Ultrafast dynamics of antiferromagnets: switching vs rotation

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INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

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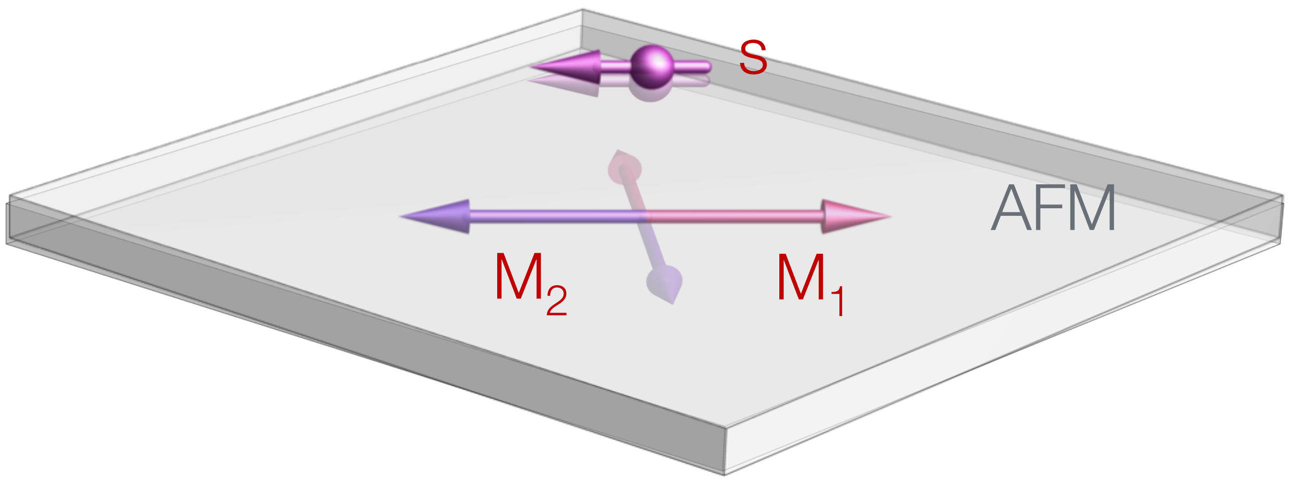
SPICE-Workshop
Ultrafast Antiferromagnetic Writing

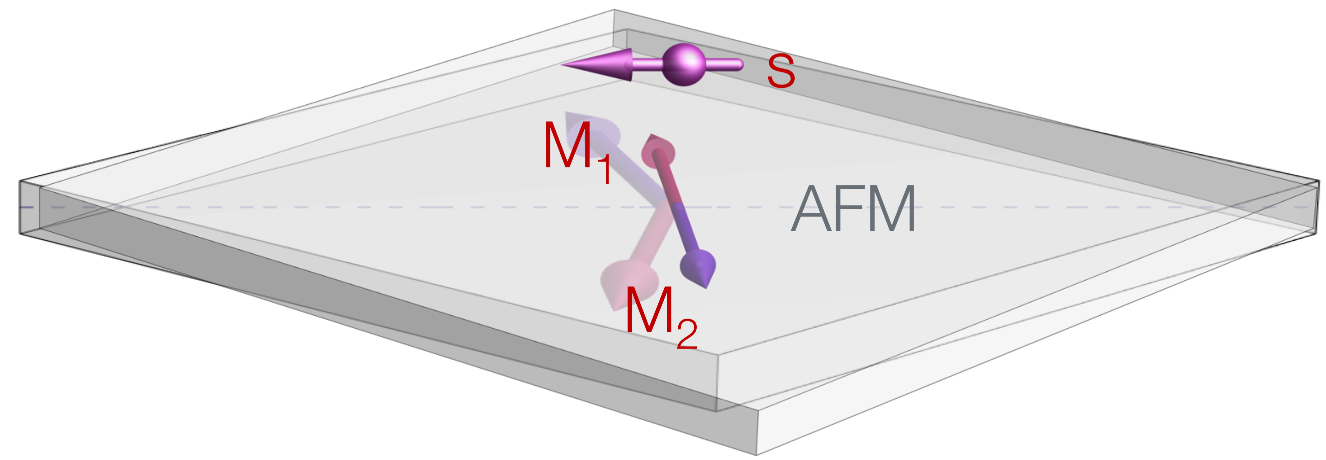
DFG

Alexander von Humboldt Stiftung/Foundation

erc European Research Council

Motivation





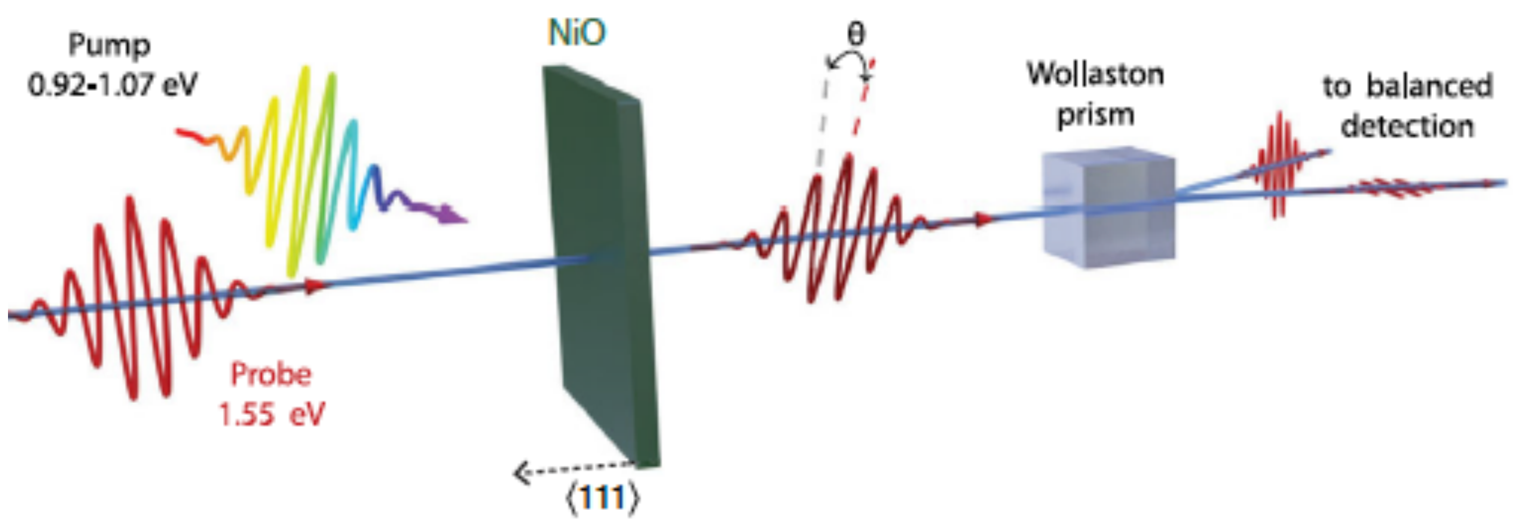
Field-like Antidamping

Motivation

$$\frac{\partial \boldsymbol{M}_1}{\partial t} + \ldots = \Lambda_{fl} \boldsymbol{M}_1 \times \boldsymbol{s}(t) + \Lambda_{dl} \boldsymbol{M}_1 \times \boldsymbol{s}(t) \times \boldsymbol{M}_1$$

?

$$\frac{\partial \boldsymbol{M}_2}{\partial t} + \ldots = \Lambda_{fl} \boldsymbol{M}_2 \times \boldsymbol{s}(t) + \Lambda_{dl} \boldsymbol{M}_2 \times \boldsymbol{s}(t) \times \boldsymbol{M}_2$$



Take-home message

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- Antidamping SOT induces fast AFM dynamics (autooscillations)
- Tailoring pulse shape => switching
- Time-dependent field-like SOT => switching control
- Magnetoelasticity => additional functionality

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Outlook

- SOT-induced dynamics of three-sublateral antiferromagnet
- Time-dependent SOT: field-like vs antidamping torque
- Switching with the fast pulses
- Optically-induced dynamics of T-domain walls

References

1. O.G. and V. Loktev (2015) Low Temp.Phys. http://dx.doi.org/10.1063/1.4931648
2. Th. Chirac, OG, et al, 2020, 10.1103/PhysRevB.102.134415
3. D. Bossini, O.G. et al (2021), 10.1103/PhysRevLett.127.077202
4. O.G. and D. Bossini, et al (2021), J. Phys. D 10.1088/1361-6463/ac055c

Collinear AFM, SOT

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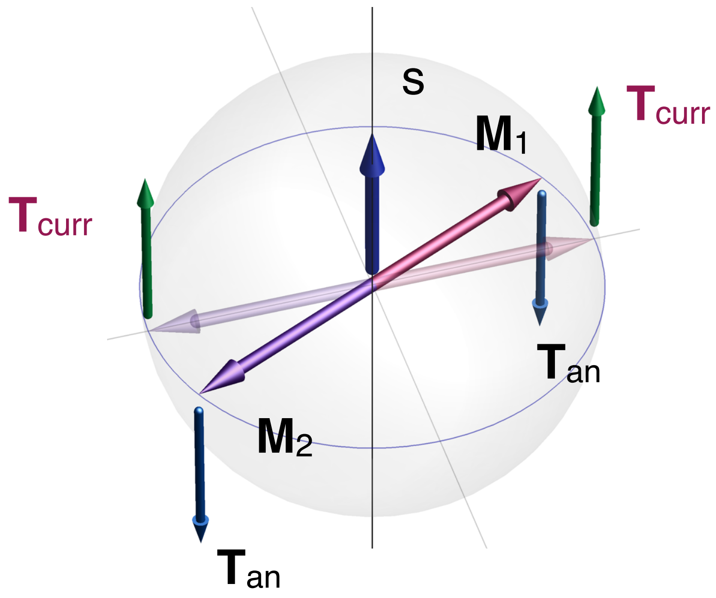
$$\boldsymbol{n} \times (\ddot{\boldsymbol{n}} + \gamma^2 H_{ex} \boldsymbol{H}_{an}) = \gamma^2 H_{ex} \boldsymbol{n} \times (\boldsymbol{\Lambda}_{dl}\, \boldsymbol{s} \times \boldsymbol{n} - \alpha_G \dot{\boldsymbol{n}})$$



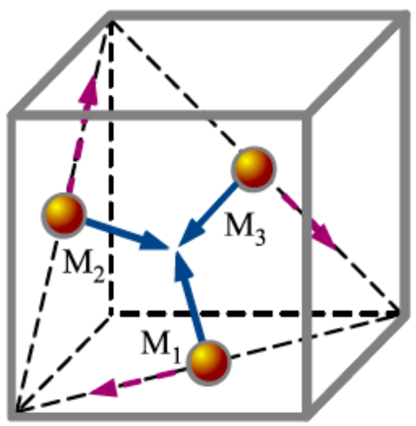
$$J_{crit} \propto H_{an} t_{AF}$$

$$\Omega_{prec} \propto j/\alpha_G$$

$$\Omega_{prec} \propto \omega_{AFMR} \propto \sqrt{H_{ex} H_{an}}$$

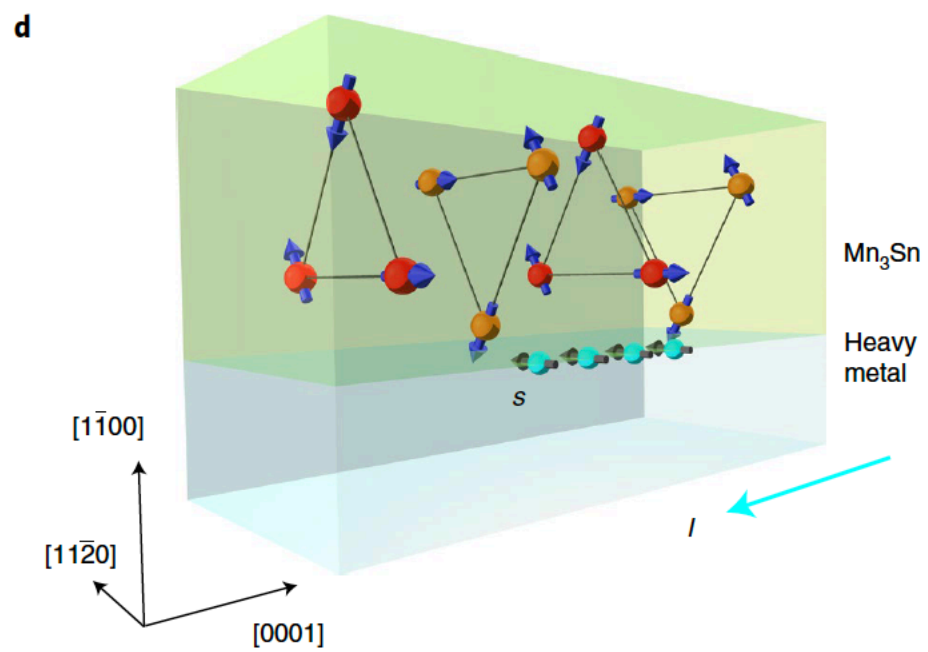
H.Gomonay, V.Loktev, (2014). *Fizika Nizkikh Temperatur*, 40, 22.

Three-sublattice AFM

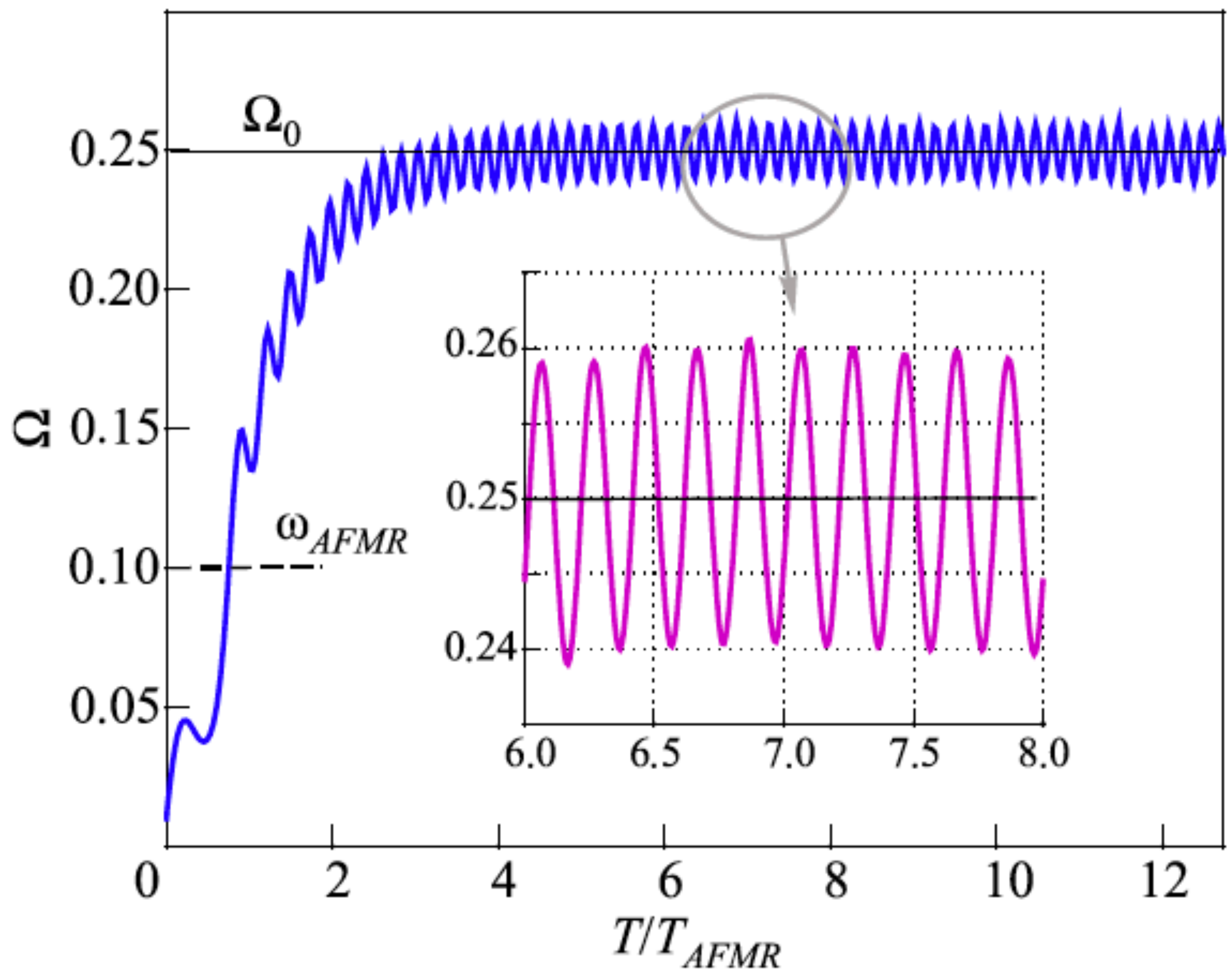


O.G., Loktev,(2015) Low Temp.Phys.
http://dx.doi.org/10.1063/1.4931648

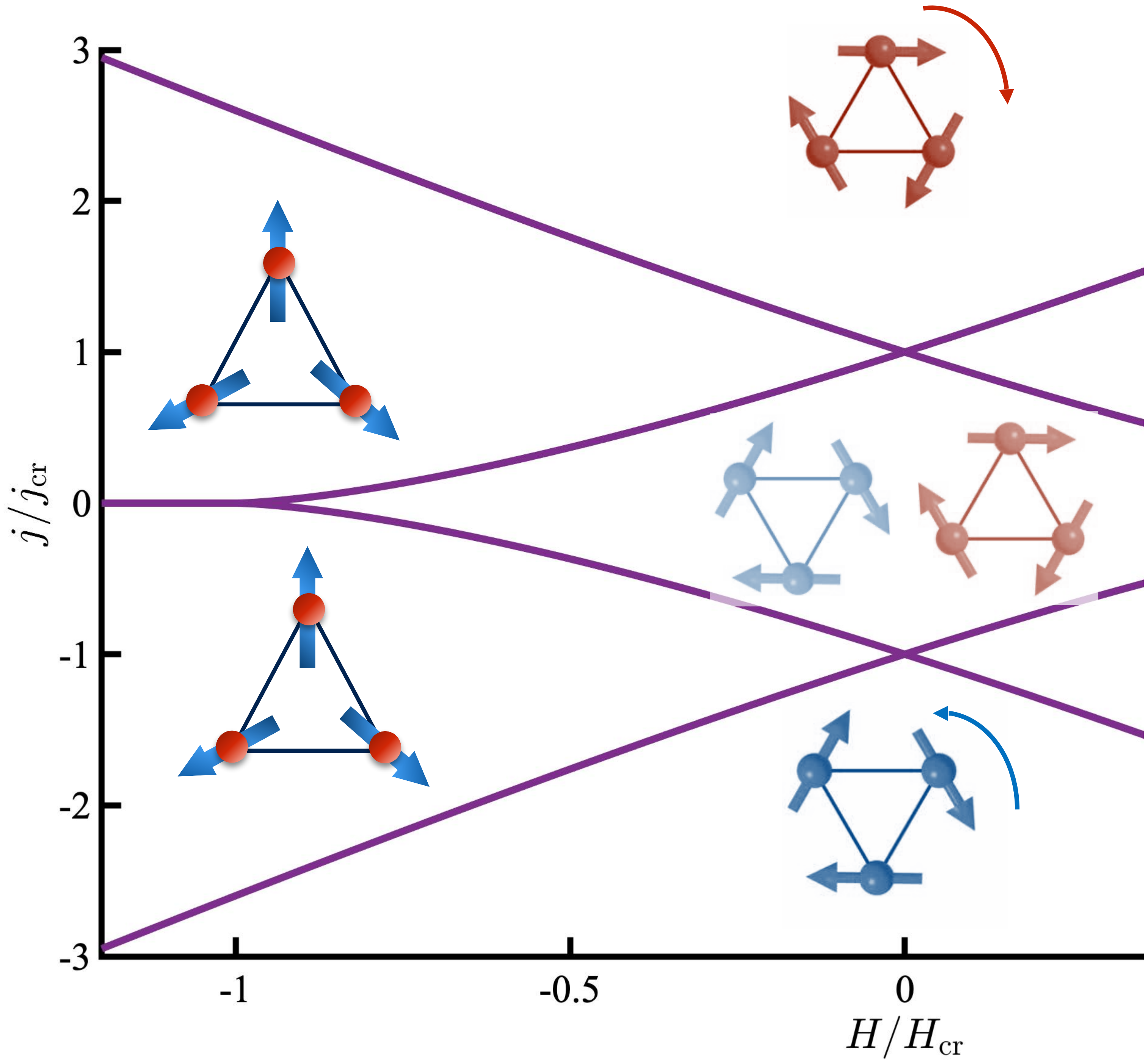
$$\ddot{\theta} + 2\gamma_{AF}\dot{\theta} + \omega_{AF}^2 \sin\theta\cos\theta + \gamma\omega_D H \sin\theta = \gamma^2 H_{ex} \left(\Lambda_{fl}\, \dot{s} + \Lambda_{dl}\, s\right)$$

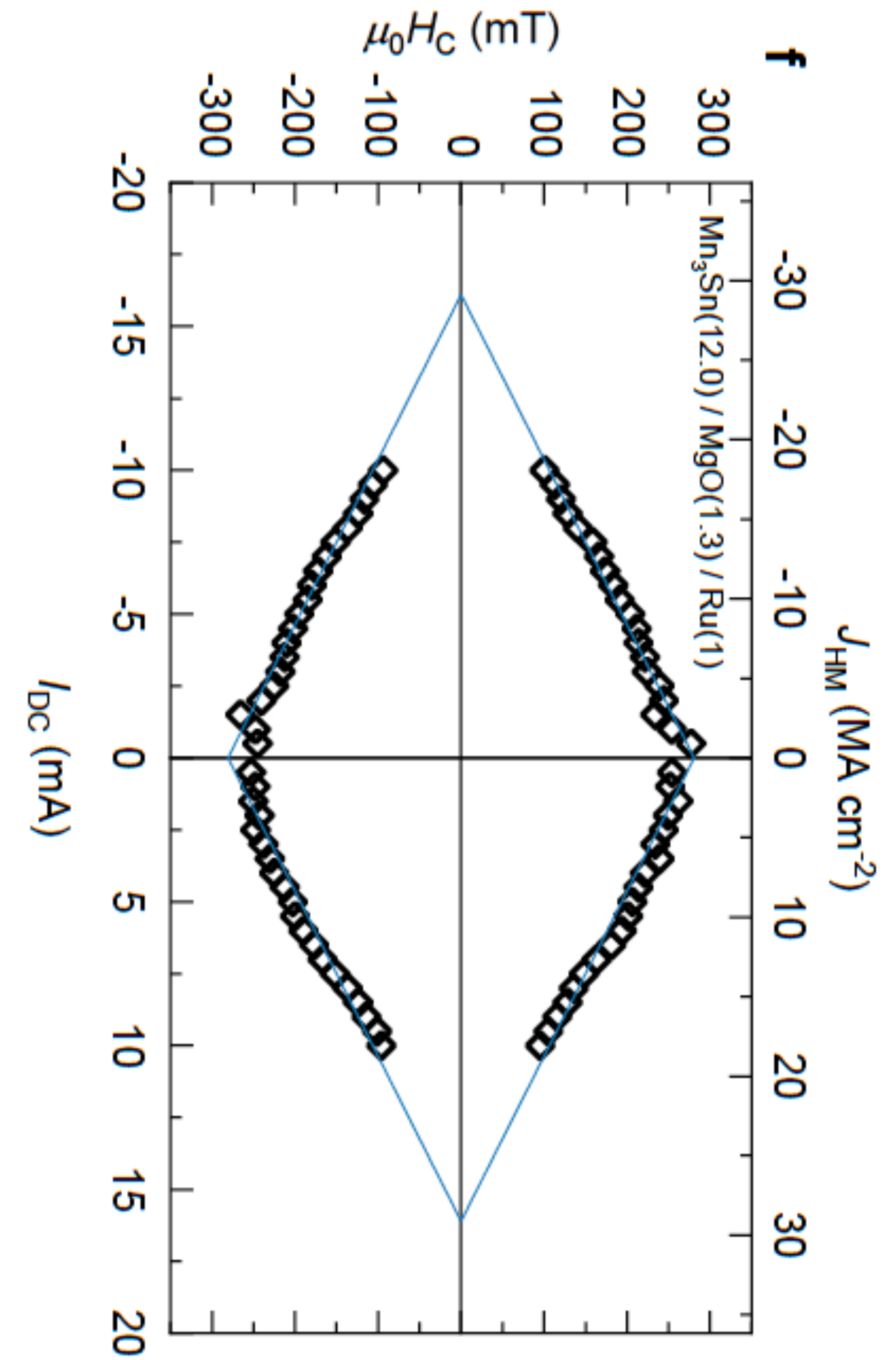


Yu. Takeuchi, et al, (2021) Nature Materials
https://doi.org/10.1038/s41563-021-01005-3



Phase diagram, field-current

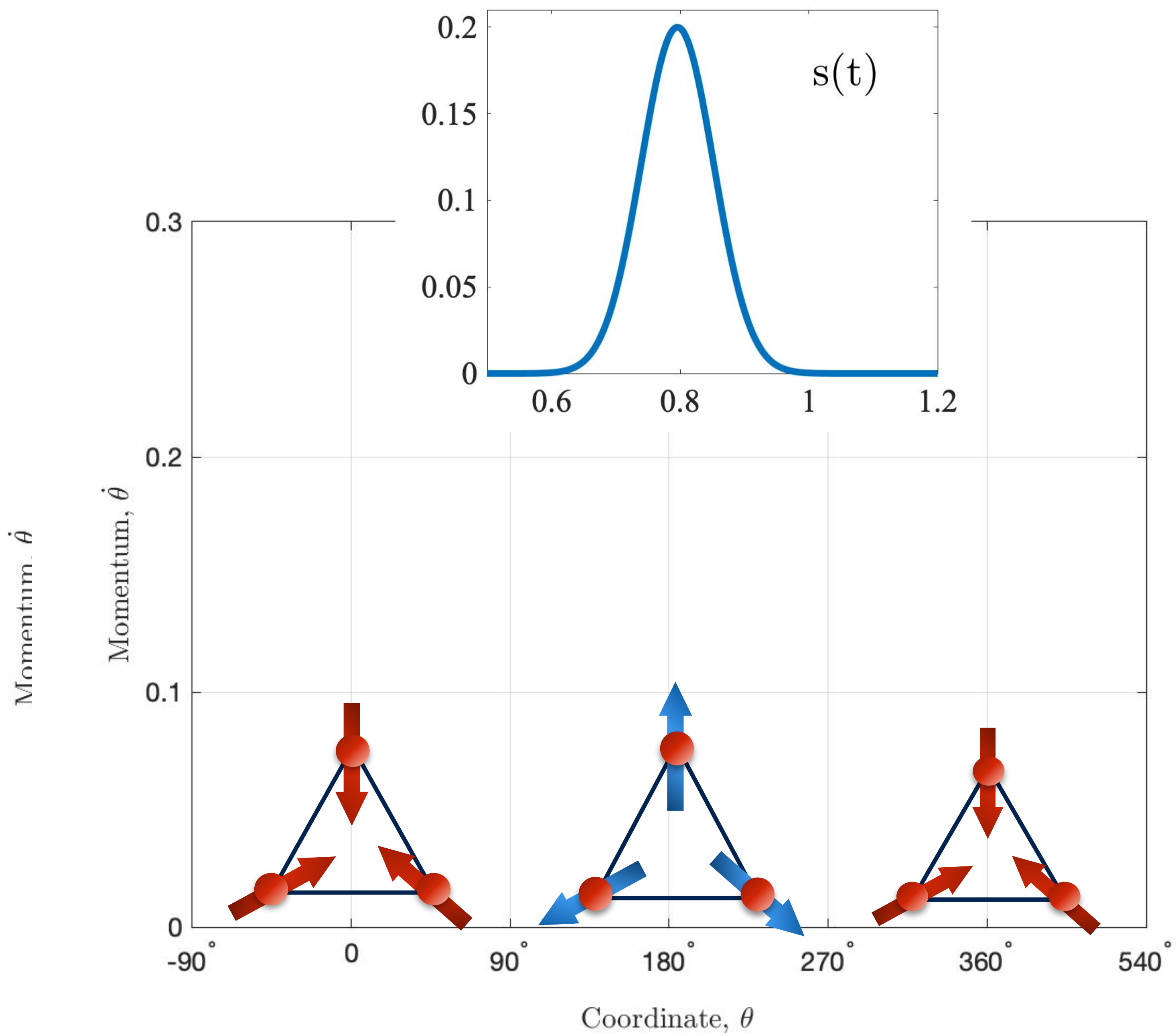




Yu. Takeuchi, et al, (2021) Nature Materials
https://doi.org/10.1038/s41563-021-01005-3

