FACULTY
OF SCIENCES

DEPARTMENT OF SOLID STATE SCIENCES
RESEARCH GROUP DYNAMAT

Introduction to MuMax3

June 11th, 2019

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Outline

- Micromagnetism
  - Introduction
  - Theory
  - Simulations
- MuMax³
  - Introduction
  - Requirements & Performance
  - Examples and new features

Micromagnetism

Micromagnetism: Introduction

- *"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: Theory

Energy densities Ground state → minimize total energy

$$E = \int_V \mathcal{E}_{\text{total}} d\mathbf{r}$$

- Exchange energy

$$\mathcal{E}_{\text{exchange}} = A_{\text{ex}} (\nabla \mathbf{m})^2$$

$$(\nabla \mathbf{m})^2 = (\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2$$

- Zeeman energy

$$\mathcal{E}_{\text{Zeeman}} = -\mu_0 M_s \mathbf{m} \cdot \mathbf{H}_{\text{ext}}$$

- Anisotropy energy

$$\mathcal{E}_{\text{Anisotropy}} = K(1 - (\mathrm{m} \cdot \mathrm{u})^2)$$

- Magnetostatic energy

$$\mathcal{E}_{\text{Magnetostatic}} = -\frac{1}{2} \mu_0 M_s \mathbf{m} \cdot \mathbf{H}_{\text{magnetostatic}}$$

$$\mathbf{H}_{\text{magnetostatic}} = \frac{\mu_0}{4\pi} \int_V M_s \left(3 \frac{(\mathbf{m} \cdot \mathbf{r})\mathbf{r}}{\|\mathbf{r}\|^5} - \frac{\mathbf{m}}{\|\mathbf{r}\|^3} \right) d\mathbf{r}$$

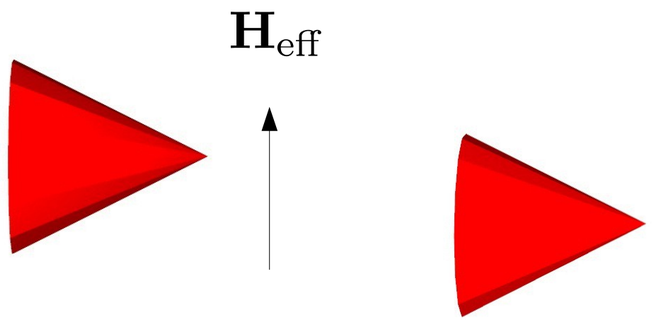
- …

Micromagnetism: Theory

Dynamics

- Landau-Lifshitz equation $\dot{\mathbf{m}} = \underline{-\gamma_0 \mathbf{m} \times \mathbf{H}_{\text{eff}}} \underline{- \lambda \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})}$ with $\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s} \frac{d\mathcal{E}}{d\mathbf{m}}$

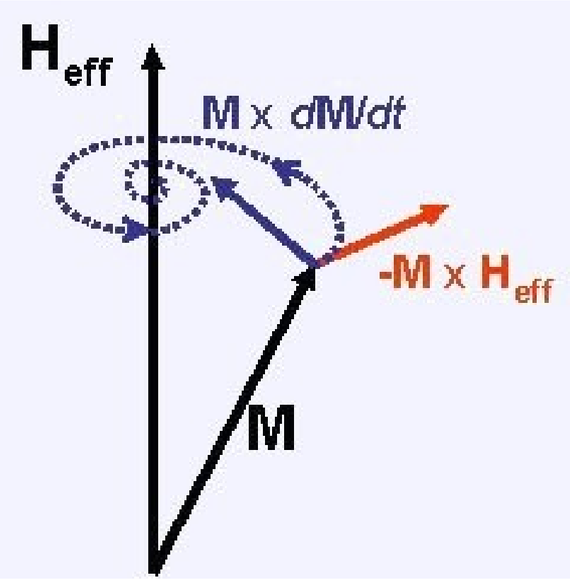
Precession damping

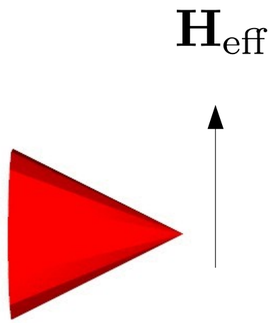


Micromagnetism: Theory

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





Micromagnetism: Simulations

- *“At the outset it was not at all clear how much could be accomplished with the computer simulation with a reasonable investment of effort. The numerical integration of the equations of motion presented in itself an interesting and difficult problem. It quickly became apparent that unless the character of the motion was reasonably simple, the integration would not be economically feasible.”*

Schryer & Walker, *J. Appl. Phys., 45(12):5406–5421, (1974)*

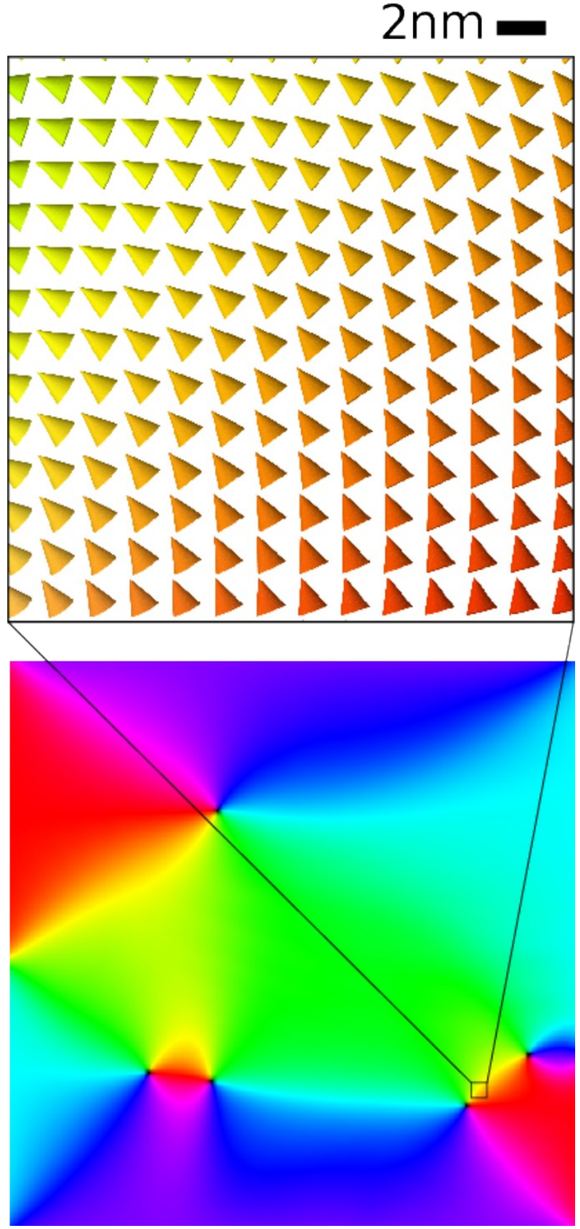
Micromagnetism: Simulations

The prevalence of the words “micromagnetic theory” and “micromagnetic simulations” in the corpus “English” between 1940 and 2008, smoothed out over a 4-year period according to google Ngram Viewer (https://books.google.com/ngrams)

