Solitons/instantons in electronic properties:
Born in theories of late 70's, Found in experiments of early 80's.
Why in 2000's ?
New conducting polymers,
New events in organic conductors,
New accesses to Charge Density Waves,
New interests in strongly correlated systems as semiconductors

Many evidences for solitons in the ground or stationary states
Until now : little or no evidences in dynamics,
on direct conversion of electrons into solitons –
Breakthrough described below

What are the solitons: Nonlinear self-localized excitations on top of a ground state with a spontaneously broken symmetry.
They carry a charge or a spin – separately, even in fractions.
Their macroscopic aggregated forms are the domain walls – e.g. counted in Giga's at the hard drive of this computer.

Solitons and dislocations in overlap tunnelling junctions of incommensurate Charge Density Waves.

Yu.I.Latyshev[1], P.Monceau[2], S.Brazovskii[3], A.I.Orlov[1], Th.Fournier[2]
[1]Moscow, [2]Grenoble, [3]Orsay

Observation of Charge Density Wave Solitons in Overlapping Tunnel Junctions Phys. Rev. Lett., **95**, 266402 (2005)

Subgap collective tunneling and its staircase structure in charge density waves Phys. Rev. Lett., **96**, 116402 (2006).

Yu.I. Latyshev, P. Monceau, S.B., *et al,* : *ECRYS-05 proceedings*
Interlayer tunneling spectroscopy of layered CDW materials

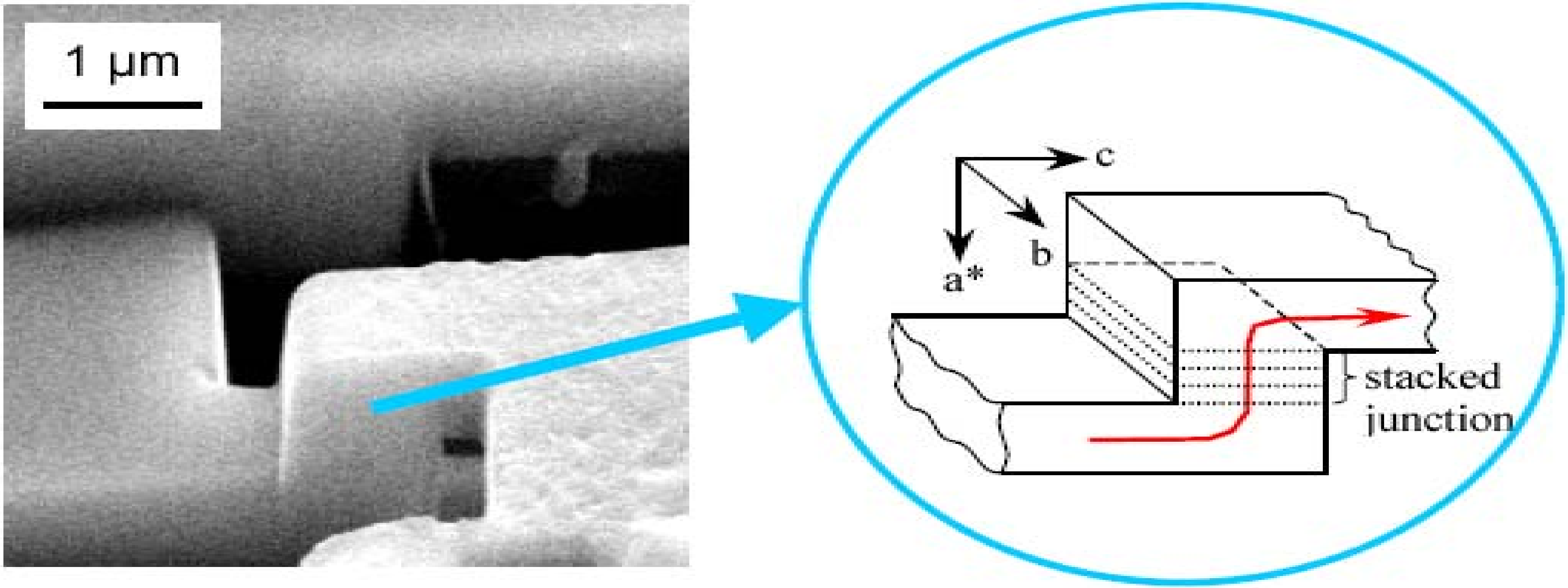
S.B.,Yu.I. Latyshev, S.I. Matveenko and P. Monceau *ECRYS-05 proceedings*
Recent views on solitons in Density Waves

S. I. Matveenko and S. B. *ECRYS-05 proceedings*
Subgap tunneling through channels of polarons and bipolarons in chain conductors
Theory of subgap interchain tunneling in quasi 1D conductors

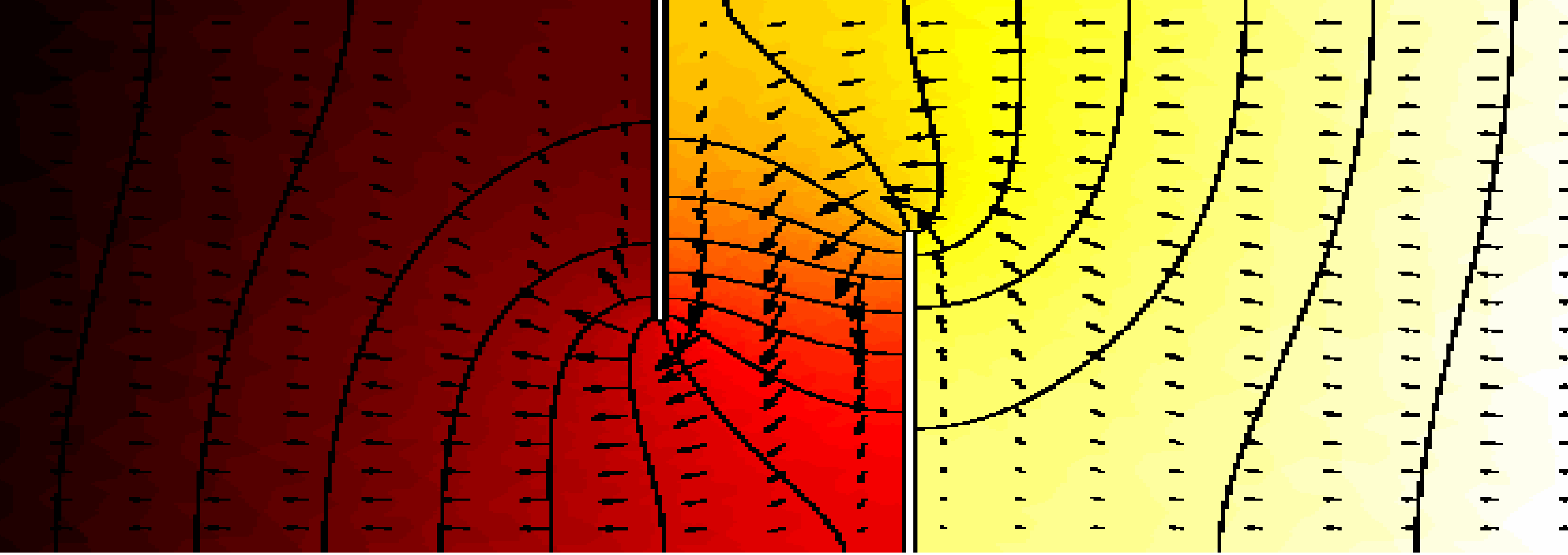
Yurii Latyshev technology of mesa structures: fabrication by focused ion beams.
All elements – leads, the junction – are pieces of the same single crystal whisker

Inorganic compounds MX3 : NbSe3 TaS3, etc
Whisker crystals of chains bearing incommensurate Charge Density Waes

Figure : Scanning electron microscopy picture of $NbSe_3$ stacked structure and its scheme.



