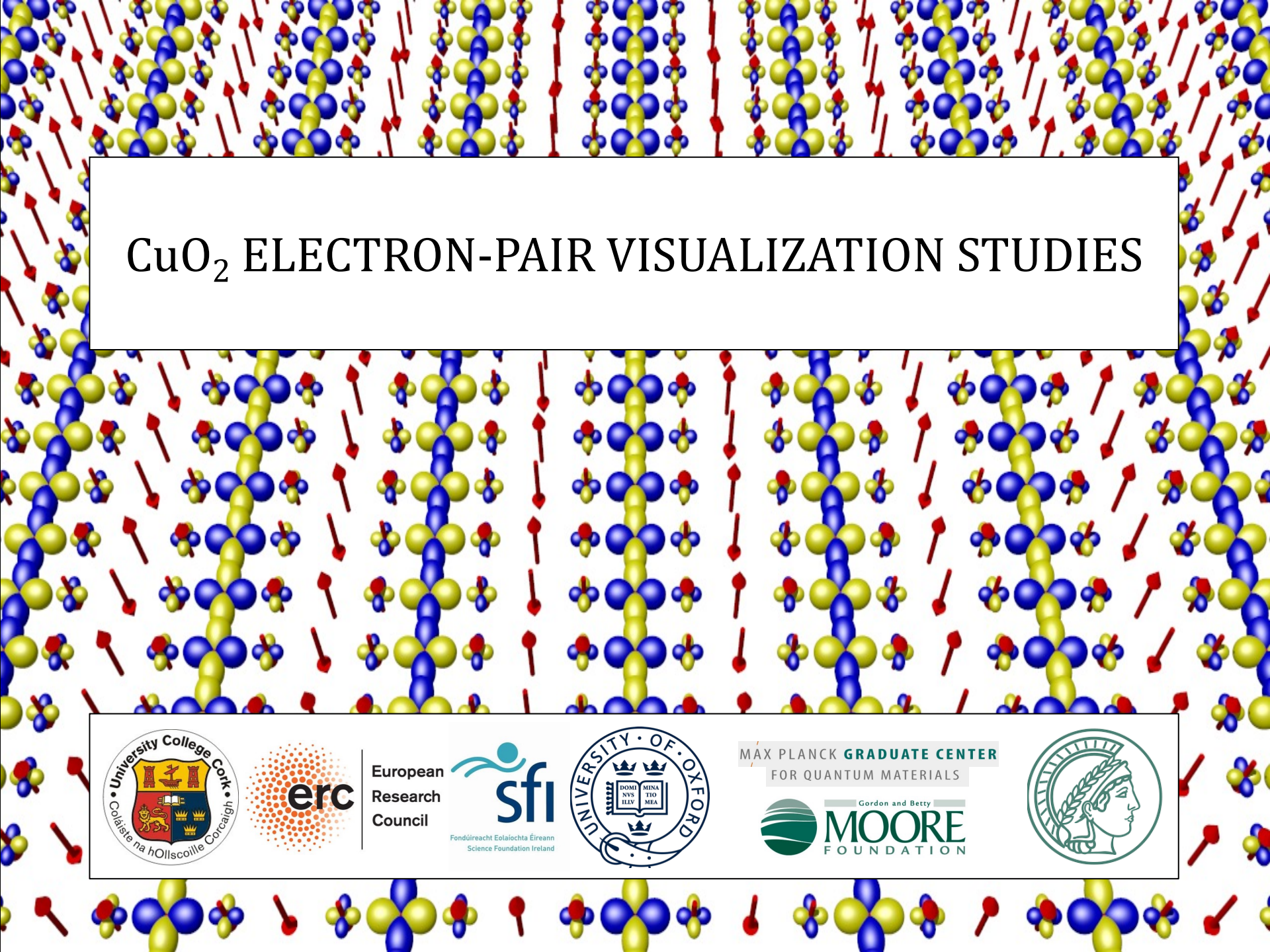
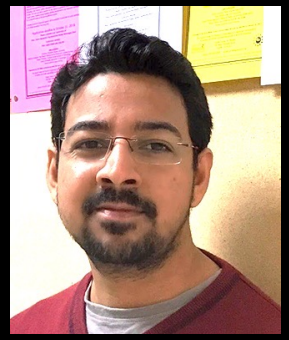
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES



Xiaolong Liu
Notre Dame

Shuqiu Wang
Oxford



P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford

Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

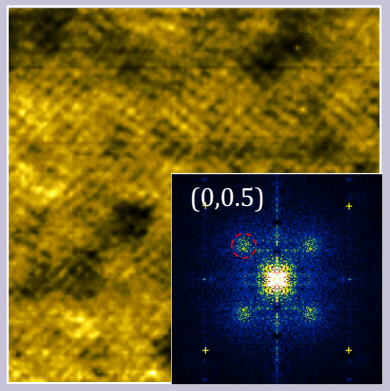
M. H. Hamidian
Cornell

S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

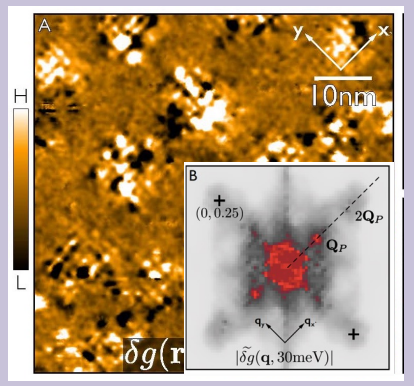
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



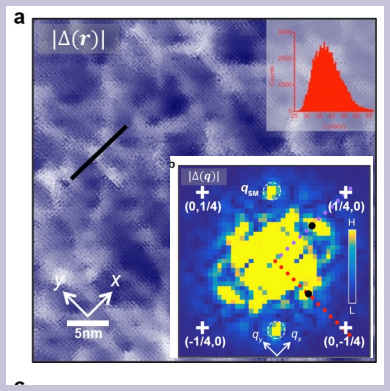
Nature 532, 343 (2016)

VORTEX HALO



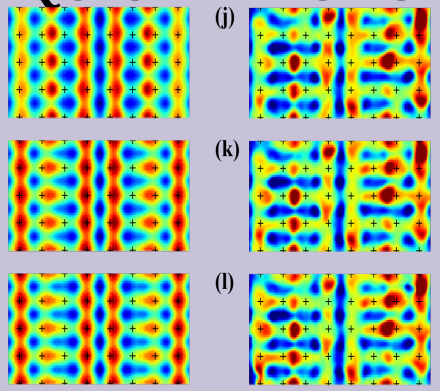
Science 364, 976 (2019)

ENERGY GAP



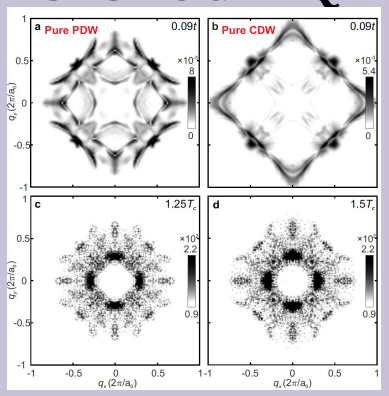
Nature 580, 6570 (2020)

QUASIPARTICLES



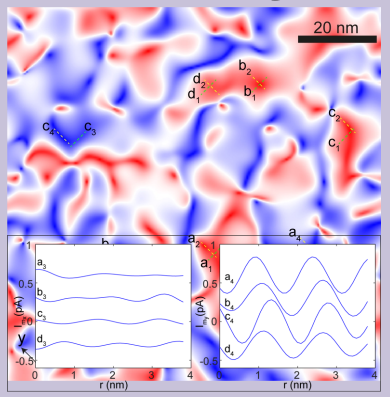
PNAS 117, 14850 (2020)

PSEUDOGAP QPI



Nat.Comm 12, 6087 (2021)

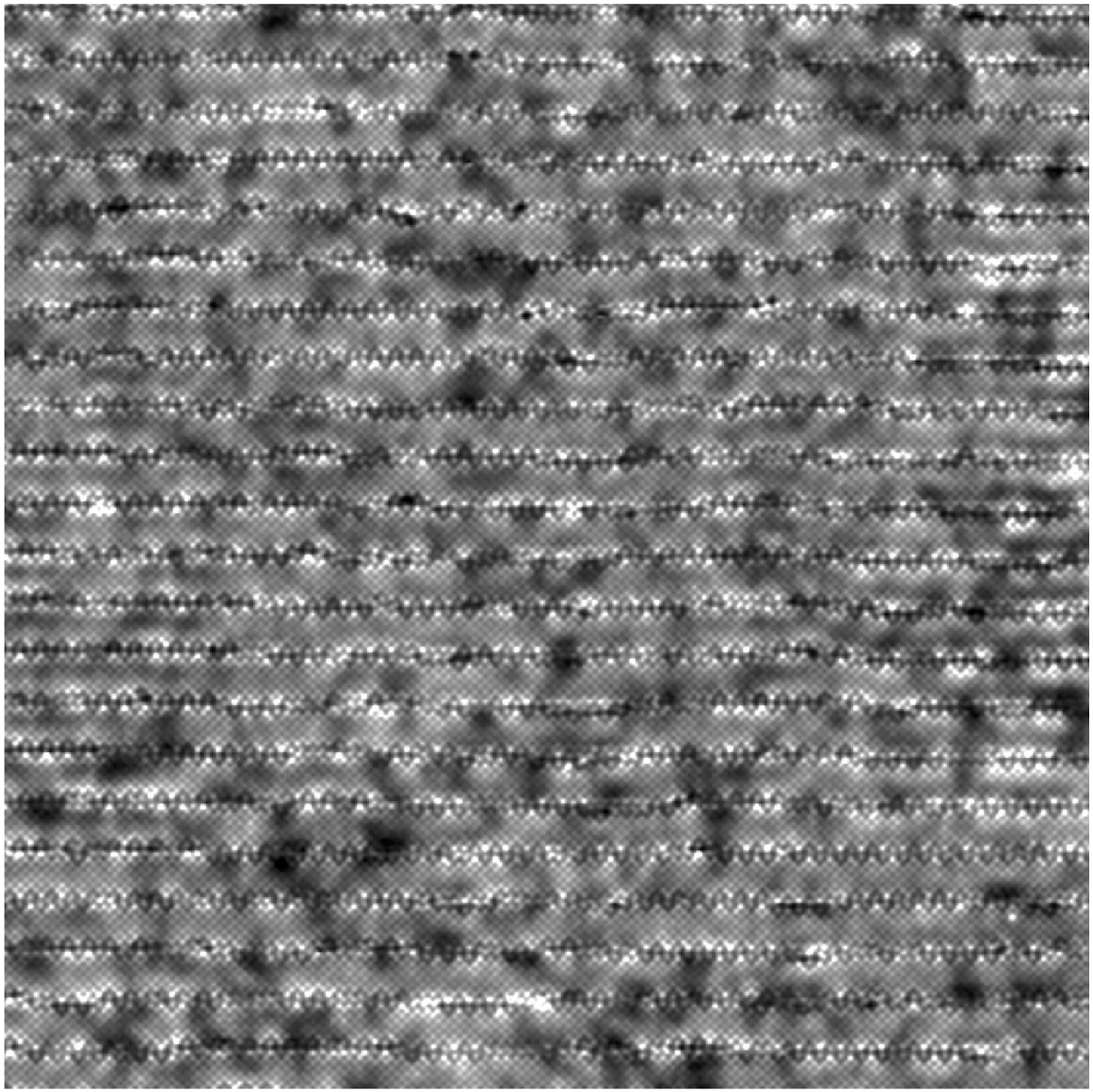
NEMATIC



Weijiong Chen *et al* (2022)

TOPOGRAPHIC IMAGING STM

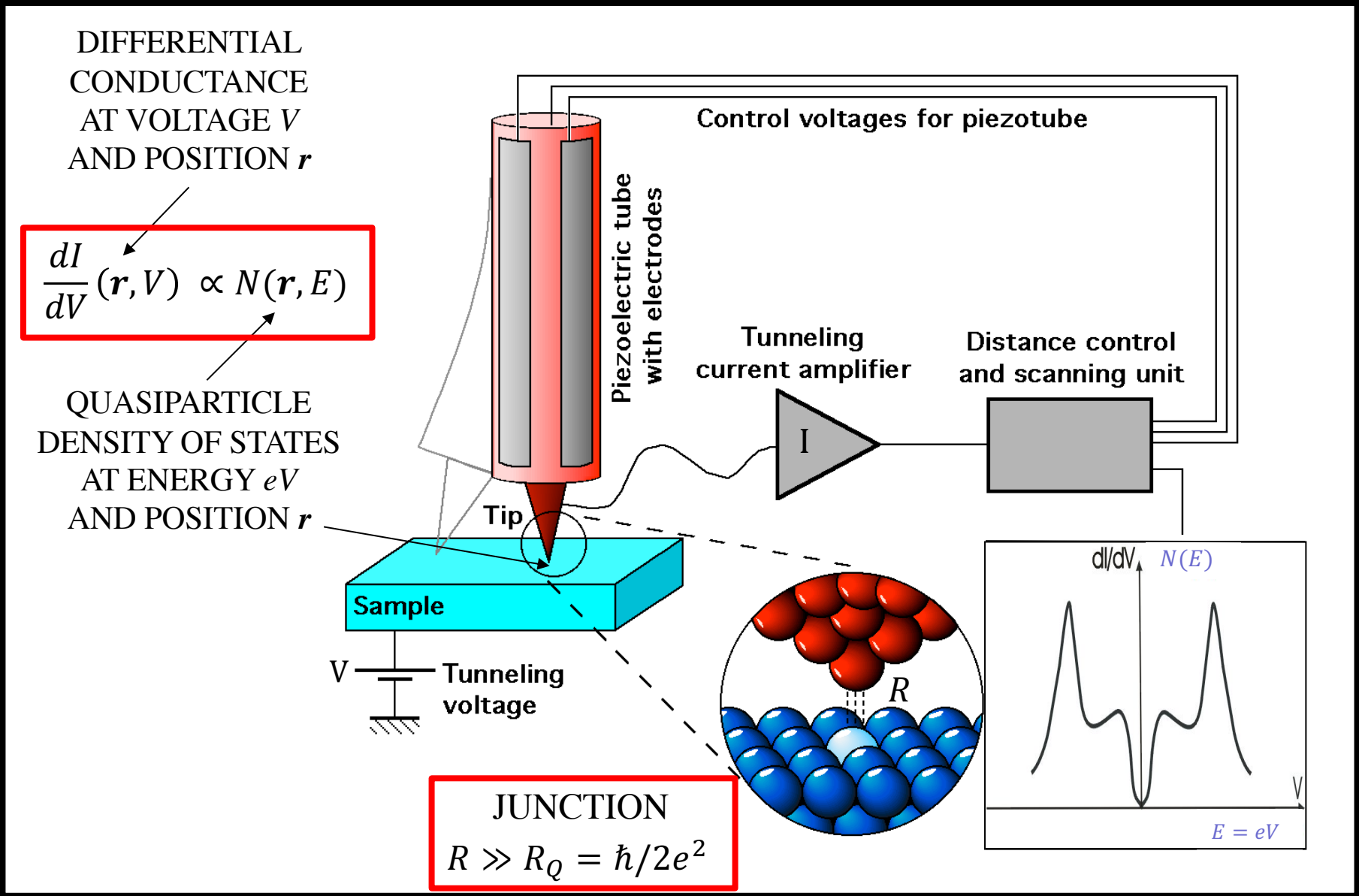
$ln \int_0^{V_0} N(r, \epsilon) d\epsilon$



575 Å

$T(r, V_0)$

SPECTROSCOPIC IMAGING STM

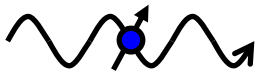


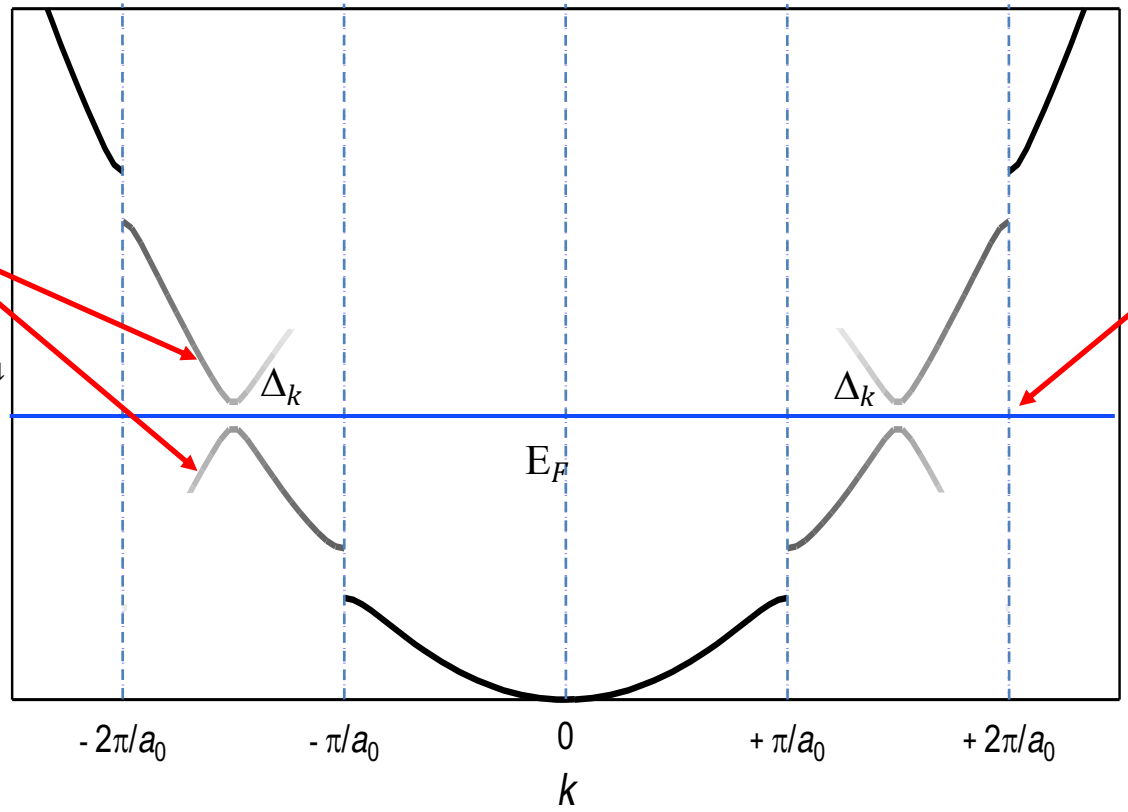
TUNNELING TO SUPERCONDUCTORS

$$\Delta_k = \left\langle c^{\dagger}_{k\uparrow}\, c^{\dagger}_{-k\downarrow} \right\rangle \qquad \Psi = \prod_k \left(u_k + v_k c^{\dagger}_{k\uparrow} c^{\dagger}_{-k\downarrow}\right)|0>$$

QUASIPARTICLES

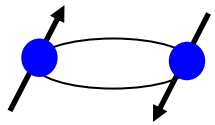
$$\gamma^{\dagger}_{-k\downarrow} = u_k\, c^{\dagger}_{-k\downarrow} - v_k\, h^{\dagger}_{-k\downarrow}$$





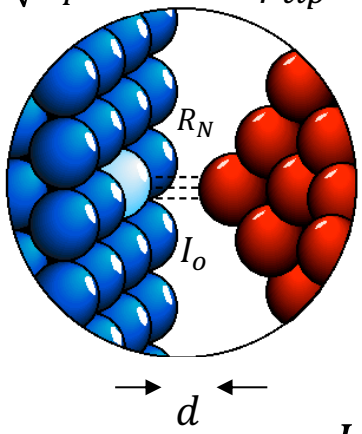
ELECTRON-PAIR FLUID

$$\prod_k \left(u_k + v_k c^{\dagger}_{k\uparrow} c^{\dagger}_{-k\downarrow}\right)|0>$$



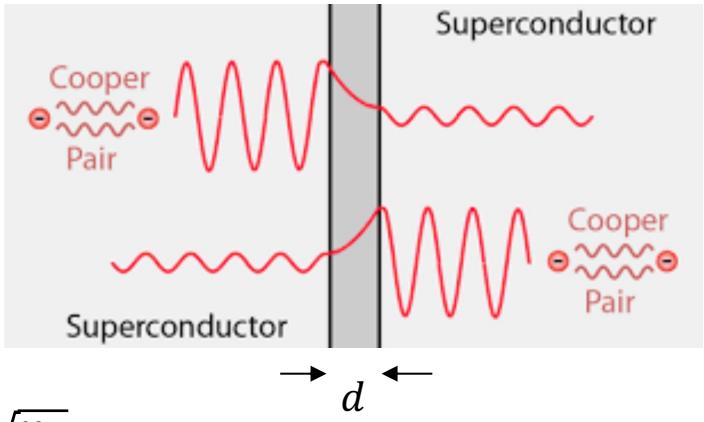
JOSEPHSON EFFECT : SUPERCONDUCTIVE STM TIP

$\psi_{sample} = \sqrt{n_P} e^{i\theta_s}$ $\psi_{tip} = \sqrt{n_t} e^{i\theta_t}$



$$J = J_0 Sin(\theta_t - \theta_s)$$

$\psi_{sample} = \sqrt{n_P} e^{i\theta_s}$ $\psi_{tip} = \sqrt{n_t} e^{i\theta_t}$



$$J_0 = \frac{e\hbar}{m}\left\{\frac{2}{\lambda} e^{-2d/\lambda}\right\}\sqrt{n_P}\,\sqrt{n_t}$$

ELECTRON-PAIR CURRENT

$$I_0 R_N \propto \sqrt{n_P}\,\sqrt{n_t} \implies I_0^2(r) R_N^2(r) \propto n_P(r)$$

VISUALIZE ELECTRON-PAIR DENSITY

AMBEGAOKAR-BARATOFF

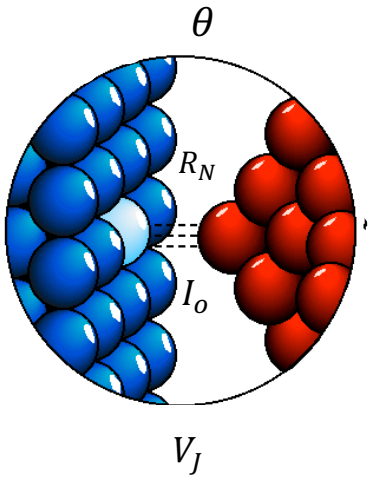
$$I_0 R_N \approx \frac{\pi\Delta}{2e} \approx 1.5\ mV \qquad (T \to 0; \sqrt{n_P} = \sqrt{n_t})$$

STM TUNNEL JUNCTION

$$I_0 \approx 1.5\ pA \quad @\ R_N = 1\ G\Omega \implies E_J = \frac{\hbar I_0}{2e} \approx 5\ neV \to 30\ \mu K$$

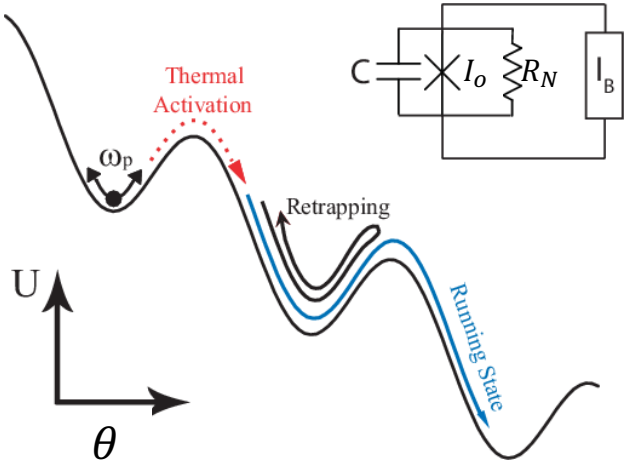
IMPOSSIBLE ?

SCANNED JOSEPHSON TUNNELING MICROSCOPY (SJTM)



$$\frac{\hbar C}{2e}\ddot{\theta} + \frac{\hbar}{2eR_N}\dot{\theta} + I_o Sin\theta = I_B$$

$$I = I_o \int_{-\infty}^{\infty} d\theta \, Sin\theta \, \mathrm{W}(\theta_t, \theta_o)$$



Ivanchenko & Zilberman, ***JETP 28***, 1272 (1969)

$kT >> E_J$ *and* $C \to 0$

$$U(\theta) = E_J(1 - Cos\theta - I_B\theta/I_o)$$

ELECTRON-PAIR CURRENT

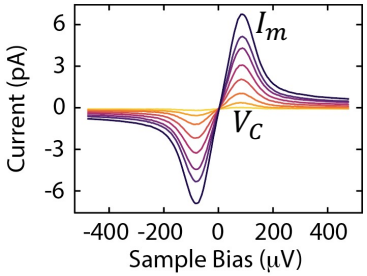
$$I(V_J) = \frac{1}{2} I_0^2 Z \frac{V_J}{V_J^2 + V_C^2}$$

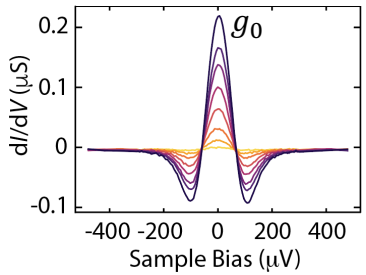
ELECTRON-PAIR CURRENT MAX.

$$I_m = \frac{\hbar}{8ek_B T^*} I_0^2$$

ELECTRON-PAIR V=0 CONDUCTANCE

$$g_0 \equiv \left.\frac{dI}{dV_J}\right|_{V=0} = \frac{\hbar I_m}{ek_B T^* Z}$$





VISUALIZE ELECTRON-PAIR DENSITY

$$n_P(r) \propto I_m(r) {R_N}^2(r)$$

$$n_P(r) \propto g_0(r) {R_N}^2(r)$$

SJTM EXAMPLE : SC+CDW @ $NbSe_2$

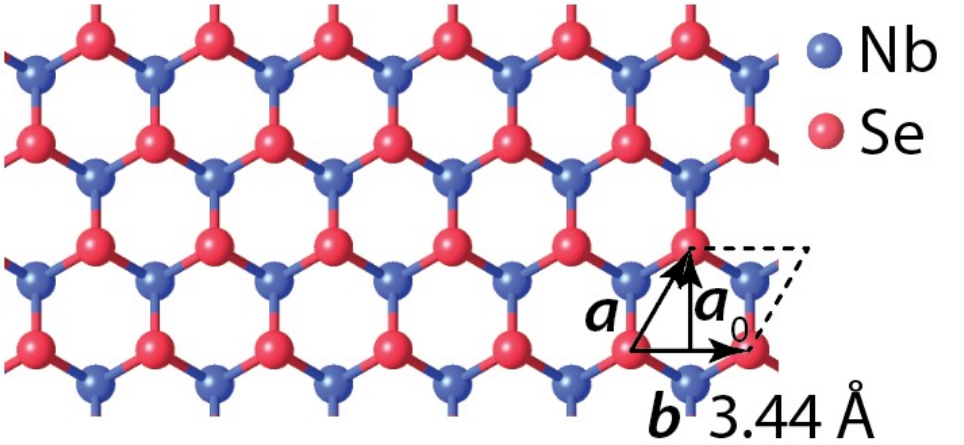
SUPERCONDUCTOR

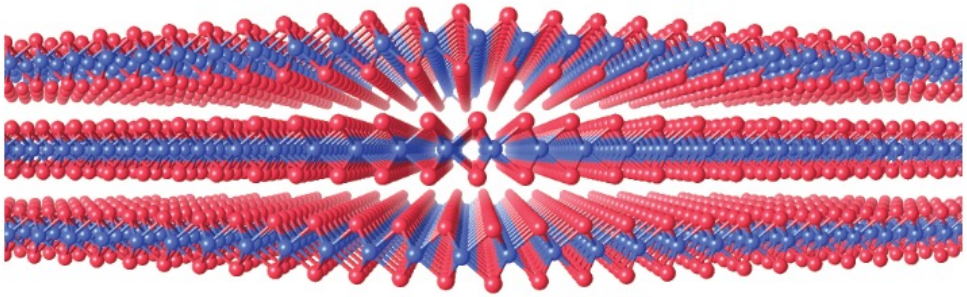
$T_C \approx 7.2$ K

$T_{CDW} \approx 33$ K

$\Delta_0 \approx 1.2$ meV

CHARGE DENSITY WAVE





SJTM EXAMPLE : SC+CDW @ $NbSe_2$

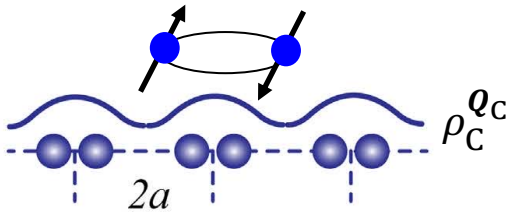
SUPERCONDUCTOR

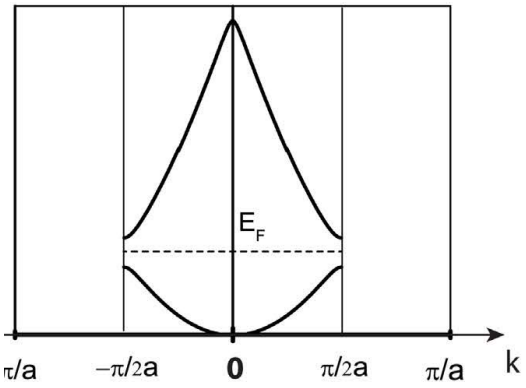
$$\Delta_S = \Delta_0 e^{i\phi}$$

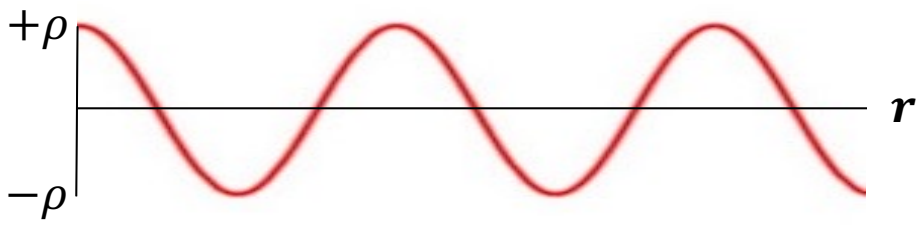
CHARGE DENSITY WAVE

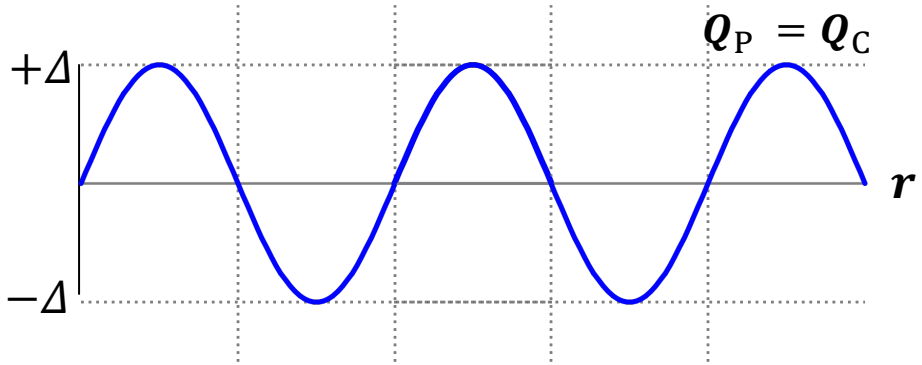
$$\rho_C^{\boldsymbol{Q}_C}(\boldsymbol{r}) = \rho e^{i\boldsymbol{Q}_C\cdot\boldsymbol{r}} + \rho^* e^{-i\boldsymbol{Q}_C\cdot\boldsymbol{r}}$$

$$\mathcal{F} = \mathcal{F}_S + \mathcal{F}_C + \mathcal{F}_P - \lambda \rho_C^{Q} \Delta_S^* \Delta_P^{-Q}$$







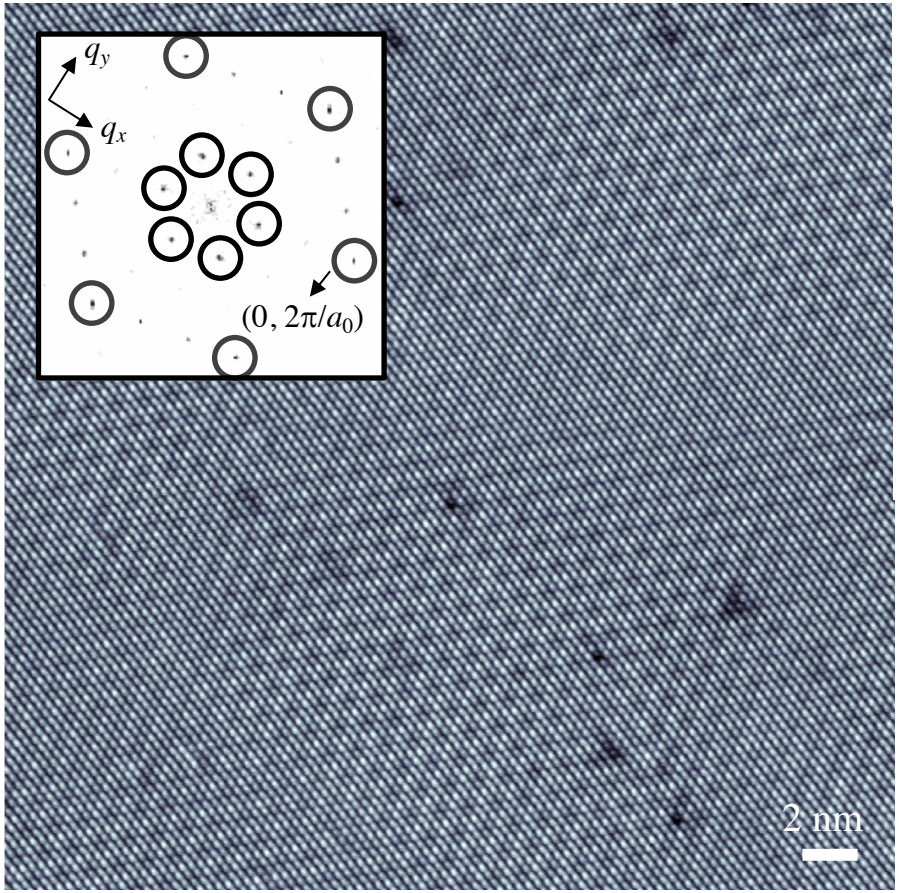


$$\Delta_P^{\boldsymbol{Q}_P}(\boldsymbol{r}) = \left[\Delta e^{i\boldsymbol{Q}_P\cdot\boldsymbol{r}} + \Delta^* e^{-i\boldsymbol{Q}_P\cdot\boldsymbol{r}}\right] e^{i\phi}$$

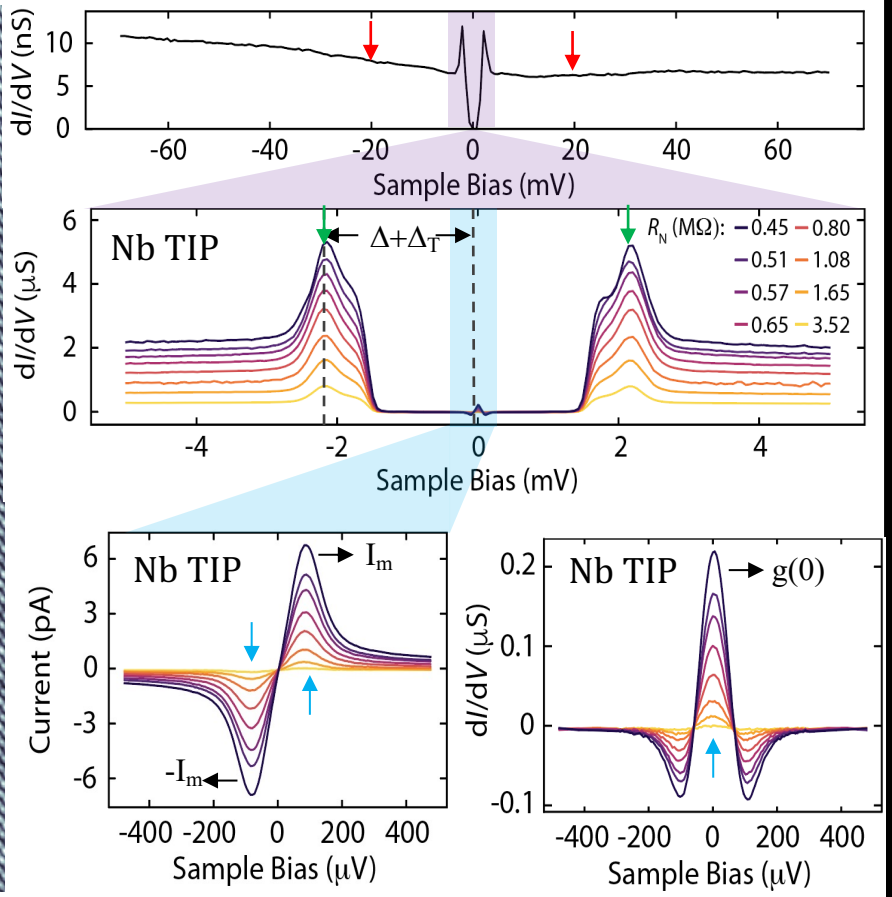
SJTM : $NbSe_2$

CHARGE DENSITY WAVE + SUPERCONDUCTOR

CONDUCTANCE IMAGE DYNAMIC RANGE >10^5



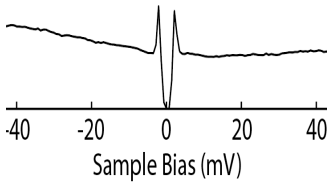
T(r, -20 mV)

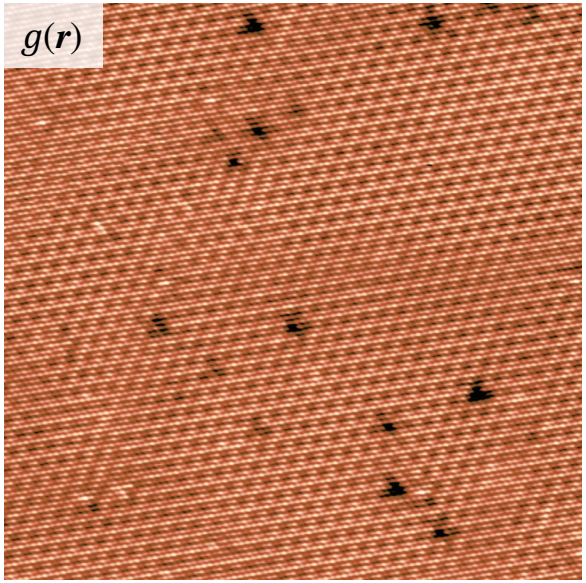


T = 280mK

Science 372, 1447 (2021)

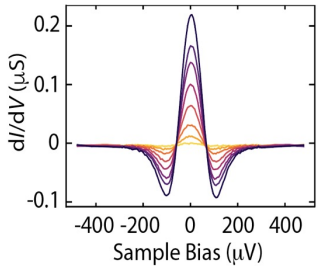
VISUALIZE ELECTRON-PAIR DENSITY $n_P(\boldsymbol{r})$

