# Micromagnetic Calculation of the High Frequency Dynamics of Nano-Size Rectangular Ferromagnetic Stripes

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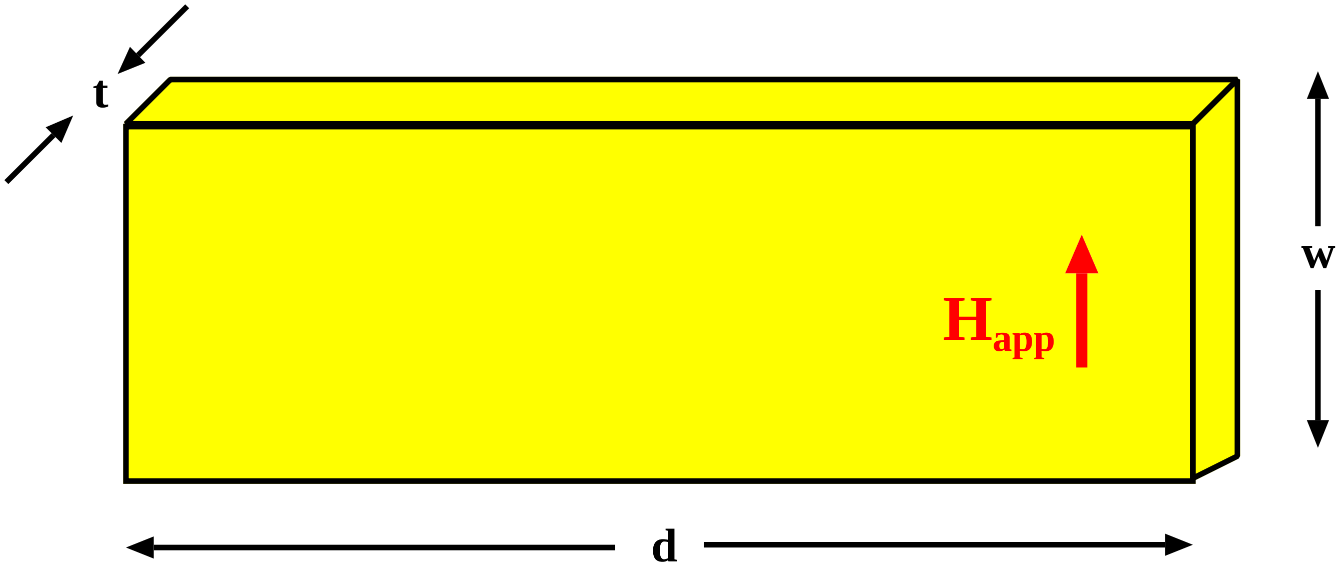
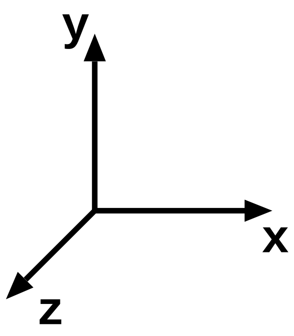
# Simulation Schematic



