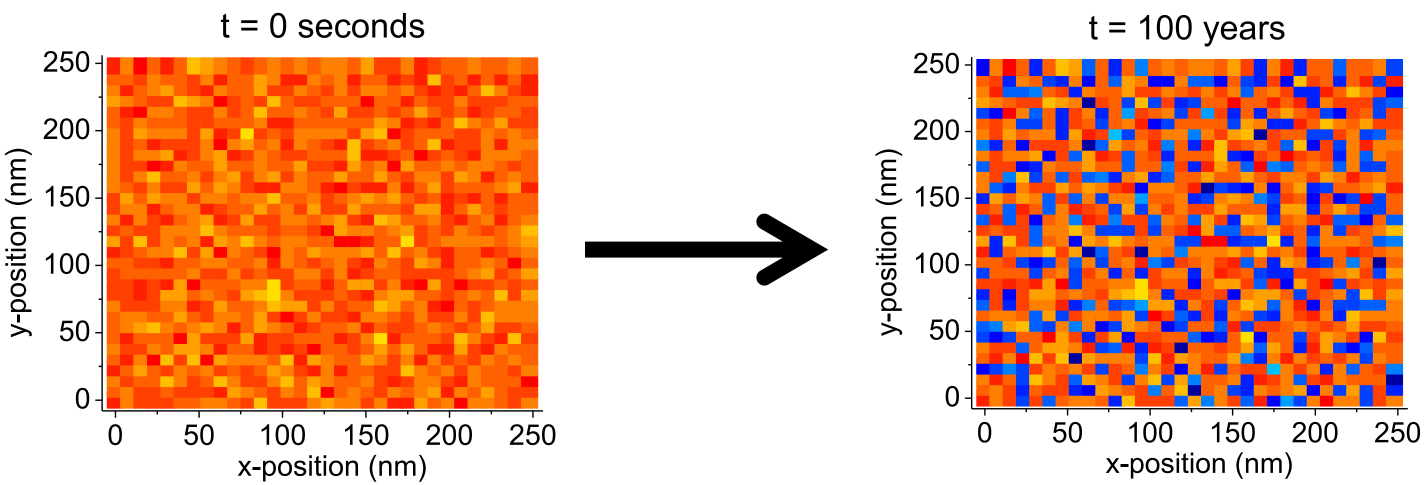
Evaluating Thermal Decay over Long Time Scales with a Wait-time Monte-Carlo Algorithm (WMCA)



Memorial University of St. John's, Newfoundland

Tim Fal

Western Digital

- **Jan van Ek**

Memorial University

- **Martin Le Blanc , Jason Mercer, Martin Plumer, and John Whitehead**

Motivation

- Evaluating the time-evolution of magnetic structures at finite temperatures.
- **Conventional dynamic simulations** are limited to **micro-second** time scales.
- What is the warranty on your Magnetic Hard Drive?

Outline

- **The Wait-time Monte-Carlo Algorithm**
  - Use Arrhenius-Neel arguments
  - Start with non-interacting particles
  - Add Interacting Particles

- **Results and checks**
  - Thermal Decay of a Ferromagnetic system
  - M-H loops
  - SNR of bit patterns

Monte-Carlo scheme

A similar method by **Charap, Pu-Ling Lu,and Yanjun He** in **1997.**

IEEE TRANSACTIONS ON MAGNETICS, VOL. 33, NO. 1, JANUARY 1997

Thermal Stability of Recorded Information at High Densities

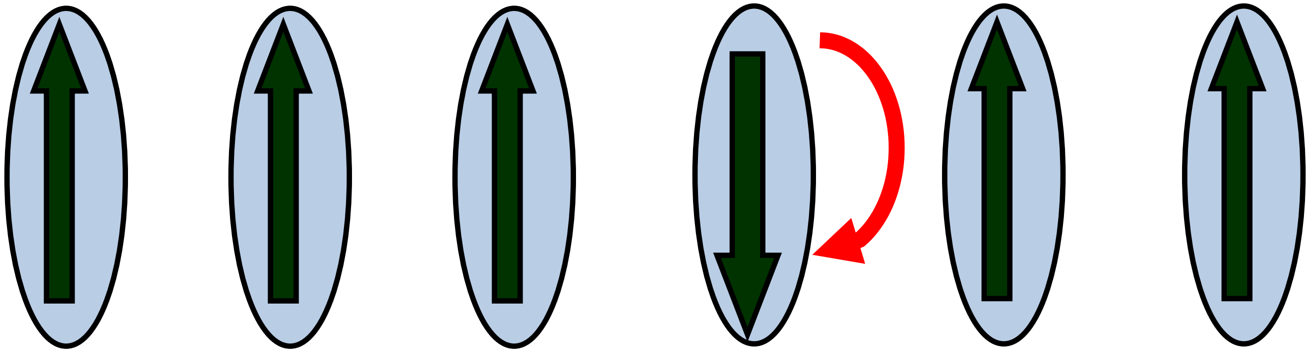
S. H. Charap, Pu-Ling Lu, and Yanjun He
DSSC, Carnegie Mellon University, Pittsburgh, PA

Abstract—-Simulations have been carried out with the purpose of identifying the thermal stability limits on data storage density in longitudinal recording on thin film media. The simulations use a combination of molecular dynamics based upon the Landau–Lifshitz–Gilbert equation of motion and a Monte Carlo method for dealing with magnetic viscosity. Based upon the limits on media coercivity imposed by available heads and SNR considerations, but assuming that sufficient head resolution can be achieved, an upper bound of about 36 Gbit/in.^{2} is projected.

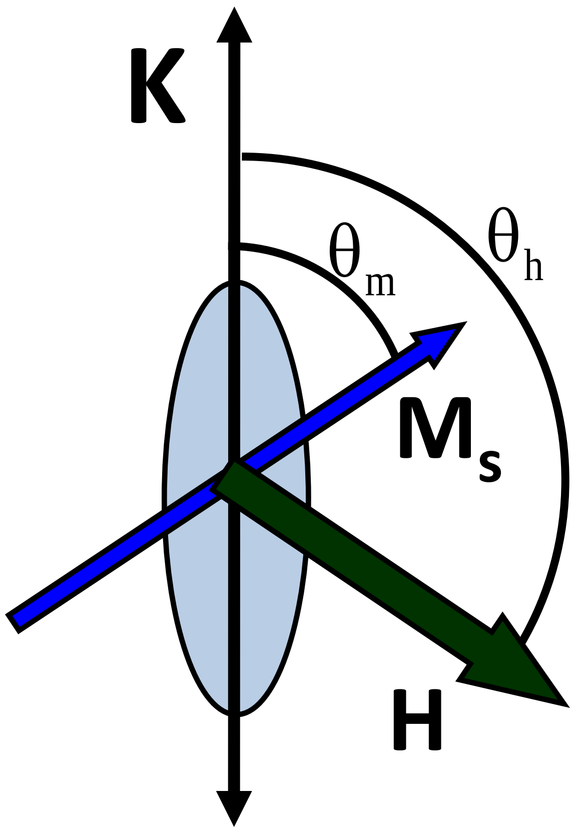
and to construct heads that will write on them. It may also be practical to operate a drive at temperatures below ambient. On the other hand the analysis is, in another sense, optimistic, since the stability criterion used above is not strictly germane to the magnetic storage situation; it is evaluated only for non-interacting magnetic particles. The interactions among the grains in the media and, particularly, the demagnetizing field acting in the vicinity of the stored transitions must affect the thermal stability profoundly and, all else being equal, hasten the onset of thermal instability of the stored information as storage density is increased.

Magnetic **thermal transitions** using Arrhenius-Néel

$$N(t) = N_o e^{-rt}$$



Represent a magnetic media as a collection of **single domain** magnetic grains.



V = the volume of the grain.

K = the uniaxial anisotropy constant.

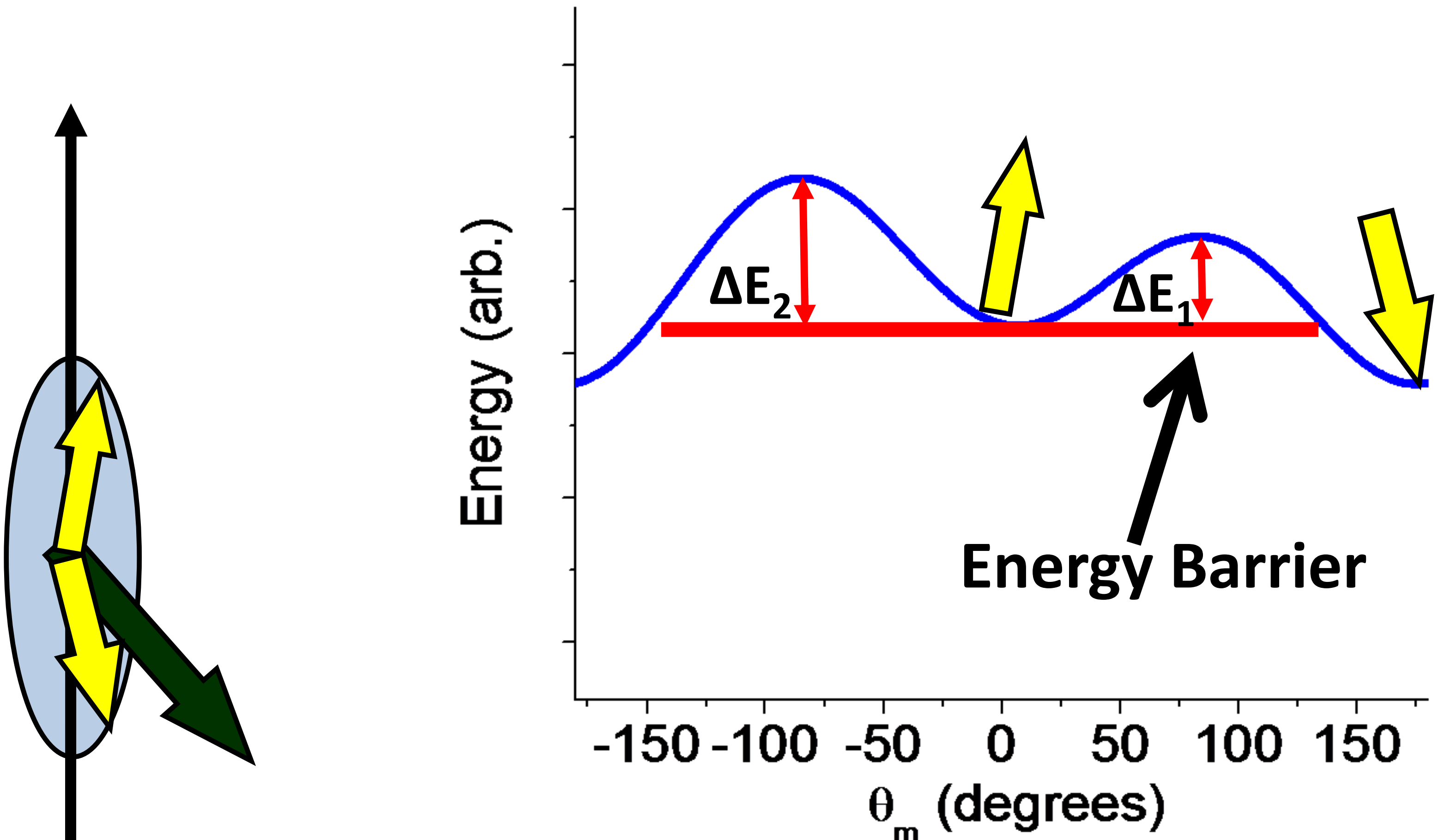
M = the saturation magnetization.

H = the effective field the particle is in.

θ_m = the angle between the magnetization and the anisotropy axis.

θ_h = the angle between the effective field and the anisotropy axis.