Micromagnetism: Simulations

Challenging

- Magnetostatic interaction is long-range interaction.
- Small length scales (typically nanometers)
- Small timescales (typically femto to picoseconds)

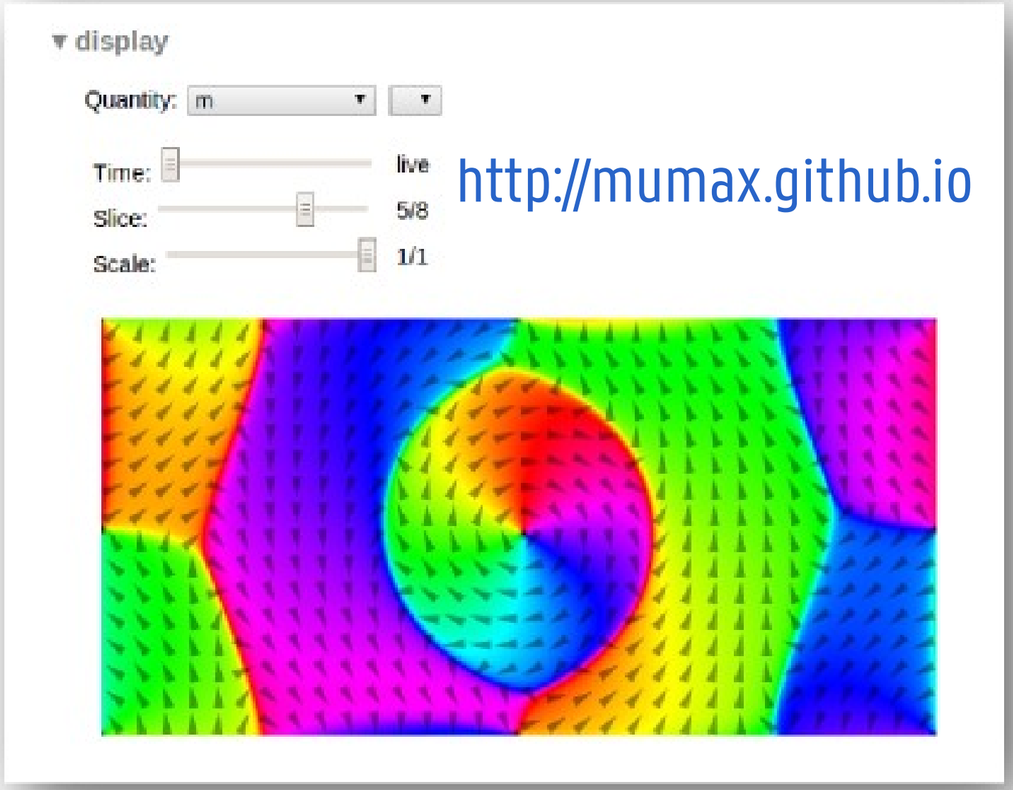


MuMax³

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

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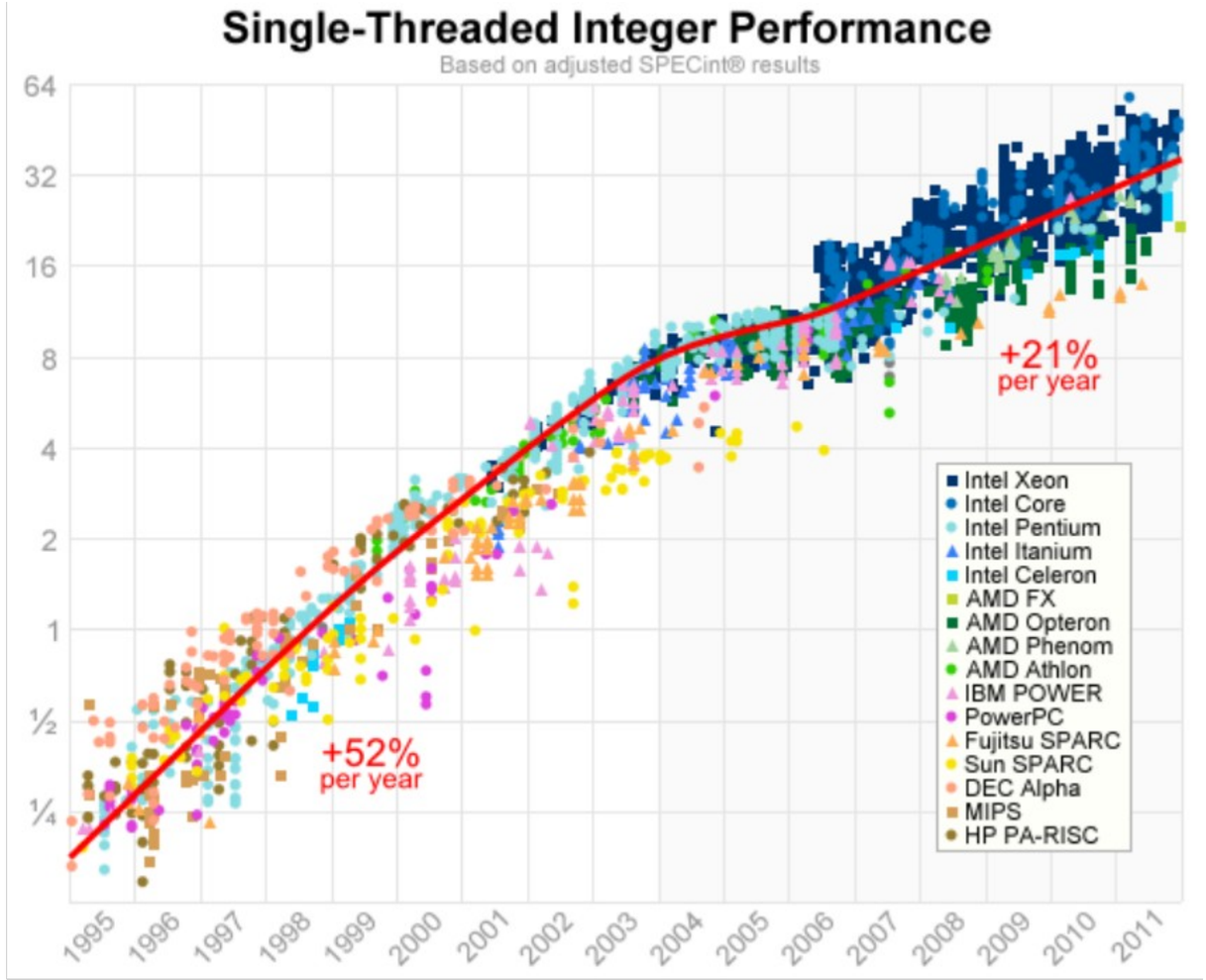
MuMax³: Introduction

