Magnetization reversal processes

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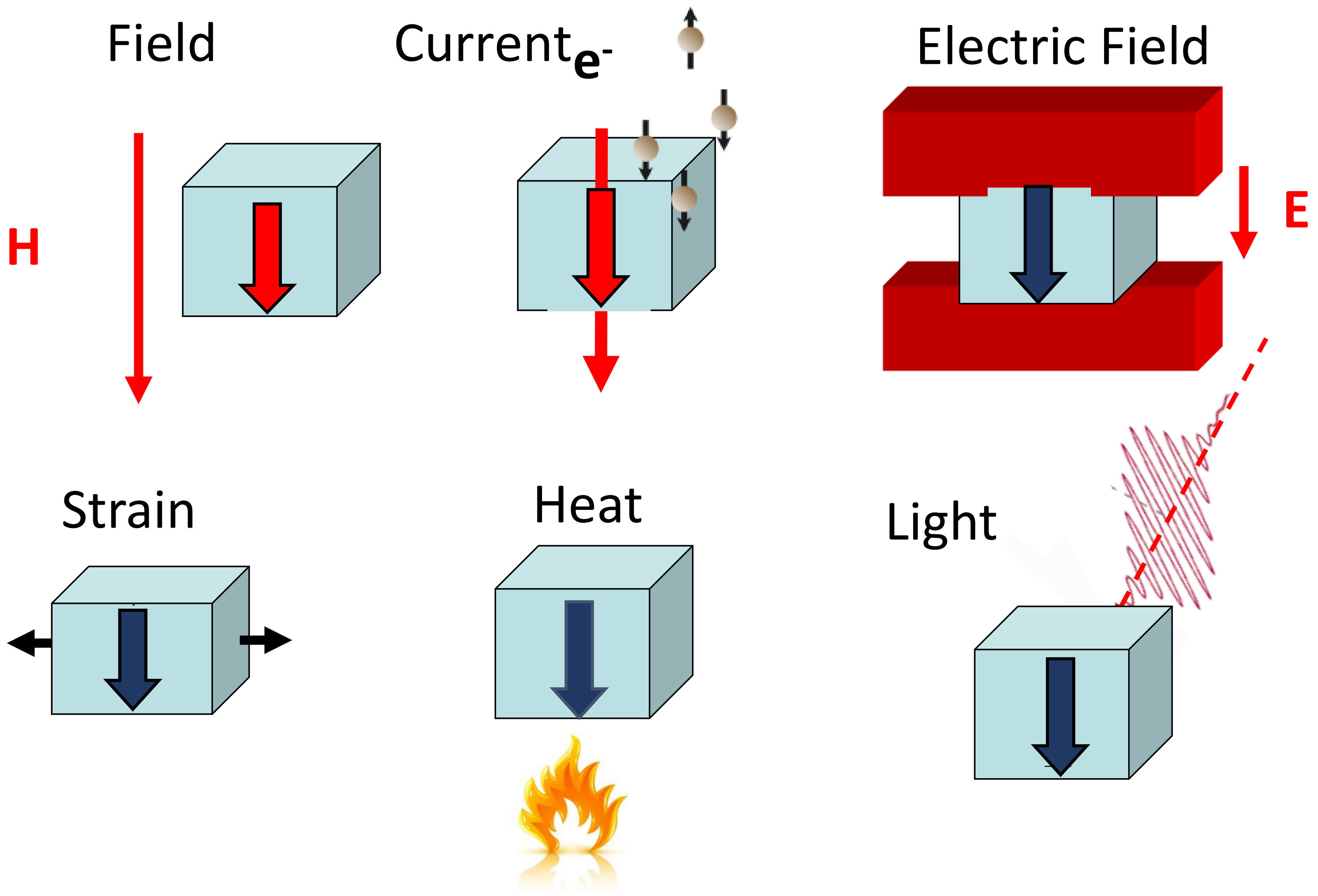
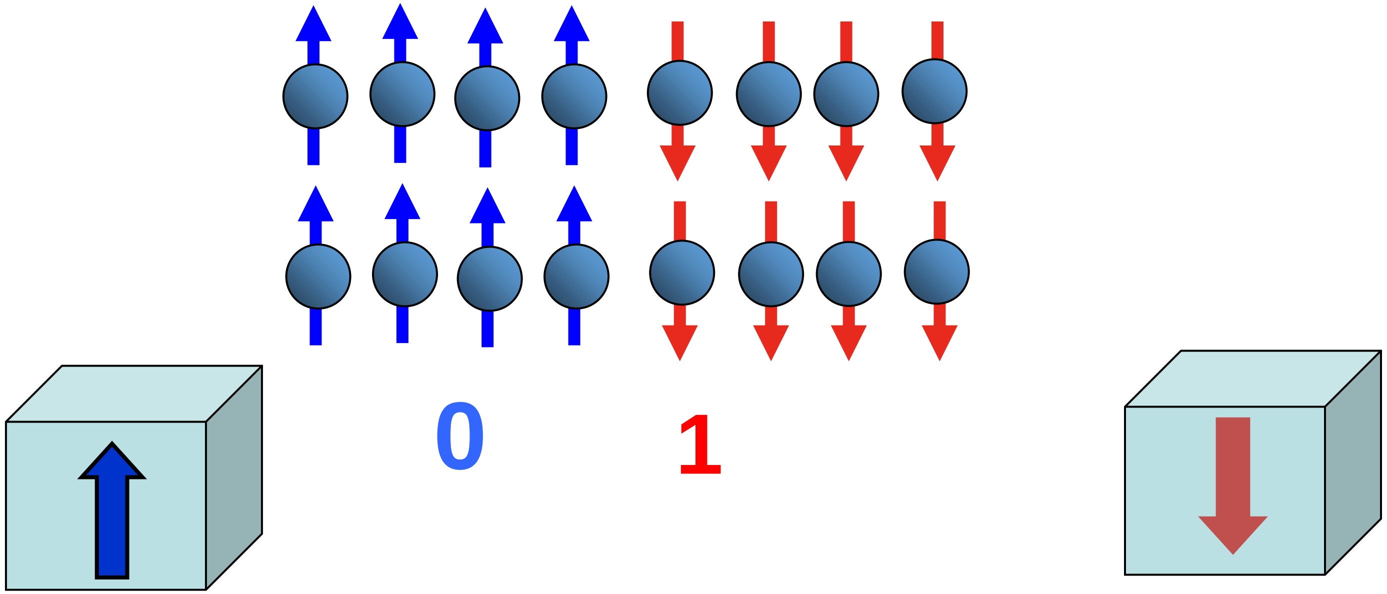
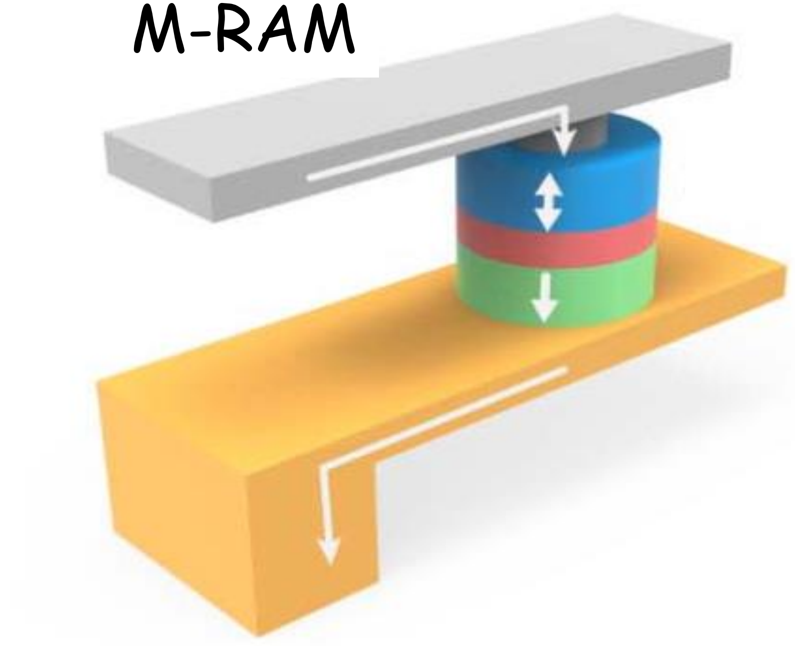
Magnetization reversal



Magnetic Memory



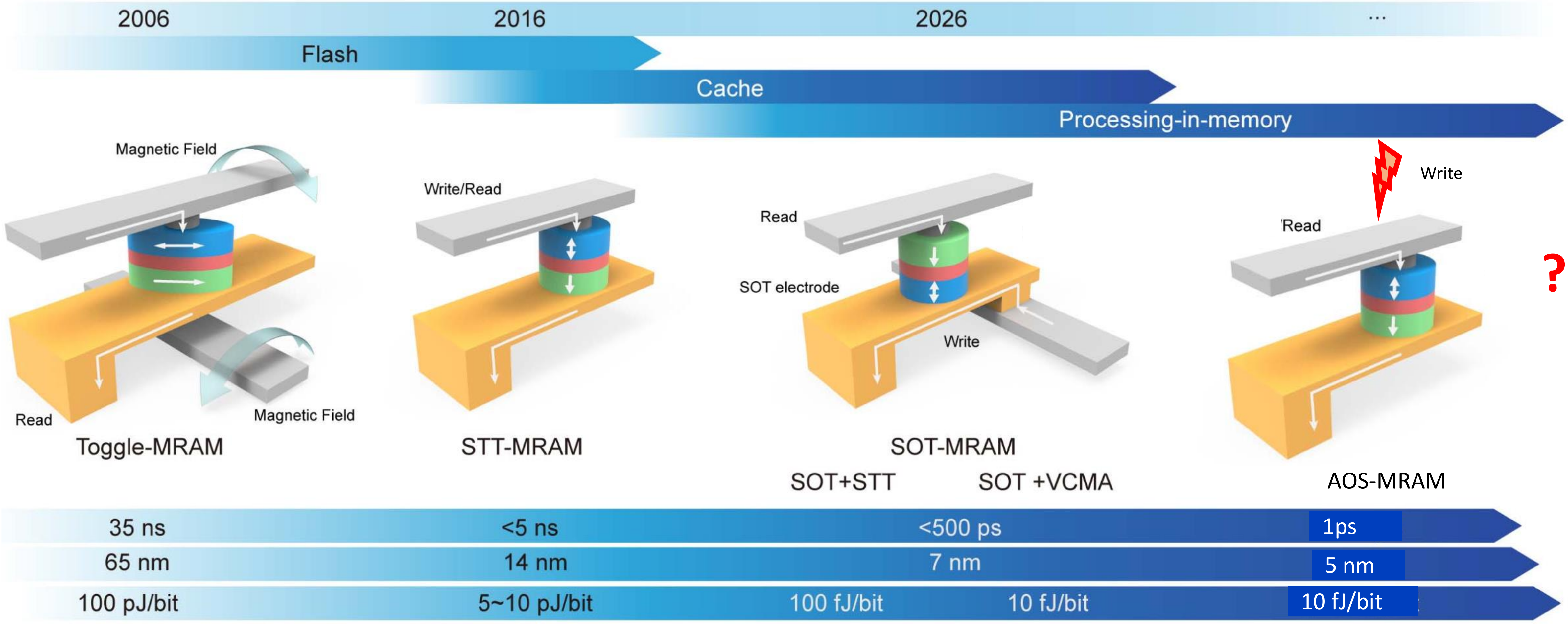


Store : define a “ 0 ” and a ” 1 ”

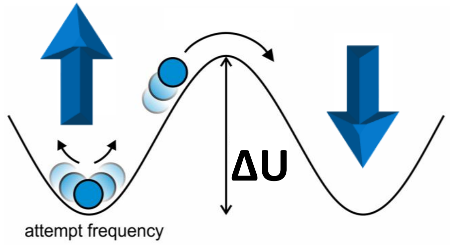
Read : to different electrical current for a “ 0 ” and a ” 1 ”

Write : be able to change a “ 0 ” to a ” 1 ” and a ” 1 ” “ 0 ”

Writing MRAM

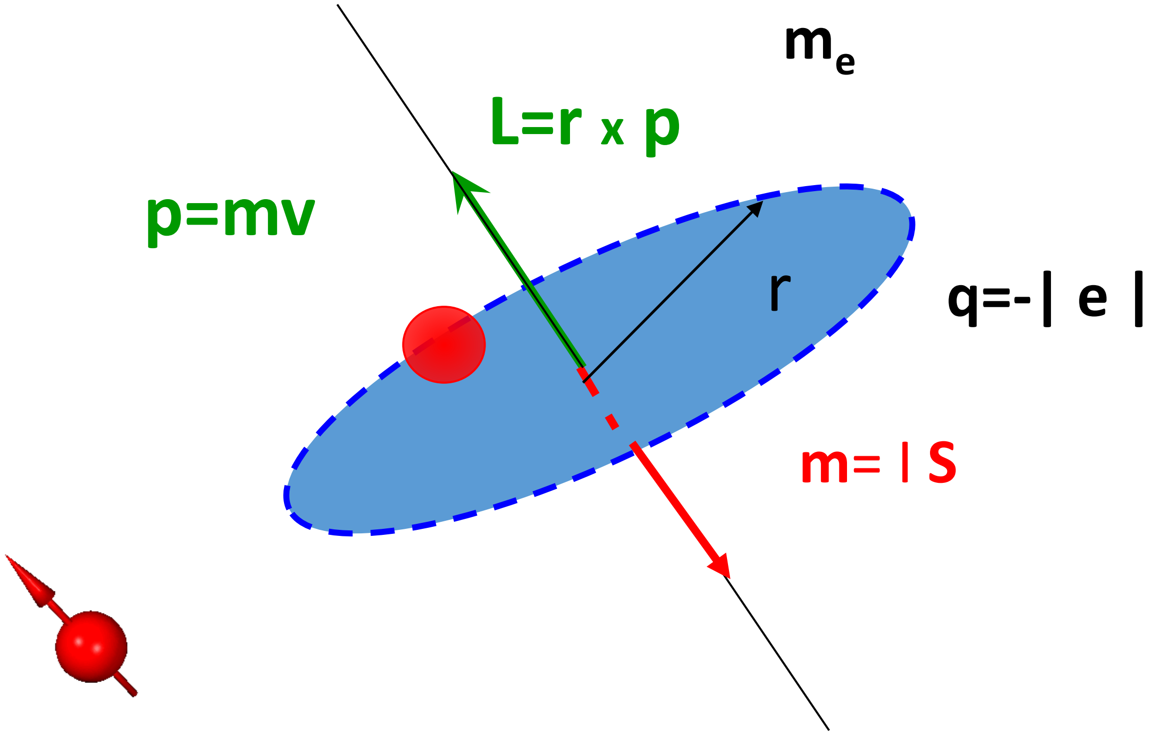


from Z. Guo *et al, Proc. IEEE 2021*



Thermal Stability given by ΔU = KV

Angular momentum / magnetism



$$m = g\,L$$

$$g = -\,|e|/2m_e$$

Electron spin ⟷ $m_S = g_s\,(e/2m_e)\,S$

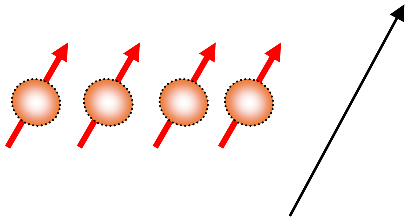
$g_s = 2.0...$

Magnetization ⟷ Electrons rotating around nucleus

$m_J = g_J\,(q/2m_e)\,J$

Interactions

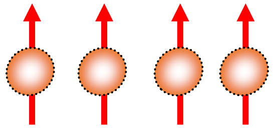
Zeeman Energy



H

$$E_{zee} = - \mu_0 \vec{M} \cdot \vec{H}$$

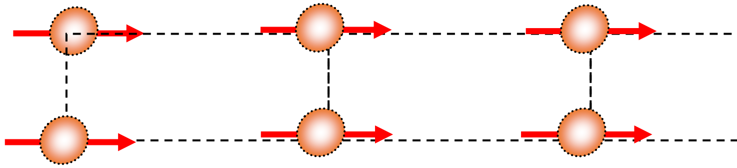
Exchange



1000 K, 100 T

$$E_{exc} = -J\vec{S}_1 \cdot \vec{S}_2$$

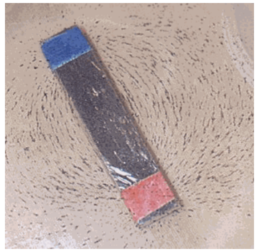
Magneto-crystalline anisotropy



10 K, 0.01 to 10 T

$$E_K = -K\cos^2(\theta)$$

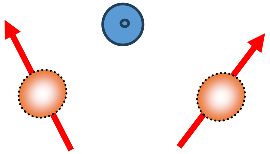
Dipolar



1 K, 10 mT

$$E_{dip} = - \mu_0 \vec{M} \cdot \vec{H}_{dip}$$

Dzyaloshinskii–Moriya interaction (DMI)



$$E_{DMI} = \vec{D}_{12} \cdot (\vec{S}_1 \times \vec{S}_2)$$

$$E_{total} = - \mu_0 \vec{M} \cdot \vec{H}_{eff}$$

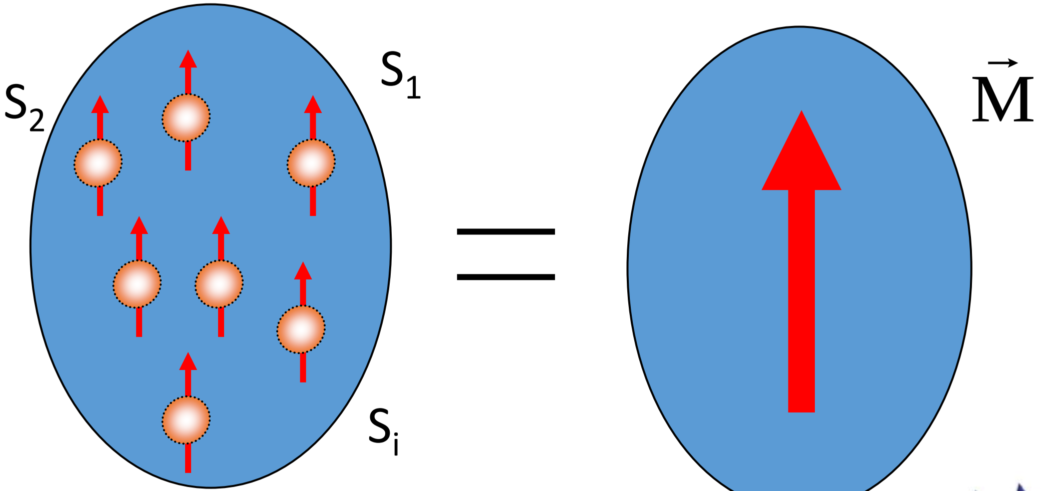
Configuration results from competition of the different interactions

Macro SPIN : Stoner - Wohlfarth

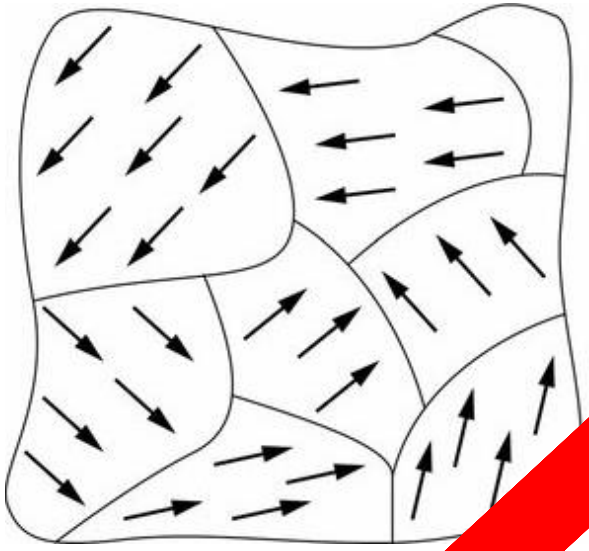
Hypotheses

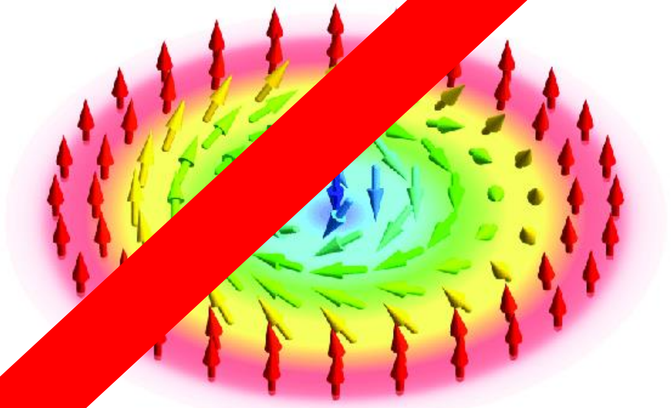
Large $E_{exc} = -J\vec{S}_1 \cdot \vec{S}_2$

