Pumping Iron:
Revealing Counterintuitive Mechanisms of Magnetization Dynamics

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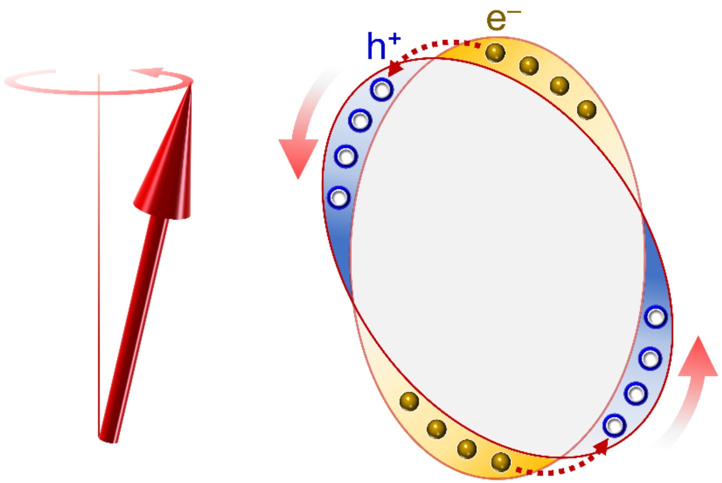


IEEE Magnetics Society Distinguished Lecture
Club Español de Magnetismo (CEMAG)
8th November, 2024

IEEE Magnetics Society

conferences

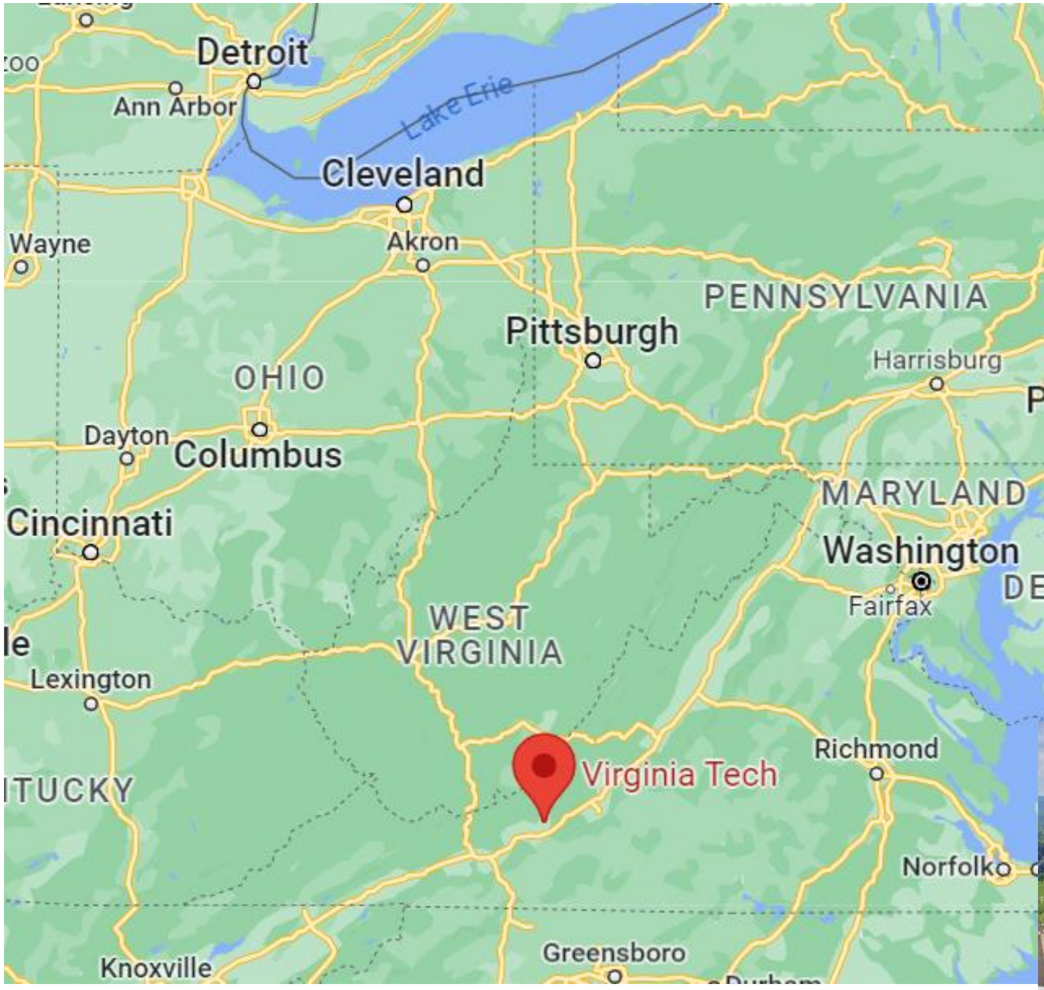
MMM
Intermag
Magnetic Recording Conference (TMRC)
Magnetic Frontiers
…

community programs

Magnetics Summer School
Students in Magnetism
Women in Magnetism
…

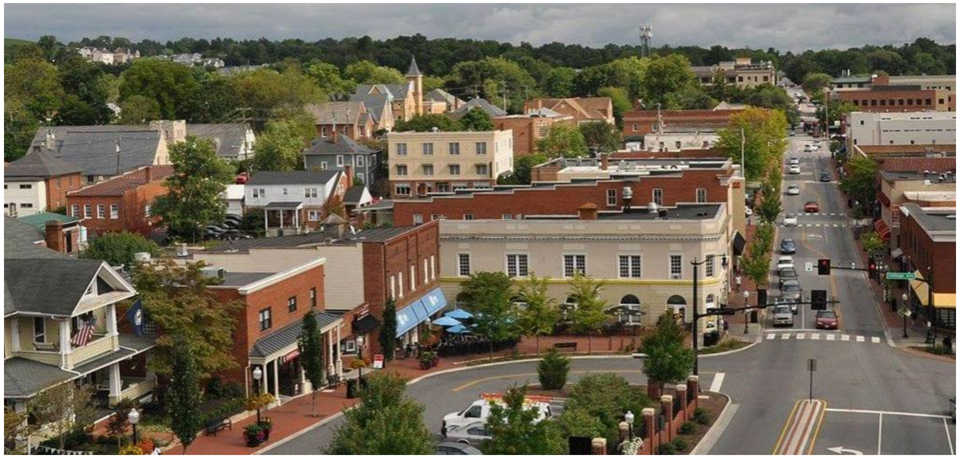
If you're doing research in magnetism, please consider becoming an IEEE Magnetics Society member!

Where is Virginia Tech?



near the Appalachian Mountains

What's it like around Virginia Tech?



Downtown Blacksburg

McAfee Knob

Rising Silo Brewery

Cascades National Recreation Trail

Dixie Caverns

Emori Lab members

Rachel Maizel (current PhD student)
Galen Street (current PhD student)
Omolara Bakare (current PhD student)
Sachli Abdizadeh (current PhD student)
Muhammad Zubair (current PhD student)

Behrouz Khodadadi (former postdoc)
Shuang Wu (former postdoc)

Youngmin Lim (former PhD student)
David Smith (former PhD student)

Collaborators

Virginia Tech
Jean Heremans, Zijian Jiang, **Dwight Viehland**, Min Gao, Jie-Fang Li, **Marc Michel**, Jing Zhao

all FMR measurements in this presentation

University of Alabama
Tim Mewes, Claudia Mewes, Anish Rai, Bhuwan Nepal, Arjun Sapkota, Abhishek Srinivasta, **Adam Hauser**, Sujan Budhathoki

University of Virginia
Prasanna Balachandran, Timothy Hartnett

Advanced Light Source
Christoph Klewe, Padraic Shafer

NIST Center for Neutron Research
Alexander Grutter, Purnima Balakrishnan

ISIS Neutron and Muon Source
Andrew Caruana, Christy Kinane

“Pumping Iron”?

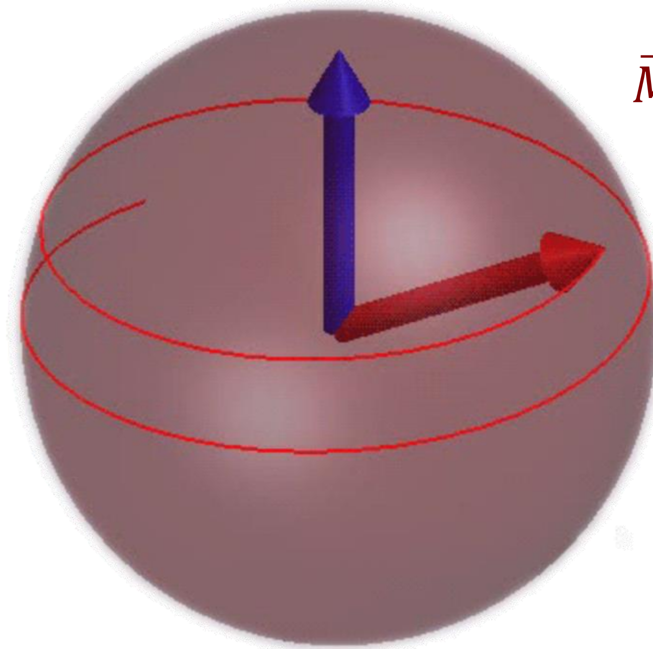
exciting magnetization in ferromagnetic material (e.g., thin film of iron) with microwave, etc.

“Pumping Iron”?

exciting magnetization in ferromagnetic material (e.g., thin film of iron) with microwave, etc.

$\vec{H}_{eff}$: effective field

$\vec{M}$: magnetization



precession
(rotation about field)

Gilbert **damping**
(aligning along field)

animation courtesy of Profs. C. Mewes & T. Mewes

Outline

- Gilbert damping: basics, applications, measurement
- Highly crystalline iron (Fe) films as model systems
- Experimental results on Gilbert damping
- Mechanism for observed Gilbert damping & comparison with published calculations

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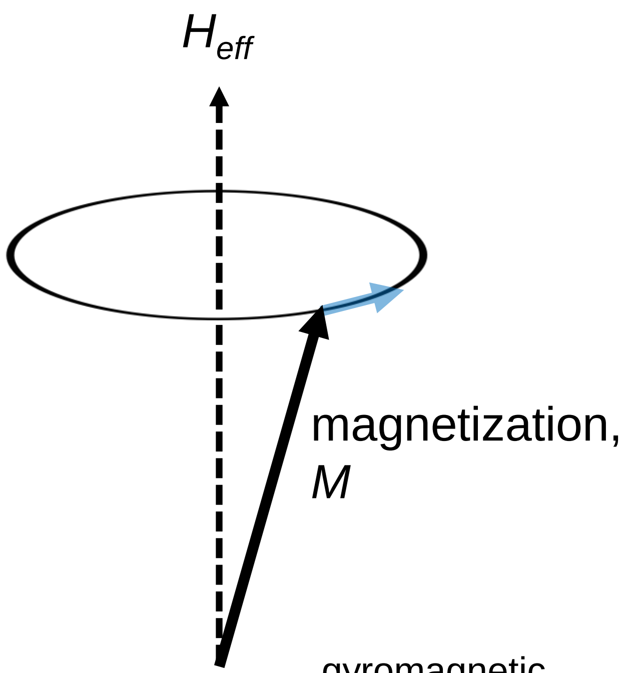
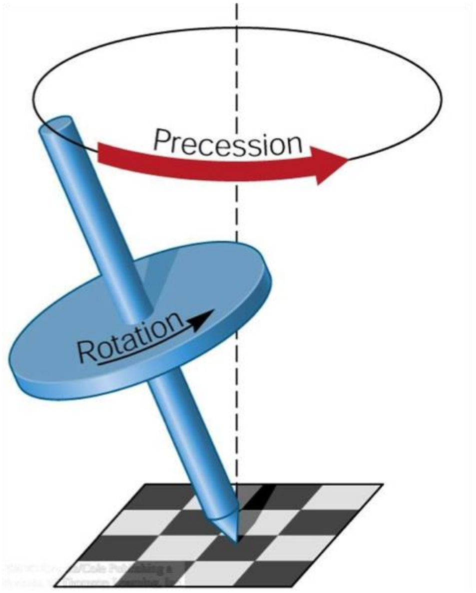
Magnetic precession

Magnetization precesses about effective magnetic field H_{eff}

(precessing top)

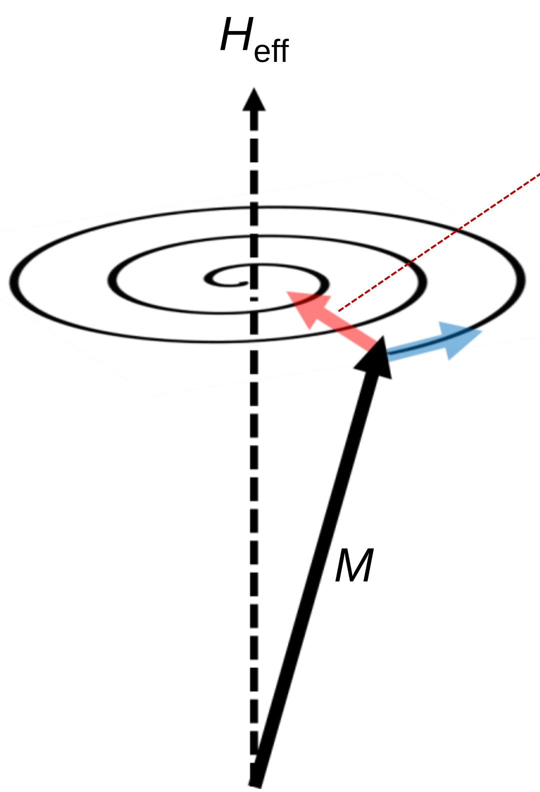




gyromagnetic ratio

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{eff}$$

Gilbert damping



In *all* real magnetic materials,
damping relaxes magnetization → H_{eff}
(time scale: ~ ps – ns)

damping allows for *magnetizing* materials

Gilbert damping parameter

$$\frac{\partial \vec{M}}{\partial t} = \underbrace{-\gamma \vec{M} \times \vec{H}_{eff}}_{\text{precessional torque}} + \underbrace{\frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t}}_{\text{Gilbert damping torque}}$$

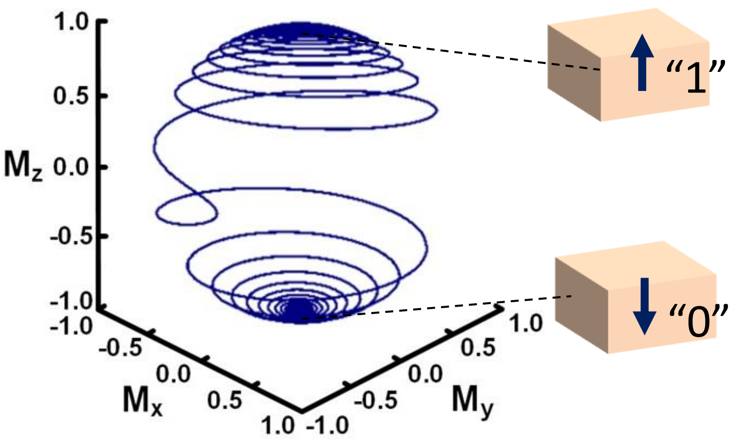
Landau-Liftshitz-Gilbert equation:
net torque on magnetization M

