Bayerische Akademie der Wissenschaften

Technische Universität München

All Acoustic Manipulation and Probing of Spin Ensembles

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Walther-Meißner-Institut
Bayerische Akademie der Wissenschaften

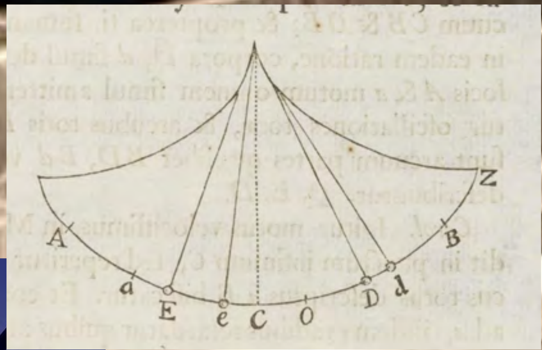
Deutsche Forschungsgemeinschaft DFG

nanosystems initiative munich

Mechanical Oscillators

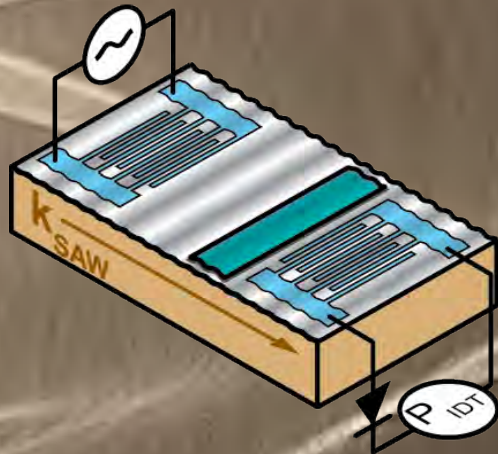
Andrew Davidhazy

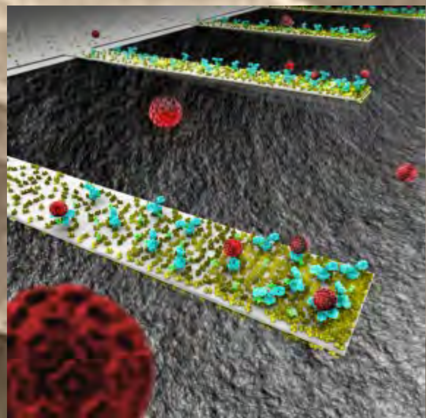
beginnersguitarstudio.com



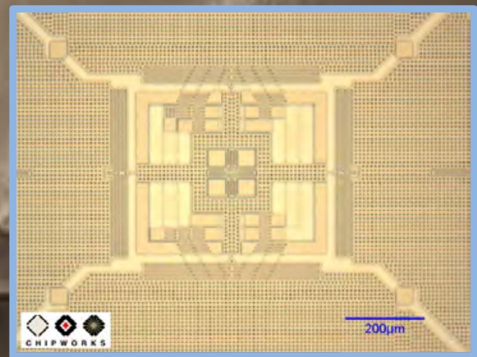
Newton, Philosophiae Naturalis Principia Mathematica (1687)

Gina Waga (2014) – National Geographics

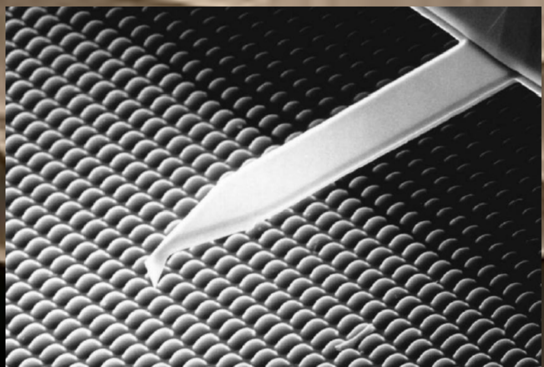




Perdue – Bashir group (2006)



iPhone4 gyroscope - Ifixit



AFM, Giessibl, Rev. Mod. Phys. 79, 949 (2003)

Mechanics with *magnetic* systems

Magnetism

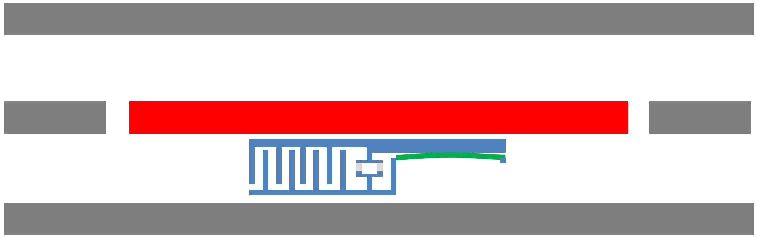
typical classical representation:
magnetization vector

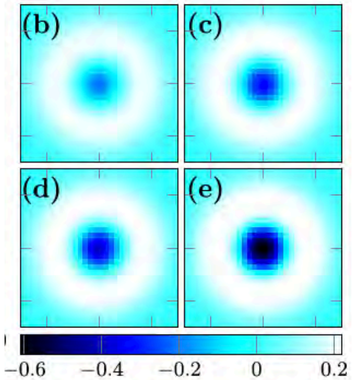
Mechanics

motional amplitude

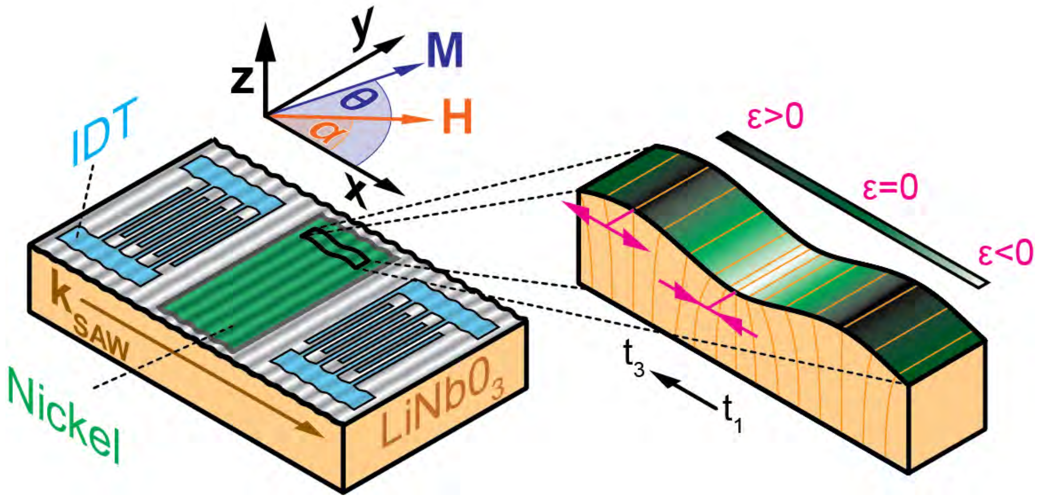
- quantum effects in large objects

Acoustics @ Walther-Meißner-Institute

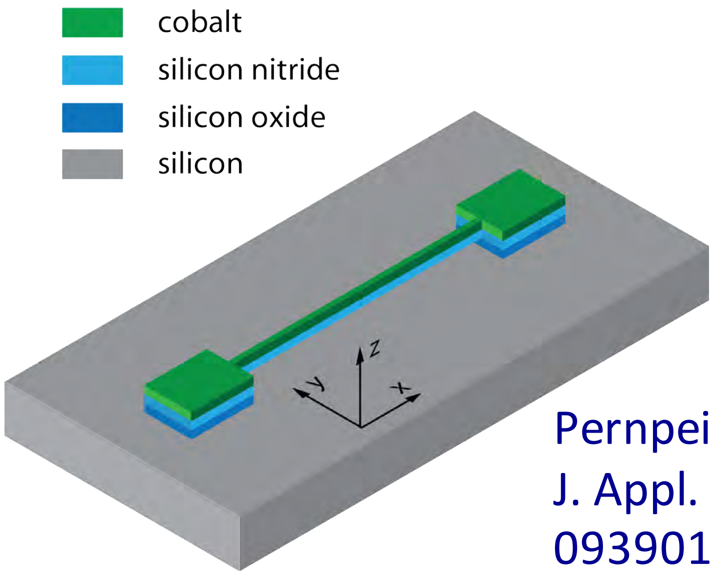




Abdi et al.,
Phys. Rev. Lett. **114**, 173602 (2015)



Weiler et al.,
Phys. Rev. Lett. **106**, 117601 (2011)
Dreher et al.,
Phys. Rev. B **86**, 134415 (2012)
Weiler et al.,
Phys. Rev. Lett. **108**, 176601 (2012)

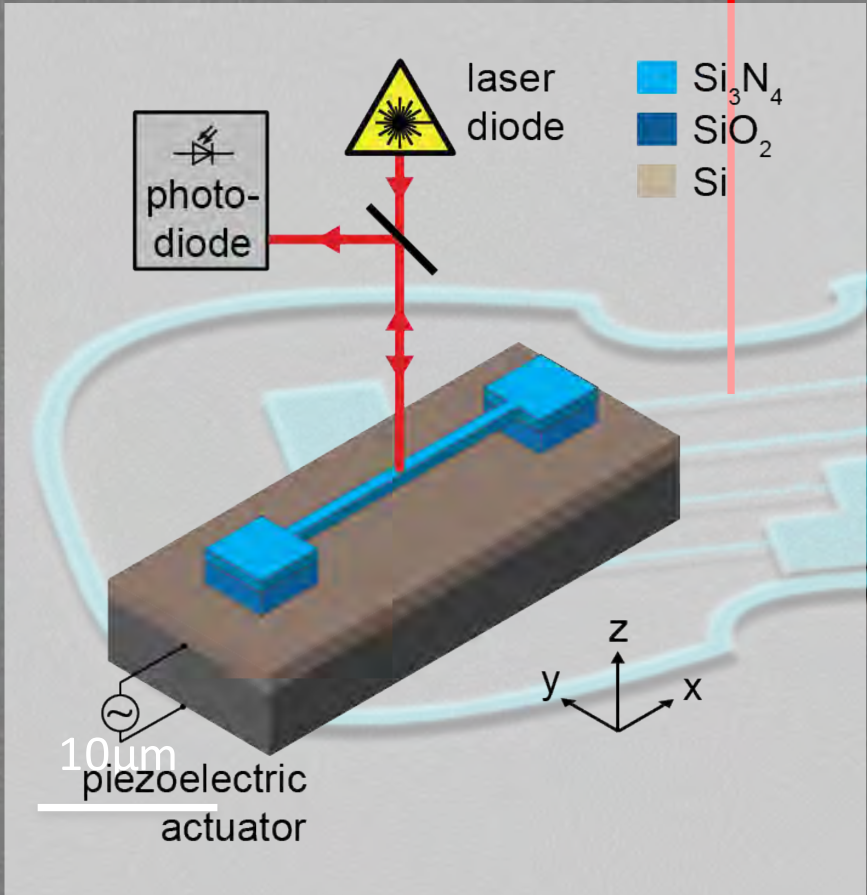


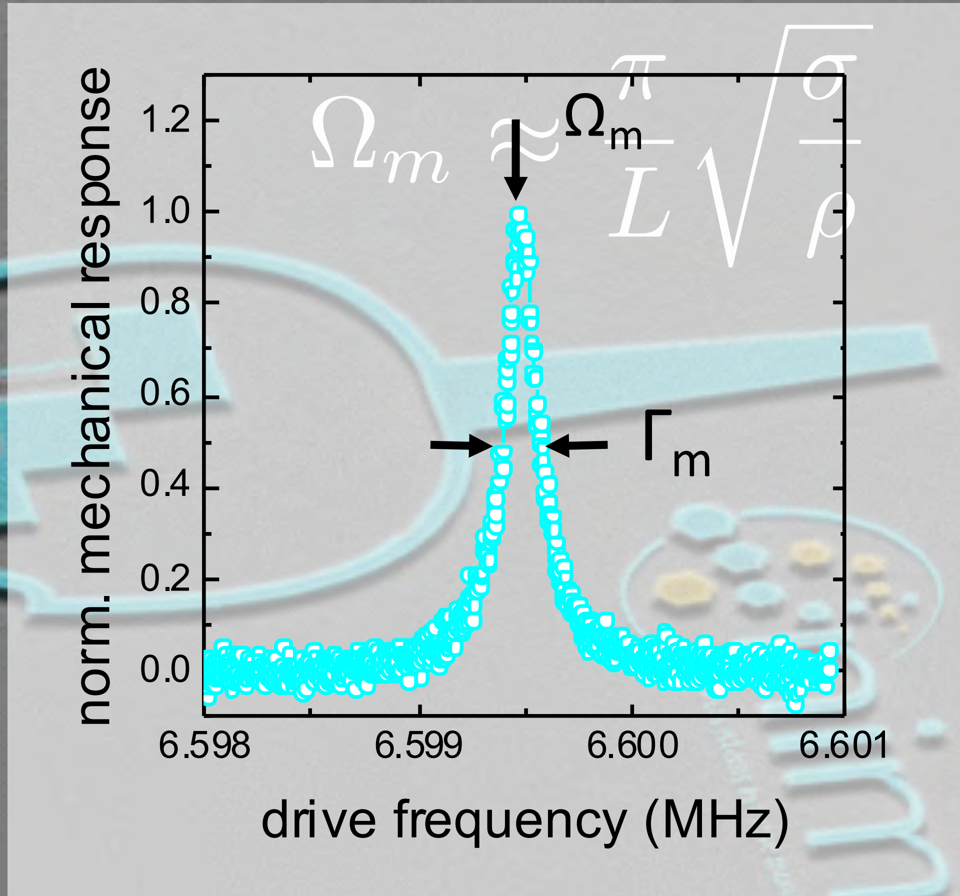
Pernpeintner et al.,
J. Appl. Phys. **119**, 093901 (2016)

