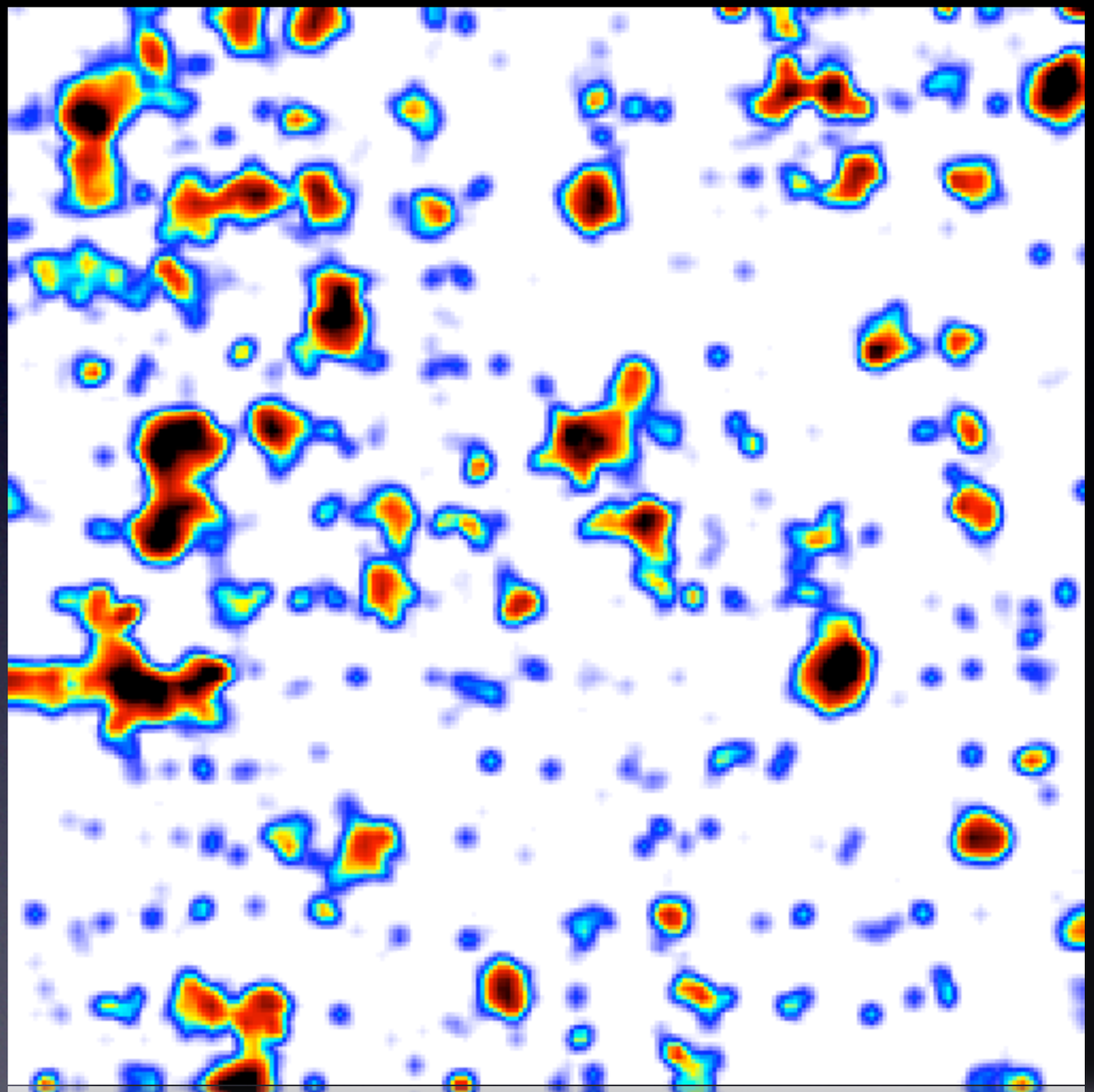
STM on High-Tc Superconductors

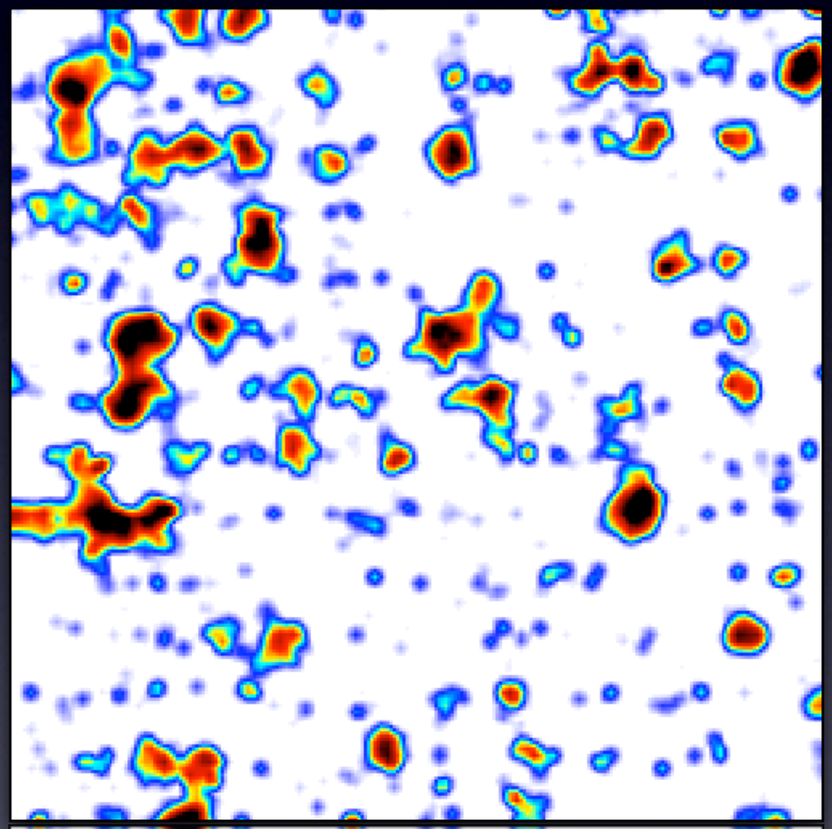


This talk:

- Basic STM on cuprates: inhomogeneity, qp interference, signs of d-wave
- New technique: Watching superconductivity develop on the atomic scale
- Precise measurements of electron-boson coupling on the atomic scale
- Connection between normal and superconducting states

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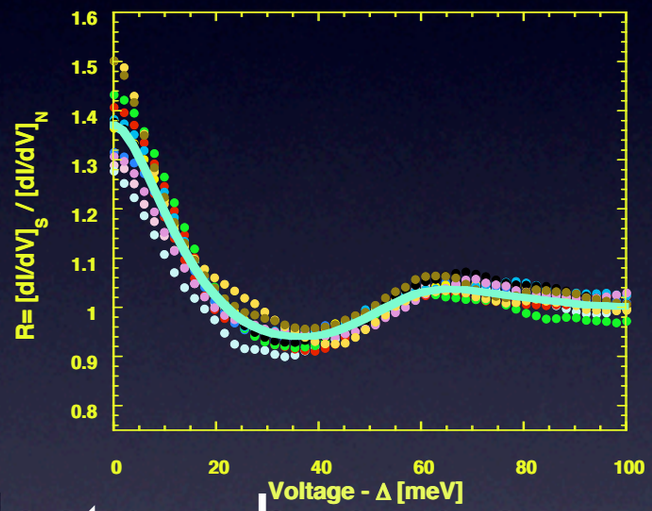
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This talk:

- Basic STM on cuprates: inhomogeneity, qp interference, signs of d-wave
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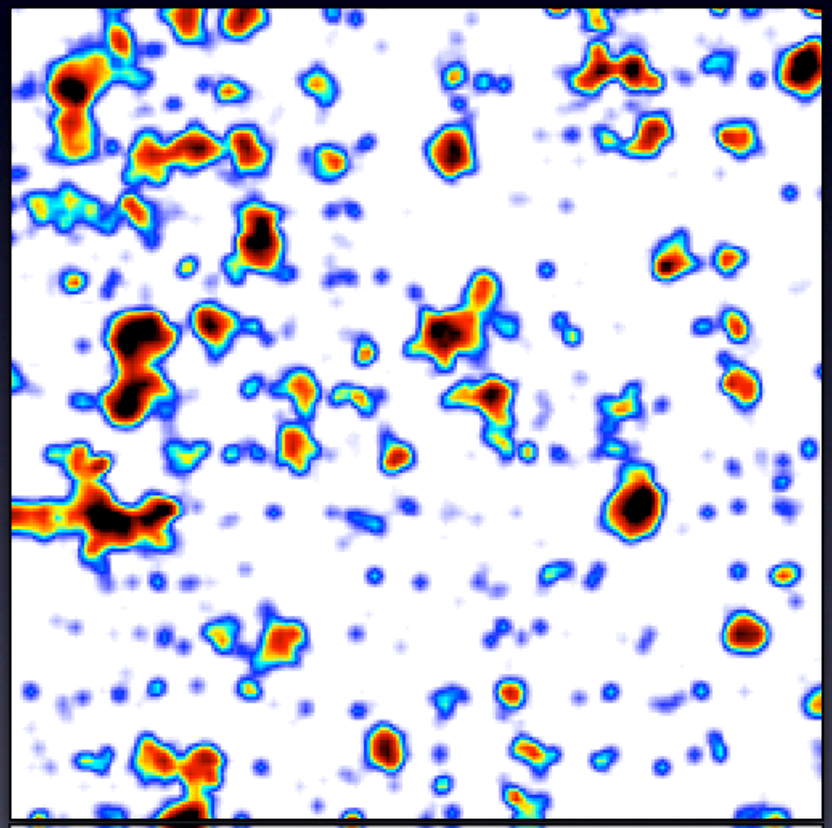
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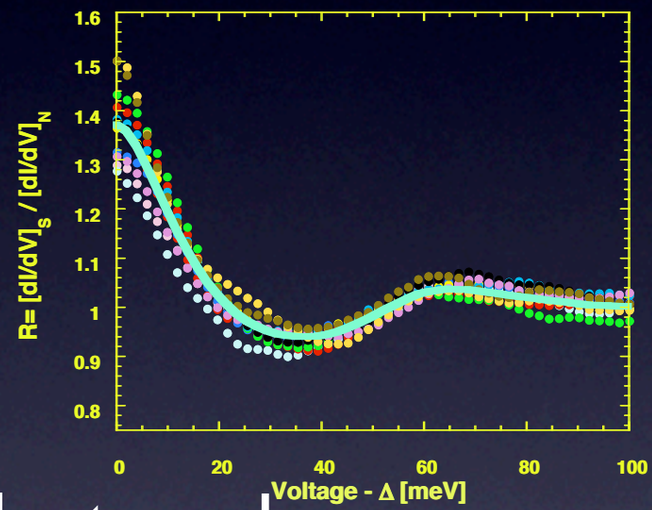
Electron-boson coupling?

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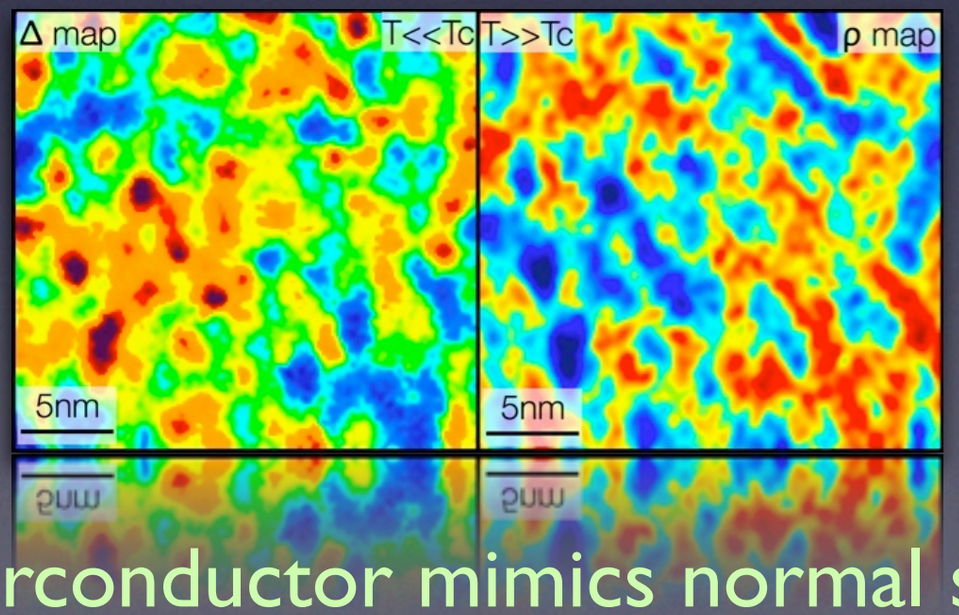
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Electron-boson coupling?

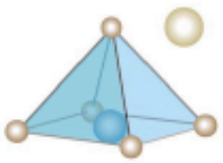


Superconductor mimics normal state

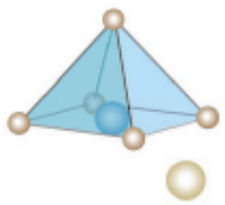
Families of Hole-doepd Cuprate Superconductors

Highest Tc~135K

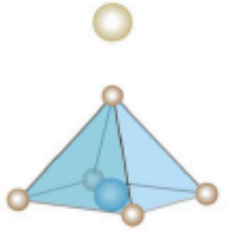
Halogen Family	Bi Family
Pb Family	1L Tl Family
La Family	2L Family
YBCO Family	Hg Family



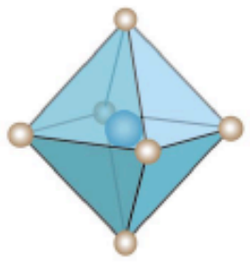
(a)



(b)



(c)



(1)



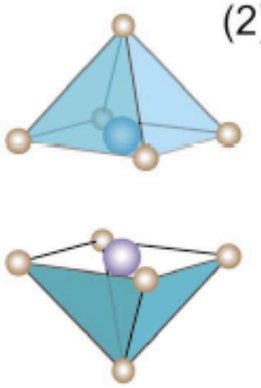
(a-1)

	T_c
$Ca_{2-x}Na_xCuO_2Cl_2$	26
$Pb_2Sr_{2-x}La_xCu_2O_z$	33
$La_{2-x}M_xCuO_4$	39
$Bi_2Sr_{1-x}Ln_xCuO_{6+\delta}$	38
$TlBa_{1+x}La_{1-x}CuO_5$	45

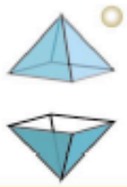


(c-1)

	T_c
$Sr_2CuO_2F_{2+x}$	46
$La_2CuO_{4+\delta}$	45
$Tl_2Ba_2CuO_{6+\delta}$	93
$HgBa_2CuO_{4+\delta}$	98

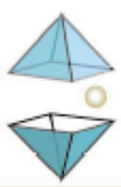


(2)



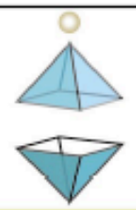
(a-2)

	T_c
$La_{2-x}Sr_xCaCu_2O_6$	60
$(La_{1-x}Ca_x)(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$	80
$Bi_{2+x}Sr_{2-x}CaCu_2O_{8+\delta}$	90



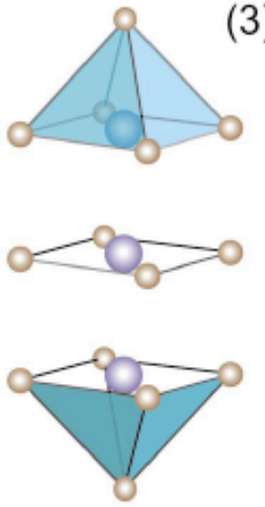
(b-2)

	T_c
$Pb_2Sr_2Y_{1-x}Ca_xCu_3O_{8+\delta}$	80
$Y_{1-x}Ca_xBa_2Cu_3O_{7-\delta}$	90
$Bi_2Sr_2Ca_{1-x}Y_xCu_3O_{8+\delta}$	96

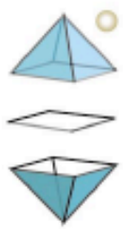


(c-2)

	T_c
$YBa_2Cu_3O_{7-\delta}$	93
$TlBa_2CaCu_2O_{7+\delta}$	110
$Tl_2Ba_2CaCu_2O_{8+\delta}$	110
$HgBa_2CaCu_2O_{6+\delta}$	120

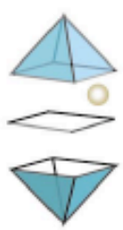


(3)



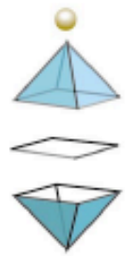
(a-3)

	T_c
$Bi_{2+x}Sr_{2-x}Ca_2Cu_3O_{10+\delta}$	110
$TlBa_{2-\epsilon}Ca_2Cu_3O_{9+\delta}$	123



(b-3)

	T_c
$TlBa_2Ca_{2-\epsilon}Cu_3O_{9+\delta}$	131

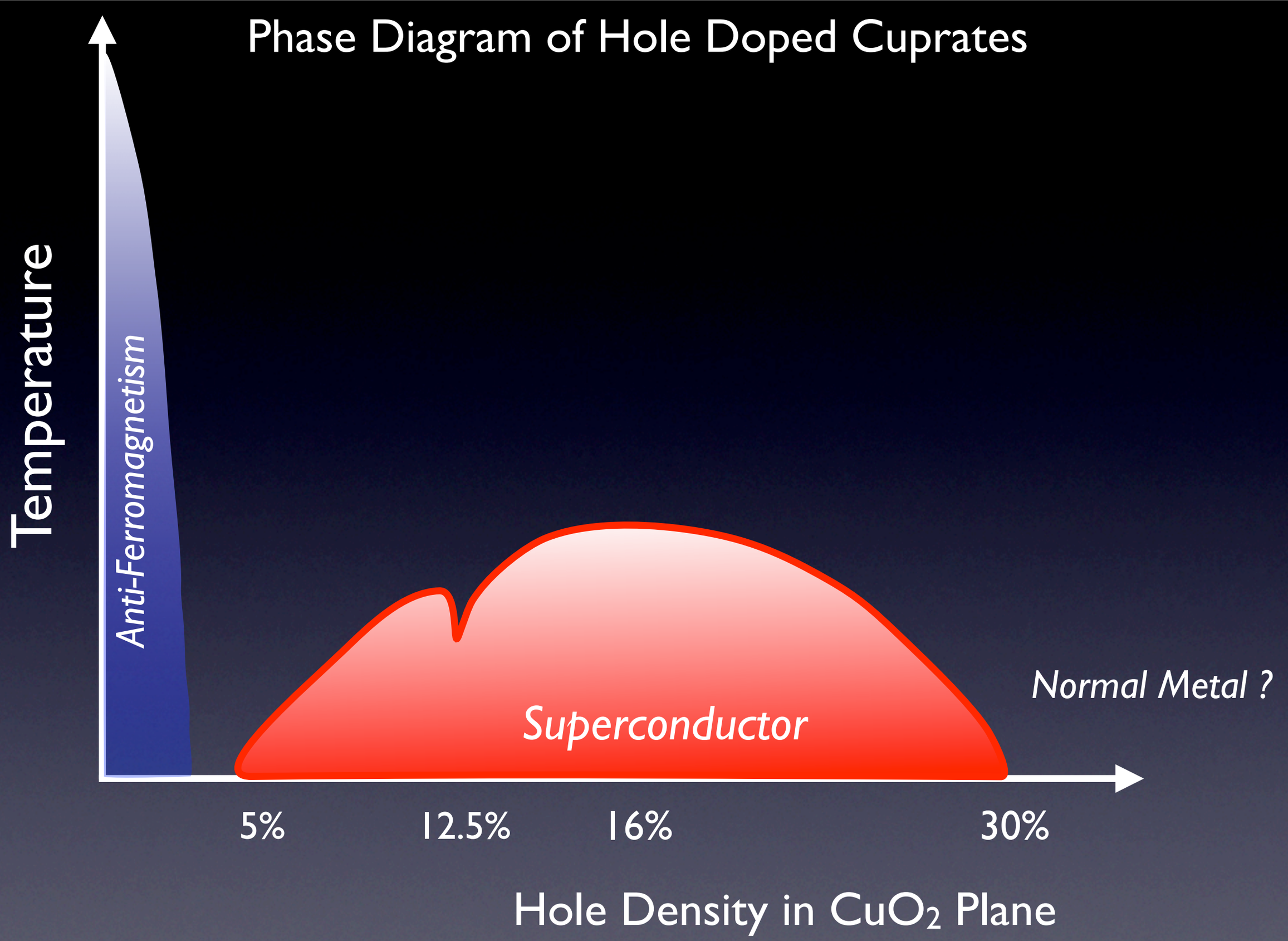


(c-3)

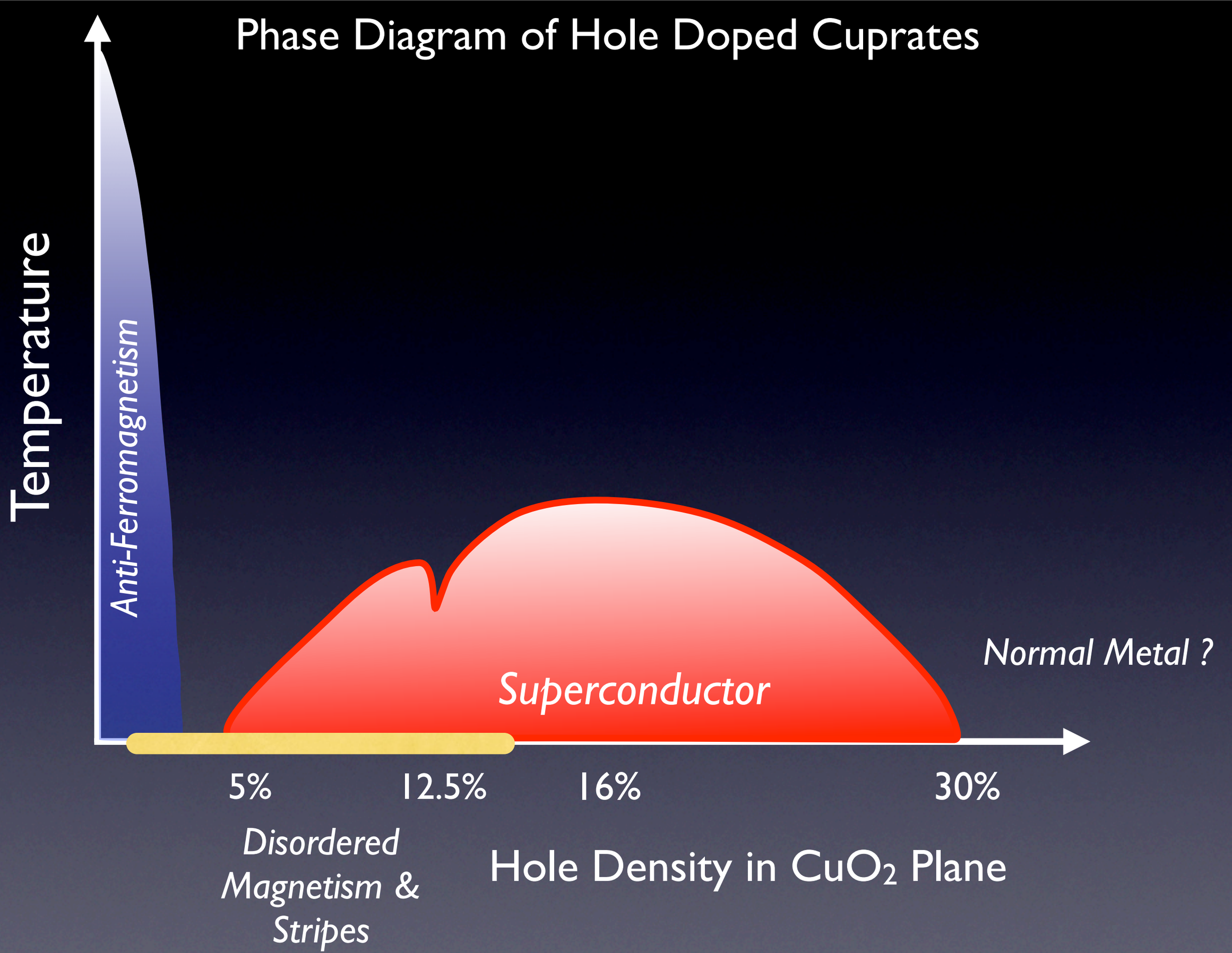
	T_c
$TlBa_2Ca_2Cu_3O_{9+\delta}$	133
$Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$	125
$HgBa_2Ca_2Cu_3O_{10+\delta}$	135

From Esaki et al 2004

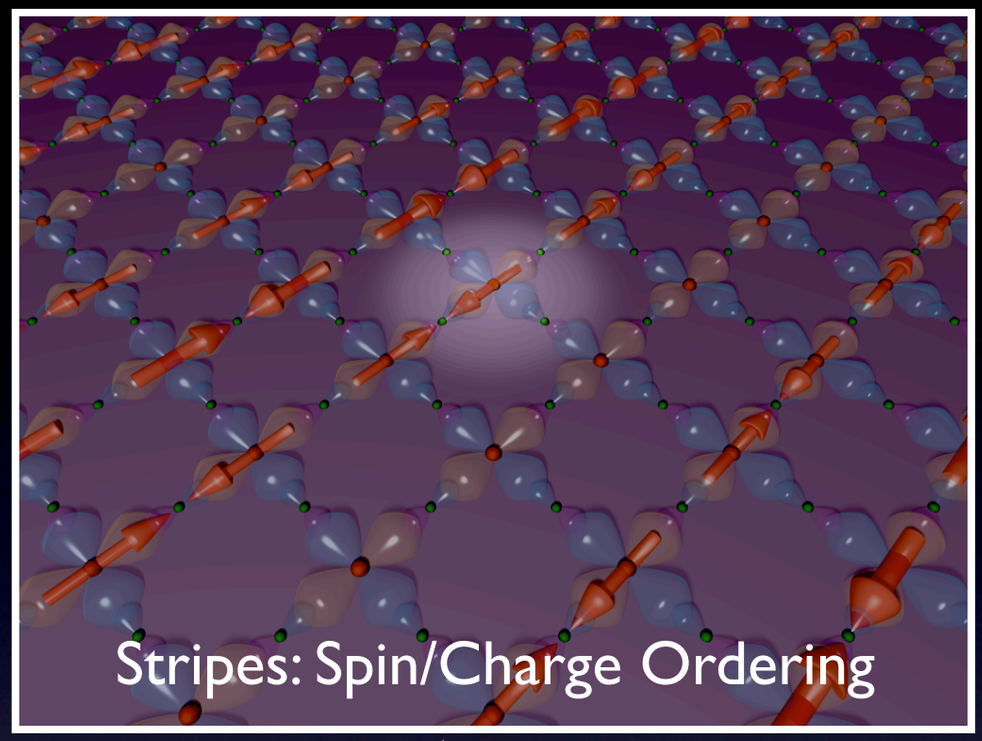
Phase Diagram of Hole Doped Cuprates



Phase Diagram of Hole Doped Cuprates



Phase Diagram of Hole Doped Cuprates



Temperature

Anti-Ferromagnetism

Superconductor

Normal Metal ?

5%

12.5%

16%

30%

Disordered Magnetism & Stripes

Hole Density in CuO_2 Plane

Phase Diagram of Hole Doped Cuprates

Temperature

Anti-Ferromagnetism

Pseudogap "Phase"

Superconductor

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5%

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Hole Density in CuO_2 Plane

Phase Diagram of Hole Doped Cuprates

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Pseudogap "Phase"

Fluctuating Superconductor

Superconductor

Normal Metal ?

5%

12.5%

16%

30%

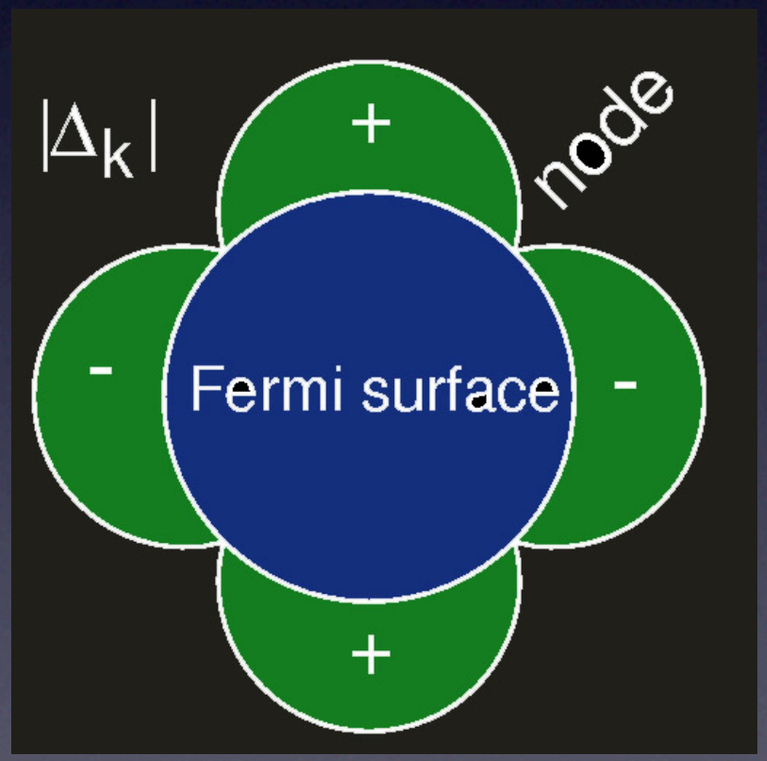
Disordered Magnetism & Stripes

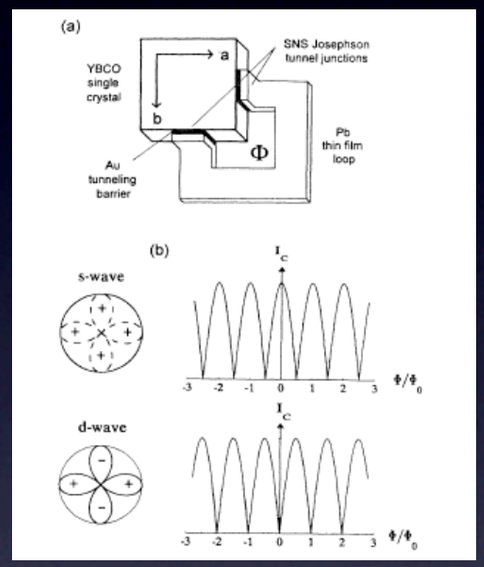
Hole Density in CuO_2 Plane

What have been accomplished after 20 years?

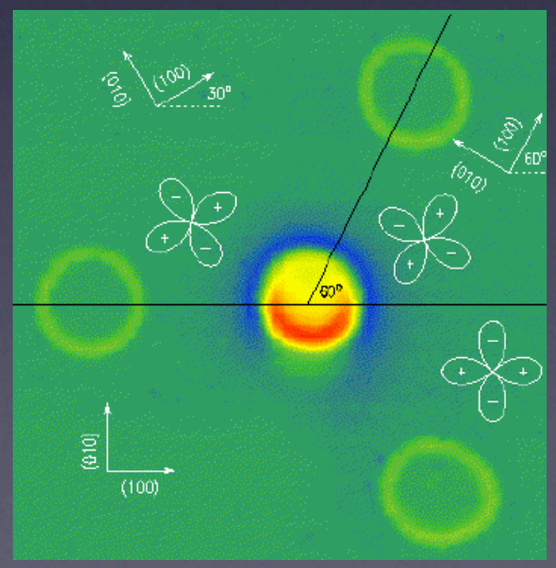
- Superconducting state involves Cooper pairs
- The pair wavefunction has d-wave symmetry, change of sign and nodes
- Demonstrated by phase sensitive & angle resolved photoemission experiments

Wavefunction & Order Parameter Symmetry

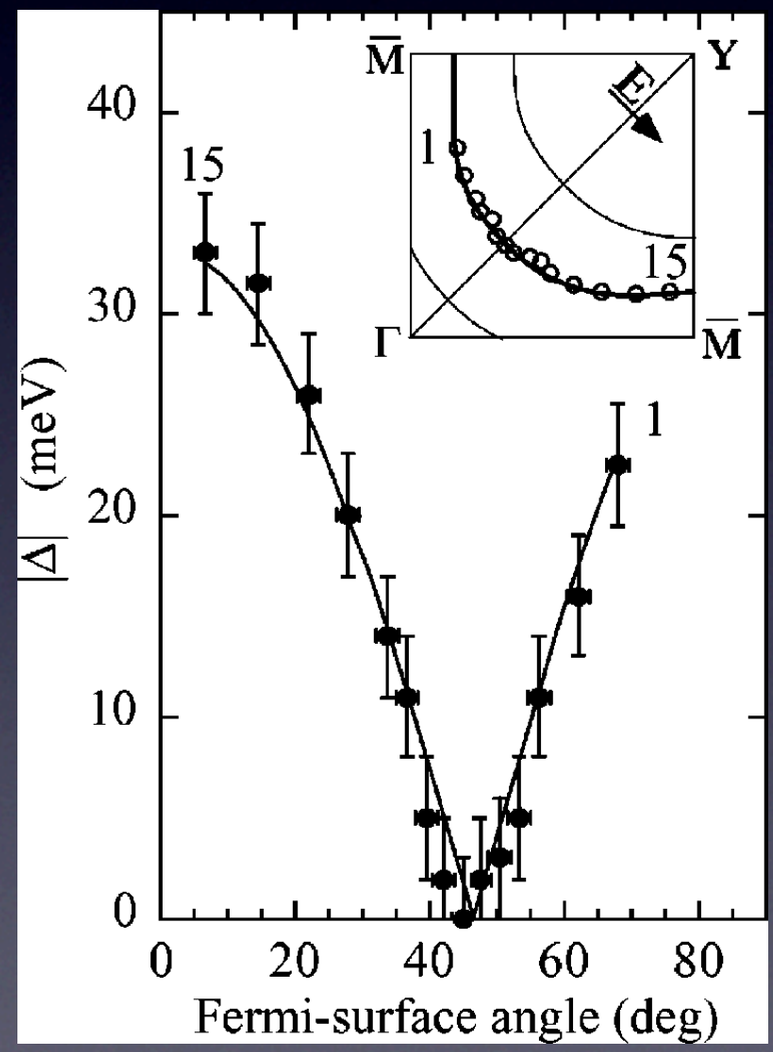




Van Harlingen et al. '93



Tsuei & Kirtley et al. '93



Shen et. al. '93-Data from Campuzano et al. '96

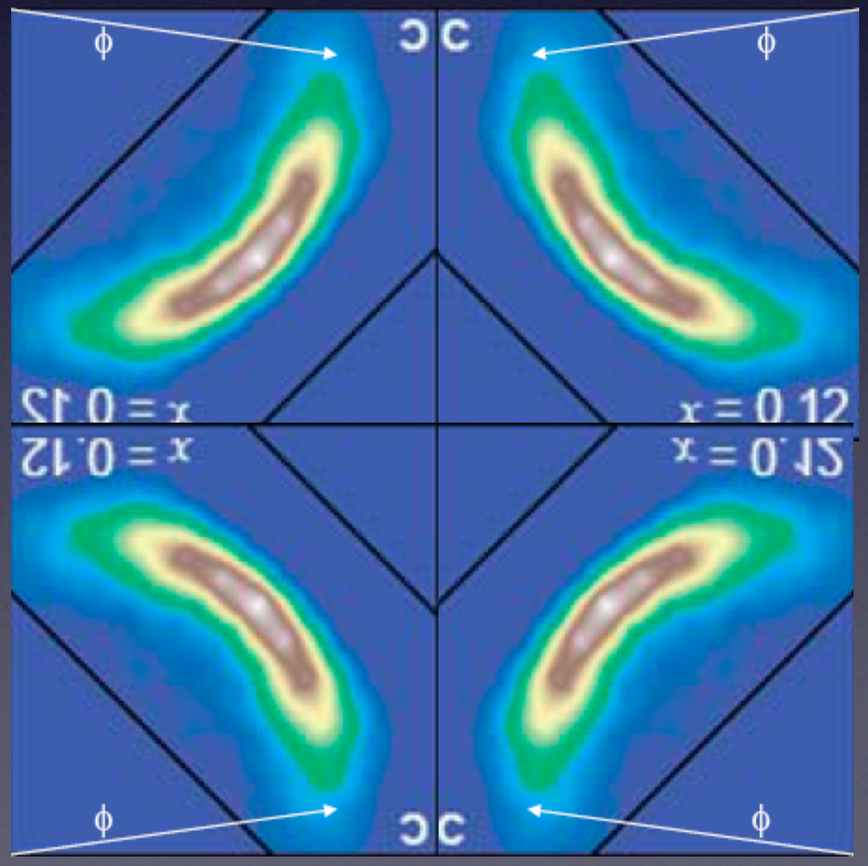
What have been accomplished after 20 years?

- The Fermi surface on the overdoped side of the phase diagram
- Large hole barrels for hole doped cuprates on overdoped side
- Strange partially gapped Fermi surface in underdoped side
- Nature of underdoped samples FS still highly debated

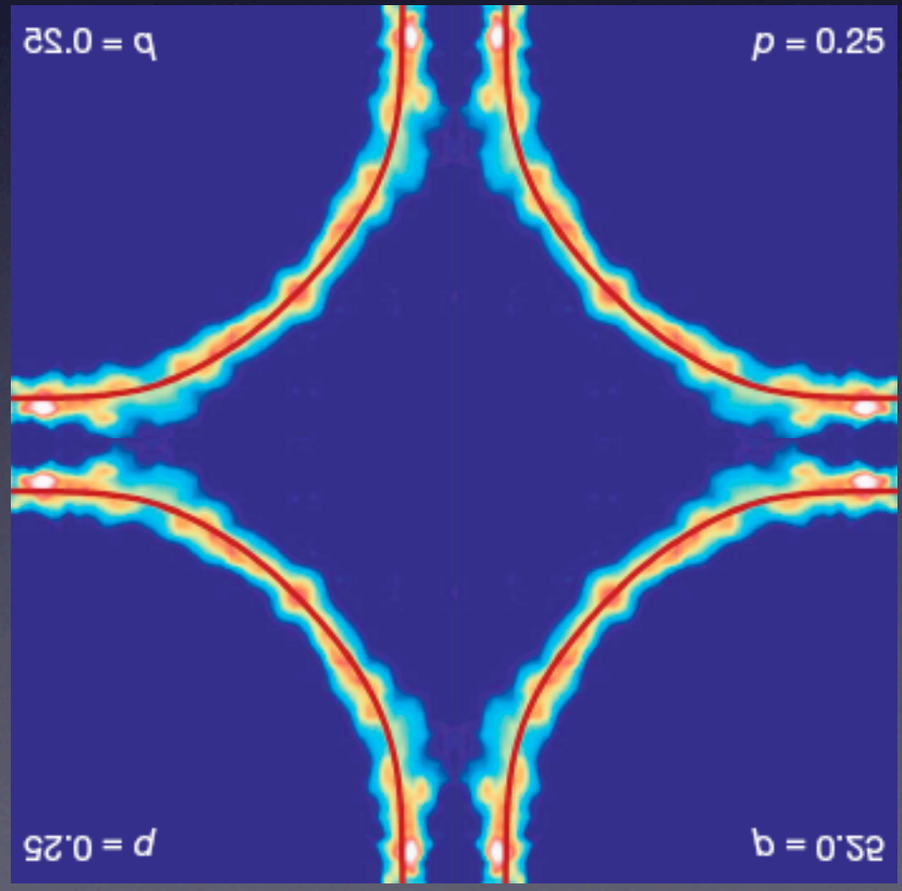
Fermi Surface

T>Tc underdoped pseudogap state

T>Tc Overdoped



Shen et al. Science 307,902 (2005)

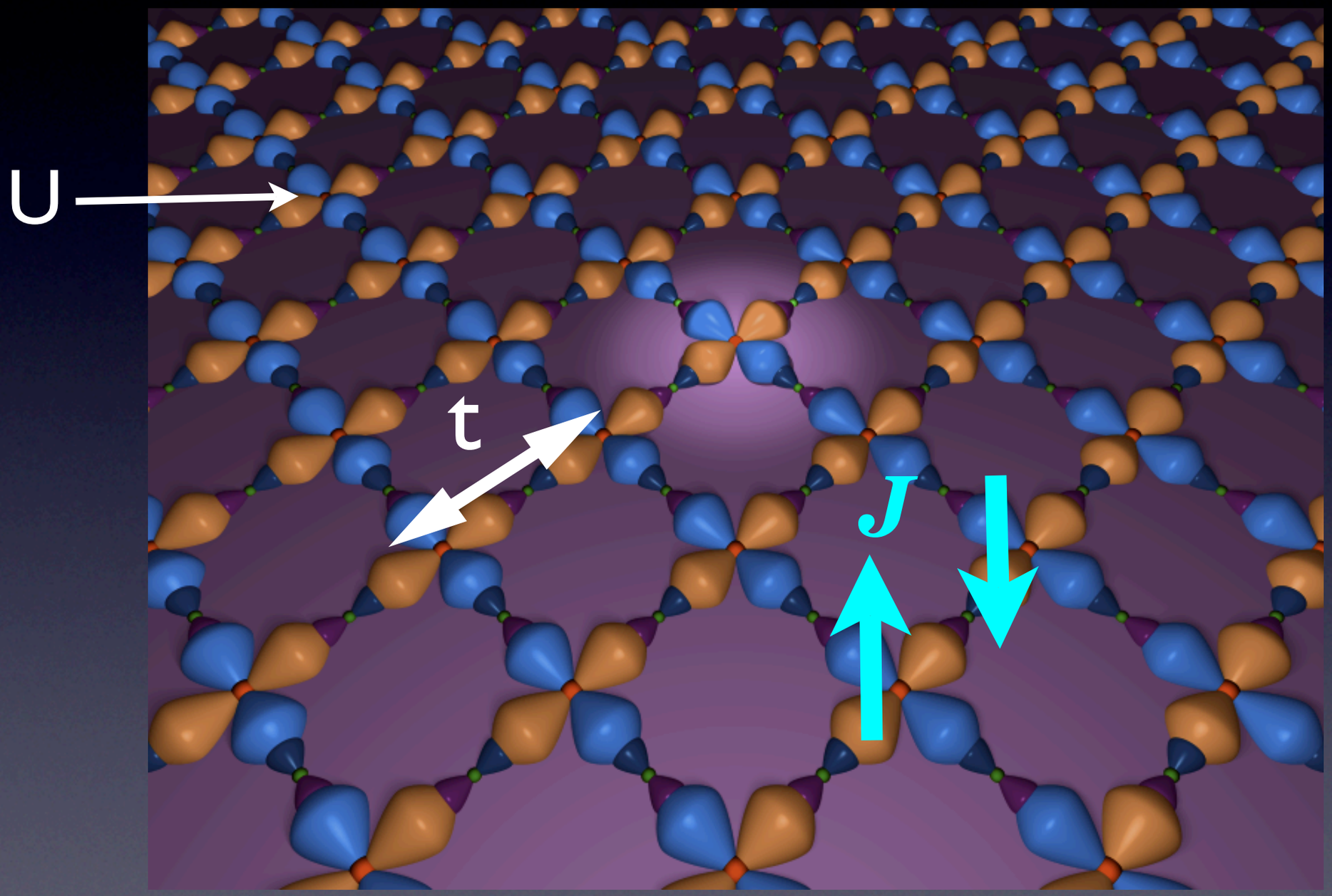


Plate´, M. et al. Phys. Rev. Lett. 95, 077001 (2005)

Key Questions I:

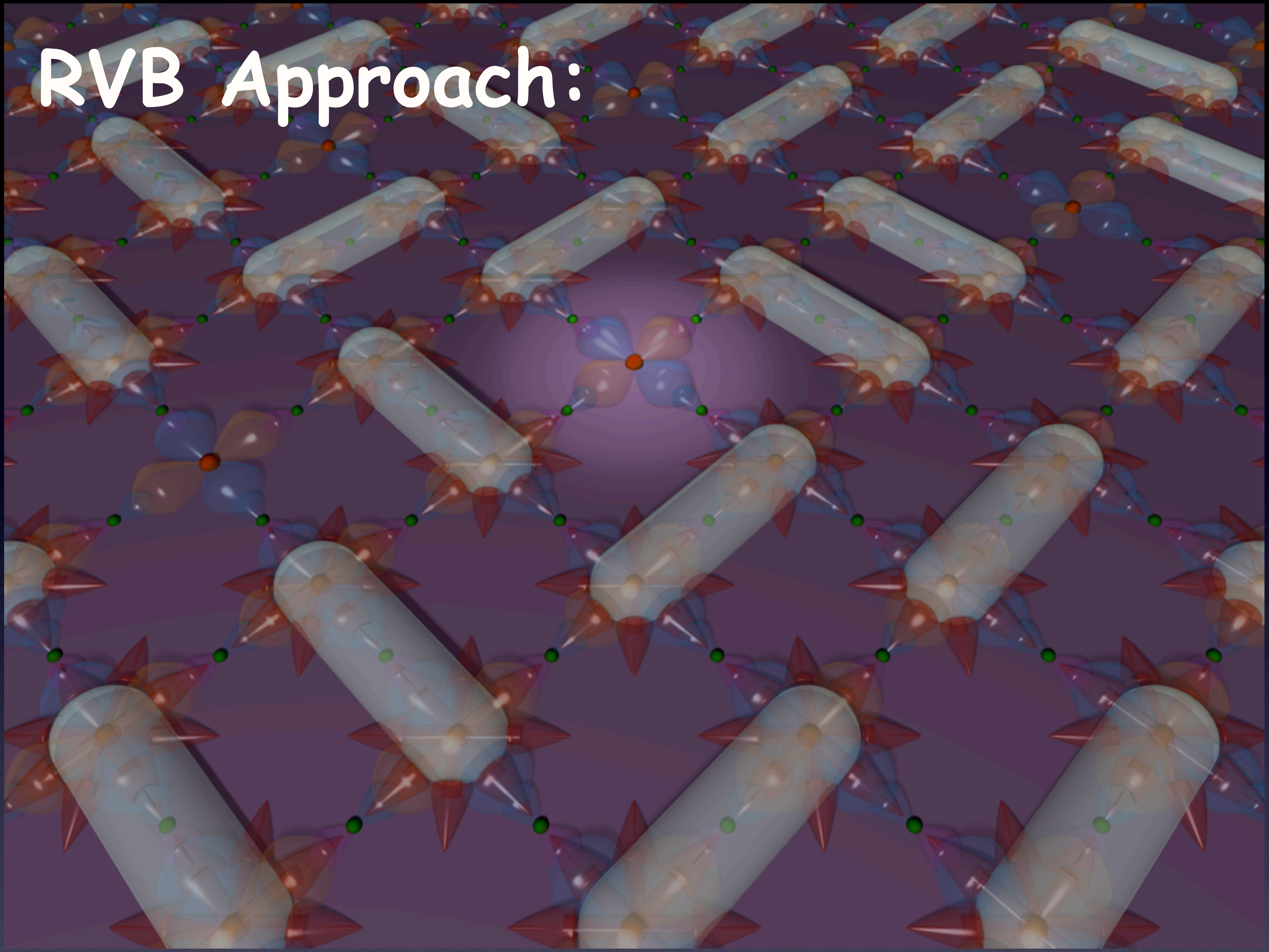
- What is the correct microscopic Hamiltonian?

Reduce to one band Hubbard Model ?



Anderson (1987) Zhang & Rice(1988)

- Pairing Mechanism?



$$r \bullet\!\!-\!\!\bullet\, r' = \frac{|\uparrow_r \downarrow_{r'}\rangle - |\downarrow_r \uparrow_{r'}\rangle}{\sqrt{2}}$$

- nearest neighbor d-wave pairing

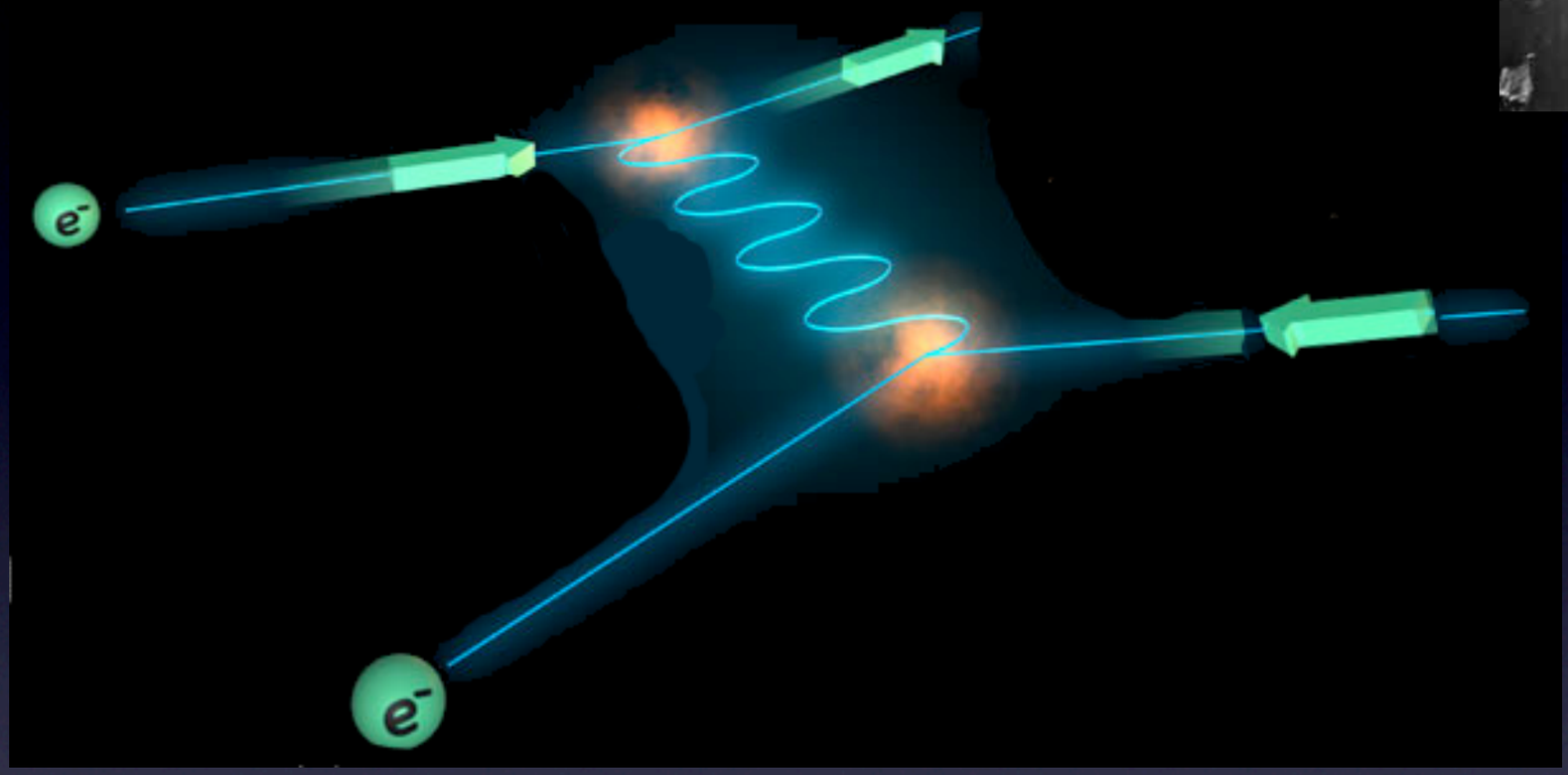
Anderson (1987); Kotliar & Lu (1988); others

Numerical Calculations of the Hubbard Model: n.n. d-wave pairing

BCS-like Scheme?



Boson-Exchange Mechanism

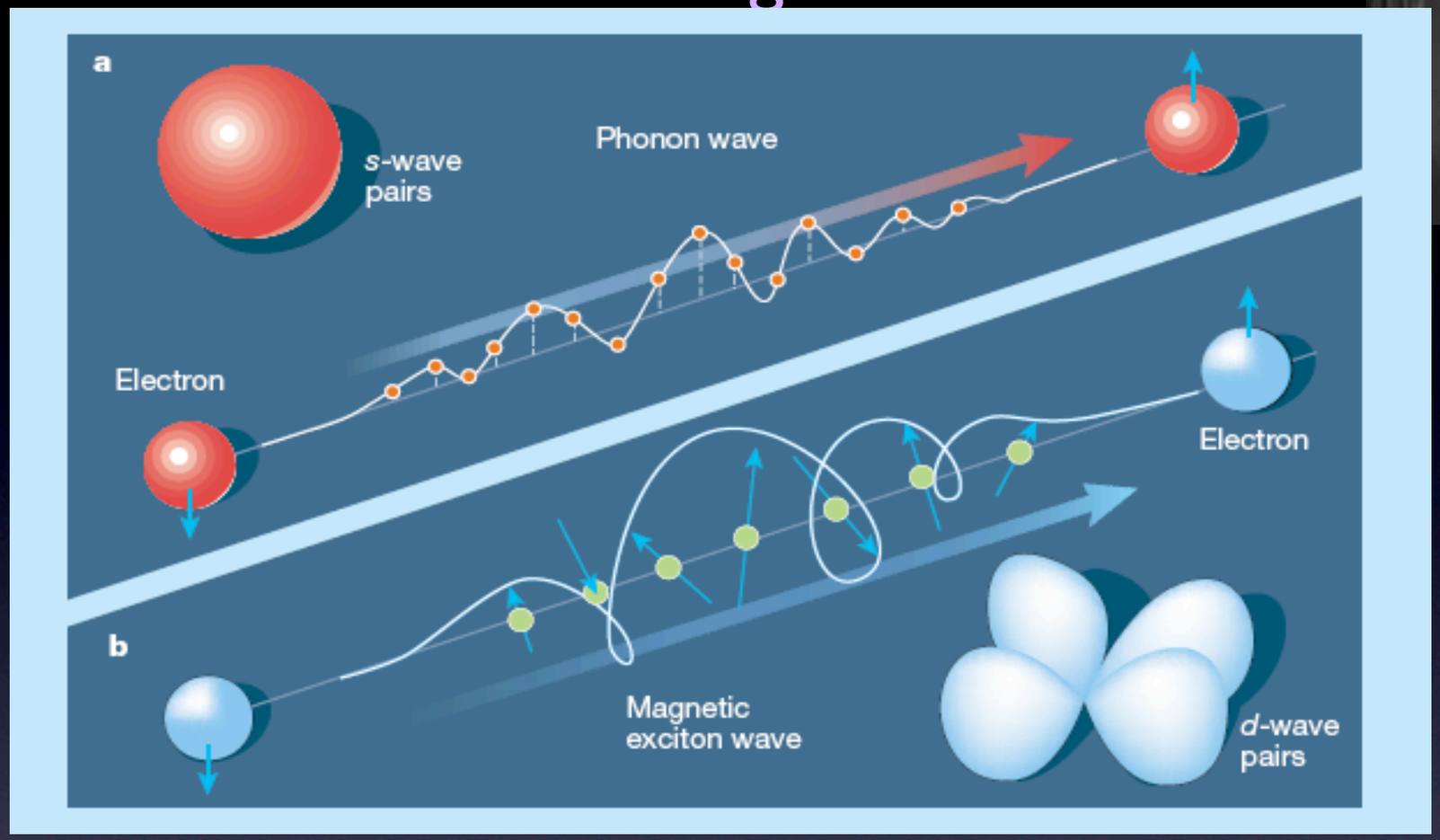


- Somehow a retarded interaction can be constructed
- Perhaps at sufficiently high doping close to normal metal
- A Pairing glue? Even in the Hubbard model
- Example: Spin Fluctuations

BCS-like Scheme?



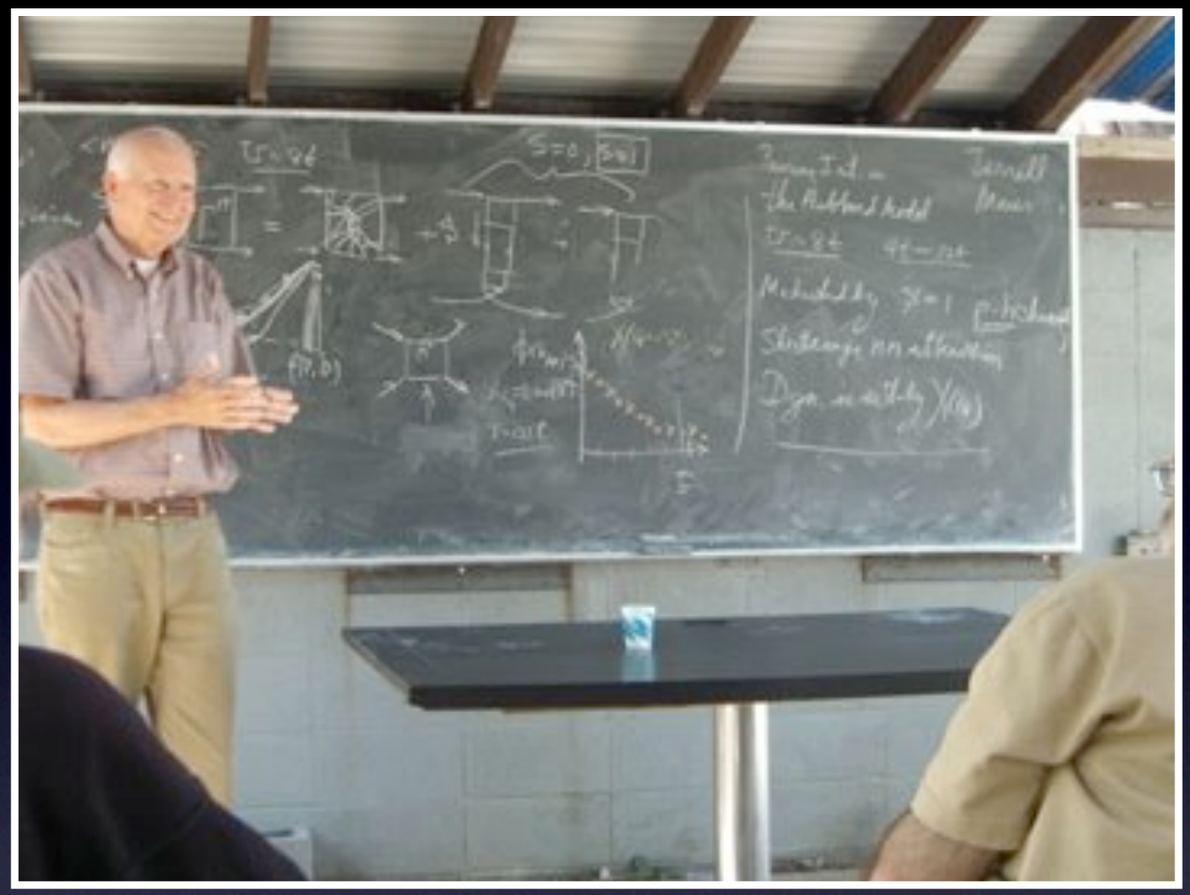
Boson-Exchange Mechanism

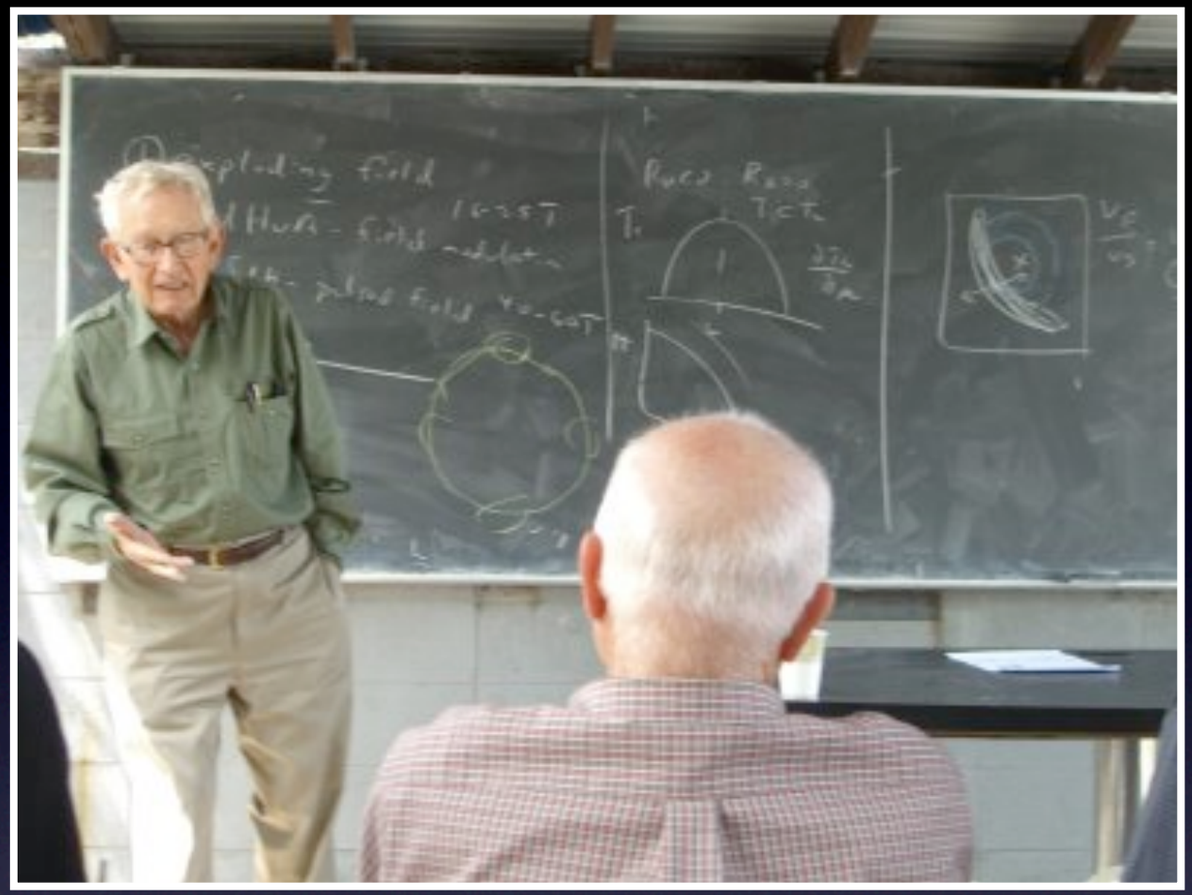


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Anderson-Scalapino Debate

See *Science* Letters 2007

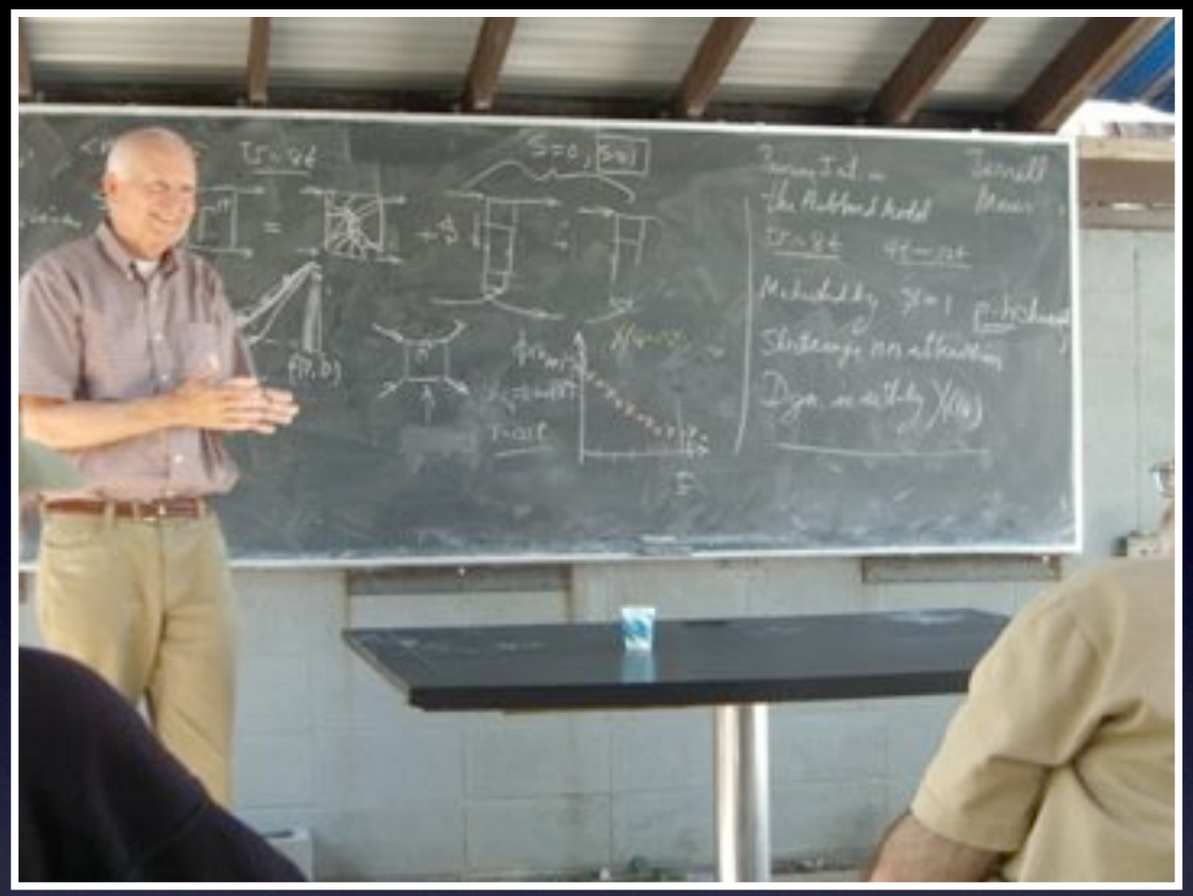


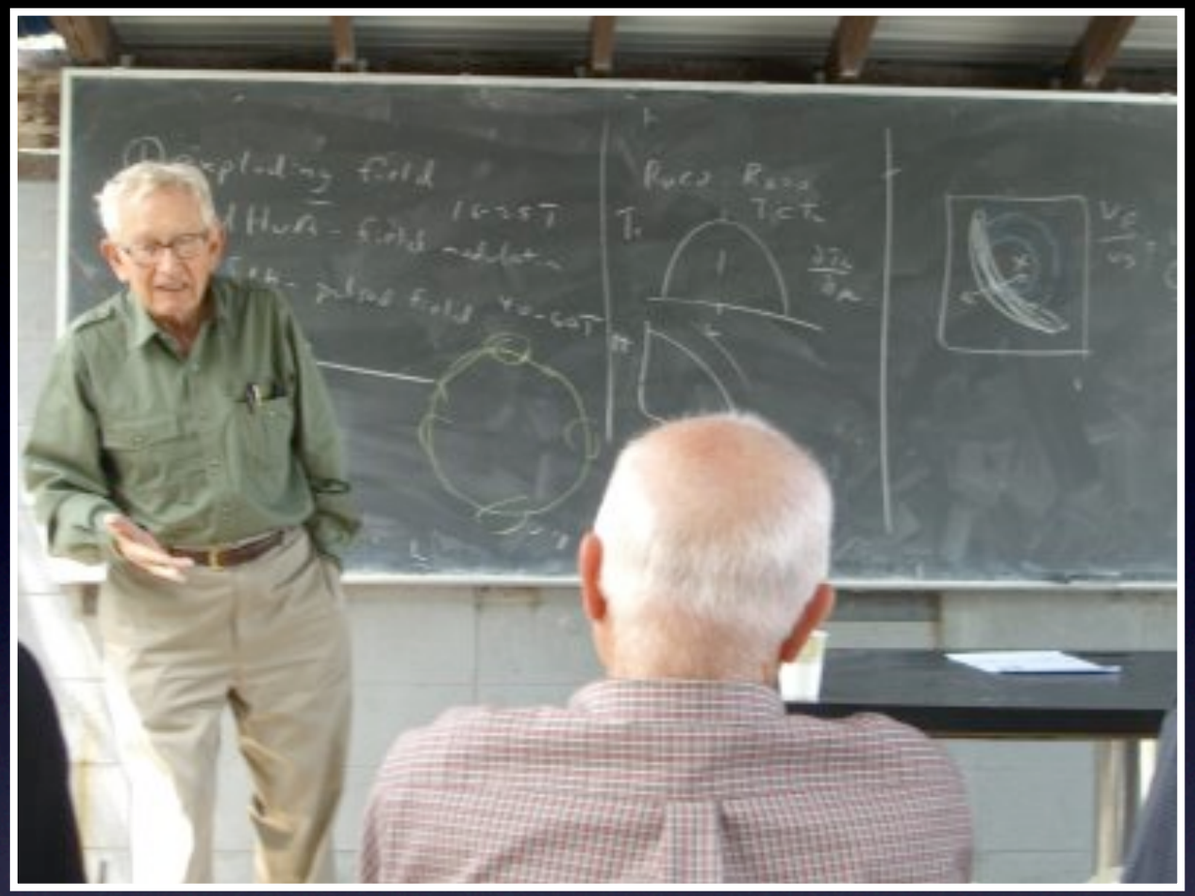


Aspen 2007

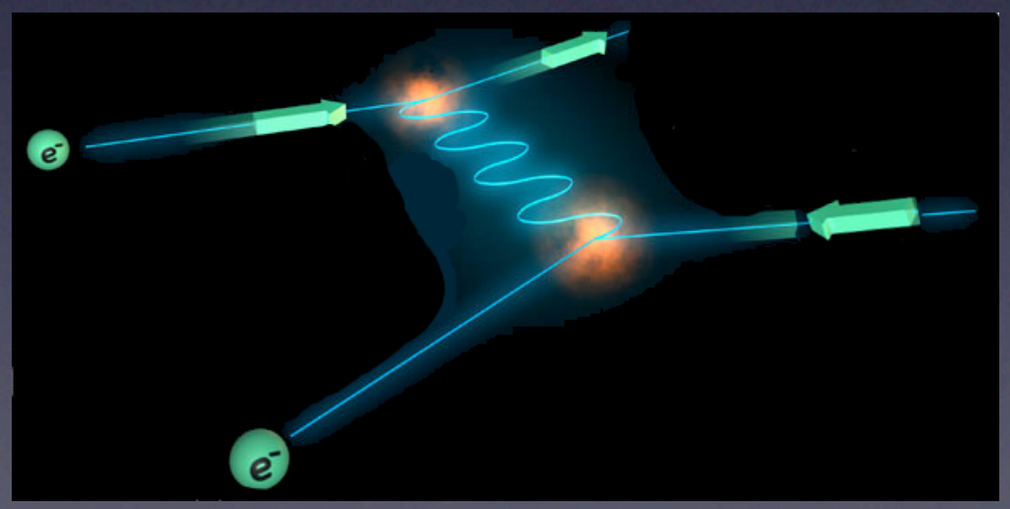
Anderson-Scalapino Debate

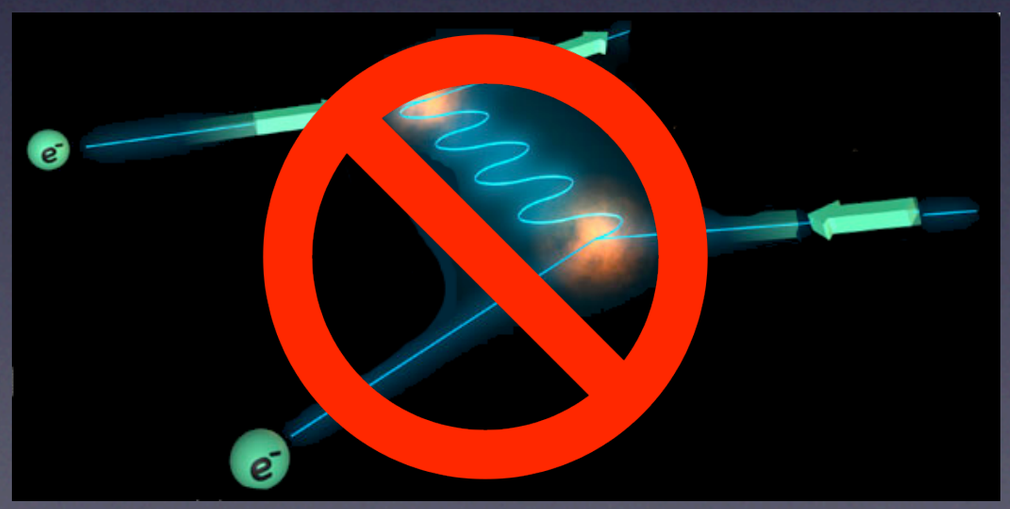
See *Science* Letters 2007





Aspen 2007





Phil: No glue required!

Doug: A separation of energy scales as in BCS may be still possible

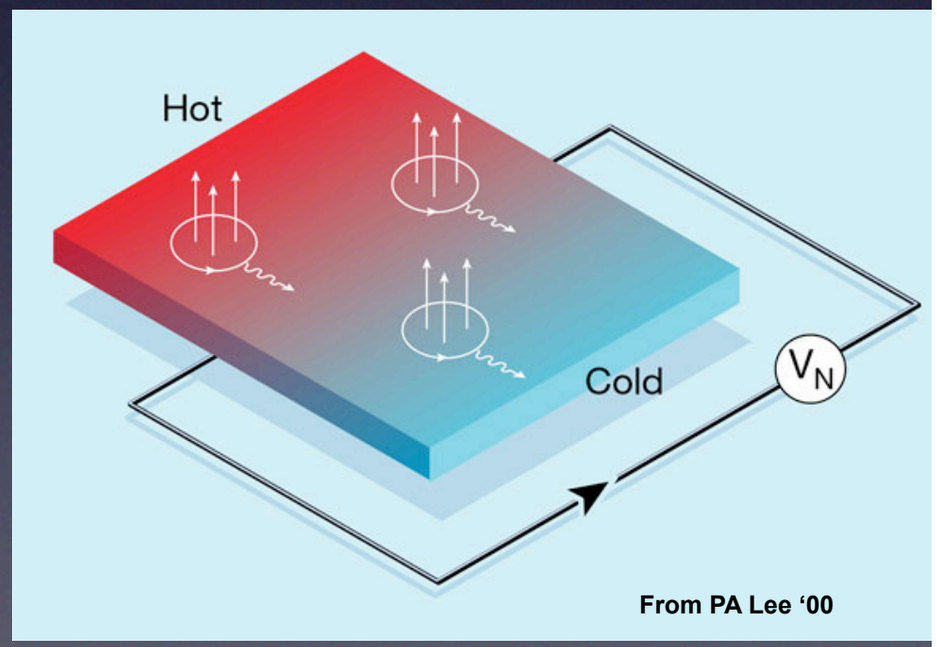
Key Questions II:

- When do pairs form? At Tc or above? $\Psi = |\Delta| \exp(i\Phi)$
- Pseudogap? What is it?
- Due to competing orders or pairing?
- Tc occurs due to phase coherence? paired above?

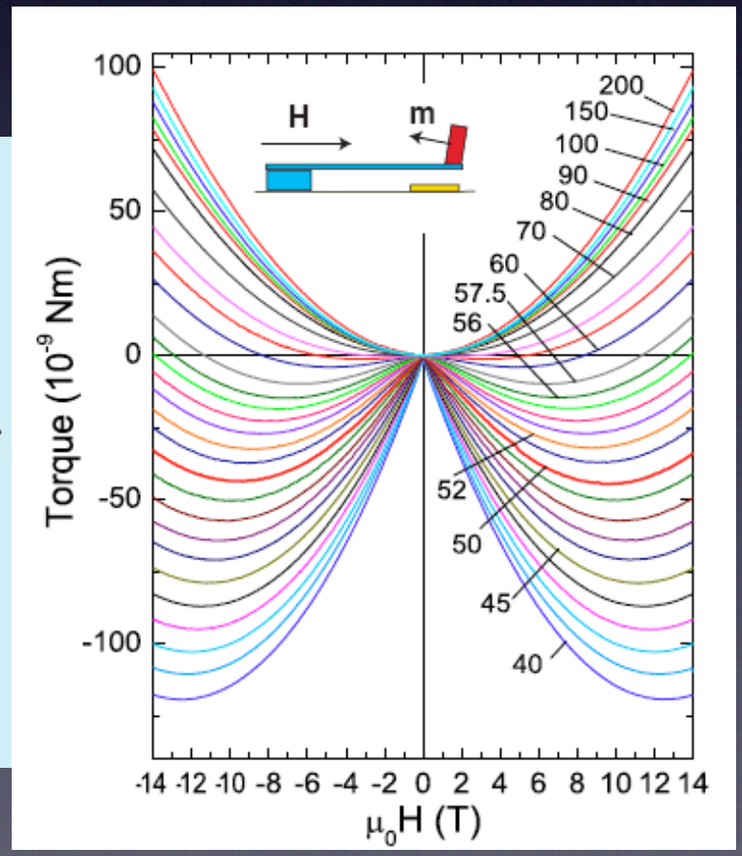
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Experiment by Wang, Li, Ong and coworkers 2002



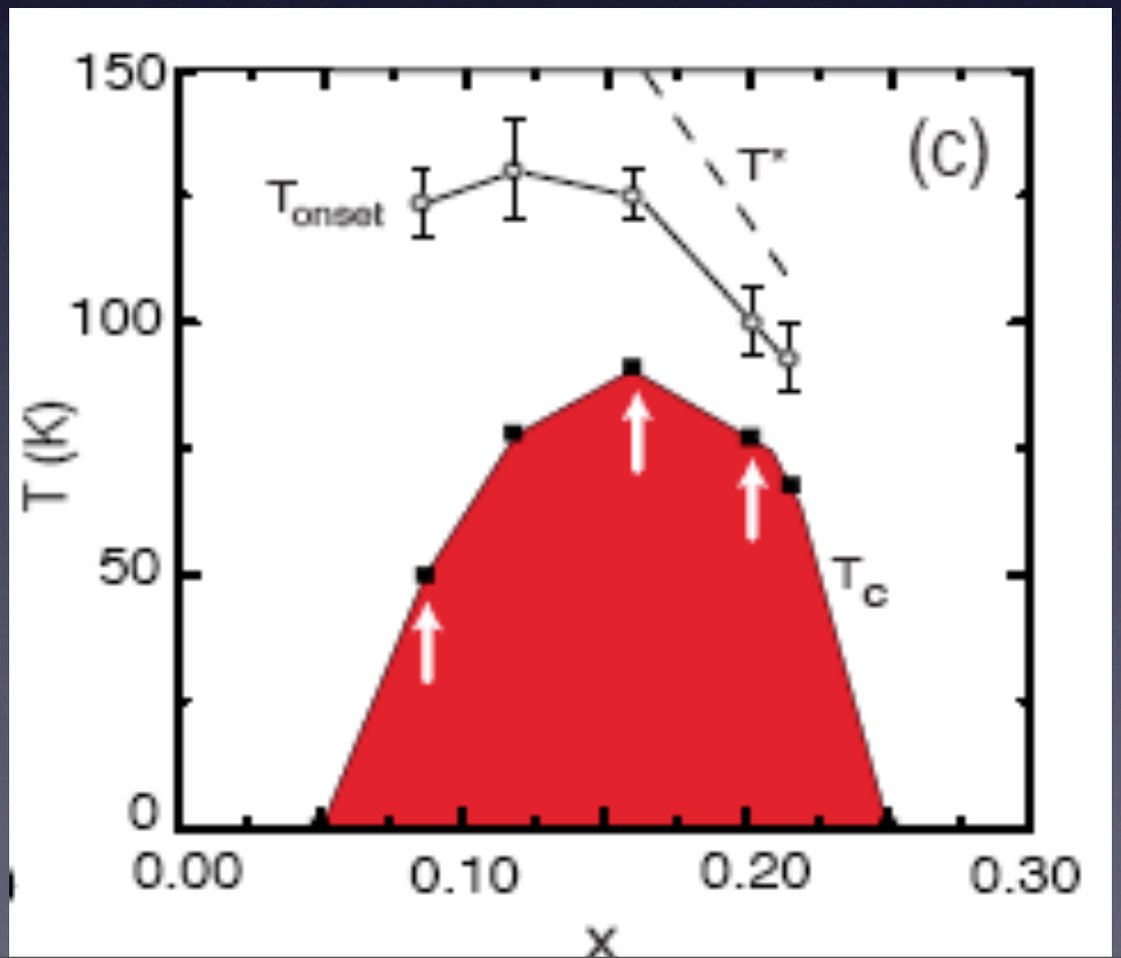
From PA Lee '00



Key Questions II:

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Enhanced Diamagnetism Exp
Li, Wang, & Ong et al.



Gaiver Tunneling in the Cuprates:

Due to d-wave nature of the order parameter very sensitive to interface disorder.

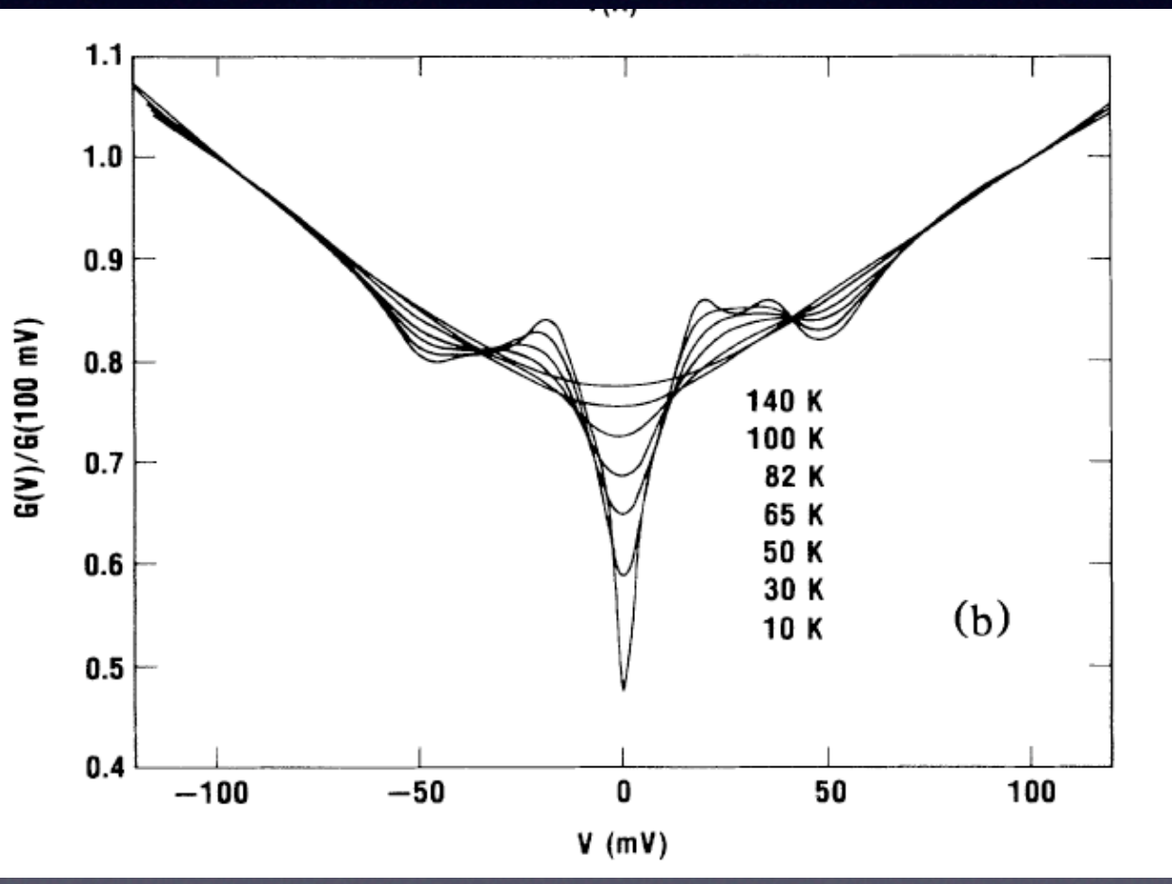
VOLUME 63, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1989

Reproducible Tunneling Data on Chemically Etched Single Crystals of $YBa_2Cu_3O_7$

M. Gurvitch, J. M. Valles, Jr., A. M. Cucolo,[(a)] R. C. Dynes, J. P. Garno, L. F. Schneemeyer, and J. V. Waszczak

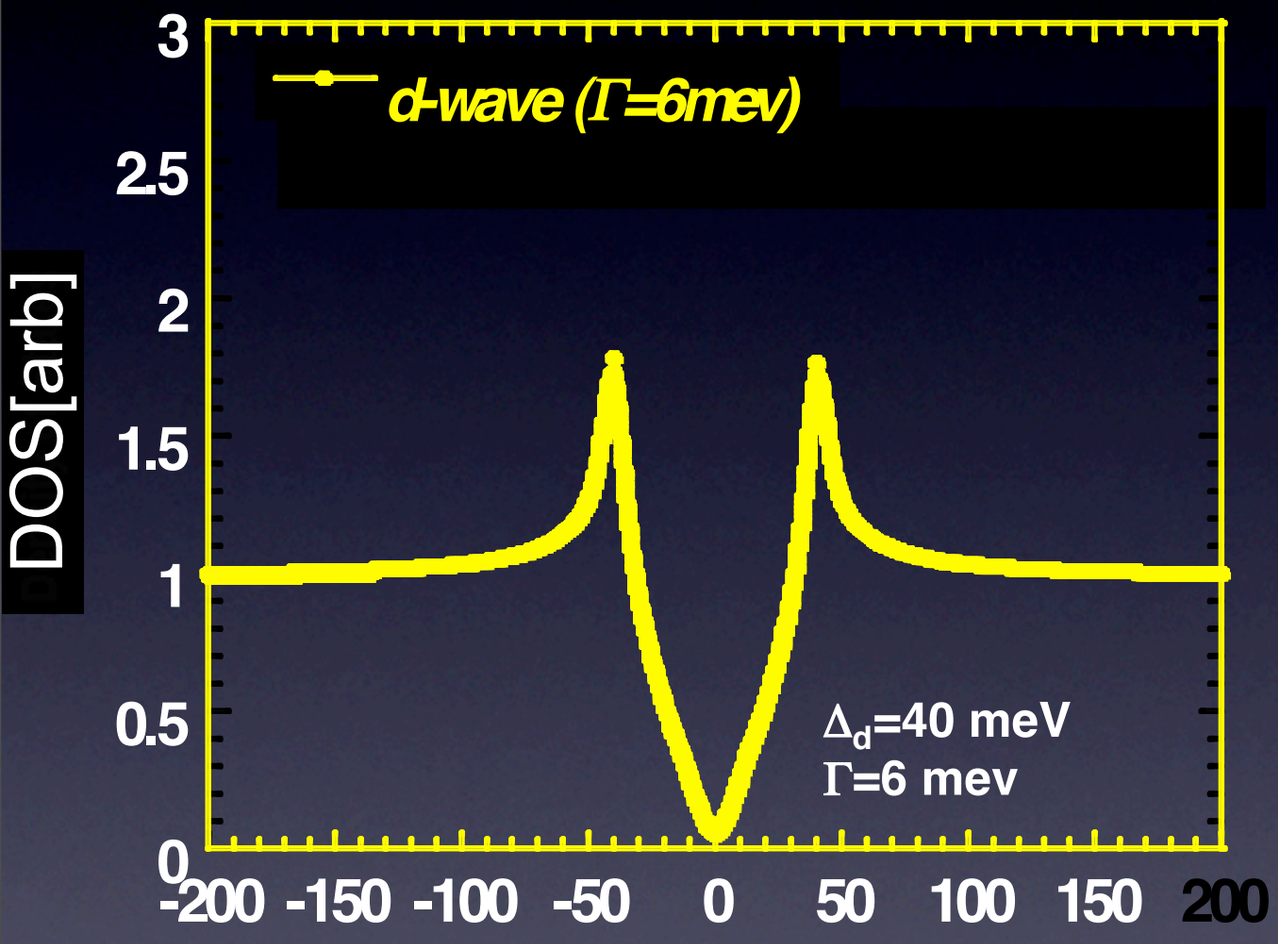
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

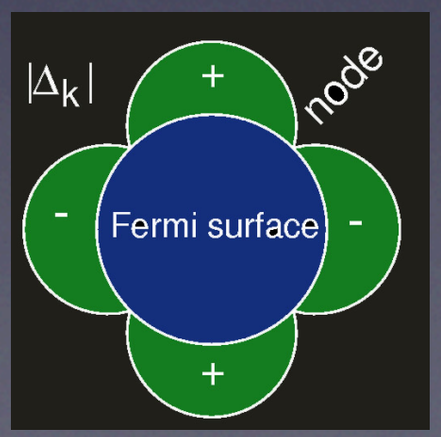
(Received 26 May 1989)



Gaiver Tunneling in the Cuprates:

Due to d-wave nature of the order parameter very sensitive to interface disorder.