Overlap junction forms a tunneling bridge of 200A width -- 20-30 weakly coupled conducting plains of a layered material.

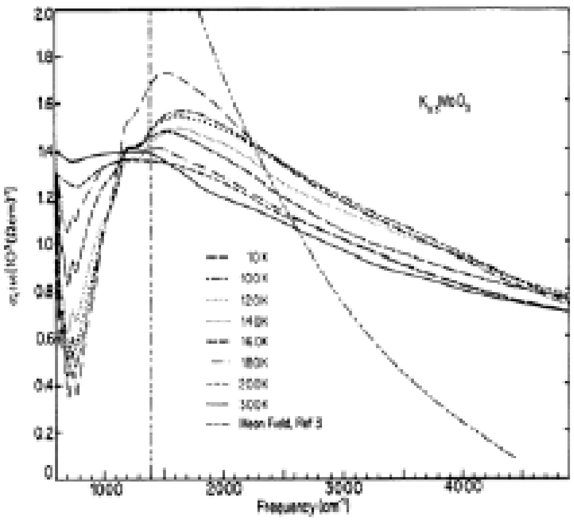


Distribution of potentials in linear regime of normal conductance (values in colours, equipotential lines in black) and currents (arrows) for moderate conductivity anisotropy (A=100). Thickness (vertical) axis is rescaled as anisotropy $A^{1/2}$=10 times.

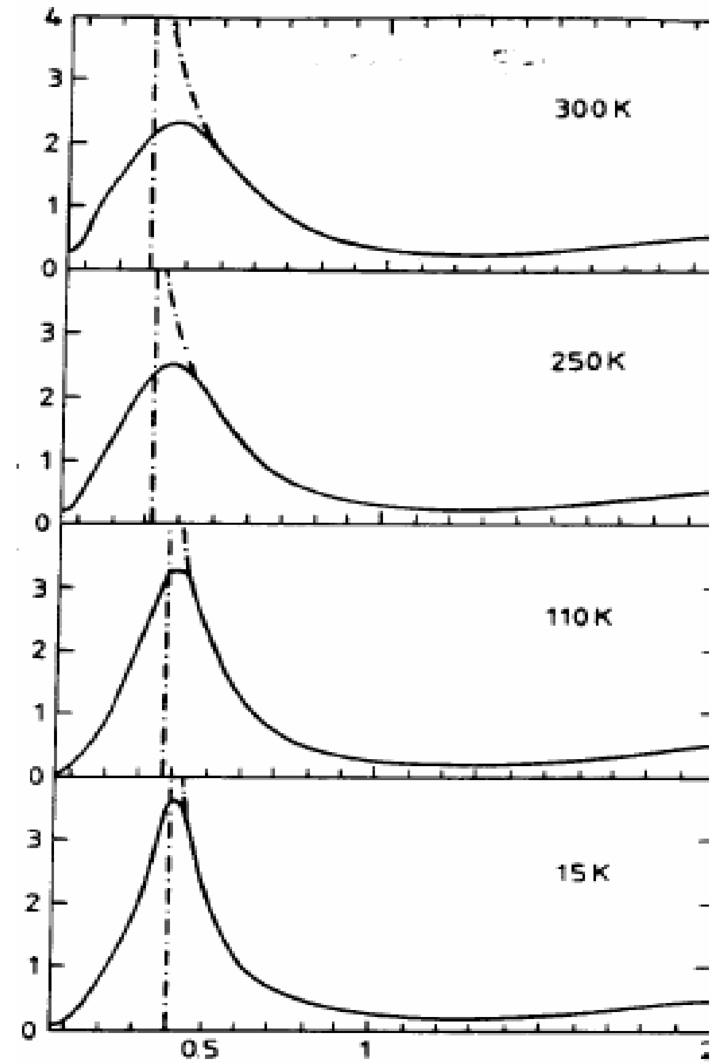
Analytic solution for junction vicinity: Complex coordinate **z** as a function of the complex potential **S**:

$$z = Z(S,Q) = \frac{1}{\pi}\left(-\frac{\sinh S}{\sinh Q} + iS\right)$$

Incommensurate CDWs in quasi 1D conductors.
Pseudogap, subgap transitions due to nonadiabatic quantum fluctuations.
Already a long standing problem in optics :



PG in optics
Degiorgi
group



Microscopics of electrons conversion in ICDW:

Incommensurate CDW : $A\cos(Qx+\varphi)$ $Q=2K_f$

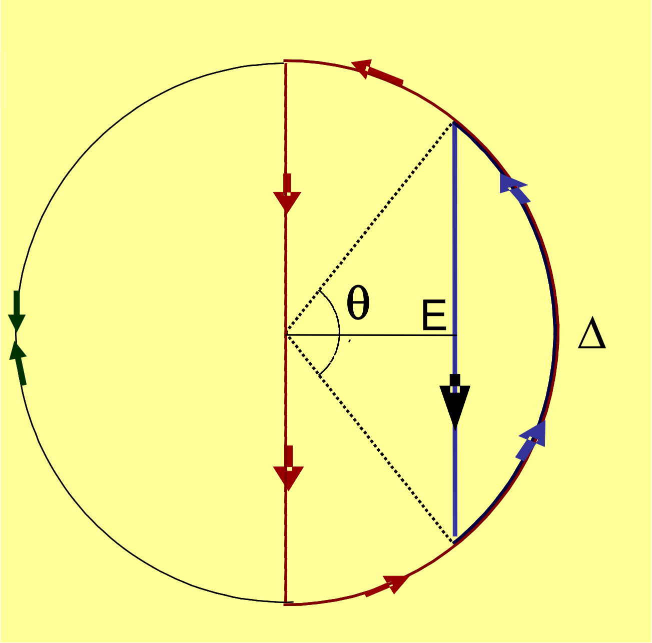
Order parameter : $\Delta\sim A\exp(i\varphi)$

Electronic states $\Psi = \Psi_+\exp(iK_f x+i\varphi/2) + \Psi_-\exp(-iK_f x-i\varphi/2)$

$$\begin{vmatrix} k-E & \Delta^* \\ \Delta & -k-E \end{vmatrix} \begin{pmatrix} \Psi_+ \\ \Psi_- \end{pmatrix} = 0 \quad , \quad k = K - K_f = -i\partial_x$$

