FACULTY
OF SCIENCES

DEPARTMENT OF SOLID STATE SCIENCES
RESEARCH GROUP DYNAMAT

Thermally driven micromagnetic systems

visit to JG Universität Mainz
August 22nd, 2017

Dr. Jonathan Leliaert

GHENT
UNIVERSITY

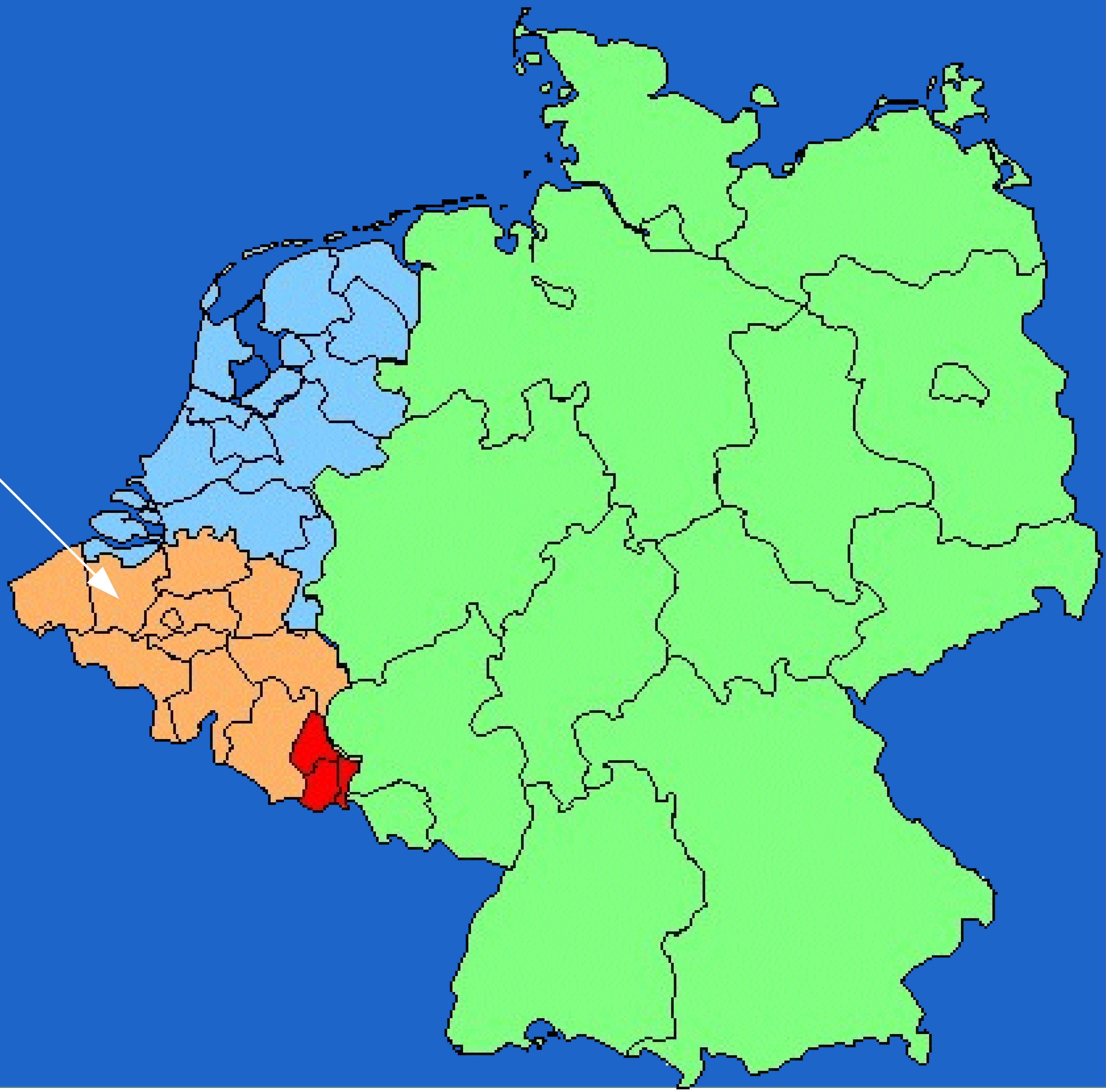
Jonathan.Leliaert@ugent.be

Outline: Thermally driven micromagnetic systems

- Short introduction to micromagnetism
- Experimental study: Thermal magnetic noise spectroscopy
- Numerical study: Thermally activated domain wall motion

Jonathan.Leliaert@ugent.be

200 YEARS
GHENT
UNIVERSITY



Where do we come from?

[redacted]

Introduction to micromagnetism

Jonathan.Leliaert@ugent.be

Micromagnetism

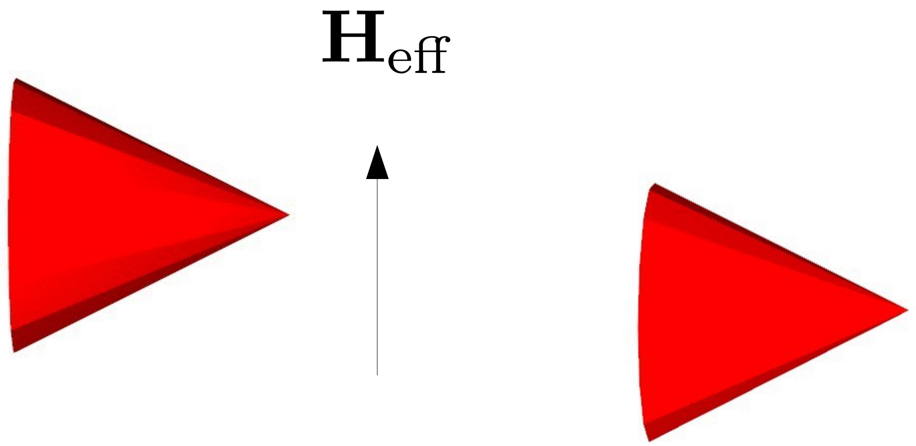
- *"To understand ferromagnetic materials, we must examine them on a smaller scale than that of ordinary observations. On one such scale we speak of domains; on another, of lattice sites. This tract analyses them on an intermediate scale: small enough to reveal details of the transition regions between domains, yet large enough to permit the use of a continuous magnetisation vector rather than of individual atomic spins."*

William Fuller Brown, *"Micromagnetics"* (1963)

- Micromagnetism is the continuum theory of magnetic materials at the picosecond timescale and nanometer to micrometer length scale

Micromagnetism: Dynamics

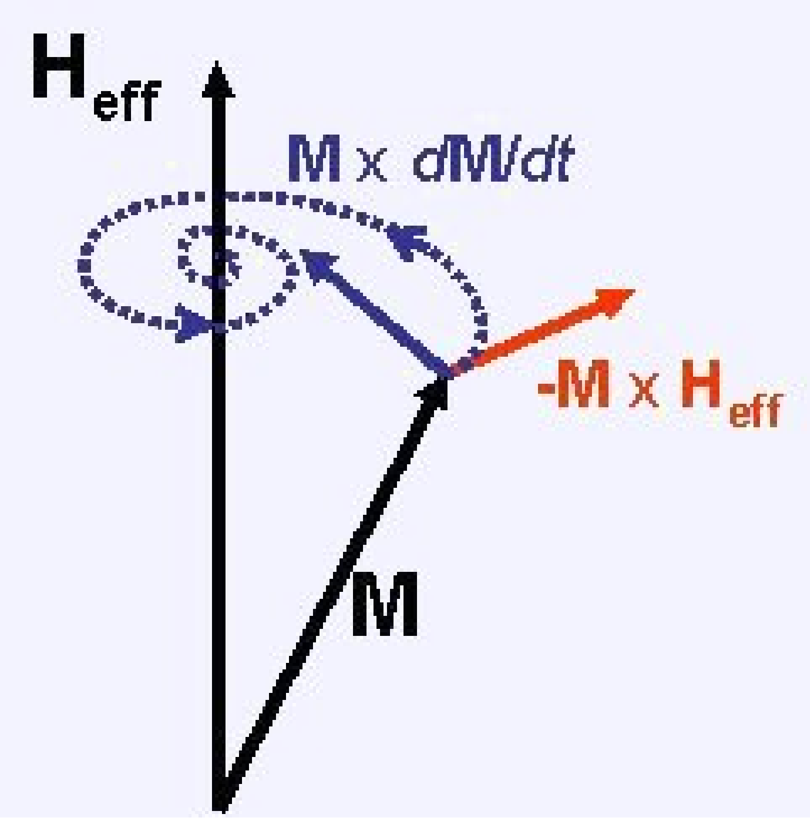
- Landau-Lifshitz equation $\dot{\mathbf{m}} = \underbrace{-\gamma_0 \mathbf{m} \times \mathbf{H}_{\text{eff}}}_{\text{Precession}} - \underbrace{\lambda \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})}_{\text{damping}}$

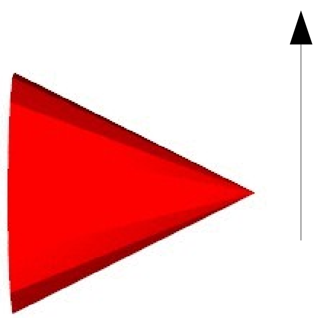


GHENT UNIVERSITY

Micromagnetism: Dynamics

- Landau-Lifshitz equation $\dot{\mathbf{m}} = -\gamma_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} - \lambda \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})$





with $\mathbf{H}_{\text{eff}} = -\dfrac{1}{\mu_0 M_s} \dfrac{d\mathcal{E}}{d\mathbf{m}}$

Micromagnetism: Effective Field

- Exchange interaction
- Dzyaloshinskii-Moriya interaction
- Zeeman energy
- Anisotropy energy
- Magnetostatic energy
- …
- Thermal fluctuations

Micromagnetism: Thermal field properties

- Zero average $$\langle \mathbf{H}_{\mathrm{th}}(t) \rangle = 0$$
- No correlation in time and space $$\langle \mathbf{H}_{\mathrm{th,i}}(t) \mathbf{H}_{\mathrm{th,j}}(t') \rangle = q\delta(t - t')\delta_{ij}$$
- Size given by q $$q = \frac{2k_{\mathrm{B}}T\alpha}{M_{\mathrm{s}}\gamma_0\mu_0 V}$$

PHYSICAL REVIEW VOLUME 130, NUMBER 5 1 JUNE 1963

Thermal Fluctuations of a Single-Domain Particle

WILLIAM FULLER BROWN, JR.*
Department of Electronics, Weizmann Institute of Science, Rehovoth, Israel
(Received 21 January 1963)

A sufficiently fine ferromagnetic particle has a uniform vector magnetization whose magnitude is essentially constant, but whose direction fluctuates because of thermal agitation. The fluctuations are important in superparamagnetism and in magnetic aftereffect. The problem is approached here by methods familiar in the theory of stochastic processes. The "Langevin equation" of the problem is assumed to be Gilbert's equation of motion augmented by a "random-field" term. Consideration of a statistical ensemble of such particles leads to a "Fokker-Planck" partial differential equation, which describes the evolution of the probability density of orientations. The random-field concept, though convenient, can be avoided by use of the fluctuation-dissipation theorem. The Fokker-Planck equation, in general, is complicated by the presence of gyroscopic terms. These drop out in the case of axial symmetry: then the problem of finding nonequilibrium solutions can be restated as a minimization problem, susceptible to approximate treatments. The case of energy barriers large in comparison with kT is treated both by approximate minimization and by

GHENT UNIVERSITY

FACULTY OF SCIENCES

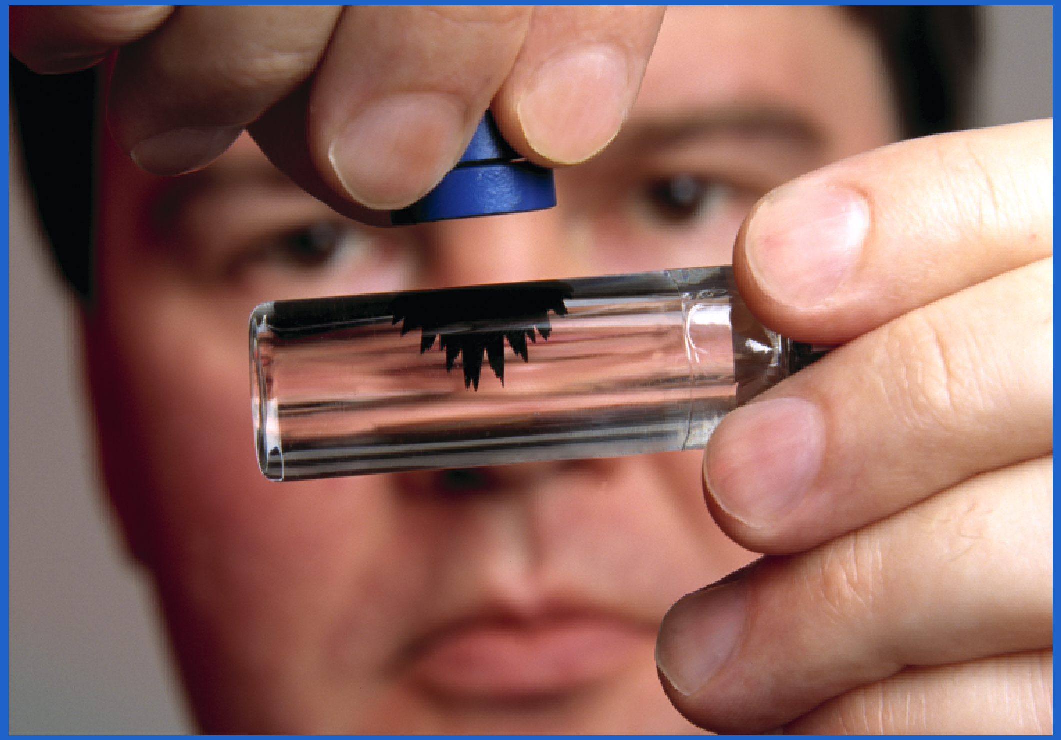
DEPARTMENT OF SOLID STATE SCIENCES
RESEARCH GROUP DYNAMAT

Experimental study:
Thermal magnetic noise spectroscopy of magnetic nanoparticle ensembles

GHENT UNIVERSITY

Jonathan.Leliaert@ugent.be

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin



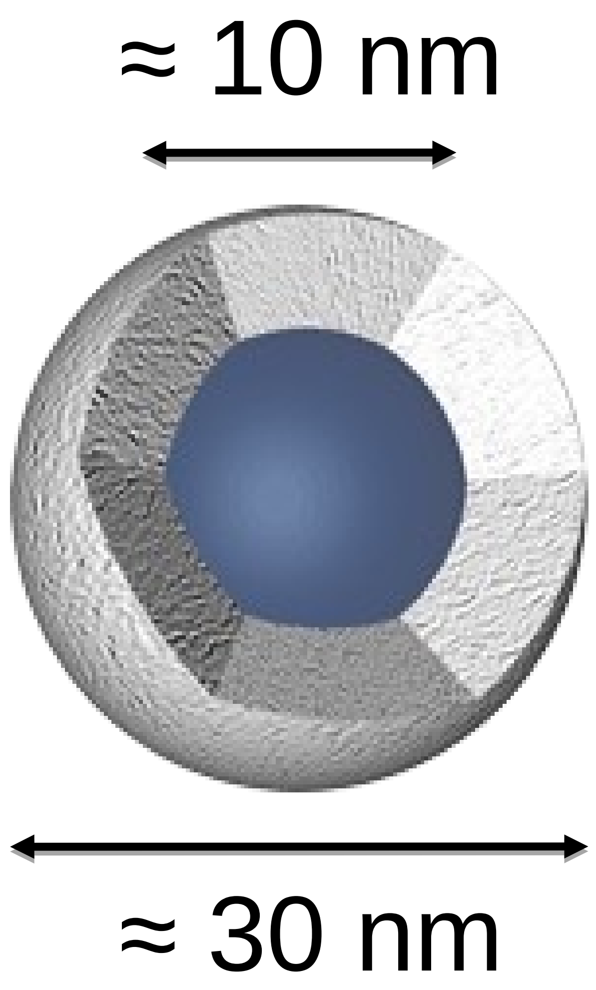
Magnetic Nanoparticles

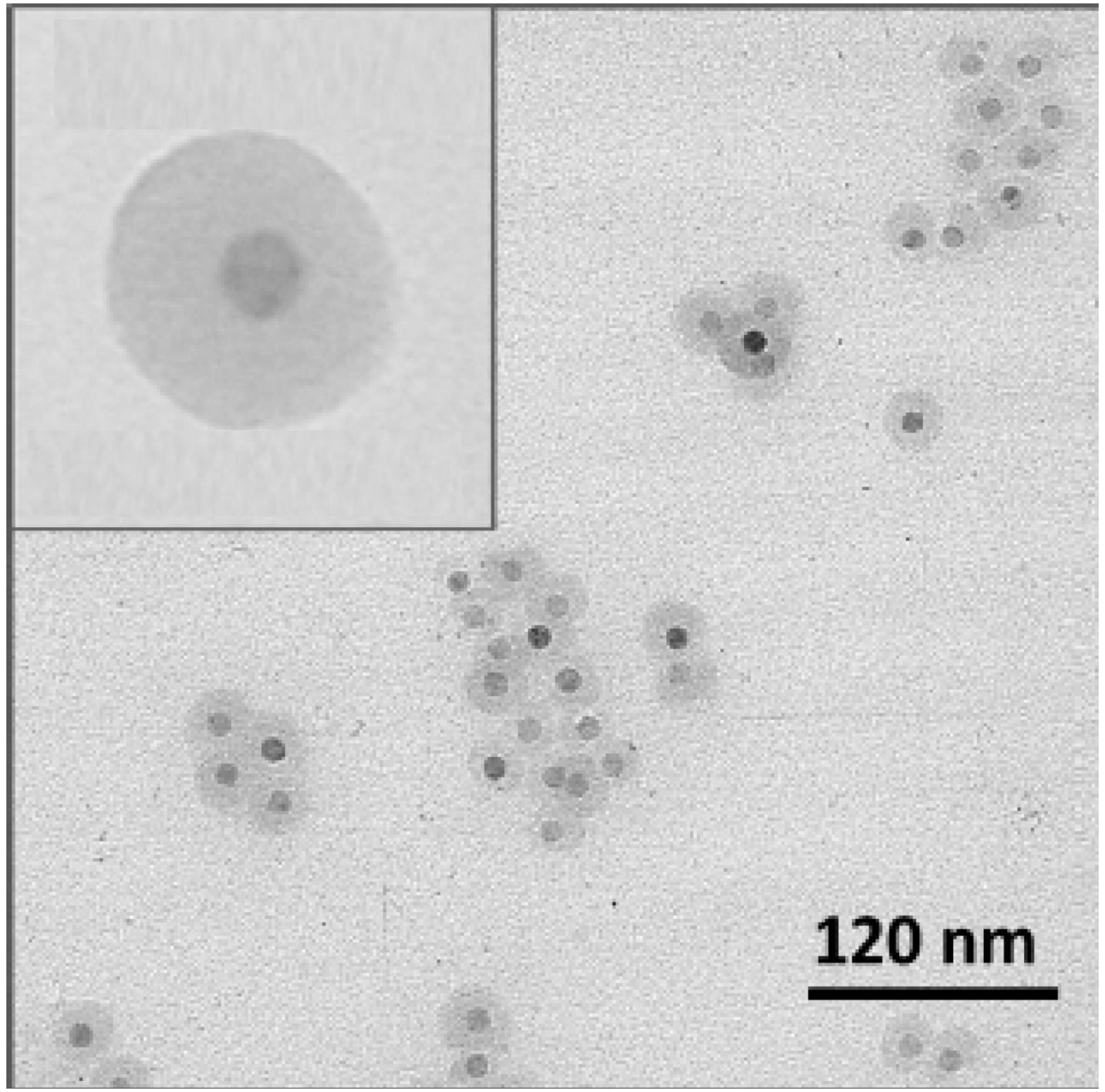
GHENT UNIVERSITY

Jonathan.Leliaert@ugent.be

Magnetic Nanoparticles

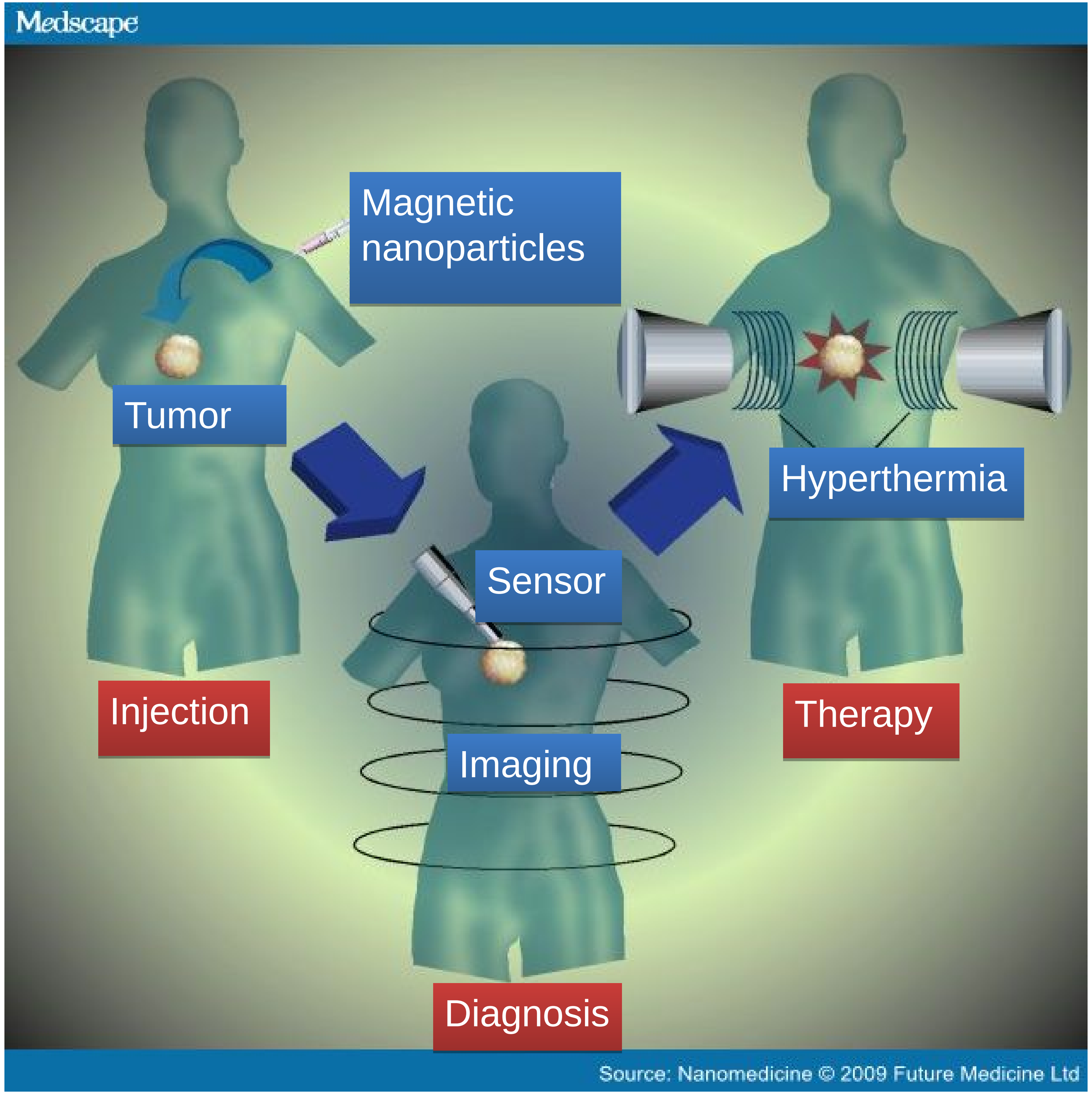
- Magnetic
- Nanometer size
- Core-shell





