Analyzing LDOS and energy gap fluctuations: quantifying the interplay between electron-electron interactions and disorder in 2D superconductors

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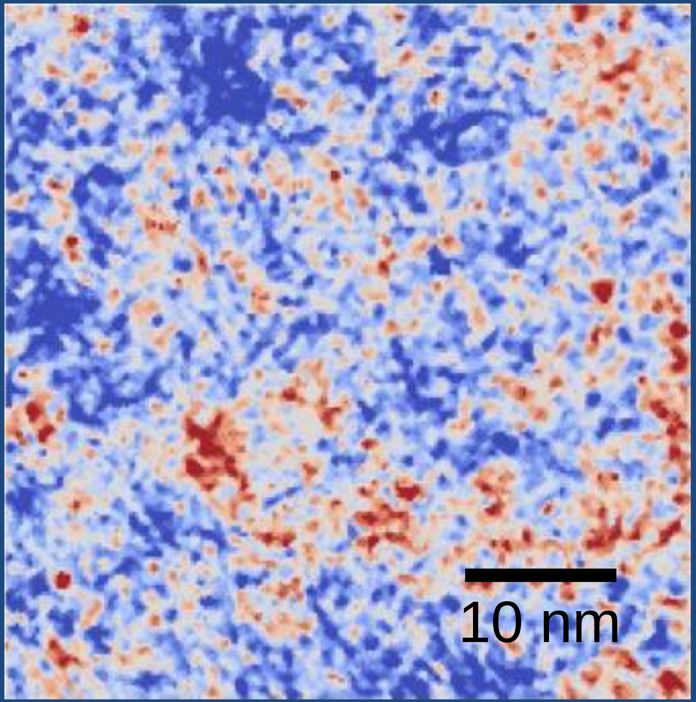

Motivation

Effects produced by the interplay between disorder and electron-electron interactions in 2D superconductors

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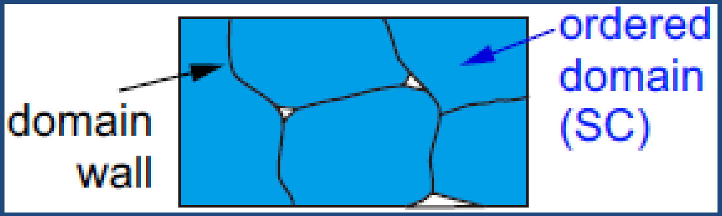
Effects produced by the interplay between disorder and electron-electron interactions in 2D superconductors

2D means $d < (<)\ \xi$

Structure matters !!



Thin film top view

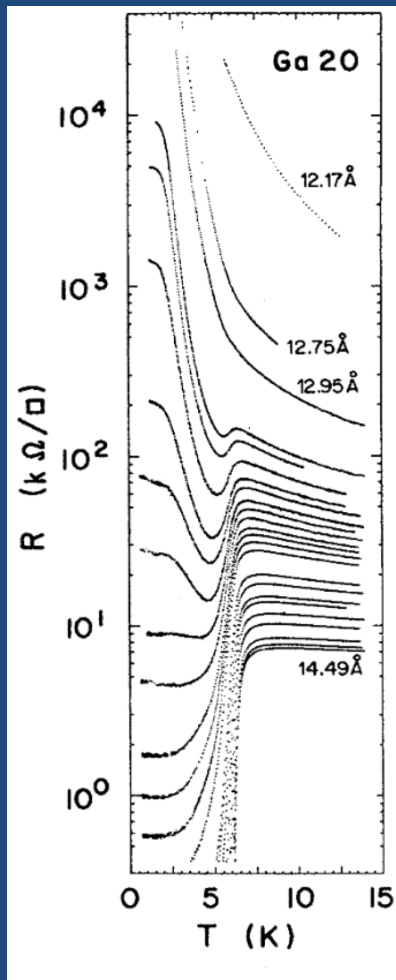
Motivation

Effects produced by the interplay between disorder and electron-electron interactions in 2D superconductors

$$\Delta(\vec{r})e^{i\varphi(\vec{r})}$$

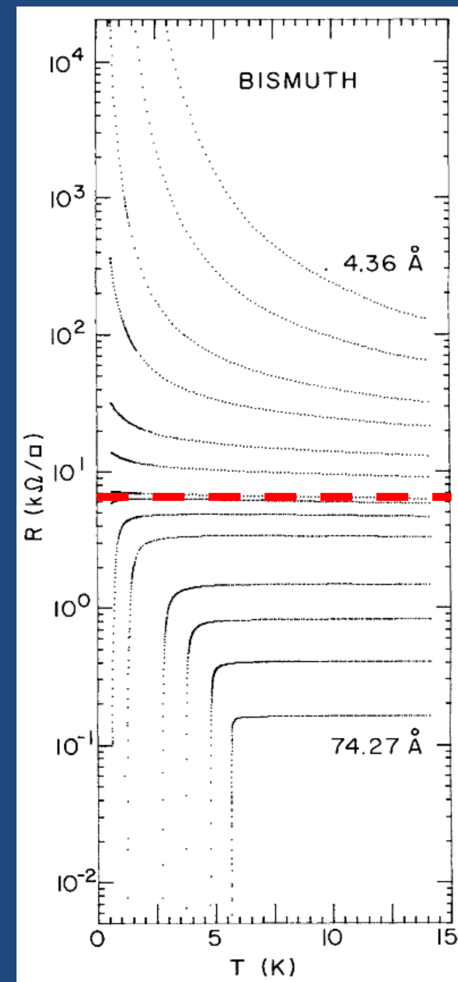
Disordered superconducting ultrathin films

Granular thin films



Jaeger et al. PRB 40, 182 (1989)

Homogeneous thin films



$h/4e^2 = 6.45 k\Omega$

Haviland et al. PRL 62, 2180 (1989)

Reviews: Goldman & Markovic Phys. Today 51, 39–44 (1998) Gantmakher & Dolgopolov Phys. Usp. 53, 1–49 (2010)

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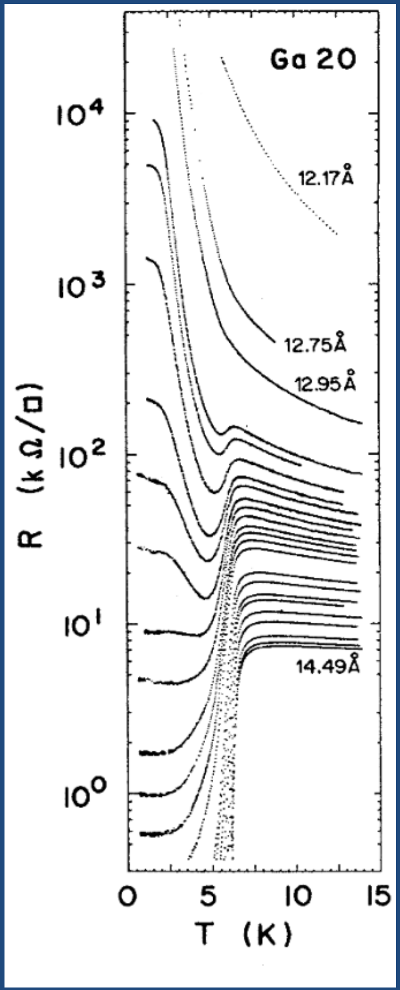

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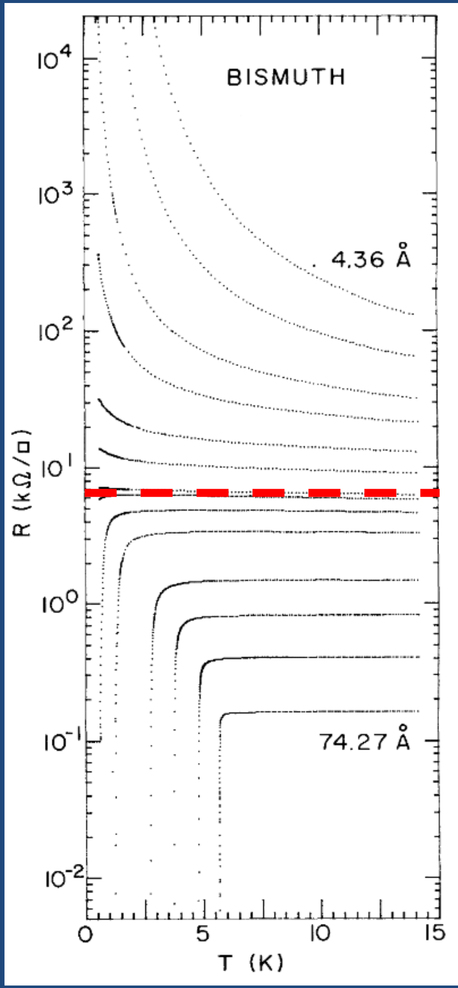

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Homogeneous thin films

$$\Delta(\vec{r})e^{i\varphi(\vec{r})}$$

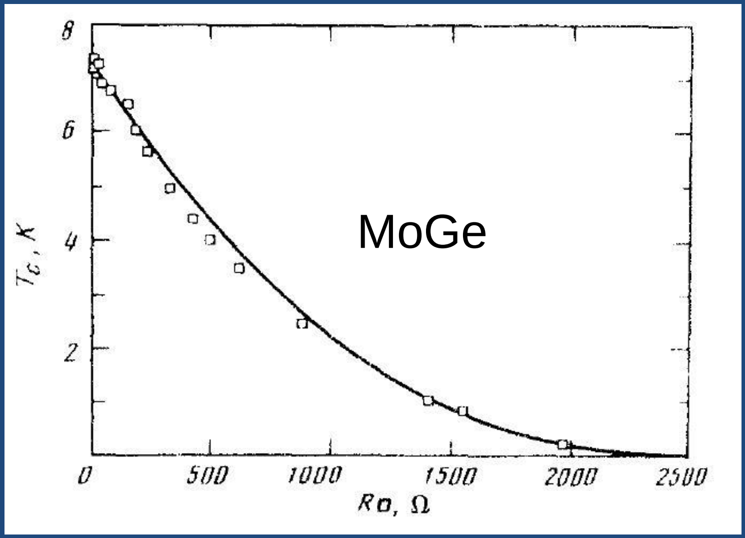
Fermionic scenario $k_F l \to 1$ **Bosonic scenario**

Finkelstein mechanism

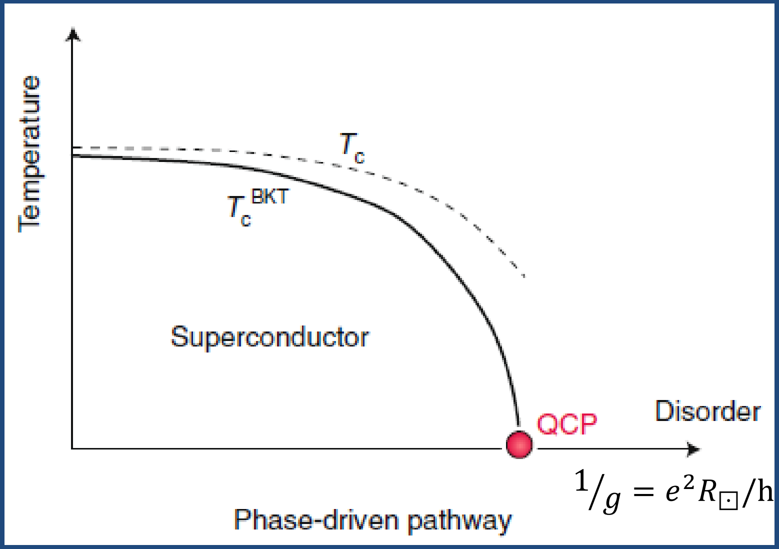
increased Coulomb repulsion:
poor electronic screening reduces λ

Anderson localization

local phase fluctuations



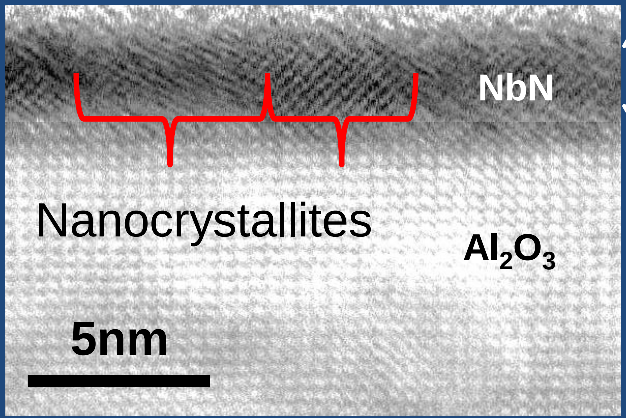
Finkelstein Pis'ma Zh. Eskp. Teor. Fis. 1987



Review: Sacépé et al Nat. Phys. 2020

Local scale picture of nominally homogeneous thin films

Structure of NbN on Al_2O_3 (ex situ growth)

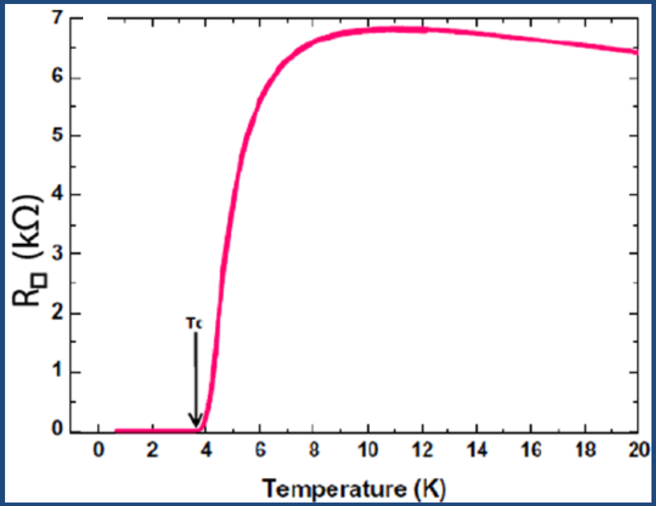


$d_{NbN} = 2.33$ nm

$l_{grain} = 2 - 8$ nm

TEM image

STM and in-situ 4 probe R(T)



In situ R(T)

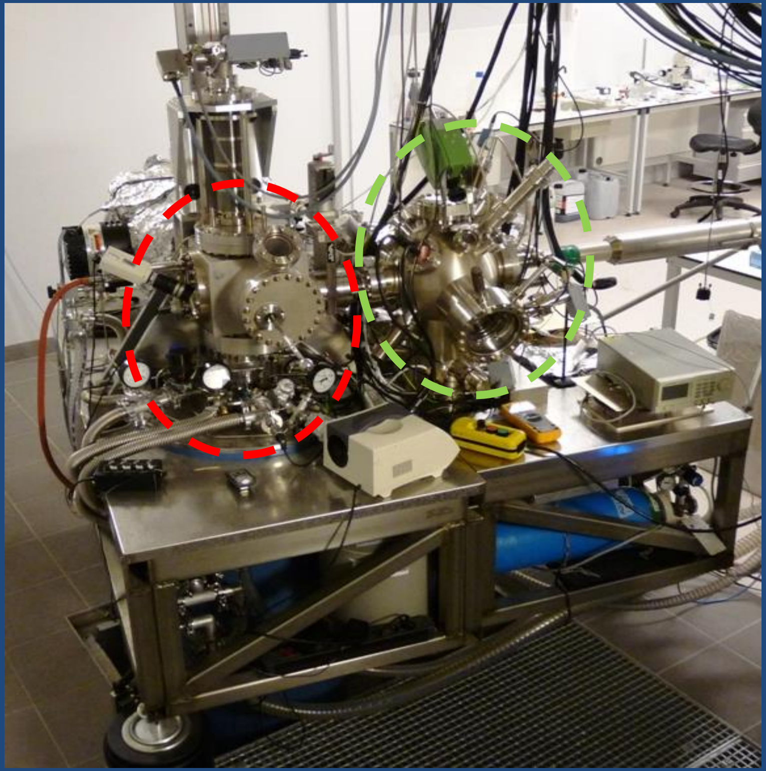
Moderate disorder

$$k_F \ell_e \approx 2 - 3$$

$$T_c \approx 0.3\ T_{c-bulk}$$

$$R_\square \approx 7\ \mathrm{k\Omega}$$

Carbillet et al PRB 93, 144509 (2016)



Home-made apparatus

STM head

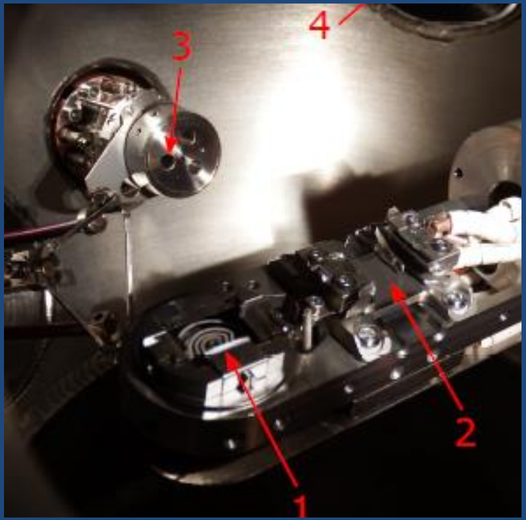
STM/STS

UHV : P < $5x10^{-11}$ mbar

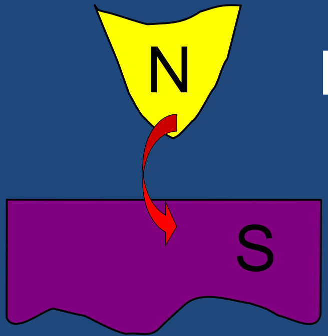
In situ growth @ P < $1x10^{-10}$ mbar

Base T° 300 mK (He_3 single shot)
$T_{electrons}$~380 mK (55 hours)

