Pair Density Waves in Cuprates

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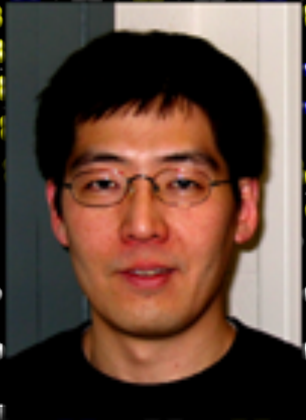
Binghamton/ Cornell

Eun-Ah Kim
Cornell

Andy Mackenzie
MPI CPS Dresden /
St. Andrews

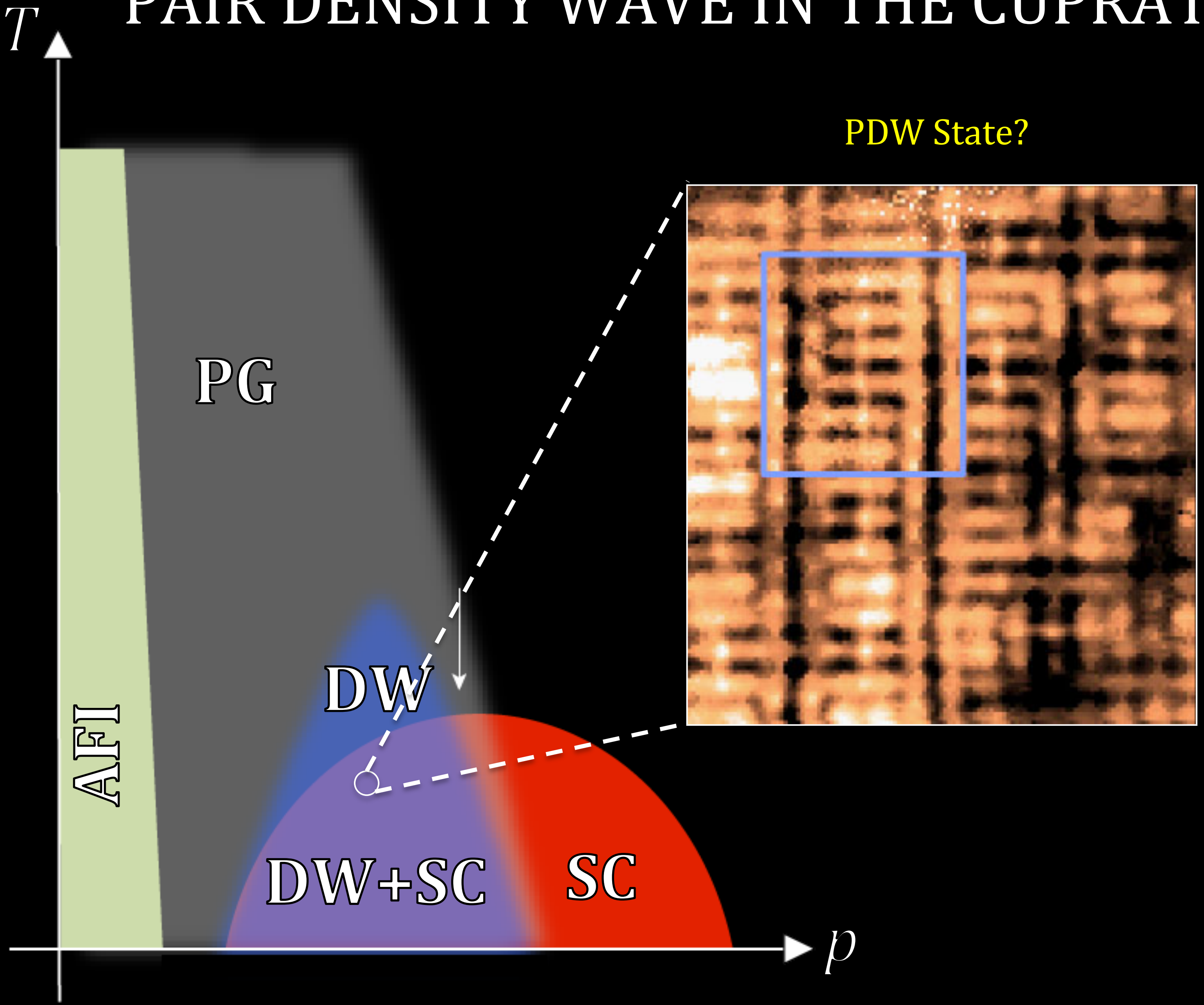


Jinho Lee
Seoul National University

Séamus Davis
Cornell / St. Andrews

Cornell **Stanford** **St Andrews**

PAIR DENSITY WAVE IN THE CUPRATES?



1964

Prediction of Pair Density Wave

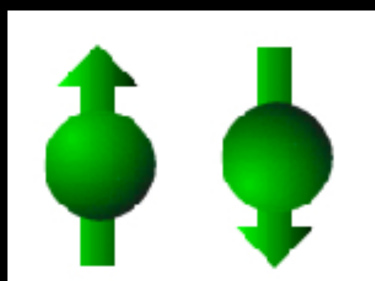
Sov. Phys. JETP **20** 762 (1964)

Physical Review **135** A550 (1964)

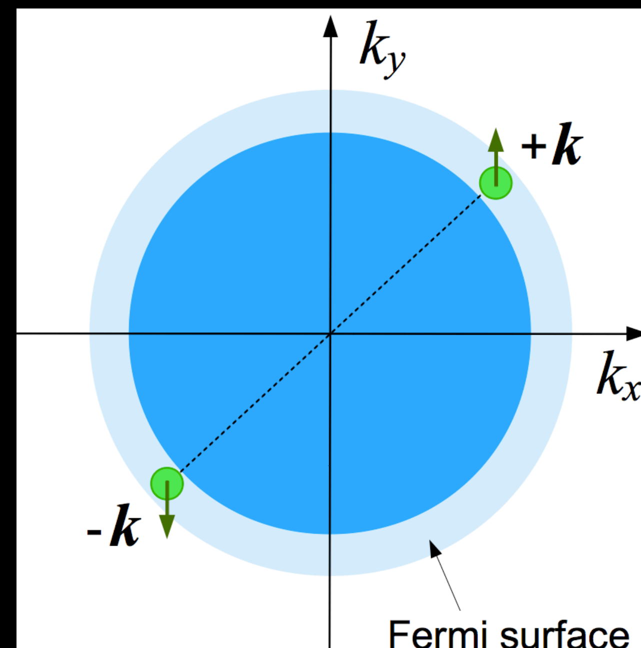
Microscopic Theory of Superconductivity*

J. BARDEEN, L. N. COOPER, AND J. R. SCHRIEFFER
Department of Physics, University of Illinois, Urbana, Illinois
(Received February 18, 1957)

S=0



L=0



Zero Centre of Mass Momentum

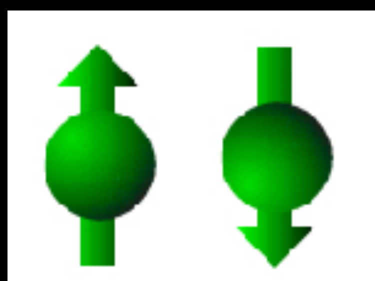
Microscopic Theory of Superconductivity*

J. Bardeen, L. N. Cooper, and J. R. Schrieffer

Department of Physics, University of Illinois, Urbana, Illinois

(Received February 18, 1957)

S=0



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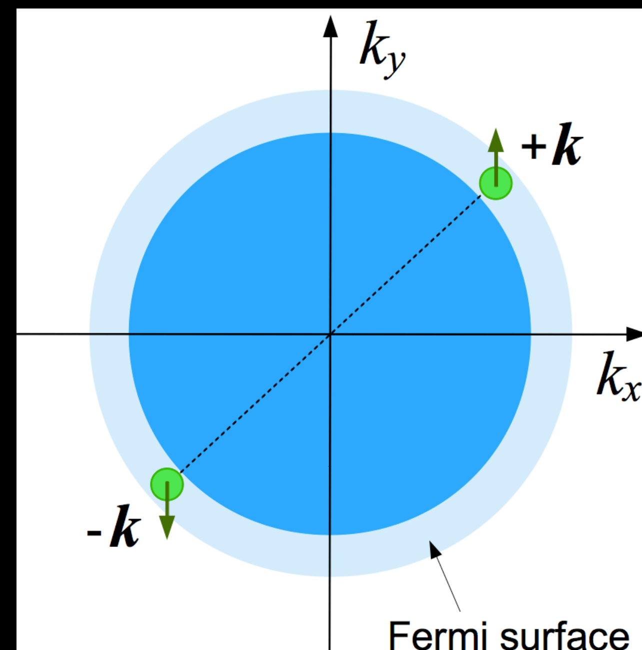


Homogeneous Cooper Pair Density

FULDE-FERRELL / LARKIN-OVCHINNIKOV

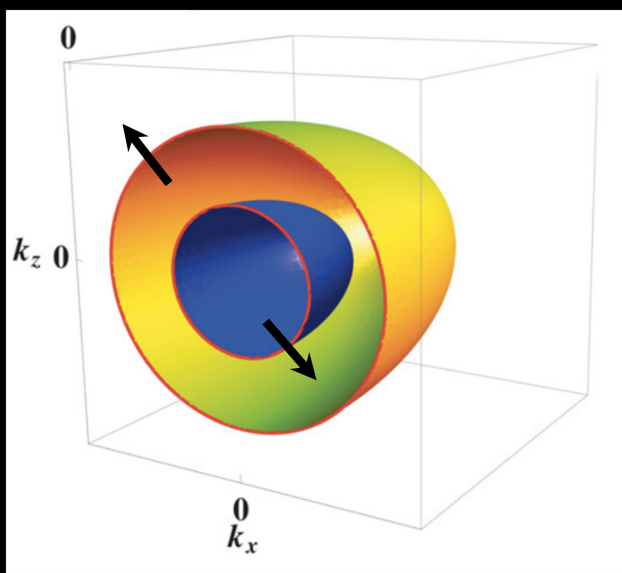
PHYSICAL REVIEW VOLUME 135, NUMBER 3A 3 AUGUST 1964

Superconductivity in a Strong Spin-Exchange Field*

PETER FULDE AND RICHARD A. FERRELL
University of Maryland, College Park, Maryland
(Received 23 December 1963; revised manuscript received 17 April 1964)

Fulde, P & Ferrell, R. A. *Phys. Rev.* 135, A550 (1964).

Larkin, A. I. & Ovchinnikov, Yu. N. *Zh. Eksp. Teor.* Fis. 37 , 1146 (1964).



$$(\mathbf{k}\uparrow, -\mathbf{k}+\mathbf{q}\downarrow)$$

Cooper Pairs acquire non-zero COM Momentum

FULDE-FERRELL / LARKIN-OVCHINNIKOV

PHYSICAL REVIEW VOLUME 135, NUMBER 3A 3 AUGUST 1964

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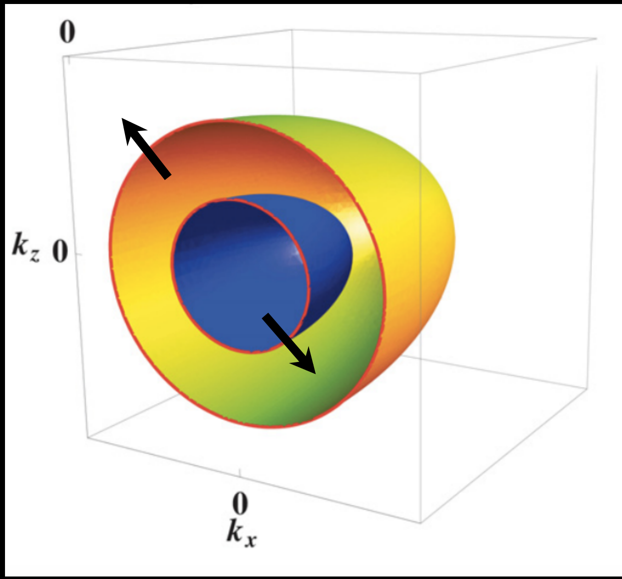

$$(\mathbf{k}\uparrow, -\mathbf{k}+\mathbf{q}\downarrow)$$

$$\Delta_{SC}(\mathbf{r}) \propto \langle \psi^\dagger_\downarrow(\mathbf{r})\psi^\dagger_\uparrow(\mathbf{r})\rangle \propto \exp(i\mathbf{q}\cdot\mathbf{r})$$

