Nonlinear Meissner Effect and ABS in d-wave Superconductors

Outline

: Microwave response of a $d_{x^2-y^2}$ superconductor

– anisotropic nonlinear Meissner effect (aNLME)

Bulk superconducting state → diamagnetic NLME

Surface Andreev Bound State (ABS) → paramagnetic NLME

: Photoresponse (PR) measurement for imaging NLME

: Temperature dependence of paramagnetic NLME from ABS

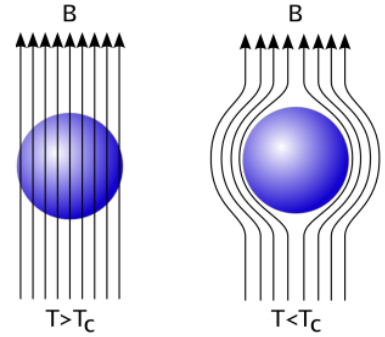
Alexander P. Zhuravel, Seokjin Bae, Sergey N. Shevchenko, Alexander N. Omelyanchouk, Alexander V. Lukashenko, Alexey V. Ustinov, Steven M. Anlage, "**Imaging the paramagnetic nonlinear Meissner effect in nodal gap superconductors**," Phys. Rev. B 97, 054504 (2018).

Seokjin Bae, Seunghun Lee, Xiaohang Zhang, Ichiro Takeuchi, Steven M. Anlage, "**Microwave Meissner screening properties of proximity-coupled topological-insulator / superconductor bilayers**," Phys. Rev. Materials 3, 124803 (2019).

Seokjin Bae, Microwave Study of the Properties of Unconventional Superconducting Systems DOI: https://doi.org/10.13016/vaw5-bot5

Response of **Bulk** superconductor under external microwave field

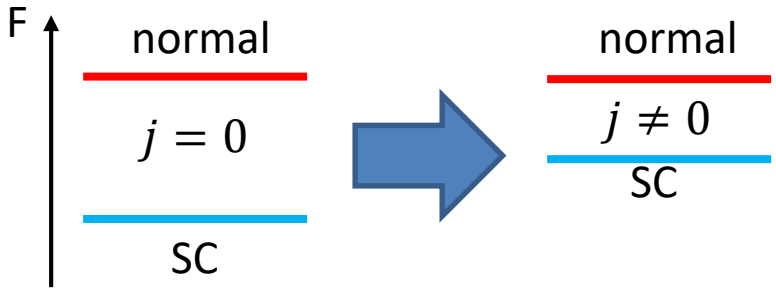
Diamagnetic nonlinear Meissner effect (NLME)



Diamagnetic response

$$B(x) = B_0 e^{-x/\lambda}$$

λ : magnetic penetration depth



$$\lambda^2(T,j) \cong \lambda^2(T)\left(1 + b_\Theta(T)\left(\frac{j}{j_{c0}}\right)^2 + \cdots\right)$$

$b_\Theta(T)$: nonlinear Meissner coefficient

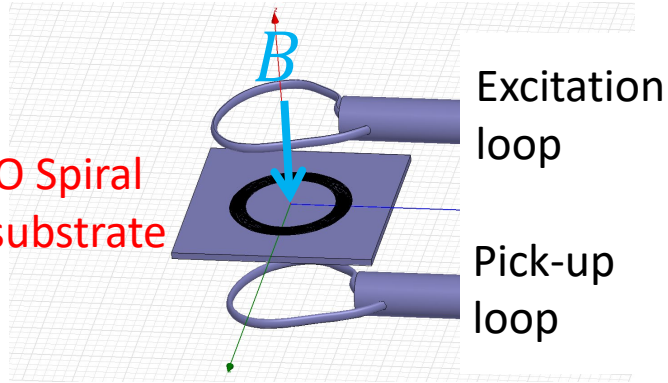
$* \Theta$: $\angle$ gap anti-nodal direction vs. j

