LOCAL PINNING, METASTABILITY, SLIDING: CHARGE and SPIN DENSITY WAVES

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LOCAL PINNING, METASTABILITY, SLIDING: CHARGE and SPIN DENSITY WAVES

in light of

Larkin legacy in science of pinning.

Minnesota Memorial conference
Anatoli Larkin 1932 – 2005

Background :
Collaboration with Larkin at random meetings through 1993-1999
Grenoble, Rehovot, Minneapolis, Trieste, Moscow

What's new today ?
Experimental proofs :
Thorne (Cornell) , Miyano and Ogawa (Tokyo)
Relations to other theories: T. Nattemann and S.B. review 2003
Experimental (Thorne; Monceau, …,S.B.)
and theoretical (Kirova and S.B.) progress in plastic flows.

TOPICS:

Plastic deformations and topological defects.
Solitons in quasi 1d system.
Local Metastable States.
Dislocation loops: generation, divergence, grouth.
Kinetics and relaxation, velocity – force v-f characteristics.
Quantum effects.
Linear response.
Ensemble averaging of pinning forces.
Interference of local and collective pinnings.
Applications to Density Waves.
Nonlinear f(v) == voltage-current relation.
Low T low ω susceptibility peak.

Incommensurate Charge (Spin)Density Wave – CDW

-- simplest sliding crystal

$$\cos(\vec{q}\vec{r} + \varphi(r,t))$$

CDW specific versus universal notations:

currnt	I	–	velocity	$v = \partial\phi/\partial t$
electric field	E	–	driving force	f
phase	ϕ	--	displacement	u
susceptibility	ε	--	response	$\delta\phi/\delta f$

Energy -- elastic, pinning, driving :

$$\int d\vec{r}\left[\frac{1}{2}C(\nabla\varphi)^2 - \sum_i V\cos(\varphi(r_i) - \theta_i) - E\varphi\right], \theta_i = -\vec{q}\vec{r}_i$$

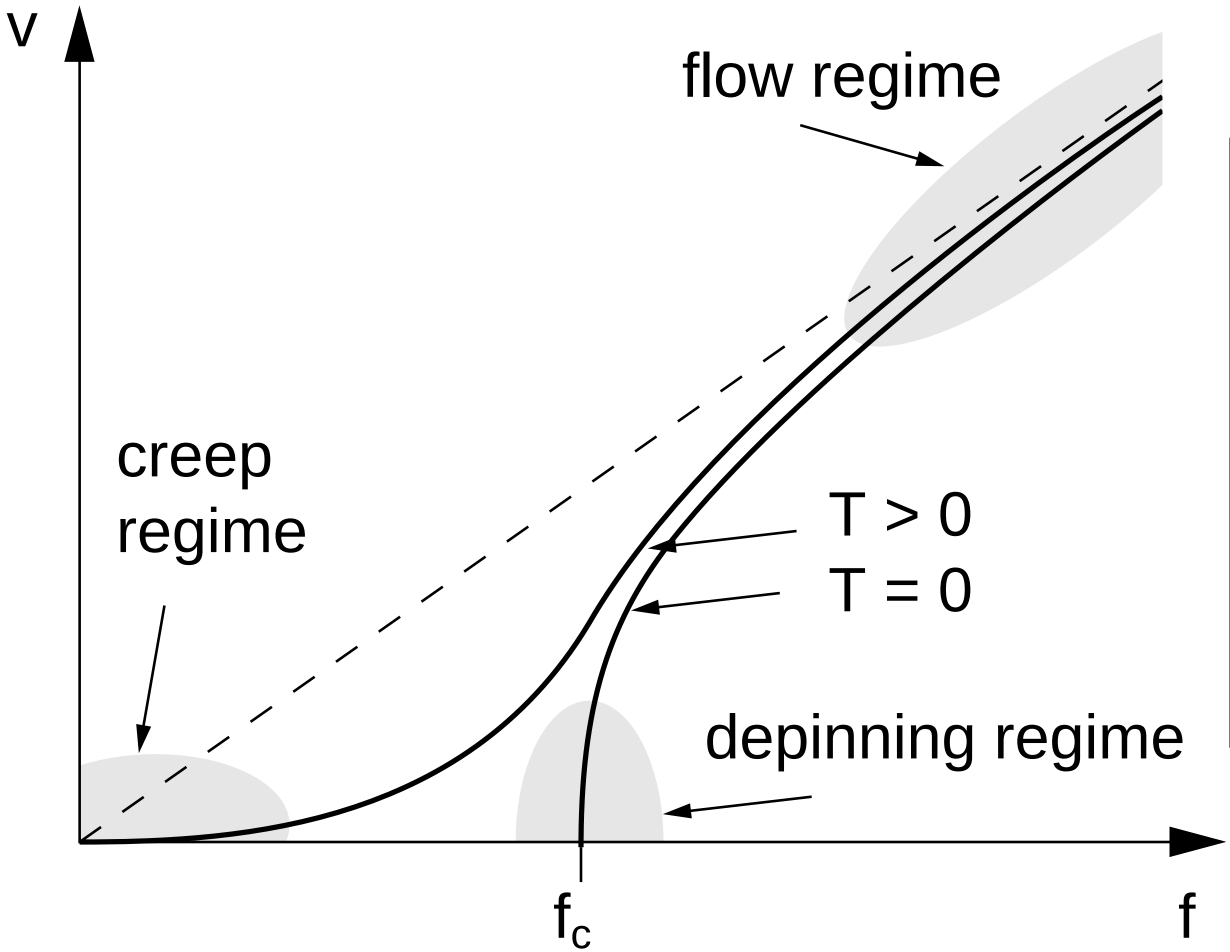
Implying the periodicity mapping $\phi = \phi + 2\pi$

Facilities: T-Tc dependencies of parameters C,V, etc (FLR);

Comparison of CDWs and SDWs (Maki)

Coulomb hardening of C at low T (Larkin with Efetov and S.B.)

Traditional expectations for the velocity – driving force dependence

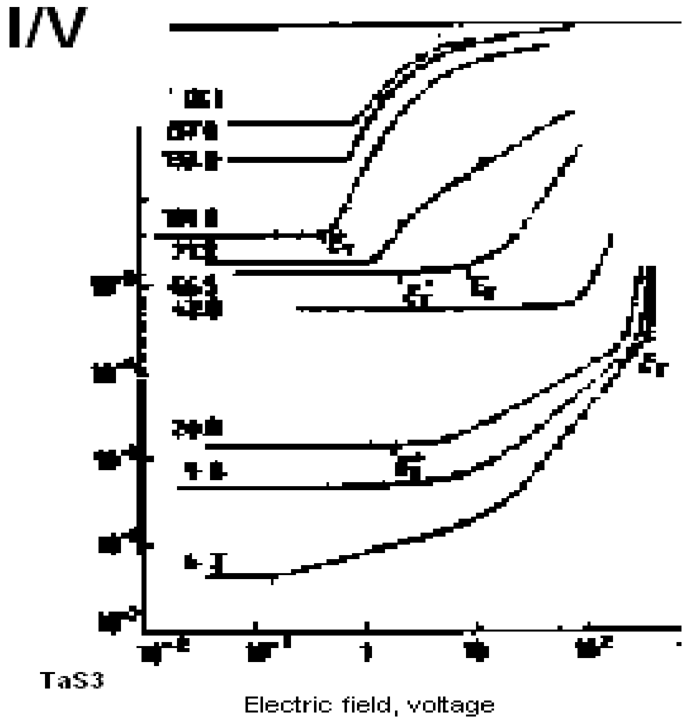


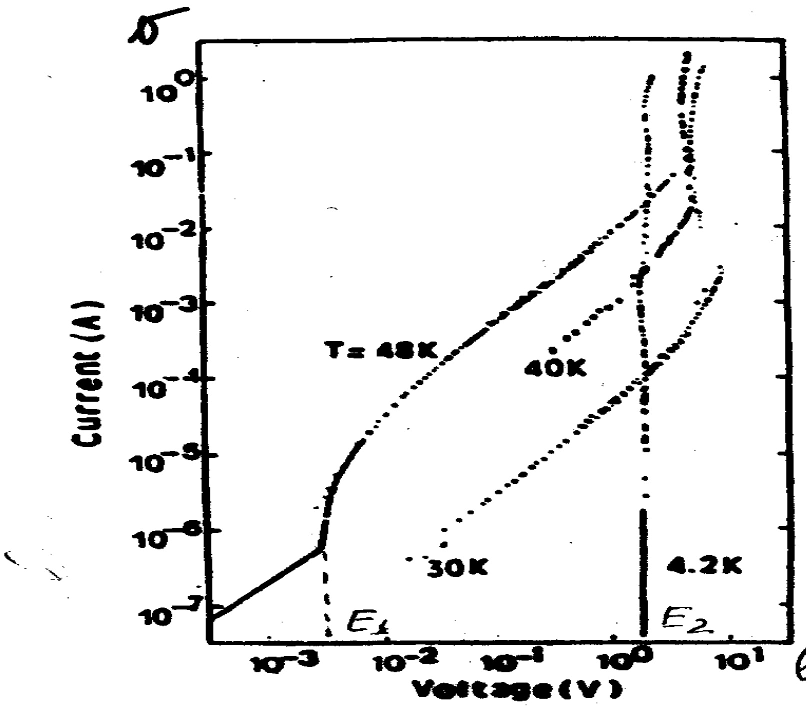
Empirical assignment :
Negative curvature – collective pinning, smooth sliding.

Positive curvature – creep = relaxation of metastable states

Surprises of sliding I-V characteristics at low T:
Second critical field E_2 , Overall curvature change.

TaS3 *M. Itkis et al* ~1992   Blue Bronze *G.Mihaly* ~ 1982





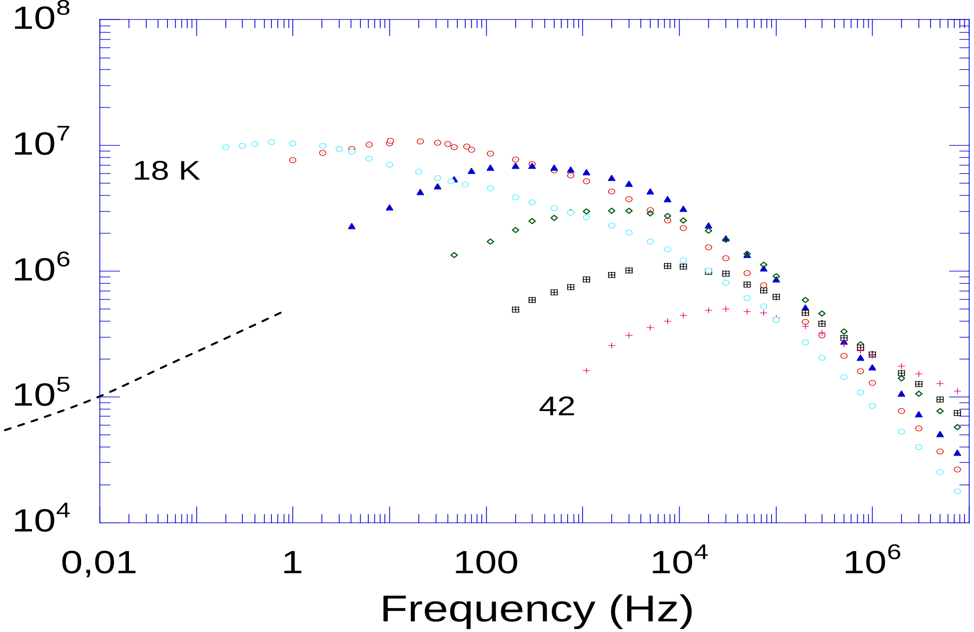
Recent clarifications (*Thorne et al 02, ;* Ogawa, Miyano, S.B. 04)

linear law $I \sim E$ at small E ;

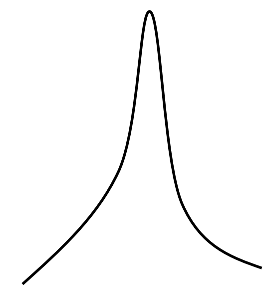
exponential growth $I \sim exp[E]$ until E_2

E_2 is a steep but resolved crossover.