Magnetic Field: 0 –10 T



Preparation chamber
e-beam evaporators

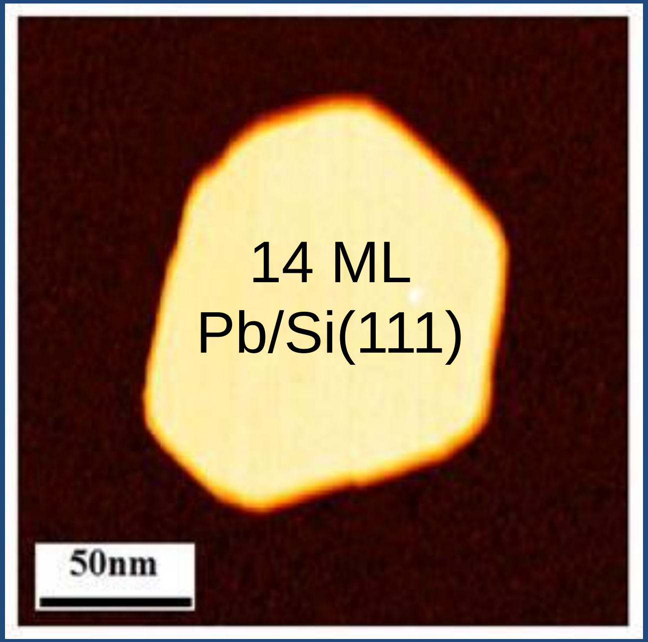


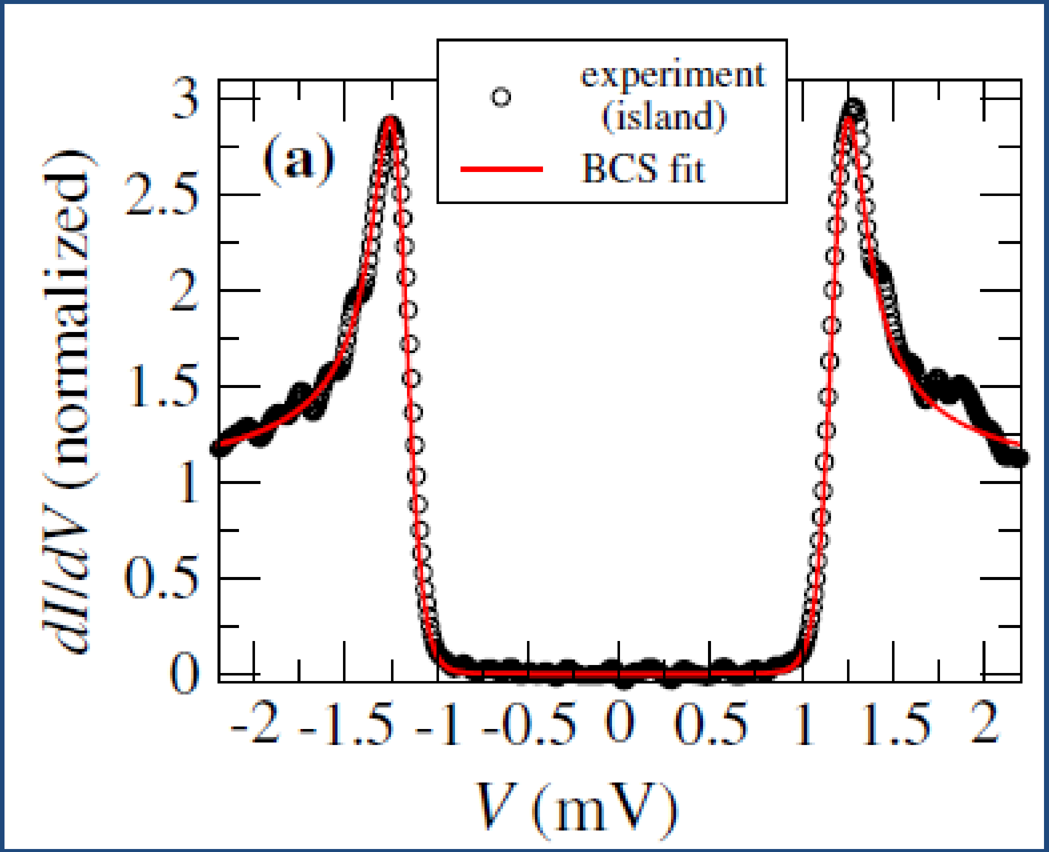
Recap: tunneling spectroscopy of superconductors

$$dI/dV(\mathbf{r}) = \int_{-\infty}^{\infty} N_s(E,\mathbf{r}) \left[\frac{-\partial f(E+eV)}{\partial(eV)} \right] dE$$

BCS DOS

$$N_S(E) = N_N(E) \frac{E}{\sqrt{E^2 - \Delta^2}}$$





Δ = 1.20 meV T_{eff} = 0.38K

Serrier-Garcia et al. PRL 110, 157003 (2013)

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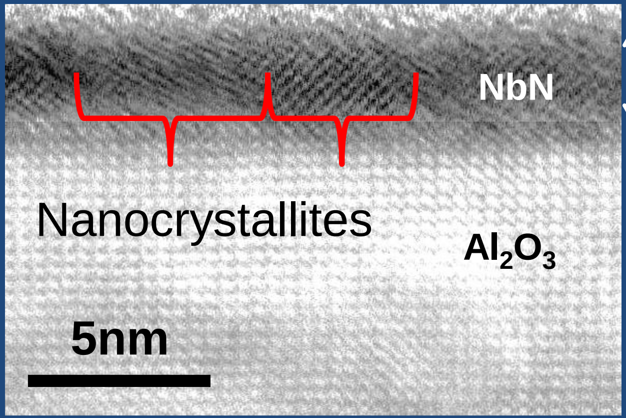

TEM image

$d_{NbN} = 2.33$ nm

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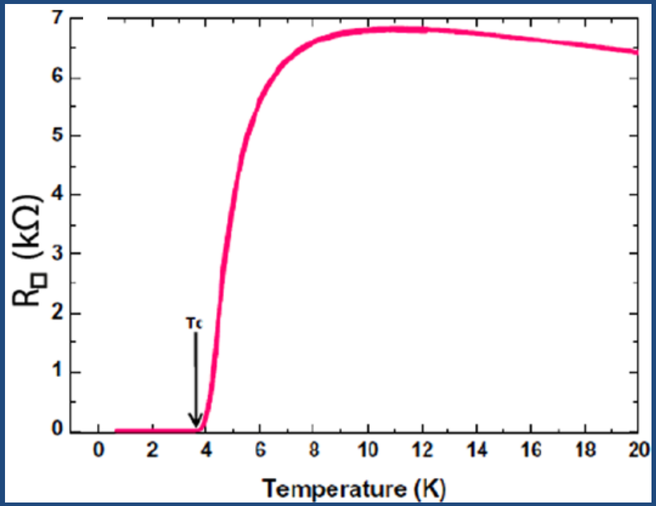
STM and in-situ 4 probe R(T)



In situ R(T)

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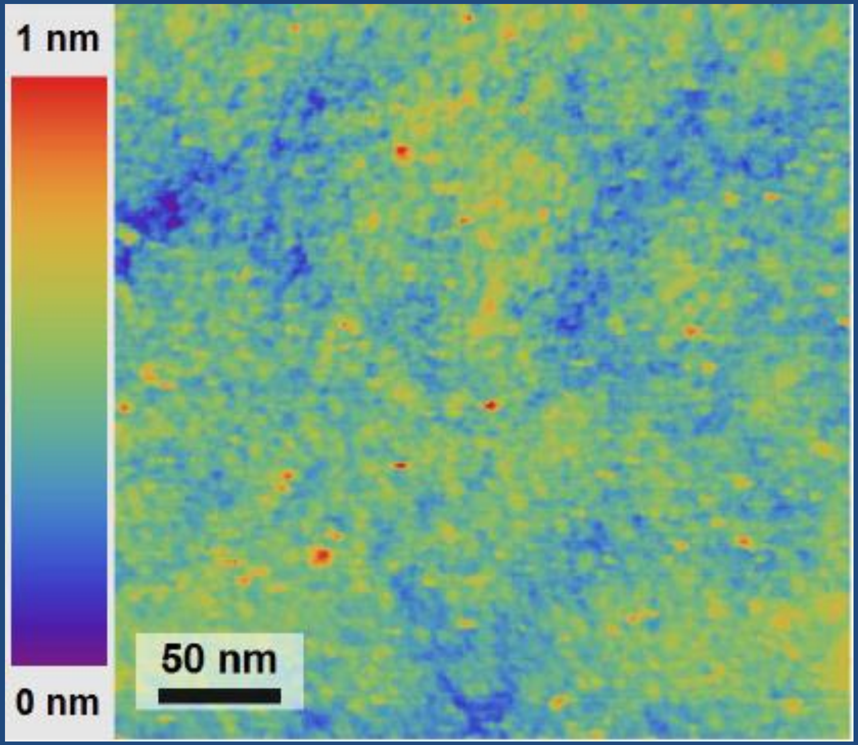
Carbillet et al PRB 93, 144509 (2016)

Local scale picture of nominally homogeneous thin films

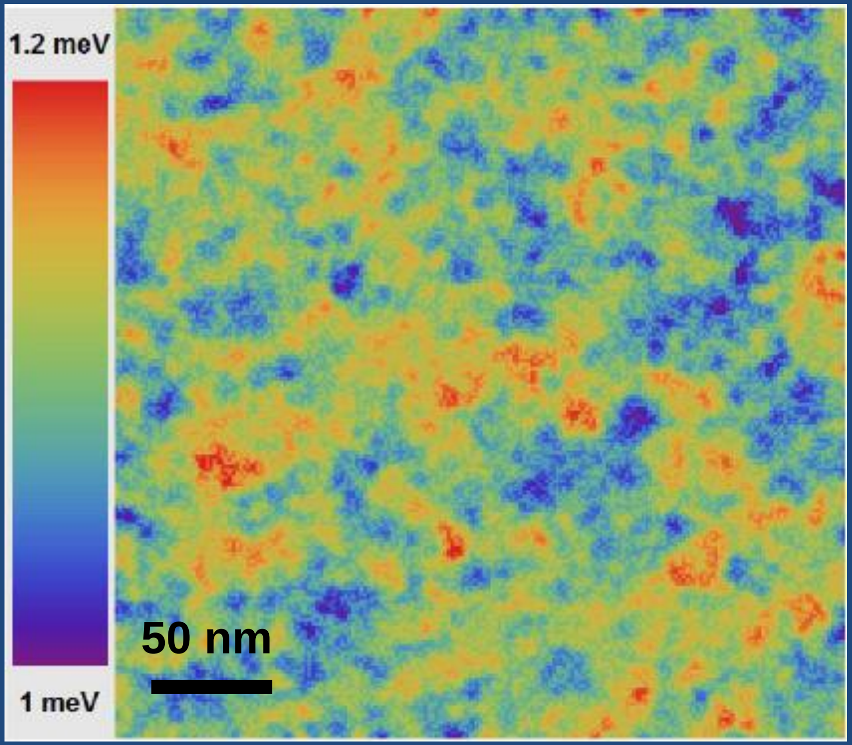
➡ Emerging electronic and superconducting inhomogeneities

STM topography



$z(\vec{r})$

Gap map



$|\Delta|(\vec{r})$

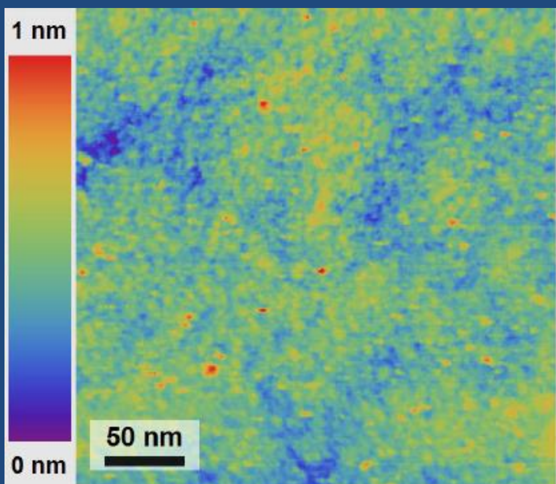
Carbillet et al PRB 93, 144509 (2016)

See also: Sacepe et al PRL 2008, Chand et al PRLB 2012, Noat et al PRB 2013…

Local scale picture of nominally homogeneous thin films

Emerging electronic and superconducting inhomogeneities

STM topography



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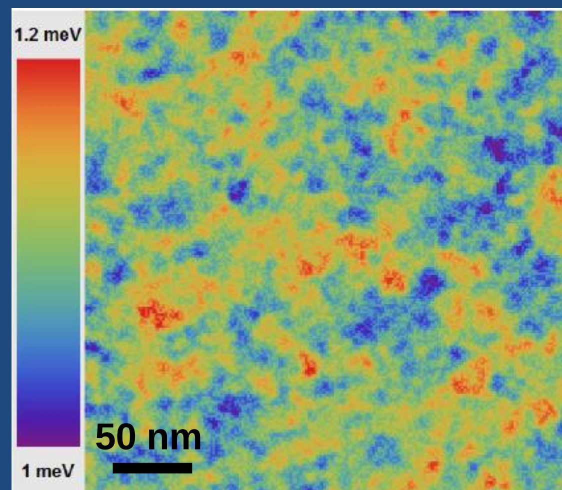
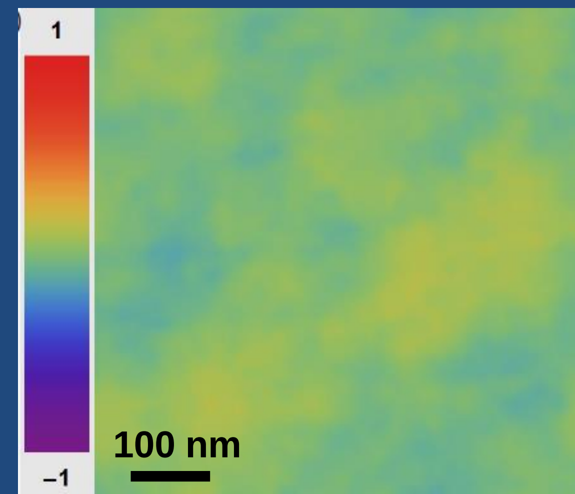


$|\Delta|(\vec{r})$

cross correlation



$\rho_{cross}(\vec{r}) = z * |\Delta|(\vec{r})$

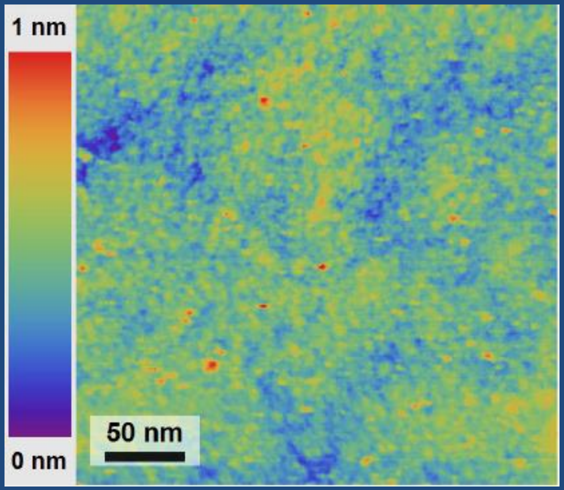
→ No local cross-correlation between the grain structure and gap inhomogeneities

Carbillet et al PRB 93, 144509 (2016)

Local scale picture of nominally homogeneous thin films

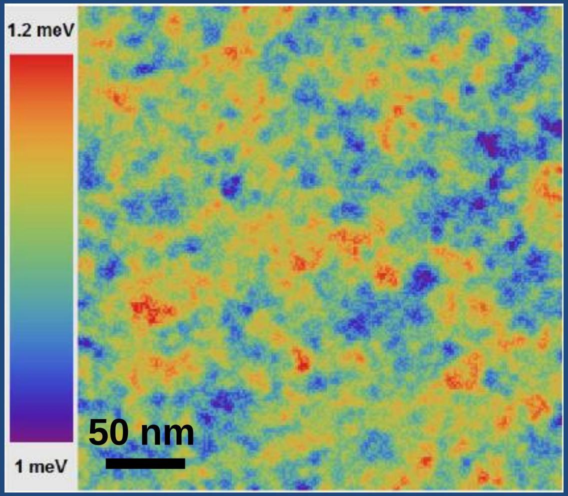
Emerging electronic and superconducting inhomogeneities

STM topography



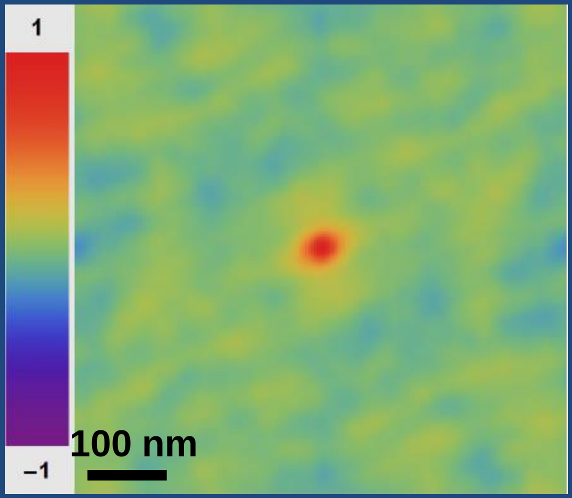
$z(\vec{r})$

gap map



$|\Delta|(\vec{r})$

auto correlation



$\rho_{|\Delta|}(\vec{r}) = |\Delta| * |\Delta|(\vec{r})$

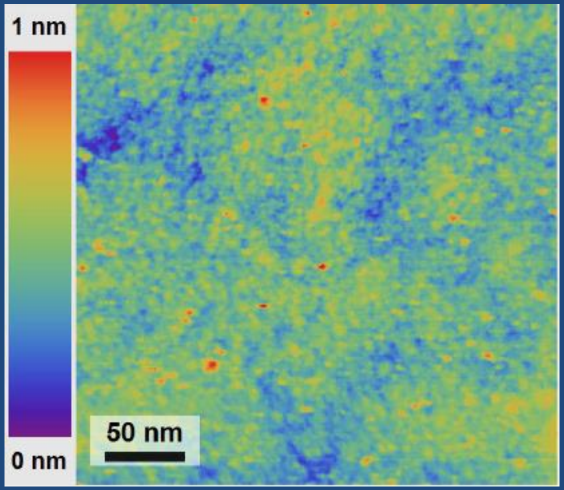
➡ Superconducting puddles much larger than NbN nanocrystals

Carbillet et al PRB 93, 144509 (2016)

Local scale picture of nominally homogeneous thin films

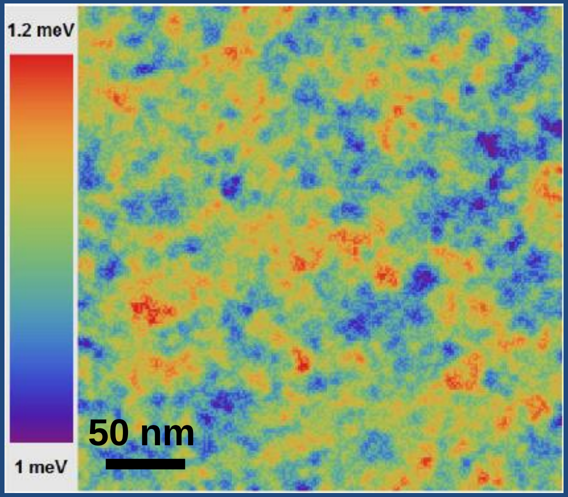
Emerging electronic and superconducting inhomogeneities

STM topography



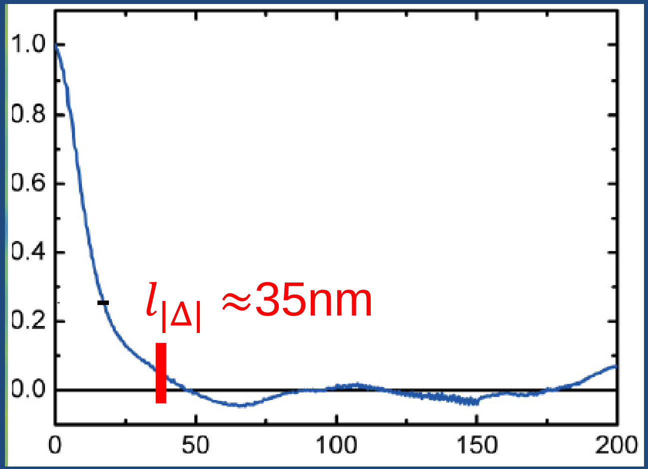
$z(\vec{r})$

gap map



$|\Delta|(\vec{r})$

auto correlation



$\rho_{|\Delta|}(\vec{r}) = |\Delta| * |\Delta|(\vec{r})$

$l_{|\Delta|} \approx 35\text{ nm} \gg \xi \approx 5\text{nm} \approx l_{grain}$

Carbillet et al PRB 93, 144509 (2016)

Content

Revealing quantitatively the interplay between disorder and electron-electron interactions in 2D superconductors from LDOS analysis

1. Case of moderate disorder in NbN thin films

PHYSICAL REVIEW B **102**, 024504 (2020)

