Local Characterization of Superconductivity in Iron Pnictides

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See: Lamhot et al., PRB **91**, 060504 (2015)

Technion Israel Institute of Technology

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Samples & discussion:
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- Tatsuya Watashige (Kyoto)
- Takasada Shibauchi (Tokyo)
- Yuji Matsuda (Kyoto)

also discussions w/ Erez Berg, Jenny Hoffman, Beena Kalisky, Amit Kanigel, Amit Keren, Max Khodas, Alex Levchenko & Kam Moler

BSF

SEVENTH FRAMEWORK PROGRAMME

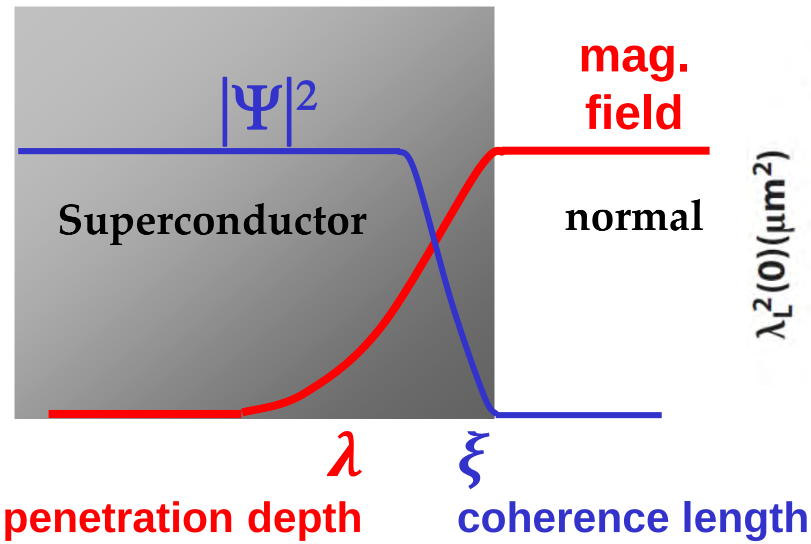
MARIE CURIE ACTIONS

ISRAEL SCIENCE FOUNDATION

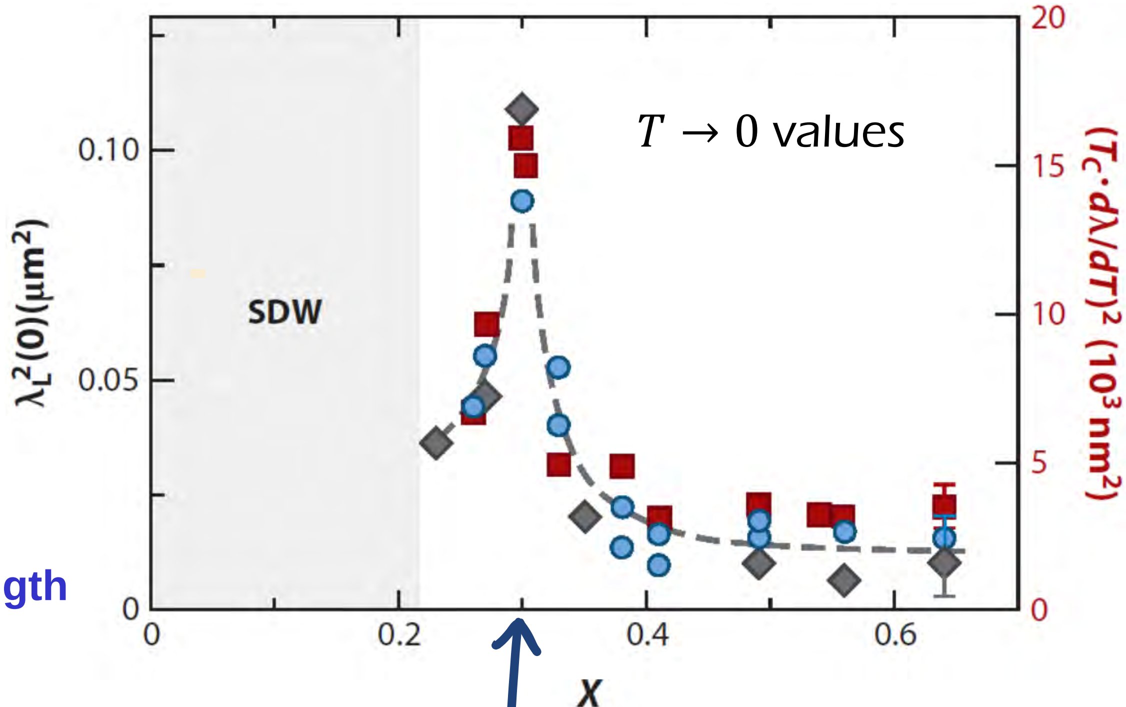
Penetration Depth Maximal Near Optimal Doping

Peak in λ_{ab} in sample-wide measurements on $BaFe_2(As_{1-x}P_x)_2$

- e.g. tunnel diode osc., cavity perturbation



Hashimoto et al., Science **336**, 1554 (2012)



optimal doping

Meissner weak where T_C maximal!

$$\lambda^2 \propto \frac{m^*}{n_S}$$

Very Different from Other Pnictides

Peak in λ_{ab} in sample-wide measurements on $BaFe_2(As_{1-x}P_x)_2$

- e.g. tunnel diode osc., cavity perturbation

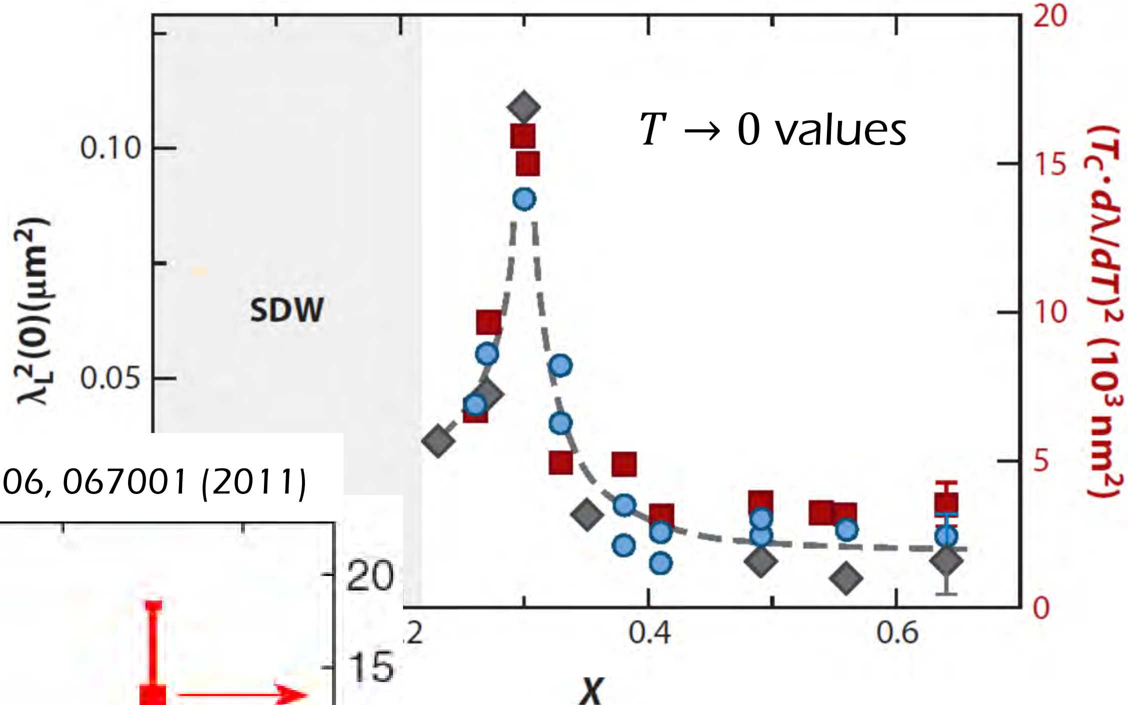
contrast with $Ba(Fe_{1-x}Co_x)_2As_2$

Gordon et al., PRB '10

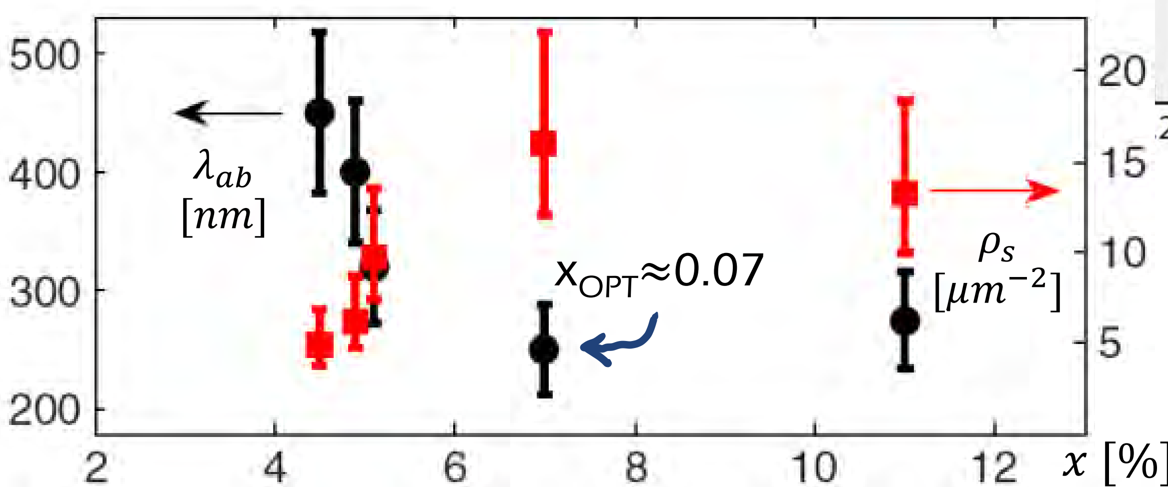
Luan et al., PRL '11

- no peak
- sharp rise at low doping
    - competing magnetic phase takes up carriers

Hashimoto et al., Science **336**, 1554 (2012)



Luan et al., PRL 106, 067001 (2011)

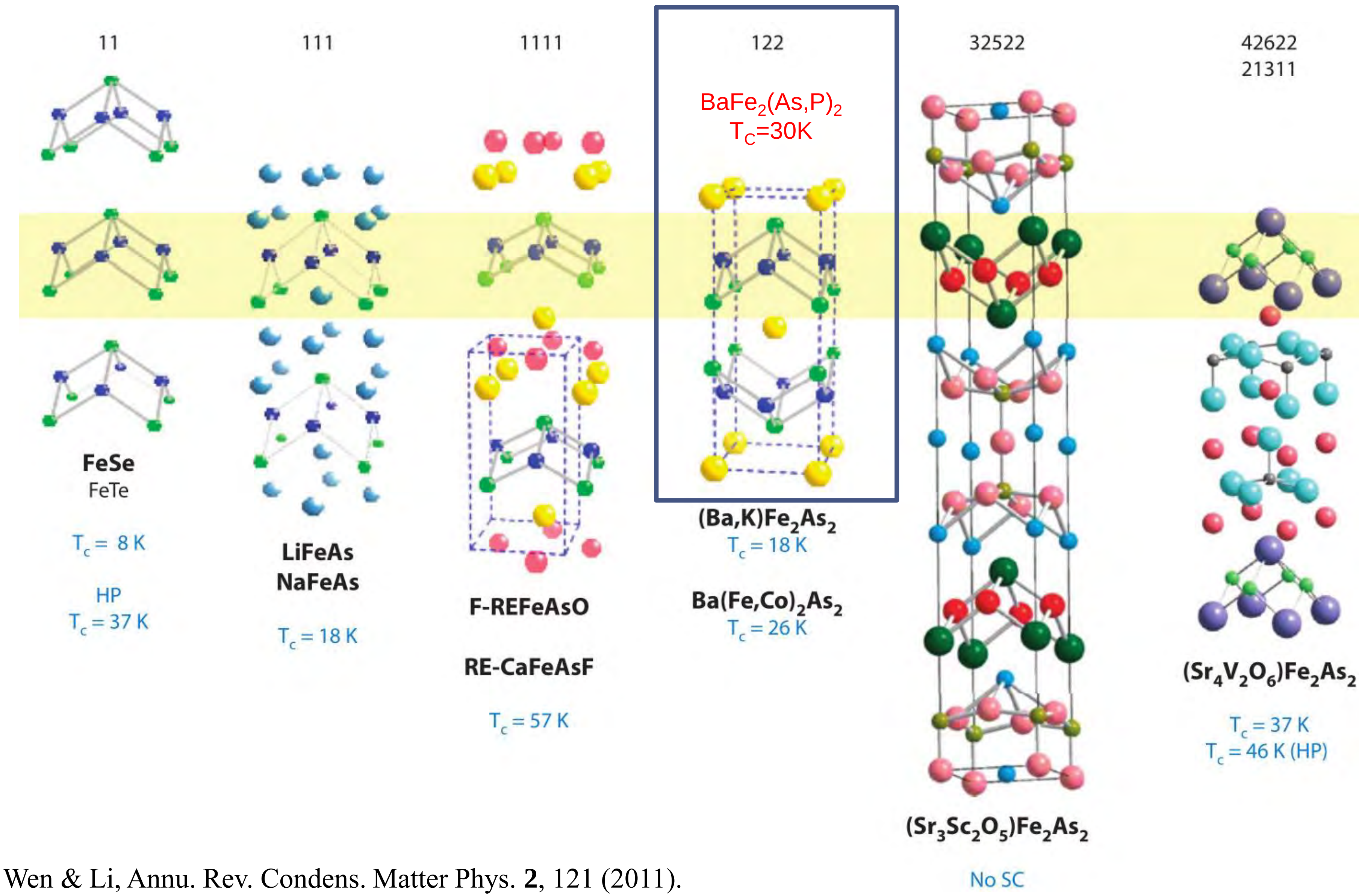


$$\lambda^2 \propto \frac{m^*}{n_S}$$

outline

- the pnictides
  - in particular P-Ba122 [$\equiv BaFe_2(As_{1-x}P_x)_2$]
  - our samples
- MFM – a local probe for superconductivity
- the penetration depth
- vortex decoration & manipulation

Several Families of Fe-Based Supercond.



Wen & Li, Annu. Rev. Condens. Matter Phys. **2**, 121 (2011).

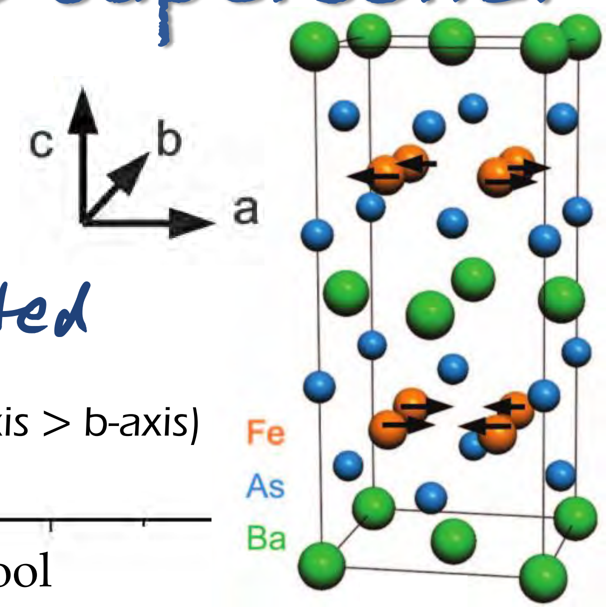
nematicity, antiferromag. & supercond.

