Noncentrosymmetric Superconductivity

M. B. Salamon and H. Q. Yuan and D. Vandervelde, Univ. Illinois

D. F. Agterberg, U. Wisconsin, Milwaukee

P. Badica, Tohoku Univ. and Nat'l Inst. Materials, Romania

K. Togano, Nat'l Inst. Mater. Sci., Tsukuba

N. Hayashi and M. Sigrist, ETH-Hönggerberg, Zürich

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UTD

What we (think we) know

The gap function of a superconductor has the form:

$$\Delta(\vec{k}) = \Delta_0(\vec{k}) + \vec{\sigma} \cdot \vec{d}(\vec{k})$$

$$\Delta_0(-\vec{k}) = \Delta_0(\vec{k}) \ \text{ and } \vec{d}(-\vec{k}) = -\vec{d}(\vec{k})$$

If the crystal has inversion symmetry, even parity states have zero spin ($d(k) = 0$) and odd parity states have unit spin ($\Delta_0(k) = 0$)

But, what if the crystal lacks a center of inversion?

Consequences of missing inversion symmetry

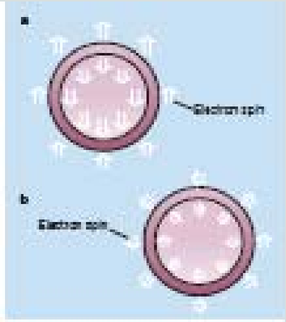
- Rashba-type antisymmetric spin-orbit (ASOC) coupling is allowed:

$$\alpha \mathbf{g}_k \cdot \mathbf{S}, \text{ with } \mathbf{g}_{-k} = -\mathbf{g}_k$$

- This lifts the spin degeneracy of the bands, causing the spin in each sub-band to rotate around the Fermi surface
- The Cooper-pair wavefunction may be a mixture of spin-singlet and spin-triplet pairing {Gor'kov and Rashba, PRL **87**, 037004 (2001)}.

“Everything not forbidden is compulsory”

T.H. White, *The Sword in the Stone* (1938)



← Inversion-symmetric case

← With Rashba-type ASOC

Saxena and Monthoux,
Nature **427**, 799 (2004)

Proper treatment considers two bands

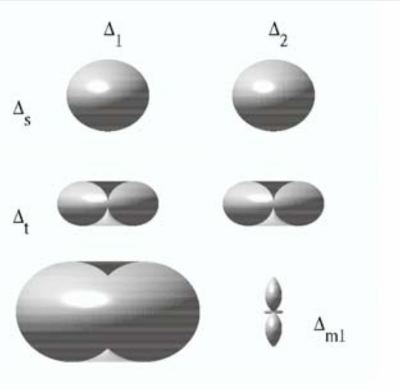
- The pairing potential must also reflect broken parity
- Treat *g(**k**)* as the basis for an odd parity representation
- A pure triplet potential can exist in each band along with an interband term.
- If the triplet d-vector is parallel to the *g*-vector, triplet superconductivity is possible.
- Even in the absence of a triplet channel, interband terms can mix singlet and triplet states.

P. Frigeri, D Agterberg, M. Sigrist, Cond-Mat/0505108

Each ASOC-split band has its own gap function

$$\Delta_{1,2} = \psi \pm t\left|g_{\mathbf{k}}\right|$$

The relative magnitudes of ψ and *d* depend on the strength of the ASOC



← ψ dominates—pure singlet

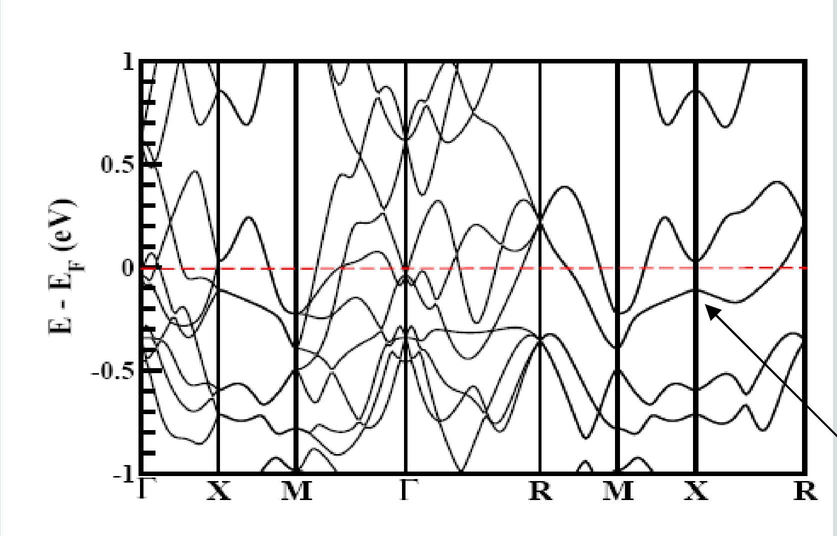
← t dominates—pure triplet

← ψ ≤ t—nodes in one gap

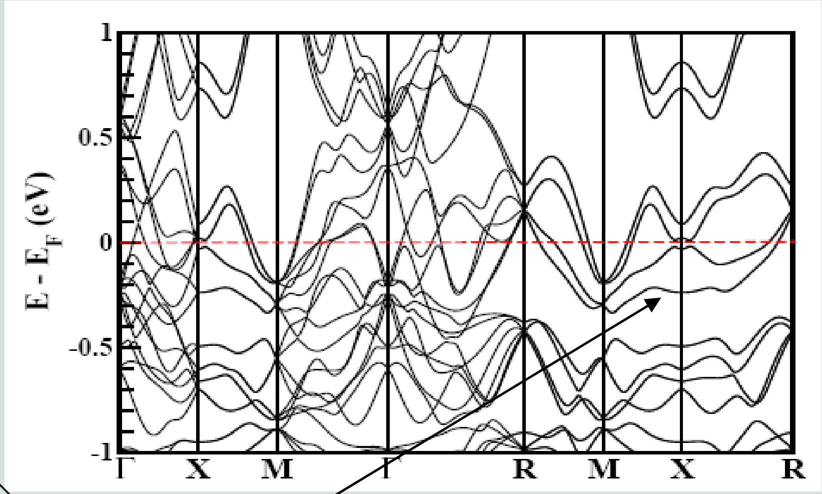
What materials might exhibit this?