- Calculates the space and time dependent magnetization dynamics using a **finite-difference discretization** (similar to OOMMF/MicroMagnum)
- ↔ **finite elements codes** like Nmag, TetraMag, MagPar and FastMag offer more flexibility in the geometry at the expense of performance
- Independently designed from predecessors MuMax 1&2
- Open-source, written in go and CUDA, freely available under GPLv3 License on http://mumax.github.io

MuMax³: Requirements & Performance

- Requirements
  - Linux/ Windows/ Mac Platform
  - NVIDIA GPU

MuMax³ Performance



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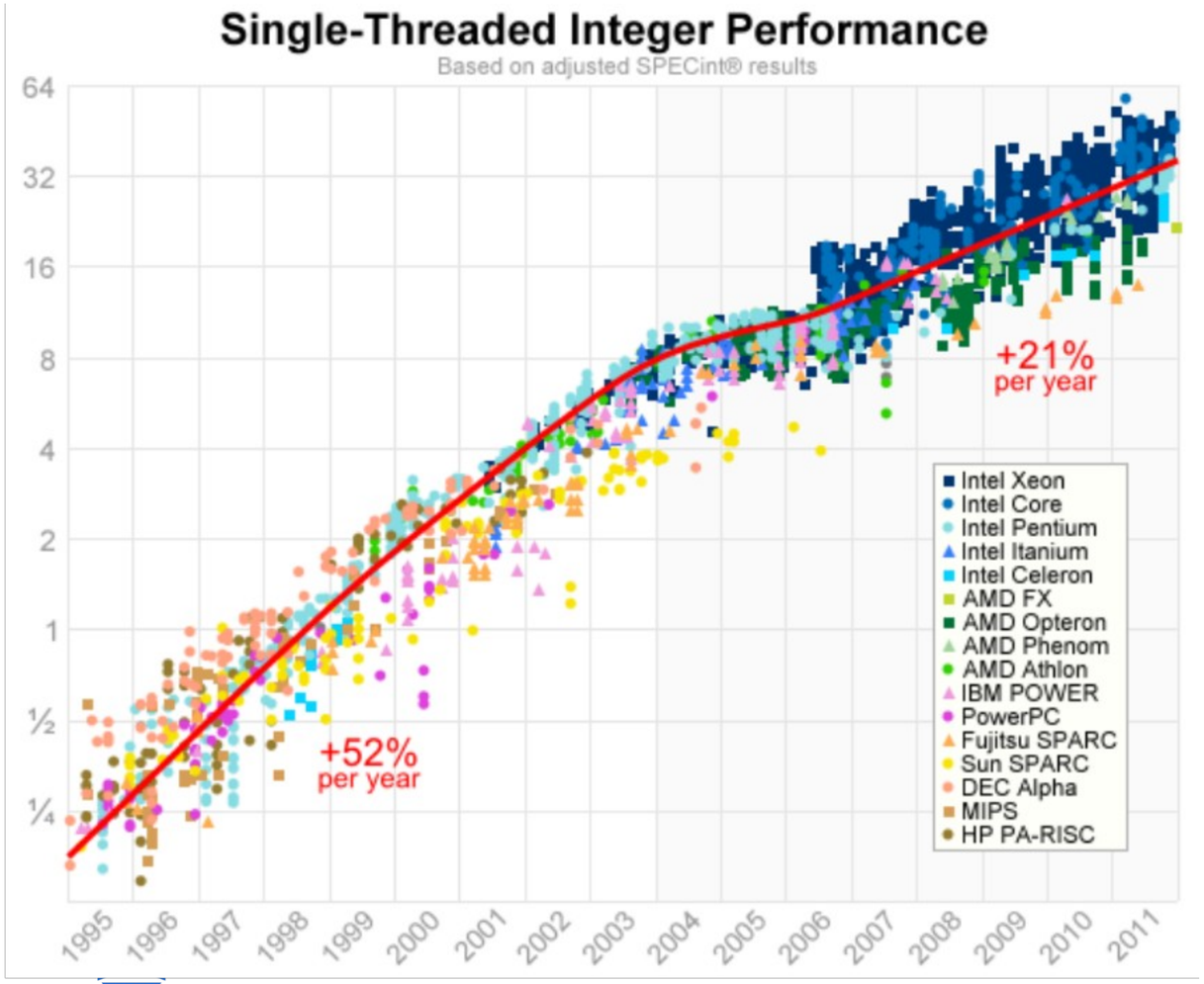
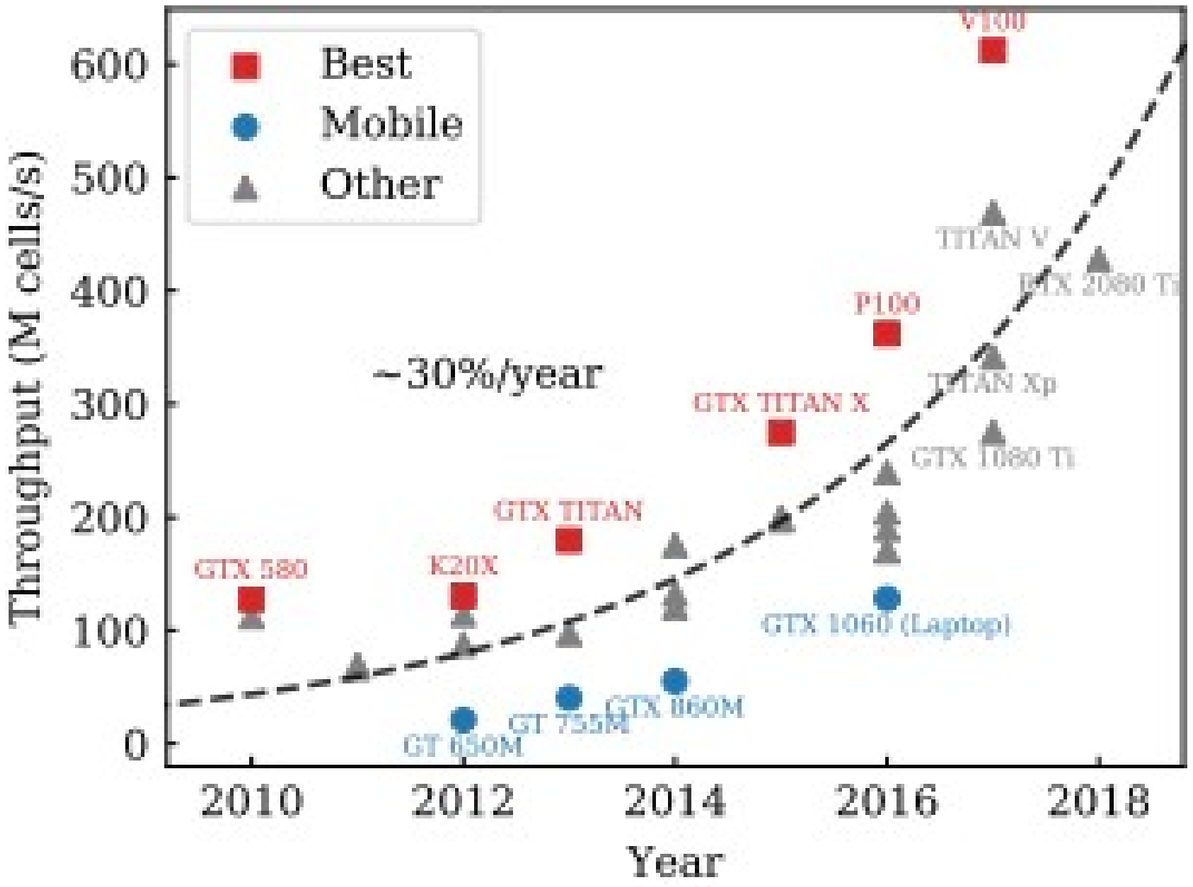
MuMax³ Performance