Depolarization or heat response
- hours, days

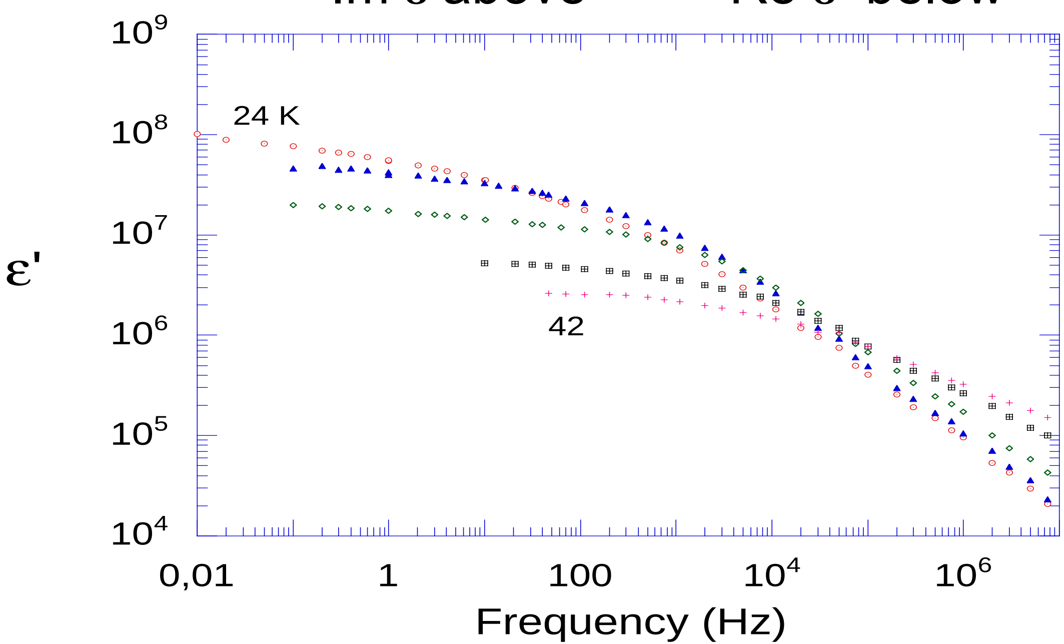


10^{10} Hz – local pinning mode

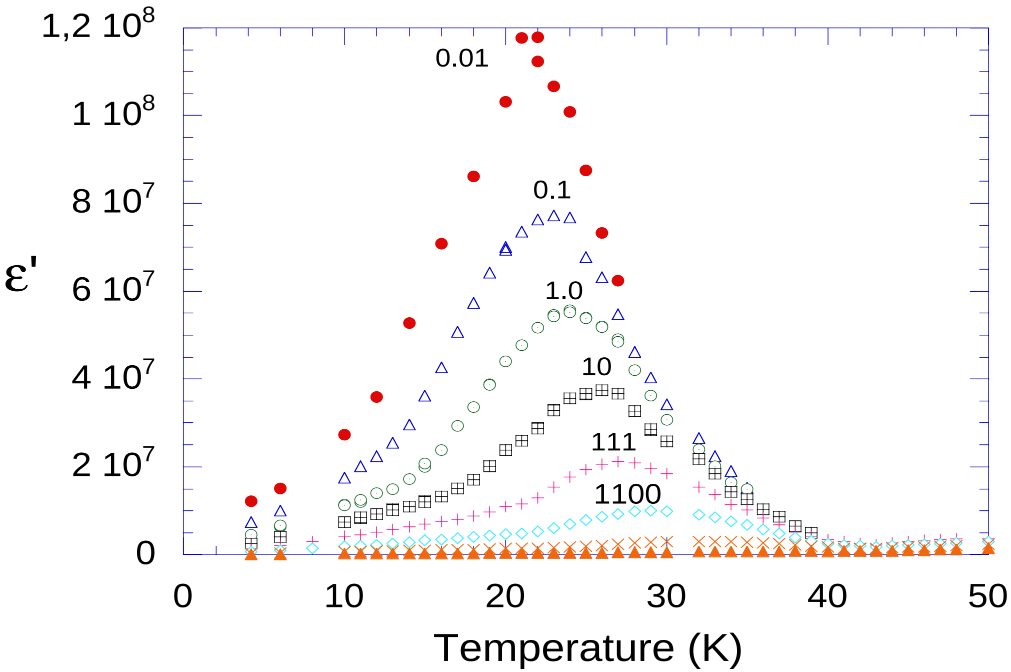


Glassy dissipation through the response function in CDWs.

– Im ε above – Re ε below



Surprises of the response function.
Real part ε' of the dielectric permittivity
as a function of T at different ω :



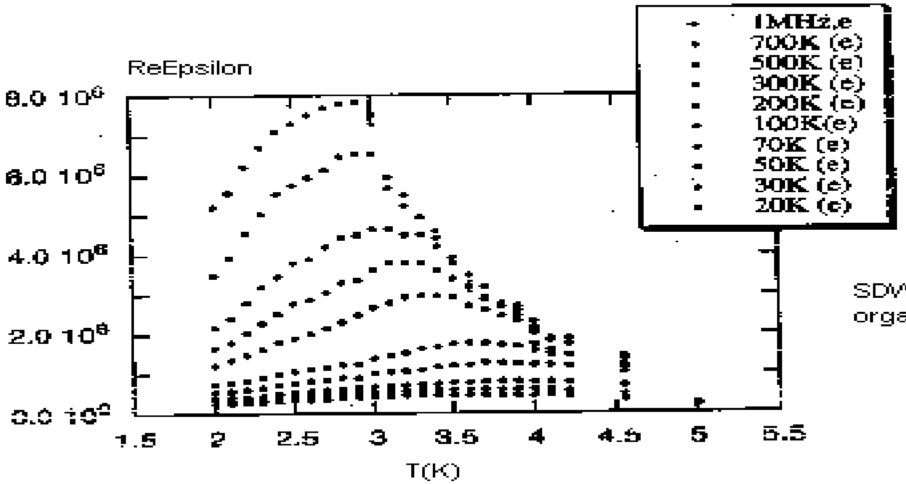
Ong, Nad, Beljakovic , …
since 1993
Universal for most of CDWs and SDWs

Here :
Experiments on Blue Bronzes.

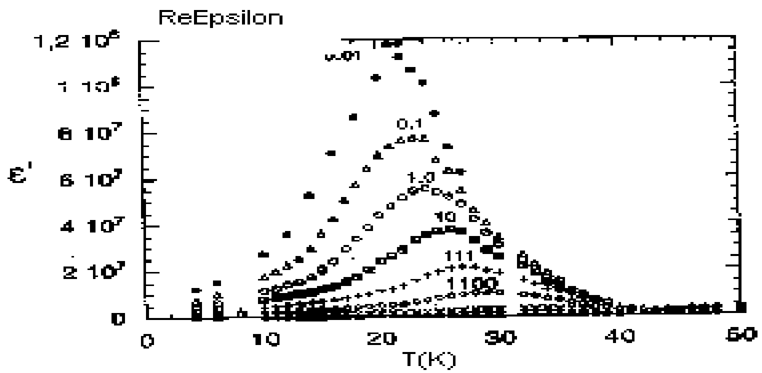
Dramatic non monotoneous T dependence
First glance Larkin hints:

- Master curve at the high T slope – too high barriers
- Strong ω dispersion at the low T slope – accessible relaxation rate

Universality of the temperature peak :
Examples of another CDW compound TaS_3 and of a SDW case in an organic metal. *F.Nad, P.Monceau et al.*



SDW case in organic compound



CDW case, TaS3

Promise for applications:

To fit quantitatively, within the same set of parameters:
the *I-E* dependence over several orders of magnitude of *I*
encompassing three different regimes of
the theory versus experiment.

To model the temperature anomaly in the response function ε.

Common CDW/SDW=DW experience:

High $T \approx T_c$ - general predictions of the collective pinning *for T=0*
are well fulfilled: $f_c \propto 1/\Re\varepsilon \sim n_i^2$

$f_c(T-T_c)$ corresponds to $T-T_c$ dependence of elastic moduli;
$v(f)$ saturates to the linear law $v \sim f$ at high v.

Drastic change at $T \ll T_c$: *R. Thorne, ECRYS-02, review*

Usual sliding threshold $f_c = f_1$ drops down, even below observations;
Sharp upturn in $v(f)$ at second threshold field f_2.
Overall v-f curvature is opposite to high T one --
and to expectations of the collective pinning.

ε becomes ω and T dependent:

$Im\varepsilon = \varepsilon_2$ -- maximum as a function of ω

$Re\varepsilon = \varepsilon_1$ - sharp peak as a function of T

Still at lowest T the collective pinning renters at ultra low ω
as a time delayed heat response -- no thermodynamics at all!
(K.*Beljakovic, et al*). Convergence to usual glass physics.

COLLECTIVE / WEAK versus LOCAL / STRONG types of pinning
Larkin,Ovchinnikov / Fukuyama,Lee,Rice

COLLECTIVE pinning =CP:
Elastic interference of many impurities.
Its characteristic features:
Small : critical field $E_1 \propto 1/\varepsilon$
Large : response $\varepsilon \sim L_2$,
correlation volumes and barriers *Vb* between MS
Huge: relaxation times $\tau \sim \exp(V_b/T)$

Collective pinning is dramatically affected by anomalous *T* dependence of the DW elasticity -
effect of long range Coulomb interactions ≡
incompressibility of the DW as an Electronic Crystal –
monitored by thermally activated normal screening;
it leads to low *T* release of the collective pinning.

LOCAL pinning =LP:

Rare metastable centers $\rightarrow$
Finite barriers $\rightarrow$
reachable relaxation times τ.

Local pinning is an easy source of
ω dispersion,
relaxation and dissipation;
it releases at low ω or v .

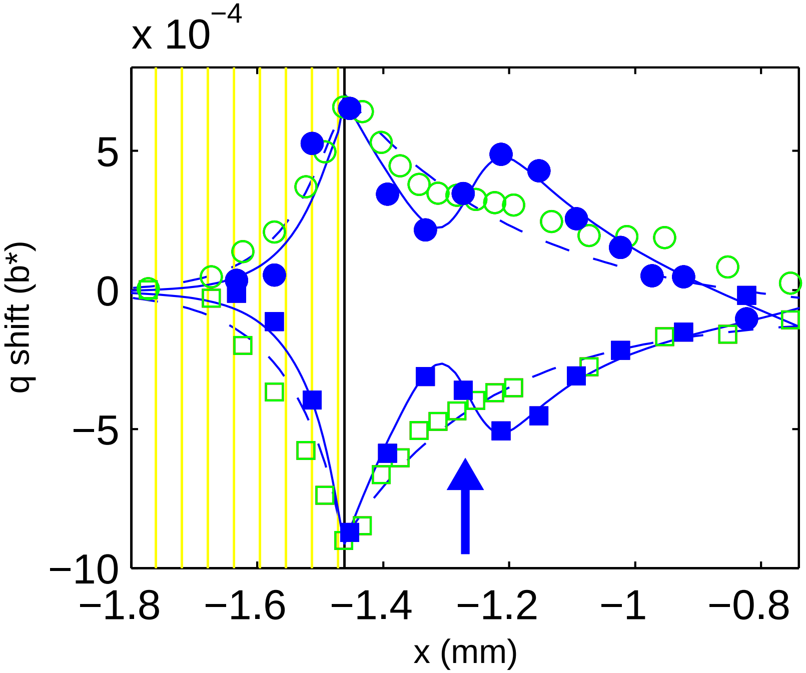
LP is a easy route to plastic deformations.
LP transfers creep from low to high velocities.

