μSR Studies of Electron-doped 122 Pnictide Superconductors

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Outline

- Introduction & Crystal Growth
- Underdoped Samples – ZF- & TF-μSR Measurements
- Two-Gap Model & Fitting
- Doping Dependence of $n_S(0)$
- μSR Frequency Shift below T_C
- Conclusions

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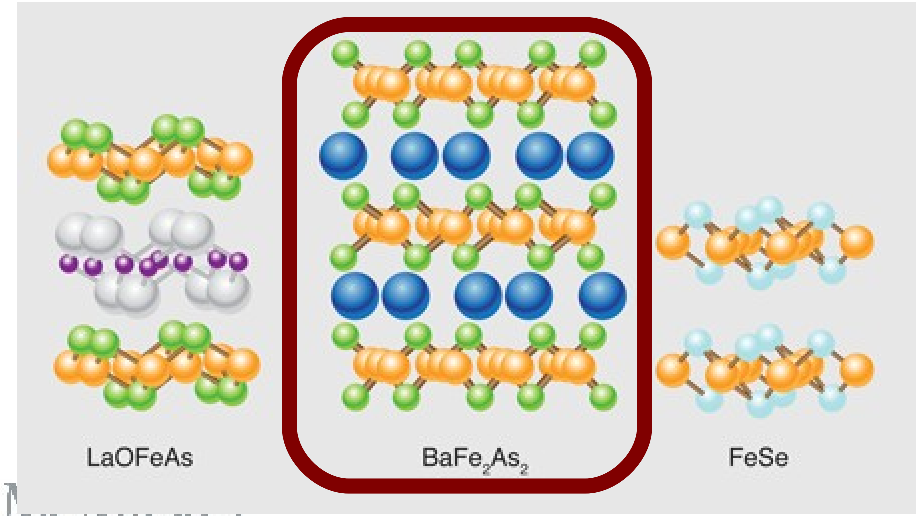
Introduction - Materials

- “122” family; parent is $BaFe_2As_2$ or $SrFe_2As_2$.
- Co-doping for Fe introduces extra electrons, and dopes onto the FeAs layer.
- These crystals have been the most successfully grown of any of the iron pnictides.



- Doping range from 3.8% to 13.0% (all superconducting).

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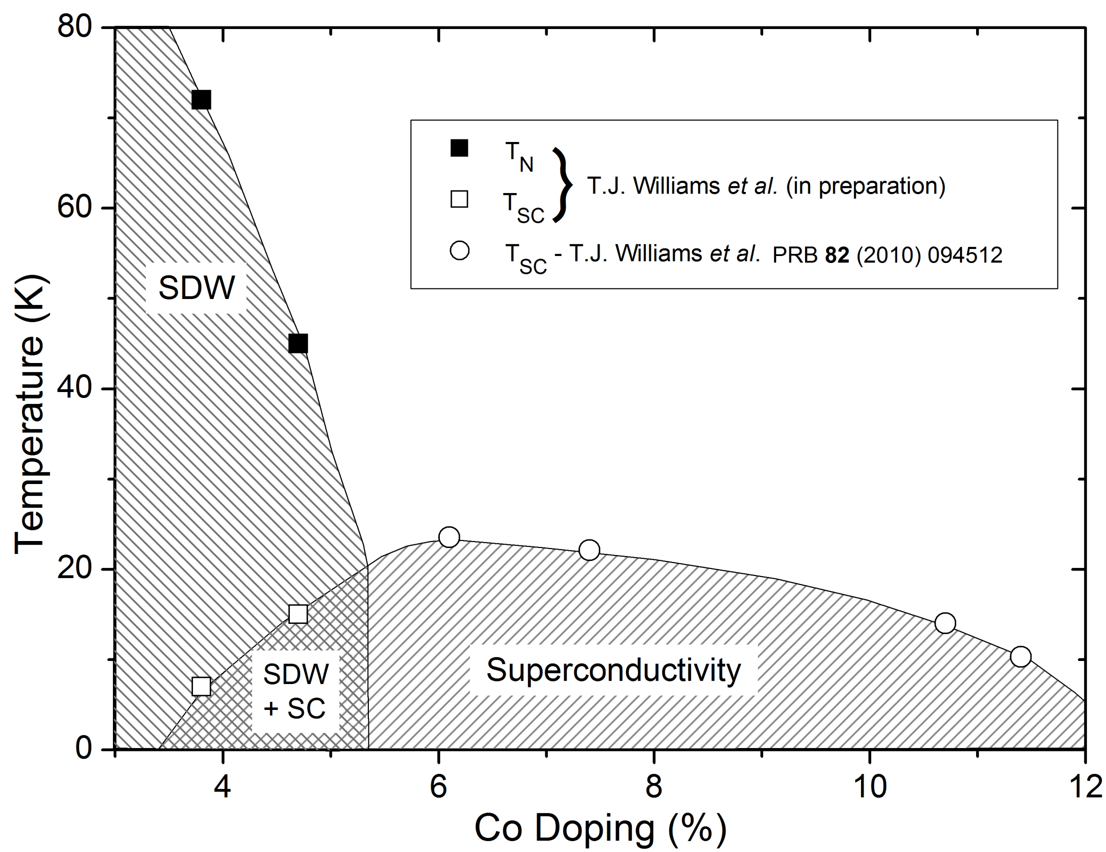
Crystal Growth

- Single crystals of $Ba(Fe_{1-x}Co_x)_2As_2$ with x = 0.038, 0.047, 0.061, 0.074, 0.107 and 0.114 were grown by self-flux at Ames Laboratory.



- A single crystal of $Sr(Fe_{0.87}Co_{0.13})_2As_2$ was grown by self-flux at the University of Maryland.

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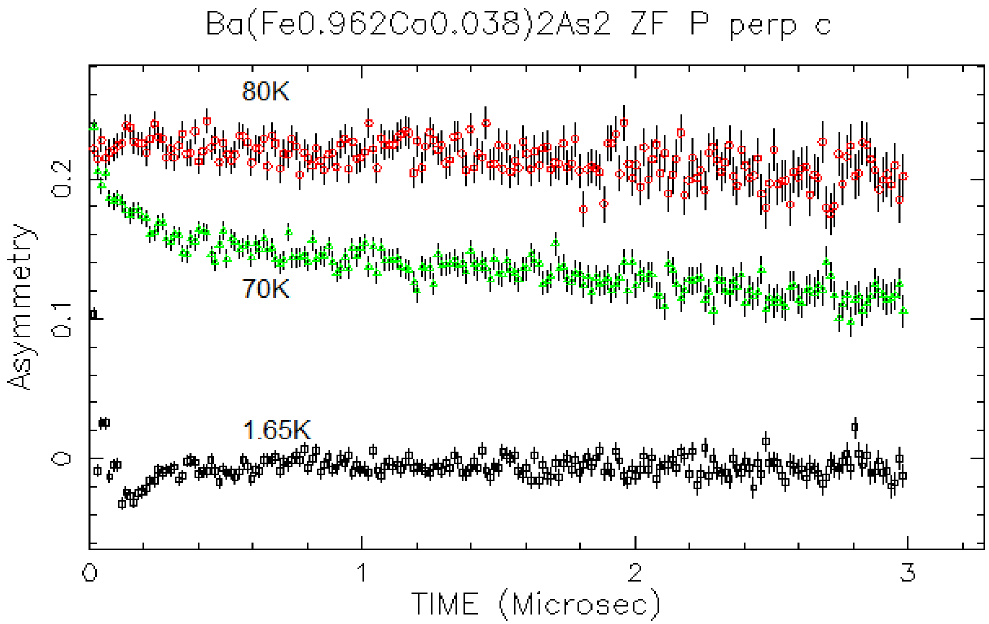
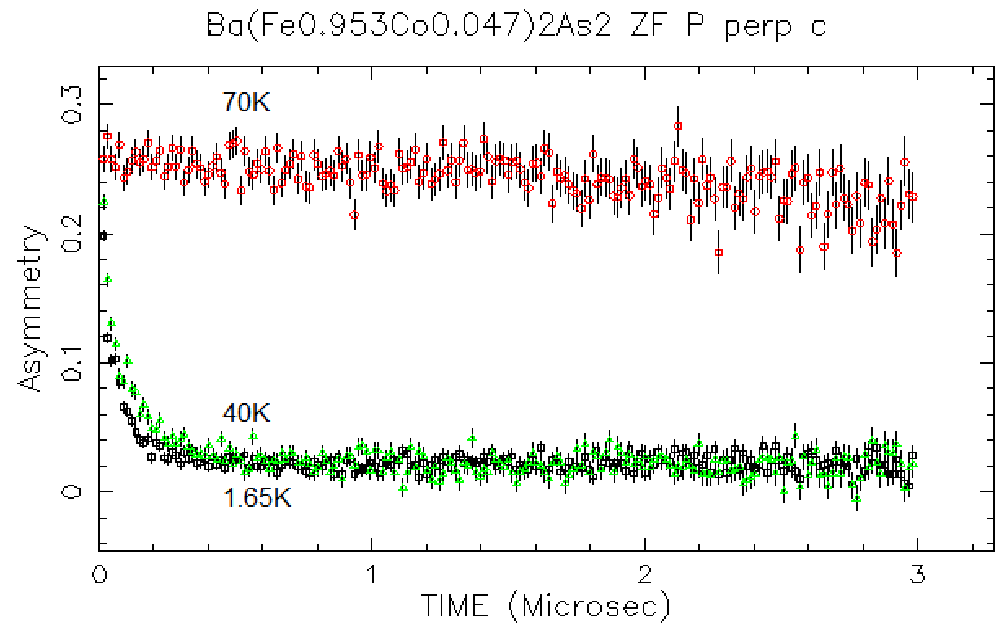
Underdoped Ba-122 - ZF-μSR

