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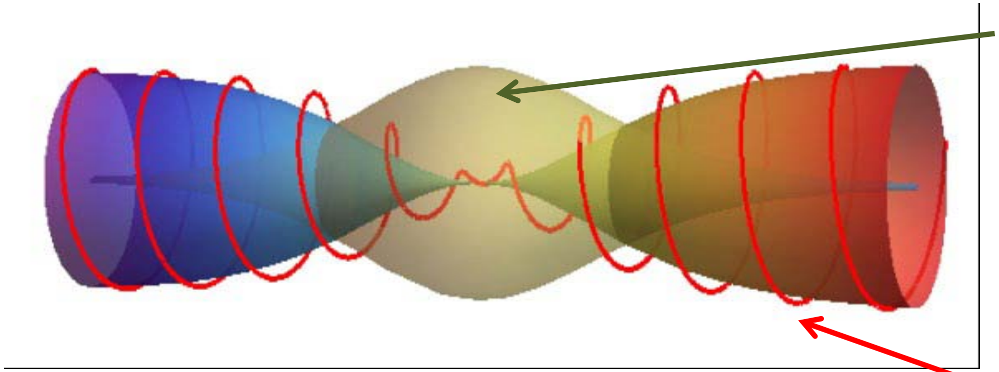
Solitons in quasi one dimensional conductors *and beyond*

Sources of this talk: Joint work with experimental groups of
Grenoble (P. Monceau), Moscow (F. Nad, Yu. Latyshev),
Orsay area (C. Brun & Z.Z. Wang; C. Pasquier & D. Jerome),
Ljubljana (D. Mihailovic), Seoul (Y.W. Park).

On theory: N. Kirova, S. Matveenko, T. Yi, ...

Modeling for the amplitude π-soliton = spinon in the CDW



Distribution of the self-trapped electron

(A, ϕ) trajectory of the CDW order parameter $A\cos(Qx+\phi)$

Solitons in correlated electronic systems:
Born in theories of late 70's, Seen in experiments of early 80's.

Why the explosion in 2000's ?
New optically active conducting polymers,
New ferroelectric charge ordering in organic conductors,
New STM and tunneling observations in Charge Density Waves.

Further expected areas:
Transformations of symmetry broken electronic phases by
IMPACTs of optical pumping and electrostatic field effect doping.

Best suited playgrounds for solitons among IMPACT studies:

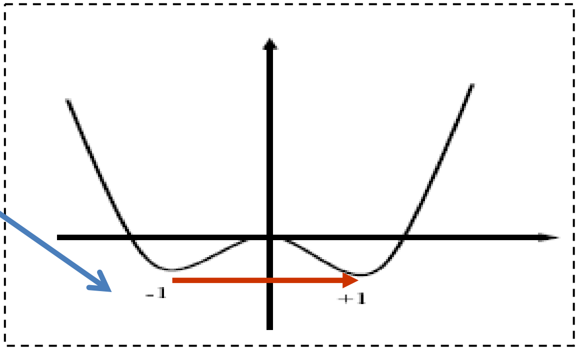
1. Charge ordering in organic materials –
   well defined 1D regime at high transition temperatures.

2. CDWs in inorganic chain and plain materials – very low
   phonon frequencies in comparison with electronic scales.

Solitons in general : propagating isolated profiles (Russel 1834) – from the tsunami wave to magnetic domain walls

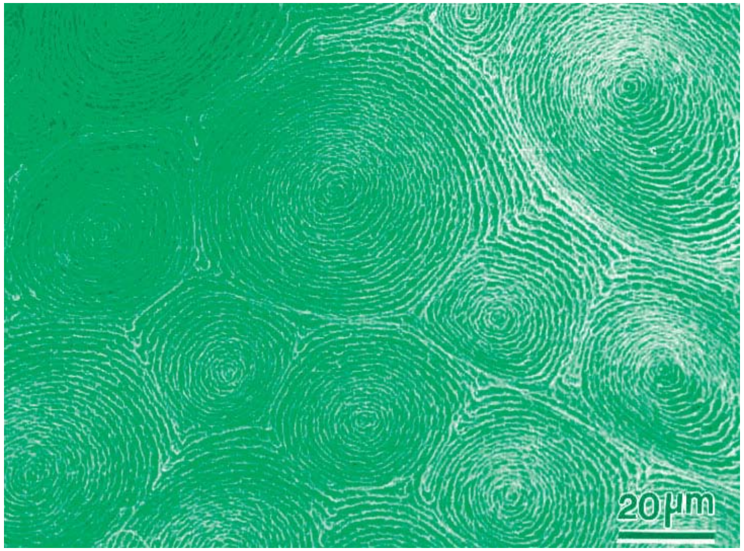
Solitons in our perspective of electronic systems :
Self-localized excitations on top of a ground state with a spontaneously broken symmetry:
superconductor, CDW, SDW, AFM .
Solitons carry a charge or a spin – separately, even in fractions.
They bring associated spectral features
(electronic mid-gap states, vibrational modes)
They give definitions of hypothetic holons and spinons in strongly correlated systems

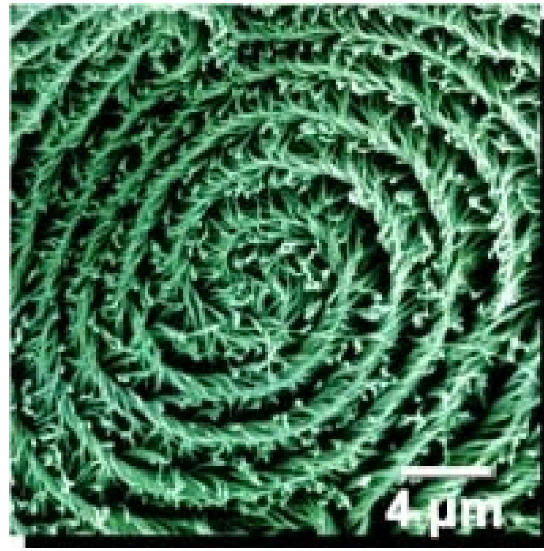
Symmetry breaking : Soliton = trajectory between equivalent states.

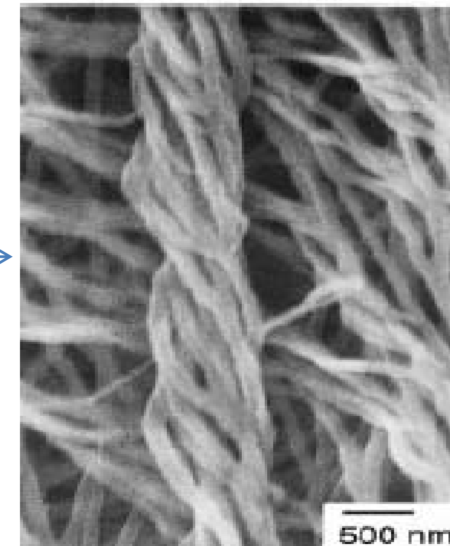


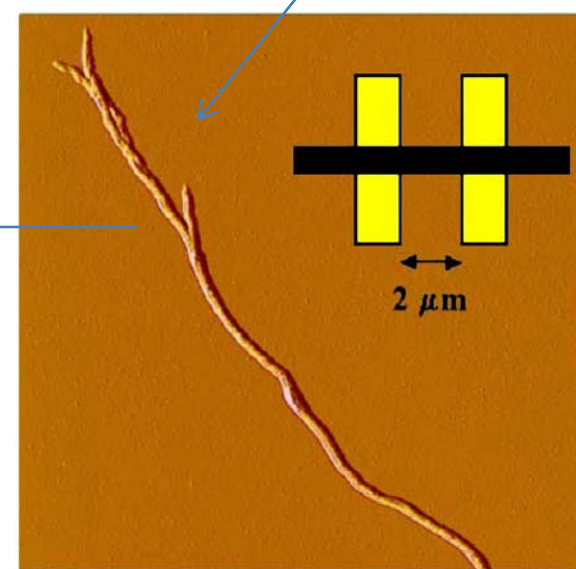
Helicoidal polyacethelene PA - multi-scale material:

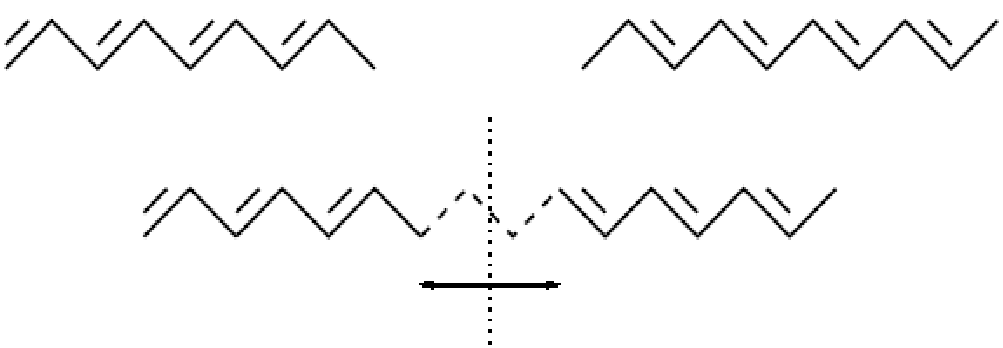
cells -> spirals -> threads -> crystalline fibers -> polymer chains -> π-electrons -> Peierls-dimerization -> solitons -> confinement