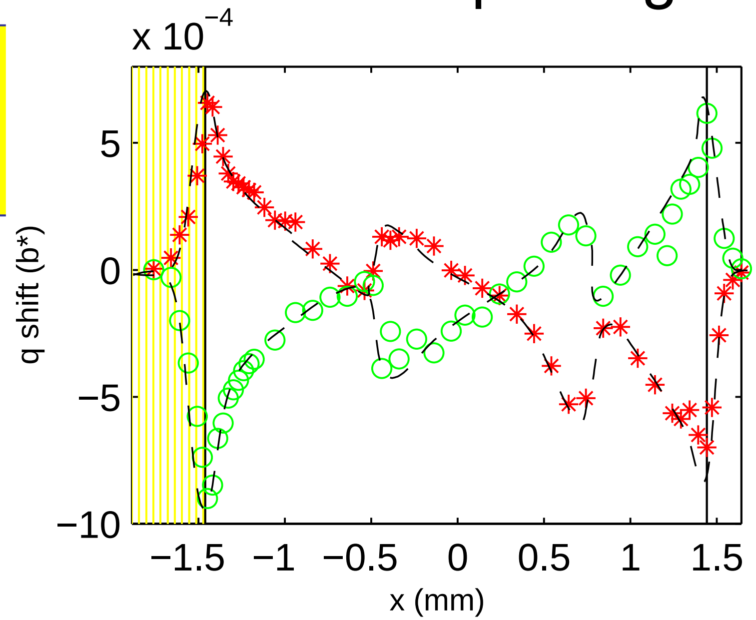
Local pinning does not show up at high T :
barriers U cannot be higher than Tc,
relaxation is too fast for any observations.

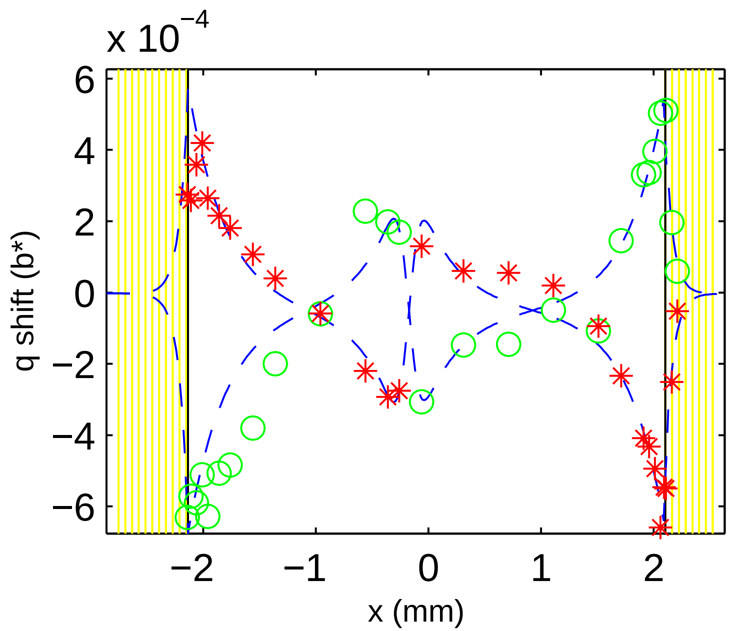
LP major drawback: lack of an intrinsic random distributions.

Pinning and plasticity at makroscopic scales.
CDW flow throw a crossection with an enhanced pinning force

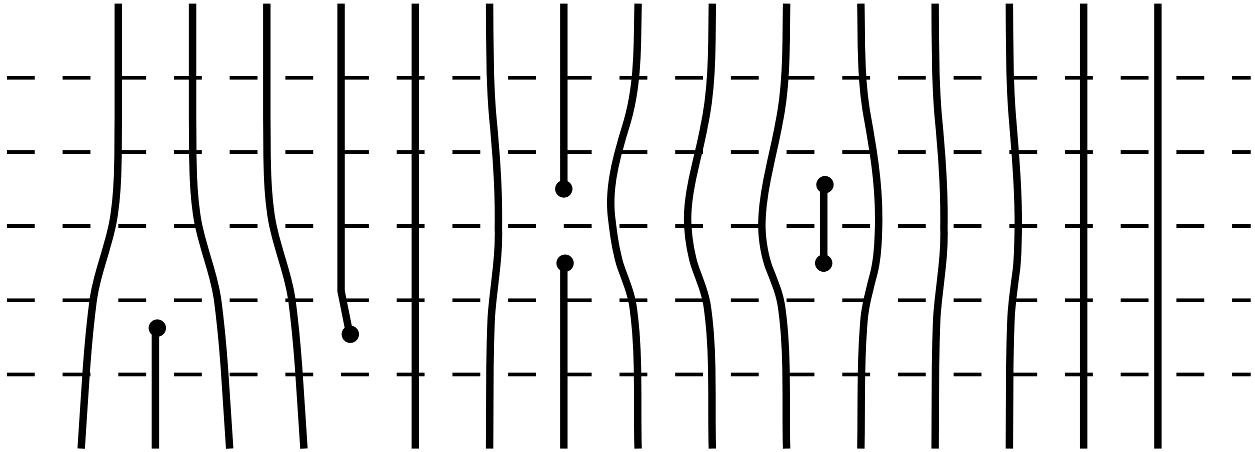
Measuring local strain $q = \partial\varphi/\partial x$ via space resolved X-ray diffraction







D. Rideau et al
Europhysics Letters **56** (2001) 289

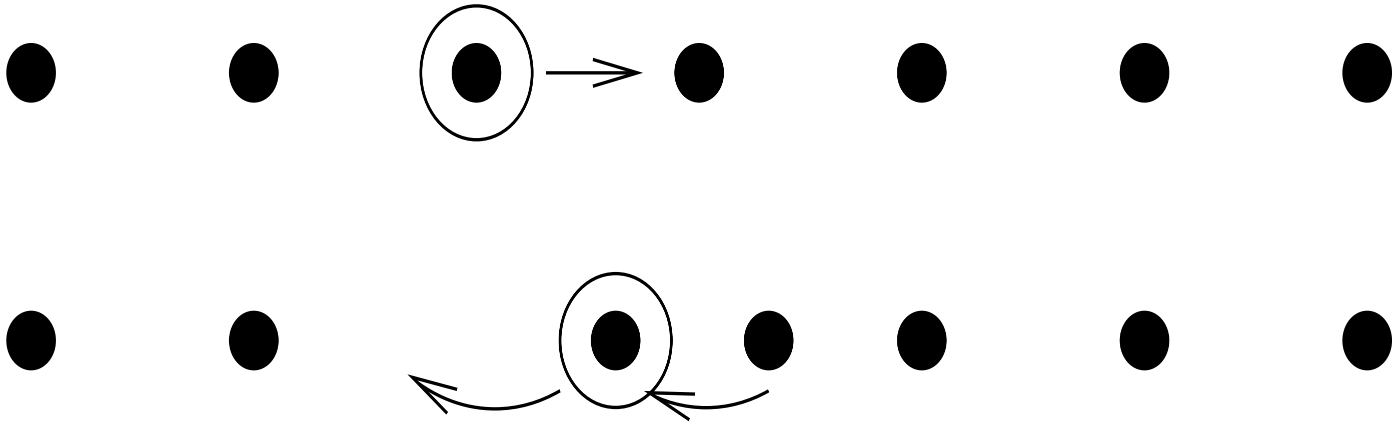


Topological defects in a CDW.
Solid lines: maxima of the charge density.
Dashed lines: chains of the host crystal.
From left to right: dislocations of opposite signs and their pairs of opposite polarities.

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.

Sliding of an atomic array through the strong attractive pinning center (co-moving frame).

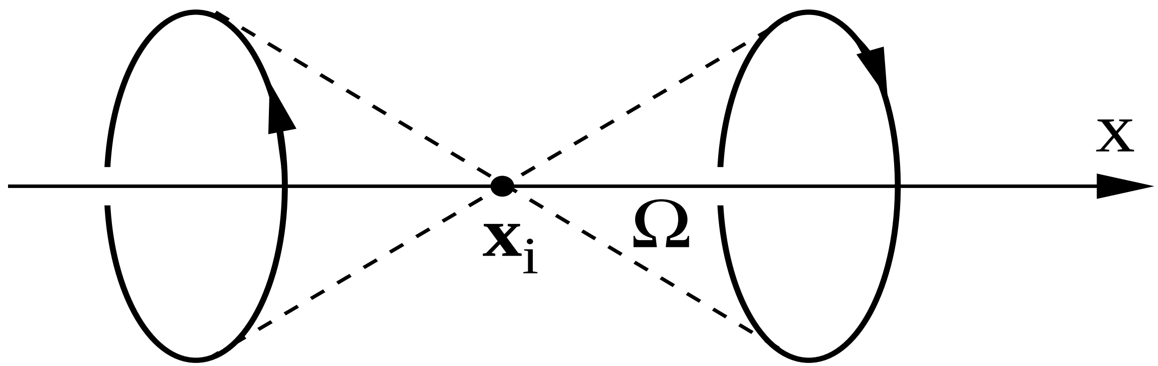


Upper raw, straight arrow:
relative impurity displacement together with the trapped atom.

Lower raw, left arc arrow: after more than half of the period, trapped atom is released to its ealier, distant now, position;

right arc arrow:
the more close now next atom is trapped instead

In case of no relaxation –
Impurity is strong enough to drag the atom over the whole periond



Pair of D-loops generated by a strong pinning center
after a nearly complete period of sliding.

The cross-section (the figure's plane) corresponds to
the quaternion of dislocations (*recall Blatter et al review*).

CDW – quantatively an opposite case to the atomic one:
density is smoothly distributed over the whole period,
Still a qualitatively equivalent picture of MS states.
Vision of quasi 1D CDW :
Bisolitons -- non topological configurations,
readily created by driving the DW.

Solitons in quasi 1D: short range model.

Quasi 1D system with an impurity at the chain *n=0,* at *x=0*

$$\int dx \sum_n \left[\frac{1}{2} C_{\|} (\nabla_{\|} \varphi_n)^2 - \sum_m C_{mn}^{?} \cos(\varphi_n - \varphi_m) \right]$$

$$- V \cos(\varphi_0(0) - \theta)$$

2π periodicity of the pinning allows to skip the 2π quanta
to optimize the total energy.

2π periodicity of lattice energy allows for topological defects, solitons.
Only pairs of solitons can be continuously developed by driving θ.

Single 2π soliton ≡ nucleus D-loops:
Energy E_s ;
Profile: $0 \leq \varphi_s(x-x_s) \leq 2\pi$ hence one DW period stretching along the defected chain relative to the surrounding ones.

