λ as a Measure of the Superfluid

$$n_s = \frac{mc^2}{4\pi e^2}\frac{1}{\lambda^2}$$

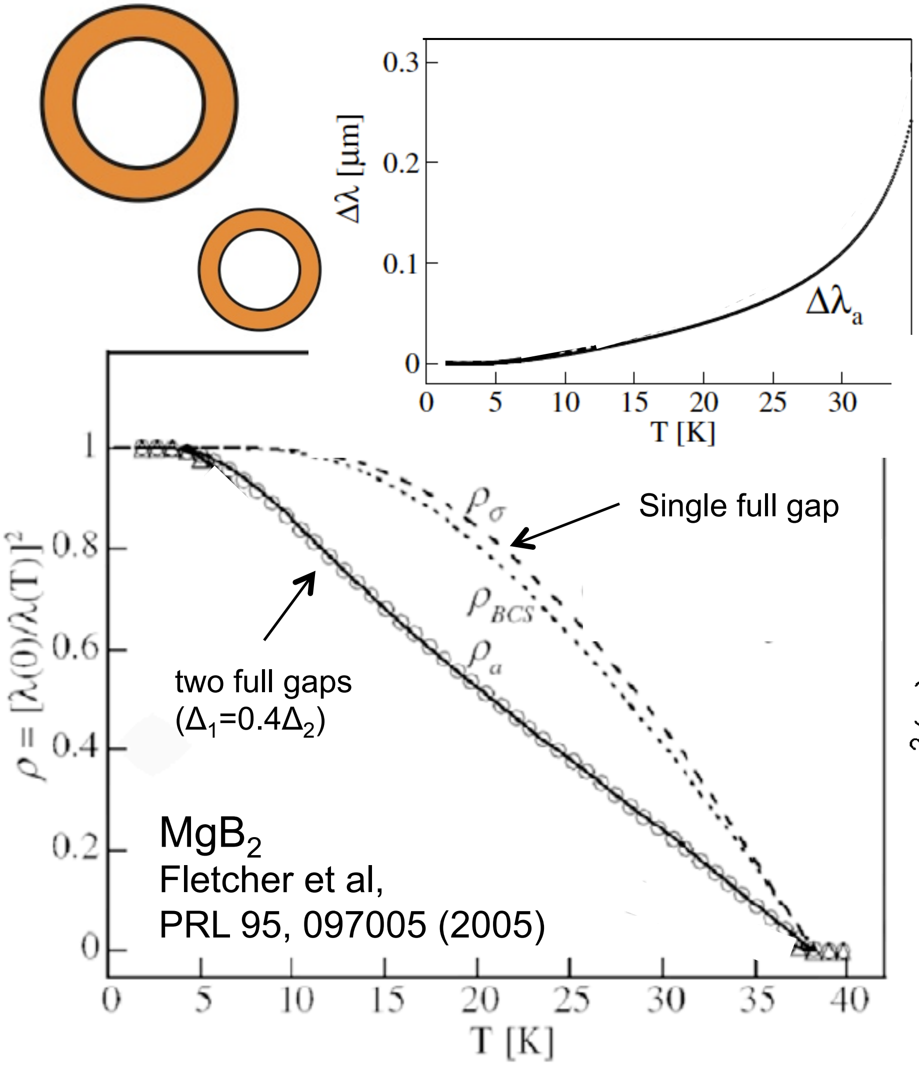
$$\rho_s \equiv 1/\lambda^2$$

Only a few techniques can measure the absolute value, λ, : most average over the sample or the sample surface

λ as a Measure of the Superfluid

The temperature dependence, $\Delta\lambda(T)$, usually is determined by the gap structure

Two-full-gap superconductivity

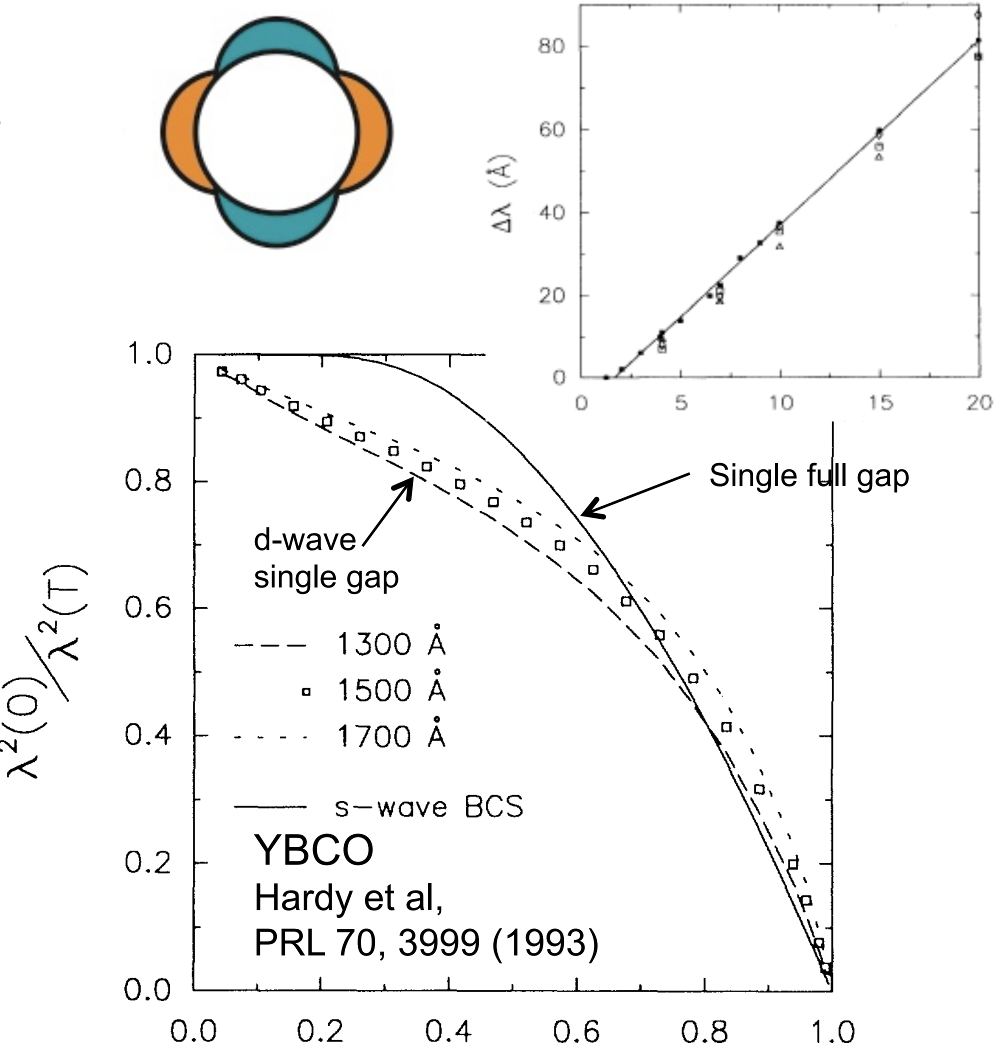


Single full gap

two full gaps
($\Delta_1=0.4\Delta_2$)

MgB_2
Fletcher et al,
PRL 95, 097005 (2005)

Nodal superconductivity



d-wave
single gap

Single full gap

YBCO
Hardy et al,
PRL 70, 3999 (1993)

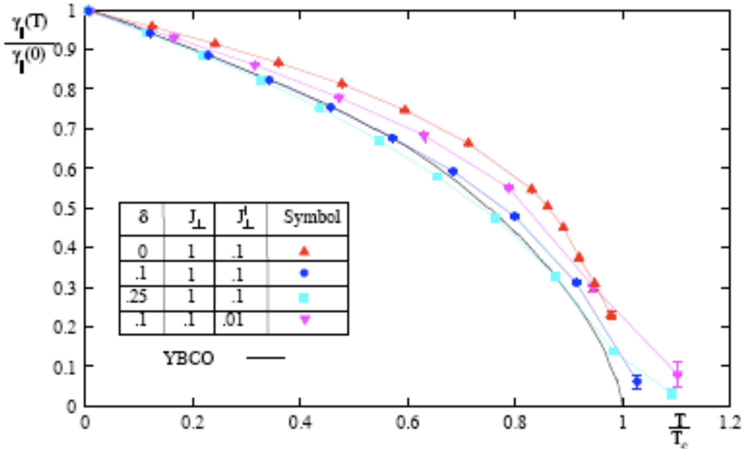
λ as a Measure of the Superfluid

$\Delta\lambda(T)$ is also sensitive to

- scattering
e.g., Hirschfeld, Putikka, and Scalapino in YBCO

- phase fluctuations
Carlson et al, 1999

- loss of carriers to competing order parameters

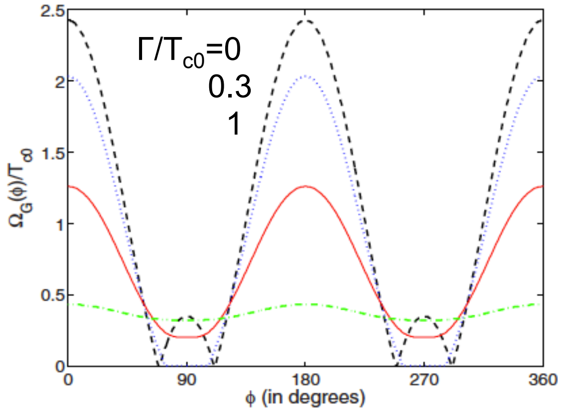


Pnictide penetration depth theory (not comprehensive)

Different materials have different gap symmetry

-- hypothesis:

Nodal and nodeless states are nearly degenerate; pnictogen height is a possible switch (Kuroki *et al*, PRB 79, 224511 (2009))



Impurity scattering can alter the intrinsic behavior

a) intrinsic nodal:

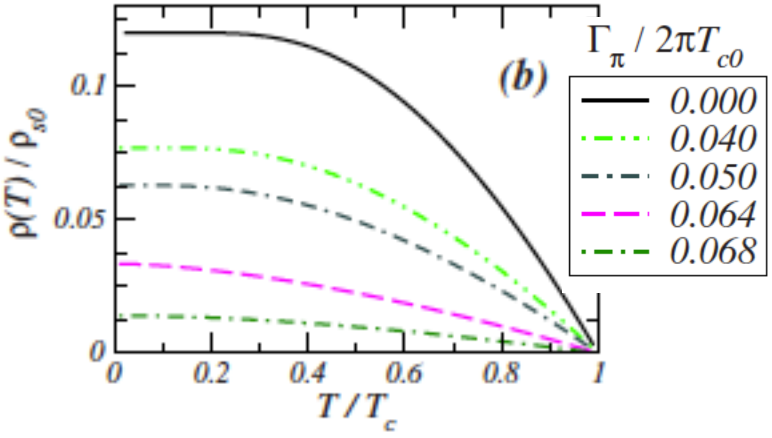
impurity scattering lifts the nodes

Mishra *et al*, PRB 79, 094512 (2009)

b) intrinsic nodeless s+- :

interband scattering gives power law ρ_s

Vorontsov *et al*, PRB 79, 140507(R)



Questions in the Pnictides

- What is the order parameter?

Neutron scattering and STM qpi indicate that it's s+- in at least some materials, but are there important further details or significant variation across materials?

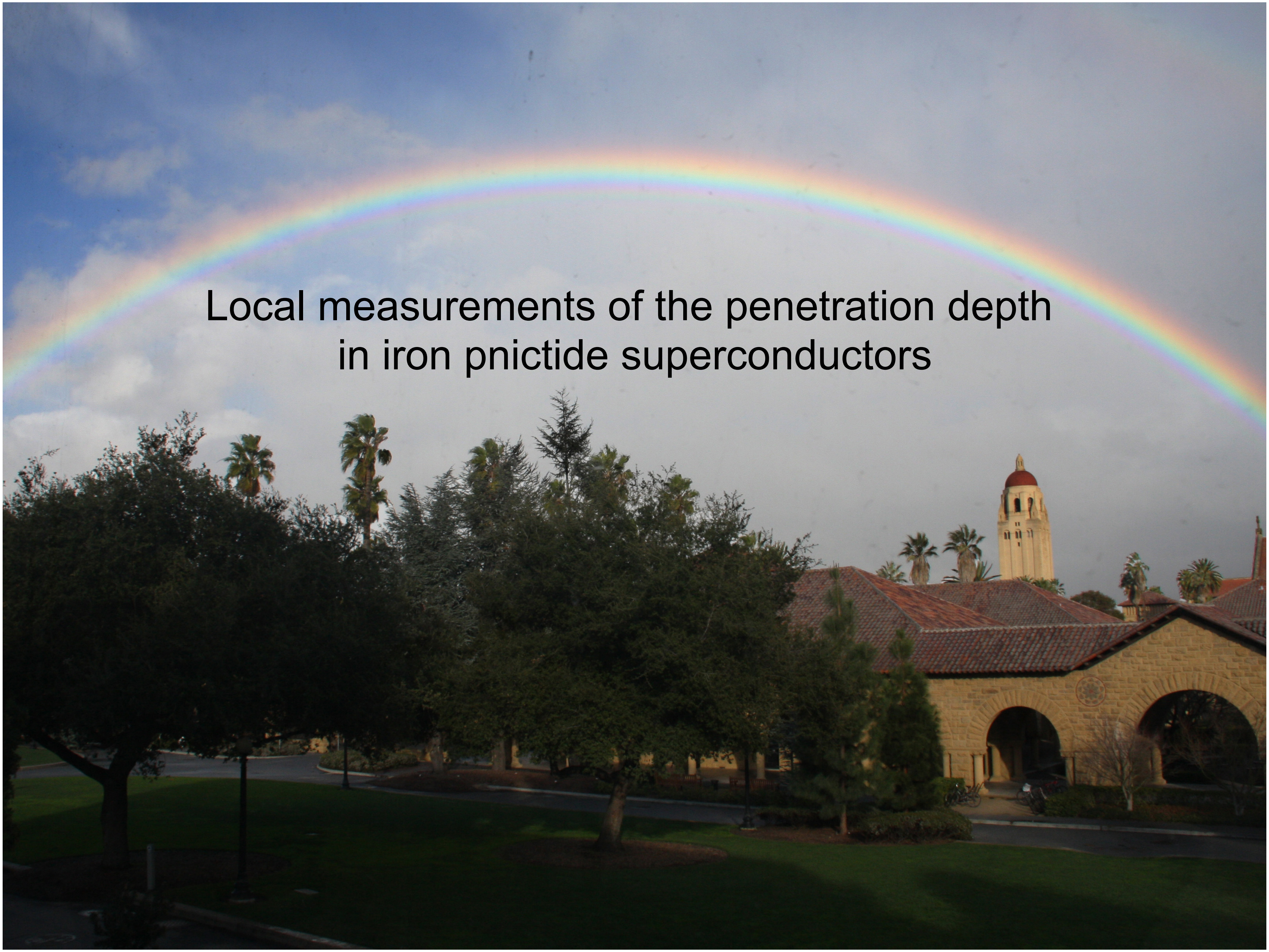
- Are phase fluctuations important for the low-temperature behavior?

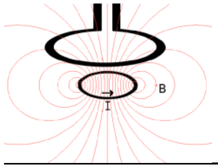
Probably not

- How does the neighboring magnetic phase impact the superconductivity?

- Is inhomogeneity or sample variability prevalent? If yes, why?

Local measurements of the penetration depth in iron pnictide superconductors





Collaborators and Funding

MFM Experiments
Lan Luan
Ophir Auslaender

SQUID Experiments - 0.3 K and up
Clifford Hicks
Tom Lippman

SQUID Experiments - 4 K and up
Beena Kalisky
John Kirtley

Also thanks to: Jenny Hoffman, Nick Koshnick, Eric Straver, Hendrik Bluhm, Dan Rugar

Pnictides
Jiun-Haw Chu
James Analytis
Ian Fisher

Zhi-An Ren
Zhong-Xian Zhao

Hideo Hosono

Athena Safa-Sefat
Michael McGuire
Brian Sales
David Mandrus

YBCO
Doug Bonn
Ruixiang Liang
Walter Hardy

SQUIDs
Martin Huber

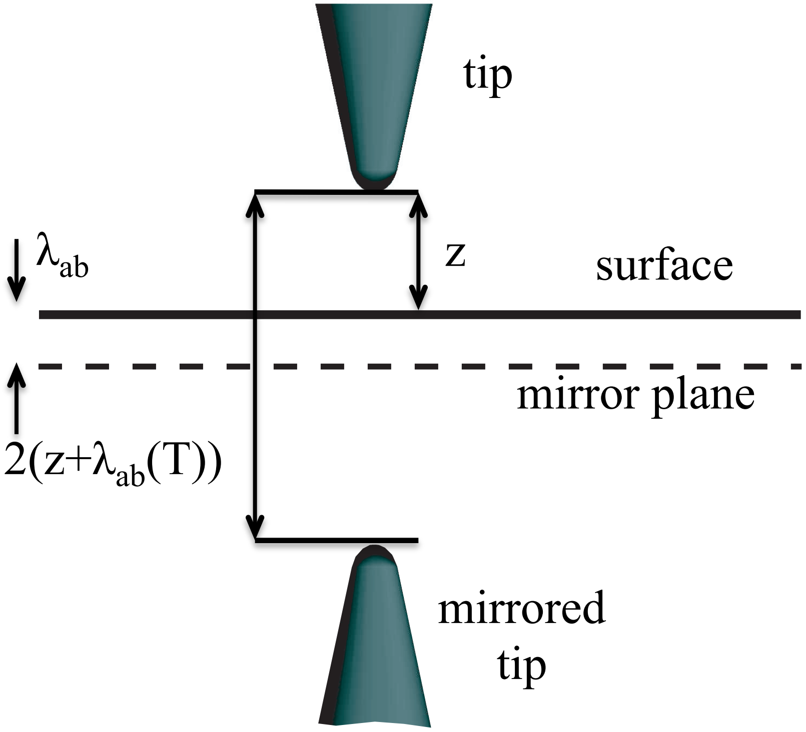
BES/SIMES

IBSF
Rothschild
L'Oreal

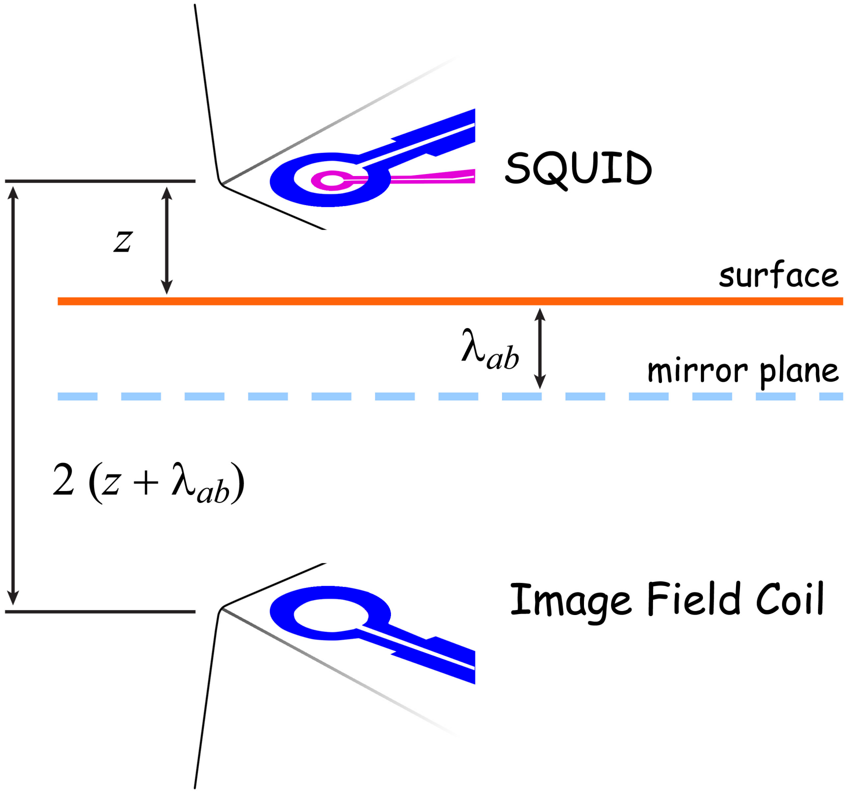
Primarily Funded by DOE BES as part of SIMES