Strings

- mechanical resonance frequency

$$\Omega_m \approx \frac{\pi}{L}\sqrt{\frac{\sigma}{\rho}}$$





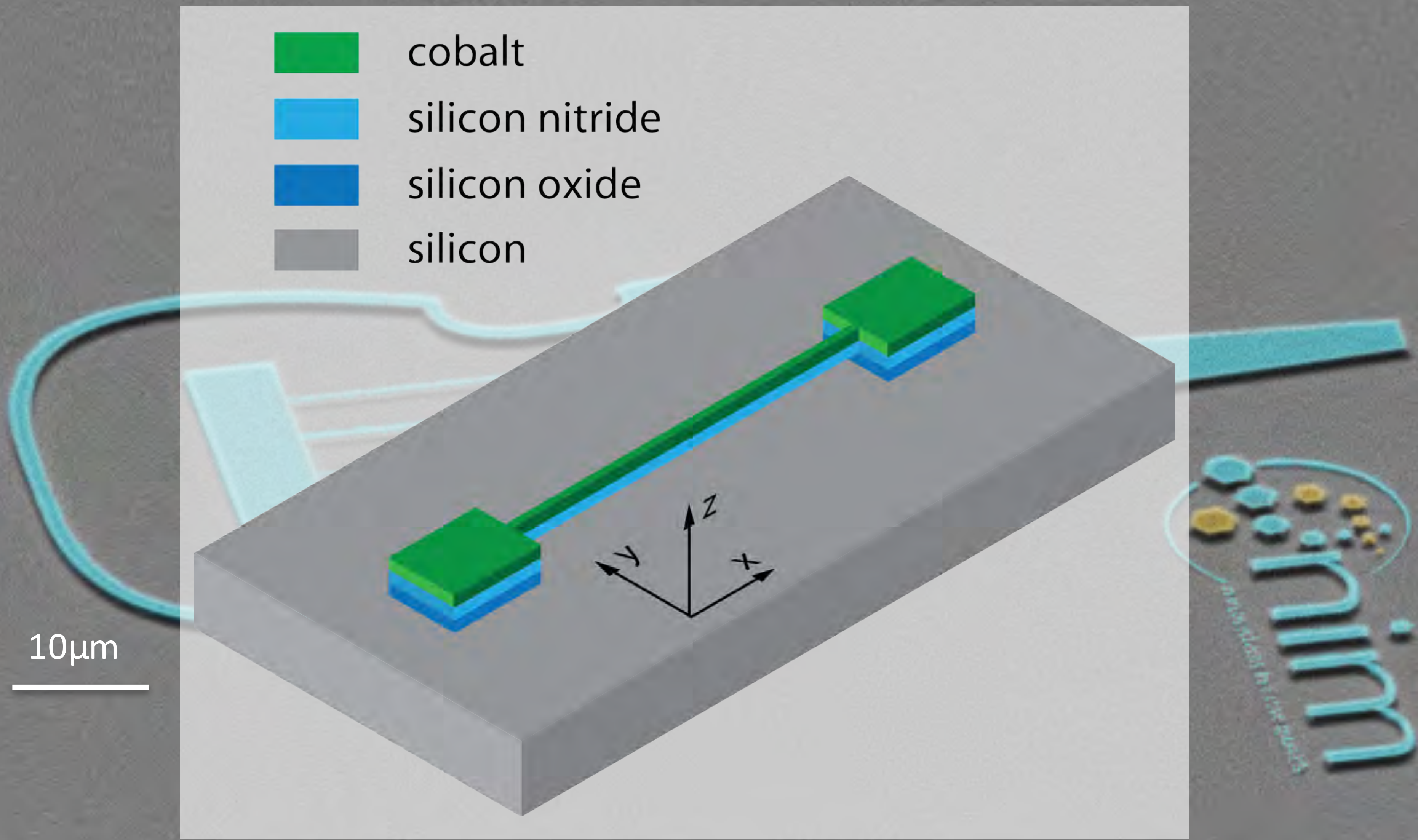
nano-string

σ ≡ tensile stress (≈ 800 MPa)
ρ ≡ material density (≈ 2700 kg/m³)
L ≡ length of the nanostring (≈ 30 µm)

violine

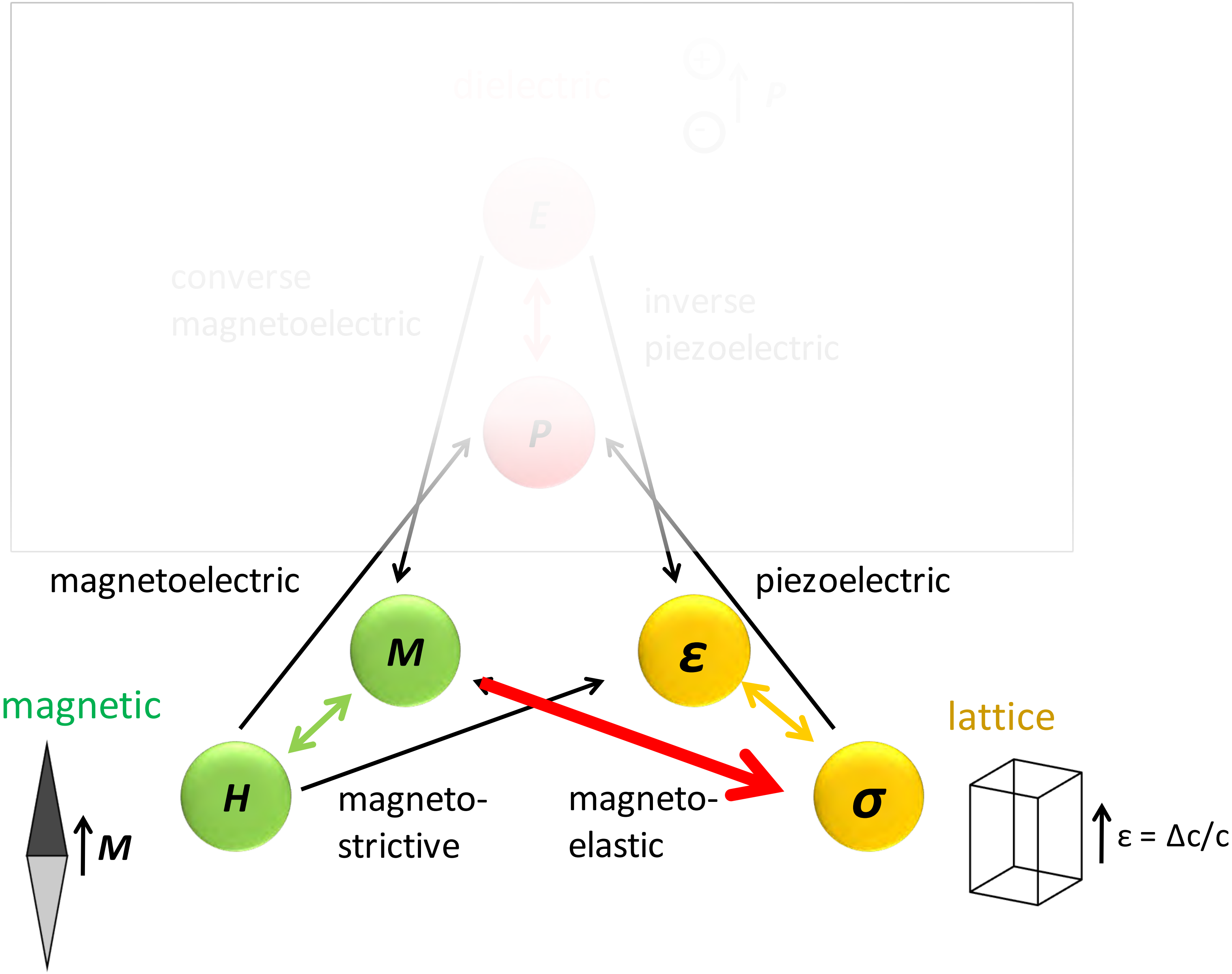
σ ≡ tensile stress (≈ 1200 MPa)
ρ ≡ material density (≈ 7800 kg/m³)
L ≡ length of the string (≈ 300 mm)

Nano-spinmechanics - magnetostriction



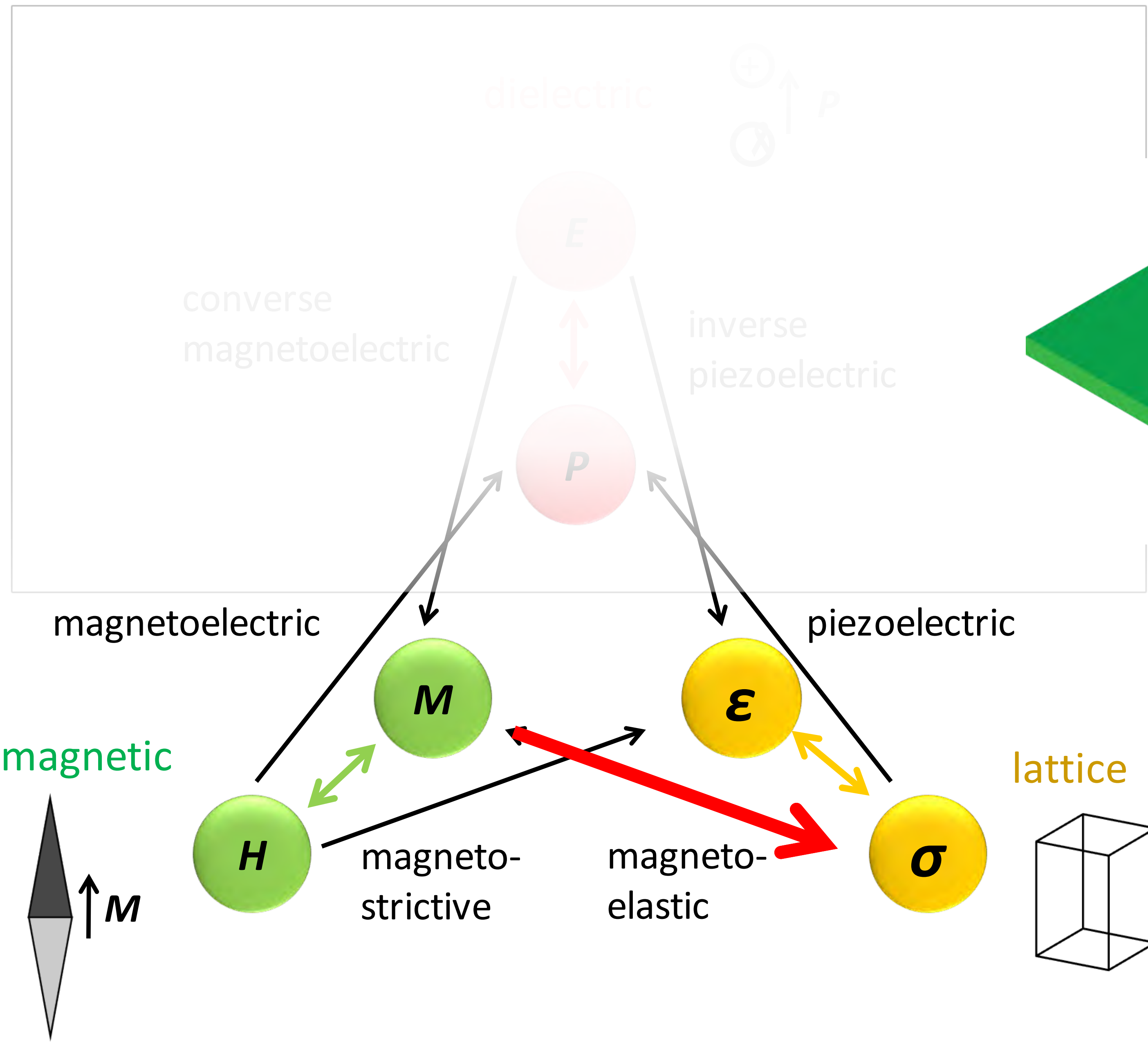
- Magnetostriction in thin magnetic films
- Mangon-phonon interaction

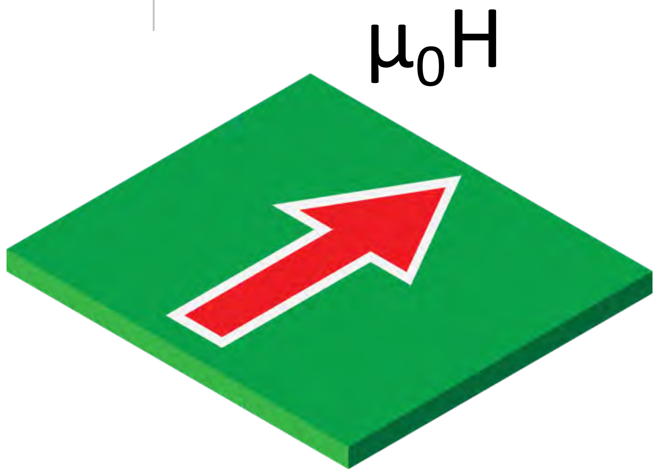
Magnetic strain control



Spaldin & Fiebig, Science **309**, 391 (2005).