- In the 3.8% and 4.7% samples, we observe a sharp transition at 70K and 45K, respectively.





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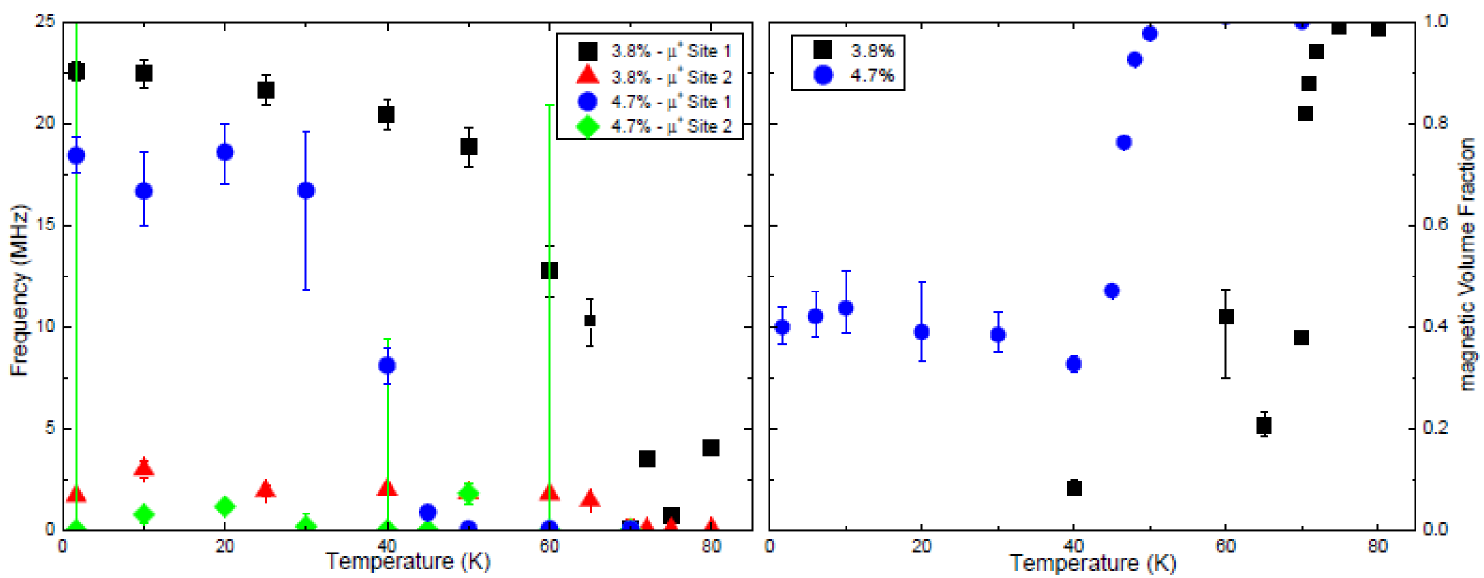
Underdoped Ba-122

- In the 3.8% and 4.7% samples, we observe a sharp transition at 70K and 45K, respectively.
- The frequency remains unchanged below the SC transition.
- Asymmetry indicates a weakly magnetic volume fraction.



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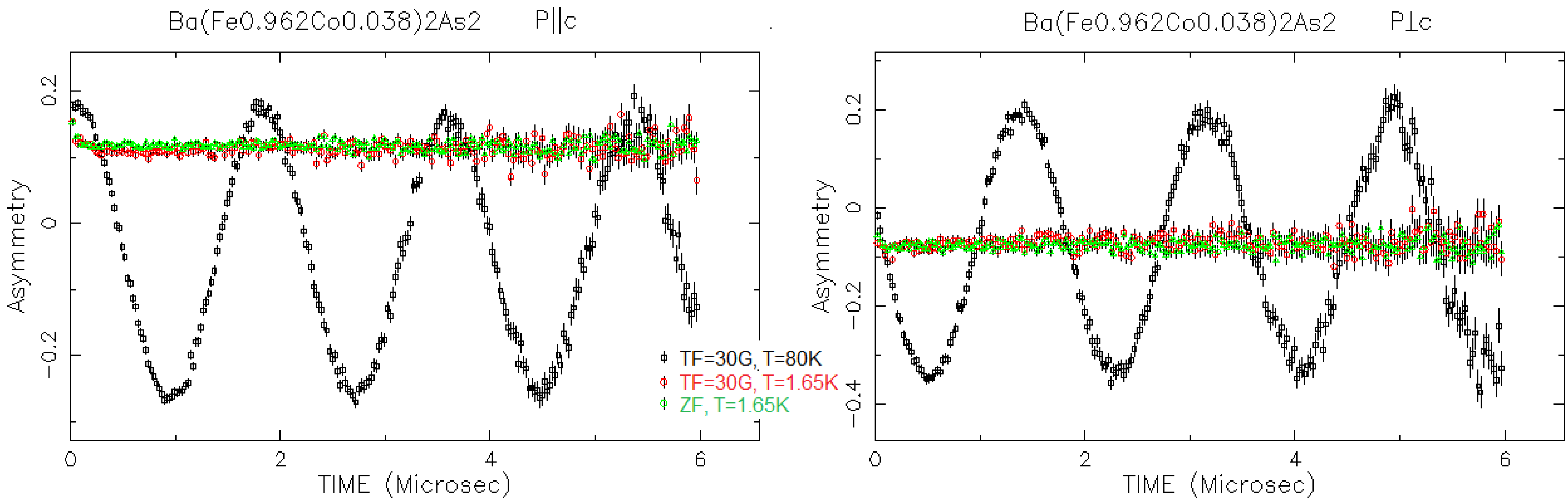
Underdoped Ba-122 – TF-μSR

- The spectra do not relax to zero in B/F configuration, but do in U/D, corresponding to ĉ-axis magnetism.