Local Diamagnetism as a Measure of λ

Magnetic force microscopy



Scanning SQUID susceptometry



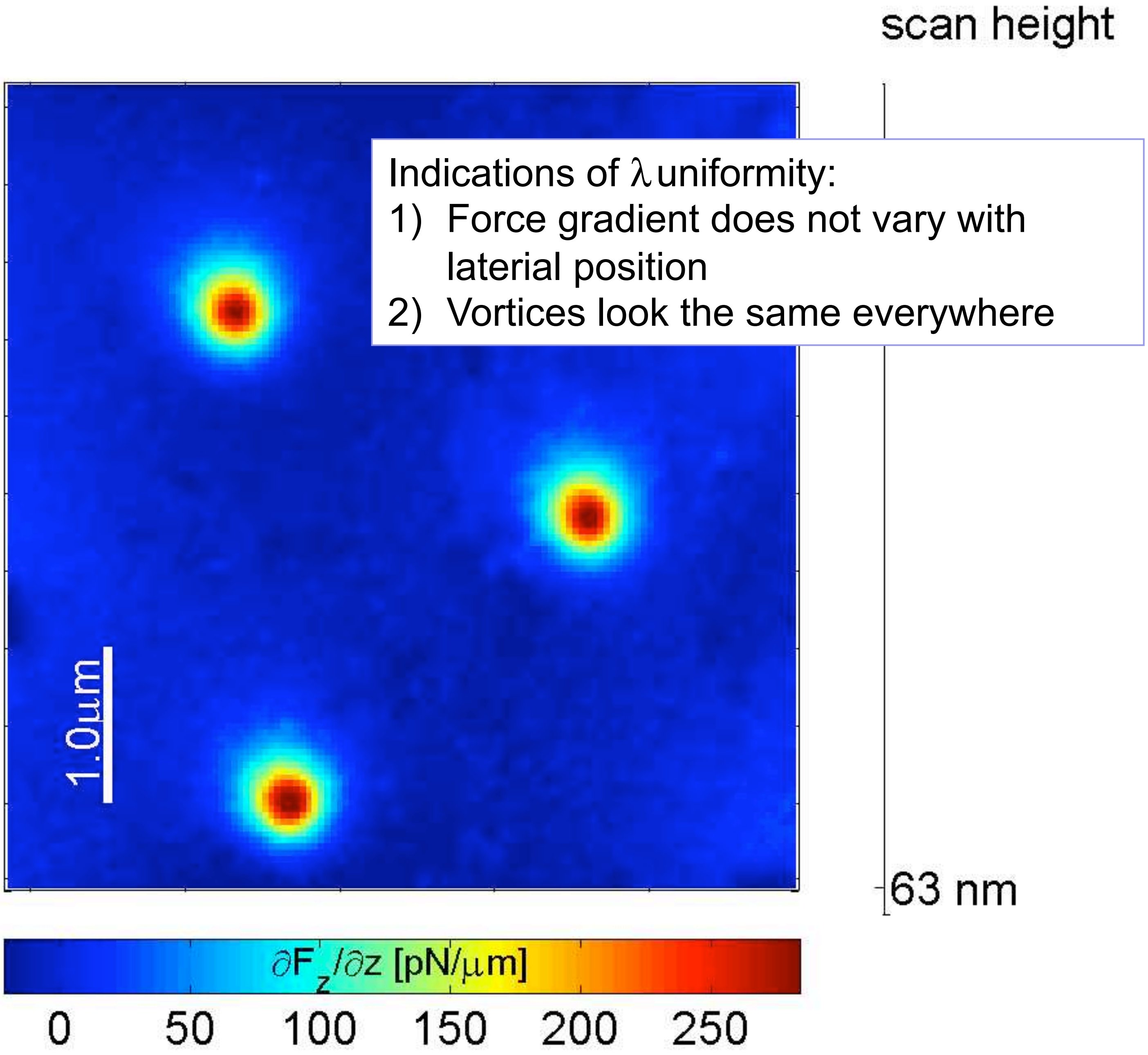
- local measurement: observe local variations / check sample homogeneity "at no additional cost"
- avoid artifacts from edges and topography
- avoid mixing of λ_c and λ_{ab} (if the sample surface is parallel to the crystal axes)
- time consuming

Want to see more details of technique and calibration data on known samples? Please ask.

Examples of fairly homogeneous samples

Indications of λ uniformity:

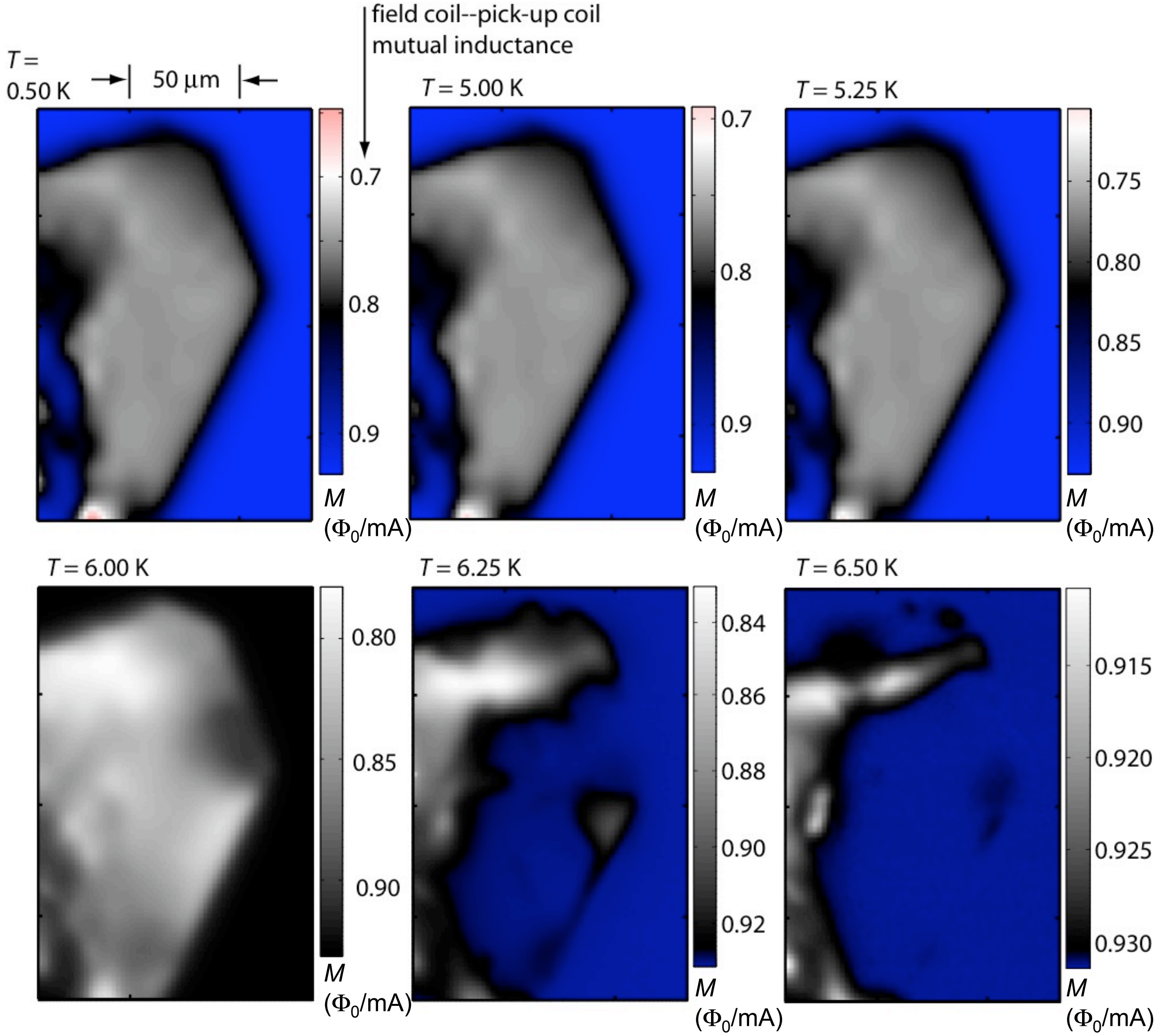
1) Force gradient does not vary with lateral position
2) Vortices look the same everywhere

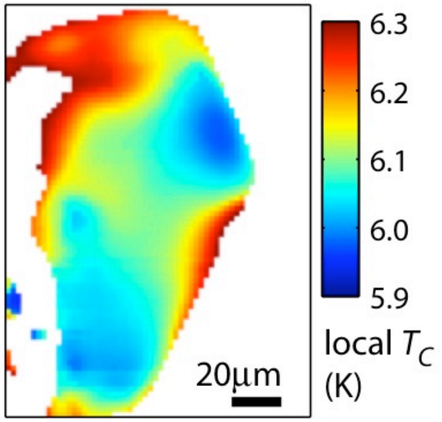


Susceptibility scans of LaFePO

local T_C varies by ~0.4 K across the sample.

Scan just above the sample, and measure the field coil -- pick-up coil mutual inductance
To get local T_C: pixel-by-pixel, extract $h_{eff}(T)$, convert to superfluid density, and extrapolate to zero.

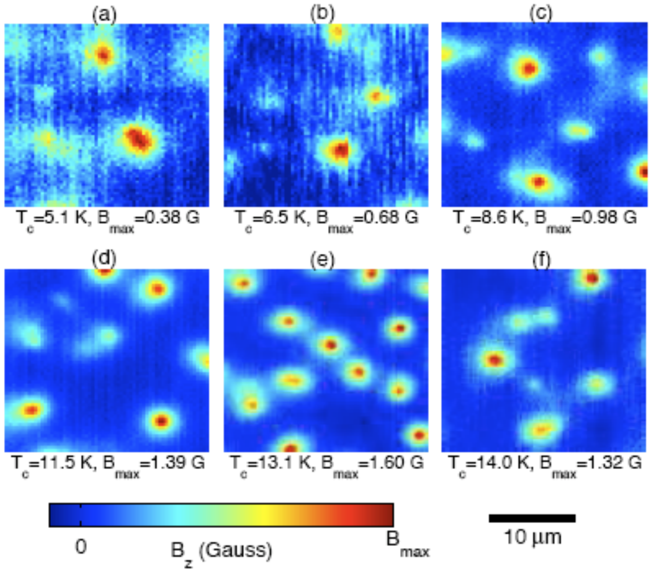


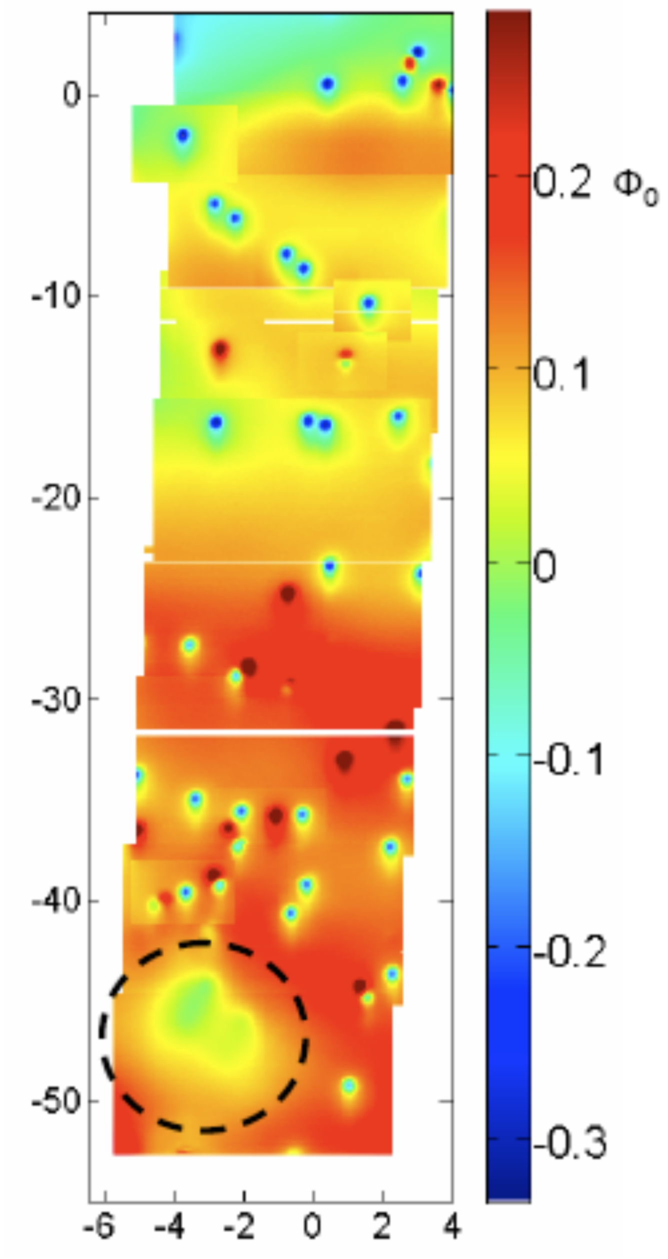


(~0.1 K systematic error on T_C)

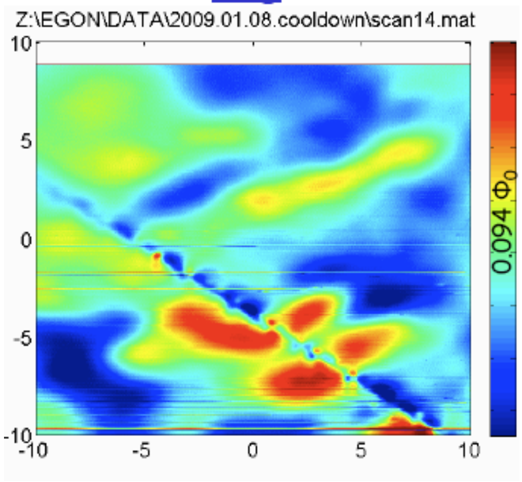
Examples of “less homogeneous” and “inhomogeneous” samples

