# Minimum energy consumption in isolated and interacting magnetic nanoswitches

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## GHOST research group

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## Current Research Projects:

"**LANDAUER**" - European Community (FP7/2007-2013)

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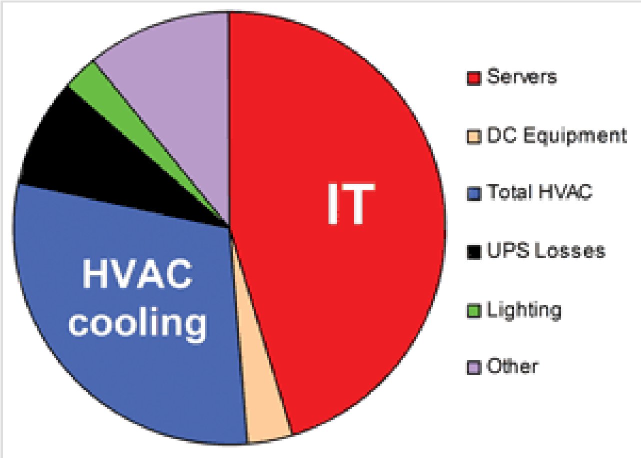
"**DyNanoMag**" – PRIN Project, Ministero Italiano dell'Universotà e della Ricerca (MIUR)

# Motivation

Energy dissipation during information processing is an **hot topic** in current (ICT) research field.




- The complementary metal-oxide semiconductor technology (CMOS) is facing fundamental challenges as **increased power dissipation** and rapidly approaching the **limits of scaling**

- The research in the field of data storage is driven by the need of: **bit size** reduction as well as **fast**, **reliable**, **energy efficient** switching mechanisms

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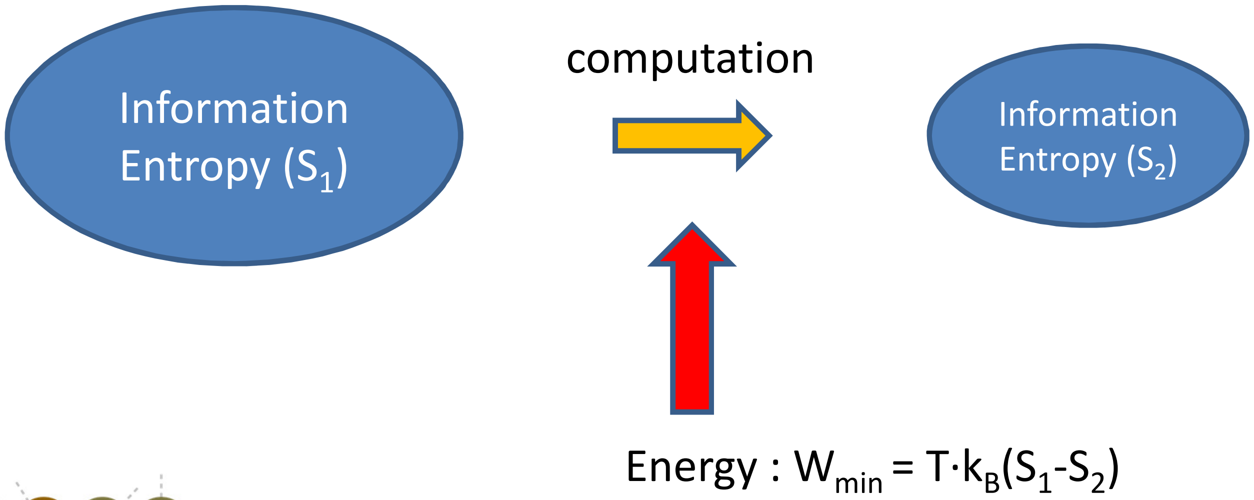
# Landauer principle

The logical operation to restore to “1” a single bit (*Landauer erasure*) requires a minimum generation of heat of $\boldsymbol{k_B T \cdot \ln(2)}$ <- Landauer limit

R. Landauer, IBM J. Res. Dev. 5, 183 (1961).

**Landauer principle**: All logically irreversible operations require a generation of heat of $\boldsymbol{k_B T \cdot \ln(2)}$ energy per bit of information lost.

C. H. Bennett, International Journal of Theoretical Physics **21**, 905–940 (1982).

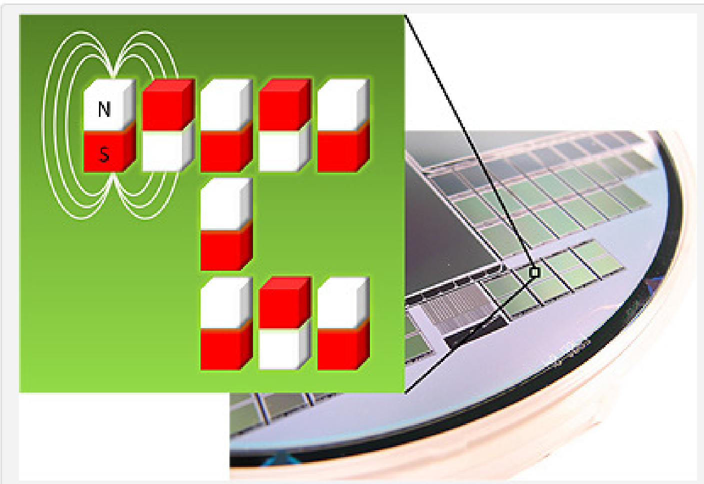


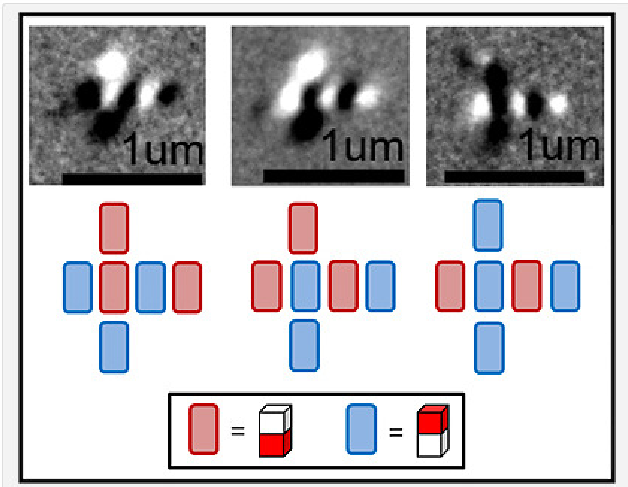
# Nanomagnetic switches

- Bistable nanomagnetic switches (i.e. magnetic systems of **nanometric** dimensions and **two** degenerate **minimum energy configurations**) can be used, in principle, to both:

  a) encode information (two degenerate energy minima: “0” and “1”)

  b) process information: **nanomagnetic logic devices** (NML) such as the magnetic quantum cellular automata (MQCA)




- **Nanometer scale devices, non-volatile, low-power**

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Images courtesy of Prof. J. Bokor, http://www.eecs.berkeley.edu/

# Outline

- Introduction to the micromagnetic approach
- Landauer erasure of nano-magnetic *bits*
- Reversible (*adiabatic*) switching of nano-magnetic *bits*
- Results of recent **measurements** on Landauer erasure of nano-magnetic *bits*

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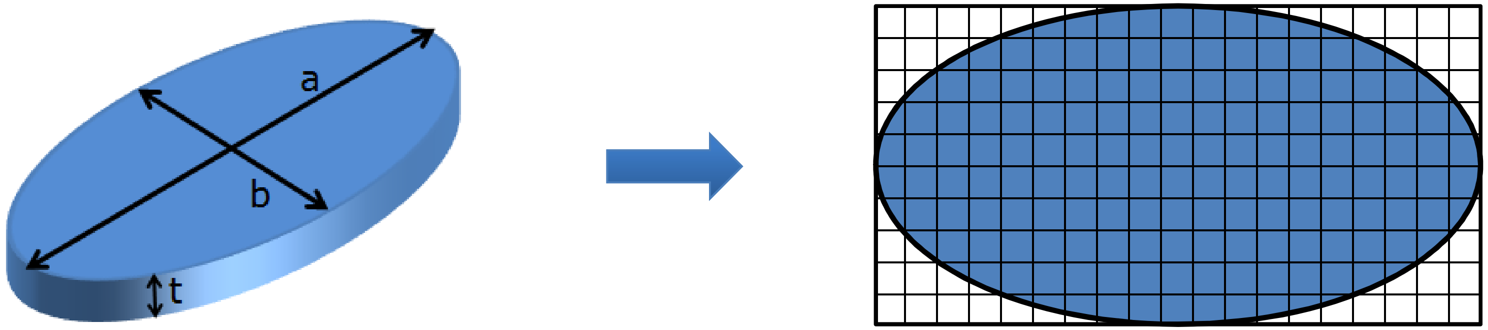
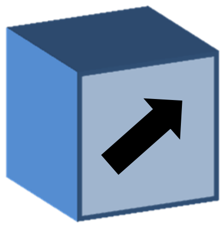
# Micromagnetic approach



Each cell contains a <u>single spin:</u>

1) constant **modulus ($M_s$)** and **position**

2) its **orientation** in 3 dimensions may vary

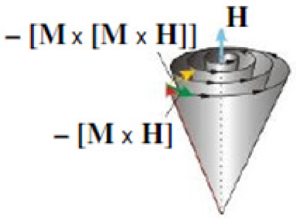
Typical dimensions of the elementary cells: 1-5 nm