- $CePt_3Si$ (P4mm) but magnetic and heavy Fermion SC
- UIr lacks inversion symmetry under pressure—very low T_c
- Li_2Pd_3B and Li_2Pt_3B ($P4_332$) T_c = 7.5K and 2.5K respectively, not magnetic, different SO coupling
- LaRhSi and LaIrSi ($P2_13$) T_c = 4.3 K and 2.3 K respectively. Not magnetic. Not studied (yet).

Is spin orbit coupling important?—strong band splitting



Li_2Pt_3B without SOC

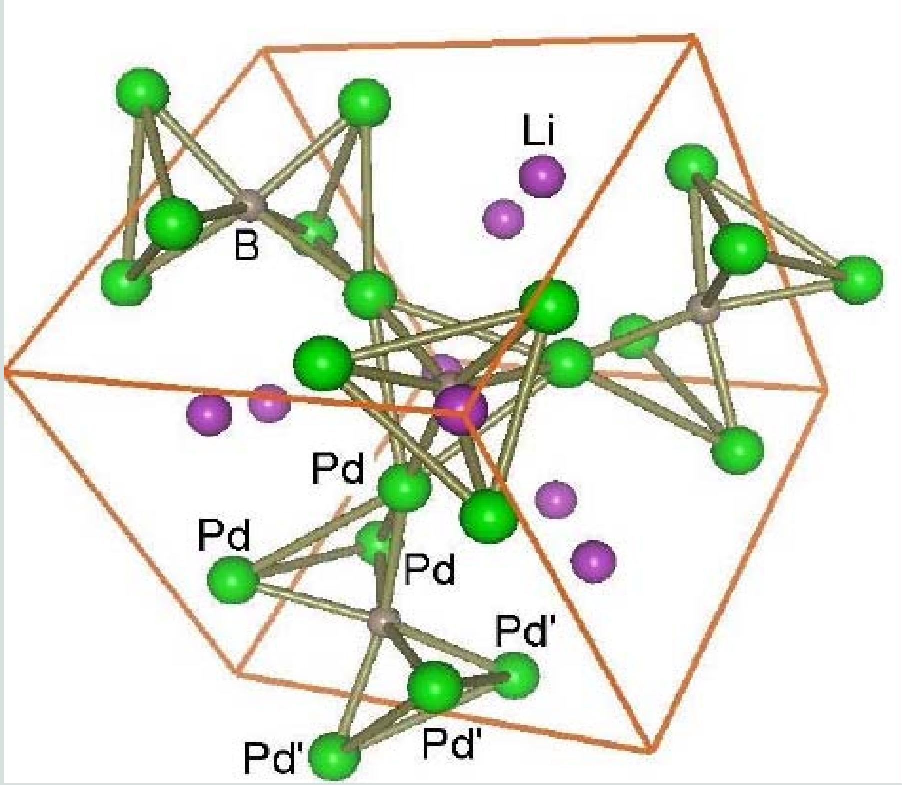


Li_2Pt_3B including SOC

Compare—sizable fraction
of the bandwidth

Lee and Pickett, cond-mat/0507105

Li_2Pd_3B (Pt version is the same)



Space group: cubic $P4_332$

Contains 4 BPd_6 octahedra

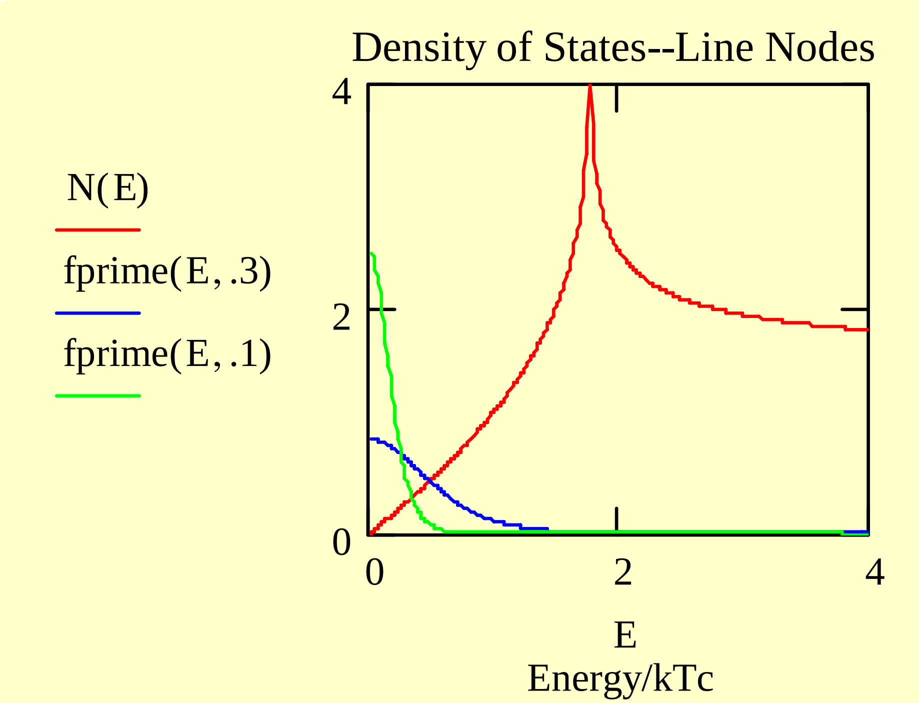
Distinct from perovskite—distorted antiperovskite

Lacks inversion symmetry

Li_2Pd_3 is a 7.5 K superconductor; Li_2Pt_3B superconducting at 2.5 K

[Togano, et al. PRL **93**, 247004 (2004); Badica et al. JPSJ **74**, 1014 (2005)]

Detection: low-energy (temperature) excitations out of the gap



$T/T_c = 0.1$

$T/T_c = 0.3$

The density of available excited states increases linearly with energy, as does the area. This gives an increase in the penetration depth that is linear in temperature; i.e. $\lambda(T) \propto T$. [So-called d-wave state]

The best measure: the London penetration depth

$$\lambda(T) = \left(\frac{mc^2}{4\pi n_s(T) e^2}\right)^{\frac{1}{2}}$$

Classical radius of the electron:

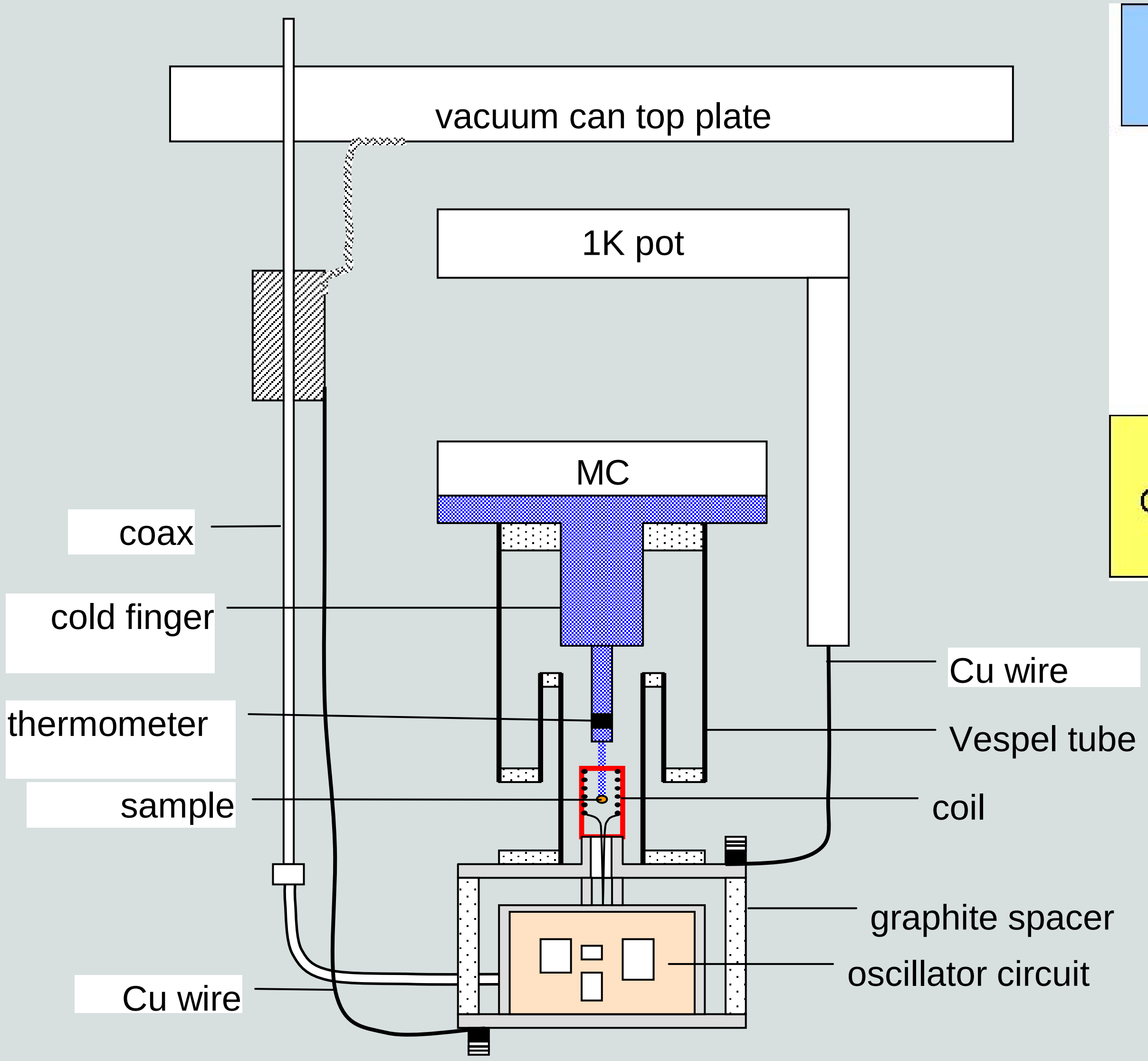
$e^2/mc^2 = 2.8\times10^{-13}$ cm

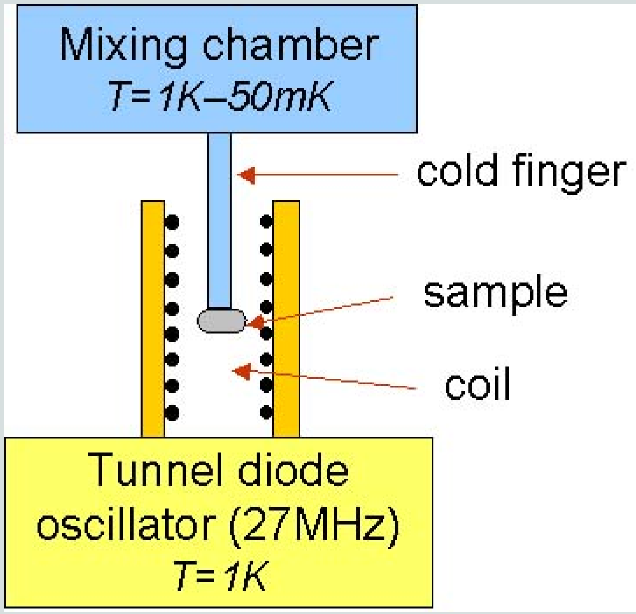
Density of pairs: $n_s \approx 10^{22}$ cm^{-3}