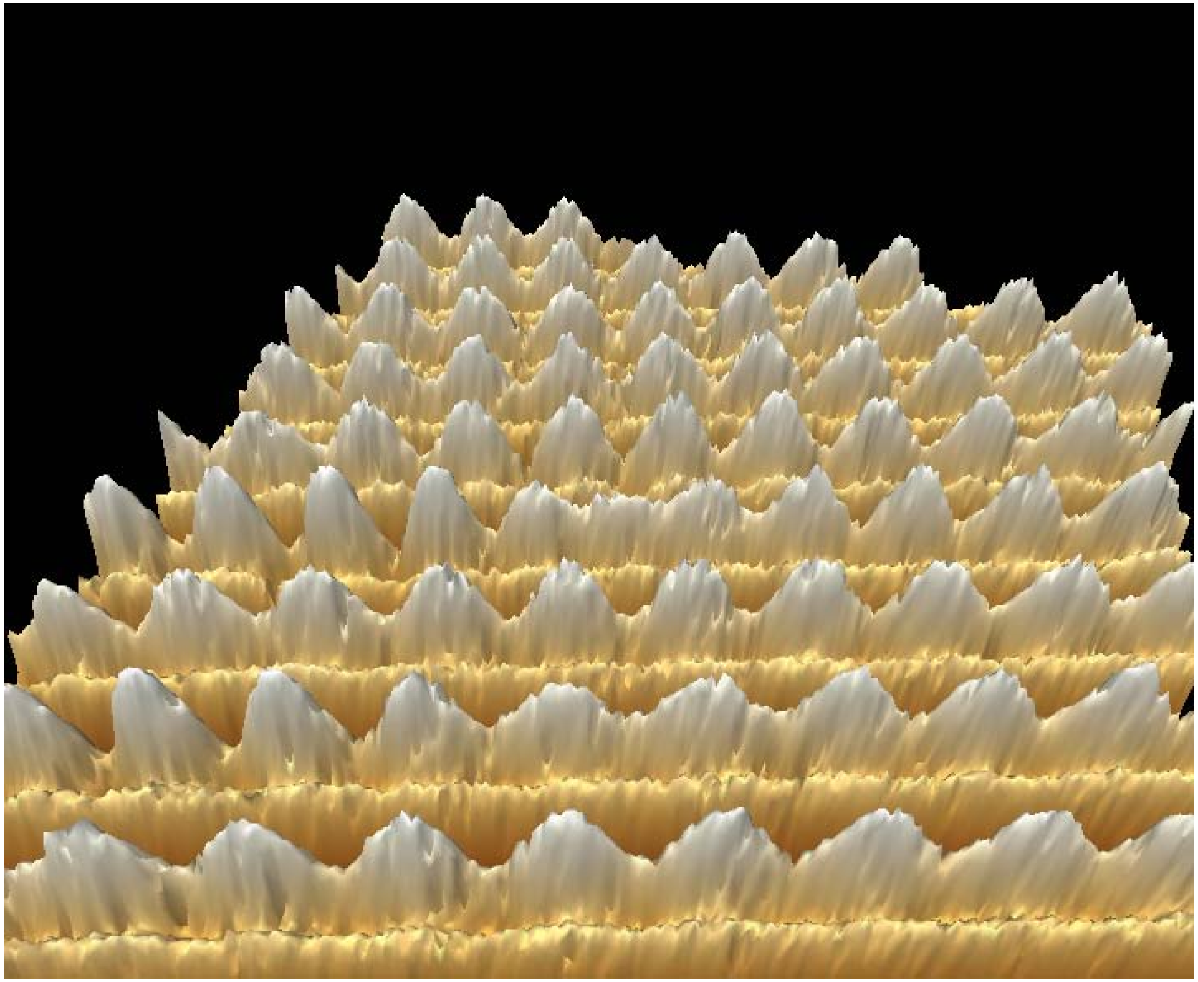








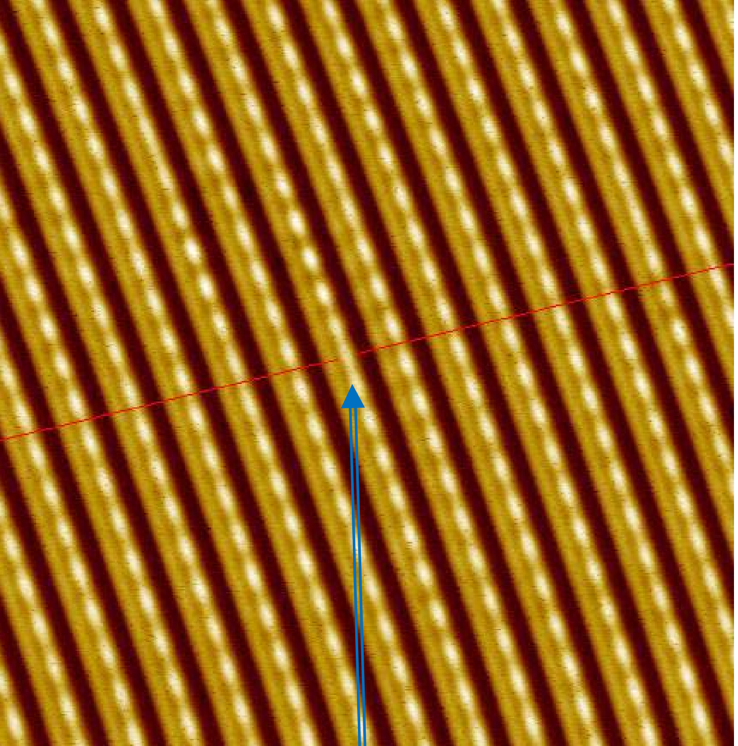
Recall the talk by Y.W. Park



Christophe Brun et al. CDW I in NbSe3

STM scan of a CDW in NbSe3, capturing the soliton

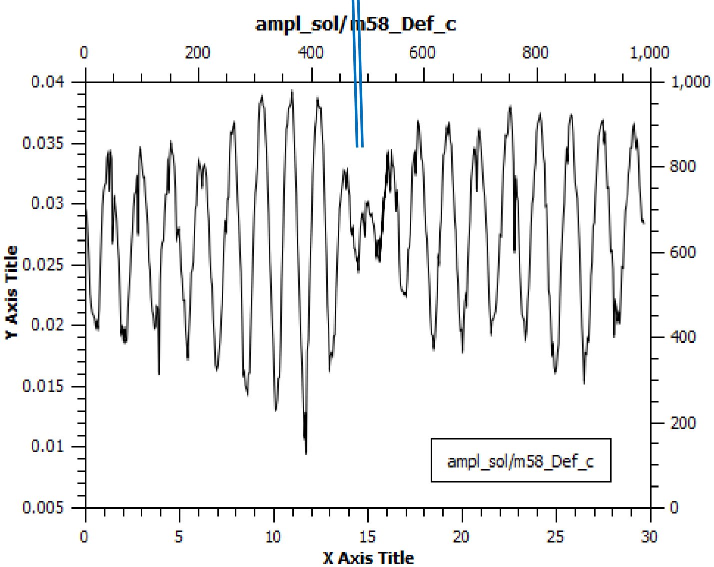
Brun, Wang, Monceau & S.B.



At the (red) front line the defected chain is displaced by half of the period.

Along this chain, the whole period **2π** is missed (or may be gained).

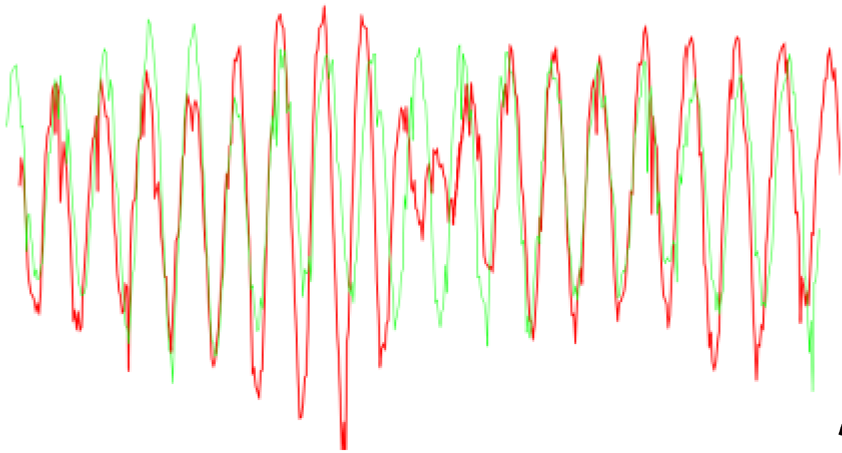
A particle with the charge -**2e** ? Not, just -**e** - might be doped by just one electron.



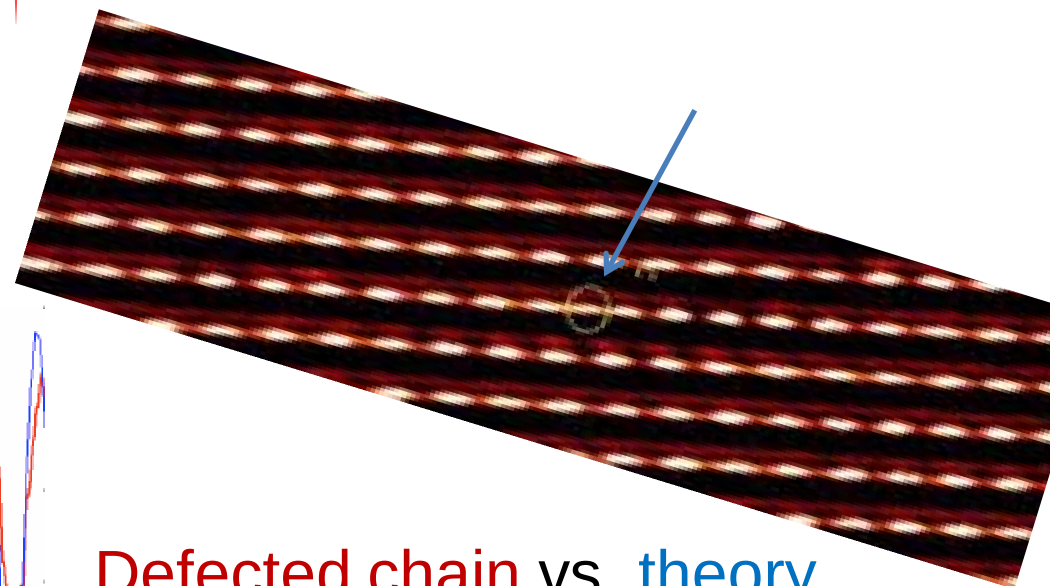
Soliton profile along the defected chain

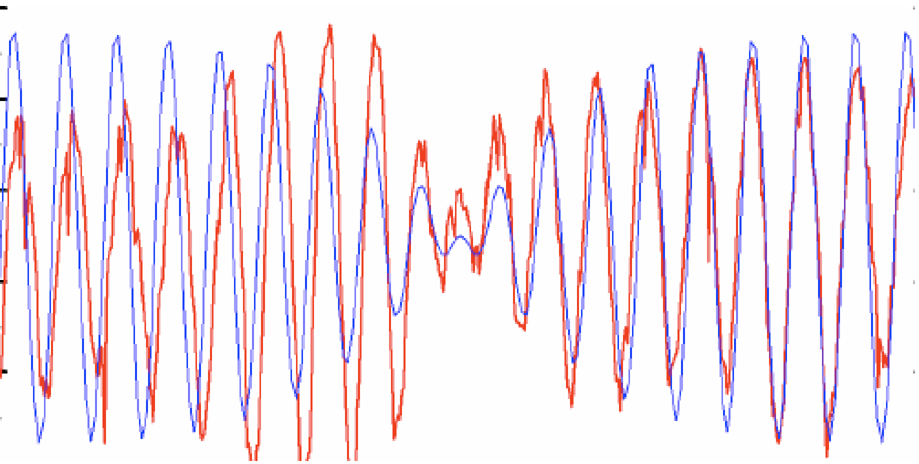
The CDW adopts itself by half a period shift and its amplitude vanishes to accommodate the electron or the hole.