# Magnetization dynamics at T=0 K

**Landau-Lifshitz-Gilbert equation**

$$\frac{d\mathbf{M}_i}{dt} = -\gamma\left[\mathbf{M}_i \times \mathbf{H}_i^{\mathrm{eff}}\right] - \gamma\frac{\lambda}{M_S}\left[\mathbf{M}_i \times \left[\mathbf{M}_i \times \mathbf{H}_i^{\mathrm{eff}}\right]\right]$$

precession — relaxation (dissipation)




$\gamma$ - gyromagnetic ratio
$\lambda$ - dissipation constant

$\mathbf{H}^{\mathrm{eff}}$ ( $= \mathbf{H}^{\mathrm{ext}} + \mathbf{H}^{\mathrm{an}} + \mathbf{H}^{\mathrm{exch}} + \mathbf{H}^{\mathrm{dip}}$) – **deterministic** effective field

**No** fluctuations field - **no thermal** fluctuations

'**Normal**' (deterministic) ODE

Methodical problems:

- discretization effects (cell size < char. length !)
- solution of ODE (example: NIST standard problem # 4)

Courtesy of D. Berkov, author of Micromagus

# Magnetization dynamics at T>0 K

**Landau-Lifshitz-Gilbert equation including a random field**

$$\frac{d\mathbf{M}_i}{dt} = -\gamma \cdot \left[\mathbf{M}_i \times (\mathbf{H}_i^{\text{eff}} + \mathbf{H}_i^{\text{fl}})\right] - \gamma \cdot \frac{\lambda}{M_S} \cdot \left[\mathbf{M}_i \times \left[\mathbf{M}_i \times (\mathbf{H}_i^{\text{eff}} + \mathbf{H}_i^{\text{fl}})\right]\right]$$

$\mathbf{H}^{\text{eff}}\ (= \mathbf{H}^{\text{ext}} + \mathbf{H}^{\text{an}} + \mathbf{H}^{\text{exch}} + \mathbf{H}^{\text{dip}})$ – deterministic effective field

$\mathbf{H}^{\text{fl}}$ – random (fluctuation) field

$$\langle H_{\xi,i}^{\text{fl}} \rangle = 0, \qquad D = \lambda \cdot \frac{kT}{\gamma M_S V} \qquad (\xi, \eta = x, y, z)$$

$$\langle H_{\xi,i}^{\text{fl}}(t) \cdot H_{\eta,j}^{\text{fl}}(0) \rangle = D \cdot \delta(t) \cdot \delta_{ij} \cdot \delta_{\xi\eta}$$

**Fluctuation field mimics the effect of thermal fluctuations**

**Stochastic ODE**

Methodical problems:
- solution of the stochastic differential equation
- correlation properties of the fluctuation field

Courtesy of D. Berkov, author of Micromagus

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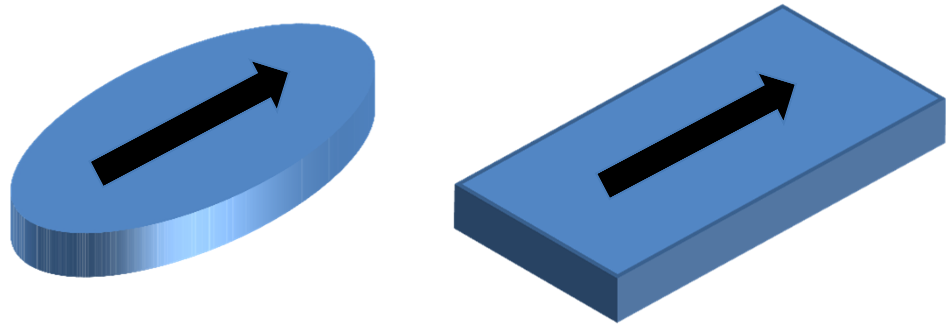
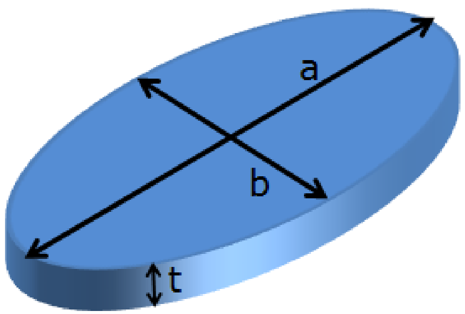
# A nano-magnetic bistable system (magnetic *bit*)

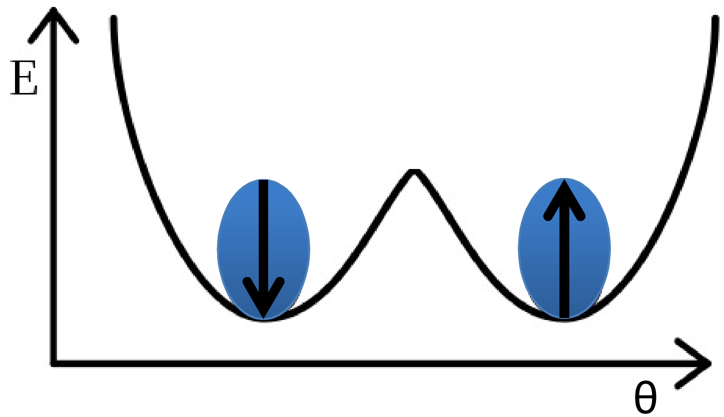
$Ni_{80}Fe_{20}$ elliptical or rectangular dots:

major axis (a): **300-50 nm**
minor axis (b): **120-30 nm**
in-plane aspect ratio (a/b): **5.0-1.7**
thickness (t): **5 nm**
**cell size: 5×5×5 nm$^3$**

The dot shape defines an **in-plane uniaxial anisotropy** with the **easy axis** along the ellipse **major axis**






The energy landscape, with $H_{ext}$=0, is effectively described by a **symmetric bistable** potential

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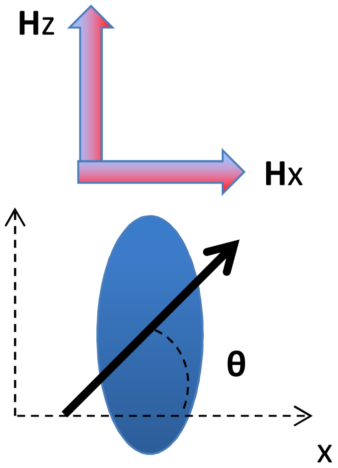
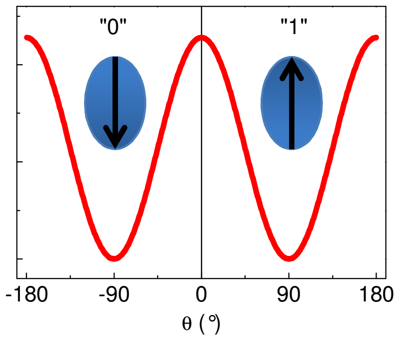
# Energy profile for a magnetic *bit*

Let us consider a magnetic *bit* with **volume** (**V**), **magnetization** (**$M_S$**) and a **uniaxial anisotropy** (**$K_1$**) – e.g. a shape anisotropy, in <u>single-spin approximation</u>.



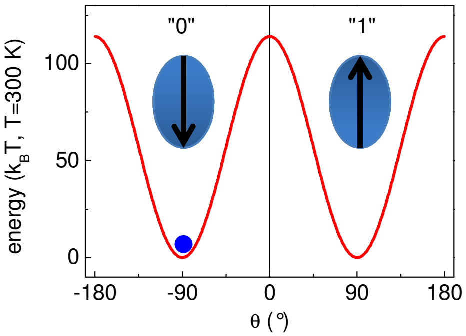

$$E(\theta) = V\left(K_1 \cos^2(\theta) - M_S\left(H_x \cos(\theta) + H_z \sin(\theta)\right)\right)$$

if the external field is zero it reduces to: $E(\theta) = V\left(K_1 \cos^2(\theta)\right)$

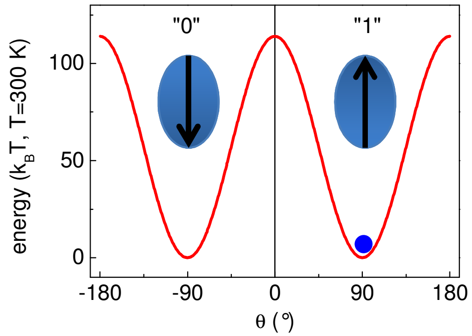


# Switching vs. Erasure

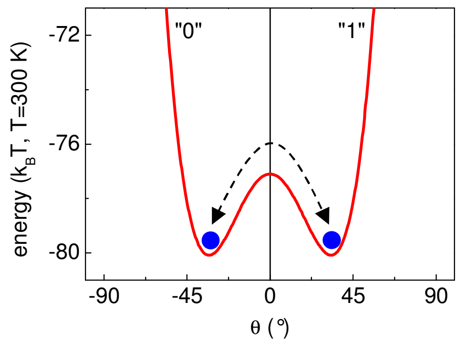
**Switch (adiabatic)**: is a logical **reversible** process which brings the system from an initial **known** state to a final (opposite) **known** state



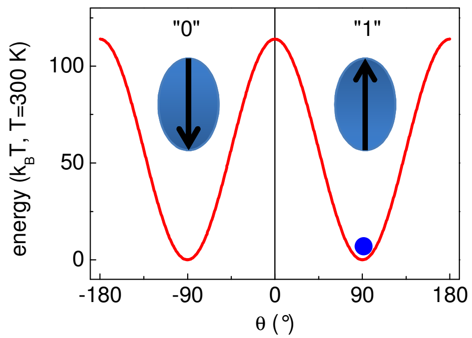

$E_{min} = 0$




**Erasure**: is a logical **irreversible** process which brings the system from an initial **unknown** state to a final **known** state