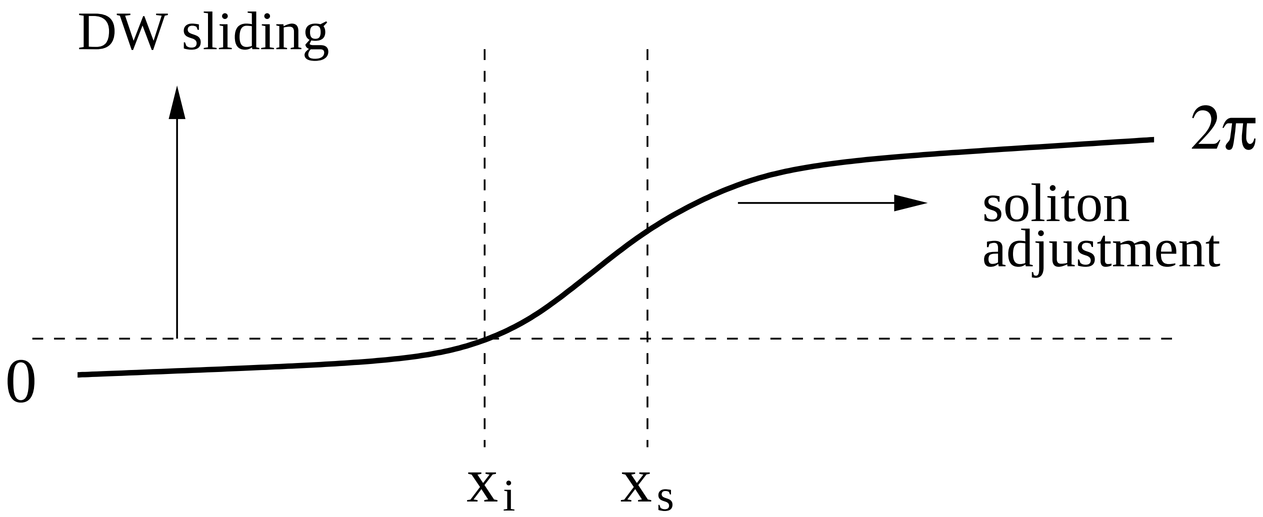
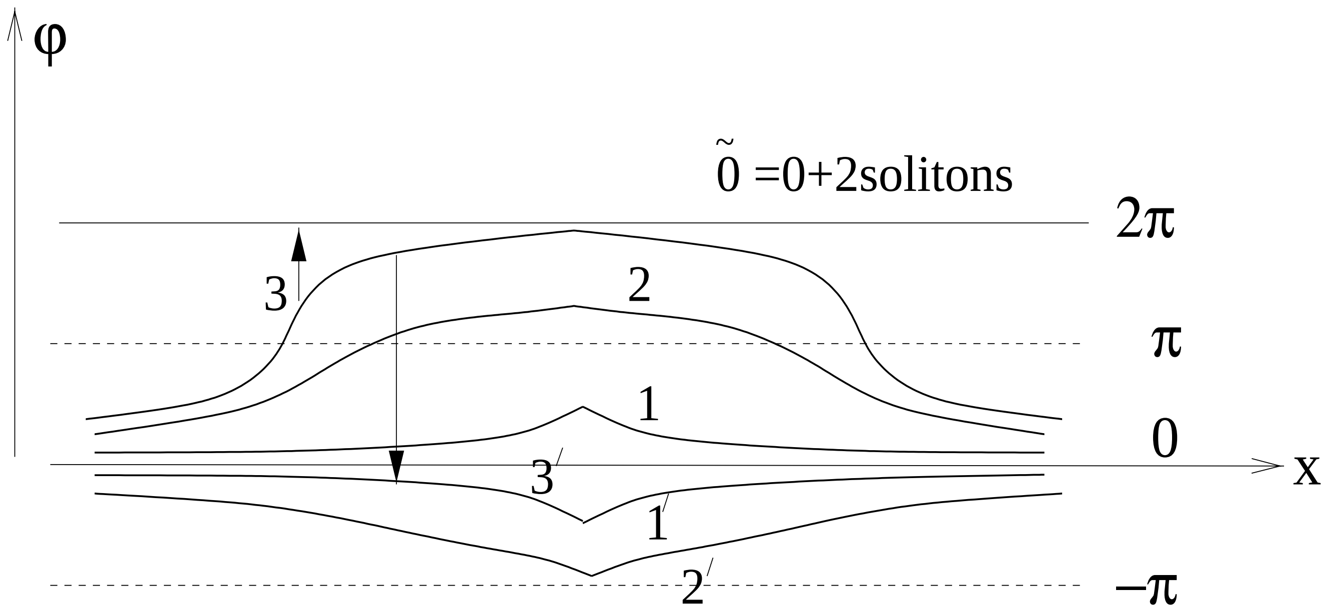
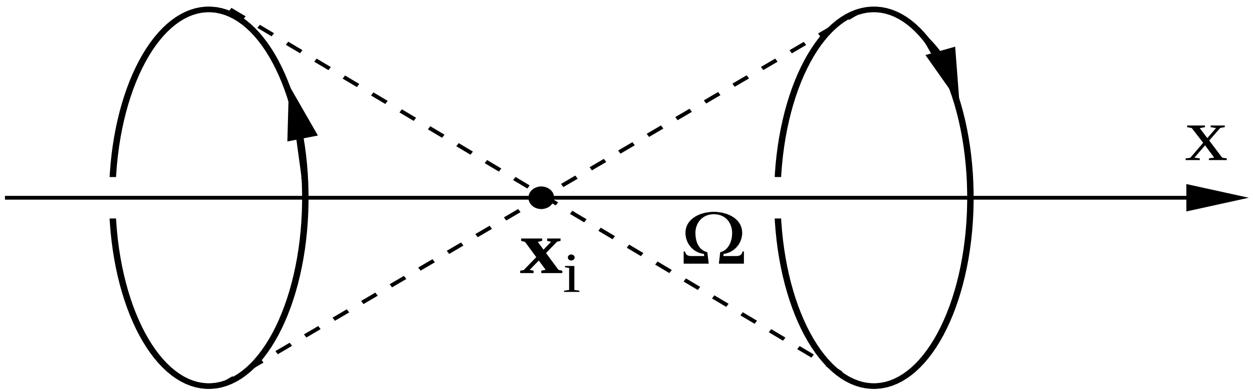


Figure:
Extinction of a point impurity pinning at presence of the 2π soliton.
Phase profile $\varphi(x-x_s)$ can be adapted (vertical arrow) to the phase mismatch at the impurity position x_s
by adjustment (horizontal arrow) of the soliton position x_s.



Phase profiles $\varphi_s(x)$: evolution for the chain passing through the impurity.
Starts at equilibrium configuration 0: $\varphi(x) \equiv 0$;
Evolves through shapes 1,2,3,0+2π into bisoliton.
These configurations form retarded branch E_+ which becomes metastable after $\varphi(0)$ crosses π. Since then, advanced profiles 1',2',3',0 of the branch E_- are less deformed, hence cost a smaller energy W.
If no relaxation $E_+ \rightarrow E_-$, then the new circle starts with the profile 0+2π: infinitely divergent pair of solitons.

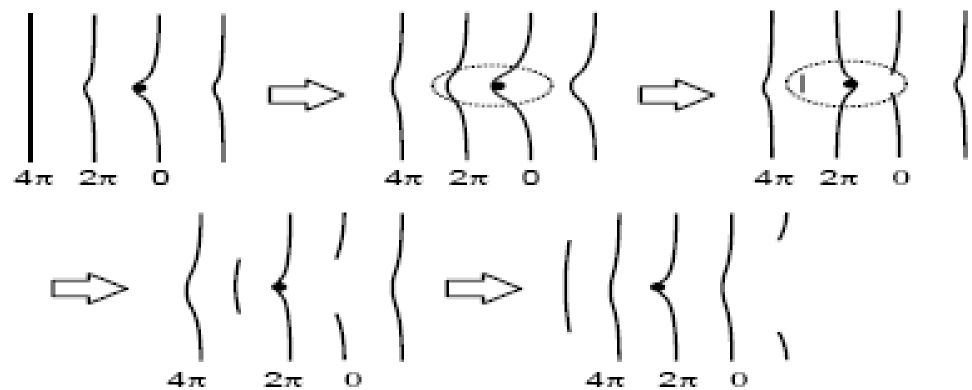
Weak impurity: level π is never reached, a smooth reversible evolution through shapes 0,1,0,1',0

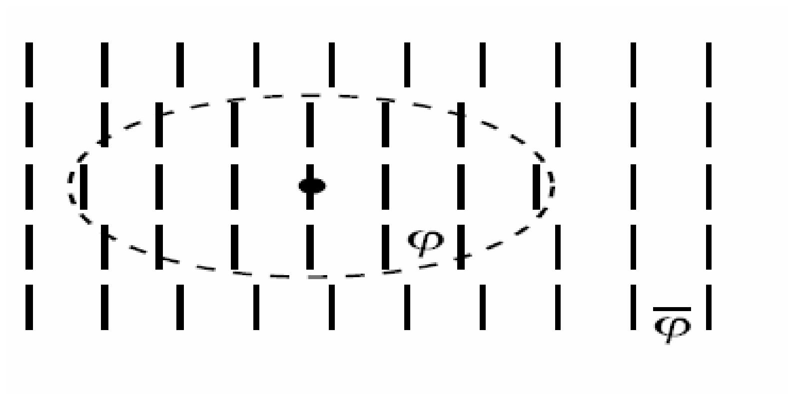


Generalization of bisolitons:

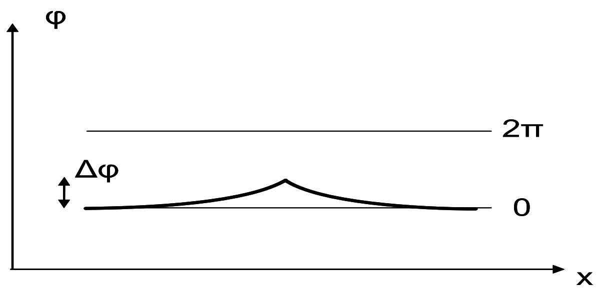
Pair of D-loops generated by a strong pinning center after a nearly complete period of sliding.
The cross-section (the figure's plane) corresponds to the quaternion of dislocations.
The phase deficit at the impurity point x_i is determined by the steric angle Ω of the loop.

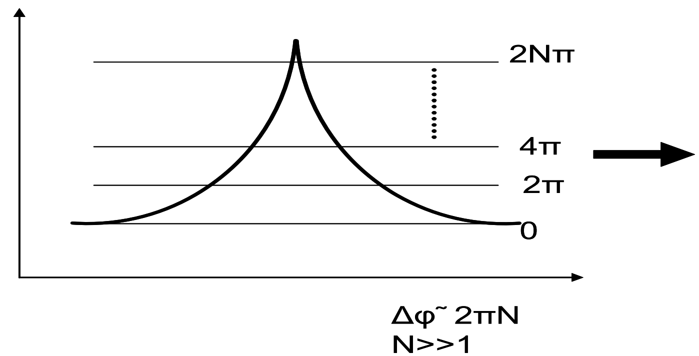
Next page: Moving through a very strong pinning center
--such that allows for retardation by many periods *N>>1* :

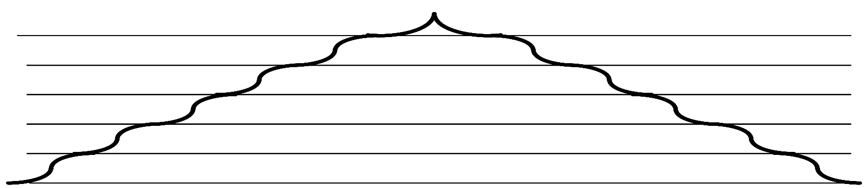

4π 2π 0
4π 2π 0
4π 2π 0
4π 2π 0
4π 2π 0

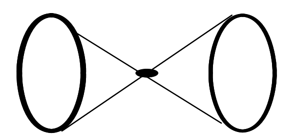

φ
φ̄

Moving through a very strong pinning center
--such that allows for retardation by many periods *N>>1* :







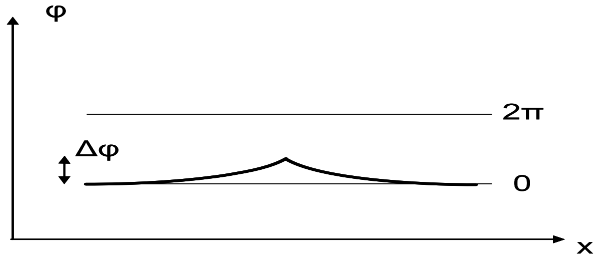


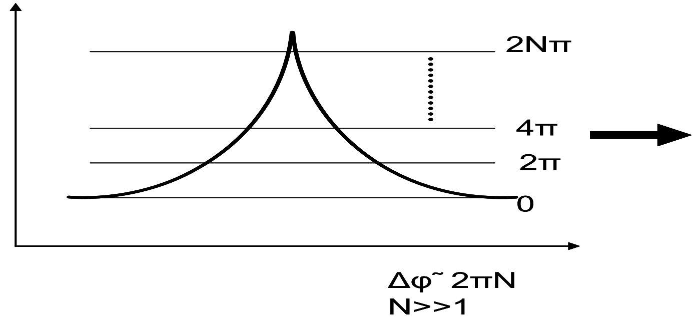
Efficiency of plastic regime at large local retardation $\Delta\varphi \approx 2\pi N$, $N>>1$:

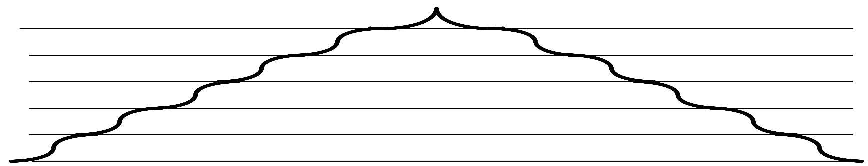
1. Elastic regime: energy $W_{el} \sim (\Delta\varphi)^2 \sim N^2$.

