MuMax^3

GPU-accelerated micromagnetism

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1. Intro micromagnetism
2. What is MuMax^3
3. How to use MuMax^3
4. Live Demo
5. Examples

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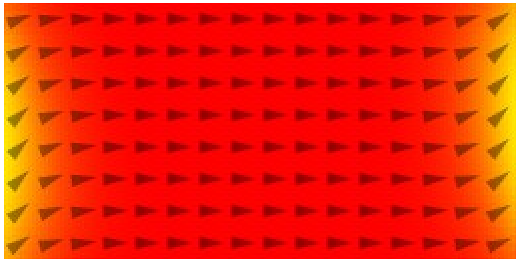
1. Micromagnetism

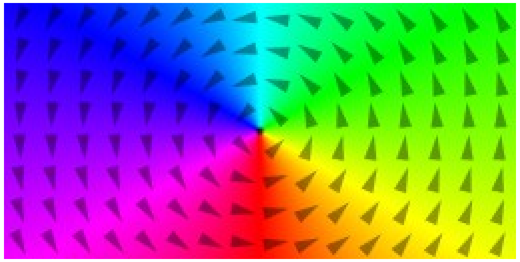
Magnetisation described by a continuous vector field

$$\bar{M}(\bar{r},t)=M_{sat}\bar{m}(\bar{r},t)$$

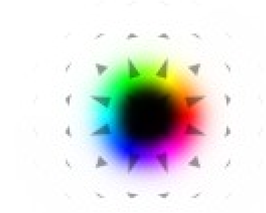
on the picosecond time scale and submicrometer length scale



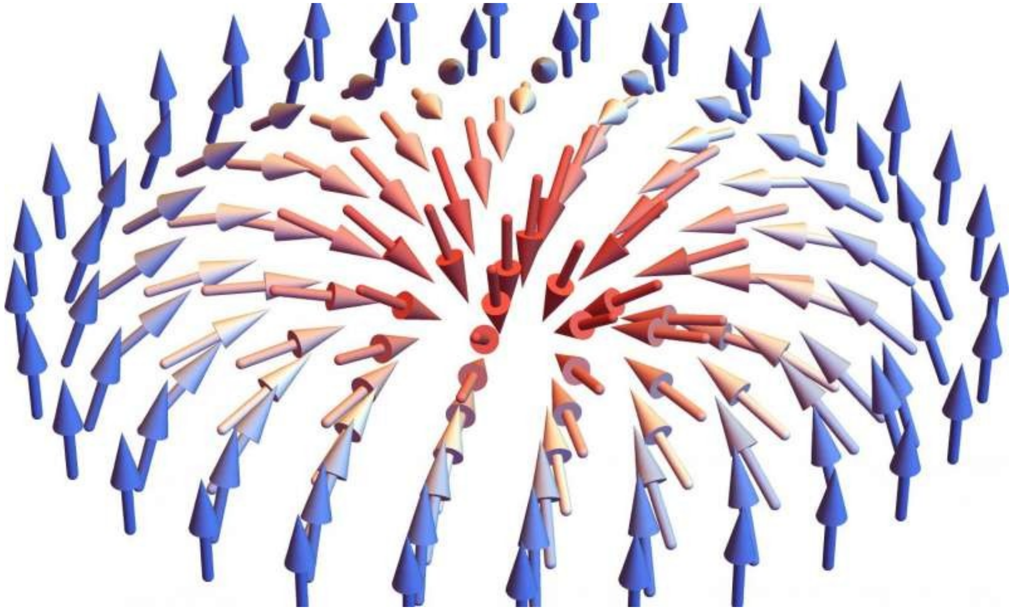
Quasi-uniform state



Vortex



Néel Skyrmion



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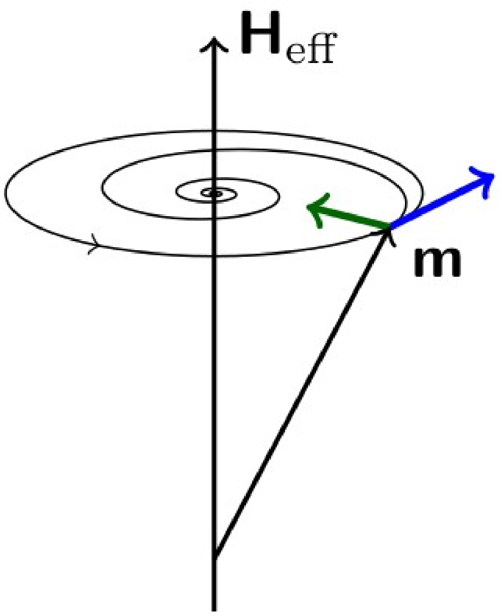
1. Micromagnetism