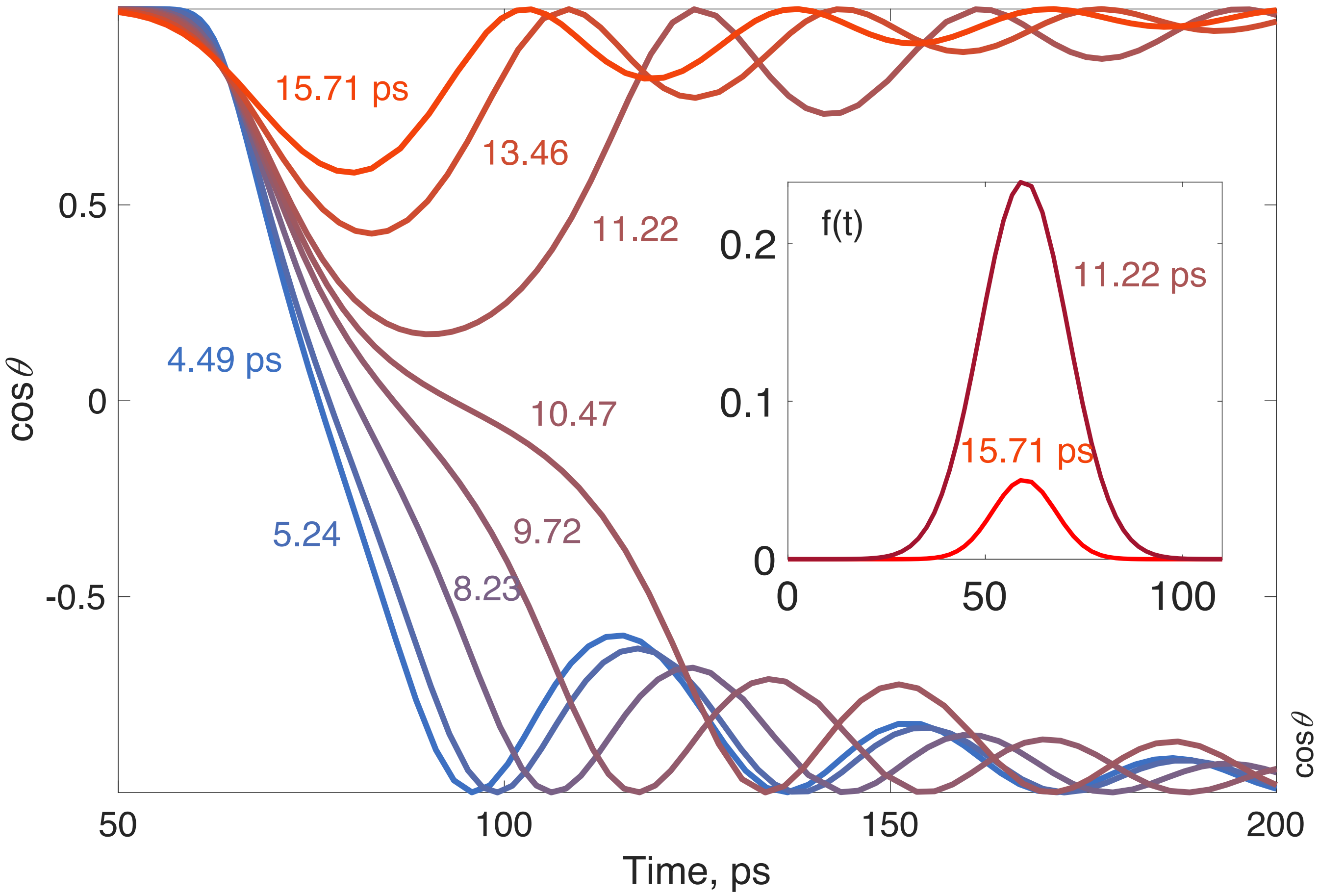
Switching with the short pulses

$$\ddot{\theta} + 2\gamma_{AF}\dot{\theta} + \omega_{AF}^2 \sin\theta\cos\theta + \gamma\omega_D H \sin\theta = \gamma^2 H_{ex} (\boldsymbol{\Lambda}_{fl}\,\dot{\boldsymbol{s}} + \boldsymbol{\Lambda}_{dl}\,\boldsymbol{s})$$

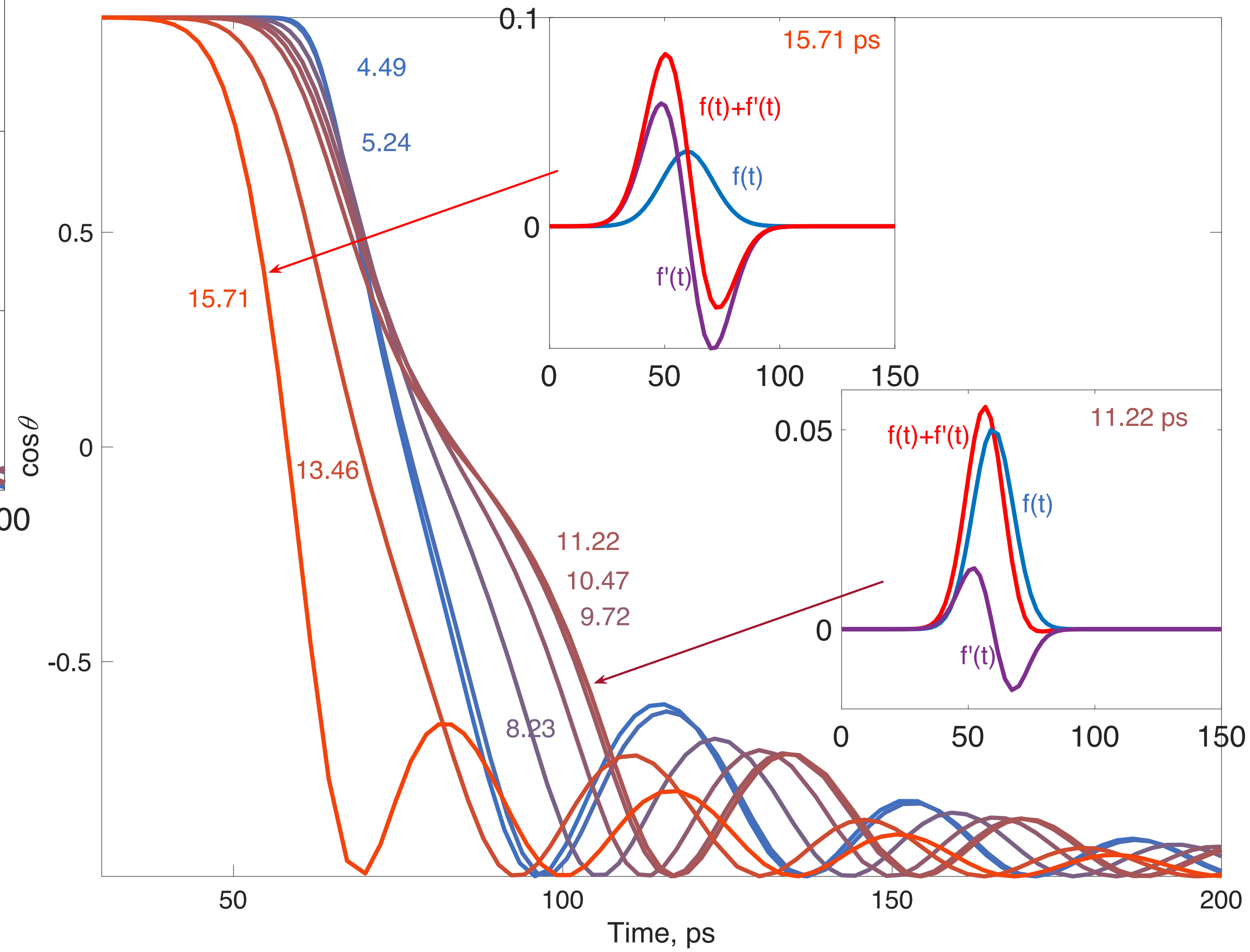


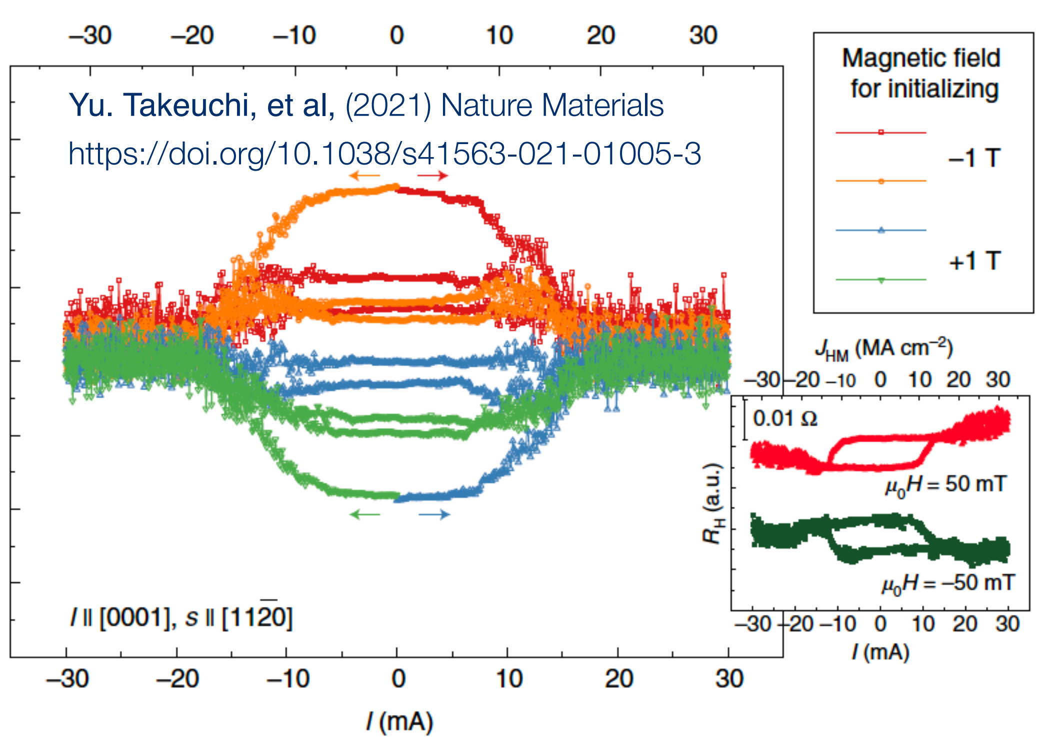
Field-like-vs damping-like torque

Pulse width



Field+antidamping

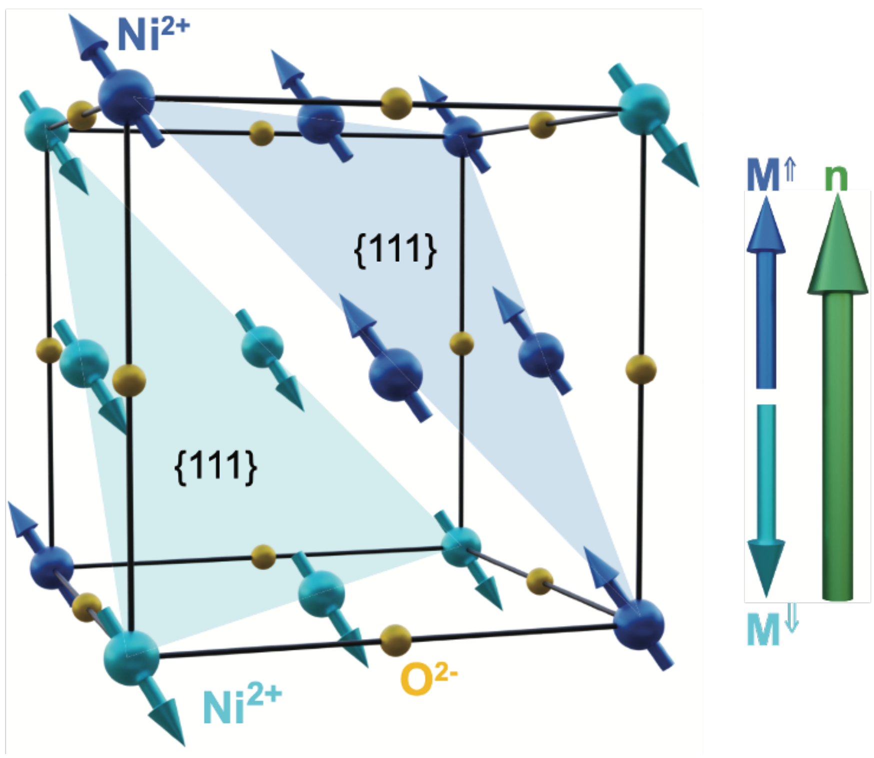




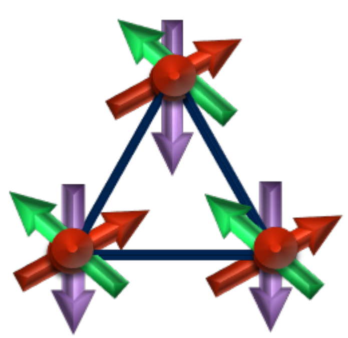
$$\ldots\theta+\gamma\omega_D H\sin\theta = \gamma^2 H_{ex}\left(\Lambda_{fl}\,\dot{s}+\Lambda_{dl}\,s\right)$$

Switching in a collinear AFM

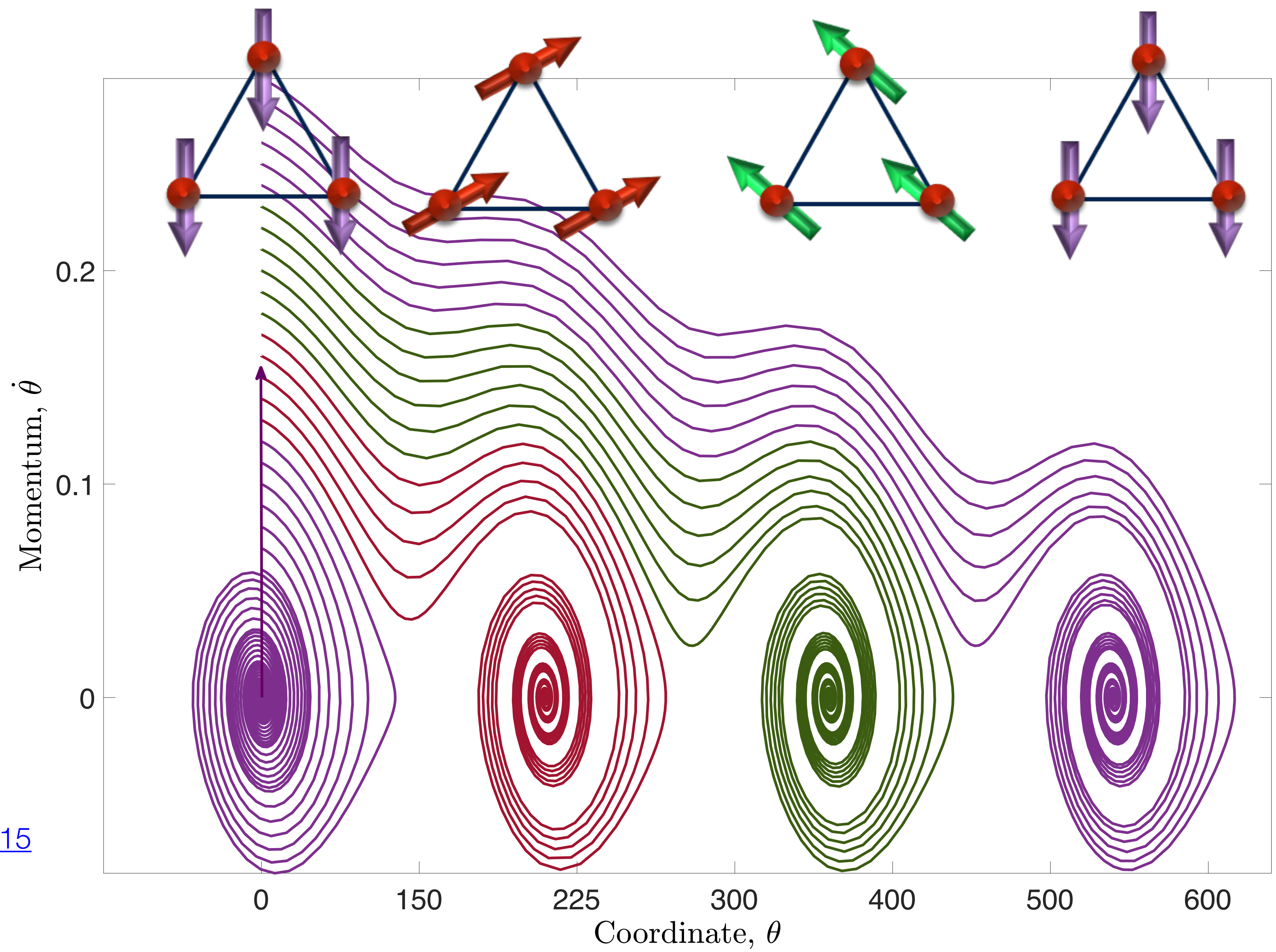
$$\ddot{\theta} + 2\gamma_{AF}\dot{\theta} + \omega_{AF}^2 \sin 6\,\theta = \gamma^2 H_{ex} \boldsymbol{\Lambda_{dl}}\, \boldsymbol{s}$$



NiO

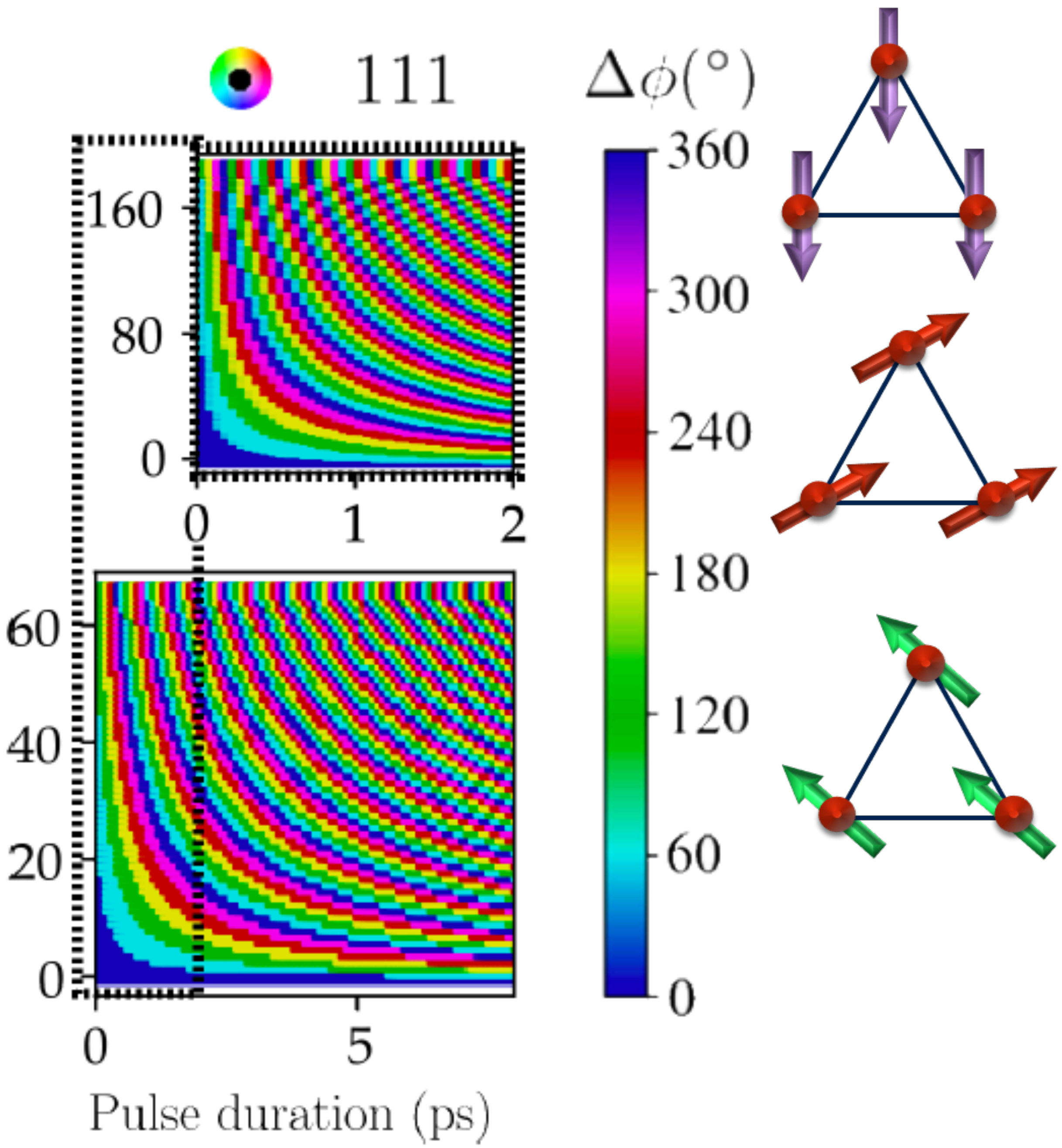


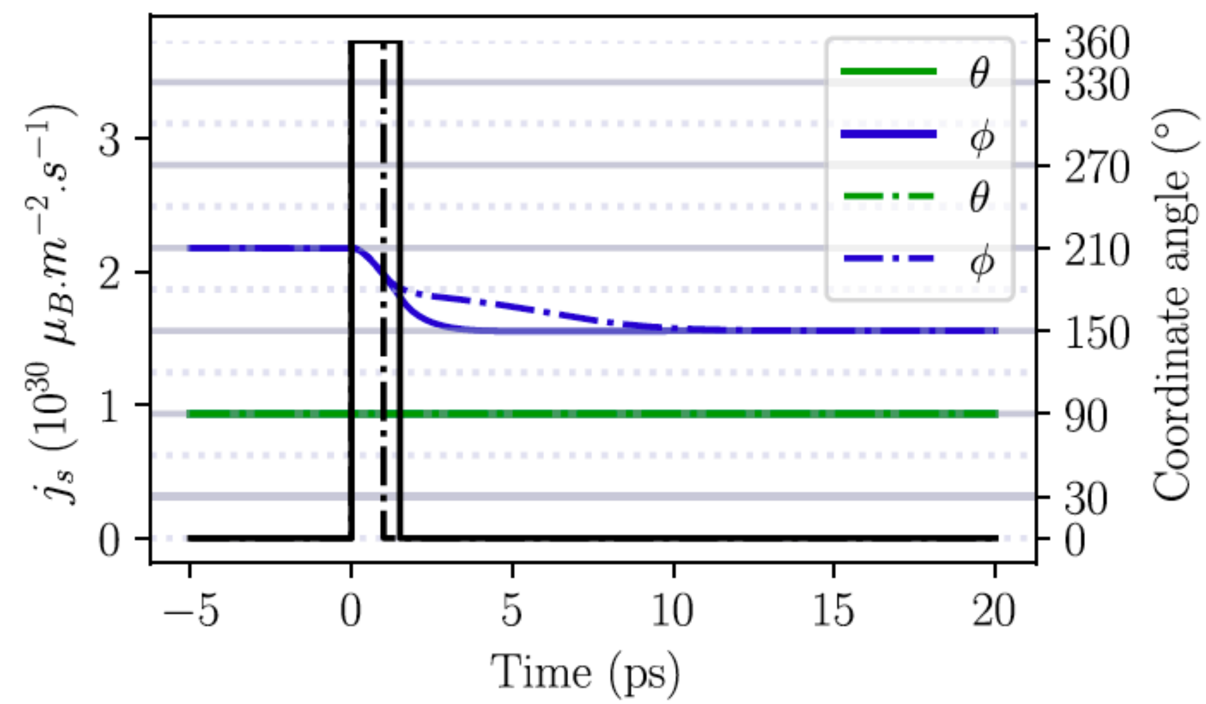
S-domains



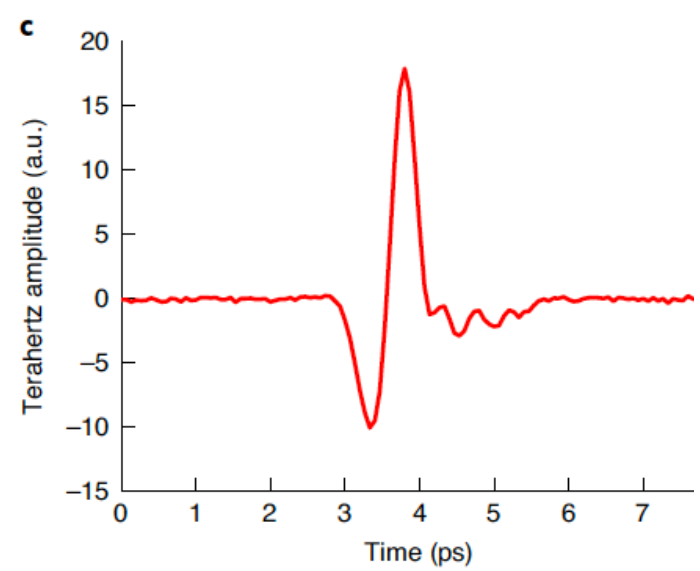
Th. Chirac, OG, et al, 2020, [10.1103/PhysRevB.102.134415](https://doi.org/10.1103/PhysRevB.102.134415)