One of many cases for the STM identification of amplitude solitons



Profiles along the defected chain vs its nearest neighbor





Defected chain vs theory

$$-\tanh(x/\xi)*\sin(2\pi x/\lambda+\arctan(x/l))$$

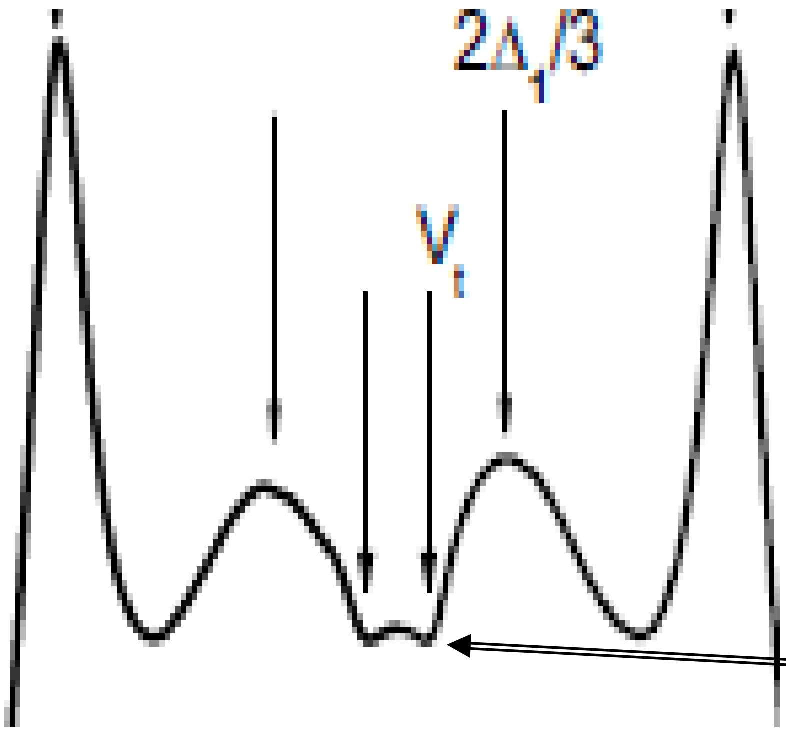
The CDW is perforated here and there by nodes of amplitude – spinons - carrying self-trapped electrons at their mid-gap states

Dynamics of solitons in tunneling experiments on $NbSe_3$

Latyshev, Monceau, Orlov, & SB *PRL 2005*

creation of the amplitude soliton at $E_s = 2\Delta/\pi$

All features scale with $\Delta(T)$!

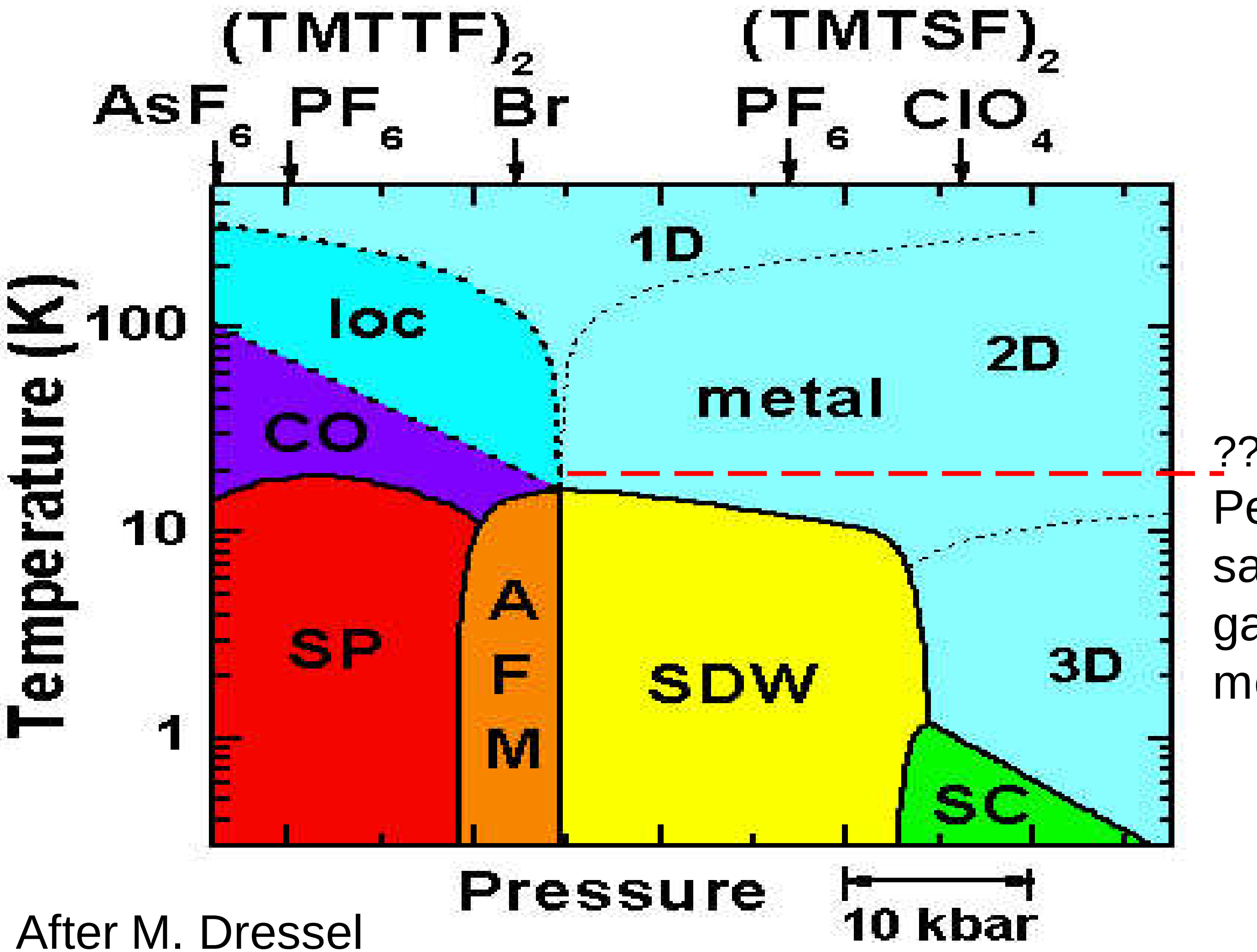


peak 2Δ for inter-gap creation of e-h pairs

absolute threshold at low $V_t \approx 0.2\Delta$ and the oscillating fine structure - ground state reconstruction:
N. Kirova and T. Yi presentations

What tunnels at the subgap voltages ? – same seen by the STM ?