Cooper Pairs acquire non-zero COM Momentum

FULDE-FERRELL / LARKIN-OVCHINNIKOV

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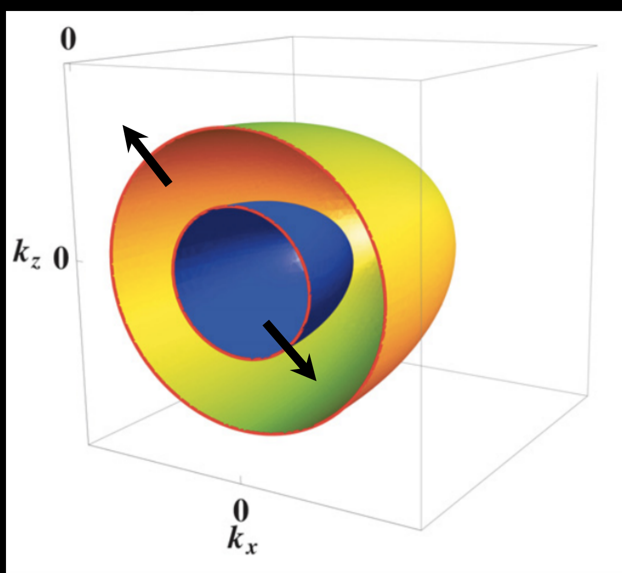
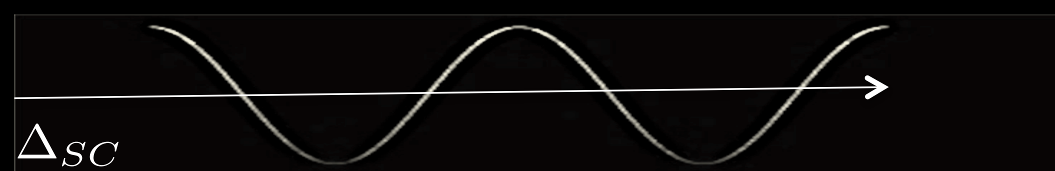


$$(\mathbf{k}\uparrow, -\mathbf{k}+\mathbf{q}\downarrow)$$

$$\Delta_{SC}(\mathbf{r}) \propto \langle \psi^\dagger_\downarrow(\mathbf{r})\psi^\dagger_\uparrow(\mathbf{r})\rangle \propto \exp(i\mathbf{q}\cdot\mathbf{r})$$



Spatially Modulated Cooper-pair Density

FULDE-FERRELL / LARKIN-OVCHINNIKOV

PHYSICAL REVIEW VOLUME 135, NUMBER 3A 3 AUGUST 1964

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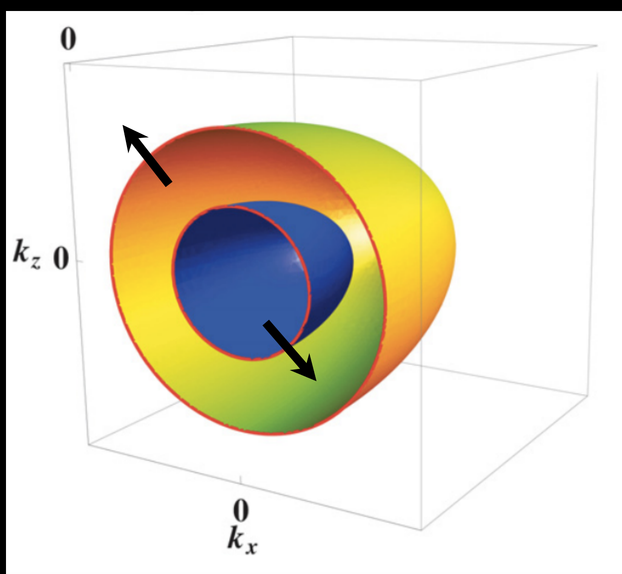
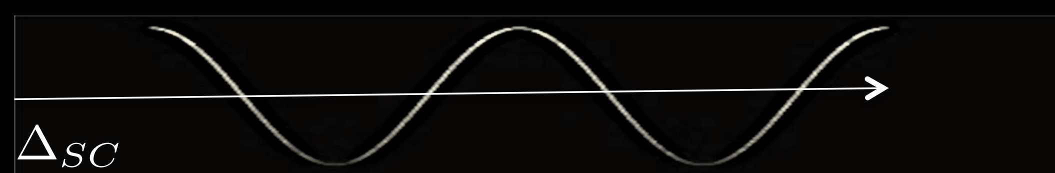


$$(\mathbf{k}\uparrow, -\mathbf{k}+\mathbf{q}\downarrow)$$

$$\Delta_{SC}(\mathbf{r}) \propto \langle \psi_\downarrow^\dagger(\mathbf{r})\psi_\uparrow^\dagger(\mathbf{r})\rangle \propto \exp(i\mathbf{q}\cdot\mathbf{r})$$



No direct detection of FFLO state.

CUPRATE PDW PREDICTION FROM VARIOUS APPROACHES

Himeda, A., Kato, T. & Ogata, M. Stripe states with oscillating *d*-wave superconductivity in the two-dimensional *t-t'-J* model. *Phys. Rev. Lett.* 88, 117001 (2002).

Raczkowski, M. *et al*, Unidirectional *d*-wave superconducting domains in the two-dimensional *t-J* model. *Phys. Rev. B* 76, 140505 (2007).

Yang, K.-Y., Chen, W. Q., Rice, T. M., Sigrist, M. & Zhang F.-C. Nature of stripes in the generalized t-J model applied to cuprate superconductors. *New J. Phys.* 11, 055053 (2009).

Loder, F., Graser, S., Kampf, A. P. & Kopp, T. Mean-field pairing theory for the charge-stripe phase of high-temperature cuprate superconductors *Phys. Rev. Lett.* 107, 187001 (2011).

Corboz, P., Rice, T. M. & Troyer, M. Competing states in the *t-J* model: uniform *d*-wave state versus stripe state. *Phys. Rev. Lett.* 113, 046402 (2014).

Chen, H. -D., Vafek, O., Yazdani, A., & Zhang, S.-C. Pair Density Wave in the Pseudogap State of High Temperature Superconductors. *Phys. Rev. Lett*. 93, 187002 (2004).

Berg, E. *et al*. Dynamical layer decoupling in a stripe ordered high-T_c superconductor. *Phys. Rev. Lett.* 99, 127003 (2007).

Seo, K., Chen, H.-D. & Hu, J. Complementary pair-density-wave and *d*-wave-checkerboard orderings in high-temperature superconductors. *Phys. Rev. B.* 78, 94510 (2008).

Berg, E., Fradkin, E. & Kivelson, S.A. Charge-4*e* superconductivity from pair-density-wave order in certain high-temperature superconductors. *Nature Phys.* 5, 830 (2009).

Lee, P. A. Amperean Pairing and the Pseudogap Phase of Cuprate Superconductors. *Phys. Rev. X* 4, 31017 (2014).

Zelli, M., Kallin, K., & Berlinksy, J. Quantum oscillations in a *π*-striped superconductor. *Phys. Rev. B* 86 104507 (2012).

Pépin, C., de Carvalho, V. S., Kloss, T. & Montiel, X. Pseudogap, charge order, and pairing density wave at the hot spots in cuprate superconductors. *Phys. Rev. B* 90, 195207 (2014).

Wang, Y. & Chubukov, A. Charge-density-wave order with momentum (2Q, 0) and (0, 2Q) within the spin-fermion model: *Phys. Rev. B* 90, 035149 (2014).

Wang, Y., Agterberg, D. F. & Chubukov, A. Coexistence of charge-density-wave and pair-density-wave orders in underdoped cuprates. *Phys. Rev. Lett.* 114, 197001 (2015).

EVIDENCE FOR 'STRIPED SC' IN La-CUPRATES

$\rho_c/\rho_{ab} \sim 2 \times 10^3$

$T_{co} = 54K$ — Static Charge Stripes

$\rho_c/\rho_{ab} \sim 5 \times 10^3$

$T_{spin} = 42K$ — Static Spin Stripes

$\rho_c/\rho_{ab} \sim 8 \times 10^4$

$T^{**} = 35K$

$\rho_{ab} \sim 10 \times 10^{-3} \mathrm{m\Omega cm}$
$\max\{\rho_c\} \sim 8 \times 10^2 \mathrm{m\Omega cm}$

(2D SC Fluctuations: from T_{spin} down to T_{KT})

$T_{KT} = 16K$

$\rho_{ab} \sim 0 \; \rho_c \sim 10 \mathrm{m\Omega cm}$

$T_{3D} = 10K$

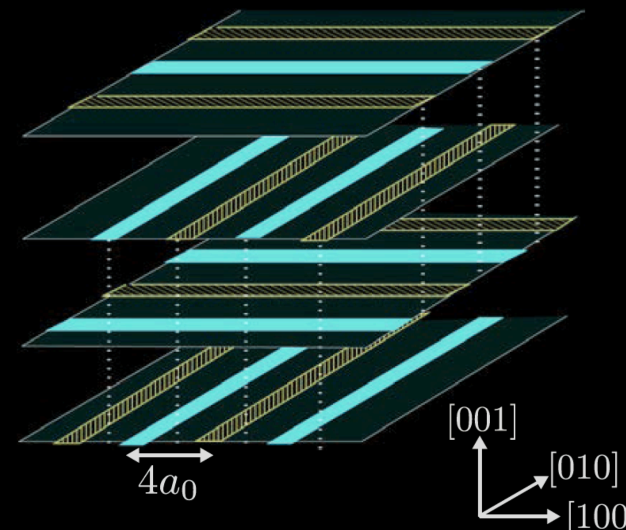
$\rho_{ab} \sim 0 \; \rho_c \sim 0$

$T_c = 4K$

Meissner State

0K

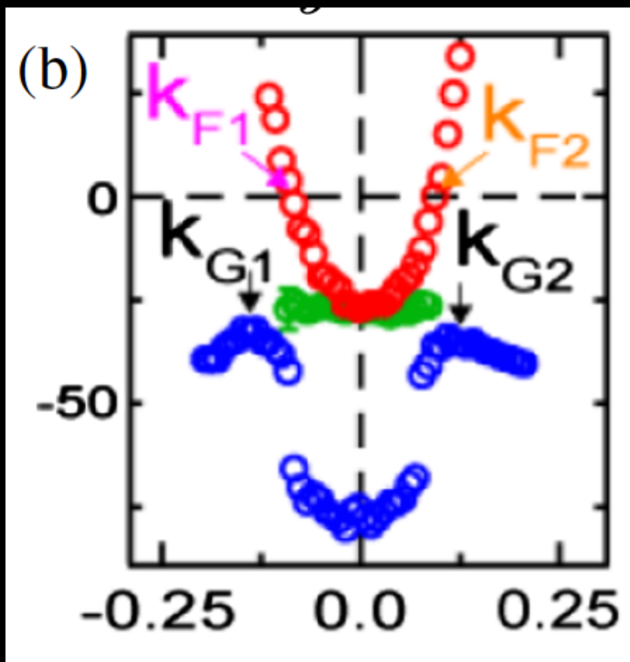
('Striped' Supercondutor PDW: from T_{spin} down to 0K)



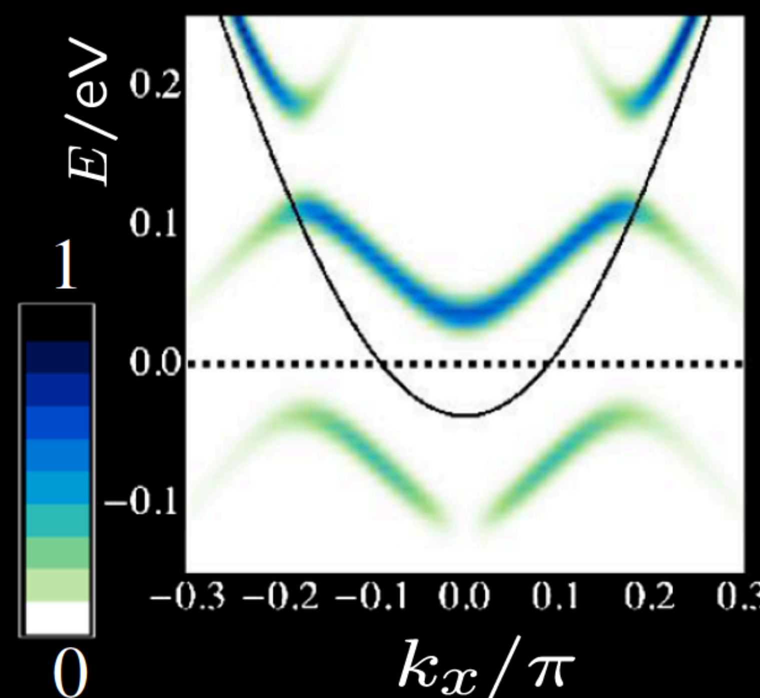
Q. Li *et al.* PRL 99, 067001 (2007)
E. Berg *et al.* PRL 99, 127003 (2007)