Low Gilbert damping for applications

lower damping = lower loss

energy-efficient information/signal processing

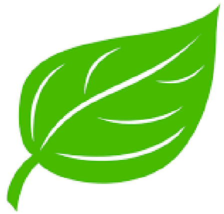
magnetization switching
(magnetic memories)



http://cspin.umn.edu/news/newsletters/newsletter_aug2014.html

tradeoff

low damping
→ energy efficiency



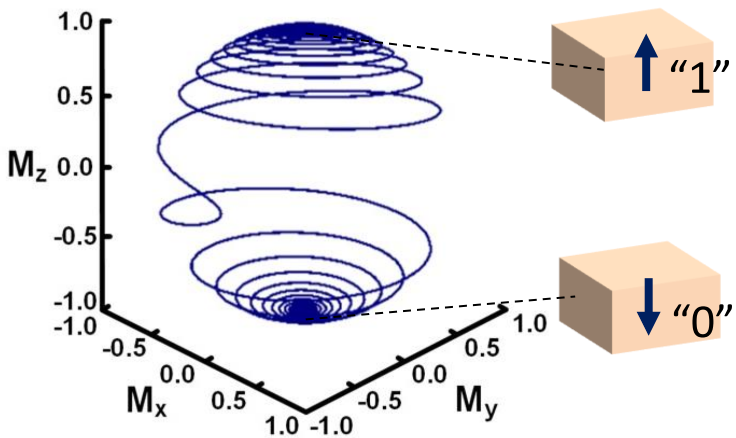
high damping
→ faster switching

Low Gilbert damping for applications

lower damping = lower loss

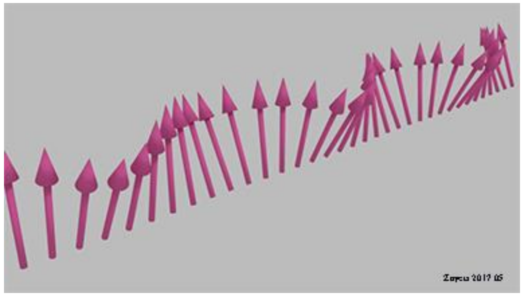
energy-efficient information/signal processing

magnetization switching
(magnetic memories)



http://cspin.umn.edu/news/newsletters/newsletter_aug2014.html

spin wave propagation
(wave computing)

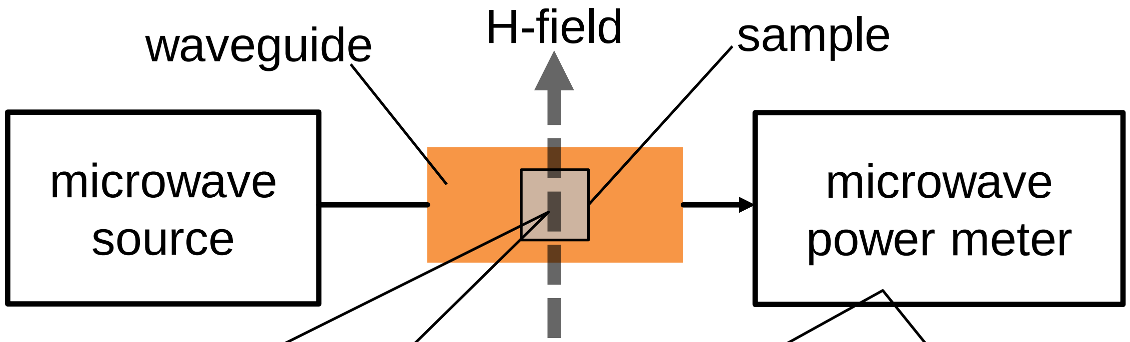


https://staff.aist.go.jp/v.zayets/spin3_47_exchange.html

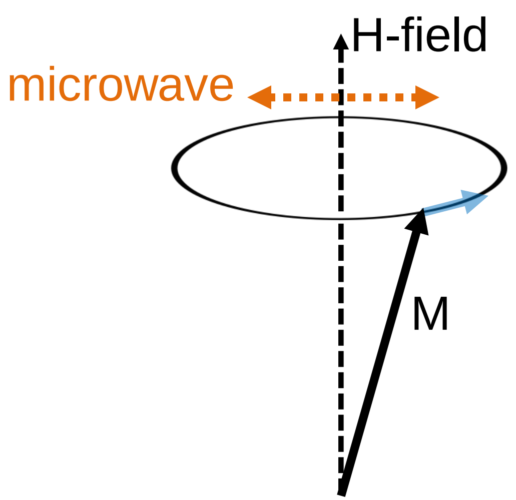
mechanisms of damping not well understood…
even in seemingly 'simple' magnetic materials

How to measure Gilbert damping

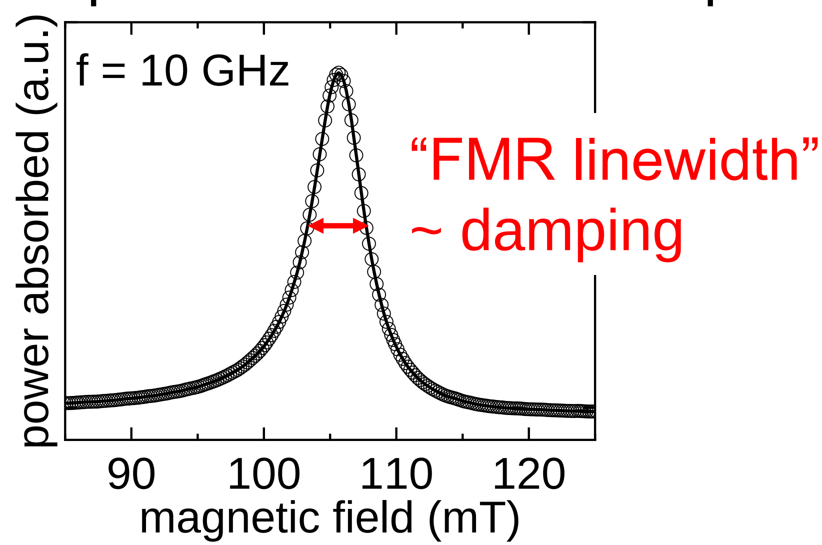
ferromagnetic resonance (FMR) spectroscopy



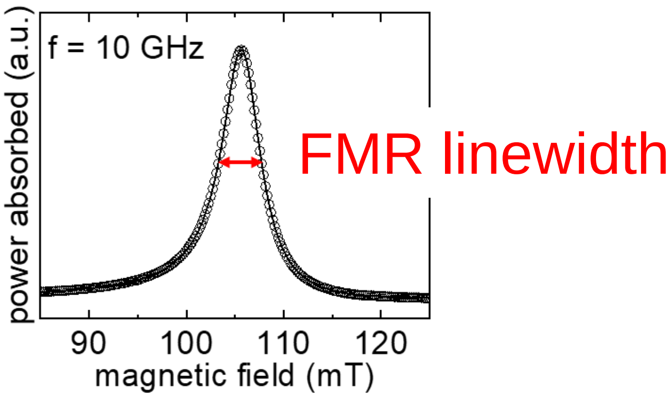
“forced oscillation” with microwave (GHz)

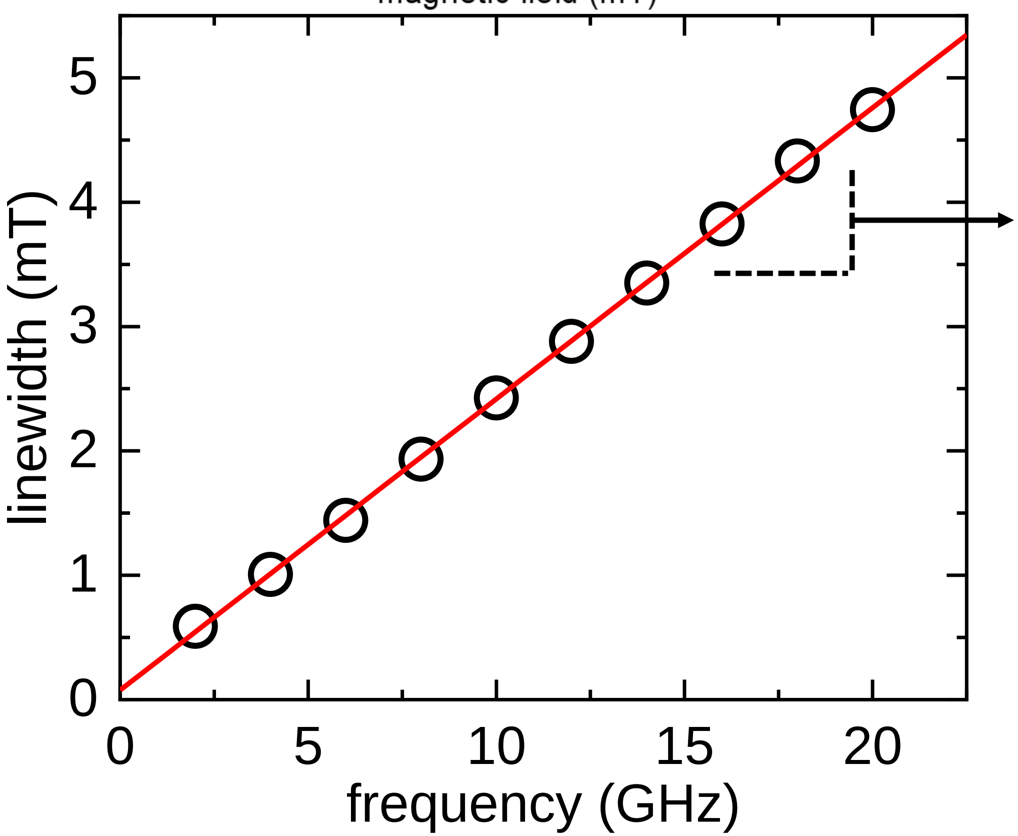


at resonance: magnetization precesses & sample absorbs microwave power



How to measure Gilbert damping





Damping parameter *α*: proportional to *slope* of linewidth vs frequency

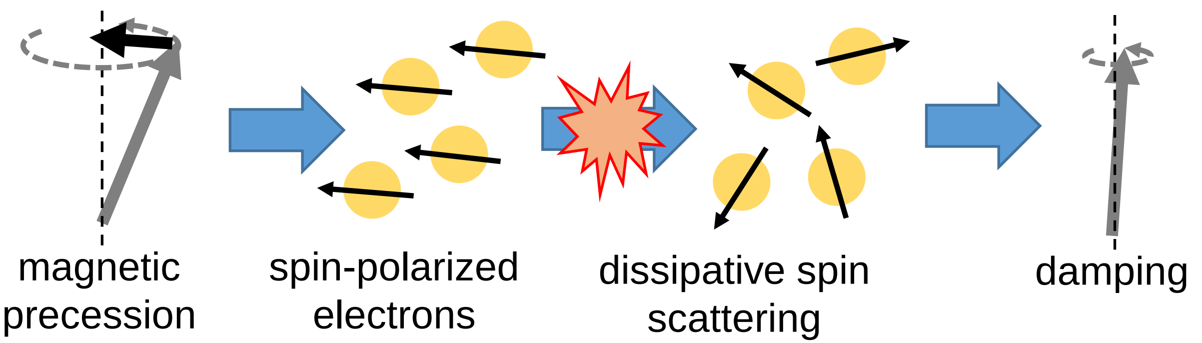
***α* ≈ 0.007** for permalloy

(*α* ~ 0.001-0.1 typical for magnetic metals)

Gilbert damping mechanism?

intuitive expectation:

less disorder, scattering
better crystalline quality
lower temperature
→ **lower damping**



Can we identify mechanisms of Gilbert damping experimentally?

Outline

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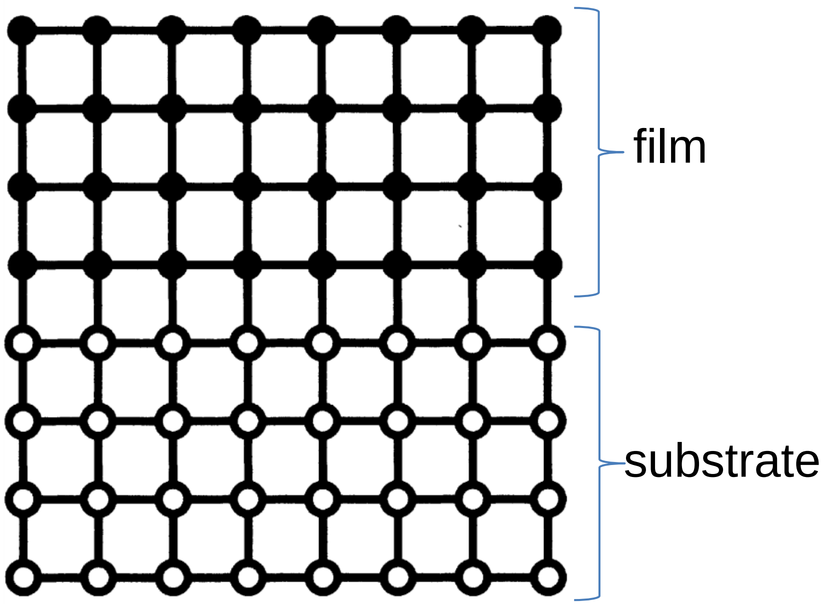
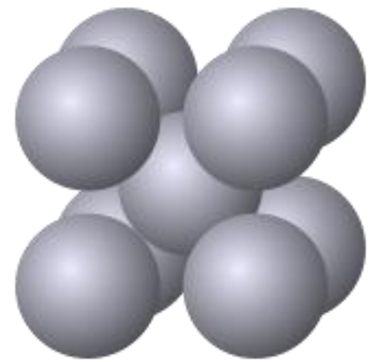
Epitaxial BCC Fe: Simple model system

Epitaxial film:
highly crystalline film grown on crystal substrate



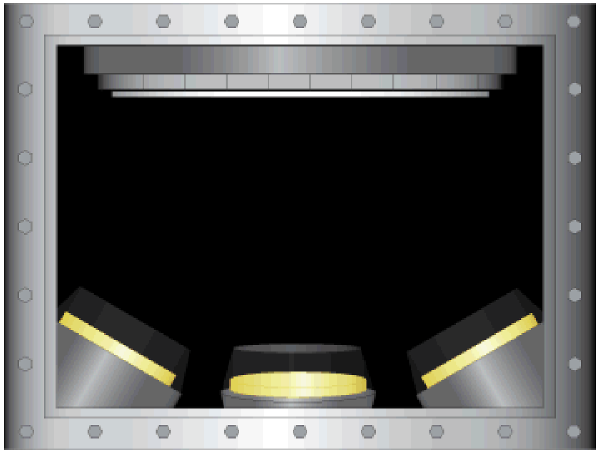
J. R. Arthur, *Surf. Sci*. 500, 189 (2002)