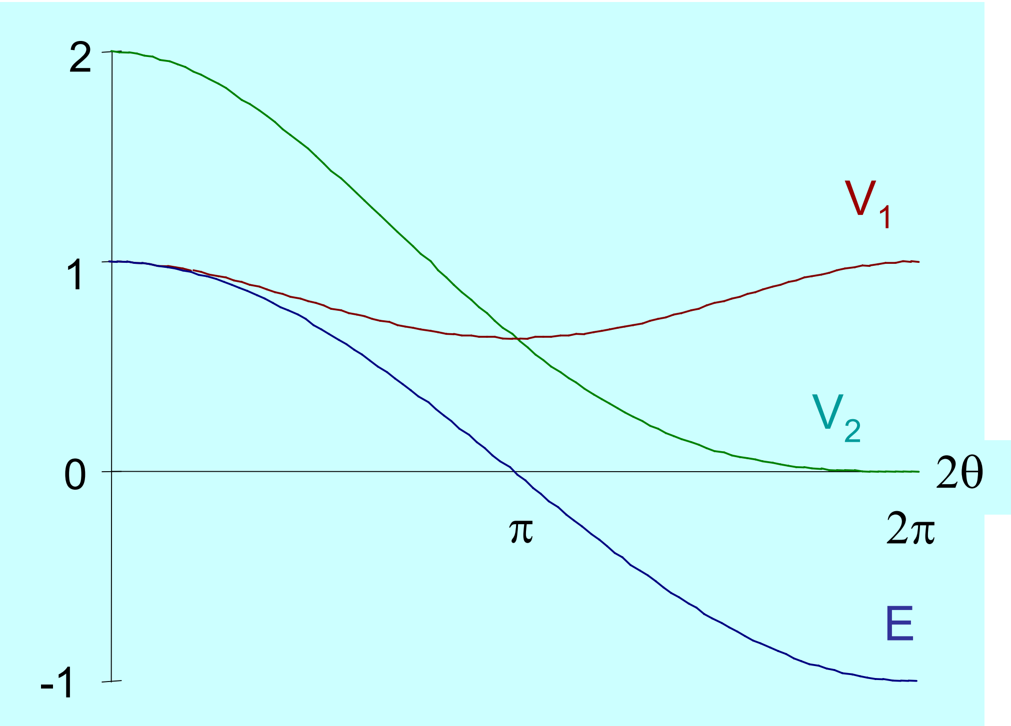
Peierls-Frohlich, chiral Gross-Neveu models.
Spectra are related to the nonlinear Schroedinger equation for Δ:
Fateev, Novikov, Its, Krichever; Matveenko and S.B.

In equillibrium : $\mathbf{\Delta=\Delta_0=const,\ \ E=\pm(\Delta_0^2+k^2)^{1/2}}$
Major interest: spectral flow between the two branches of allowed states $E>\Delta_0$ and $E<-\Delta_0$ and the related conversion of added particles to the extended ground state



Soliton trajectories in the complex plane of the order parameter.
Red line: stable amplitude soliton.
Blue line: intermediate chordus soliton within chiral angle θ (black radial lines).
The value θ=100° is chosen which corresponds to the optimal configuration for the interchain tunnelling

S.Matveenko and S.B.

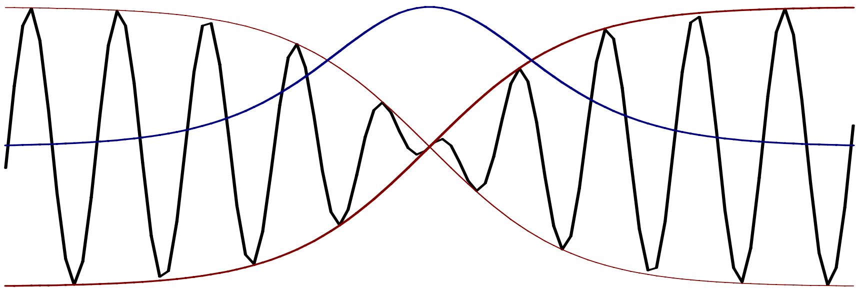


Selftrapping branches $V_n(\theta)$ for chordus solitons
for fillings n =1 and n=2,
Energy $E_0(\theta)$ of localized split-off state
as functions of the chiral angle θ.
Scale : Δ_0=1

Self-trapping process through the chiral angle θ provides :

1. Spectral flow by transferring the split-off state between the gap edges $\Delta_0 \rightarrow -\Delta_0$ while θ evolves from 0 to 2π
2. Microscopic phase slip, by adding/subtracting the 2π winding of the order parameter, i.e. one wavelength of the CDW. Each CDW wavelength is composed with two electrons with ↑↓ spins, then a pair is required to enforce the complete phase slip.
3. In case of single particle – electron/hole added at Δ_0 / $-\Delta_0$ self-trapping will still proceed but passing only half way to the stable form of the amplitude soliton.

This creature will appear in tunneling :
Amplitude soliton with energy $\approx 2/3\Delta$, total charge 0, spin ½
This is the CDW realization of the SPINON



Oscillating electronic density,
Overlap soliton A(x),
Midgap state =spin distribution

Phase mode action : (u- phase velocity)

$$S_{snd} = \frac{v_f}{4\pi}\int\int dxdt((\partial_t\varphi/u)^2 + (\partial_x\varphi)^2)$$

Chordus soliton forming around $x_s = 0$ enforces the discontinuity $\varphi(t,\pm 0) = \mp\theta(t)$.

Integrate out $\varphi(x,t)$ from $\exp\{-S_{snd}[\varphi,\theta]\}$ - arrive for $\theta(t)$ at the typical action for the problem of quantum dissipation

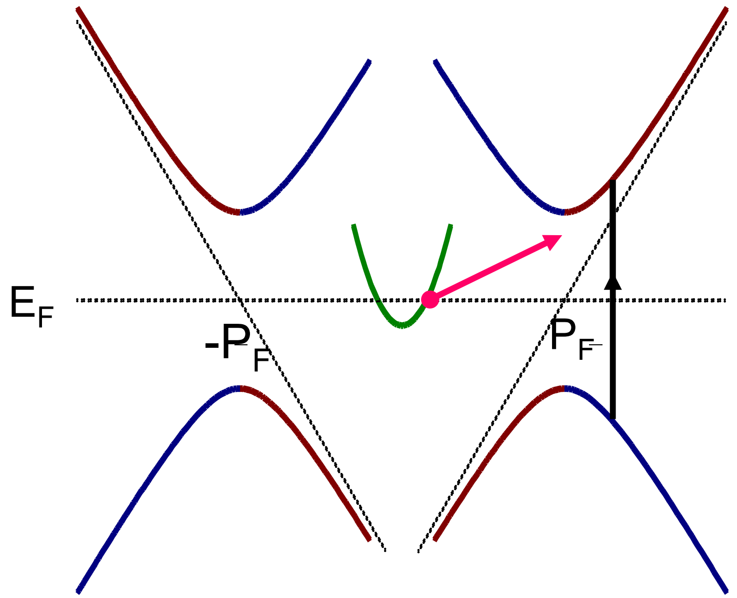
$$S \sim \sum|\omega||\theta_\omega|^2 \qquad S_{snd}\{\theta] \approx -\frac{v_F/u}{2\pi^2}\int\int dt_{1,2}\dot{\theta}(t_1)\ln|(t_1 - t_2)|\dot{\theta}(t_2)$$

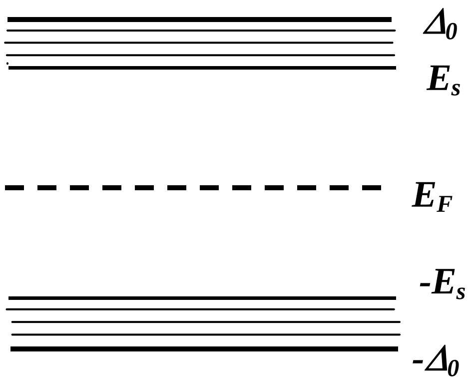
Dissipation comes from emission of phase phonons while forming the long range tail in the course of the chordus soliton development.