Magnetic strain control

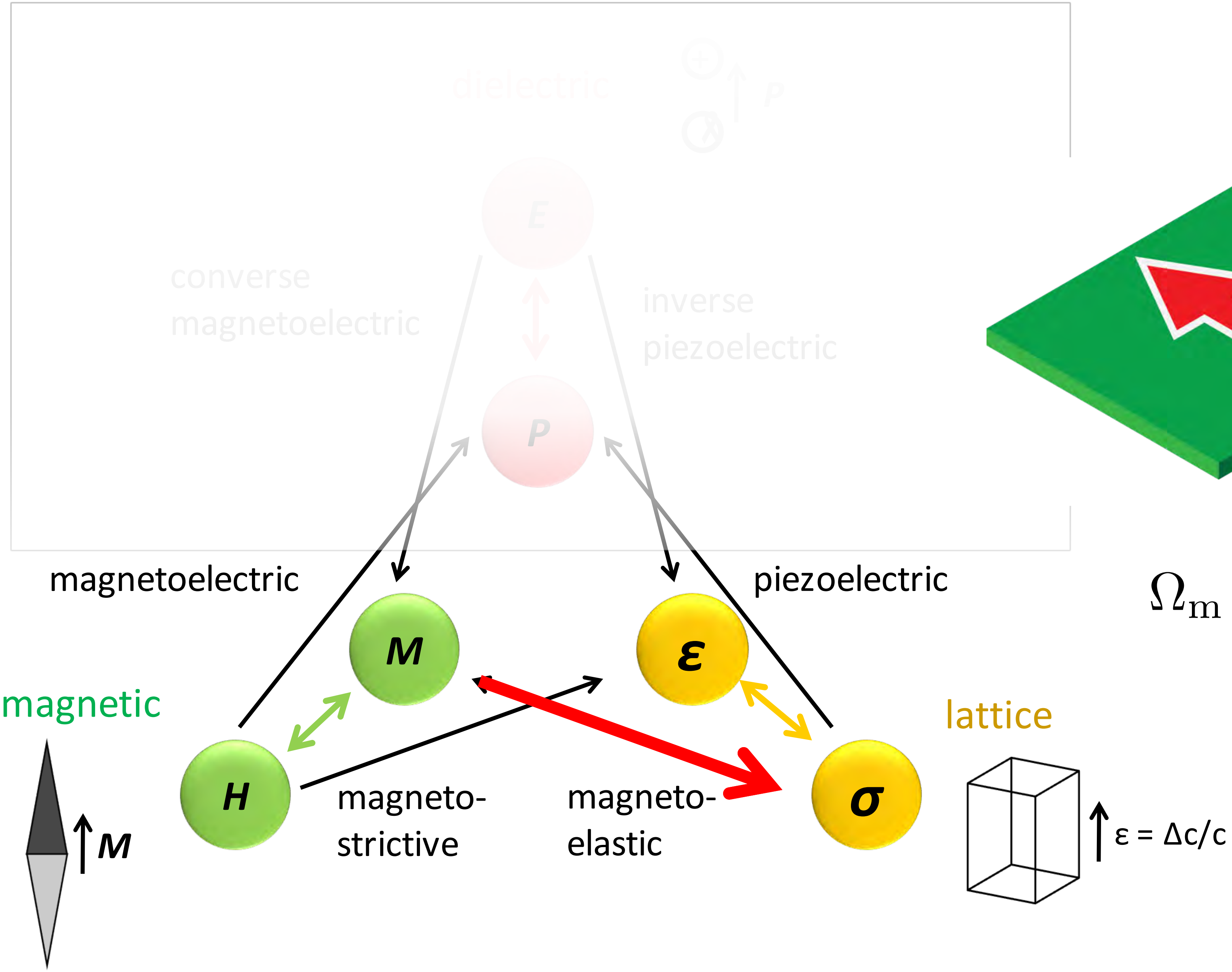


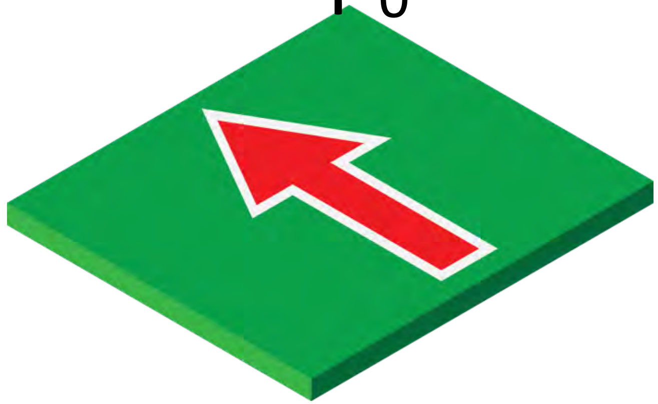


$$\Omega_\mathrm{m} \approx \frac{\pi}{L}\sqrt{\frac{\sigma}{\rho}}$$

Spaldin & Fiebig, Science **309**, 391 (2005).

Magnetic strain control





$$\Omega_{\mathrm{m}} \approx \frac{\pi}{L}\sqrt{\frac{\sigma}{\rho}}$$

Spaldin & Fiebig, Science **309**, 391 (2005).

Magnetostriction – nanomechanical detection

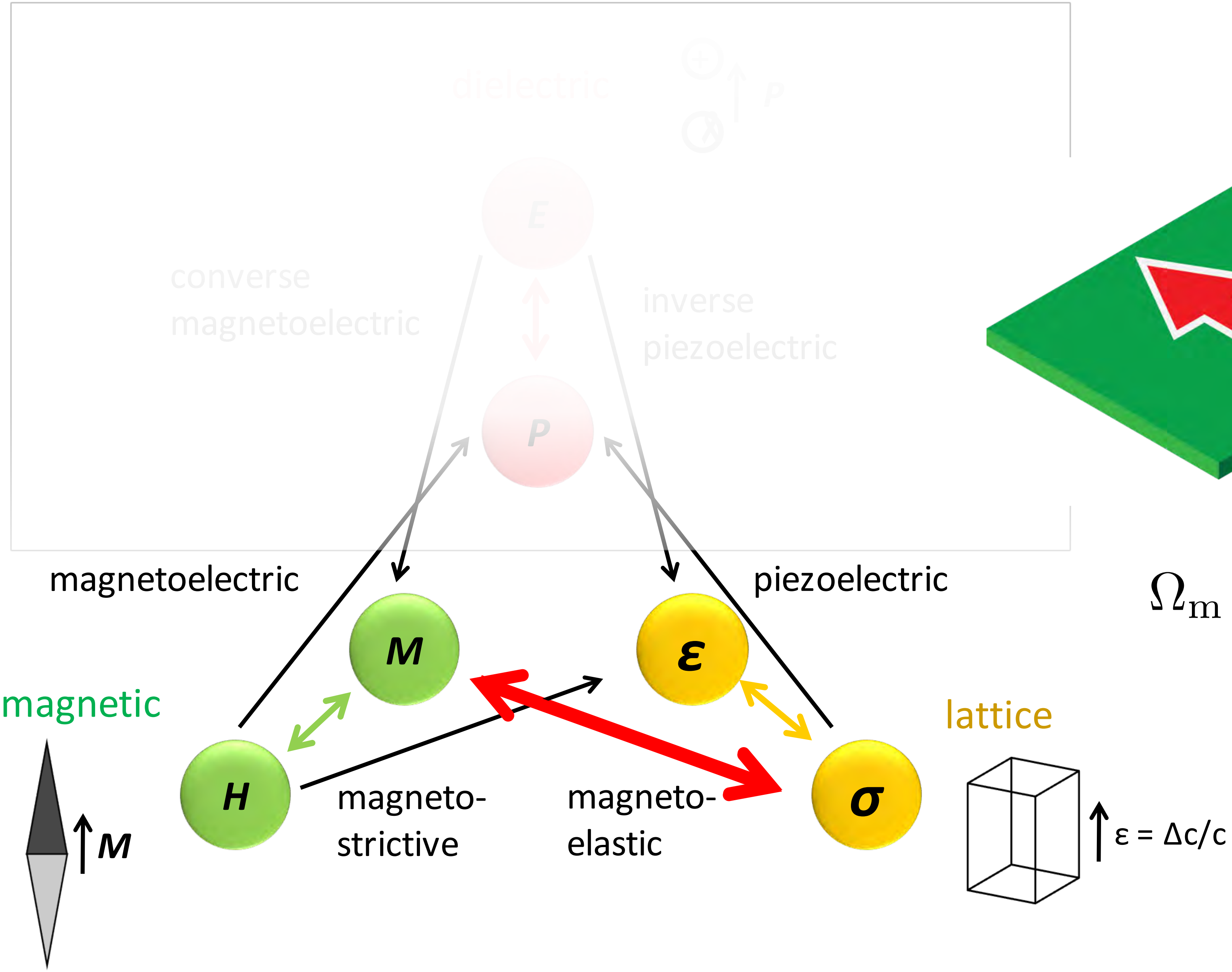
- 10 nm thin magnetic Co film

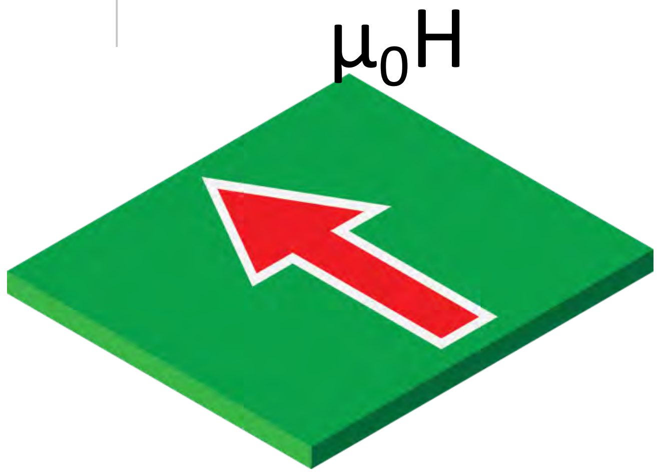
$$\frac{\omega_{\mathrm{res}}(\phi)}{2\pi} = \frac{1}{2l}\sqrt{\frac{\sigma_{\mathrm{eff}}}{\rho_{\mathrm{eff}}}} = \frac{1}{2l}\sqrt{\frac{\sigma_0 - \sigma_1\cos^2(\phi)}{\rho_{\mathrm{eff}}}}$$

$$\sigma_1 = E t_{\mathrm{film}} \lambda_{\|} / (t_{\mathrm{SiN}} + t_{\mathrm{film}})$$

Pernpeintner et al., J. Appl. Phys. **119**, 093901 (2016)

Magnetic strain control



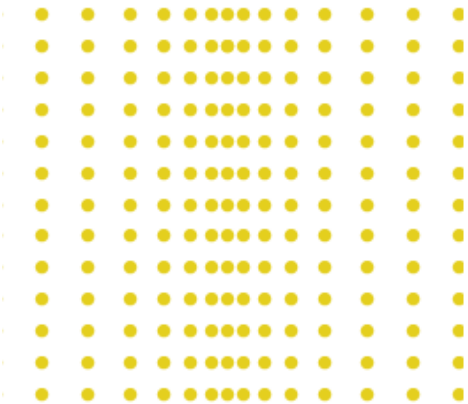


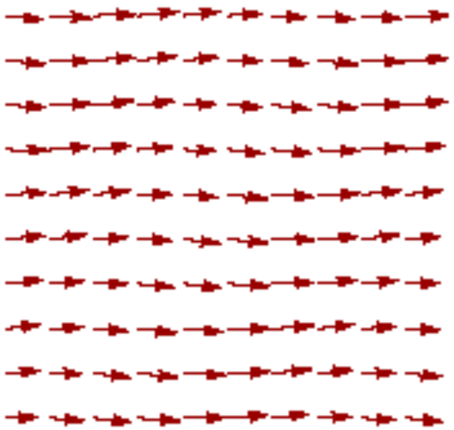
$$\Omega_\mathrm{m} \approx \frac{\pi}{L}\sqrt{\frac{\sigma}{\rho}}$$

Spaldin & Fiebig, Science **309**, 391 (2005).