S. Bogren, et al., "Classification of Magnetic Nanoparticle Systems—Synthesis, Standardization and Analysis Methods in the NanoMag Project" Int. J. Mol. Sci., 16(9), 20308-20325 (2015)

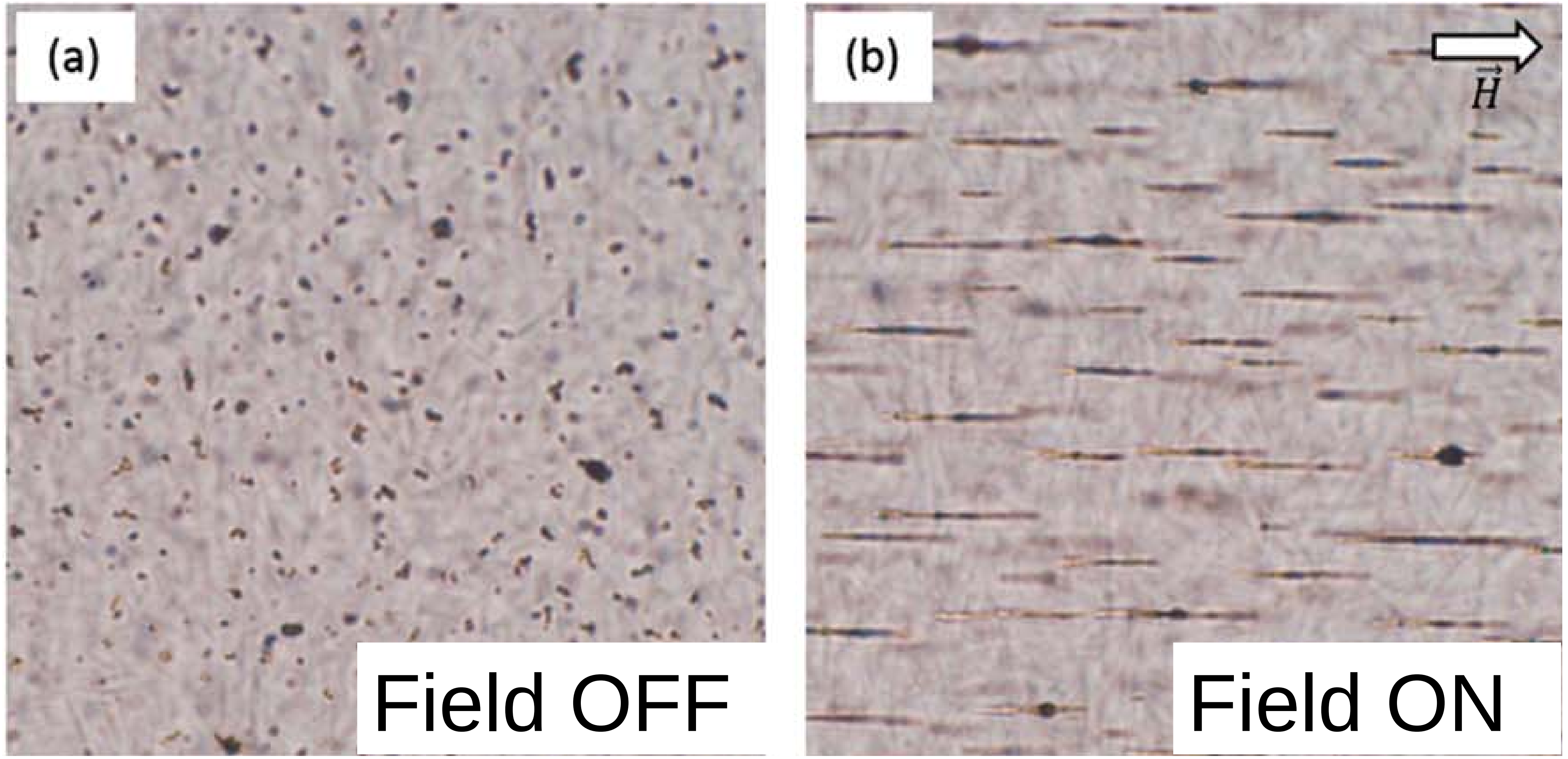
Applications



Adapted from: N.S. Barakat, et. al., "Magnetically Modulated Nanosystems: A Unique Drug-delivery Platform", Nanomedicine.,4(7):799-812, (2009)

Problem statement

- Applications require a good characterization (e.g. size distribution)
- All magnetic characterization techniques require external fields
- External fields affect characterization results

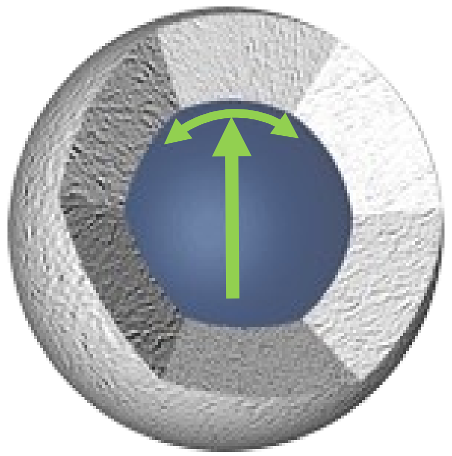


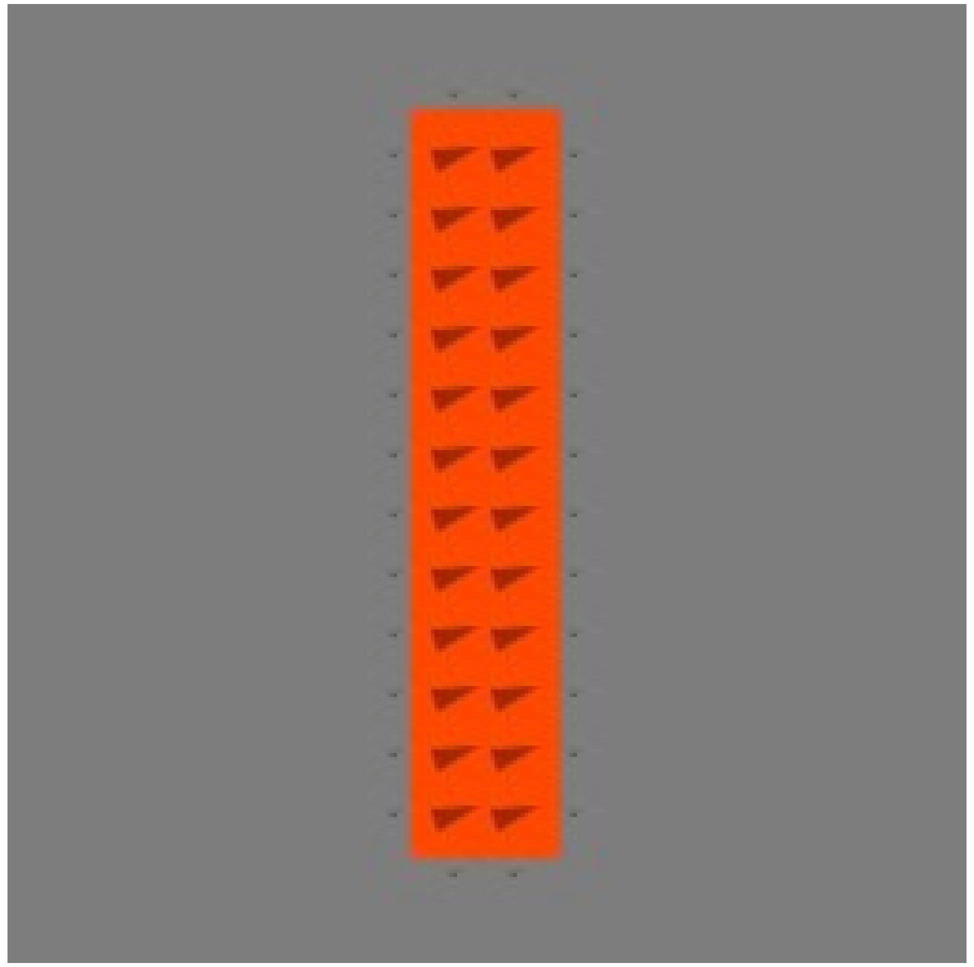
B. Bharti, et. al., “Magnetophoretic assembly of flexible nanoparticles/ lipid microfilaments”, Faraday discussions, 181, 437-448 (2015)