Every particle has an Energy Landscape

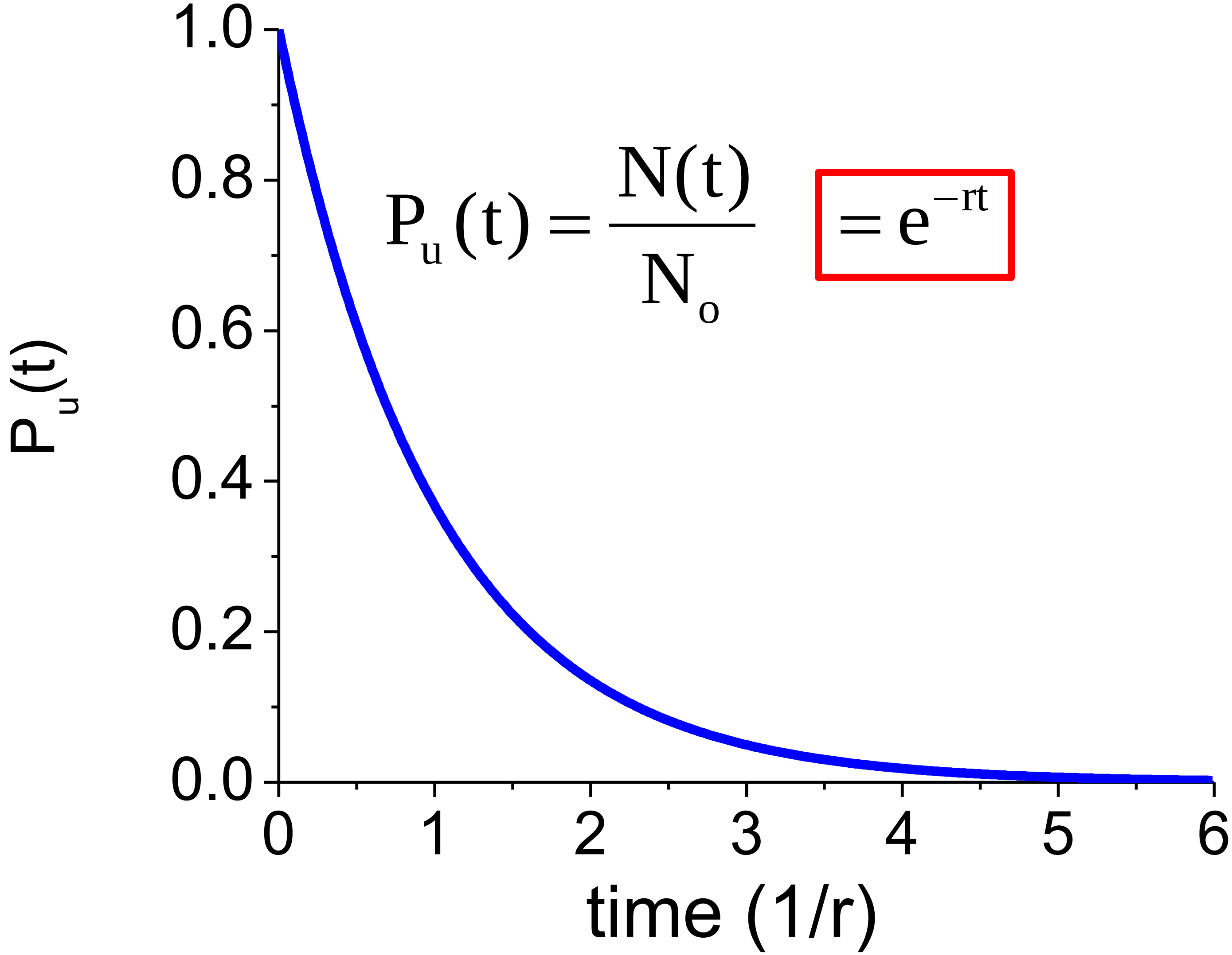


The probability of looking at a particle at it being **"up"** depends on the energy barrier

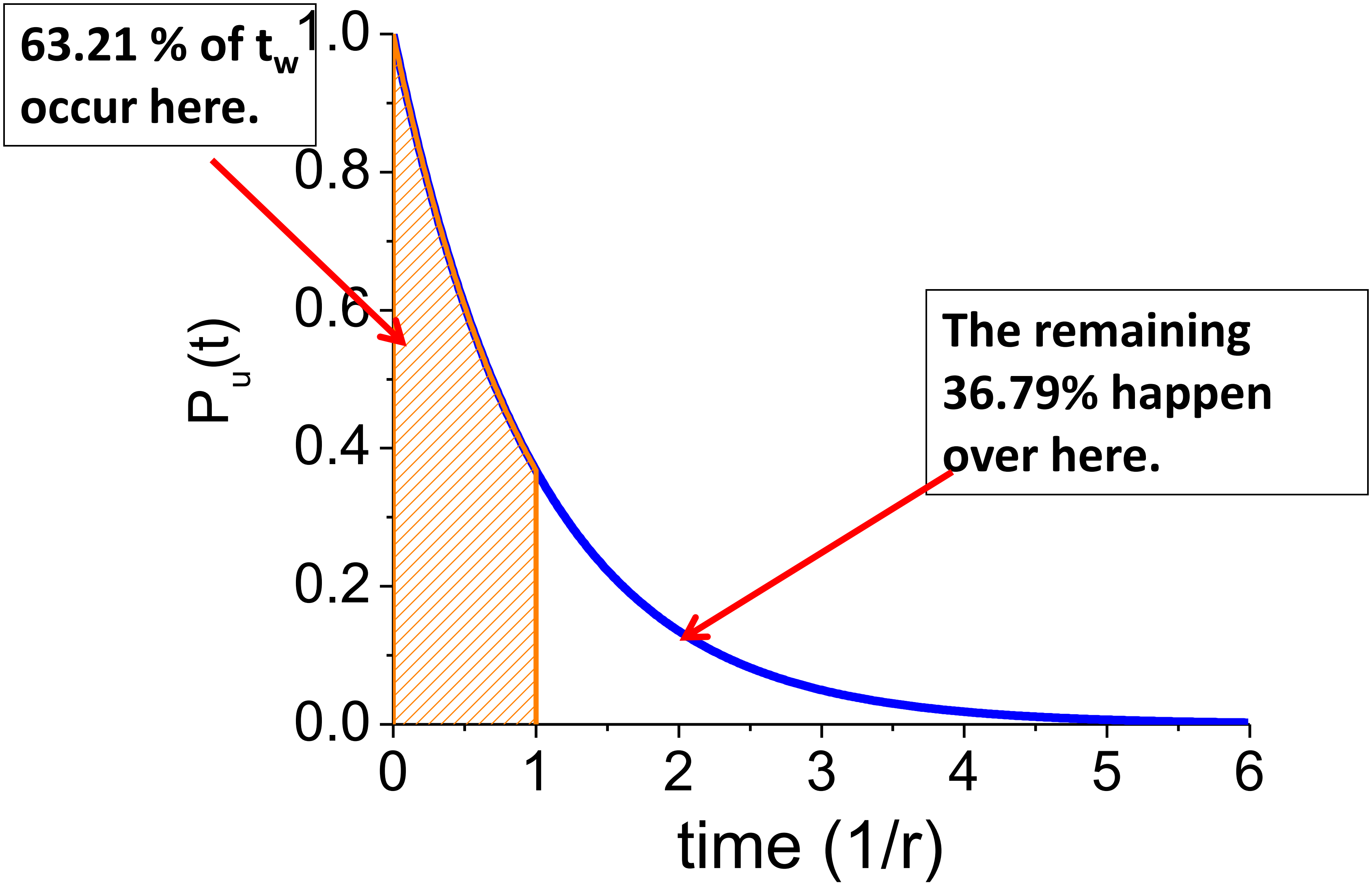
r → **ΔE**

$$r = f_o e^{-\frac{\Delta E}{kT}}$$

With the decay rate…
We have the probability of a member of the ensemble being "up"

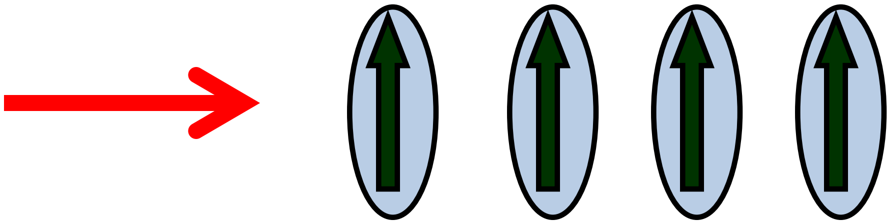


OR.. We have the distribution of wait times.



The toy model..

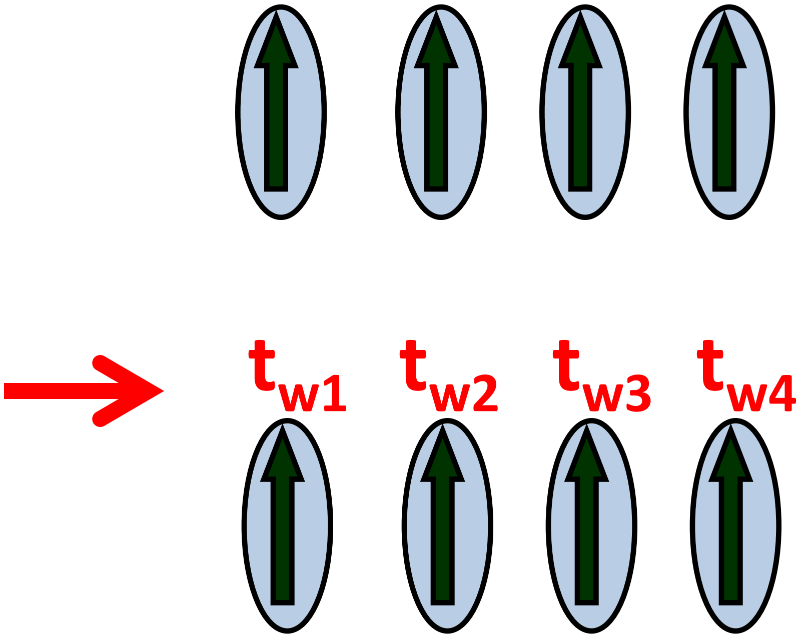
- Consider a collection **of identical grains.**



The toy model..

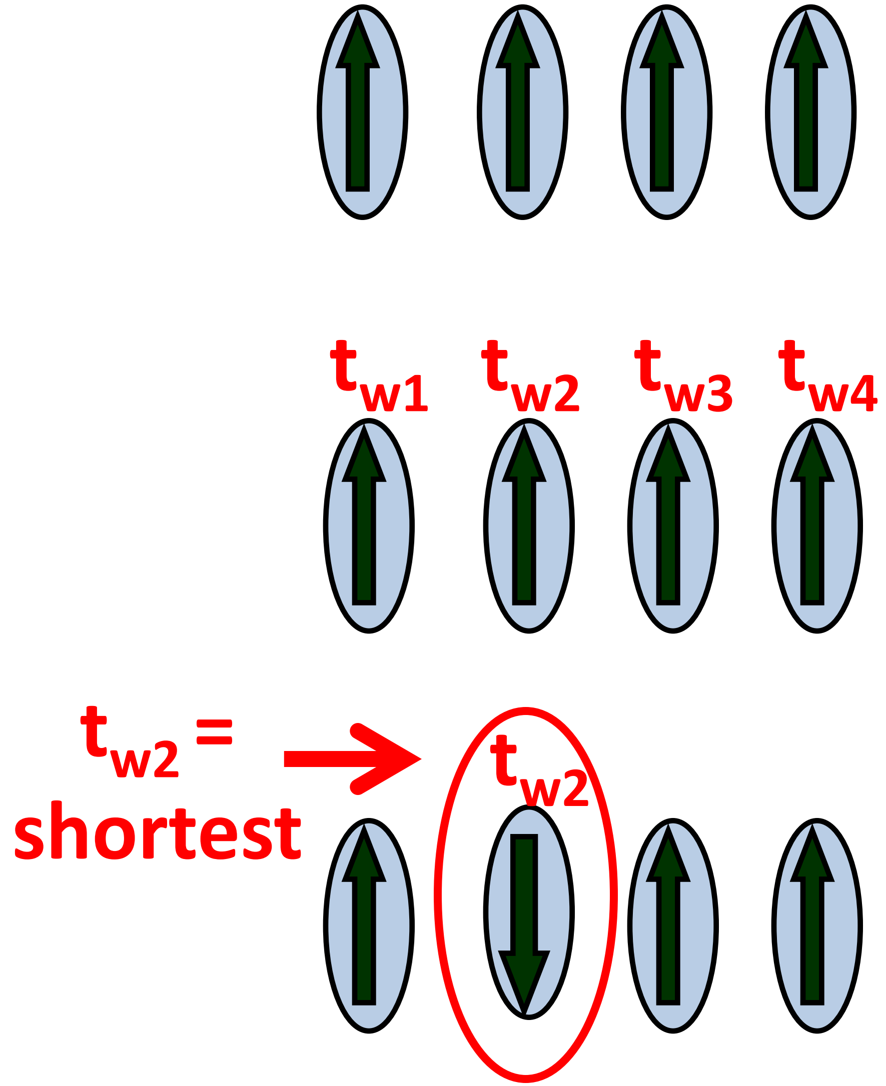
- Consider a collection of identical grains.
- Based on **the wait time distribution**, randomly choose a wait time for each particle.

