

# NEMS memory bit at Landauer limit

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The 2nd ICT-Energy International Doctoral Symposium  
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Bristol, UK

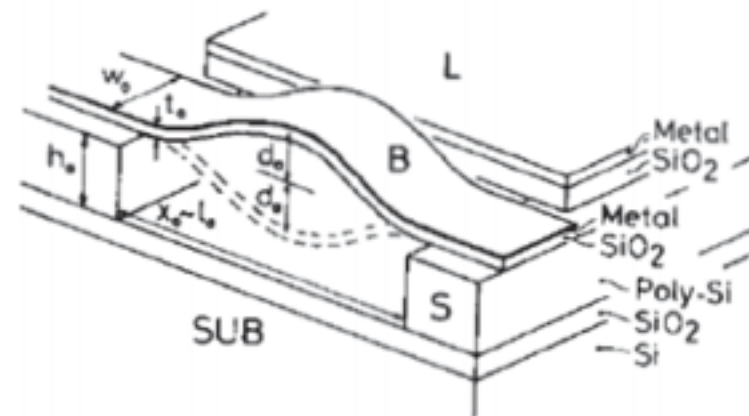
# Outline

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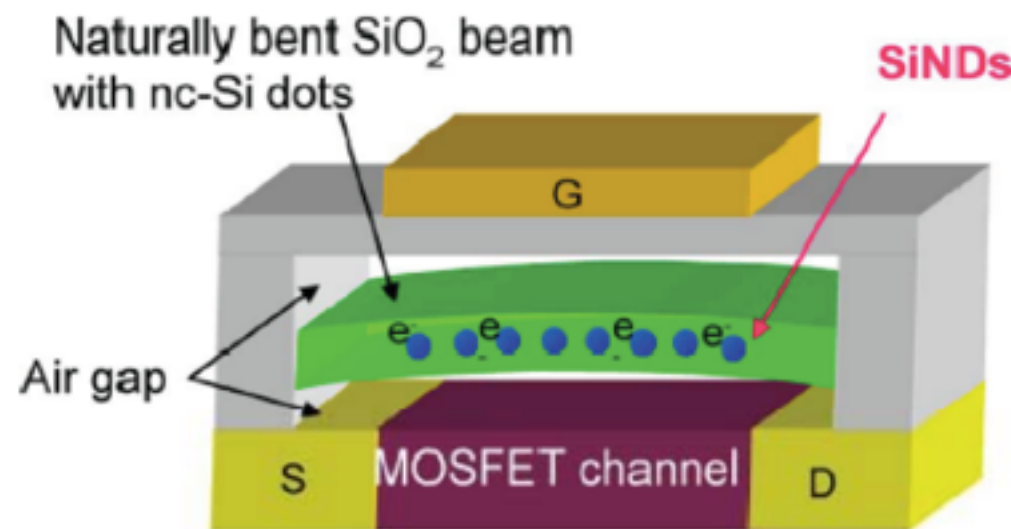
- Problem definition
- Methodology
- Modeling
- Reset protocol
- Switch protocol
- Conclusion

# NEMS Memory Devices

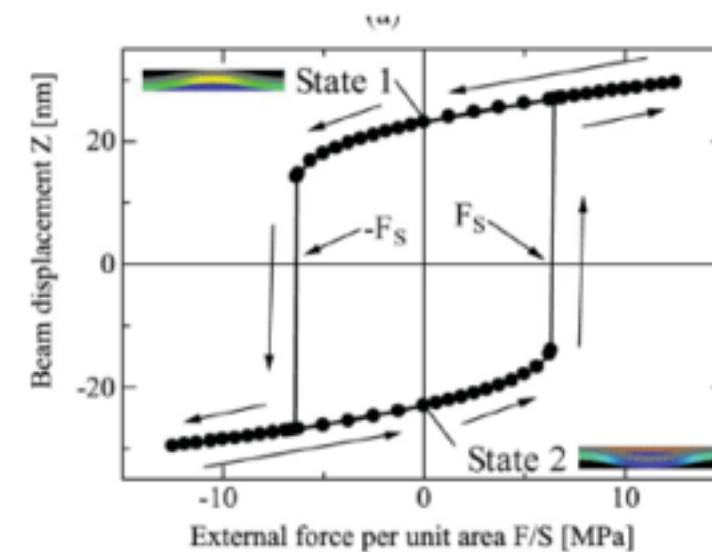
HÄLG: MICRO-ELECTRO-MECHANICAL NONVOLATILE MEMORY CELL



(a)



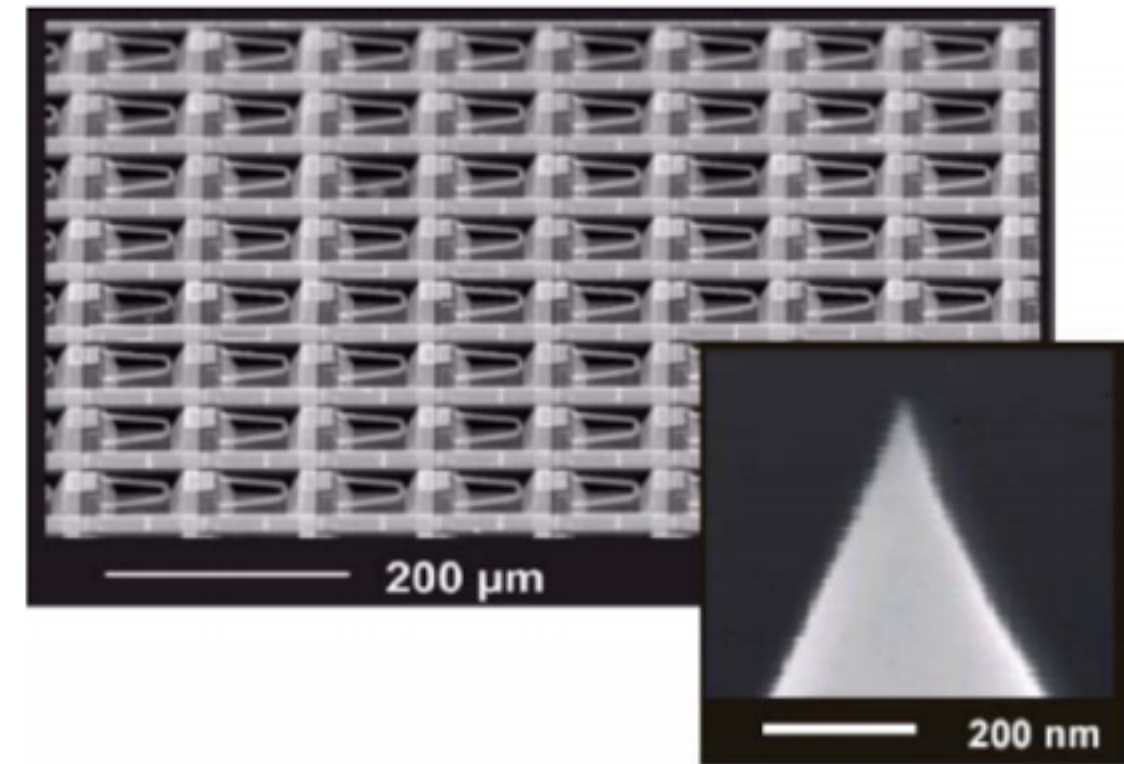
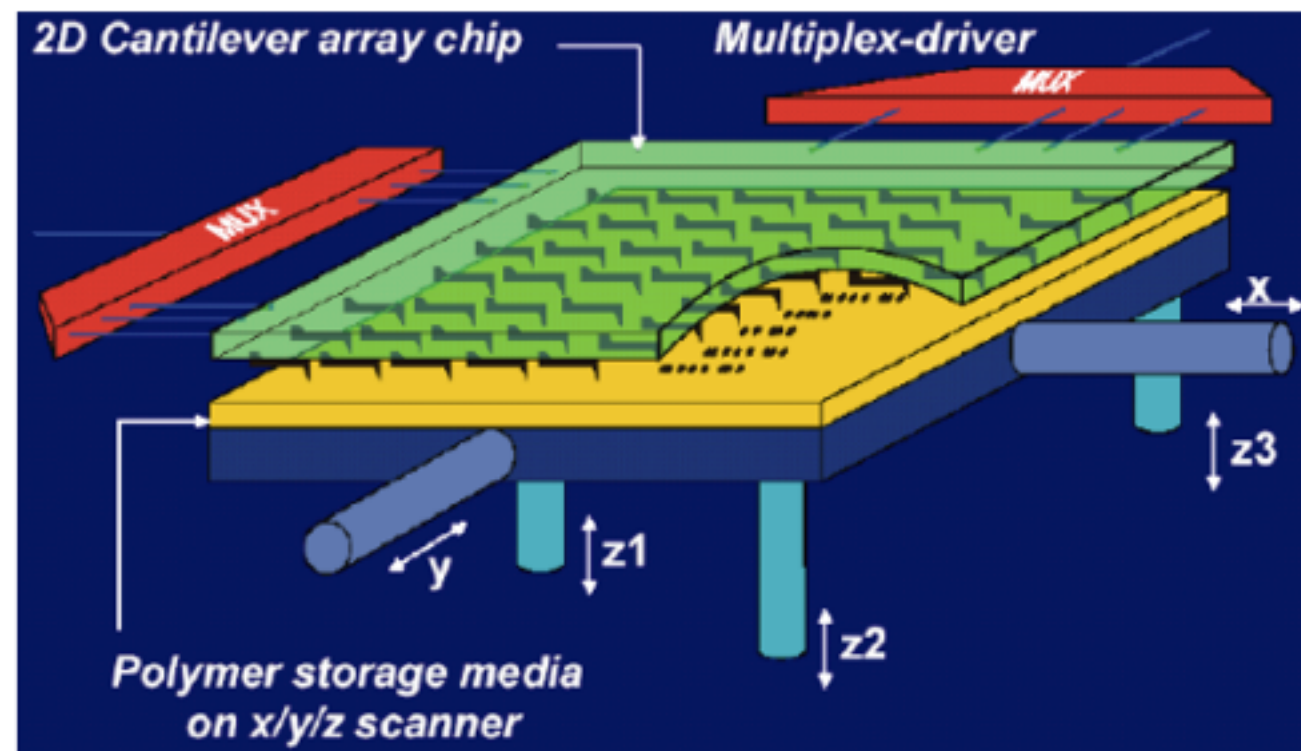
(b)



(c)

