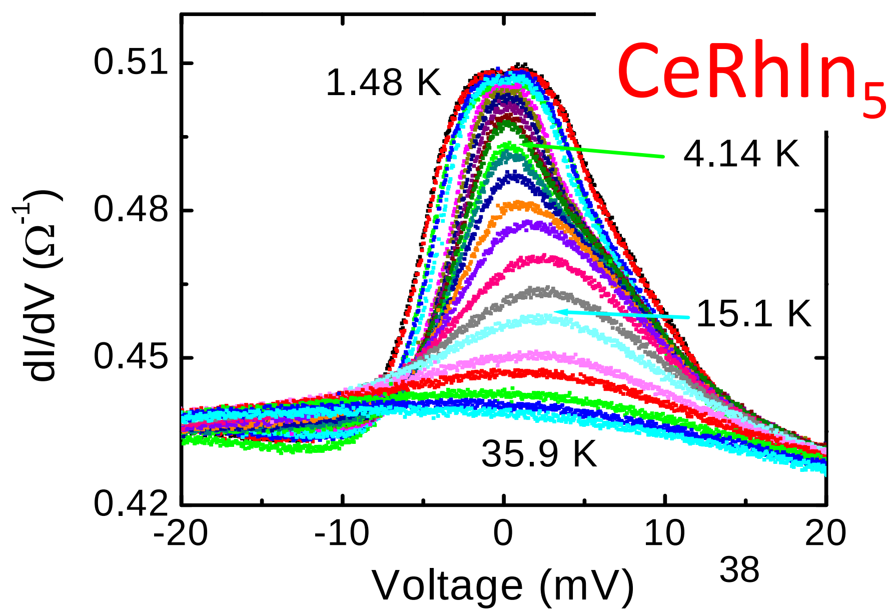


- PCS is detecting a signal only for samples with magnetism.
- However, the signal survives well above T_N.
- We speculate that orbital ordering might be responsible for our conductance spectra.

Antiferromagnetism (& Kondo): $CeMIn_5$







- Asymmetry: robust & reproducible in pure and Hg- & Cd-doped 1-1-5.
- Co: asymmetry follows HF spectral weight qualitatively (two-fluid model, Nakatsuji-Pines-Fisk).
- Rh: enhancement due to AFM

Quasiparticle Tunneling into a Kondo Lattice

PRL **103**, 206402 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

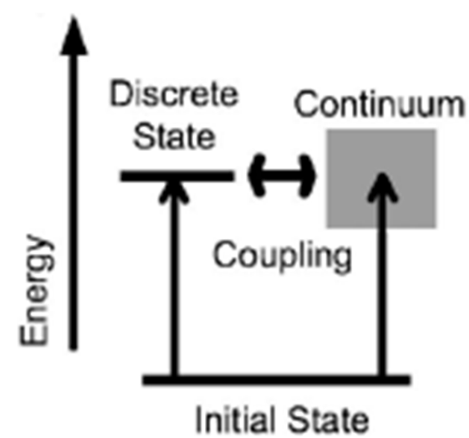
Electron Cotunneling into a Kondo Lattice

Marianna Maltseva, M. Dzero, and P. Coleman
Center for Materials Theory, Rutgers University, Piscataway, New Jersey 08854, USA