$$t_w = -\frac{1}{r(\Delta E, T)} \ln(x)$$



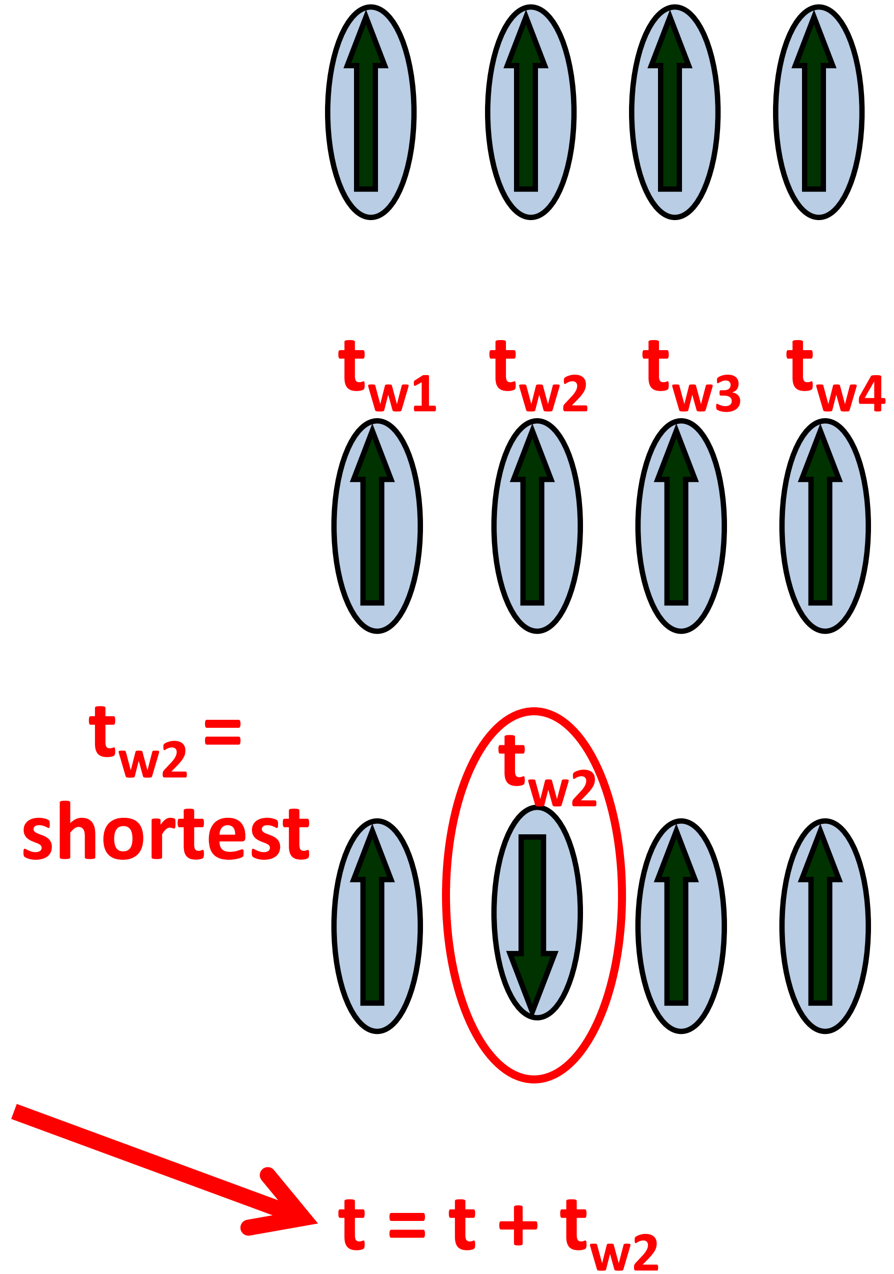
The toy model..

- Consider a collection of identical grains.
- Based on the wait time distribution, randomly choose a switching time for each particle.
- Choose the particle with the **shortest** wait time and flip it.

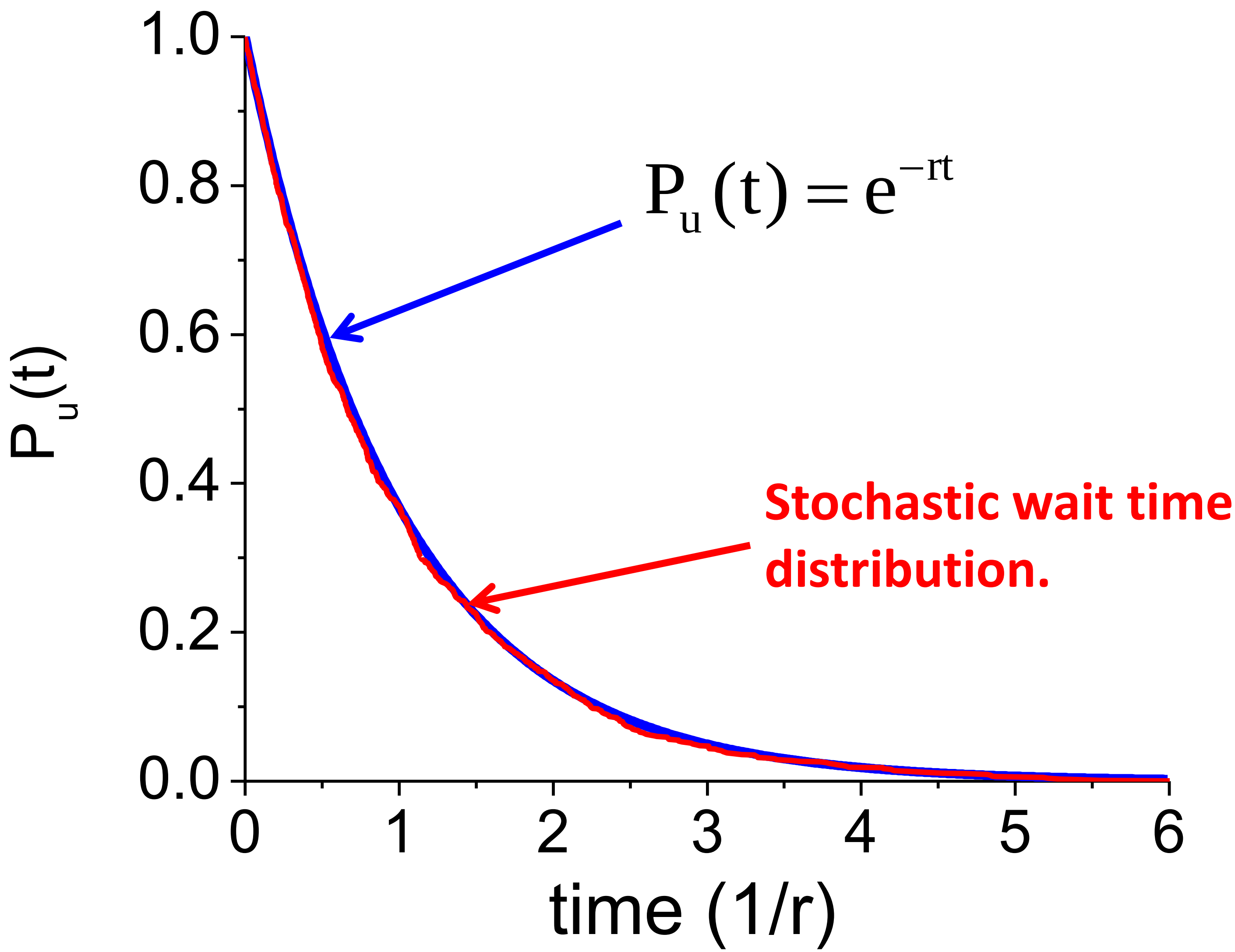


The toy model..

- Consider a collection of identical grains.
- Based on the wait time distribution, randomly choose a switching time for each particle.
- Choose the particle with the shortest wait time and flip it.
- **Increase time** by the chosen wait time and **repeat** with the remaining “up” particles.

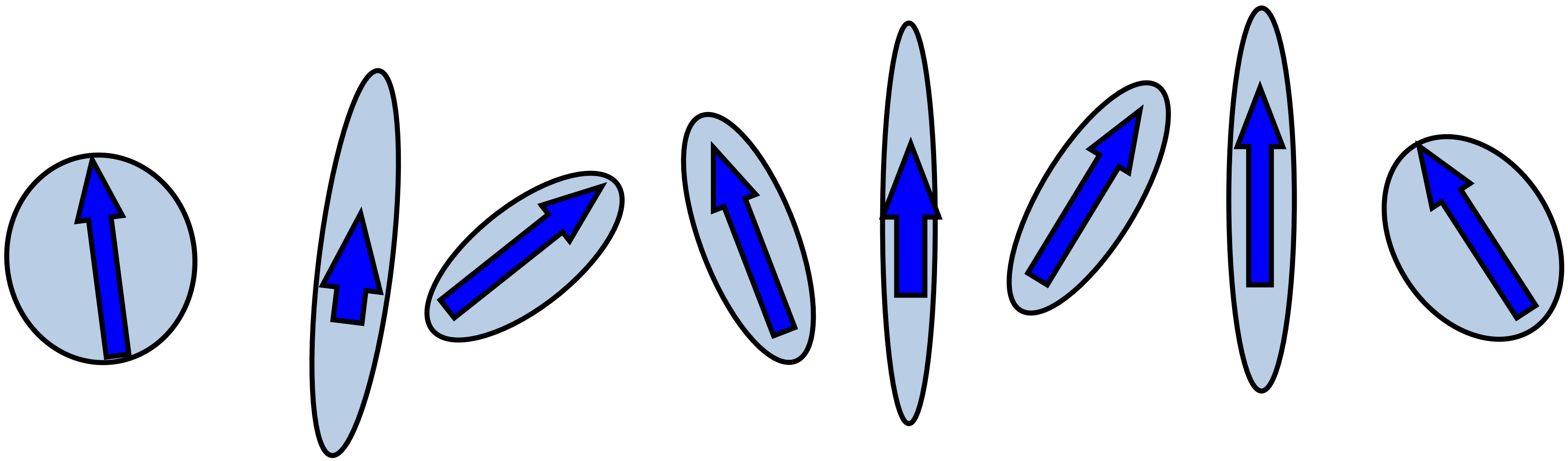


Collecting **random Dwell Times** based on the decay rate.

