

# Temperature Echoes in Proteins

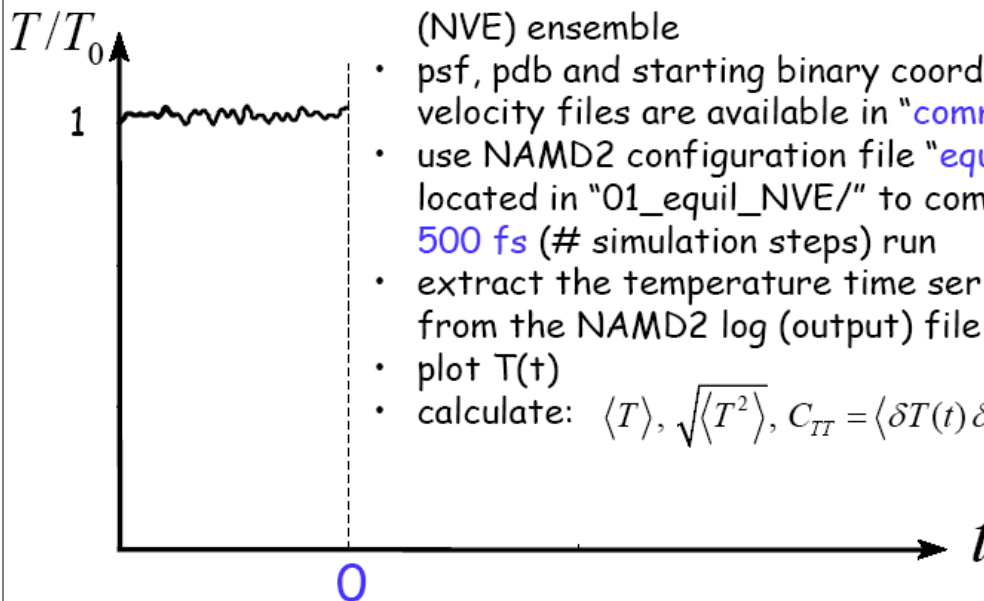
- ▶ Coherent motion in proteins: Echoes
- ▶ Generation of echoes in *ubiquitin* via velocity reassignments
  - 1) Temperature quench echoes
  - 2) Constant velocity reassignment echoes
  - 3) Velocity reassignment echoes

temperature  $\leftrightarrow$  velocities

kinetic temperature:

$$T(t) = \frac{2}{(3N - 6)k_B} \sum_{n=1}^{3N-6} \frac{m_n v_n^2(t)}{2}$$

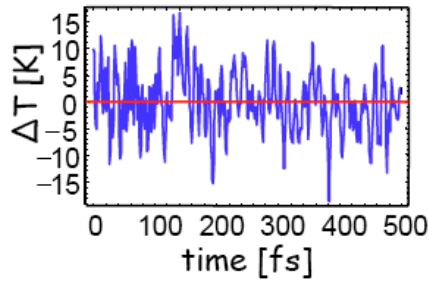
## Generating T-Quench Echo: Step1



- your system is ubiquitin (1UBQ) in vacuum, pre-equilibrated at  $T_0=300\text{K}$
- run all simulations in the *microcanonical* (NVE) ensemble
- psf, pdb and starting binary coordinate and velocity files are available in "common/"
- use NAMD2 configuration file "equil.conf" located in "01\_equil\_NVE/" to complete a 500 fs (# simulation steps) run
- extract the temperature time series  $T(t)$  from the NAMD2 log (output) file
- plot  $T(t)$
- calculate:  $\langle T \rangle$ ,  $\sqrt{\langle T^2 \rangle}$ ,  $C_{TT} = \langle \delta T(t) \delta T(0) \rangle$

# Temperature Autocorrelation Function

$$\Delta T(t) = T(t) - \langle T(t) \rangle$$



$$C(t) = \langle \Delta T(t) \Delta T(0) \rangle$$

$$\rightarrow C(t_i) \approx \frac{1}{N-i} \sum_{n=1}^{N-i} \Delta T(t_{n+i}) \Delta T(t_n)$$

$$C(t) = C(0) \exp(-t/\tau_0)$$

Temperature relaxation time:

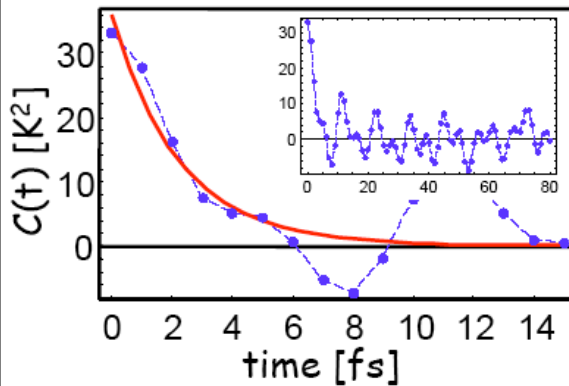
$$\tau_0 \approx 2.2 \text{ fs}$$

Mean temperature:

$$\langle T \rangle = 299 \text{ K}$$

RMS temperature:

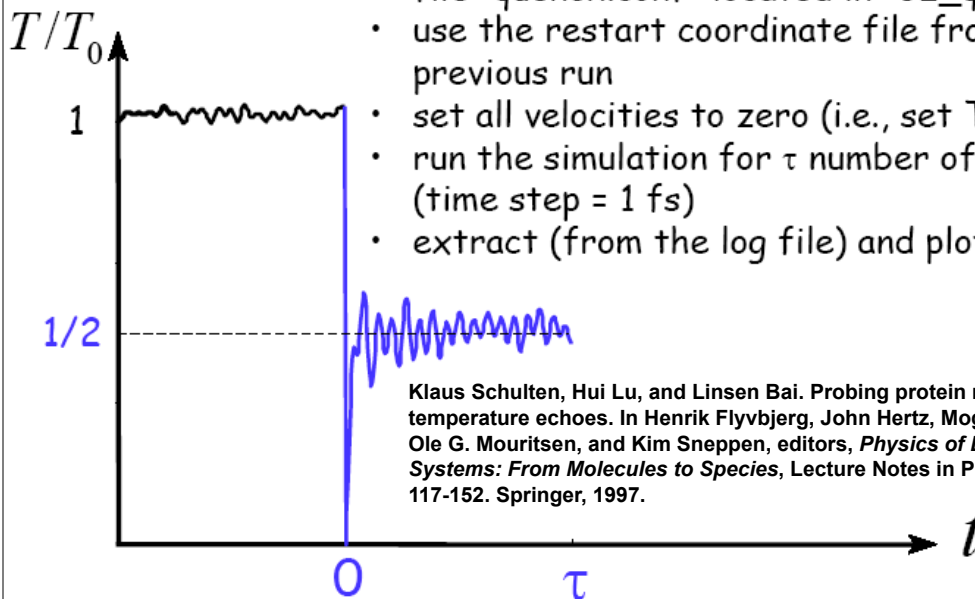
$$\sqrt{\langle \Delta T^2 \rangle} = \sqrt{C(0)} = 6 \text{ K}$$



## Generating T-Quench Echo: Step2

Perform the 1<sup>st</sup> temperature quench

- start a new simulation using configuration file "quench.conf" located in "02\_quencha/"
- use the restart coordinate file from the previous run
- set all velocities to zero (i.e., set  $T=0$ )
- run the simulation for  $\tau$  number of steps (time step = 1 fs)
- extract (from the log file) and plot  $T(t)$

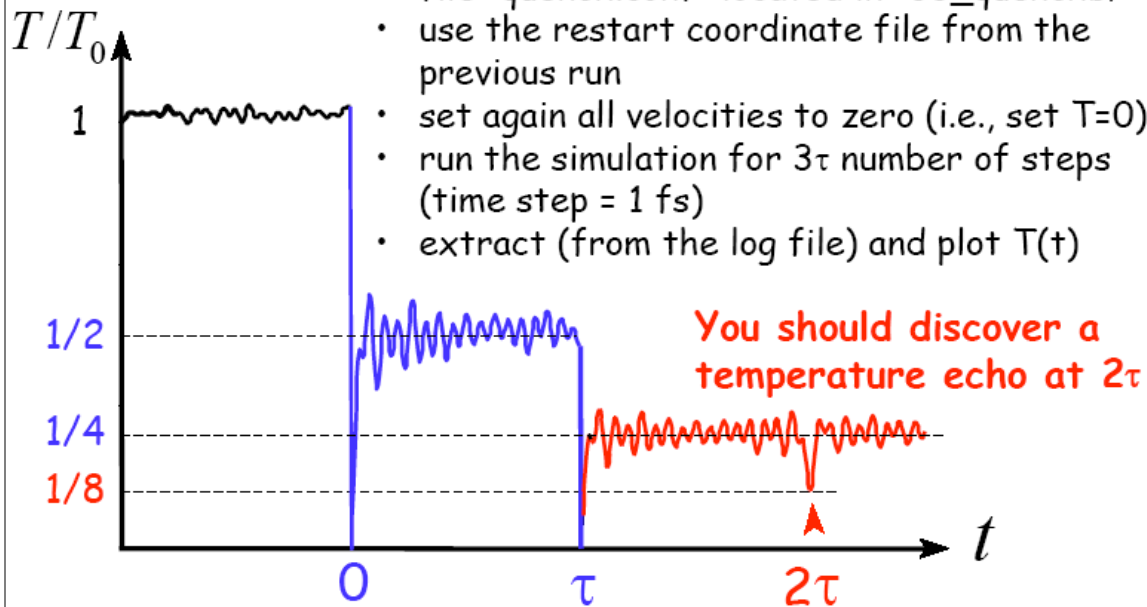


Klaus Schulten, Hui Lu, and Linsen Bai. Probing protein motion through temperature echoes. In Henrik Flyvbjerg, John Hertz, Mogens H. Jensen, Ole G. Mouritsen, and Kim Sneppen, editors, *Physics of Biological Systems: From Molecules to Species*, Lecture Notes in Physics, pp. 117-152. Springer, 1997.