$E_{min} = k_BT \cdot ln(2)$

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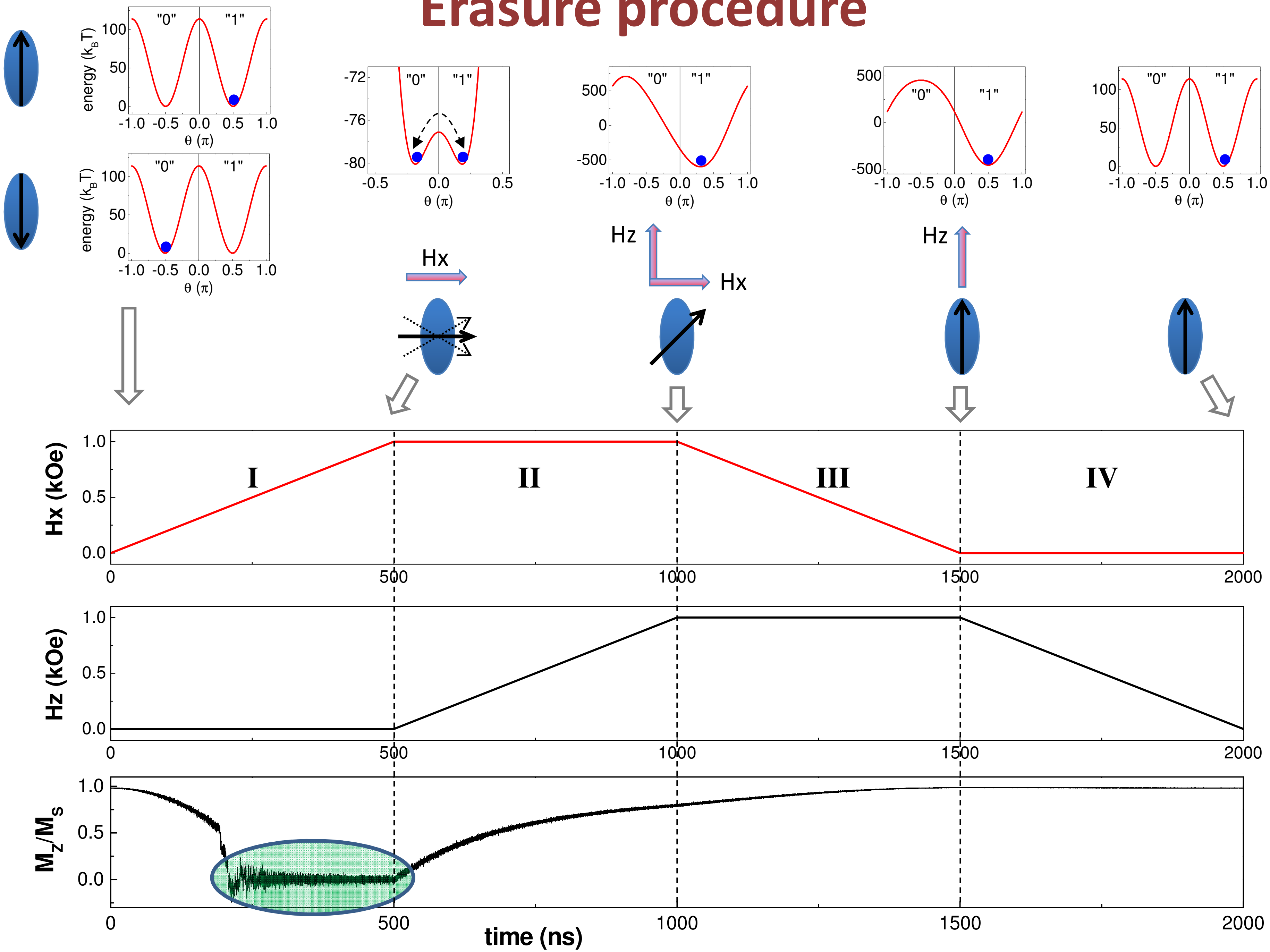
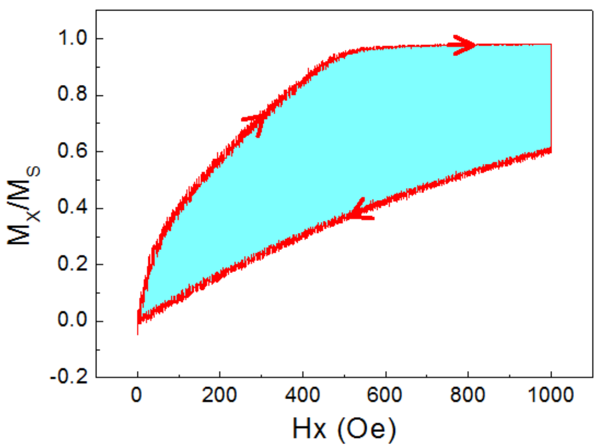
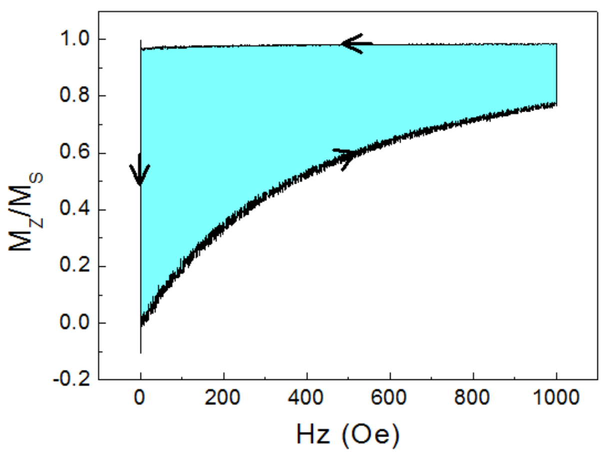
# Erasure procedure



# Dissipated energy in the erasure process

$$E = \int \vec{H} \cdot d\vec{M} = \left( \int H_X \cdot dM_X + \int H_Z \cdot dM_Z \right) \qquad \vec{M} = \sum_i \vec{m}_i$$

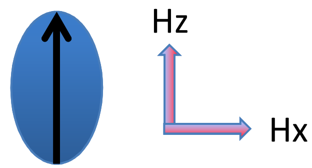


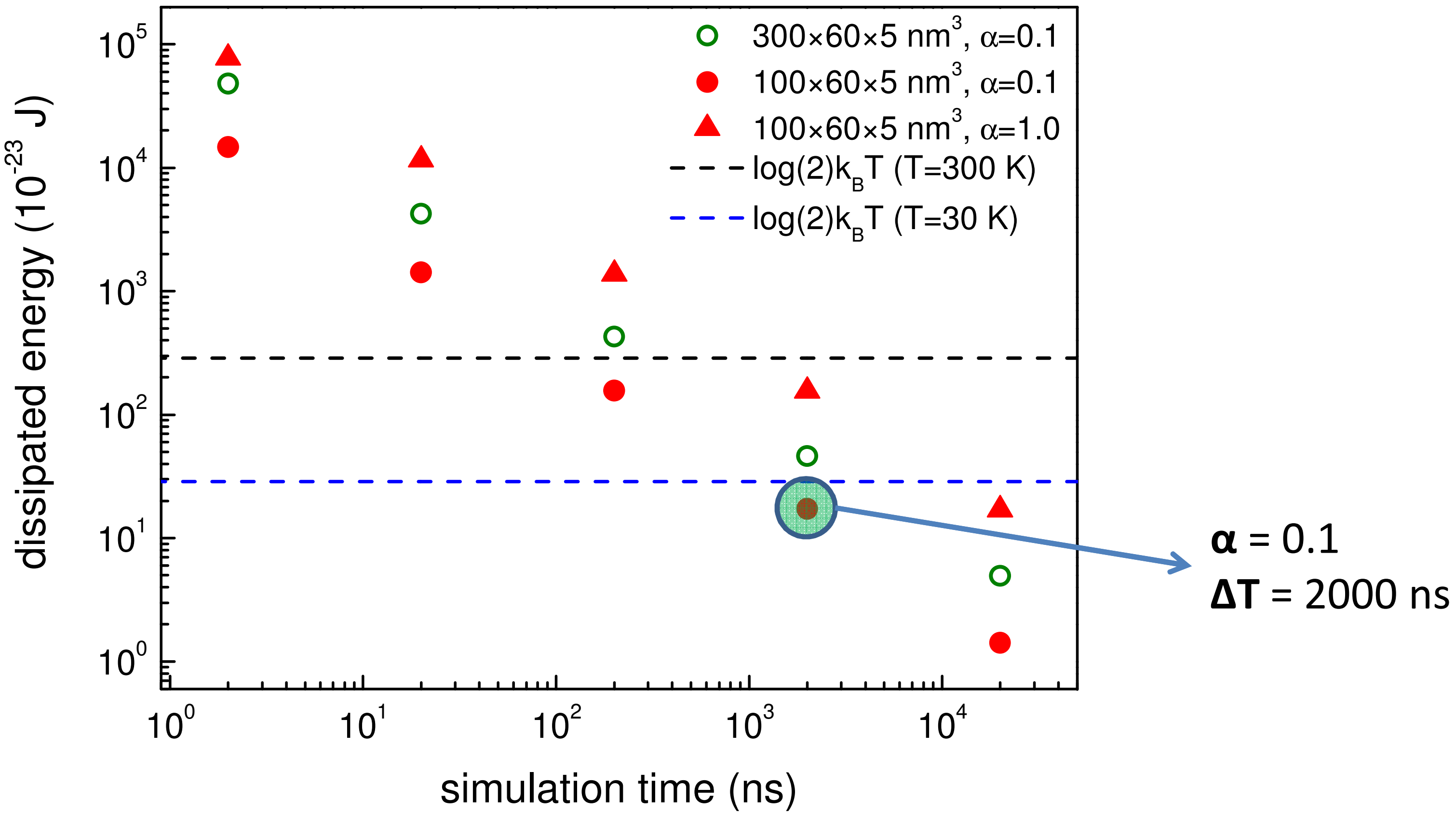




The dissipated energy ***E*** depends on the values of both **α** (damping) and **ΔT** (total simulation time). How do you choose them?