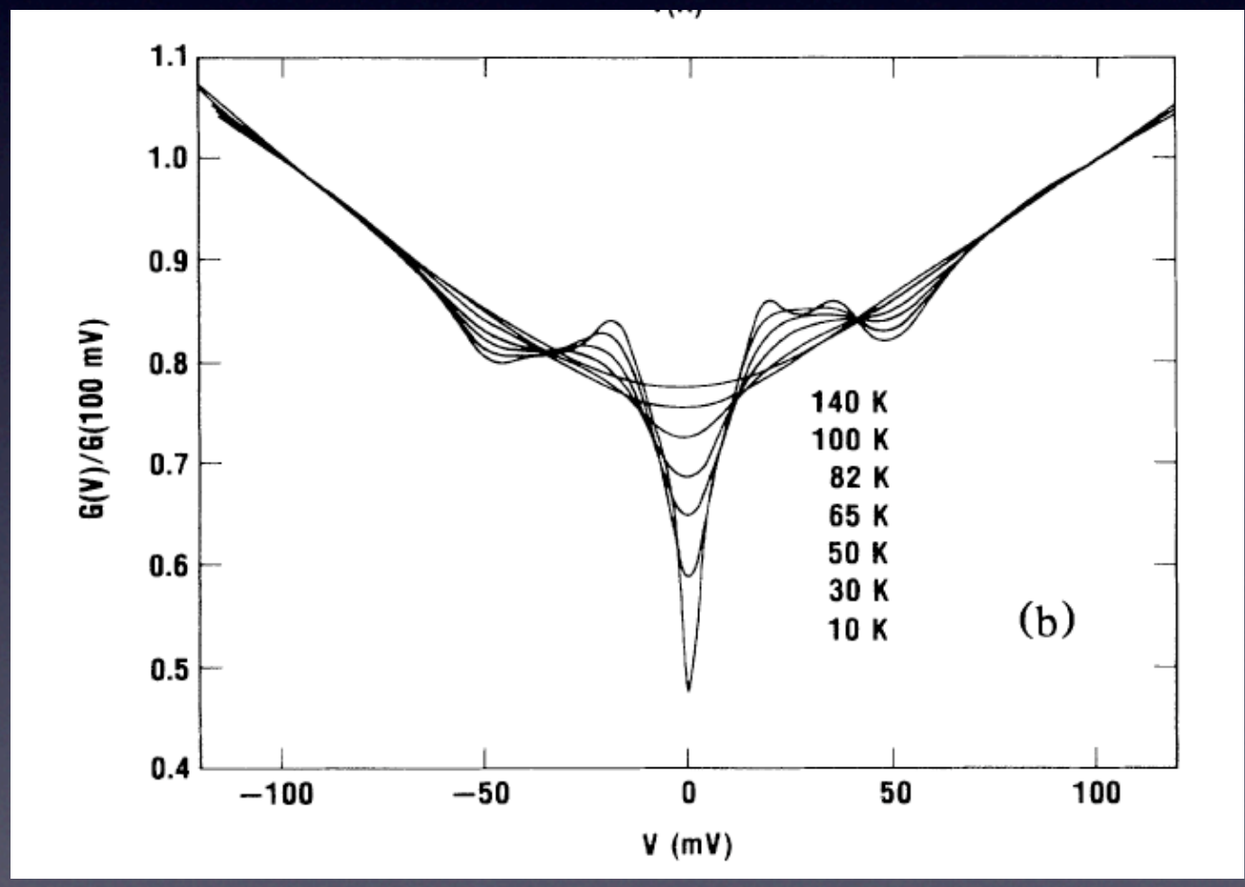




VOLUME 63, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1989

Reproducible Tunneling Data on Chemically Etched Single Crystals of $YBa_2Cu_3O_7$

M. Gurvitch, J. M. Valles, Jr., A. M. Cucolo,[a] R. C. Dynes, J. P. Garno, L. F. Schneemeyer, and J. V. Waszczak
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 26 May 1989)

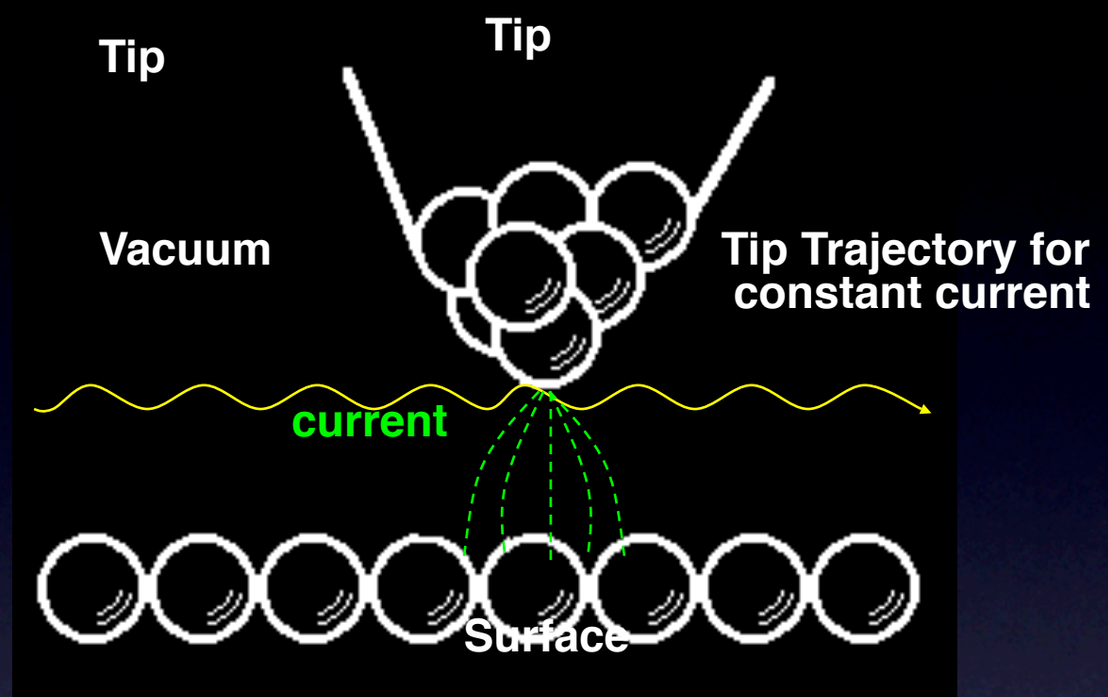


Probing Electronic States With the STM

- Imaging:

  Tip trajectory at constant current is an image of the contours of constant electron density

$$I(r,V) \propto \int_{E_F}^{E_F+V} \left|\Psi(r,E)\right|^2 T(E)\, dE$$

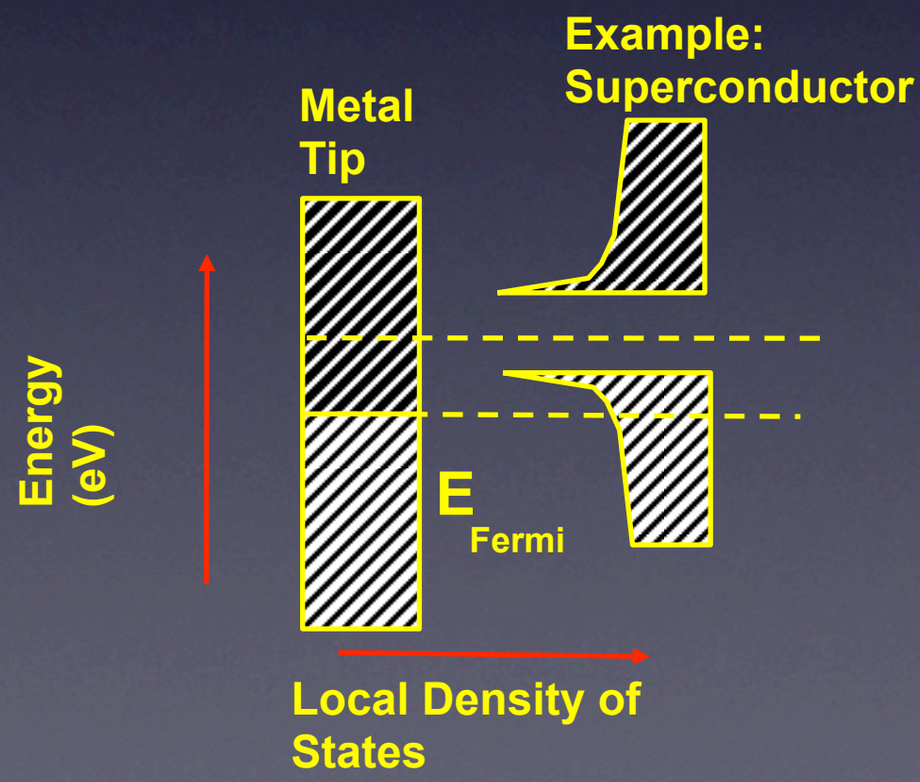


- Spectroscopy:

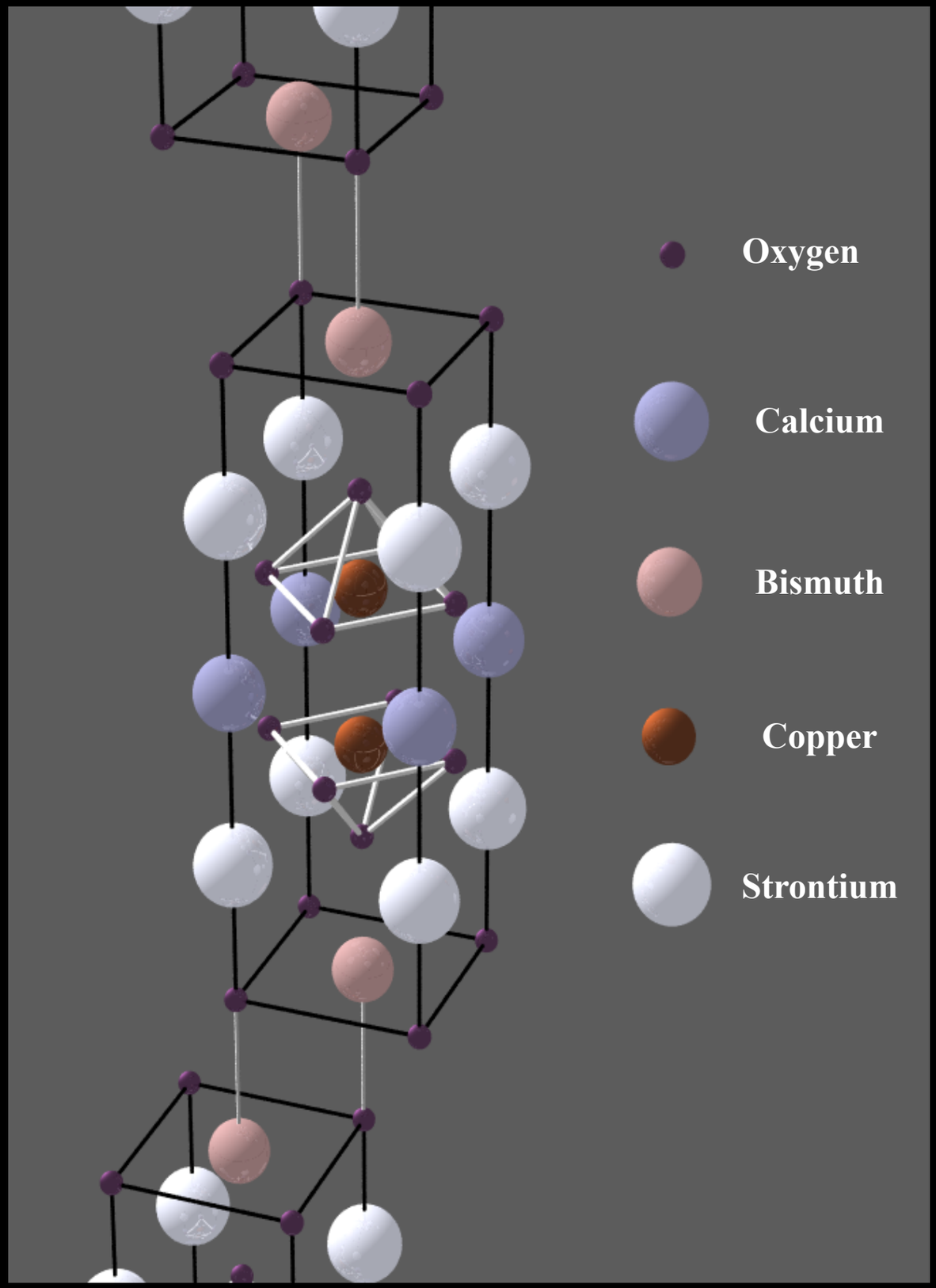
$$dI/dV(V) \propto \rho(r, V)$$

Local density of state of the sample

as a function of position & energy

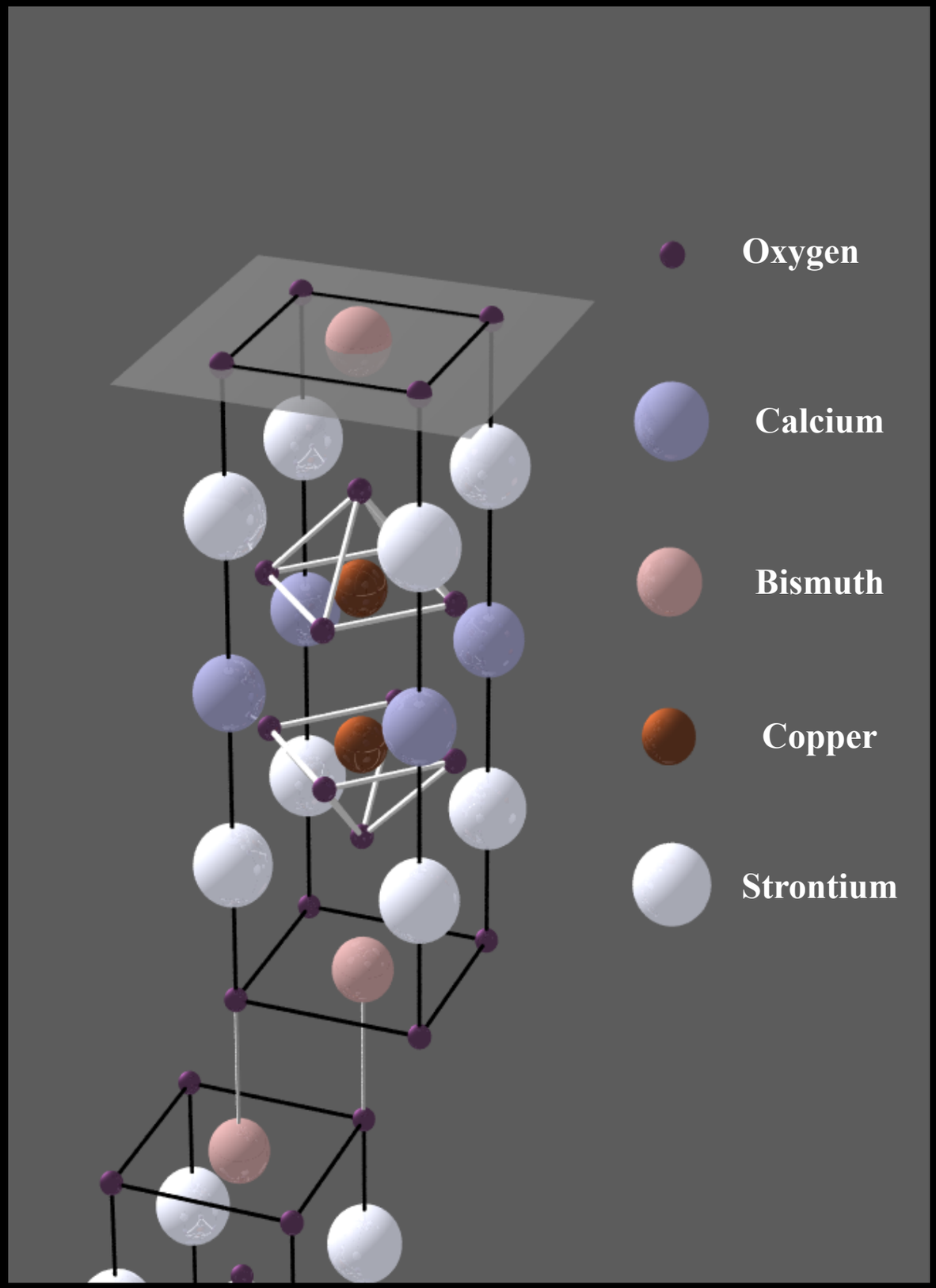


High-Tc Material System: $Bi_2Sr_2CaCu_2O_{8+\delta}$



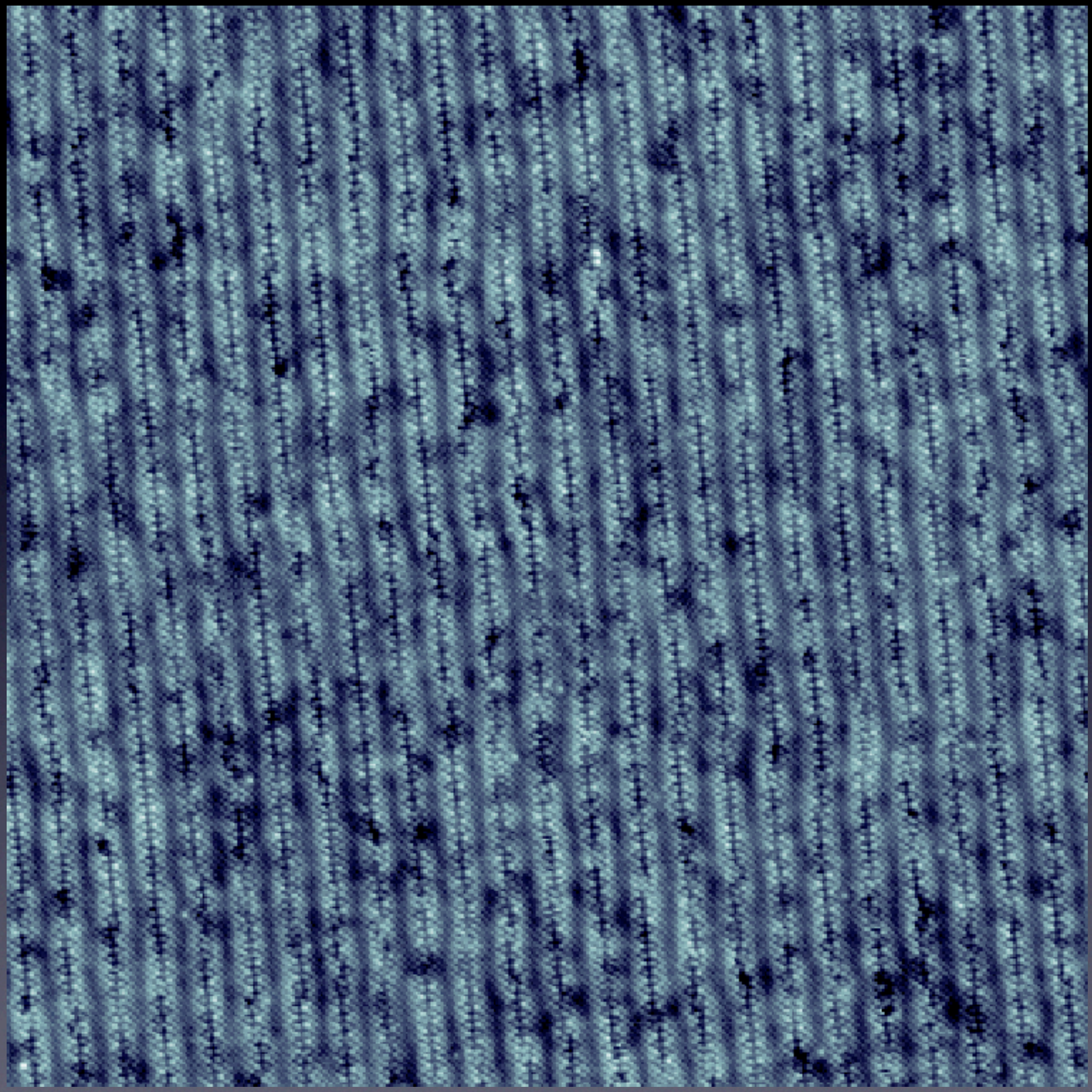
At Optimal Doping for this system: Tc~93K

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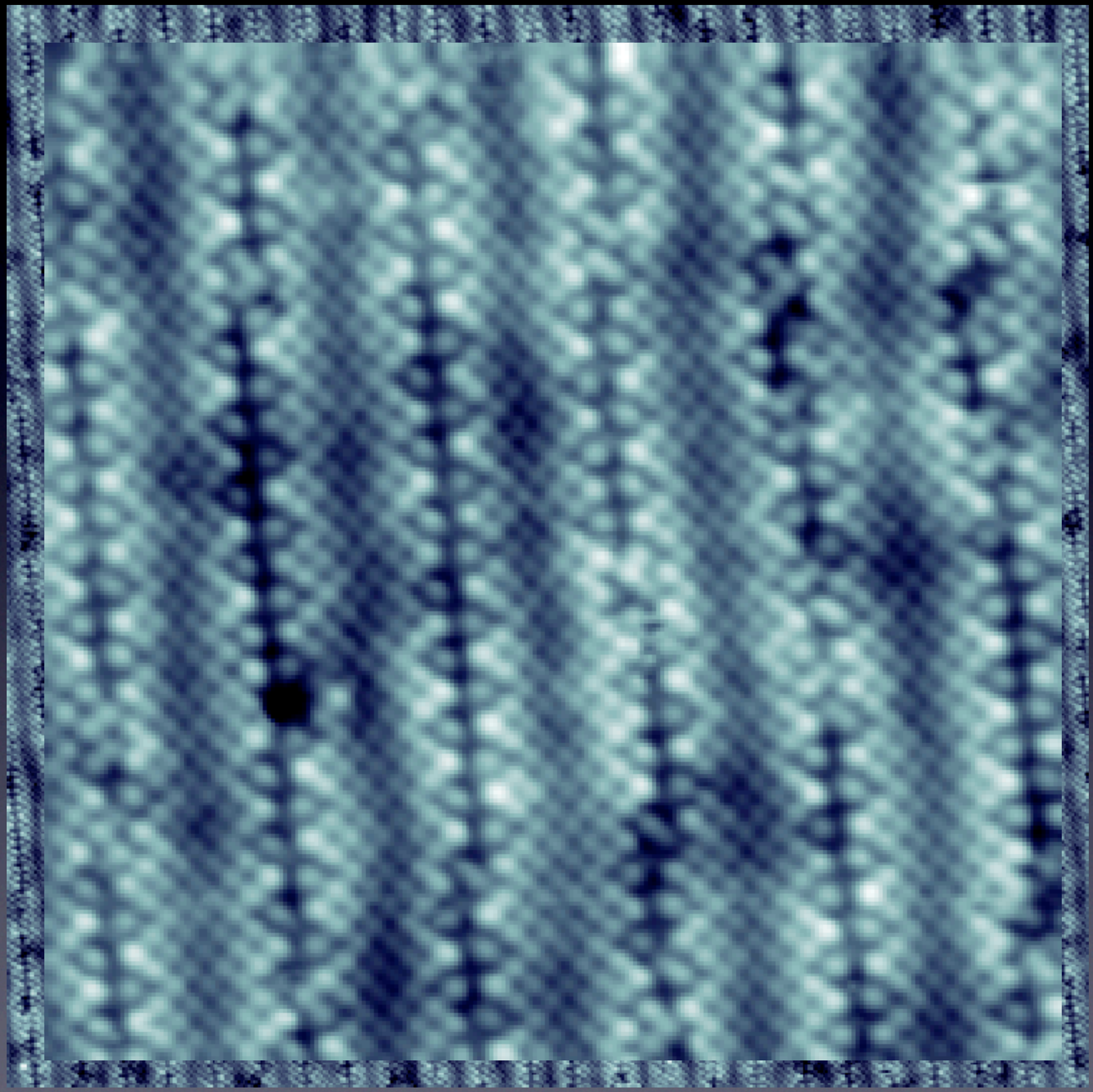
At Optimal Doping for this system: Tc~93K

Cleaved $Bi_2Sr_2CaCu_2O_{8+d}$



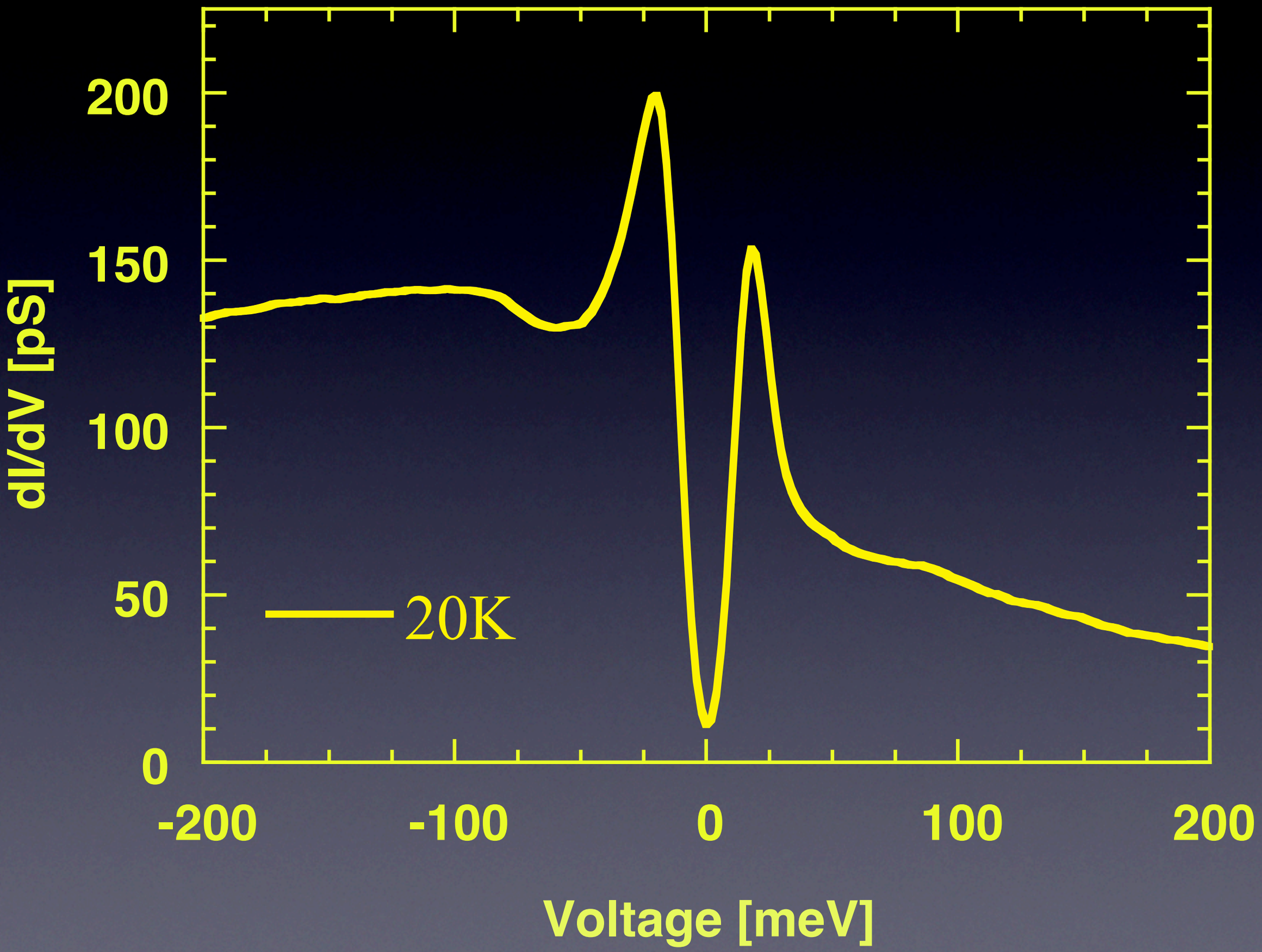
650 Å x 650 Å

Cleaved $Bi_2Sr_2CaCu_2O_{8+d}$

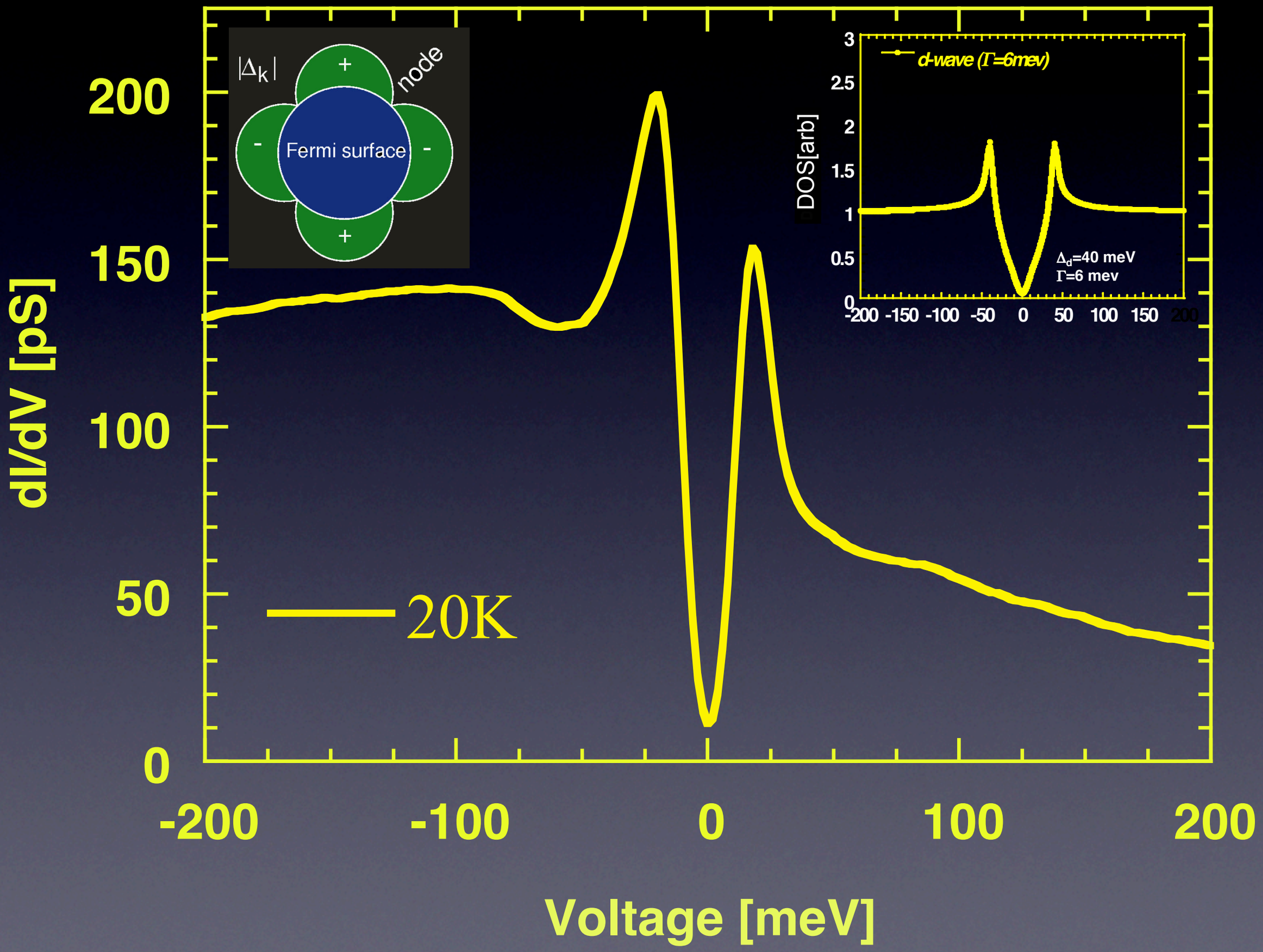


650 Å x 650 Å

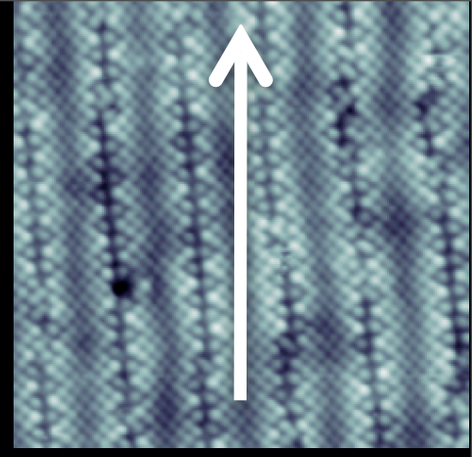
Superconducting State Tunneling Spectra for an overdoped sample (x=0.225) Tc=65K sample



Superconducting State Tunneling Spectra for an overdoped sample (x=0.225) Tc=65K sample



Spatial Variation of the tunneling spectra in superconducting state (overdoped doping Tc=65K, T=40K)



200pS

15pS

2Δ

250

0

Tip Position (A)

-200

-100

0

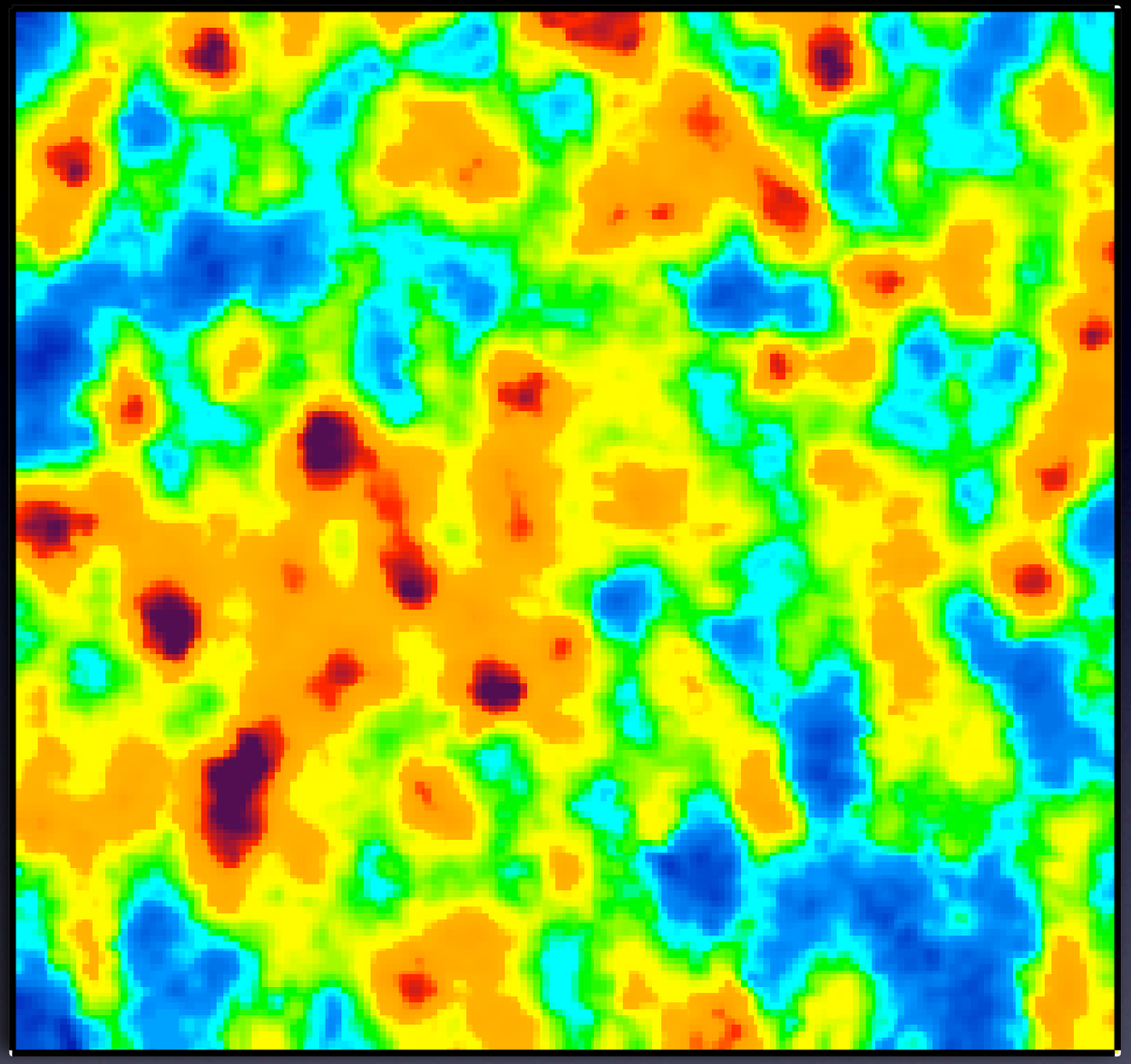
Bias Voltage (meV)

100

200

Inhomogeneous Gaps

300 Å x 300 Å



Δ(mV)

18mV

38mV

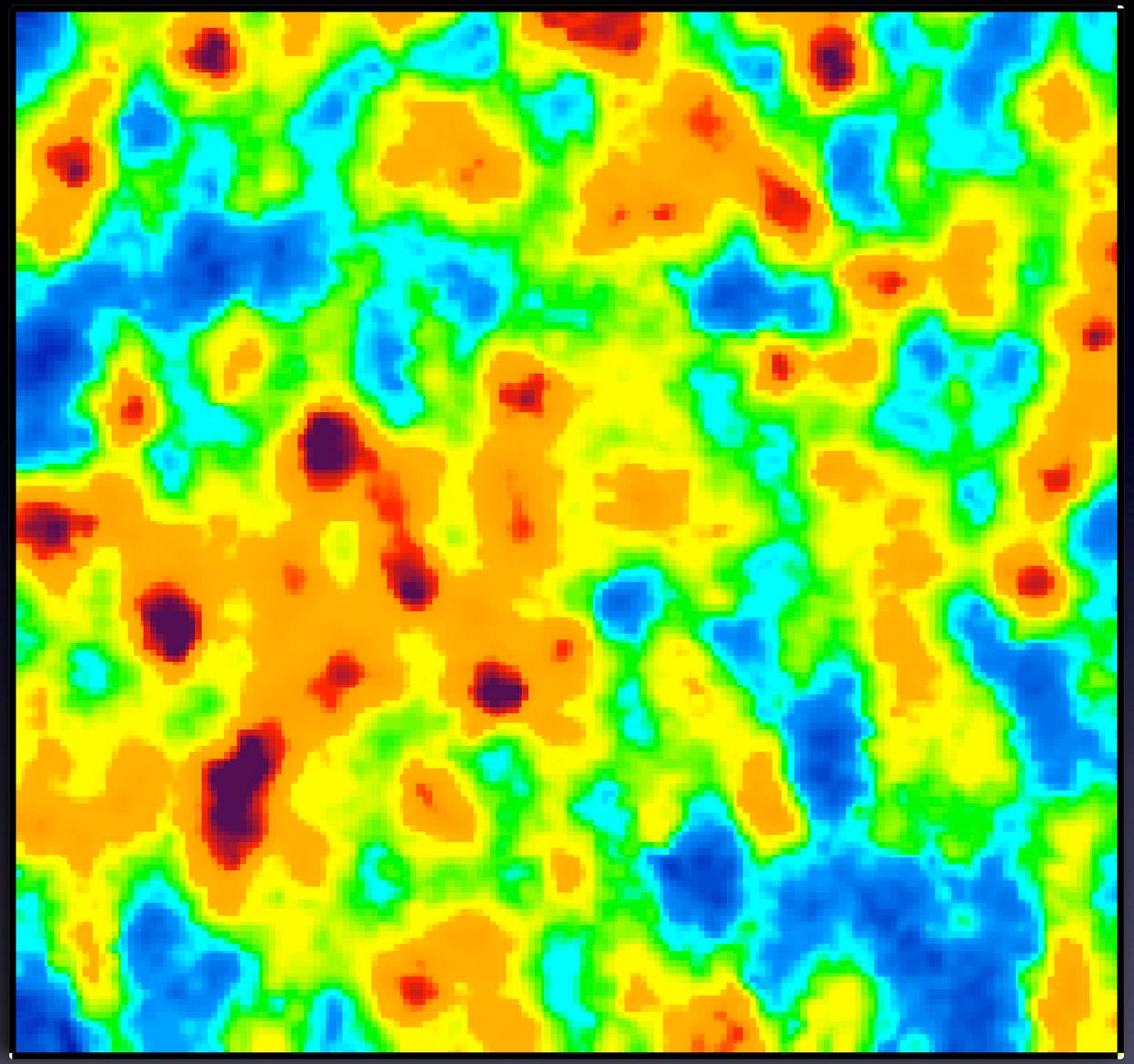
overdoped sample

T< Tc (T=30K, Tc=68K)

Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik

Inhomogeneous Gaps

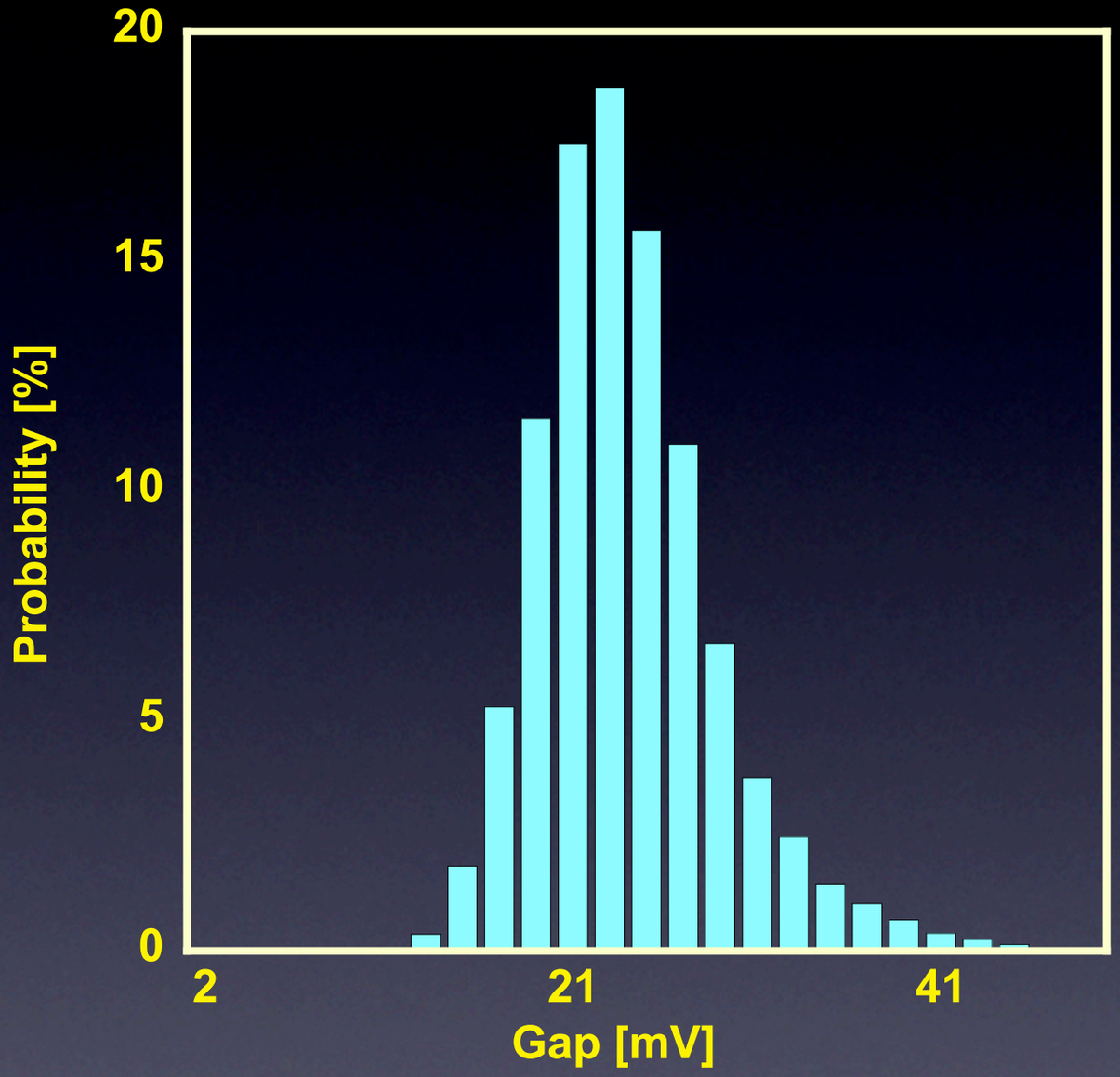
300 Å x 300 Å



Δ(mV)

18mV

38mV



overdoped sample

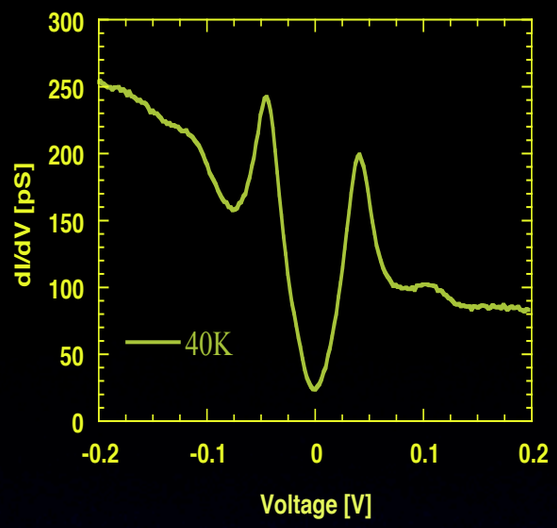
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Spatial Structure of Electronic States
&
Quantum Interference for a d-wave Superconductor

Optimally doped Sample Tc=93K

520 Å x 520 Å



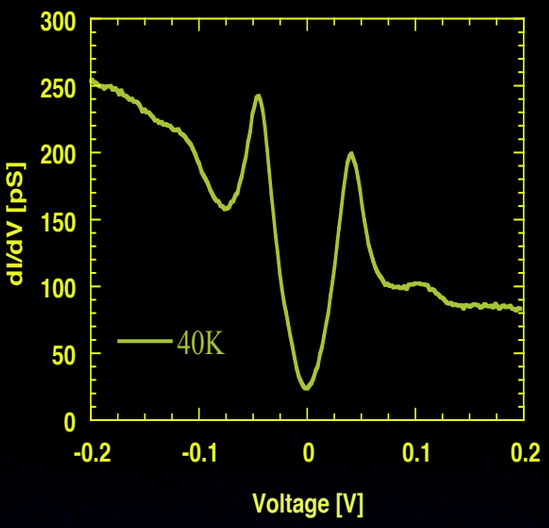
300pS

25pS

Conductance Maps Below Tc

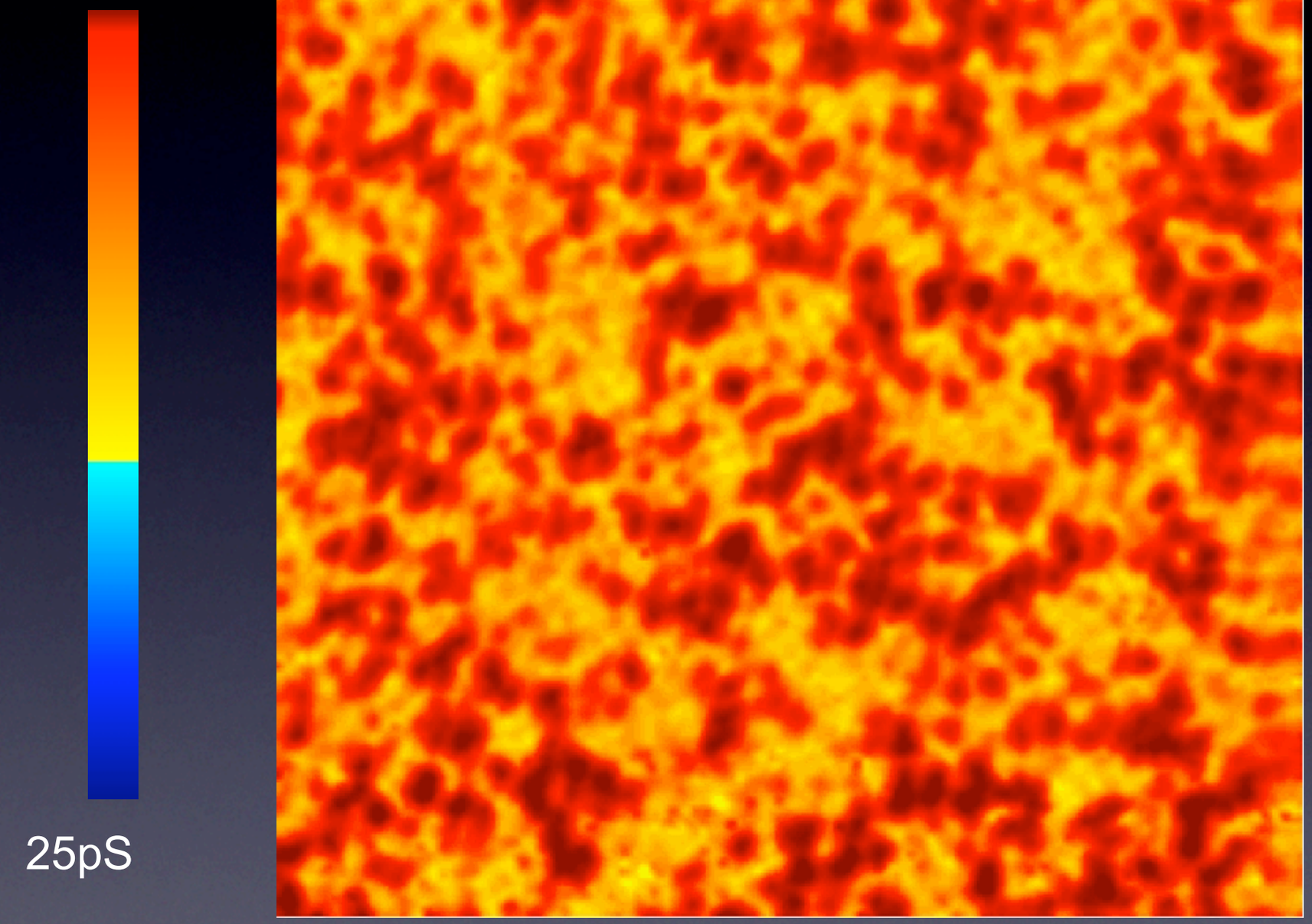
Homogeneity of Nodal QP

Optimally doped Sample Tc=93K



520 Å x 520 Å

300pS



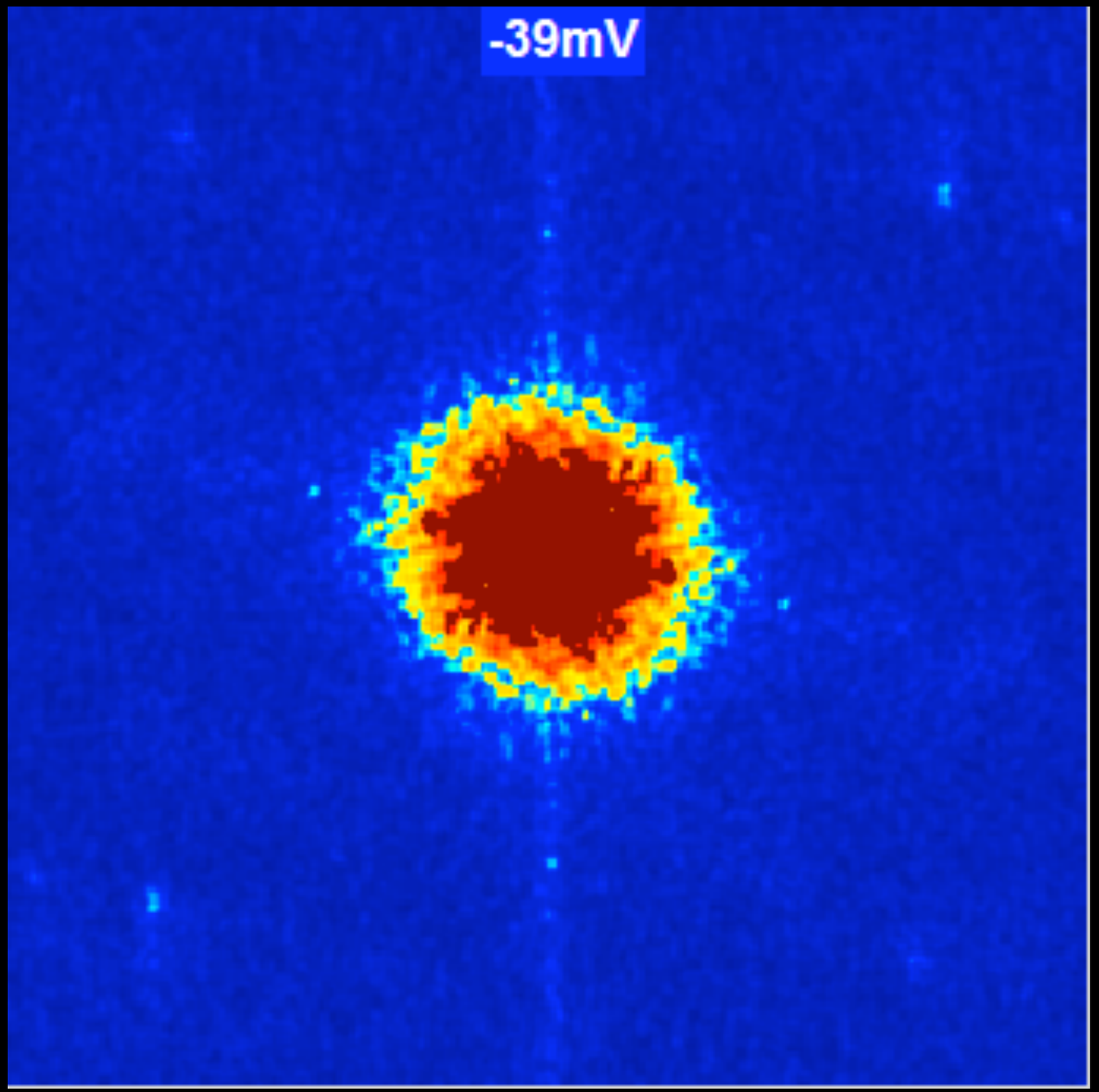
25pS

Conductance Maps Below Tc

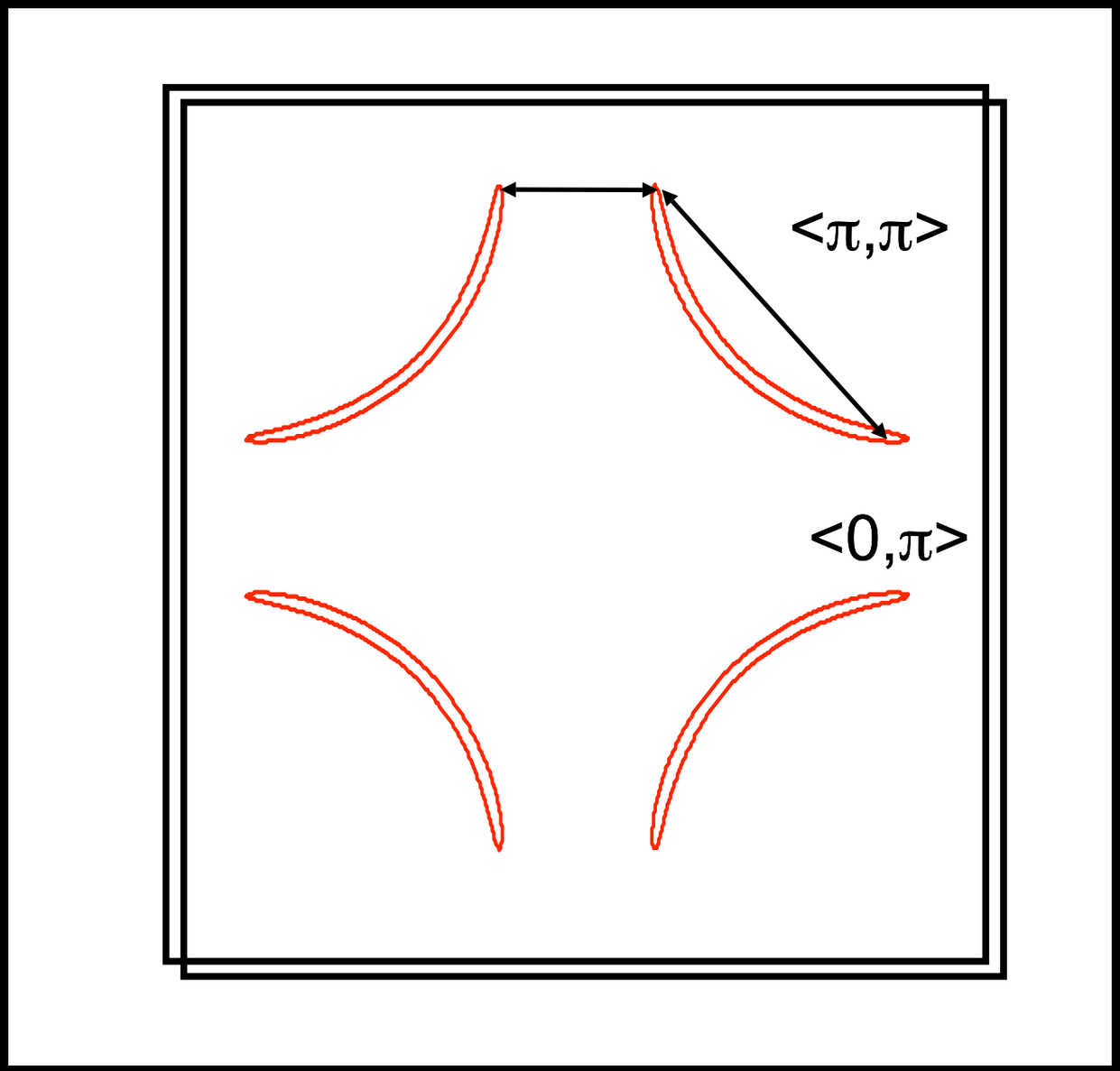
Homogeneity of Nodal QP

Fourier analysis of the modulation in the local density of states of the superconducting state (T=Tc/2)

Fourier analysis of the modulation in the local density of states of the superconducting state (T=Tc/2)



Quantum Interference in the Superconducting State of a Cuprate Superconductor



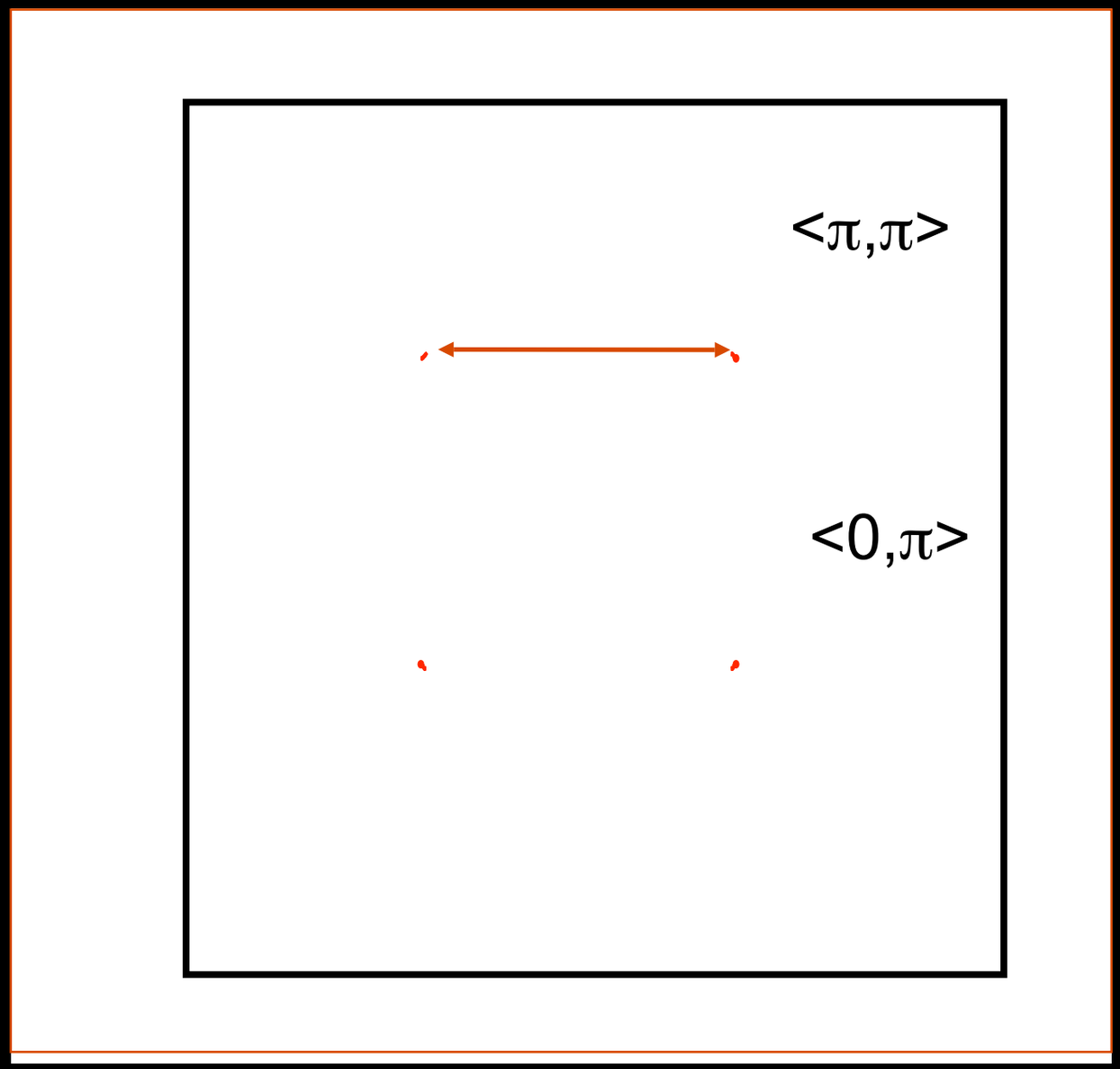
$$n(E) = \oint_{E(k)=E} \frac{1}{|\nabla_k E(\bar{k})|} dk$$

Scattering between equal energy counters.

The belief is that scattering is dominated by points with large density of states

Hoffman et al., Science 2002, McElroy et al. Nature 2003 ,Flatte et al. PRL 1993, Q.-H. Wang and D.-H. Lee, PRB 67, 20511 (2003); A. Polkovnikov, S. Sachdev and M. Vojta, Physica C 388-389, 19 (2003).; L. Capriotti, D.J. Scalapino, and R.D. Sedgewick, PRB 68 14508 (2003); L. Zhu, W.A. Atkinson and P.J. Hirschfeld, PRB 69, 60503 (2004)

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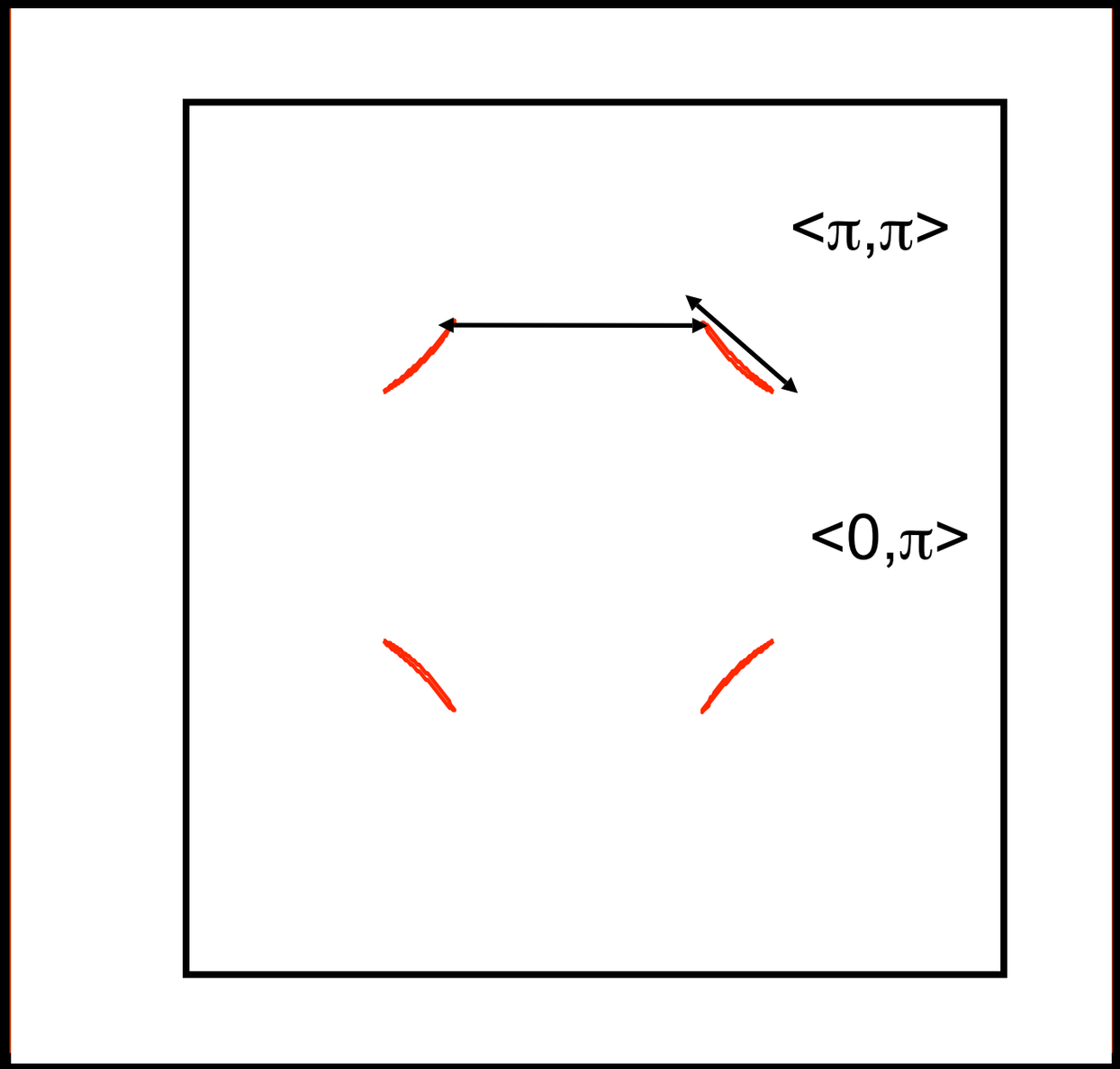
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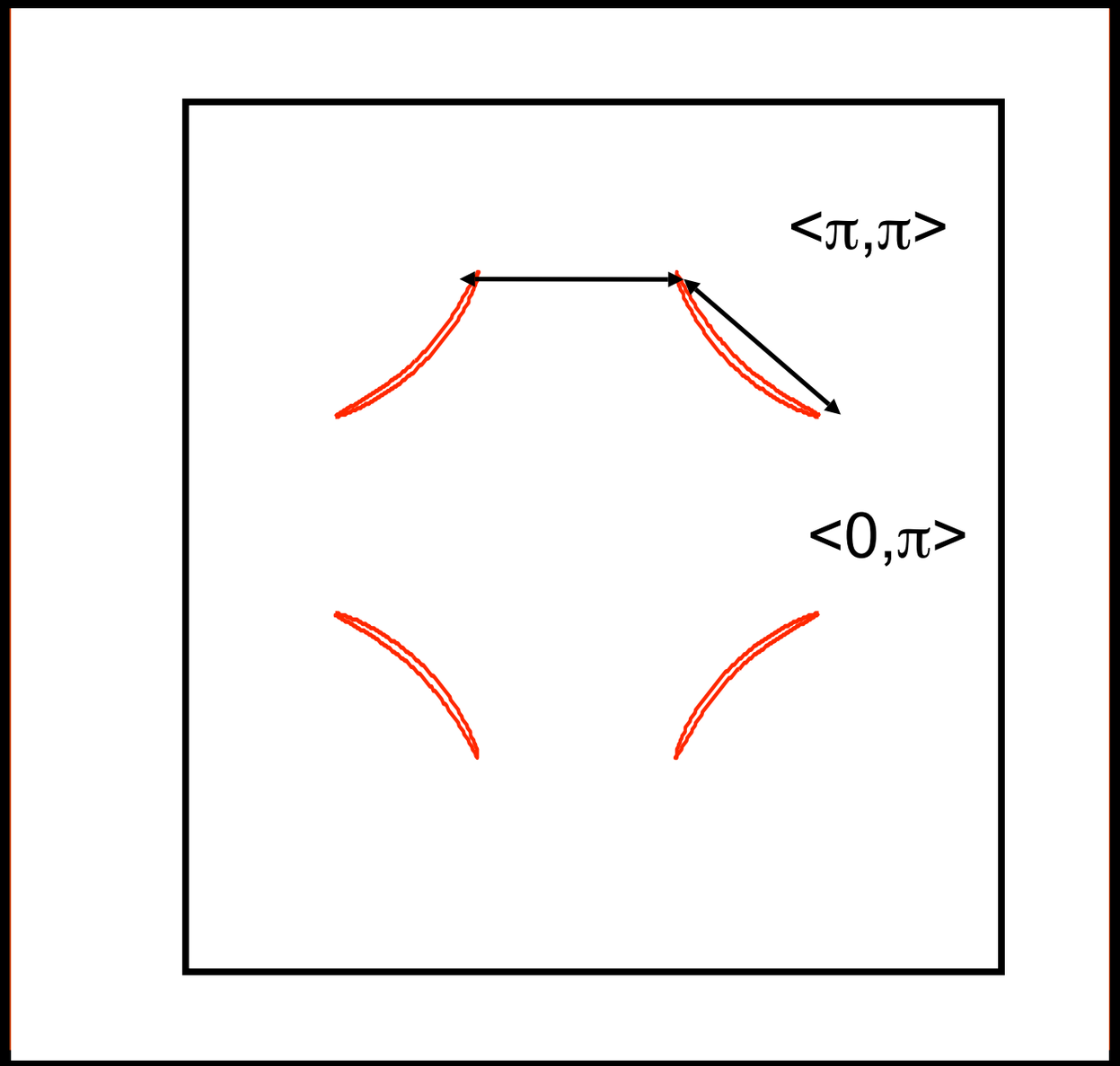
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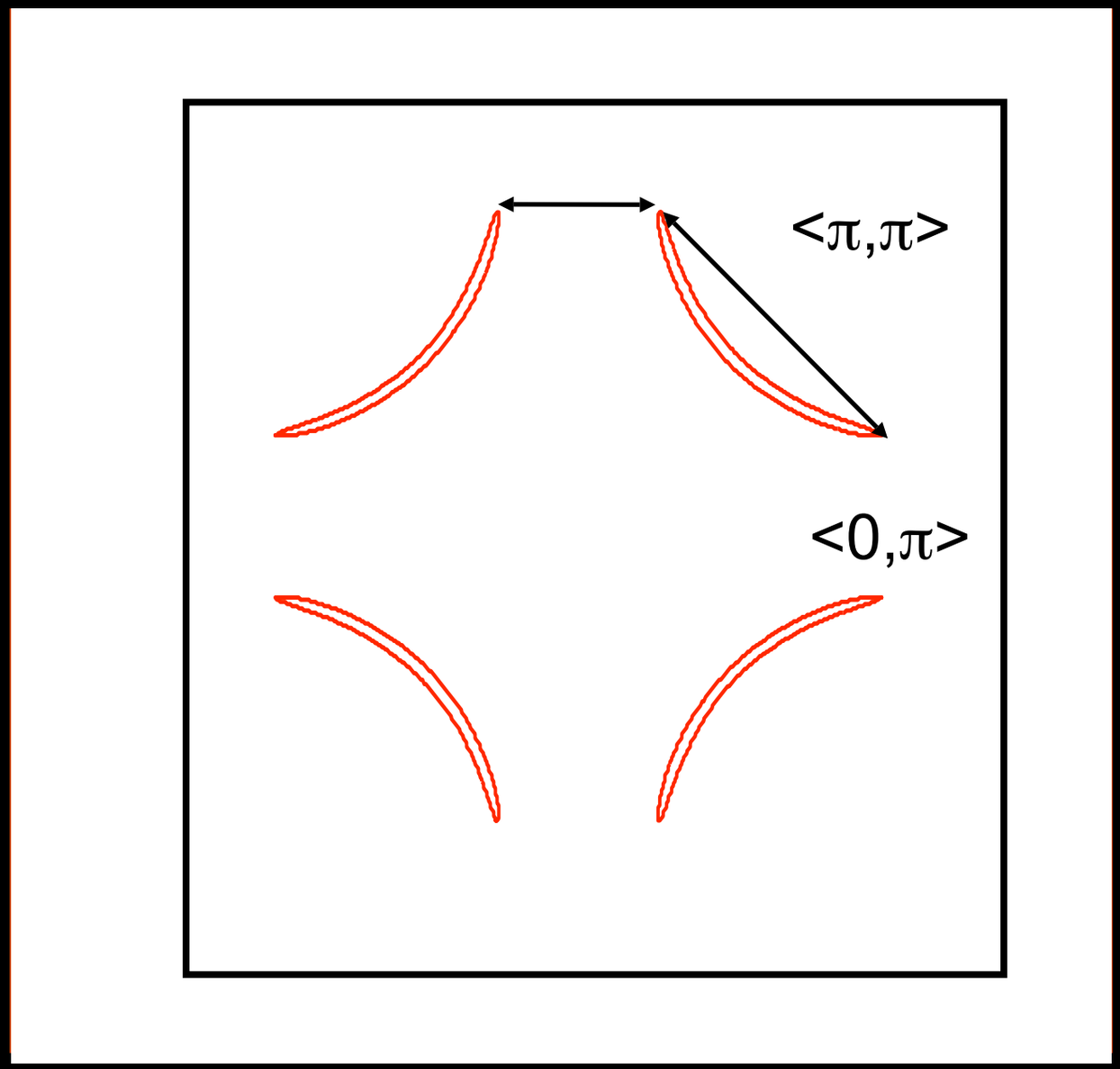
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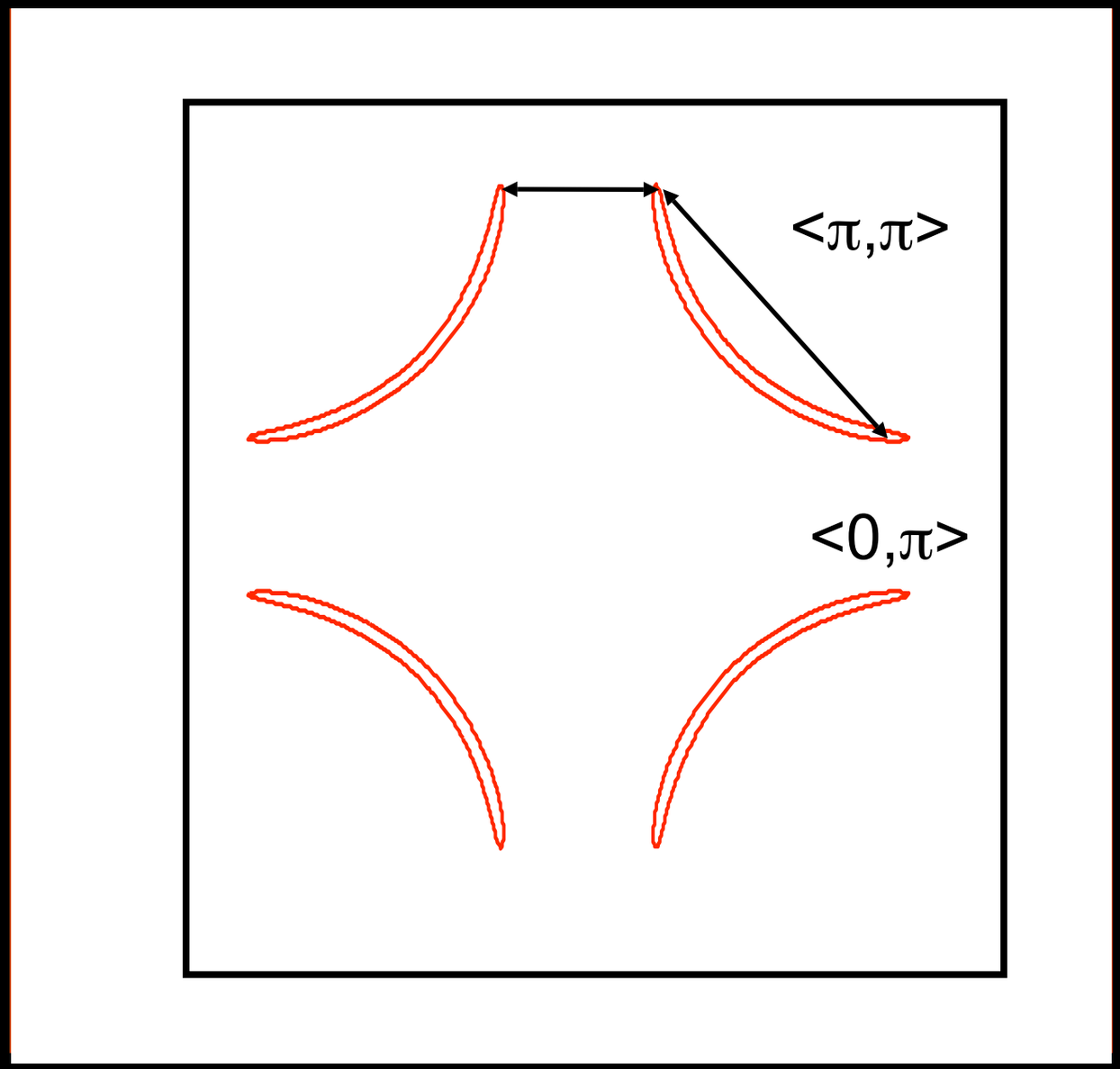
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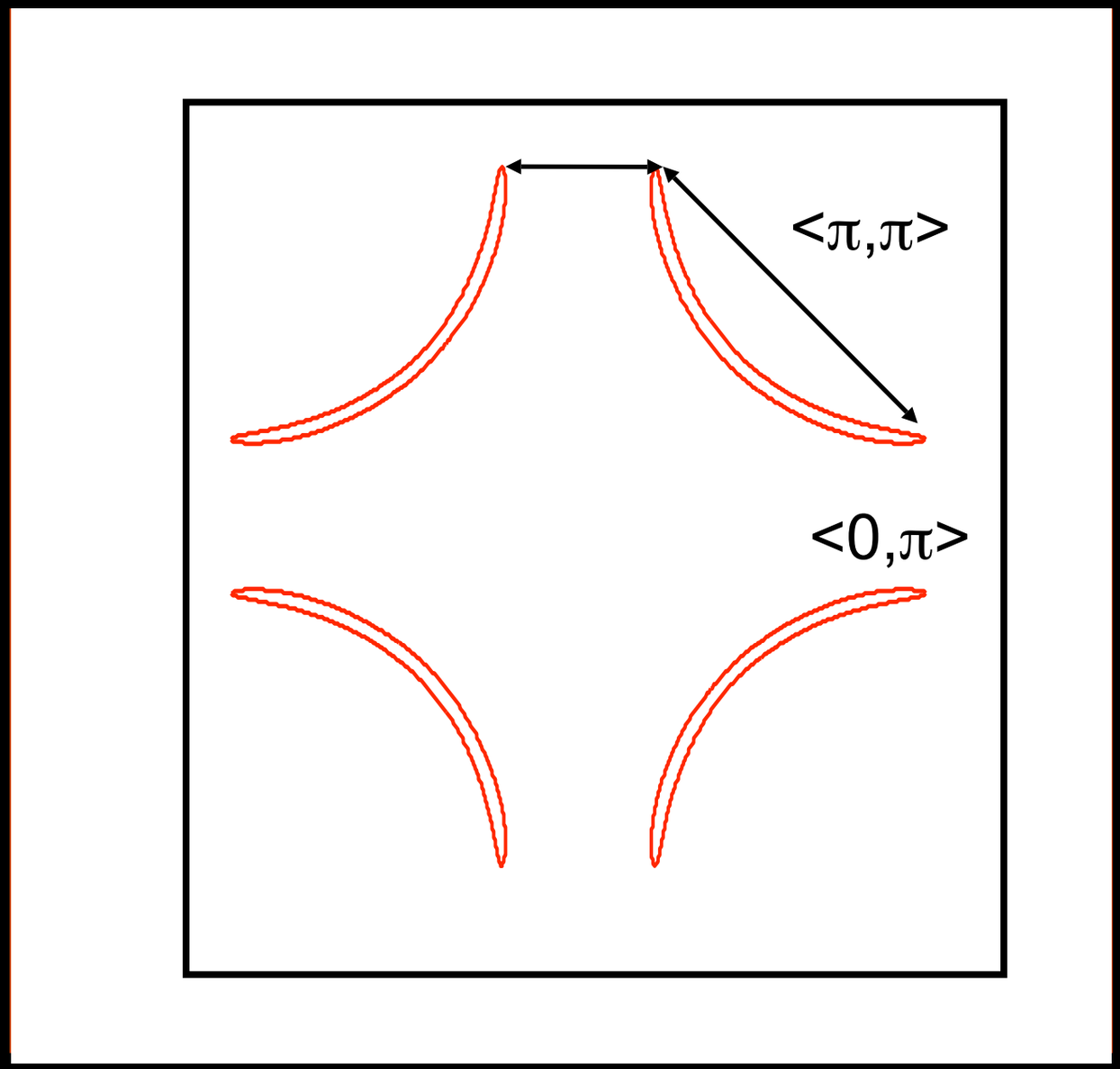
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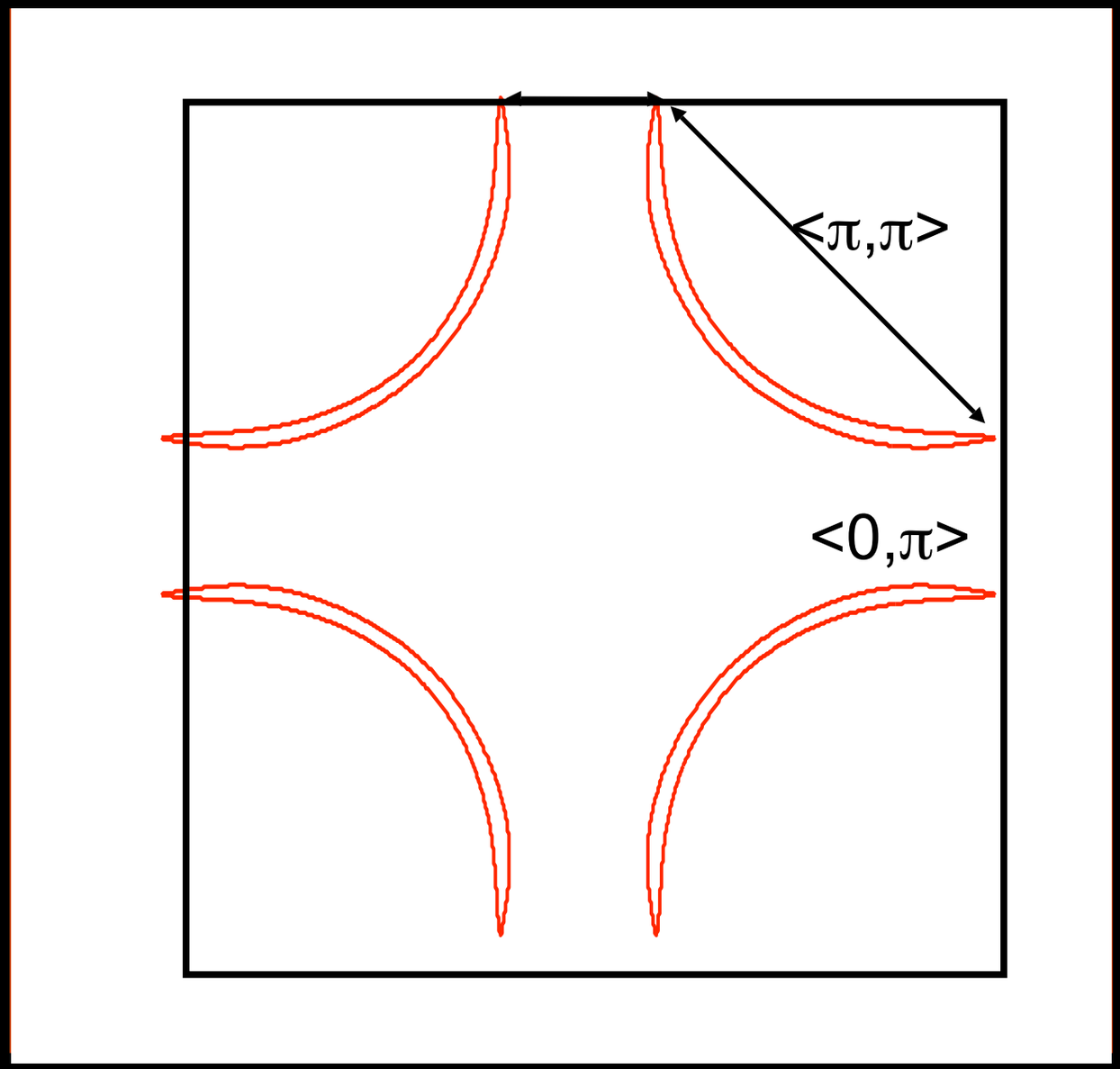
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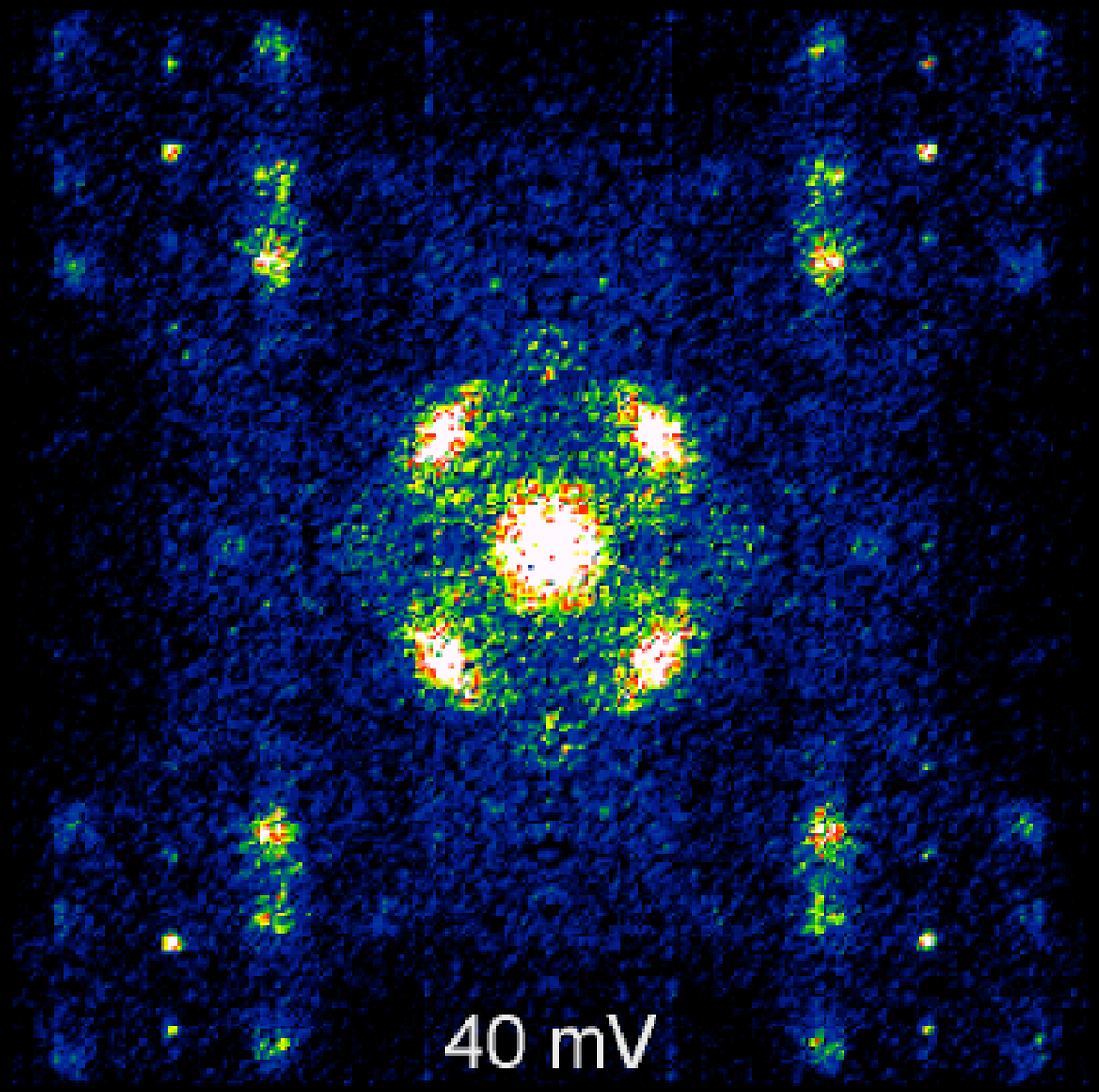
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Scattering between equal energy counters.