Gives: $\lambda(0) \approx 5\times10^{-6}$ cm

Metal	London depth (10^{-6} cm)
Sn	3.4
Al	1.6
Pb	3.7
Cd	11
Nb	3.9

How we measure it: Resonant Oscillator Technique

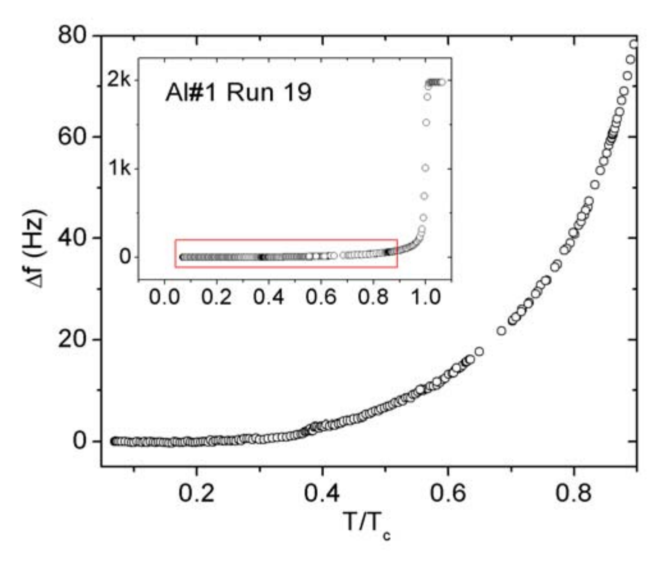




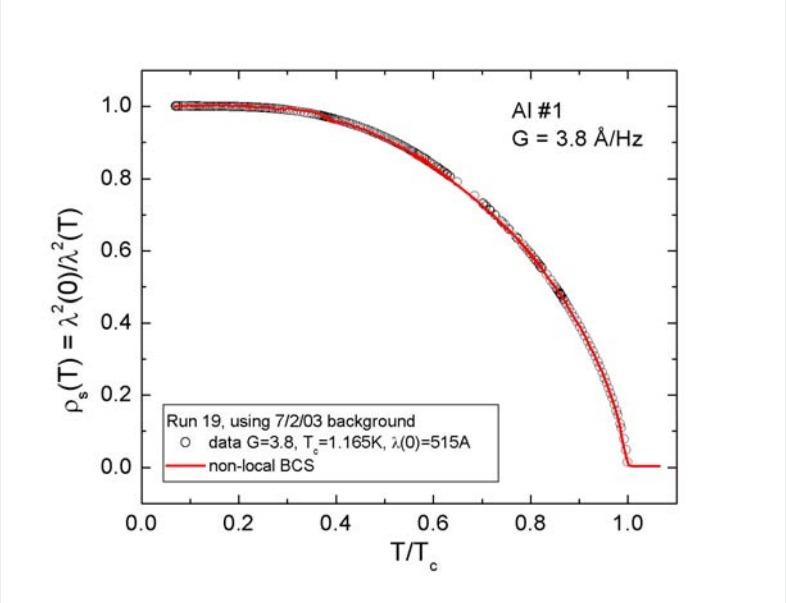
$$\Delta\lambda = \underset{\text{Calibration factor}}{\underset{\uparrow}{G}}\,\Delta f$$

Design:
C. Van Degrift
R. Giannetta

Example: Aluminum with T_c near 1 K

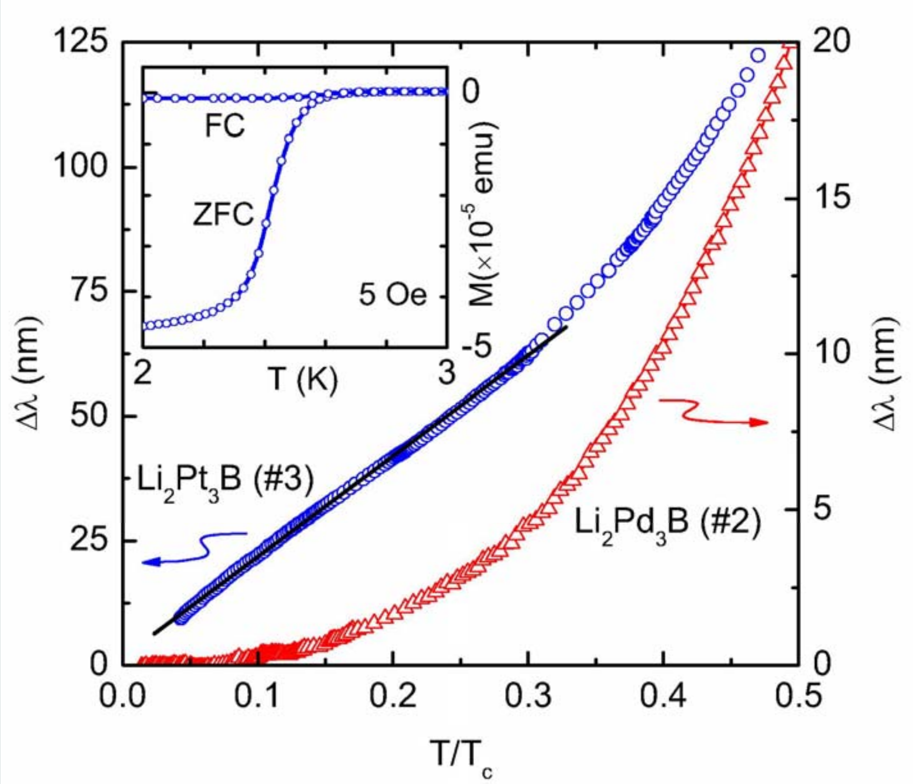


Raw data



Converted to superconducting fraction $n_{s;}$ red line, BCS calculation; dots, data

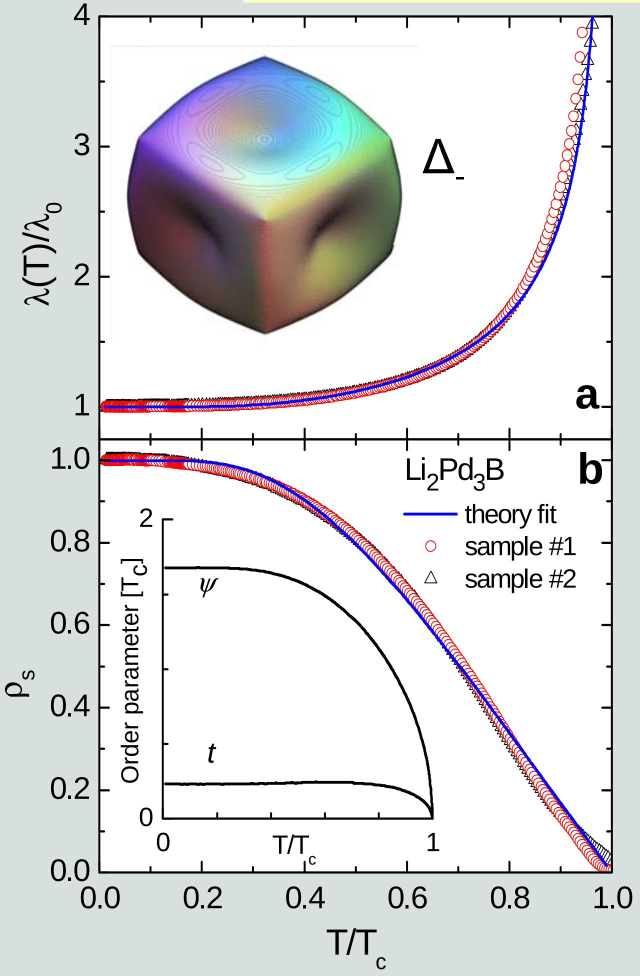
The Pd and Pt materials show quite different behavior



Spin-Orbit coupling is in ratio $(Z_{Pt}/Z_{Pd})^2 = 3$ => larger ASOC

The Pd version has smaller spin-orbit effect--gapped

$$\vec{g}(\hat{k}) = \{k_x[1-a(k_y^2+k_z^2)], k_y[1-a(k_x^2+k_z^2)], k_z[1-a(k_x^2+k_y^2)]\}$$



Actual form (per Agterberg):

