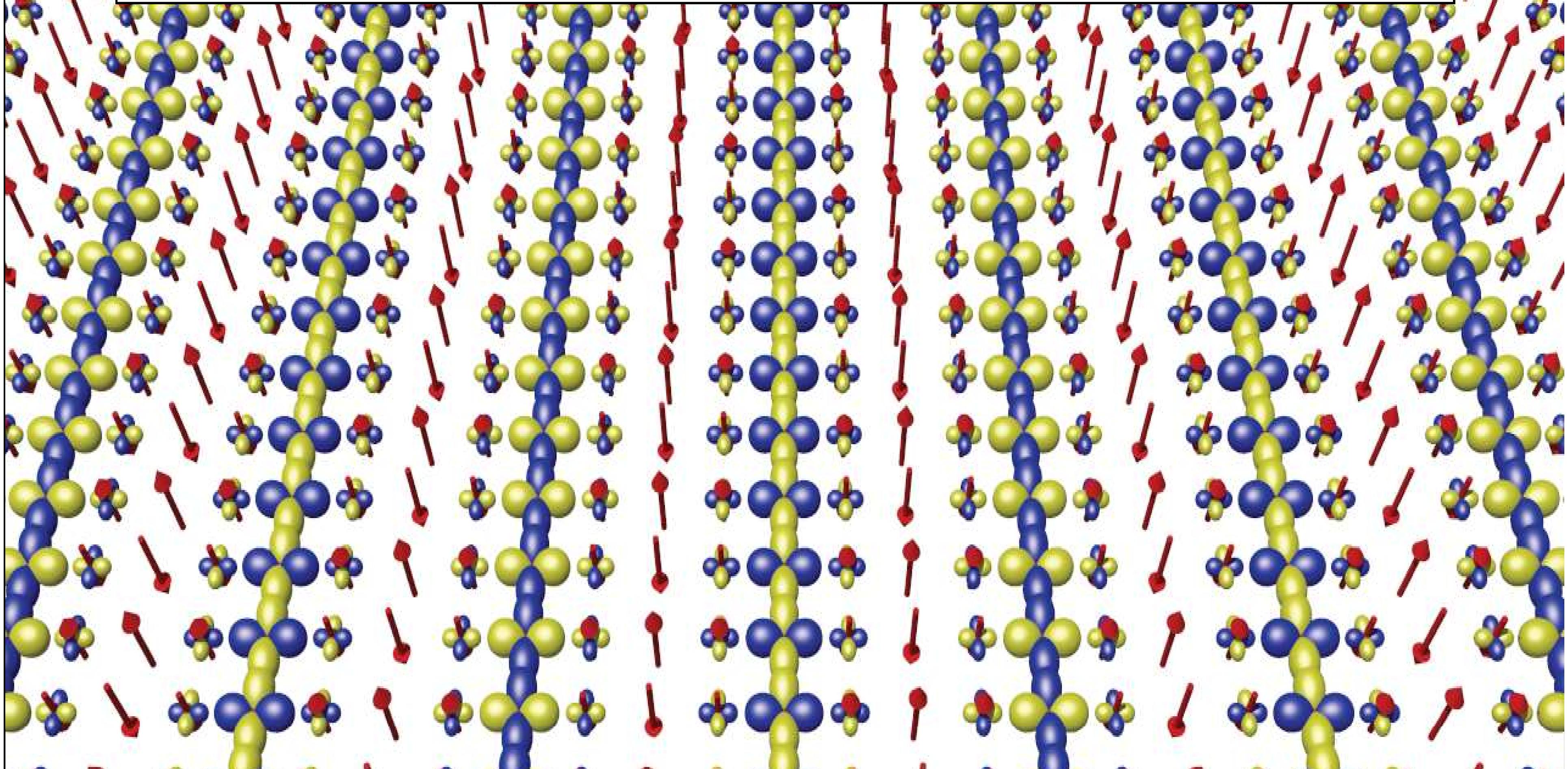
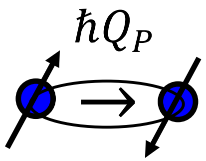
DISCOVERY & EXPLORATION of the CUPRATE PAIR DENSITY WAVE STATE



University College Cork
Coláiste na hOllscoille Corcaigh
erc European Research Council
sfi
eacht Eolaíochta Éireann
ience Foundation Ireland
University of Oxford
Gordon and Betty Moore Foundation
Cornell University Founded A.D. 1865

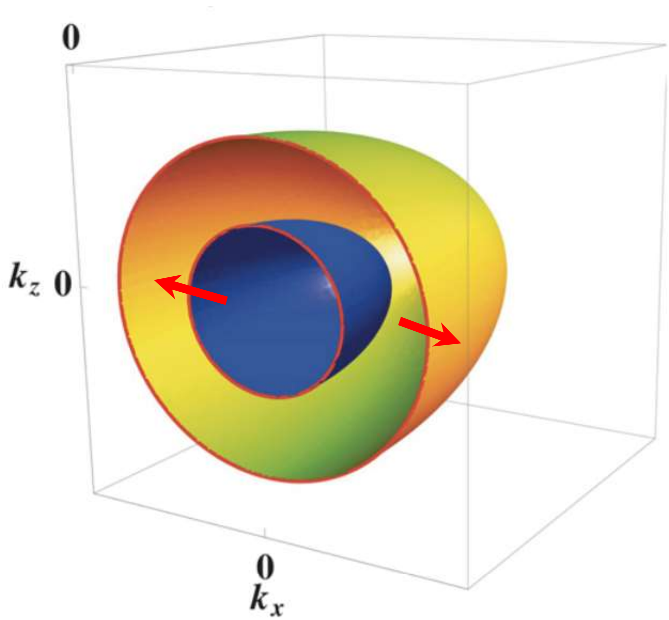
COOPER-PAIR DENSITY WAVE (FFLO) THEORY

COOPER PAIR DENSITY WAVE STATE (PDW)

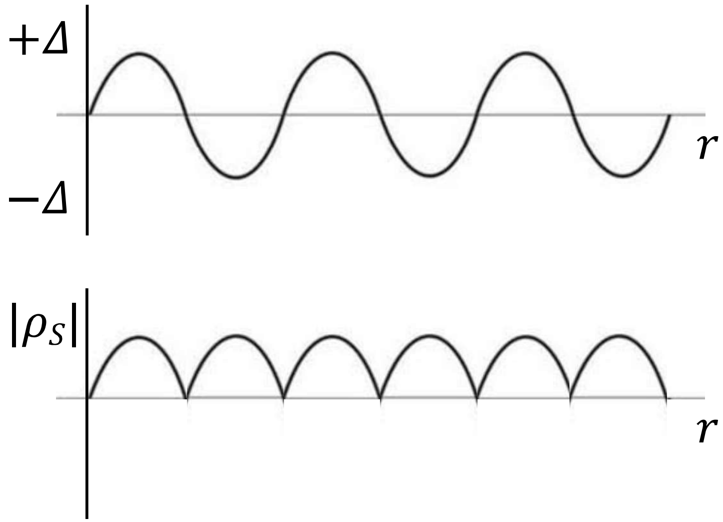


$$\left\langle c^{\dagger}_{k\uparrow}, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$

Phys. Rev. 135, A550 (1964) ; *Zh. Eksp. Teor.* Fis. 37 , 1146 (1964).

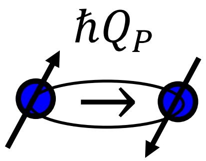


$$\boldsymbol{\Delta}(\boldsymbol{r}) = \boldsymbol{\Delta_P}\left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$



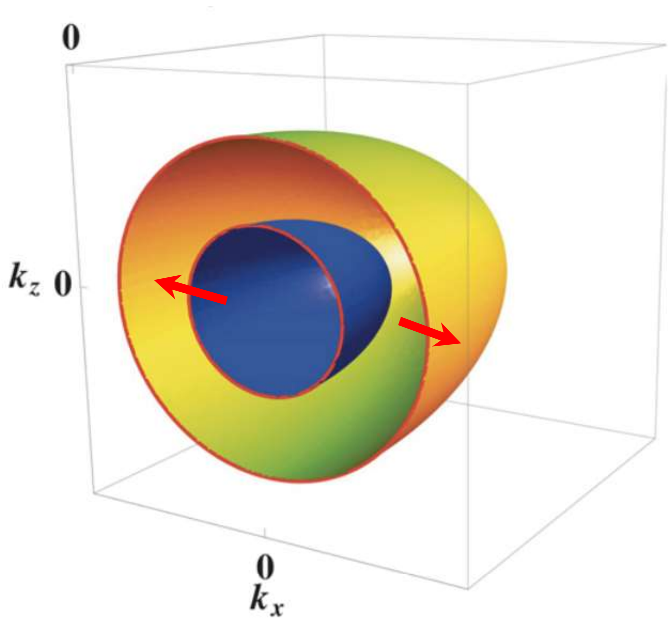
Cooper-pairs non-zero COM momentum: Modulating Cooper-pair Density

COOPER PAIR DENSITY WAVE STATE (PDW)

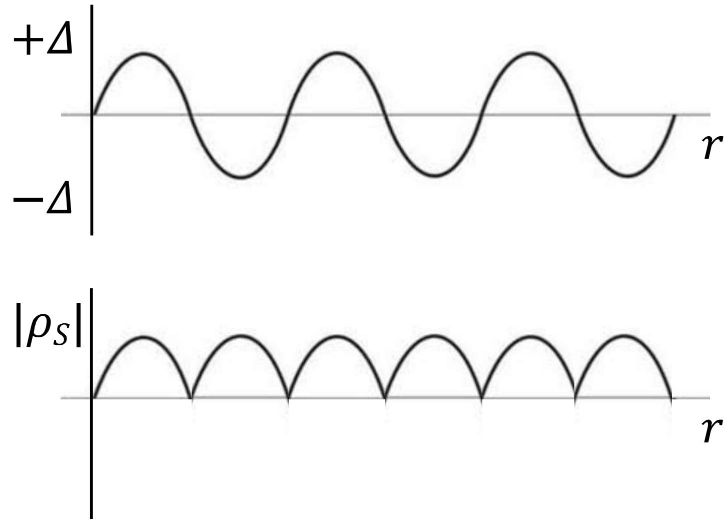


$$\left\langle c^{\dagger}_{k\uparrow}, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$

Phys. Rev. 135, A550 (1964) ; *Zh. Eksp. Teor.* Fis. 37 , 1146 (1964).



$$\boldsymbol{\Delta}(\boldsymbol{r}) = \boldsymbol{\Delta_P}\left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$



NEVER OBSERVED DIRECTLY

EXCITON PAIR DENSITY WAVE (CDW)

PDW

$$\left\langle c^{\dagger}_{k\uparrow}, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$

$$H = \sum_k \Psi^+_k \hat{h}_k \Psi_k$$

$$\hat{h}_k = \begin{pmatrix} \varepsilon_{\vec{k}} & \Delta_0 & \Delta_{\vec{k}+\vec{Q}_x/2} & \Delta_{\vec{k}-\vec{Q}_x/2} \\ \Delta_0 & -\varepsilon_{-\vec{k}} & 0 & 0 \\ \Delta_{\vec{k}+\vec{Q}_x/2} & 0 & -\varepsilon_{-(\vec{k}+\vec{Q}_x)} & 0 \\ \Delta_{\vec{k}-\vec{Q}_x/2} & 0 & 0 & -\varepsilon_{-(\vec{k}-\vec{Q}_x)} \end{pmatrix}, \Psi_k = \begin{pmatrix} c_{k,\uparrow} \\ c^+_{-k,\downarrow} \\ c^+_{-(\vec{k}+\vec{Q}_x),\downarrow} \\ c^+_{-(\vec{k}-\vec{Q}_x),\downarrow} \end{pmatrix}$$

CDW

$$\left\langle c^{\dagger}_{k\uparrow}, c_{k+Q_C\downarrow} \right\rangle$$

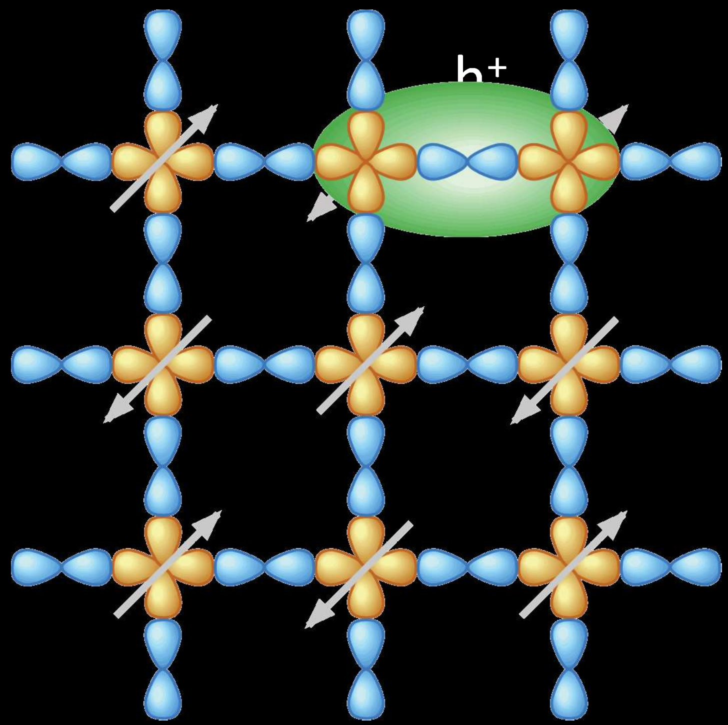
$$H = \sum_k \Psi^+_k \hat{h}_k \Psi_k$$

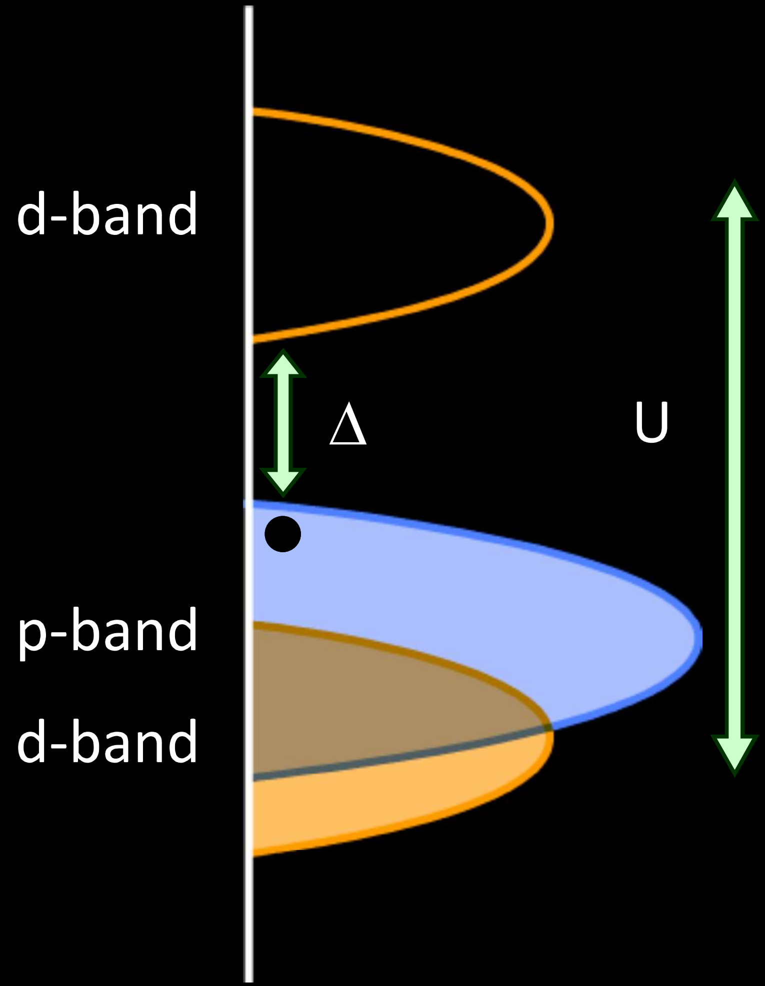
$$\hat{h}_k = \begin{pmatrix} \varepsilon_{\vec{k}} & \Delta_0 & 0 & 0 \\ \Delta_0 & -\varepsilon_{-\vec{k}} & V_{\vec{k}+\vec{Q}_x/2} & V_{\vec{k}-\vec{Q}_x/2} \\ 0 & V_{\vec{k}+\vec{Q}_x/2} & -\varepsilon_{-(\vec{k}+\vec{Q}_x)} & 0 \\ 0 & V_{\vec{k}-\vec{Q}_x/2} & 0 & -\varepsilon_{-(\vec{k}-\vec{Q}_x)} \end{pmatrix}, \Psi_k = \begin{pmatrix} c_{k,\uparrow} \\ c^+_{-k,\downarrow} \\ c^+_{-(\vec{k}+\vec{Q}_x),\downarrow} \\ c^+_{-(\vec{k}-\vec{Q}_x),\downarrow} \end{pmatrix}$$

