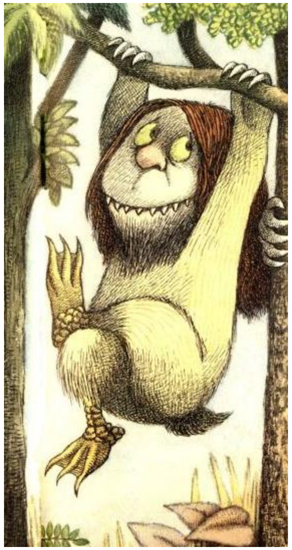
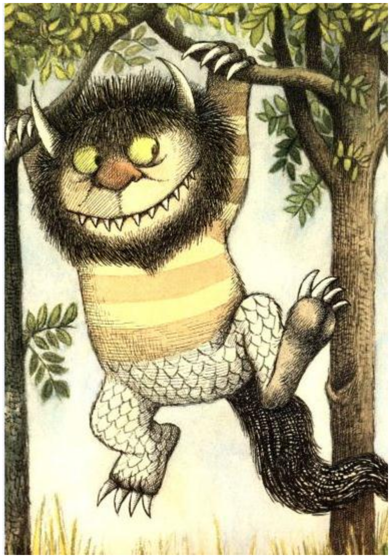
Damped expectations for <u>the second generation:</u>

