FIELD-INDUCED PAIR DENSITY WAVE

MAGNETIC FIELD CONTROL OF CUPRATE DENSITY WAVE

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

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

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

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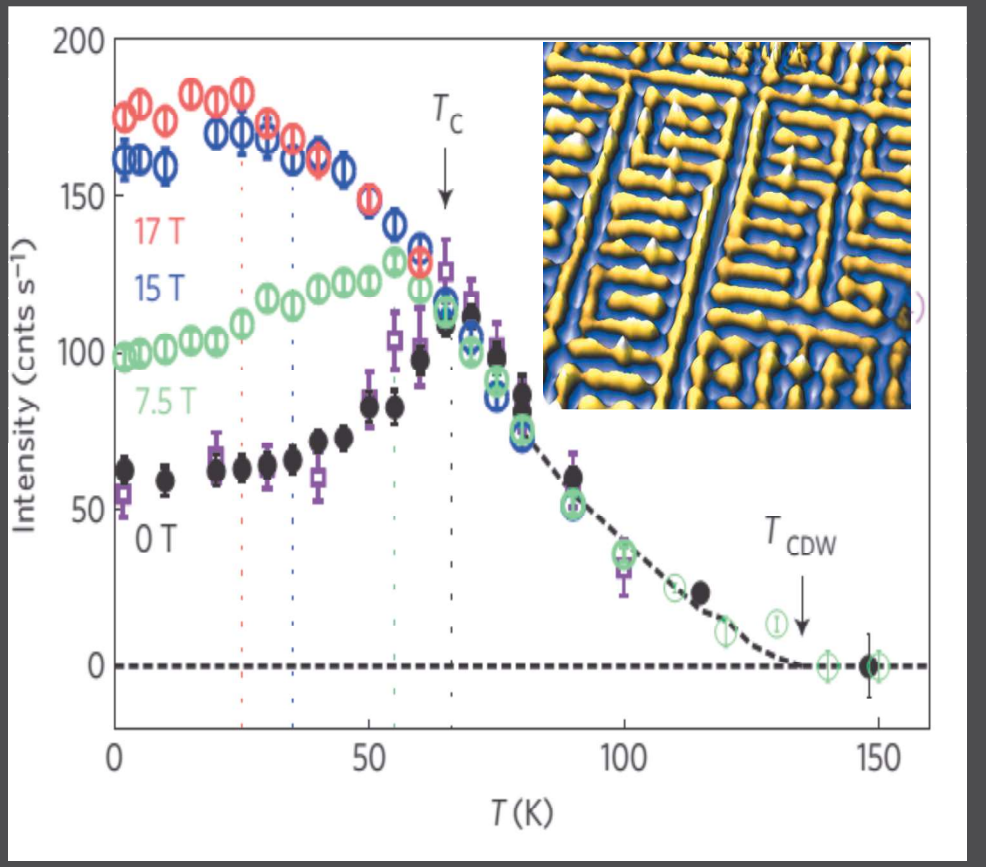
T. Wu *et al. Nat Comm.* 6, 1 (2015)

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

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

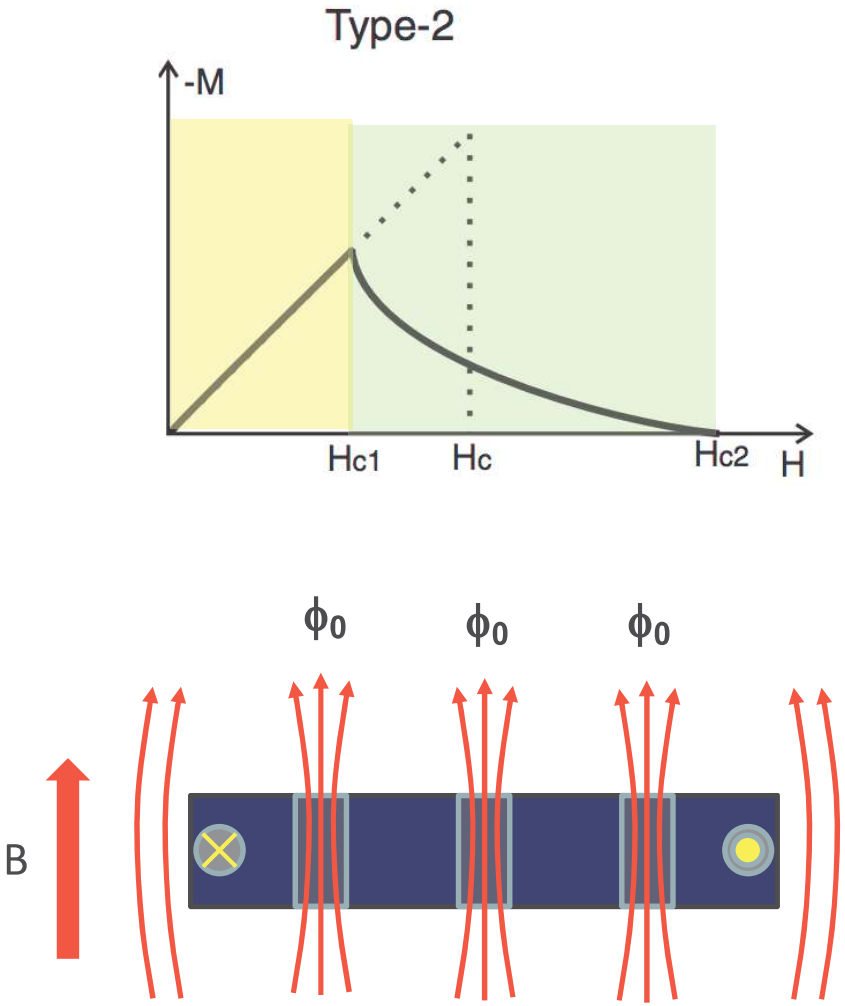
H. Jang *et al. PNAS* 113 14645–14650 (2016)

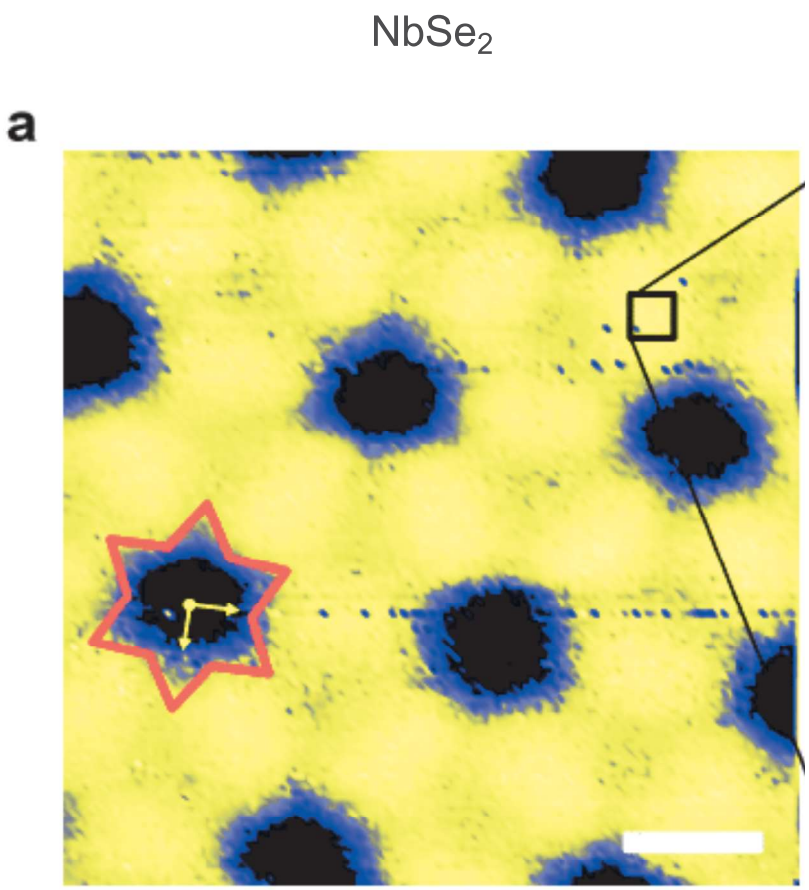


Chang *et al*. *Nat Phys* 8, 871 (2012)

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

SUPERCONDUCTOR+MAGNETIC FIELD => VORTEX LATTICE





PAIR DENSITY WAVE INDUCED AT VORTEX

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

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

Daniel F. Agterberg[1] and Julien Garaud[2,*]

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[2]*Department of Theoretical Physics, KTH-Royal Institute of Technology, Stockholm, SE-10691 Sweden*

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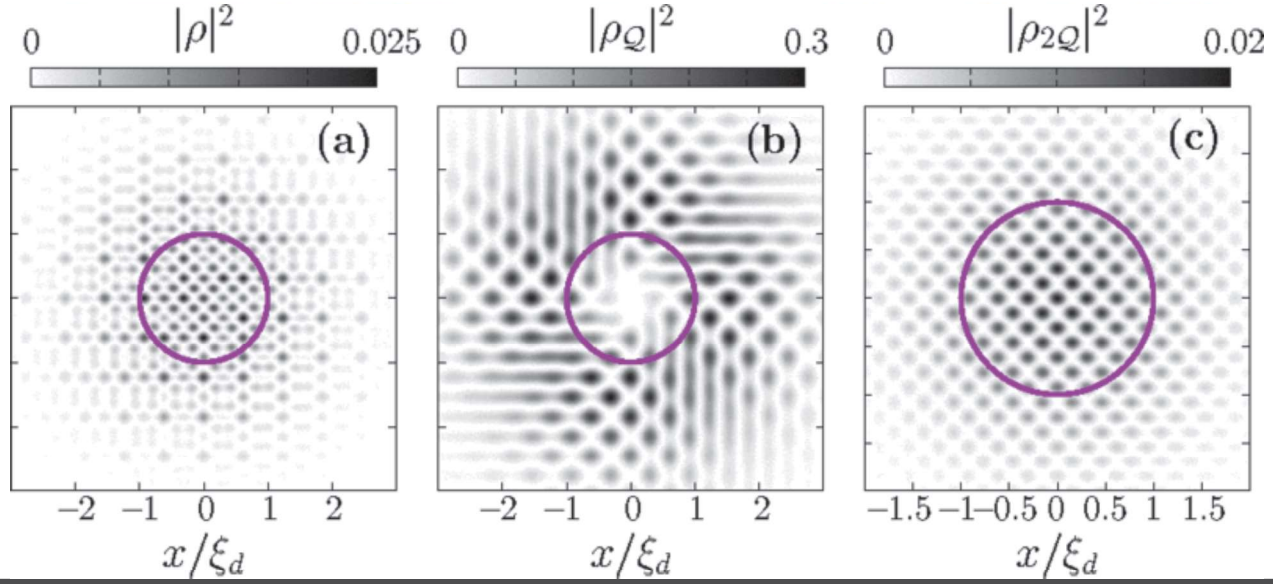
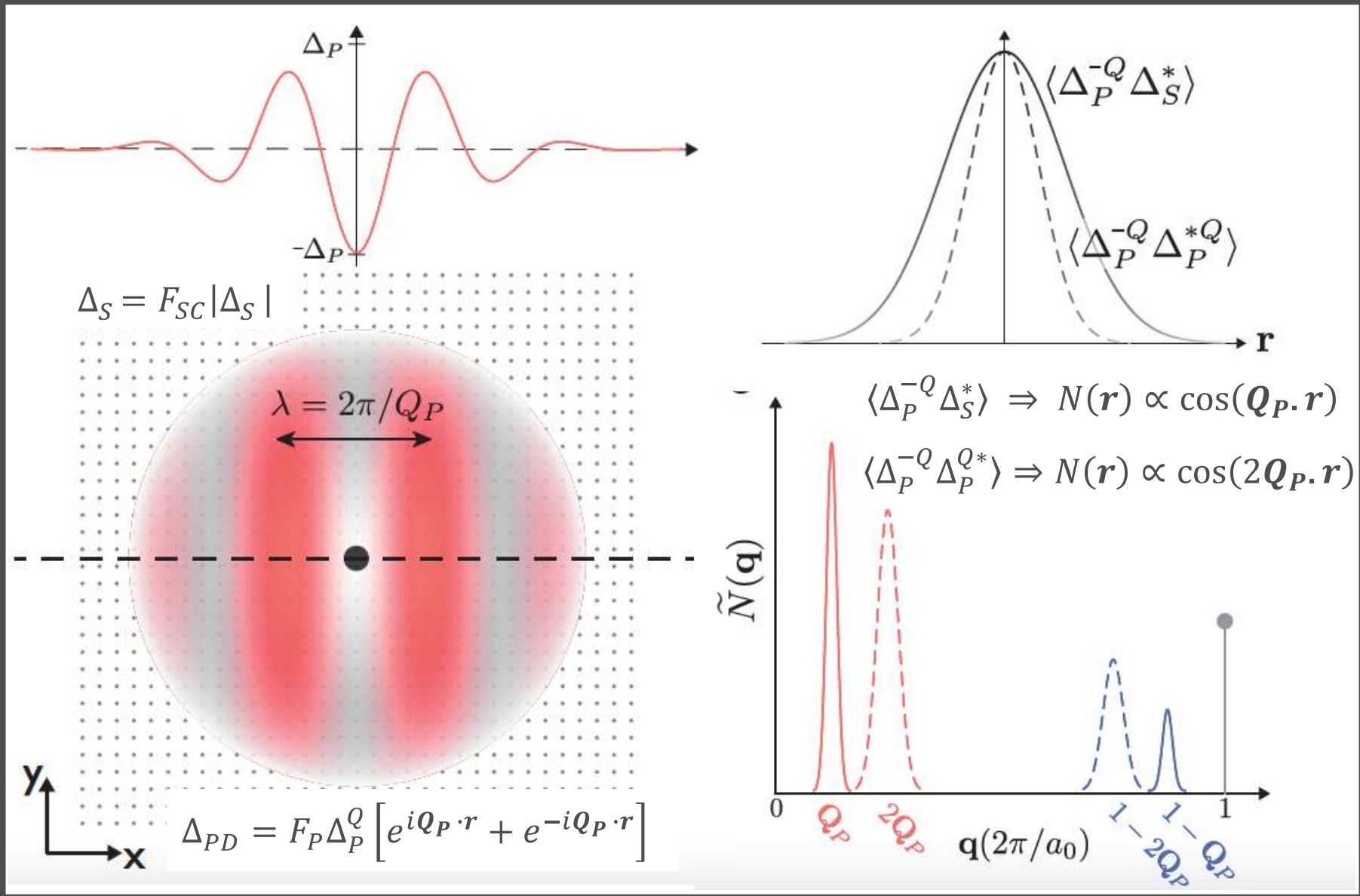
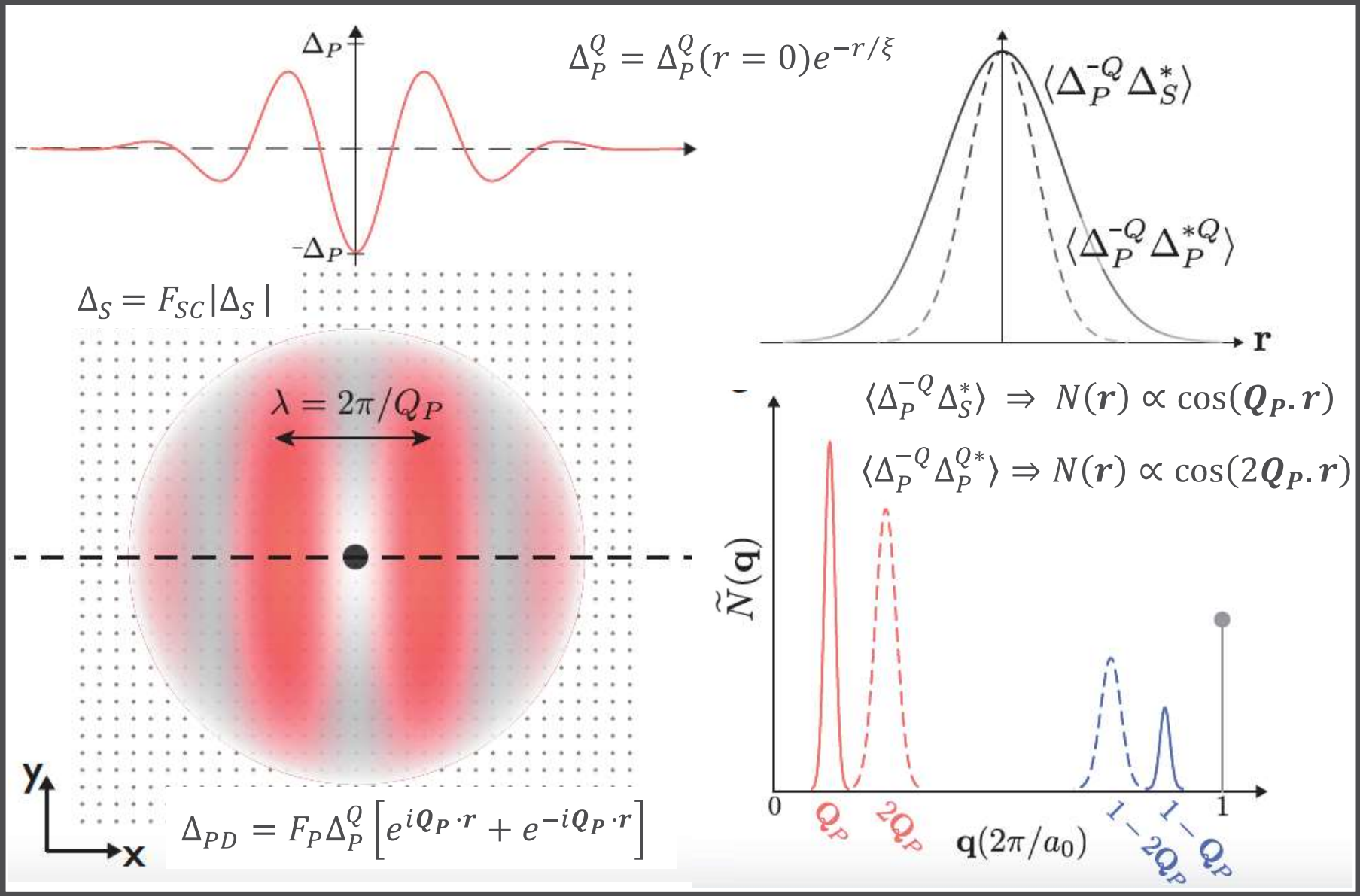
We consider competing pair-density-wave (PDW) and d-wave superconducting states in a magnetic field. We show that PDW order appears in the cores of d-wave vortices, driving checkerboard charge-density-wave (CDW) order in the vortex cores, which is consistent with experimental observations. Furthermore, 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.