$\vec{g}(\hat{k})$: a measure of the asymmetric spin orbit splitting of the bands

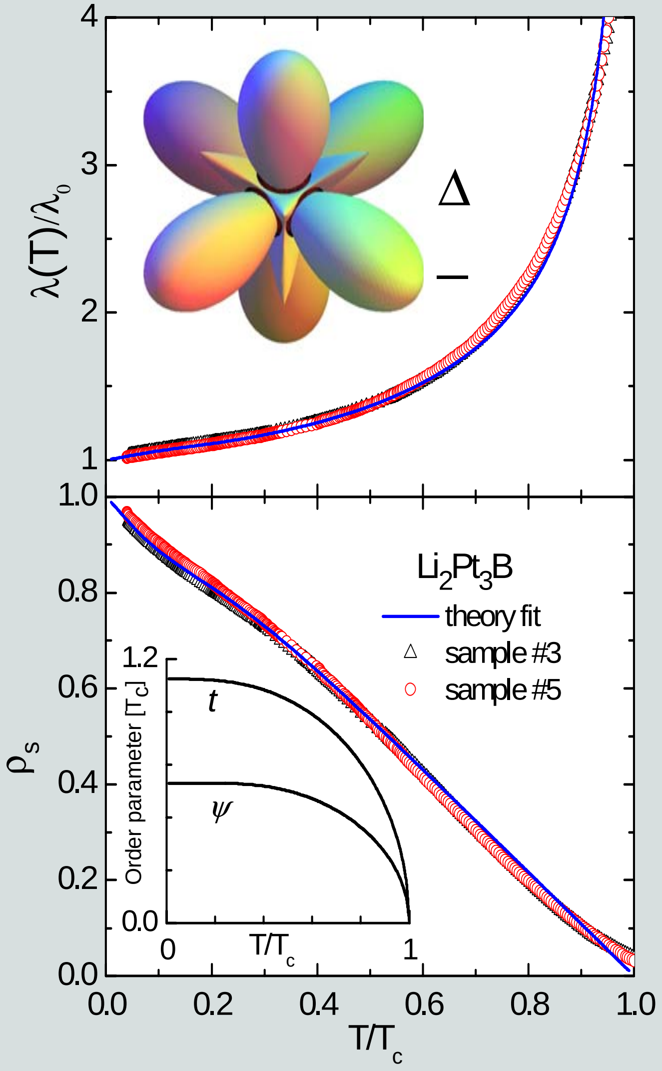
$$\Delta_+ = \psi_s + t|\vec{g}(\hat{k})|$$

$$\Delta_- = \psi_s - t|\vec{g}(\hat{k})|$$

Calculated by N. Hayashi with

$\psi_s \approx 10.5$ K; $t \approx 2.1$ K

Li$_2$Pt$_3$B is definitely not fully gapped—linear in *T*



Best fit with $\psi_s \approx 1.8$ K and *t* ≈ 2.6 K.

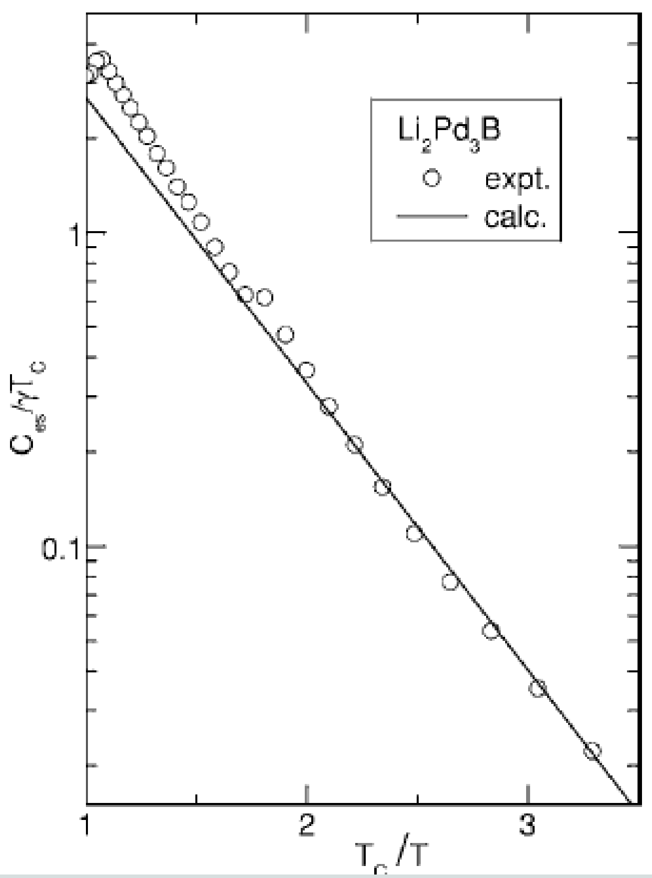
N.B. *t* is nearly the same as for Pd; the singlet gap is smaller.

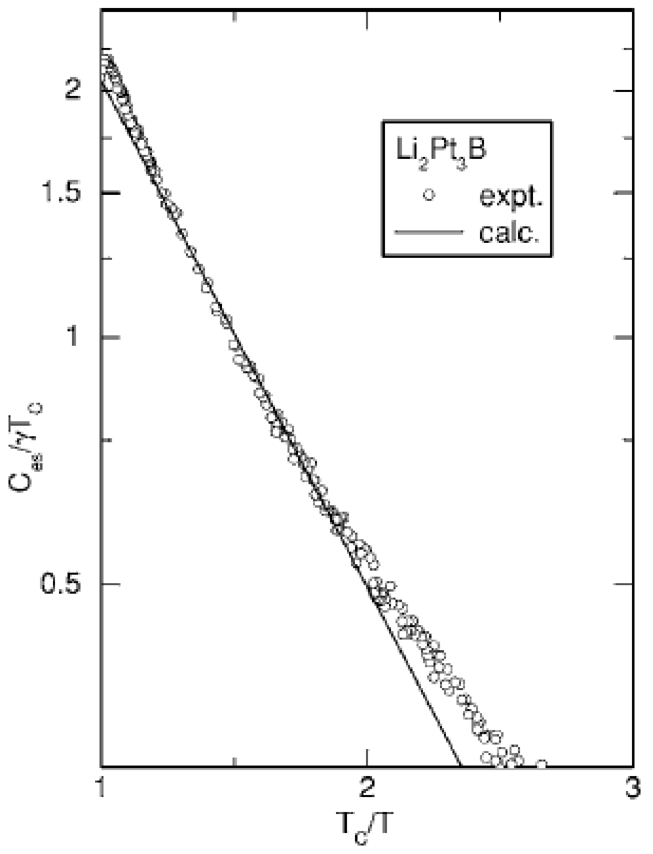
The parameter δ measures the relative densities of states:

$N_\pm(E_F)/N_{tot}(E_F) = (1\pm\delta)/2$

Experimental problems with Pt samples–Li oxide appears when exposed to air.