BCC (body-centered cubic):
crystal structure of solid Fe



Advantages:
- simple – single element!
- commercially available lattice-matched substrates
- epitaxial films: straightforward to compare with theory

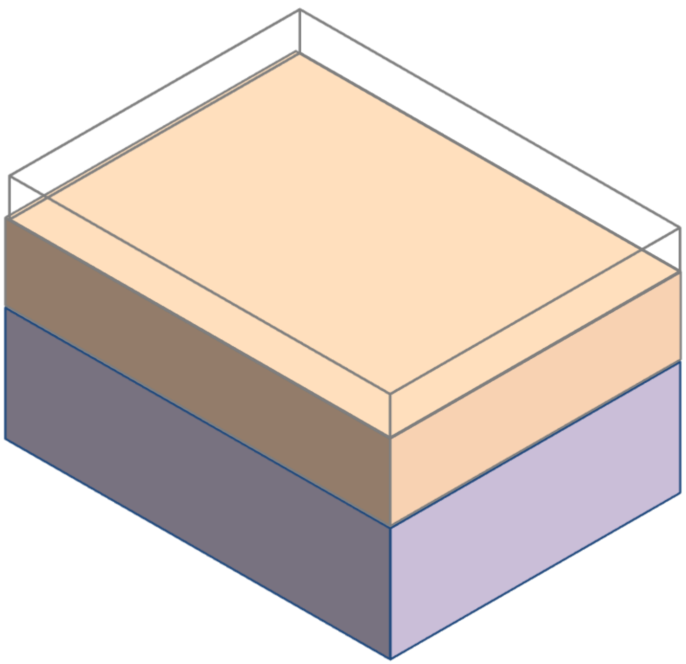
Epitaxial BCC Fe: Simple model system



substrate held at 200 ^{o}C

Fe thin films grown by sputter deposition

http://www.ajaint.com/what-is-sputtering.html



Ti capping layer

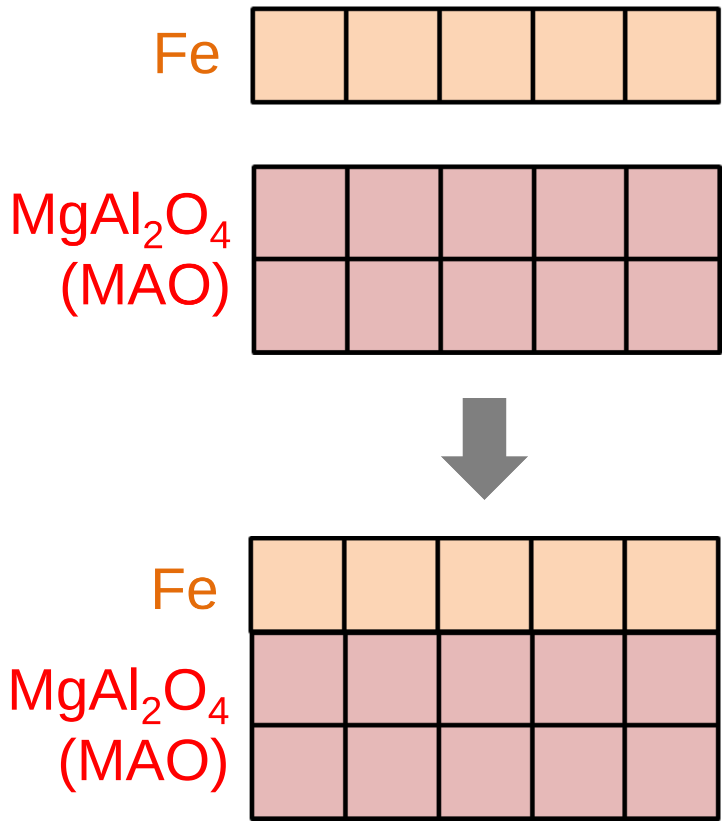
Fe 25 nm

single-crystal substrate

$MgAl_2O_4$ (MAO), MgO

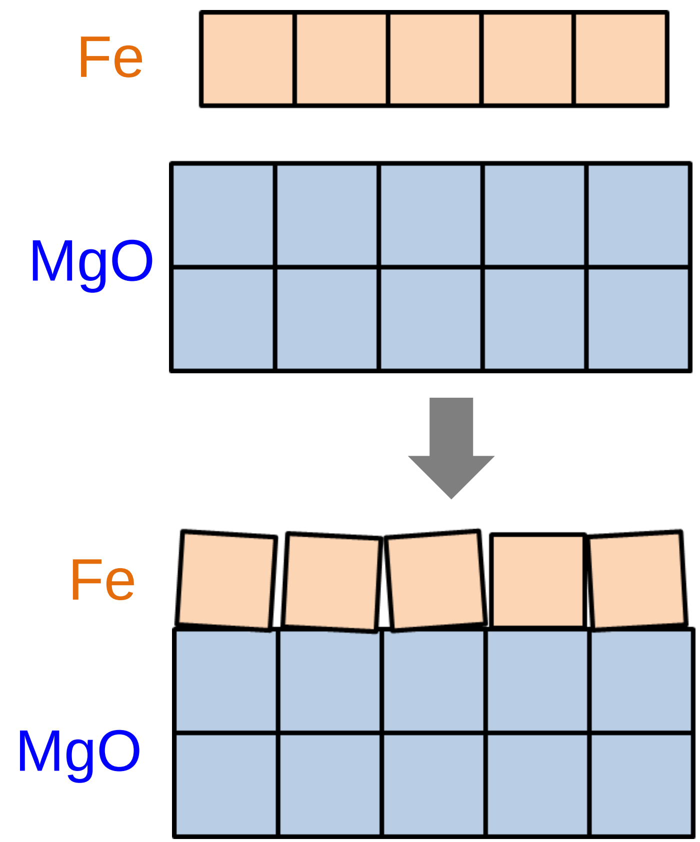
Model systems: oxide-substrate/epi-Fe

< 0.4% lattice mismatch



MAO/Fe: coherently strained
(better crystallinity)

≈ 4% lattice mismatch

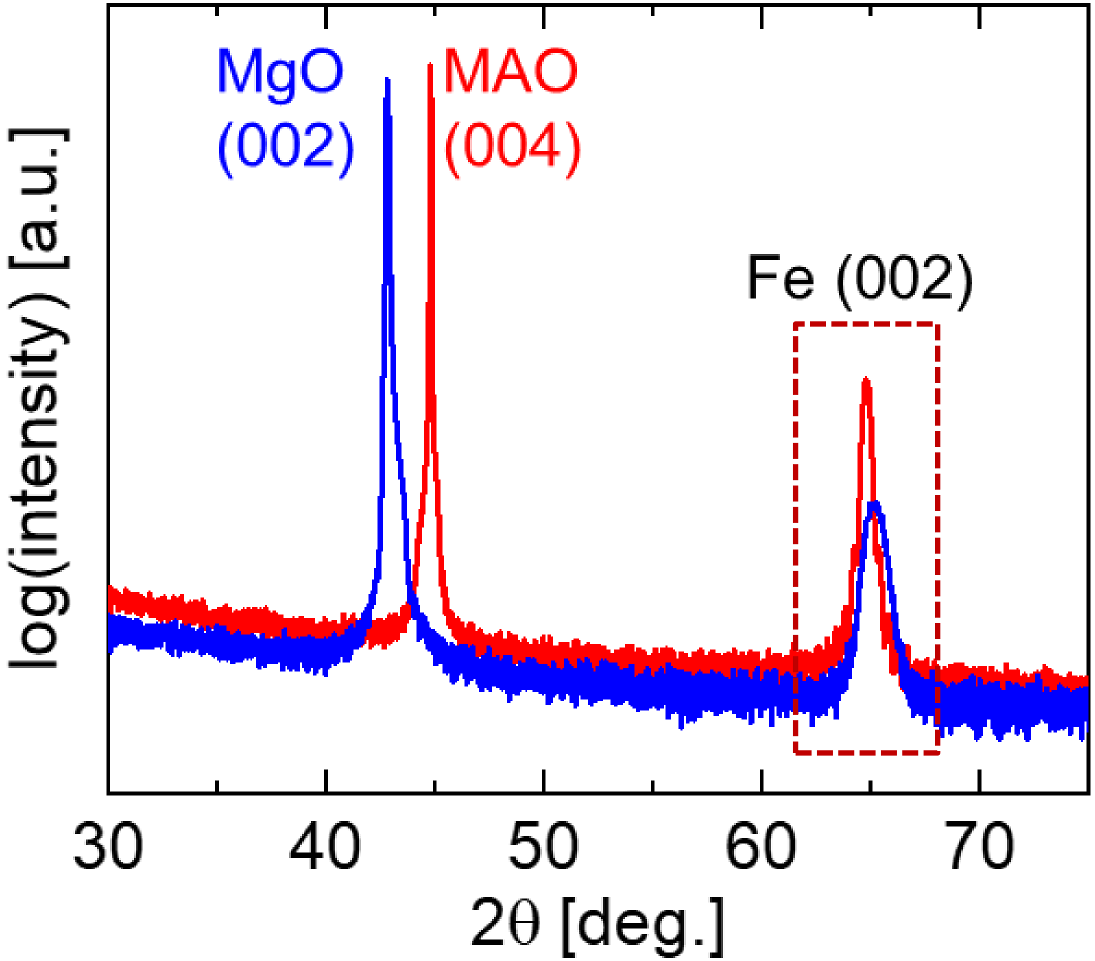


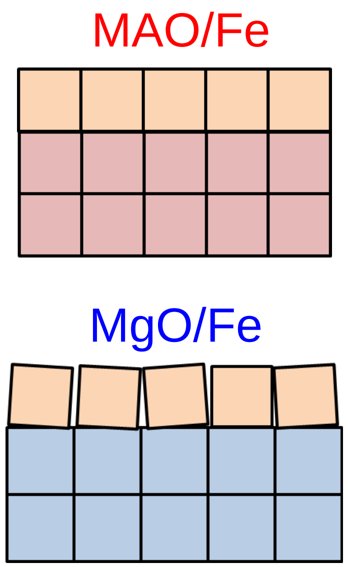
MgO/Fe: relaxed
(poorer crystallinity)

Inspired by A. Lee *et al. Nat. Commun*. **8**, 234 (2017)

Epitaxy of Fe films

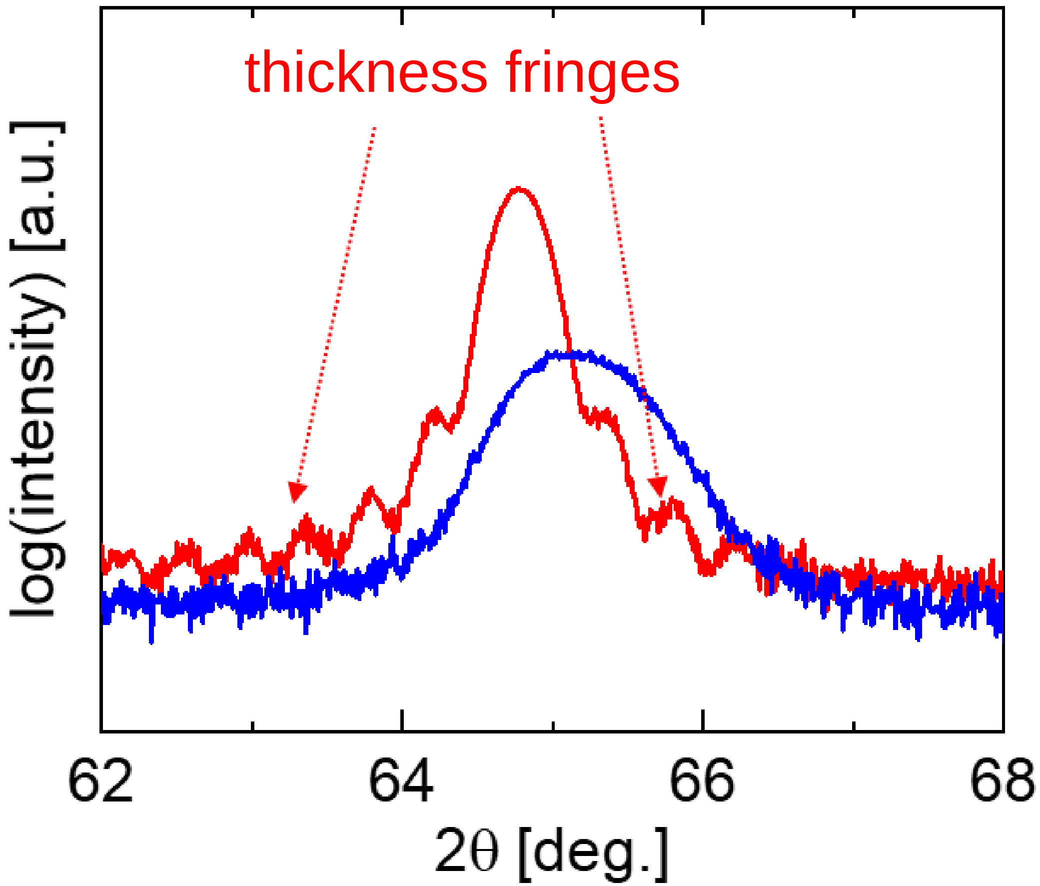
X-ray diffraction confirms epitaxial growth;
no secondary phases observed