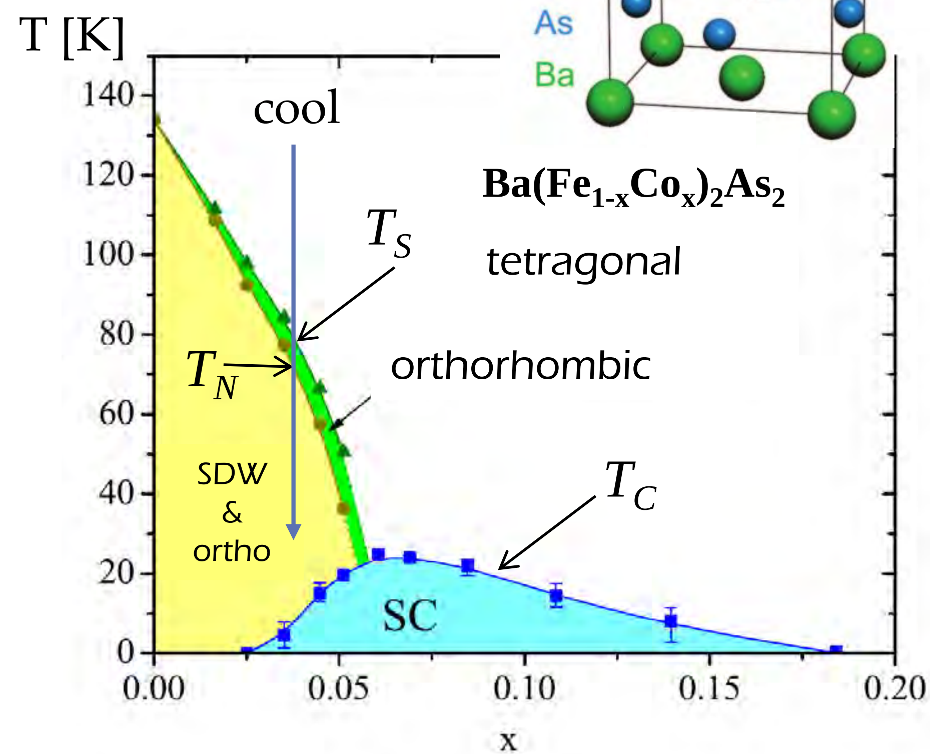
Cooling from the high T tetragonal phase:

1. $T < T_S$ – nematic
   - tetragonal (a-axis ≡ b-axis) → orthorhombic (a-axis > b-axis)

closely associated

2. $T < T_N$ – SDW
   - Ferromag. along b-axis
   - AFM along a-axis
3. $T < T_C$ - superconductivity



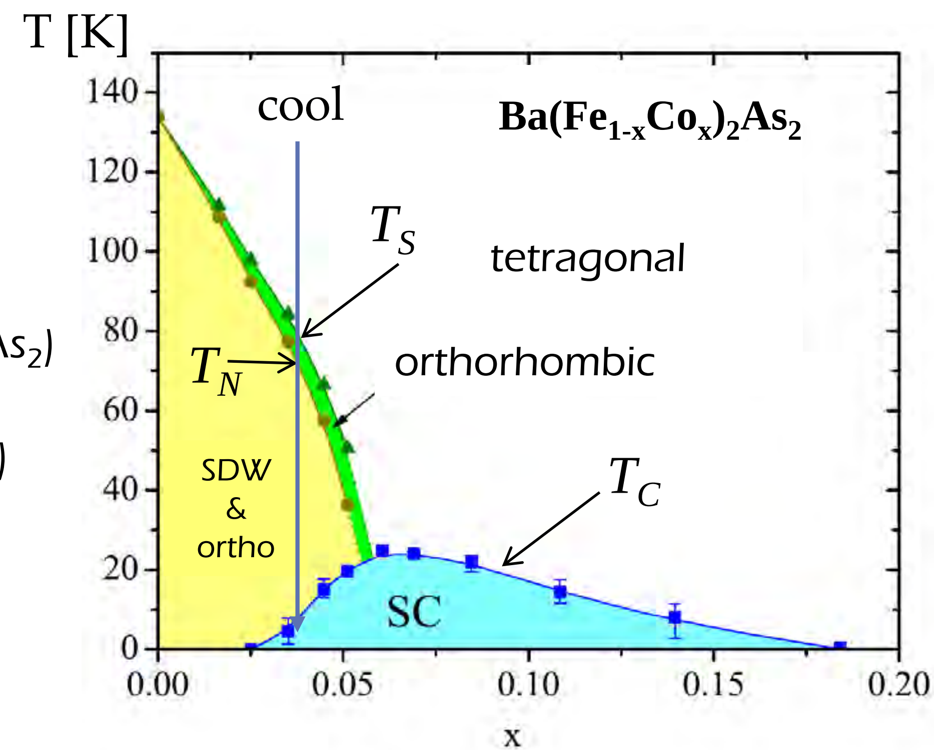


Chu et al., PRB **79** 014506 (2009)

nematicity, antiferromag. & supercond.

Cooling from the high T tetragonal phase:

1. $T < T_S$ – nematic
2. $T < T_N$ – SDW
3. $T < T_C$ superconductivity
   - can be induced by doping
     - by electrons (e.g. $Ba(Fe_{1-x}Co_x)_2As_2$)
     - or by holes (e.g. $(Ba_{1-x}K_x)Fe_2As_2$)
   - or by pressure
   - or by chemical pressure
     - isovalent doping (e.g. BaFe2(As1-xPx)2)



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

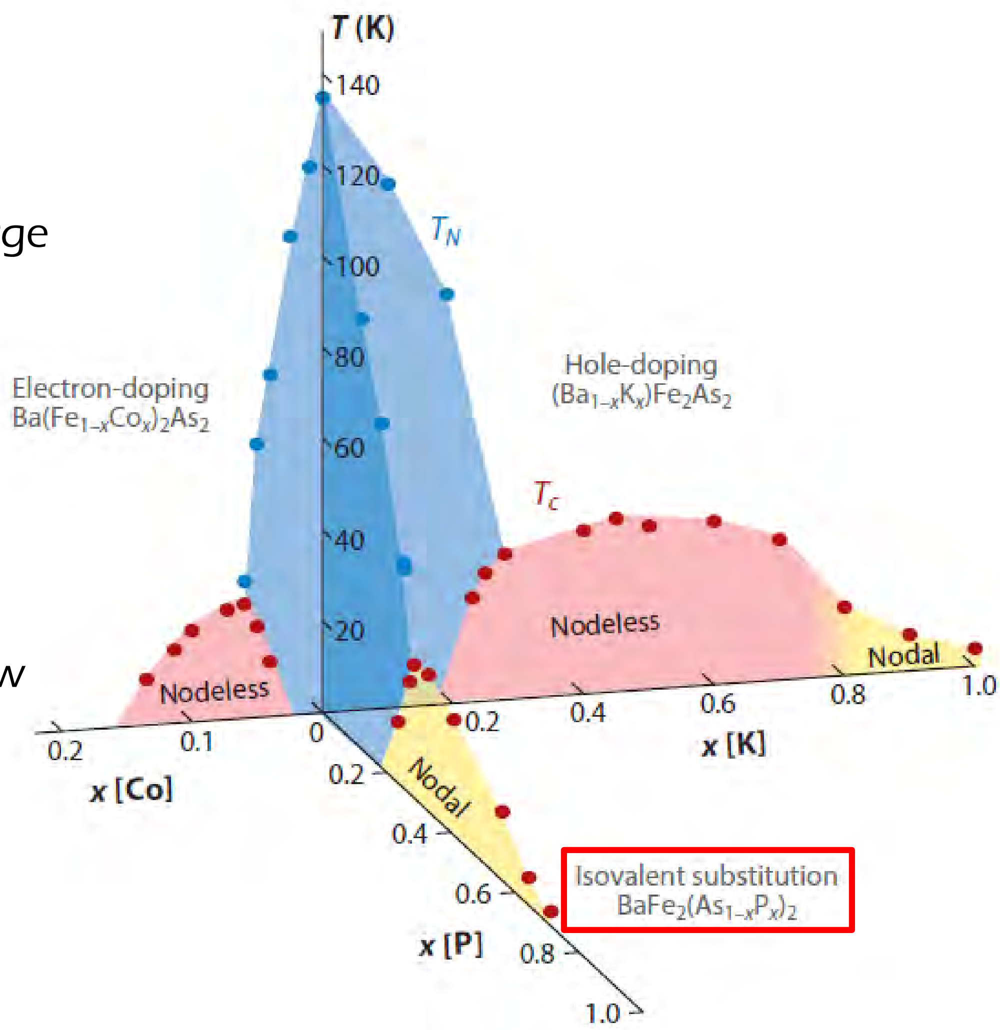
$BaFe_2(As_{1-x}P_x)_2$ – Isovalent Doping

<u>isovalent doping: $\mathbf{As^{-3} \leftrightarrow P^{-3}}$</u>

- doping affects the lattice not the net charge
- less disorder than elec / hole doped

<u>typical phase diagram for 122 pnictides</u>

- evidence for co-existence of superconductivity & magnetic order at low doping [e.g. Nakai *et al.*, PRL '10].



Shibauchi T, Carrington A, Matsuda Y., Annu. Rev. Condens. Matter Phys. **5**, 113 (2014).

$BaFe_2(As_{1-x}P_x)_2$ - Anomalous Properties Near x_{opt}

- anomalous transport
  - "wrong" power in $\rho \propto T^\alpha$

Kasahara et al., PRB '10

Analytis et al., Nat. Phys. '14

- enhanced mass

Walmsley et al., PRL '13

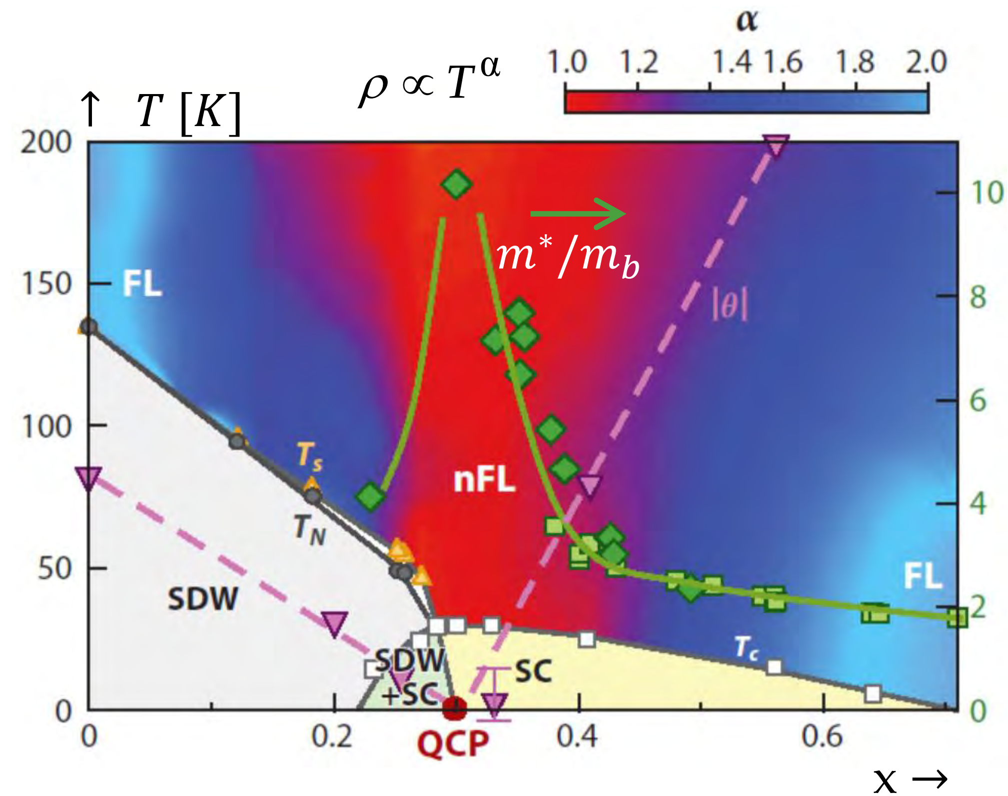
- strong magneto-elastic coupling

Kuo et al., PRB '12

- peak in λ

Hashimoto et al., Science '12

Lamhot et al., PRB '15



from Shibauchi et al.,
Annu. Rev. Condens. Matter Phys. **5**, 113 (2014)

all of this hints at something weird beneath the dome

Origin of the Peak in $\lambda(x)$ – an Open Question

A quantum critical point in the dome may be playing a role

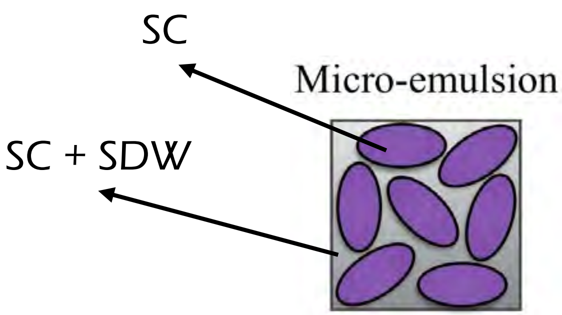
- transition: (conventional supercond.) ↔ (mixed supercond.-SDW state)

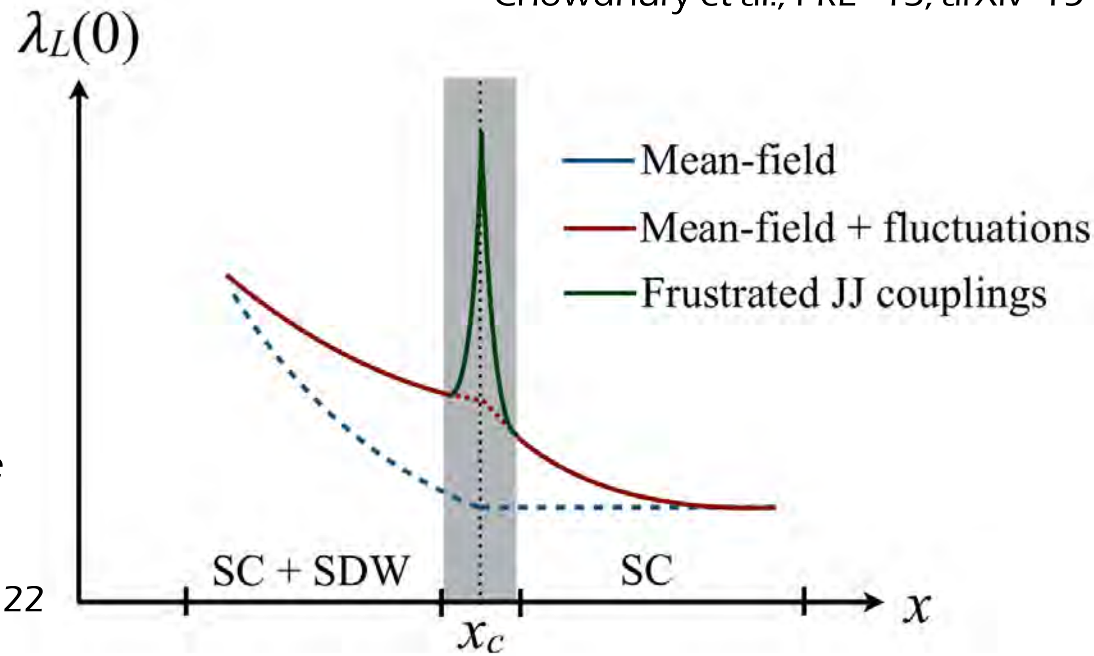
Shibauchi et al. Annu. Rev. Condens. Matter Phys. **5**, 113 (2014)

The relationship between quantum criticality and a peaked $\lambda_{ab}(x)$ is not simple.

see e.g.

Levchenko et al., PRL '13
Nomoto & Ikeda, PRL '13
Fernandes et al. PRL '13
Chowdhury et al., PRL '13, arXiv '15





recent idea:

quenched disorder gives rise to emulsion which suppresses the superfluid density n_s.

→ λ increases because n_s decreases not because m^* increases.

Chowdhury et al., arXiv:1502.04122

Local, Spatially Resolved Measurements

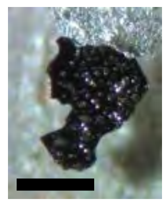
Our *goals*:

- Measure $\lambda_{ab}(x)$
  - tricky (worth repeating)
  - our method is very different from prev. (*sample wide*) *measurements*
    - *more stringent test for a very unique result*
  - our measurement is spatially resolved
    - we *average over microns (at most) and not over the whole sample*
    - *can give limits on scale of inhomogeneities*
- *Image magnetically for hints of competing phases*

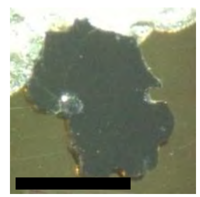
High Quality P-Ba122 Single Crystals Spanning the Supercond. Dome

- from the Matsuda group, Kyoto Japan.
- grown by the self-flux method and annealed in vacuum.
- cleaved before each cooldown

x=0.550

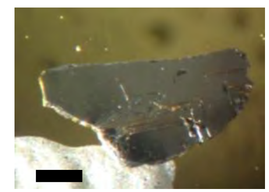


0.48

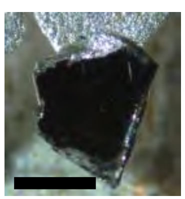


0.33

0.30

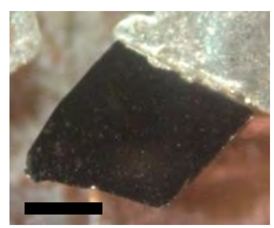


0.29

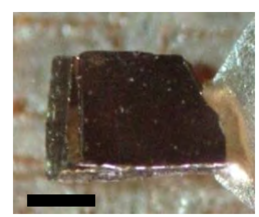


0.285

0.26



0.26



0.22

0.22

- scale bars: 0.5mm
- x from EDS

outline

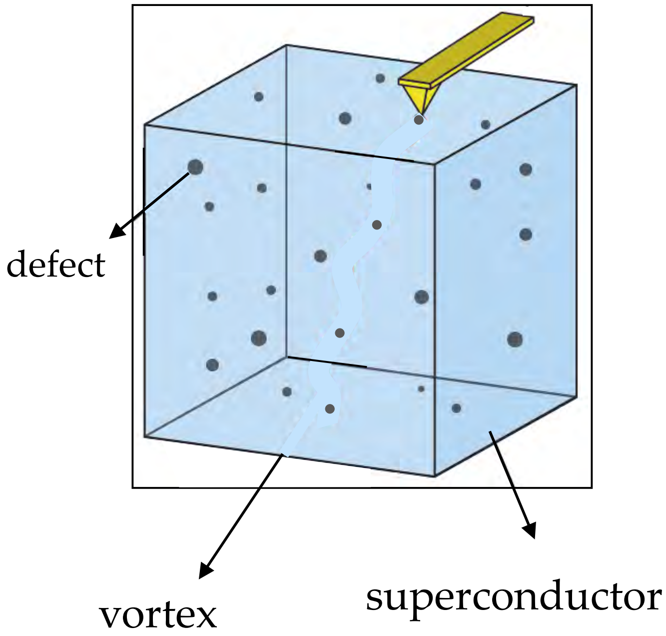
- the pnictides
  - in particular P-Ba122 [$\equiv BaFe_2(As_{1-x}P_x)_2$]
  - our samples
- MFM – a local probe for superconductivity
- the penetration depth
- vortex decoration & manipulation