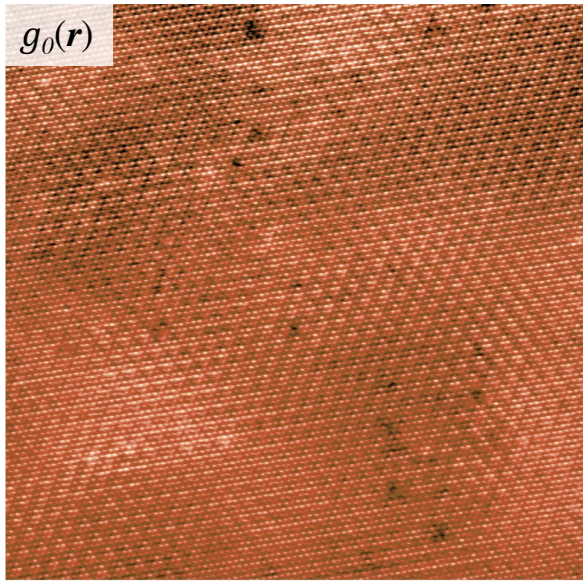




43 nS

24 nS



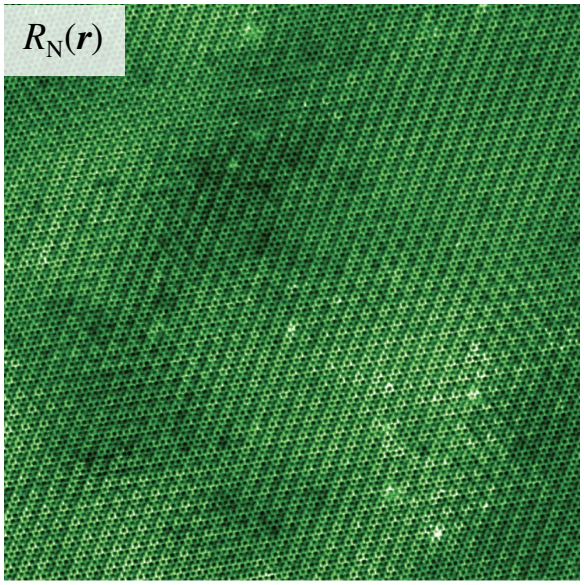


225 nS

133 nS

T = 280mK

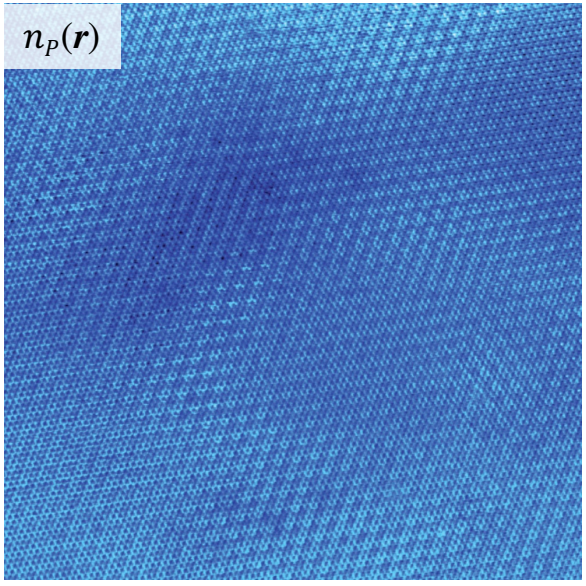
35 nm



0.73 MΩ

0.49 MΩ

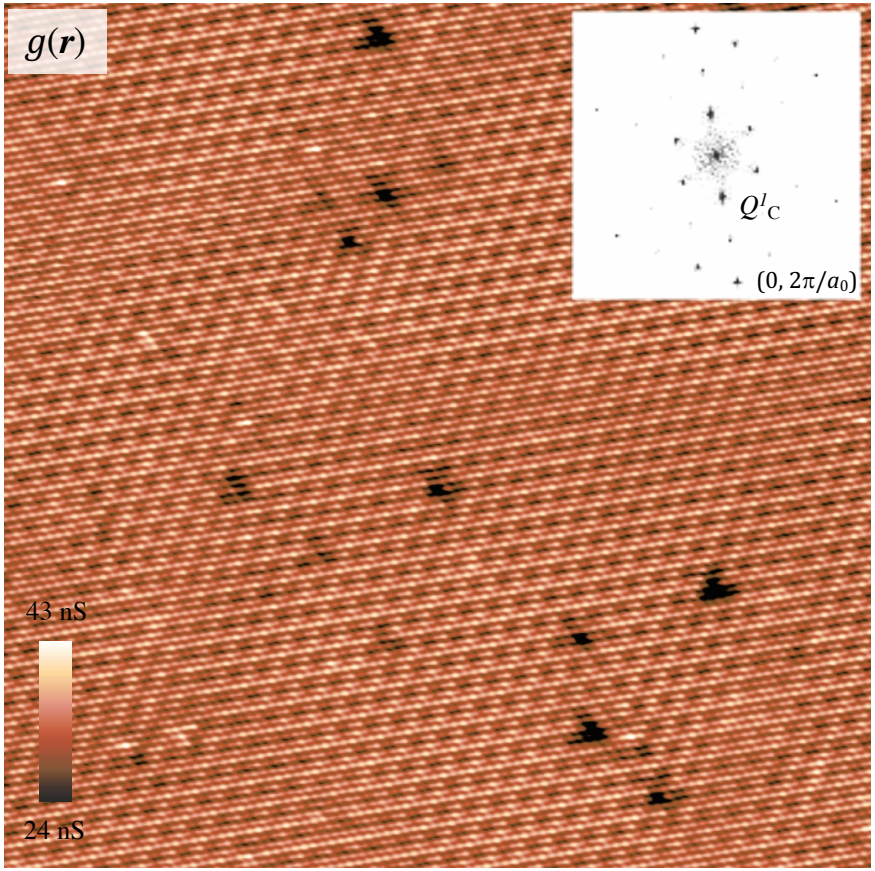
35 nm

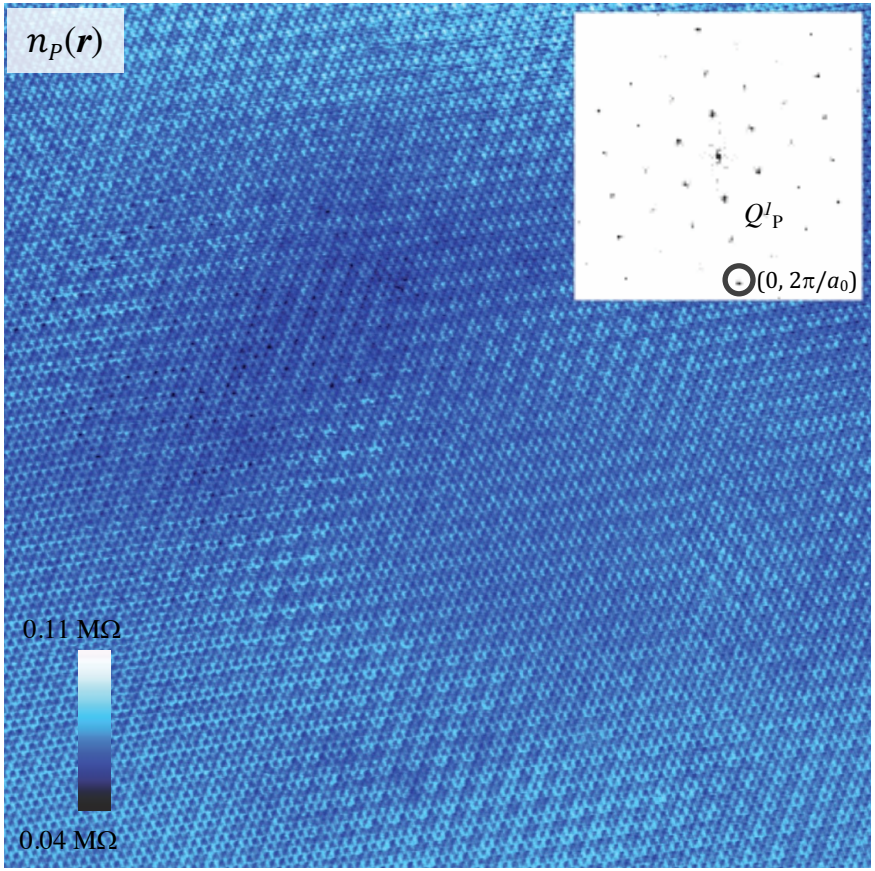


0.11 MΩ

0.04 MΩ

CHARGE DENSITY & PAIR DENSITY MODULATIONS





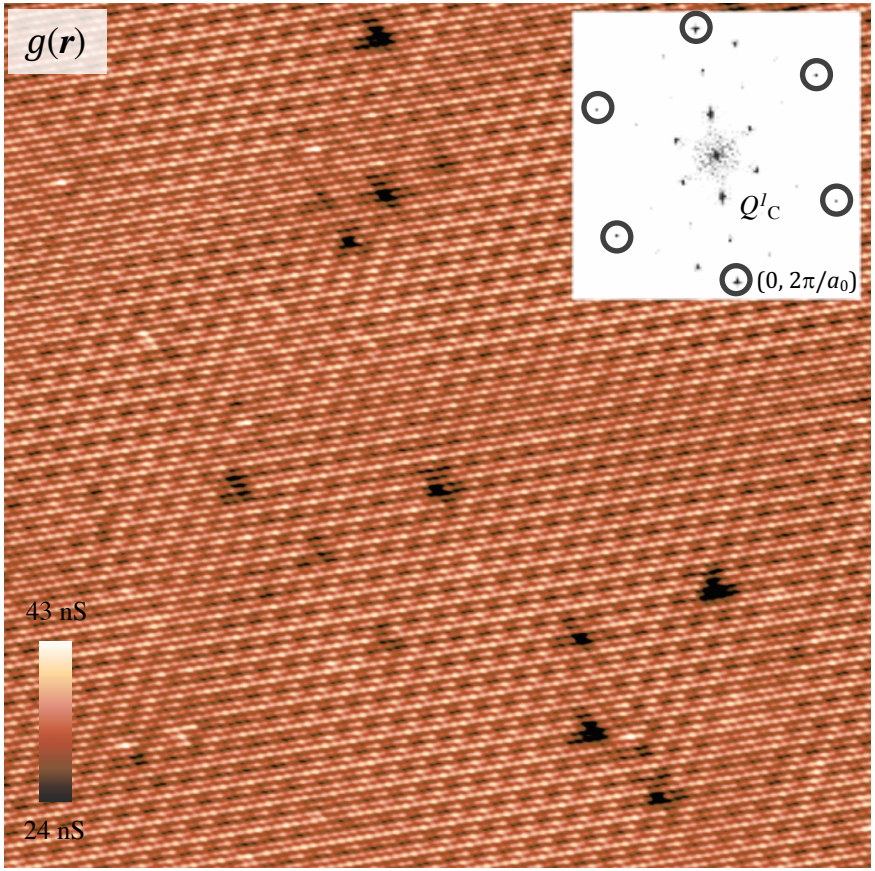
T = 280mK

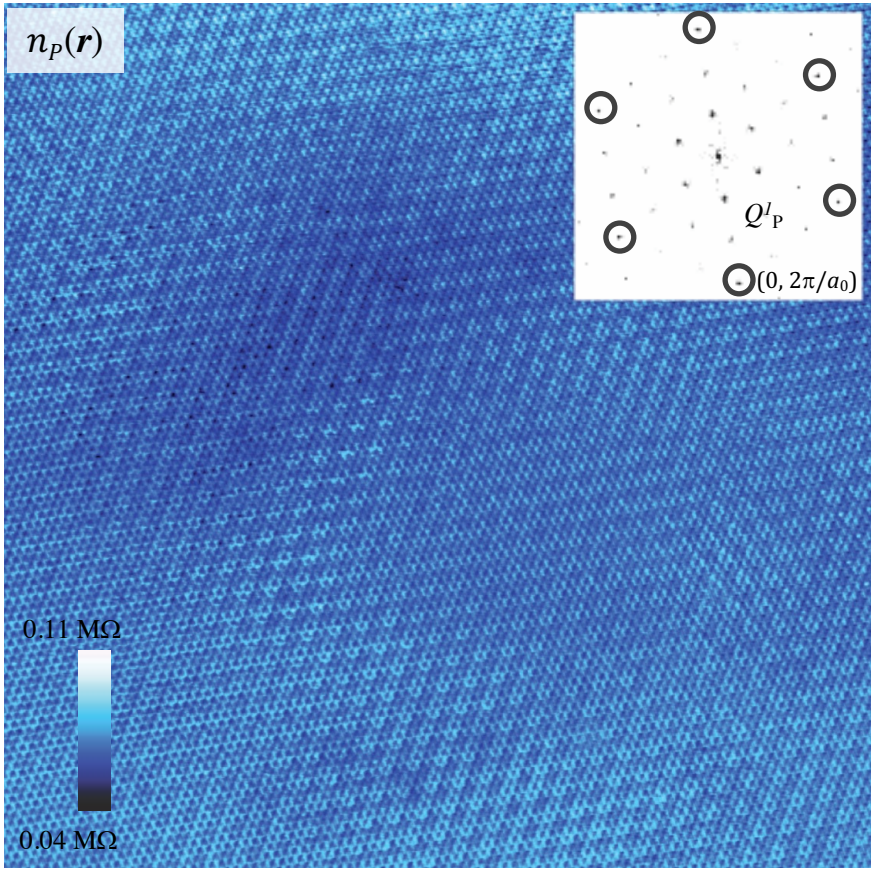
Science 372, 1447 (2021)

CHARGE DENSITY & PAIR DENSITY MODULATIONS

CRYSTAL LATTICE

CRYSTAL LATTICE



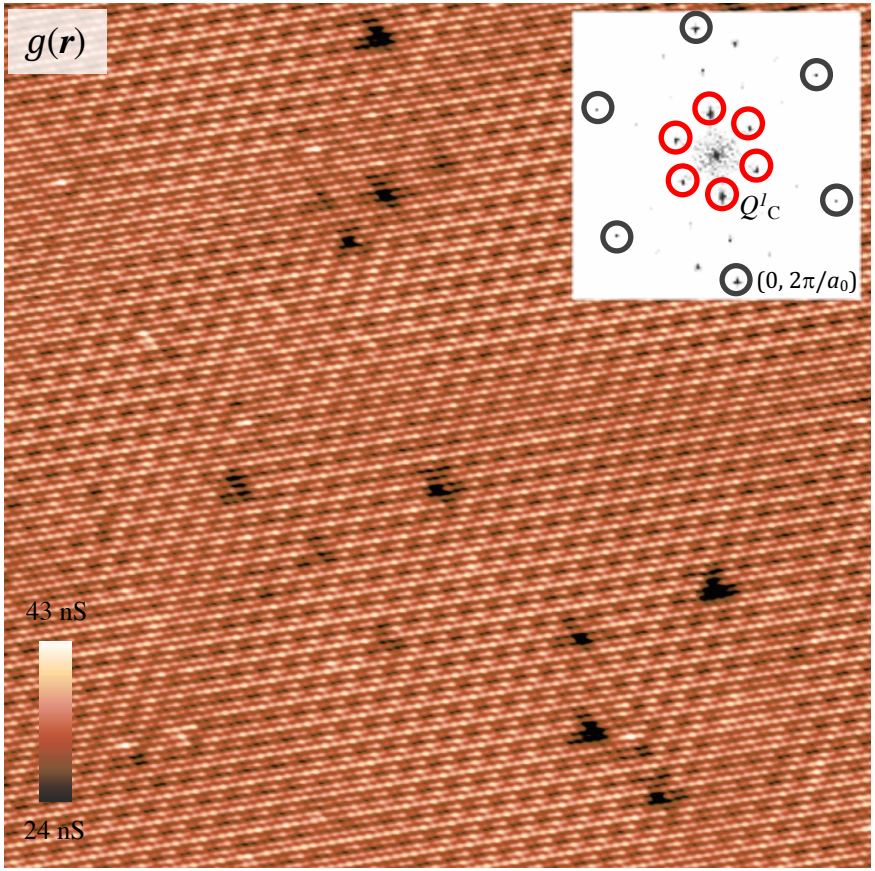


T = 280mK

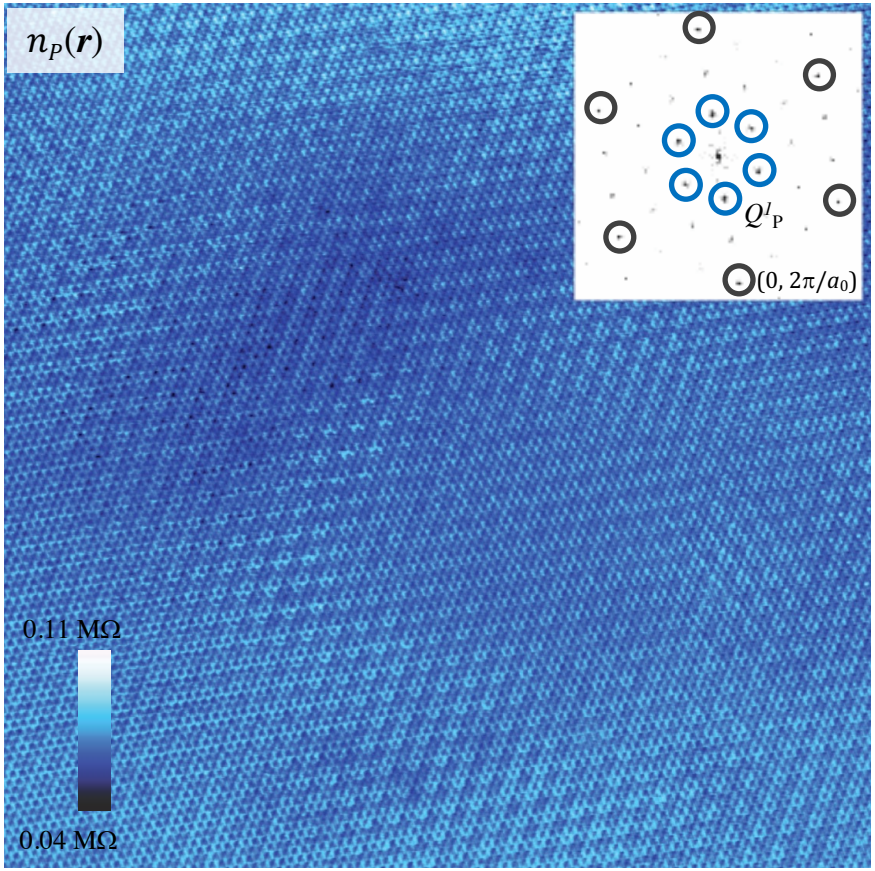
Science 372, 1447 (2021)

CHARGE DENSITY & PAIR DENSITY MODULATIONS

CHARGE DENSITY WAVE + CRYSTAL LATTICE



PAIR DENSITY WAVE + CRYSTAL LATTICE

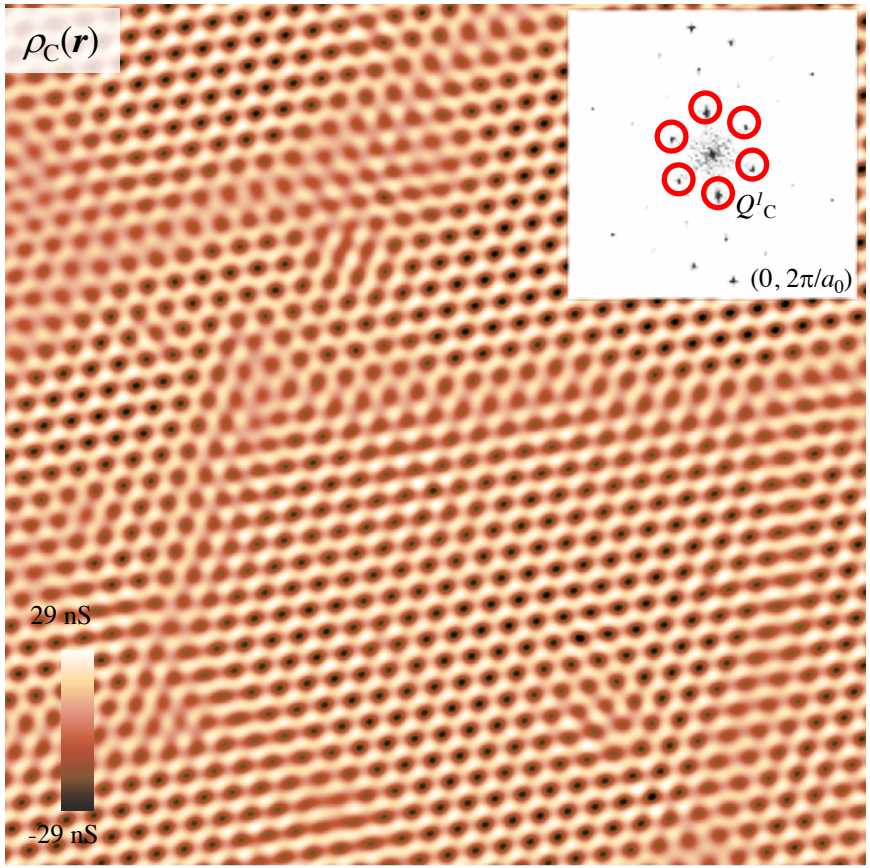


T = 280mK

Science 372, 1447 (2021)

SIMULTANEOUS VISUALIZATION CDW AND PDW

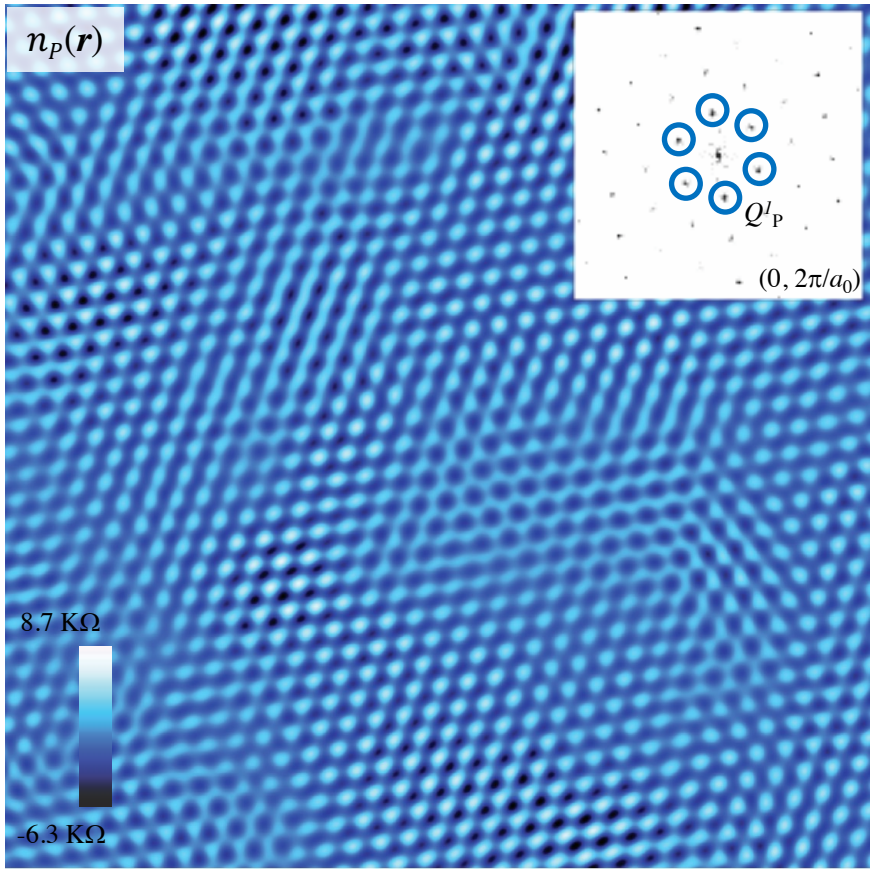
CHARGE DENSITY WAVE



$$\rho_C^{\boldsymbol{Q}_C}(\boldsymbol{r}) = \rho e^{i\boldsymbol{Q}_C\cdot\boldsymbol{r}} + \rho^* e^{-i\boldsymbol{Q}_C\cdot\boldsymbol{r}}$$

T = 280mK

PAIR DENSITY WAVE

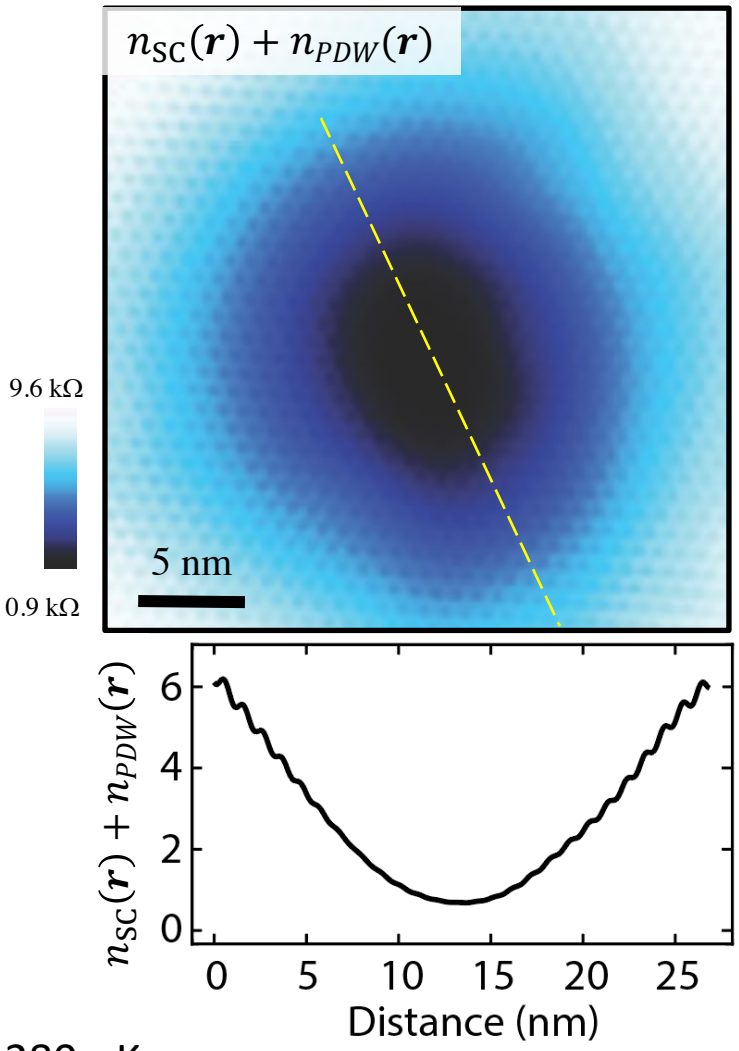


$$\Delta_P^{\boldsymbol{Q}_P}(\boldsymbol{r}) = \left[\Delta e^{i\boldsymbol{Q}_P\cdot\boldsymbol{r}} + \Delta^* e^{-i\boldsymbol{Q}_P\cdot\boldsymbol{r}}\right] e^{i\phi}$$

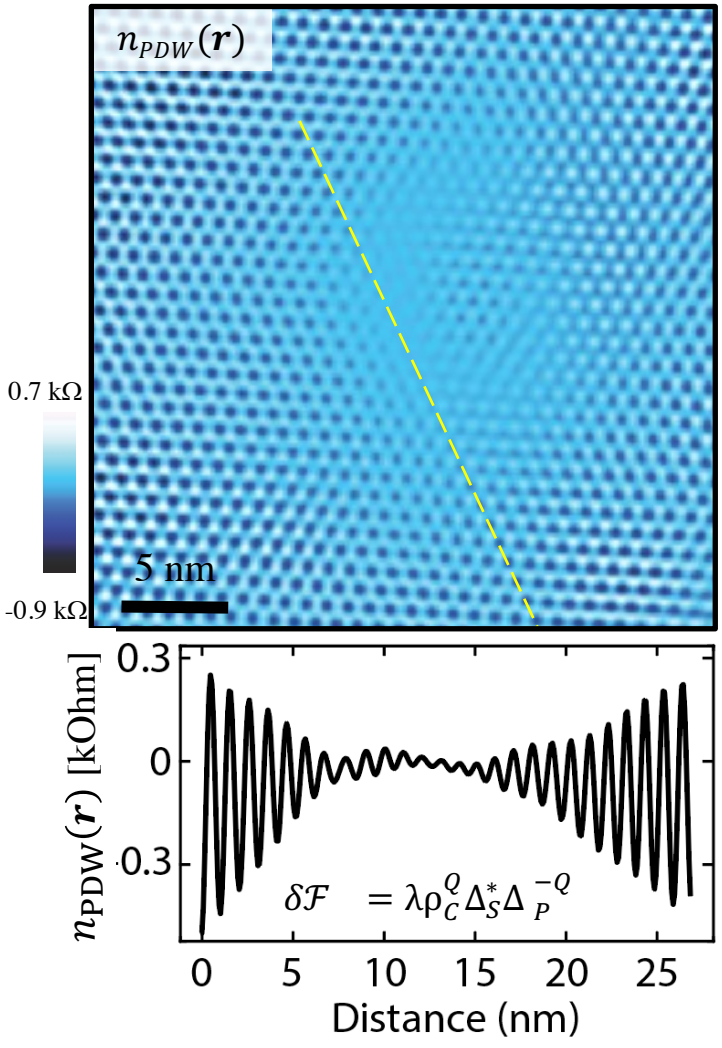
Science 372, 1447 (2021)

VORTEX ELECTRON-PAIR DENSITY $n_P(\boldsymbol{r})$

$n_P(r) \propto g_0(r) {R_N}^2(r)$



PAIR DENSITY WAVE

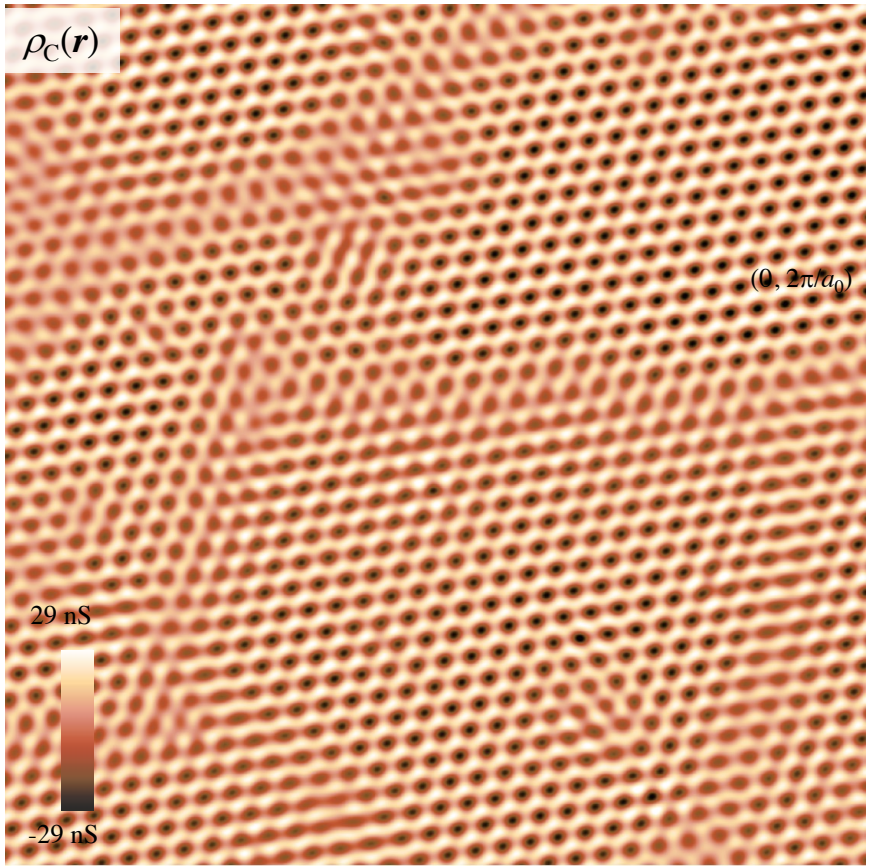


T = 280mK

Science 372, 1447 (2021)

CDW:PDW DISTINCT ATOMIC-SCALE STRUCTURES

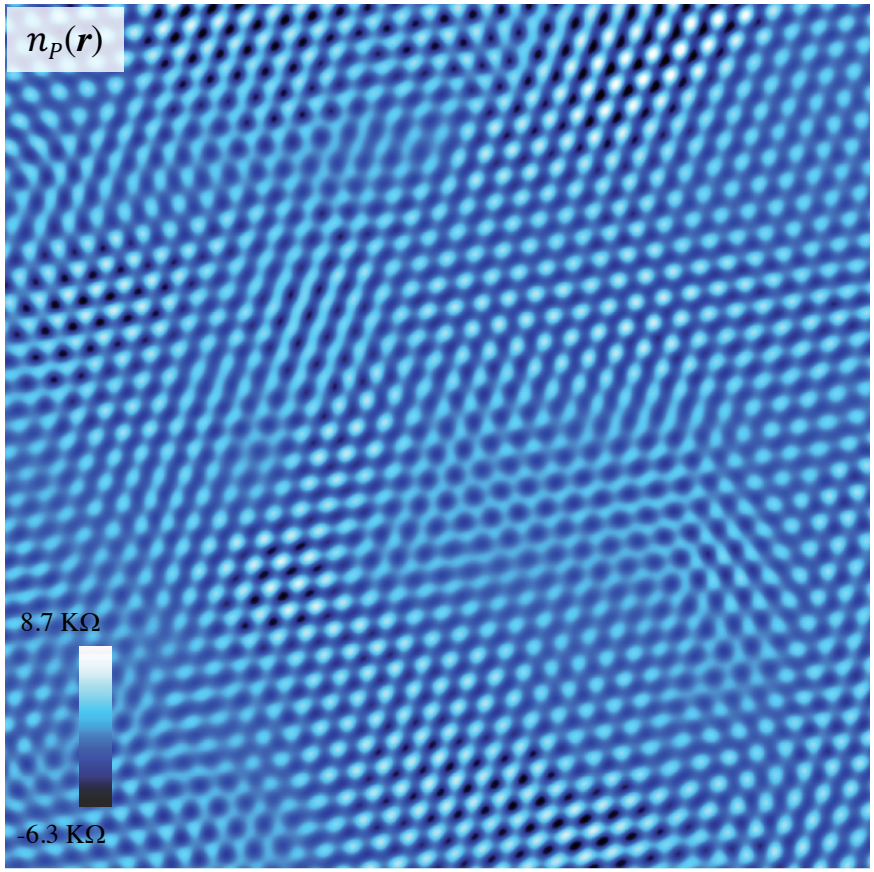
CHARGE DENSITY WAVE



$$\rho_C^{\boldsymbol{Q}_C}(\boldsymbol{r}) = \rho e^{i\boldsymbol{Q}_C\cdot\boldsymbol{r}} + \rho^* e^{-i\boldsymbol{Q}_C\cdot\boldsymbol{r}}$$

T = 280mK

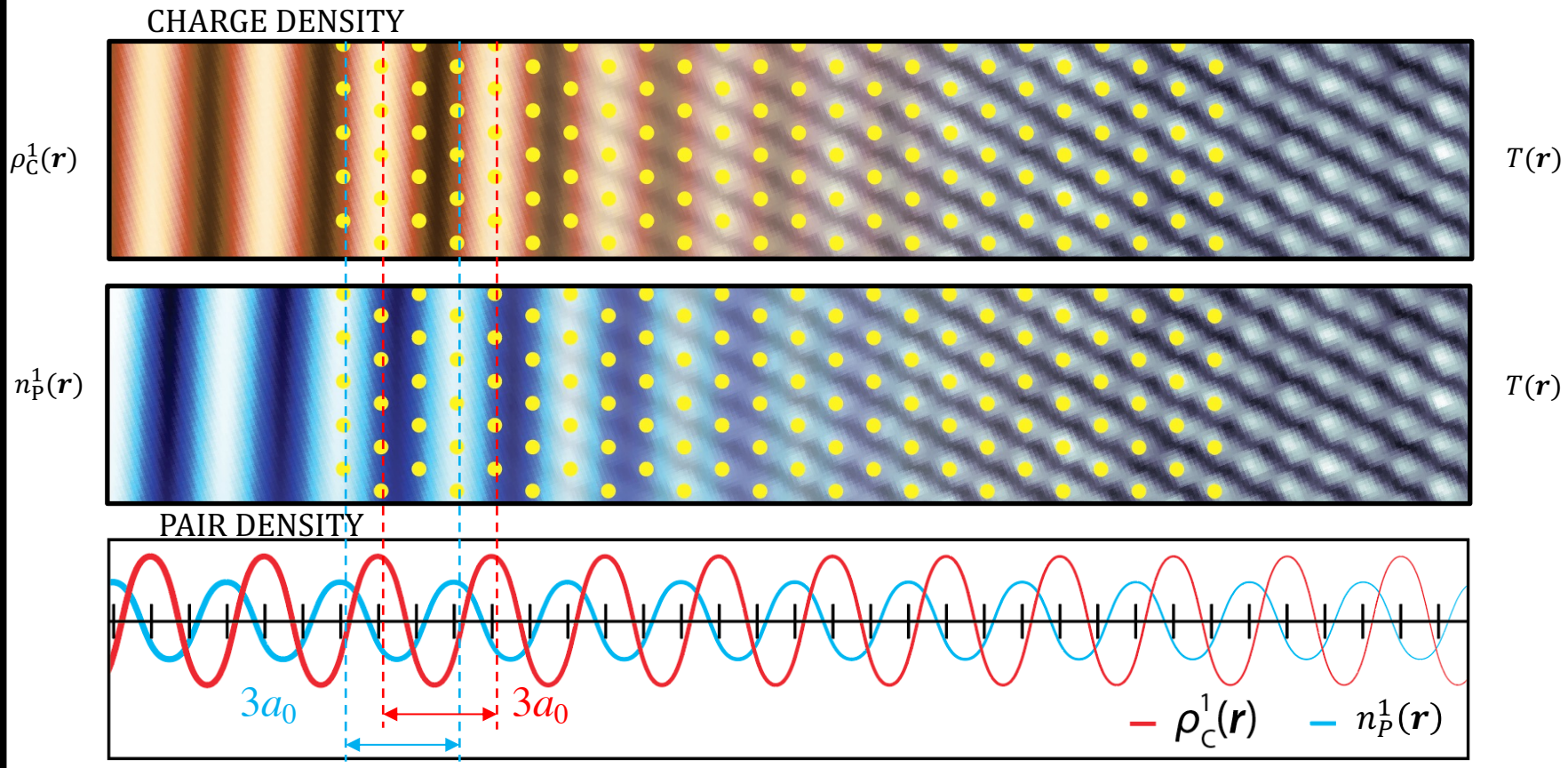
PAIR DENSITY WAVE



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

Science 372, 1447 (2021)

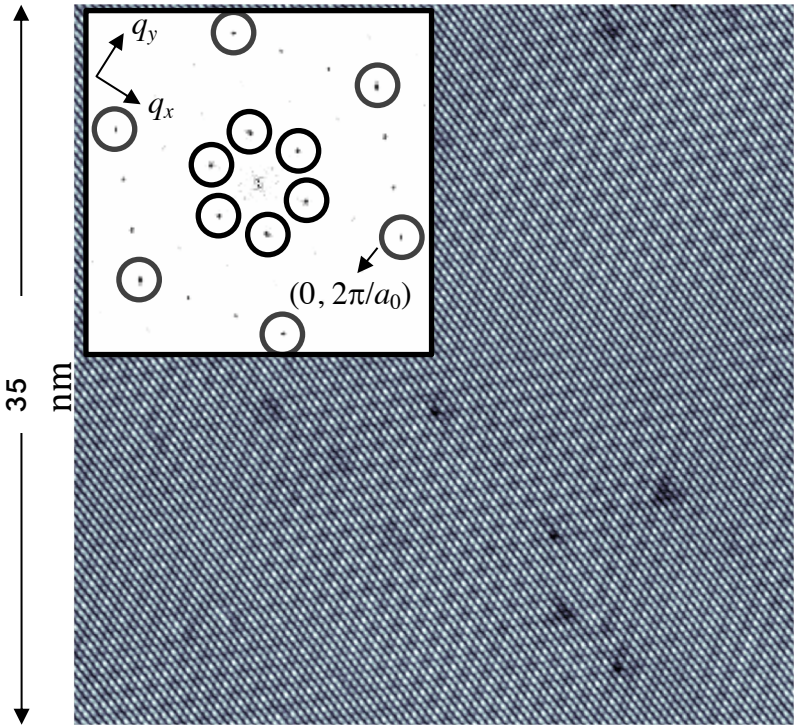
CDW:PDW PHASE SHIFT = $2\pi/3$ UNIVERSALLY

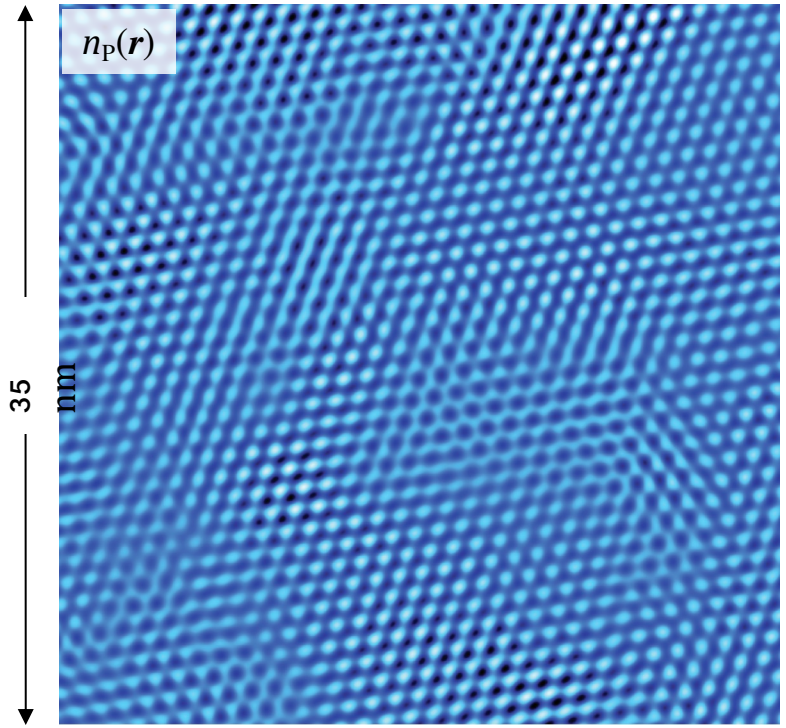


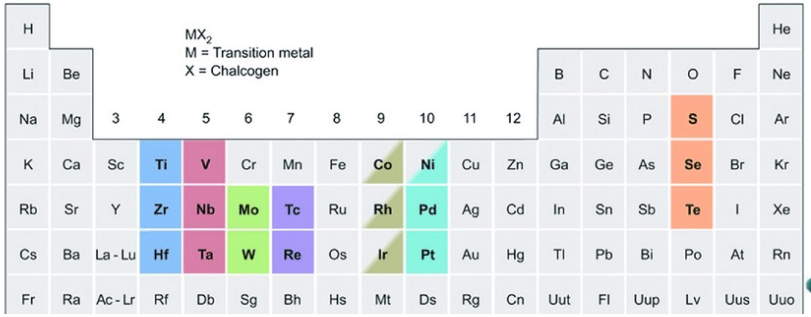
T = 280mK

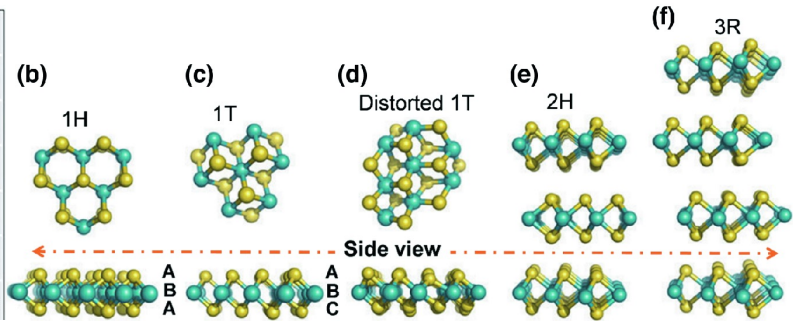
Science 372, 1447 (2021)

SJTM: ELECTRON-PAIR VISUALIZATION





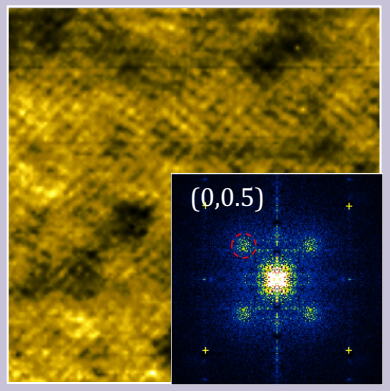




Science 372, 1447 (2021)

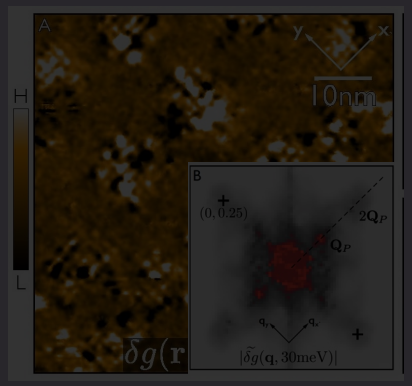
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