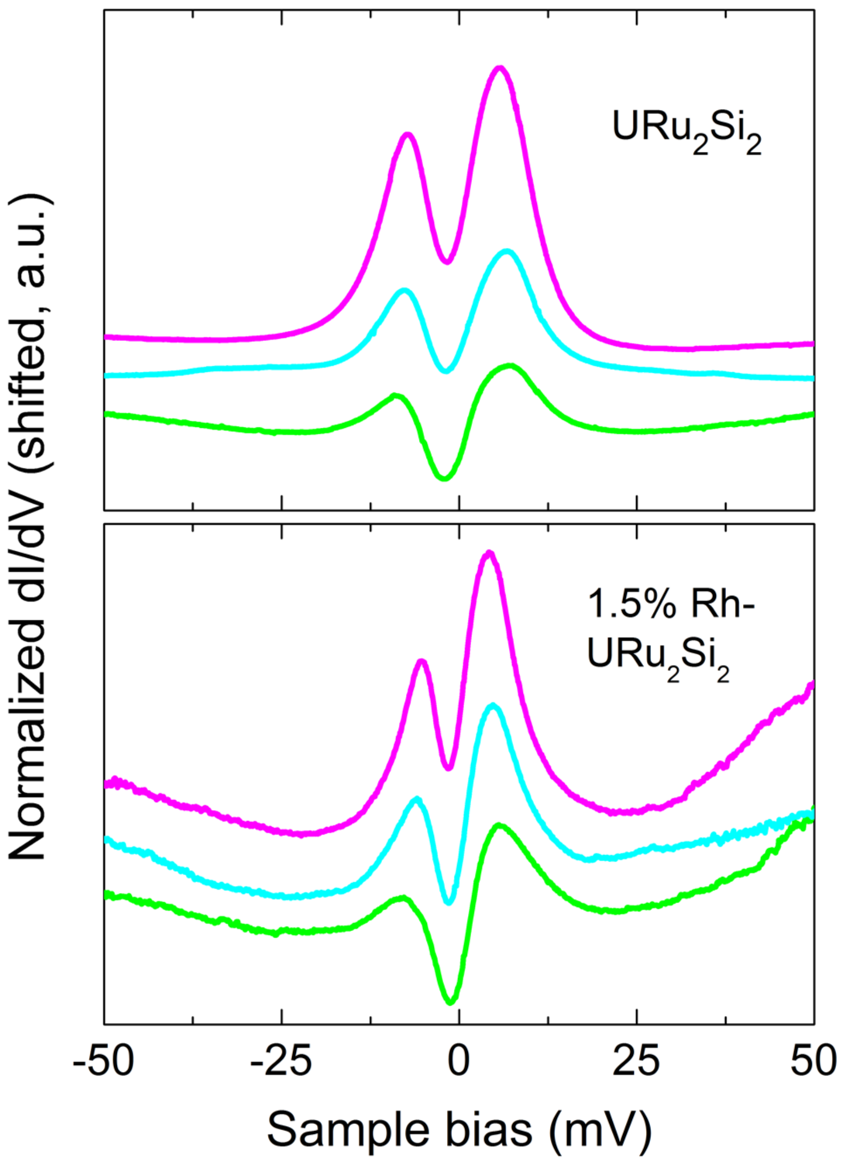
$$\left.\frac{dI}{dV}\right|_{FR} \propto \mathrm{Im}\,\tilde{G}_\psi^{KL}(eV);\ \tilde{G}_\psi^{KL}(eV) = \left(1+\frac{q_F W}{eV-\lambda}\right)^2 \ln\left[\frac{eV+D_1-\frac{V^2}{eV-\lambda}}{eV-D_2-\frac{V^2}{eV-\lambda}}\right]+\frac{2D/t_c^2}{eV-\lambda}$$

- q_F: Fano asymmetry parameter ($\equiv A/B$; A = probability for tunneling into heavy bands, B = into cond. band)
- $W = \pi N(0)V^2$: width of the Kondo resonance
- λ: renormalized f-level
- $-D_1$, D_2: cond. band edges; $2D = D_1 + D_2$: band width
- If $D_1 = D_2$, $\Delta_{hyb} = 2V^2 / D$ (hybridization gap)
- t_c: amplitude of direct tunneling into cond. band

Fano resonance!