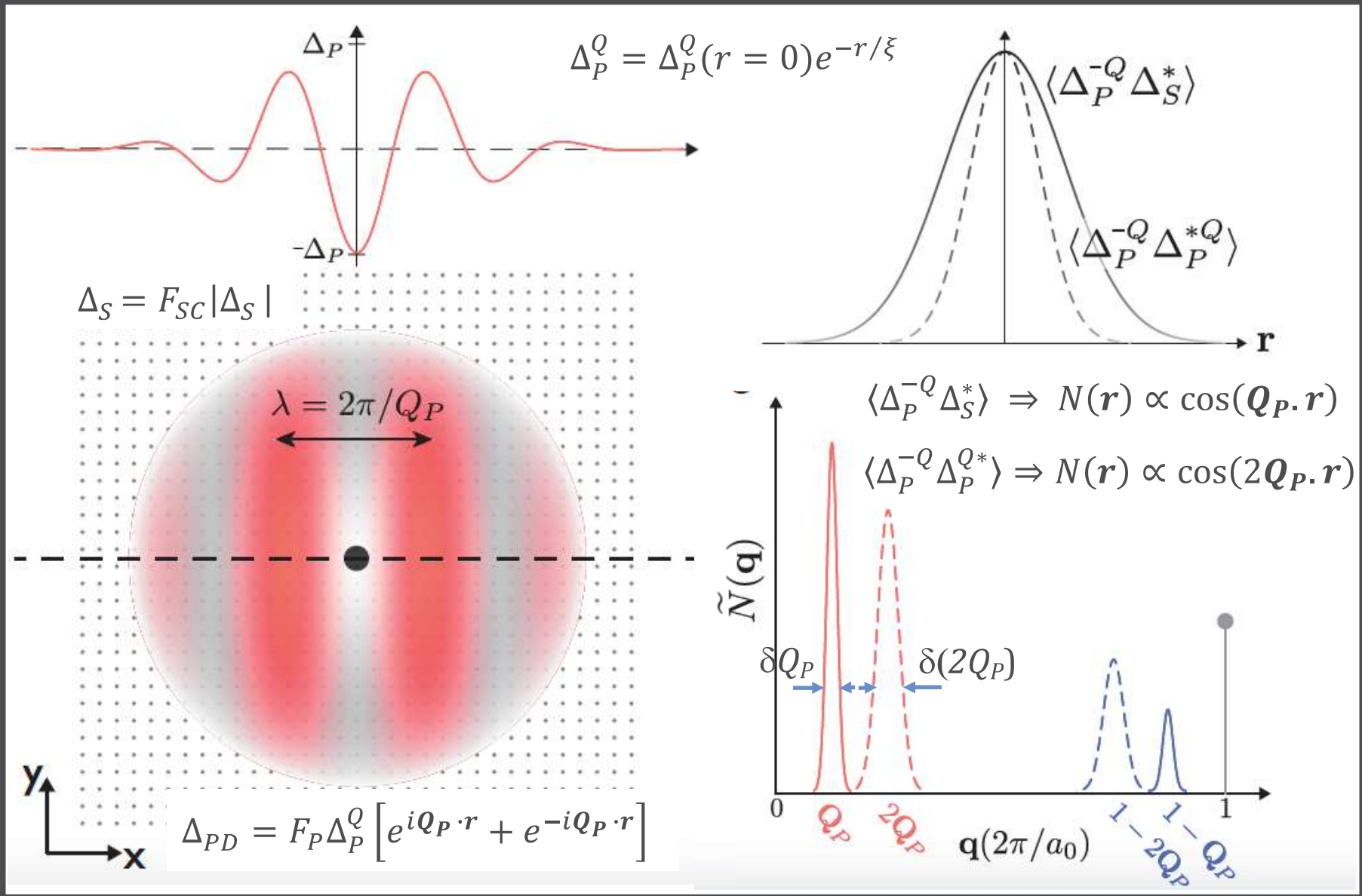
PDW IN VORTEX HALO ⇒ Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS



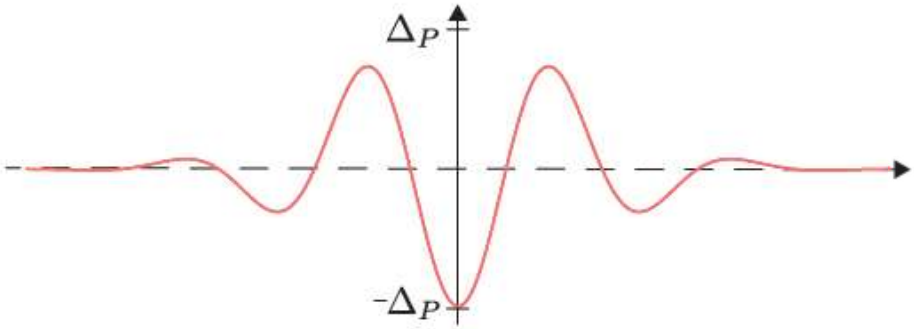
PDW IN VORTEX HALO ⇒ Q_P & $2Q_P$ MODULATION DECAY LENGTHS



PDW IN VORTEX HALO ⇒ LINEWIDTHS $\delta(2Q_P)= 2(\delta Q_P)$

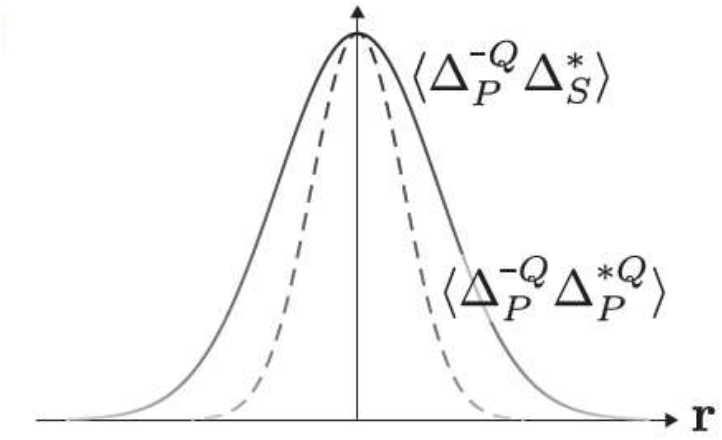


PDW IN VORTEX HALO ⇒ EXPECTED PHENOMENOLOGY



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

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



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

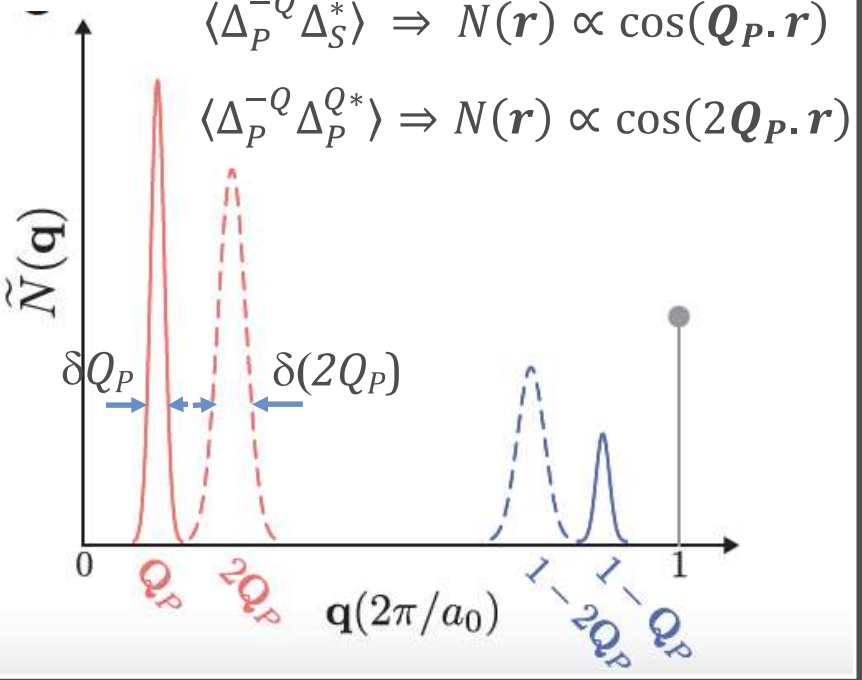
$\langle\Delta_P^{-Q}\Delta_P^{Q*}\rangle \Rightarrow N(\boldsymbol{r}) \propto \cos(2\boldsymbol{Q_P}.\boldsymbol{r})$

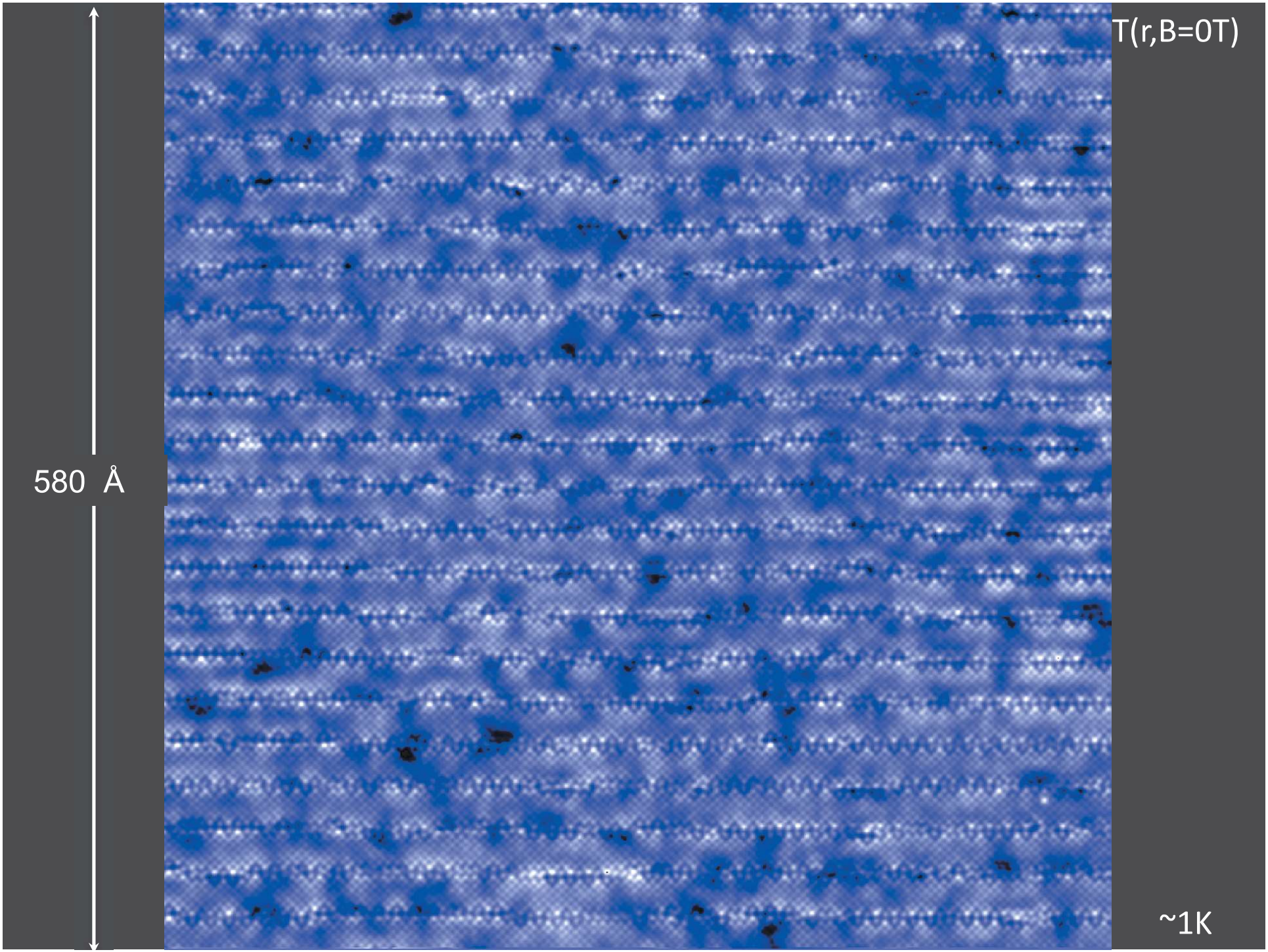
PDW Q_P WITHIN VORTEX HALO

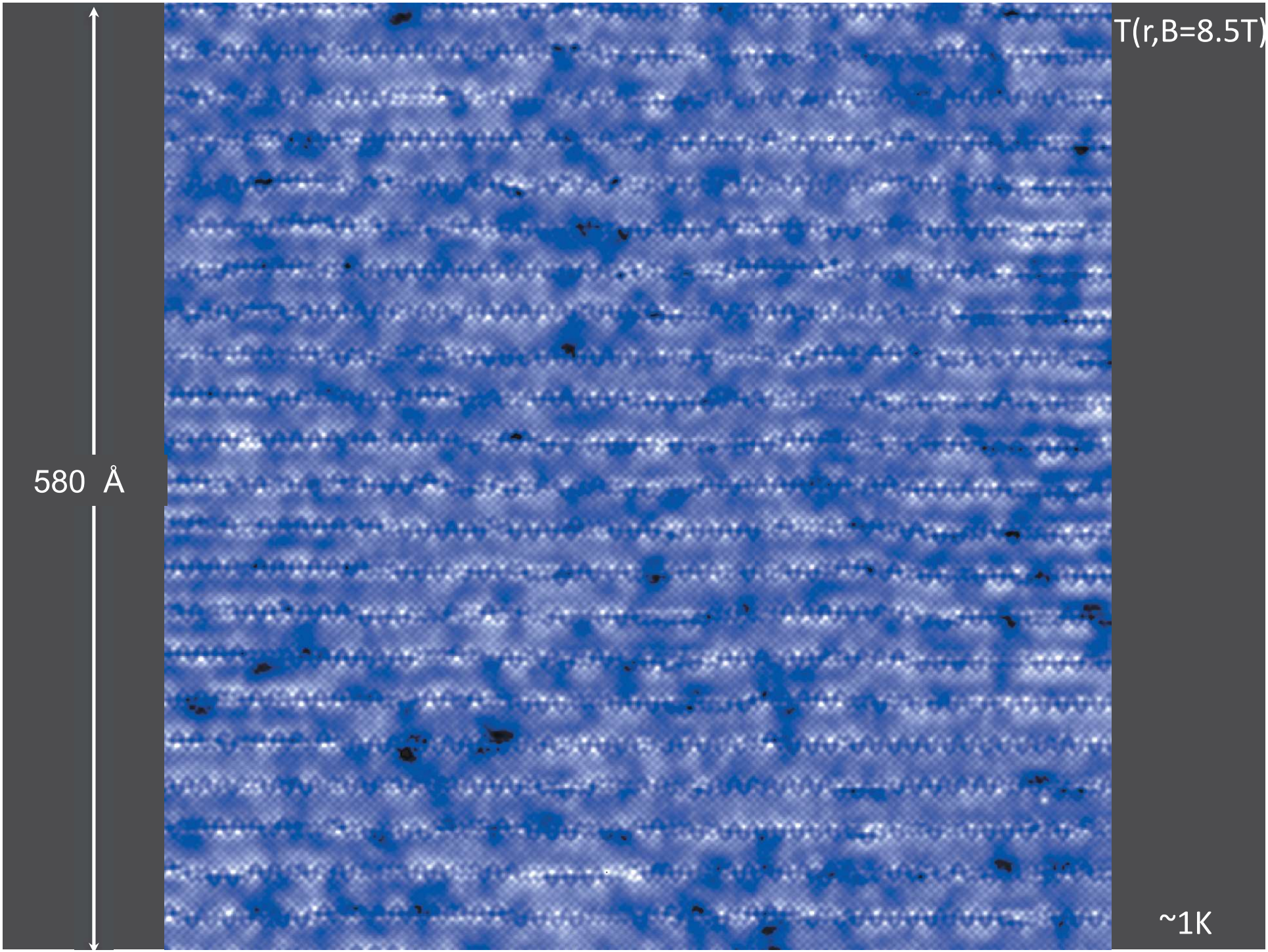
Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