Examples of “not perfectly homogeneous” samples

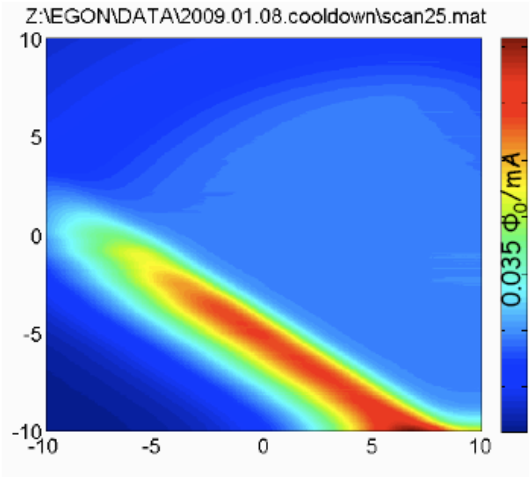




mag

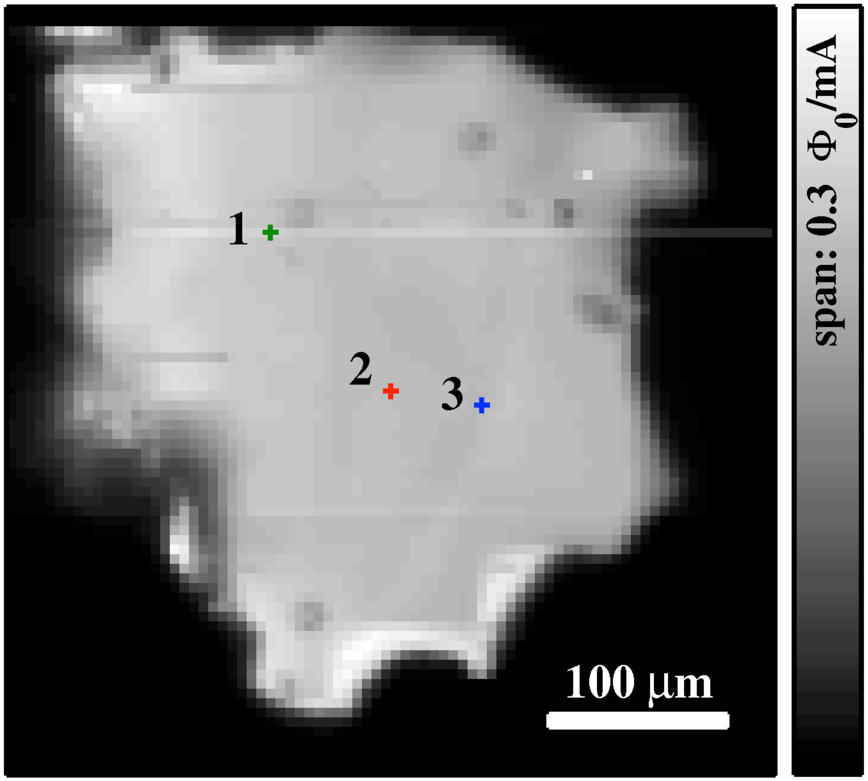


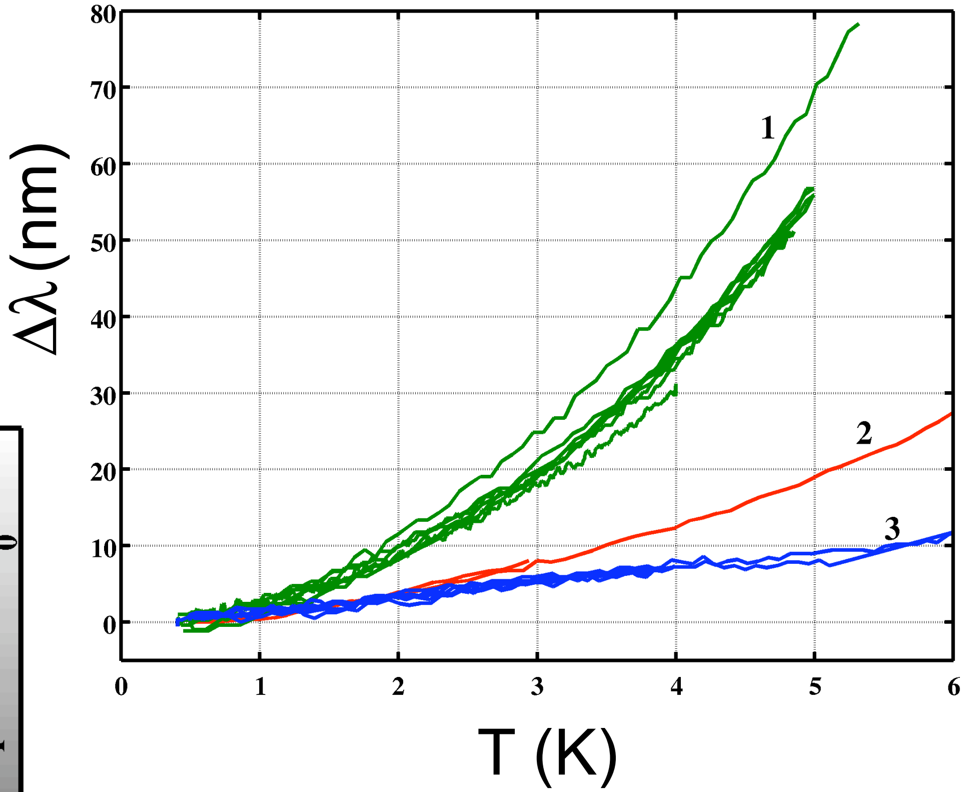
susc



Examples of “not perfectly homogeneous” samples

$BaFe_2(As_{0.77}P_{0.23})_2$





Local Measurements of Penetration Depth in Pnictides

Experiments

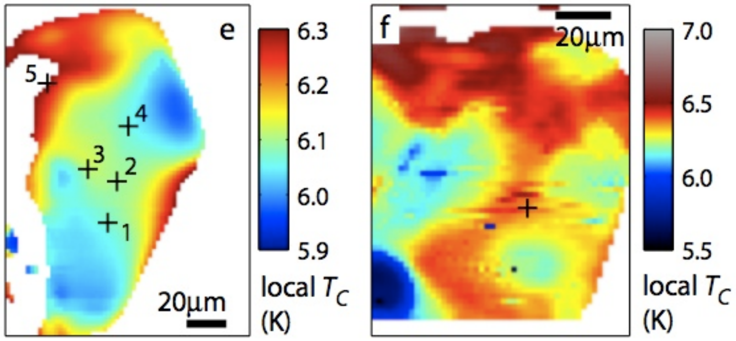
1. $\Delta\lambda(T)$ of LaFePO (scanning SQUID)
2. Superfluid density on twin boundaries in $Ba(Fe_{1-x}Co_x)_2As_2$
3. $\Delta\lambda(T)$ and λ_0 of $Ba(Fe_{1-x}Co_x)_2As_2$ (scanning SQUID & MFM)

Scanning SQUID Microscopy of Single-Crystal LaFePO (Tc = 6 K)

Cliff Hicks

$\Delta\lambda(T)$ of LaFePO: linear, with a slope of 143±15 Å/K

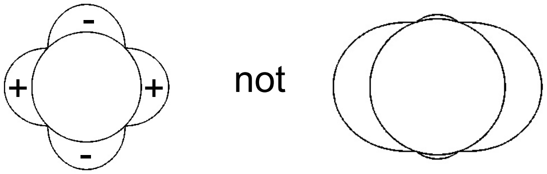
1. measurement points:



2. $d\lambda/dT$ over $0.7<T<1.6$ K:
   sample #1: 1. 146
   2. 139
   3. 136
   4. 150
   sample #2: 1. 142 Å/K

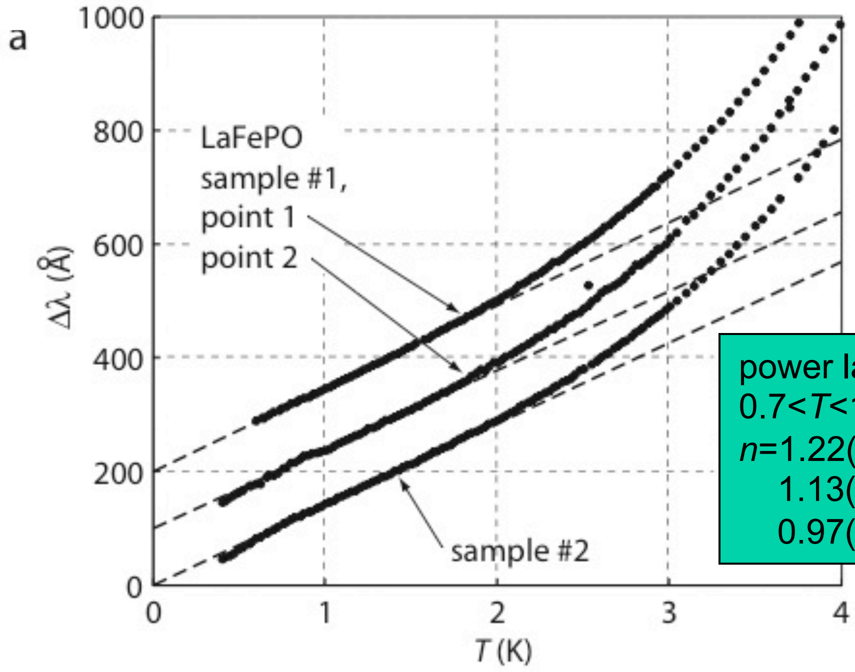
$d\lambda/dT$ of LaFePO at $T\to0$:
143±15 Å/K
(including systematic errors)

3. nodes are well-formed.



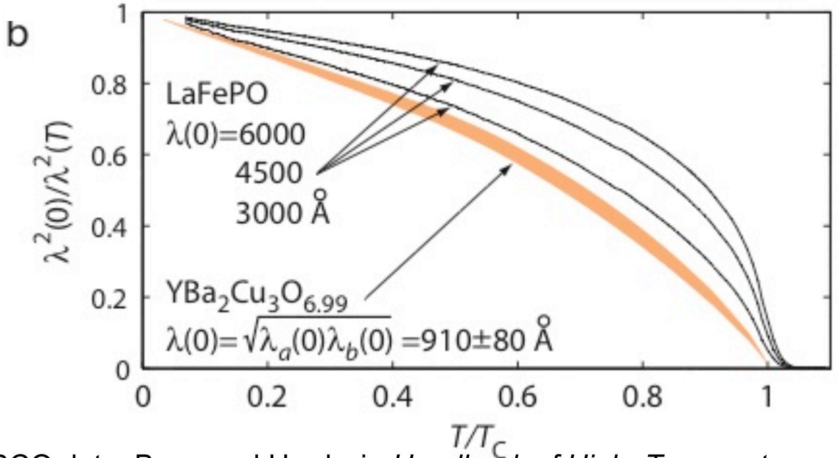
not

4. ρ_s rises sharply just below T_C.



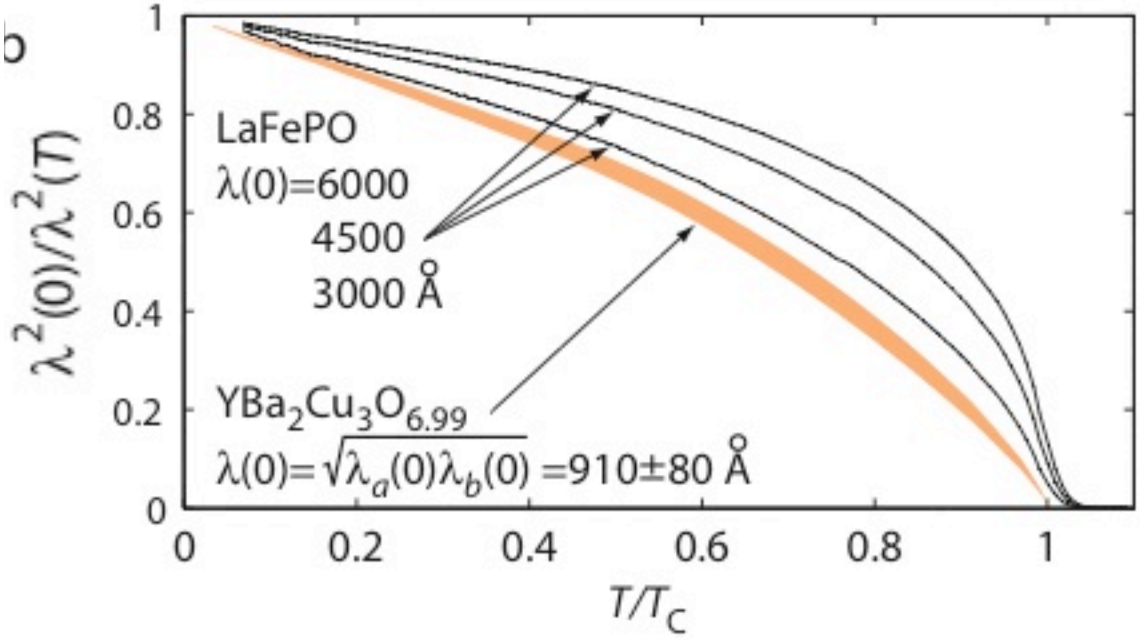
Å/K:
146
139
142

power law,
$0.7<T<1.6$ K:
n=1.22(4)
1.13(10)
0.97(5)

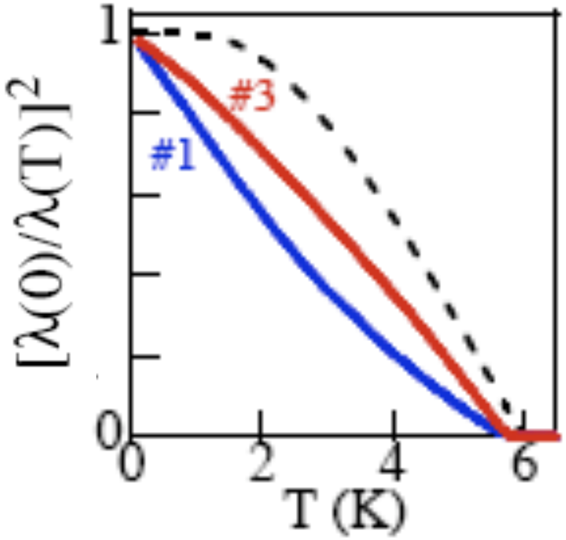


(YBCO data: Bonn and Hardy, in *Handbook of High- Temperature Superconductivity*, and Pereg-Barnea *et al*, PRB **69** (2004) 184513.)

$\Delta\lambda(T)$ of LaFePO: linear, with a slope of 143±15 Å/K

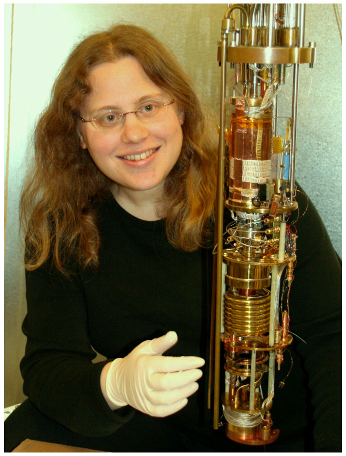


Note: Carrington group also sees $\Delta\lambda(T)$ ~ T in LaFePO, (published before us) but with a slope that varies between samples, and a different overall temperature dependence.



low-temperature $\Delta\lambda(T)$ ~ T,
ρ_s rises sharply just below T_C.

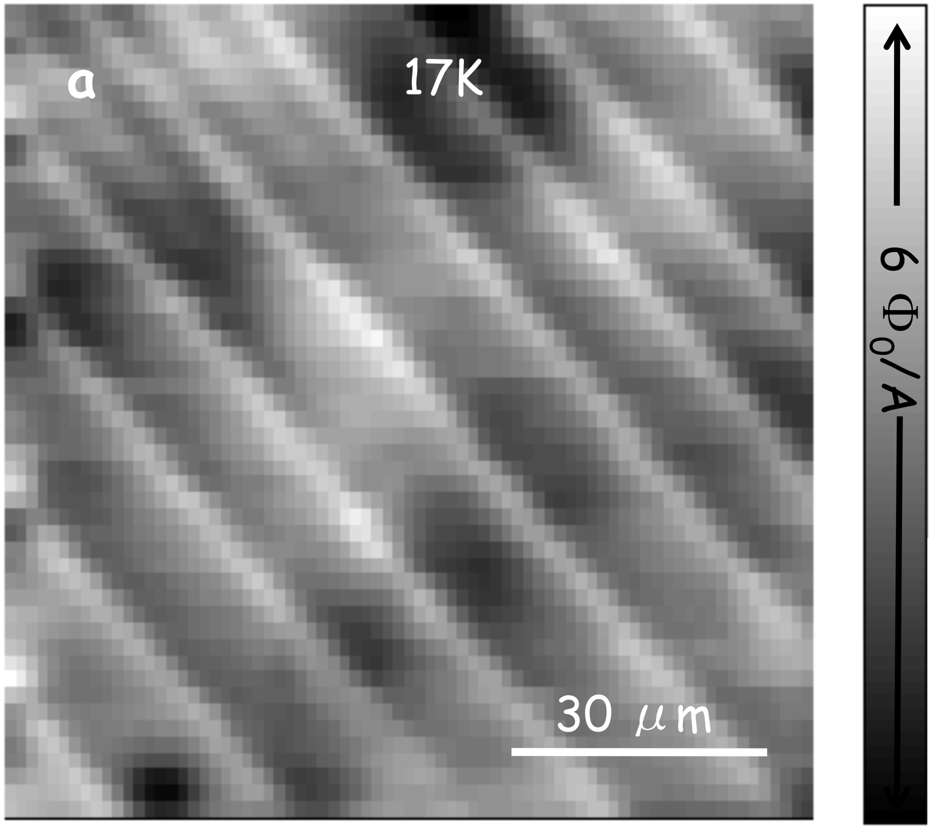
Enhanced superfluid density on twin boundaries of $Ba(Fe_{1-x}Co_x)_2As_2$