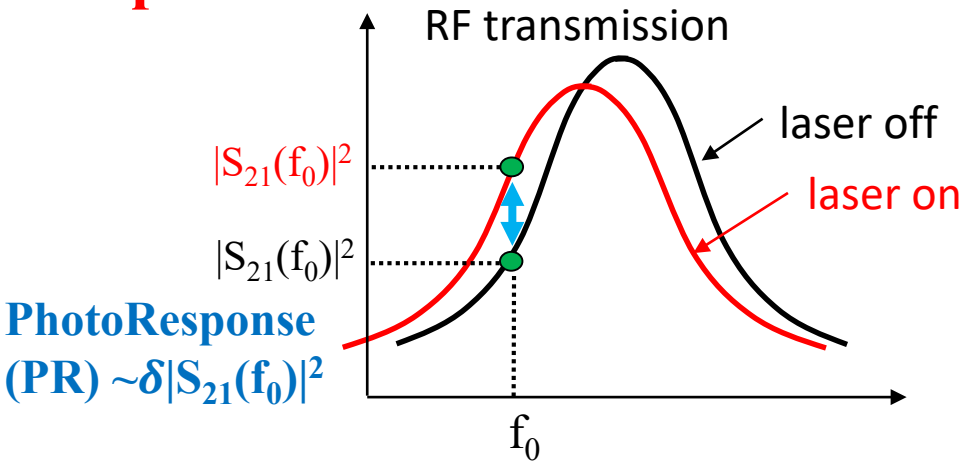
(T. Dahm and D. J. Scalapino, J. Appl. Phys. 81, 2002 (1997))

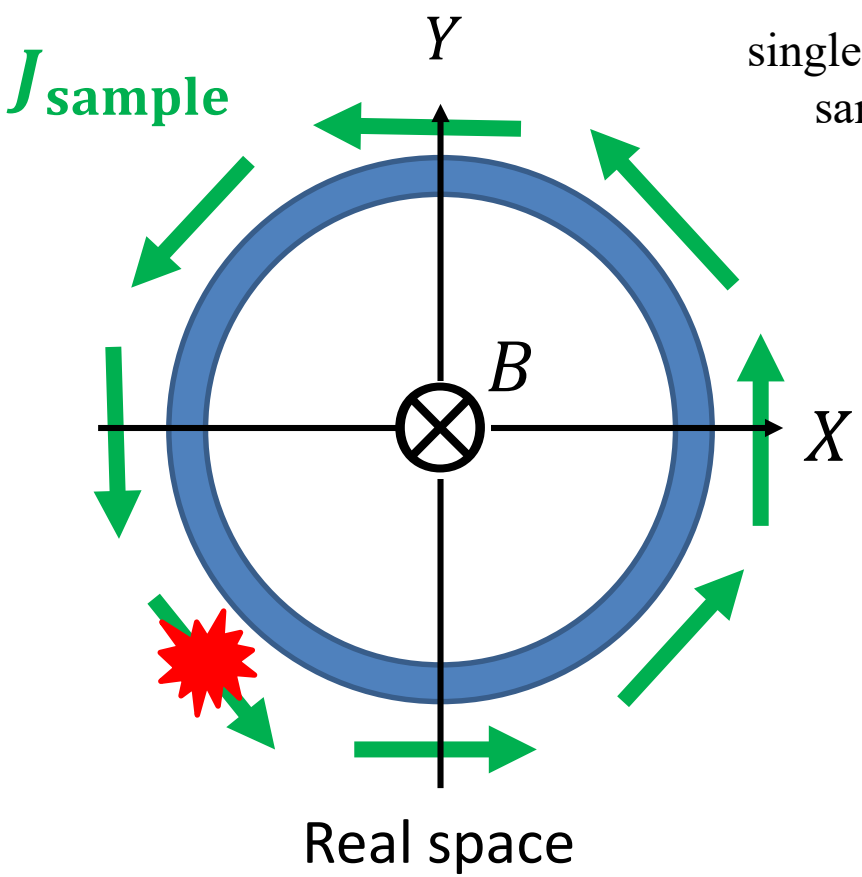
Gap nodal structure $\leftrightarrows$ anisotropy in $b_\Theta(T)$