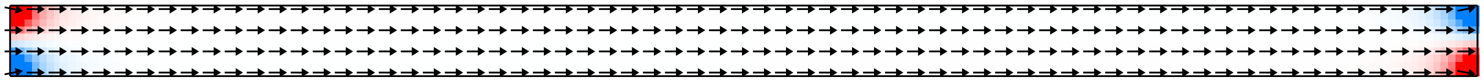

**d = 1000 nm (varies)**

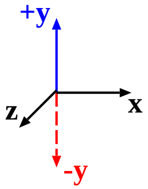
**w = 50 nm (varies)**

**t = 5 nm**

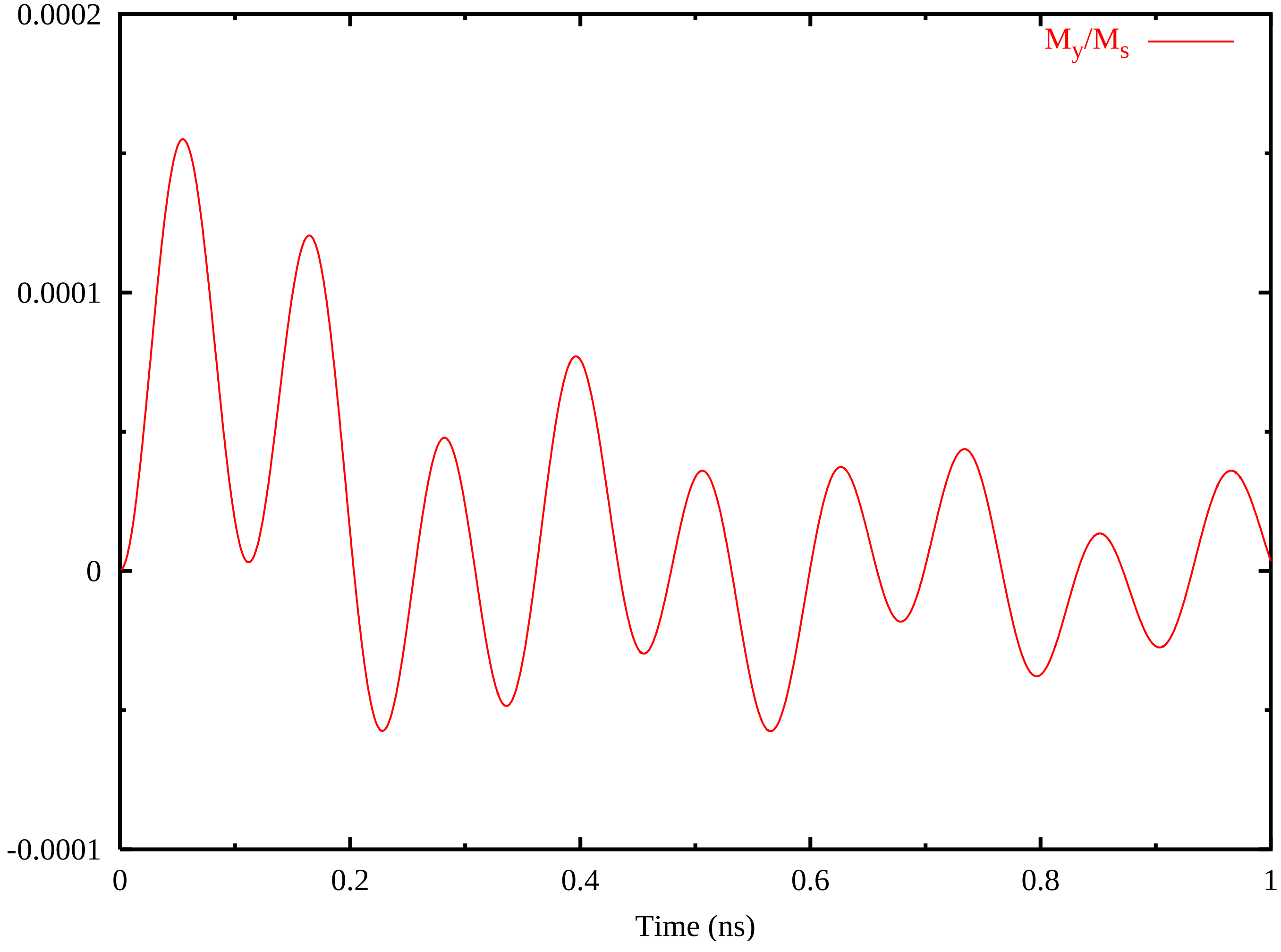
**Permalloy parameters**

# Remanent State





# Time Series Response



# High Frequency Susceptibility

Define susceptibility $\chi$ by

$$< \mathbf{M}(t) > \cdot \mathbf{u} = \int_{-\infty}^{+\infty} \chi(t-t')[\mathbf{h}(t') \cdot \mathbf{u}]dt',$$

or in Fourier domain

$$M(t) = \chi(t) \star h(t) \leftrightarrow M(\omega) = \chi(\omega) \cdot h(\omega).$$

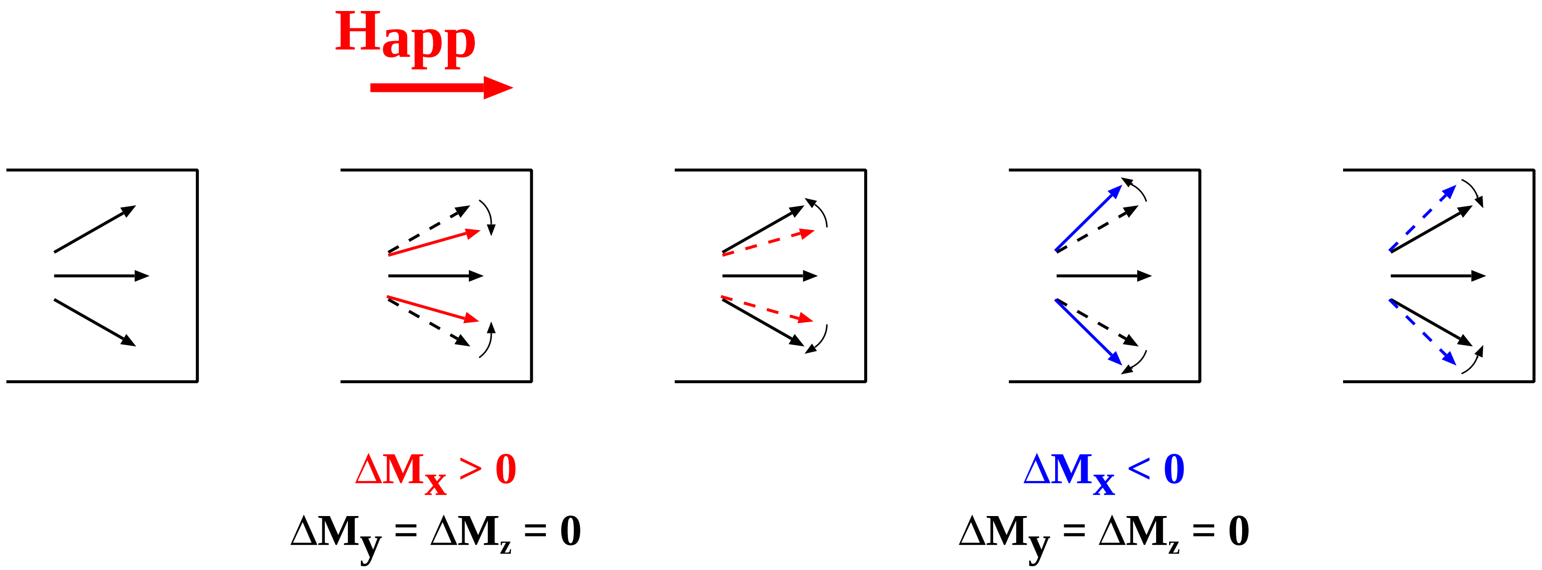
In the following we use

$$h(t) = 1_{[0,\infty]} Ce^{-7.675t} \leftrightarrow h(\omega) = \frac{C}{7.675 + 2\pi i\omega}$$