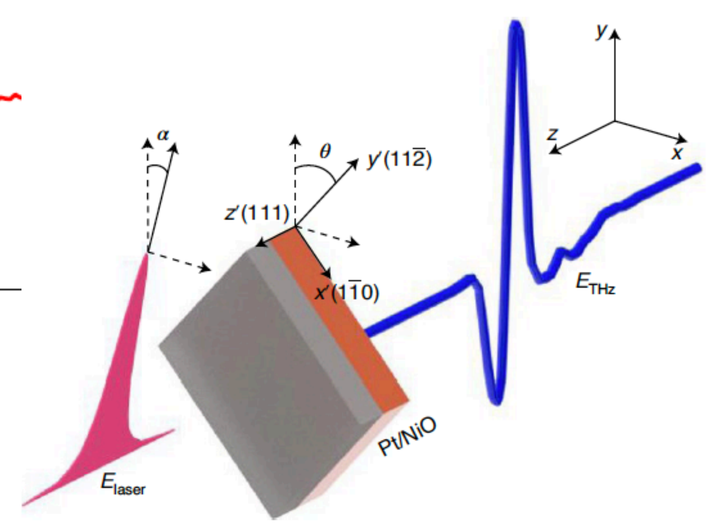
Switching with the short pulses





Th. Chirac, OG, et al, 2020, [10.1103/PhysRevB.102.134415](https://doi.org/10.1103/PhysRevB.102.134415)





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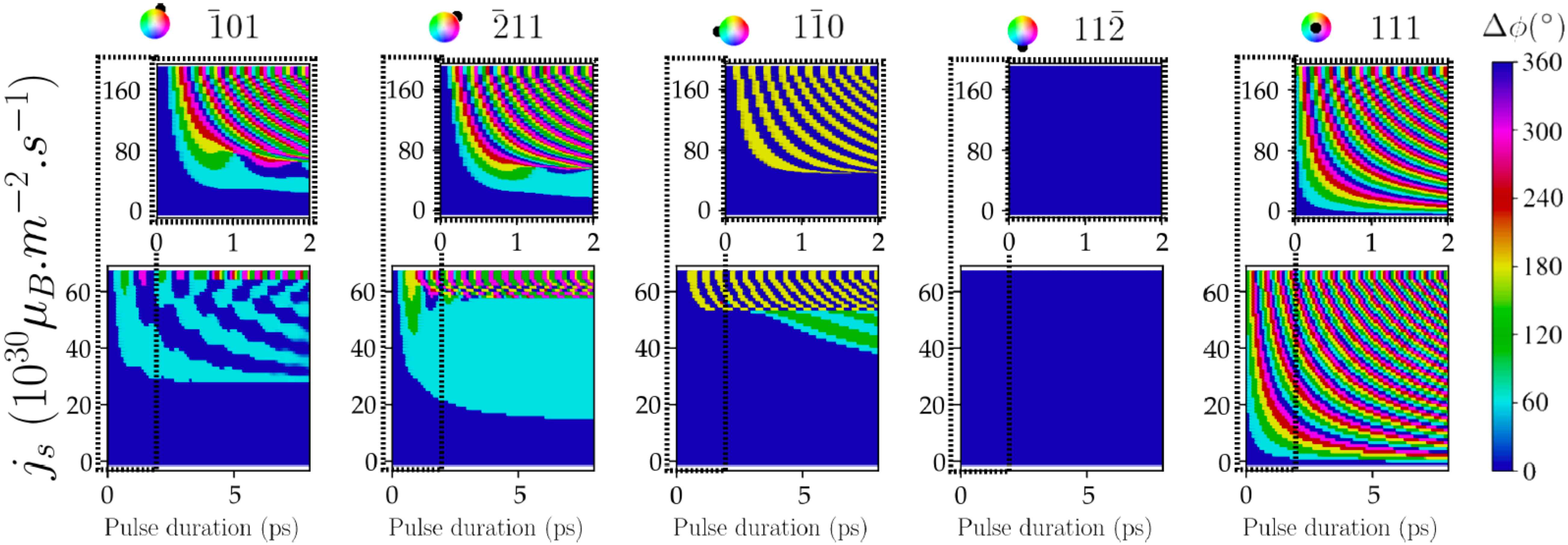
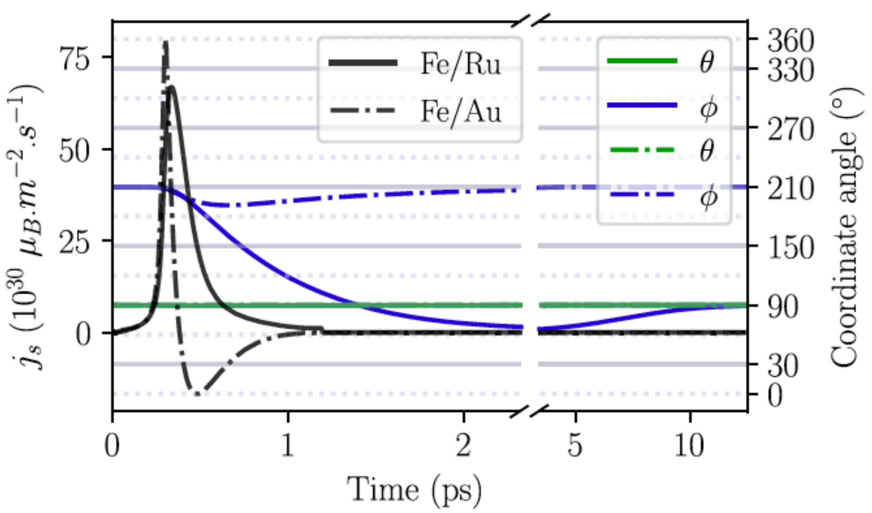
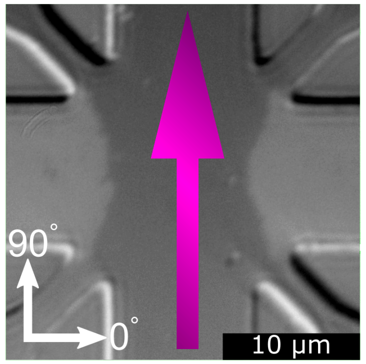
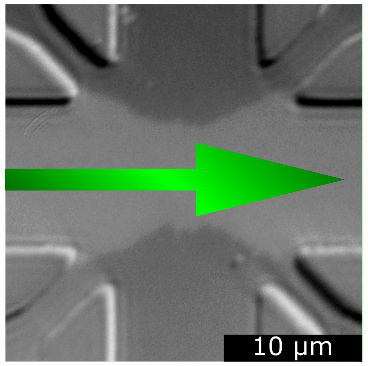
Switching with the short pulses





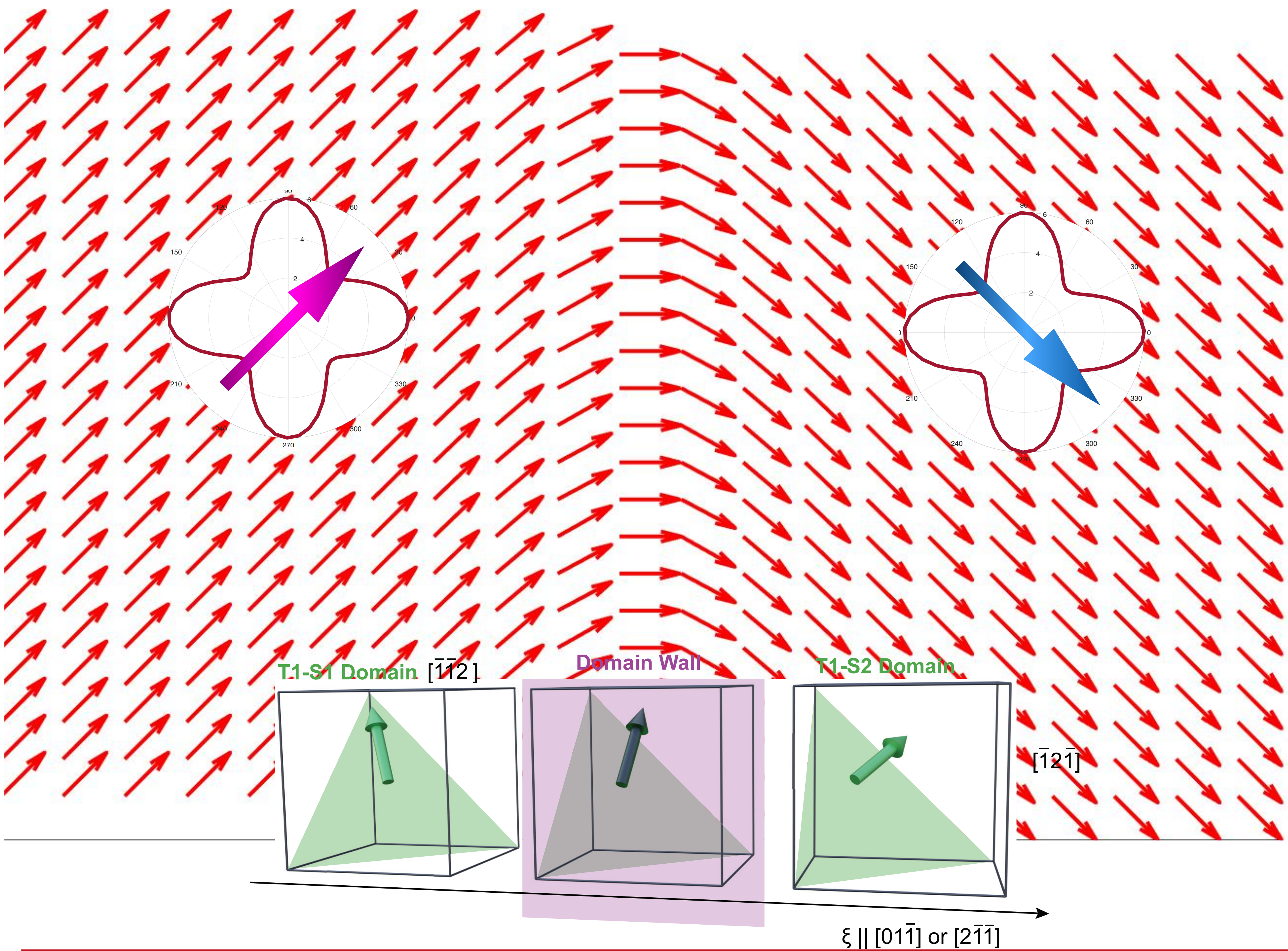




Th. Chirac, OG, et al, 2020, 10.1103/PhysRevB.102.134415

Ch. Schmitt et al (2021), 10.1103/PhysRevApplied.15.034047

Switching via magnetic DW motion



Free magnetic domain wall motion

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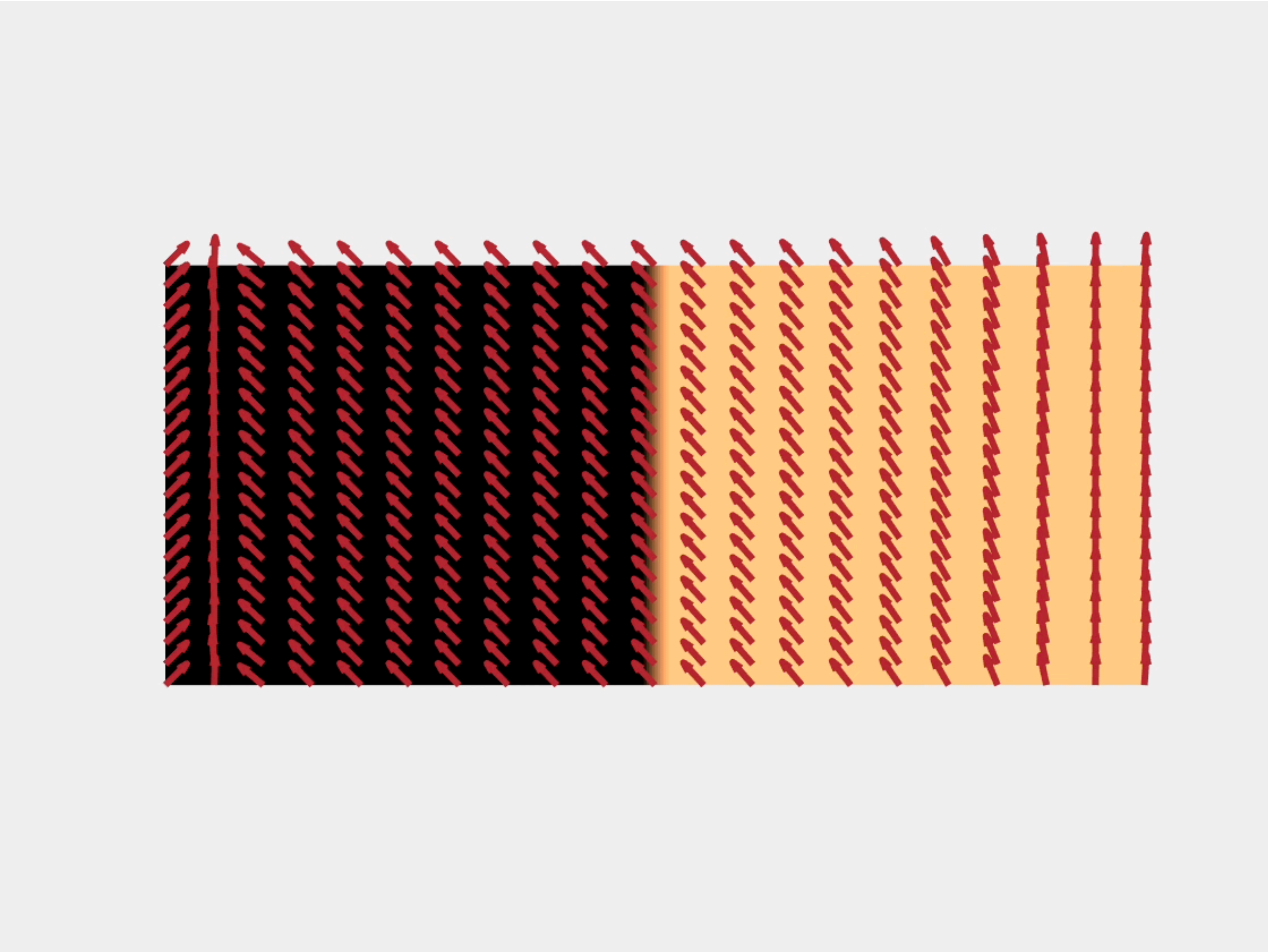
$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}\right) = 0$$



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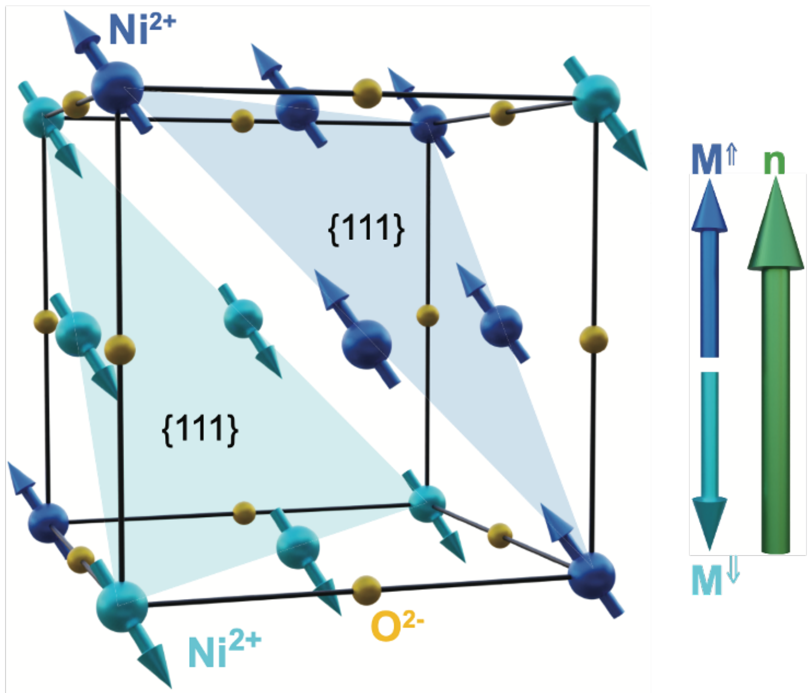
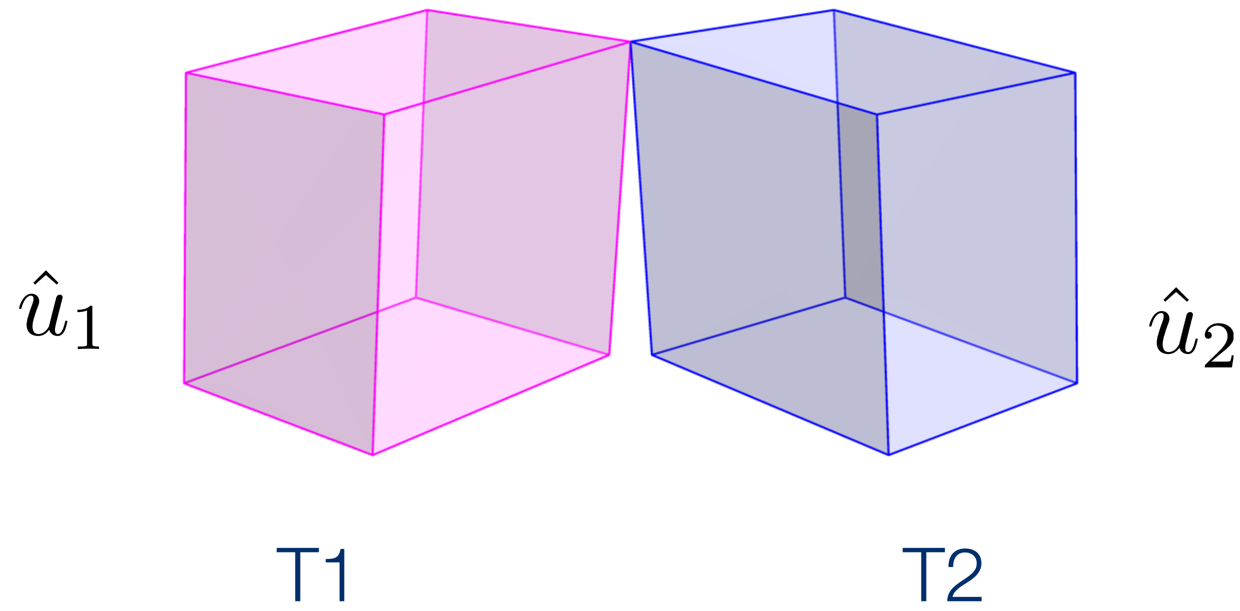
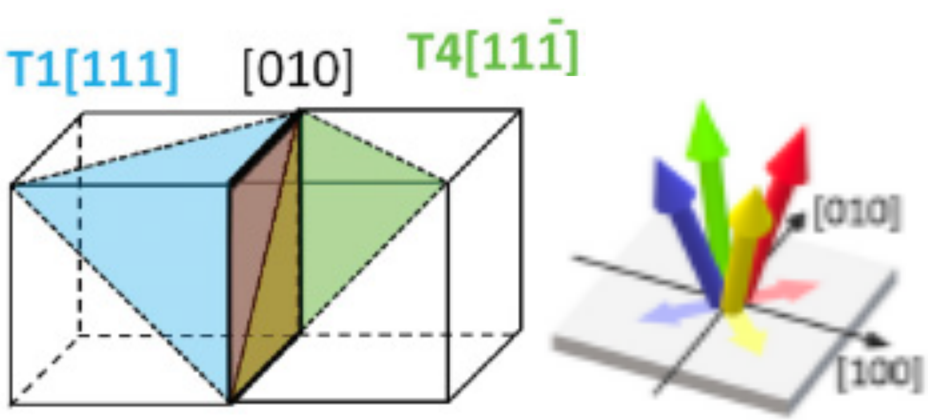
Switching in NiO, T domains



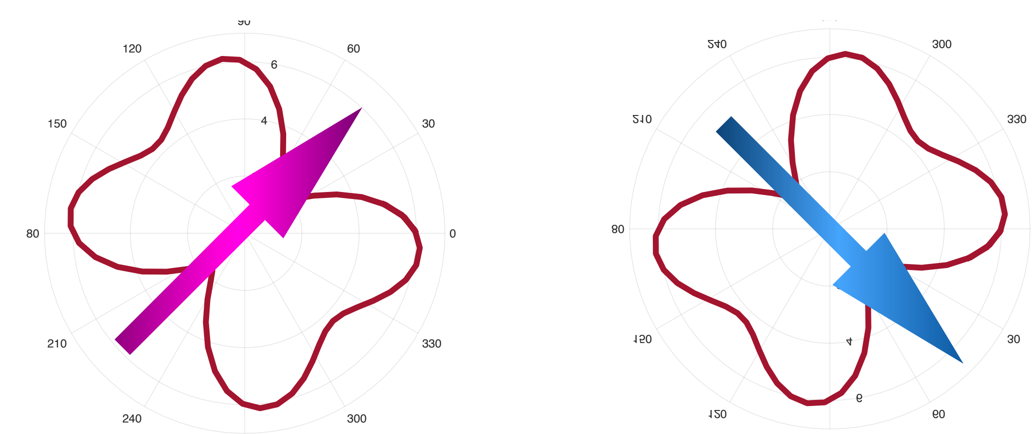
Distortion



NiO



Effective anisotropy



D. Bossini, O.G. et al (2021), 10.1103/PhysRevLett.127.077202

O.G. and D. Bossini, et al (2021), J. Phys. D 10.1088/1361-6463/ac055c

Magnetoelastic domain wall

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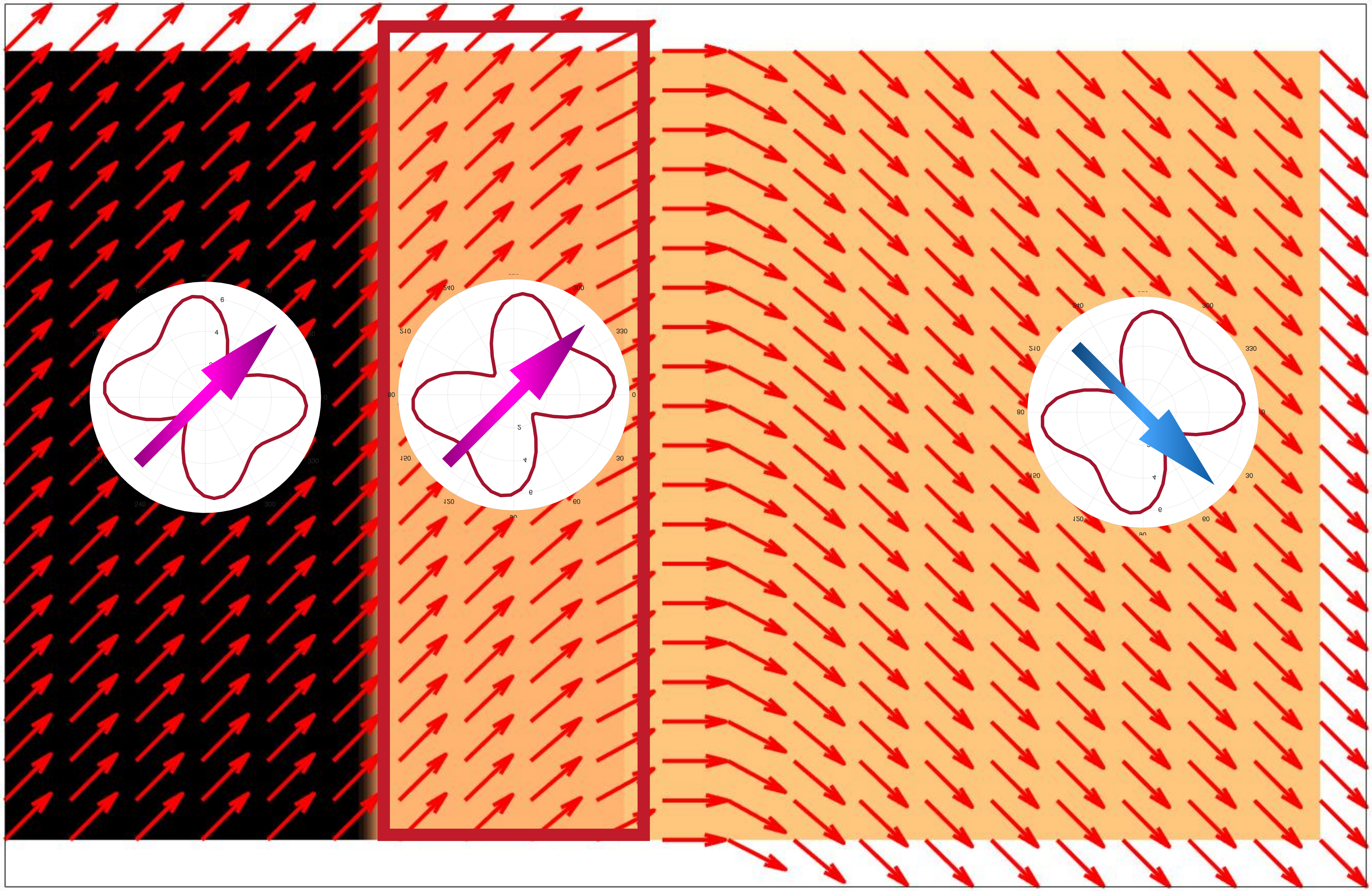
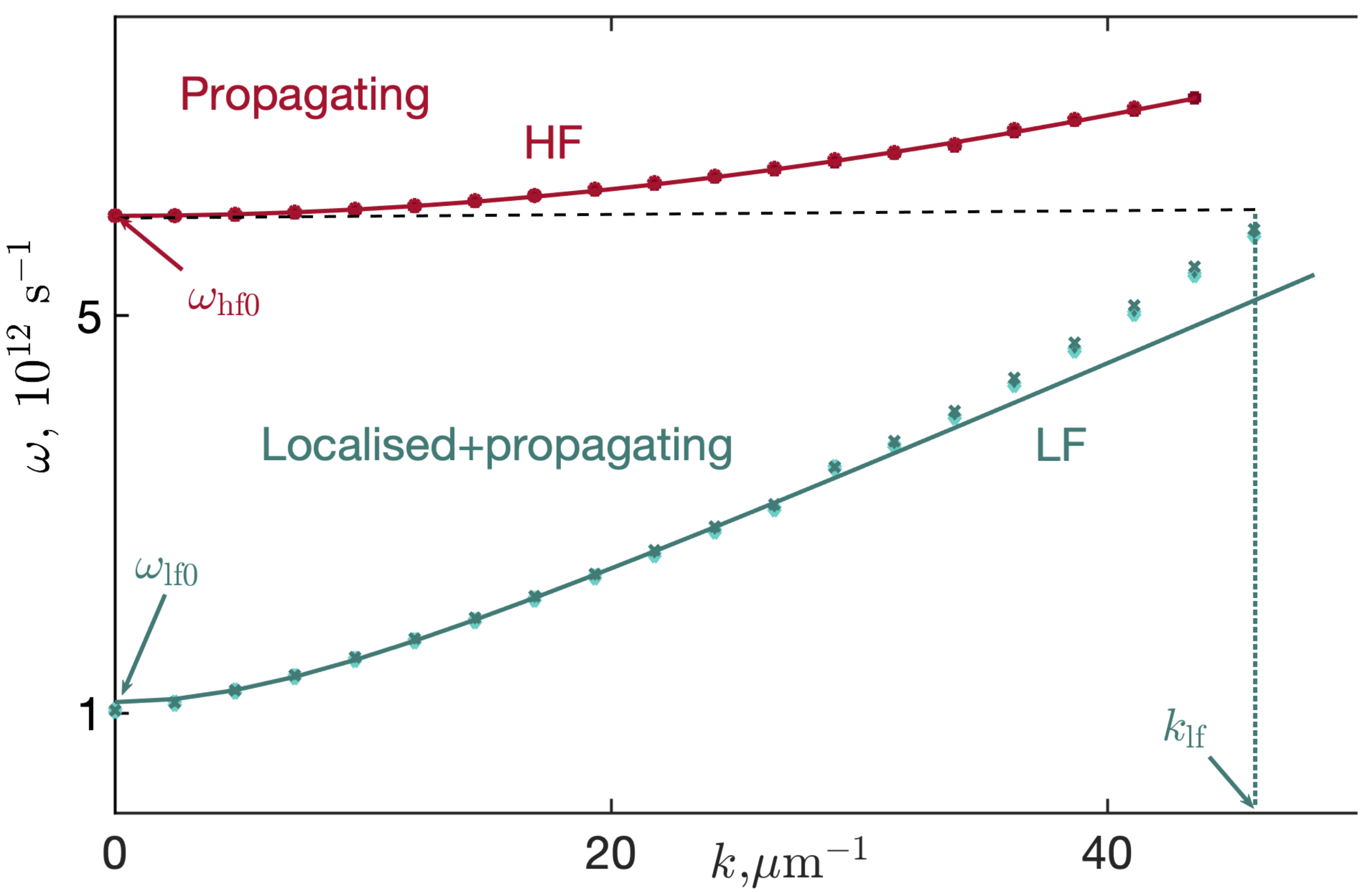