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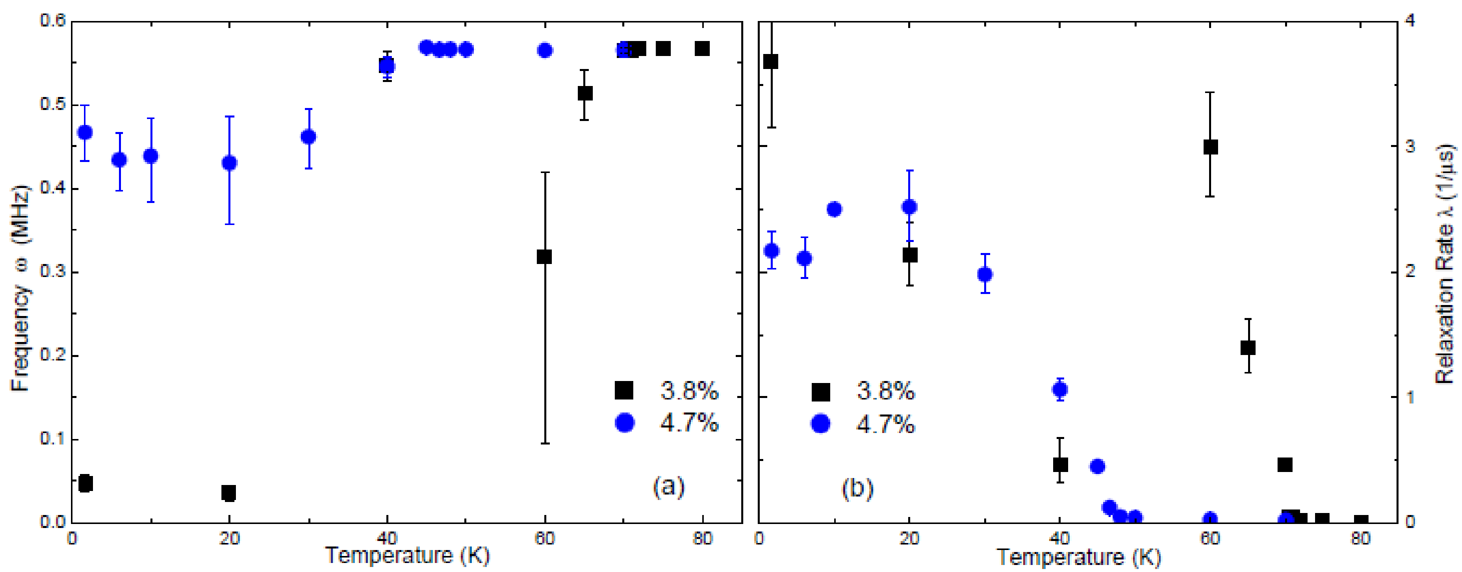
Underdoped Ba-122 – TF-μSR

- The spectra do not relax to zero in B/F configuration, but do in U/D, corresponding to ĉ-axis magnetism.
- Relaxation indicates large disorder in both magnetic regions, possibly due to Co-dopants.



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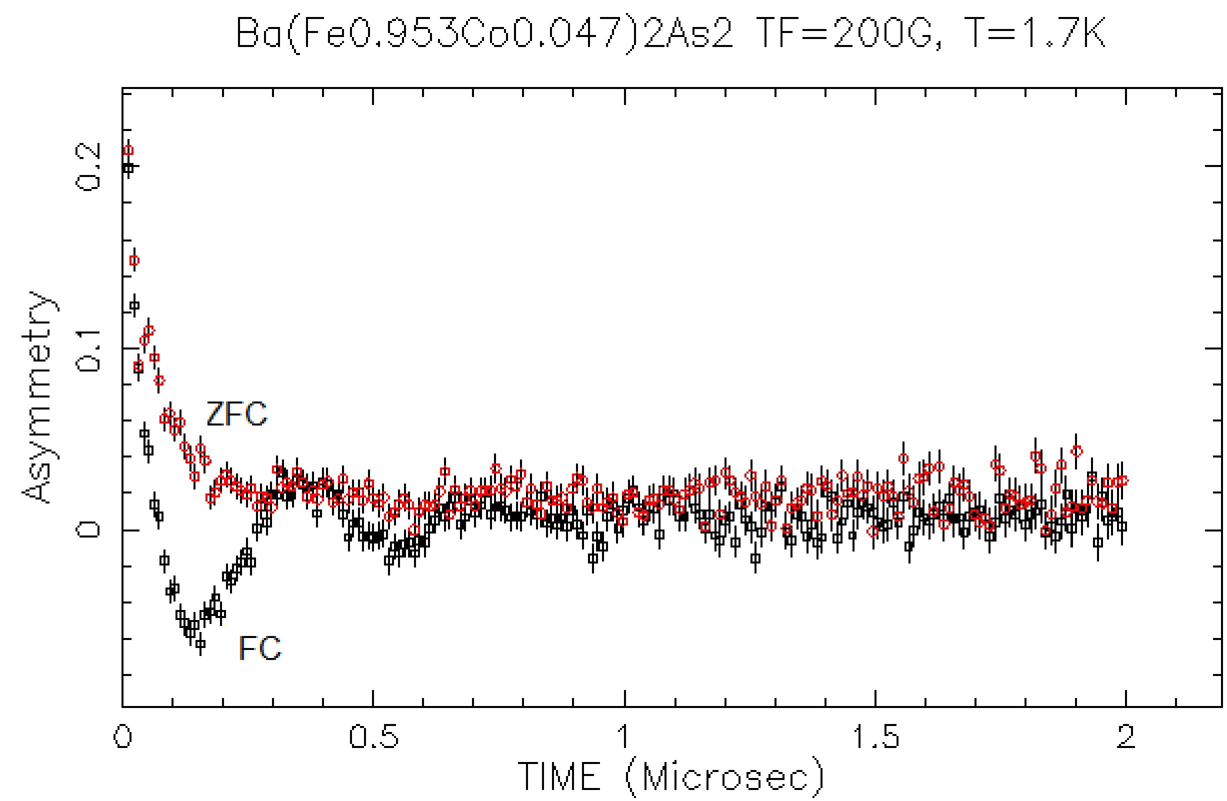
Underdoped Ba-122 – SC

- ZFC versus FC measurements in TF=200G show strong increases in relaxation, indicative of flux pinning.



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Underdoped Ba-122 – SC

- ZFC versus FC measurements in TF=200G show strong increases in relaxation, indicative of flux pinning.
- Superconductivity is in low-field regions since the signal completely relaxes, and possibly in the whole sample.
- Since the entire sample sees magnetism, SC exists near or in strongly magnetic regions.