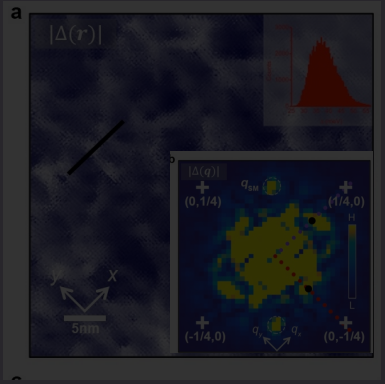
Nature 532, 343 (2016)

VORTEX HALO



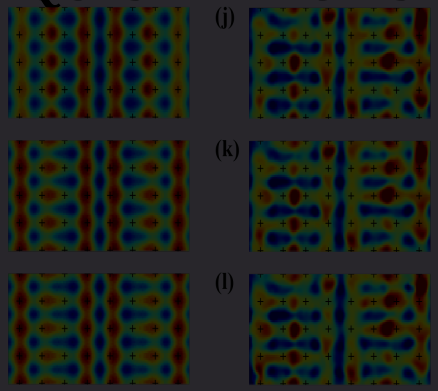
Science 364, 976 (2019)

ENERGY GAP



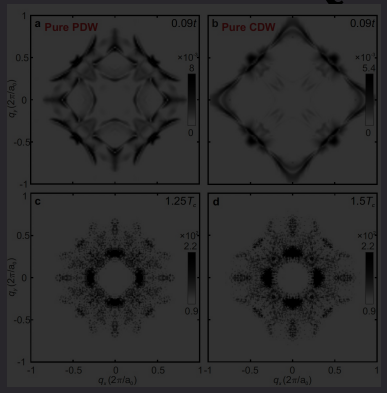
Nature 580, 6570 (2020)

QUASIPARTICLES



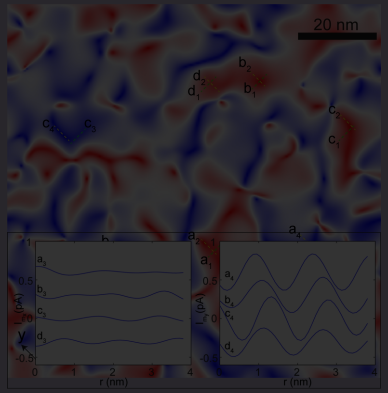
PNAS 117, 14850 (2020)

PSEUDOGAP QPI

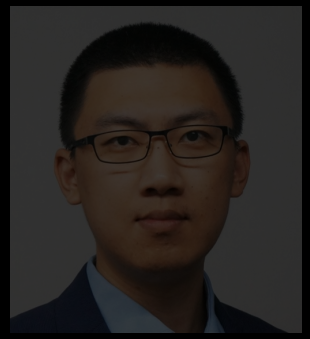


Nat.Comm 12, 6087 (2021)

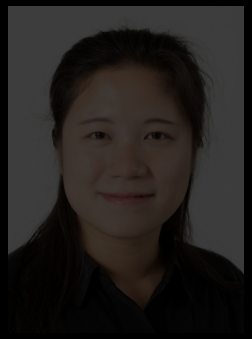
NEMATIC



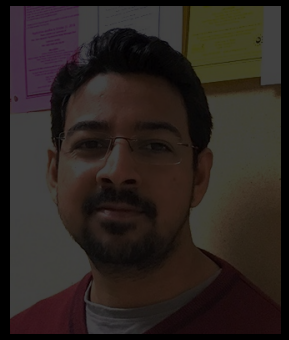
Weijiong Chen *et al* (2022)



Xiaolong Liu
Notre Dame



Shuqiu Wang
Oxford



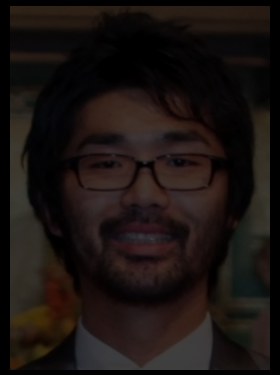
P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford



Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

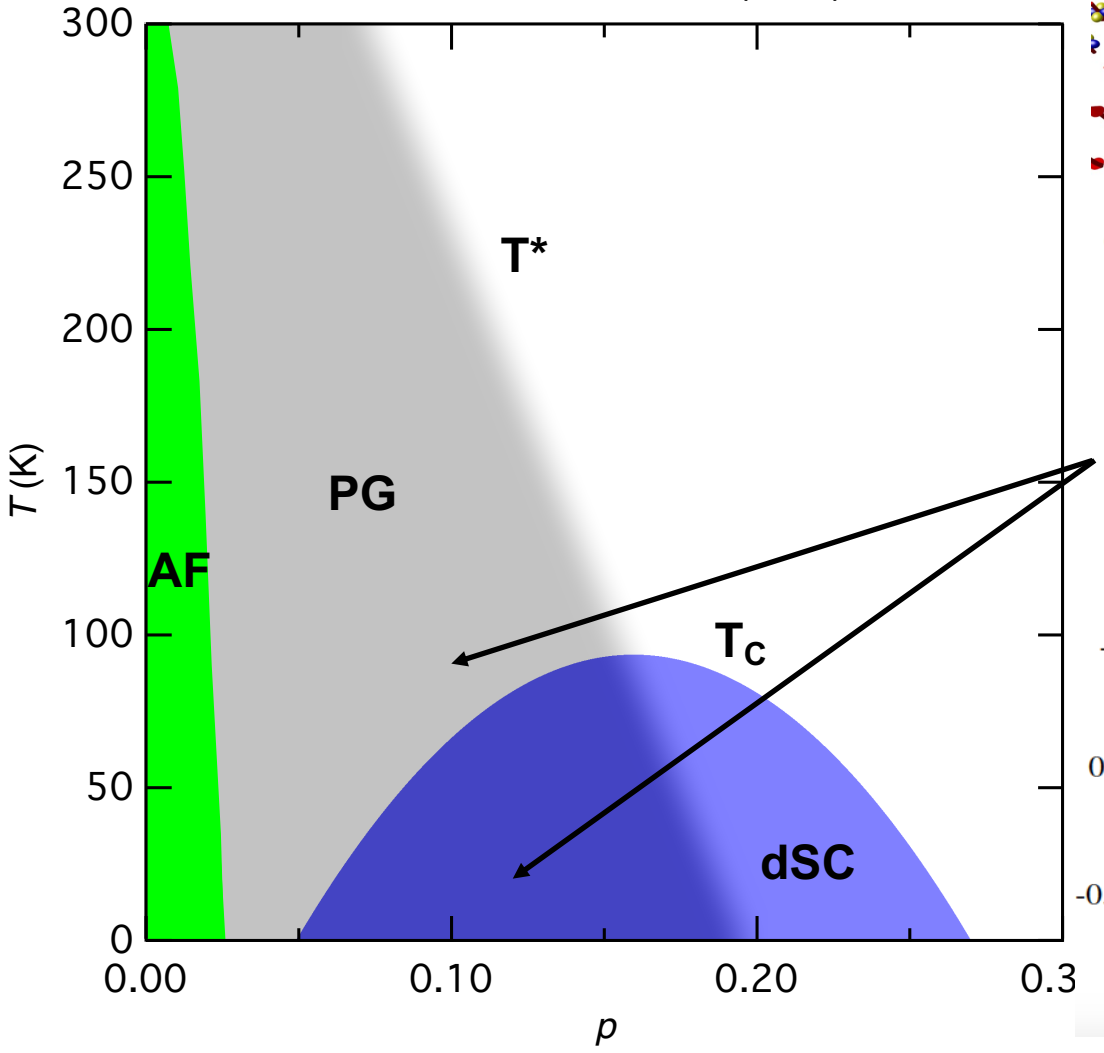
M. H. Hamidian
Cornell

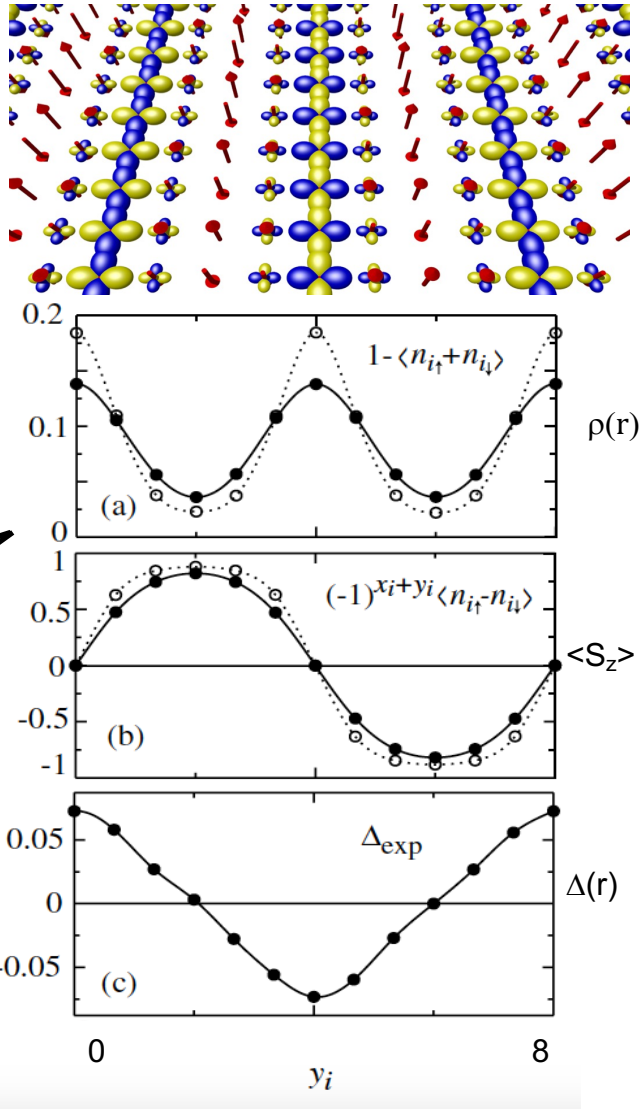
S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

DOES STRONG-COUPLING PDW STATE EXIST IN CUPRATES?

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

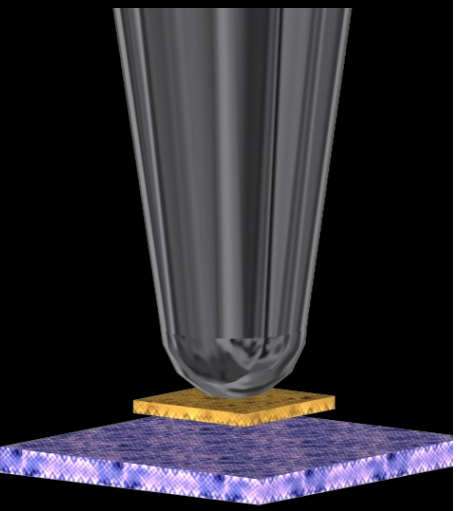




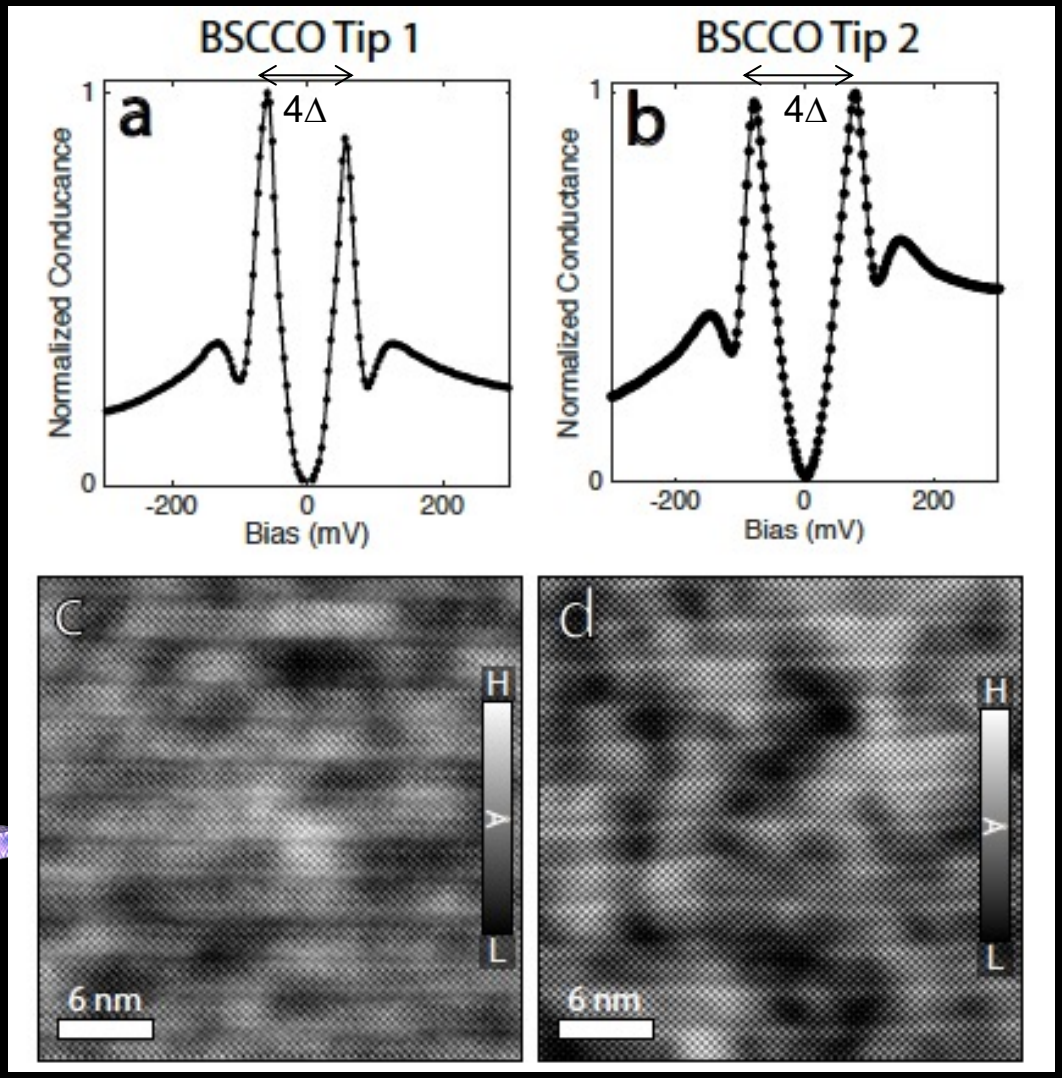
SJTM : d-WAVE HTS TIP

$$E_J = \frac{\hbar I_0}{2e} \propto \frac{\Delta}{R_N} \approx kT$$

d-WAVE HTS TIP



SIS

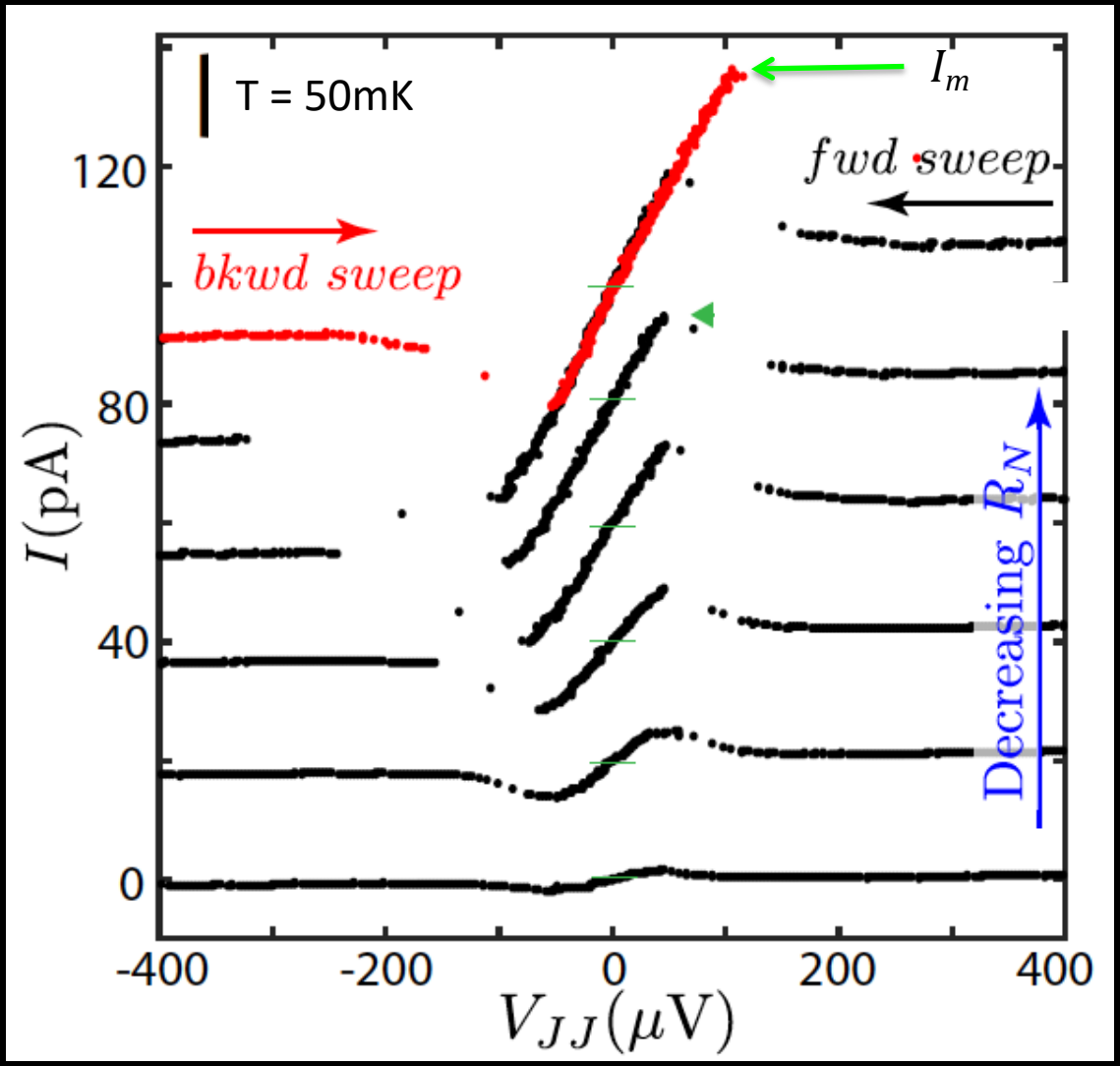


50 mK DR STM

Nature 532, 343 (2016)

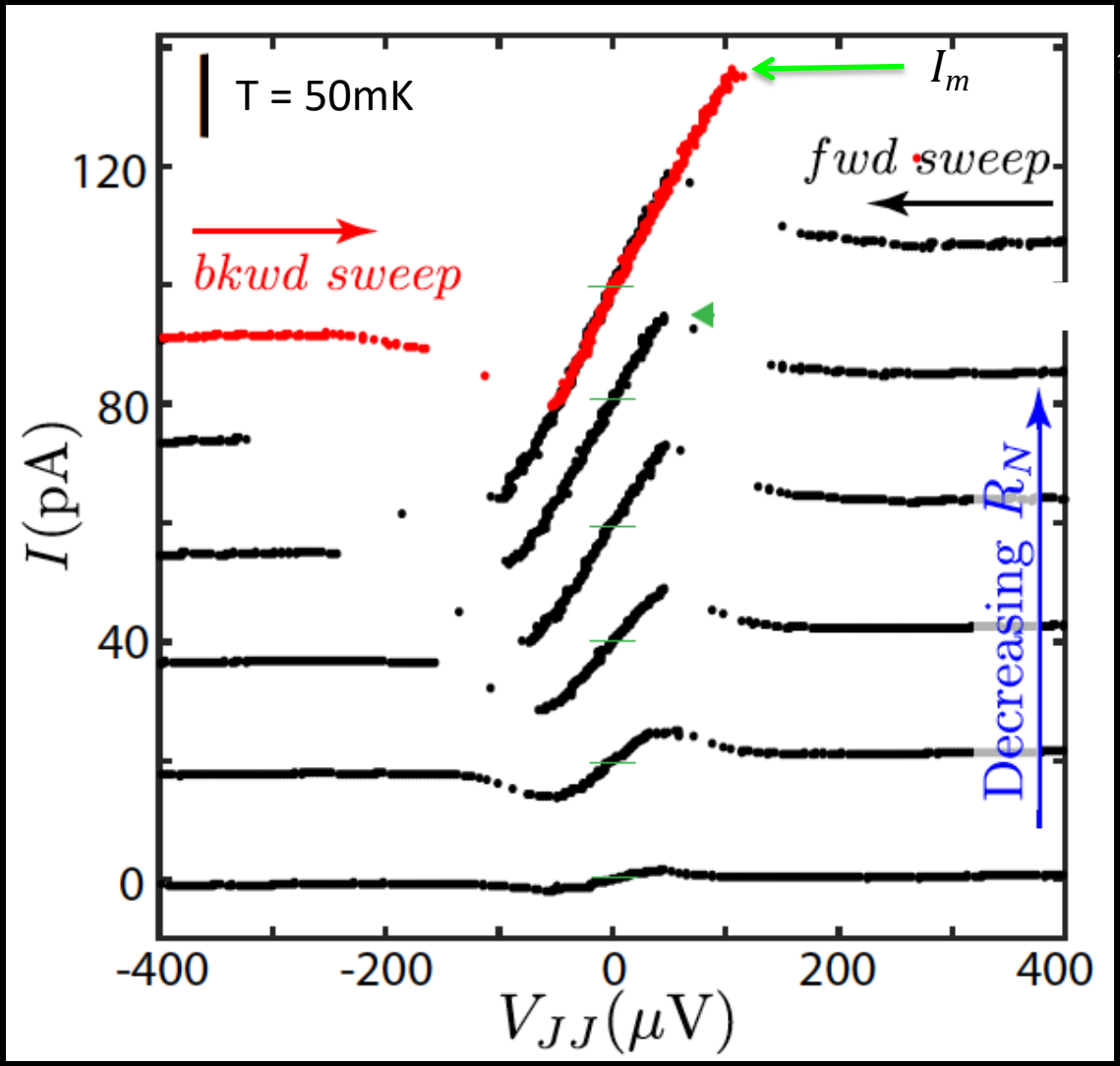
SJTM : ELECTRON-PAIR CURRENT

$$I_m = \frac{\hbar}{8ek_B T^*} I_0^2$$



Nature 532, 343 (2016)

$I_m(r)$ IMAGING OF $Bi_2Sr_2CaCu_2O_{x+8}$

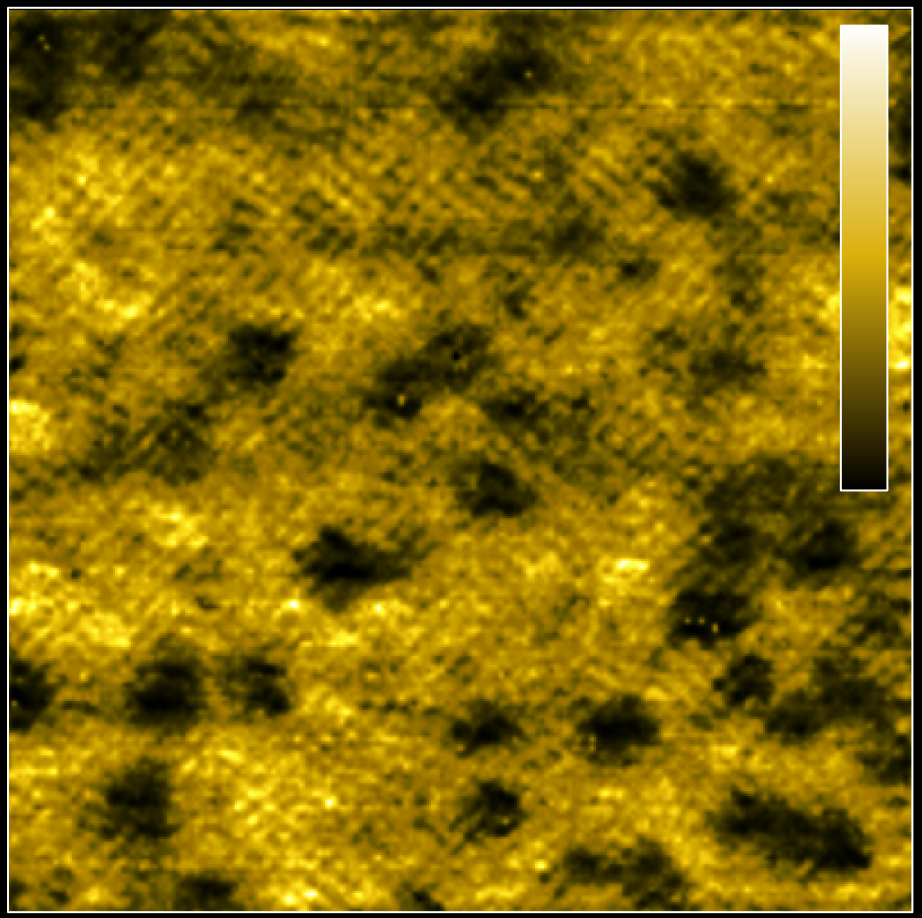


$n_P(r) \propto I_m(r) {R_N}^2(r)$

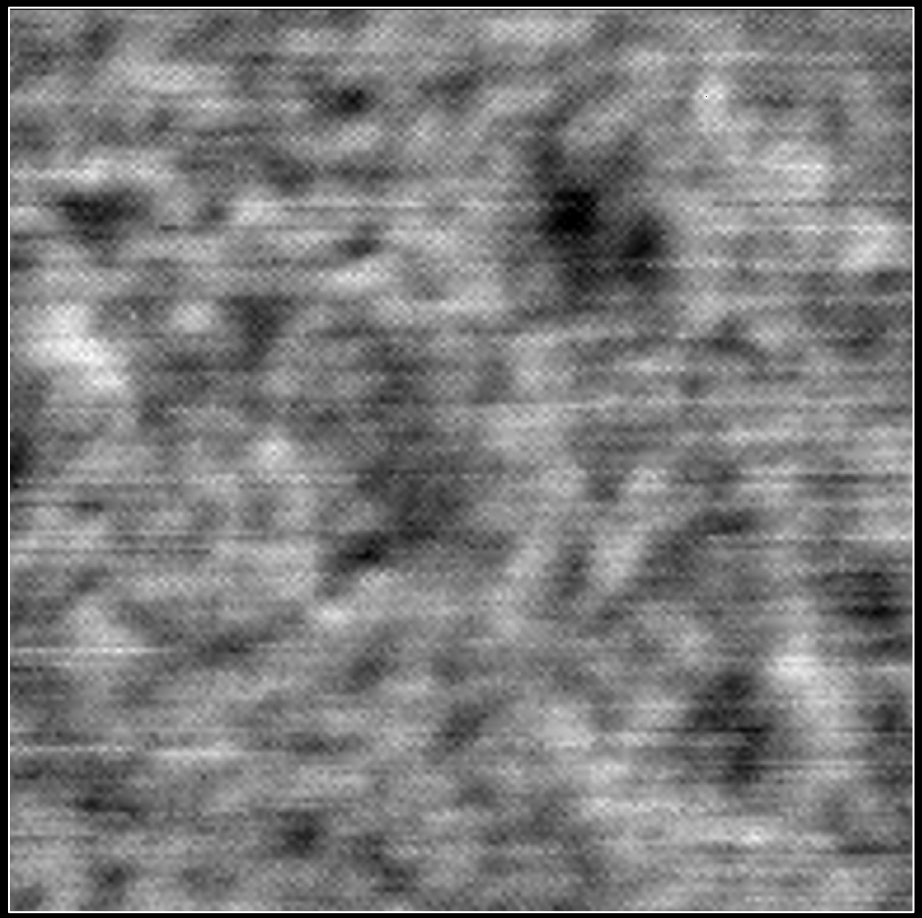
Nature 532, 343 (2016)

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

T=50mK $I_m(\boldsymbol{r})$



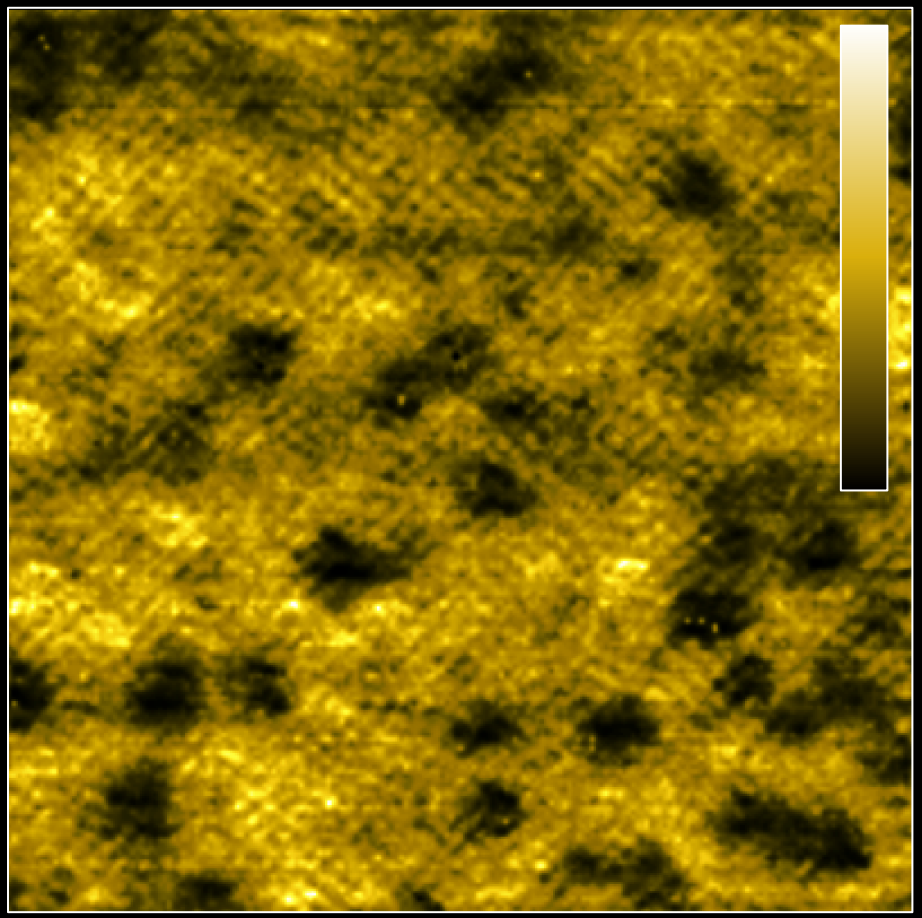
Topography 76x76nm



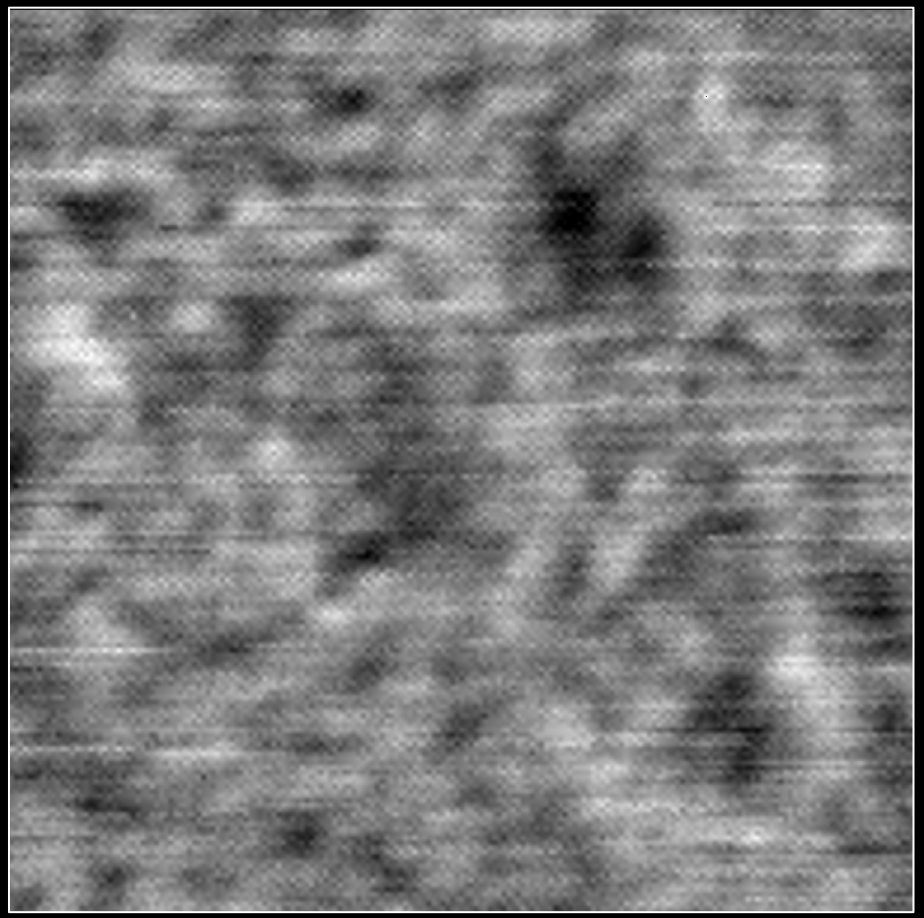
Nature 532, 343 (2016)

VALIDATE ELECTRON-PAIR DENSITY IMAGING ?

T=50mK $I_m(\boldsymbol{r})$



Topography 76x76nm



Nature 532, 343 (2016)

VALIDATE ELECTRON-PAIR DENSITY IMAGING ?

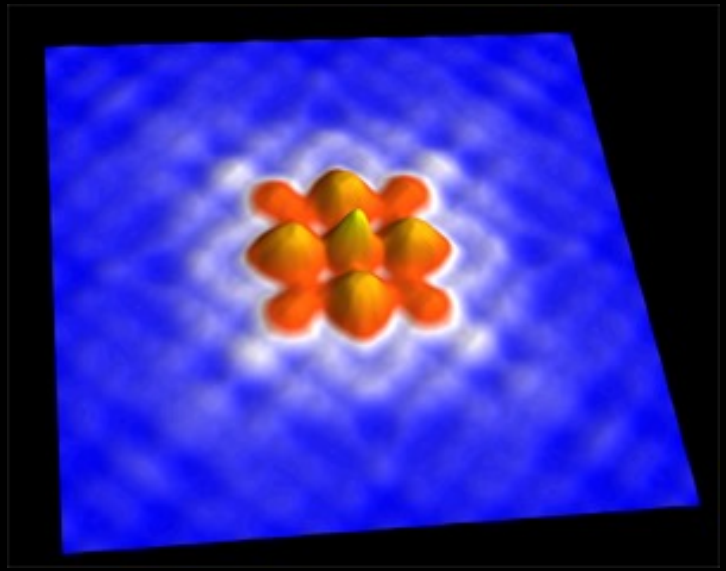
VOLUME 77, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 1996

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)

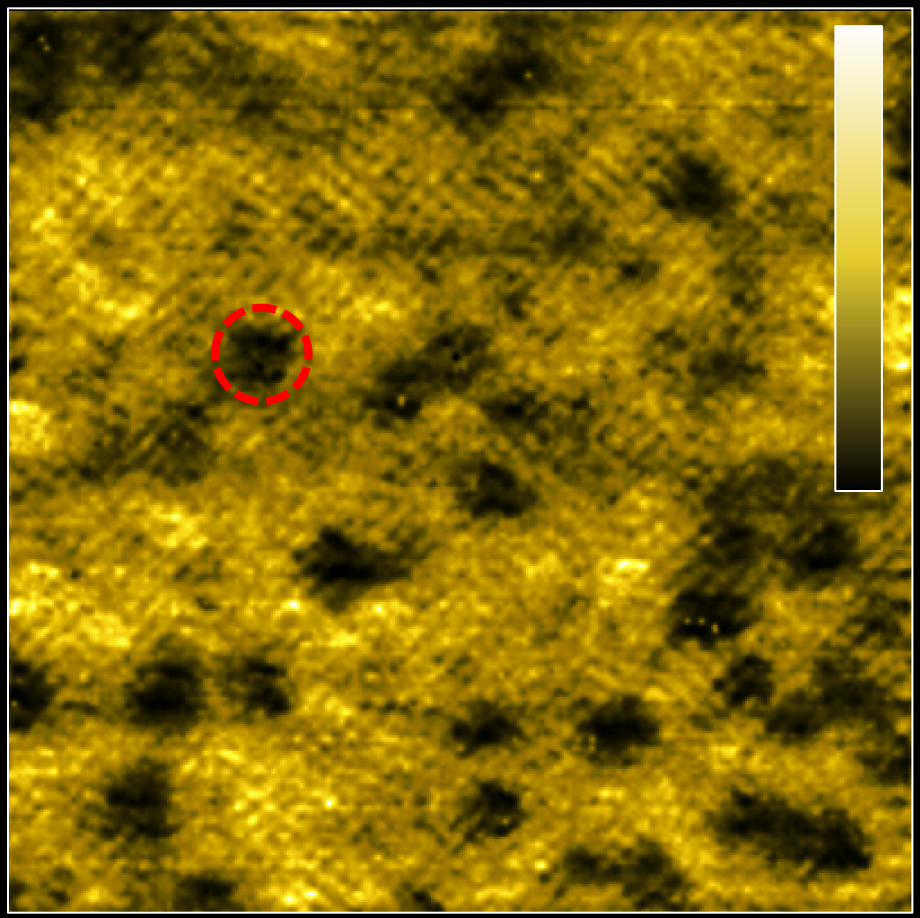
We have performed transverse-field muon spin relaxation measurements of the Zn-substituted cuprate high-T_c superconductors: $La_{2-x}Sr_x(Cu_{1-y}Zn_y)O_4$ and $YBa_2(Cu_{1-y}Zn_y)_3O_{6.63}$. The superconducting carrier density/effective mass n_s/m^* ratio at $T \rightarrow 0$ decreases with increasing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



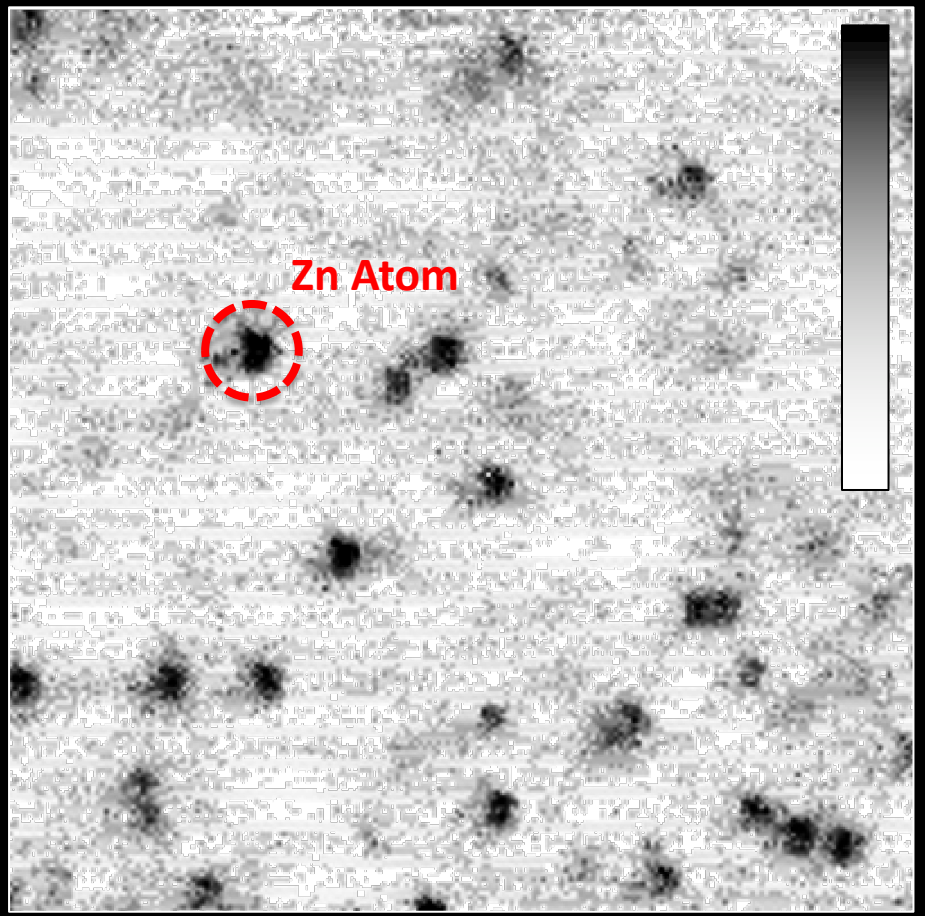
VALIDATE ELECTRON-PAIR DENSITY IMAGING

T=50mK

$I_m(\boldsymbol{r})$



dI/dV(**r,** 20mV)

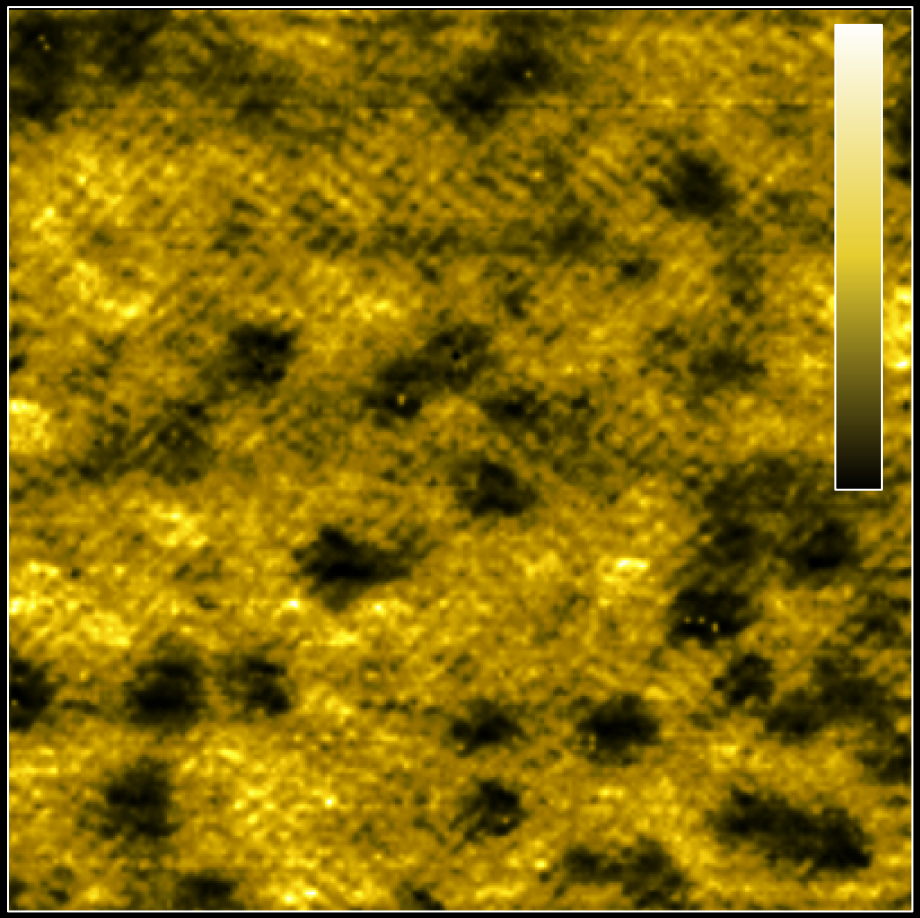


Nature 532, 343 (2016)