$\leftrightarrows$ anisotropy in EM response

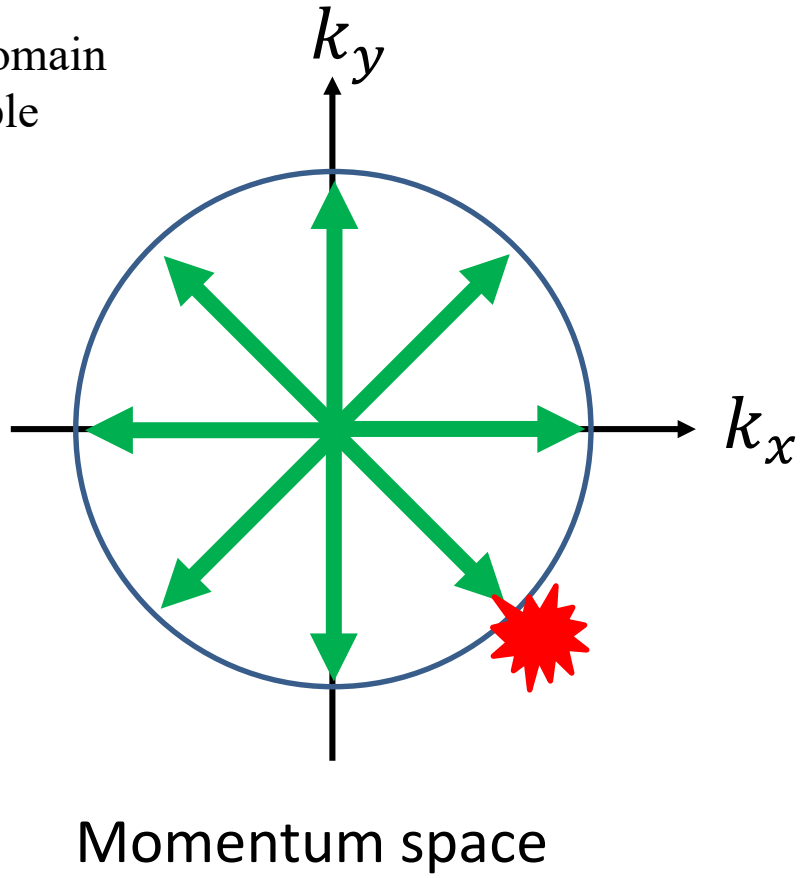
How to measure anisotropy in EM response?