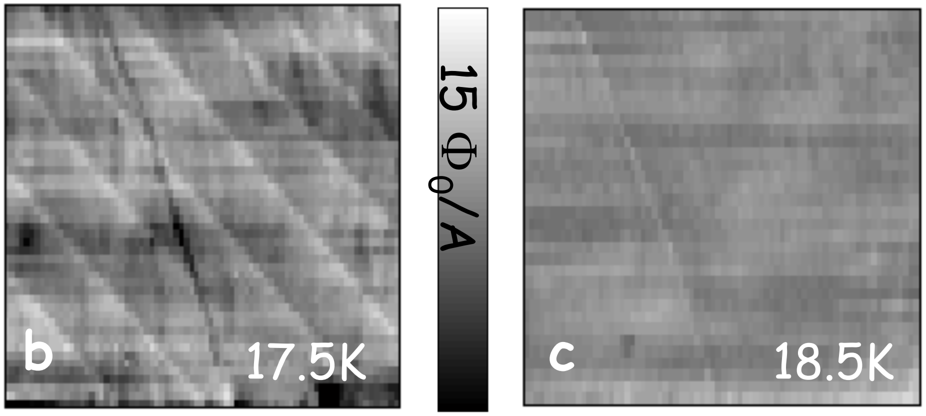


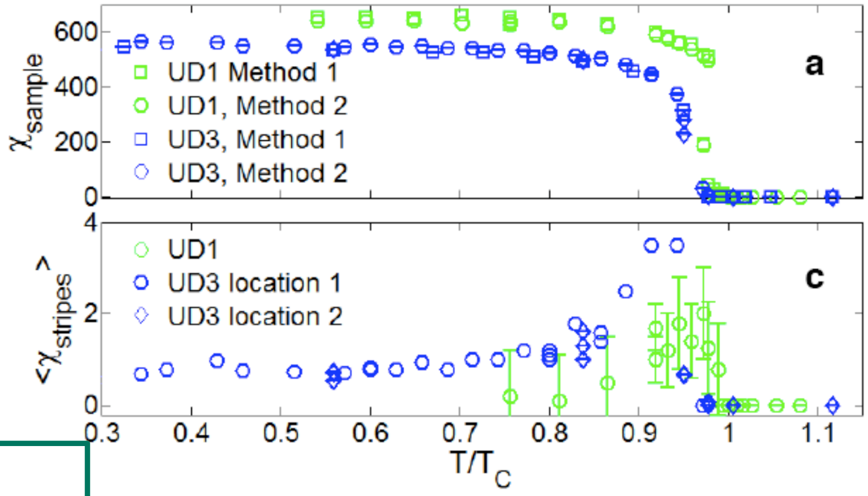
Beena Kalisky
John Kirtley

Enhanced superfluid density on twin boundaries

$Ba(Fe_{1-x}Co_x)_2As_2$



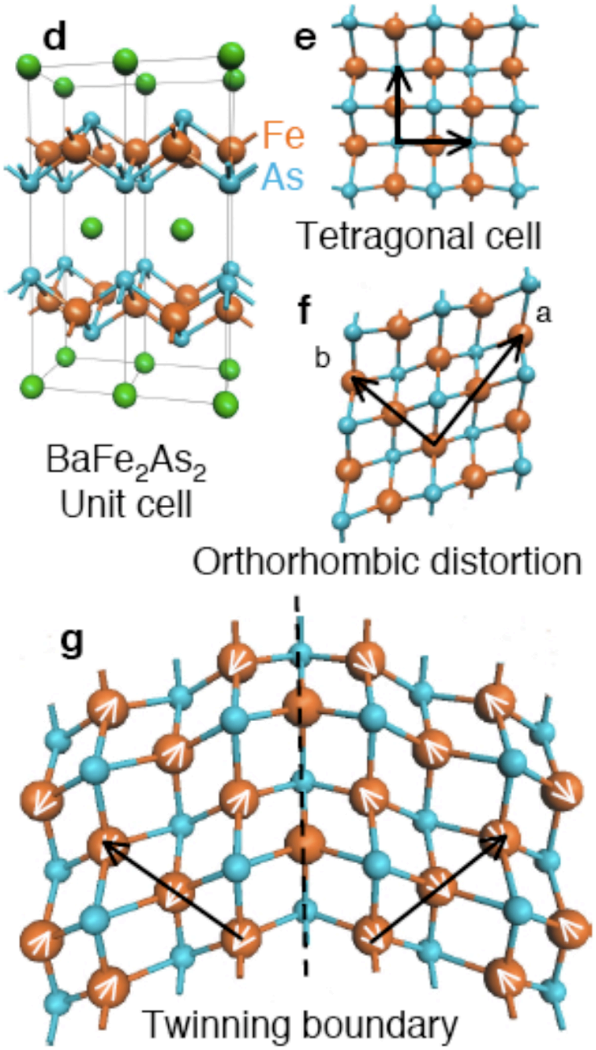




enhancement is
comparable to the bulk diamagnetism at 17 K
about 2% of the bulk diamagnetism at 5K

$Ba(Fe_{1-x}Co_x)_2As_2$

Enhanced superfluid density on twin boundaries



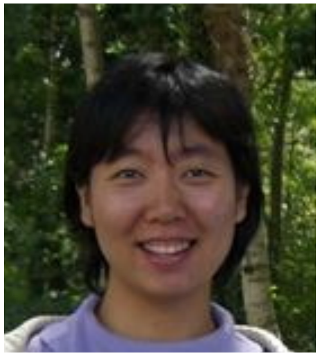
Checks:

1) Spacing is similar to that of twin boundaries observed by polarized light microscopy in similar samples.
2) Stripes do not change configuration on thermal cycling above Tc, but they do change configuration on thermal cycling above Tstructural.
3) Existence of twins in UD single crystals confirmed by x-ray of single crystals from the same batches.
4) Stripes exist only in underdoped samples (study of 5 UD, 1OPD, 2 OD)

Speculations on mechanism
-Competing order parameter,
e.g. suppression of SDW ?
-Frustrated magnetism ?
-Strain ?

Existence of twin boundaries previously demonstrated by Tanatar *et al.* by polarized light microscopy and x-ray

λ_0 and $\lambda(T)$ across the dome in $Ba(Fe_{1-x}Co_x)_2As_2$



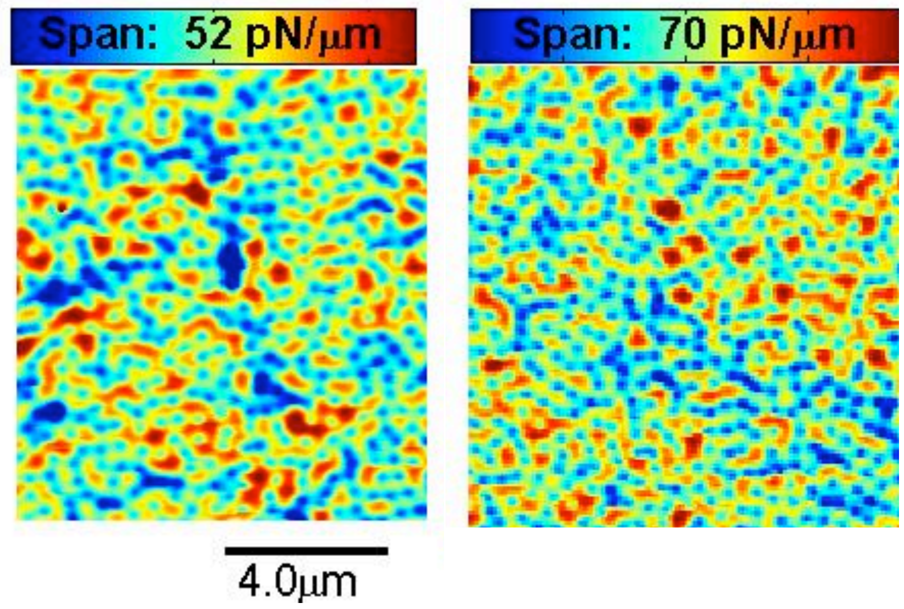
Lan Luan

Motivation for Local Measurements in $Ba(Fe_{1-x}Co_x)_2As_2$

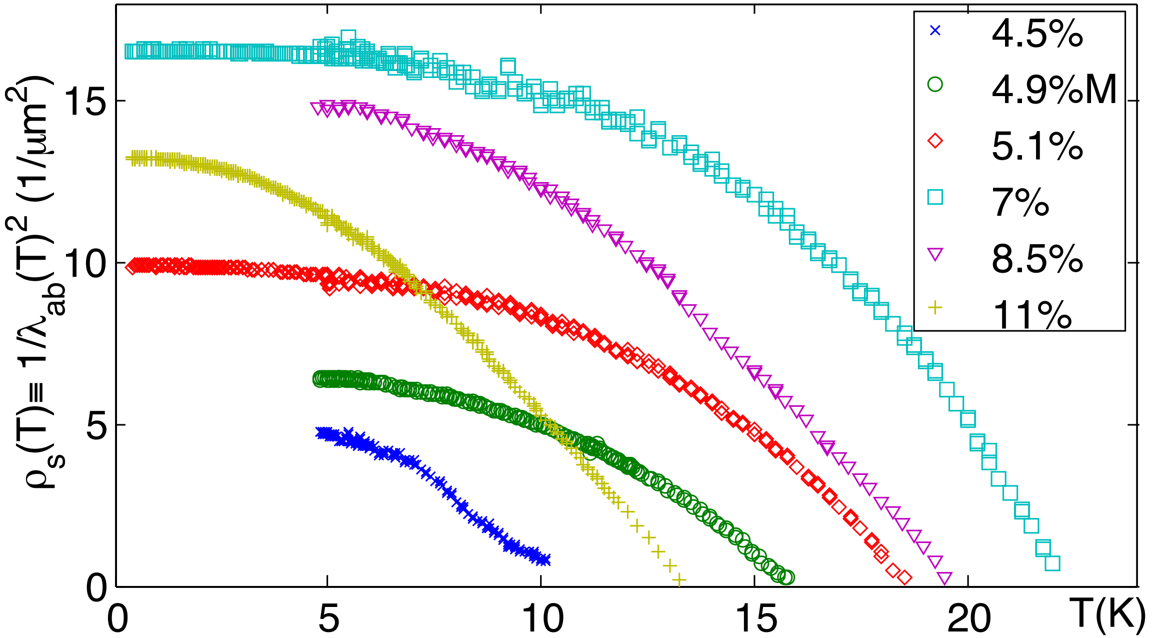
Early literature showed different results from different groups on similar samples

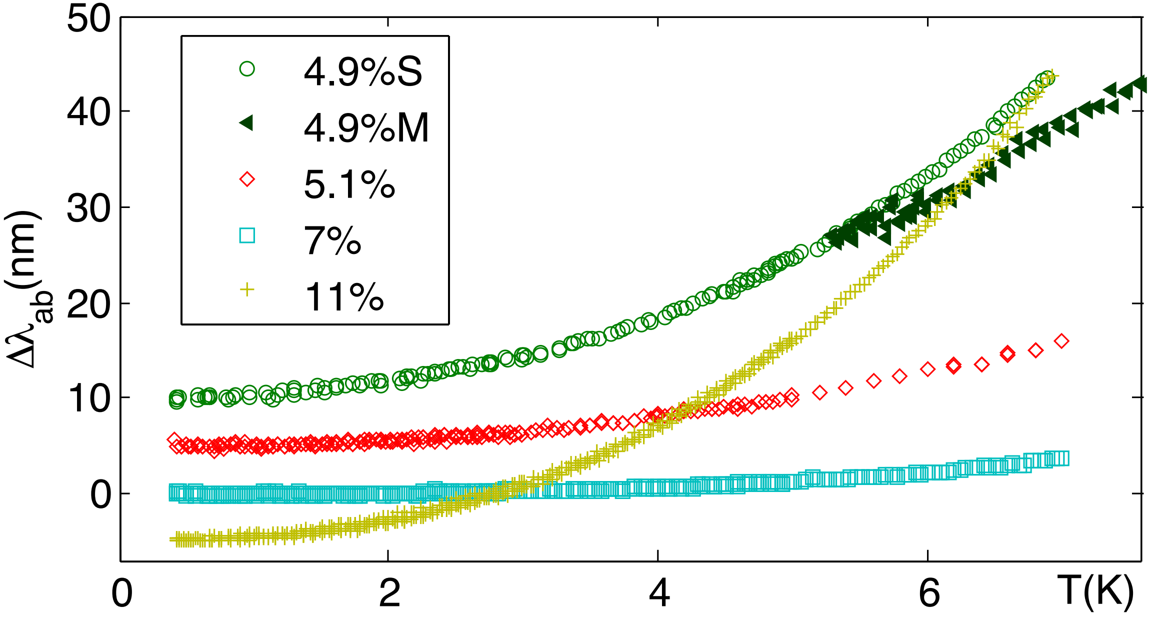
For underdoped samples, λ_0 is greatly decreased (superfluid density is greatly enhanced) on twin boundaries

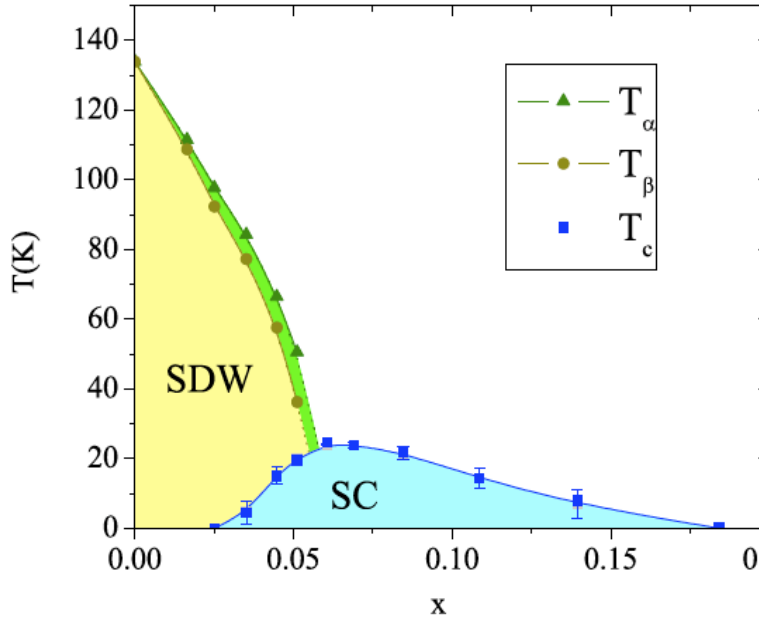
Across the dome, vortex pinning landscape is not homogenous



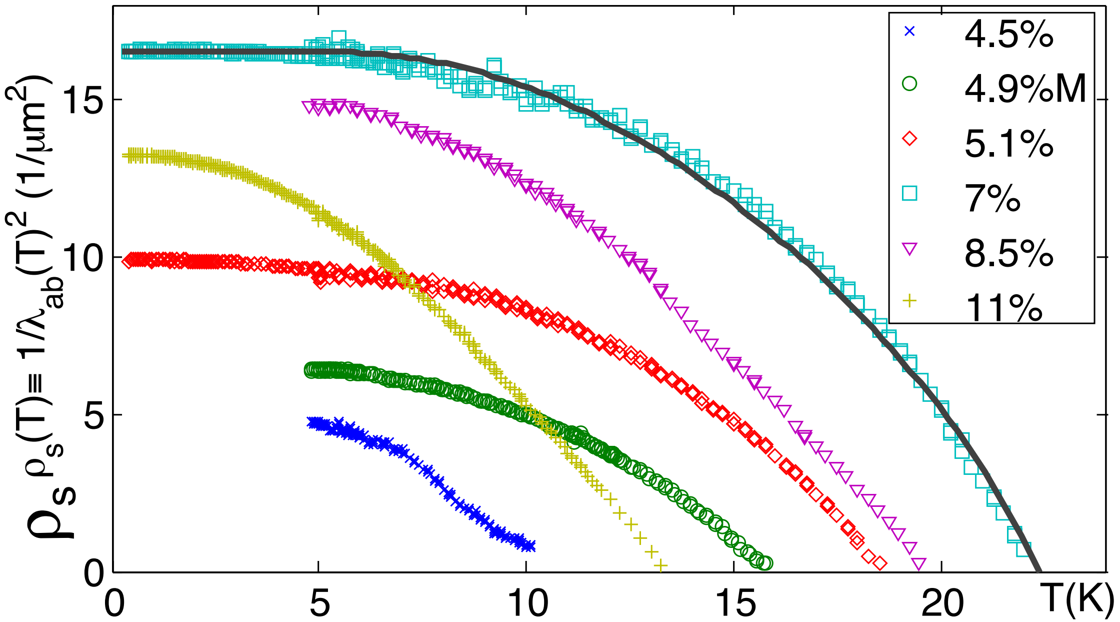
Systematic evolution of $\rho_s(T)$

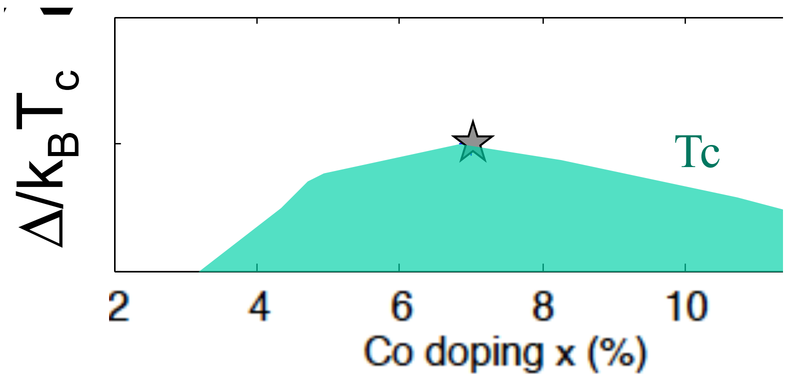


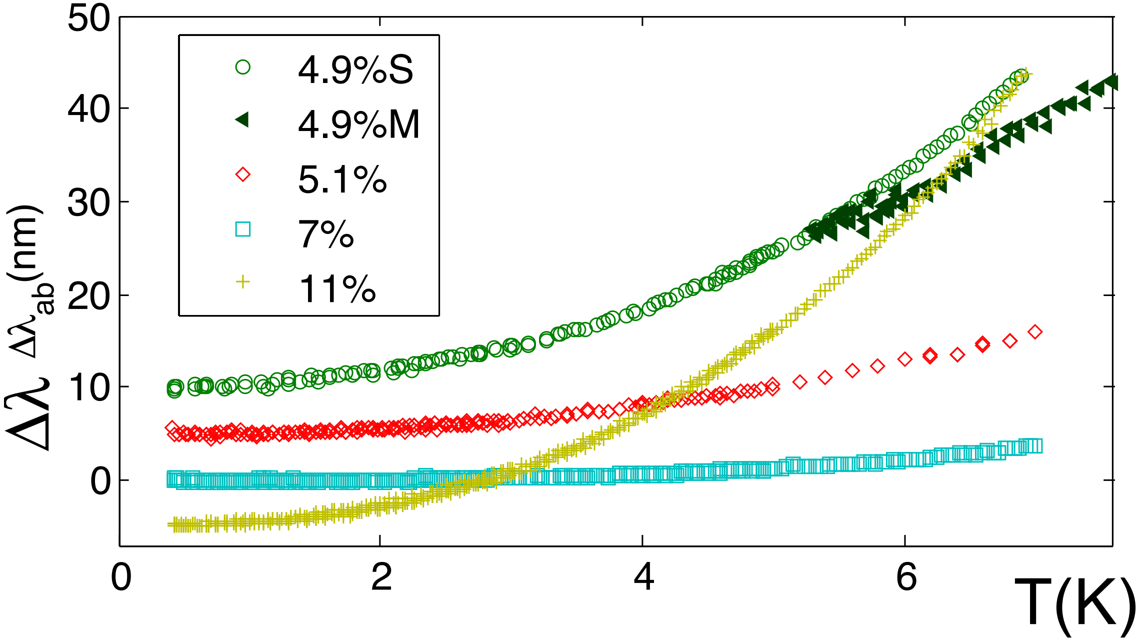




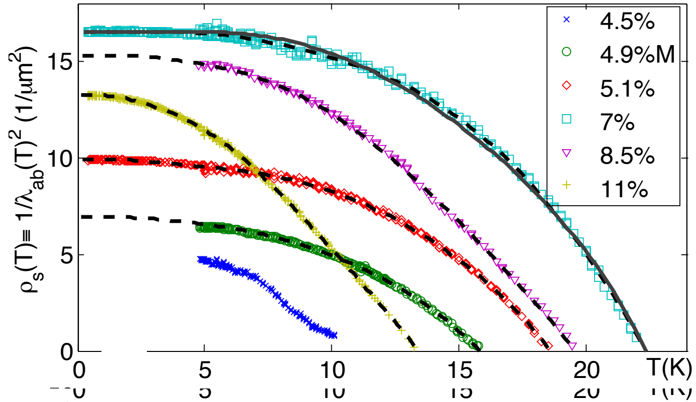
Full single gap behavior at optimal doping