# Dissipated energy at T=0 K

$Ni_{80}Fe_{20}$ elliptical nanodot
The dots are discretized into cells of **5×5×5 nm³**
$K_1$= 0 erg/cm³, shape anisotropy only

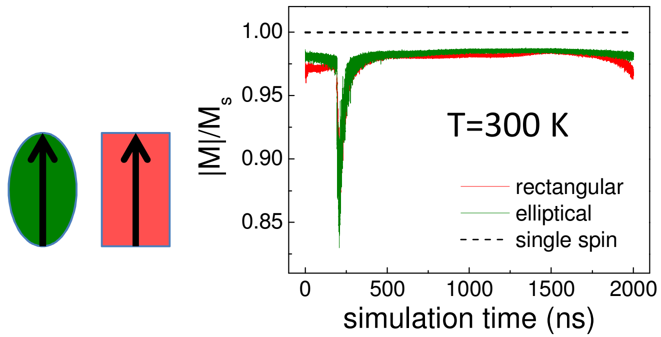


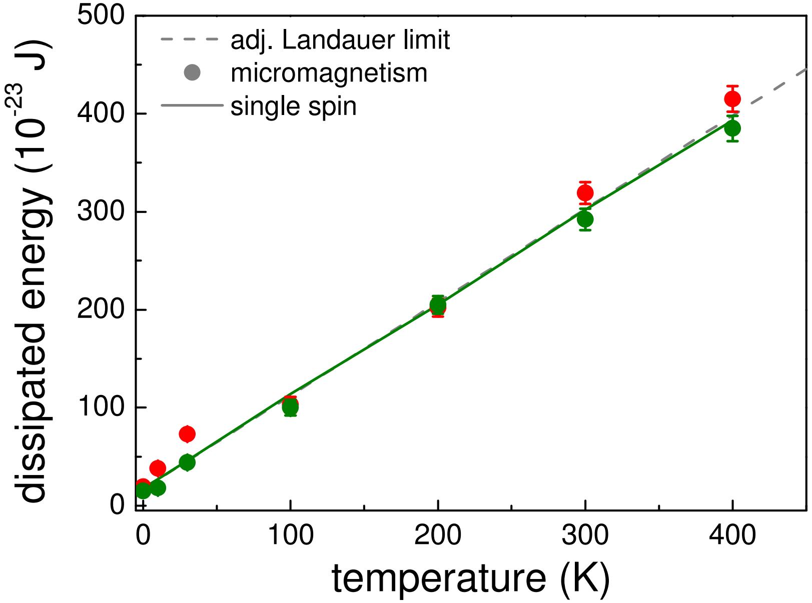




Dissipated energy scales almost linearly with volume (**V**), damping (**α**) and simulation time (**T**)$^{-1}$

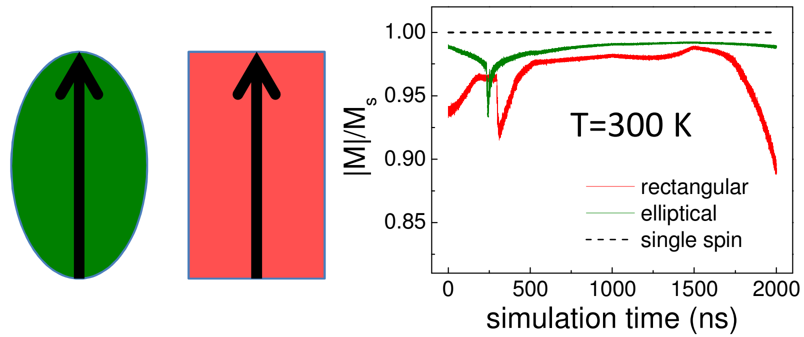
# Volume and shape

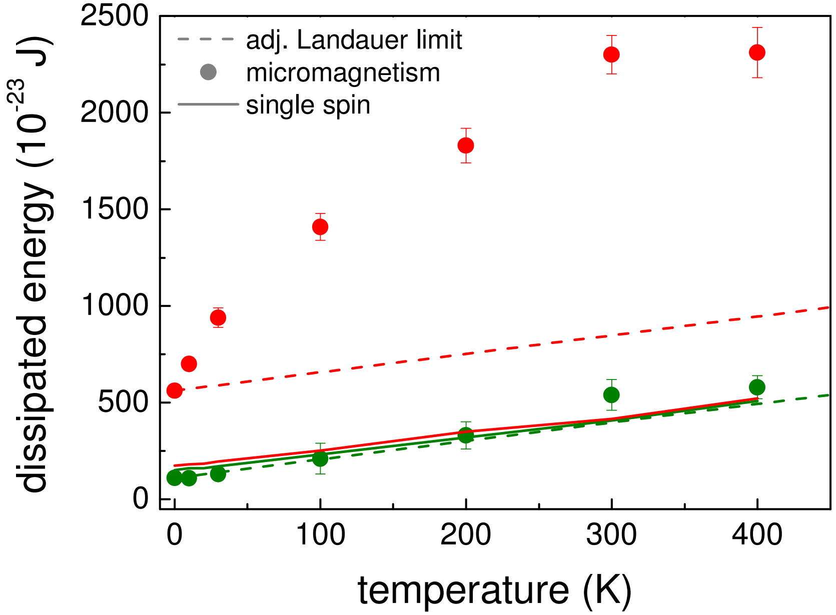
## Small dots (100×60×5 nm³)