Thermal Magnetic Noise Spectroscopy

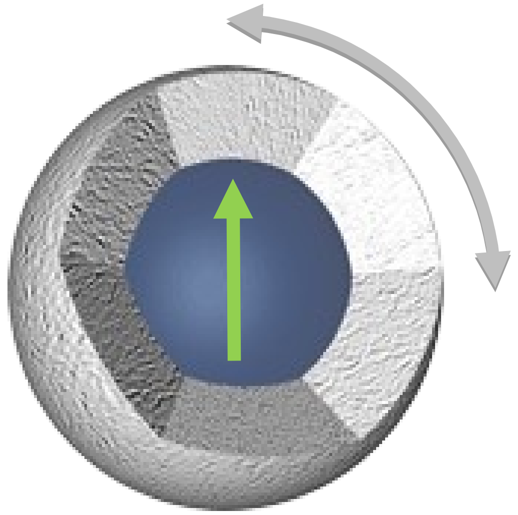
Fluctuation Mechanisms

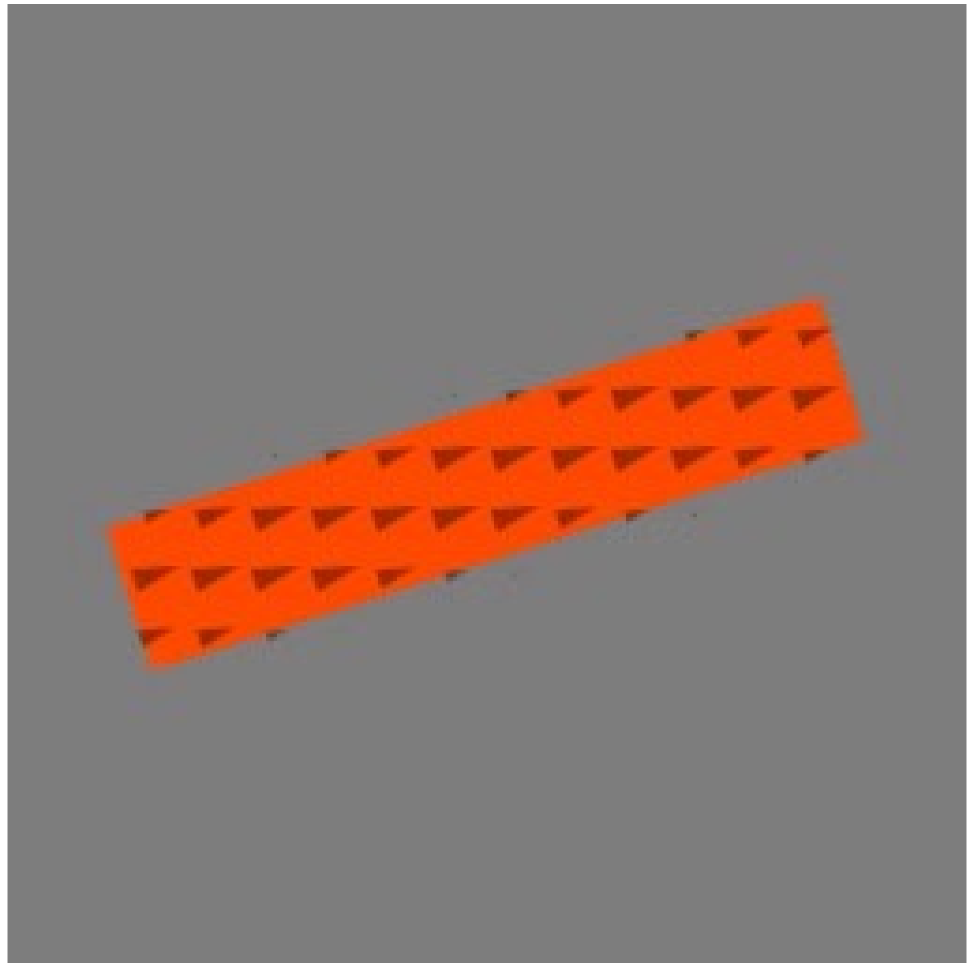
- Néel





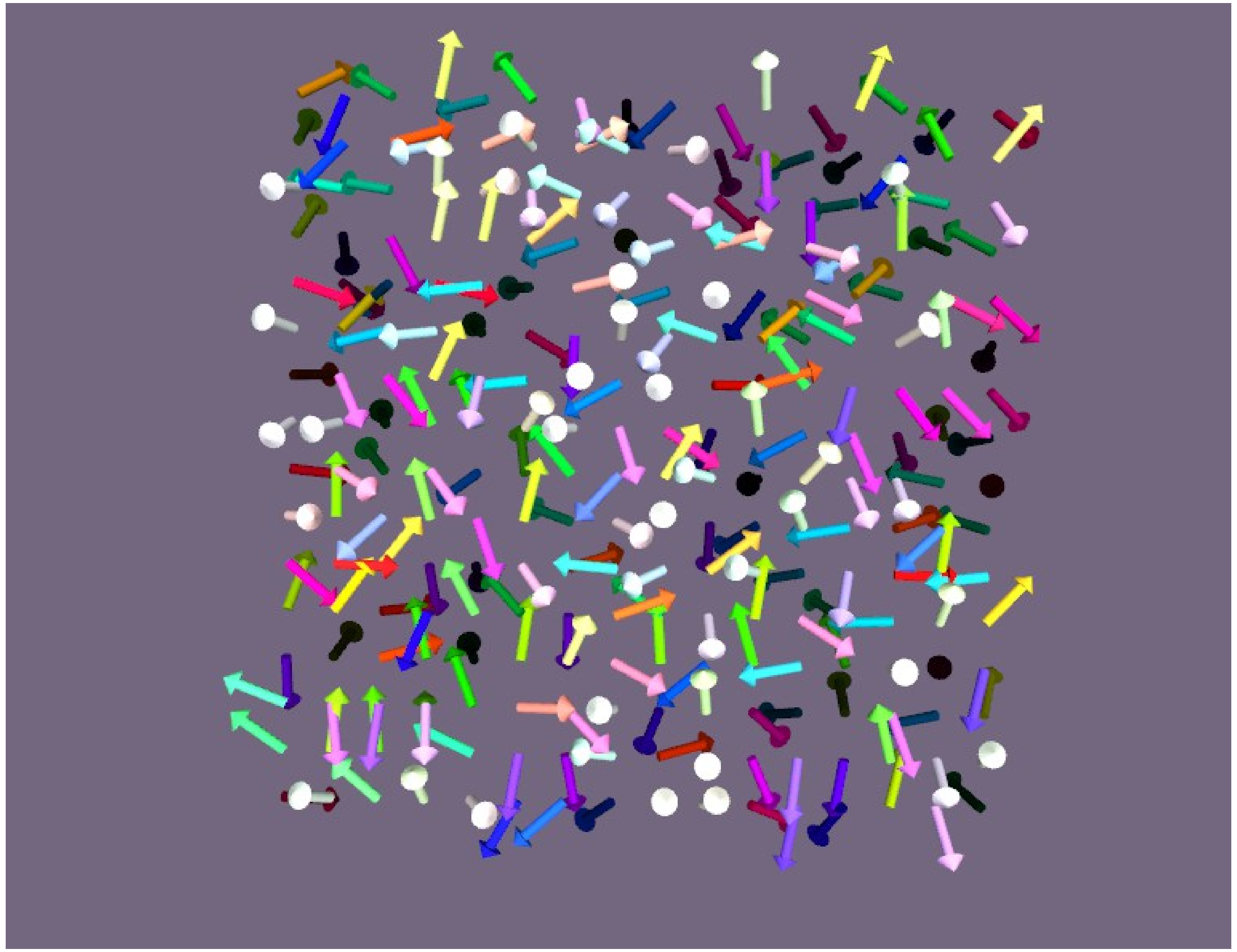
- Brown

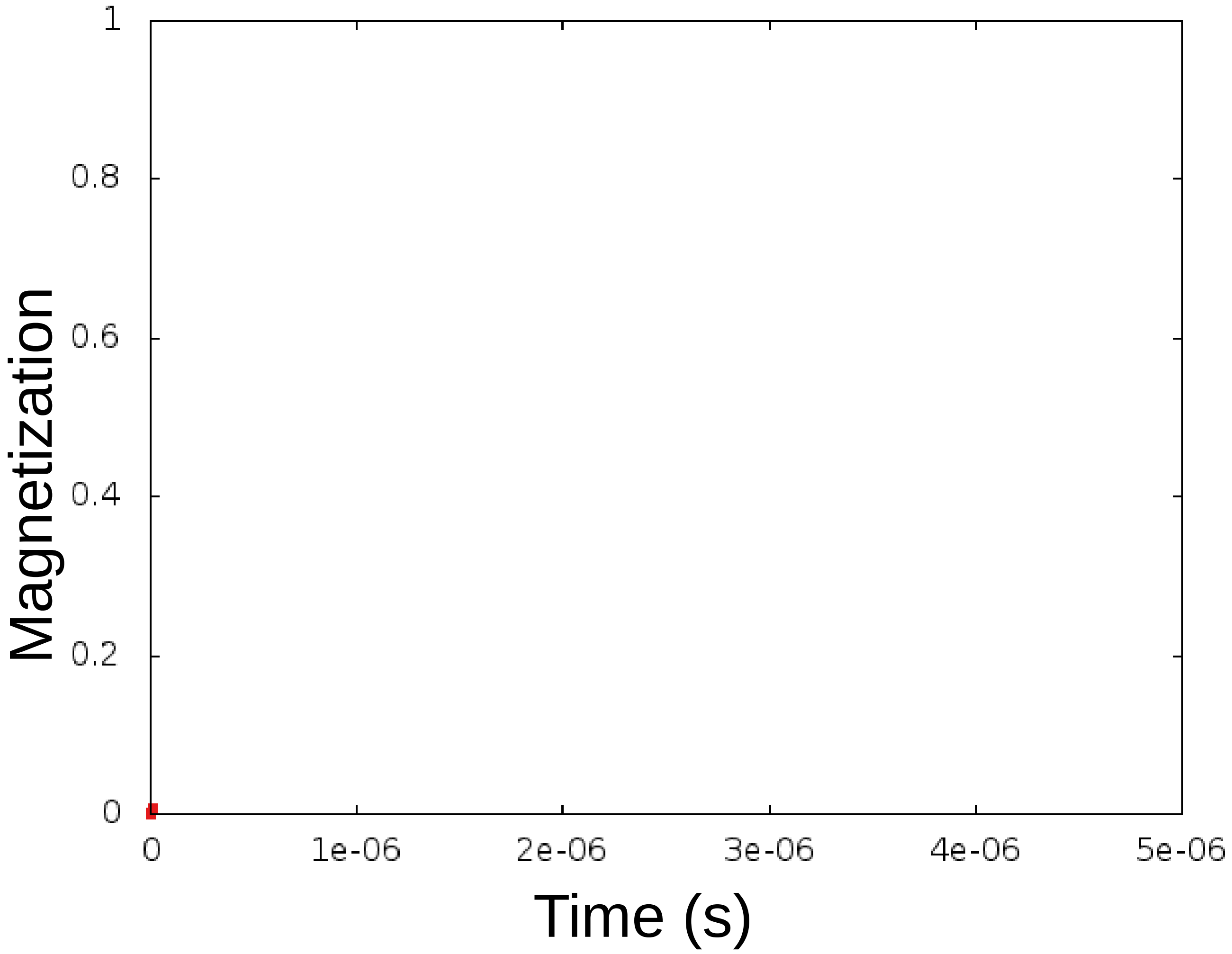




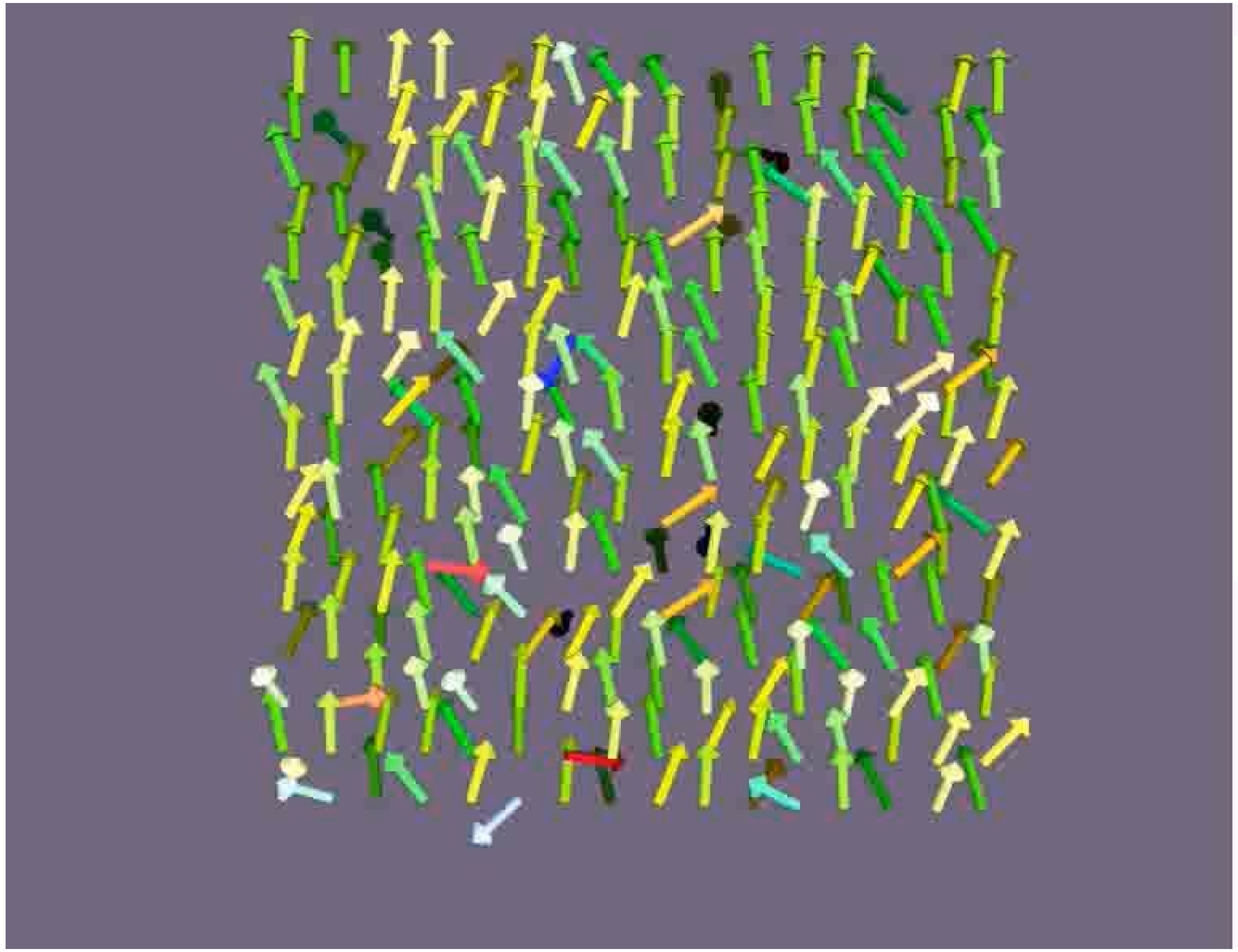
Jonathan.Leliaert@ugent.be

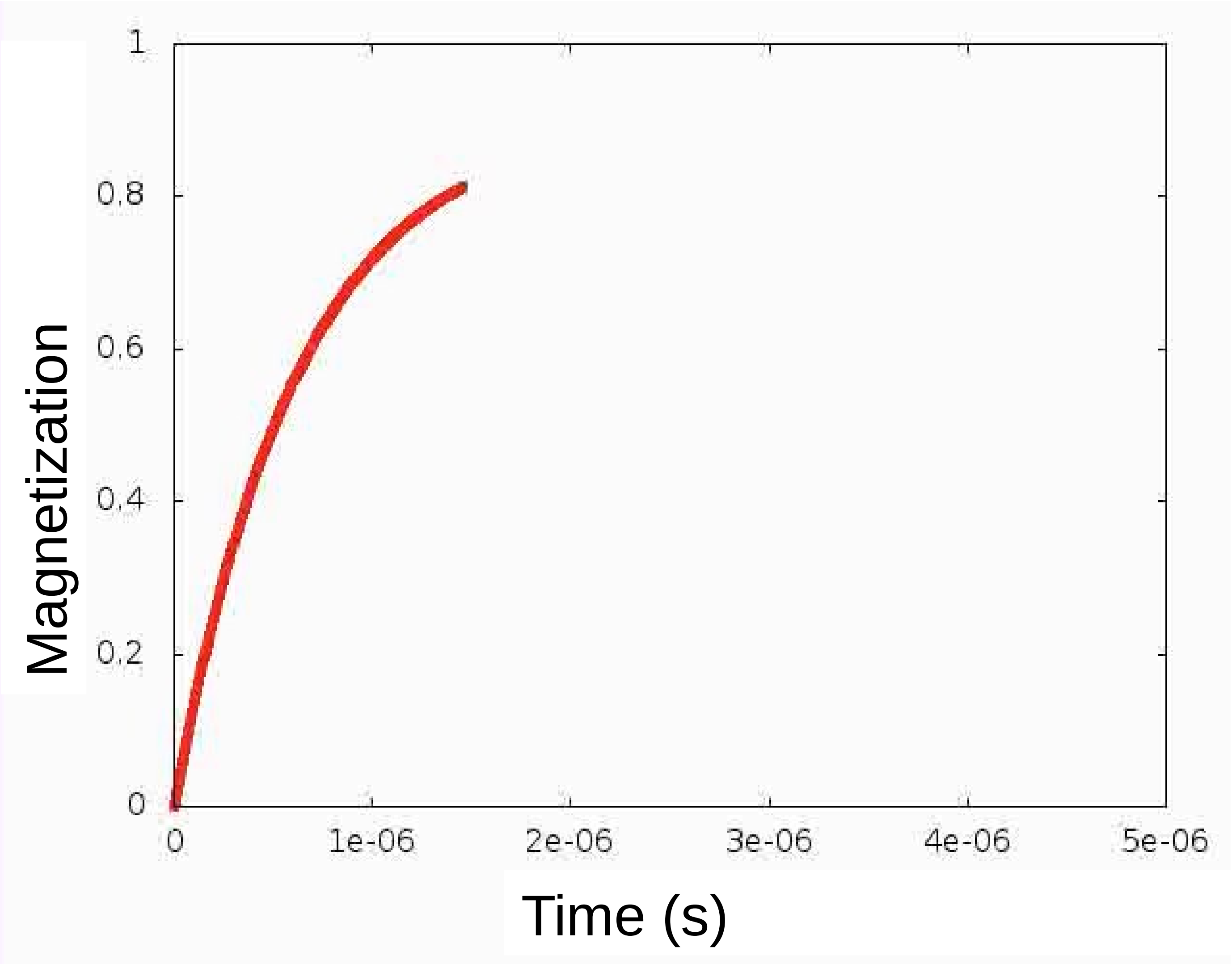
Dynamics: Magnetorelaxometry



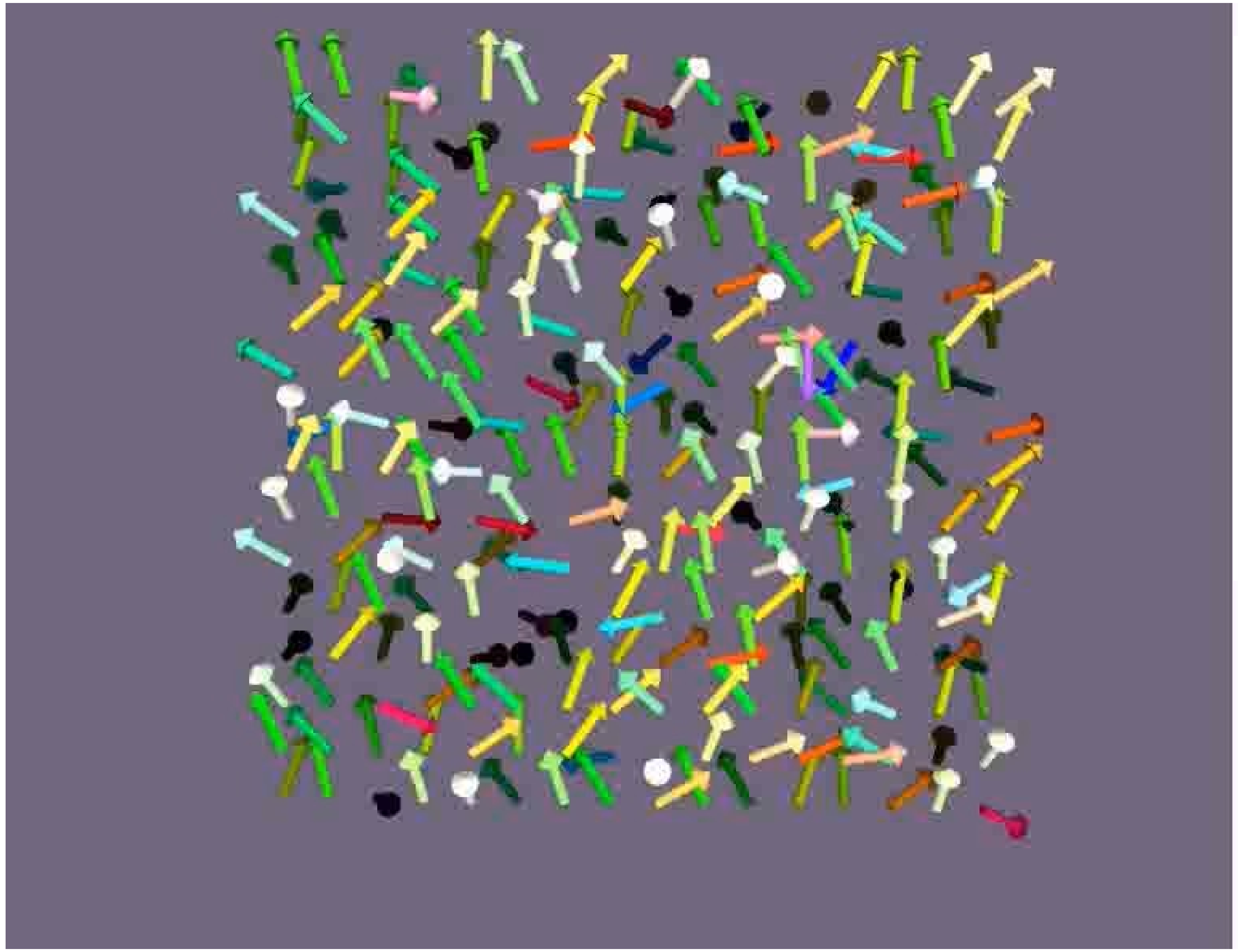


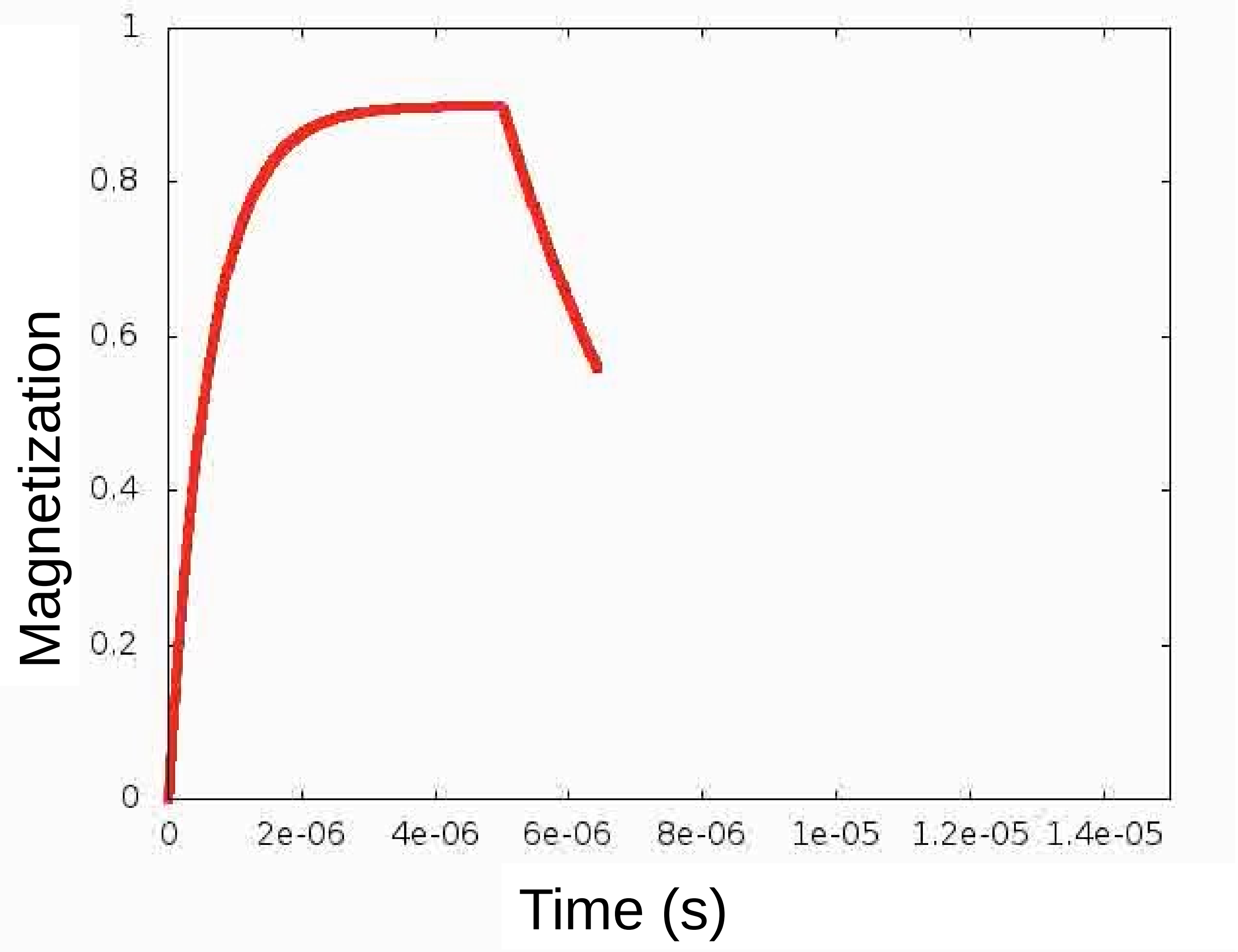