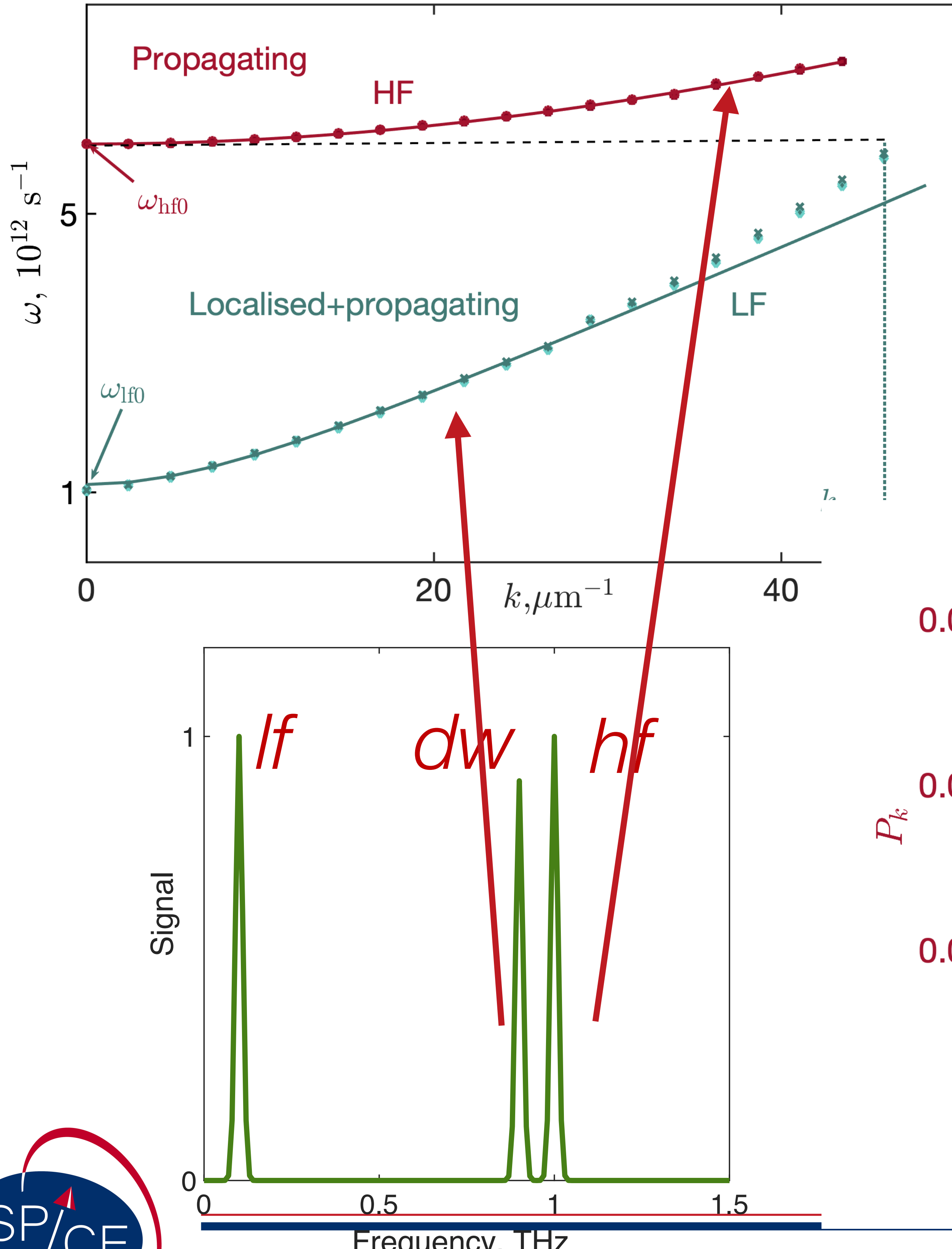
Pinned domain wall

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}(\xi)\right) = 0$$



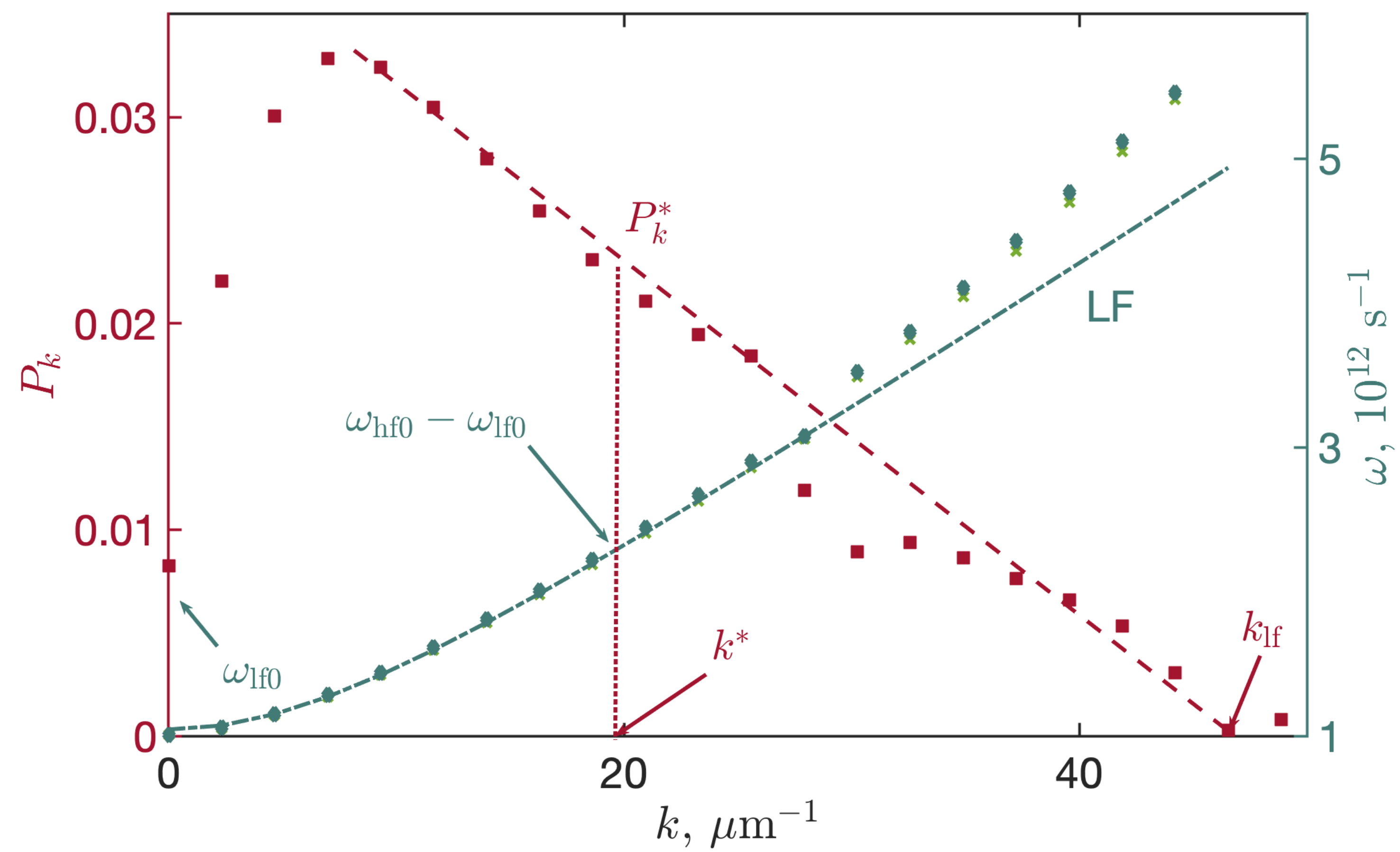
Bossini, OG, *J. Phys. D* **54,** 374004, (2021)

Localised domain wall



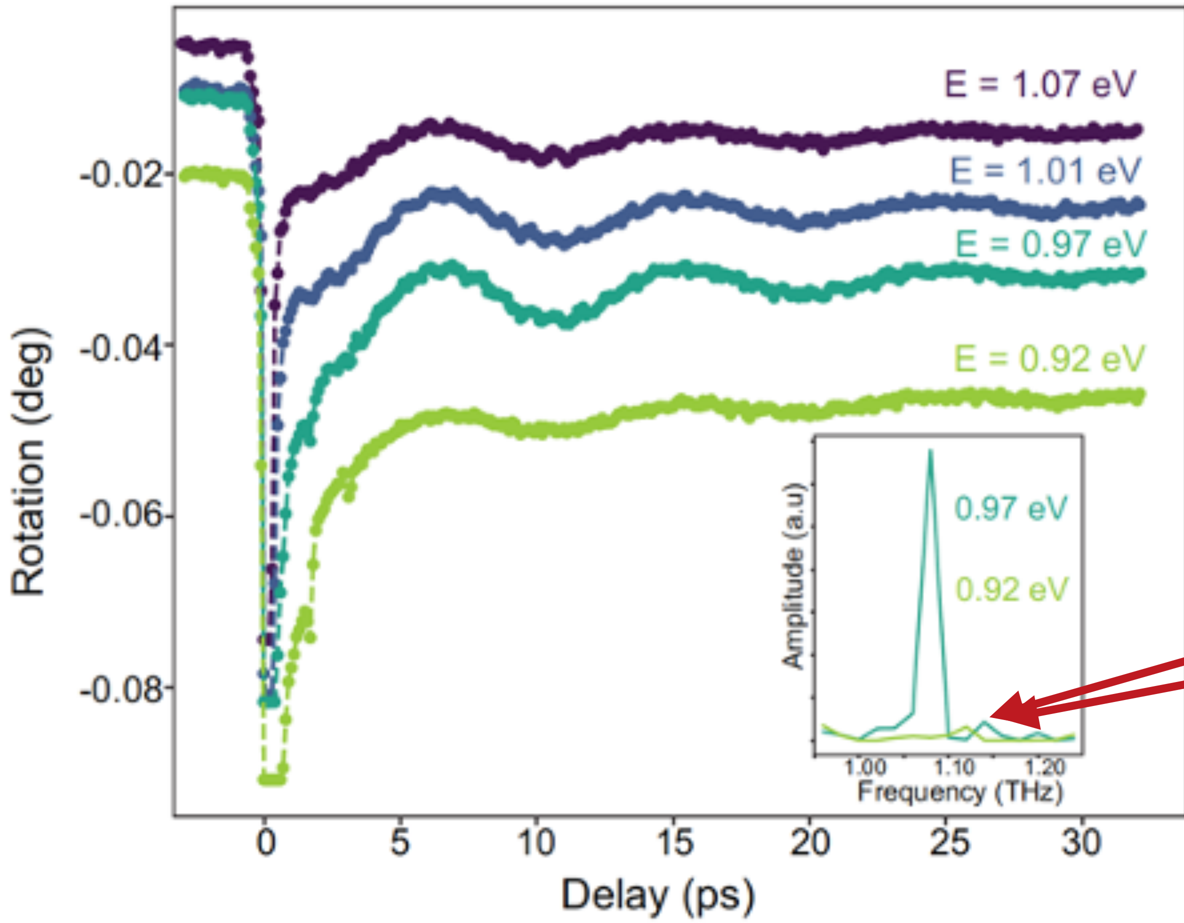
Parametric downconversion

$$aP_k\omega_{hf}^2 \geq 1/\tau$$

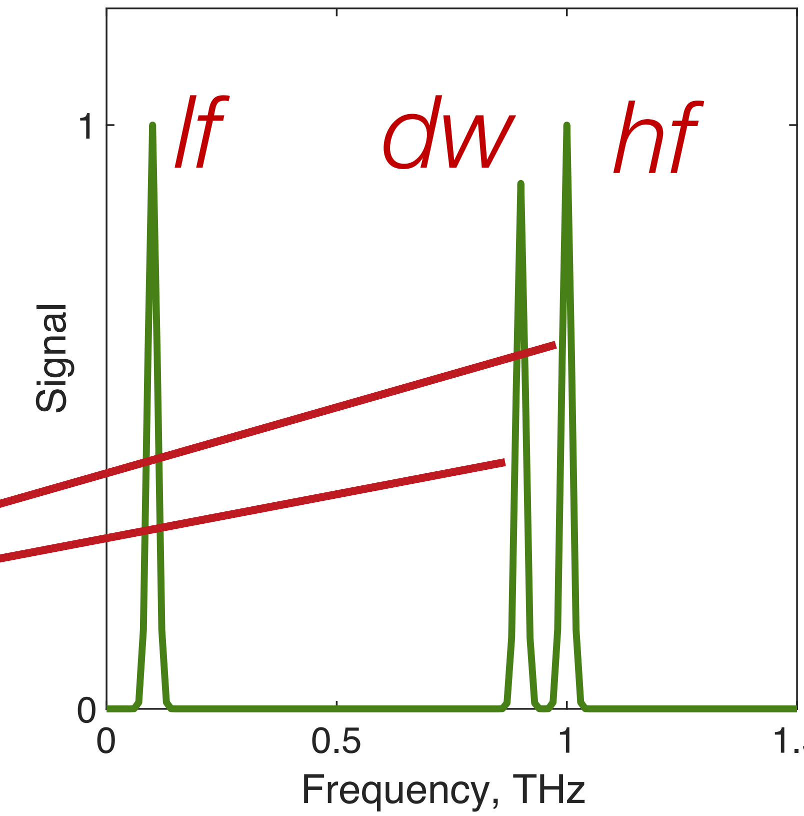


Parametric downconversion, NiO

D. Bossini, O.G. et al (2021), 10.1103/PhysRevLett.127.077202



May, 10, 10:40



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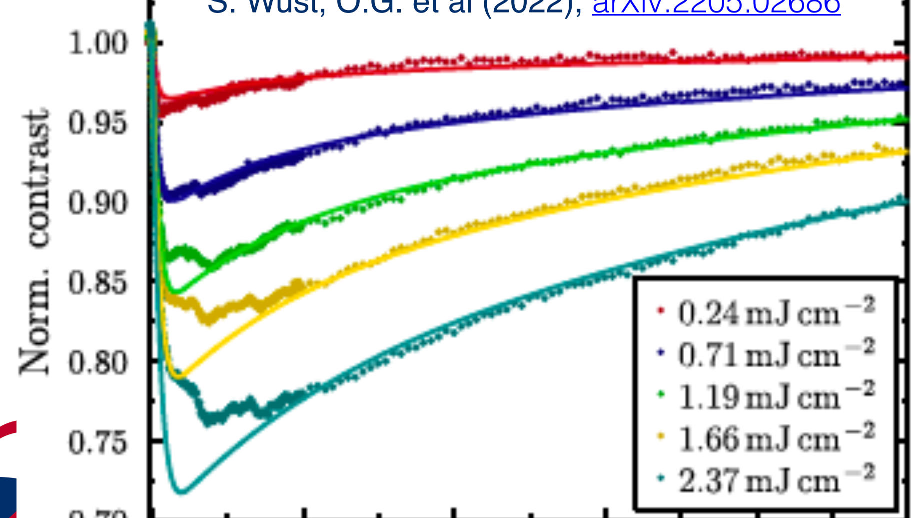
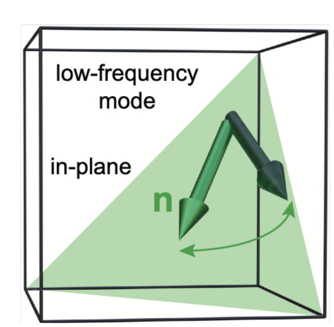
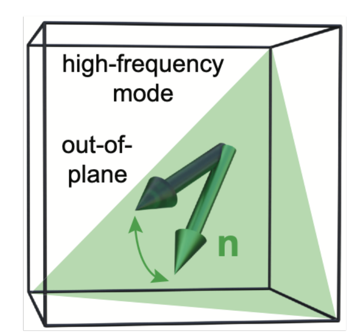


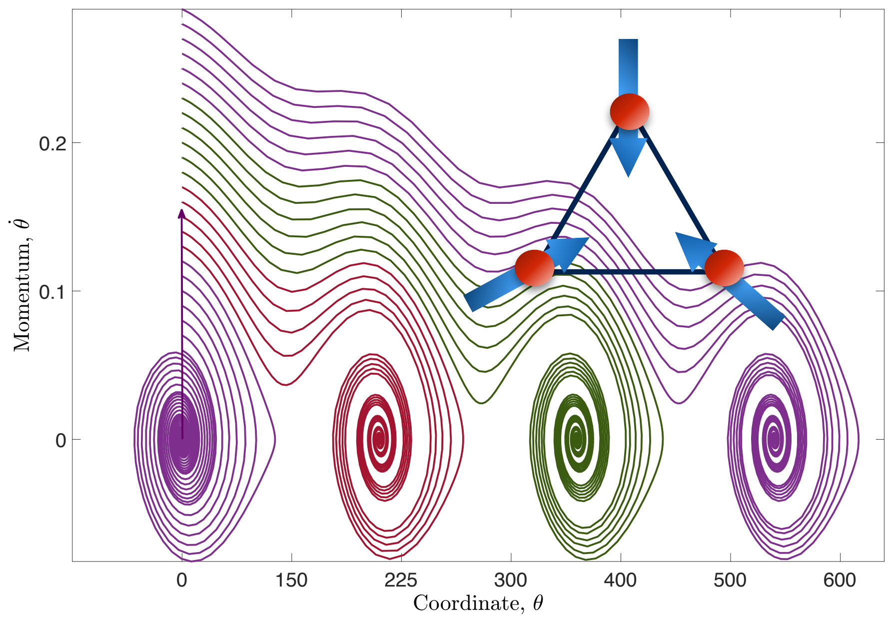
lf



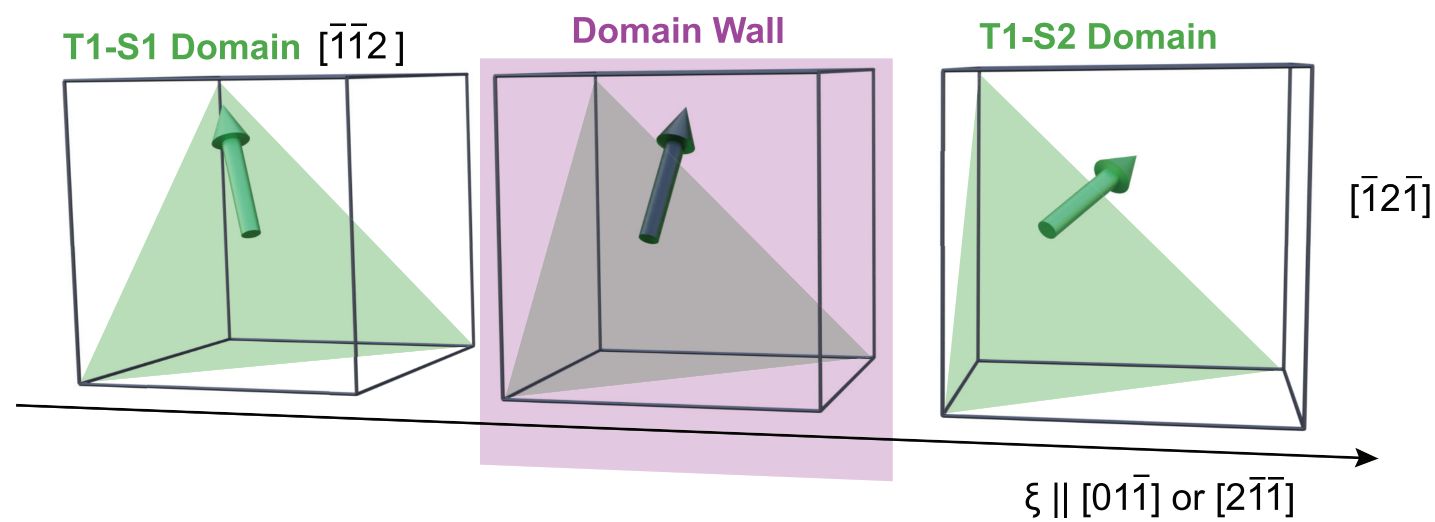
hf



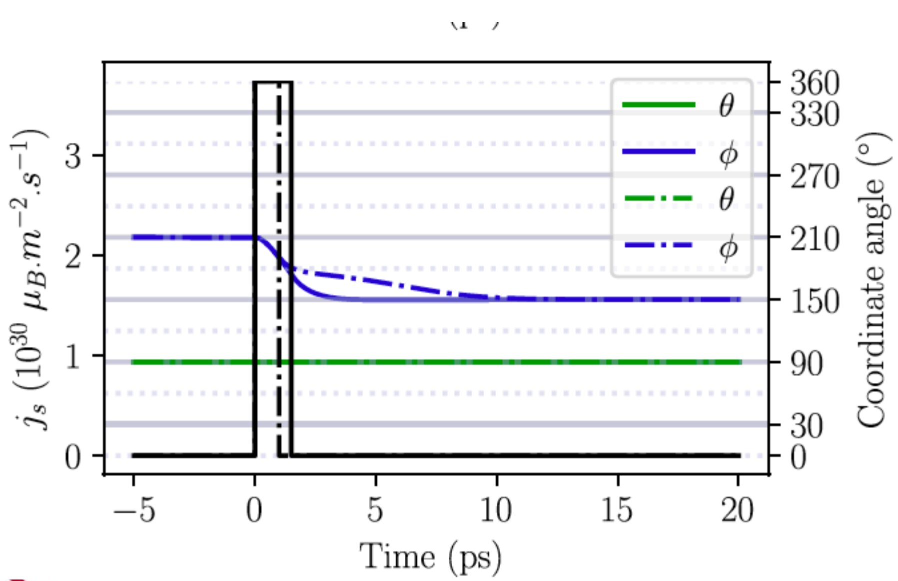
Summary

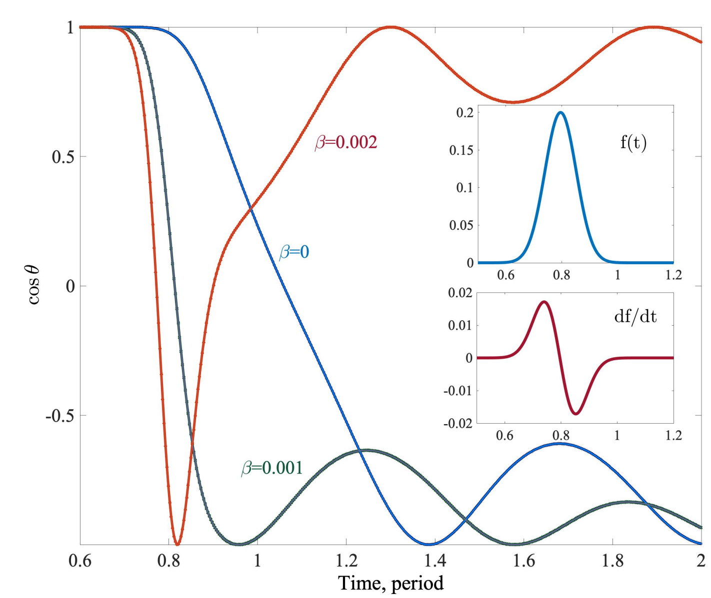


Dynamics in presence of magneto elasticity



Switching with the short pulses





Field-like torque

Collaborators

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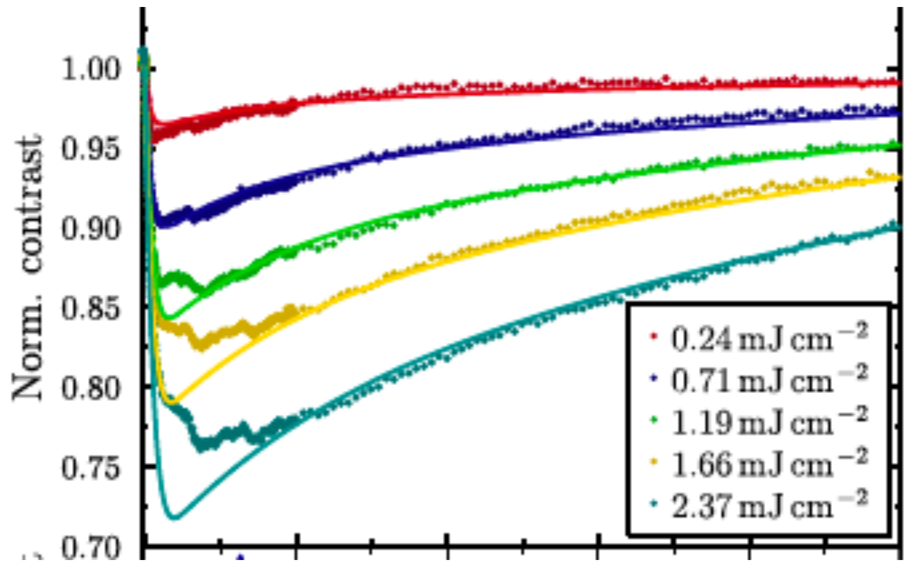
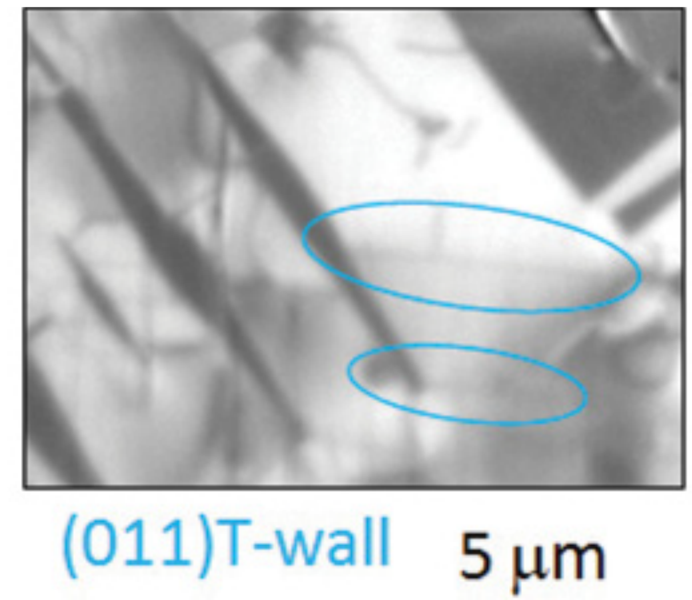
THANK YOU!