Magnetization in continuum approx.

$$\mathbf{M}(x, y) = M_{\text{sat}}\mathbf{m}(x, y)$$

Local effective field

$$\mathbf{H}_{\text{eff}} = -\frac{\delta E_{free}}{\delta \mathbf{m}}$$

Landau-Lifshitz-Gilbert equation for dynamics

$$\dot{\mathbf{m}} = -\frac{\gamma}{1+\alpha^2}\left[\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha\, \mathbf{m} \times (\mathbf{m} \times \mathbf{H}_{\text{eff}})\right]$$

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1. Micromagnetism

Interactions present in MuMax^3

In effective field:

- Exchange interaction
- Anisotropy
- Zeeman interaction
- Demagnetization
- Interfacially induced DMI
- Bulk DMI
- Thermal field
- Custom interaction

Extra LLG terms:

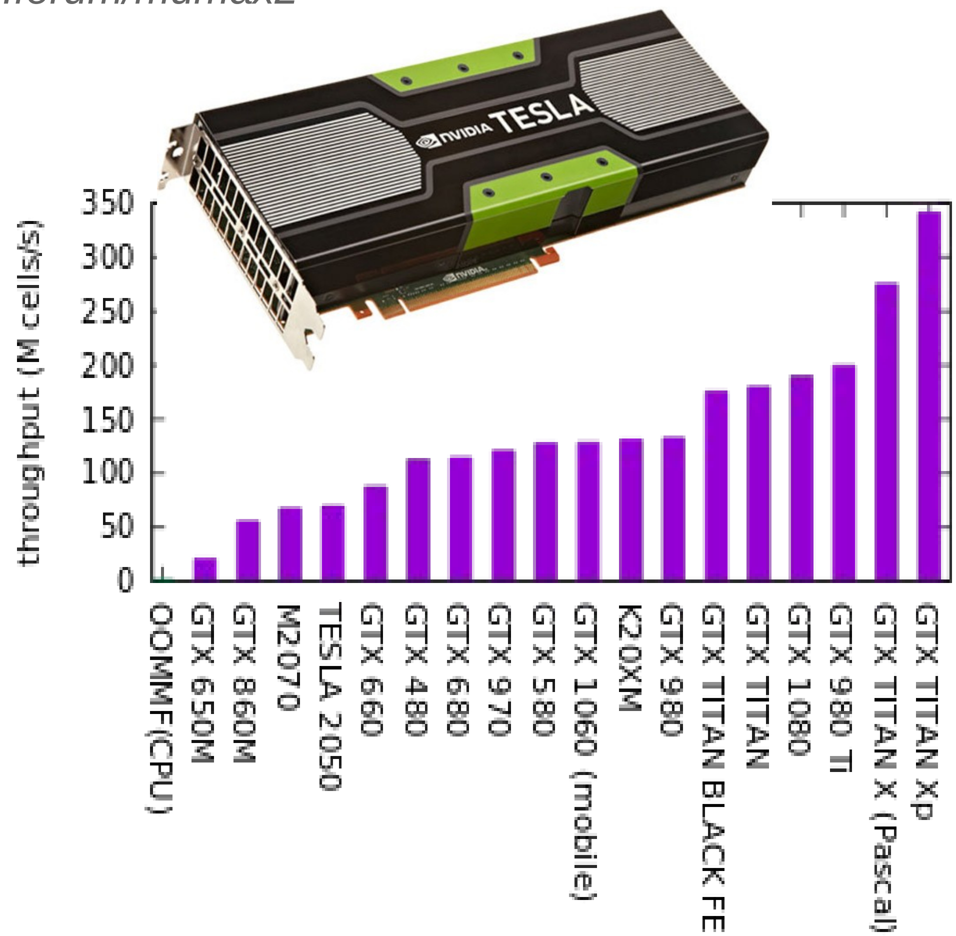
- Spin transfer torques

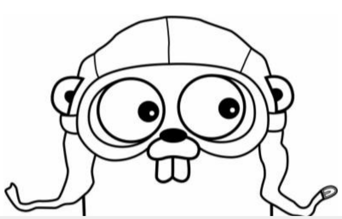
Not (yet) in MuMax^3

- Magnetoelastic effects
- ...