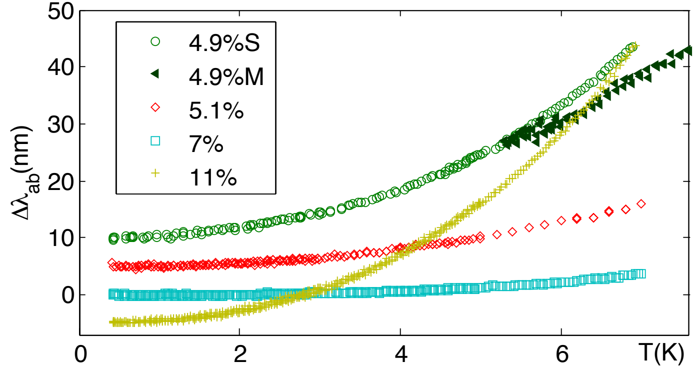




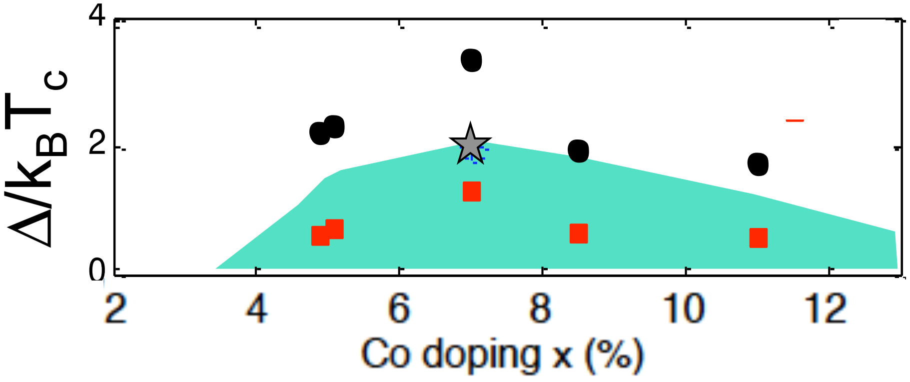


Two different gaps, or a power law, away from optimal doping

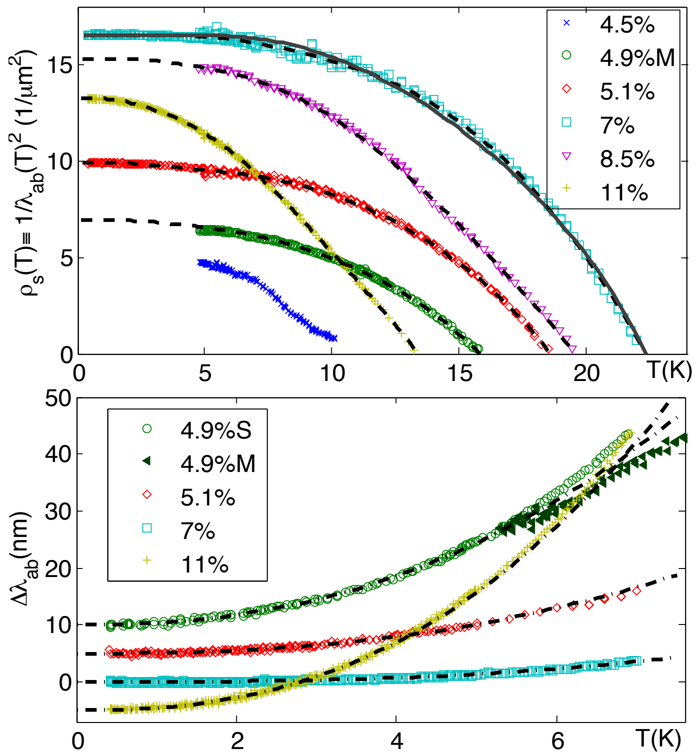




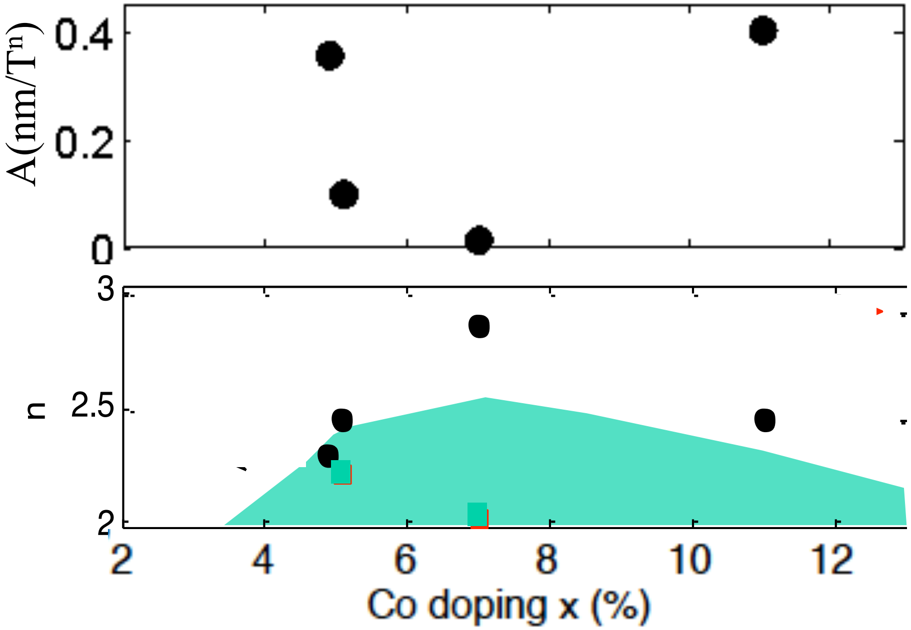
Two-full-gap fit with small second gap to account for finite Δλ



Two different gaps, or a power law, away from optimal doping

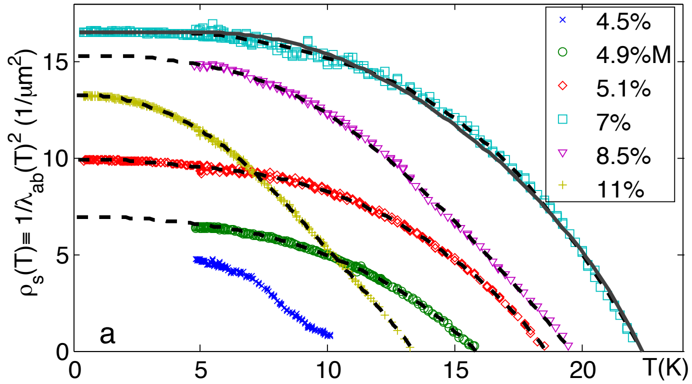


power-law fit $\Delta\lambda = AT^n$
away from optimal doping



pair breaking scattering

$\rho_s(T)$ rises sharply below T_c for underdoped and optimal doped



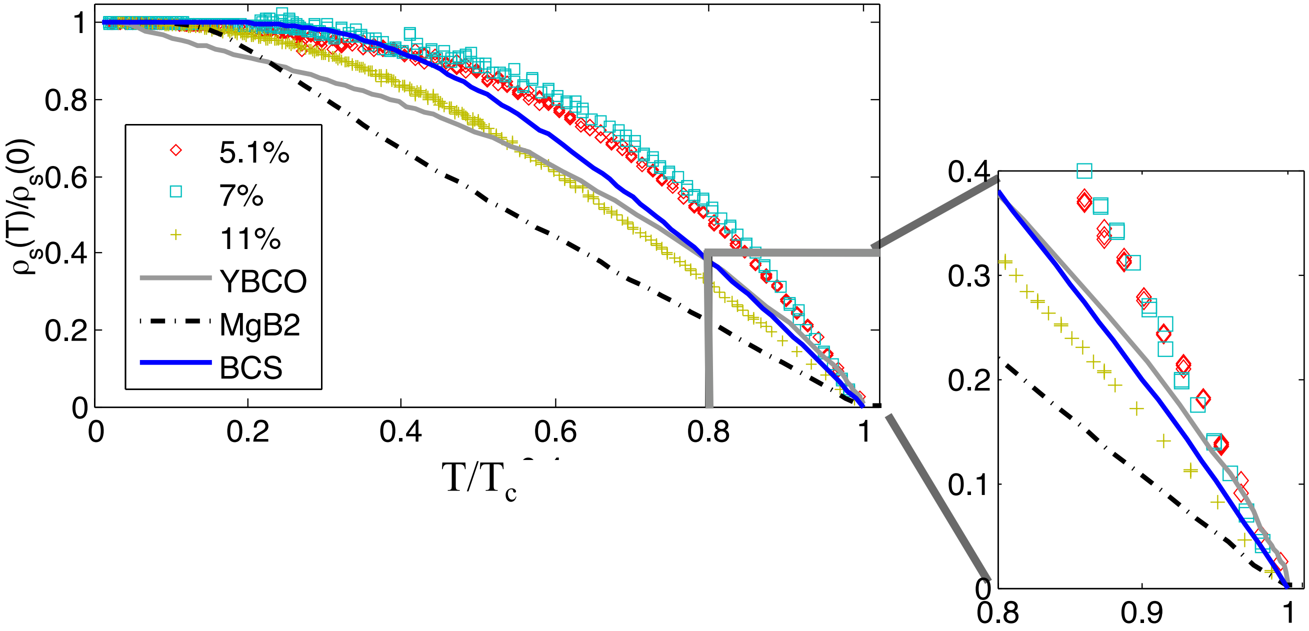
faster rise than weakly coupled BCS

$$\Delta_i(T) = \Delta_i(0)\tanh\left(\frac{\pi T_C}{\Delta_i(0)}\sqrt{a_i\left(\frac{T_C}{T}-1\right)}\right)$$

parameter a characterizes the rise,

$a \approx 1$ for weakly coupled BCS

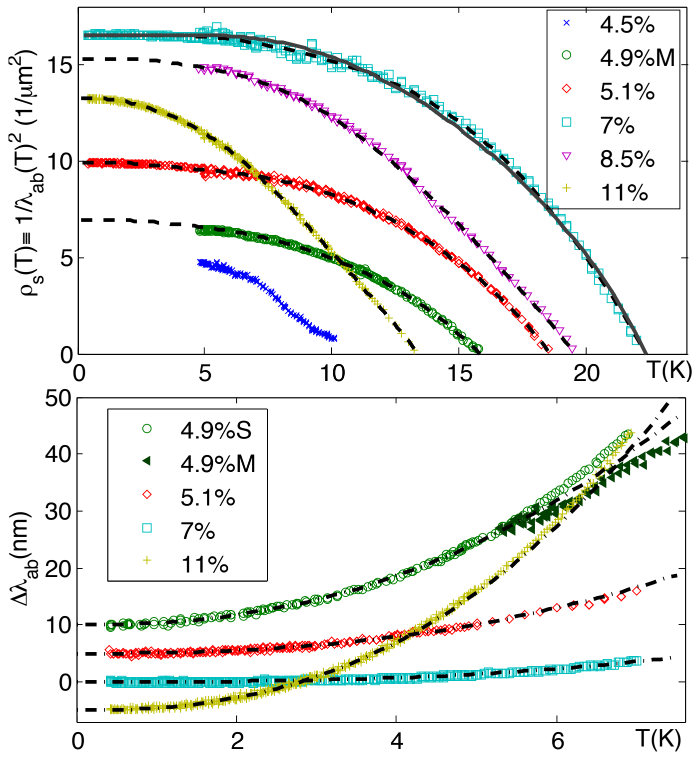
$a \approx 1.7$ for UD and OptD



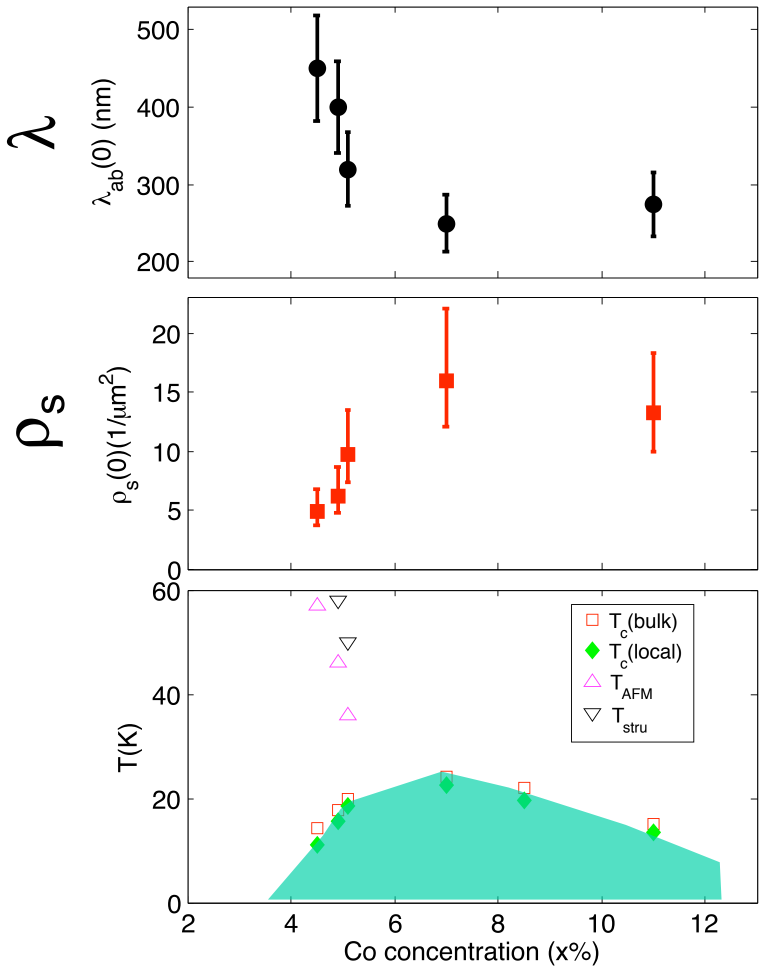
faster rise than

MgB_2 and OD

strong reduction of $\rho_s(0)$ on underdoped side



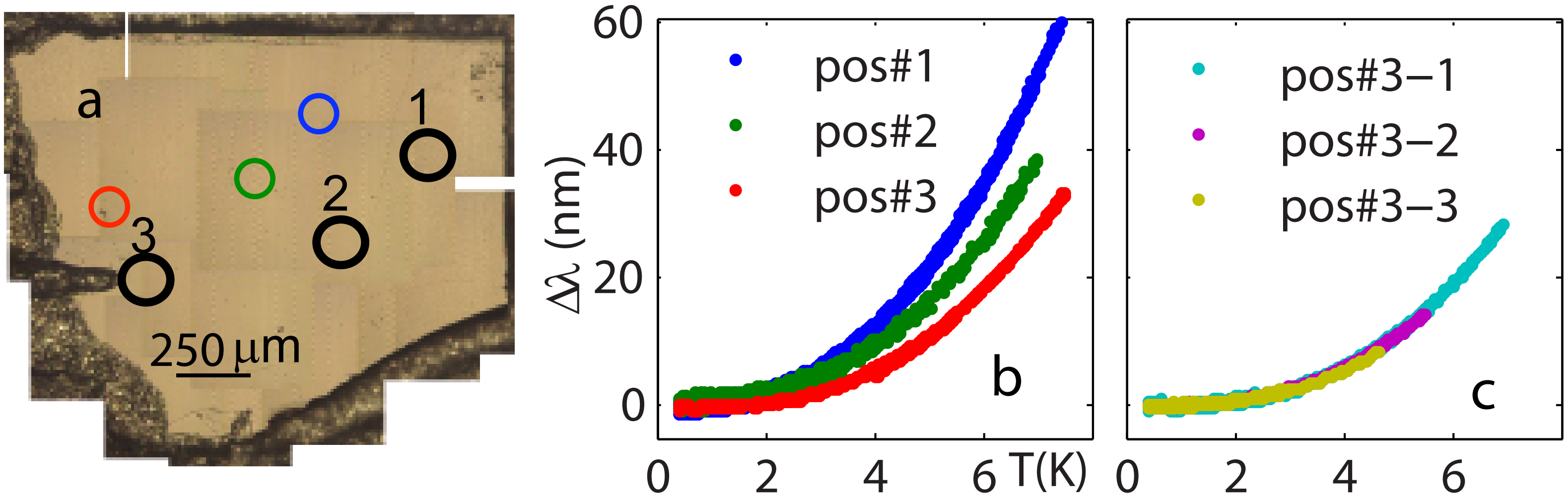
$\rho_s(0)$ is reduced on either side of optimal doping
much more pronounced drop on underdoped side