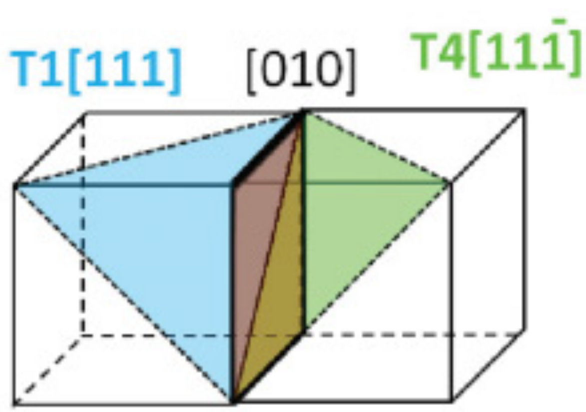
NiO and domain structure

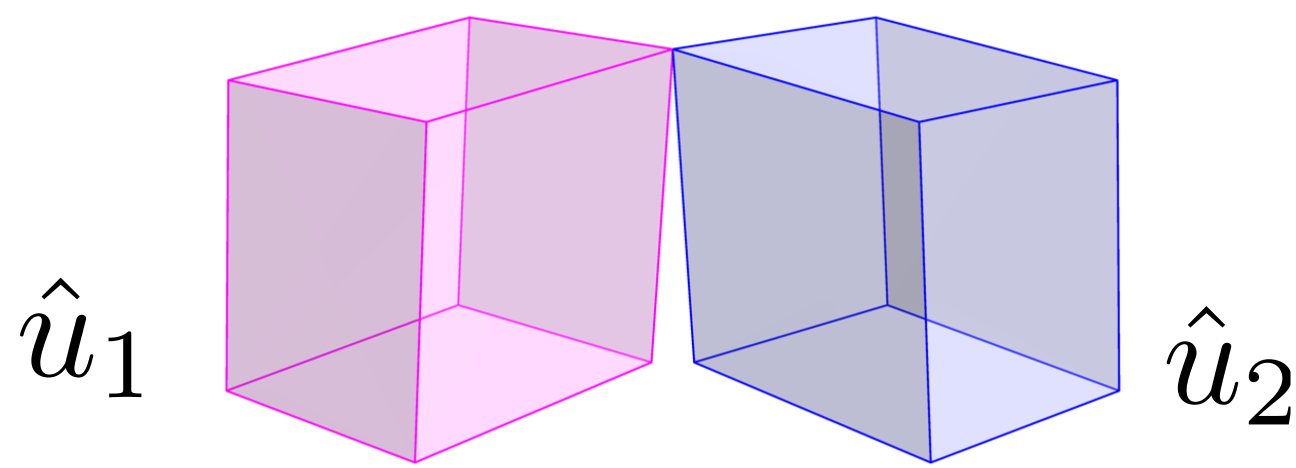




K. Arai et al, PRB, 85, 104418 (2012)

Distortion



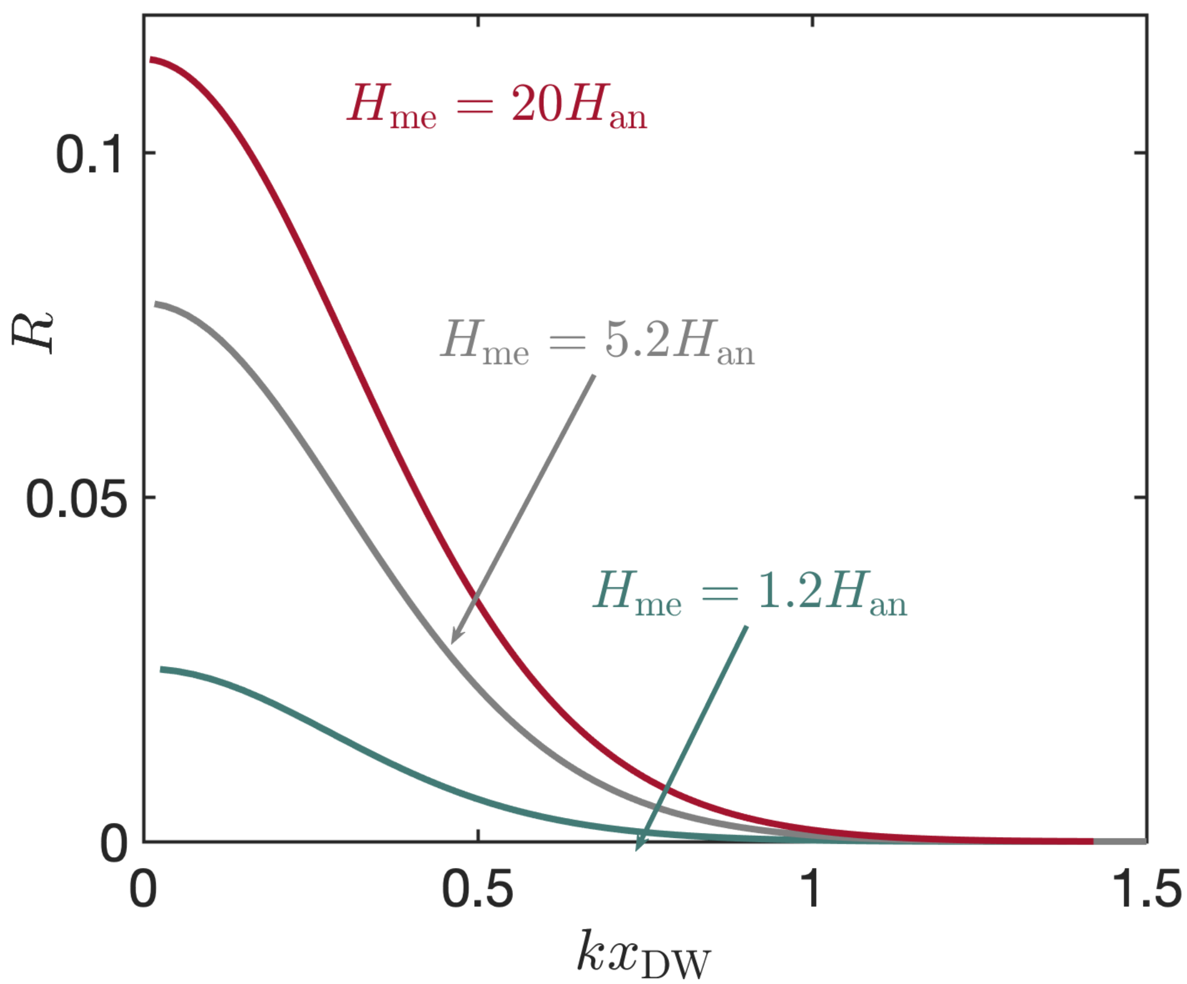


Exchange striction

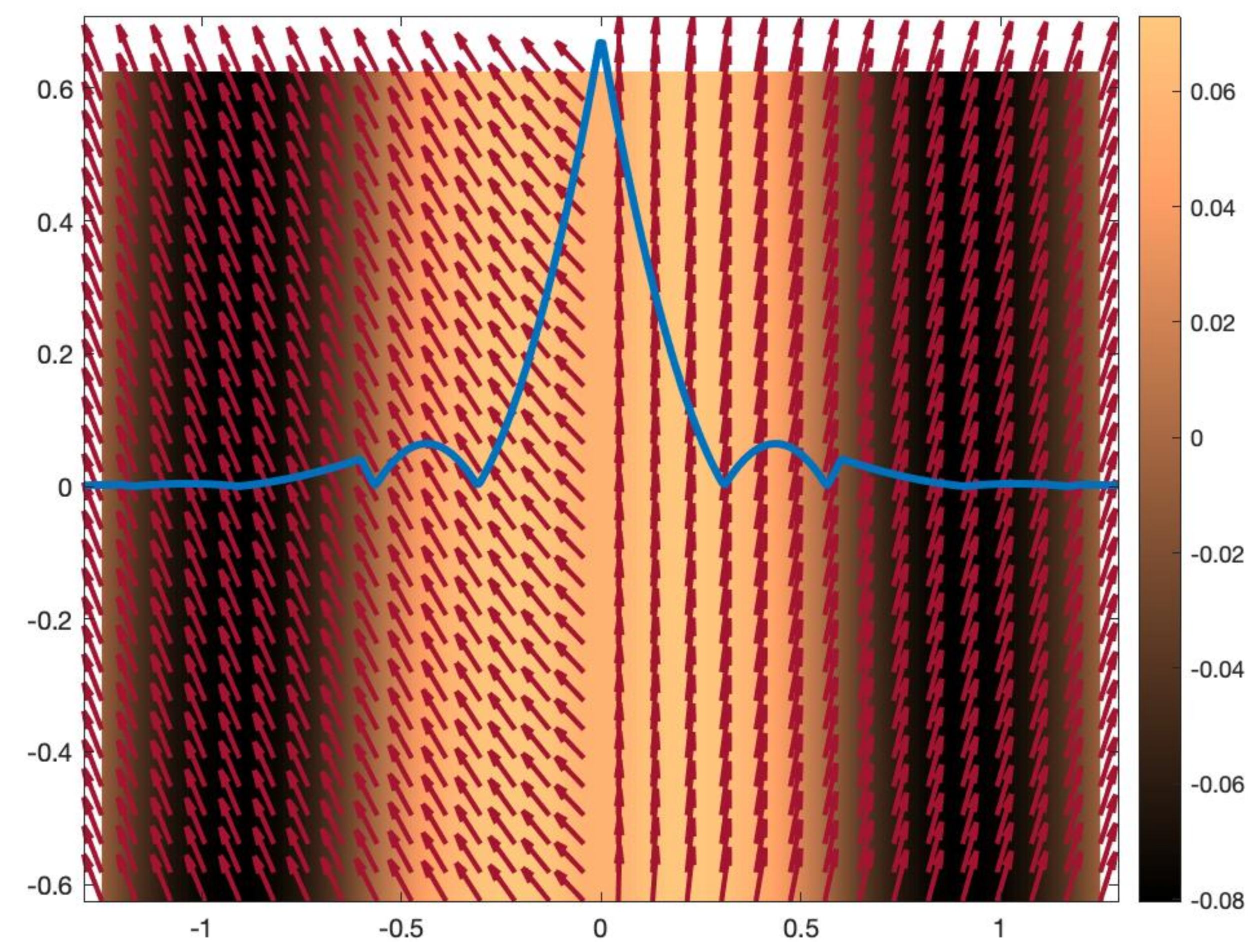
T1 T2

Pinned domain wall

$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\text{ex}}\mathbf{H}_{\text{an}}(\xi)\right) = 0$$

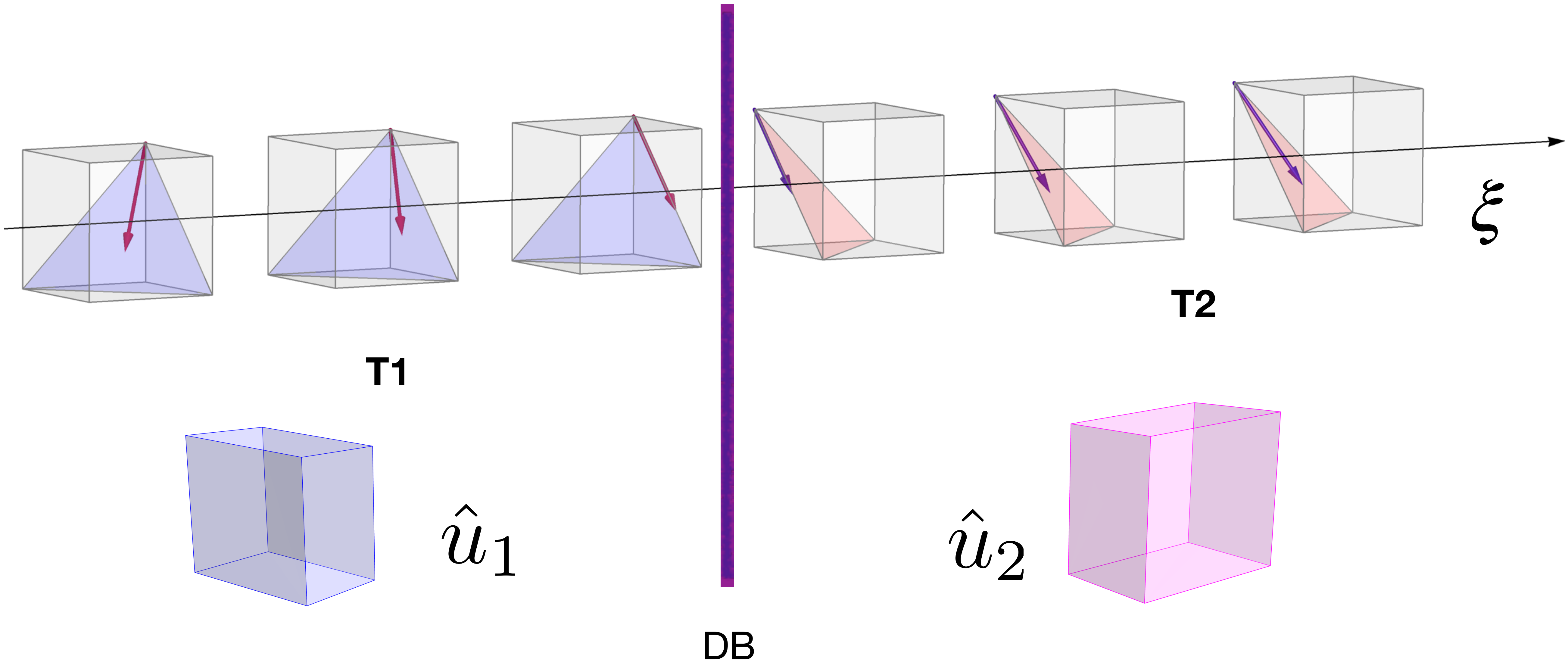


Reflection of magnons



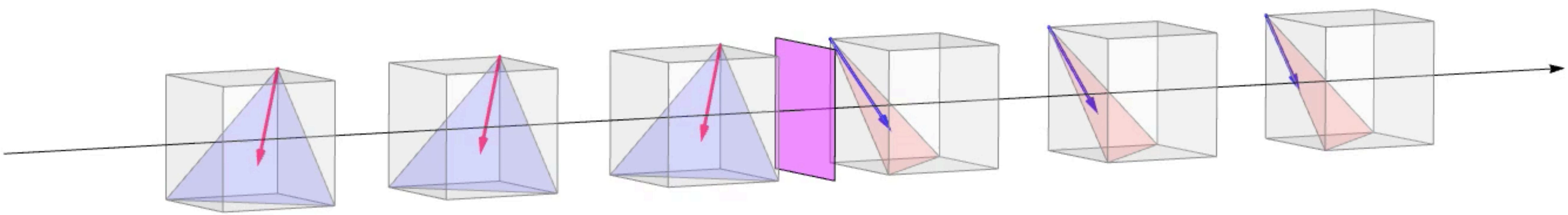
Localised mode

T domain wall



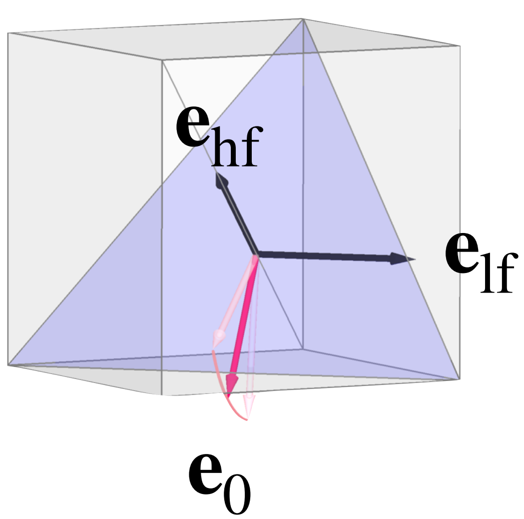
$$w_{\rm an}(\xi) = w_{\rm mag} + \begin{cases} M_s H_{\rm me} \mathbf{n} \cdot \hat{u}_1 \cdot \mathbf{n}, & \xi < 0, \\ M_s H_{\rm me} \mathbf{n} \cdot \hat{u}_2 \cdot \mathbf{n}, & \xi > 0 \end{cases}$$

Polarization of eigen modes



T1

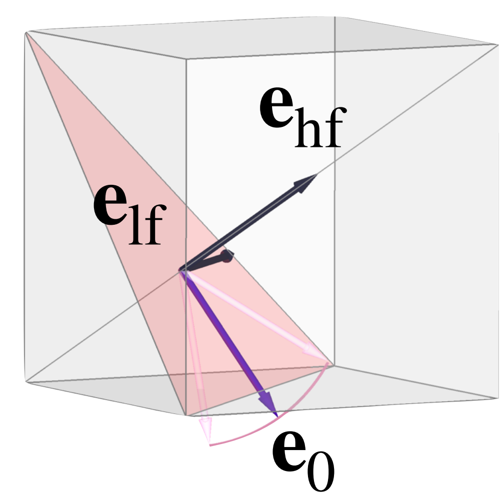
$[111]$



HF

T2

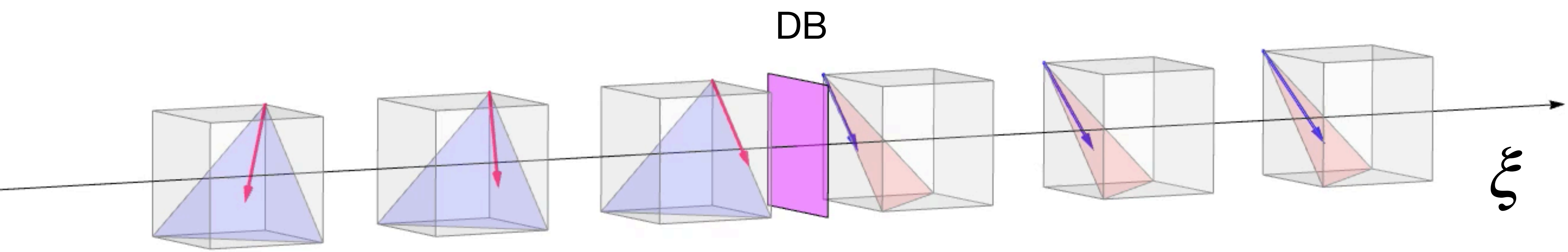
$[\bar{1}11]$

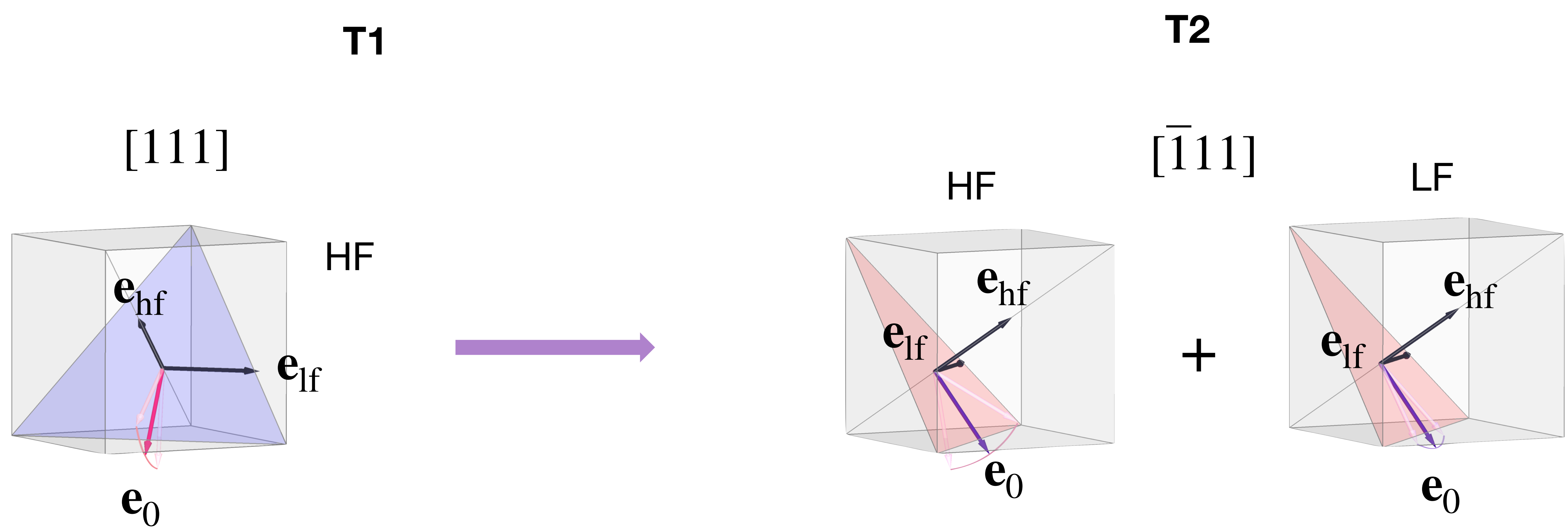


HF

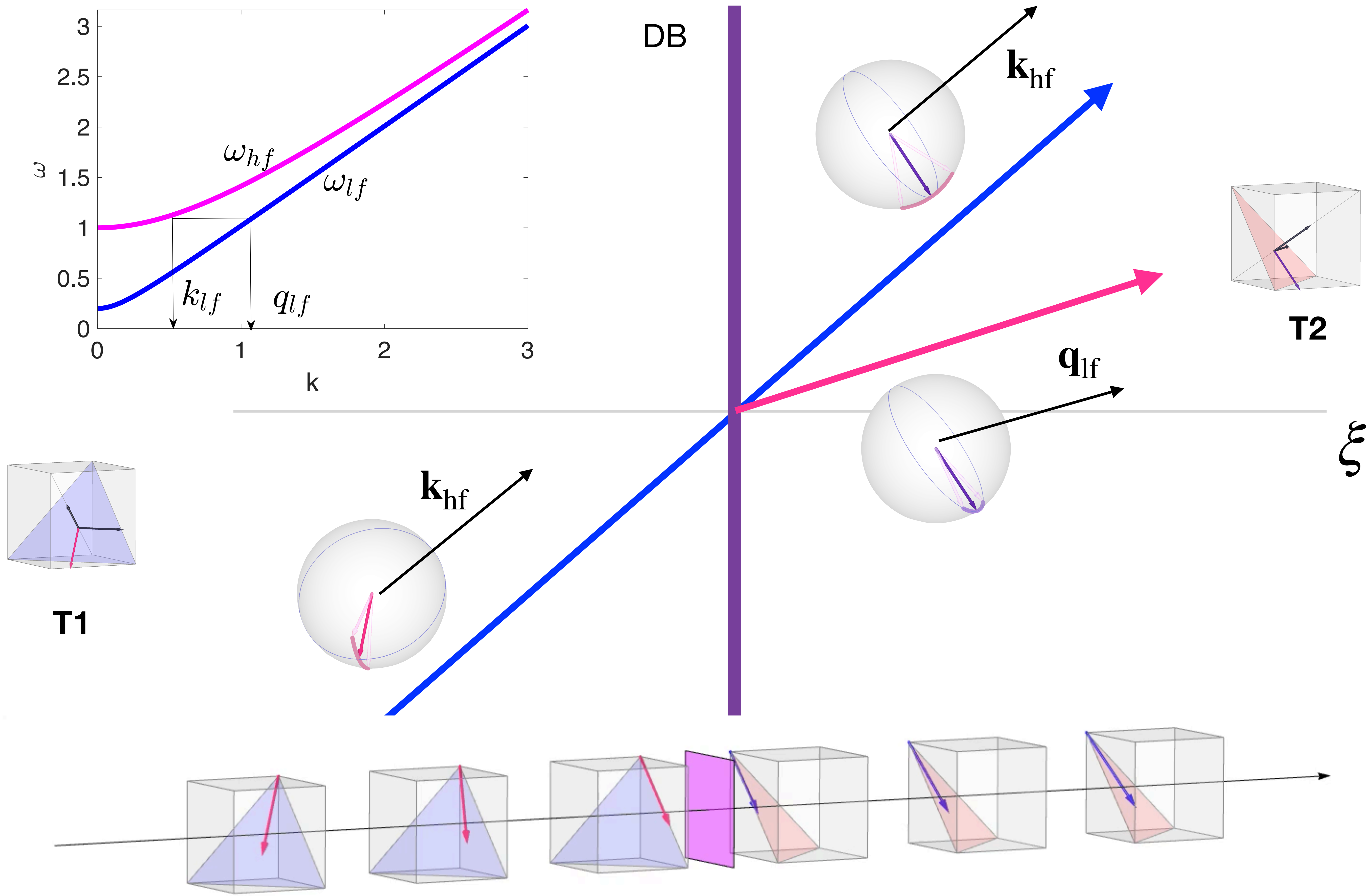
$$\mathbf{e}_{\mathrm{hf}}(\xi) = \frac{1}{\sqrt{3}} \begin{cases} [111] & \xi < 0, \\ [\bar{1}11] & \xi > 0, \end{cases} \qquad \mathbf{e}_0(\xi) = \frac{1}{\sqrt{6}} \begin{cases} [\bar{1}\bar{1}2] & \xi < 0, \\ [1\bar{1}2] & \xi > 0, \end{cases}$$