$\dot{\theta} = \partial_t\theta$ is peaked within short instances $\sim \xi_0/u$ around moments t=0 and t=T.

Then $S_{snd} \approx (v_F/4u)\ln(uT/\xi_0)$

Electronic spectrum E(P) of a rigid CDW semimetal – NbSe3.

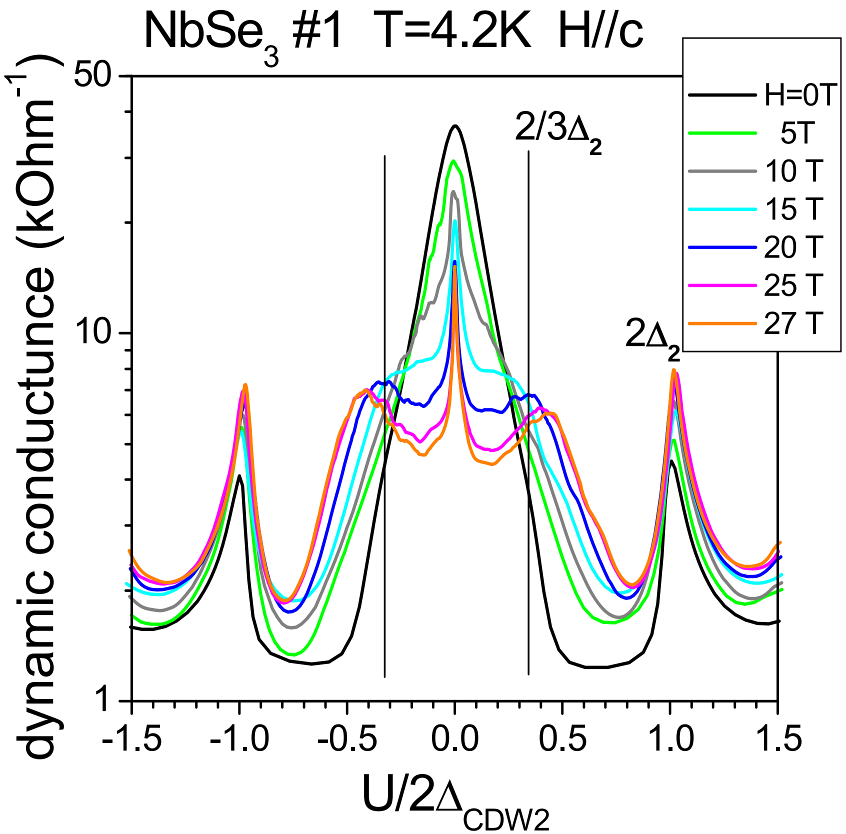


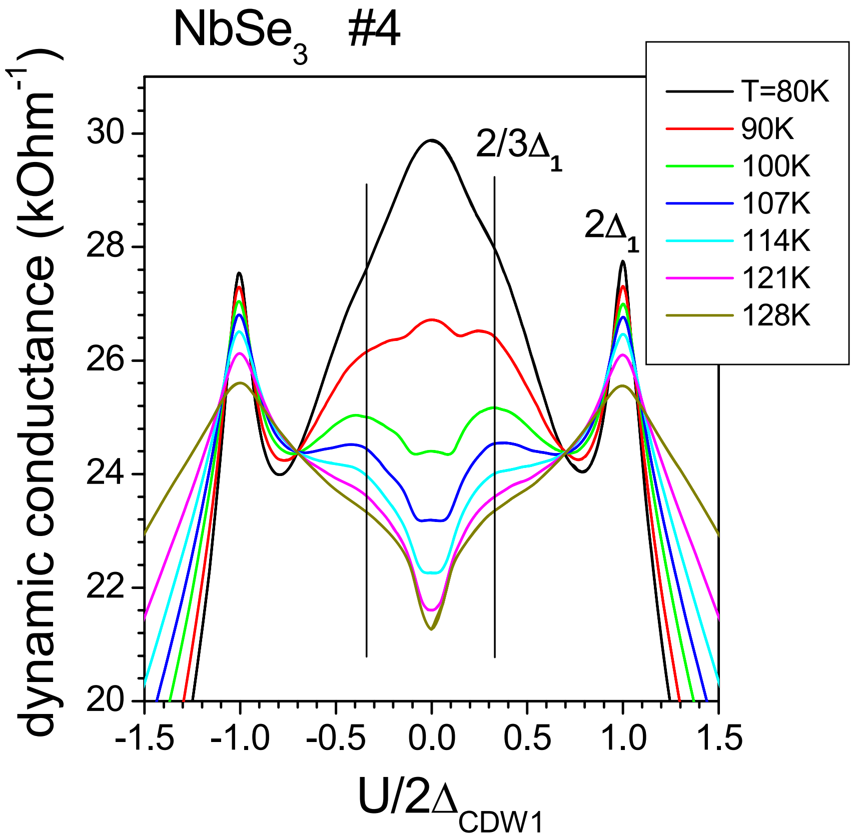


Inclined thin straight lines: branches for bare metal;
Fermi level E_F : dashed horizontal line.
Thick blue/red lines with extrema of $\pm\Delta_0$
on the verticals of Fermi momenta $\pm P_F$:
modified spectrum in CDW state.
Parabolic spectrum penetrating below E_F near P=0:
(green line) the electron pocket specific to $NbSe_3$.
Vertical black arrow: allowed intergap tunnelling or optical transition of free electrons.
Inclined light red line:
transition from the pocket to the soliton: 1 electron → 1 soliton

Direct observation of solitons in tunneling on $NbSe_3$

Thresholds 2Δ for intergap creation of e-h pairs,
followed through a pseudogap
down to the edge for electron → soliton transition at $E_s=2\Delta/\pi$.