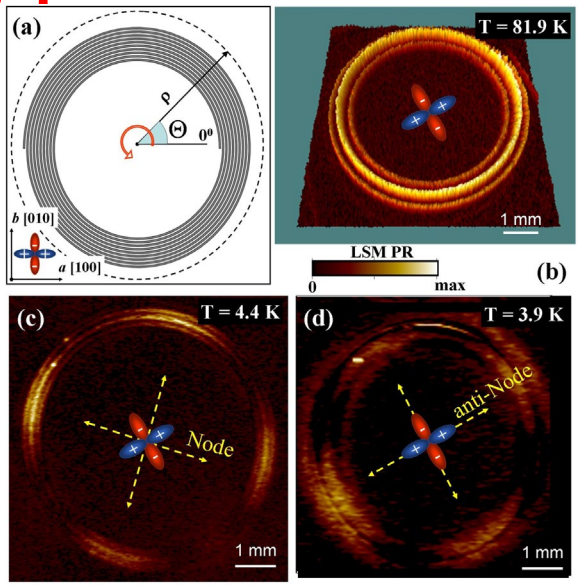
single domain
sample



Anisotropy of $b_\Theta(T)$ is directly related to SC gap nodal structure

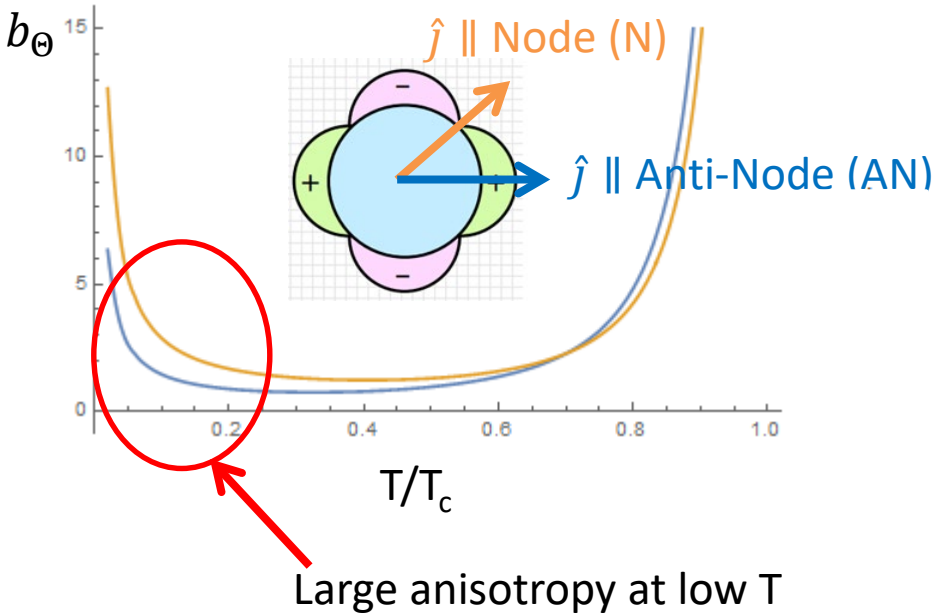
$$\mathbf{PR}(\Theta) \sim \frac{\partial b_\Theta}{\partial T}$$