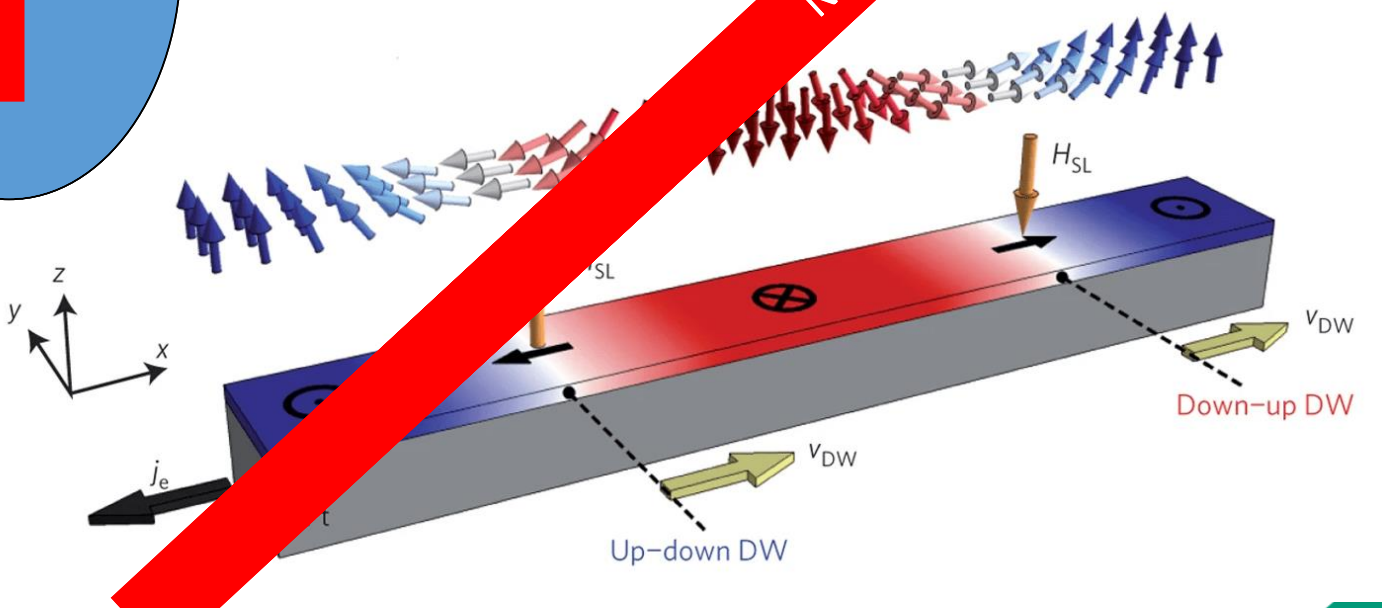
- Monodomaine Particule



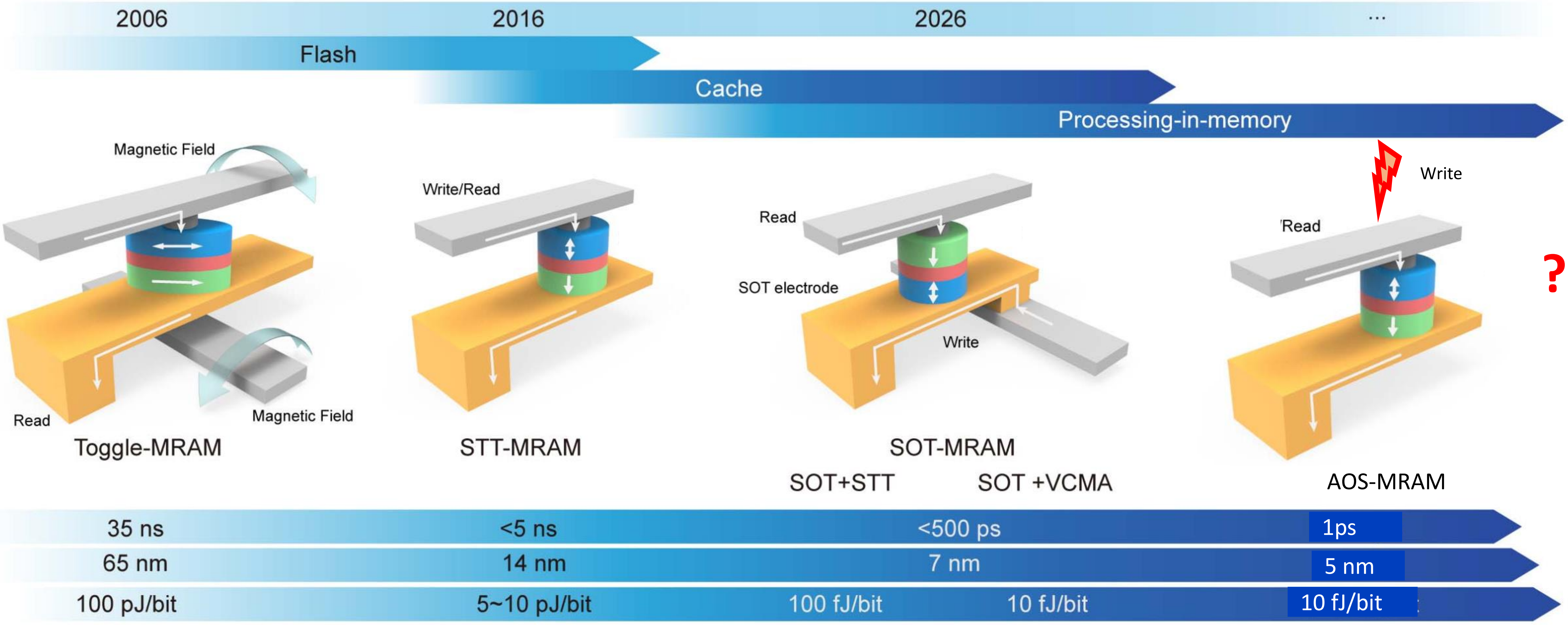
- T= 0K



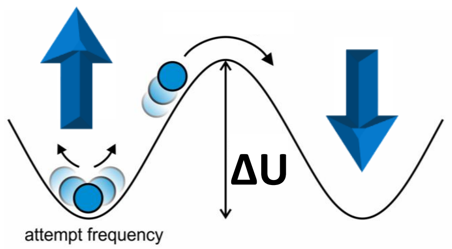




Writing MRAM



from Z. Guo *et al, Proc. IEEE 2021*



Thermal Stability given by $\Delta U = KV$

Outlines

- Magnetisation field switching
  - Energy
  - Torques

- Current induced switching
  - Spin tranfer Torque
  - Spin Orbit Torque

- All optical switching

Outlines

- Magnetisation field switching
    - Energy
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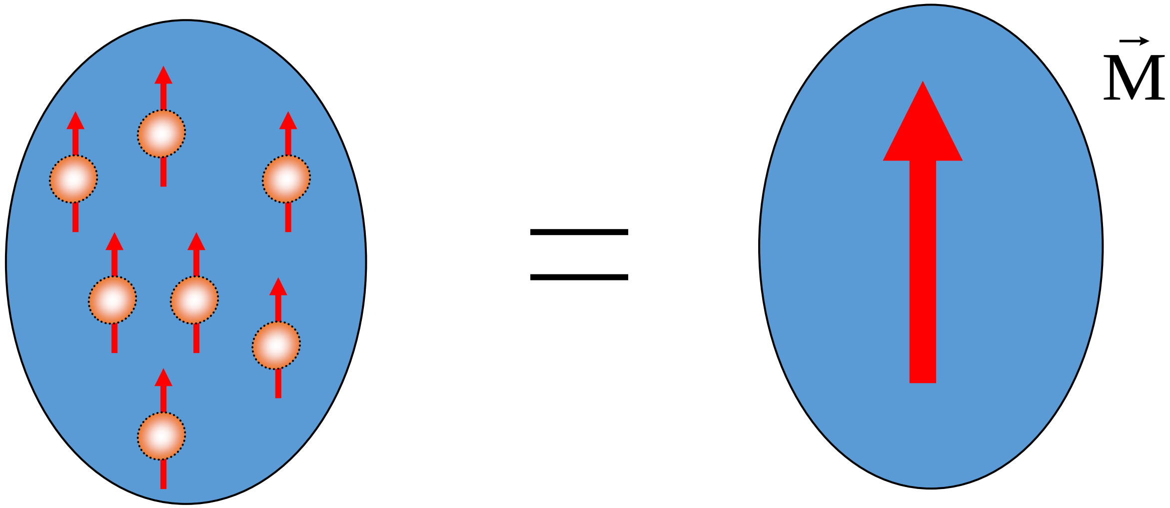
    - Spin Orbit Torque

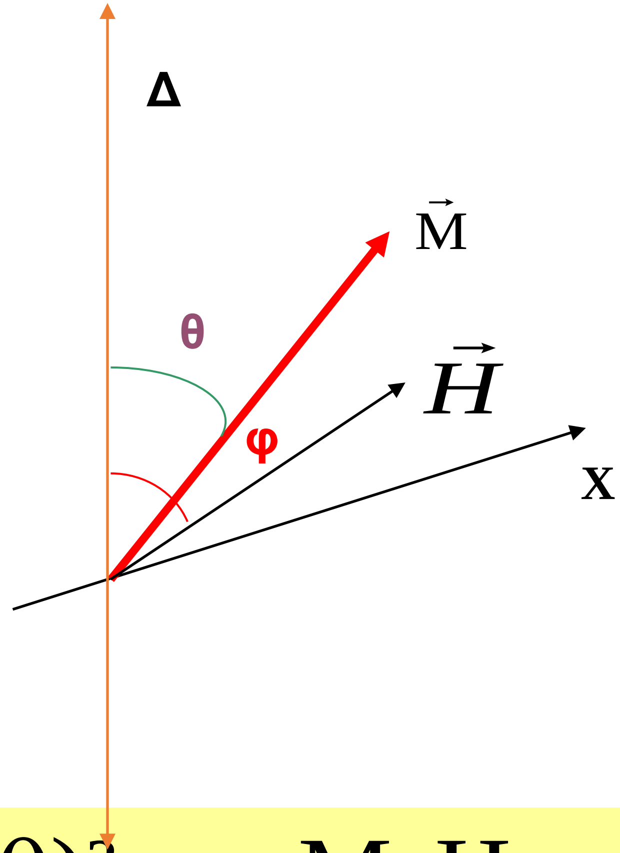
- All optical switching

Energy consideration

Hypotheses $E_{exc} = -J\vec{S}_1 \cdot \vec{S}_2$ Is large

- Monodomaine Particule





- T= 0K

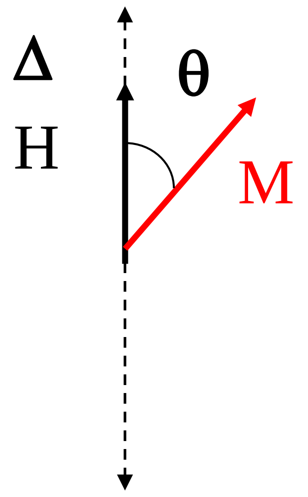
$$E_{mag} = E_{aniso} + E_{Zeeman} = KV(\sin\theta)^2 - \mu_0 M_s H\cos(\varphi - \theta)$$

