Zero-bias conductance peak in detached flakes of superconducting 2H-TaS2 probed by STS

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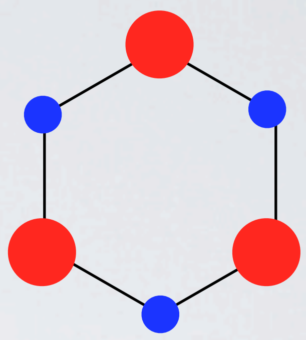
J. A. Galvis et al., Phys. Rev. B **89**, 224512 (2014)

Transition metal dichalcogenides

layered materials: van der Waals forces between layers

each layer: three atomic planes

X - M - X



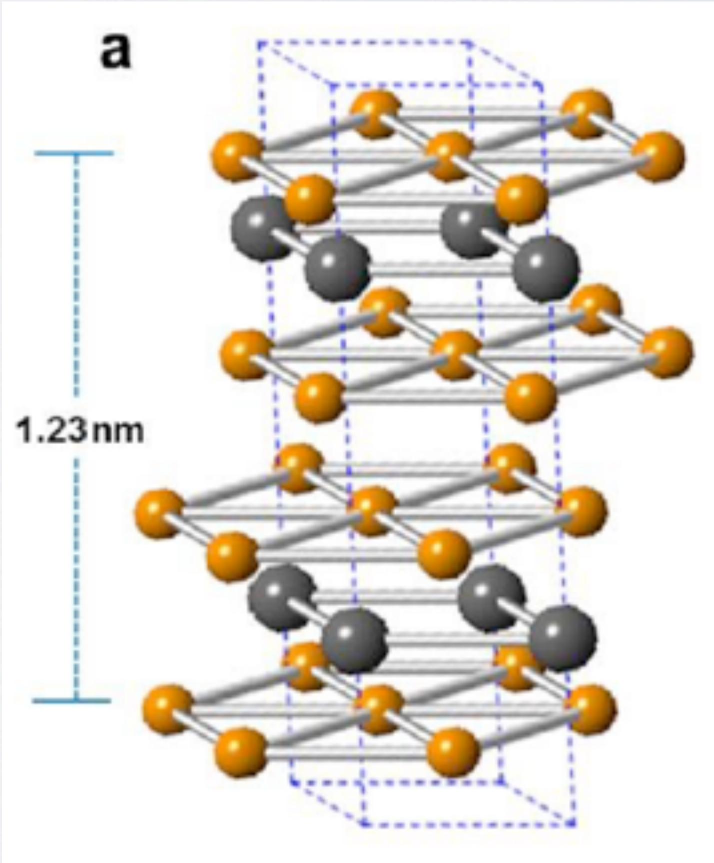
X = S, Se

M = Ta, Nb metallic

M = W, Mo semiconducting

2H polytype

Report STM measurements on single layer of 2H-TaS2



Fermi surface has a strong Ta character