Phase diagram of $(TMTCF)_2X$



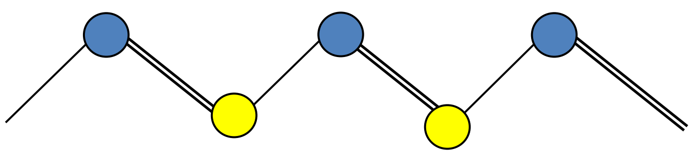
??
Persistence and saturation of the CO gap in the nominally metallic phase

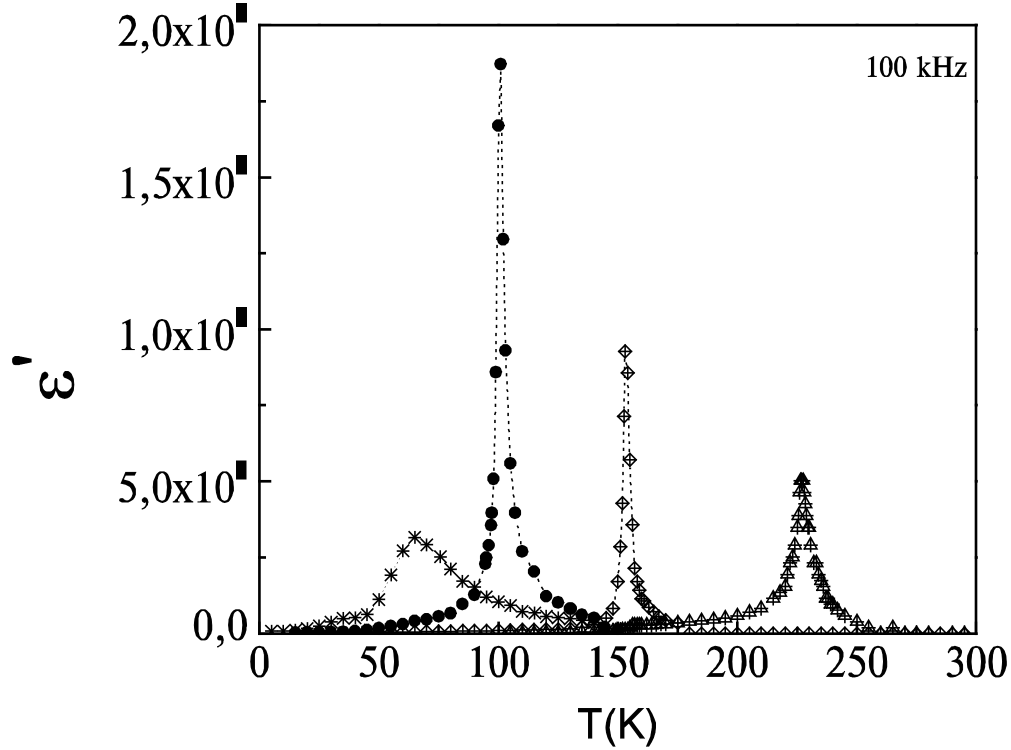
After M. Dressel

Discrete symmetry breaking – dimerizations of sites or bonds: charge disproportionation, charge ordering.

Ferroelectric anomaly ε′(T) in $(TMTTF)_2X$.
F.Nad, P.Monceau & SB - 2001.

Clear cut fitting to the Curie-Weiss-Landau law ε′(T)~1/|T-T_c| prooves the 3D ferroelectricity. Gigantic magnitude proves the unique electronic, not ionic, ferroelectric polarization.

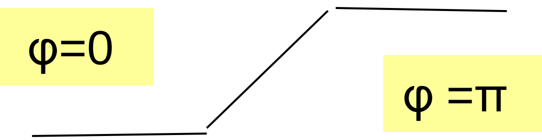




Charge ordering phase transition seen via Ferroelectricity
- anomaly in the electric polarization response ε′ -
sign of breaking inversion symmetry.
Gives rise to as many as 4 types of solitons – all observed.

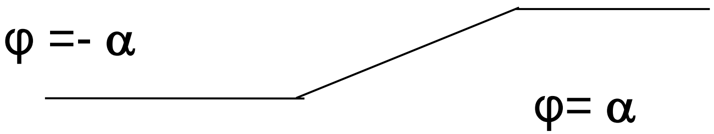
Ground state energy $\mathbf{H_U= -U\cos(2\varphi-2\alpha)}$ is doubly degenerate between $\boldsymbol{\varphi= \alpha}$ and $\boldsymbol{\varphi= \alpha+\pi}$.

It allows for phase π solitons, i.e. holons with the charge *e*.



Purely on-chain solitons, exist as conducting quasiparticles both above and below the $\mathbf{T_{FE}}$.

Spontaneous α itself can change sign between different FE domains.
Then electronic system must also adjust its ground state from α to $-\alpha$.
Hence the phase soliton : increment $\boldsymbol{\delta\varphi = -2\alpha}$,
non integer charge $\mathbf{q=-2\alpha/\pi}$ per chain.

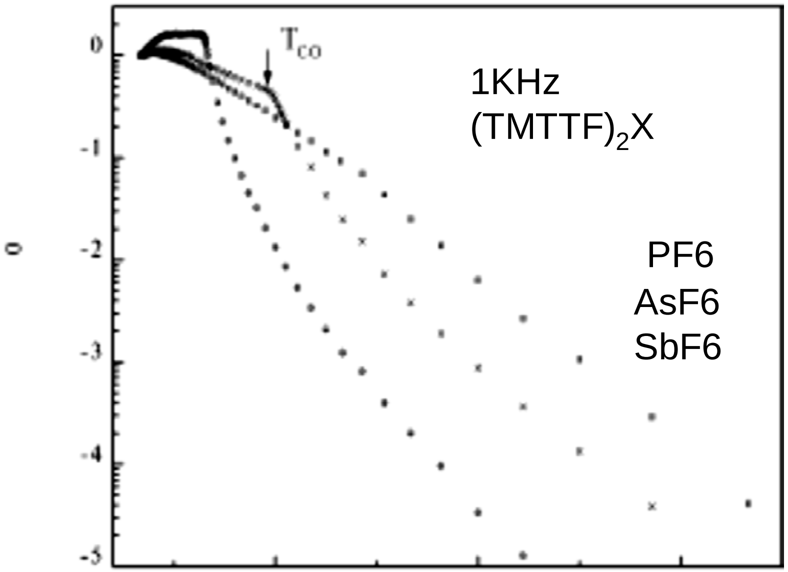


alpha- solitons are walls between domains of opposite FE polarizations

They are on-chain conducting particles only above $\mathbf{T_{FE}}$.
Below $\mathbf{T_{FE}}$ they aggregate into macroscopic walls.
They do not conduct any more, but determine the FE depolarization dynamics.

Q. Why did we invoked SOLITONS as charge carriers?

Puzzle 1. What does conduct in these “narrow gap ferroelectric semiconductors” ? NOT the electrons !



Conductance G , normalized to RT - Ahrenius plot Log G(1/T).

Gaps for thermal activation Δ range within 500-2000K.

But no gap in the spin susceptibility - $\chi(T)$ stays flat as for a metal.

The conduction by charged spinless solitons - holons.

Puzzle 2. Activation energy for interchain conductance is much bigger than the one Δ for the transport along the chains – **Solitons, as kinks, cannot jump alone between chains.**

(F. Nad for CDWs, P. Auban-Sensier et al for organics.)

Can we excite these solitons in optics?