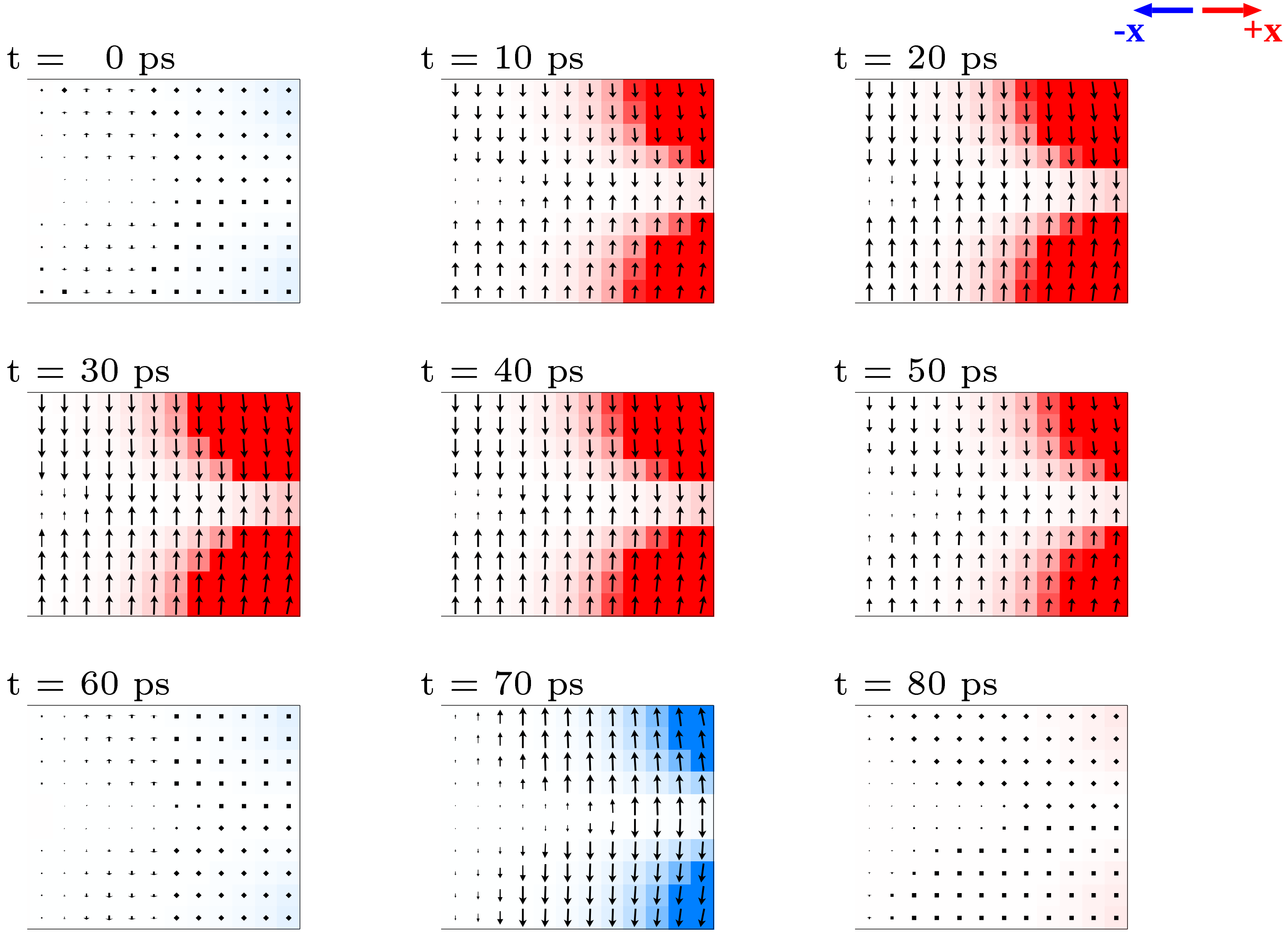
where

$$\begin{aligned} C &= 7.96 \text{ A/m } (= 0.1 \text{ Oe}), \\ t &\text{ in ns}, \\ \omega &\text{ in GHz}. \end{aligned}$$