5 d orbitals from Ta

2x3 p orbitals from S

strong spin-orbit

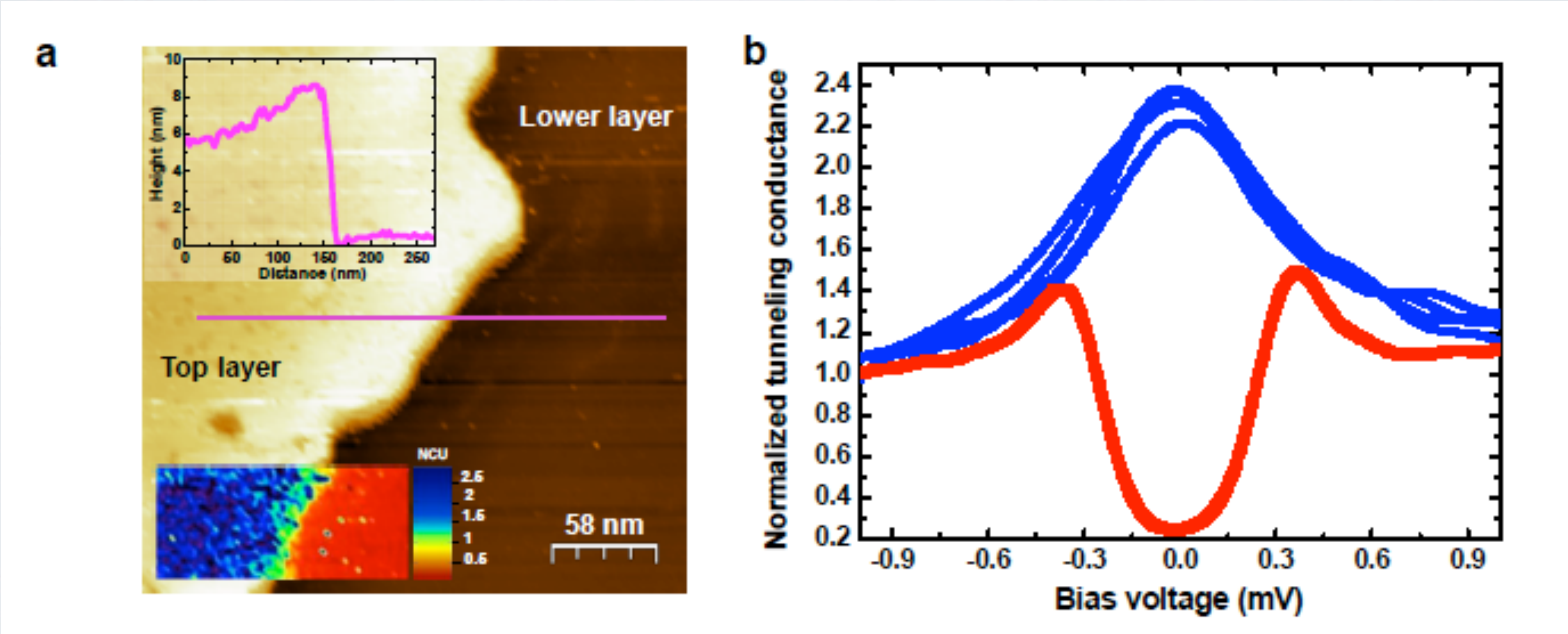
2H polytype
parity symmetric

STM measurement of surface of 2H-TaS2

scanning the **bulk** surface: **BCS like gap**

scanning the **single layer** surface: **Zero Bias Conductance Peak**

not compatible with BCS theory



Similar results for 2H-TaSe2 J. A. Galvis et al., Phys. Rev. B **87**, 094502 (2013)

Tight binding model

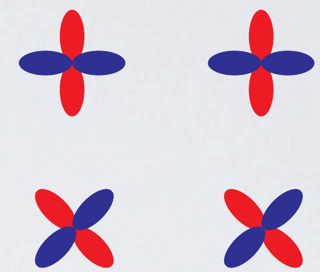
two Ta orbitals on a triangular lattice $d_{x^2-y^2}$ d_{xy}

effective model:

nearest-neighbour hopping

$t_{dd\sigma}$

$t_{dd\pi}$



$t_{dd\sigma} > t_{dd\pi}$

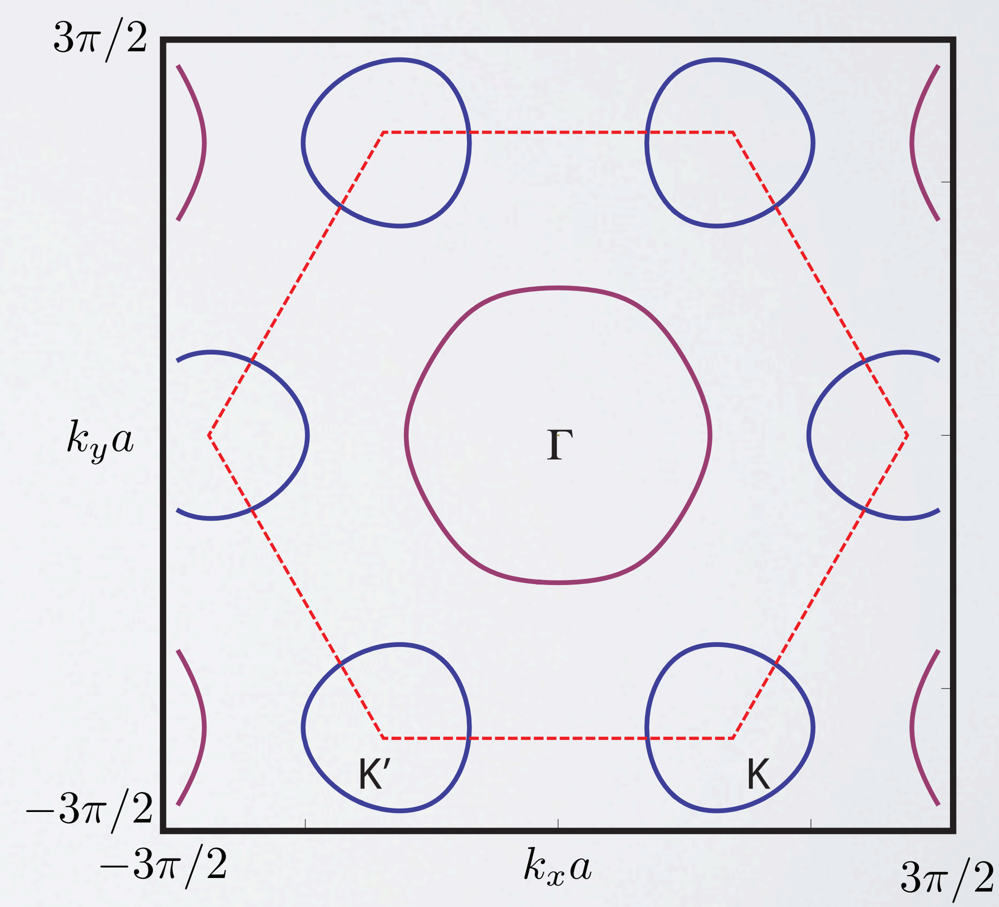
$$H_0 = -\sum_{\mathbf{R},\sigma}\sum_{i=1}^{3} \mathbf{c}^{\dagger}_{\mathbf{R},\sigma} h_i c_{\mathbf{R}+\mathbf{a}_i,\sigma} + \text{H.c.}$$

$$\mathcal{H}^0_{\mathbf{k}} = -2\sum_{i=1}^{3} h_i \cos(\mathbf{k}\cdot\mathbf{a}_i)$$

two orbitals → two bands Γ K

K K′ inequivalent points in the BZ

→ **three bands**



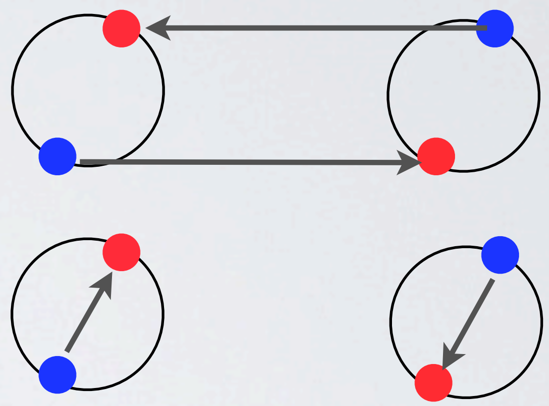
Possible odd-momentum superconductivity

Fermi surface has a strong Ta 5d character

non-negligible role of Coulomb interaction

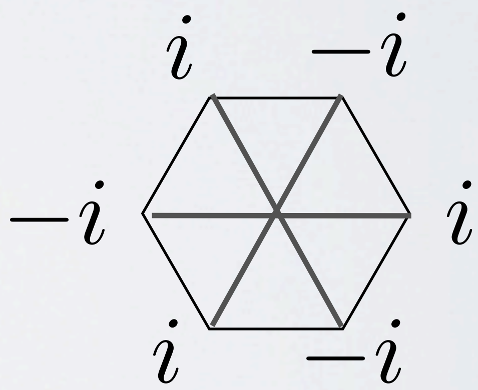
Strong K, K' interband scattering due to short range Coulomb repulsion