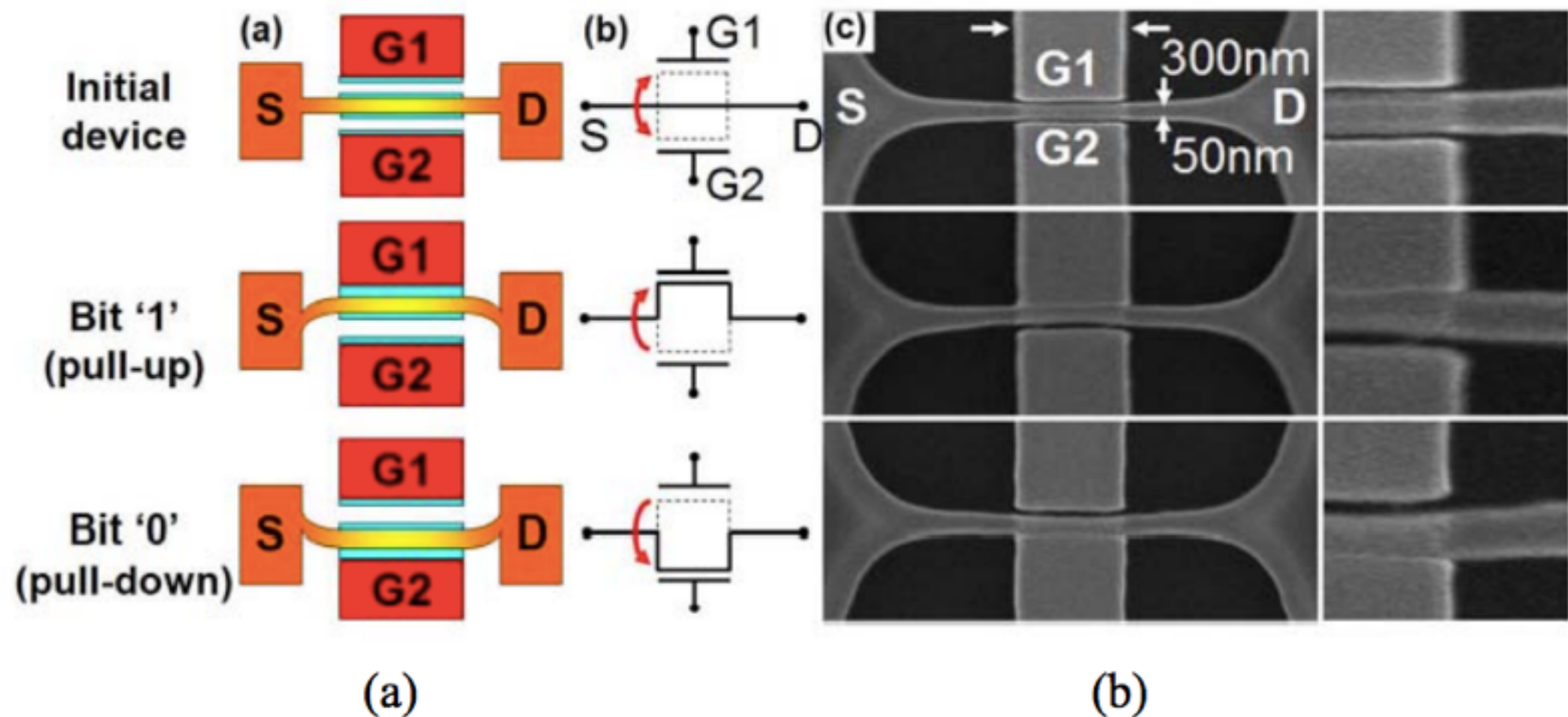
**Figure 1:** (a) Halg's and (b) Oda's bistable micro/nano-electro-mechanical memory concepts. (c) mechanical hysteresis in device (b).

# NEMS Memory Devices



**Figure 3:** Millipede AFM storage proposed and demonstrate by IBM for Tera-bit memory.

# NEMS Memory Devices

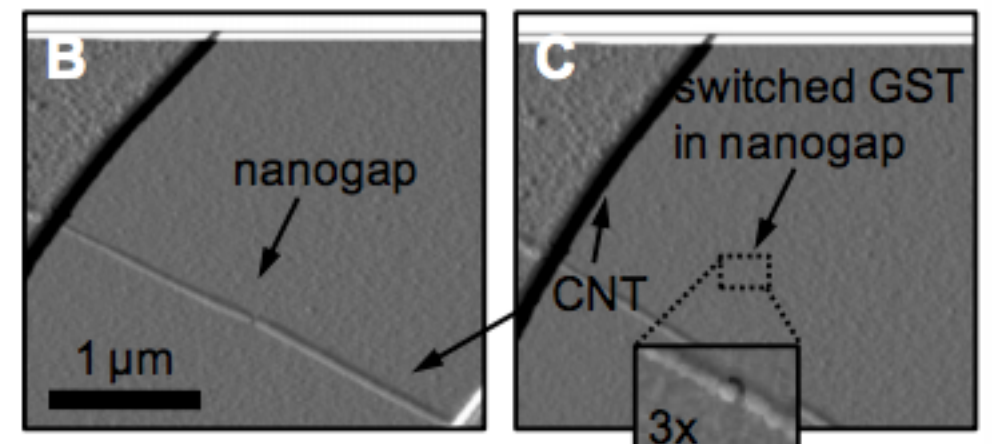
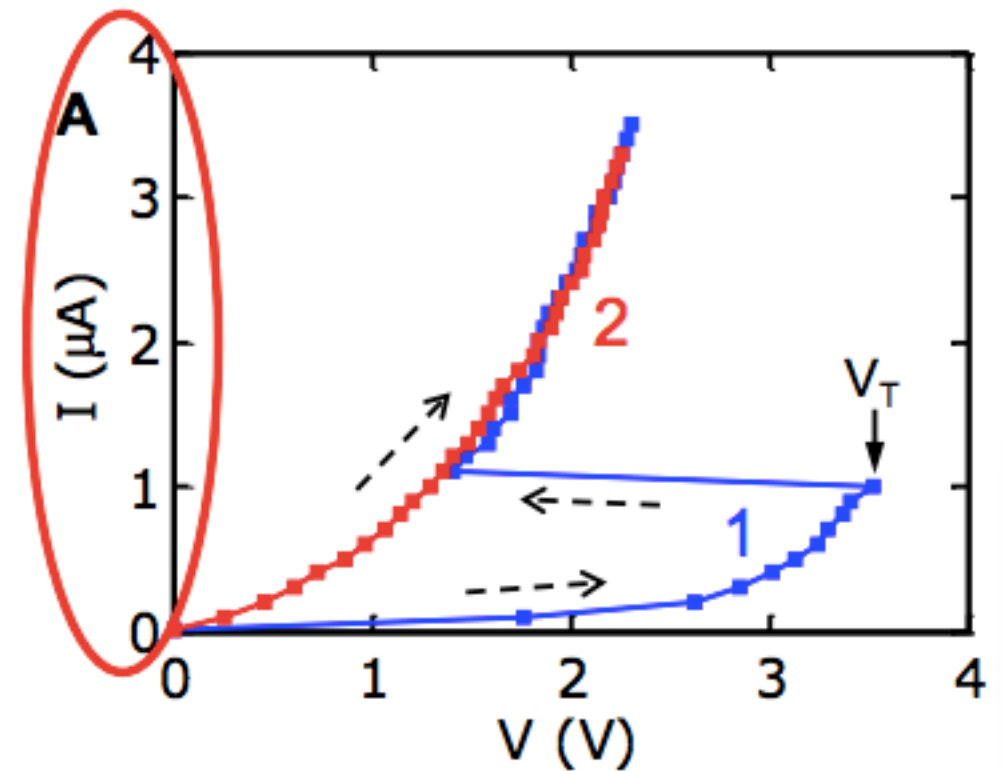
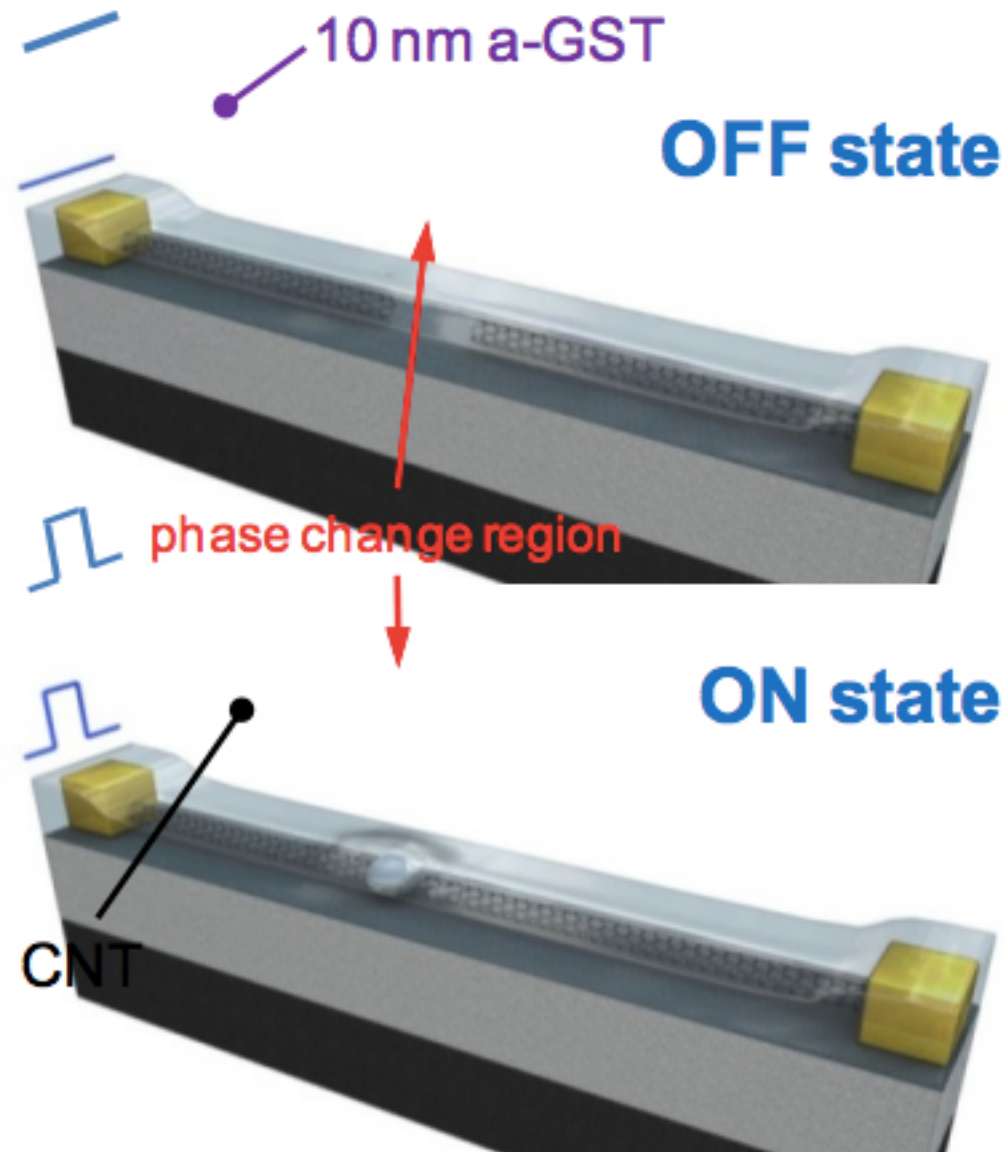


**Figure 7:** Illustration of Fin-FACT mechanical states for memory application: (a) device schematic and symbol, and (b) SEM images. The fin remains straightened at the initial state. Bit '1' and bit '0' are distinguished when the fin is in contact with G1 and G2, respectively.