First evidence for soltons = holons – charged spinless particles: the activated conductivity with gapless spin susceptibility

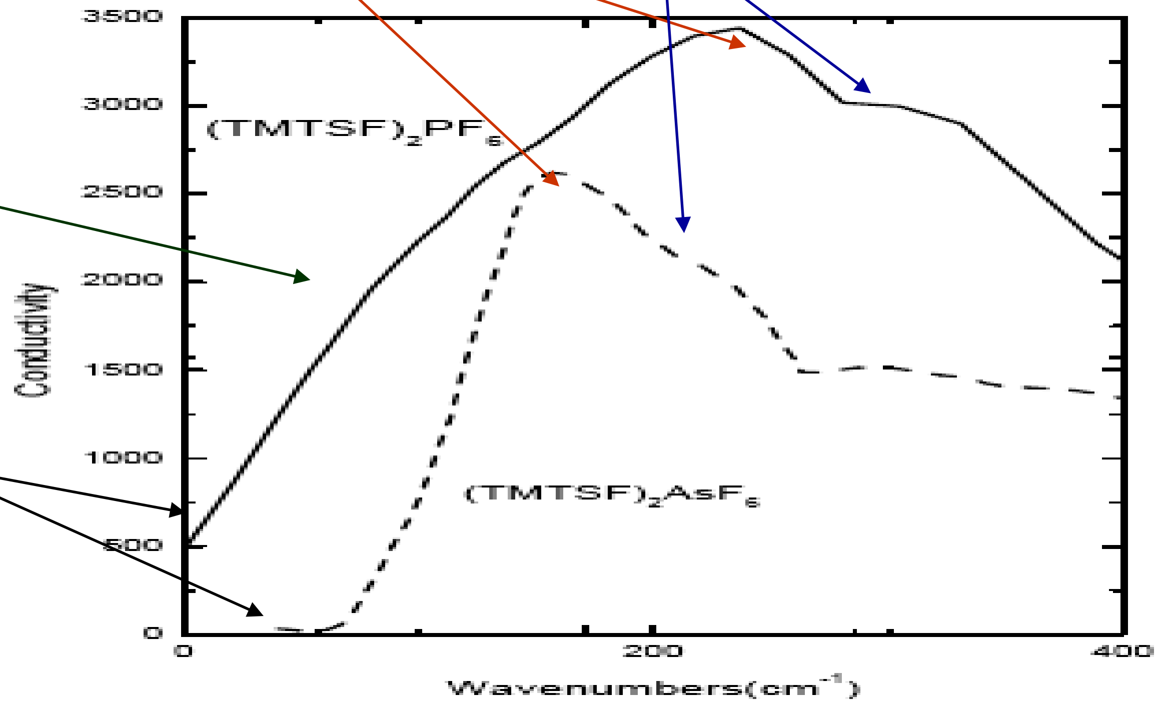
Second evidence – optical gaps, even in case of remnant metals.

Exciton = two-kinks bound state

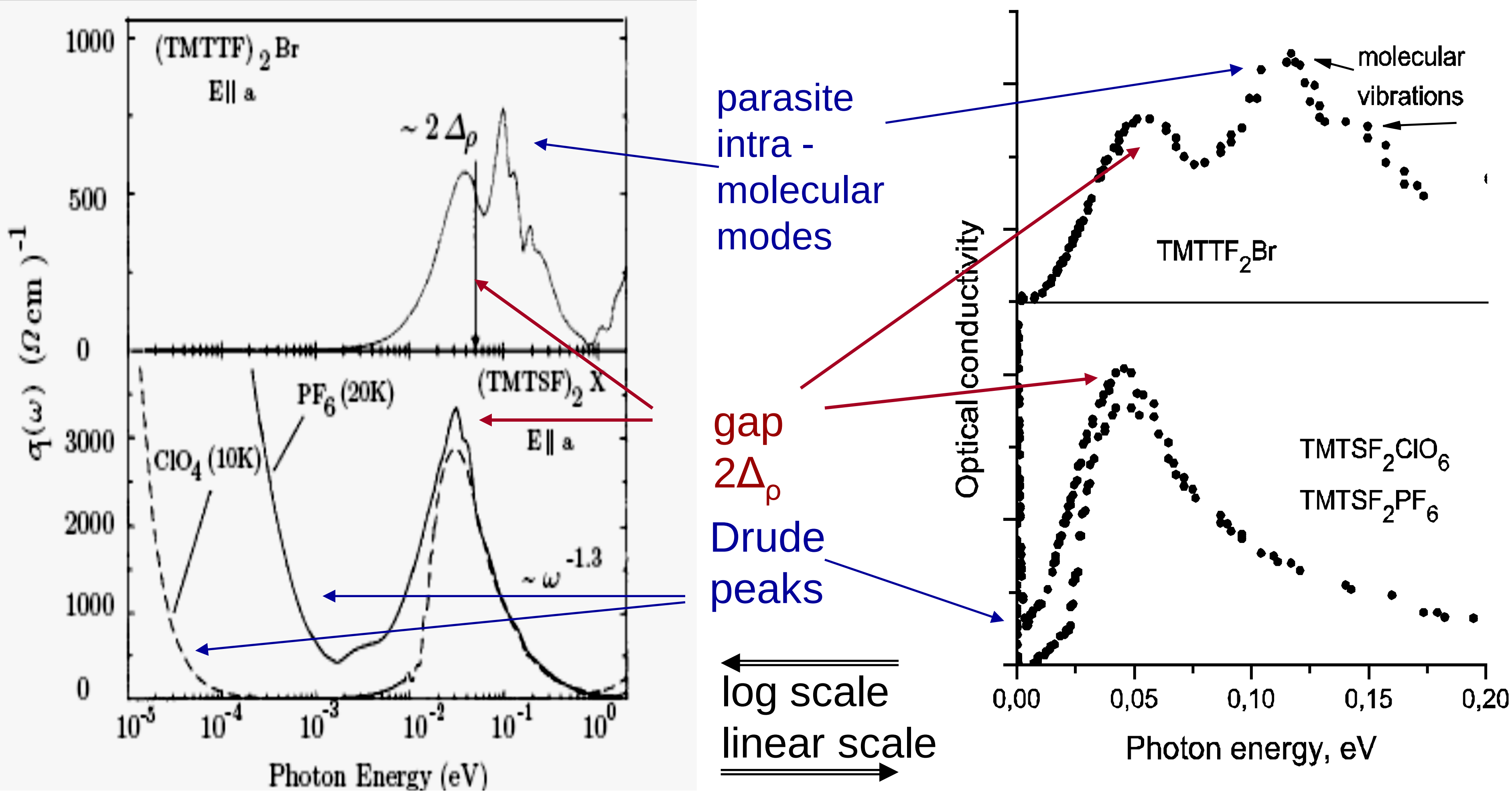
$E_g = 2\Delta$ - unbound pair of kinks

Peierls spin gap

Drude peaks



Optical conductivity (absorption): M. Dressel, L. Degiorgi et al



Comparison of optical absorption in two subfamilies:

Mott insulator TMTTF (*upper plots*) and a “metal” TMTSF (*lower plots*)