controlling the chaos





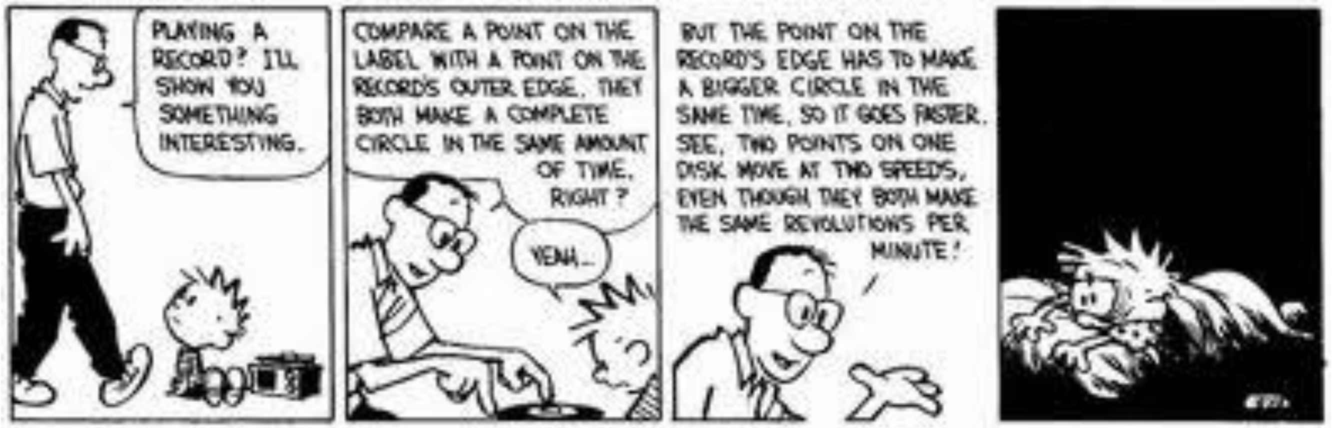
Theorist

Theorist

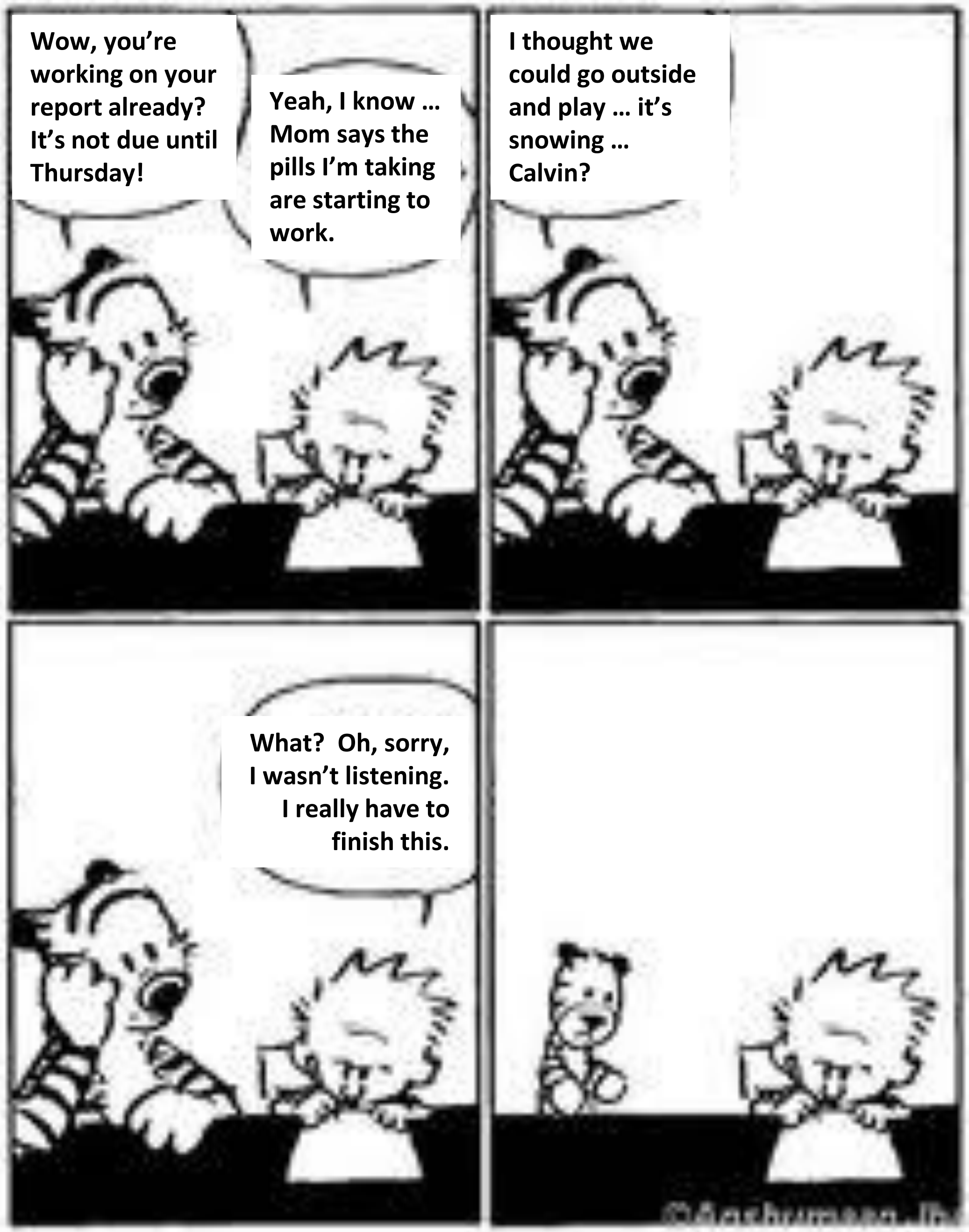
or

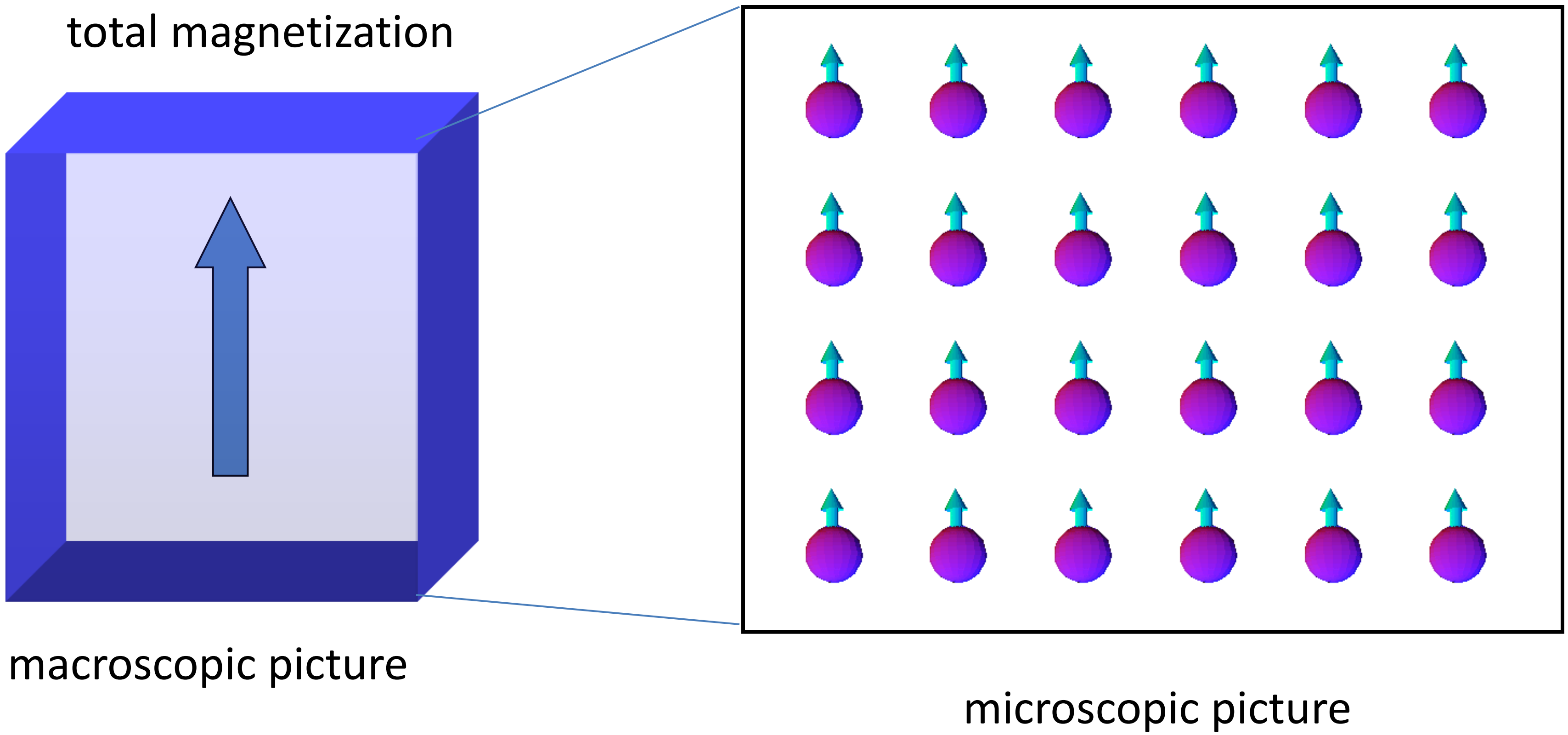
Experimentalist

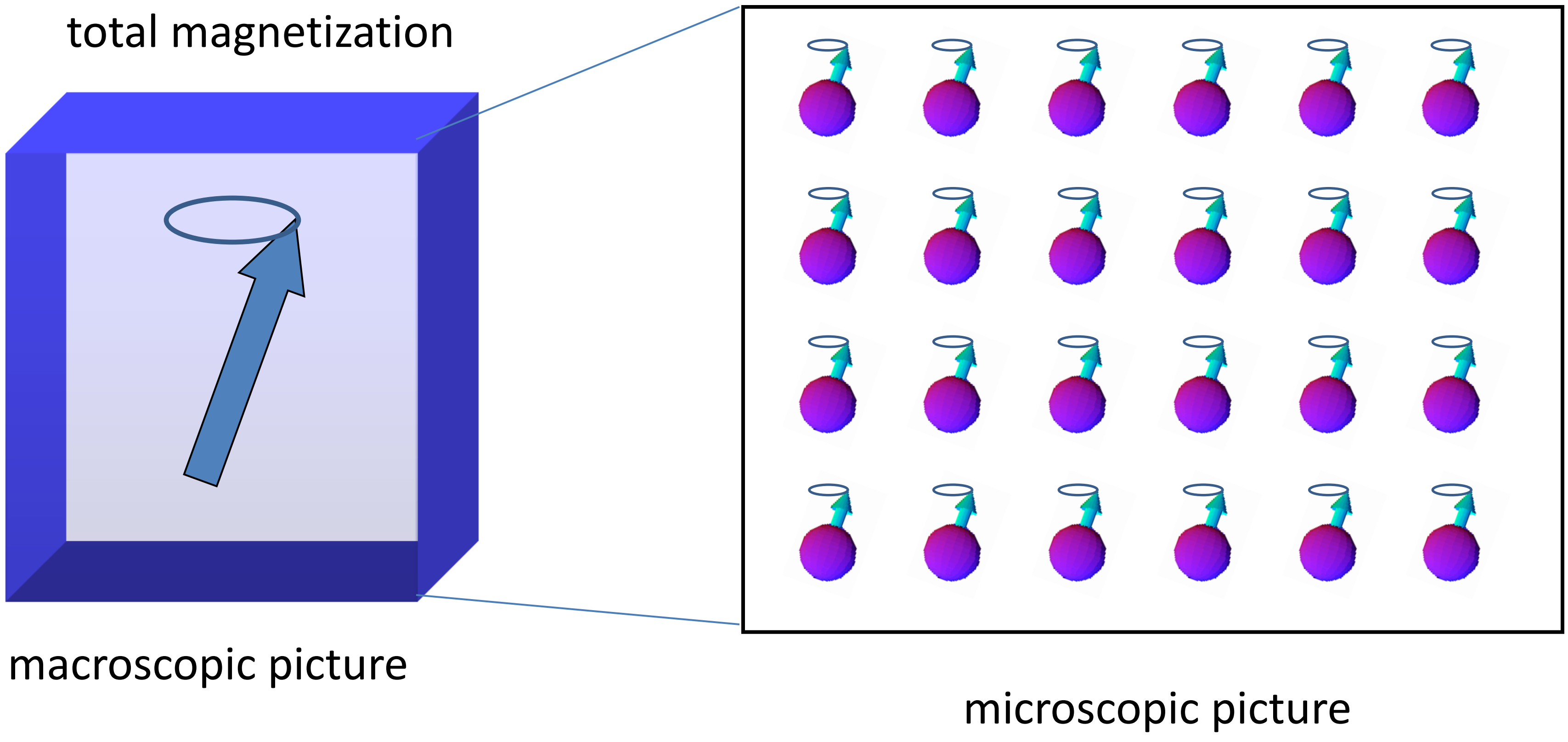

REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.


PLAYING A RECORD? I'LL SHOW YOU SOMETHING INTERESTING.
COMPARE A POINT ON THE LABEL WITH A POINT ON THE RECORD'S OUTER EDGE. THEY BOTH MAKE A COMPLETE CIRCLE IN THE SAME AMOUNT OF TIME, RIGHT?
YEAH...
BUT THE POINT ON THE RECORD'S EDGE HAS TO MAKE A BIGGER CIRCLE IN THE SAME TIME, SO IT GOES FASTER. SEE, TWO POINTS ON ONE DISK MOVE AT TWO SPEEDS, EVEN THOUGH THEY BOTH MAKE THE SAME REVOLUTIONS PER MINUTE!


DAD, WHAT CAUSES WIND?
TREES SNEEZING.
REALLY??
NO, BUT THE TRUTH IS MORE COMPLICATED.
THE TREES ARE REALLY SNEEZING TODAY.


Wow, you're working on your report already? It's not due until Thursday!
Yeah, I know … Mom says the pills I'm taking are starting to work.
I thought we could go outside and play … it's snowing … Calvin?
What? Oh, sorry, I wasn't listening. I really have to finish this.

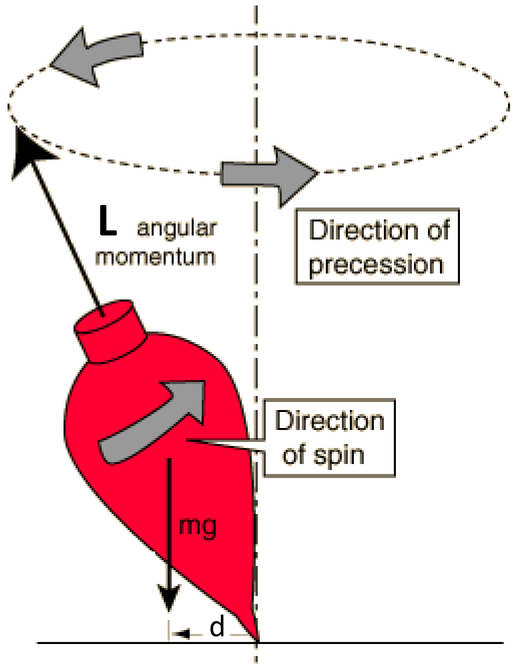

total magnetization
macroscopic picture
microscopic picture

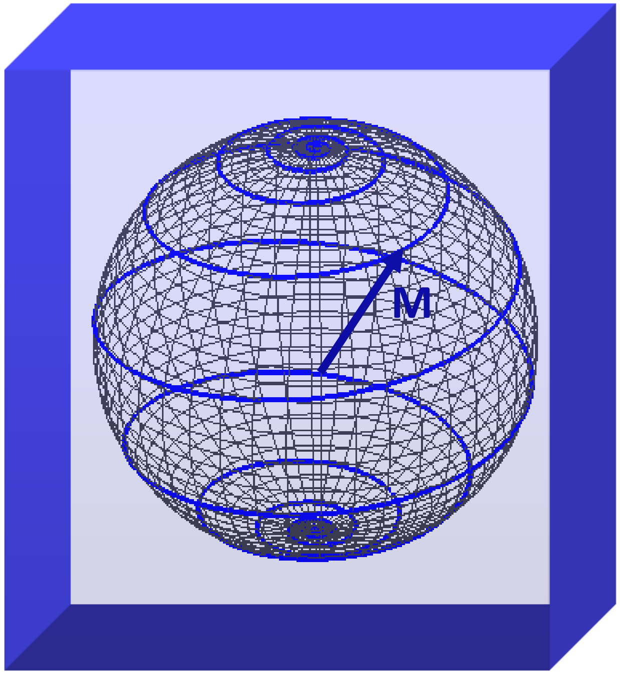

total magnetization
macroscopic picture
microscopic picture

Field driven magnetodynamics

$$dL/dt = d \times mg \quad \text{precession}$$
$$+\alpha \hat{L} \times \dot{L} \quad \text{damping}$$

$$dM/dt = -M \times \gamma H \quad \text{precession}$$
$$+\alpha \hat{M} \times \dot{M} \quad \text{damping}$$





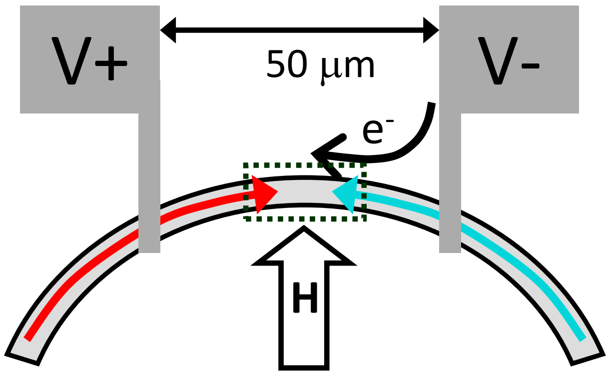
G

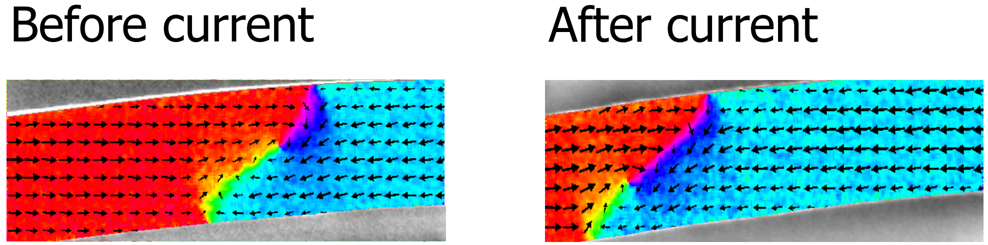
H

Equation of Motion (damped-driven oscillator)

$$\dot{\mathbf{M}} = \underbrace{-\mathbf{M}\times\gamma\mathbf{H}}_{\text{precession}} + \underbrace{\alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}}}_{\text{damping}}$$