Editors' Suggestion

Spectroscopic evidence for strong correlations between local superconducting gap and local Altshuler-Aronov density of states suppression in ultrathin NbN films

C. Carbillet,[1] V. Cherkez,[1] M. A. Skvortsov,[2,3,*] M. V. Feigel'man,[3,2] F. Debontridder,[1] L. B. Ioffe,[4,3] V. S. Stolyarov,[1,5,6] K. Ilin,[7] M. Siegel,[7] C. Noûs,[8] D. Roditchev,[1,9] T. Cren,[1] and C. Brun[1,†]

2. Case of weak disorder in Pb single atomic layer

PHYSICAL REVIEW B **107**, 174508 (2023)

Editors' Suggestion

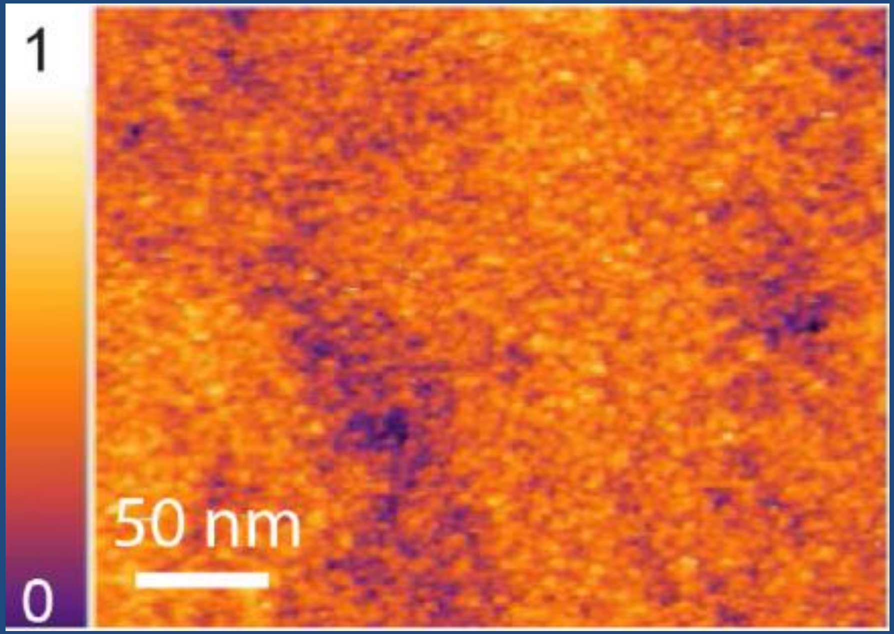
Local density of states fluctuations in a two-dimensional superconductor as a probe of quantum diffusion

Mathieu Lizée,[1,2,*] Matthias Stosiek,[3] Igor Burmistrov,[4,5,†] Tristan Cren,[2] and Christophe Brun[2,‡]

Investigating LDOS behavior at the local scale

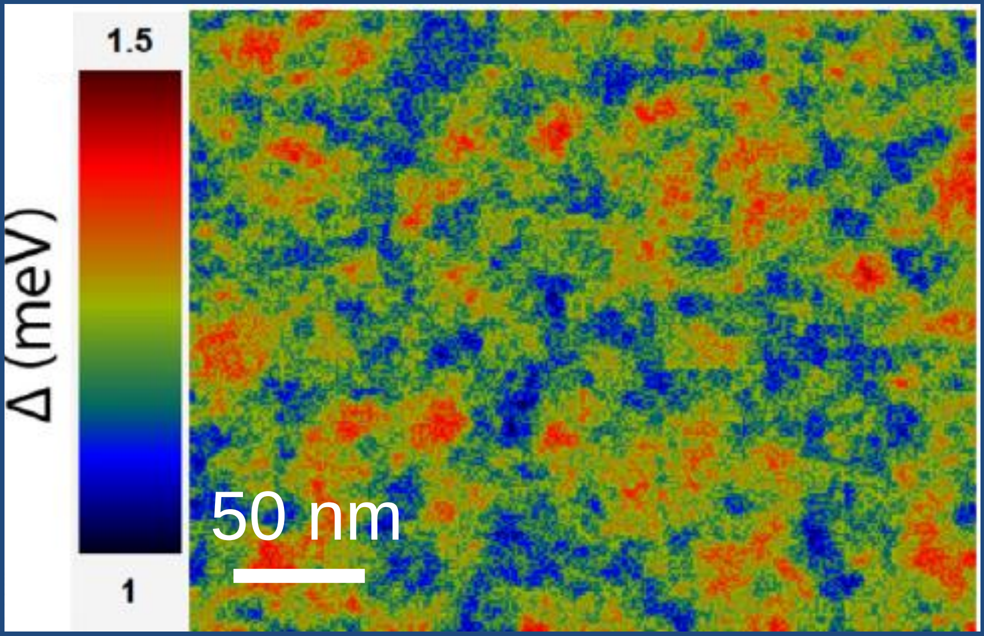
NbN film moderate disorder $k_F \ell_e \approx 2-3$ $T_c \approx 0.25\, T_{c-bulk}$

STM topography



$z(\vec{r})$

Gap map



$|\Delta|(\vec{r})$

$l_{|\Delta|} \approx 27$ nm $\gg \xi \approx 5$nm $\approx l_{grain}$

Carbillet et al PRB 102, 024504 (2020)

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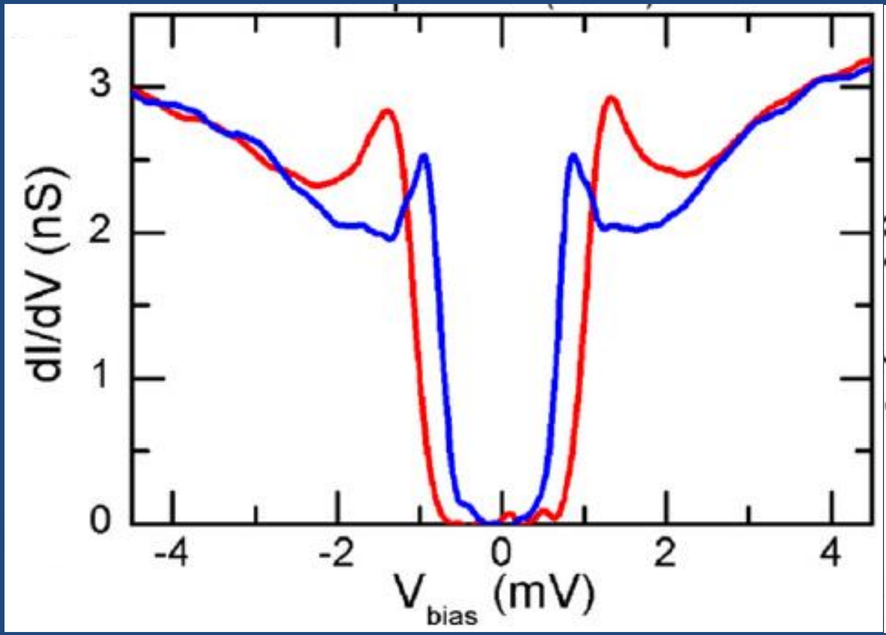
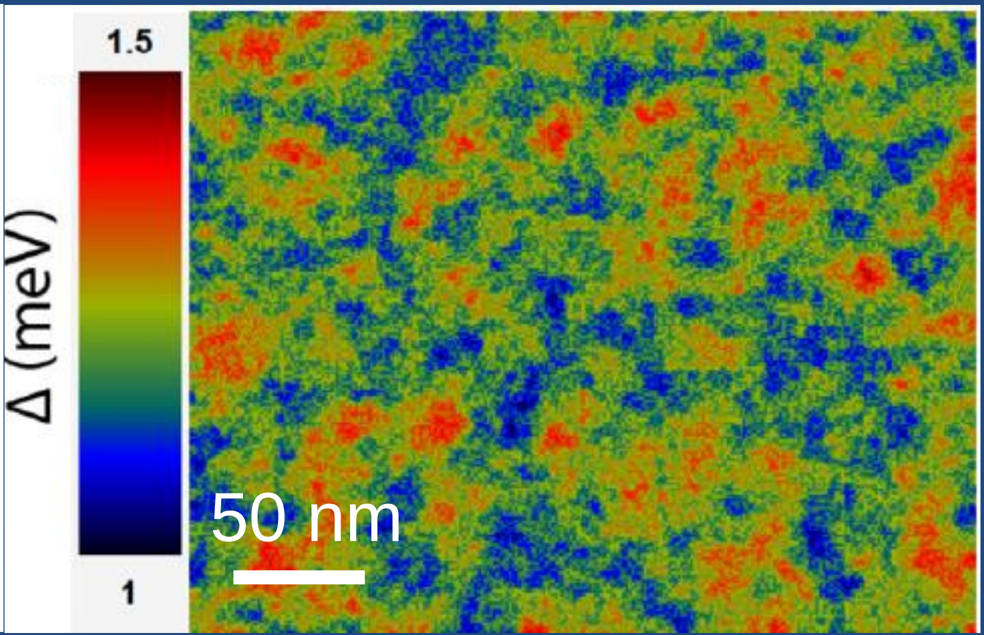
Local dI/dV spectra



Gap map



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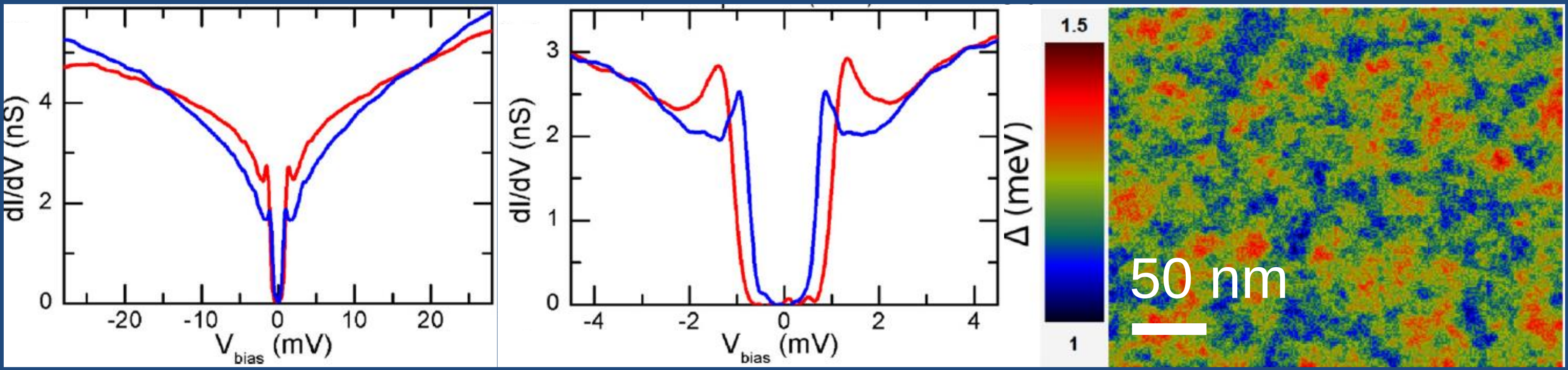
Local dI/dV spectra Gap map



$|\Delta|(\vec{r})$

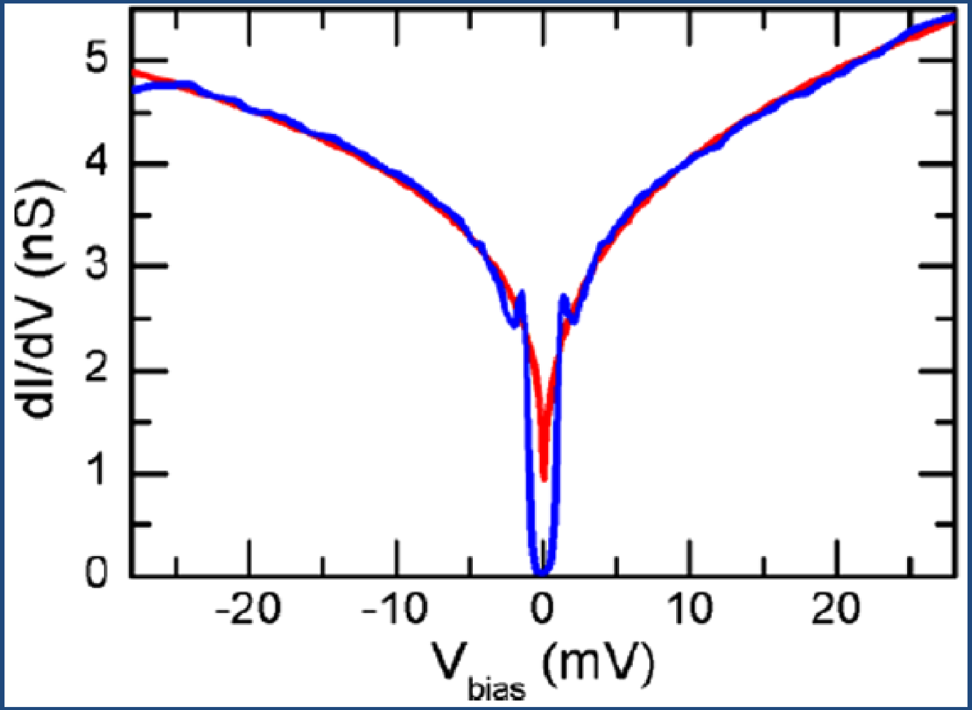
➡ Strong locally varying Altshuler-Aronov background

Carbillet et al PRB 102, 024504 (2020)

Investigating LDOS behavior at the local scale

NbN film moderate disorder $k_F \ell_e \approx 2-3$ $T_c \approx 0.25\, T_{c-bulk}$

local dI/dV spectra at location $\vec{r}$



red fit:

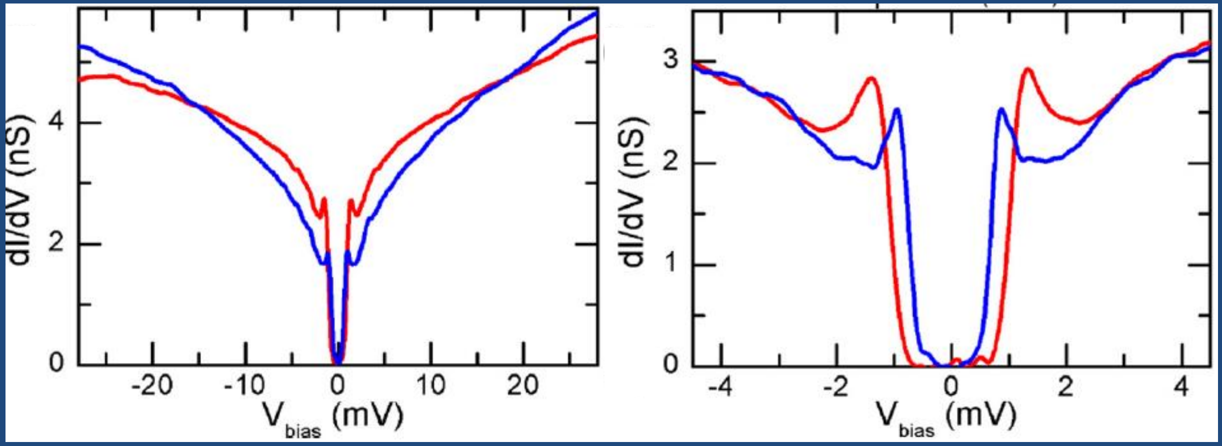
$$dI/dV\,(\vec{r}, V) = bV^{\alpha(\vec{r})}$$

➡ Power law fitting of the Altshuler-Aronov background

Carbillet et al PRB 102, 024504 (2020)

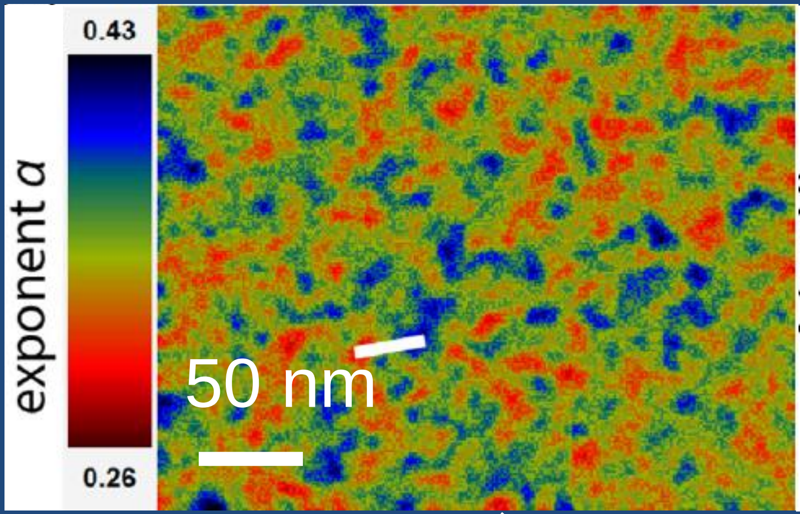
Investigating LDOS behavior at the local scale

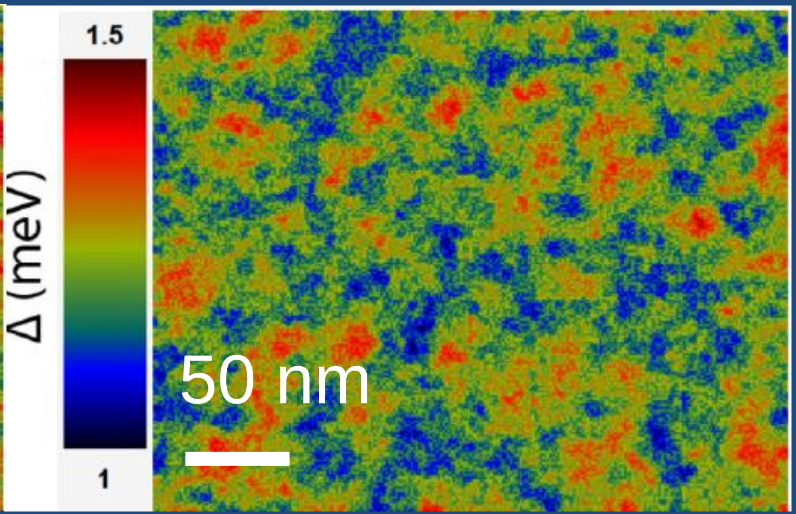
Local dI/dV spectra



Exponent map

Gap map





$\alpha(\vec{r})$

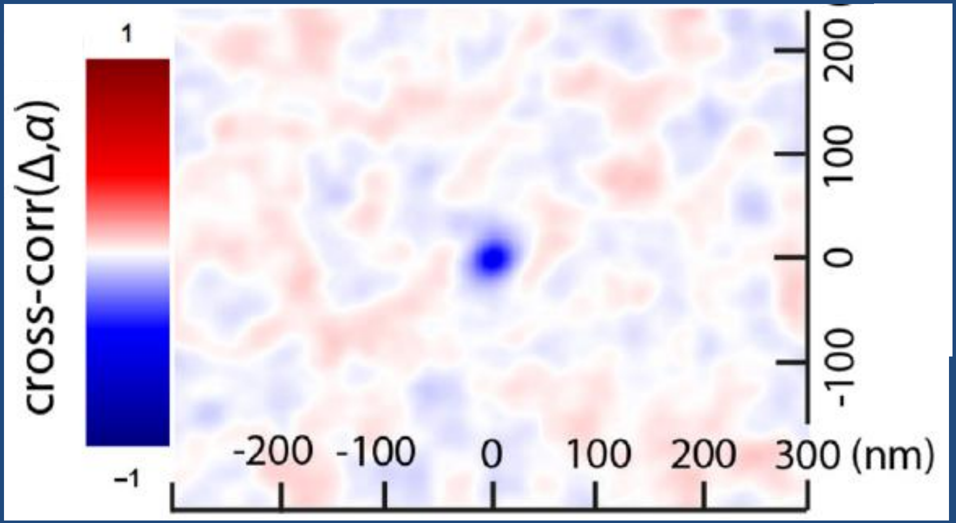
$|\Delta|(\vec{r})$

$l_\alpha \approx 18$ nm

Carbillet et al PRB 102, 024504 (2020)