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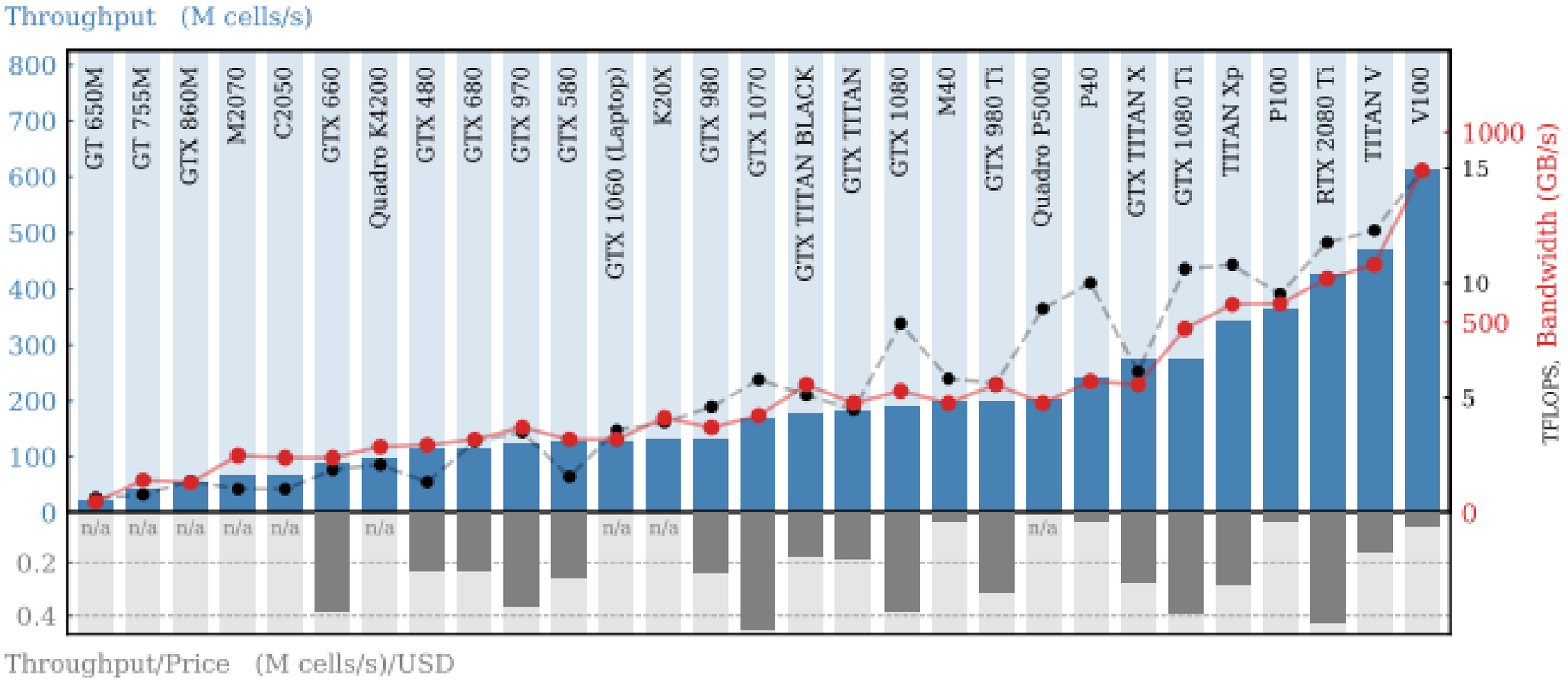
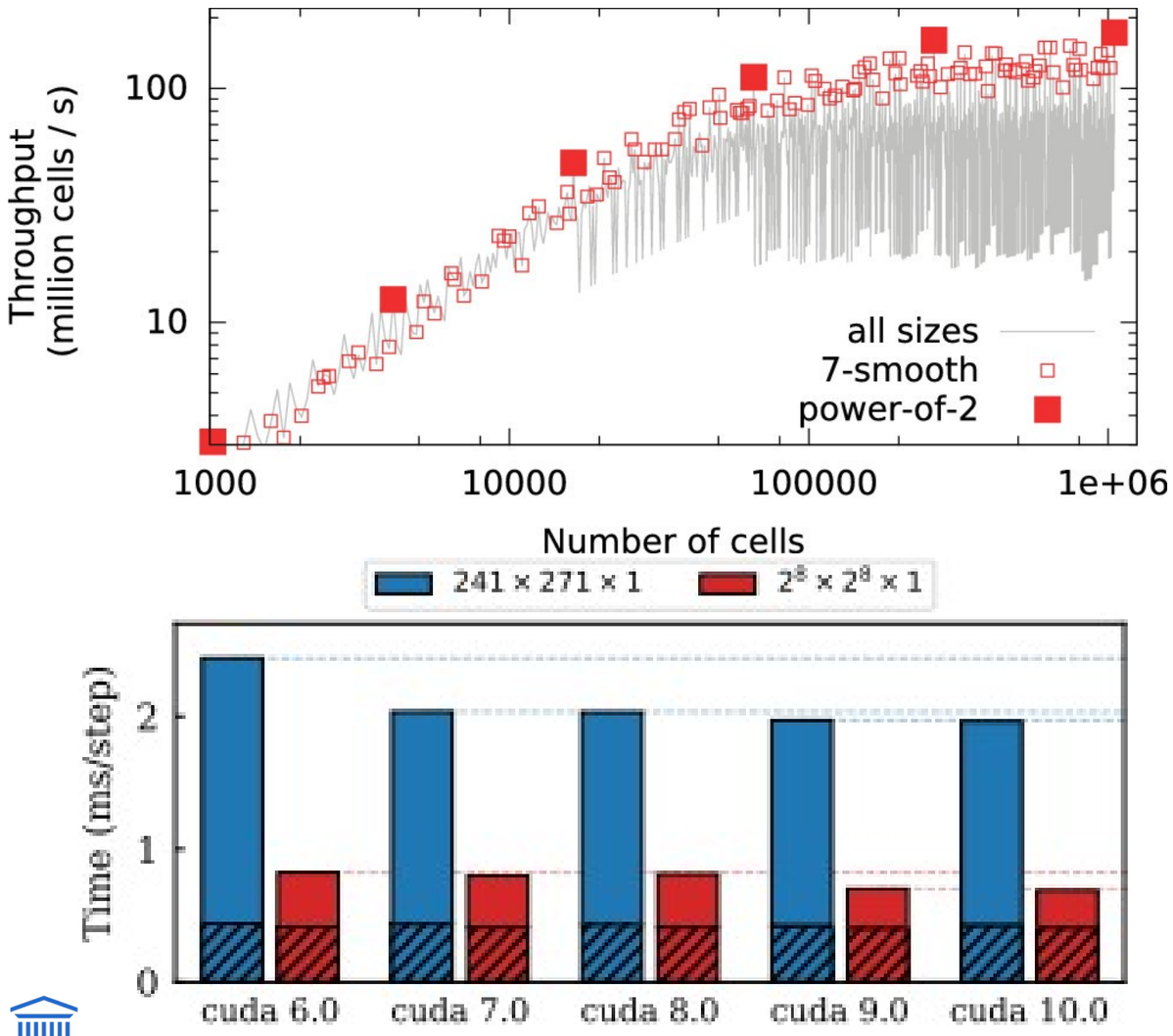
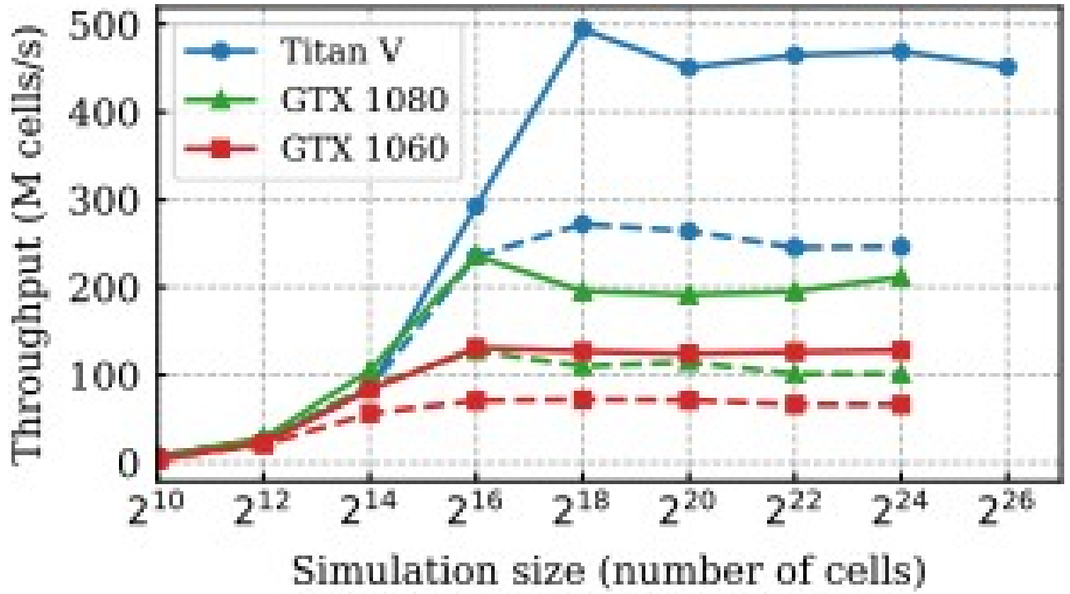
MuMax³ Performance