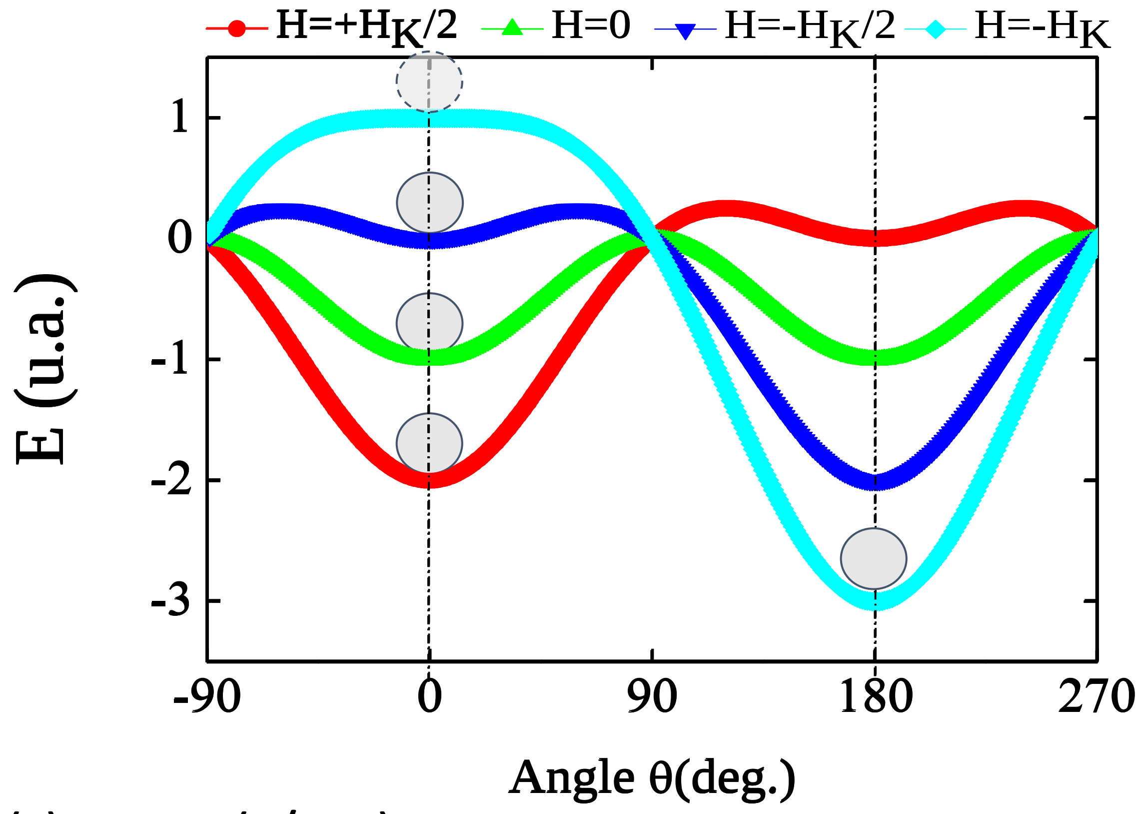
$$H_K = 2K/M$$

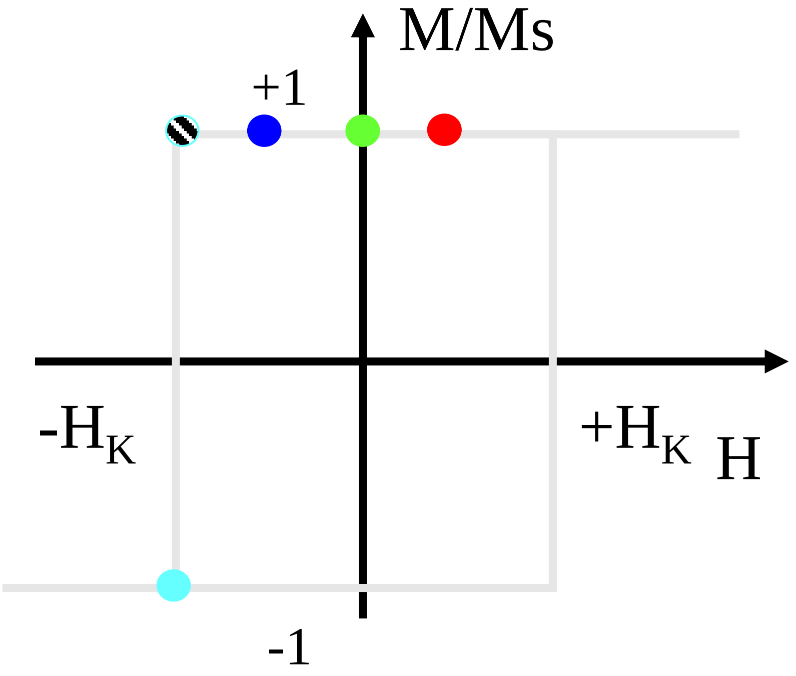
Energy consideration

$H_K = 2K/M$

$H \,//\, \Delta$ $\varphi = 0$







$P(t) = \exp(t/\tau_0)$

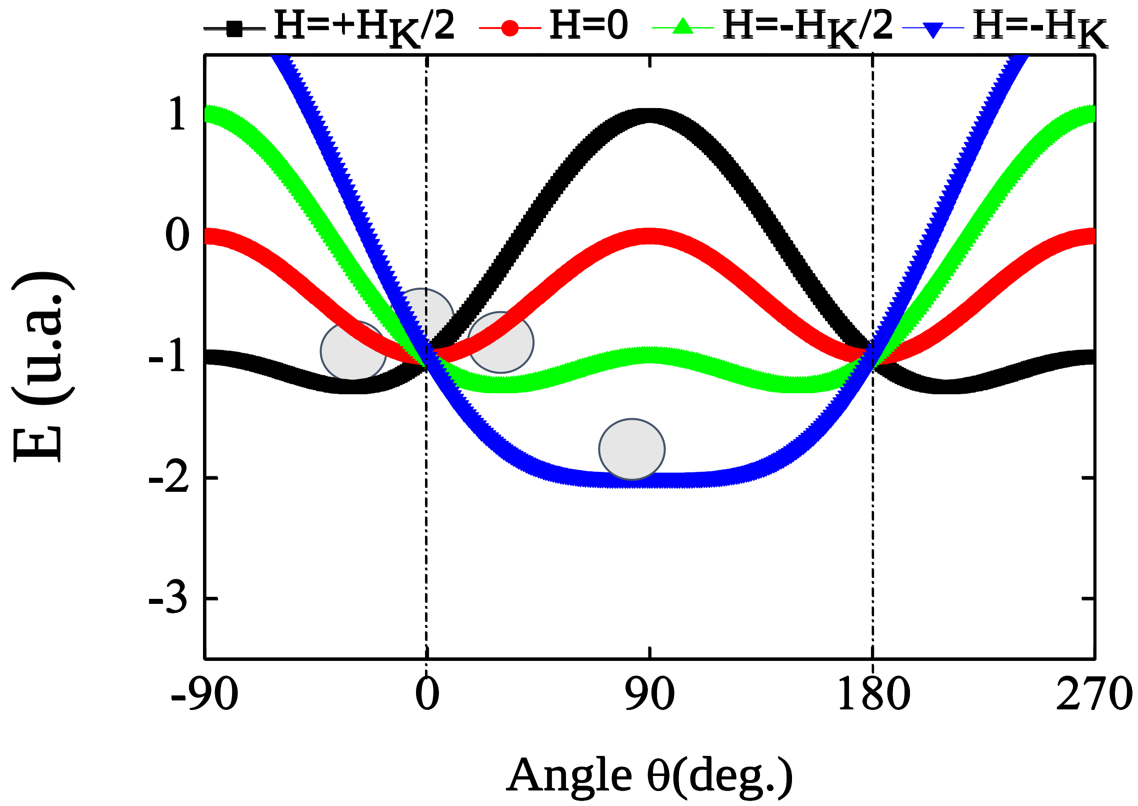
$\tau = \tau_0 \exp(-\Delta U/k_B T)$

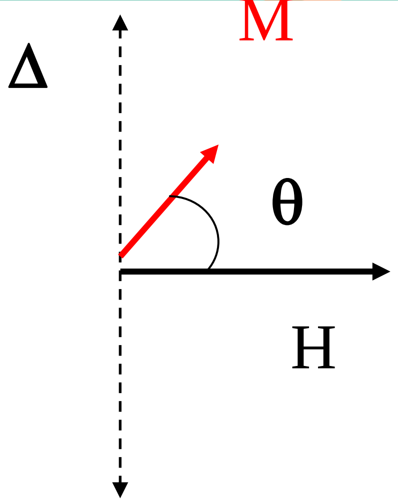
Energy consideration

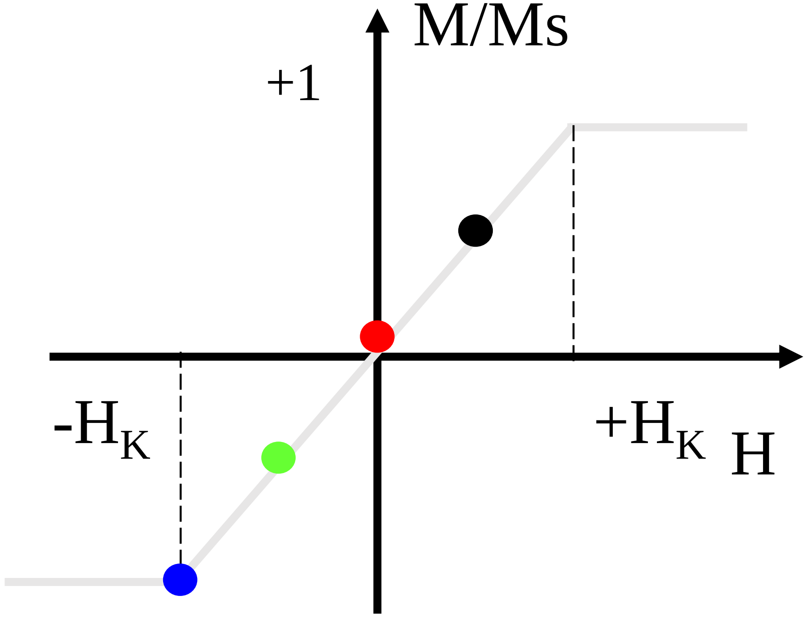
$H_K = 2K/M$

$H \perp \Delta$

$\varphi = 90$ deg

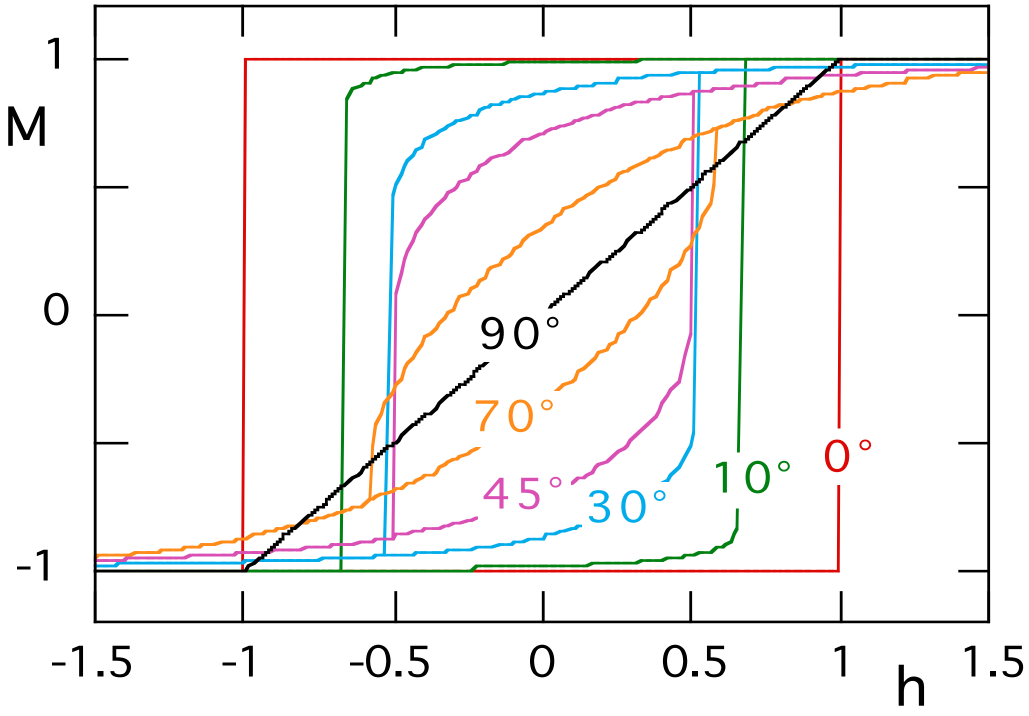


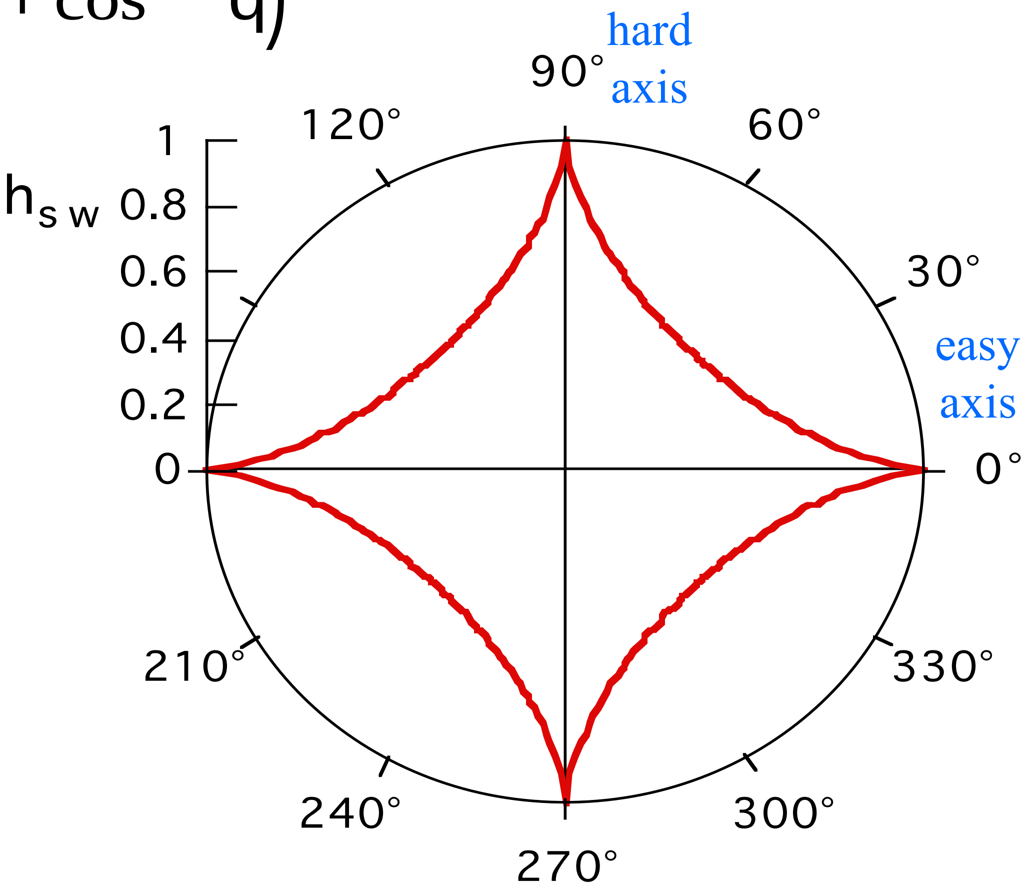




Energy consideration

$$h_{sw} = \left(\sin^{2/3}q + \cos^{2/3}q\right)^{-3/2}$$



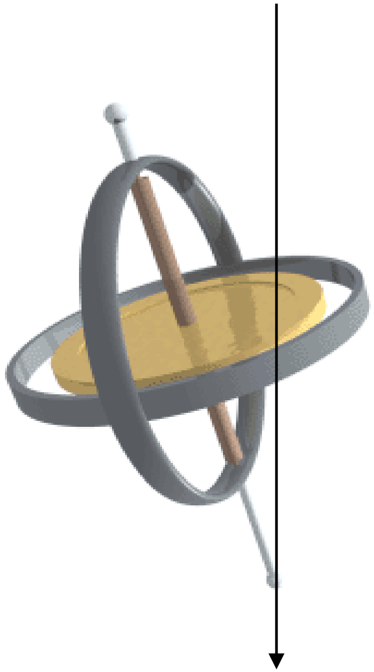


Stoner - Wohlfarth astroid

Angular momentum / Torque

p=mv

$\mathbf{L} = \mathbf{r} \times \mathbf{p}$

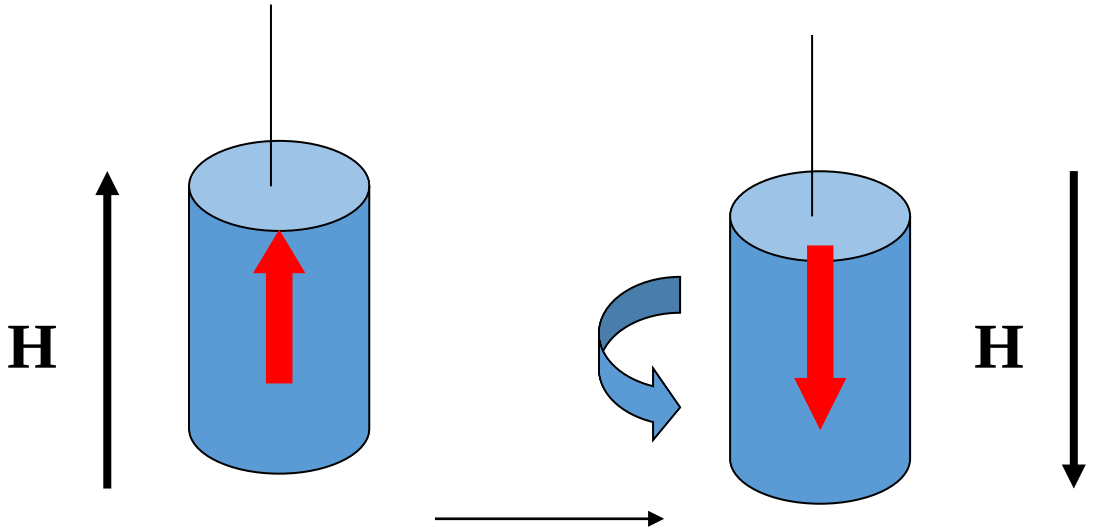


$\boldsymbol{\Gamma} = \mathbf{r} \times \mathbf{F}$

$\mathbf{F} = d\mathbf{p}/dt$ Newton's 2nd law

$$\boldsymbol{\Gamma} = \frac{d\mathbf{L}}{dt}$$

Einstein de Haas effect



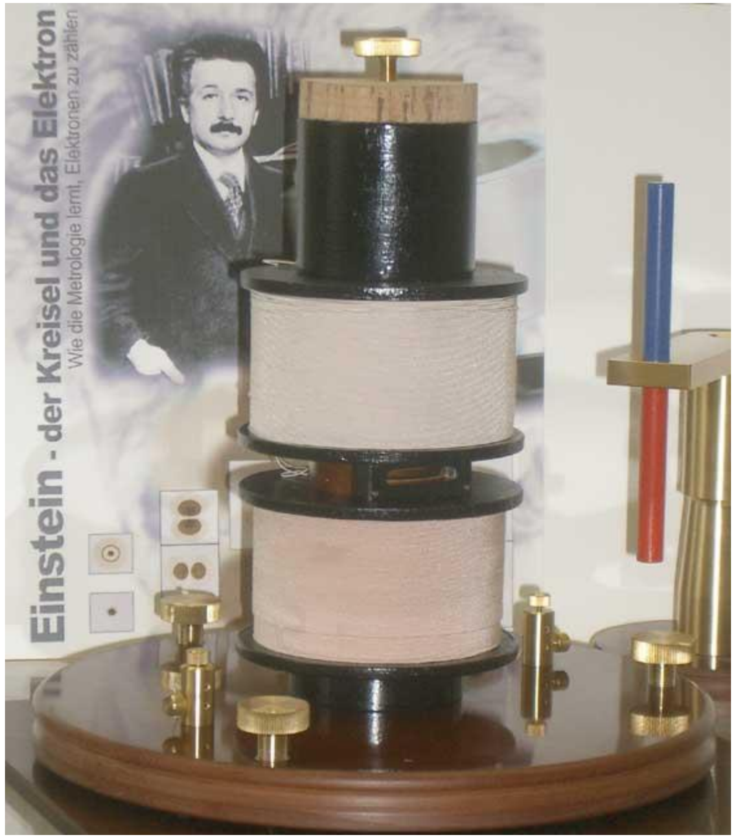
Δm

m= γ L

ΔL

$$\boldsymbol{\Gamma} = \frac{d\mathbf{L}}{dt} = \frac{1}{\gamma}\frac{dm}{dt}$$

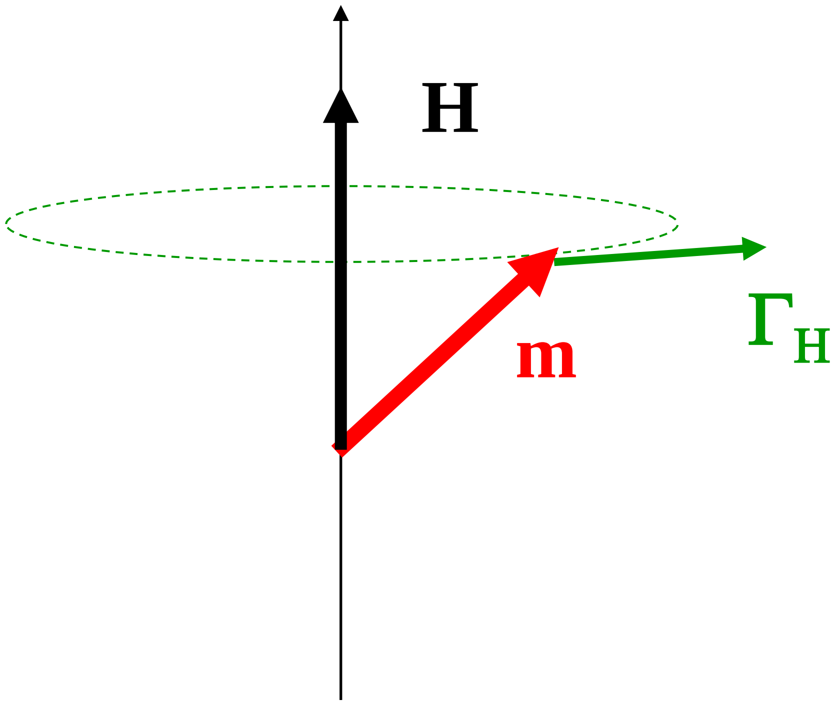
→ Rotation

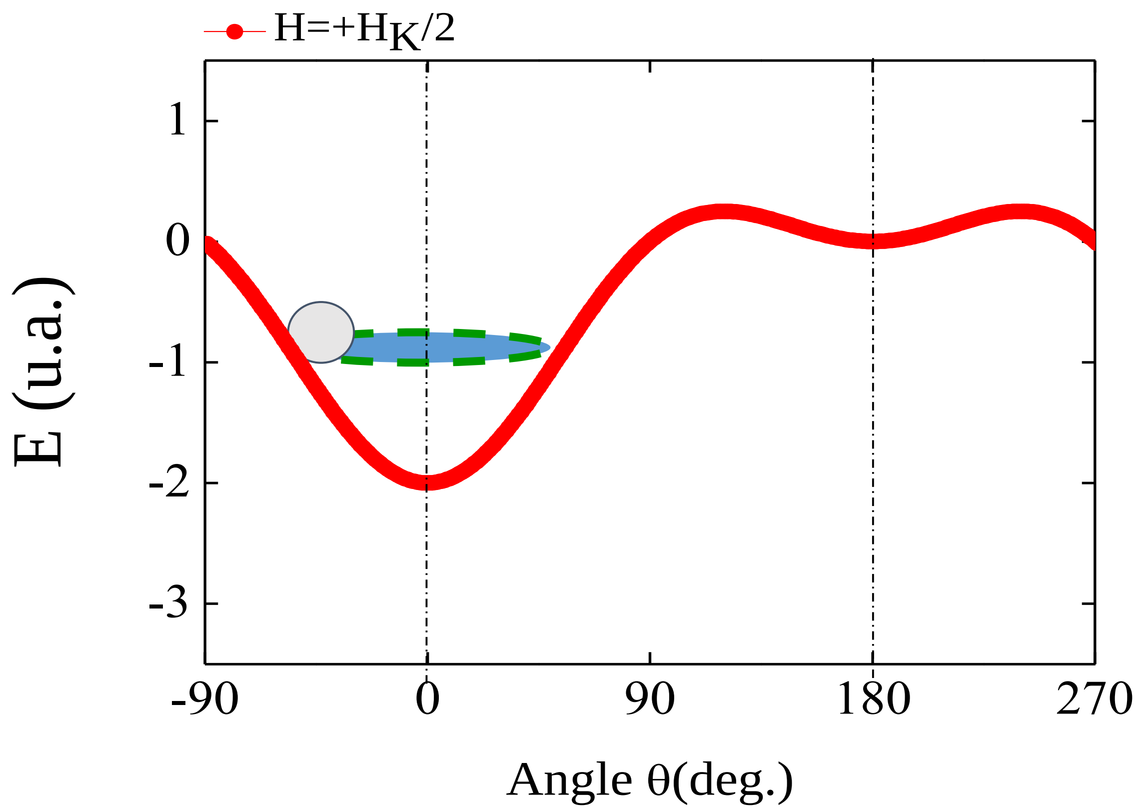


A. Einstein, W. J. de Haas, *Experimenteller Nachweis der Ampereschen Molekularstörme*, Deutsche Physikalische Gesellschaft, Verhandlungen **17**, pp. 152-170 (1915).

Torque

$$\Gamma_H = \mathbf{H} \wedge \mathbf{m} = \frac{d\mathbf{L}}{dt} \Rightarrow \mathbf{H} \wedge \mathbf{m} = \frac{1}{\gamma}\frac{d\mathbf{m}}{dt}$$





Landau Lifshitz 1935

Frequency: 28 GHtz / Tesla

Period about 100 ps

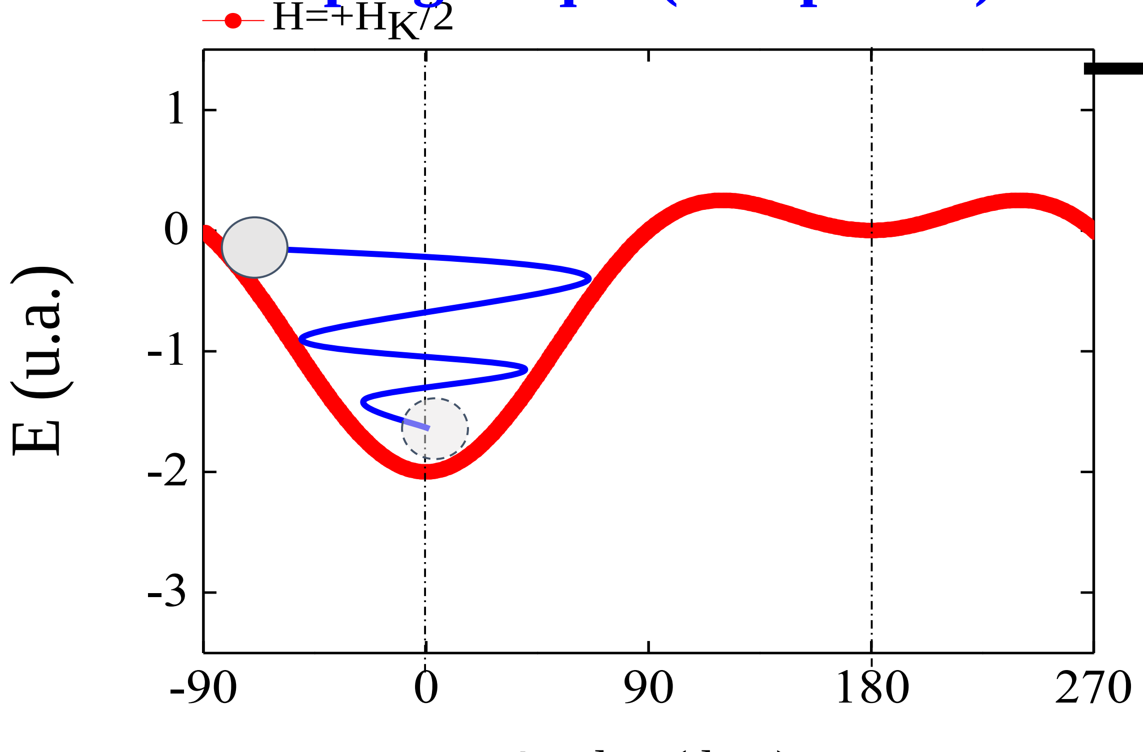
Iso-energy

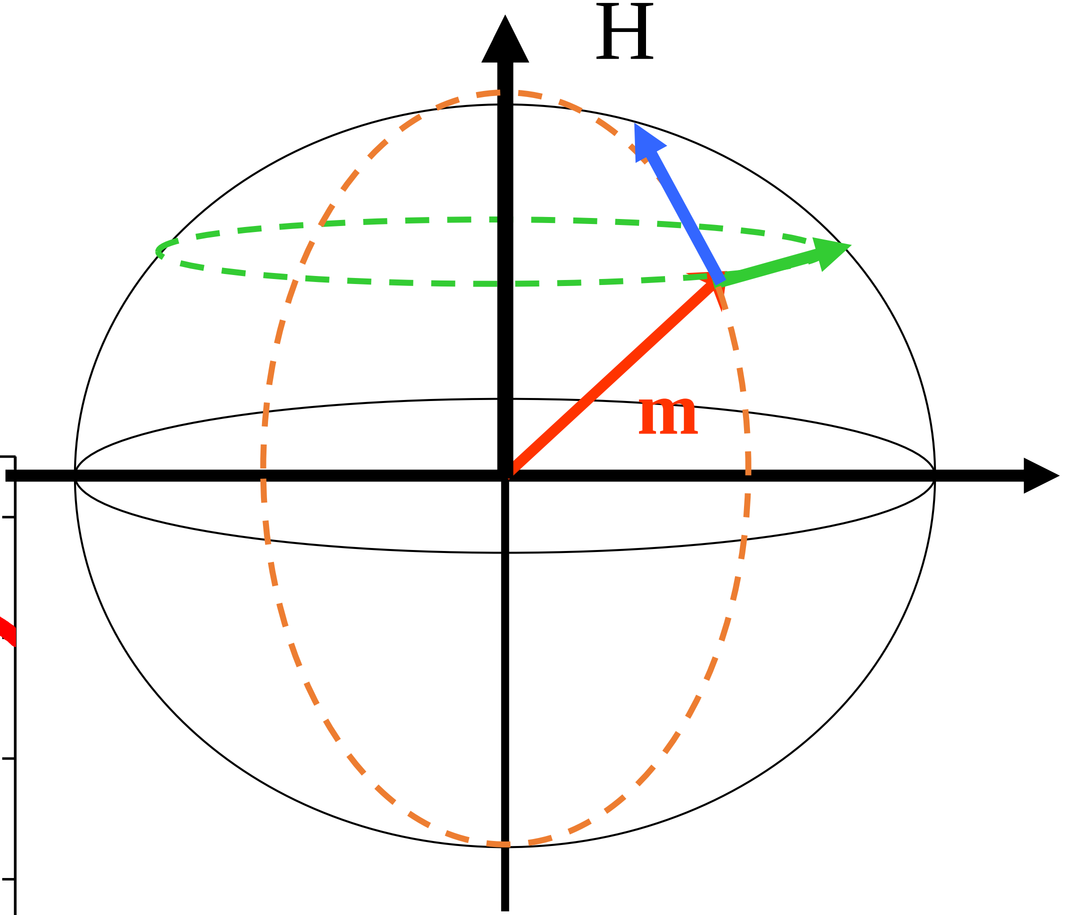
$$\frac{d\vec{\mathbf{m}}}{dt} = -\gamma(\vec{\mathbf{m}} \times \vec{\mathbf{H}})$$

Field torque (precession)

$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \wedge \mathbf{H} + \alpha\left(\mathbf{m} \wedge \frac{d\mathbf{m}}{dt}\right)$$