'Bulk' Properties from a Mag. Scanned Probe

Length scale for magnetic response - hundreds of nanometers

- Can give information about bulk
  - in a superconductor – direct (and local) information about the Meissner effect.
- Less need for sample fabrication (can be easy to deploy)
- Less susceptible to edges, cracks etc. (we can move away)
- Information about homogeneity

From: Reichhardt, Nat. Phys. news&views '09

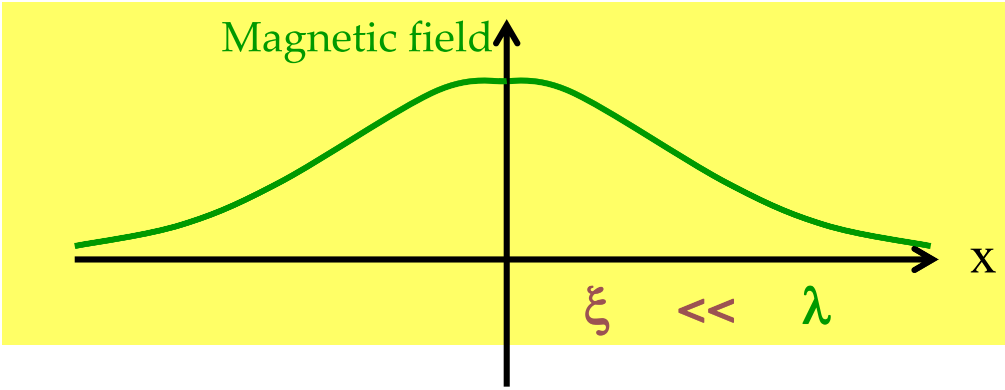


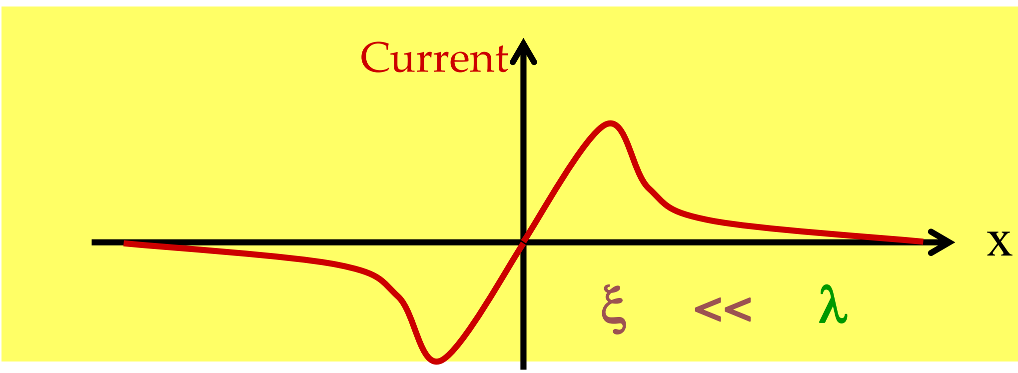
Vortex imaging and manipulation

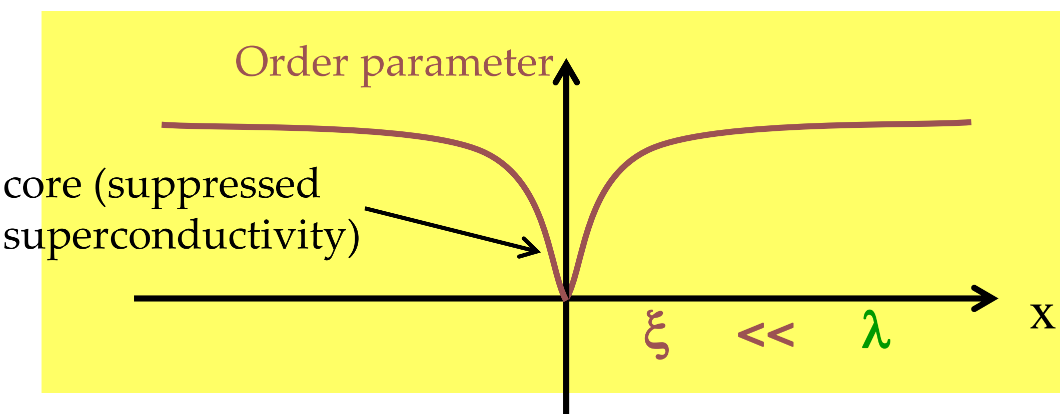
Vortices extend from the surface deep into the sample

- We can get information about the bulk:
  - Imaging: vortices are affected by defects
  - Manipulation: when we drag a vortex we are pulling it through the material

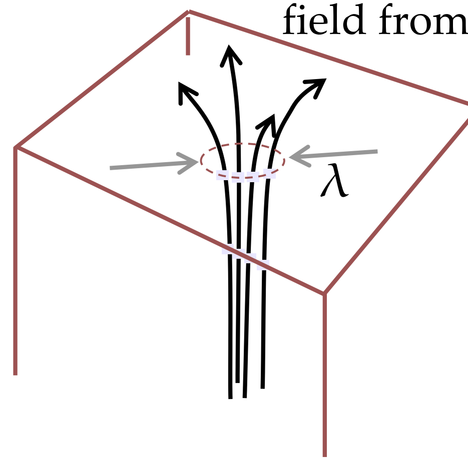
Length Scale for Imaging Magnetic Field: λ







cartoon of the magnetic field from a vortex

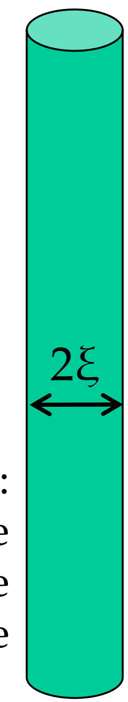


Length scales

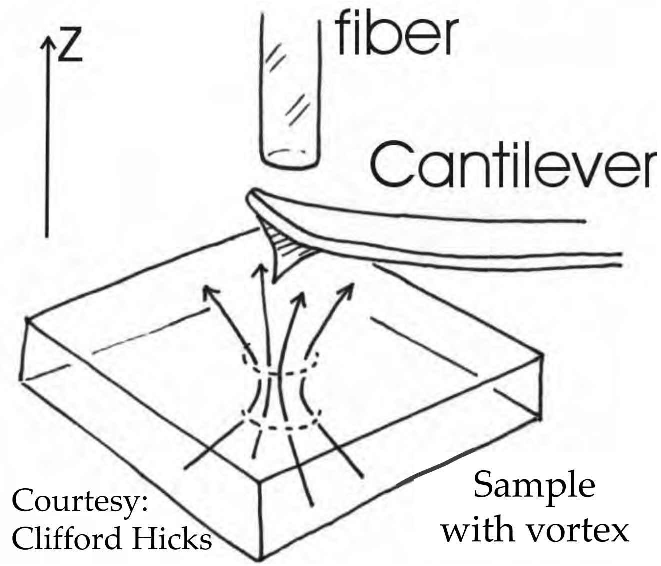
λ penetration depth (hundreds of nm)

ξ vortex core size (few nm)

"Flux Tube" cartoon: cylindrical hole punched through the condensate



MFM: Measure Force Gradients



Courtesy:
Clifford Hicks

Sample
with vortex

$$m\ddot{z} + \gamma\dot{z} + k\left(z - z_0\right) = F_z\left[z\right]$$

$$F_z[z] \approx F_z[z_0] + (z - z_0)(\partial F_z/\partial z)_{z=z_0}$$

Expansion around z_0

$$m\ddot{z} + \gamma\dot{z} + k_{eff}\left(z - z_0\right) \approx F_z\left[z_0\right]$$

$$\boxed{\vec{F} \approx \langle \vec{\nabla}(\vec{M} \cdot \vec{H}) \rangle}$$

Average over whole tip
(AFM tip with magnetic coating)

$$\boxed{k_{eff} = k - (\partial F_z/\partial z)_{z=z_0}}$$

Albrecht et al. '91

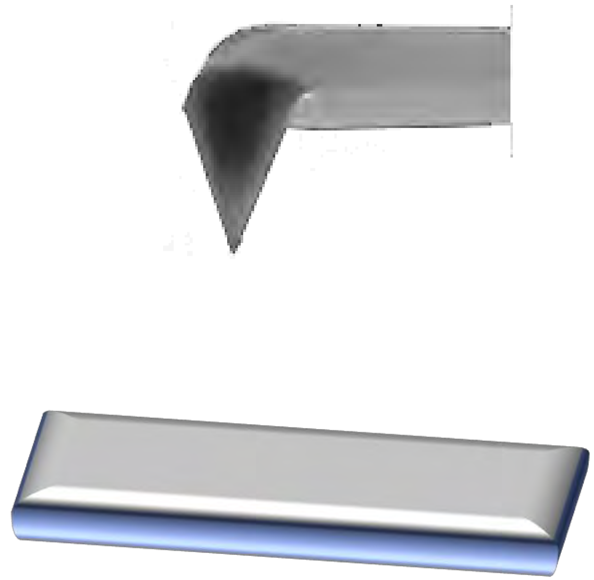
$$f_0 + \Delta f = \underbrace{2\pi\sqrt{\frac{k}{m}}}_{\boxed{f_0}}\sqrt{1 - \frac{(\partial F_z/\partial z)_{z=z_0}}{k}}$$

$f_0 >> \Delta f$

Shift in f_0 gives $\partial F_z/\partial z$

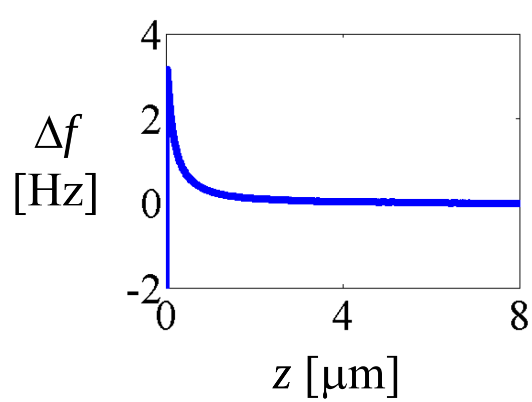
$$\boxed{\frac{\Delta f}{f_0} \sim -\frac{(\partial F_z/\partial z)_{z=z_0}}{2k}}$$

MFM Magnetic Tip is Repelled from a Superconductor



Meissner response:
a repulsive force

(attractive force would have
opposite curvature)



outline

- the pnictides
  - in particular P-Ba122 [$\equiv BaFe_2(As_{1-x}P_x)_2$]
  - our samples
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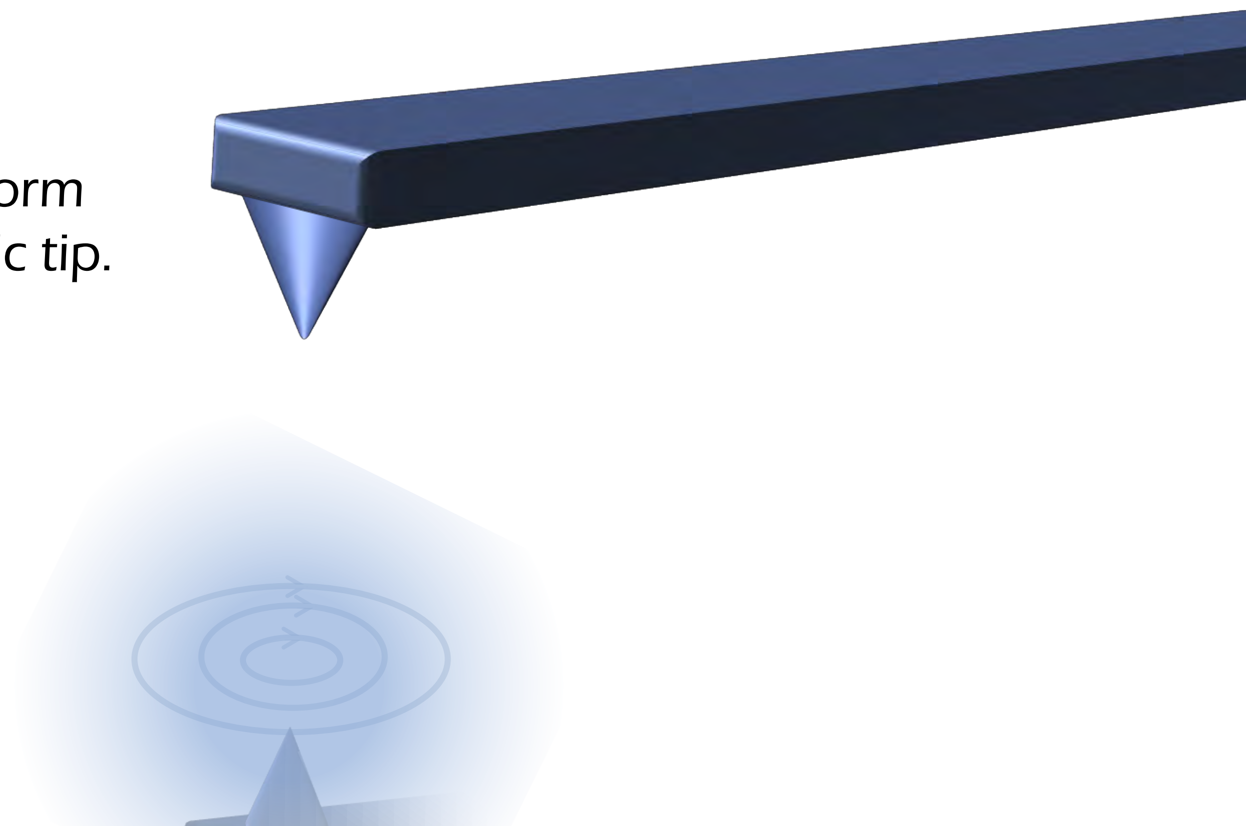
- vortex decoration & manipulation

Magnetic Interaction - Meissner

Persistent screening currents in the sample cancel the magnetic field from the tip

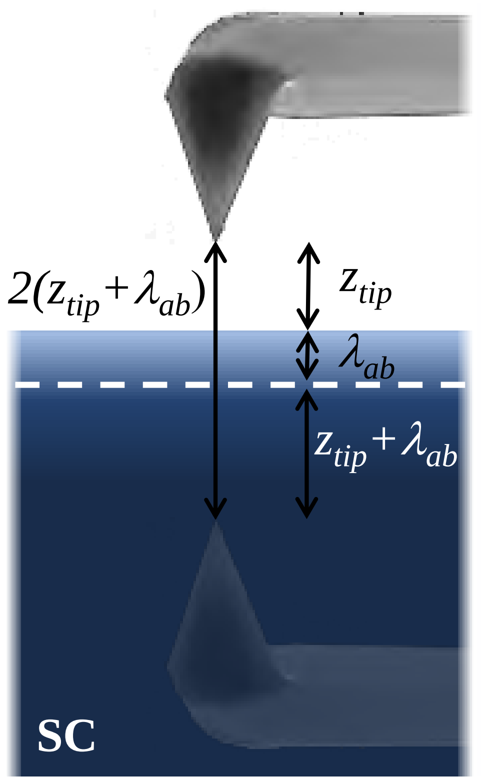
The screening currents form an image of the magnetic tip.



Xu *et. al.*, Phys. Rev. B **51**, 424 (1995).

Magnetic Interaction - Meissner

The location and strength of the magnetic image depends on λ_{ab}



For $z_{tip} \gg \lambda_{ab}$ the MFM signal is given by:

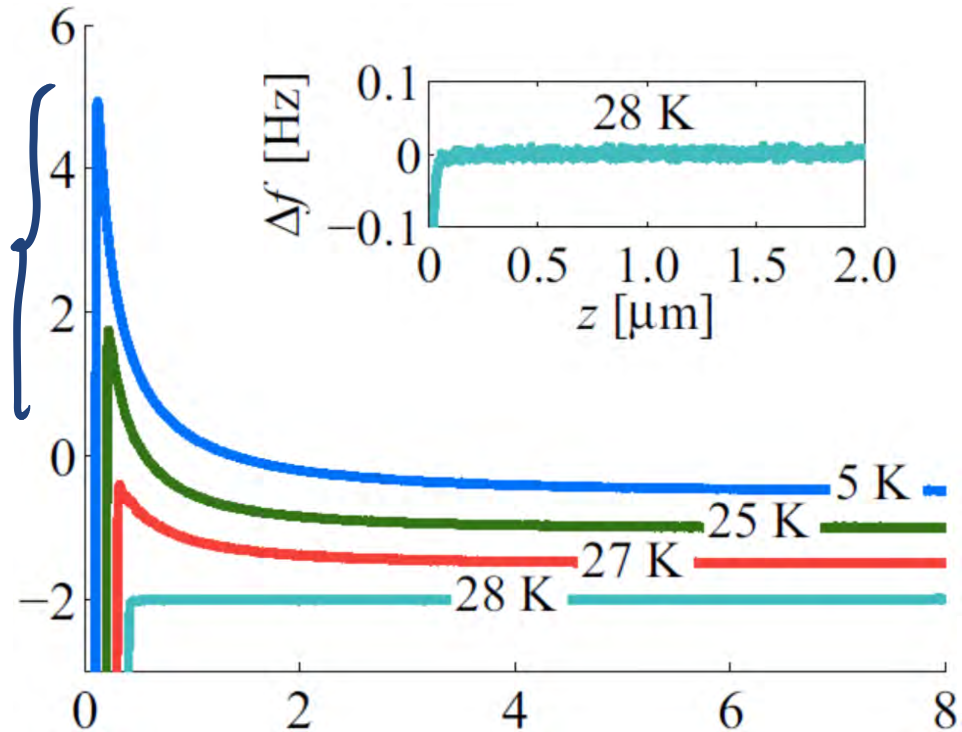
$$\boxed{\frac{\partial F_z}{\partial z} \cong -\frac{\mu_0}{2\pi}\int dk\, k^4\, e^{-2k\left(z_{tip}+\lambda_{ab}\right)} \int_{tip} d^3r\, M_{tip}\left(\vec{r}_{tip}\right) \int_{tip'} d^3r'\, M_{tip'}\left(\vec{r}_{tip}^{\,'}\right) e^{-k\left(z'+z''\right)} J_0\left(k\left|\vec{\rho}\,'(z')-\vec{\rho}\,''(z'')\right|\right)}$$

Xu *et. al.*, Phys. Rev. B **51**, 424 (1995).