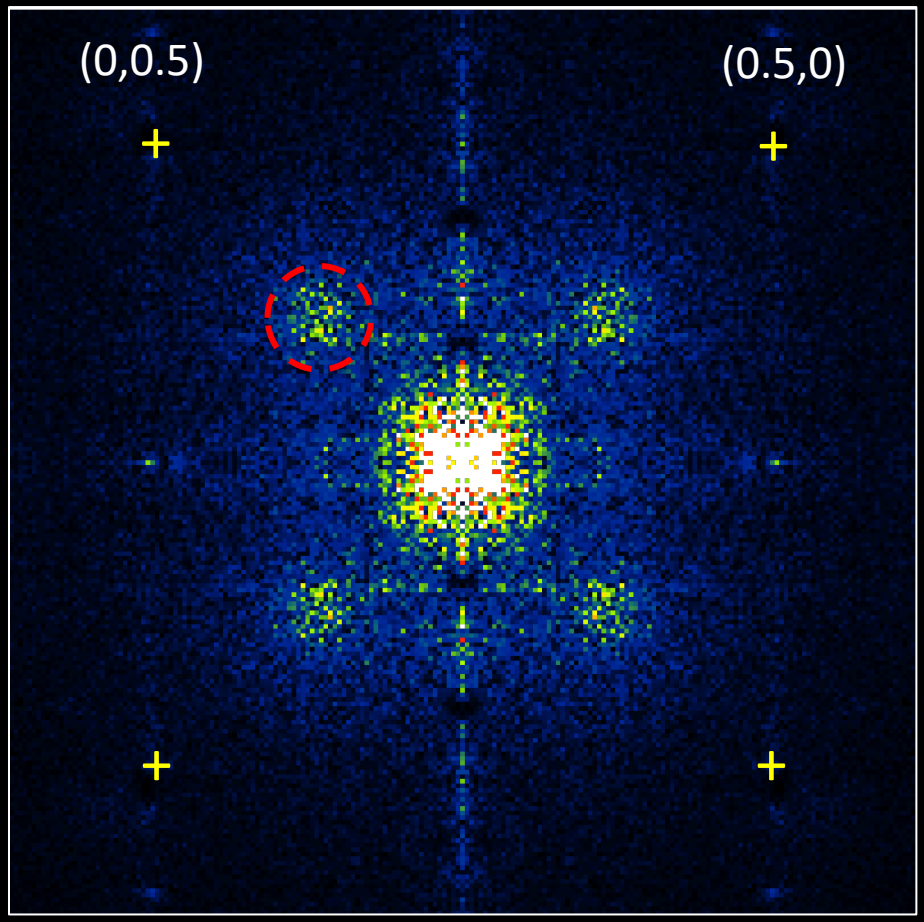
ELECTRON-PAIR DENSITY WAVE

T=50mK

$I_m(\boldsymbol{r})$



$I_m(\boldsymbol{q})$

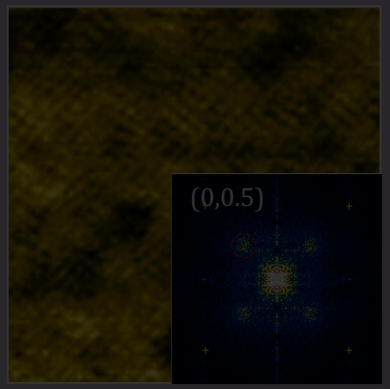


Q = (0,1/4)2π/a_o ; (1/4,0)2π/a_o

Nature 532, 343 (2016)

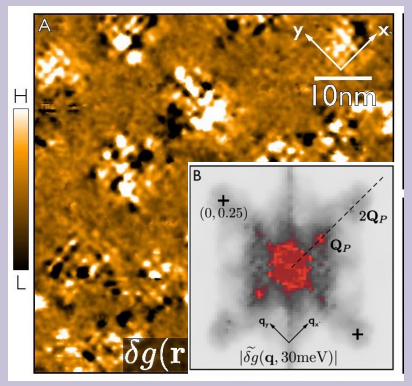
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



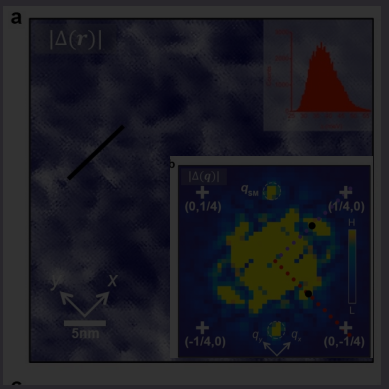
Nature ***532***, 343 (2016)

VORTEX HALO



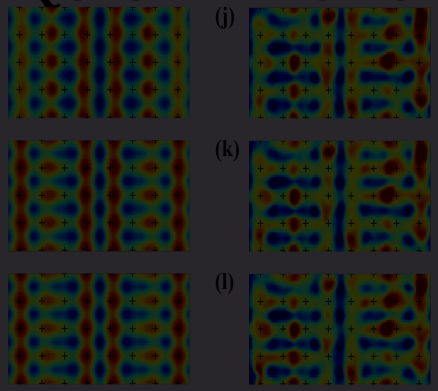
Science 364, 976 (2019)

ENERGY GAP



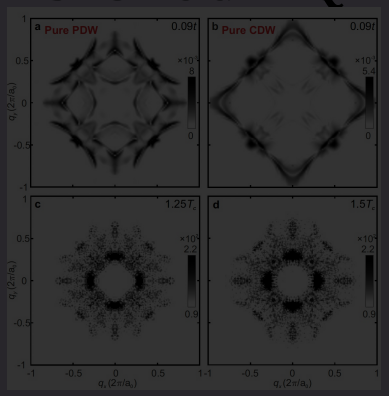
Nature 580, 6570 (2020)

QUASIPARTICLES



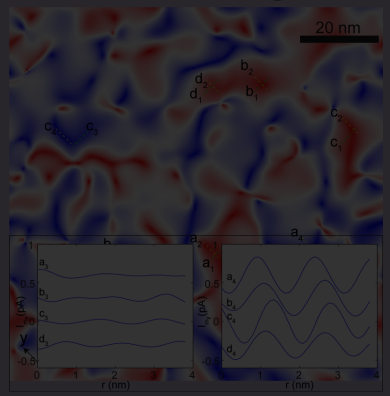
PNAS 117, 14850 (2020)

PSEUDOGAP QPI

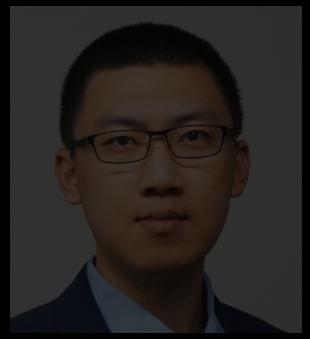


Nat.Comm 12, 6087 (2021)

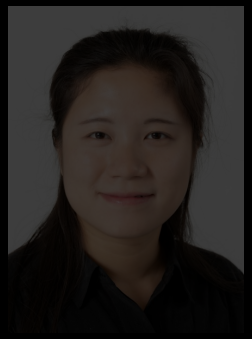
NEMATIC



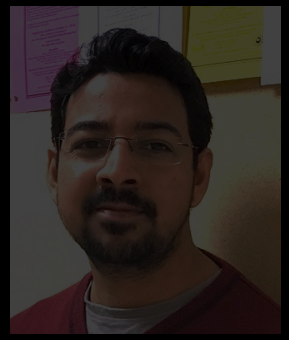
Weijiong Chen *et al* (2022)



Xiaolong Liu
Notre Dame



Shuqiu Wang
Oxford



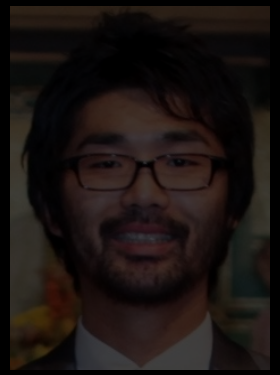
P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford



Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

M. H. Hamidian
Cornell

S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

MAGNETIC FIELD CONTROL OF CUPRATE DENSITY WAVE

J.E. Hoffman *et al*. *Science* 295, 466 (2002)

T. Wu *et al*, *Nature* 477, *191* (2011)

J. Chang *et al.*, *Nat. Phys.* 8, 871 (2012)

D. LaBoeuf *et al. Nat. Phys.* 9, 79 (2013)

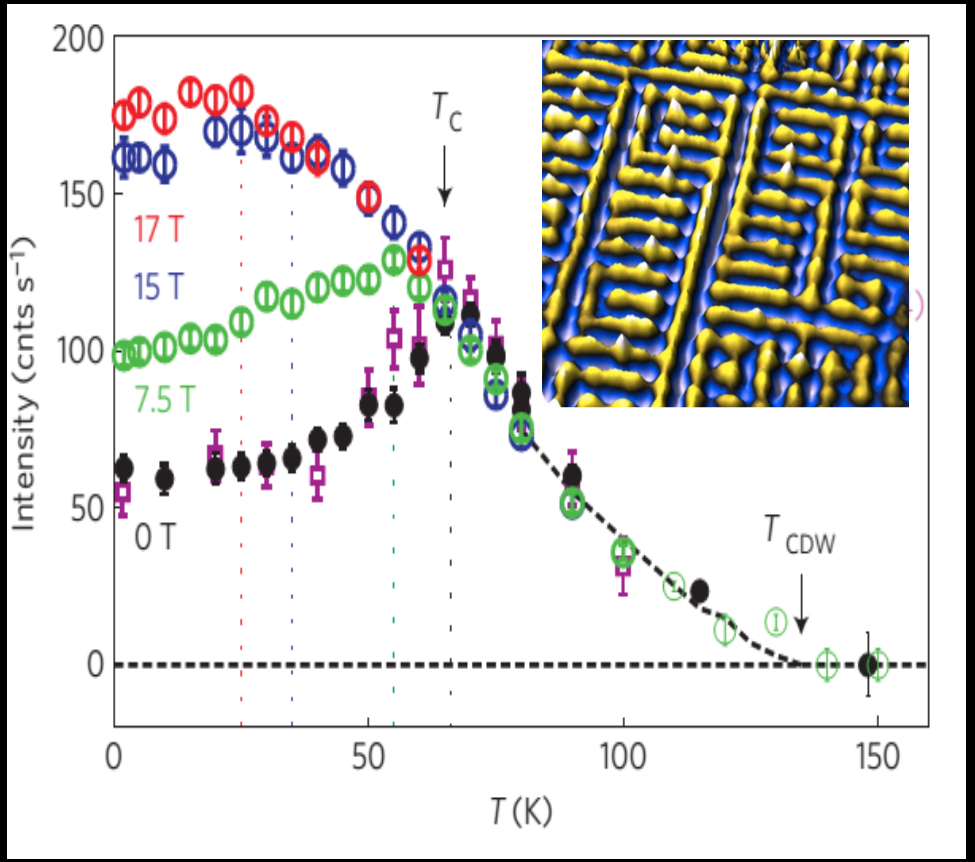
S. Blanco Canosa *et al. PRL*110, 187001 (2013)

T. Wu *et al. Nat Comm.* 6, 1 (2015)

S. Gerber *et al. Science* 350, 949 (2015)

J. Chang *et al Nature Comm.* 7, 11494 (2016)

H. Jang *et al. PNAS* 113 14645–14650 (2016)



Chang *et al*. *Nat Phys* 8, 871 (2012)

CDW $\langle c^{\dagger}_{k\uparrow}, c_{k+Q_C\downarrow}\rangle$ or PDW $\left\langle c^{\dagger}_{k\uparrow}, c^{\dagger}_{-k+Q_P\downarrow}\right\rangle$?

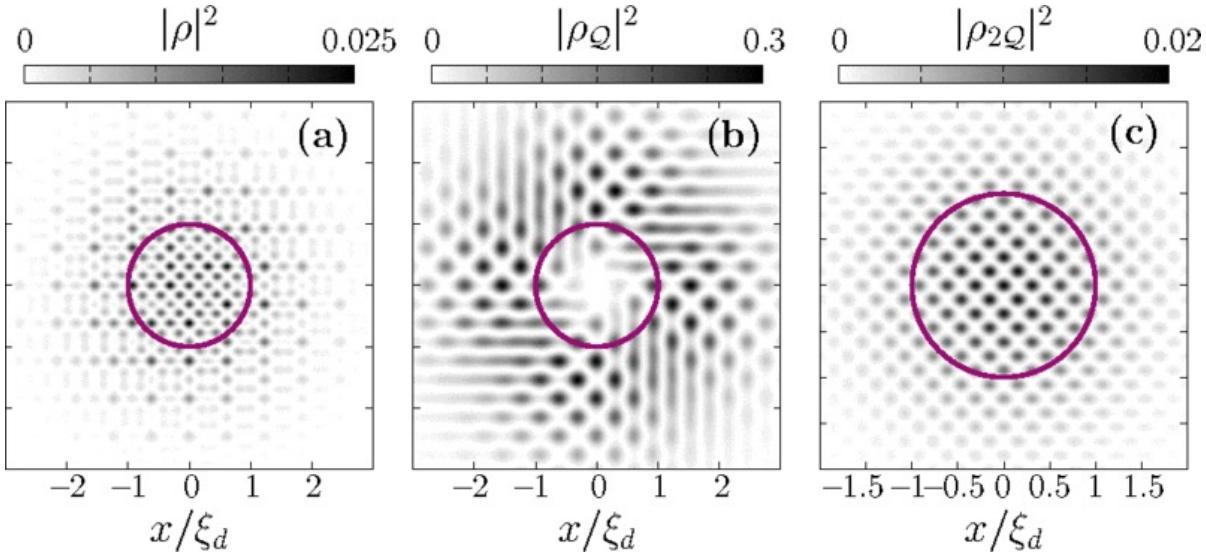
PDW @ VORTEX HALO ⇒ Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

PHYSICAL REVIEW B **91**, 104512 (2015)

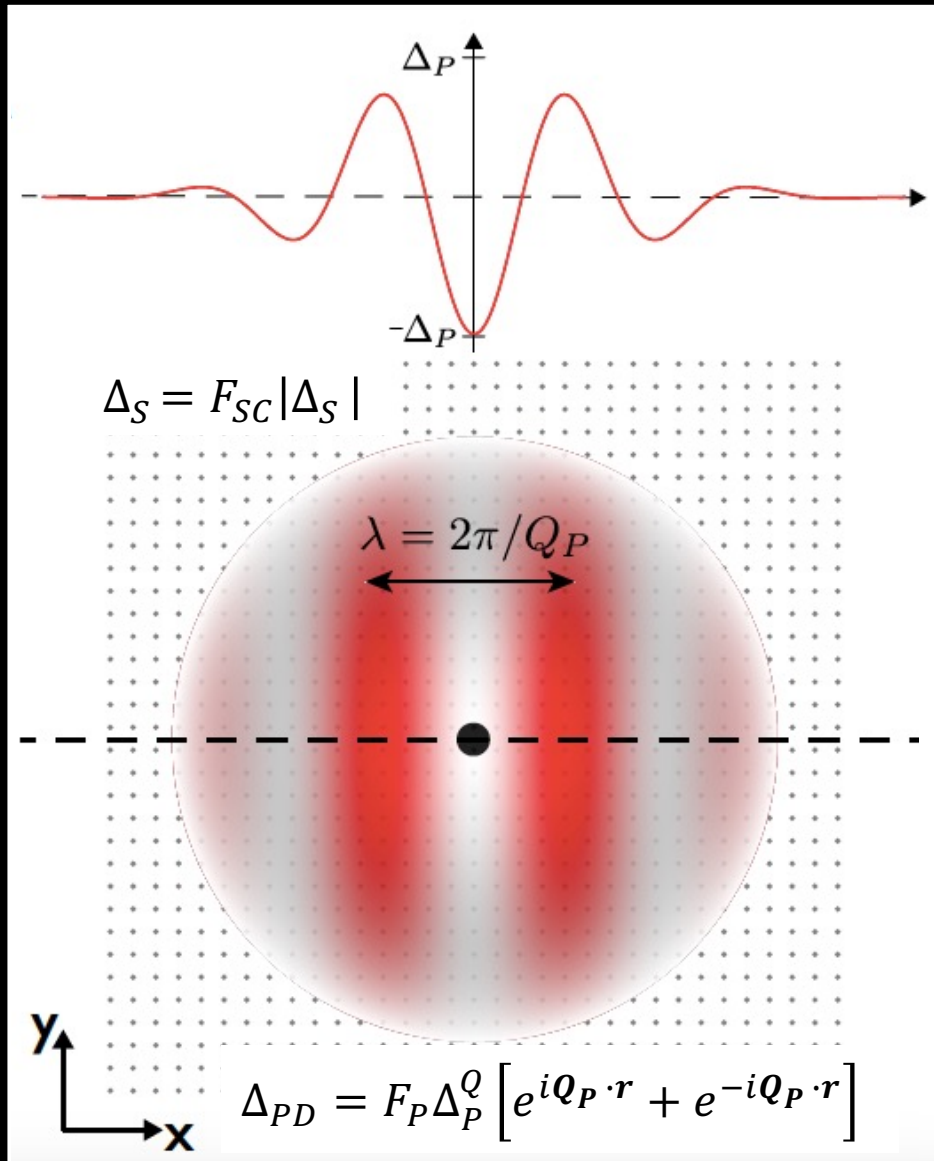
Checkerboard order in vortex cores from pair-density-wave superconductivity

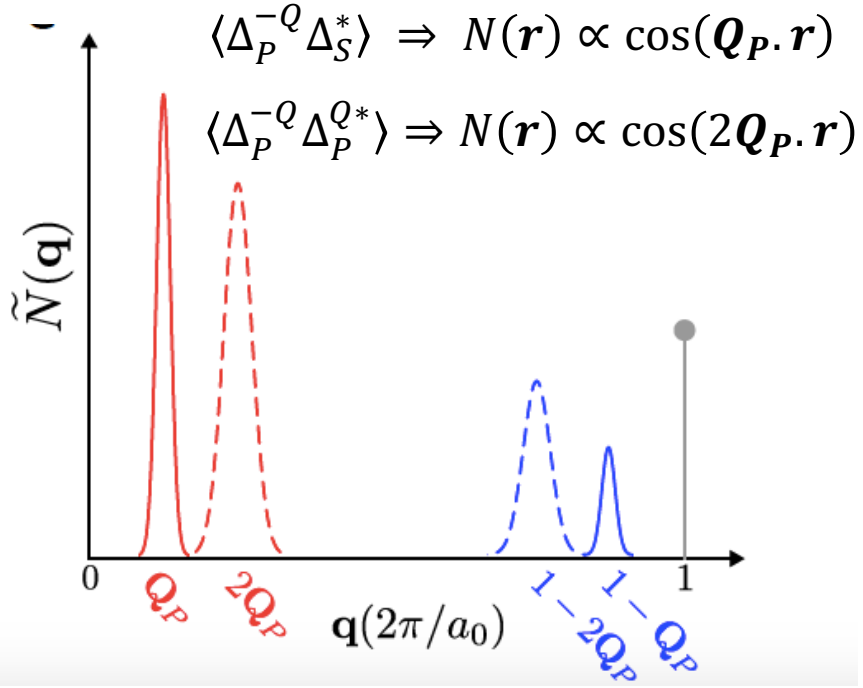
Daniel F. Agterberg[1] and Julien Garaud[2,*]
[1]*Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53211, USA*
[2]*Department of Theoretical Physics, KTH-Royal Institute of Technology, Stockholm, SE-10691 Sweden*
(Received 16 December 2014; revised manuscript received 26 February 2015; published 16 March 2015)

We consider competing pair-density-wave (PDW) and d-wave superconducting states in a magnetic field. We show that PDW order appears in the cores of d-wave vortices, driving checkerboard charge-density-wave (CDW) order in the vortex cores, which is consistent with experimental observations. Furthermore, we find an additional CDW order that appears on a ring outside the vortex cores. This CDW order varies with a period that is twice that of the checkerboard CDW and it only appears where both PDW and d-wave order coexist. The observation of this additional CDW order would provide strong evidence for PDW order in the pseudogap phase of the cuprates. We further argue that the CDW seen by nuclear magnetic resonance at high fields is due to a PDW state that emerges when a magnetic field is applied.

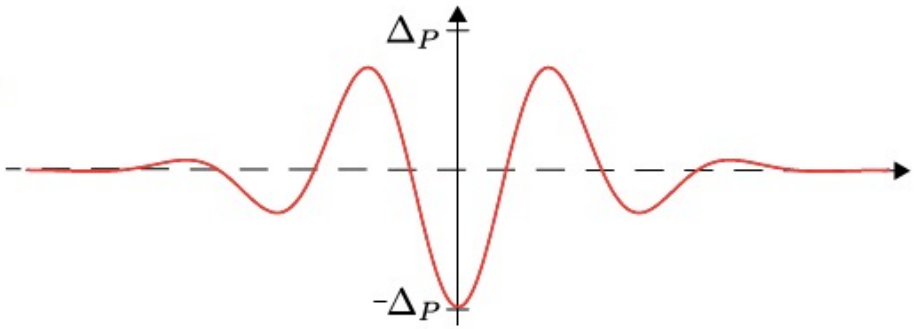


PDW @ VORTEX HALO ⇒ Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS



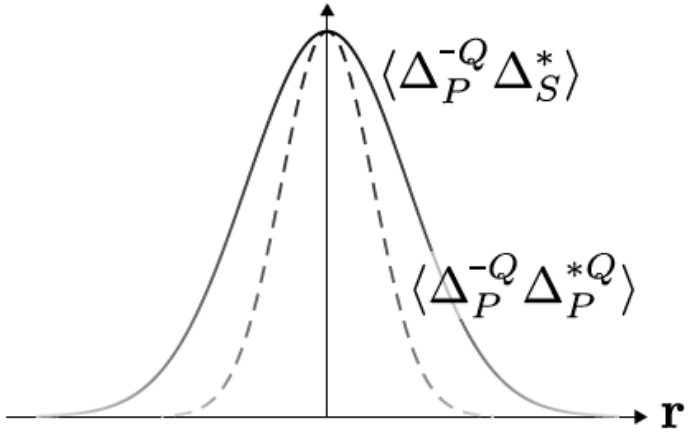


PDW IN VORTEX HALO ⇒ EXPECTED PHENOMENOLOGY



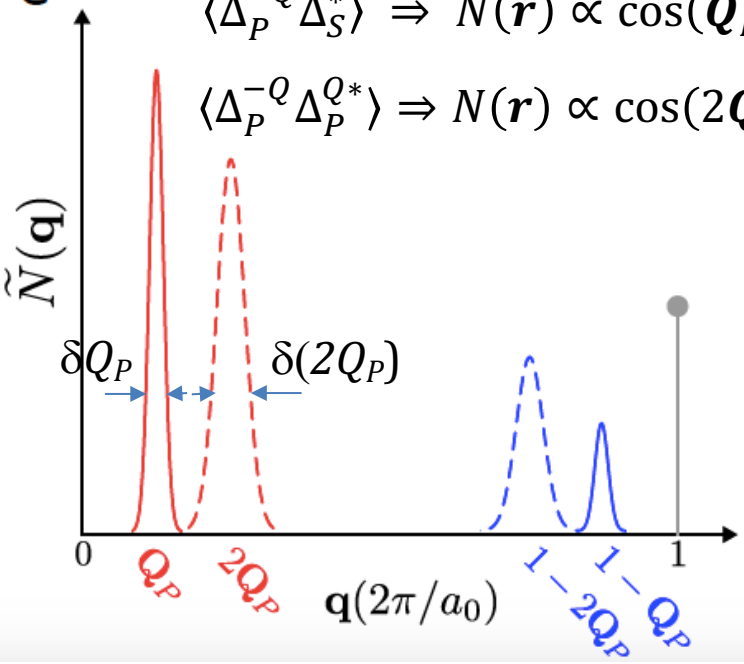
$$\Delta_S = F_{SC}|\Delta_S|$$

$$\Delta_P^Q = F_P|\Delta_P|\left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$



$$\langle\Delta_P^{-Q}\Delta_S^*\rangle \Rightarrow N(\boldsymbol{r}) \propto \cos(\boldsymbol{Q_P}.\boldsymbol{r})$$

$$\langle\Delta_P^{-Q}\Delta_P^{Q*}\rangle \Rightarrow N(\boldsymbol{r}) \propto \cos(2\boldsymbol{Q_P}.\boldsymbol{r})$$

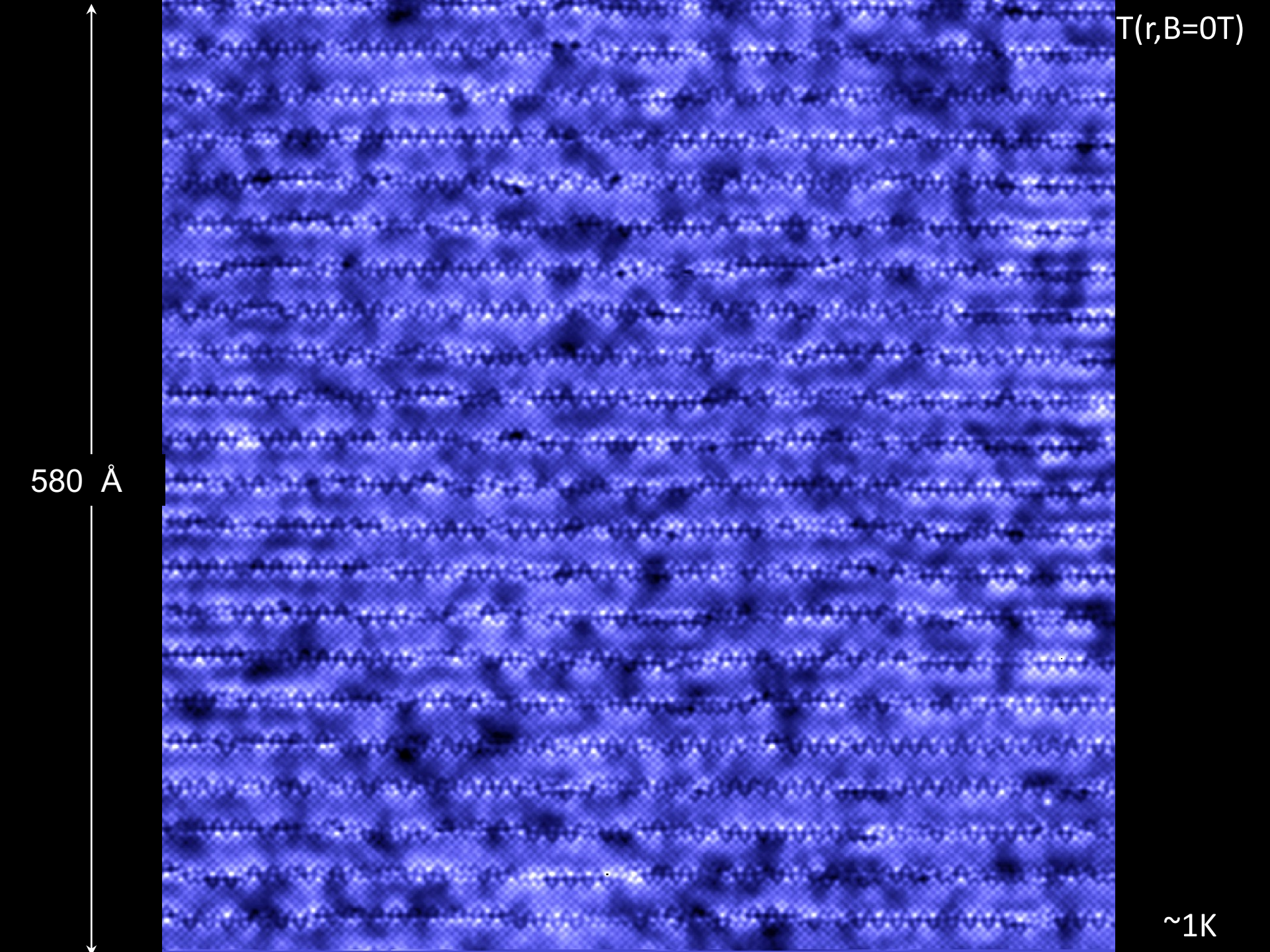


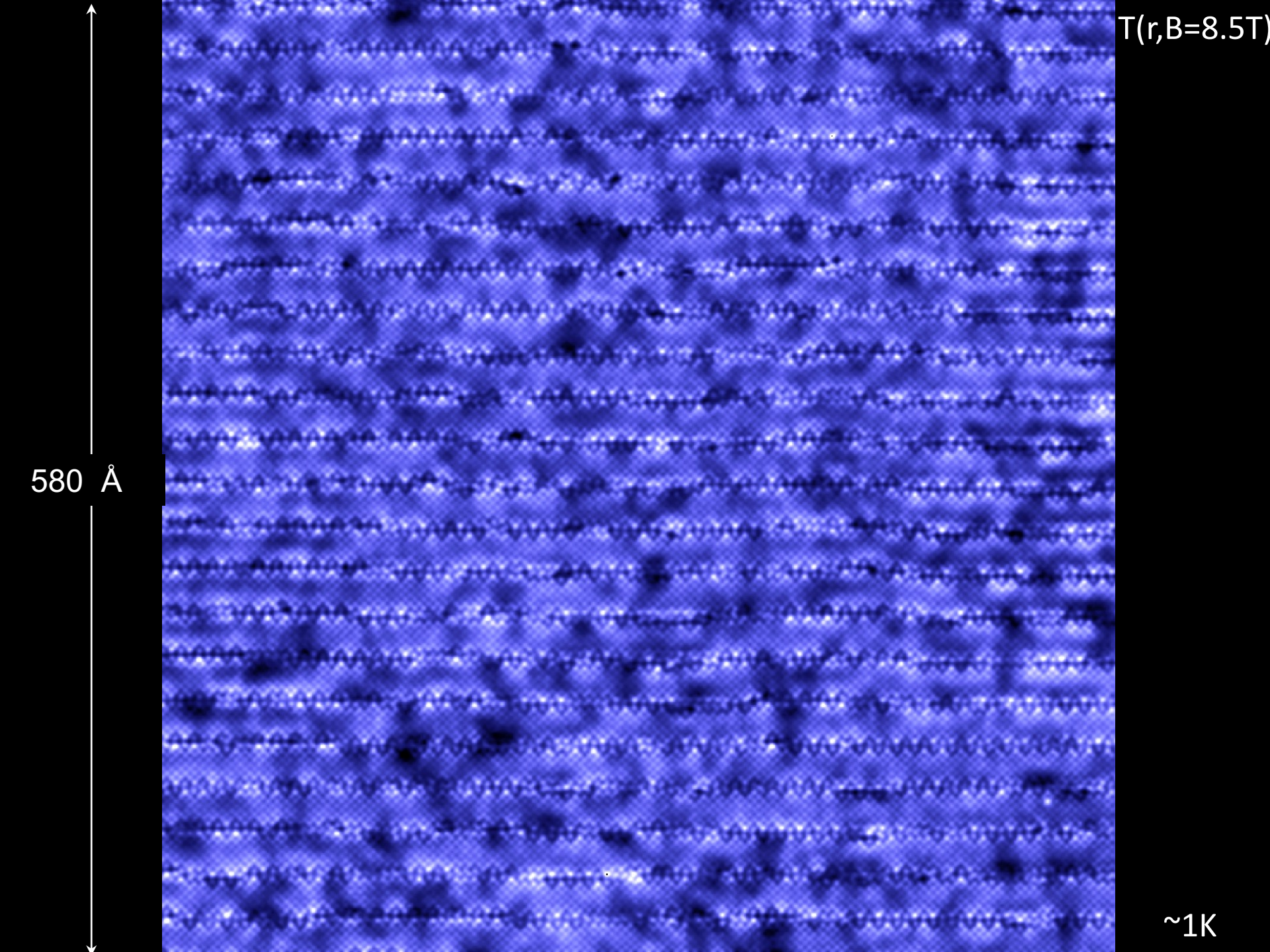
PDW Q_P WITHIN VORTEX HALO

Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

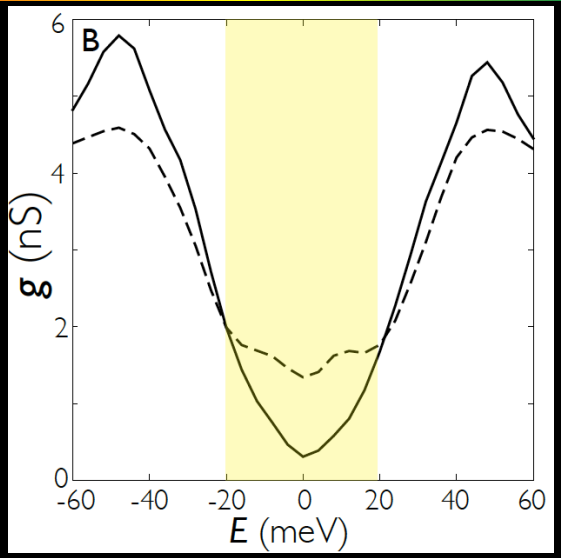
d-SYMMETRY PDW ⇒ *s*-SYMMETRY MODS

MODULATION LINEWIDTHS: $\delta(2Q_P) = 2(\delta Q_P)$


T(r,B=0T)
580 Å
~1K


T(r,B=8.5T)
580 Å
~1K

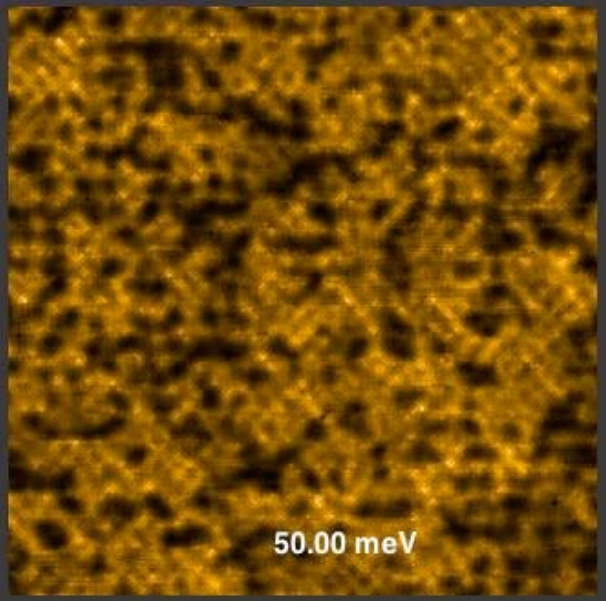
FIELD-INDUCED CHANGES TO ELECTRONIC STRUCTURE @ HALO

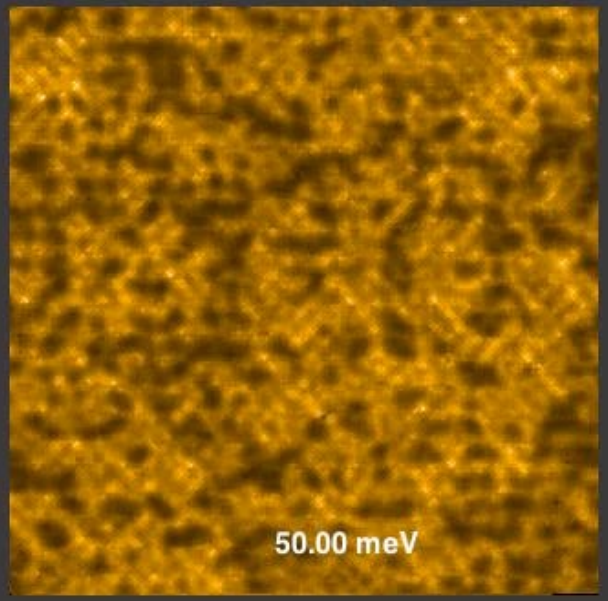


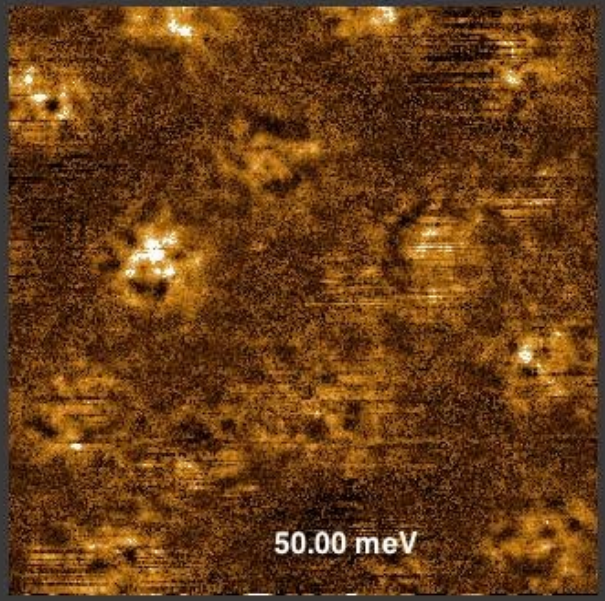
g(B=8.5T)

g (B=0T)