Polarization of eigen modes



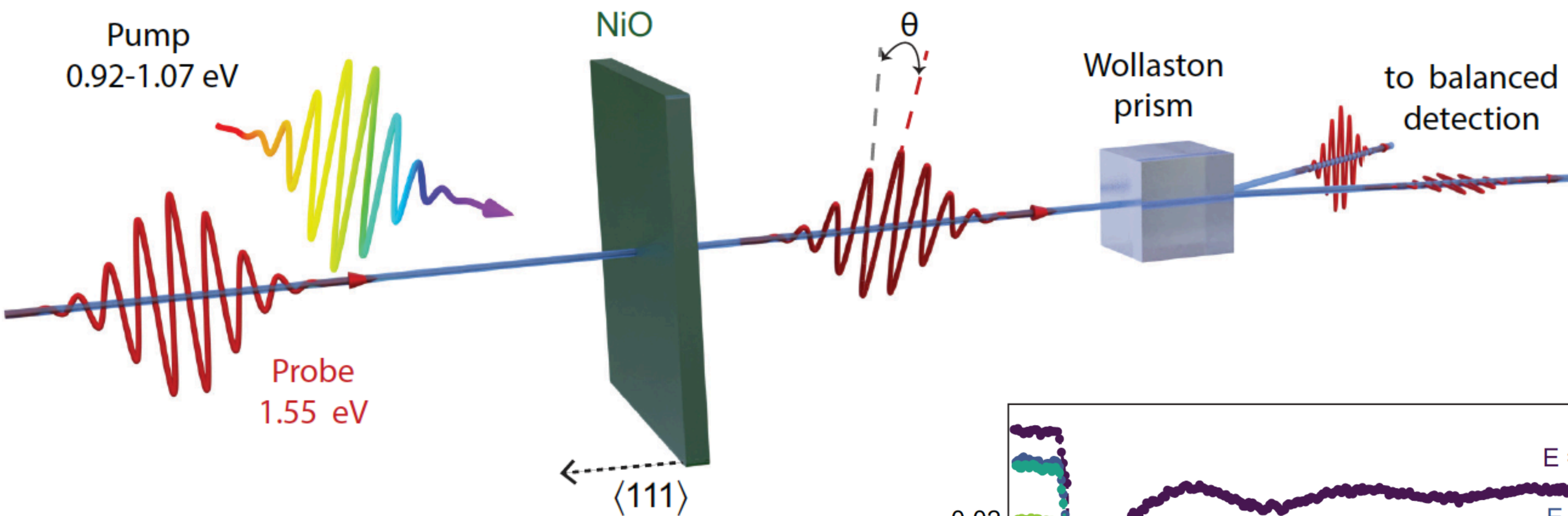


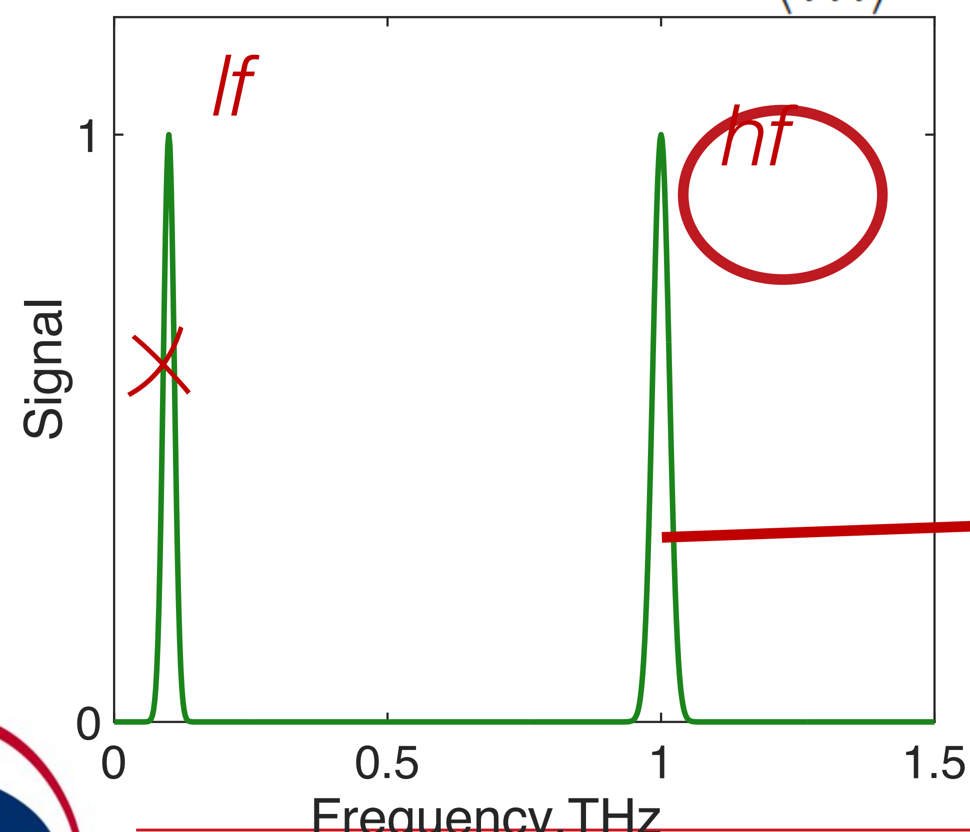
Magnon birefringence

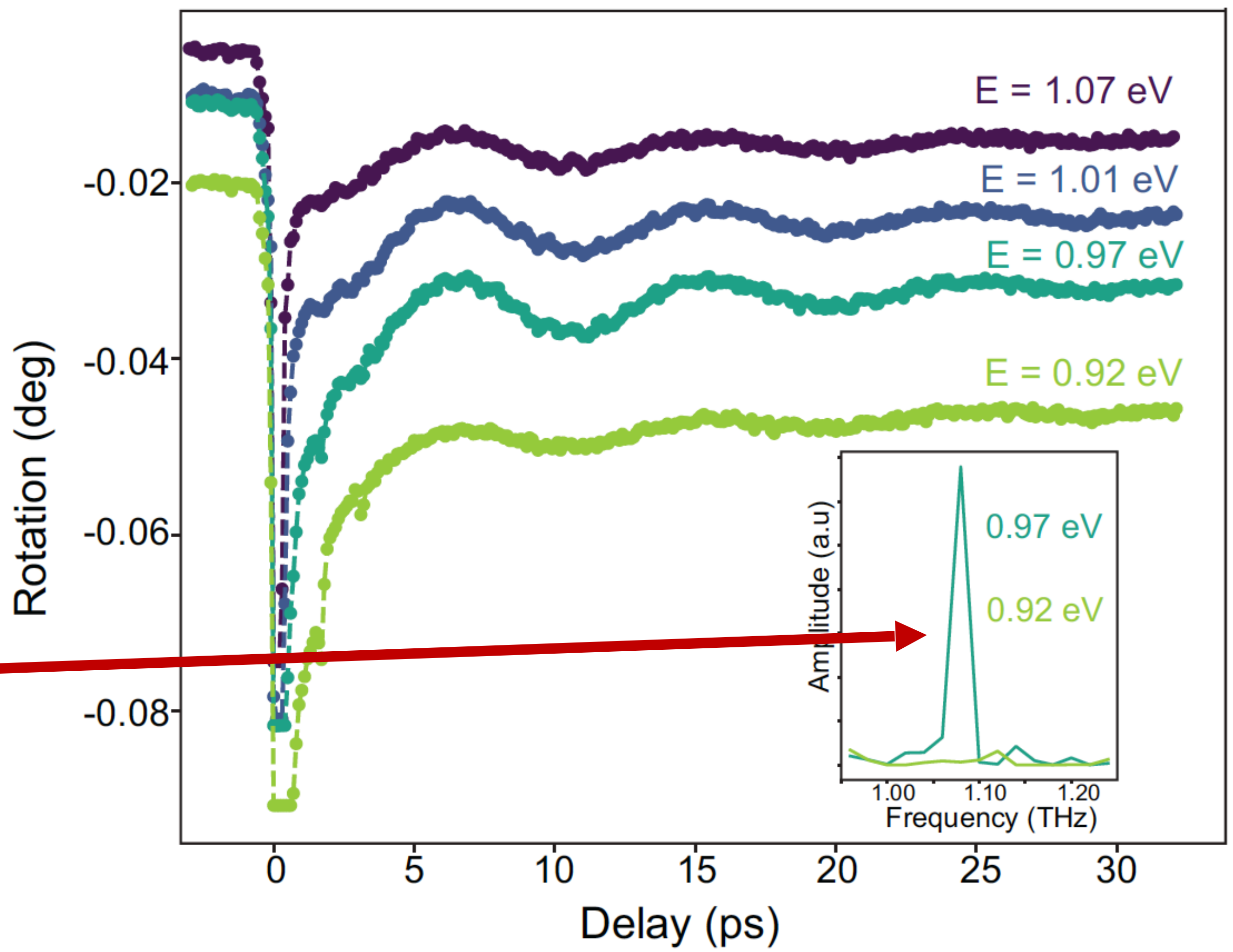


Experiment

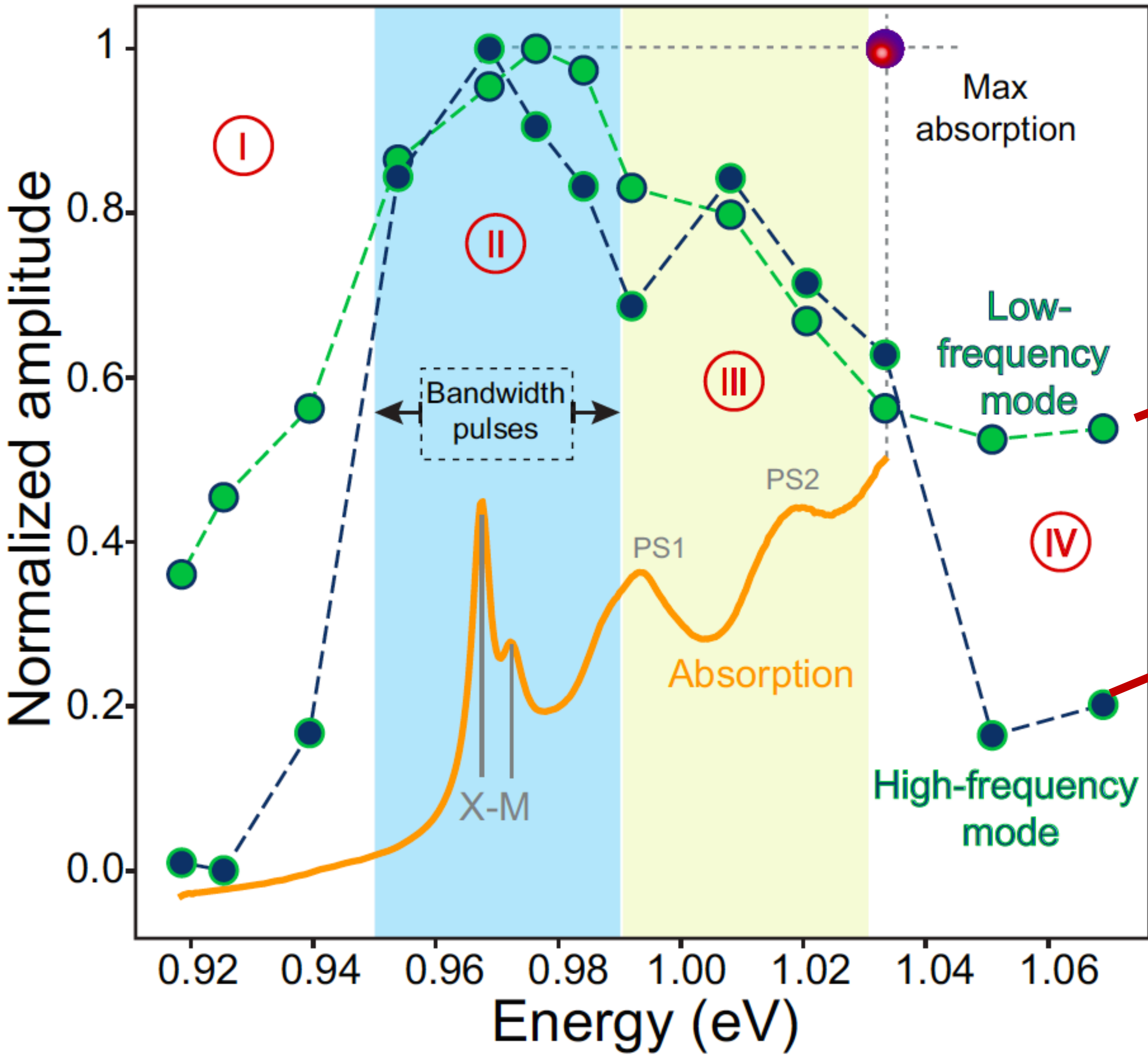
(a)

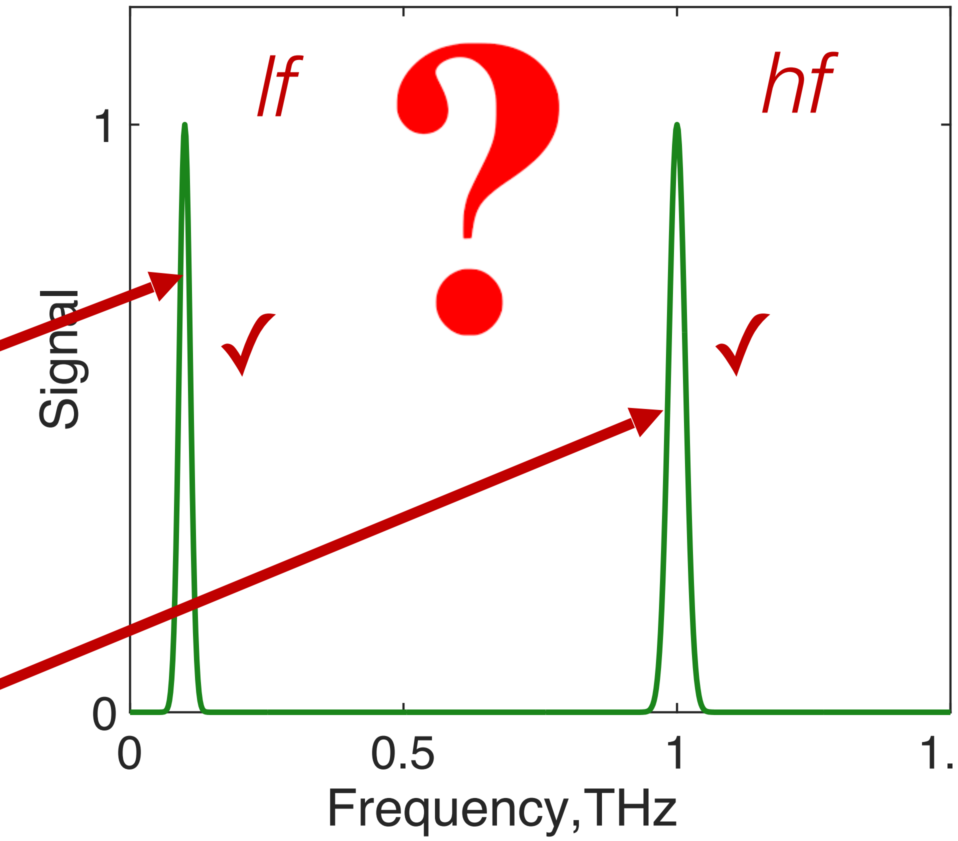


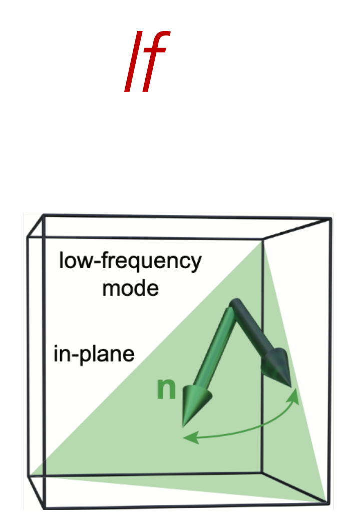


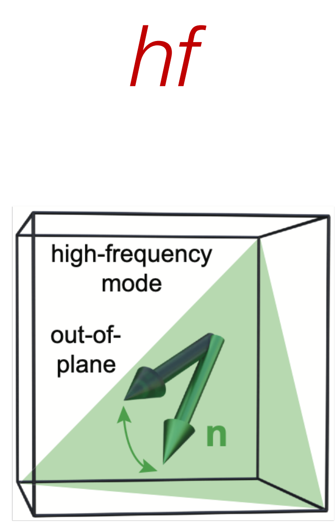


Problem

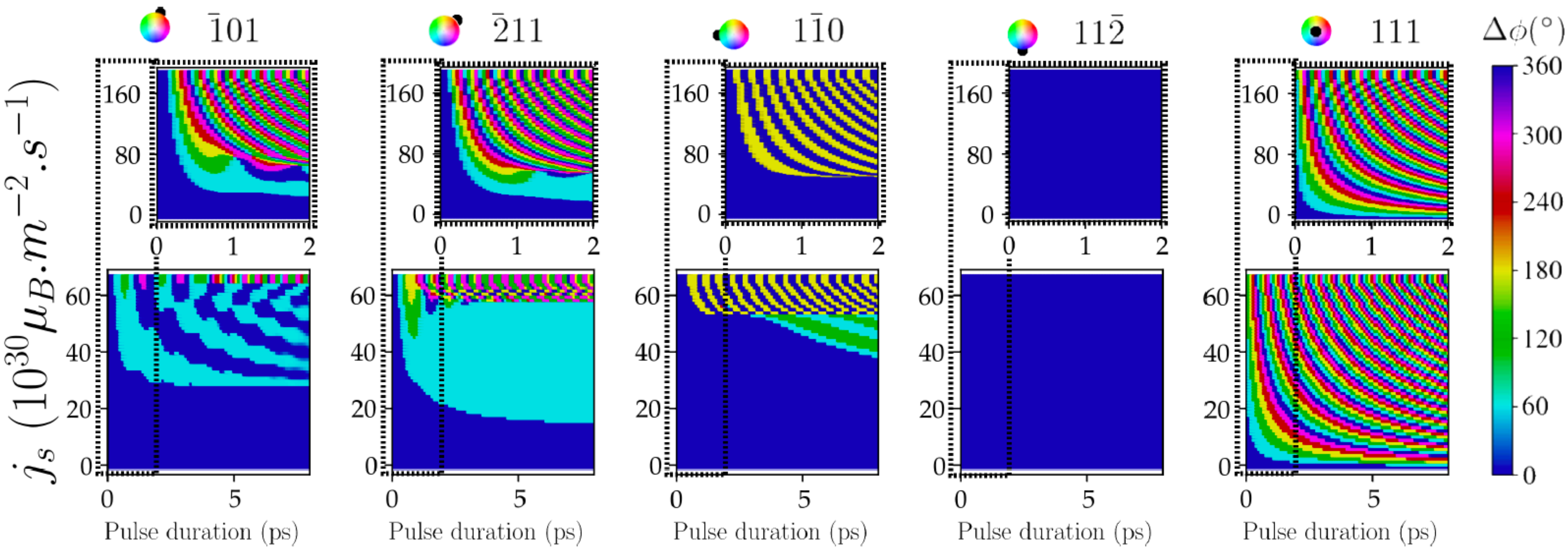

Normalized amplitude
Energy (eV)
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
0.0
0.2
0.4
0.6
0.8
1
I
II
III
IV
Bandwidth pulses
Max absorption
Low-frequency mode
High-frequency mode
Absorption
PS1
PS2
X-M

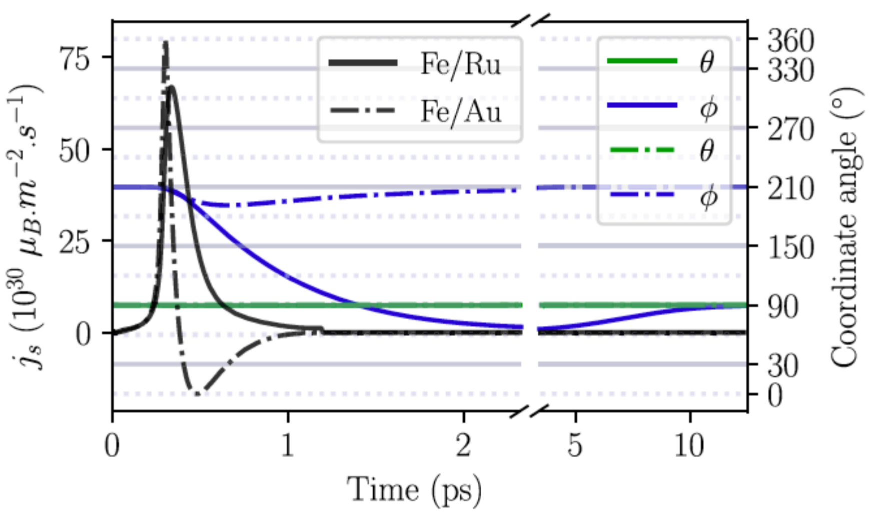

lf
hf
?
Signal
Frequency,THz
0
0.5
1
1.5
0
1


lf
low-frequency mode
in-plane
n

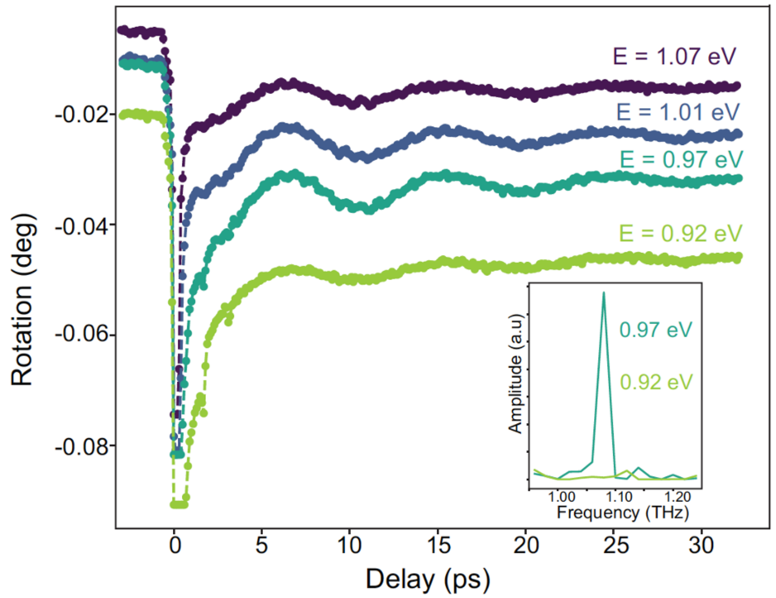

hf
high-frequency mode
out-of-plane
n

Switching with the short pulses





Th. Chirac, OG, et al, 2020, 10.1103/PhysRevB.102.134415

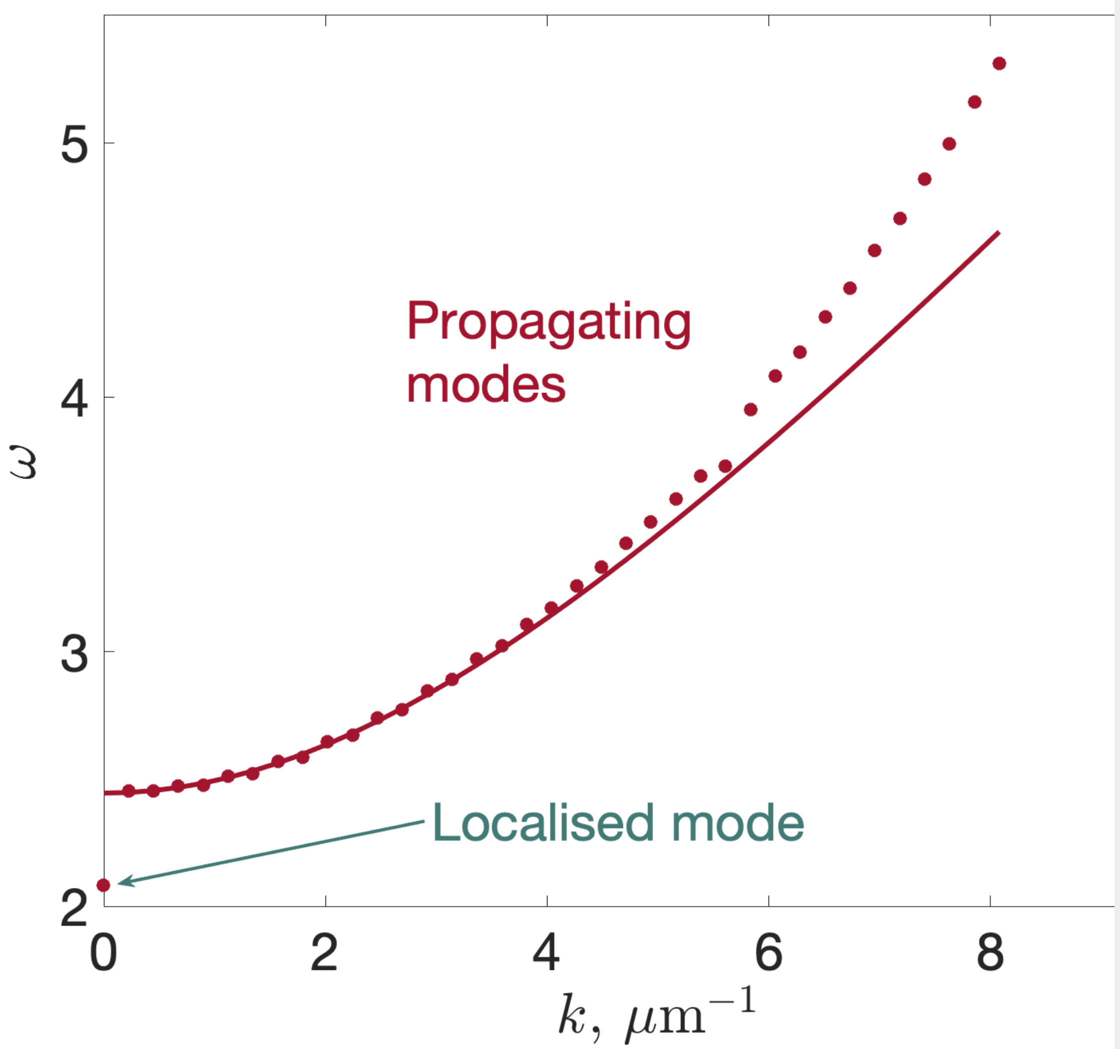


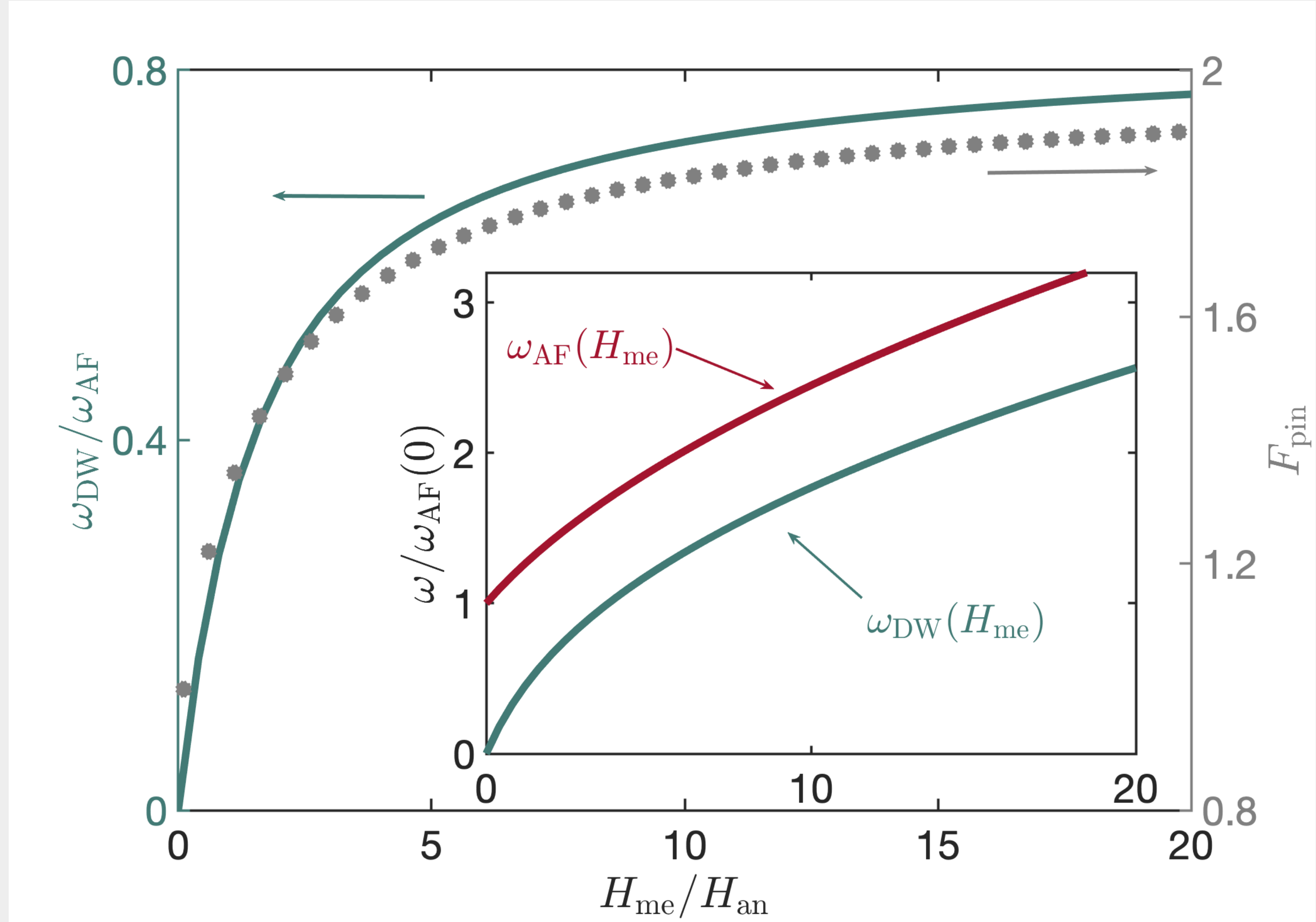
D. Bossini, O.G. et al (2021), 10.1103/PhysRevLett.127.077202