[redacted]

CUPRATE PAIR DENSITY WAVE

HOLE-DOPED CuO_2 MOTT INSULATOR

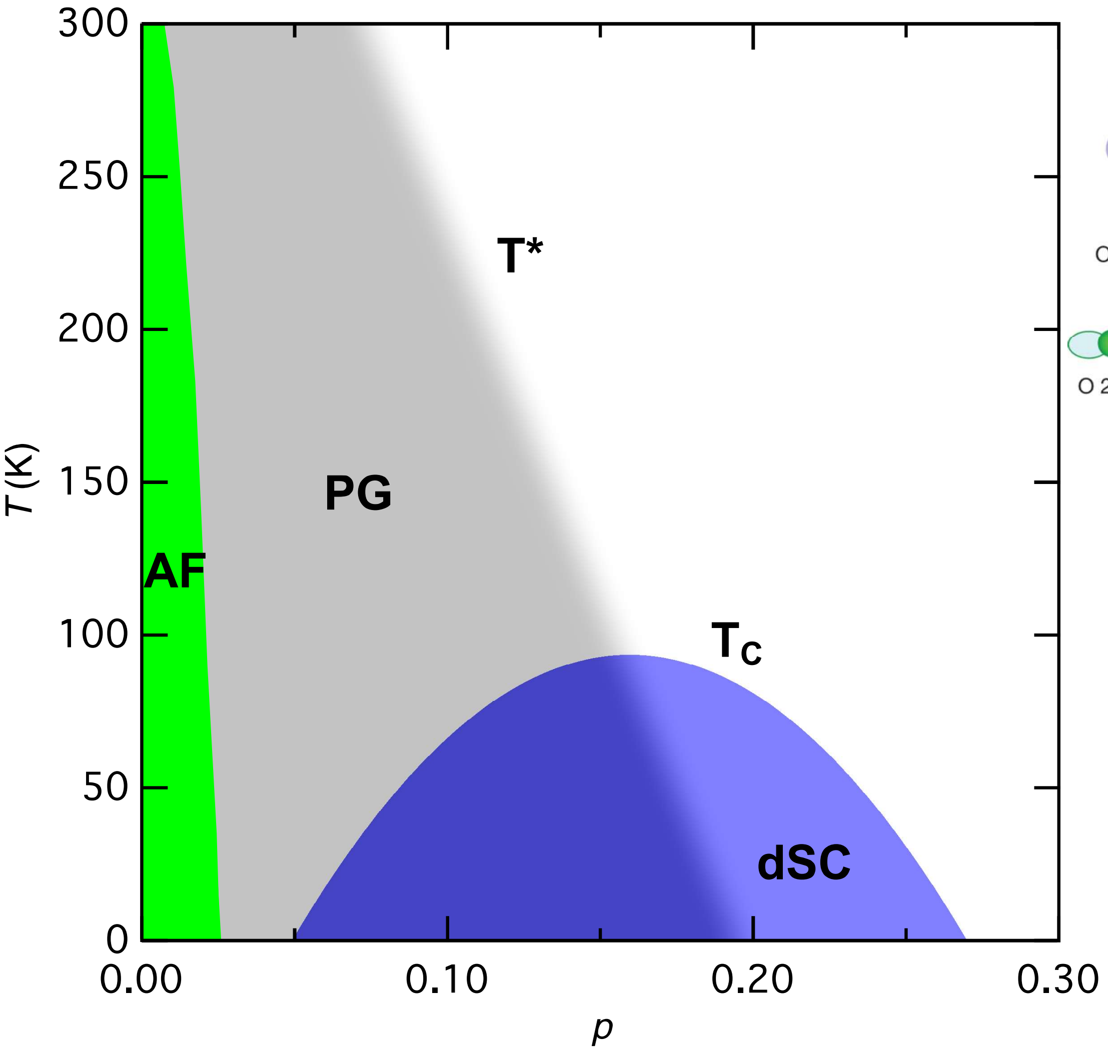


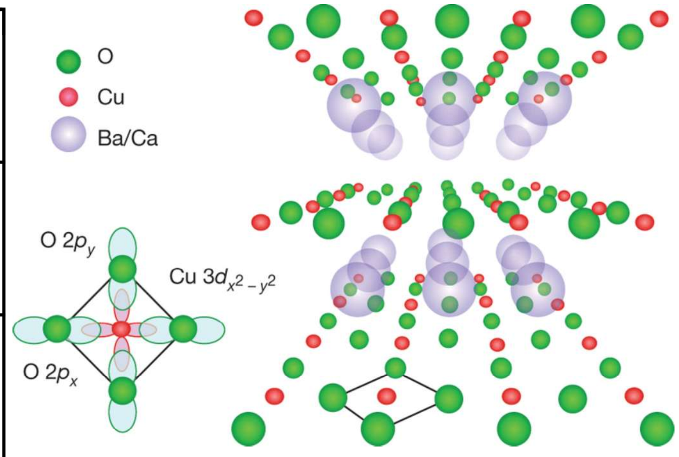


U ≃ 3eV, t≃400meV, J ≃ 150meV

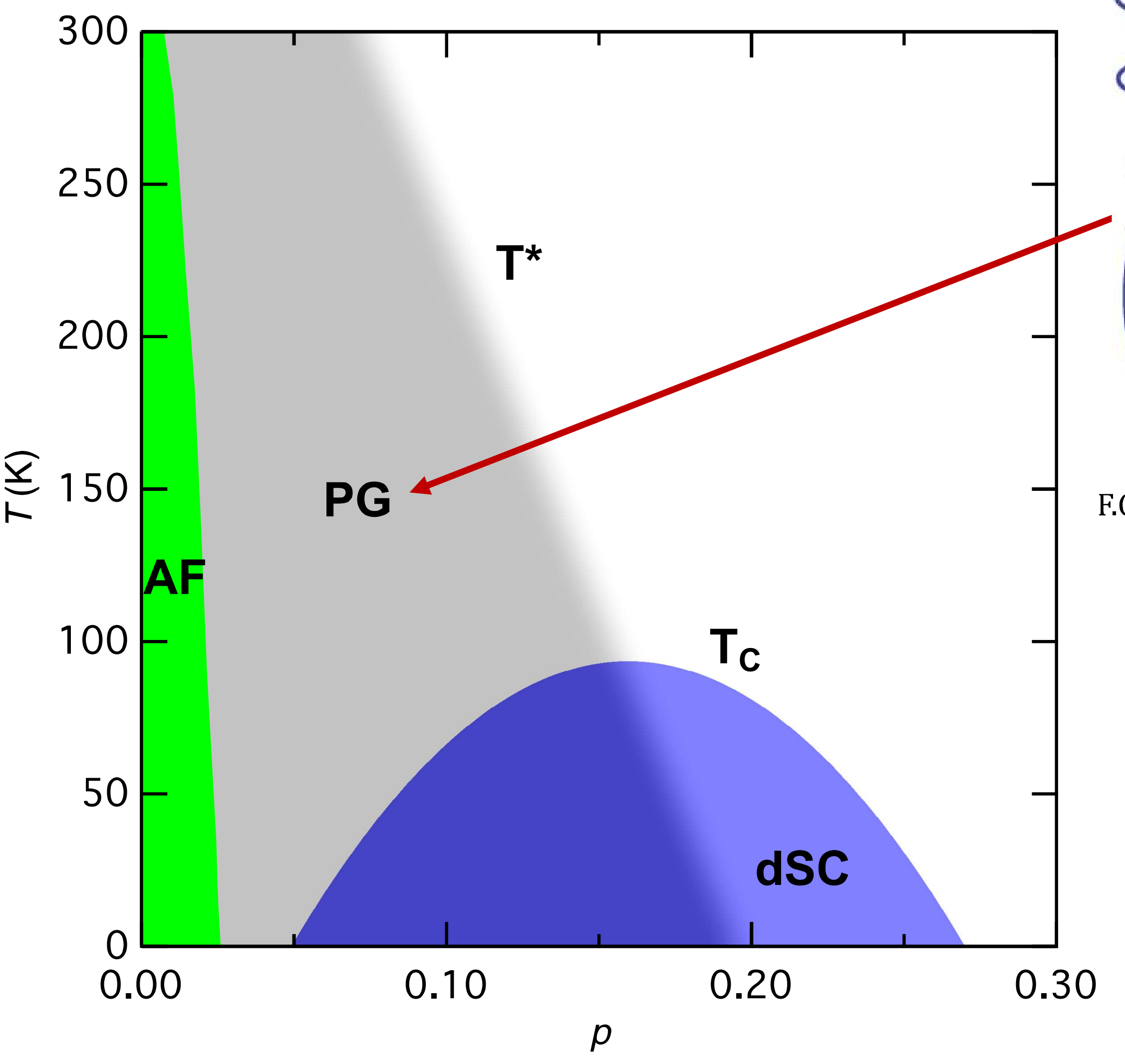
⇒ half-filling = correlated AF insulator

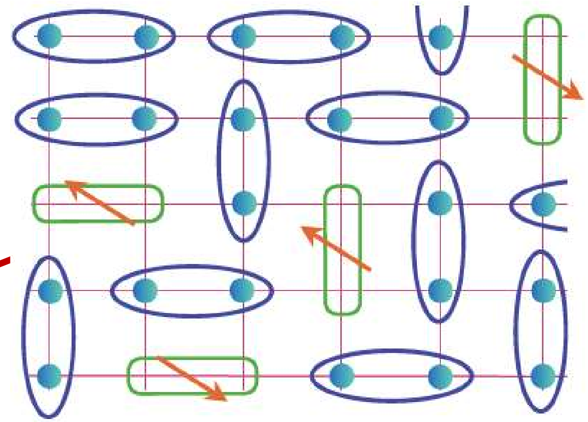
HOLE-DOPED CuO_2 MOTT INSULATOR





PSEUDOGAP = HOLE-DOPED SPIN LIQUID ?





P.W. Anderson
Science 237, 1196 (1987)

F.C. Zhang, C. Gros, T.M. Rice and H. Shiba
Super. Sci. Tech. 1, 36 (1988)

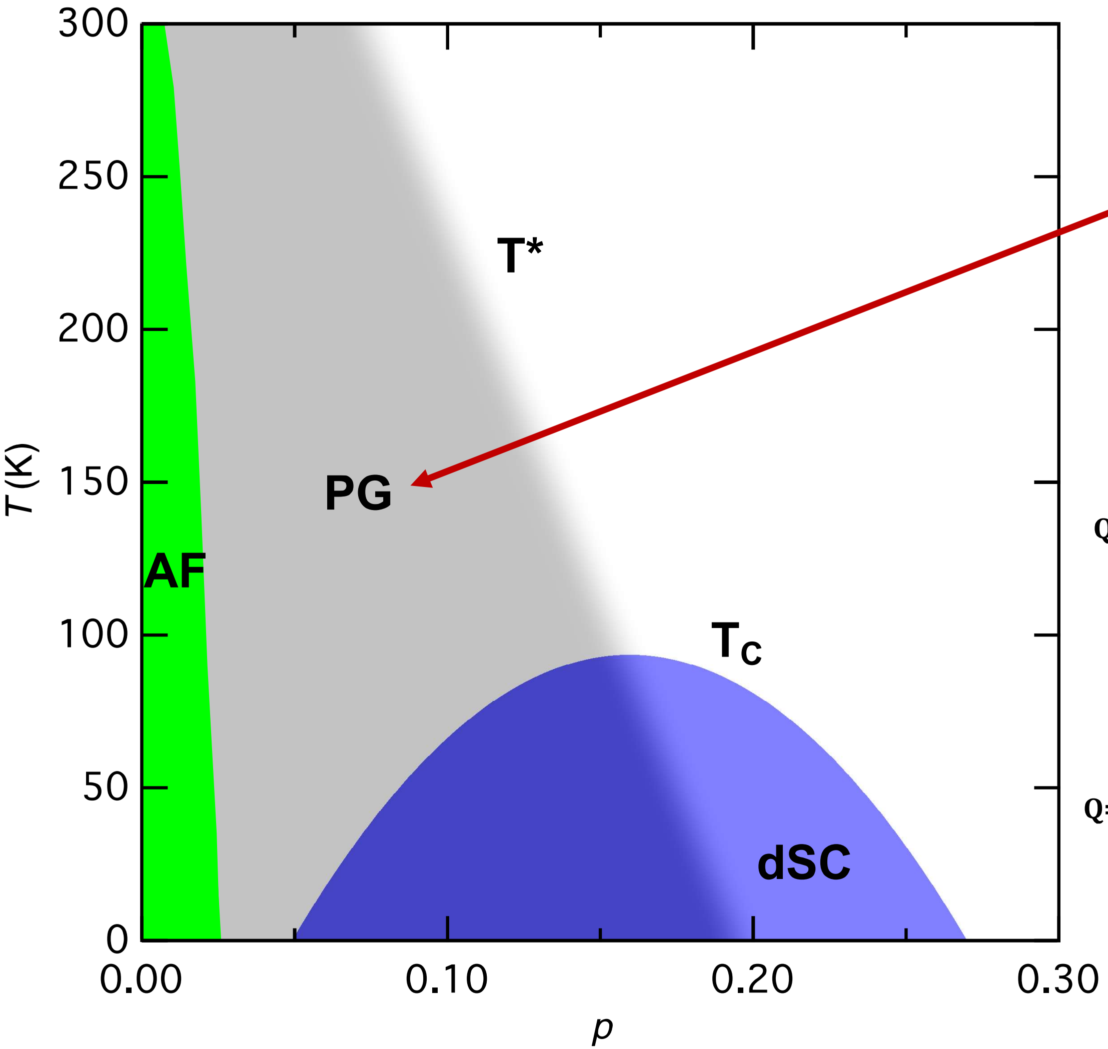
G. Kotliar & J. Liu
Phys. Rev. B38 5142 (1988)

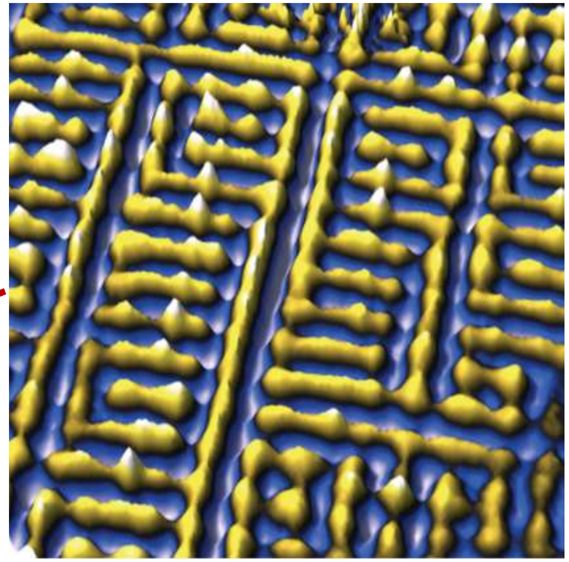
A. Georges & G. Kotliar
Rev. Mod. Phys. 68 , 13 (1996)

P.A. Lee and X.G. Wen,
Rev. Mod. Phys. 78, 17 (2006)

Punk, Allais, Sachdev
PNAS 112, 9552 (2015)

PSEUDOGAP = BROKEN-SYMMETRY STATE ?