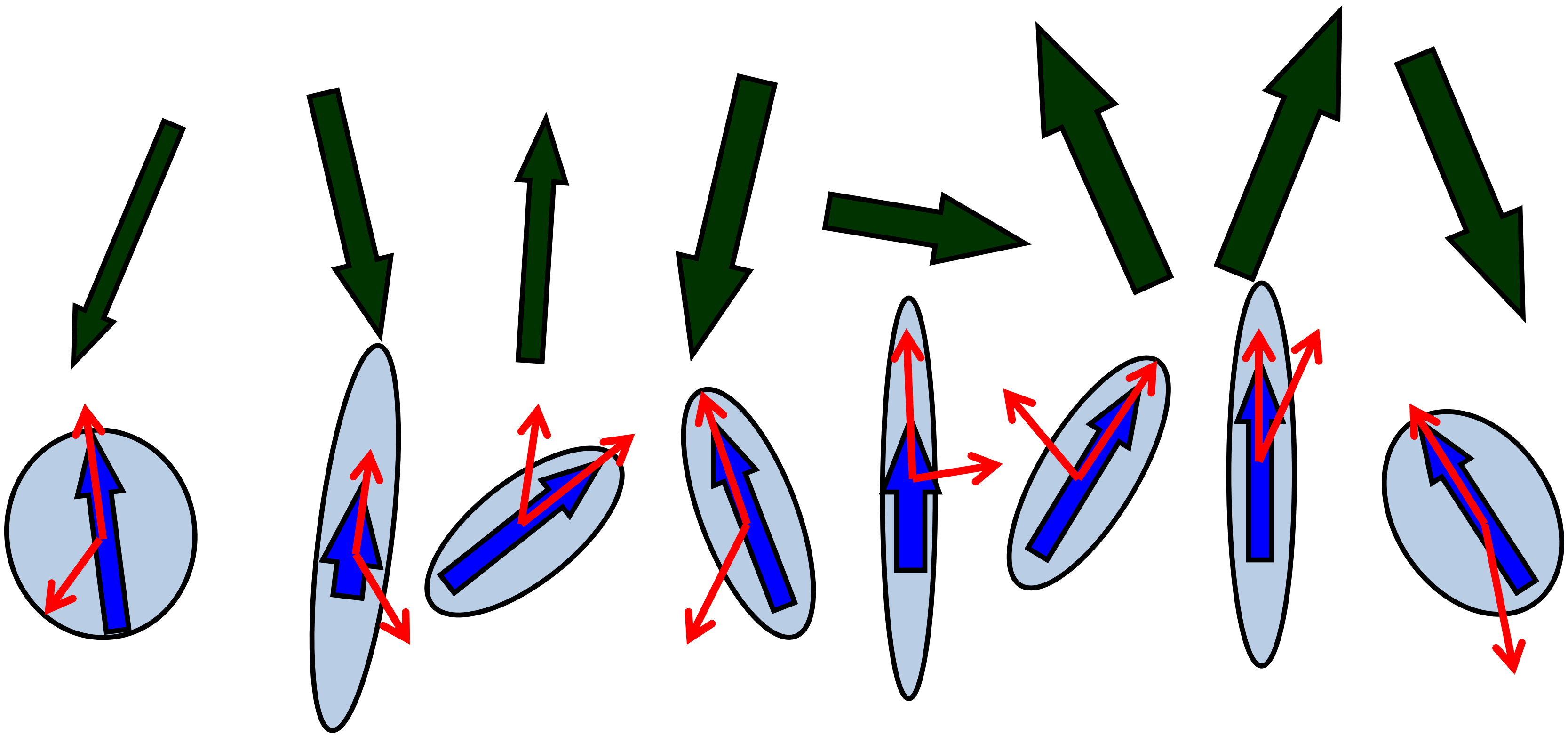


Unique particles

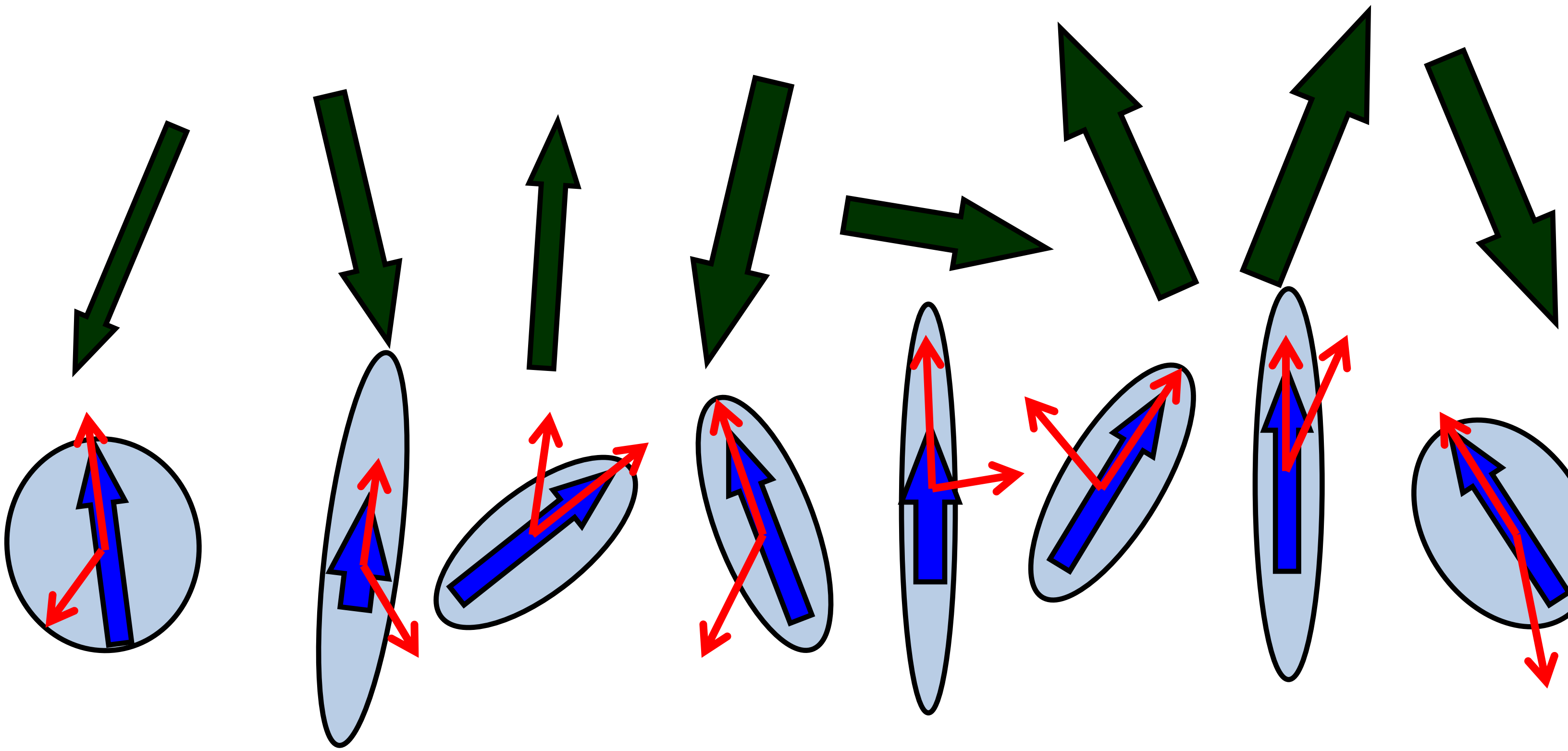
A complicated system of Stoner-Wohlfarth-like particles that all have different parameters.



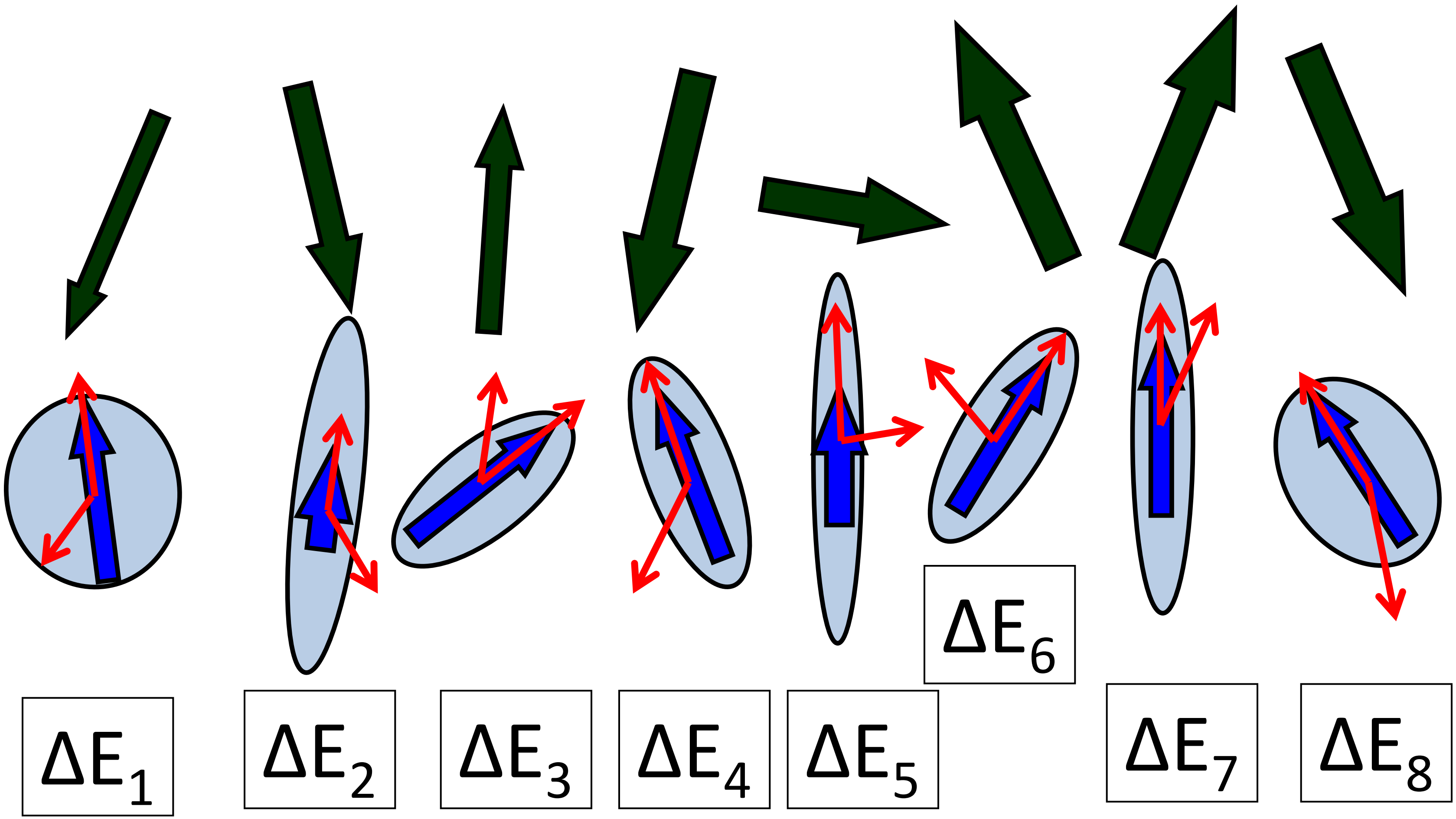
Based on the Energy for a Stoner-Wohlfarth particle, each member of this collection have **energy minima** in their **energy landscape**.



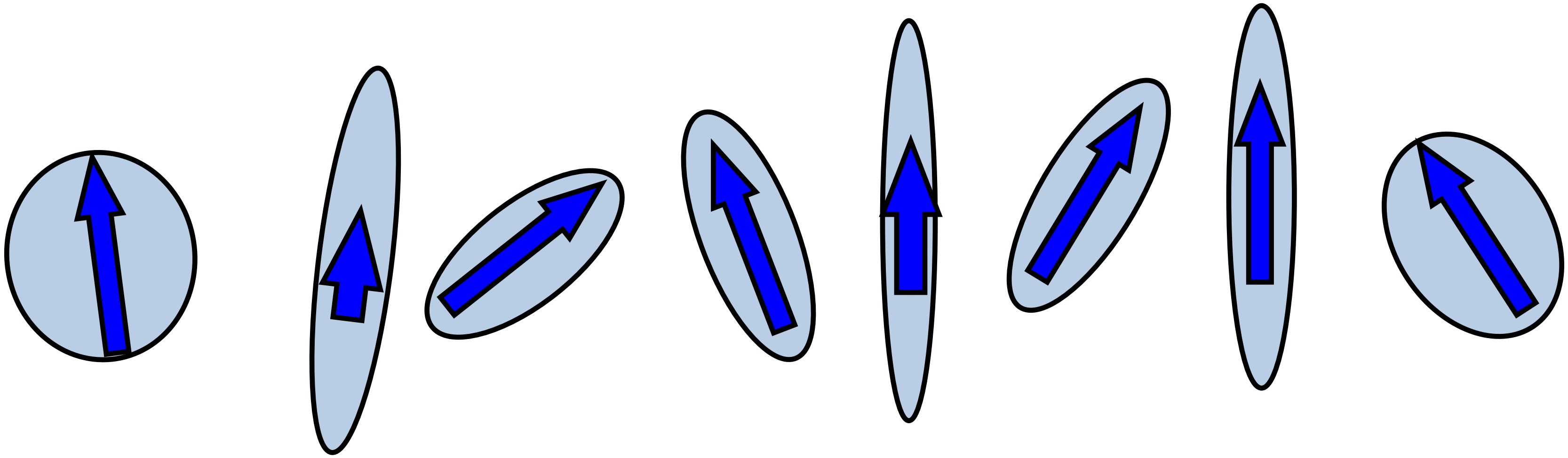
ASSUMPTION: The system is a **punctuated equilibrium**. The system remains unchanged for periods of time until a rare thermal event takes place.



Each individual particle has an **energy barrier** between their local minimums.

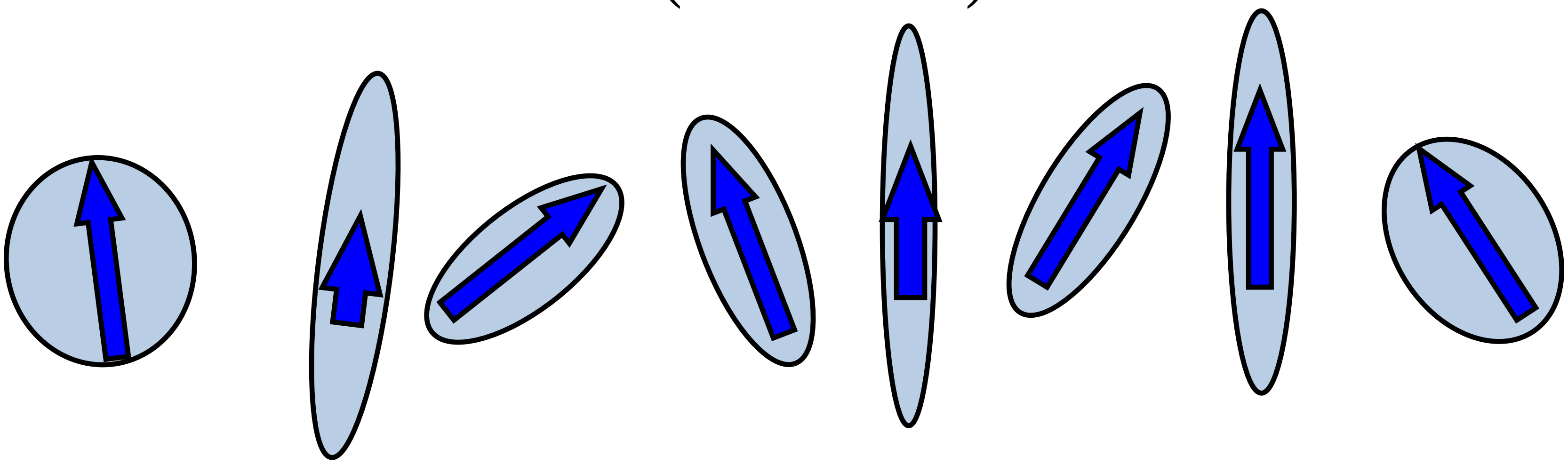


We **cannot** treat the **system** as an ensemble of **IDENTICAL** particles.