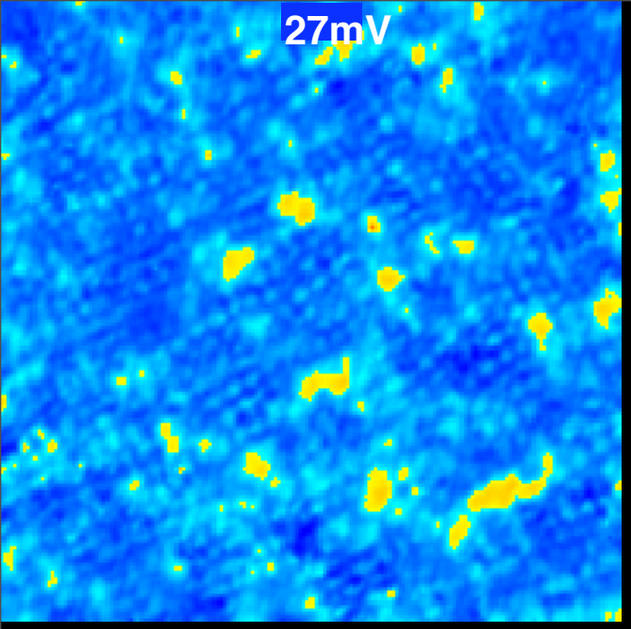
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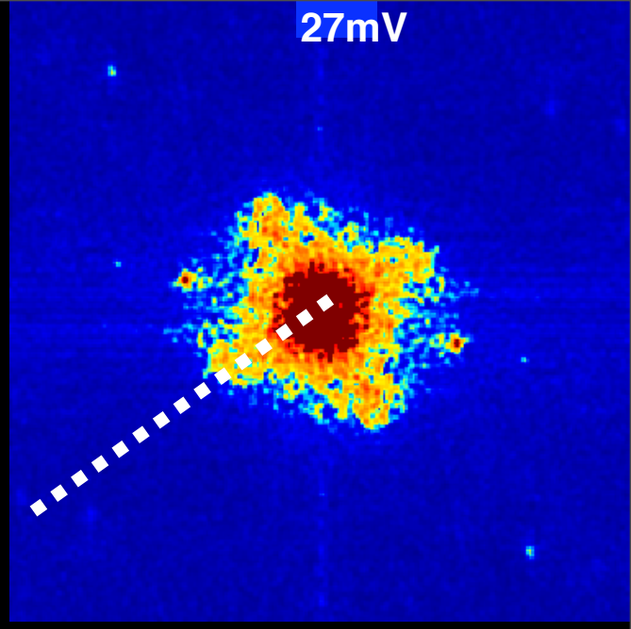
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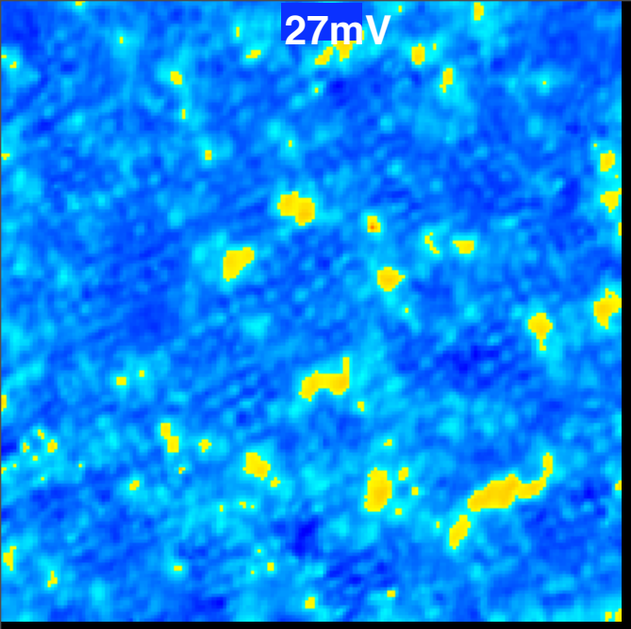
Lower temperatures measurements show more spots

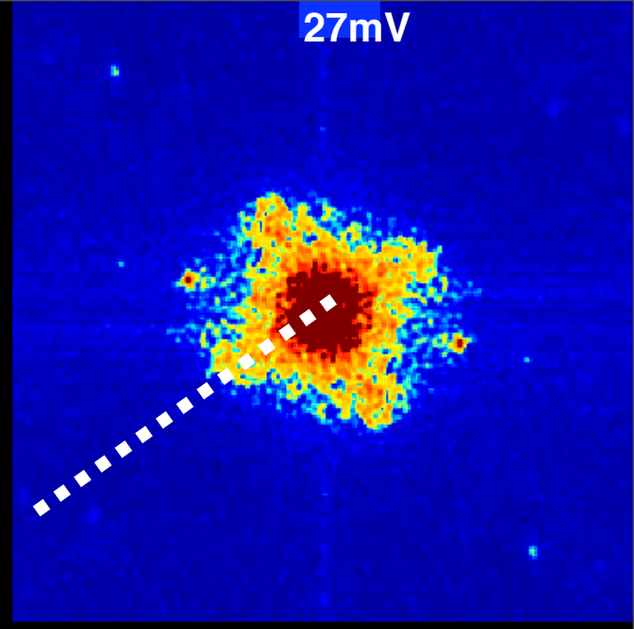


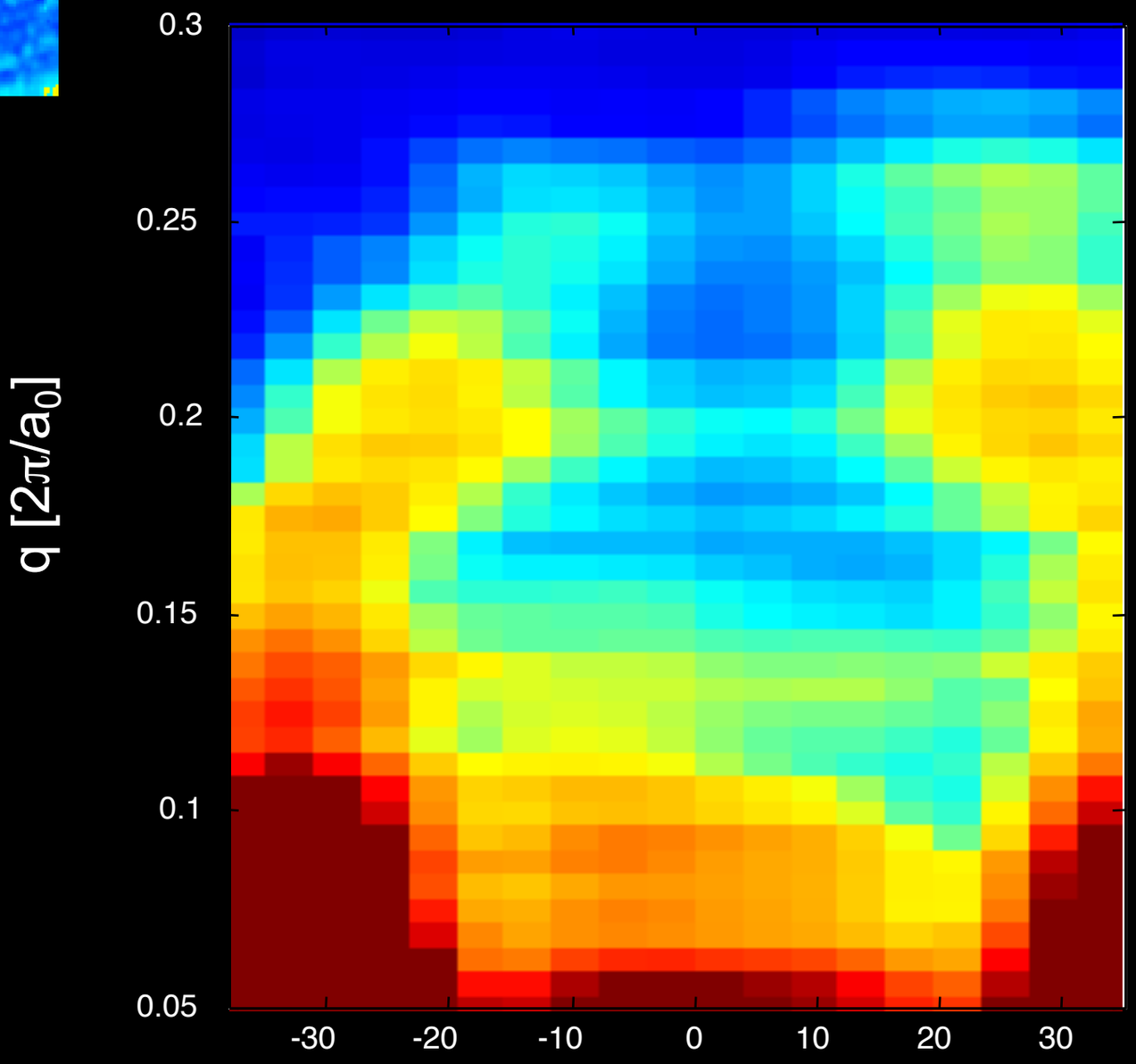
McElroy *et al*, ***Nature 422***, 520 (2003)

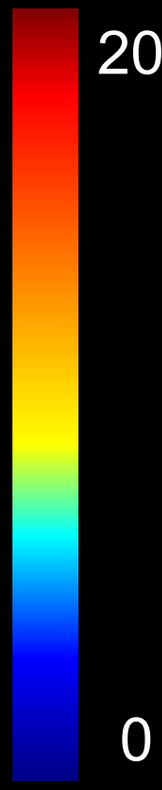

27mV

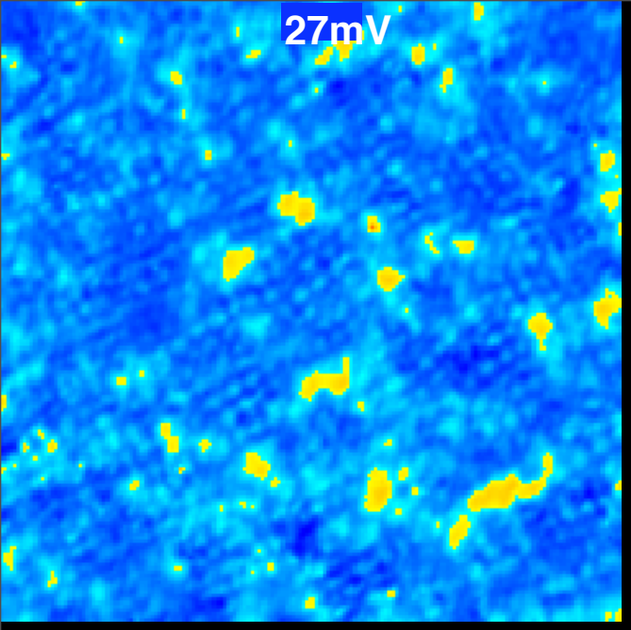

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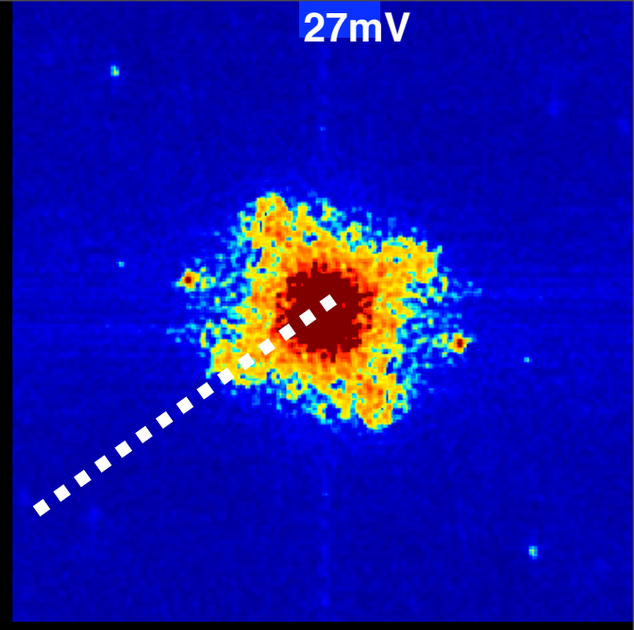

27mV

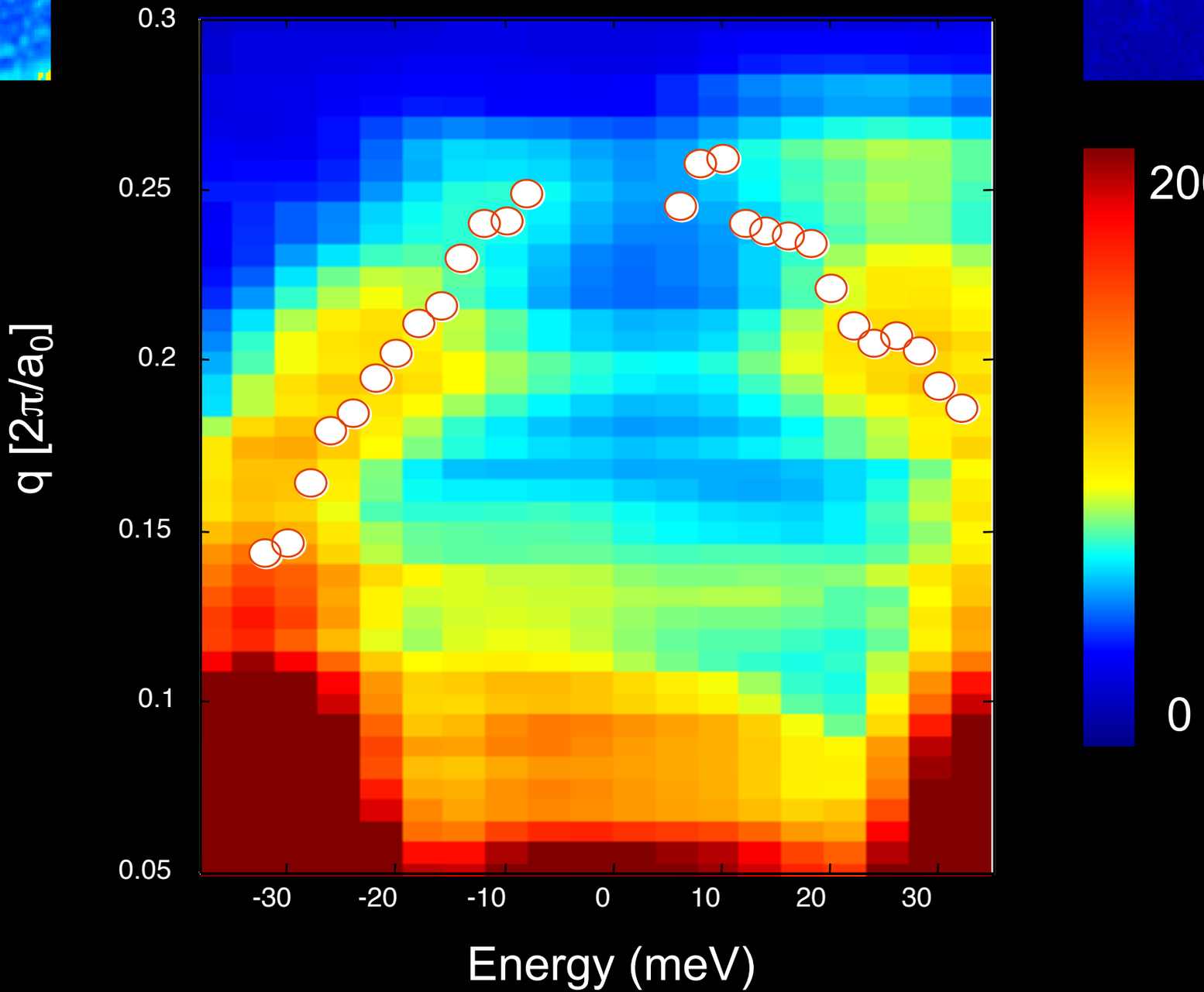

27mV


0.3
0.25
0.2
0.15
0.1
0.05
q [2π/a0]
-30
-20
-10
0
10
20
30
Energy (meV)

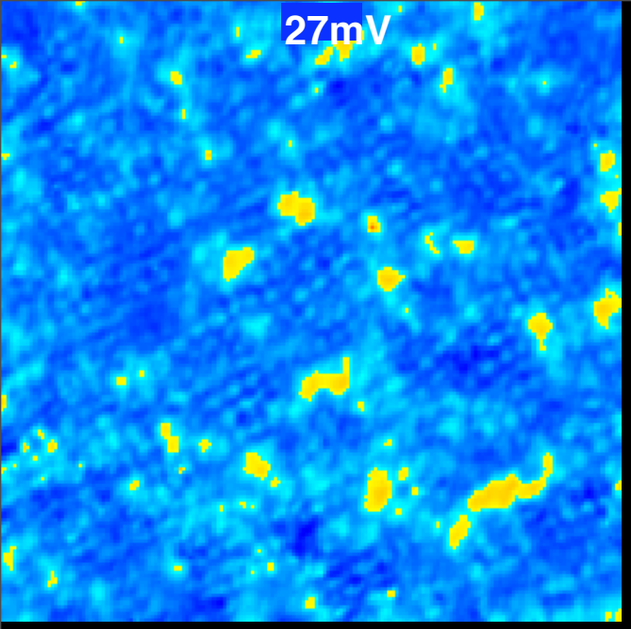

200 ps
0

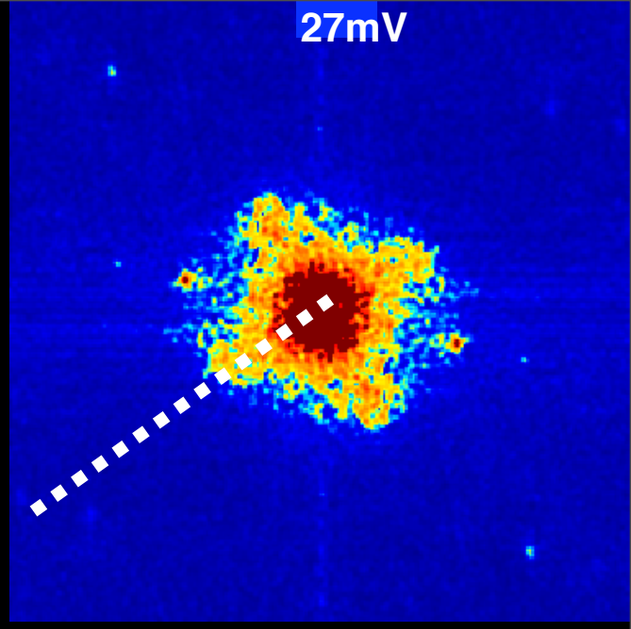


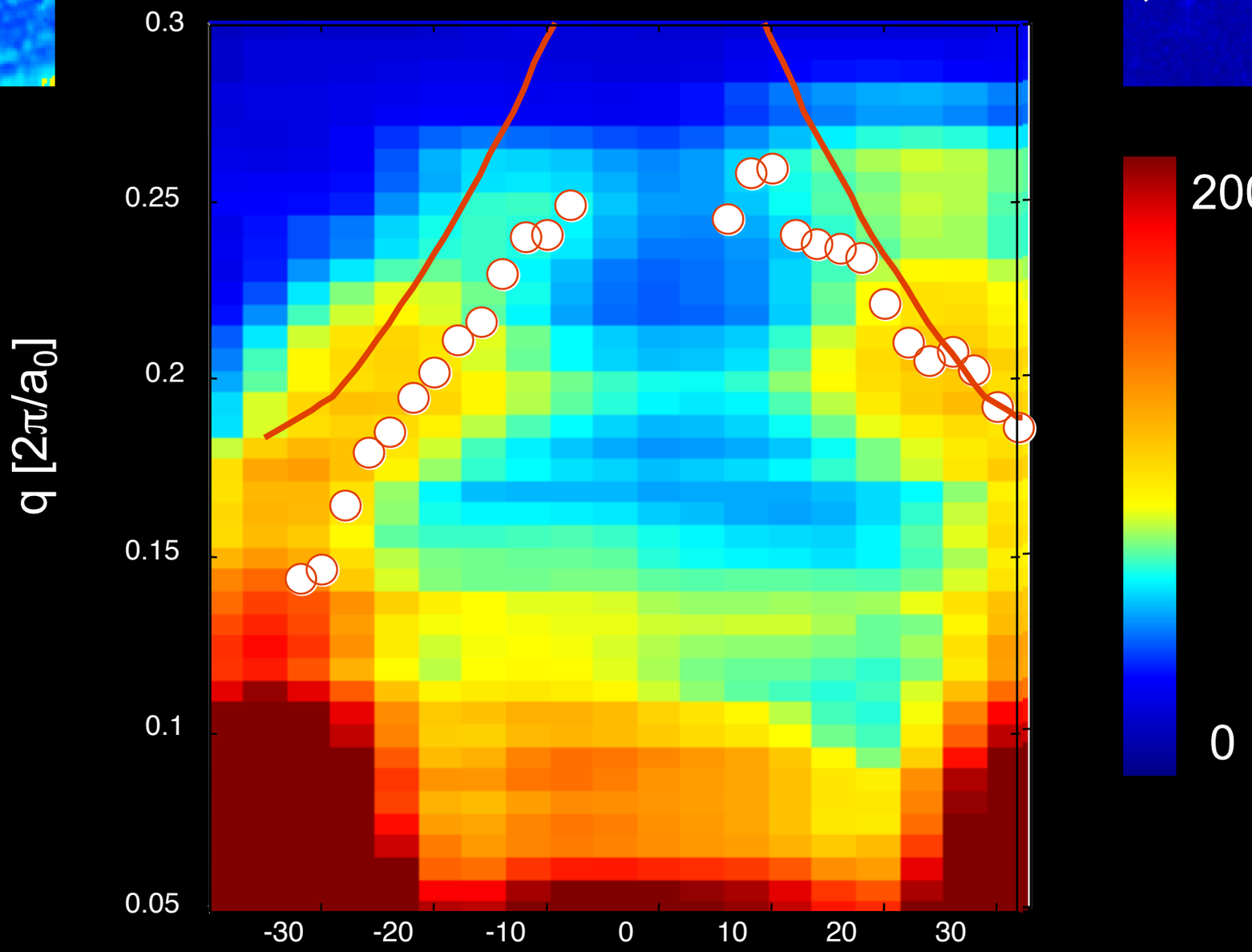




Circle data from Hoffman et al., Science 2002, McElroy et al. Nature 2003 ,Flatte et al. PRL 1993, Q.-H. Wang and D.-H. Lee, PRB 67, 20511 (2003); Howald & Kapitulnik (2002-3)





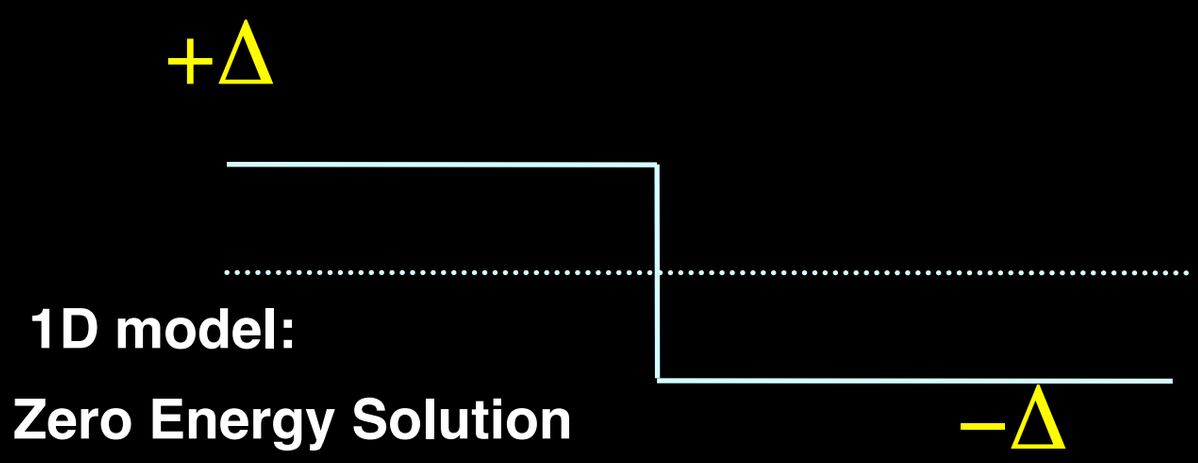


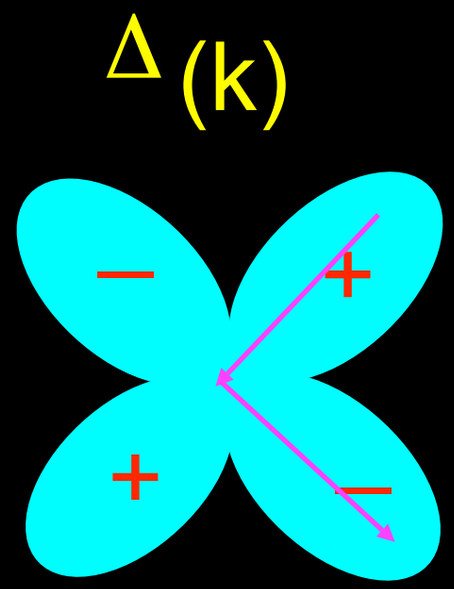
Circle data from Hoffman et al., Science 2002, McElroy et al. Nature 2003 ,Flatte et al. PRL 1993, Q.-H. Wang and D.-H. Lee, PRB 67, 20511 (2003); Howald & Kapitulnik (2002-3)

Local Signature of d-wave Pairing

Nanoscale Signatures of d-wave Pairing in the Cuprates

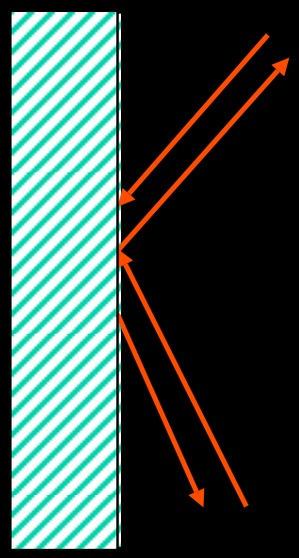
- **Changing Direction in a d-wave: π-phase shift**





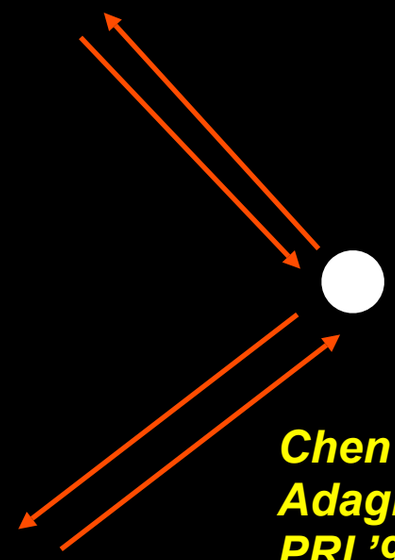
Momentum Space
Variation of Gap

- **Andreev surface bound state**



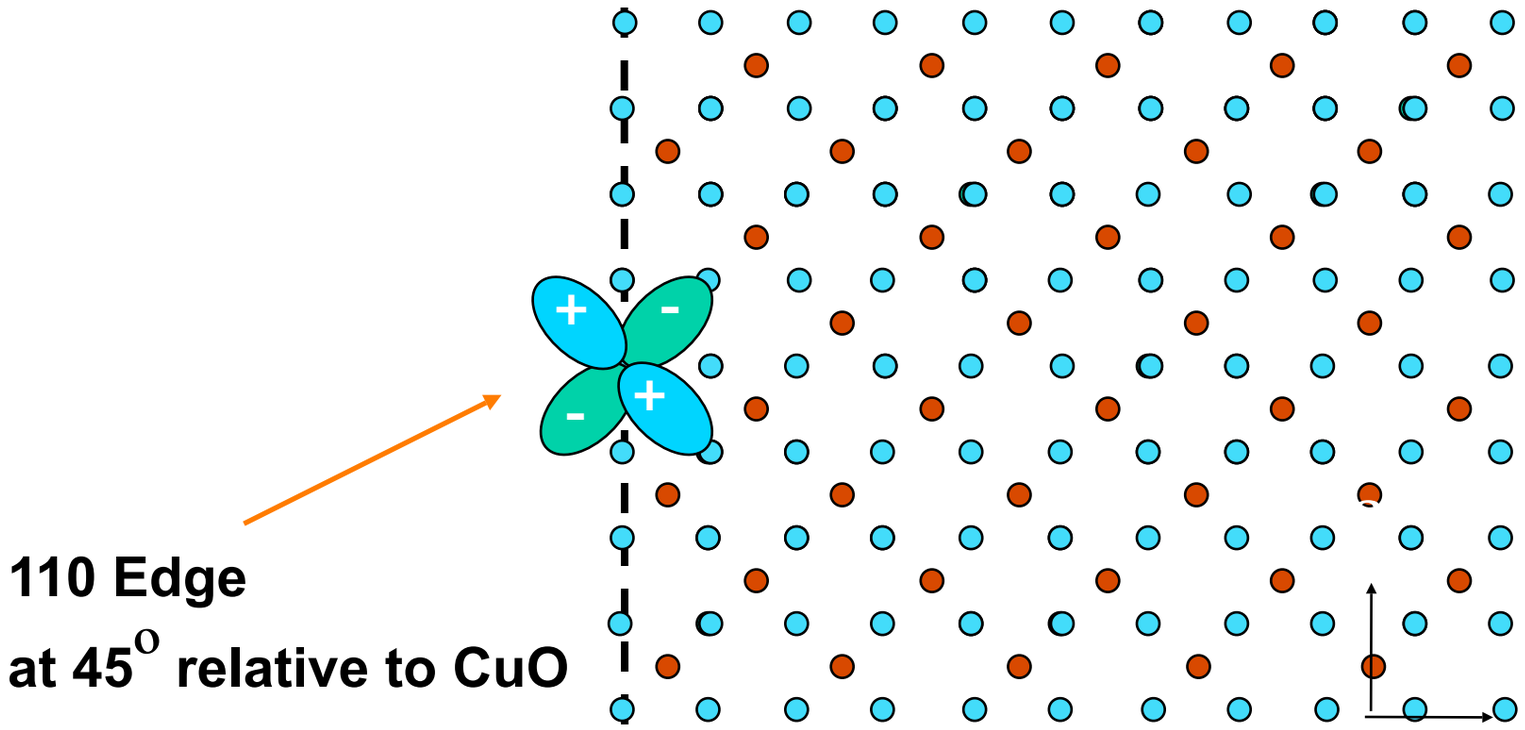
Hu '94,
Tanaka et al. '95,
Covington et al. '97, ….

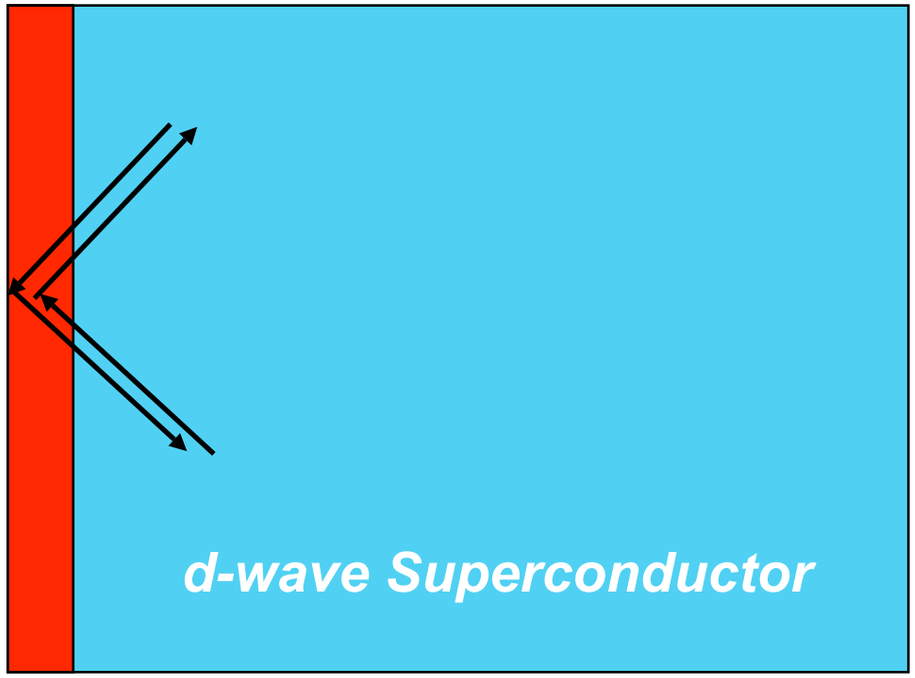
- **At defects structures**



Chen et al. '96,
Adagideli, et al.
PRL'99 (UIUC)

Andreev Bound State at a Surface of a d-wave Superconductor





One dimensional Andreev Bound State appear at $E=E_F$

C. Hu, PRL 72, 1526 (1994)

Y. Tanaka et al. (1995)

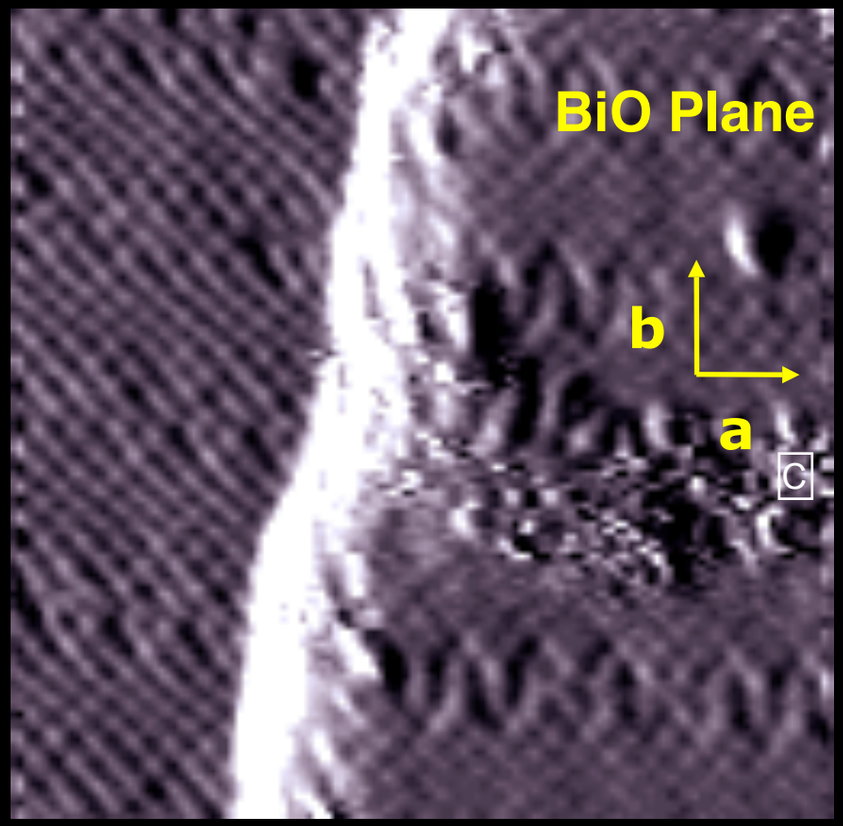
M. Covington *et al.*, PRL 79, 277 (1997)

D. Morr and E. Demler, cond-mat/ 0010460

One Dimensional Andreev Bound State at the Edge of a *d-wave*

T<<<Tc

100Å x 100Å



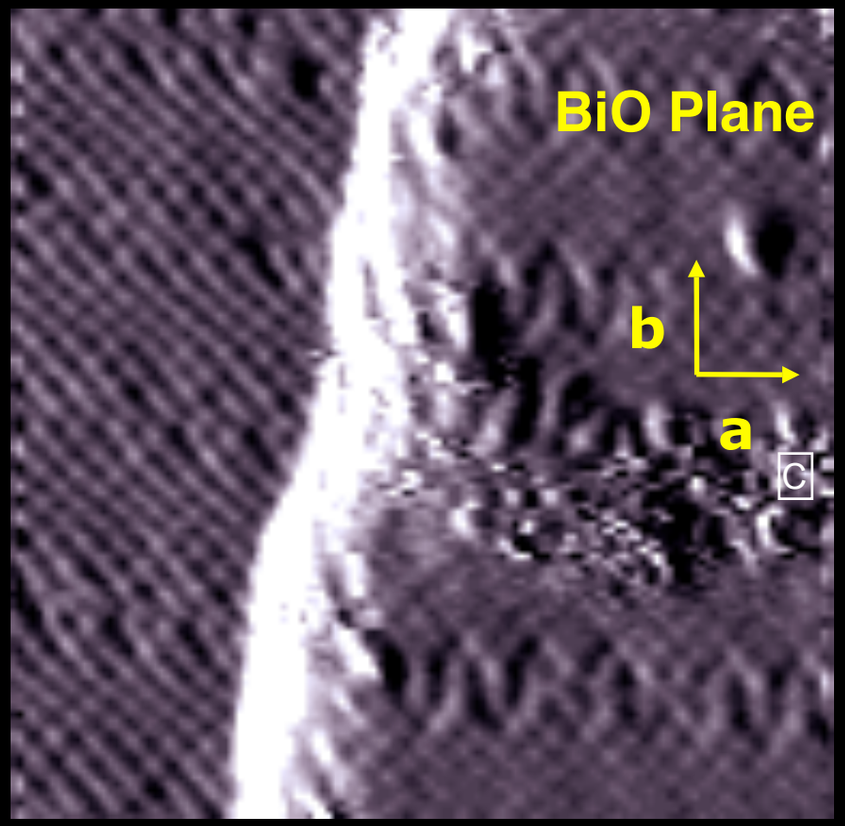
Low **High**

Step edge

One Dimensional Andreev Bound State at the Edge of a *d-wave*

T<<<Tc

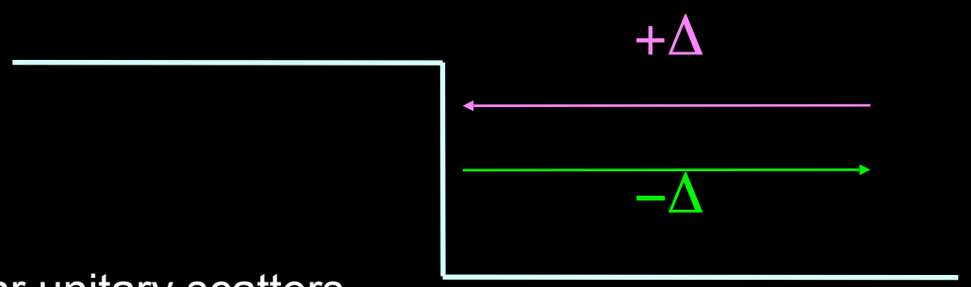
100Å x 100Å



Low **High**

Step edge

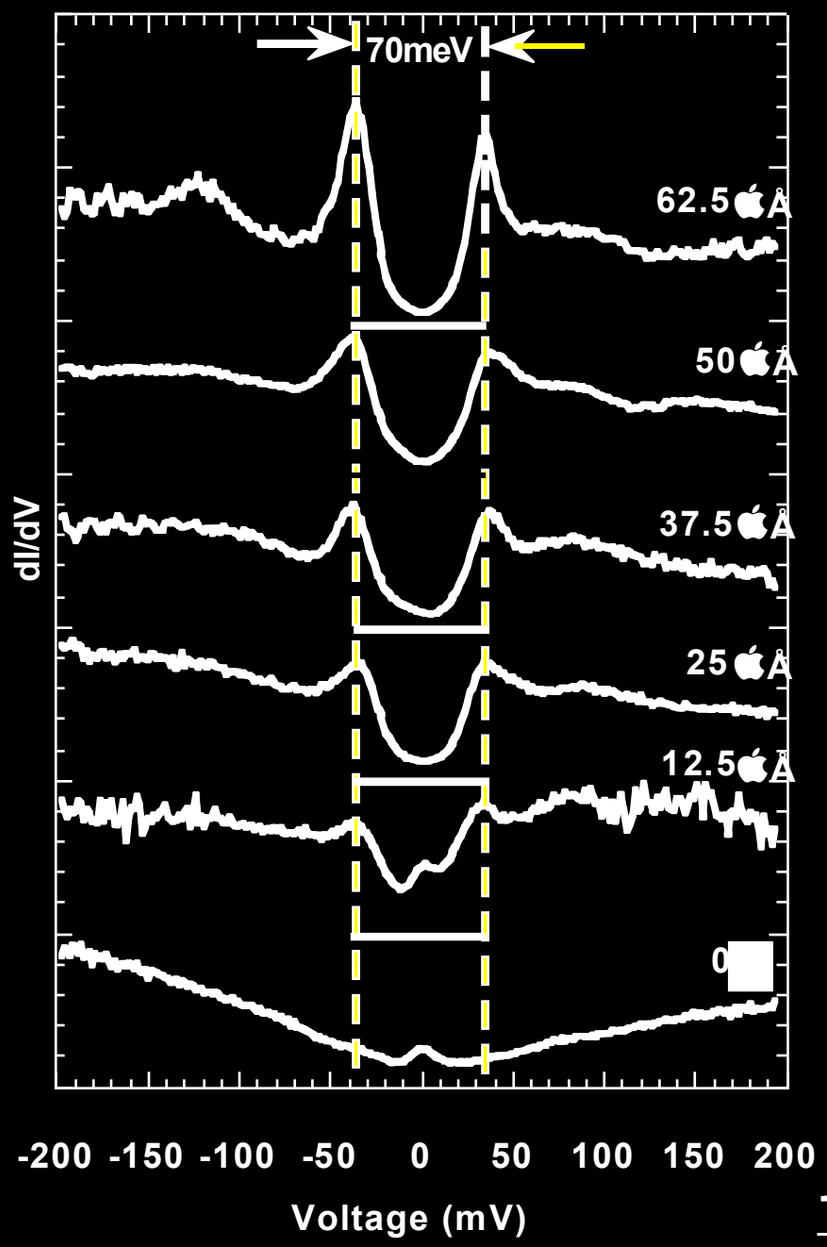
1D model: Zero Energy Solution



S. Misra *et al.* PRB RC 2002

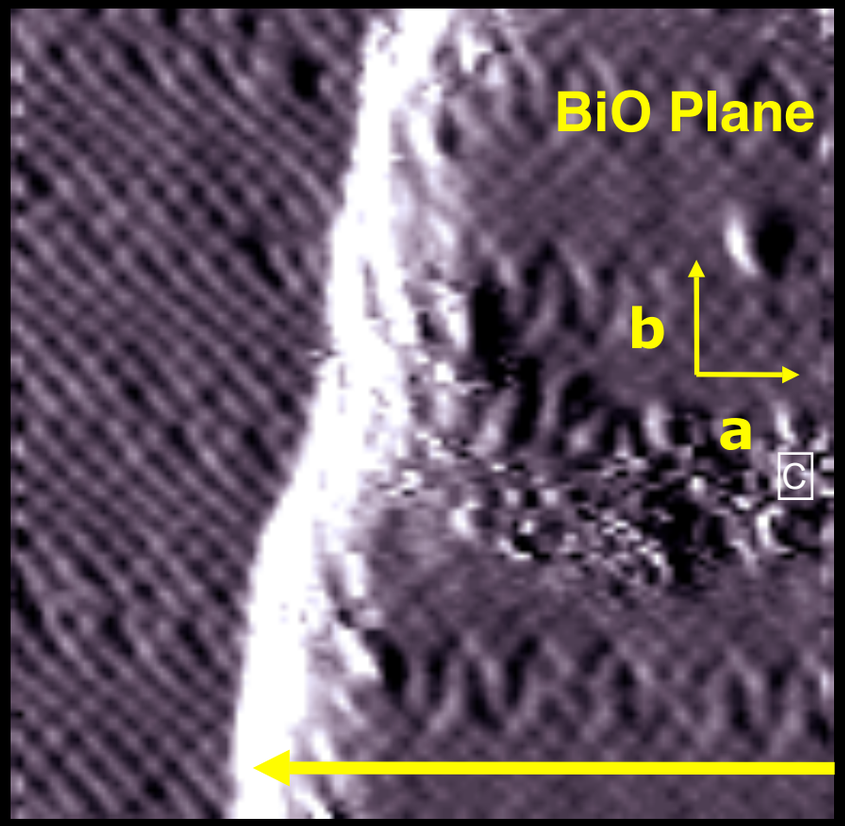
Similar zero-dimensional phenomena near unitary scatters

One Dimensional Andreev Bound State at the Edge of a *d-wave*

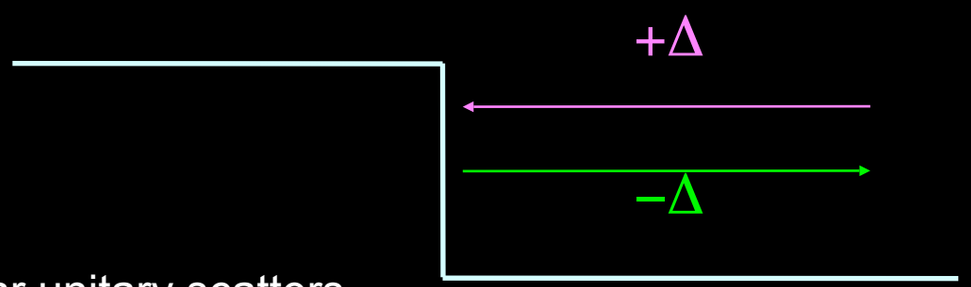


T<<<Tc

100Å x 100Å



1D model: Zero Energy Solution

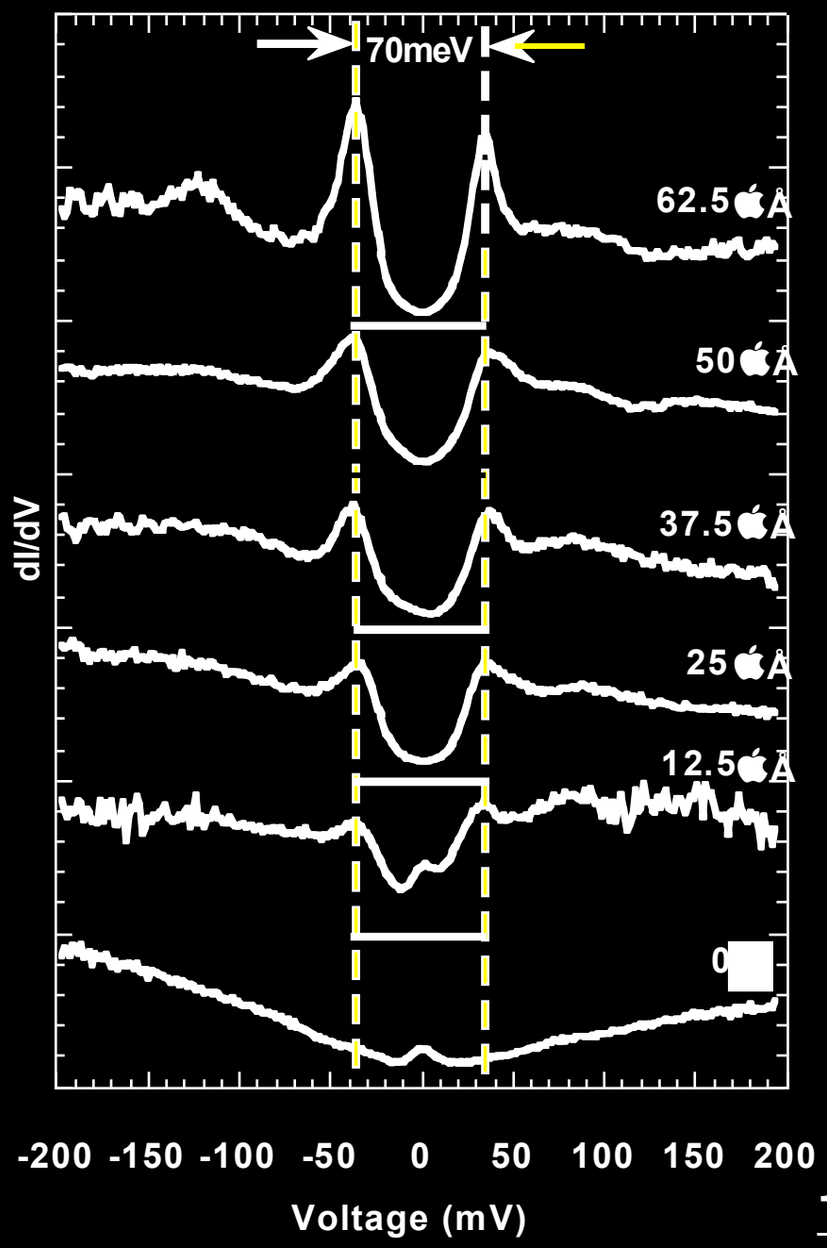


S. Misra *et al.* PRB RC 2002

Similar zero-dimensional phenomena near unitary scatters

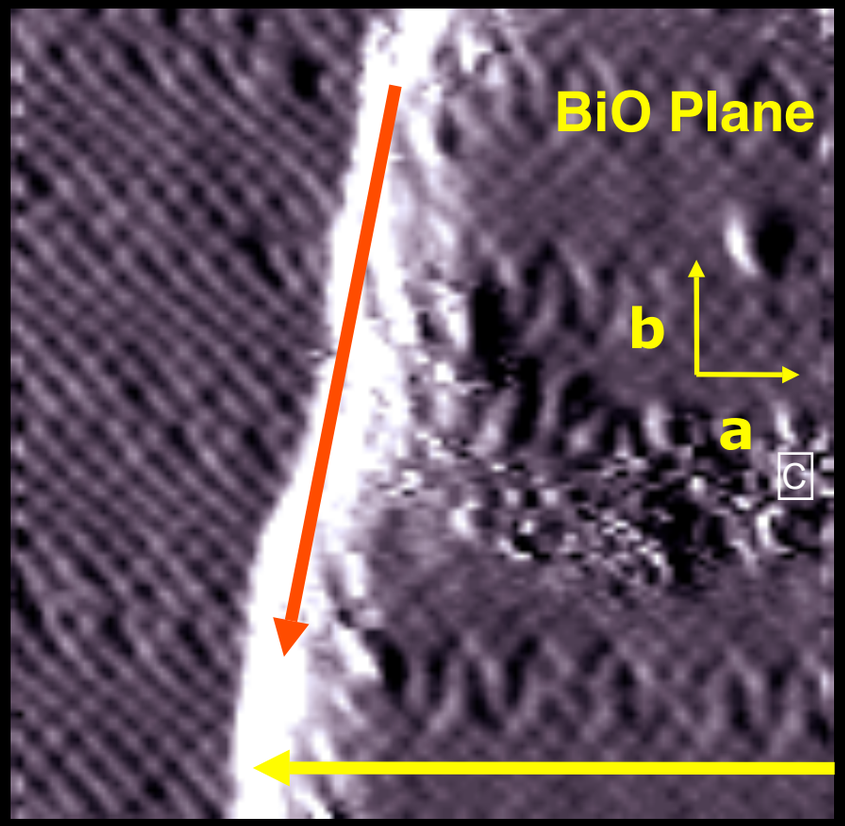
One Dimensional Andreev Bound State at the Edge of a *d-wave*

Spectra to the step

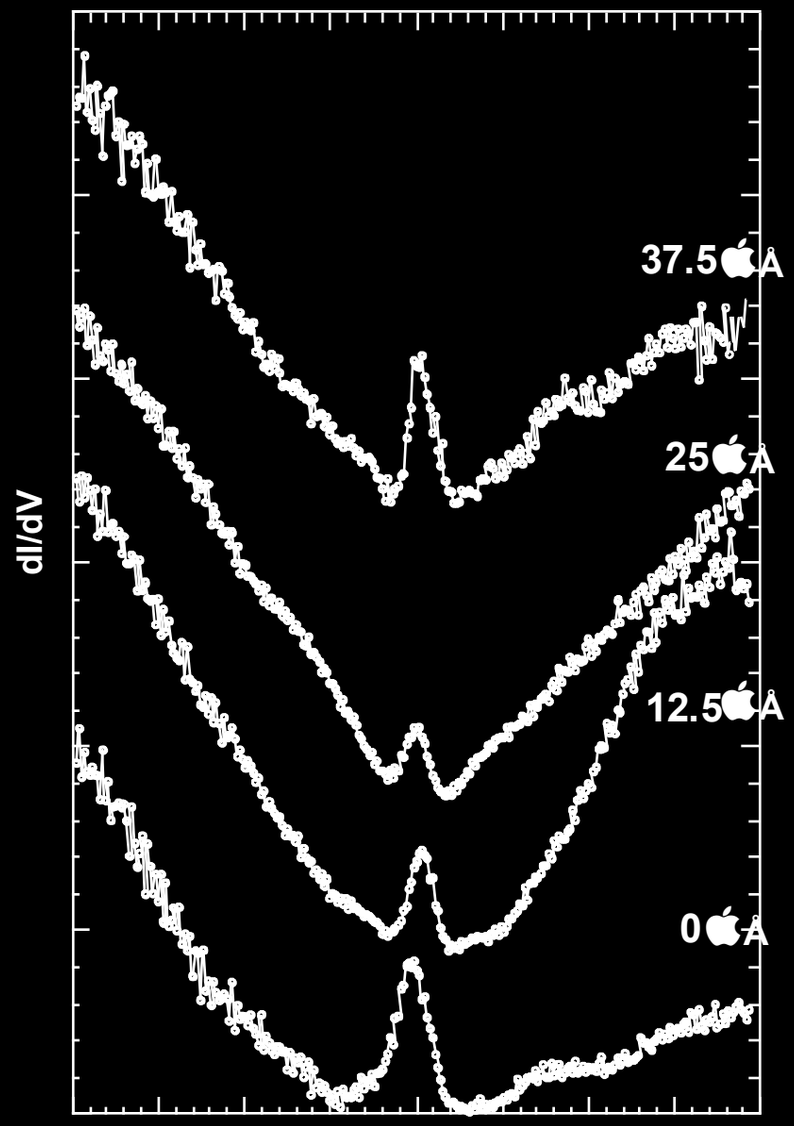


T<<<Tc

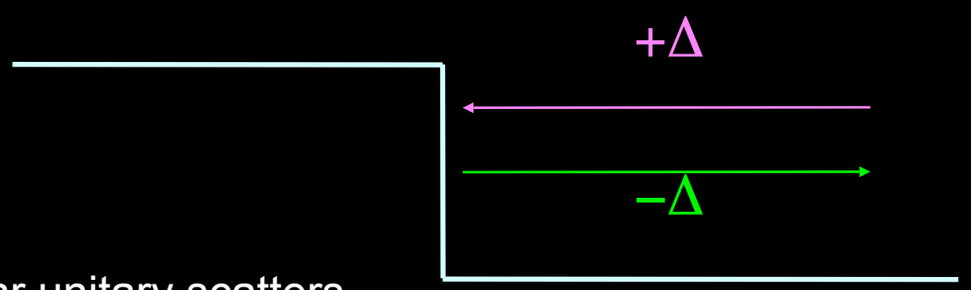
100Å x 100Å



Spectra to the step



1D model: Zero Energy Solution



S. Misra *et al.* PRB RC 2002

Similar zero-dimensional phenomena near unitary scatters

Impurity Induced Resonance in a d-wave Superconductor

Applying Shiba's Work to d-wave:

Balatsky et al. 1995, Salkola et al. 1996,

Flatte and Byers '98

- **Energy**

$$\Omega_0 \approx \frac{\Delta_0}{2UN_F(\ln 8UN_F)}$$

- **Width**

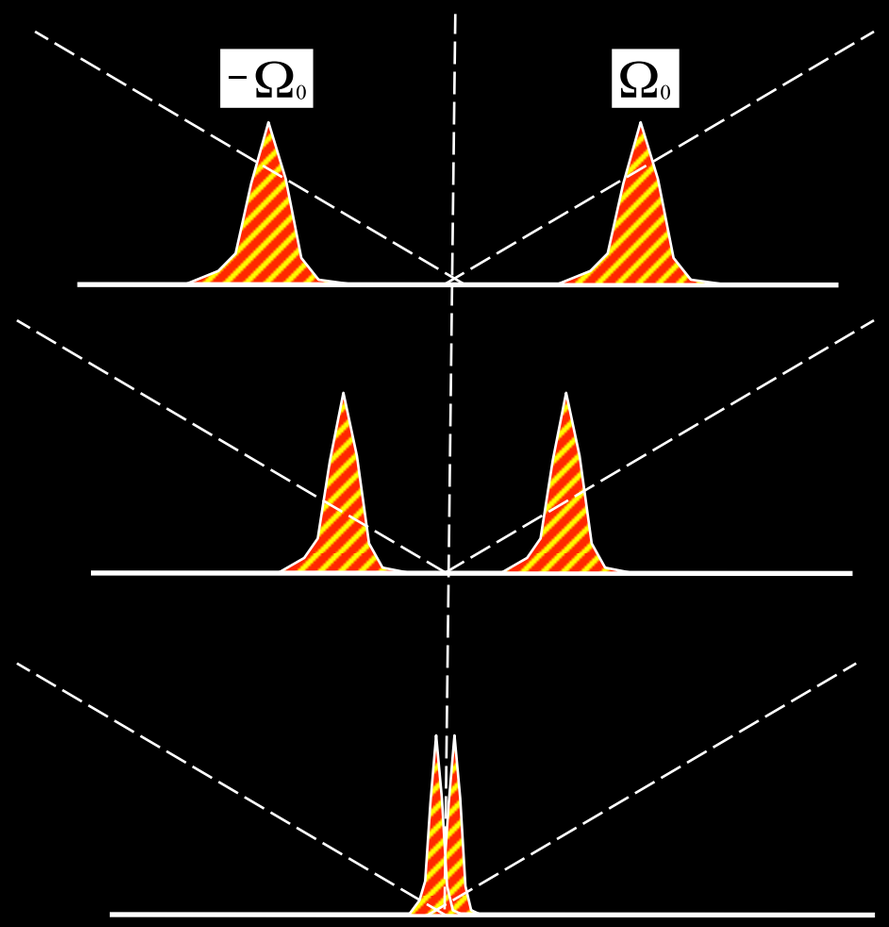
$$\Gamma \approx \frac{\pi\Omega_0}{2(\ln 8UN_F)}$$

- **Strong scattering limit:**

$$U \to \infty$$

$$\Omega_0 \to 0$$

$$\Gamma_0 \to 0$$



Simple Picture: Without e-h asymmetry
Resonance induced by nonmagnetic impurity

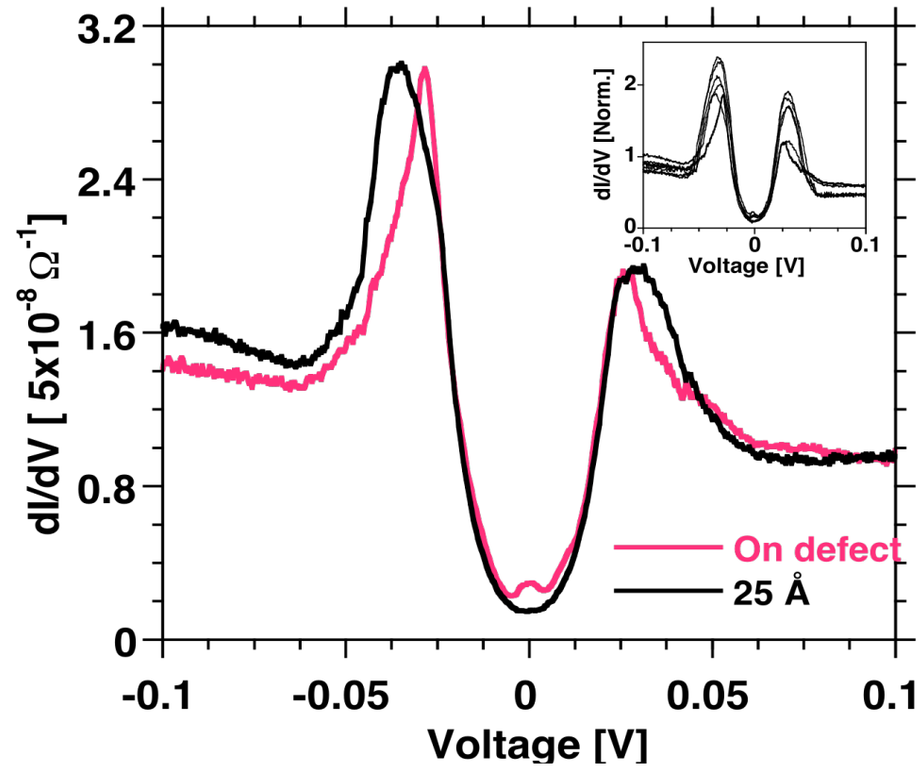
See Review by Balatsky et al.
arXiv:cond-mat/0409474

Defect Scattering on the BiO Surface:

Native Defects

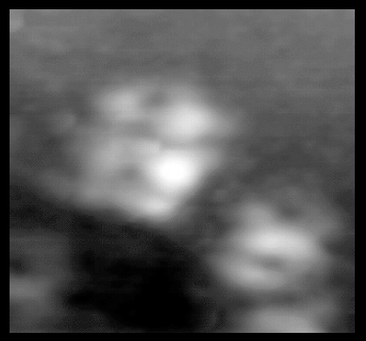
A. Yazdani *et al.* PRL 1999

Similar data by
Hudson *et al.* Science 1999



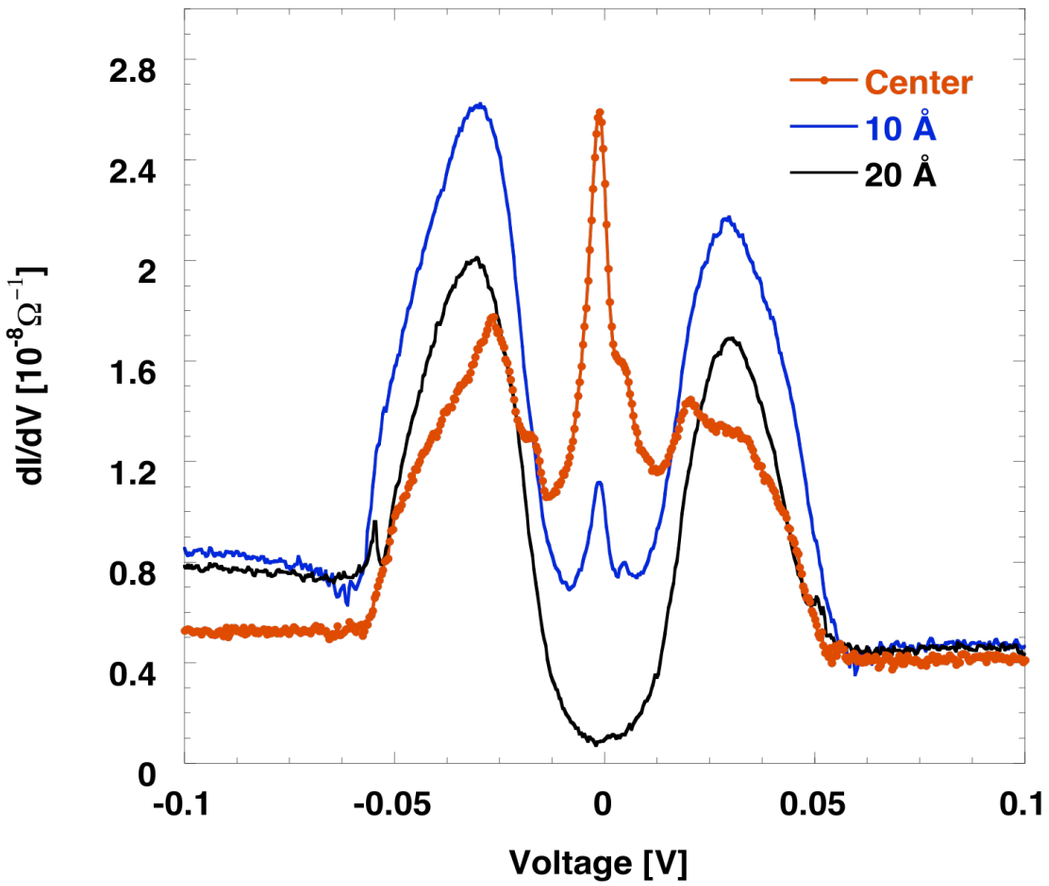
Local Density of States Near an Atomic Scale Defect

Au defects on BiO



36Å x 36Å

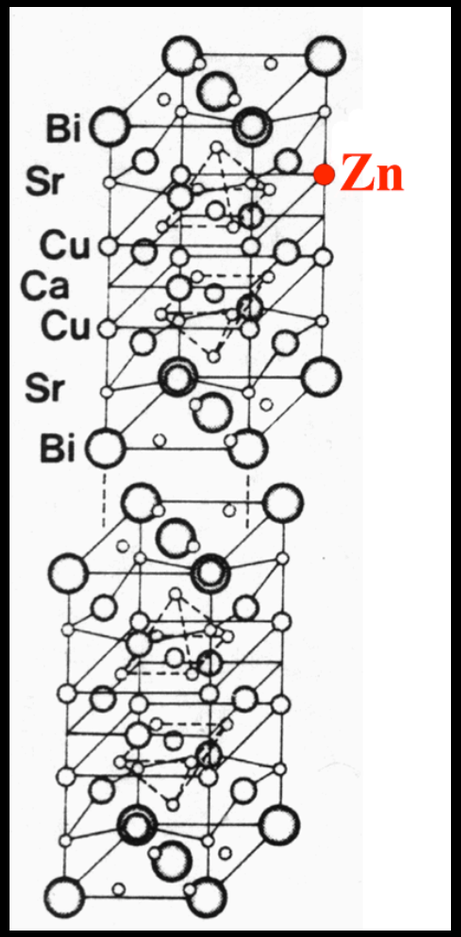
A. Yazdani *et al.* PRL 1999

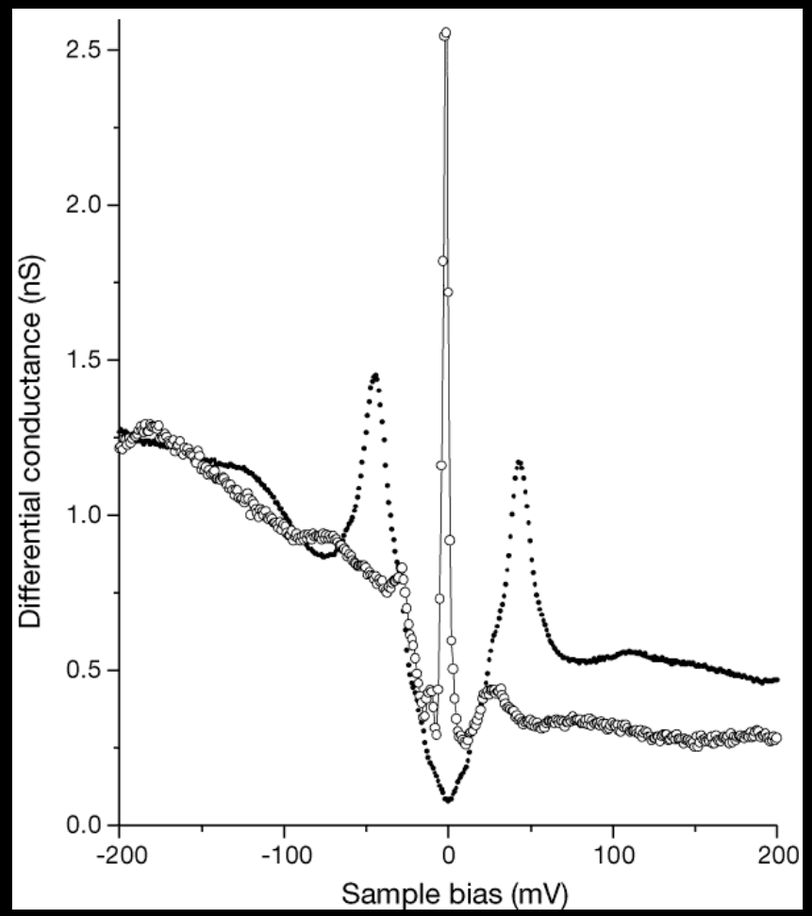


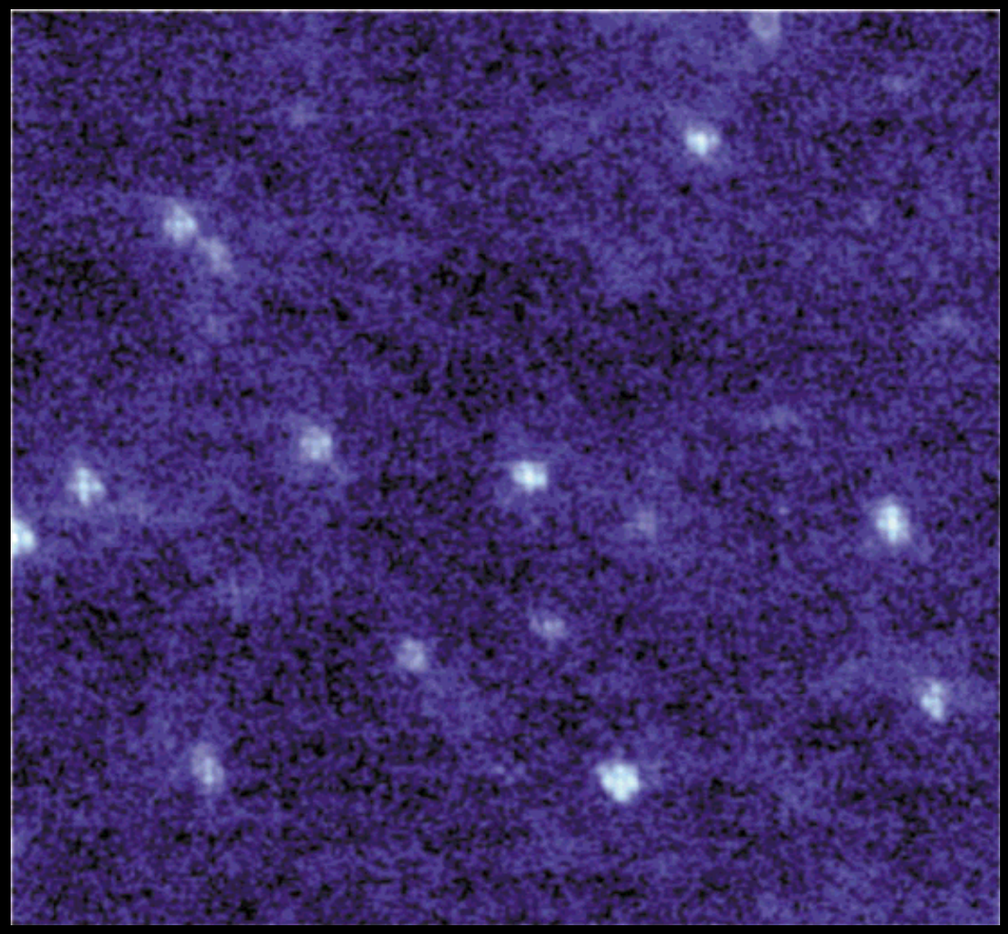
Effect of Zn-impurity on the Superconducting State

DATA FROM: S. H. Pan *et. al.* , *Nature*, **403**, 746, (2000)

Map of DOS at V=0 (Fermi level)







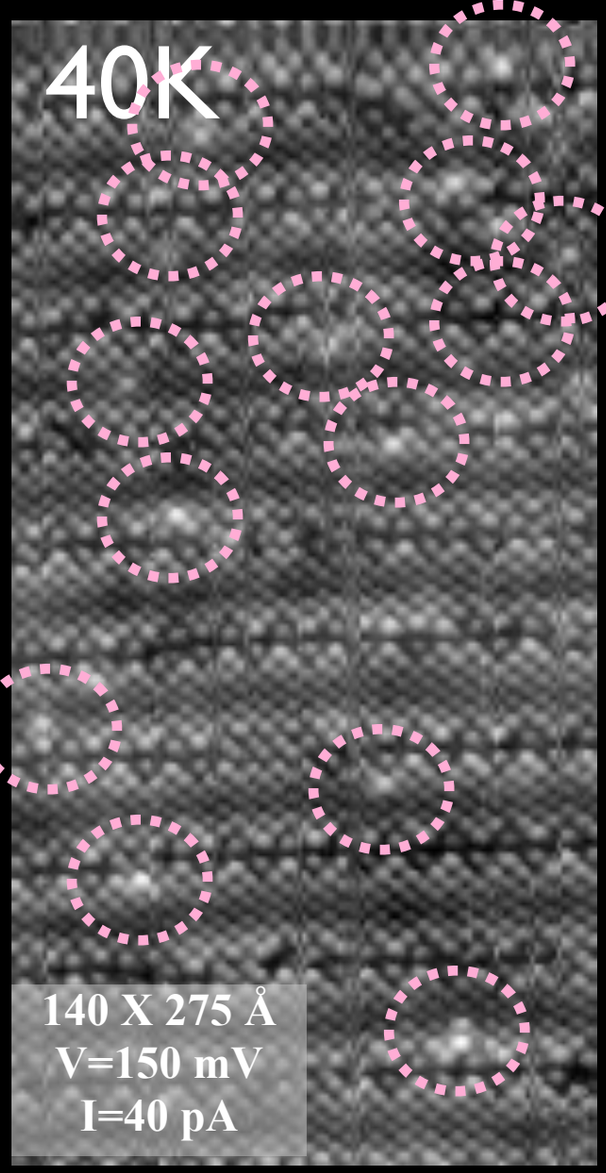
500Å x 500Å

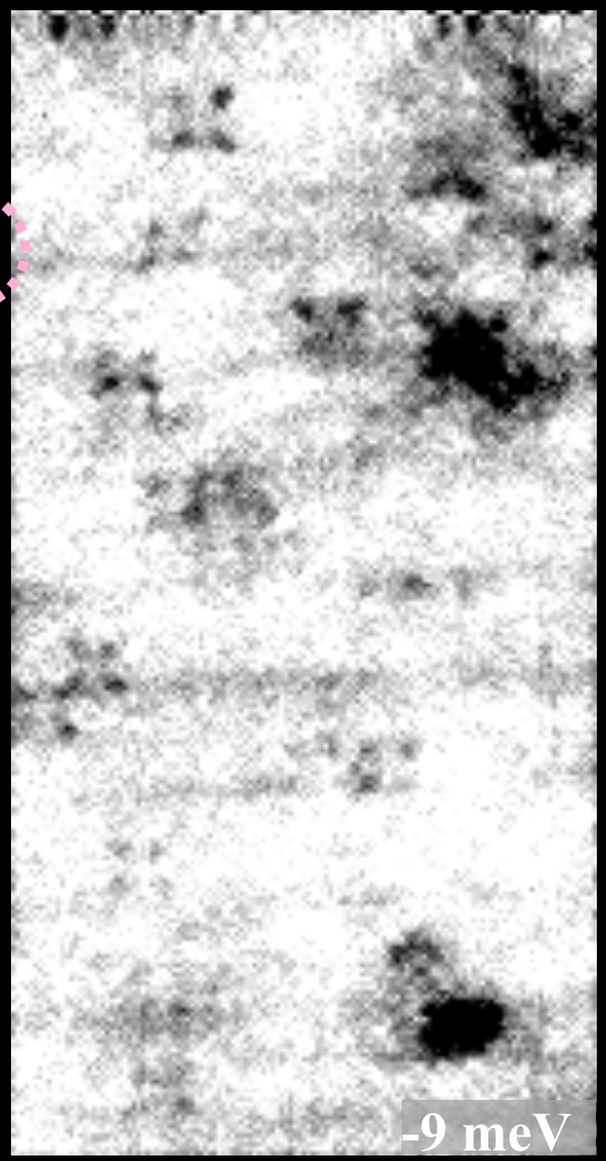
Spectroscopy on/off the Zn dopent

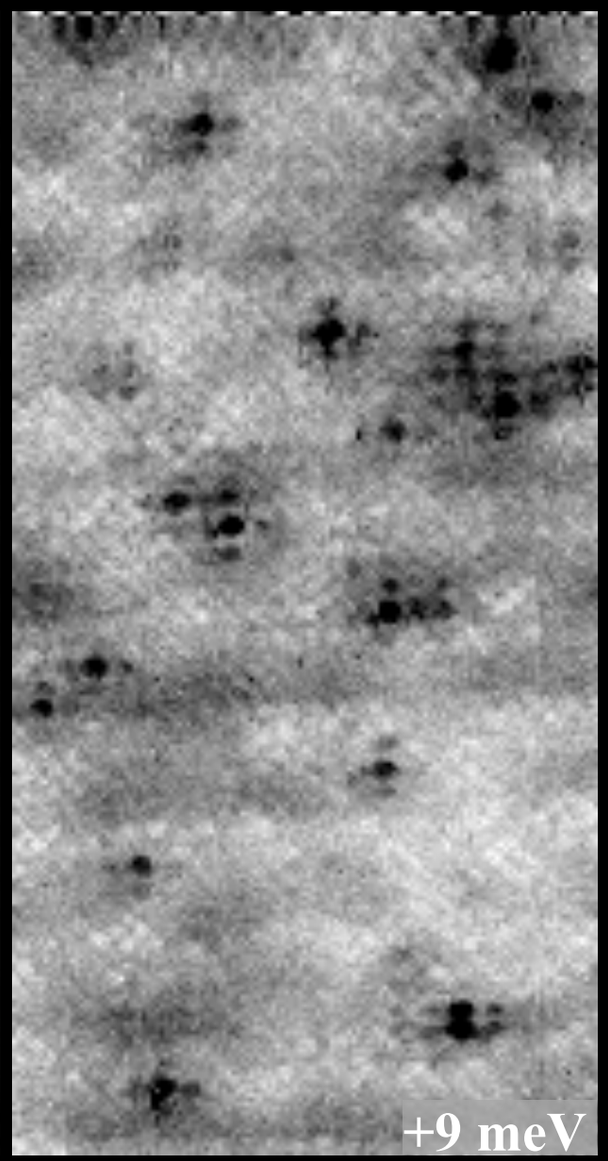
- ***Zn replaces the Cu atoms and kills Tc.***
- ***Missing Cu: At Zn site NMR experiments (normal state) see a local magnetic moment***
- ***Various models: Resonant scattering, Kondo scattering,..***

Ni Impurities as a marker for local superconductivity

- ✓ Ni produces a low energy Shiba state--with d-wave symmetry (Hudson et al. 2001)
- ✓ Bound states are spatially asymmetric with respect of electrons and hole excitations





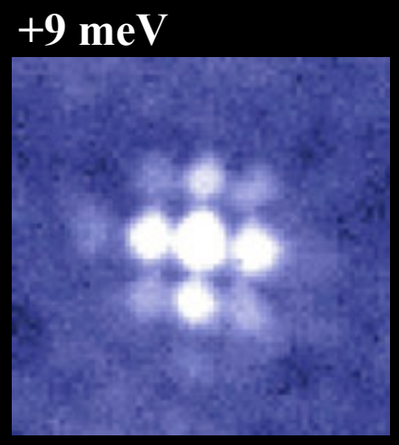


40 pS



200 pS

4K



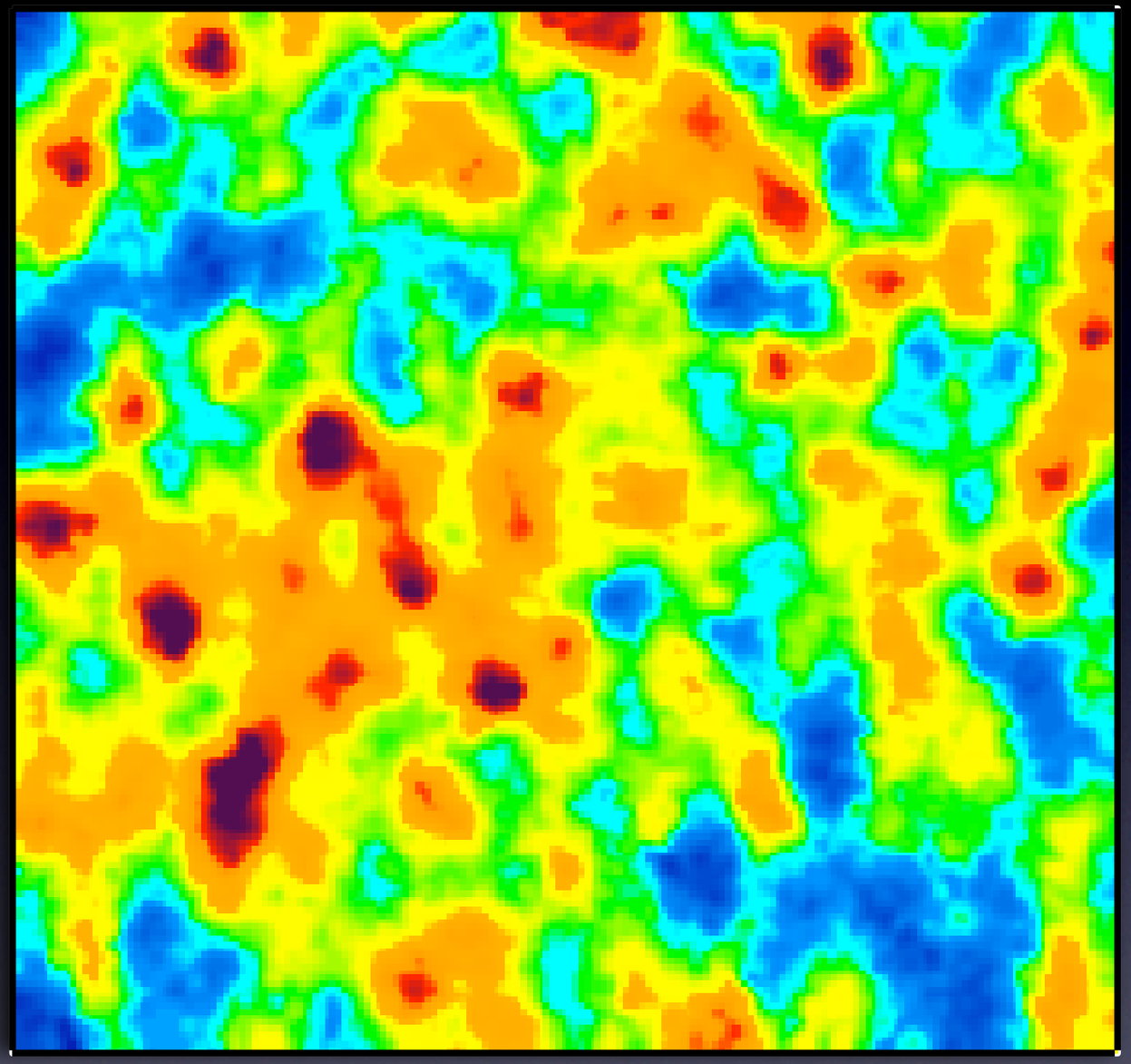
Hudson *et al.*,
Nature **411**, 920 (2001)

Questions:

- When do pairs form?
- Are there bosonic excitations that couple to electrons?
- What controls the pairing strength?