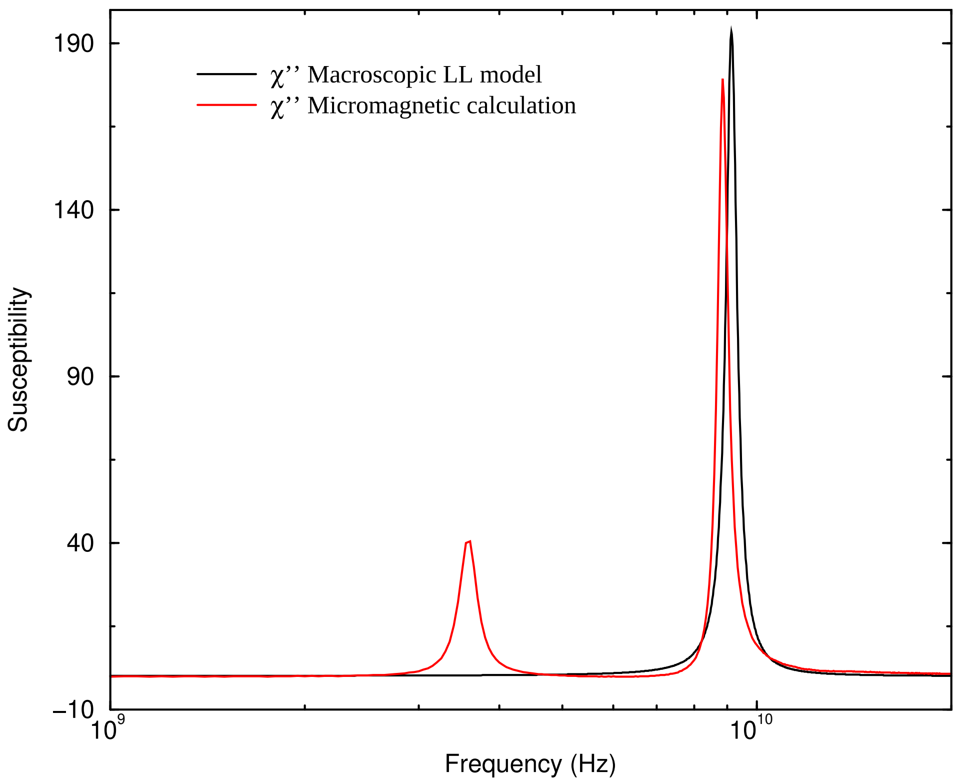
# “Breathing” mode, $x$-excitation



# $\mathbf{M}[t] - \mathbf{M}_{\text{remanence}}$, $x$-excitation



# Rotational modes, $y$-excitation

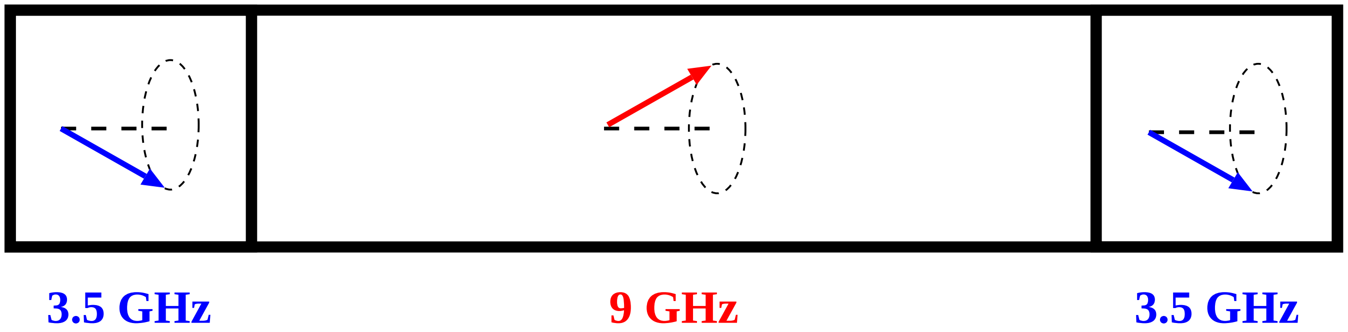



Permalloy stripe, 1 $\mu$m $\times$ 50 nm $\times$ 5 nm.

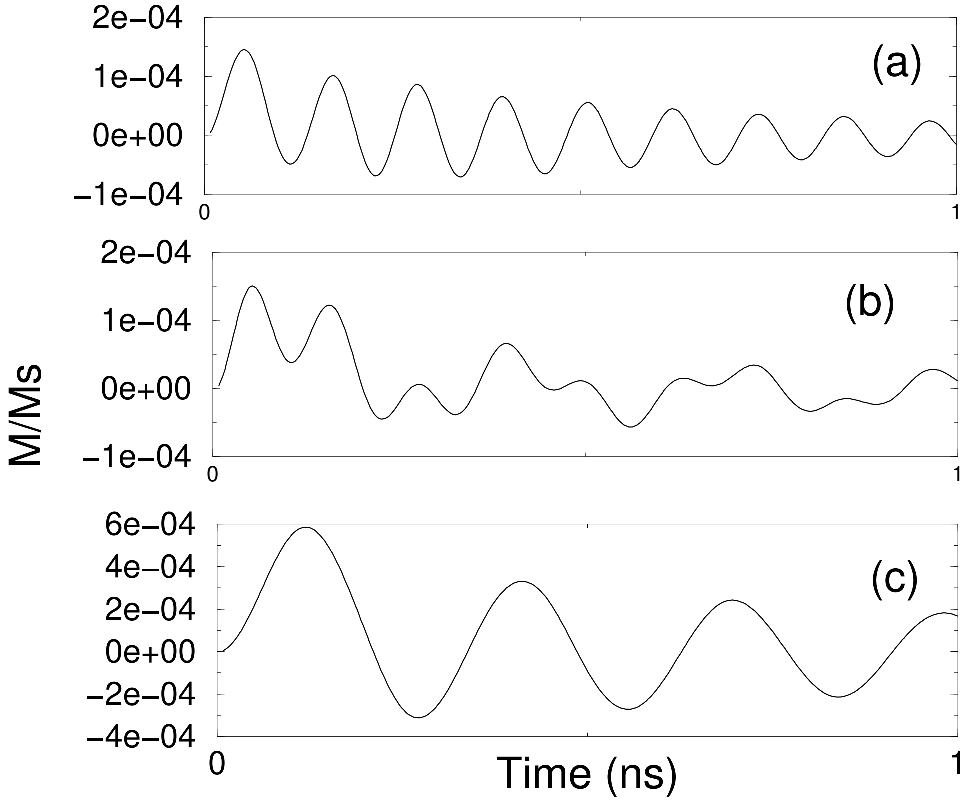
Black: uniform magnetization model.

Red: micromagnetic simulation.