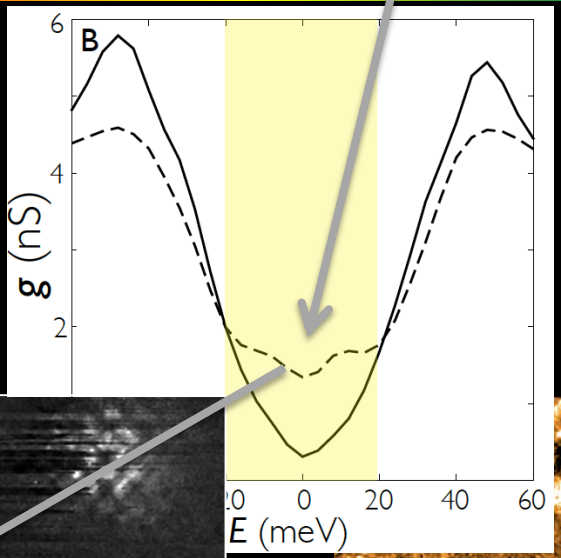
δg

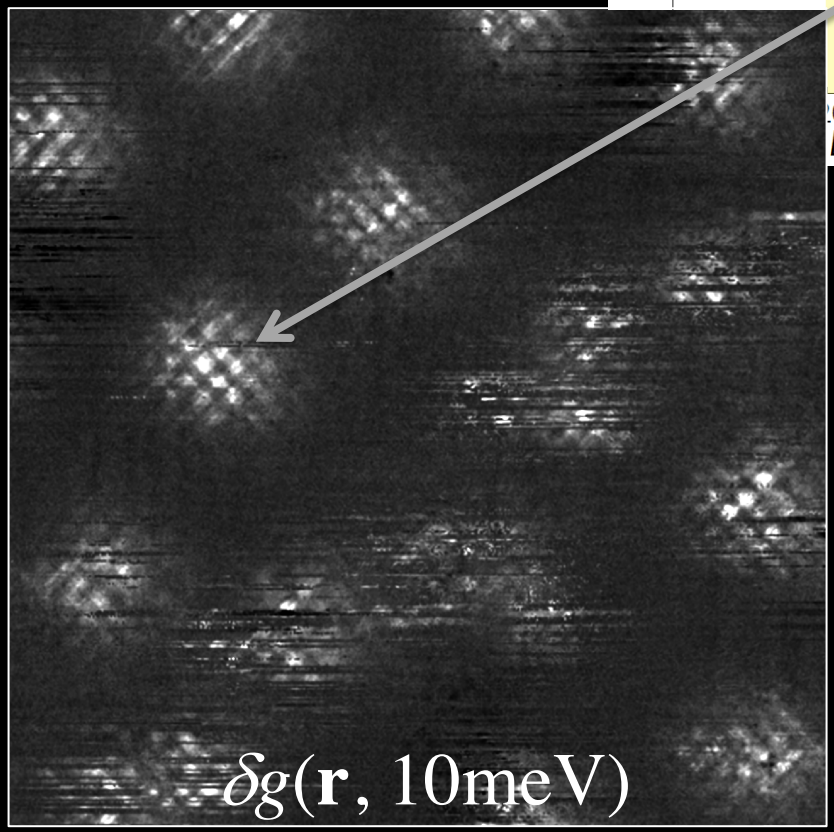


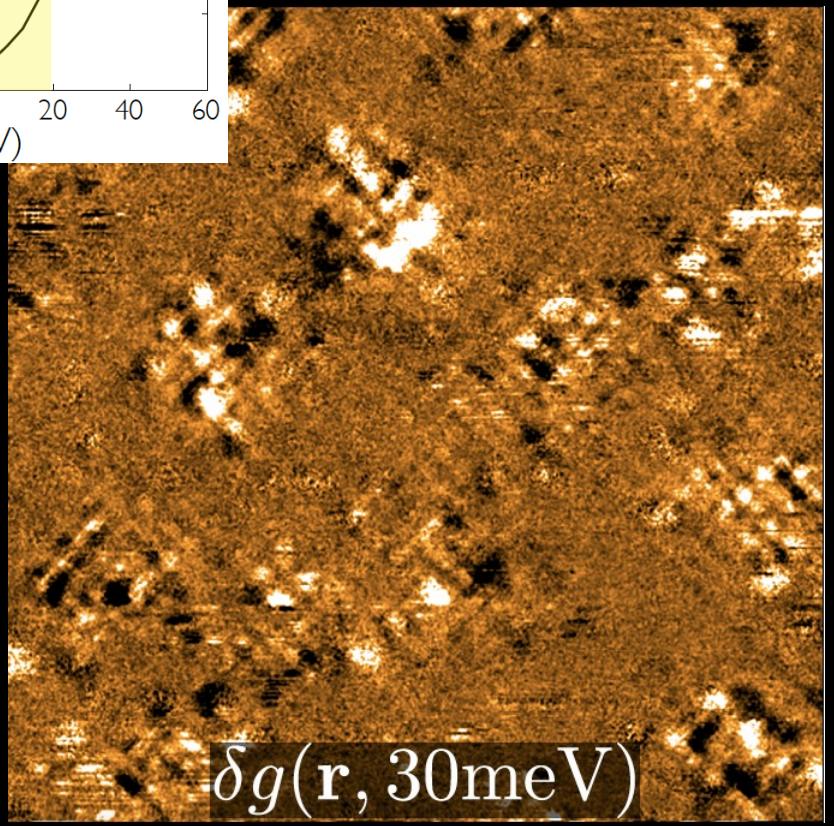




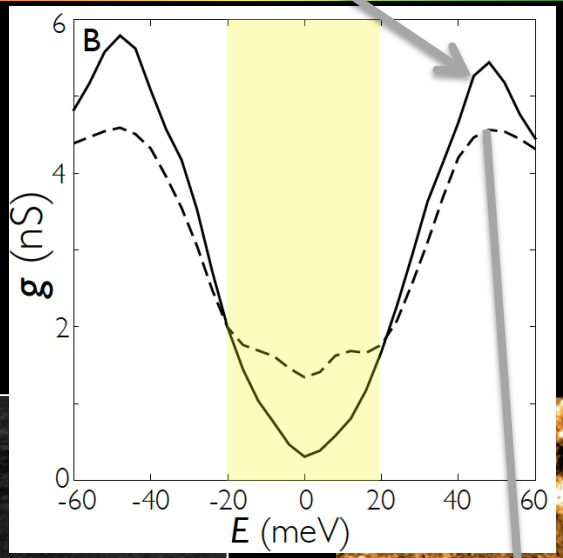
NODAL BOGOLIUBOV QUASIPARTICLES

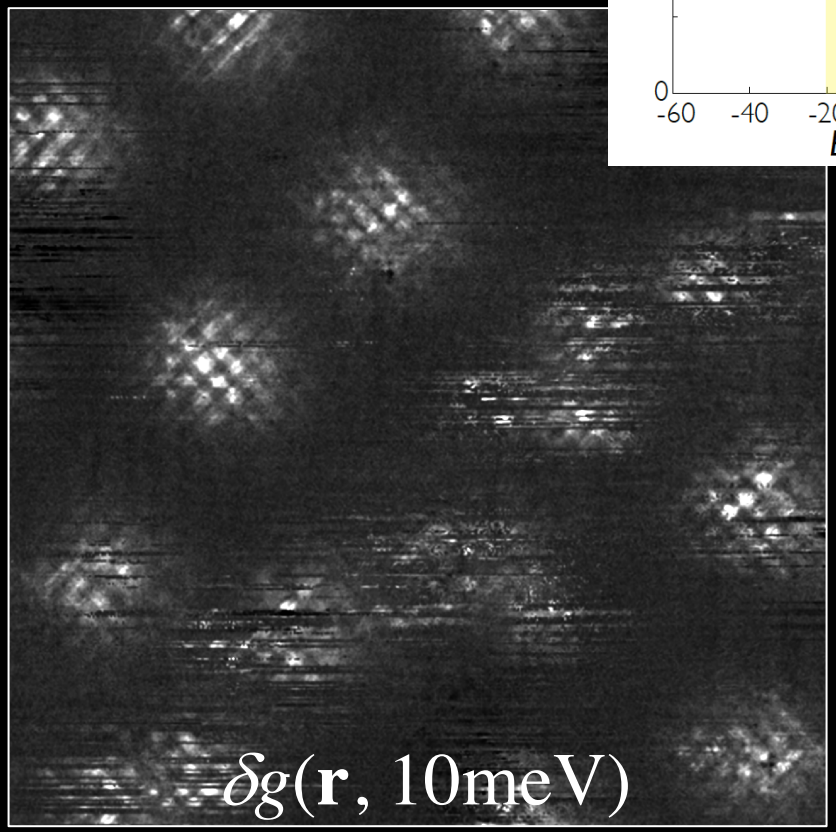


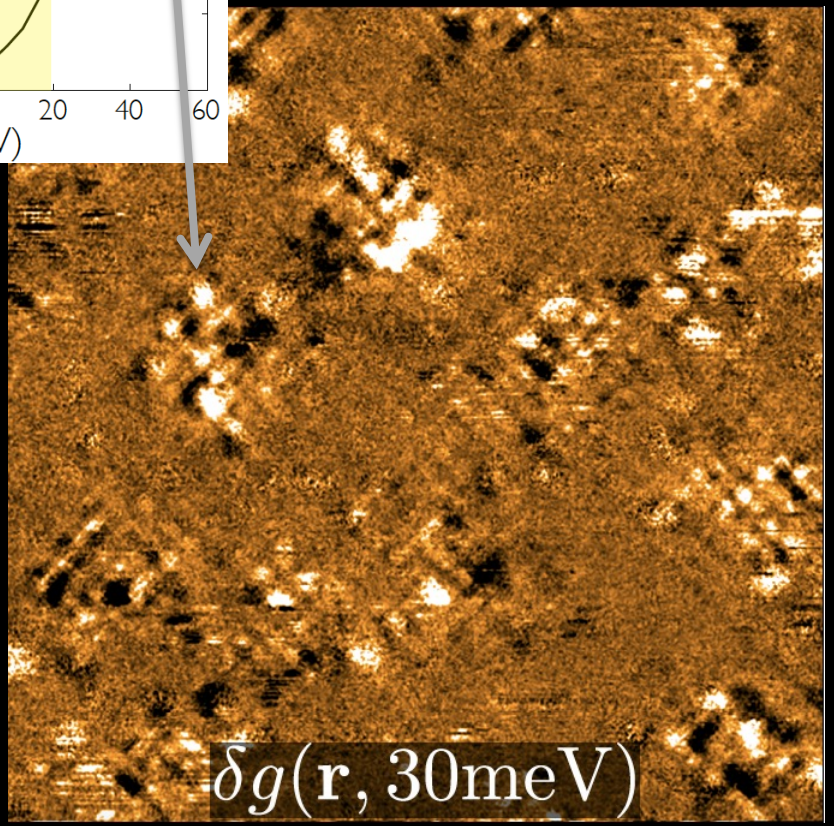




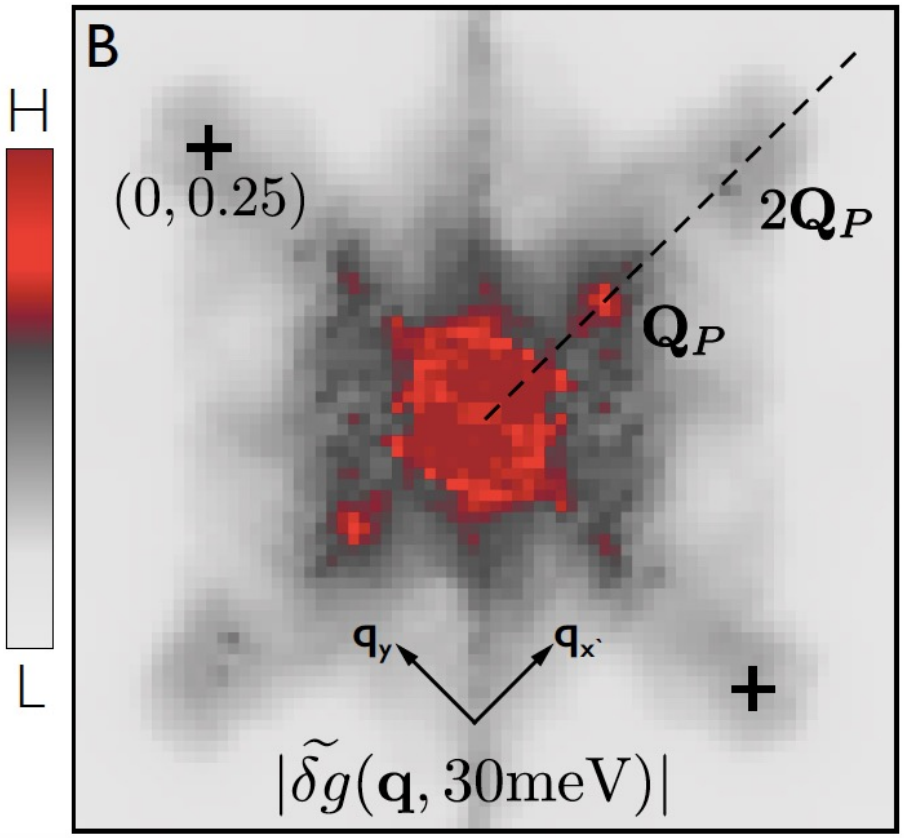
GAP EDGE STATES

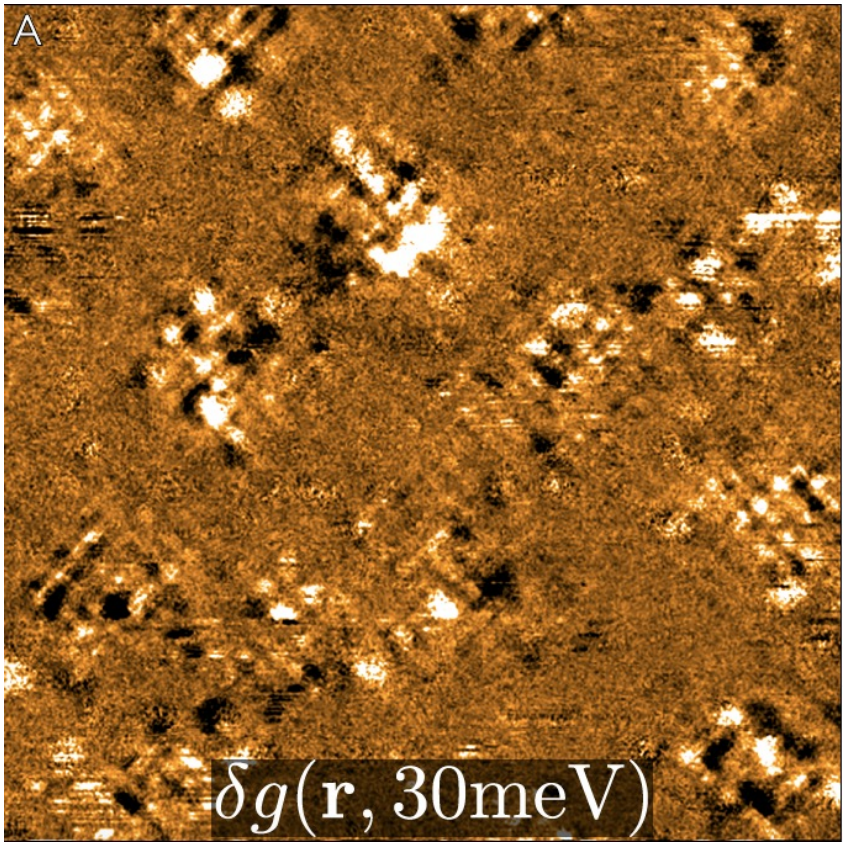






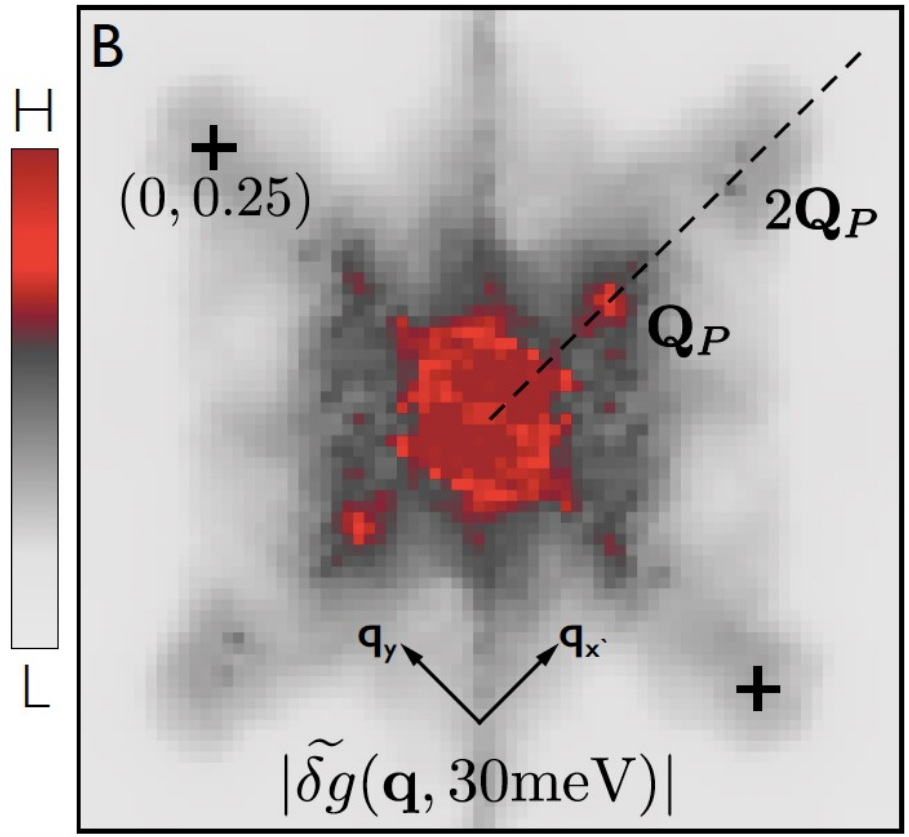
FIELD-INDUCED N(***r***,E~Δ) MODULATIONS

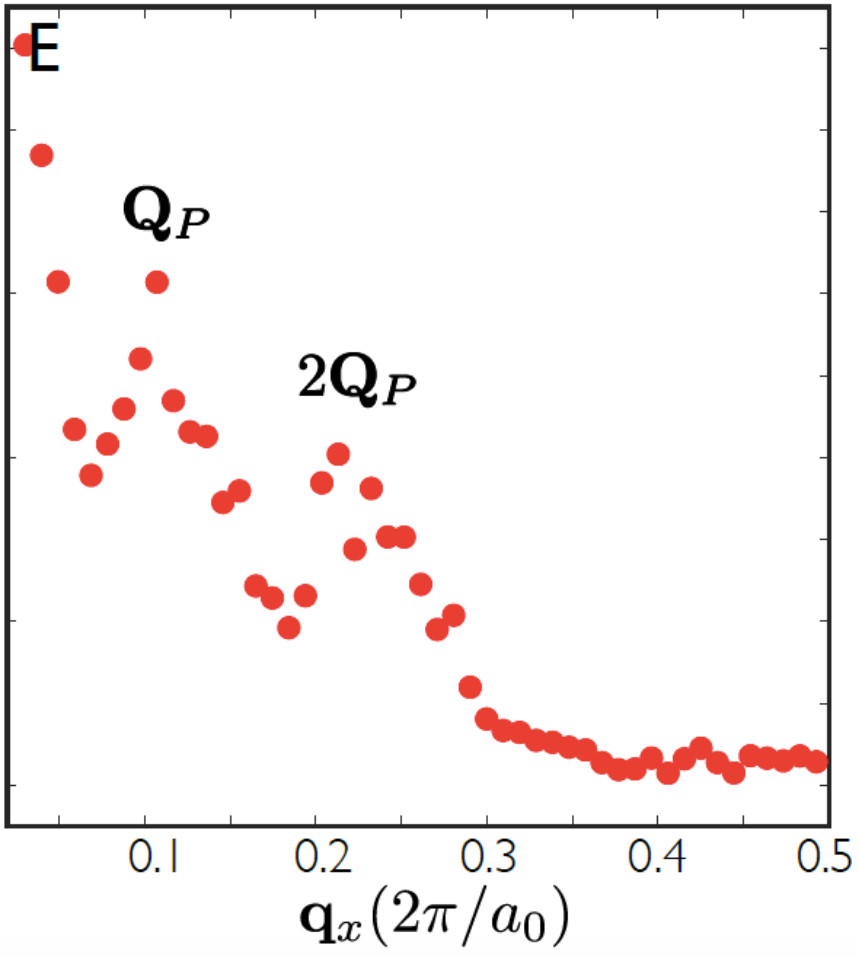




Science 364, 976 (2019)

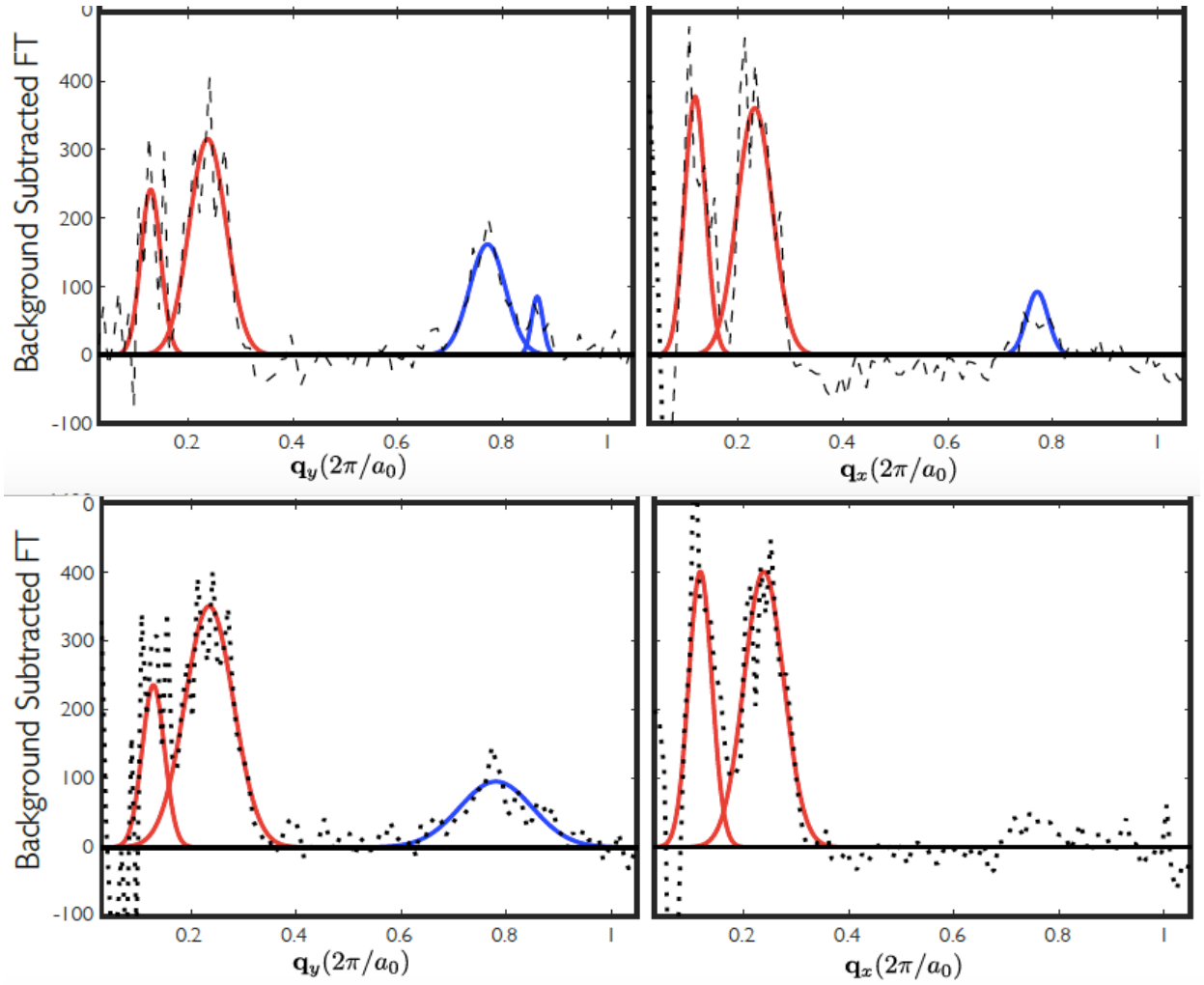
FIELD-INDUCED N(***r***,E~Δ) MODULATIONS : PEAKS at Q_P and $2Q_P$

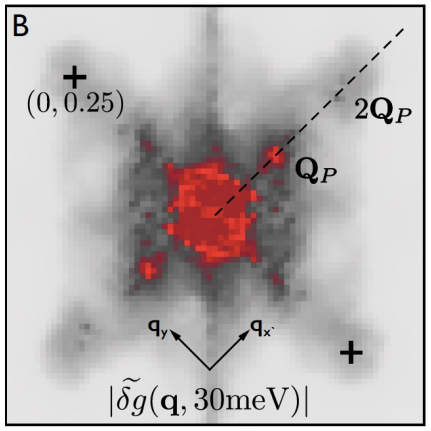


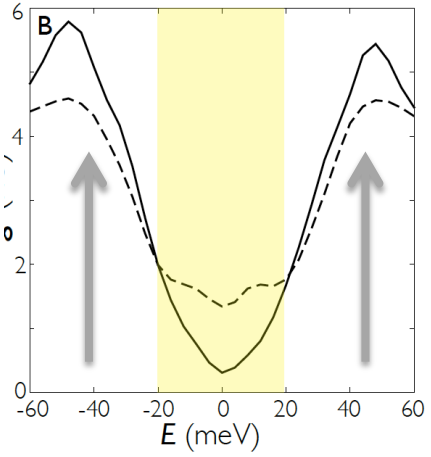


Science 364, 976 (2019)

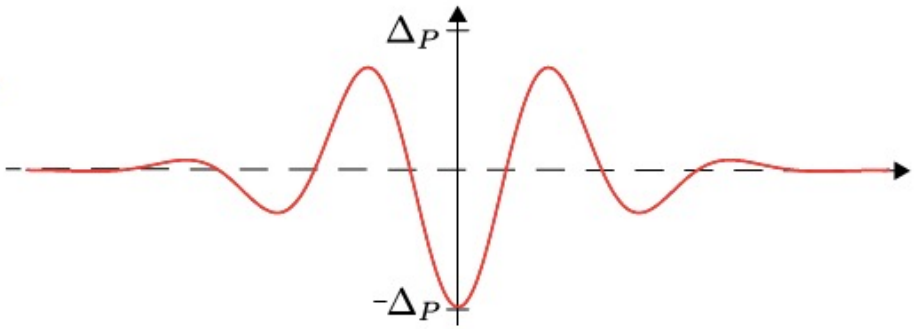
FIELD-INDUCED N($\boldsymbol{r}$,E~Δ) MODS Q_P AND $2Q_P$ $\rightleftarrows$ $\delta(2Q_P) \approx 2\delta(Q_P)$







VORTEX HALO ⇒ OBSERVED PHENOMENOLOGY



$$\Delta_S = F_{SC}|\Delta_S|$$

$$\Delta_{PD} = F_P \Delta_P^Q \left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$

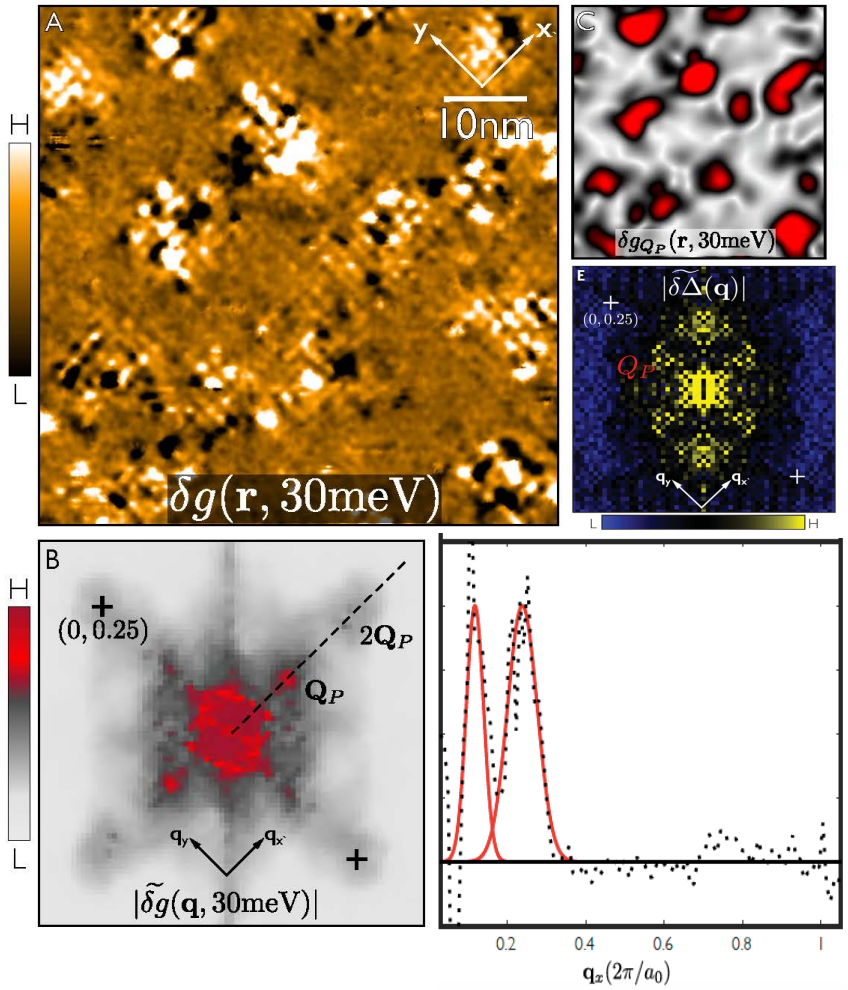
<u>PDW Q_P WITHIN VORTEX HALO</u>

Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

d-SYMMETRY PDW ⇒ *s*-SYMMETRY MODS

MODULATION LINEWIDTHS: $\delta(2Q_P) = 2(\delta Q_P)$

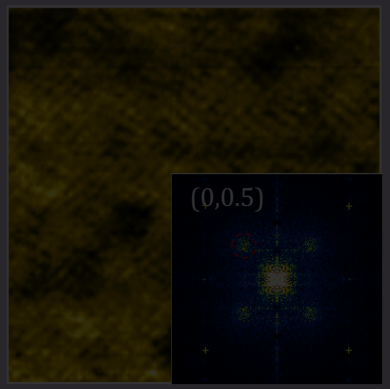
8a0 PERIODIC ENERGY GAP MODULATIONS



PRB 91, 104512 (2015); *PRB 97,* 174510 (2018); *PRB 97,* 174511 (2018); ***Science 364***, 976 (2019)

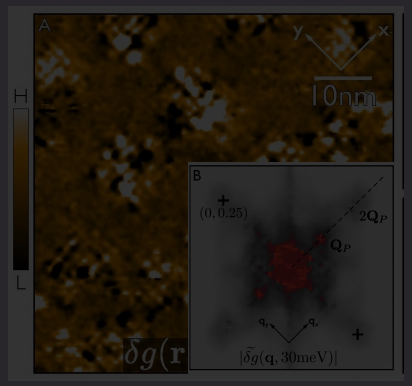
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



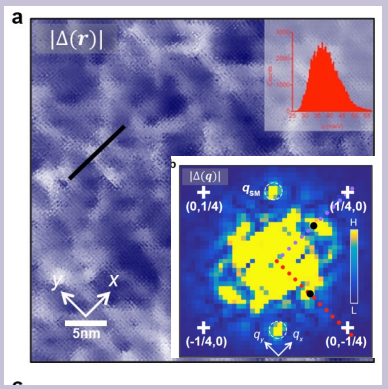
Nature **532**, 343 (2016)

VORTEX HALO



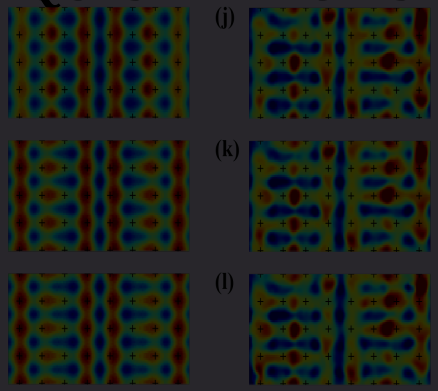
Science **364**, 976 (2019)

ENERGY GAP



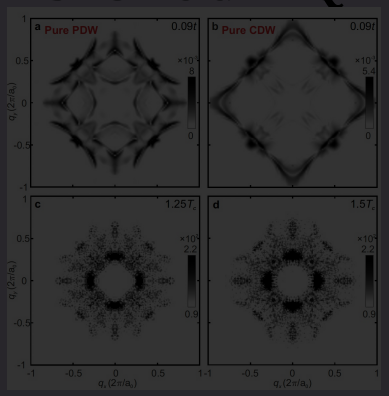
***Nature* 580,** 6570 (2020)

QUASIPARTICLES



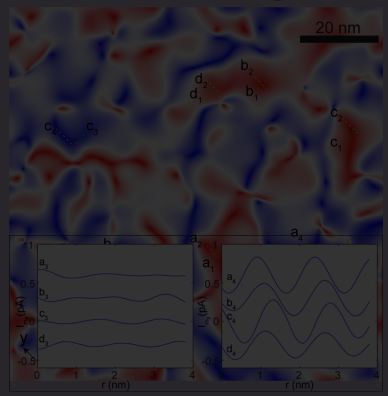
***PNAS* 117**, 14850 (2020)

PSEUDOGAP QPI

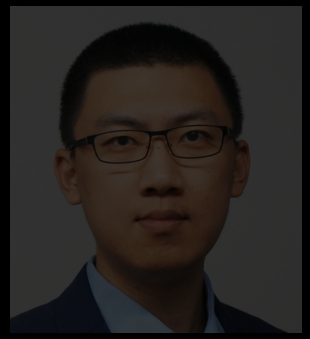


***Nat.Comm* 12**, 6087 (2021)

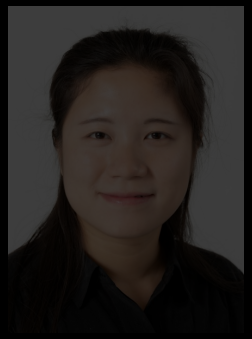
NEMATIC



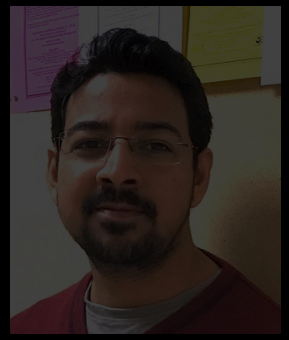
Weijiong Chen *et al* (2022)



Xiaolong Liu
Notre Dame

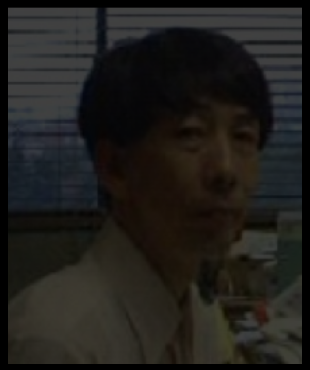


Shuqiu Wang
Oxford



P. Choubey
IIT Delhi

Weijiong Chen
Oxford



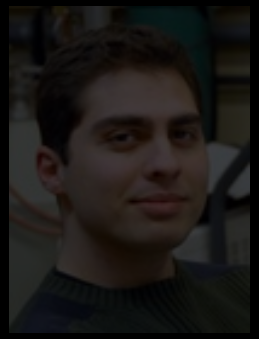
S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford

Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

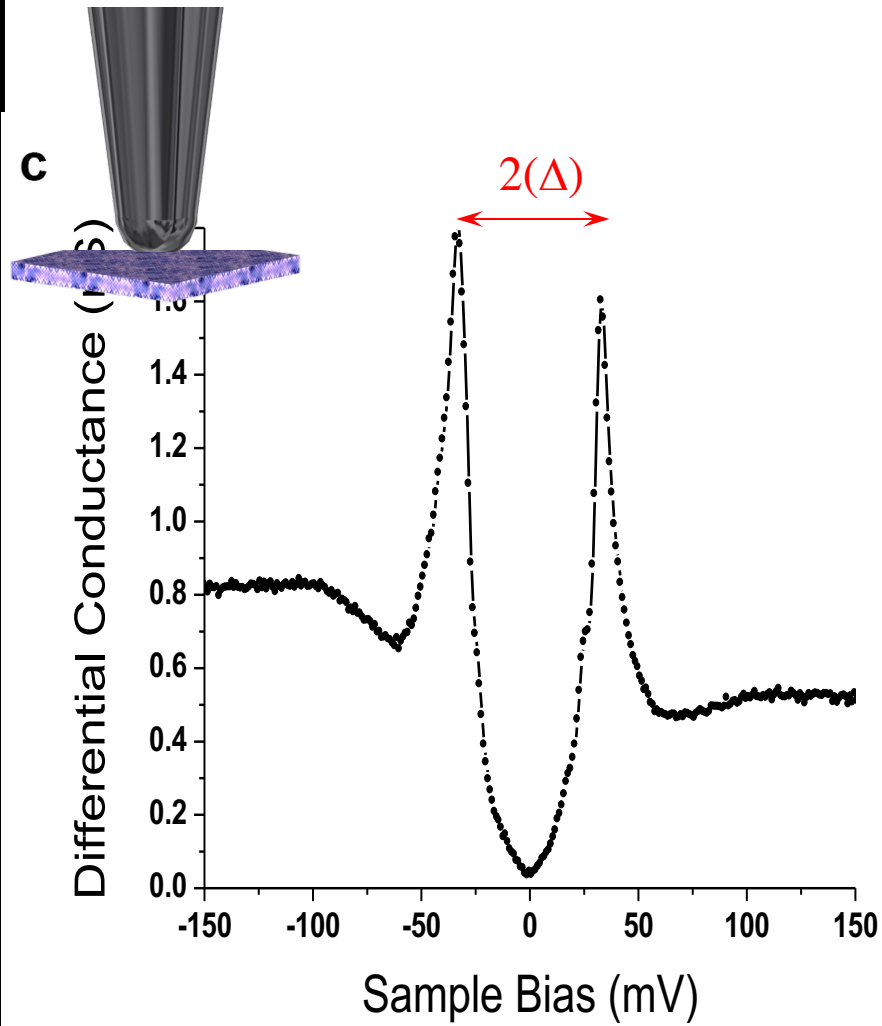


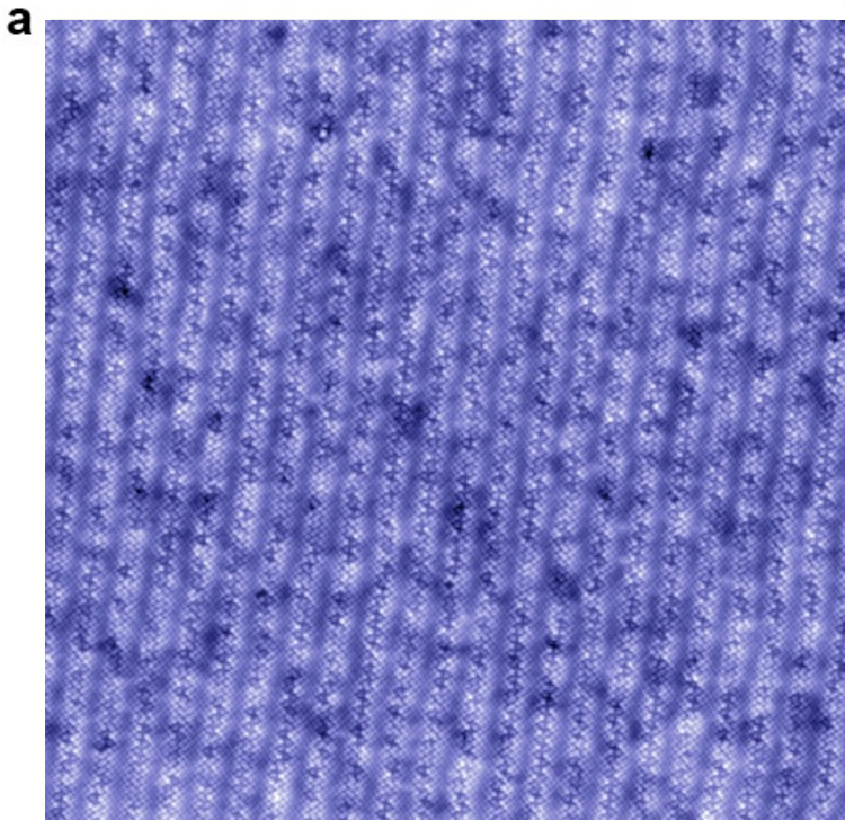
M. H. Hamidian
Cornell

S.D. Edkins
Cornell

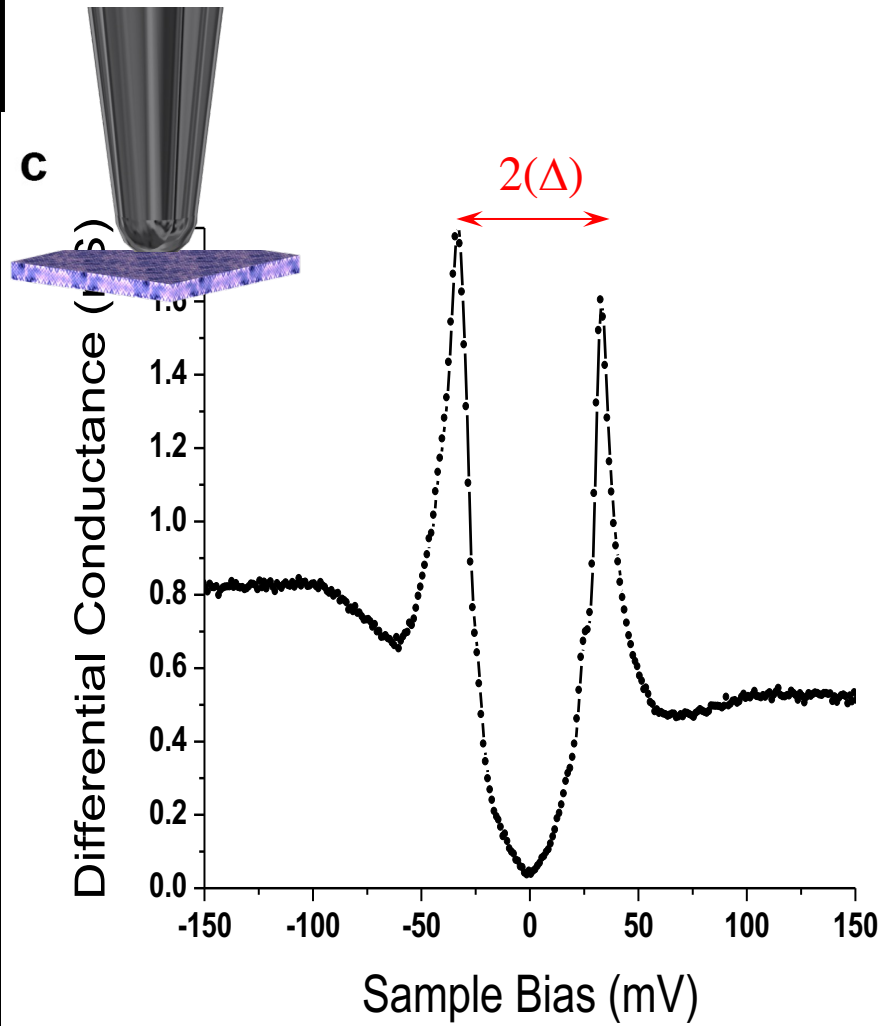
A.P. Mackenzie
Dresden

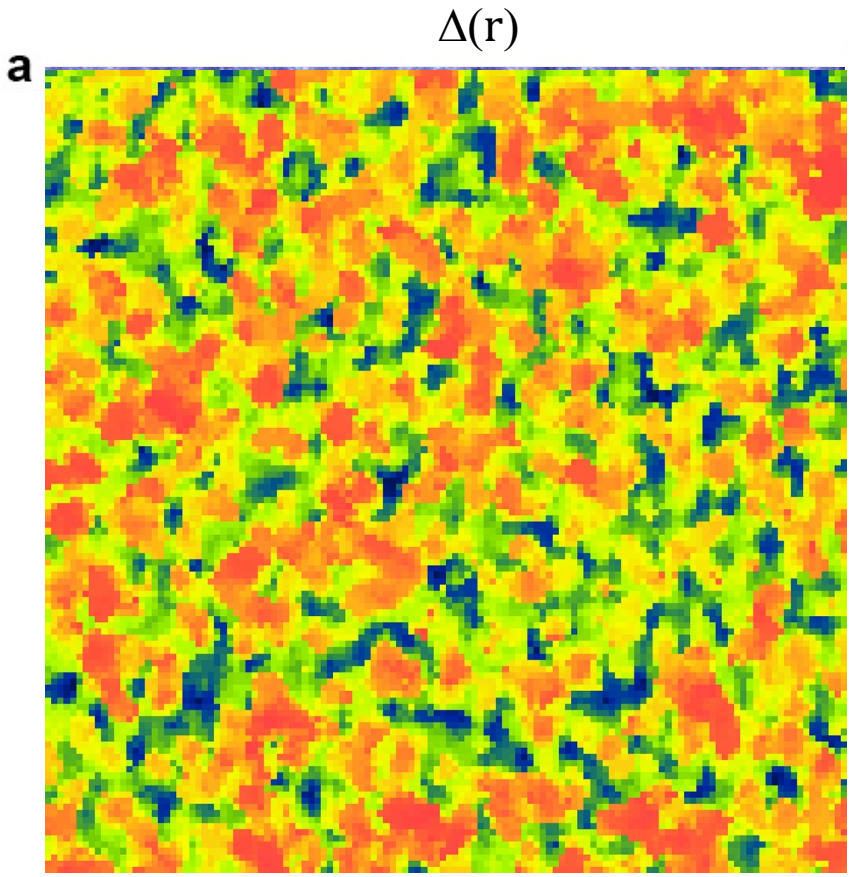
NORMAL TIP: NIS SINGLE-ELECTRON TUNNELING