favors a odd-momentum gap $\Delta_{K'} = -\Delta_K$



tight-binding imaginary nearsest neighbour pairing

$$H_{SC} = -i\delta \sum_{\mathbf{R},\alpha} \sum_{s=\pm,j=1}^{3} s(-1)^j c^\dagger_{\mathbf{R}\alpha\uparrow} c^\dagger_{\mathbf{R}+s\mathbf{a}_j,\alpha\downarrow} + \mathrm{H.c.}$$



$$\Delta_{\mathbf{k}} = 2\delta \sum_{i=1}^{3} (-1)^i \sin(\mathbf{k}\cdot\mathbf{a}_i)$$

odd-momentum gap

$$\Delta_{-\mathbf{k}} = -\Delta_{\mathbf{k}}$$

Nodal odd-momentum superconductivity

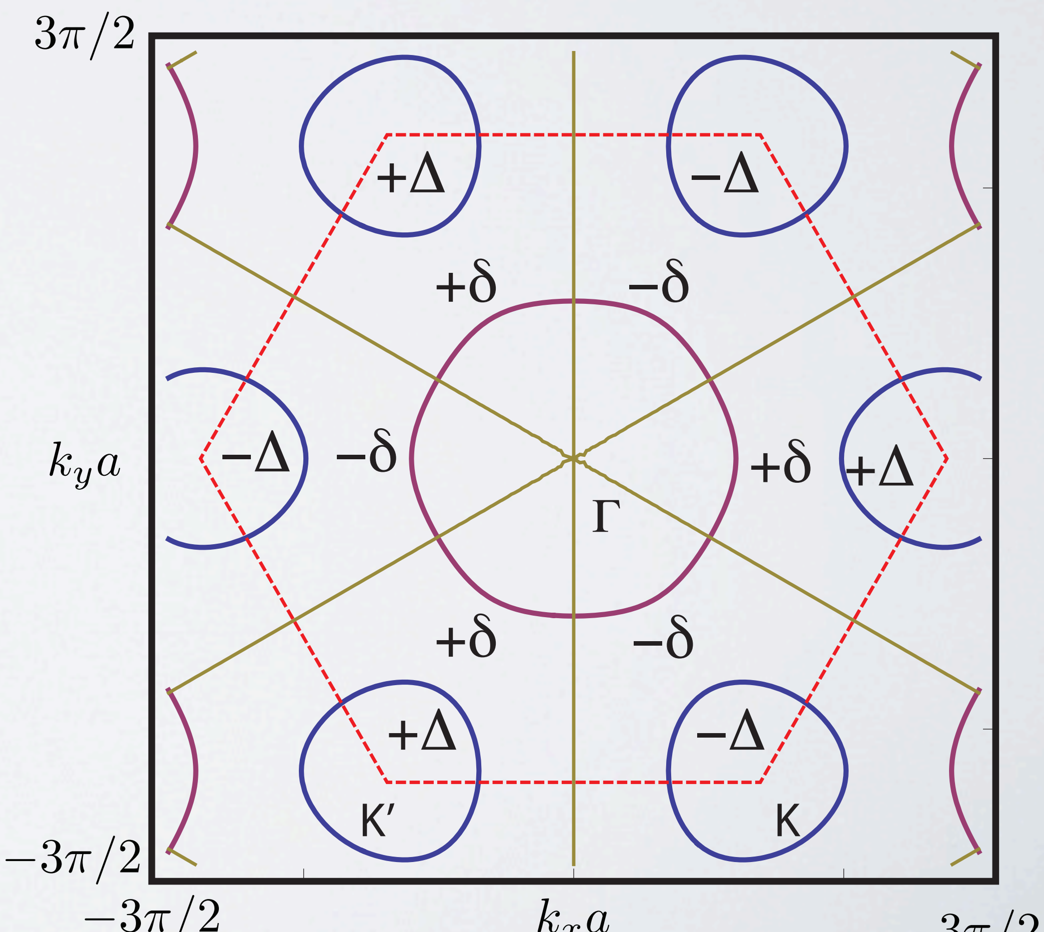
Bogoliubov de Gennes Hamiltonian $H_{\mathrm{BdG}} = \frac{1}{2}\sum_{\mathbf{k}} \psi^{\dagger}_{\mathbf{k}} \mathcal{H}^{\mathrm{BdG}}_{\mathbf{k}} \psi_{\mathbf{k}}$