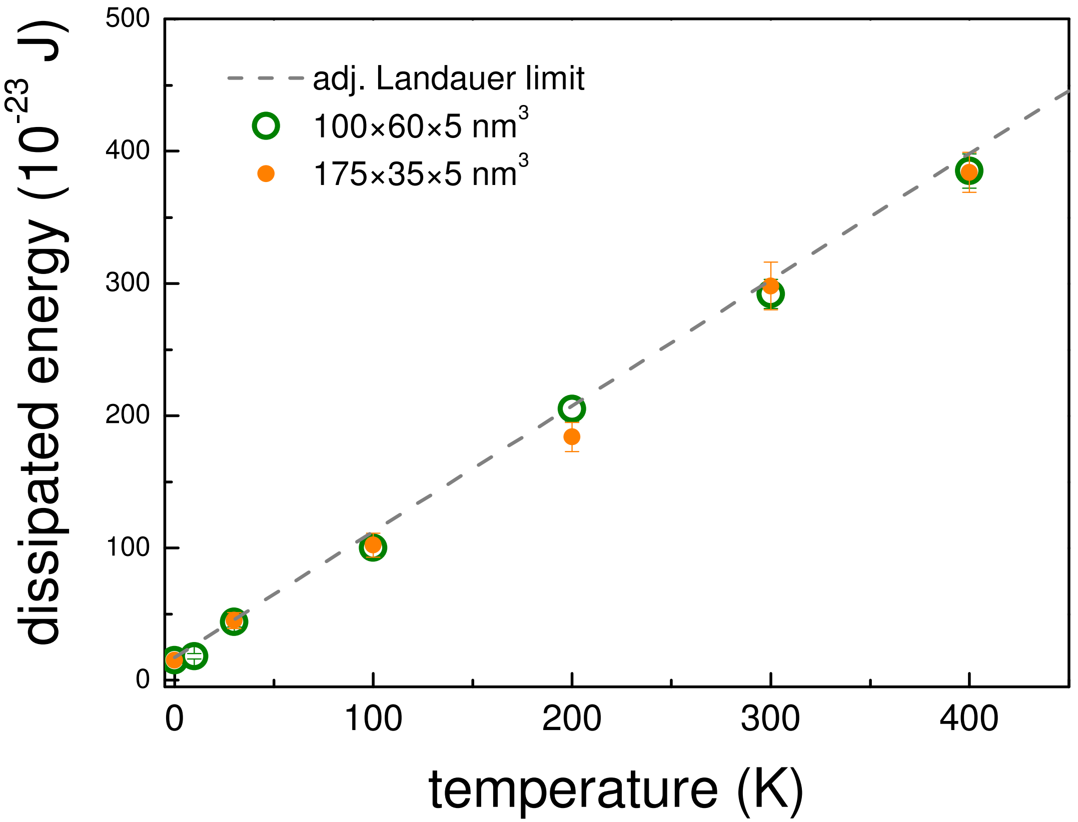



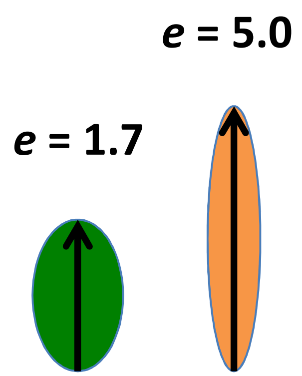

## Large dots (200×120×10 nm³)



# In-plane aspect ratio (ellipticity, *e*)




***e* > 1.05** is enough to make the dot stable on times larger than the total simulation time (**T**)

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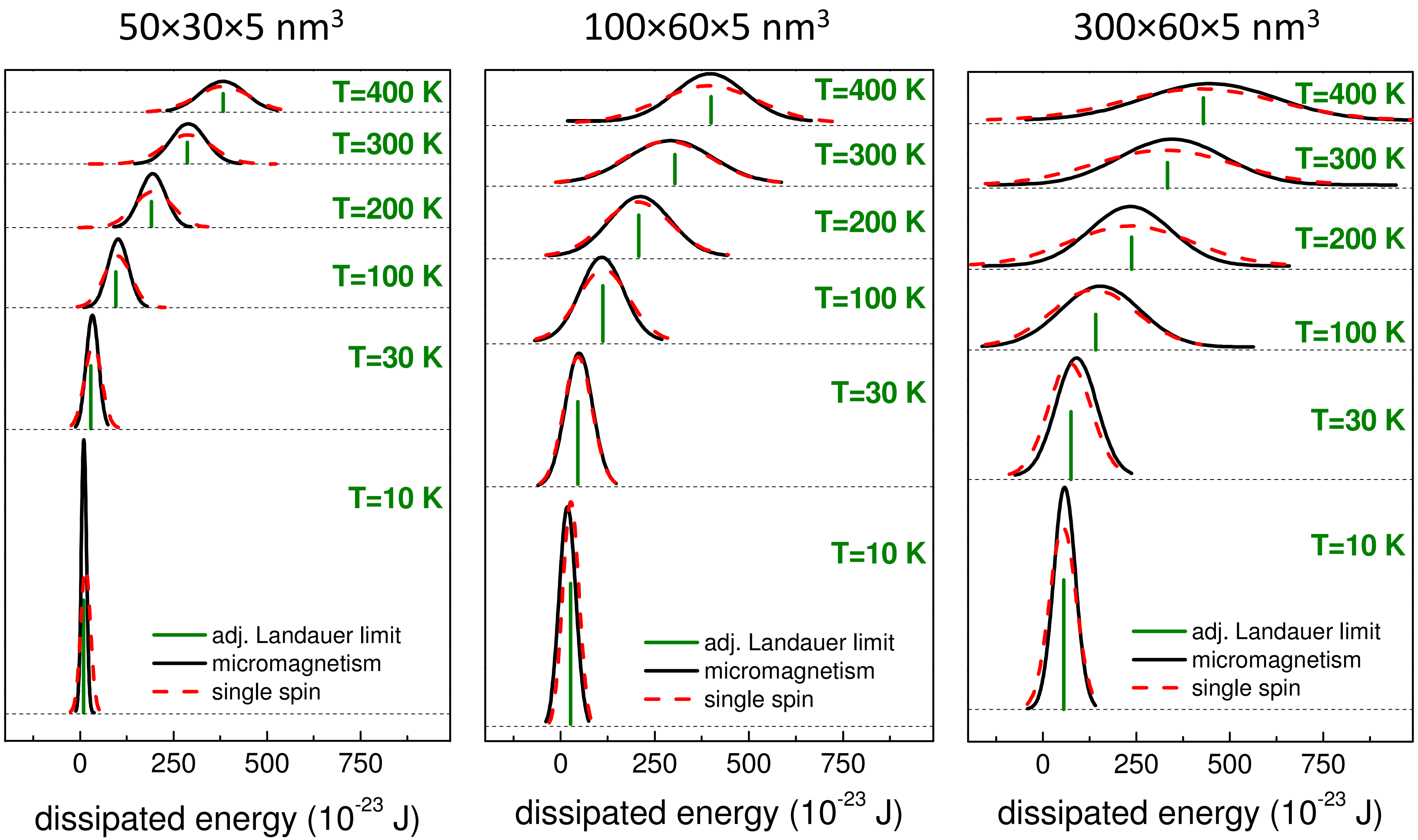
# Statistical distribution of the dissipated energy




The width ($\sigma_{Dist}$) of the statistical distribution (100 simulation runs each) increases with temperature (**T**) and volume (**V**)

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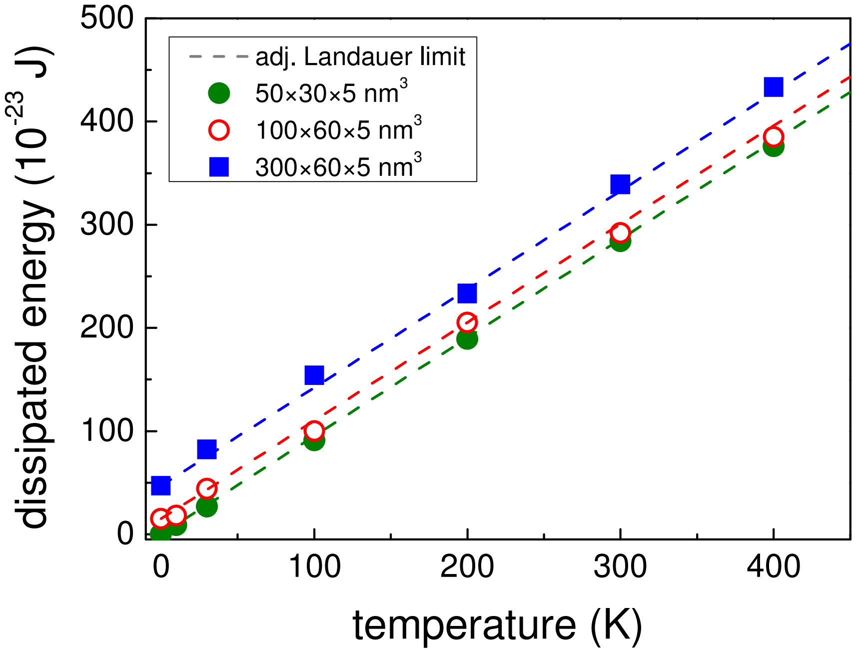
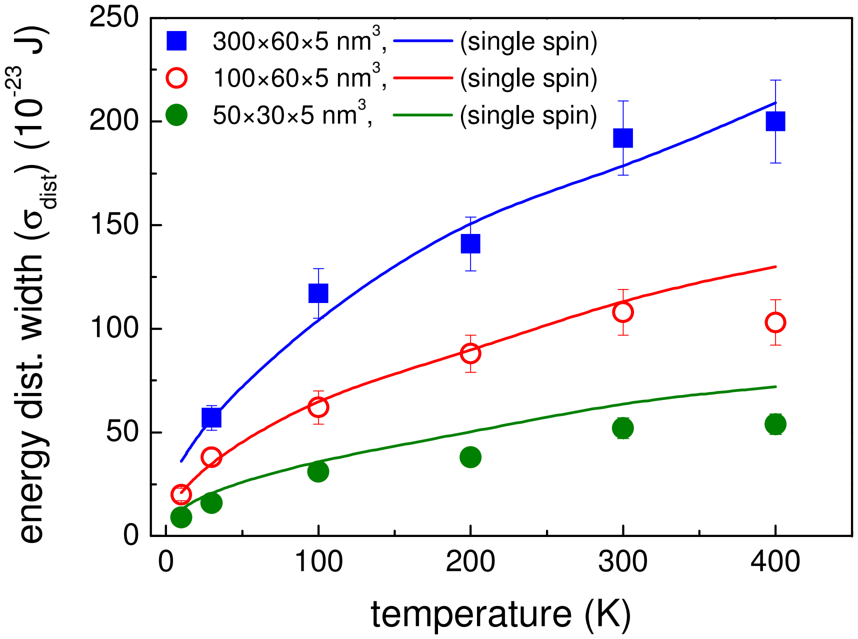
# Statistical distribution of the dissipated energy




The **mean** value is always consistent with the **adjusted Landauer limit**. Nonetheless the **width** increases of about **400%** from the smallest to the largest dot.

It's better to perform **experiment on small dots**!!