"T_C" = Temp. Where Meissner Disappears

$\Delta f\ [Hz] \uparrow$

signature of Meissner repulsion of the magnetic tip from the sample



$\rightarrow z\ [\mu m]$

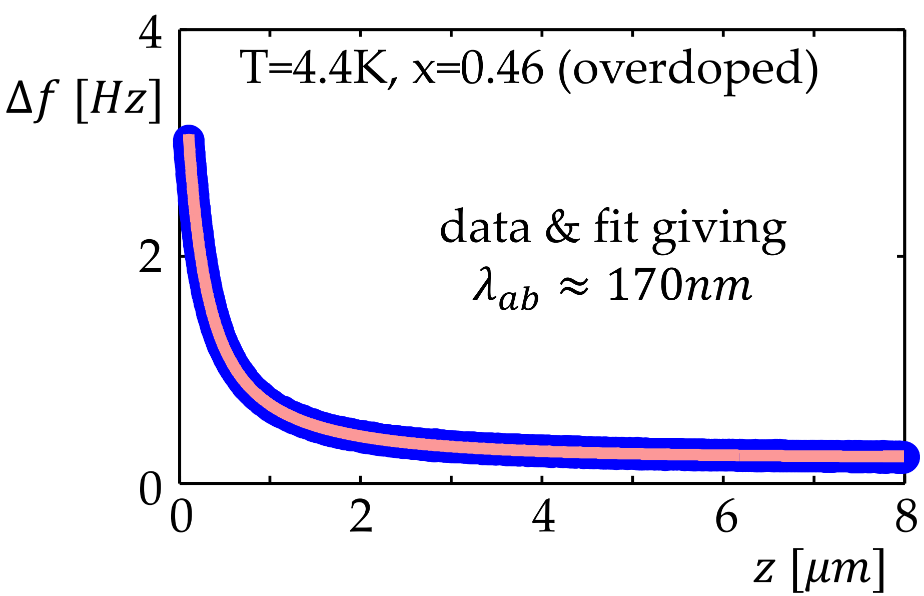
x=0.29

Curves are offset for clarity

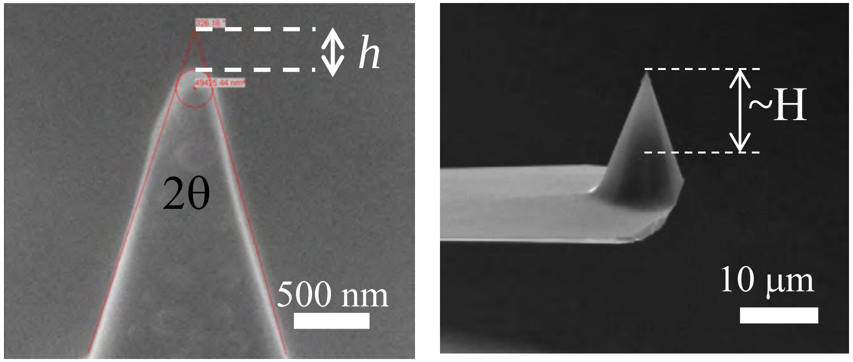
Meissner Response to the Local Field from the Magnetic Tip Gives λ_{ab}

Using a model we fit to obtain a value for λ_{ab}

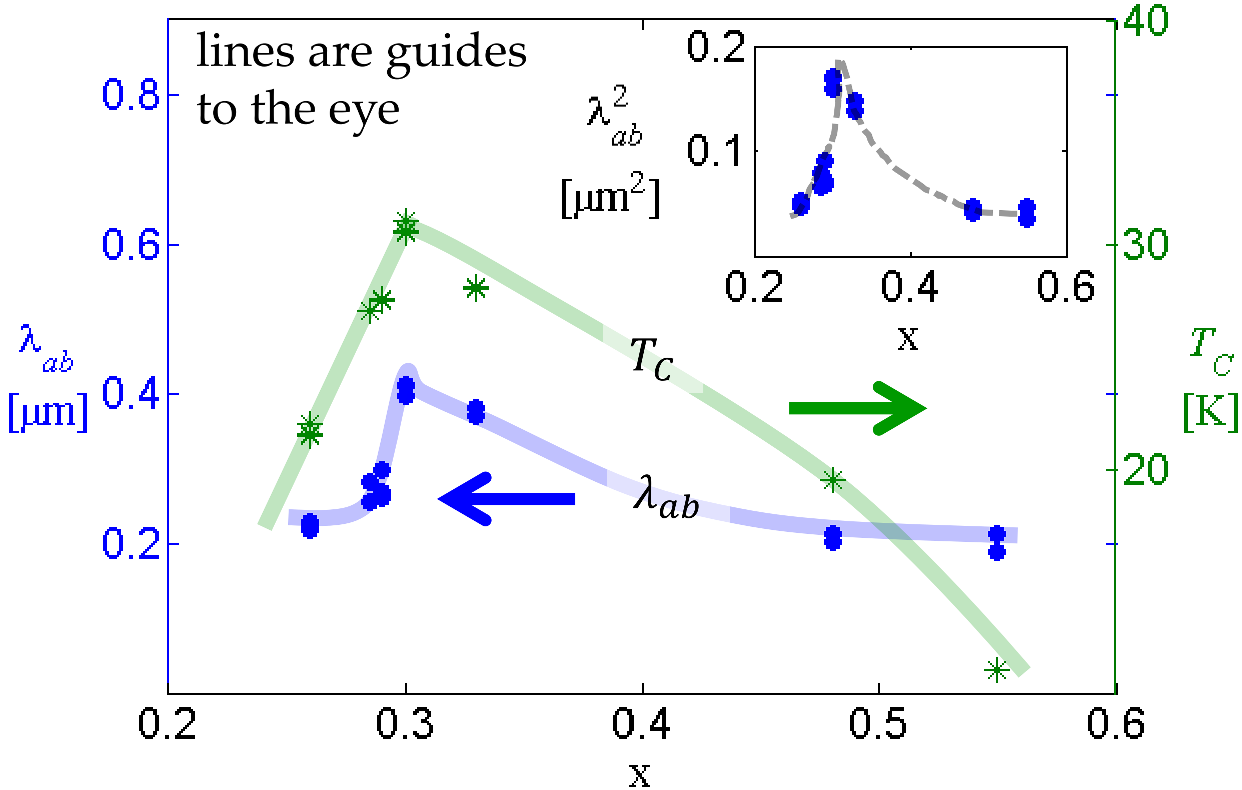
- our fit is a refinement of Luan et al. PRB `10

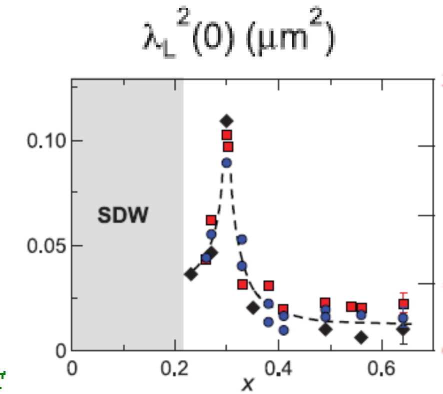


Tip model: truncated cone:



Results – peak in λ_{ab} @ optimal doping





Hashimoto et al.,
Science '12

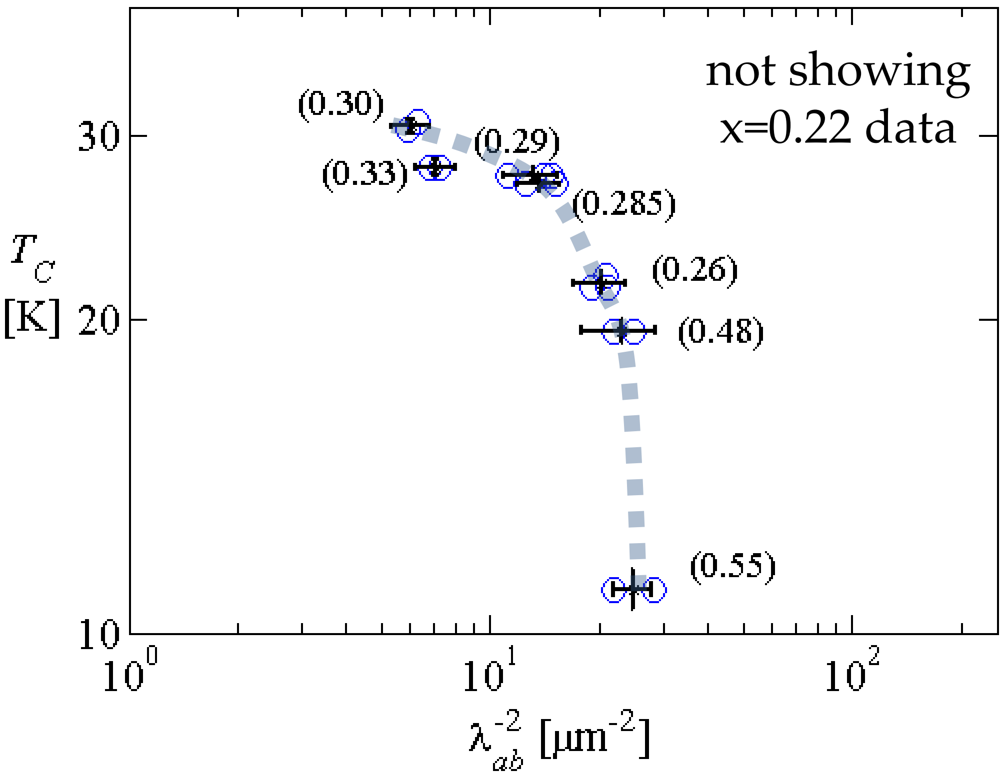
not showing results for very underdoped samples.

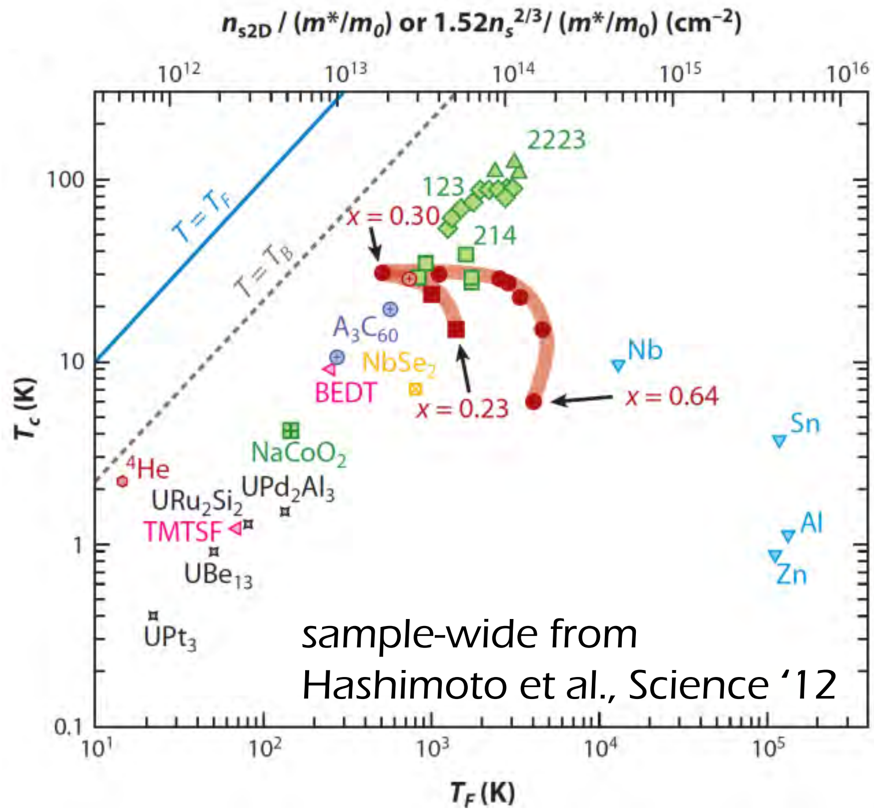
conclusion:

even though we only average over a micron scale region – the peak is there

Same $T_C(\lambda_{ab})$ on Both Sides of the Peak

local measurement





on both sides of x_{OPT} :

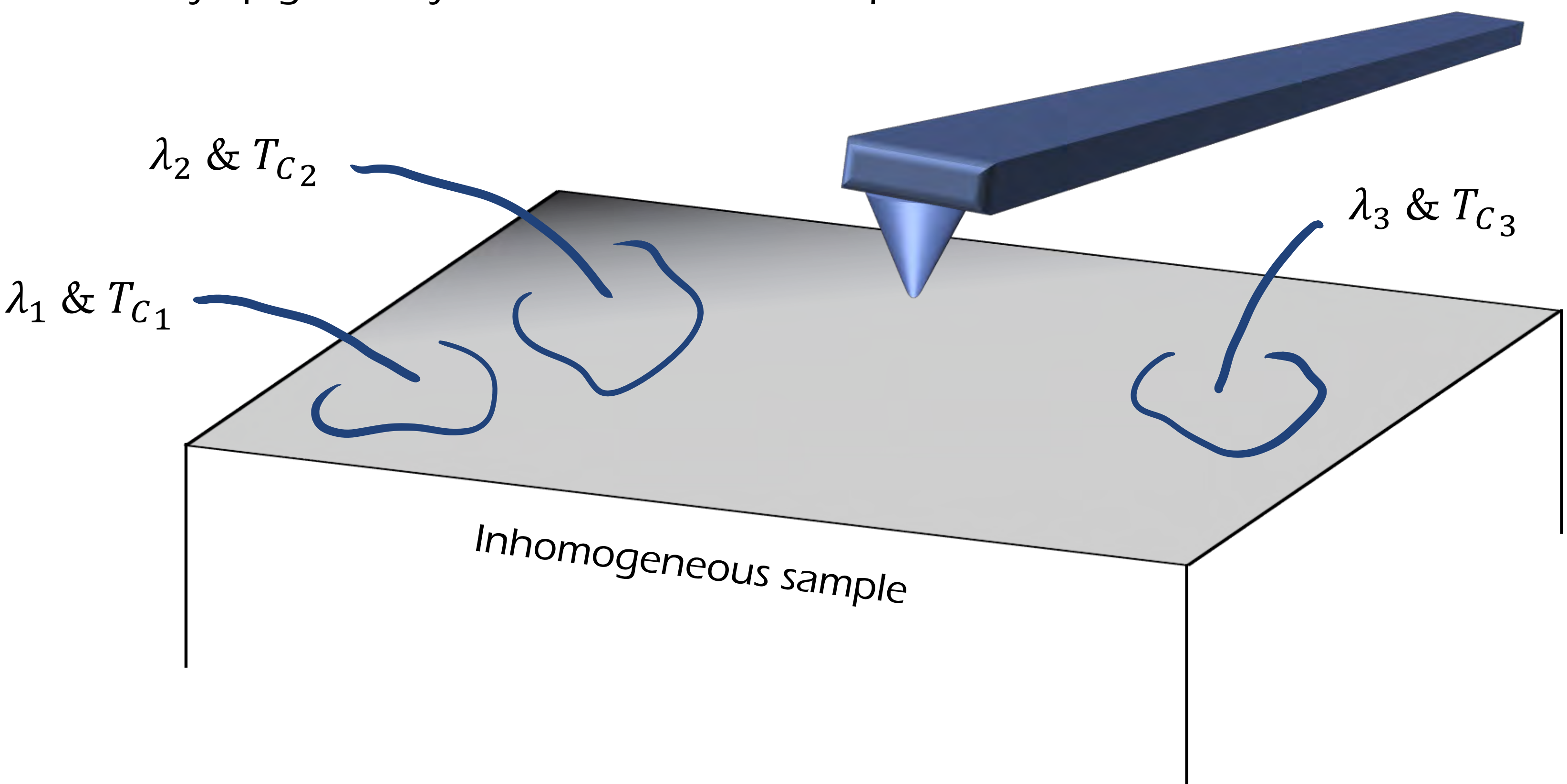
- same asymptotic T_C^{max}
- same dependence of T_C on λ_{ab}