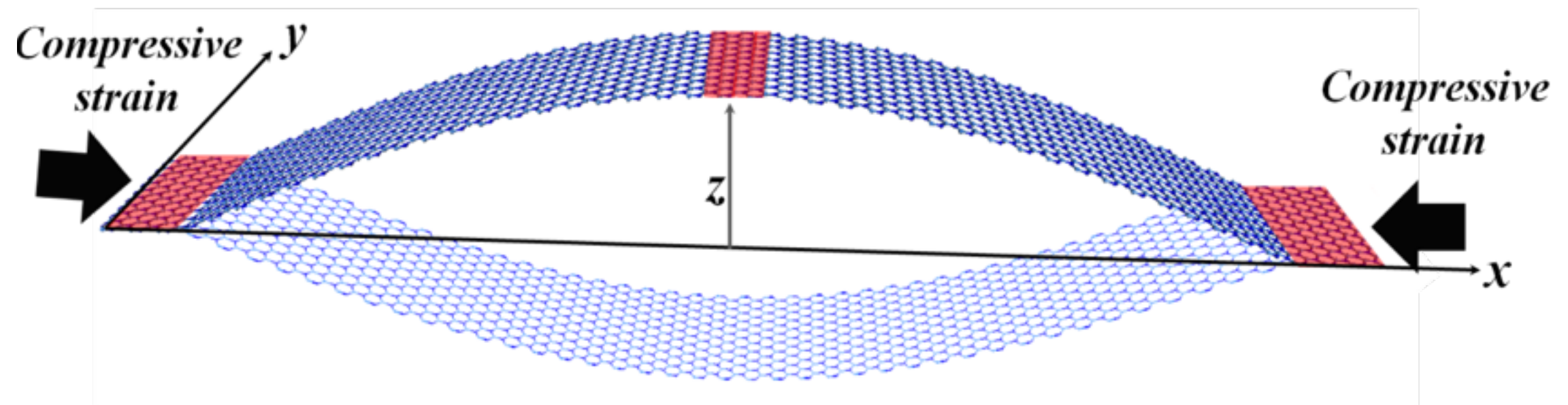
# NEMS Memory Devices

F. Xiong, A. Liao, D. Estrada, E. Pop, *Science* 332, 568 (2011, April 29 cover article)

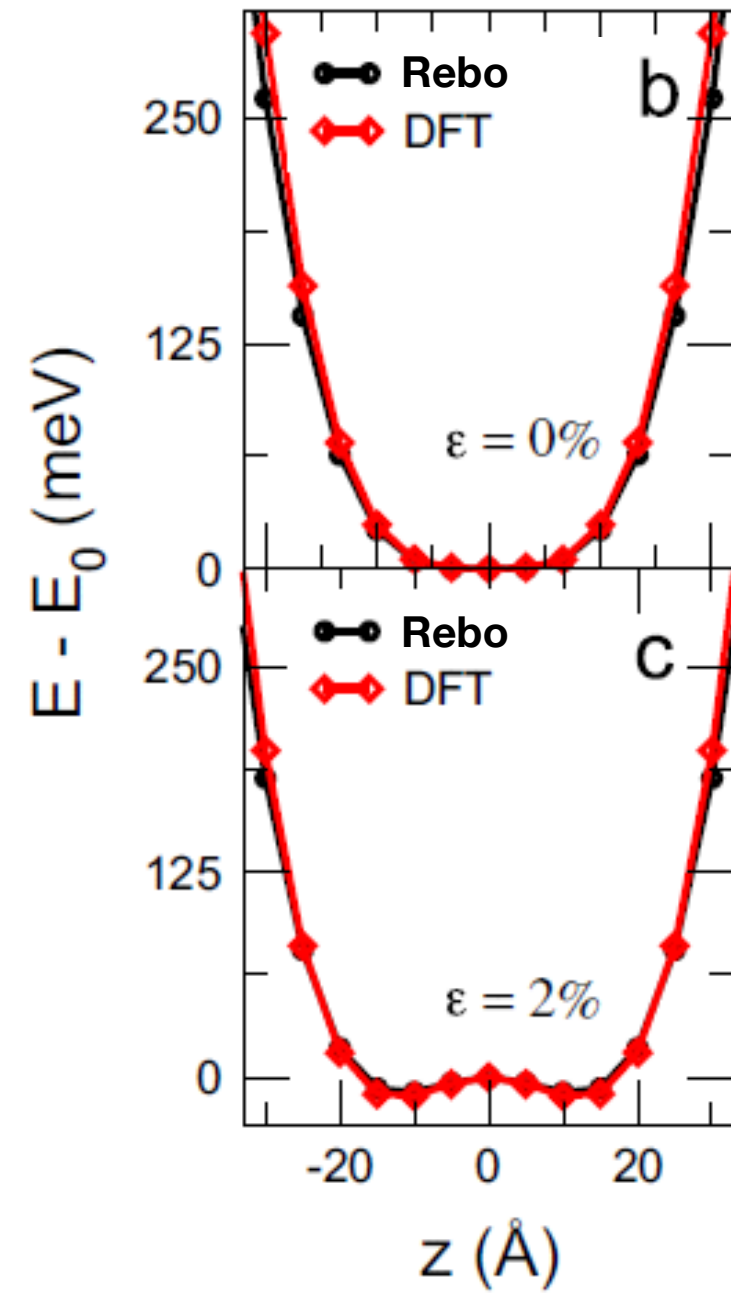
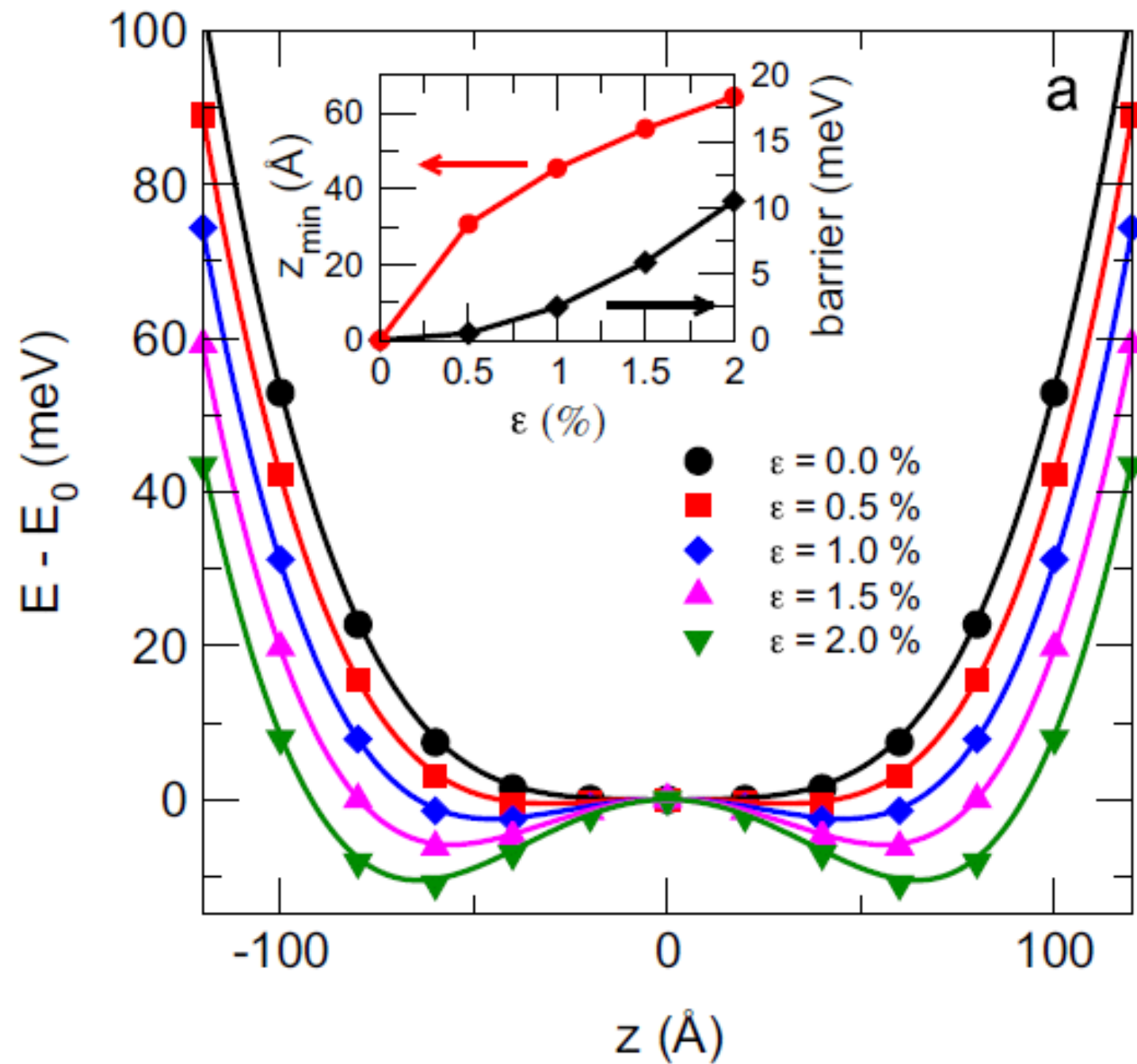


# NEMS system

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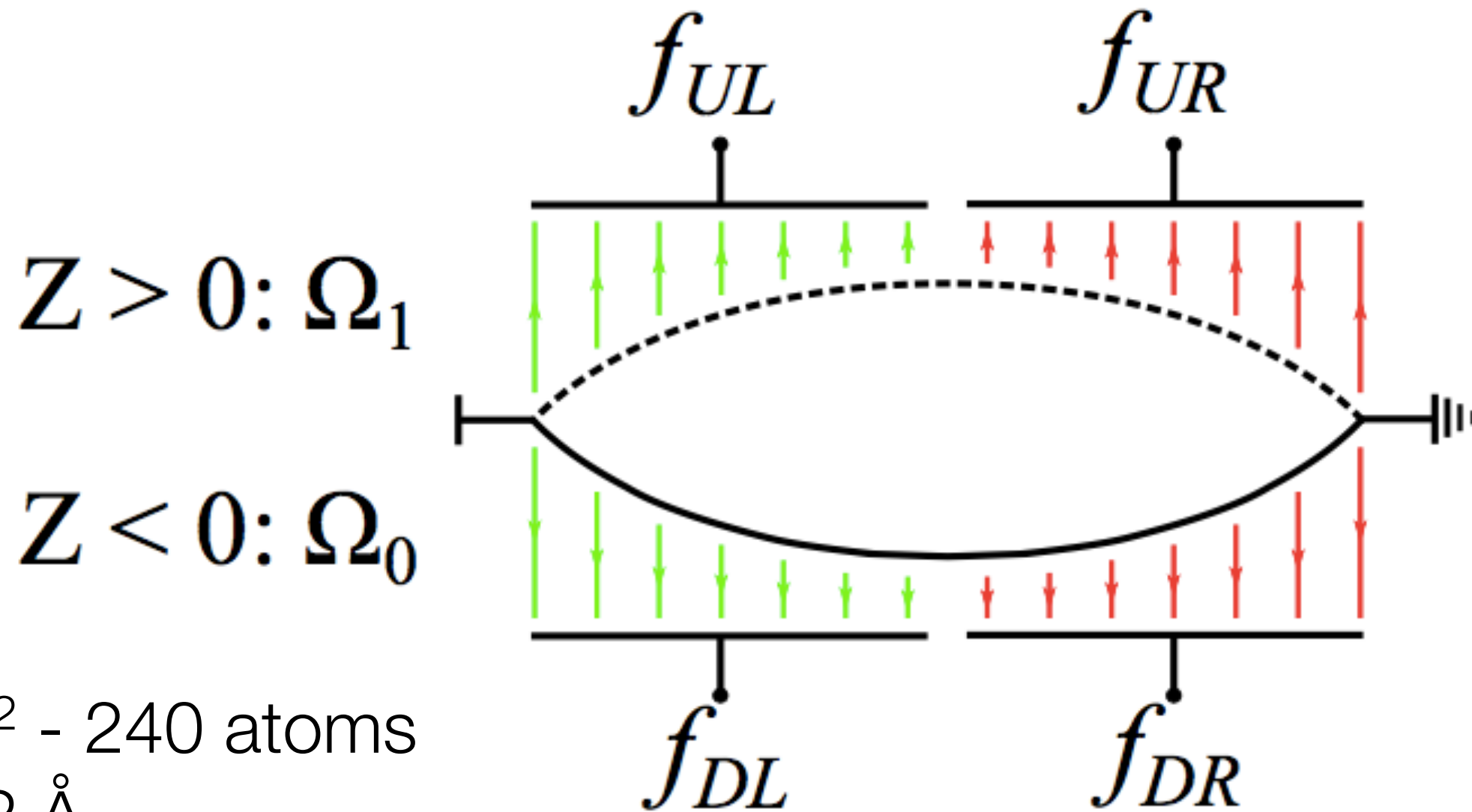
# NEMS system