MuMax³ Performance





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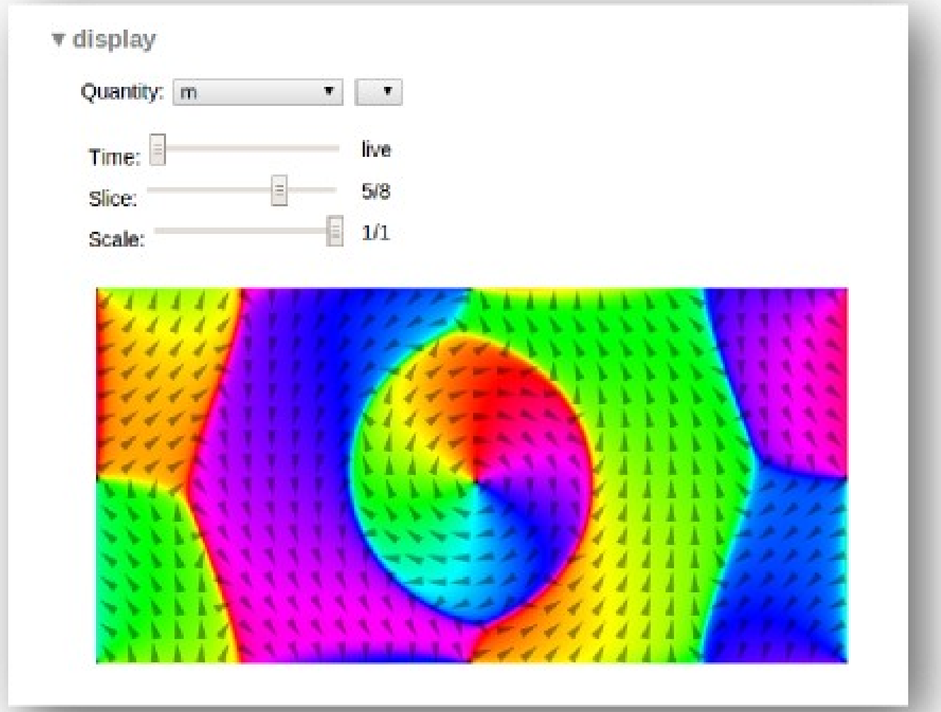
MuMax³: Examples and new features



- Interface
  - Web interface
  - Input files (also go)
  - OOMMF's OVF data format for input and output
    - can be converted with **mumax3-convert**
    - compatible with **MuView** (Graham Rowlands)

http://www.grahamerowlands.com/main/muview/

MuMax³: Examples and new features

- Geometry
  - Constructive solid geometry
  - Periodic boundary conditions

- middlesphere:=ellipsoid(D,D, D)
- spheres:=ellipsoid(D,D,D).**repeat**(xdist,ydist,zdist).**transl**(xtrans,ytrans,ztrans)
- xconnections:=cylinder(Diam,Length).**rotY**(pi/2).**repeat**(xdist,ydist,zdist).**transl**(xtrans,ytrans,ztrans)
- …
- atomium:=middlesphere.**add**(spheres).**add**(connections)