Inhomogeneous Gaps

300 Å x 300 Å



Δ(mV)

18mV

38mV

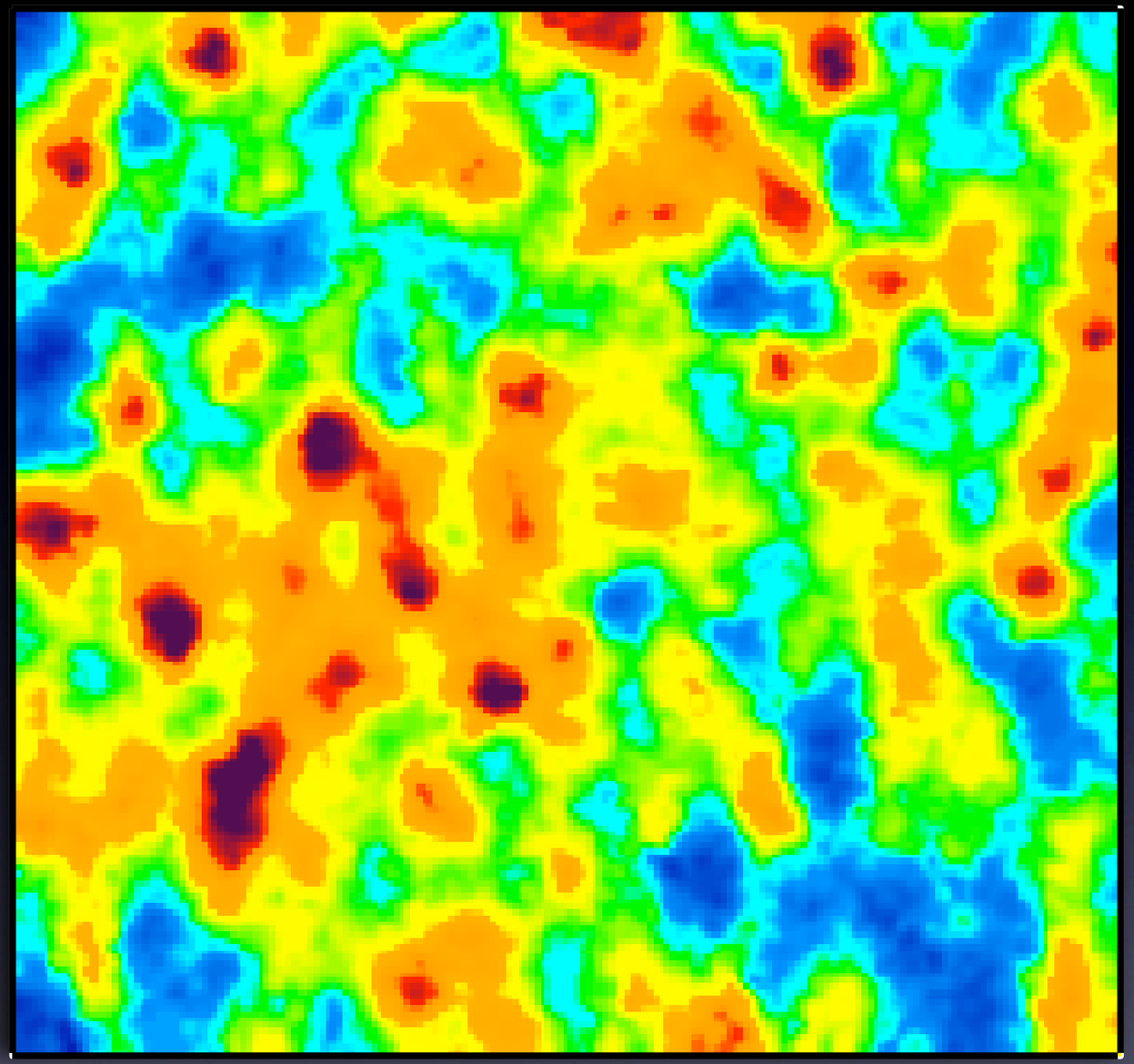
overdoped sample

T< Tc (T=30K, Tc=68K)

Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik

Inhomogeneous Gaps

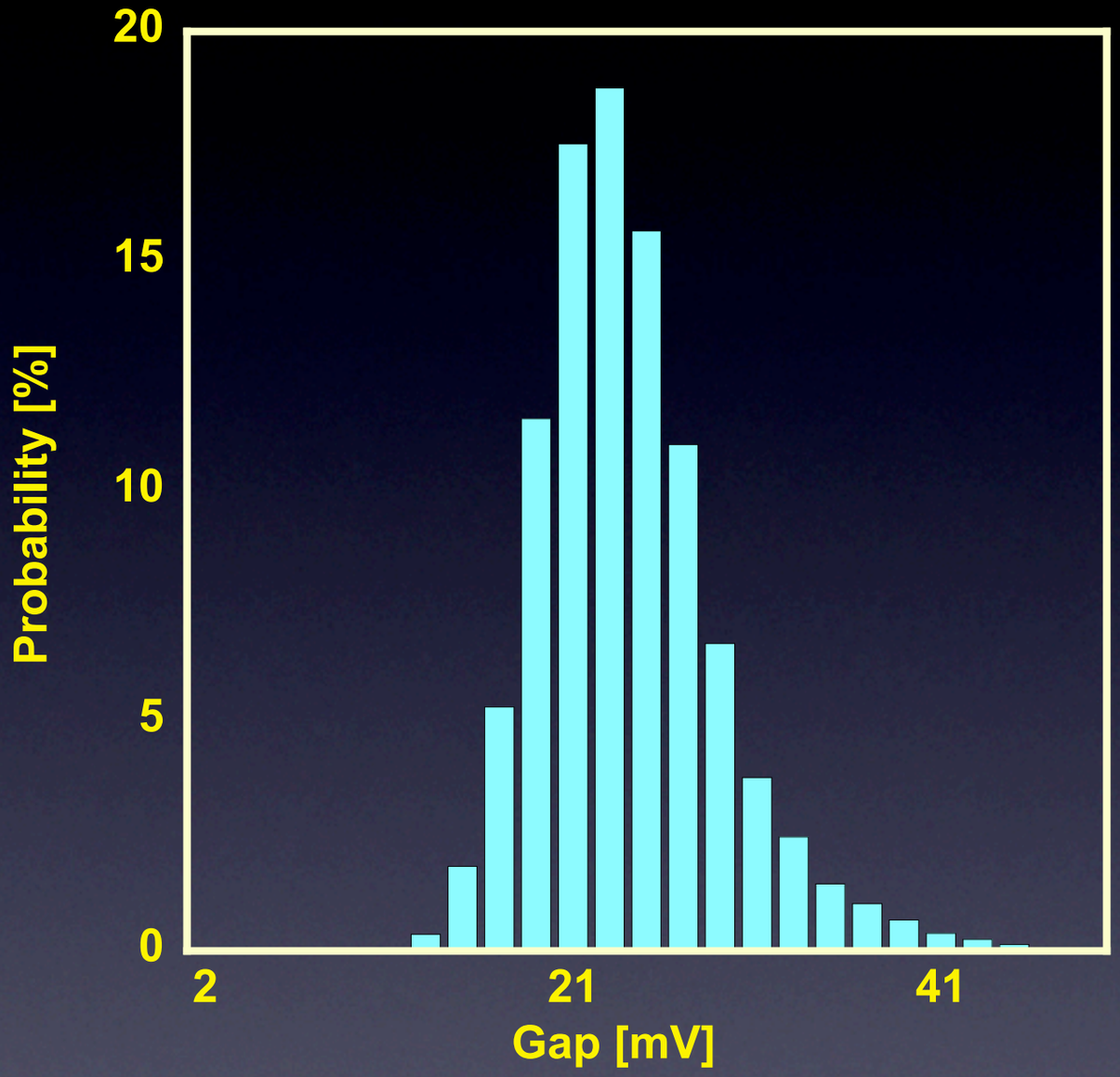
300 Å x 300 Å



Δ(mV)

18mV

38mV



overdoped sample

T< Tc (T=30K, Tc=68K)

Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik

What happens with increasing temperature?

Temperature

Ant-Ferromagnetic

Pseudogap "Phase"

Fluctuating Superconductor

Superconductor

Normal Metal ?

5%

12.5%

16%

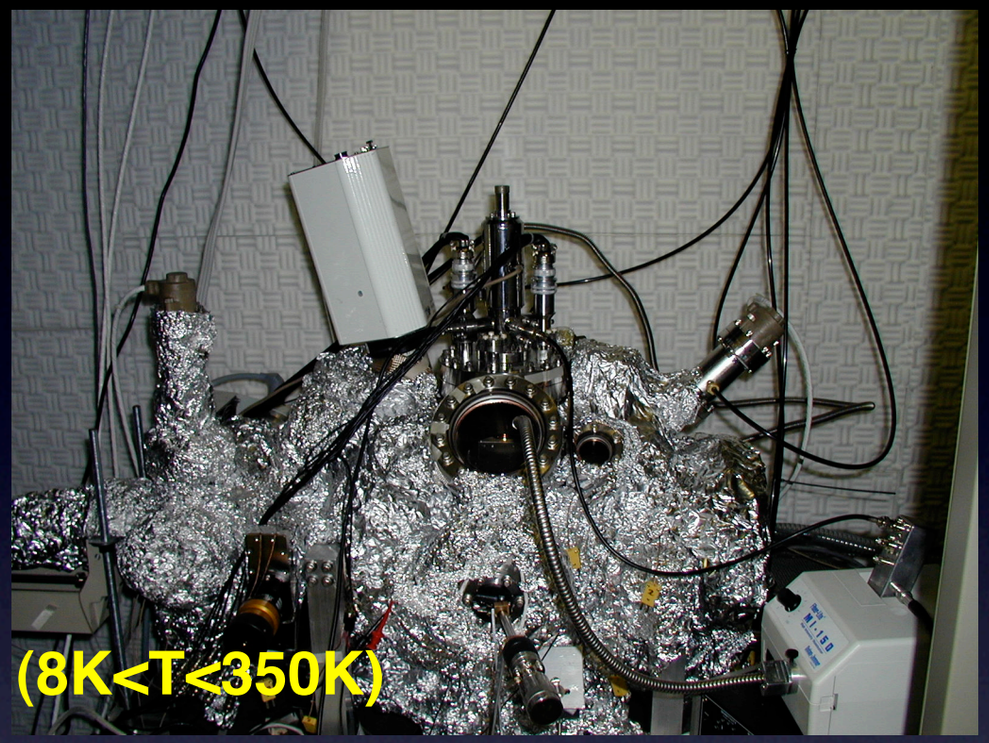
30%

Disordered Magnetism & Stripes

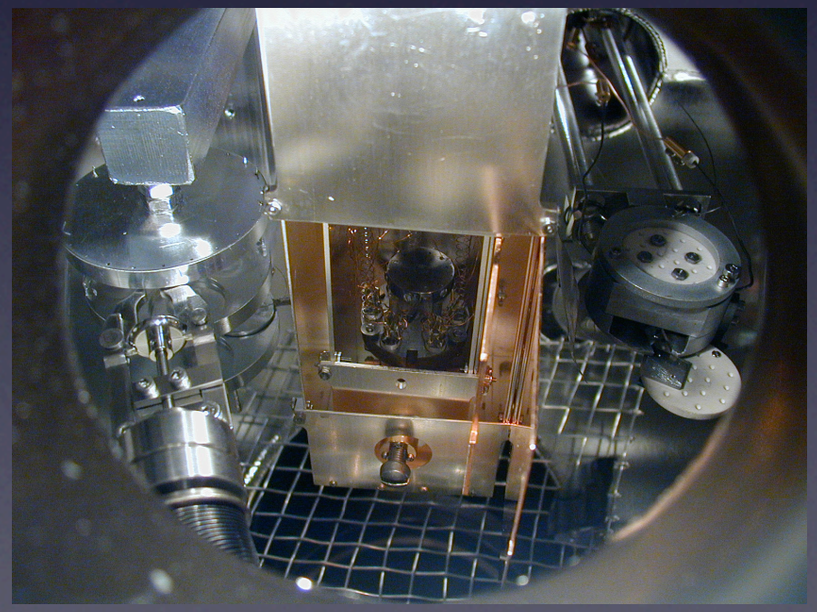
Hole Density in CuO_2 Plane

Variable Temperature UHV STM:

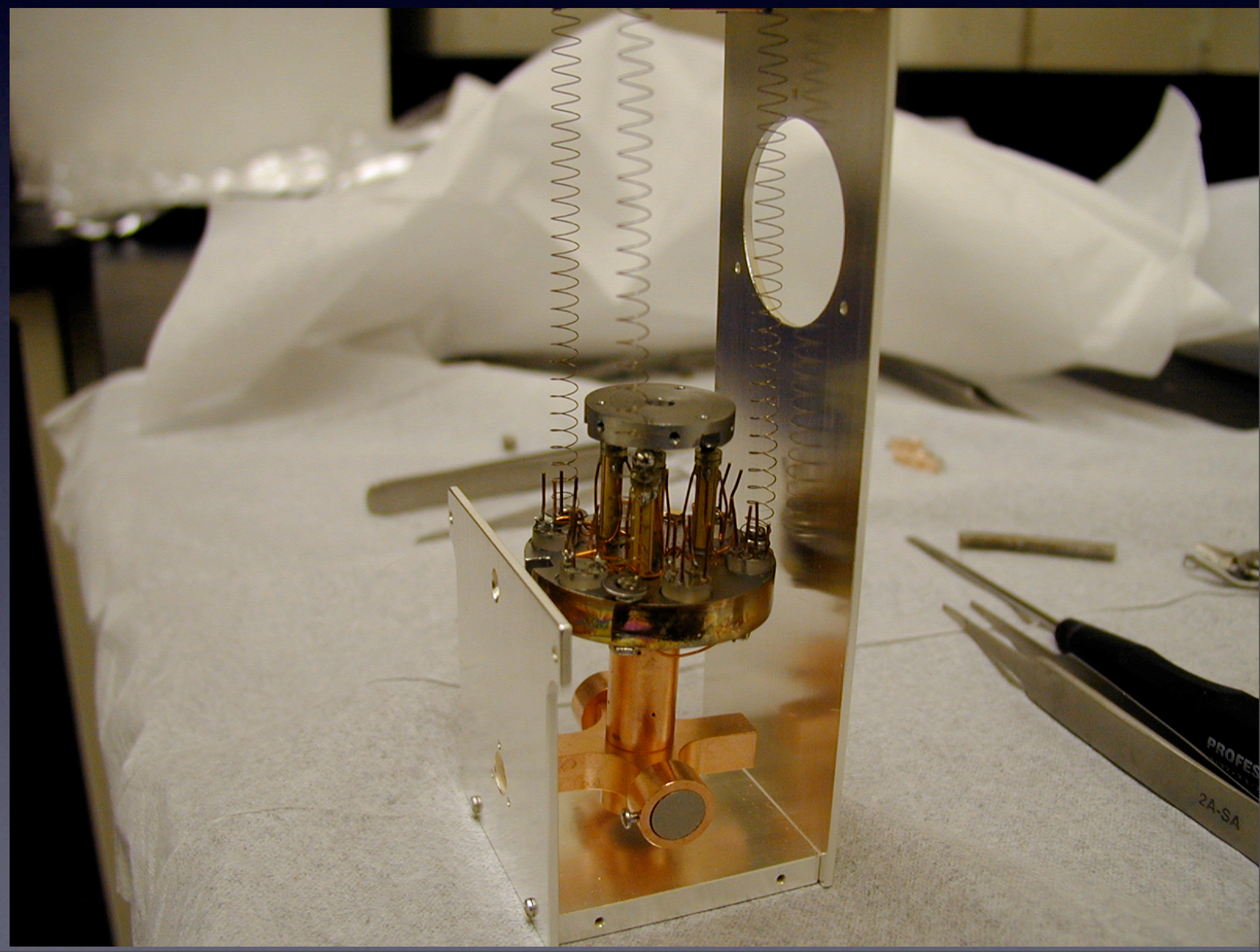
Can be used to track a single atomic site with T



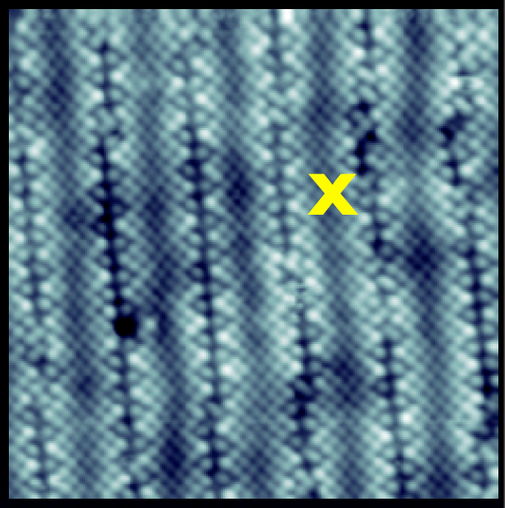
- Thermal compensation
- Compact design
- Result :
- Extremely low drift at high temperatures

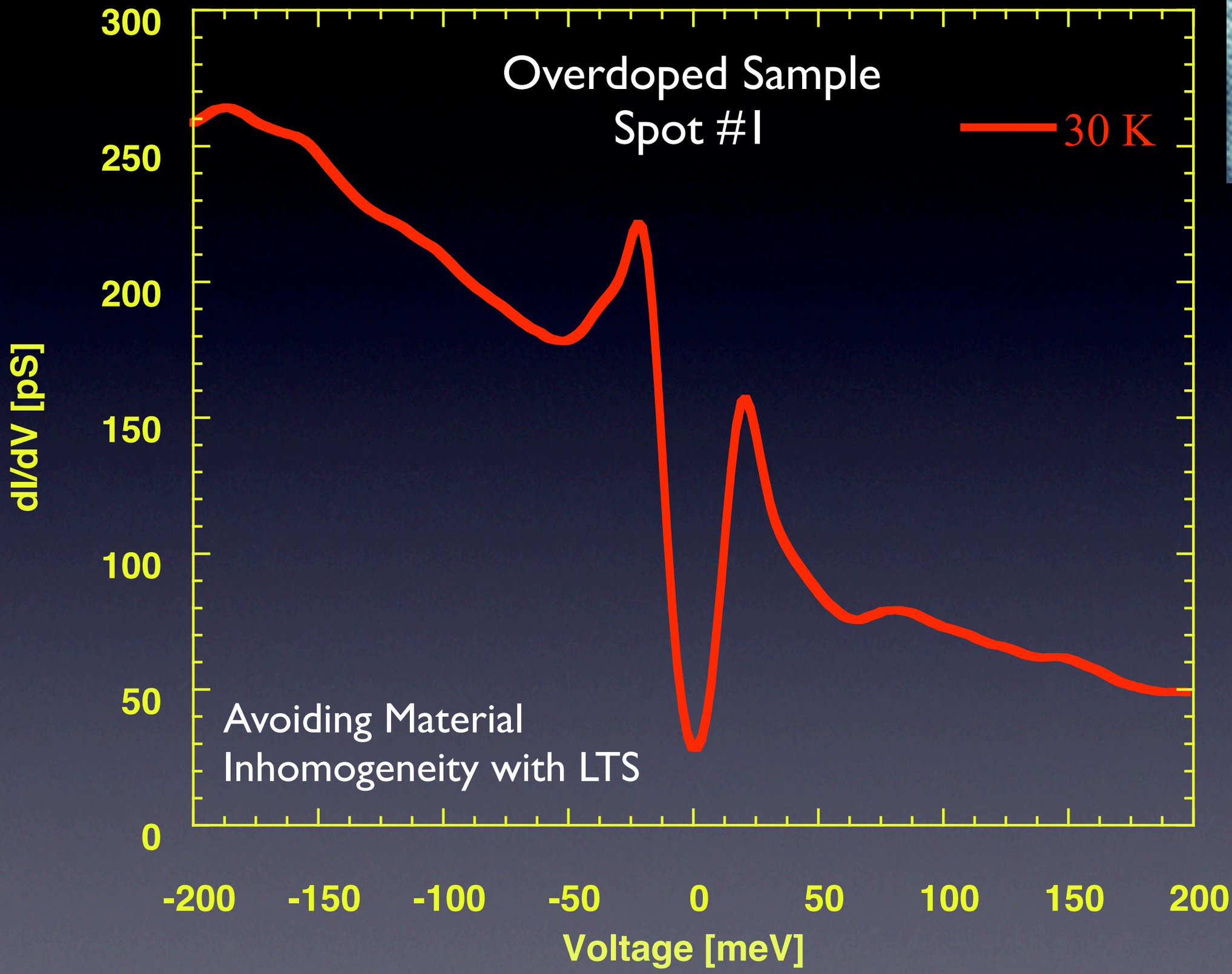


STM head



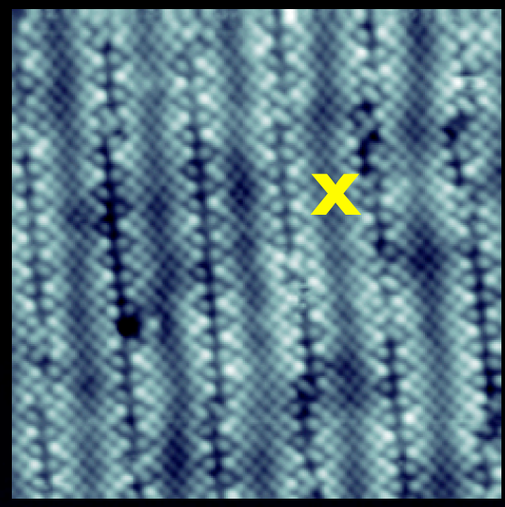
Lattice-Tracking Spectroscopy





Tc=68K

Lattice-Tracking Spectroscopy



Overdoped Sample
Spot #1

30 K
40 K

Tc=68K

Avoiding Material
Inhomogeneity with LTS

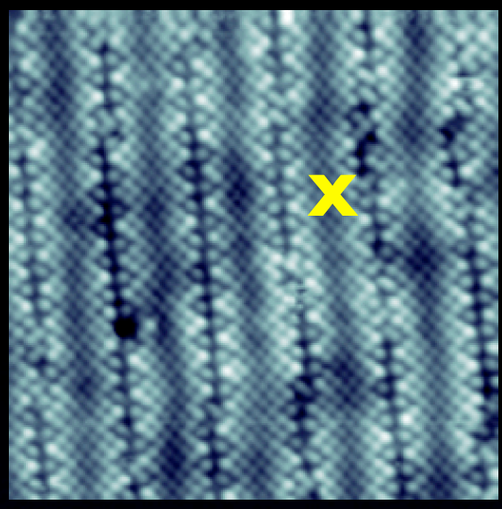
dI/dV [pS]

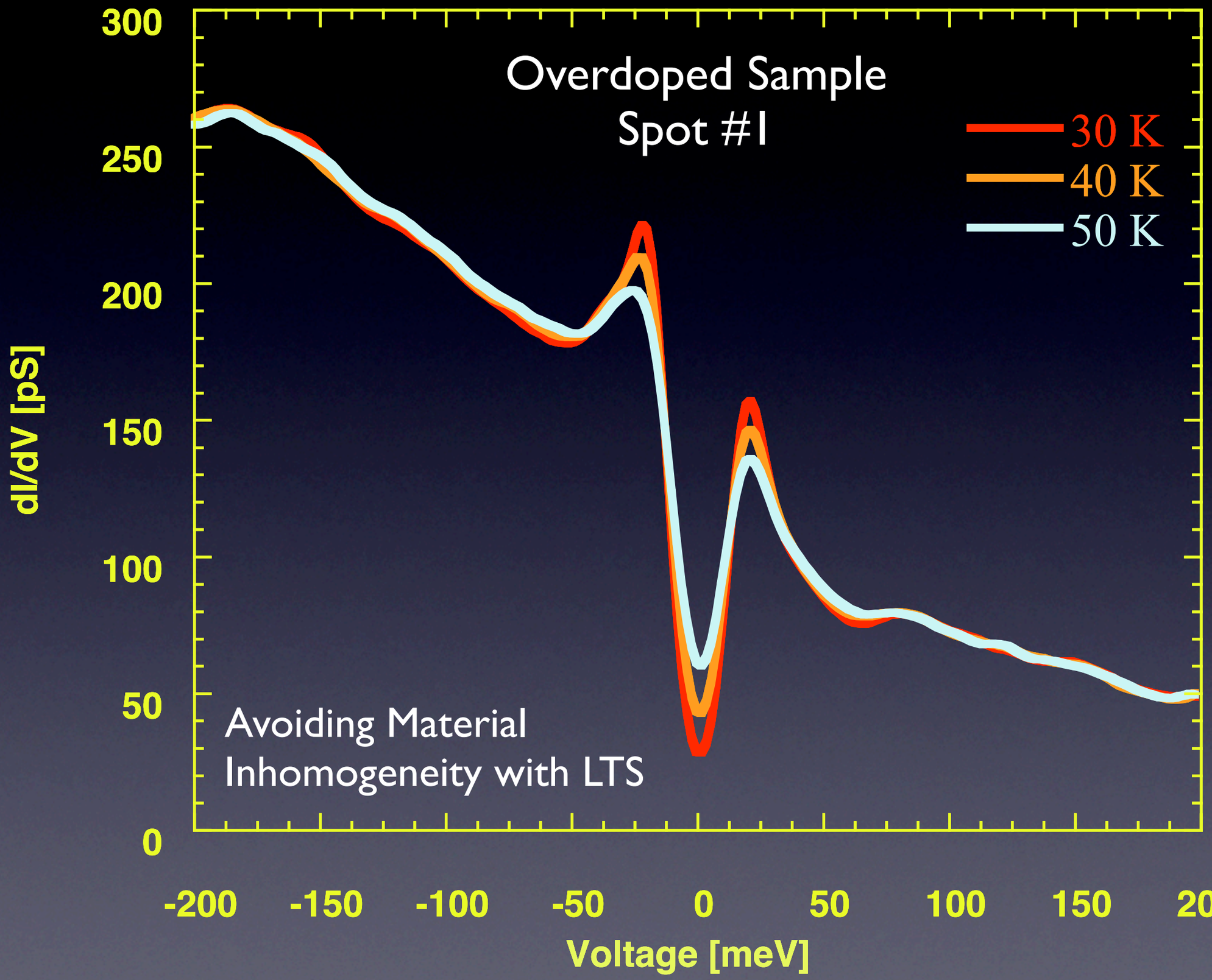
300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

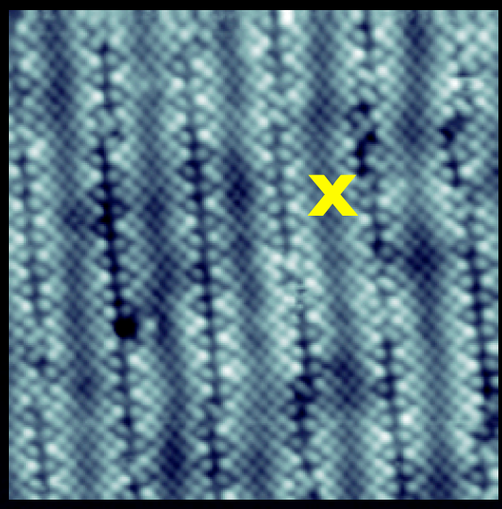
Lattice-Tracking Spectroscopy

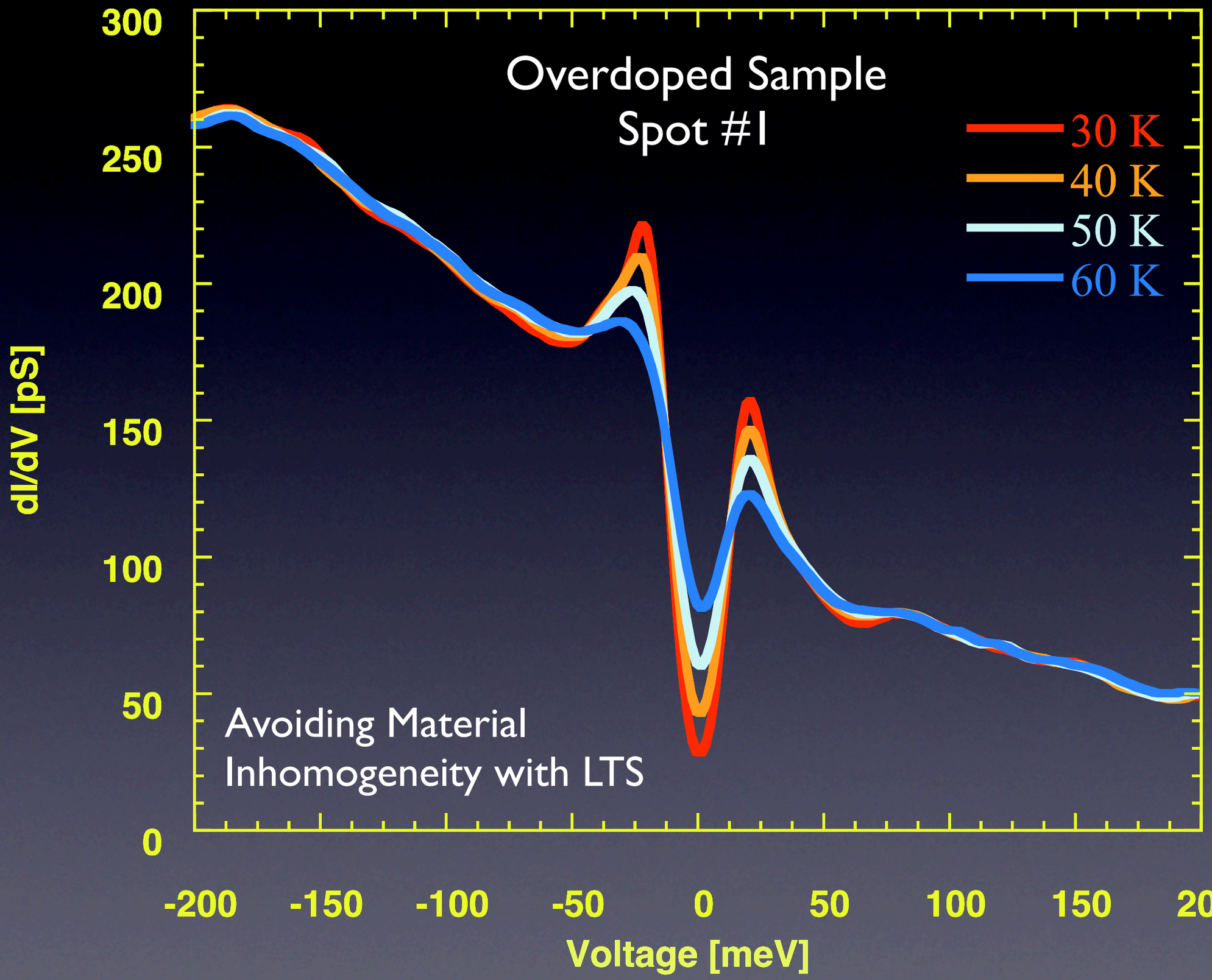




Tc=68K

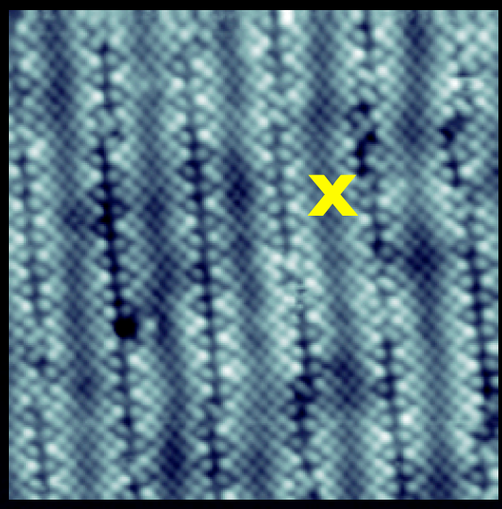
Lattice-Tracking Spectroscopy

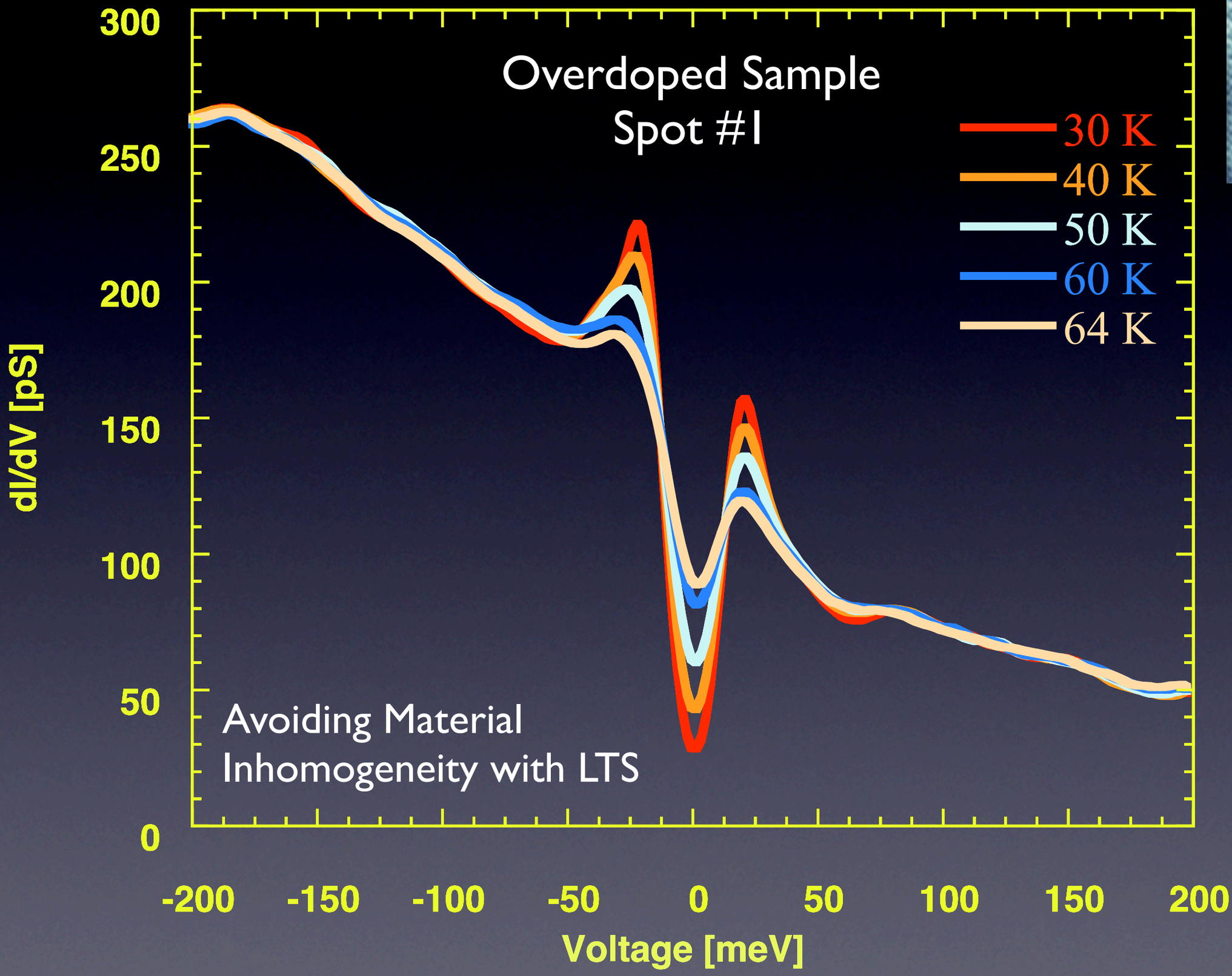




Tc=68K

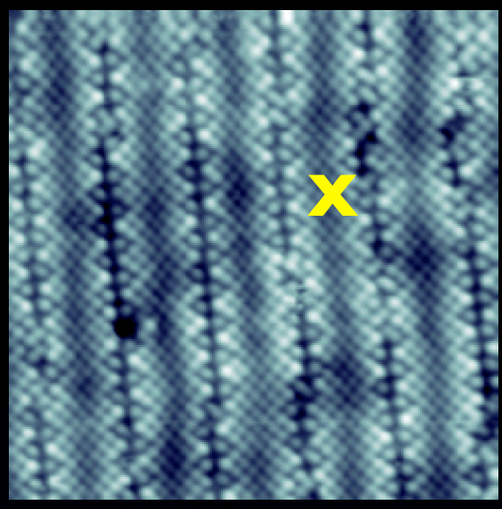
Lattice-Tracking Spectroscopy





Tc=68K

Lattice-Tracking Spectroscopy



Overdoped Sample
Spot #1

30 K
40 K
50 K
60 K
64 K
68 K

Tc=68K

Avoiding Material
Inhomogeneity with LTS

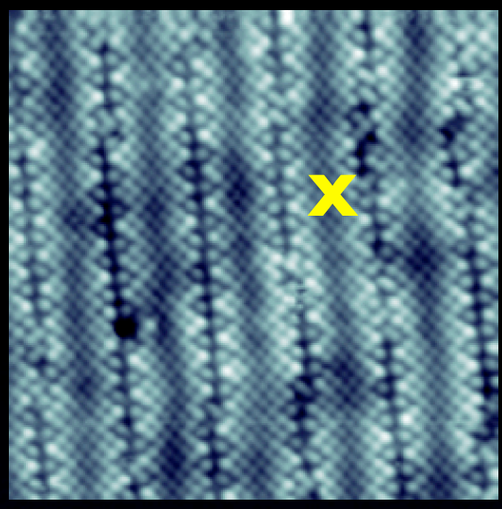
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy



Overdoped Sample
Spot #1

30 K
40 K
50 K
60 K
64 K
68 K
72 K

Tc=68K

Avoiding Material
Inhomogeneity with LTS

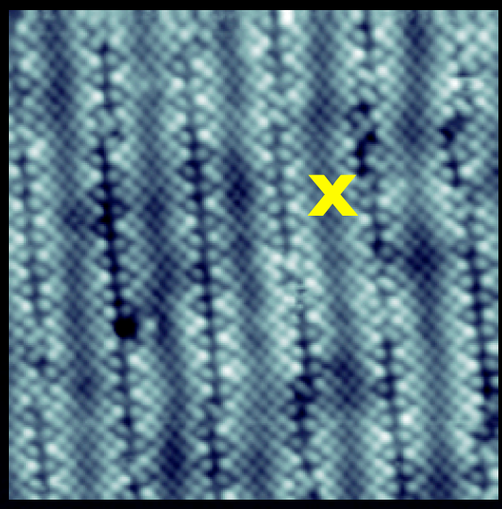
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy



Overdoped Sample
Spot #1

30 K
40 K
50 K
60 K
64 K
68 K
72 K
76 K

Tc=68K

Avoiding Material
Inhomogeneity with LTS

dI/dV [pS]

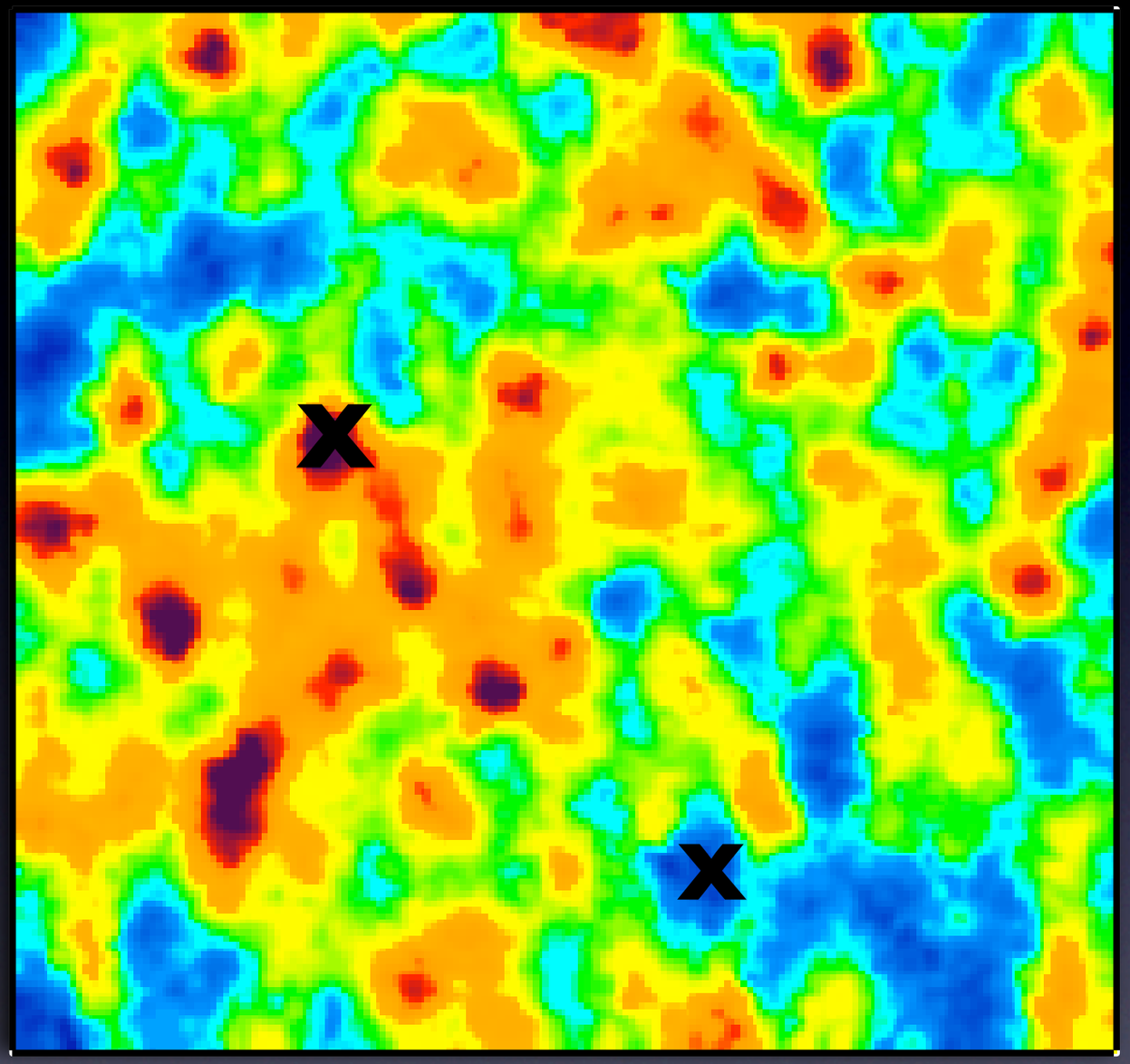
300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

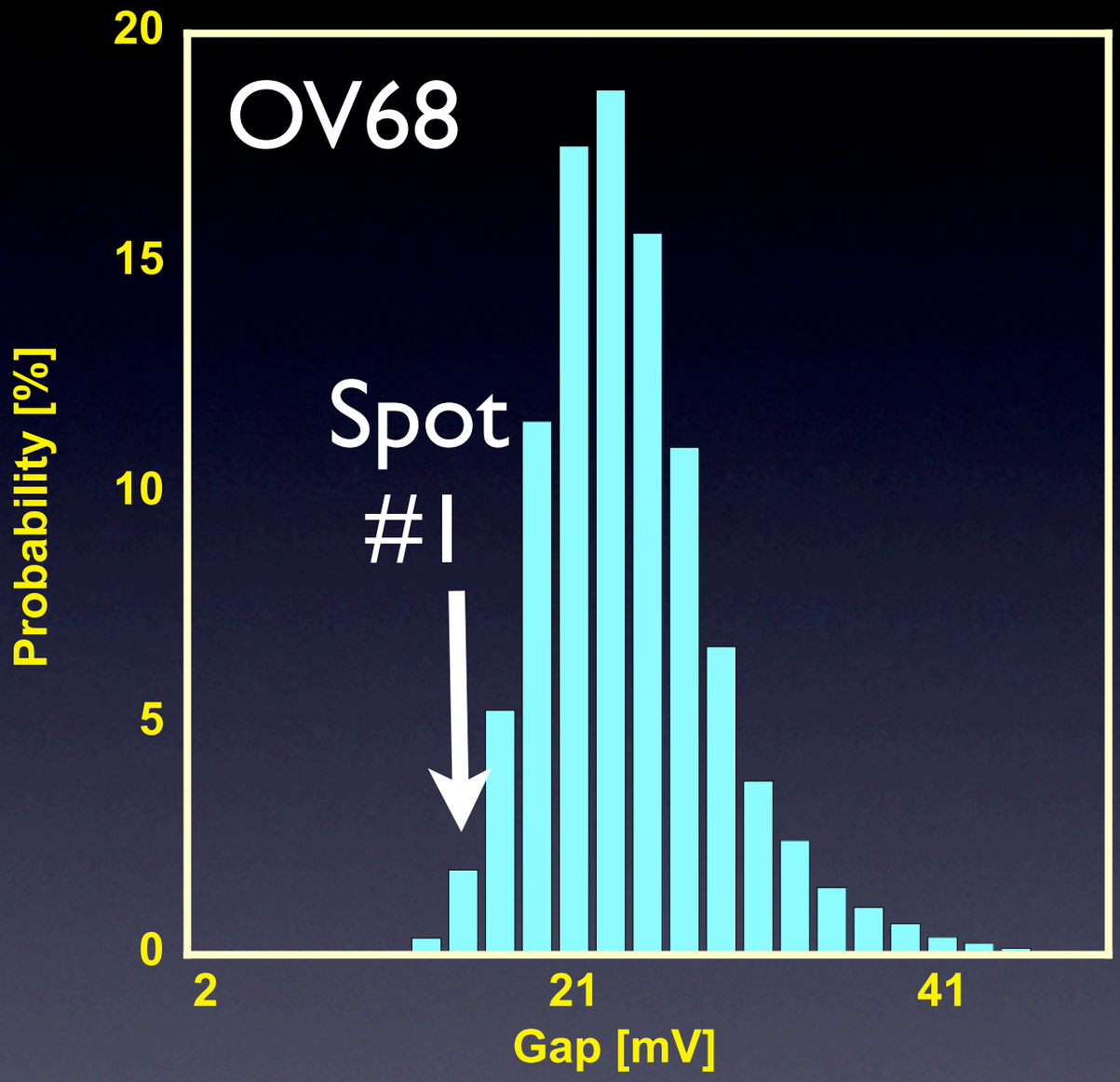
Inhomogeneous Gaps:

300 Å x 300 Å



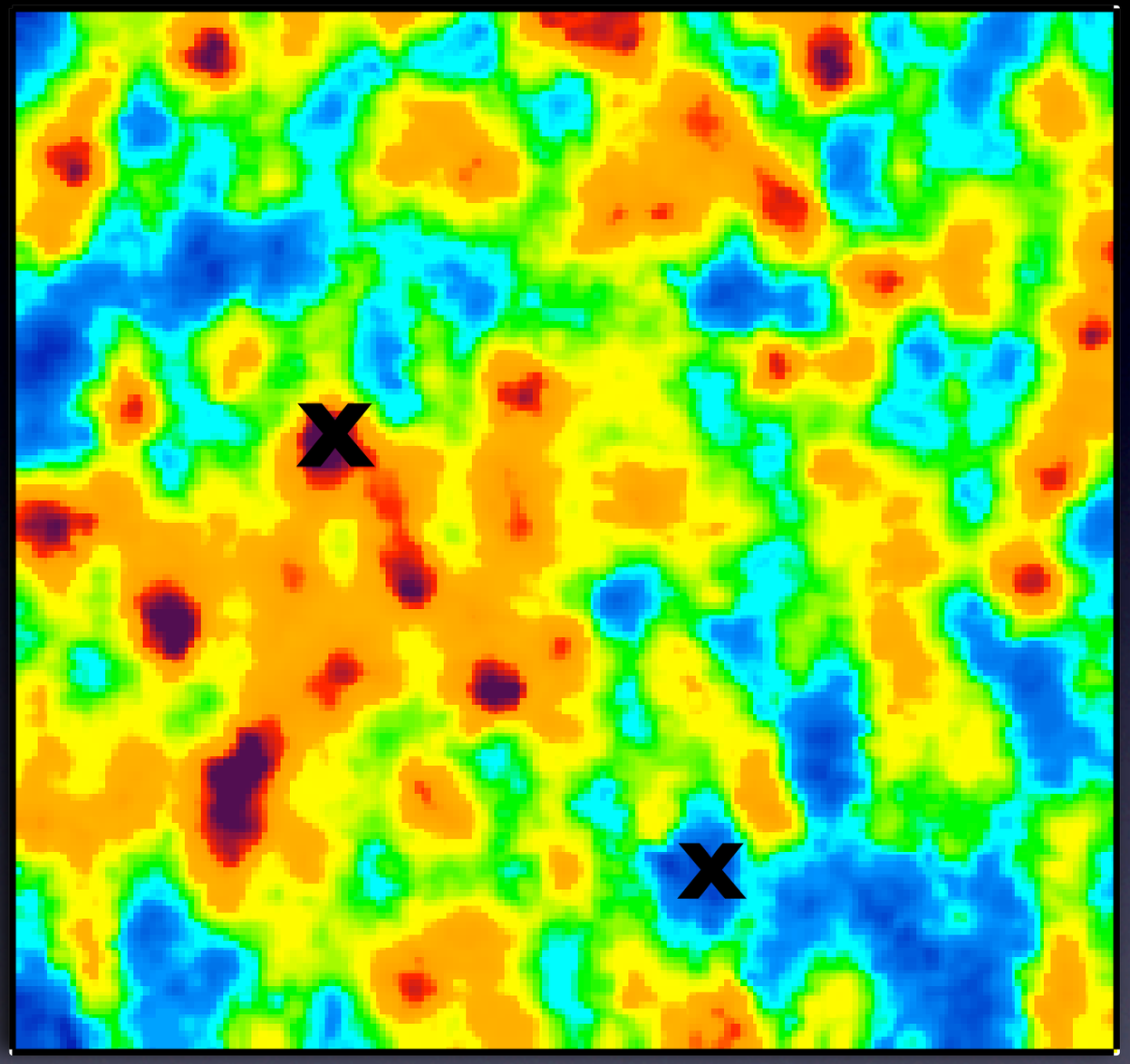
Δ(mV)

18mV 38mV



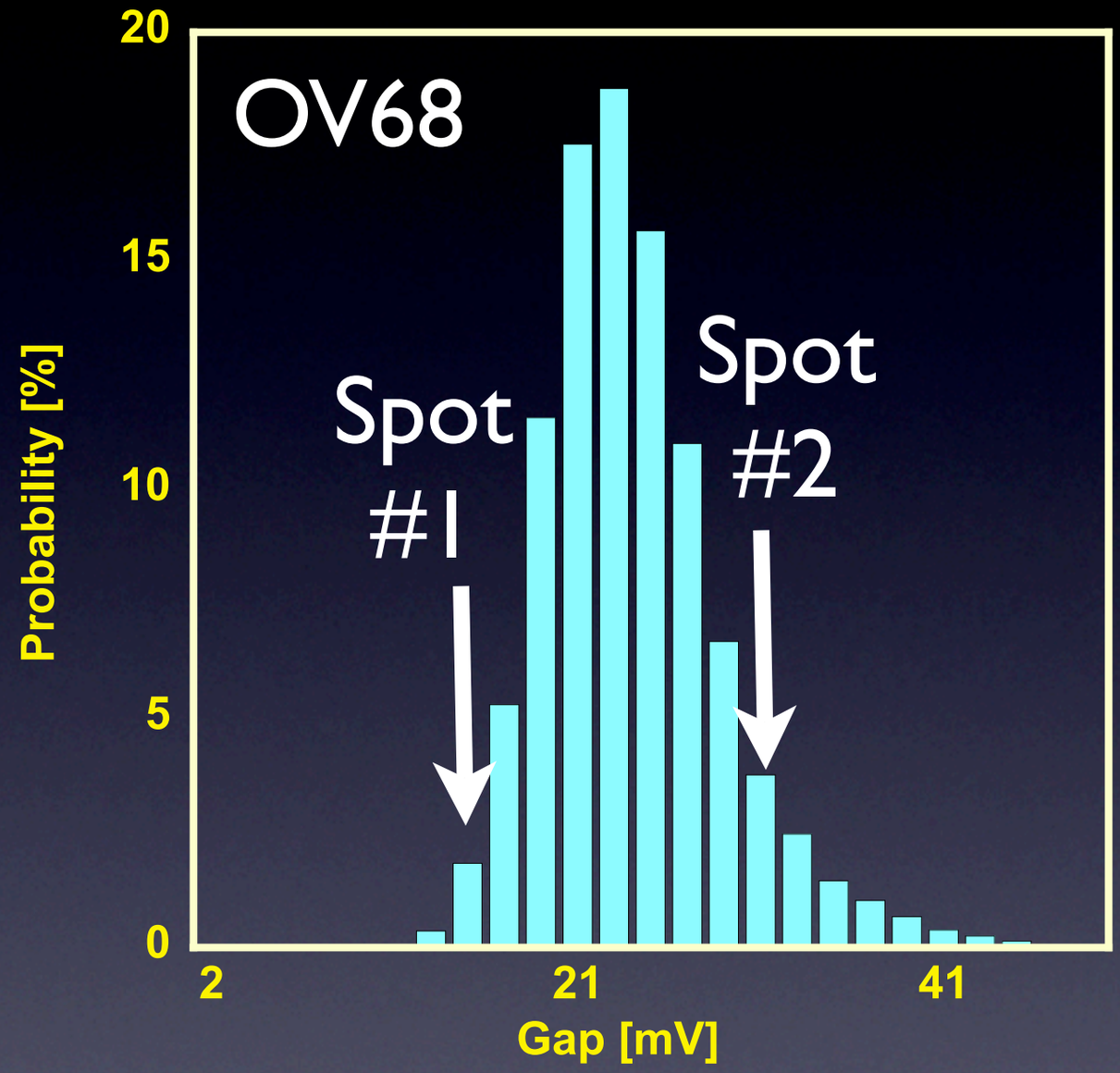
Inhomogeneous Gaps:

300 Å x 300 Å

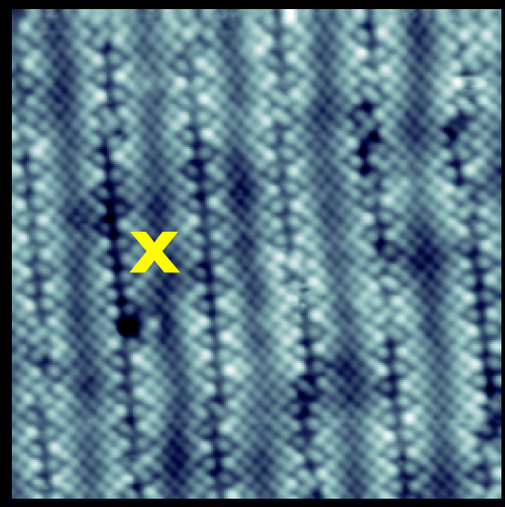


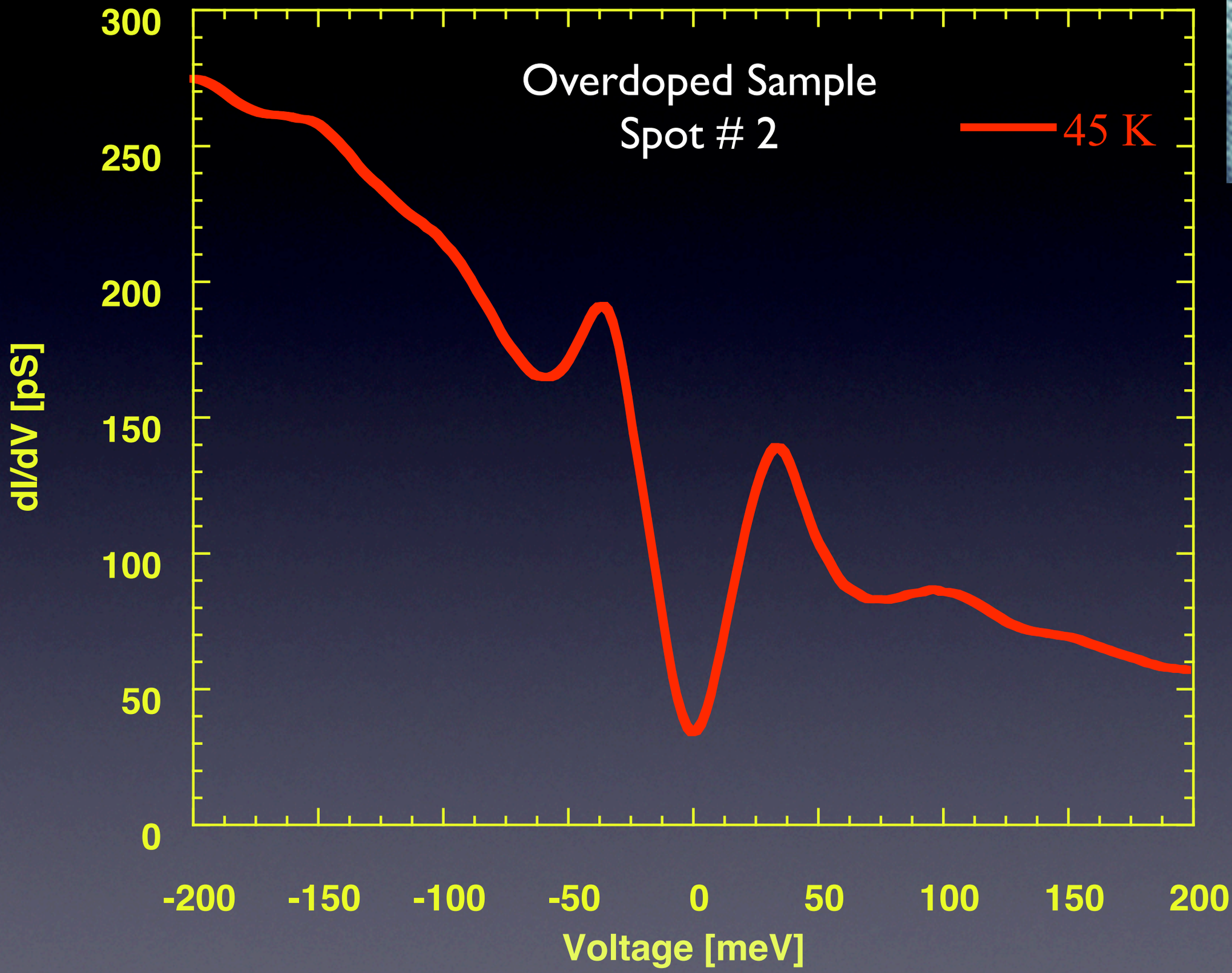
Δ(mV)

18mV 38mV



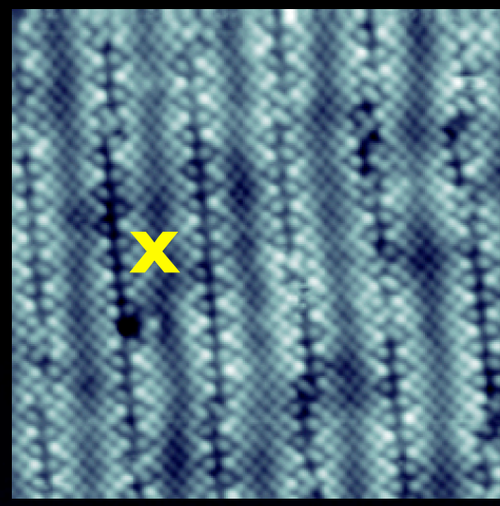
Lattice-Tracking Spectroscopy:





Tc=68K

Lattice-Tracking Spectroscopy:



Overdoped Sample
Spot # 2

45 K
50 K

Tc=68K

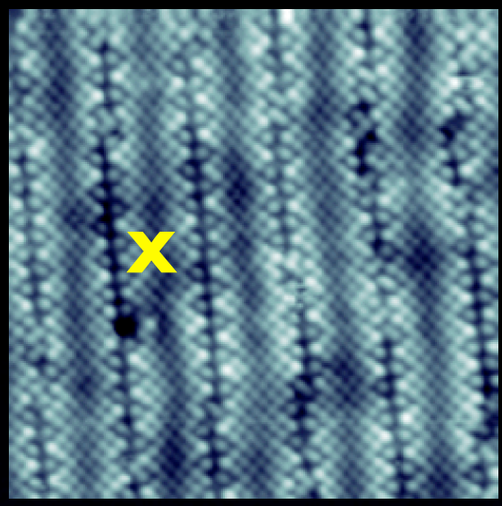
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy:



Tc=68K

Overdoped Sample
Spot # 2

45 K
50 K
60 K

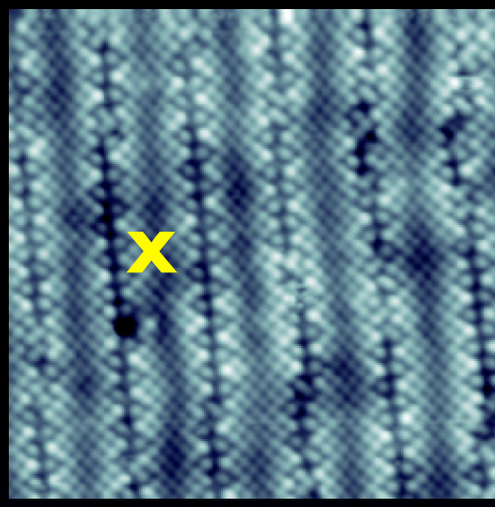
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy:



Tc=68K

Overdoped Sample
Spot # 2

45 K
50 K
60 K
70 K

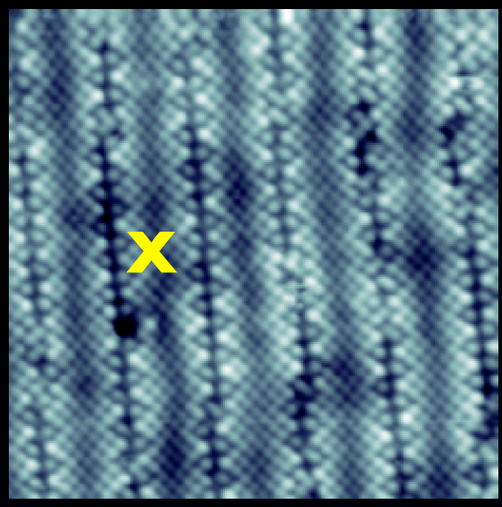
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy:



Tc=68K

Overdoped Sample
Spot # 2

45 K
50 K
60 K
70 K
80 K

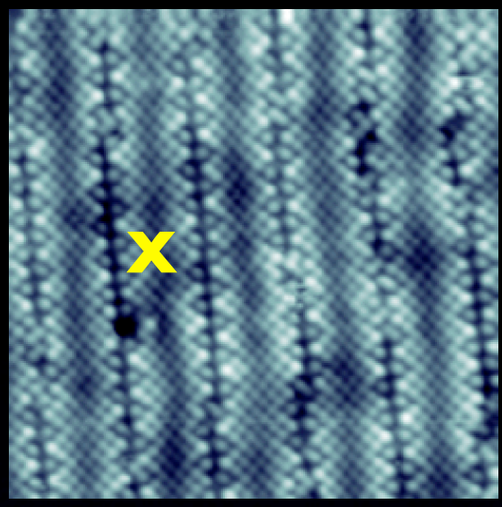
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy:



Overdoped Sample
Spot # 2

45 K
50 K
60 K
70 K
80 K
90 K

Tc=68K

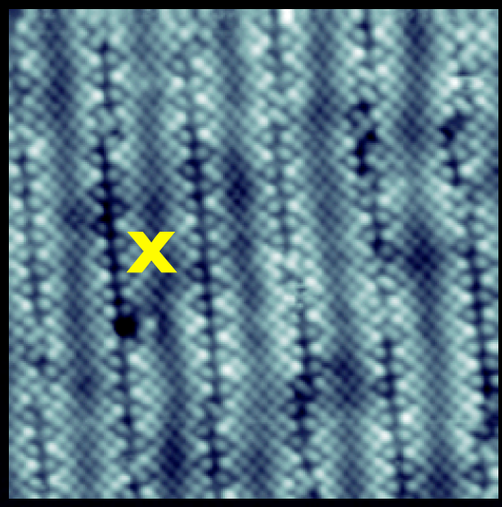
dI/dV [pS]

300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Lattice-Tracking Spectroscopy:



Tc=68K

Overdoped Sample
Spot # 2

45 K
50 K
60 K
70 K
80 K
90 K
100 K

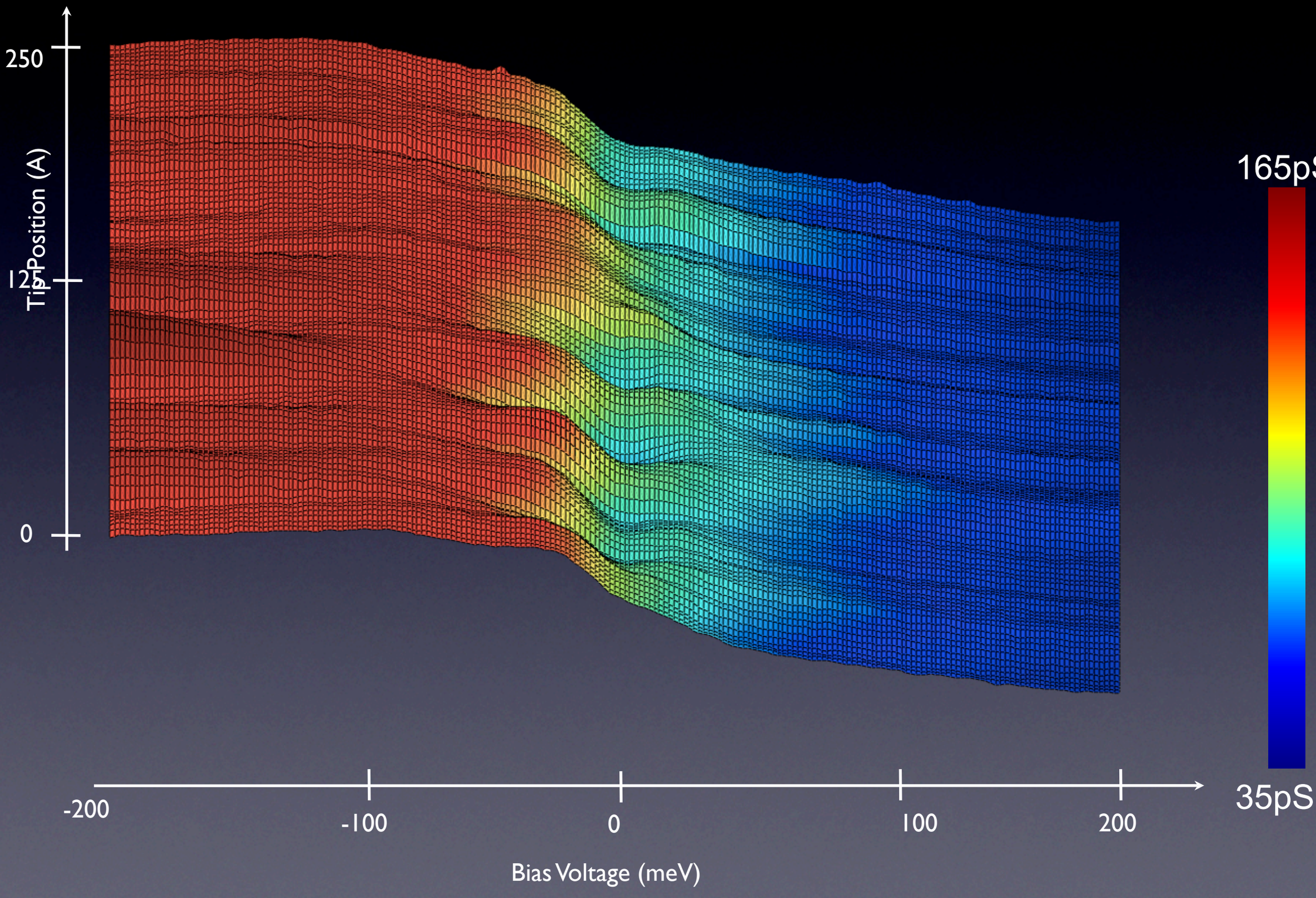
dI/dV [pS]

300
250
200
150
100
50
0

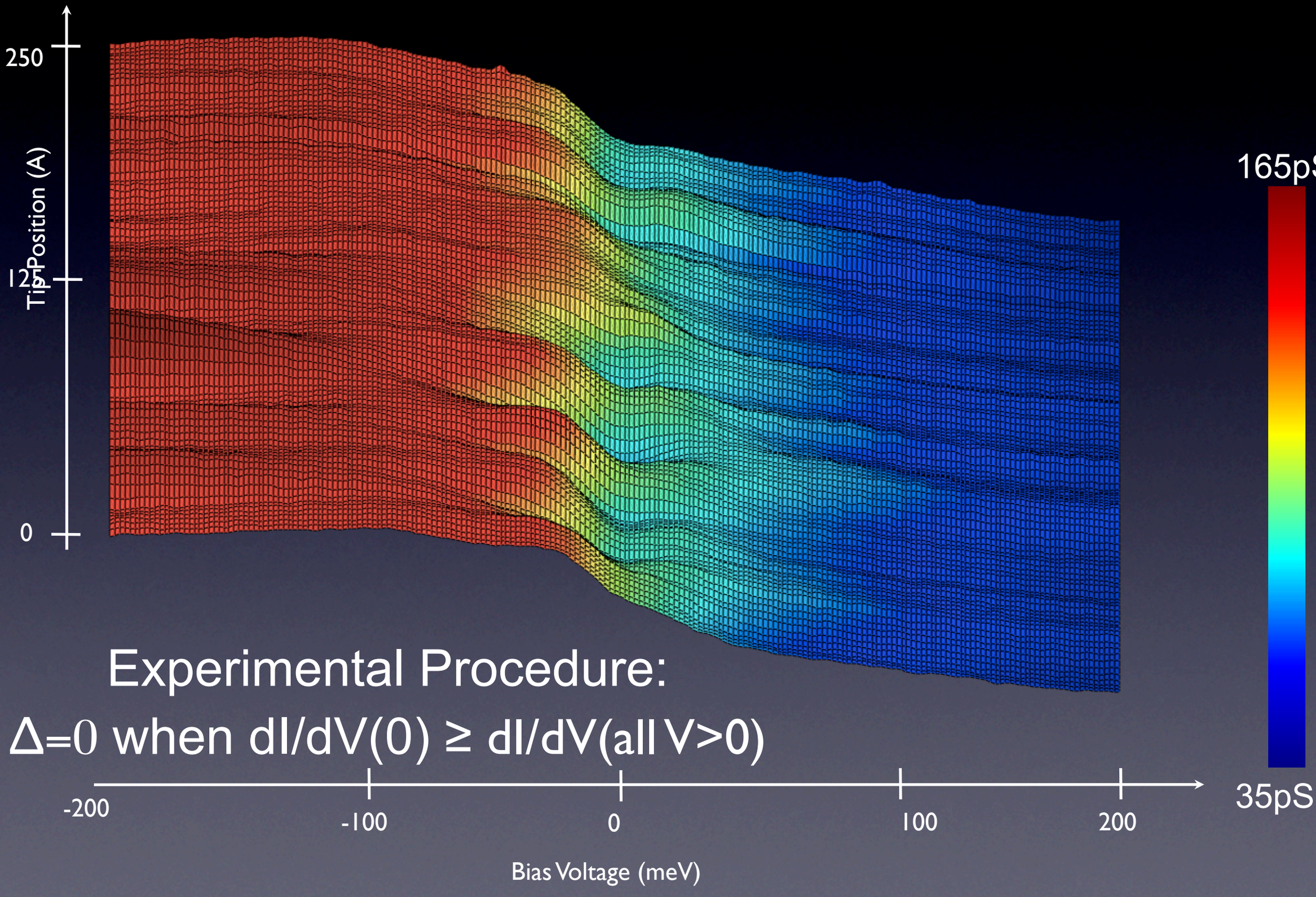
-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

Non-unifrom closing of the gaps (T=70K) for an overdoped sample (Tc=65K)



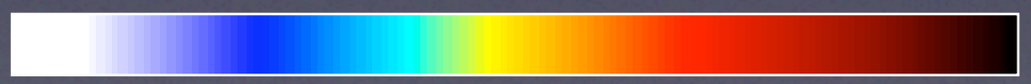
Non-unifrom closing of the gaps (T=70K) for an overdoped sample (Tc=65K)



Experimental Procedure:

$\Delta=0$ when dI/dV(0) ≥ dI/dV(all V>0)

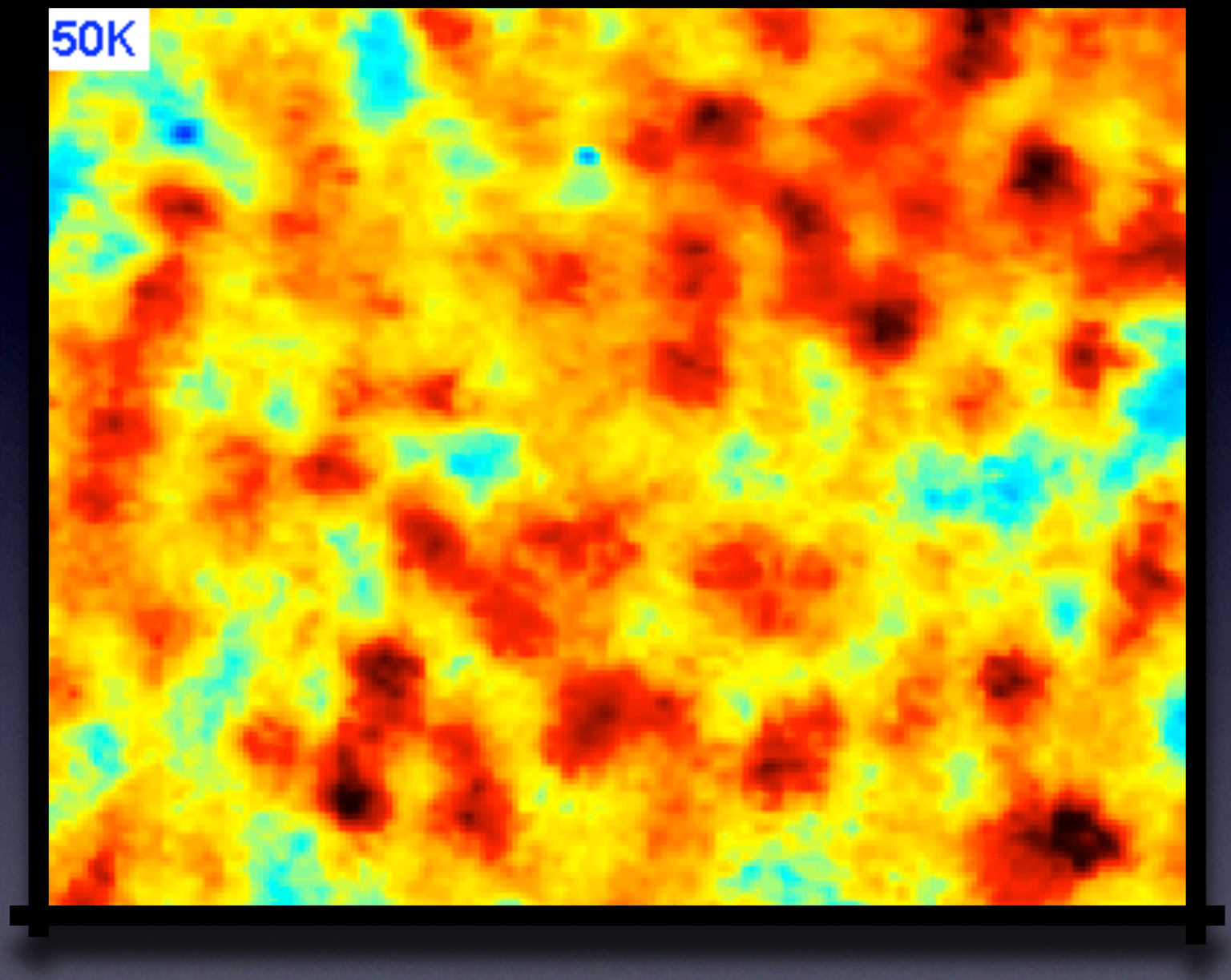
Local d-wave Pairing Gap Collapse



Ungaped State 0mV Gap size 40mV SC pairs

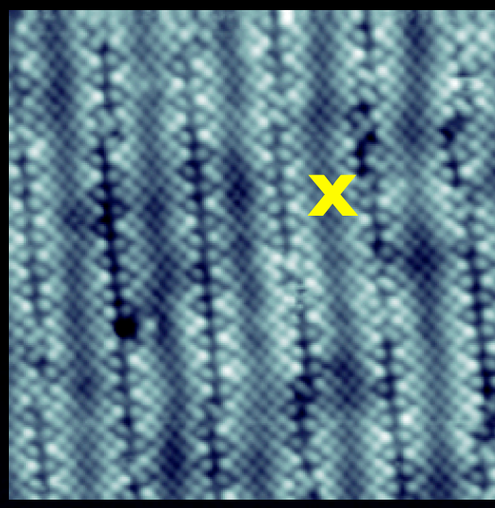
Gomes, Pasupathy, Pushp, Ono, Ando, Yazdani *Nature* **447**, 569 (2007)

Local d-wave Pairing Gap Collapse



Gomes, Pasupathy, Pushp, Ono, Ando, Yazdani *Nature* **447**, 569 (2007)

Background: Tunneling Matrix Element
Incoherent tunneling processes



Overdoped Sample
Spot #1

30 K
40 K
50 K
60 K
64 K
68 K
72 K
76 K

Tc=68K

Avoiding Material
Inhomogeneity with LTS

dI/dV [pS]

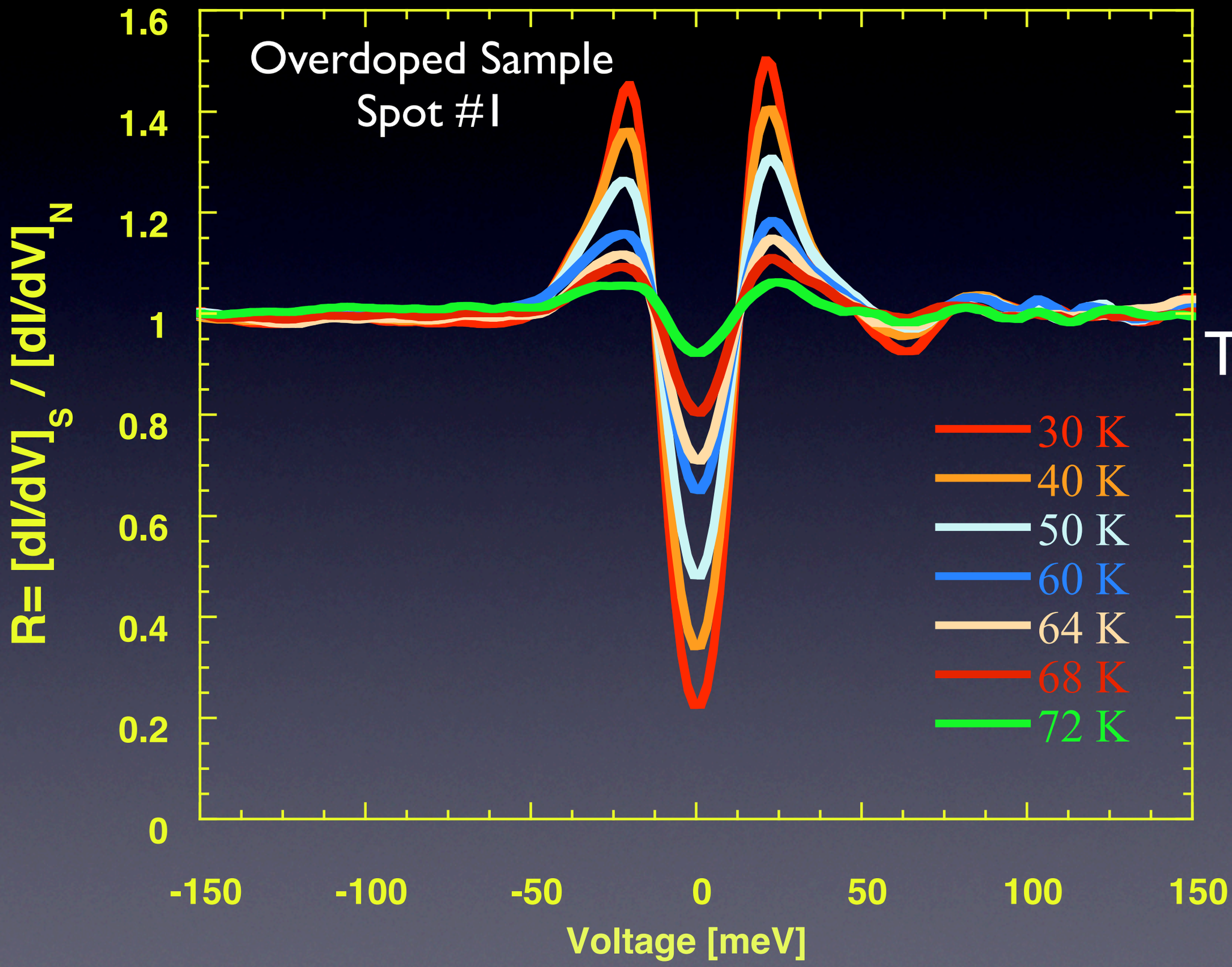
300
250
200
150
100
50
0

-200 -150 -100 -50 0 50 100 150 200

Voltage [meV]