Nambu spinor $\psi_{\mathbf{k}} = \begin{pmatrix} c_{\mathbf{k}} \\ \mathcal{T} c_{\mathbf{k}} \end{pmatrix}$

time-reversal operator $\mathcal{T} = i s_y \hat{K}$

$$\mathcal{H}^{\mathrm{BdG}}_{\mathbf{k}} = (\mathcal{H}^{0}_{\mathbf{k}} - \mu)\tau_z + \Delta_{\mathbf{k}} s_z \tau_x$$

triplet f-wave pairing



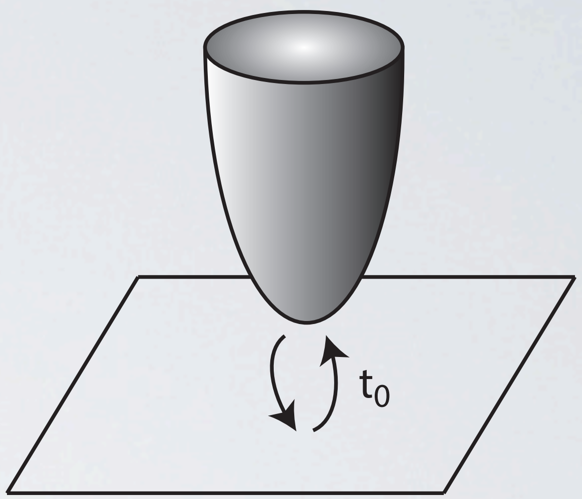
K	pocket	Δ	
K′	pocket	$-\Delta$	
Γ	pocket	**nodal**	δ

nodal gap induced by the K,K"

six nodes: symmetry robustness

STM local density of states

usually the STM measures the unperturbed density of states



Bardeen theory

$$\frac{dI}{dV} \propto \int d\omega \sum_{\lambda,\sigma} |T_\lambda|^2 A_\sigma(\lambda,\omega) f'(\omega - eV)$$

perturbative in tunneling

unperturbed spectral function

local DOS

$$|T_\lambda|^2 = \sum_\rho |M_{\lambda\rho}|^2 A_{\text{tip}}(\rho,\omega)$$

$$A_\sigma(\lambda,\omega) = -\frac{1}{\pi}\text{Im}G_\sigma(\lambda,\omega + i0^+)$$

$$\frac{dI(\mathbf{r})}{dV} \propto \rho(eV,\mathbf{r}) = -\frac{1}{\pi}\sum_\sigma \text{Im}\ G_\sigma(\mathbf{r},\mathbf{r};eV + i0^+)$$

Effective Dirac BdG Hamiltonian

Expand BdG Hamiltonian around nodal points $t_{dd\sigma} \gg t_{dd\pi}$

$$\mathcal{H}_Q^{\mathrm{BdG}} \simeq v_F k_y \tau_z + v_\Delta k_x \tau_x$$

$$\epsilon_Q(\mathbf{k}) \simeq \sqrt{v_\Delta^2 k_x^2 + v_F^2 k_y^2}$$

$v_F \simeq a t_{dd\sigma}$

$v_\Delta \simeq a\delta$

retarded Green'sfunction

$$g^{\mathrm{r}}(\epsilon) \simeq \frac{N_f A_c}{2\pi v_F v_\Delta}\left[-2\epsilon \ln \frac{\delta}{|\epsilon|} - i\pi|\epsilon|\right]$$