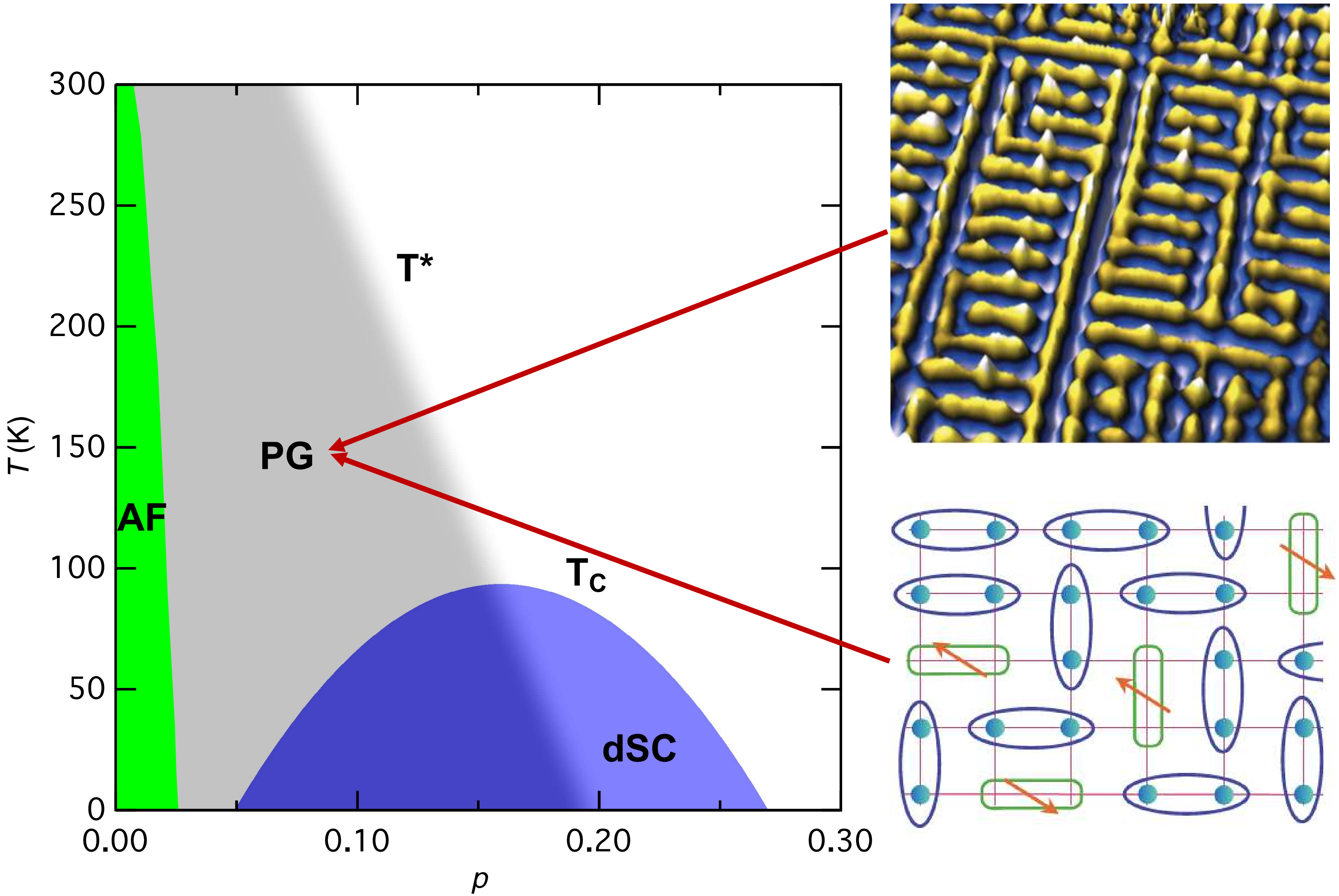




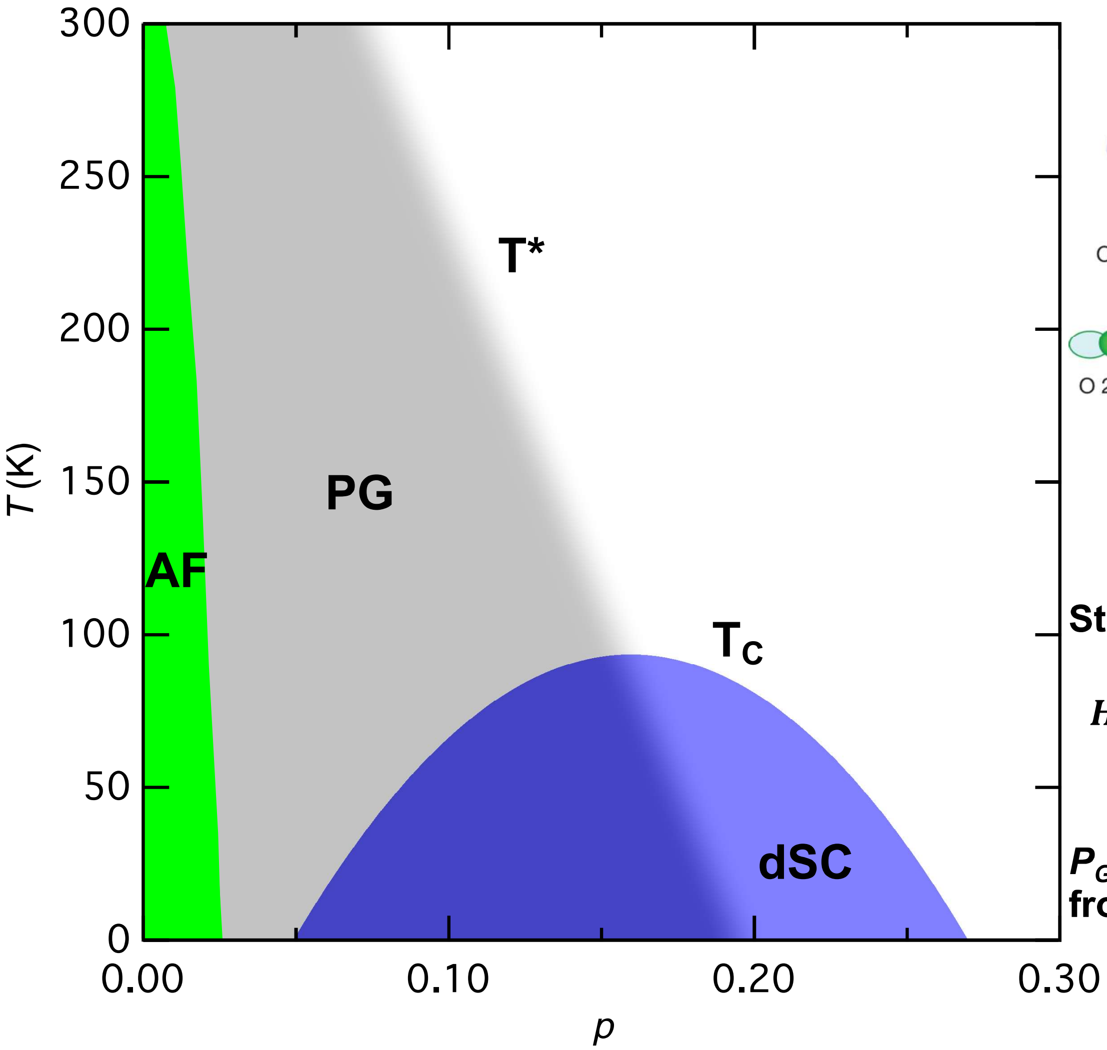
Q=0 (2002) *Nature* 416 (6881):610-613.
(2006) *Phys Rev Lett* 96 (19):197001
(2008) *Nature* 455 (7211):372–375.
(2010) *Nature* 463 (7280):519-522.
(2013) *Nature* 498 (7452):75–77.
(2017) *Nat Phys* 13 (3):250–254.
(2017) *Nat Phys* 13 (11):1074–1078.

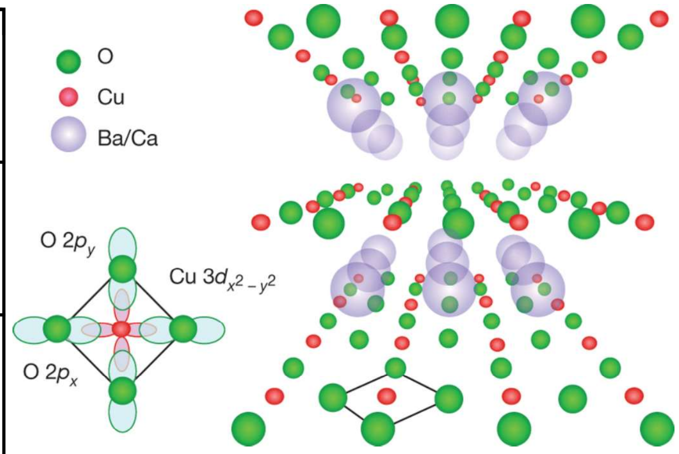
Q=Q_{DW} (1995) *Nature* 375 (6532): 561–563.
(2012) *Nat Phys* 8 (12):871–876.
(2012) *Science* 337 (6096):821–825.
(2014) *Science* 343 (6169):390–392.
(2015) *Science* 350 (6263):949–952.
(2015) *Nat. Mat.* 14 (8):796–800.

HOLE-DOPED SPIN LIQUID + BROKEN SYMMETRY STATE ?



CuO_2 STRONG-COUPLING THEORY





Strong-Coupling CuO_2 plane *t-J* Model

$$H = -\sum_{(i,j),\sigma} P_G t_{ij}\left(c_{i\sigma}^{\dagger} c_{j\sigma} + h.c.\right) P_G + J \sum_{<i,j>} S_i \cdot S_j,$$

P_G projects out doubly occupied sites from the Hilbert space.

CuO_2 STRONG-COUPLING THEORY ⇒ PAIR DENSITY WAVE

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).**

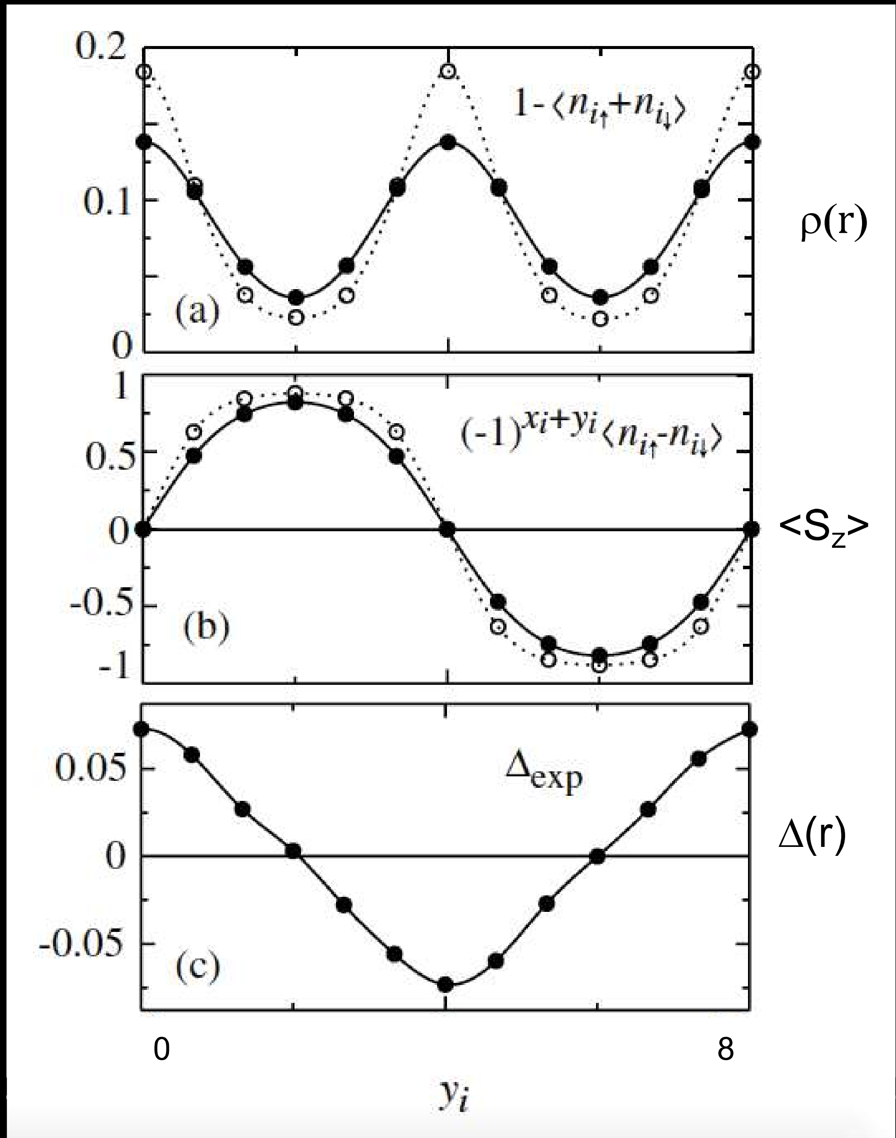
Loder, F., Graser, S., Kampf, A. P. & Kopp, T. Mean-field pairing theory for the charge-stripe phase of cuprate superconductors
Phys. Rev. Lett. **107, 187001 (2011).**

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) .**

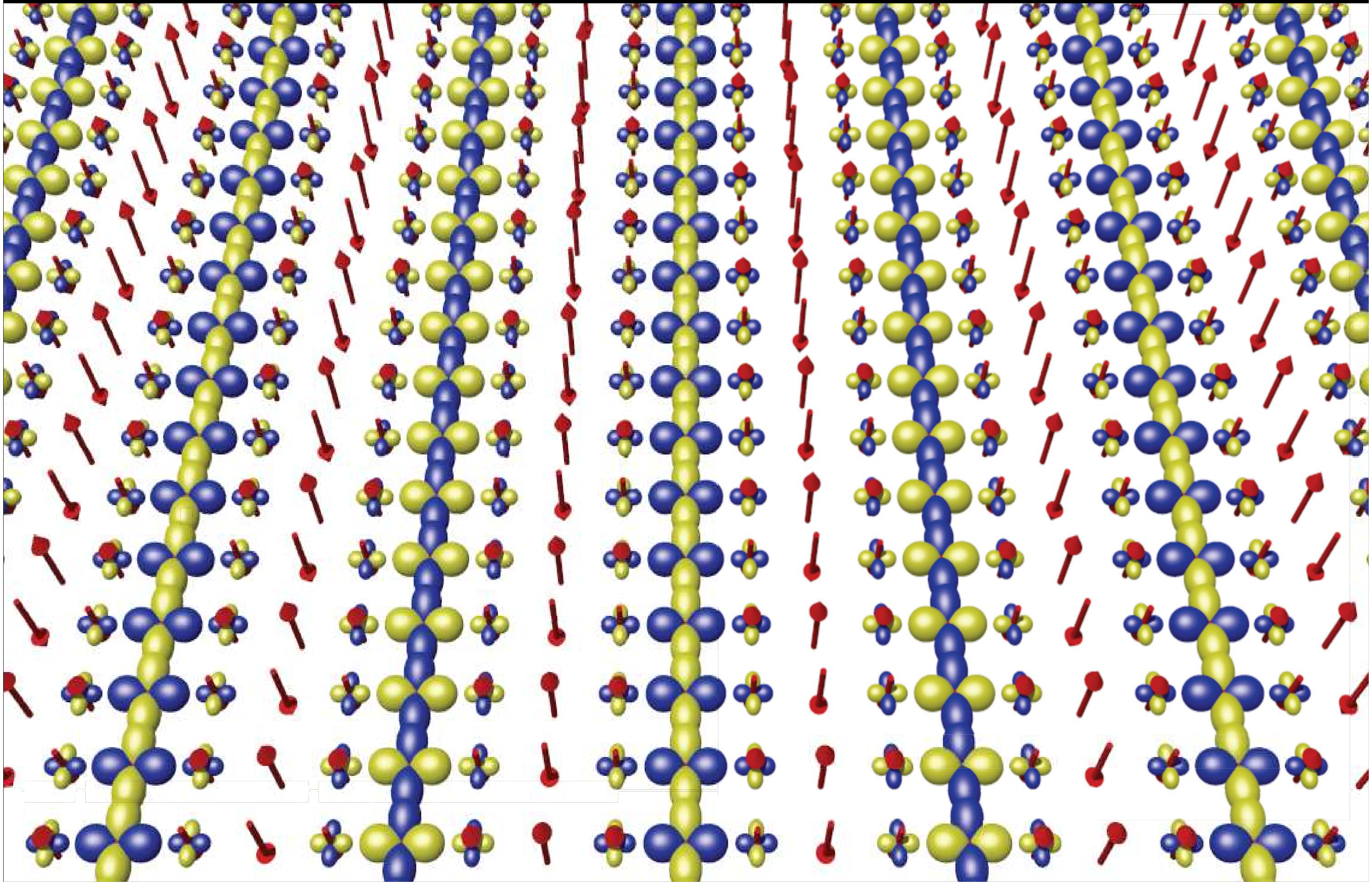
Choubey P., Wei-Lin Tu, Ting-Kuo Lee and P. J. Hirschfeld Incommensurate charge ordered states in the t−t′−J model
New J. Phys. **19, 013028 (2017)**