Dynamic strain – magnetization coupling

phonons (sound wave)

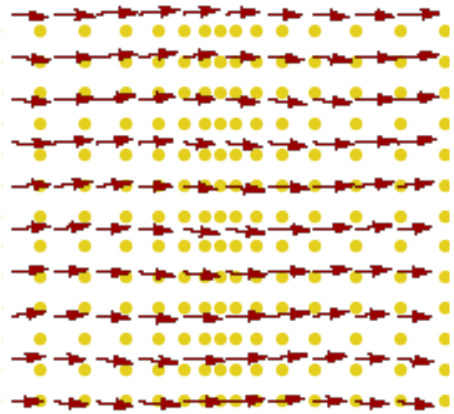




magnons (spin wave)

+

magnon-phonon-coupling (spin-sound-wave)



New physics
(e.g. acoustic FMR)
Natural mode matching
$\mathbf{v_{sound} \approx v_{magnon}}$

Ferromagnetic resonance

In equilibrium: $\boldsymbol{M} \parallel \boldsymbol{H}_{\text{eff}}$ → $\boldsymbol{H}_{\text{eff}} \approx$ external magnetic field

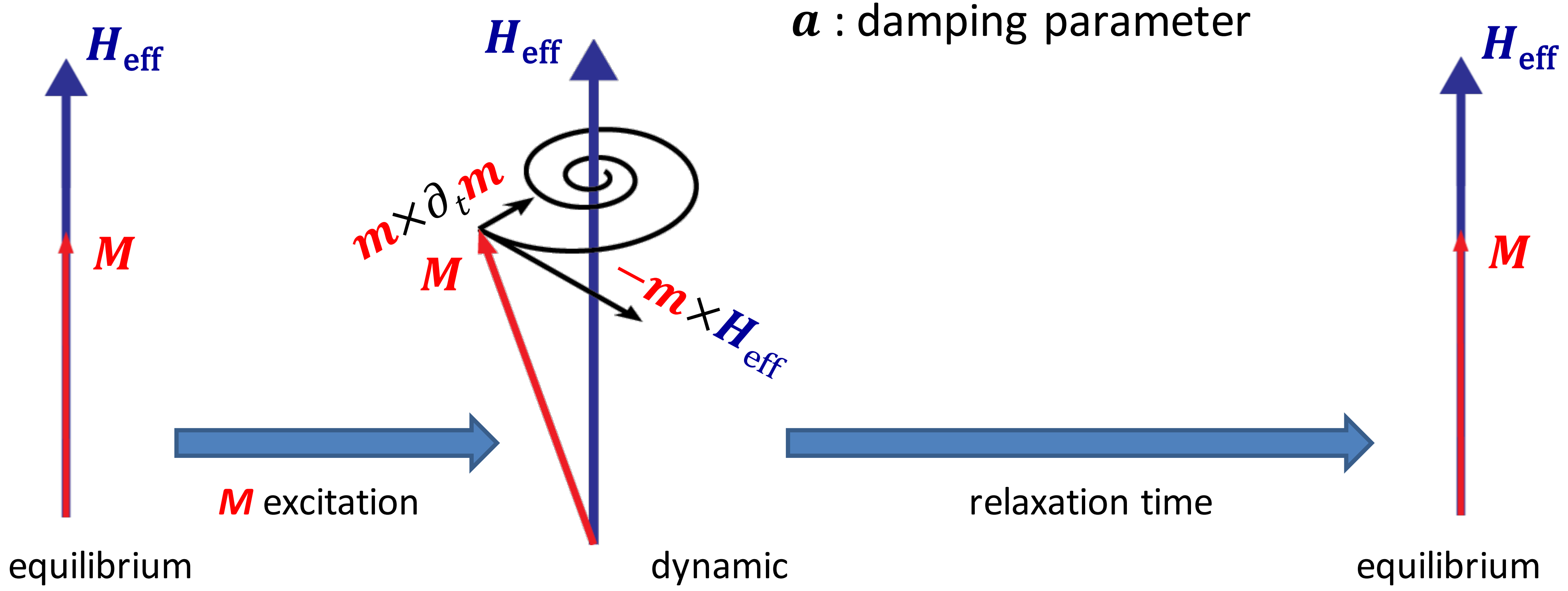
Dynamics: Landau-Lifshitz-Gilbert equation

$$\partial_t \boldsymbol{m} = -\boldsymbol{\gamma}\boldsymbol{m}\times\mu_0\boldsymbol{H}_{\text{eff}}$$ ← precession

$$+\boldsymbol{a}\ \boldsymbol{m}\times\partial_t\boldsymbol{m}$$ ← damping

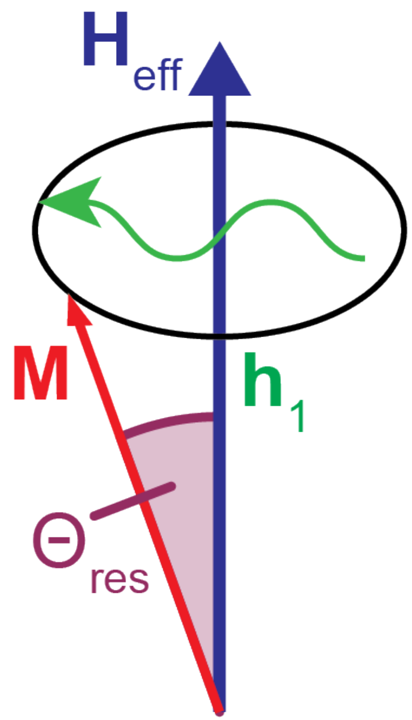
$\boldsymbol{\gamma}$: gyromagnetic ratio

$\boldsymbol{a}$: damping parameter



Ferromagnetic resonance – excitation schemes

(microwave) photon-driven ferromagnetic resonance

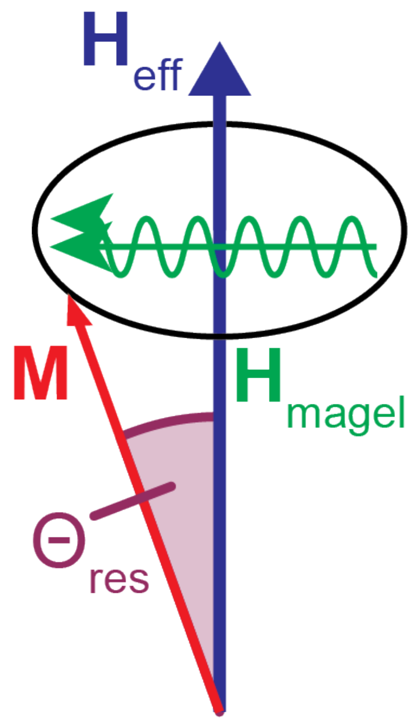


$h_1(t) = h_1 \cos(\omega_{res} t)$

real, external magnetic driving field

$$\omega_{\mathrm{res}} = \gamma \mu_0 H_{\mathrm{eff}}$$

phonon-driven ferromagnetic resonance

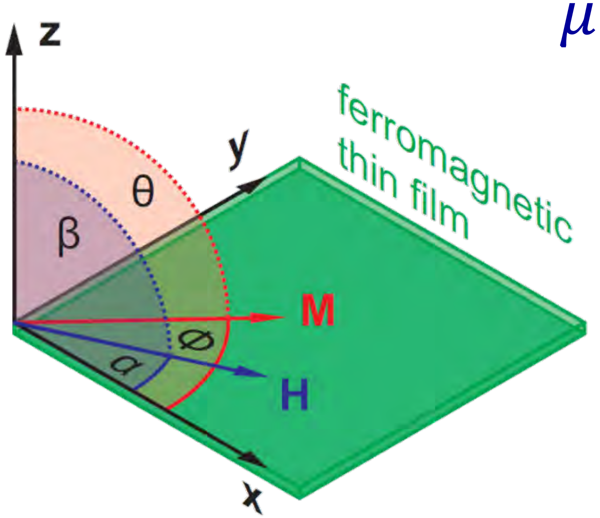


$H_{\mathrm{magel}}(t) = H_{\mathrm{magel}} \cos(\omega_{res} t)$

virtual, internal magnetic driving field

this talk

Ferromagnetic resonance – free energy



$$\mu_0 \boldsymbol{H}_{\text{eff}} = -\nabla_{\boldsymbol{m}} F^{DC}$$ effective magnetic field

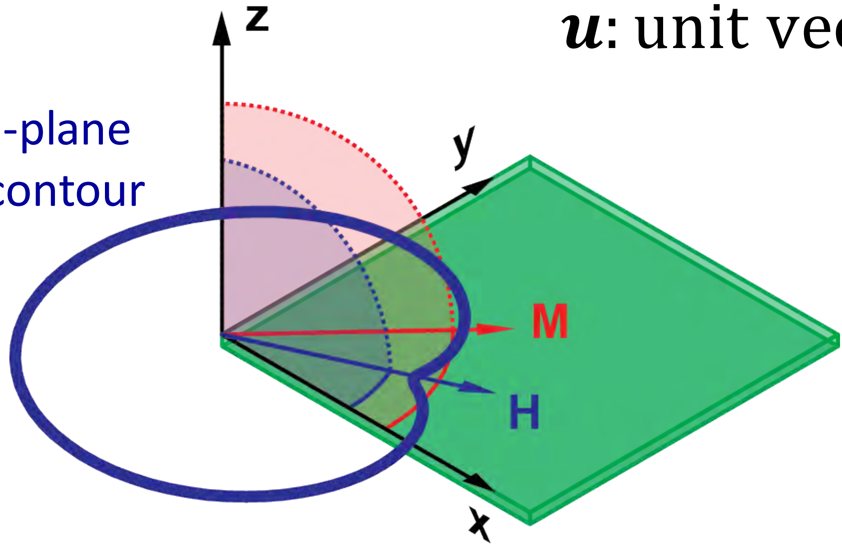
$$F^{DC} = -\mu_0 \boldsymbol{H} \cdot \boldsymbol{m} + B_u (\boldsymbol{u} \cdot \boldsymbol{m})^2 + B_d m_z^2$$

Zeeman term | in-plane anisotropy $2B_{\mathrm{u}} \approx 10\ \mathrm{mT}$ | shape anisotropy $2B_{\mathrm{d}} \approx 1\mathrm{T}$