Current-driven magnetodynamics

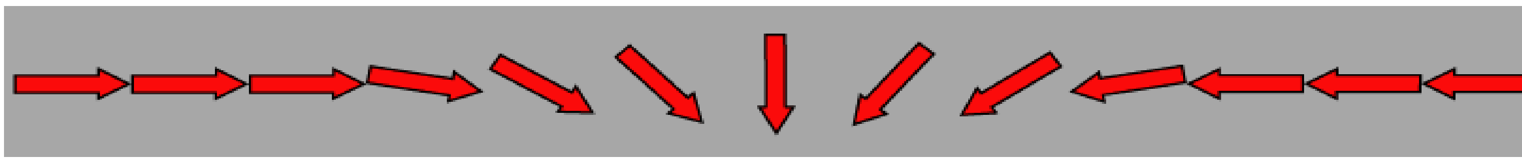




Current driven magnetodynamics

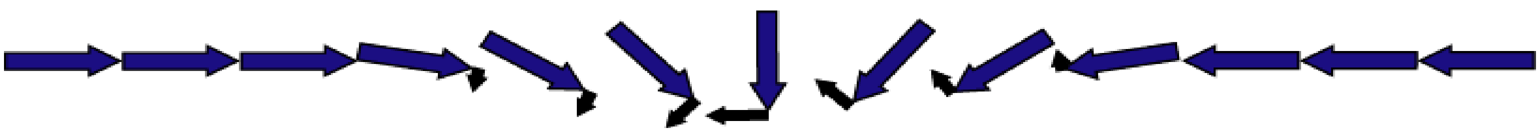
Wide domain wall

Adiabatic spin-transfer torque

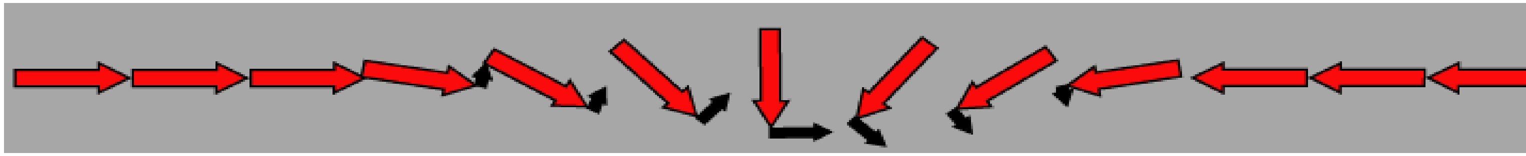


Electron flow

If spins follow magnetization direction



Reaction torque on magnetization



Domain wall translates

$$\mathbf{v}_s = \frac{-P\mu_B j}{eM_s}$$

Equation of Motion

Field (H) driven terms

Current (v_s) driven terms

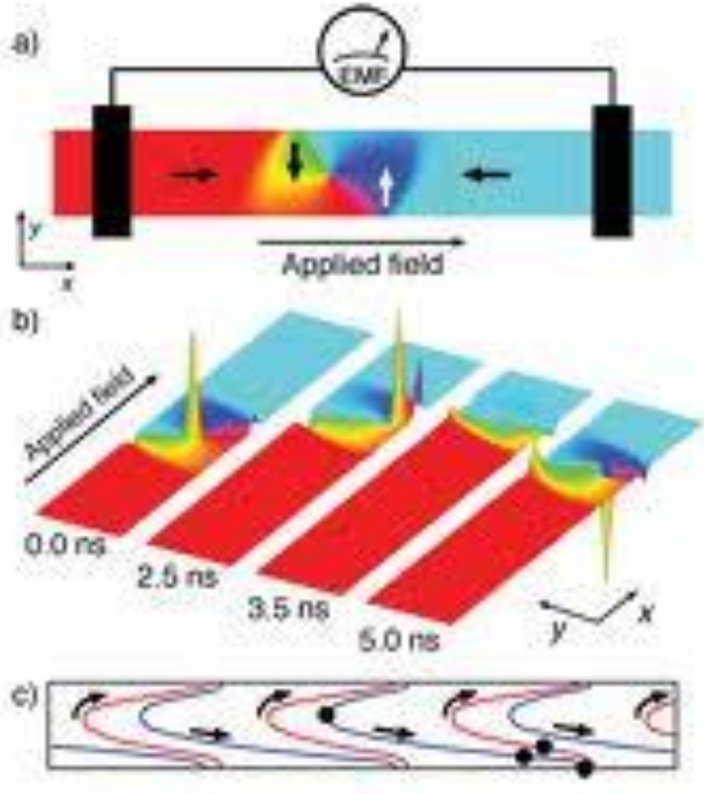
$$\dot{\mathbf{M}} = \underbrace{-\mathbf{M}\times\gamma\mathbf{H}}_{\text{precession}} + \underbrace{\alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}}}_{\text{damping}} + \underbrace{-(\mathbf{v}_s\cdot\nabla)\mathbf{M}}_{\text{adiabatic spin torque}} + \underbrace{\beta\hat{\mathbf{M}}\times(\mathbf{v}_s\cdot\nabla)\mathbf{M}}_{\text{non-adiabatic spin torque}}$$

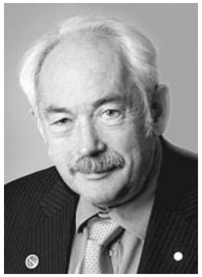
precession

damping

adiabatic spin torque

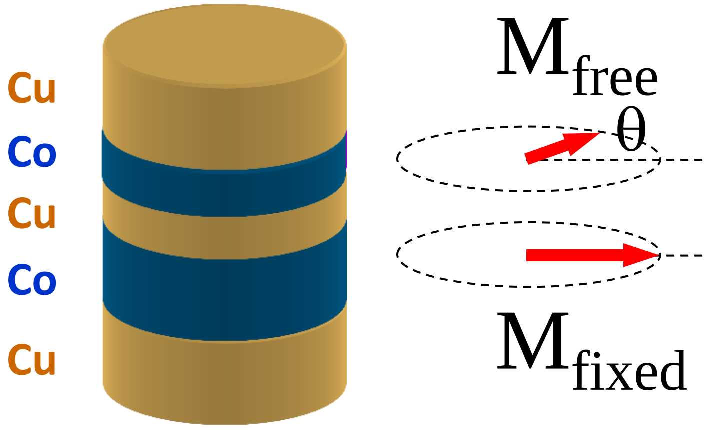
non-adiabatic spin torque

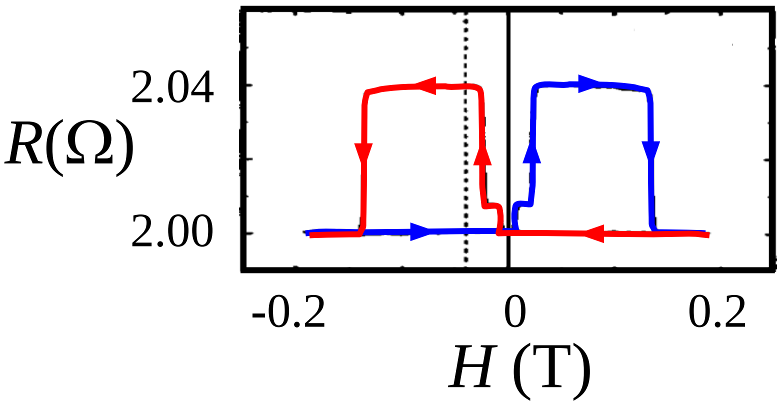

a)
EMF
y
x
Applied field
b)
Applied field
0.0 ns
2.5 ns
3.5 ns
5.0 ns
y
x
c)