2. What is MuMax^3

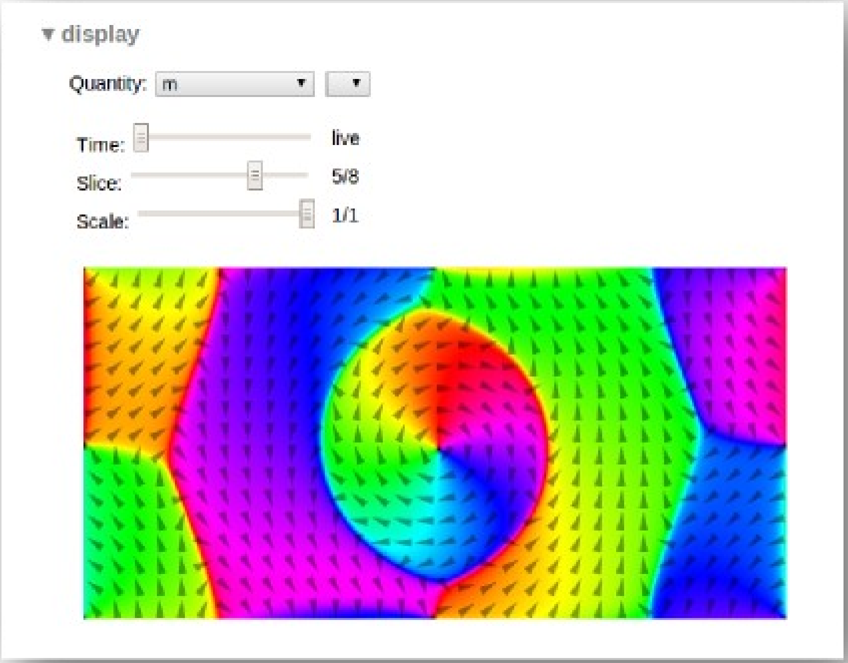
- Finite-difference based micromagnetic simulation package
- Developed at DyNaMat (UGent) by Arne Vansteenkiste
- Active community *groups.google.com/forum/#!forum/mumax2*
- Well documented *mumax.github.io*
- Open source (GPLv3) *github.com/mumax/3*
- Mainly written in golang
- CUDA C kernels for heavy lifting





3. How to use MuMax^3

- Web interface with Mumax^3 running locally or remotely
- MuMax^3 scripting language
- Golang program `import github.com/mumax/3/engine`




```
setgridsize(128, 32, 4)
setcellsize(5e-9, 5e-9, 5e-9)
Msat = 860e3
Aex  = 13e-12
alpha= 0.2
m=uniform(1, 1, 0)

f := 1e9  // 1GHz
A := 0.01 // 10mT
B_ext = vector(0.1, A*sin(2*pi*f*t), 0)

run(10e-9)
```

3. How to use MuMax^3

Basic concepts

- **Scripting**
- Grid and cells
- Shapes
- Regions
- Output
- Run/Minimize

- MuMax^3's scripting language is subset of golang
- MuMax^3 scripts have the .mx3 file extension

```
// saturation magnetisation
Msat = 5e6

// declare new variable
Freq := 1e9

// External time dependent field
B_ext = vector(0,0,0.1*sin(2*pi*Freq*t))

for ( i:=0; i<10; i++){
     print(i)
}

if 1+8 == 9 {
     print("Of course 1+8=9")
}
```