A. Zhuravel *et al*,
Phys. Rev. Lett. 110, 087002 (2013)
Phys. Rev. B 97, 054504 (2018)

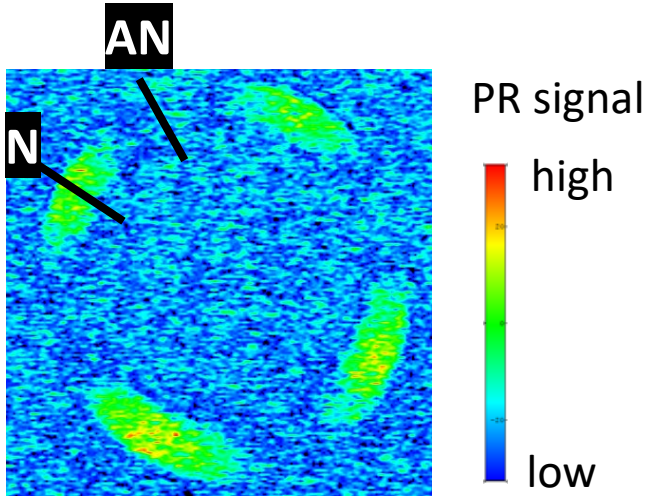


For $d_{x^2-y^2}$ wave SC

b_Θ from bulk SC state



Corresponding bulk PR image

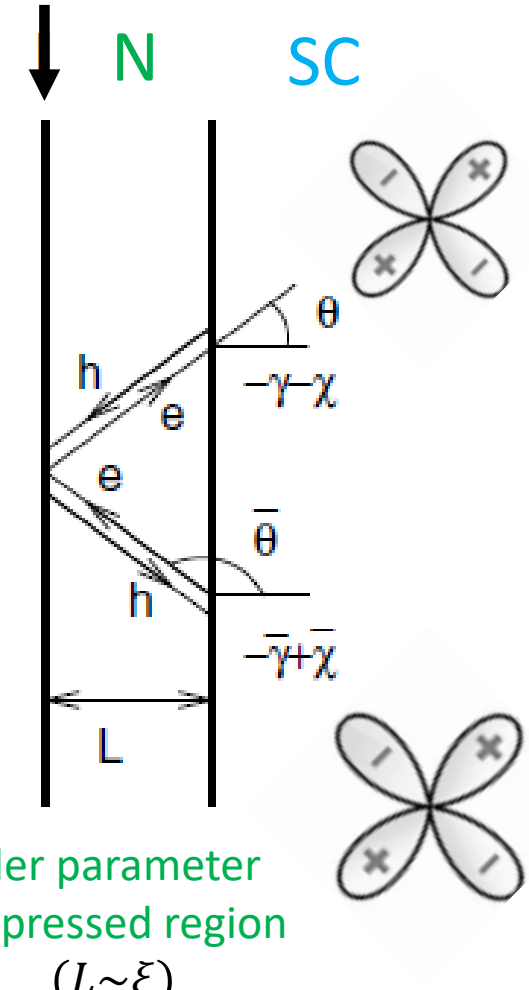


$T \sim 7$ K

$$\boldsymbol{PR(AN) < PR(N)}$$

Andreev Bound State (ABS) in Gap Nodal Superconductor

(110) boundary surface of
$d_{x^2-y^2}$ superconductor



Order parameter
suppressed region
$(L \sim \xi)$

T Löfwander *et al*,
Supercond. Sci. Technol. 14 R53

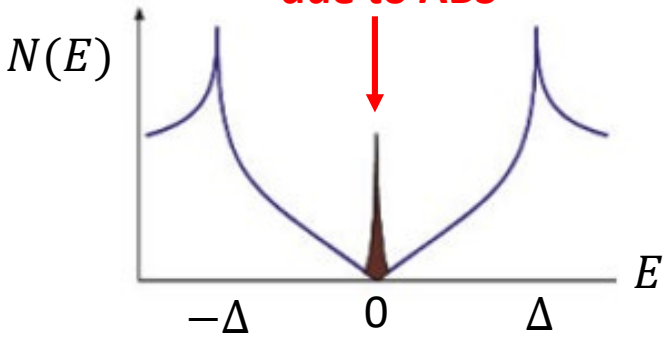
Bohr-Sommerfeld quantization condition:

$$-(\gamma + \bar{\gamma}) \mp \delta\chi + \beta(E) = 2n\pi$$

$-\gamma \pm \chi$: phase from reflection
$\delta\chi$: phase difference in Δ
$\beta(E)$: phase obtained while traveling

$E = 0$ solution always exist
If there is a sign change in Δ

Zero bias conductance peak (ZBCP)
due to ABS



Paramagnetic Meissner effect of ABS – splitting of ZBCP due to Doppler shift

Superfluid motion
: gives diamagnetic screening against external microwave

v_S

Superfluid (v_s) frame

$-v_F$ $+v_F$

Counter (ct) moving QP

Co (co) moving QP

Lab frame

$-v_F$ $+v_F$ v_S

v_S

v_{ct} v_{co}

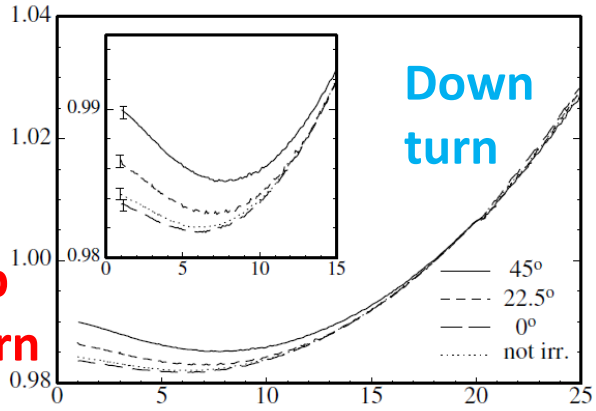
DOS

E_{ct} 0 E_{co}

(paramag) (diamag)

E

λ(a.u.)



Down turn

Up turn

Bulk diamagnetic response

Surface (ABS) Paramagnetic response

T (K)

H. Walter *et al*, Phys. Rev. Lett. 80, 3598

Bulk vs Surface response compete with each other!