$l_{|\Delta|} \approx 27$ nm

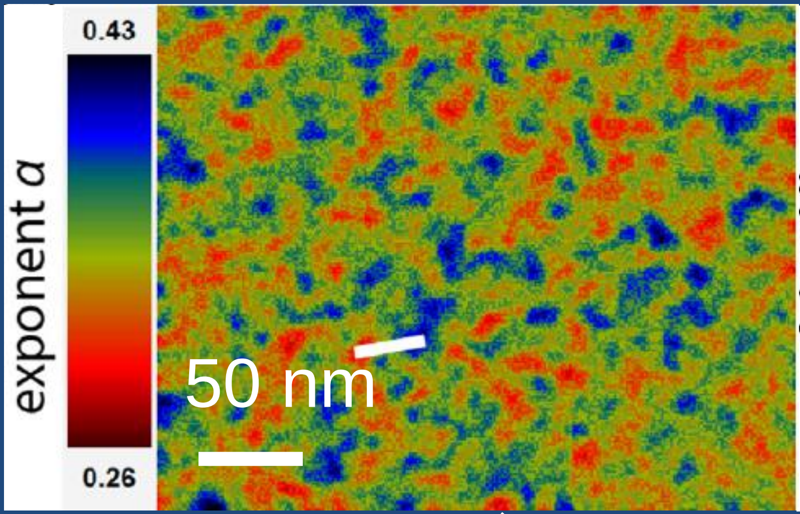
cross correlation

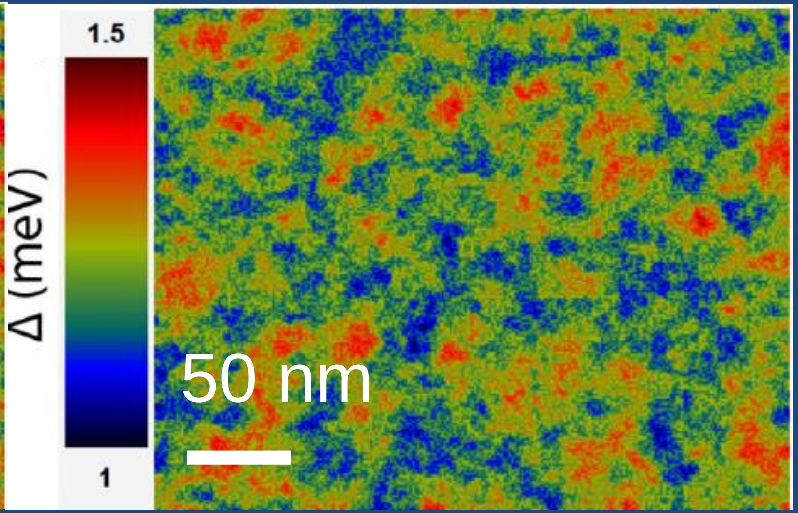


$\rho_{cross}(0) = -0.55$

$l_{cross} \approx$ 25 nm

$\rho_{cross}(\vec{r}) = \alpha * |\Delta|(\vec{r})$





$\alpha(\vec{r})$

$|\Delta|(\vec{r})$

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$l_{|\Delta|} \approx$ 27 nm

Carbillet et al PRB 102, 024504 (2020)

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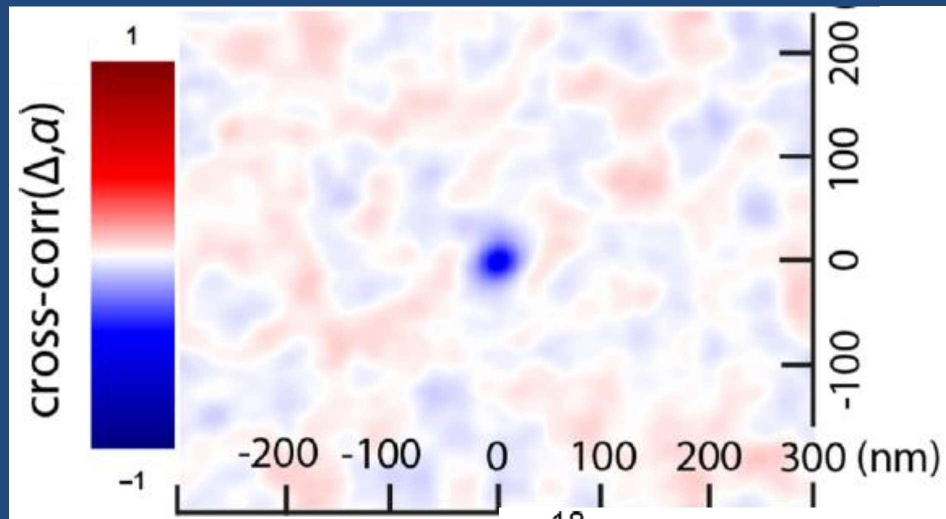

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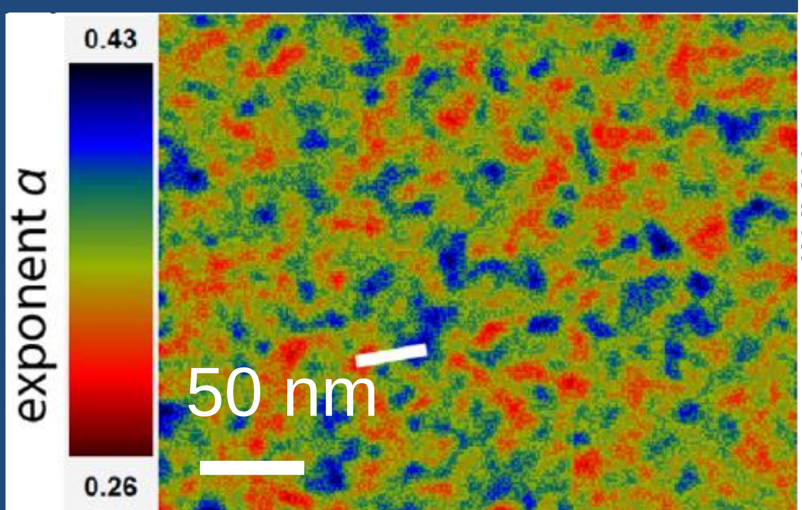
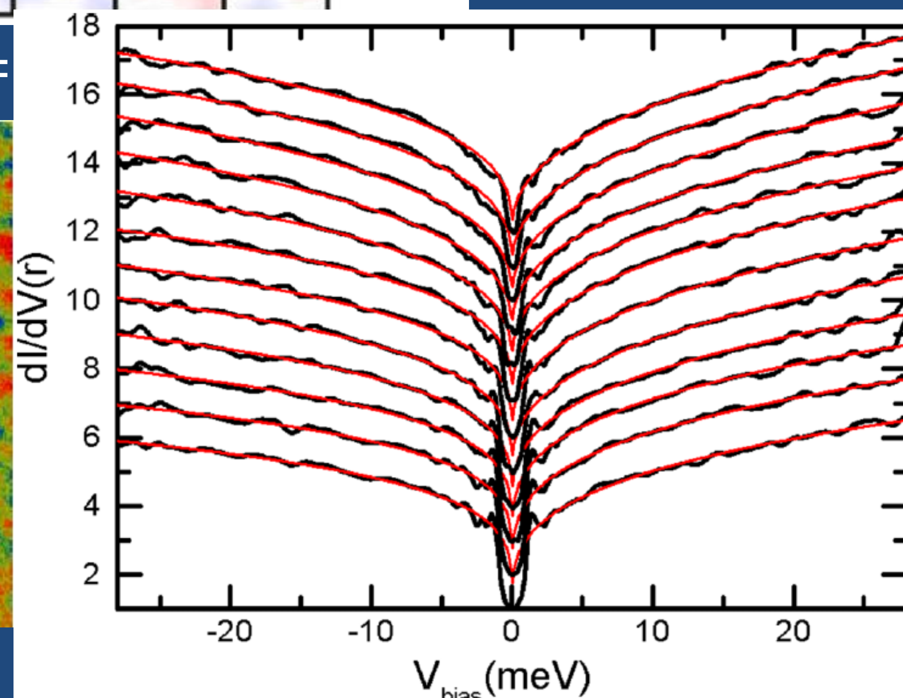
$\rho_{cross}(\vec{r}) =$





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Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

suppression of the tunneling DOS induced by Coulomb effect

$$\nu(E) = \nu_0 e^{-S(E)}$$

$$S(E) = \frac{2}{R_Q} \int_E^{1/\tau} \frac{d\omega}{\omega} R(\omega)$$

with $R_Q = h/e^2$

$R(\hbar\omega)$ spreading resistance between the diffusive scale $r_{in}\ (\hbar\omega)$ and field propagation scale $r_{out}\ (\hbar\omega)$

Altshuler et al PRL 1980, Levitov & Shytov JETP Lett. 1997, Andreev & Kamenev PRB 1999
Finkelstein JETP 1983

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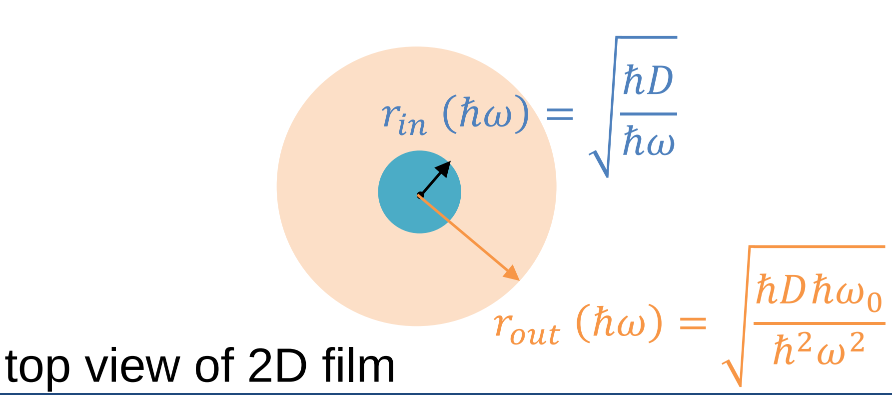

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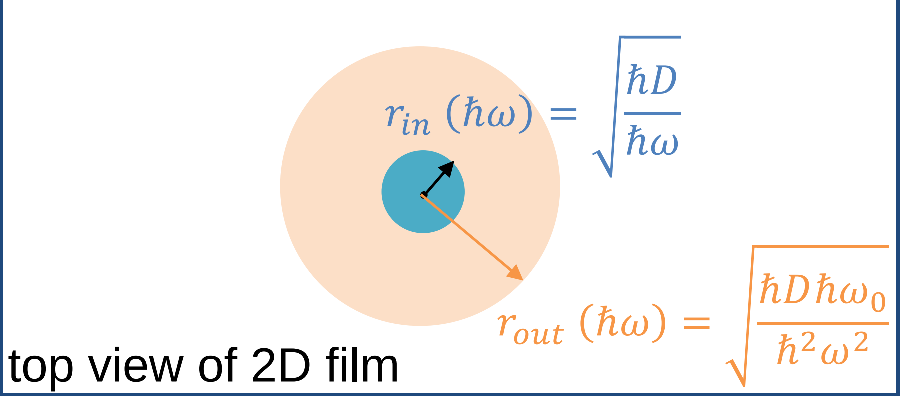

$$R(\hbar\omega) = \frac{R_\square}{2\pi} ln\,\frac{r_{in}\,(\hbar\omega)}{r_{out}\,(\hbar\omega)}$$

$$R(\hbar\omega) = \frac{R_\square}{2\pi} ln\,\frac{\omega_0}{\omega}$$

Altshuler et al PRL 1980, Levitov & Shytov JETP Lett. 1997, Andreev & Kamenev PRB 1999
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➡ Homogeneous case: $\nu(E) \propto E^{\alpha(E)}$

$$\alpha(E) = \frac{R_\square}{2\pi R_Q} ln \frac{\hbar\omega_0}{E}$$

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suppression of the tunneling DOS induced by Coulomb effect

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➡ Homogeneous case: $\nu(E) \propto E^{\alpha(E)}$

$$\alpha(E) = \frac{R_\square}{2\pi R_Q} ln \frac{\hbar\omega_0}{E}$$

$\hbar/\tau \approx 0.3\ \mathrm{eV}$

$\hbar\omega_0 \approx 10\ \mathrm{eV}$

$R_\square \approx 7\ \mathrm{k\Omega}$

$E = 5 - 30\ \mathrm{meV}$

$$\alpha_{th}(E) \approx 0.29$$

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

suppression of the tunneling DOS induced by Coulomb effect

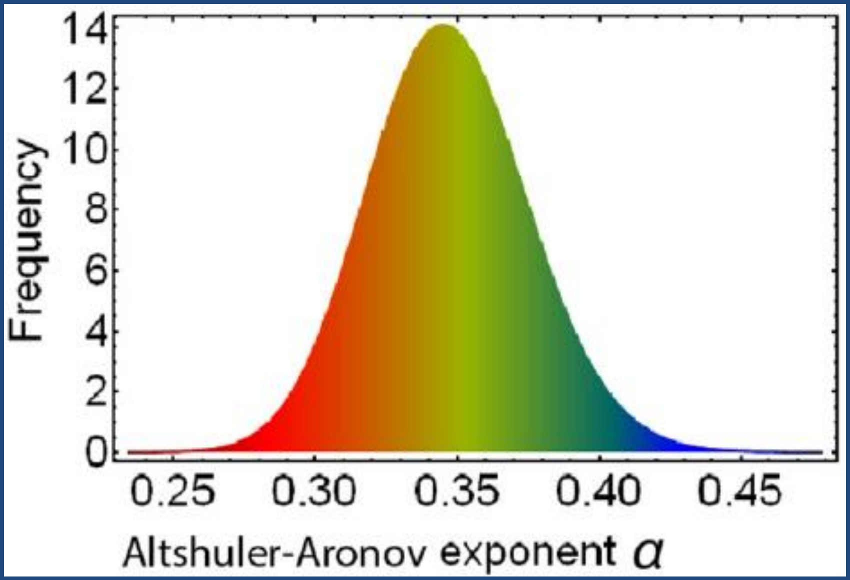
$$\nu(E) = \nu_0 e^{-S(E)}$$

$$S(E) = \frac{2}{R_Q} \int_E^{1/\tau} \frac{d\omega}{\omega} R(\omega)$$

with $R_Q = h/e^2$

➡ Homogeneous case: $\nu(E) \propto E^{\alpha(E)}$

$\alpha(\vec{r})$ experimental distribution



$\hbar/\tau \approx 0.3$ eV

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$R_\square \approx 7\ \mathrm{k\Omega}$

$E = 5 - 30$ meV

$\alpha_{th}(E) \approx 0.29$

$\hbar\omega_0$ and $\hbar/\tau$ from Semenov et al. PRB 2009

Theoretical modelling

Inhomogeneous case:

➡ Assumption that fluctuations of $\alpha(\vec{r})$ and $|\Delta|(\vec{r})$ originate from fluctuations in 2D resistivity:

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

Carbillet et al PRB 102, 024504 (2020)

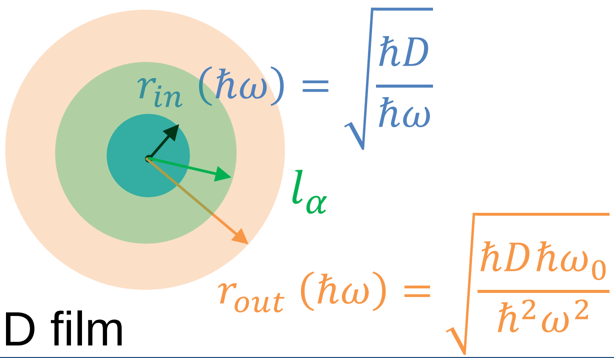
Theoretical modelling

Inhomogeneous case:

Assumption that fluctuations of $\alpha(\vec{r})$ and $|\Delta|(\vec{r})$ originate from fluctuations in 2D resistivity:

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

➡ The spreading resistance possess a local term for $|\vec{r} - \vec{r}_0| < l_\alpha$



top view of 2D film

$$R(\vec{r}, \hbar\omega) = \frac{\rho(\vec{r})}{2\pi} ln \frac{l_\alpha}{r_{in}(\hbar\omega)} + \frac{R_{\square}}{2\pi} ln \frac{r_{out}(\hbar\omega)}{l_\alpha}$$

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

Inhomogeneous case:

Assumption that fluctuations of $\alpha(\vec{r})$ and $|\Delta|(\vec{r})$ originate from fluctuations in 2D resistivity:

$$\rho(\vec{r}) = R_\square + \delta\rho(\vec{r})$$

$$\delta\alpha(\vec{r}, E) = \frac{\delta\rho(\vec{r})}{2\pi R_Q} ln \frac{E}{\hbar D / l_\alpha^2}$$

$$\Rightarrow \quad \alpha(\vec{r}) = \langle\alpha\rangle + \delta\alpha(\vec{r})$$

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

Inhomogeneous case:

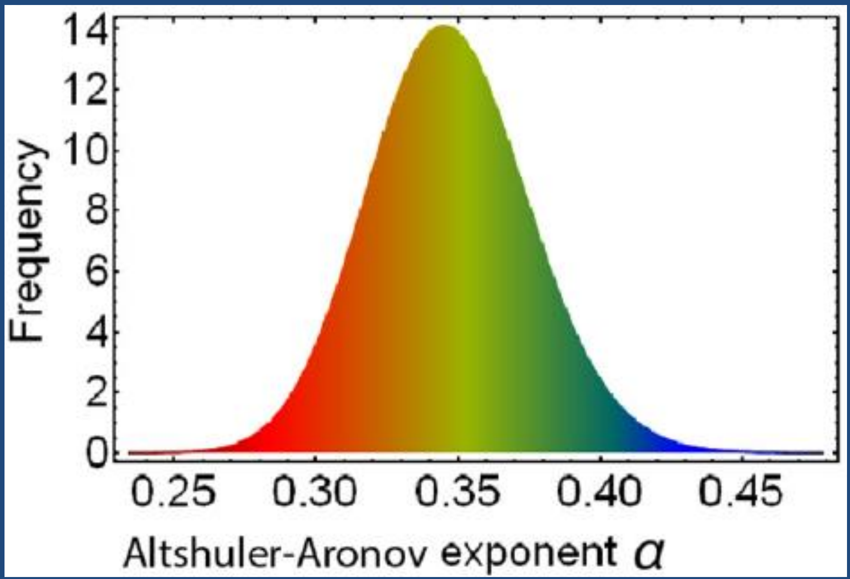
Assumption that fluctuations of $\alpha(\vec{r})$ and $|\Delta|(\vec{r})$ originate from fluctuations in 2D resistivity:

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

$$\alpha(\vec{r}) = \langle\alpha\rangle + \delta\alpha(\vec{r})$$

$$\delta\alpha(\vec{r}, E) = \frac{\delta\rho(\vec{r})}{2\pi R_Q} ln \frac{E}{\hbar D / l_\alpha^2}$$

$\alpha(\vec{r})$ experimental distribution



$l_\alpha \approx 18$ nm

$\sigma_\alpha \approx 0.03$ ➡ σ_ρ ?