Dynamics: Magnetorelaxometry



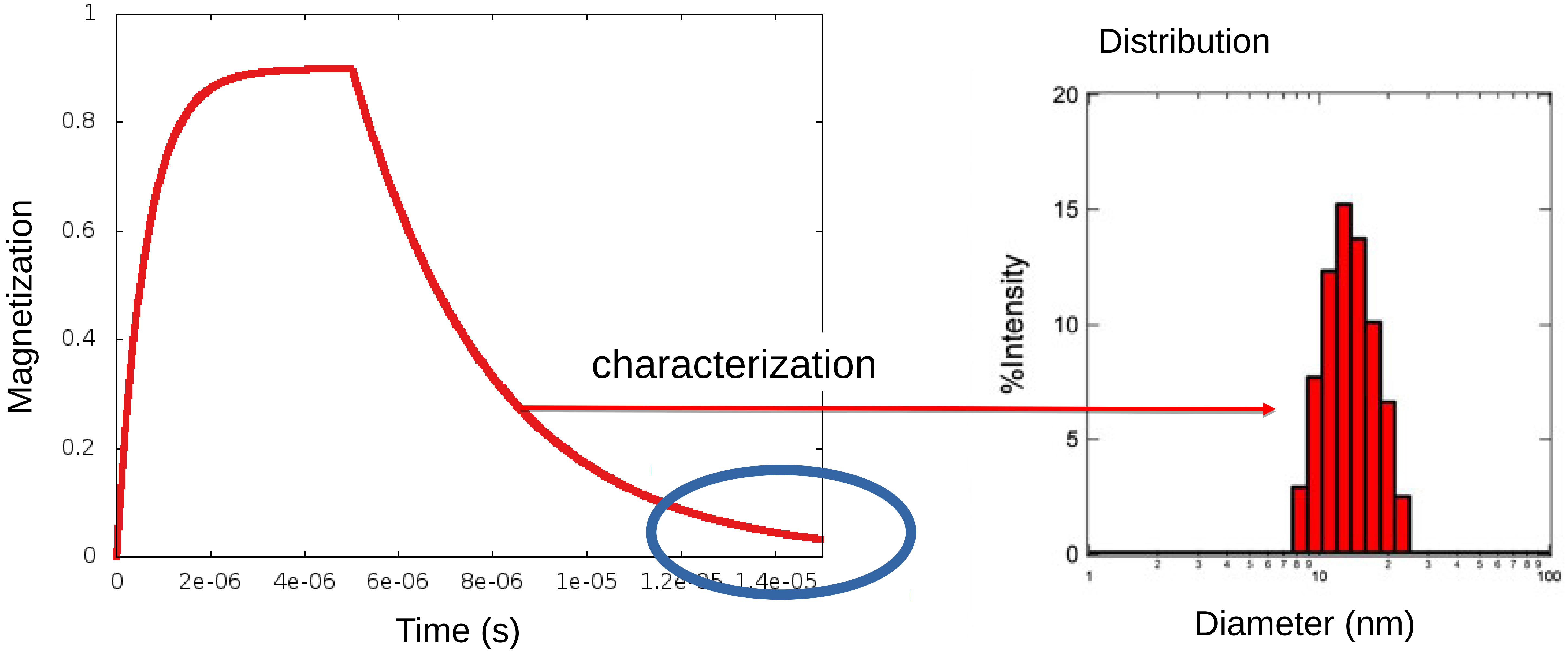


Dynamics: Magnetorelaxometry

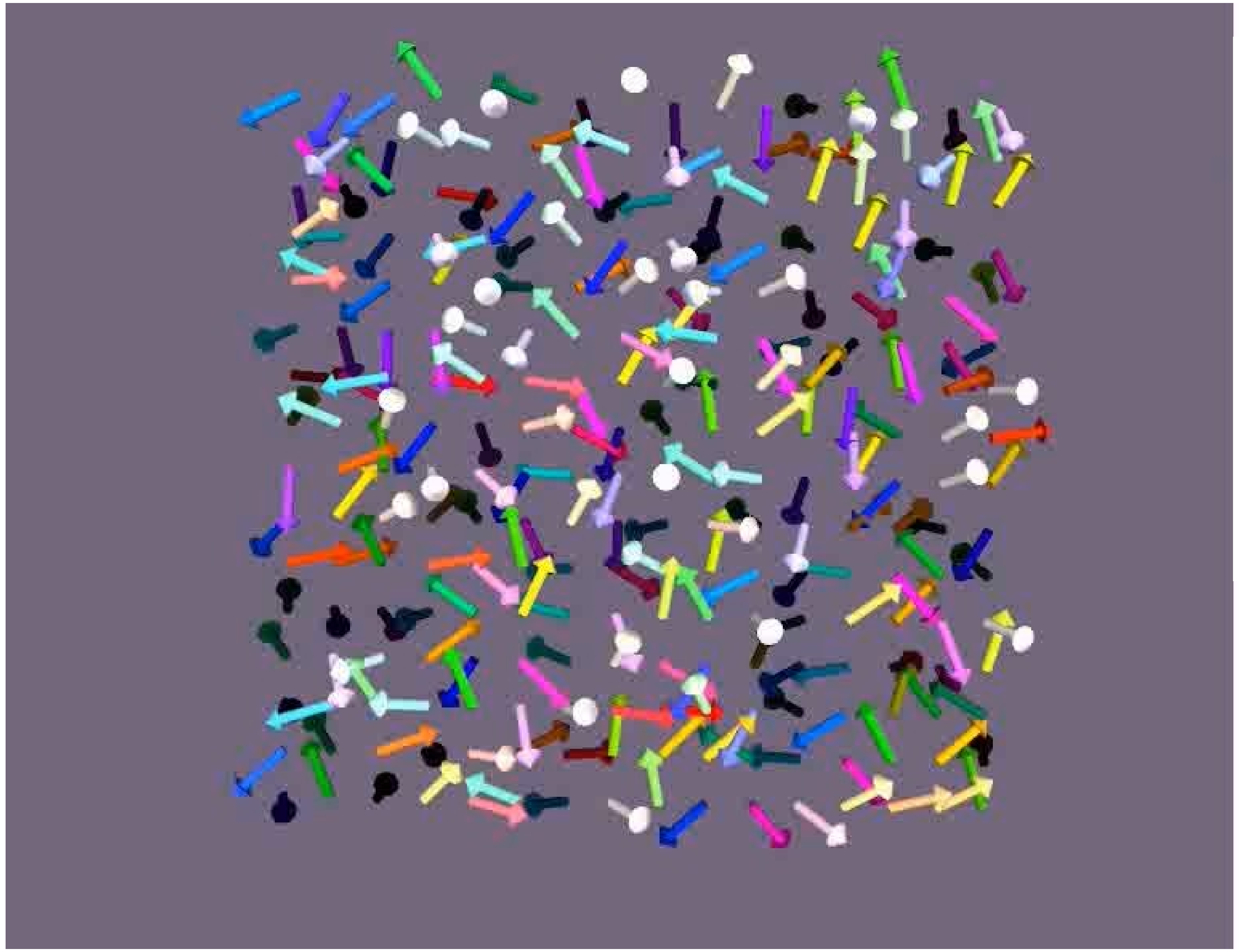


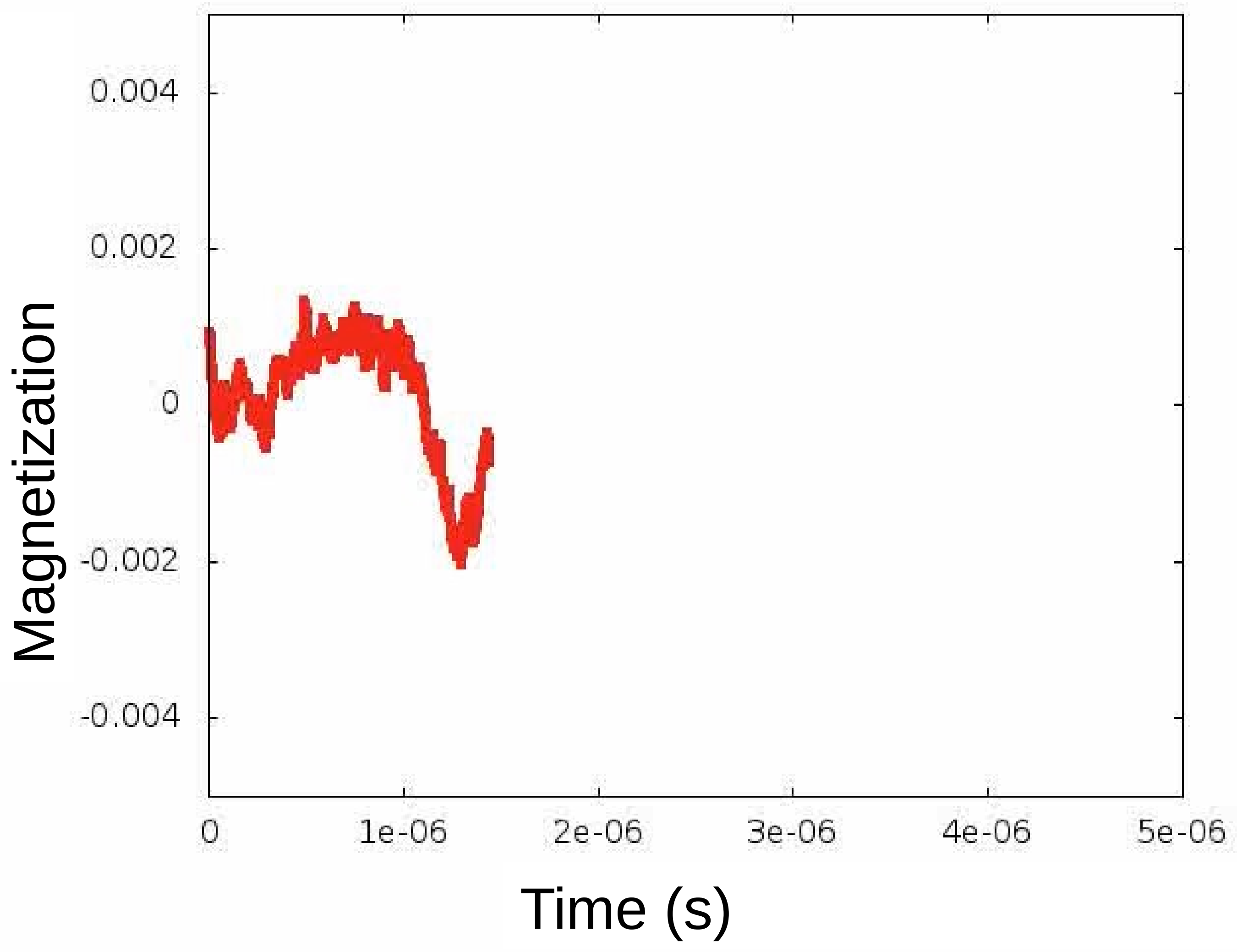


Dynamics: Magnetorelaxometry

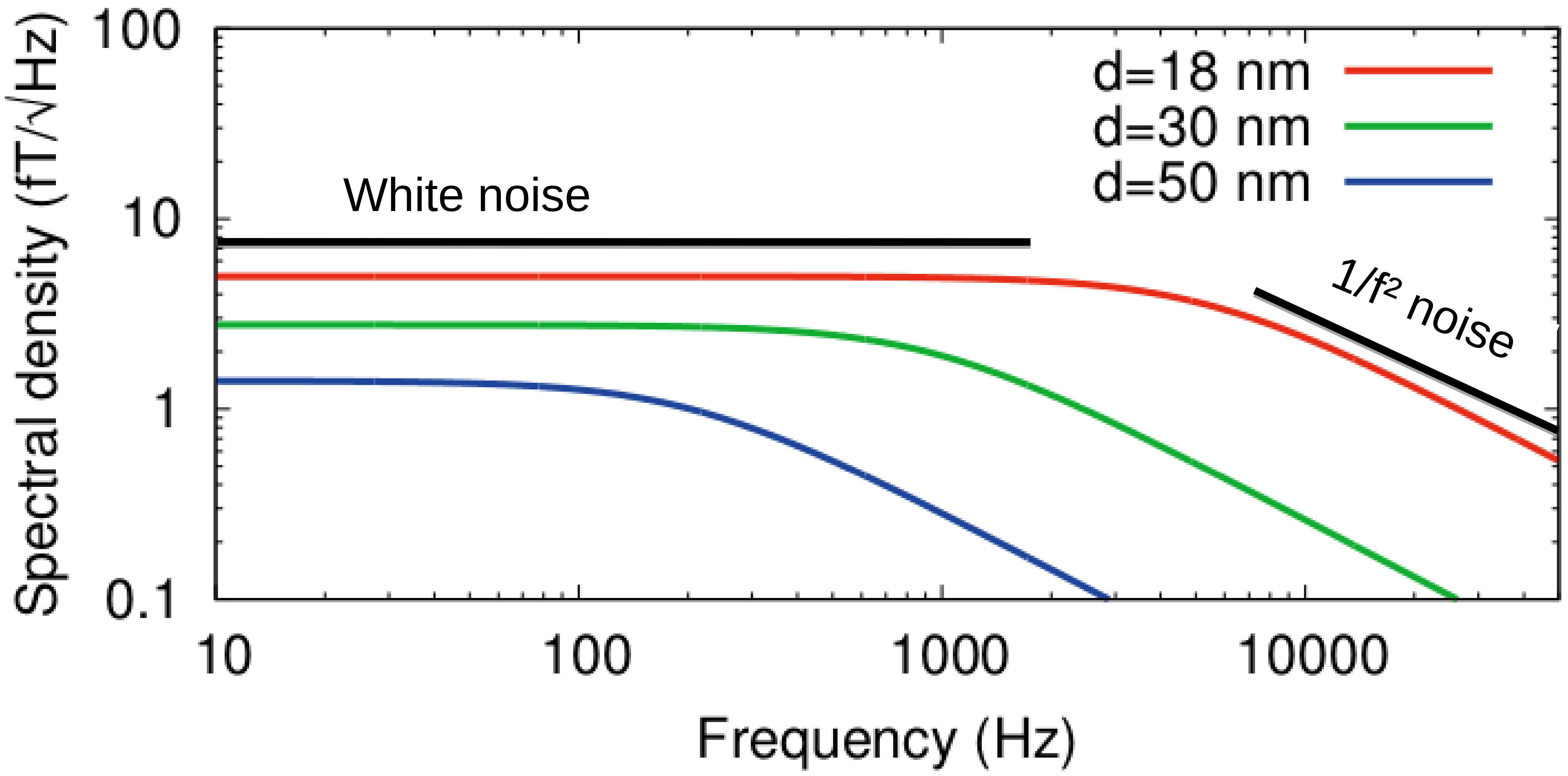


Dynamics: Noise

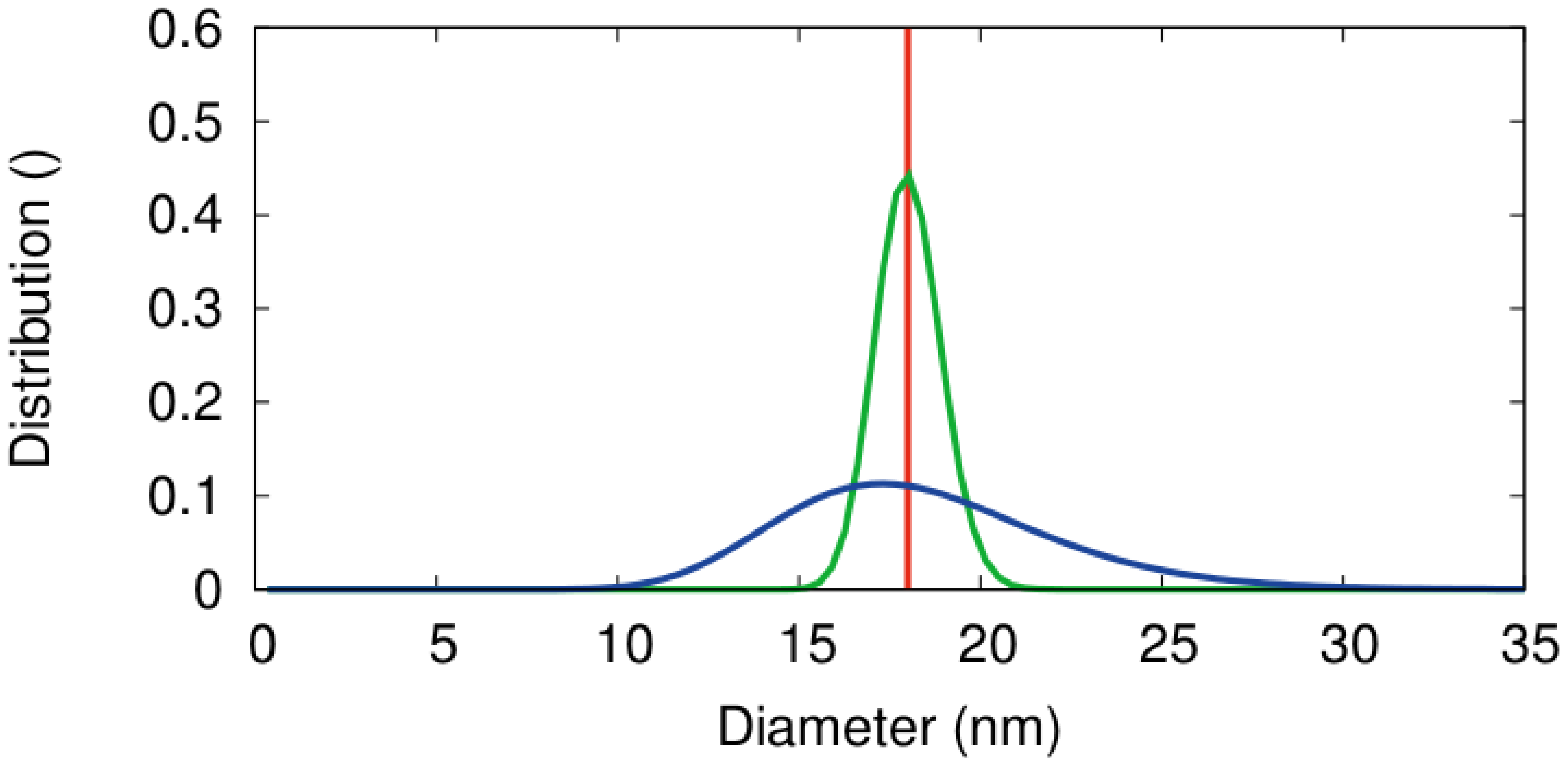


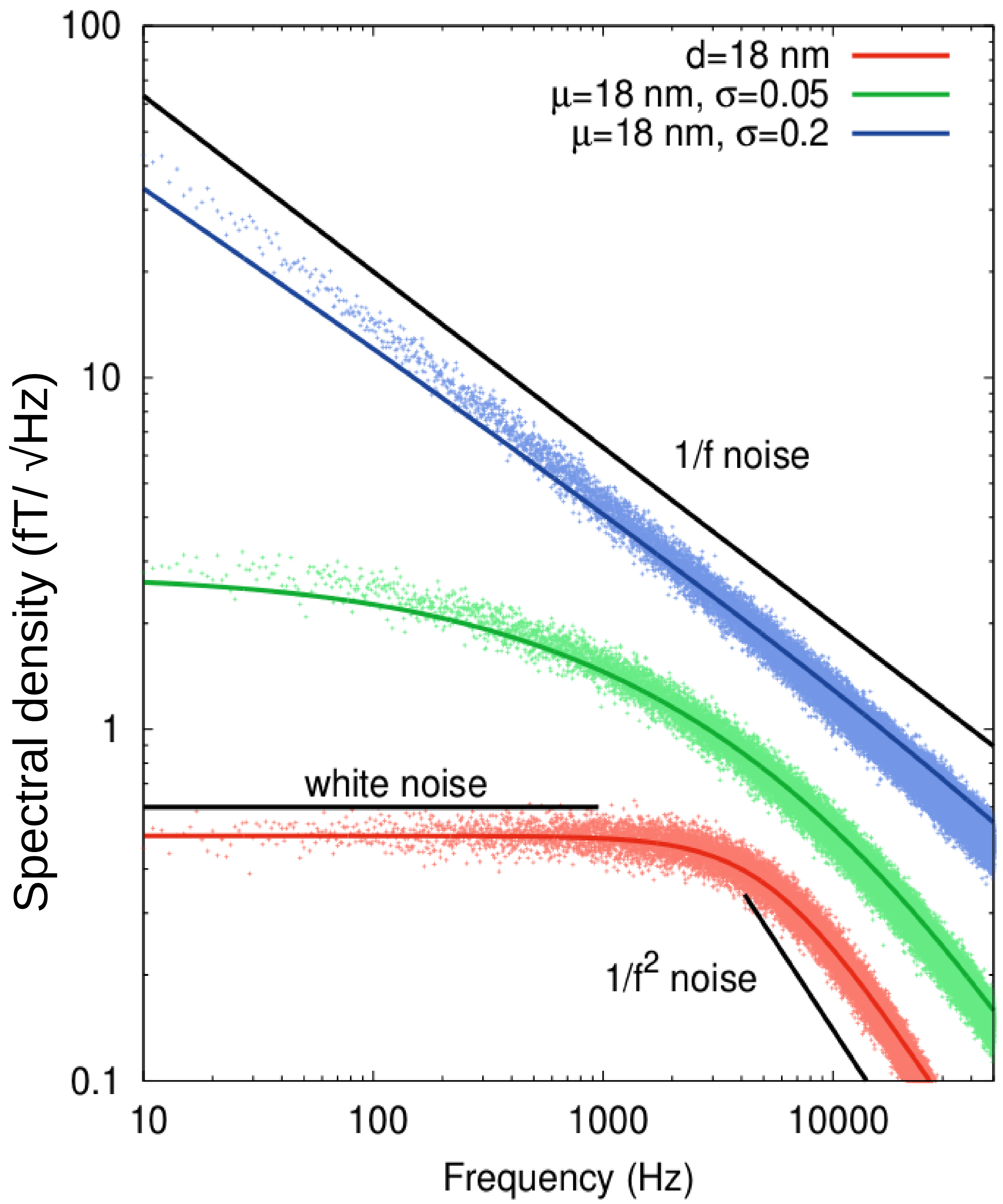


Dynamics: Noise spectrum



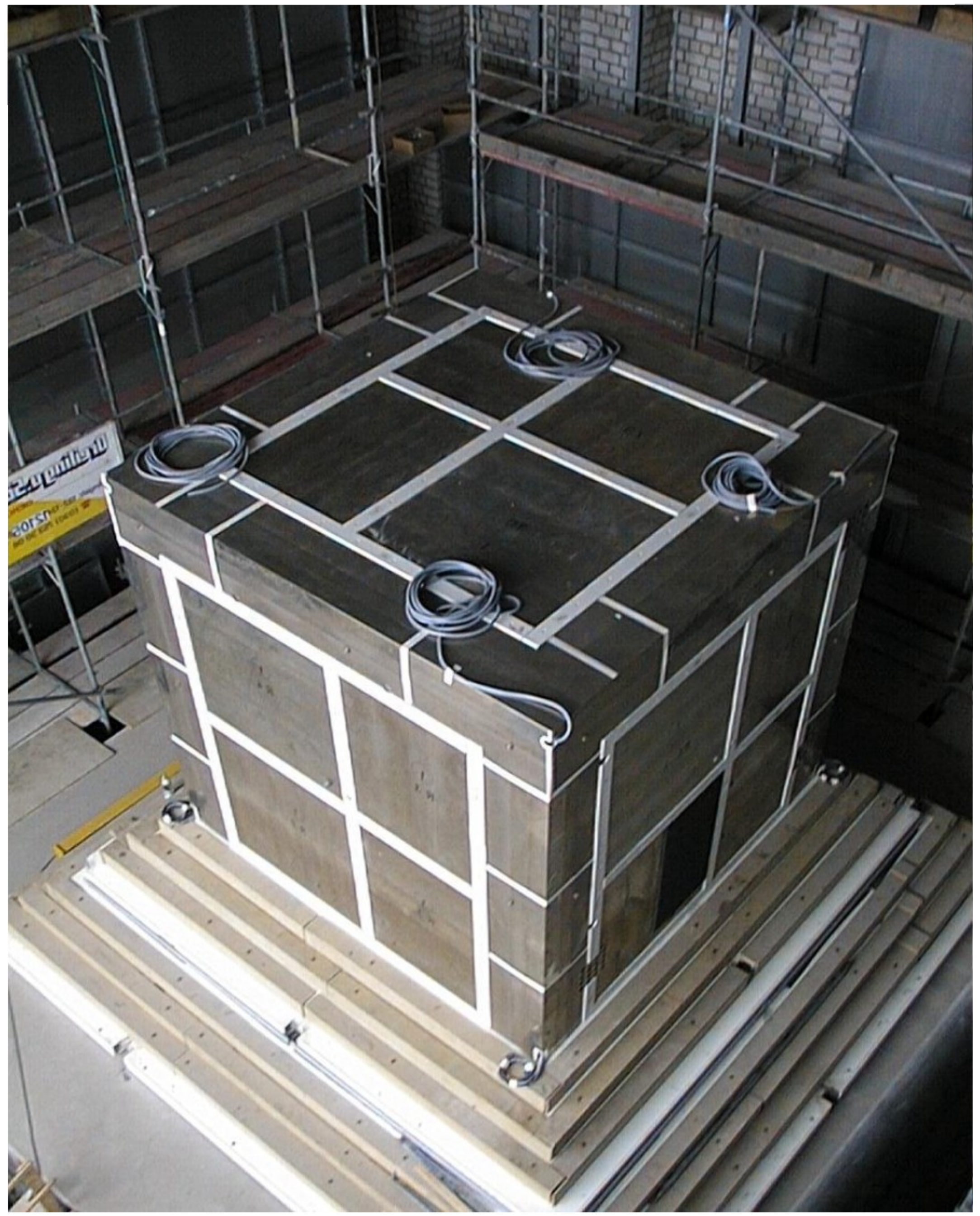
Dynamics: Noise spectrum

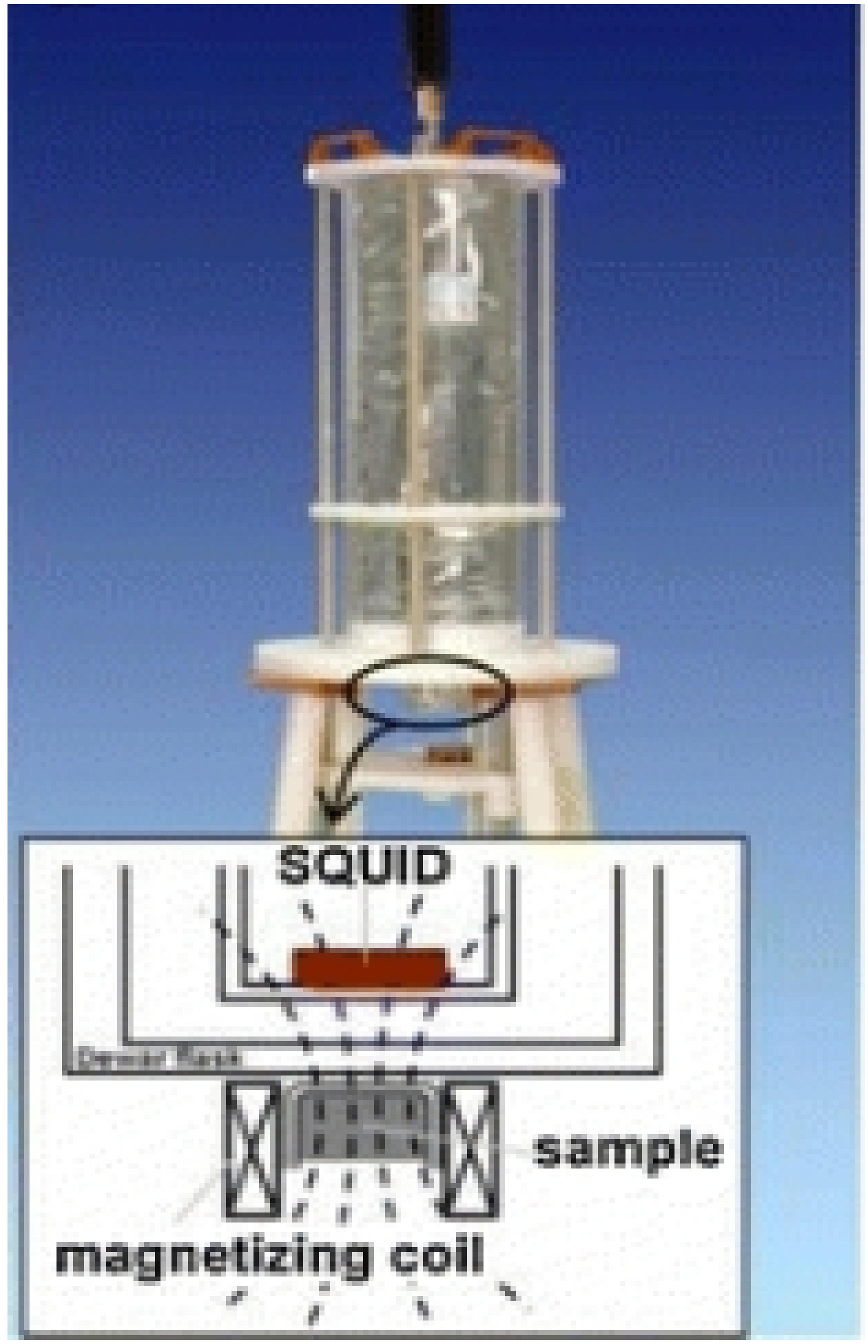