S. Verret *et al* Subgap structure and pseudogap in cuprates superconductors ***Phys. Rev. B 95*****, 544518 (2017)**

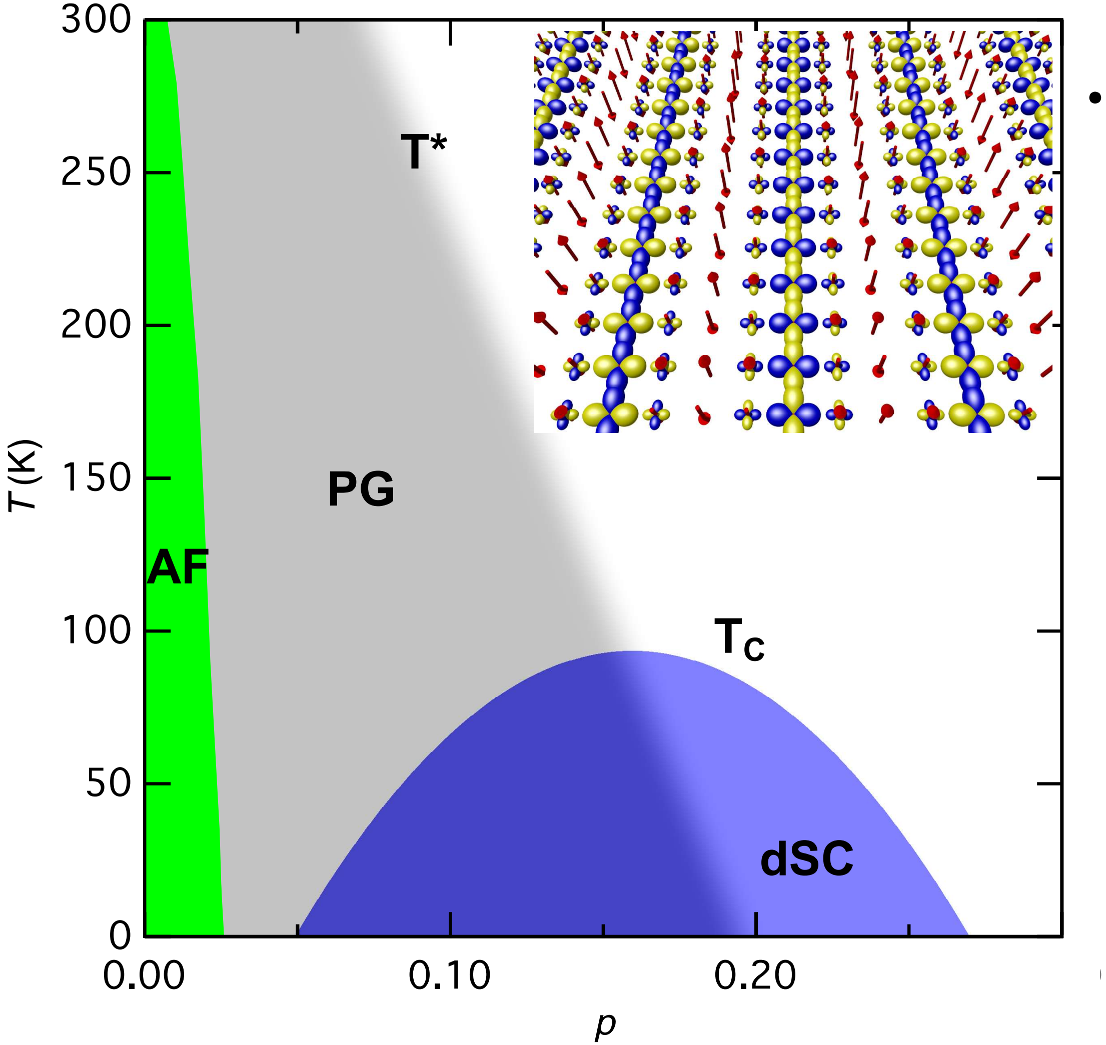
Rong-Gen Caia, Li Lia, Yong-Qiang Wang, and Jan Zaanen
Phys. Rev. Lett. **119, 181601 (2017)**



CuO_2 STRONG-COUPLING THEORY ⇒ PAIR DENSITY WAVE

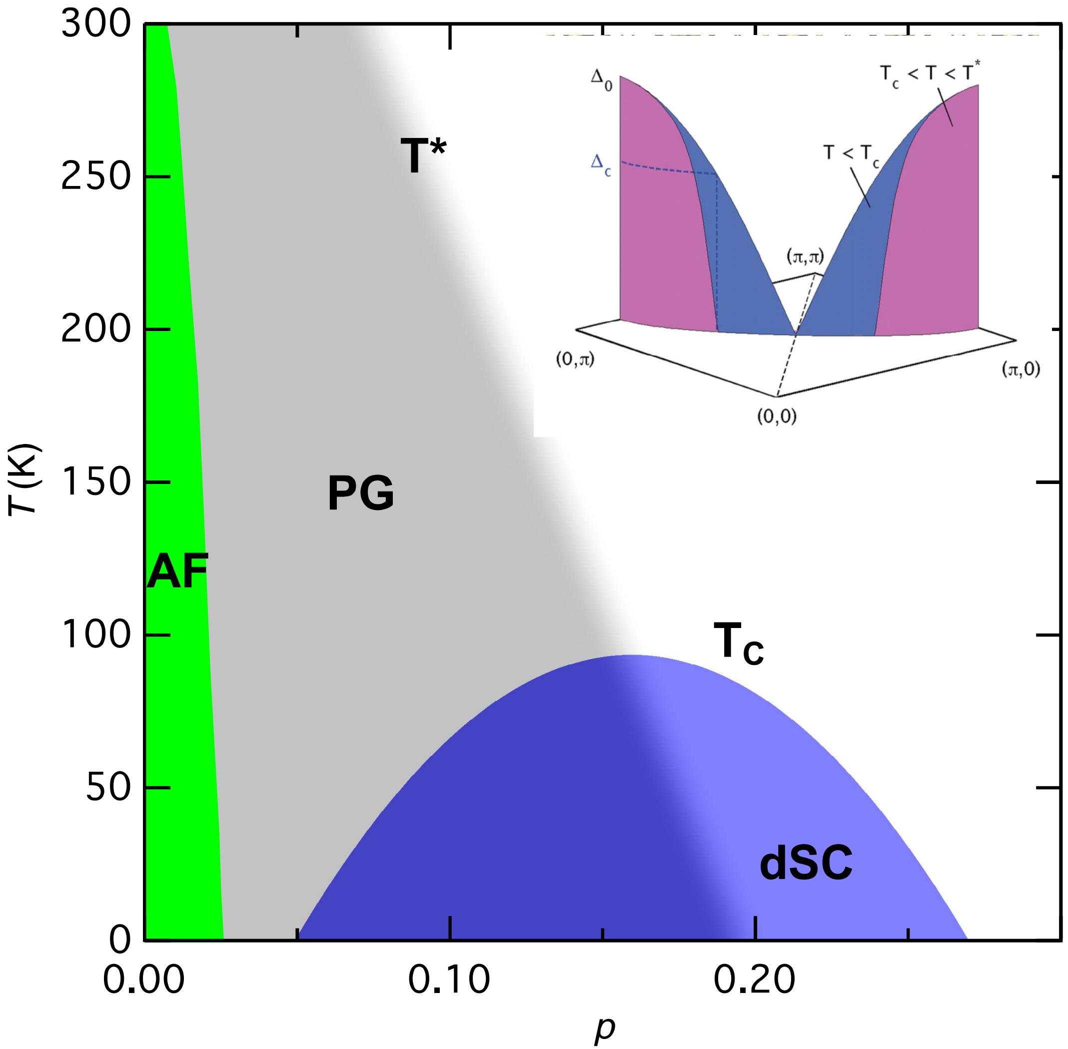


PSEUDOGAP ⇔ PAIR DENSITY WAVE



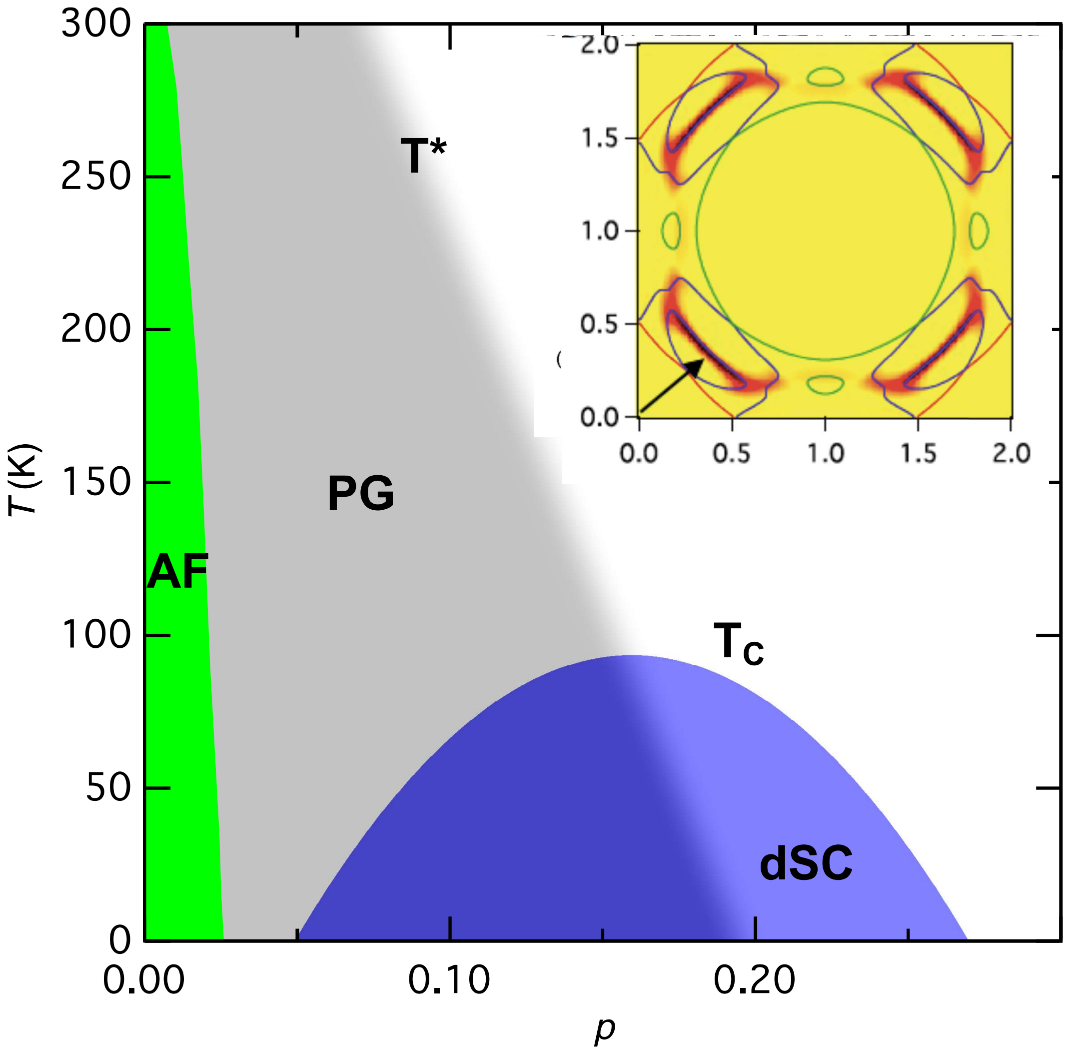
- Natural in strong coupling theory of hole-doped CuO_2
- PDW free energy density very close to that of DSC

PSEUDOGAP ⟺ PAIR DENSITY WAVE



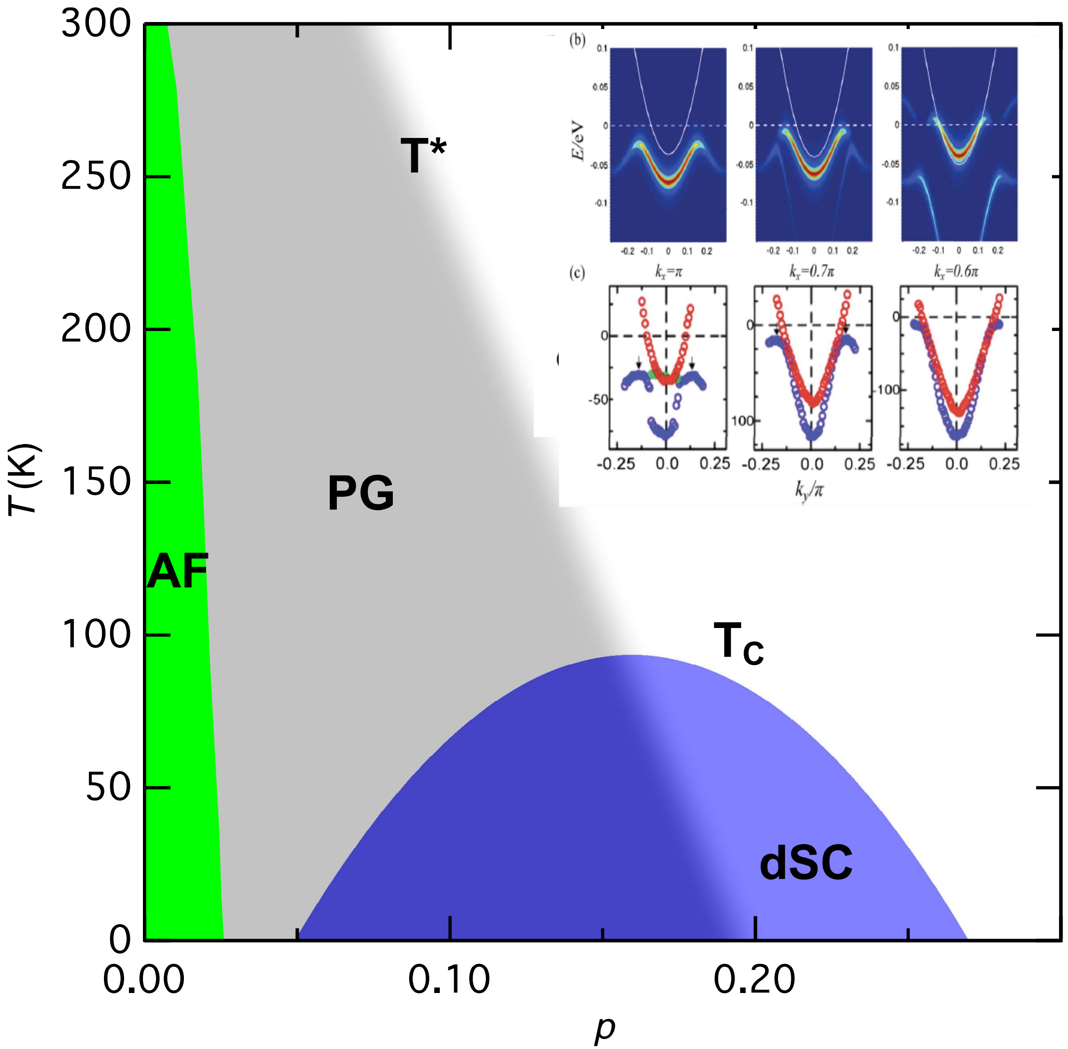
- Natural in strong coupling theory of hole-doped CuO_2
- PDW free energy density very close to that of DSC
- PDW exhibits a particle-hole symmetric antinodal gap
- PDW exhibits k-space 'Fermi Arc' of unbound electrons