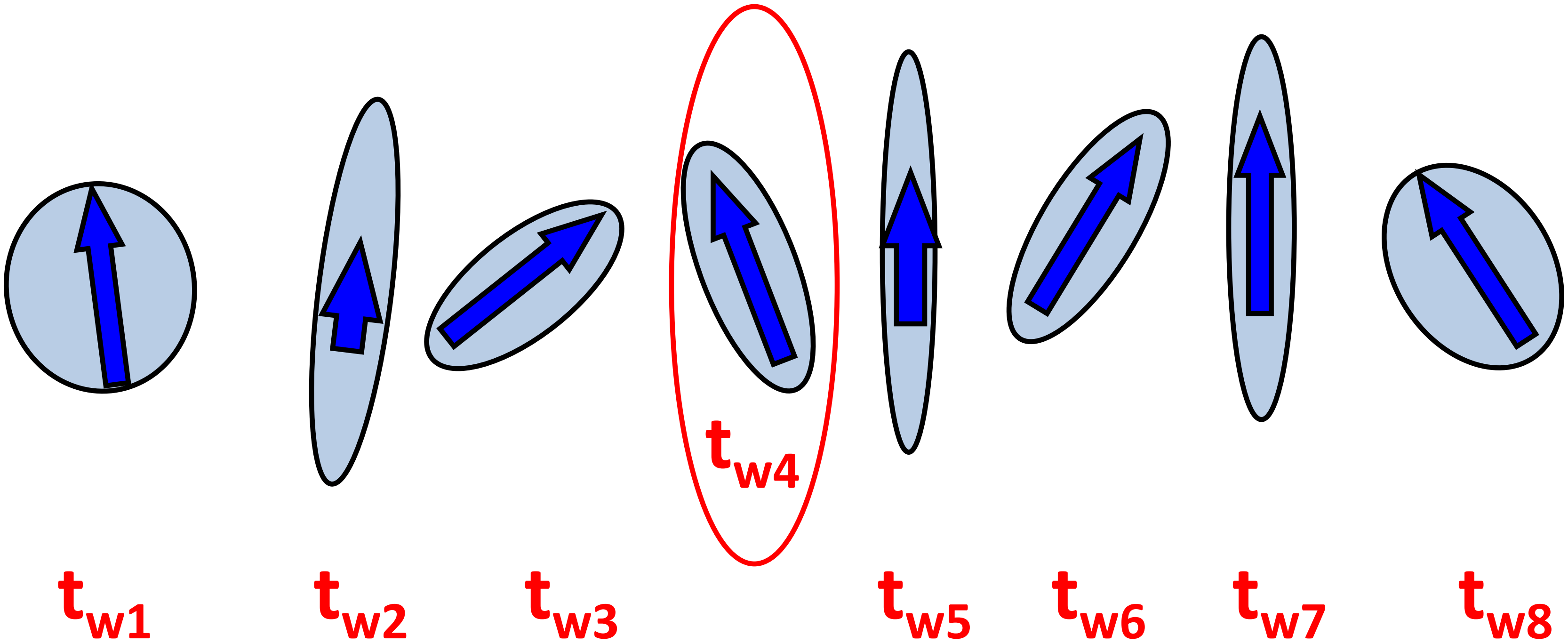
Each individual particle will have its own distribution of wait times and will randomly have a wait time selected based on its own distribution.

$$t_{wn} = -\frac{1}{r(\Delta E_n, T)} \ln(x)$$



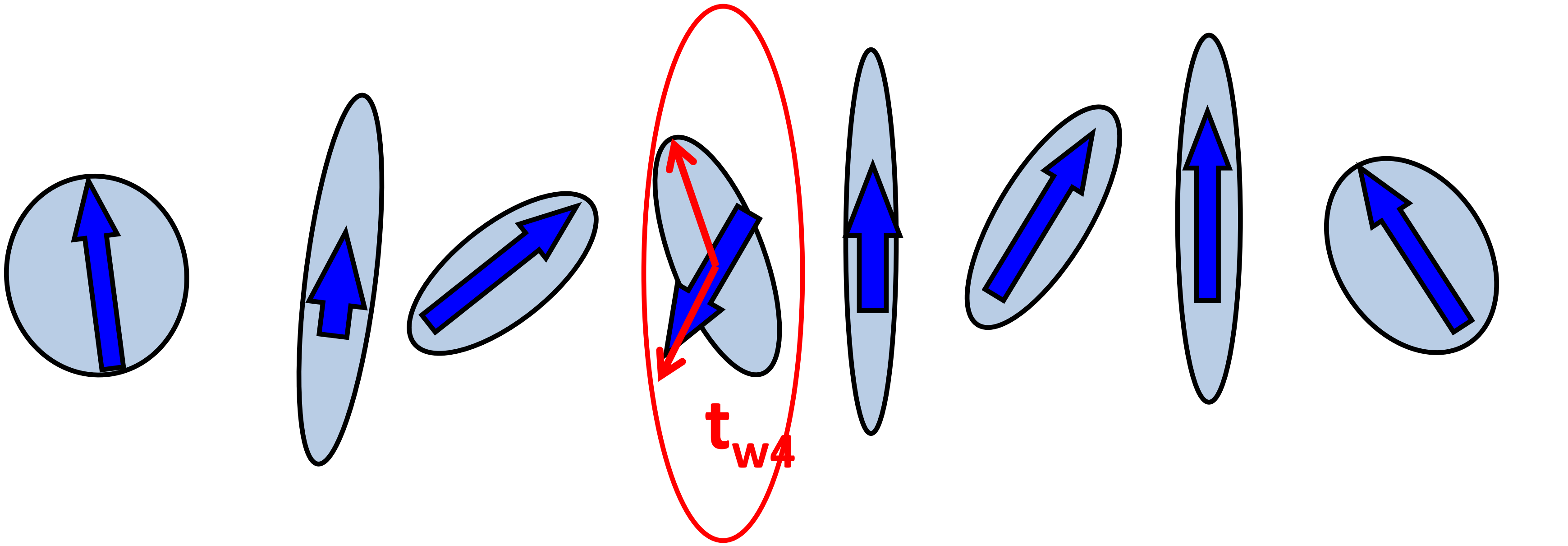
t_{w1} t_{w2} t_{w3} t_{w4} t_{w5} t_{w6} t_{w7} t_{w8}

The particle with the shortest wait time is chosen.



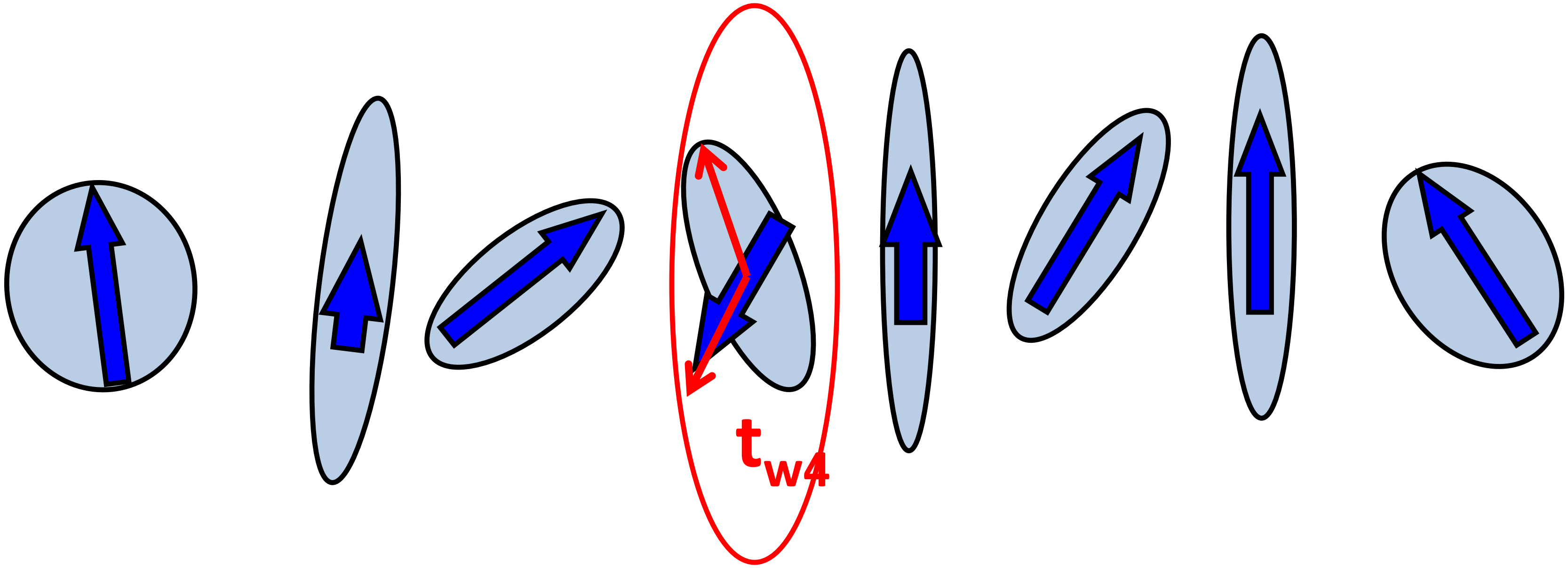
That particle makes a transition to another energy minimum, and time is advanced.

$$t = t + t_{w4}$$



ASSUMPTION: **The switching times are much smaller than the wait times, and are ignored.**

$$t = t + t_{w4}$$



Wait-time Monte-Carlo Algorithm (WMCA):

1) Look at all particles and find a stable state for ZERO temperature. This includes evolving the fields of the structure through a **relaxation** method.

2) Consider the **wait time distribution** for each individual particle.

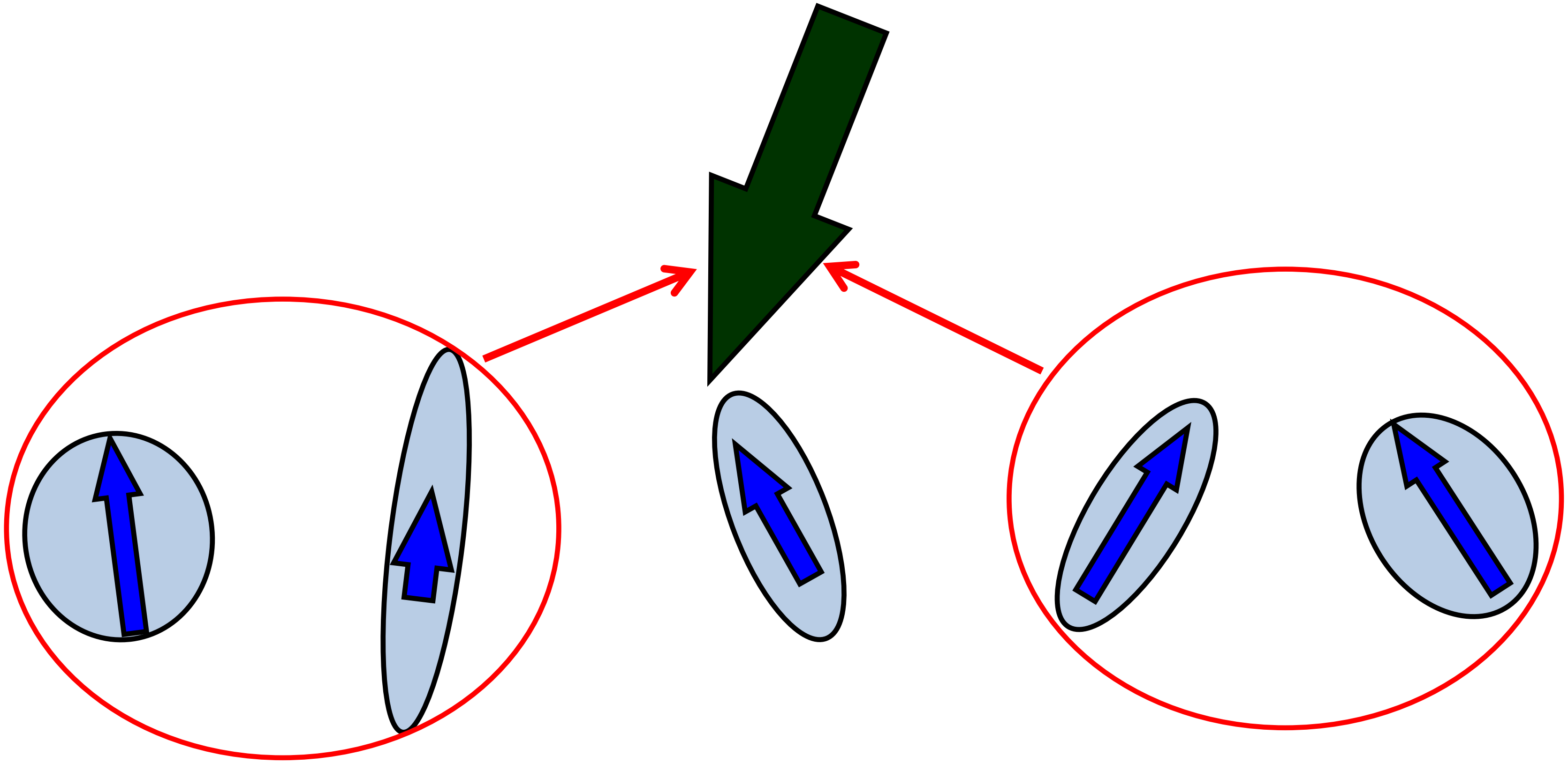
3) Generate a **wait time “guess” for each particle** based on its own distribution.