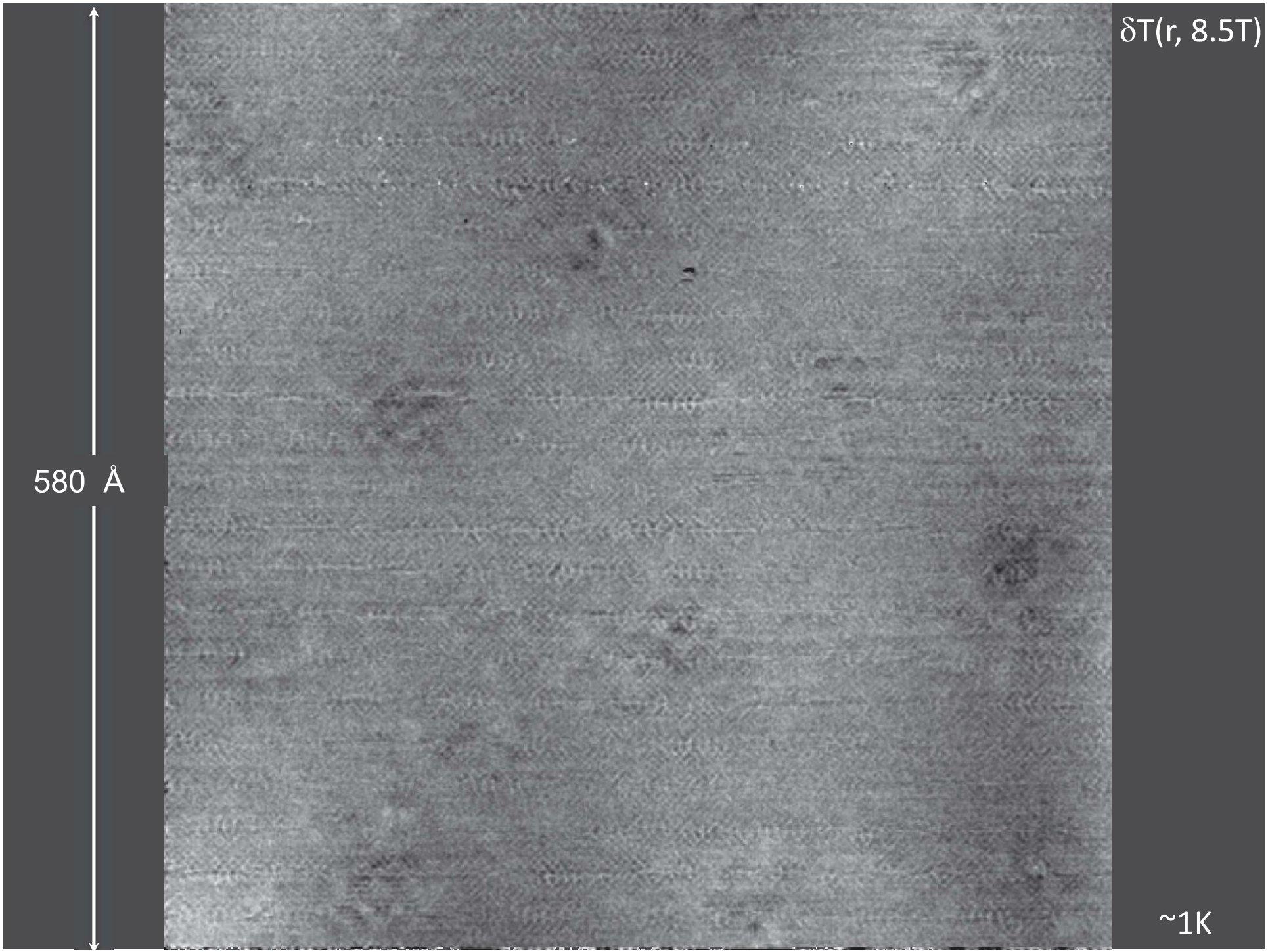
d-SYMMETRY PDW ⇒ s-SYMMETRY MODS

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

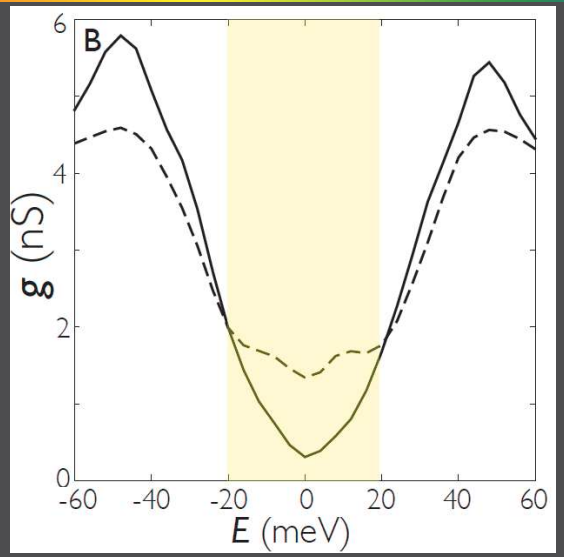



T(r,B=0T)
580 Å
~1K

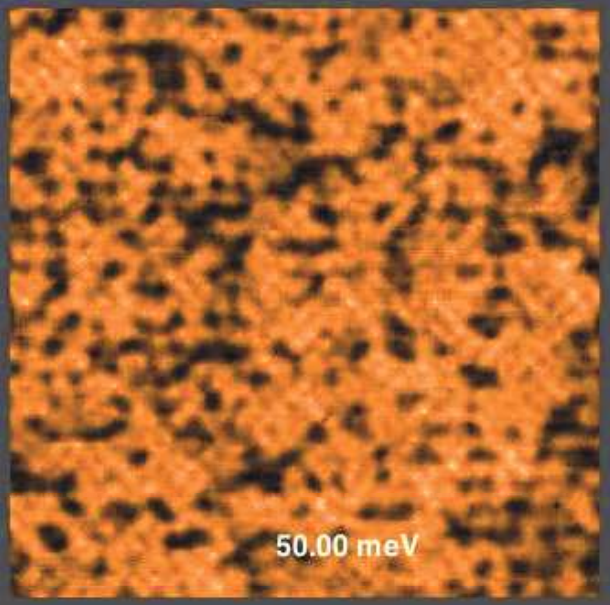

T(r,B=8.5T)
580 Å
~1K


580 Å
δT(r, 8.5T)
~1K

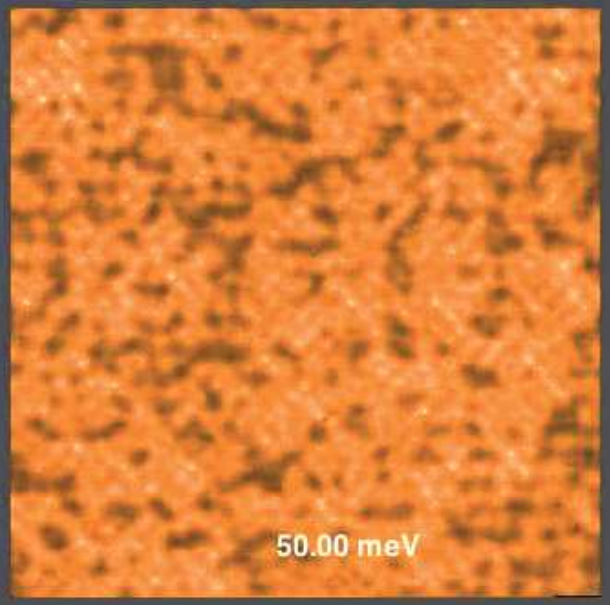
FIELD-INDUCED CHANGES TO ELECTRONIC STRUCTURE @ HALO



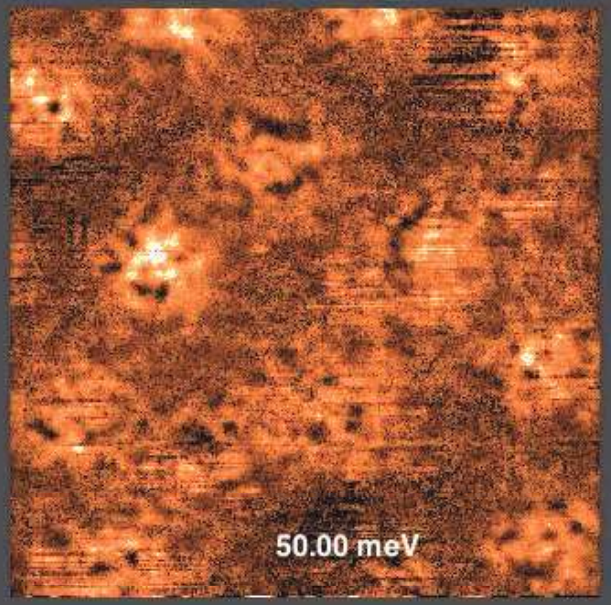
g(B=8.5T)



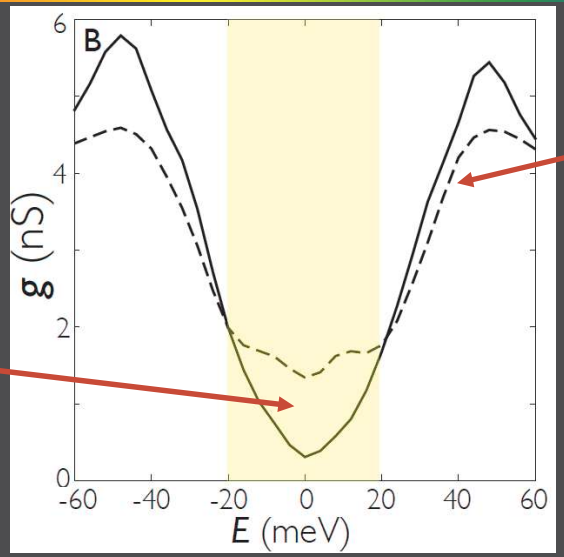
g (B=0T)



δg



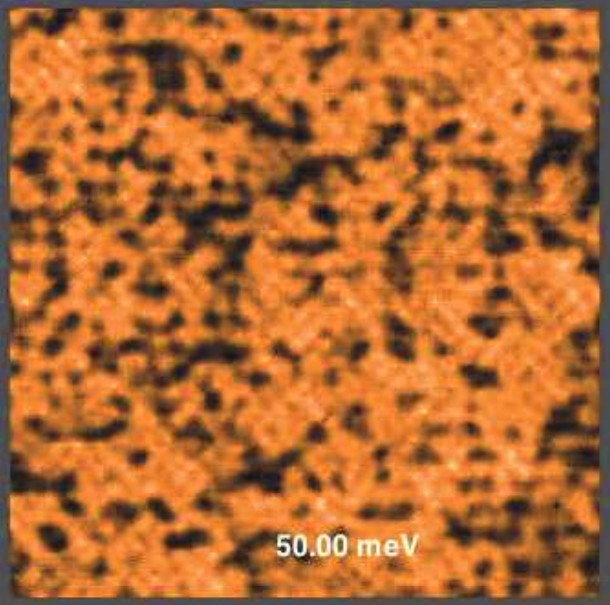
FIELD-INDUCED CHANGES TO ELECTRONIC STRUCTURE @ HALO



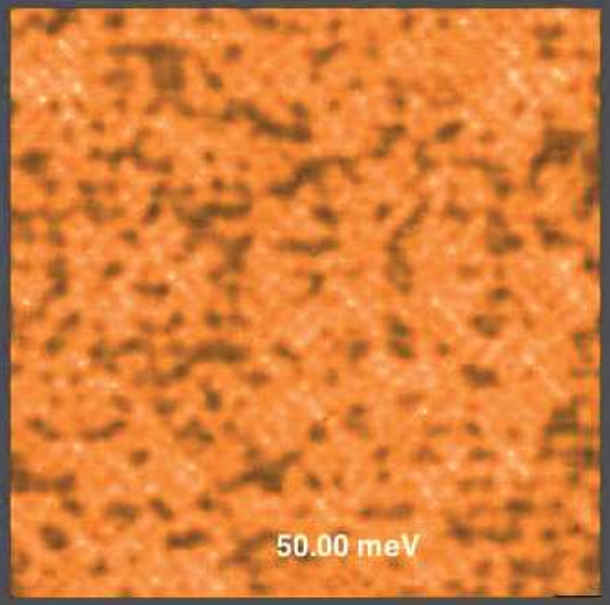
GAP-EDGE STATES

NODAL BOGOLIUBOV QP

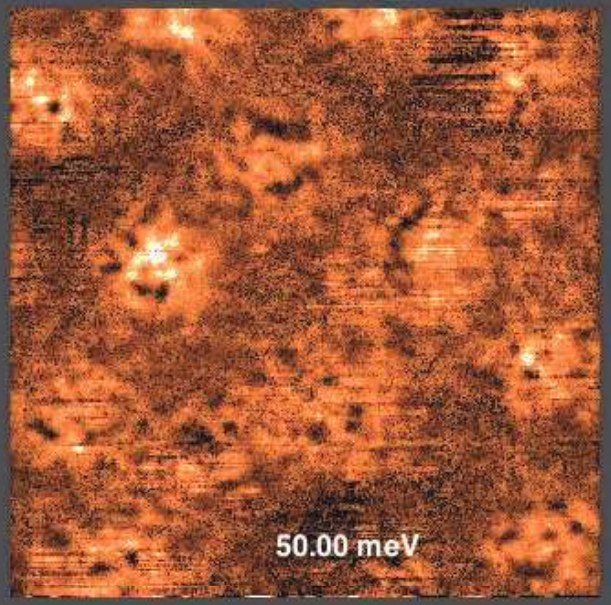
g(B=8.5T)



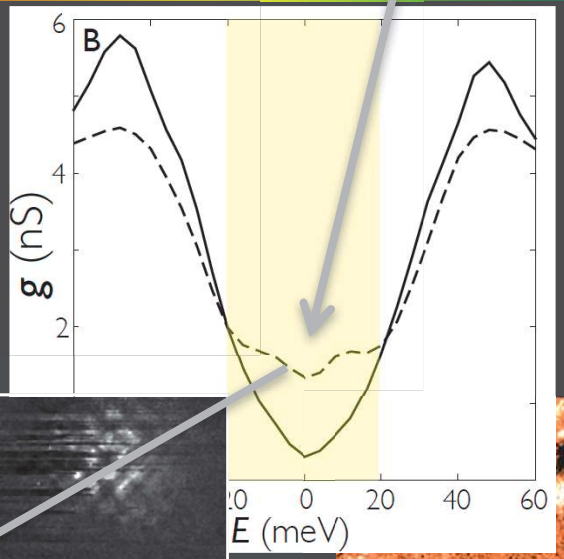
g (B=0T)