PSEUDOGAP ⇔ PAIR DENSITY WAVE



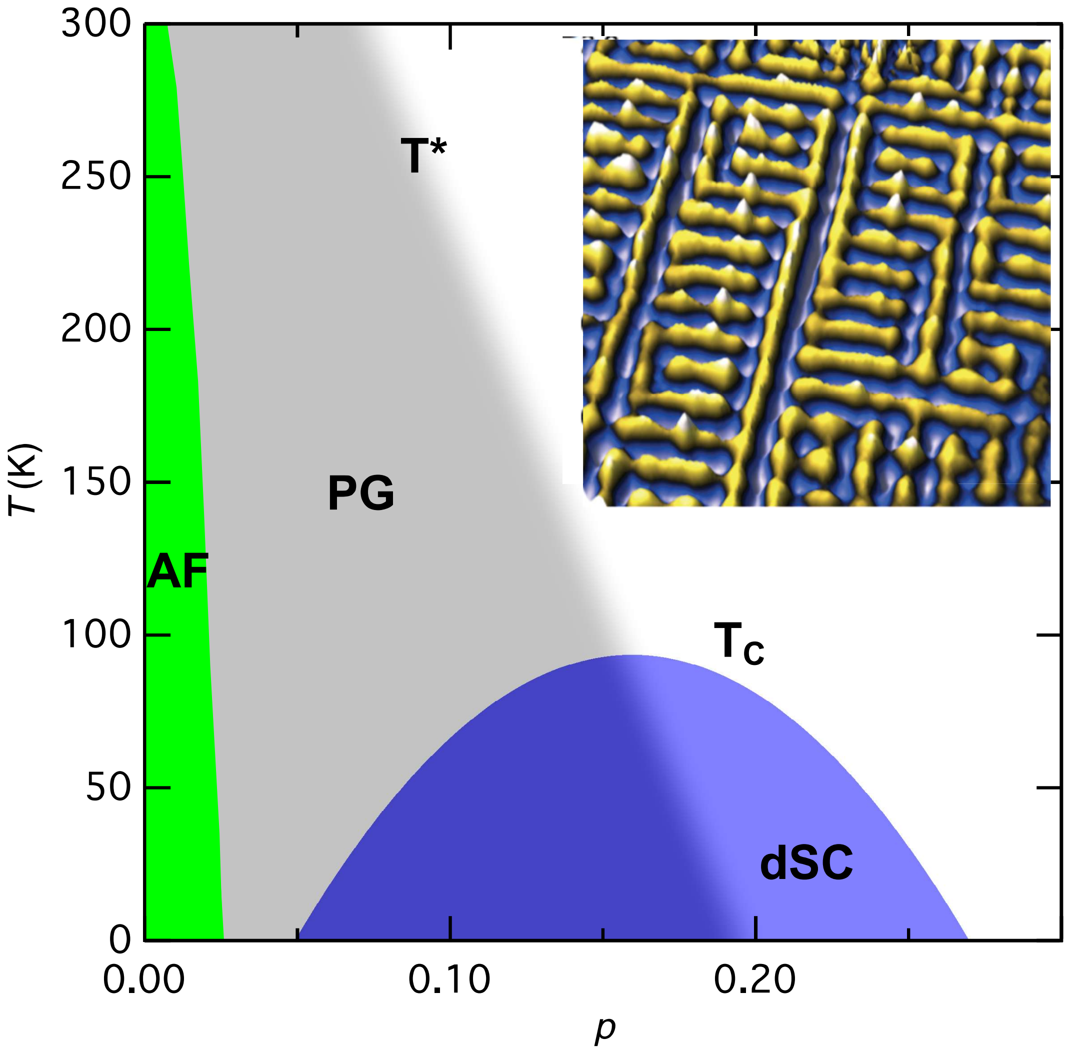
- Natural in strong coupling theory of hole-doped CuO_2
- PDW free energy density very close to that of DSC
- PDW exhibits a particle-hole symmetric antinodal gap
- PDW exhibits k-space ‘Fermi Arc’ of unbound electrons
- PDW yields small electron-like pocket with correct frequency of quantum oscillations

PSEUDOGAP ⟺ PAIR DENSITY WAVE



- Natural in strong coupling theory of hole-doped CuO_2
- PDW free energy density very close to that of DSC
- PDW exhibits a particle-hole symmetric antinodal gap
- PDW exhibits k-space 'Fermi Arc' of unbound electrons
- PDW yields small electron-like pocket with correct frequency of quantum oscillations
- PDW gives the correct spectral functions for underdoped CuO_2

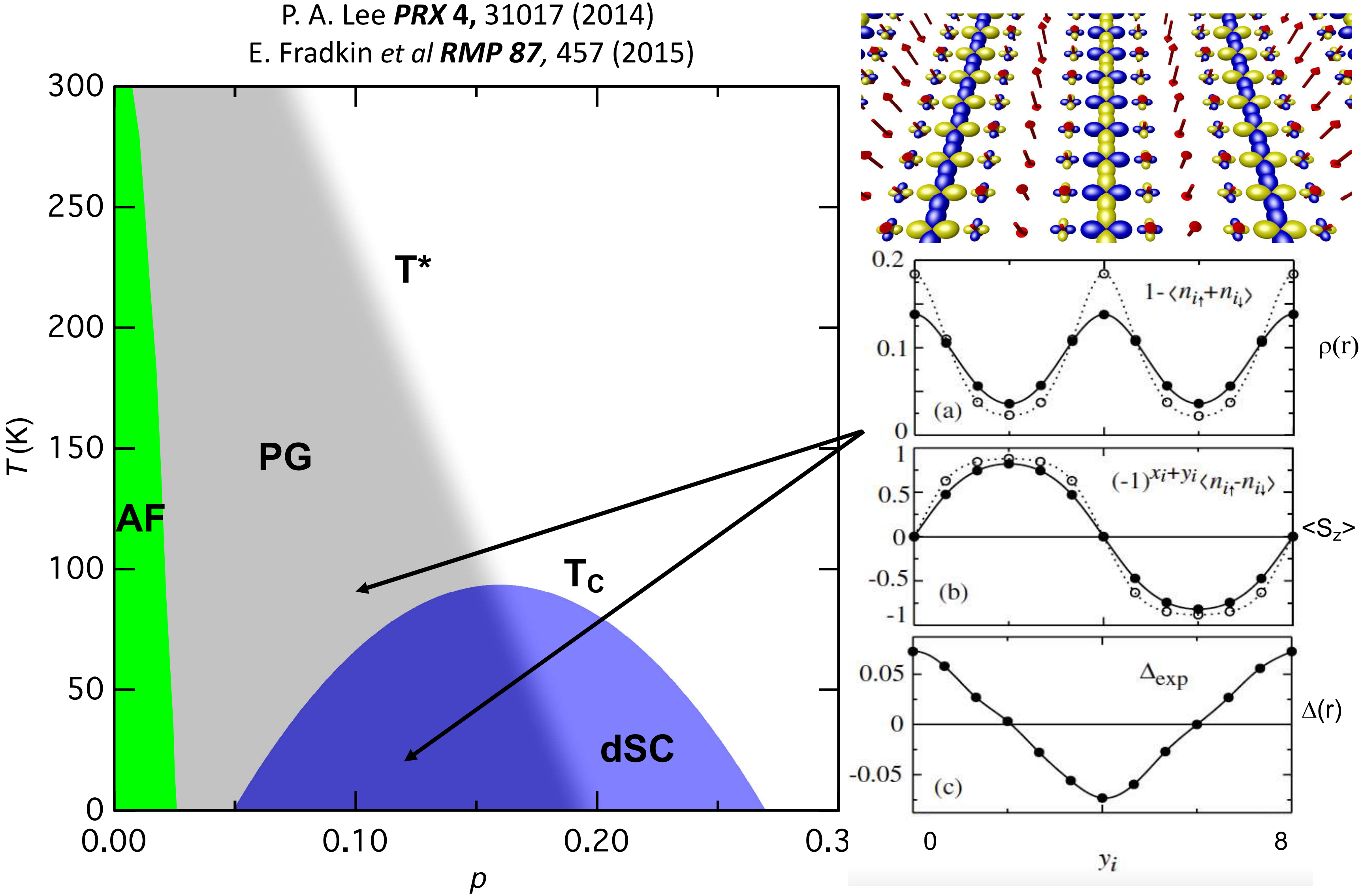
PSEUDOGAP ⟺ PAIR DENSITY WAVE



- Natural in strong coupling theory of hole-doped CuO_2
- PDW free energy density very close to that of DSC
- PDW exhibits a particle-hole symmetric antinodal gap
- PDW exhibits k-space 'Fermi Arc' of unbound electrons
- PDW yields small electron-like pocket with correct frequency of quantum oscillations
- PDW gives the correct spectral functions for underdoped CuO_2
- PDW generates charge density modulations primarily $2Q_P$.

DOES STRONG-COUPLING PDW STATE EXIST IN CUPRATES?

P. A. Lee ***PRX* 4,** 31017 (2014)
E. Fradkin *et al* ***RMP* *87*,** 457 (2015)

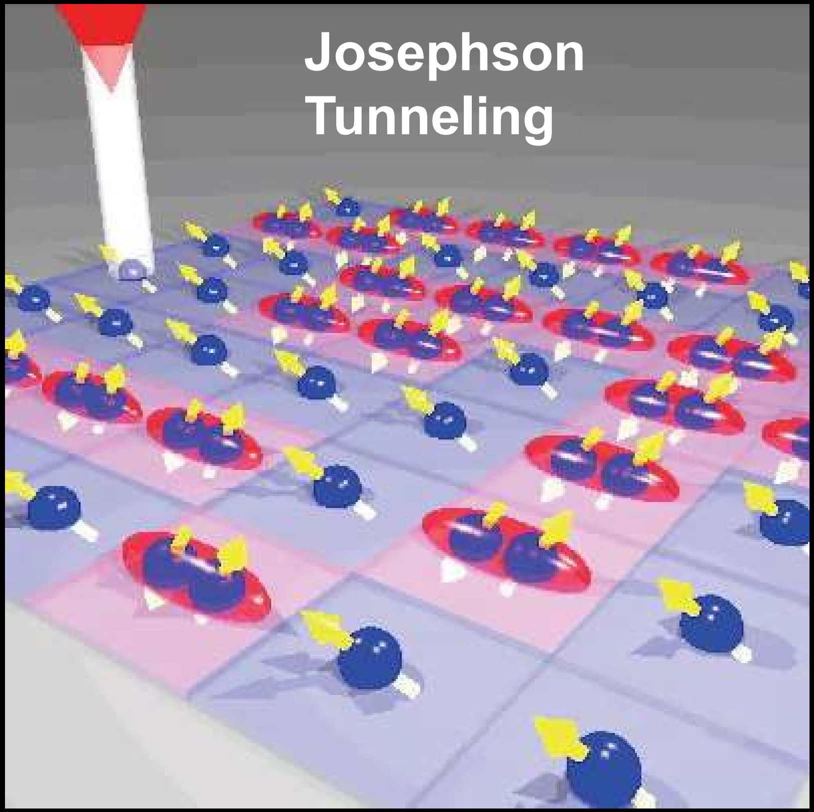


[redacted]

VISUALIZE COOPER-PAIR CONDENSATE: $\langle c_k^\dagger c_{-k+Q_P}^\dagger \rangle$

VISUALIZE COOPER-PAIRS ?

Superconducting Tip



Pan S., Hudson E., & Davis J.C.
***Appl. Phys. Lett*, 73**, 2992 (1998).

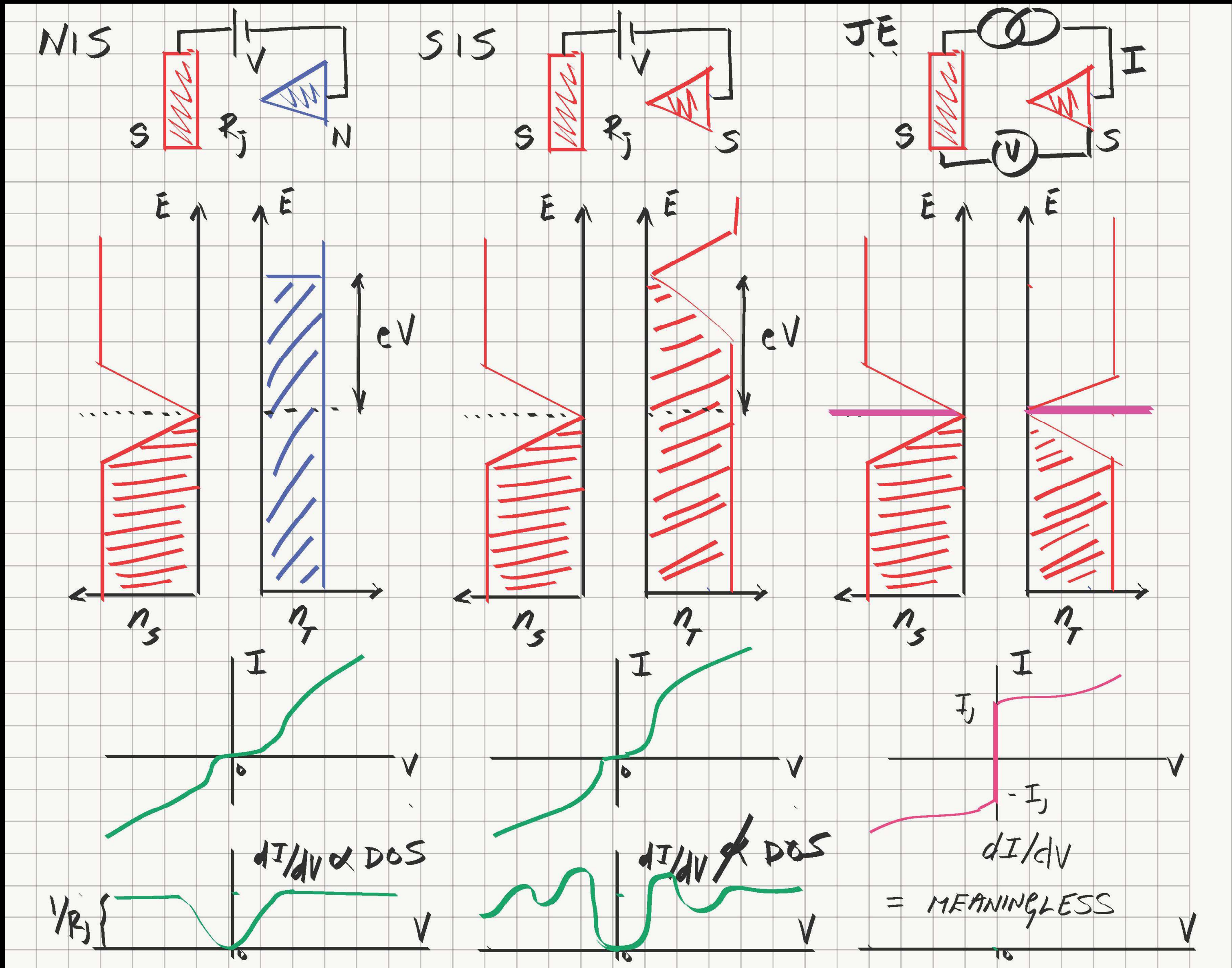
Naaman, O., Teizer, W. & Dynes, R. C.
Fluctuation dominated Josephson tunneling with STM. ***Phys. Rev. Lett.*** 87, 097004 (2001).

Rodrigo J. G., Suderow H. & Vieira, S.
On the use of STM superconducting tips at very low temperatures. ***Eur. Phys. J.*** *B* 40, 483-488 (2004).

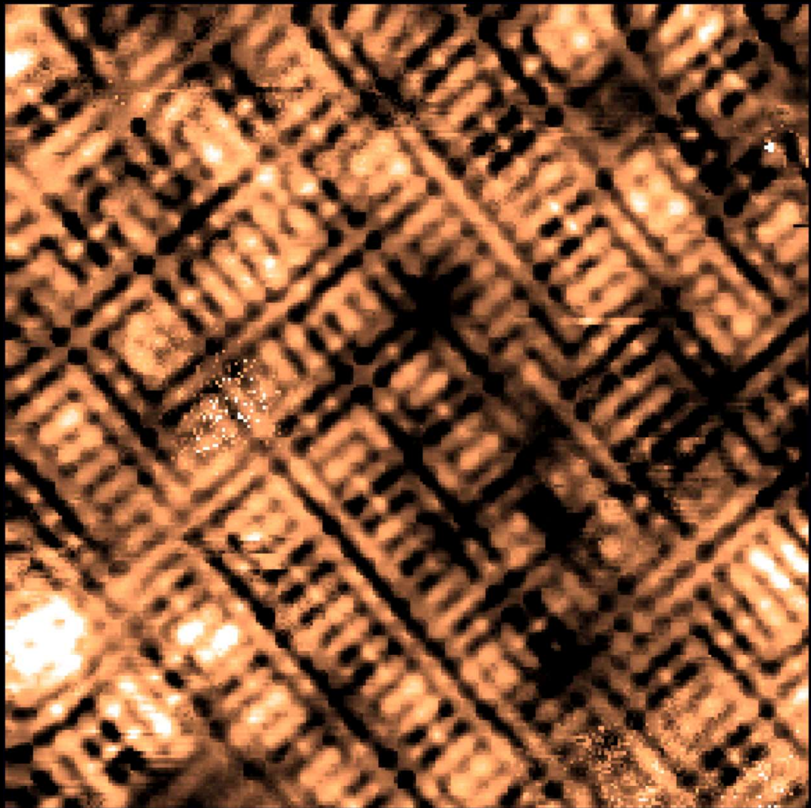
Proslier, Th. *et al.* Probing the superconducting condensate on nanometer scale. ***Europhys. Lett.*** 73, 962-968 (2006).