Other Data—Heat Capacity



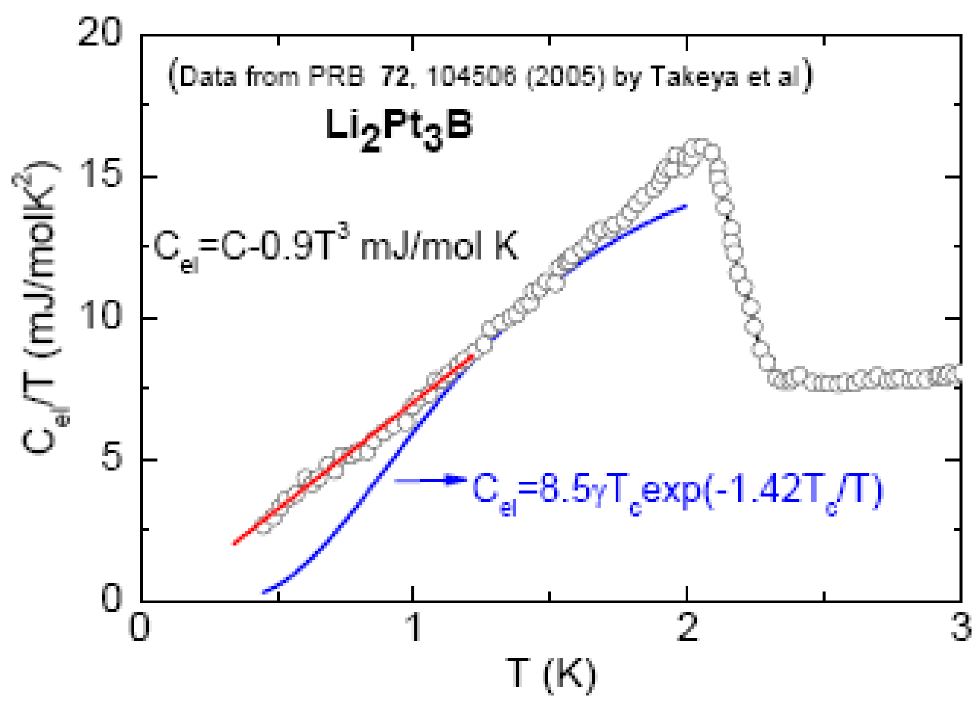


Clearly exponential at low T

Not so clear—deviation at low T

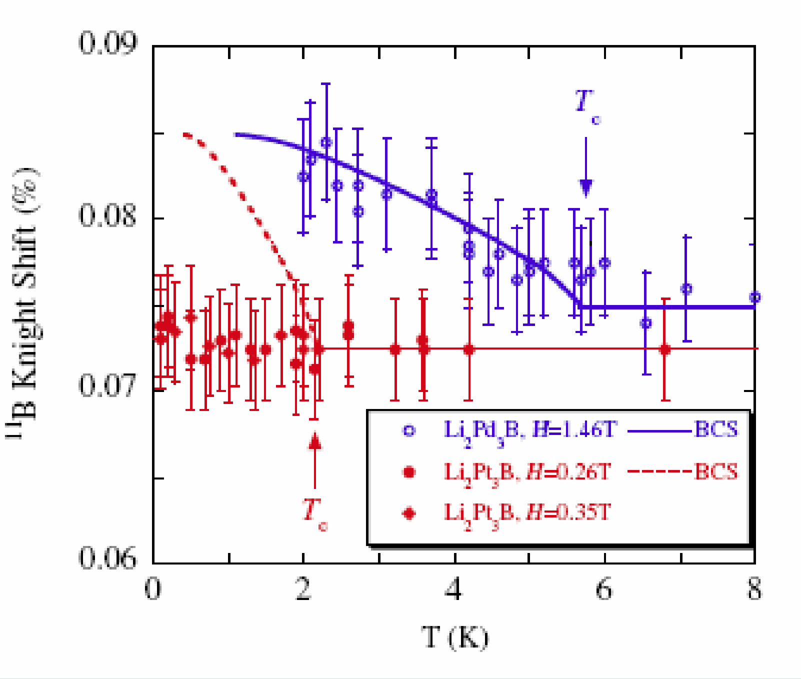
H. Takeya et al., PRB **72**, 104506 (2005)

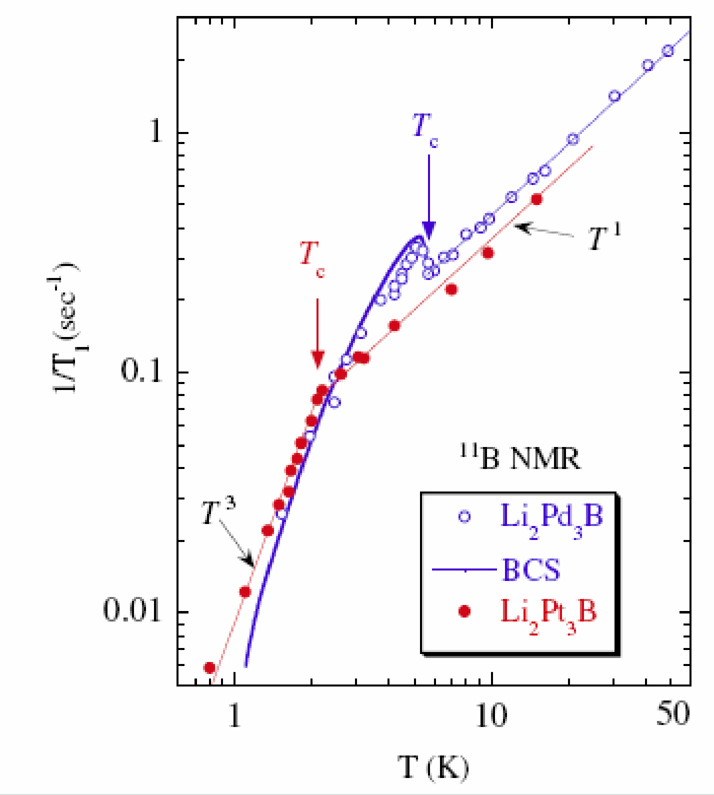
Reanalysis of Takeya, et al. data—linear at low T