$N_f = 12$

δ **cutoff of the liner dispersion**

6 spin-degenerates nodes

$$\rho(\epsilon) \sim \frac{N_f A_c}{2\pi v_F v_\Delta}|\epsilon|$$

V-shaped gap around the Fermi energy

analogous to graphene

this is not what is measured

Possible explanation

within the theoretical model **two** assumptions: $\left\{ \begin{array}{l} \text{nodal odd-momentum superconductivity} \\ \text{perturbative tip-sample coupling} \end{array} \right.$

no magnetic impurities ➡ simple s-wave BCS superconductivity **cannot** expalin a ZBCP

strong short range interaction ➡ odd-momentum superconductivity

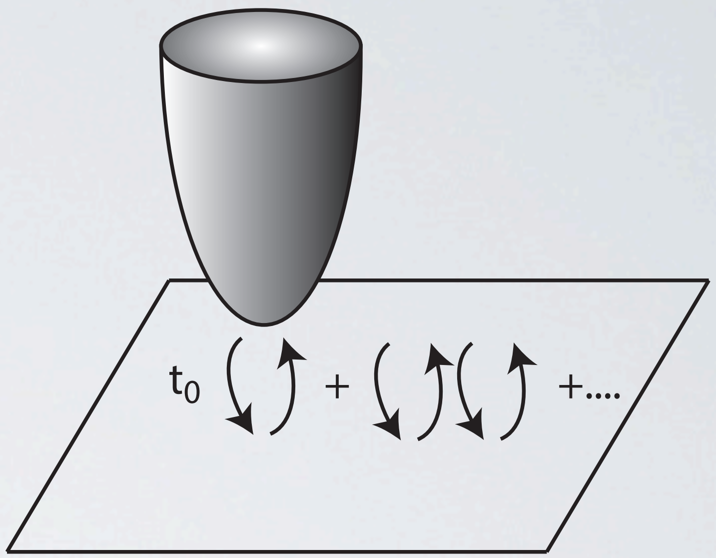
Can we relax the perturbative tip-sample coupling assumption?

two gaps: $\left\{ \begin{array}{llll} \mathrm{K} \;\; \mathrm{K}' & \text{pocket} & \Delta & -\Delta \\ \Gamma & \text{pocket} & \delta & \textbf{nodal} \end{array} \right.$ $\qquad \delta \ll \Delta$

tip-sample coupling $\left\{ \begin{array}{ll} \mathrm{K} \;\; \mathrm{K}' & \text{perturbative} \\ \Gamma & \textbf{non-perturbative} \end{array} \right.$ ➡ **tip-modified local DOS**

Non-perturbative tip-sample coupling

assume point-like tunneling t_0



SC Green's function $\hat{g}_{\rm sc}(z) = \sum_{\mathbf{k}} (z - \mathcal{H}^{\rm BdG}_{\mathbf{k}})^{-1}$

odd gap $\Delta_{-\mathbf{k}} = -\Delta_{\mathbf{k}}$ $\sum_{\mathbf{k}} \frac{\Delta_{\mathbf{k}}}{E_{\mathbf{k}}} = 0$

No Andreev current

analogous to tunneling to a **semiconductor**

analogous to tunneling to a **graphene**

differential conductance $$\sigma(\omega) = \frac{e^2}{h} \frac{4\pi^2 t_0^2 \rho_{\rm tip}(\omega - eV)\rho_{\rm sc}(\omega)}{|1 - t_0^2 g_{\rm tip}(\omega - eV) g_{\rm sc}(\omega)|^2}$$

tip self-energy $\Sigma_{\rm tip}(\omega) = t_0^2 g_{\rm tip}(\omega) \simeq -i\pi t_0^2 \rho_{\rm tip}$

Resonant behaviour

$$1 - \Sigma_{\rm tip} g_{\rm sc}(\Omega) = 0$$

retarded Green's function defined in the upper half of complex energy plane

$$g_{\rm sc}(z) = Cz\ln(-iz) \qquad z = \epsilon/\delta$$

$$1 + i\lambda z\ln(-iz) = 0 \qquad \lambda = t_0^2 \rho_{\rm tip} C$$

effective coupling $C = \dfrac{N_f A_c \delta}{\pi v_\Delta v_F}$

$z = ix$	**purely imaginary resonance**

$$x \ln x = 1/\lambda$$

for strong coupling solution compatible with cutoff

broad resonance at zero energy

compatible with experimental observation

Zero Bias Conductance Peak

the tip-sample coupling is usually perturbative

effective coupling $\lambda = N_f \tilde{\lambda}$ $\rho_{\rm sys} = A_c / a v_F$