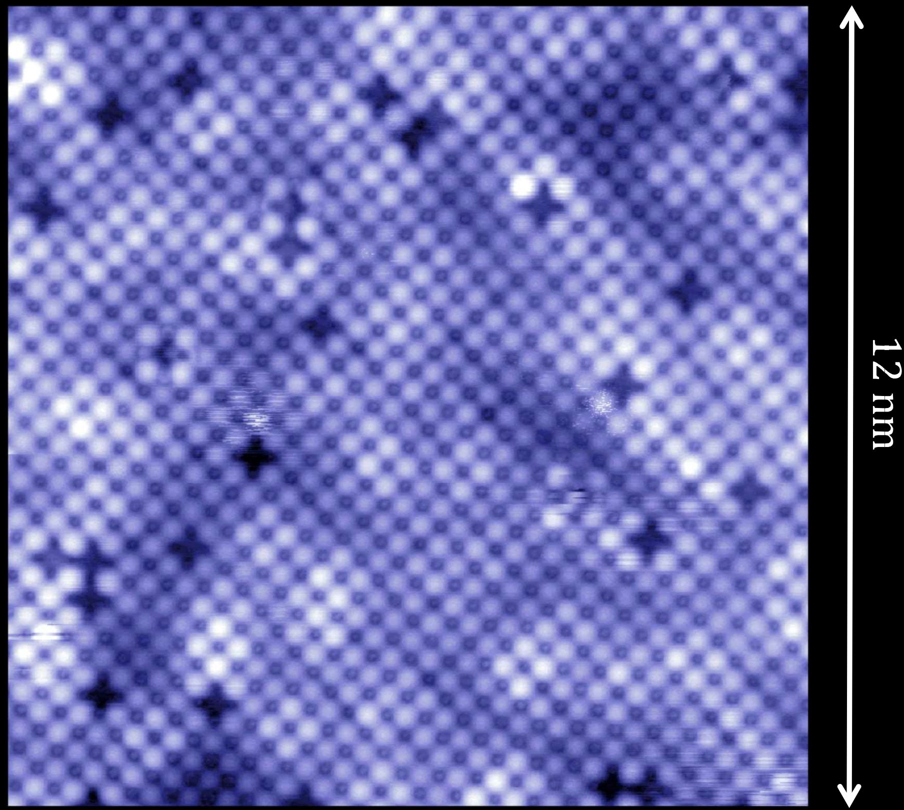
Randeria M.T. *et al* Scanning Josephson Spectroscopy on Atomic Scale. ***Phys. Rev. B*** 93, 161115 (2016)

NIS / SIS/ JE STM



VISUALIZE CUPRATE COOPER-PAIRS



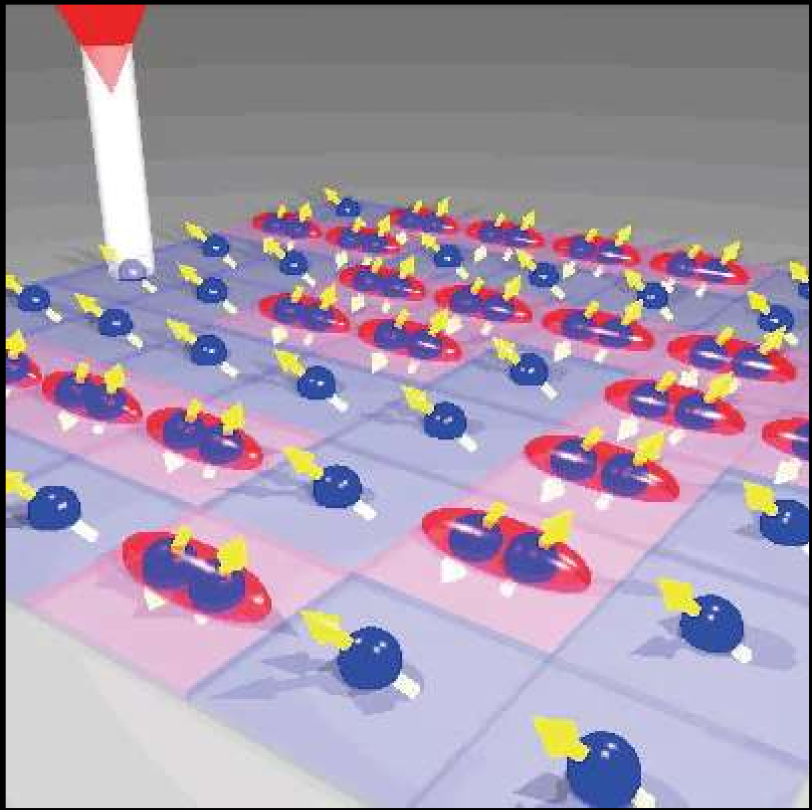


$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

Requires SJTM with Spatial Resolution ~1nm

VISUALIZE CUPRATE COOPER-PAIRS

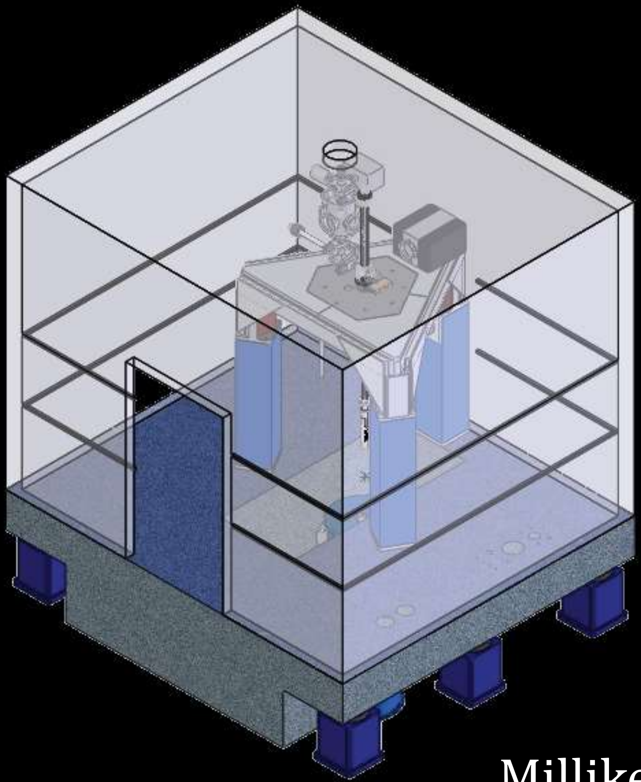
$I_J R = \Delta$	*Josephson (Cooper Pair) Current*
$E_J = \frac{\hbar}{2e} I_J$	*Josephson Energy*
$E_J > kT$	*Phase Stabilization Temperature*



Requires high gap Δ>10meV & Millikelvin Temperatures T<<1K

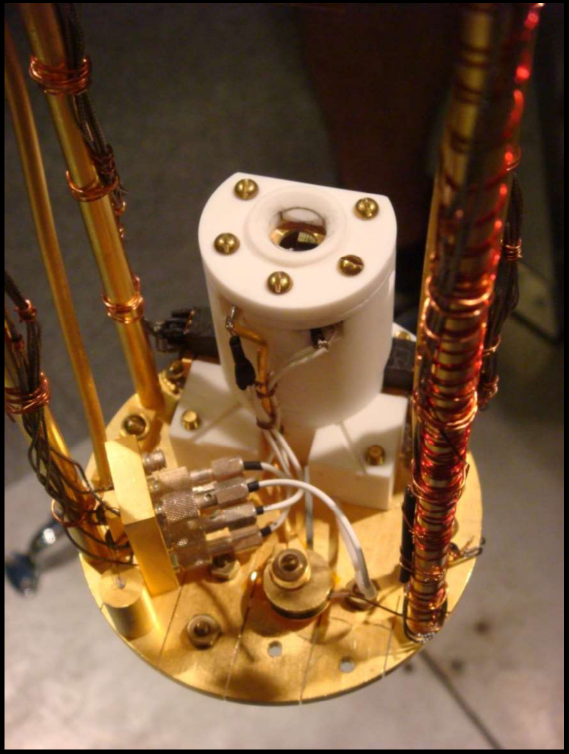
VISUALIZE CUPRATE COOPER-PAIRS

Ultra-low Vibration
RF Shielded Cryostat



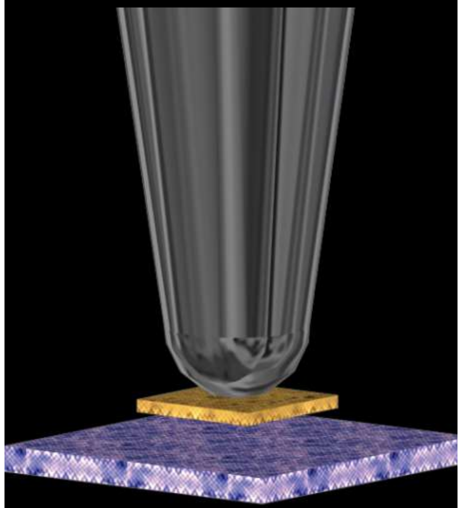
Custom Designed
Ultra-low-vibration
Dilution Refrigerator

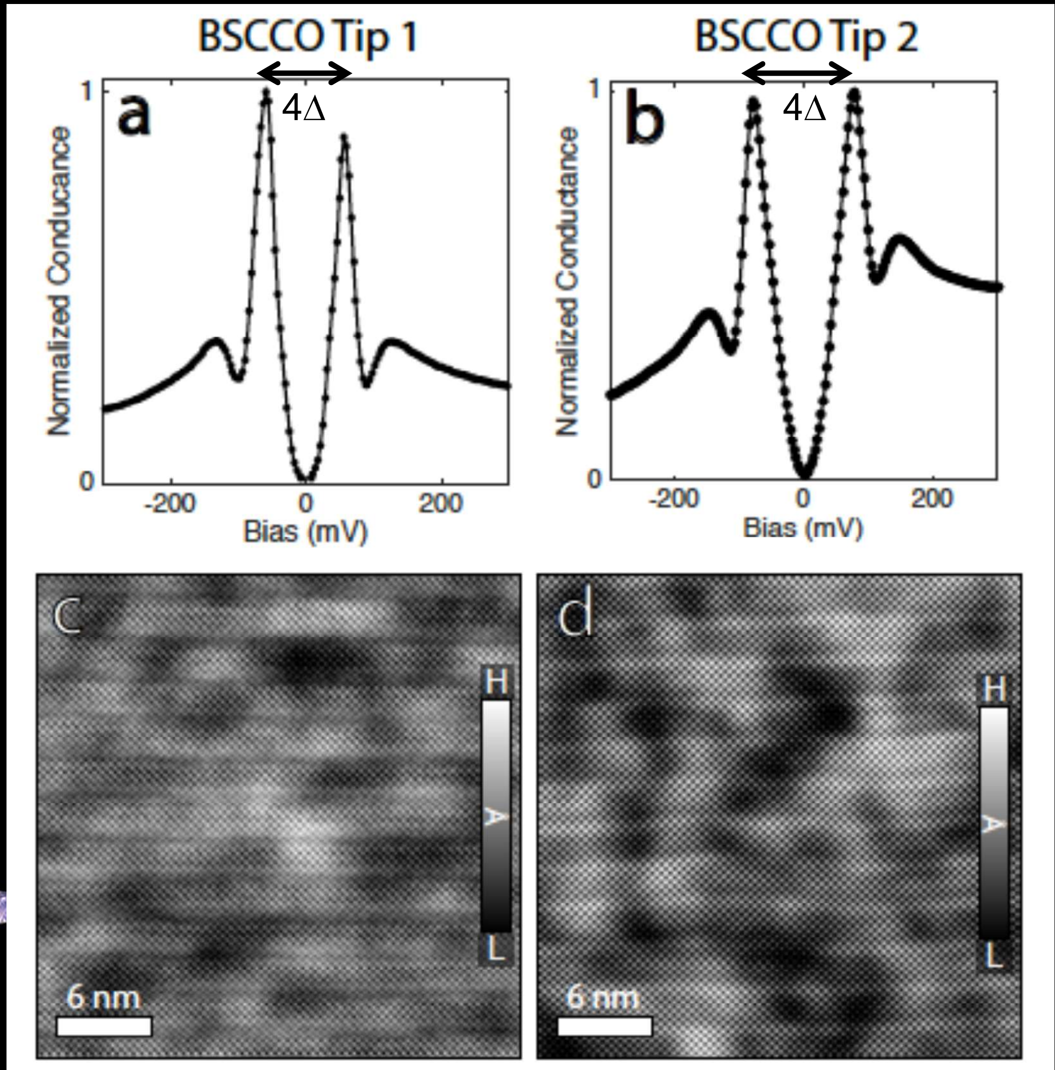
Custom Designed and Built
mK-STM head



Millikelvin Operating Temperature STM

HTS STM TIP: Δ~25 meV

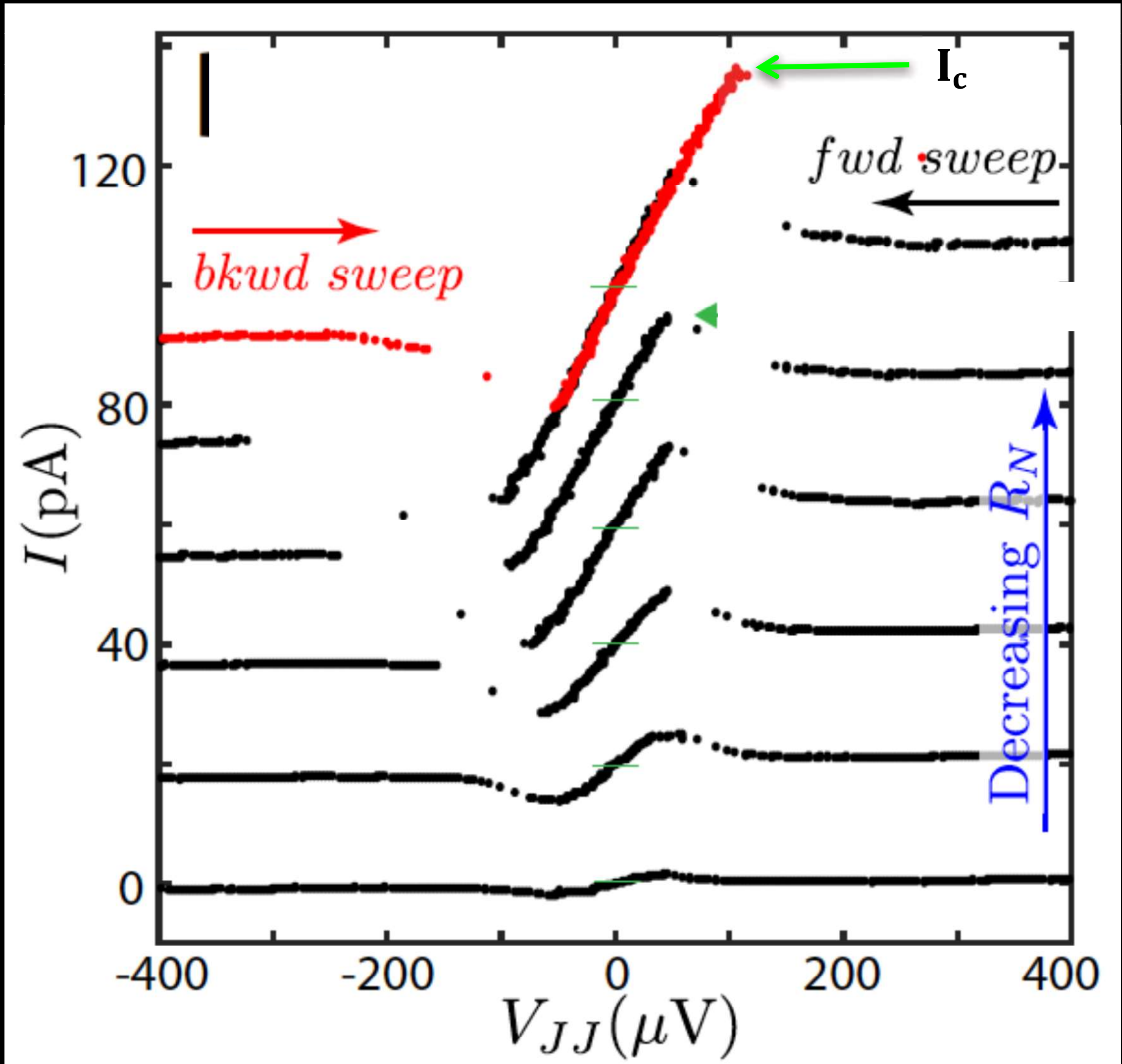




High-T_c SC tip with ~nm resolution

Nature* *532, 343 (2016)