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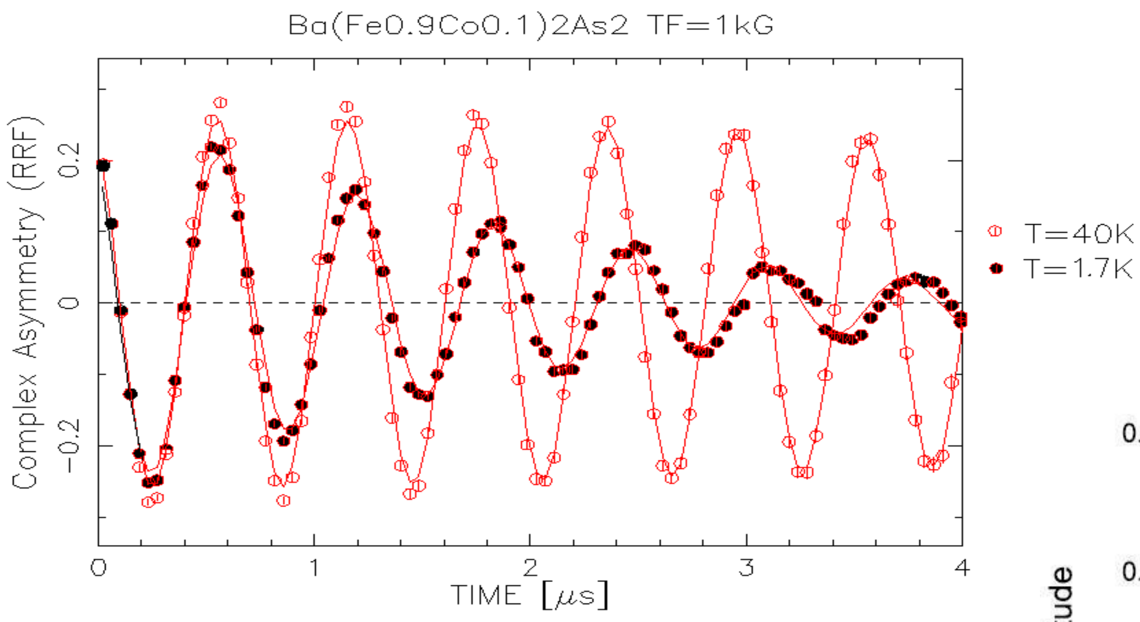
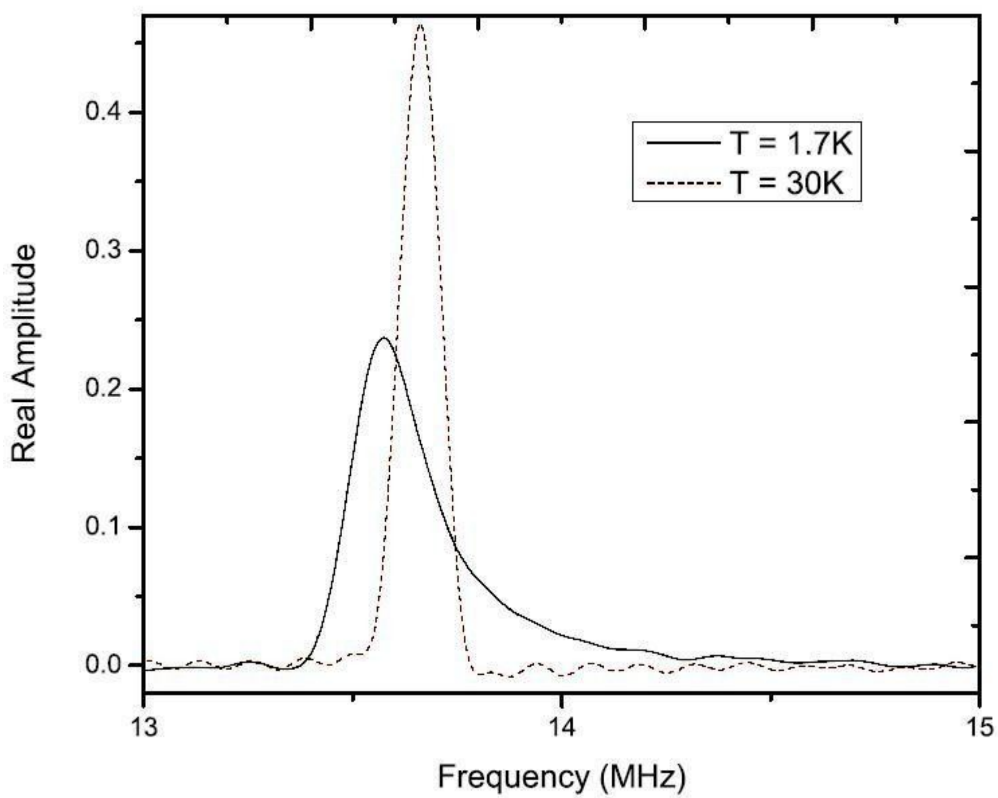
Optimal Doping – TF-μSR



- Fit using a Rotating Reference Frame



- An FFT shows an Abrikosov lineshape below T_C.
- This can be fit to extract the penetration depth.

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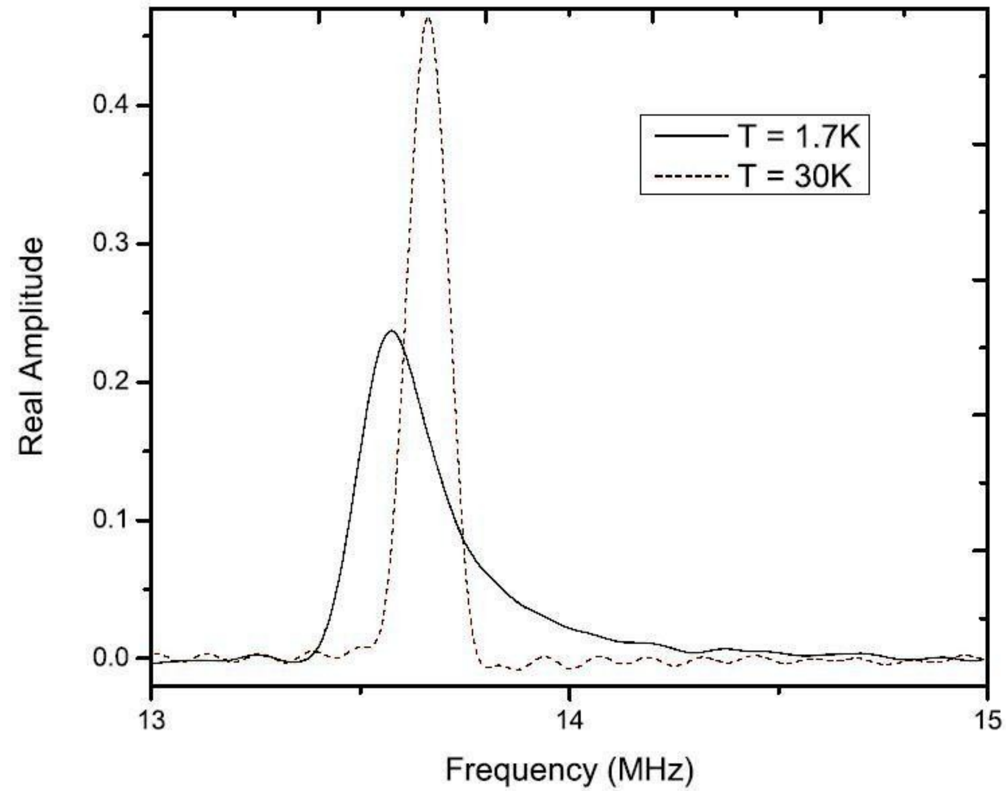
Fitting

- This is fit to an analytic GL model, and included an additional term for lattice disorder.

- We obtained $\kappa = \lambda/\xi = 44$, verifying that we are in the clean limit.



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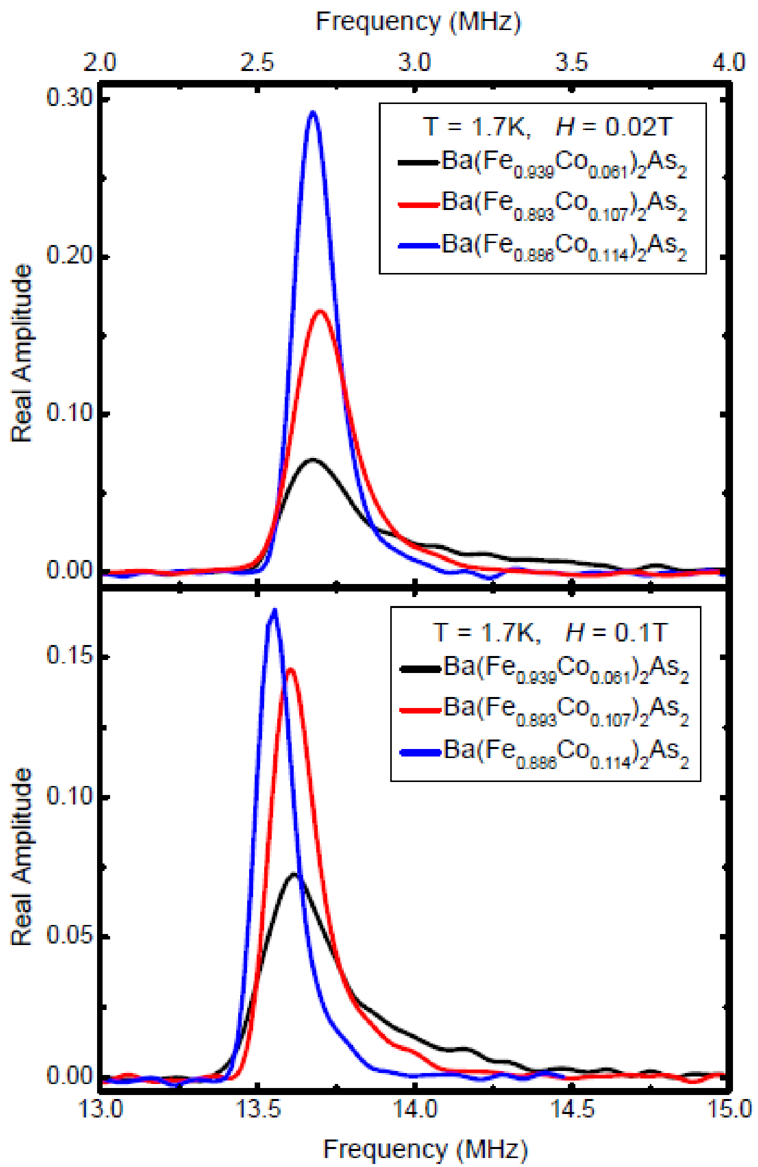
Fitting – Lattice Disorder



- The lattice disorder was incorporated via an additional Gaussian broadening of the lineshape.
- The amount of lattice disorder was found to increase with decreasing field, and with decreasing temperature.