# Simple Three Domain Model



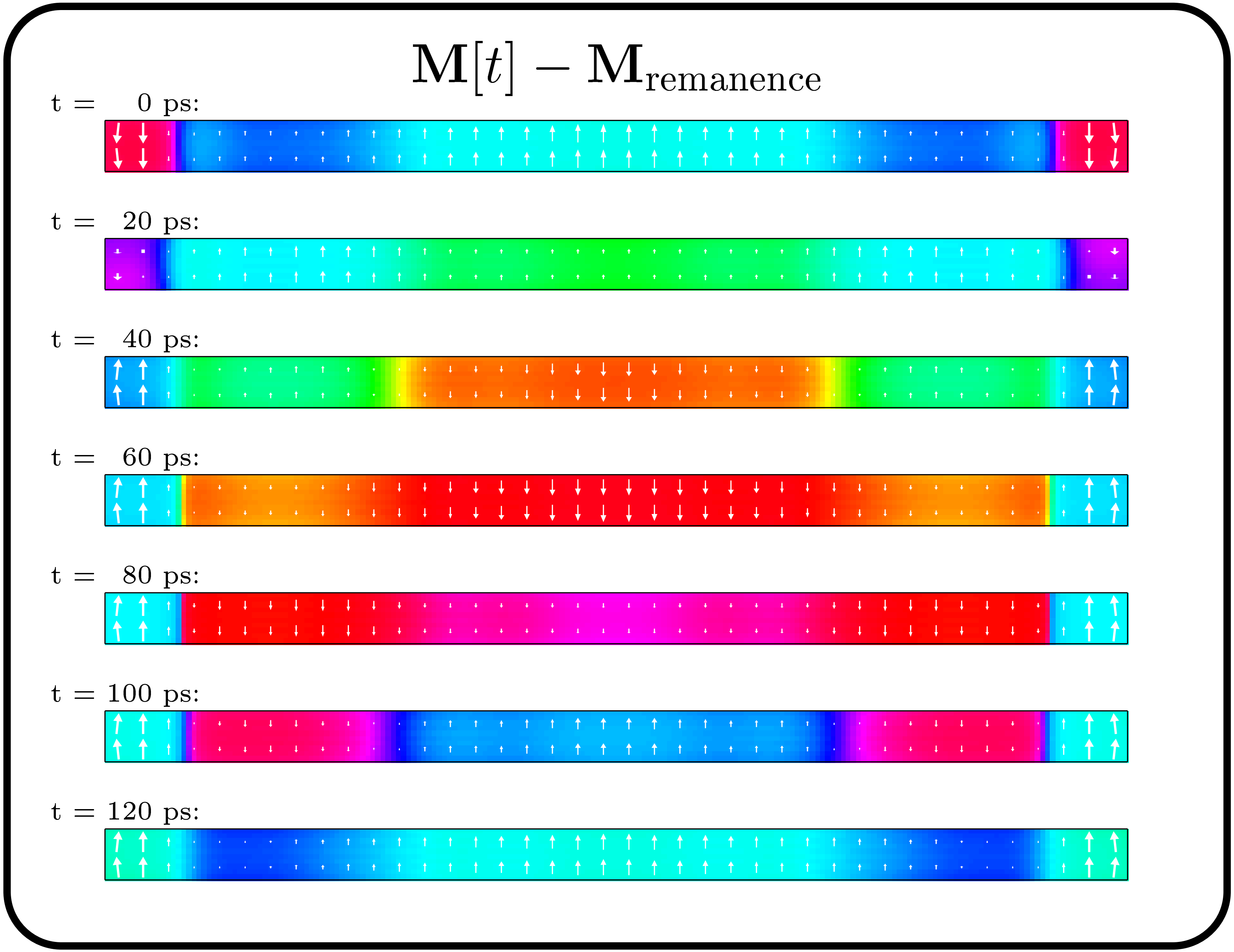
# Single Spin Dynamics



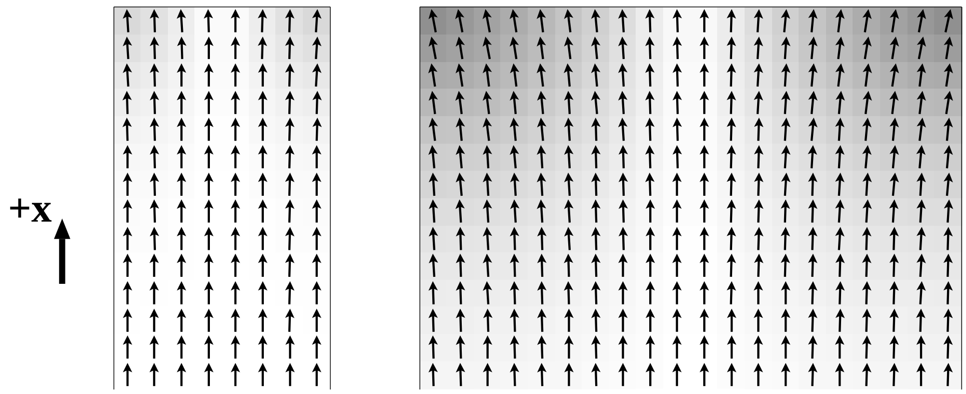

(a) Center spin

(b) Intermediate spin

(c) End spin

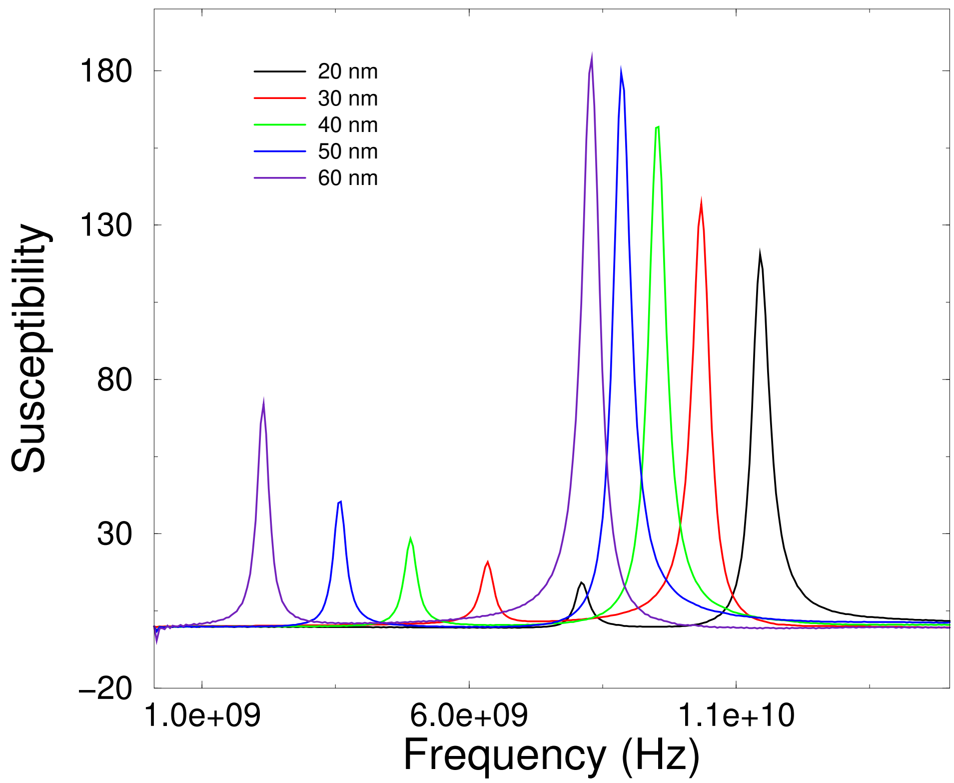

$\mathbf{M}[t] - \mathbf{M}_{\text{remanence}}$
t = 0 ps:
t = 20 ps:
t = 40 ps:
t = 60 ps:
t = 80 ps:
t = 100 ps:
t = 120 ps:

# Stripe Width Effects

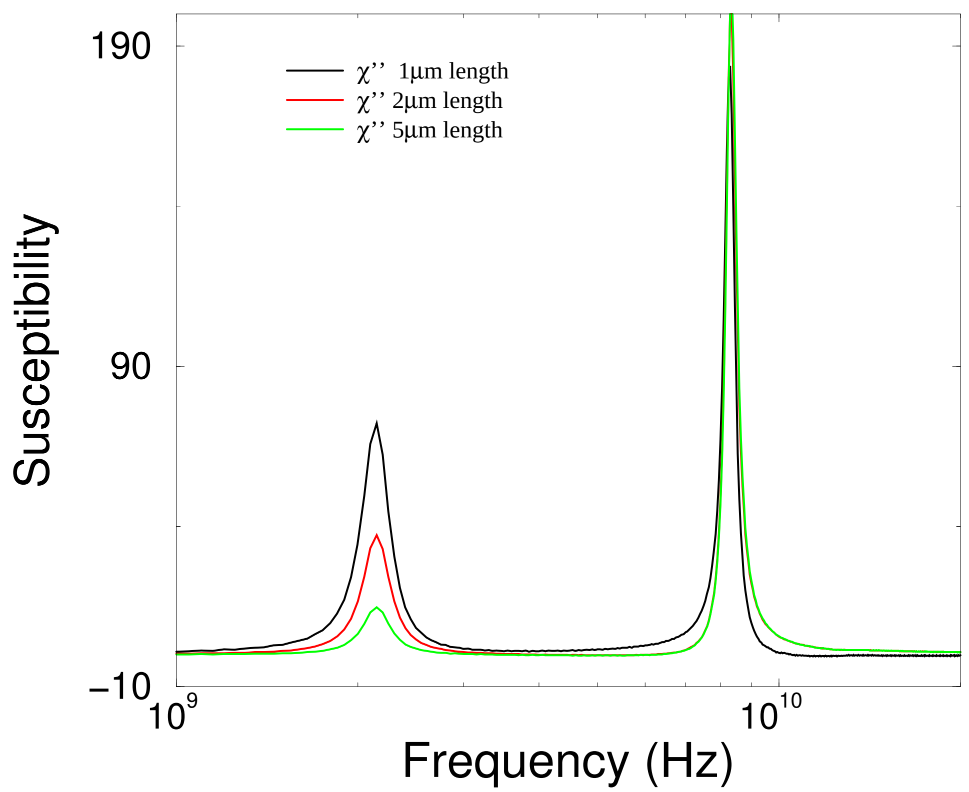