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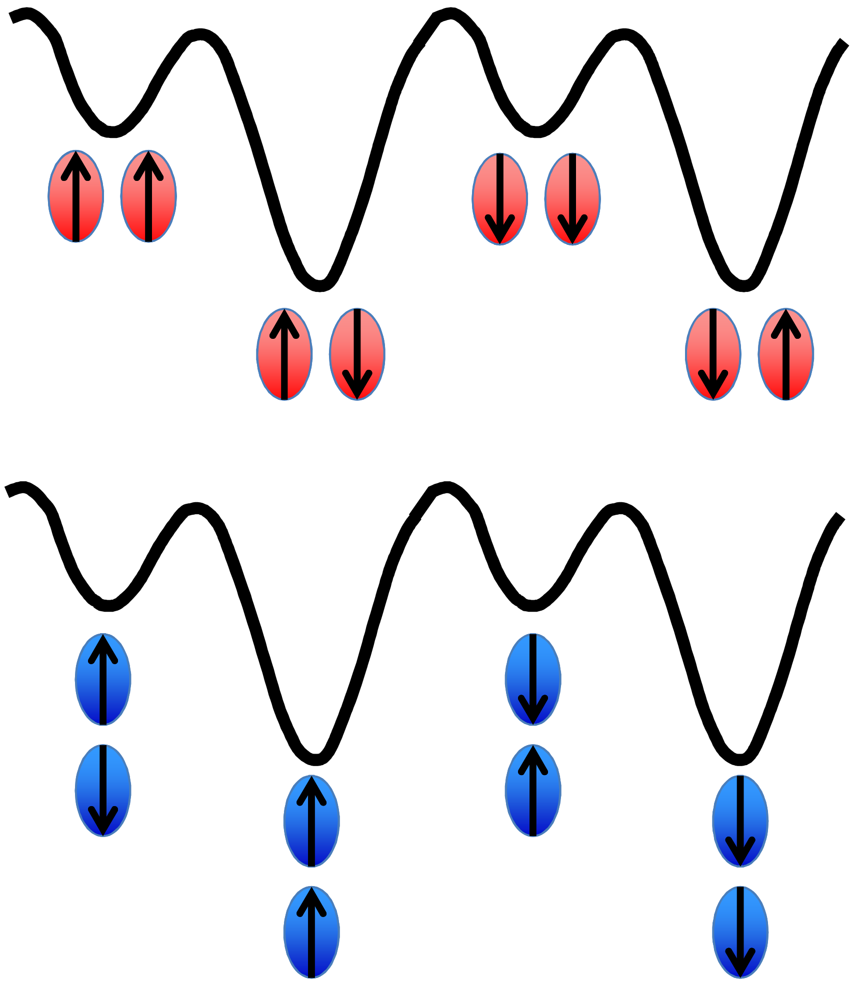
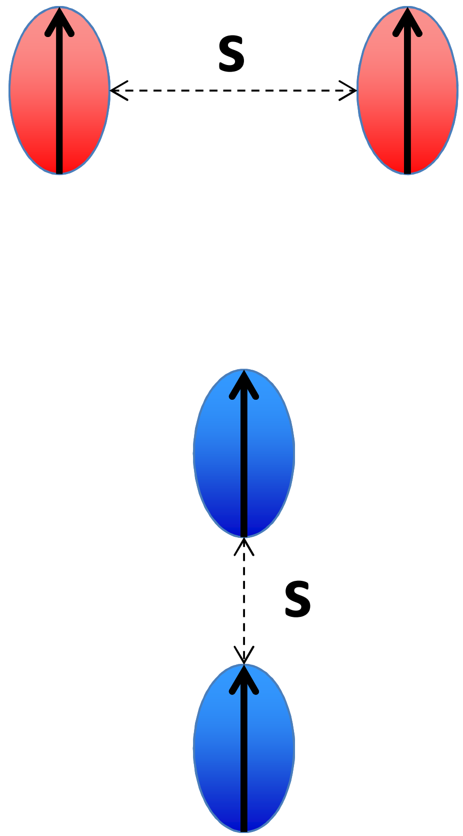
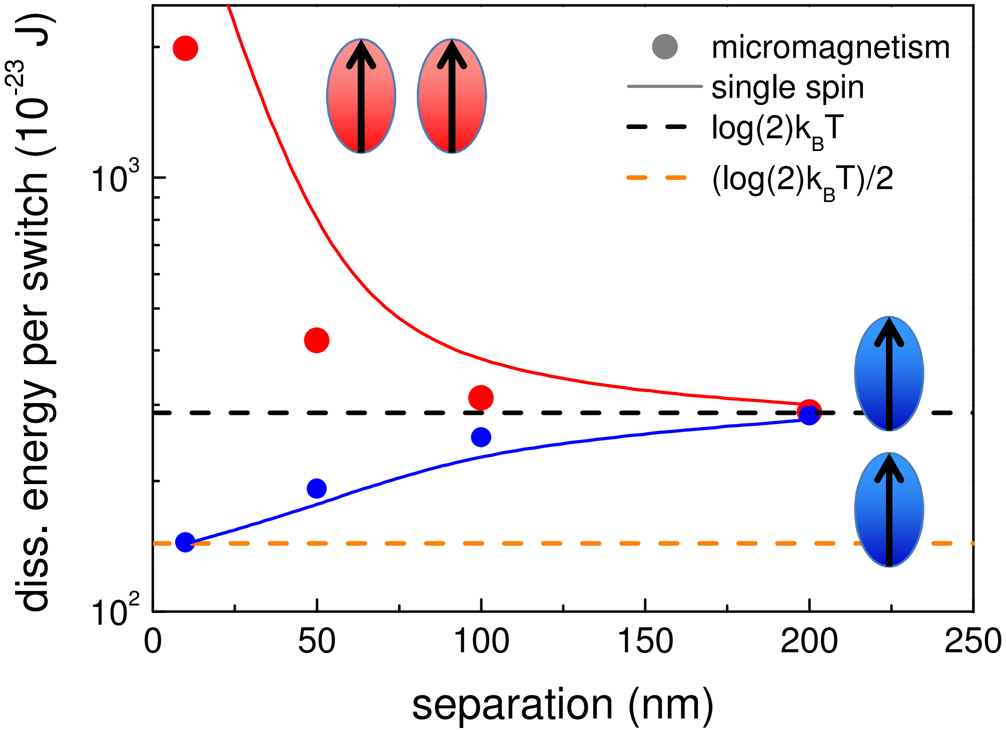
# Interacting dots – (couples)

$Ni_{80}Fe_{20}$ elliptical nanodot, dimensions: 50×30×5 $nm^3$
edge-edge spacing (**s**): 200 – 10 nm
Two possible configurations: **side-by-side**, **head-to-tail**





# Interacting dots – (couples)




- at large separation distances the dots behave like isolated dots
- on reducing the separation distance (**s**) the **head-to-tail** couples behave like **a single dot**
- on reducing the separation distance (**s**) the energy dissipated by the **side-by-side** couples seems to **diverge**

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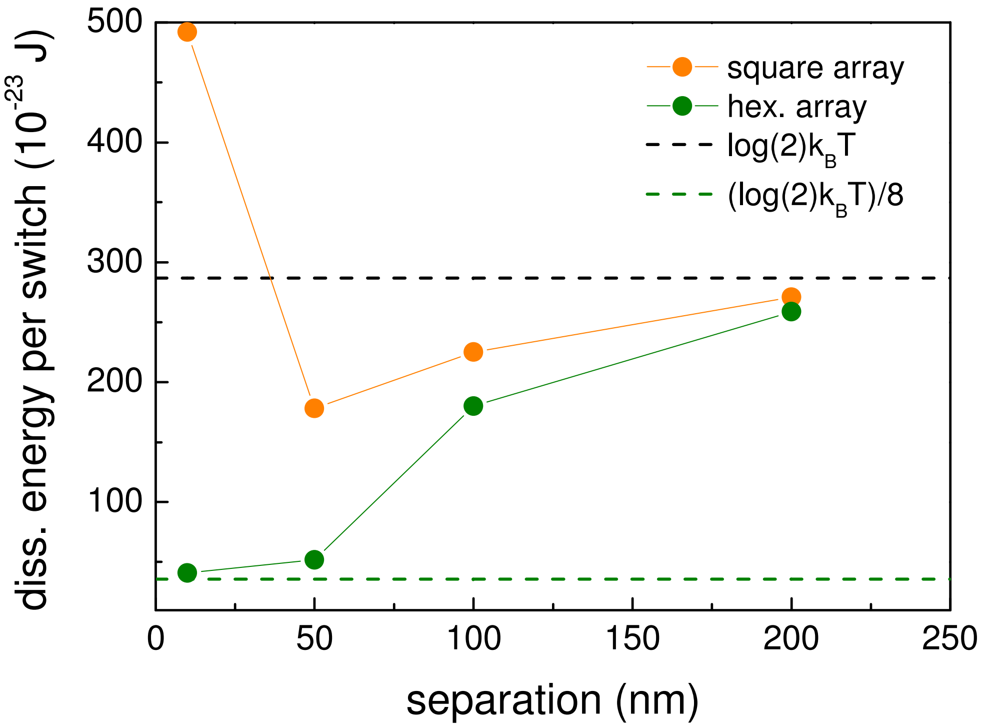
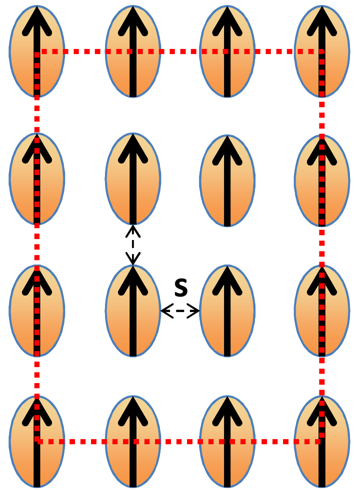
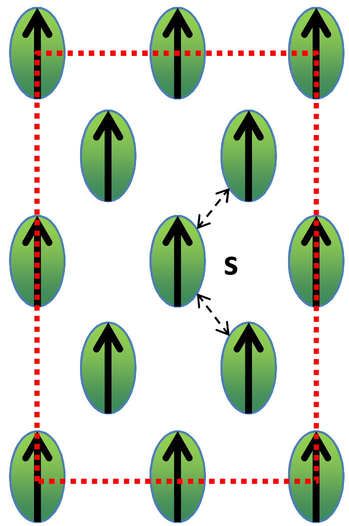
# Interacting dots – (arrays)




