Energy relaxation in disordered charge density waves

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Work done in collaboration with **K. Bilakovic (Zagreb),**

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1. Introduction.

2. The CRTBT heat relaxation experiments (J.C. Lasjaunias, K. Biljakovic et al.).

3. Theoretical approaches

3. a. Phenomenological trap model (power-law relaxation + interrupted ageing).

3. b. Microscopic dynamical renormalization group of the strong pinning model ($1/T^2$ specific heat + power-law relaxation + interrupted ageing).

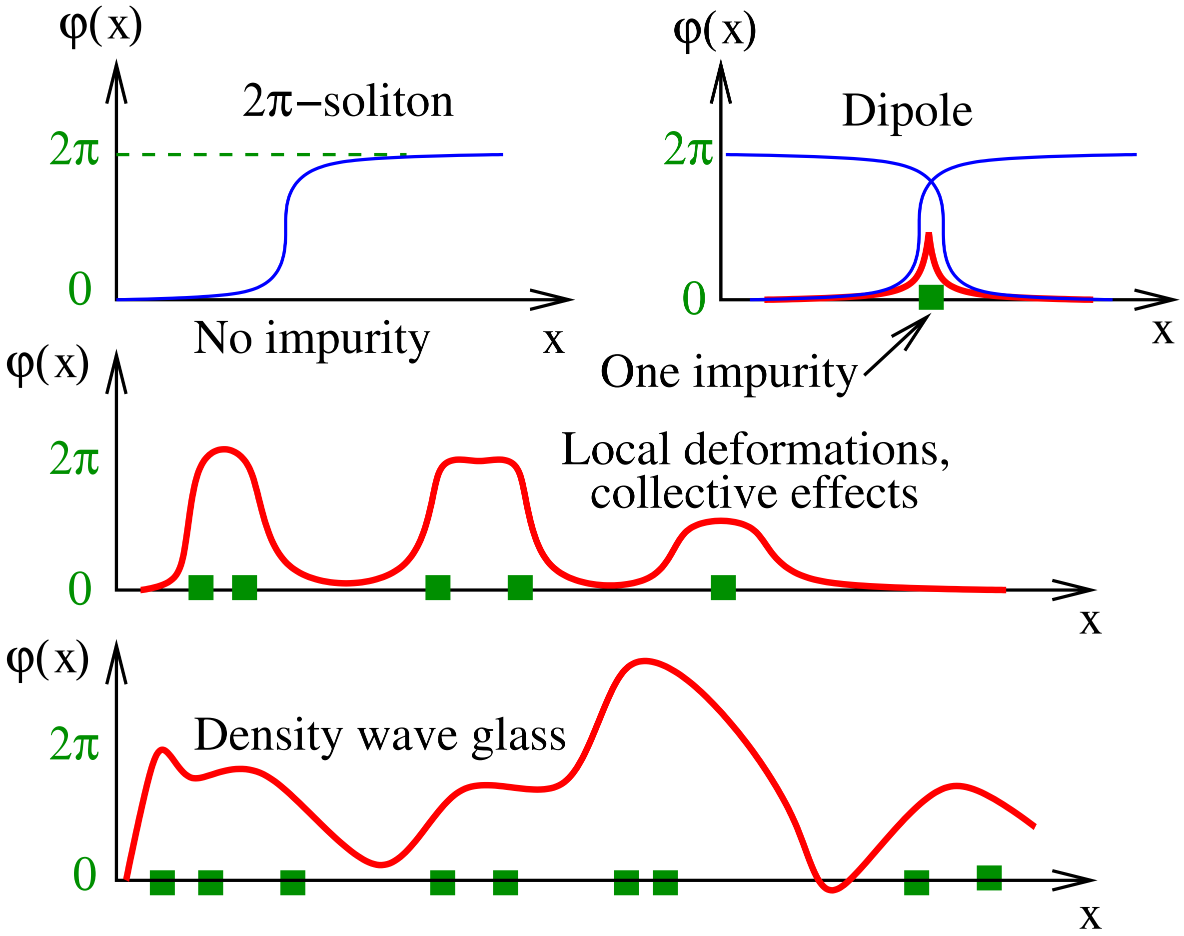
4. c. Green's functions for substitutional disorder in the quantum limit (power-law specific heat and susceptibility).

Local model of strong pinning with a single impurity

1. The soliton profile can be calculated explicitly by minimizing the energy and matching the solutions at the right and left of the impurity.

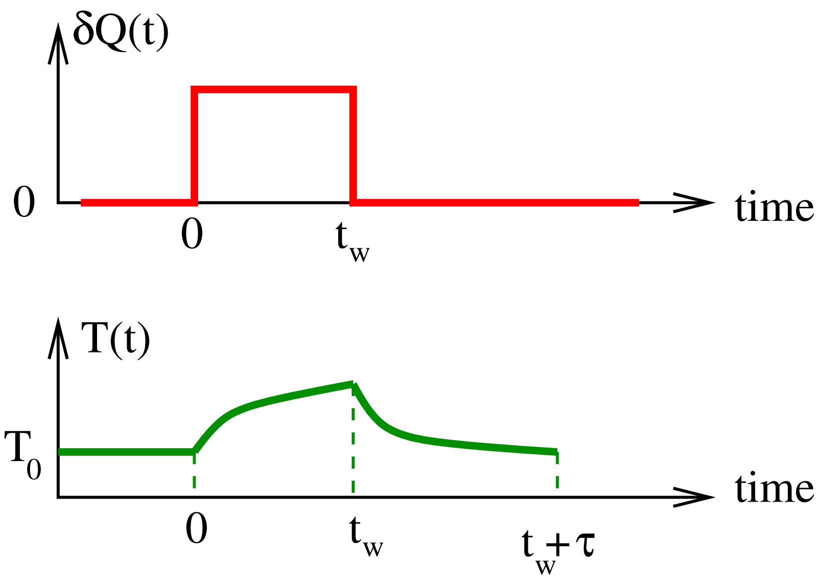
2. Result: possibility of metastable states separated by energy barriers (Fukuyama, Lee, Rice, Brazovskii, Larkin, Abe, Larkin, Ovchinikov ....).

Increasing the concentration of impurities



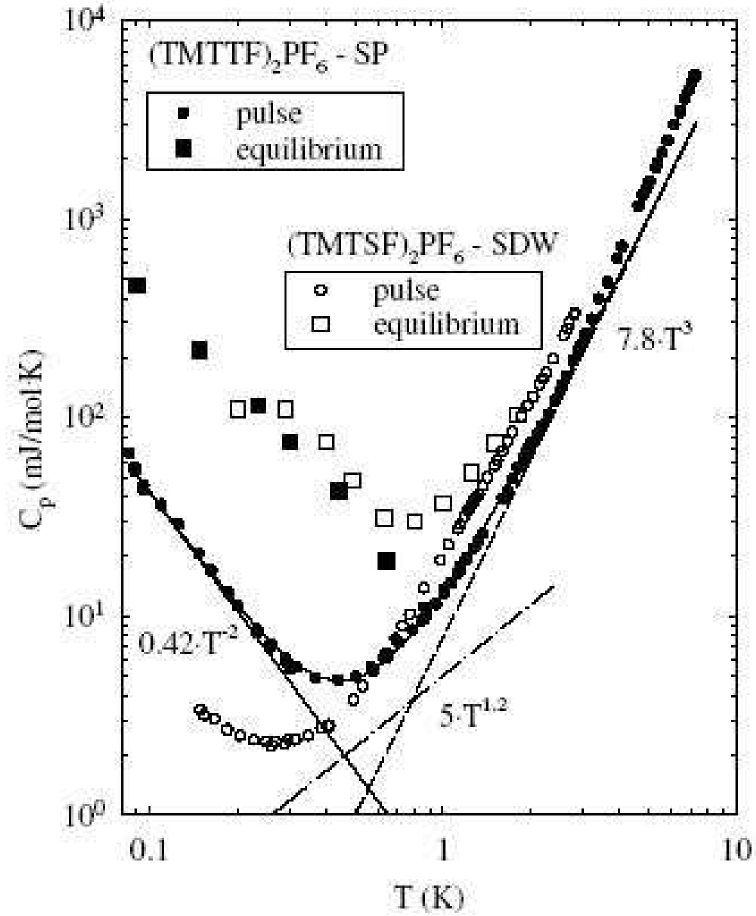
Ageing experiments

Sample connected to a thermal reservoir by a weak link used to warm the system. Temperature of the sample measured as a function of time for different values of a the heat pulse