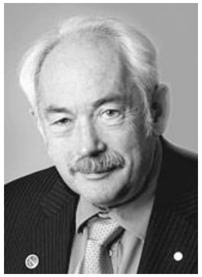
Magnetic state affects current

Giant Magnetoresistance





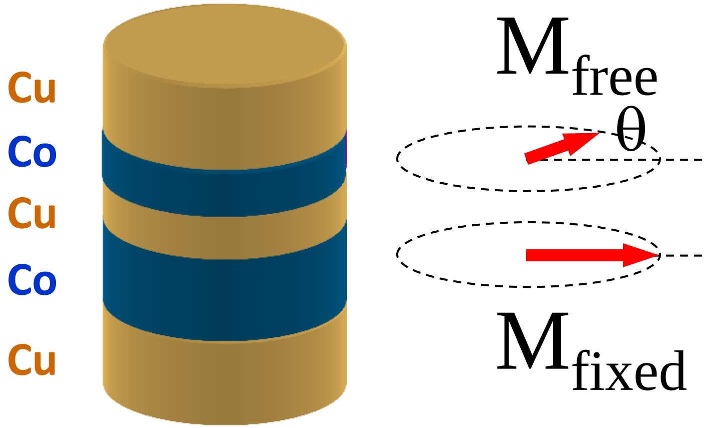
Albert Fert

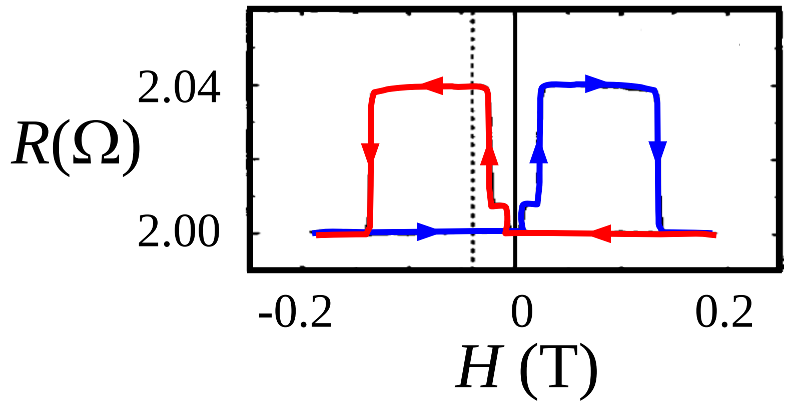


Peter Grünberg

Magnetic state affects current

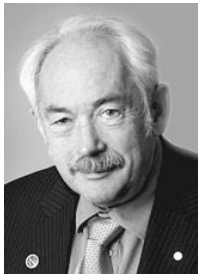
Giant Magnetoresistance





Albert Fert

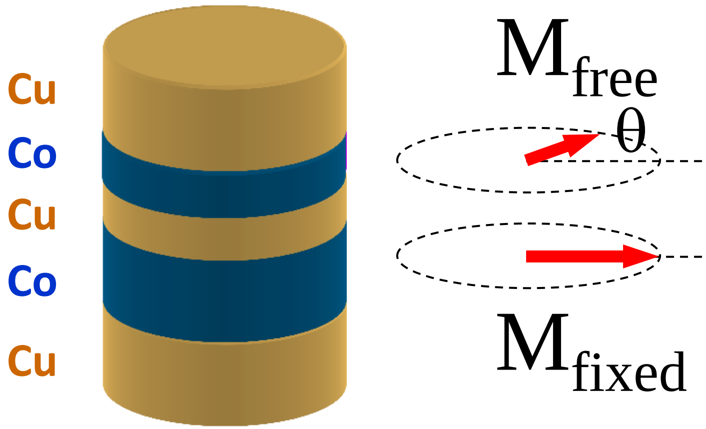
Nobel prize
2007

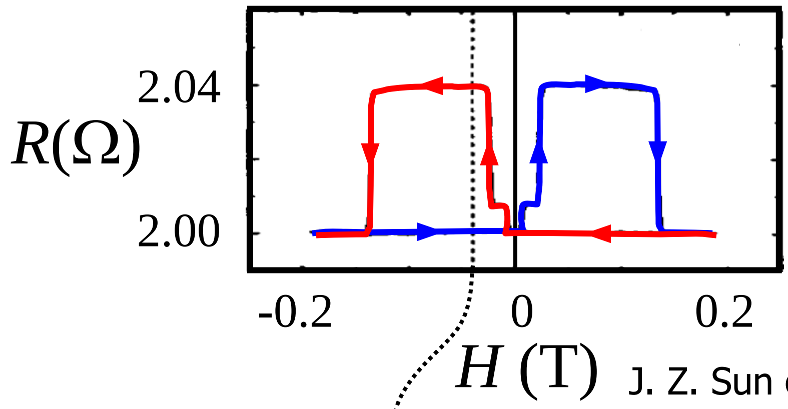


Peter Grünberg

Currents control magnetic state

Giant Magnetoresistance

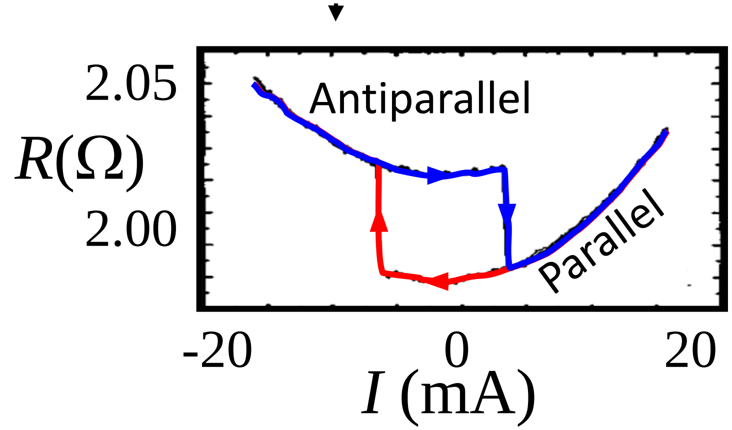




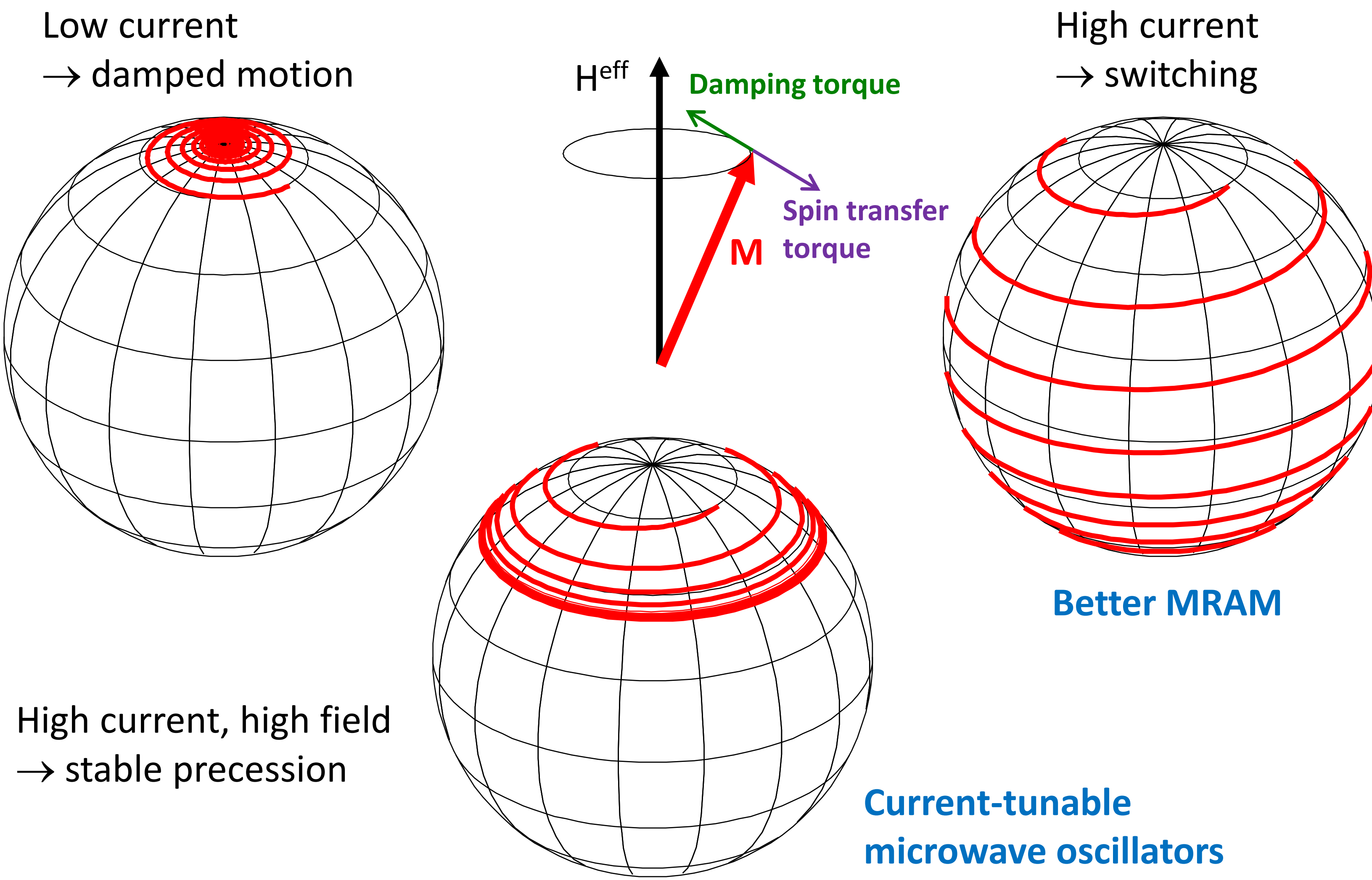
J. Z. Sun et al.
JAP (2003)

Spin-Transfer Torque

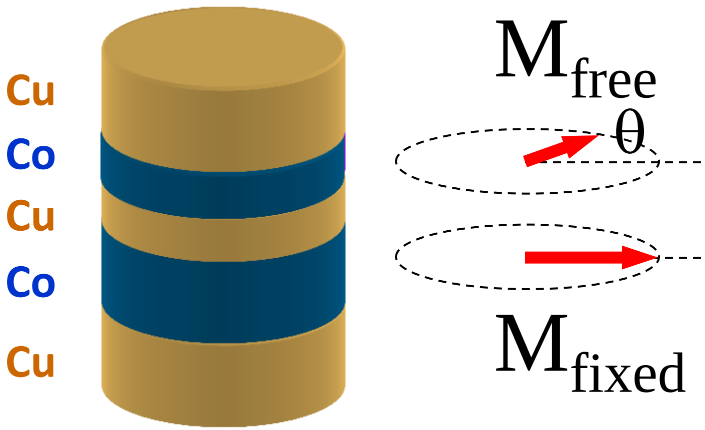
Spin currents can
switch magnetization!

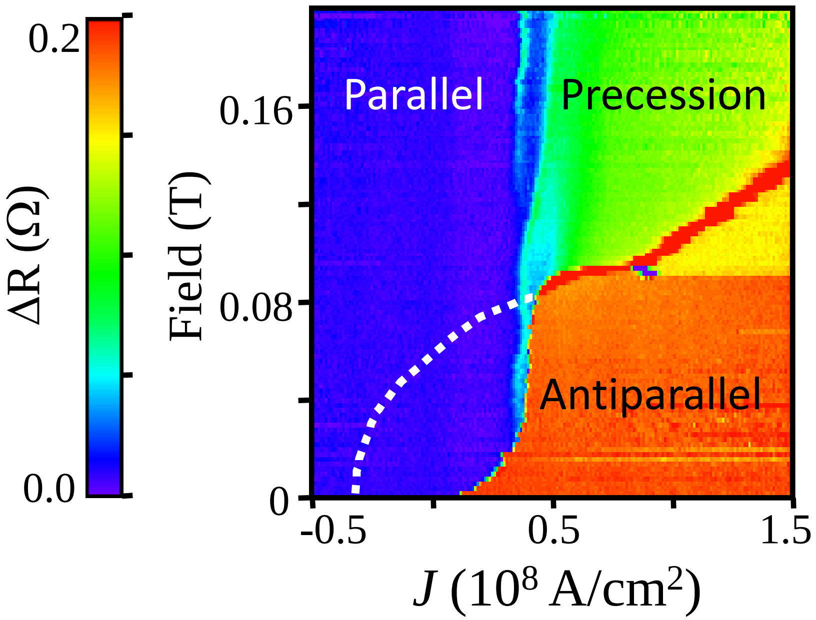


Current-induced switching dynamics



Complex phase diagram





Equation of Motion

Field (H) driven terms

well understood, conservative — precession

less well understood, dissipative — damping

Current (v_s) driven terms

well understood, conservative — adiabatic spin torque

less well understood, dissipative — non-adiabatic spin torque

$$\dot{\mathbf{M}} = \underbrace{-\mathbf{M}\times\gamma\mathbf{H}}_{\text{precession}} + \underbrace{\alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}}}_{\text{damping}} + \underbrace{-(\mathbf{v}_s\cdot\nabla)\mathbf{M}}_{\text{adiabatic spin torque}} + \underbrace{\beta\hat{\mathbf{M}}\times(\mathbf{v}_s\cdot\nabla)\mathbf{M}}_{\text{non-adiabatic spin torque}}$$

Equation of Motion

We want to understand the origin of these parameters

well understood, conservative

precession

adiabatic spin torque

$$\dot{\mathbf{M}} = -\mathbf{M}\times\gamma\mathbf{H} + \alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}} + -(\mathbf{v}_s\cdot\nabla)\mathbf{M} + \beta\hat{\mathbf{M}}\times(\mathbf{v}_s\cdot\nabla)\mathbf{M}$$

damping

non-adiabatic spin torque

less well understood, dissipative

Equation of Motion

well understood,
conservative

precession

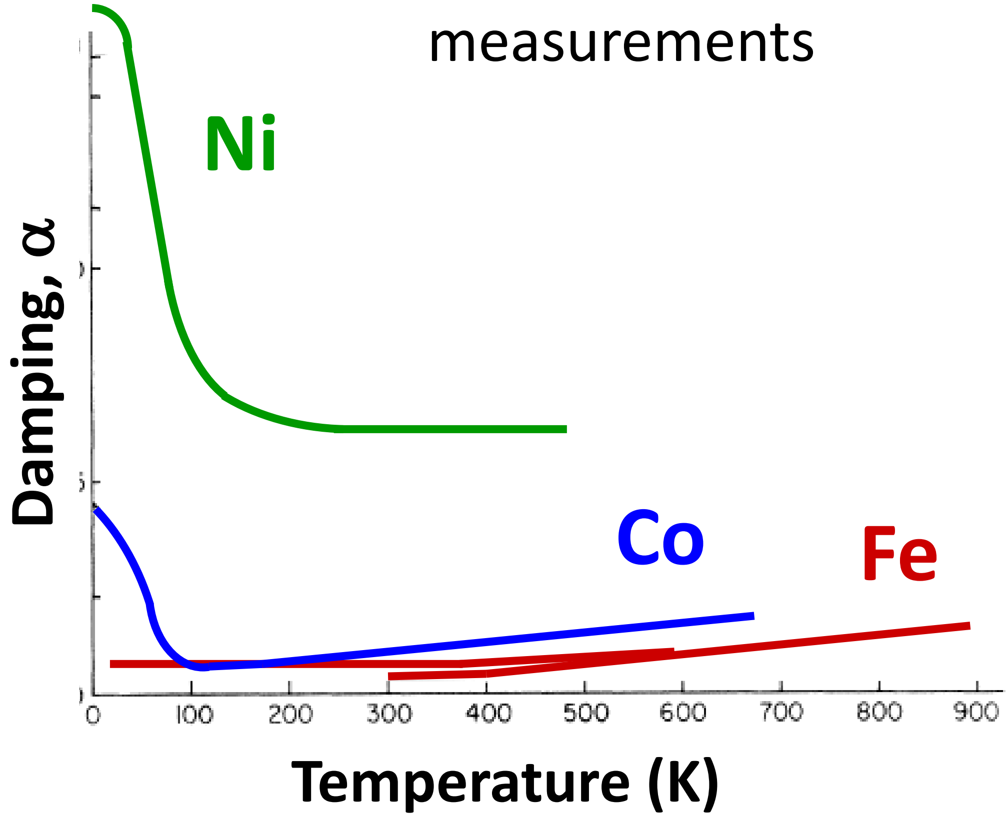
$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}}$$