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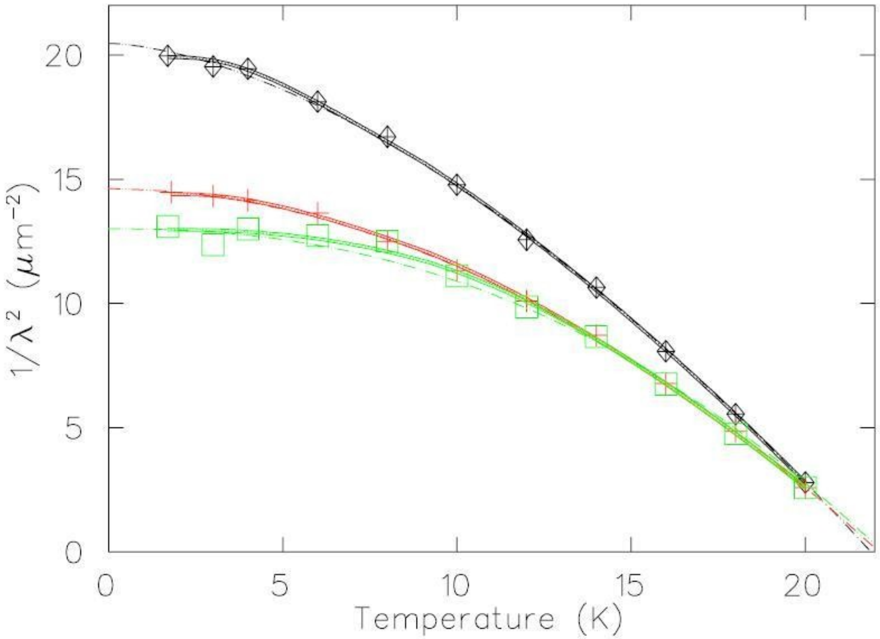
Fitting – T-dependence of λ



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- Power Law:

$$n_s(T)=n_s(0)\left[1-\left(T/T_C\right)^p\right]$$

- Two-Gap Model:

$$n_s(T)=n_s(0)-w\cdot\delta n_s(\Delta_{1,}T)-(w-1)\cdot\delta n_s(\Delta_{2,}T)$$

$$\delta n(\Delta,T)=\frac{2n_s(0)}{k_B T}\int_0^\infty f(\epsilon,T)\cdot[1-f(\epsilon,T)]\,d\epsilon$$

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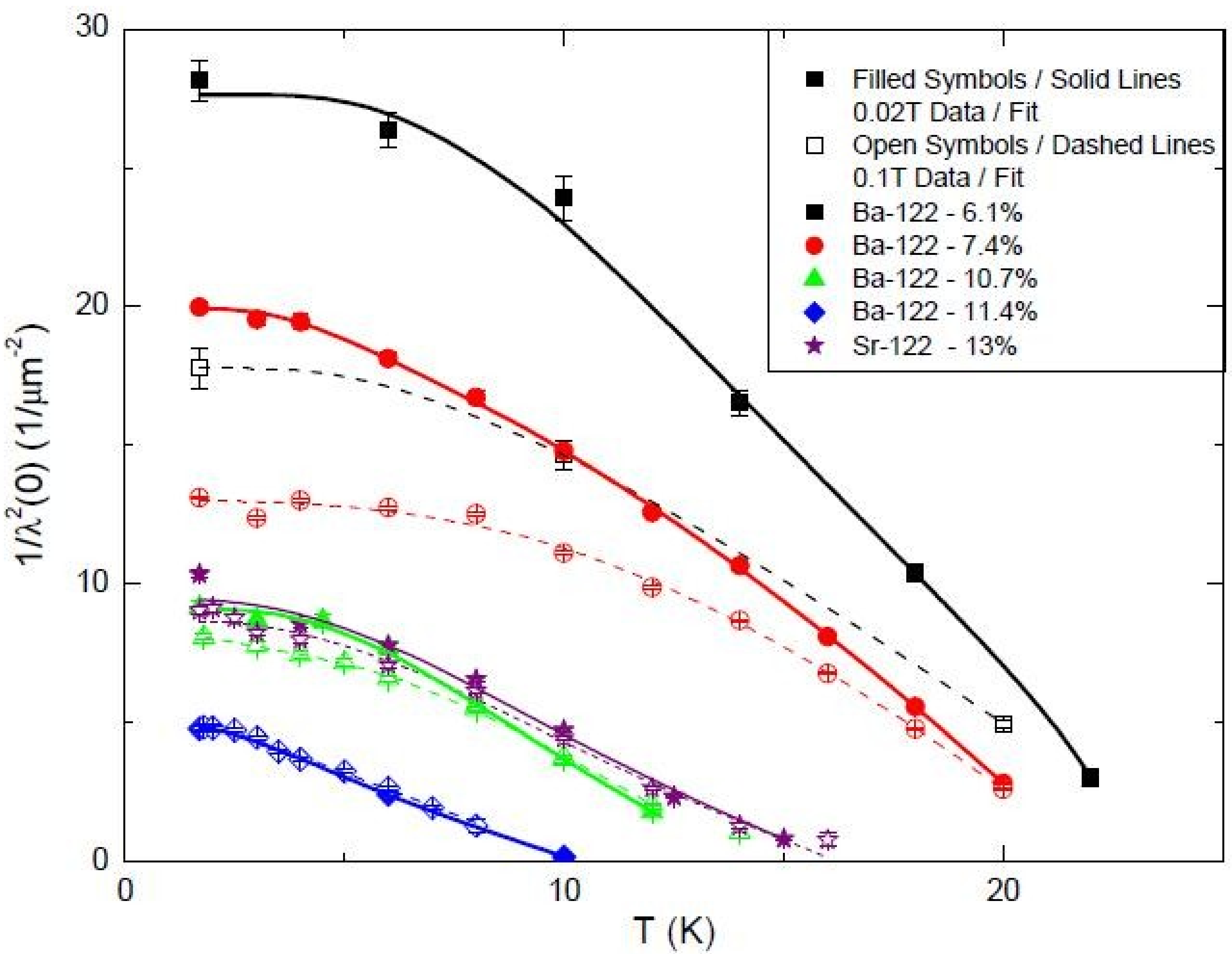
Fitting – T-dependence of λ



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- The two-gap model show good agreement for all dopings.
- The Sr-122 sample also follows the trend.
- There is strong field-dependence for lower dopings.