4) Choose the particle with the **shortest wait time** and **flip it.**

5) **REPEAT.**

Interactions?

- Exchange and Magnetostaic interactions can be added by including them as an effective field.

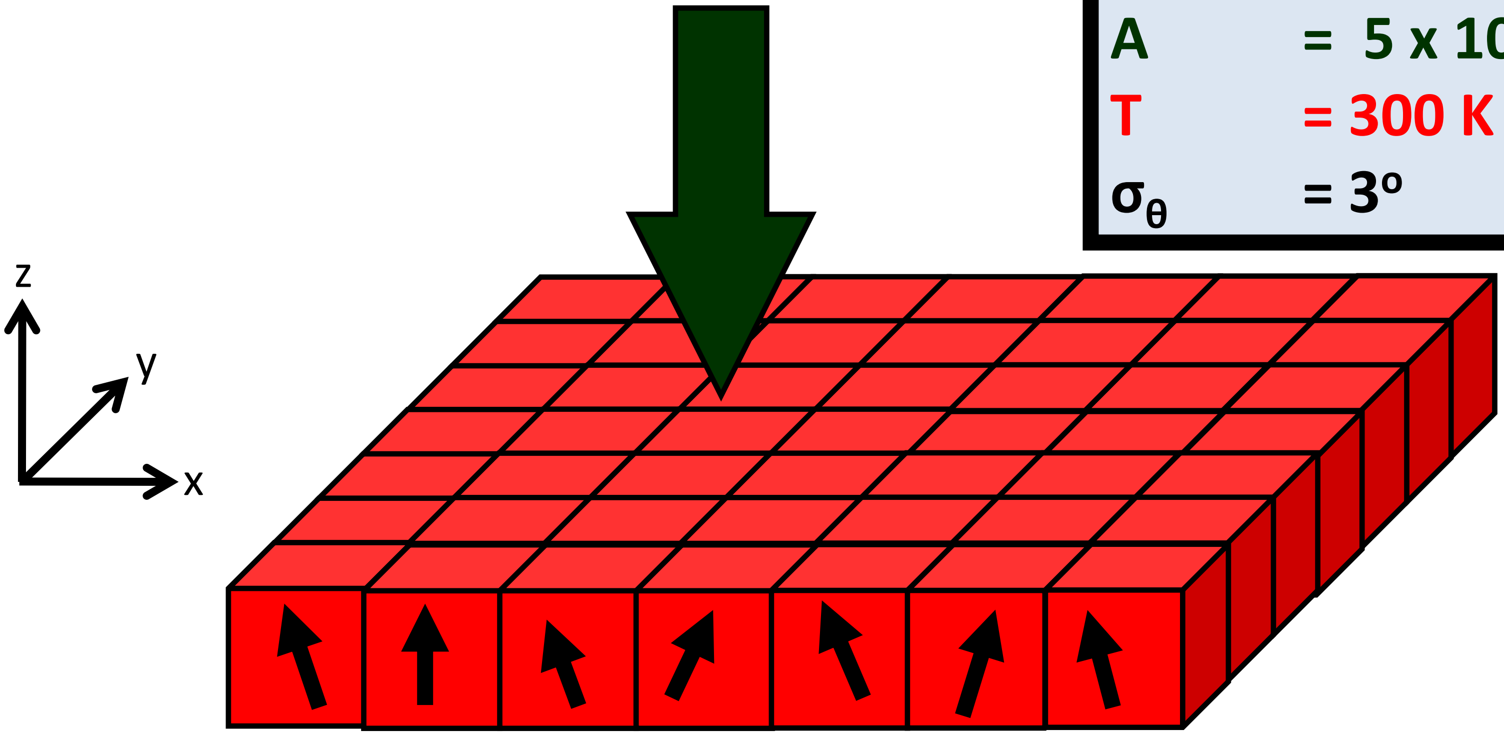


Does it work?

- Compare with dynamic simulations…

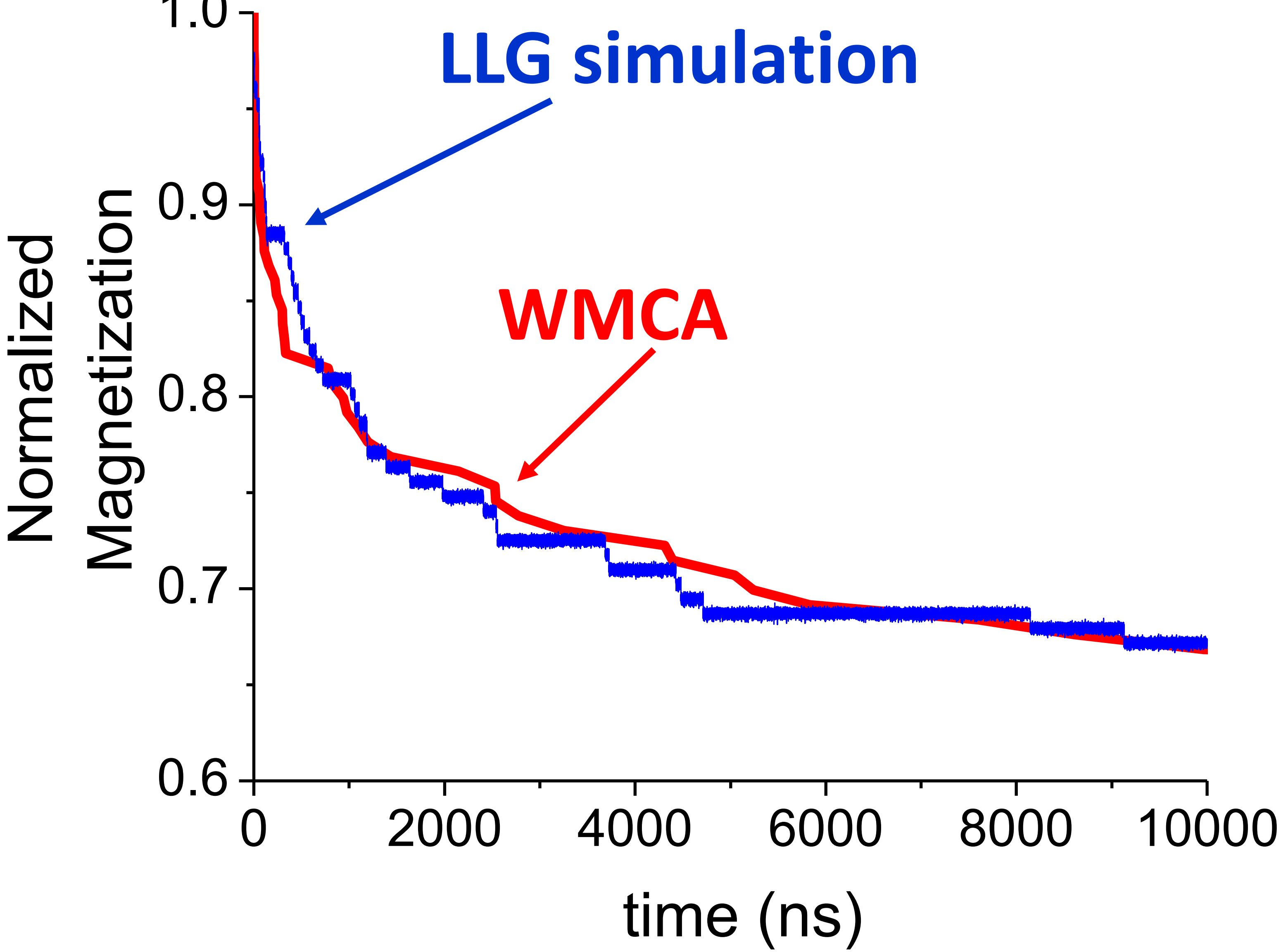
H_o=5 kOe

M_s	= 500 emu/cc
K	= 3.75×10^6 erg/cc
A	= 5×10^{-8} erg/cm
T	= 300 K
σ_θ	= 3^o



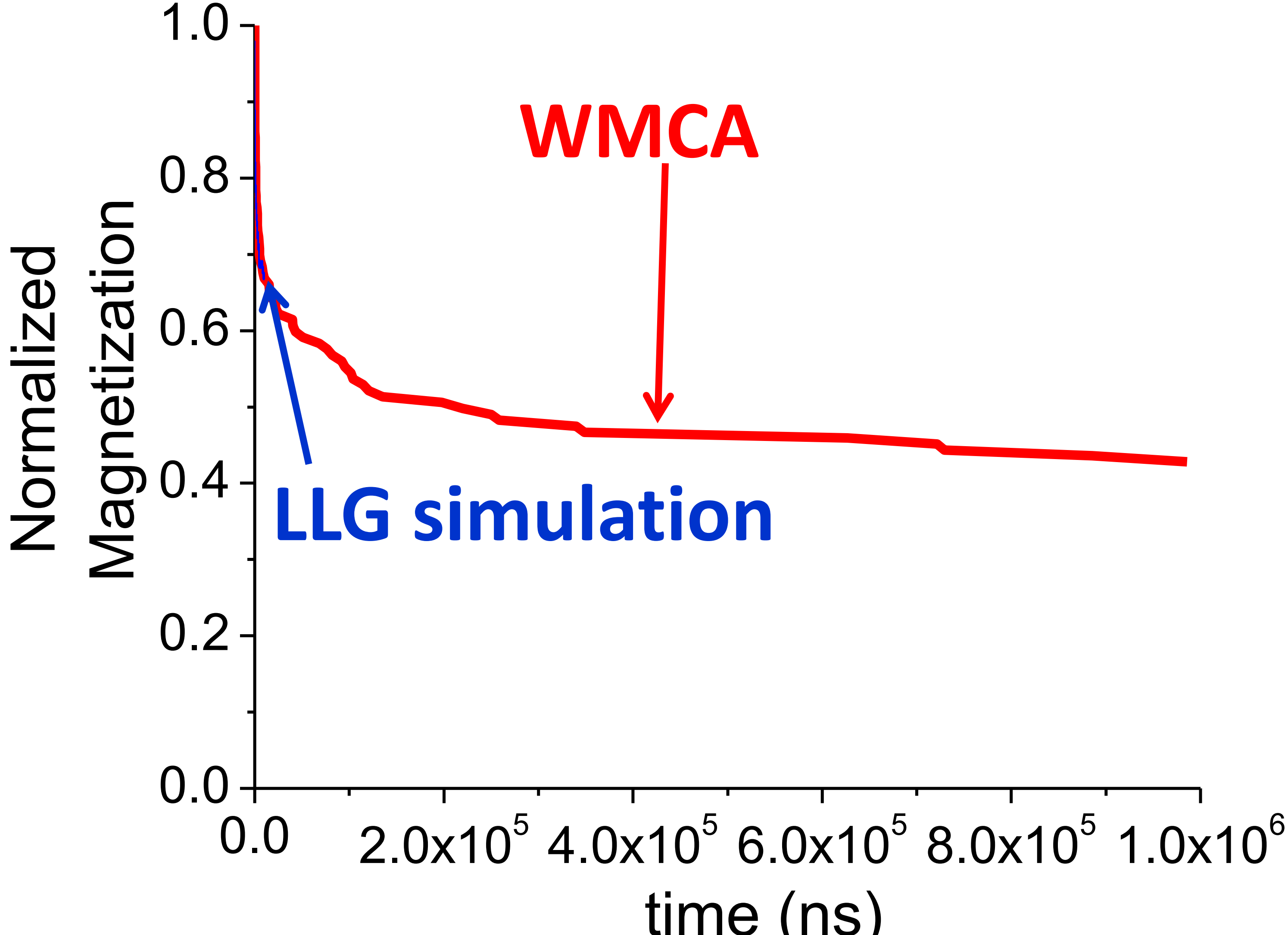
System with distributions and interactions.