# NEMS system

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$6 \times 1 \text{ nm}^2$  - 240 atoms  
 $a = 2.42 \text{ \AA}$   
 $Y = 0.85 \text{ TPa}$   
 $T = 10 \text{ K}$

# Heat production evaluation

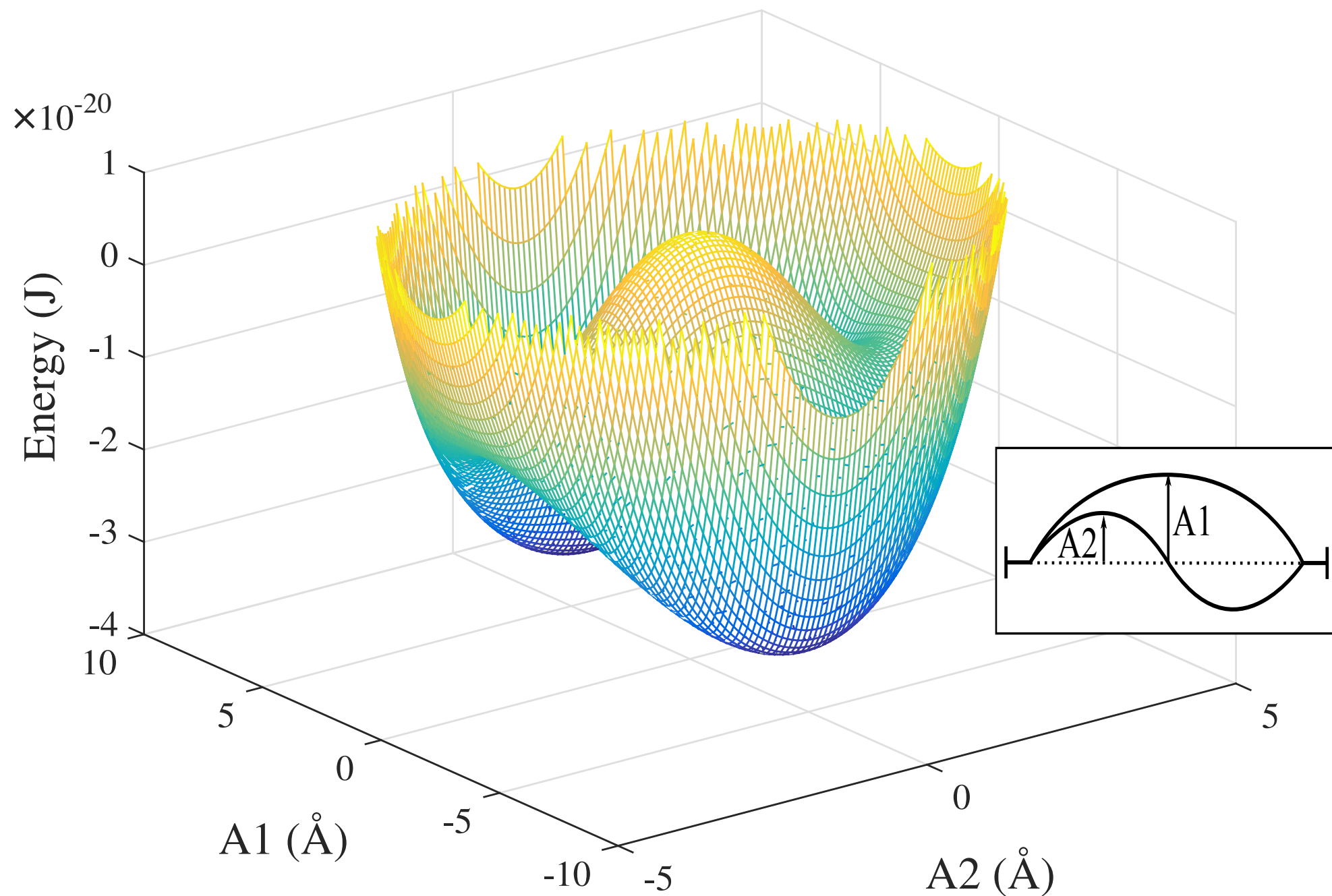
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$$H(\mathbf{P}, \mathbf{R}, t) = H_{kin}(\mathbf{P}) + H_{int}(\mathbf{R}) + H_{ext}(\mathbf{R}, t)$$

$$H_{ext}(\mathbf{R}, t) = \sum_{i=1}^n \left[ \theta \left( x_i - \frac{l}{2} \right) \left( \frac{f_{UL}(t)}{(g - z_i)} - \frac{f_{DL}(t)}{(g + z_i)} \right) + \right. \\ \left. + \theta \left( \frac{l}{2} - x_i \right) \left( \frac{f_{UR}(t)}{(g - z_i)} - \frac{f_{DR}(t)}{(g + z_i)} \right) \right]$$

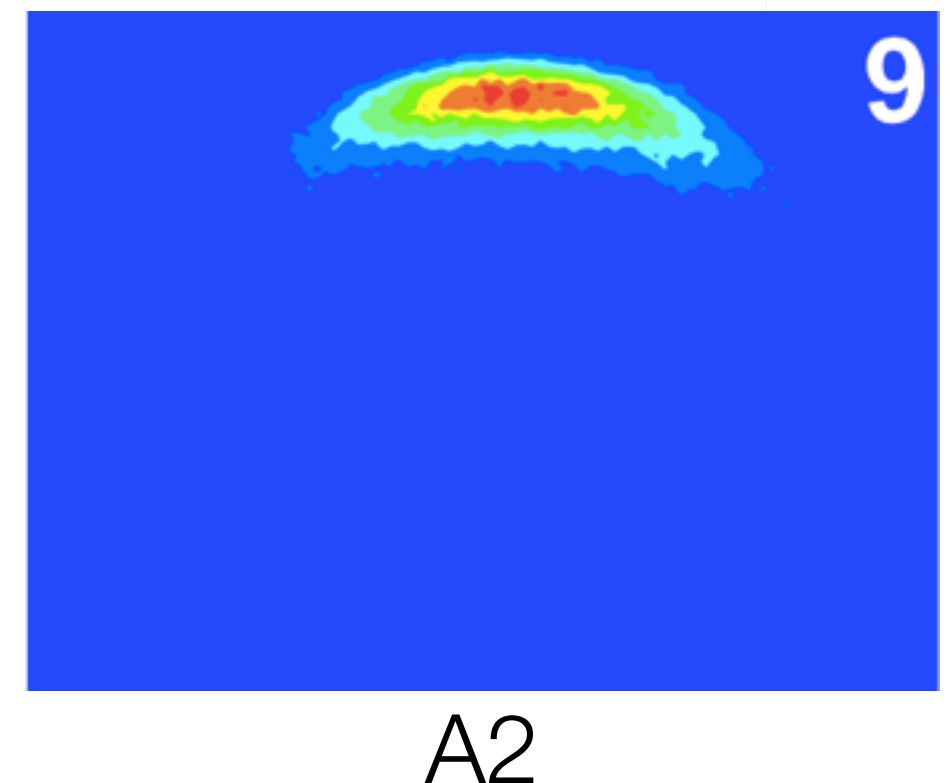
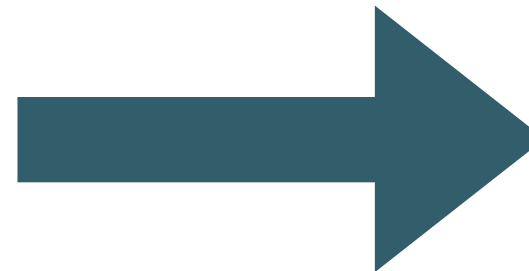
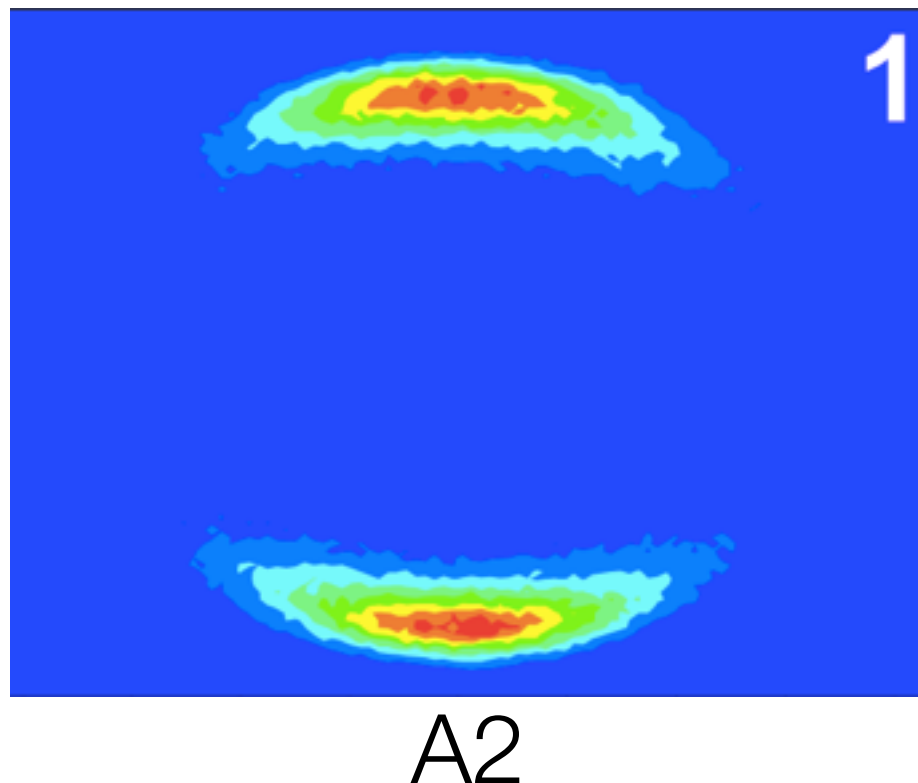
$$W = \left\langle \int_{t_0}^{t_{end}} \frac{\partial H_{ext}(\mathbf{R}, t)}{\partial t} dt \right\rangle \quad \Delta H = 0 \quad Q = W$$

# 2-DOF potential landscape



# Reset protocol

- Objective: move the system from an unknown state to known state
- $\Delta S = k_B \log(2)$
- $Q_{\min} = k_B T \log(2)$



# Reset protocol

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Quick and dirty: apply a positive force along Z on all atoms