$D \approx 0.5\ \mathrm{cm}^2/\mathrm{s}$

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

Inhomogeneous case:

Assumption that fluctuations of $\alpha(\vec{r})$ and $|\Delta|(\vec{r})$ originate from fluctuations in 2D resistivity:

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

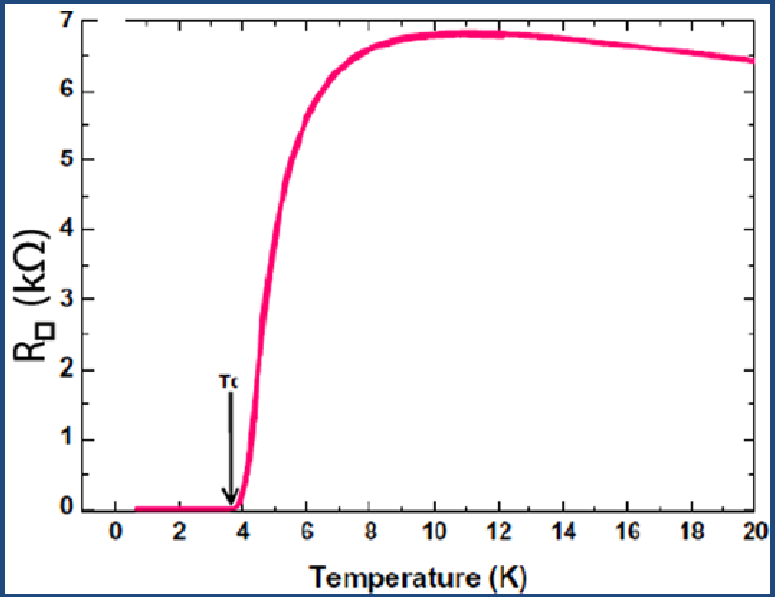
$$\delta\alpha(\vec{r}, E) = \frac{\delta\rho(\vec{r})}{2\pi R_Q} ln \frac{E}{\hbar D / l_\alpha^2}$$

$$\alpha(\vec{r}) = \langle\alpha\rangle + \delta\alpha(\vec{r})$$

$l_\alpha \approx 18$ nm

$\sigma_\alpha \approx 0.03$ ⇒ $\sigma_\rho \approx 1.1$ kΩ

$D \approx 0.5\ \mathrm{cm}^2/s$ ⇒ $\sigma_\rho / R_{\square max} \approx 16\%$



In situ R(T)

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

Inhomogeneous case:

local Finkelstein picture to explain of $|\Delta|(\vec{r})$ fluctuations

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

$$\Delta(\vec{r}) = \langle\Delta\rangle + \delta\Delta(\vec{r})$$

$$\delta\Delta(\vec{r}) = -\frac{\delta\rho(\vec{r})}{6\pi R_Q} ln^3 \frac{\hbar\omega_D}{\Delta_{bare}}$$

Carbillet et al PRB 102, 024504 (2020)

Theoretical modelling

Inhomogeneous case:

local Finkelstein picture to explain of $|\Delta|(\vec{r})$ fluctuations

$$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$$

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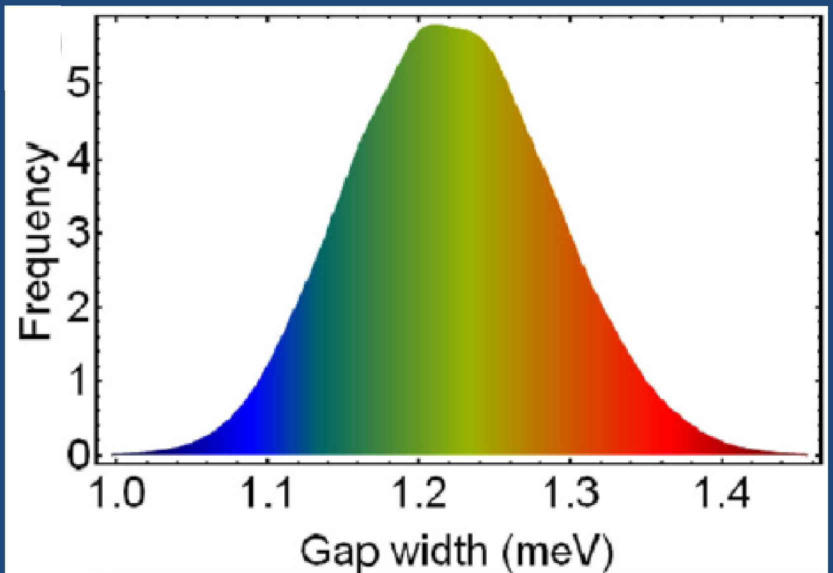
$$\delta\Delta(\vec{r}) = -\frac{\delta\rho(\vec{r})}{6\pi R_Q} ln^3 \frac{\hbar\omega_D}{\Delta_{bare}}$$

$\Delta(\vec{r})$ experimental distribution



$\sigma_\rho \approx 1.1\ \mathrm{k\Omega}$

$\langle\Delta\rangle \approx 1.22\ \mathrm{meV}$

$\hbar\omega_D \approx 300\ \mathrm{K}$ ⟹ $\sigma_\Delta \approx 0.09\ \mathrm{meV}$

$\Delta_{bare} \approx 2.85\ \mathrm{meV}$ $\quad \sigma_\Delta/\langle\Delta\rangle \approx 7.4\%$

Carbillet et al PRB 102, 024504 (2020)

Conclusion of part 1

Moderate disorder in ultrathin NbN films $\begin{cases} k_F \ell_e \approx 2-3 \\ T_c \approx 0.25\, T_{c-bulk} \end{cases}$

Emergent electronic inhomogeneities explained by a local Finkelstein picture: meV scale and tens meV scale linked

$\rho(\vec{r}) = R_{\square} + \delta\rho(\vec{r})$	$\sigma_\rho / R_{\square}^{max} \approx 16\%$	l_{grain} = 2-8 nm $\xi \approx$ 5 nm
$\alpha(\vec{r}) = \langle\alpha\rangle + \delta\alpha(\vec{r})$	$\sigma_\alpha / \alpha \approx 10\%$	$l_\alpha \approx$ 18 nm
$\Delta(\vec{r}) = \langle\Delta\rangle + \delta\Delta(\vec{r})$	$\sigma_\Delta / \langle\Delta\rangle \approx 7\%$	$l_{\lvert\Delta\rvert} \approx$ 27 nm

➡ Low $q < q_D$ matter !!

Interface resistance of nanocrystals mostly contribute to $\delta\rho(\vec{r})$ thus linked to the grain structure

Carbillet et al PRB 102, 024504 (2020)

Funding ANR Superstripes

Thanks

Experiments

Clémentine Carbillet PhD

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Tristan Cren

François Debontridder

Christophe Brun

Theory

Misha Skvortsov

Misha Feigel’man

Lev Ioffe

Growth of NbN films

Kostia Ilin, KIT Germany

Content

Revealing quantitatively the interplay between disorder and electron-electron interactions in 2D superconductors from LDOS analysis

1. Case of moderate disorder in NbN thin films

Carbillet et al PRB 102, 024504 (2020)

2. Case of weak disorder in Pb atomic monolayer

Lizée et al. PRB 107, 174508 (2023)

Motivation

Th

PRL **108,** 017002 (2012) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2012

Enhancement of the Critical Temperature of Superconductors by Anderson Localization

I. S. Burmistrov,[1] I. V. Gornyi,[2,3,4] and A. D. Mirlin[2,4,5,6]

2D systems, electron-electron interaction in particle-hole and Cooper channels, σ-model renormalization group framework

Short-range spatial fluctuations of $\lambda(r)$ over $l_\lambda \ll \xi$

this physically corresponds to screened Coulomb interactions

Motivation

Th

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this physically corresponds to screened Coulomb interactions

Extension of the works of Feigel'man et al.:

Th

PRL **98,** 027001 (2007) PHYSICAL REVIEW LETTERS week ending 12 JANUARY 2007

Eigenfunction Fractality and Pseudogap State near the Superconductor-Insulator Transition

M. V. Feigel'man,[1] L. B. Ioffe,[2,1] V. E. Kravtsov,[3,1] and E. A. Yuzbashyan[2]

and also Feigel'man et al. Annals of physics 325, 1390 (2010)

3D systems, close to the mobility edge

Motivation

Th

PRL **108**, 017002 (2012) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2012

Enhancement of the Critical Temperature of Superconductors by Anderson Localization

I. S. Burmistrov,[1] I. V. Gornyi,[2,3,4] and A. D. Mirlin[2,4,5,6]

Motivation

Th

PRL **108,** 017002 (2012) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2012

Enhancement of the Critical Temperature of Superconductors by Anderson Localization

I. S. Burmistrov,[1] I. V. Gornyi,[2,3,4] and A. D. Mirlin[2,4,5,6]

Exp

Disorder induced multifractal superconductivity in monolayer niobium dichalcogenides

Zhao et al. Nature Phys. 15, 904 (2019)

Exp

Visualization of Multifractal Superconductivity in a Two-Dimensional Transition Metal Dichalcogenide in the Weak-Disorder Regime

Rubio-Verdu et al. Nano Lett. 20, 5111 (2020)

→ Puzzling: in both experiments the level disorder $k_F \ell_e > 10$ is too low for theory to explain T_c enhancement

Motivation

Th

PRL **108,** 017002 (2012) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2012

Enhancement of the Critical Temperature of Superconductors by Anderson Localization

I. S. Burmistrov,[1] I. V. Gornyi,[2,3,4] and A. D. Mirlin[2,4,5,6]

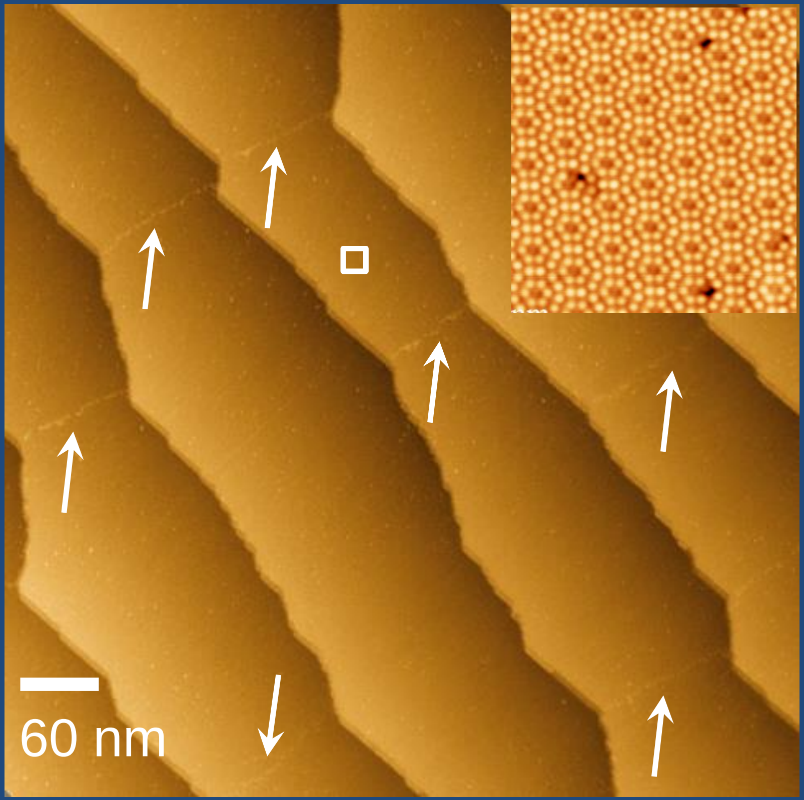
➡ Choose an appropriate 2D superconductor to probe first the weak-disorder limit !

➡ Check consistency between experiment and theory for LDOS and gap energy spatial fluctuations

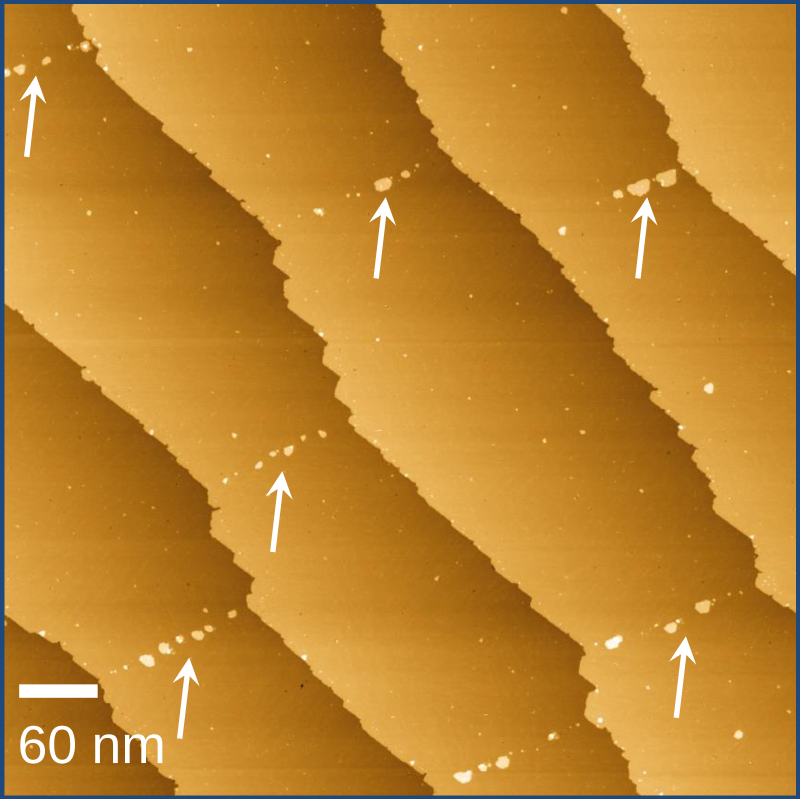
Model 2D system: Pb/Si(111) single atomic layer

ultrahigh vacuum growth: P~10^{-11} mbar range

Si(111)-7x7



monolayer Pb/Si(111)

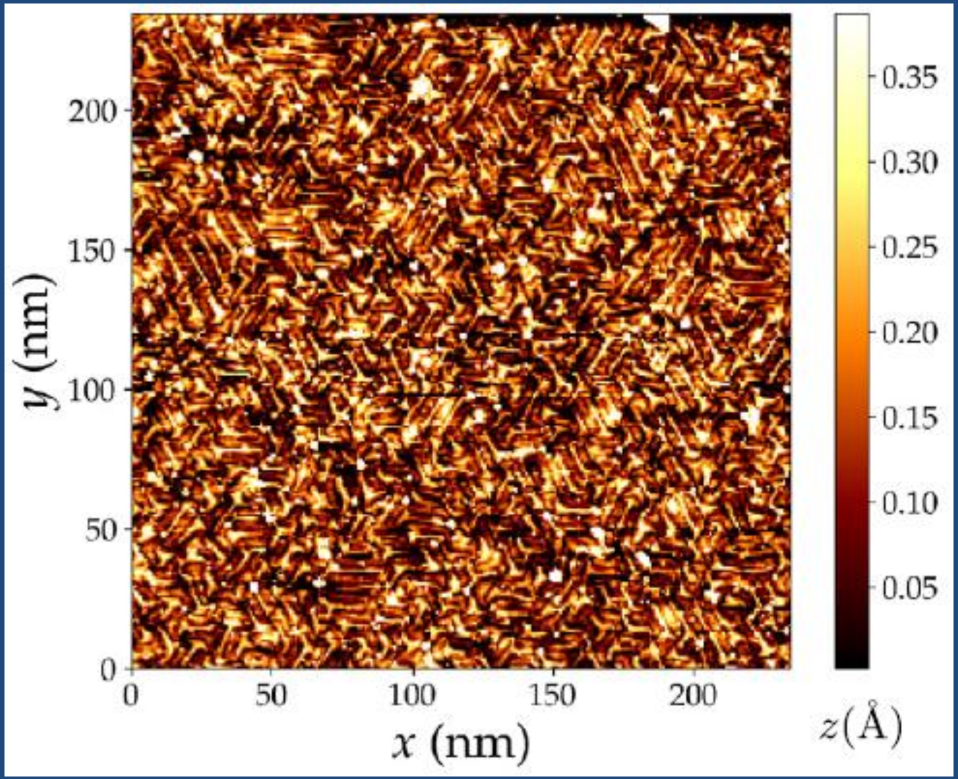


C. Brun et al. Nature Physics 10, 444 (2014)

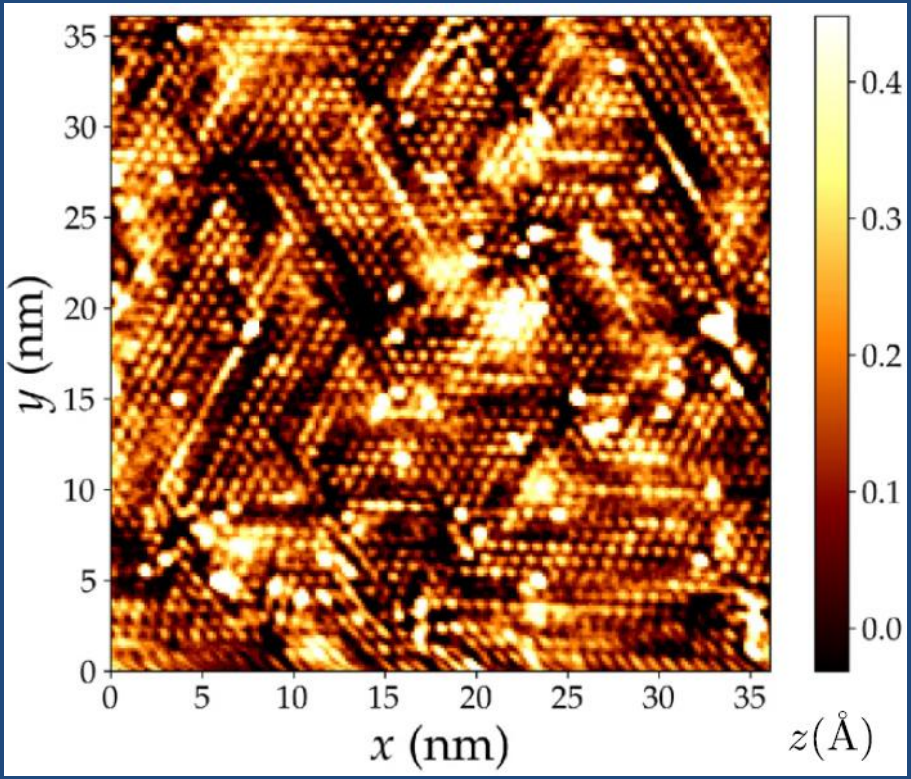
C. Brun et al. Supercond. Sci. Technol. 30, 013003 (2017)