EVIDENCE FOR PDW ORDER IN Bi-CUPRATES

ARPES gap opening around the antinodes is not consistent with CDW order or Q = 0 pairing



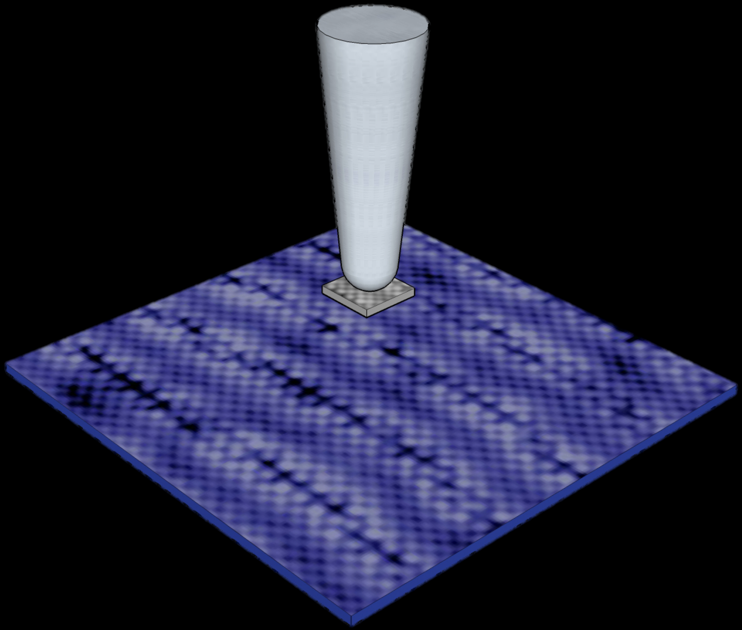
R. He *et al.* Science 331, 1579 (2011)



P. Lee, PRX 4, 031017 (2014)

VISUALIZE CUPRATE COOPER-PAIR CONDENSATE

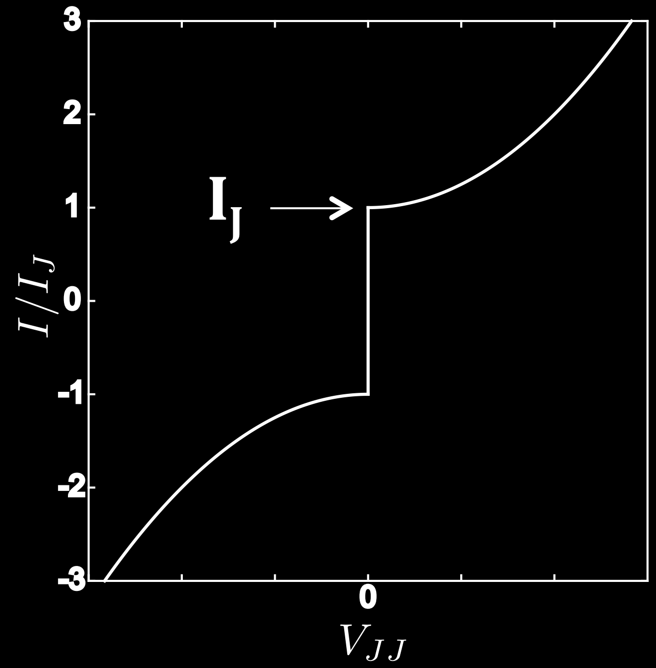
Cooper-Pair Tunneling



Requires Scanned Josephson Tunneling Microscopy (SJTM)

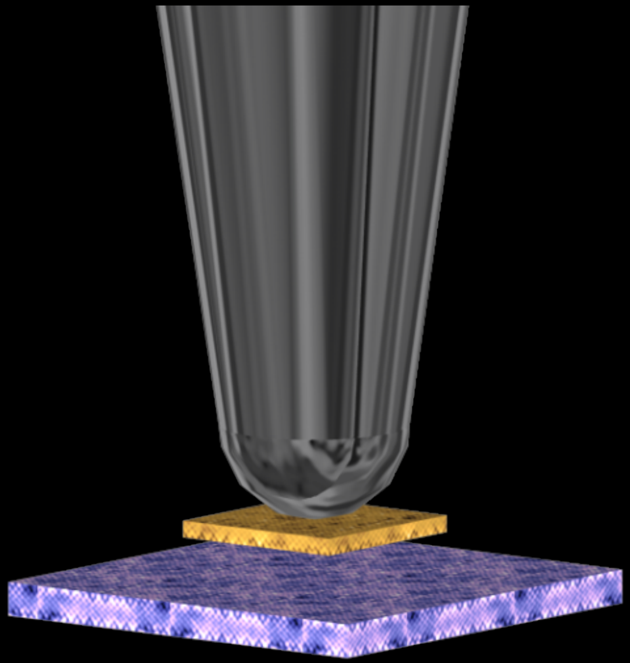
VISUALIZE CUPRATE COOPER-PAIR CONDENSATE