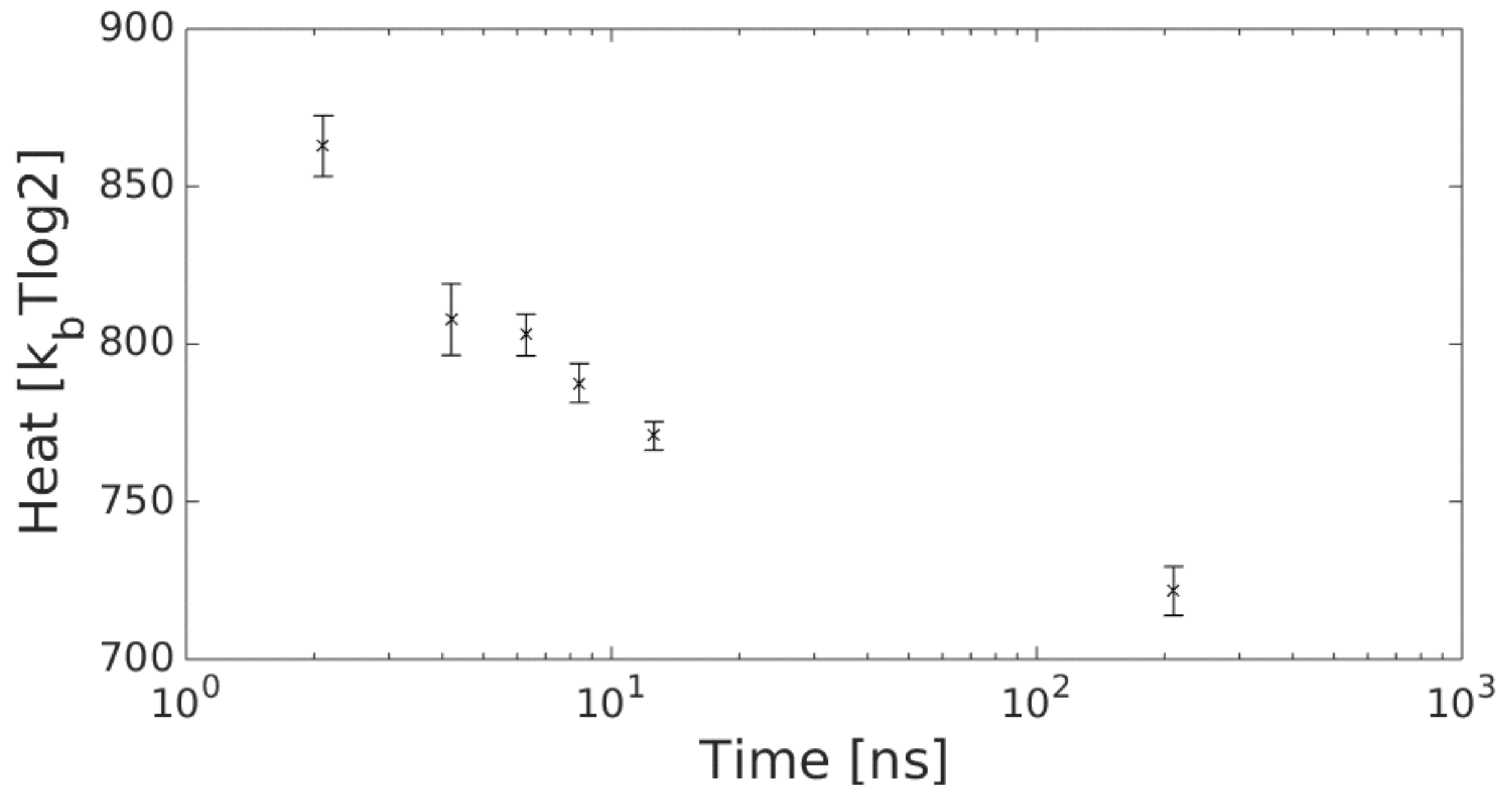
**WRONG:** it is not possible to control the velocity!



# Reset protocol

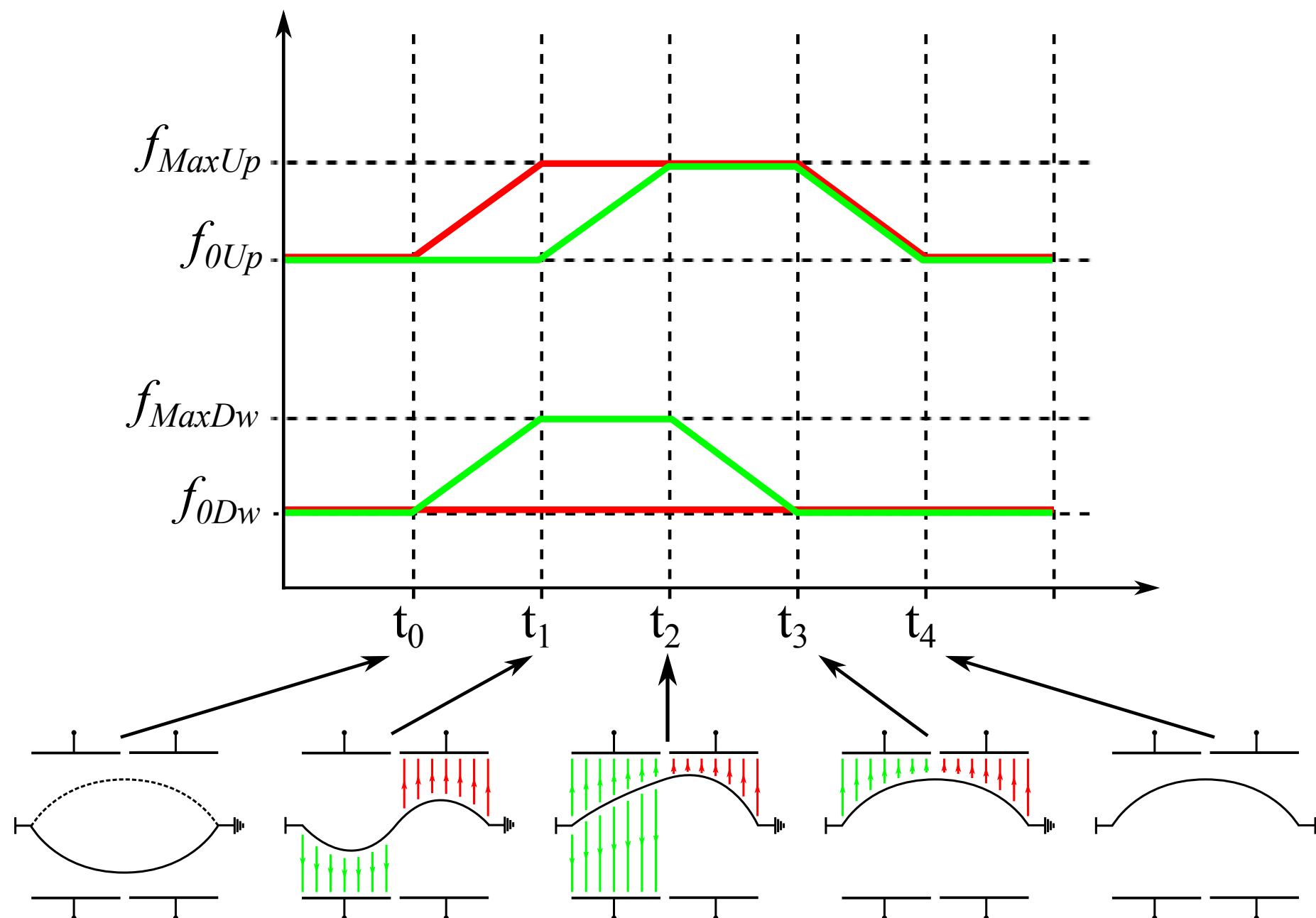
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Quick and dirty: apply a positive force along Z on all atoms



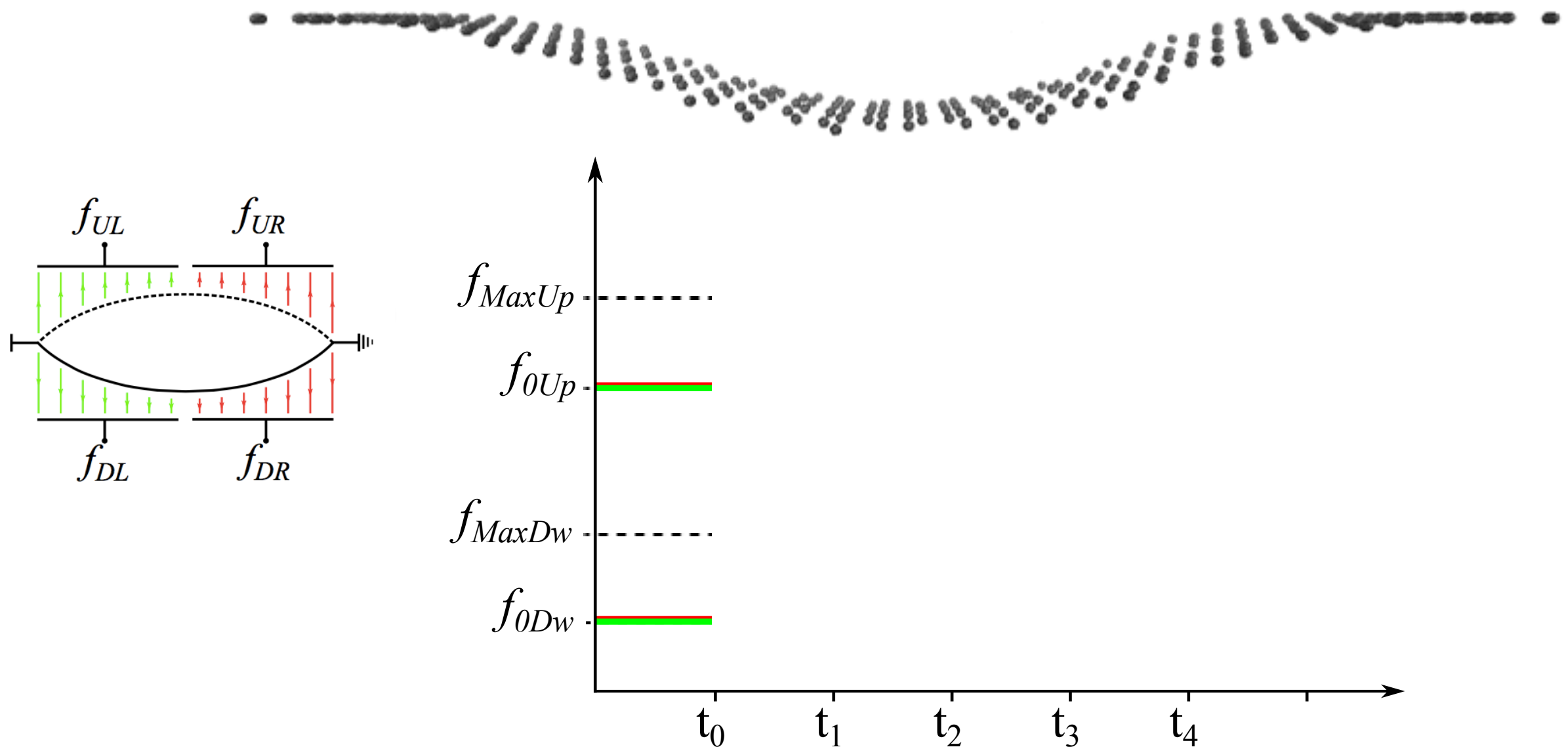
# Reset protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration



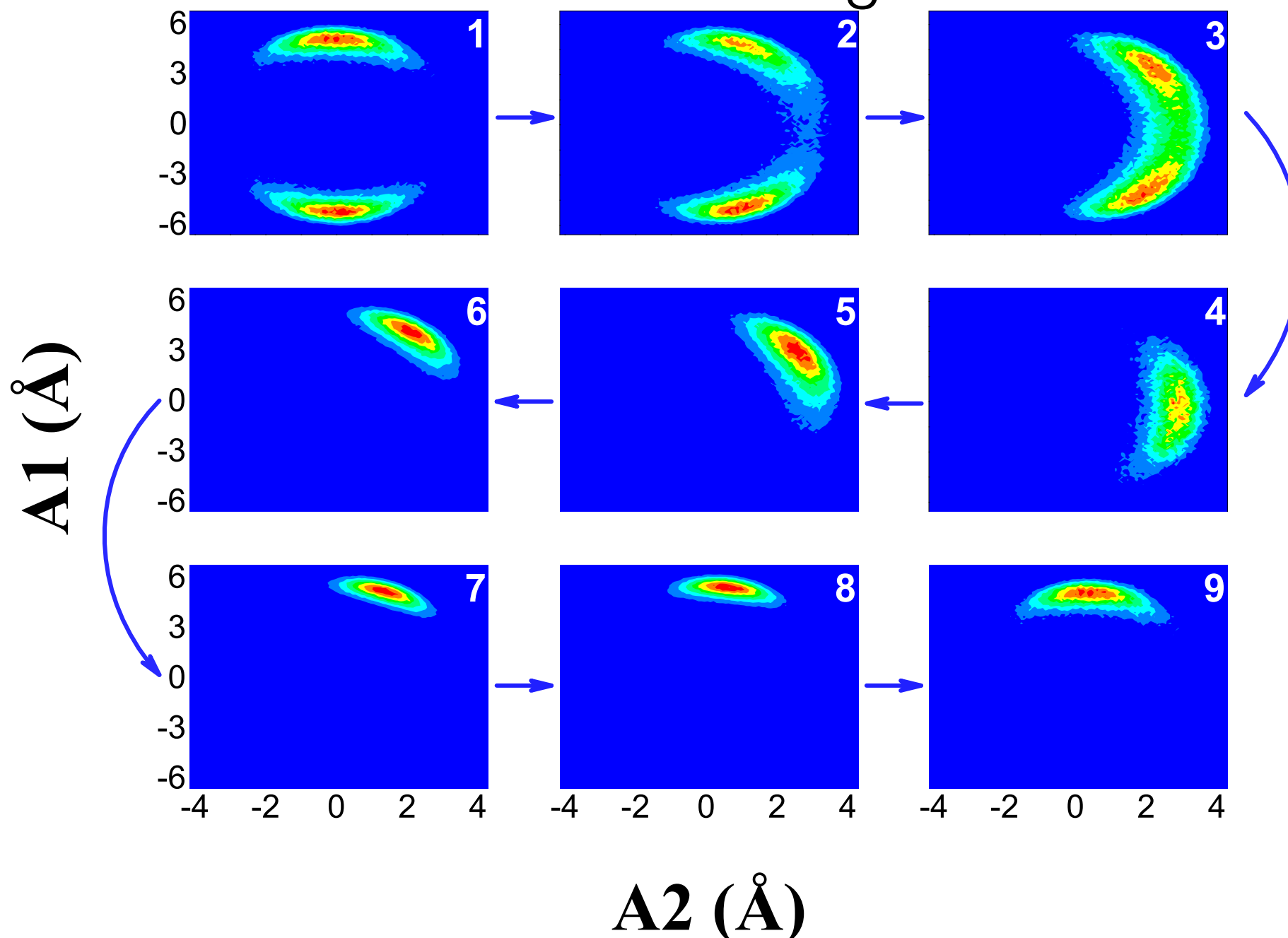
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Controlled way: apply a set of forces in to gently put the system in the desired configuration



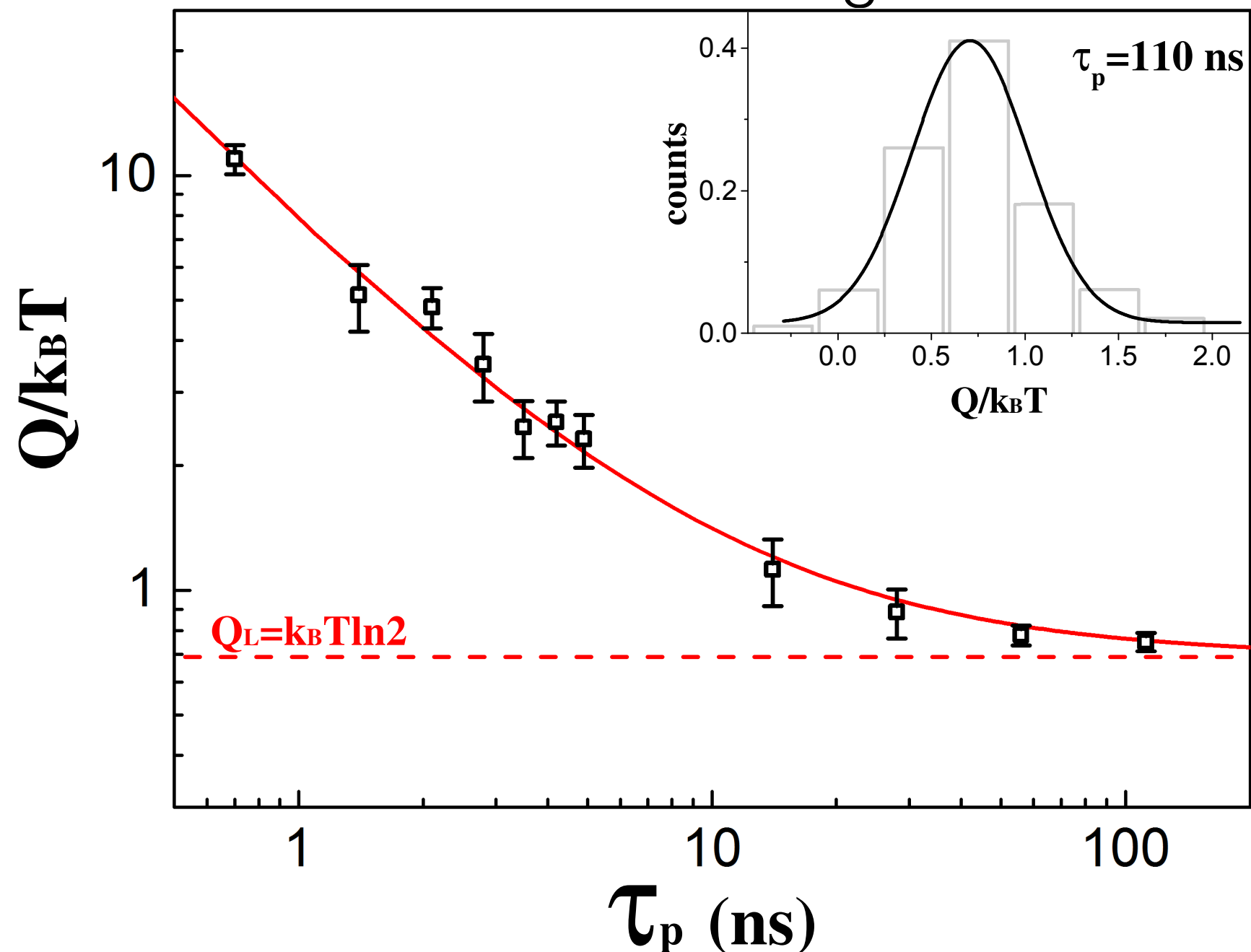
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# Reset protocol

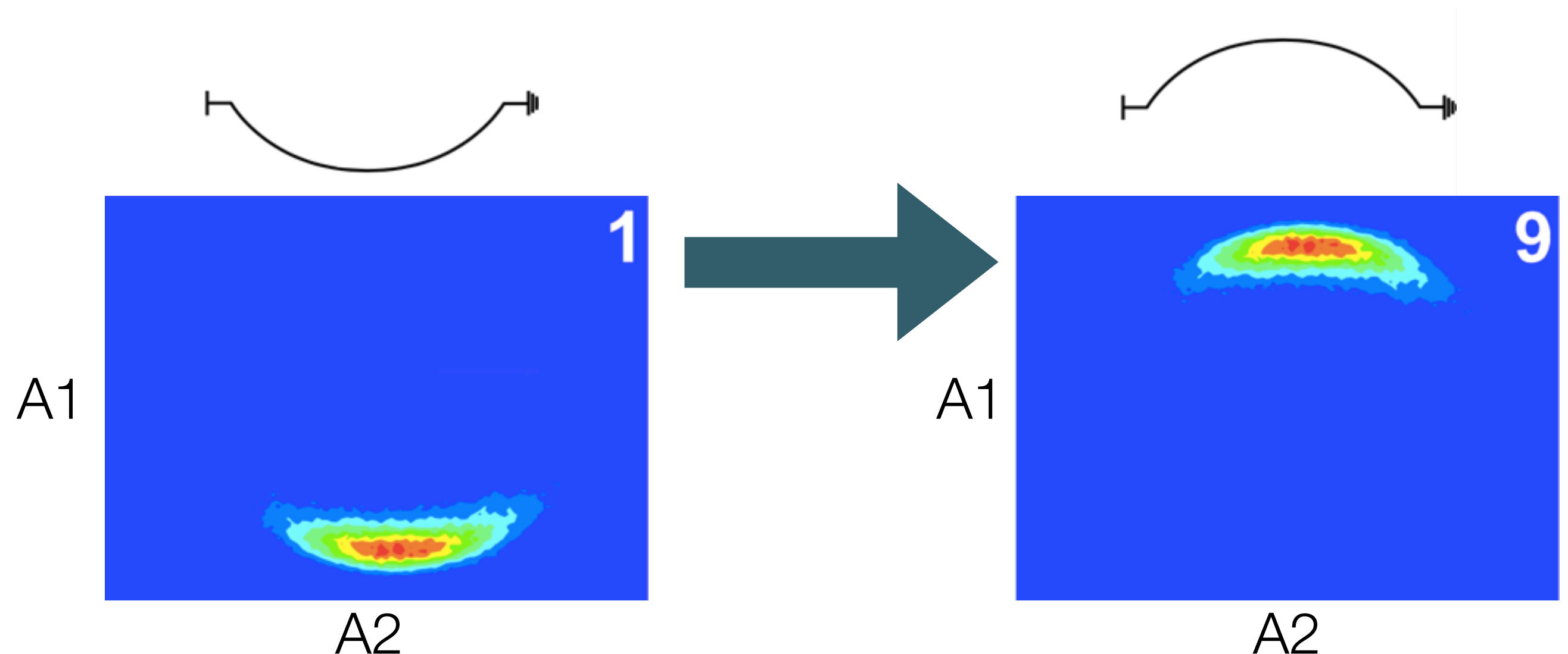
Controlled way: apply a set of forces in to gently put the system in the desired configuration