damping

less well understood,
dissipative

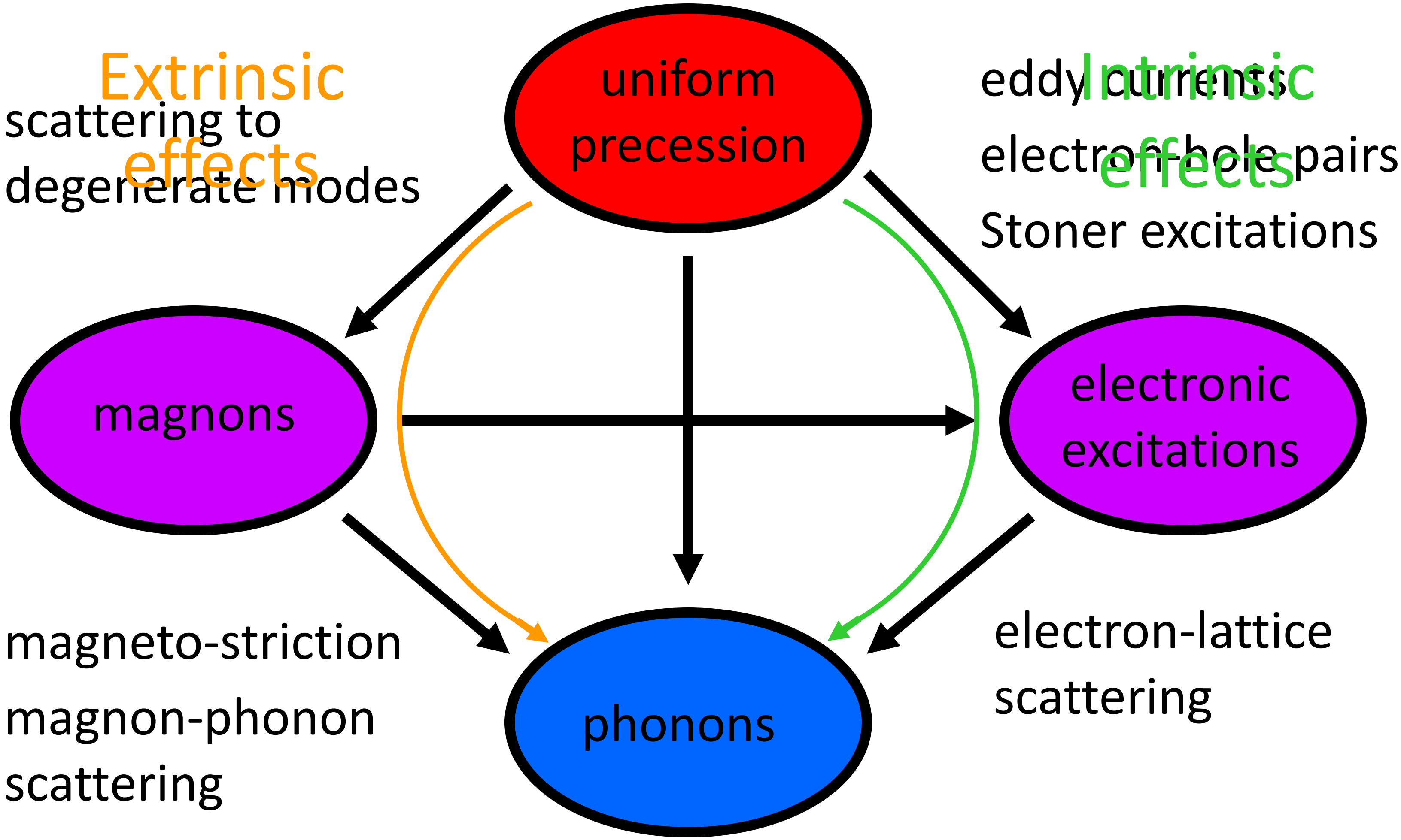
Motivating data

Ferromagnetic resonance measurements



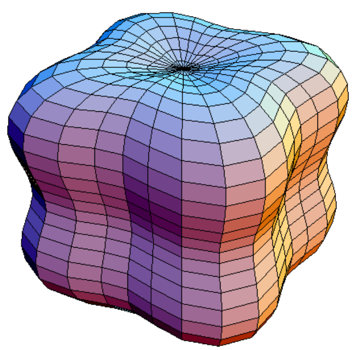
$$\dot{\mathbf{M}} = -\mathbf{M}\times\gamma\mathbf{H} + \alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}}$$

Coupling to the environment

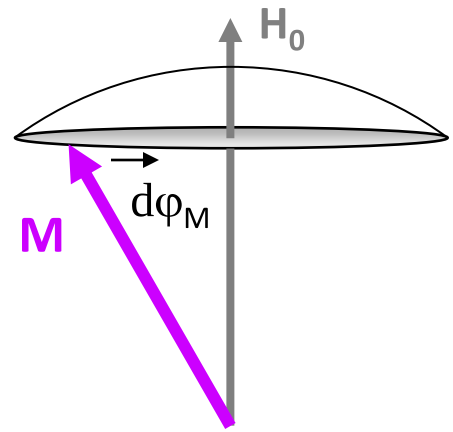


Effective Field Model

reversible



magnetocrystalline anisotropy

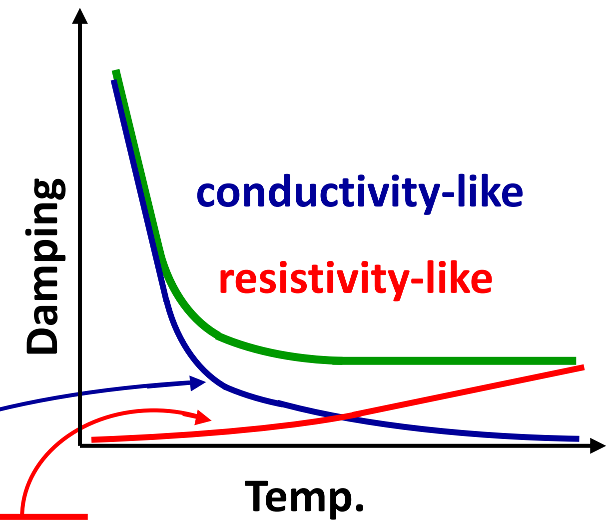


$$\mu_0 H^{eff} = -\frac{1}{M}\frac{\partial E}{\partial \varphi_M}$$

$$E = \sum_{nk} f_{nk}\varepsilon_{nk}$$

$$\mu_0 H^{eff} = -\frac{1}{M}\sum_{nk}\left[f_{nk}\frac{\partial \varepsilon_{nk}}{\partial \varphi_M} + \frac{\partial f_{nk}}{\partial \varphi_M}\varepsilon_{nk}\right]$$