3. How to use MuMax3:
Basic concepts

- Scripting
- **Grid and cells**
- Shapes
- Regions
- Output
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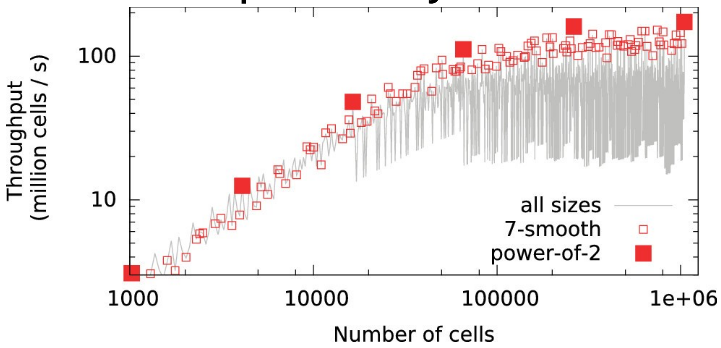
- MuMax3 uses finite differences on a regular rectangular grid
- Single magnetic moment in every cell (possibly zero)
- Grid dimensions preferably 2^n



- Cell size < exchange length
- PBC values are number of virtual repetitions of the simulation box used to calculate dipolar interactions

```
setcellsize(4e-9,4e-9,4e-9)
setgridsize(128,64,4)
setpbc(2,4,0)
```

2. What is MuMax^3

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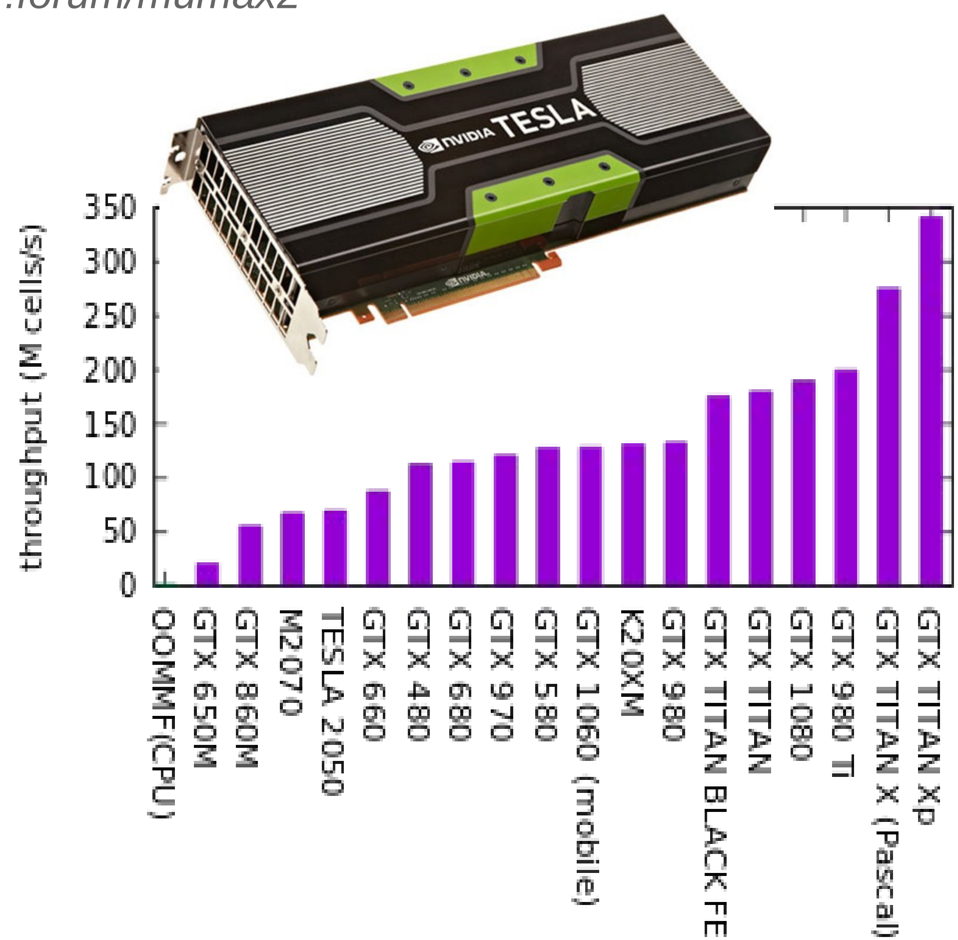


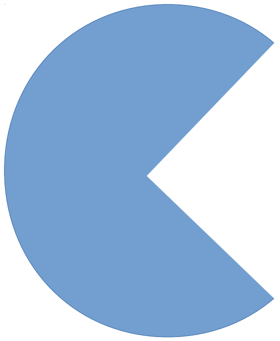
3. How to use MuMax^{3}:

Basic concepts

- Scripting
- Grid and cells
- **Shapes**
- Regions
- Output
- Run/Minimize

- Does not depend on the grid
- Default location: center of universe (0,0,0)
- Object methods to translate, rotate, add, intersect, …

```
myCirc := circle(100e-9)
myRect := rect(60e-9,60e-9).rotZ(pi/4).transl(30e-9,0,0)
pacman := myCirc.Sub(myRect)
```



- To outline the geometry of your magnet: `setgeom(pacman)` sets magnetization to zero in cells outside the shape

3. How to use MuMax^3

Basic concepts

- Scripting
- Grid and cells
- Shapes
- **Regions**
- Output
- Run/Minimize

- Each cell is assigned to a single region
- 256 regions in total (index 0→ 255)
- Each region can have its own set of material parameters
- A region can be defined by a shape

```
// Circular region with large Msat
Msat = 500e3 //  A/m
myCirc := circle(20e-9)
Defregion(1,myRect)
Msat.setRegion(1,1000e3)
```

3. How to use MuMax^{3}:

Basic concepts

- Scripting
- Grid and cells
- Shapes
- Regions
- **Output**
- Run/Minimize

3 output media:

- log file for input, logging and printing
- table.txt (t, mx, my, mz, …)

```
tableadd(E_total)
tableaddvar(myVar,"myVar","unit")
tablesave() // write single line
tableautosave(1e-12) // write periodically
```

- .ovf files voor scalar and vector fields

```
save(Edens_total)
saveas(Edens_total,"edens.ovf")
autosave(Edens_total 1e-10) // write perdiodically
```

3. How to use MuMax3:
Basic concepts

- Scripting
- Grid and cells
- Shapes
- Regions
- Output
- **Run/Minimize**

Most important solver settings

```
SetSolver(5) // 5th order Dormand-Prince
fixdt = 1e-14 // if 0: adaptive
```

Solve LLG equation for certain period of time, number of steps, or until condition is met

```
run(time)
steps(100)
runWhile(condition)
```

Relaxation using LLG without precession term

```
relax()
```

Steepest gradient method to minimize the energy

```
minimize()
```

4. Live demo

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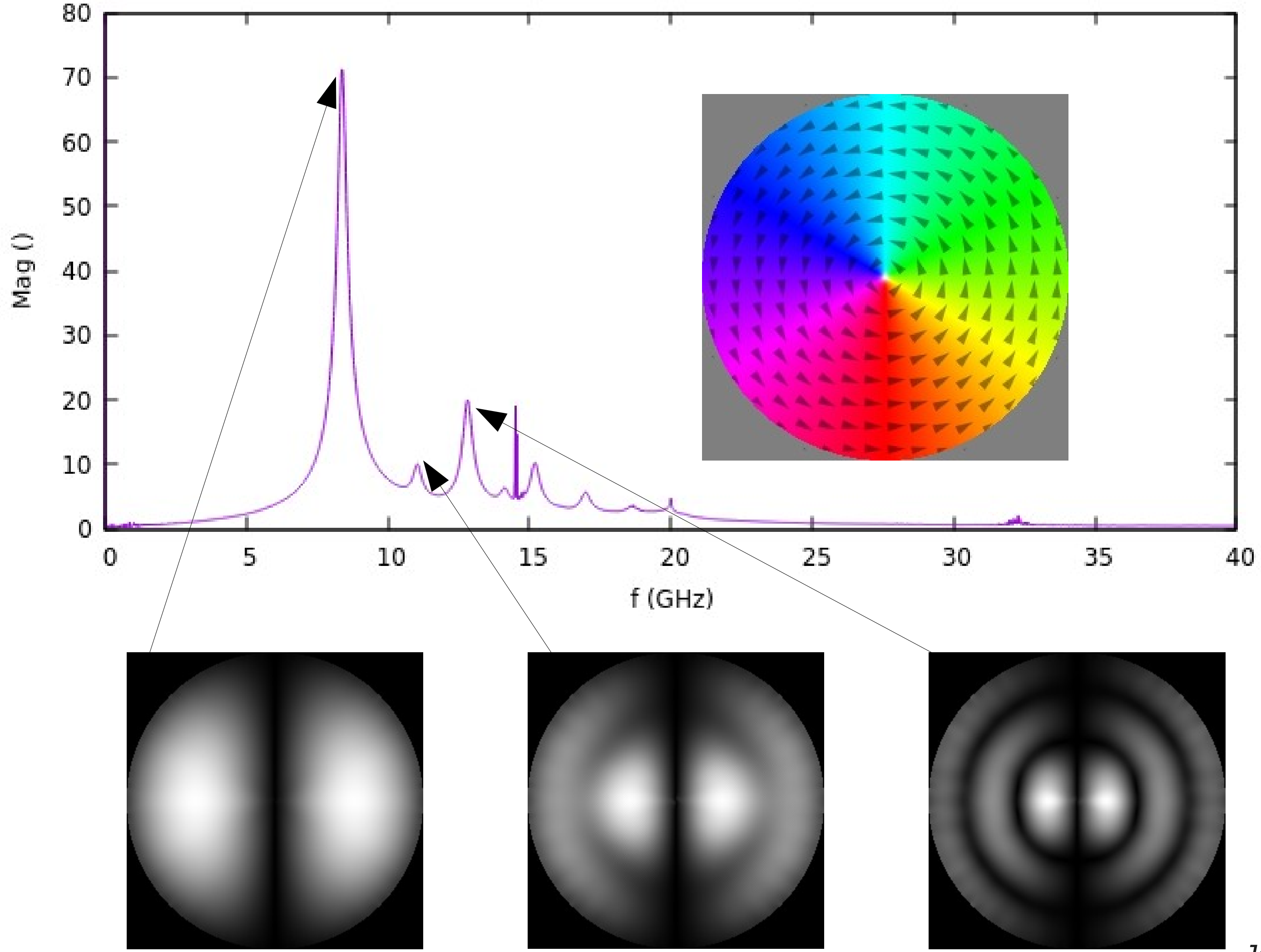
5. Examples
vortex eigenmodes