20 nm

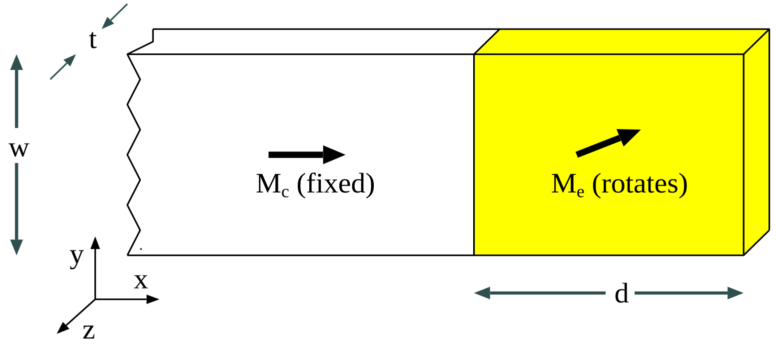
50 nm



# Stripe Length Effects



# Simple Edge Spin Model




$$H_{\text{exch}} = \left(2A/(\mu_0 M_s d^2), 0, 0\right)$$

$$H_{\text{demag}} = (-N_x M_x/2, -N_y M_y, -N_z M_z)$$

Then

$$\text{Freq} = \frac{\gamma M_s}{2\pi}\sqrt{\left(\frac{2A}{\mu_0 M_s^2 d^2} - \frac{N_x}{2} + N_y\right)\left(\frac{2A}{\mu_0 M_s^2 d^2} - \frac{N_x}{2} + N_z\right)}$$