possibly our results are different because

we do not average over the whole sample

We Measure T_C & λ_{ab} in the Same Area

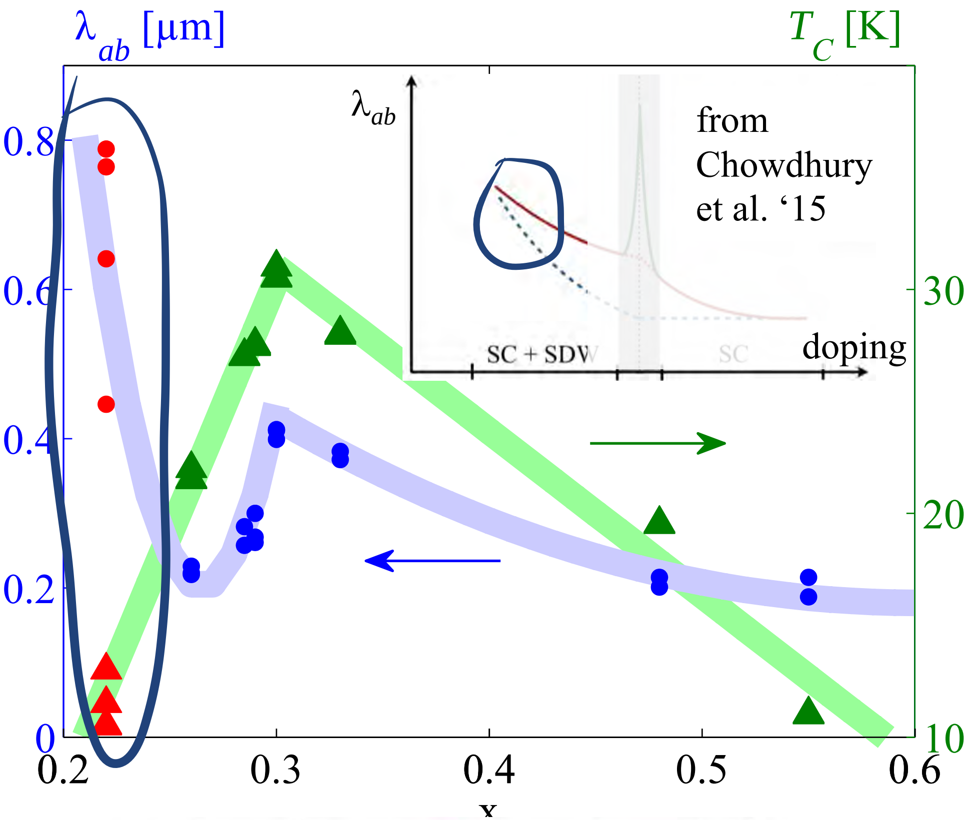
The magnetic field inducing the Meissner response is local on a length scale set by tip geometry and distance from sample.

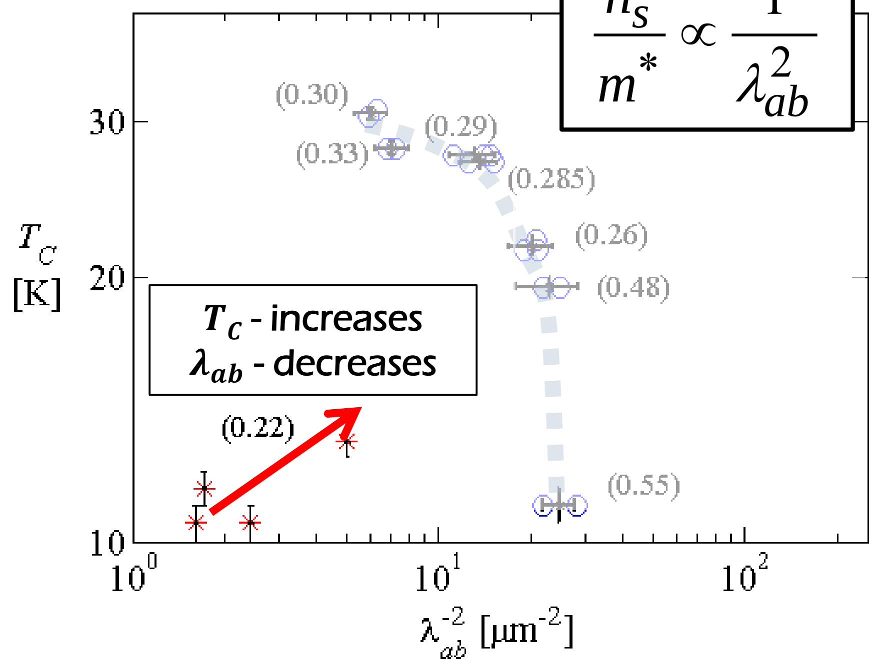


Our results are not sample averaged.

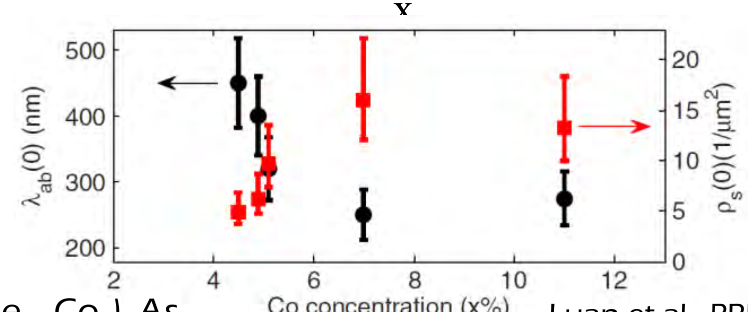
Sharp Rise of λ_{ab} at Very Low Doping

x=0.22 samples were less homogenous in composition than other samples.





$$\frac{n_s}{m^*} \propto \frac{1}{\lambda_{ab}^2}$$



$Ba(Fe_{1-x}Co_x)_2As_2$ Luan et al., PRL '11

The sharp rise of λ_{ab} means that n_s is suppressed:

- nothing dramatic happens to m^*

outline

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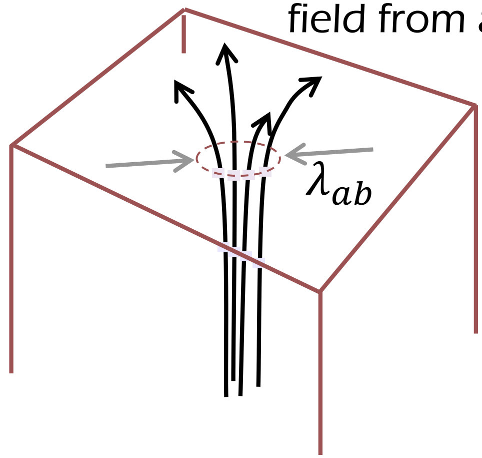
a Vortex Looks Like a Magnetic Monopole

cartoon of the magnetic field from a vortex

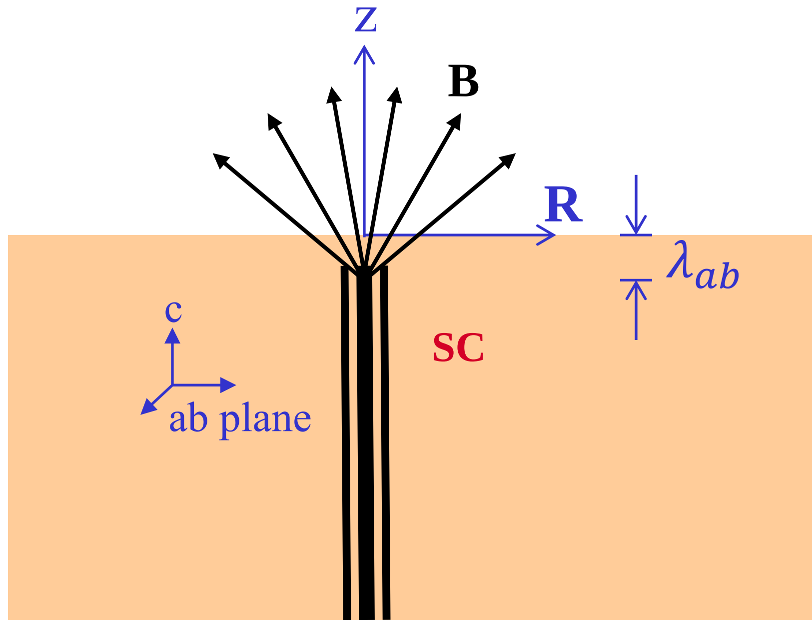


For $R^2 + z^2 \gg \lambda_{ab}^2$ – a vortex looks like a monopole:

$$\vec{B}(\vec{R}, z) \sim \frac{\Phi_0}{2\pi} \frac{\vec{R} + (z + \lambda_{ab})\hat{z}}{\left[R^2 + \left(z + \lambda_{ab}\right)^2\right]^{3/2}}$$

Scale for resolution is $z + \lambda_{ab}$

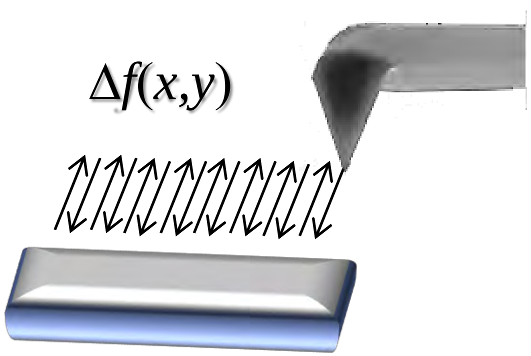
i.e. scale for imaging is down to 100 nm



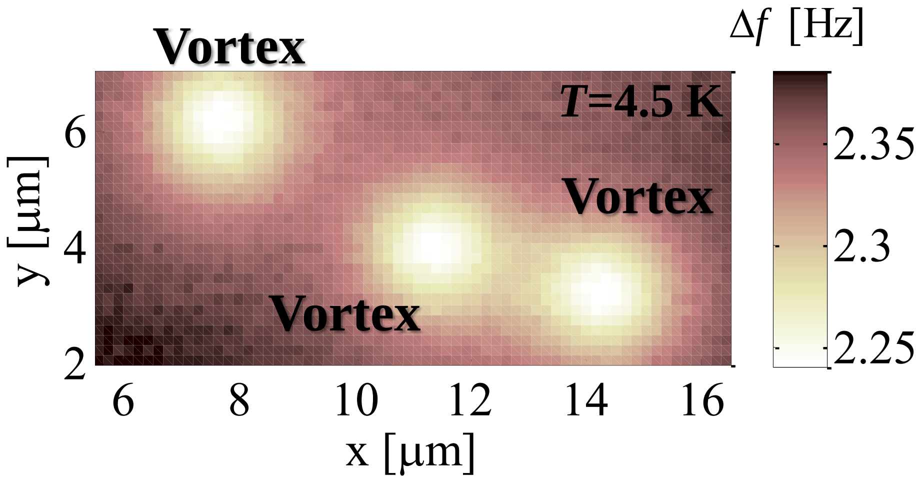
Magnetic Imaging

Field cooling through T_C creates magnetic vortices

- each carrying one quantum of flux $\Phi_0 = h/2e \approx 20.7\ G\mu m^2$
- each giving a looking roughly like a magnetic monopole at $z = -\lambda_{ab}$



raster pattern
for scanning

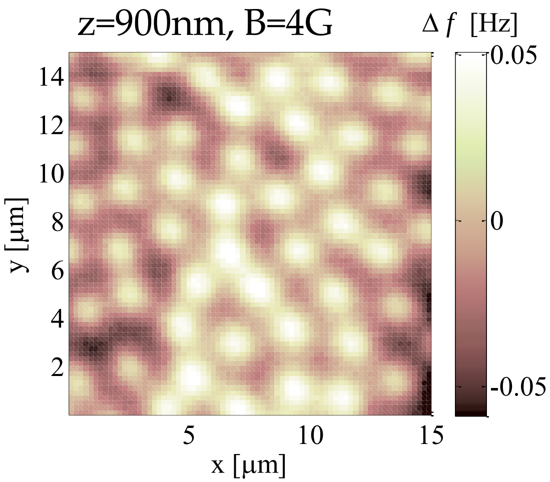


Vortices interact with defects

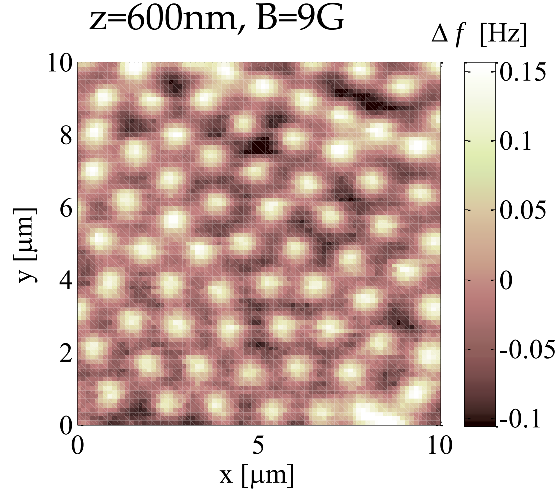
allow us to detect them by imaging

x > 0.28: "ordered" vortex array

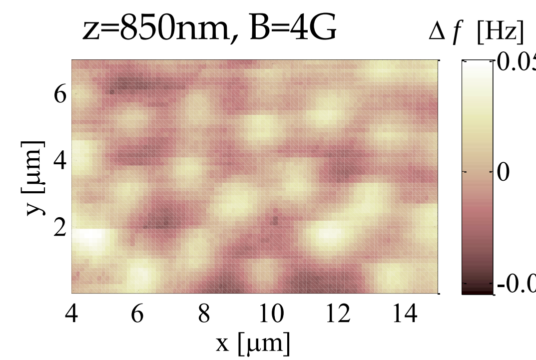
scans at $T \cong 4.5$ K:



x=0.29



x=0.33

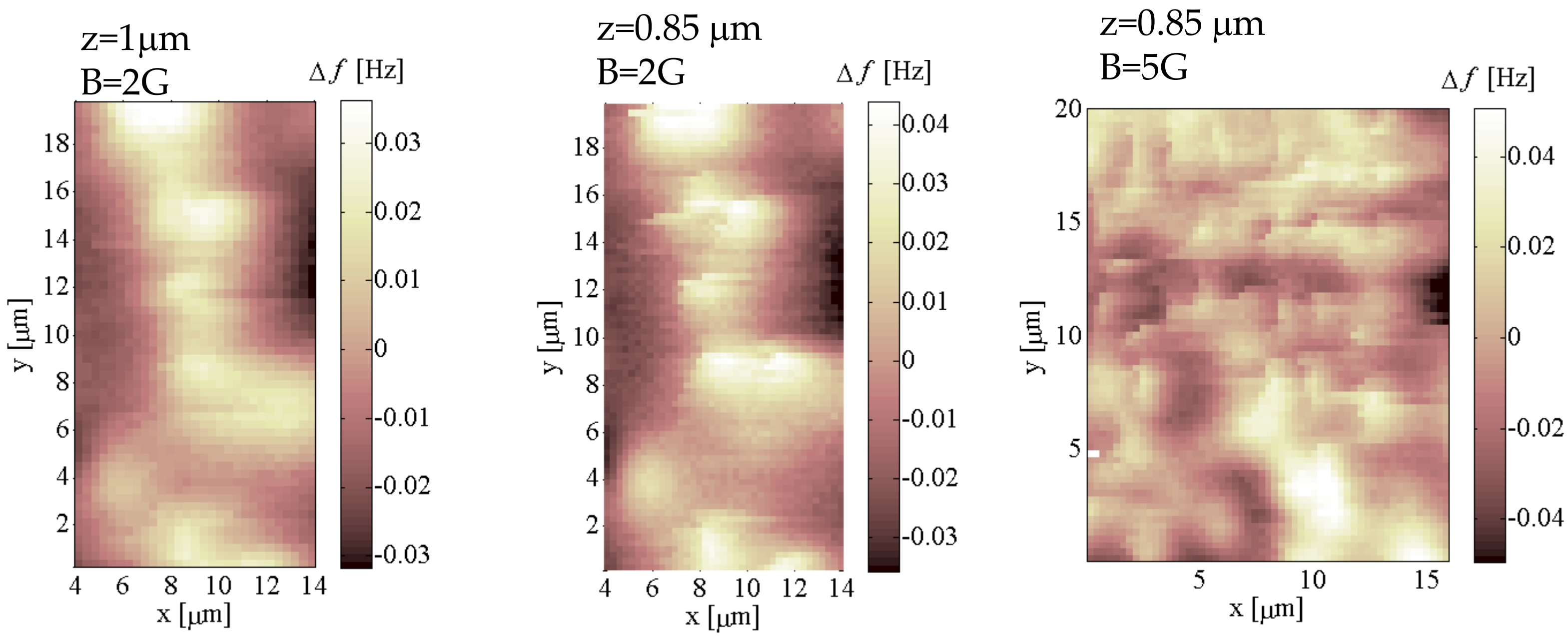


x=0.55

optimal doping: x=0.3

x=0.22: weak pinning

scans at $T \cong 4.5$ K:



at x=0.22 λ_{ab} is large (450-800nm)

1. large vortices
2. weak tip-vortex interaction

BUT

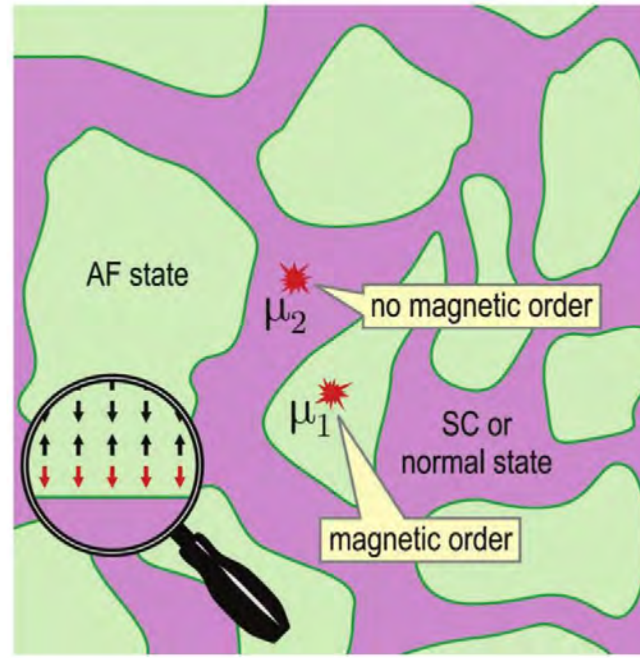
vortices move very readily → weak pinning

optimal doping: x=0.3

Pinning in Very Underdoped Samples is Weak

possibly:

1. a lot of disorder
   - material defects
   - intrinsic – underdoped samples are in the mixed phase
     - we cannot resolve inhomogeneities directly but the vortices may be probing them
       - scale is nm's in most pnictides.
       - perhaps more in P-Ba122

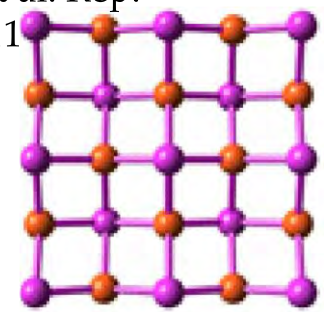


Carretta et al., Phys. Scr. **88**, 068504 (2013).