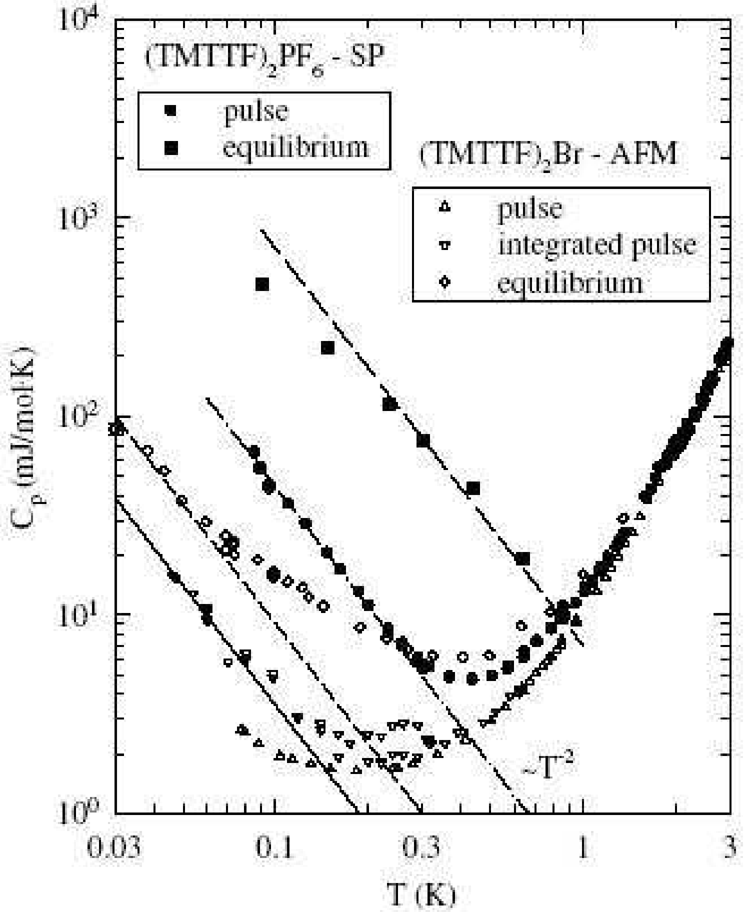


The system is equilibrated at T_0 ! (interrupted ageing)

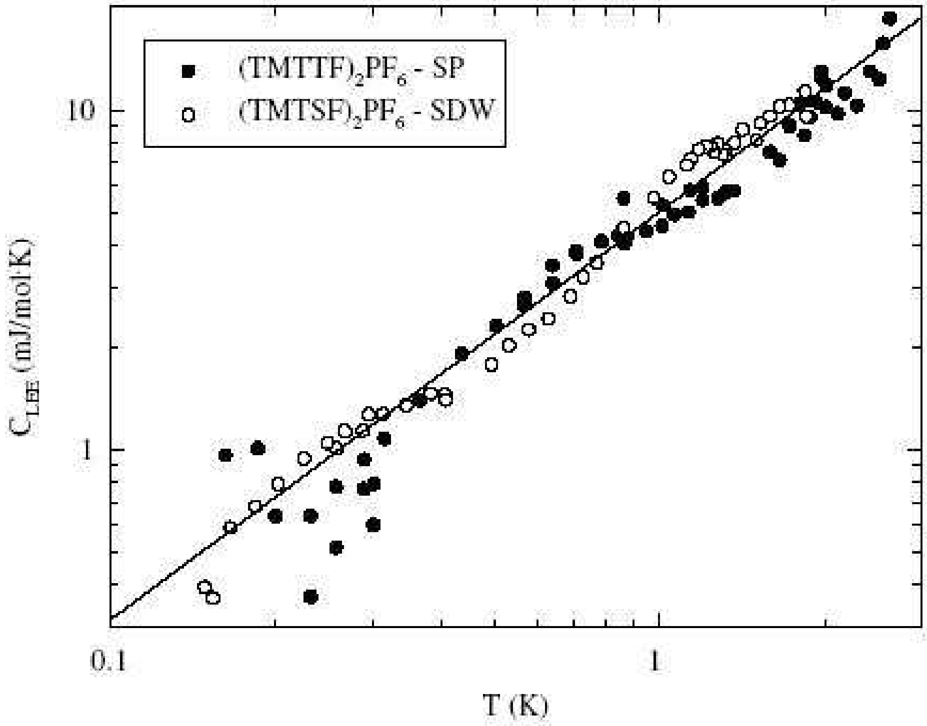
Total specific heat versus temperature (1)



Total specific heat versus temperature (2)