MuMax³: Examples and new features

- Geometry
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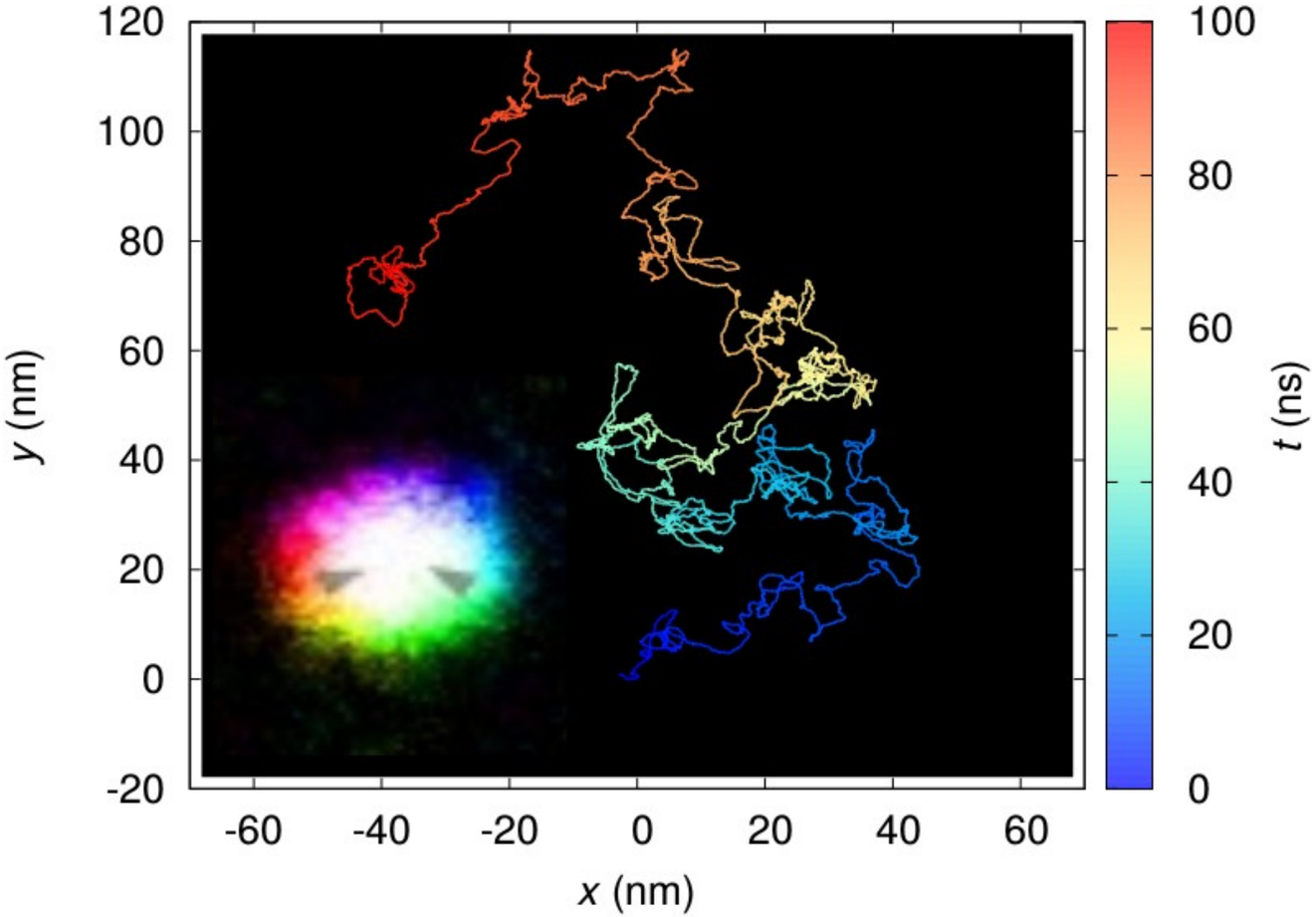
- …
- atomium:=middlesphere.**add**(spheres).**add**(connections)

MuMax³: Examples and new features

- Thermal diffusion of Skyrmions
  - Center bubble
  - Adaptive timestep

    @ nonzero temperature



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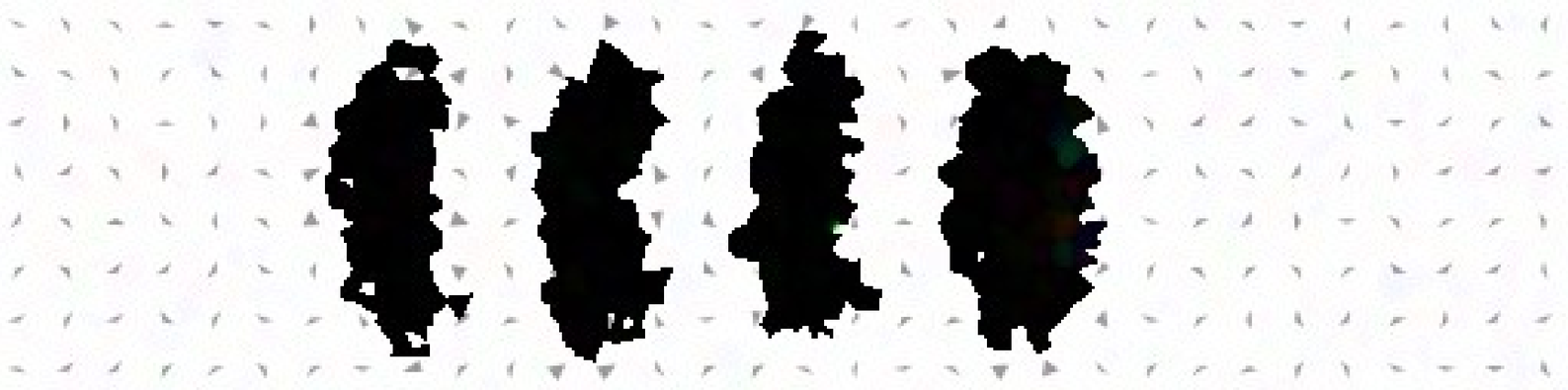
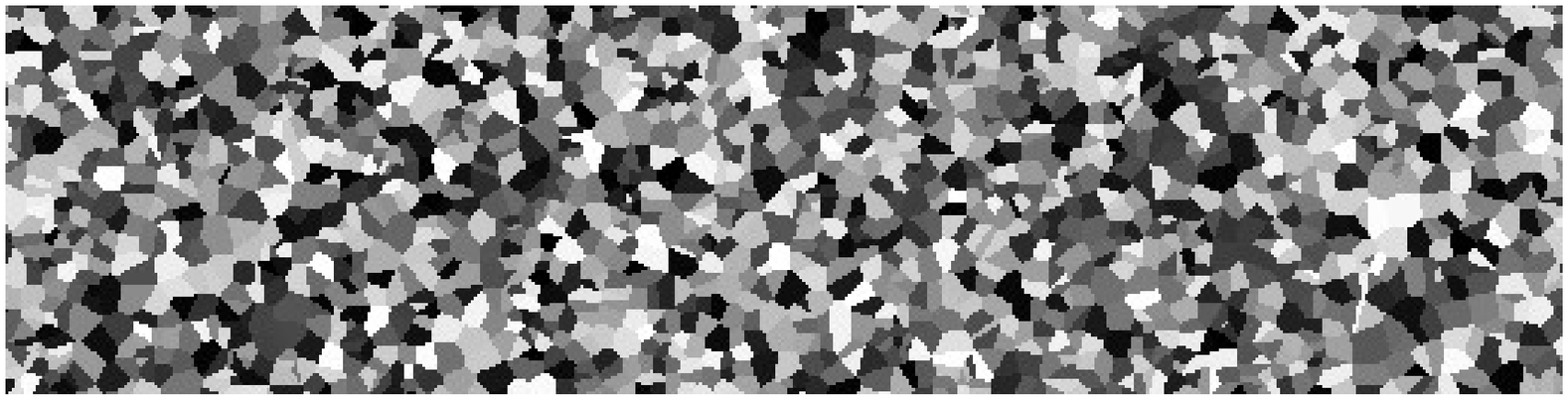
MuMax³: Examples and new features