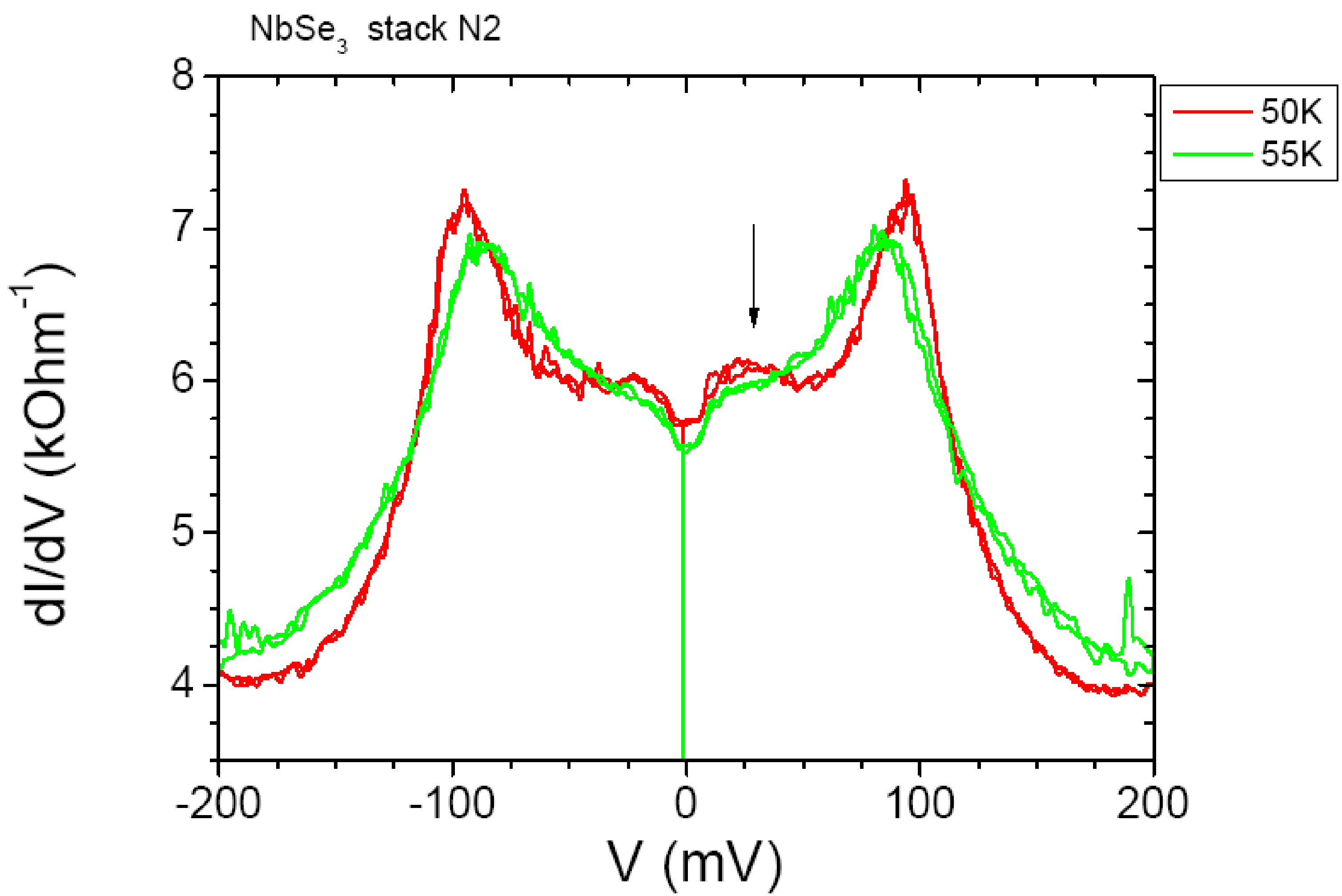


Zero Bias Conduction Peak from remnant carriers need to be suppressed by :

Left : high magnetic field   Right : elevated temperature

Intrigues #2,3:

Universal threshold at low $V_t \approx 0.2\Delta(T)$ and subsequent regular oscillations

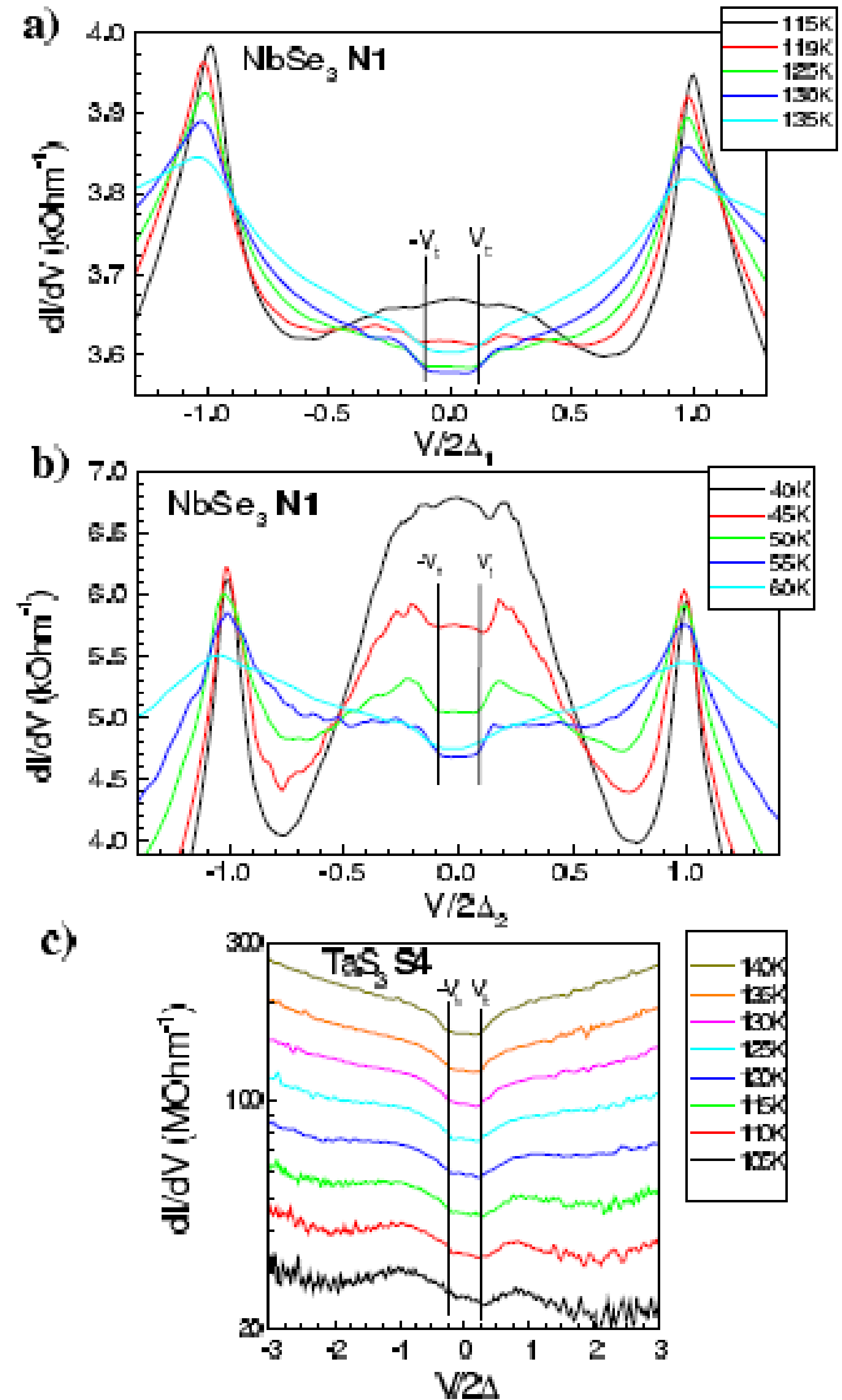


Tunneling spectra *dI/dV* as function of voltage *V* normalized to CDW gap 2Δ at different *T*:

a) CDW1 in NbSe3,
b) CDW2 in NbSe3,
c) c) o-TaS3.

Major peaks - expected free particle gap edge singularities at V=±2Δ.