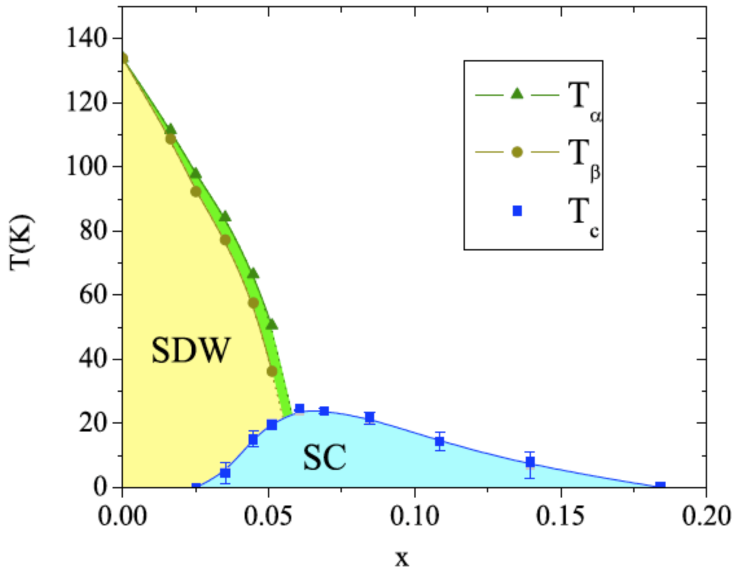
Homogeneity checks

x	# by MFM	# by SSS	resolve vortices	sample uniform	pos uniform
4.5%(UD)	1	0	✖	N/A	N/A
4.9%(UD)	1	1	✔	✖	✔
5.1%(UD)	1	2	✔	✔	✔
7% (OptD)	1	1	✔	✔	✔
8.5%(OD)	1	0	✔	N/A	✔
11%(OD)	1	1	✔	✖	✖

x=11%



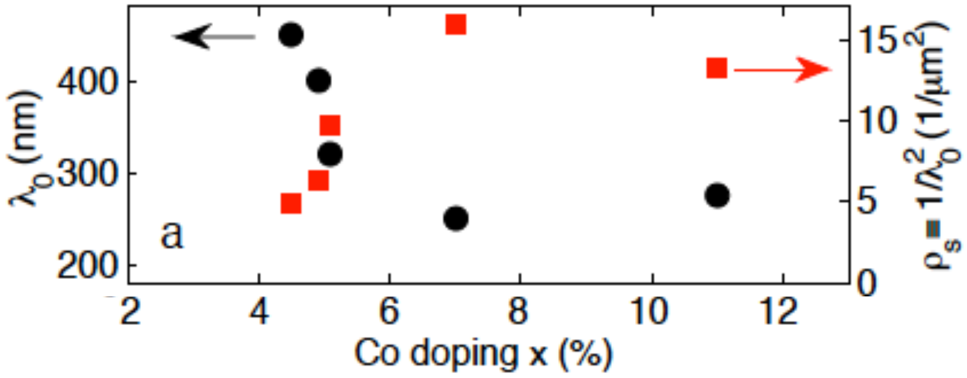
Interpretation: features that evolve with doping

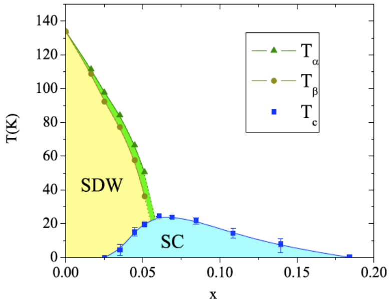


- the structure of the gap in *k* space
- scattering process
  - magnetic scattering
  - impurity scattering
- strength of magnetic order and magnetic fluctuations
- inhomogeneity

Interplay between magnetism and superconductivity

Interpretation: strong reduction of $\rho_s(0)$ on UD: magnetic phase taking charge carriers



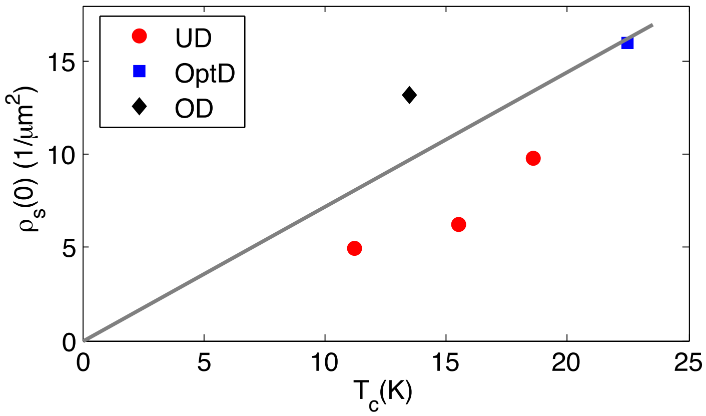


coexisting magnetic order removing a large number of charge carriers that might otherwise enter the SC phase

consistent with

UD: $\rho_s(0)$ decreases faster than T_c

SC not limited by phase fluctuation but by competing phase

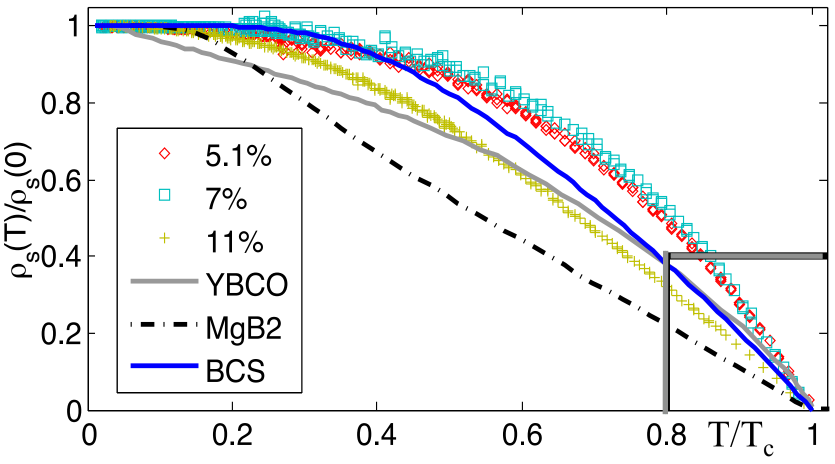


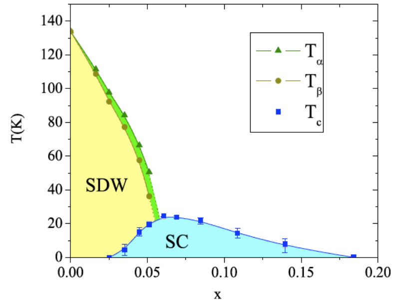
magnetic transitions leads to Fermi surface reconstruction

ARPES (Liu *et al*, Nat. Phys. 6, 419 (2010))

Quantum oscillations: Analytis et al., PRB 80, 064507 (2009).

Interpretation: Sharp rise of $\rho_s(T)$ near T_c: magnetic fluctuation mediated pairing





UD and OptD: in vicinity of AFM order

onset of SC and suppression of AFM going on simultaneously

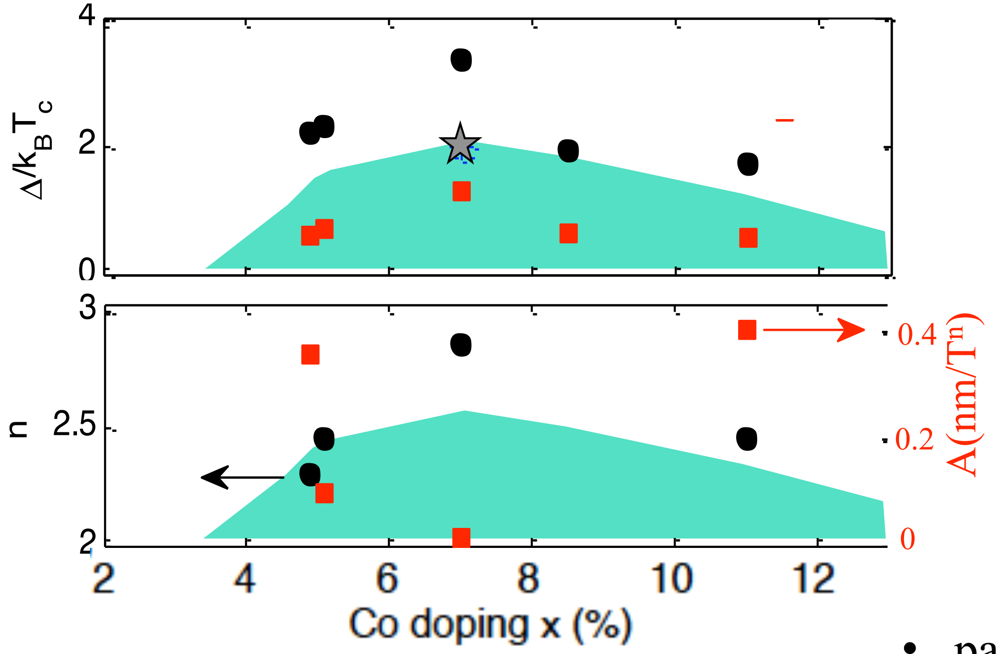
Forming of SC pushes the low-freq fluctuation to higher spectrum, favoring of SC

Monthoux and Scalapino, PRB50, 10339 (1994)

OD:

not so many low-freq fluctuations since away from magnetic order

Interpretation: weakened full gap behavior away from OptD: magnetic scattering and magnetic mediated pairing



consistent with heat transport (Reid et al, PRB 82, 064501)

- pair-breaking scatterings
- anisotropic gap

UD

- FS reconstruction may lead to gap deep minima
- stronger AFM order=> more low-freq magnetic fluctuation=> more pair-breaking scattering

OD

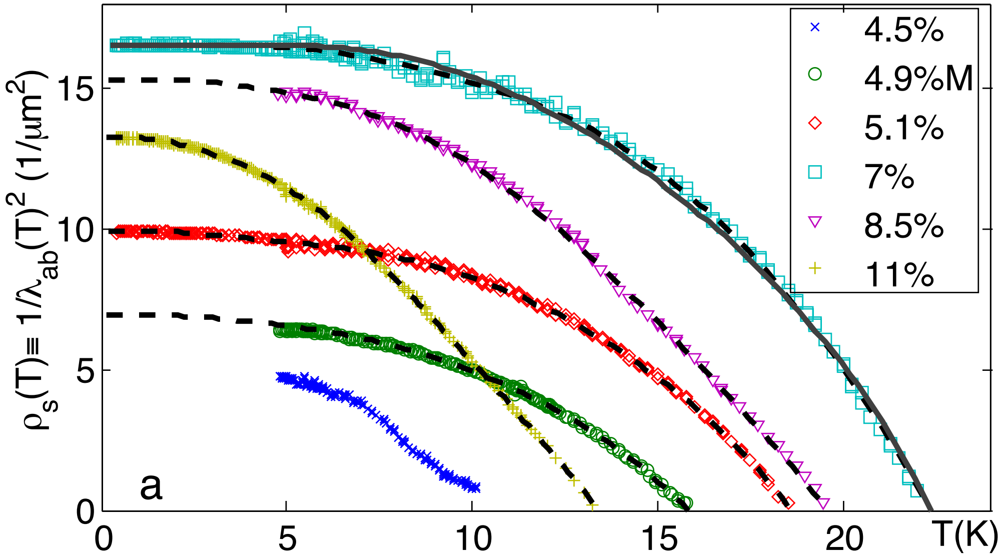
far away from AFM order=> reduce pairing strength=> modulation of the gap

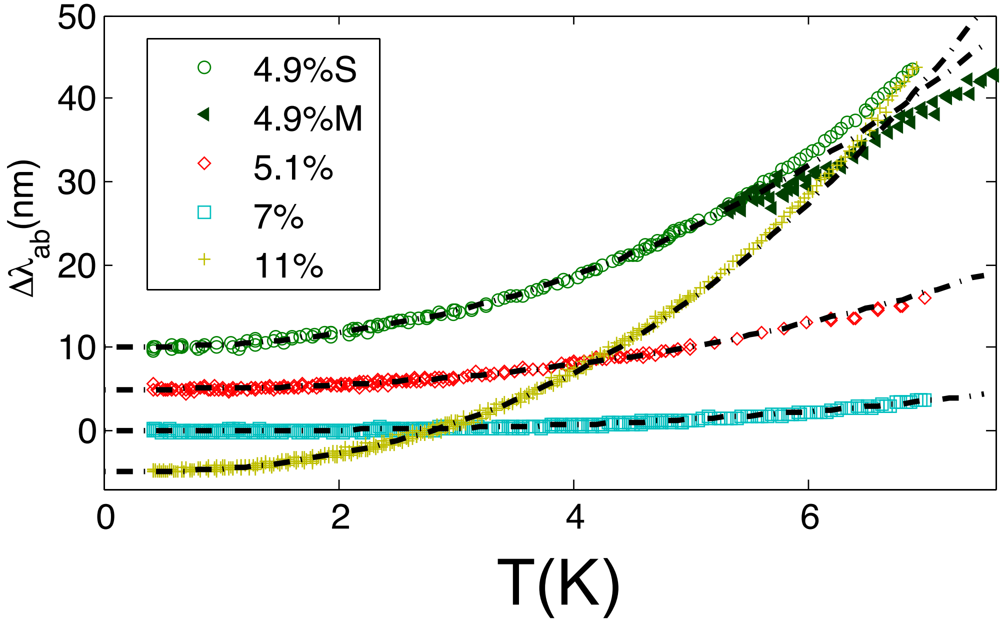
Summary on $Ba(Fe_{1-x}Co_x)_2As_2$

systematic change with doping of $\rho_s(T)$

- fast reduction of $\rho_s(0)$ for underdoping
- sharp rise of $\rho_s(T)$ near Tc for underdoped and optimally doped
- increasing Δλ magnitude away from optimally doped

Strong relation between superconductivity and magnetism

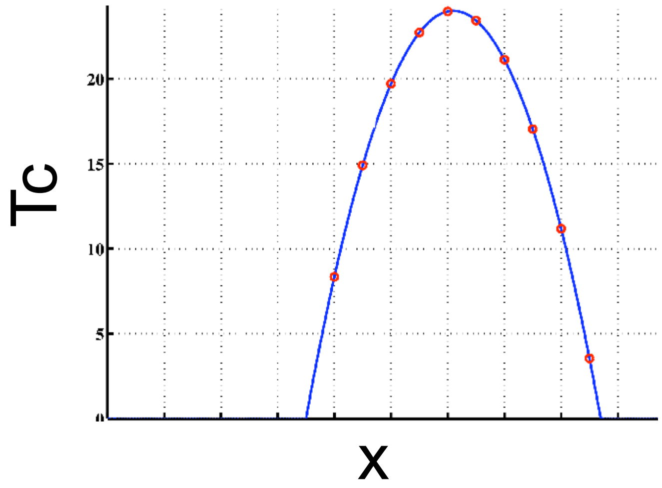




Speculation

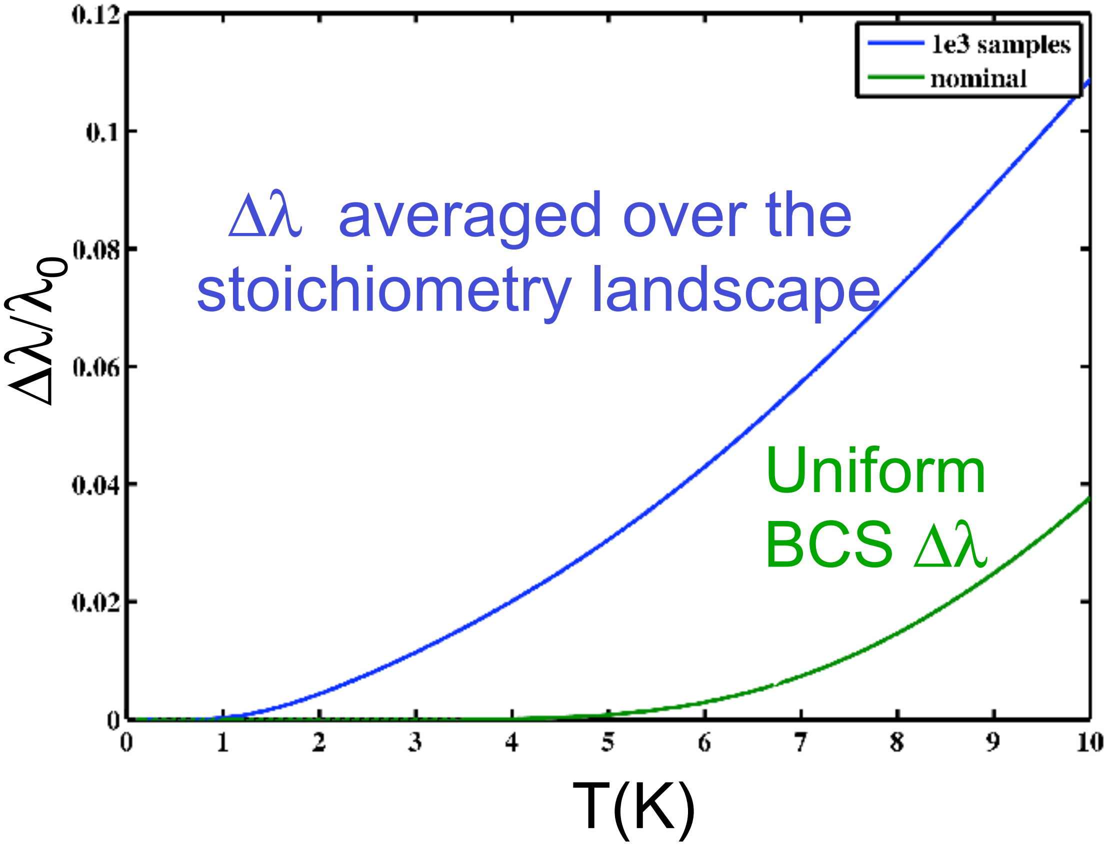
Is there intrinsic nanoscale spatial variation in these materials due to the stoichiometry?
If yes, how would the measured penetration depth reflect that?

Silly toy model en route to a better one:
- model the dome



- give each unit cell 0, 1, or 2 Cobalts with Poisson statistics
- average a coherence volume to get the "local doping"
- assign a penetration depth based on the Tc associate with the local doping
- average the penetration depths (or n_s)

Parameters inspired by $Ba(Fe_{1-x}Co_x)_2As_2$



$\Delta\lambda$ averaged over the stoichiometry landscape

Uniform BCS $\Delta\lambda$

Useful conversations with Jim Sethna, Steve Kivelson, Catherine Kallin, Lan Luan
Calculations by Tom Lippman

Local Measurements of Penetration Depth in Pnictides

Experimental Results

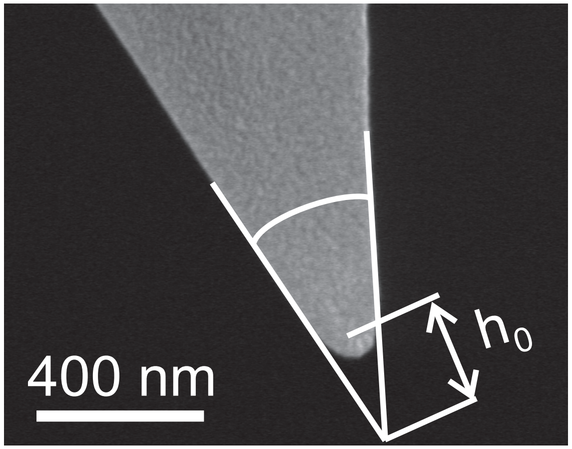
1. Superfluid density on twin boundaries in $Ba(Fe_{1-x}Co_x)_2As_2$
    - strongly enhanced
    - repels vortices
2. $\Delta\lambda(T)$ of LaFePO (scanning SQUID)
    - $\Delta\lambda(T) \sim T$ at low temperature
    - ρ_s rises steeply below Tc
3. $\Delta\lambda(T)$ and λ_0 of $Ba(Fe_{1-x}Co_x)_2As_2$ across the dome
    - fast reduction of ρs(0) for underdoping
    - sharp rise of ρs(T) near Tc for overdoped and optimally doped
    - increasing Δλ magnitude away from optimally doped

Question: How does the existence of an intrinsic stoichiometry landscape on coherence length scales in at least most underdoped samples influence the theory?