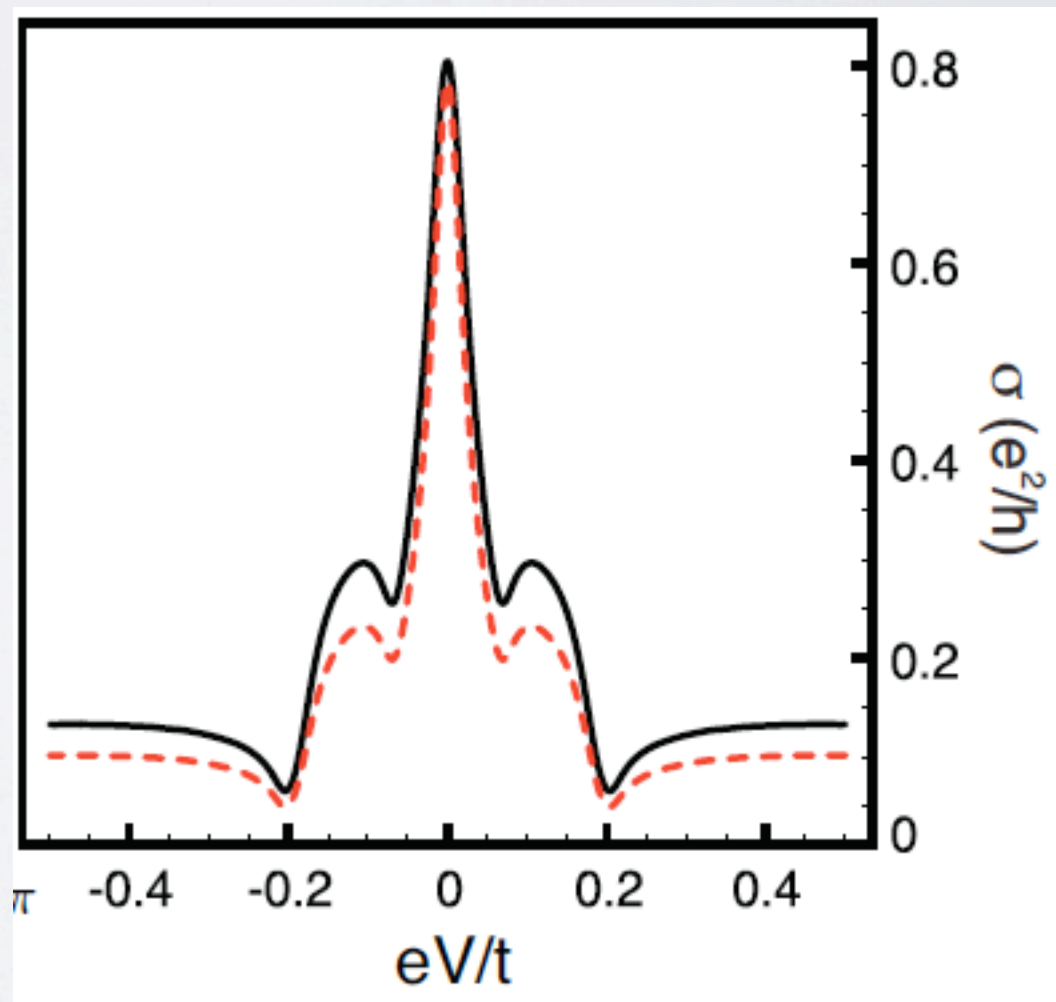
microscopic coupling $\tilde{\lambda} = t_0^2 \rho_{\rm tip} \rho_{\rm sys}$ $\tilde{\lambda} \ll 1$ perturbative

for a large N the **effective coupling** can become **non-perturbative**

conductance with the full tight-binding

valid at all energies

broad ZBCP



Summary and Conclusions

experimentally observed Zero Bias Conductance Peak in single layer 2H-TaS2

ZBCP found in a large area

ruled out any local mechanism such as magnetic impurity

non-compatible with BCS-like theory

strong short range Coulomb repulsion can induce odd-parity gao at K and K'

nodal induced gap on the Gamma pocket

perturbative STM cannot explain measurements

on the Gamma pocket a **weak tip-sample coupling can become non-perturbative**