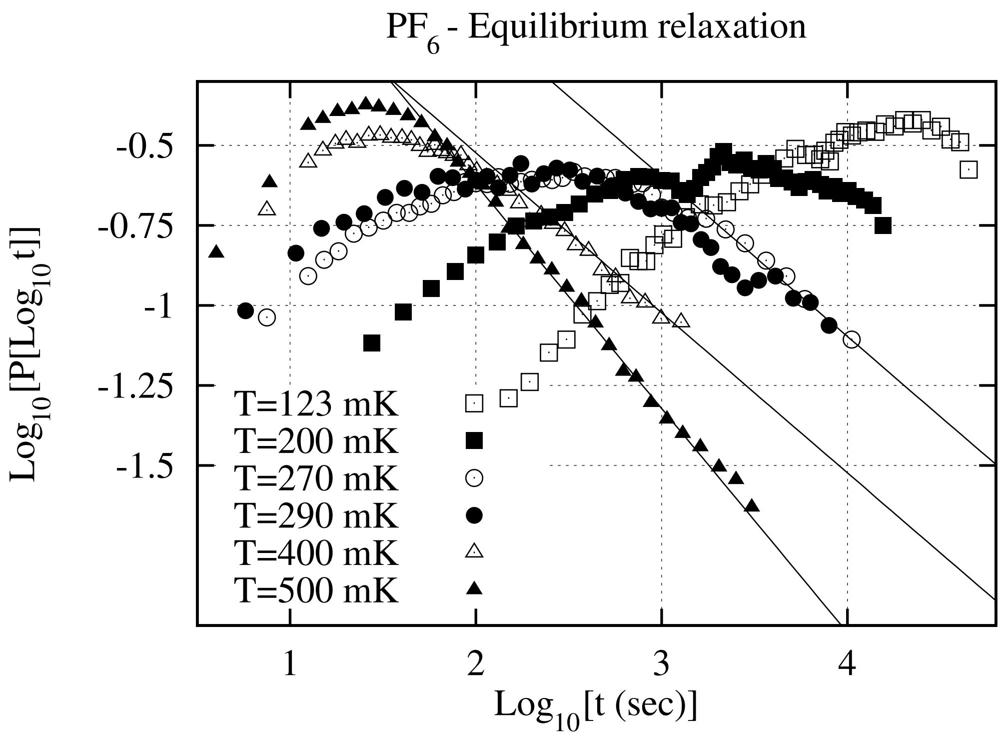


Power-law contribution

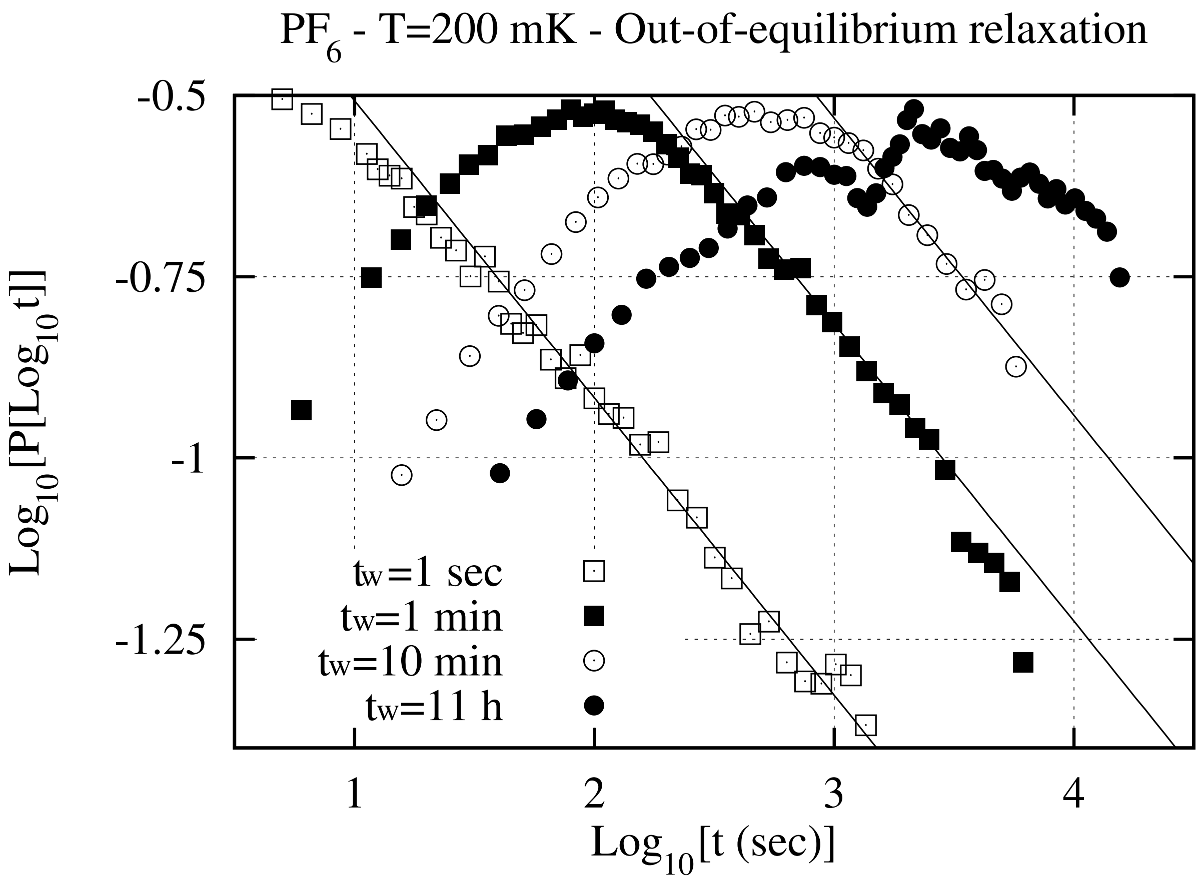


Spectrum of relaxation times (1)

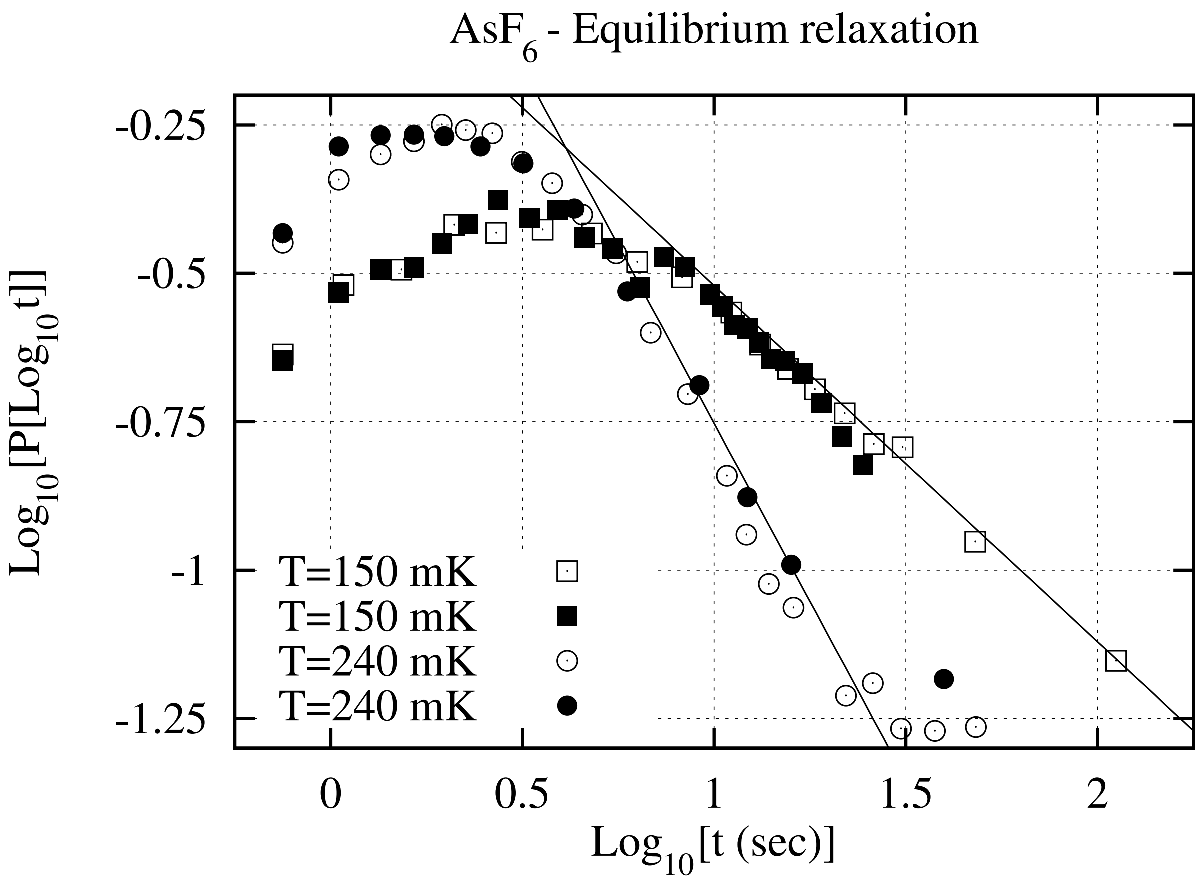
$$P_{t_w}(\ln \tau) = \partial U(t_w, t_w + \tau)/\partial \ln \tau$$