Mumax3-fft for time→frequency Fourier transform



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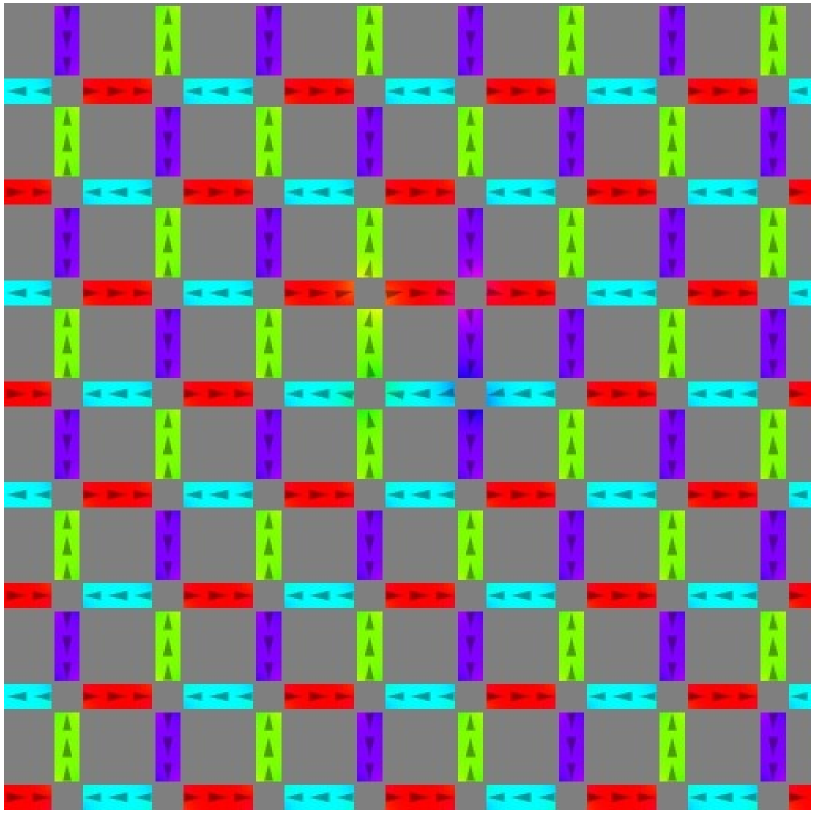
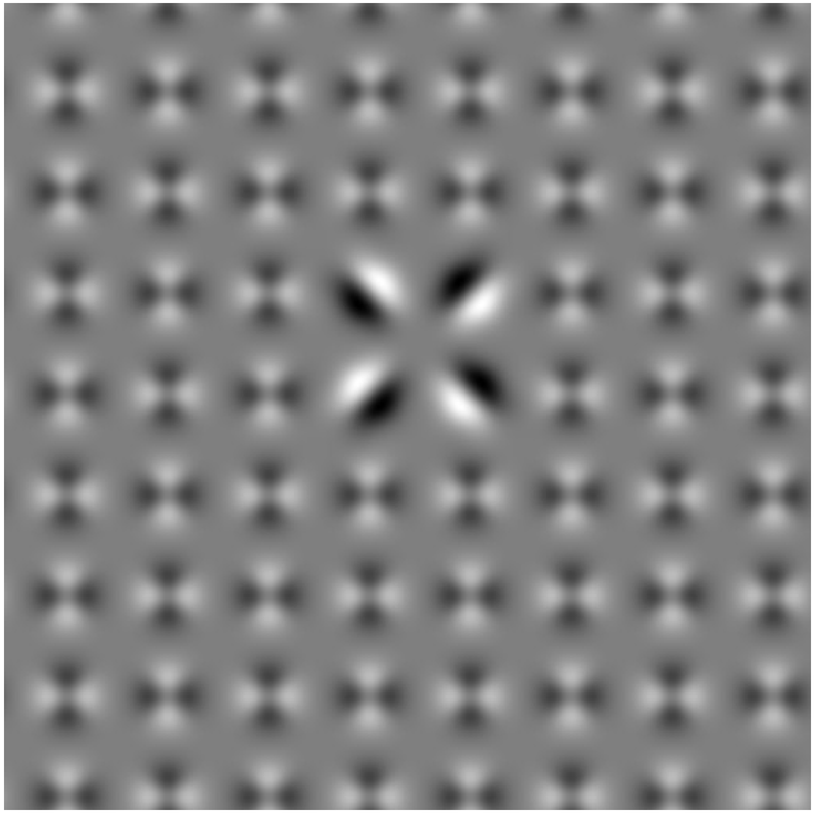
5. Examples
Artificial spin ice