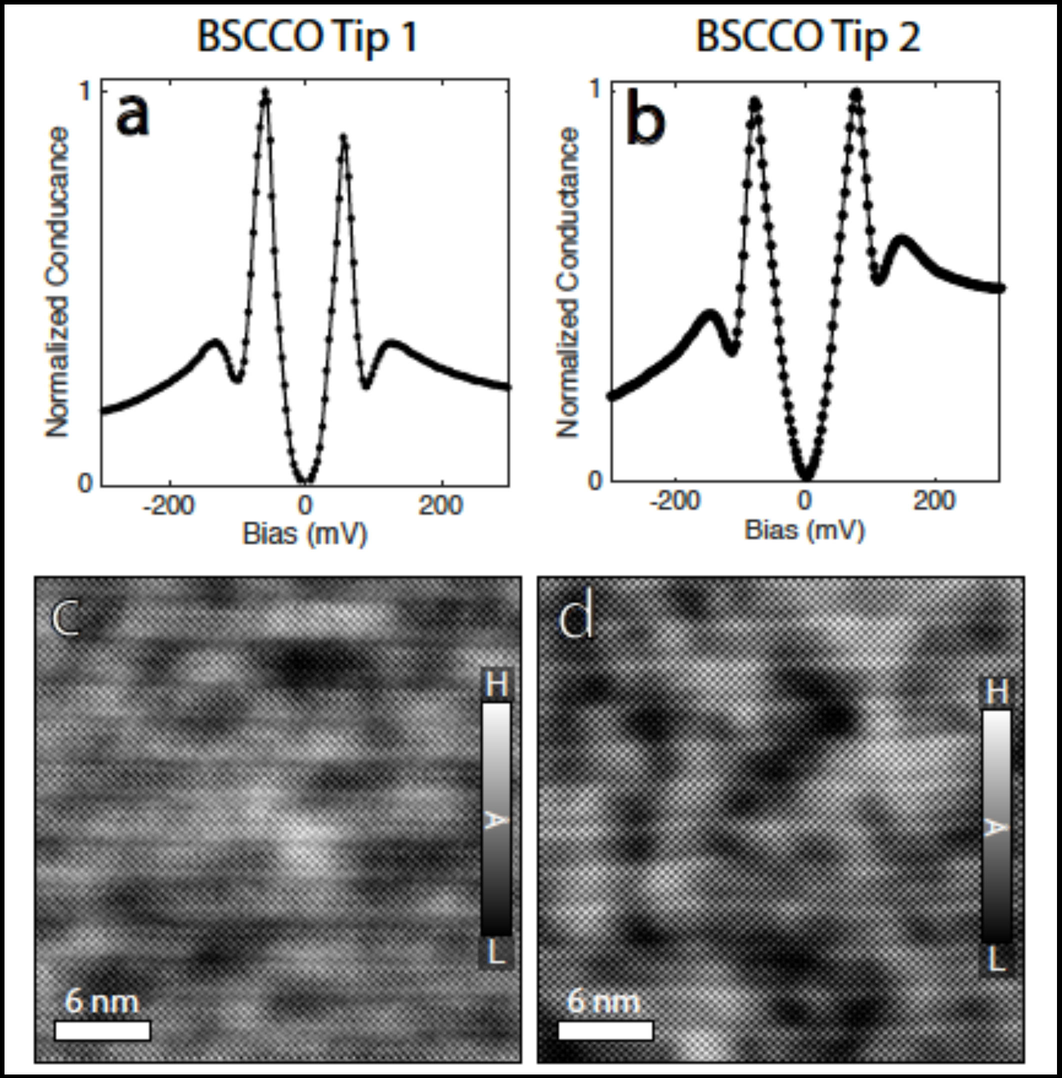
Josephson Tunneling



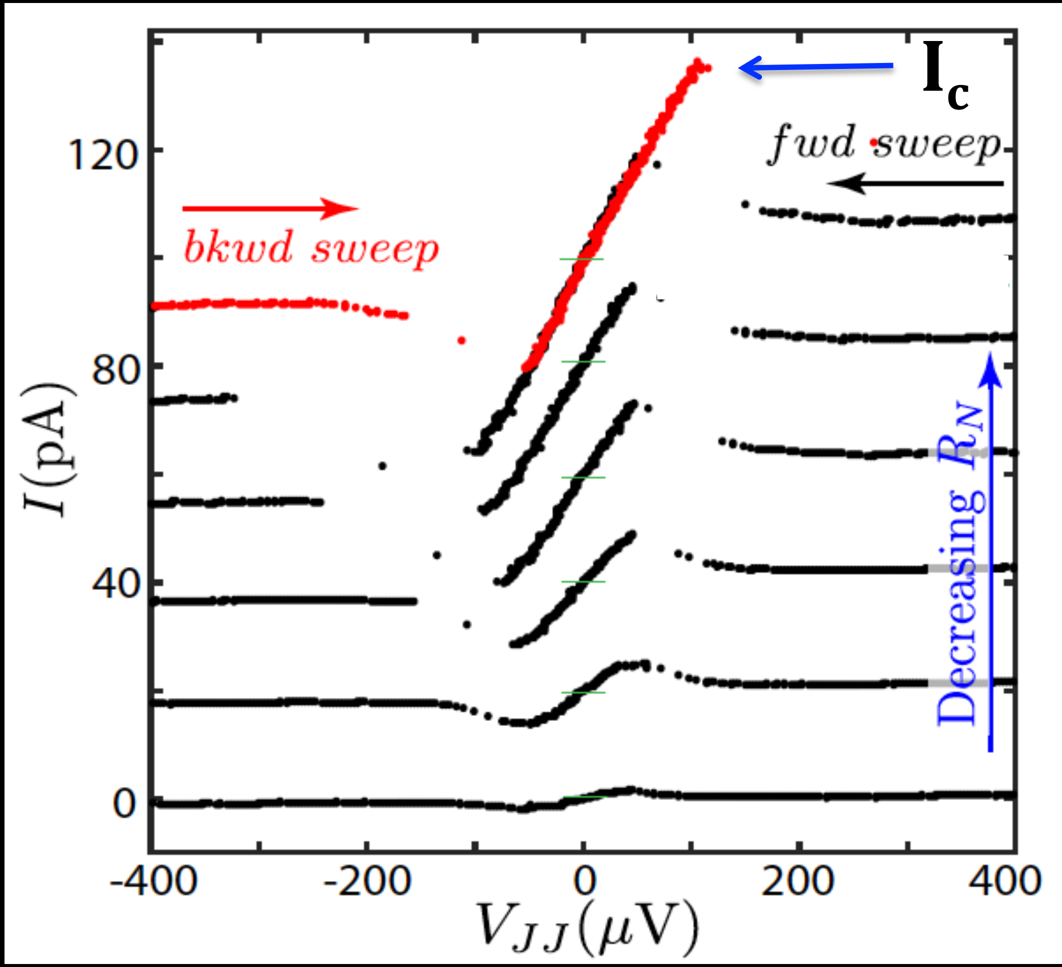
$$I_J \propto \Psi_{SC}$$

d-WAVE SC HTS TIP: Δ~25 meV





SJTM IMAGING $I_C(\boldsymbol{r})$ OF $Bi_2Sr_2CaCu_2O_{x+8}$



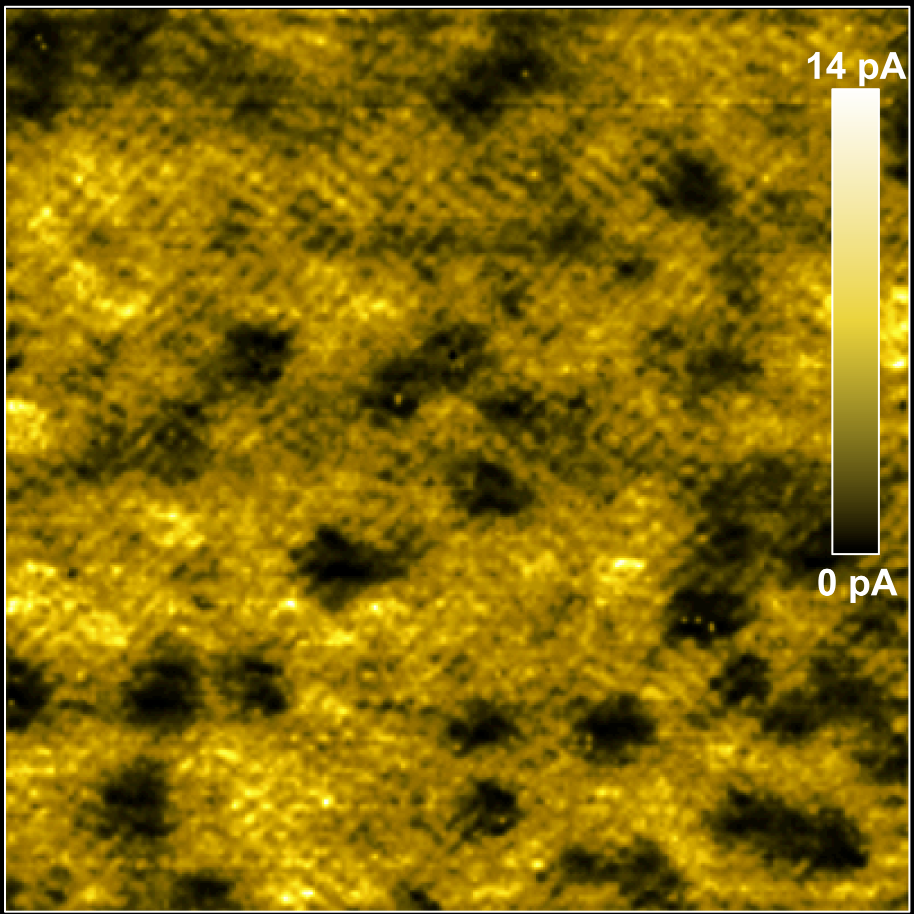
d-wave BSCCO tip / T = 50mK

$$I_C(\boldsymbol{r}) \;\alpha\; I_J^{\,2}(\boldsymbol{r})$$

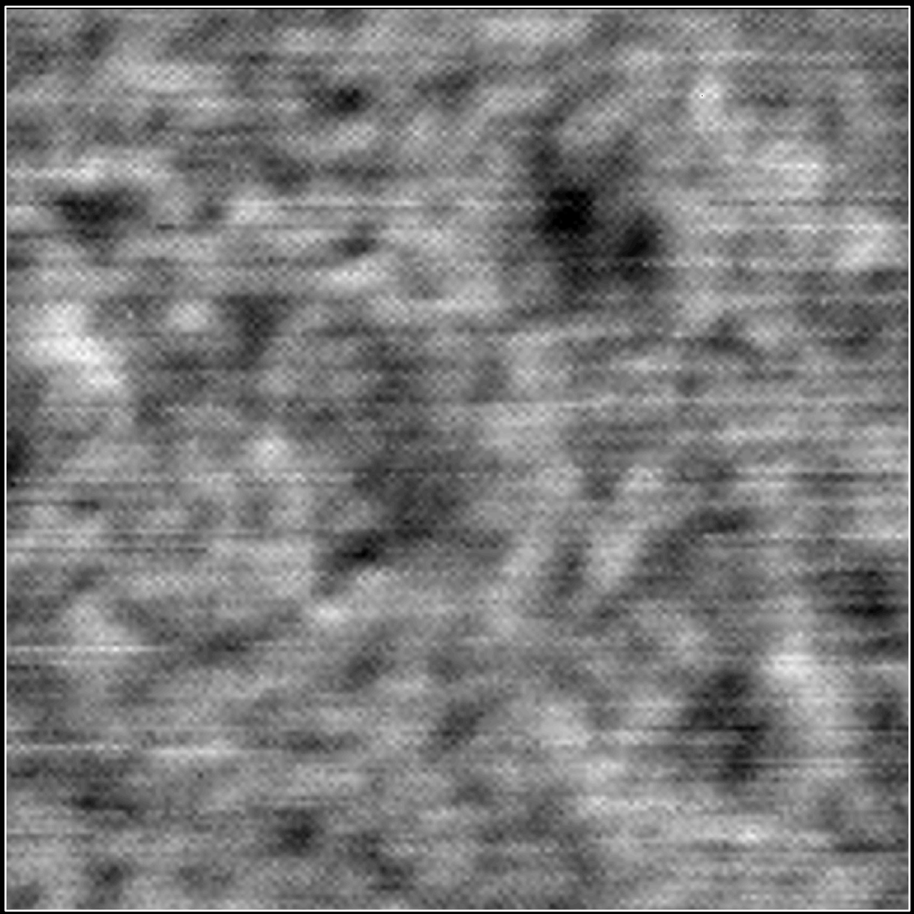
SJTM IMAGING $I_C(\mathbf{r})$ OF $Bi_2Sr_2CaCu_2O_{x+8}$

Optimal Doping
T=50mK

$I_c(\mathbf{r})$



Topography 76x76nm



M. H. Hamidian* & S.D. Edkins* *et al.* *Nature* **532**, 343 (2016)

VALIDATE COOPER-PAIR CONDENSATE IMAGING ?

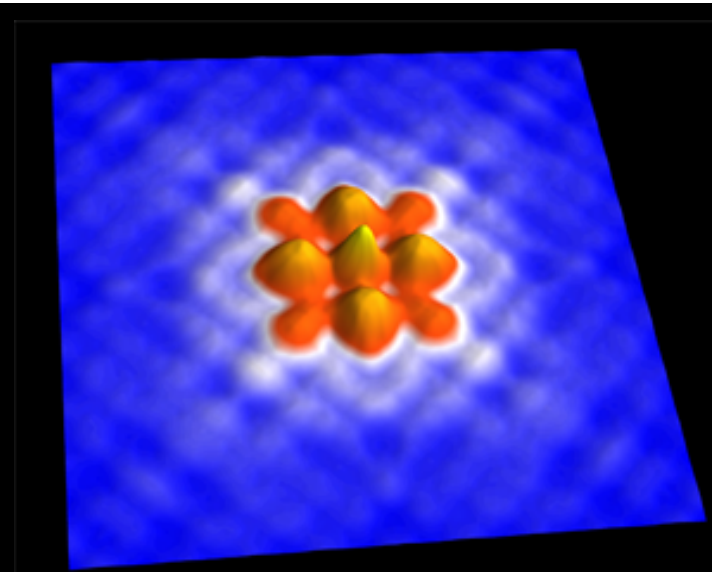
VOLUME 77, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 1996

Muon Spin Relaxation Studies of Zn-Substitution Effects in High-T_c Cuprate Superconductors

B. Nachumi, A. Keren, K. Kojima, M. Larkin, G. M. Luke, J. Merrin, O. Tchernyshöv, and Y. J. Uemura
Physics Department, Columbia University, New York, New York 10027

N. Ichikawa, M. Goto, and S. Uchida
Department of Superconductivity, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan
(Received 12 September 1996)

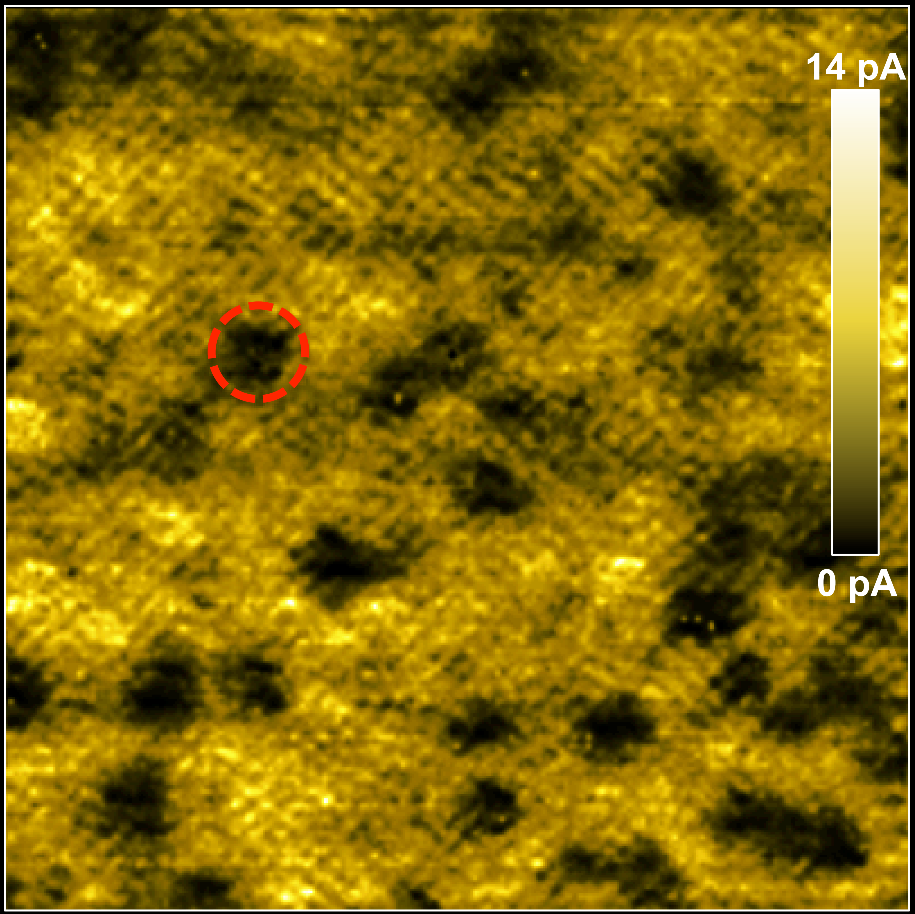
We have performed transverse-field muon spin relaxation measurements of the Zn-substituted cuprate high-T_c superconductors: $La_{2-x}Sr_x(Cu_{1-y}Zn_y)O_4$ and $YBa_2(Cu_{1-y}Zn_y)_3O_{6.63}$. The superconducting carrier density/effective mass n_s/m^* ratio at $T \to 0$ decreases with increasing Zn concentration, in a manner consistent with our "swiss cheese" model in which charge carriers within an area $\pi\xi_{ab}^2$ around each Zn are excluded from the superfluid. We discuss this result in the context of Bose condensation, pair localization, and pair breaking. [S0031-9007(96)02011-X]