Model 2D system: Pb/Si(111) single atomic layer

large scale



small scale

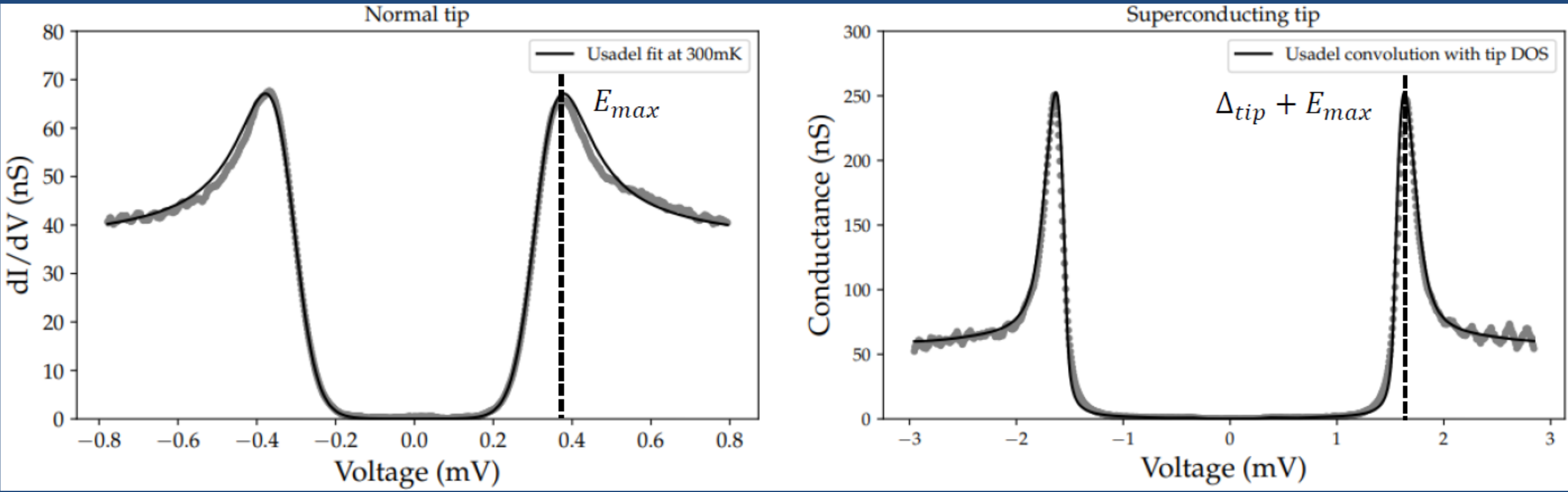


Polycrystalline structure with grain size l_{grain} = 2-10 nm

ARPES: single 2D band with strong Rashba spin-orbit coupling

Model 2D system: Pb/Si(111) single atomic layer

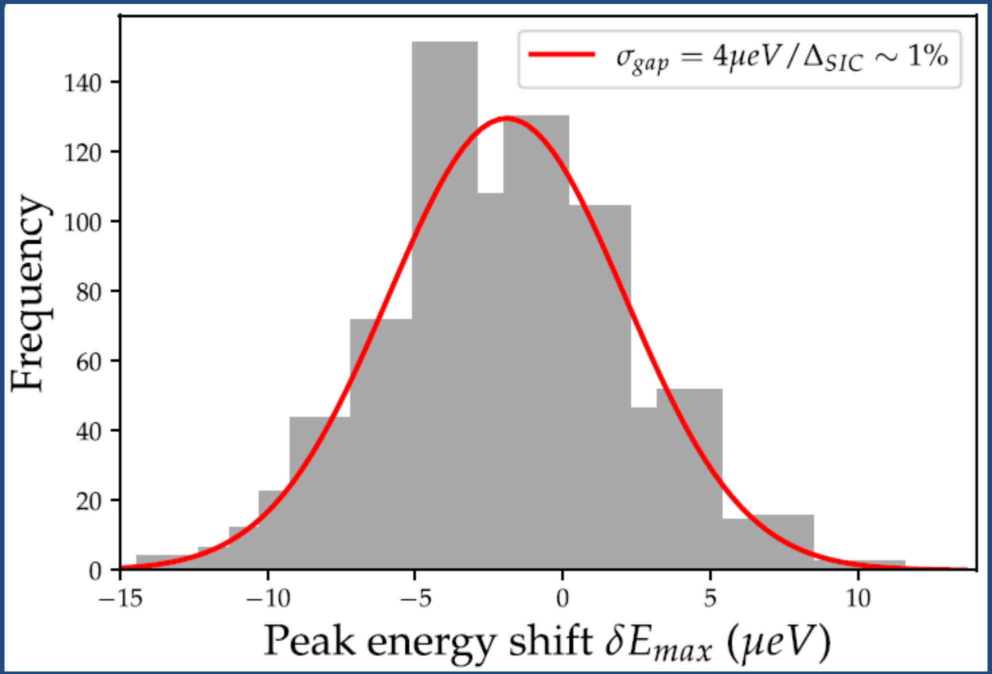
average superconducting properties at $T = 0.3$ K



$\langle \Delta \rangle \approx 350$ μeV $\quad \Gamma \approx 10$ μeV $\quad T_c \approx 1.8$ K

estimated $k_F \ell_e \approx 30 - 100$ $\quad \xi \approx 50$ nm $\gg l_{grain}$

consistent with Zhang et al. Nature Phys. 2010, Yamada et al. PRL 2013, Cherkez et al PRX 2014 very small local energy gap fluctuations at $T = 0.3$ K



Exp: $\sigma_\Delta/\langle\Delta\rangle \approx 1.1\ \%$

Th: $\sigma_\Delta/\langle\Delta\rangle \approx 0.5 - 1\ \%$

$\sigma_{E_{max}} \approx \sqrt{c/g}\,(\Gamma/\langle\Delta\rangle)^{2/3}$

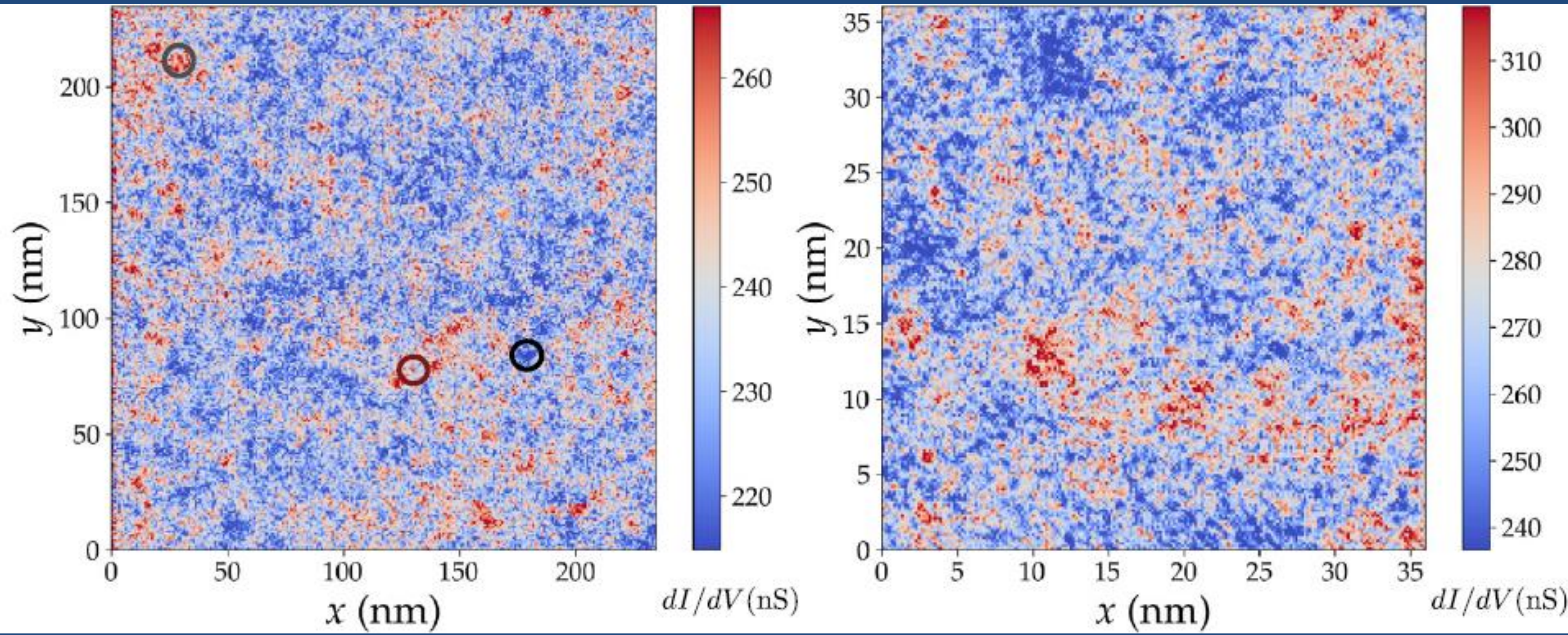
with $c \approx 0.3$

$\langle\Delta\rangle \approx 350\ \mu eV$ $\sigma_\Delta \approx 4\ \mu eV$

$\Gamma \approx 10\ \mu eV$ estimated $g = k_F \ell_e \approx 30 - 100$

large local density of states fluctuations at $T = 0.3$ K

large scale $E = E_{max}$ small scale

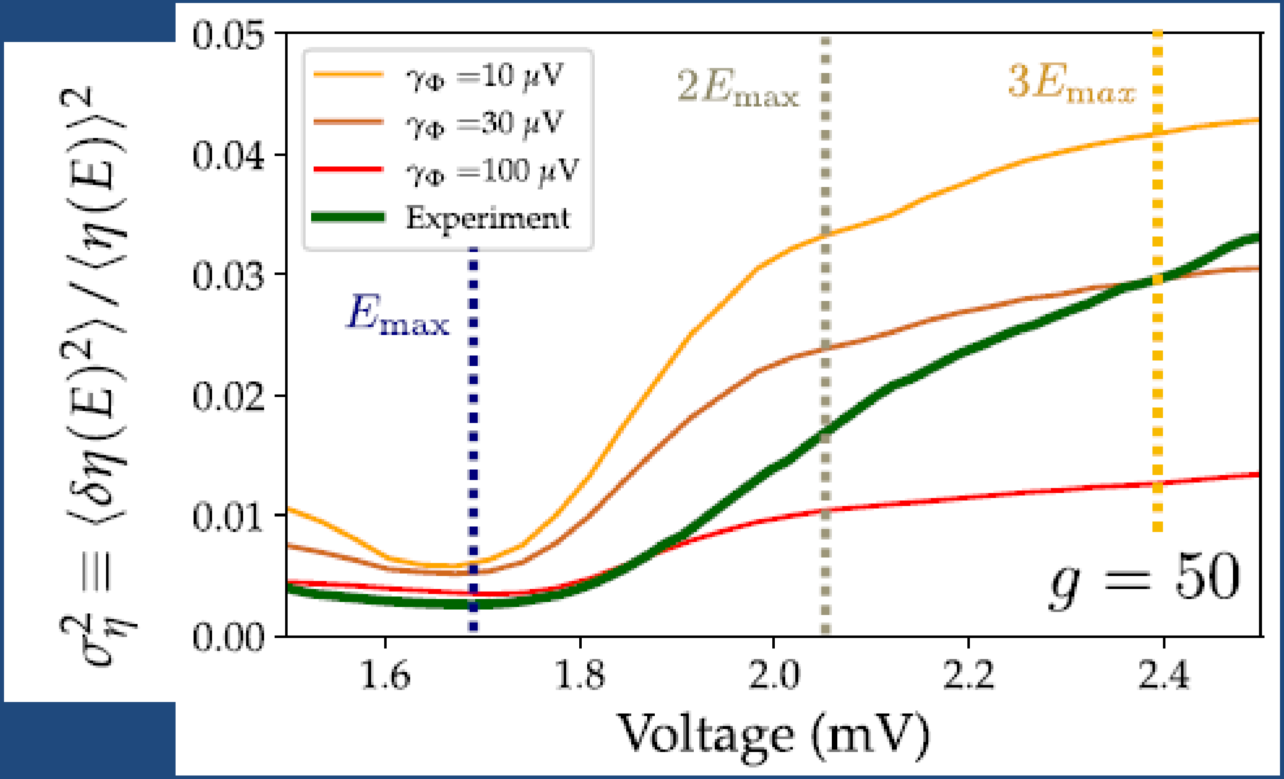


reminder: $\xi(0) \approx 50$ nm !!

➡ reveal the multifractality of the underlying wavefunctions

quantifying local density of states fluctuations at $T = 0.3$ K

normalized variance of $\eta(E) \propto dI/dV\,(E)$



reminder: $g = k_F \ell_e \approx 30 - 100$

$\sigma_{\eta-exp}(E) \in [6 - 20]\%$

➡ quasi-quantitative agreement $\gamma_\varphi = \hbar D / l_\varphi^2$

Conclusion of part 2

weak disorder in a Pb/Si(111) 2D single layer $k_F\ell_e \approx 30 - 100$

l_{grain} = 2-10 nm

screening of e-e interaction: spatial fluctuations of $\lambda(r)$ over $l_\lambda \ll \xi$

relative LDOS fluctuations $\approx 10\ \%$ $\sigma_\Delta/\langle\Delta\rangle \approx 1\ \%$

quantitative agreement with multifractal 2D superconductivity

Lizée et al. PRB 107, 174508 (2023)