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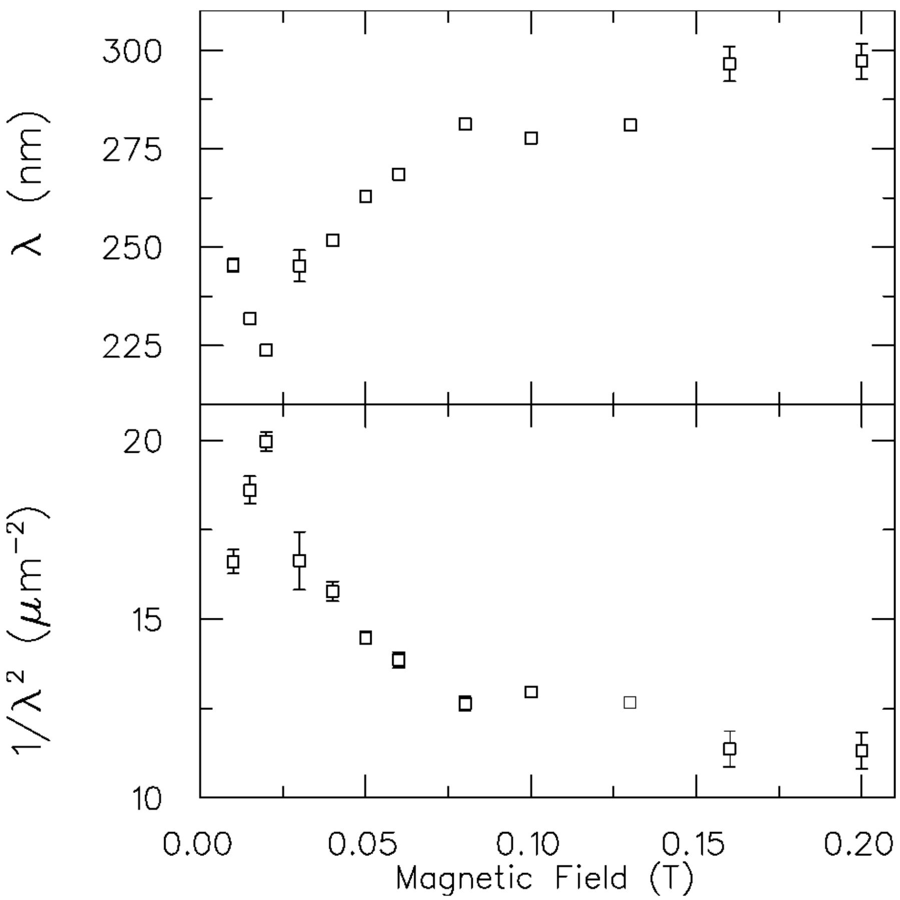
Magnetic Field Dependence



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- The behaviour of λ vs *H* is consistent with measurements of H_{c1} [Gordon *et al.* PRL (2009)].
- The flattening of λ at higher fields may indicate all of the spectral weight on the larger gap.

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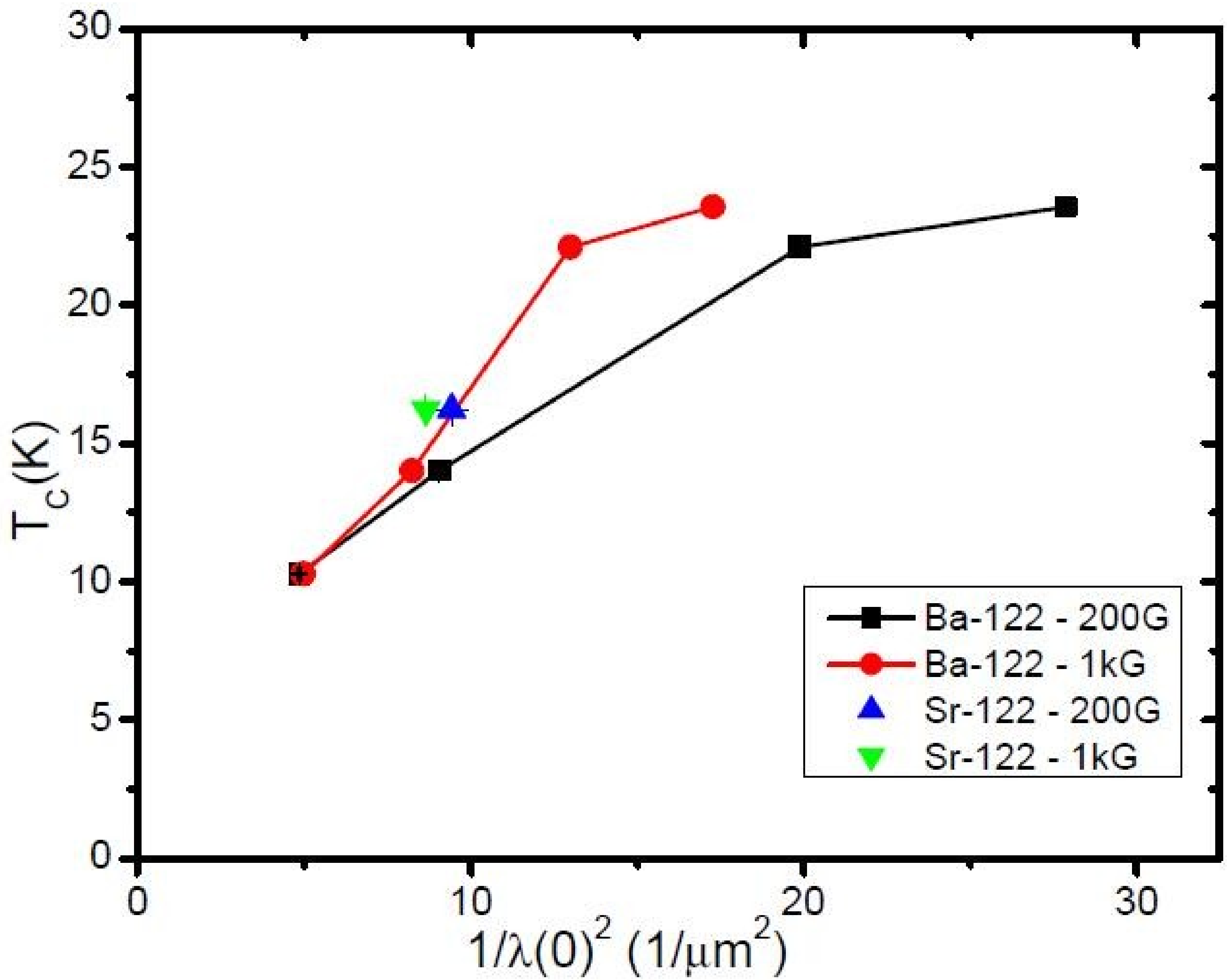
Doping Dependence of $n_S(0)$

- We find a monotonic dependence of $n_S(0)$ on T_C.
- This holds for both measured fields, and for the Sr-122 sample.