Extra Slides

Local Diamagnetism as a Measure of λ

Magnetic force microscopy



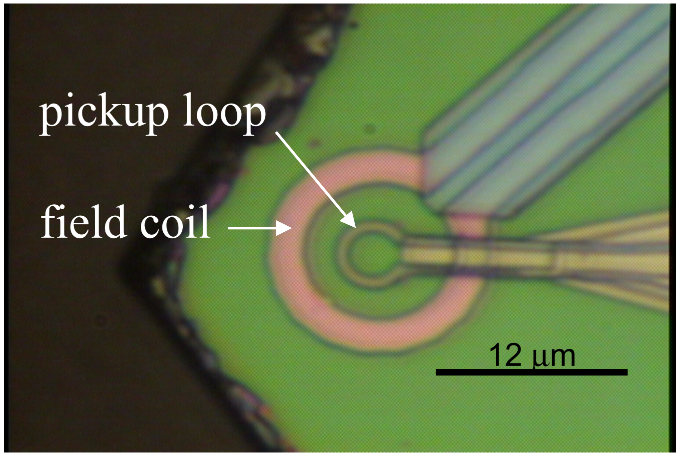
Cantilever frequency shift

$$\Delta f = -f_0 \frac{1}{2k} \frac{\partial F_z}{\partial z}$$

Related to gradient of force on tip

$$\vec{F} \approx \int_{tip} \vec{\nabla}\left(\vec{M} \cdot \vec{H}\right) dv$$

Scanning SQUID susceptometry



Mutual inductance between field coil and pick-up loop

Local Diamagnetism as a Measure of λ

Magnetic force microscopy

Lan Luan

Scanning SQUID susceptometry

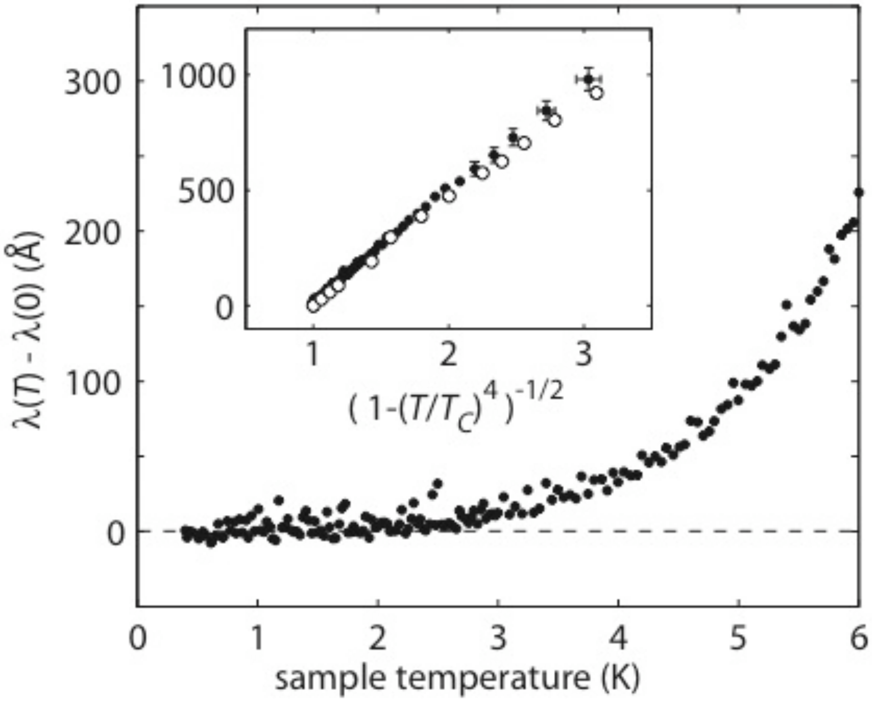
Tom Lippman

Measurement accuracy of $\Delta\lambda$: ±7 %

Test: penetration depth of Pb

Dominant source of error: imperfect calibration of the *z*-piezo

thermal gradients between sample and sensor: less than 20 Å effect on *h* over 1 K < T_{sample} < 8 K.

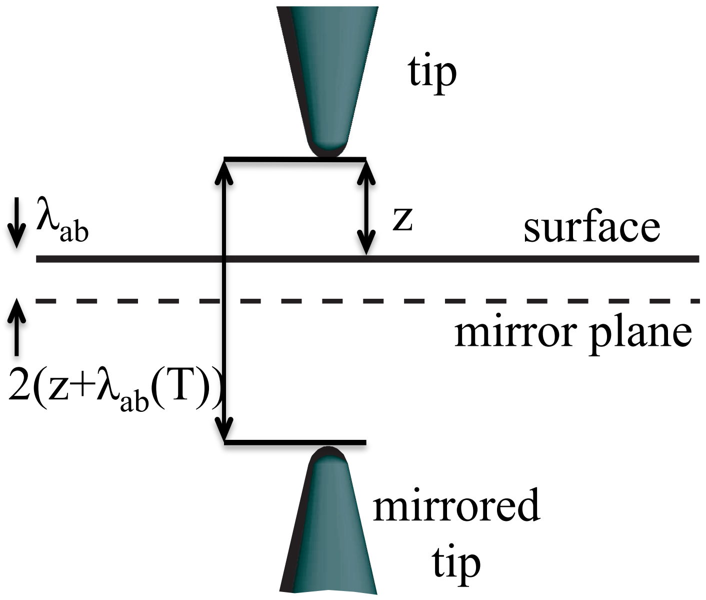


Filled: our data.
Open: Gasparovic and McLean, PRB **2** (1970) 2519

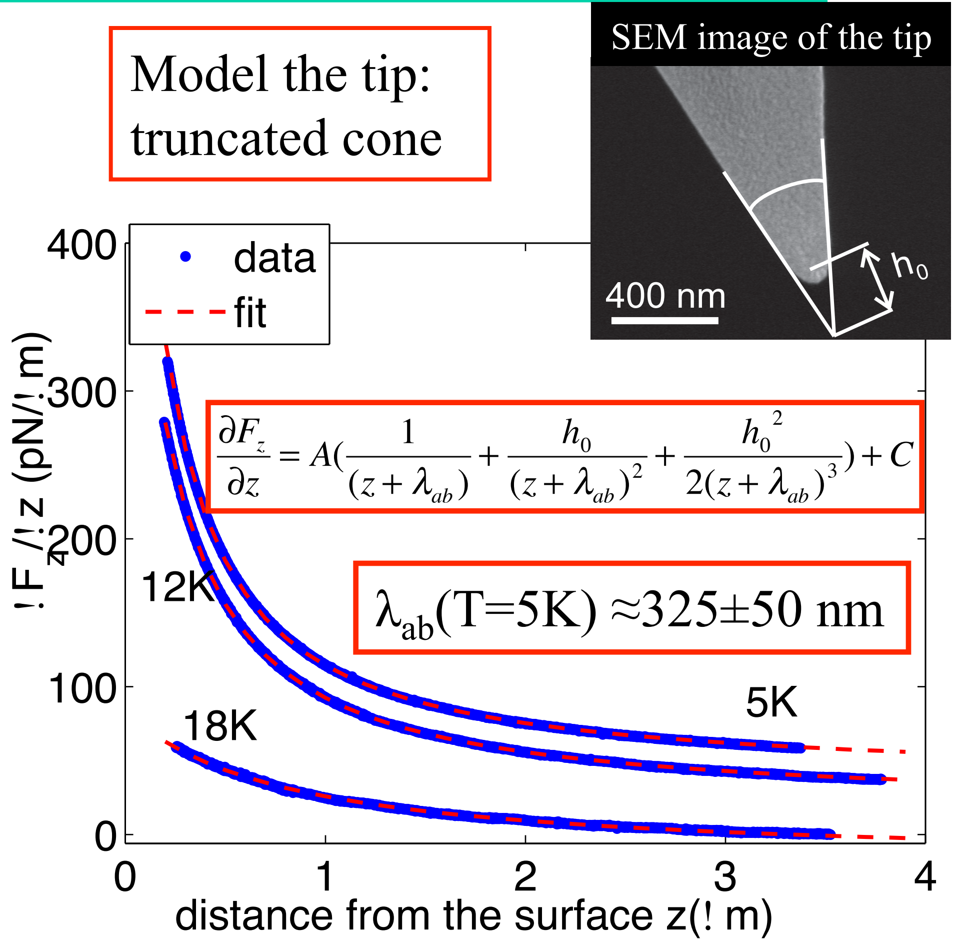
Measure local λ_0 by MFM

$Ba(Fe_{0.95}Co_{0.05})_2As_2$

tip-SC interaction can be approximated by tip interacting with its mirrored image separated by $2(z+\lambda_{ab}(T))$ for $z>>\lambda_{ab}(T)$



Model the tip: truncated cone



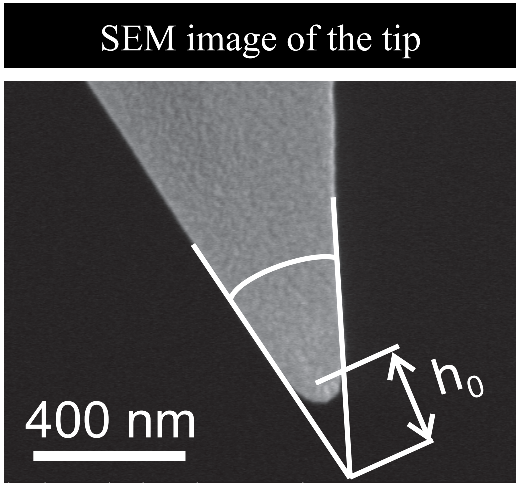
$$\frac{\partial F_z}{\partial z} = A\left(\frac{1}{(z+\lambda_{ab})} + \frac{h_0}{(z+\lambda_{ab})^2} + \frac{h_0^{\,2}}{2(z+\lambda_{ab})^3}\right) + C$$

$\lambda_{ab}(T=5K) \approx 325\pm50$ nm

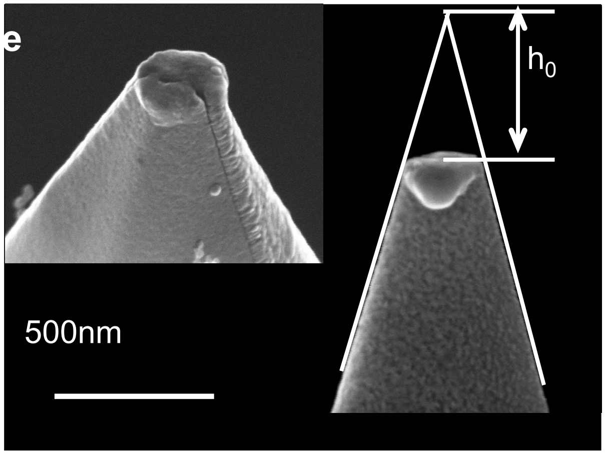
Measurements with different tips give same λ

$Ba(Fe_{0.95}Co_{0.05})_2As_2$

before an accidental crash


SEM image of the tip

after the crash



λ=330±50 nm

λ=325±50 nm

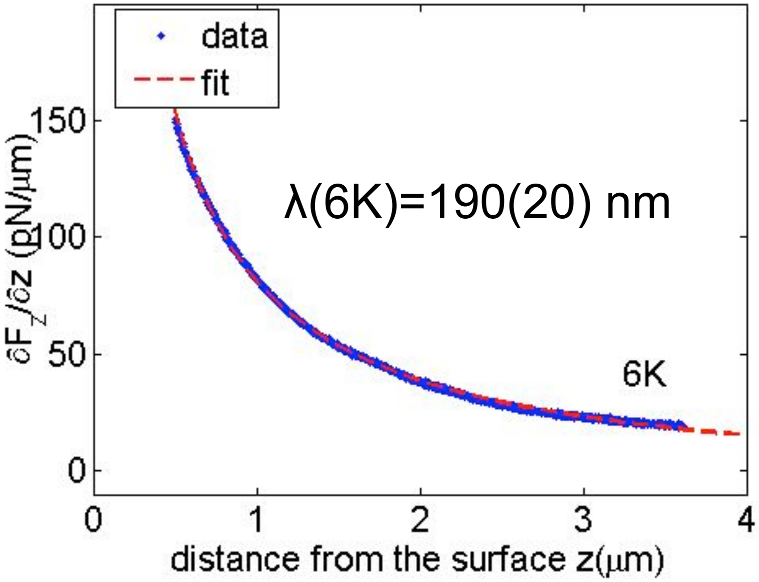
Systematic errors dominate: mostly from uncertainty in the tip geometry

Calibrating λ_0 measurement

Sample: $YBa_2Cu_3O_{6+x}$ single crystal Ortho-II, x=0.56, Tc=58K

previous measurements:

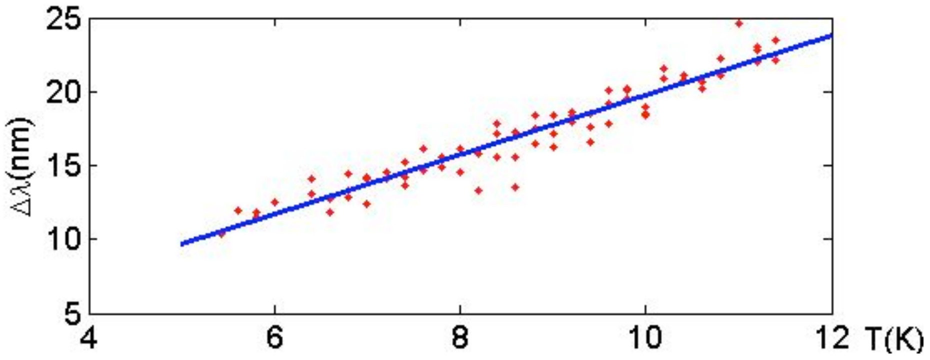
method	λ_0(nm)	T_m(K)	T_c(K)	reference
mu-SR	**175 (@0.5T)**	1.25	59	Sonier *et al PRL* **79**, 2875 (1997)
lower critical field	**175(6)**	0	56	Liang *et al PRL* **94**, 117001 (2005)
ESR(Gd-doped)	**λ_a=202(22)** **λ_b=140(28)**	0	56	Pereg-Barnea *et al PRB* **69**, 184513 (2004)
Infrared spectroscopy	**λ_a=248** **λ_b=183**	12	59	Homes *et al PRB* **60**, 9782 (1999)



λ(6K)=190(20) nm

Our measurements

extrapolate to λ(0)=180 nm



Penetration Depth in Single Crystal Pnictides

	Sample (single crystal)	1 full gap	2 full gaps	T: nodal	T^2	method	group	reference
1111	$SmFeAsO_{0.8}F_{0.2}$	✖	✔	✖	-	RF oscillator	Bristol	PRB 79, 140501
	$PrFeAsO_{1-y}$	✖	✔	✖	-	microwave	Kyoto	PRL 102, 017002
	$LaFeAsO_{0.9}F_{0.1}$ $NdFeAsO_{0.9}F_{0.1}$	✖	?	✖	✔	RF oscillator	Ames	PRL 102, 247002
P-based	LaFePO	✖	✖	✔	✖	RF oscillator	Bristol	PRL 102, 147001
	LaFePO	✖	✖	✔	✖	scanning SQUID	Stanford	PRL 103, 127003
122	$BaFe_2(As_{1-x}P_x)_2$	✖	✖	✔	✖	microwave	Kyoto	arXiv 0907.4399
	$(Ba_{1-x}K_x)Fe_2As_2$	✖	✔	✖	-	microwave	Kyoto	PRL 102, 207001
	$(Ba_{1-x}K_x)Fe_2As_2$	✖	?	✖	✔	RF oscillator	Ames	PRB 80, 020501
	$Ba(Fe_{1-x}Co_x)_2As_2$	✖	?	✖	✔	RF oscillator	Ames	PRL 102, 127004 PRB 79, 100506
	$Ba(Fe_{1-x}Co_x)_2As_2$	✖	✔	✖	✖	MFM & SQUID	Stanford	PRB 81, 100501

✖: ruled out

✔: preferred explanation by authors

	Sample (single crystal)	1 full gap	$\lambda_{ab}^2(T)/\lambda_{ab}^2(0)$	$\Delta\lambda_{ab}$		method	group	reference
			2 full gaps	T: nodal	T^2			
11	$Fe_{1+y}(Te_{1-x}Se_x)$ $Fe_{1+y}(Te_{1-x}S_x)$	✖	dirty	✖	✔	RF oscillator	Ames	PRB 81, 180503(R)
1111	$SmFeAsO_{0.8}F_{0.2}$	✖	✔	✖	-	RF oscillator	Bristol	PRB 79, 140501
	$PrFeAsO_{1-y}$	✖	✔	✖	-	microwave	Kyoto	PRL 102, 017002
	$LaFeAsO_{0.9}F_{0.1}$ $NdFeAsO_{0.9}F_{0.1}$	✖	?	✖	✔	RF oscillator	Ames	PRL 102, 247002
P-based	LaFePO	✖	✖	✔	✖	RF oscillator	Bristol	PRL 102, 147001
	LaFePO	✖	✖	✔	✖	SQUID	Stanford	PRL 103, 127003
122	$BaFe_2(As_{1-x}P_x)_2$	✖	✖	✔	✖	microwave	Kyoto	PRB 81,220501(R)
	KFe_2As_2	✖	✖	✔	✖	microwave	Kyoto	PRB 82, 014526
	$(Ba_{1-x}K_x)Fe_2As_2$	✖	✔	✖	-	microwave	Kyoto	PRL 102, 207001
	$(Ba_{1-x}K_x)Fe_2As_2$	✖	?	✖	✔	RF oscillator	Ames	PRB 80, 020501(R)
	$Ba(Fe_{1-x}Co_x)_2As_2$	✖	?	✖	✔	RF oscillator	Ames	PRL 102, 127004 PRB 79, 100506
	$Ba(Fe_{1-x}Ni_x)_2As_2$	✖	?	✖	✔	RF oscillator	Ames	PRB 82, 060518(R)
	$Ba(Fe_{1-x}Co_x)_2As_2$	✖	✔	✖	?	MFM & SQUID	Stanford	PRB 81,100501(R)