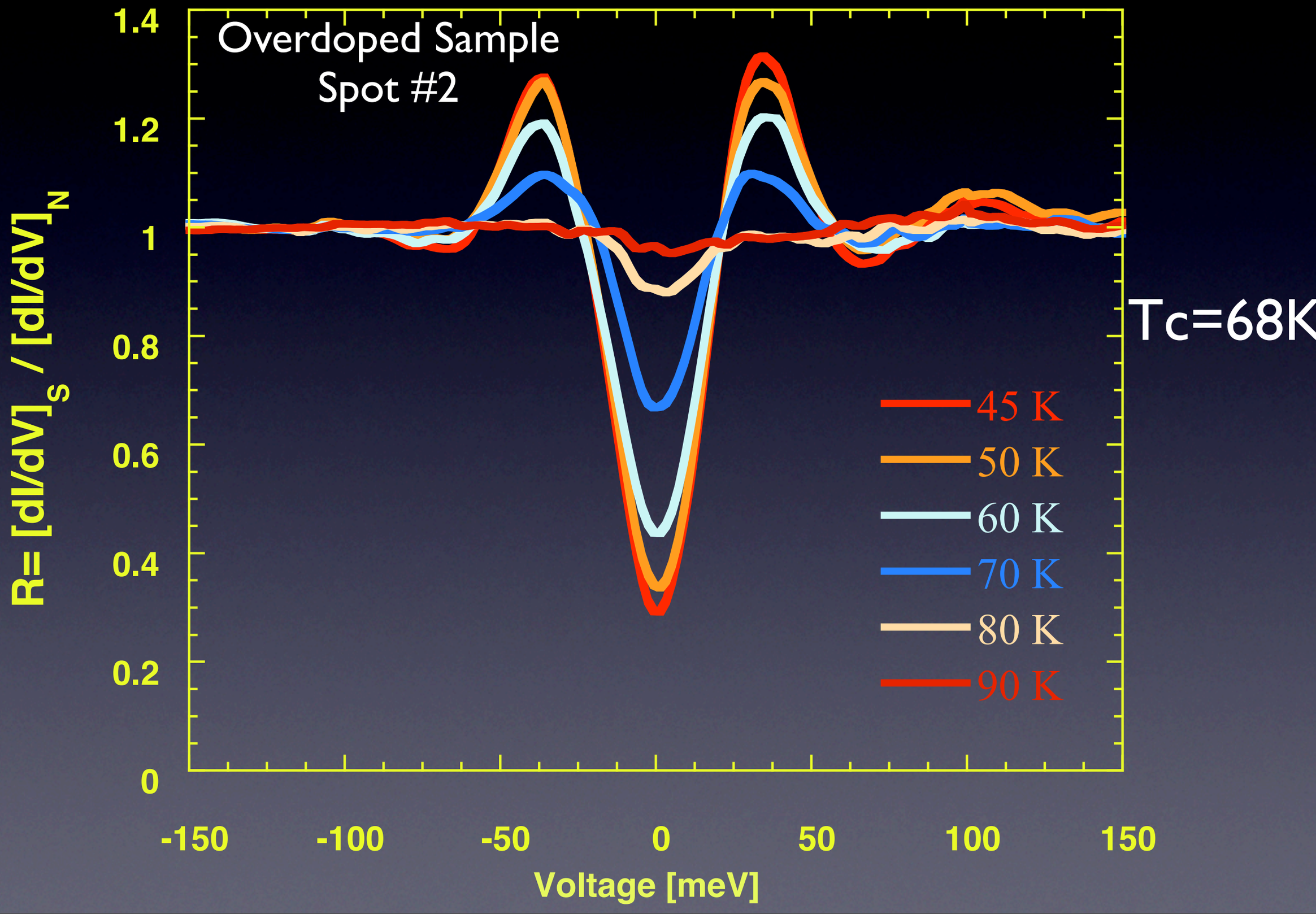
Conductance Ratio: $R=[dI/dV]_s/[dI/dV]_n$

For the case that the "normal state" is T-independent



Conductance Ratio: $R=[dI/dV]_s/[dI/dV]_n$

For the case that the normal state is T-independent



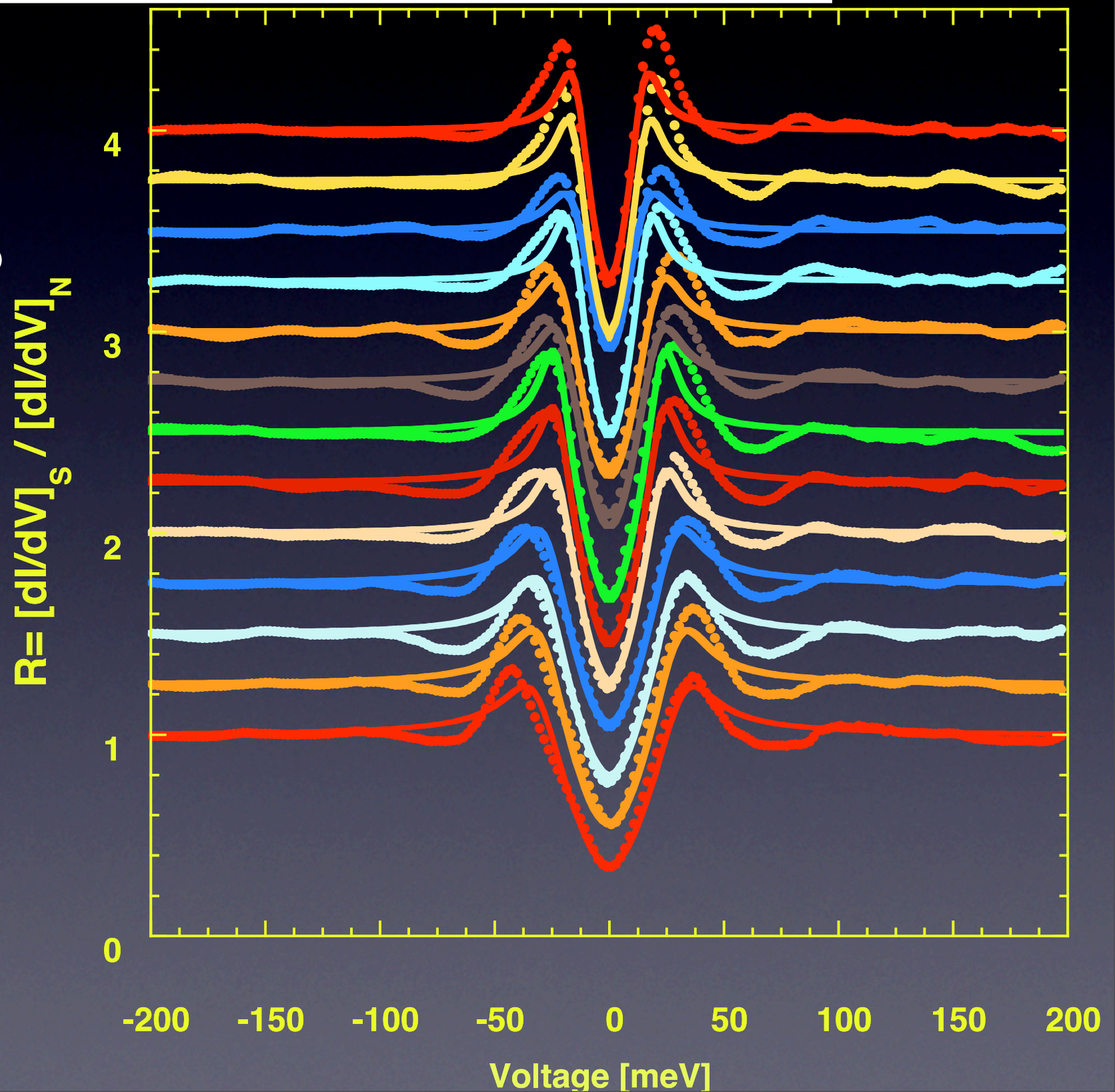
Fitting Conductance Ratio with a Local d-wave Model:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E-i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

$\Delta(r,T)$ - local d-wave gap

$\Gamma(r,T)$ - local inverse QP lifetime

Different Spots on the OV68 at T=30K

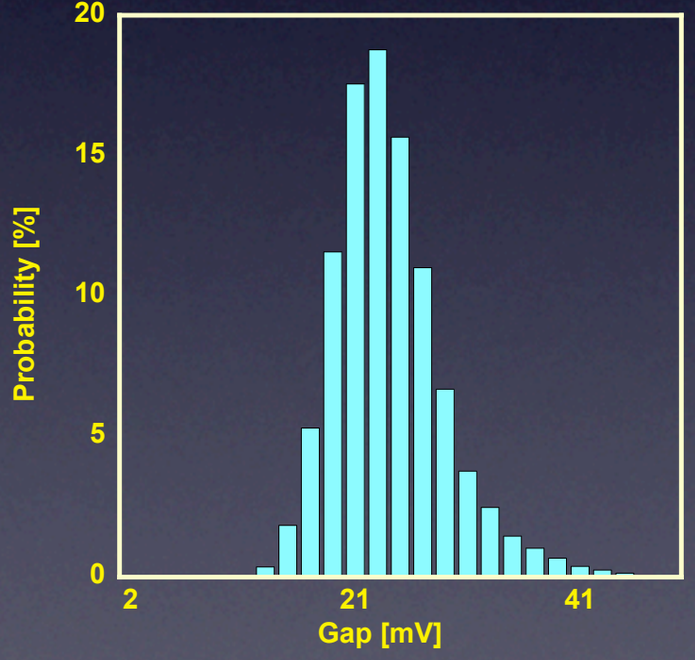


Fitting Conductance Ratio with a Local d-wave Model:

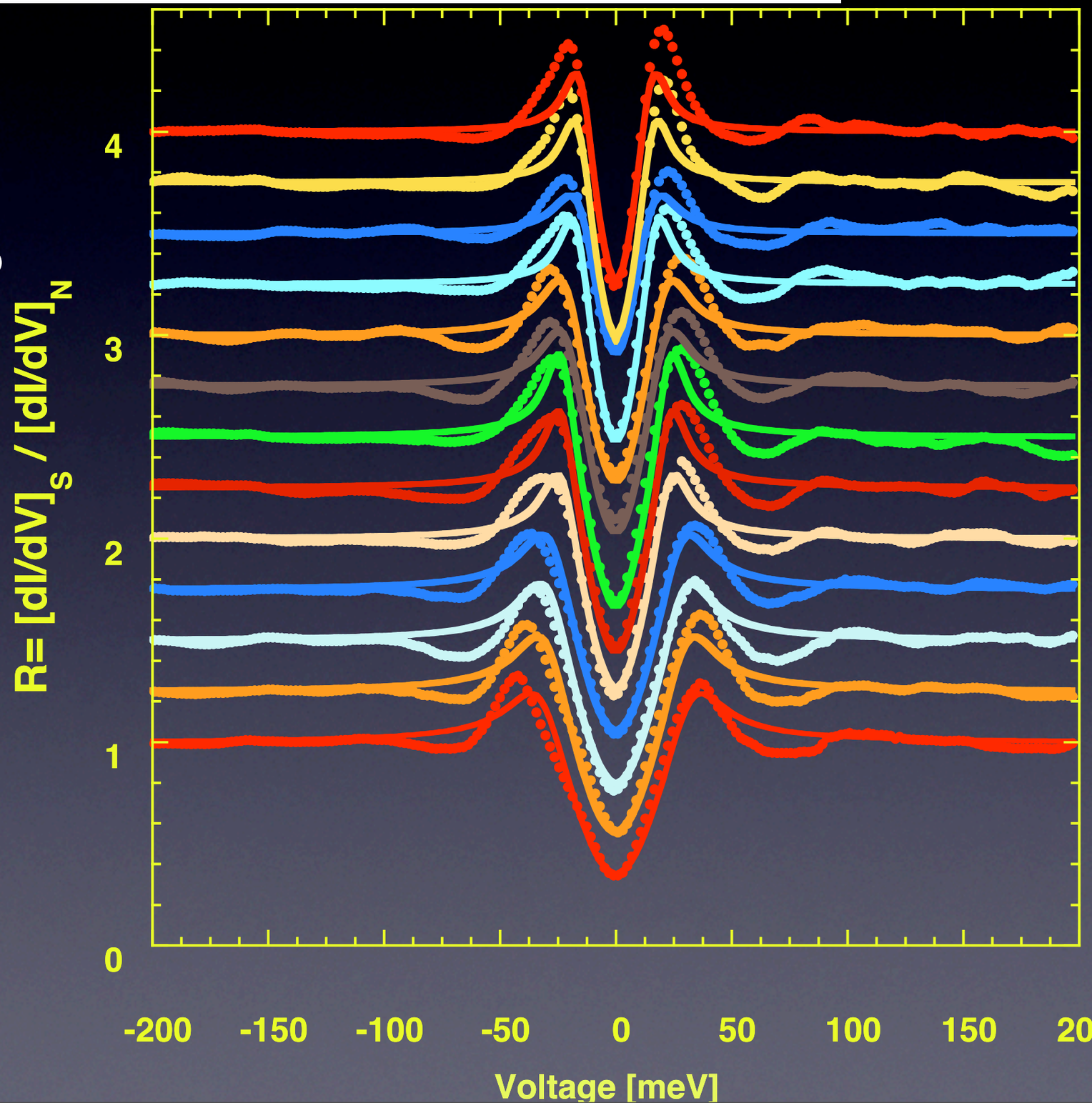
$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E-i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

Δ(r,T) - local d-wave gap

Γ(r,T) - local inverse QP lifetime



Different Spots on the OV68 at T=30K



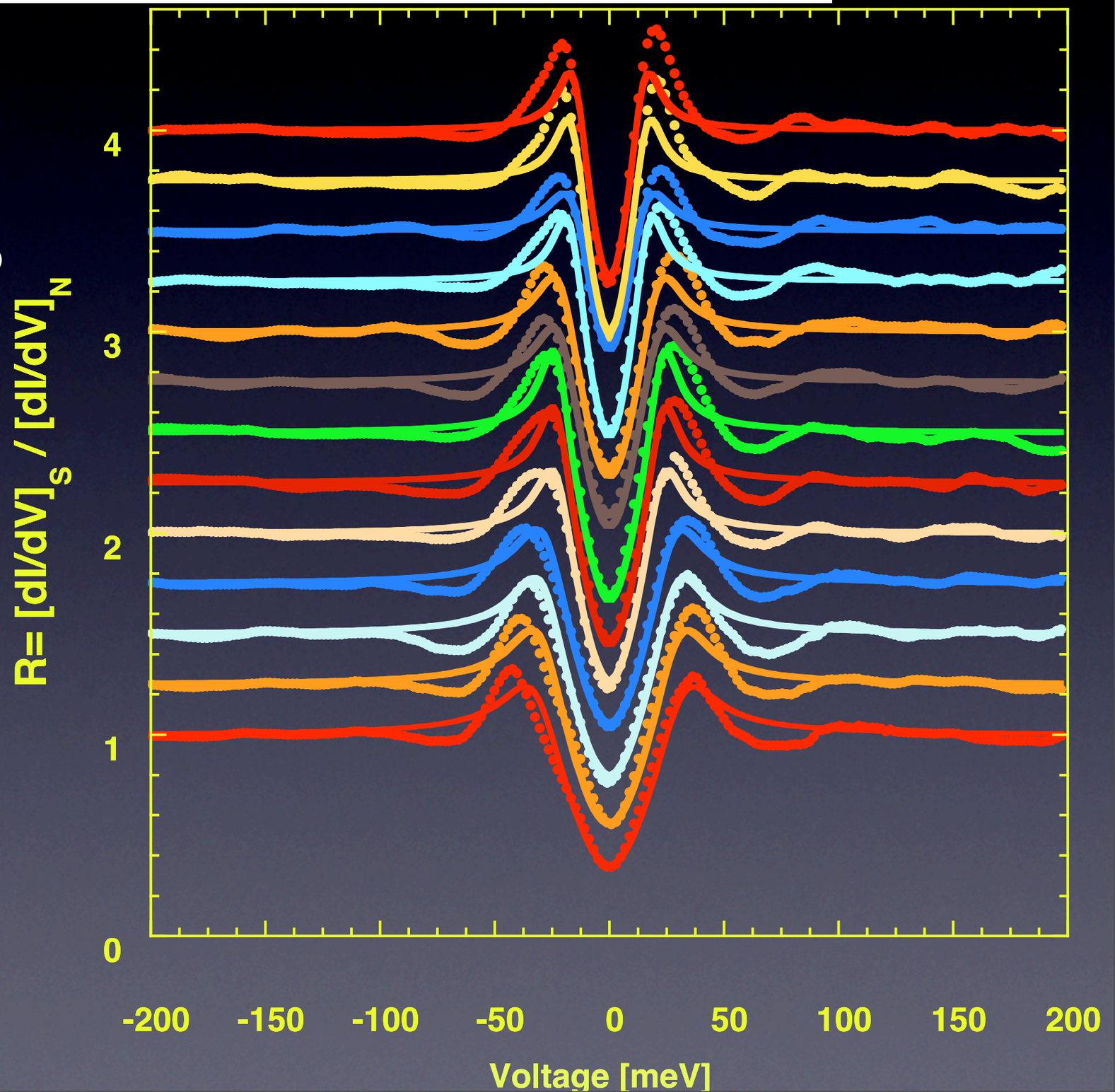
Fitting Conductance Ratio with a Local d-wave Model:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E-i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

$\Delta(r,T)$ - local d-wave gap

$\Gamma(r,T)$ - local inverse QP lifetime

Different Spots on the OV68 at T=30K



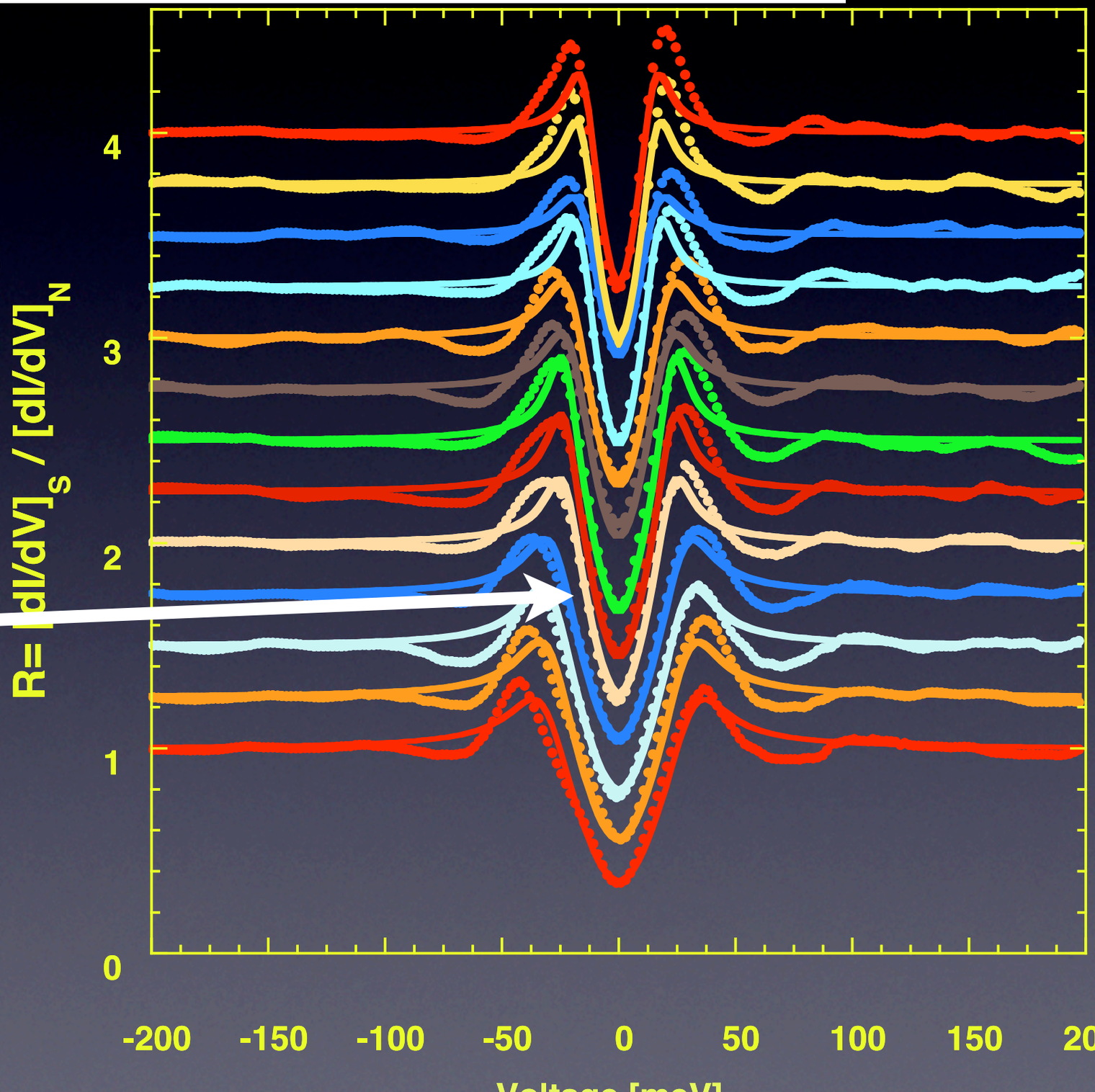
Fitting Conductance Ratio with a Local d-wave Model:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

$\Delta(r,T)$ - local d-wave gap

$\Gamma(r,T)$ - local inverse QP lifetime

Excellent fit at low E

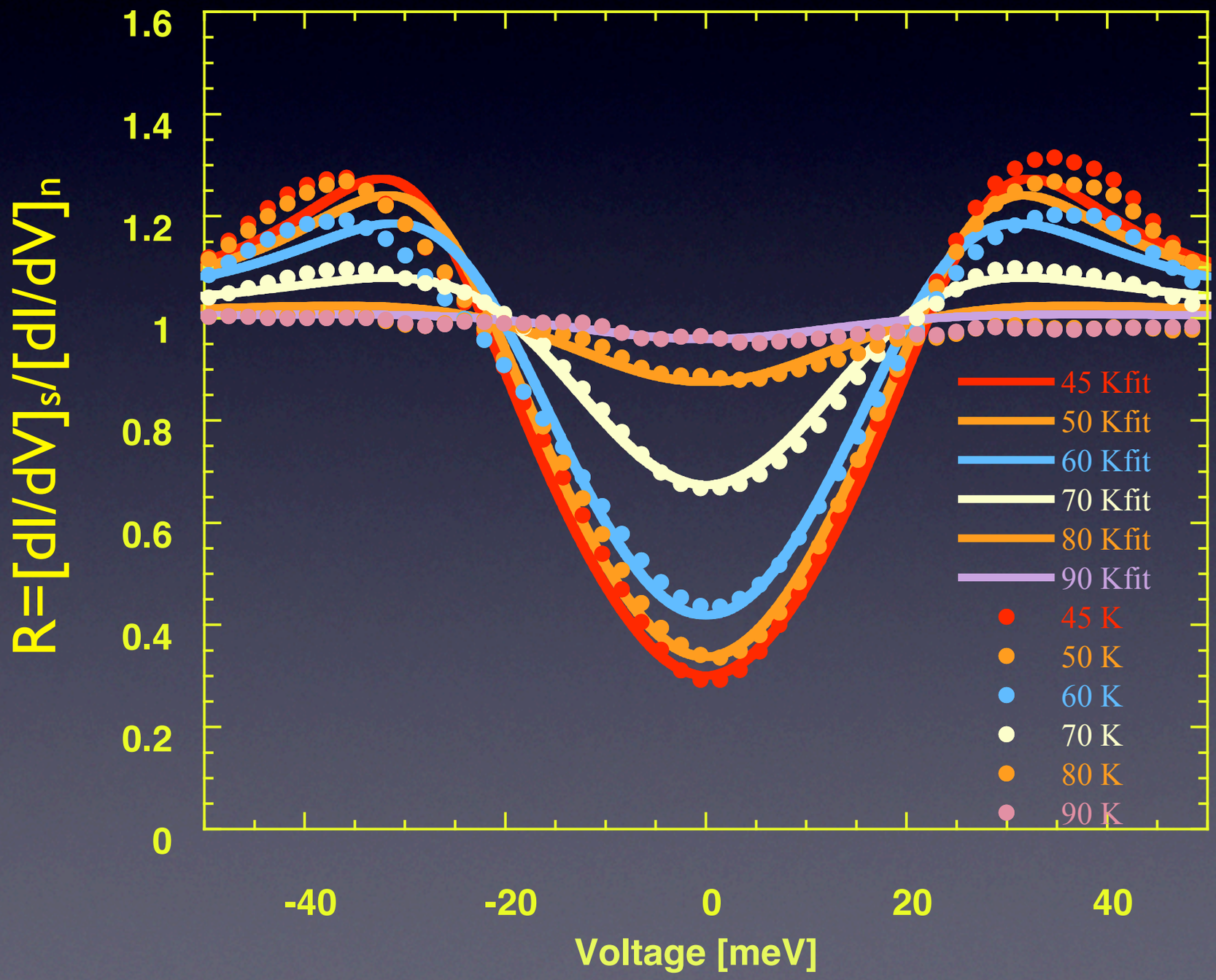


Different Spots on the OV68 at T=30K

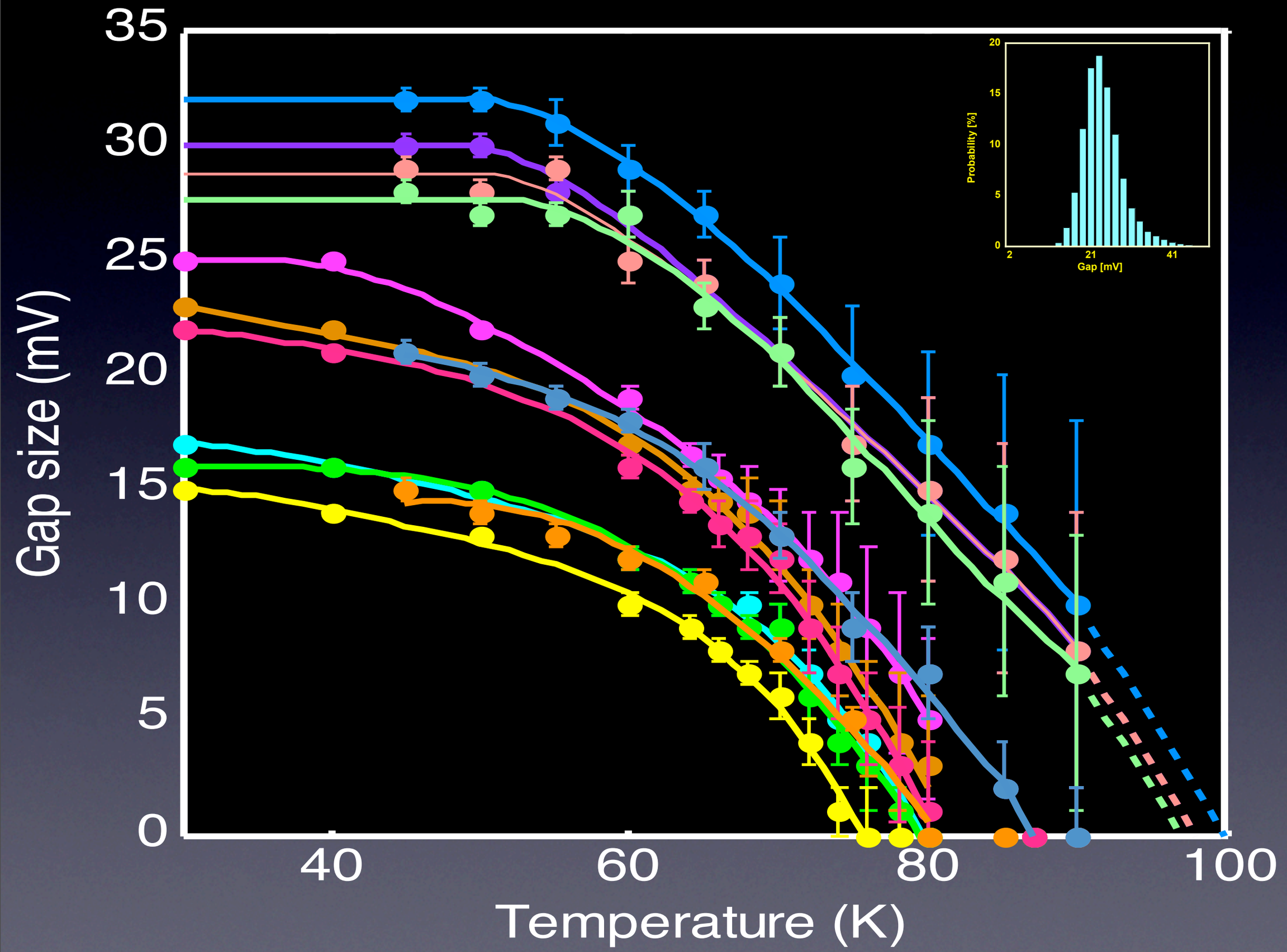
Fitting the T-dependence of the Conductance Ratio:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

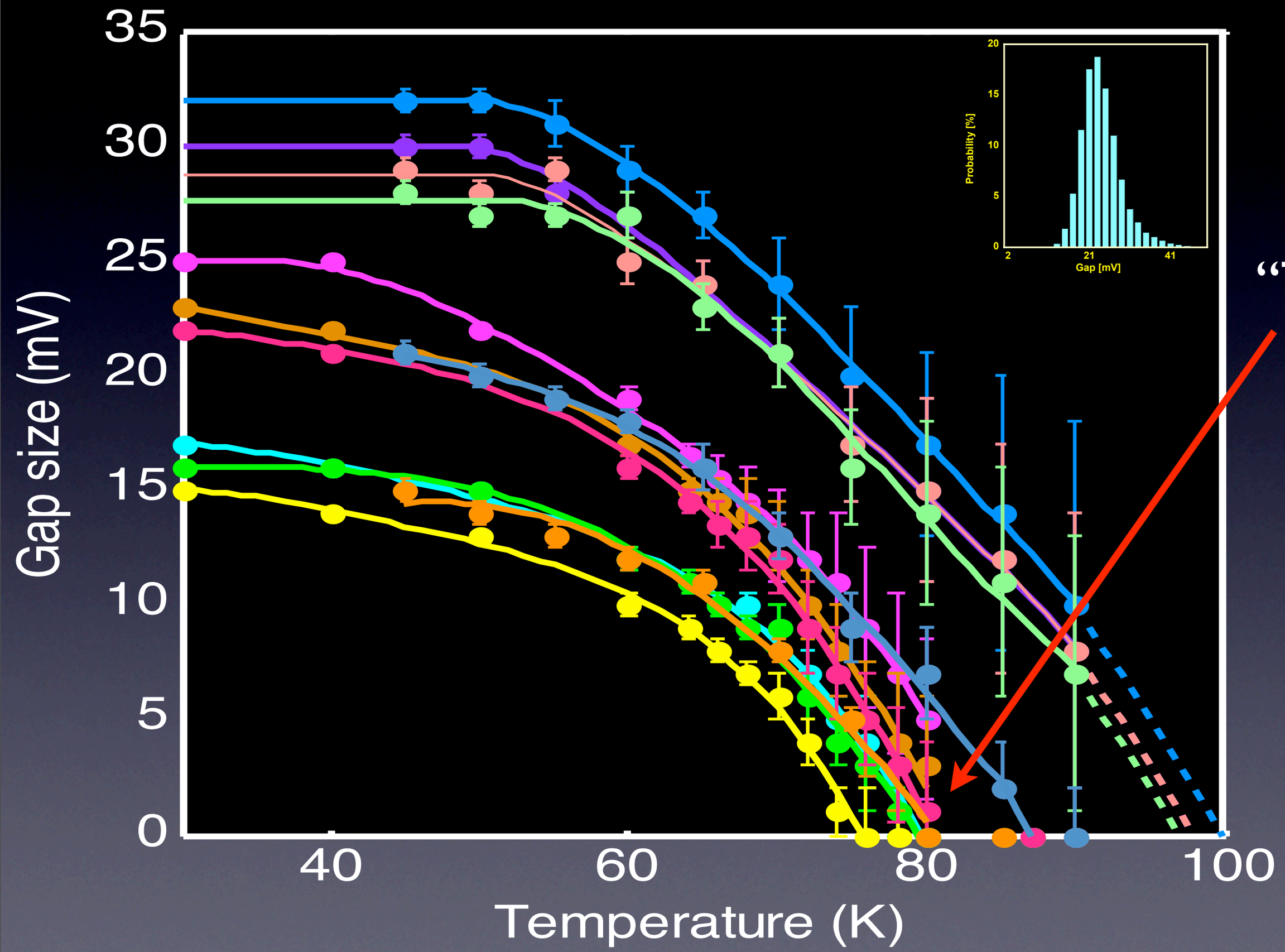
Δ(r,T) - local d-wave gap Γ(r,T) - local inverse QP lifetime



Extract the local d-wave Pairing Gap

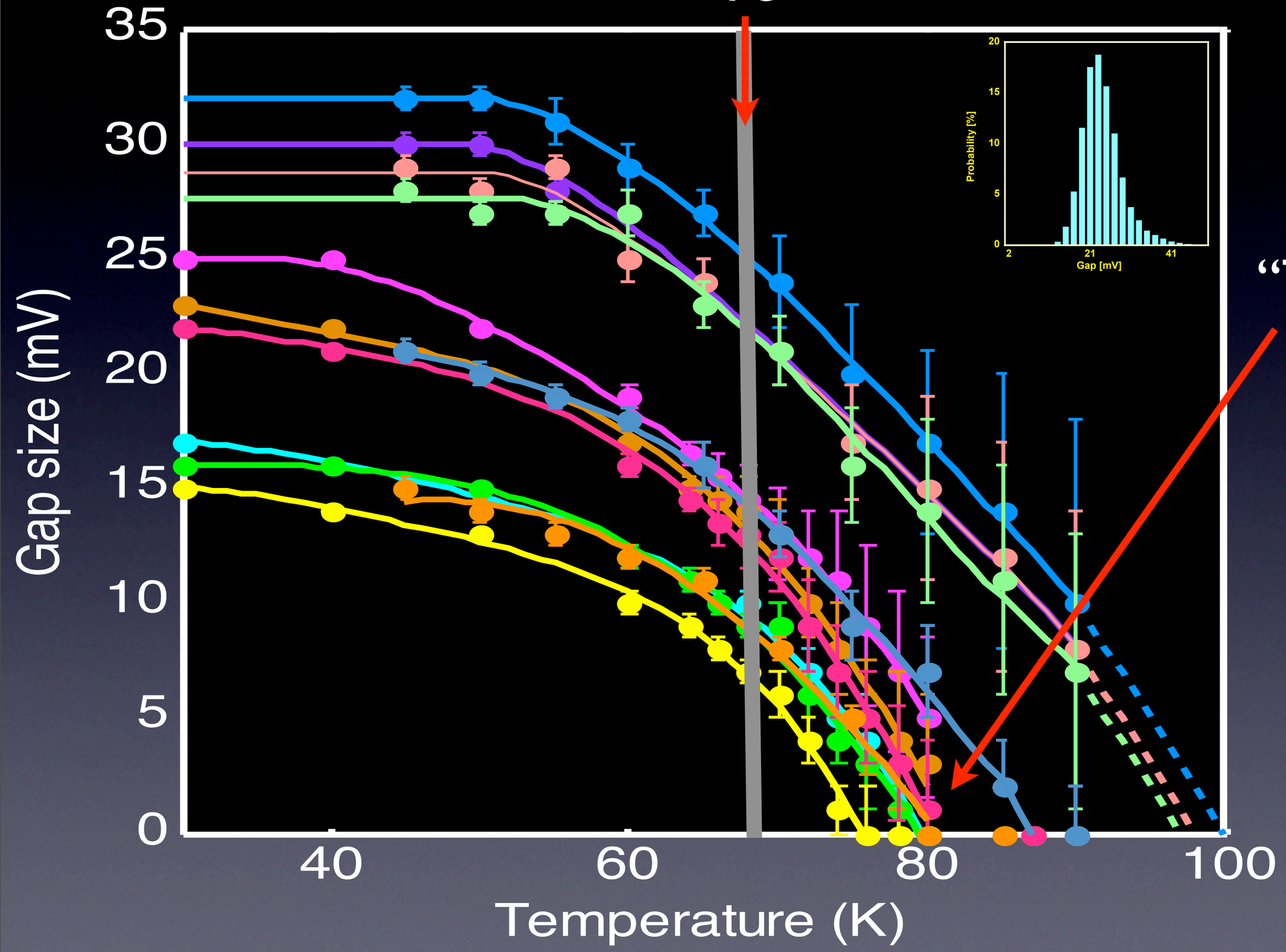


Extract the local d-wave Pairing Gap

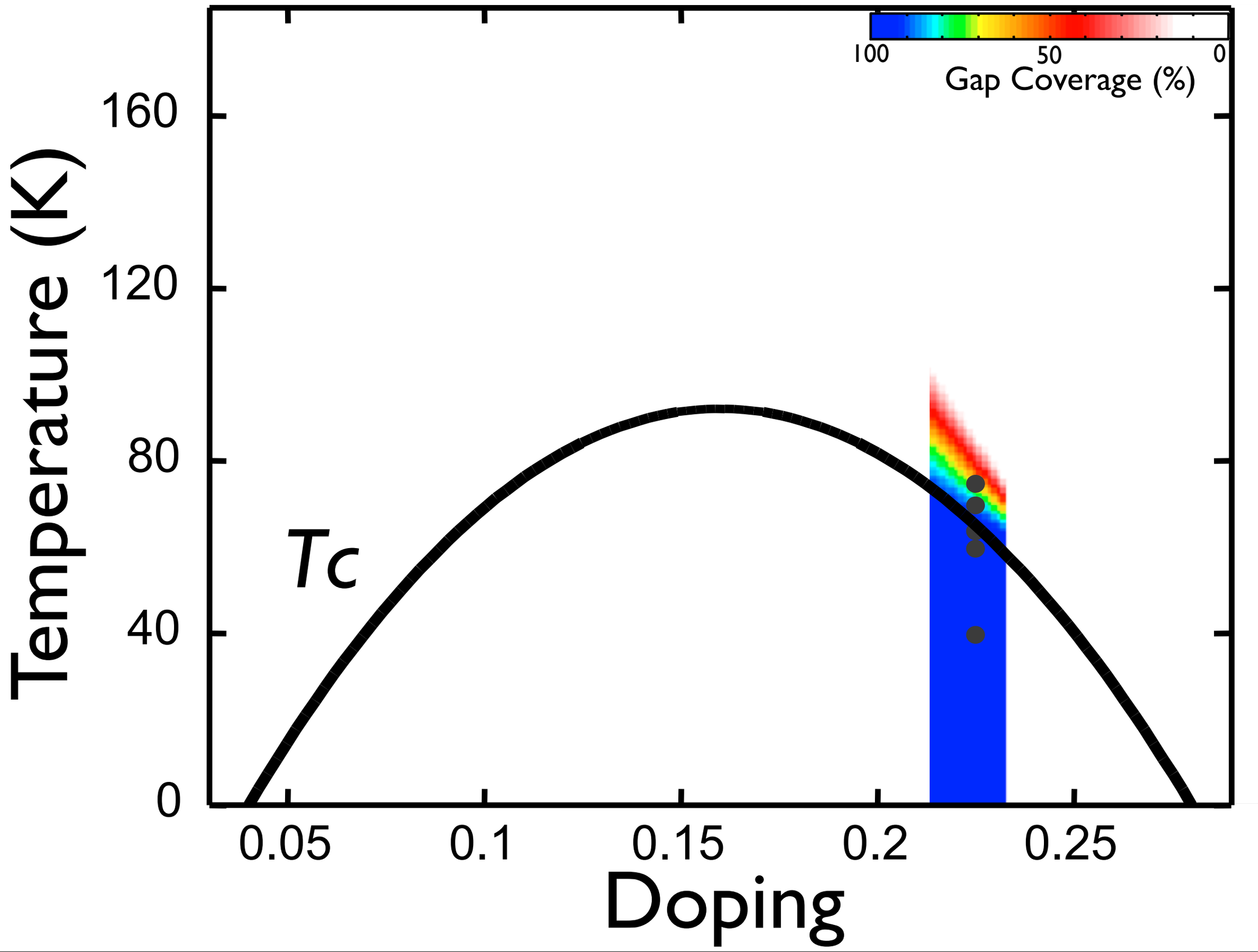


Extract the local d-wave Pairing Gap

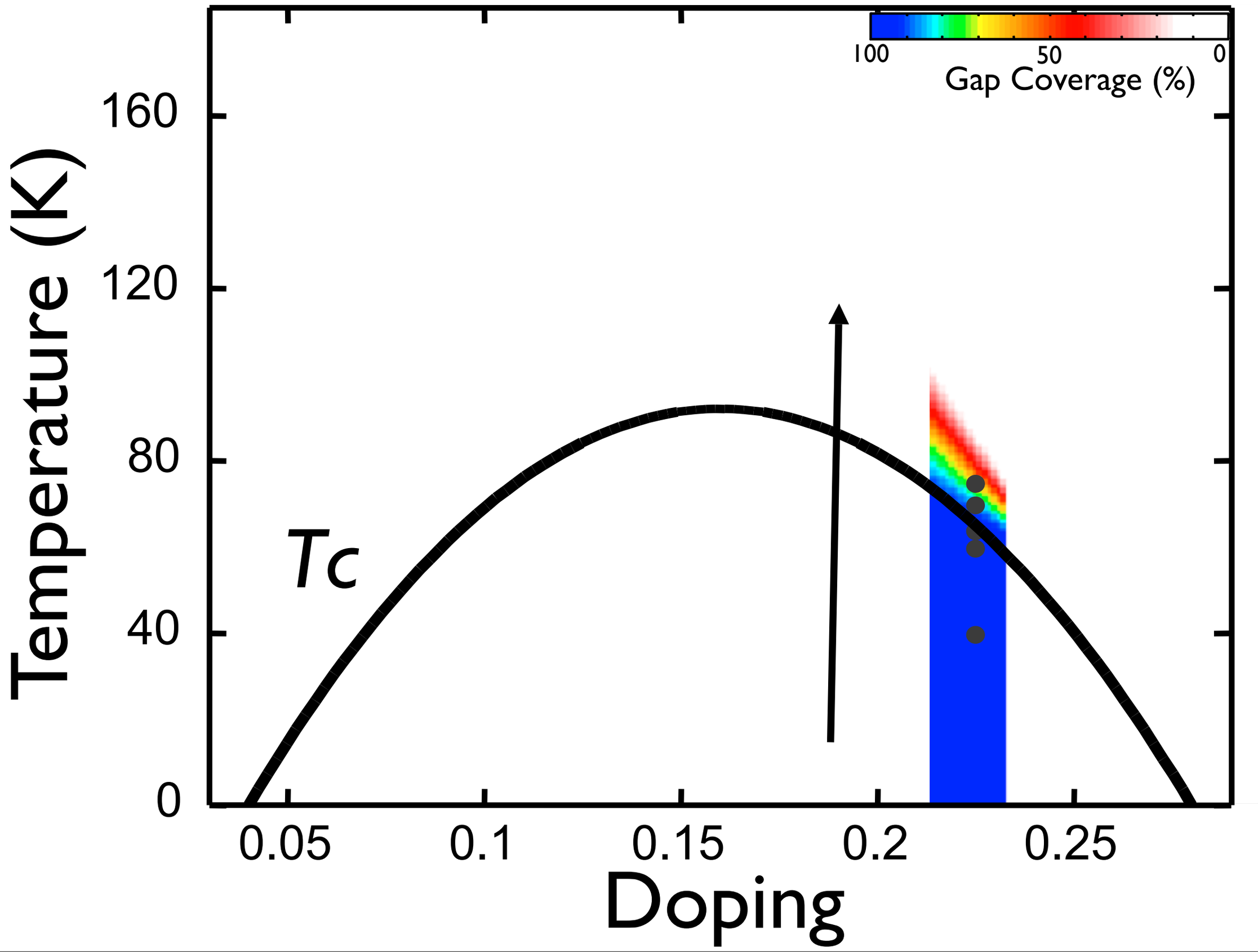
Tc



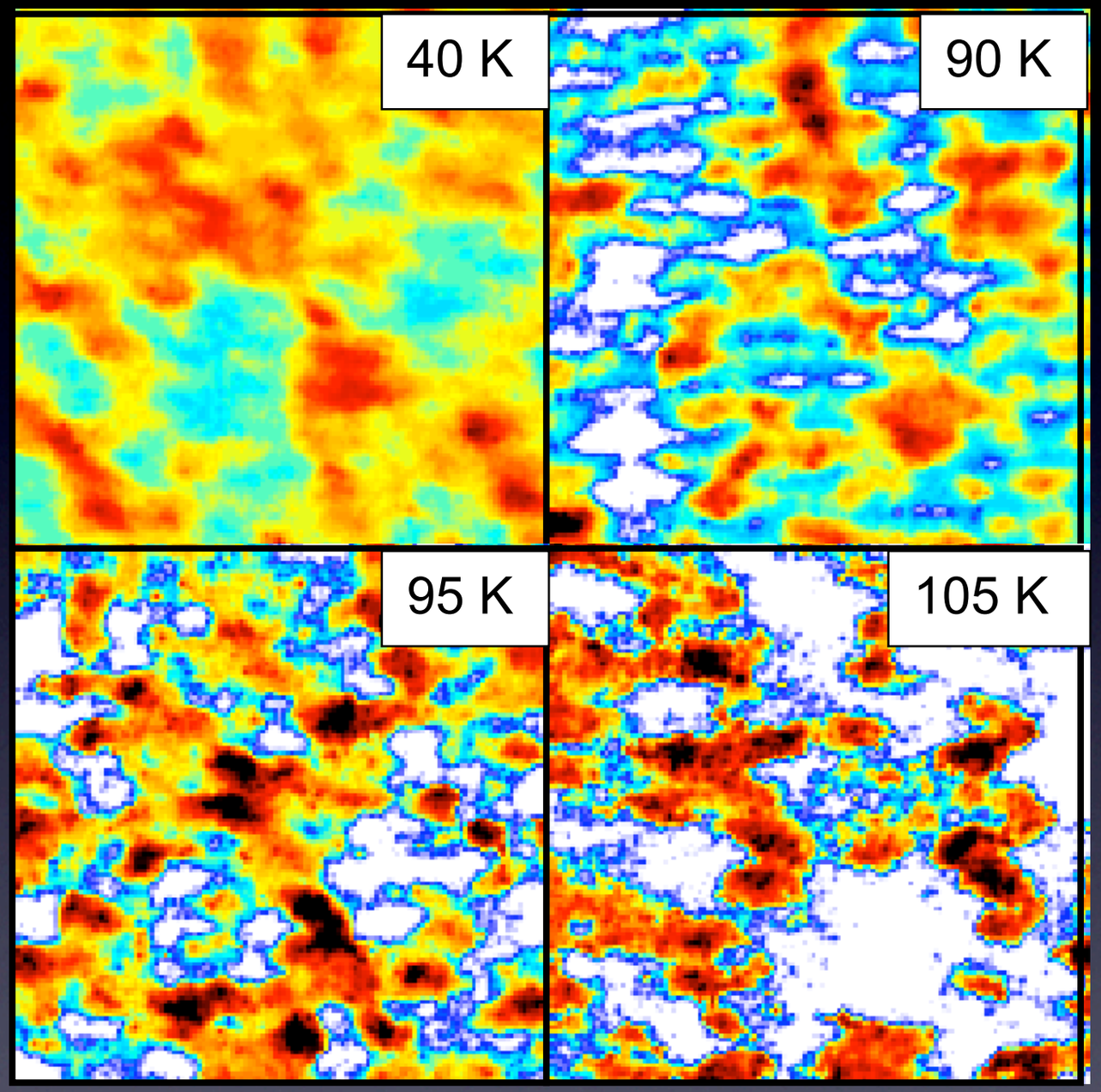
Evolution of gaps in the overdoped regime



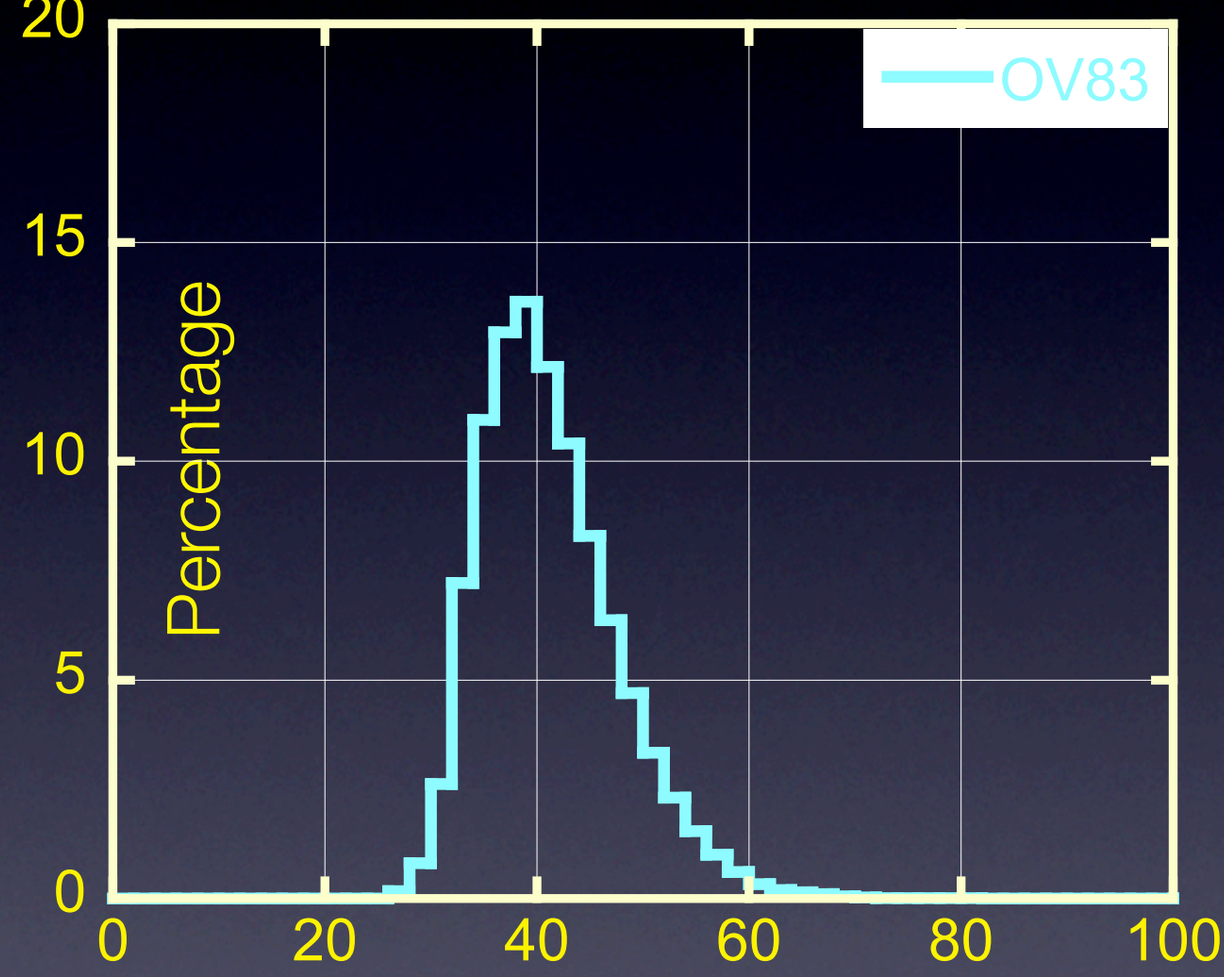
Evolution of gaps in the overdoped regime



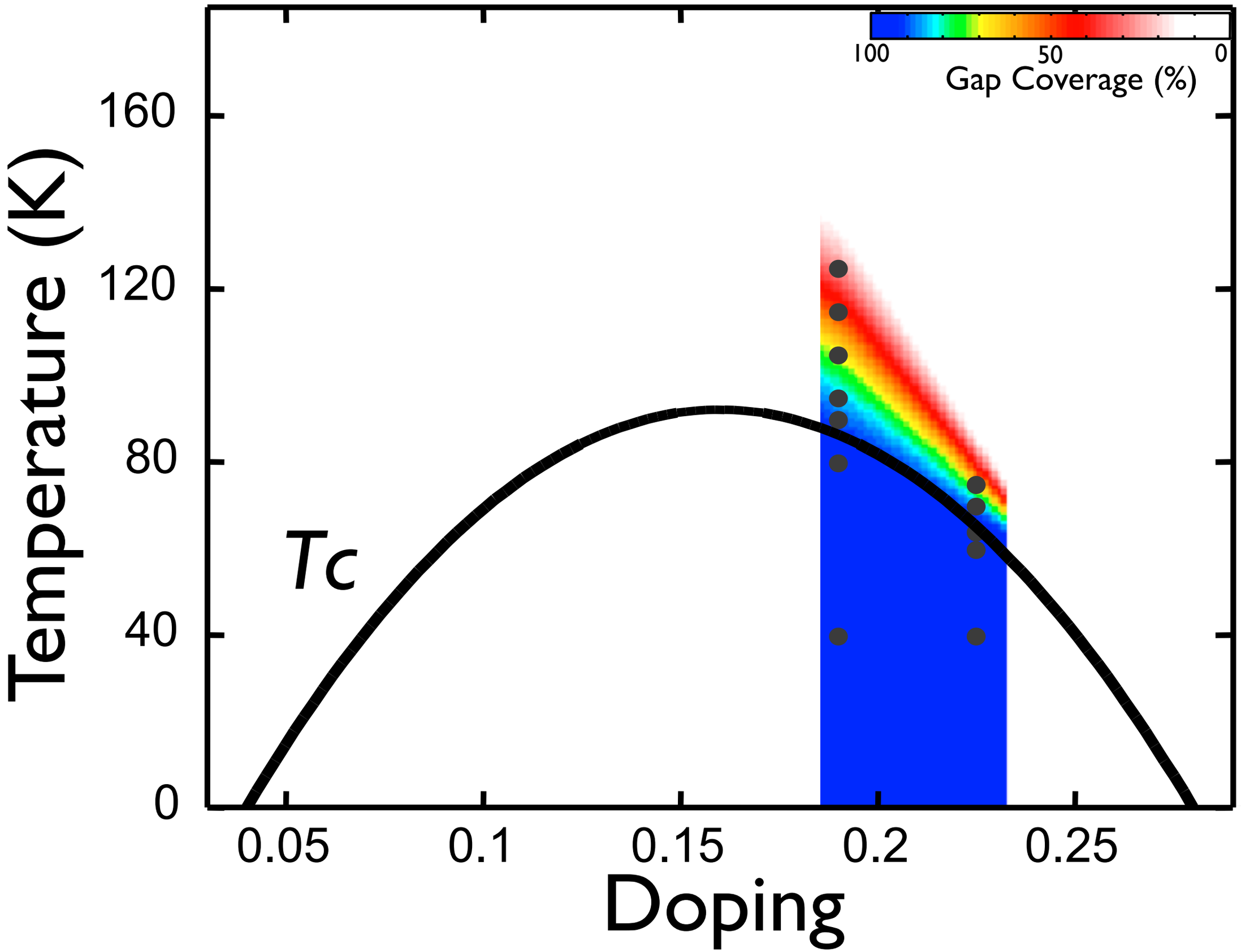
Slightly overdoped Sample Tc=83K



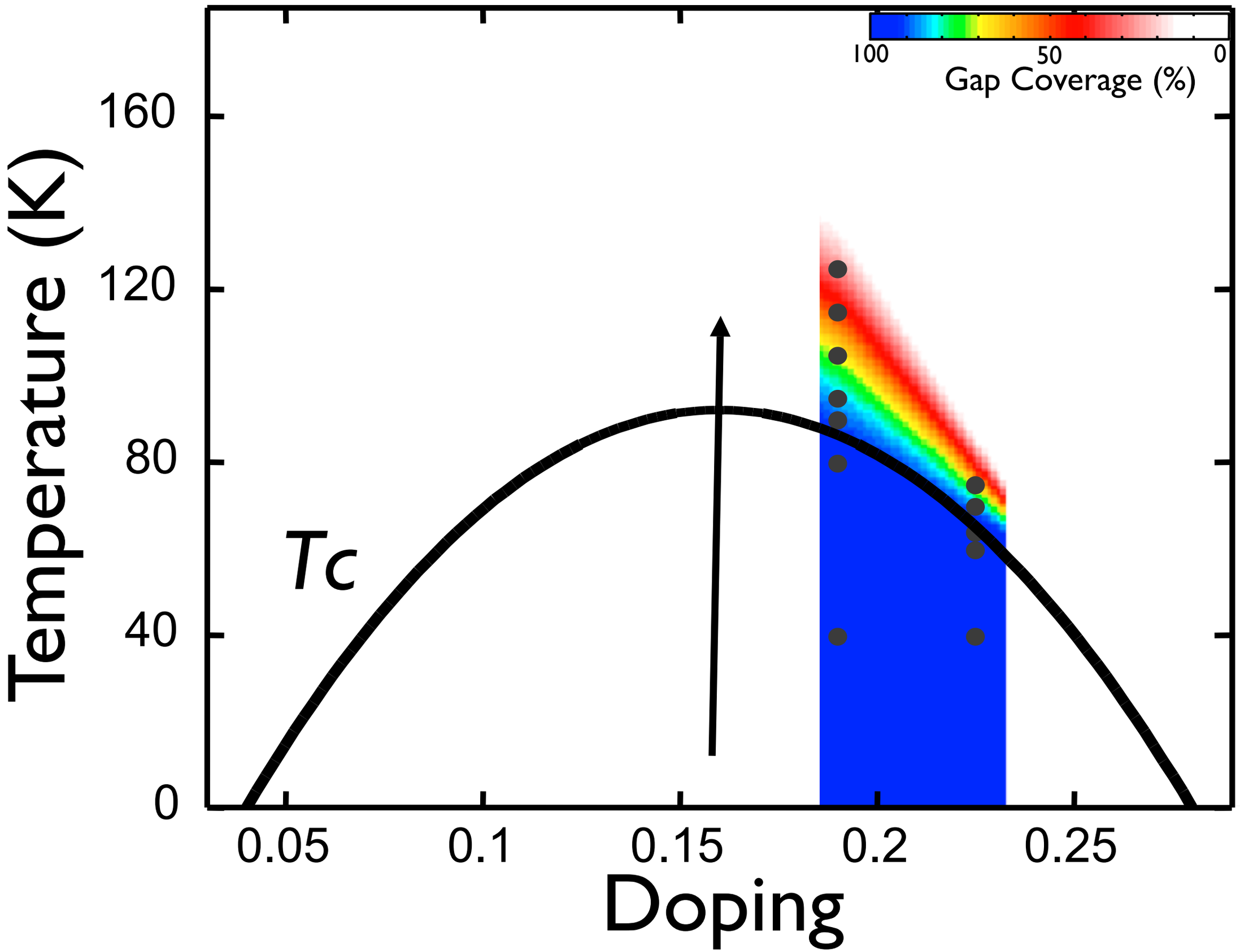
Gaps get large with reduced doping



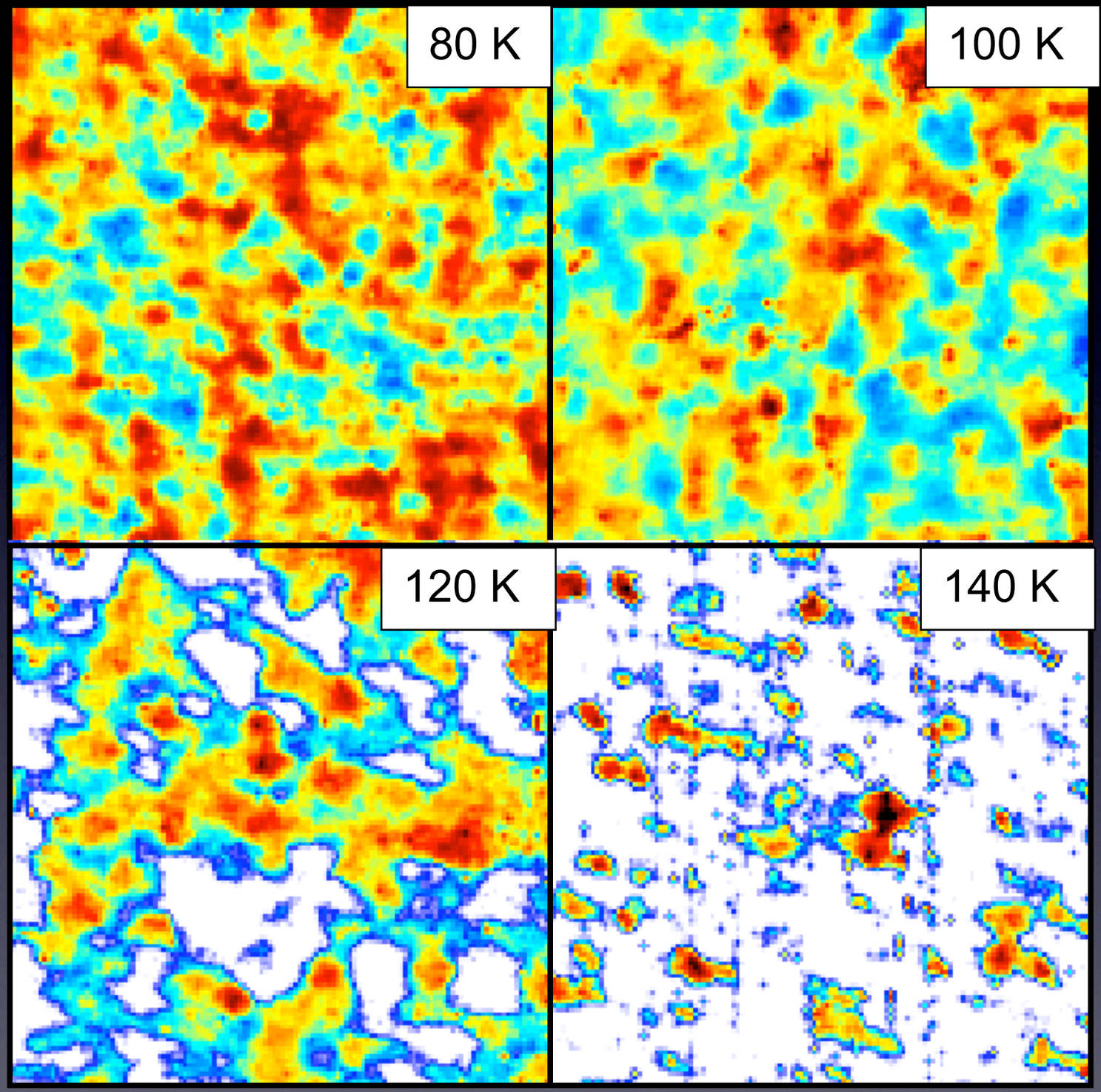
Evolution of gaps in the overdoped regime

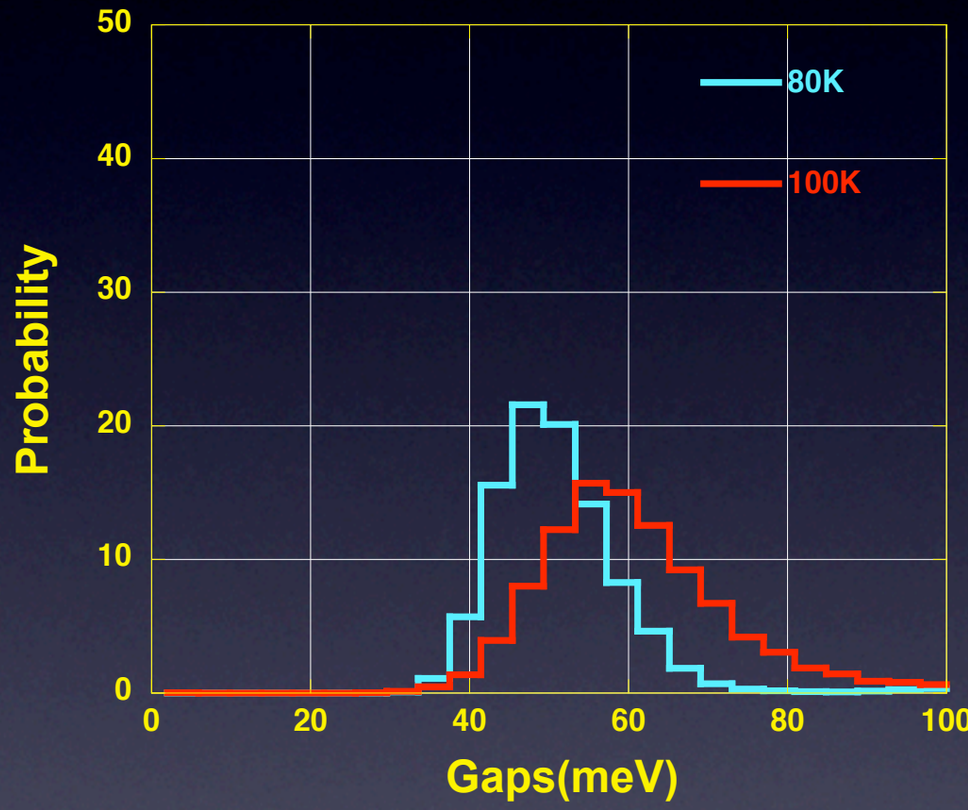


Evolution of gaps in the overdoped regime



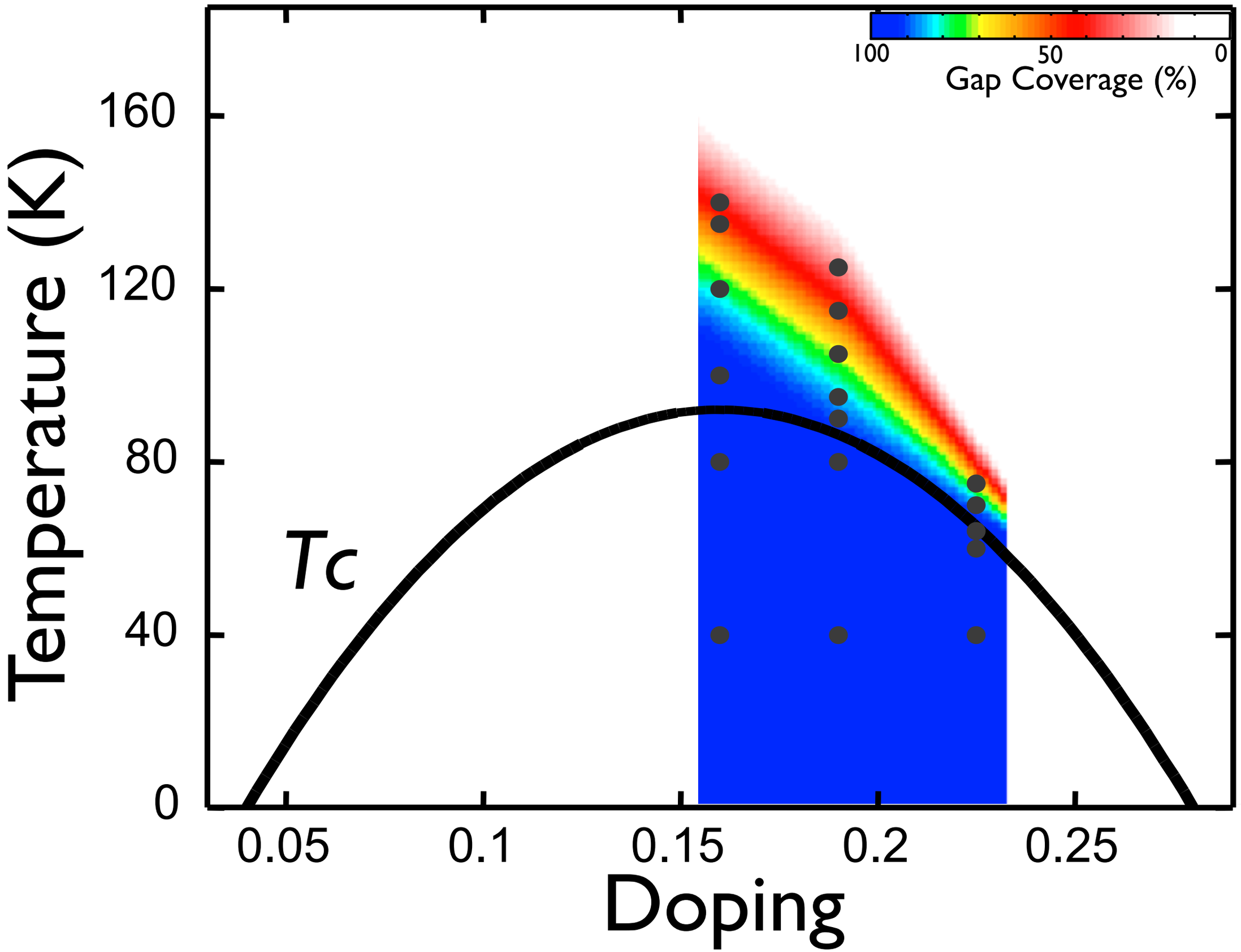
Optimally doped Sample Tc=93K



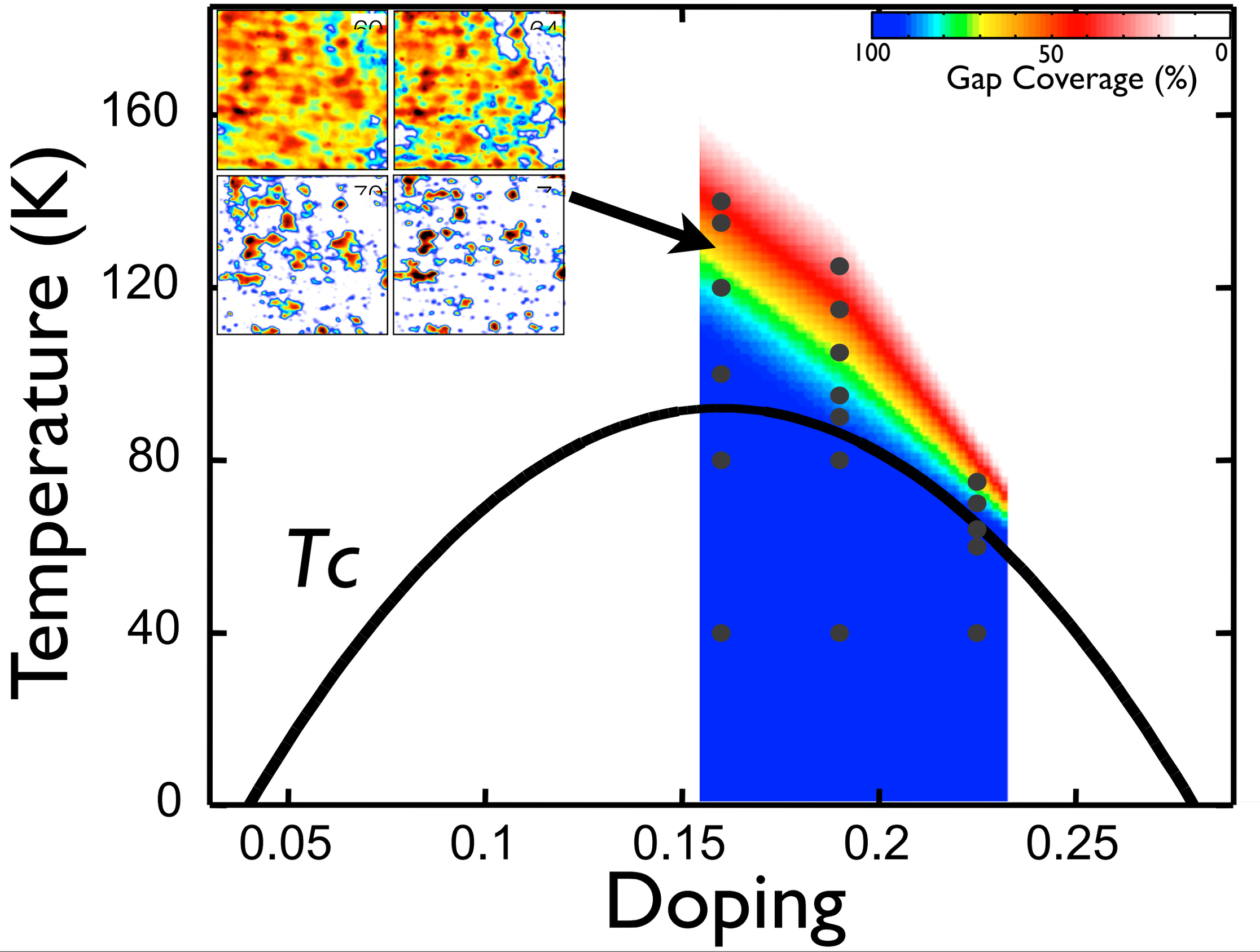




Local Pairing Gap Detected Above Tc

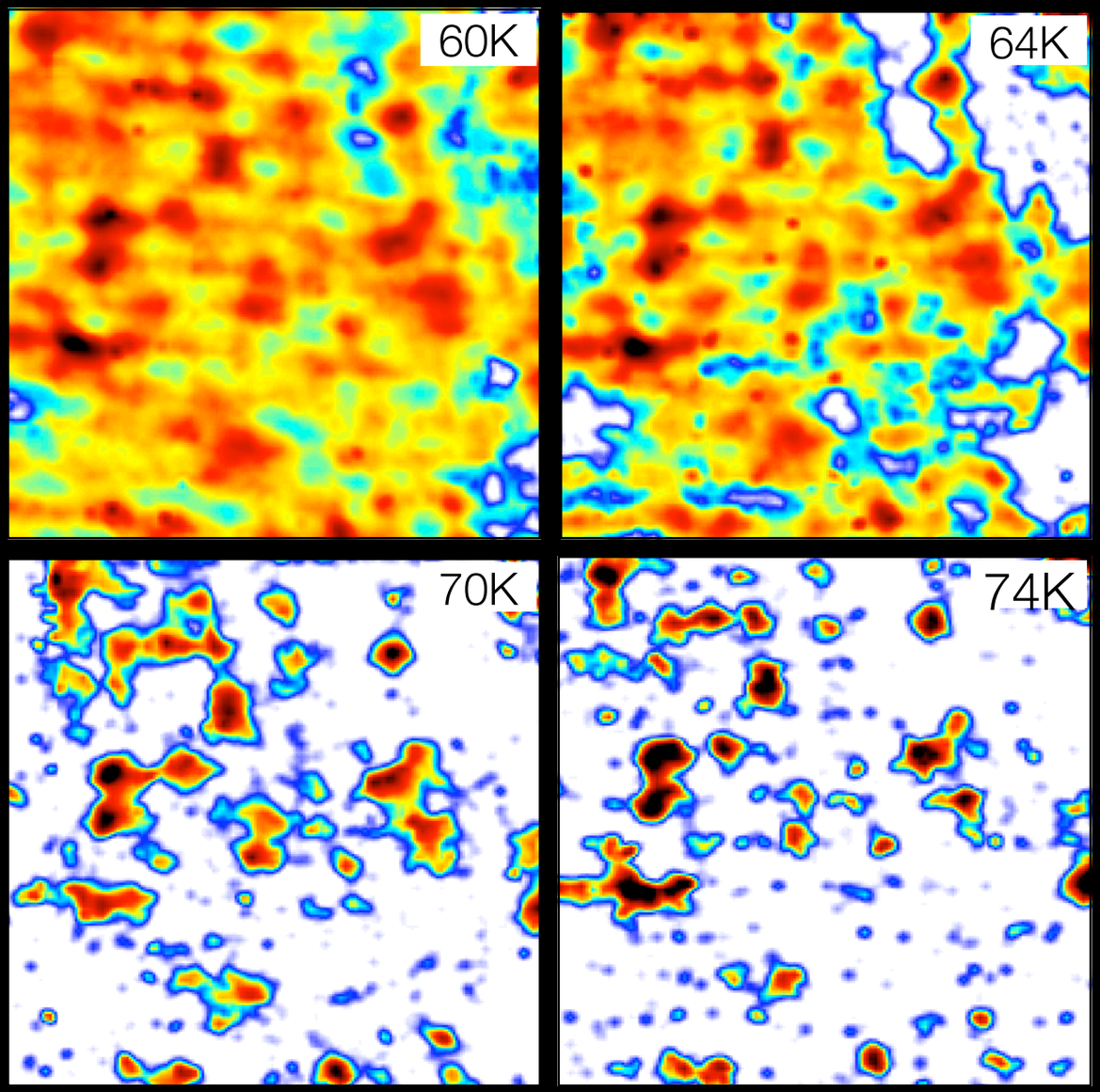


Local Pairing Gap Detected Above Tc



Thermodynamic transitions in inhomogeneous d-wave superconductors

Brian M. Andersen[1,2], Ashot Melikyan[1], Tamara S. Nunner[3], and P. J. Hirschfeld[1,4]
[1]*Department of Physics, University of Florida, Gainesville, Florida 32611-8440, USA*
[2]*Laboratoire de Physique Quantique (CNRS), ESPCI, 10 Rue de Vauquelin, 75231 Paris, France*
[3]*Institut für Theoretische Physik, Freie Universtität Berlin, Arnimallee 14, 14195 Berlin, Germany*
[4]*Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France*
(Dated: April 3, 2006)



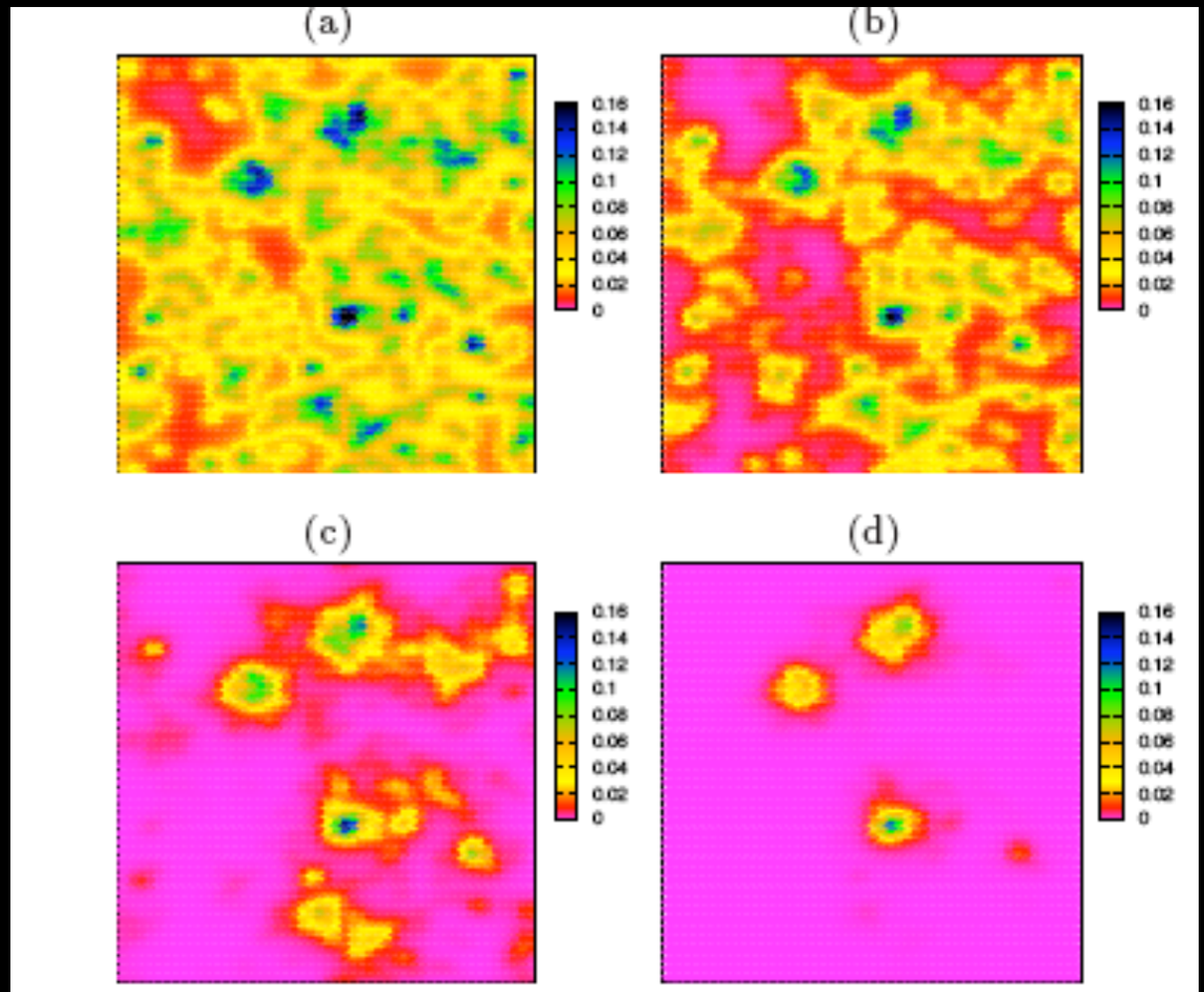
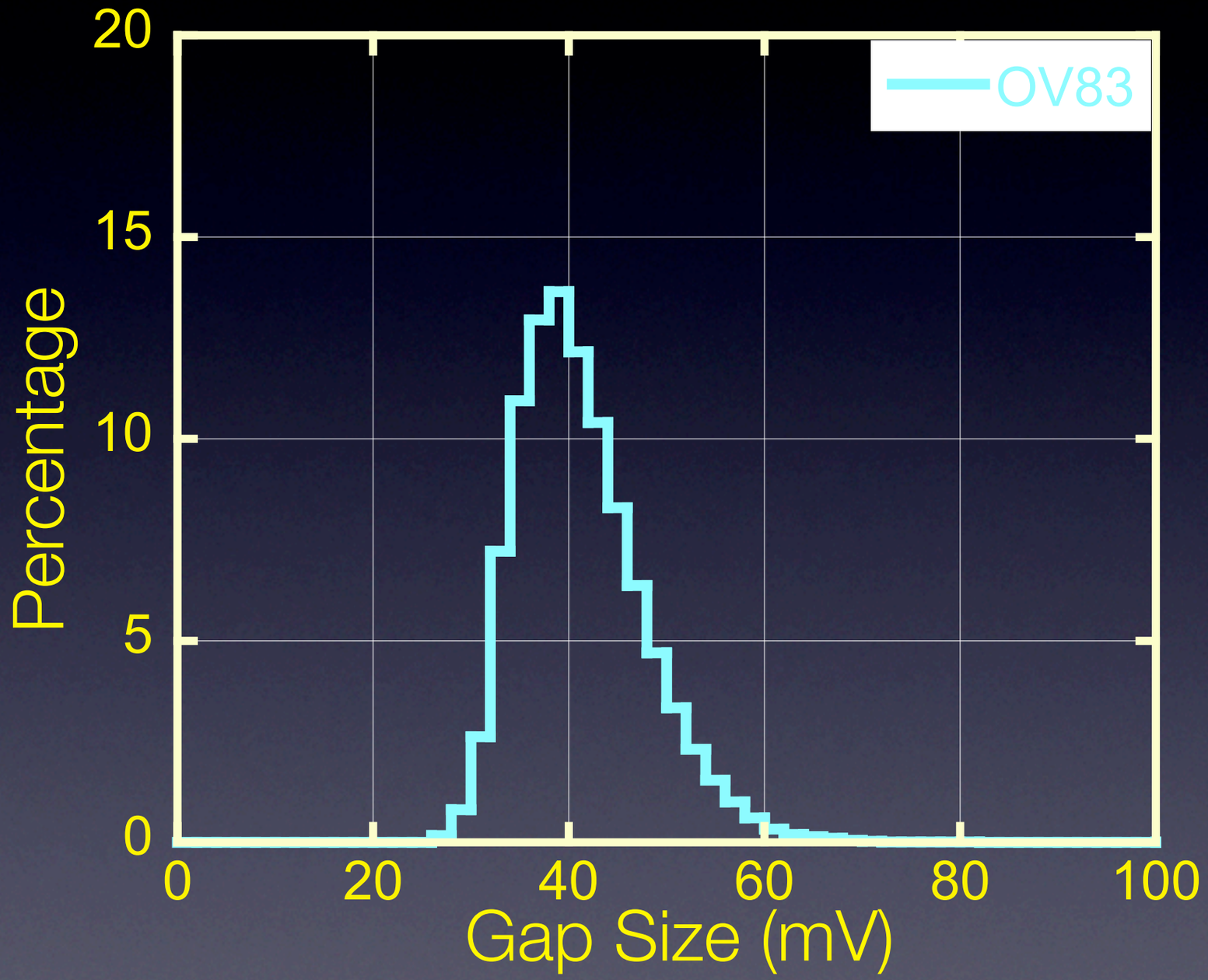


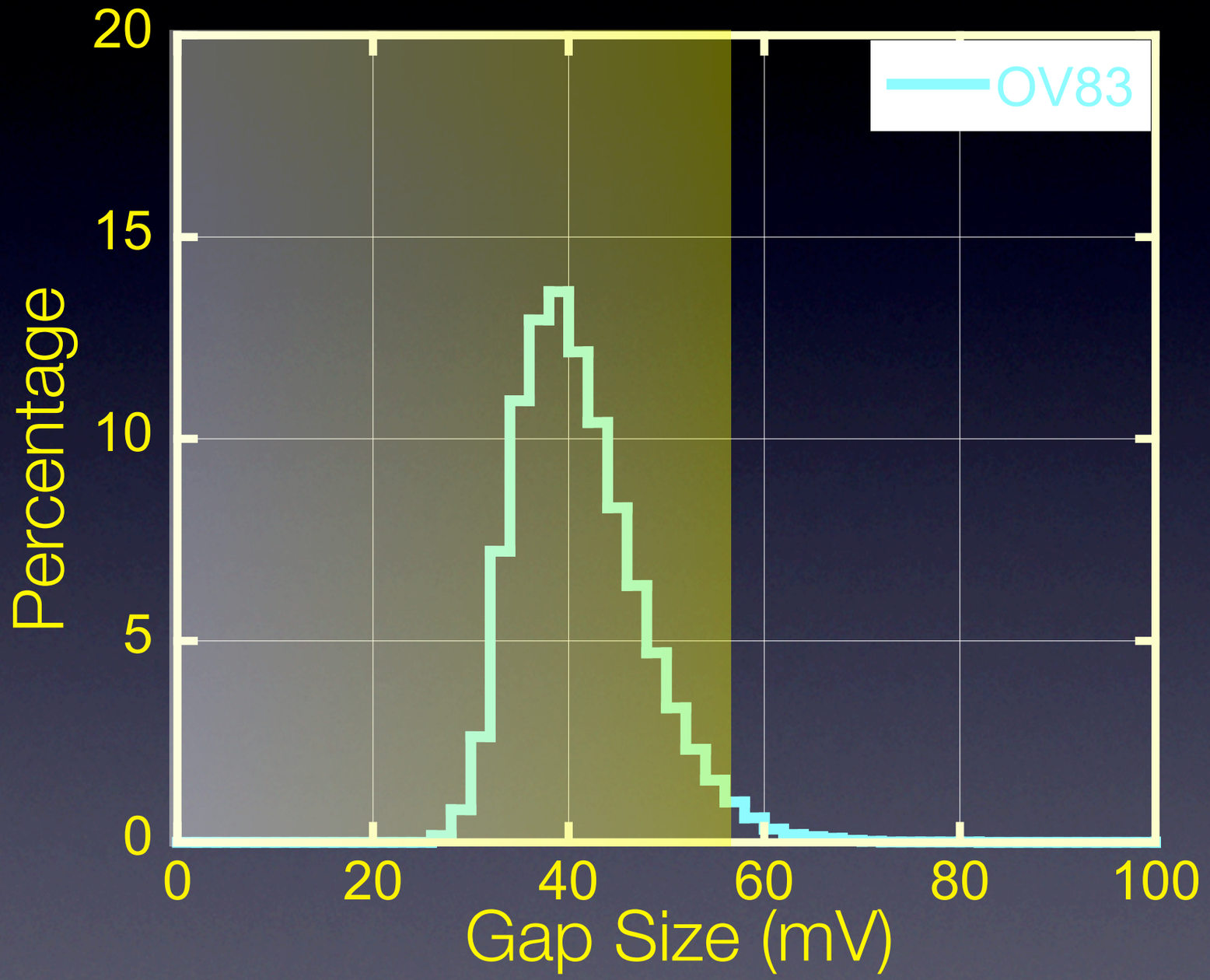
FIG. 2: (Color online) OP maps, parameters from Fig. 1(d): $T=0.18t$ (a), $T=0.20t$ (b), $T=0.22t$ (c), and $T=0.24t$ (d).