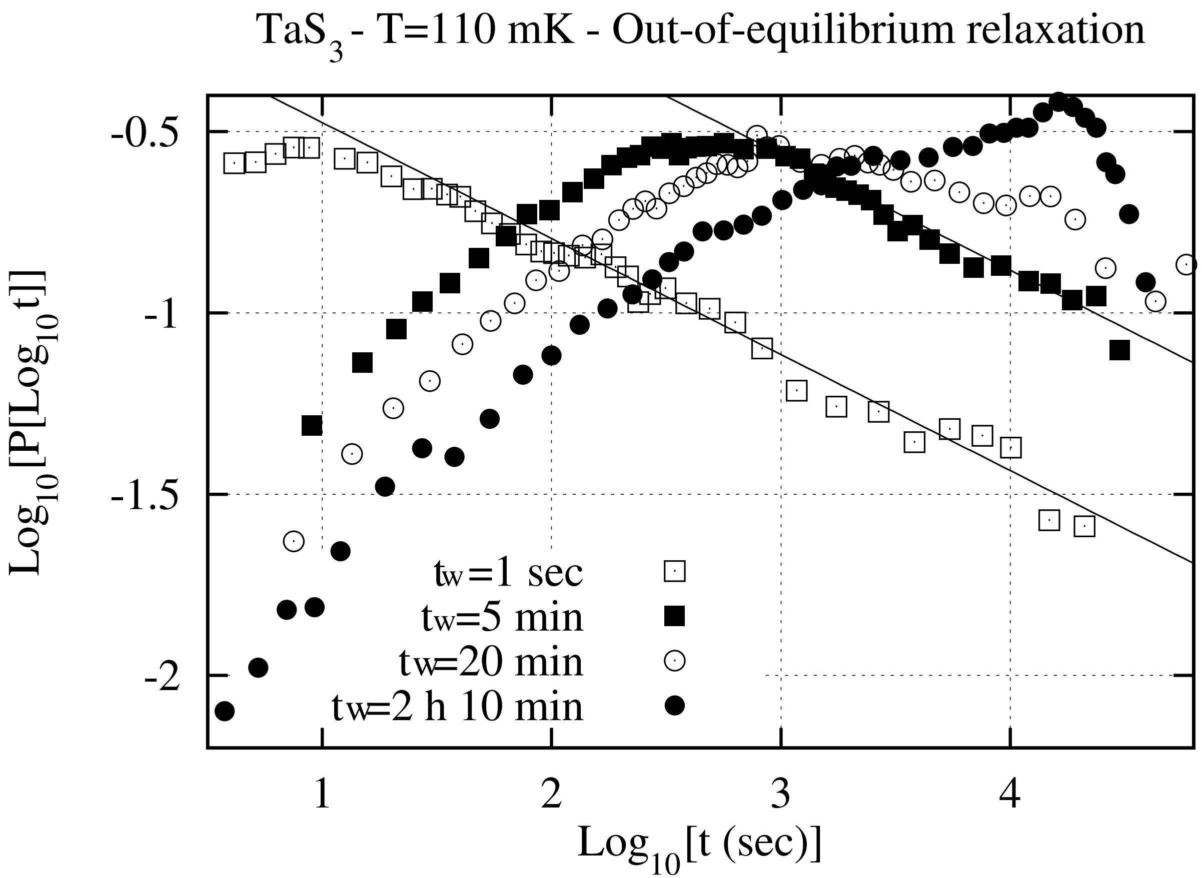
Spectrum of relaxation times (2)



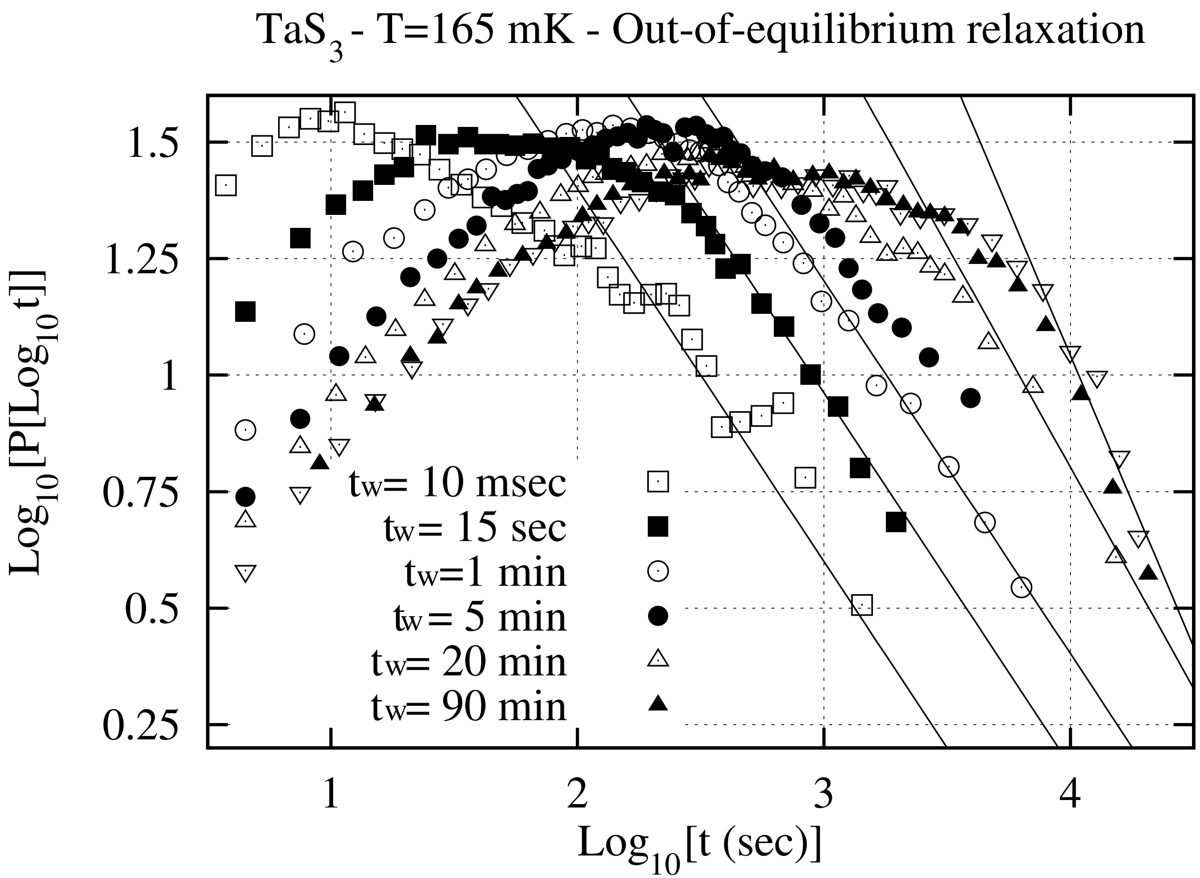
Spectrum of relaxation times (3)



Spectrum of relaxation times (4)



Spectrum of relaxation times (5)



Summary of the experiments

1. $1/T^2$ specific heat at low temperature.

2. Interrupted ageing (existence of a maximal relaxation time).

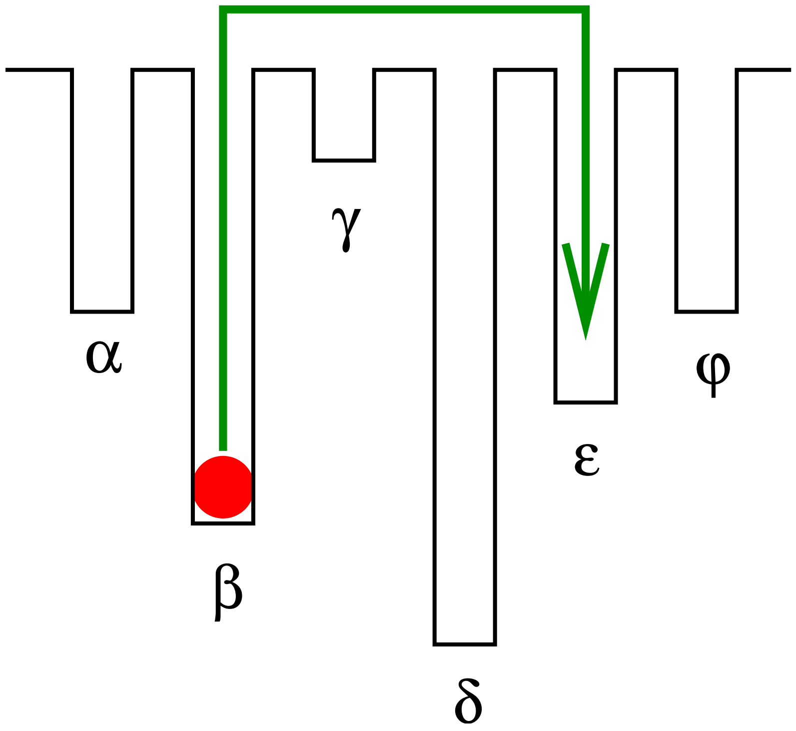
3. Power-law relaxation.

4. Commensurate systems relax faster than incommensurate systems.

The point 3. can hardly be explained by independent impurities. This is why we consider collective effects.