✖: ruled out
✔: preferred explanation by authors

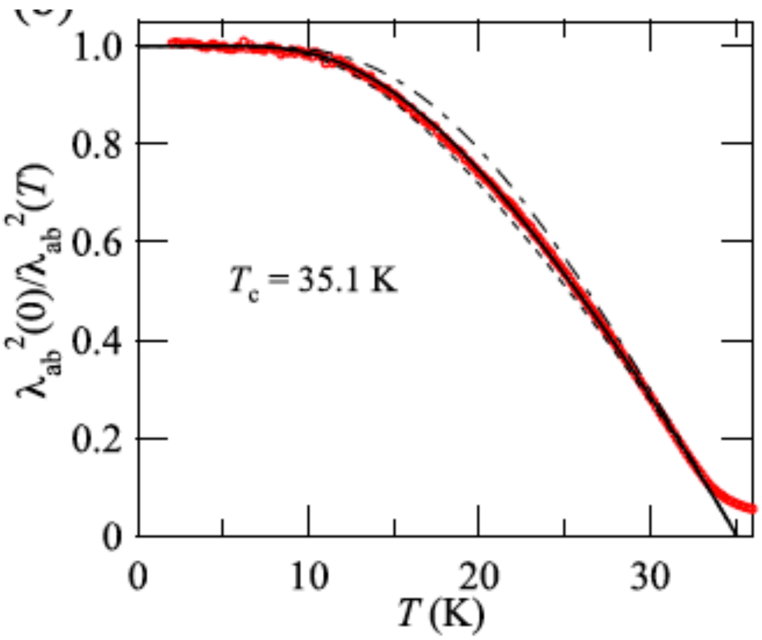
? : not ruled out
- : no comment

Literature on pnictides penetration depth measurements

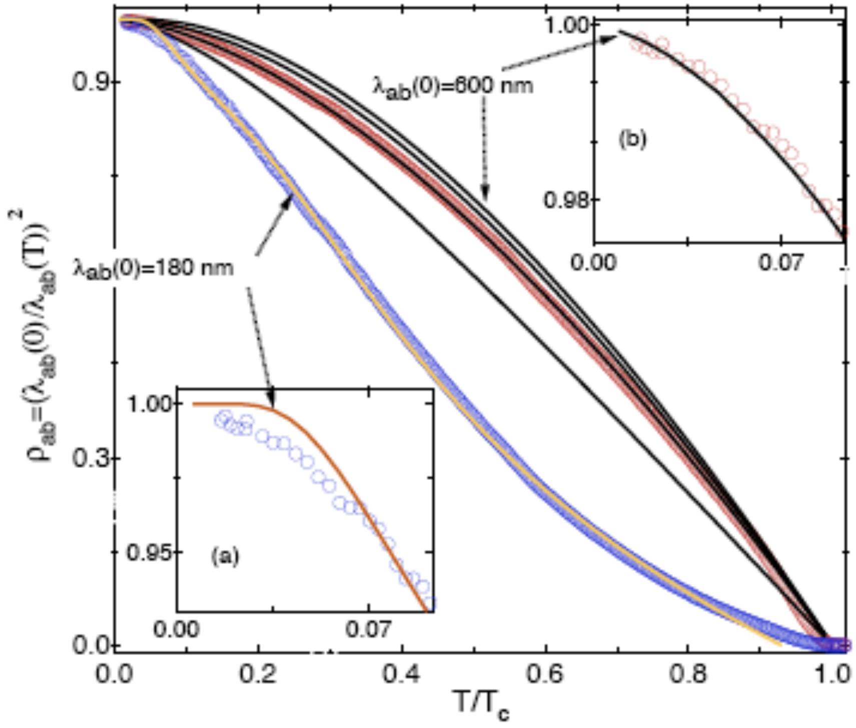
Different measurement techniques/groups/samples yield different results

$(Ba_{1-x}K_x)Fe_2As_2$
Tc = 30 K

Kyoto group



Ames group



hypotheses:

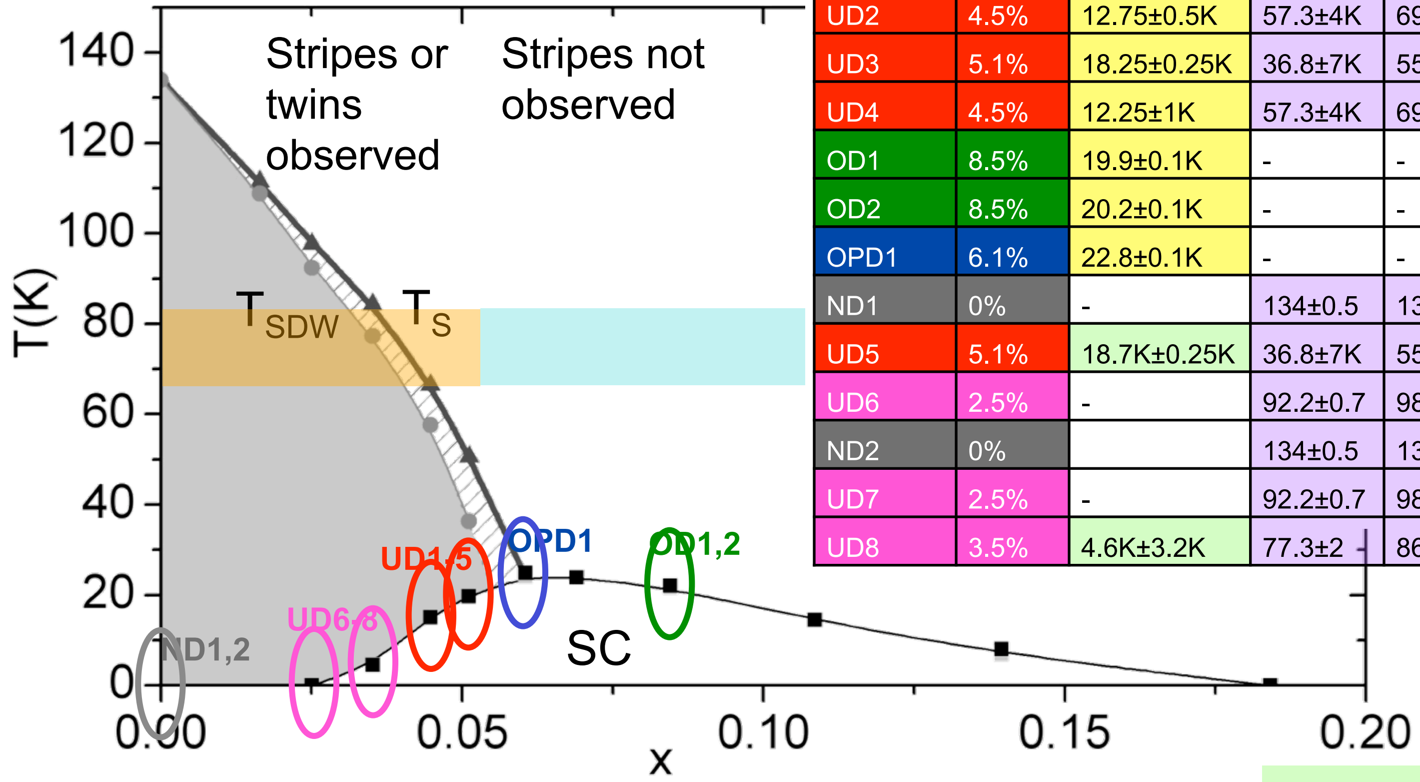
- intrinsic or extrinsic inhomogeneity and/or sample variability
- λ_{ab} and λ_c mixing
- unknown λ_0 limits $\Delta\lambda$ measurements

$Ba(Fe_{1-x}Co_x)_2As_2$

Enhanced superfluid density on twin boundaries

Stripes observed in under-doped, but not in over or optimally-doped

Name	Doping	T_C	T_{SDW}	T_S	Tool	observed
UD1	5.1%	18.25±0.25K	36.8±7K	55±5K	SSM	Stripes
UD2	4.5%	12.75±0.5K	57.3±4K	69.5±2K	SSM	Stripes
UD3	5.1%	18.25±0.25K	36.8±7K	55±5K	SSM	Stripes
UD4	4.5%	12.25±1K	57.3±4K	69.5±2K	SSM	Stripes
OD1	8.5%	19.9±0.1K	-	-	SSM	
OD2	8.5%	20.2±0.1K	-	-	SSM	
OPD1	6.1%	22.8±0.1K	-	-	SSM	
ND1	0%	-	134±0.5	134±0.5	XRD	Twin boundaries
UD5	5.1%	18.7K±0.25K	36.8±7K	55±5K	XRD	Twin boundaries
UD6	2.5%	-	92.2±0.7	98.5±1	XRD	Twin boundaries
ND2	0%		134±0.5	134±0.5	POL	Twin boundaries
UD7	2.5%	-	92.2±0.7	98.5±1	POL	Twin boundaries
UD8	3.5%	4.6K±3.2K	77.3±2	86.7±2	POL	Twin boundaries



Susceptibility measured in situ

susceptibility using Quantum Design 5T MPMS

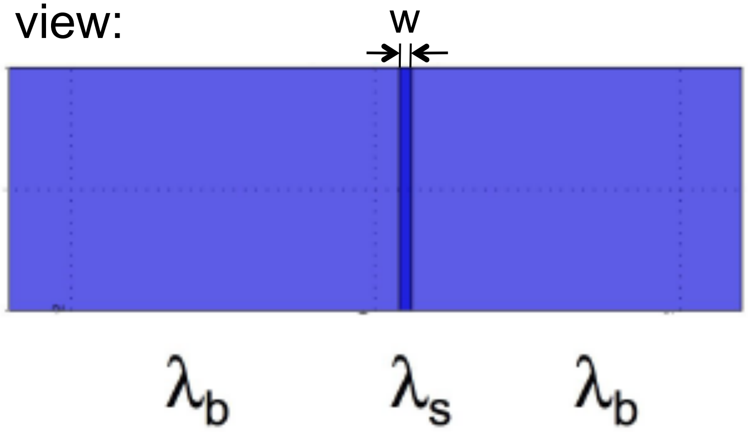
determined by the temperature derivatives of resistivity

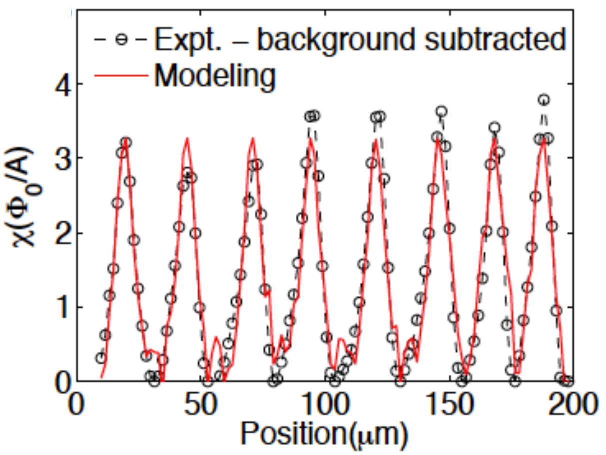
$Ba(Fe_{1-x}Co_x)_2As_2$

Enhanced superfluid density on twin boundaries

Modeling geometry:
2-D sheet of enhanced superfluid density

side view:





the stripe width w is resolution limited;
the excess Cooper pair density ΔN_s scales with w

$$3nm < w < 5\mu m$$

$$10^{19}m^{-2} < \Delta N_s < 10^{20}m^{-2}$$

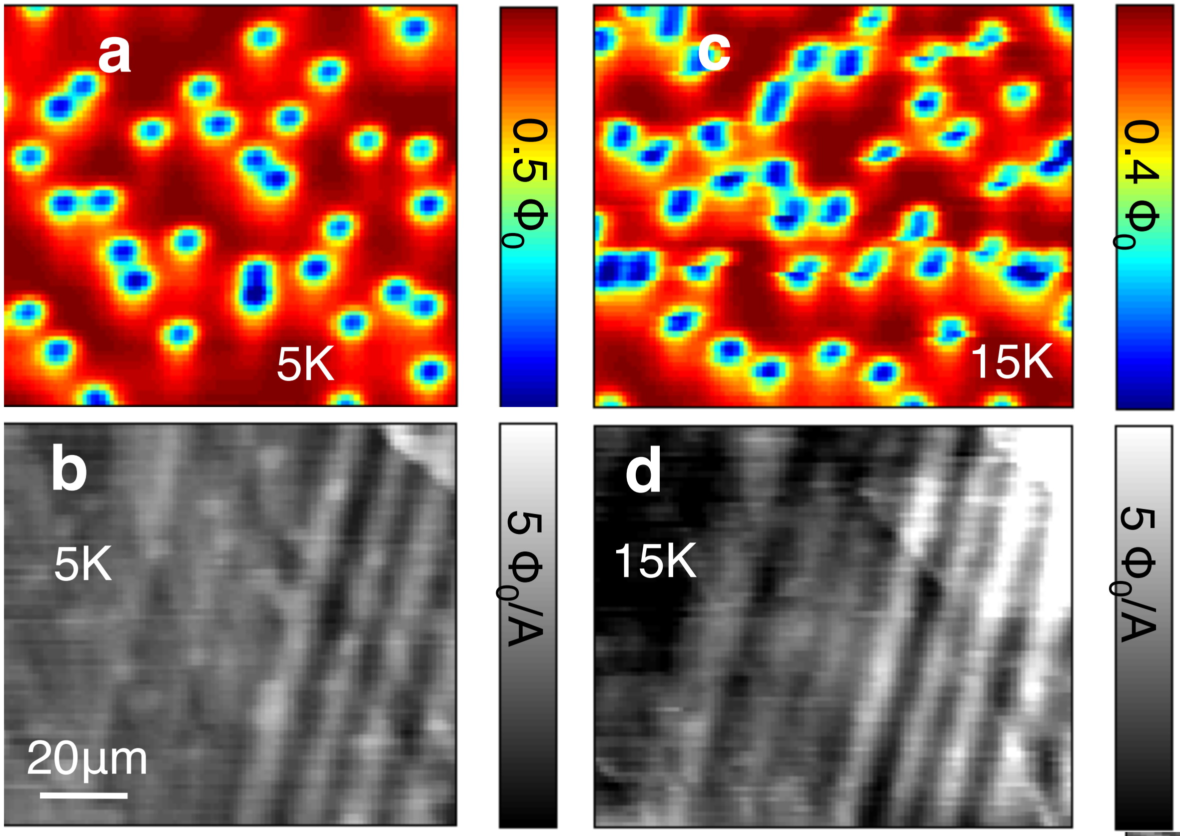
Effect of Twin Boundaries on Vortex Pinning and Motion

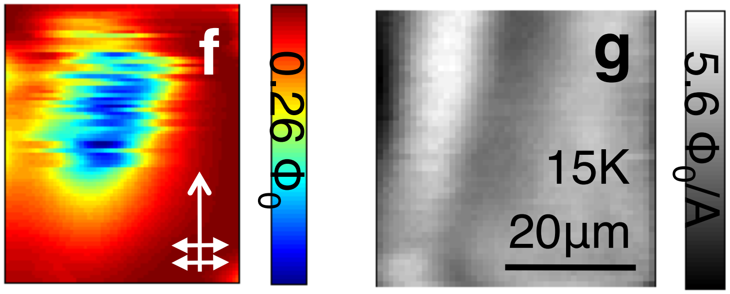
$Ba(Fe_{1-x}Co_x)_2As_2$

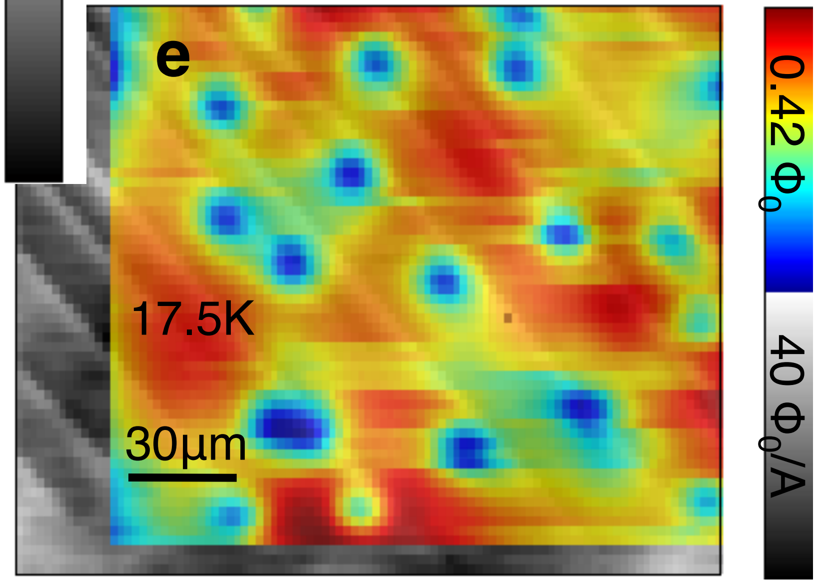
- Vortices do not pin on stripes
- Vortices avoid stripes even when deliberately dragged by applied force

Questions :

- What is the physics of twin boundaries with higher ns?
- What is the effect of caging by the twin boundaries on the vortex state?
- Does it enhance Jc?







figures from the paper