where

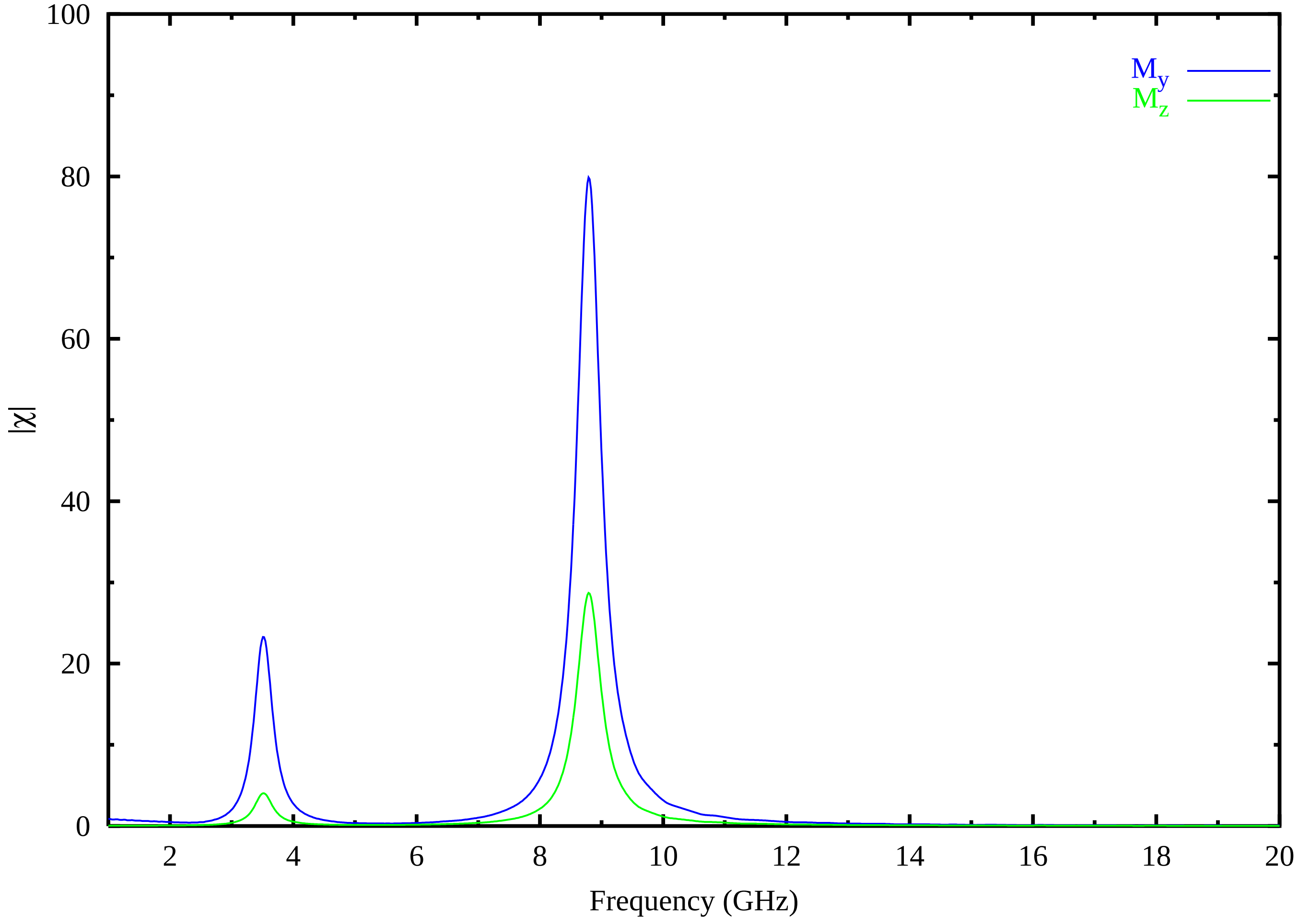
$$d \approx 4\, l_{\text{ex}} = 4\sqrt{2A/\mu_0 M_s^2}$$

# Simple Model Results

| Part width (nm) | Frequency (GHz) | $N_x$ | $N_y$ | $N_z$ |
|---|---|---|---|---|
| 20 | 9.6 | 0.00422 | 0.229 | 0.767 |
| 30 | 7.8 | 0.00481 | 0.173 | 0.822 |
| 40 | 6.5 | 0.00524 | 0.141 | 0.854 |
| 50 | 5.4 | 0.00558 | 0.120 | 0.875 |
| 60 | 4.5 | 0.00585 | 0.104 | 0.890 |

$$\mathrm{Freq} = \frac{\gamma M_s}{2\pi}\sqrt{\left(\frac{2A}{\mu_0 M_s^2 d^2} - \frac{N_x}{2} + N_y\right)\left(\frac{2A}{\mu_0 M_s^2 d^2} - \frac{N_x}{2} + N_z\right)}$$