Paramagnetic nonlinear Meissner effect from ABS

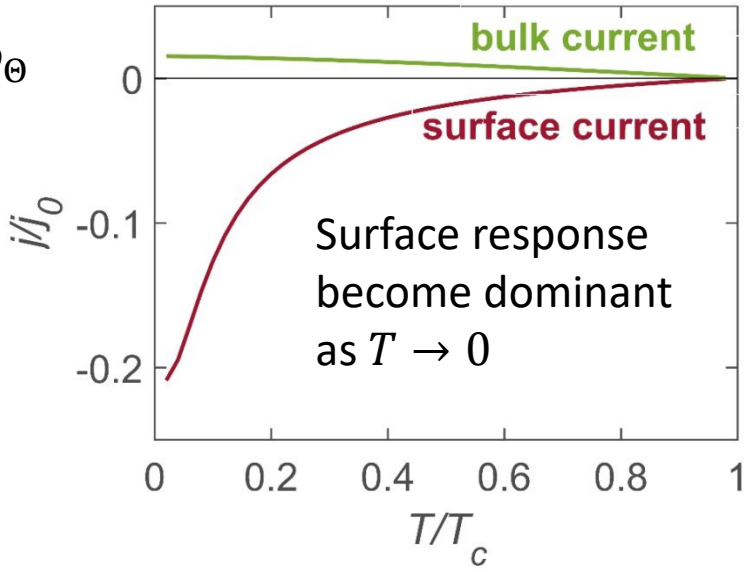
Quasi-classical Green function formalism to calculate
: surface (ABS) current density j_{surf}
: surface (ABS) paramag nonlinear Meissner coefficient b_Θ

$$g(\infty) = \frac{\tilde{\omega}}{\Omega_{\mathrm{L,R}}} \quad : \text{Bulk Green fcn}$$

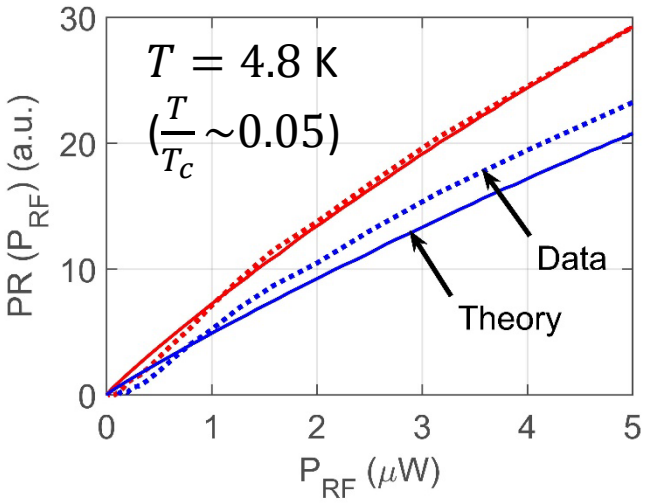
$$g(0) = \frac{\tilde{\omega}(\Omega_{\mathrm{L}} + \Omega_R)}{\Omega_{\mathrm{L}}\Omega_{\mathrm{R}} + \tilde{\omega}^2 + \Delta_L\Delta_R} \quad : \text{Surf Green fcn}$$

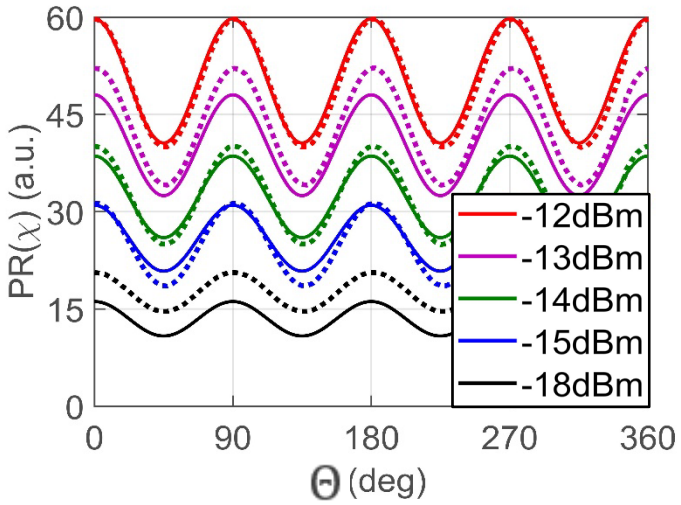
For details, see Phys. Rev. B 97, 054504 (2018)