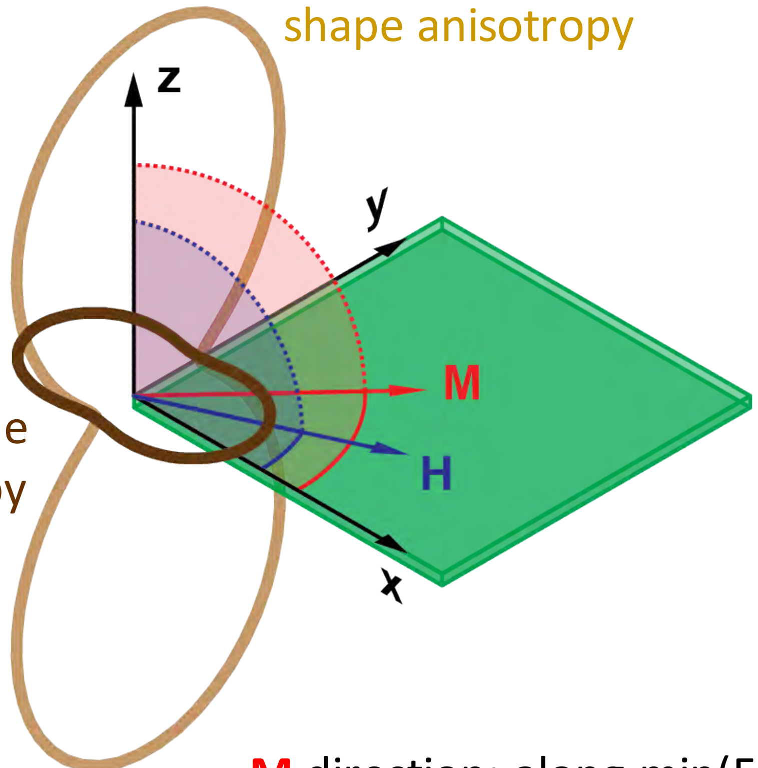
$\boldsymbol{m} = \boldsymbol{M}/M_s$

$\boldsymbol{u}$: unit vector

in-plane F^{DC} contour



shape anisotropy



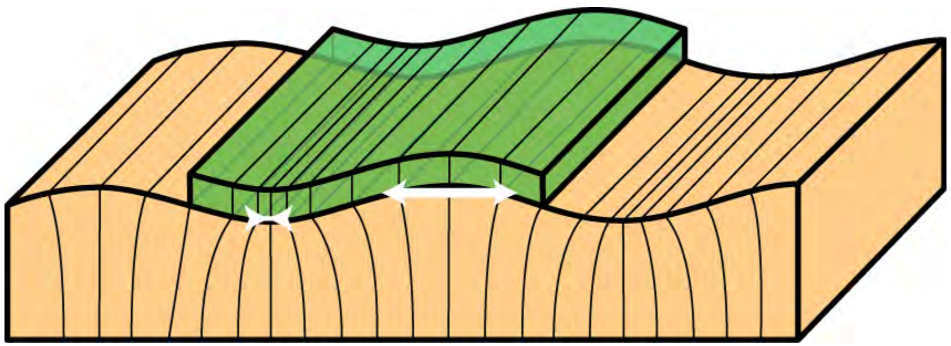
in-plane anisotropy

M: magnetization

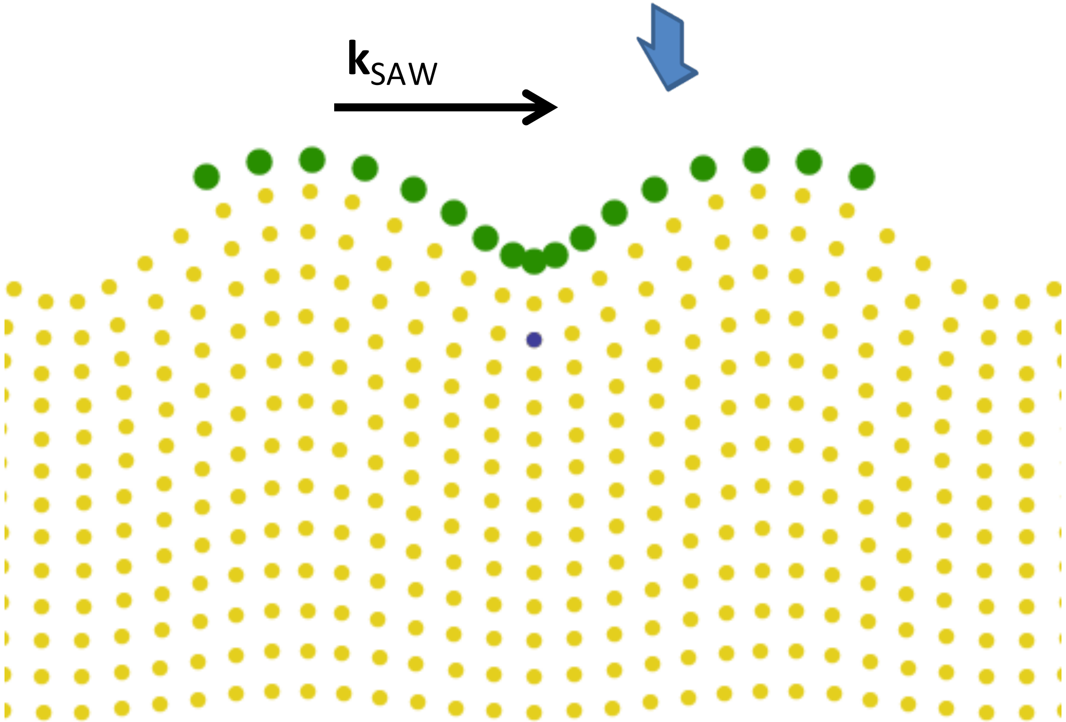
H: external magnetic field

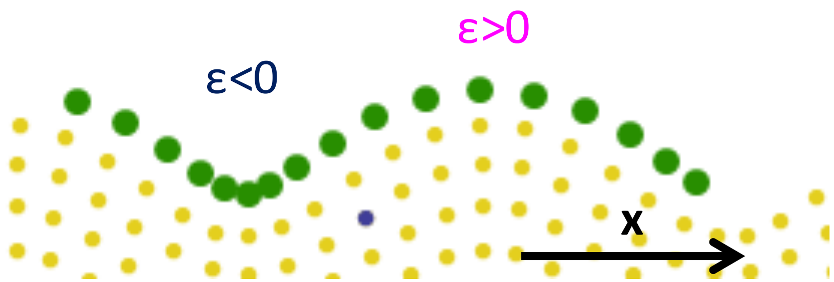
M direction: along min(F^{DC})

Surface acoustic waves (SAWs)



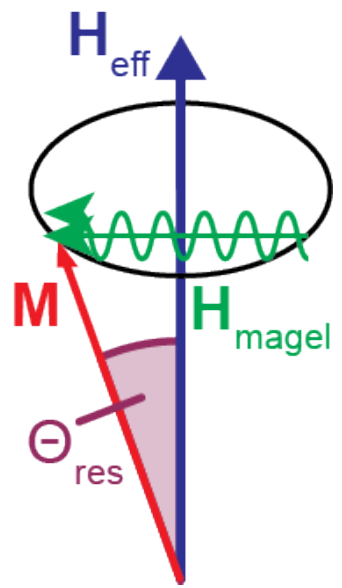
- Nickel/Cobalt thin film
- $LiNbO_3$ substrate
- Surface acoustic wave
- Magnetoelastic coupling



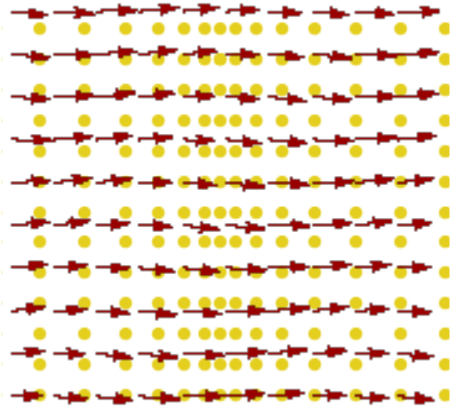


- rf strain $\varepsilon(t) \approx 10^{-5}$ along **x**
- velocity ≈ 3500 m/s (λ_{SAW}=20µm, f=175 MHz)

Magnetoelastic drive



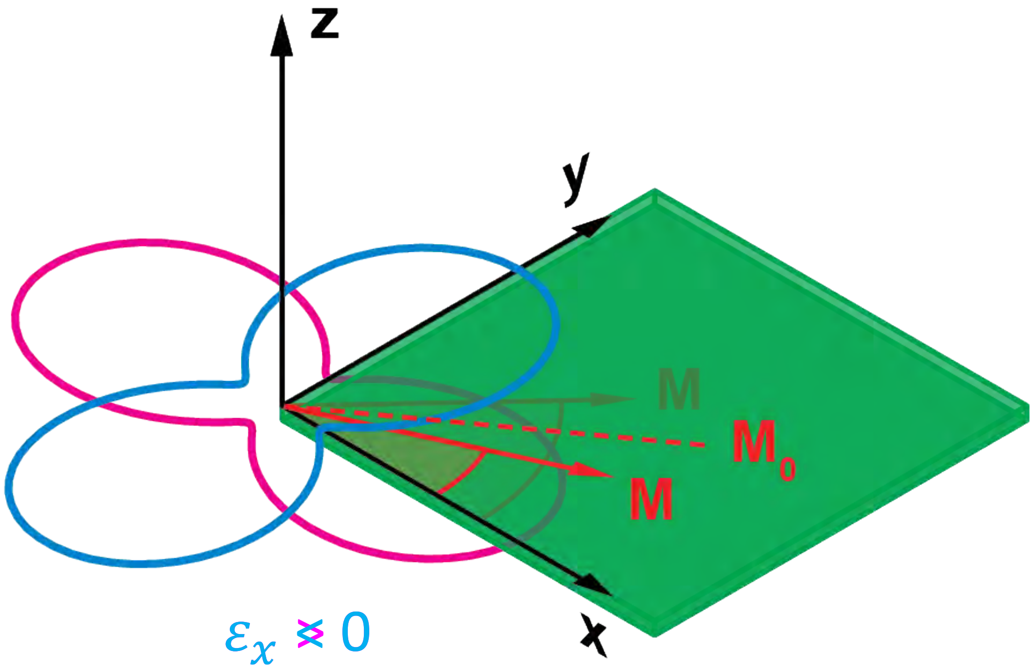
$$\mu_0 \boldsymbol{H}_{\text{magel}} = -\nabla_{\boldsymbol{m}} F^{\text{AC}}$$



$$F^{\text{AC}}(t) = B_1 \varepsilon_x(t) m_x^2$$

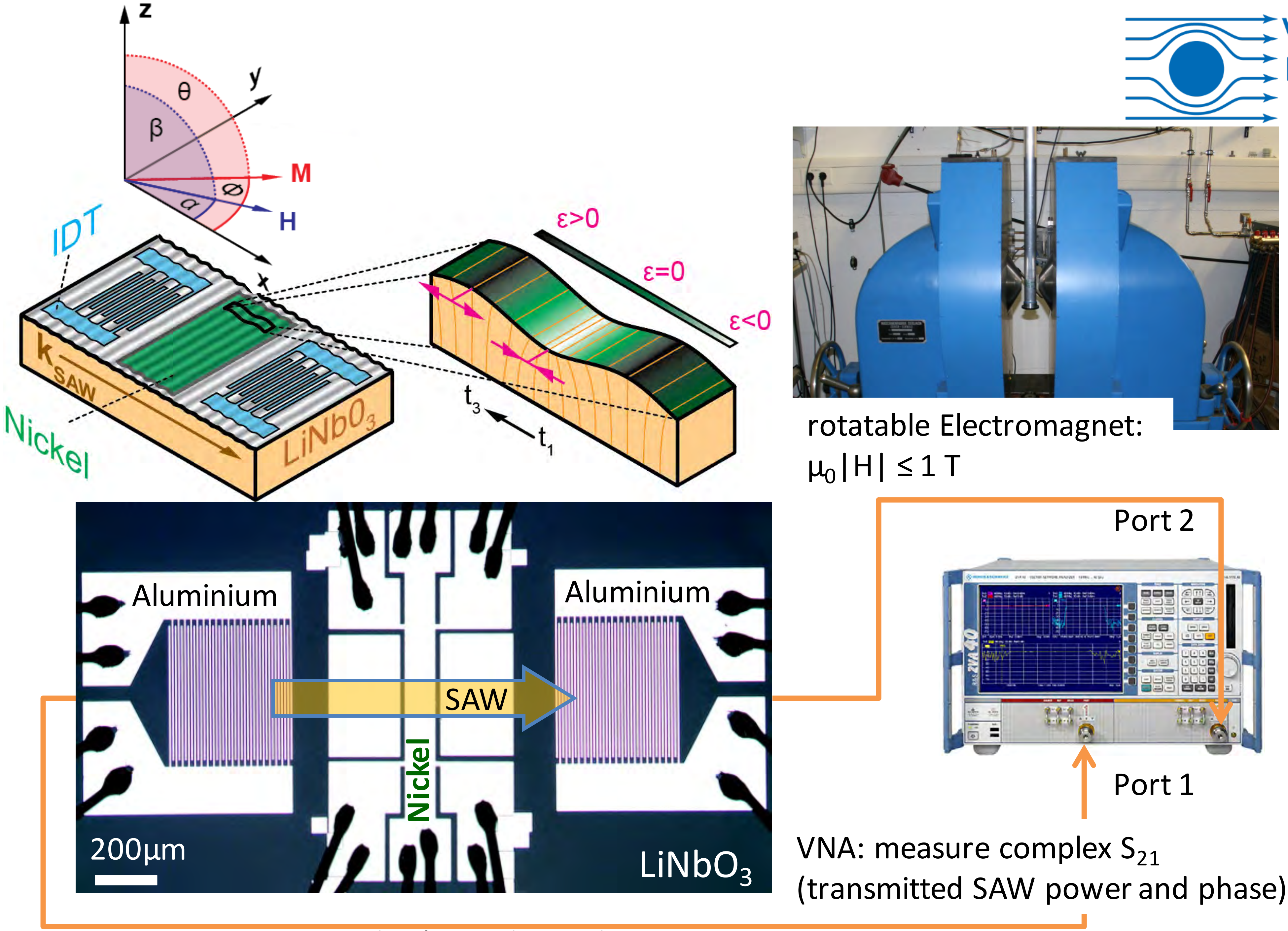
magnetoelastic
coupling constant (≈20 T)