irreversible



Fermi Surfaces

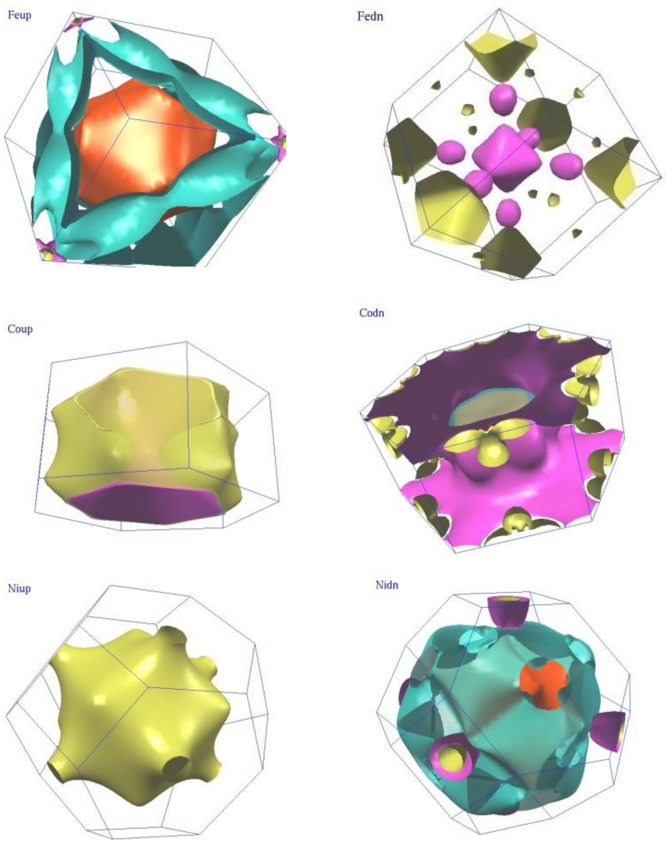
Real Fermi Surfaces

Up Spin | Down Spin

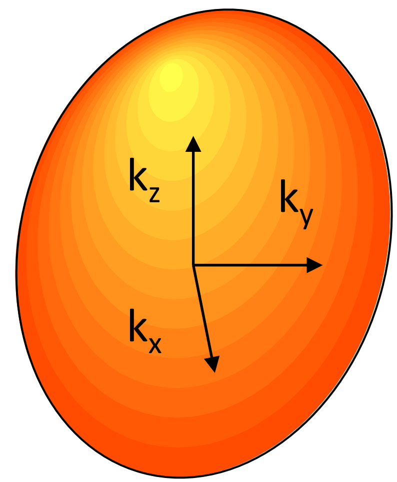
Iron

Cobalt

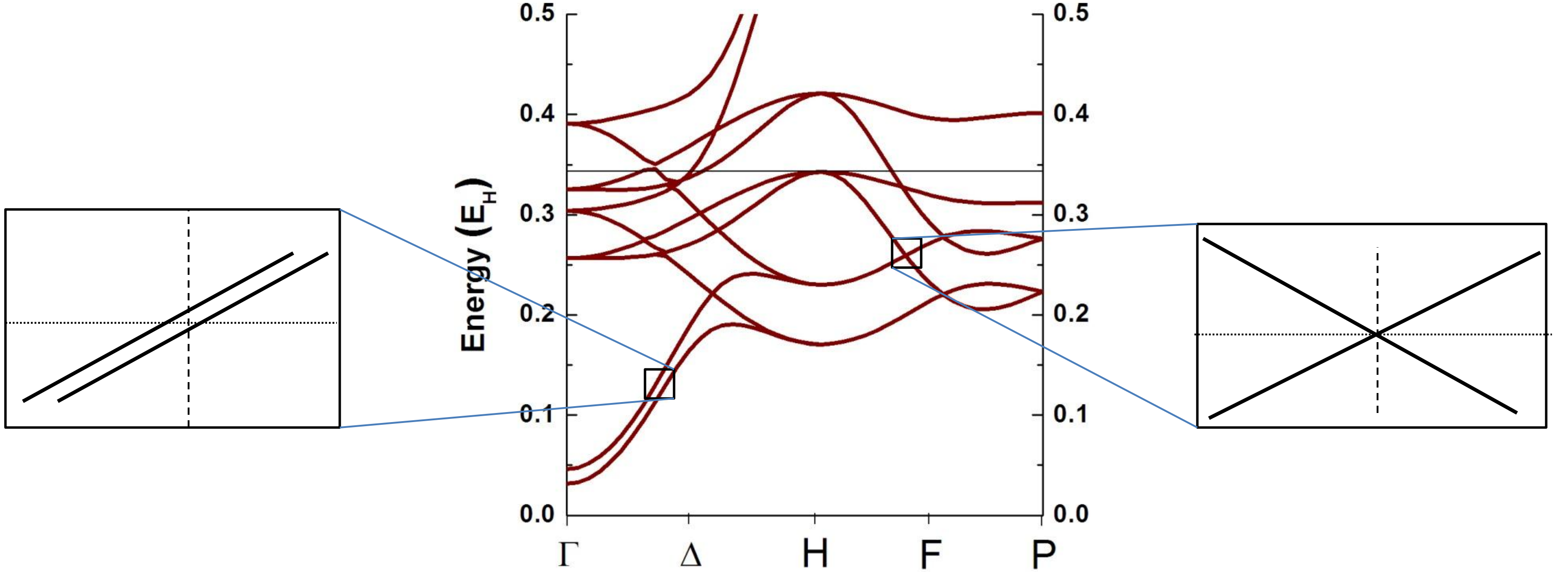
Nickel



Representative Fermi Surfaces

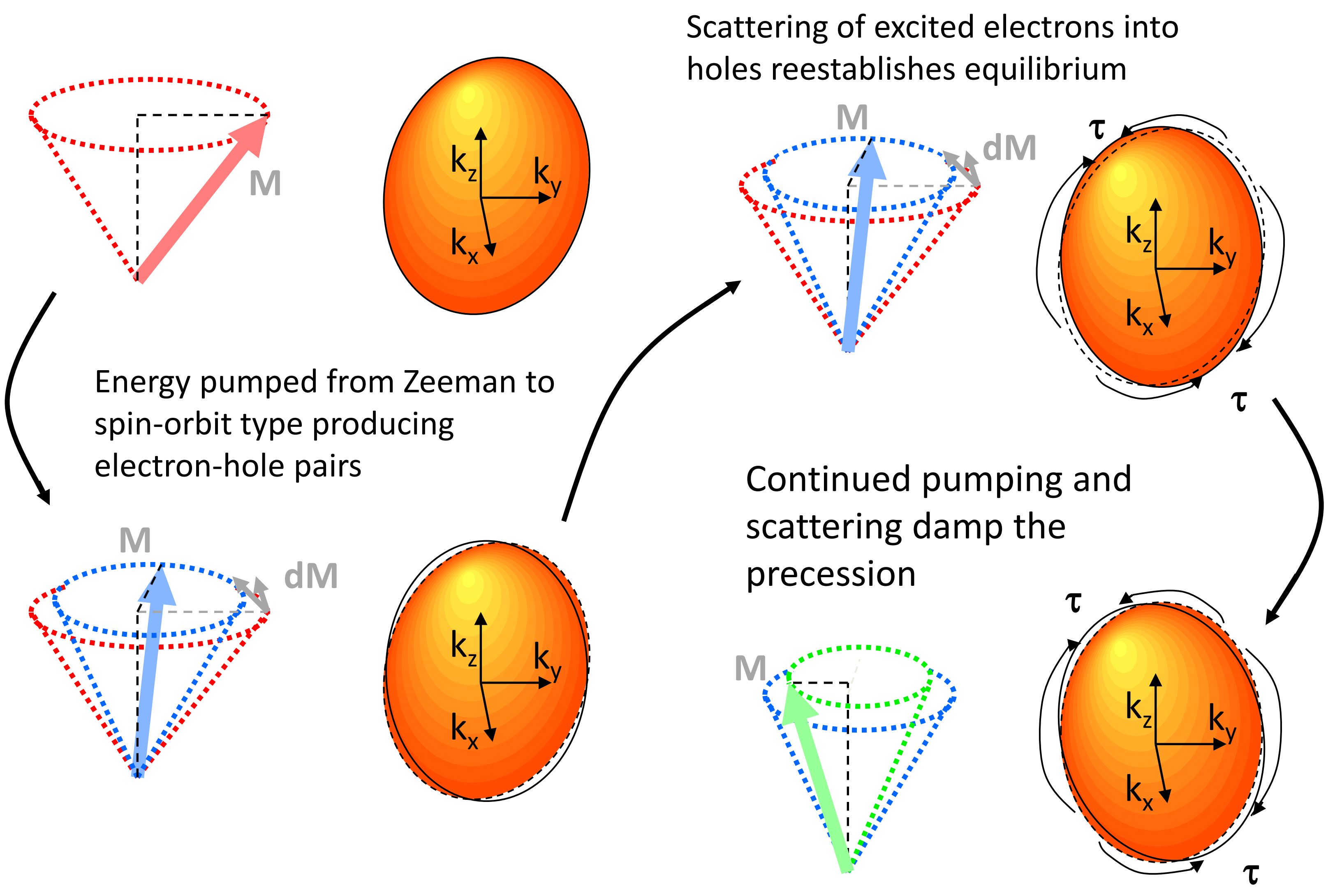


Band Structure



$$H\ \varphi_{nk} = \varepsilon_{nk}\ \varphi_{nk}$$

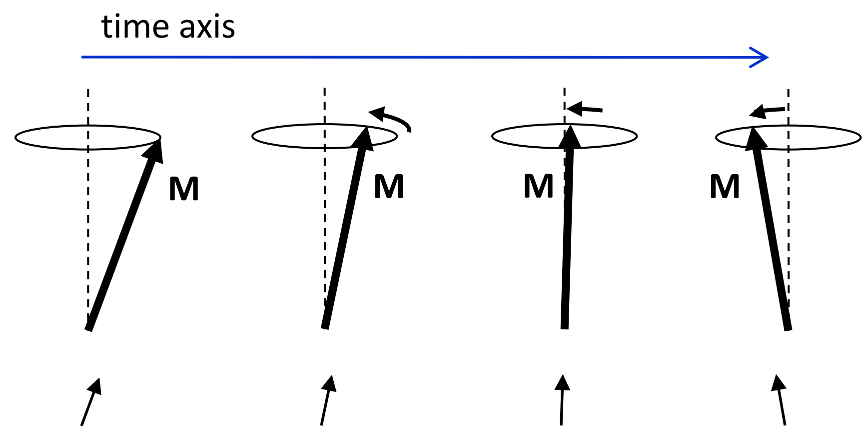
Breathing Fermi Surface : $H_{so}(t) = -\xi\, \boldsymbol{\ell} \cdot s(t)$



State energies change with precession

Spin-orbit energy depends on spin direction (σ)

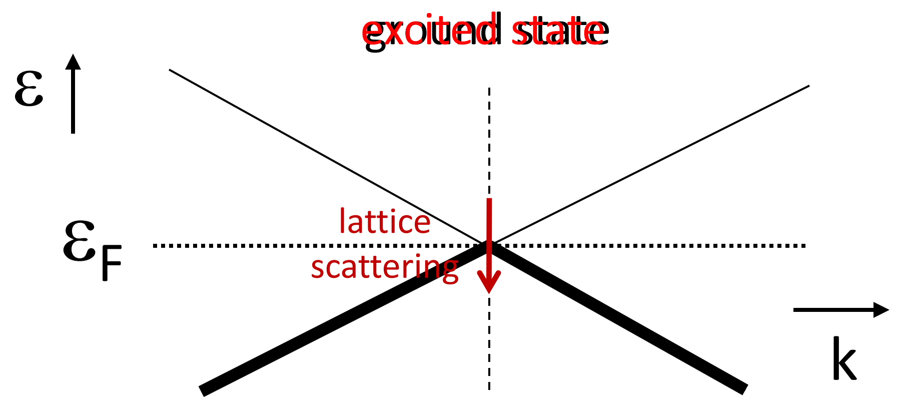
$$H_{so} \approx -\xi \sum_{nk} \ell_{nk} \cdot \sigma_{nk}(\hat{m})$$



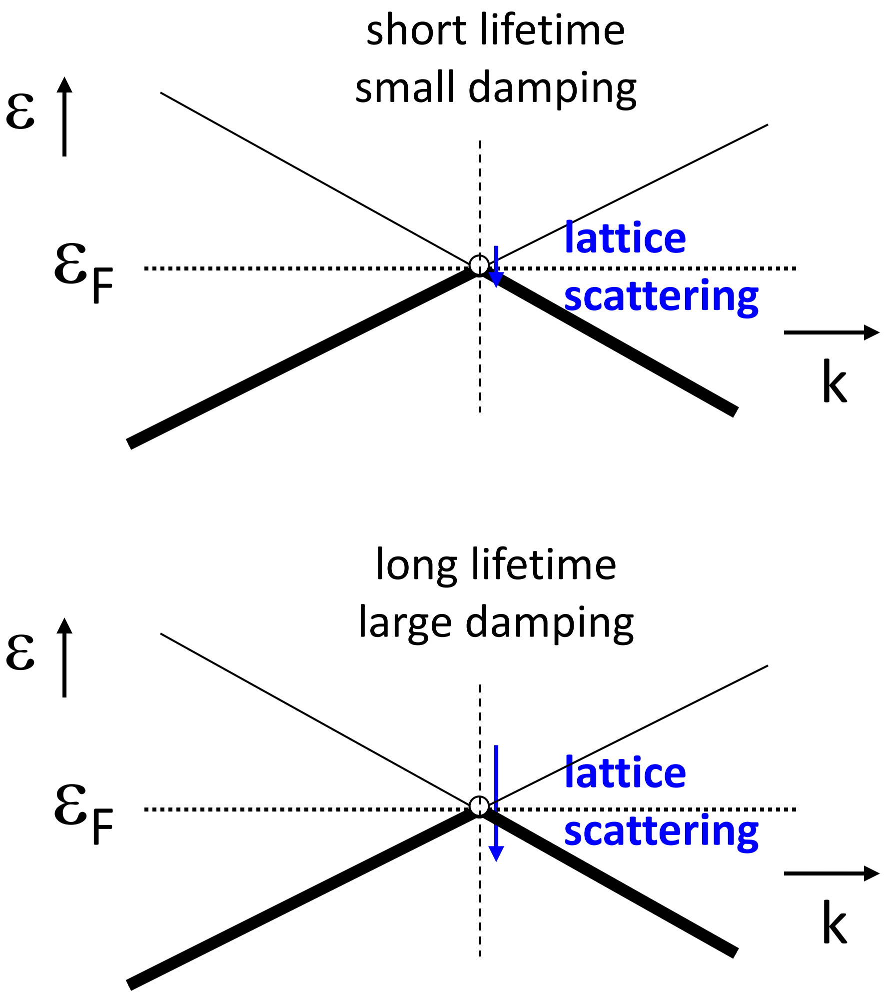
Representative spin:

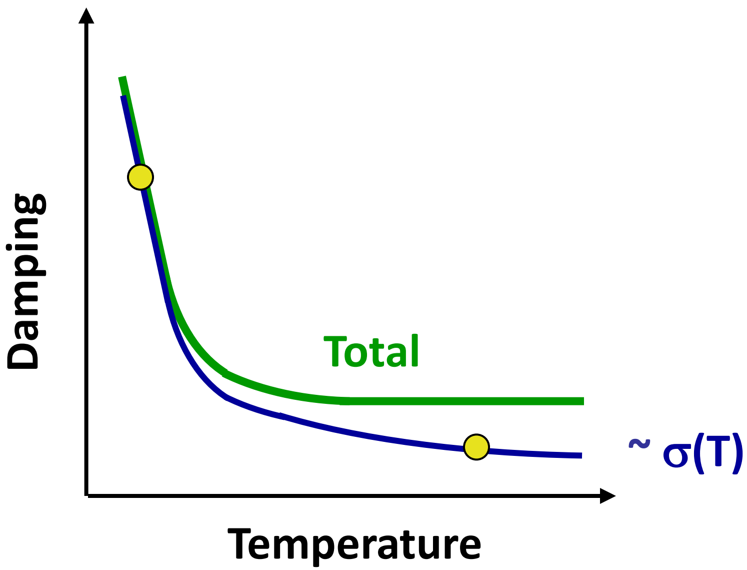
Generation of electron-hole pairs due to energy changes – breathing Fermi surface

$$\mu_0 \mathbf{H}^{\mathbf{eff}} = -\frac{1}{\mathrm{M}} \sum_{nk} f_{nk} \frac{\partial \varepsilon_{nk}}{\partial \varphi_{\mathrm{M}}}$$



Conductivity-like term *decreases* as scattering rate increases

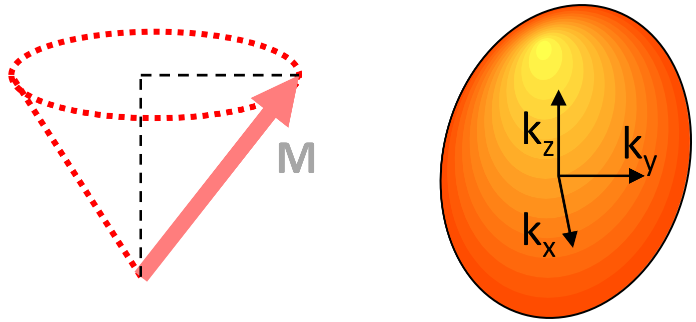




The breathing Fermi surface contribution

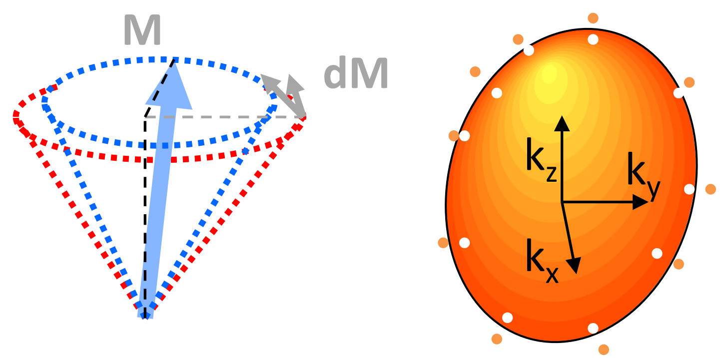
Bubbling Fermi Surface : $V(t) = H_{so}(t) - H_{so}$

$V(0) = 0$



The effective perturbation generates electronic excitations over the Fermi surface, reducing the Zeeman energy.