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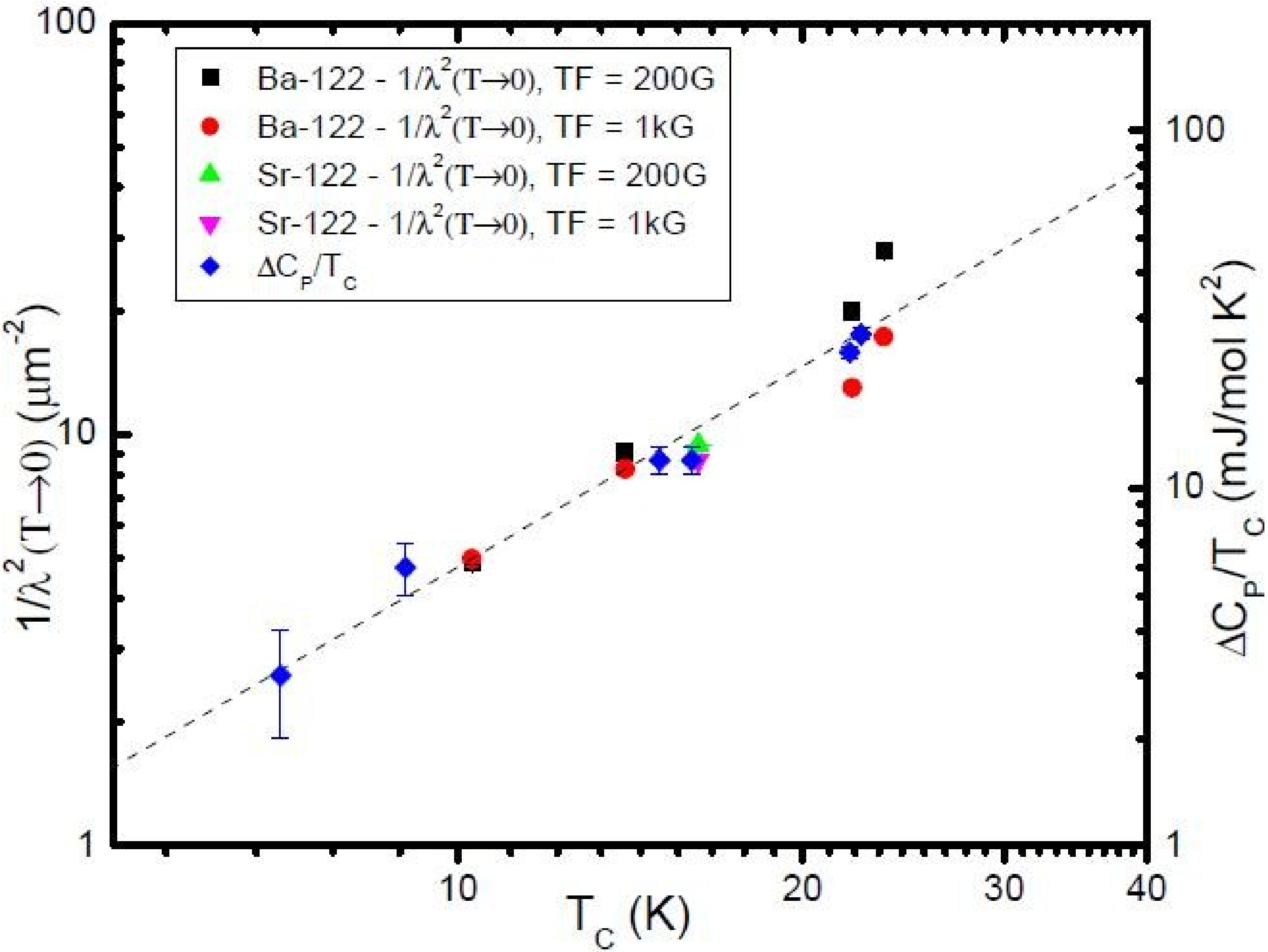
Comparison to ΔC_P / T_C

- The superfluid density also scales with the magnitude of the specific heat anomaly.



Bud'ko et al. PRB **79** (2009) 220516(R)

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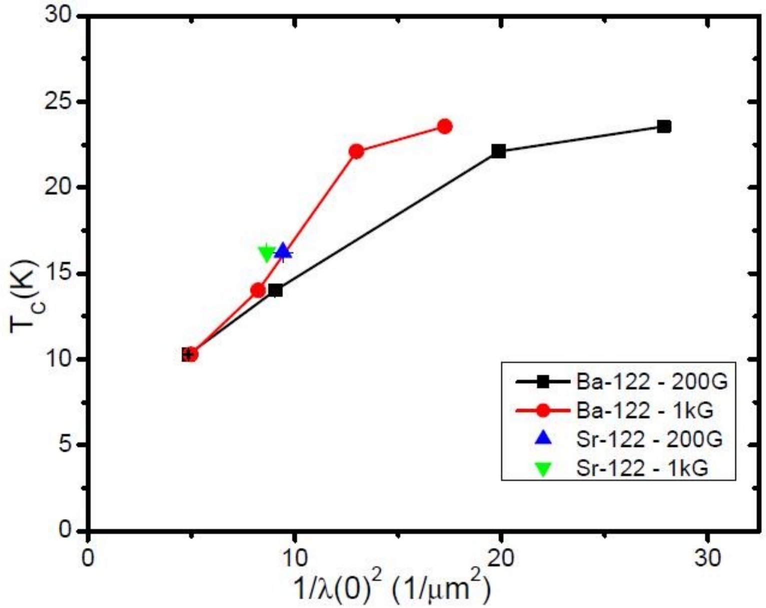
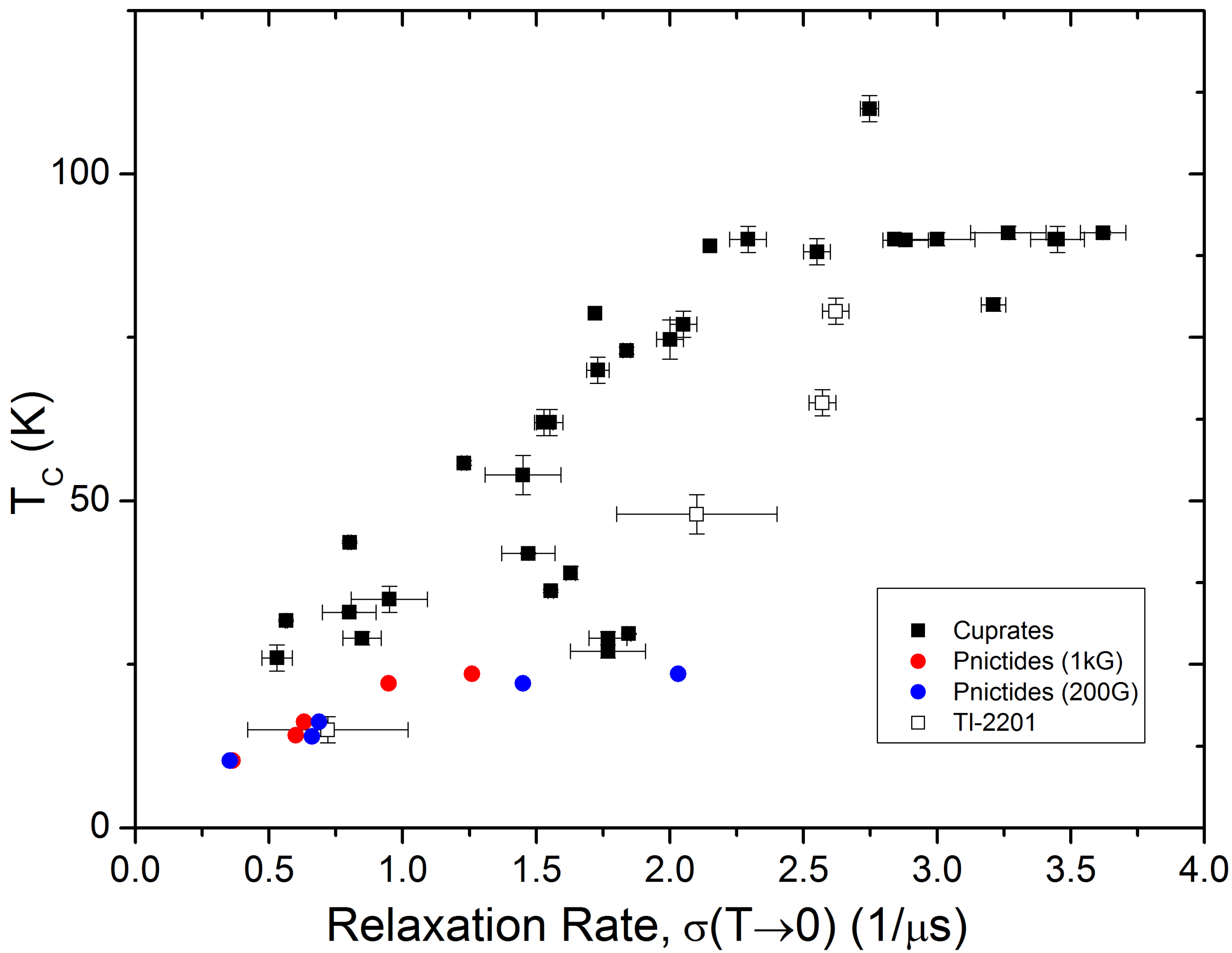
Uemura Plot