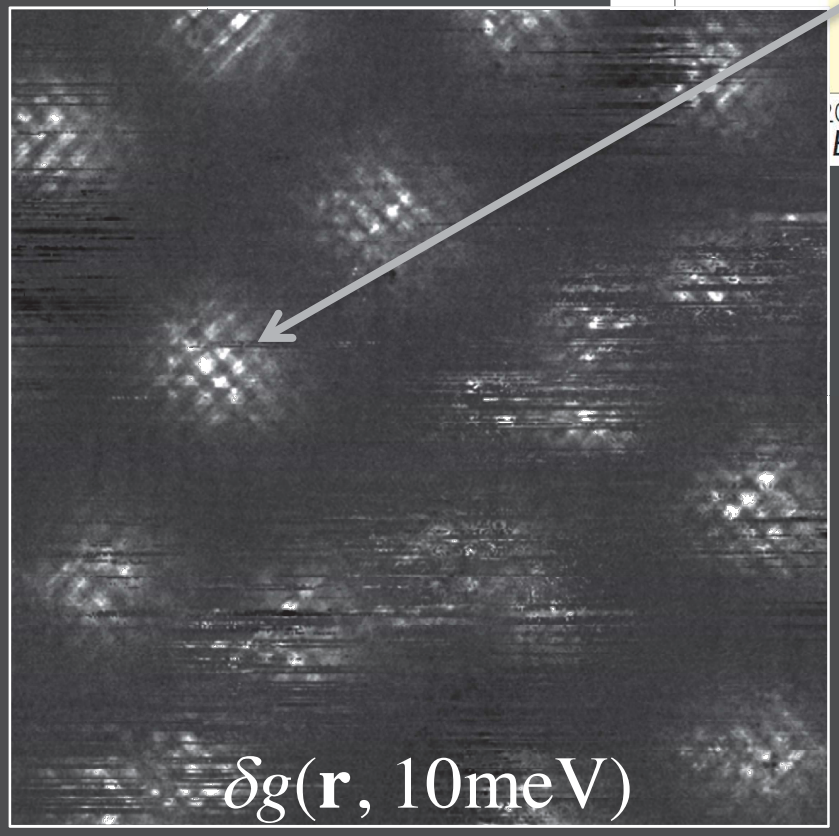


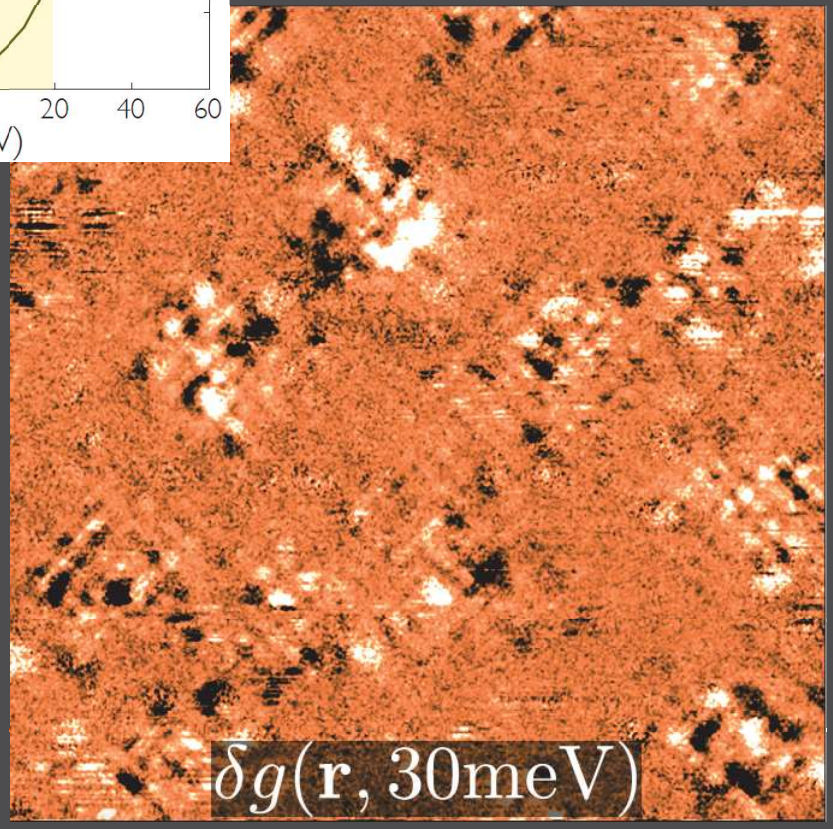
δg



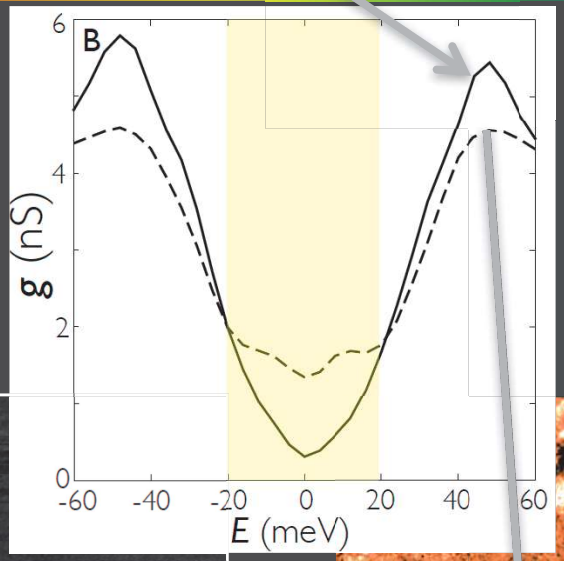
NODAL BOGOLIUBOV QUASIPARTICLES

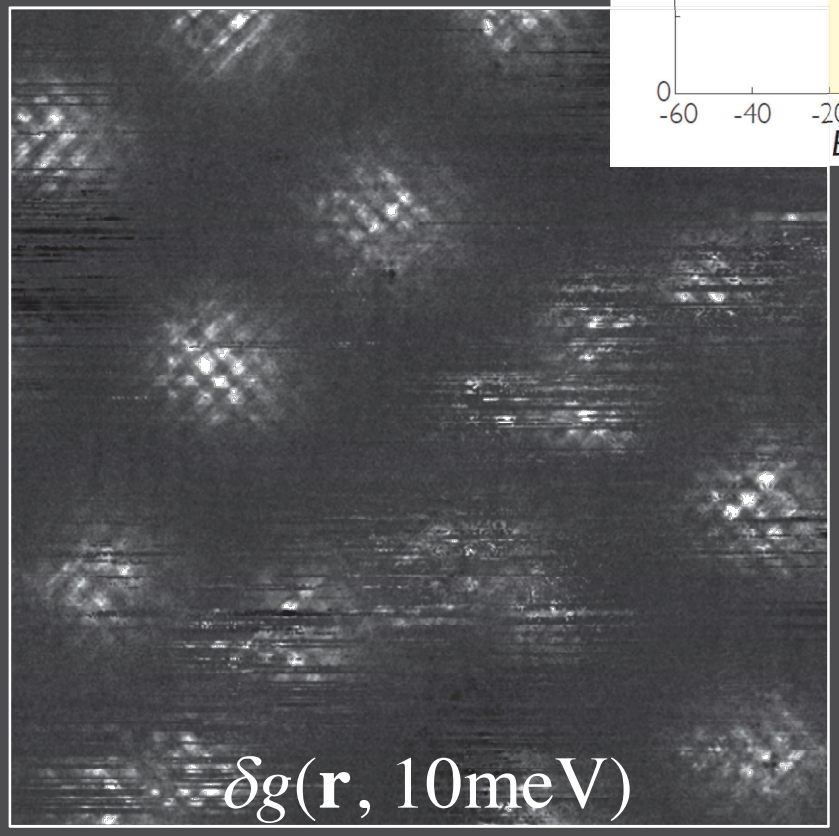


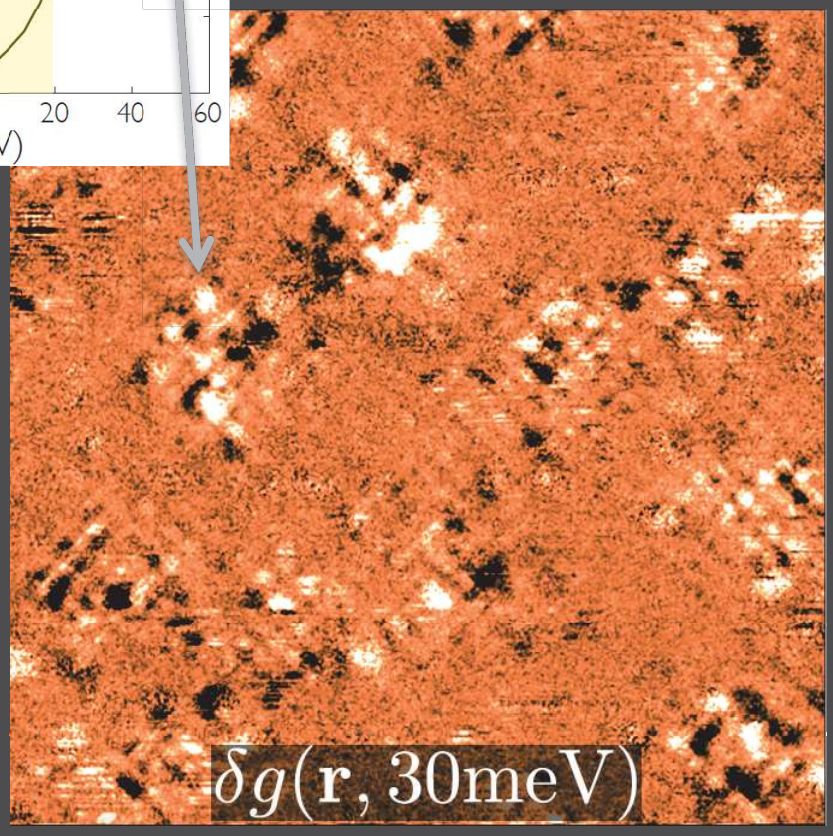




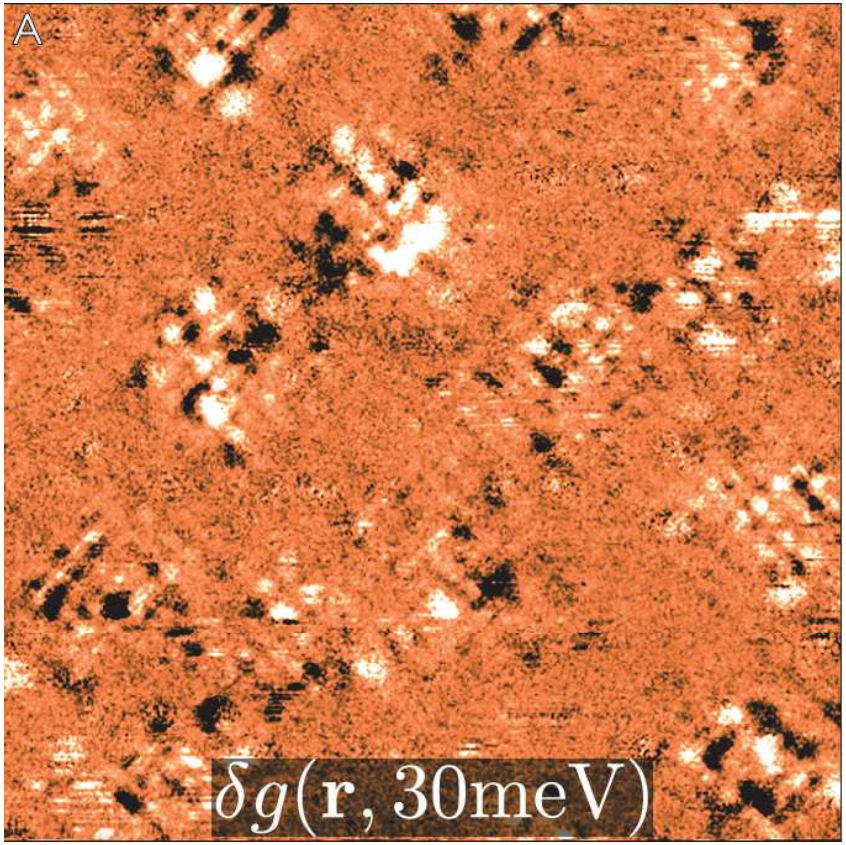
GAP EDGE STATES





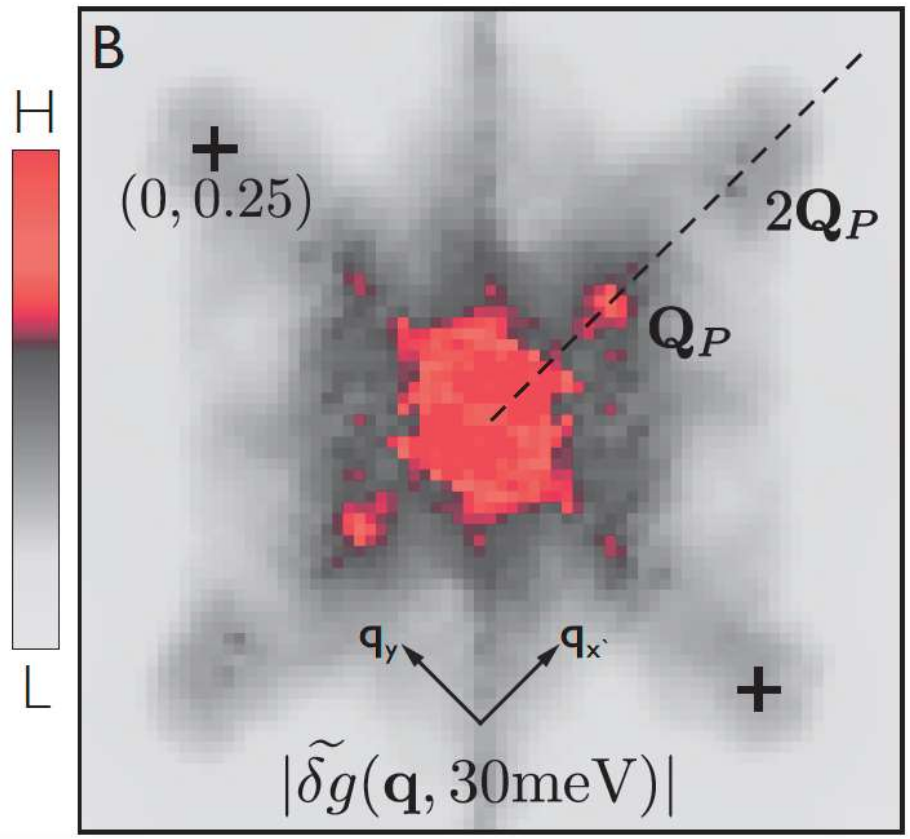


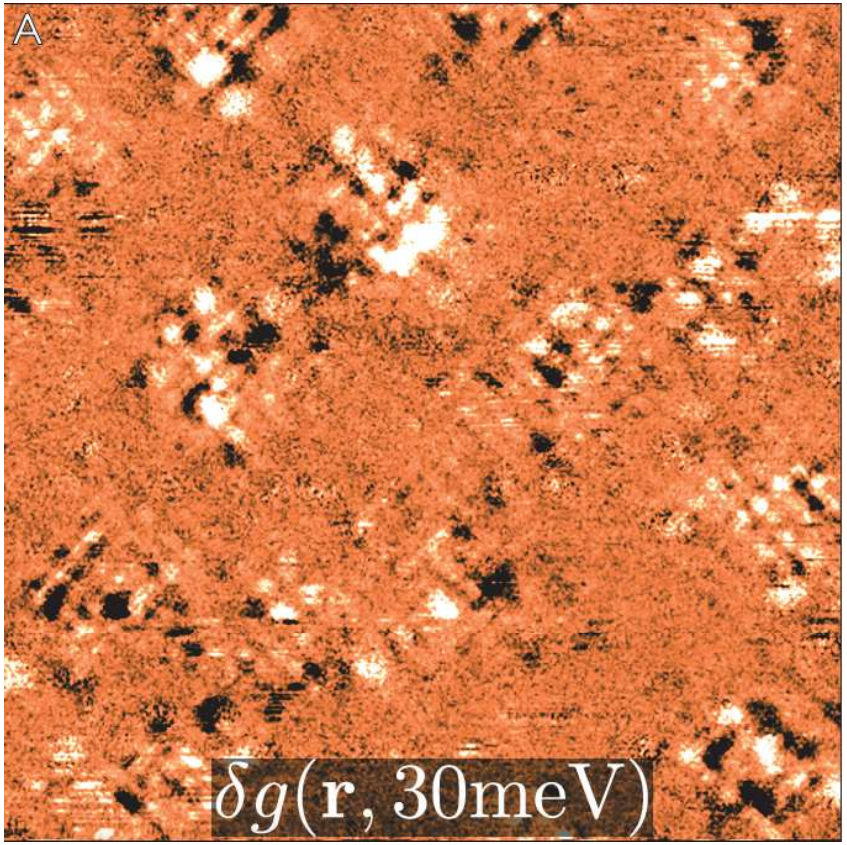
FIELD-INDUCED N(r) MODULATIONS



Science 364, 976 (2019)