## Generating T-Quench Echo: Step3

### Perform the 2<sup>nd</sup> temperature quench

- start a new simulation using configuration file "quench.conf" located in "03\_quenchb/"
- use the restart coordinate file from the previous run
- set again all velocities to zero (i.e., set  $T=0$ )
- run the simulation for  $3\tau$  number of steps (time step = 1 fs)
- extract (from the log file) and plot  $T(t)$



## Explanation of the T-Quench Echo

**Assumption:** protein  $\approx$  collection of weakly interacting harmonic oscillators with dispersion  $\omega = \omega_\alpha$ ,  $\alpha = 1, \dots, 3N - 6$

**Step1:**  $t < 0$

$$\begin{aligned} x(t) &= A_0 \cos(\omega t + \theta_0) \\ v(t) &= -\omega A_0 \sin(\omega t + \theta_0) \end{aligned}$$

**Step2:**  $0 < t < \tau$

$$\left. \begin{aligned} x_1(t) &= A_1 \cos(\omega t + \theta_1) \\ v_1(t) &= -\omega A_1 \sin(\omega t + \theta_1) \end{aligned} \right\} \xrightarrow{v_1(0)=0} \begin{cases} A_1 = A_0 \cos \theta_0 \\ \theta_1 = 0 \end{cases}$$

**Step3:**  $t > \tau$

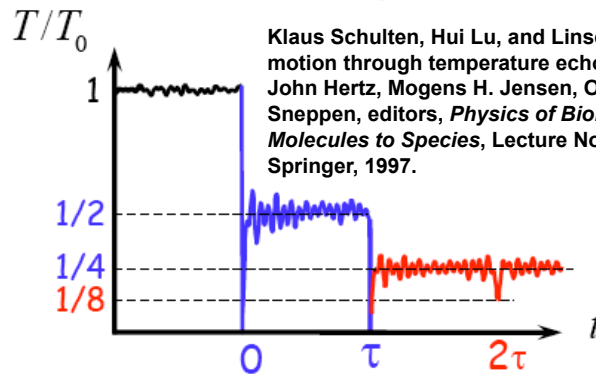
$$\left. \begin{aligned} x_2(t) &= A_2 \cos(\omega t + \theta_2) \\ v_2(t) &= -\omega A_2 \sin(\omega t + \theta_2) \end{aligned} \right\} \xrightarrow{v_2(\tau)=0} \begin{cases} A_2 = A_1 \cos \omega \tau \\ \theta_2 = -\omega \tau \end{cases}$$

## T-Quench Echo: Harmonic Approximation

$$T(t) \approx \frac{T_0}{4} \left[ 1 - \langle \cos(2\omega(t - \tau)) \rangle - \frac{1}{2} \langle \cos(2\omega(t - 2\tau)) \rangle \right]$$

$$\approx \begin{cases} 0 & \text{for } t = \tau \\ T_0/8 & \text{for } t = 2\tau \\ T_0/4 & \text{otherwise} \end{cases}$$

$$\Rightarrow \text{echo depth} = T(2\tau) - T_0/4 = T_0/8$$



## $T(t)$ and $C_{TT}(t)$

It can be shown:

$$\langle \cos(2\omega t) \rangle = \frac{\langle \delta T(t) \delta T(0) \rangle}{\langle \Delta T^2 \rangle} = C_{TT}(t), \quad \delta T(t) = T(t) - \langle T \rangle$$