$V(t) = H_{so}(t) – H_{so}(0)$

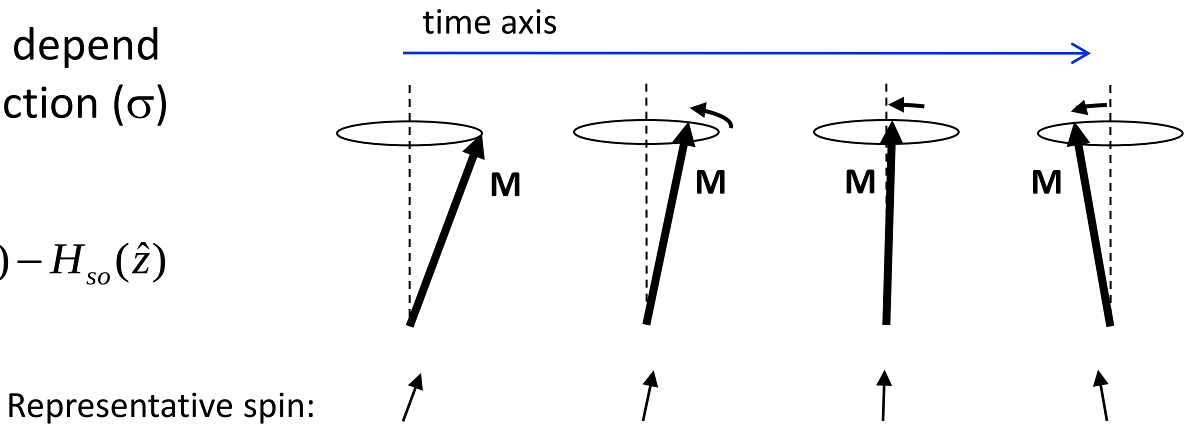


Electron-electron and electron-lattice scattering restores equilibrium.

State populations change with precession

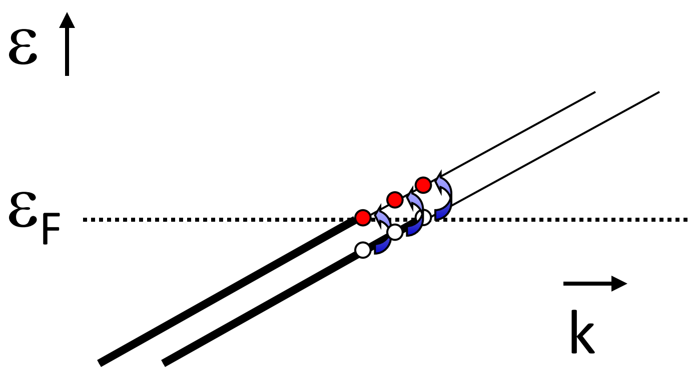
Eigenstates depend on spin direction (σ)

$$V_{so} = H_{so}(\hat{m}) - H_{so}(\hat{z})$$

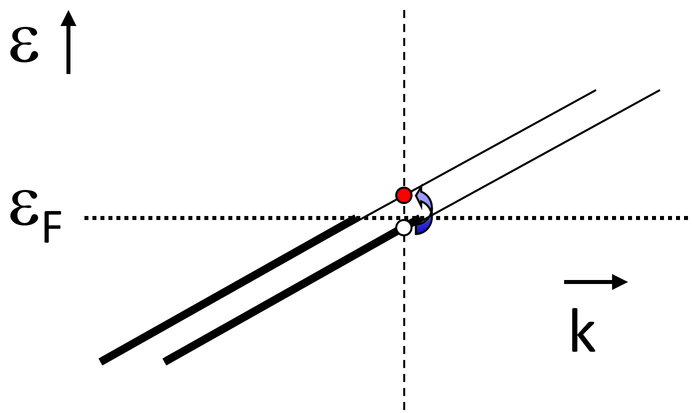


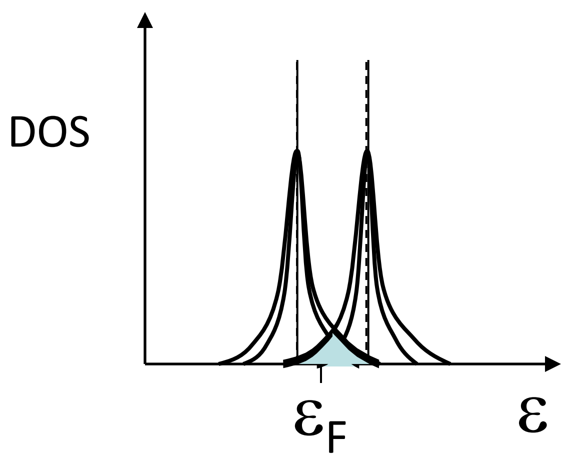
Generation of electron-hole pairs due to population changes – bubbling Fermi surface

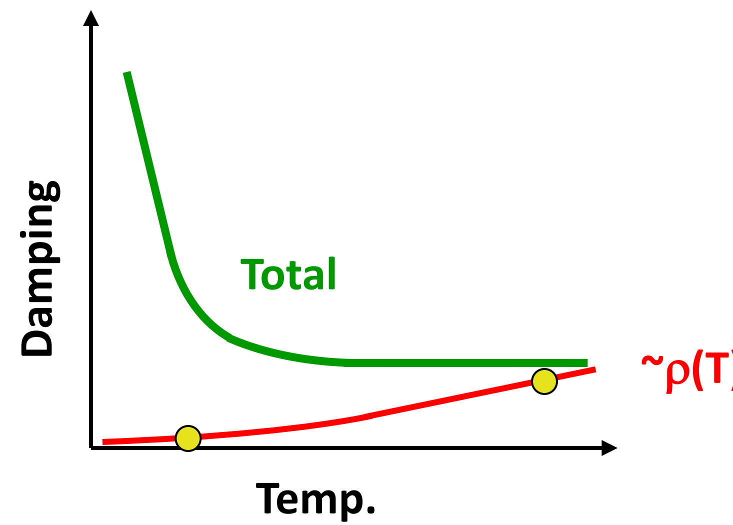
$$\mu_0 \mathbf{H}^{\mathbf{eff}} = -\frac{1}{\mathrm{M}} \sum_{nk} \frac{\partial f_{nk}}{\partial \varphi_{\mathrm{M}}} \varepsilon_{nk}$$



Resistivity-like term *increases* as scattering rate increases







The bubbling Fermi surface contribution

Qualitative prediction

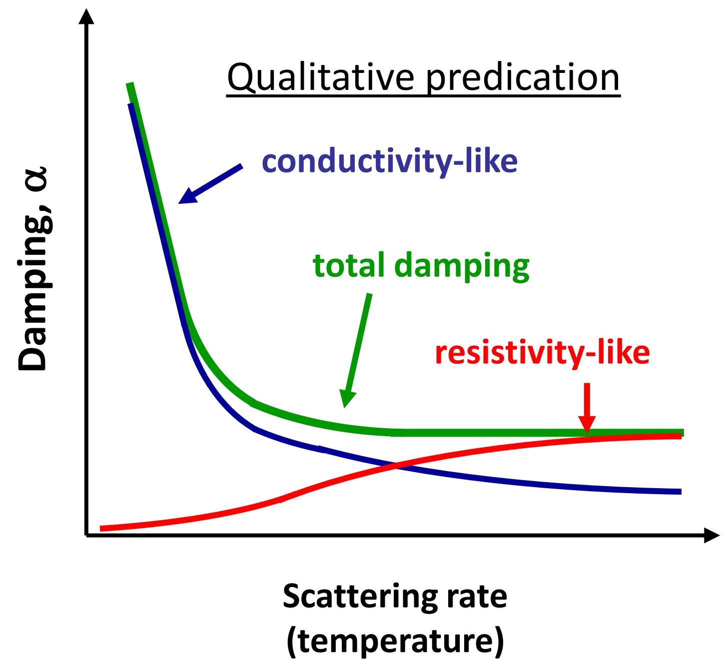
$$\mu_0 \mathrm{H}^{\mathrm{eff}} = -\frac{1}{\mathrm{M_s}} \sum_{nk} \left[f_{nk} \frac{\partial \varepsilon_{nk}}{\partial \varphi_{\mathrm{M}}} + \frac{\partial f_{nk}}{\partial \varphi_{\mathrm{M}}} \varepsilon_{nk} \right]$$

conductivity-like ‘breathing’ terms

$$\mu_0 \mathrm{H}^{\mathrm{eff}}_{(1)} = -\frac{1}{\mathrm{M_s}} \sum_{nk} f_{nk} \frac{\partial \varepsilon_{nk}}{\partial \varphi_{\mathrm{M}}}$$

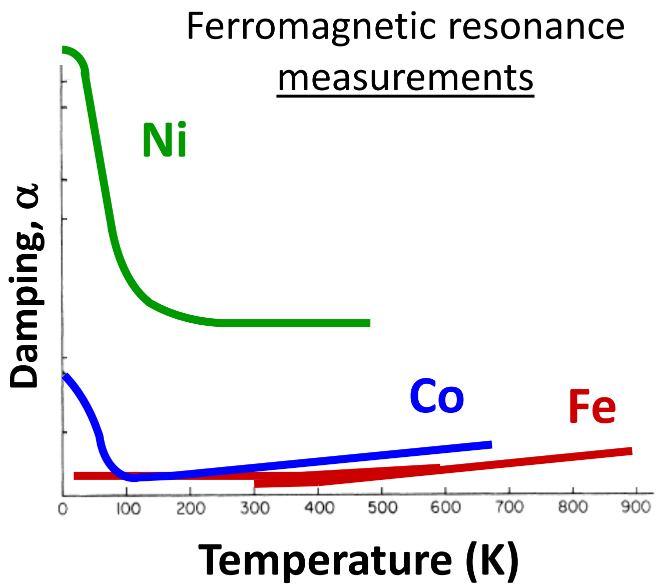
Resistivity-like ‘bubbling’ terms

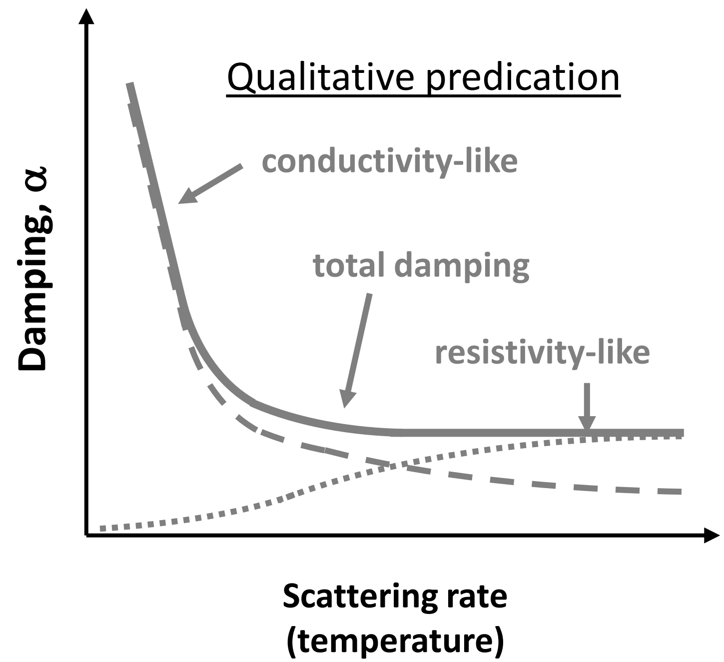
$$\mu_0 \mathrm{H}^{\mathrm{eff}}_{(2)} = -\frac{1}{\mathrm{M_s}} \sum_{nk} \frac{\partial f_{nk}}{\partial \varphi_{\mathrm{M}}} \varepsilon_{nk}$$