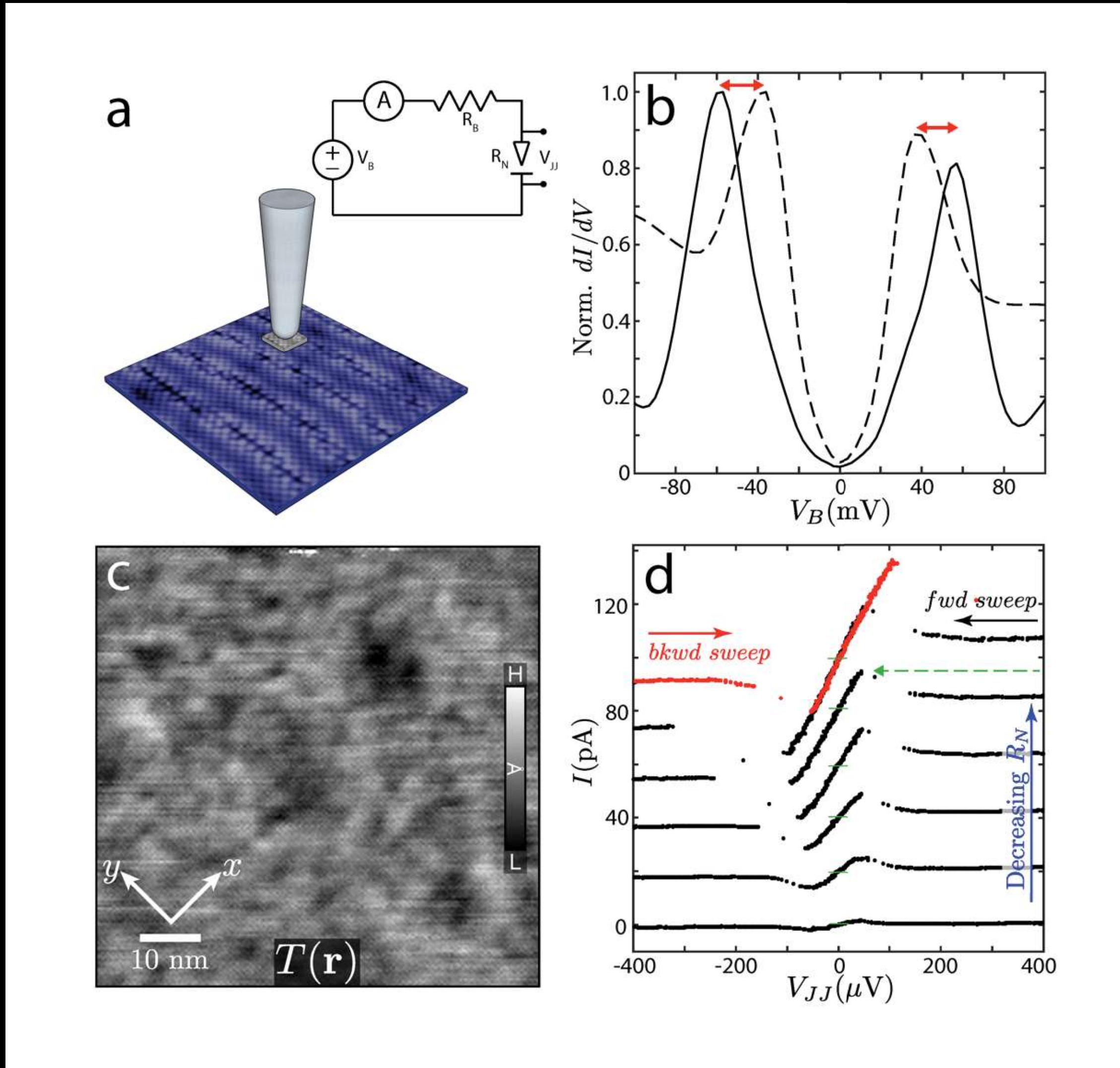
JOSEPHSON CURRENT / HTS STM TIP



d-wave BSCCO tip
T = 50mK

Nature 532, 343 (2016)

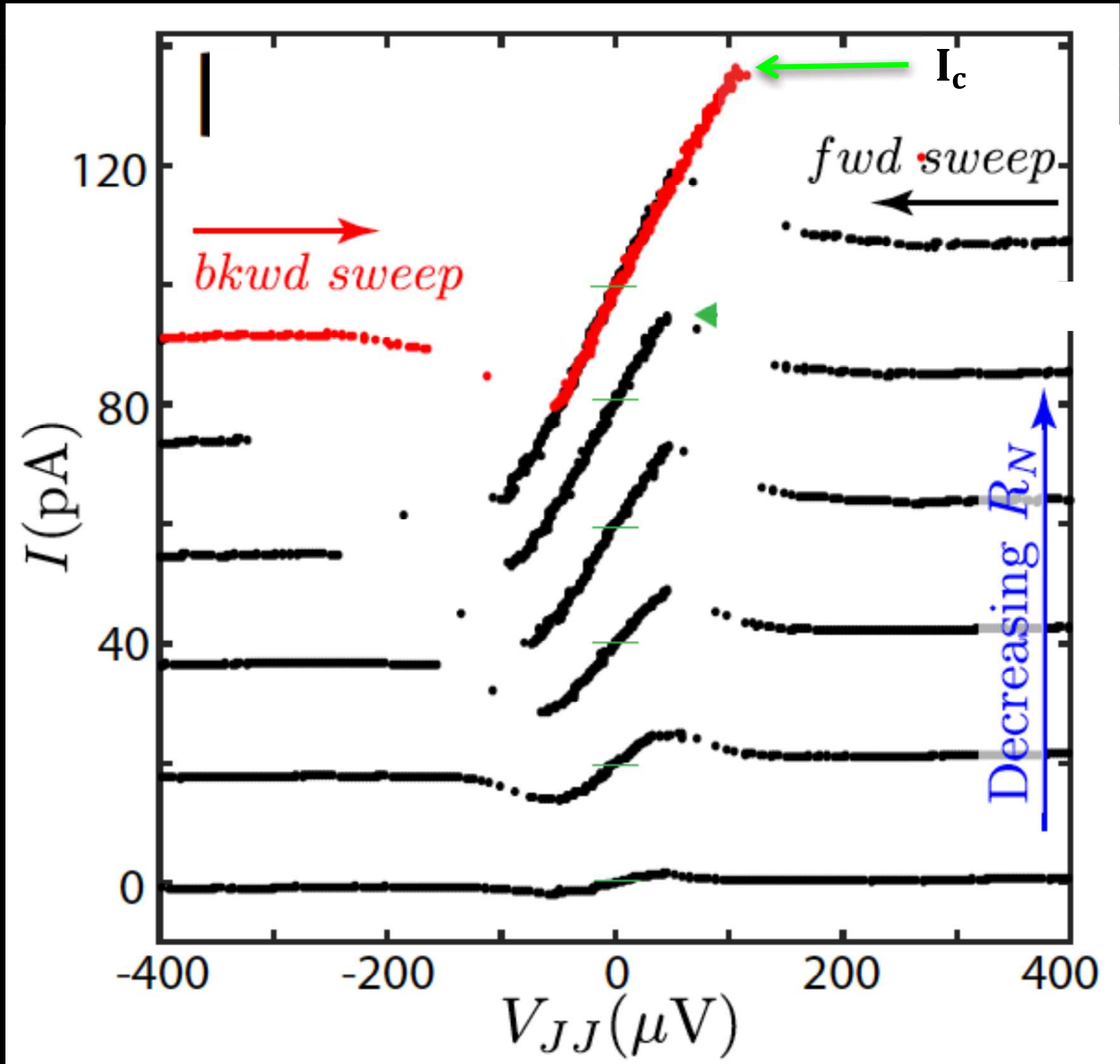
50mK / Δ_{TIP}~25 meV / nm RESOLUTION / R_N=10 MΩ / 256X256



Nature 532, 343 (2016)

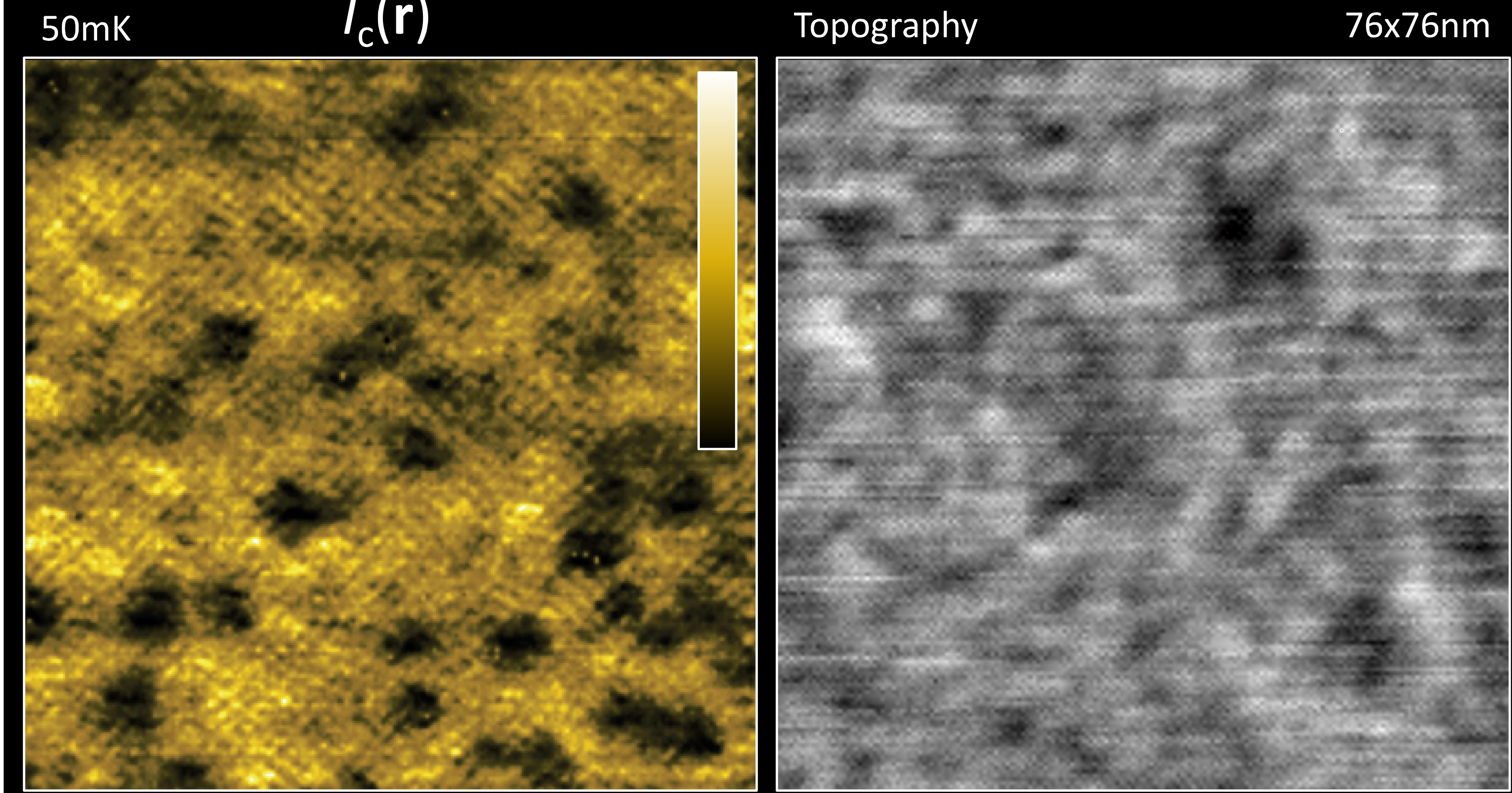
SJTM IMAGING of $I_C(\mathbf{r})$ on $Bi_2Sr_2CaCu_2O_{x+8}$

$I_C(r)\ \alpha\ I_J^2(r)$



Nature 532, 343 (2016)

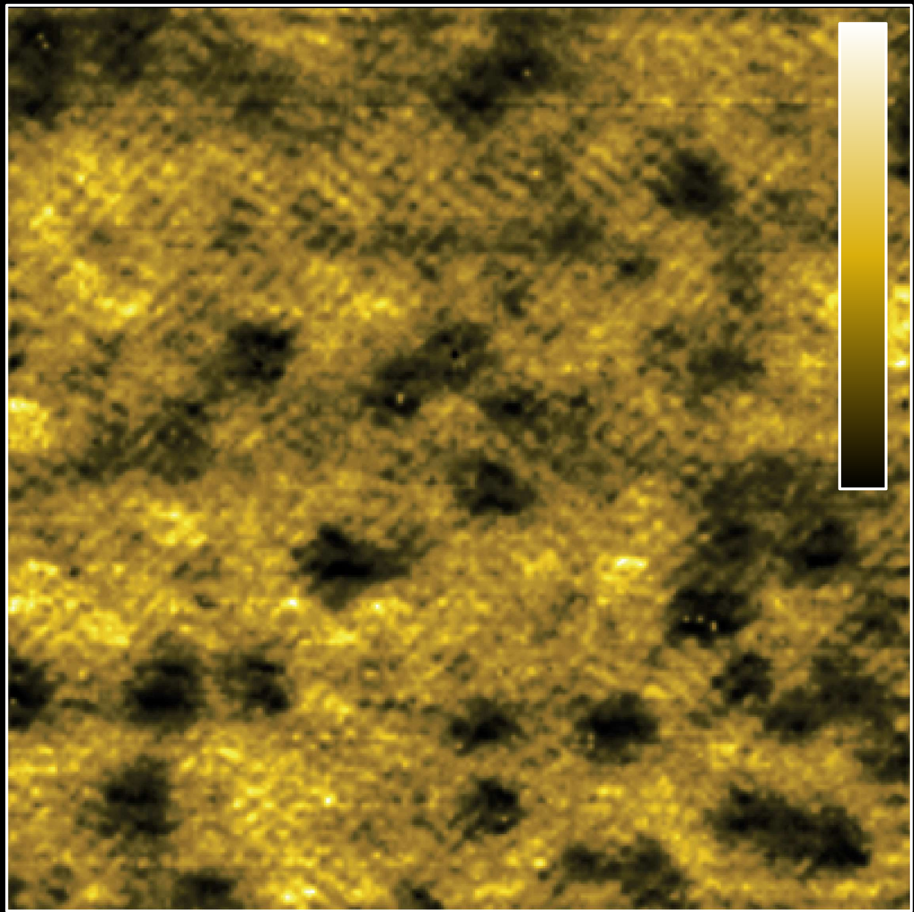
SJTM IMAGING of $I_C(\mathbf{r})$ on $Bi_2Sr_2CaCu_2O_{x+8}$



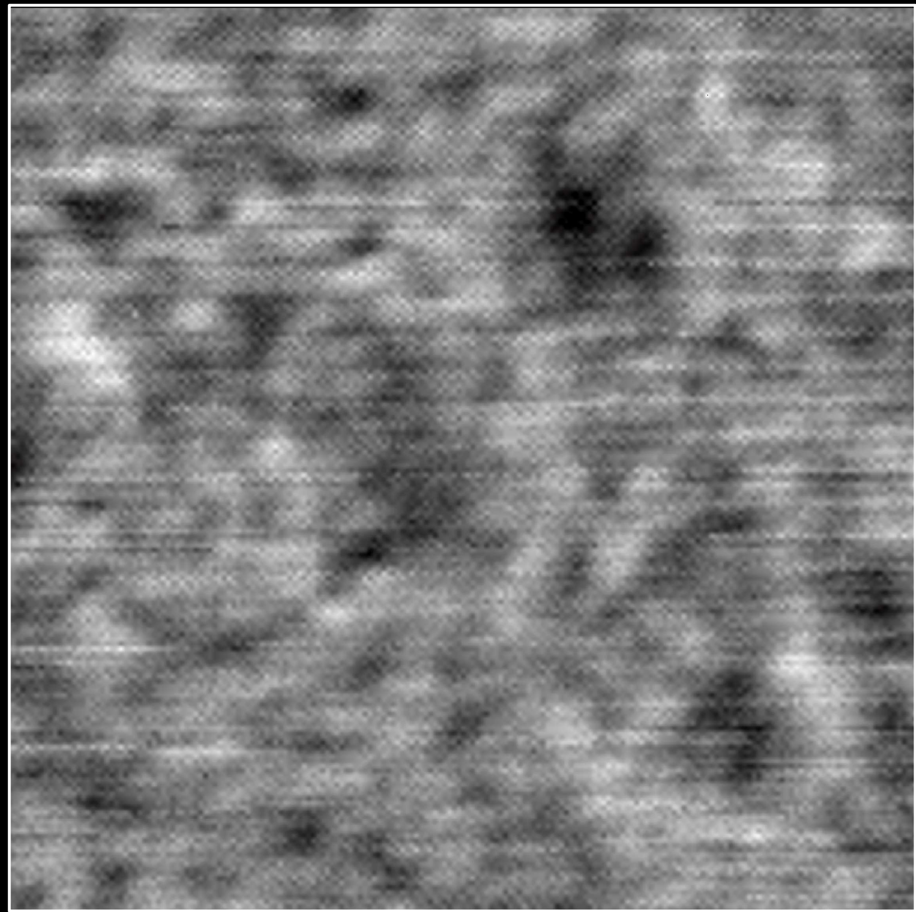
***Nature* 532**, 343 (2016)

VALIDATE COOPER-PAIR CONDENSATE IMAGING ?