Is there a relation between T_p and Δ?



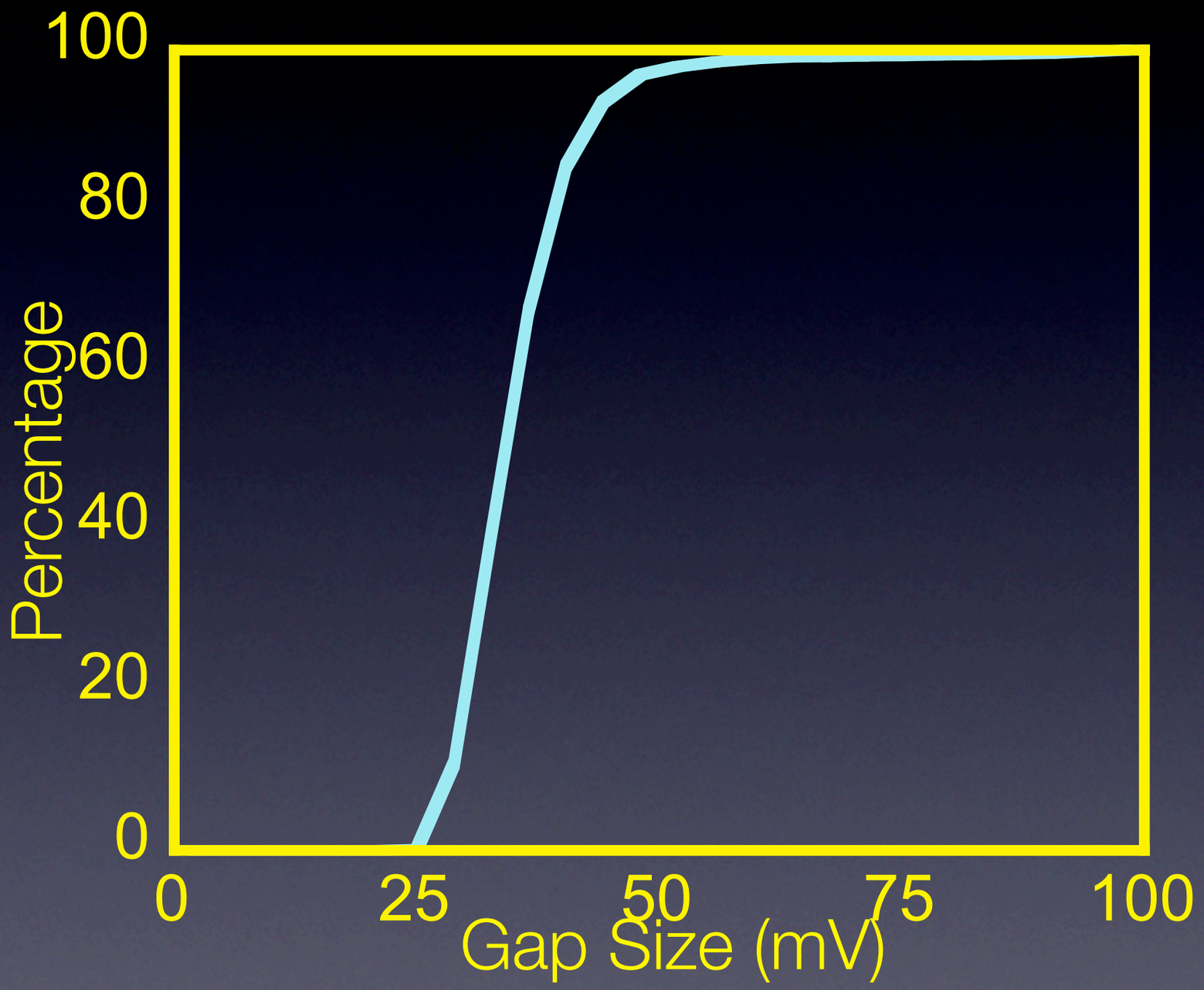
- Smaller Δ will vanish first
- $T_p \propto \Delta$?
- Gap distribution is also T_p distribution

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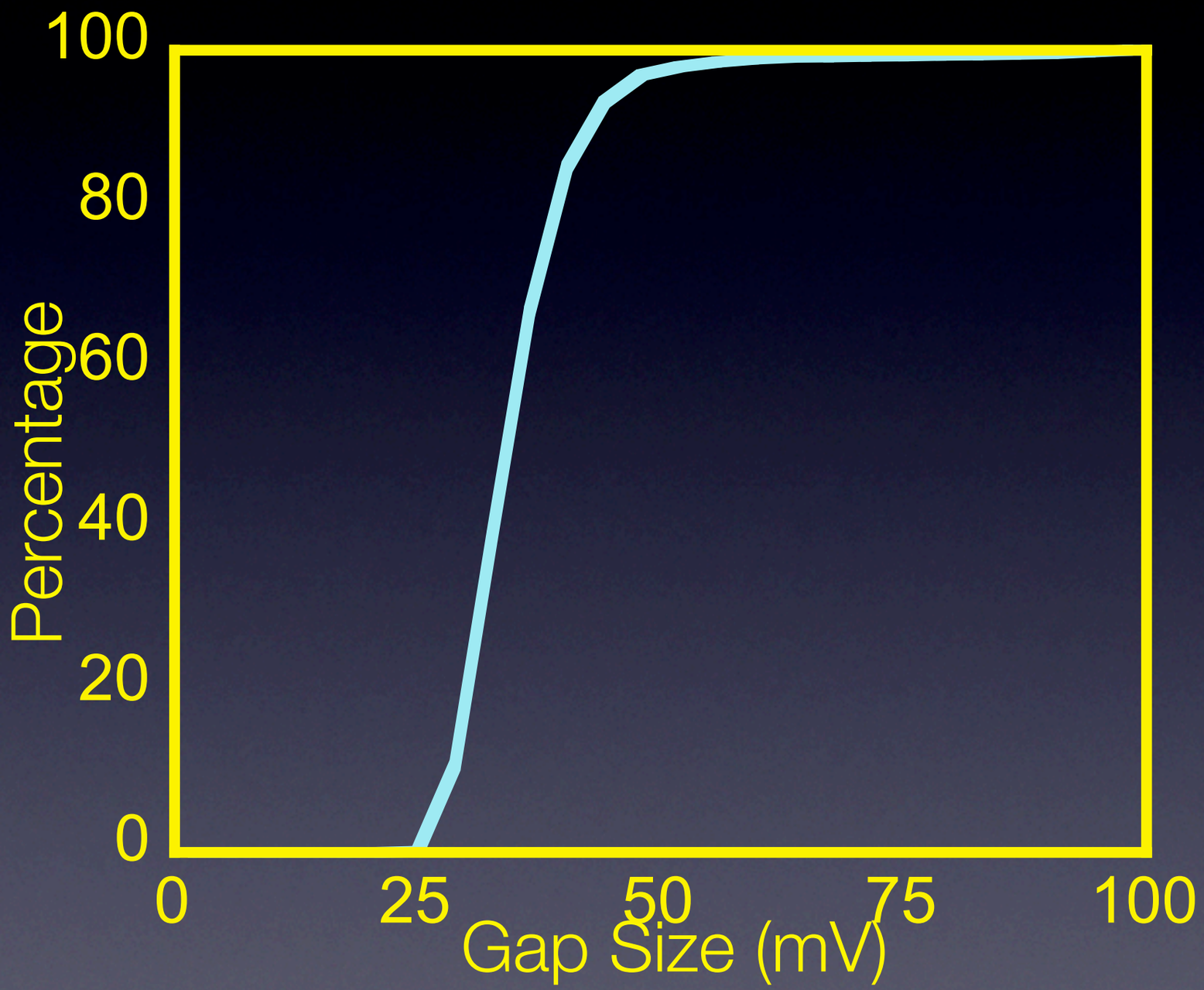
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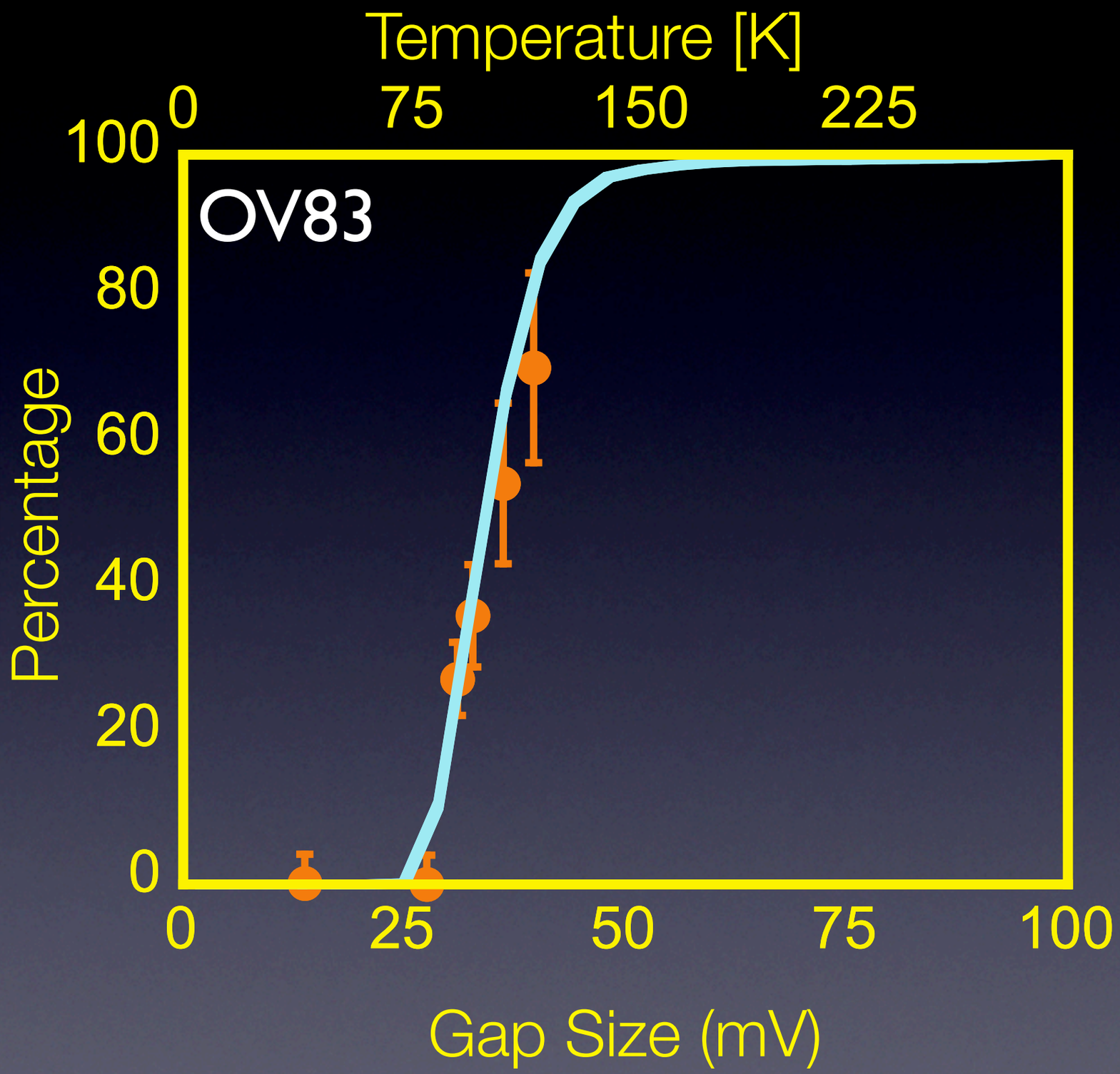
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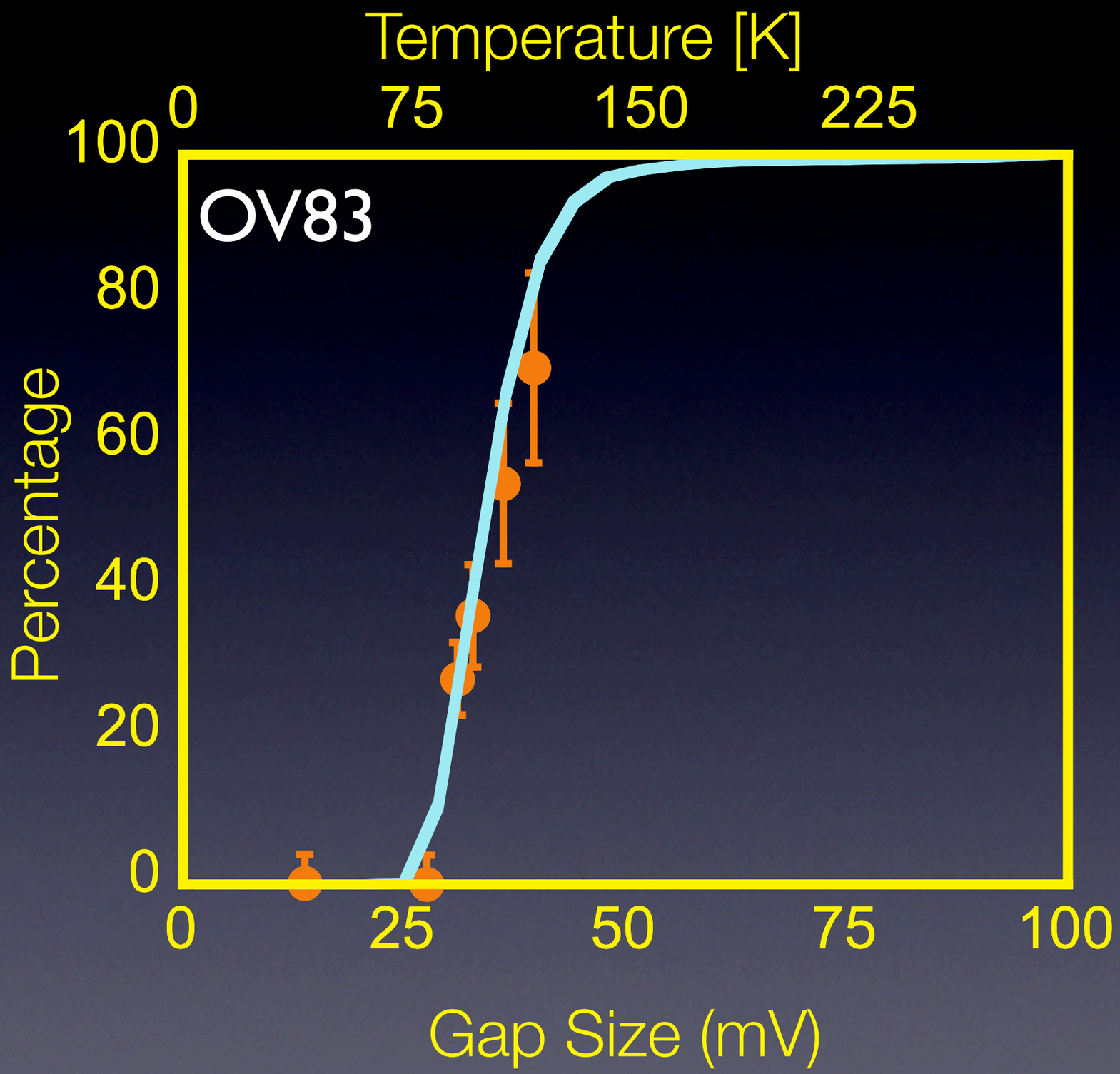
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Integral of Gap Histogram = Percentage of Ungaped Regions

Relation between T_p and Δ?

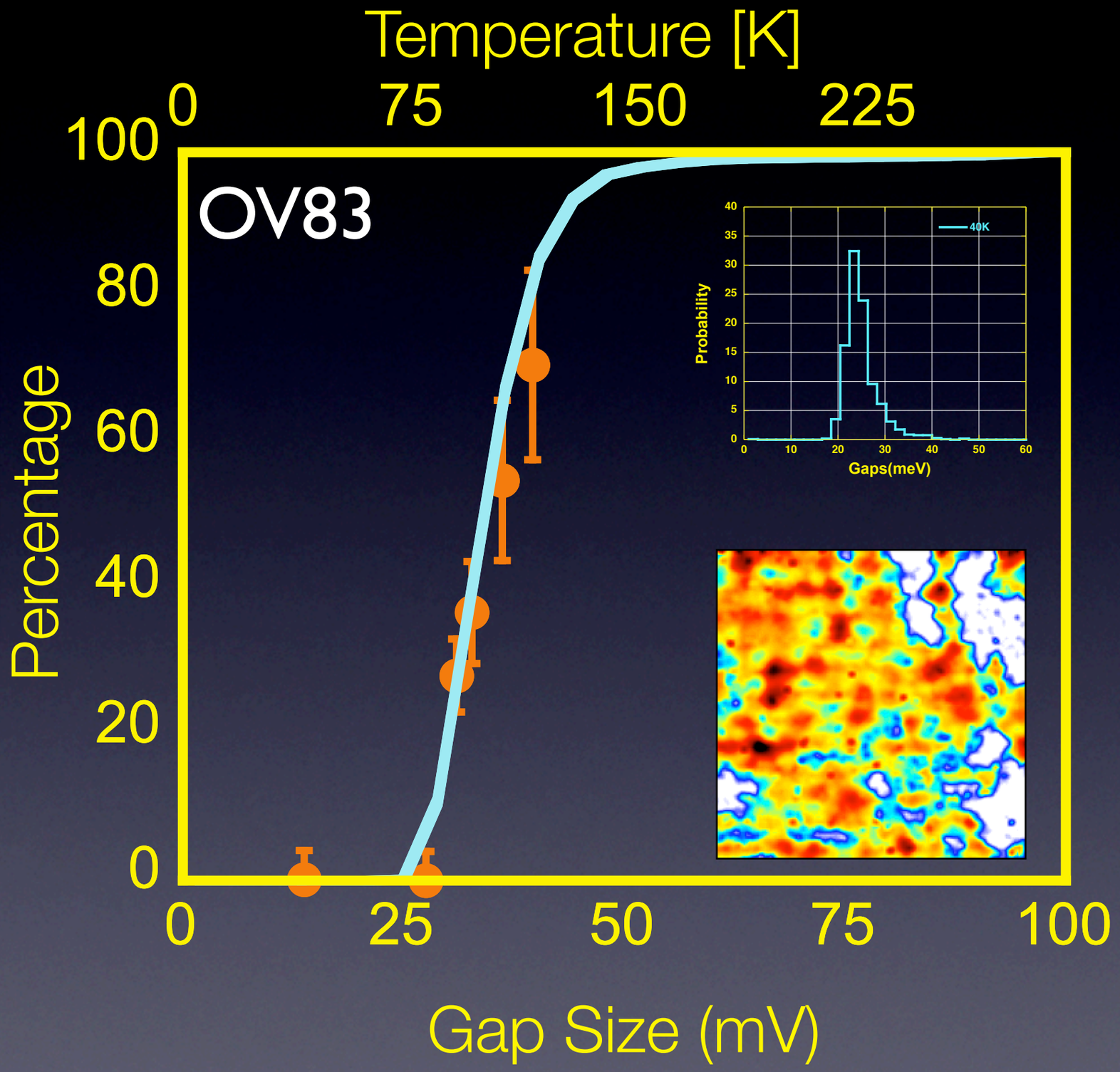


Relation between T_p and Δ?



$$\frac{2\Delta}{k_B T_P} = 7.9 \pm 0.2$$

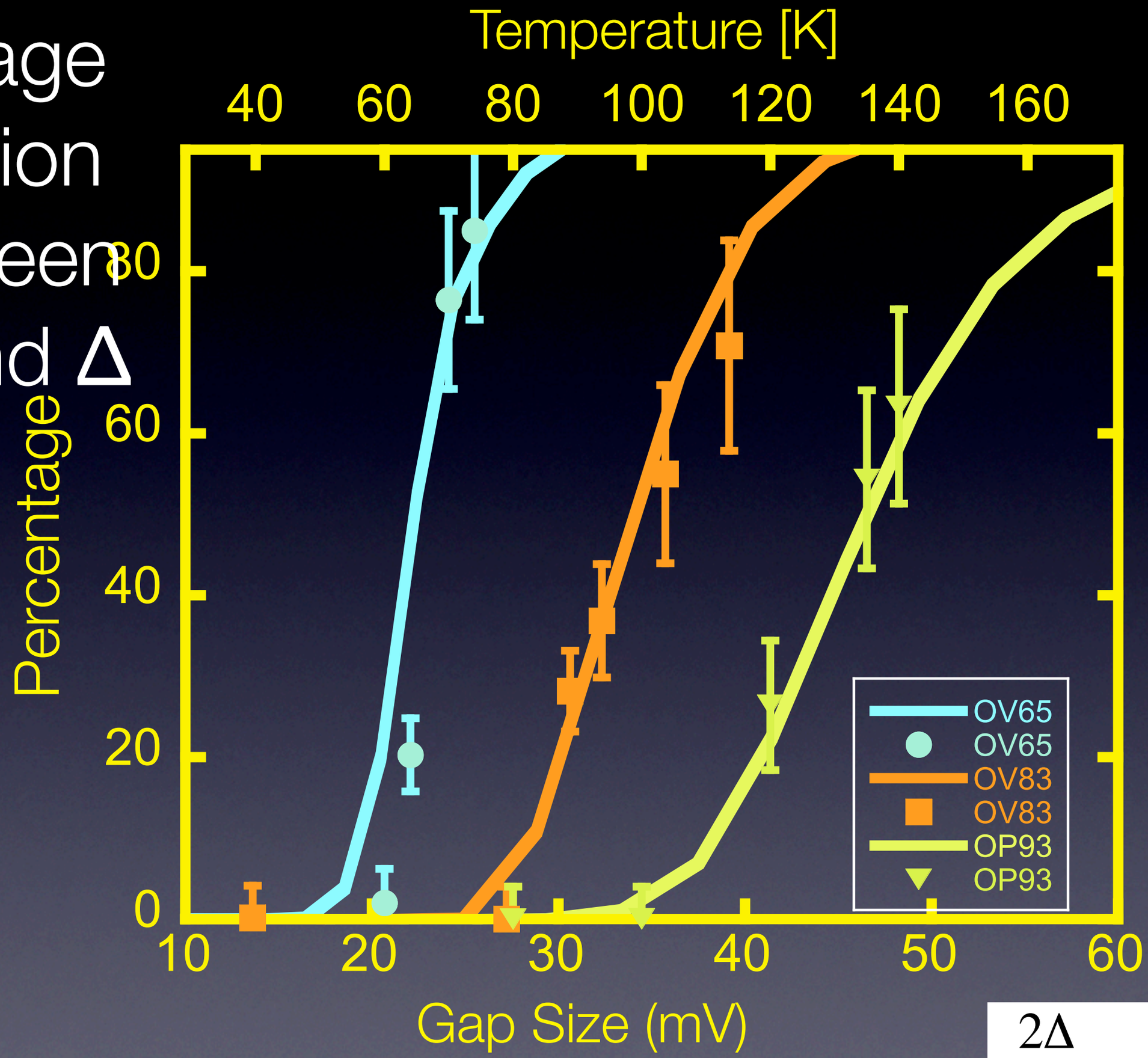
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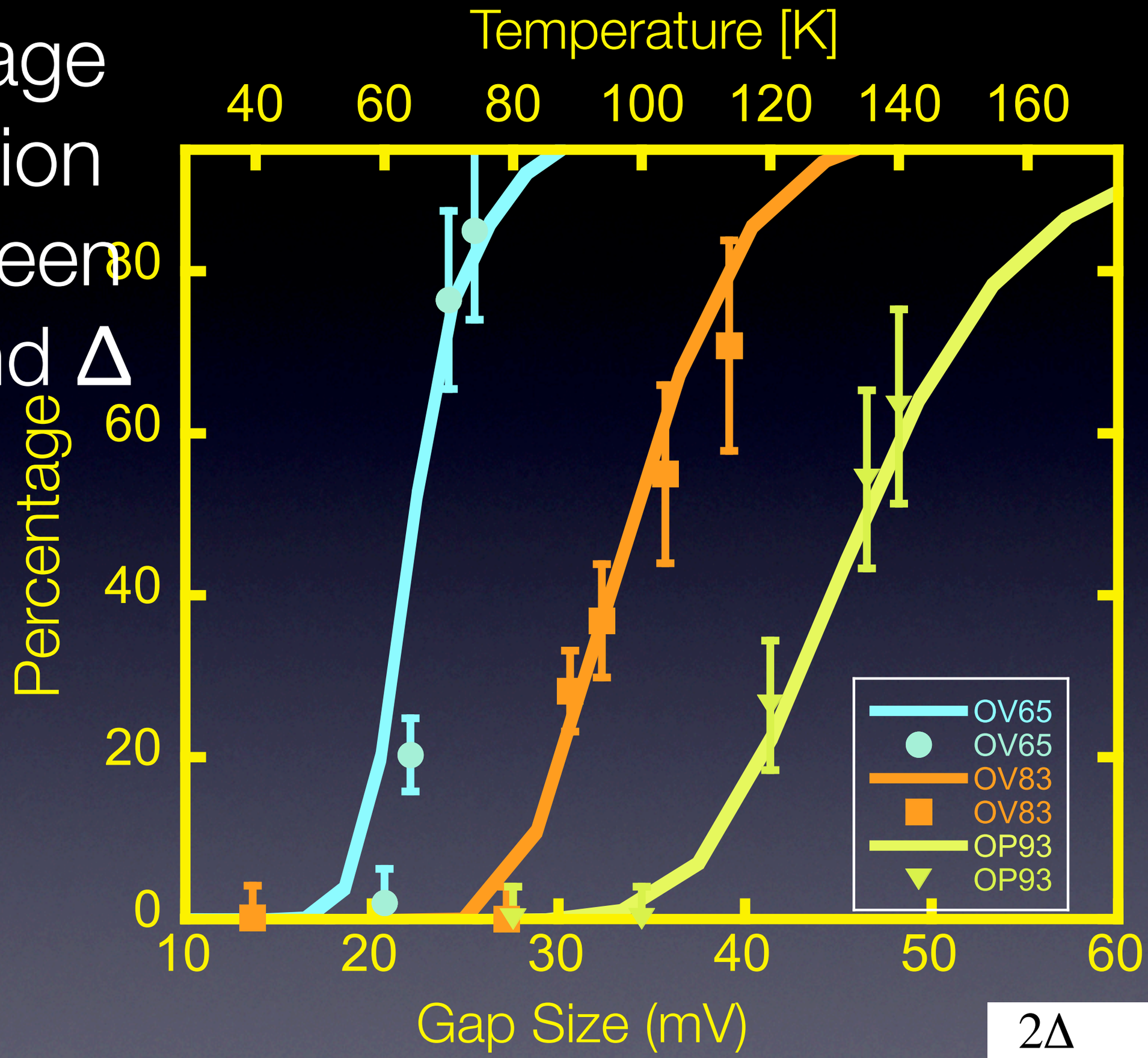
- The ratio is much higher than BCS weak coupling limit (~4 for d-wave).
- Optimal/Overdoped samples appear to have only one energy scale, the pairing gap

Average Relation between T_p and Δ



$$\frac{2\Delta}{k_B T_P} = 8.0 \pm 0.5$$

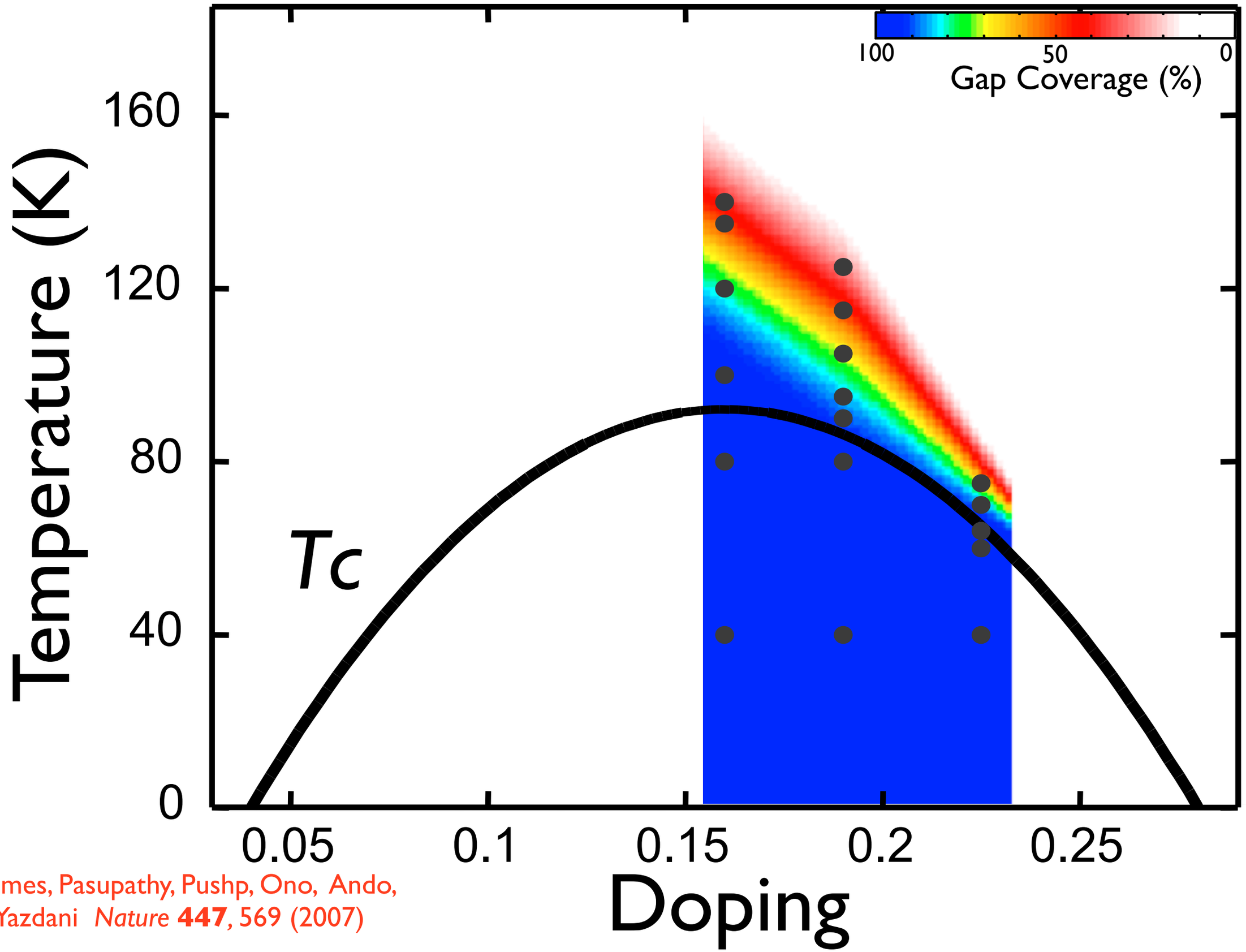
Average Relation between T_p and Δ



~ 1,000,000 Independent Measurements

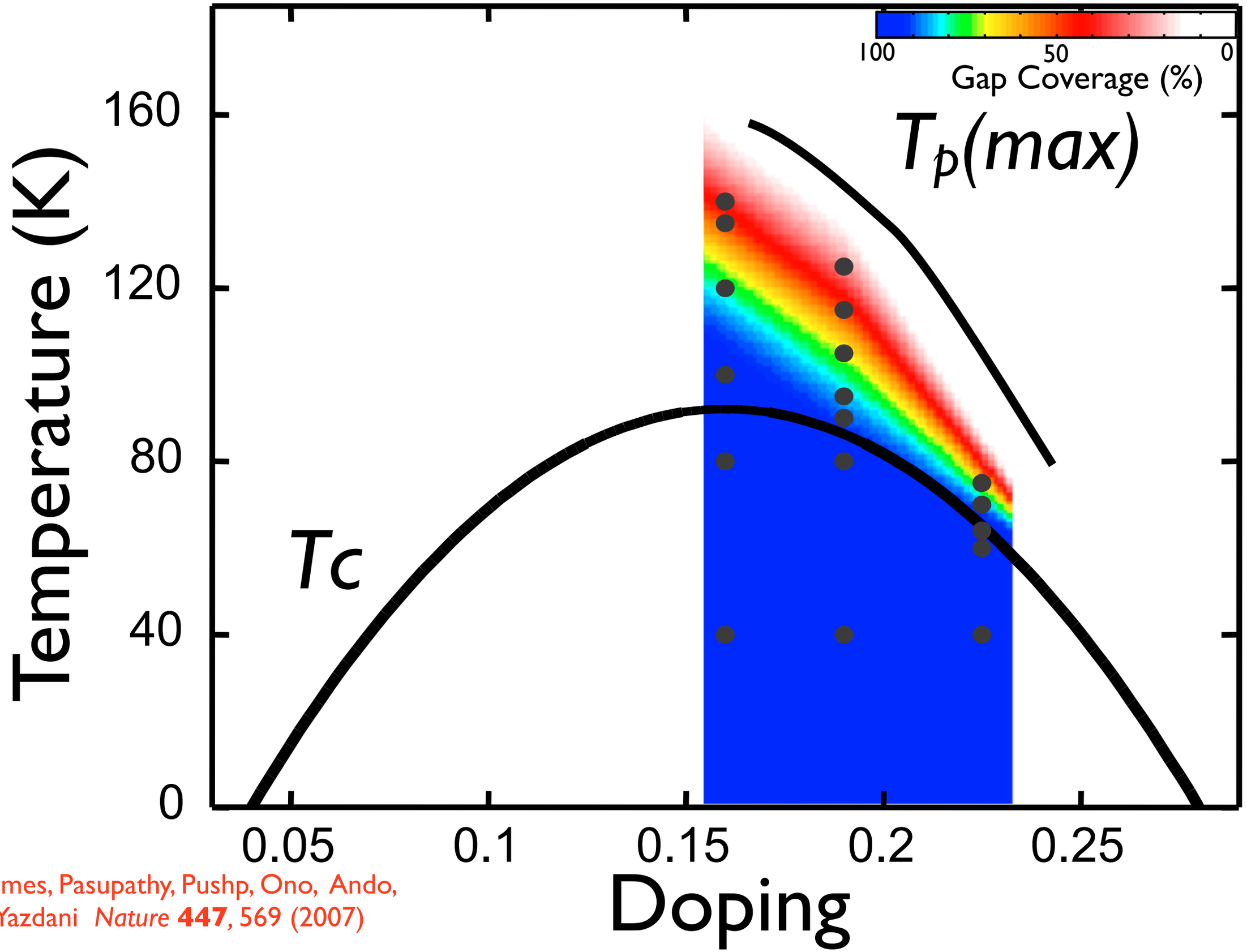
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Compare to other experiments?



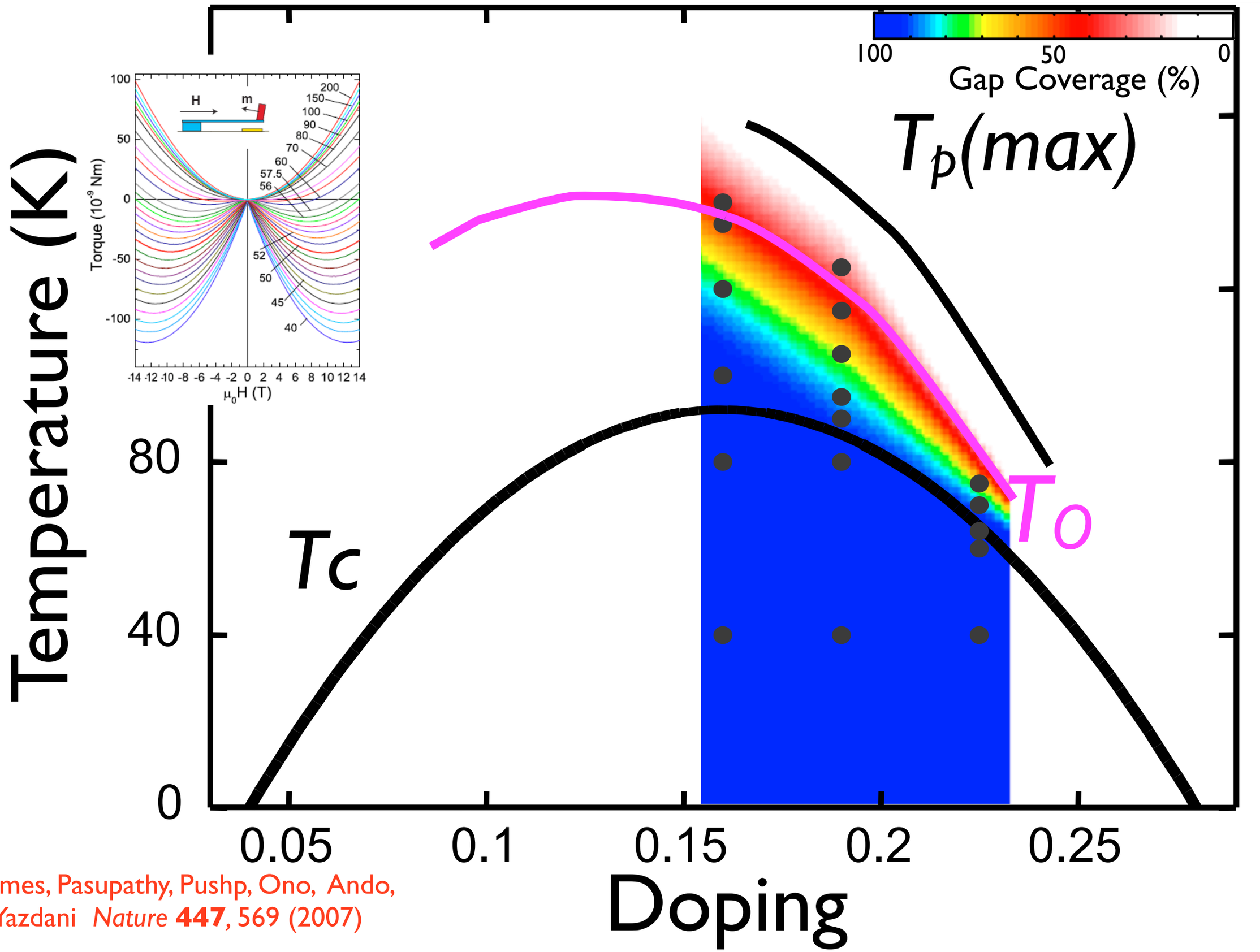
Gomes, Pasupathy, Pushp, Ono, Ando, Yazdani *Nature* **447**, 569 (2007)

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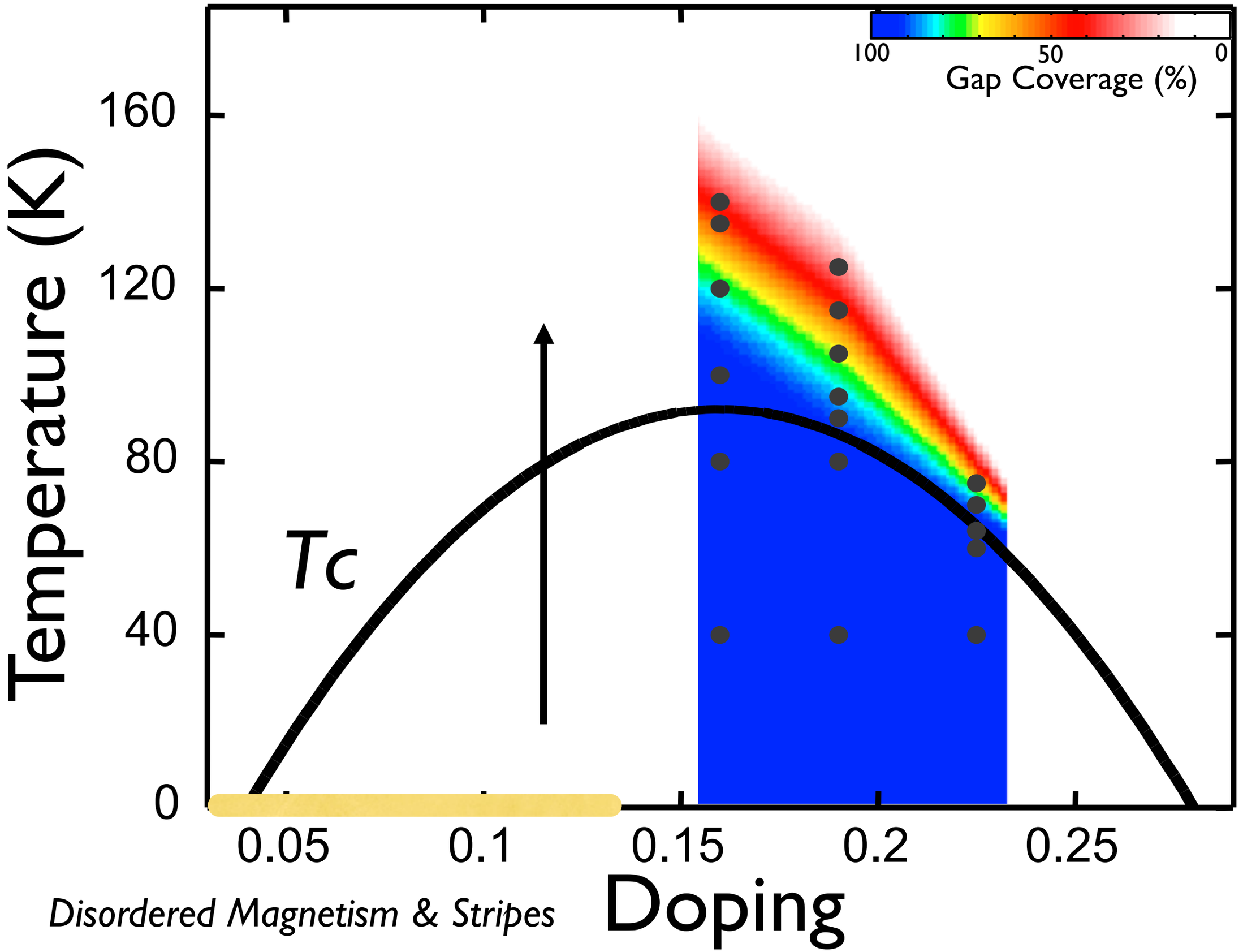
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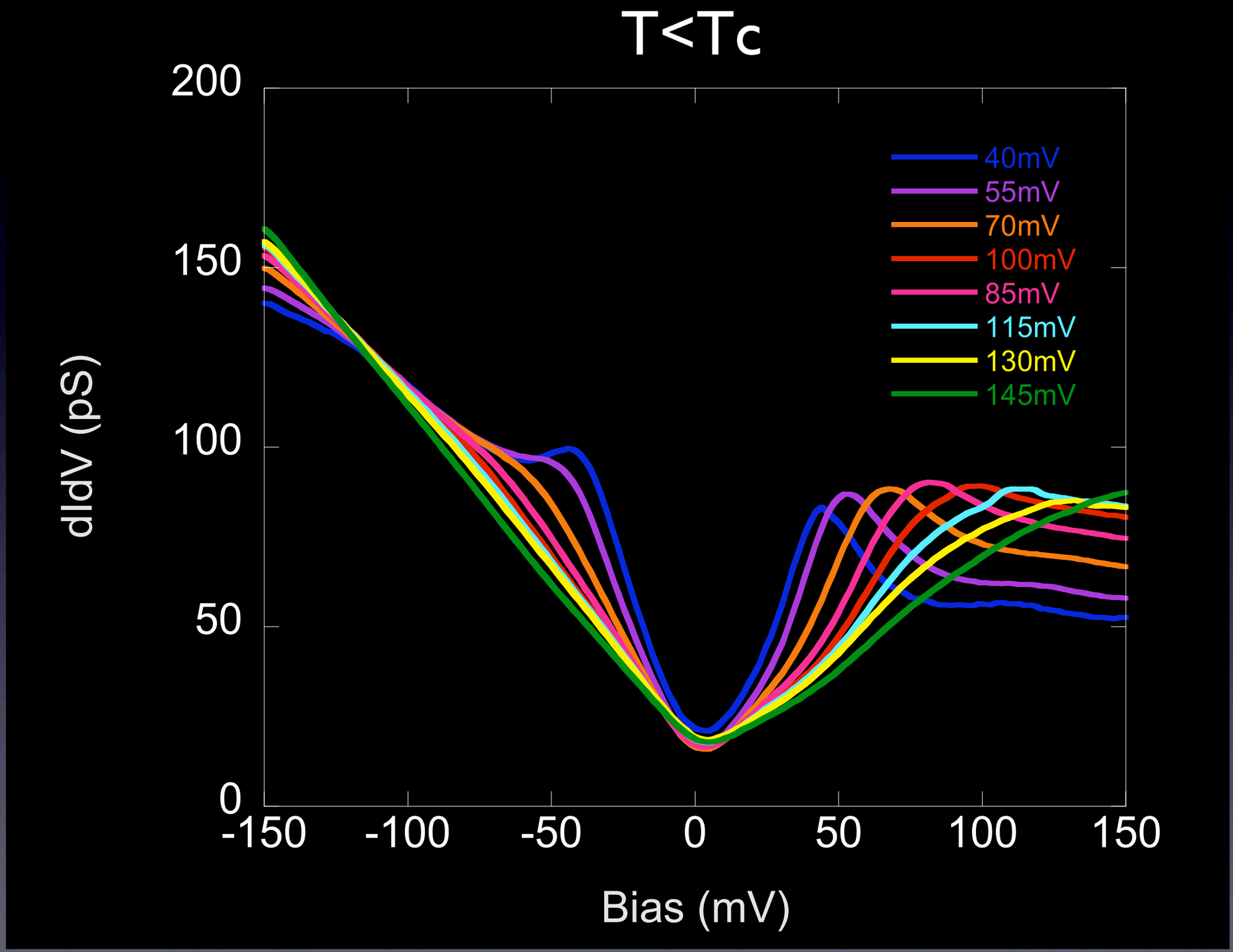


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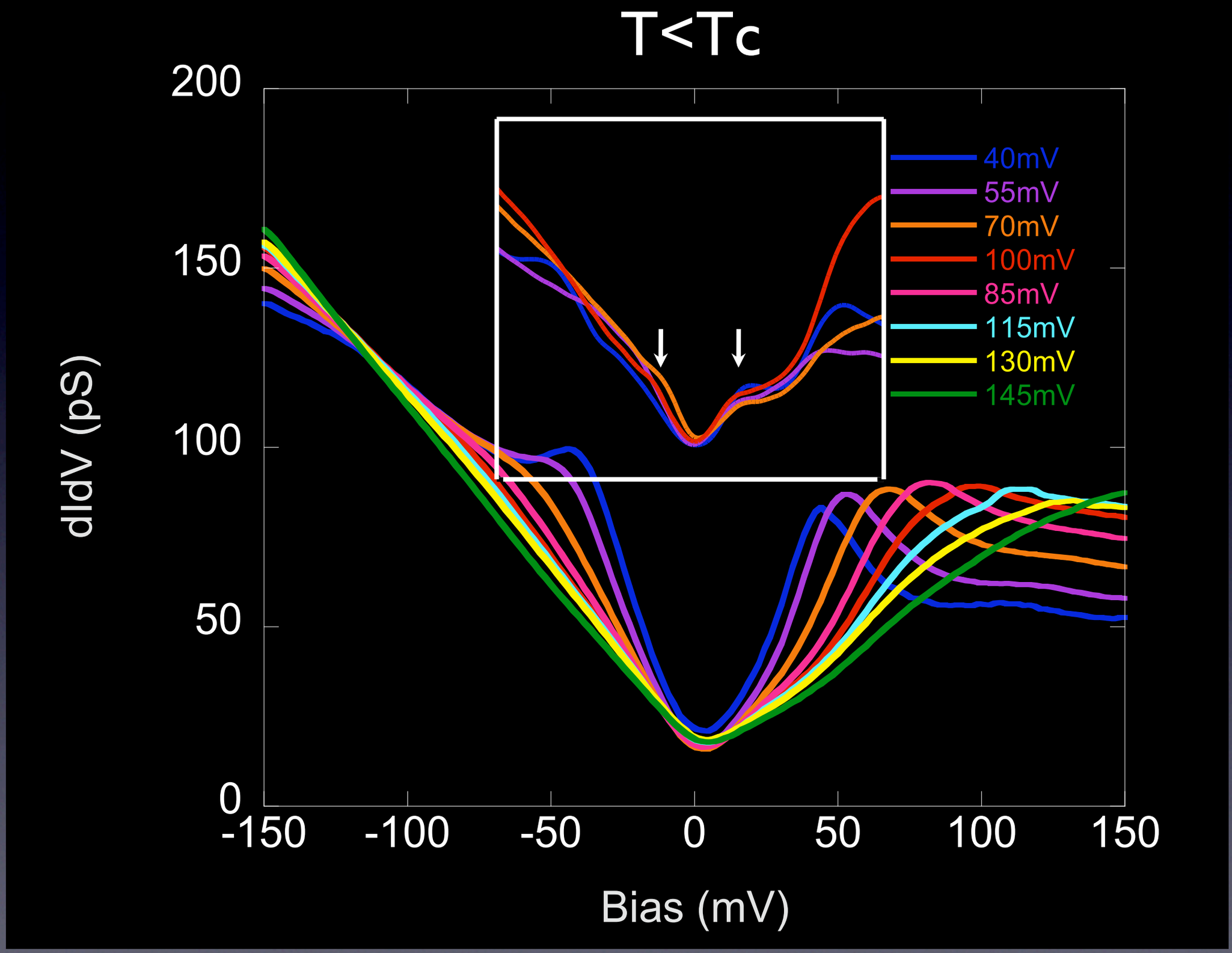
What happens on the dark side ?



Underdoped Samples: Unusual shaped spectra



Underdoped Samples: Unusual shaped spectra



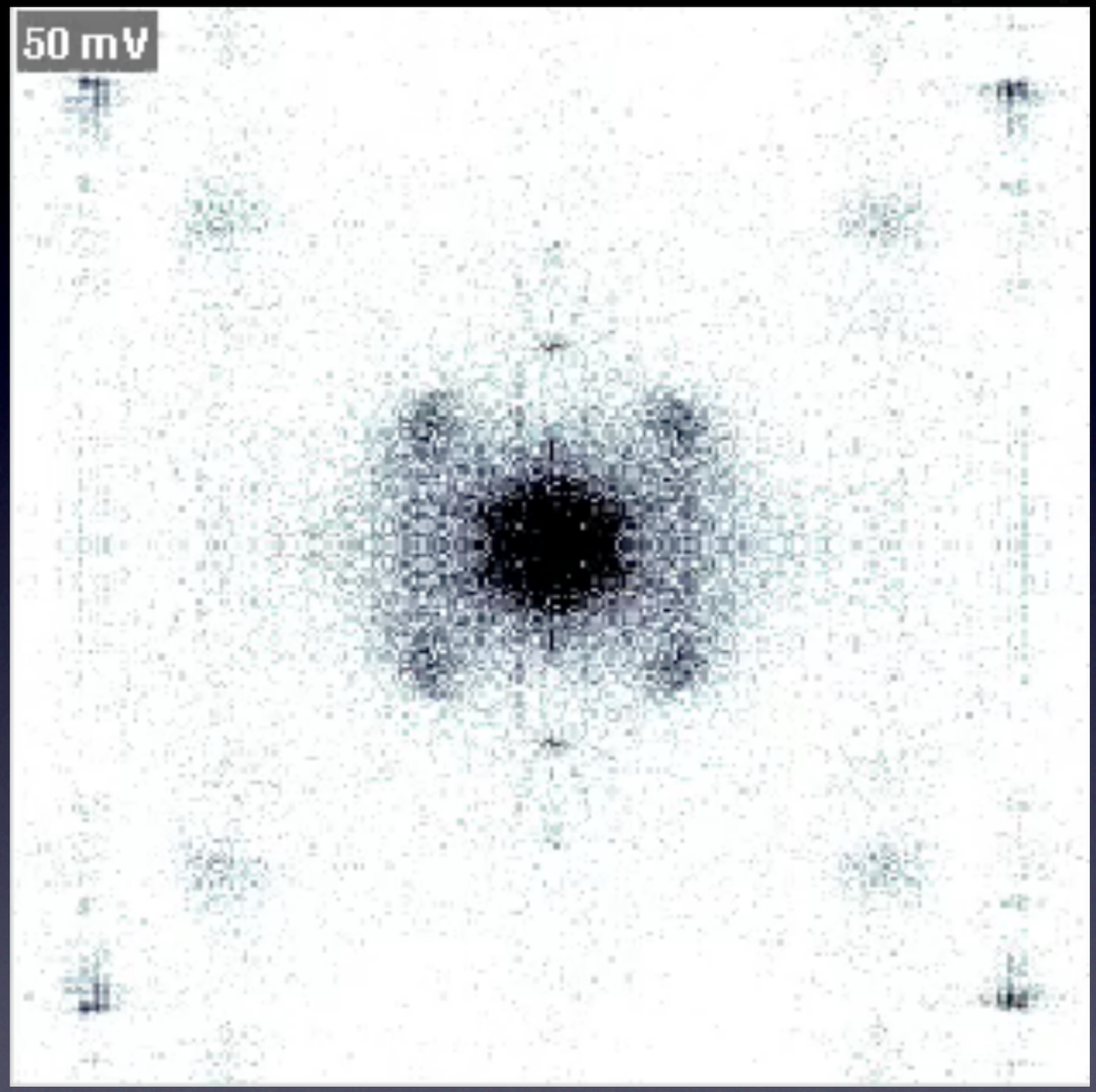
Underdoped Samples: Static Electronic Modualations

FFT of conductance maps for T<Tc

T<Tc

Underdoped Samples: Static Electronic Modualations

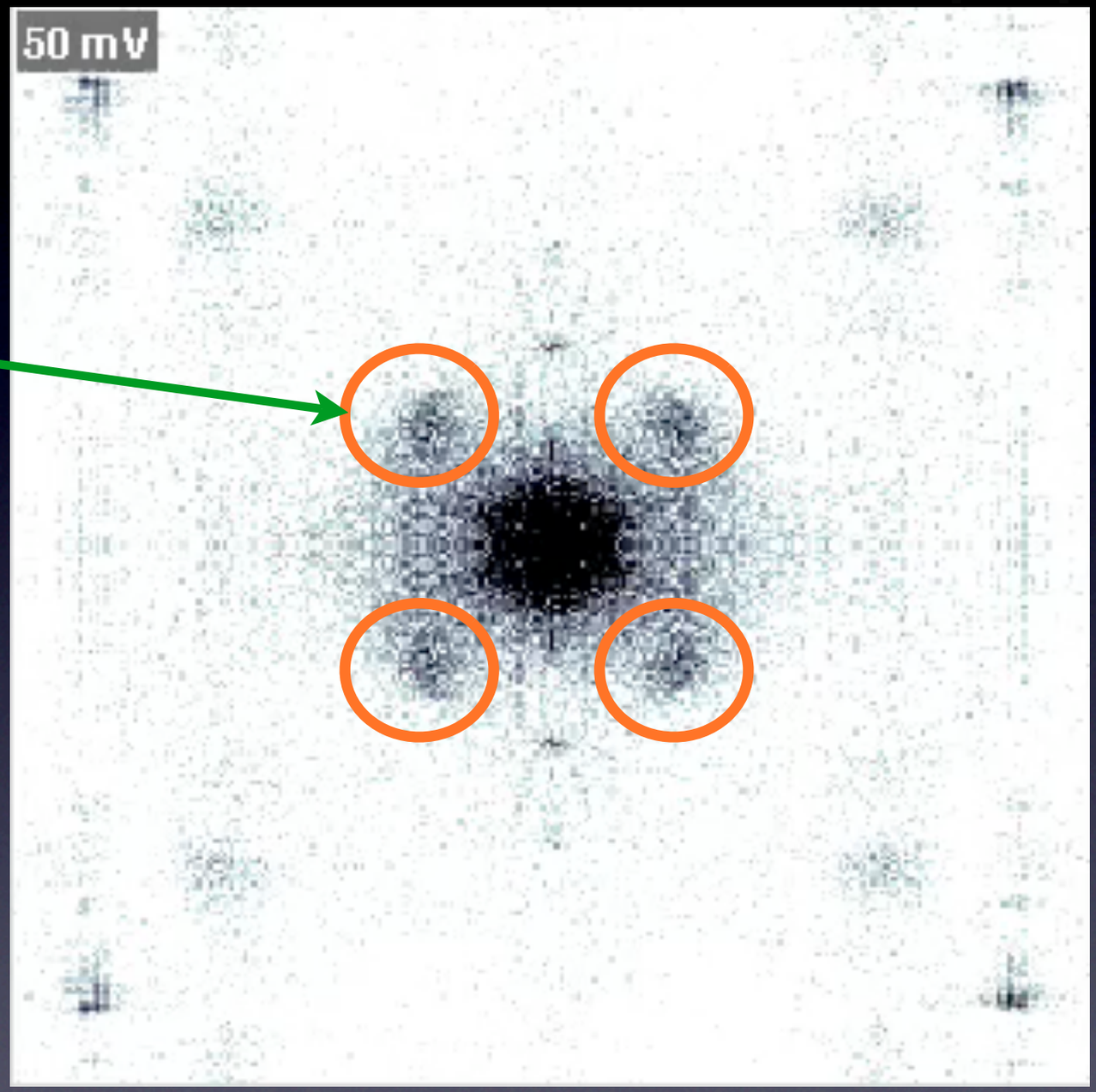
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Underdoped Samples: Static Electronic Modualations

FFT of conductance maps for T<Tc

Static Modulations with close to 4a spacing

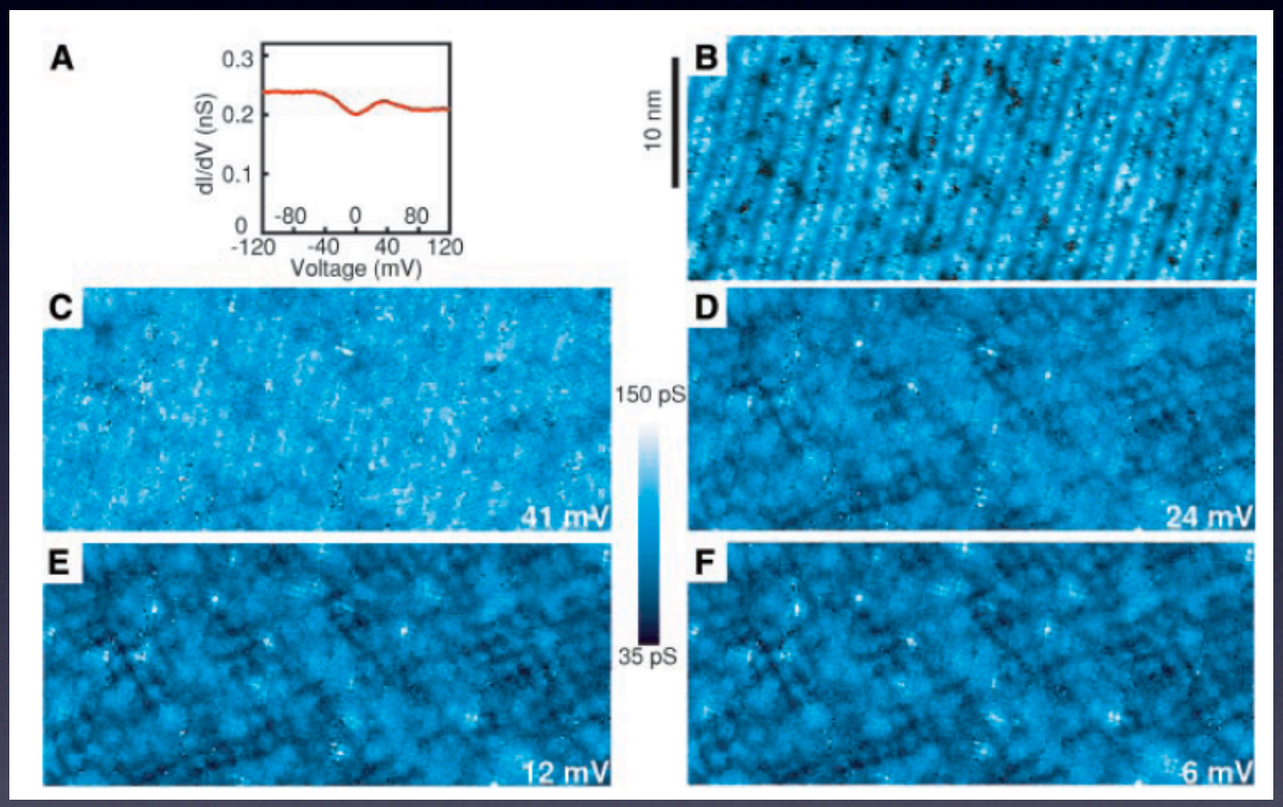


Underdoped Samples: Static Electronic Modualations

Local Ordering in the Pseudogap State of the High-T_c Superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$

Michael Vershinin,[1]* Shashank Misra,[1]* S. Ono,[2] Y. Abe,[2]†
Yoichi Ando,[2] Ali Yazdani[1]‡§

Science **303**, 1995 (2004)



Energy-resolved conductance maps at T>Tc

Static Patterns appear for E< PG

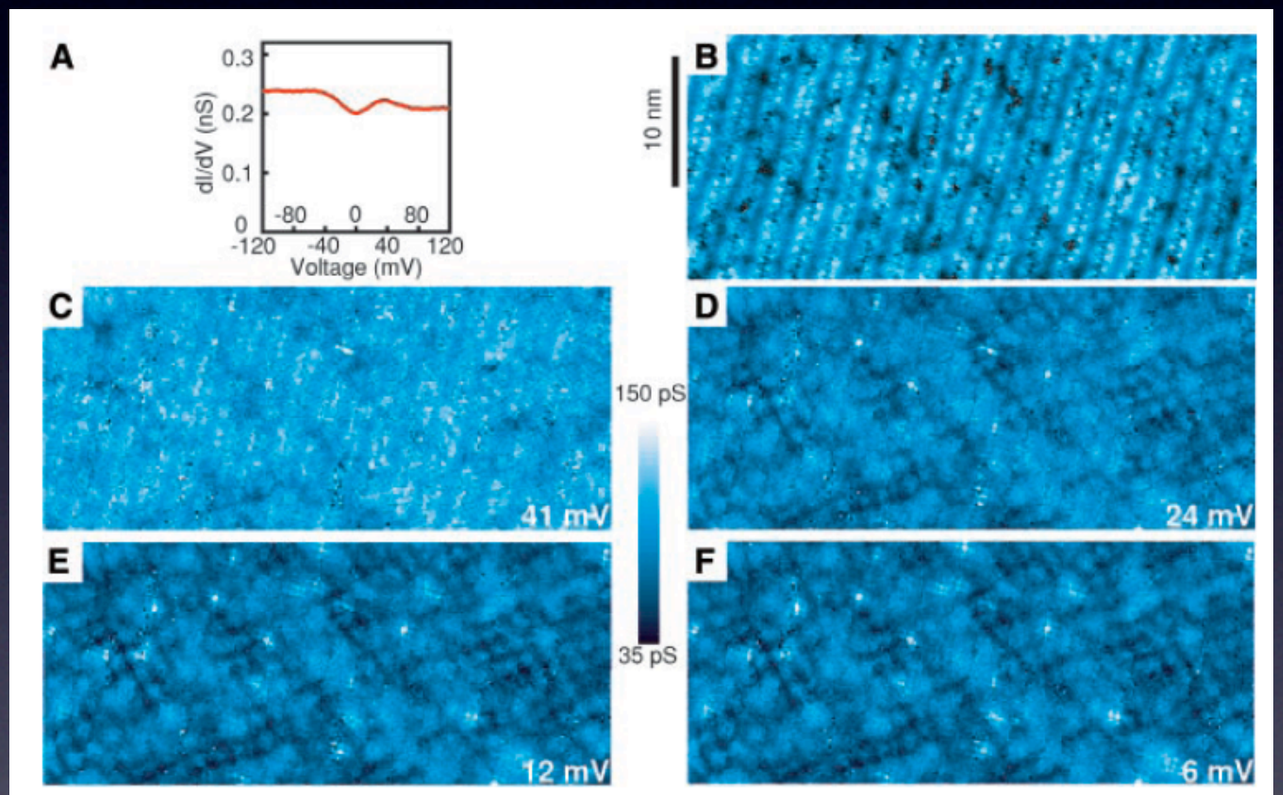
FFT of conductance maps

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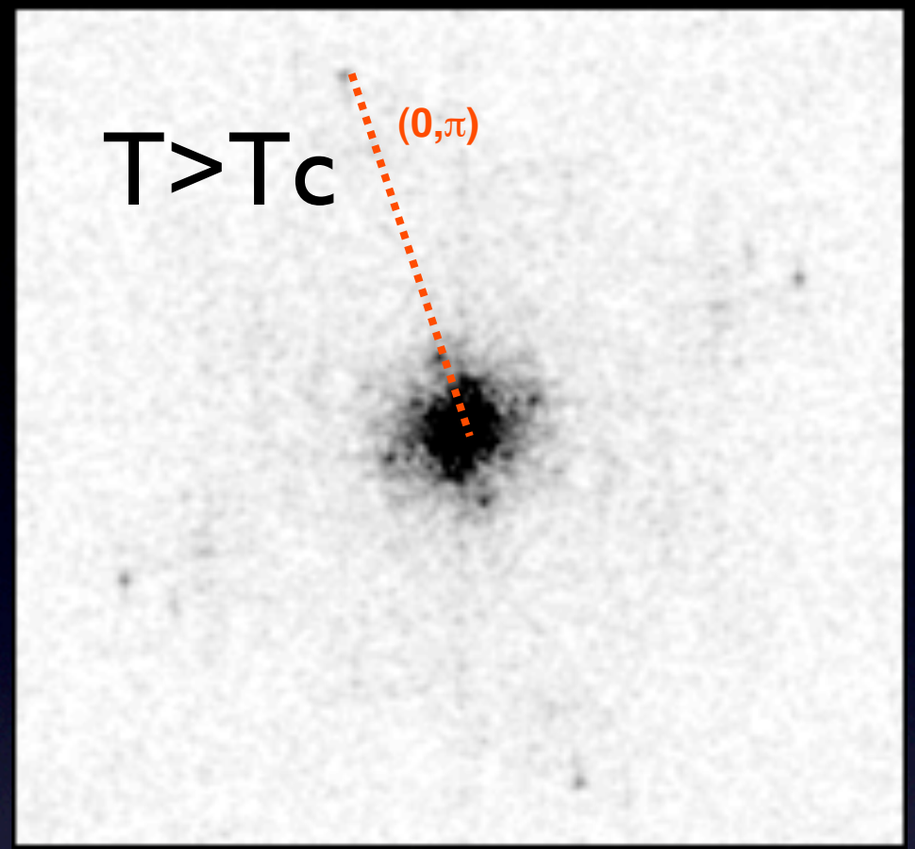
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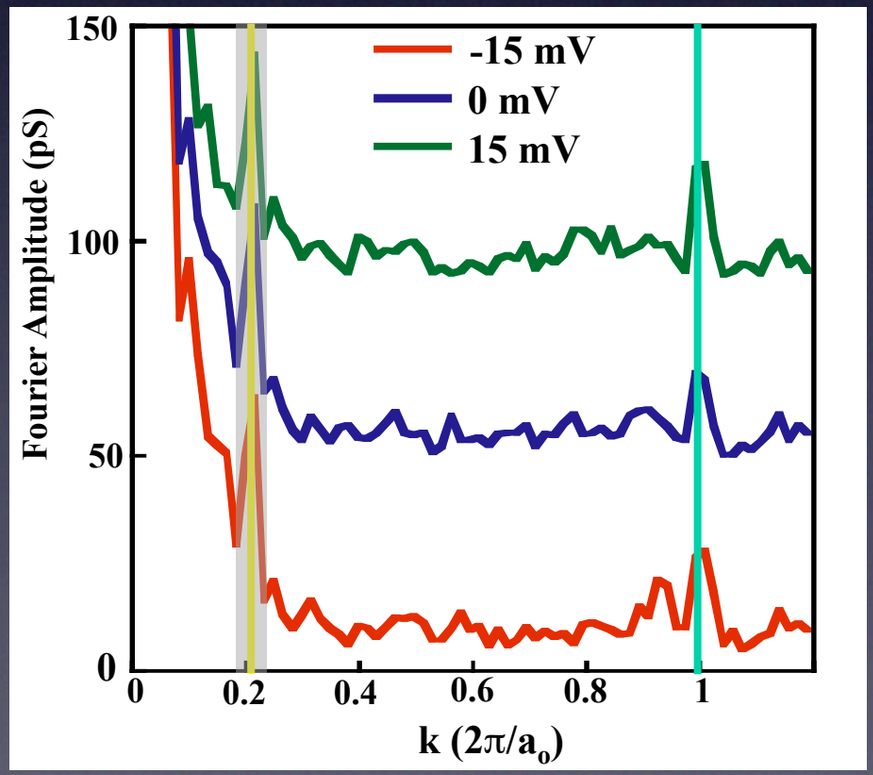
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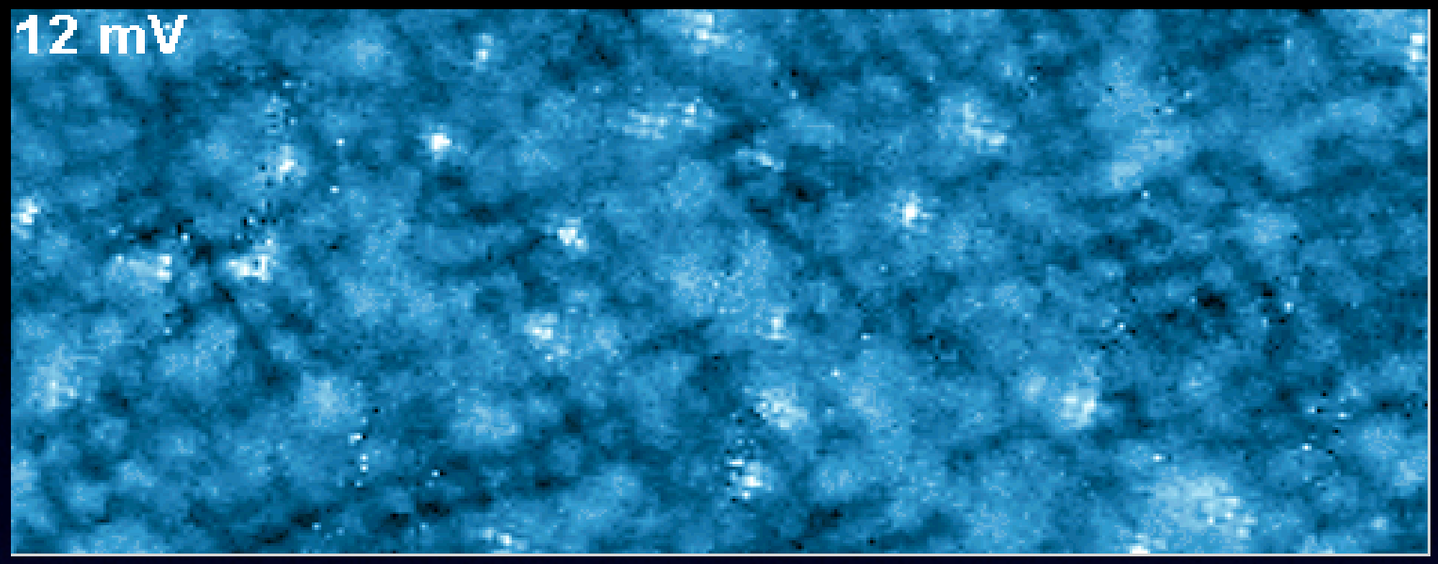
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Origin of Static Patterns in the Pseudogap State

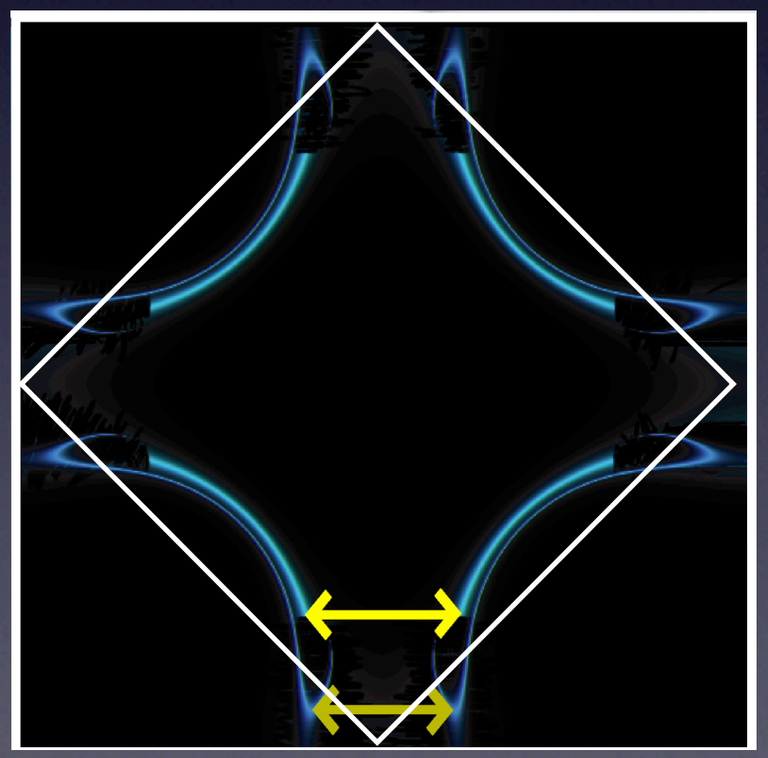
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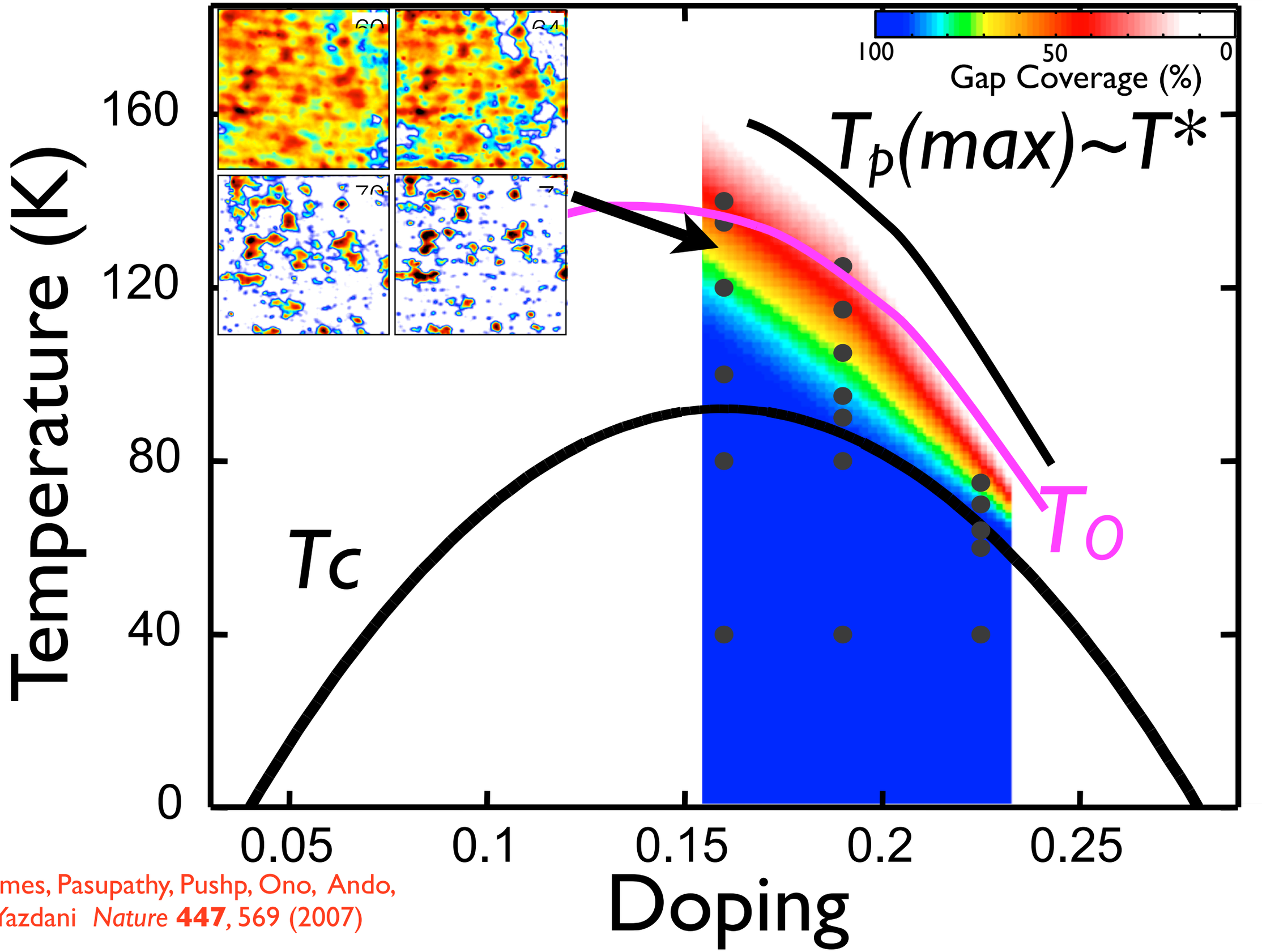


- Disordered Stripes?
- Nesting of FS?
- AF zone boundary?
- Valance bond solid?
- Regardless: correlate with PG



Related work by Hanaguri, Kosaka and Davis (2004) & (2006)

Local Pairing is Pseudogap Physics above Optimal doping



Gomes, Pasupathy, Pushp, Ono, Ando, Yazdani *Nature* **447**, 569 (2007)

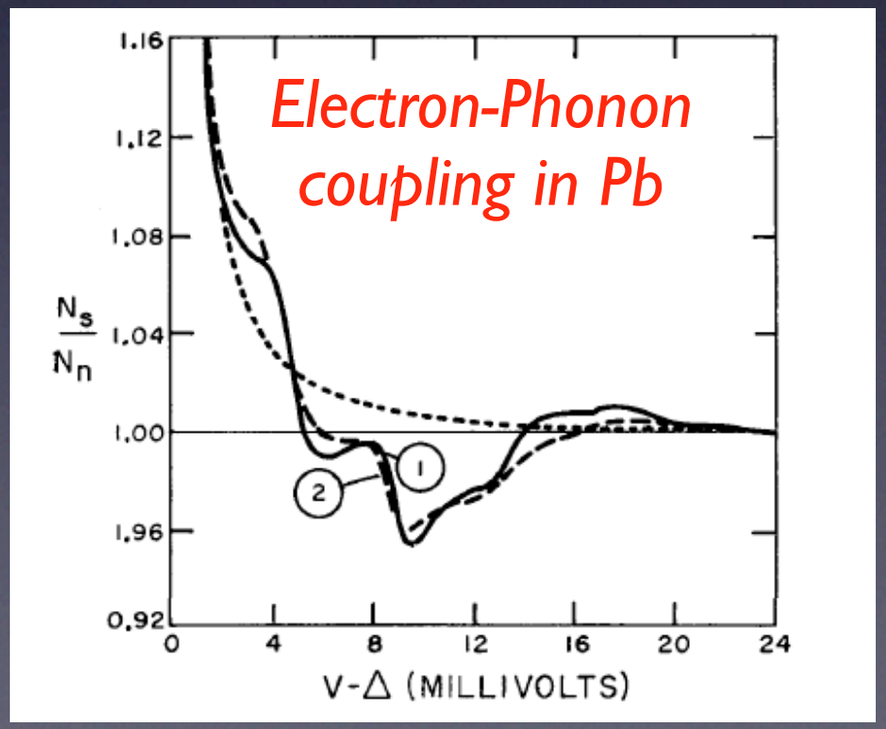
Questions:

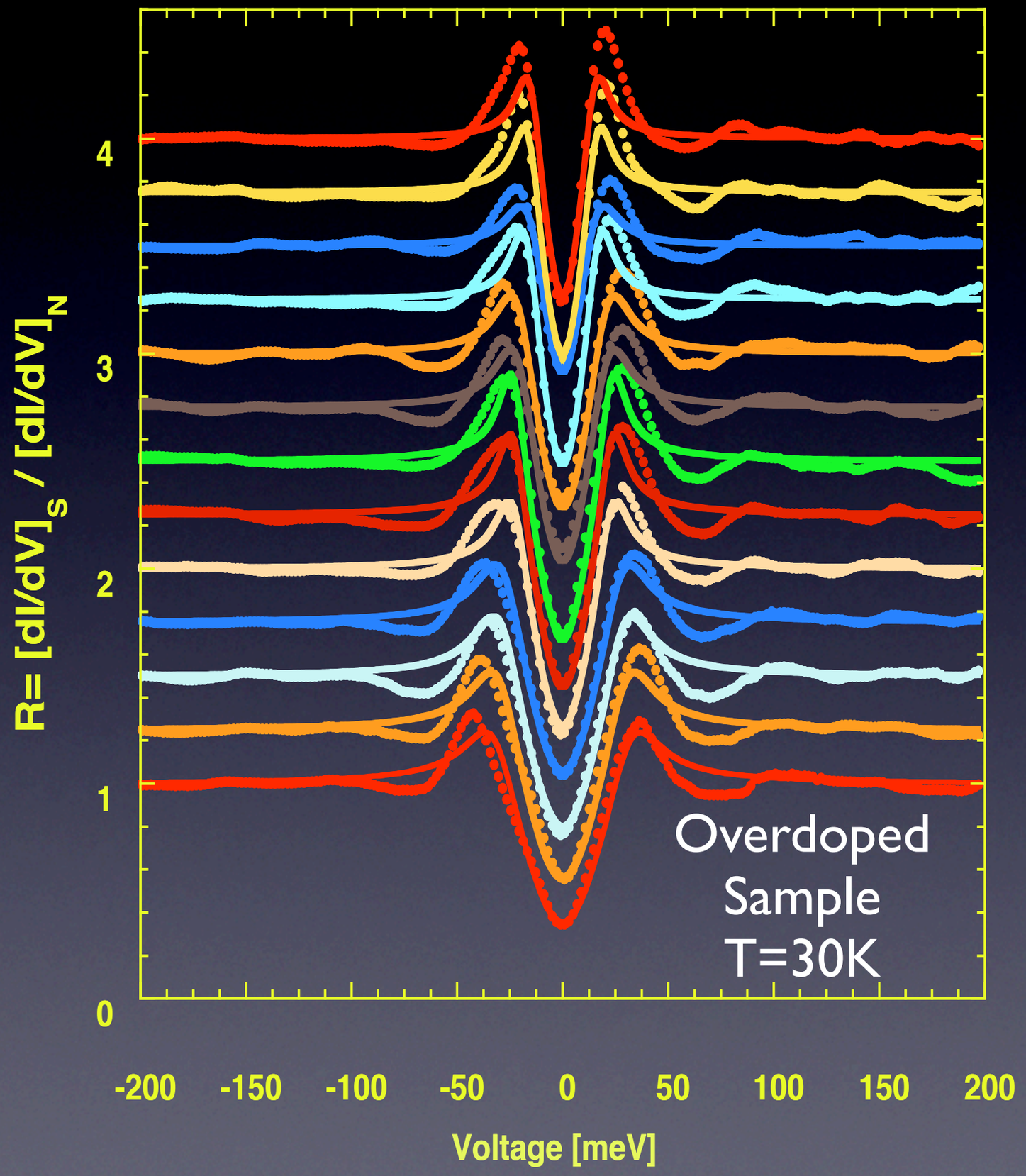
- When do pairs form? *From locally over a range of temperatures above Tc.*
- Are there bosonic excitations that couple to electrons?
- What controls the pairing strength?