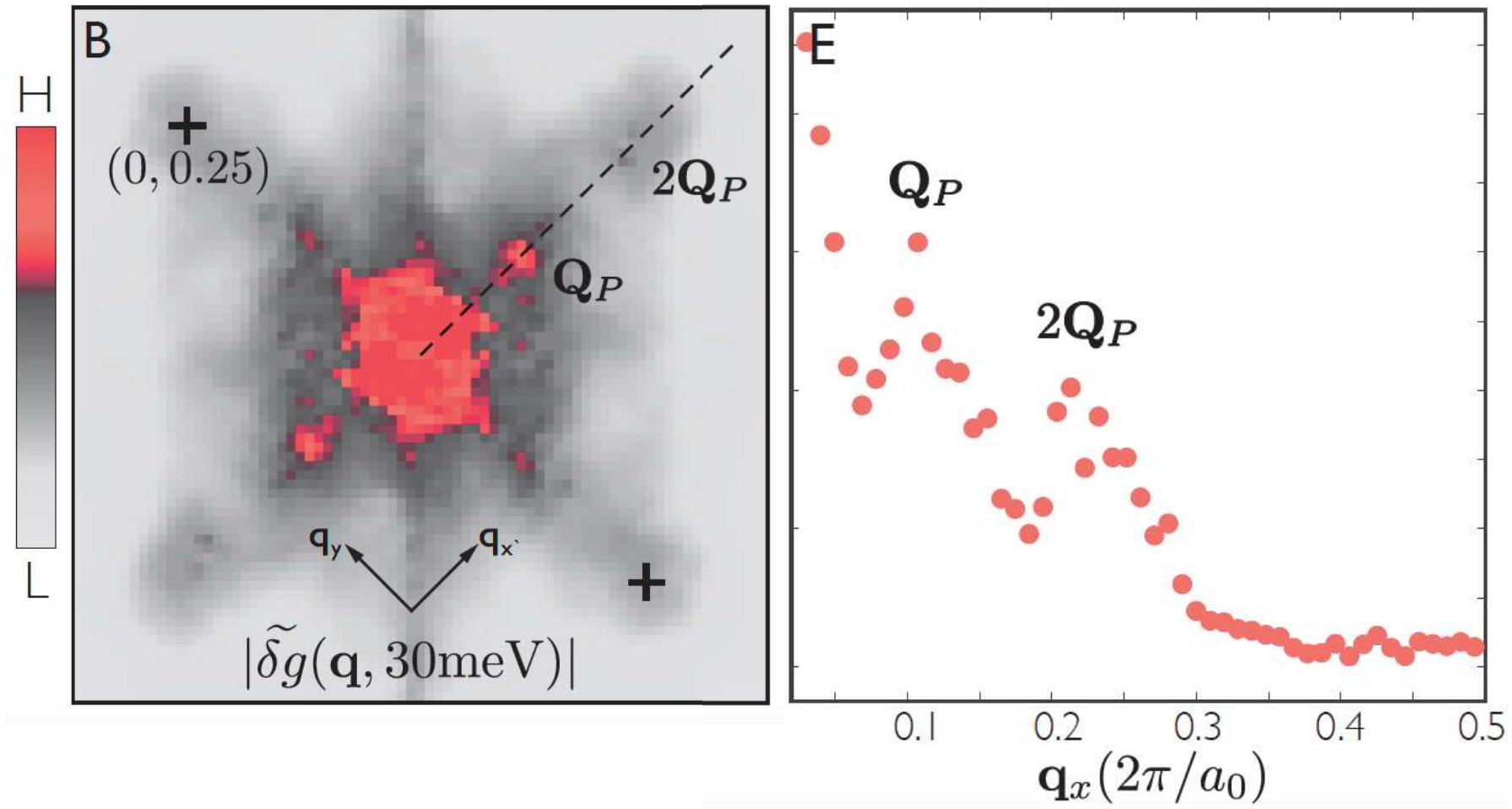
FIELD-INDUCED N(r) MODULATIONS





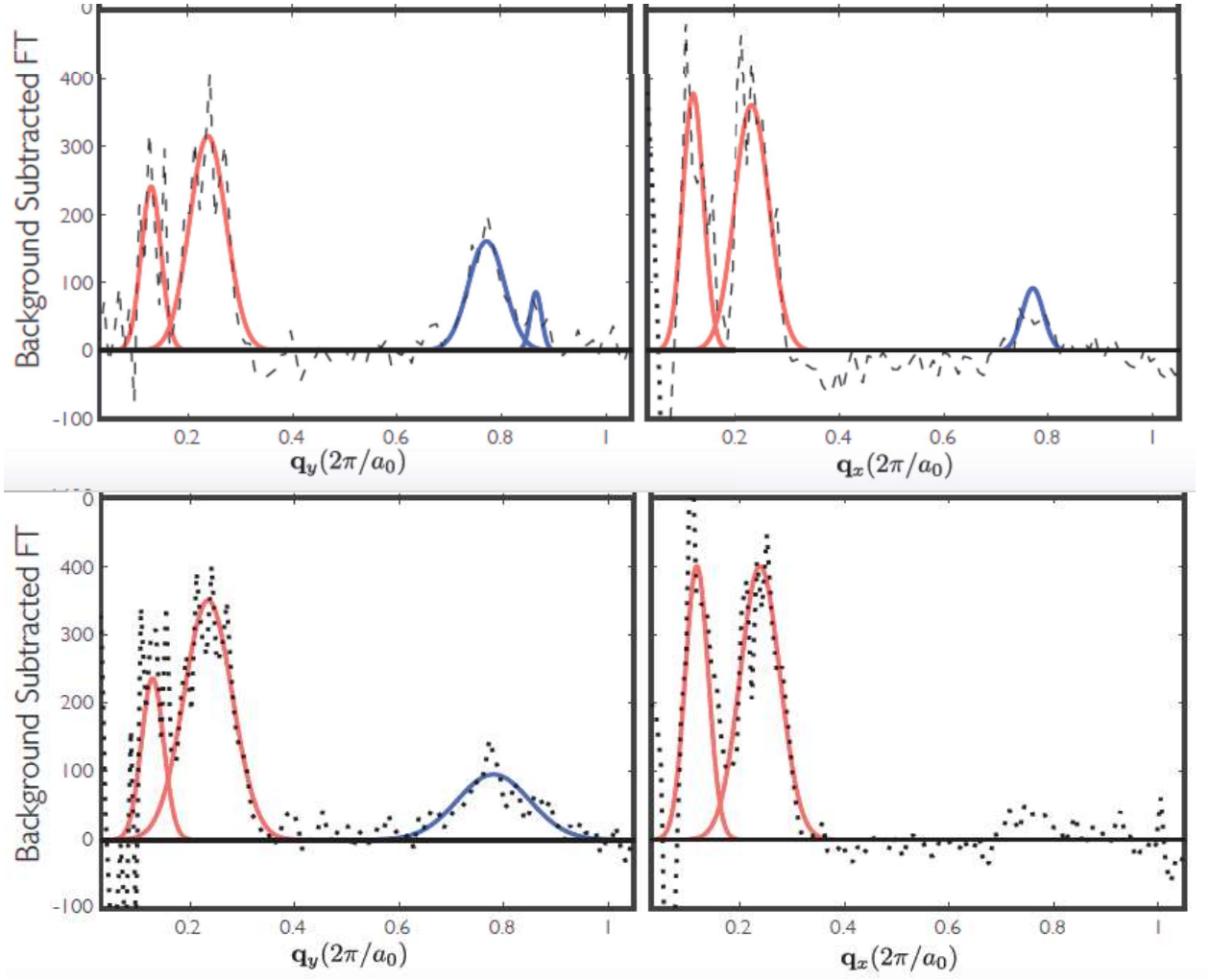
Science 364, 976 (2019)

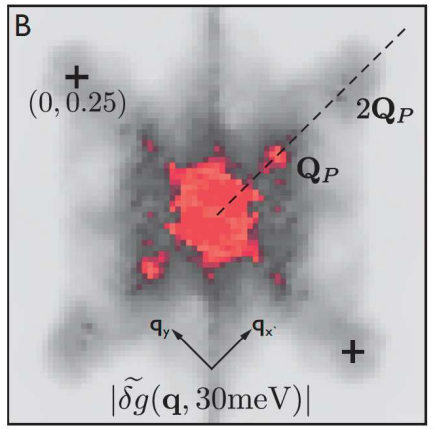
FIELD INDUCED N(r) MODULATIONS : PEAKS at Q_P and $2Q_P$

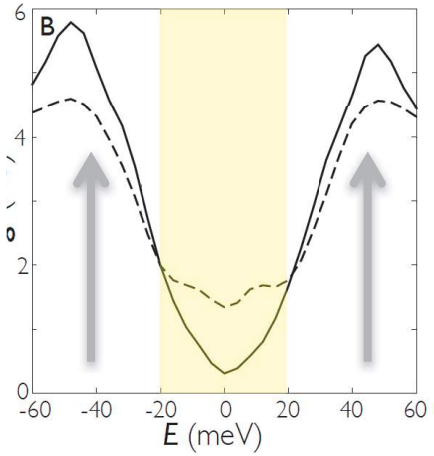


Science 364, 976 (2019)

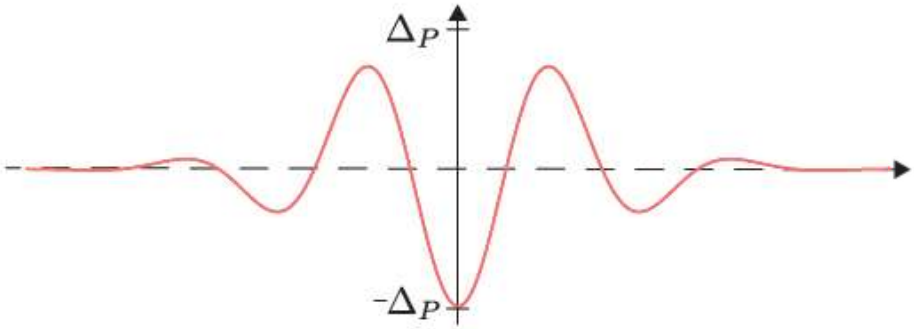
FIELD-INDUCED N(r) MODS Q_P AND $2Q_P$ $\rightleftarrows \delta(2Q_P) \approx 2\delta(Q_P)$







PDW IN VORTEX HALO ⇒ EXPECTED PHENOMENOLOGY



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

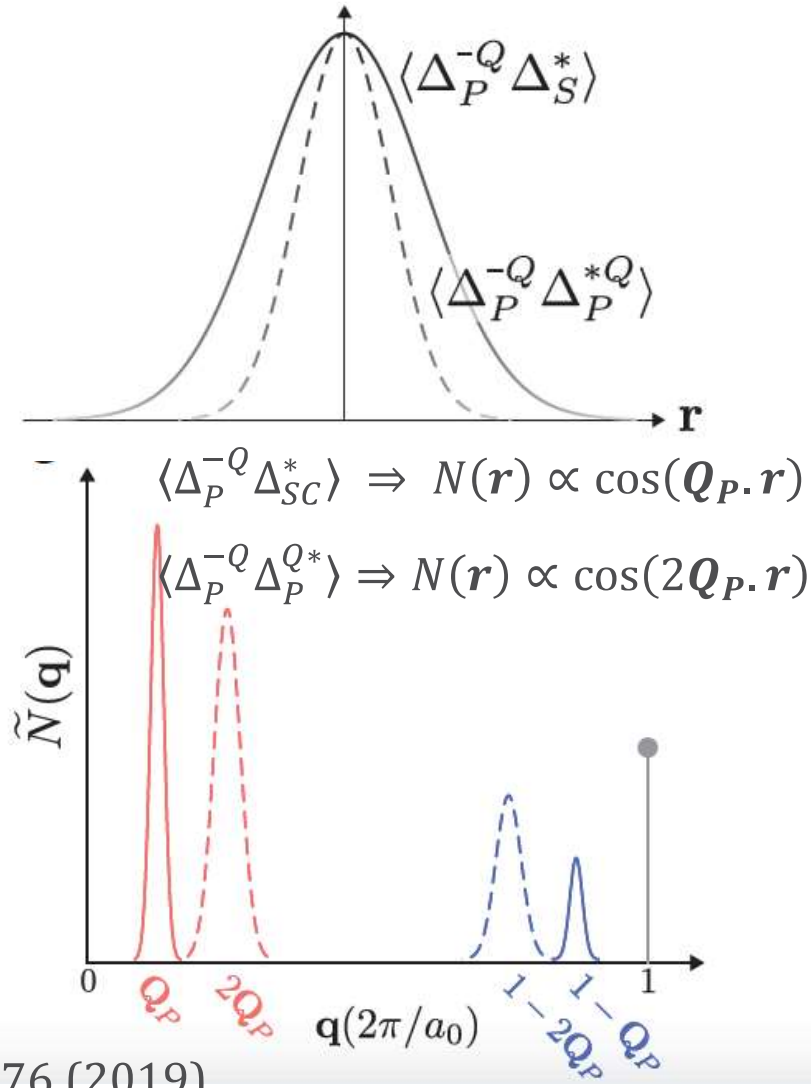
$$\Delta_{PD} = F_P \Delta_P^Q \left[e^{i\boldsymbol{Q_P}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{Q_P}\cdot\boldsymbol{r}}\right]$$

PDW Q_P WITHIN VORTEX HALO

Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

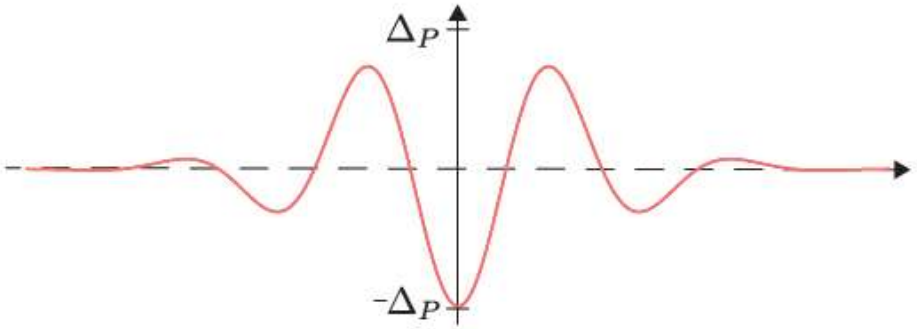
d-SYMMETRY PDW ⇒ s-SYMMETRY MODS

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



Science 364, 976 (2019)