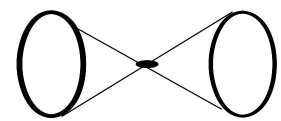
2. Plastic alternative: to emit a pair of elementary D-loops $= 2\pi$ solitons after each period of retardation;

plastic energy $W_{pl} \approx 2E_s N$ grows only as $\sim N$.







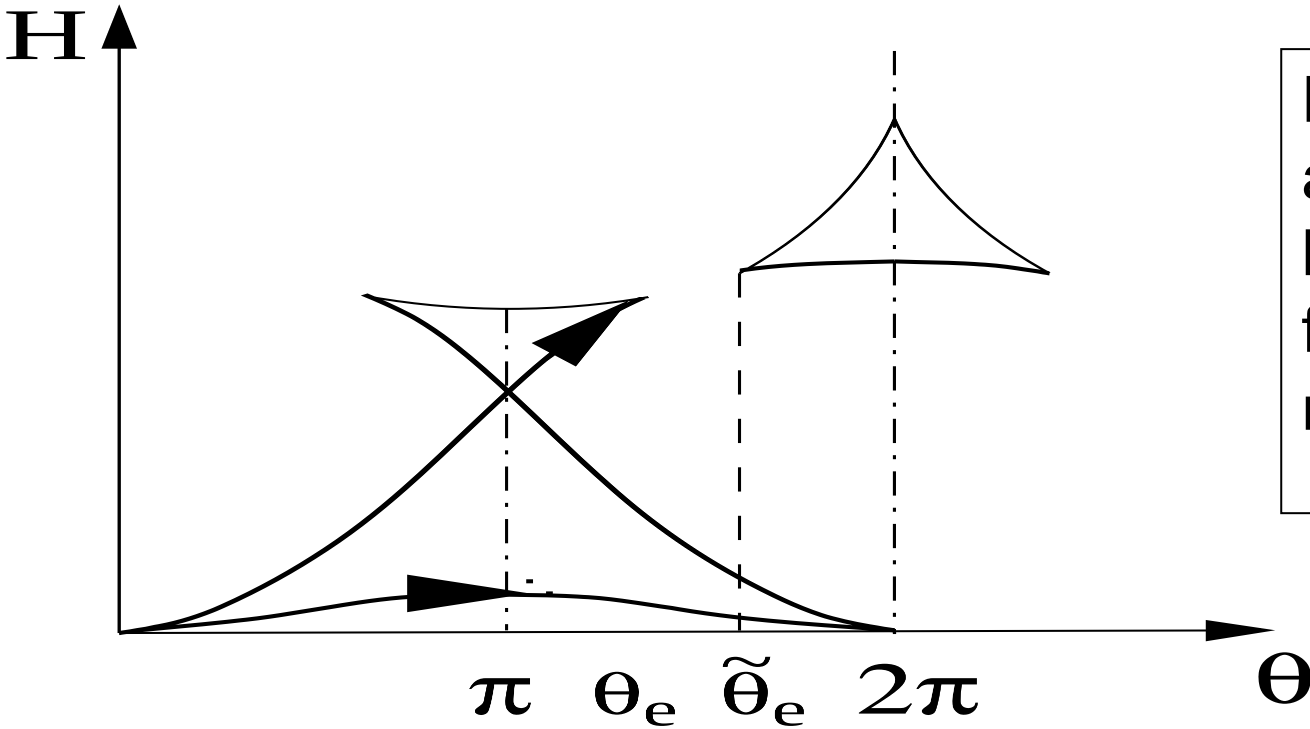


3. **Further evolution** of plastic deformations: drastic energy reduction from ~N to ~$N^{1/2}\ln N$ in d=3 or to ~ln*N* in d=2:

Aggregate N emitted elementary D-loops into the growing single loop embracing N chains.

Loop energy ~ln*N* per length unity.

D-loop expansion redistributes the retardation by multiple periods along the defected line to retardation by single period over many lines embraced by D-loop.



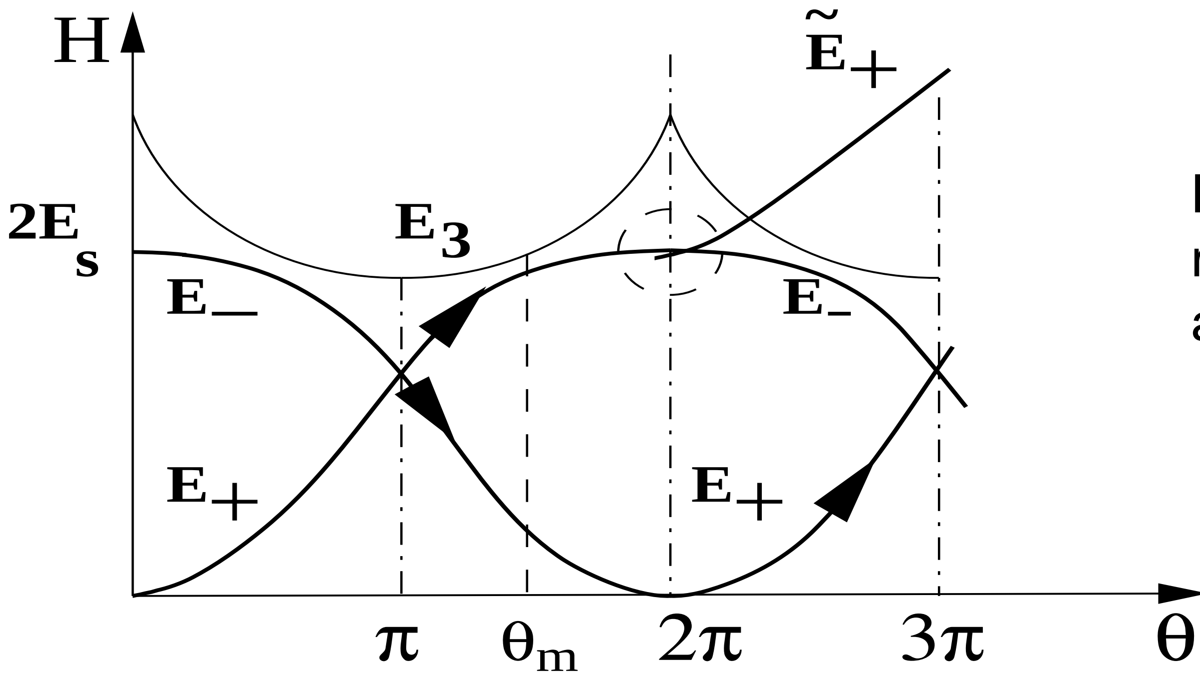
Energy of stable and metastable branches as a function of the mismatch phase θ

Thick lines: energy branches $E_a(\theta)$.
Uppermost thin lines – the barriers.

Weak strength $V<V_1$ - lowest thick curve.
Intermediate $V_1 <V<V_2$ - other thick curves.

Notice disconnected region of higher energy branches around $\theta = 2\pi$.

Termination points of the two regions, θ_e and $\tilde{\theta}_e$, coalesce at $V=V_2$ giving rise to the the regime $V>V_2$.



Dashed circle: region expanded at next figure.

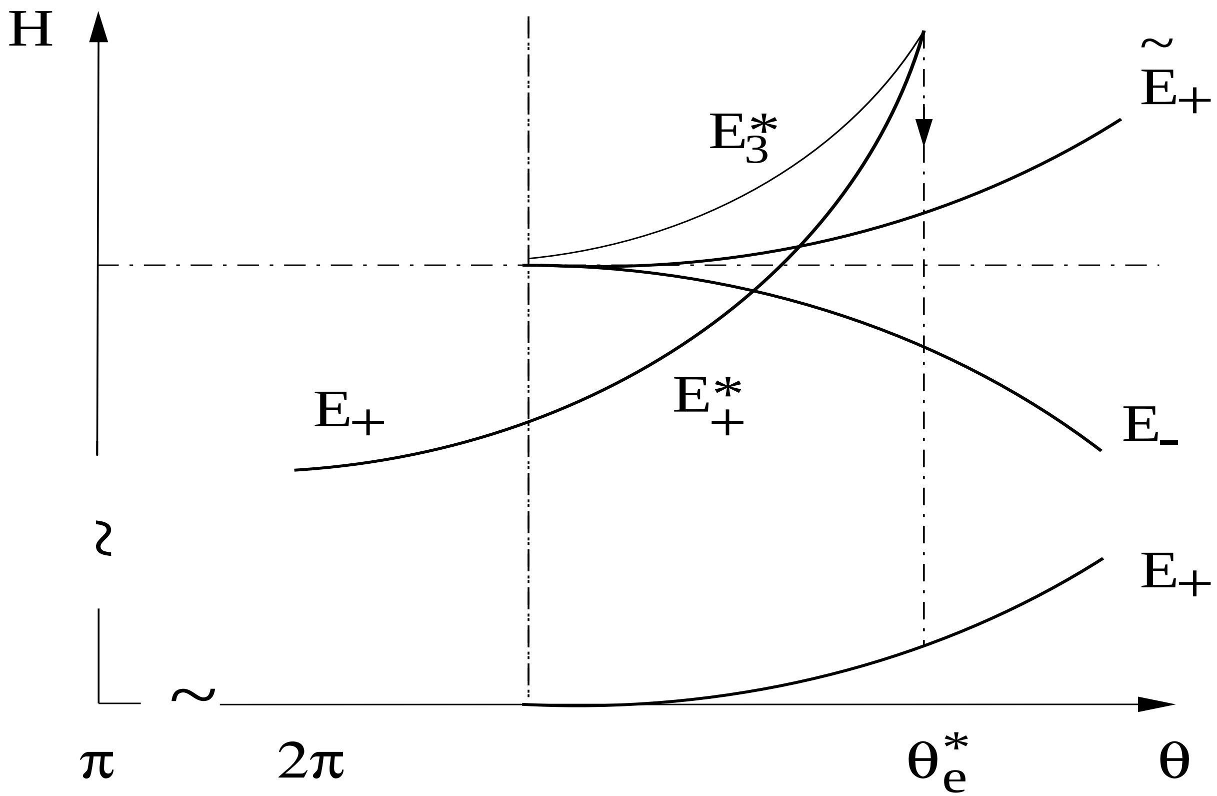
Strong pinning centers $V>V_2$

θ_m -- point of minimal activation energy U.