Blue line is the fit for Pt data from the previous slide

NMR data on the same compounds confirms this



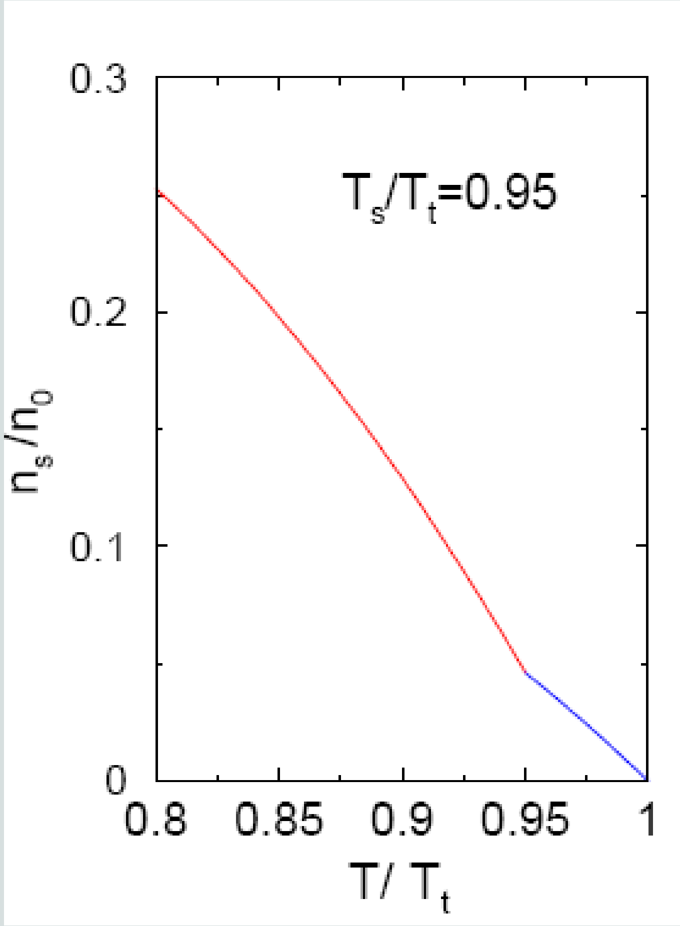


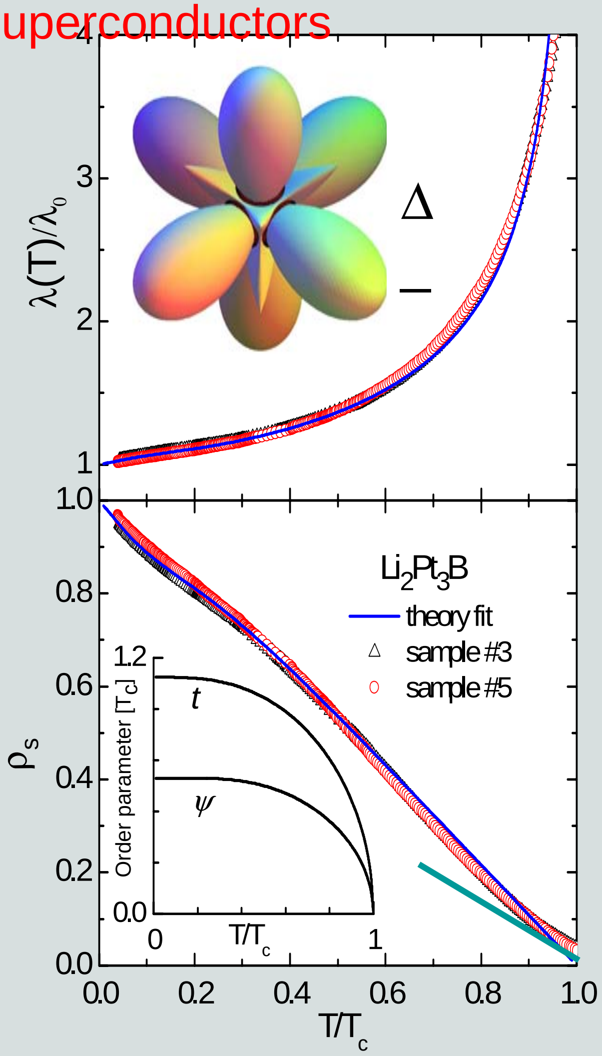
No change in Knight shift

No coherence peak

Same result for Pt NMR—Nishiyama, et al. PRL **98**,047002(2007)

GL Theory of Noncentrosymmetric Superconductors

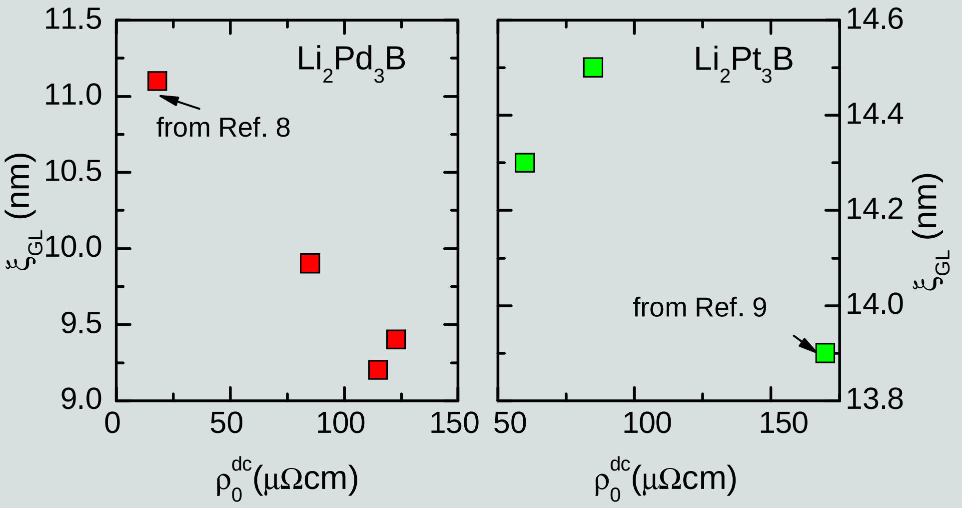




S. P. Mukherji and S. S. Mantal cond-mat0709.4121

Other sources of linear dependence: are samples dirty?