strain (≈10^{-5})
Pure strain **ε** along **x**



Magnetoelastic material ($B_1 \neq 0$): Nickel thin film

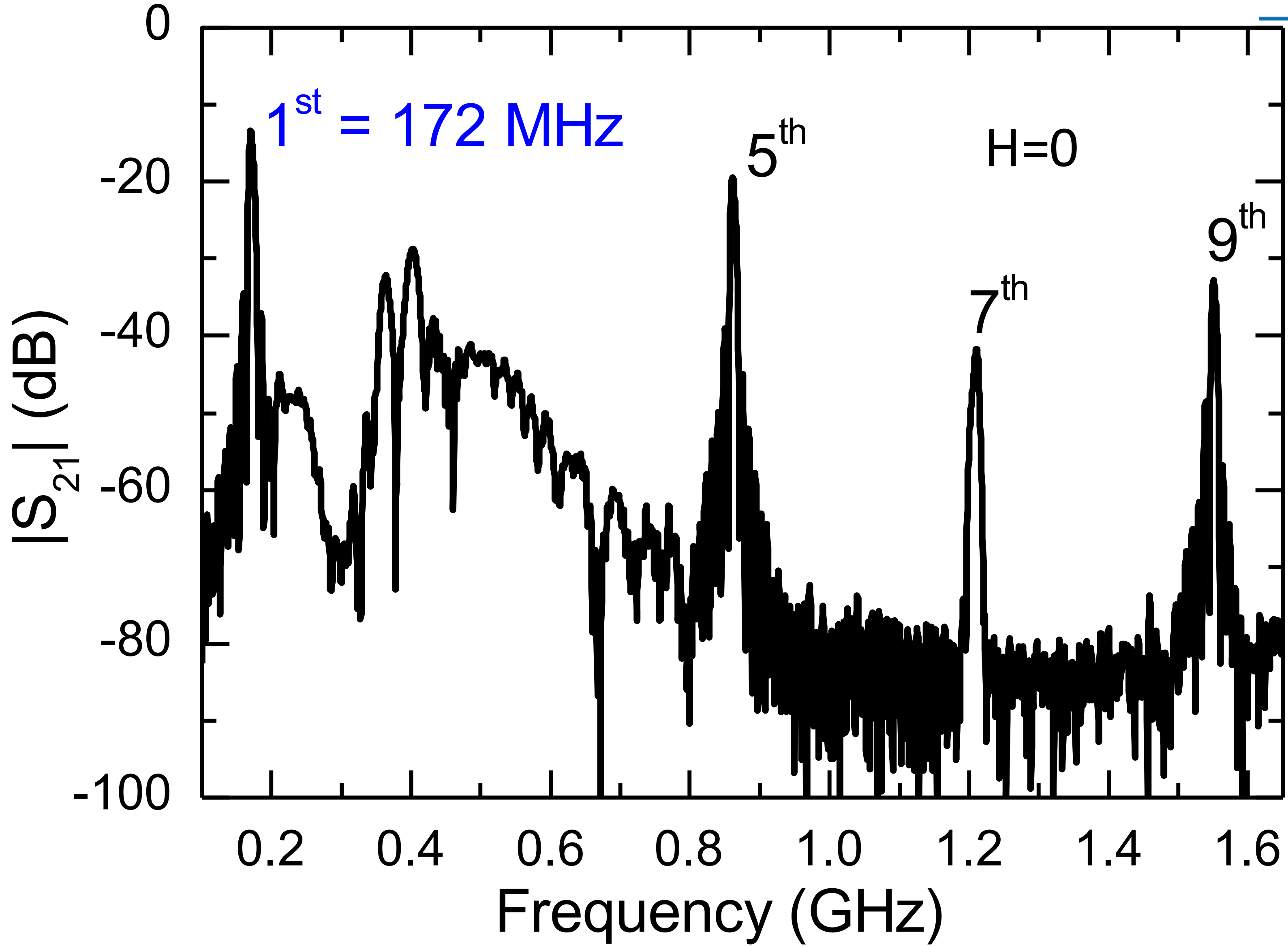
radio frequency strain ε: surface acoustic wave



micrograph of actual sample

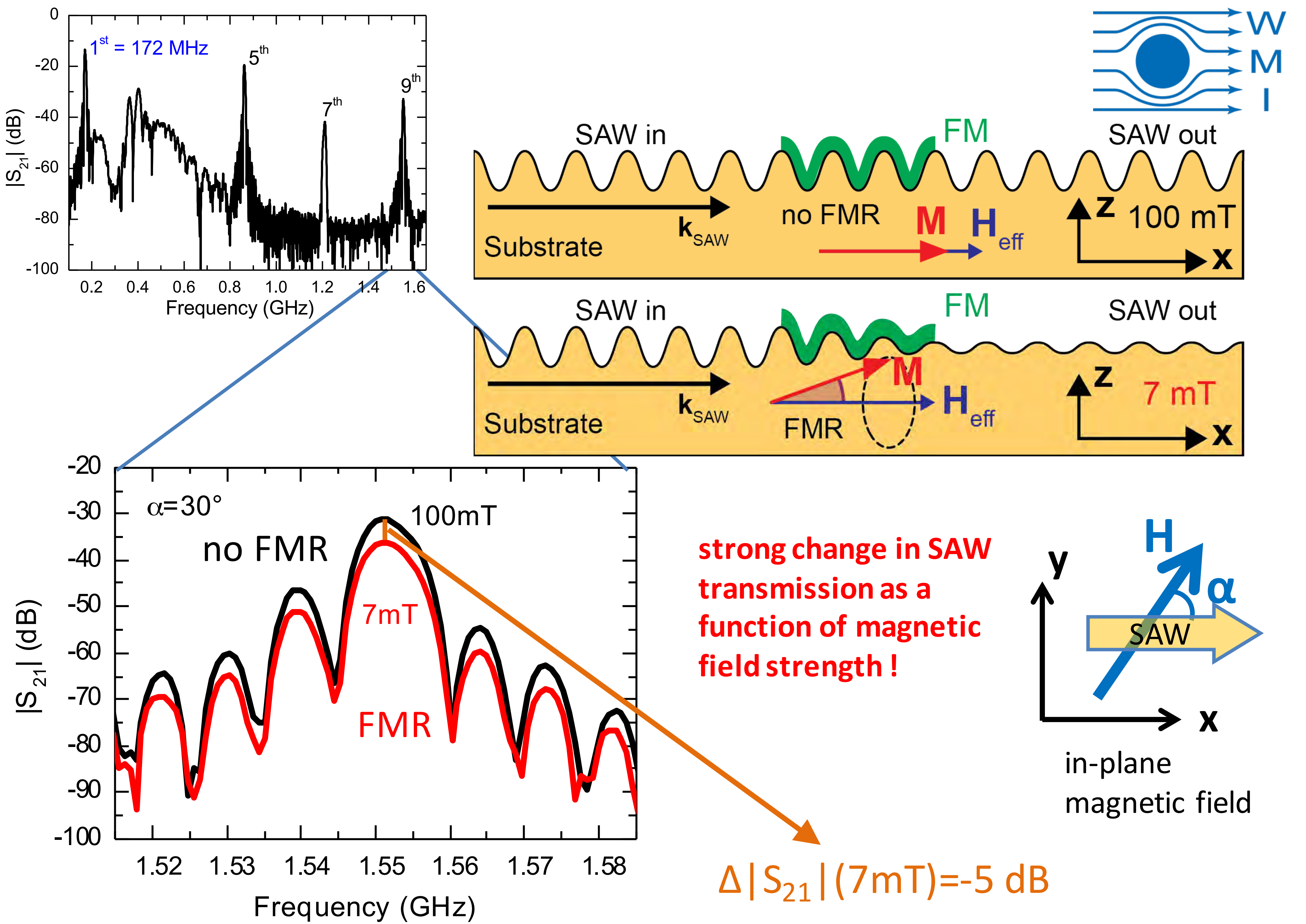
Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Microwave transmission



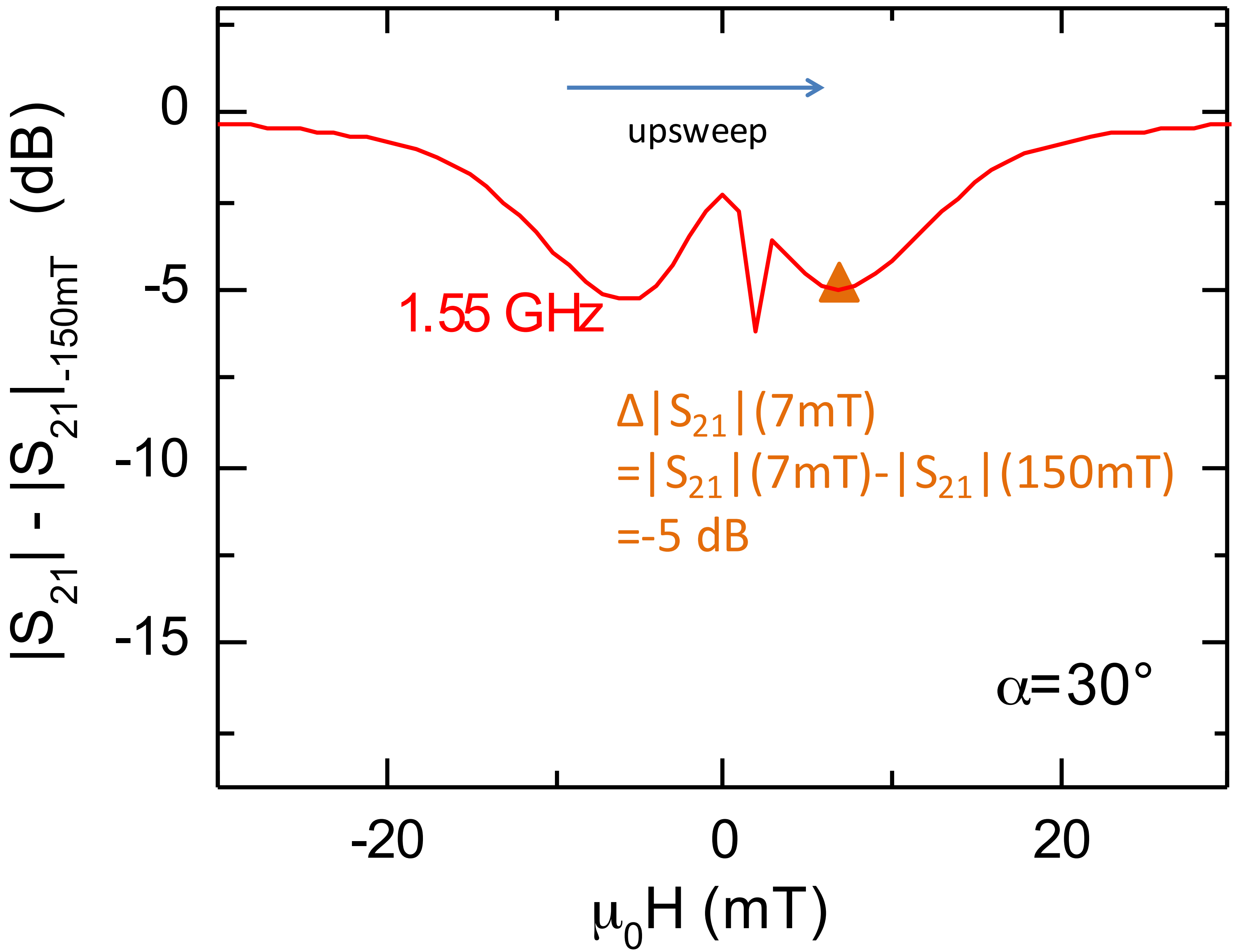
Several SAW transmission maxima

Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)



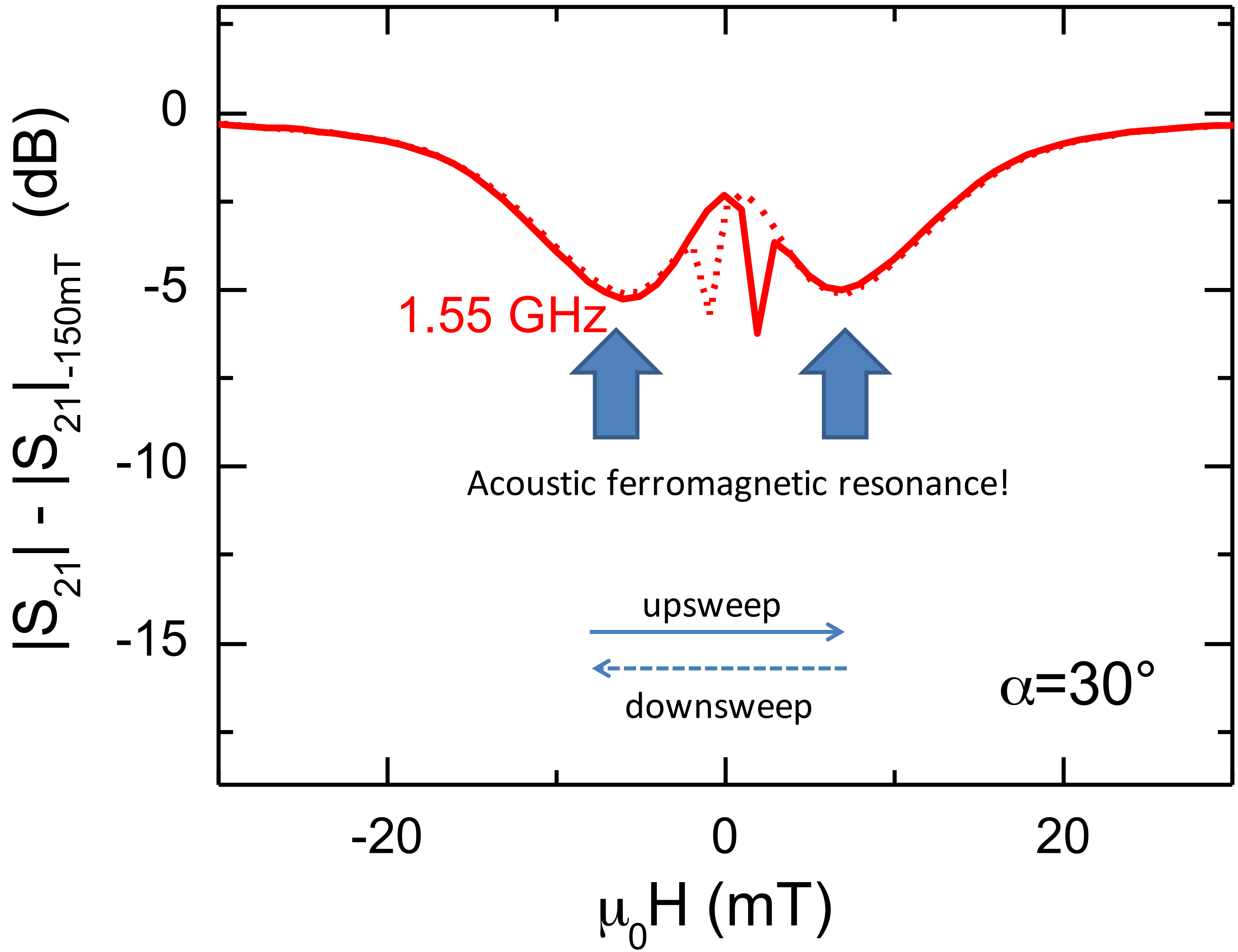
Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Acoustic ferromagnetic resonance