PDW IN VORTEX HALO ⇒ OBSERVED PHENOMENOLOGY



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

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

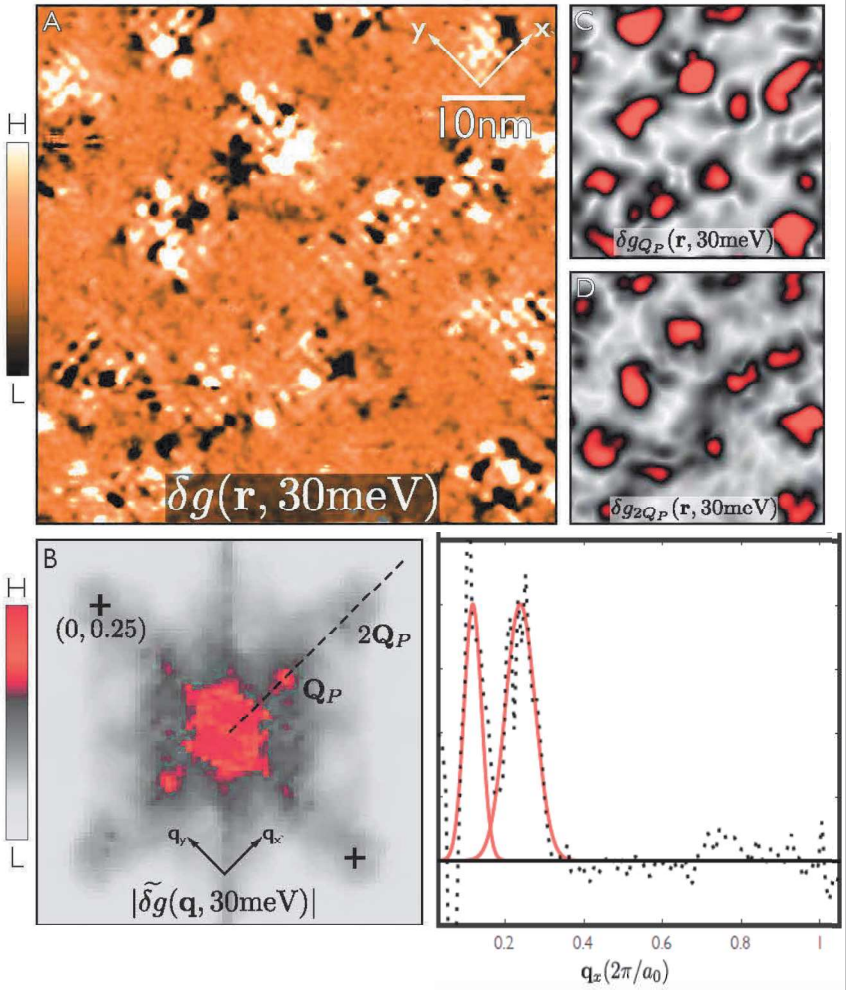
PDW Q_P WITHIN VORTEX HALO

Q_P & $2Q_P$ CHARGE DENSITY MODULATIONS

d-SYMMETRY PDW ⇒ s-SYMMETRY MODS

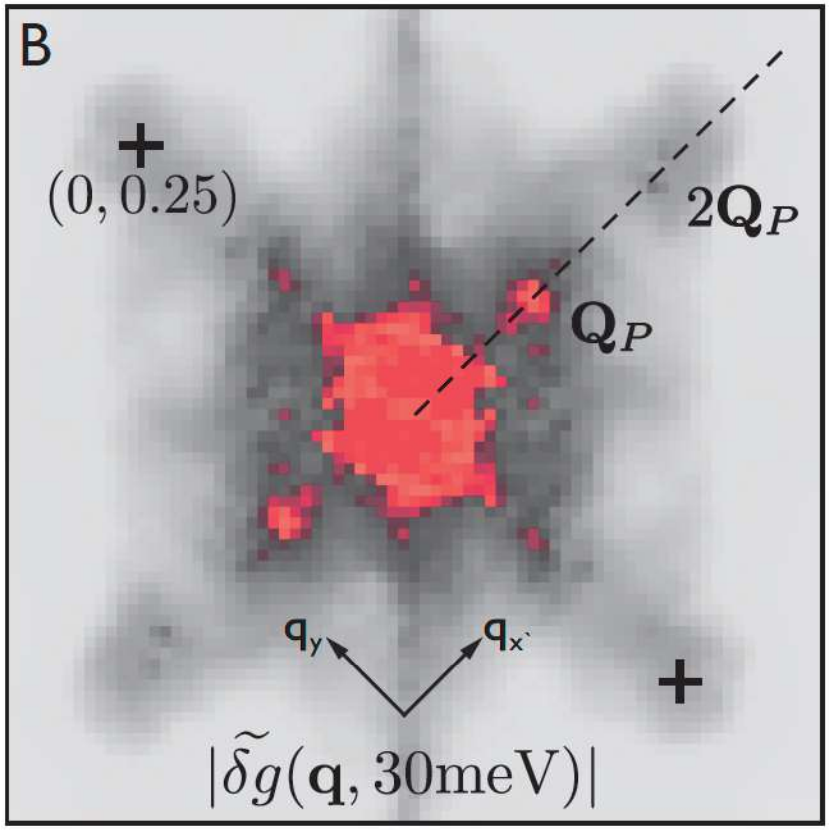
MODULATION LINEWIDTHS: $\delta(2Q_P) = 2(\delta Q_P)$

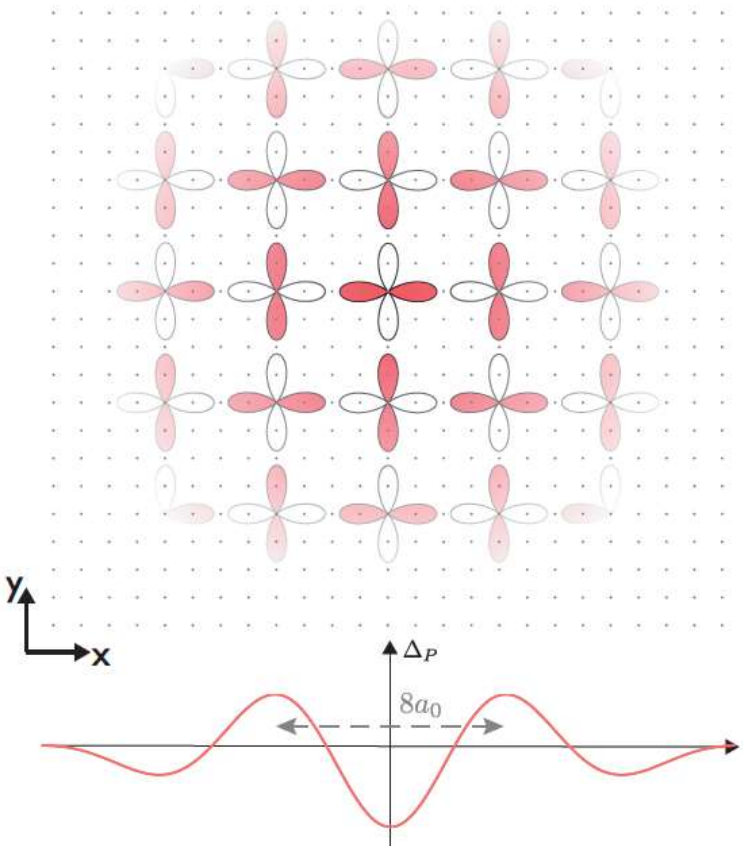
PARTICLE-HOLE SYMMETRY



Science 364, 976 (2019)

BIAXIAL $8a_0$ PDW INDUCED BY MAGNETIC FIELD





D. Agterberg *et al* , *Phys Rev B* 91, 104512 (2015)
Yuxuan Wang *et al Phys Rev. B 97,* 174510 (2018)
Zhehao Dai *et al Phys Rev. B 97,* 174511 (2018)

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

Science 364, 976 (2019)

MAGNETIC FIELD CONTROL OF CUPRATE PDW

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)

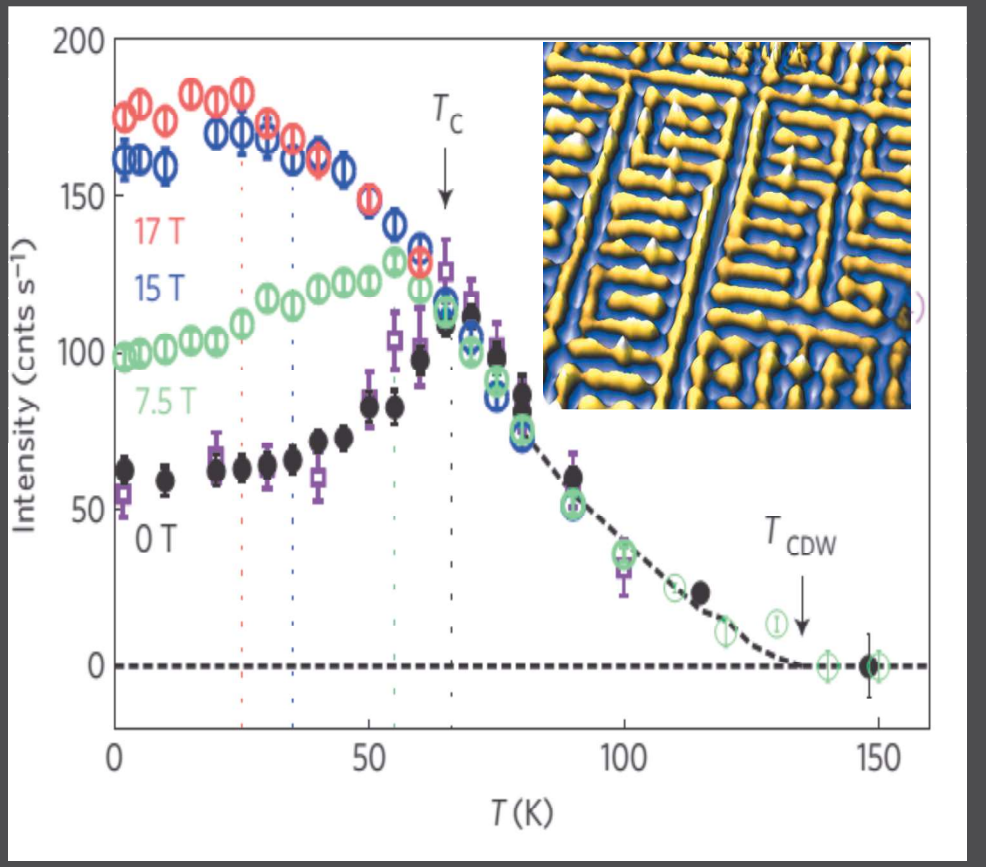
S. Blanco Canosa *et al. PRL*110, 187001 (2013)

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)

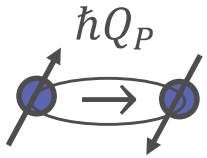


Chang *et al*. *Nat Phys* 8, 871 (2012)

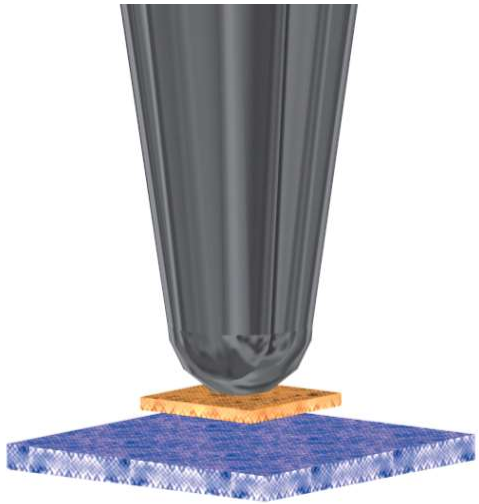
PDW $\left\langle c^{\dagger}_{k\uparrow,}\, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$

VISUALIZE PDW GAP MODULATION: $\Delta_0 cos(Q_P . r)$

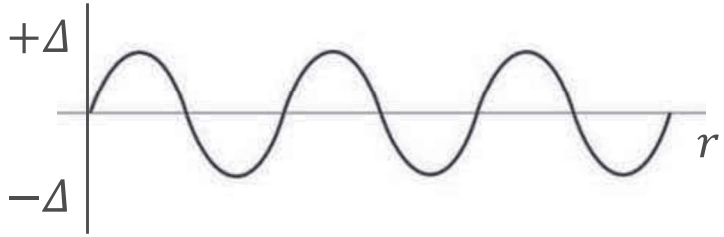
CUPRATE PDW GAP MODULATIONS

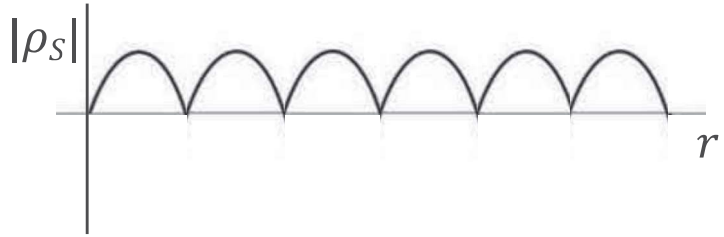


$$\left\langle c^{\dagger}_{k\uparrow,}\, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$

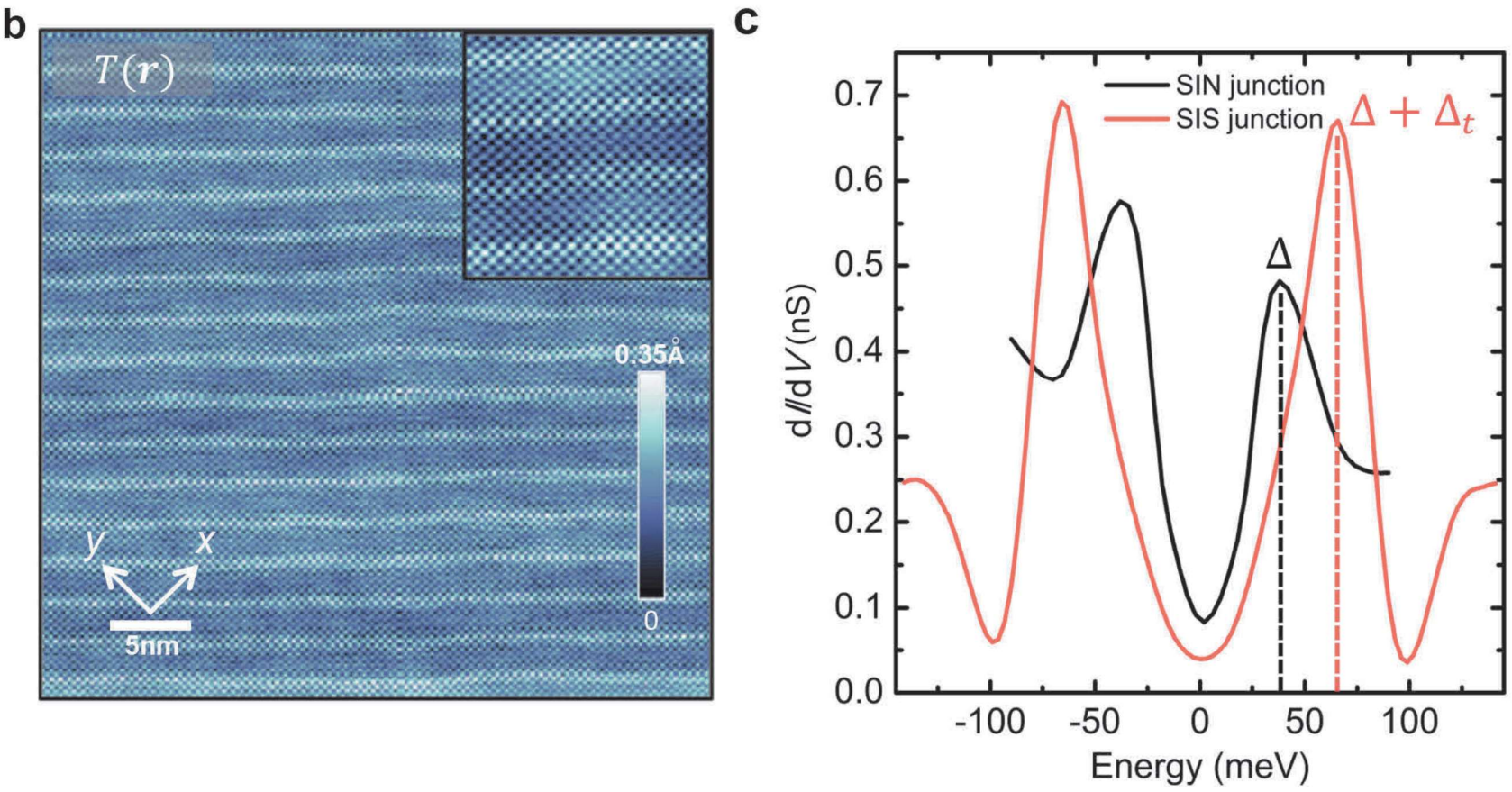


$$\boldsymbol{\Delta(r) = \Delta_P \left[e^{iQ_P \cdot r} + e^{-iQ_P \cdot r} \right]}$$



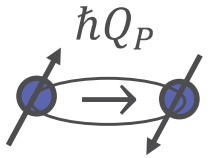


SIS SINGLE-PARTICLE TUNNELING



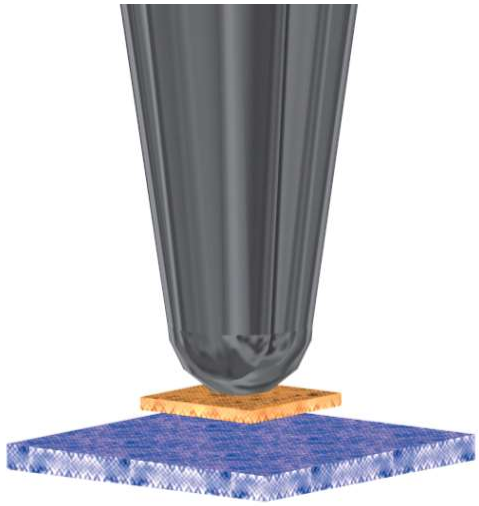
Kazuhiro Fujita *et al* (2019)