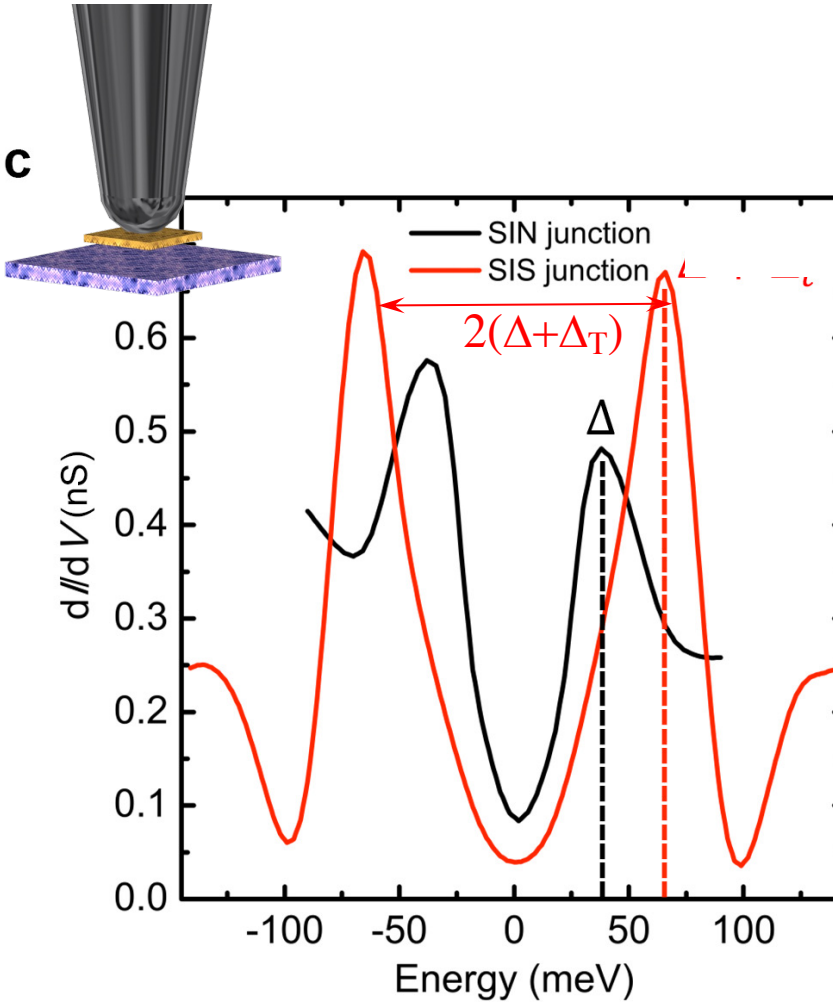
NORMAL TIP: NIS SINGLE-ELECTRON TUNNELING

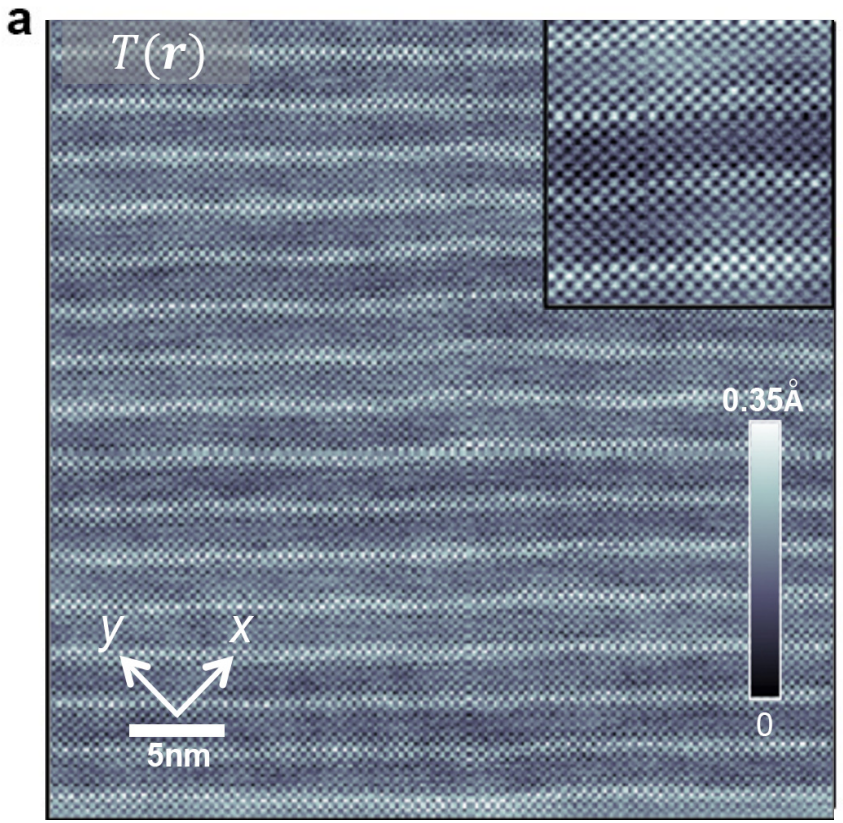




NO ENERGY GAP MODULATIONS OBSERVED

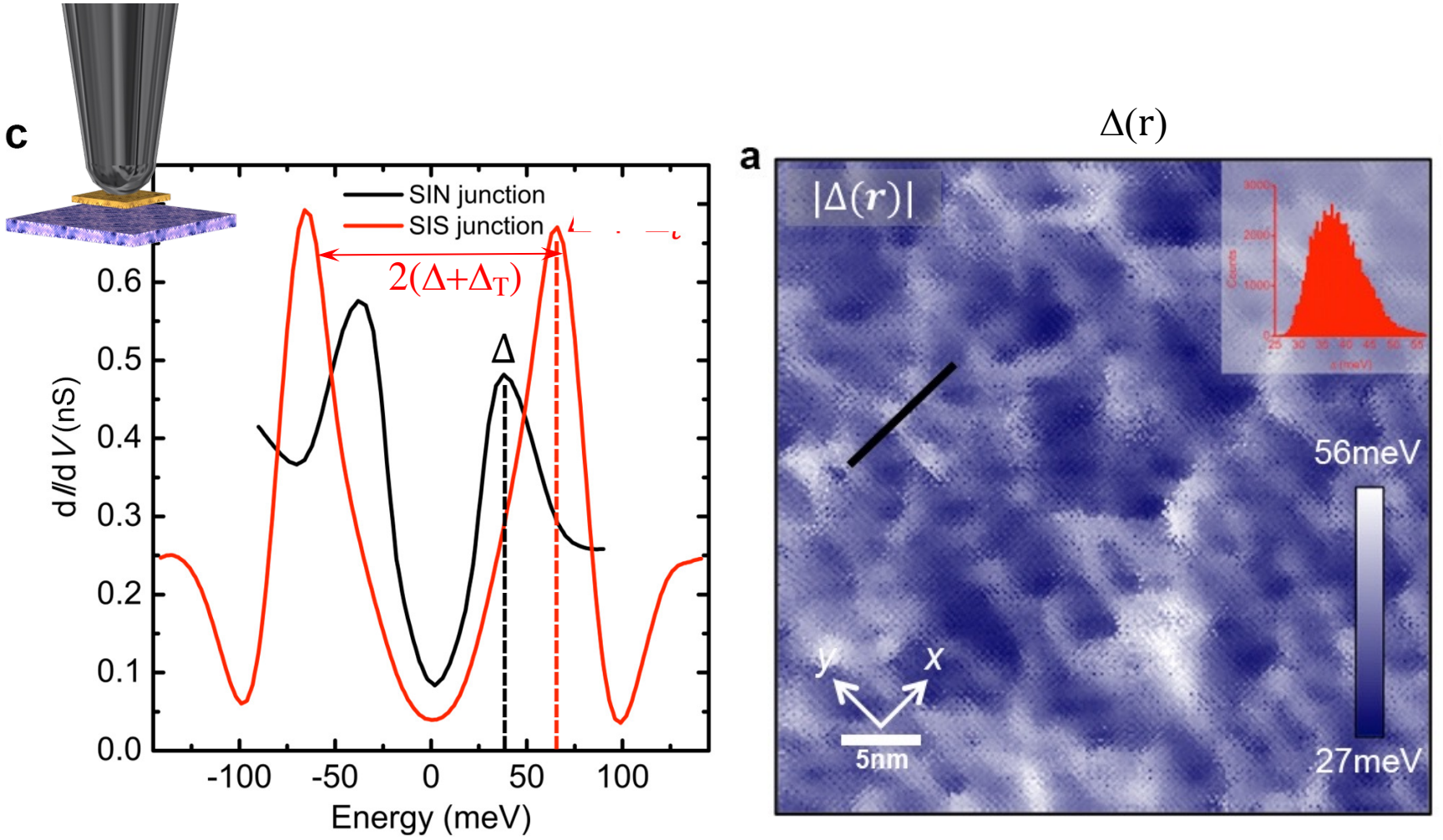
SUPERCOND TIP: SIS SINGLE-ELECTRON TUNNELING





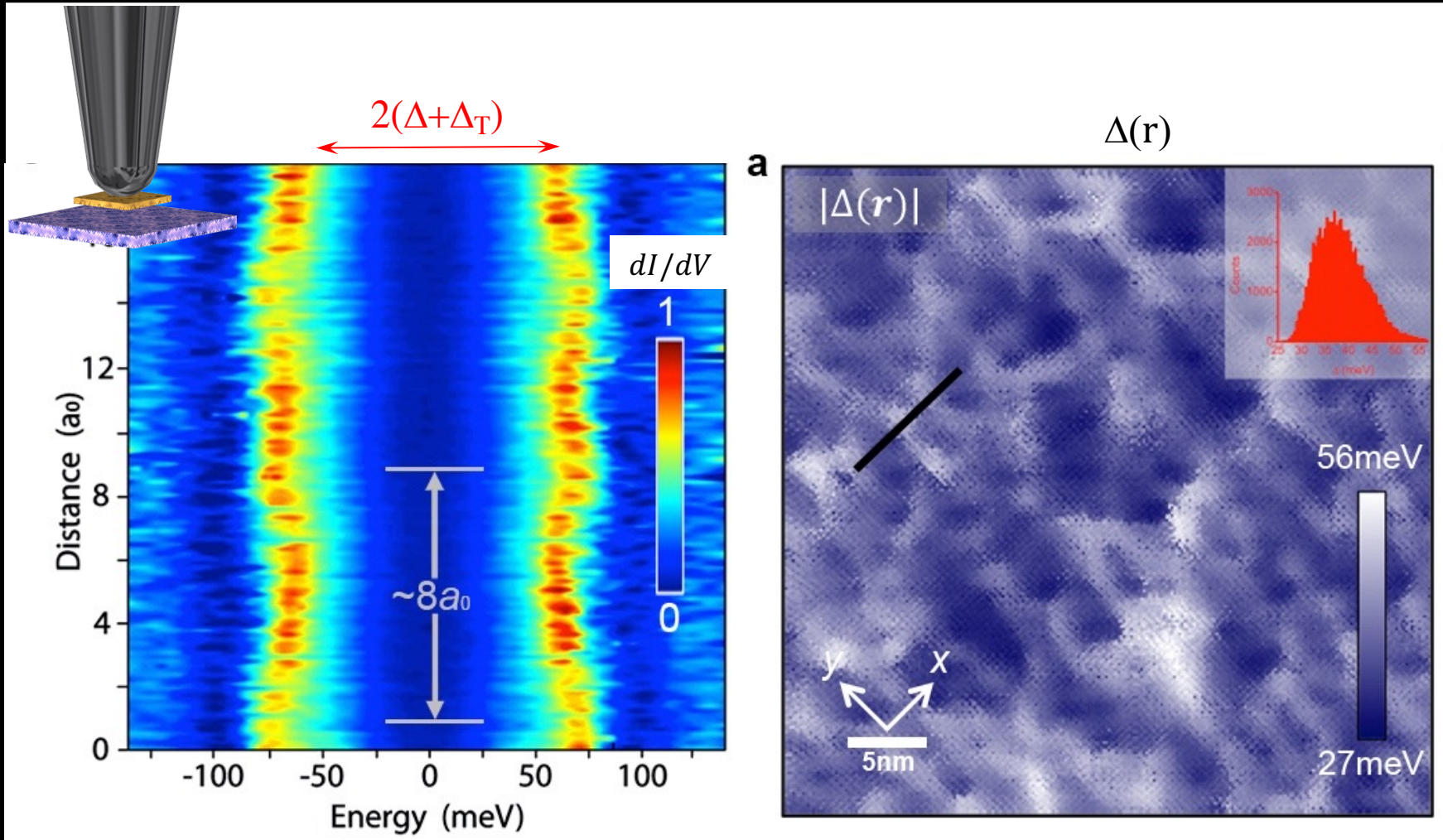
Nature 580, 6570 (2020)

SUPERCOND TIP: SIS SINGLE-ELECTRON TUNNELING



Nature 580, 6570 (2020)

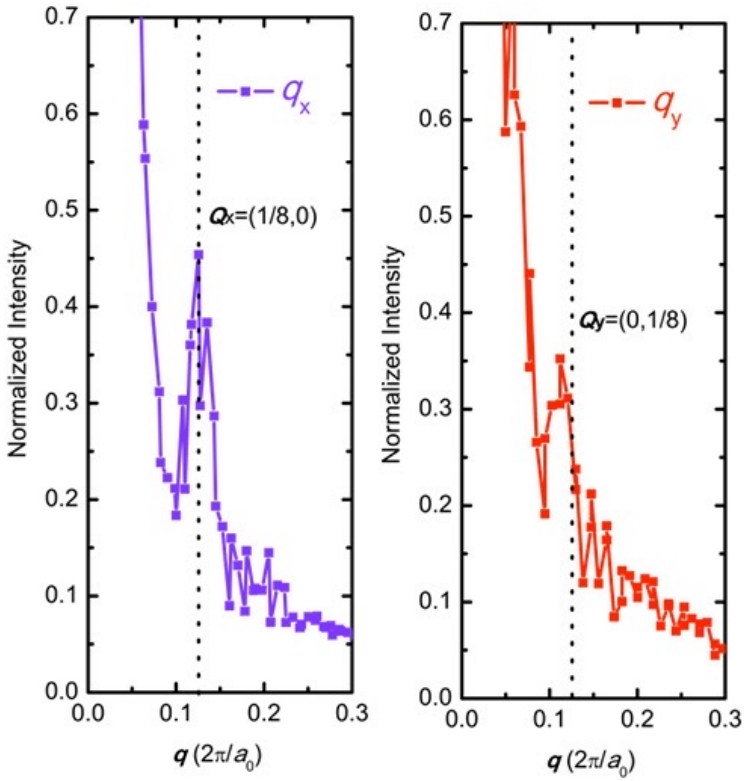
ELECTRON-PAIR ENERGY GAP MODULATION



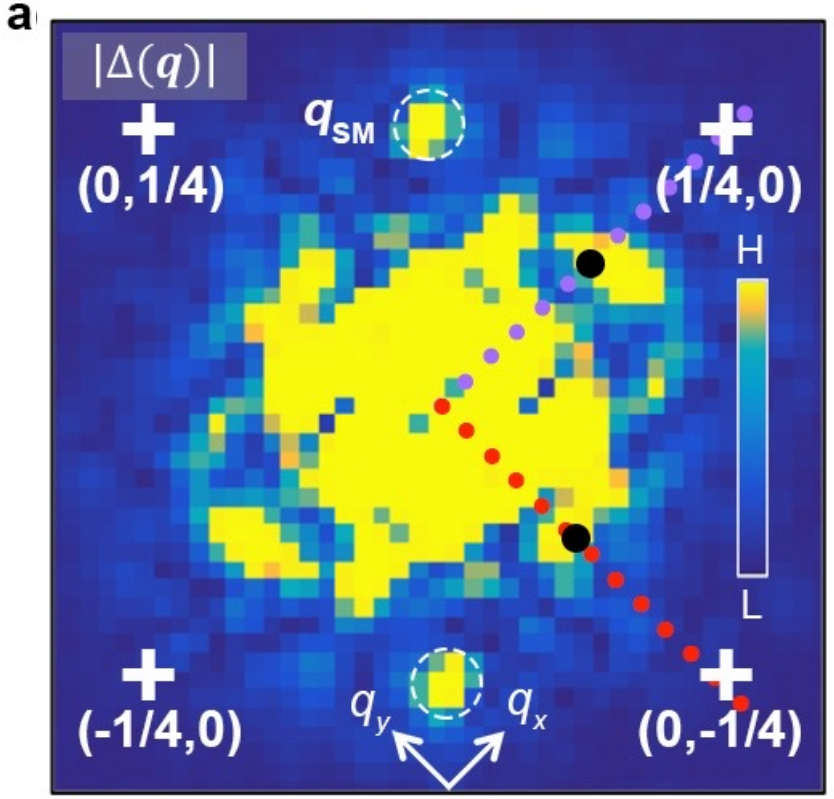
Nature 580, 6570 (2020)

ELECTRON-PAIR ENERGY GAP MODULATION

$Q = (0,1/8)2\pi/a_o ; (1/8,0)2\pi/a_o$



$\Delta(\boldsymbol{q})$

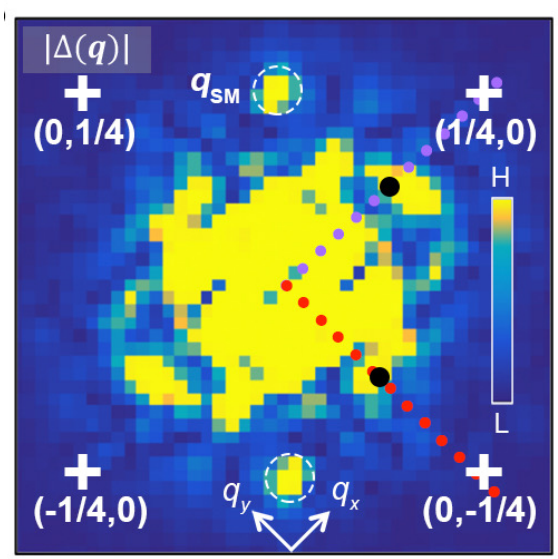


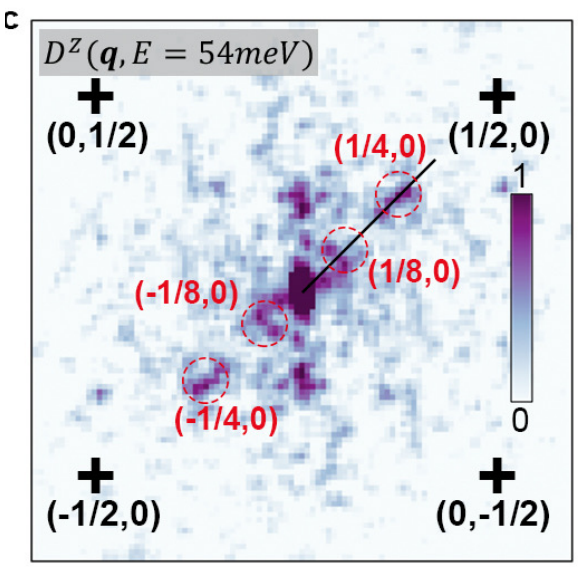
Nature 580, 6570 (2020)

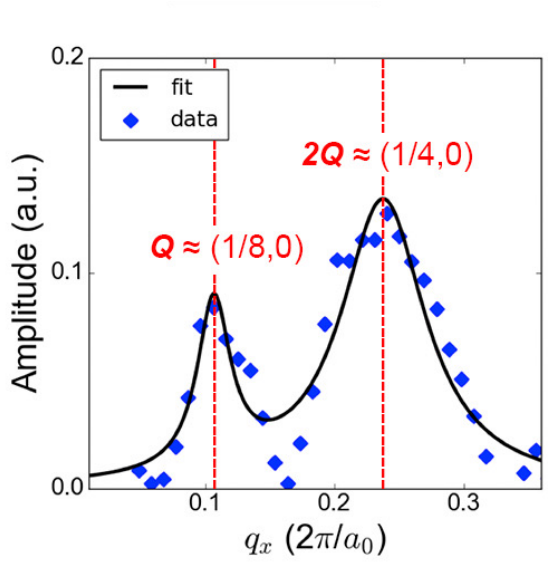
CDW APPEARS at $\boldsymbol{Q_P}$ and $\boldsymbol{2Q_P}$

$$\langle \Delta_P^{-Q} \Delta_S^{*} \rangle \Rightarrow N(\boldsymbol{r}) \propto \cos(\boldsymbol{Q_P}.\boldsymbol{r})$$

$$\langle \Delta_P^{-Q} \Delta_P^{Q*} \rangle \Rightarrow N(\boldsymbol{r}) \propto \cos(2\boldsymbol{Q_P}.\boldsymbol{r})$$



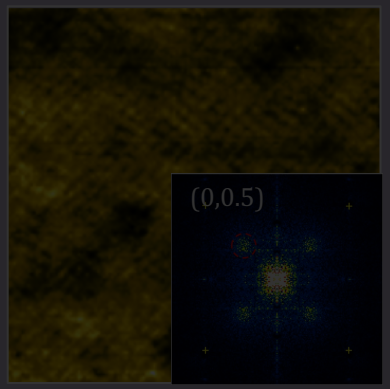




Nature 580, 6570 (2020)

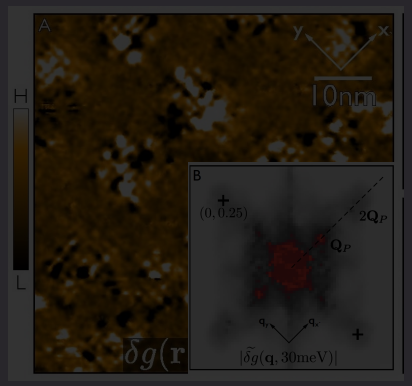
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



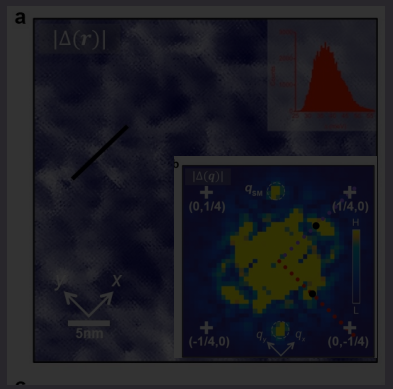
Nature 532, 343 (2016)

VORTEX HALO



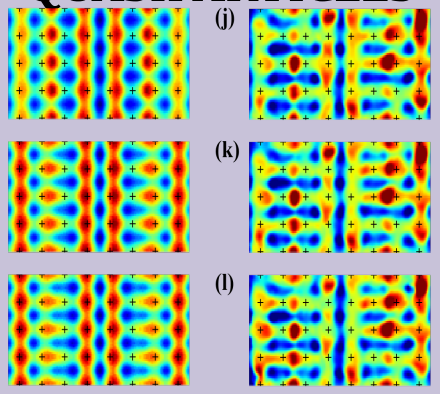
Science 364, 976 (2019)

ENERGY GAP



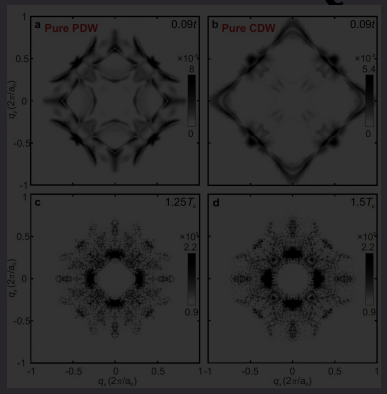
Nature 580, 6570 (2020)

QUASIPARTICLES



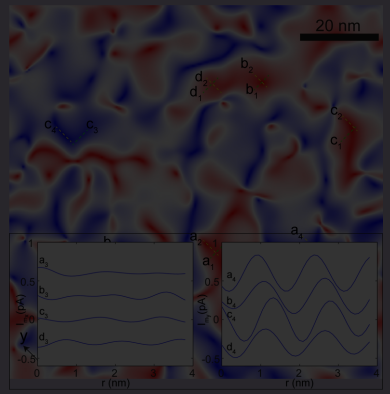
PNAS 117, 14850 (2020)

PSEUDOGAP QPI

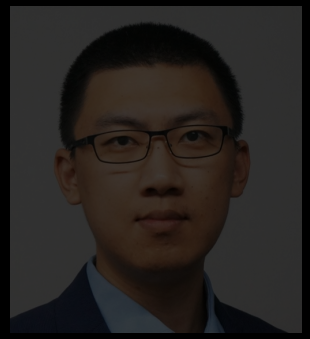


Nat.Comm 12, 6087 (2021)

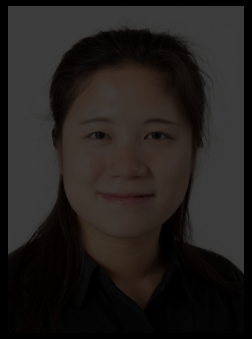
NEMATIC



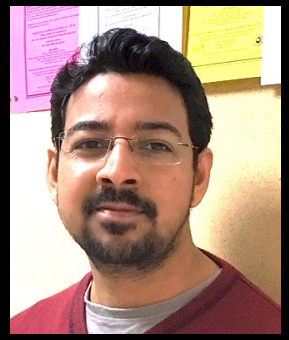
Weijiong Chen *et al* (2022)



Xiaolong Liu
Notre Dame



Shuqiu Wang
Oxford



P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford

Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

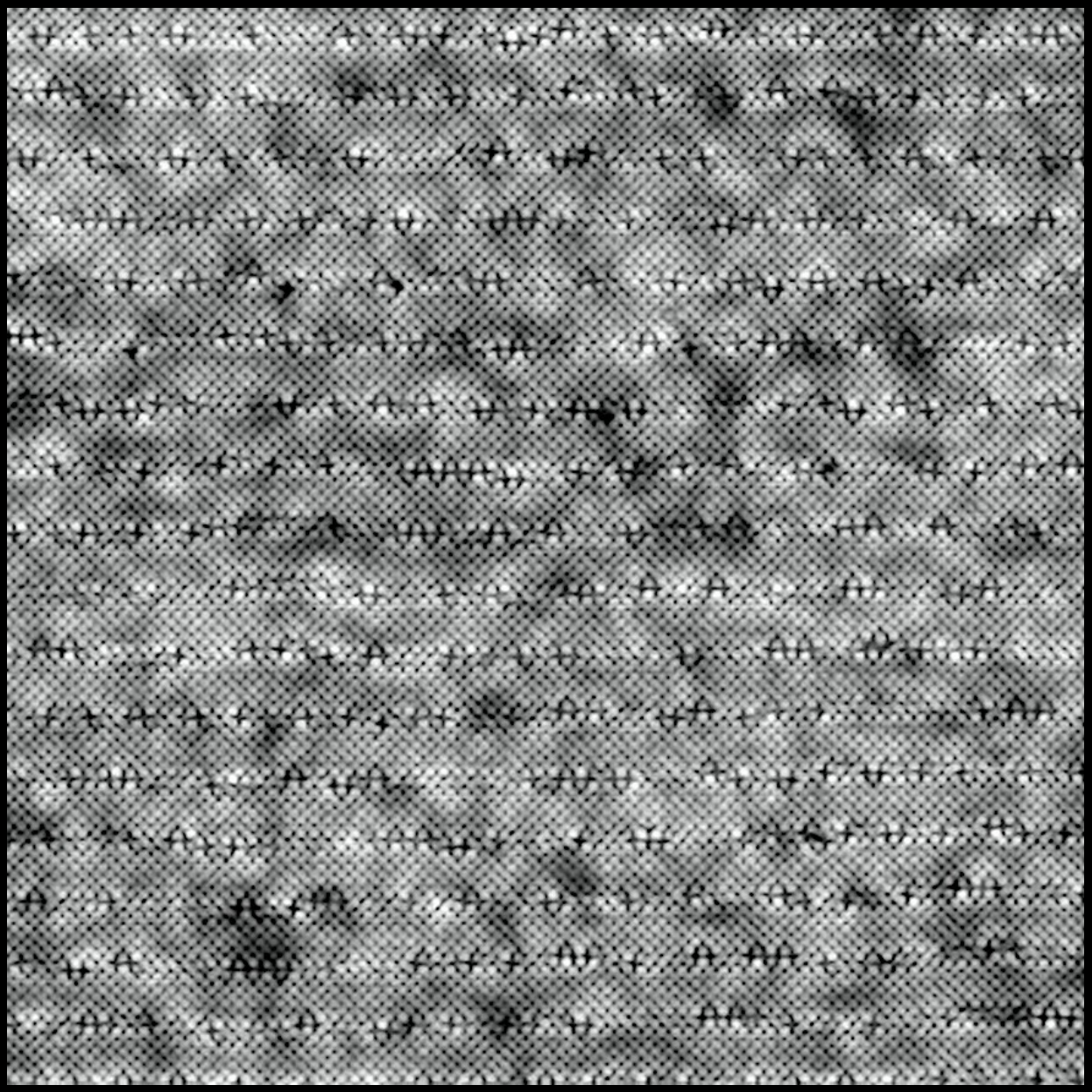
M. H. Hamidian
Cornell

S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

ACTUAL ELECTRONIC STRUCTURE of $p\sim10\%$ CuO_2

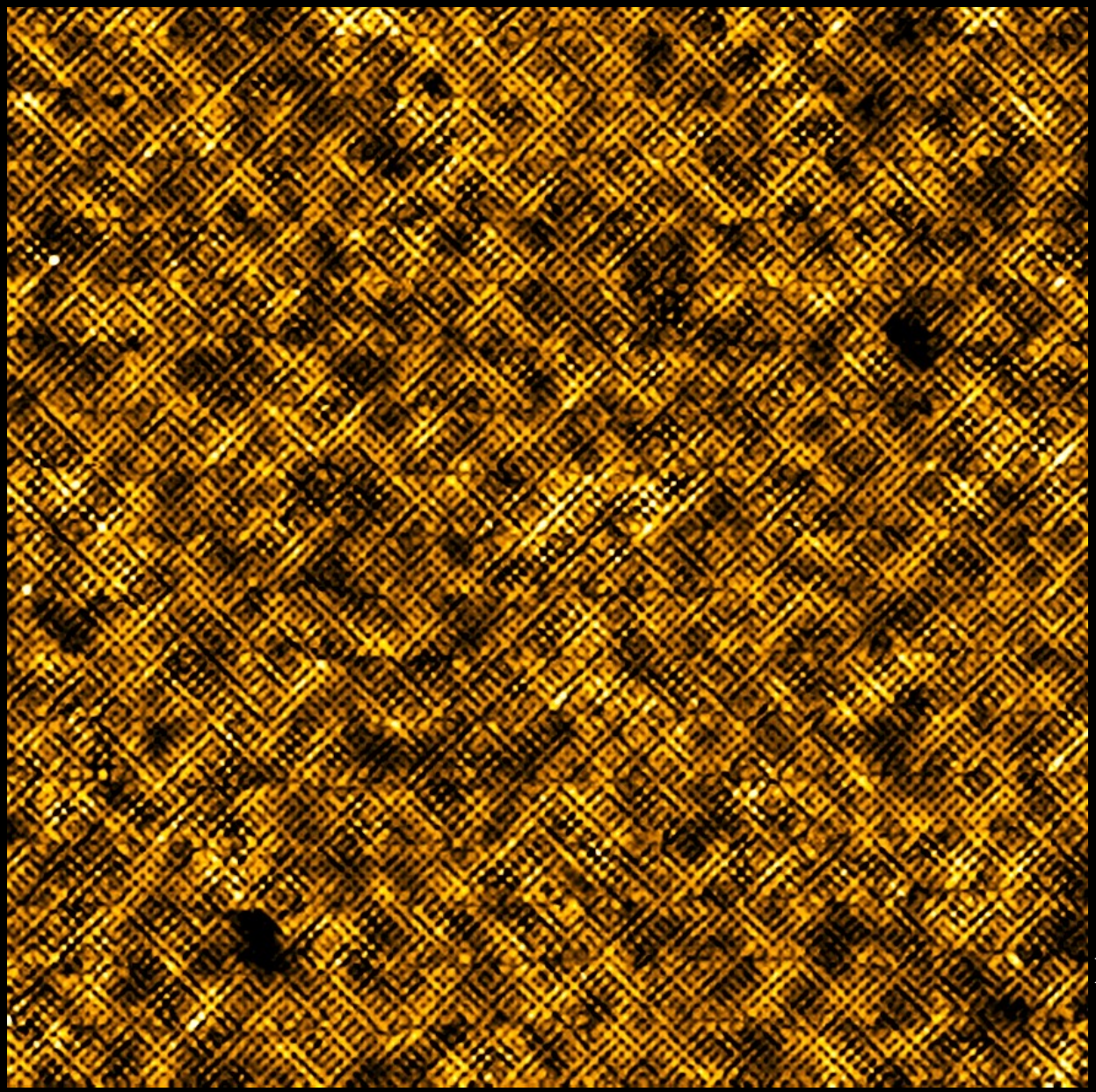
$p\sim10\%$



45 nm

ACTUAL ELECTRONIC STRUCTURE of $p\sim10\%$ CuO_2

$\frac{dI}{dV}(\boldsymbol{r},\Delta_1)$



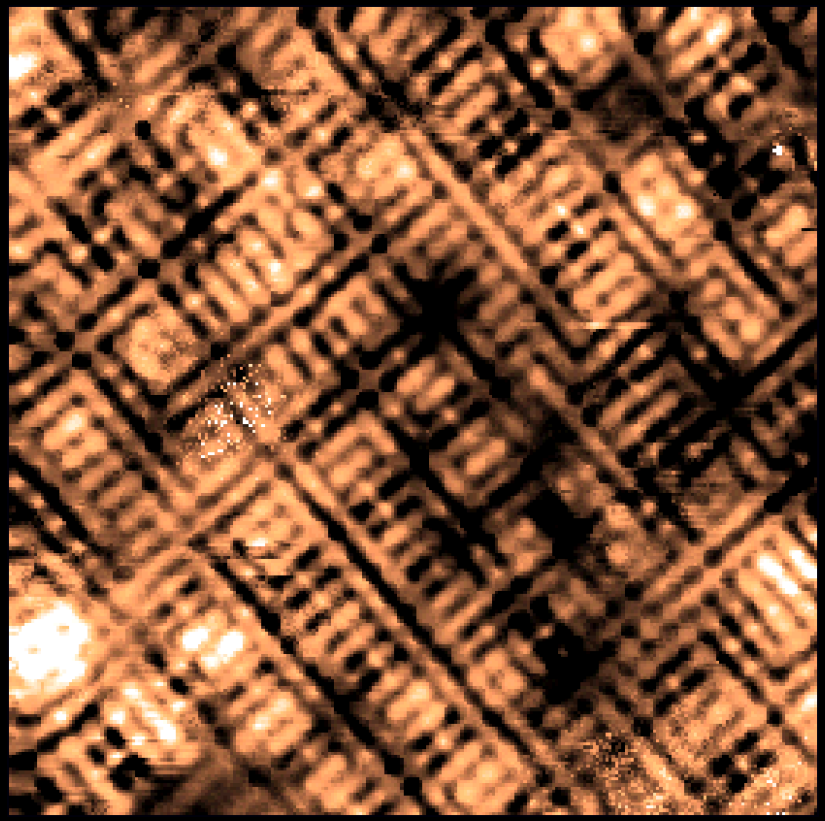
$p\sim10\%$

45 nm

"An Intrinsic Bond-Centered Electronic Glass..." ***Science 315***, 138 (2007)

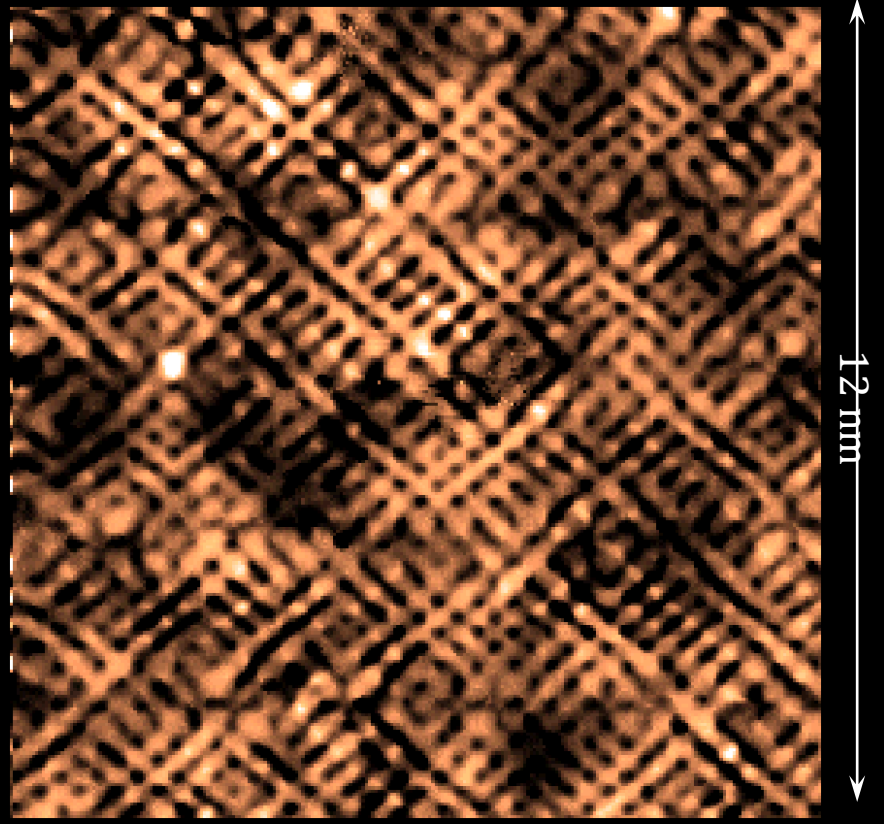
BOND-CENTERED *d*-SYMMETRY FF UNIDIRECTIONAL 'MOTIF'

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



p~10%

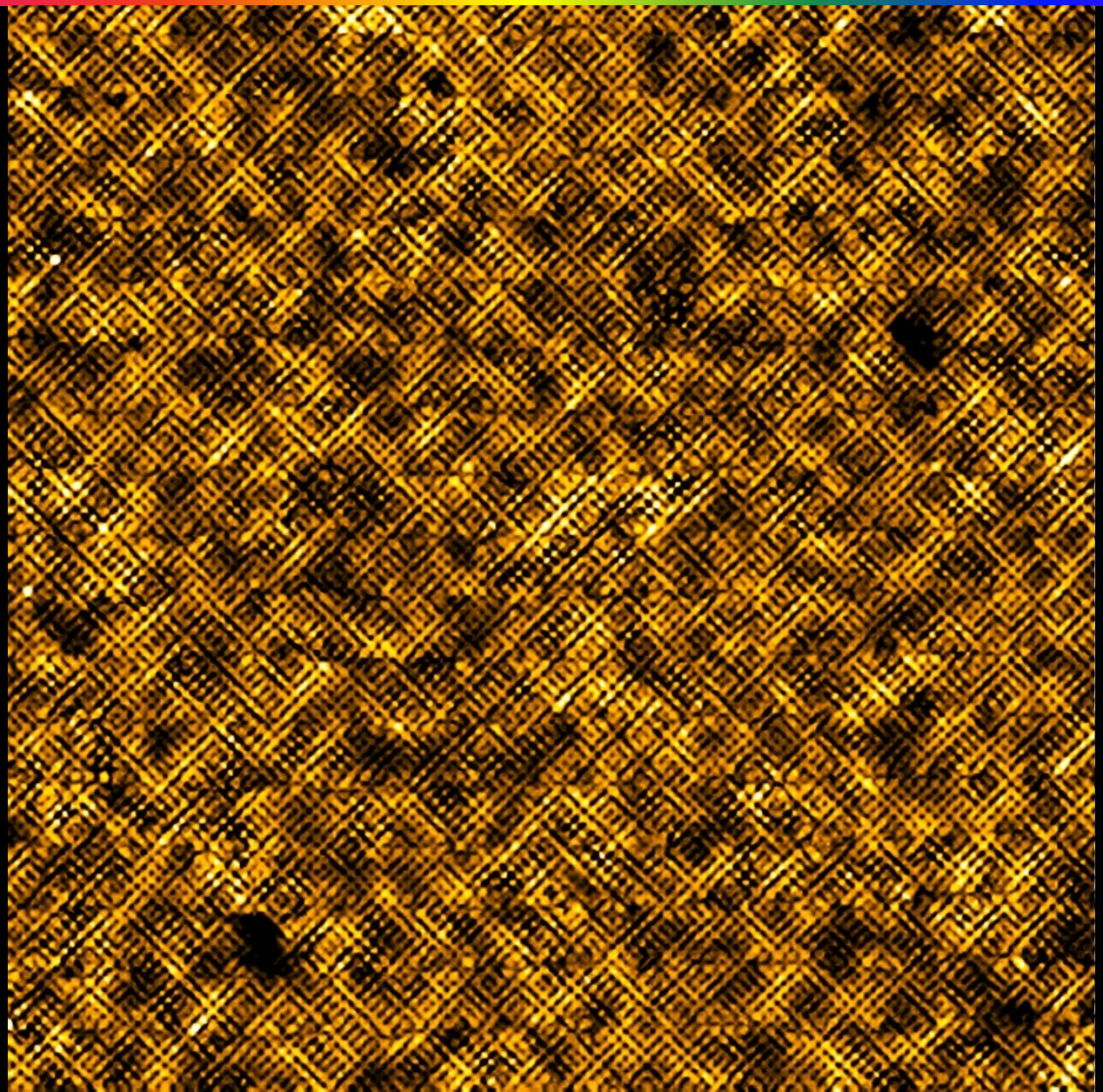
$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



p~10%

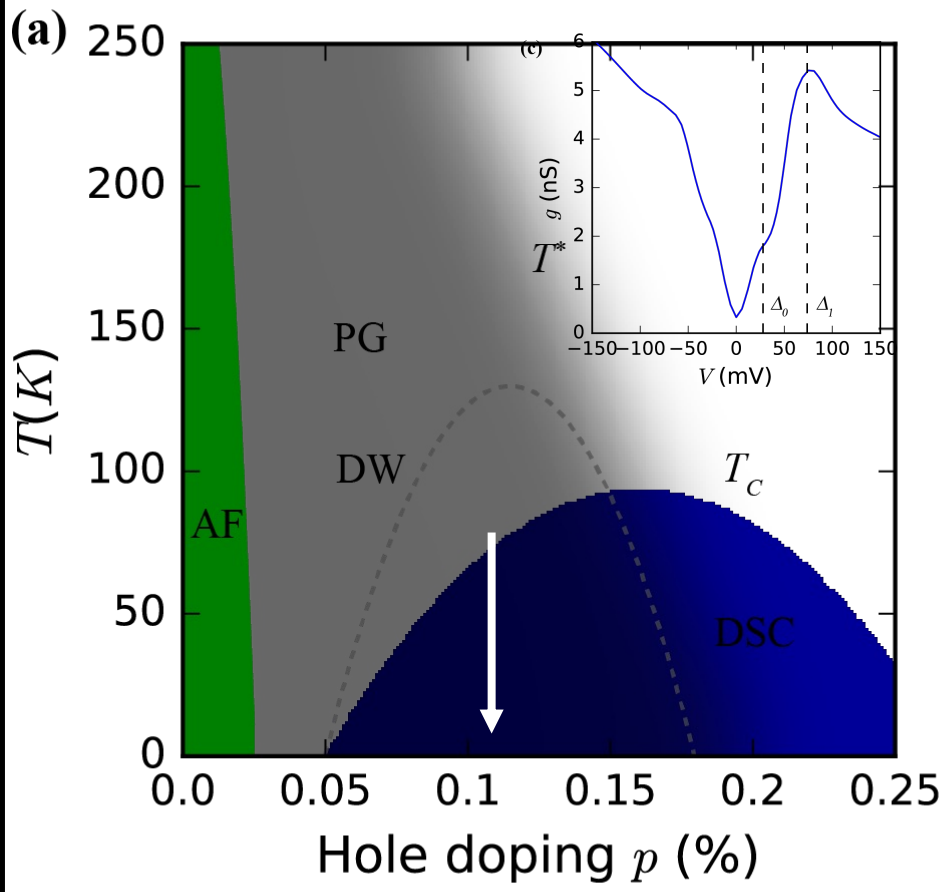
MACHINE LEARNING IDENTIFIES THIS ‘MOTIF’ UNIVERSALLY

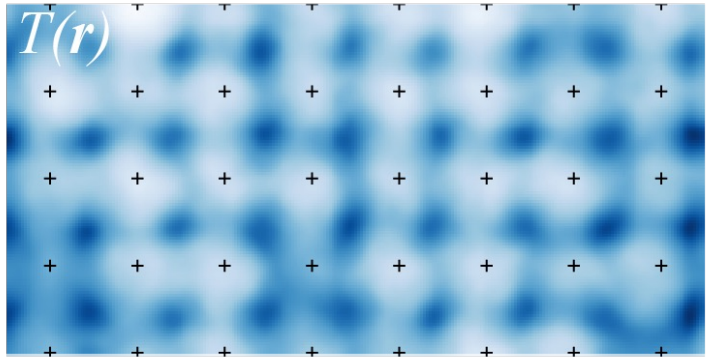
Yi Zhang…
EAK. *et al*
Nature 570,
484 (2019)