**Square** array
(9 independent bits)




**Hexagonal** array
(8 independent bits)

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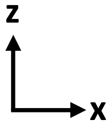
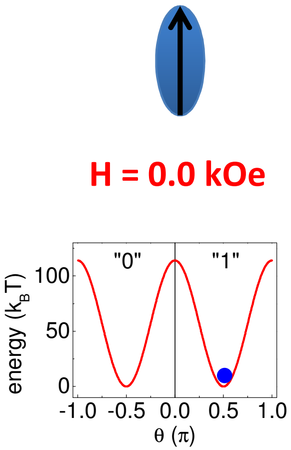
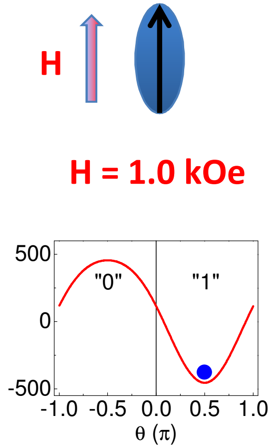
# Switching procedure



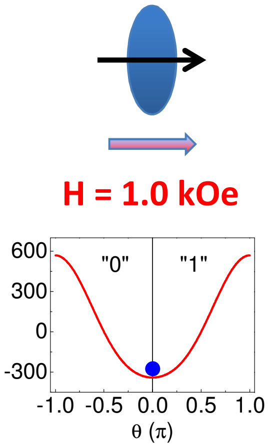

**t = 0 ns**



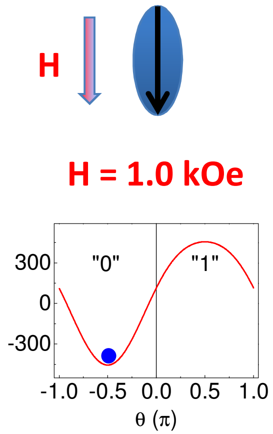

**t = 100 ns**



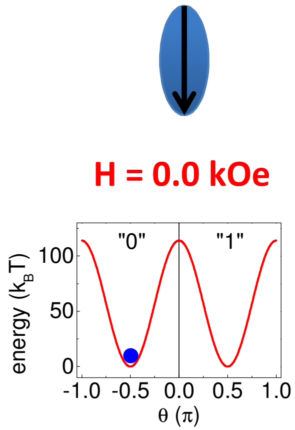

**t = 1000 ns**




**t = 1900 ns**




**t = 2000 ns**




$$E = \int \vec{H} \cdot d\vec{M} = \left( \int H_X \cdot dM_X + \int H_Z \cdot dM_Z \right)$$

***Dissipated energy***
it depends on the total simulation time (**T**)

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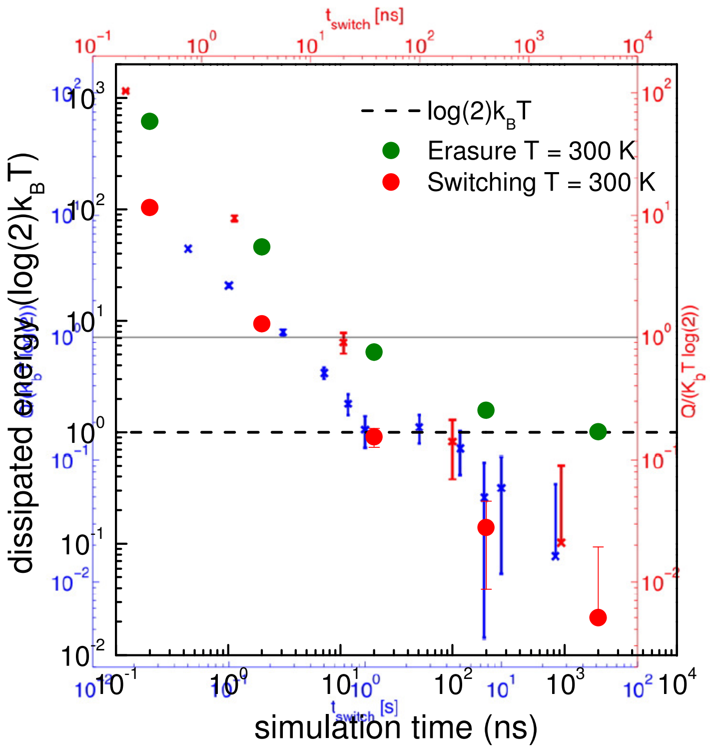
# Zero-power switching




Micromagnetic simulations performed at T=300 K

Numerical solution of the Langevin equation:

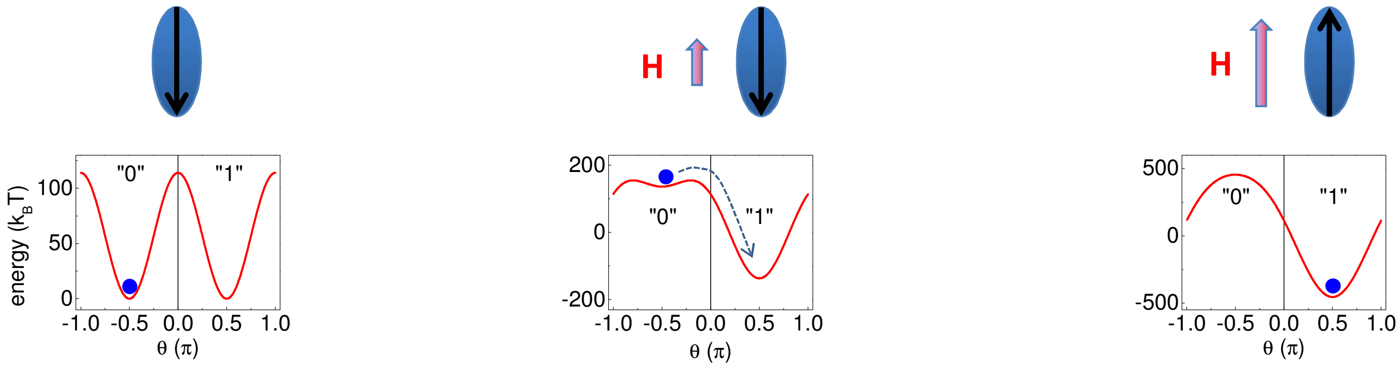
$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} + \xi(t) + f(x,t)$$

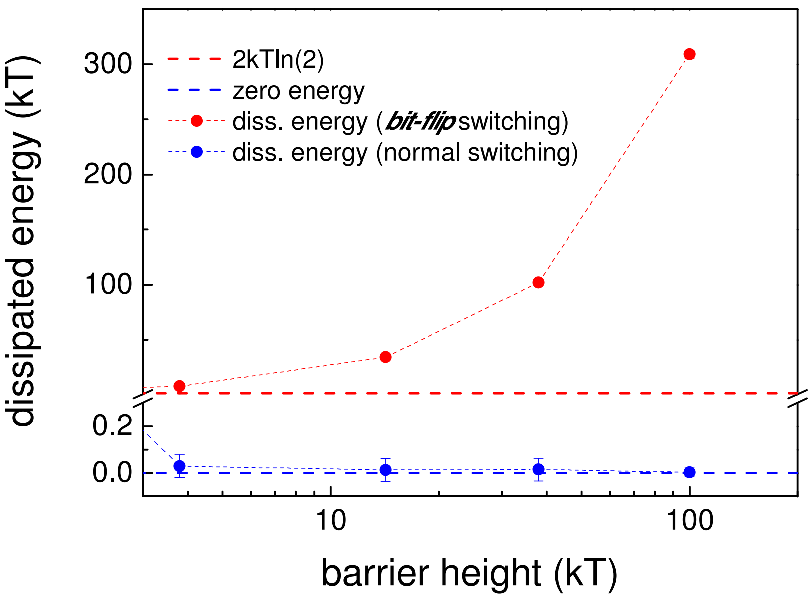
L. Gammaitoni, D. Chiuchiù, M. Madami and G. Carlotti, arXiv:1403.1800 [cond-mat.mes-hall], (2014).

Required conditions to perform a zero-power switching:

1) The particle average position is always close to the minimum of the potential well (zero total force)
2) The switch procedure has to performed as slow as possible (zero friction)
3) The system entropy has to remain constant during the procedure ***(zero entropic cost)***

# Switching and *bit-flip* events




- to switch a ***flipped* bit** requires an energy toll to be paid (while *normal* switching can be done for free)

- energy dissipation for switching a *flipped* bit depends on the **energy barrier height**