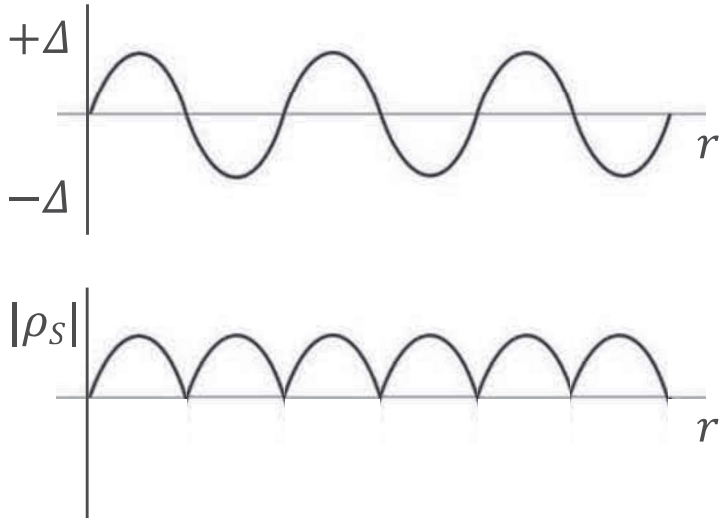
CUPRATE PDW GAP MODULATIONS

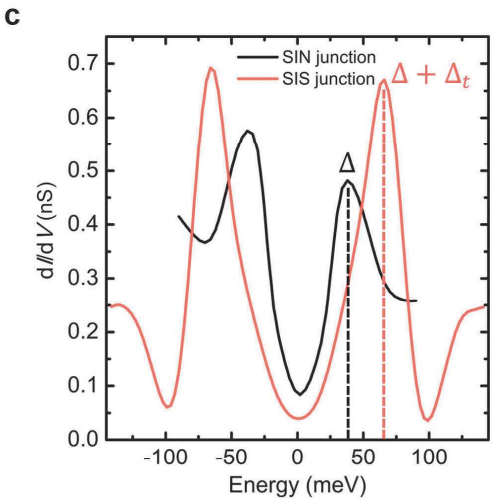


$$\left\langle c^{\dagger}_{k\uparrow,}\, c^{\dagger}_{-k+Q_P\downarrow} \right\rangle$$

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



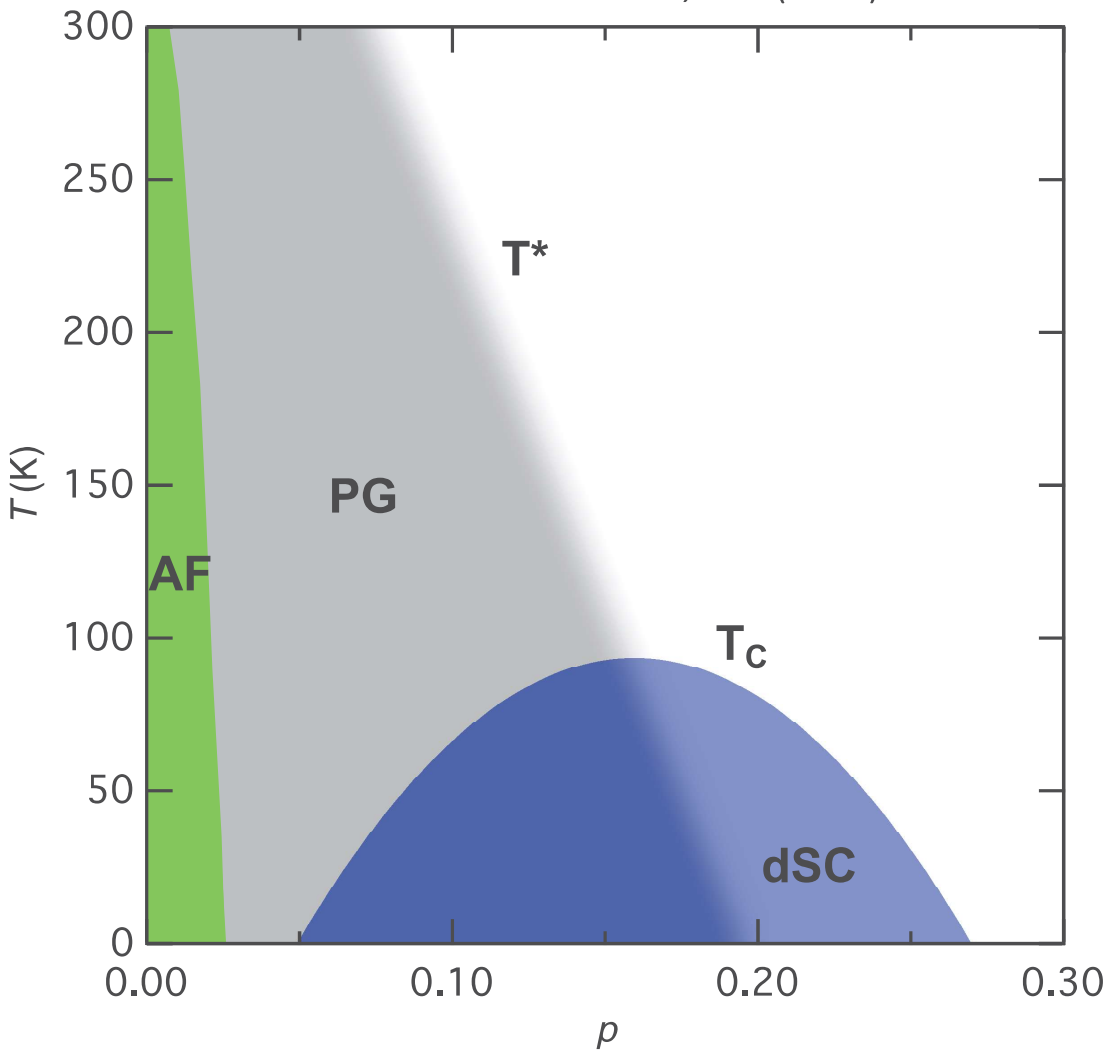




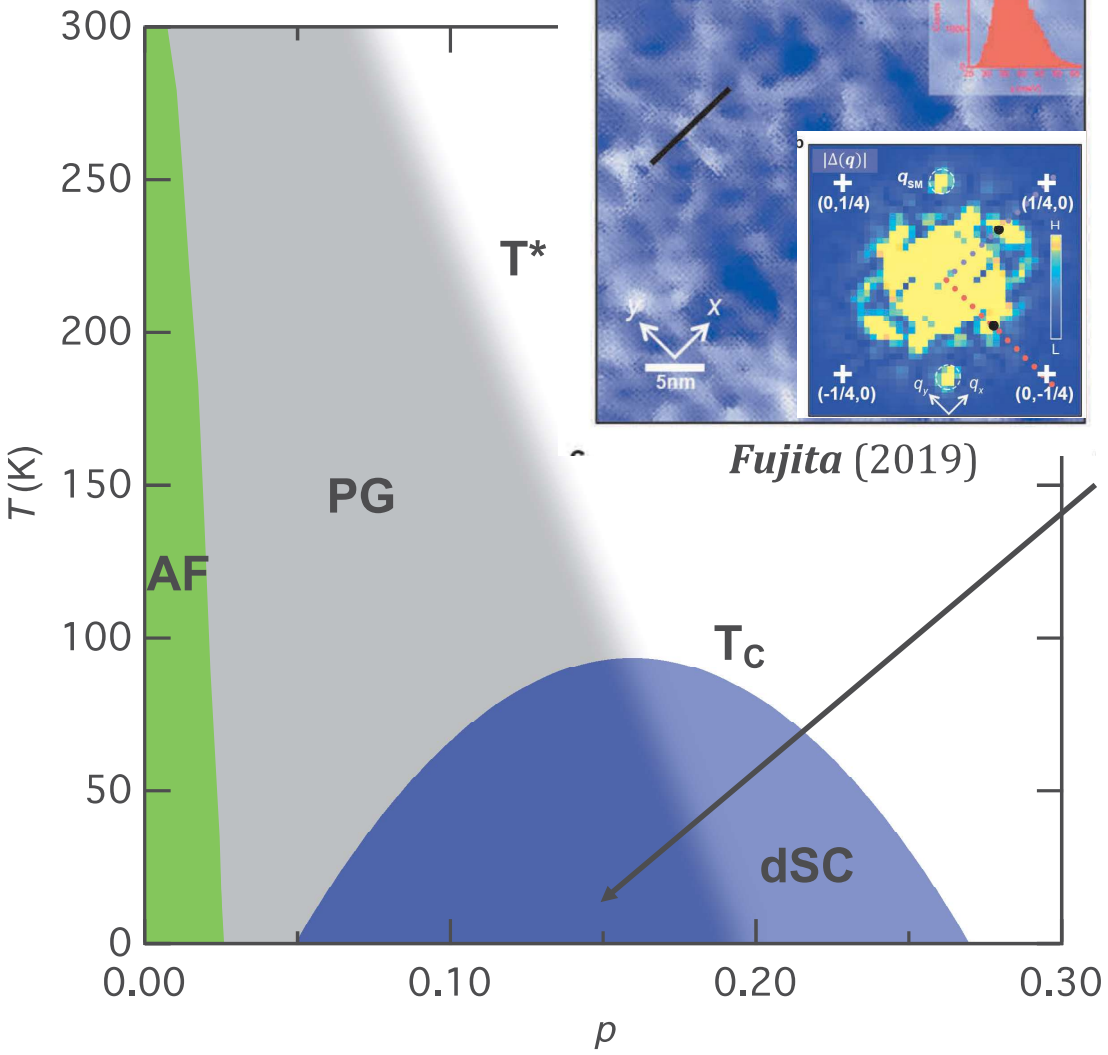
DISCUSSION

DOES STRONG-COUPLING PDW STATE EXIST IN CUPRATES?

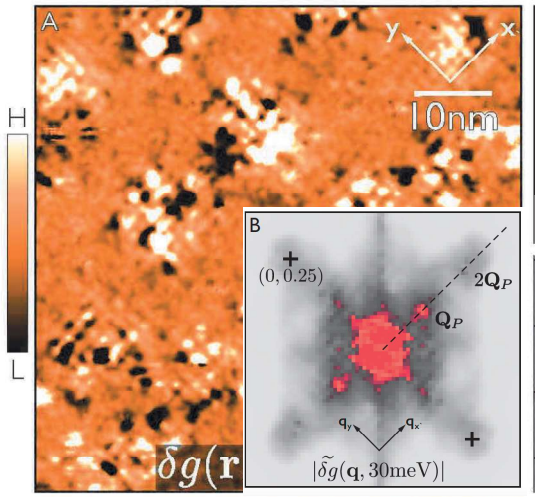
P.A. Lee ***PRX* 4,** 31017 (2014)
E. Fradkin *et al* ***RMP* 87,** 457 (2015)



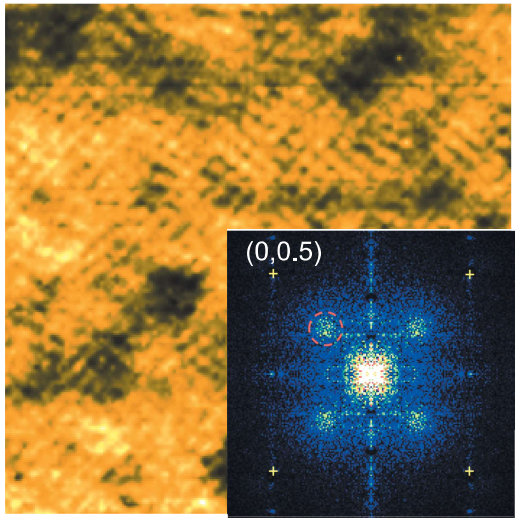
YES!



Fujita (2019)



Science 364, 976 (2019)



Nature 532, 343 (2016)

PAIR DENSITY WAVE = PSEUDOGAP PHASE ?

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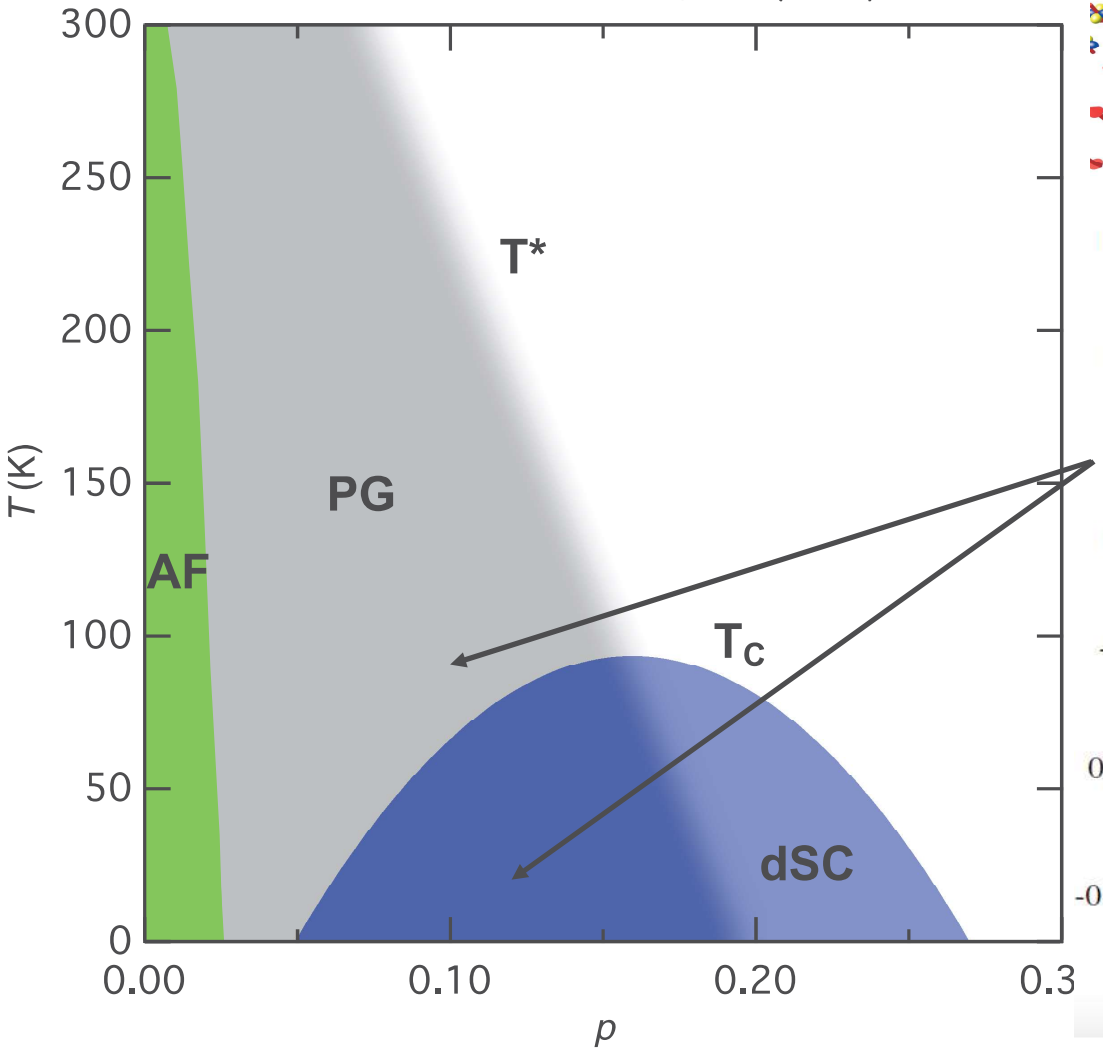