Universal feature appearing when the central peak is
1. suppressed (NbSe$_3$)
2. absent (TaS$_3$)
- threshold voltage V_t for the onset of tunneling



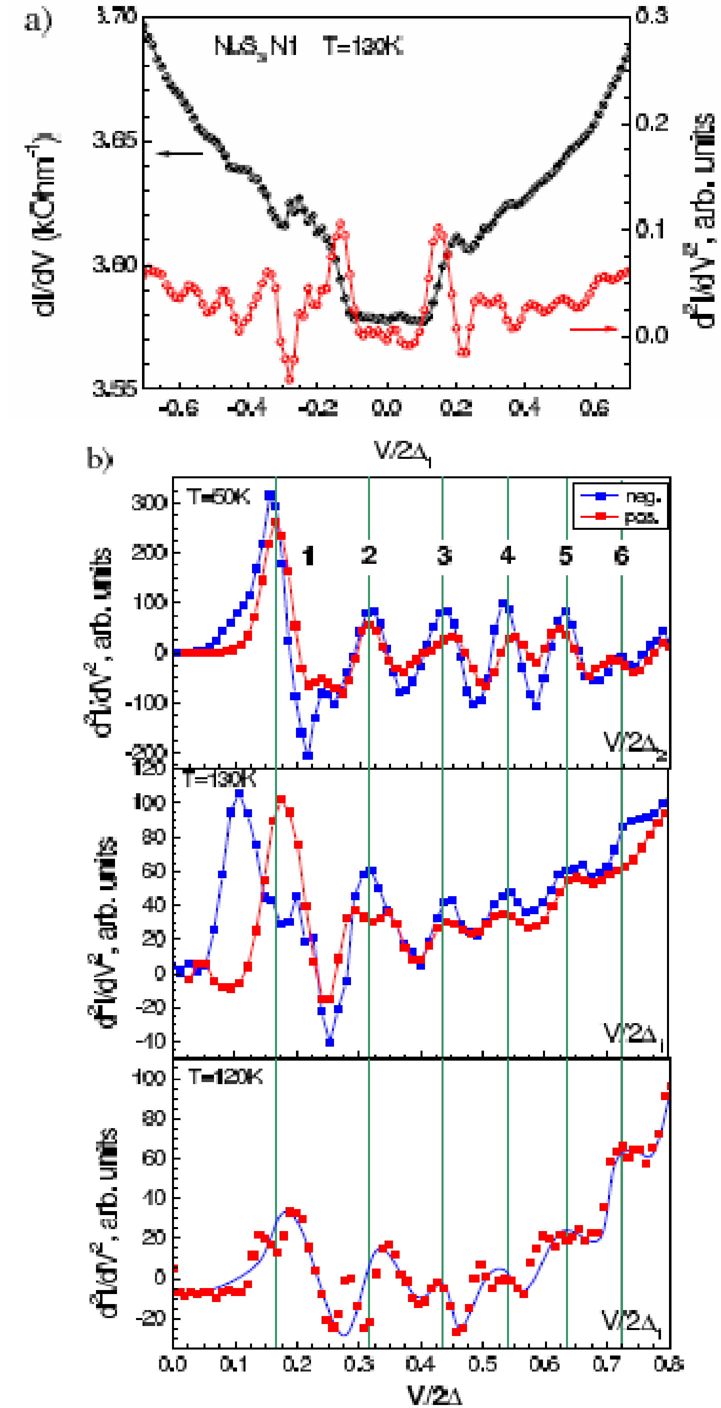
Fine structure of tunneling spectra within the magnifed threshold region.

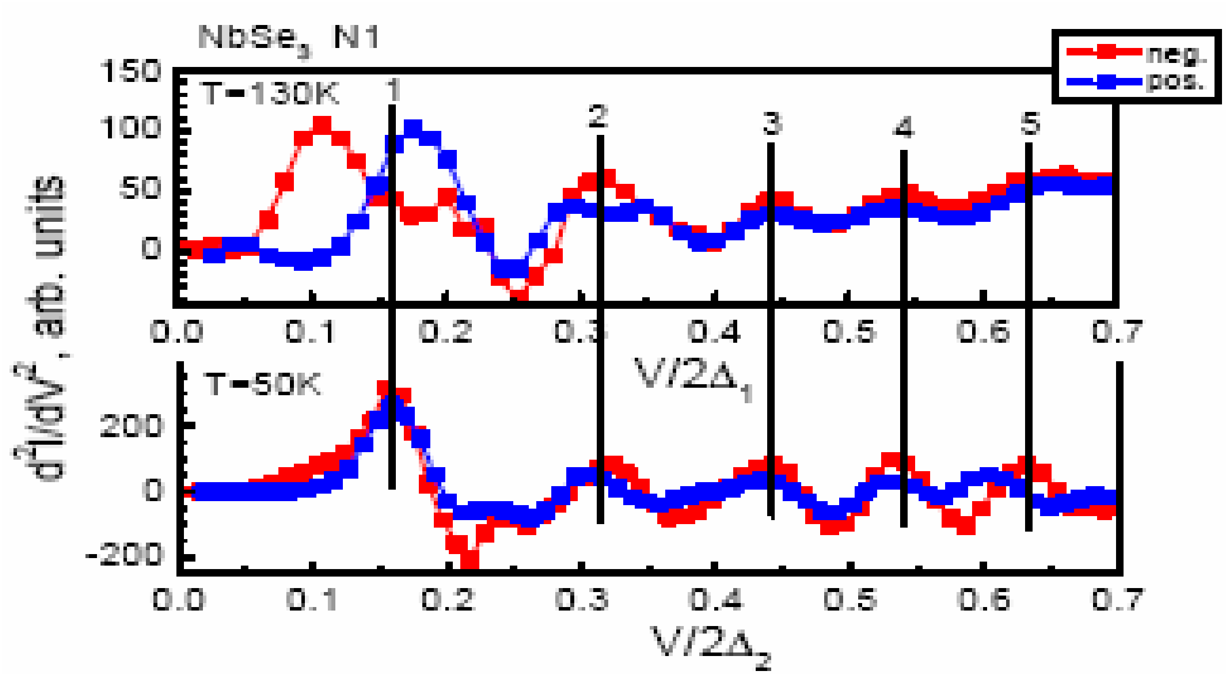
Conductance *dI/dV* and its derivative d^2I/dV^2

Voltage *V* is normalized to the CDW gap.

Comparison of d^2I/dV^2 for two voltage polarities for both CDWs, at T=130K and 50K; the positive polarity at T=120K

Peaks interpretation : sequential entering of dislocation lines into the junction area.





NbSe$_3$ N1
neg.
pos.
T=130K
1
2
3
4
5
150
100
50
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
$V/2\Delta_1$
T=50K
200
0
-200
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
$V/2\Delta_2$
d^2I/dV^2, arb. units

ICDW is a self-adjusting electronic crystal –
number of particles in the ground state is not fixed: $n \rightarrow n+\delta n$
It can float with the gap being attached to them $\delta E_f = v_f \delta K_f = \delta n v_f \pi/2$
Excess screening charge can come directly from the condensate density, if it is allowed to change across the layers (numbered by an integers m)

$$\delta n \Rightarrow \delta n_m \qquad \delta n = \varphi' / \pi$$

But it requires a difference in $\varphi'_m - \varphi'_{m\pm1}$

which means a mismatching of CDW periodicities at adjacent chains corresponding to wave numbers $2K_{fm}$: $2\delta K_{fm} = \varphi'_m$

To onset the collective screening
the interplane structural correlation must be broken,
while normally the phases are correlated at $T<T_c$

Decoupling threshold:

arrays of solitons or dislocations.

Discommensurations in a two layers model.

Minimal model:
Interlayer decoupling as an incommensurability effect.
Only two layer 1,2 - kept at potentials ±*V*/2

$$\int dx \left\{ \frac{\hbar v_F}{4\pi} \left[\varphi_1'^2 + \varphi_2'^2\right] + \frac{V}{2\pi}\left[\varphi_1' - \varphi_2'\right] - J_z \cos(\varphi_1 - \varphi_2) \right\}$$

Its minimization: lattice of discommensurations (solitons in phase difference).
It develops from the isolated discommensuration which is the 2π soliton in Δφ.
The critical voltage is identified as the energy necessary to create the first discommensuration:

CDW junction as an array of dislocation lines DLs.