# Susceptibility: Other Components



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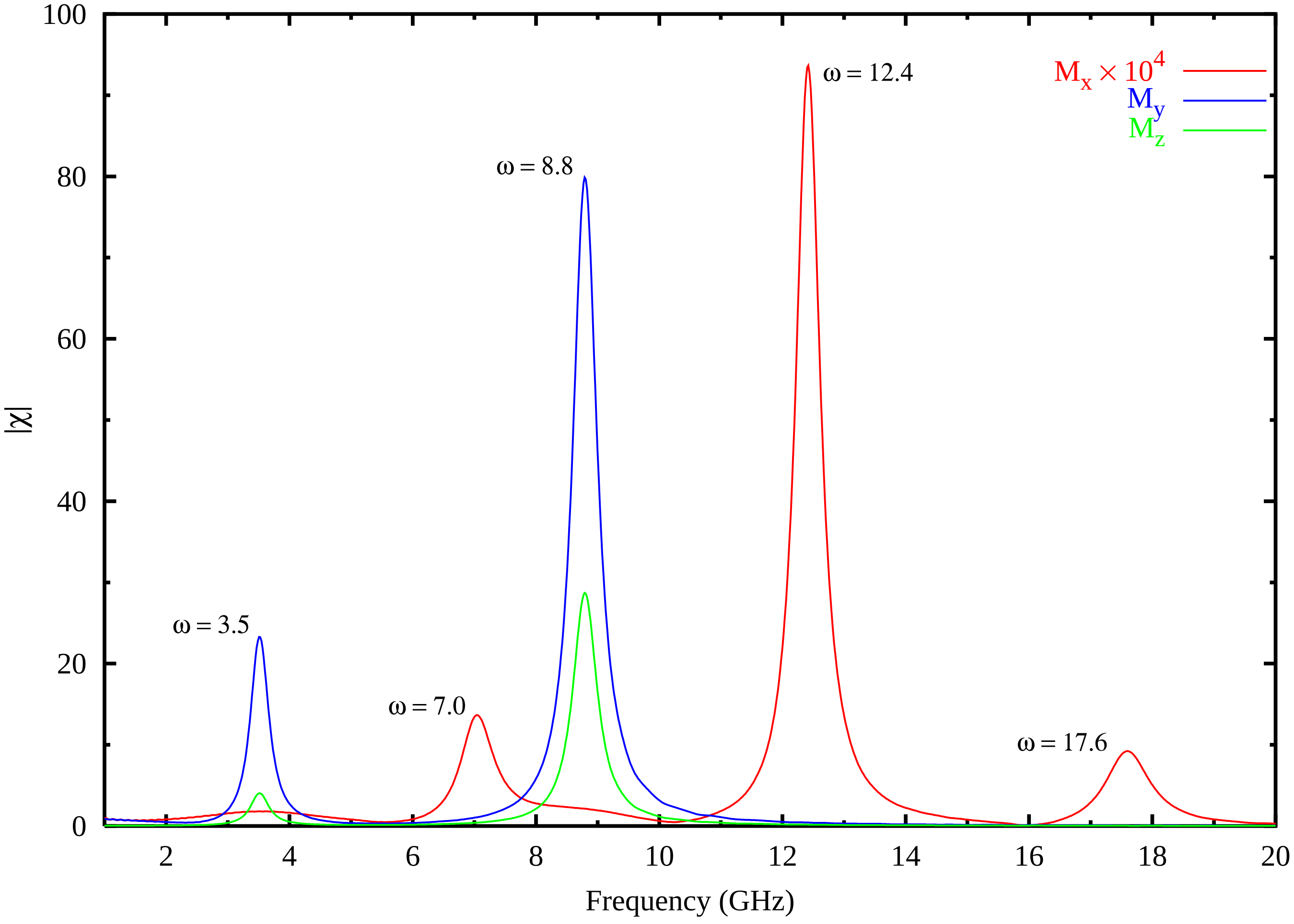

# Single Spin Rotation

Let

$$m_y(t) = a\cos\omega t \qquad m_z(t) = b\sin\omega t$$

with $0 < b < a \ll 1$.

Then

$$\begin{aligned} m_x(t) &= \sqrt{1 - m_y^2(t) - m_z^2(t)} \\ &= \sqrt{1 - \frac{a^2+b^2}{2} - \frac{a^2-b^2}{2}\cos 2\omega t} \\ &\approx 1 - \frac{a^2-b^2}{4}\cos 2\omega t \end{aligned}$$

# Conclusions:

- Identified 3 modes:
  1. "Breathing" mode from $x$-axis excitation.
  2. Central core rotation from tranverse excitation.
  3. End domain rotation from transverse excitation.
- Resonance frequencies sensitive to part geometry.

Thursday 4:00 pm

**HF-11** Switching Dynamics and Ring Down Response of Standard Problem #4

J. Eicke, M. Donahue, R. McMichael, D. Porter

# References

**Micromagnetics of the Dynamic Susceptibility for Coupled Permalloy Stripes,** O. Gérardin, J. Ben Youssef, H. Le Gall, N. Vukadinovic, P. M. Jacquart and M. J. Donahue, *Journal of Applied Physics,* **88**, pp 5899–5903 (2000).

**Behavior of muMAG Standard Problem No. 2 in the Small Particle Limit,** M. J. Donahue, D. G. Porter, R. D. McMichael and J. Eicke, *Journal of Applied Physics,* **87**, pp 5520–5522 (2000).

**Exchange Energy Representations in Computational Micromagnetics,** M. J. Donahue and R. D. McMichael, *Physica B,* **233**, pp 272–278 (1997).

## Web Pages

- Home Page:

  `http://math.nist.gov/~MDonahue/`

- OOMMF:

  `http://math.nist.gov/oommf/`

- $\mu$MAG:

  `http://www.ctcms.nist.gov/~rdm/mumag.org.html`