2. at the edge of the dome S-C is weaker because of the competing phase
   - gap and pairing are suppressed → ξ is larger → pinning is weaker.

Mild Underdoping: Lines of Vortices

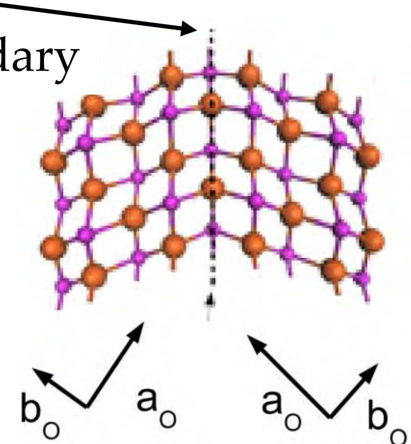
from Fisher et al. Rep. Prog. Phys. '11



$T>T_S$: tetragonal

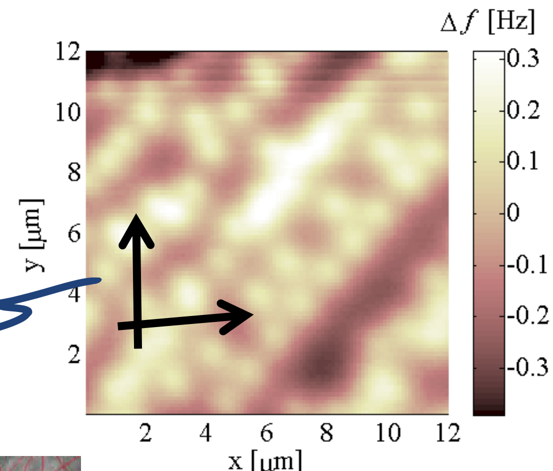
$T<T_S$: orthorhombic

twin boundary

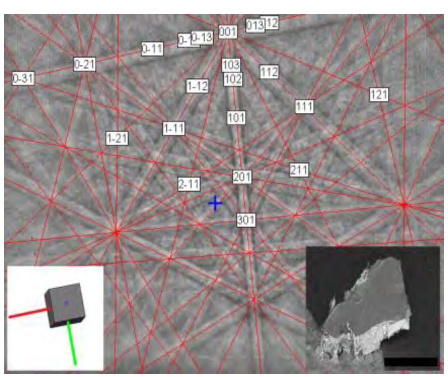


Linear vortex arrays orientated 45° to the crystal axes

- probably parallel to twin boundaries
- The existence of twin boundaries is a signature of nematic order
  - their presence implies an orthorhombic unit cell.
- this implies that supercond. coexists with other phases at low doping



Crystal axes



EBDS @ RT
Kikuchi lines

Twin Boundaries - Usually Vortex Traps

usually - expect the order parameter to be suppressed on a twin boundary

e.g.

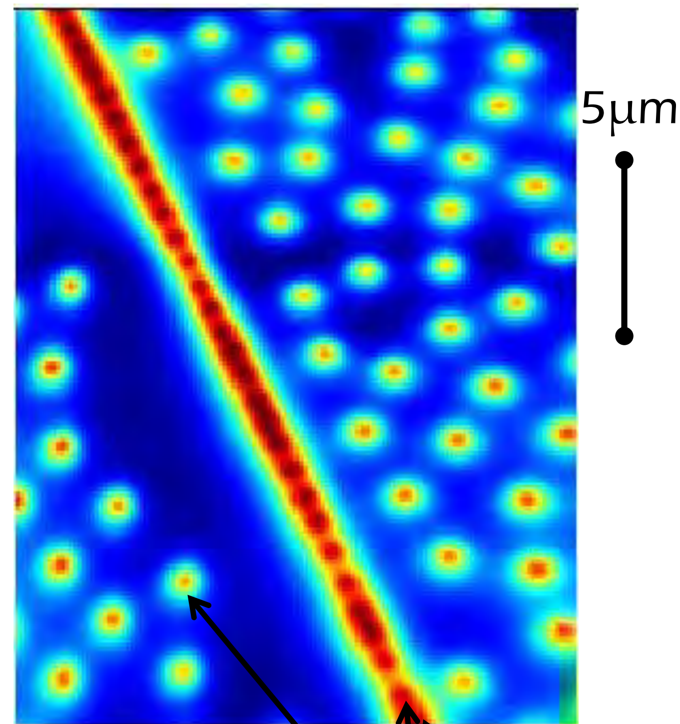
- MFM on YBCO near optimal doping
  - vortices are on a line
  - no modulation off the line

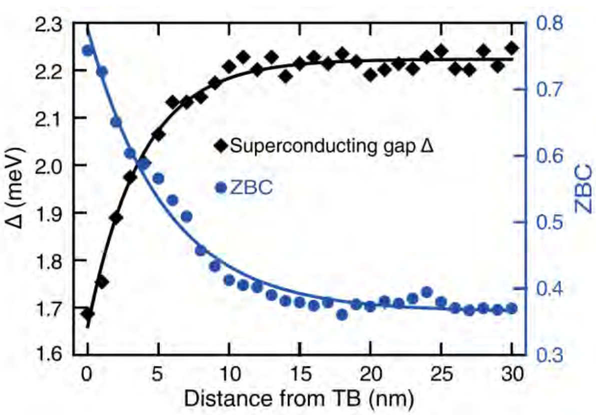
[Shapira et al., PRB 2015]

- STM on FeSe thin films [Song et al., PRL 2012]
  - gap is suppressed on the twin boundaries
  - vortices are on the twin boundaries

MFM on YBCO (T~4.3K) z~150nm

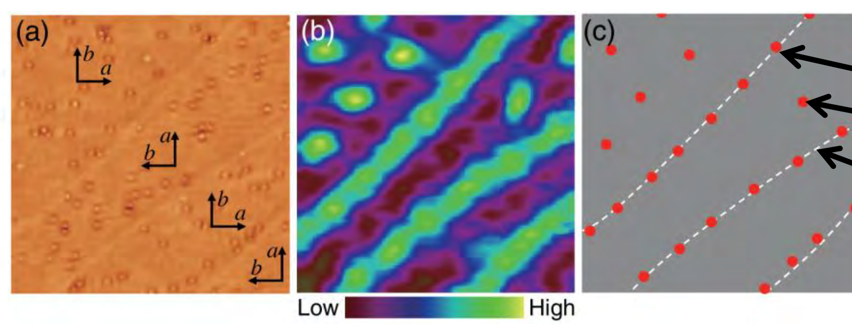
color span: ~0.75Hz





STM on FeSe thin films

[Song et al., PRL 2012]



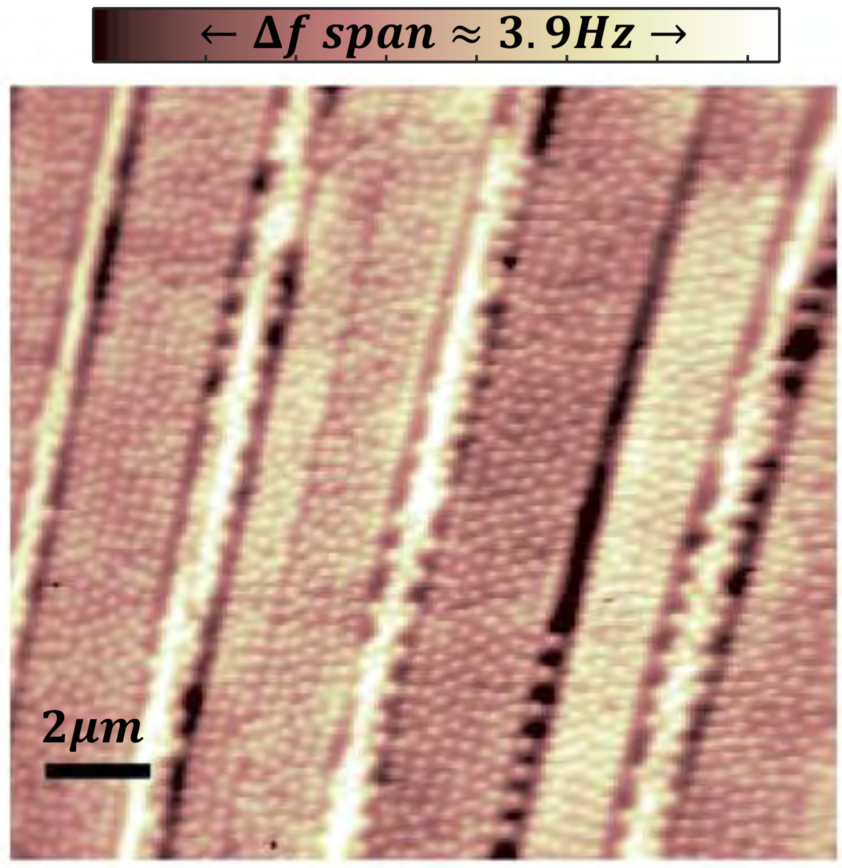
vortices

twin boundaries

150nm x 150nm

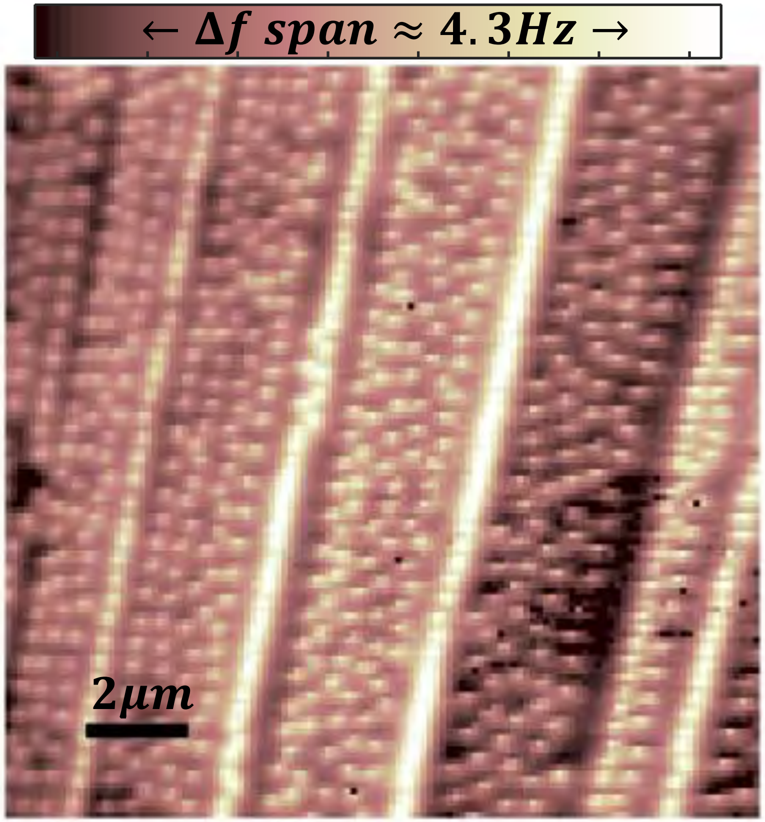
High Field – Lines of Vortices

T = 4.5K
B > 130G
$z \approx 70nm$



High Field – Lines of Vortices

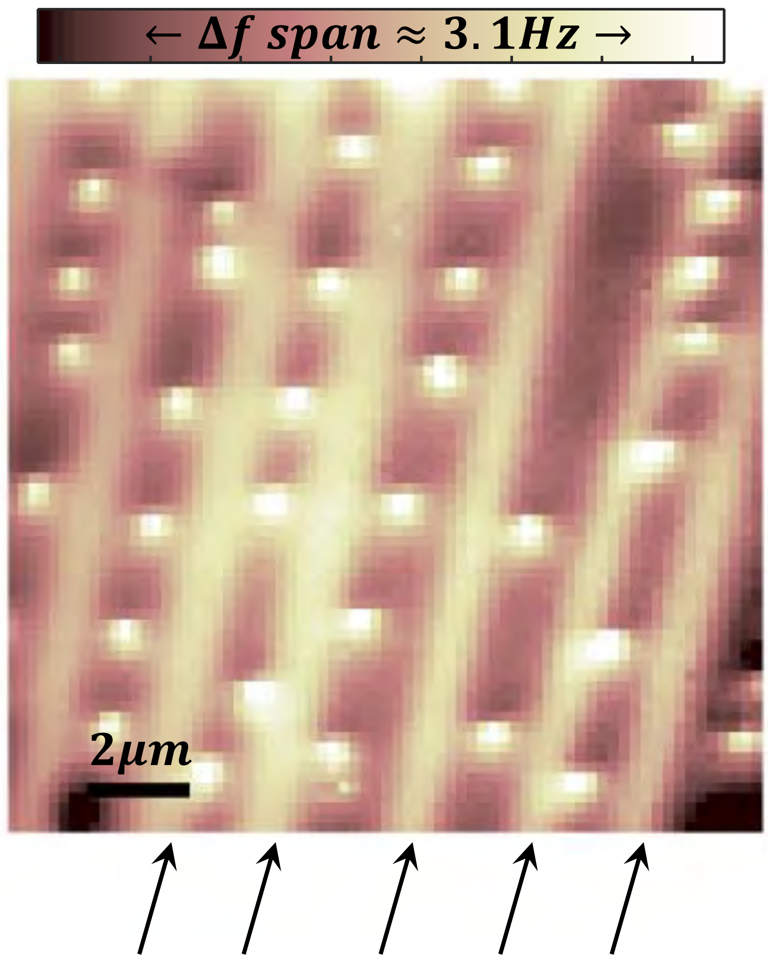
T = 4.5K
B ≈ 60G
z ≈ 100nm



Low Field: Vortices Avoid Stripes

T = 4.5K
$B \approx 3G$
$z \approx 170nm$

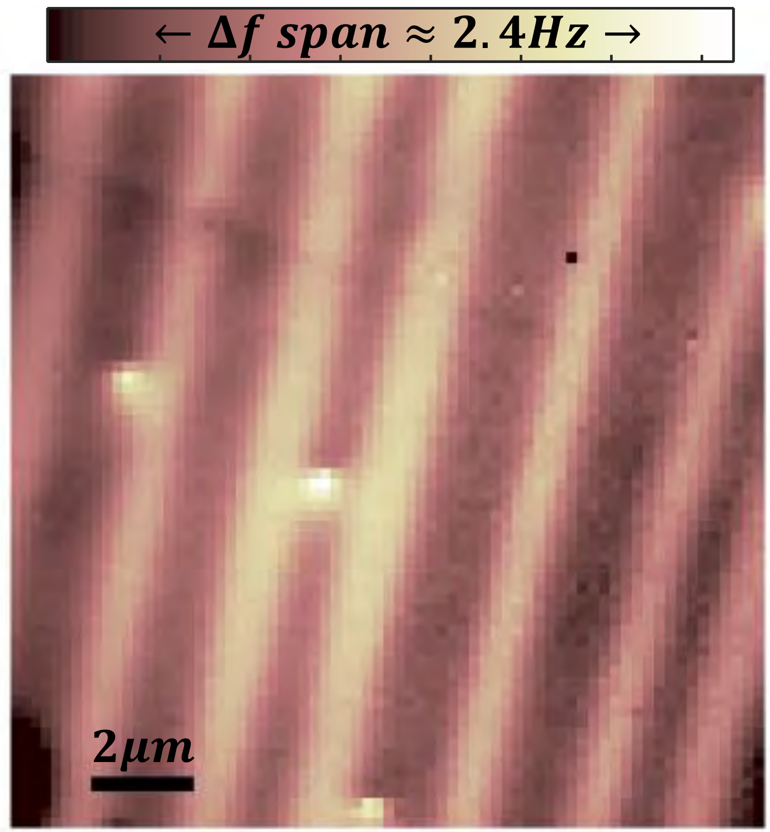
stripes are NOT periodic



stripes of enhanced Meissner repulsion
- width – hundreds of nanometers (scale probably given by $\lambda_{ab} \approx 220nm$)