Property	Li_2Pd_3B	Li_2Pt_3B	source
GL coherence length	9.6 nm	14.5 nm	dH_{c2}/dT
Residual resistance	20 μΩcm	28 μΩcm	Normal skin depth
Mean free path	24 nm	42 nm	BCS expression
T_c	7.5 K	2.5 K	Magnetization



Dirty limit:

$$\xi_{GL} \propto \rho_0^{-1/2}$$

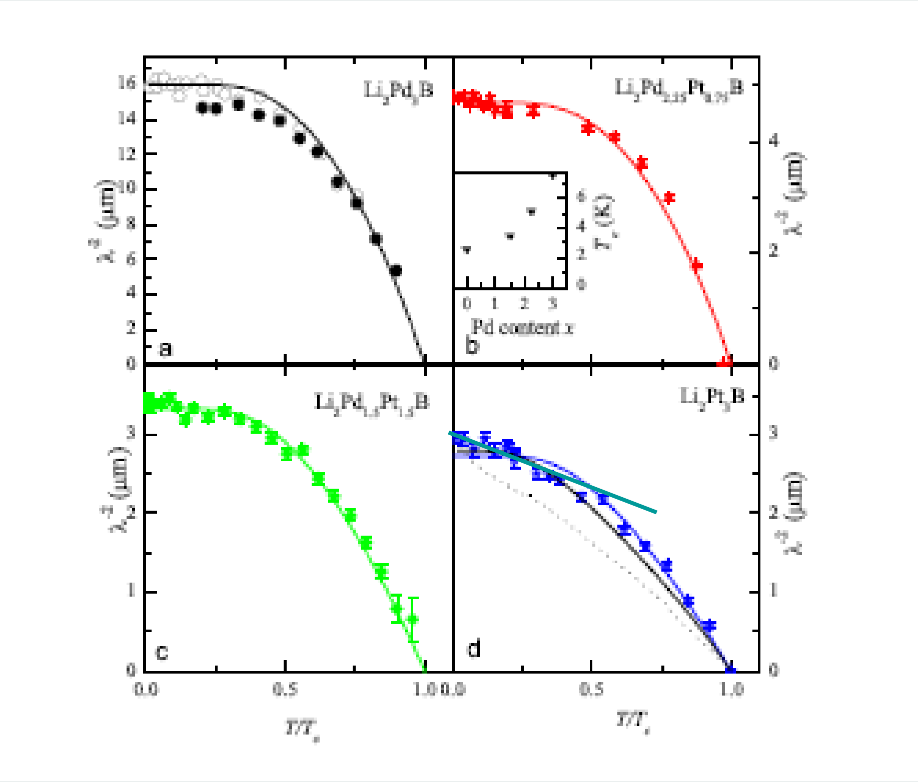
Little variation observed

Another possibility—Josephson coupling

- The samples are polycrystalline
- If grains are weakly Josephson coupled, there can be phase fluctuations that are thermally activated
- The effect is inversely proportional to grain volume
- Both samples have comparable, and large (100 μm)
- Transition temperature should depend on intergranular (dc) resistance, but does not
- Both samples should show linear T-dependence if phase fluctuations were dominant.

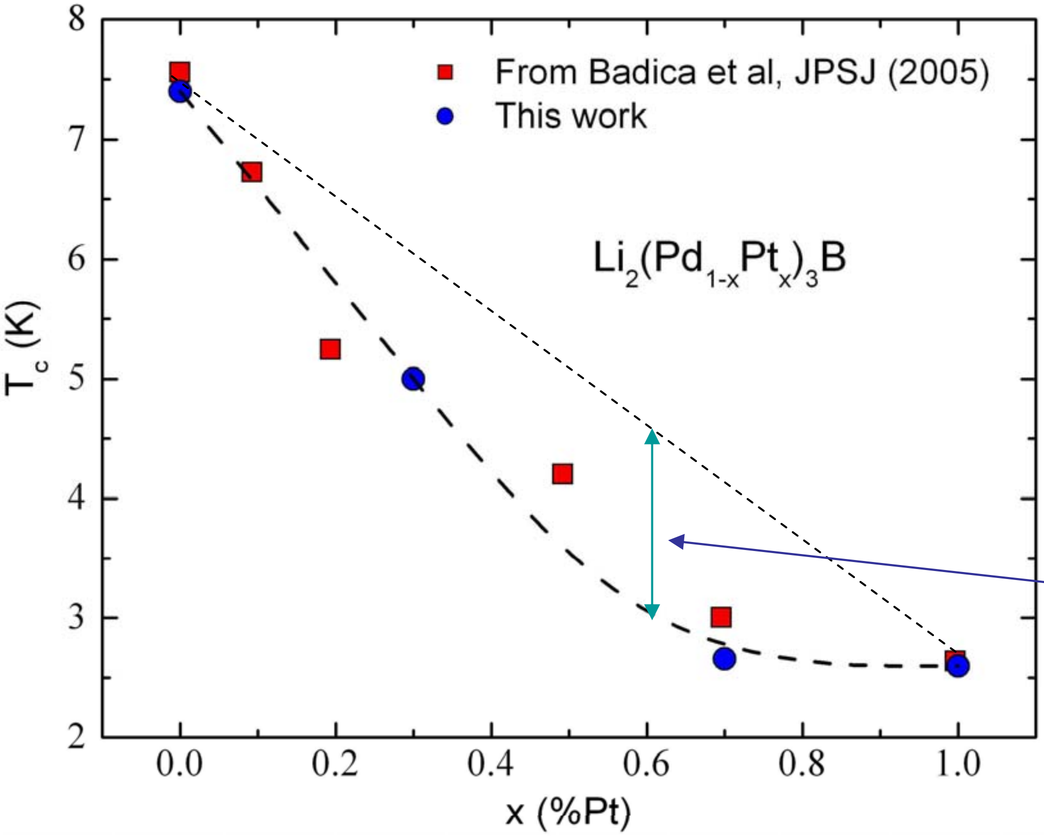
Conclusion: linear T-dependence in Pt compound is intrinsic

Muon penetration depth data disagrees with us (maybe)



P. Häflinger et al., Cond-Mat 0709.3777v1

Alloy studies (work in progress)



Suppression of triplet phase by impurities?

Summary and Conclusions

- Strong evidence for (and some against) mixed singlet and triplet pairing in an $\ell = 0$ state
- What are the properties of FFLO-like and vortex phases?
- Is a triplet pairing channel necessary or can interband terms lead to singlet-triplet mixtures?
- Should the Hebel-Slichter peak be absent?
- Is there a second transition at $0.9T_c$? What is the higher-T phase?
- What about the normal state? Are there spin currents in a field?