Phenomenological REM-like trap model

Collection of traps with energies $-E_\alpha$ chosen in a distribution $p(E_\alpha)$. All traps are connected with each other.



Application to density waves

1. We introduce a cut-off in the trap distribution: $p_1(E_\alpha) \propto \exp(-E_\alpha/T_g)$ for $E_\alpha < E_{max}$, and $p_1(E_\alpha) = 0$ if $E_\alpha > E_{max}$.

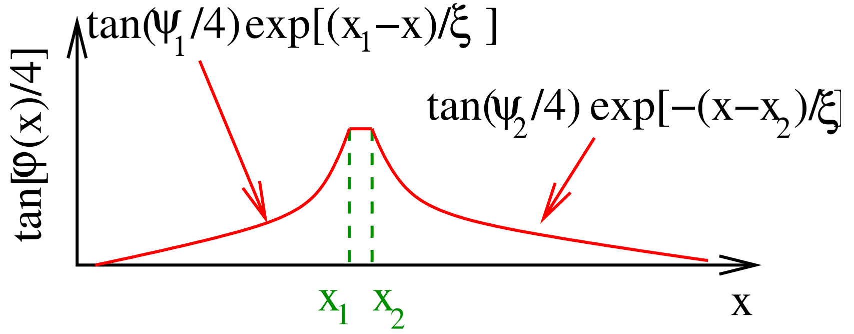
2. We calculate the dynamical correlation functions by replacing $\exp(-\tau/\tau_\alpha)$ by $\theta(\tau_\alpha - \tau)$, which leads to the correct exponents but wrong prefactors.

3. We obtain **interrupted ageing** and a **power-law relaxation**. A comparison to experiments leads to $T/T_g = 1.4 \div 2.2$ so that $T_g = 80 \div 300$ mK, smaller than the experimental temperature.

Two strong pinning impurities at distance R (approximate)

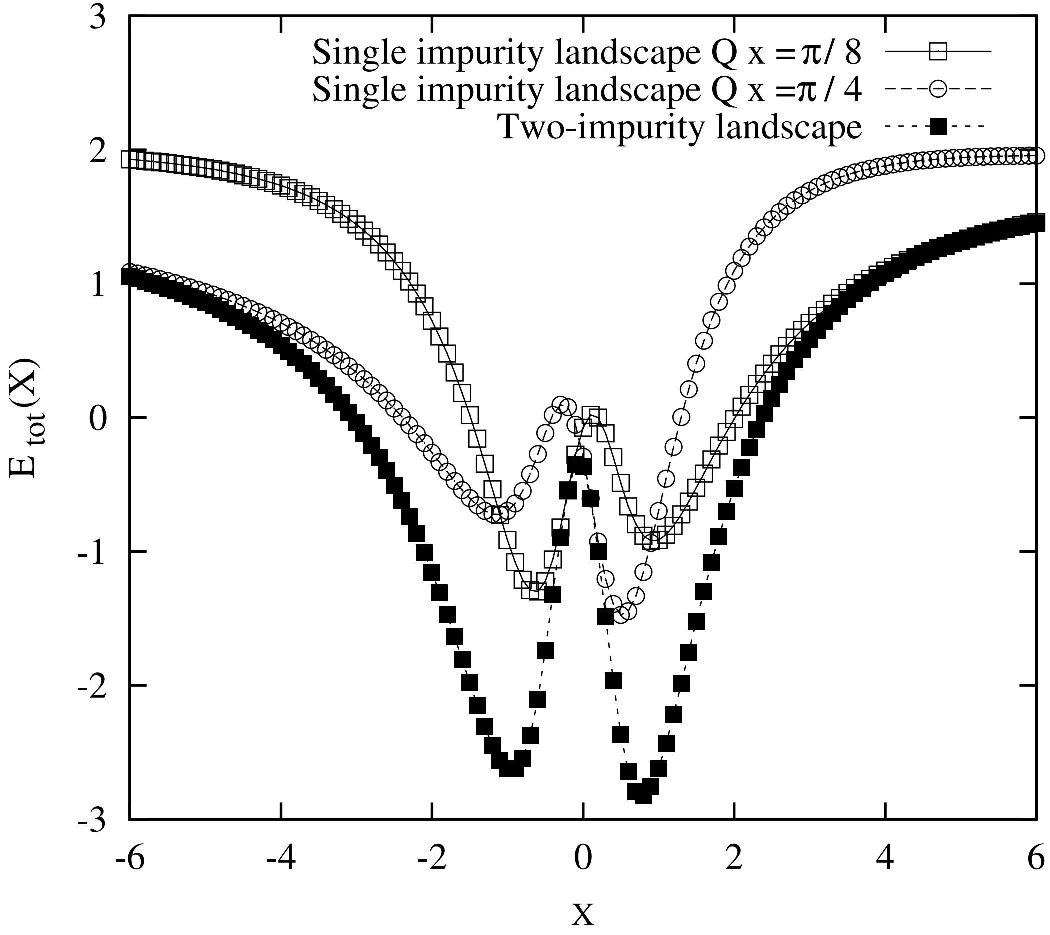
1) Independent impurities if $R \gg \xi_0$.

2) R is much smaller than ξ_0: pinning energy is additive



3) Intermediate values of R: interpolation between the two limits.

Example

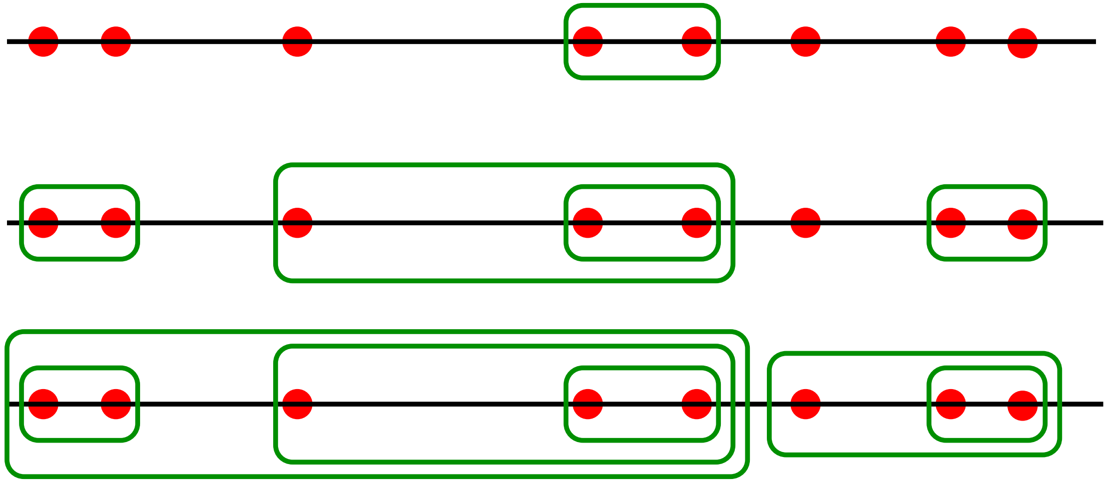


Single impurity landscape Q x =π/ 8
Single impurity landscape Q x =π / 4
Two-impurity landscape
$E_{tot}(X)$
X
3
2
1
0
-1
-2
-3
-6
-4
-2
0
2
4
6