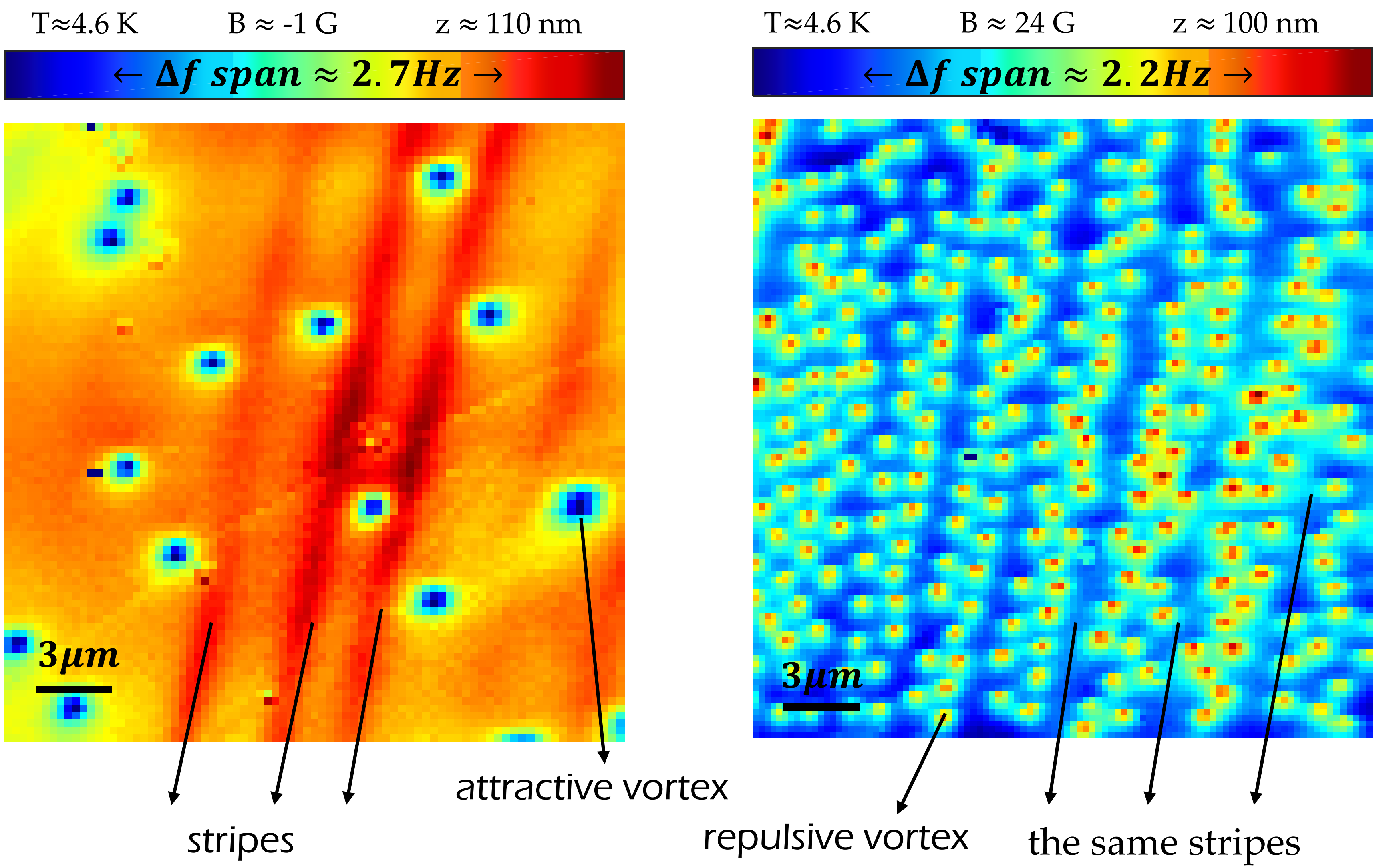
Stripes Are Visible w/o Vortices

T = 4.5K
B ≈ 0.2G
z ≈ 130nm

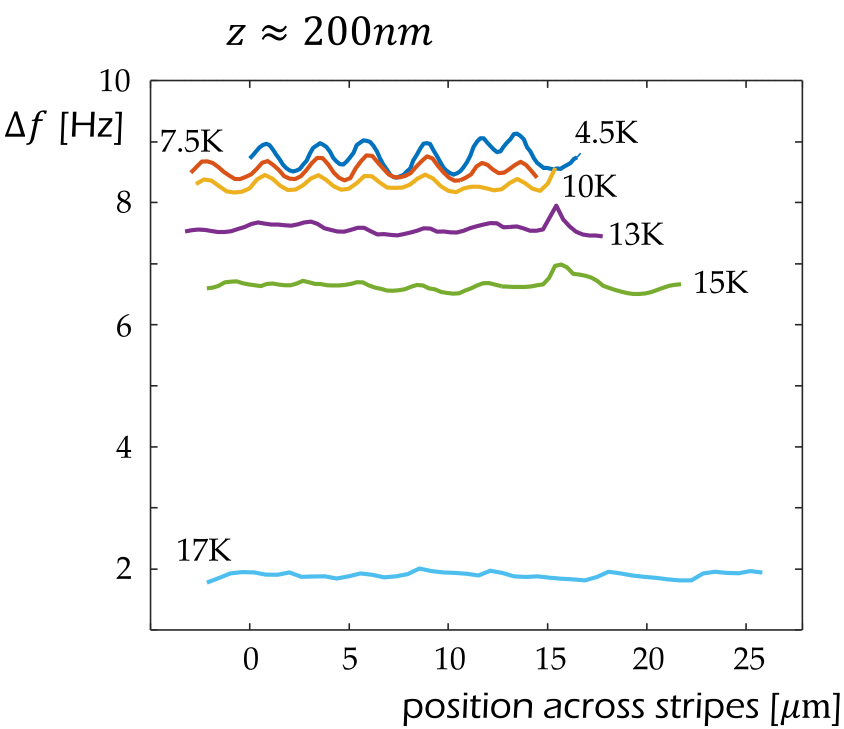


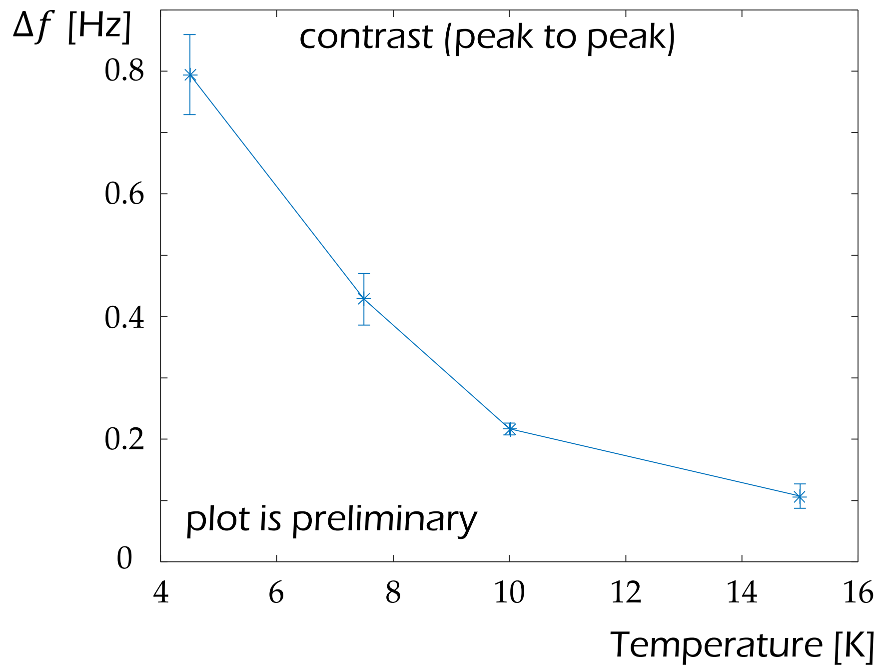
Similar Behavior When We Flip the Field

same area at different field – vortices are repelled from the stripes



Stripes Disappear When T increased

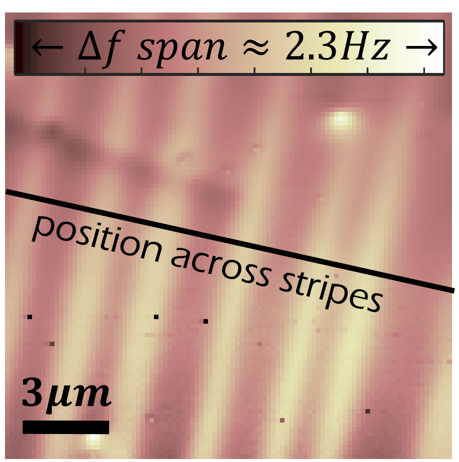




T ≈ 4.5K

z ≈ 220nm

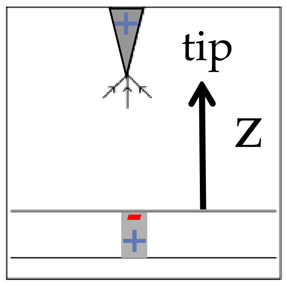
B ≈ 0.2G



We lose track of the stripes @ $T < T_C \approx 22K$

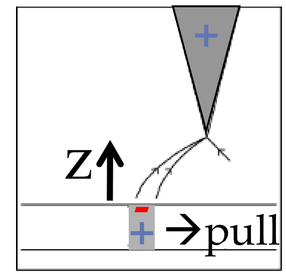
Vortex Manipulation: Stripes Are Barriers

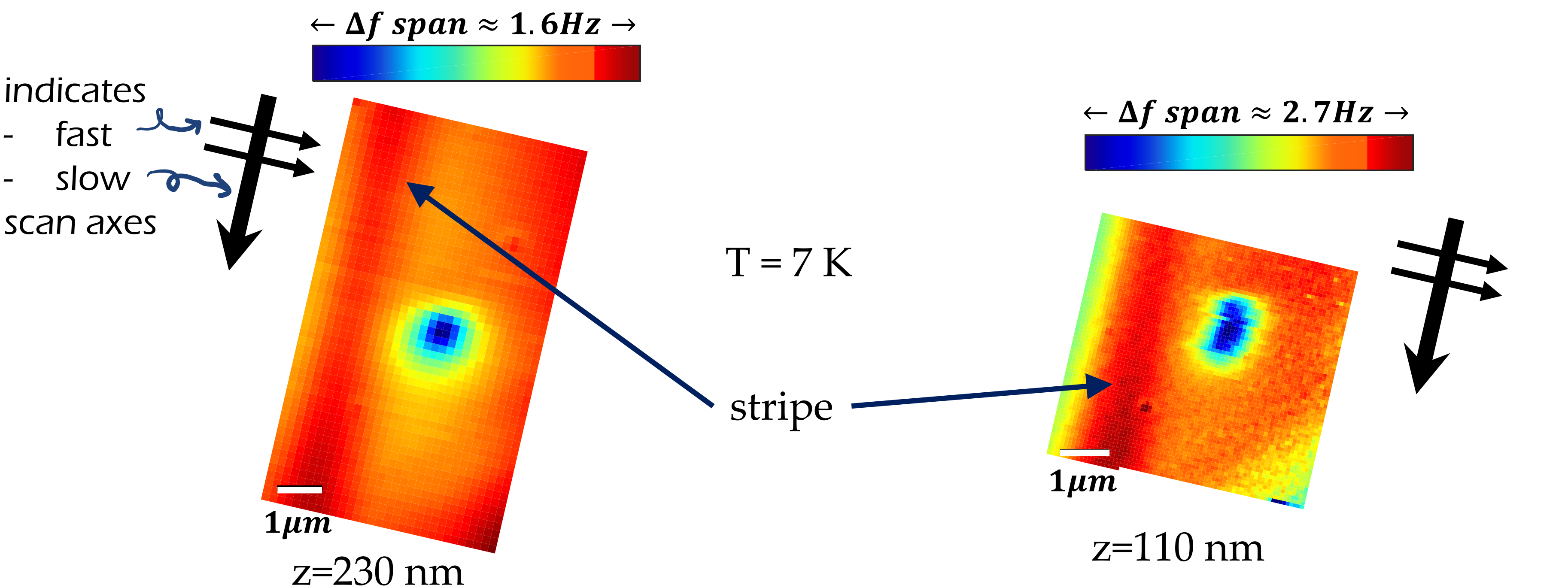
Surveillance



$$\left|\vec{F}_{\max}\right| \sim \frac{1}{z}$$

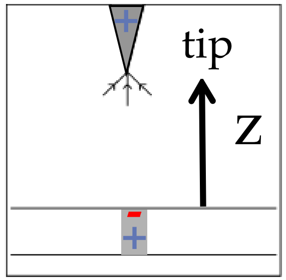
Manipulation





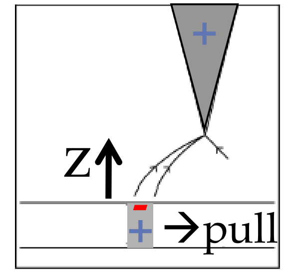
Same Vortex, Different Scan Direction

Surveillance



$$\left|\vec{F}_{\max}\right| \sim \frac{1}{z}$$

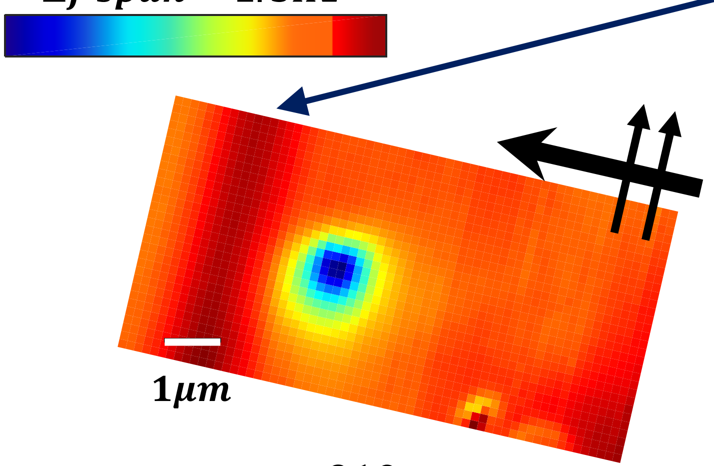
Manipulation



T = 7 K

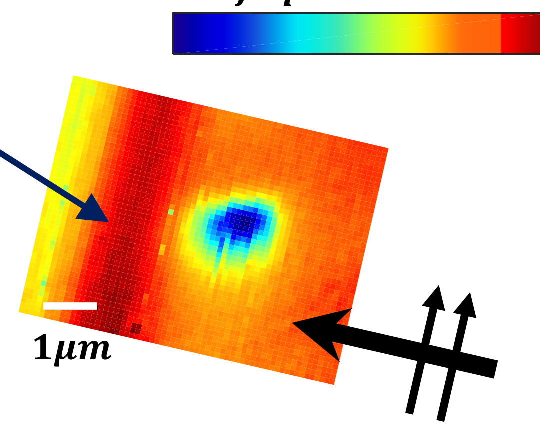
stripe

$\leftarrow \boldsymbol{\Delta f\ span \approx 1.3Hz} \rightarrow$



z=310 nm

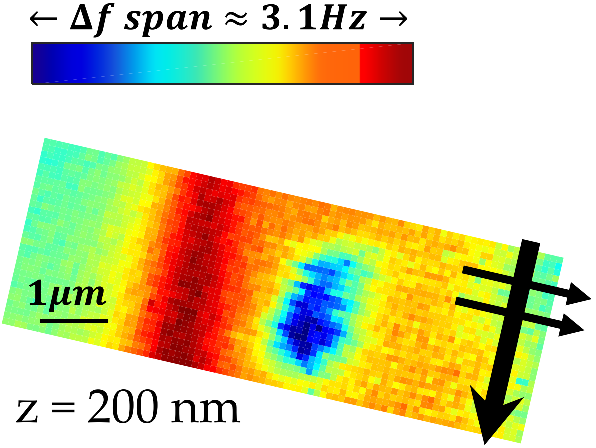
$\leftarrow \boldsymbol{\Delta f\ span \approx 2.4Hz} \rightarrow$