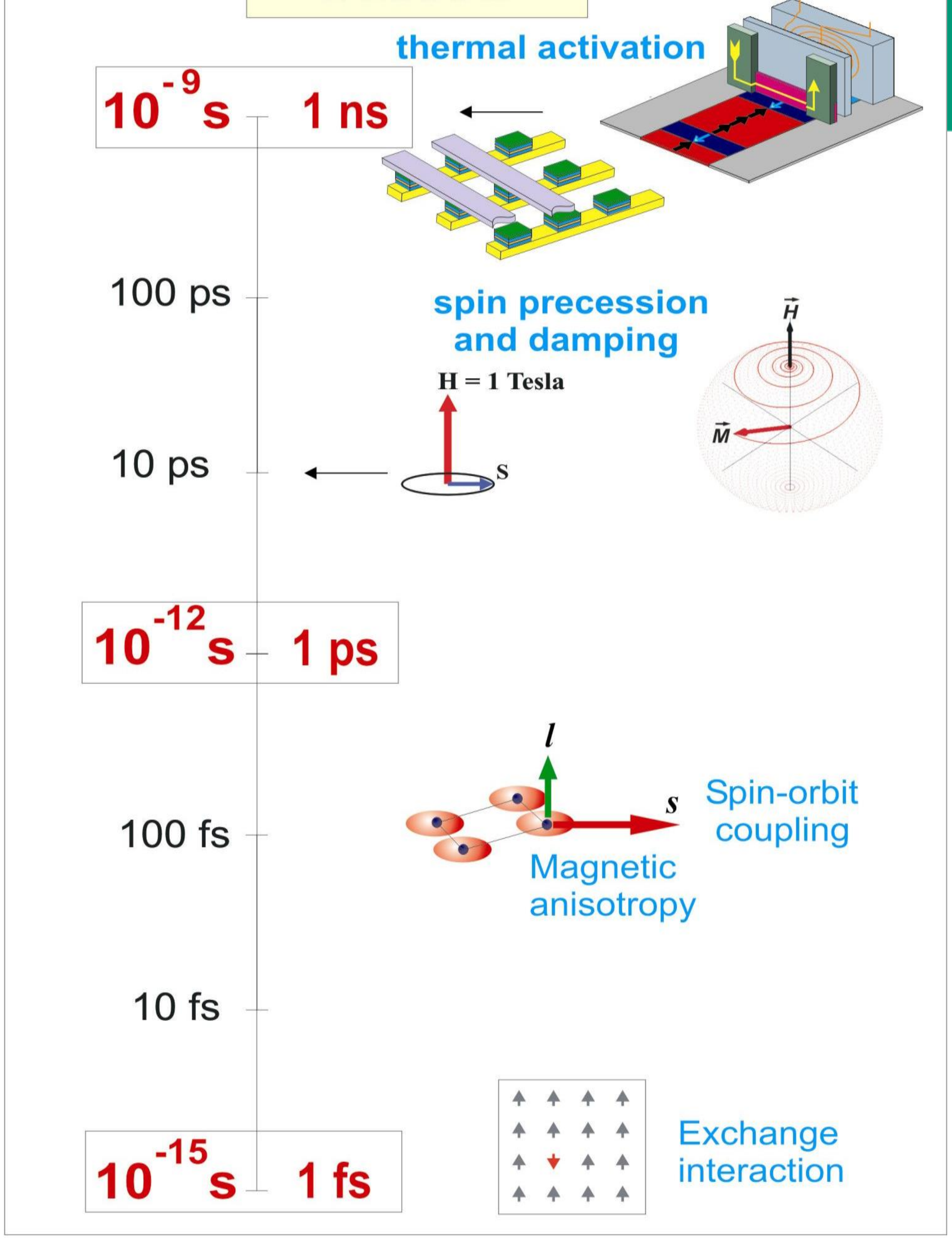
Damping torque (dissipation)





Magnetization Field Switching

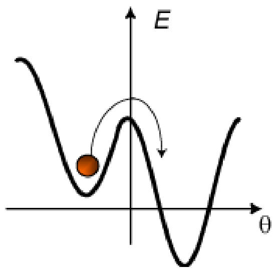
Typical times



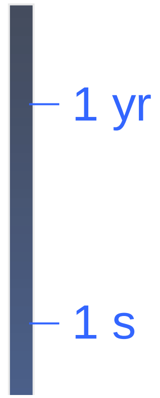
Typical times

- Exchange interactions
- Magnetocrystalline anisotropy
- Dipolar coupling

STABILIZE

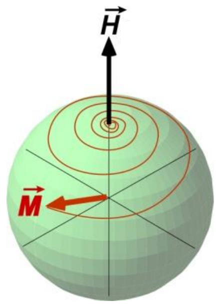


slow relaxation

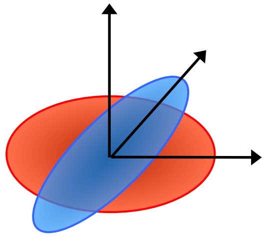


- Magnetic fields
- Spin torques
- Light

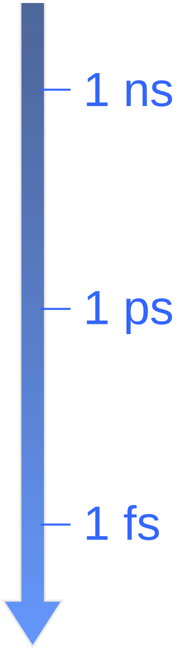
DESTABILIZE



precession



spin-orbital couplings



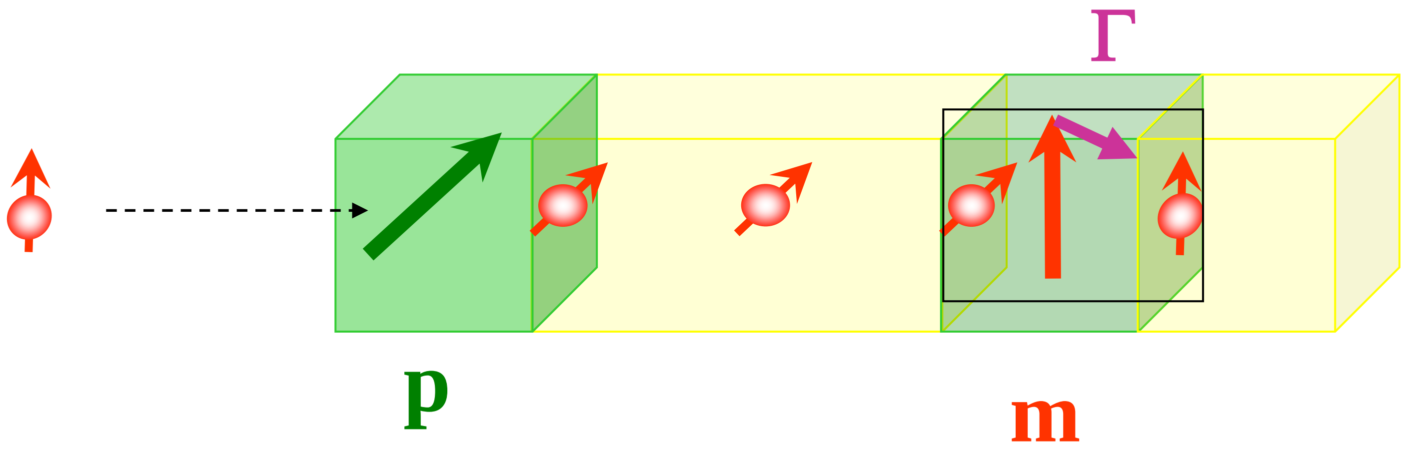
Outlines

- Magnetisation field switching
  - Energy
  - Torques

- Current induced switching
  - Spin tranfer Torque
  - Spin Orbit Torque

- All optical switching

Spin Transfer Torque STT



- Angular momentum conservation

$$\frac{d\mathbf{L}_e}{dt} = -\frac{d\mathbf{L}_m}{dt}$$

- Spin Transfer torque

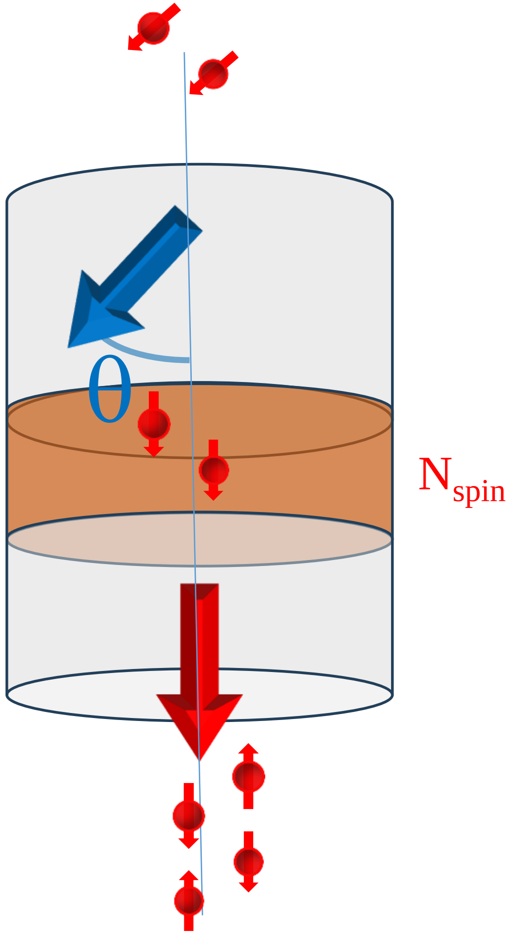
$$\boldsymbol{\Gamma}_{\mathrm{m}} = \frac{\mathrm{d}\mathbf{L}_{\mathrm{e}}}{\mathrm{dt}}$$

Spin Transfer Torque

$$N_{spin} = P_i \frac{Idt}{e}$$

$$\Delta m_e^{\perp} = P_i g \mu_B (\sin\theta)$$

$$-\Delta L_e = \frac{1}{\gamma_0} \frac{Idt}{e} P_i g \mu_B (\sin\theta)$$

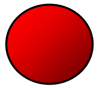
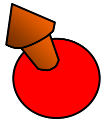
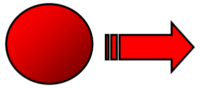
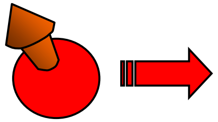


Newton second law

$$\boldsymbol{\Gamma} = \frac{d\mathbf{L}}{dt}$$

$$\boldsymbol{\Gamma} = \frac{d\mathbf{L}_e}{dt} = -\frac{1}{\gamma_0} \frac{IP_i g \mu_B}{e} (m \wedge (m \wedge u_z))$$

Spin Transfer Torque

Number	Spin
$n = \mathrm{Re}\sum_{i\sigma} \psi_{i\sigma}^{*} \psi_{i\sigma}$	$\mathbf{m} = \mathrm{Re}\sum_{i\sigma\sigma'} \psi_{i\sigma}^{*} \left[\mathbf{s}_{\sigma,\sigma'} \right] \psi_{i\sigma'}$
	
$\mathbf{j} = \mathrm{Re}\sum_{i\sigma} \psi_{i\sigma}^{*} [\hat{\mathbf{v}}] \psi_{i\sigma}$	$\mathrm{J_S} = Re \sum_{i\sigma\sigma'} \psi_{i\sigma}^{*} \left[\mathrm{s}_{\sigma,\sigma'} \otimes \hat{\mathrm{v}} \right] \psi_{i\sigma}$
	
$\frac{\partial \mathrm{n}}{\partial \mathrm{t}} = -\mathrm{j}$	$\frac{\partial \mathbf{m}}{\partial \mathrm{t}} = -\mathrm{J_S}$

$$\frac{\partial \mathbf{m}}{\partial \mathrm{t}} = -\mathrm{J_S} + \mathbf{m} \times \mathbf{B}_{\mathrm{eff}} + \mathrm{damping}$$

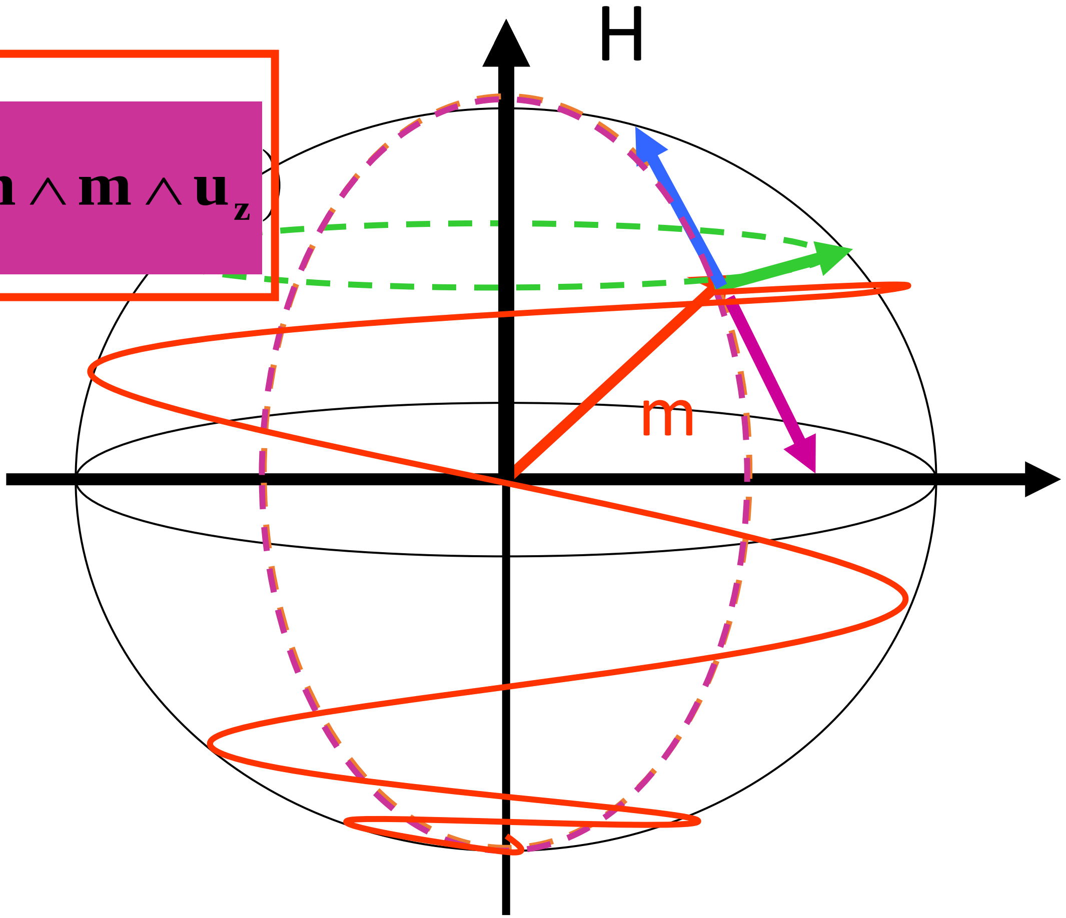
Magnetisation Dynamic : LLG

Field torque (precession)

Spin torque (negative friction)

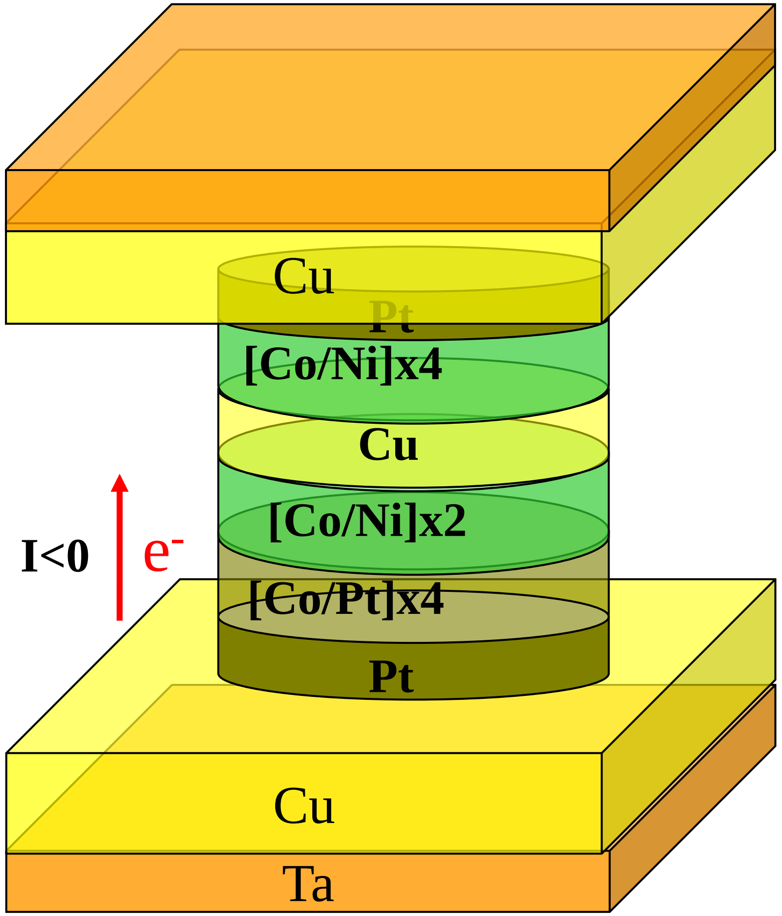
$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \wedge \mathbf{H} + \alpha \left(\mathbf{m} \wedge \frac{d\mathbf{m}}{dt} \right) + \beta\, \mathbf{I} \left(\mathbf{m} \wedge \mathbf{m} \wedge \mathbf{u_z} \right)$$

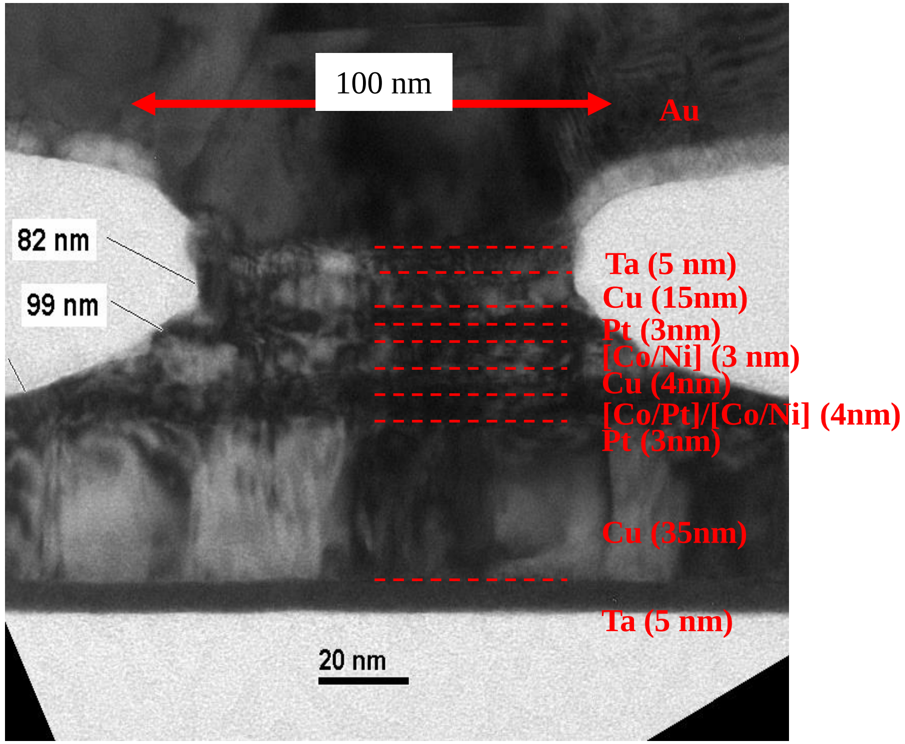
Damping torque (dissipation)



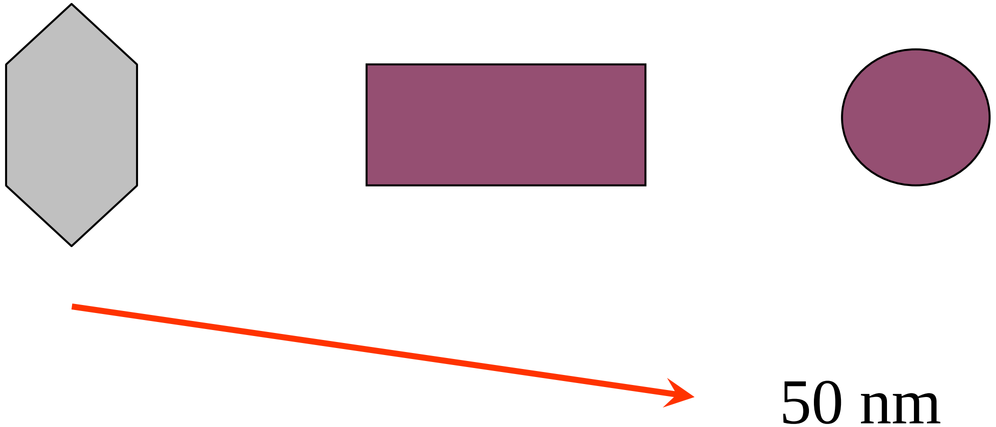
Description is valid at equilibrium:
Amplitude of M is a Cst / long time scale t > 100ps)