Funding ANR
Rodesis

Thanks

Experiments, data analysis

Mathieu Lizée
student

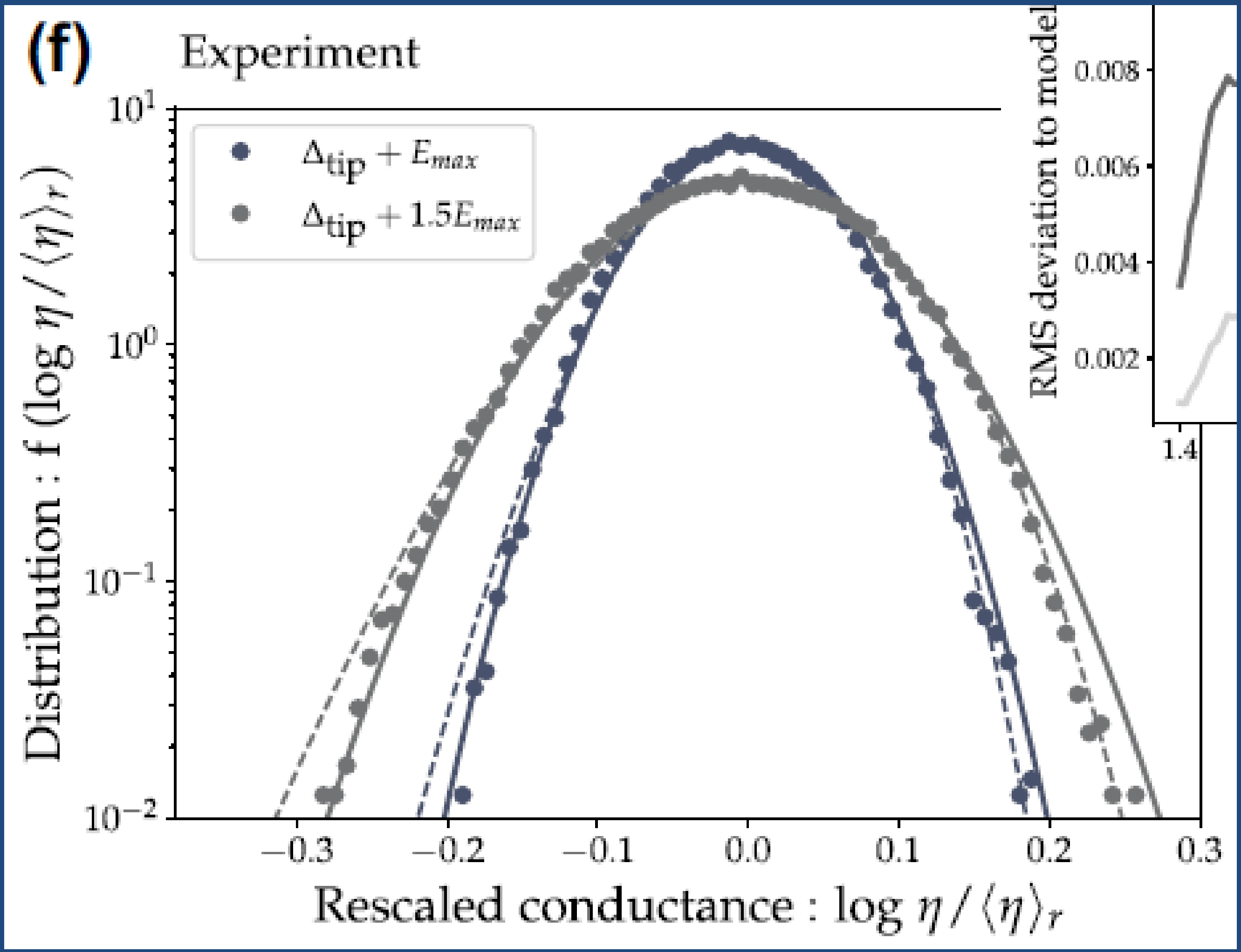
Tristan Cren

Christophe
Brun

Theory

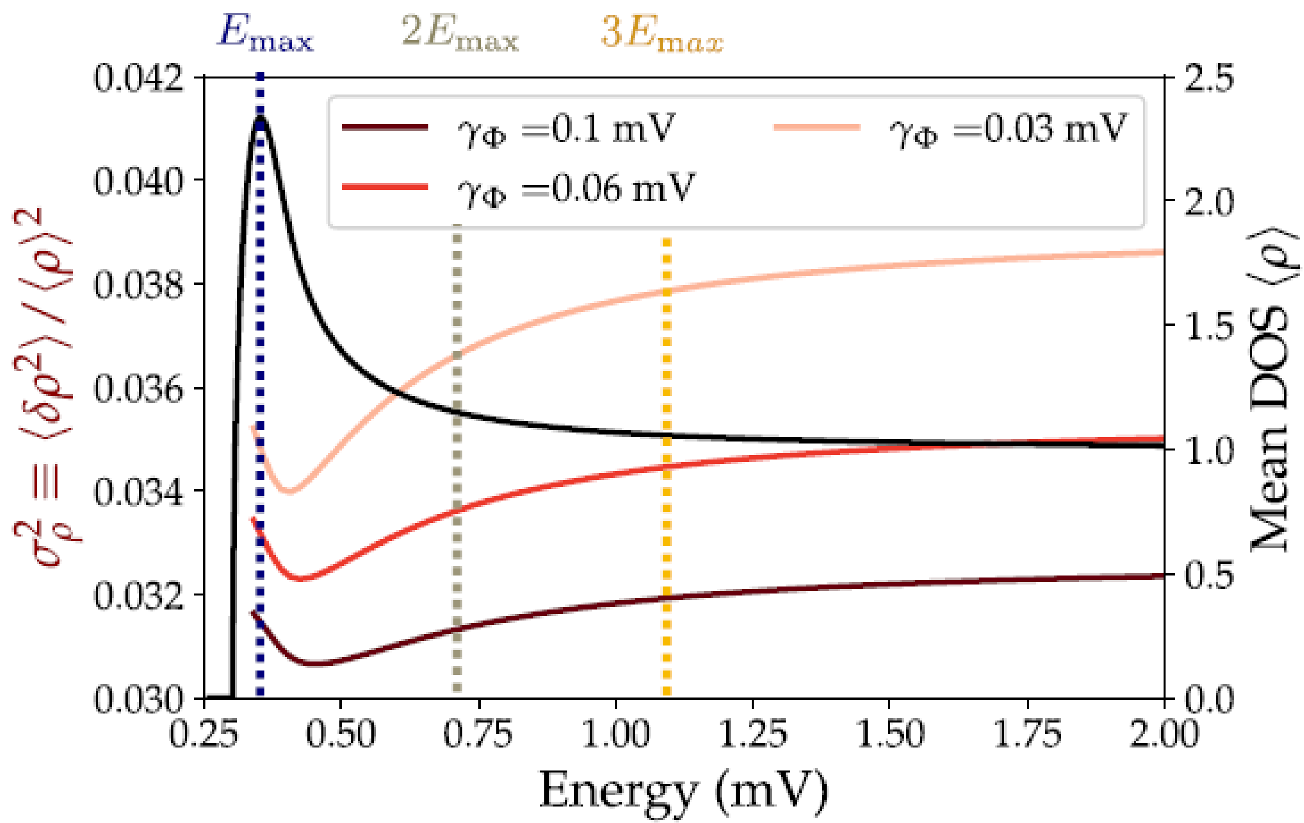
Igor Burmistrov
Landau Institute
Russia

Matthias Stosiek
Post-doc
Japan

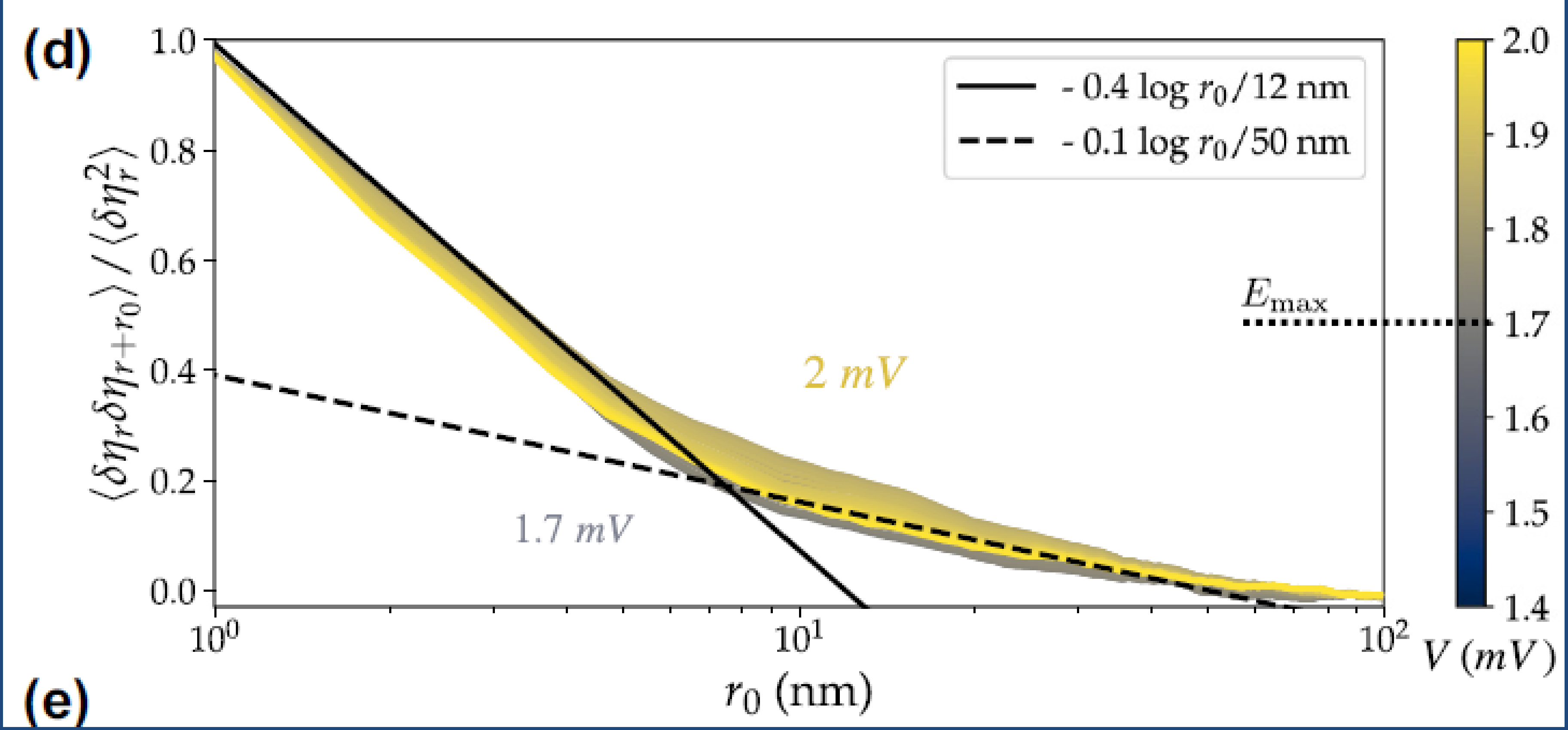


(f)
Experiment
$\Delta_{tip} + E_{max}$
$\Delta_{tip} + 1.5E_{max}$
Distribution : f (log η / $\langle\eta\rangle_r$)
10^{1}
10^{0}
10^{-1}
10^{-2}
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
Rescaled conductance : log η / $\langle\eta\rangle_r$
RMS deviation to model
0.008
0.006
0.004
0.002
1.4

$$\langle \delta\rho(E_1, \boldsymbol{r}_1)\delta\rho(E_2, \boldsymbol{r}_2)\rangle = \frac{\rho_0^2}{2\pi g}\mathrm{Re}\Bigg\{[1 + X_{E_1}X_{E_2}^*]K_0\left(R\sqrt{\frac{2\gamma_\Phi - iE_1/X_{E_1} + iE_2/X_{E_2}^*}{\hbar D}}\right) - [1 - X_{E_1}X_{E_2}]K_0\left(R\sqrt{\frac{2\gamma_\Phi - iE_1/X_{E_1} - iE_2/X_{E_2}}{\hbar D}}\right)\Bigg\},$$

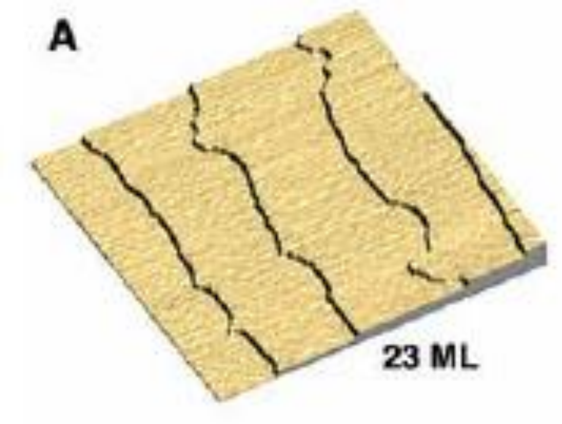


Experimental dependence of auto-correlation

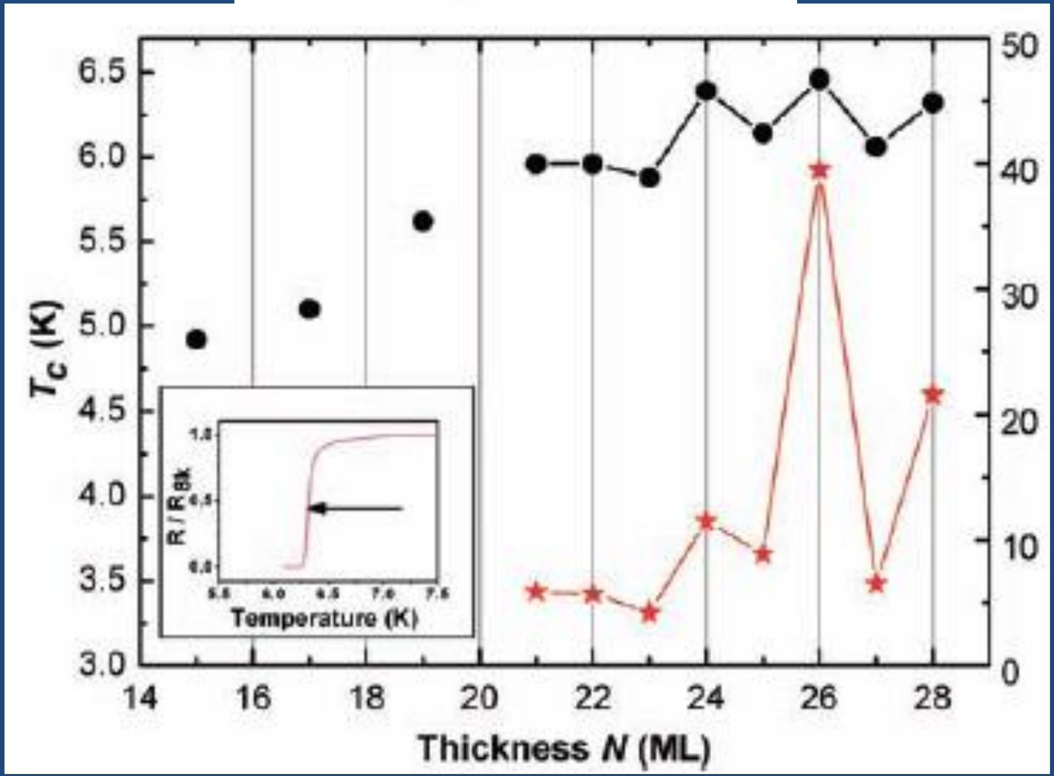


Reducing the thickness of crystalline thin films

2x2um^2



Pb films grown on Si(111) in ultrahigh vacuum



Guo et al. Science 2004

Not exhaustive !

Strongin et al. PRL 1973

Pfennigstorf et al. PRB 2002

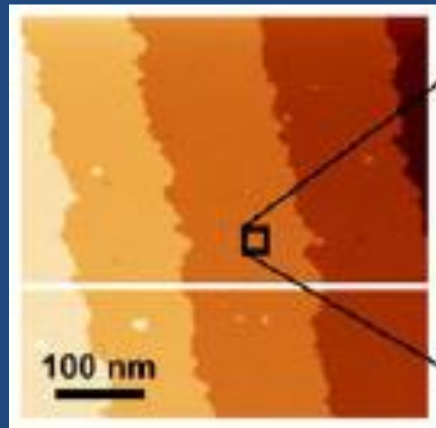
Ozer et al. Nat. Phys. 2006

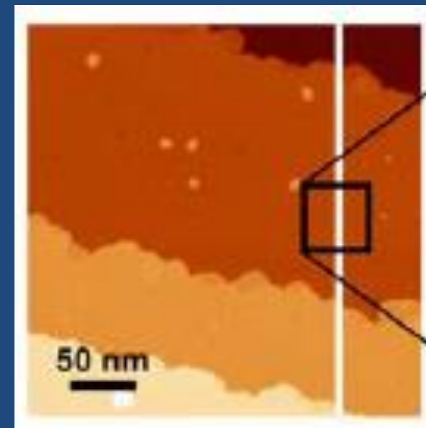
Eom et al. PRL 2006

Brun et al. PRL 2009

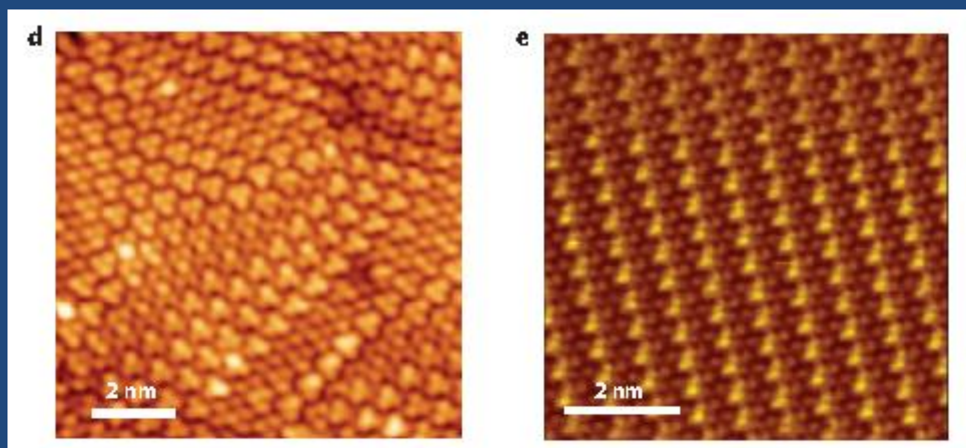
Qin et al. science 2009

Superconductivity in 1 atomic layer of Pb/Si(111)





Striped-incommensurate (SIC)

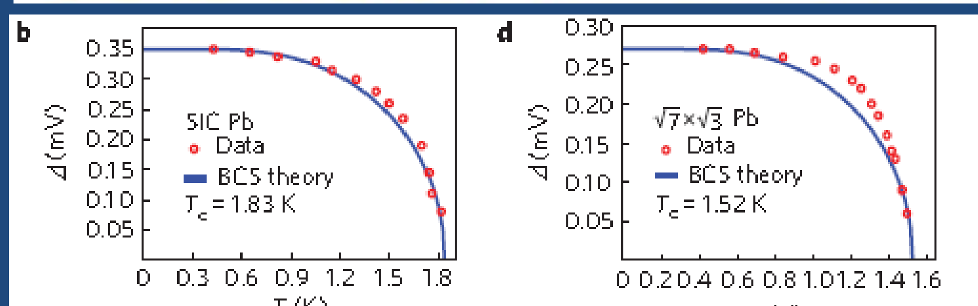


$\sqrt{7} \times \sqrt{3}$

Coverage:1.30 Pb atom for 1 Si

Coverage:1.20 Pb atom for 1 Si

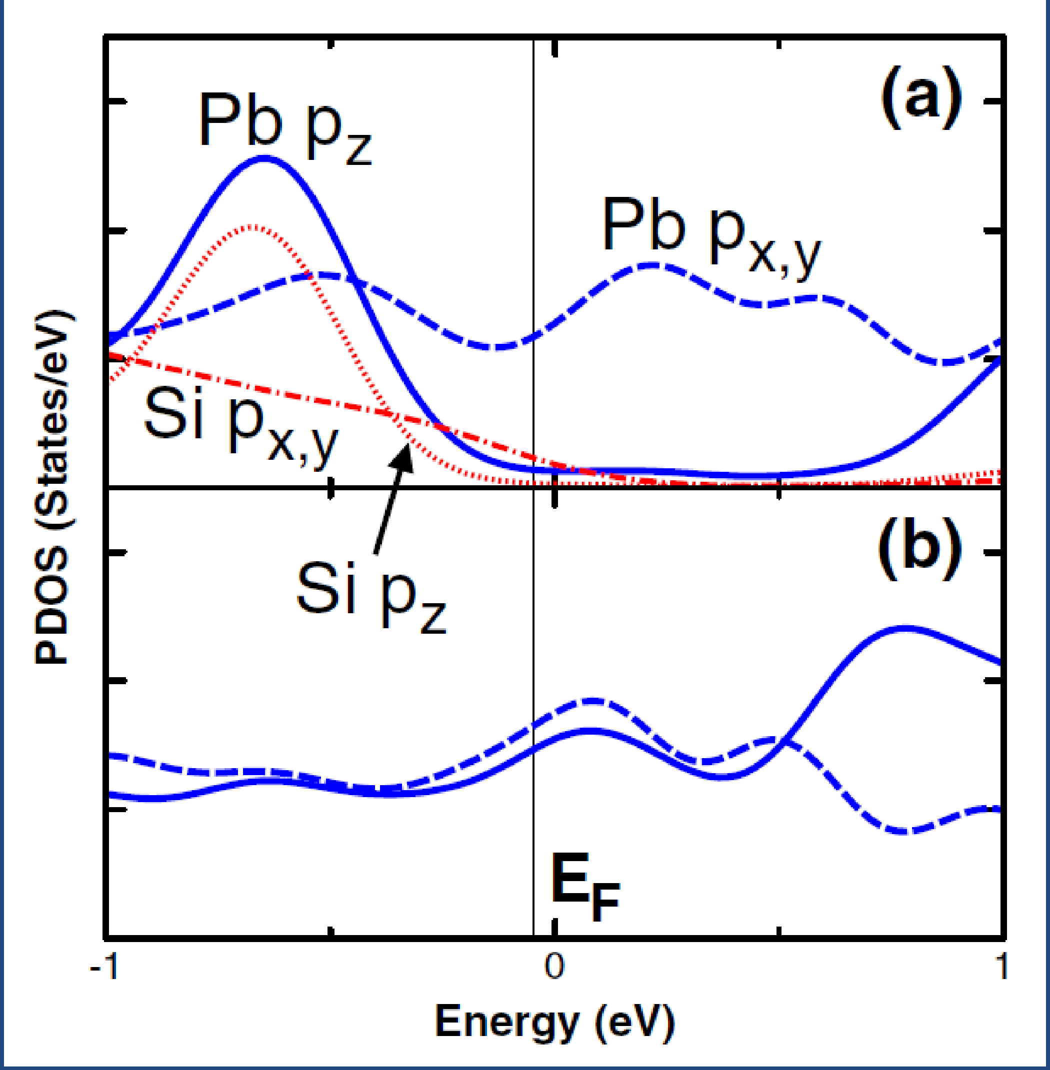
T_c = 1.8 K



T_c = 1.5 K

Zhang et al. Nat. Phys. 6, 104 (2010)

DFT : decoupling of surface states from bulk at E_F



√7×√3-Pb/Si(111)

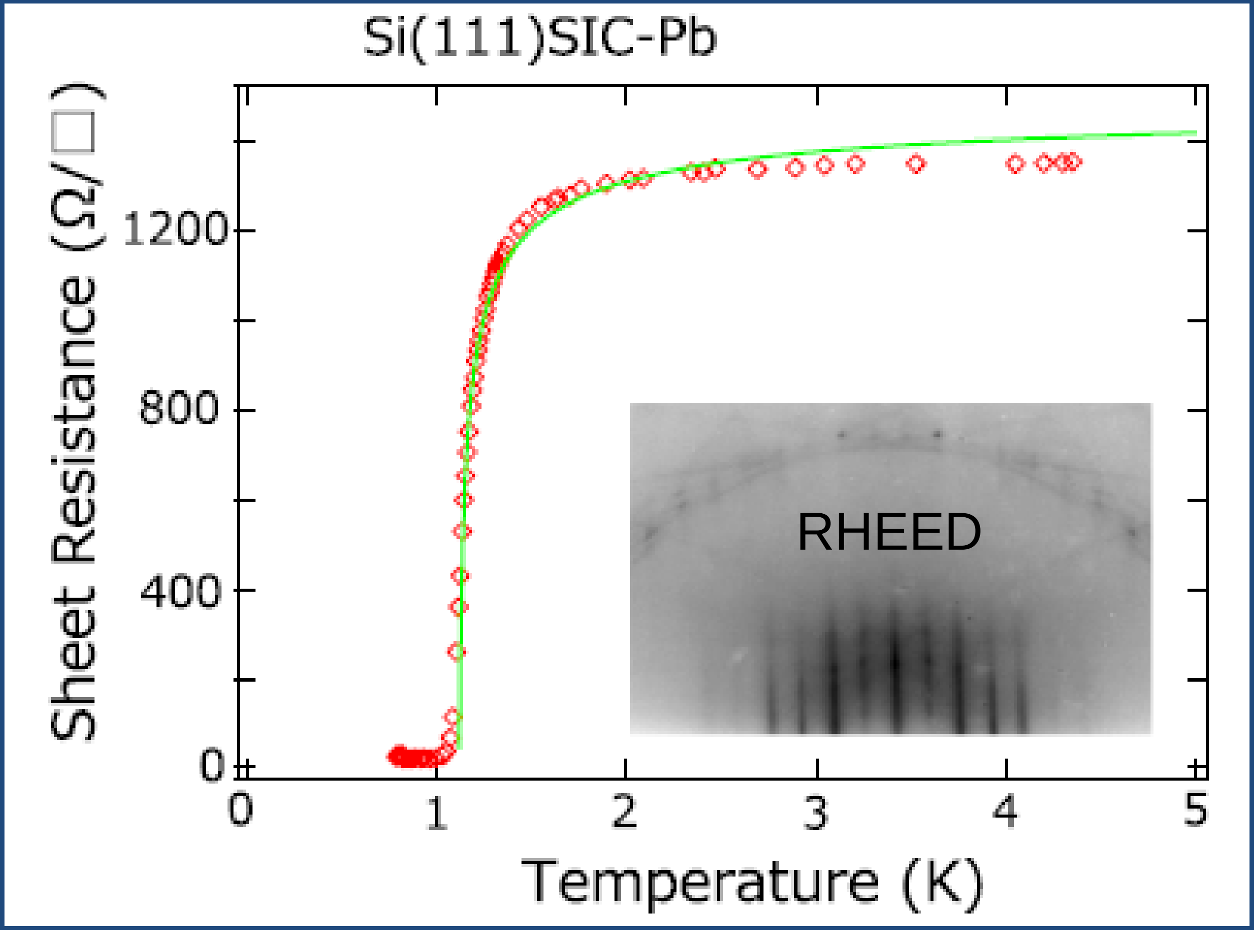
Free standing √7×√3-Pb

Small changes of the Pb-6px,y states due to the substrate

DFT : Jung and Kang Surf. Sci 601, 555 (2011)