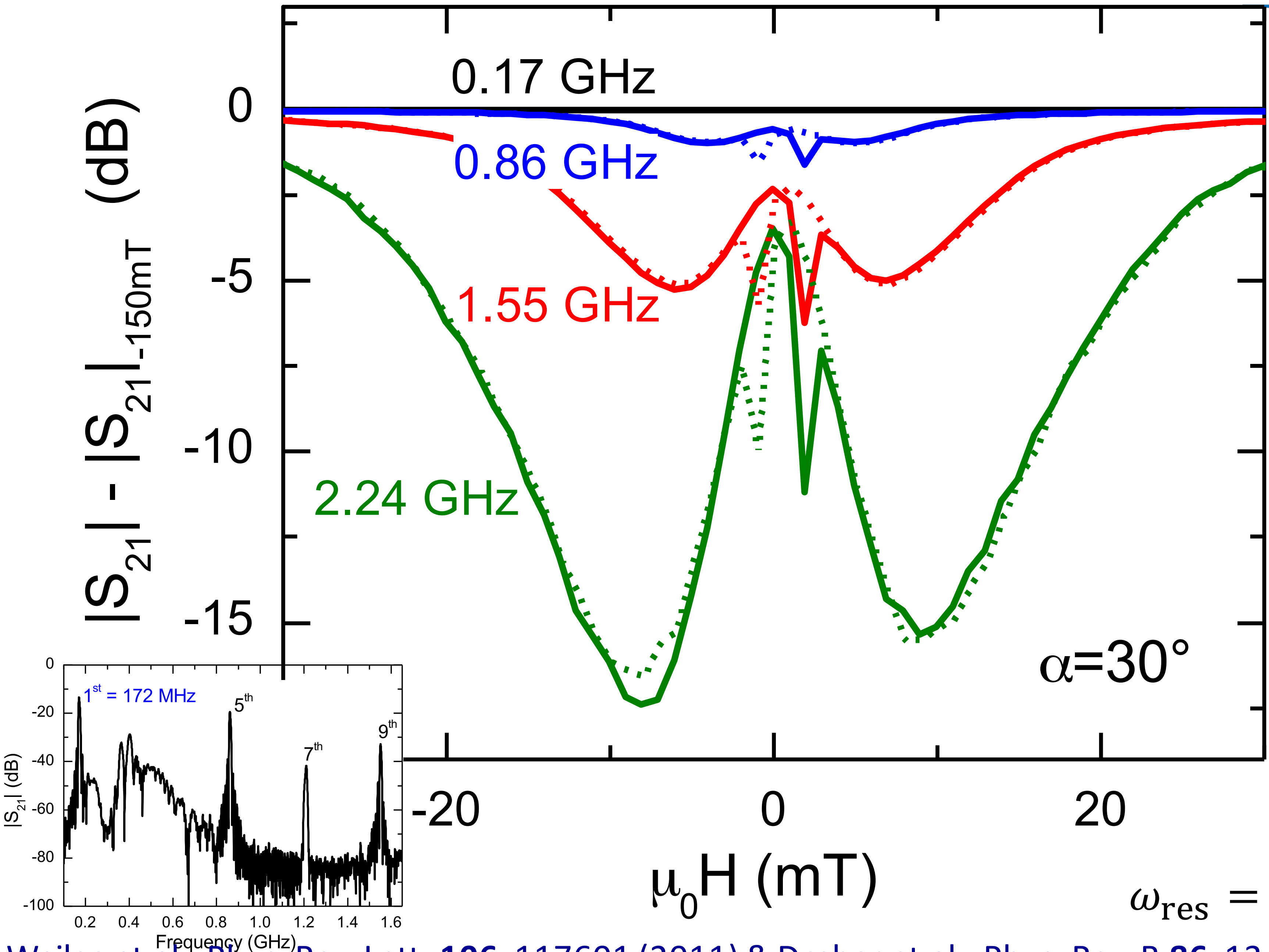
Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Acoustic ferromagnetic resonance



Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

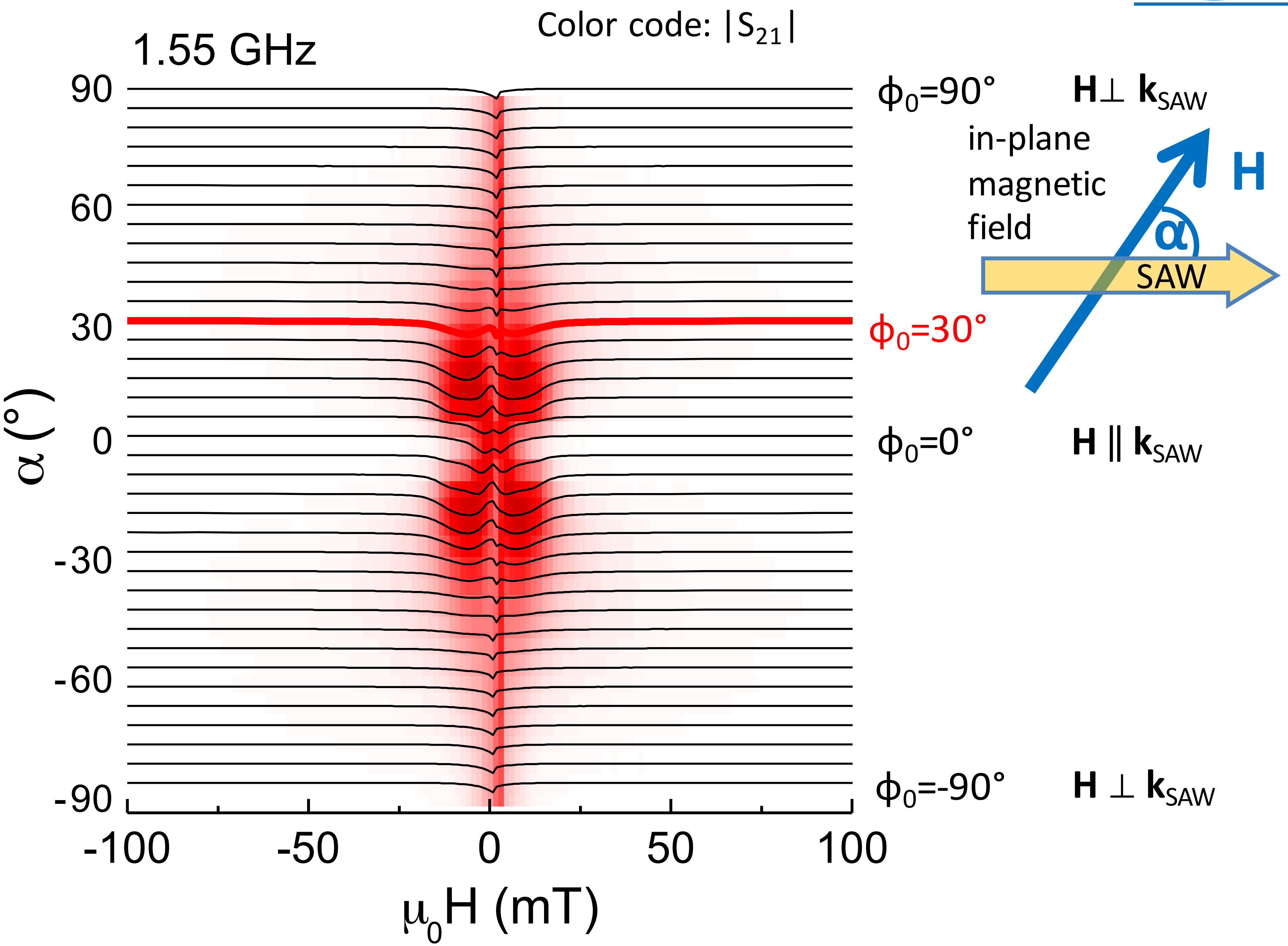
Acoustic ferromagnetic resonance



$$\omega_{\mathrm{res}} = \gamma \mu_0 H_{\mathrm{eff}}$$

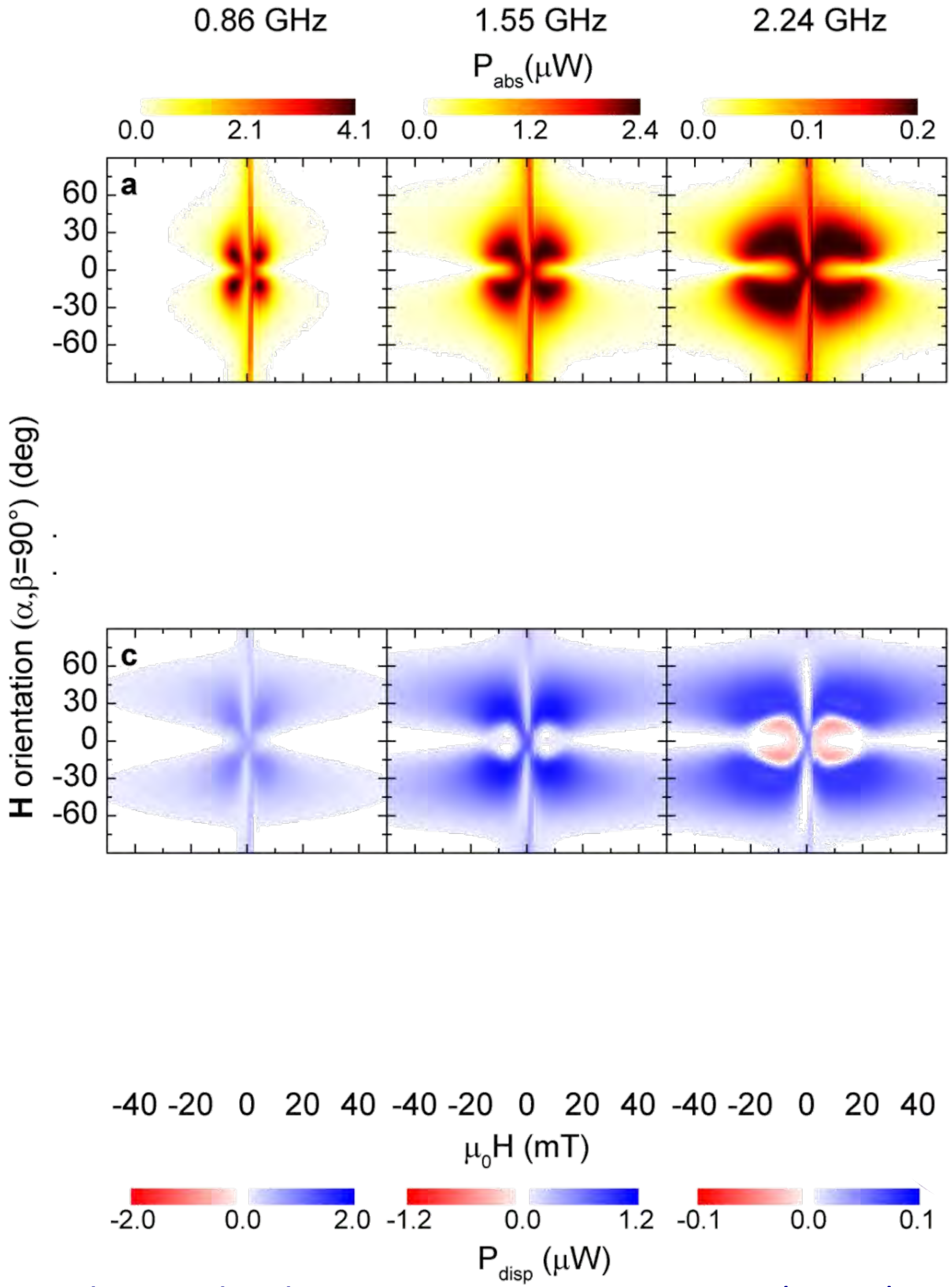
Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Acoustic ferromagnetic resonance



Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Comparison: Measurement vs. simulation