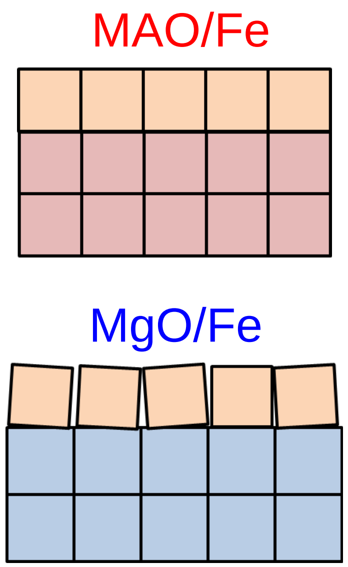




Epitaxy of Fe films

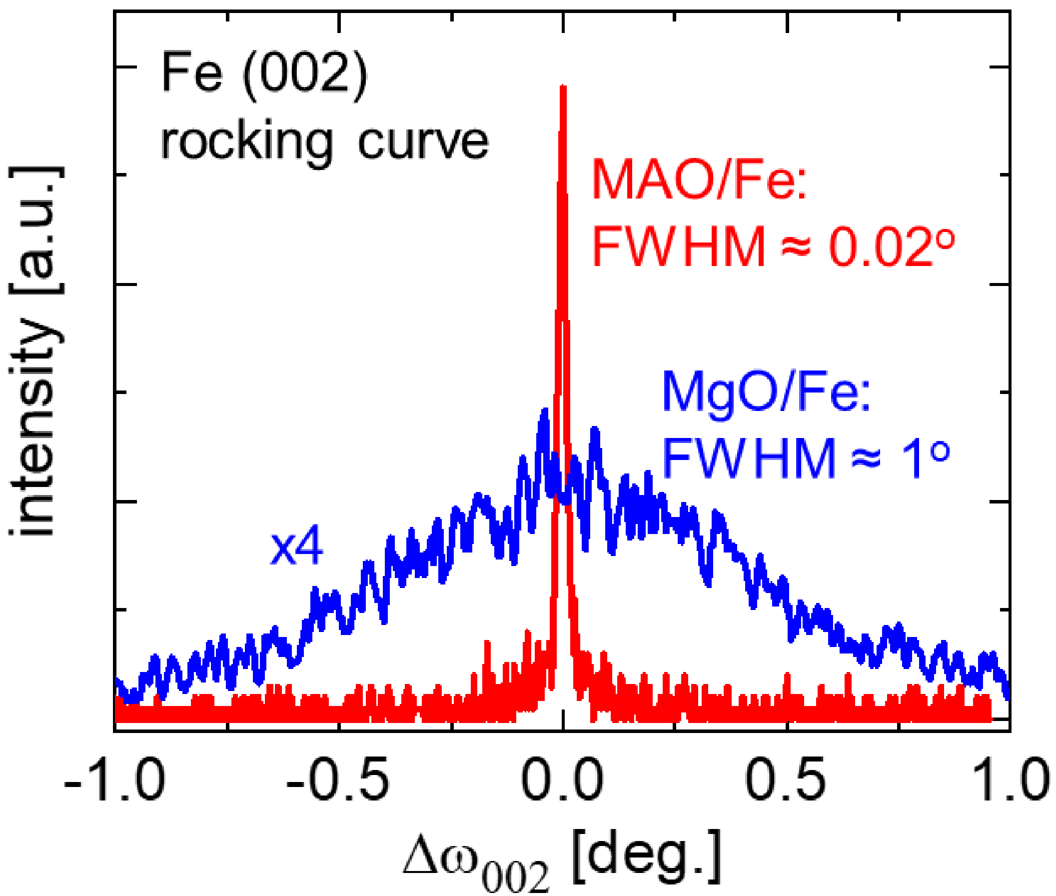
MAO/Fe exhibits better crystallinity, smoother interfaces (narrower peak & pronounced thickness fringes) than MgO/Fe

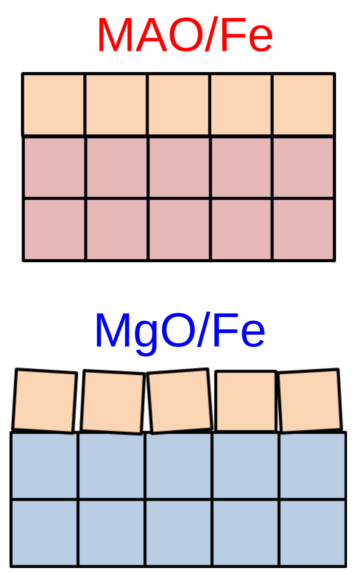




Epitaxy of Fe films

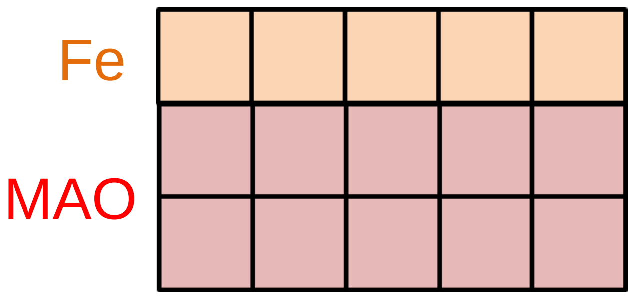
MAO/Fe exhibits better-aligned crystallites (narrower rocking curve) than MgO/Fe





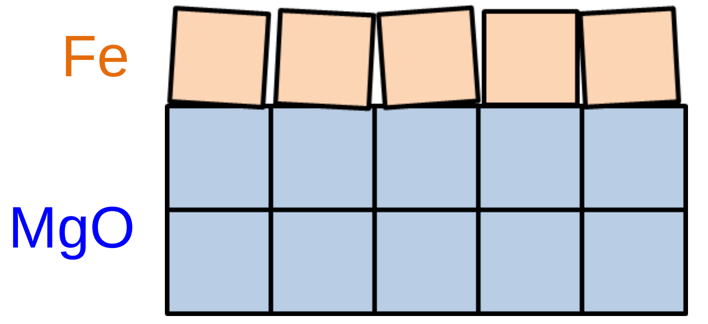
Hypothesis

Lower damping?



coherently strained
(less disorder)

Higher damping?



relaxed
(more disorder)

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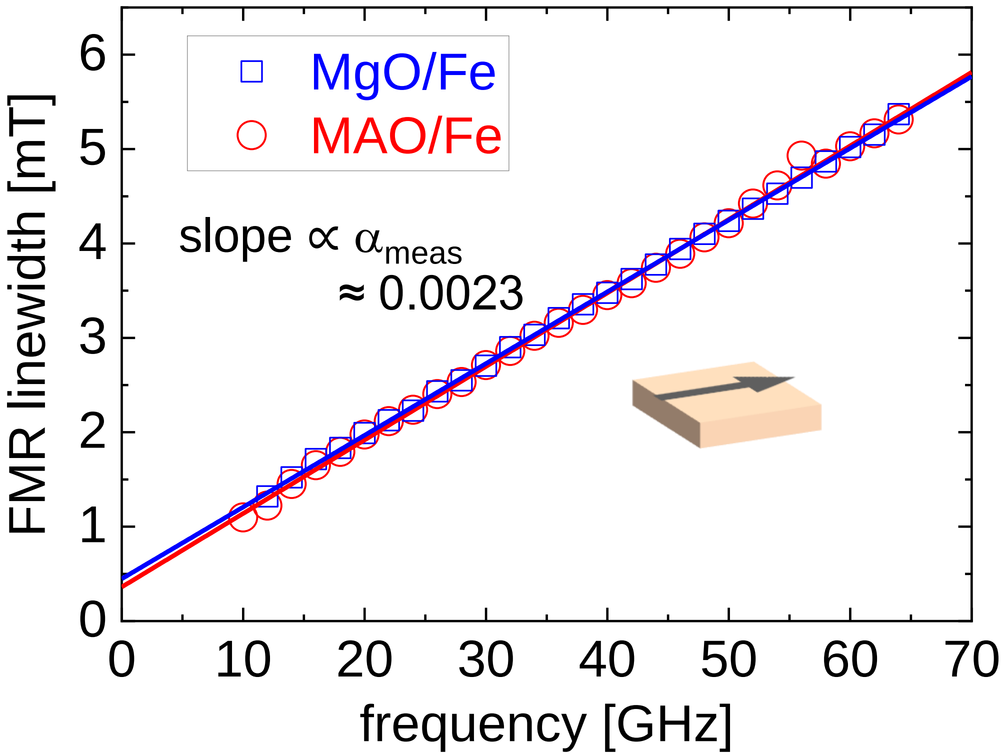
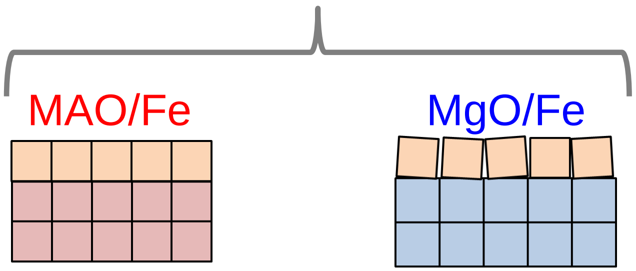
Room-temperature Gilbert damping

measured damping parameter α_{meas}
from broadband FMR



identical,
irrespective of disorder



Room-temperature Gilbert damping

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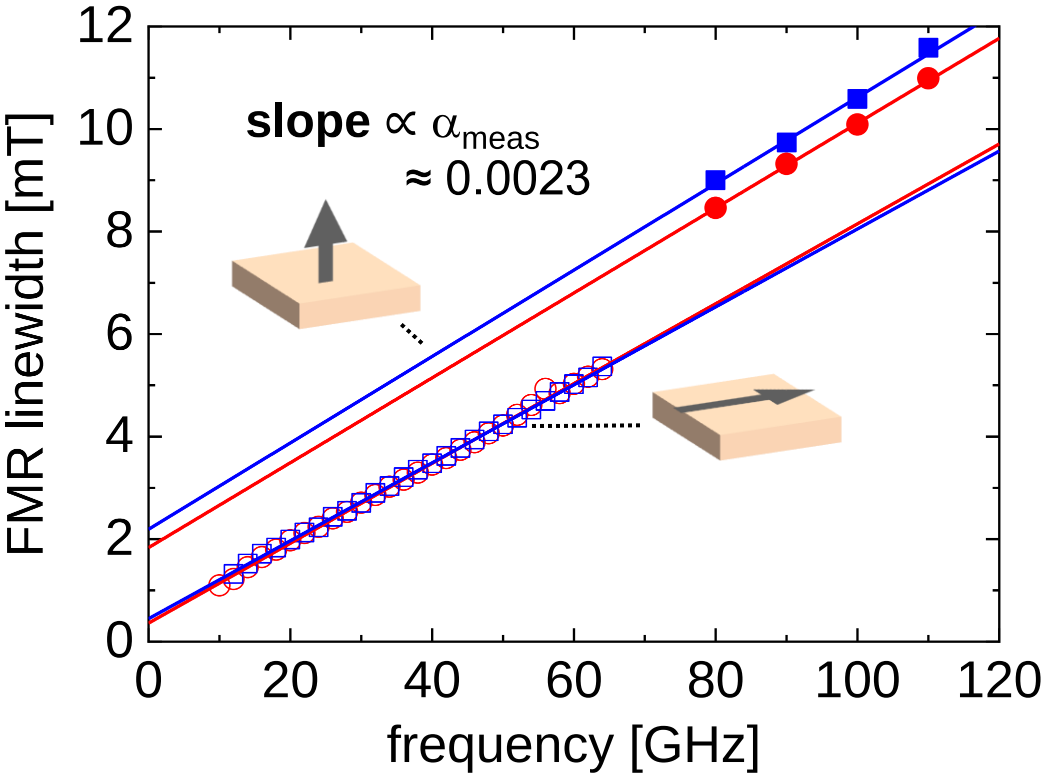
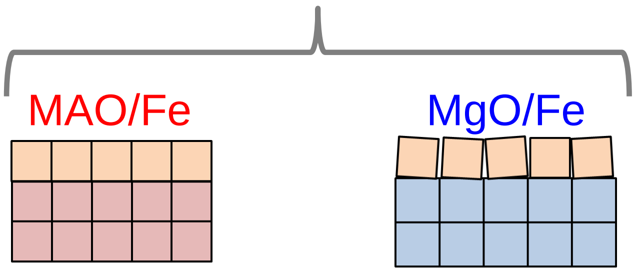


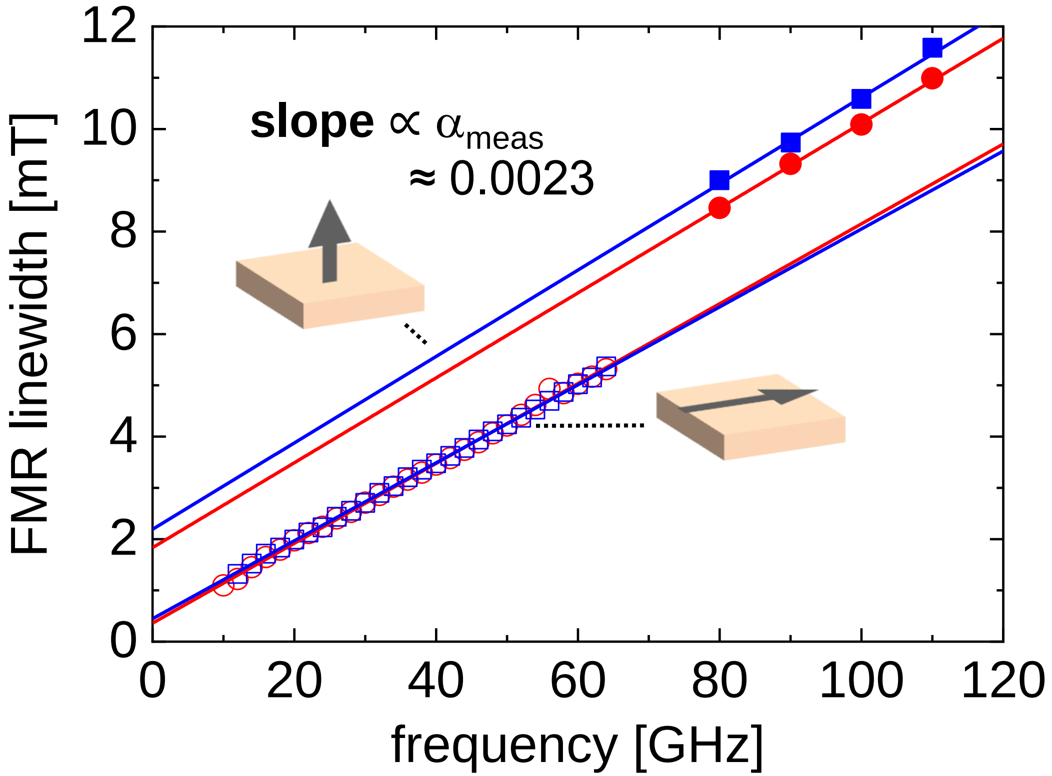
identical,
irrespective of disorder



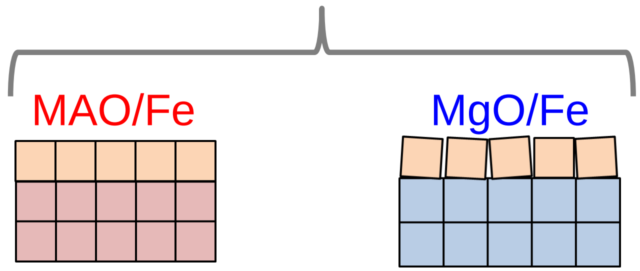
isotropic damping,
identical in & out of plane