- its minimum value is **$2k_BTln(2)$**

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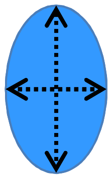
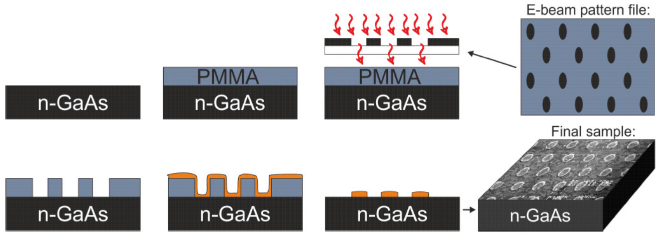
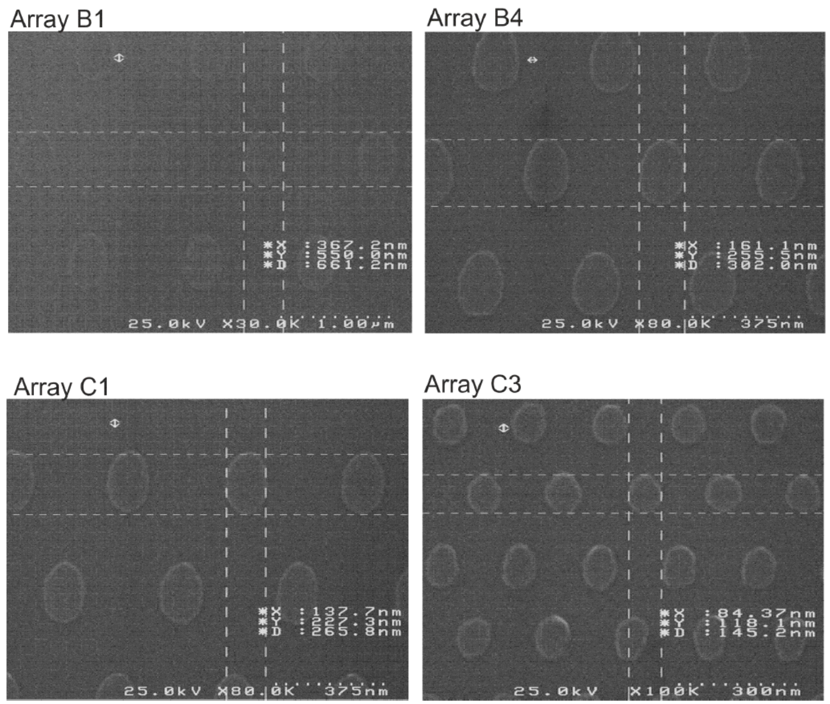
# Landauer erasure - samples

Samples: arrays of $Ni_{80}Fe_{20}$ elliptical elements of different size prepared by conventional e-beam lithography and lift-off at **Wurzburg University**, Germany (F. Hartmann et al.)



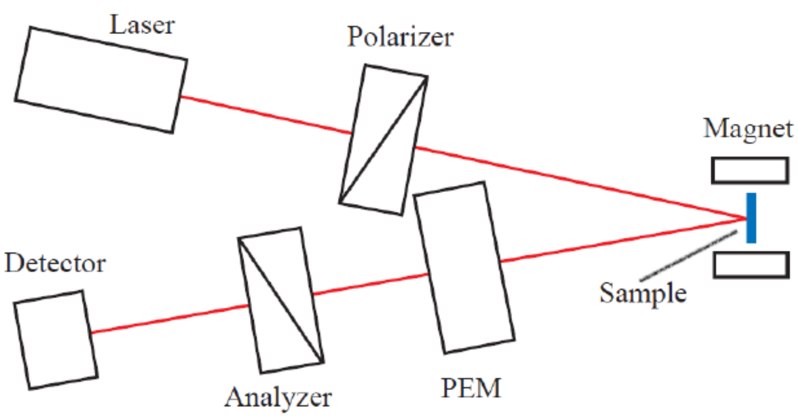


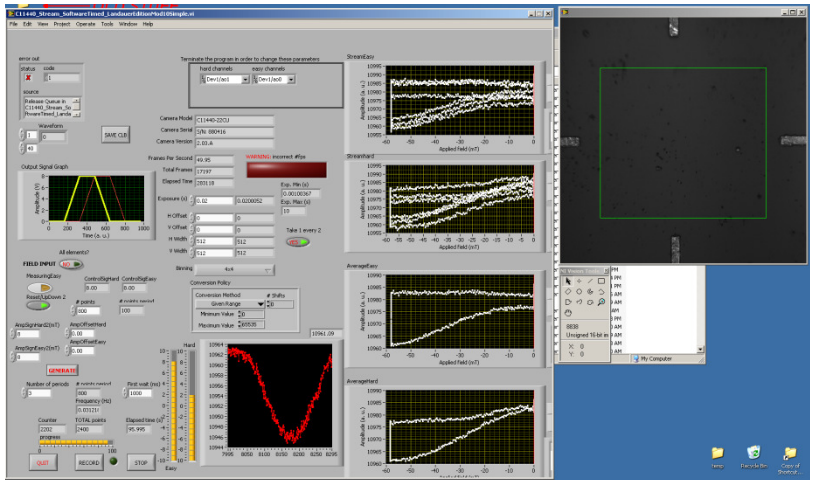

| Array | Major axis (nm) | Minor axis (nm) | Ratio |
|---|---|---|---|
| A1 | 946 | 562 | 0.59 |
| A2 | 816 | 516 | 0.63 |
| A3 | 775 | 445 | 0.57 |
| A4 | 706 | 375 | 0.53 |
| B1 | 550 | 367 | 0.67 |
| B2 | 406 | 284 | 0.70 |
| B3 | 349 | 213 | 0.61 |
| B4 | 256 | 161 | 0.63 |
| C1 | 227 | 138 | 0.61 |
| C2 | 181 | 117 | 0.65 |
| C3 | 118 | 84 | 0.71 |



# Landauer erasure – MOKE setup

Measurements: performed with a conventional Magneto-Optical Kerr Effect (MOKE) setup by Leonardo Martini and Matteo Pancaldi at: **Nanoscience Cooperative Research Center (NANOGUNE)**, San Sebastian, Spain (Prof. Paolo Vavassori)



**Longitudinal configuration**: the detected signal is proportional to the component of the magnetization in the reflection plane.

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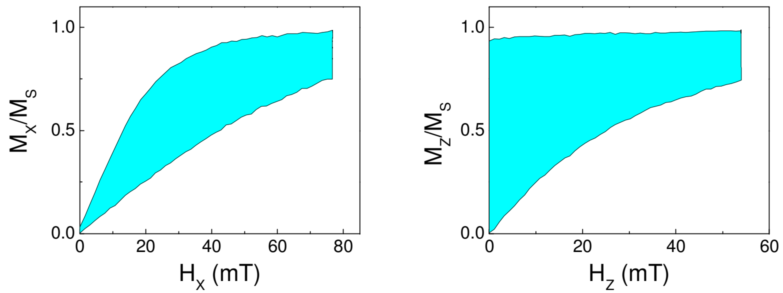
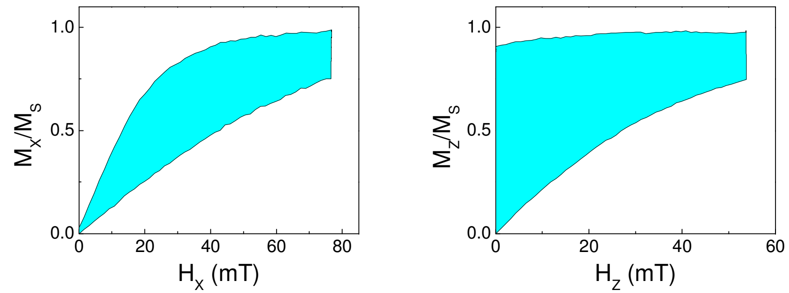
# Landauer erasure – results

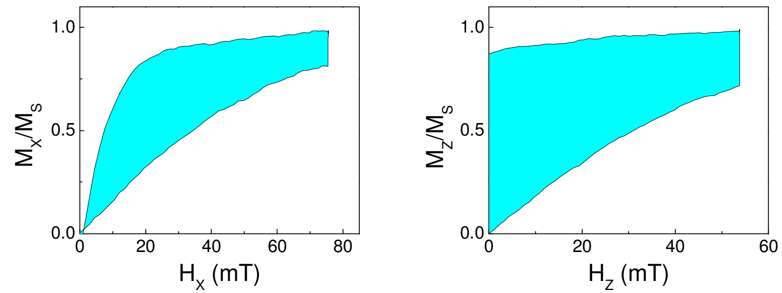
Sample C3 ($118×84×10\ nm^3$)



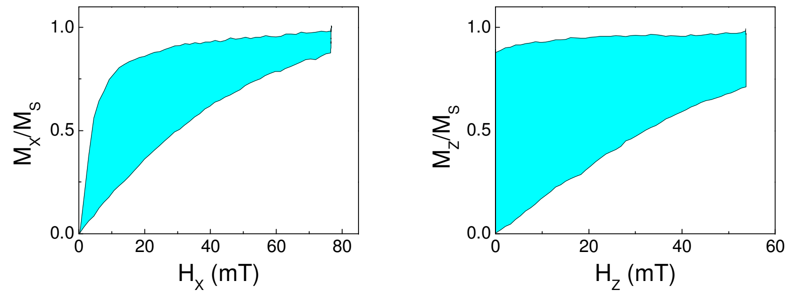

Sample C2 ($181×117×10\ nm^3$)




Sample B2 ($406×284×10\ nm^3$)




Sample A1 ($946×562×10\ nm^3$)




The difference between the areas of the *hard* and *easy* loops is multiplied by the value of $\mathbf{M_S}$ (800 Gauss), and the **volume** (**V**) of the magnetic dot in order to obtain the **energy dissipated** in the erasure process.

# Landauer erasure – results

| sample | measurements ($k_B T\ln(2)$, T=300 k) | simulations ($k_B T\ln(2)$, T=300 k) |
|---|---|---|
| C3 (118×84×10 $nm^3$) | 30 ± 30 | 1.2 ± 0.1 |
| C2 (181×117×10 $nm^3$) | 250 ± 100 | 1.3 ± 0.2 |
| B2 (406×284×10 $nm^3$) | 2000 ± 1000 | 14 ± 2 |
| A1 (946×562×10 $nm^3$) | 10000 ± 2000 | 190 ± 10 |