Next circle, $\theta > 2\pi$:

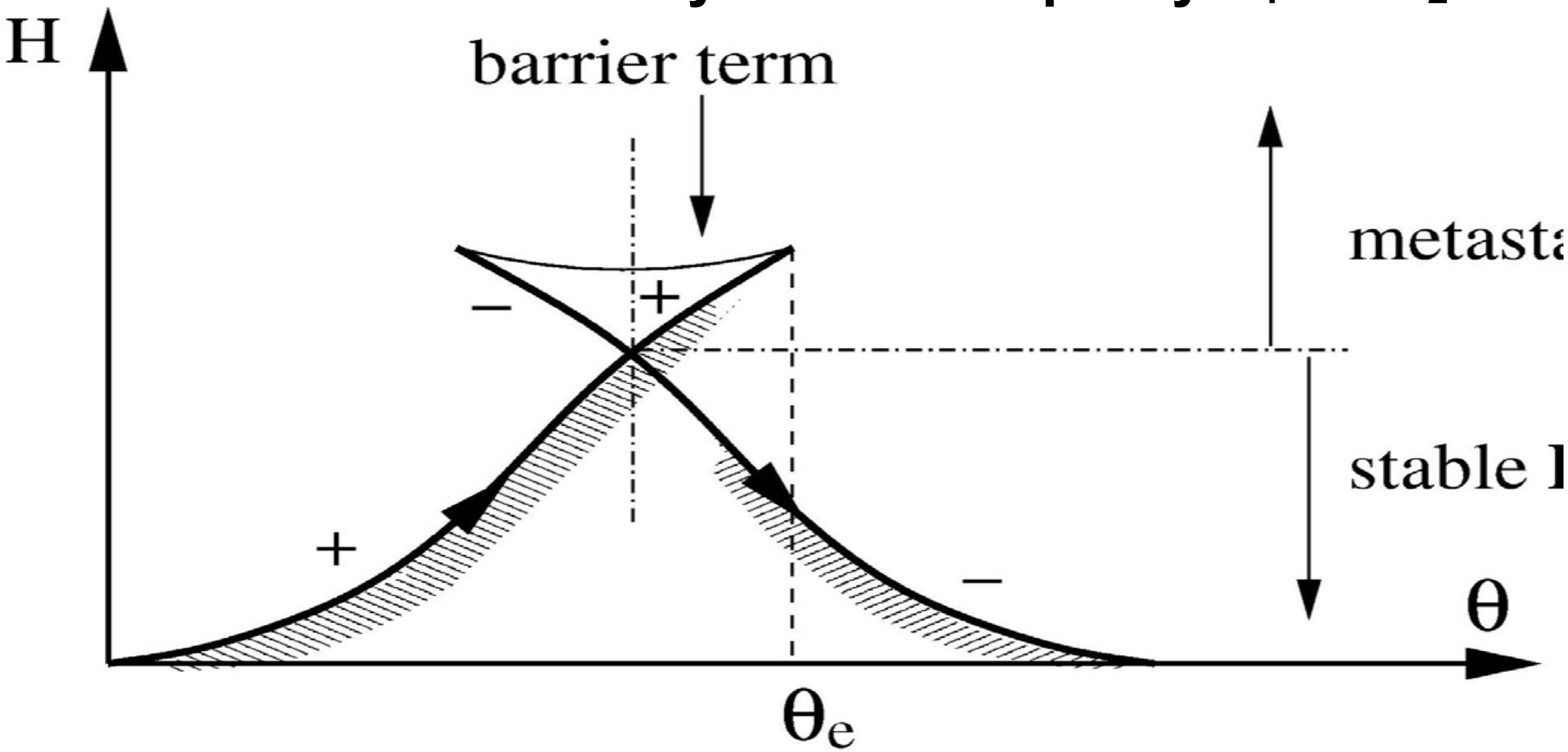
branches E_+,E_- are identical to those at $0< \theta <2\pi$, if the system is fully relaxed.

Special effects near the crossover between two successive periods which are originated by interactions of distant dislocation loops.



Actual adiabatic continuation of the branch E**+** is E~+;
it differs by presence of two solitons at infinity:
they have been created over the previous circle of the branch E**+**.
E*+ is the overshooting part of the branch E+.
Branch E~+ differs from the lowest branch E+
by presence of two solitons at ±∞.

Restrictedly bistable impurity $V_1<V<V_2$.



Energy branches over one period of sliding.

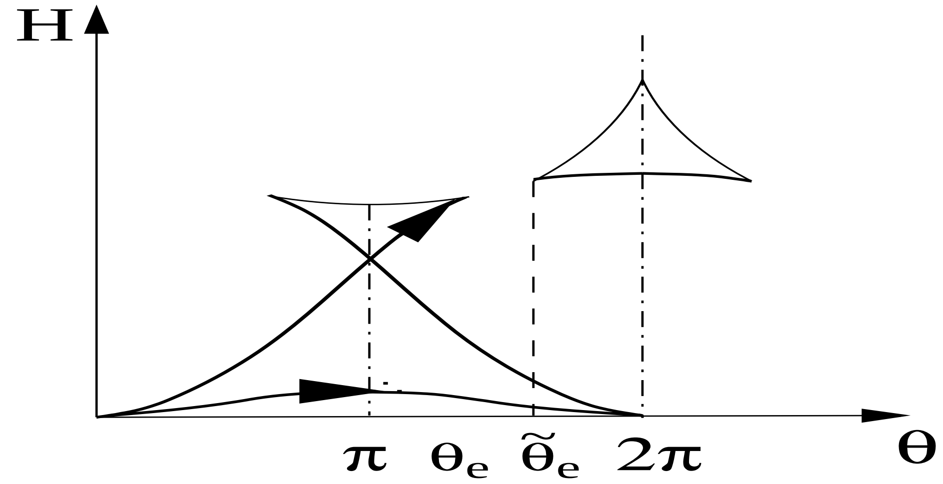
Thick lines -- locally stable branches $E_{\pm}$, also classified as $E_2>E_1$.

Their difference gives the dissipated energy $\Delta E= E_2-E_1$

Uppermost thin line -- barrier branch E_3.

$U=E_3-E_2$ -- barrier energy for the decay of the metastable state E_2.

Exploration of a close vicinity of π :



1. Small velocities –

1a. Very small velocities :

Decay happens as soon as the branch becomes MS in a vicinity of π , even before the θ dependence of $\mathbf{E_b}$ is seen.

-- the regime of linear collective conductivity ***$f \sim v\tau_\pi F_\pi n_i$*** .

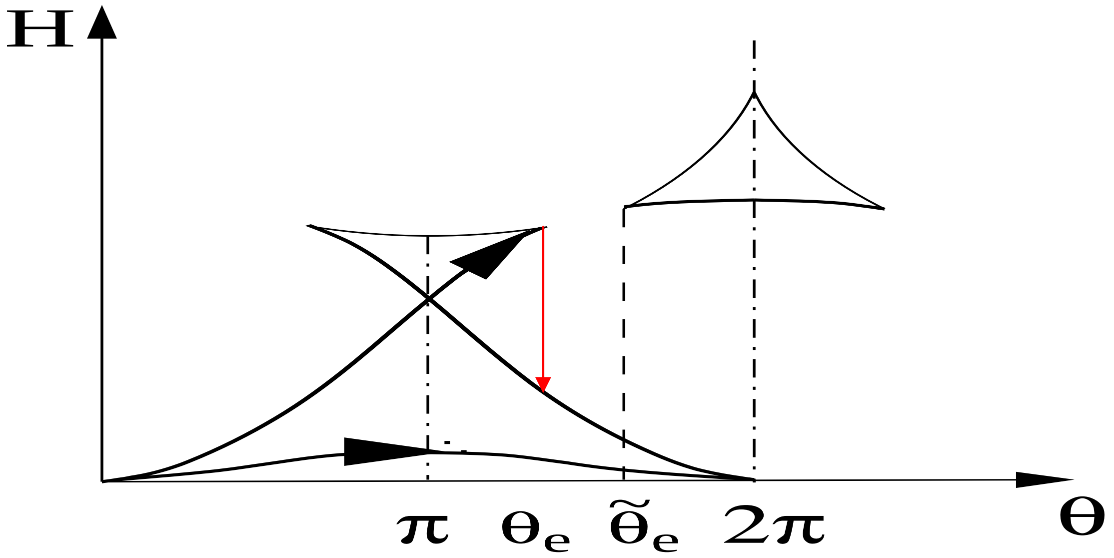
Activated behavior via *$\tau\pi$ can emulate the bare viscosity* ***and the normal conductivity; agrees with experiment.***

1b. Moderately small velocities : Decay still happens not far from crossing $\theta=\pi$ but deviations $\theta-\pi$ are already large enough to see the decrease of the barrier height:

$f \sim n_i T \, Log(v)$ $v \sim exp(f/n_i T)$

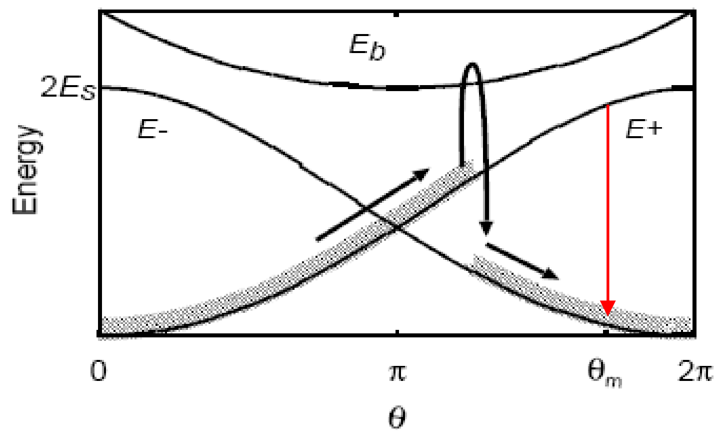
2a. High velocities – case of restricted metastability $V_1<V<V_2$

Termination point becomes reachable.