Jonathan.Leliaert@ugent.be

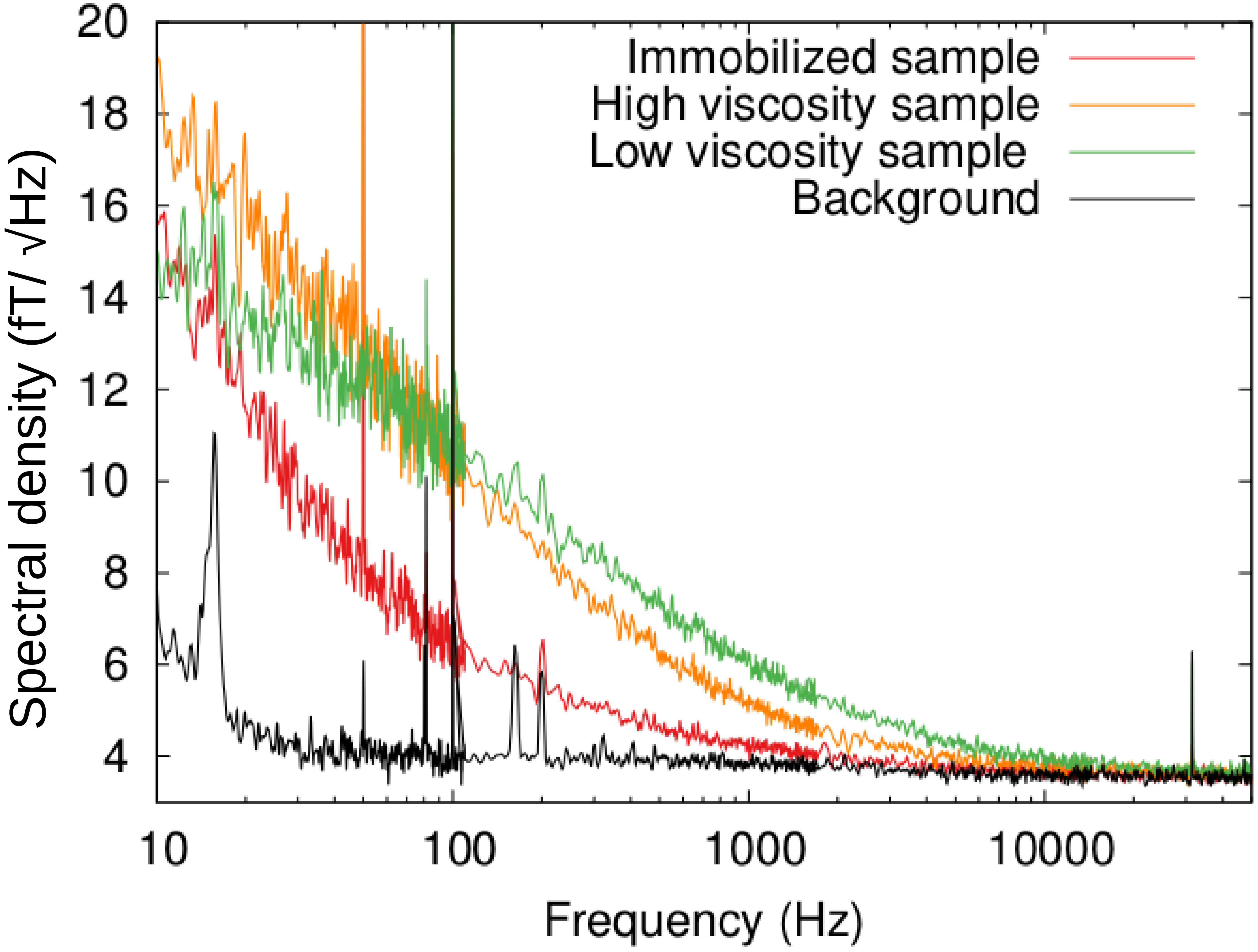
Method: Noise measurements





J. Bork, et. al., “The 8-layered magnetically shielded room of the PTB: Design and construction”. In Biomag 2000, Proc. 12th Int. Conf. on Biomagnetism (2001)

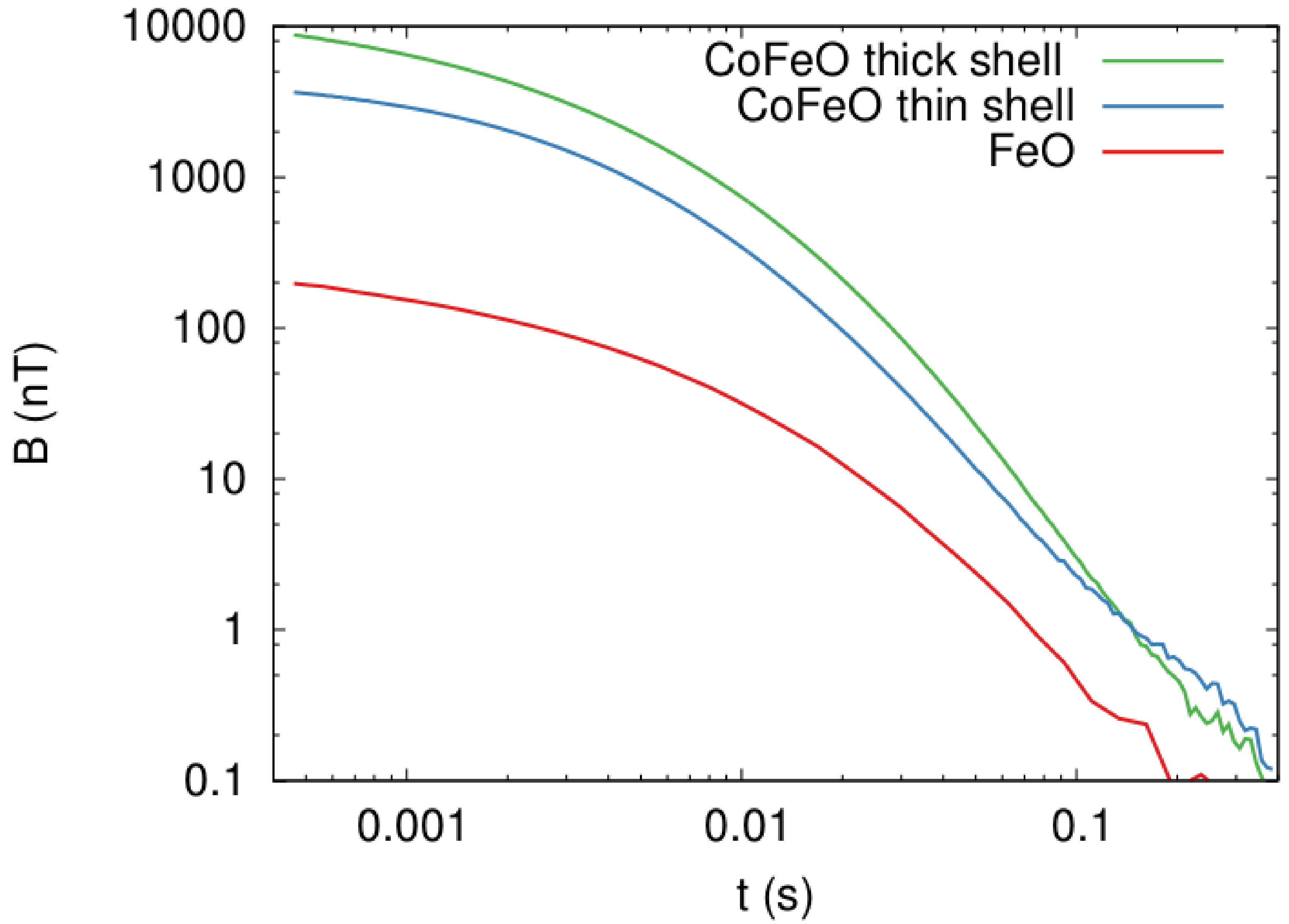
Results



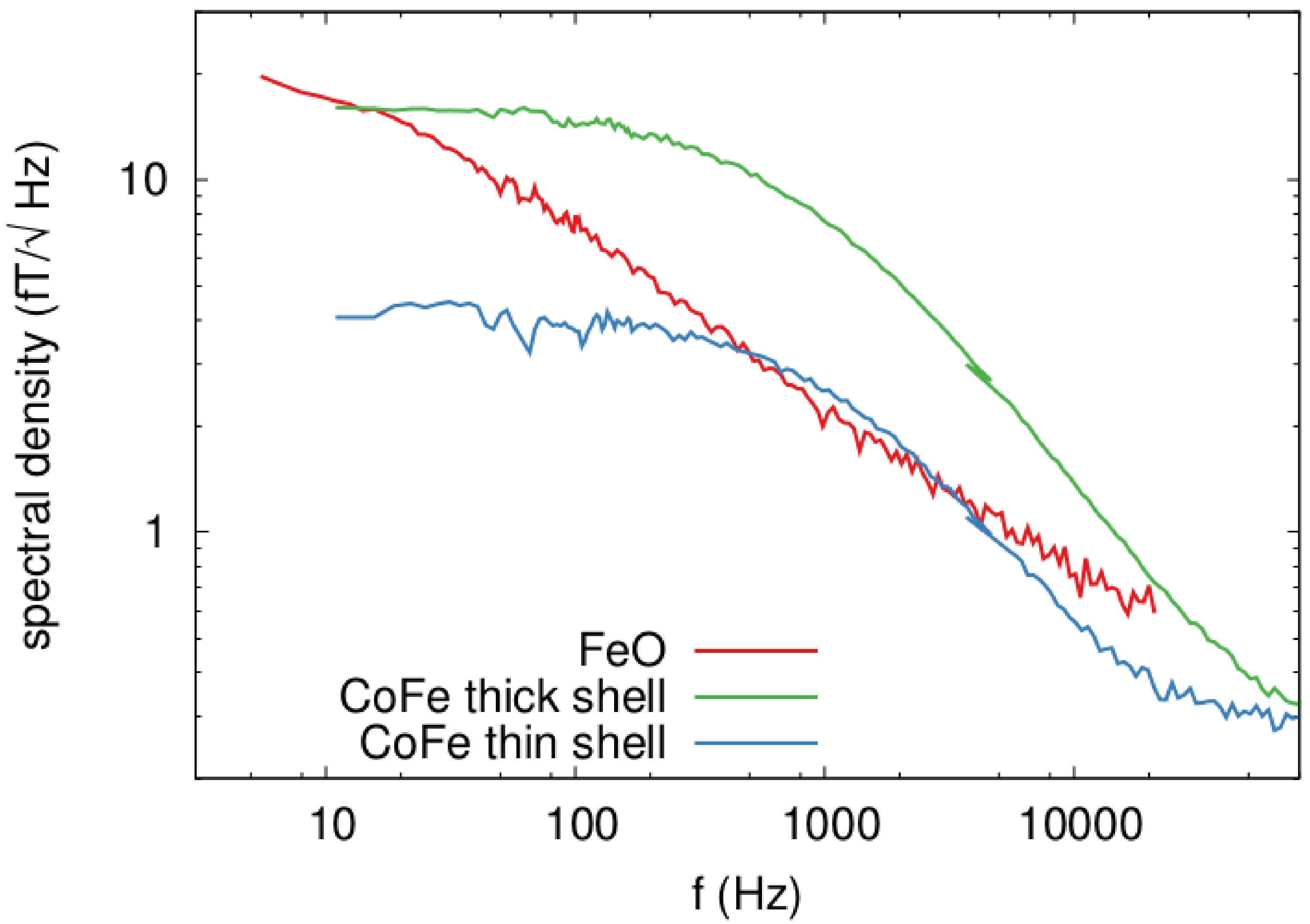
J. Leliaert, et. al., “Thermal magnetic noise spectra of nanoparticle ensembles”, Applied Physics Letters, 107(22), 222401 (2015)