"Electron-Boson coupling" Features:

- Data shows a dip below "weak-coupling" d-wave

- Definite signature of coupling to some sort of a boson



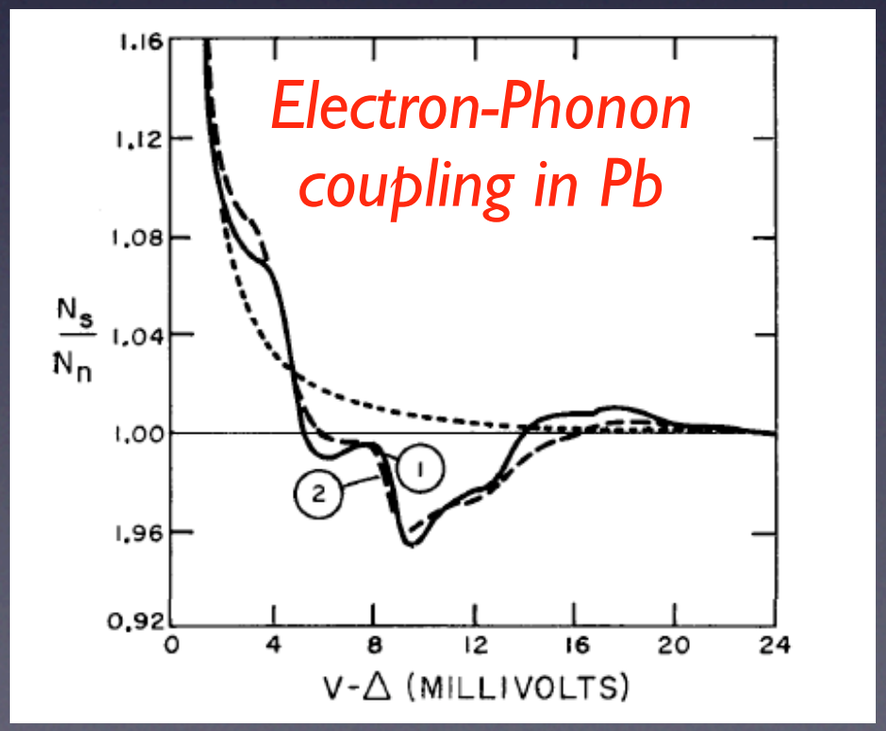


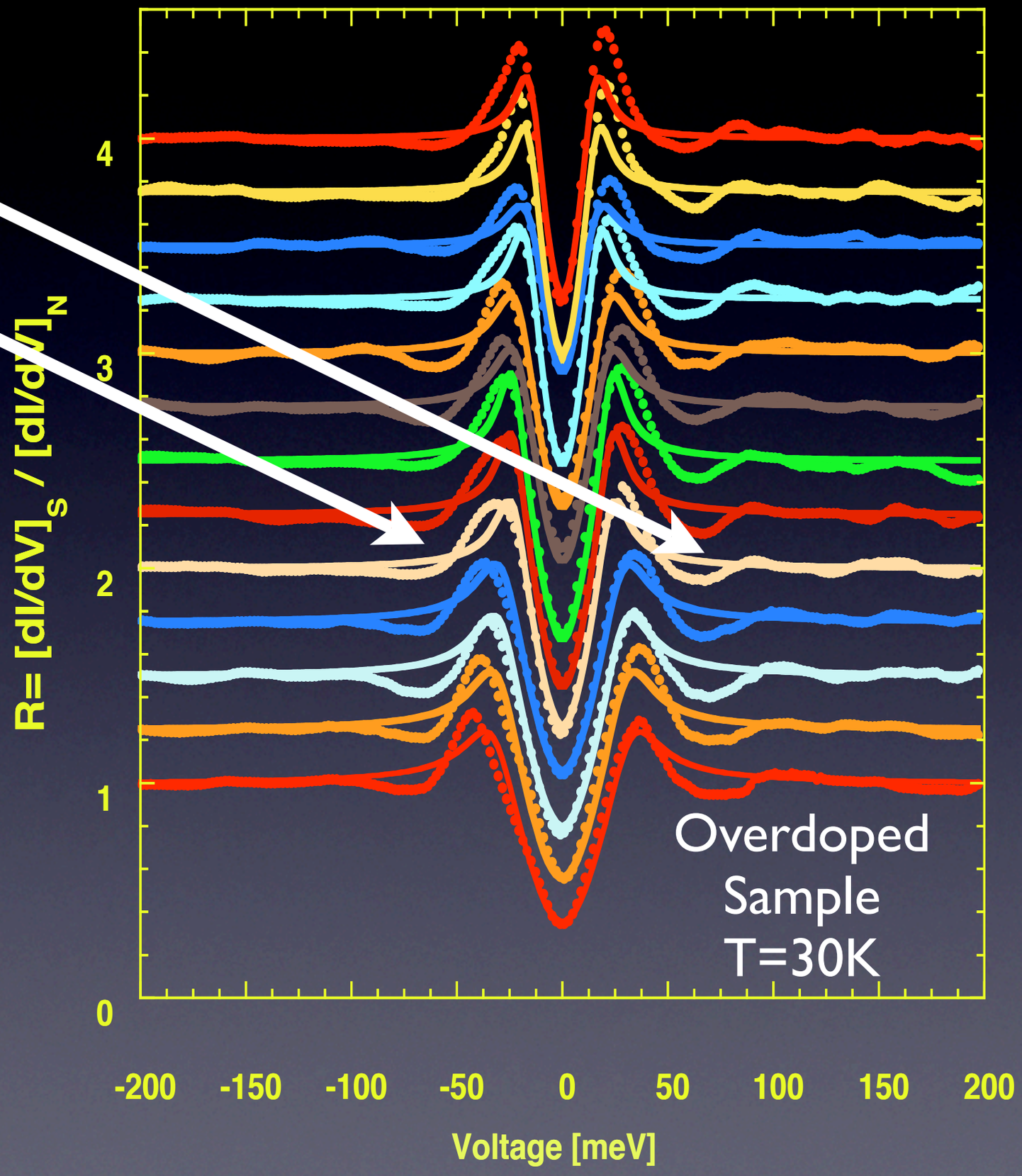
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Systematic Deviation from local d-wave model

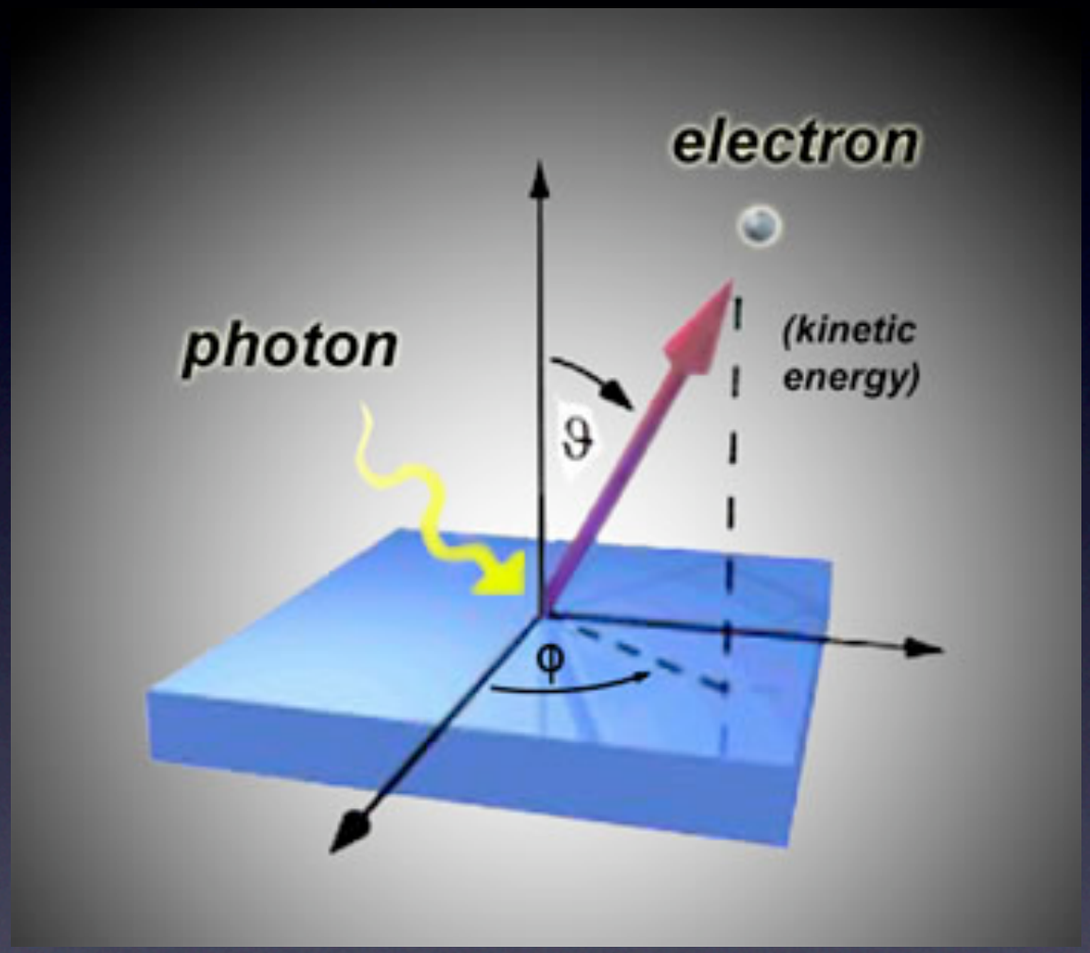
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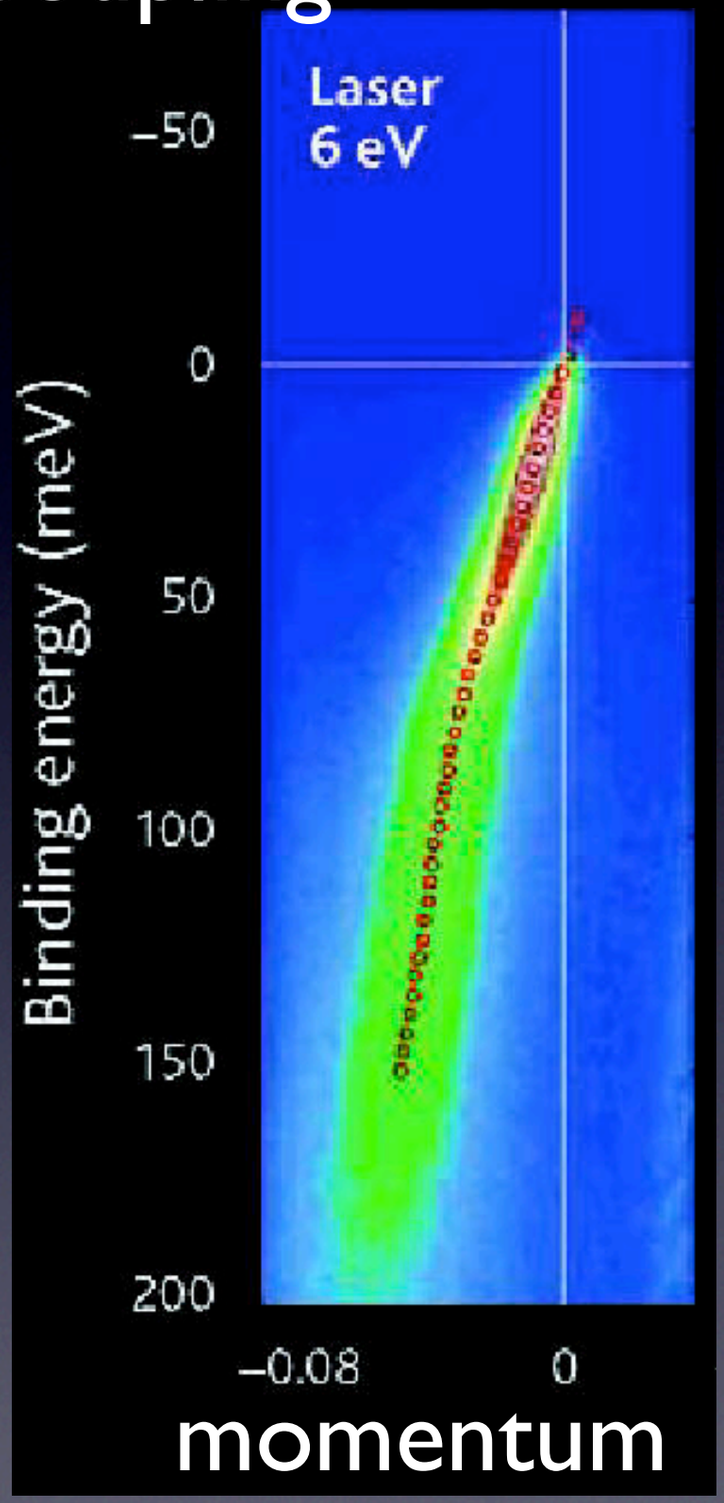
- Definite signature of coupling to some sort of a boson





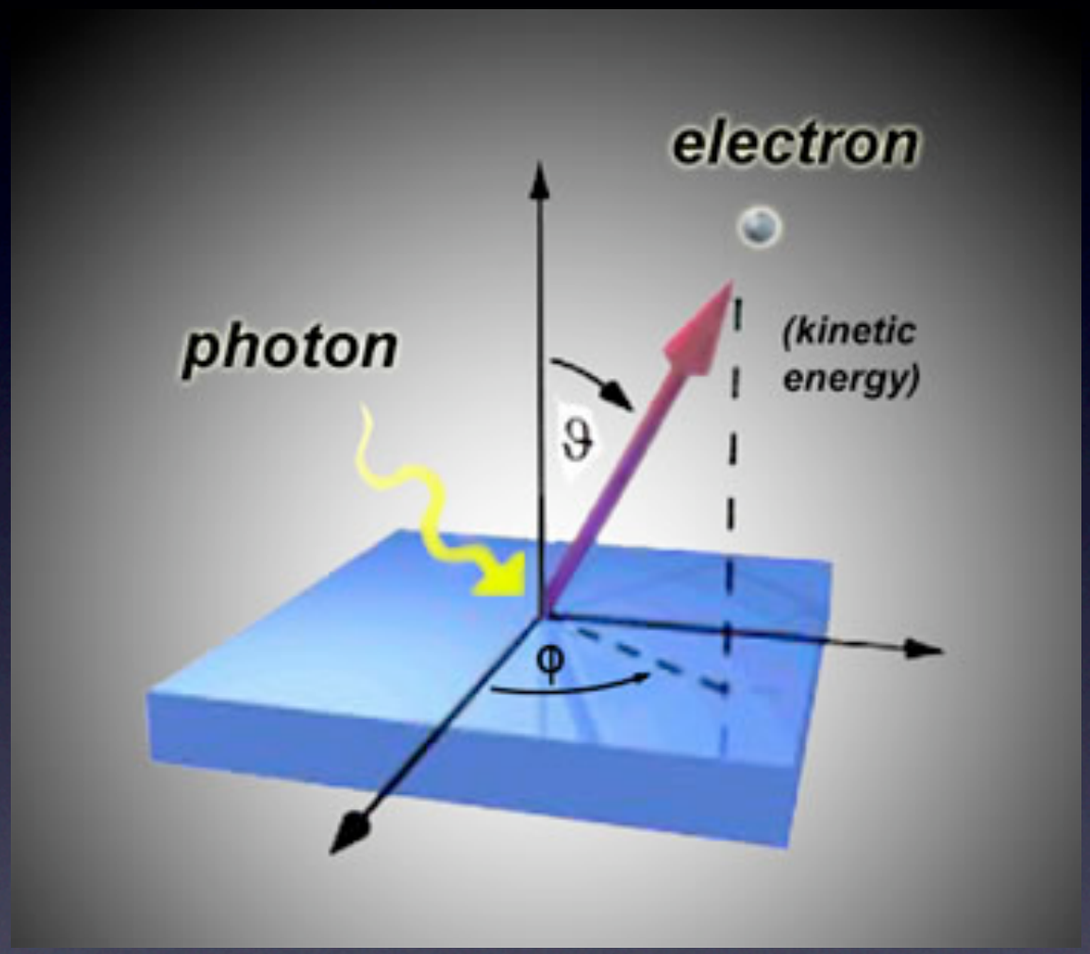
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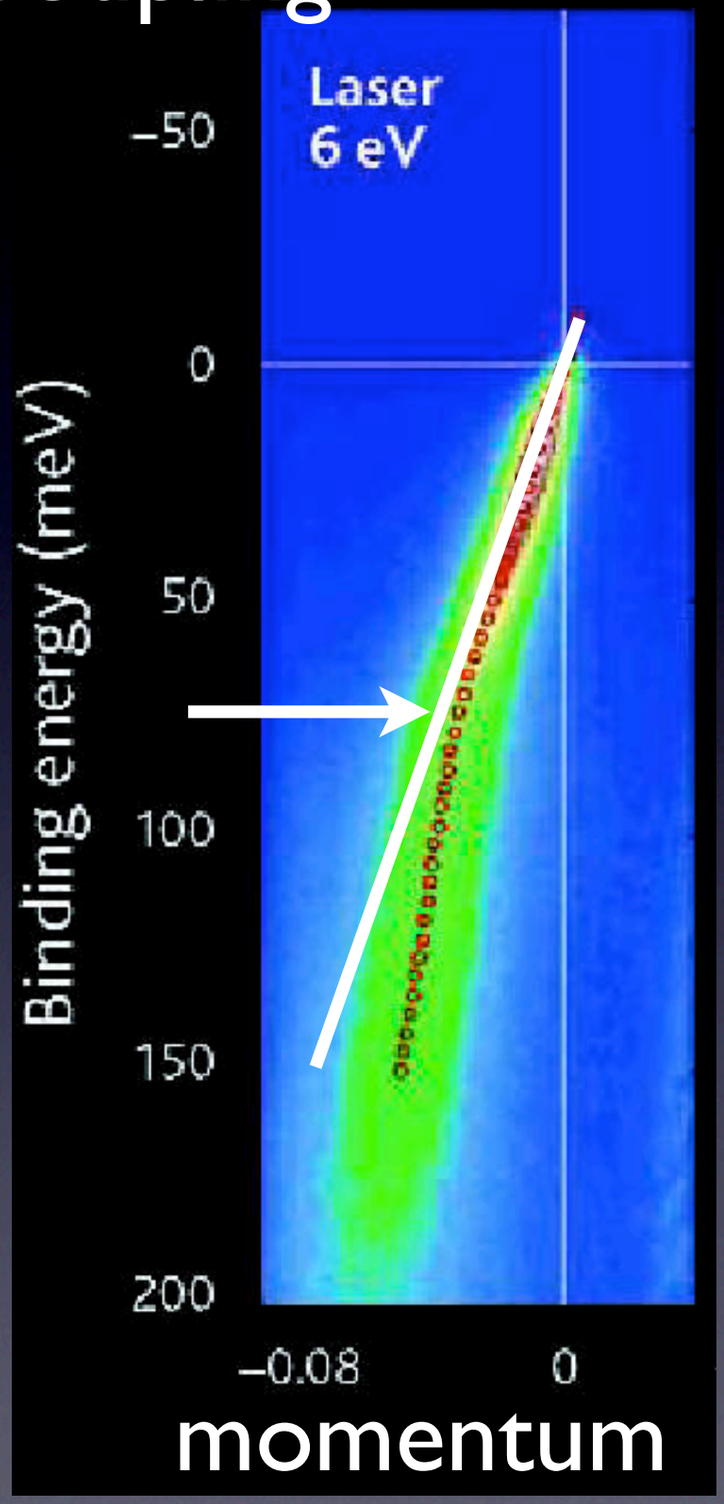




Data from D. Dessau (U of Col.) seen by all photoemission groups

Angle Resolved Photoemission Spectroscopy & Electron-Boson Coupling





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STM/ARPES Spectra features & the “Glue”

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* Department of Physics, Applied Physics and Stanford Synchrotron Radiation Laboratory, Stanford University, Stanford, California 94305, USA
† Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
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J. P. Ca

* Depart Ontario
† Institu Austria

Quantitative test of a microscopic mechanism of high-temperature superconductivity

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ford University, Stanford, California

December 2007 | doi:10.1038/nature06430

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and Astronomy, McMaster University, Hamilton,
ada
Brookhaven National Laboratory, Upton, New York

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nature Vol 442|3 August 2006|doi:10.1038/nature04973

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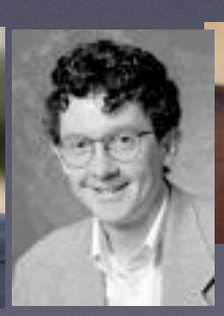
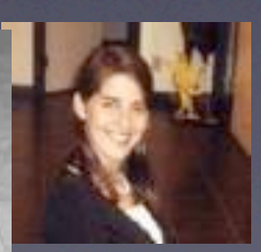
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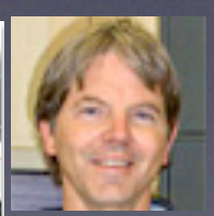
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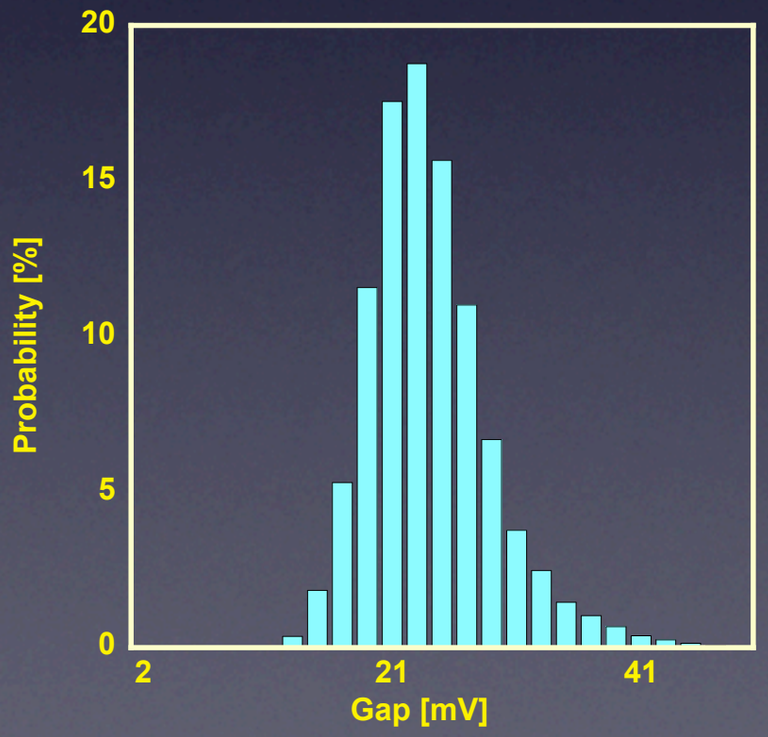


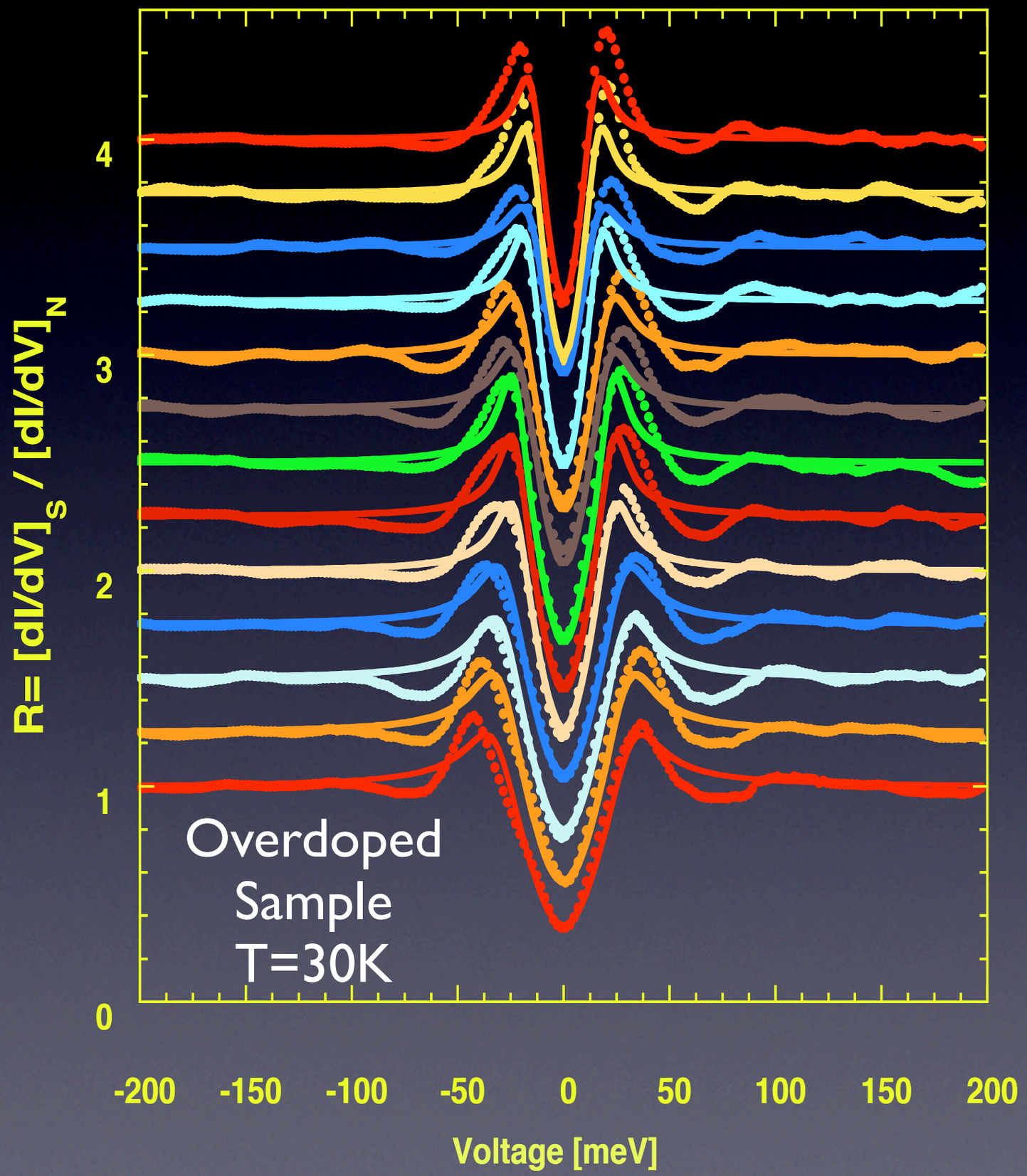



....& many others

What is the relation between bosonic features & the gap?

- Quantitative analysis using the locally measured conductance ratio
- Avoids inelastic tunneling & matrix element effects
- Do they control the gap?



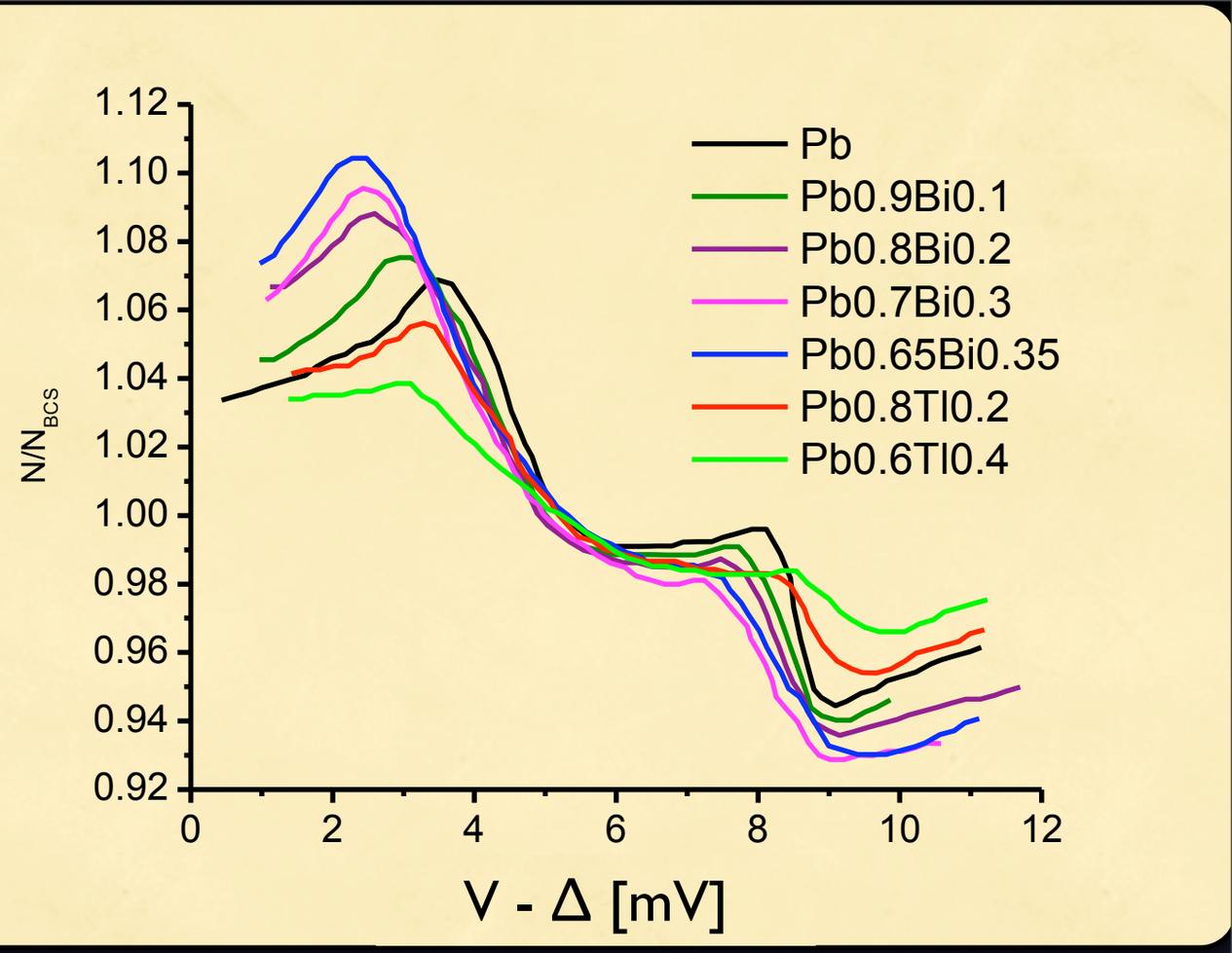


Electron-Boson Coupling & the SC Gap

Lessons From the Past:

Size of the boson mediate features scale with the gap size in a BCS-Eliashburg superconductors

Dynes and Rowell, PRB **11**, 1884 (1975)



Electron-Boson Coupling & the SC Gap

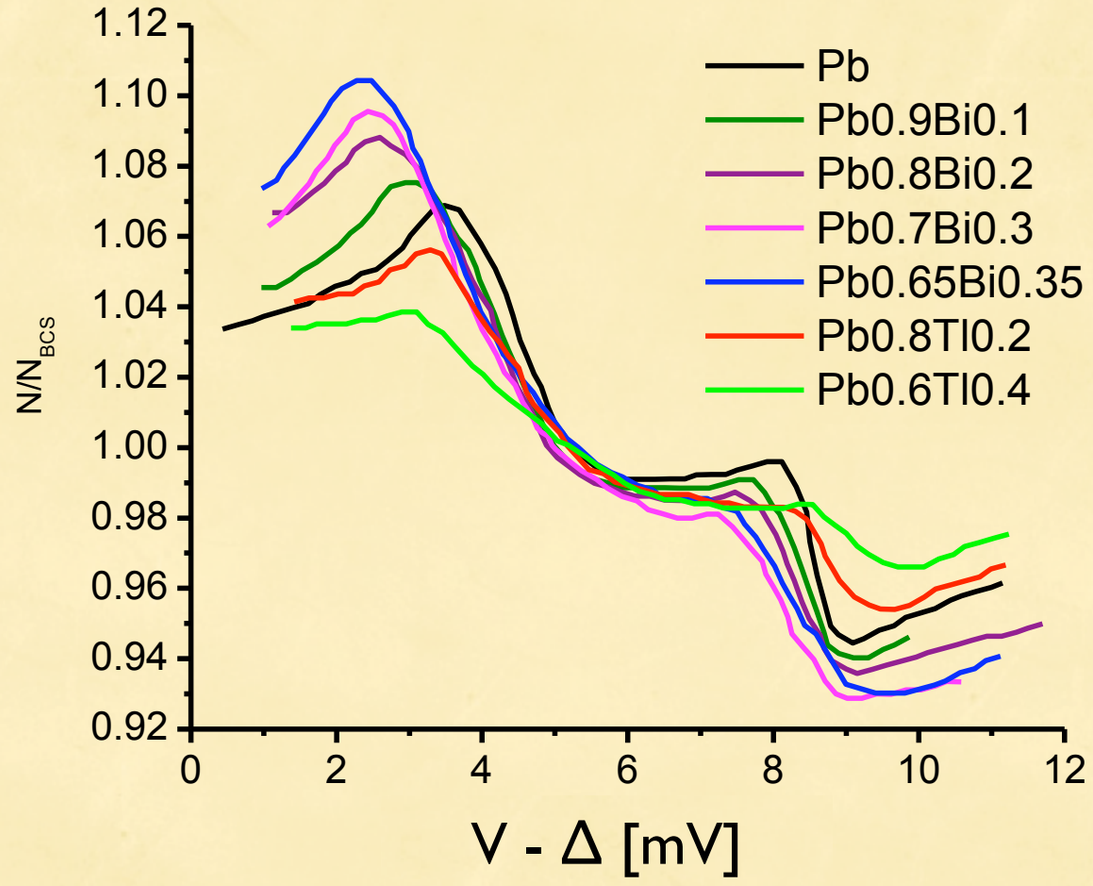
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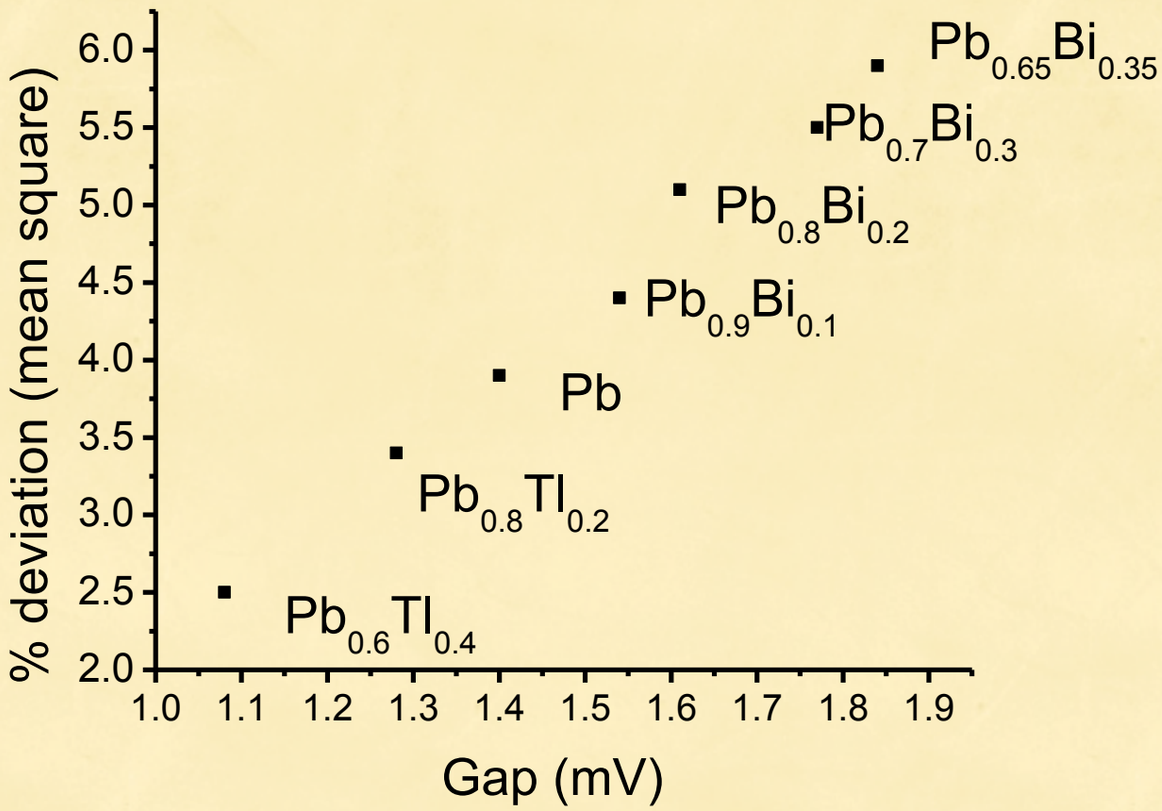
Size of the boson mediate features scale with the gap size in a BCS-Eliashburg superconductors

Dynes and Rowell, PRB **11**, 1884 (1975)

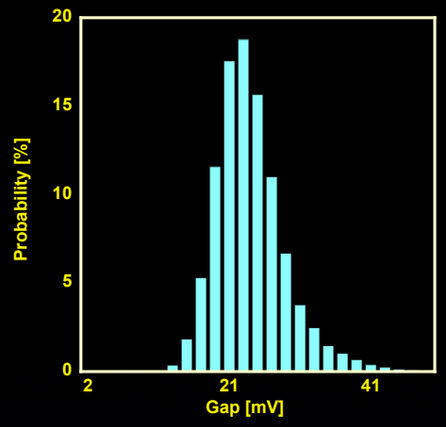
Different gaps can be achieved via doping it causes changes to electron-phonon coupling

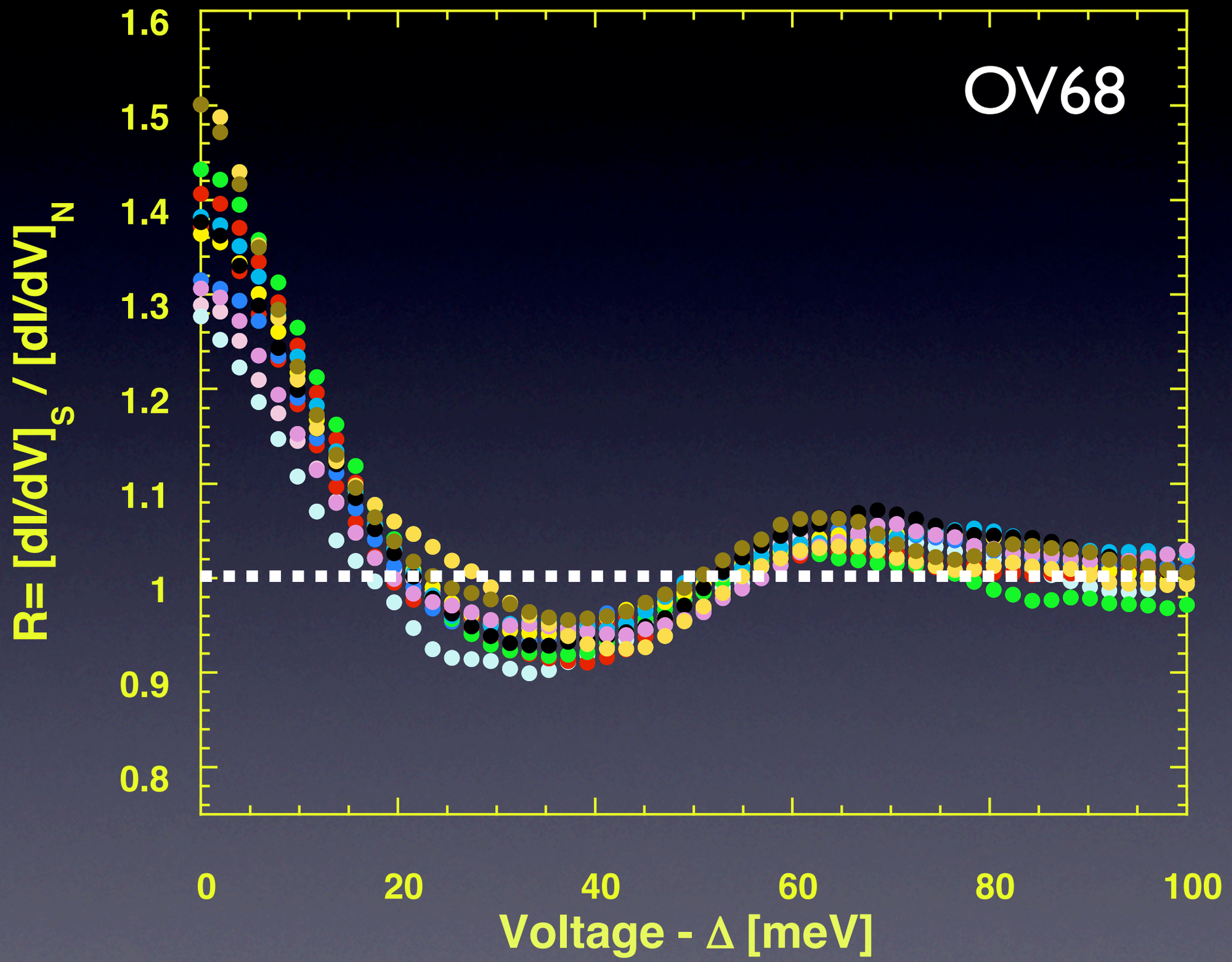
$$\Delta = \hbar\omega_c e^{-\frac{1}{\lambda}}$$



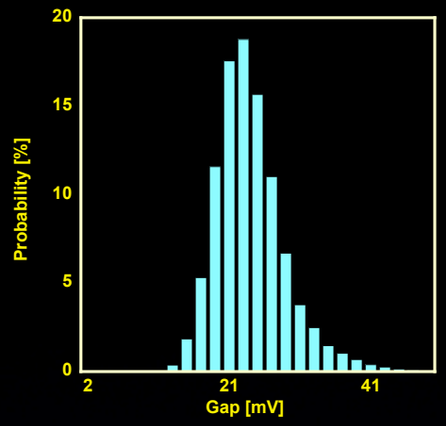


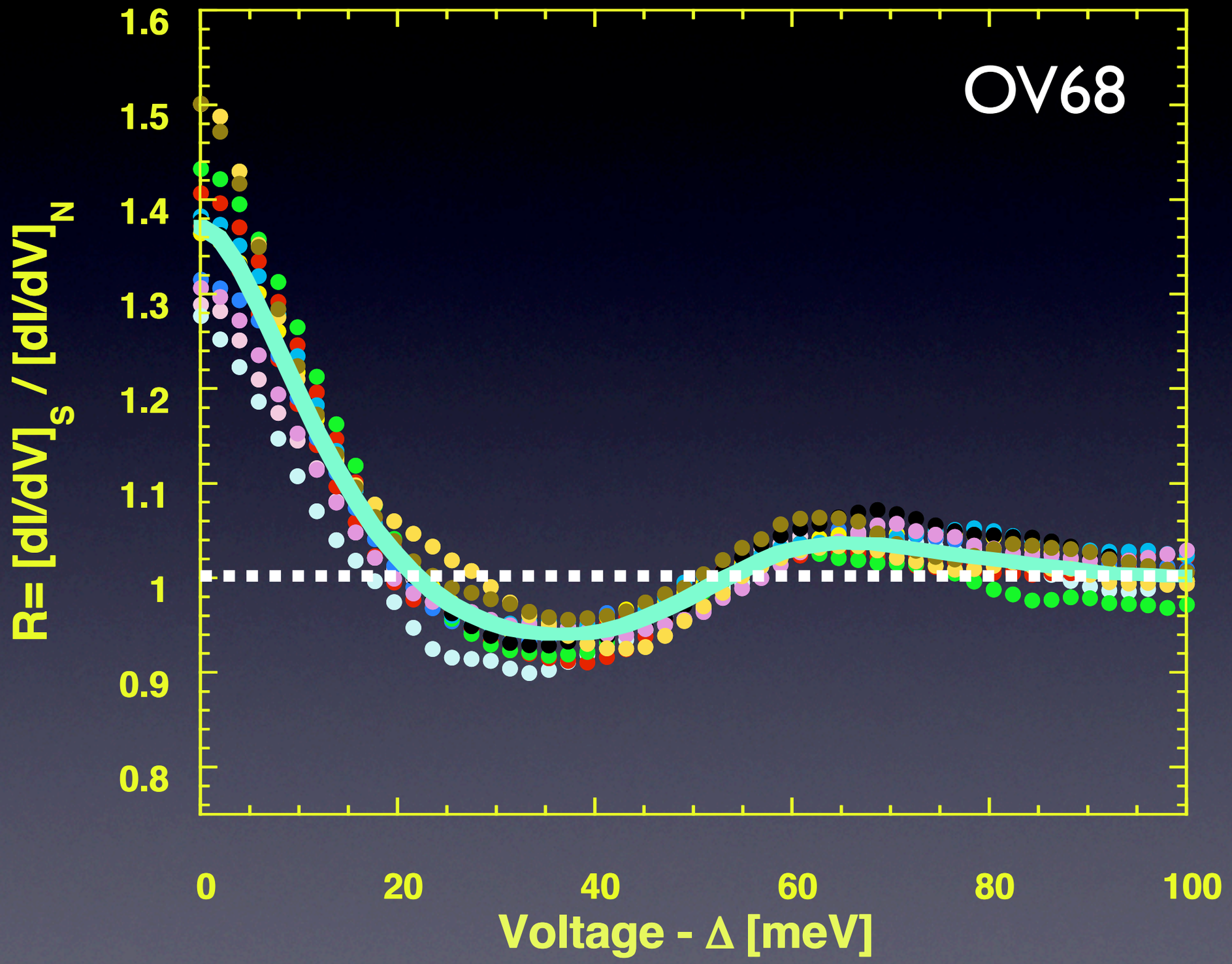
Electron-Boson Coupling & the Gaps



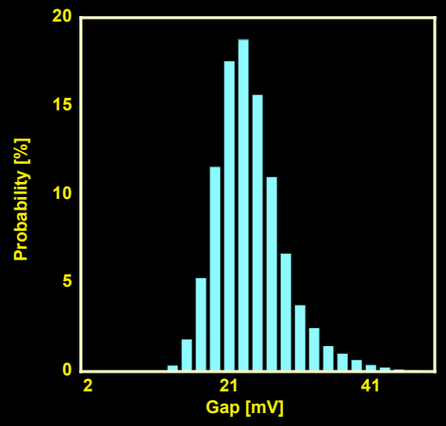


Electron-Boson Coupling & the Gaps





Electron-Boson Coupling & the Gaps



$$\Delta = \hbar\omega_c e^{-\frac{1}{\lambda}}$$

OV68

shifts features in energy

shifts features in magnitude

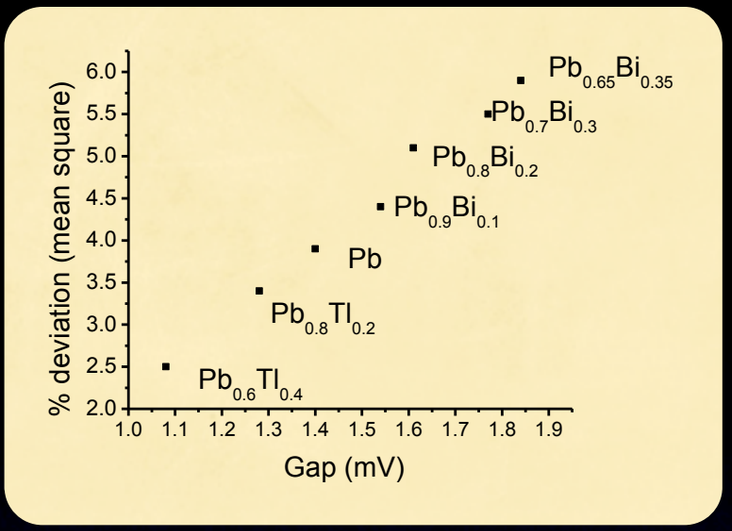
$R = [dI/dV]_S / [dI/dV]_N$

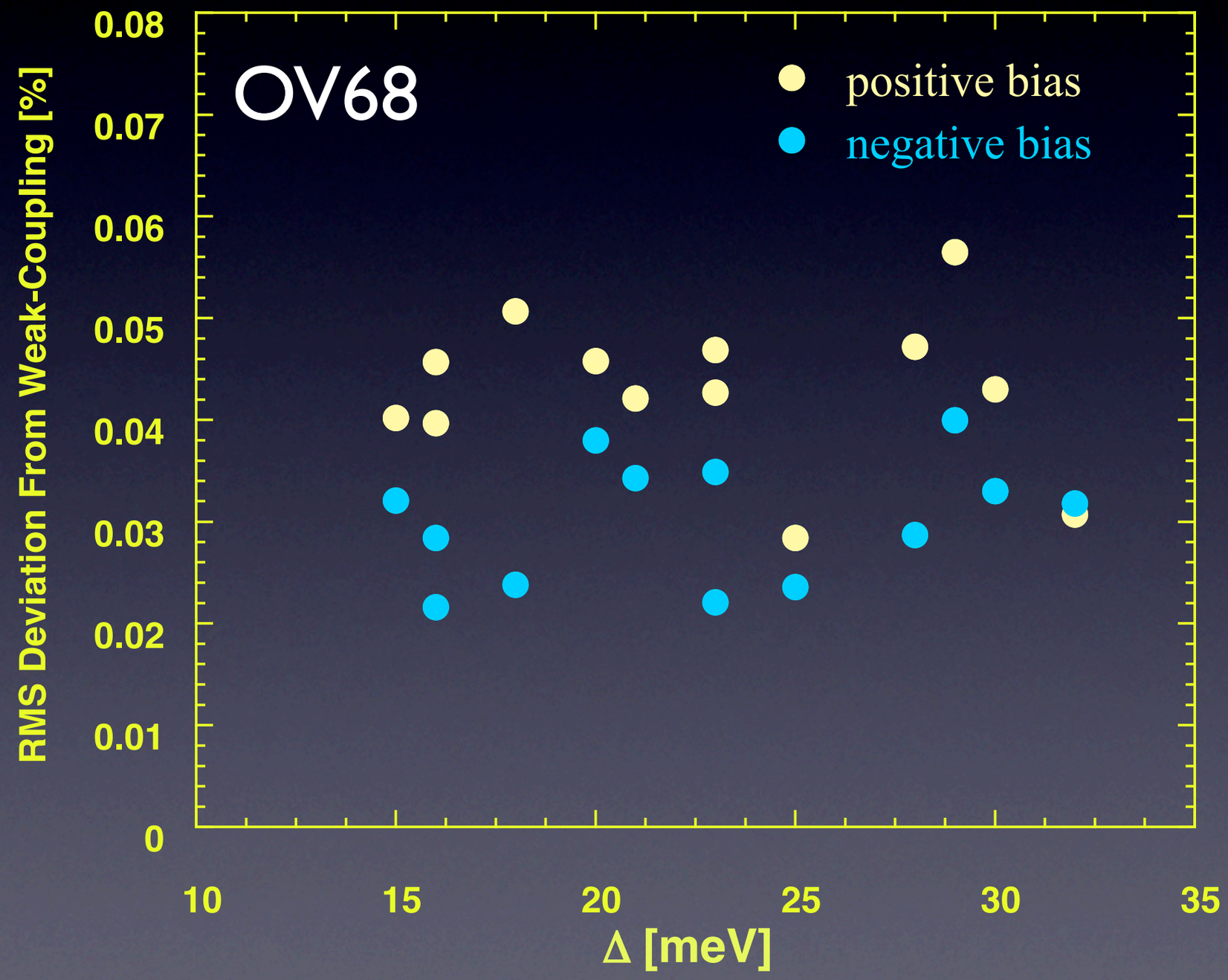
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8

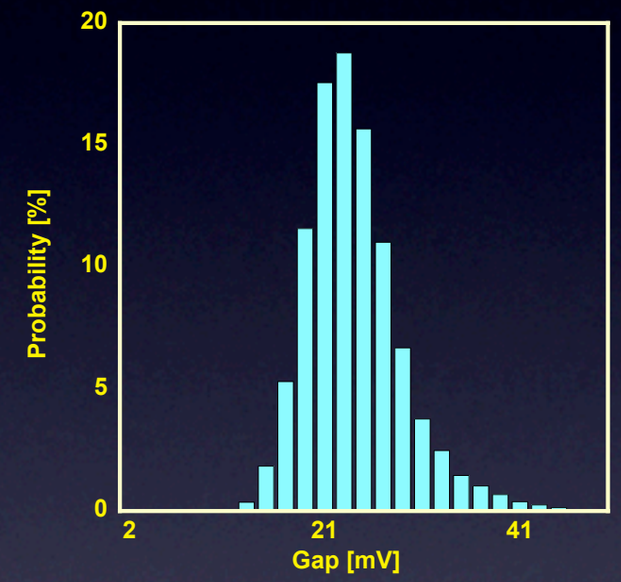
0
20
40
60
80
100

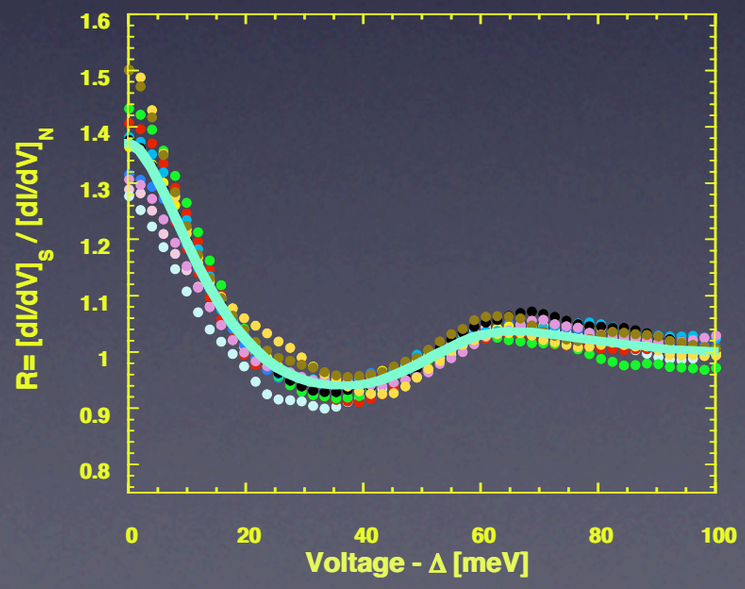
Voltage - Δ [meV]

Lack of Correlation Between Electron-Boson Coupling & the Gaps !









Pasupathy, Pushp, Gomes, Parker, Gu, Ono, Ando, Yazdani Science, **320**, 196 (2008)

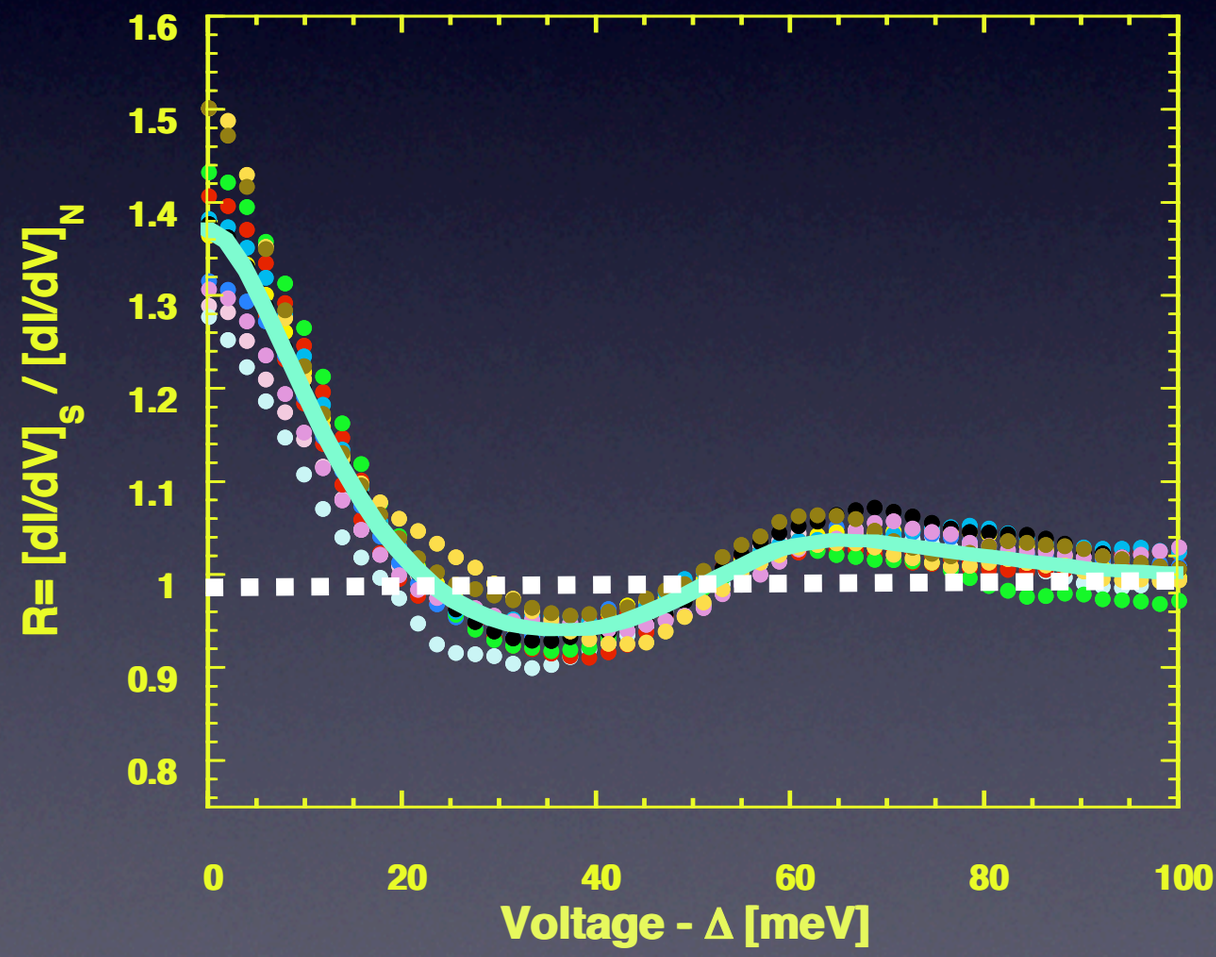
Electron Boson Coupling & Frequency Dependent of the Pairing Interaction:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi}\int dE \frac{df(E+V,T)}{dE}\int_0^{\pi} d\theta \,\mathrm{Re}\frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2\cos^2 2\theta}}$$

Ns(V)/Nn(V) is a function of V and can be less than 1

<u>Within the model:</u>

- Δ must have some ω dependence
- $\Delta(\omega) = \Delta_R(\omega) + i\,\Delta_I(\omega)$
- Near dip $\Delta_I(\omega) \sim 25$mV



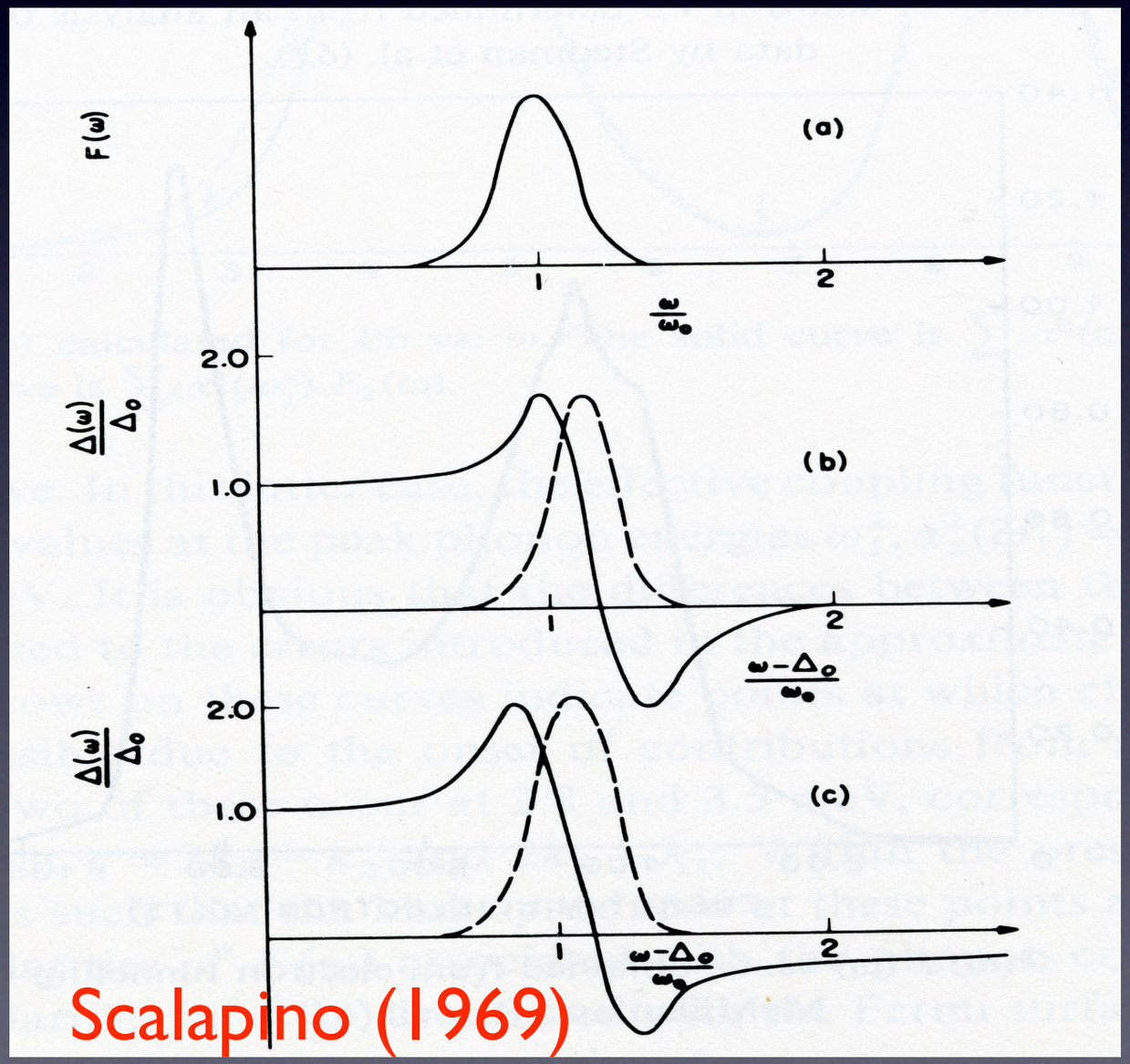
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Scalapino (1969)

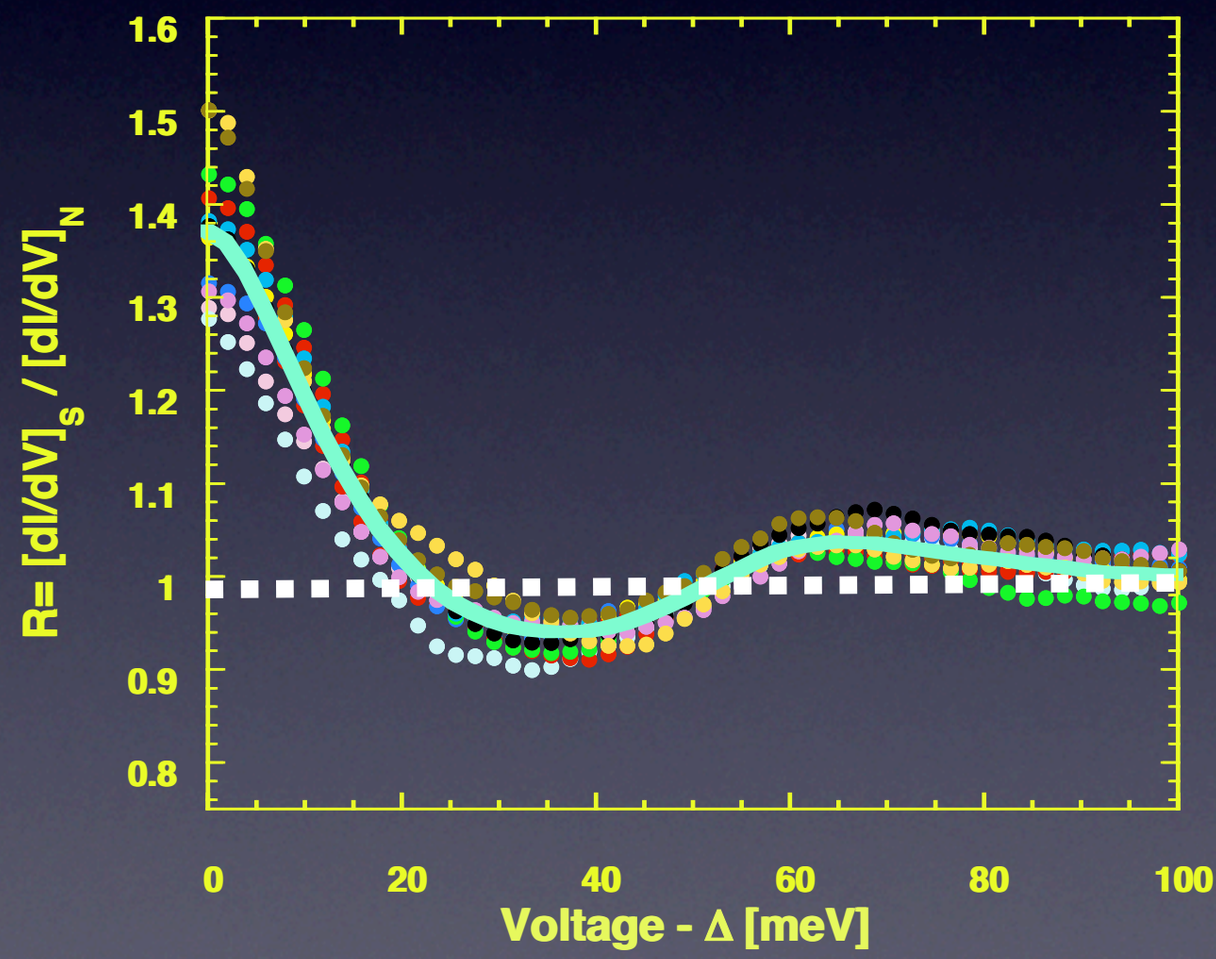
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Ns(V)/Nn(V) is a function of V and can be less than 1

Bottom Line:

- Δs are equally "affected" by bosons (20-120meV)
- Unlikely "cause" of inhomogeneous Δs

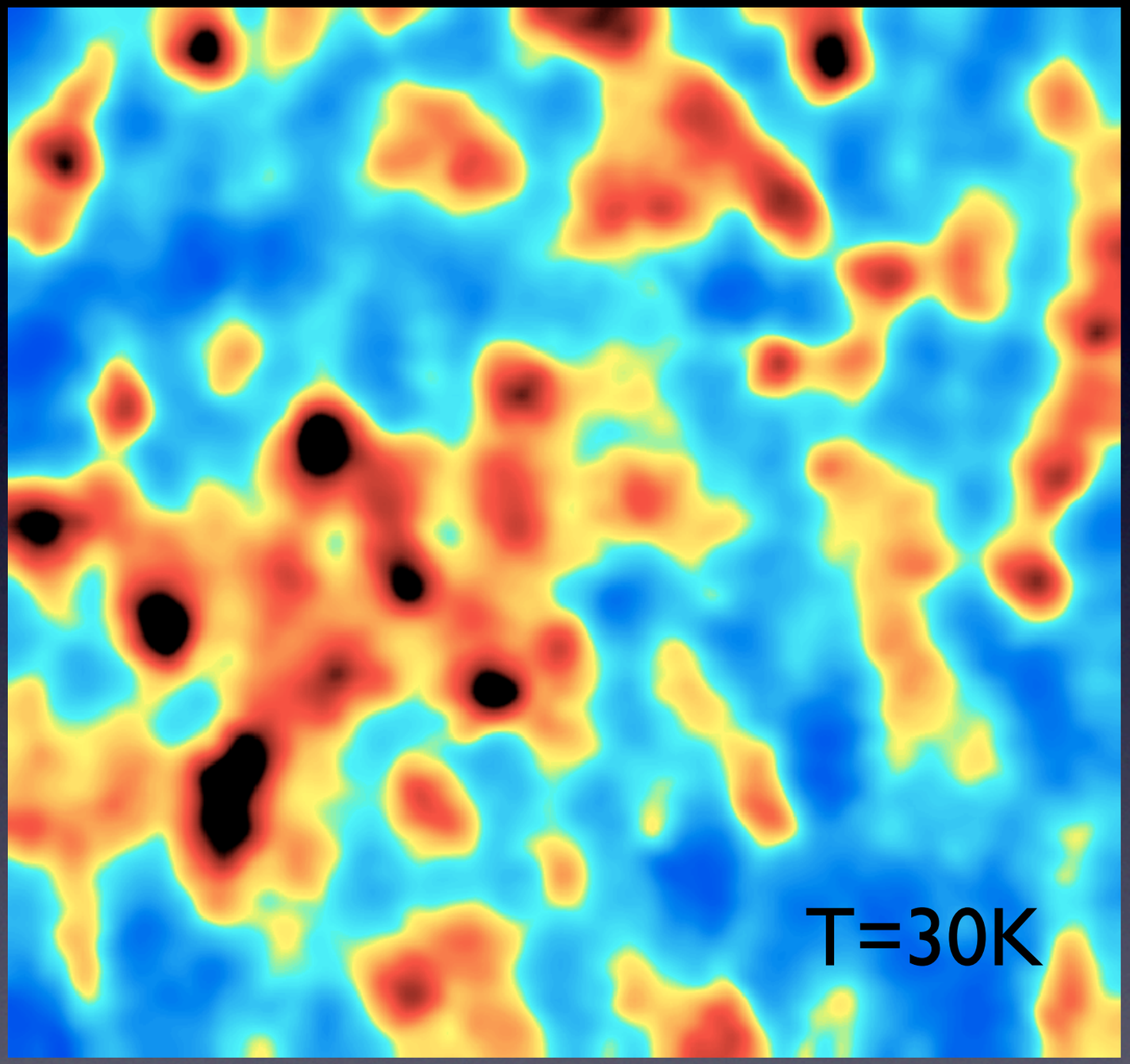


Questions:

- When do pairs form? *Over a range of temperatures above Tc.*
- Are there bosonic excitation that couple to electrons? Sure. Unlikely cause the major cause of pairing interaction.
- What controls the pairing strength?

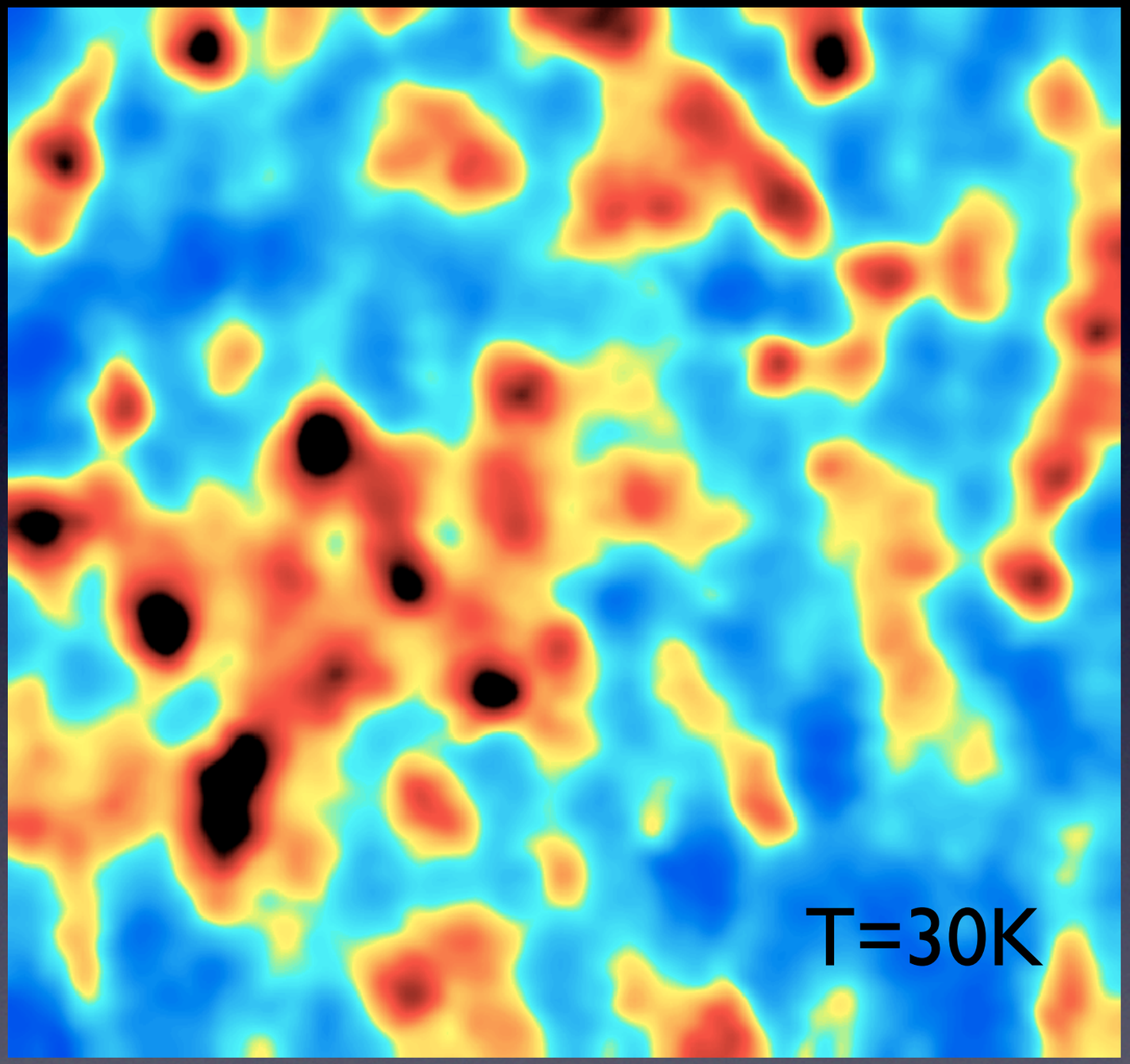
Why does the pairing gap vary spatially?

Pairing Gap Map

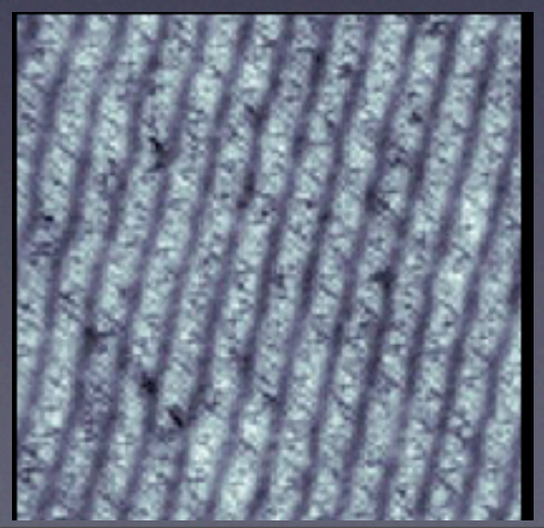


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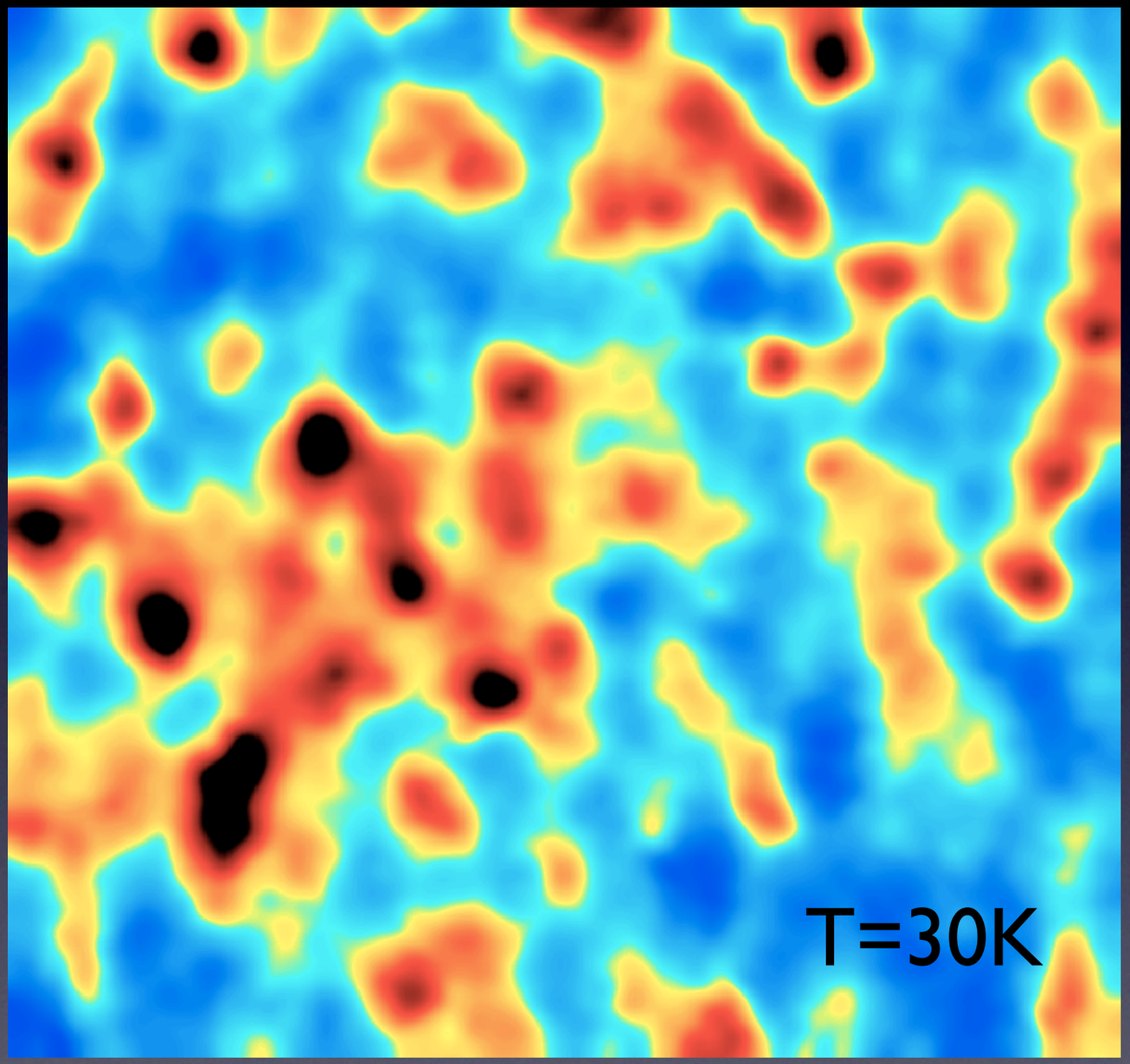


Structural Features?

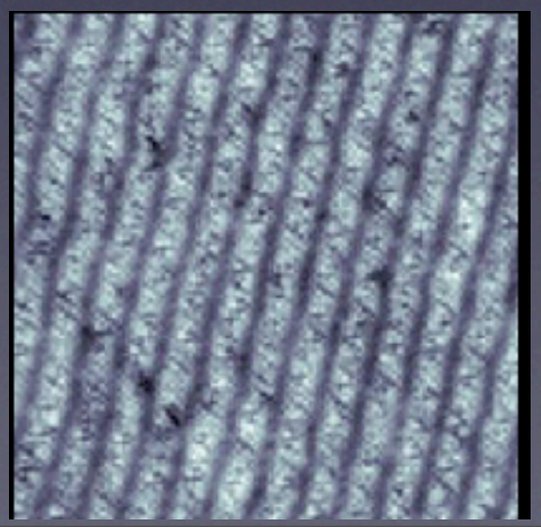


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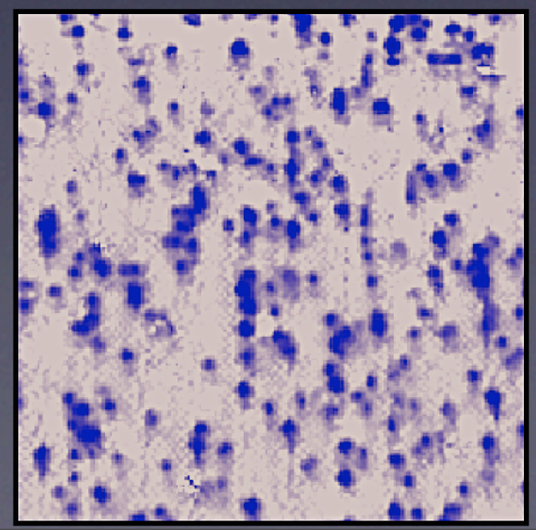
Pairing Gap Map



Structural Features?

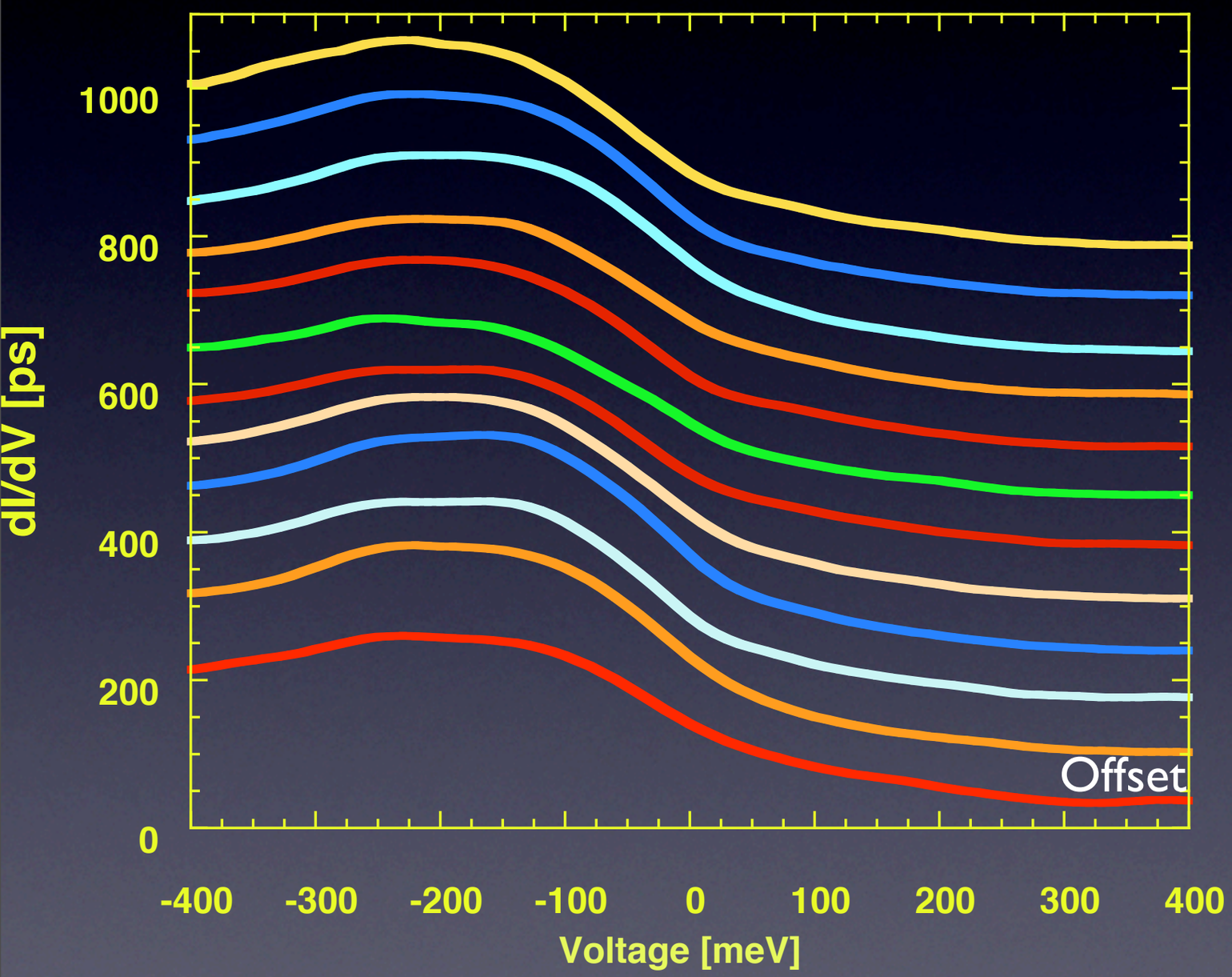


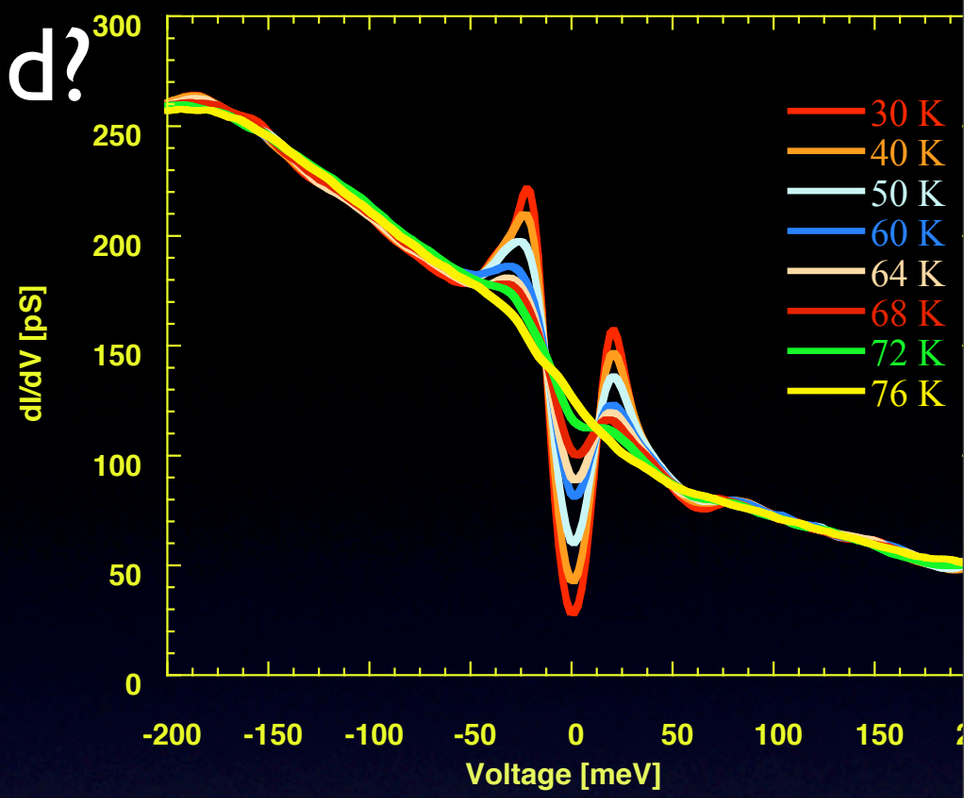
Defects/ Dopants?