Nanopillars



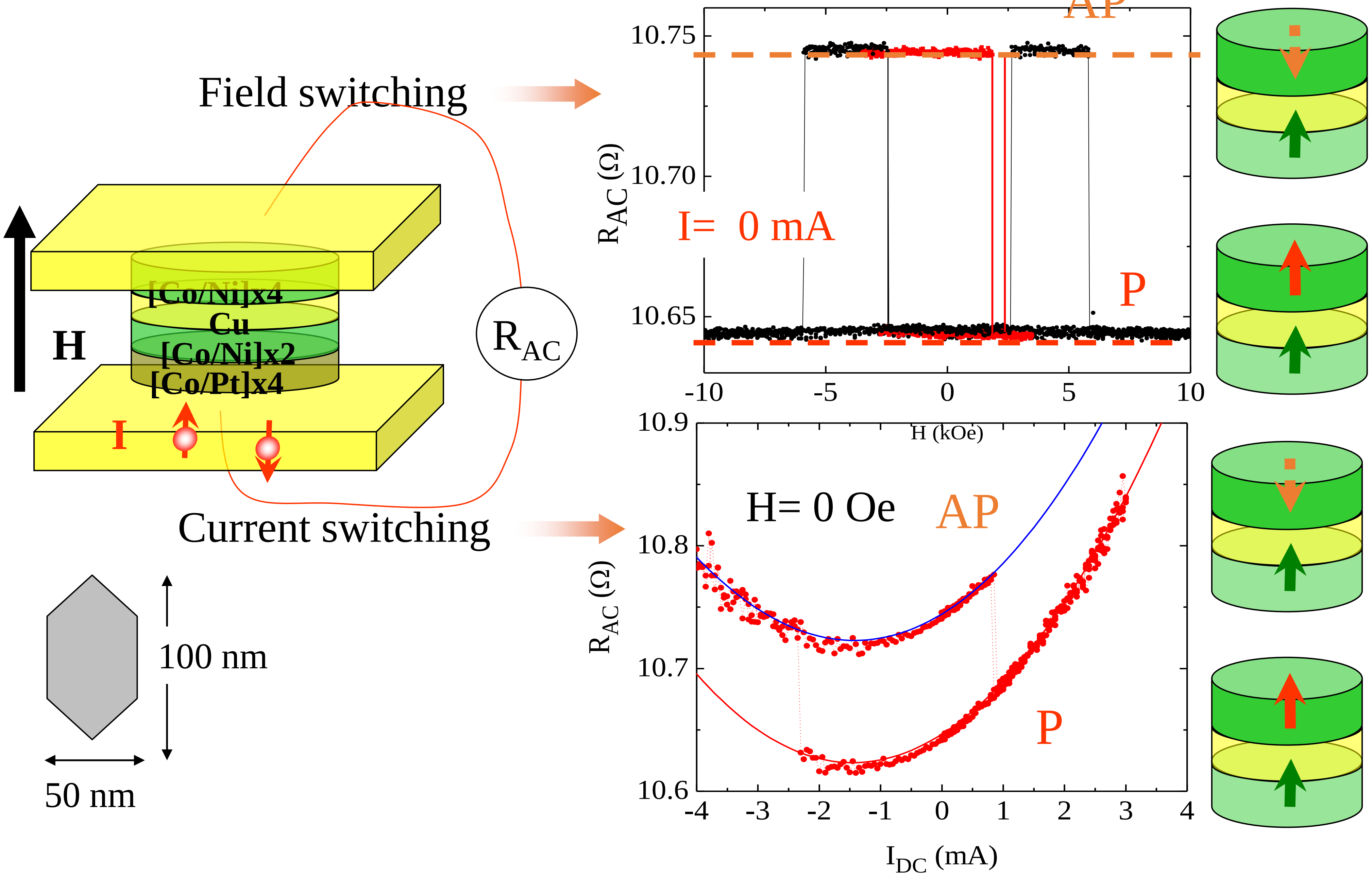


5 µm

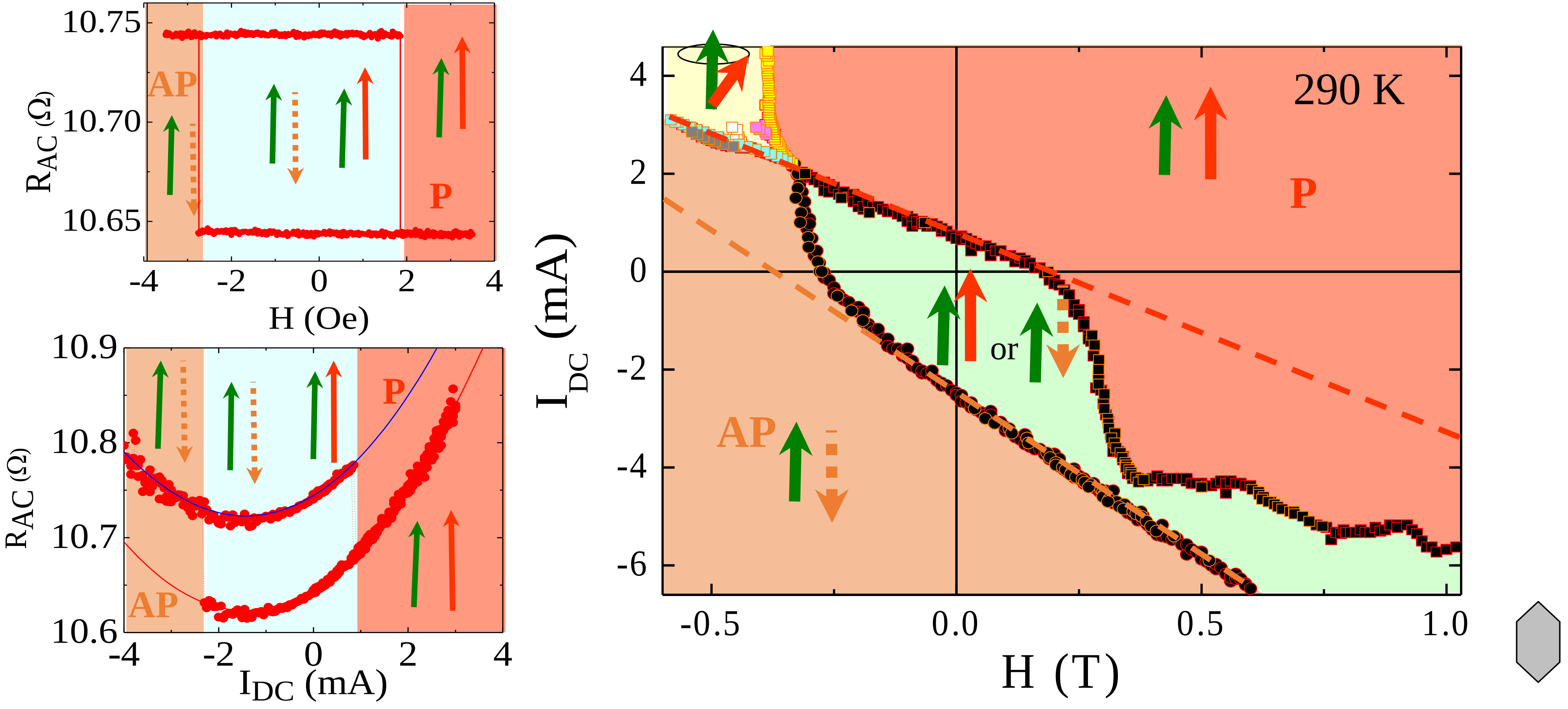


50 nm

Magnetization switching



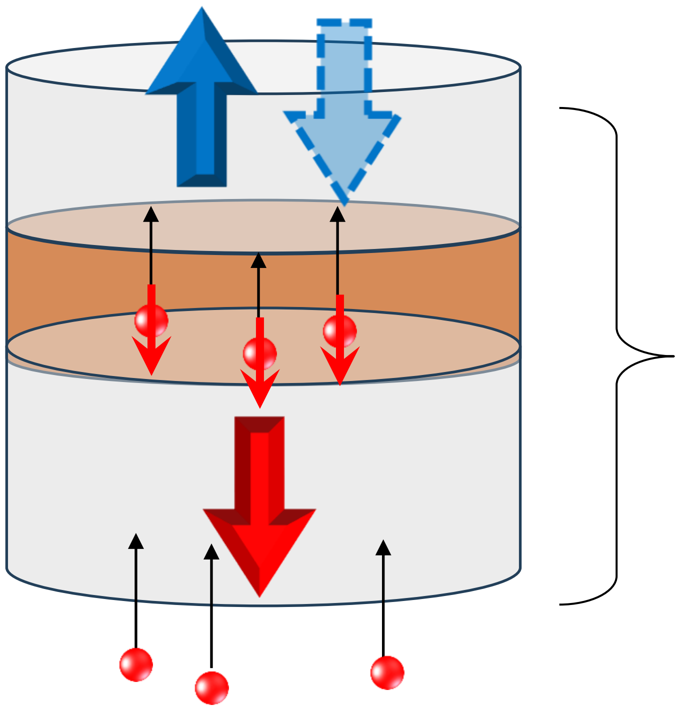
Model system



S. Mangin et al Nat. Mat. ***5*** *210 (2006)*

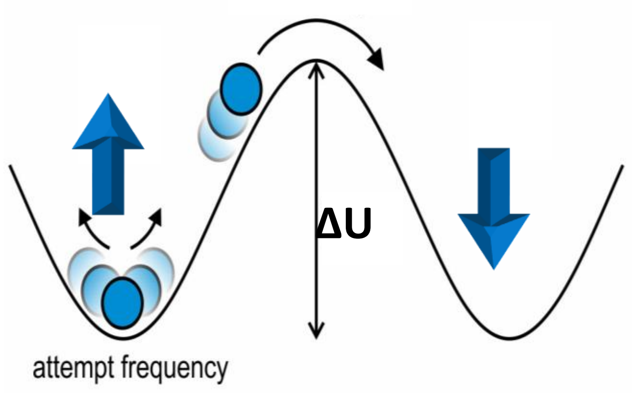
Current induced switching

LLG $$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \wedge \mathbf{H}_{eff} + \alpha(\mathbf{m} \wedge \mathbf{m} \wedge \mathbf{H}_{eff}) + \beta\, \mathbf{I}(\mathbf{m} \wedge \mathbf{m} \wedge \mathbf{u}_z)$$ m = cst



$$I_{SW} = \frac{\alpha\gamma}{\beta} H_{eff}$$

$$I_{SW} = \left(\frac{2e}{\hbar}\right) \frac{\alpha M_S V}{g(\theta)p} (H_{eff})$$



- For application

High efficiency → Low current

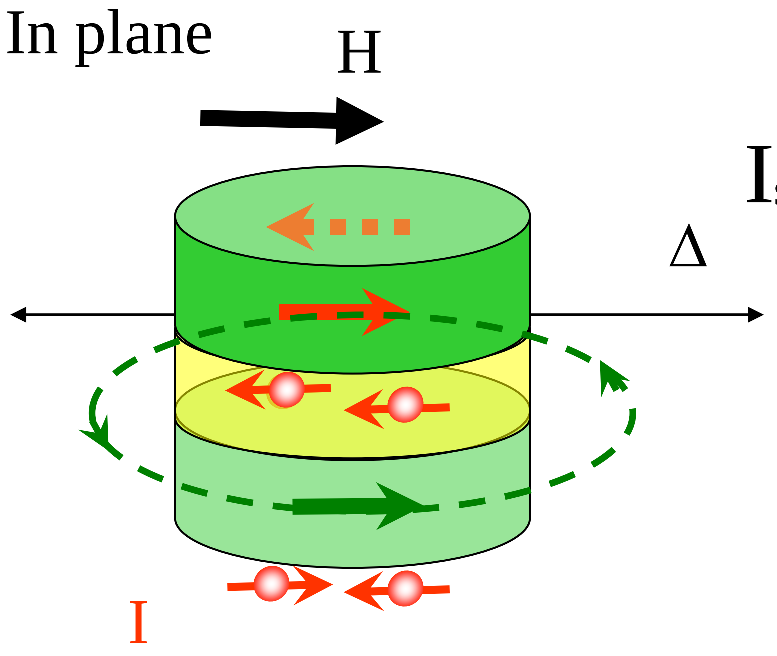
Thermal Stability → High energy Barrier

$$U_K \geq 50 k_B T$$

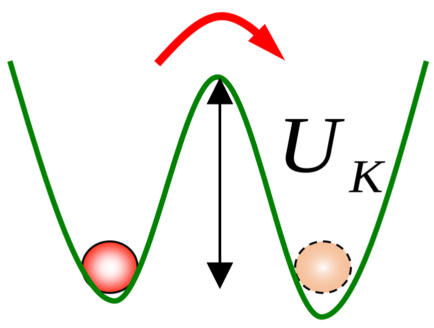
J. Z. Sun, IBM J. Res. & Dev. 50, 81 (2006)

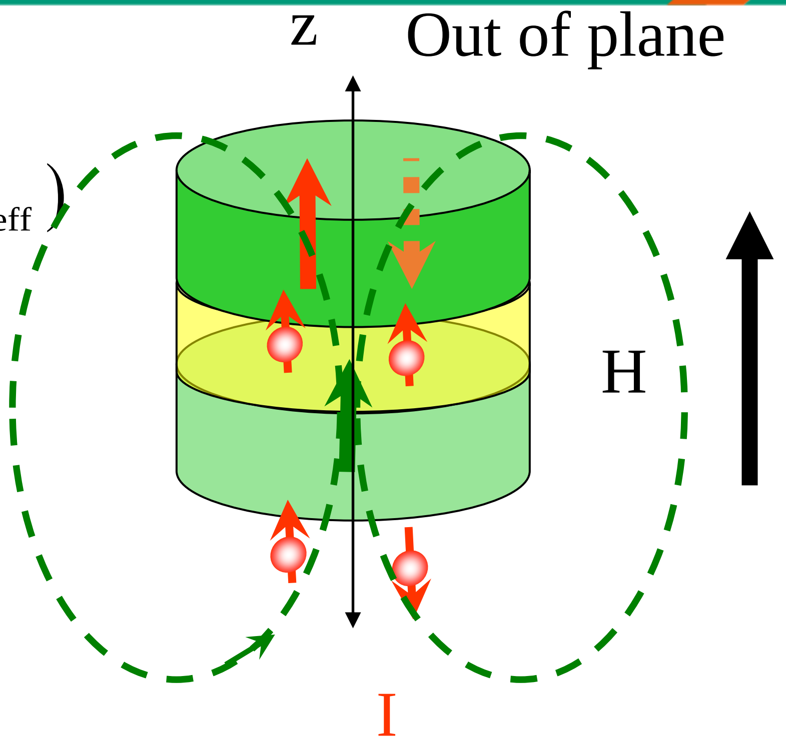
D. Chiba et al Phys. Rev. Lett. 93, 216602 (2004)

Perpendicular = Efficiency + Stability



$$I_{SW} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\theta)p}(H_{eff})$$

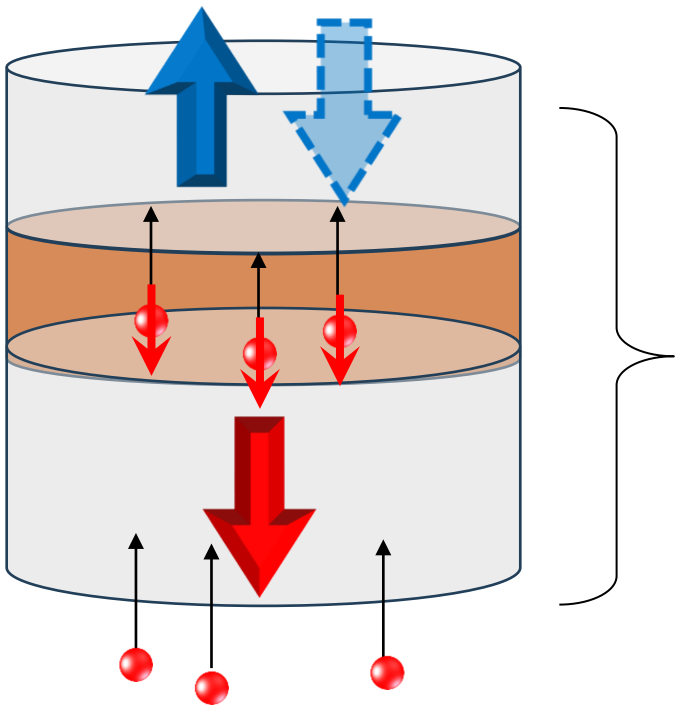




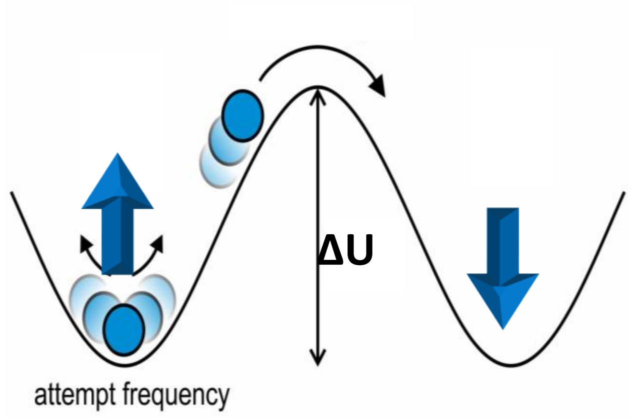
$H_{eff}^{P\rightarrow AP}$	$H + H_{dip} + H_{K//} + 2\pi M_S$	$H + H_{dip} + (H_{K\perp} - 4\pi M_S)$
U_K	$(M_s V H_{K//})/2$	$(M_s V(H_{K\perp} - 4\pi M_S))/2$
$\lvert I_{SW}\rvert$	$\left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}\left(U_K + \pi M_S{}^2 V\right)$	$\left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}(U_K)$

Current induced switching

LLG $$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m}\wedge\mathbf{H}_{eff} + \alpha\left(\mathbf{m}\wedge\mathbf{m}\wedge\mathbf{H}_{eff}\right) + \beta\,\mathbf{I}\left(\mathbf{m}\wedge\mathbf{m}\wedge\mathbf{u}_z\right)$$ m = cst



$$I_{SW} = \frac{\alpha\gamma}{\beta} H_{eff}$$



For PMA system $$I_0 = \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}(\Delta U)$$

J. Z. Sun, IBM J. Res. & Dev. 50, 81 (2006)

S. Mangin et al Nature materials 5 (3), 210-215 (2006)

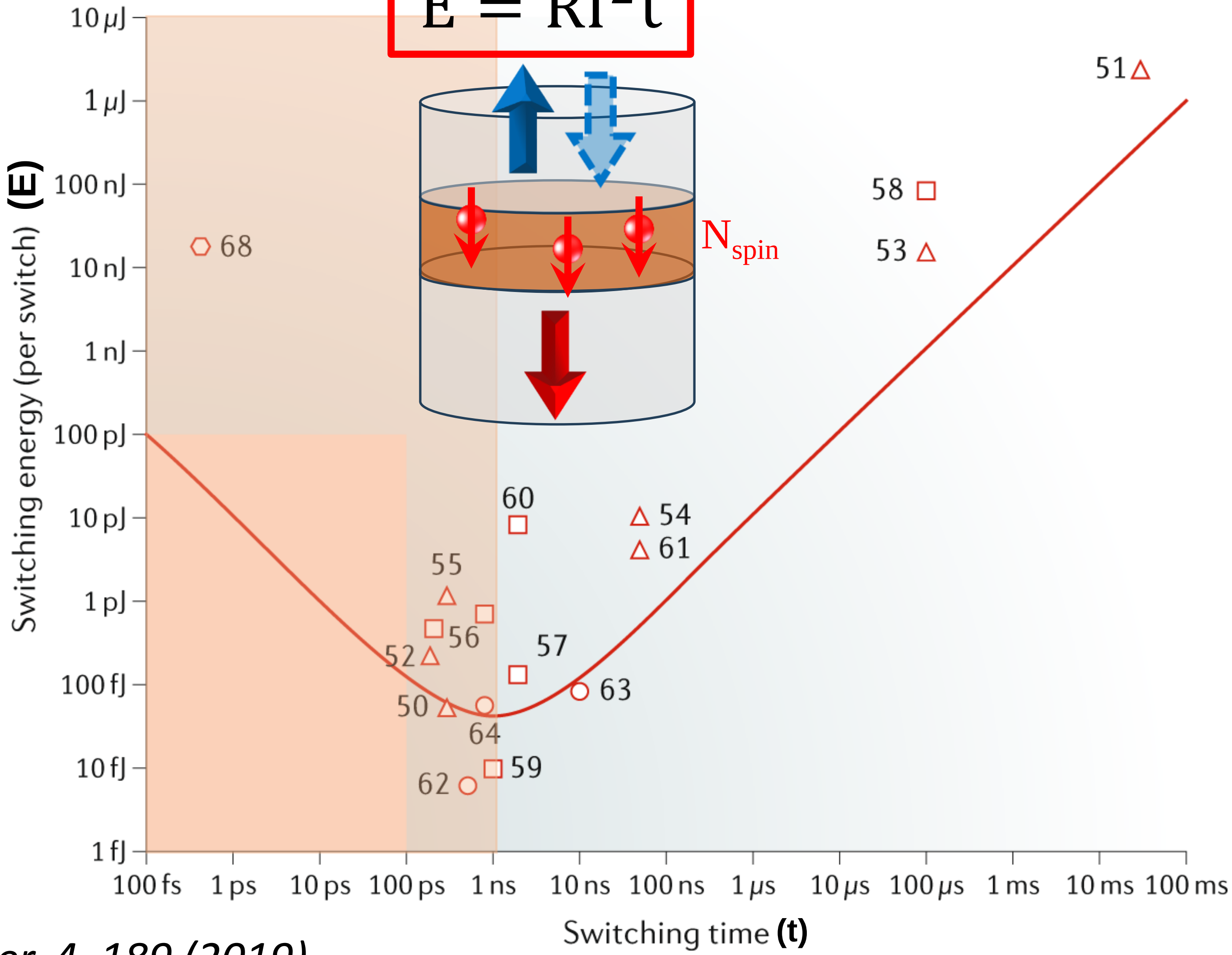
S. Mangin et al Appl. Phys. Lett ***94*** *012502 (2009)*