Room-temperature Gilbert damping

measured damping parameter α_{meas}
from broadband FMR



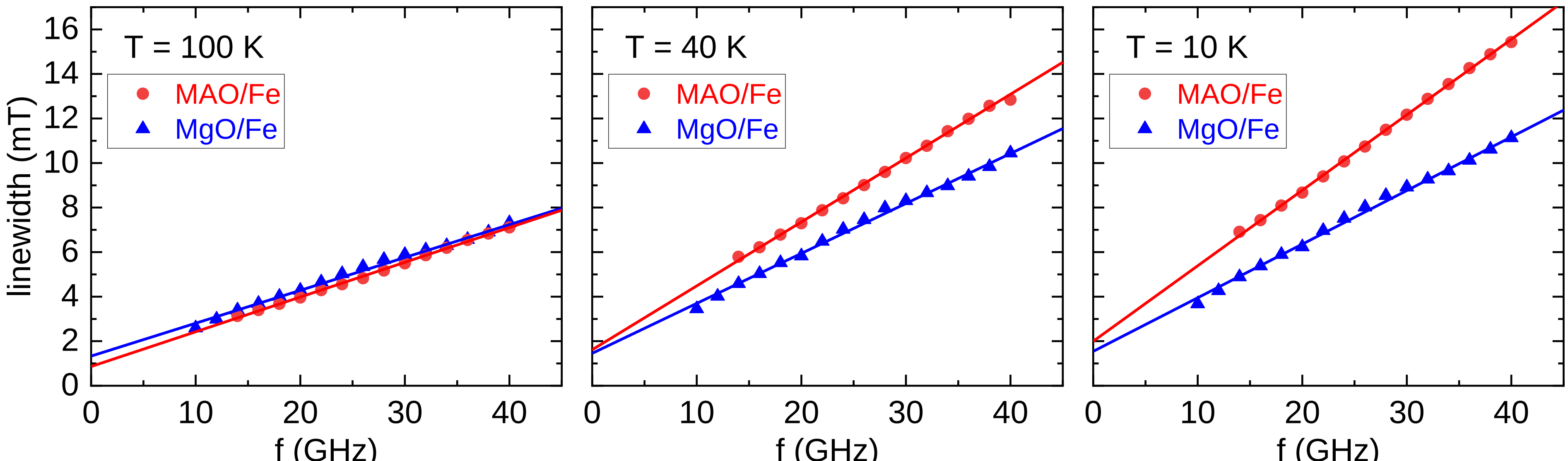
identical,
irrespective of disorder



isotropic damping,
identical in & out of plane

Gilbert damping parameter α_{meas} vs T

broadband FMR at low temperatures



MAO/Fe: $\alpha_{meas} \approx 0.0043$

MgO/Fe: $\alpha_{meas} \approx 0.0038$

MAO/Fe: $\alpha_{meas} \approx 0.0078$

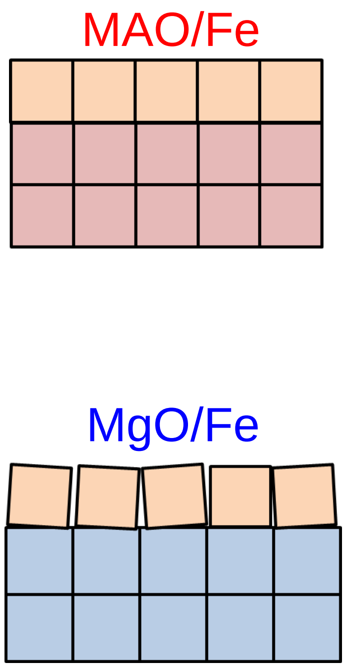
MgO/Fe: $\alpha_{meas} \approx 0.0055$

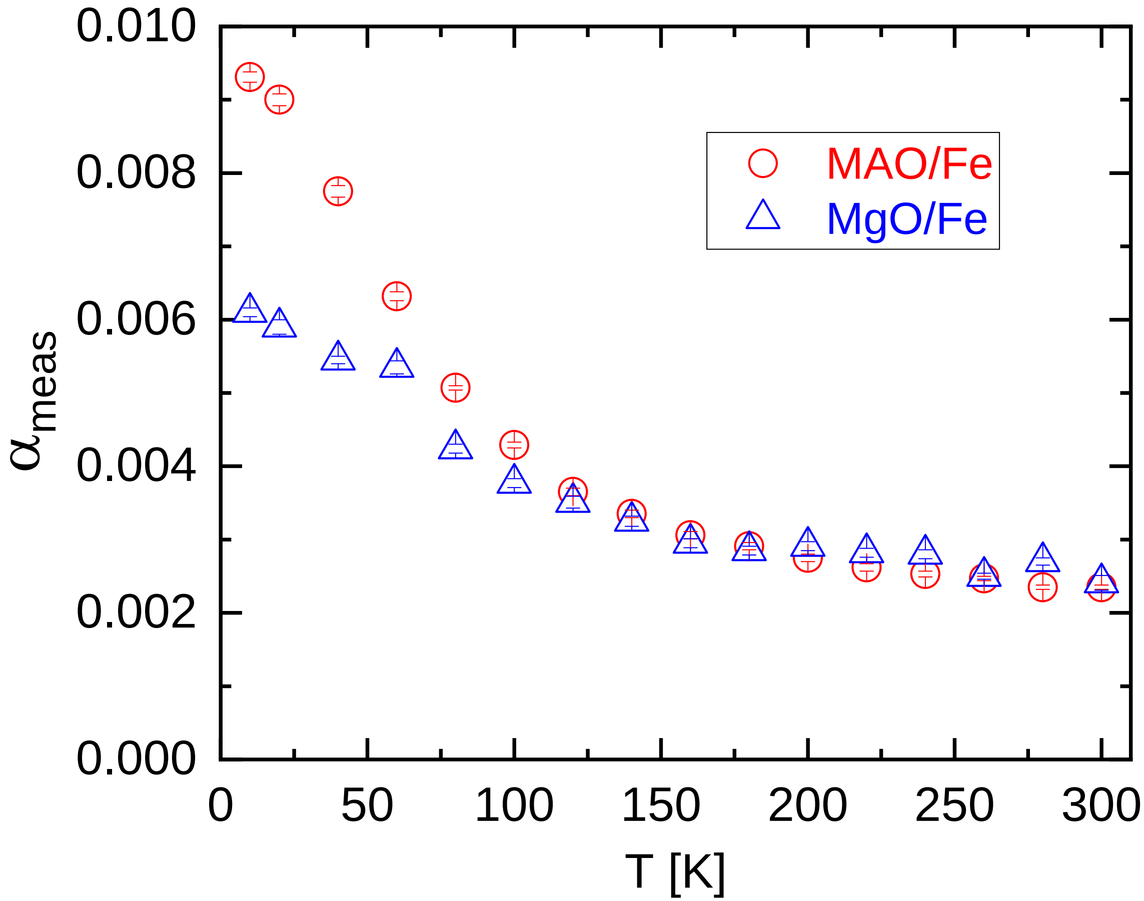
MAO/Fe: $\alpha_{meas} \approx 0.0093$

MgO/Fe: $\alpha_{meas} \approx 0.0061$

- Damping increases with decreasing temperature
  - At low T, damping is greater for MAO/Fe

Gilbert damping parameter α_{meas} vs T

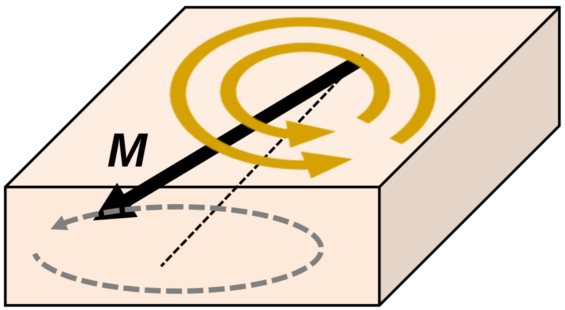




Less scattering (better crystallinity, lower T)
→ higher damping!

…Why?

Damping due to eddy currents?



$$\frac{\partial \vec{M}}{\partial t} \sim \frac{\partial \Phi_B}{\partial t} \sim I_{\text{eddy}}$$

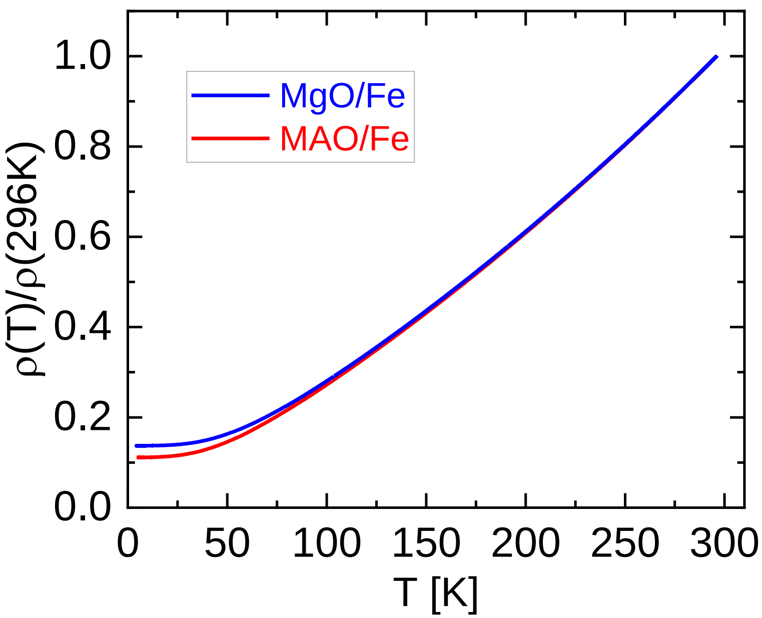
As magnetization ***M*** precesses in conductive film, some energy may be dissipated via eddy currents

lower T
→ higher conductivity σ in Fe
→ more eddy currents
→ higher eddy-current damping α_{eddy}?

$$\alpha_{\text{eddy}} \sim \sigma(T)$$

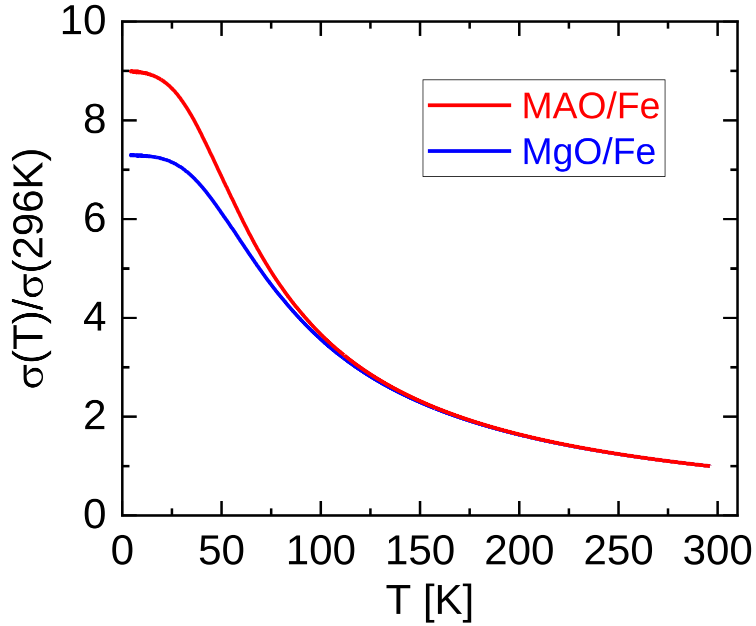
T dependence of conductivity

resistivity $\rho(T)$

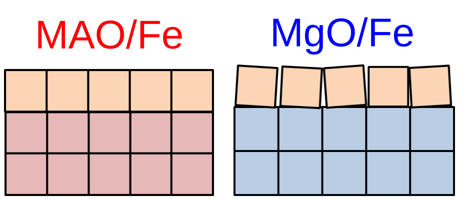


$$\rho(T) = \frac{1}{\sigma(T)}$$

conductivity $\sigma(T)$



- Conductivity σ increases significantly at lower T
- Low-T conductivity σ of MAO/Fe is ≈1.2x greater than MgO/Fe

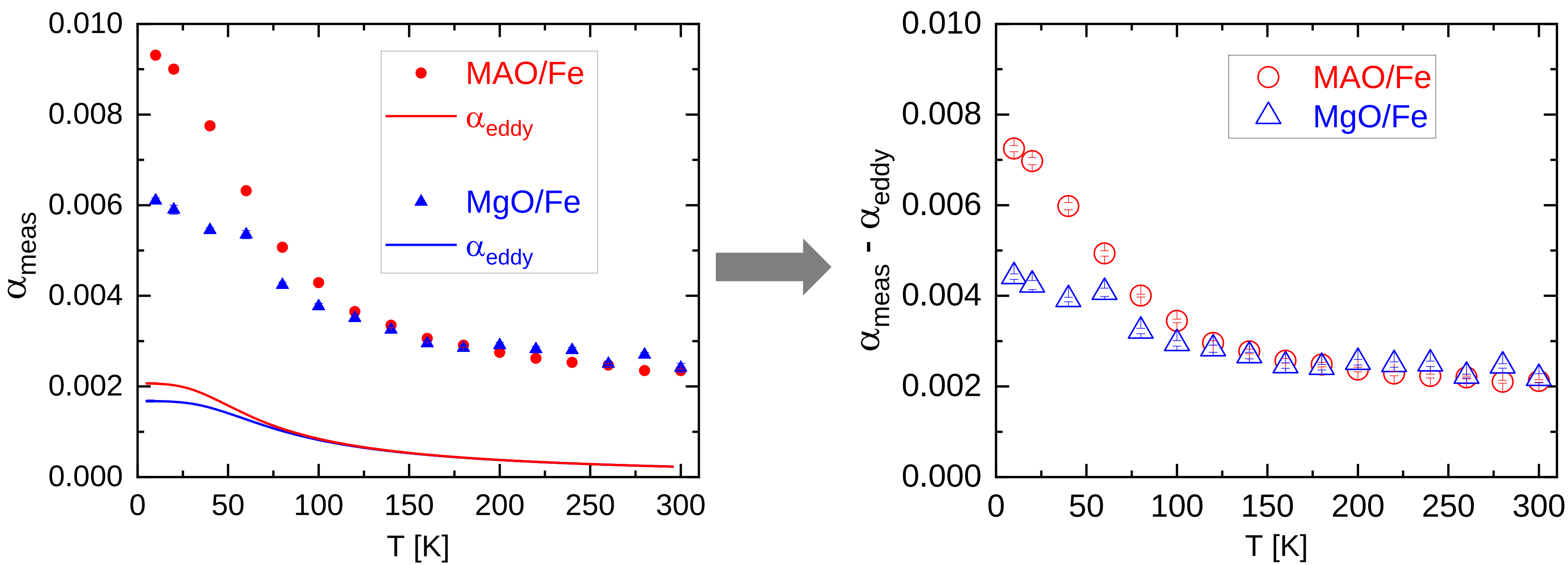


Can eddy-current damping α_{eddy} account for "less scattering = high damping"?