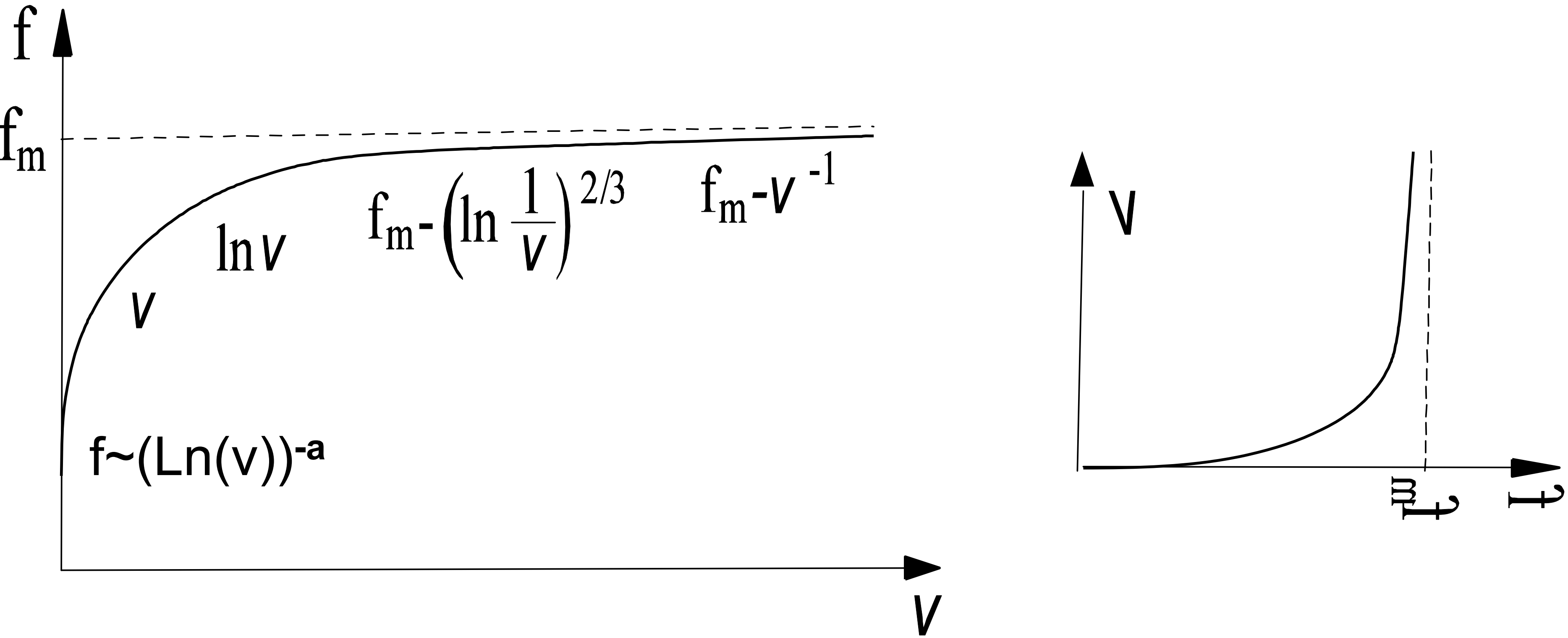


$$f_{\max} = n_i \Delta E(\theta_{\max})$$

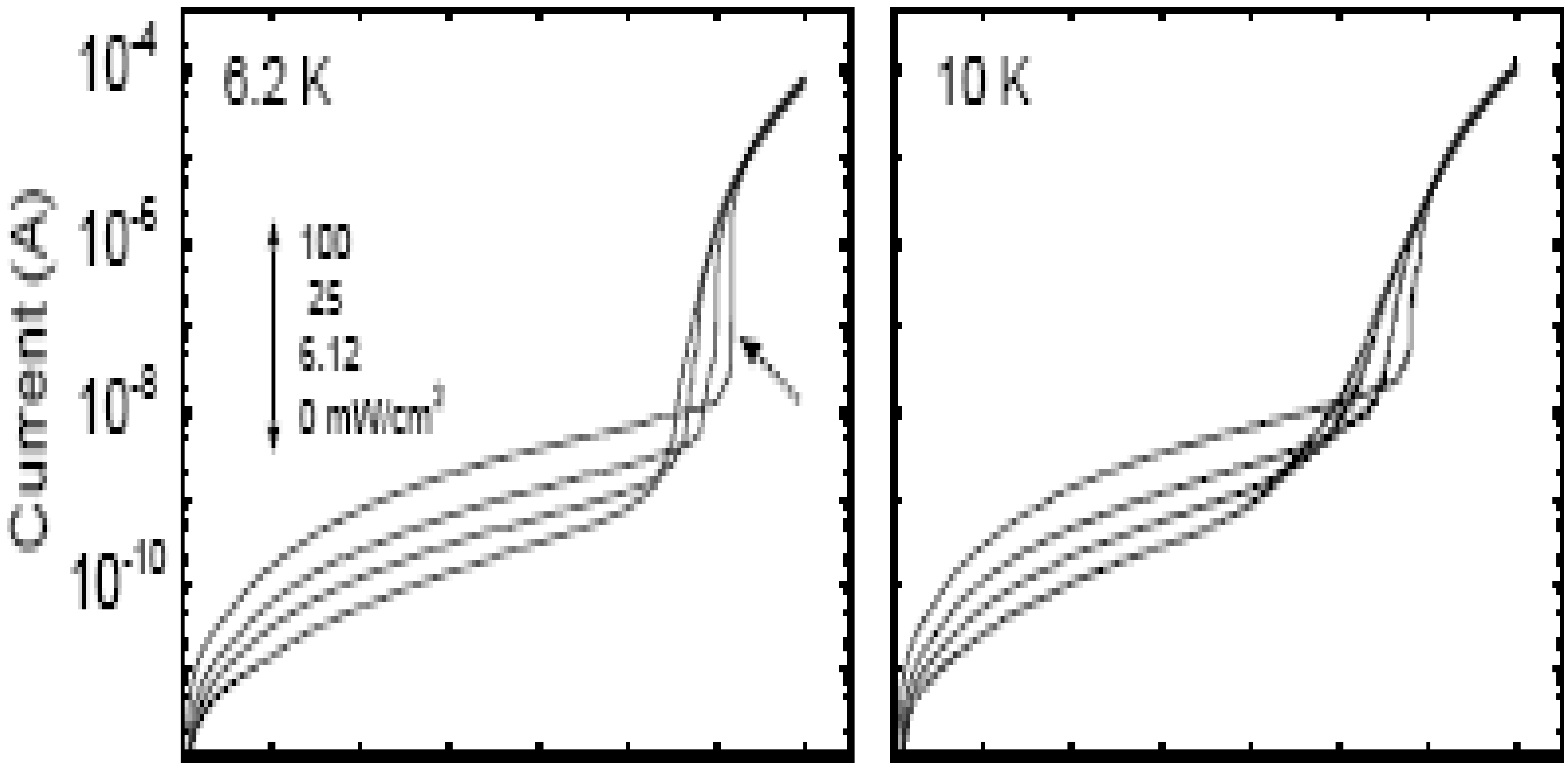
-- energy dissipation by falling from the termination point;



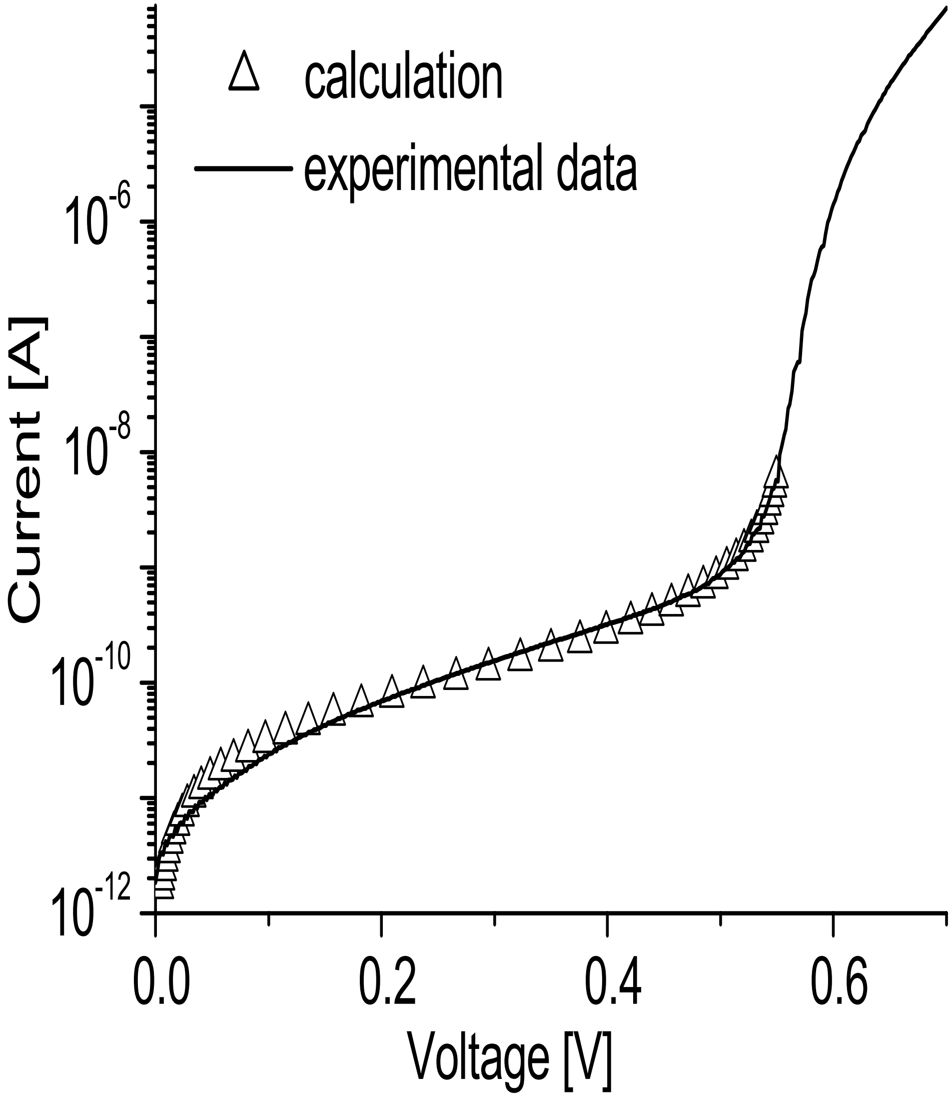
2b. High velocities – case of unrestricted metastability $V>V_2$:
Both MS branches and the barrier branch stretch over all θ and $\mathbf{E_b} \neq 0$ everywhere.
Hot point θ_m of minimal barrier originates shortest relaxation time.
If it is passed nevertheless, a pair of topological defects is created.



Schematic plot of *f(v)* showing several regimes of relaxation. The viscous force background is not included.



Ogawa, Miyano and S.B.
Effect of illumination and temperature upon sliding I-V.
Presumably, the light helps to relax the metastable states.
The arrow indicates the recovery of switching transition through illumination.



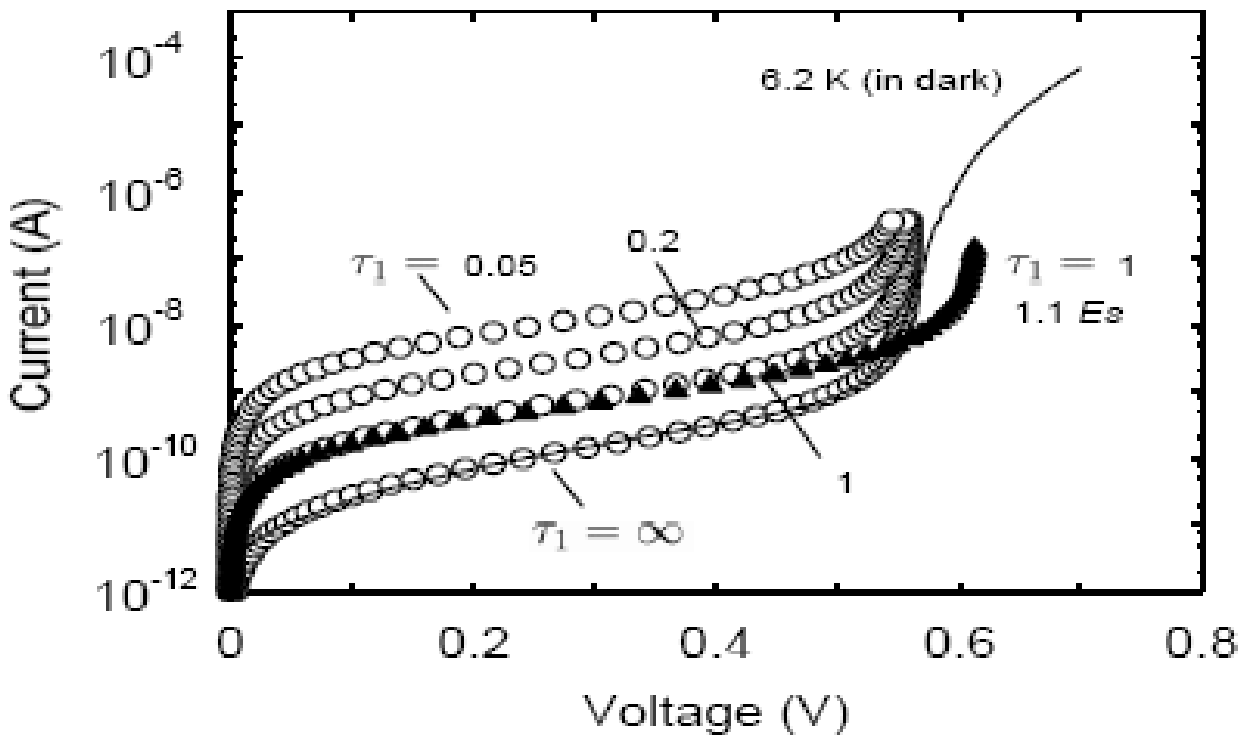
Single model fits of theoretical *v(f)* to experimental I-V curve (*Ogawa, Miyano, S.B.*) Works through three regimes.