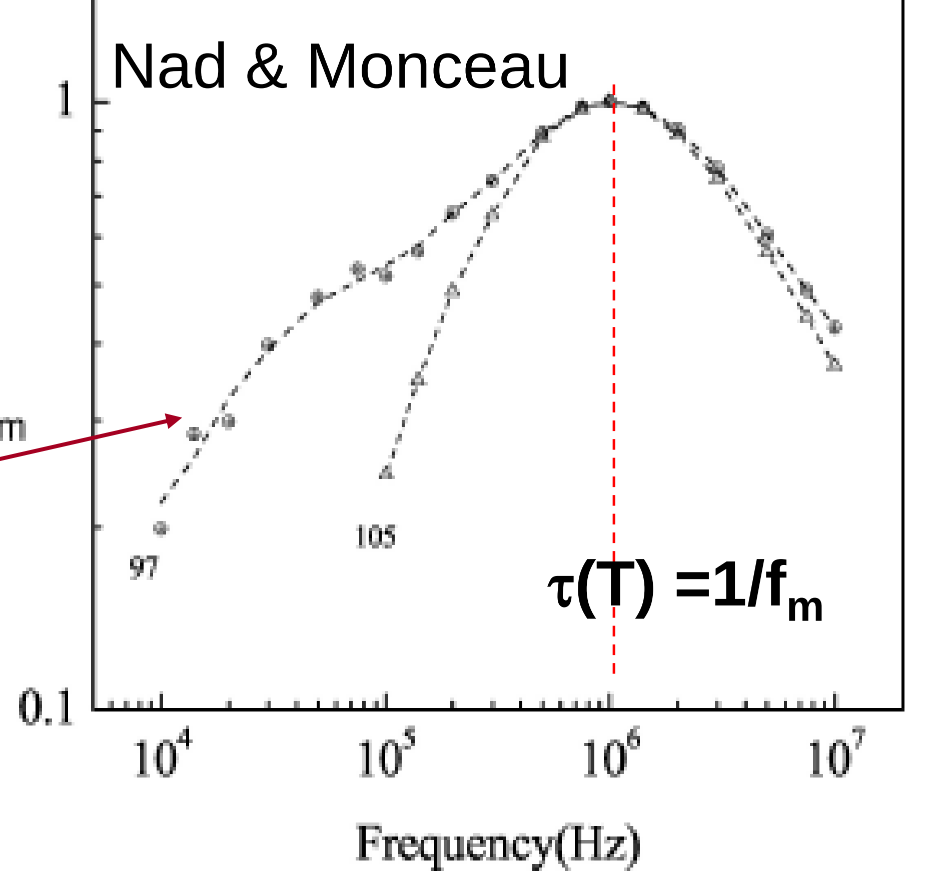
Dressel &Degiorgi

Resemblance of static (TMTTF) and fluctuational (TMTSF) Mott states

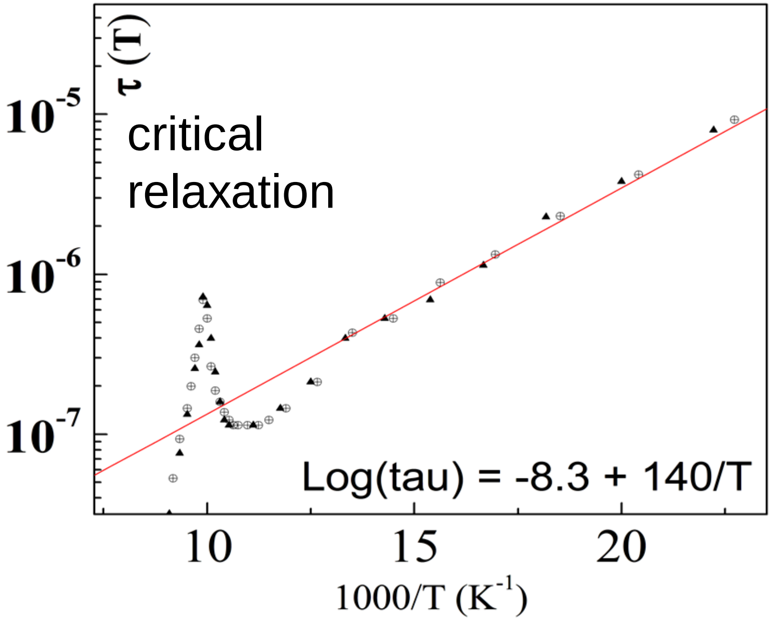
Only the weakest CO in Bromine allows to see the expected gap.

Photoconductivity may be a tool for other cases, c.f. polymers

$\varepsilon''(f)$ curves at two temperatures around T_c=102K, above - 105K and below - 97K.



Low frequency shoulder – only at T<Tc : pinning of FE domain walls i.e. hidden hysteresis ?

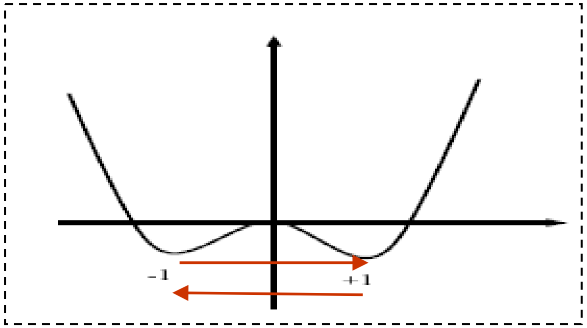


Perfect low T activation law. Activation energy Δ_τ**=322K** well correlates with the conductivity activation Δ_σ**≈350K** ➔ ferroelectric polarization dissipates via charge carriers - spinlesss solitons (holons).

Puzzle and inspiration of experiments on CDWs:
amplitude solitons has been observed within
the 3D long range ordered phase at $T<T_c$

Obstacle : ***confinement – self-mapping of the order parameter***

Changing the minima on one chain would lead to
a loss of interchain ordering energy ~ total length.
Need to activate other modes to cure the defect !



FINITE TEMPERATURE, ENSEMBLES OF SOLITONS, PHASE TRANSITIONS OF CONFINEMENT AND AGGREGATION. DISCRETE SYMMETRY only.

Fatal effect upon kinks: global lifting of degeneracy, hence confinement.

Nontrivial but still spectacular:

local lifting in the state with long range order.

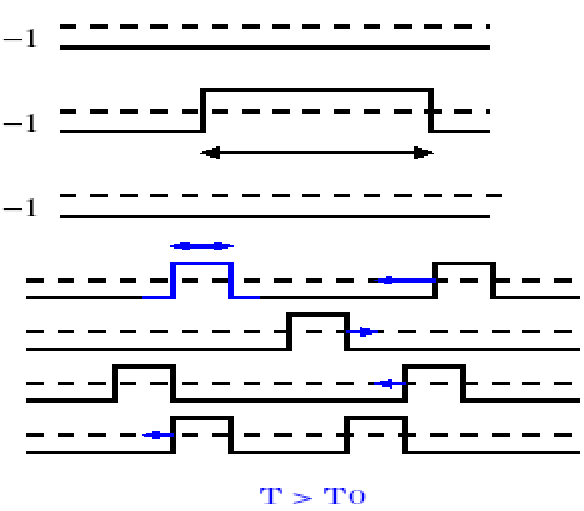
Interchain coupling of the order parameter.

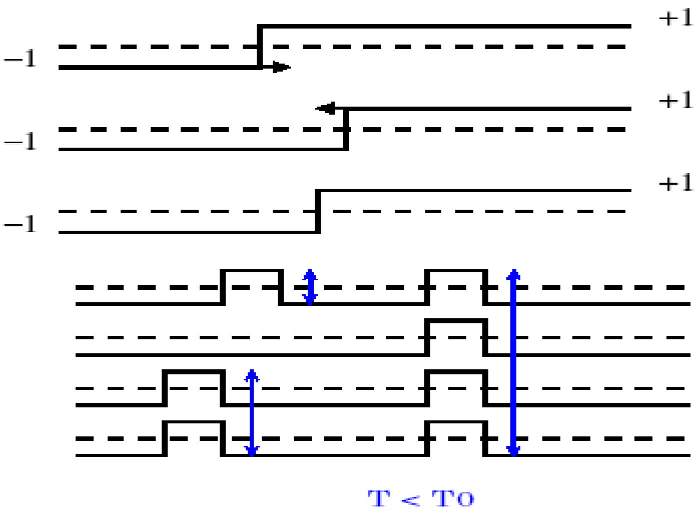
Two competing effects:

$$H_I = -\sum_{<\alpha,\beta>} \int dx V_\perp \Delta_\alpha(x) \Delta_\beta(x)$$

Binding of kinks into pairs at $T<T_c$;

Aggregation into macroscopic domain walls at $T<T_0<T_c$.