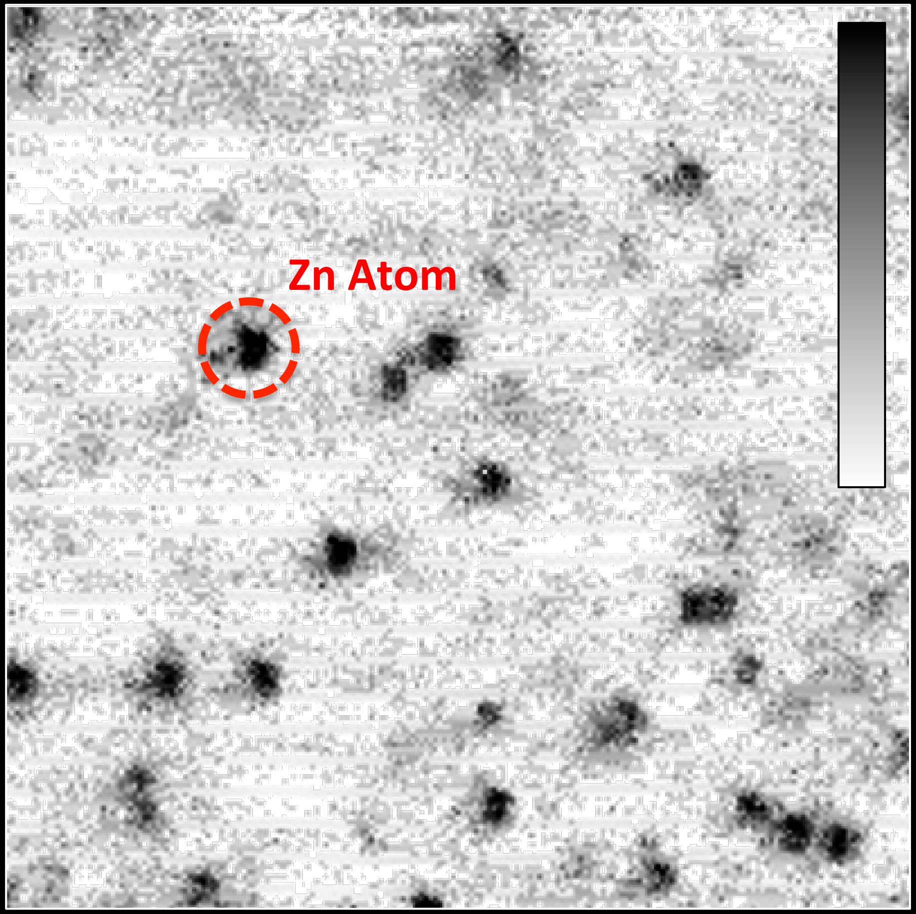
VALIDATE COOPER-PAIR CONDENSATE IMAGING

Optimal Doping
T=50mK

$I_c(\mathbf{r})$



$dI/dV(\mathbf{r}, 20mV)$

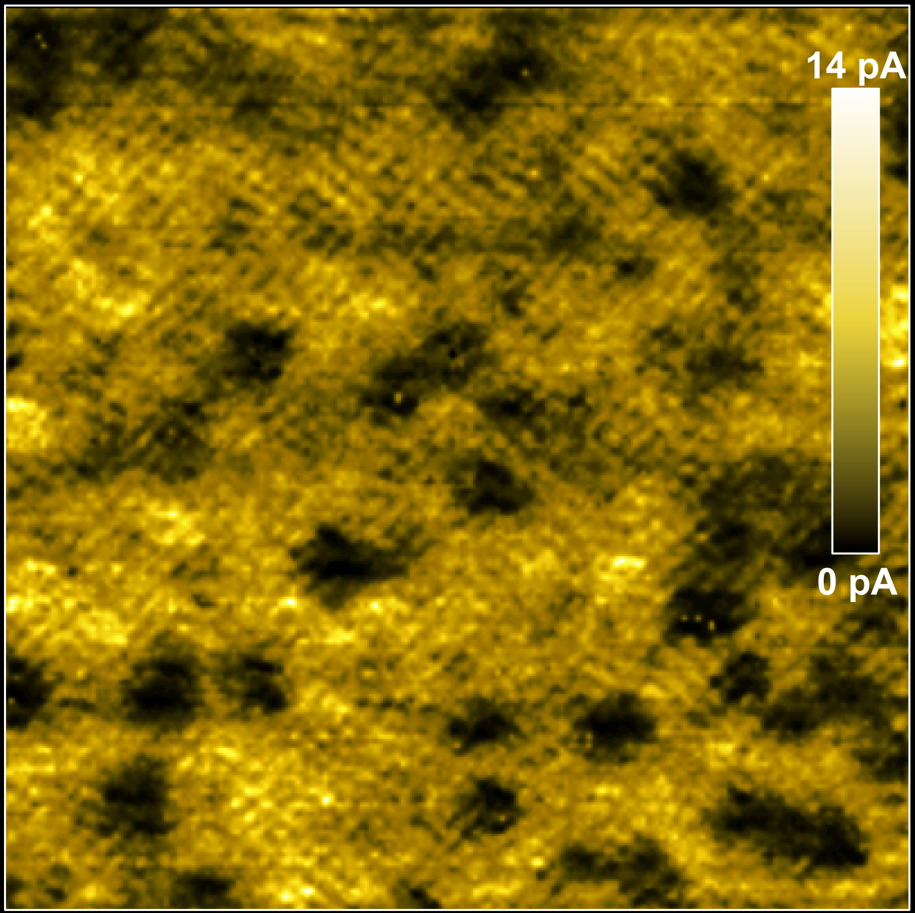


M. H. Hamidian* & S.D. Edkins* *et al.* *Nature* **532**, 343 (2016)

CUPRATE PAIR DENSITY WAVE?

Optimal Doping
50mK

$I_c(\mathbf{r})$

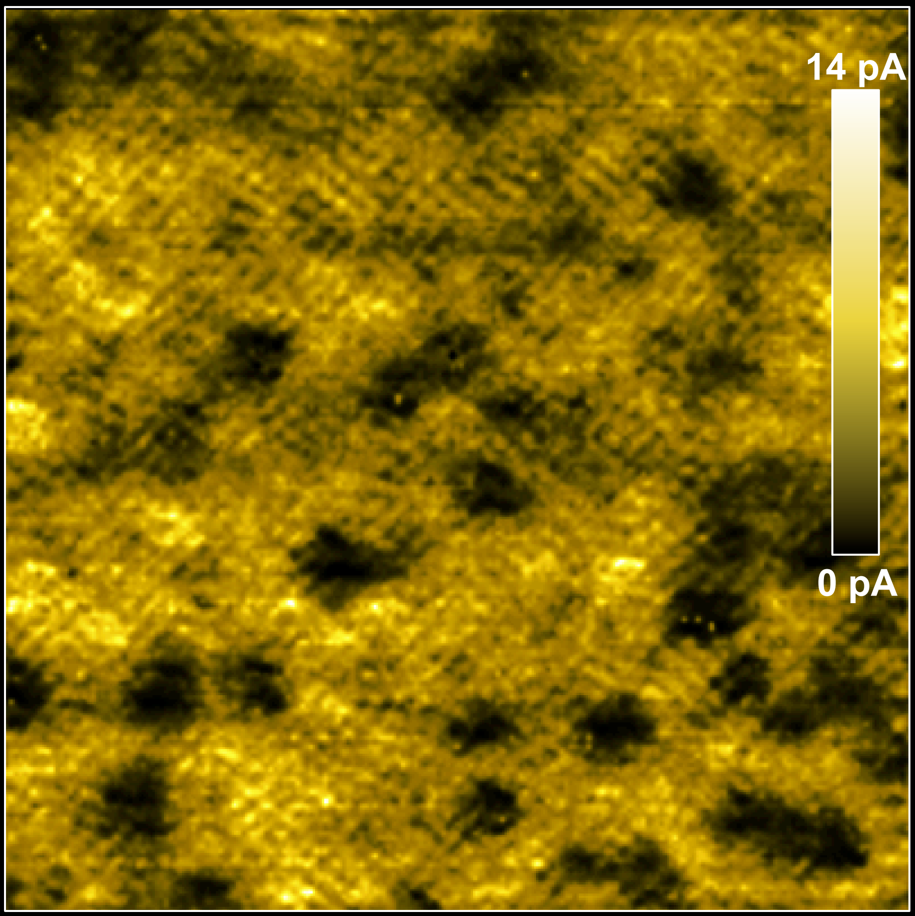


M. H. Hamidian* & S.D. Edkins* *et al.* *Nature* **532**, 343 (2016)

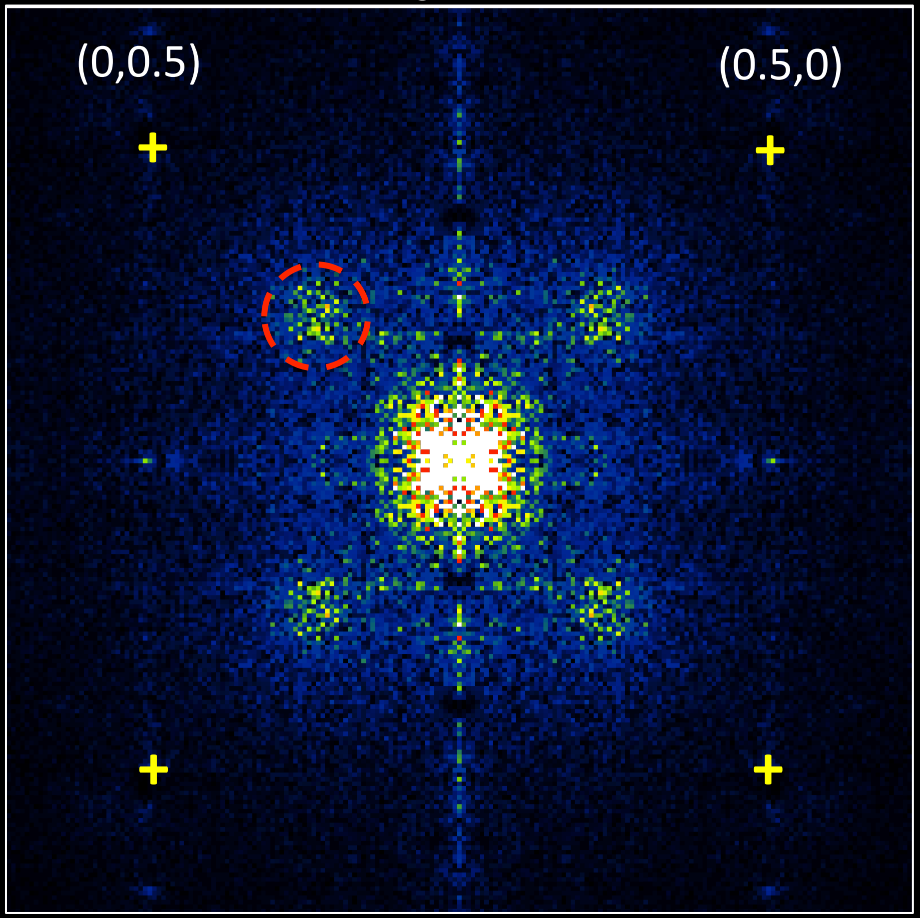
$4a_0$ Modulation in Condensate

Optimal Doping
50mK

$I_c(\mathbf{r})$



$I_c(\mathbf{q})$



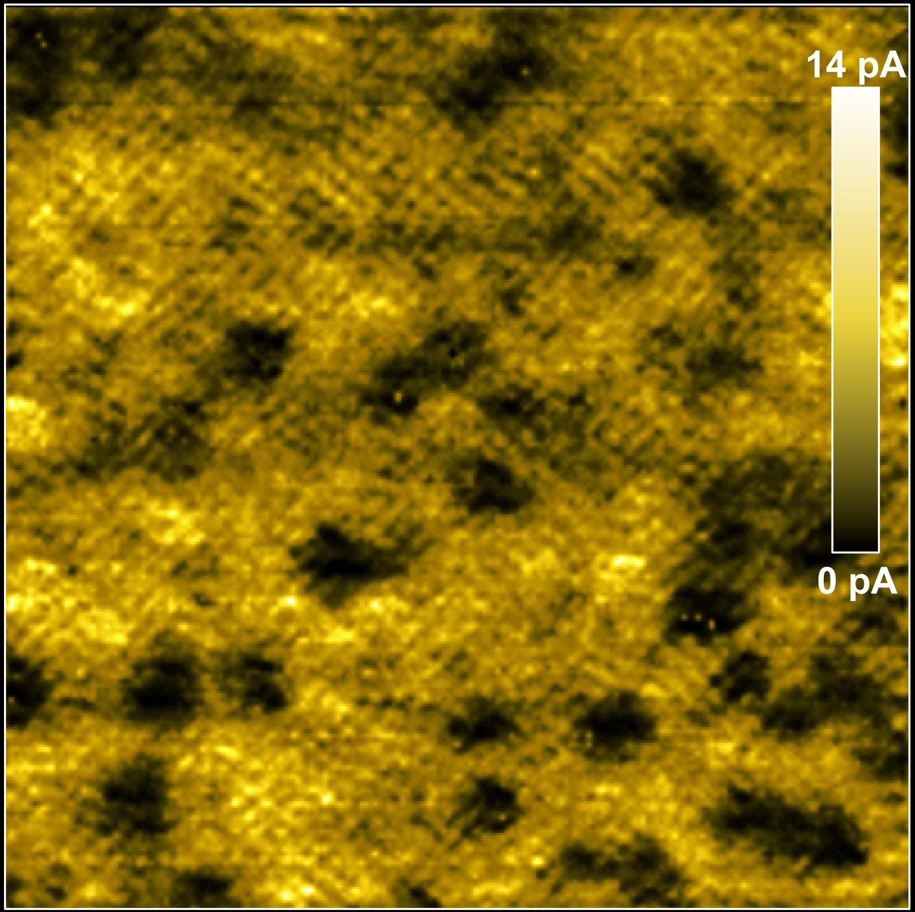
$Q = (0,0.25)2\pi/a_o\ ;\ (0.25,0)2\pi/a_o$