Accounting for eddy-current damping

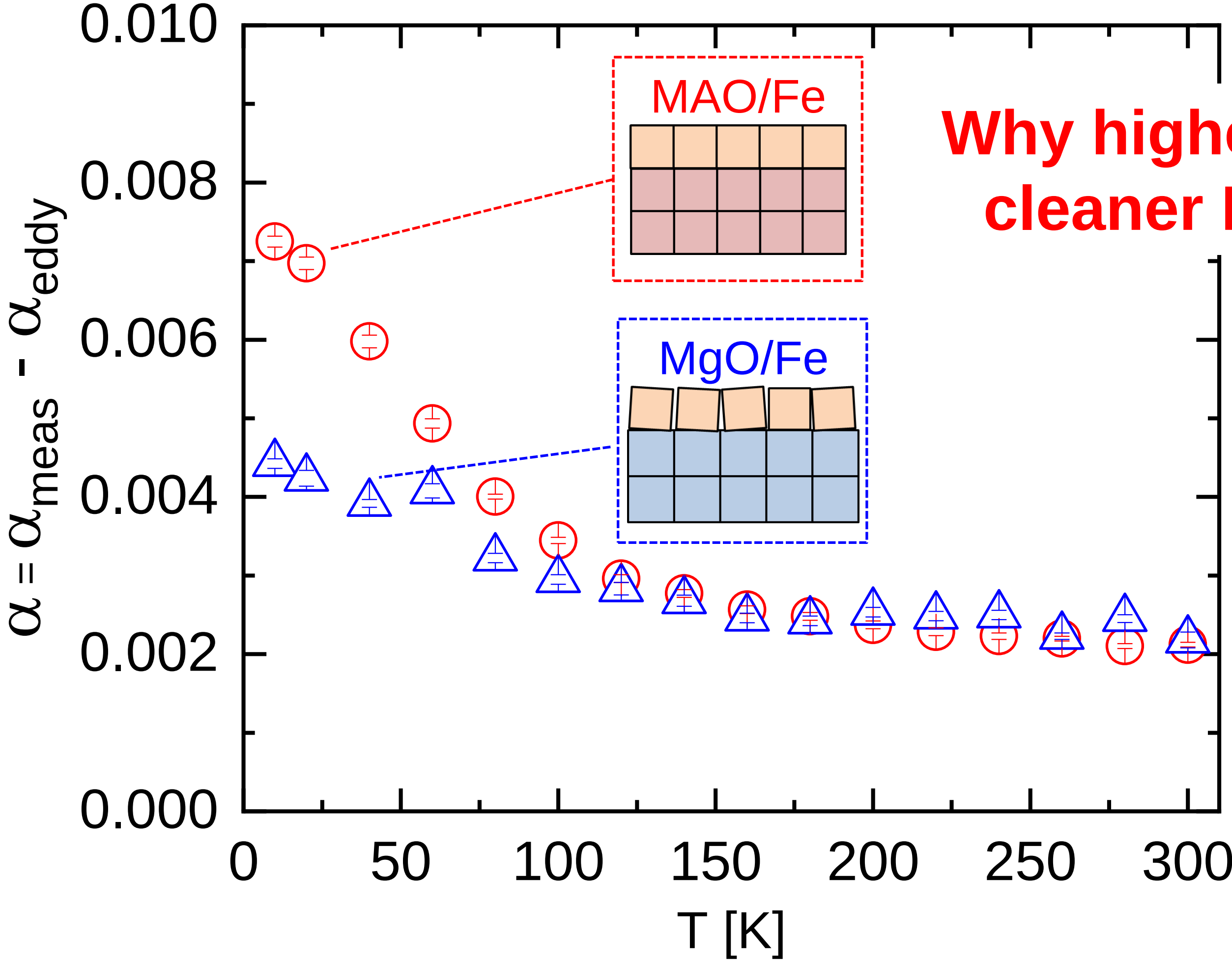
Calculated eddy-current damping α_{eddy}

J M Lock, *Br. J. Appl. Phys.* **17**, 1645 (1966)



Eddy current damping does **not** account for the entire T dependence of damping

Origin of Gilbert damping in epi-Fe?



Why higher damping for cleaner Fe at low T ?!

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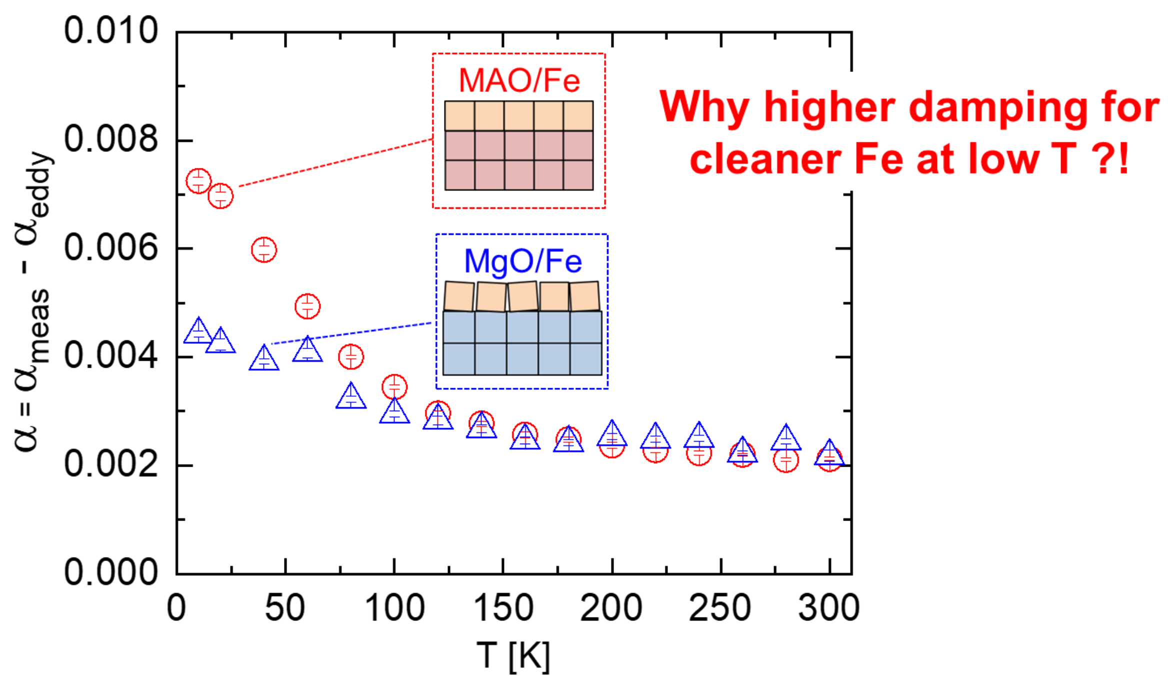
- **Mechanism for observed Gilbert damping & comparison with published calculations**



Theory: origin of Gilbert damping in metals

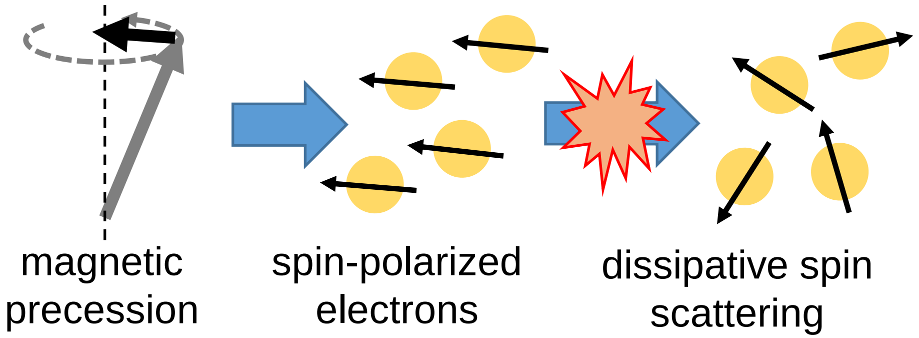
B. Heinrich, *et al. J. Appl. Phys.* **50**, 7726 (1979)
K. Gilmore, Y. U. Idzerda, & M.D. Stiles, *Phys. Rev. Lett.* **99**, 027204 (2007)

Resistivity-like damping

$$\alpha \propto \frac{1}{\tau_m} \propto \rho$$

electron momentum relaxation time

more scattering
→ higher damping



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Resistivity-like damping

$$\alpha \propto \frac{1}{\tau_m} \propto \rho$$

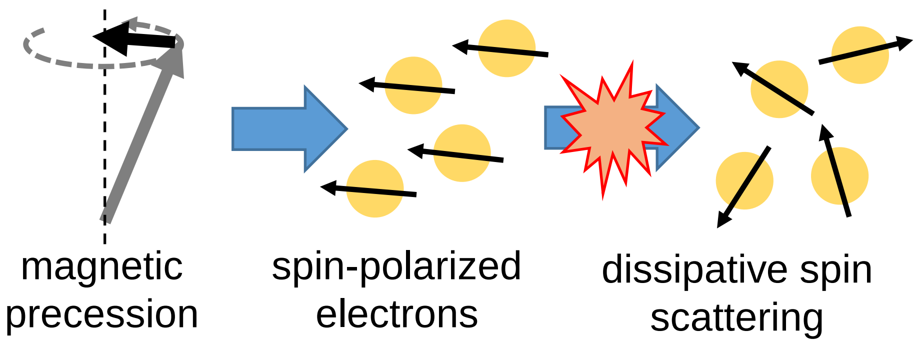
electron momentum relaxation time

Conductivity-like damping

$$\alpha \propto \tau_m \propto \sigma$$

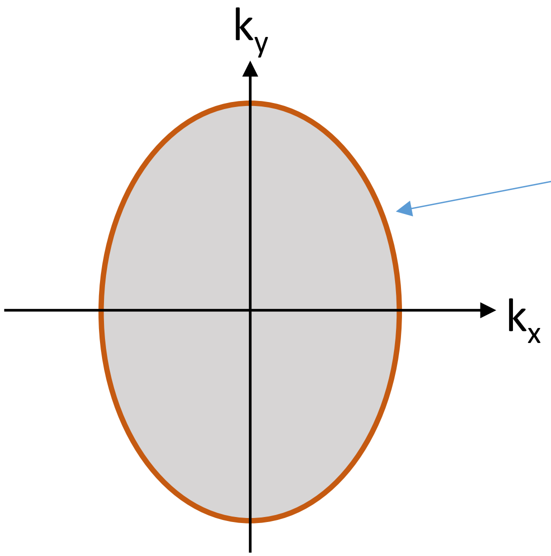
more scattering
→ higher damping

less scattering
→ higher damping



?

Conductivity-like damping from “breathing Fermi surface”

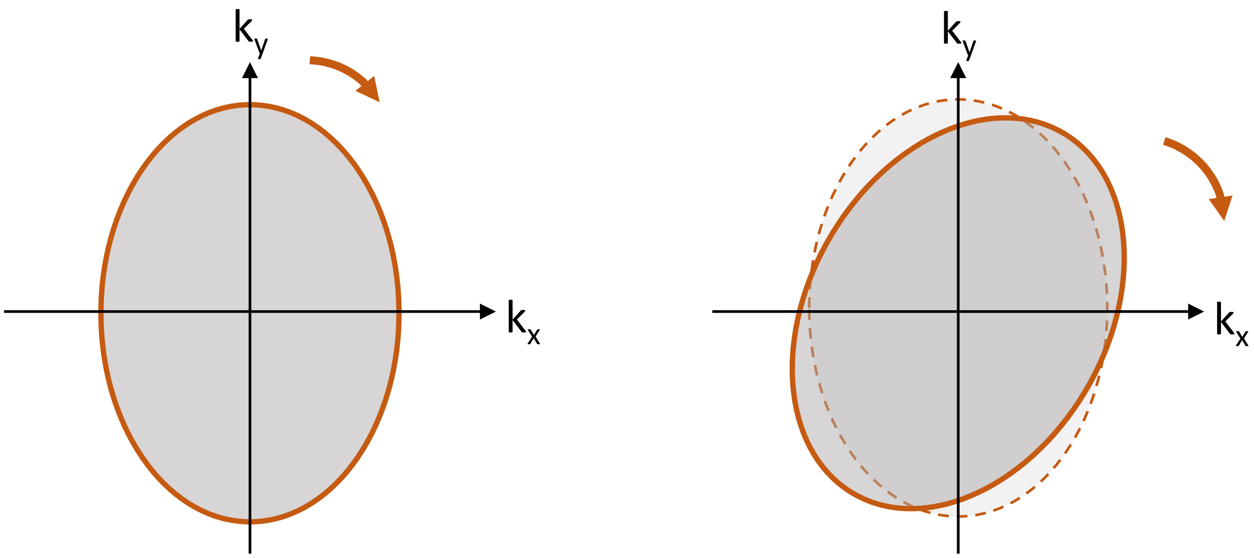


Fermi surface: highest energy states occupied by electrons, when the metal is at <u>equilibrium</u>

Cartoon inspired by J. M. Shaw, IEEE DL 2019

Conductivity-like damping from "breathing Fermi surface"

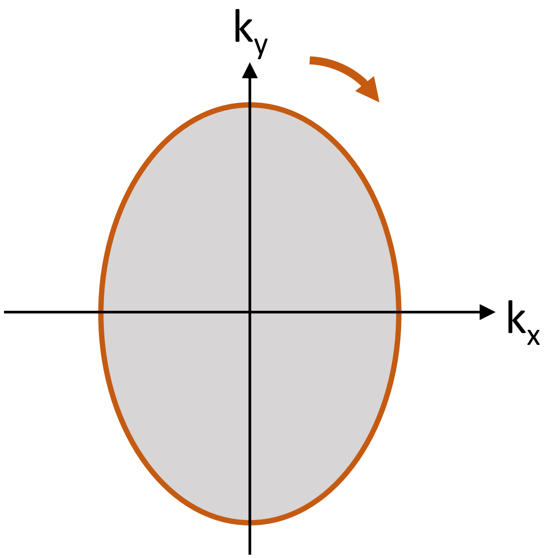
As magnetization precesses,
coupling between magnetization & electronic/orbital structure (spin-orbit coupling) distorts Fermi surface

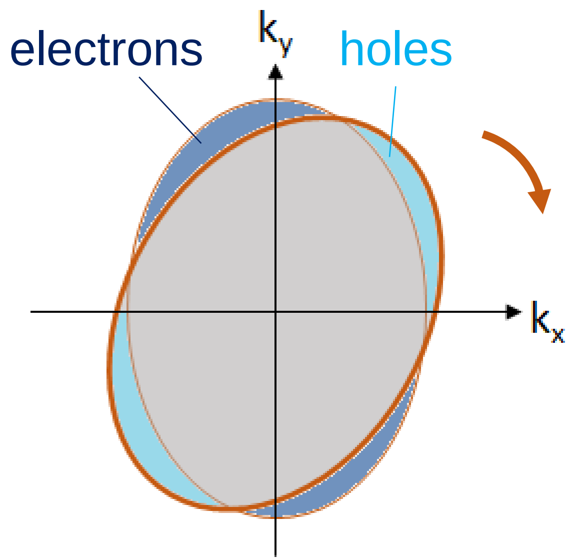


Cartoon inspired by J. M. Shaw, IEEE DL 2019

Conductivity-like damping from “breathing Fermi surface”

As magnetization precesses,
coupling between magnetization & electronic/orbital structure (spin-orbit coupling) distorts Fermi surface