Current induced switching

$$E = RI^2t$$

$$1/\tau = \alpha\,(I - I_0)$$

$$I_0 = \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}(\Delta U)$$



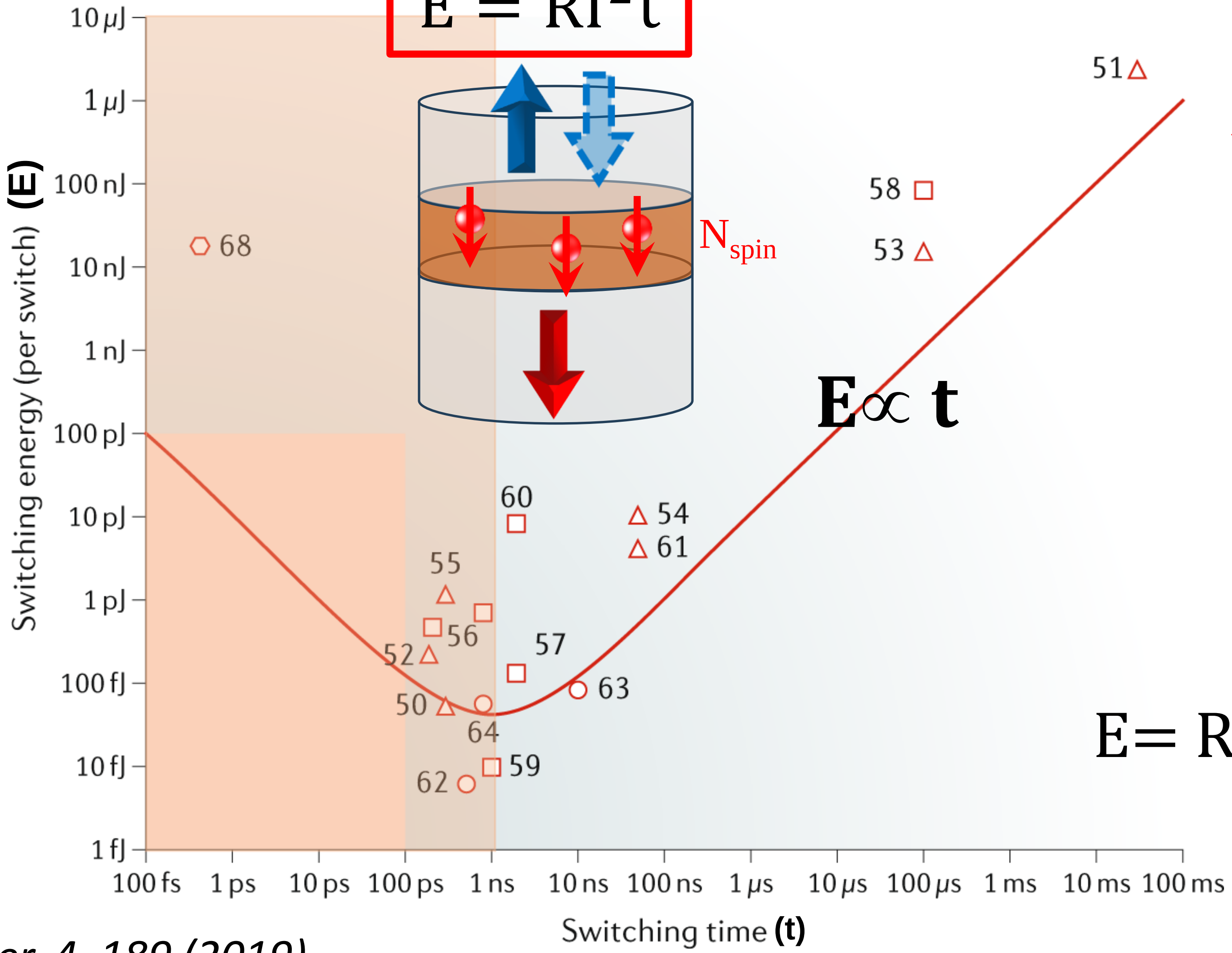
A.V. Kimel et al Nat. Rev. Mater. 4, 189 (2019)

K. Garrelo Appl. Phys. Lett. 105, 212402 (2014)

H.Liu et al JMMM 358 233-258 (2014)

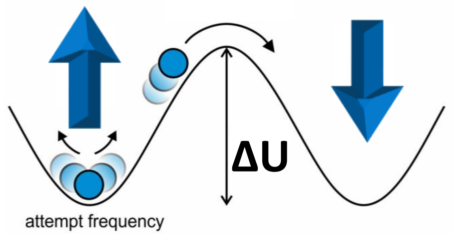
Current induced switching

$$E = RI^2t$$



$$1/\tau = \alpha\,(I - I_0)$$

$$I_0 = \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}(\Delta U)$$



$$I_0 \propto \Delta U$$

$$E = RI_0^2t = A\,R\,\Delta U^2 t$$

A.V. Kimel et al Nat. Rev. Mater. 4, 189 (2019)

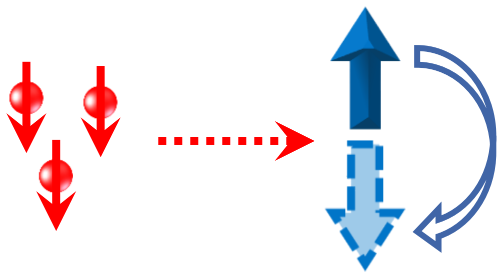
K. Garrelo Appl. Phys. Lett. 105, 212402 (2014)

H.Liu et al JMMM 358 233-258 (2014)

Current induced switching

Angular momentum conservation

$N_{spin} > \Delta M = 2M$



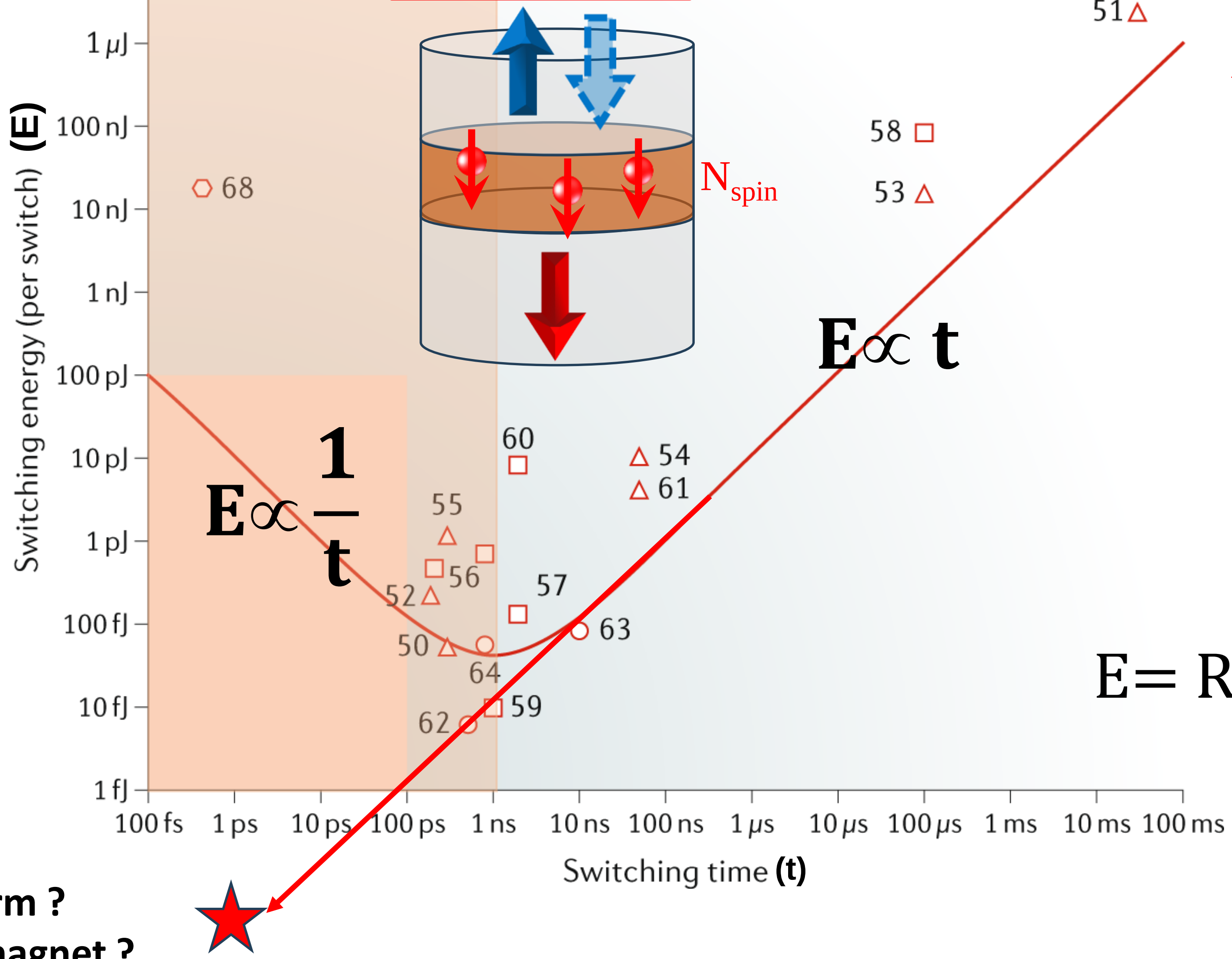
$$I = \alpha \frac{N_{spin}\, e^-}{t}$$

$$E = \alpha \frac{R N_{spin}^2}{t}$$

Need to reduce ΔM ?

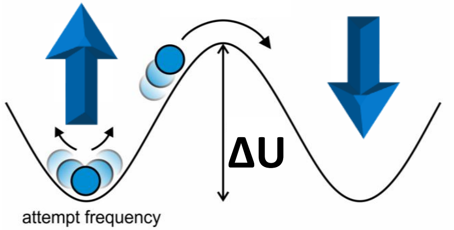
- **Non uniform ?**
- **Antiferromagnet ?**
- **Out of equilibrium ?**

$$E = RI^2t$$



$1/\tau = \alpha\ (I - I_0)$

$$I_0 = \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}(\Delta U)$$



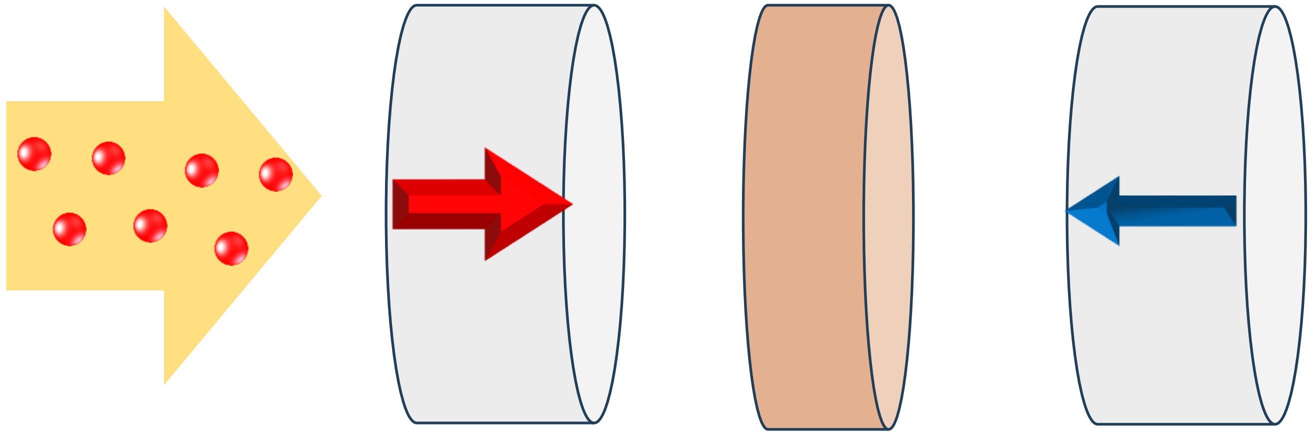
$I_0 \propto \Delta U$

$E = RI_0^2 t = A\, R\, \Delta U^2 t$

Current induced switching

Spin Transfer Torque

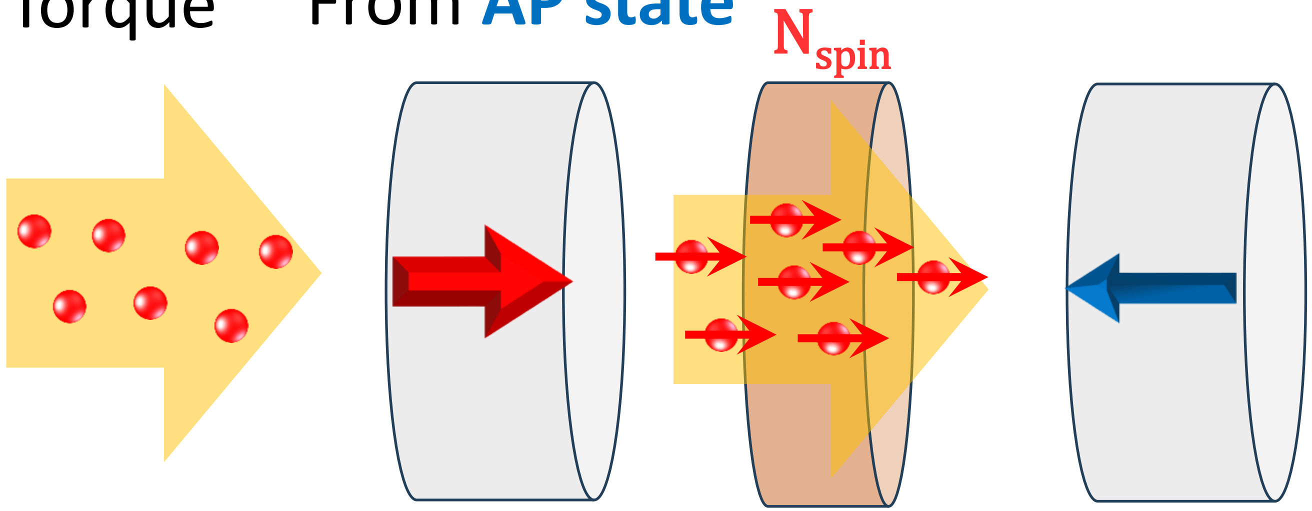
From **AP state**



Current induced switching

Spin Transfer Torque

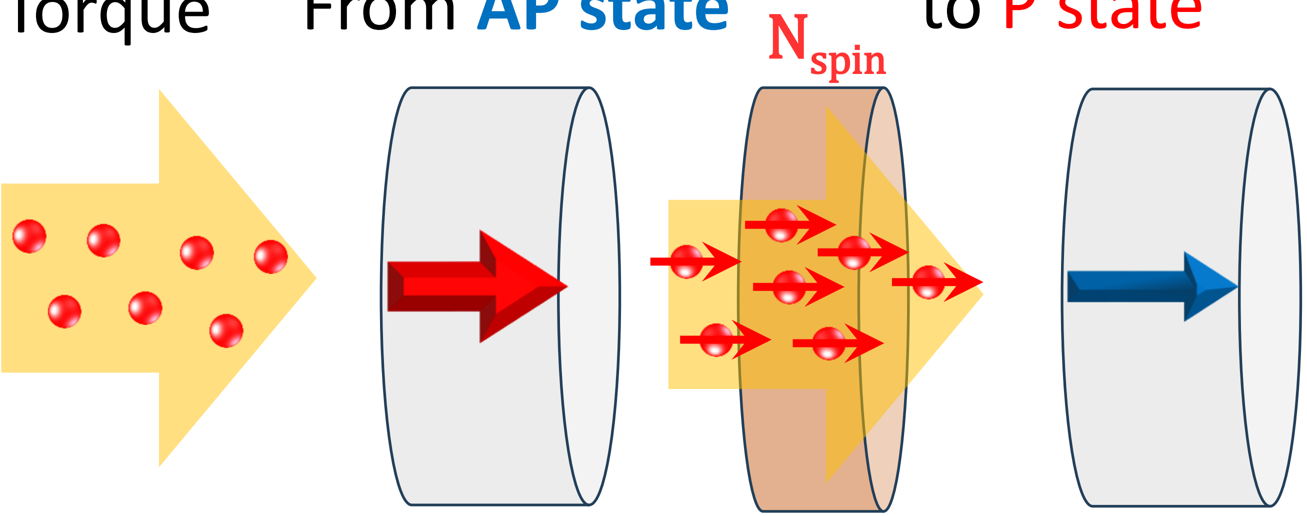
From **AP state**



Current induced switching

Spin Transfer Torque

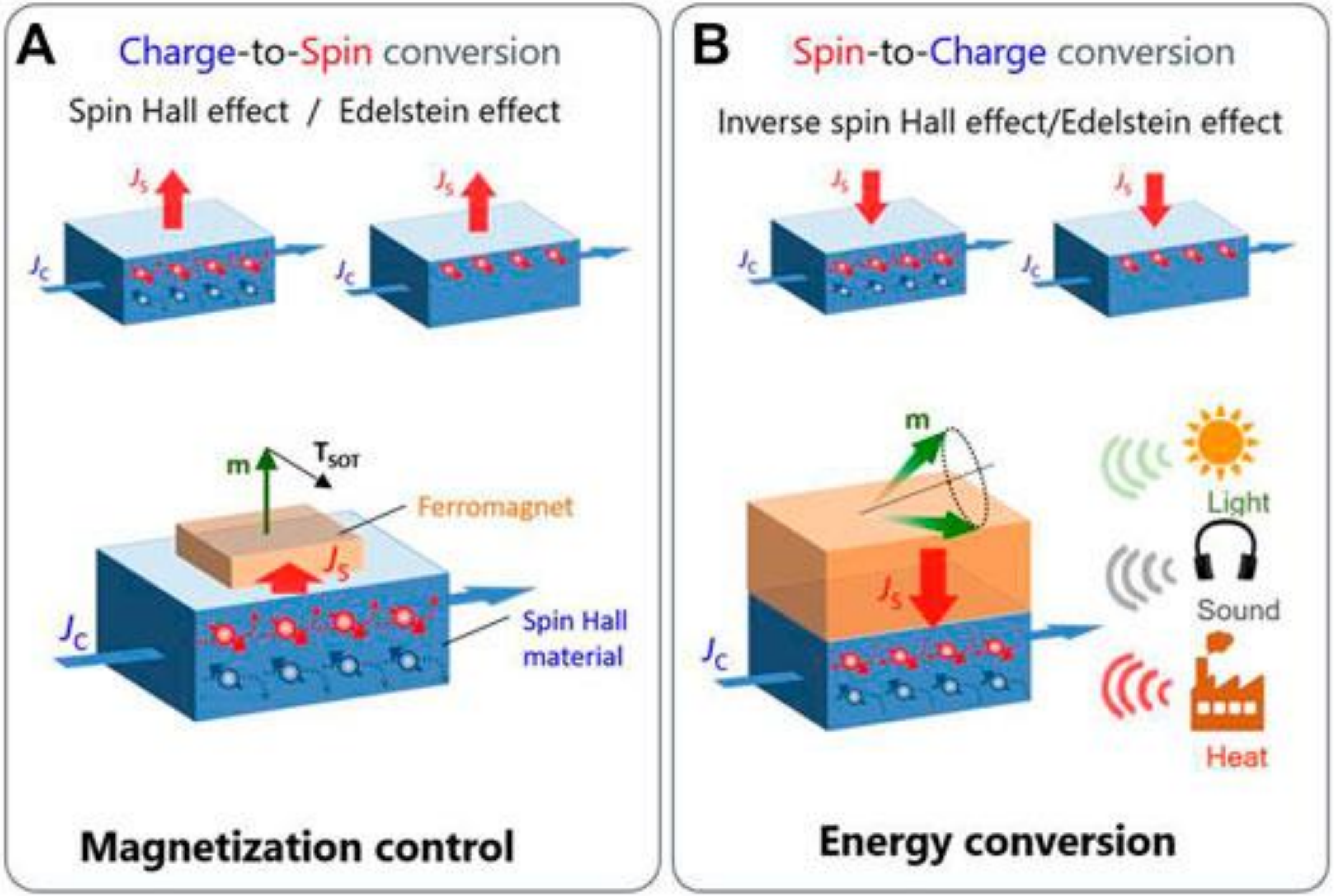
From **AP state** to P state



Criteria:

$N_{spin} > \Delta M = 2M$

Charge to spin / Spin to charge

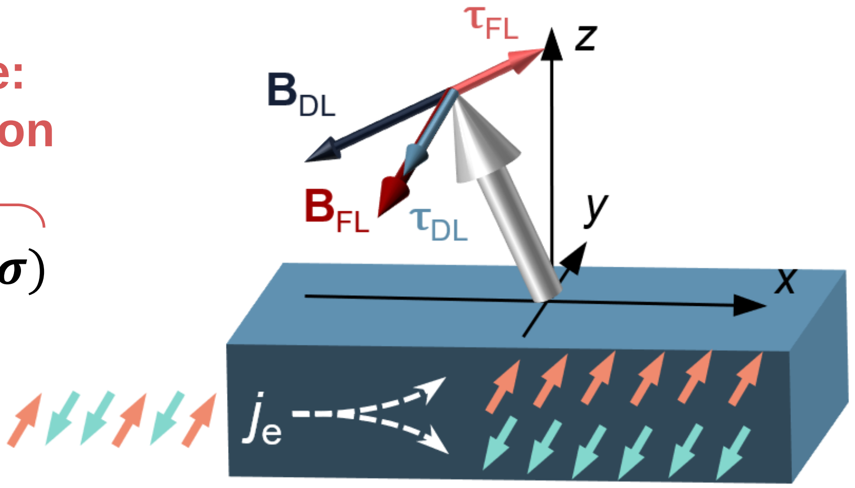


K. Kondou & Y. Otani Front. Phys., 23 March 2023

Macrospin model of SOT-induced magnetization dynamics

Damping-like: reversal **Field-like: precession**

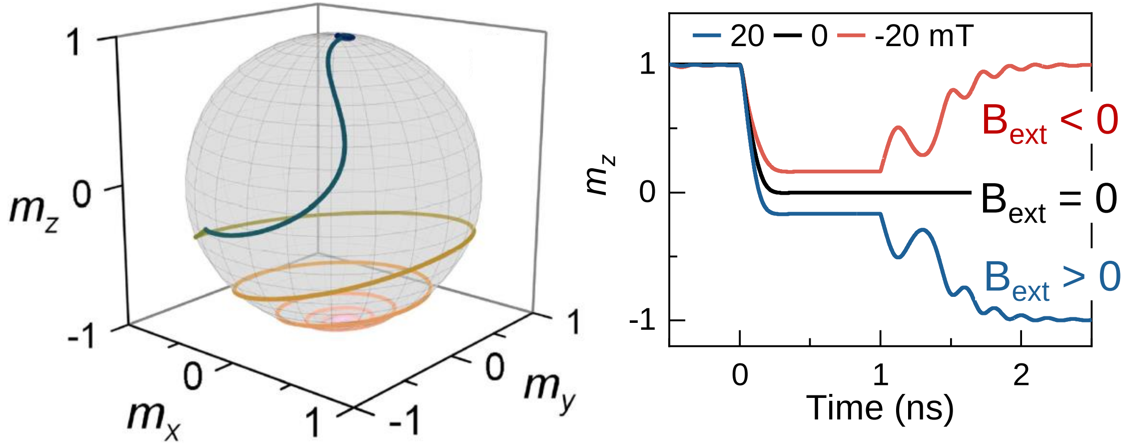
Spin-orbit torque: $\boldsymbol{\Gamma} = \tau_{\mathrm{DL}} \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{\sigma}) + \tau_{\mathrm{FL}} (\boldsymbol{m} \times \boldsymbol{\sigma})$



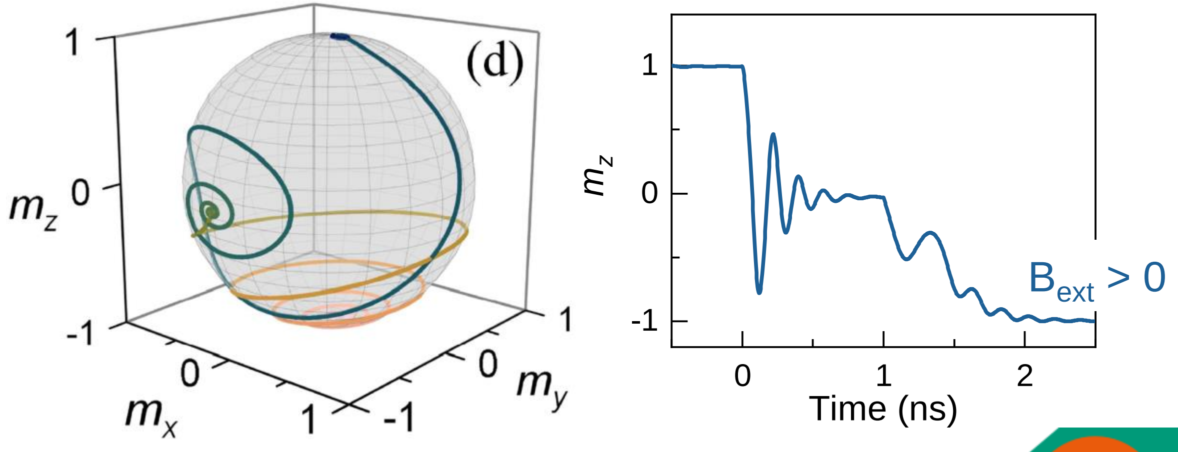
symmetry breaking

B_{ext}

Dampinglike torque + Longitudinal mag. field

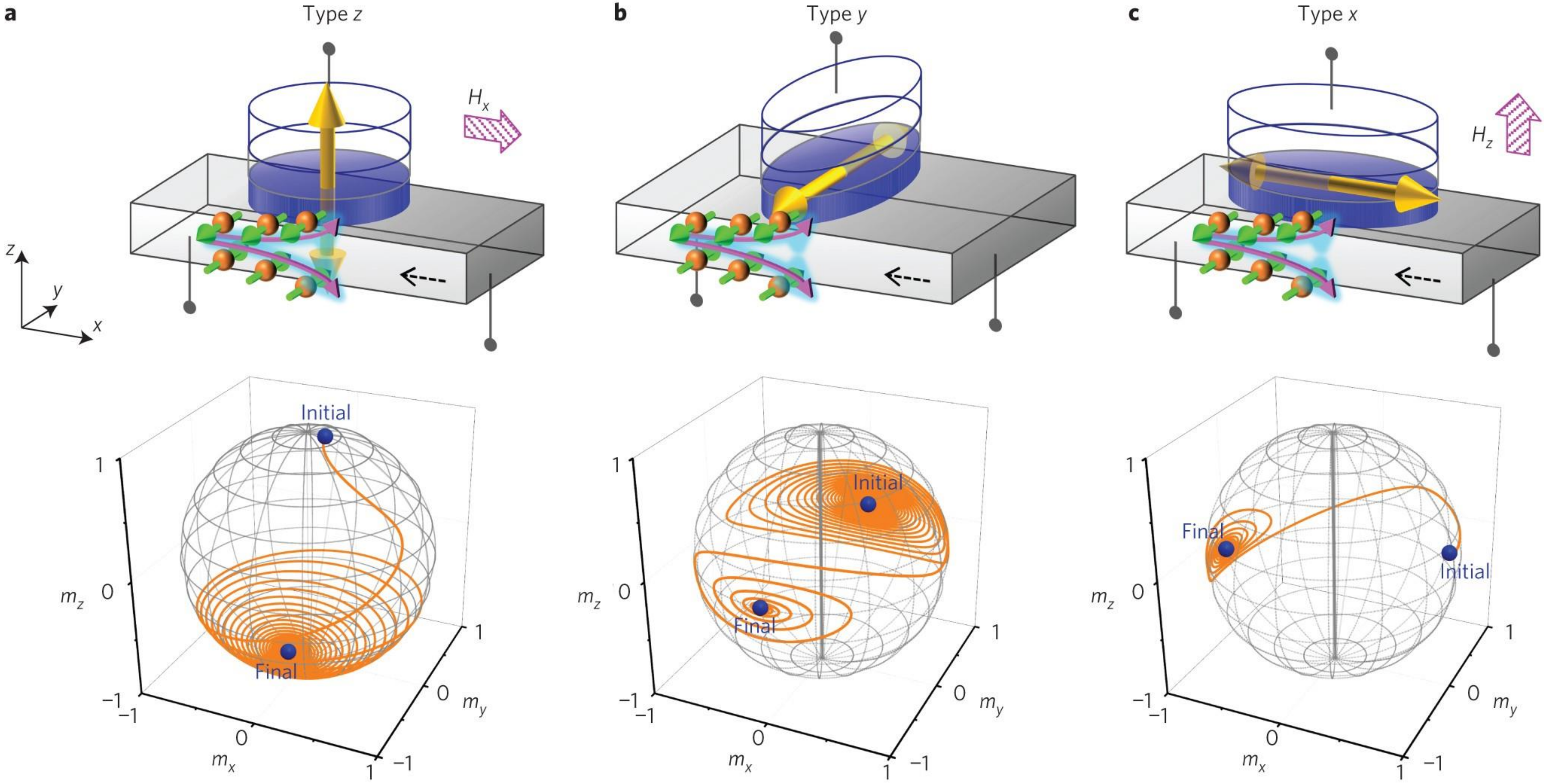


+ Fieldlike torque



Krizakova, PG et al., *J. Magn. Magn. Mater.* **562**, 169692 (2022)

Spin Orbit Torque vs geometries



S. Fukami, *Nature Nanotech* **11**, 621–625 (2016).

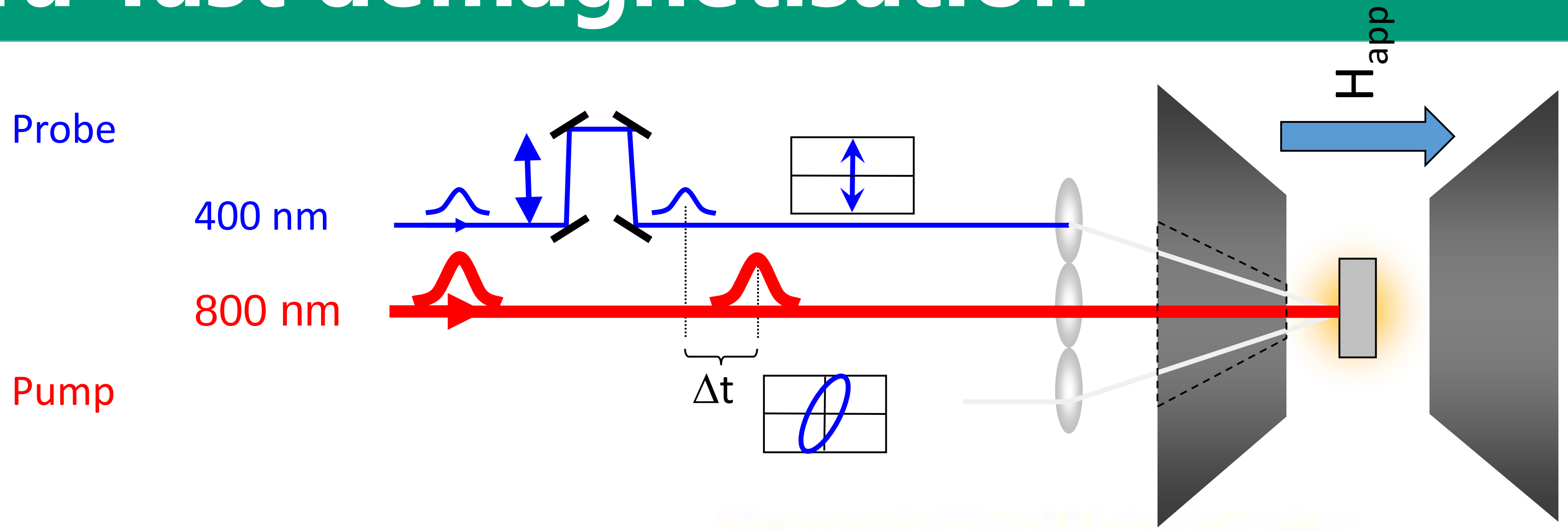
Outlines

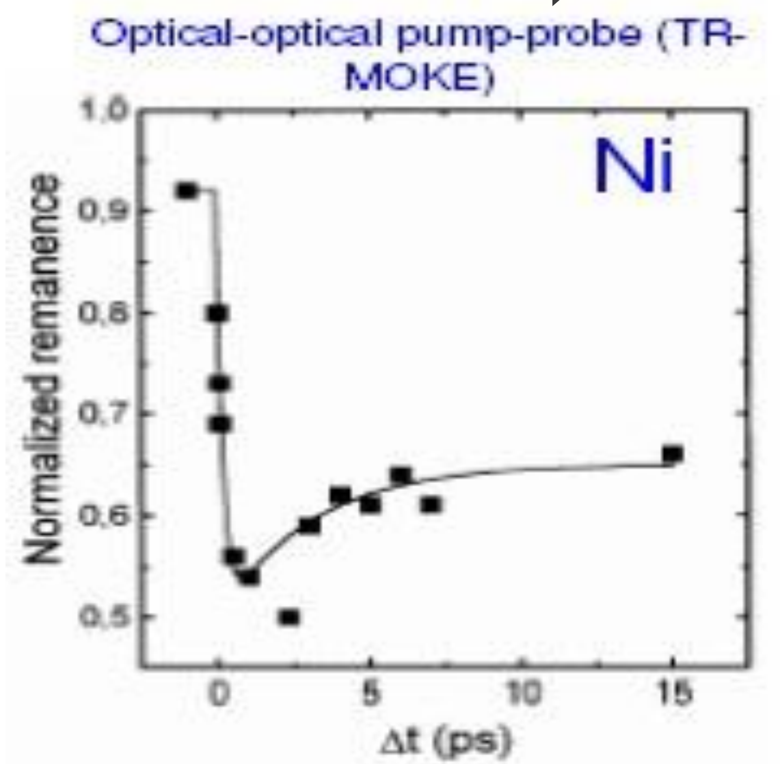
- Magnetisation field switching
    - Energy
    - Torques

- Current induced switching
    - Spin tranfer Torque
    - Spin Orbit Torque

- All optical switching

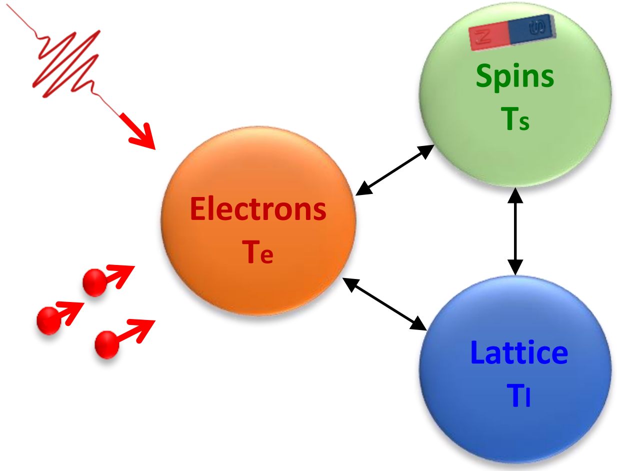
Ultra-fast demagnetisation



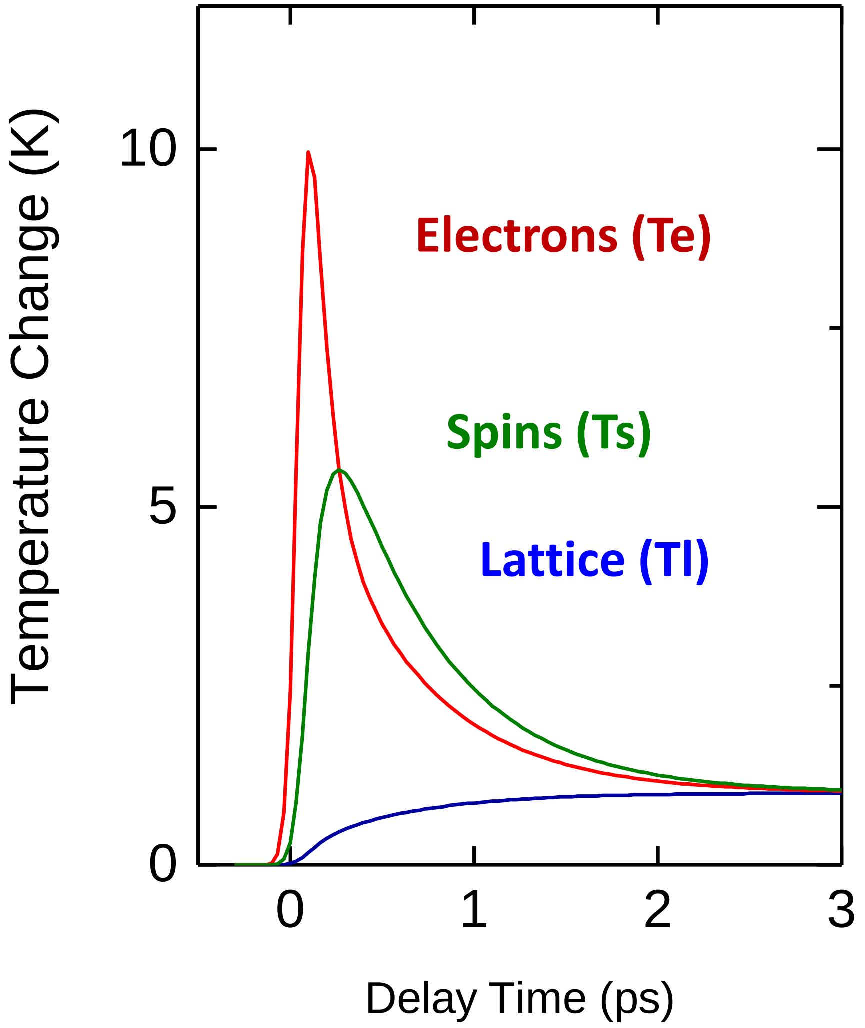


E. Beaurepaire, et al Phys. Rev. Lett. 76, 4250 (1996)

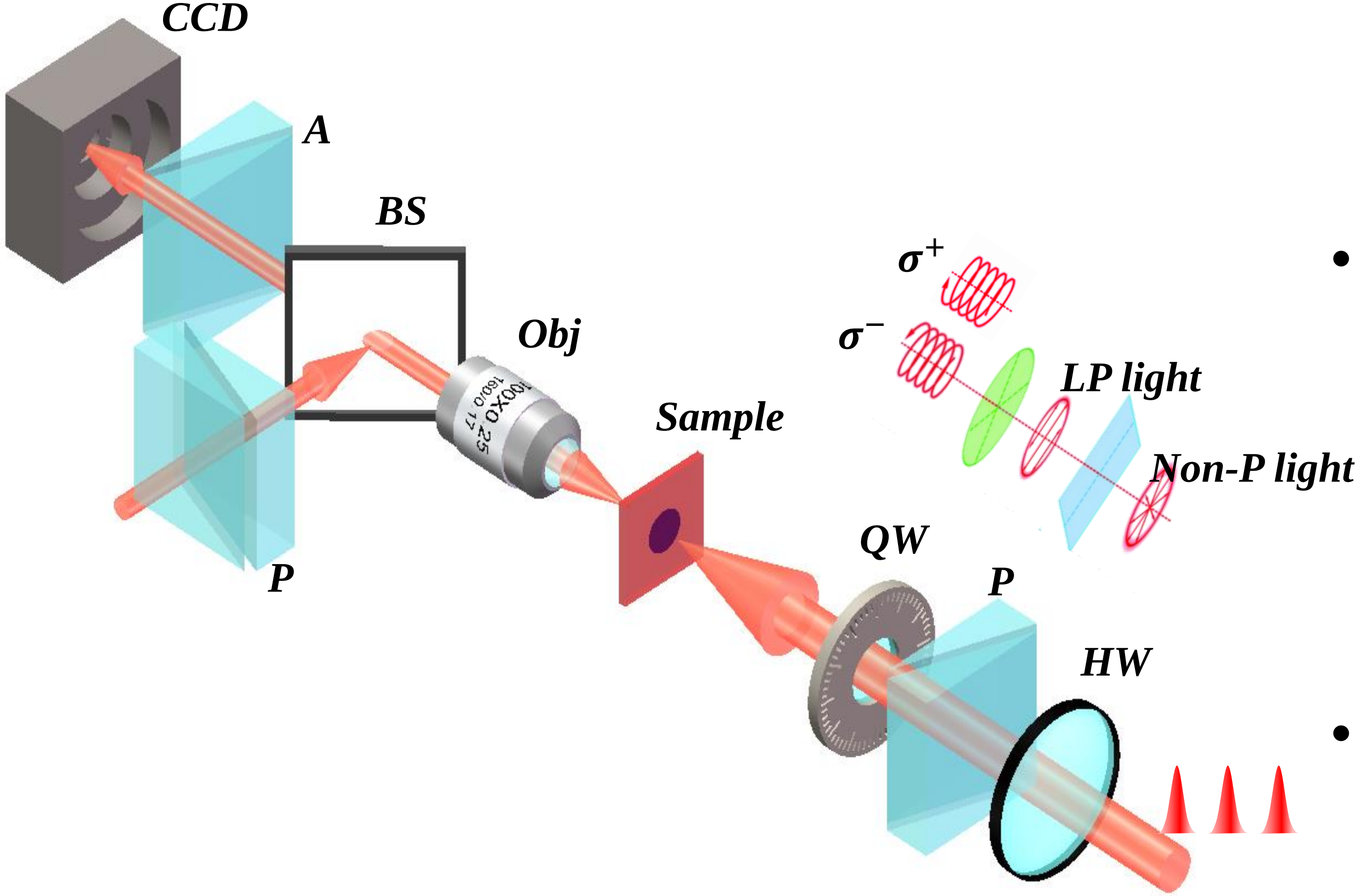
Ultra-fast magnetism



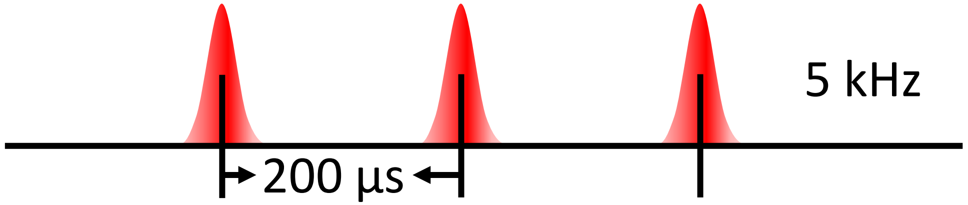
- Energy Transfer
- Angular Momentum Transfer
- Charge / Spin Current Transfer