Results: Comparison

- Magnetorelaxometry

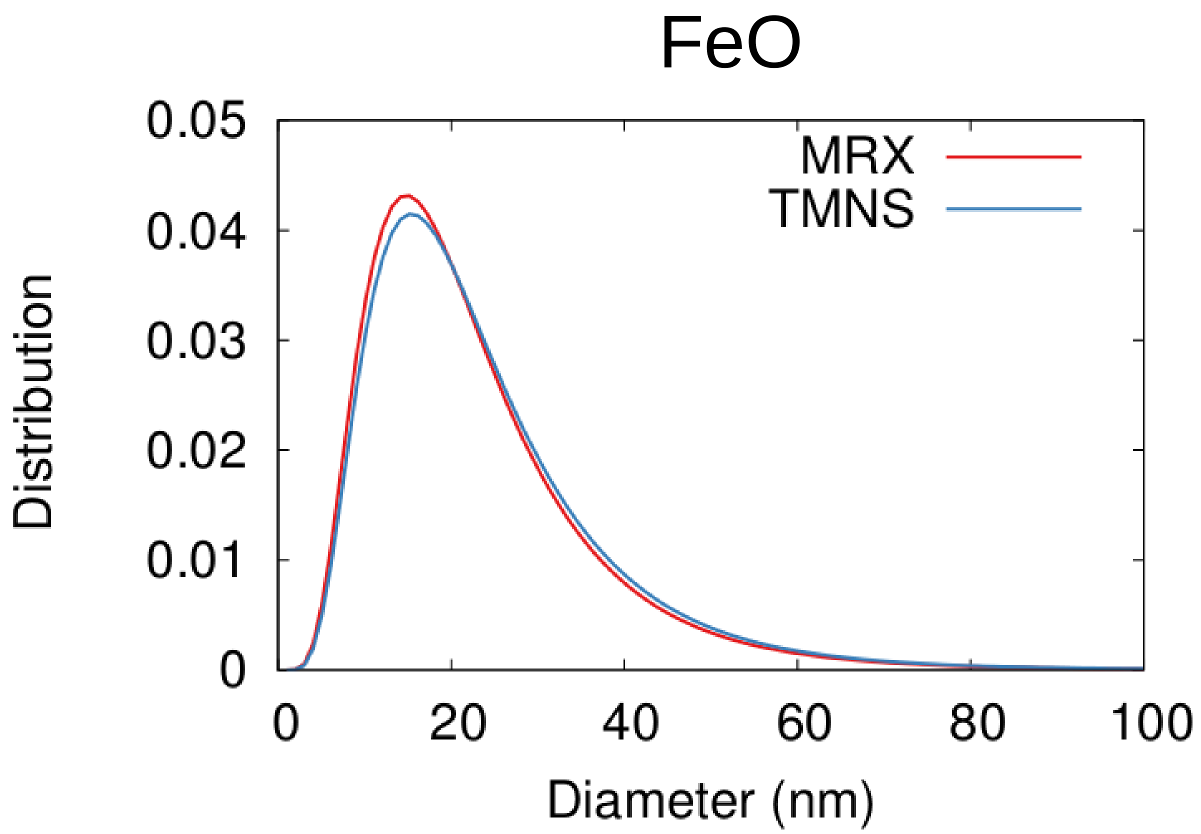


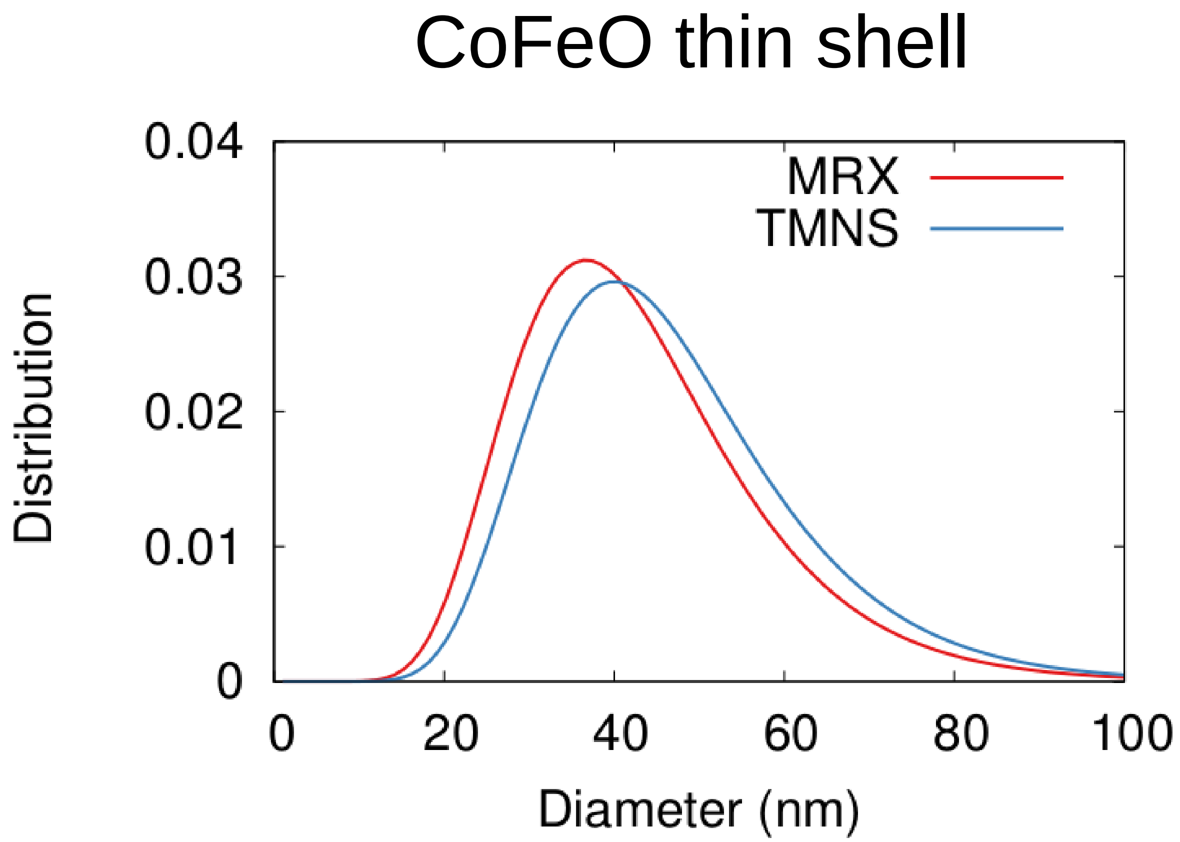
- Thermal magnetic noise spectroscopy

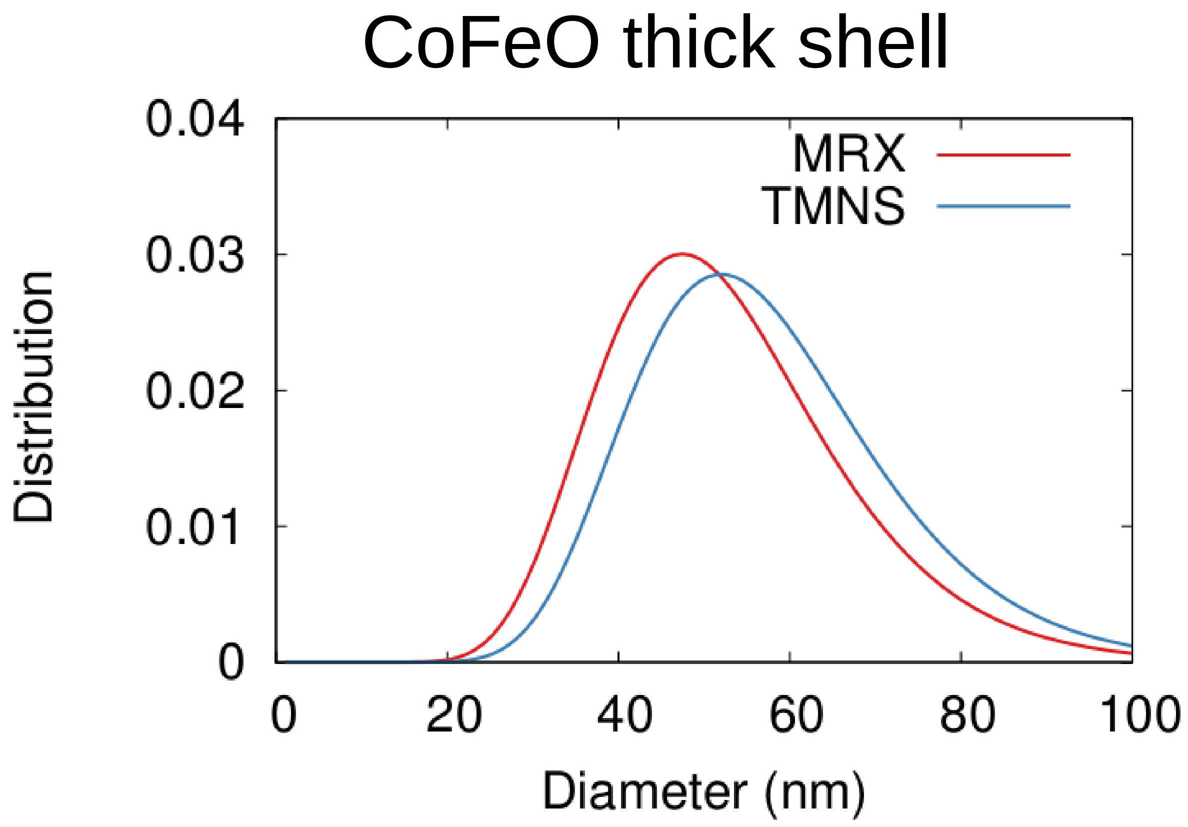


J. Leliaert, et. al. ,"The complementarity and similarity of magnetorelaxometry and thermal magnetic noise spectroscopy for magnetic nanoparticle characterization", J. Phys. D: Appl. Phys. , 50(8), 085004 (2017)

Results: Comparison



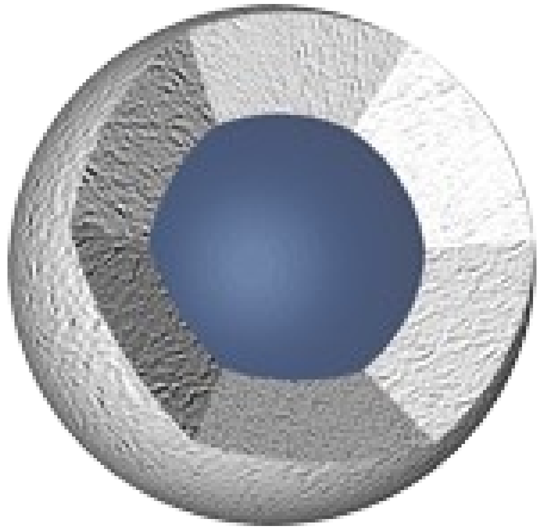




- Agreement between MRX (Magnetorelaxometry) and TMNS (thermal magnetic noise spectroscopy)
- Small differences due to excitation and interaction effects

Jonathan.Leliaert@ugent.be

Conclusion part 1



- Thermal magnetic noise spectroscopy
  = magnetic characterization technique without external fields
- Tool to investigate the influence of fields used in other methods
- Provides path towards better characterization and applications

“Thermal magnetic noise spectra of nanoparticle ensembles”, Applied Physics Letters, 107(22), 222401 (2015)

“The complementarity and similarity of magnetorelaxometry and thermal magnetic noise spectroscopy for magnetic nanoparticle characterization”, Journal of Physics D: Applied Physics , 50(8), 085004 (2017)

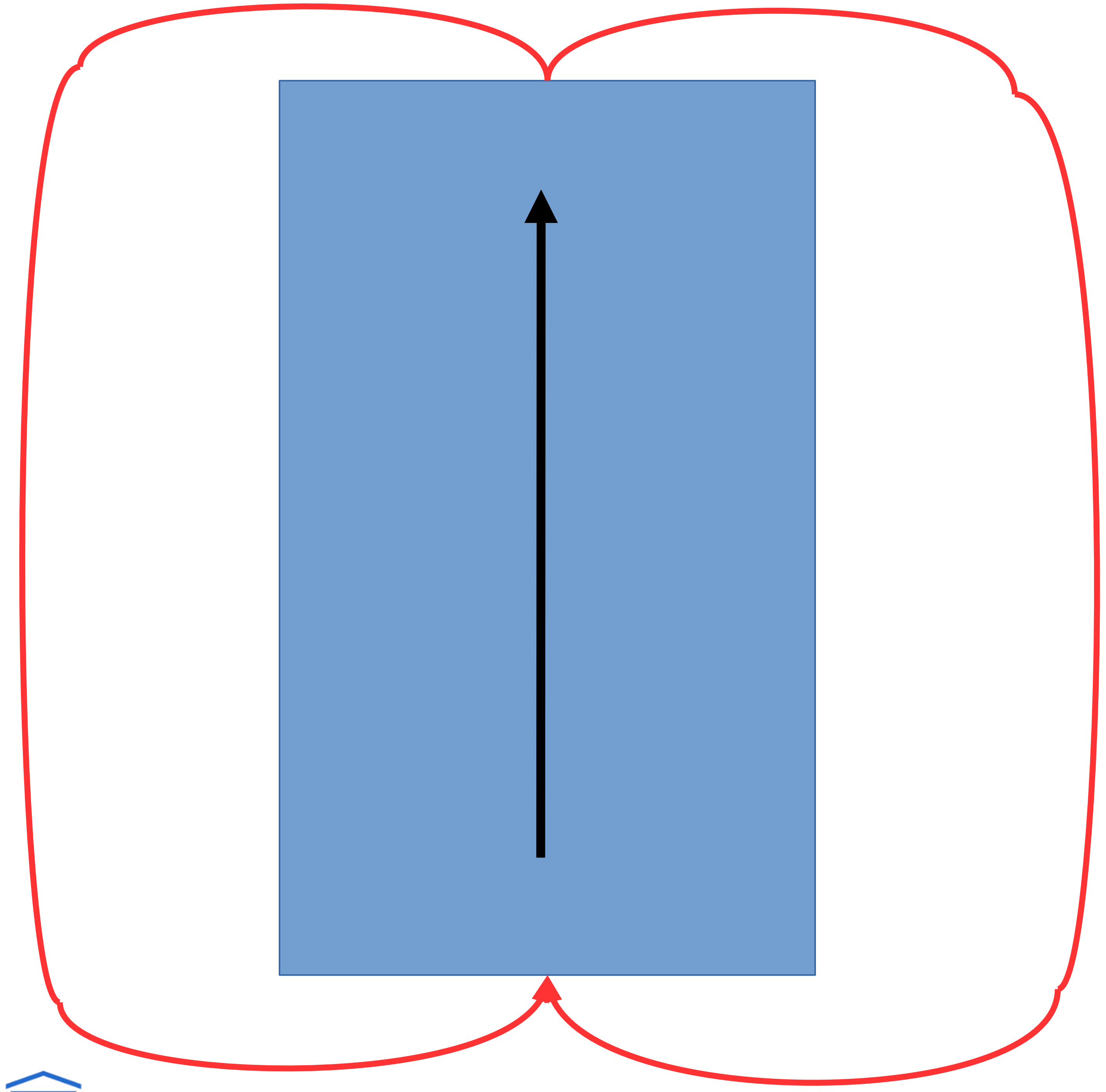
GHENT
UNIVERSITY

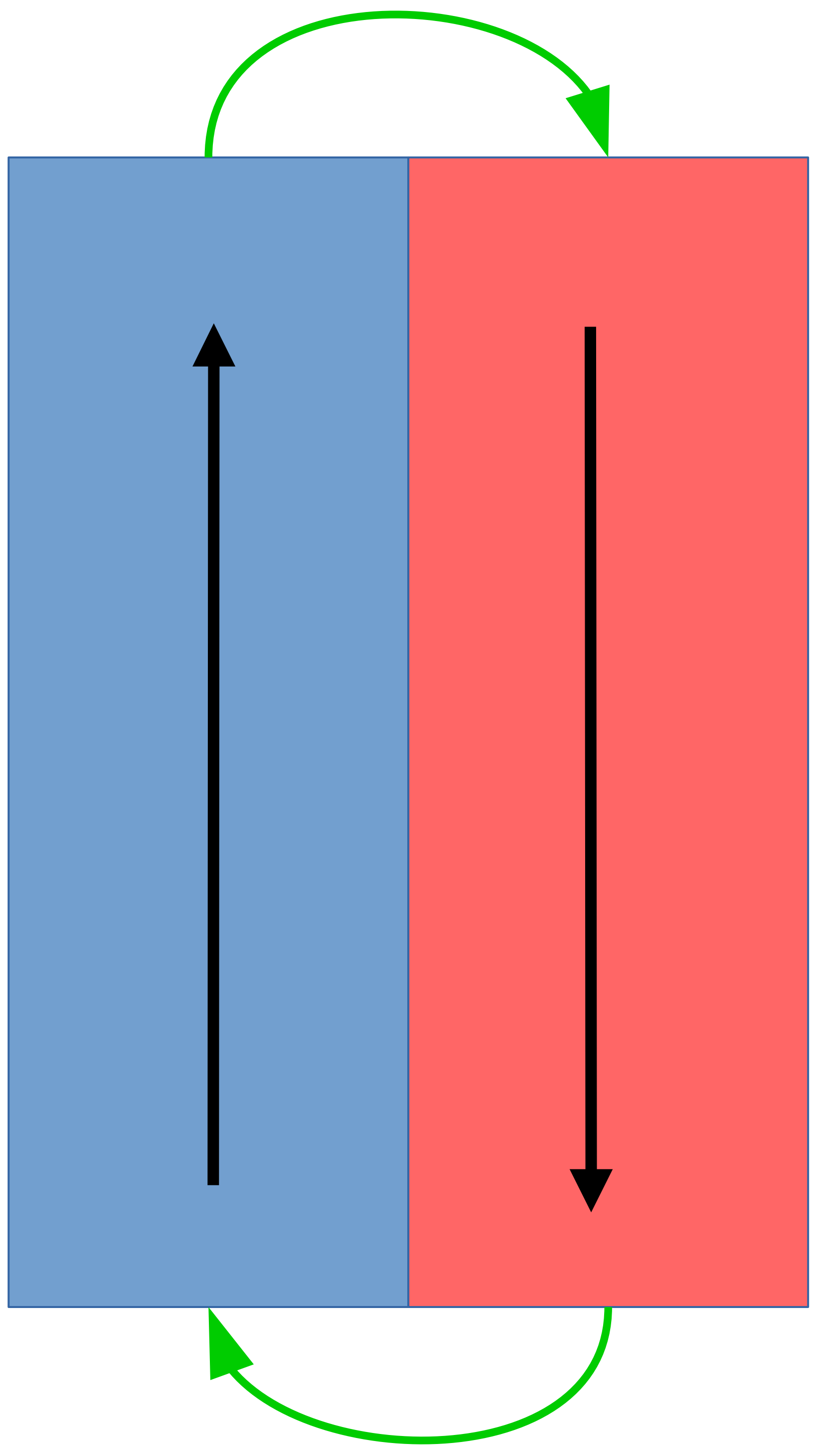
Jonathan.Leliaert@ugent.be

Numerical Study:
Thermally activated domain wall motion

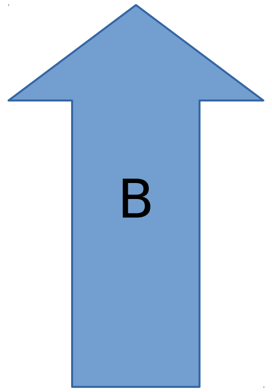
Jonathan.Leliaert@ugent.be

Domains and domain walls in magnetism

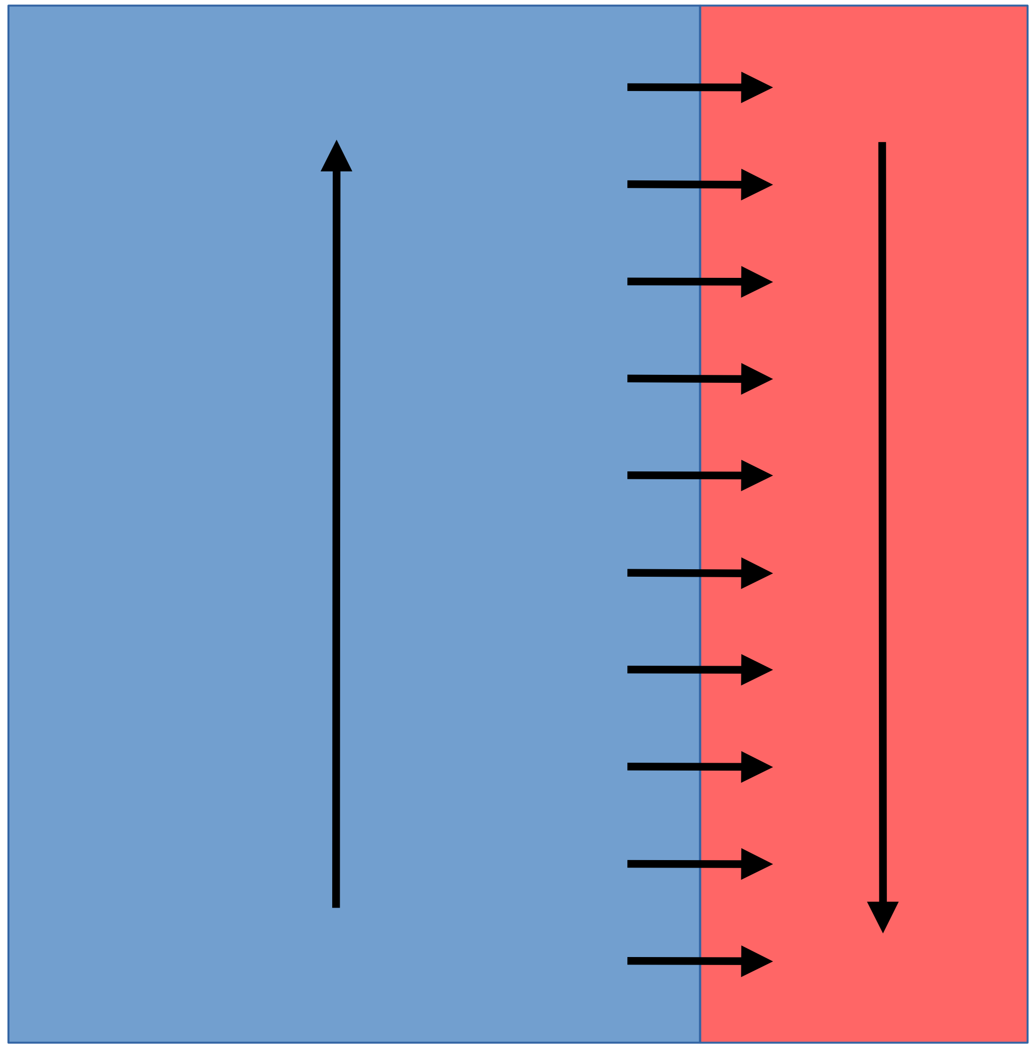




Field driven domain wall motion

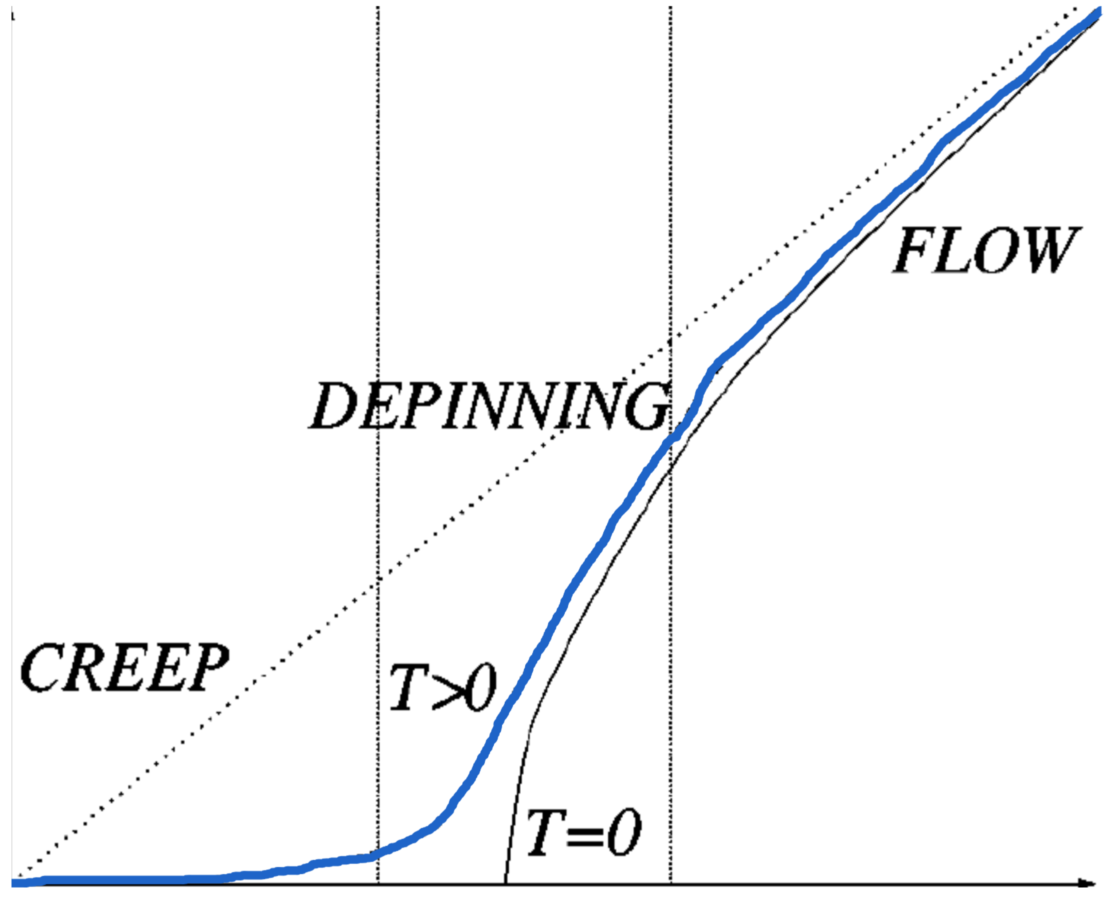


Externally applied
magnetic field



Elastic fronts moving in weakly disordered systems

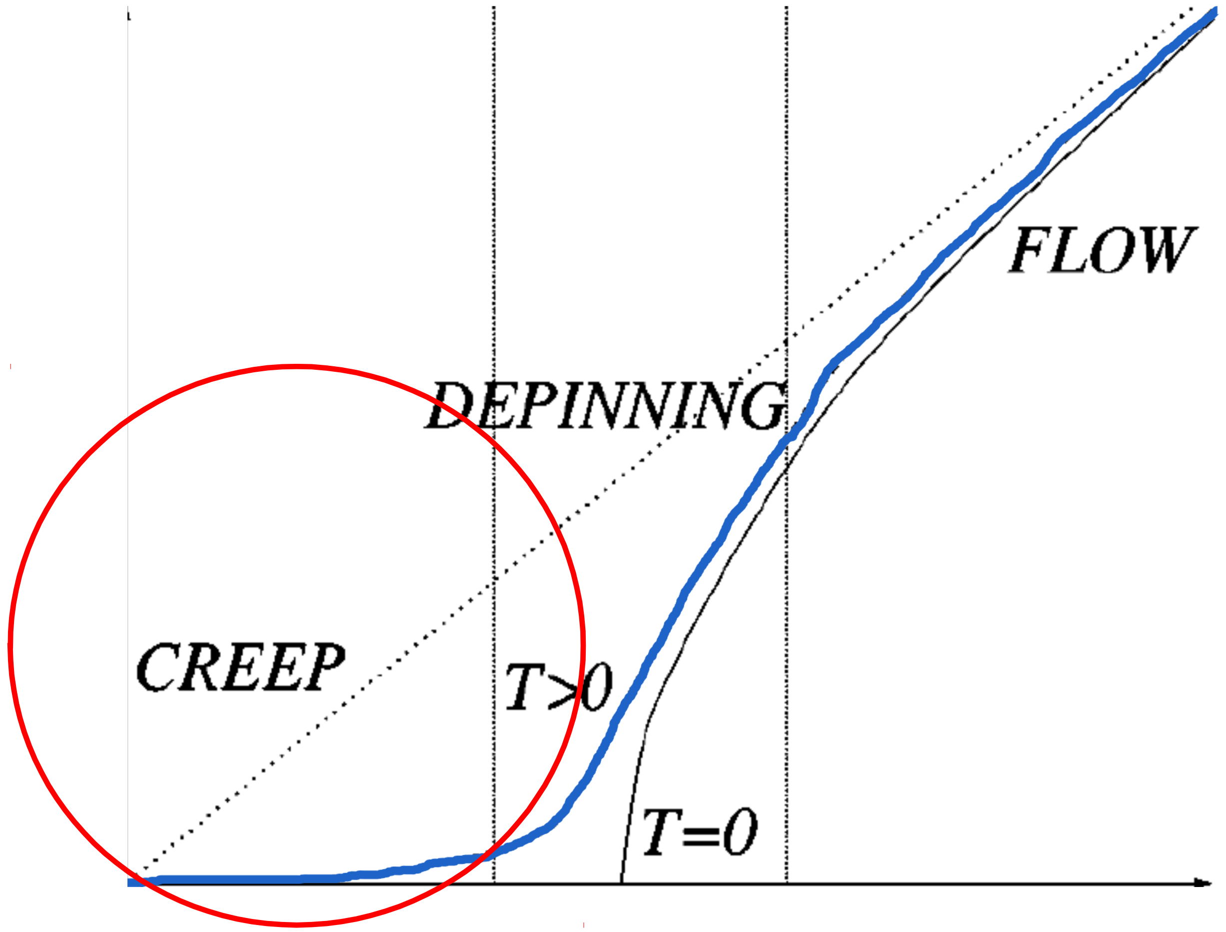
- Small driving force f
- Non-zero temperature T