M. H. Hamidian* & S.D. Edkins* *et al.* *Nature* **532**, 343 (2016)

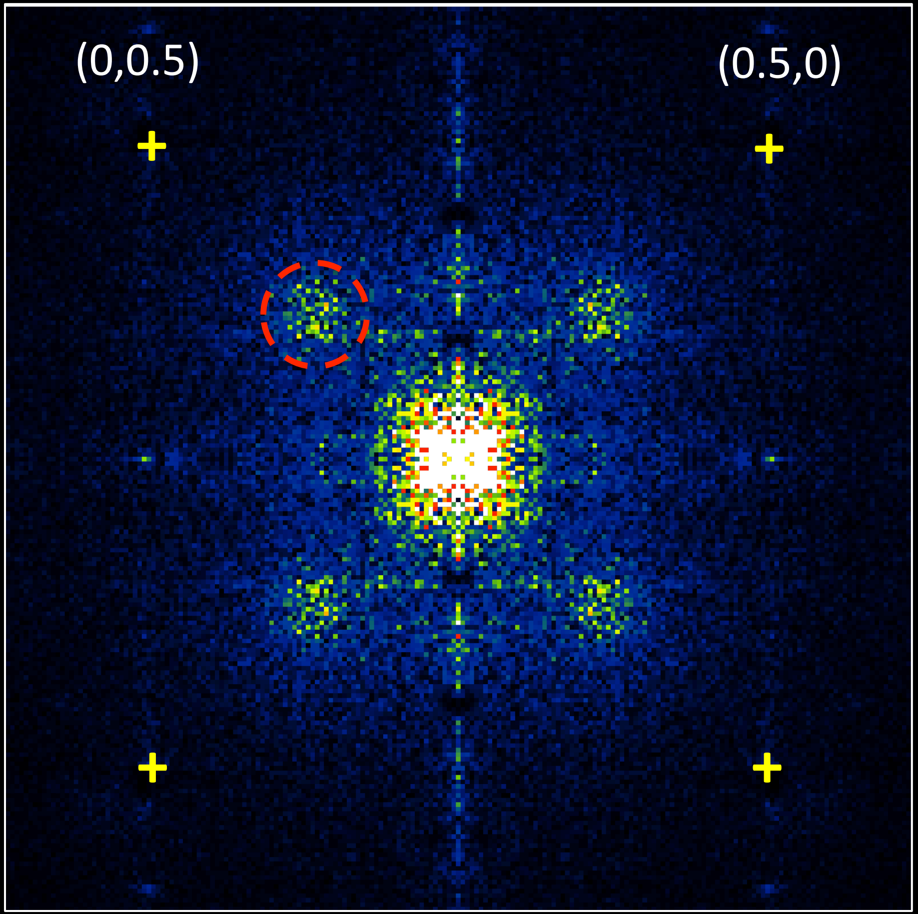
First Direct Detection of Periodically Modulating Condensate

Optimal Doping
T=50mK

$I_c(\mathbf{r})$



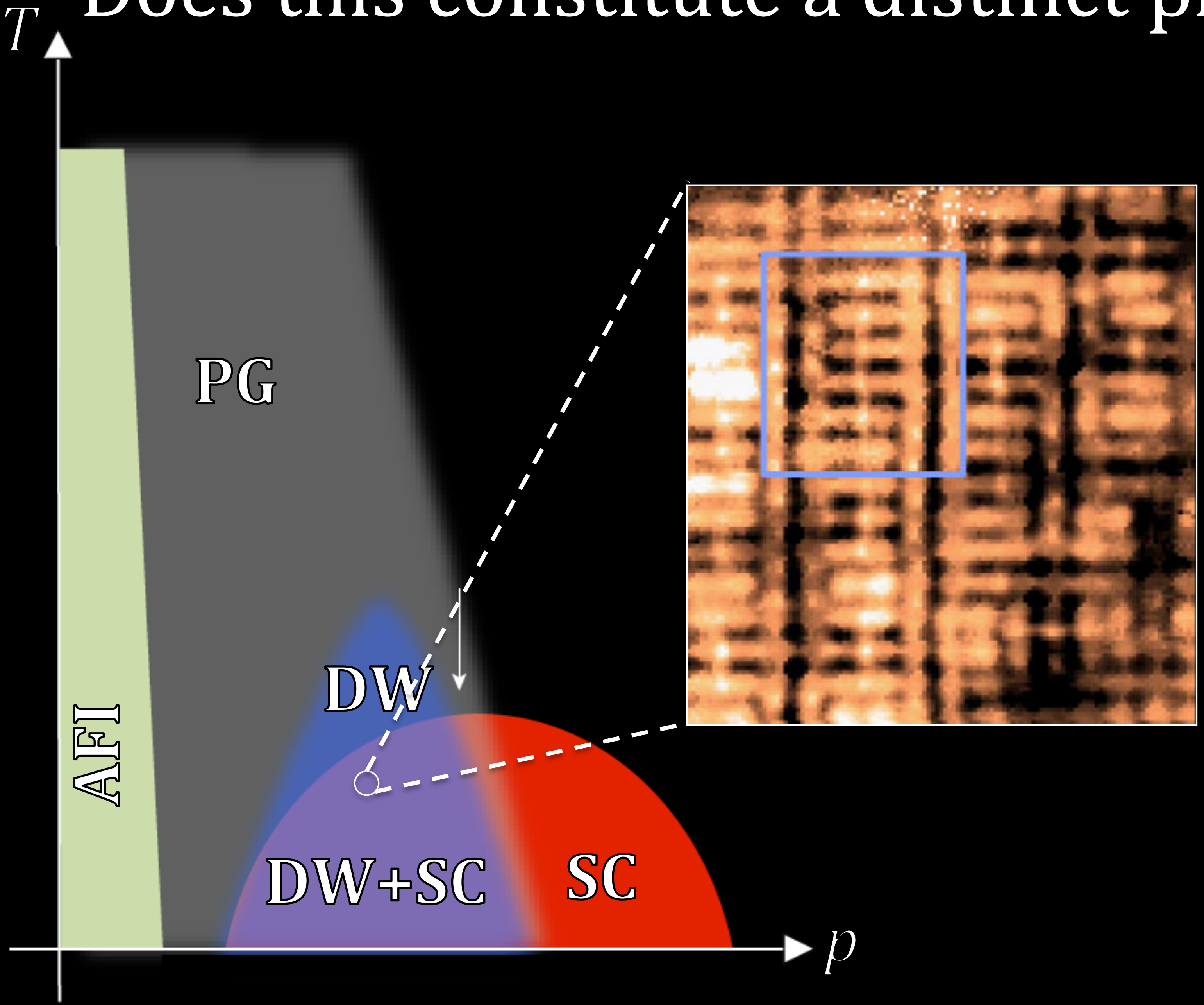
$I_c(\mathbf{q})$



$Q = (0,0.25)2\pi/a_o\ ;\ (0.25,0)2\pi/a_o$

M. H. Hamidian* & S.D. Edkins* *et al.* *Nature* **532**, 343 (2016)

Does this constitute a distinct phase ?



Classify Phases using Broken Symmeties

Uniform SC + PDW breaks …

Global phase and translation symmetries

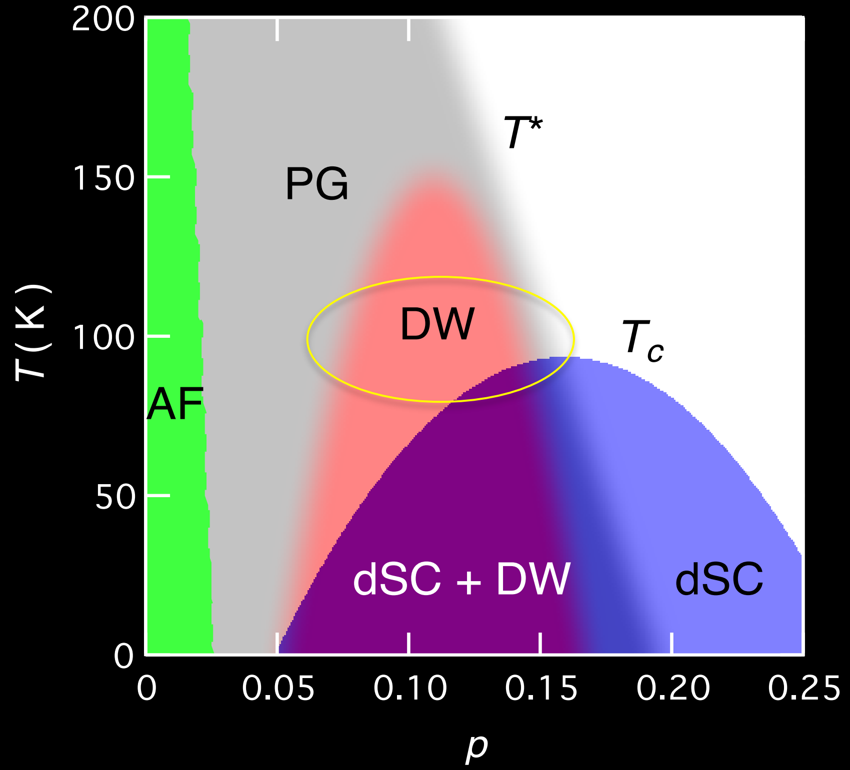
Uniform SC + CDW breaks …

Global phase and translation symmetries

➔ We have not directly detected distinct phase of matter @ $T < T_c$

Is pure PDW present above T_c?

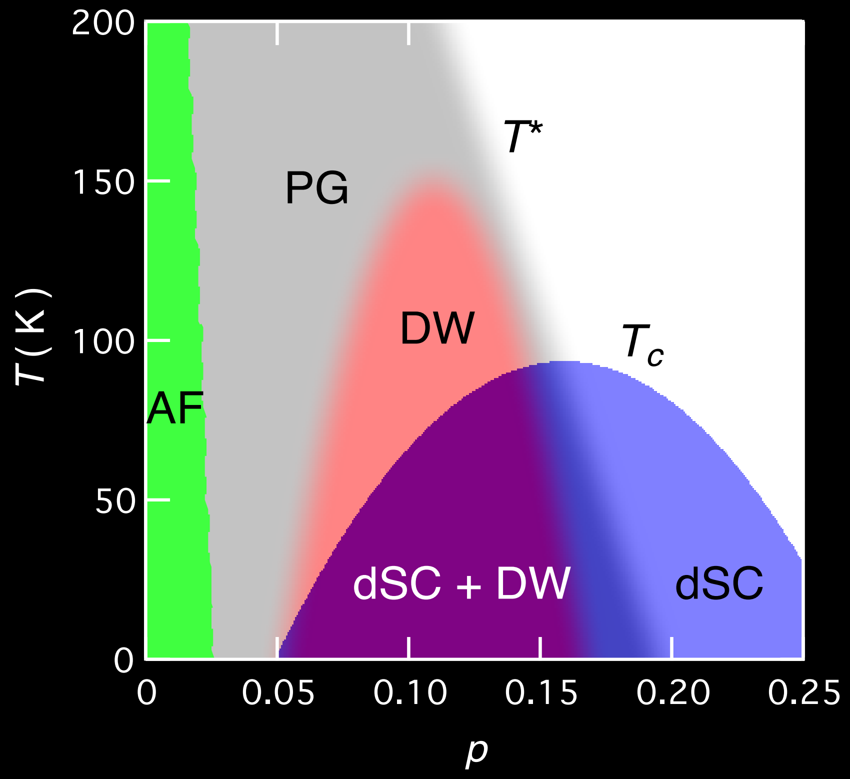
Approach 1



<u>SJTM above Uniform T_c</u>

Extremely technically challenging!