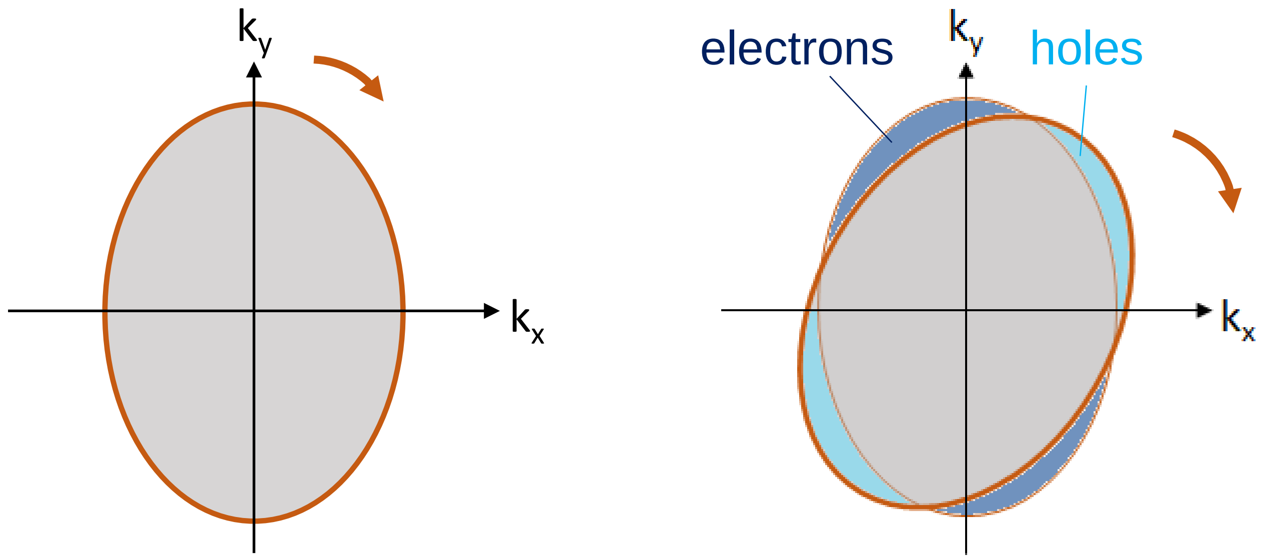


<u>Non-equilibrium</u> electron-hole pairs are generated

Cartoon inspired by J. M. Shaw, IEEE DL 2019

Breathing Fermi surface model

Non-equilibrium electron-hole pairs survive for lifetime $\sim\tau_m$, until annihilated by scattering



longer non-equilibrium electron-hole pairs survive
→ further deviation from equilibrium
→ more energy dissipated when they annihilate

conductivity-like damping:
less frequent electronic scattering (longer τ_m)
→ higher damping

Analogy for damping mechanisms…

scattering = reminders (nagging)

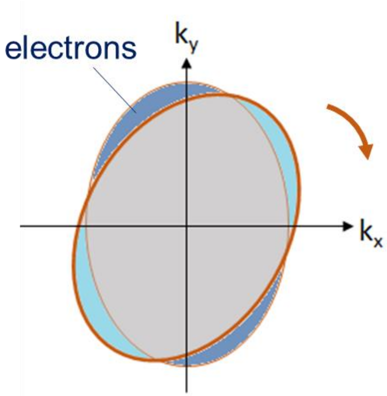
damping = stress that you feel

resistivity-like damping:
more frequent scattering
→ higher damping

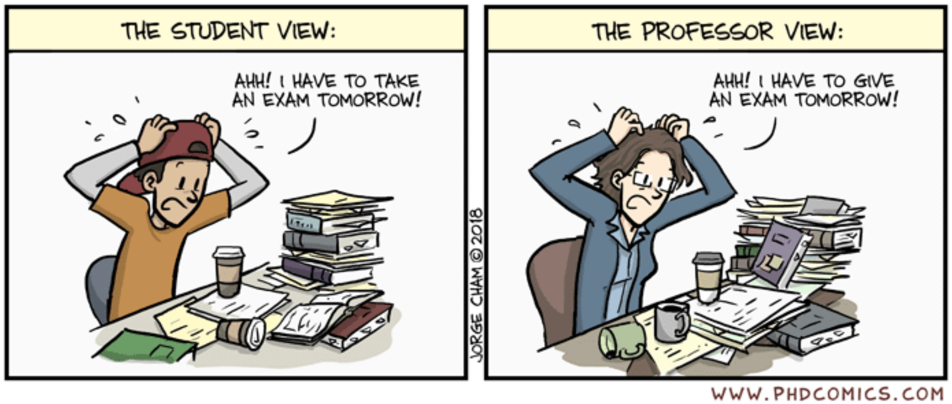
too much nagging:
more reminders
→ higher stress

conductivity-like damping:
less frequent scattering
→ higher damping

procrastinating too much:
not enough reminders
→ higher stress



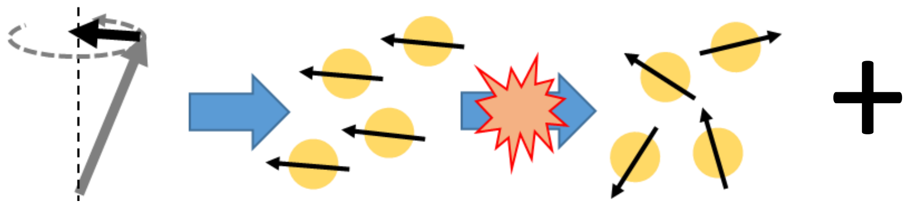
electrons "procrastinating"

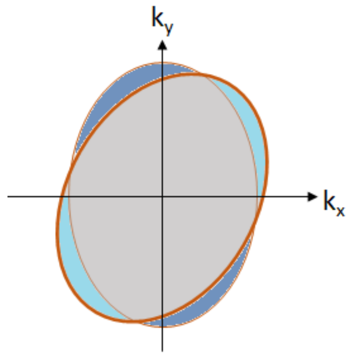


https://sites.google.com/a/vt.edu/emori/blurbs/pumping-iron

A general theoretical model

resistivity-like damping conductivity-like damping





→ Gilbert damping parameter α can be computed from realistic band structure of ferromagnetic metal crystal (e.g., BCC Fe)

Many calculation results available:

K. Gilmore, Y. U. Idzerda, & M.D. Stiles, Phys. Rev. Lett. **99**, 027204 (2007);
A. A. Starikov, et al. Phys. Rev. Lett. **105**, 236601 (2008);
Y. Liu, et al. Phys. Rev. B. **84**, 014412 (2011);
S. Mankovsky, et al., Phys. Rev. B **87**, 014430 (2013);
E. Barati, et al. EPJ Web Conf. **40**, 18003 (2013);
T. Qu & R. H. Victora, J. Appl. Phys. **115**, 17C506 (2014);
A. A. Starikov et al. Phys. Rev. B **97**, 214415 (2018);
…

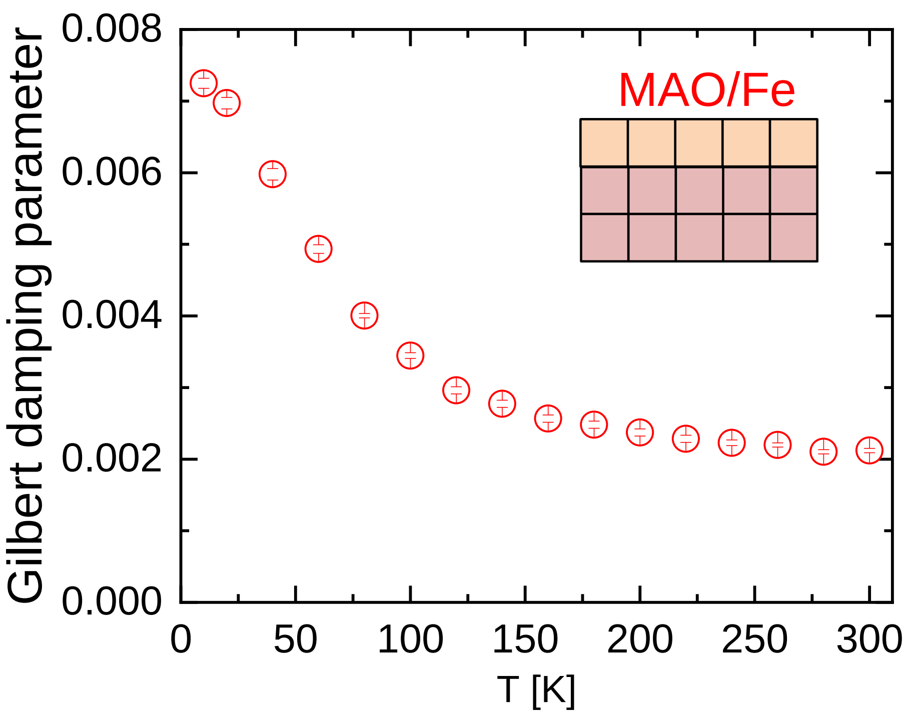
…But no experiment confirming predictions for Fe
(until 2020)

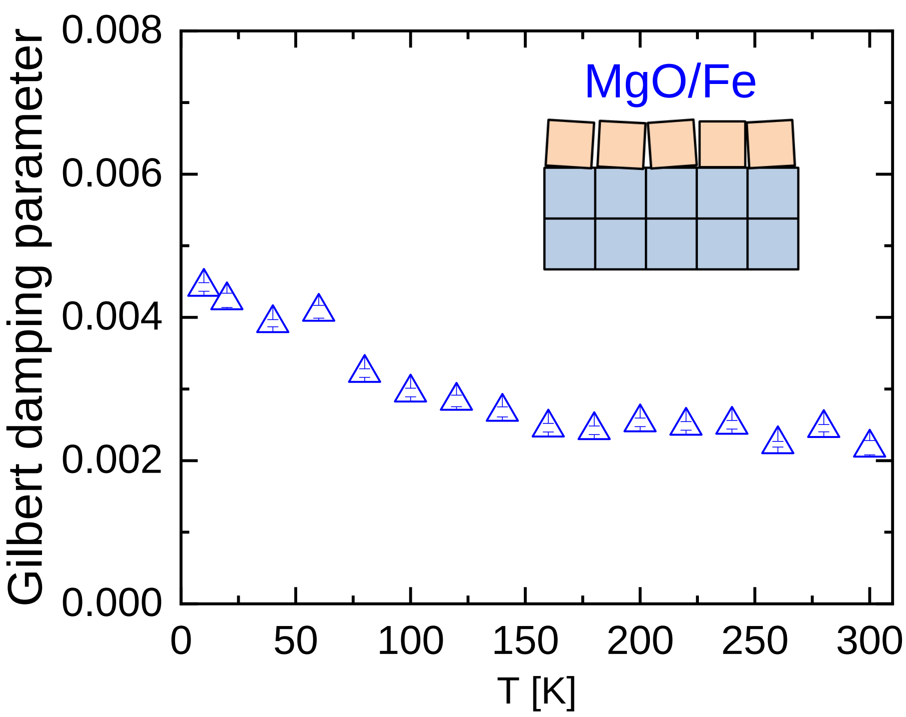
Phenomenological fit

$$\alpha = c\,\frac{\sigma(T)}{\sigma(RT)} + d\,\frac{\rho(T)}{\rho(RT)}$$

conductivity-like damping

resistivity-like damping





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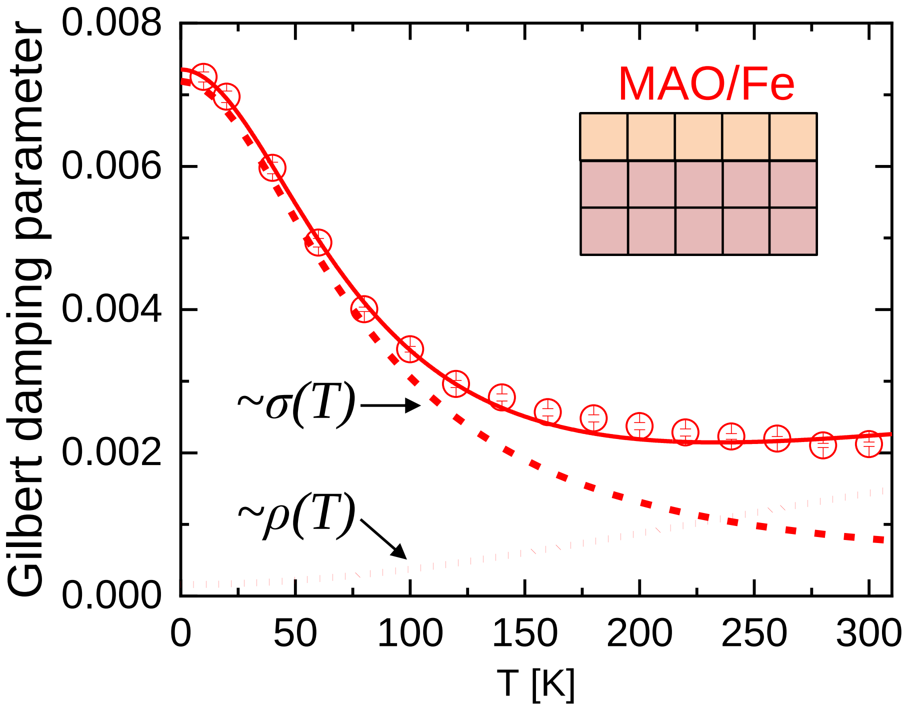
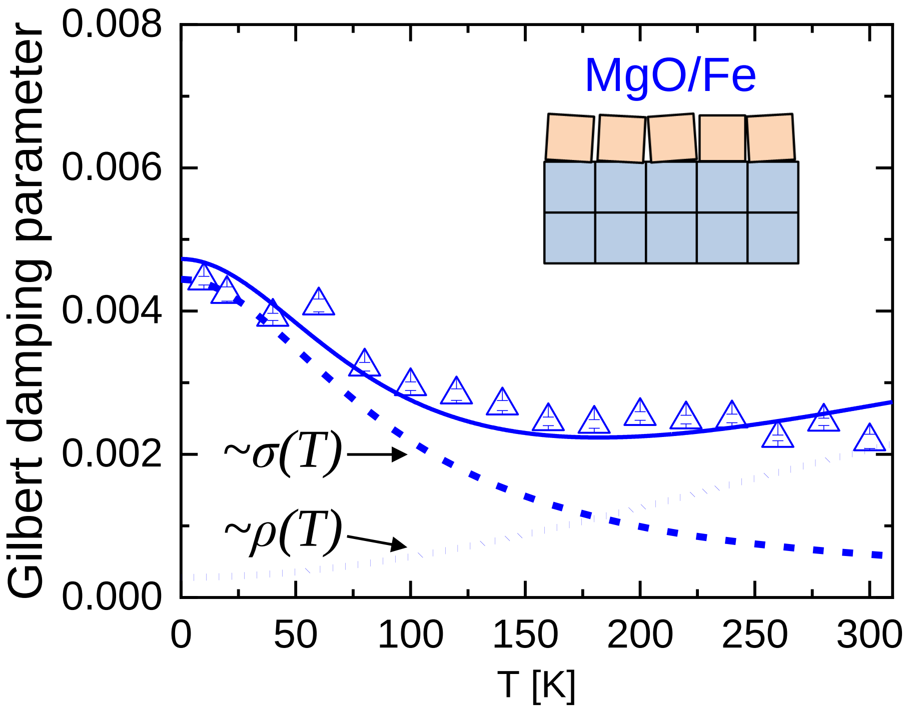
conductivity-like damping