Accordingly,

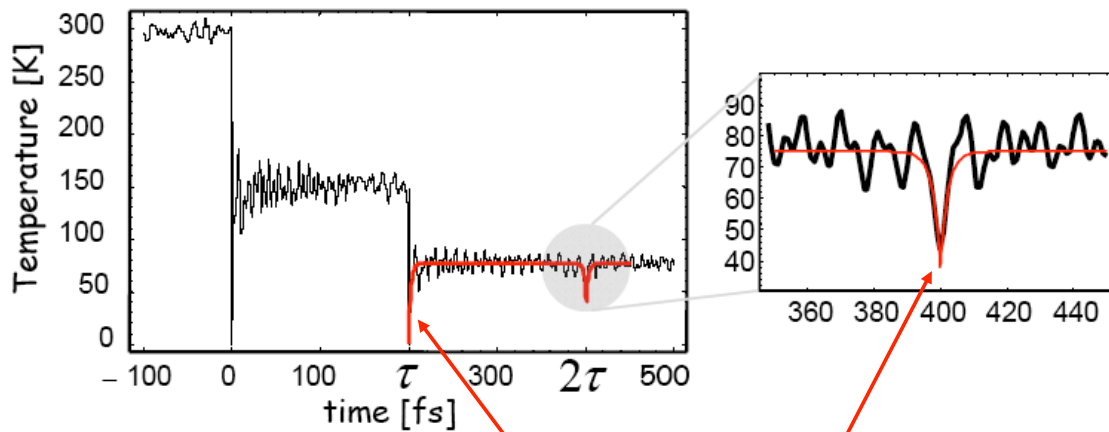
$$T(t) \approx \frac{T_0}{4} \left[ 1 - \langle \cos(2\omega(t - \tau)) \rangle - \frac{1}{2} \langle \cos(2\omega(t - 2\tau)) \rangle \right]$$



$$= \frac{T_0}{4} \left[ 1 - C_{TT}(t - \tau) - \frac{1}{2} C_{TT}(t - 2\tau) \right]$$

Klaus Schulten, Hui Lu, and Linsen Bai. Probing protein motion through temperature echoes. In Henrik Flyvbjerg, John Hertz, Mogens H. Jensen, Ole G. Mouritsen, and Kim Sneppen, editors, *Physics of Biological Systems: From Molecules to Species*, Lecture Notes in Physics, pp. 117-152. Springer, 1997.

## T-Quench Echo: Harmonic Approximation

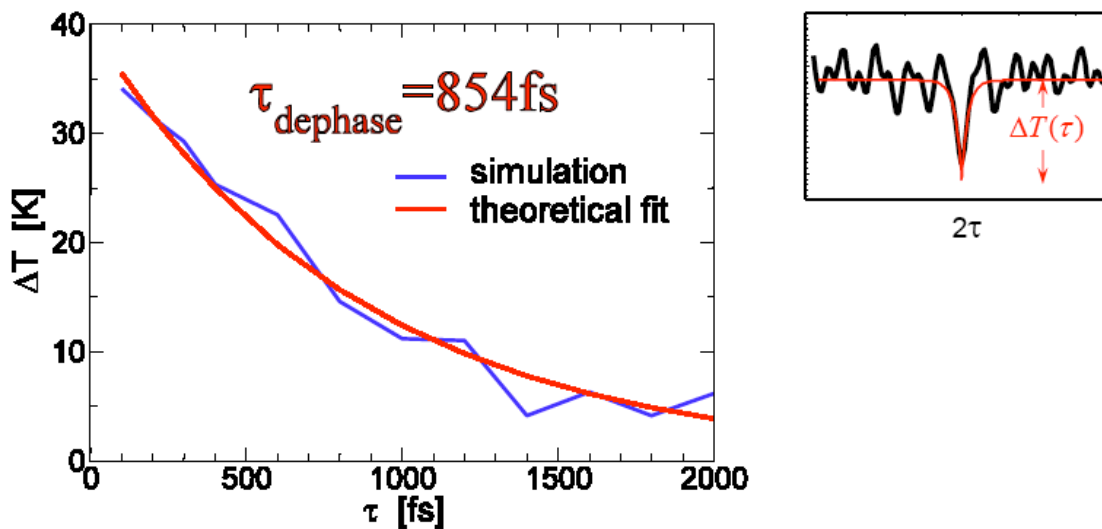


$$T(t) \approx \frac{T_0}{2} \left( 1 - C_{TT}(t - \tau) - \frac{1}{2} C_{TT}(|t - 2\tau|) \right)$$

$$C_{TT}(t) = \exp(-t/\tau_0), \quad \tau_0 \approx 2.2 \text{ fs}$$

Klaus Schulten, Hui Lu, and Linsen Bai. Probing protein motion through temperature echoes. In Henrik Flyvbjerg, John Hertz, Mogens H. Jensen, Ole G. Mouritsen, and Kim Sneppen, editors, *Physics of Biological Systems: From Molecules to Species*, Lecture Notes in Physics, pp. 117-152. Springer, 1997.

## Dephasing Time of T-Quench Echoes



$$\Delta T(\tau) = \Delta T(0) \exp[-\tau / \tau_{dephase}]$$

Klaus Schulten, Hui Lu, and Linsen Bai. Probing protein motion through temperature echoes. In Henrik Flyvbjerg, John Hertz, Mogens H. Jensen, Ole G. Mouritsen, and Kim Sneppen, editors, *Physics of Biological Systems: From Molecules to Species*, Lecture Notes in Physics, pp. 117-152. Springer, 1997.