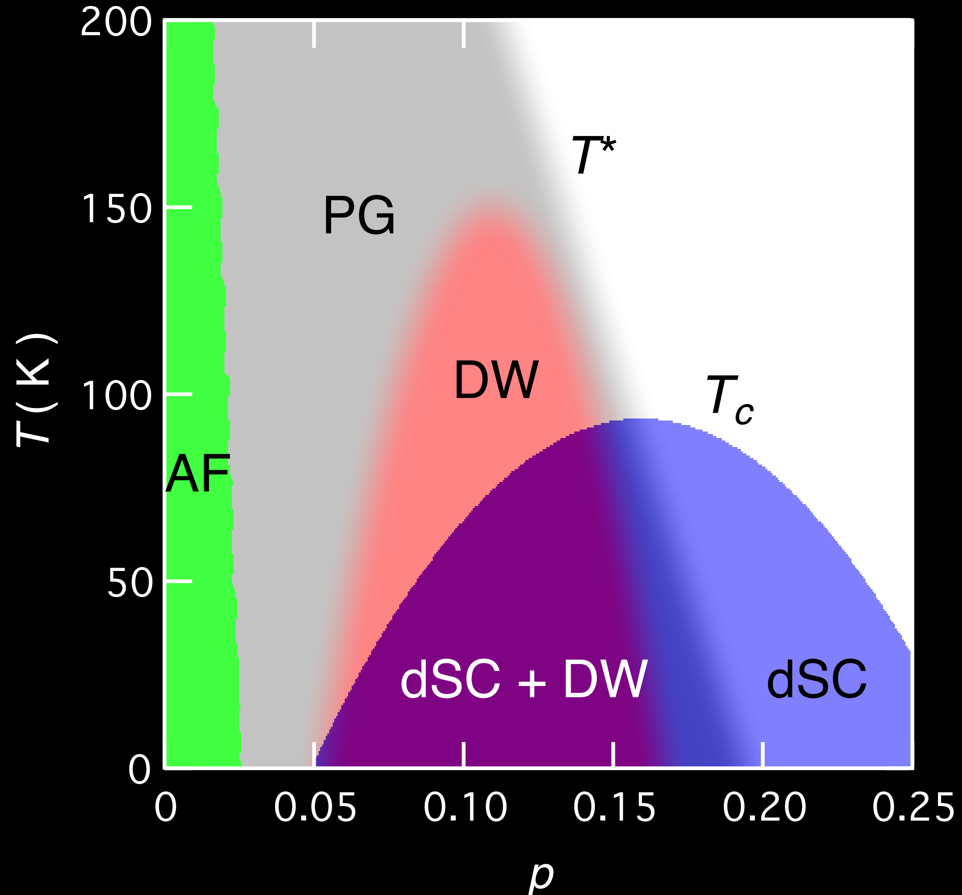
Approach 2



<u>Charge Modulation Wave-vectors</u>

Looks at difference with and without uniform SC component

Symmetry Allowed Couplings:



$$\rho_{2Q}\Psi^*_{-\vec{Q}}\Psi_{-\vec{Q}} + c.c$$

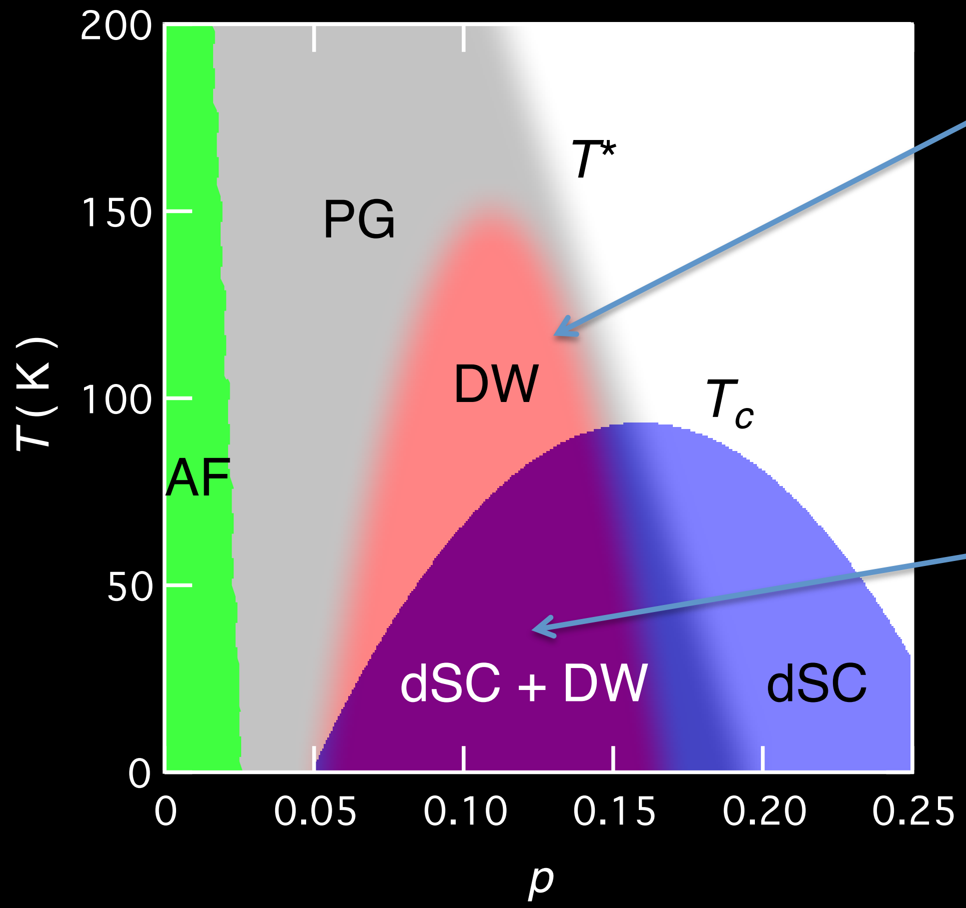
PDW Q ➔ CDM 2Q

$$\rho_{Q}\Psi^*_{0}\Psi_{-\vec{Q}} + c.c$$

PDW Q + SC ➔ CDM Q

Fradkin *et al.*, Rev. Mod. Phys. **87**, 457 (2015)
D. Agterberg, D. Tsunesugu, Nature Phys. **4**, 639–642 (2008)

Key Signature of Pure PDW



$\underline{T > T_c}$

PDW Q ➔ CDM 2Q

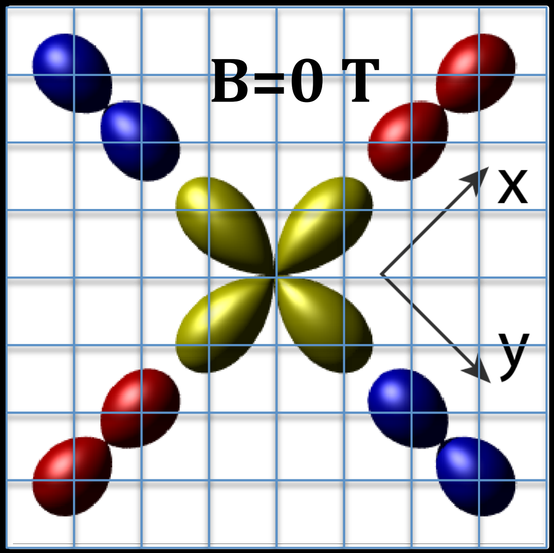
$\underline{T < T_c}$

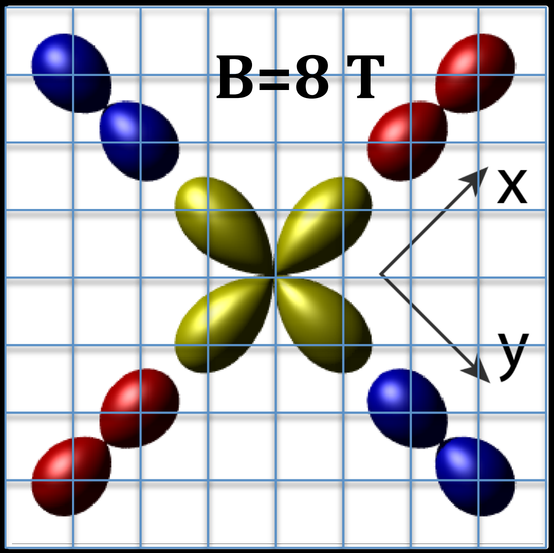
PDW Q ➔ CDM 2Q
and CDM Q

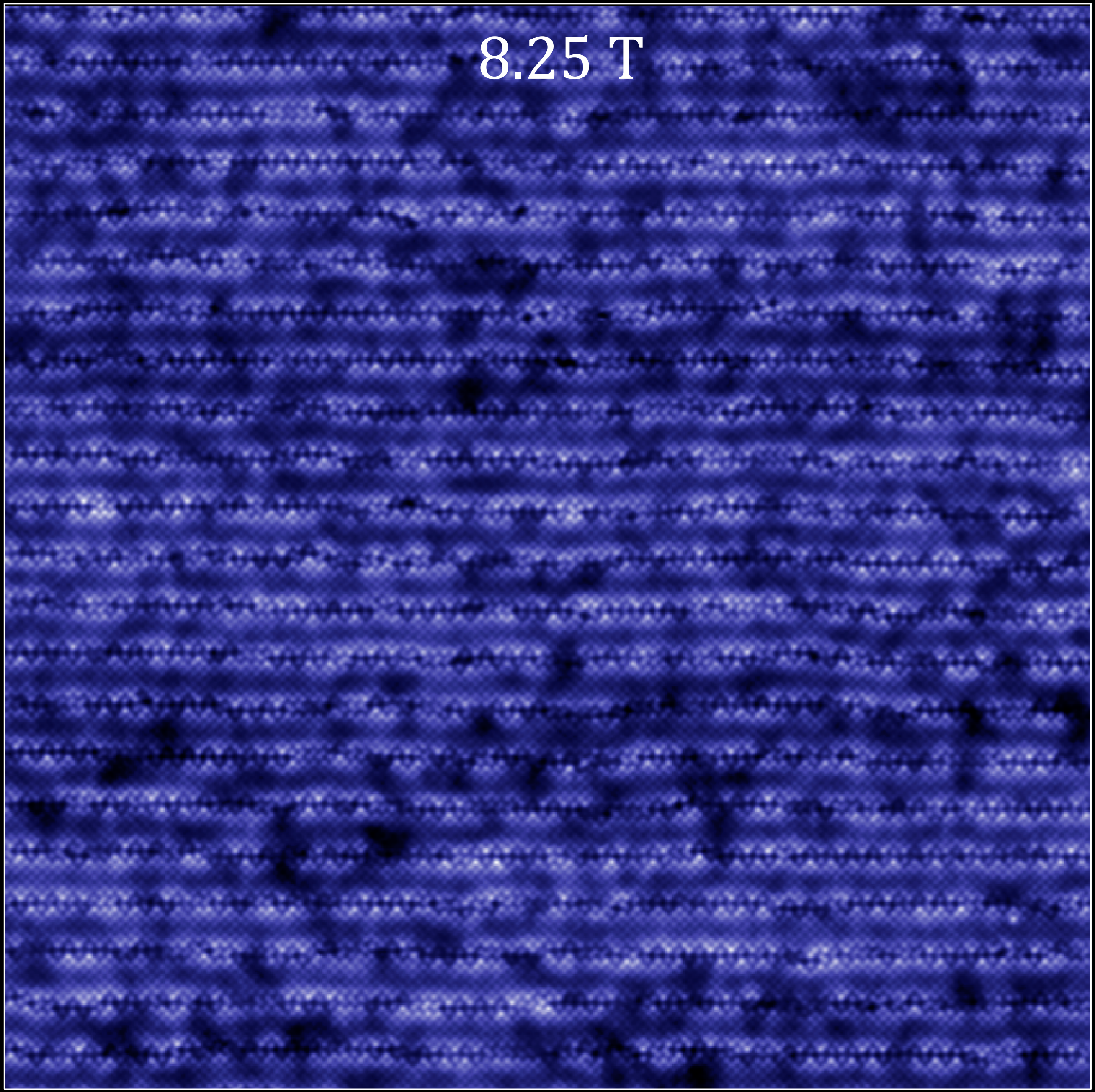
Look for sub-harmonic of CDM modulation that appears in SC state using STM, x-ray, neutron…