What about normal state background?

Different Locations for OV68 @ 100K

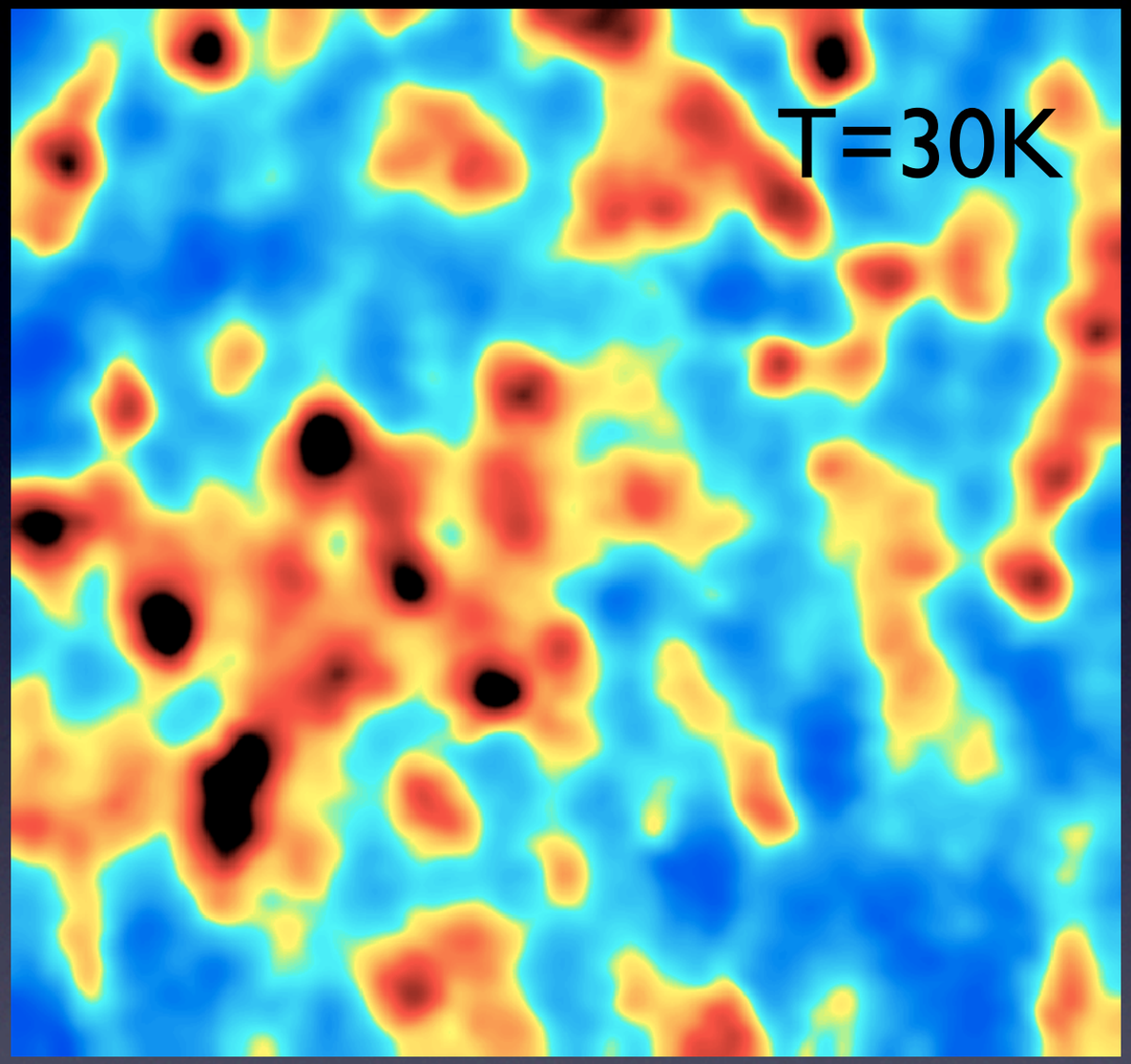




What can the "Normal State" Tell us?

300 Å x 300 Å

Gap Map



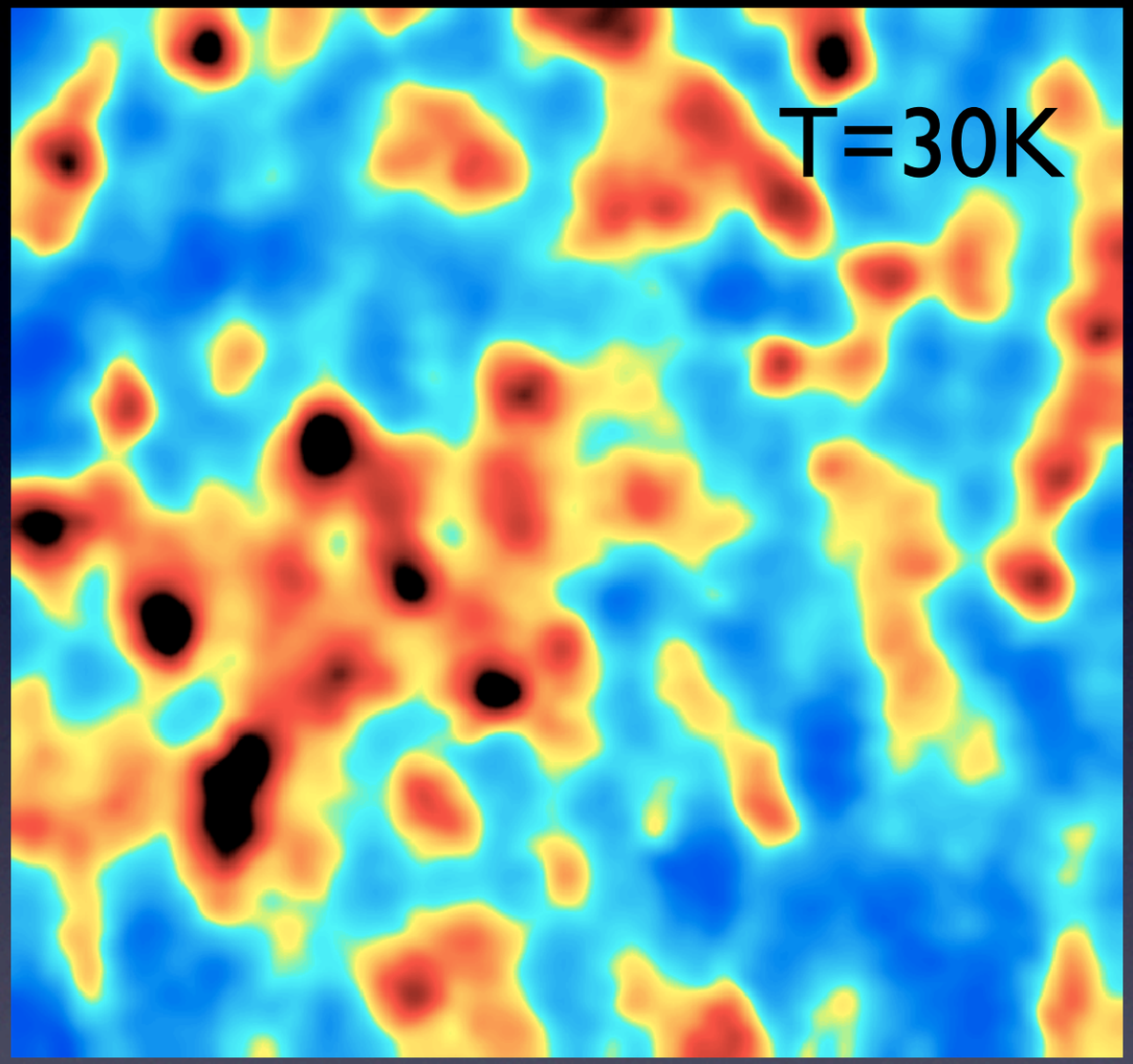


OV68

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300 Å x 300 Å

Gap Map

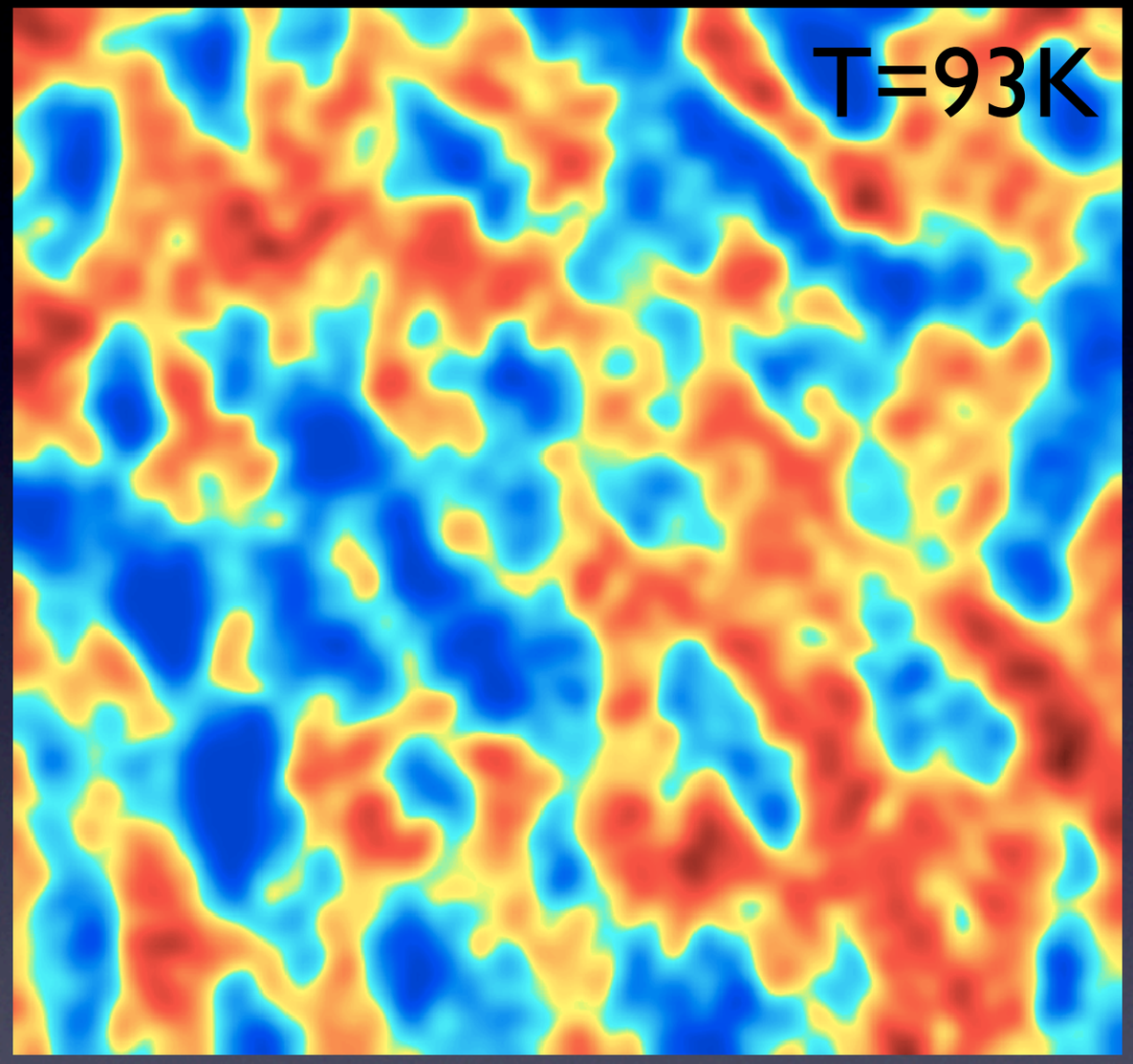


18 — 38

Δ (meV)

300 Å x 300 Å

dI/dV Map at E_F



160 — 290

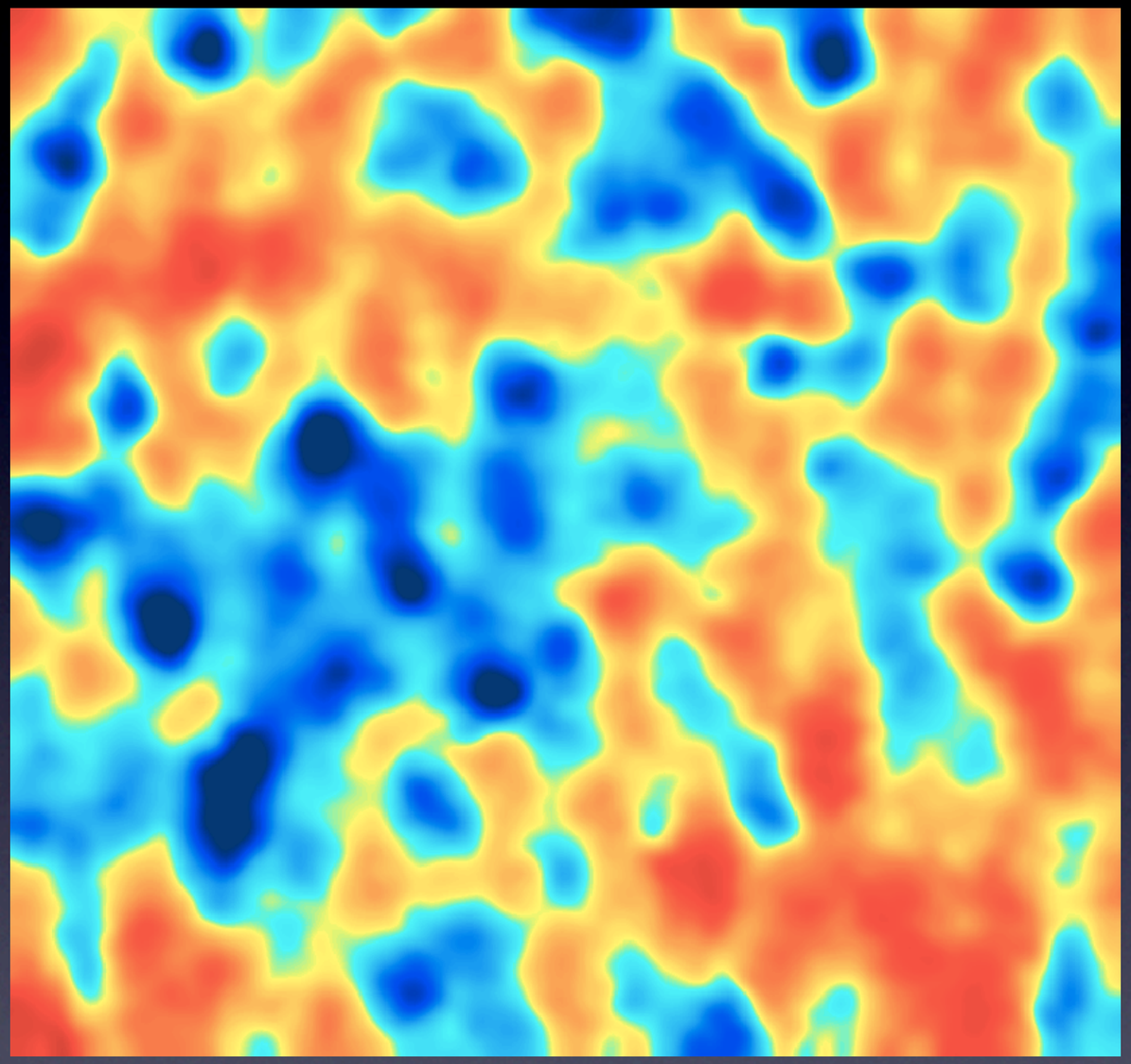
dI/dV (pS)

OV68

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Gap Map

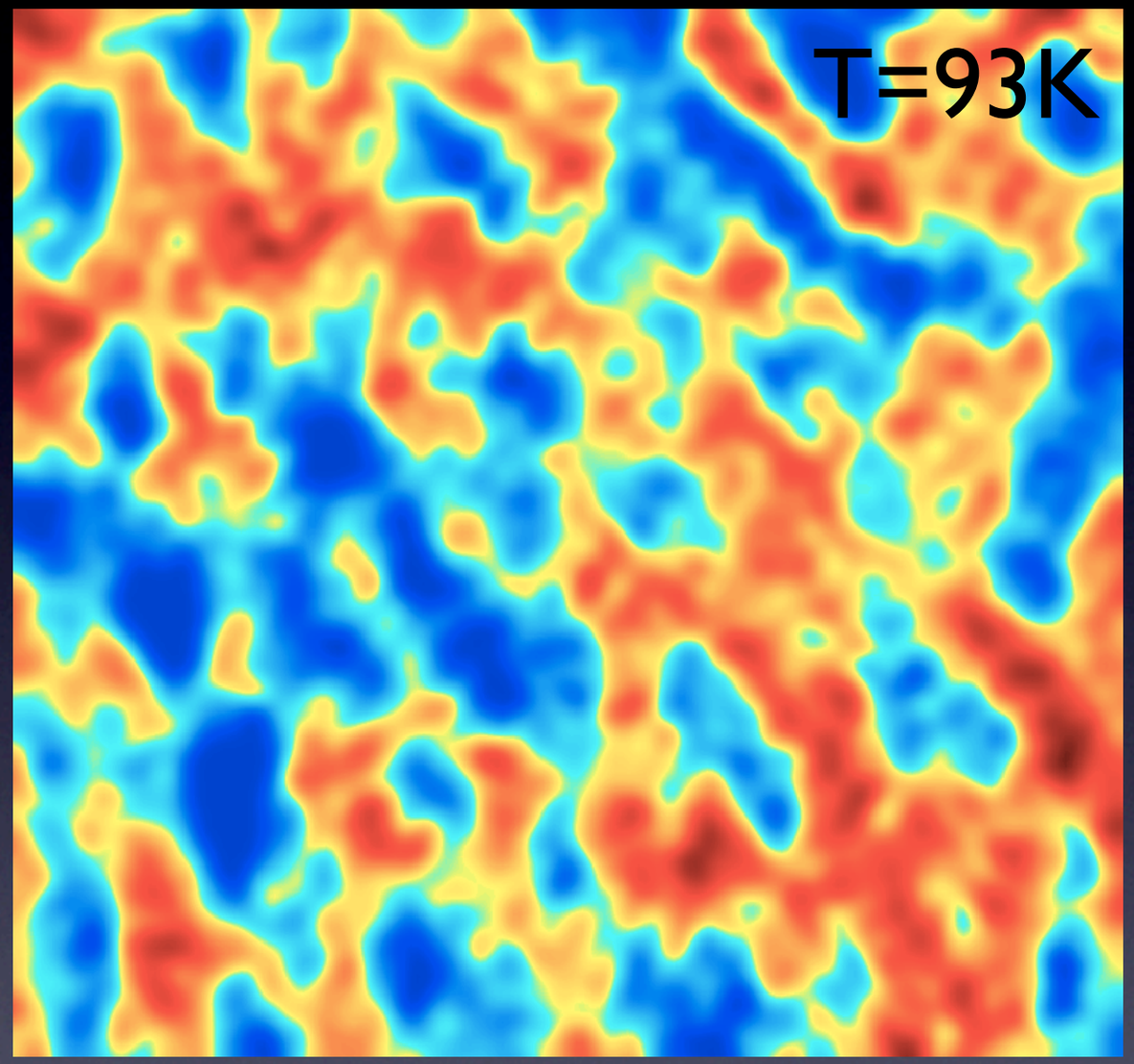


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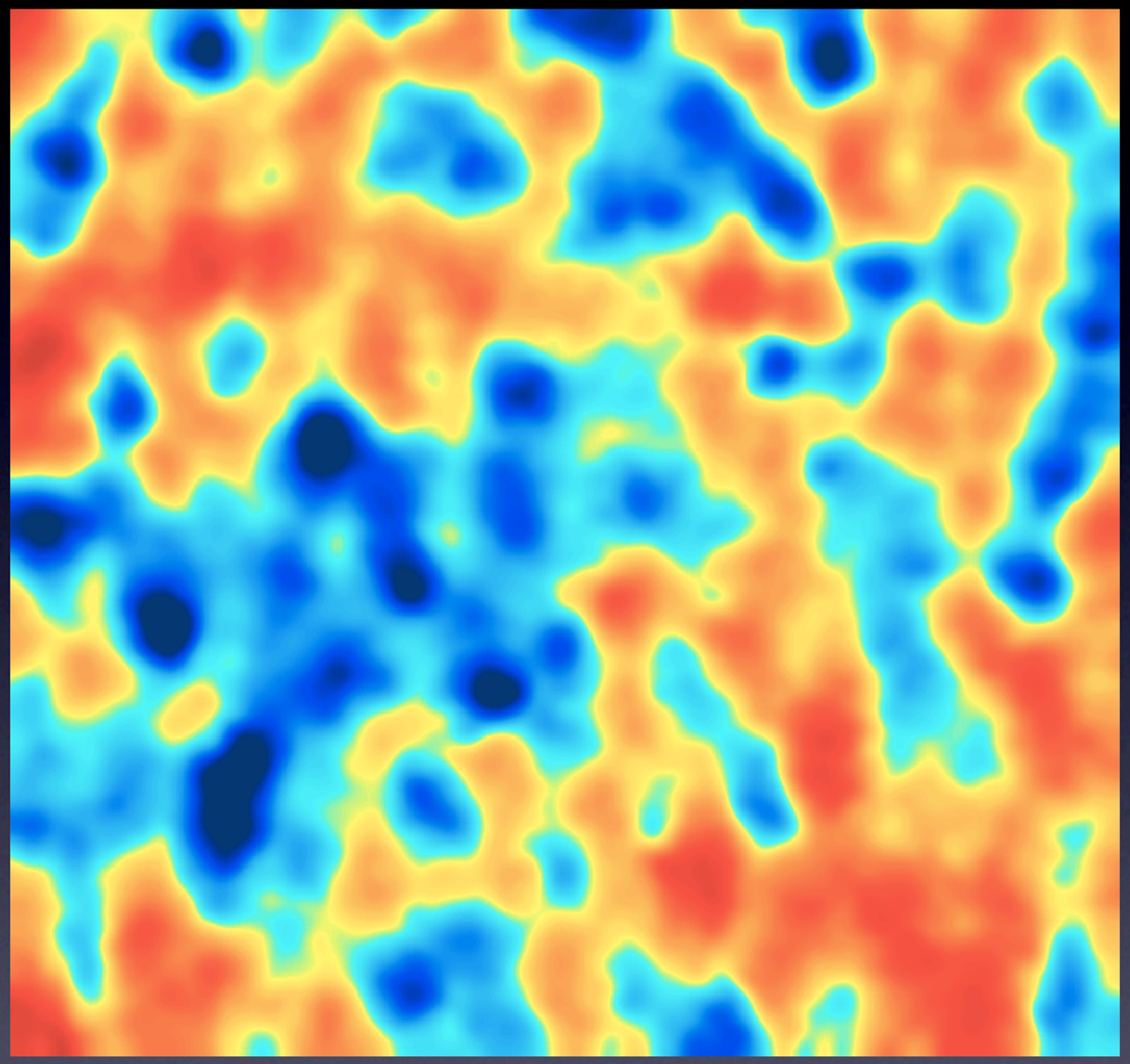
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Gap Map

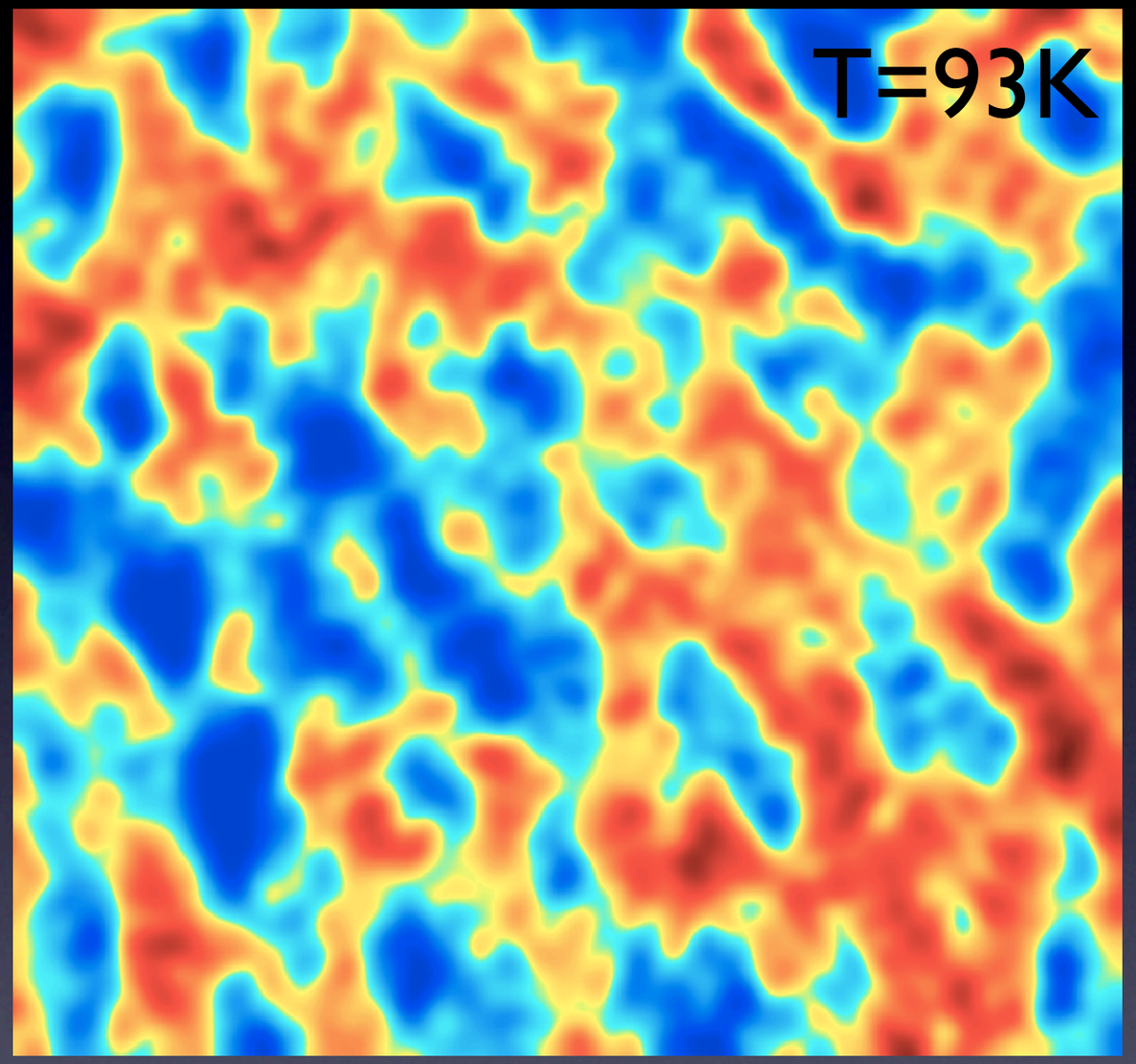


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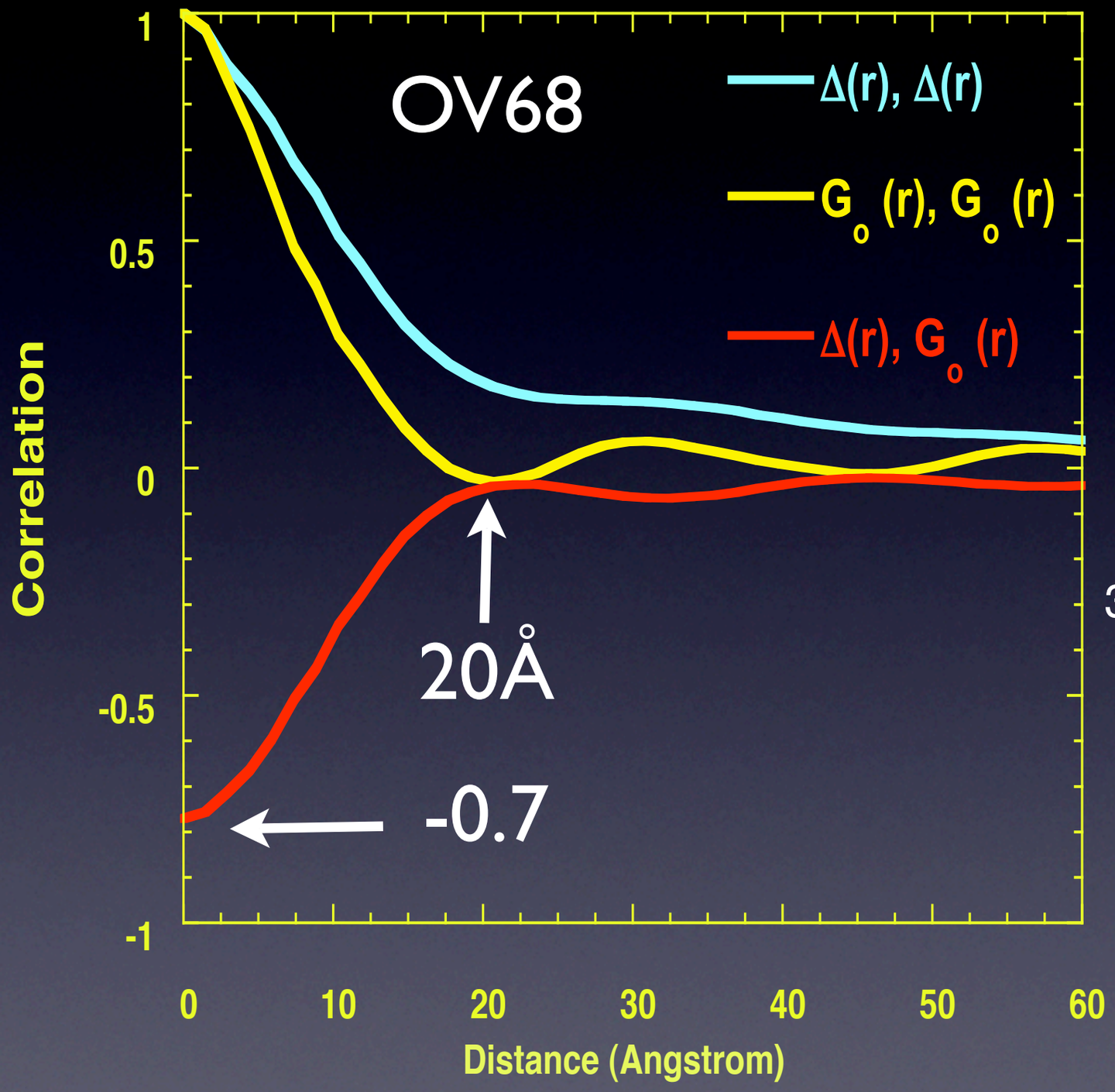
160 — 290

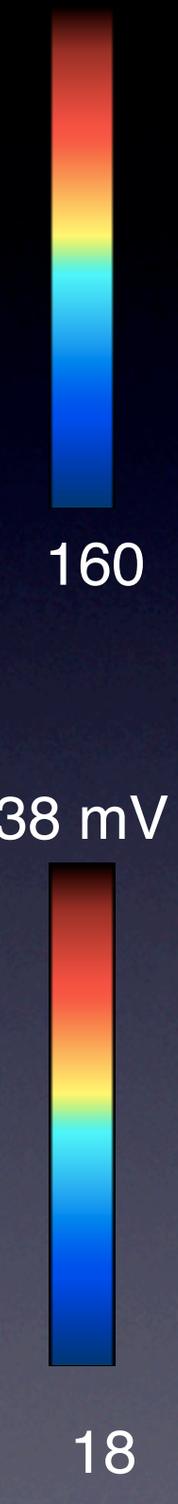
dI/dV (pS)

Normal State & Gap Maps are anticorrelated!

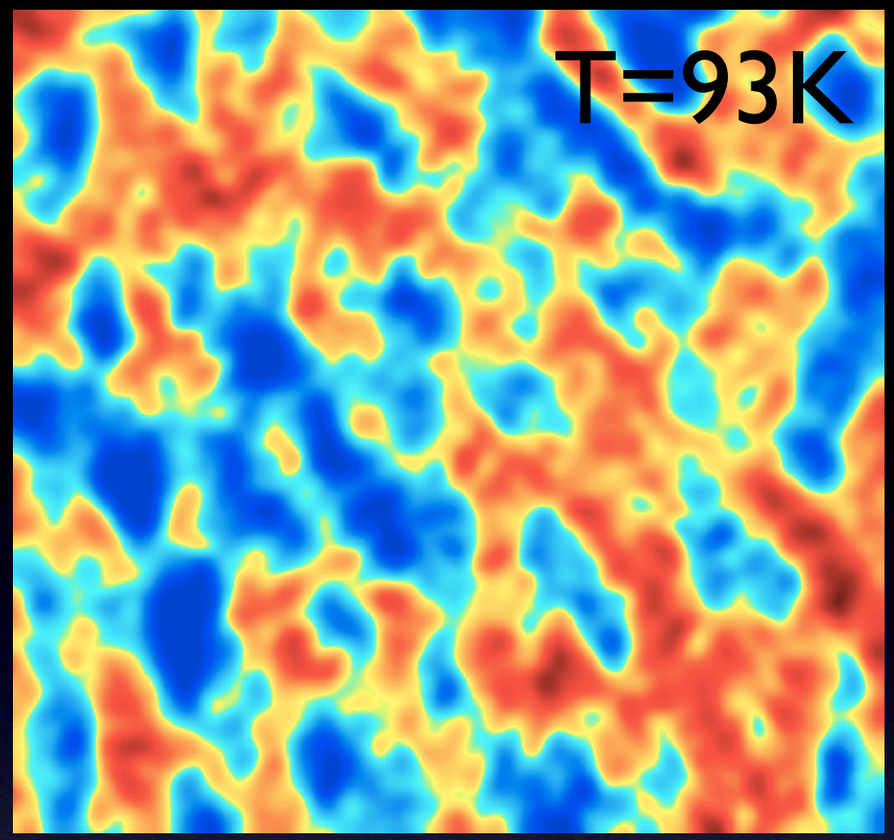
OV68

Strong Anti-Correlation between "Normal" and SC states



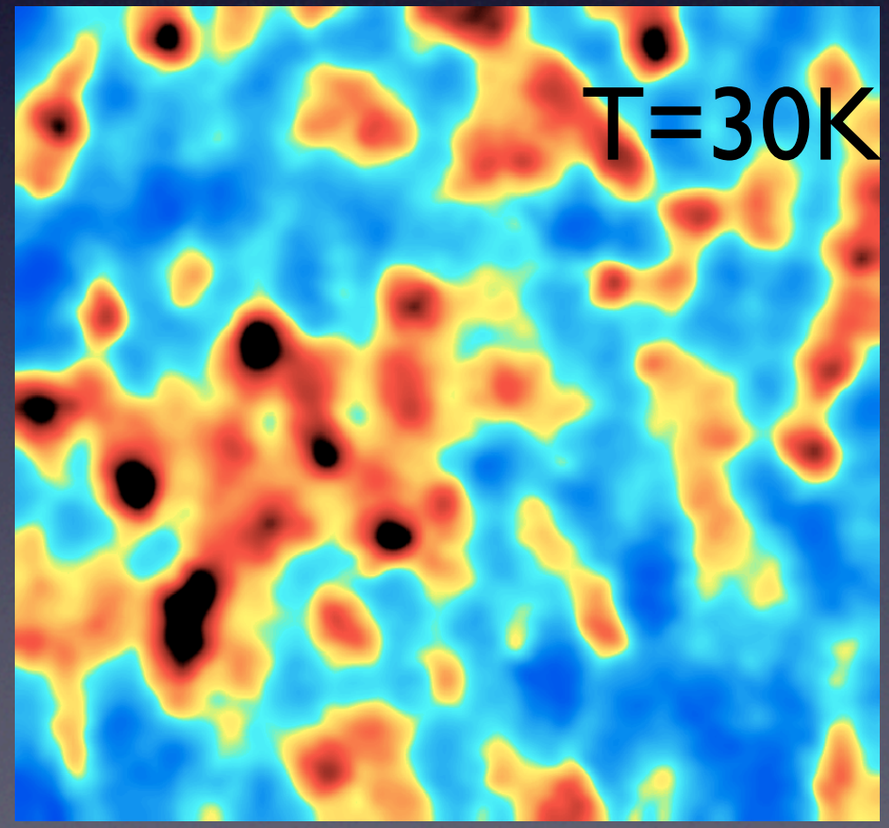


dI/dV Map at E_F



Gap Map

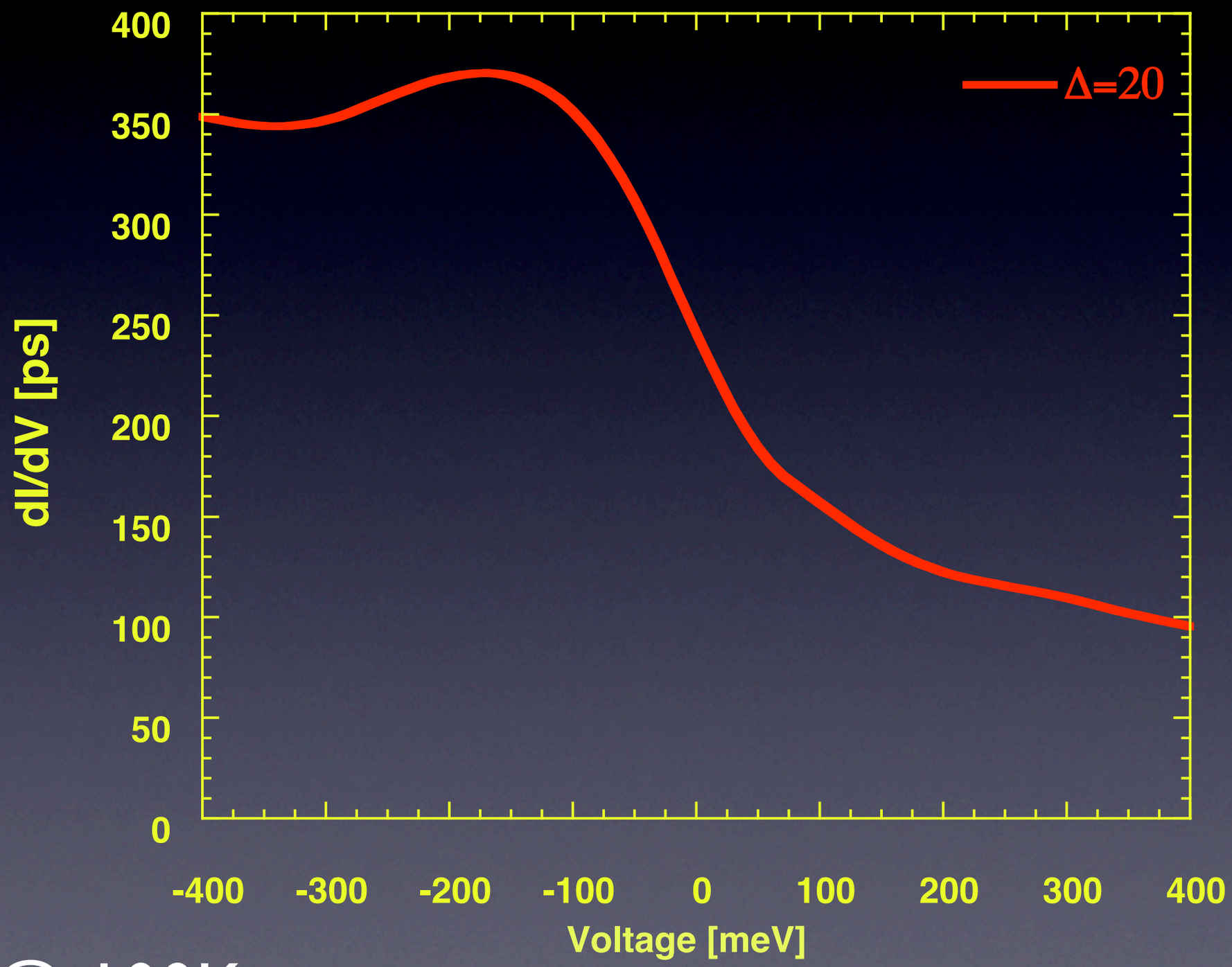
400 Å x 400 Å



Length scale of gap inhomogenouity is set by normal state

“Normal State” Spectra Foreshadow the Gaps

Systematic correlation between shape & eventual gaps

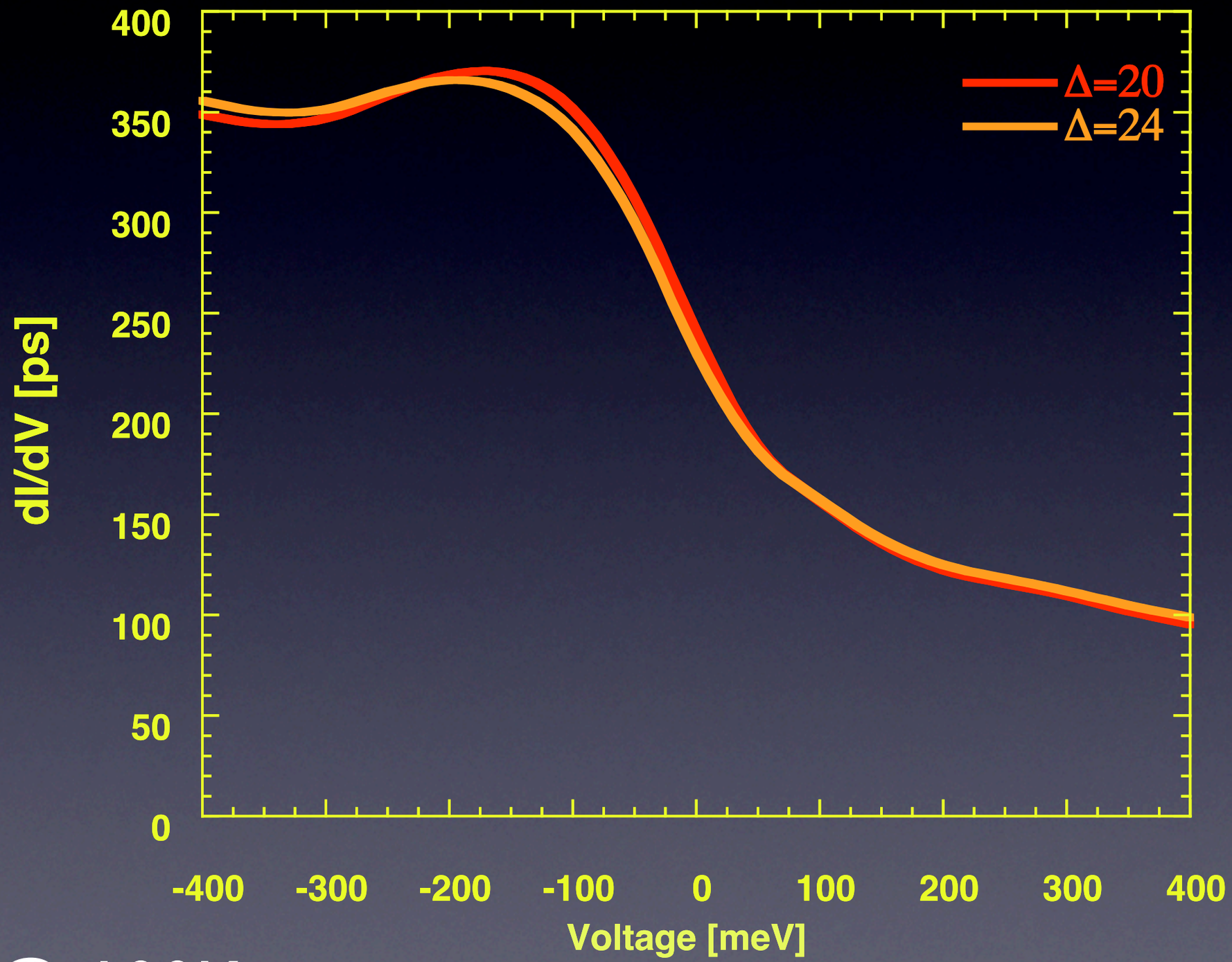


OV68@ 100K

Pasupathy, Pushp, Gomes, Parker, Gu, Ono, Ando, Yazdani *Science*, **320**, 196 (2008)

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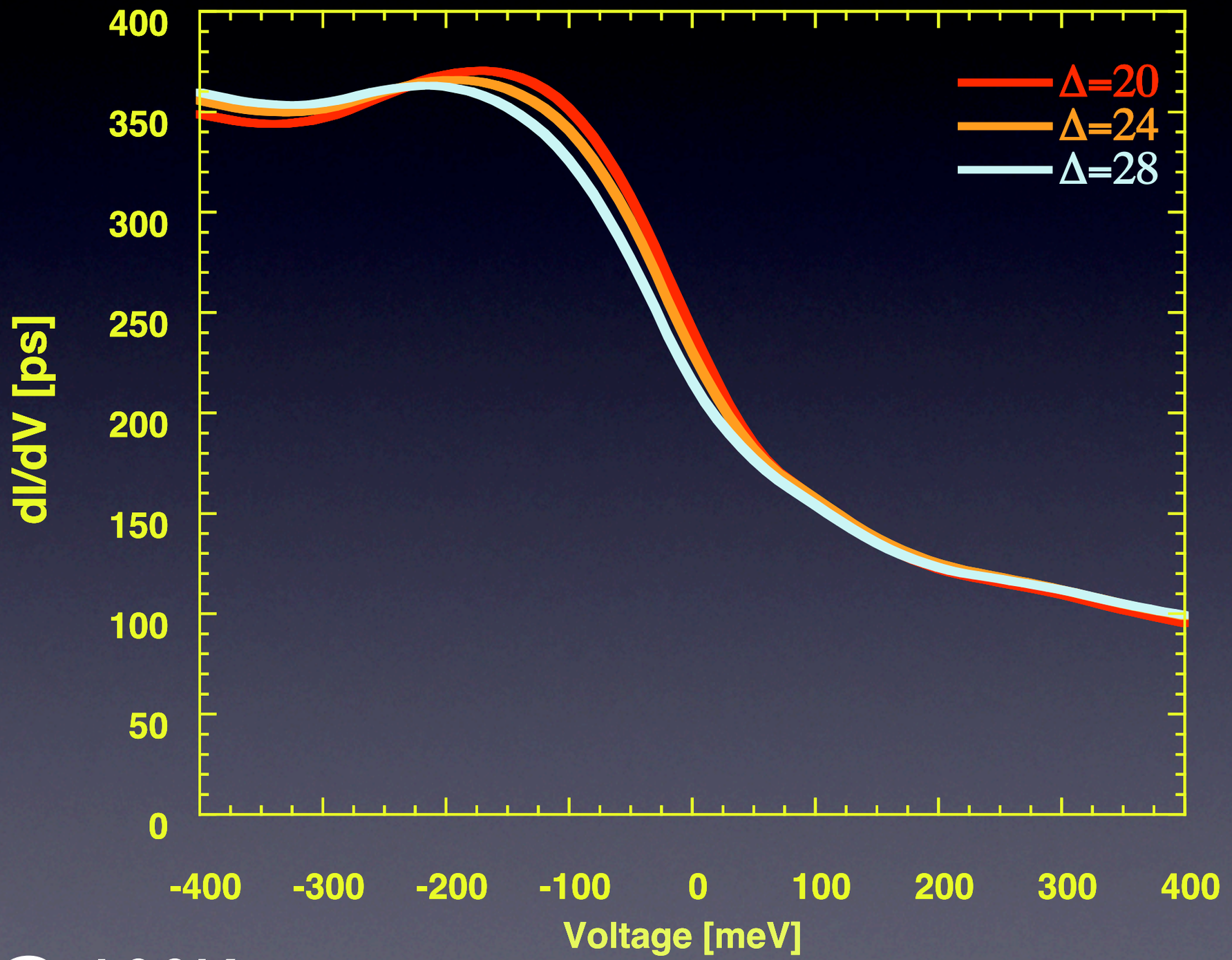


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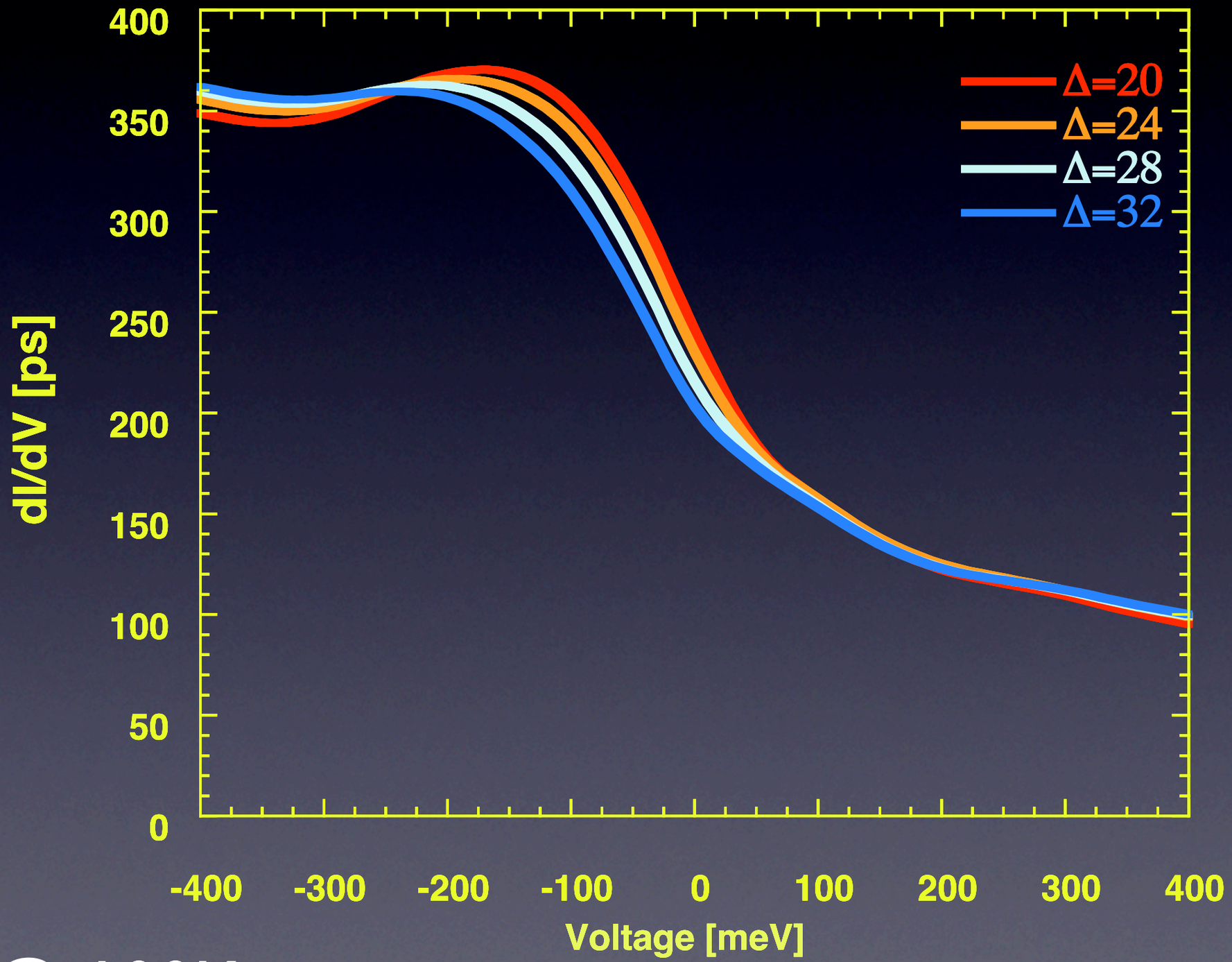


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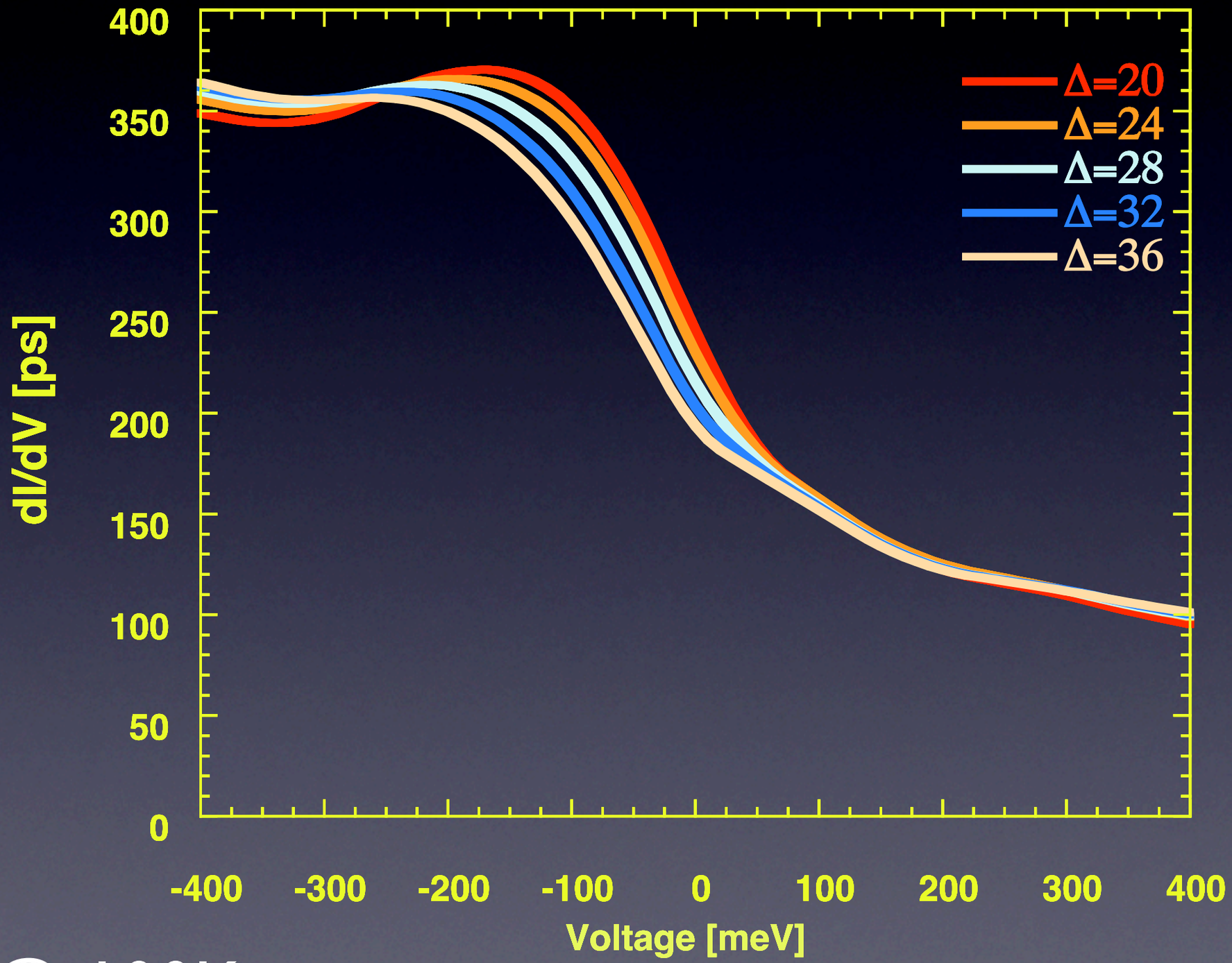


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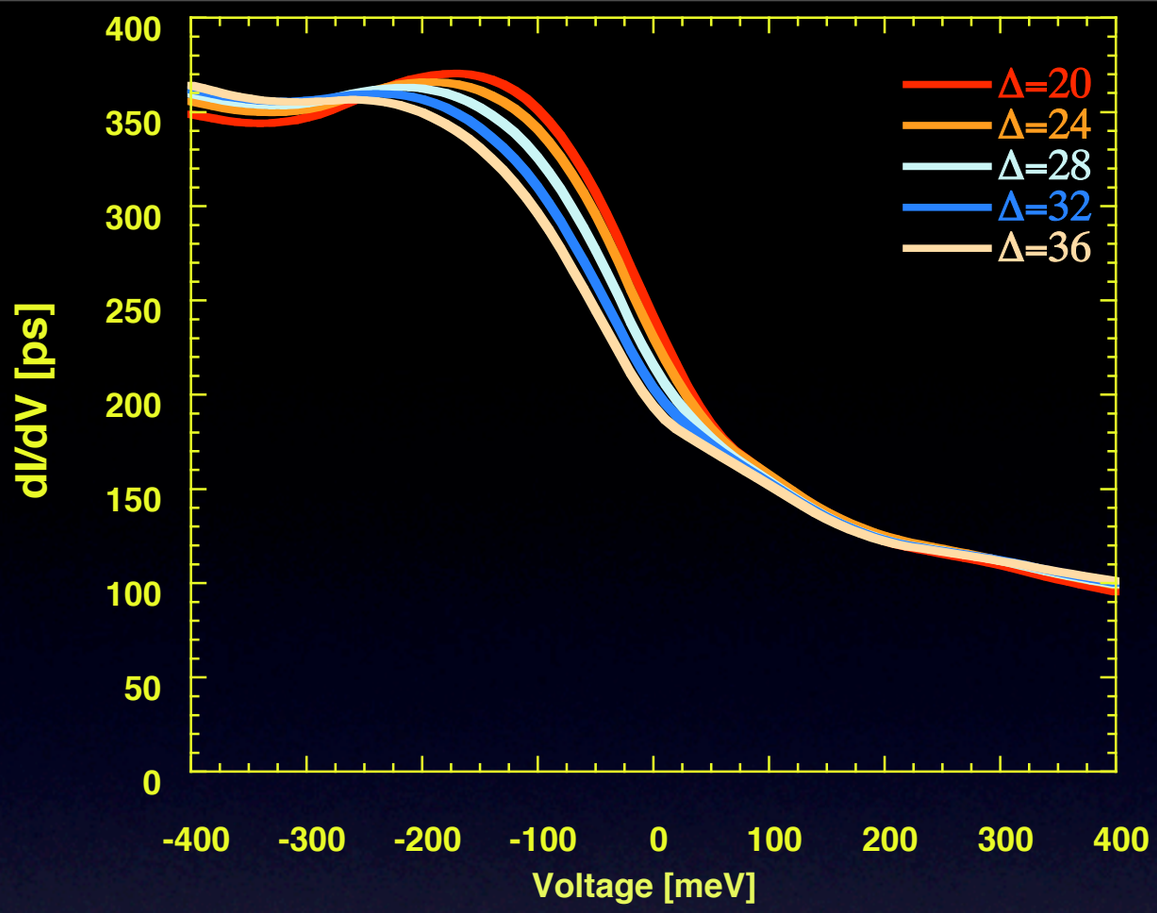


OV68@ 100K

Pasupathy, Pushp, Gomes, Parker, Gu, Ono, Ando, Yazdani *Science*, **320**, 196 (2008)

“Normal State” Spectra Reference by Low-T Gaps

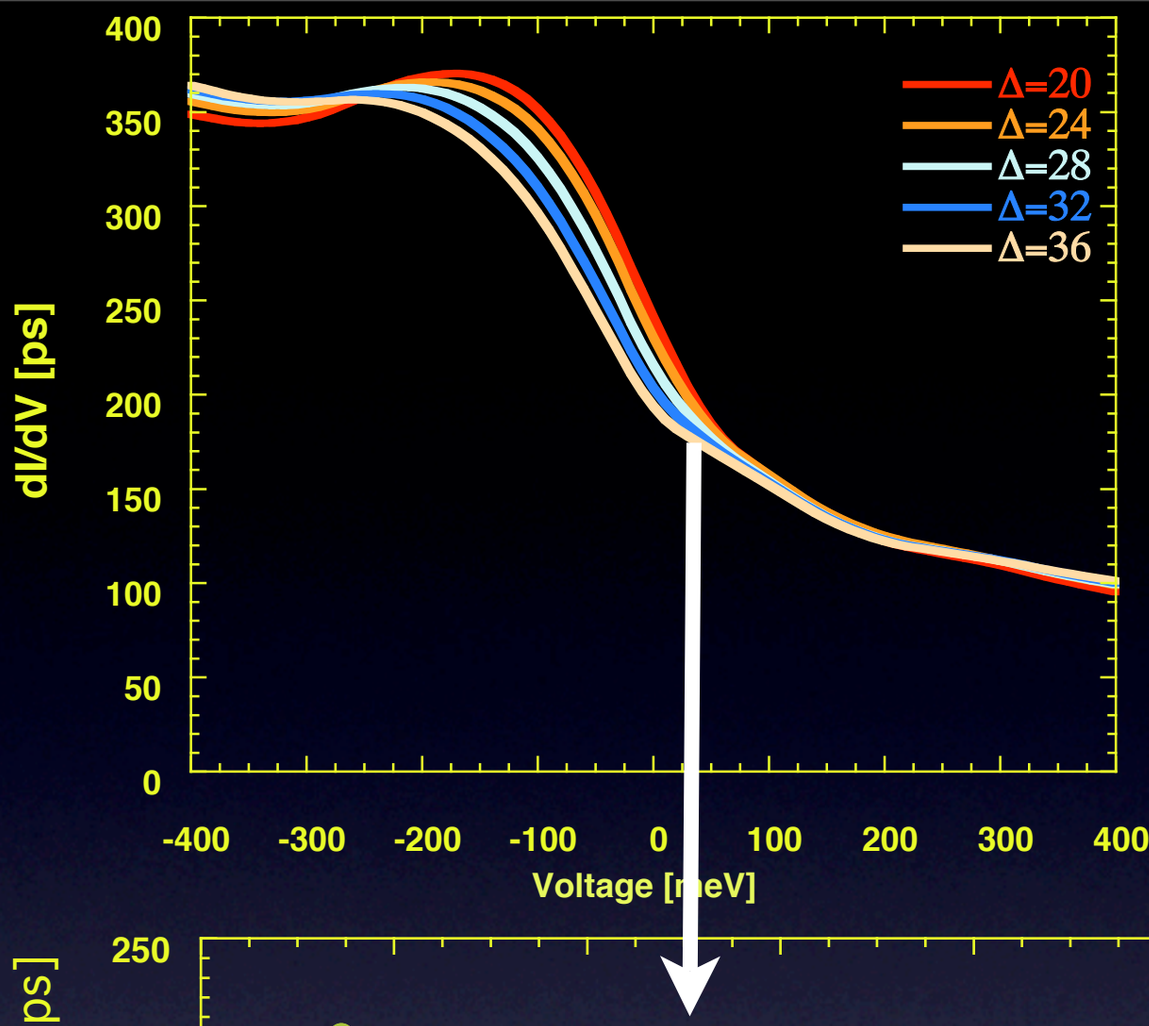
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OV68@ 100K

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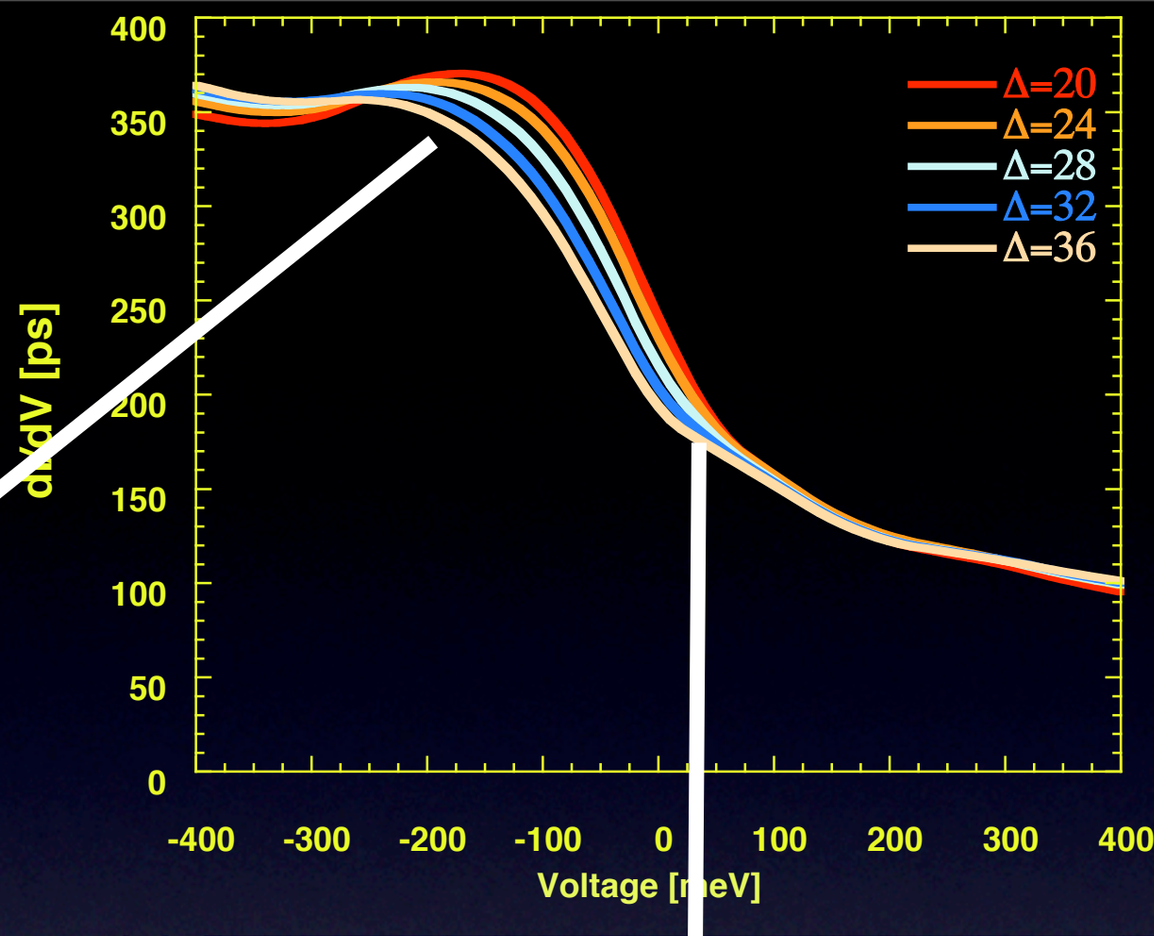
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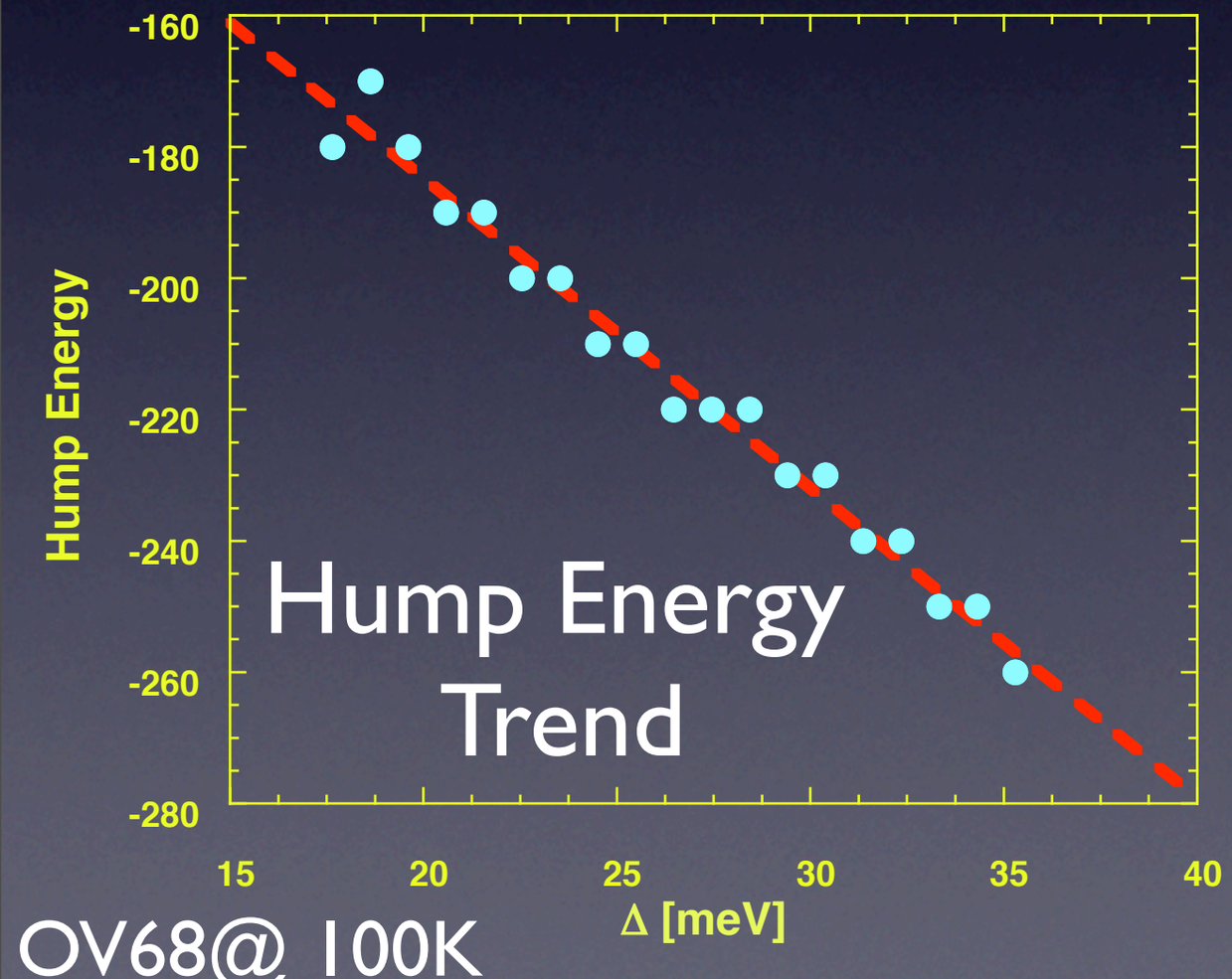


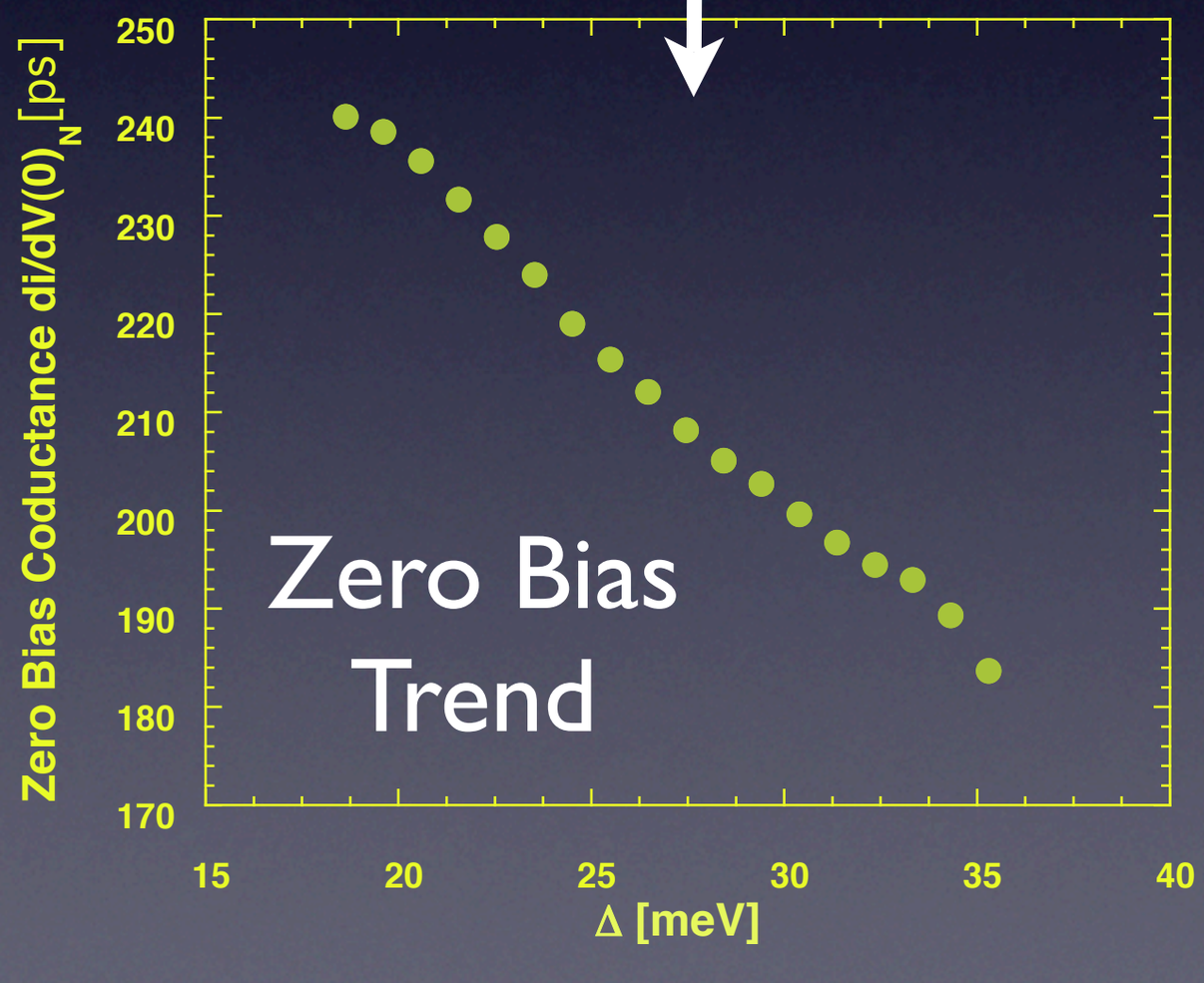
OV68@ 100K

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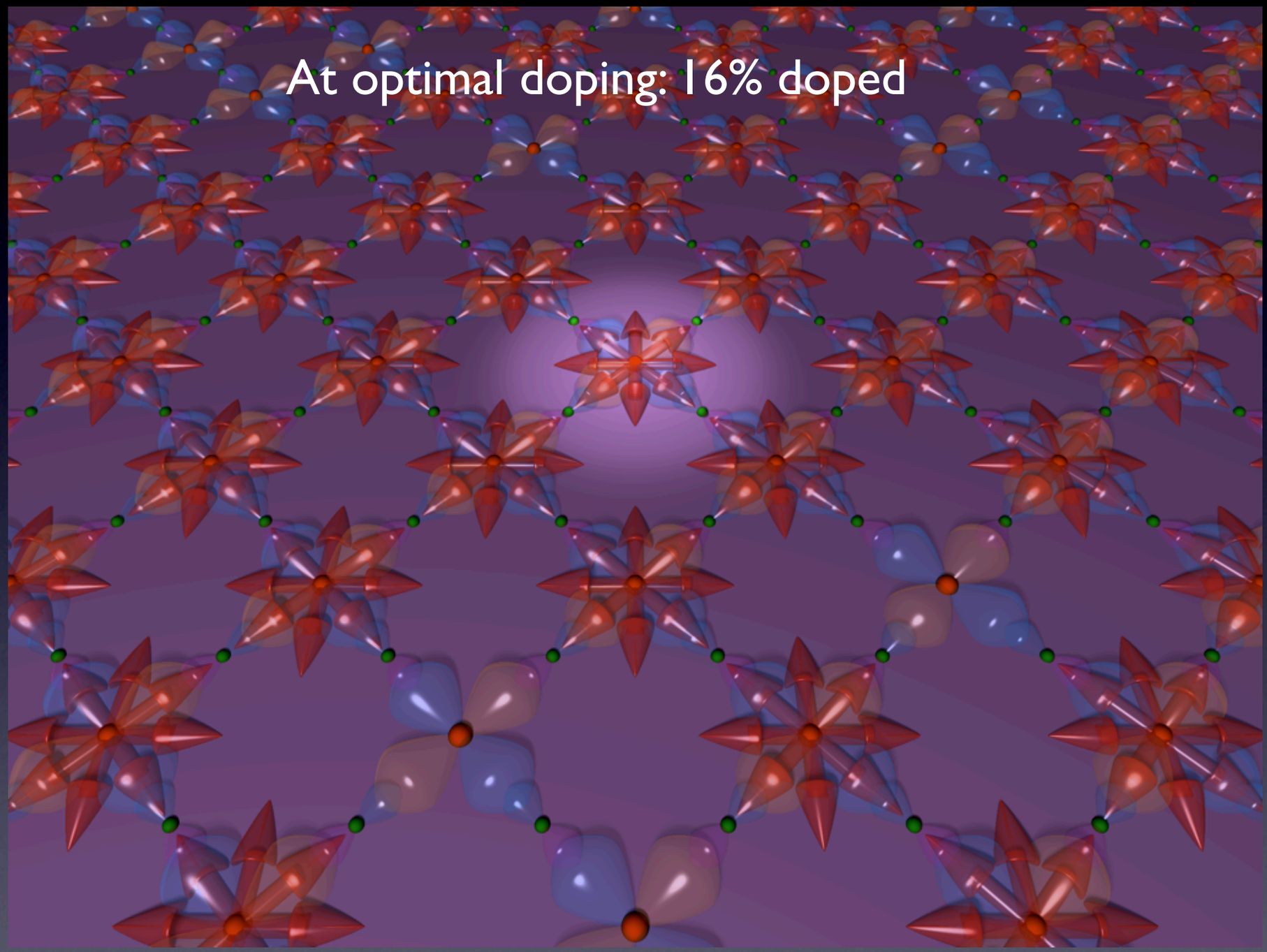






OV68@ 100K

Spectra Asymmetry & Mott Physics



Adding electrons hard

Removing electrons easy

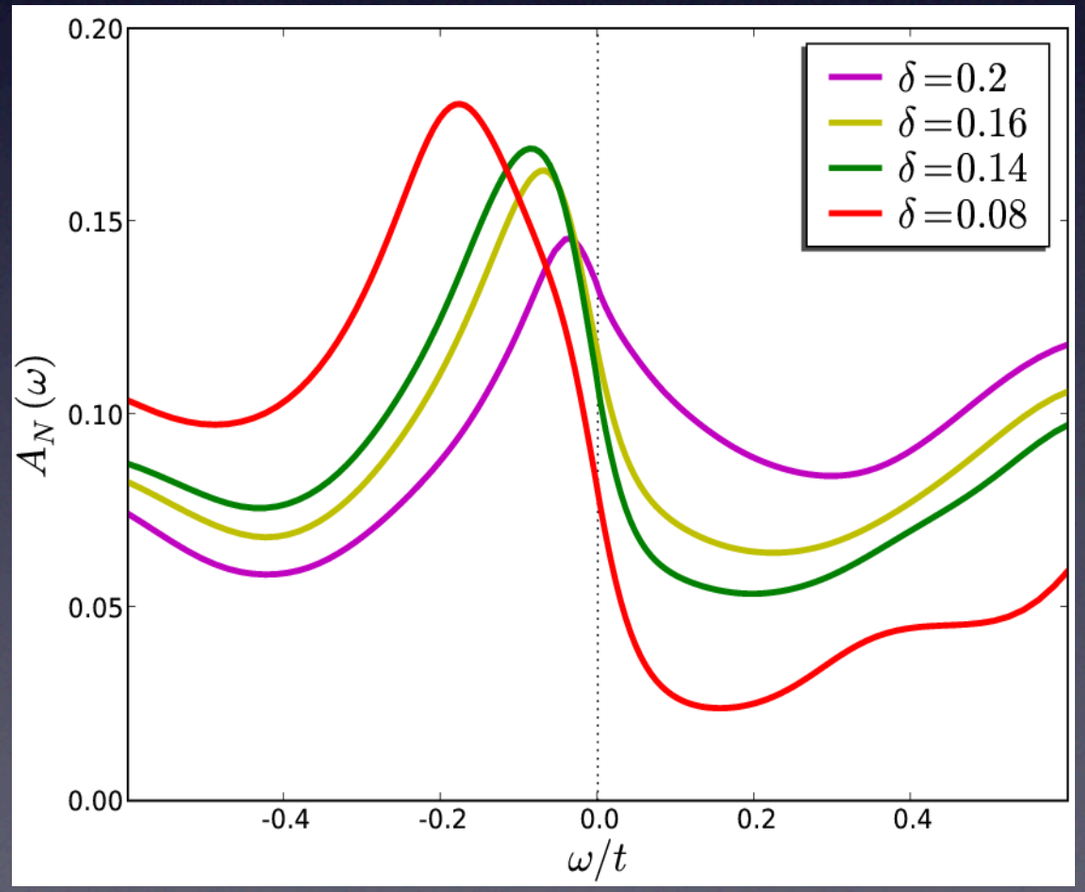
Origin of "Hump" in the so-called "Normal Metal"??

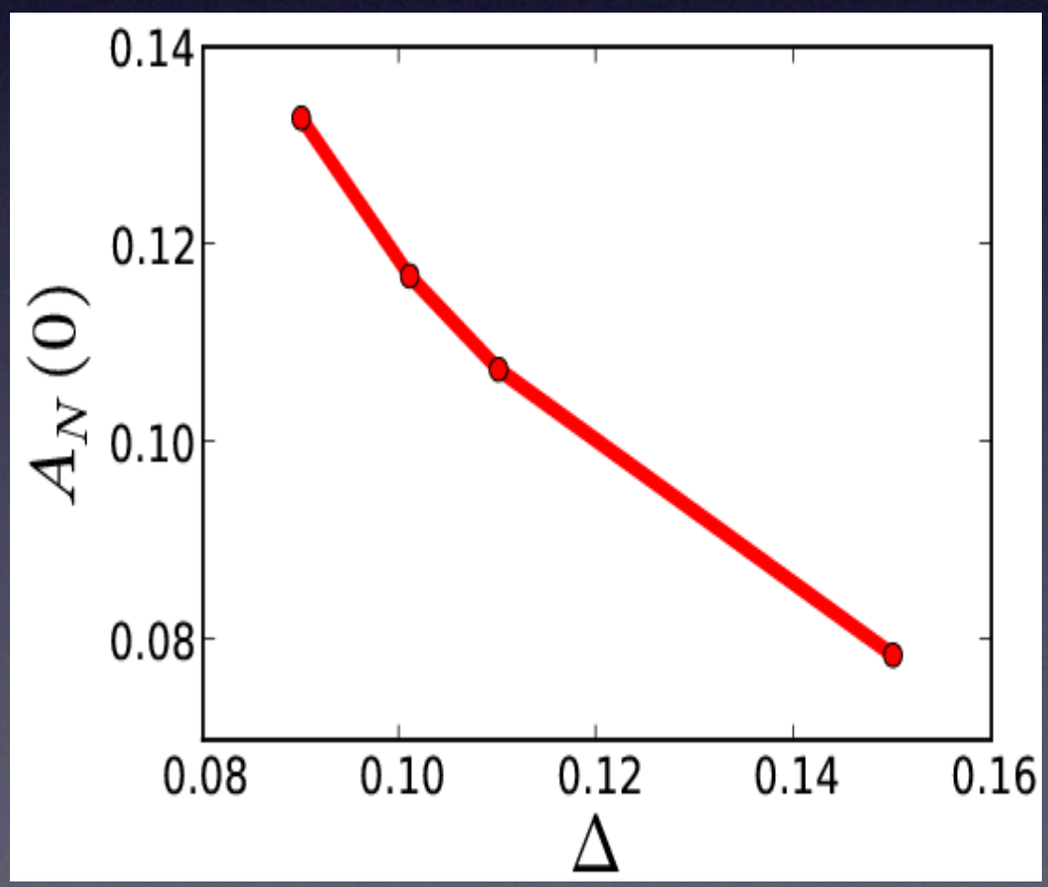
- Mott Physics?
- Projected schemes: asymmetric e-h excitation
- Even a "hump"

PHYSICAL REVIEW B **76**, 104509 (2007)

Strongly correlated superconductivity: A plaquette dynamical mean-field theory study

Kristjan Haule and Gabriel Kotliar
Department of Physics, Rutgers University, Piscataway, New Jersey 08854, USA
(Received 31 May 2007; published 13 September 2007)





Conclusions

- Pairing is local and occurs above Tc

- Electron-boson coupling unlikely cause of the inhomogeneous local pairing

- Electron-hole asymmetric excitations of the normal state determine both magnitude and variation of pairing at low T