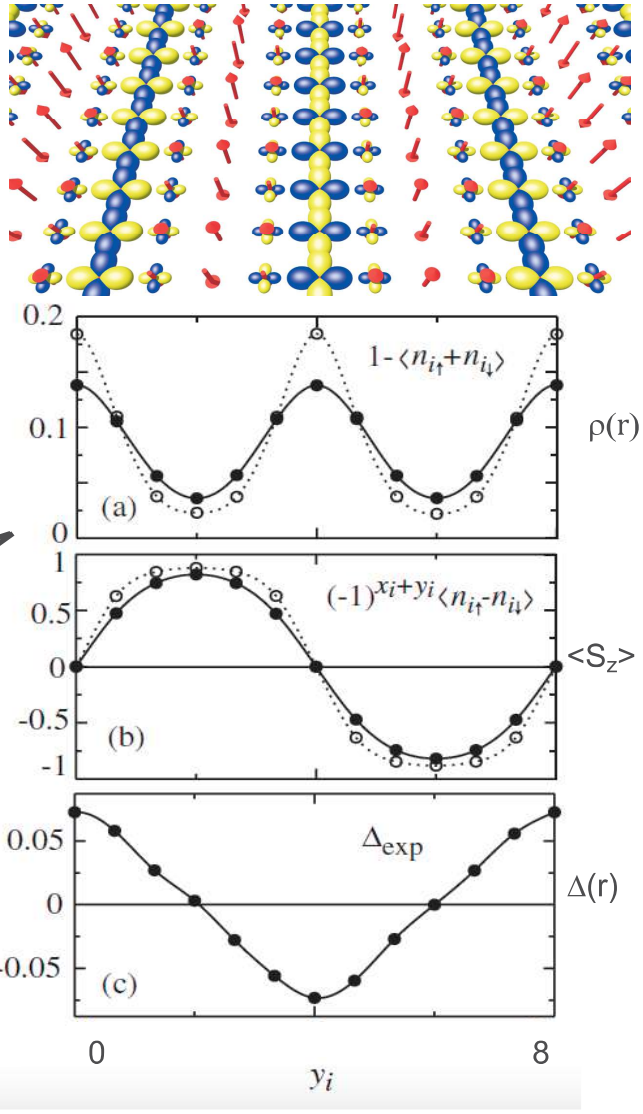

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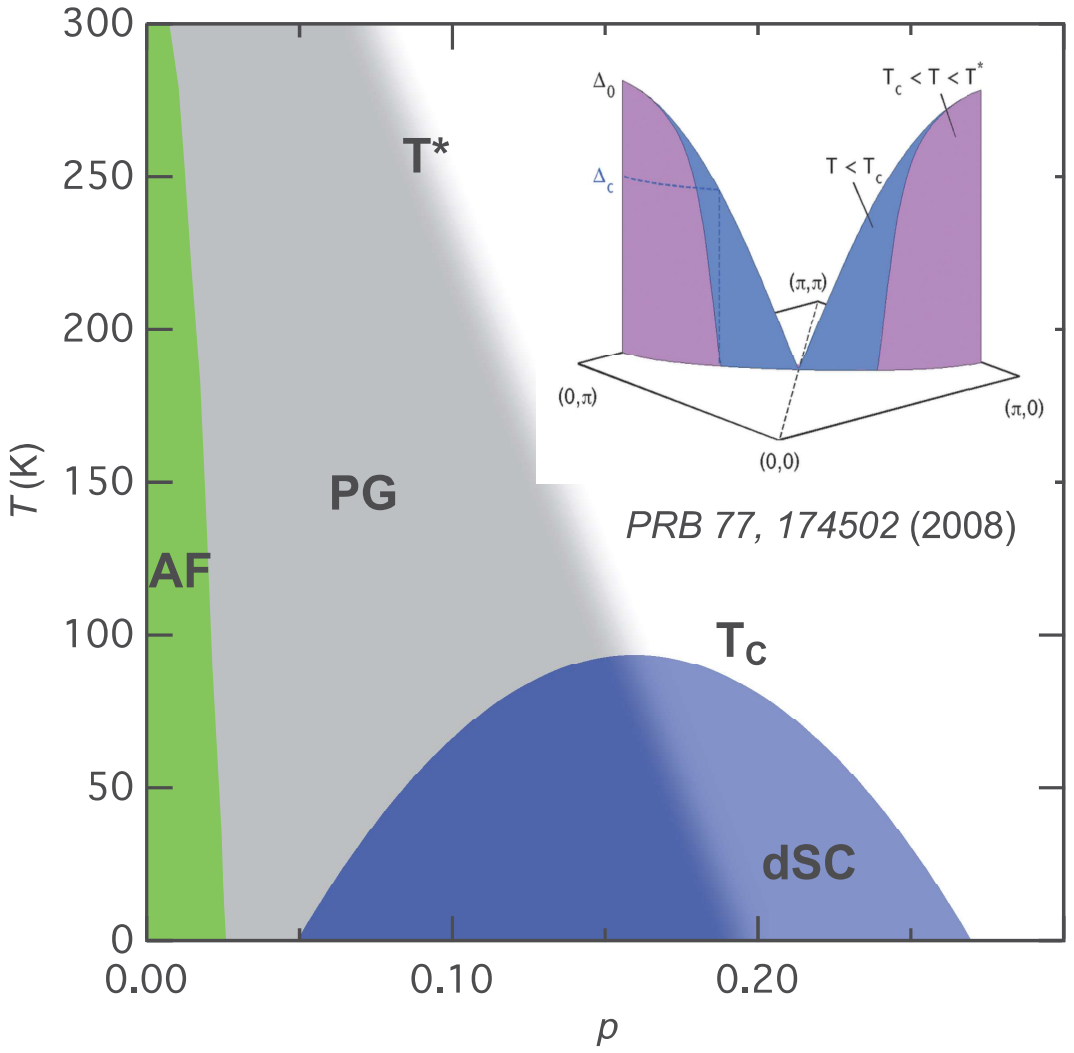

- PDW exhibits a particle-hole symmetric antinodal gap
- PDW gives the correct spectral functions for underdoped CuO_2
- PDW exhibits k-space 'Fermi Arc' of unbound electrons
- PDW yields small electron-like pocket with correct frequency of quantum oscillations
- PDW spin modulations at Q_P and charge modulations primarily at $2Q_P$.

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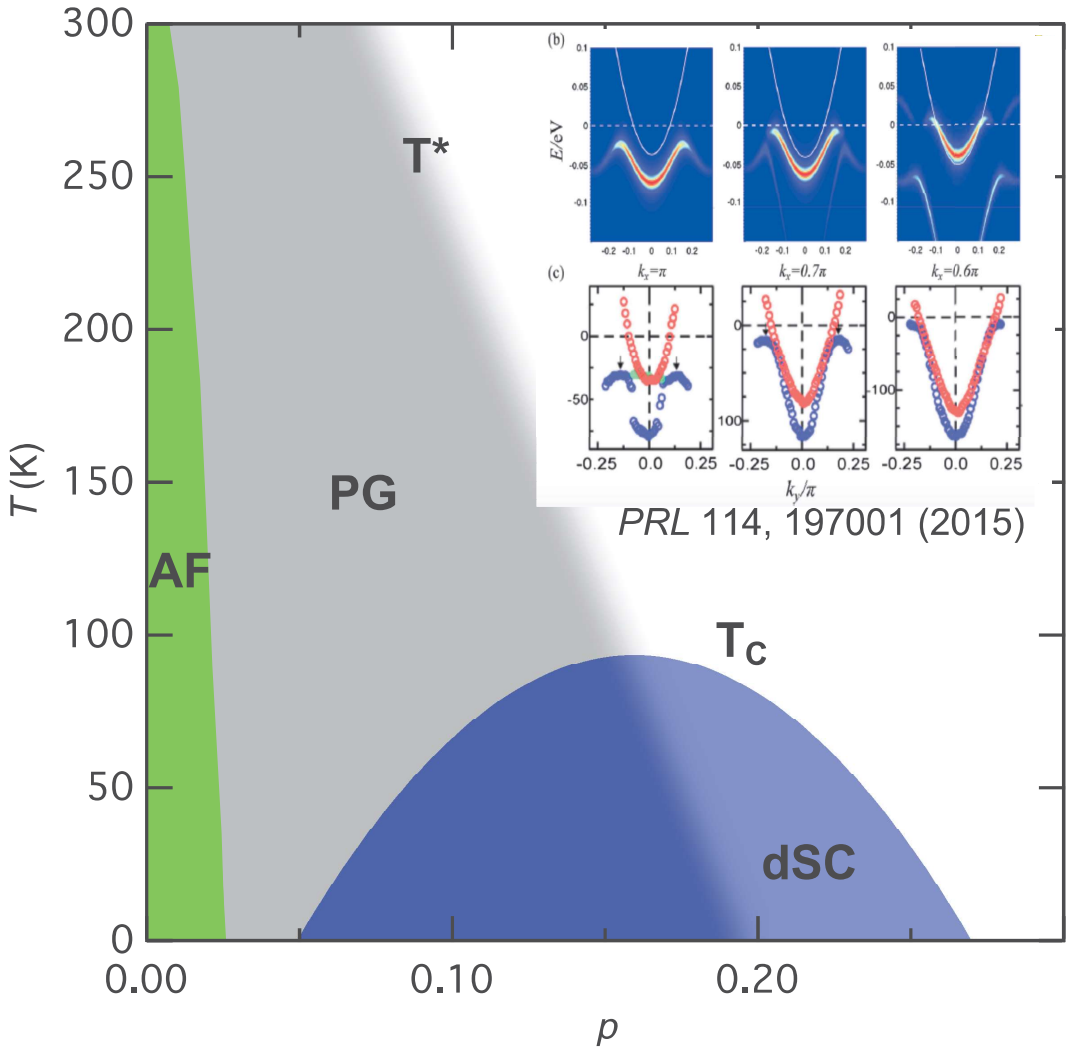

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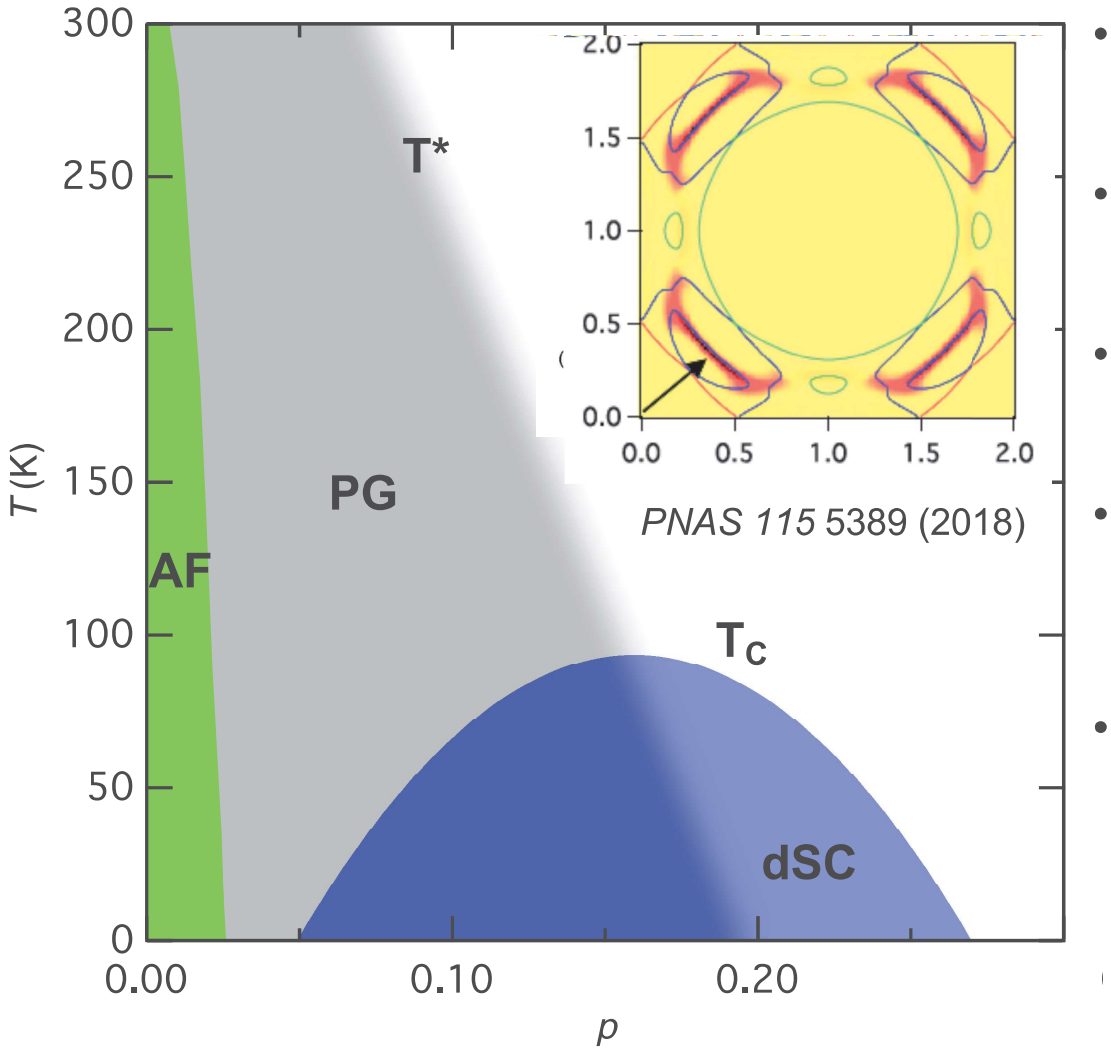

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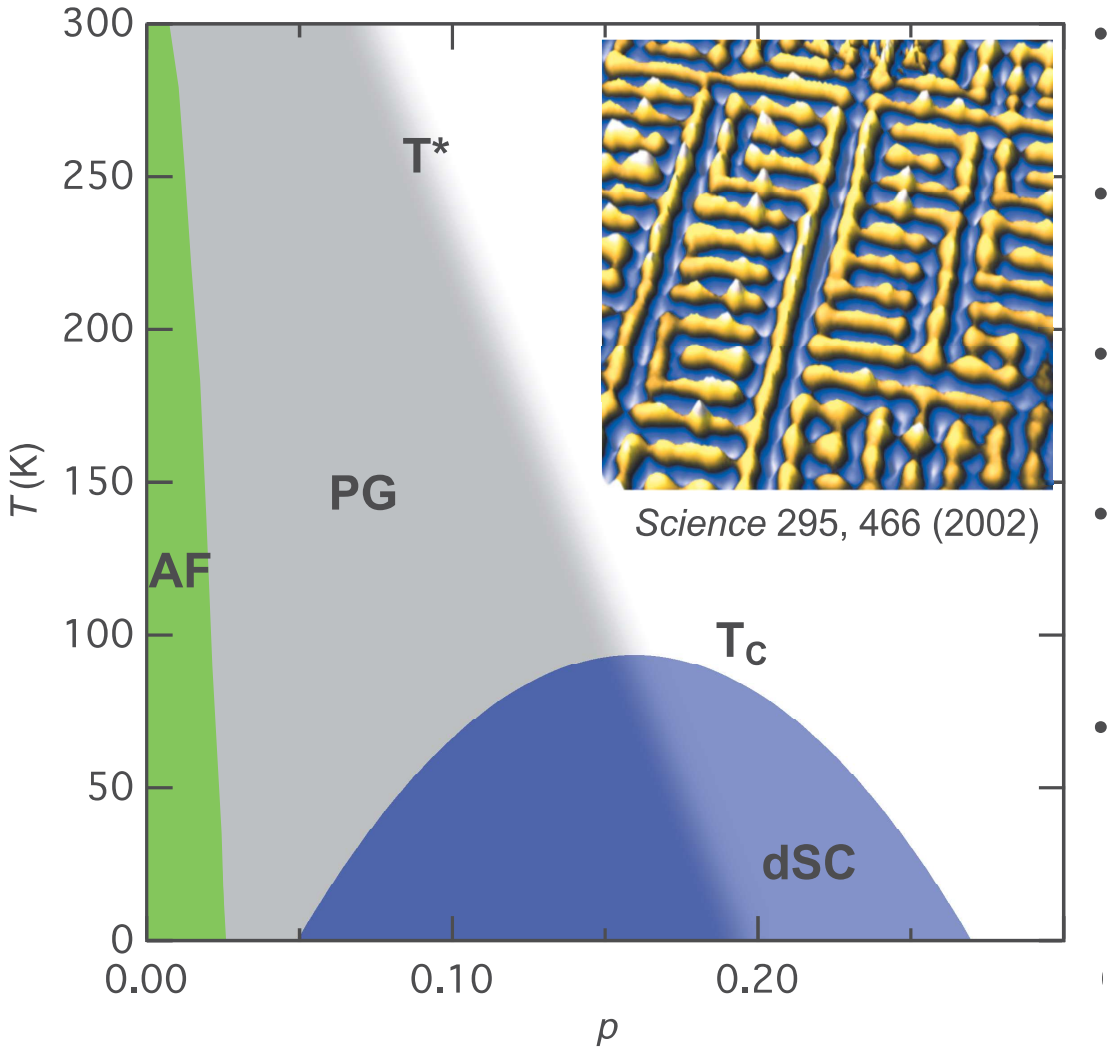

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