Macroscopic resistivity of 1 atomic layer of Pb/Si(111)

Micro-four point probes – spacing = 20 microns



$T_{c\text{-transport}} = 1.1\text{K} < T_{c\text{-STM}} = 1.8$ K

Uchihashi et al. PRL 107, 207001 (2011) (In monolayer)

Yamada et al. PRL 110, 237001 (2013) (Pb monolayer)

Existence of strong Rashba SOC in Pb/Si(111)

- Strong spin-orbit coupling in Pb/Si(111) layer
- 3D inversion always broken in a surface layer

→ Split-off in (x,y) plane of the 2D electron bands

$$H_{so} = \alpha(\boldsymbol{\sigma} \times \mathbf{p}) \cdot \mathbf{n}$$

Spins put in plane by H_{SO}

Spins ⊥ to ***p***

Existence of strong Rashba SOC in Pb/Si(111)

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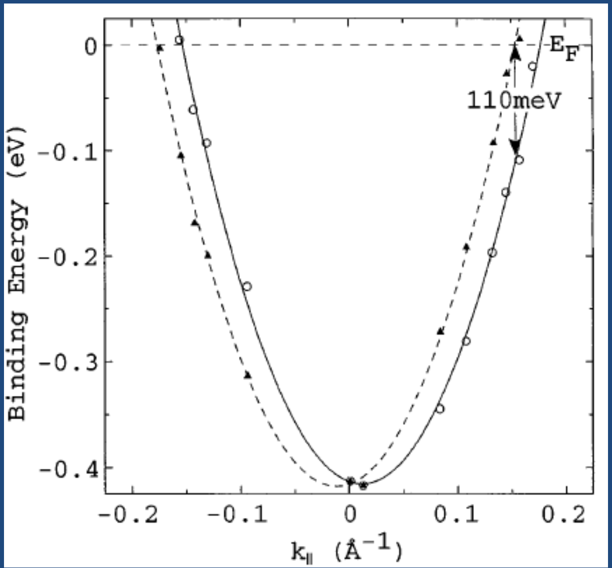
- 3D inversion always broken in a surface layer

→ Split-off in (x,y) plane of the 2D electron bands

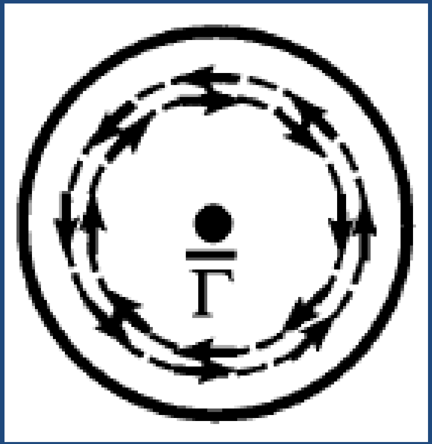
$$H_{so} = \alpha(\boldsymbol{\sigma} \times \mathbf{p}) \cdot \mathbf{n}$$

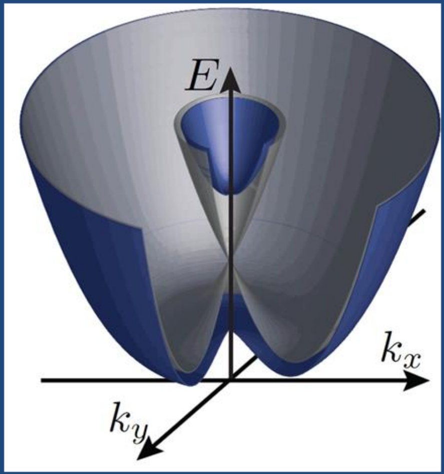
Spins put in plane by H_{SO}

Spins $\perp$ to $\boldsymbol{p}$



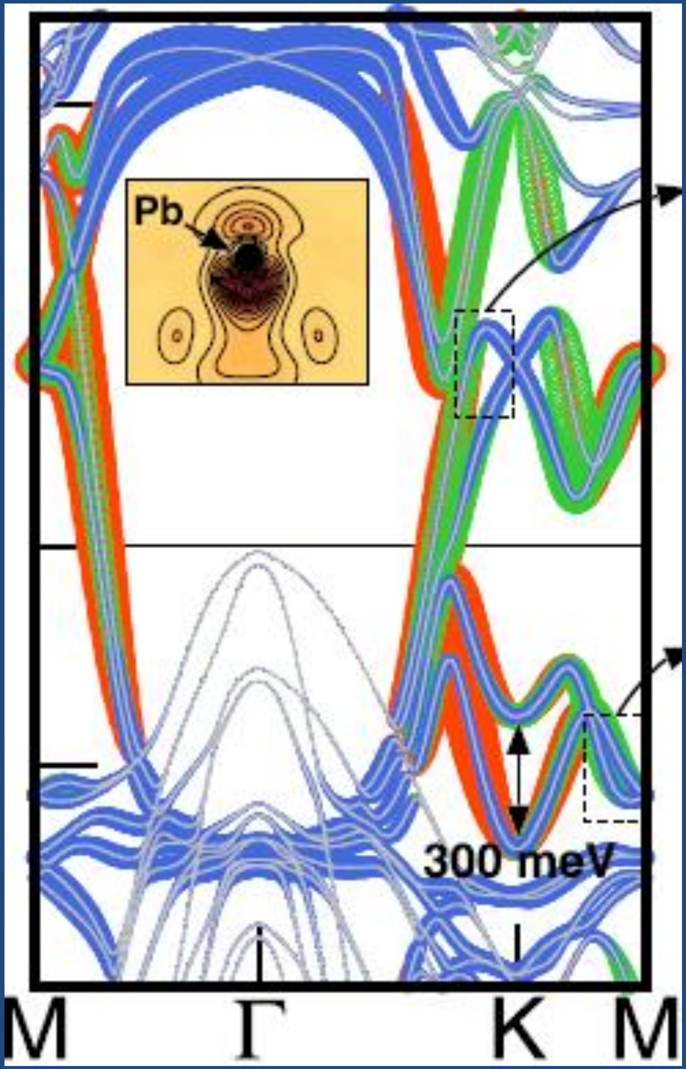
Au(111)



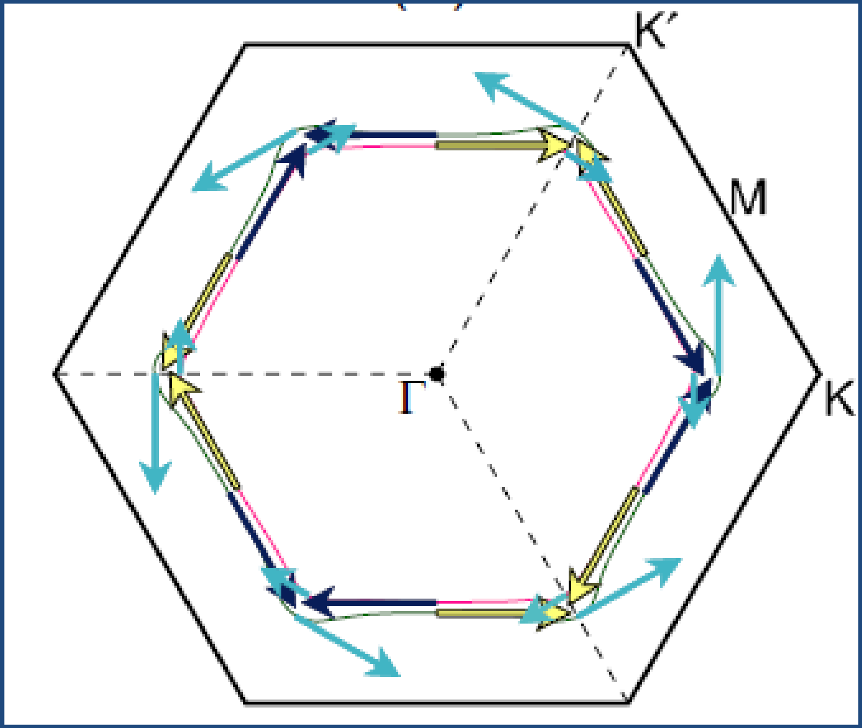


Bychkov,Rashba, JETP Lett. 39, 78 (1984) *LaShell et al. PRL77, 3419 (1996)*

DFT+SOC and spin-ARPES of the Pb-SIC monolayer



Fermi surface



Helical spin texture

DFT: Ren PRB 94, 07543 (2016) *spin-ARPES: Brand PRB 96, 035432 (2017)*

Summary of the electronic properties of the Pb-SIC monolayer

1 Rashba split band (Pb $6p_{x,y}$ orbitals)

$m \sim 1.2\ m_0$

$E_F \sim 0.8$ eV

$k_F \sim 1.36$ Å^{-1}

$\lambda_F \sim 4.6$ Å

→

True 2D electronic confinement
$6p_{x,y}$ states at E_F

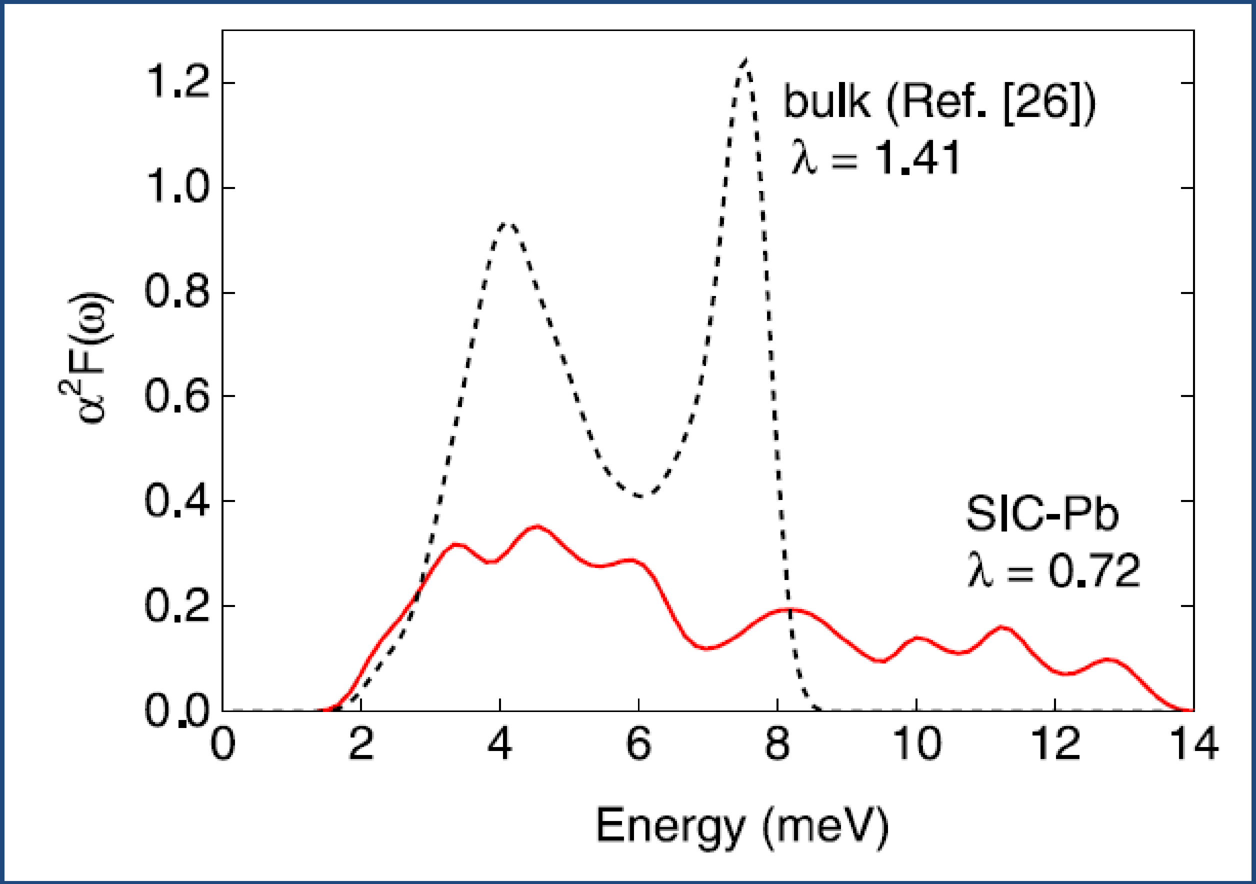
Δ	<<	$2|\alpha|p_F$	<<	E_F
0.3meV		100meV		800meV

$\xi \sim 50$ nm

$\ell_e \sim 5$ nm, $k_F\ell_e > 20$ very far from SIT !

Mean-level spacing of single-electron states in a coherence volume
$\delta = E_F/(\xi/a)^2 \sim 0.1$ meV $\sim \Delta/3$

Electron-phonon coupling from DFT



Assumptions: perfect √3x√3 Pb/Si(1111) - No SOC - Fixed Si atoms

Noffsinger and Cohen Solid State Commun. 151, 421 (2011)

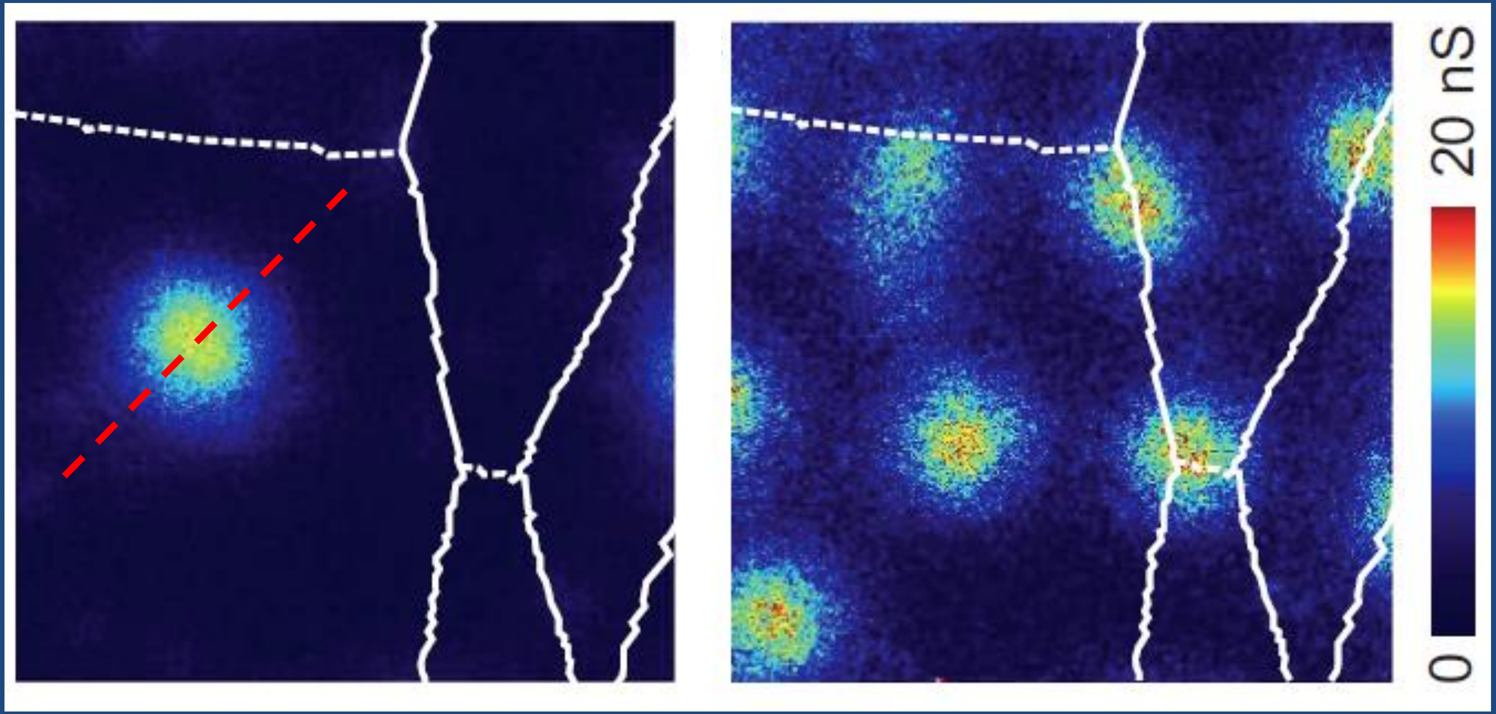
Vortices in SIC T_c~1.8K

dI/dV (V=0) map dI/dV (V=0) map

T=0.3K

600x600 nm²

$\vec{B}$ ⊙



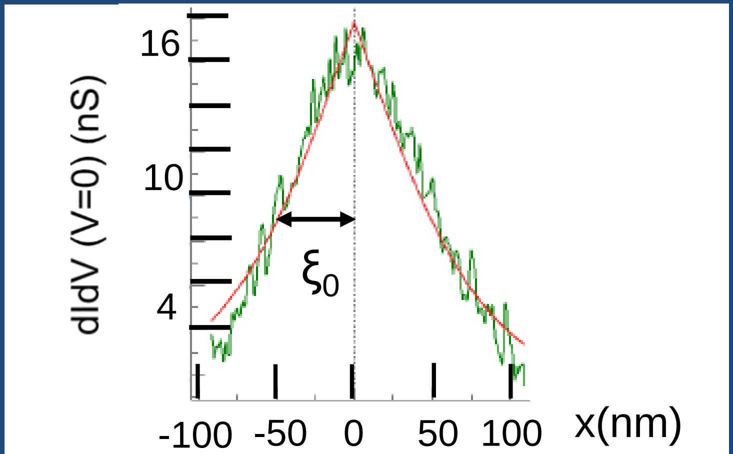
B=10mT B=40mT

$\xi_0 = (\hbar D/\Delta)^{1/2} \approx 47$nm

Nat. Phys. 10, 444 (2014)

Very good agreement also with:

Cherkez et al PRX 2014



Justification: see 3D Usadel calculations by Kupriyanov & Golubov

Nature Commun. 9, 2277, 2018