- Extensions
- Moving simulation window
- Voronoi Tesselation
- Edge charge removal





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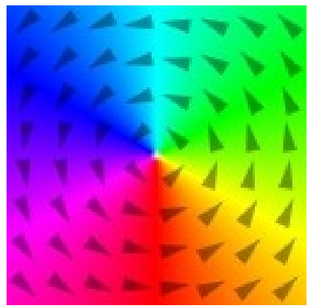
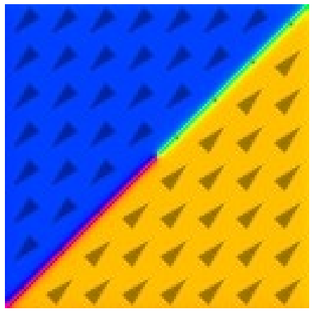
MuMax³: Examples and new features

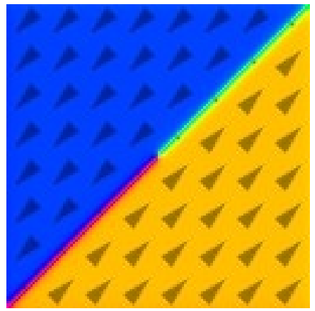
- Custom energy terms



```
Ku1 = 0.5e6
anisU=vector(1,1,0)
```

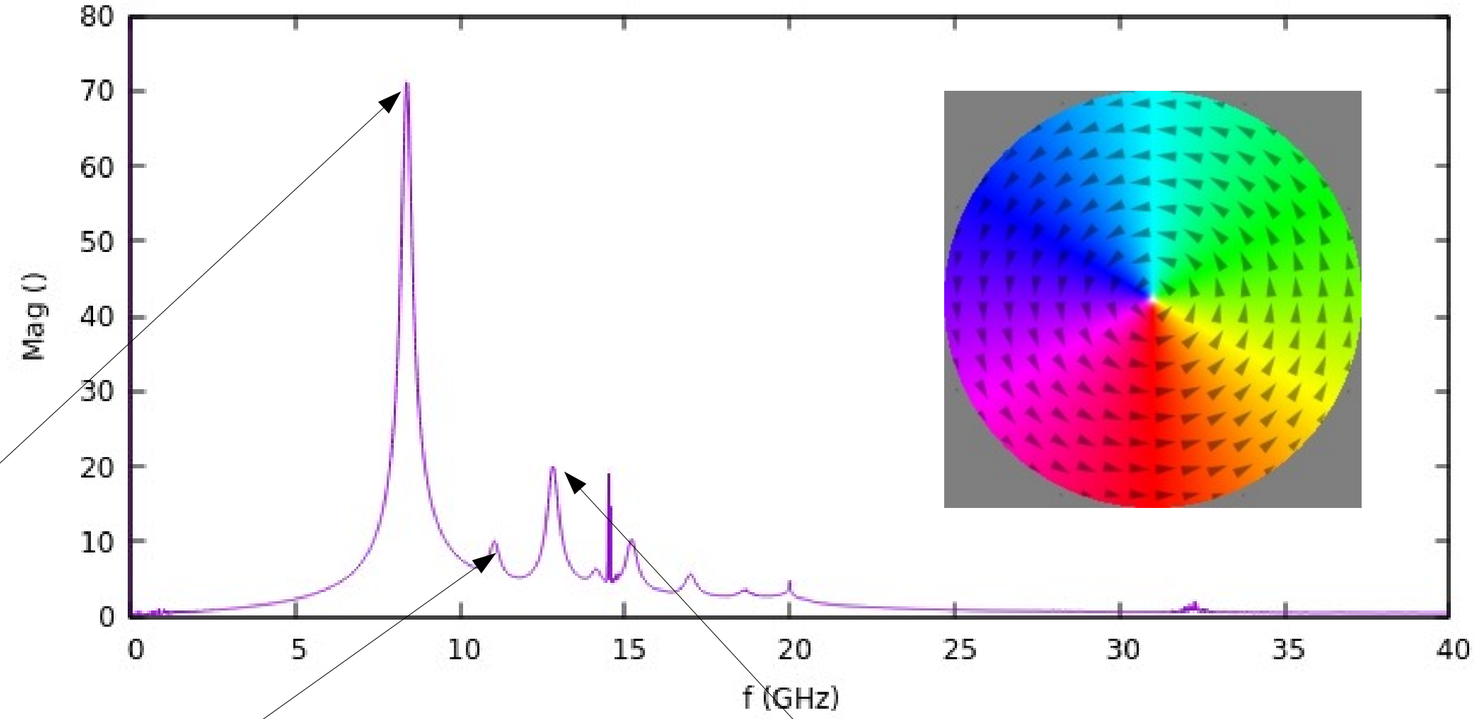
```
K := 0.5e6
u := ConstVector(1, 1, 0)

prefactor := Const( (2 * K) / (Msat.Average()))
MyAnis := Mul(prefactor, Mul( Dot(u, m), u))
AddFieldTerm(MyAnis)
```