In reality: a bulk of many planes, voltage difference monitored at its sides, decoupling will happen in-between.

Lattice of discommensurations - generalized to sequence of DLs.

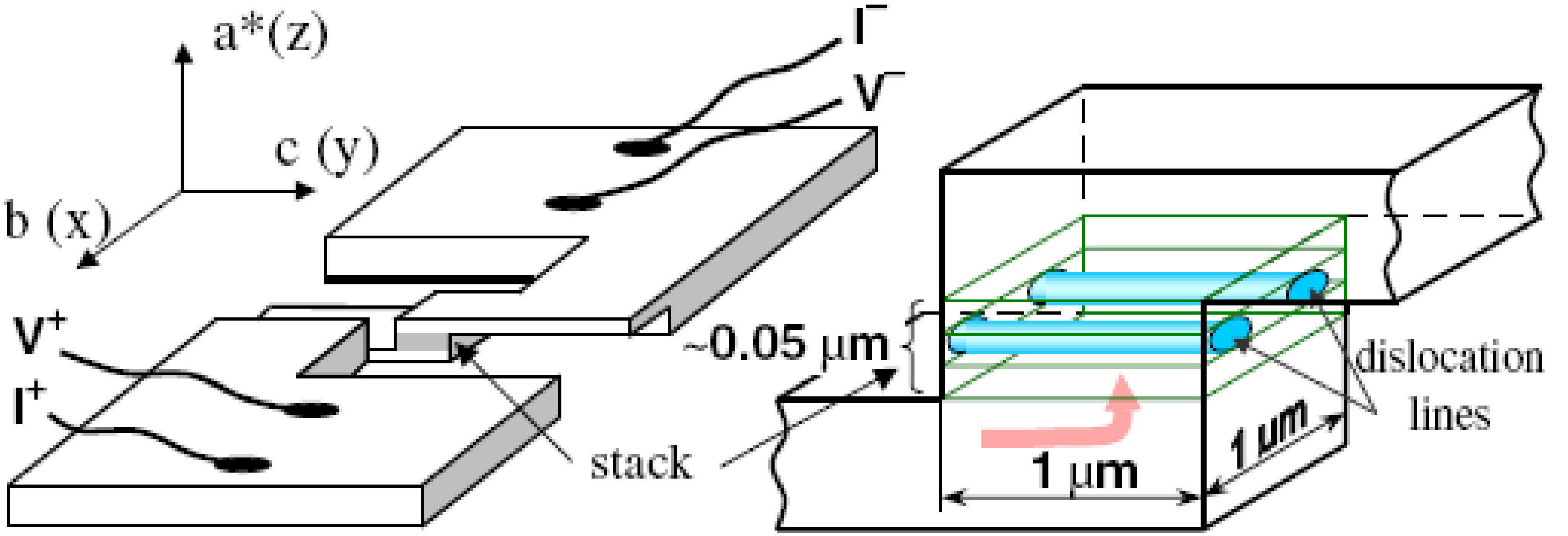
Critical voltage - DL entry energy, like H_{c1} in superconductors.

(*Old theories by Feiberg-Friedel, S.B.-Matveenko*)

Closely to the spacing of decoupled planes,

DLs array looks almost like the solitonic lattice.

At distant planes, discommensurations become more diffused, described by vorticites of DLs.



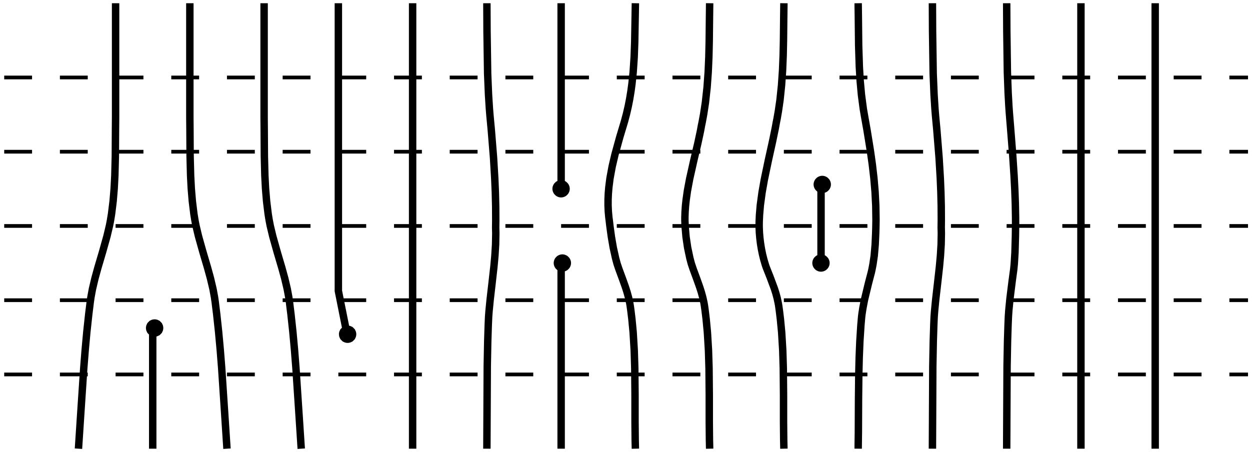


Figure from S.B. and T. Natterman Adv. In Physics 2004

Topological defects in a CDW.
Solid lines: maxima of the charge density.
Dashed lines: chains of the host crystal.
From left to right: dislocations of opposite signs and their pairs of opposite polarities.

Embracing only one chain of atoms, the pairs become a vacancy or an interstitial or $\pm 2\pi$ solitons in CDW language.

Bypassing each of these defects, the phase changes by 2π thus far from the defect the lattice is not perturbed.

The two-planes interaction is generalized as a distributed shear stress Augmented by Long range Coulomb interaction

$$\frac{1}{2}C_x\left[(\nabla_x\varphi)^2+\beta^2(\nabla_{y,z}\varphi)^2\right]+\nabla_x\varphi\frac{1}{r_0^2\nabla^2}\nabla_x\varphi$$

Coulomb energy is very costly for charged phase variations along the chain ; hence they must be slow relative to other directions.
The DL core has the atomic width d_z and a longer length l~100A

$$l=d_z^2/\beta r_0\sim d_z\omega_p/T_p>>d_z$$

Electric field E_z is concentrated closely to the DL plane (x,y,0)
Matveenko and SB, 1992

$$E_z \sim (\Phi_0 / d_z)(l / |x|)^{1/2} \exp\left(-(z / d_z)^2 (l / |x|)\right)$$

Potential drop across the total junction width is $V_t = \Phi_0 = \pi \beta \omega_p$ per each entering DL, which determines the threshold voltage and gives the same quantization for further steps I(V)

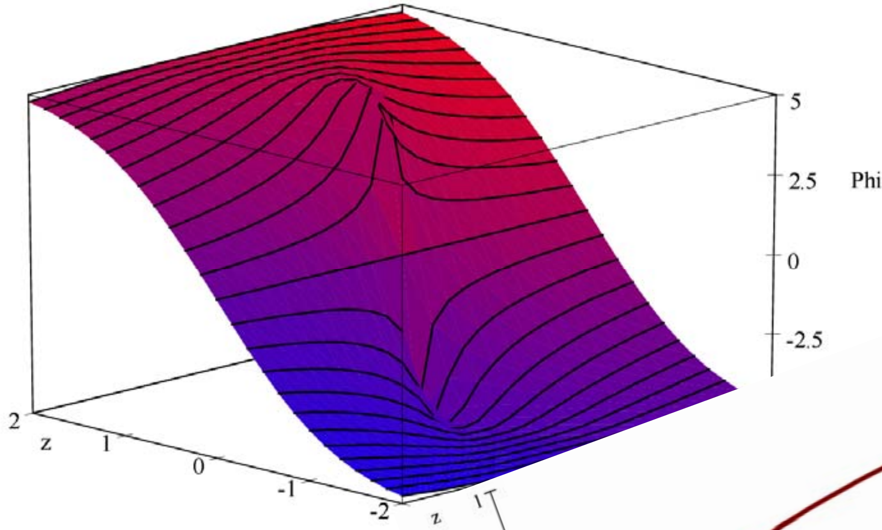
Coulomb increases the energy cost to create DLs,
but also enlarge their efficiency in building the potential:
only a few DLs are sufficient to cover the whole gap interval $|V|<2\Delta_0$

β (T) hence Φ_0(T) and finally V_t(T) have the same T dependence governed by the factor Δ(T) - in accordance with the experiment.