Conjecture on a Fano Resonance

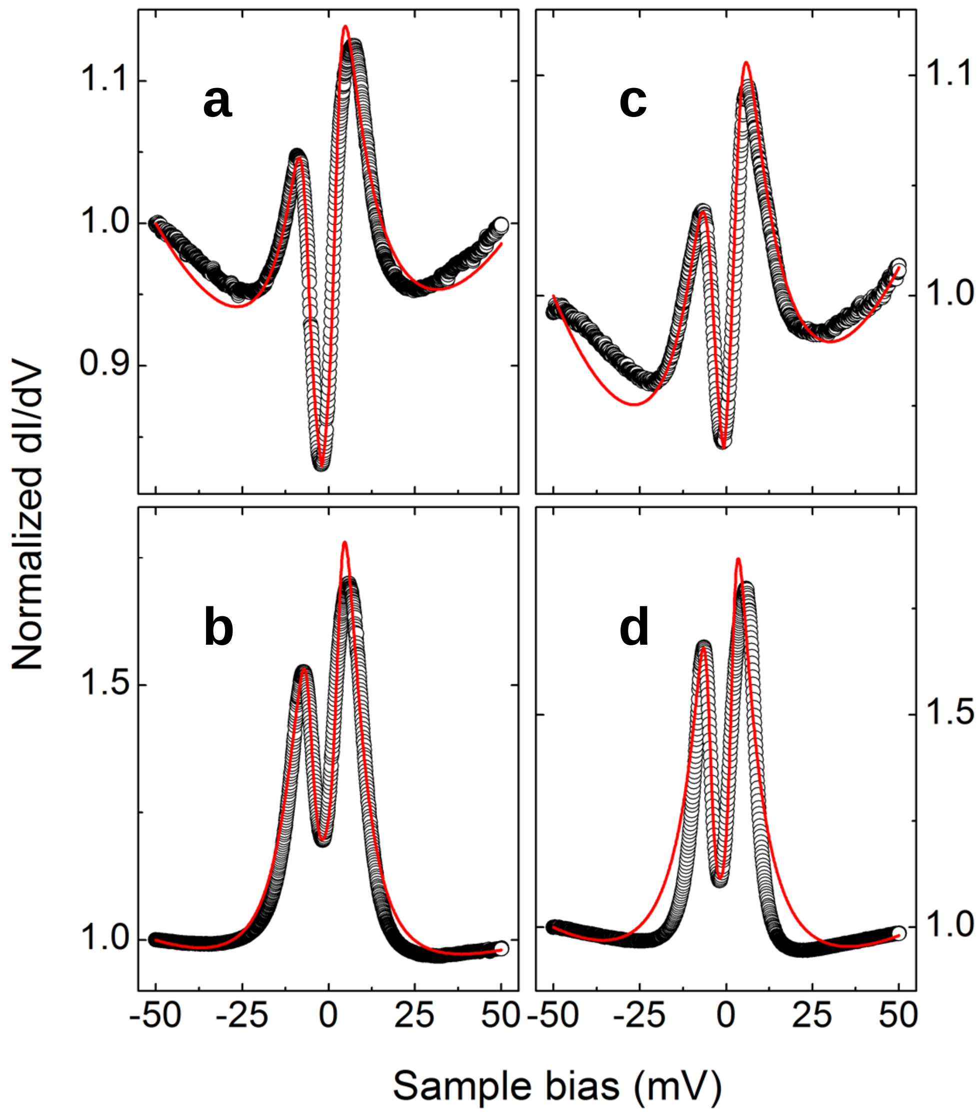


- Data taken from different junctions, showing a systematic variation.
- Asymmetric double-peak structure is reproducibly observed.
- Positive-bias conductance peak is always higher ($\Rightarrow q_F > 0$).
- V_{min} = -3 ~ -0.5 mV < 0 @ $T \ll T_{HO}$

$\Rightarrow$ These observations lead us to conjecture on a Fano resonance in a Kondo lattice, as predicted by Maltseva-Dzero-Coleman (PRL 2009).

- Interference between channels into the hybridized heavy bands (A) and the conduction band (B). $q_F \equiv A/B$.

Analysis Using a Fano Resonance Model



$$\frac{dI}{dV} = \left.\frac{dI}{dV}\right|_{FR} + \omega \cdot \left.\frac{dI}{dV}\right|_{bg}$$

Fano resonance (Maltseva et al., 2009)