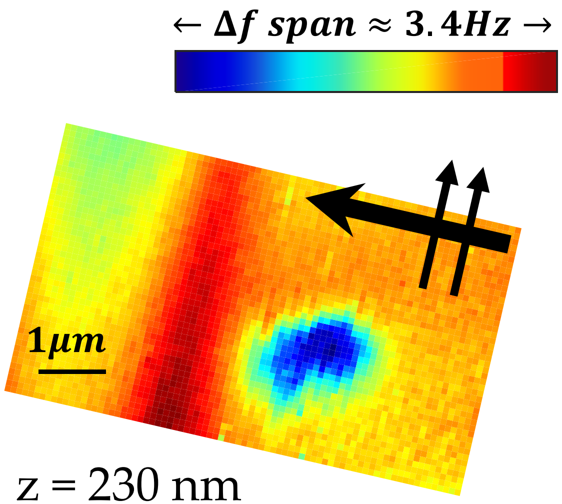
z=130 nm

Pulling in Different Directions @ Higher T, Same Story

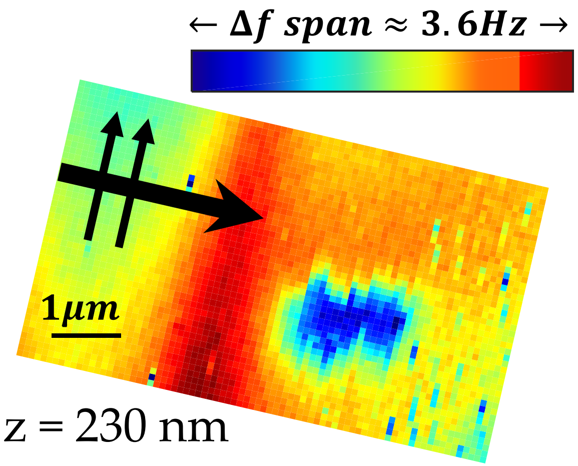
T = 8.5 K



z = 200 nm



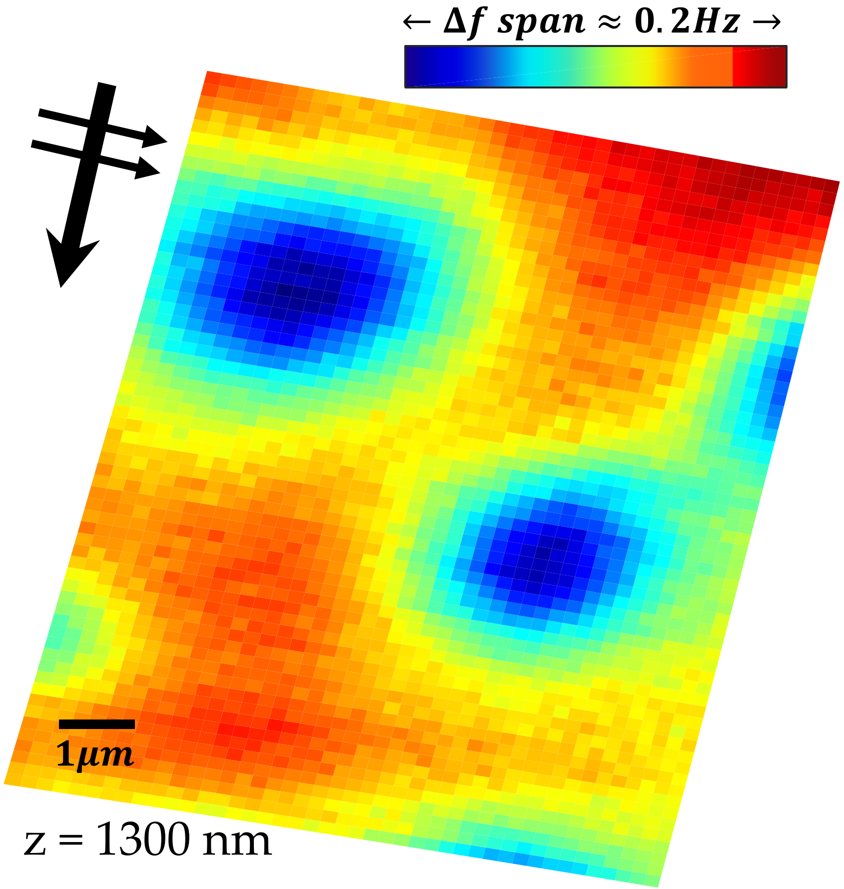
z = 230 nm



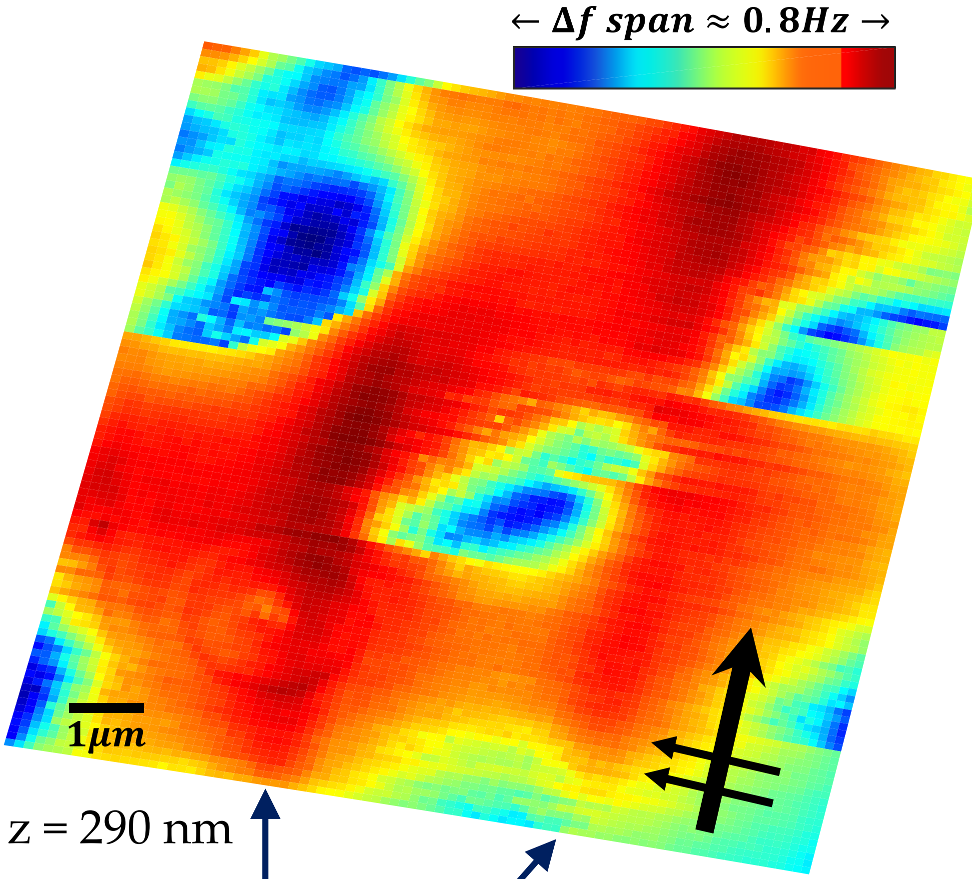
z = 230 nm

Still Higher T, Still Can't Cross

T = 15 K



z = 1300 nm

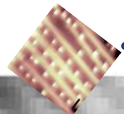


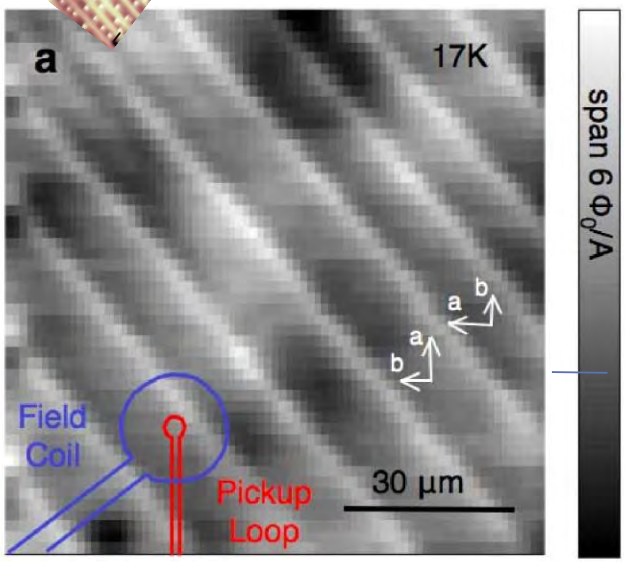
z = 290 nm

stripes

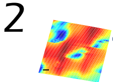
Similar to SQUID results in Co-Ba122

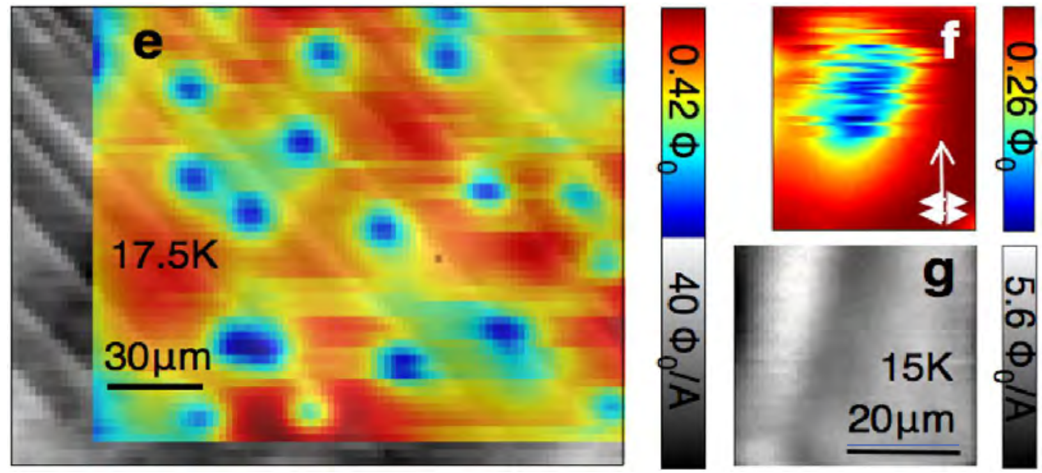
our MFM scan
on P-Ba122





our MFM scan
on P-Ba122





Scanning SQUID on $Ba(Fe_{1-x}Co_x)_2As_2$ (electron doped) from the Moler group @ Stanford.

Kalisky, Kirtley et al., PRB **81**, 184513 (2010); PRB **81**, 184514 (2010); PRB **83**, 064511 (2011).

SQUID images are resolution limited to a few microns

phenomenological model (next slide) predicts MFM should have seen such lines

- as we do in P-Ba122

BUT – in MFM in $Ba(Fe_{1-x}Co_x)_2As_2$ – no stripes were observed

Phenomenological Model - λ Not Uniform

Slightly modified London eqn.

$$\boldsymbol{h} + \boldsymbol{\nabla} \times (\lambda^2 \boldsymbol{j}) = 0$$

approximation results consistent with the SQUID data

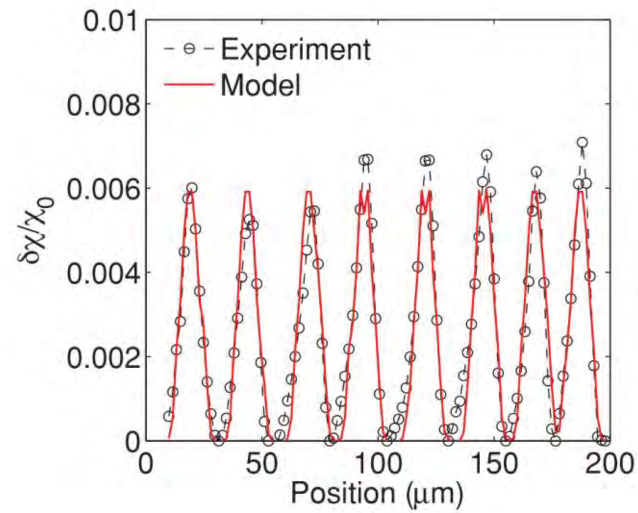
- assume variation in λ^2 is weak
- on every twin boundary λ^2 is reduced
    - $\lambda^2(x) = \lambda_0^2 - \beta^3 \delta(x)$

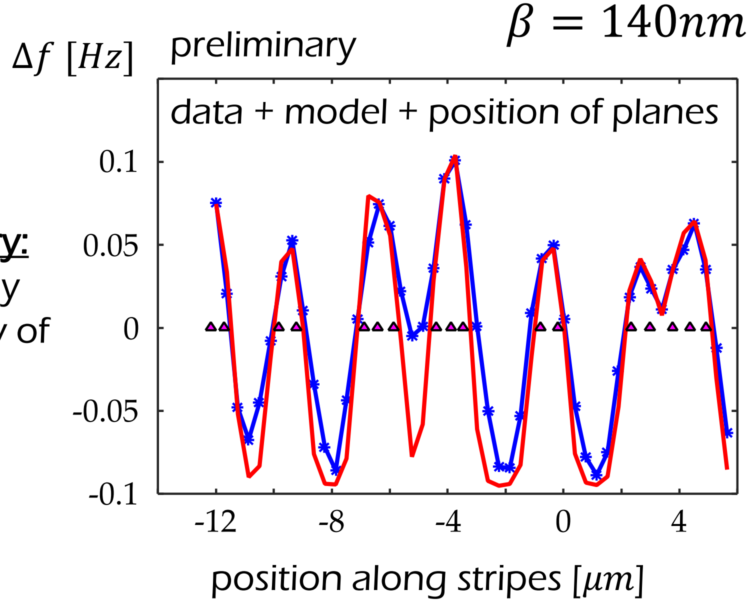
we have implemented for MFM

- lots of algebra & asymptotics

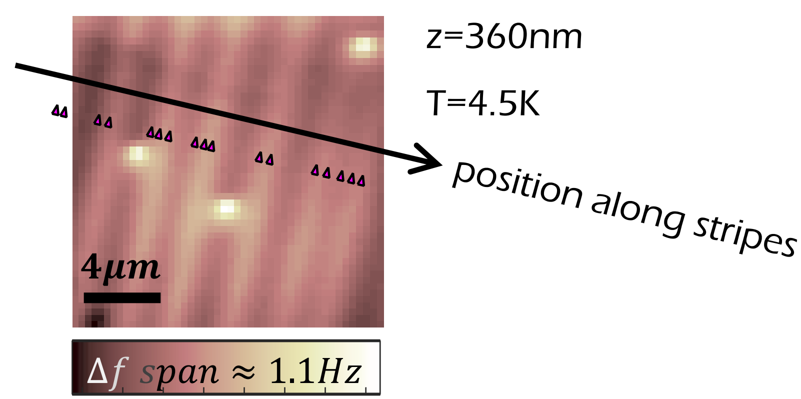
$$\lambda = 230nm$$
$$\beta = 140nm$$

Kogan & Kirtley, PRB **83**, 214521 (2011)





preliminary:
shows only plausibility of model
not to be taken too seriously



Origin of the Stripes Is Not Clear

Planes of enhanced superconductivity:

- Khlyustikov & Buzdin, Adv. Phys. '87: enhanced T_C in many (pre-HTSC) metals
    - think of a twin boundary as an embedded 2D superconductor
- Mironov & Buzdin, PRB '12: mostly for type-I
- Bo Li et al., New J. Phys. '13: stripes consistent w/ simulations for pnictides

Stripes exist in Co-Ba122 (electron doped) & in P-Ba122 (isovalent doping):

- enhanced diamagnetism
- vortex repulsion
- vortex barrier

UNLIKE in many other superconductors.

the reason for the different behavior can be mundane (i.e. details).

BUT for FeSe (a FeSC, cousin to pnictides) :

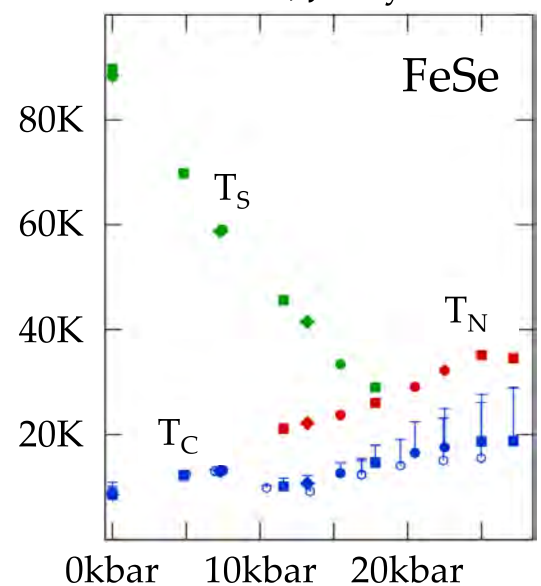
- vortices are trapped & gap is suppressed on twin boundaries

[Song et al., PRL '12]

- FeSe has no magnetic phase

so possibly in FeSe there are no stripes because there is no magnetic phase.

Terashima et al., J. Phys. Soc. '15



Summary

- Peak in λ_{ab} at optimal doping - verified by local measurements.
  - we average over several microns – this gives an upper bound to any texture.
- $T_C(\lambda_{ab})$ is the same on both sides of the peak in λ_{ab}.
- λ_{ab} is enhanced towards the underdoped edge of the superconducting dome.
  - indication of mixing between superconductivity and other phases.
- Vortex decoration
  - ordered vortex arrays for x>0.28
  - in very underdoped samples - very weak pinning
    - suppressed pairing or disorder? if disorder –is the source intrinsic?
  - in mildly underdoped samples:
    - linear vortex arrays - co-existence of superconductivity and magnetic order
    - stripes in the absence of magnetic field
      - stripes repel vortices & act as barriers

see PRB **91**, 060504 (2015)

The End