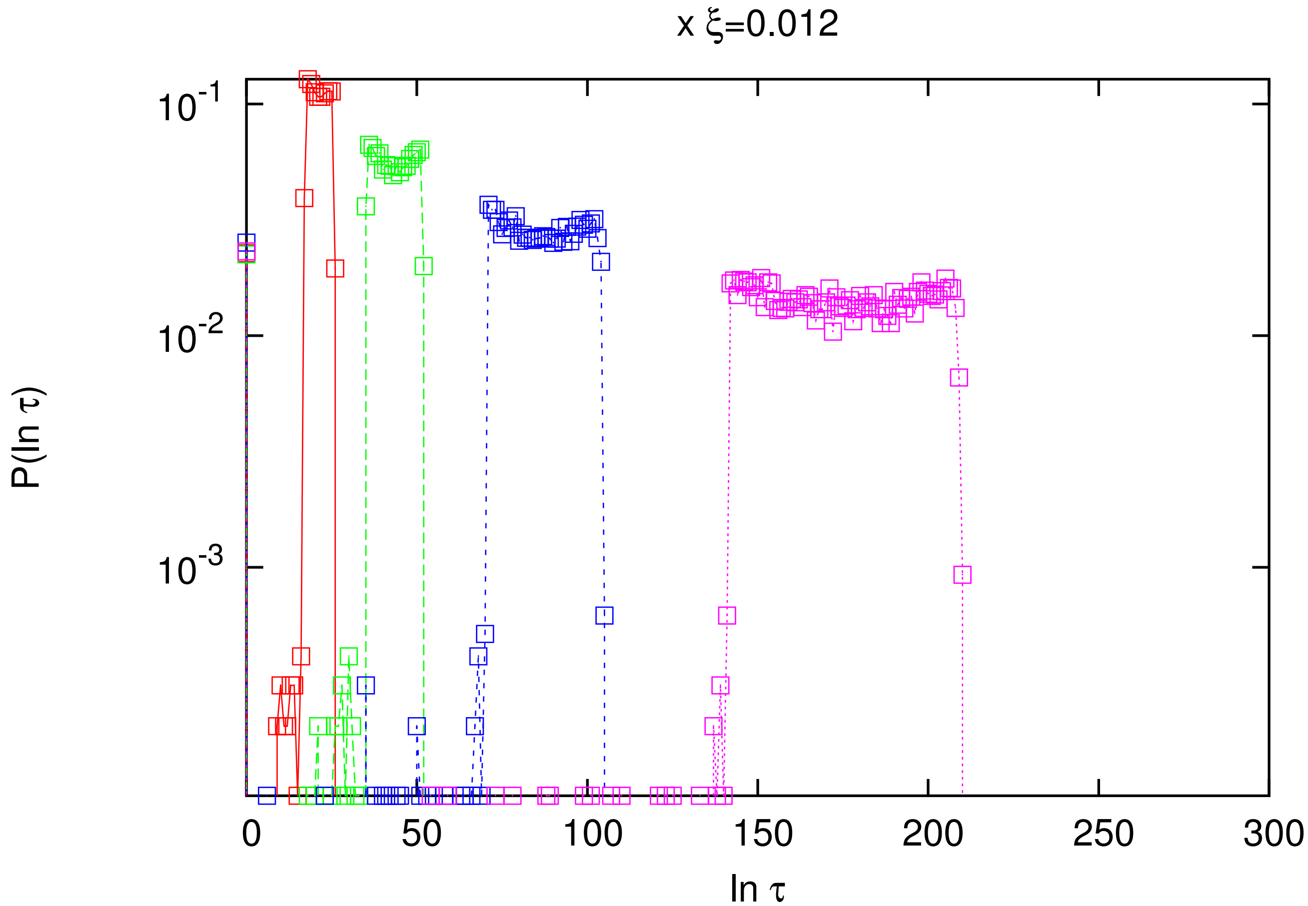
Dynamical renormalization group

Similar to the discussion of the dynamics of the 1D random field Ising model (Fisher, Le Doussal, Monthus, ’98).

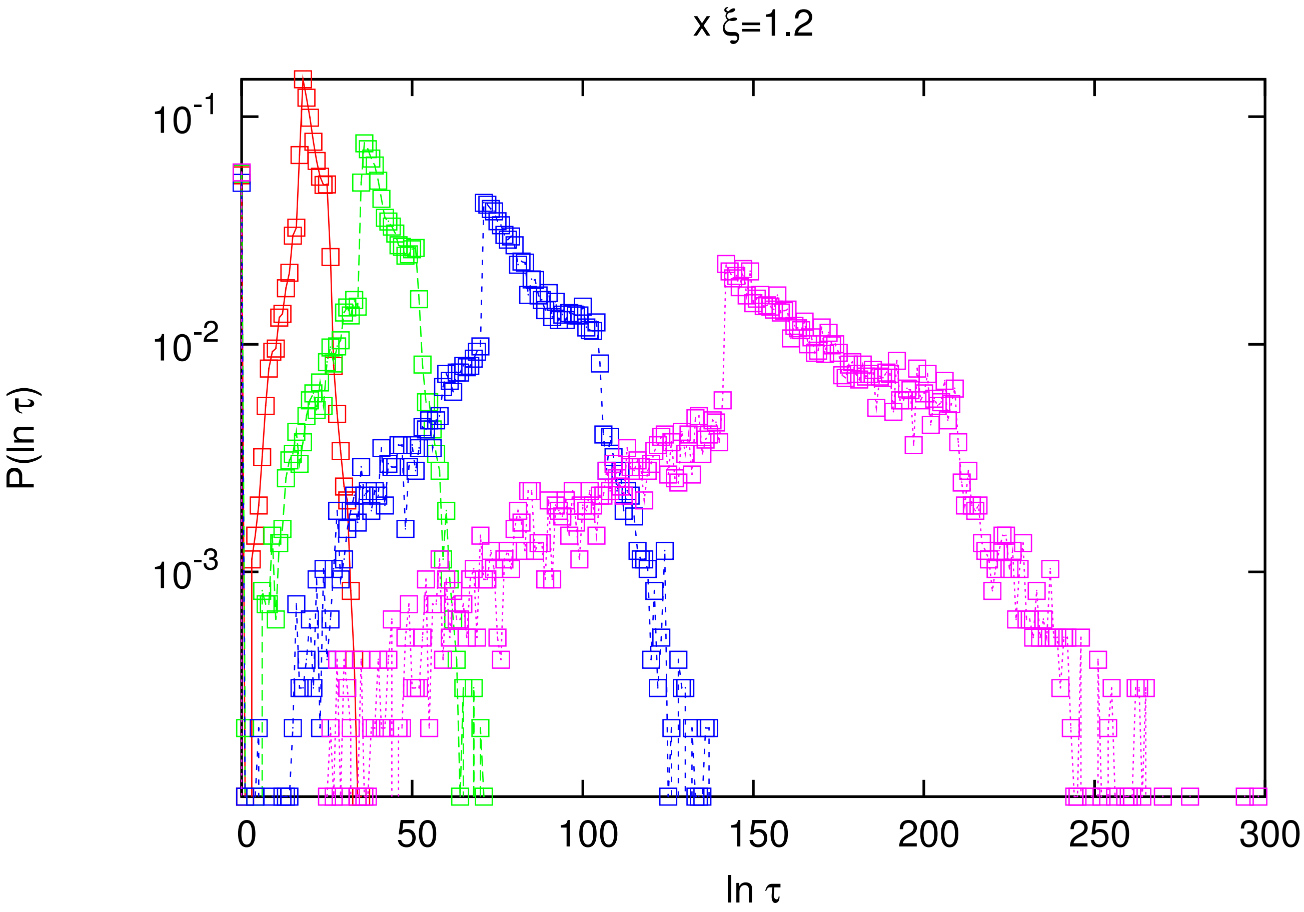
We suppose a quench from high temperature (not like in the experiment !). The temperature is fixed but time increases. Small objects with fast relaxation merge into bigger objects with slower relaxation:



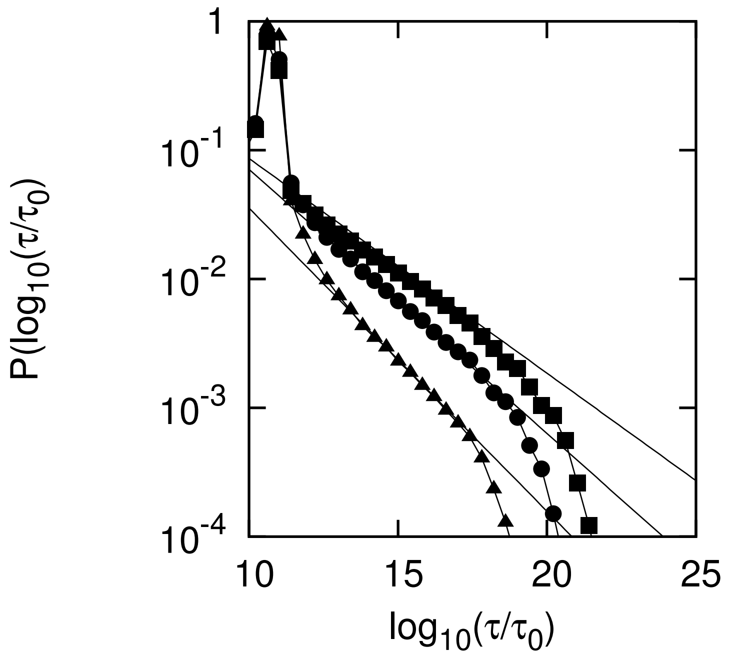
$x\xi \simeq 0.01$



$x\xi \simeq 1$



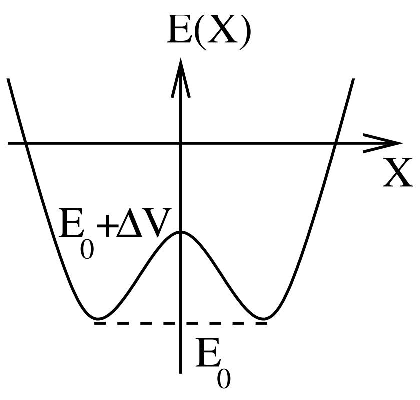
More statistics: $x\xi = 0.5, 1, 1.5$



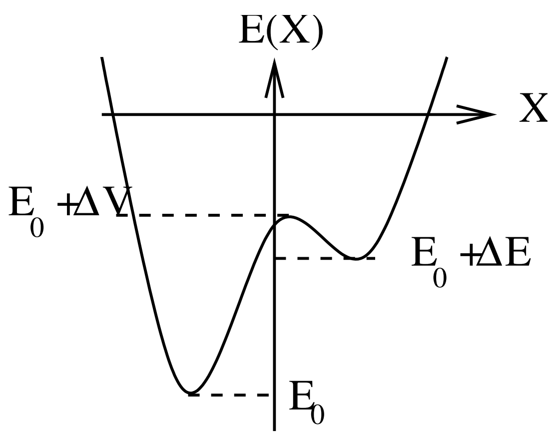
Power-law relaxation + **interrupted ageing** due to the fluctuations of the phase in between two impurities

Energy landscape for several impurities

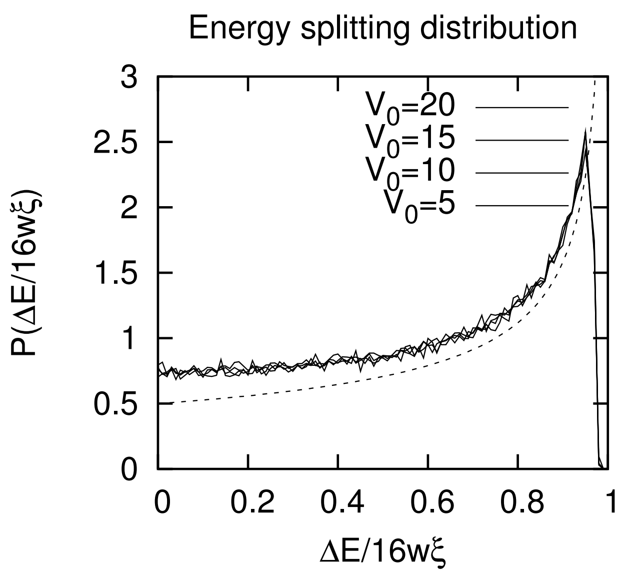
Let us make the asumption that the phase cannot vary between two impurities at a distance smaller than ξ.



(a)



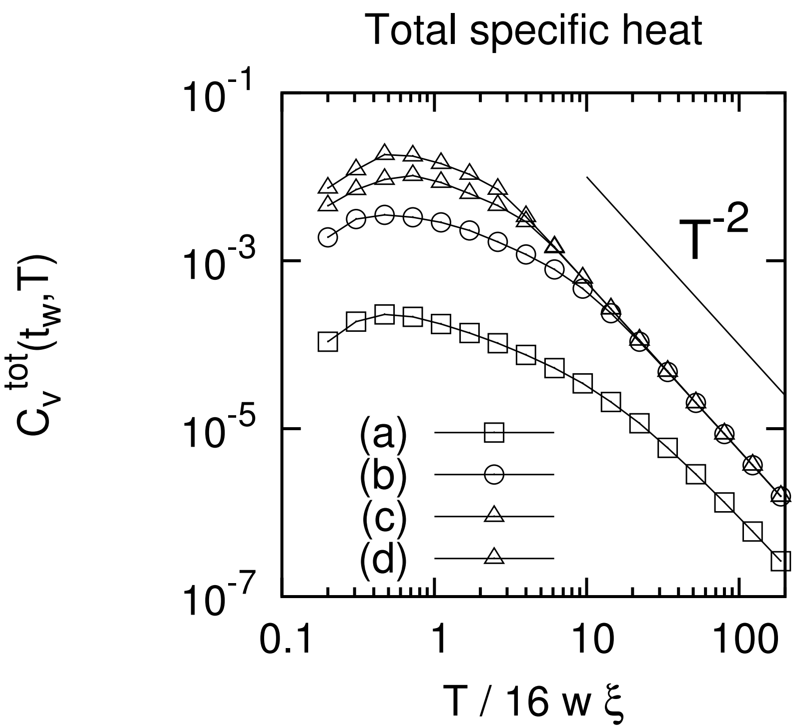
(b)

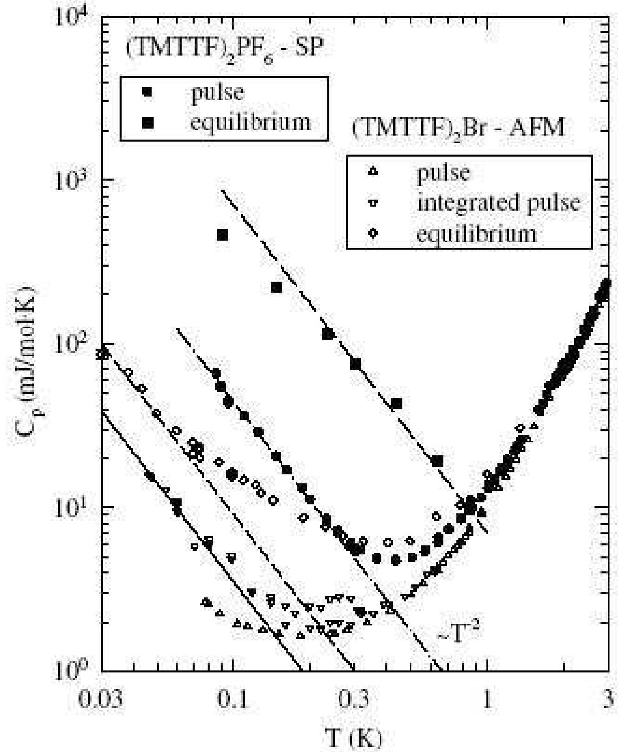


$\Delta E = 0$ in the commensurate case $(E(-X) = E(X))$; $\Delta E_{typ} = 16w\xi$ in the incommensurate case (independent on Δ and T_c)= energy of a 2π-soliton.