1. Middle part : regime ***f~logv***.

2. Left part, if plotted in the normal scale, - linear law ***f~v***.

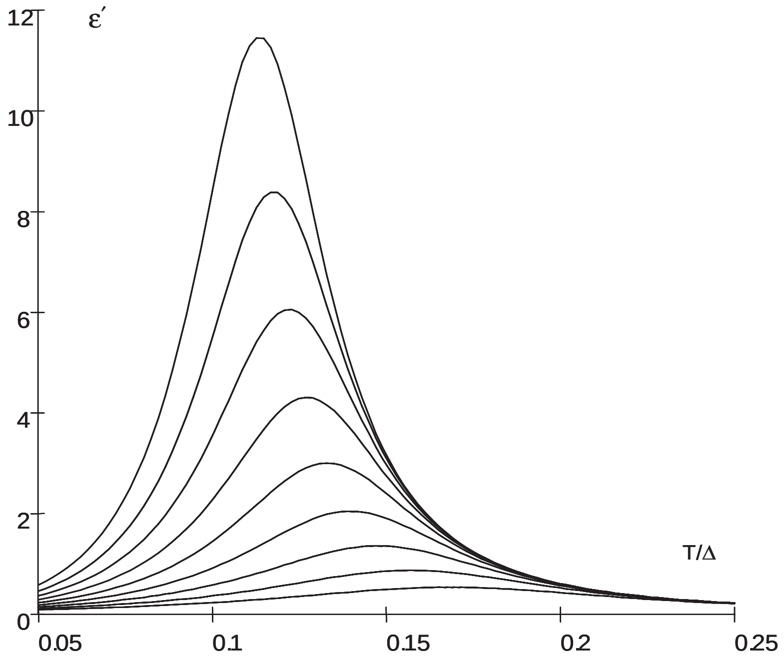
3. Right part: sharp upturn discriminates in favor of the high strengths – unrestricted bistability $f=f_{max}-cnst/v$.

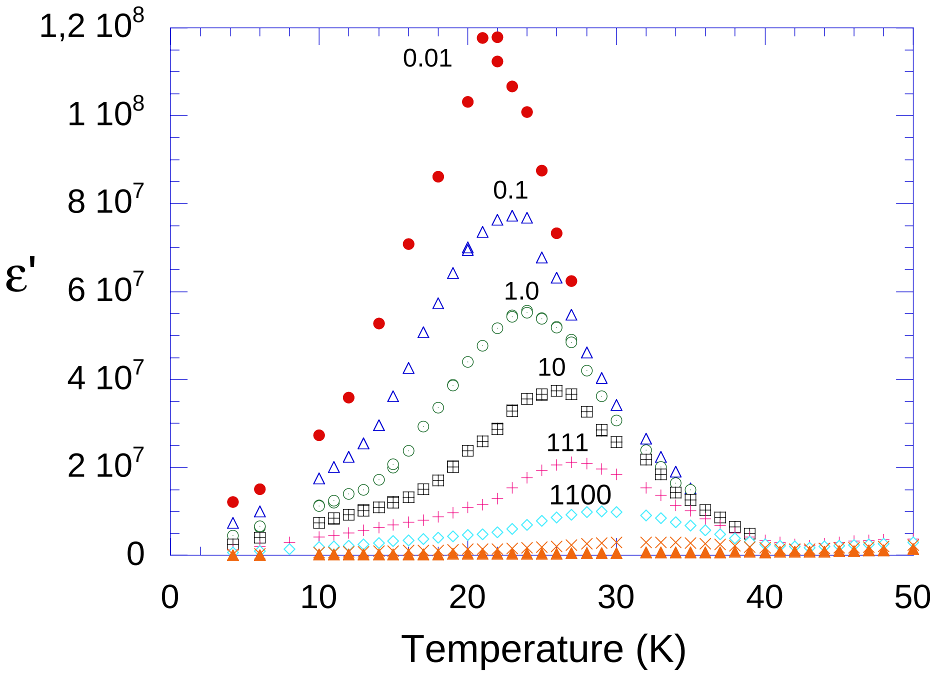
Curvature sign changing at low v is an artifact of logarithmic rescaling of the current axis.



Ogawa, Miyano and S.B.
Effect of illumination upon sliding I-V. τ_1 – exposition time
Presumably, the light helps to relax the metastable states.
Solid line:
Fitting of the I-V curve measured with the theory.
Filled triangles show the effect of Es on the threshold eld.

Susceptibility Reε=ε' T dependence at various ω -- from interference of local and collective pinnings.

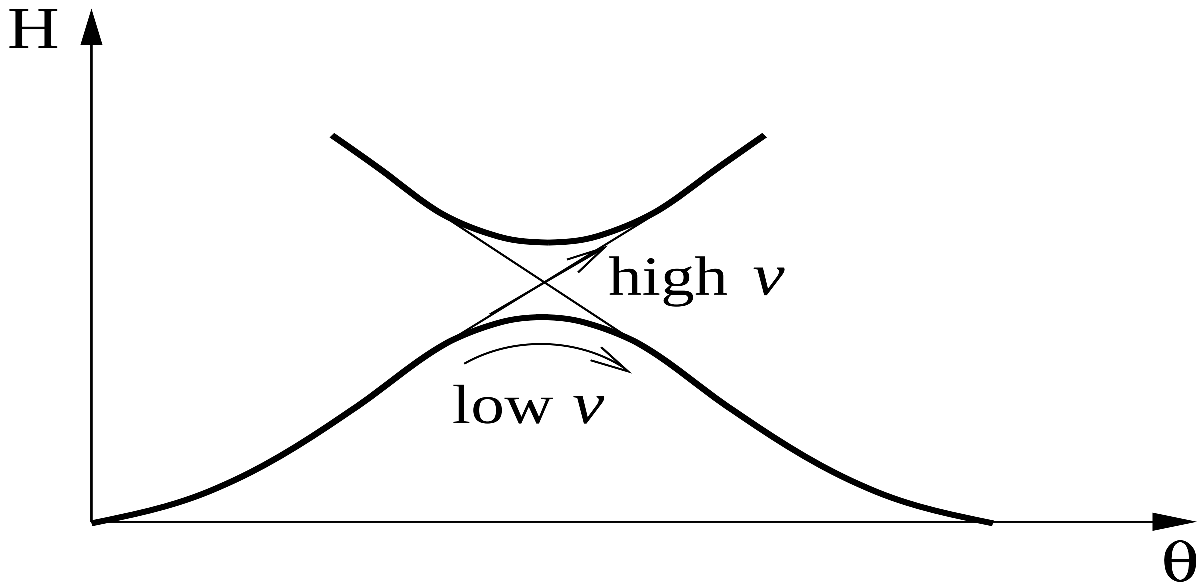




While the rising high T slope is specific to CDWs and SDWs, this example shows several ingredients of a general importance:

- sensitivity of the collective pinning to elastic parameters;
- separation of time scales between the two types of pinning,
- as well as their interference in observations.

Quantum effects.



Pinning extinction by the quantum tunneling between branches $E_{\pm}$
Gap δ_q opens between $E_{1,2}$ which were nearly degenerate at $\theta \approx \pi$.
Adiabatically the system follows (the arc arrow) the lowest branch E_1
giving the zero force in average over one period.
Only nonadiabatic transitions (diagonal arrow) from E_1 to E_2
allow to reach the metastable branch to yield the net pinning force.

$$f \sim \exp(-1/v\tau_q);\, \hbar/\tau_q = \delta_q$$

Ensemble averaging of pinning forces.

Distributions of strengths: for applications and to build a bridge to collective pinning regime where the broad distribution is the basic ingredient.

EXAMPLES:

Exponential distribution:

change from the Ohm low $f \sim v$ at low v to the nonlinear regime $f \sim v^T$ with a diverging differential resistance at lowest v.

Scaling of the collective pinning:

reproduces the CP scaling expectations.

Empirical unification of different and differently derived results of the collective pinning theory and rather different views of the local pinning theory.

Skiped questions:

Pinnings' Interference.
Additivity of pinning forces.

See the review

S. Brazovskii and T. Nattermann

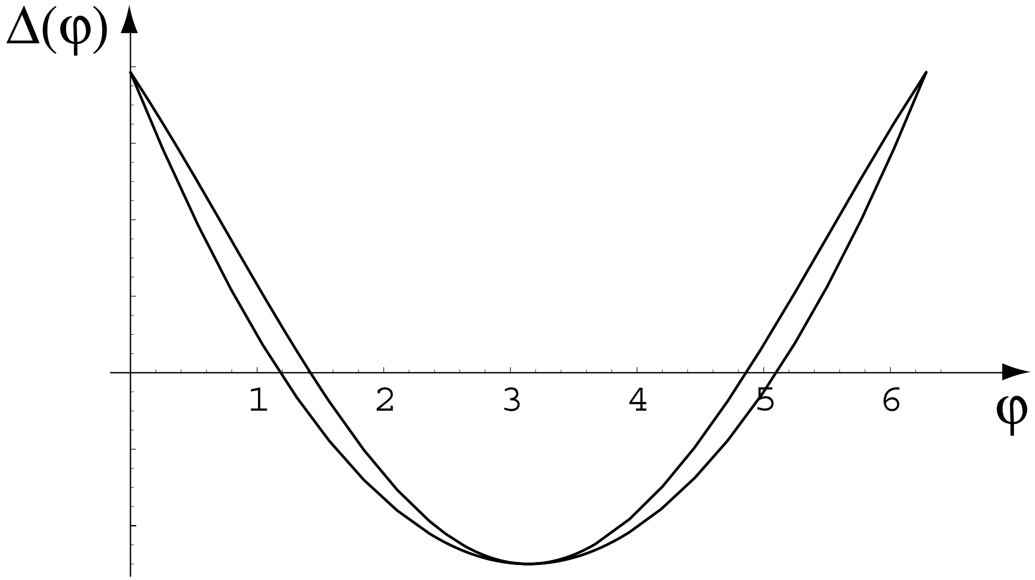
Pinning and Sliding of Driven Elastic Systems:
Domain Walls and Charge Density Waves

Advances in Physics, 53 (2004) 177; cond-mat/0312375

Convergence of Local Pinning theory and of Collective Pinning of the Functional RG:

Force becomes discontinuous at $\theta=\pi$.

Its correlator develops cusp - kink in inclination



Straightforward derivation and the direct interpretation of the key result of Functional RG theory of the collective pinning: Kink is formed by choosing the lowest state each time when the retarded and advanced branches cross each other changing their character from stable to metastable and vice versa.

Challenges to the collective pinning:

1. Fraction of MS branches terminate at end points or relax fast at “hot” points of minimal barrier. These points determine f(v) at high *v* -- not accounted in the collective pinning theory.

2. Fraction of stronger metastable branches do not posses this instability which seems to allow for the large *v* perturbative approach. But it results in even more obscure effect of generation of sequence of dislocations or solitons. Now *v-f* dependences are determined by competing process: annihilation against aggregation. They are not accessible yet to existing theories except for our simple treatment which also needs to be further elaborated. Particular demanding are studies of aggregation and annihilation of dislocations, their own pinning, etc.

Conclusions

The local pinning domain:
low T and not too low frequency ω or velocity v.

Effectively explains experimental data:
qualitatively and even quantitatively.

Advantages:
Explicit treatment of metastable states, their creation and relaxation, relation to plasticity and topological defects.
Clue to quantum effects:
Repulsion of crossing branches destroys pinning;
quantum creep as tunneling between retarded and advanced configurations at moments of their degeneracy.
Emission of sound excitations makes the dynamics to be dissipative even at $T=0$.