P. Chauve, et al., "Creep and depinning in disordered media",
Phys. Rev. B, 62, 6241-6267 (2000)

Elastic fronts moving in weakly disordered systems

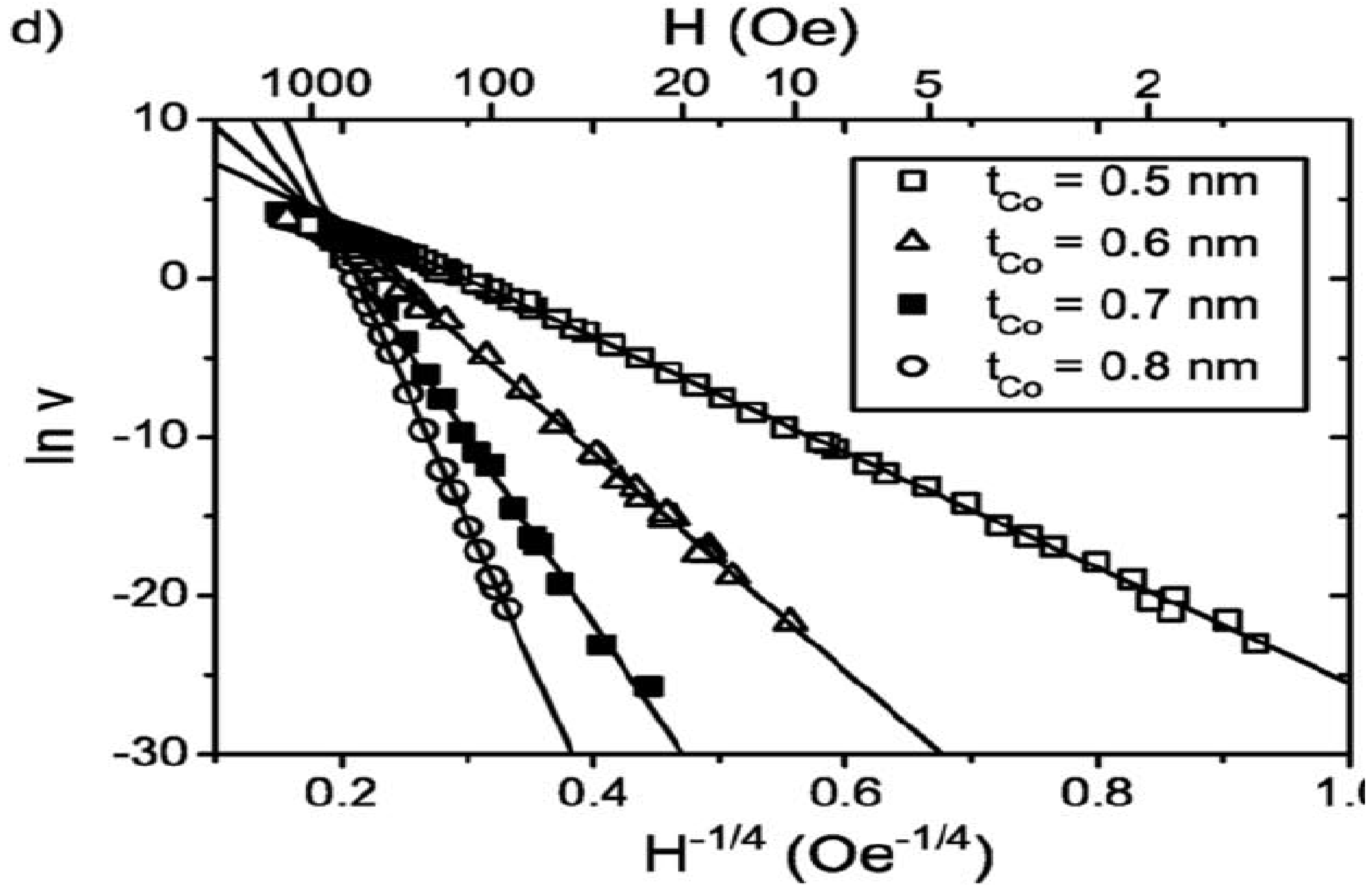
- Small driving force f
- Non-zero temperature T



P. Chauve, et al., “Creep and depinning in disordered media”, Phys. Rev. B, 62, 6241-6267 (2000)

- Universal creep scaling law with μ=1/4

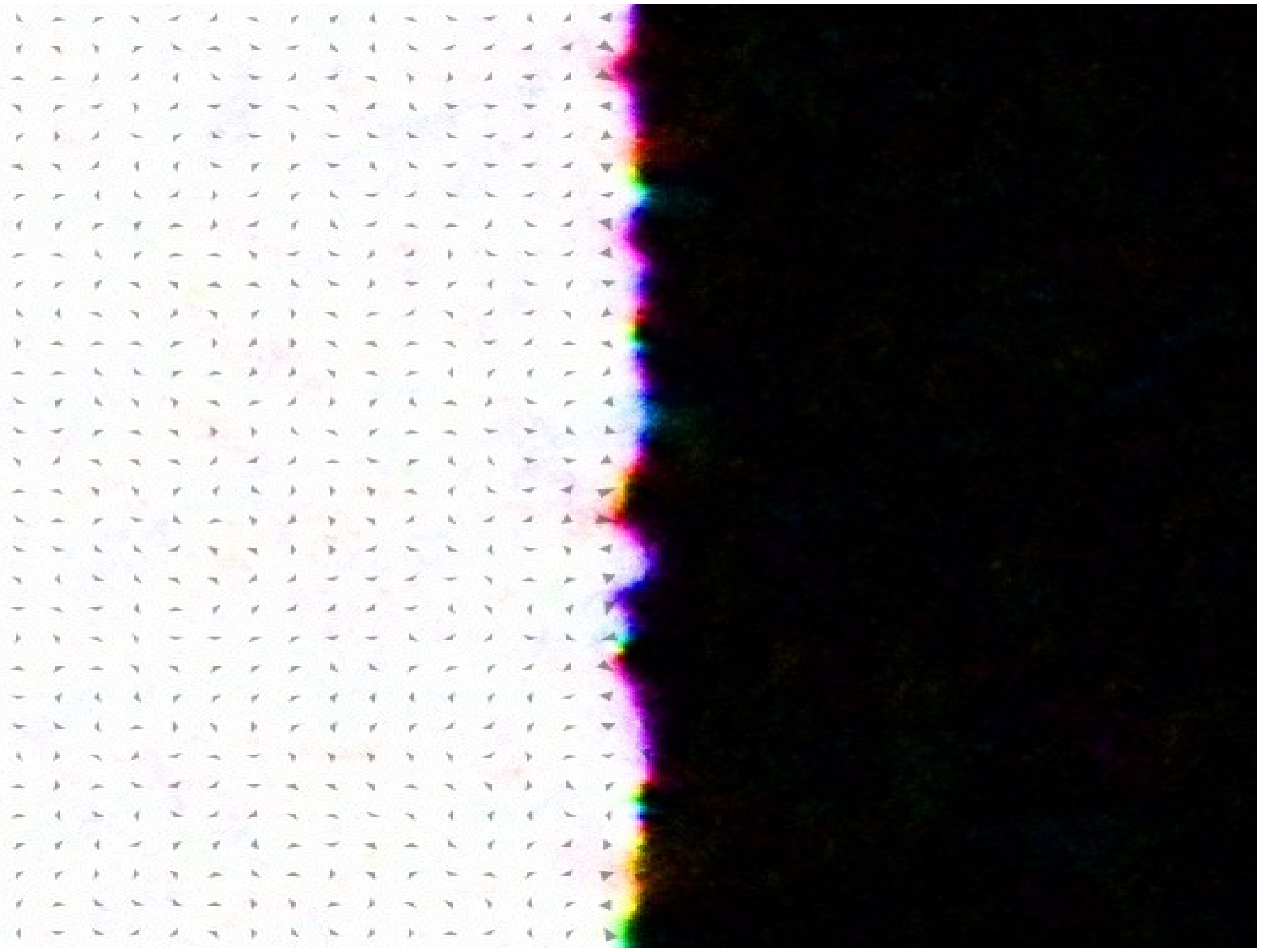
$$v \sim exp\left[-\left(\frac{T_{\rm dep}}{T}\right)\left(\frac{H_{\rm dep}}{H}\right)^{-\mu}\right]$$



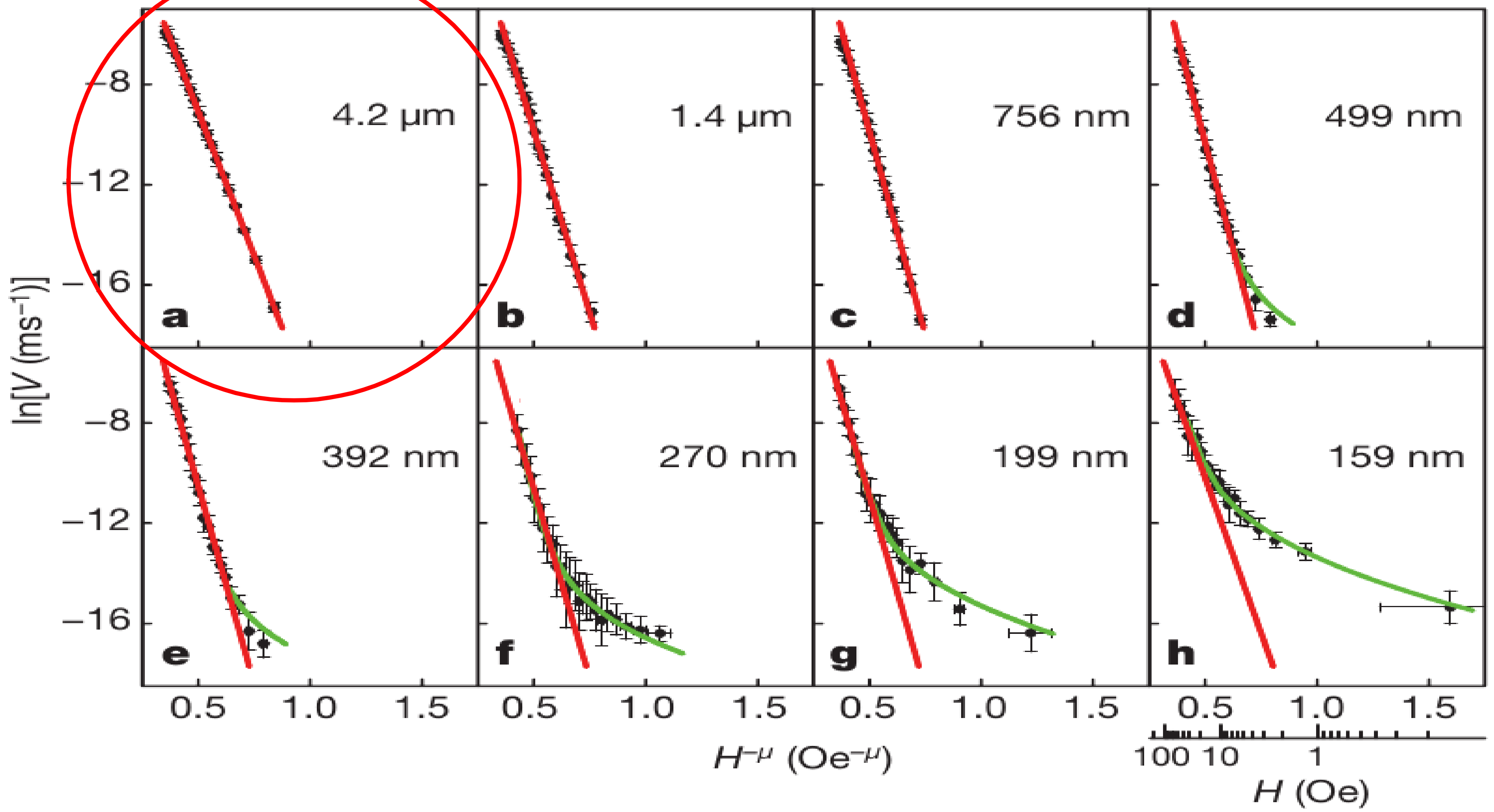
P. Metaxas, et al., “Creep and Flow Regimes of Magnetic Domain-Wall Motion in Ultrathin Pt/Co/Pt Films with Perpendicular Anisotropy”, Phys. Rev. Lett. 92, 217208 (2007)

Creep in narrow ferromagnetic nanostrips

Creep in PMA nanostrips with decreasing strip width.



1D interface through 2D medium



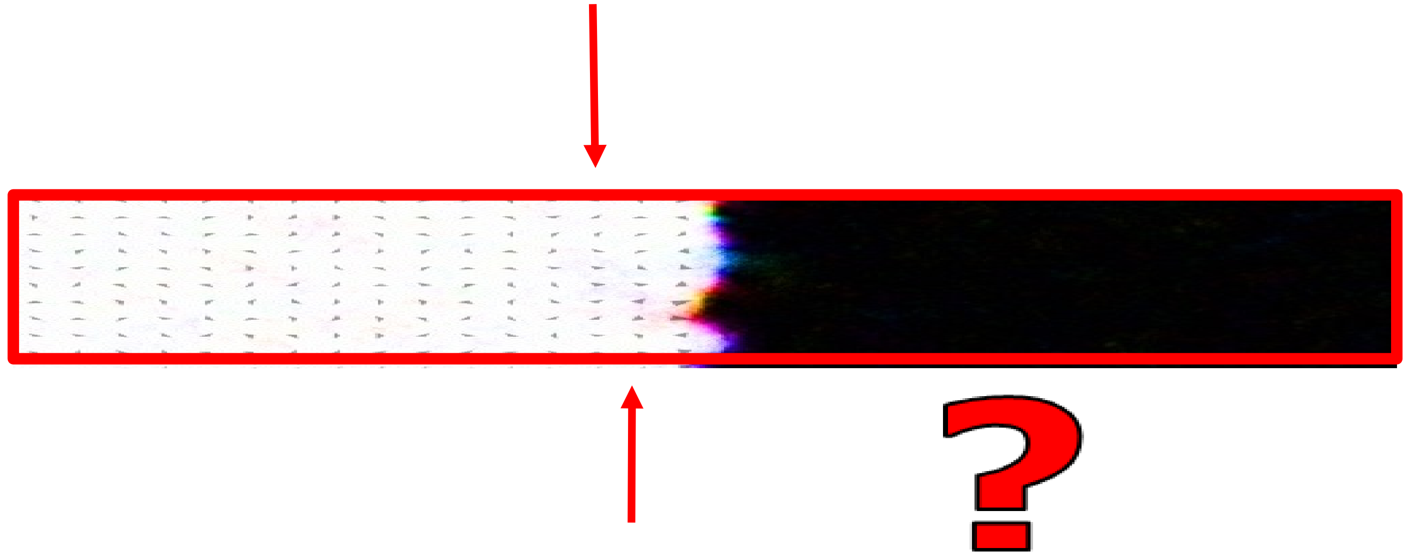
K-J. Kim, et. al., “Interdimensional universality of dynamic interfaces”, Nature, 458, 07874 (2009)

GHENT UNIVERSITY

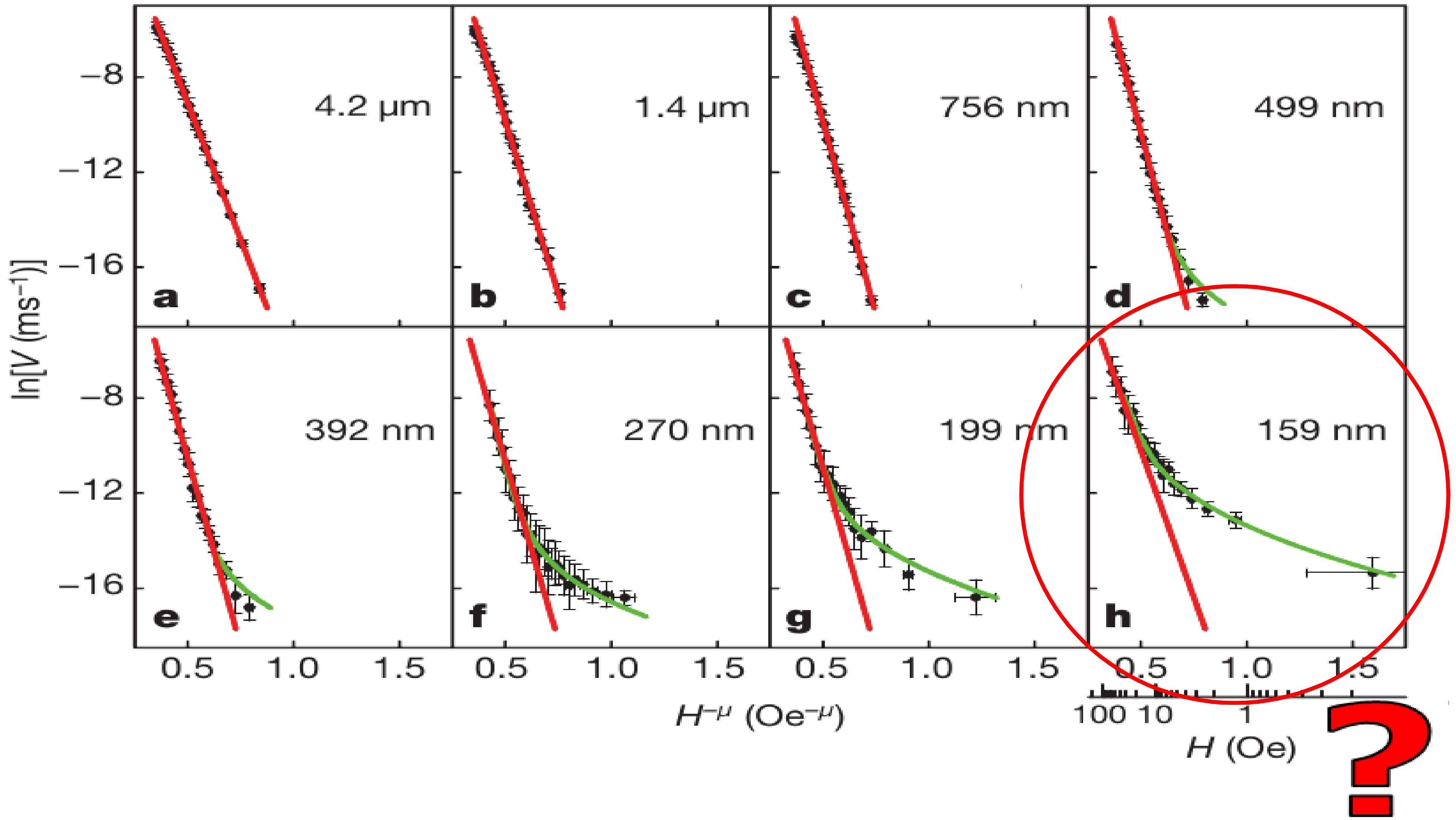
Jonathan.Leliaert@ugent.be

Creep in narrow ferromagnetic nanostrips

Creep in PMA nanostrips with decreasing strip width.