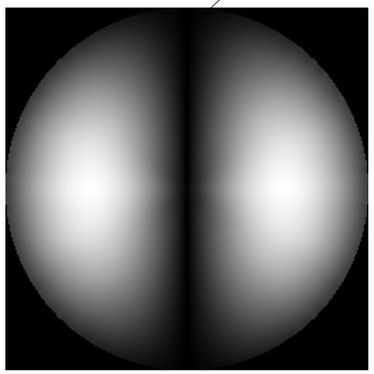


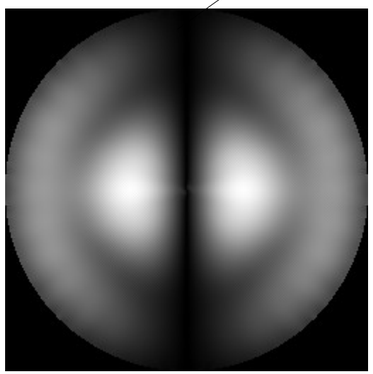


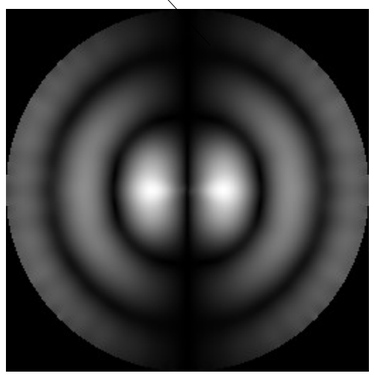
MuMax³: Examples and new features

- MuMax3-FFT



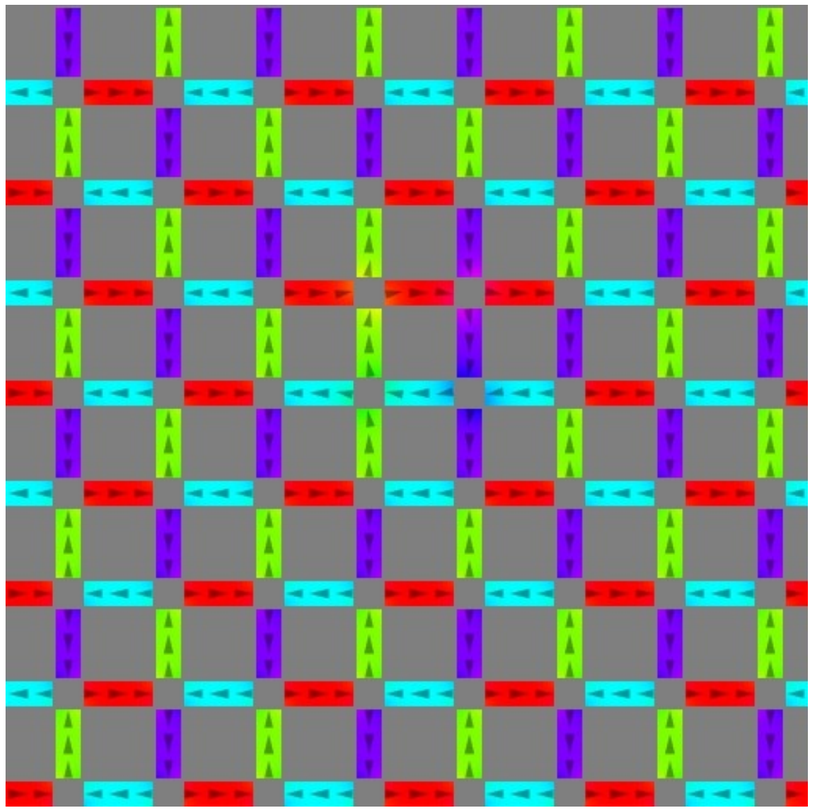


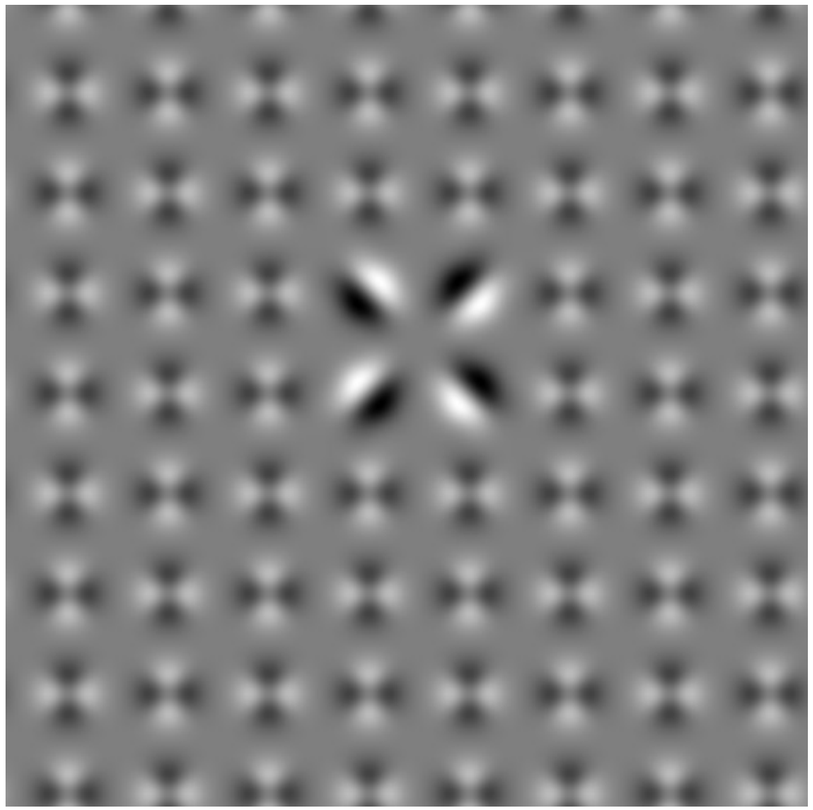




MuMax³: Examples and new features

- MFM image generation





MuMax³: Examples and new features

- MuMax3-Server

Running jobs

[monster3:35360/jonathan/inputfile1.mx3] [26s] [GUI] kill

Queue service

Users

jonathan 1 GPU-seconds has queued jobs
user2 1 GPU-seconds has queued jobs
user3 1 GPU-seconds has queued jobs
Next job for: jonathan

Jobs

Reload all (consider reloading just your own files).
Wake-up Watchdog (re-queue dead simulations right now).

jonathan

Jobs Reload (only needed when you changed your files on disk)

[jonathan/inputfile1.mx3] [.out] [rm] [monster3:35360] [] [26s]
[jonathan/inputfile2.mx3] [] [] [] [] []
[jonathan/inputfile3.mx3] [] [] [] [] []

user2

Jobs Reload (only needed when you changed your files on disk)

[user2/inputfile4.mx3] [.out] [rm] [baldur:35360] [] [25s]
[user2/inputfile5.mx3] [] [] [] [] []
[user2/inputfile6.mx3] [] [] [] [] []

user3

Jobs Reload (only needed when you changed your files on disk)

[user3/inputfile7.mx3] [.out] [rm] [baldur:35360] [] [25s]
[user3/inputfile8.mx3] [] [] [] [] []
[user3/inputfile9.mx3] [] [] [] [] []

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MuMax³: Examples and new features

- MuMax3-Server

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