MFM image generation



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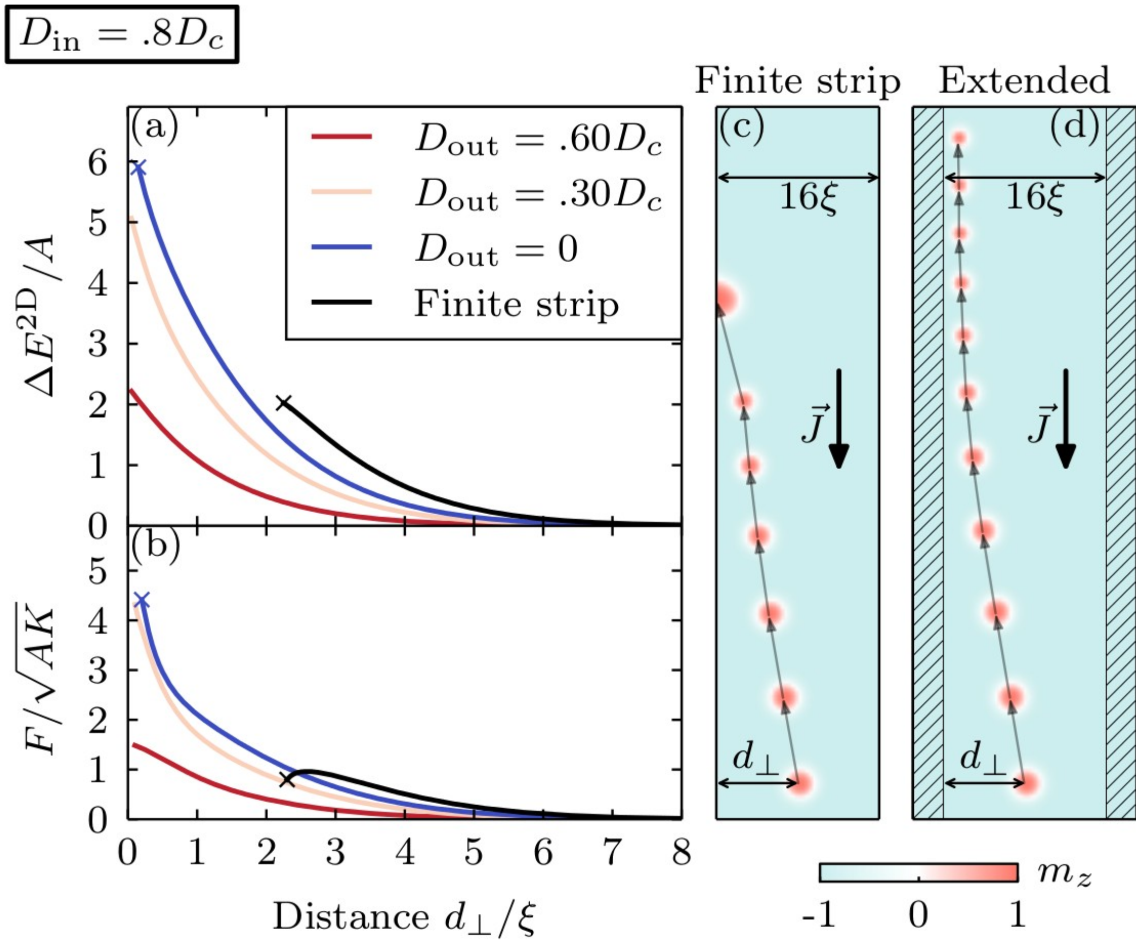
5. Examples
Skyrmion racetrack