Measurement

P_{abs}

Simulation

Measurement

P_{disp}

Simulation

u=x

B_u=2.5 mT

B_d=400 mT

B_1=25 T

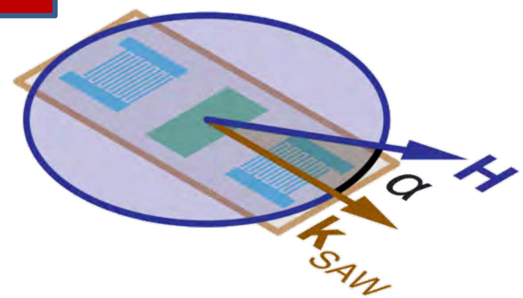
M_s=370 kA/m

a=0.1

quantitative Simulation **no further parameters**

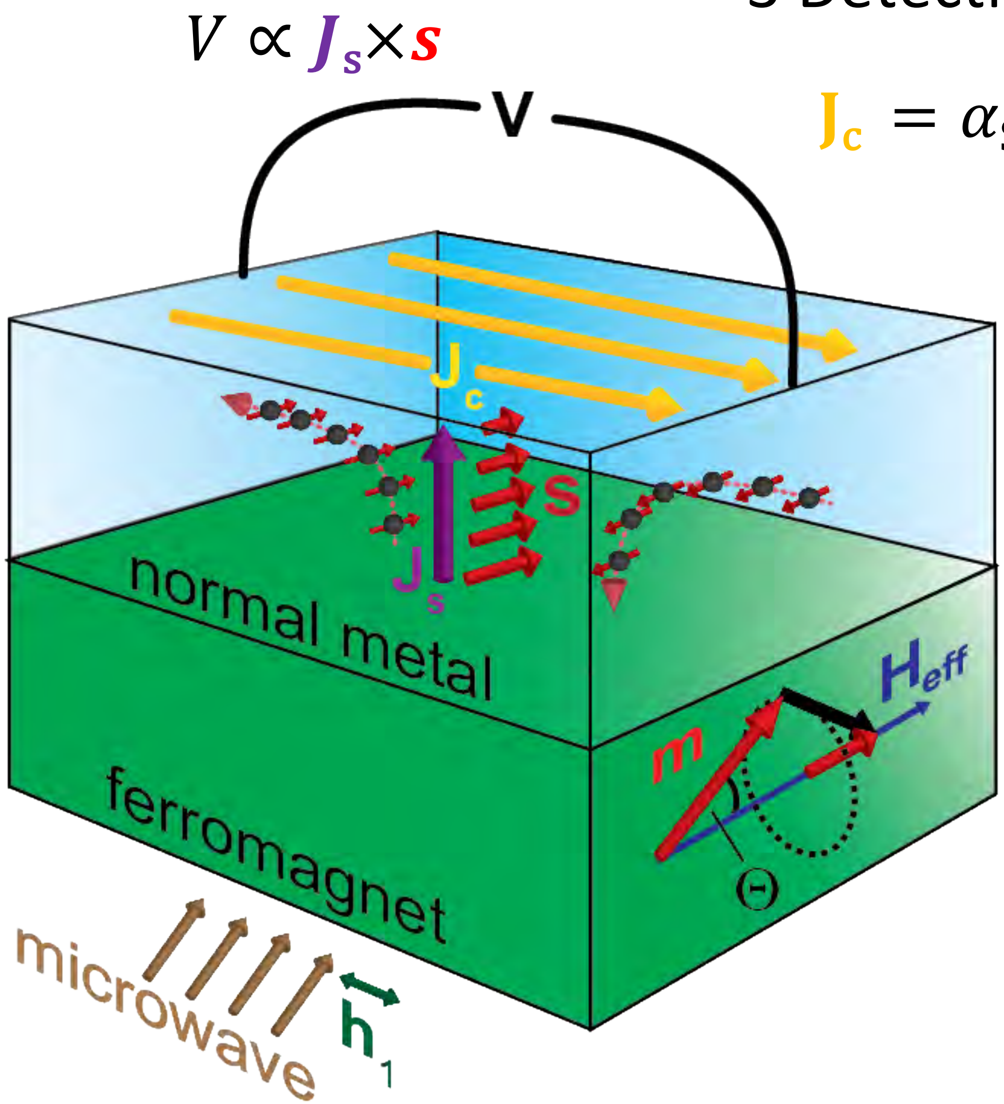
in-plane rotation

$\varepsilon \approx 5\times10^{-7}$ (measured)



Weiler et al., Phys. Rev. Lett. **106**, 117601 (2011) & Dreher et al., Phys. Rev. B **86**, 134415 (2012)

Spin pumping in a nutshell



3 Detection: Inverse spin Hall effect

$$J_c = \alpha_{SHE} \frac{2e}{\hbar} [J_s \times s]$$

α_{SHE} : Spin Hall angle
$\alpha_{SHE} \approx 0.01$ (Pt)

2 Relaxation
(Spin pumping contribution)

$$J_s = \frac{\hbar}{4\pi} g^{\uparrow\downarrow} m \times \partial_t m$$

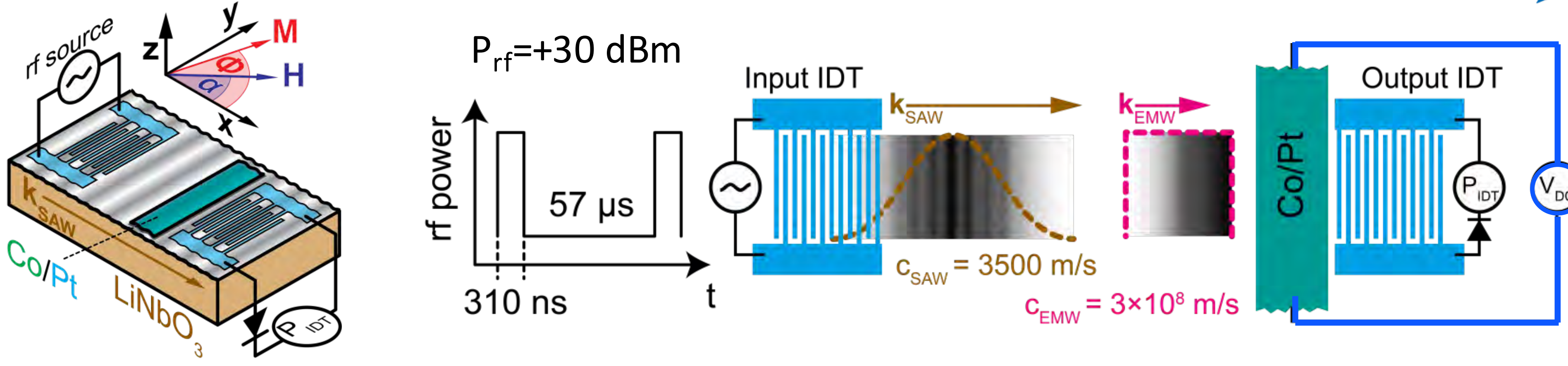
$$\langle J_s \rangle \approx \frac{\hbar\nu}{2} g^{\uparrow\downarrow} sin^2 \Theta$$

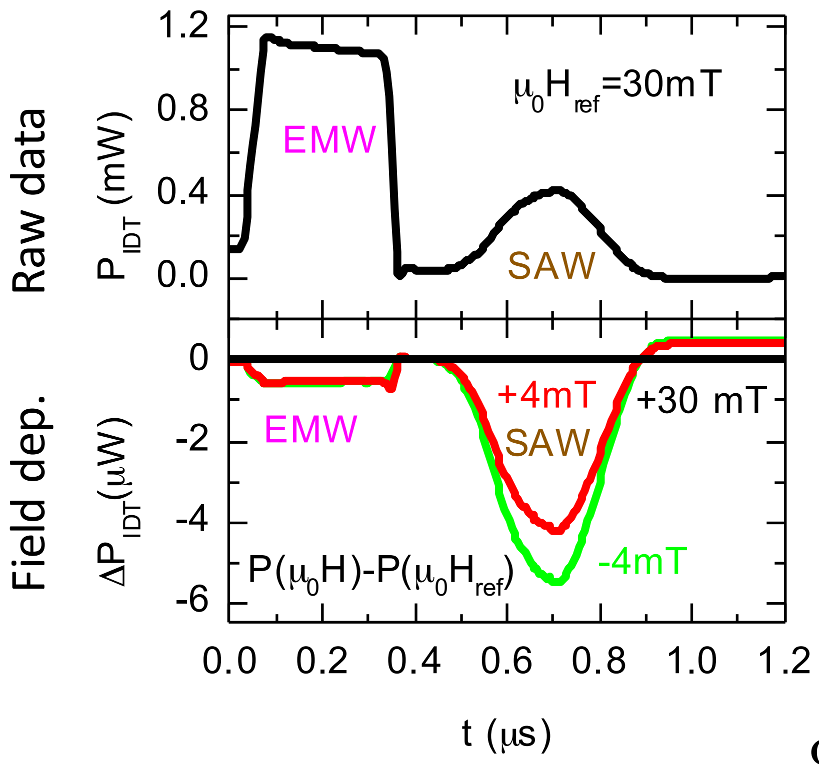
1 Ferromagnetic resonance

$$\partial_t m = -\gamma m \times \mu_0 H_{eff} + a\, m \times \partial_t m$$

F. Czeschka, PhD thesis, TUM (2011)

Acousticly driven spin pumping / time domain





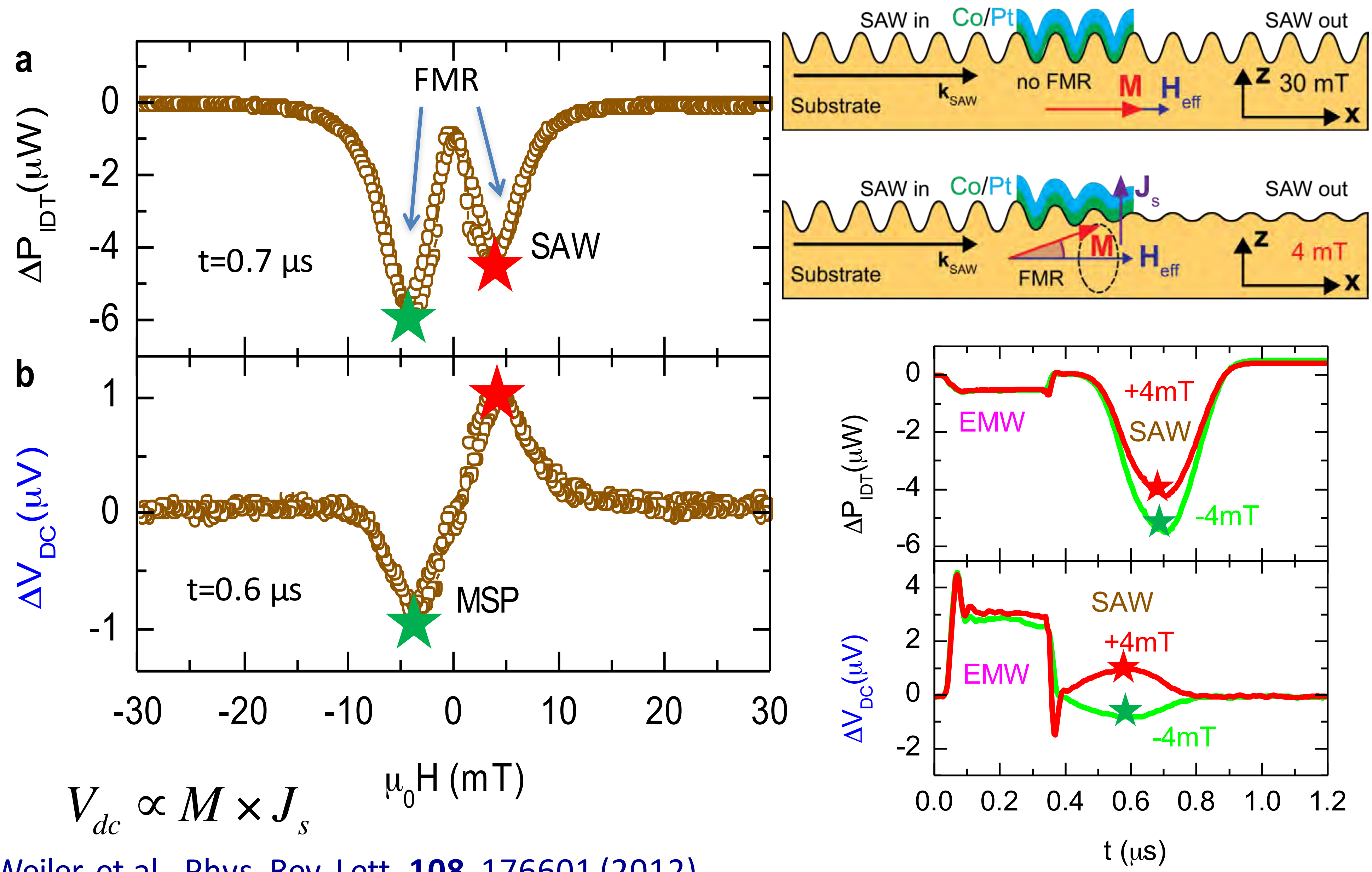
$\alpha=10°$

Separation of EMW-driven and SAW-driven contributions

EMW: Speed of light
SAW: Speed of sound

Weiler et al., Phys. Rev. Lett. **108**, 176601 (2012)

Acousticly driven spin pumping



$$V_{dc} \propto M \times J_s$$

Weiler et al., Phys. Rev. Lett. **108**, 176601 (2012)

Acknowledgements

Lukas Dreher
Martin S. Brandt

Mehdi Abdi

Michael Hartmann

"Nano-Mechanics"

Matthias Pernpeintner
Achim Marx
Philip Schmidt
Daniel Schwienbacher
Friedrich Wulschner
Rasmus Holländer
Fredrik Hocke
Anh Tu Bohn

"Magnetiker"

Franz Czeschka
Christian Heeg
Frederik S. Goerg
Matthias Opel
Stephan Geprägs

Summary

- Sensing magnetoelastics in nanostructures
- Acousticly driven ferromagnetic resonance
- Acousticly driven spin pumping