0D interface through 1D medium?



K-J. Kim, et. al., “Interdimensional universality of dynamic interfaces”, Nature, 458, 07874 (2009)

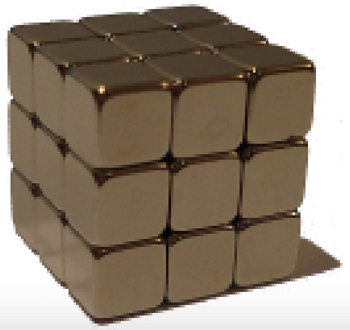
GHENT UNIVERSITY

Creep in narrow ferromagnetic nanostrip

Questions to answer:

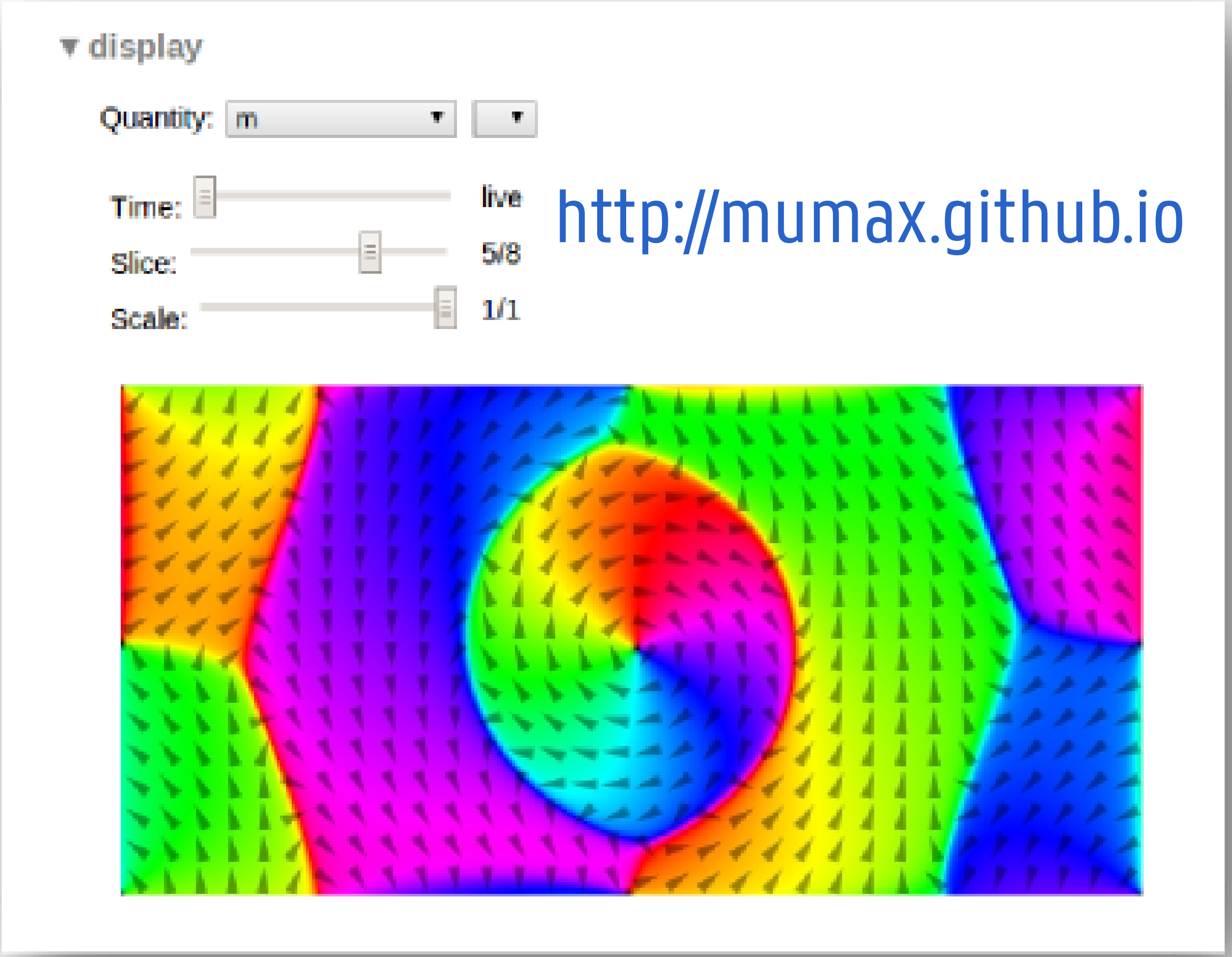
- Is the domain wall a 0D object (point) moving along a 1D landscape?
- Which scaling law does it follow?

MuMax³: Introduction



MuMax³

GPU accelerated micromagnetism

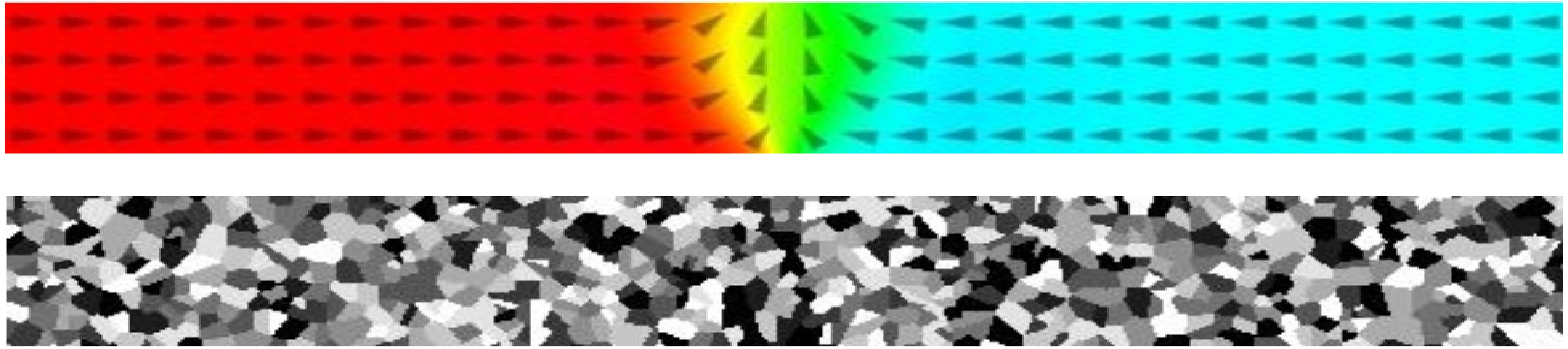


http://mumax.github.io

"The design and verification of MuMax3", AIP Advances 4, 107133 (2014); doi: 10.1063/1.4899186

Jonathan.Leliaert@ugent.be

Creep in narrow ferromagnetic nanostrip



- Permalloy nanostrip (100 nm wide, 10 nm thick) with grain structure.

  J. Leliaert, et al. "Current-driven domain wall mobility in polycrystalline Permalloy nanowires: A numerical study"
  J. Appl. Phys., 2014, 115, 233903

- Full micromagnetic simulations with MuMax3.
- 1D model description.

Is the domain wall a 0D object moving along a 1D line?

Full micromagnetic simulations:

- No assumption on domain wall nature.

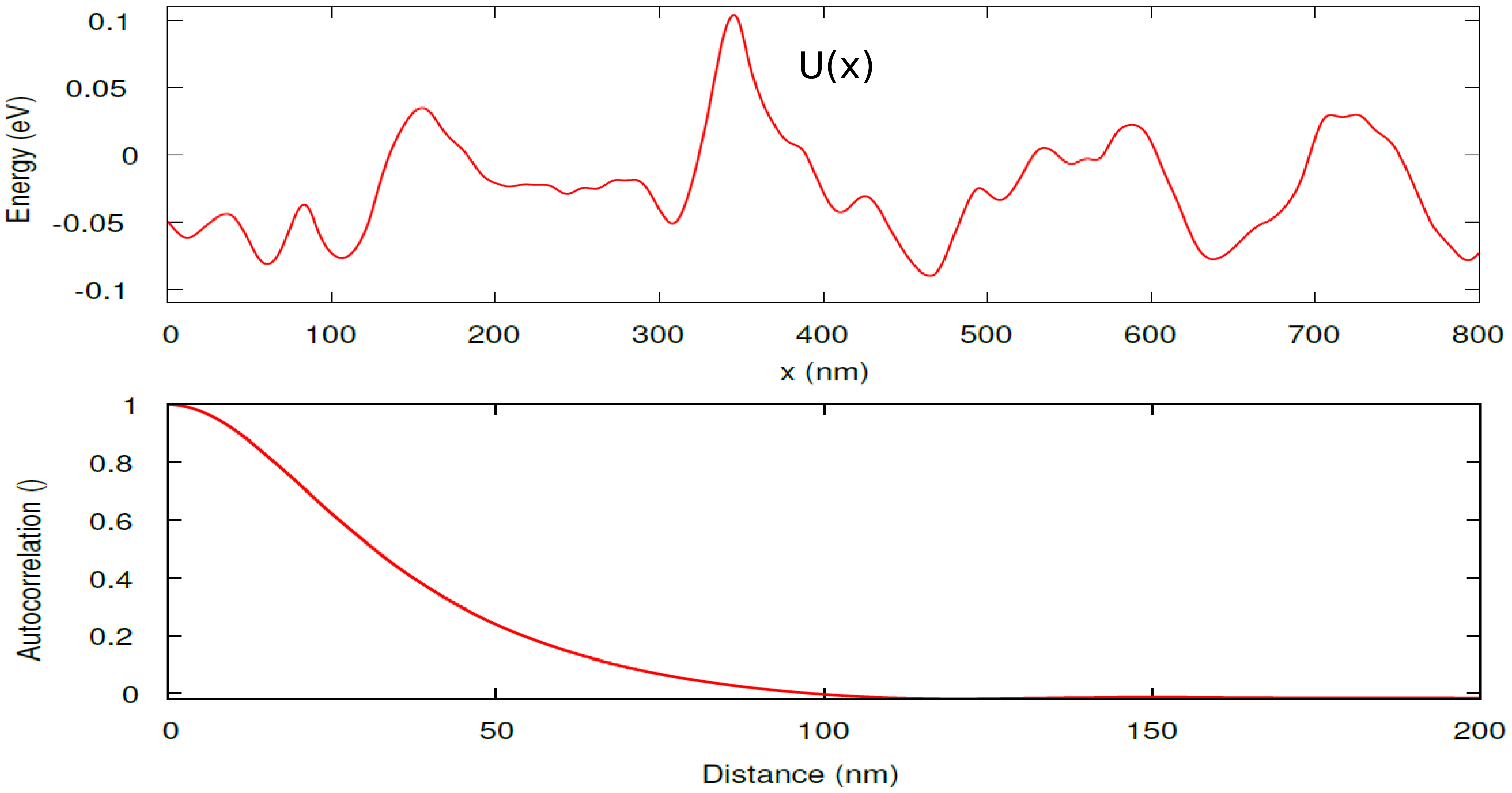
1D model description of the same system:

- Assumption: domain wall is a 0D object moving along a 1D line

$$\underbrace{m}_{\text{mass}}\overbrace{\frac{d^2x}{dt^2}}^{\text{acceleration}} = \underbrace{-\Gamma}_{\text{friction}}\overbrace{\frac{dx}{dt}}^{\text{velocity}} - \underbrace{\alpha\frac{\partial U}{\partial x}}_{\text{disorder energy landscape}} + \underbrace{\beta\sqrt{T}}_{\text{temperature}} + \underbrace{\delta J + \epsilon H_{\mathrm{ext}}}_{\text{driving forces}}$$

- No fitting: all parameters quantified for particular domain wall structure.

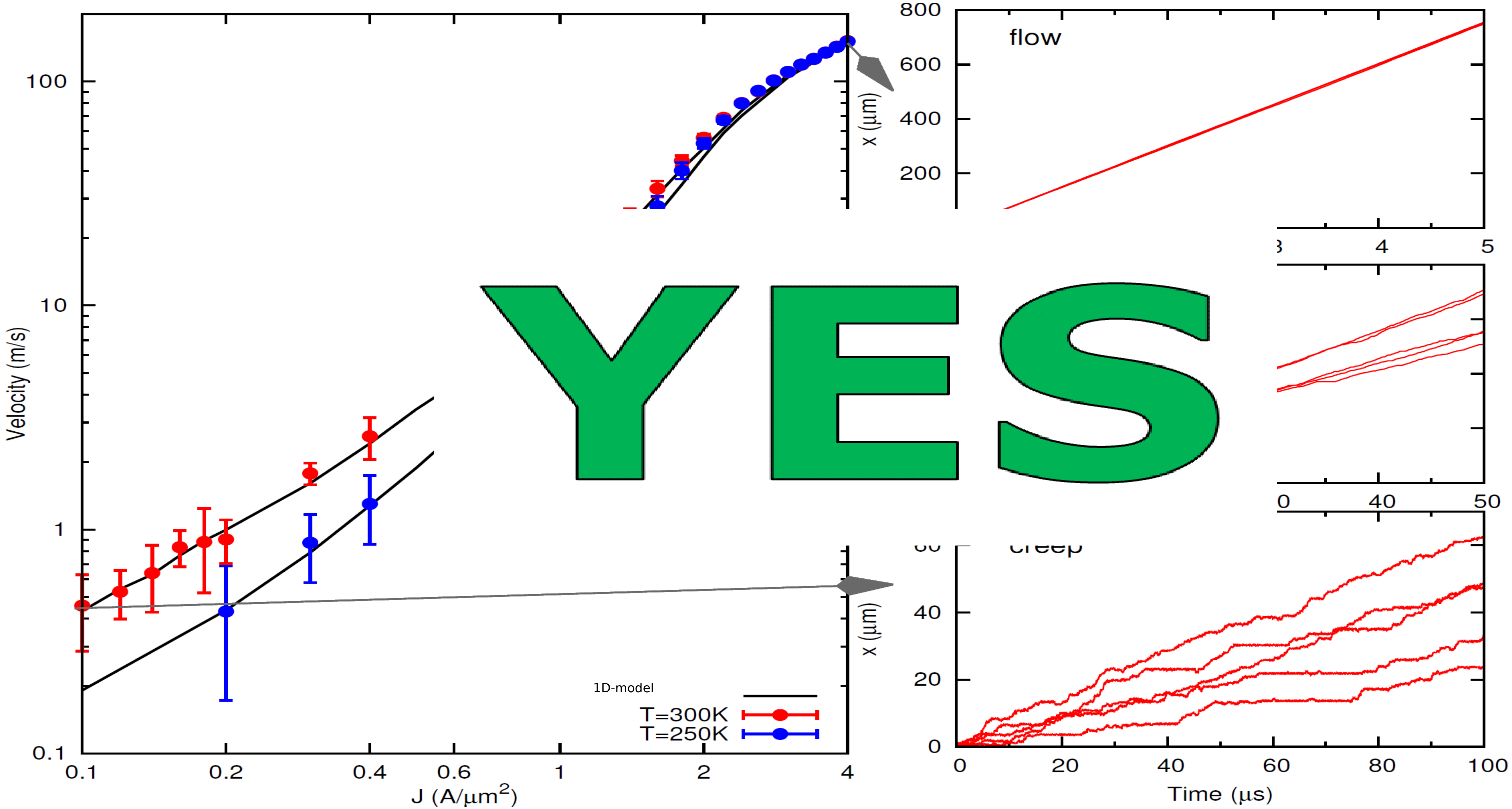
1D model description: disorder energy landscape



GHENT UNIVERSITY

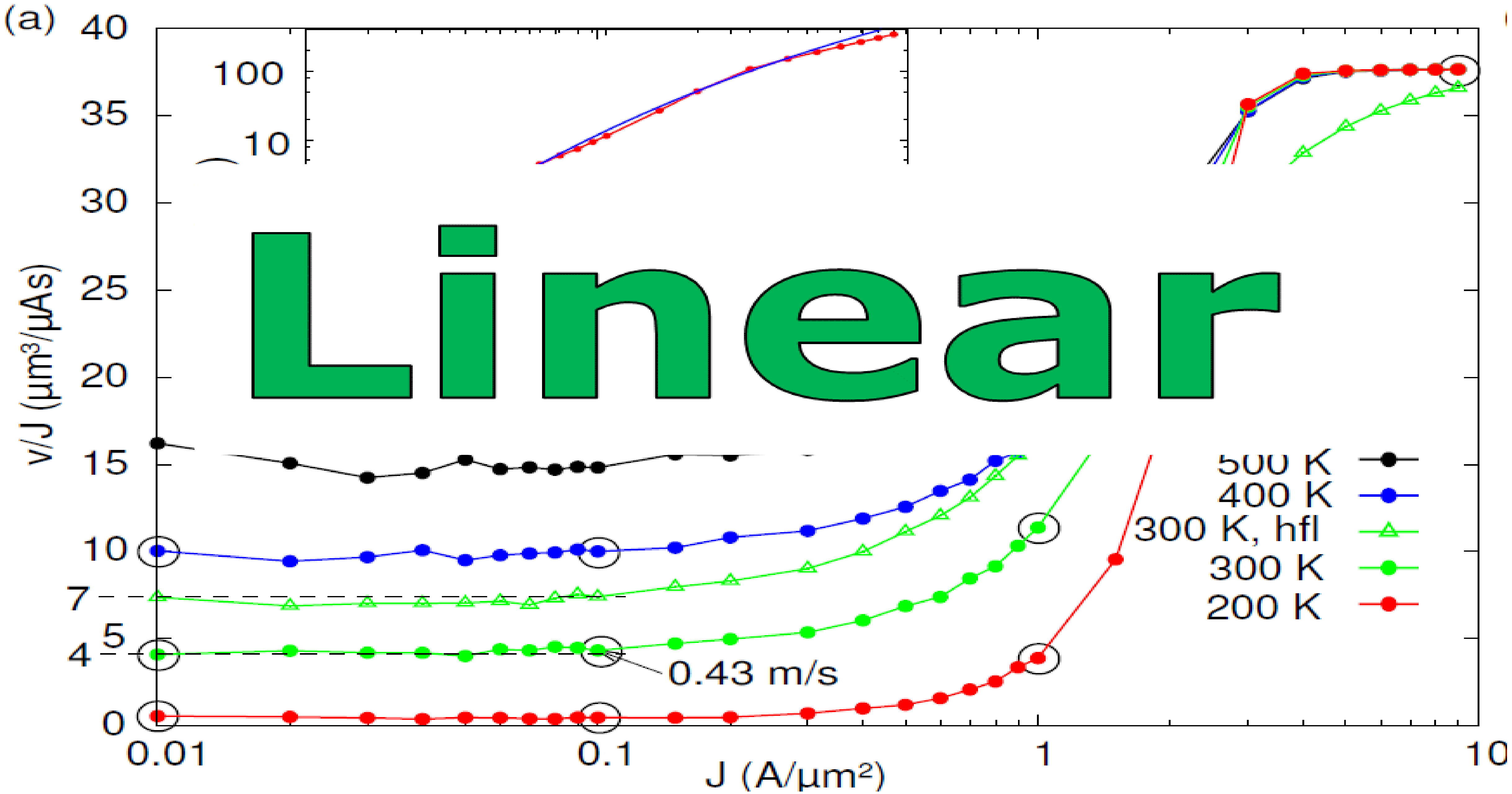
Jonathan.Leliaert@ugent.be

Is the domain wall a 0D object moving along a 1D line?



Which scaling law does the creep follow?

Smaller currents accessible with 1D-model description.



GHENT UNIVERSITY

Jonathan.Leliaert@ugent.be

Conclusion part 2

The domain wall is a 0D object (point) moving along a 1D landscape,

- Despite possible complex structure.
- Verified by micromagnetic simulations.
- Validates equation of motion.

- Domain wall velocity scales linearly with small fields/currents.
- In correspondence with experiments.

J. Leliaert, et. al., "Creep turns linear in narrow ferromagnetic nanostrips", Scientific Reports, 6, 20472 (2016)

GHENT UNIVERSITY

FACULTY
OF SCIENCES

dr. Jonathan Leliaert

BOF Postdoctoral Fellow

Department of Solid State Sciences
Research group DyNaMat

E jonathan.leliaert@ugent.be
T +32 9 264 43 72

www.dynamat.ugent.be

Ghent University
@ugent
Ghent University

GHENT
UNIVERSITY