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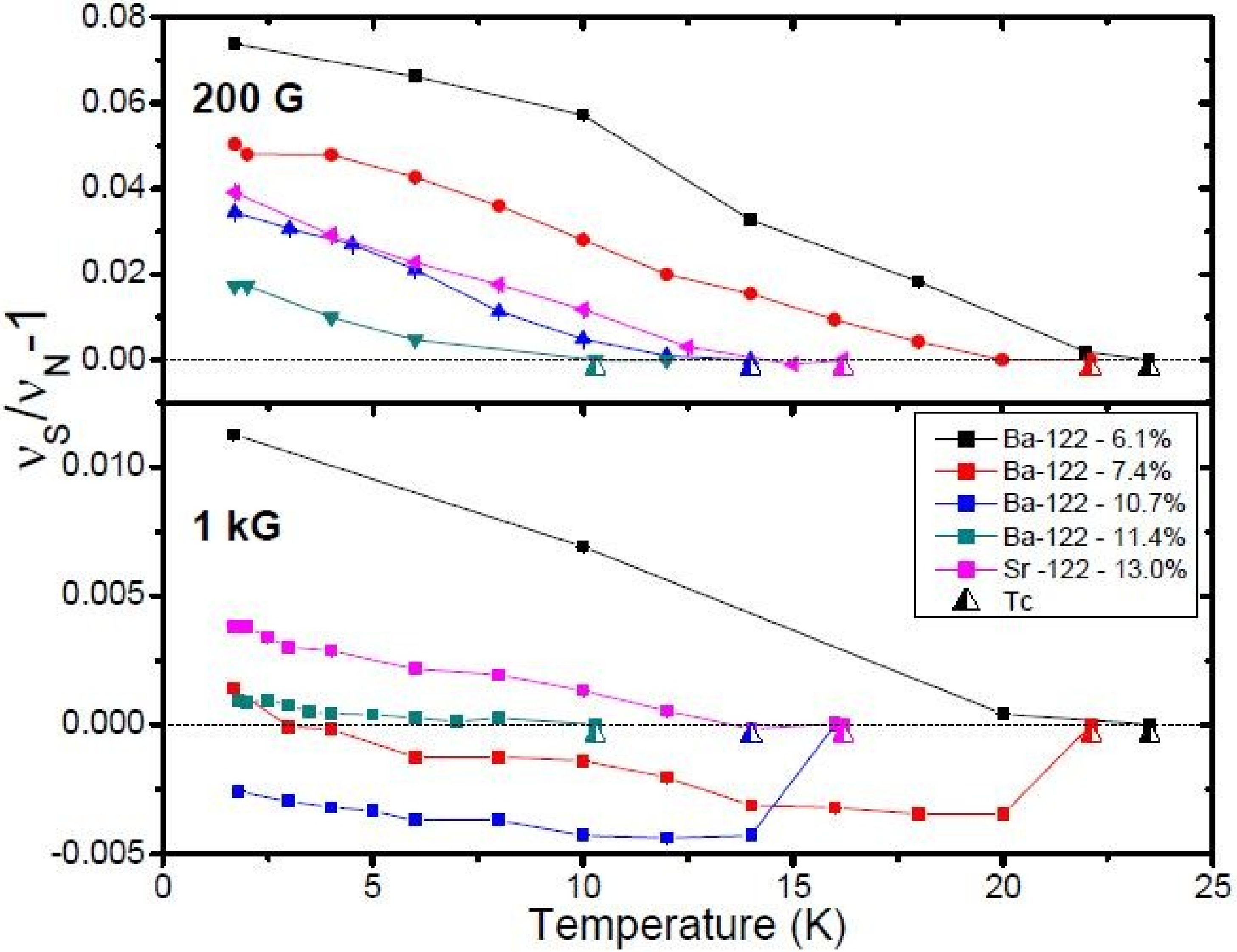
Frequency Shift below T_C



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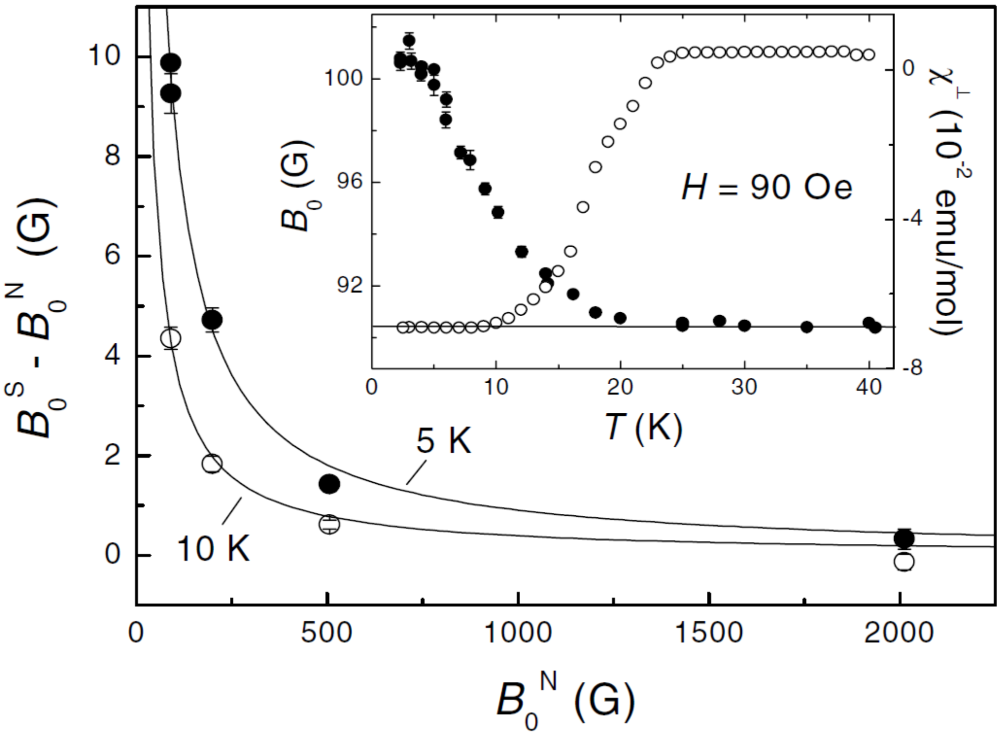
- Measurements of the muon precession frequency show a positive shift below T_C.
- This is evidence for bulk screening, and field-induced magnetism.

Frequency Shift below T_C



J.E. Sonier et al. *Phys. Rev. Lett.* **91** (2003) 147002

- Similar ordering has been seen in $Pr_{2-x}Ce_xCuO_4$ by μSR.

- Our shift it is independent of H, indicating ĉ-axis ordering.

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Conclusions

- Underdoped samples showed $\hat{c}$-axis magnetism, that was highly disordered.

- Found superconductivity in or near strong magnetism in the lowest dopings.

- The superfluid density, $n_S(0) \sim 1/\lambda(0)^2$, varies monotonically with T_C.

- The muon precession frequency increases with decreasing temperature below T_C, indicating field-induced magnetism.

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Fit Values of $\lambda_0(0)$

	T_C	$\lambda_0(0.02T)$ (nm)	$\lambda_0(0.1T)$ (nm)
$Ba(Fe_{0.939}Co_{0.061})_2As_2$	23.6	189.4 ± 1.1	240.5 ± 2.0
$Ba(Fe_{0.926}Co_{0.074})_2As_2$	22.1	224.2 ± 0.6	277.4 ± 1.0
$Ba(Fe_{0.899}Co_{0.101})_2As_2$	14.1	332.2 ± 2.2	348.3 ± 4.6
$Ba(Fe_{0.89}Co_{0.11})_2As_2$	10.3	453.8 ± 2.6	448.0 ± 2.4
$Sr(Fe_{0.87}Co_{0.13})_2As_2$	16.2	325.5 ± 0.5	339.8 ± 0.6

TABLE I: Results of fitting $1/\lambda^2(T)$ to Eqn. 1

- The field-dependence is very obvious for $x = 0.061$.
- As the doping is increased, T_C decreases, and so does the difference between λ_0 in 0.02T and 0.1T.

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