$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}}$$

Qualitative match with experiment





$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}}$$

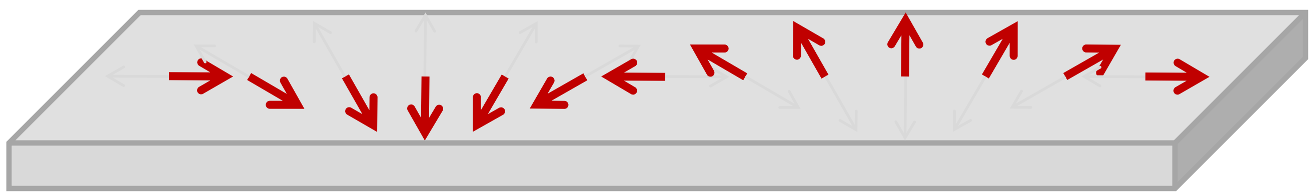
Equation of Motion

$$\dot{\mathbf{M}} =$$

Non-adiabatic STT as extension of damping

$$\alpha \propto \mathrm{Im}\,\chi(\omega, \mathbf{q}, \mathbf{E} = \mathbf{0})$$

$$\beta \propto \mathrm{Im}\,\chi(\omega = 0, \mathbf{q}, \mathbf{E})$$



Conservative torques ⟵ precession, adiabatic spin torque

$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}} - (\mathbf{v}_s \cdot \nabla)\mathbf{M} + \beta \hat{\mathbf{M}} \times (\mathbf{v}_s \cdot \nabla)\mathbf{M}$$

Dissipative torques ⟶ damping, non-adiabatic spin torque

Non-adiabatic STT as extension of damping

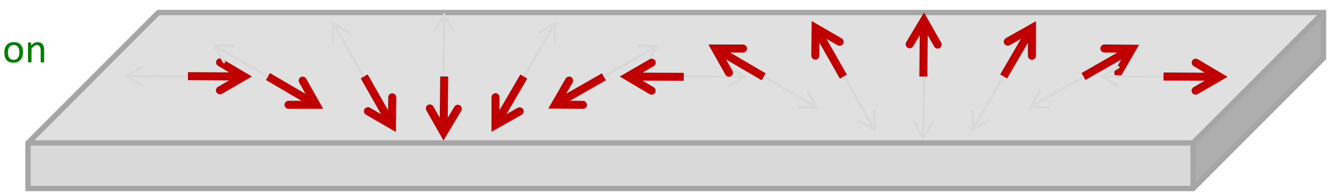
$$\alpha \propto \mathrm{Im}\,\chi(\omega, \mathbf{q}, \mathbf{E}=\mathbf{0})$$

$$\beta \propto \mathrm{Im}\,\chi(\omega = 0, \mathbf{q}, \mathbf{E})$$

Rotation in time: →

precession on

current off



precession; adiabatic spin torque ← Conservative torques

$$\dot{\mathbf{M}} = -\mathbf{M}\times\gamma\mathbf{H} + \alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}} - (\mathbf{v}_s\cdot\nabla)\mathbf{M} + \beta\hat{\mathbf{M}}\times(\mathbf{v}_s\cdot\nabla)\mathbf{M}$$

Dissipative torques → damping; non-adiabatic spin torque

Non-adiabatic STT as extension of damping

$$\alpha \propto \mathrm{Im}\,\chi(\omega, \mathbf{q}, \mathbf{E}=\mathbf{0})$$

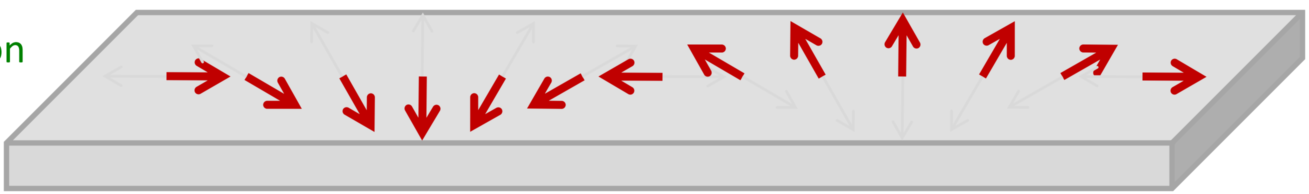
$$\beta \propto \mathrm{Im}\,\chi(\omega=0, \mathbf{q}, \mathbf{E})$$

$\boldsymbol{\alpha}$: all Fermi level electrons contribute $\alpha = \sum_{nk} \alpha_{nk}$

Rotation in time:

precession on

current off



precession

adiabatic spin torque

Conservative torques

$$\dot{\mathbf{M}} = -\mathbf{M}\times\gamma\mathbf{H} + \alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}} - (\mathbf{v}_s\cdot\nabla)\mathbf{M} + \beta\hat{\mathbf{M}}\times(\mathbf{v}_s\cdot\nabla)\mathbf{M}$$

Dissipative torques

damping

non-adiabatic spin torque

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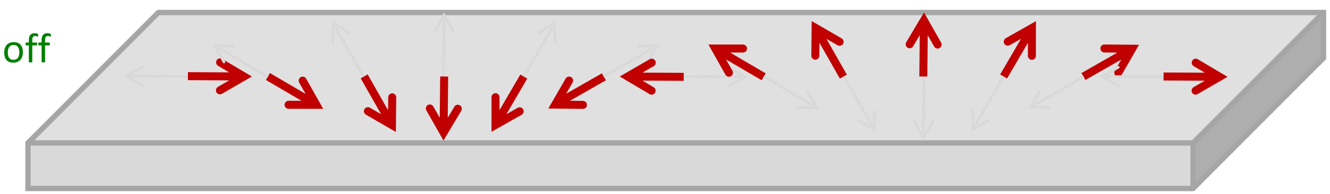
Rotation in space: →

precession off

current on



precession — adiabatic spin torque ← Conservative torques

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Dissipative torques → damping — non-adiabatic spin torque

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α: all Fermi level electrons contribute

β: Fermi level electron contributions are weighted by their velocity

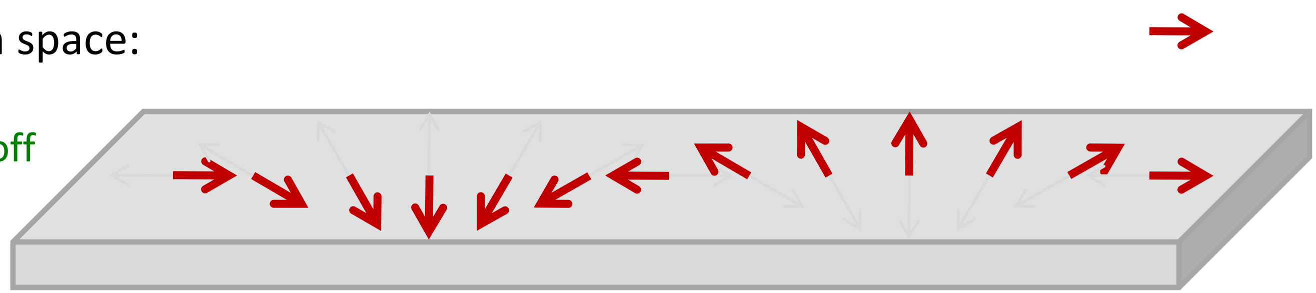
$$\alpha = \sum_{nk} \alpha_{nk}$$

$$\beta = \sum_{nk} \alpha_{nk} \frac{\mathbf{v}_{nk}}{\mathbf{v}_{\mathrm{s}}}$$

Rotation in space:

precession off

current on



precession; adiabatic spin torque ← Conservative torques

$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}} - (\mathbf{v}_{\mathrm{s}} \cdot \nabla)\mathbf{M} + \beta \hat{\mathbf{M}} \times (\mathbf{v}_{\mathrm{s}} \cdot \nabla)\mathbf{M}$$

Dissipative torques → damping; non-adiabatic spin torque

Non-adiabatic STT as extension of damping

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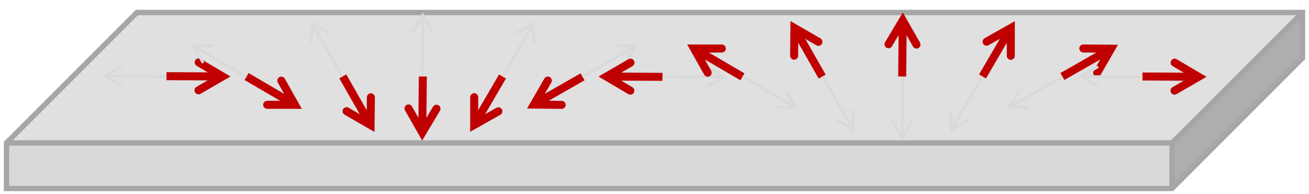
$$\frac{d\hat{s}}{dt} = \frac{\partial \hat{s}}{\partial t} + \dot{\mathbf{r}} \cdot \frac{\partial \hat{s}}{\partial \mathbf{r}}$$



$$\dot{\mathbf{M}} = -\mathbf{M} \times \gamma \mathbf{H} + \alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}} - (\mathbf{v}_s \cdot \nabla)\mathbf{M} + \beta \hat{\mathbf{M}} \times (\mathbf{v}_s \cdot \nabla)\mathbf{M}$$

precession: $-\mathbf{M} \times \gamma \mathbf{H}$

damping: $\alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}}$

adiabatic spin torque: $-(\mathbf{v}_s \cdot \nabla)\mathbf{M}$

non-adiabatic spin torque: $\beta \hat{\mathbf{M}} \times (\mathbf{v}_s \cdot \nabla)\mathbf{M}$

Conservative torques ← (precession, adiabatic spin torque)

Dissipative torques → (damping, non-adiabatic spin torque)

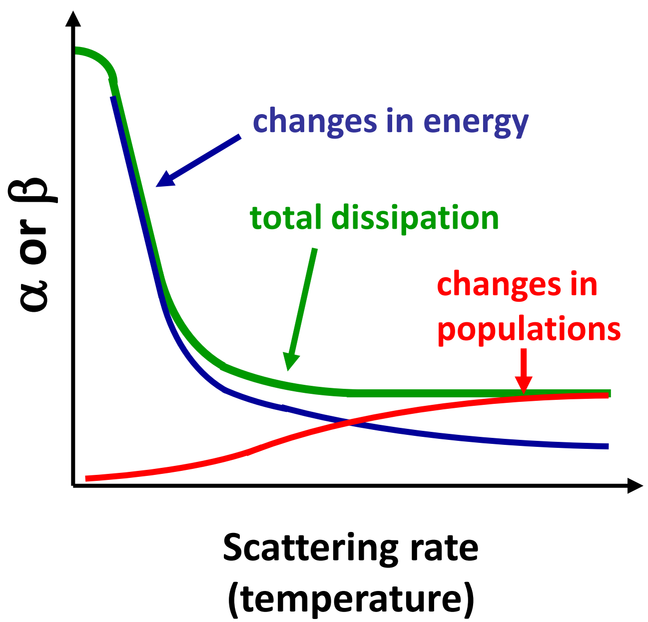
Qualitative Summary

Dissipation occurs through the spin-orbit interaction and electron-lattice scattering

α: precession dissipation parameter
β: spin-transfer torque dissipation parameter

conductivity-like breathing terms

resistivity-like bubbling terms



$$\mu_0 \mathbf{H}^{\text{eff}} = -\frac{1}{\mathrm{M}} \frac{\partial}{\partial \varphi_{\mathrm{M}}} \sum_{nk} f_{nk} \varepsilon_{nk}$$

$$\frac{d\hat{s}}{dt} = \frac{\partial \hat{s}}{\partial t} + \dot{\mathbf{r}} \cdot \frac{\partial \hat{s}}{\partial \mathbf{r}}$$

$$\beta = \sum_{nk} \alpha_{nk} \frac{\mathbf{v}_{nk}}{\mathbf{v}_{\mathbf{s}}}$$

Newton’s apple tree
England

Descendant of
Newton’s apple tree
NIST, Maryland

HAPPY BIRTHDAY!

Thanks for the chaotic upbringing

END

Damped expectations for the second generation


YELLOWSTONE