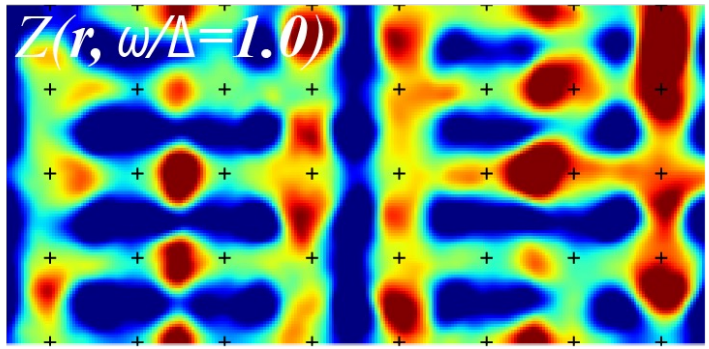


45 nm

QUASIPARTICLE N(r,E)







$$g(\boldsymbol{r},V) \equiv \frac{dI}{dV}(\boldsymbol{r},eV) \qquad Z(\boldsymbol{r},E) \equiv \frac{g(\boldsymbol{r},V)}{g(\boldsymbol{r},-V)}$$

PNAS 117, 14850 (2020)

RENORMALIZED MEAN-FIELD *t-J* : $\lambda=8a_0$ PDW + DSC

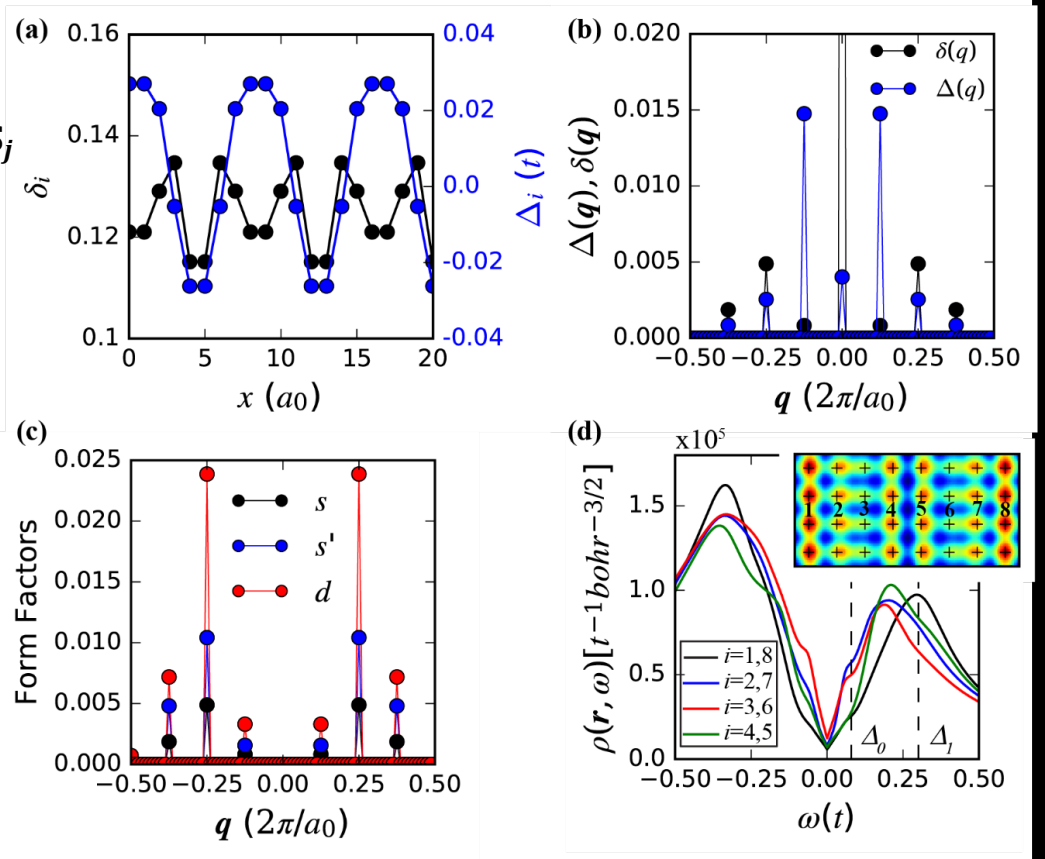
CuO_2 electronic structure & *t-J* Hamiltonian

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

- Replace PG by spin/charge renormalization factors – variable by atomic site..
- Decouple into a diagonalizable mean-field approximation using: on-site hole density δ_i, bond-order field $\chi_{ij\sigma}$, and electron-pair potential $\Delta_{ij\sigma}$.
- Initialize with a set of order parameter fields modulating at $\boldsymbol{Q}_P = (\pm 1/8, 0)2\pi/a_0$,

Predict:

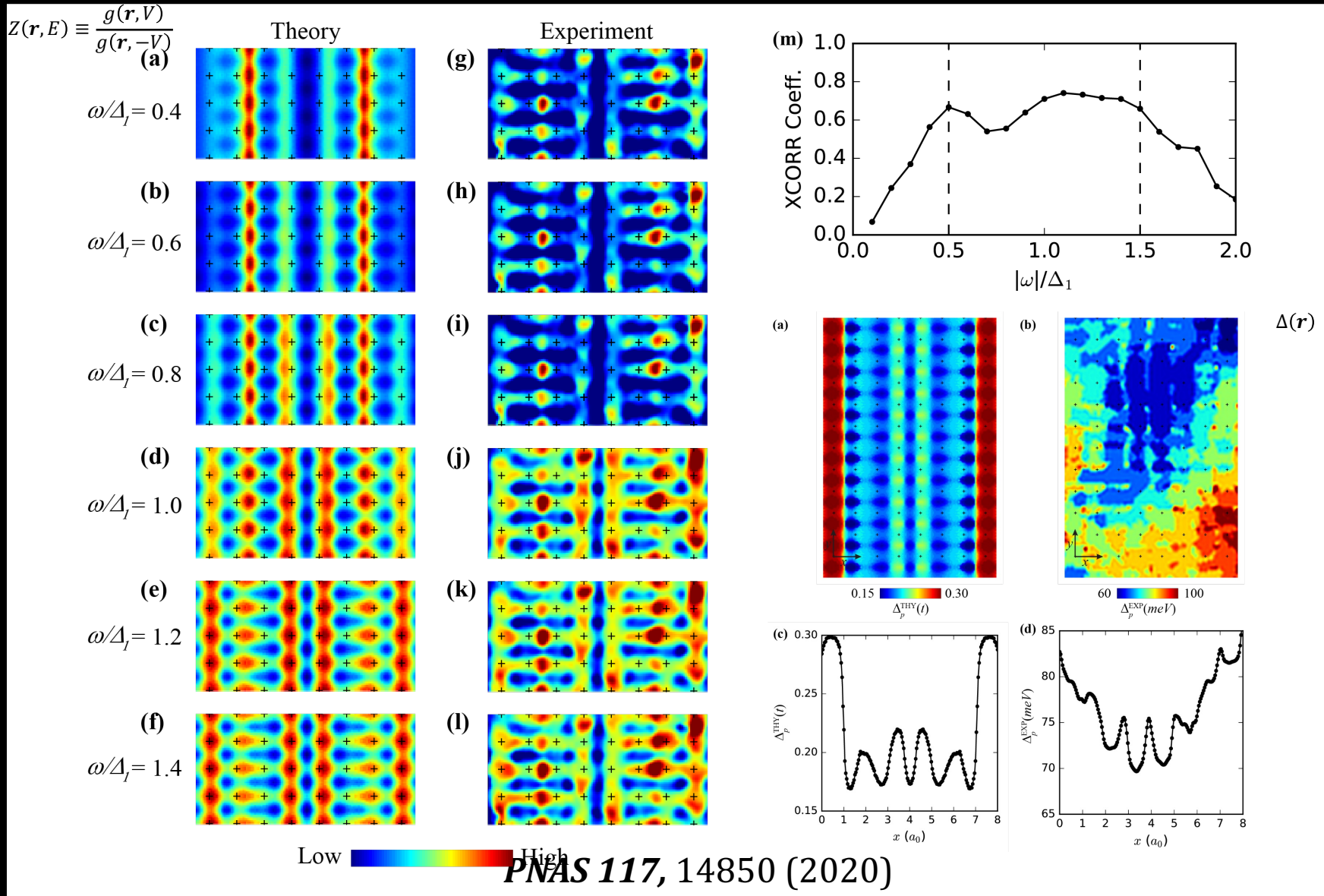
- Net charge Cu site $\delta_i = 1 - <\Psi_0|\sum_\sigma n_{i\sigma}|\Psi_0>$
- Bond-order field $\chi_{ij\sigma} = <\Psi_0|c^{\dagger}_{i\sigma}c_{j\sigma}|\Psi_0>$
- Electron-pair field $\Delta_{ij\sigma} = \sigma <\Psi_0|c_{i\sigma}c_{j\bar{\sigma}}|\Psi_0>$
- Quasiparticle density of states N_i at every site



COEXISTING ORDER PARAMETERS = INTERTWINED

Choubey *et al. New J. Phys.* **19**, 013028 (2017); . *Proc. Natl. Acad. Sci. U. S. A.* **117**, 805 (2020).

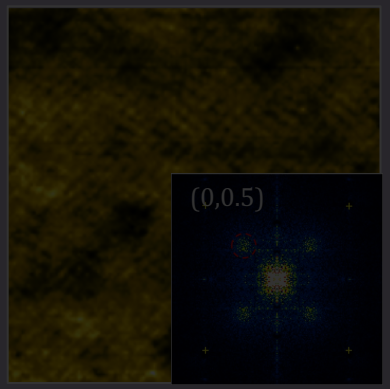
$\lambda=8a_0$ PDW + DSC : N(r,E) & $\Delta(r)$



PNAS 117, 14850 (2020)

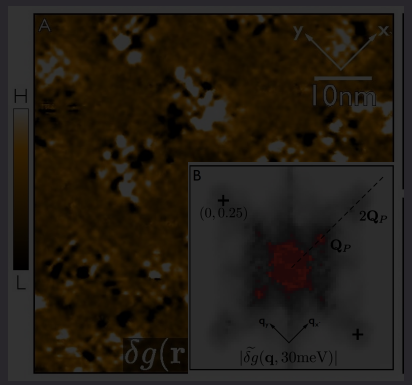
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



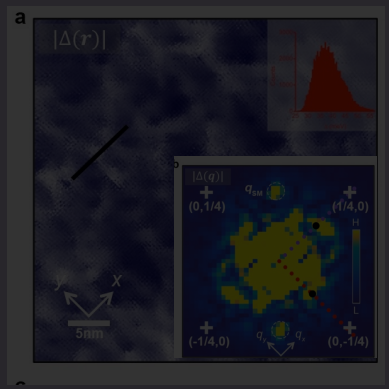
Nature 532, 343 (2016)

VORTEX HALO



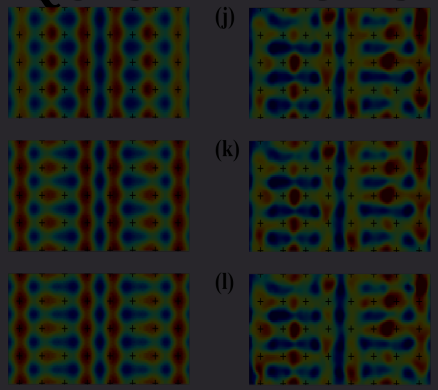
Science 364, 976 (2019)

ENERGY GAP



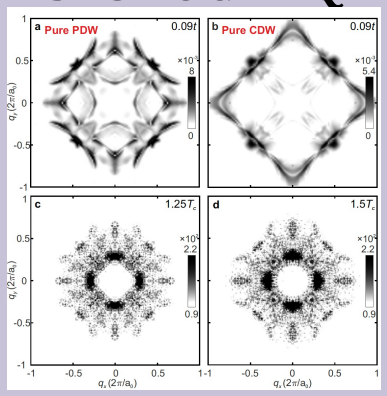
Nature 580, 6570 (2020)

QUASIPARTICLES



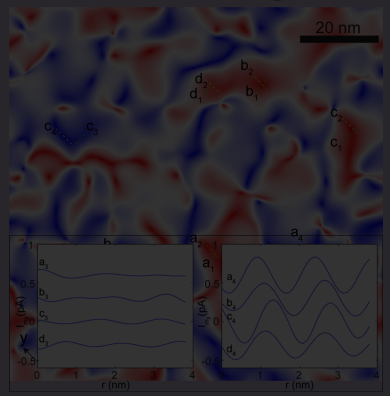
PNAS 117, 14850 (2020)

PSEUDOGAP QPI

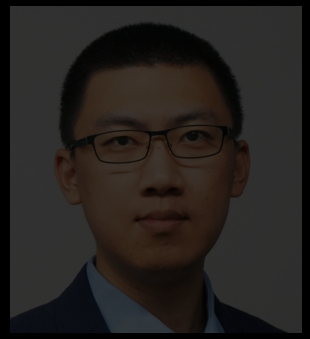


Nat.Comm 12, 6087 (2021)

NEMATIC

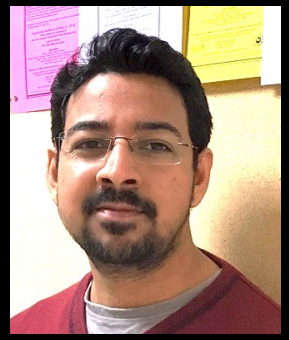


Weijiong Chen *et al* (2022)



Xiaolong Liu
Notre Dame

Shuqiu Wang
Oxford



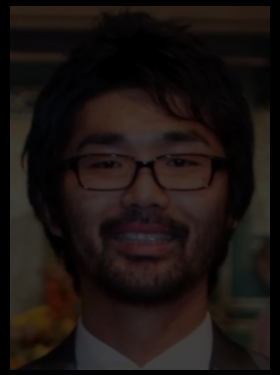
P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

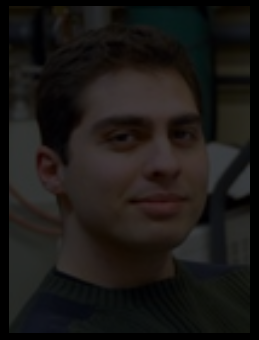
H. Eisaki
Tsukuba

P.D. Johnson
Oxford



Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

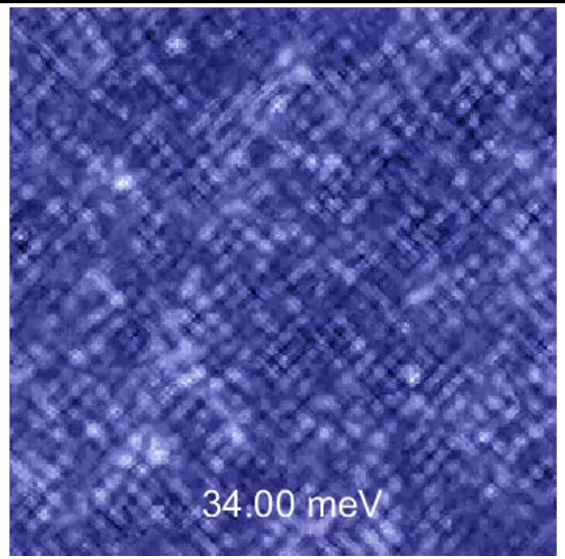


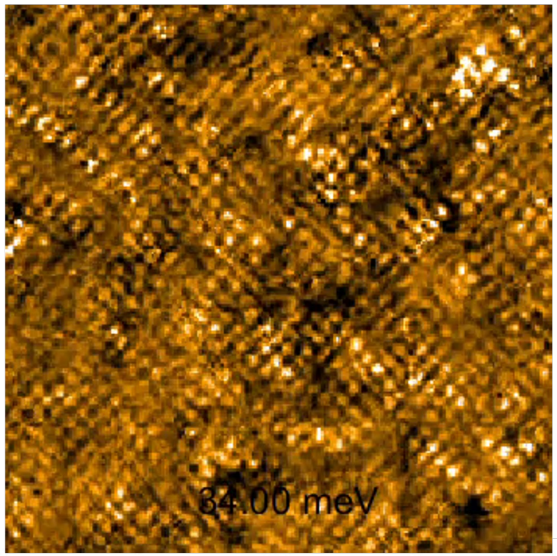
M. H. Hamidian
Cornell

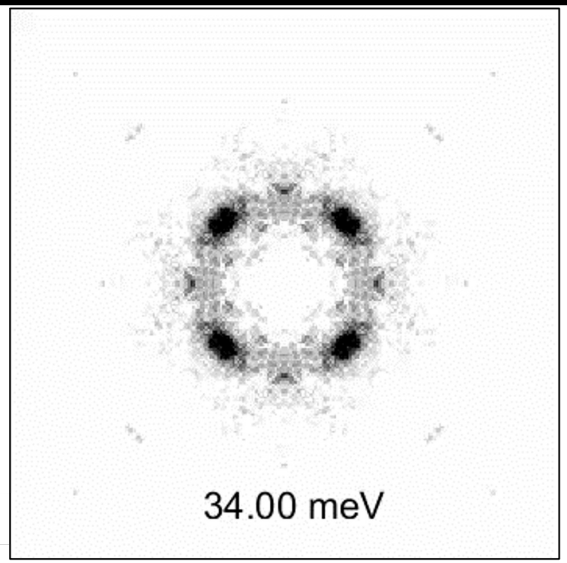
S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

QUASIPARTICLE INTERFERENCE $\Lambda(\boldsymbol{q}, \Delta_0)$



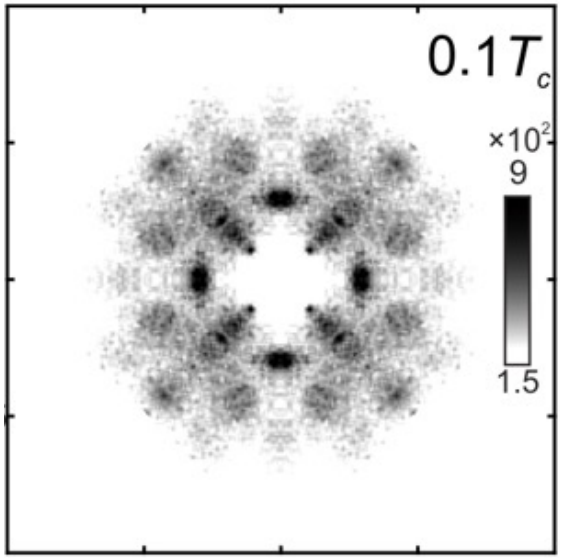




$$g(\boldsymbol{r}, V) \equiv \frac{dI}{dV}(\boldsymbol{r}, E = eV)$$

$$Z(\boldsymbol{q}, E) = \mathcal{F}Z(\boldsymbol{r}, E).$$

$$\Lambda(\boldsymbol{q}, \Delta_0) \equiv \sum_{E \cong 0}^{\Delta_0} Z(\boldsymbol{q}, E)$$



- $\Lambda(\boldsymbol{q}, \Delta_0)$ provides an efficient characteristic "fingerprint" of any ordered state that controls scattering wavevectors.

Nat.Comm 12, 6087 (2021)

RENORMALIZED MEAN-FIELD *t-J* : λ=8a_0 PDW + DSC

CuO_2 electronic structure & *t-J* Hamiltonian

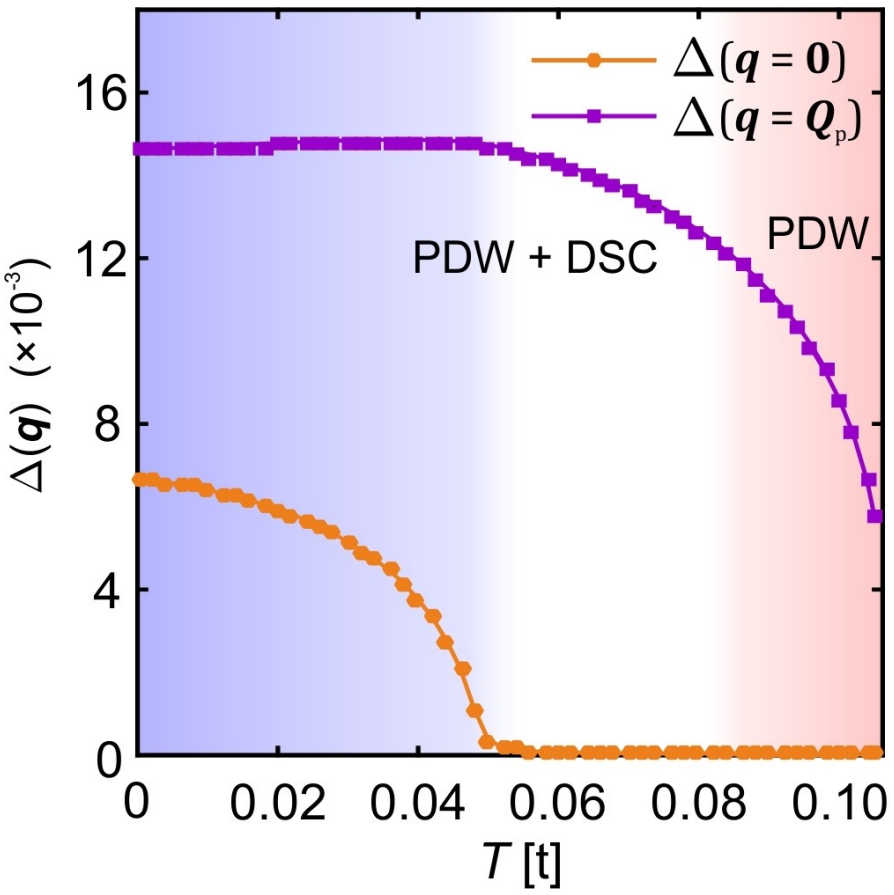
$$H = -\sum_{(i,j),\sigma} P_G t_{ij}\left(c_{i\sigma}^{\dagger}c_{j\sigma} + h.c.\right)P_G + J\sum_{<i,j>}\mathbf{S_i}\cdot\mathbf{S_j}$$

- Replace PG by spin/charge renormalization factors – variable by atomic site..
- Decouple into a diagonalizable mean-field approximation using: on-site hole density δ_i, bond-order field $\chi_{ij\sigma}$, and electron-pair potential $\Delta_{ij\sigma}$.
- Initialize with a set of order parameter fields modulating at $\boldsymbol{Q}_P = (\pm 1/8, 0)2\pi/a_0$,

Predict:

- Net charge Cu site $\delta_i = 1 - < \Psi_0 | \sum_\sigma n_{i\sigma} | \Psi_0 >$
- Bond-order field $\chi_{ij\sigma} = < \Psi_0 | c_{i\sigma}^{\dagger} c_{j\sigma} | \Psi_0 >$
- Electron-pair field $\Delta_{ij\sigma} = \sigma < \Psi_0 | c_{i\sigma} c_{j\bar{\sigma}} | \Psi_0 >$
- Quasiparticle density of states N_i at every site

$\Delta_{ij\sigma} = \sigma < \Psi_0 | c_{i\sigma} c_{j\bar{\sigma}} | \Psi_0 >$

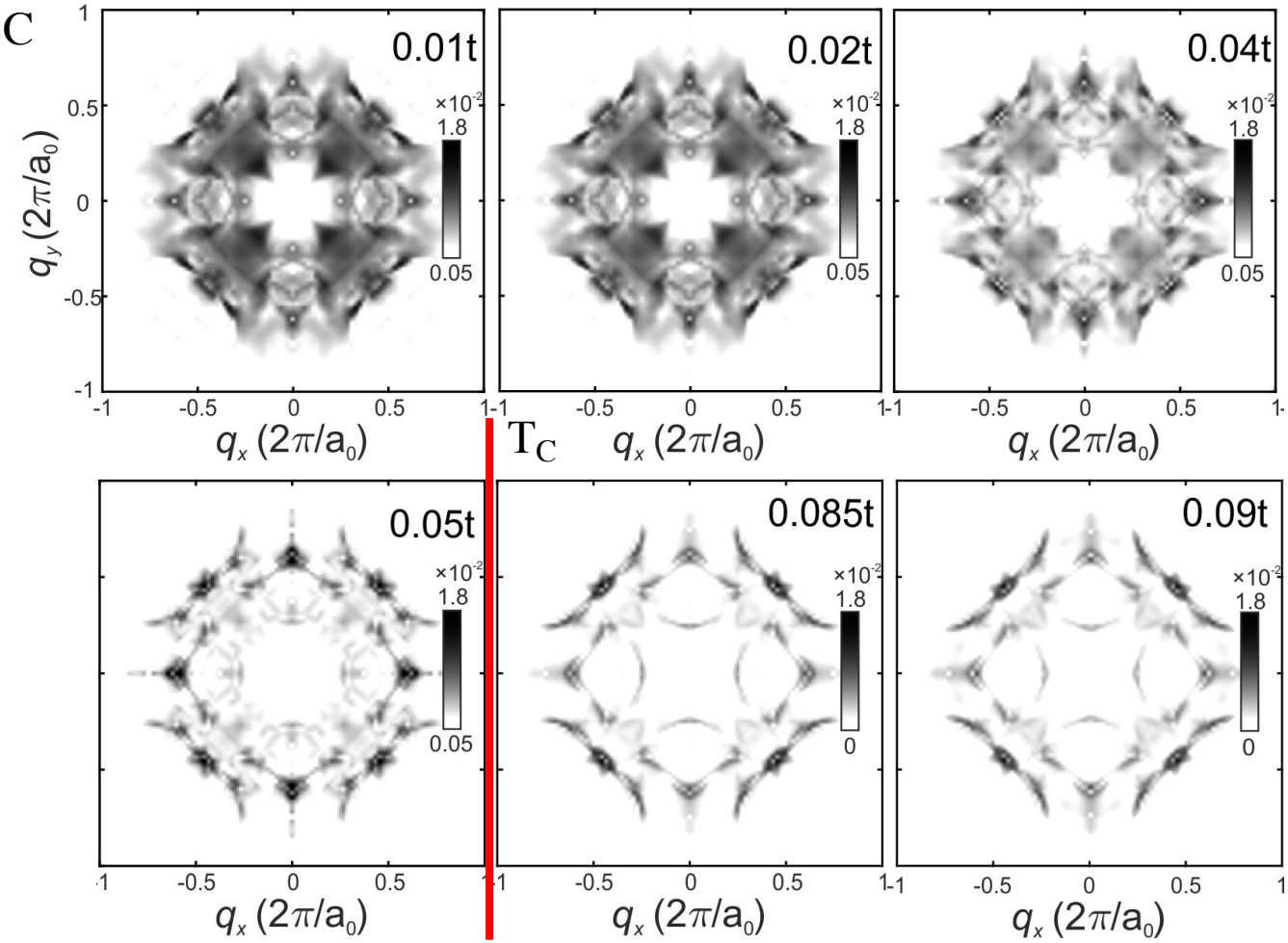


Choubey *et al. New J. Phys.* **19**, 013028 (2017); . *Proc. Natl. Acad. Sci. U. S. A.* **117**, 805 (2020).

$\lambda=8a_0$ PDW + DSC : PREDICT QPI SIGNATURE $\Lambda(\boldsymbol{q},\Delta_0)$

$$N(\boldsymbol{q},E) \propto ImG(k,E)TG(k-q,E) \implies \Lambda(\boldsymbol{q},\Delta_0) \equiv \sum_{E\cong 0}^{\Delta_0} N(\boldsymbol{q},E)\,/N(\boldsymbol{q},-E)$$

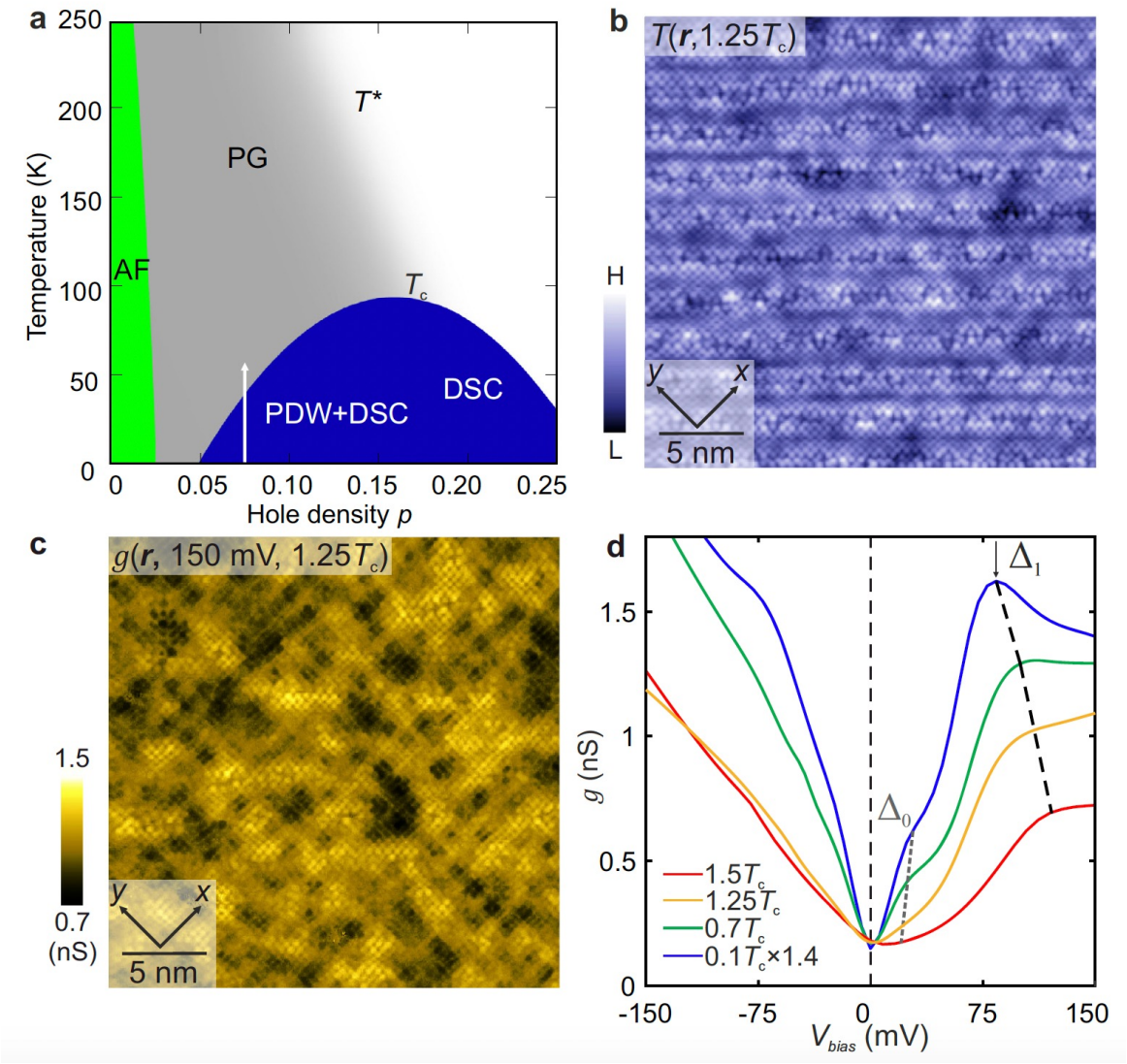
PDW+DSC



PDW

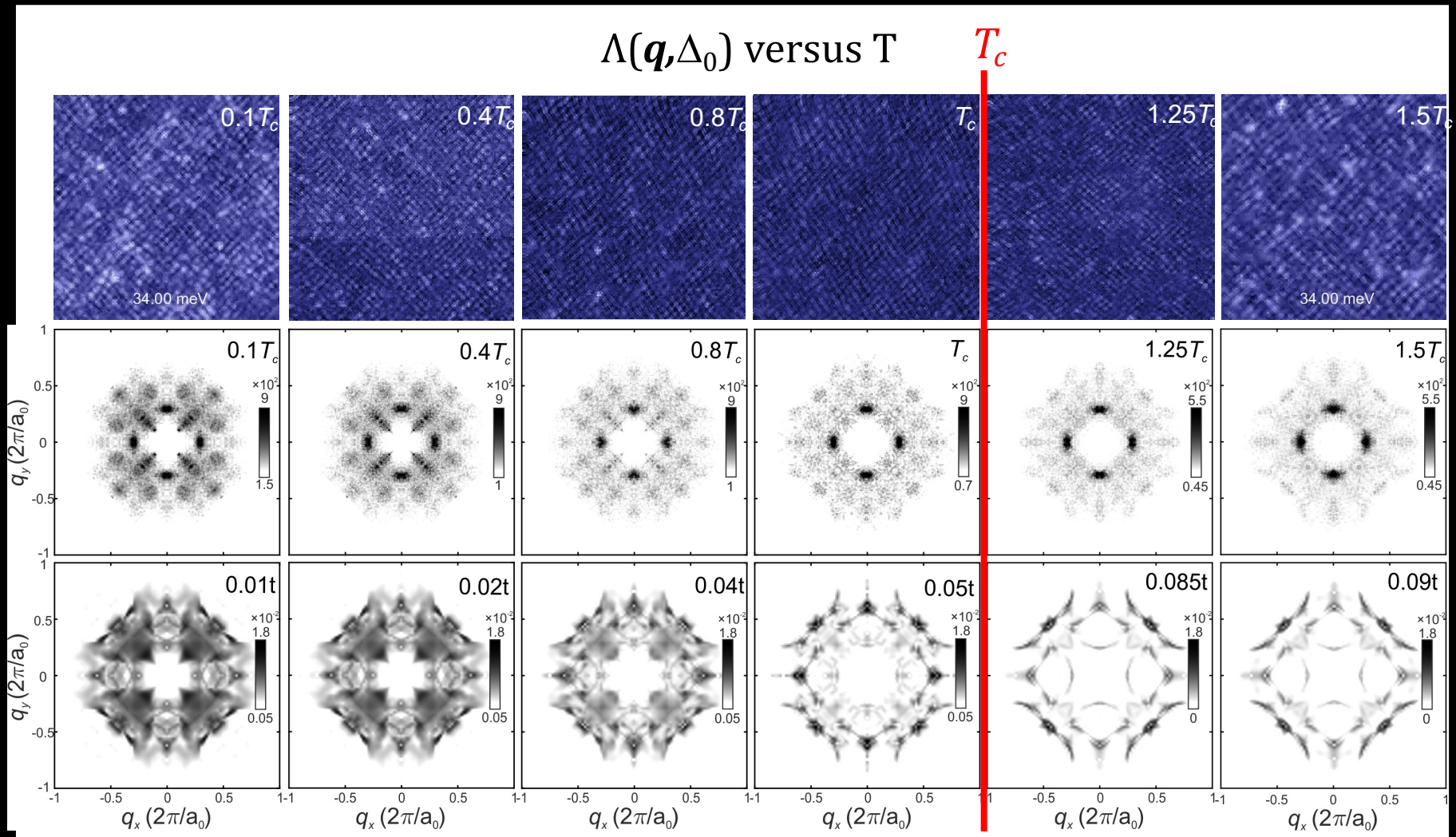
Nat.Comm 12, 6087 (2021)

MEASURE QPI SIGNATURE $\Lambda(\boldsymbol{q}, \Delta_0)$



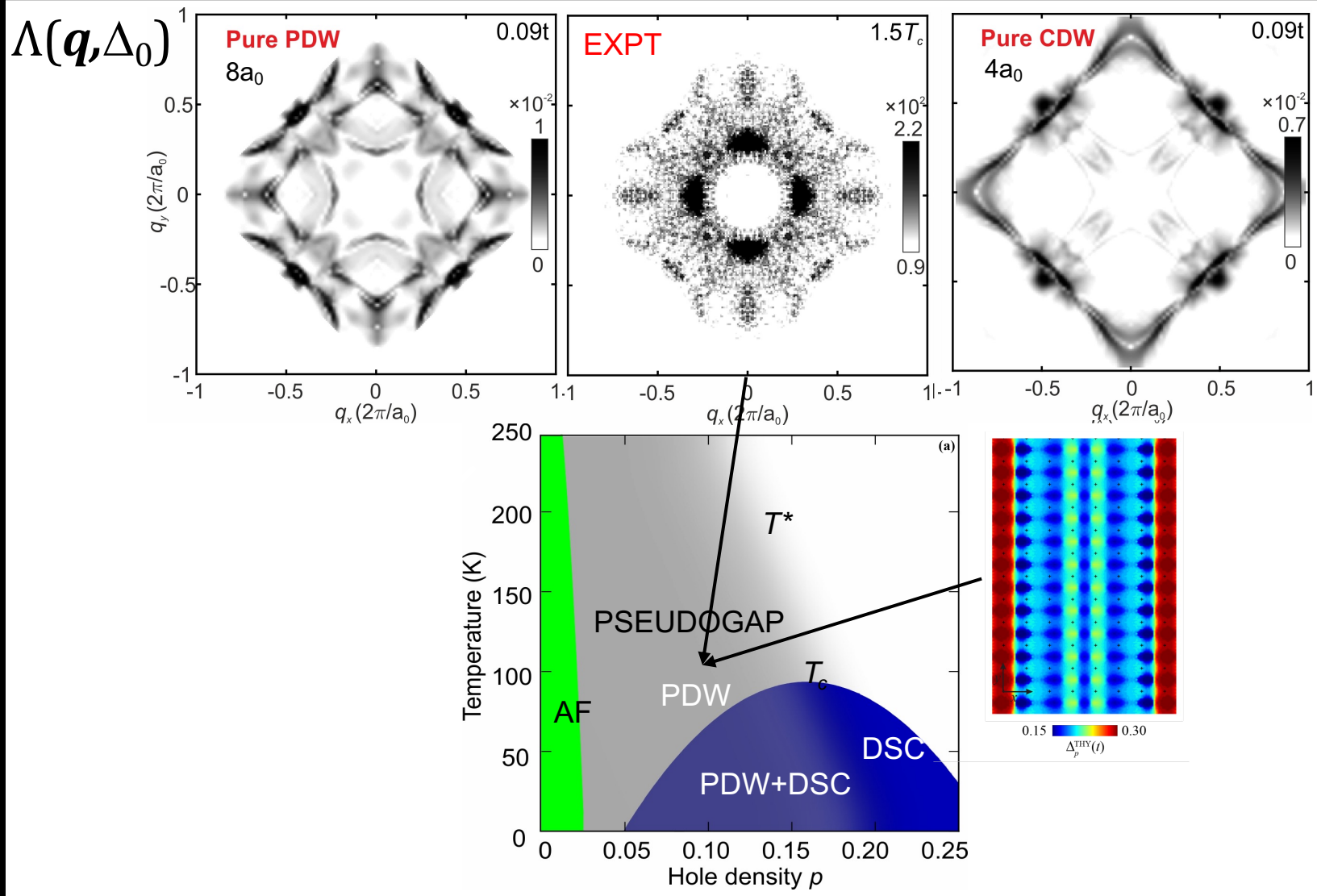
Nat.Comm 12, 6087 (2021)

$\lambda=8a_0$ PDW + DSC : $\Lambda(\boldsymbol{q}, \Delta_0)$



Nat.Comm 12, 6087 (2021)

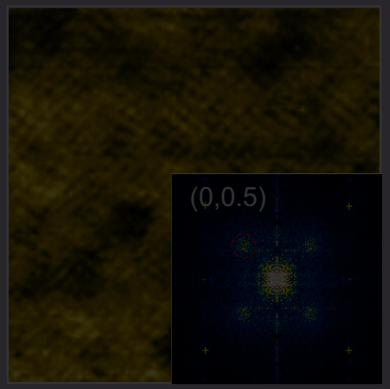
PSEUDOGAP (T>T_C): $\Lambda(q, \Delta_0)$ OF $\lambda=8a_0$ PDW



Nat.Comm 12, 6087 (2021)