After 10 microseconds



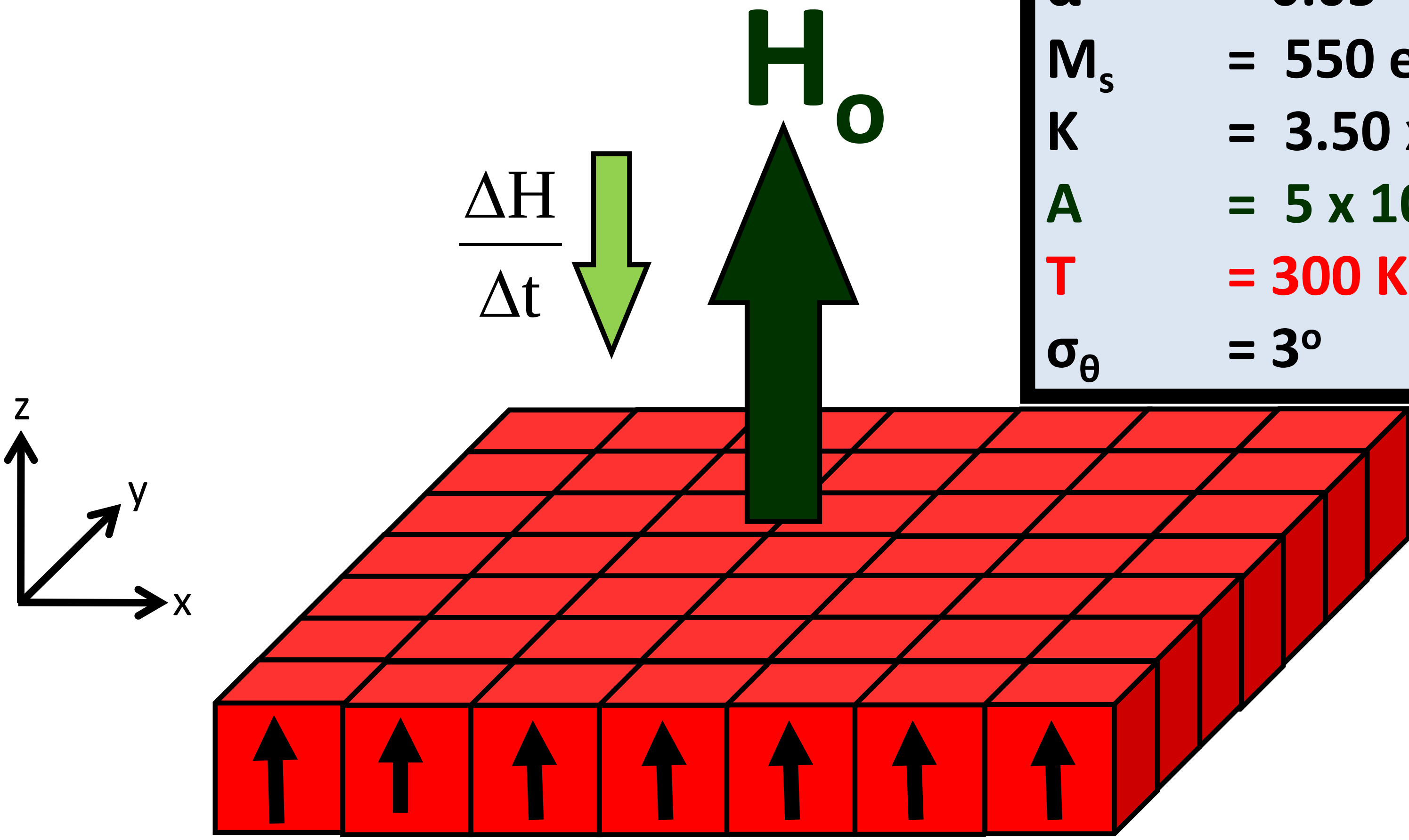
Time Event method out to 1 milliseconds

The **LLG simulations** took about **2 days** to go **10 microseconds**.
The **WMCA** ran for about **30 seconds** to go to **1 millisecond**.



Time and Temperature dependant M-H loops

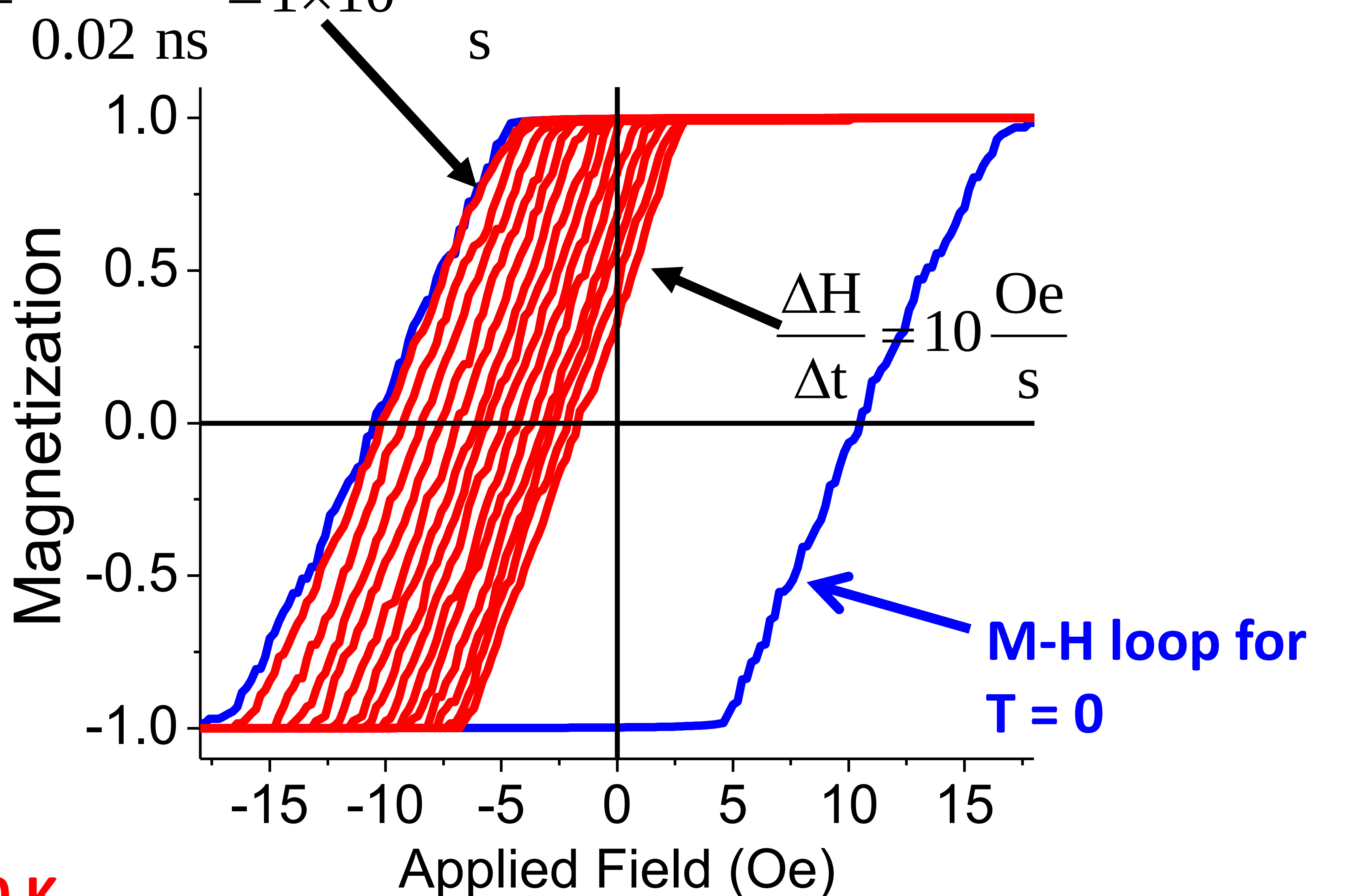
α	= 0.05
M_s	= 550 emu/cc
K	= 3.50×10^6 erg/cc
A	= 5×10^{-8} erg/cm
T	= 300 K
σ_θ	= 3^o



System with distributions and interactions.

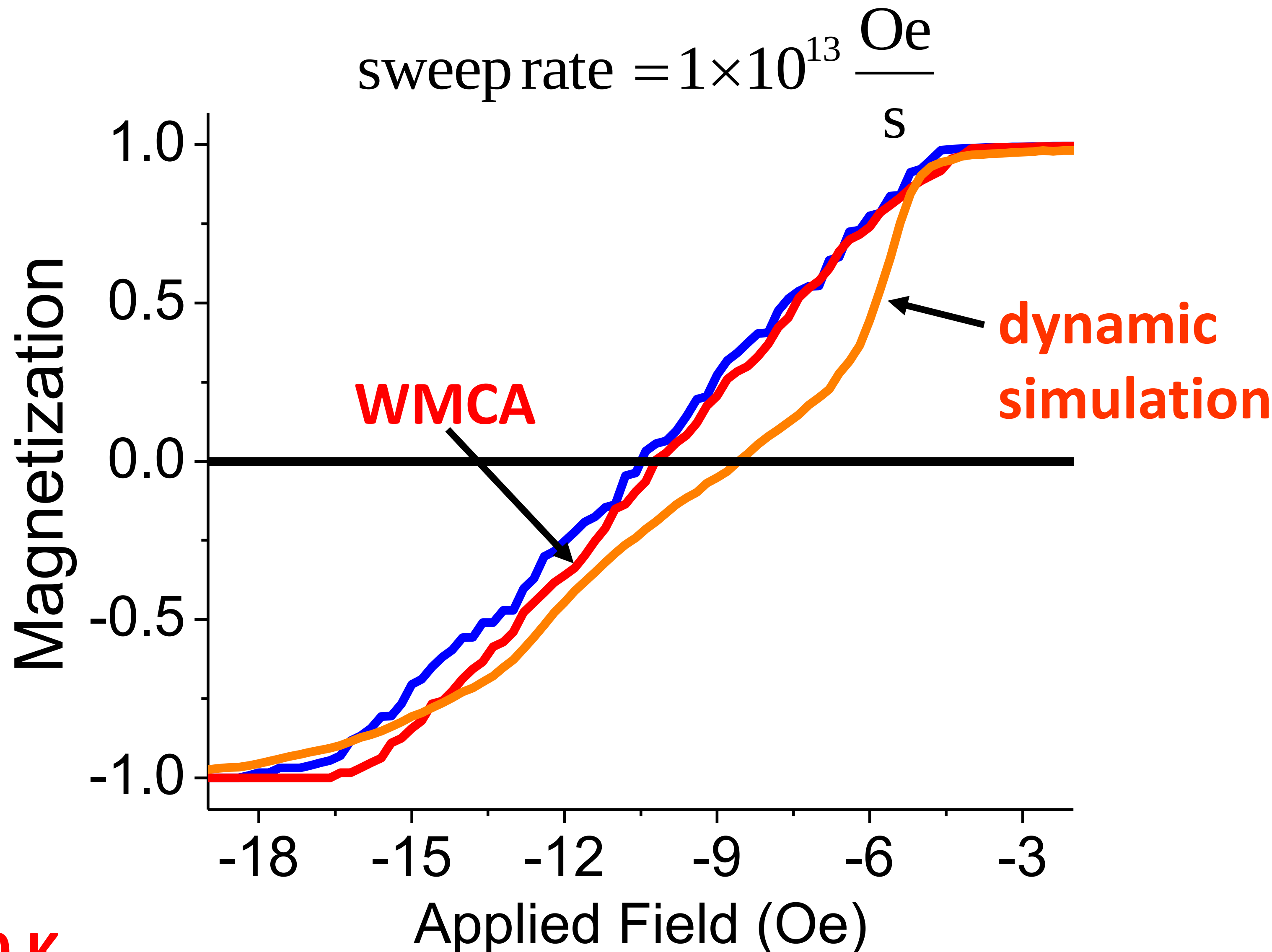
Time and Temperature dependant M-H loops

$$\frac{\Delta H}{\Delta t} = \frac{200\,\text{Oe}}{0.02\ \text{ns}} = 1\times 10^{13}\ \frac{\text{Oe}}{\text{s}}$$