Pinned domain wall

INSP/RE group
INTERDISCIPLINARY SPINTRONICS RESEARCH

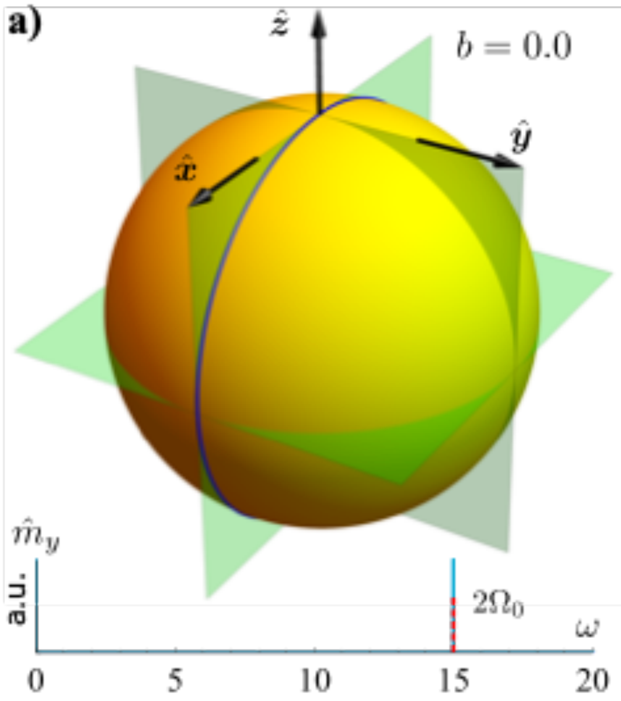
$$\mathbf{n}\times\left(\ddot{\mathbf{n}} - c^2\Delta\mathbf{n} + \gamma^2 H_{\mathrm{ex}}\mathbf{H}_{\mathrm{an}}(\xi)\right) = 0$$

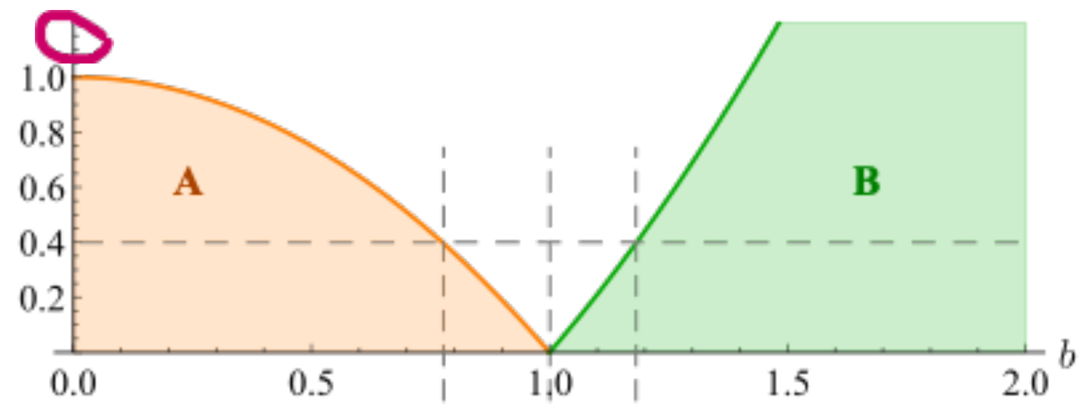


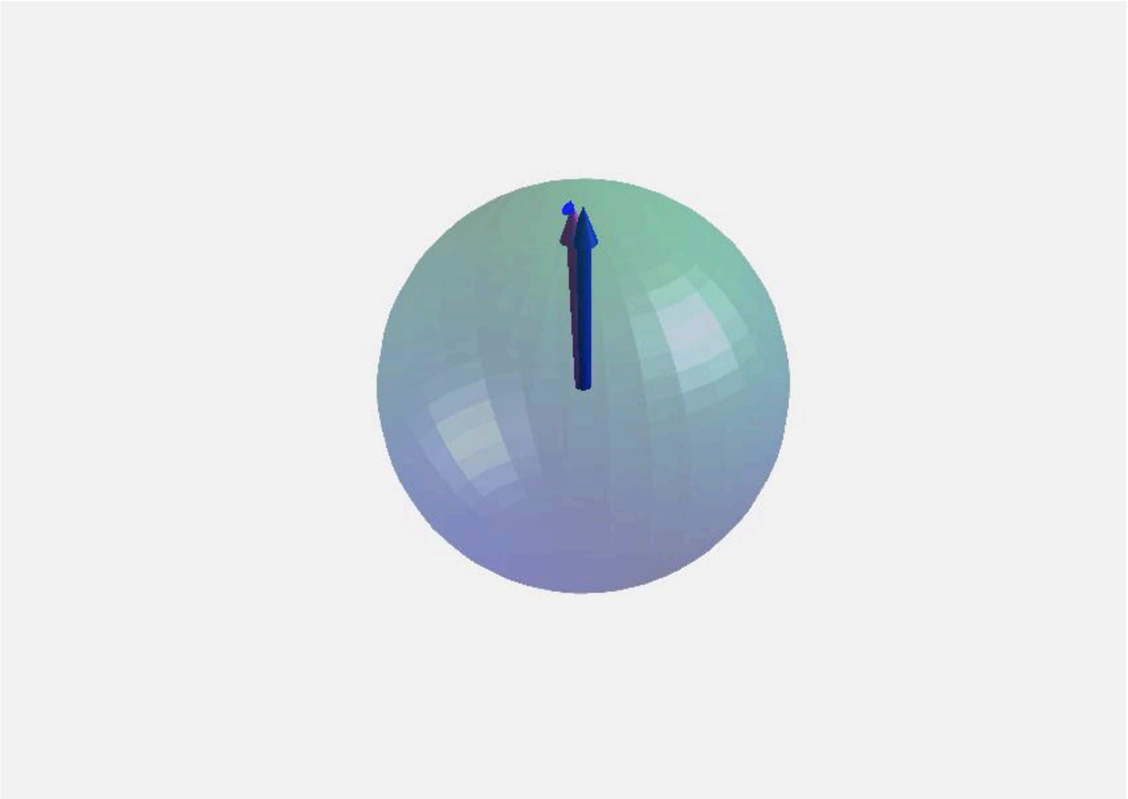


$$\omega_{\mathrm{DW}} \propto \sqrt{H_{\mathrm{me}}}$$

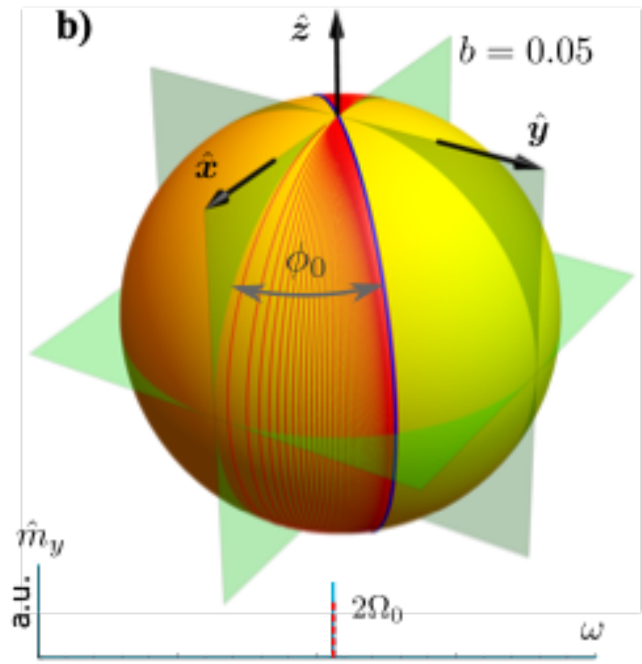
Bossini, OG, *J. Phys. D* **54,** 374004, (2021)

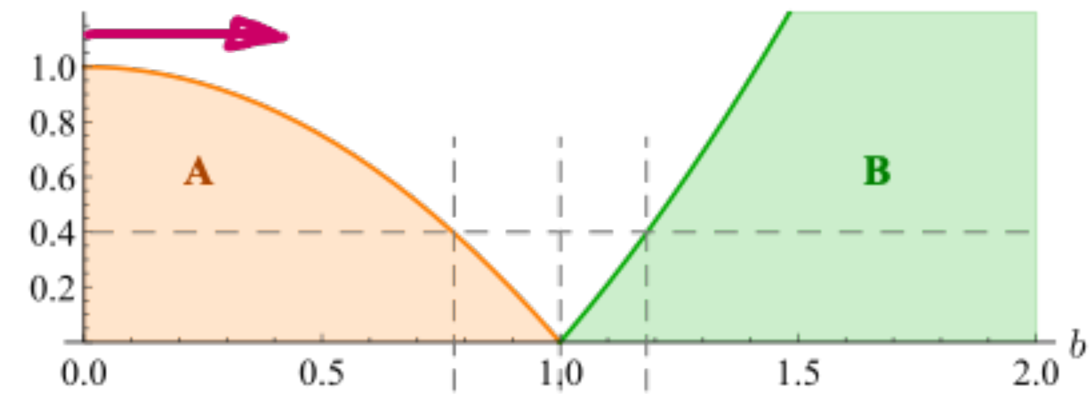

a)
$\hat{z}$
$b = 0.0$
$\hat{y}$
$\hat{x}$
$\hat{m}_y$
a.u.
$2\Omega_0$
ω
0
5
10
15
20

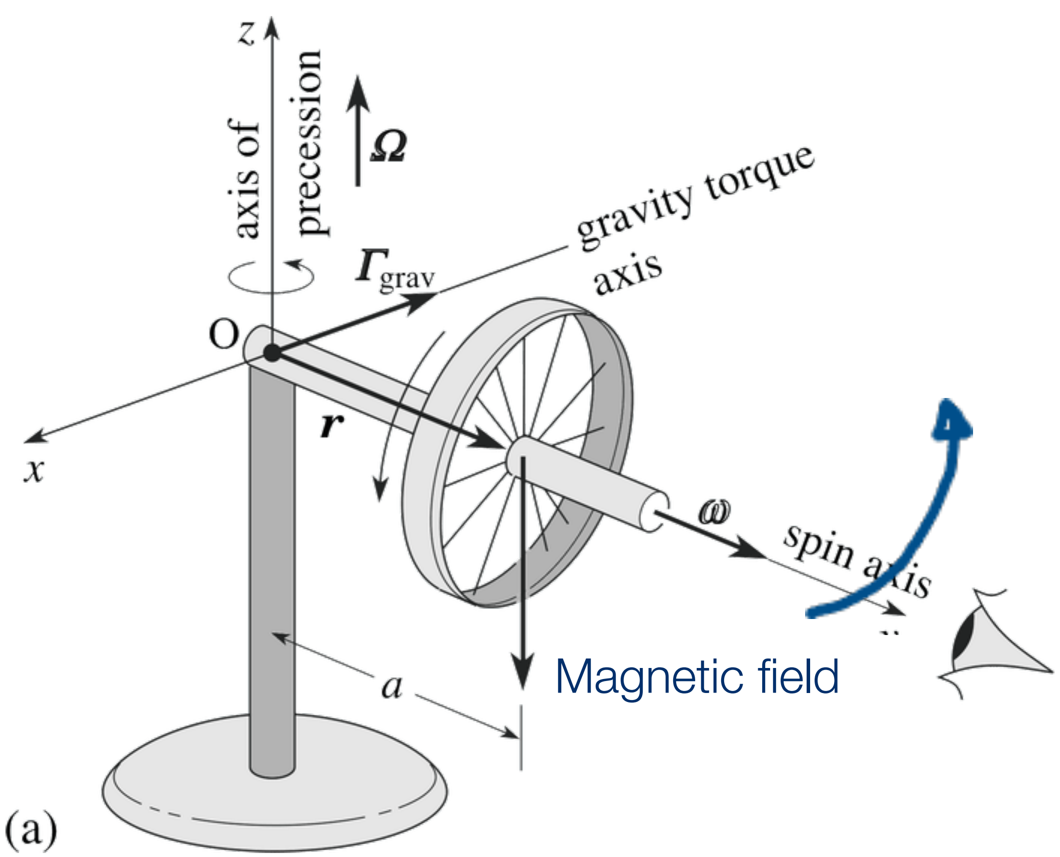

1.0
0.8
0.6
0.4
0.2
A
B
0.0
0.5
1.0
1.5
2.0
b



Precession

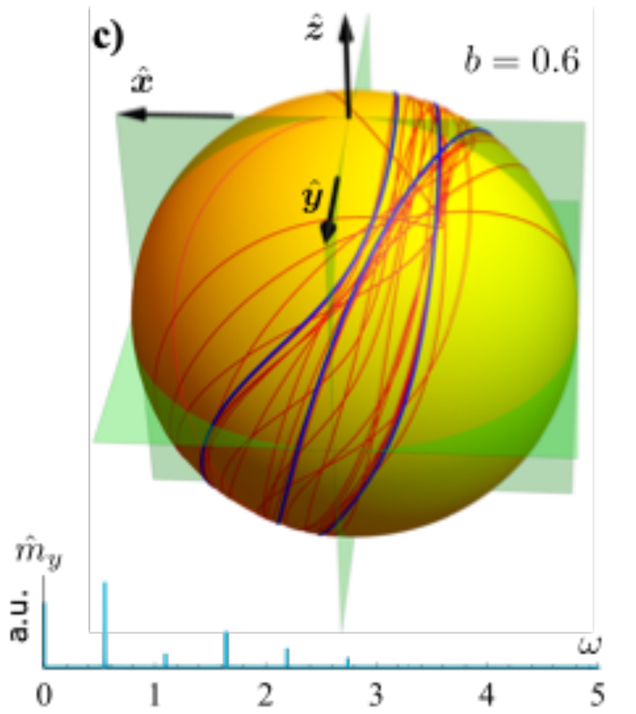


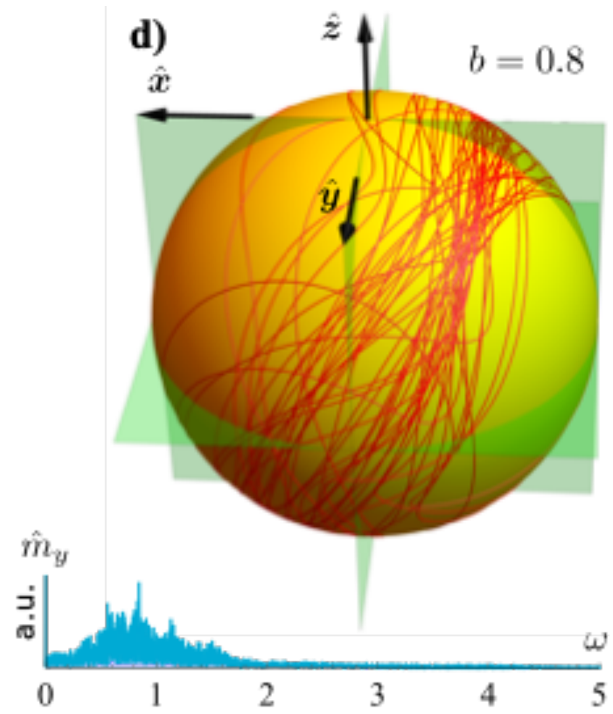


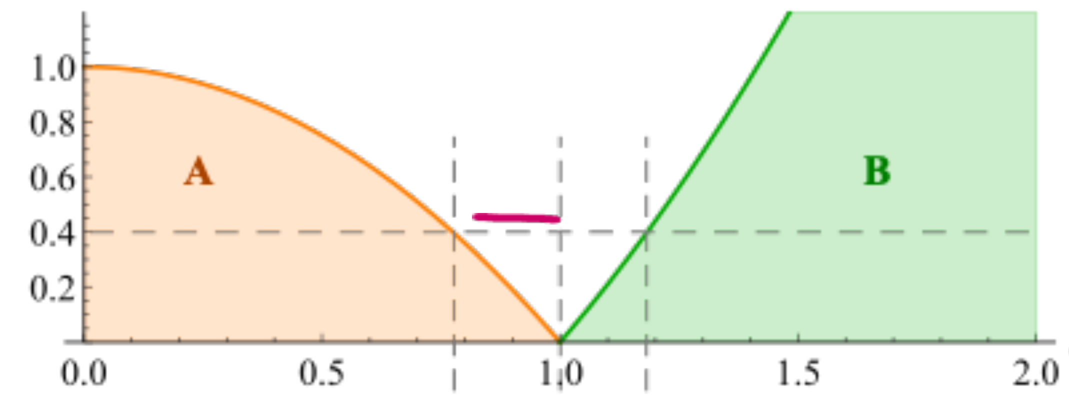


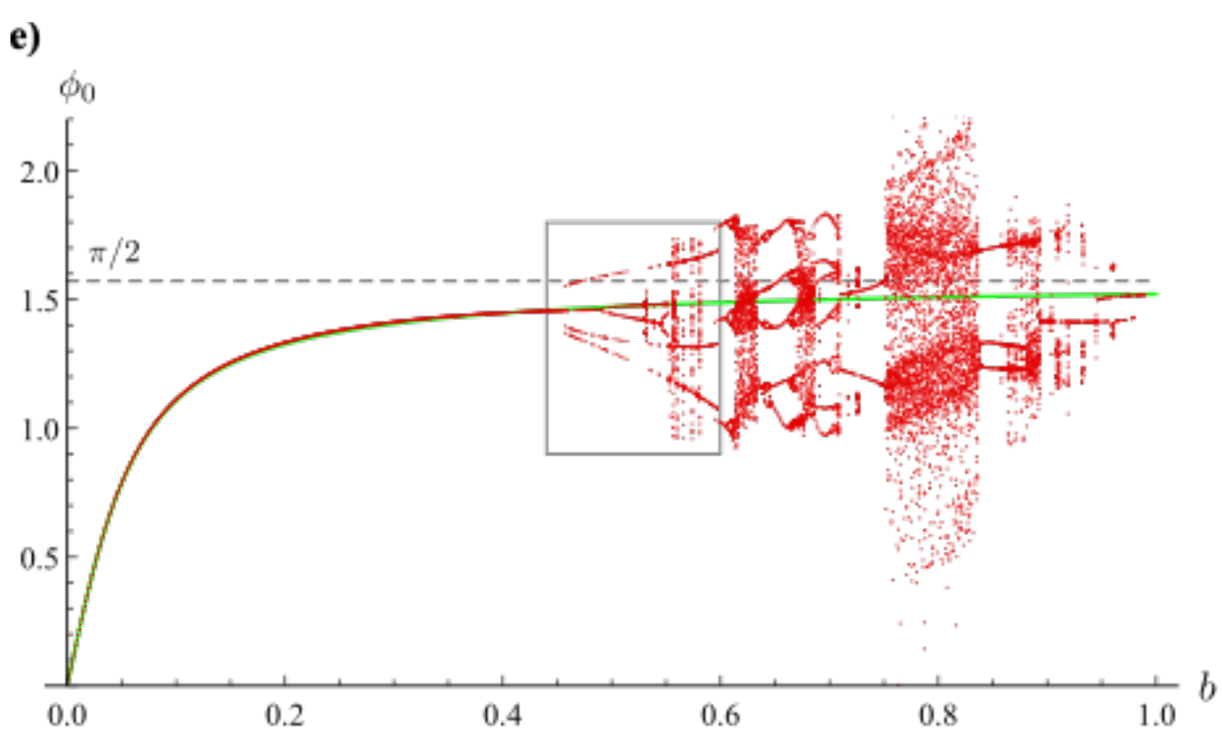
(a)