Total specific heat

$$C_v^{tot}(t_w, T) = \frac{1}{\Delta T}\left[U(t_w, t_w, T + \Delta T) - U(0, 0, T)\right].$$





Quantum effects

We start from the Peierls Hamiltonian without interchain couplings

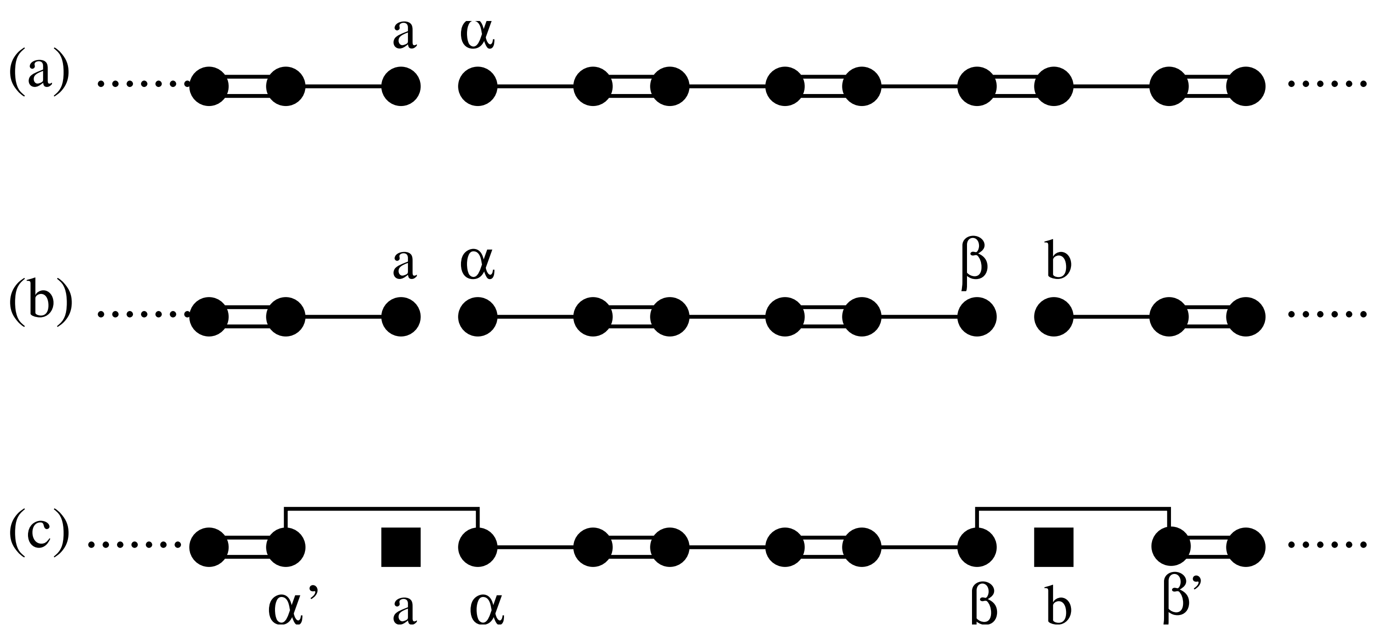
$$H = \sum_i \left[t + \epsilon \cos(2k_F x_i)\right] \left[c_{i+1}^{+} c_i + c_i^{+} c_{i+1}\right],$$

that is written in terms of right and left moving fields, and diagonalized by a Bogoliubov transformation. Impurities are treated by standard Green's function methods.

In the classical model and quantum models the width of the soliton is

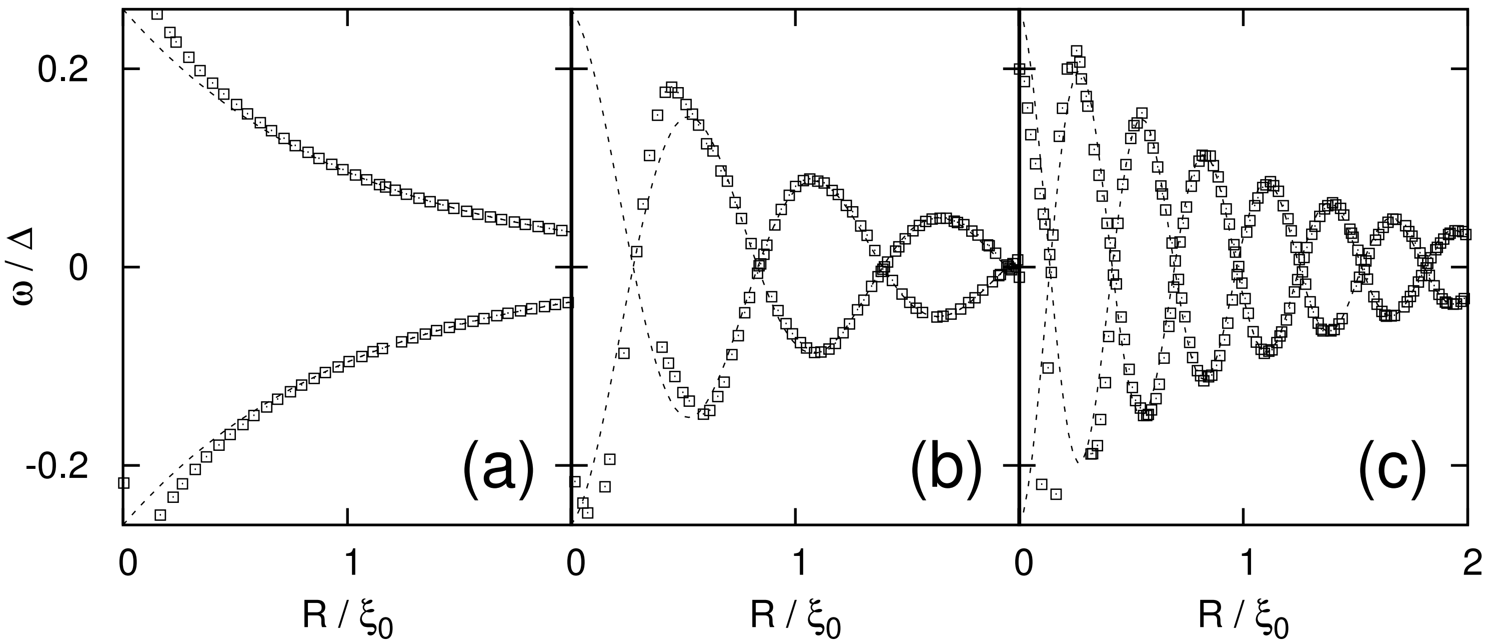
$$\xi_{cl} = \sqrt{\frac{\hbar v_F}{2\pi w}}\ , \text{ and } \xi_{qu} = \frac{2\hbar v_F}{\sqrt{\Delta^2 - E^2}}.$$

Substitutional disorder (commensurate case)



Without interactions between impurities the bound states are degenerate in the middle of the gap.

Oscillations of bound states due to substitutional impurities



(a): $k_F = \pi/2$; (b): $k_F = \pi/2 + 0.02$; (c): $k_F = \pi/2 + 0.04$.

$$E(R)/\Delta \simeq \pm 0.26 \cos(\delta k_F R) \exp(-R/\xi_0)$$

Consequences for $C_v(T)$ and $\chi(T)$

Distribution of hopping parameters:

$$P(|t|) \propto |t|^{-1+x\xi_0}.$$

The energy is

$$U \simeq \int_0^T |t|P(|t|)d|t| \propto T^{x\xi_0+1} \text{ , and } C_v \propto T^{x\xi_0}.$$

For a spin model the susceptibility is

$$\chi(T) \propto T^{-1+x\xi_0}.$$

We suggest that this can explain the power-law specific heat observed experimentally at intermediate temperatures, that depends weakly on the waiting time in experiments.

Conclusions

1. **REM-like model:** interrupted ageing and power-law relaxation.

2. **Dynamical renormalization group:** broad spectra of relaxation time for $x\xi \sim 1$, interrupted ageing and power-law relaxation following a quench.

3. **Energy landscape for several impurities:** $1/T^2$ specific heat and discussion of waiting time effects.

4. **Substitutional disorder:** oscillations of bound states. Power-law specific heat and susceptibilities.