T = 300 K

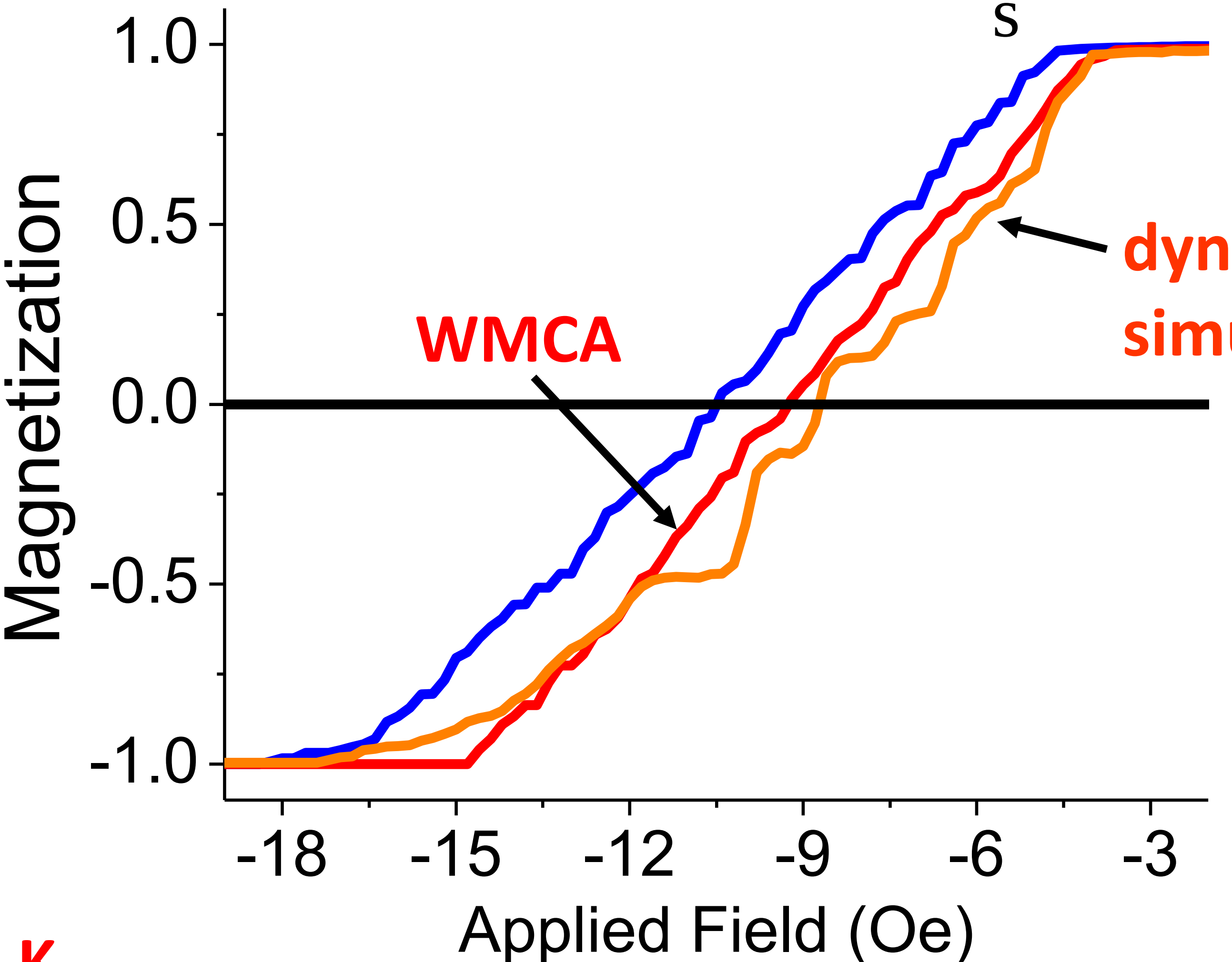
Compared with a dynamic simulation



T = 300 K

Compared with a dynamic simulation

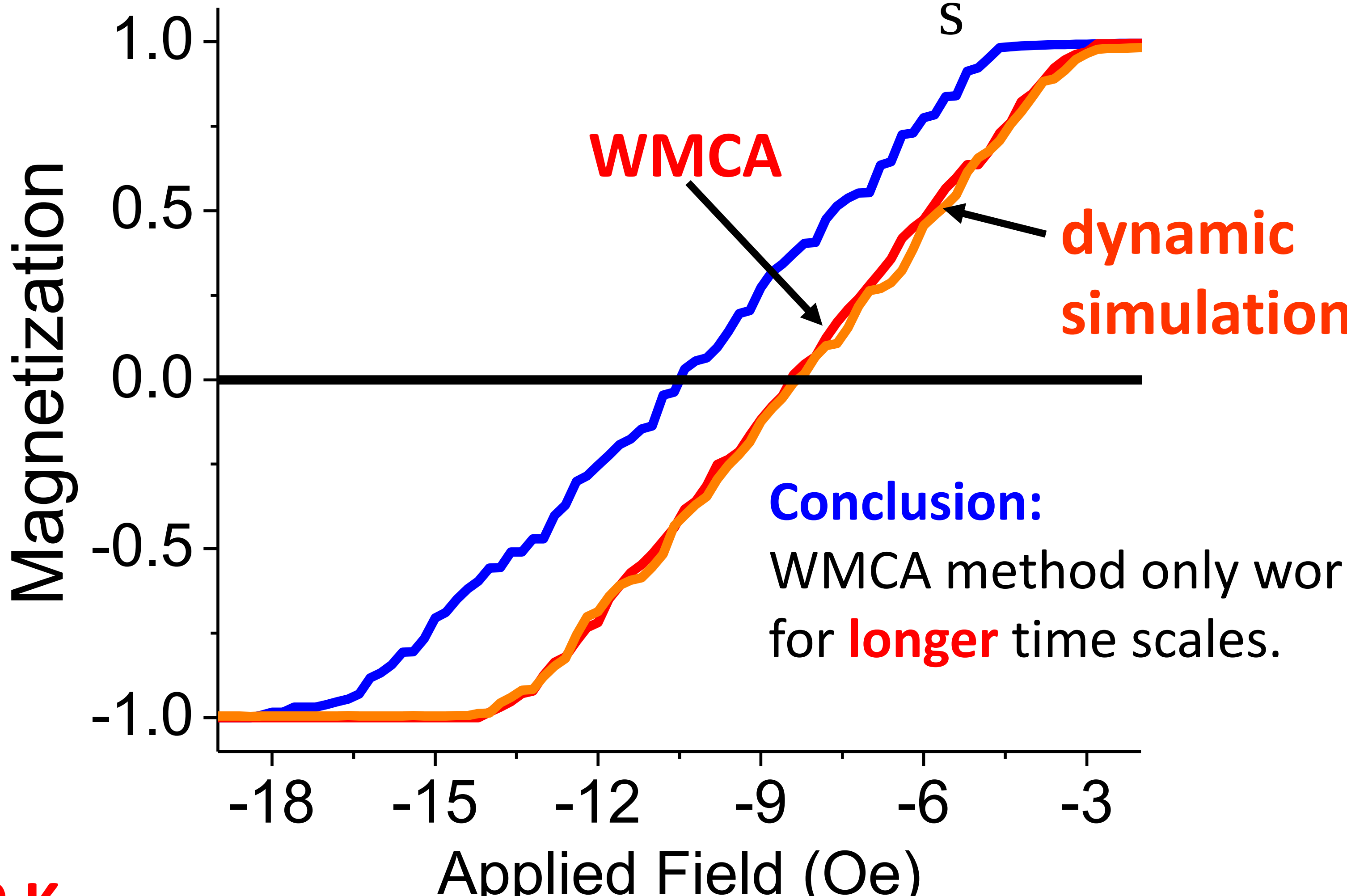
$$\text{sweep rate} = 1\times10^{12}\ \frac{\text{Oe}}{\text{s}}$$



T = 300 K

Compared with a dynamic simulation

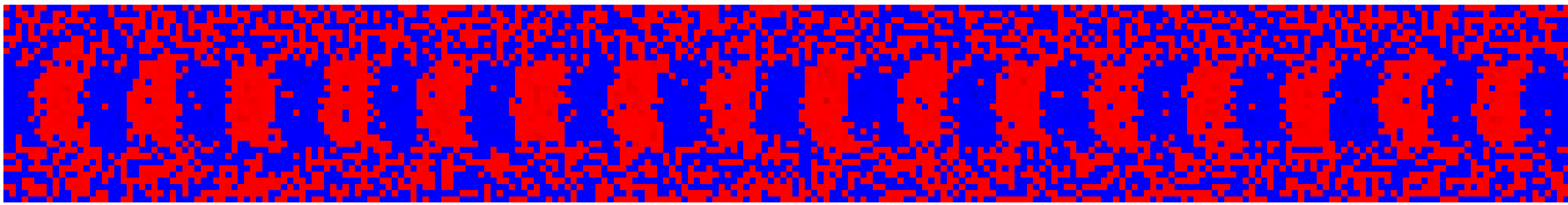
$$\text{sweep rate} = 1\times10^{10}\ \frac{\text{Oe}}{\text{s}}$$



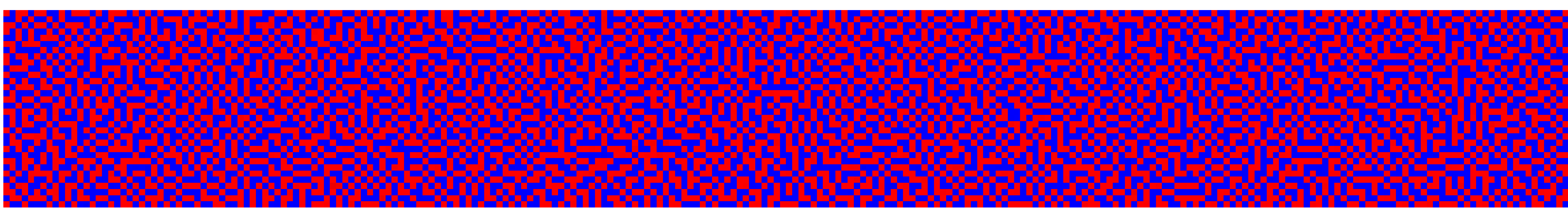
Conclusion:
WMCA method only works for **longer** time scales.

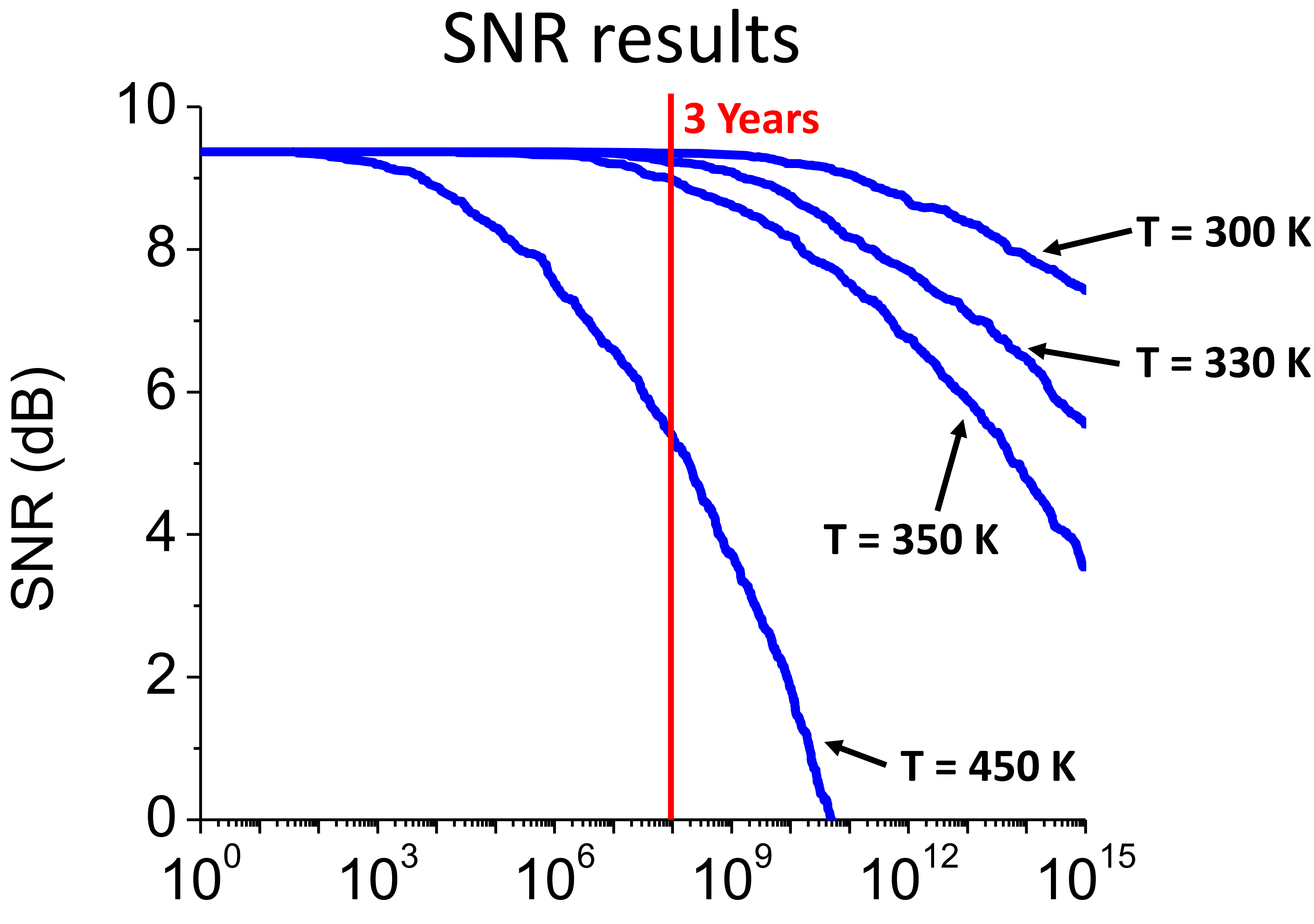
T = 300 K

Bit pattern decay: Signal to noise ratio



$$SNR = 10\log\left(\frac{\sum\limits_{site}\left\langle H_z\right\rangle^2}{\sum\limits_{site}\left(\left\langle {H_z}^2\right\rangle - \left\langle H_z\right\rangle^2\right)}\right)\ dB$$




SNR results
3 Years
T = 300 K
T = 330 K
T = 350 K
T = 450 K
SNR (dB)
10
8
6
4
2
0
10^0
10^3
10^6
10^9
10^{12}
10^{15}
time (seconds)

f_o = 10 GHz

Conclusions about WMCA

- **Promising:** Good agreement with other theoretical results.
- **Fast:** Calculations are very quick, leaving plenty of room to include complexity
- **Works at Long time scales:** In a **short-time scale**, the dynamics of the processes become more important and this method **breaks down**.
  - **But it shows agreement with dynamic simulations on a MEDIUM time scale.**
- **FUTURE WORK:**
  - **Better calculations of ΔE's**
  - **Field/temperature/damping dependence f_o.**
  - **Layered media**