Approach 2 – Continued

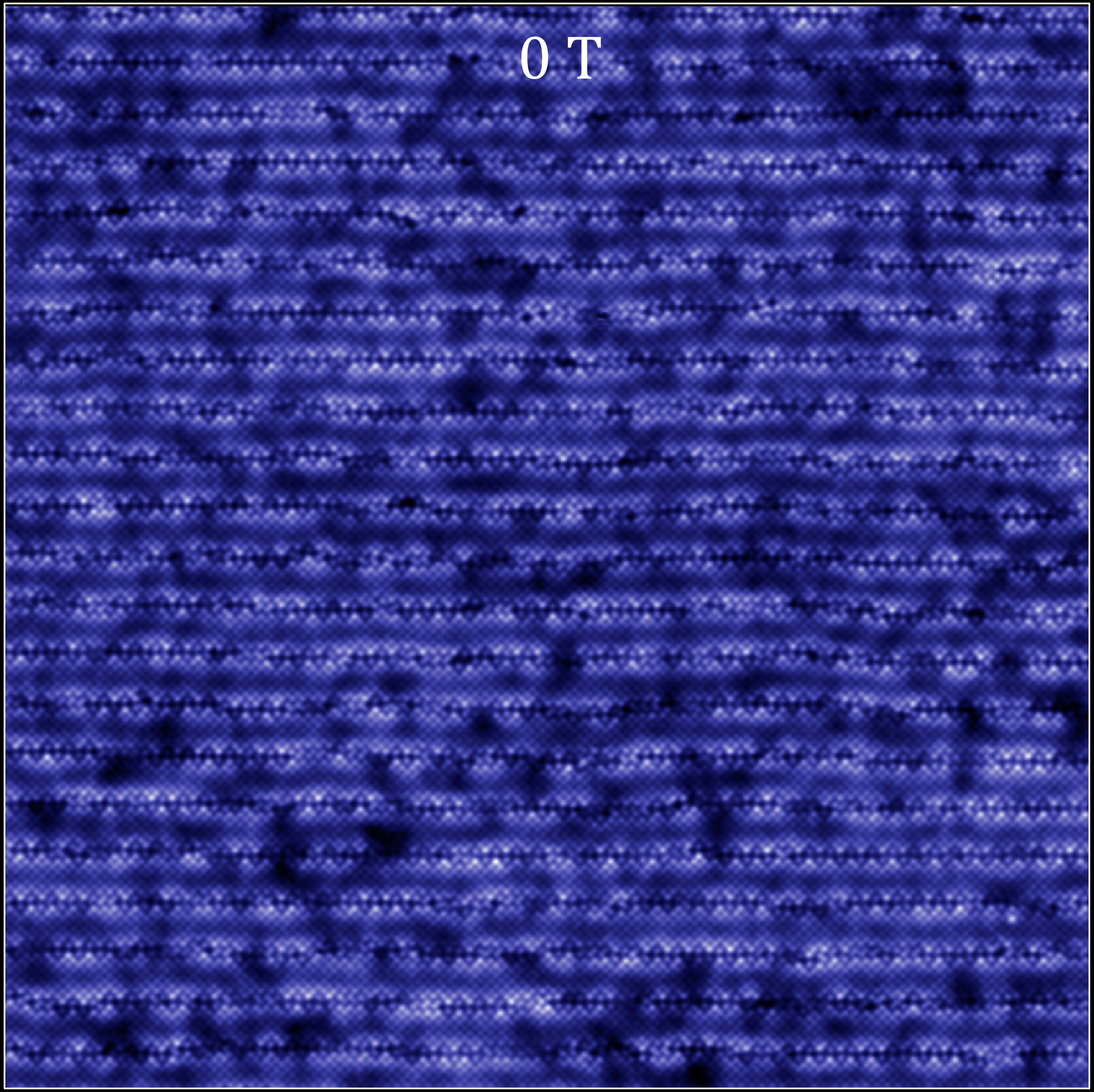
Use B instead of T



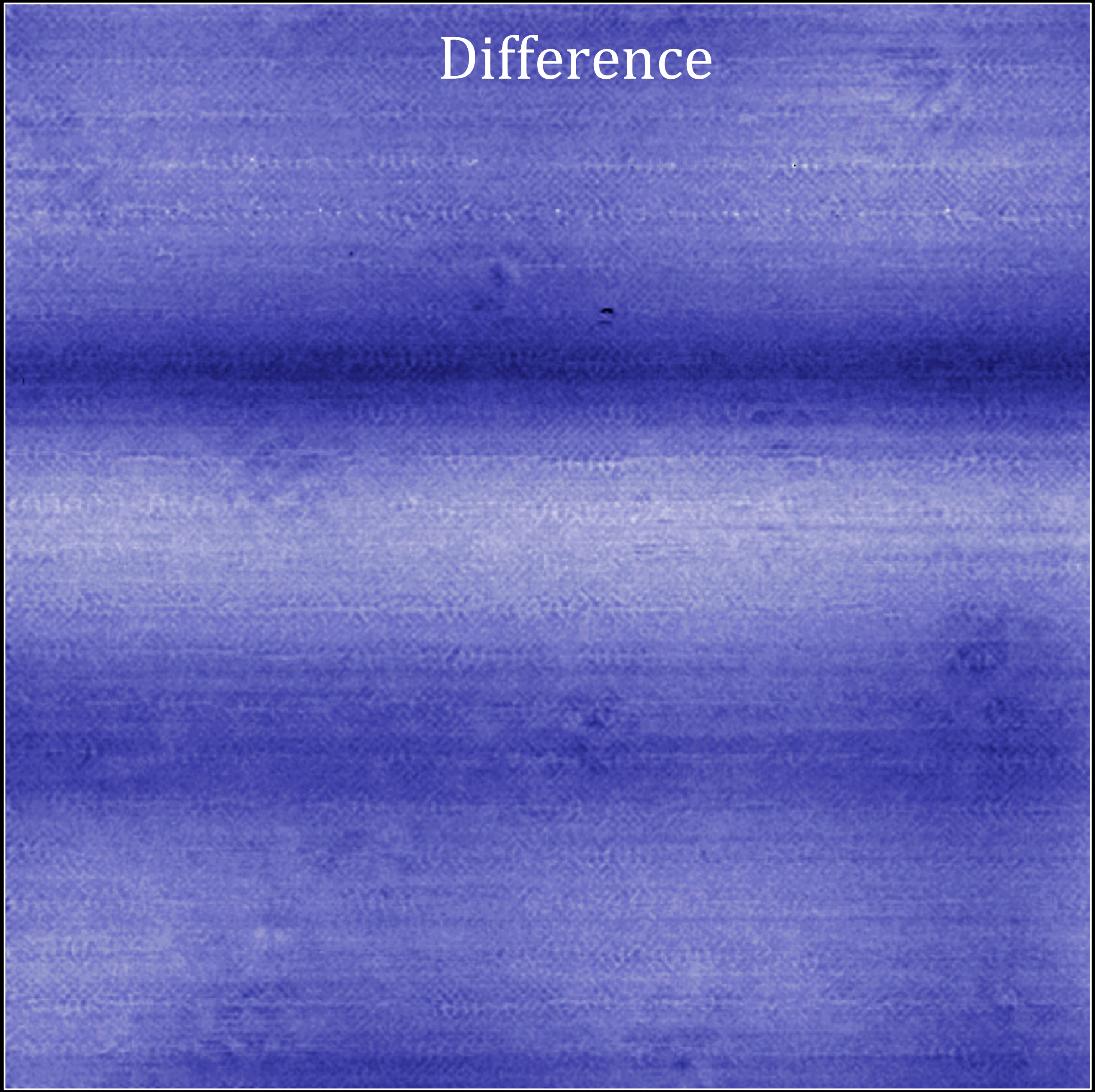




S. D. Edkins *et al.* (2017)

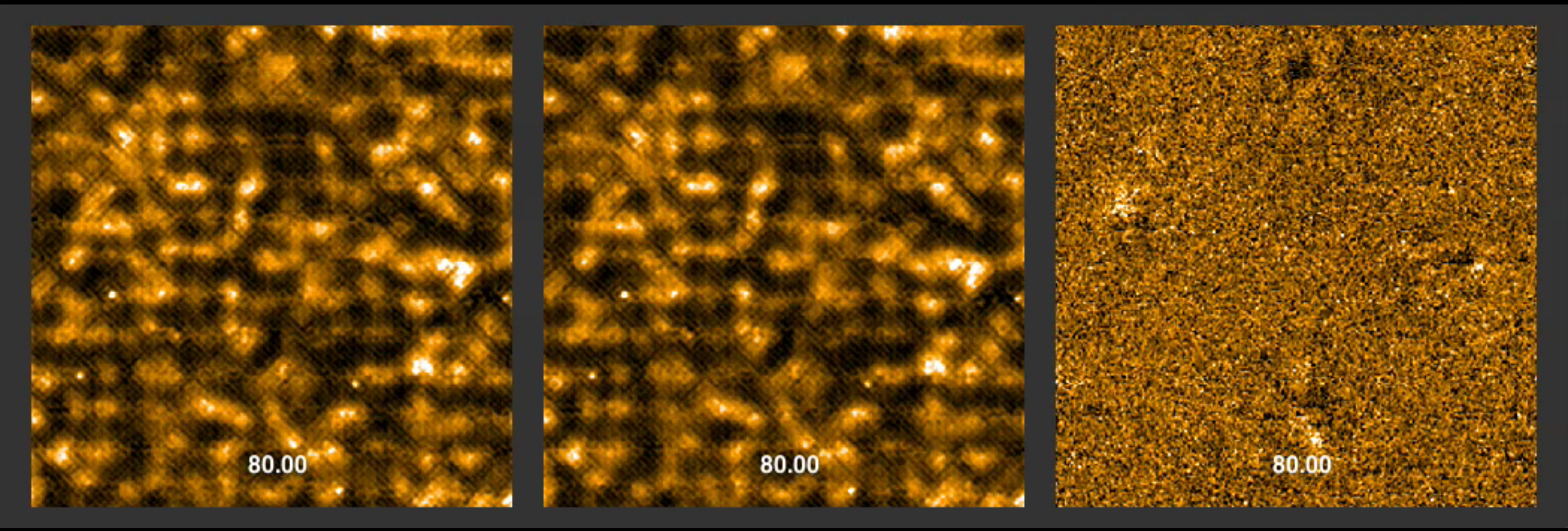


S. D. Edkins *et al.* (2017)



S. D. Edkins *et al.* (2017)

Z(B=8T) Z(B=0T) δZ=Z(8T)-Z(0T)

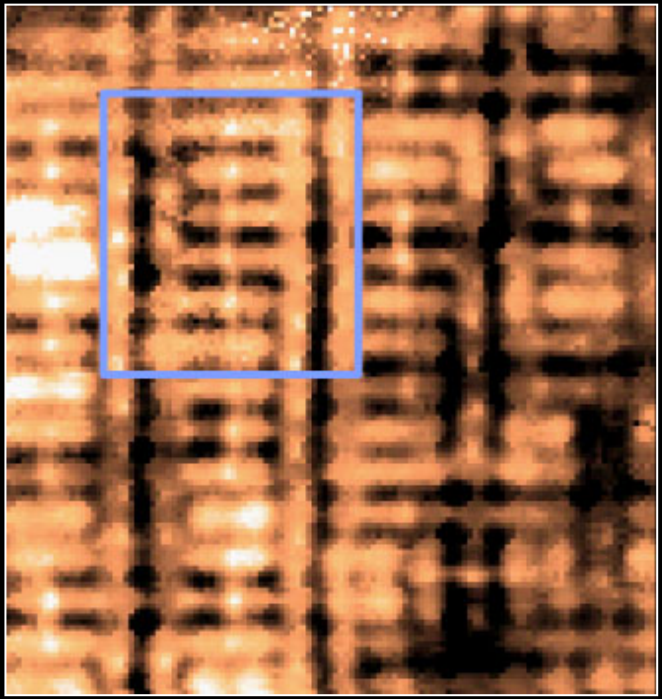


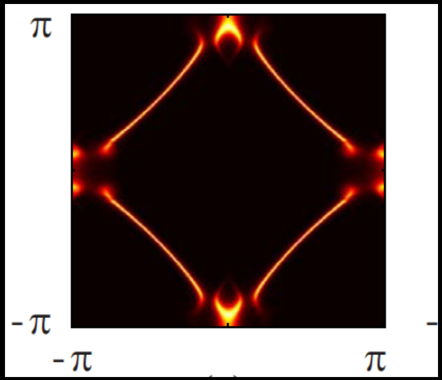
42nmx42nm

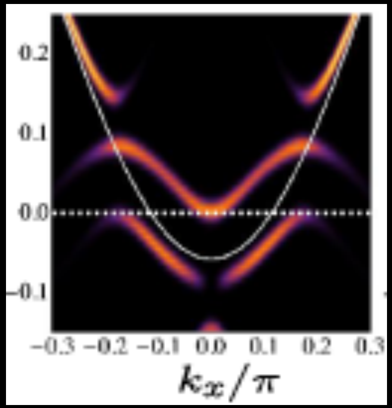
S. D. Edkins *et al.* (2017)

Approach 3

Comparison of realistic spectral function calculations with experiment







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Thanks!