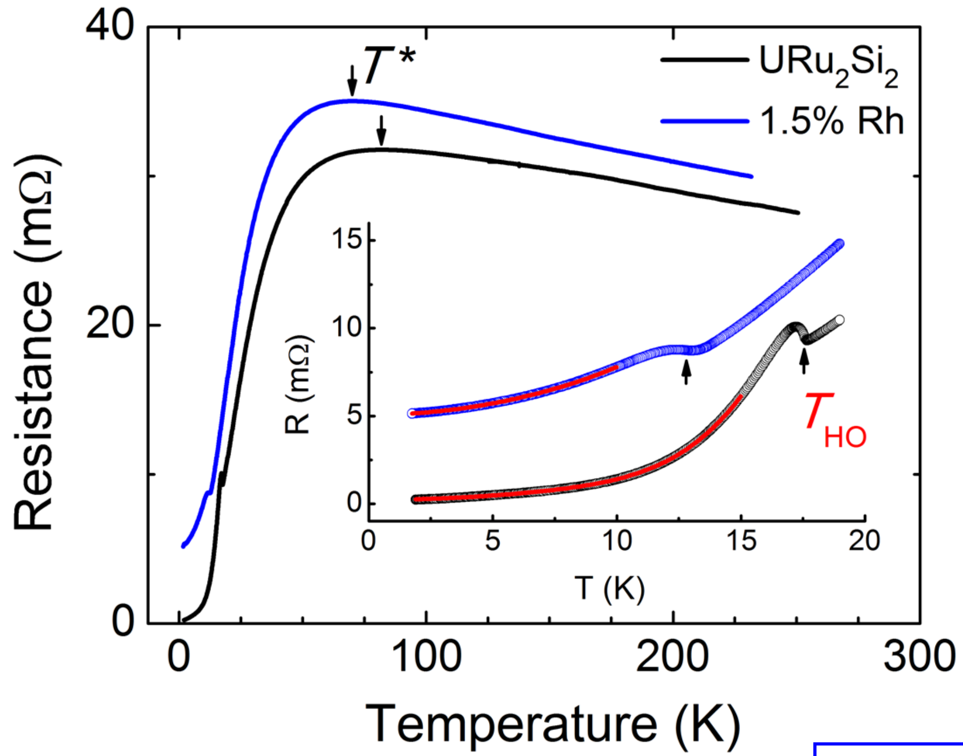
Background

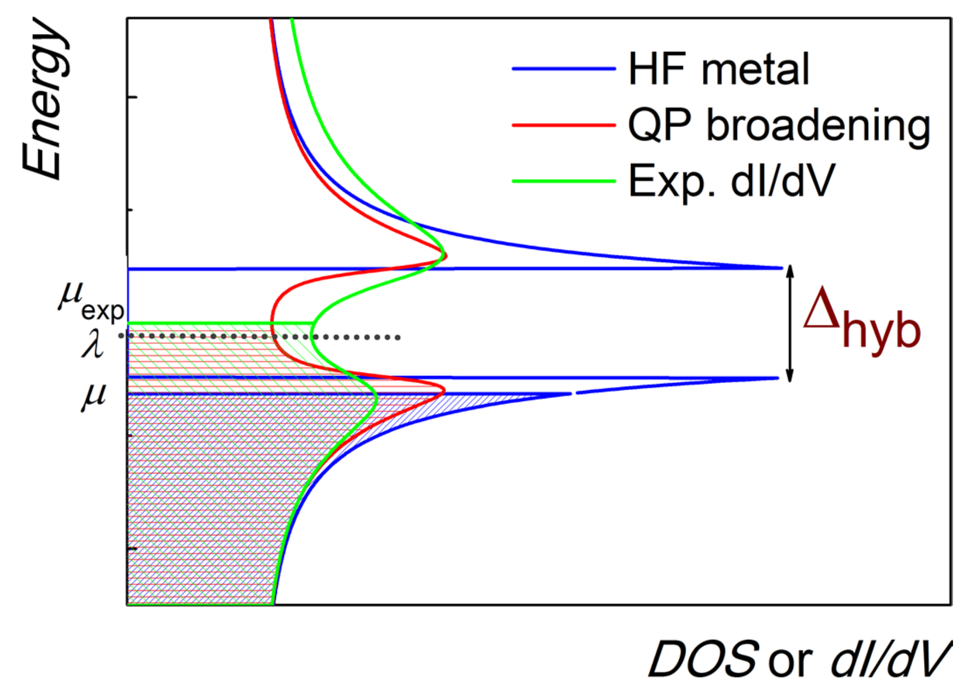
- Assume a parabolic background
- Energy-dep. quasiparticle broadening due to correlation effects, $\gamma(E)$ (Wölfle et al., PRL, 2010)

Fig. #	a	b	c	d
T (K)	2.07	3.13	4.35	2.40
R_J (W)	16.7	19.1	51.0	39.0
q_F	10	11	11	13
Δ_{hyb} (meV)	12.1	11.7	14.2	10.9
V (meV)	41.4	40.7	44.8	39.0
λ (meV)	-2.0	-0.7	-1.2	-1.6

- Average Δ_{hyb} = 13 meV, consistent with recent optical spectroscopy results by Levallois et al. (arXiv:1007.0538)

Relation to Gaps from Other Measurements





$$R = R_0 + aT^2 + b(T/\Delta)[1 + 2T/\Delta]\exp(-\Delta/T)$$

- Fitting gives rise to Δ = 6.7 meV $\approx \Delta_{hyb}/2$.

  1.5% Rh-doped (T_{HO} = 12.8 K): Δ = 4.7 meV, Δ_{hyb} = 10 meV. $\Rightarrow \Delta \approx \Delta_{hyb}/2$.
- Finite conductance within Δ_{hyb} indicates finite DOS (e.g., due to correlation effects) with the chemical potential close to the gap center.

$\Rightarrow \Delta$ is approximately half of Δ_{hyb}.