resistivity-like damping





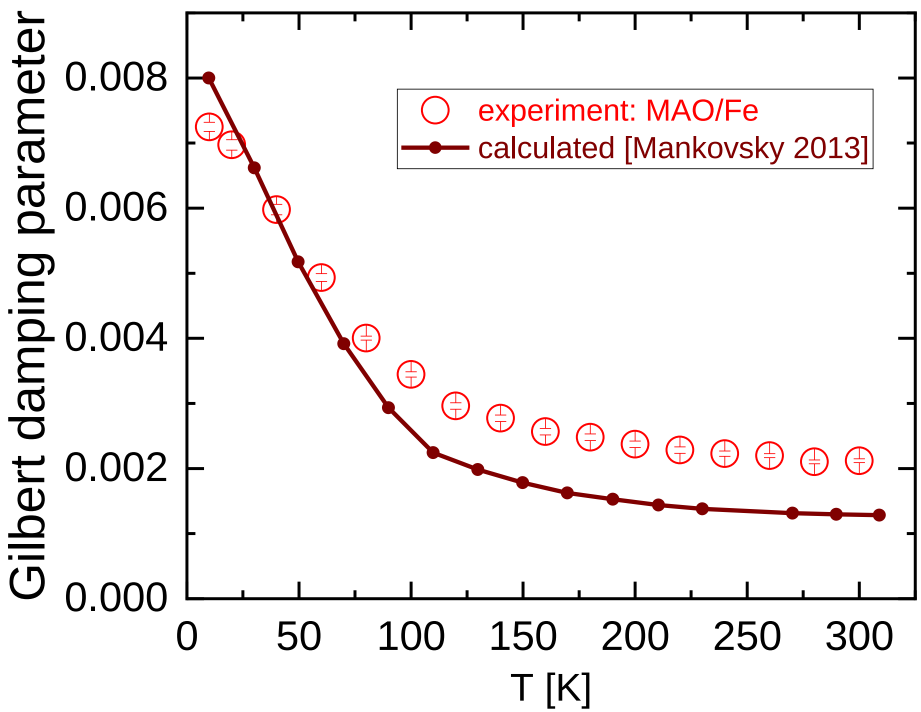
Comparison with published calculations

PHYSICAL REVIEW B **87**, 014430 (2013)

First-principles calculation of the Gilbert damping parameter via the linear response formalism with application to magnetic transition metals and alloys

S. Mankovsky,[1] D. Ködderitzsch,[1] G. Woltersdorf,[2] and H. Ebert[1]
[1] *University of Munich, Department of Chemistry, Butenandtstrasse 5-13, D-81377 Munich, Germany*
[2] *Department of Physics, Universität Regensburg, 93040 Regensburg, Germany*
(Received 2 November 2012; published 28 January 2013)

A method for the calculations of the Gilbert damping parameter α is presented, which, based on the linear response formalism, has been implemented within the fully relativistic Korringa-Kohn-Rostoker band structure method in combination with the coherent potential approximation alloy theory. To account for thermal

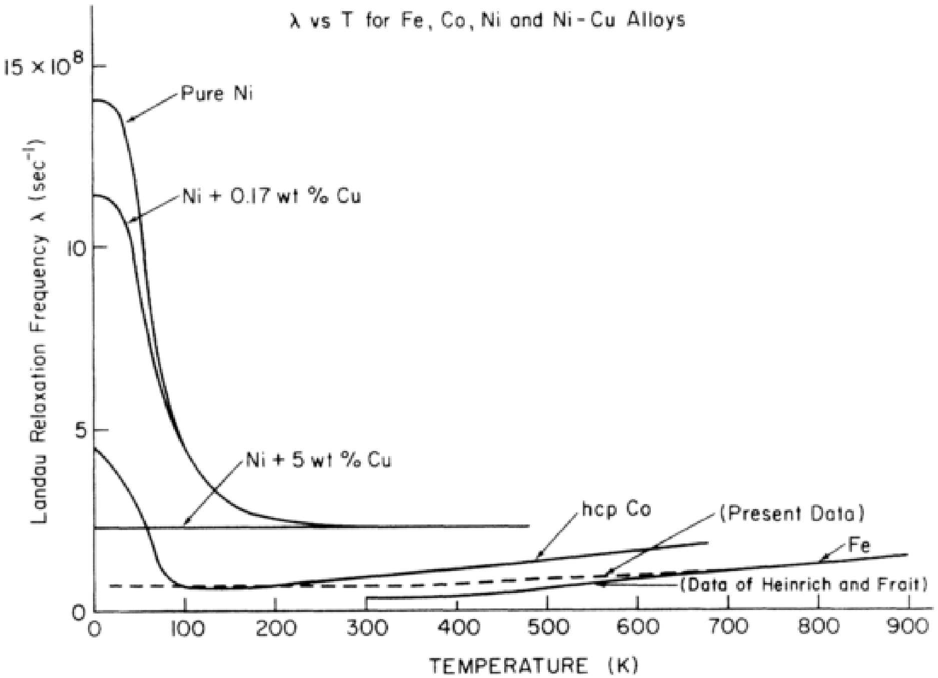


Calculations incorporate 0.1% vacancies in BCC Fe to simulate small concentration of defects

Good quantitative agreement with MAO/Fe

40+ year old mystery resolved!

1974:
Conductivity-like damping reported for <u>bulk crystals</u> of Co and Ni



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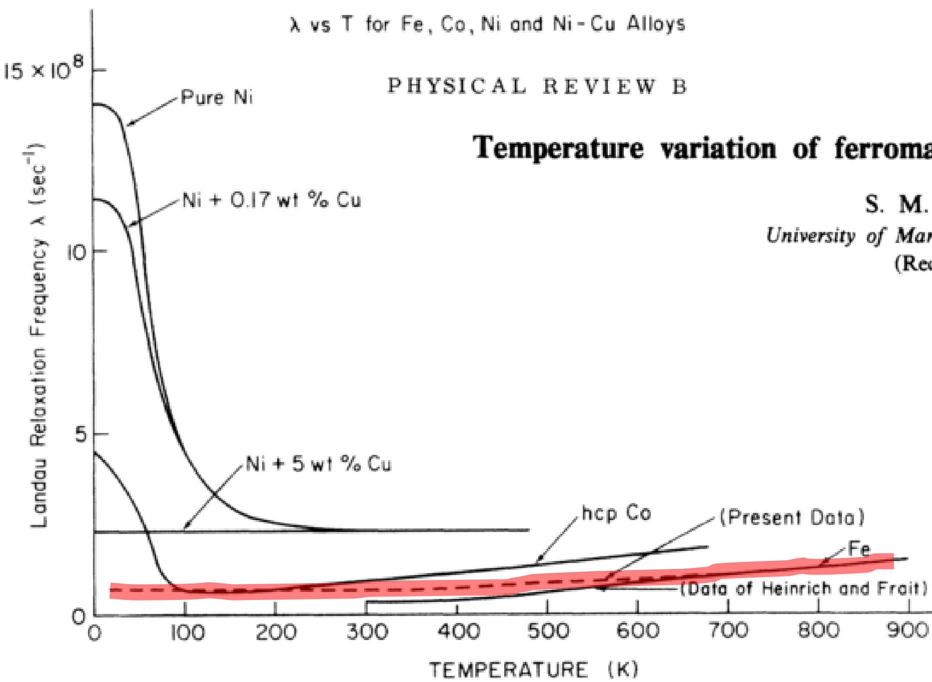
…**but not Fe**!



PHYSICAL REVIEW B VOLUME 10, NUMBER 1 1 JULY 1974

Temperature variation of ferromagnetic relaxation in the 3*d* transition metals*

S. M. Bhagat and P. Lubitz
University of Maryland, College Park, Maryland 20742
(Received 28 January 1974)

Is conductivity-like damping
(intraband scattering) even real?

IOP Publishing Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **28** (2016) 086004 (10pp) doi:10.1088/0953-8984/28/8/086004

The absence of intraband scattering in a consistent theory of Gilbert damping in pure metallic ferromagnets

D M Edwards
Department of Mathematics, Imperial College London, London SW7 2BZ, UK

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Conductivity-like damping reported for <u>bulk crystals</u> of Co and Ni
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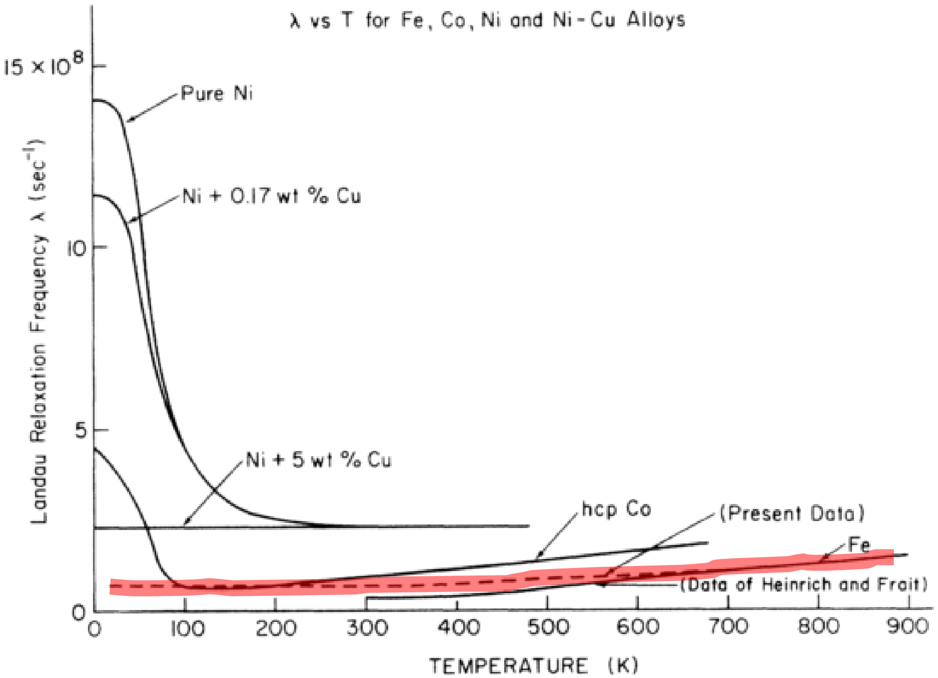
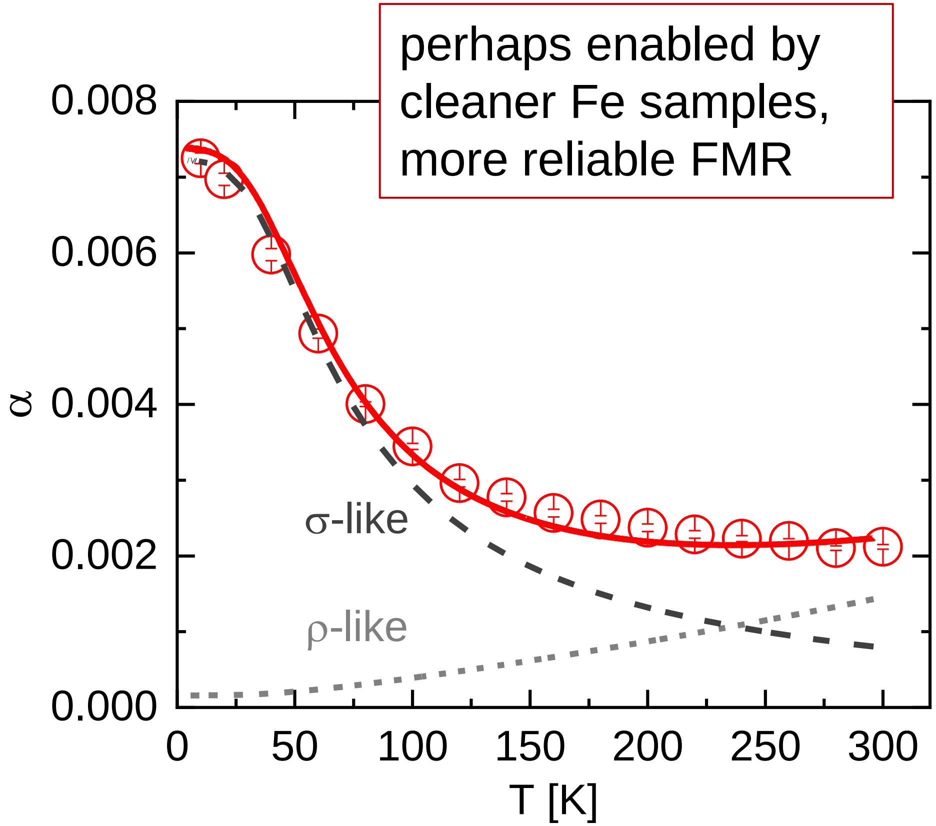
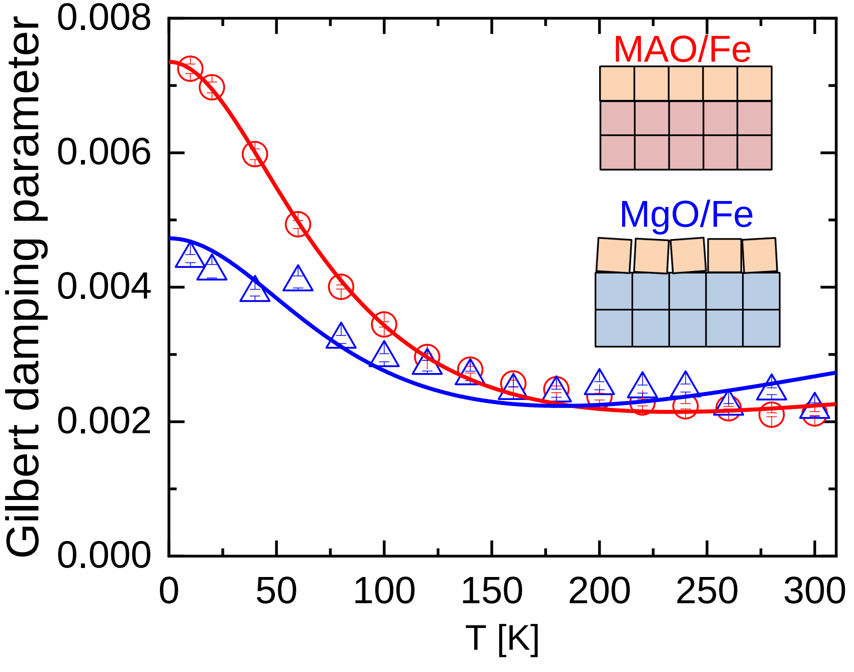


2020:
Conductivity-like damping also present in Fe



Summary

First experimental evidence of intrinsic **conductivity-like Gilbert damping** in elemental ferromagnetic metal films
(Less scattering can lead to higher damping.)



For low-T applications (e.g., quantum information technologies),
some disorder may reduce loss/improve coherence.

B. Khodadadi, … SE. *Phys. Rev. Lett.* **124**,157201 (2020)
Contact: Satoru Emori semori@vt.edu