For a $d_{x^2-y^2}$ SC with surface ABS



Measured & calculated PR and its anisotropy for paramag NLME in YBCO spiral





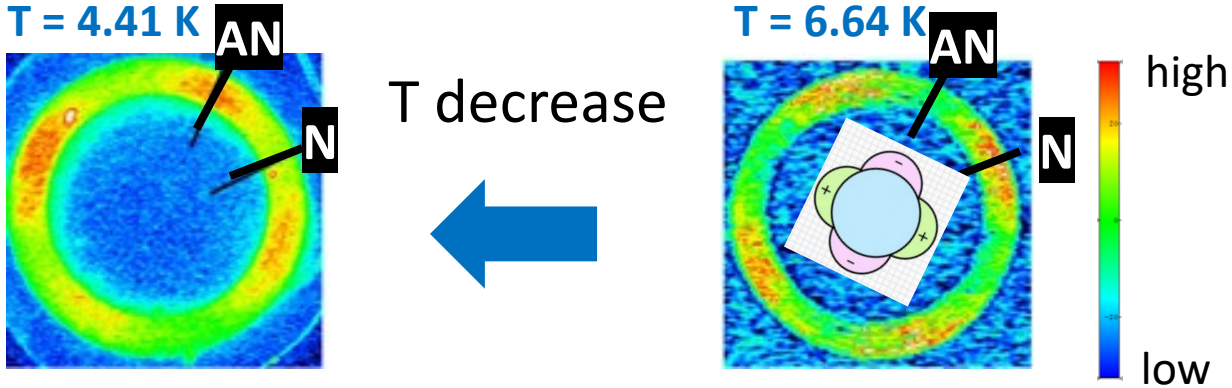
➔For PR from paramag NLME,

$PR(AN) > PR(N)$

*Note : PR from Bulk diamag NLME

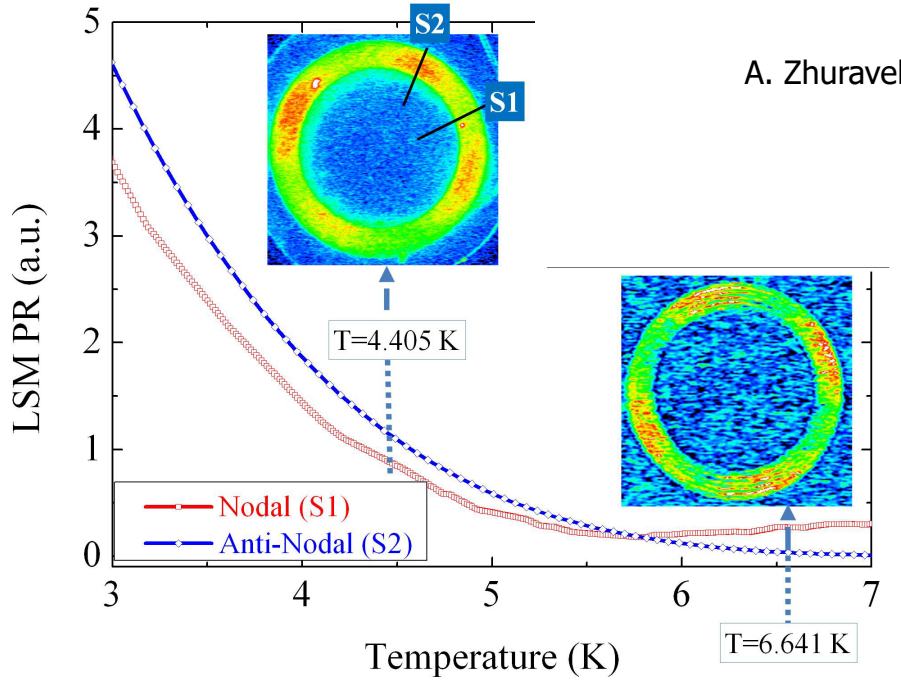
$PR(AN) < PR(N)$

Crossover between surface and bulk PR



Surface Andreev bound state response dominant

Bulk response dominant



A. Zhuravel *et al*, Phys. Rev. Lett. 110, 087002 (2013)

Conclusions

In a $d_{x^2-y^2}$ nodal superconductor,

Surface Andreev bound state → paramagnetic Meissner effect

Bulk superconducting state → diamagnetic Meissner effect

Photoresponse measurement for nonlinear Meissner effect

→ Reveal temperature dependence of ABS

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