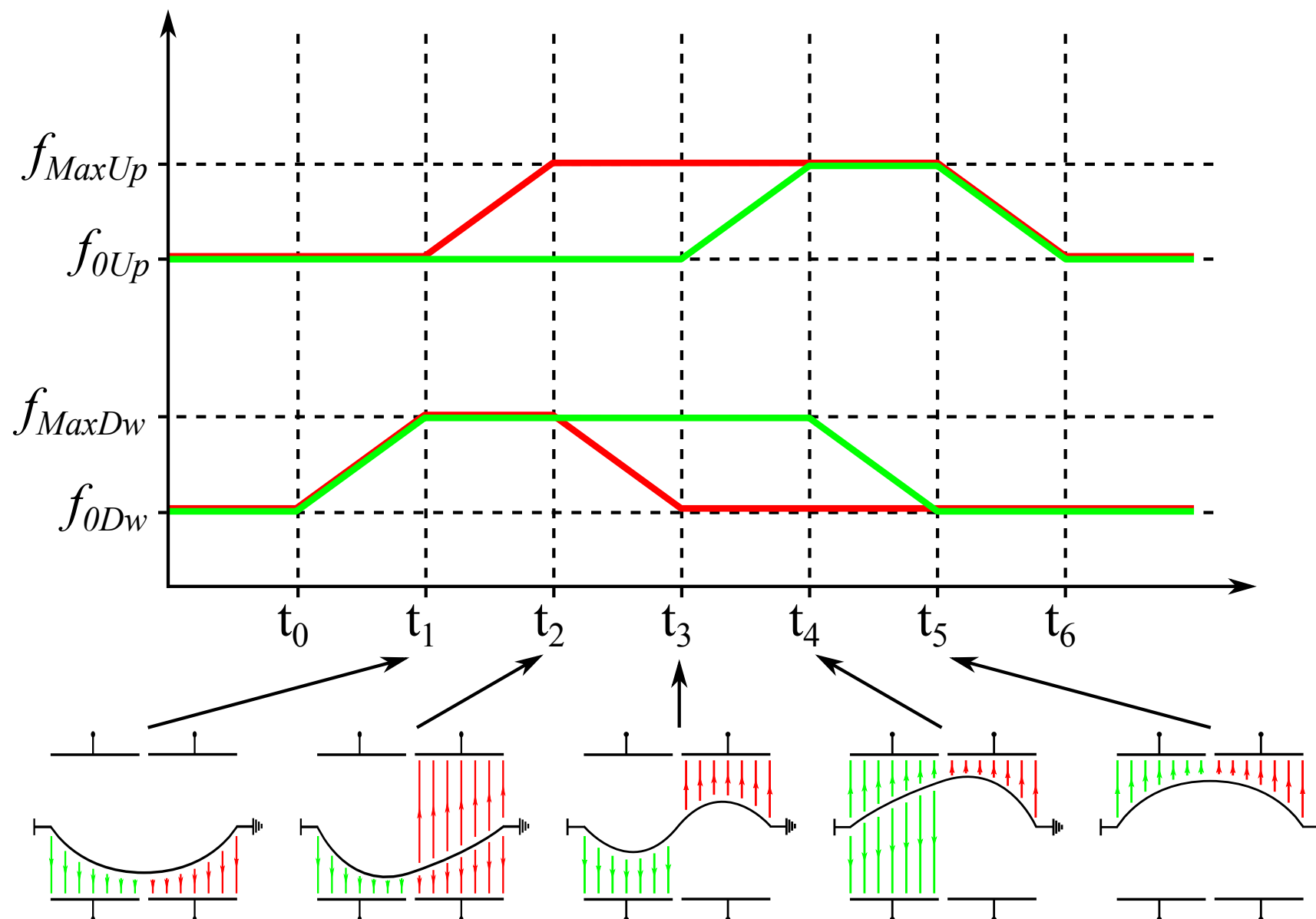
# Switch protocol

- Objective: move the system from a known state to another known state
- $\Delta S = 0$
- $Q_{\min} = 0$



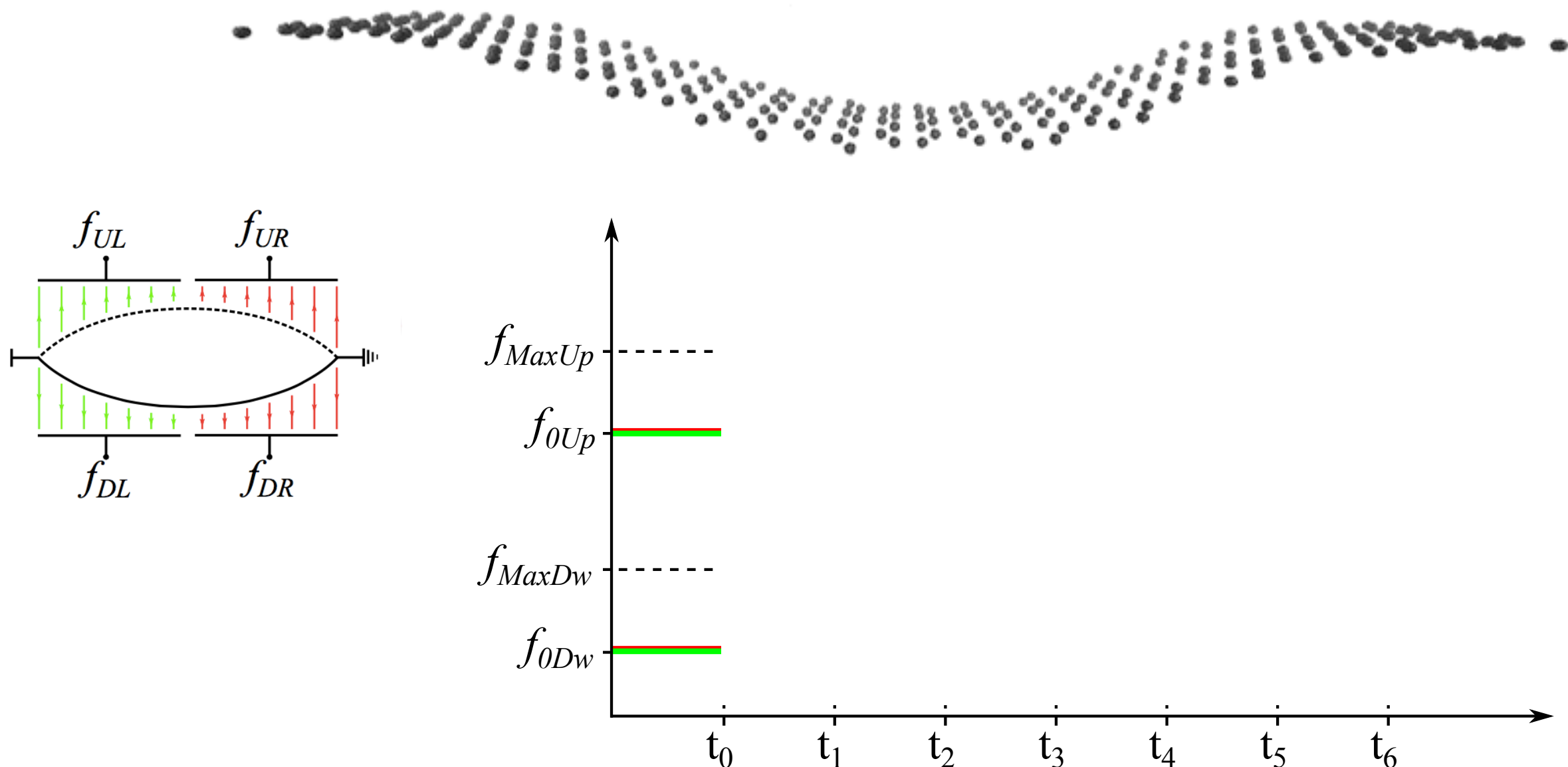
# Switch protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration



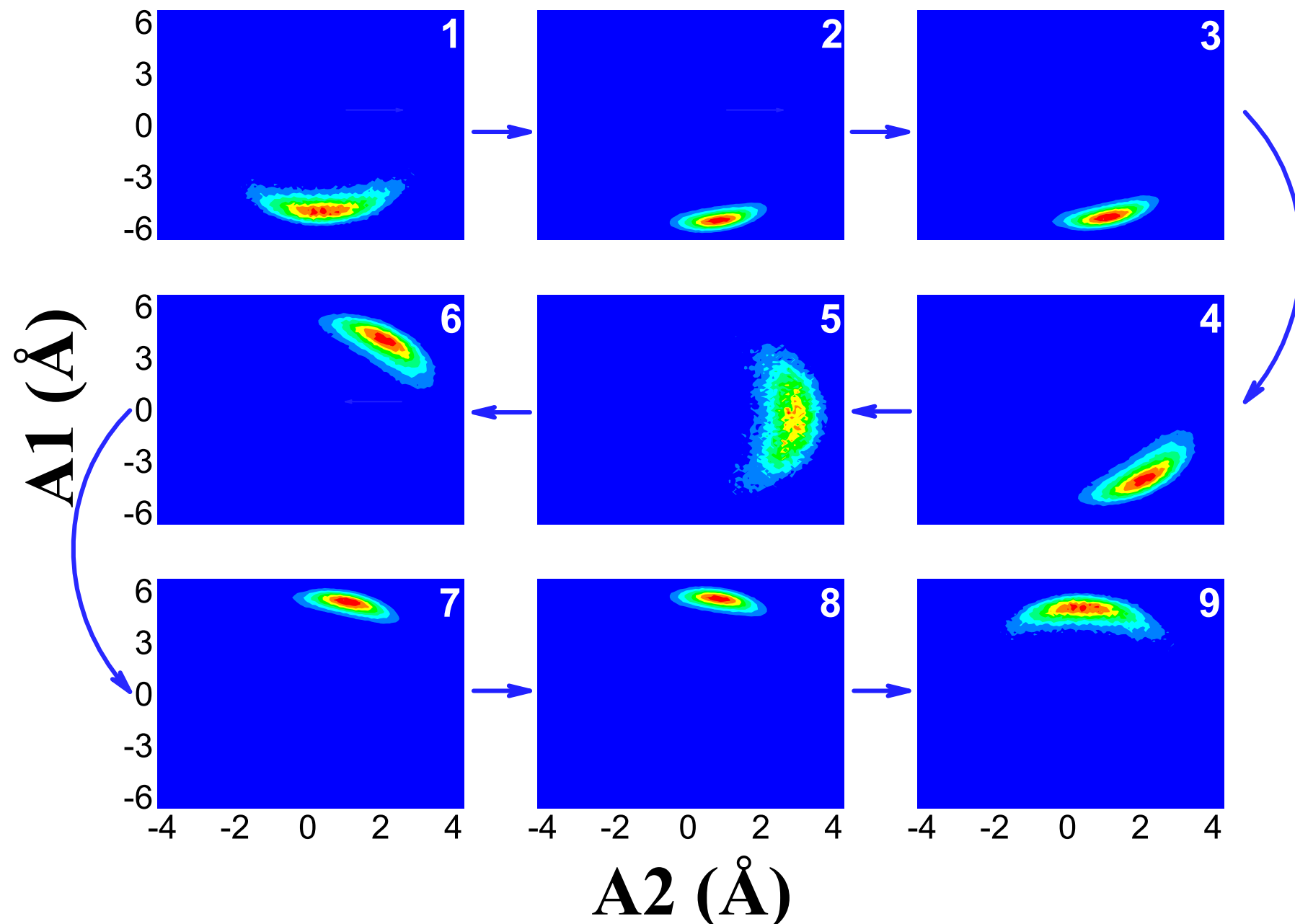
# Switch protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration



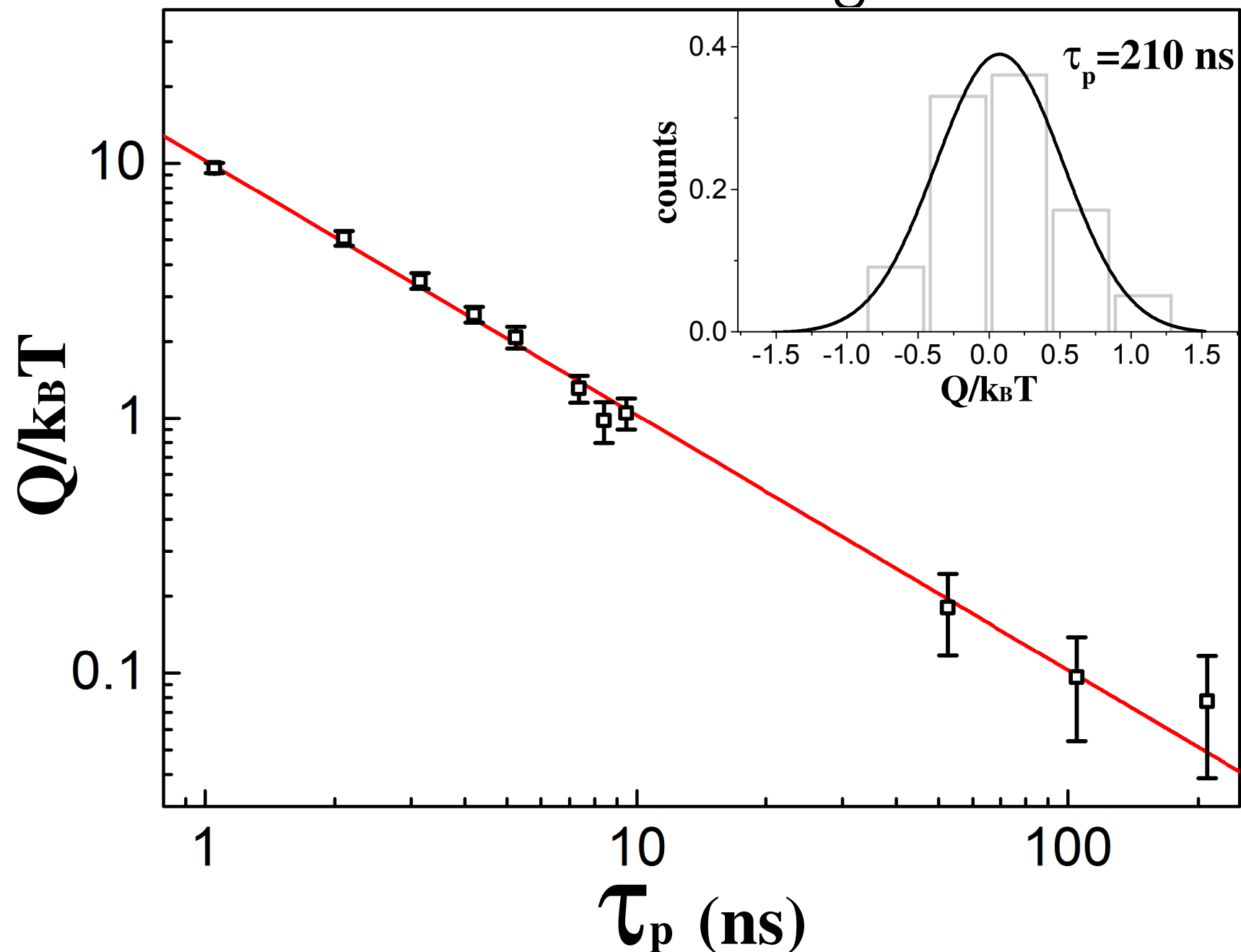
# Switch protocol

Controlled way: apply a set of forces in to gently put the system in the desired configuration



# Switch protocol

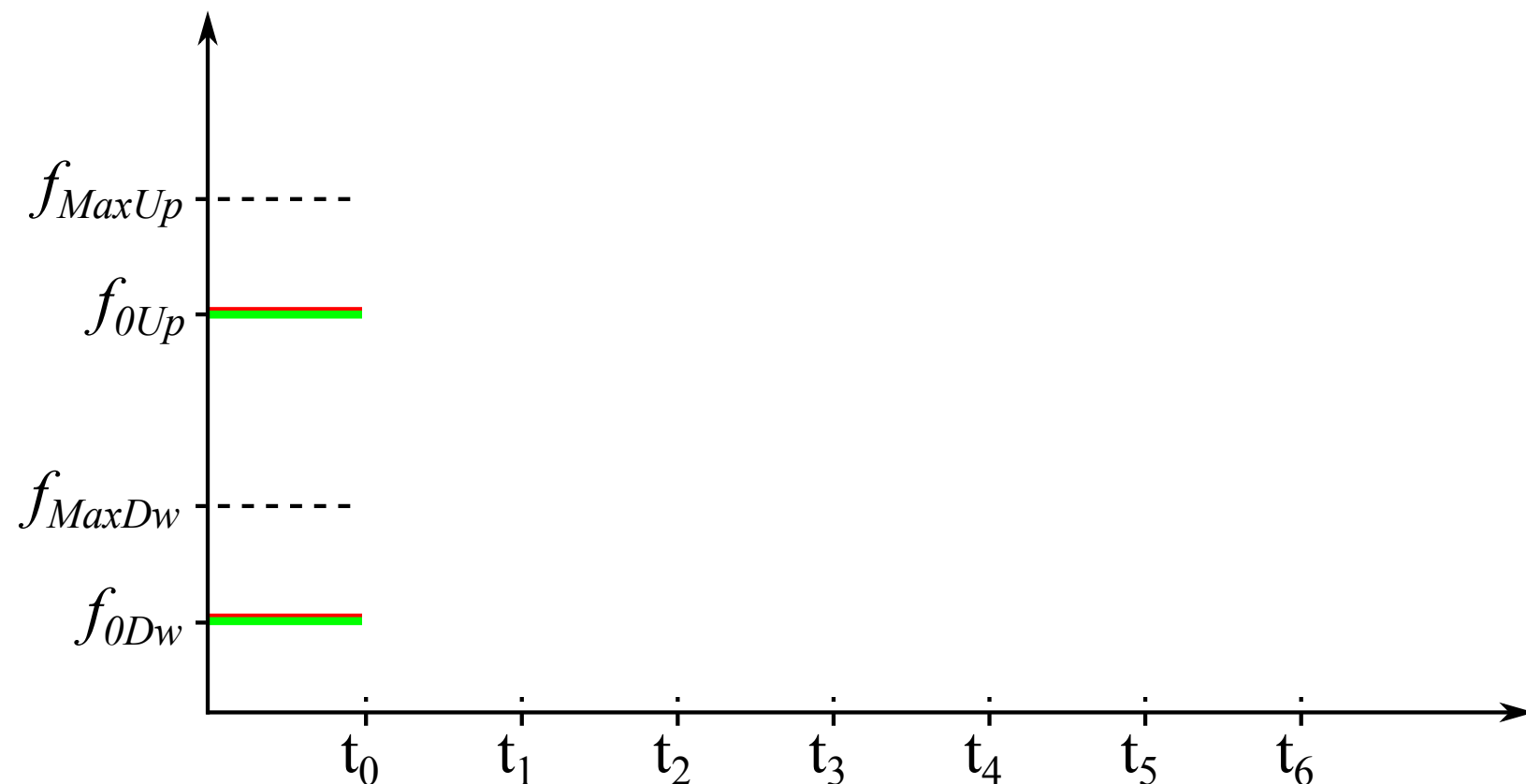
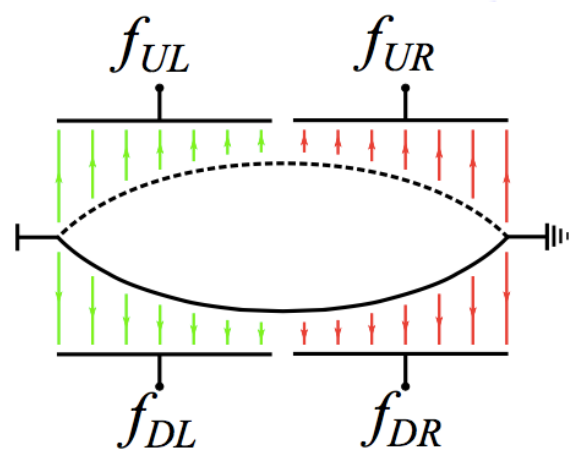
Controlled way: apply a set of forces in to gently put the system in the desired configuration





# Switch protocol

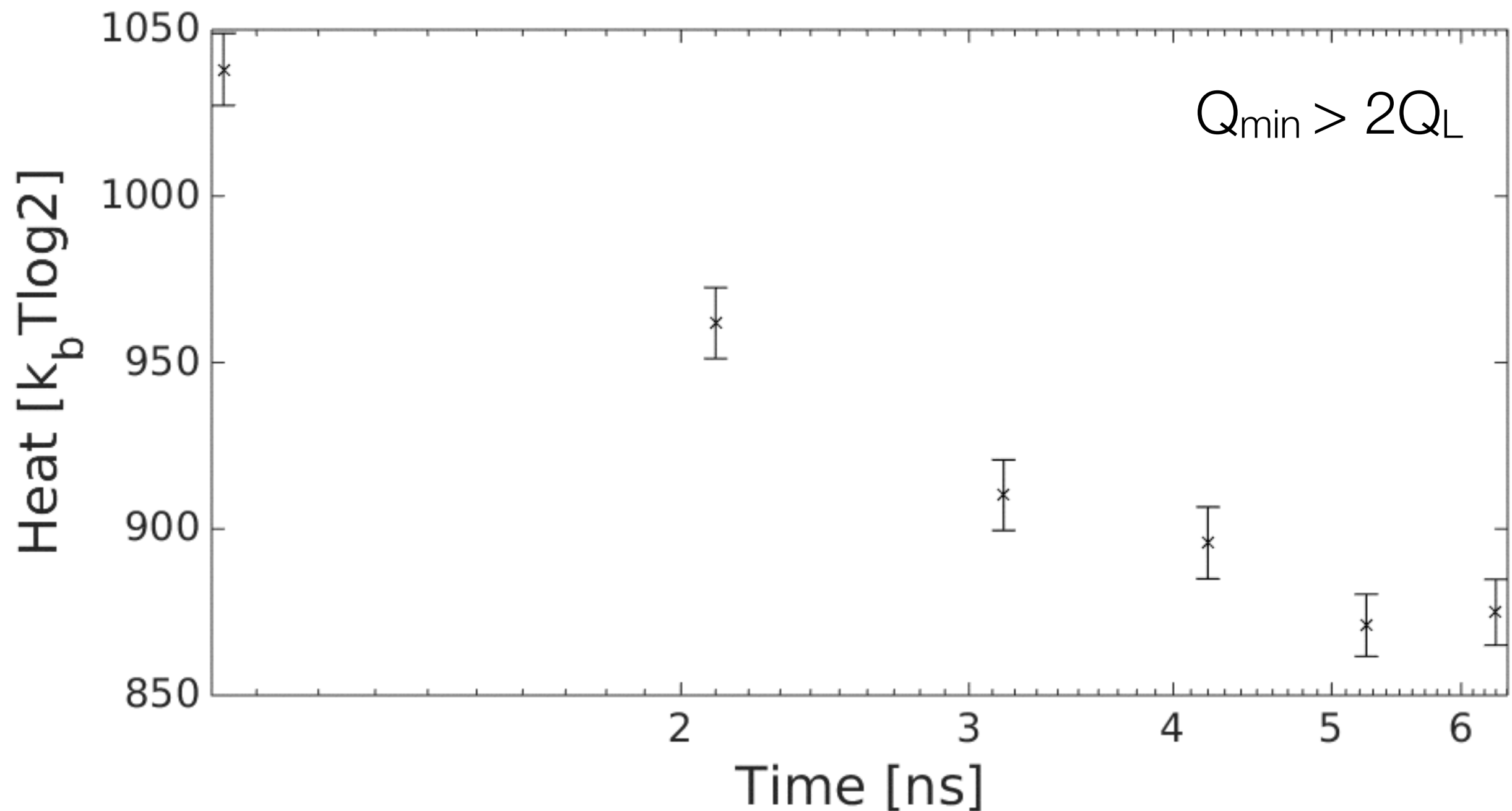
Wrong way: apply the switch protocol from the wrong initial state



# Switch protocol

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Wrong way: apply the switch protocol from the wrong initial state



# Conclusions

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- Studied minimum energy required by reset and switch protocols for a bit encoded by a compressed clamped-clamped graphene ribbon
- Proposed protocols operate at thermodynamic limit avoiding snapping
- Proposed protocols operate without altering the compression of the beam

# Thank you for your attention!

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