- Moving skyrmion due to STT
- Spatially dependent interfacially induced DMI



J. Mulkers, *et al*, Phys. Rev. B 95, 144401 (2017)

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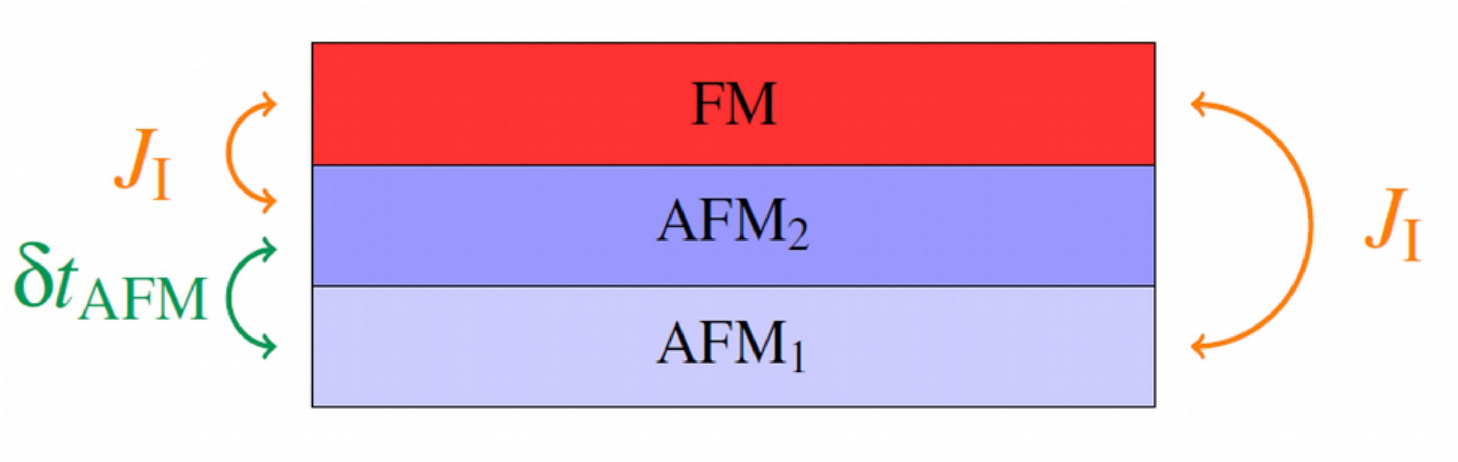
5. Examples
Modelling exchange bias

- Define custom interaction (in script) for a negative exchange coupling between layers to create a compensated antiferromagnet



J. De Clercq, et al., Journal of Physics D: Applied Physics 49.43 (2016).
J. De Clercq, et al., arXiv:1704.04030 (2017).

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Any questions?

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