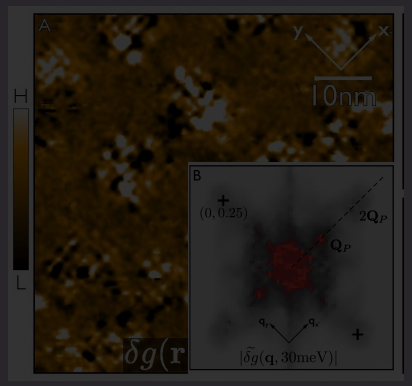
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY



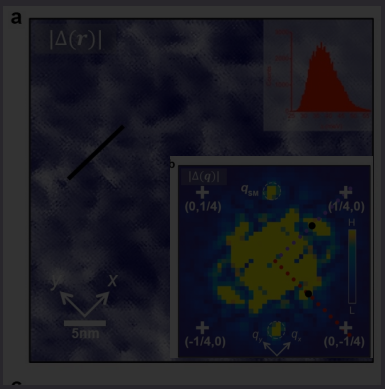
Nature 532, 343 (2016)

VORTEX HALO



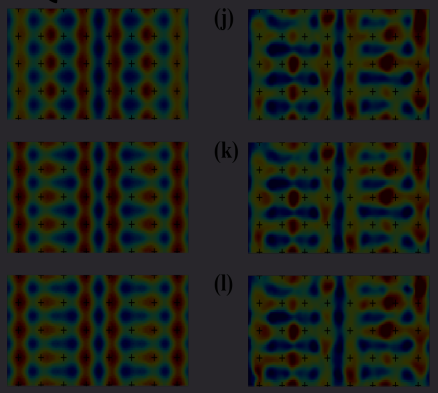
Science 364, 976 (2019)

ERGY GAP



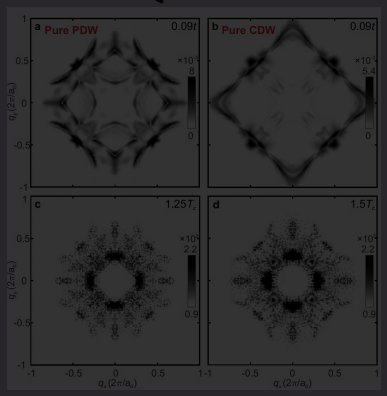
Nature 580, 6570 (2020)

QUASIPARTICLES



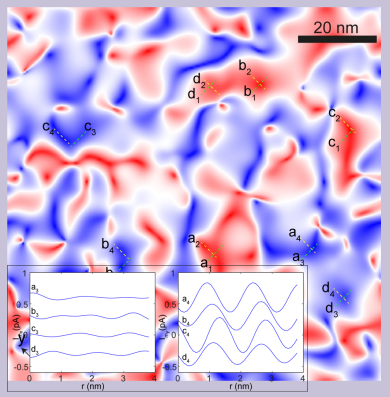
PNAS 117, 14850 (2020)

UDOGAP QPI

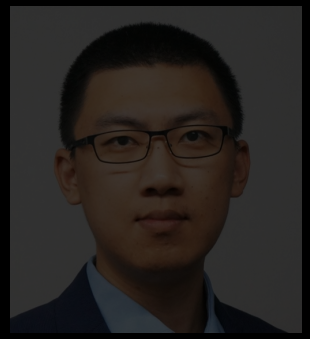


Nat.Comm 12, 6087 (2021)

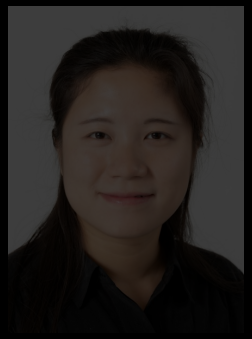
NEMATIC



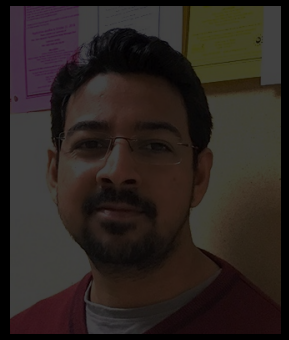
Weijiong Chen et al (2022)



Xiaolong Liu
Notre Dame



Shuqiu Wang
Oxford



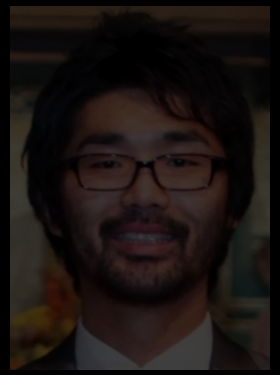
P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford



Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

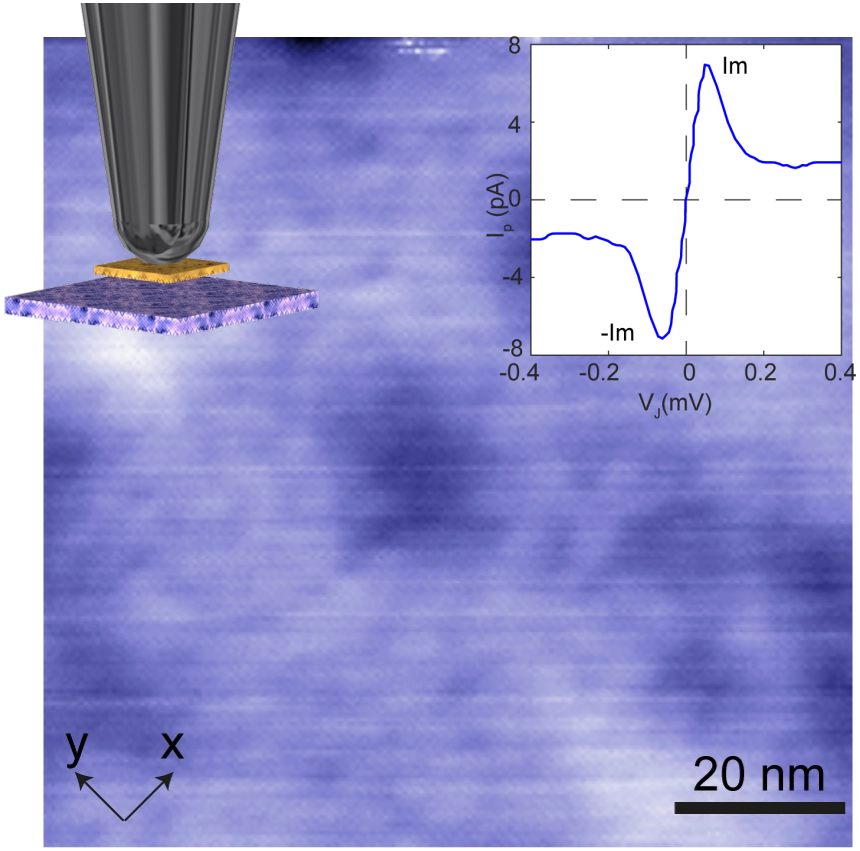
M. H. Hamidian
Cornell

S.D. Edkins
Cornell

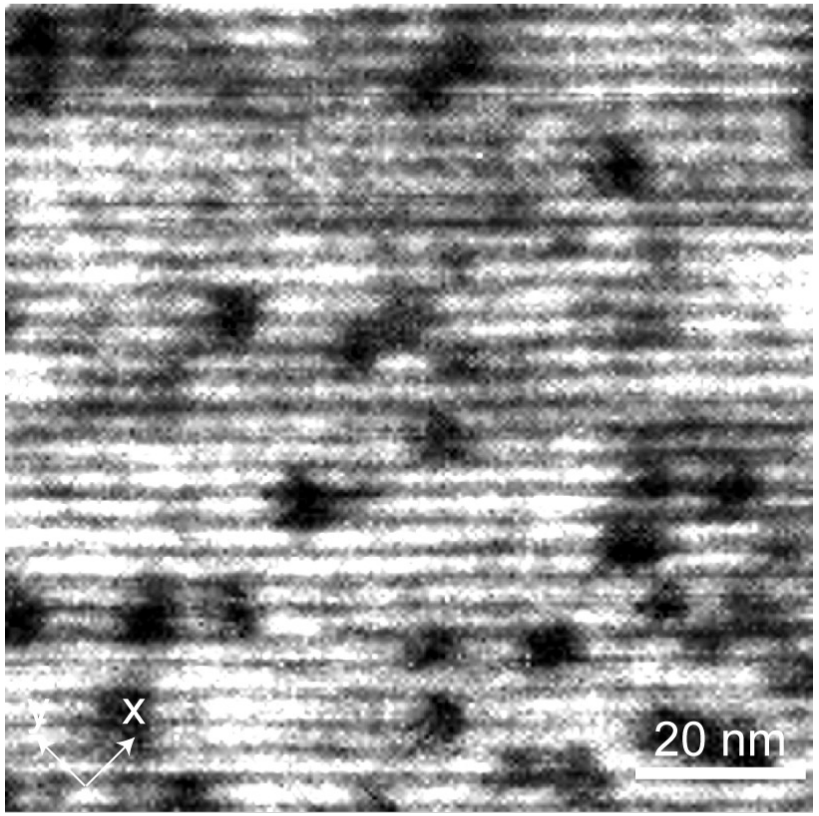
A.P. Mackenzie
Dresden

SJTM: VISUALIZATION OF ELECTRON-PAIR DENSITY $n_P(\mathbf{r})$

$T(\mathbf{r})$



$I_m(\mathbf{r})$



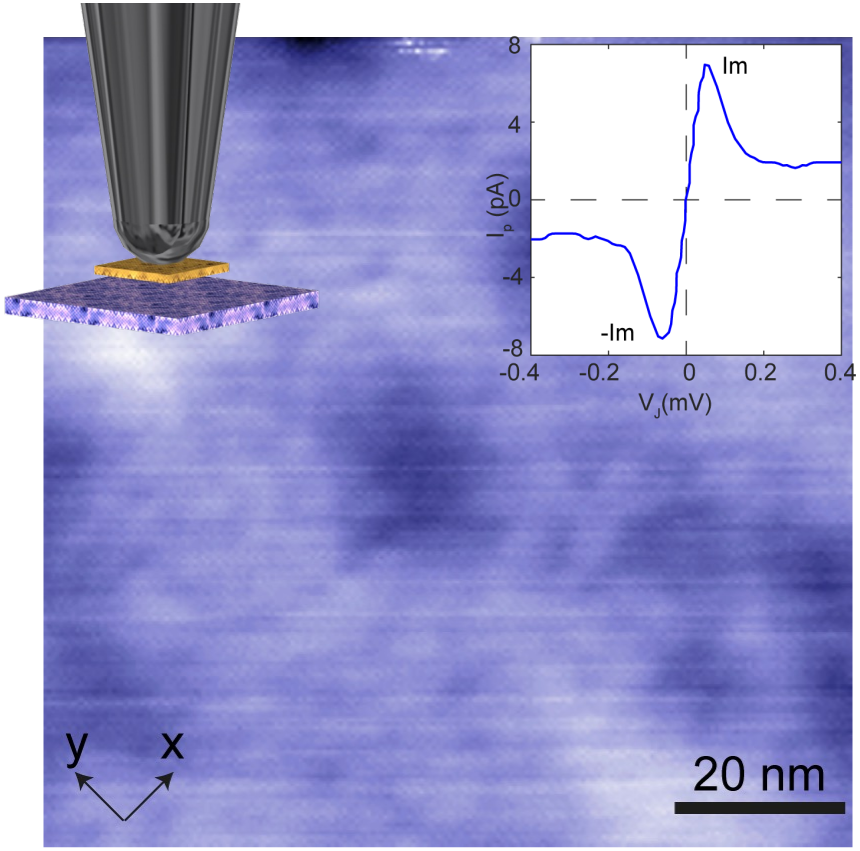
1.5 — 10

I_m (pA)

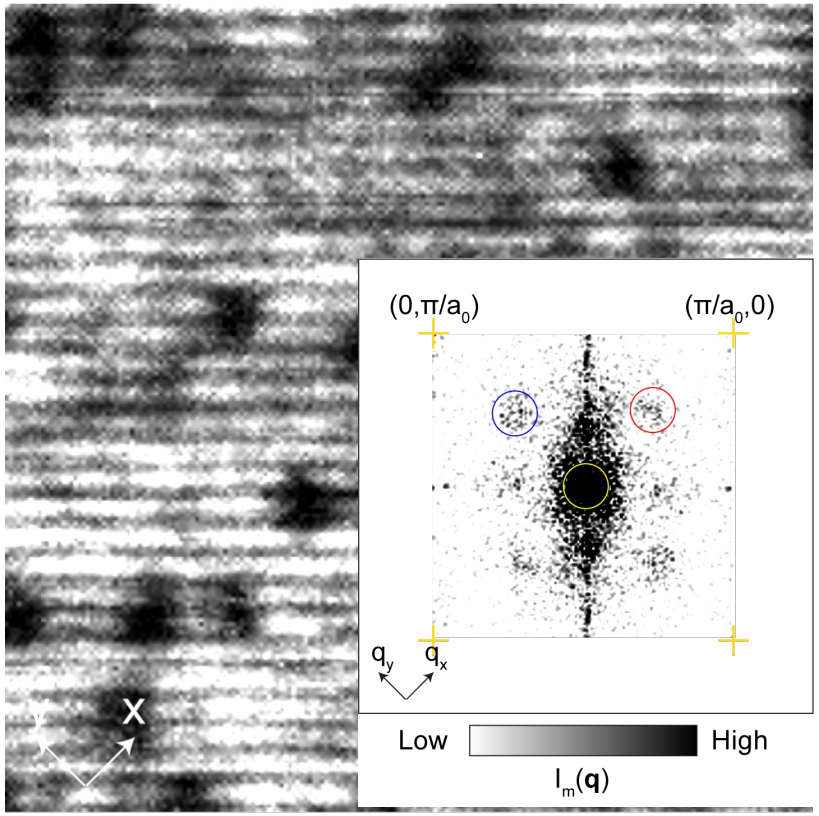
NO DETECTABLE CHARGE MODULATIONS

SJTM: VISUALIZATION OF ELECTRON-PAIR DENSITY $n_P(\mathbf{r})$

$T(\mathbf{r})$



$I_m(\mathbf{r})$

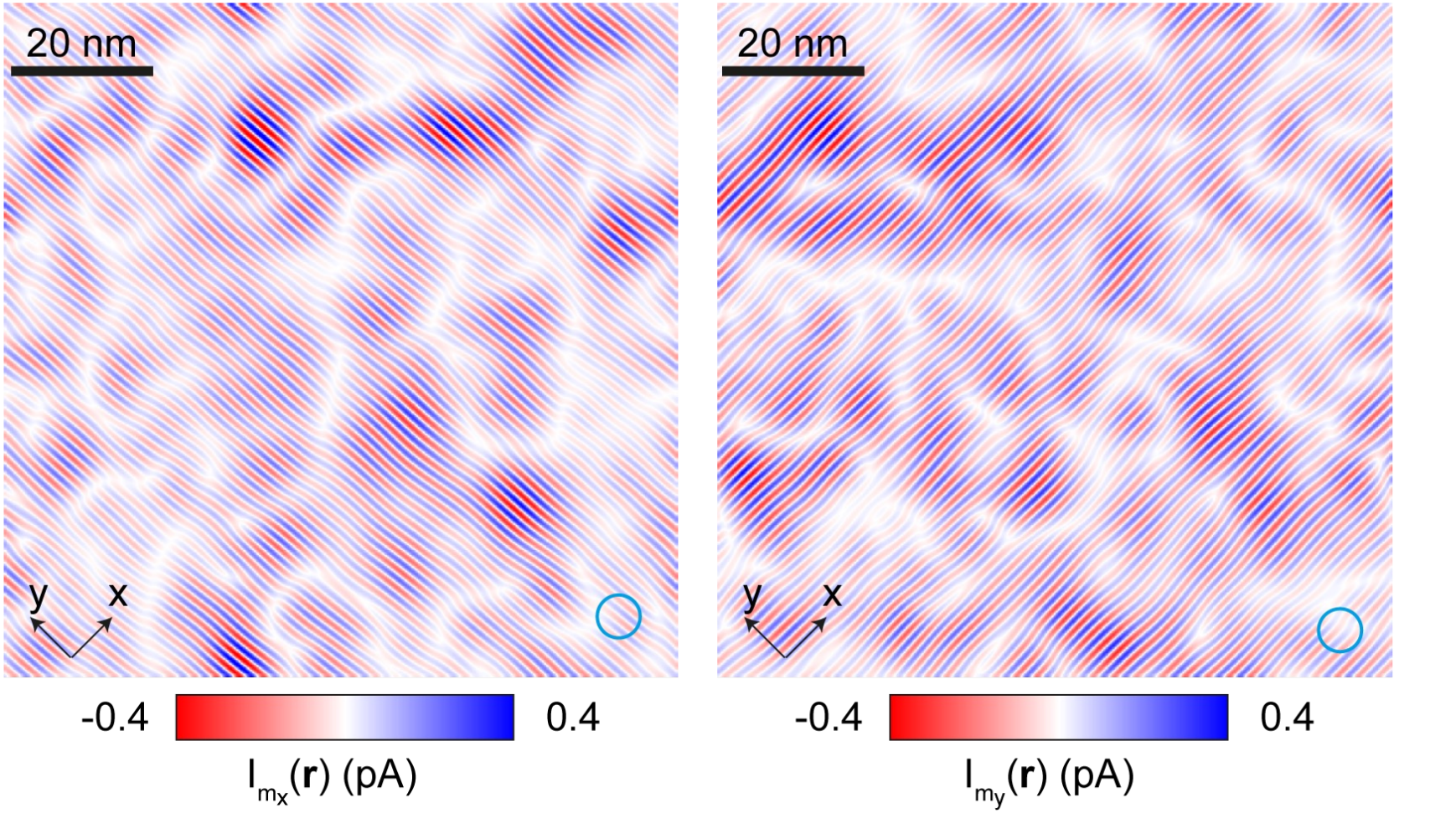


Weijiong Chen *et al* (2022)

ELECTRON-PAIR DENSITY $n_P(\boldsymbol{r})$ MODULATIONS

$\mathrm{A_x}(\mathbf{r})Cos(Q_x x + \theta_x)$

$\mathrm{A_y}(\mathbf{r})Cos(Q_y y + \theta_y)$

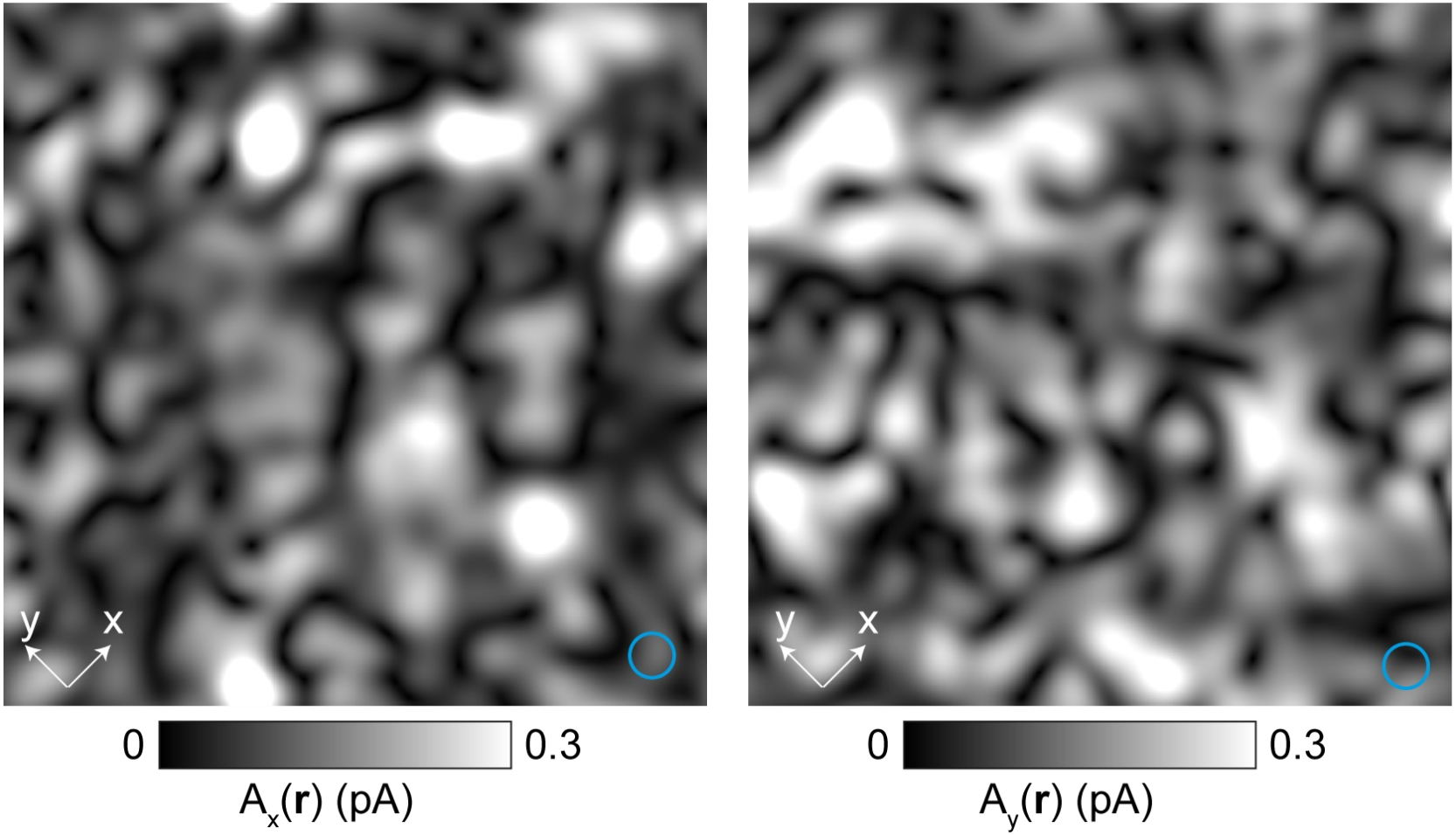


Weijiong Chen *et al* (2022)

ELECTRON-PAIR DENSITY $n_P(\boldsymbol{r})$ MODULATIONS

$\mathrm{A_x}(\mathbf{r}) \propto I_0^2 \propto |\boldsymbol{\Delta}_\mathrm{x}|^2$

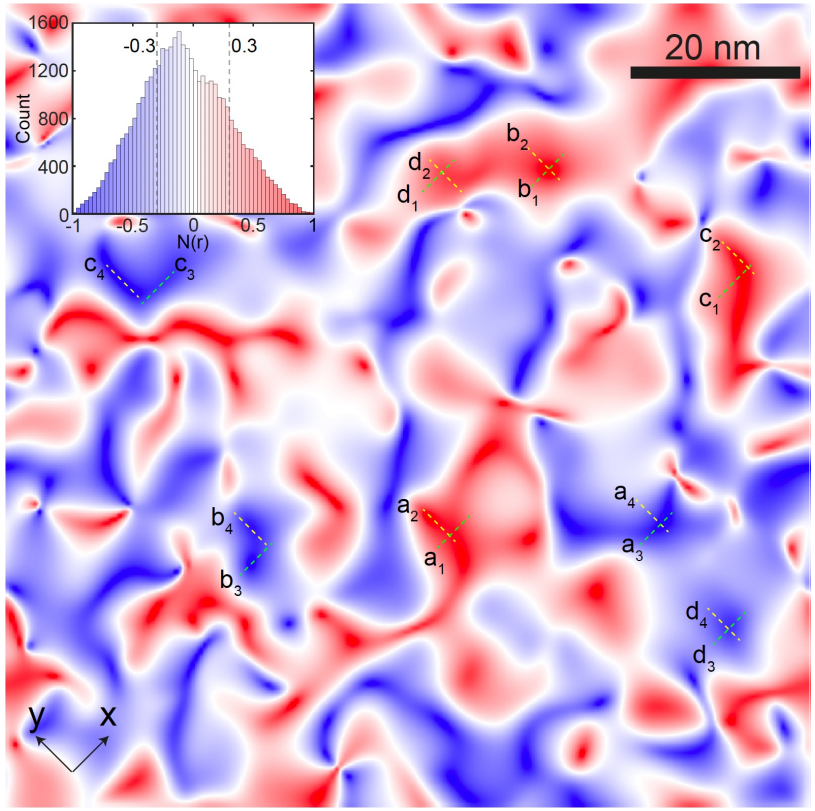
$\mathrm{A_y}(\mathbf{r}) \propto I_0^2 \propto |\boldsymbol{\Delta}_\mathrm{y}|^2$



Weijiong Chen *et al* (2022)

NEMATIC ORDER-PARAMETER FOR $n_P(\boldsymbol{r})$ MODULATIONS

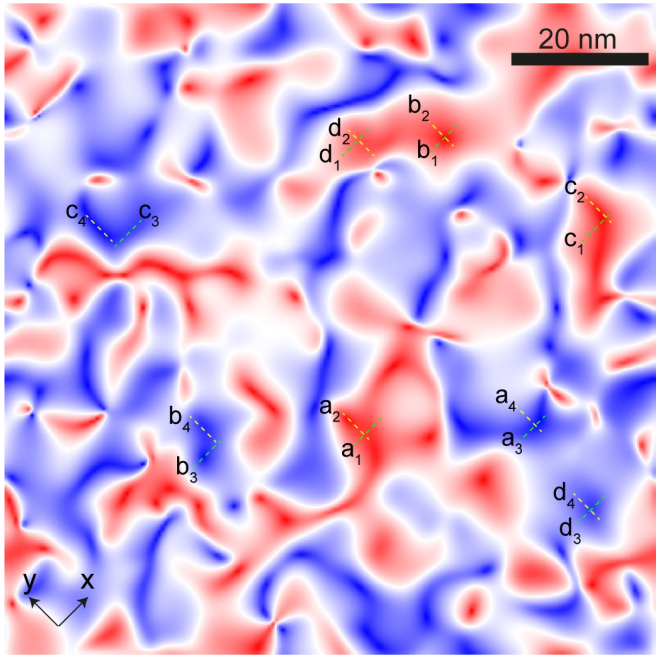
$$\mathcal{N}(\mathbf{r}) = \{A_x(\mathbf{r}) - A_y(\mathbf{r})\}/\{A_x(\mathbf{r}) + A_y(\mathbf{r})\}$$

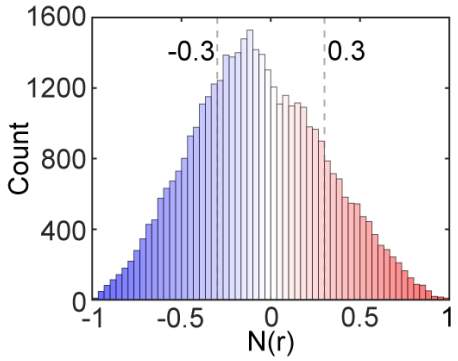


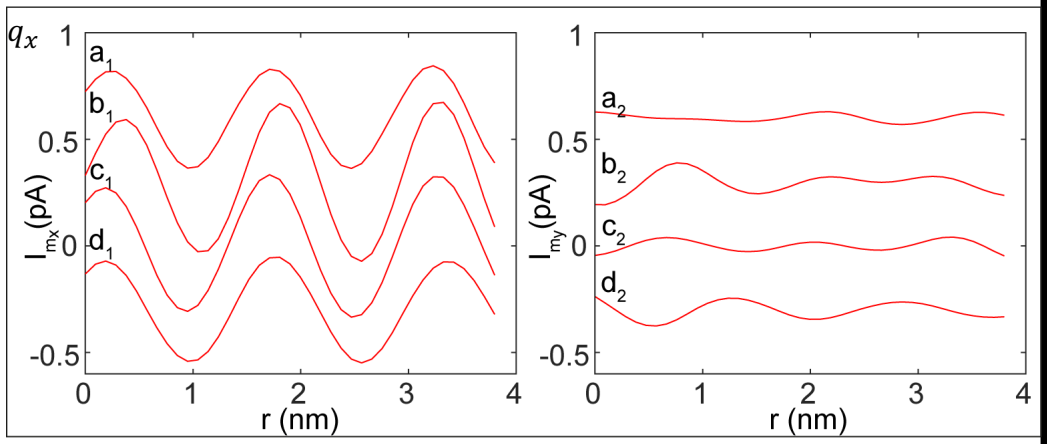
Weijiong Chen *et al* (2022)

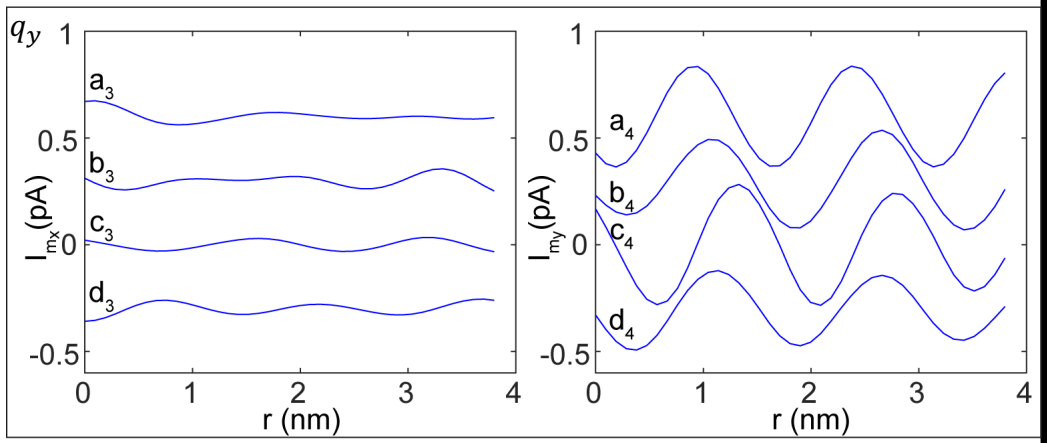
NEMATIC ORDER-PARAMETER FOR $n_P(\boldsymbol{r})$ MODULATIONS

$$\mathcal{N}(\mathbf{r}) = \{A_x(\mathbf{r}) - A_y(\mathbf{r})\}/\{A_x(\mathbf{r}) + A_y(\mathbf{r})\}$$









Weijiong Chen *et al* (2022)

Zn IMPURTY-ATOM SITES : NEMATIC DOMAIN WALLS

PHYSICAL REVIEW B **103**, L020502 (2021)

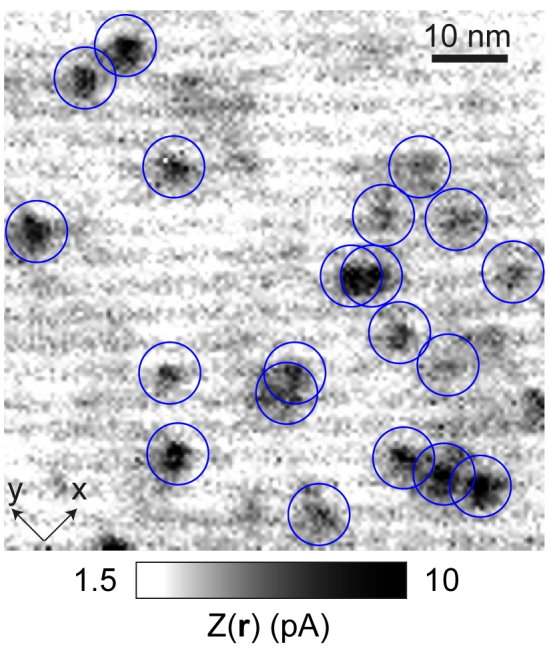
Letter

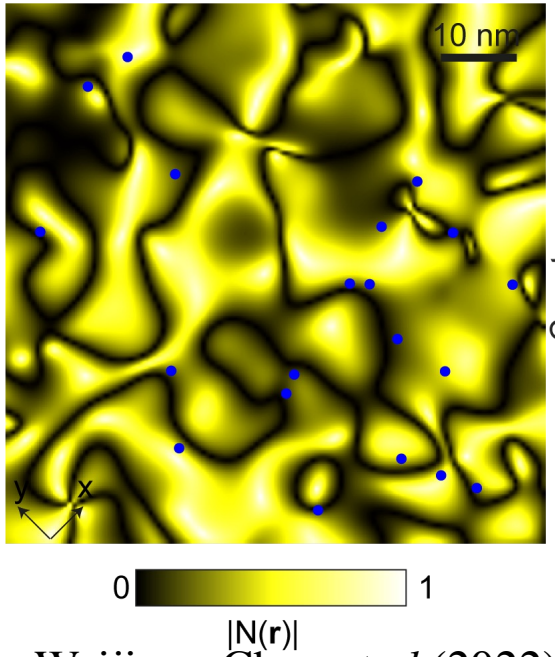
Experimental evidence that zinc impurities pin pair-density-wave order in $La_{2-x}Ba_xCuO_4$

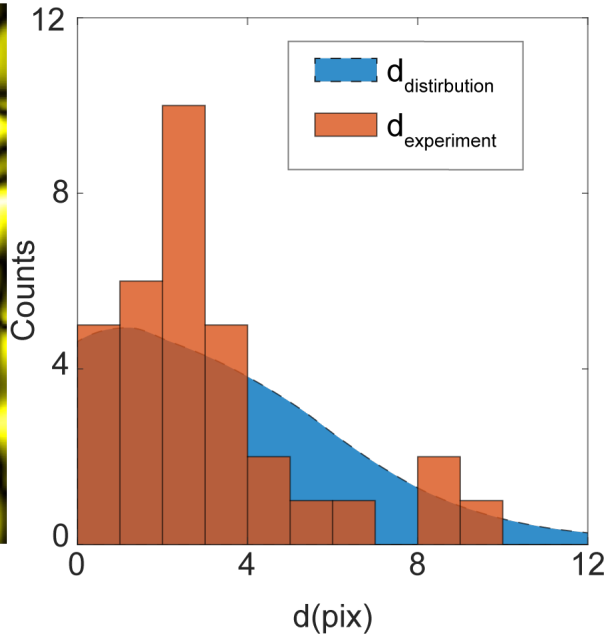
P. M. Lozano,[1,2] G. D. Gu,[1] J. M. Tranquada,[1,*] and Qiang Li[1,2,*]

[1]*Condensed Matter Physics & Materials Science Division, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

[2]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*





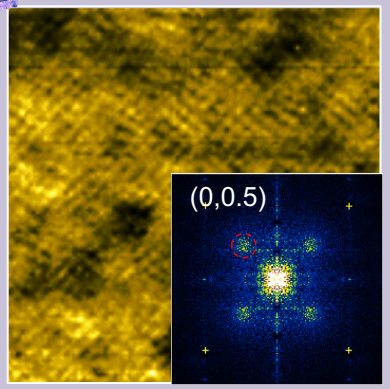


Weijiong Chen *et al* (2022)

CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

PAIR DENSITY

J E

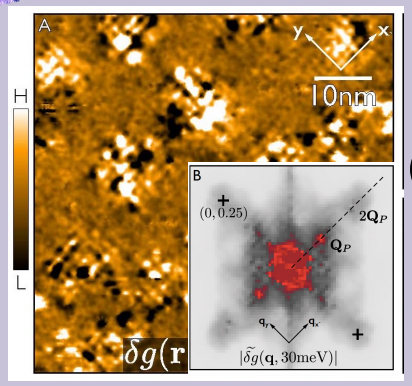


2e

Nature 532, 343 (2016)

VORTEX HALO

N I S

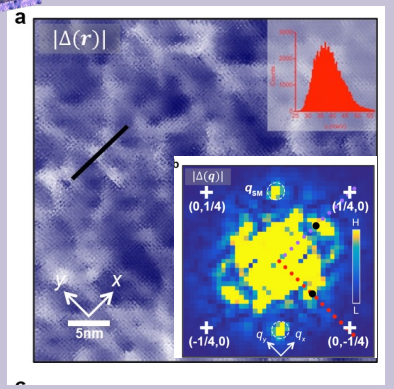


1e

Science 364, 976 (2019)

ENERGY GAP

S I S

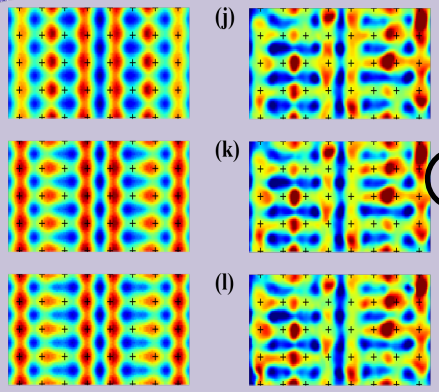


1e

Nature 580, 6570 (2020)

QUASIPARTICLES

N I S

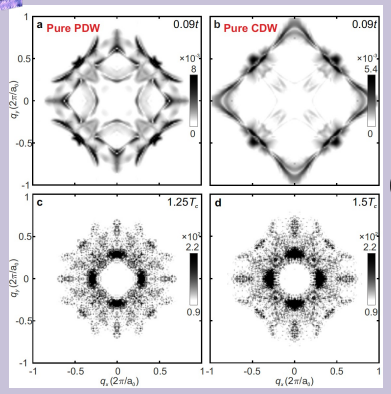


1e

PNAS 117, 14850 (2020)

PSEUDOGAP QPI

N I S

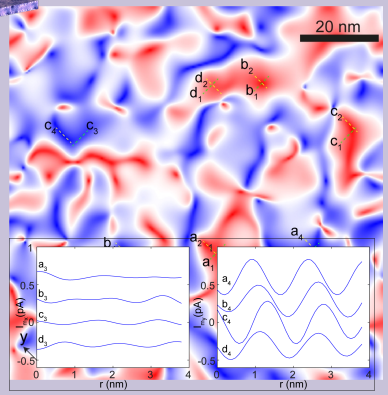


1e

Nat.Comm 12, 6087 (2021)

NEMATIC

J E



2e

Weijiong Chen *et al* (2022)

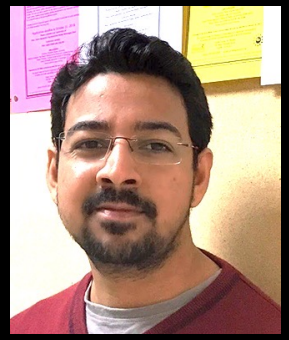
CuO_2 ELECTRON-PAIR VISUALIZATION STUDIES

		MEASURED	PAIR MODS	CHARGE MODS	MODEL
PAIRS	PAIR DENSITY	$n_P(\boldsymbol{r})$	$Q_{Im}\left(\frac{2\pi}{a}\right) = 1/4$	-	IZ
VORTEX	QP DENSITY	$N(\boldsymbol{r}, \sim\Delta_1)$	$Q_{\Delta}\left(\frac{2\pi}{a}\right) = 1/8$	$Q_C\left(\frac{2\pi}{a}\right) = 1/8$ $Q_C\left(\frac{2\pi}{a}\right) = 1/4$	GLW($8a_0$)
GAP	(PSEUDO)GAP	$\Delta(\boldsymbol{r})$	$Q_{\Delta}\left(\frac{2\pi}{a}\right) = 1/8$	$Q_C\left(\frac{2\pi}{a}\right) = 1/8$ $Q_C\left(\frac{2\pi}{a}\right) = 1/4$	GLW($8a_0$)
QP DOS	QP DENSITY	$N(\boldsymbol{r}, \sim\Delta_1)$	$Q_P\left(\frac{2\pi}{a}\right) = 1/8$	$Q_C\left(\frac{2\pi}{a}\right) = 1/8$ $Q_C\left(\frac{2\pi}{a}\right) = 1/4$	RMFtJ($8a_0$)
PG QPI	INTERFERENCE	$\Lambda(\boldsymbol{q}, \sim\Delta_0)$	$Q_P\left(\frac{2\pi}{a}\right) = 1/8$		RMFtJ($8a_0$)
PAIRS	PAIR DENSITY	$n_P(\boldsymbol{r})$	$Q_{Im}\left(\frac{2\pi}{a}\right) = 1/4$	NONE	IZ

Xiaolong Liu
Notre Dame

Shuqiu Wang
Oxford

THANKS!



P. Choubey
IIT Delhi

Weijiong Chen
Oxford

S. Uchida
Tokyo

H. Eisaki
Tsukuba

P.D. Johnson
Oxford

Kazuhiro Fujita
BNL

P.J. Hirschfeld
Florida

M. H. Hamidian
Cornell

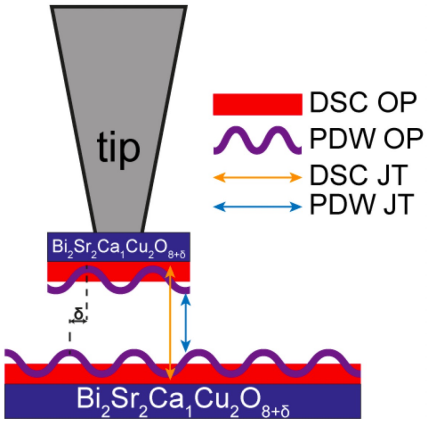
S.D. Edkins
Cornell

A.P. Mackenzie
Dresden

‘FUJITA CONJECTURE’

DSC part

$$\Delta_T^S = |\Delta_0| e^{i\theta_T}$$
$$\Delta_S^S = |\Delta_0| e^{i\theta_S}$$



PDW part

$$\Delta_T^D = |\Delta_0| \alpha e^{i(Q(x-\delta))} e^{i\theta_T}$$
$$\Delta_S^D = |\Delta_0| \alpha e^{i(Qx)} e^{i\theta_S}$$

Josephson Current

$$I_J^S = \frac{K}{i\hbar}(\Delta_T \Delta_S^* - \Delta_T^* \Delta_S) = \frac{2K}{\hbar}|\Delta_0|^2[\sin(\theta_T - \theta_S)]$$

Josephson Current

$$I_J^D = \frac{K}{i\hbar}(\Delta_T \Delta_S^* - \Delta_T^* \Delta_S)$$
$$= \frac{2K}{\hbar}|\Delta_0|^2 \alpha^2[\sin(-Q\delta + \theta_T - \theta_S)]$$

Normal Josephson effect

$$I_J = I_c \sin(\theta_T - \theta_S)$$

$$I_m R_N^2 \propto I_c^2$$

Assume $\theta_T - \theta_S = \frac{\pi}{2}$

$$I_m R_N^2 \propto {I_J^S}^2 + {I_J^D}^2 = \left(\frac{2K}{\hbar}\right)^2 |\Delta_0|^4 (1 + \alpha^2 \sin(\mathrm{Q}\delta)^2)$$