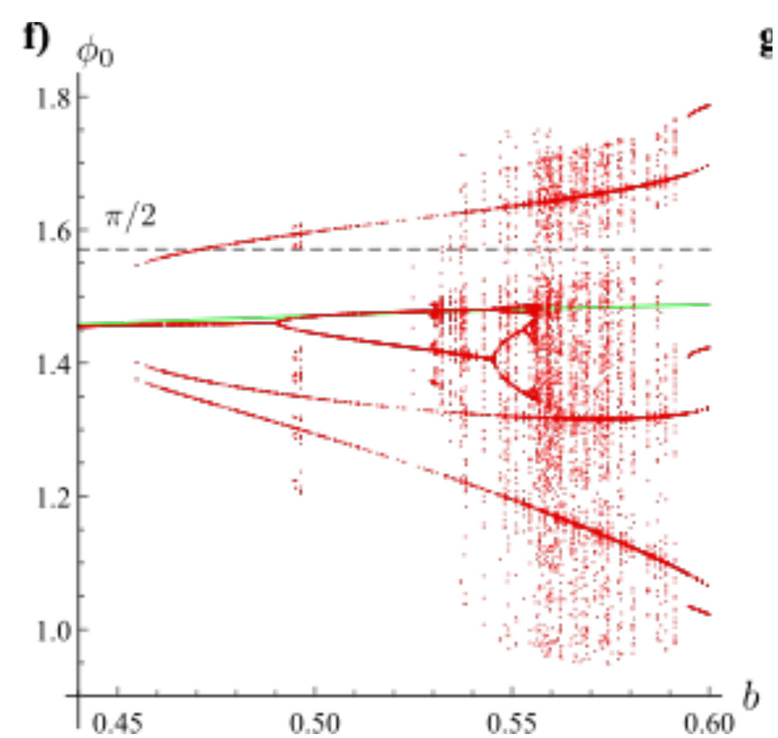
Transition to chaotic regime



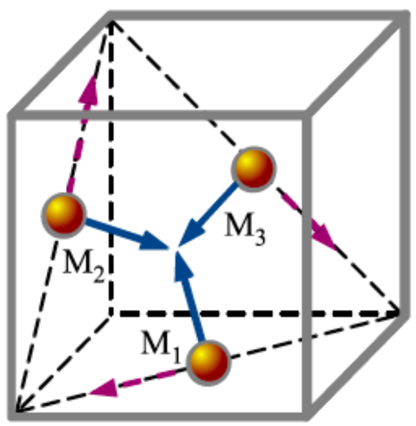






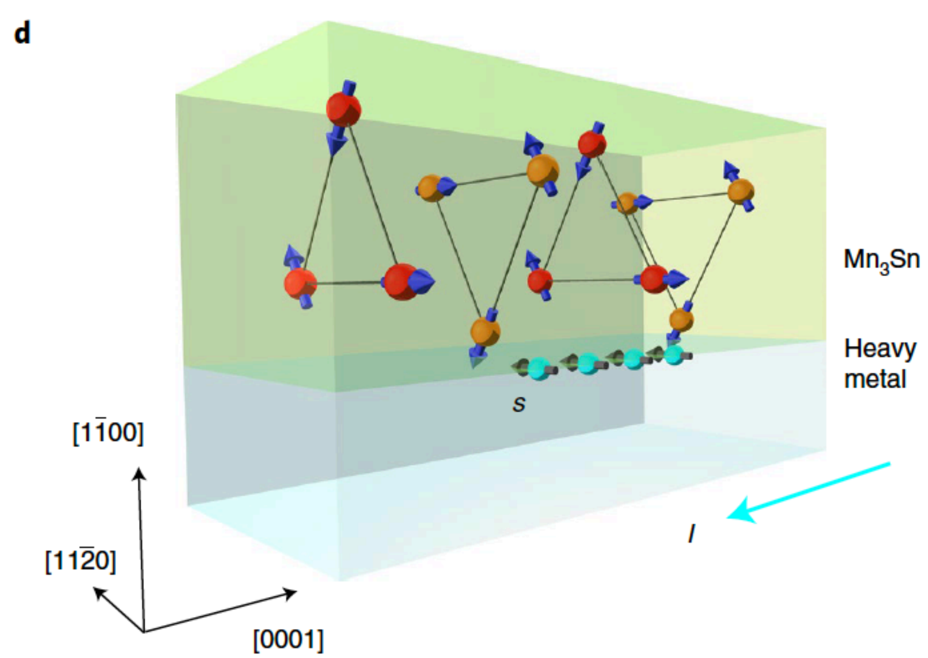


Switching in non collinear AFM

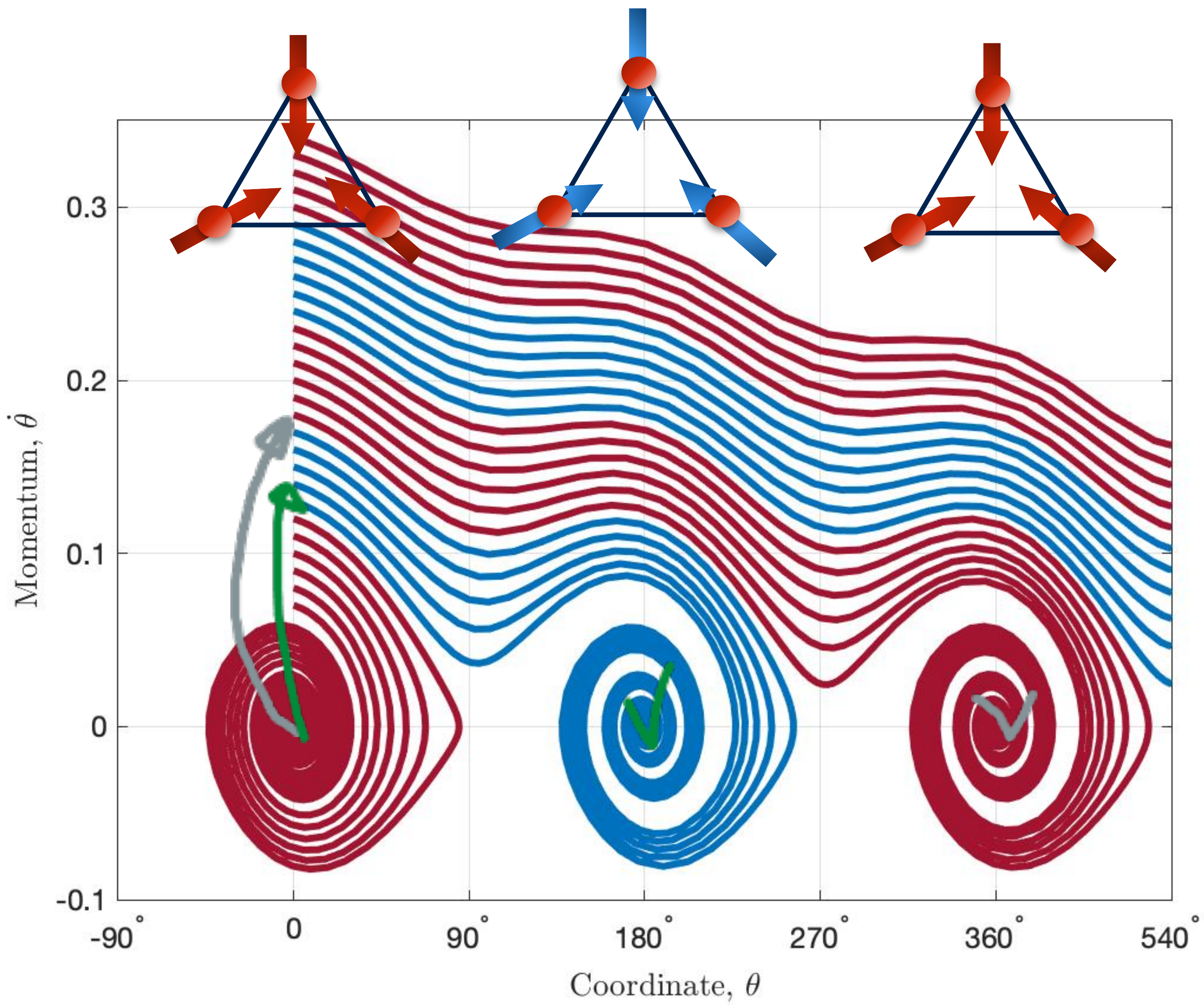


O.G., Loktev,(2015) Low Temp.Phys.
http://dx.doi.org/10.1063/1.4931648

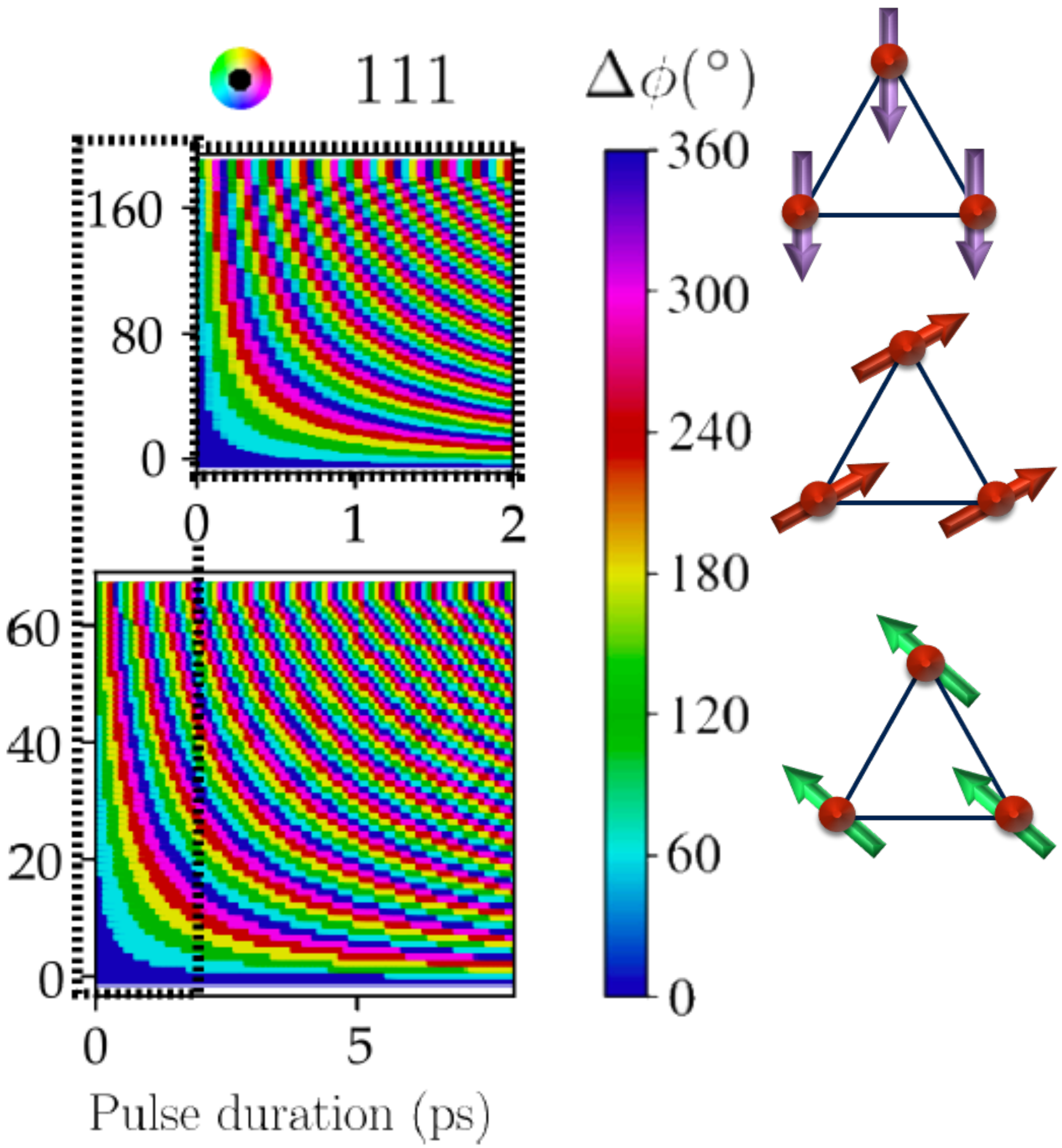
$$\ddot{\theta} + 2\gamma_{AF}\dot{\theta} + \omega_{AF}^2 \sin\theta\cos\theta + \gamma\omega_D H \sin\theta = \gamma^2 H_{ex}\left(\Lambda_{fl}\,\dot{\mathbf{s}} + \Lambda_{dl}\,\mathbf{s}\right)$$

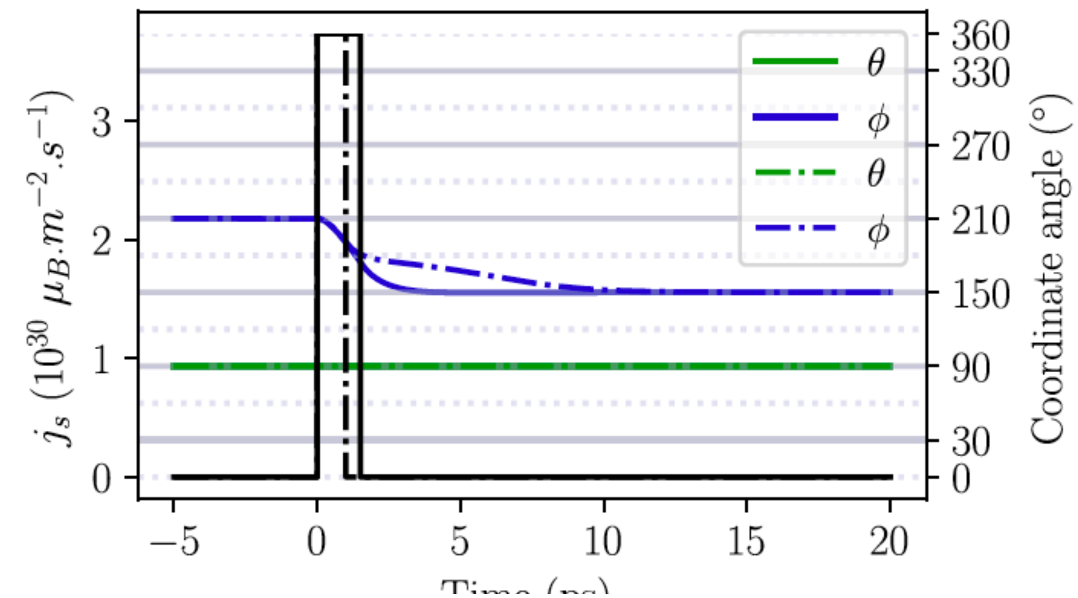


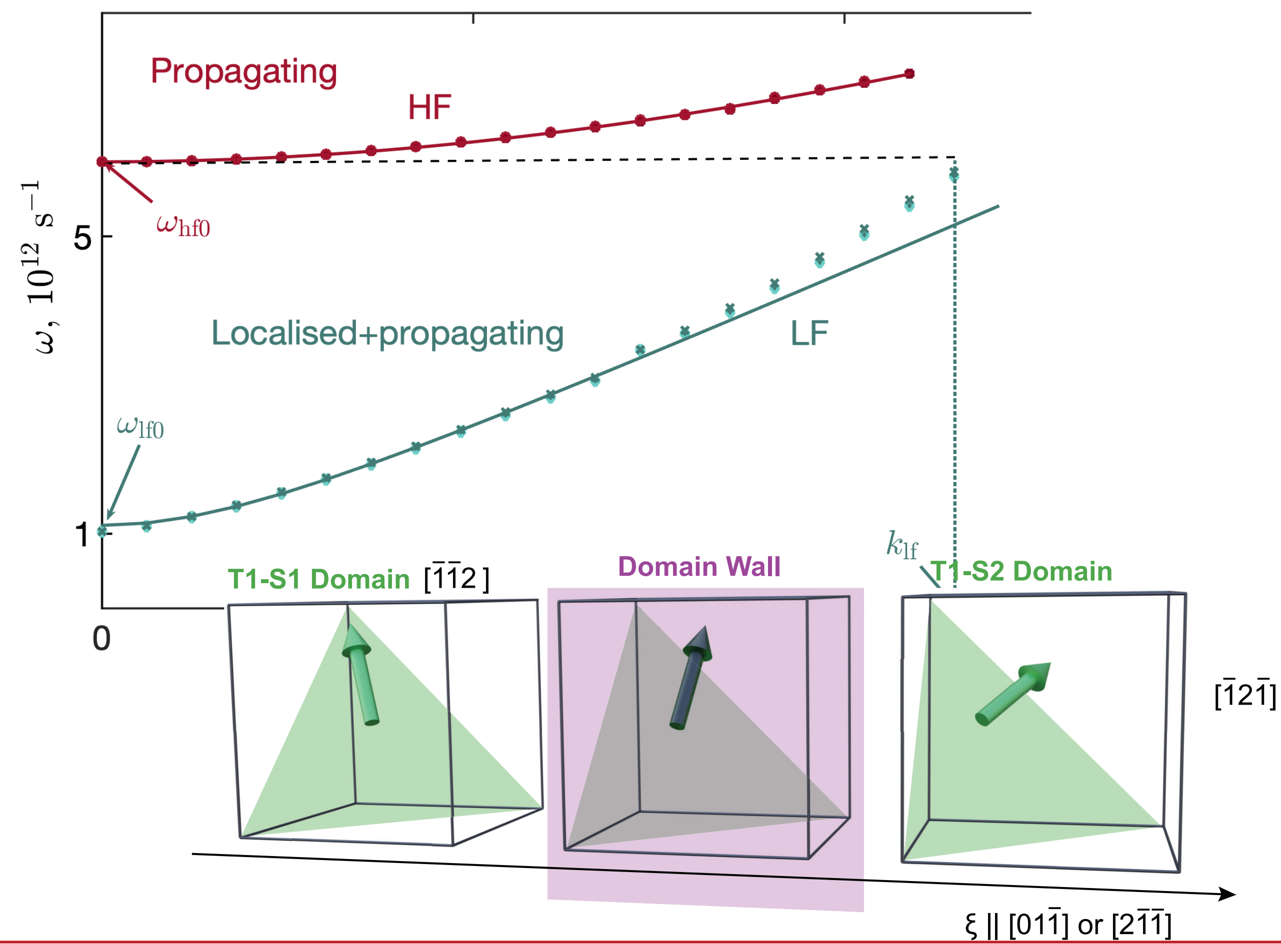
Yu. Takeuchi, et al, (2021) Nature Materials
https://doi.org/10.1038/s41563-021-01005-3



Switchingand dynamics of NiO



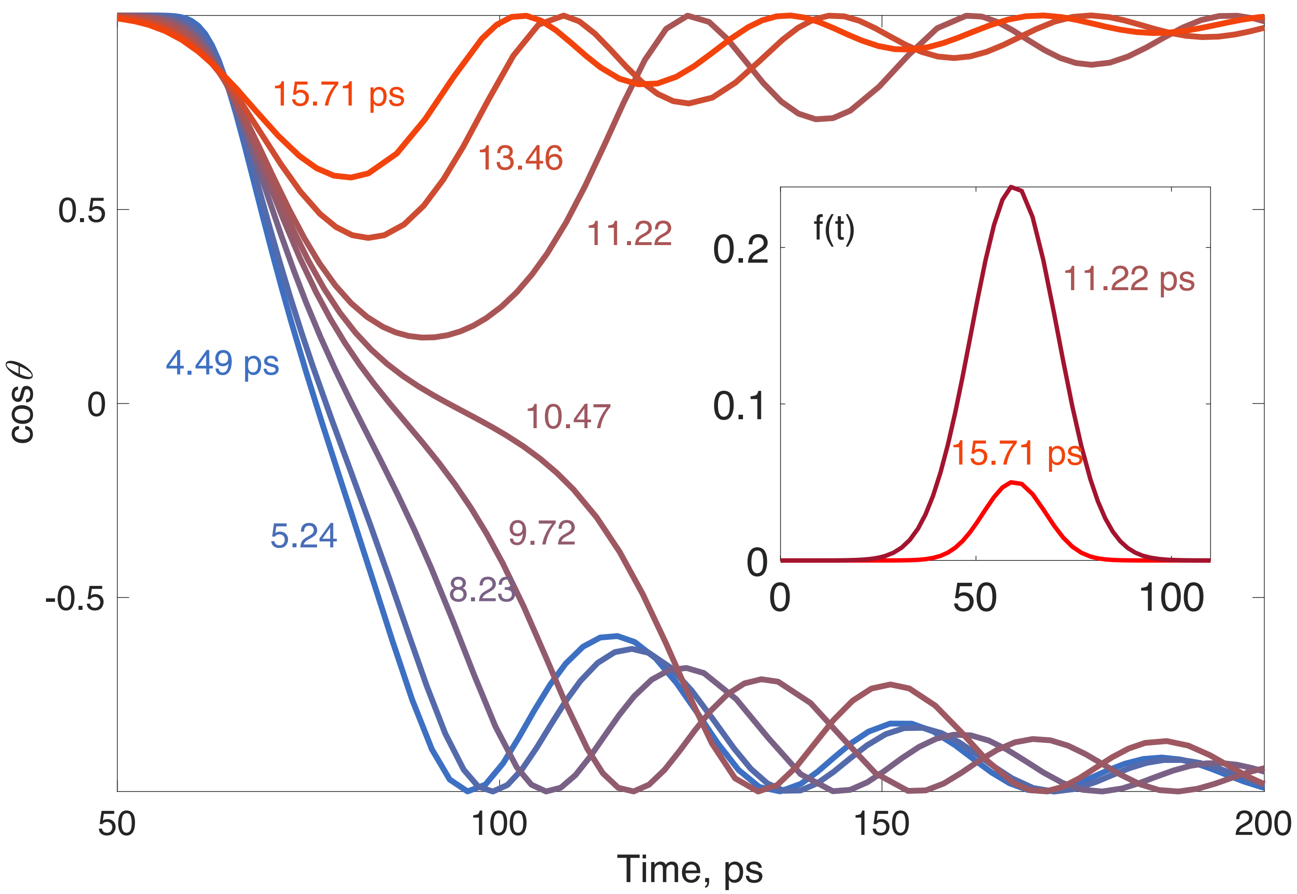




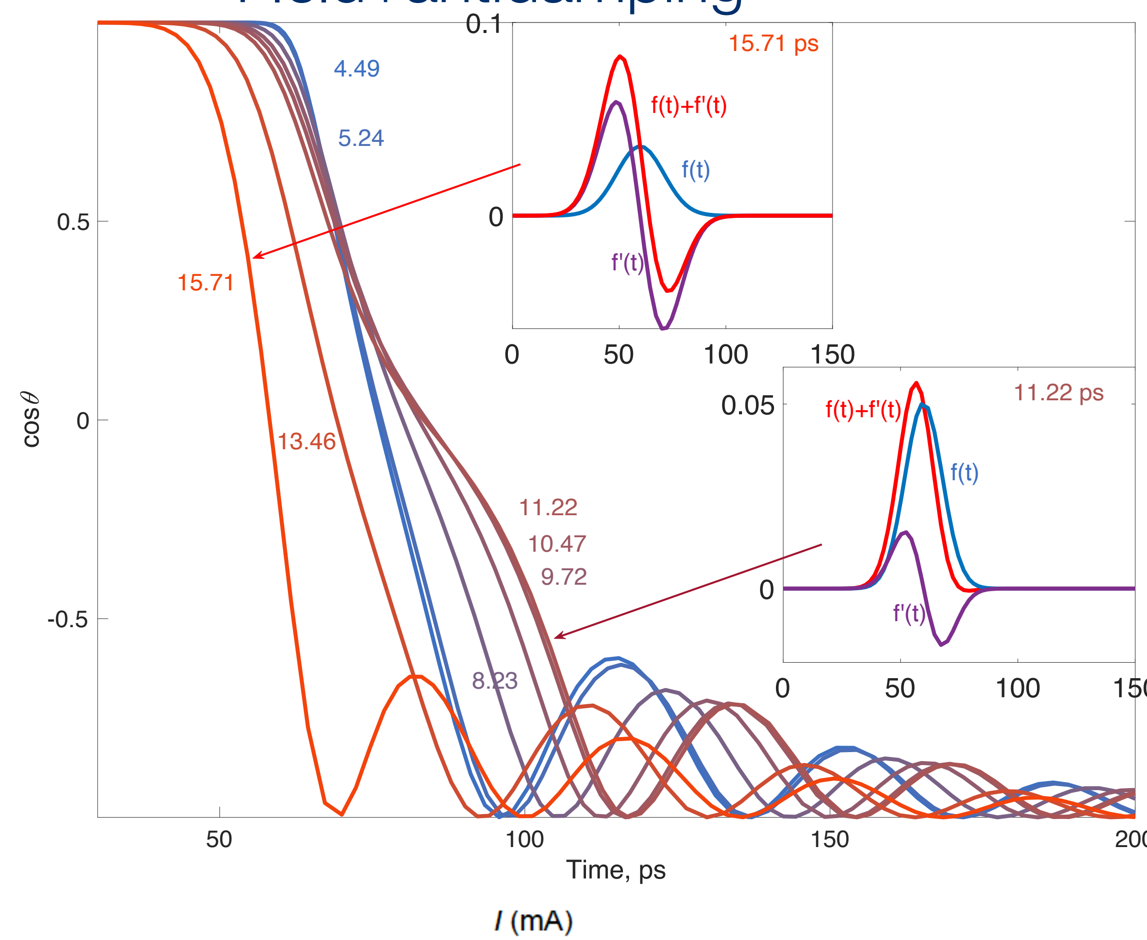
Th. Chirac, OG, et al, 2020, [10.1103/PhysRevB.102.134415](https://doi.org/10.1103/PhysRevB.102.134415)

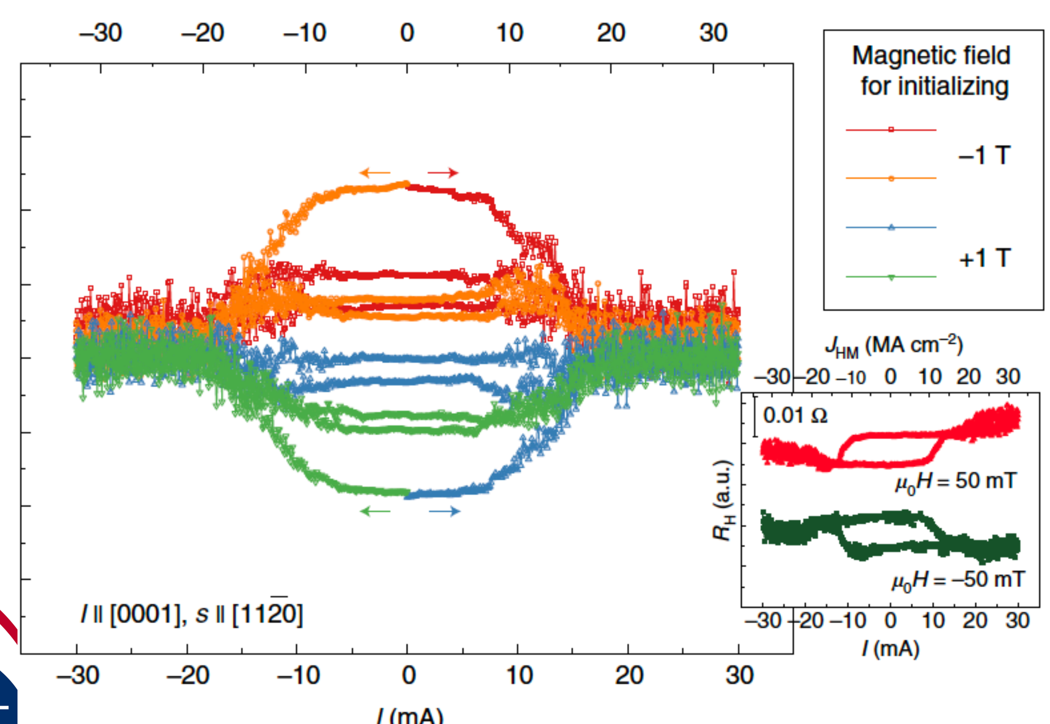
Field-like-vs damping-like torque

Pulse duration



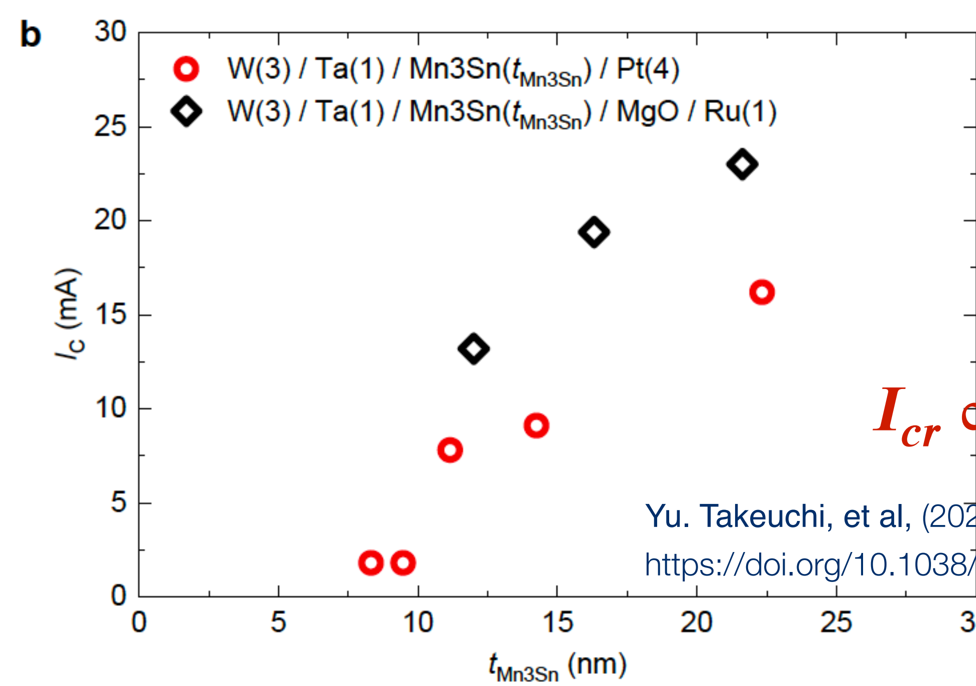
FIeld+antidamping





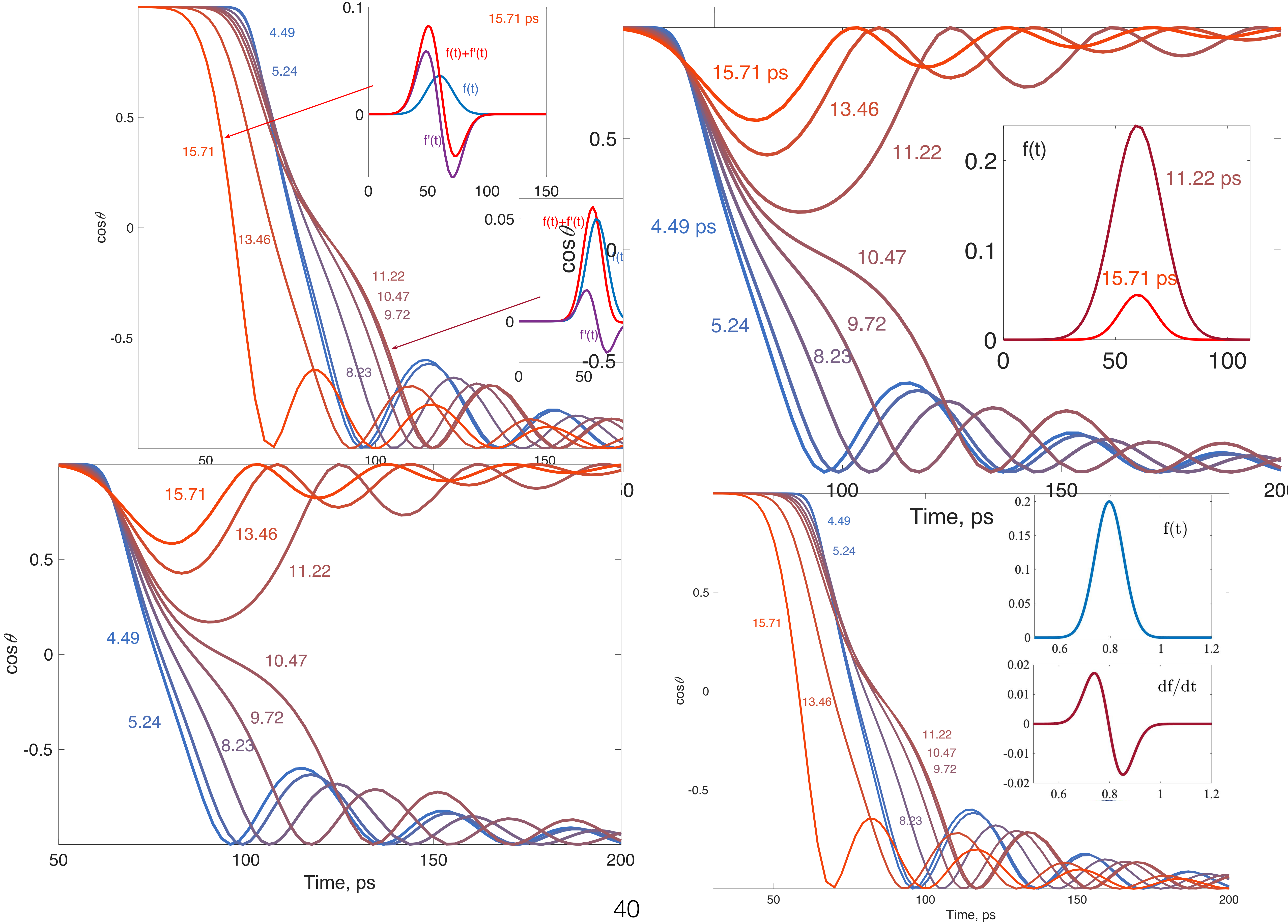
*I*si

b



$I_{cr} \propto t_{AF}$

Yu. Takeuchi, et al, (2021) Nature Materials
https://doi.org/10.1038/s41563-021-01005-3


4.49
5.24
15.71
13.46
11.22
10.47
9.72
8.23
cosθ
f(t)+f'(t)
f(t)
f'(t)
15.71 ps
4.49 ps
11.22 ps
Time, ps
df/dt