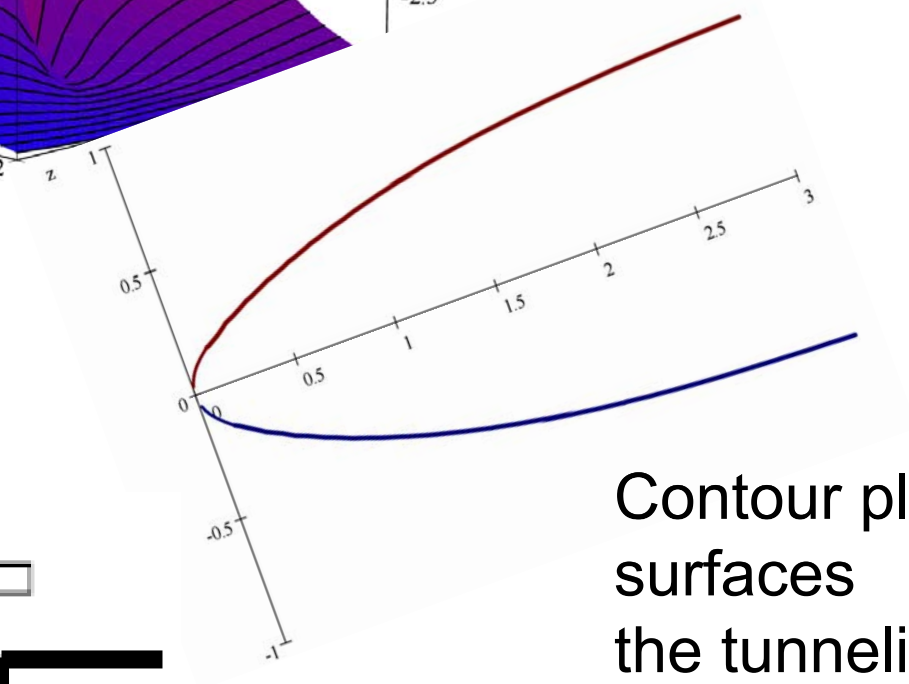
Tunneling takes place between matching points
$\pm z(x)$ of surfaces $\Phi(x,z)=\pm\Delta$.
Probability P is exponentially enhanced towards smaller x where z(x) is small, i.e. the tunneling is confined within the DL core.
Only here the potential changes fast enough
to give a short path for tunneling.

$$P \sim \exp\left(-2z(x)/d_z\right) \sim \exp\left(-2\sqrt{x/l}\right)$$

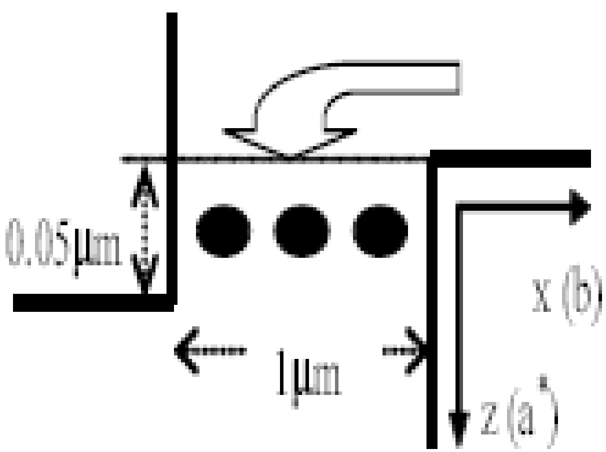
Tunneling takes place over the distance $$2z(x) \sim \sqrt{x/l}$$



Potential distribution in a DL vicinity. Notice concentration of potential Φ(x,z) drop facilitating the tunneling.



Contour plots ±*z*(*x*) for surfaces Φ(x,z)±Δ where the tunneling takes place.



Junction scheme with crossections of dislocations

Nature of the microscopic dynamical processes of tunneling at $V>V_t$.
Several plausible mechanisms can be excluded.

Special design eliminates interference with threshold for CDW sliding.

Usual tunneling through creation of e-h pairs is forbidden at $V<2\Delta$.

Dressed single electron states - "amplitude solitons",
reduce the energy Δ by 2/3, but still lye too high for $V_t/\Delta \sim 0.2$.

Contribution of normal carriers gives opposite dependence I(V) :
i. Threshold phenomenon appears when the ZBCP is suppressed;
ii. Concentration of the potential drop upon one layer can only reduce the normal current

The only remnant picture :
excess tunneling conductivity above V_t
can be only provided by the low energy phase channel.

What does tunnel at these low subgap voltages ?

Necessary energy scale: low activation energies $\mathbf{E_a \sim 200K}$ for on-chain conductivity in contrast to high $\Delta_0\mathbf{\sim 800K}$ for the transverse one.

E_a comes from $\pm\mathbf{2}\pi$ phase solitons -- stretching/squeezing of a chain by one period, $\delta\phi = \pm 2\pi$, with respect to the surrounding ones.

Contrary to their aggregated form of static dislocation lines, the solitons exist as single chain items: elementary particles with the charge $\pm\mathbf{2e}$ and the energy $\mathbf{E_s \sim}$ **3D** ordering temperature $\mathbf{T_p}$.

Their dynamic creation might be very sensitive to the threshold proximity $\mathbf{\delta V = V - 2E_s}$ and to the number $\mathbf{M = 2z/d_z}$ of chains to tunnel through: tunneling rate drops as [*Matveenko and SB 2005*]

$\mathbf{(\delta V/2E_s)^{M\alpha}}$ - index $\alpha\mathbf{\sim v_f/u >> 1}$

is big because of the low phase velocity $u << v_f$.

Outcome :

pair of 2π solitons can be created by tunneling almost exclusively within the dislocation core, which process can be interpreted as a excitation of the dislocation line as a quantum string.

Conclusions:
Specifics of strongly correlated electronic systems inorganic CDW, organic semiconductors, conjugated polymers, conducting oxides, etc…

Electronic processes, in junctions at least, are governed by solitons or more complex nonlinear configurations.

As proved by presented experiments and recent ones on charge ordered states, they can lead to :

- Conversion of a single electron into a spin solitons
- Conversion of electrons pair into the 2π phase slip
- Pair creation of solitons (tunneling and optics)
- Arrays of solitons aggregates

– dislocation lines, walls of discommensurations –

reconstruct the junction state and provide self-assembled micro-channels for tunneling;