Solution for a statistical model *T. Bohr and S.B. 1983, S.Teber et al 2000's*

Unifying observation for SCs, CDWs, SDW,AFM:
combination of a discrete and continuous symmetries

Complex Order Parameter **O= A exp[iφ]** ; **A** - amplitude , φ - phase

Ground State with an odd number of particles:

In 1D - *Amplitude Soliton* **O(x=-∞) ⇔ - O(x=∞)**

performed via **A ⇔-A** at arbitrary φ=cnst

Favorable in energy in comparison with an electron, but:

Prohibited to be created dynamically even in 1D

Prohibited to exist even stationary at D>1

RESOLUTION – Combined Symmetry :

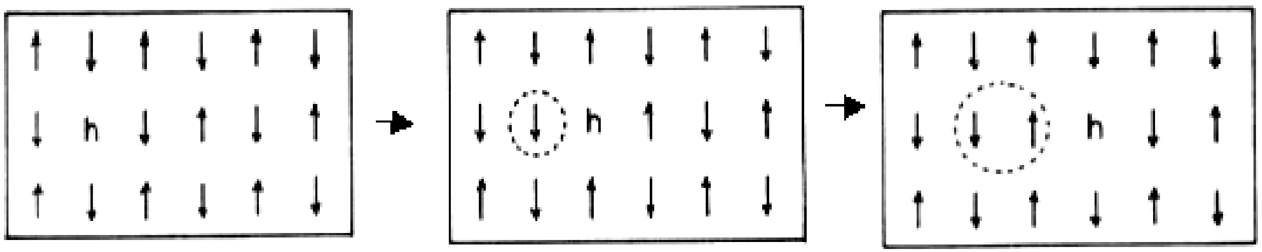
A ⇔-A combined with **φ→ϕ+π** – phase wings =

semi-vortex of phase rotation -

compensate for the amplitude sign change

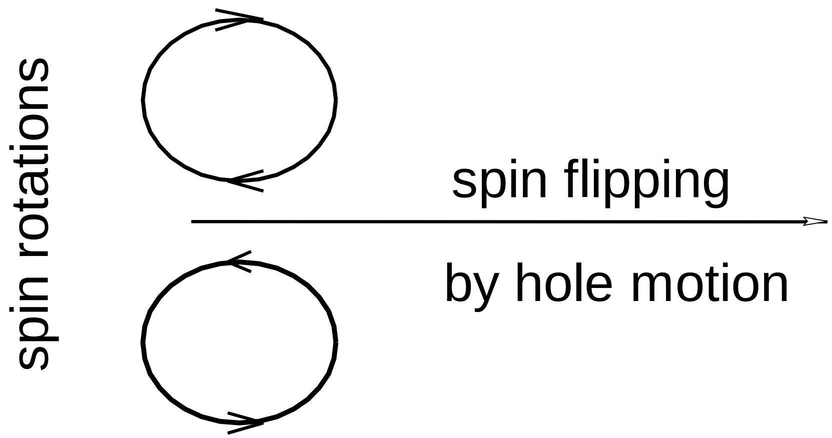
Propagating hole as an amplitude soliton.

Its motion permutes AFM sublattices ↑,↓
creating a string of the reversed order parameter:
staggered magnetization.   It blocks the direct propagation.



Bulaevskii, Khomskii, Nagaev. Brinkman and Rice.

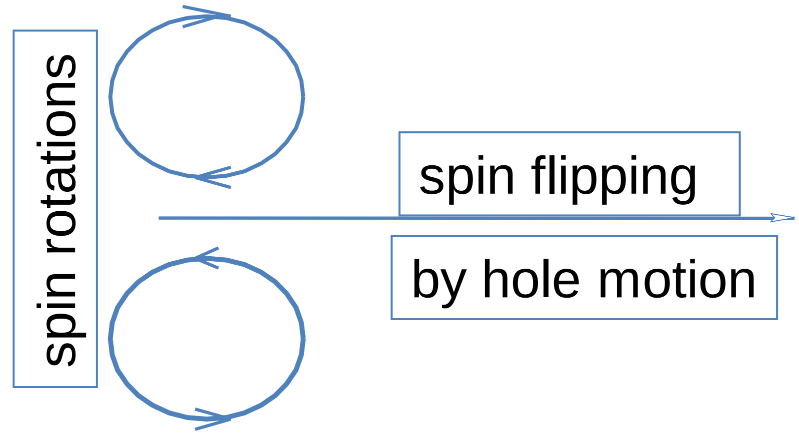
Adding the semi-vorticity to the string end heals the permutation thus allowing for propagation of the combined particle.



Alternative view:
Nucleus of the stripe phase or the minimal element of its melt.

Half filled band with repulsion.
SDW rout to the doped Mott-Hubbard insulator.

$$H_{1D} \sim (\partial\varphi)^2 - U\cos(2\varphi) + (\partial\theta)^2$$



U - Umklapp amplitude
(*Dzyaloshinskii & Larkin ; Luther & Emery*).

φ - chiral phase of charge displacements

θ - chiral phase of spin rotations.

Degeneracy of the ground state:

$\varphi \rightarrow \varphi+\pi$ = translation by one site

Staggered magnetization $\equiv$ *AFM=SDW order parameter:*

$O_{SDW} \sim \cos(\varphi)\exp\{\pm i(Qx+\theta)\}$, amplitude $A = \cos(\varphi)$ changes the sign

To survive in D>1 : The π soliton in φ : $\cos\varphi \rightarrow -\cos\varphi$
enforces a π rotation in θ to preserve O_{SDW}

Bulaevskii, Nagaev, and Khomskii. Brinkman and Rice

Propagating hole as an amplitude soliton.
Its motion permutes AFM sublattices $\uparrow,\downarrow$
creating a string of the reversed order parameter: staggered magnetization.
It blocks the direct propagation unless the 180 rotation is added.

SUMMARY

- Existence of solitons is proved experimentally in single- or bi-electronic processes of CDWs in several quasi 1D materials.
- They feature self-traping of electrons into mid-gap states and separation of spin and charge into spinons and holons, sometimes with their reconfinement at essentially different scales.
- Topologically unstable configurations are of particular importance allowing for direct transformation of electrons into solitons.
- Continuously broken symmetries allow for solitons to enter D>1 world of long range ordered states: SC, ICDW, SDW.
- Solitons take forms of amplitude kinks, topologically bound to semi-vortices of gapless modes – half integer rotons.
- These combined particles substitute for electrons certainly in quasi-1D systems – valid for both charge- and spin- gaped cases
- The description is extrapolatable to strongly correlated isotropic cases. Here it meets the picture of fragmented stripe phases.