50mK $I_c(\mathbf{r})$



Topography 76x76nm



Nature 532, 343 (2016)

VALIDATE COOPER-PAIR CONDENSATE IMAGING ?

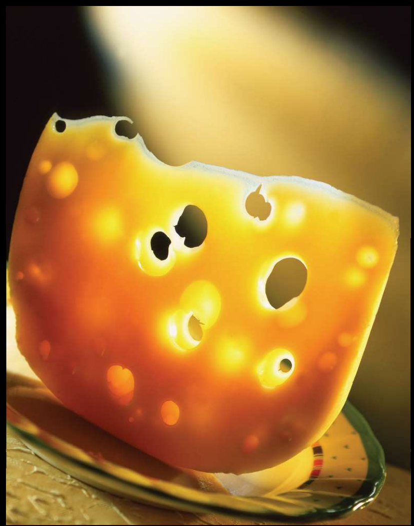
VOLUME 77, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 1996

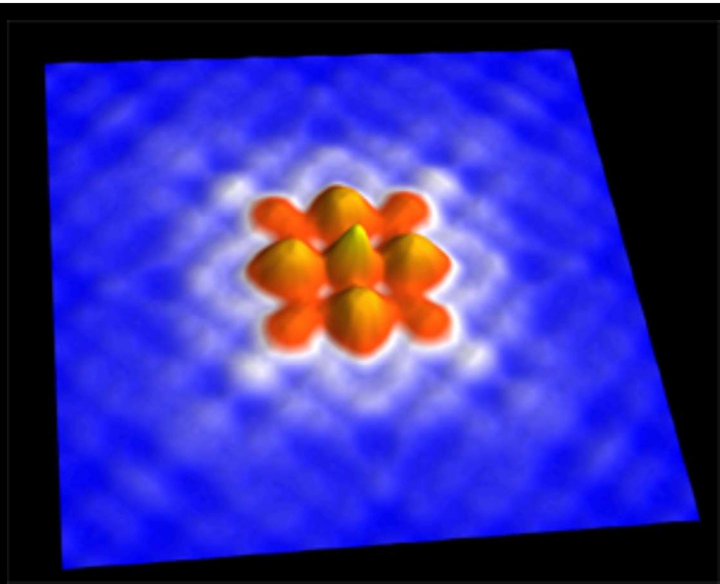
Muon Spin Relaxation Studies of Zn-Substitution Effects in High-T_c Cuprate Superconductors

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)

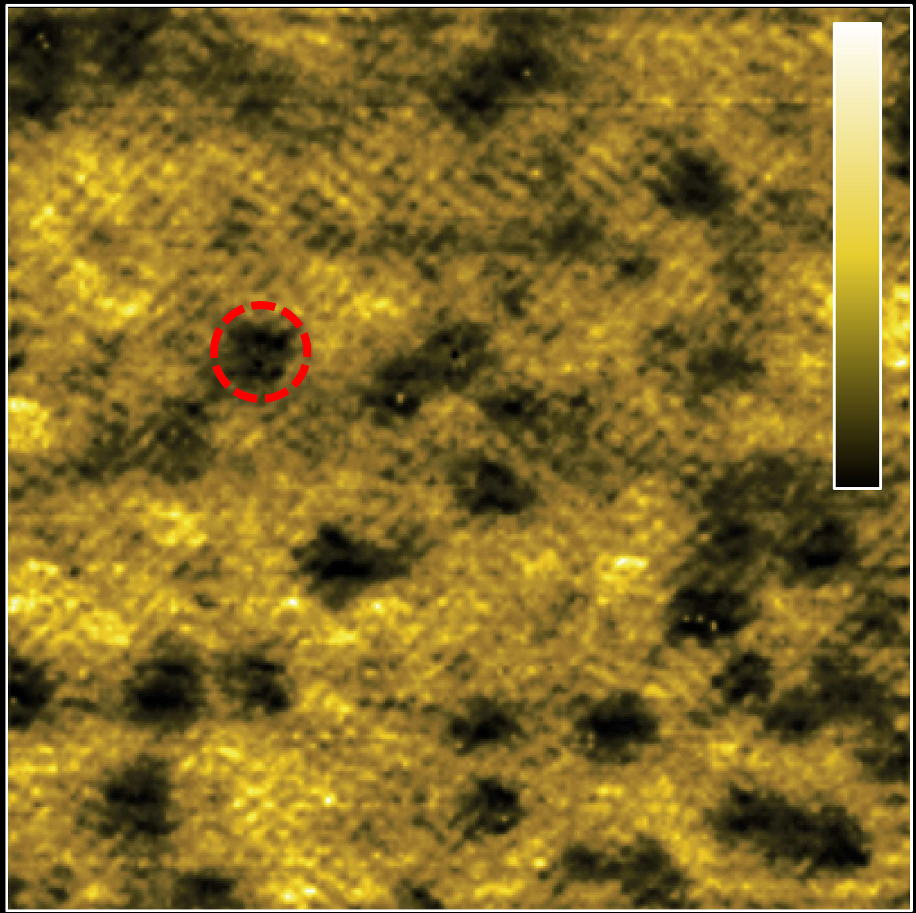
We have performed transverse-field muon spin relaxation measurements of the Zn-substituted cuprate high-T_c superconductors: $La_{2-x}Sr_x(Cu_{1-y}Zn_y)O_4$ and $YBa_2(Cu_{1-y}Zn_y)_3O_{6.63}$. The superconducting carrier density/effective mass n_s/m^* ratio at $T \rightarrow 0$ decreases with increasing 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]



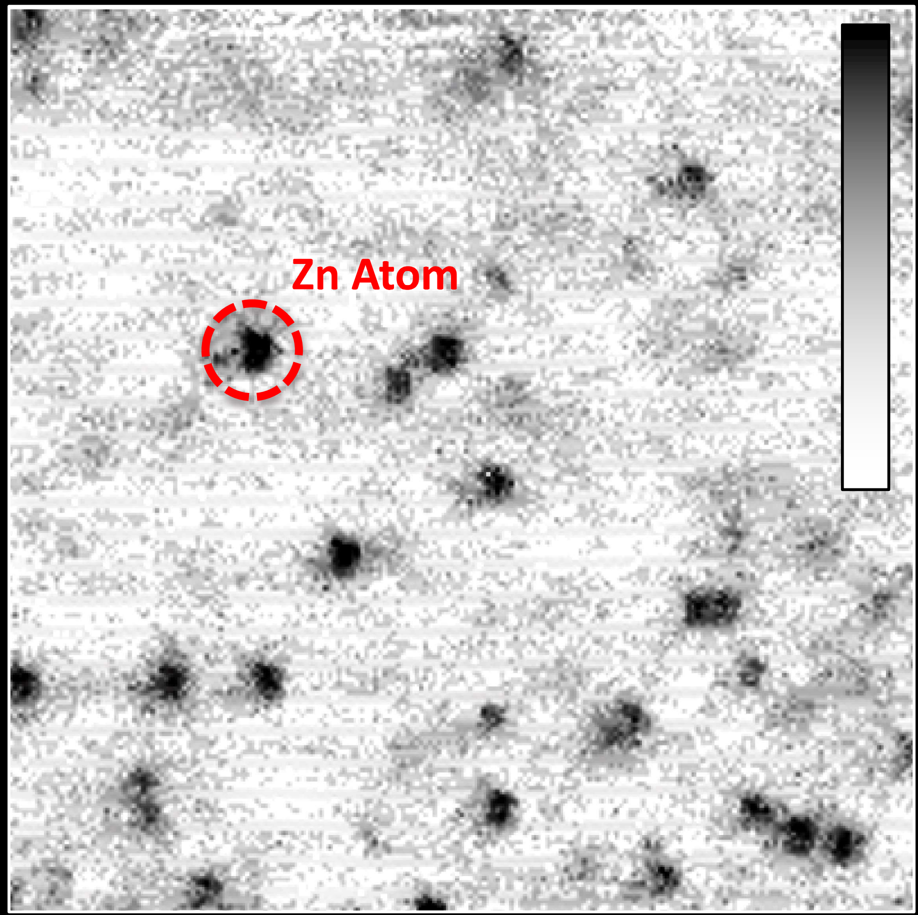


VALIDATE COOPER-PAIR CONDENSATE IMAGING

50mK $I_c(\mathbf{r})$



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

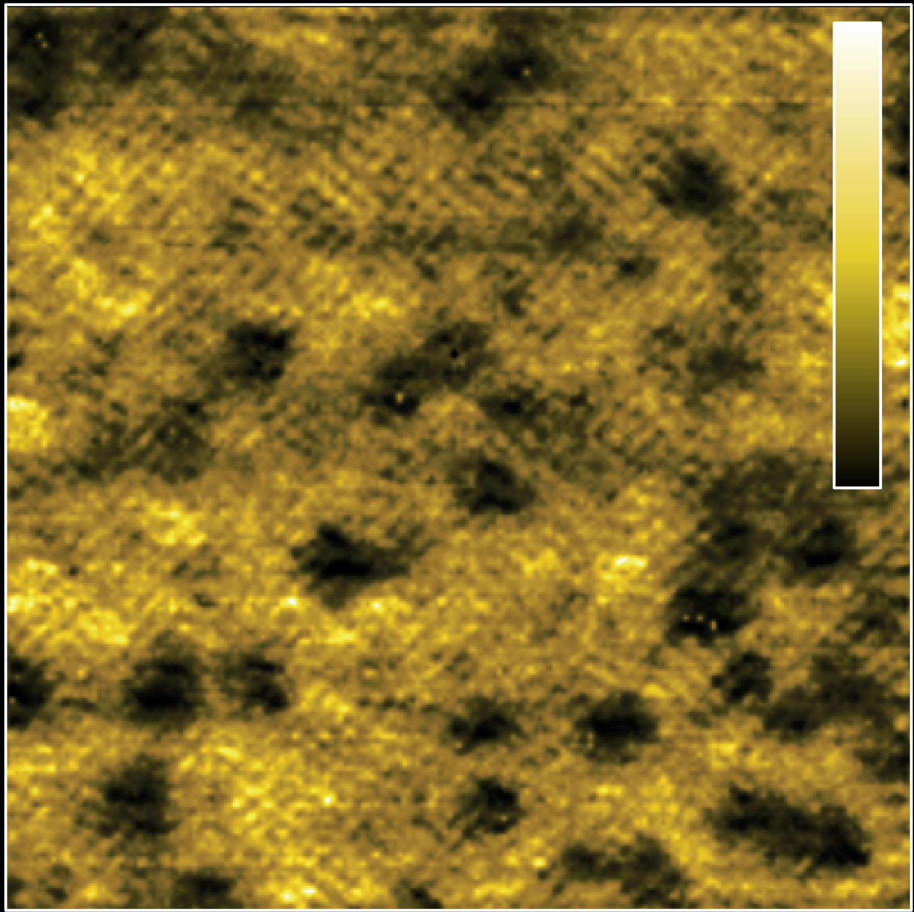


Nature 532, 343 (2016)

SJTM IMAGING COOPER-PAIR CONDENSATE

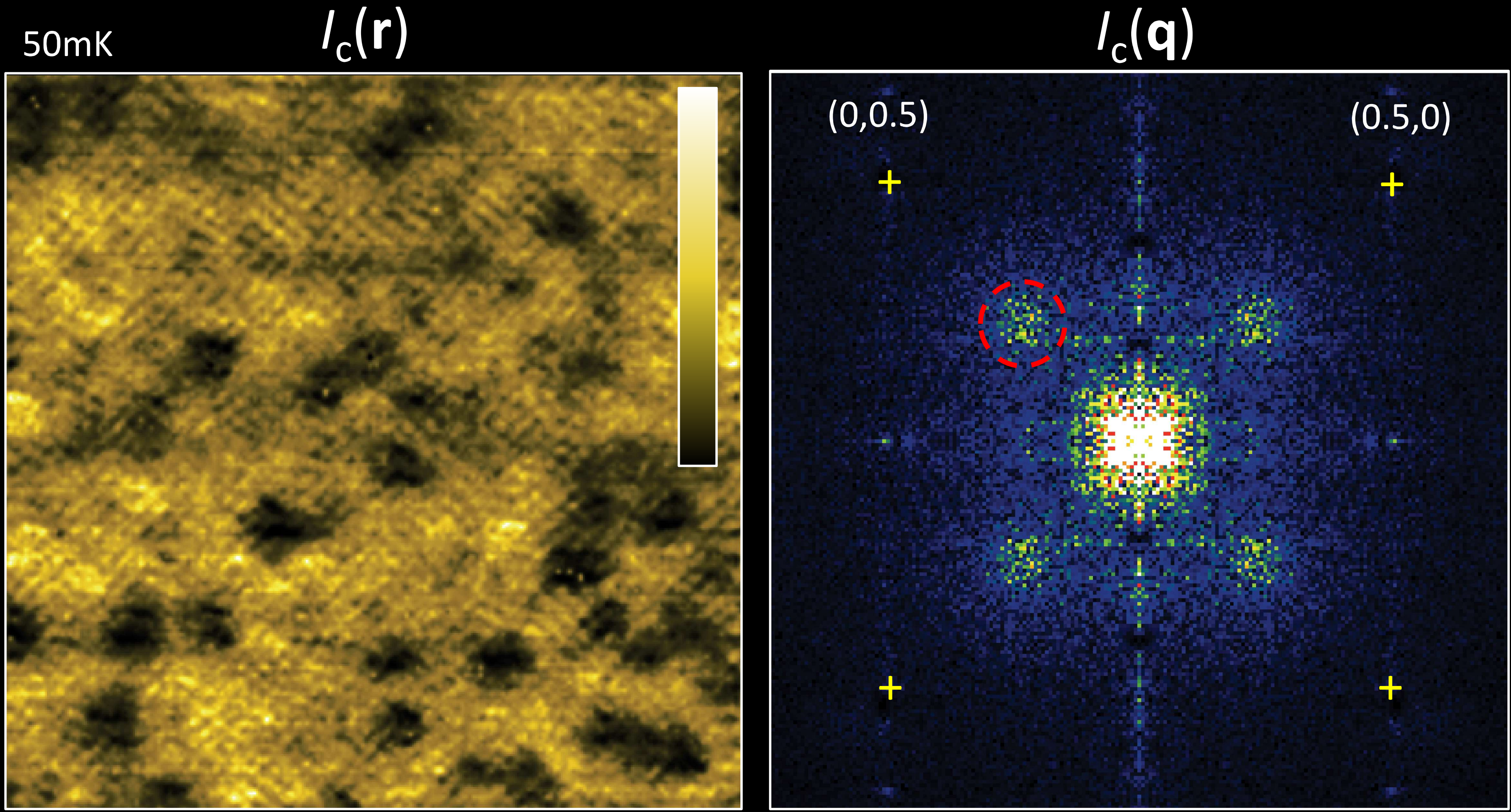
50mK

$I_c(\mathbf{r})$



Nature 532, 343 (2016)

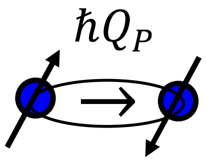
CUPRATE COOPER-PAIR DENSITY MODULATIONS



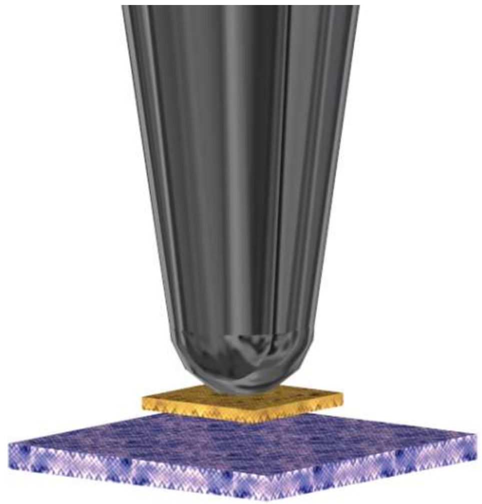
$Q = (0,0.25)2\pi/a_o\ ;\ (0.25,0)2\pi/a_o$

Nature 532, 343 (2016)

CUPRATE COOPER-PAIR DENSITY MODULATIONS



$$\left\langle c^{\dagger}_{k\uparrow}, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$



$$\boldsymbol{\Delta}(\boldsymbol{r}) = \boldsymbol{\Delta_P}\left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$