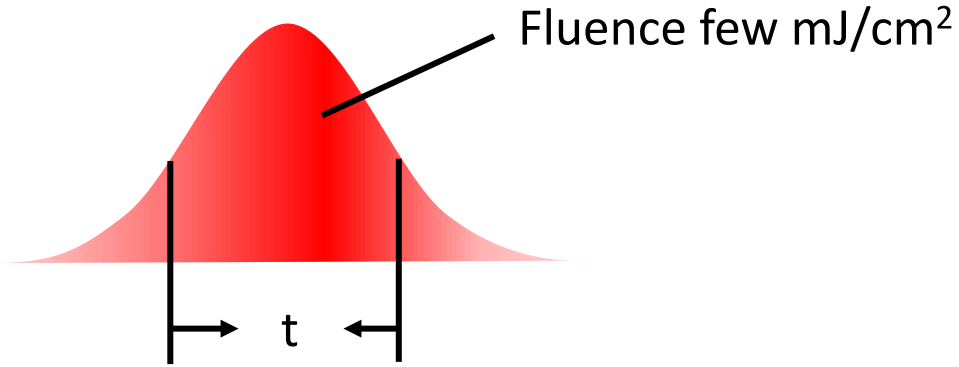
Femto second laser



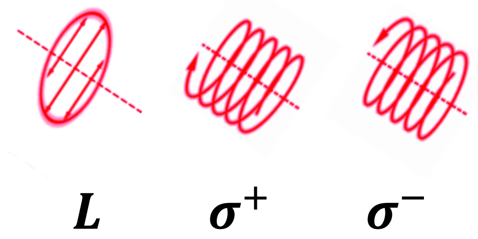
- **Pulse number / repetition rate**



- **Pulse duration / Laser Fluence**

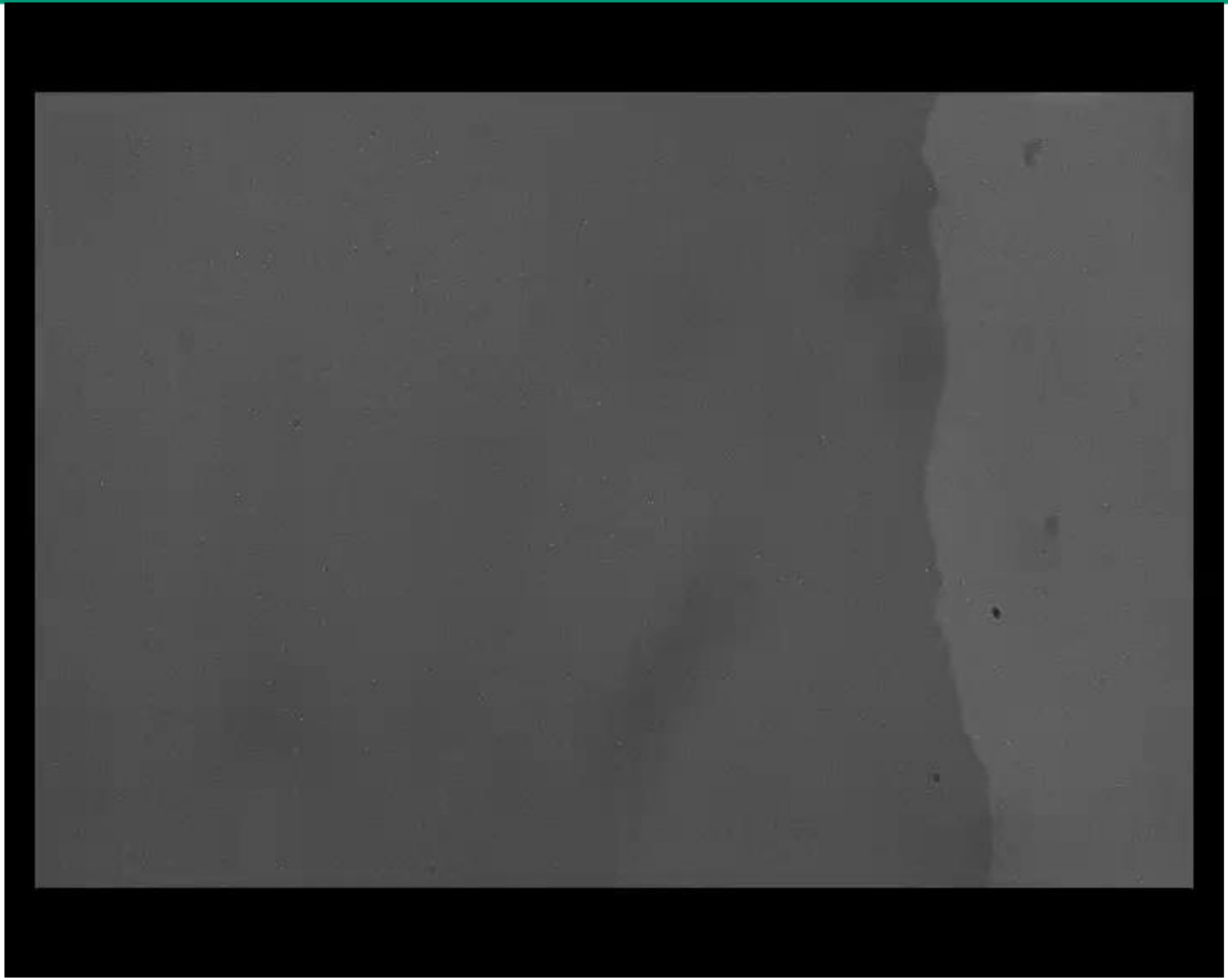


- **Light Helicity**

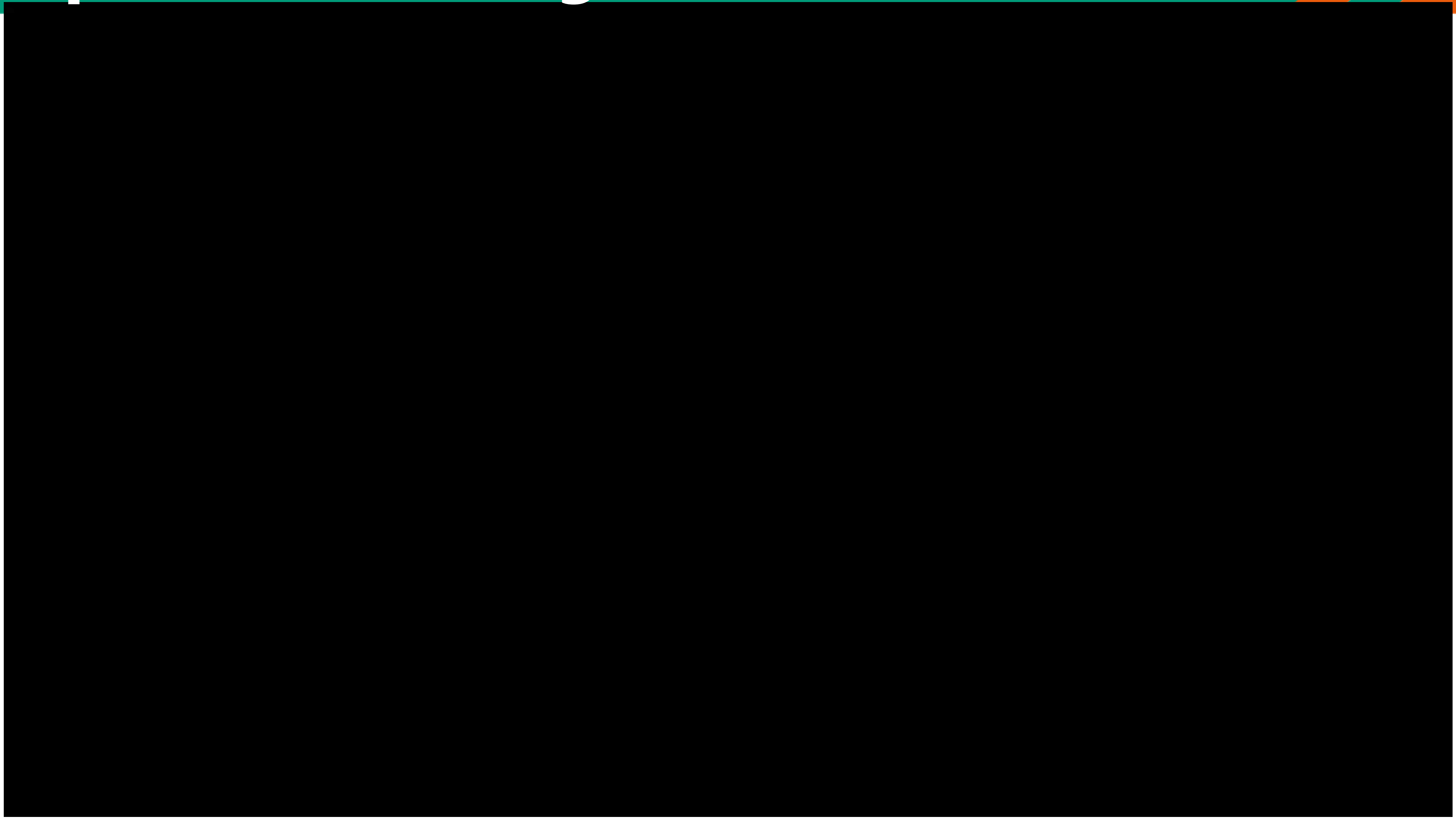


Pulse diameter around 100 μm

All optical switching

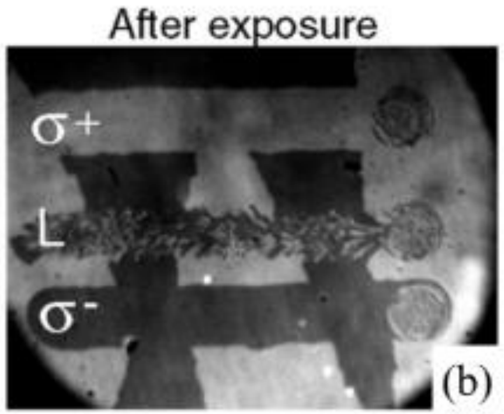


All optical switching



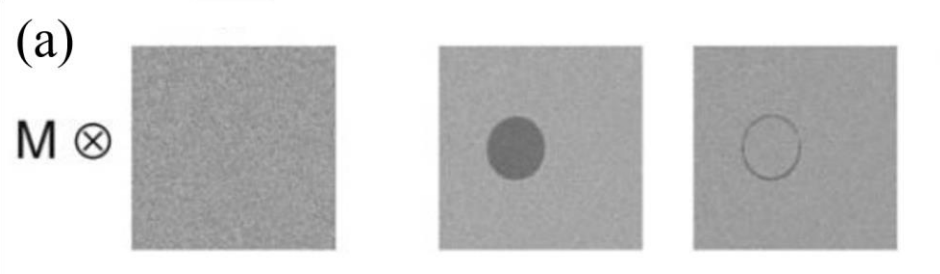
3 types of All Optical Switching

All Optical –
Helicity dependent switching



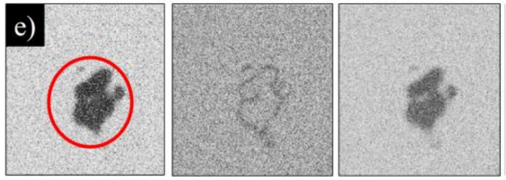
Stanciu, C. D. et al. Phys. Rev. Lett. ***99****, 047601 (2007).*

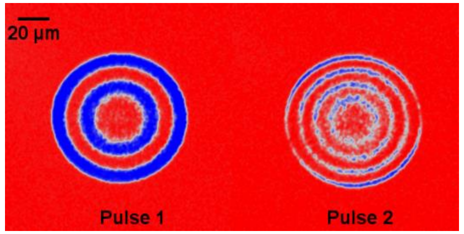
All Optical –
Helicity Independent switching



Radu, I. et al. Nature ***472****, 205–208 (2011).*

All Optical –
Precessional switching





Avilés-Félix, L. et al. Sci Rep ***10****, 5211 (2020).*

AO-HDS

- Switching given by light helicity
- Multiple pulses
- Ferro-, Ferri-magnets…

AO-HIS

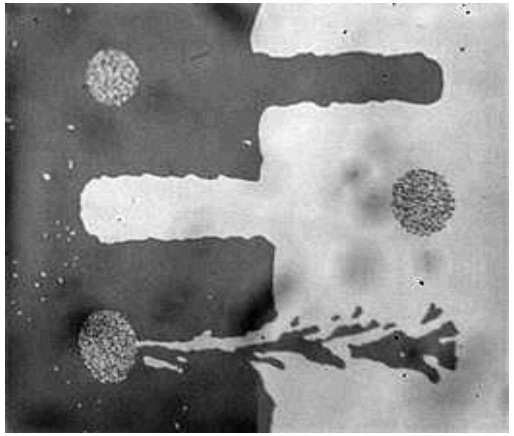
- Switching given by initial state
- Ultra-fast single pulse
- Gd Based + MnRuGa close to compensation

AO-PS

- Single pulse
- Inplane re-orientation
- Heterostructure

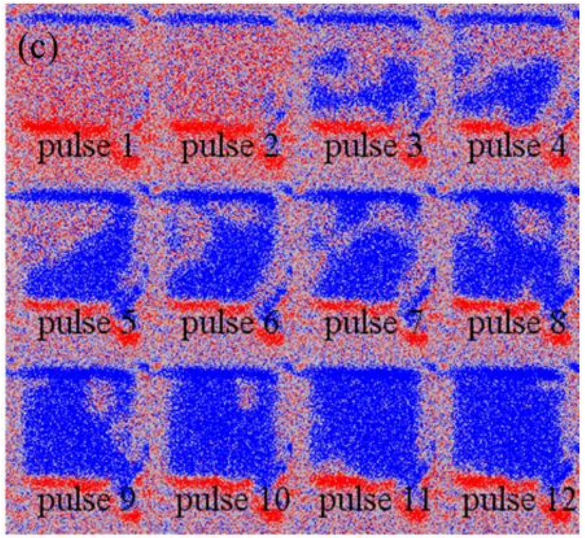
All Optical – Helicity dependent switching

Characteristics

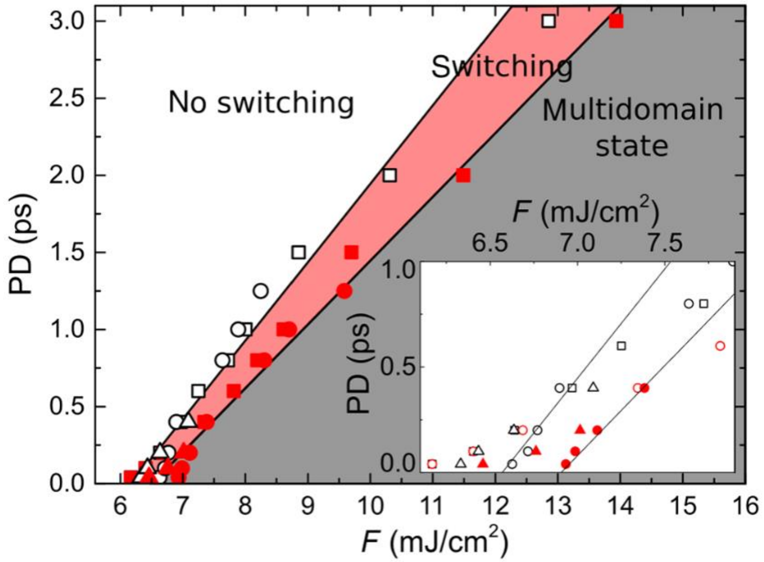


All types of materials

➡ Ferrimagnetic alloys, Multilayers
➡ Ferromagnet Co/Pt , Co/Ni
➡ Granular Media



Multiple pulses



Characteristic State diagram

S. Mangin et al., Nat. Mater. 13, 286-292 (2014)

*C.H. Lambert et al Science **345** (6202), 1337 (2014)*

J-W Liao et al, Advanced Science. 6, 1901876 (2019)

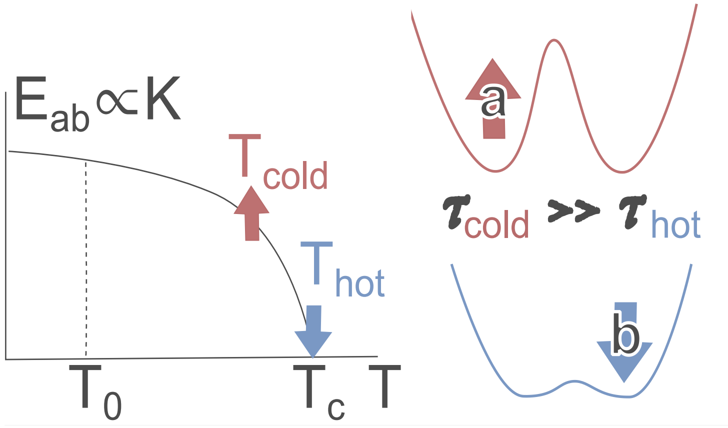
Huang , T et al. Physical Review B 111 (14), 144408 (2025)

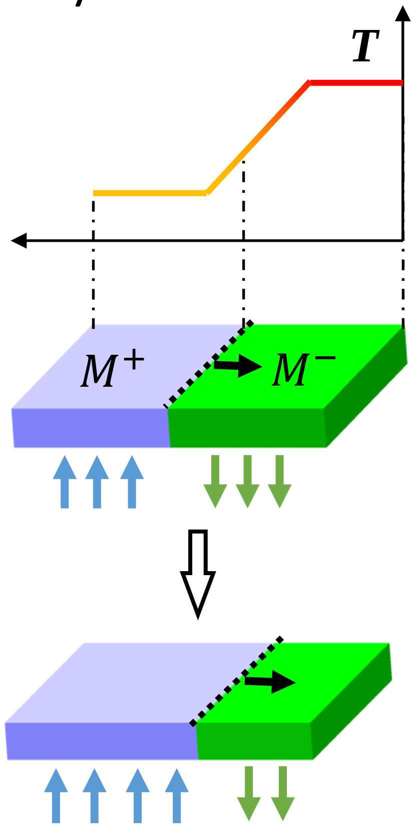
Kichin, G. et al.
*Phys. Rev. Applied **12**, 024019 (2019).*

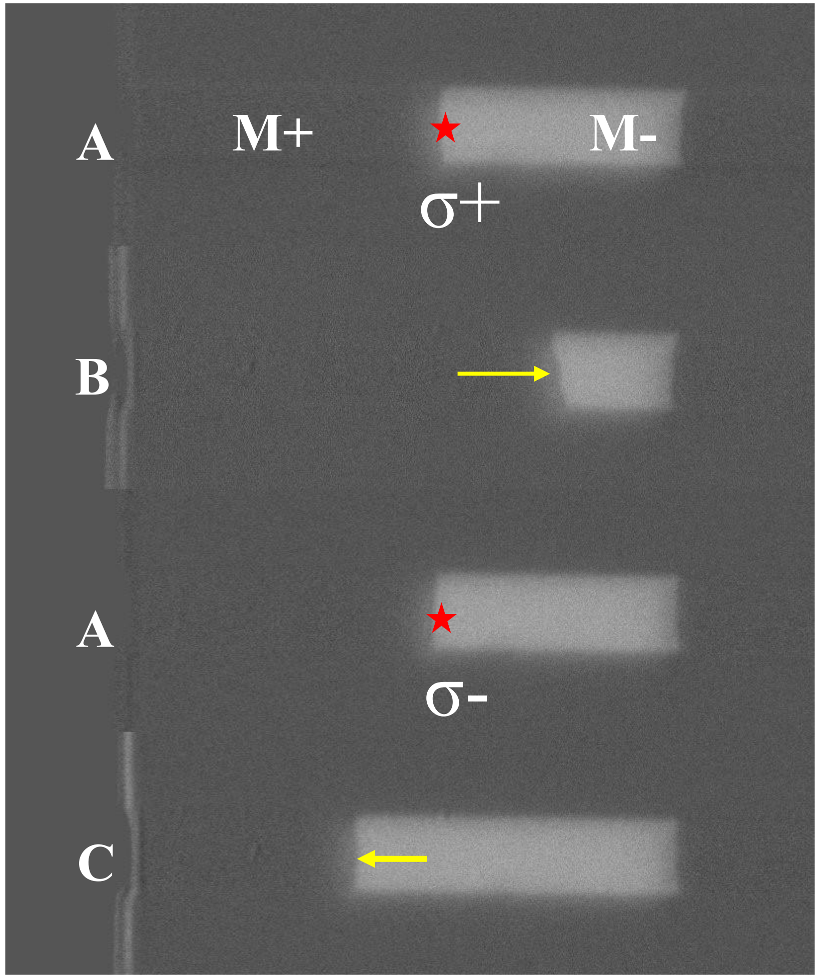
All Optical – Helicity dependent switching

Mechanism

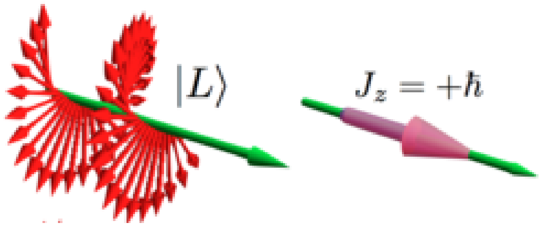
MCD Helicity dependence
Absorption asymmetry / heating Asymmetry







Inverse Faraday Effect : Angular Mt transfer ?



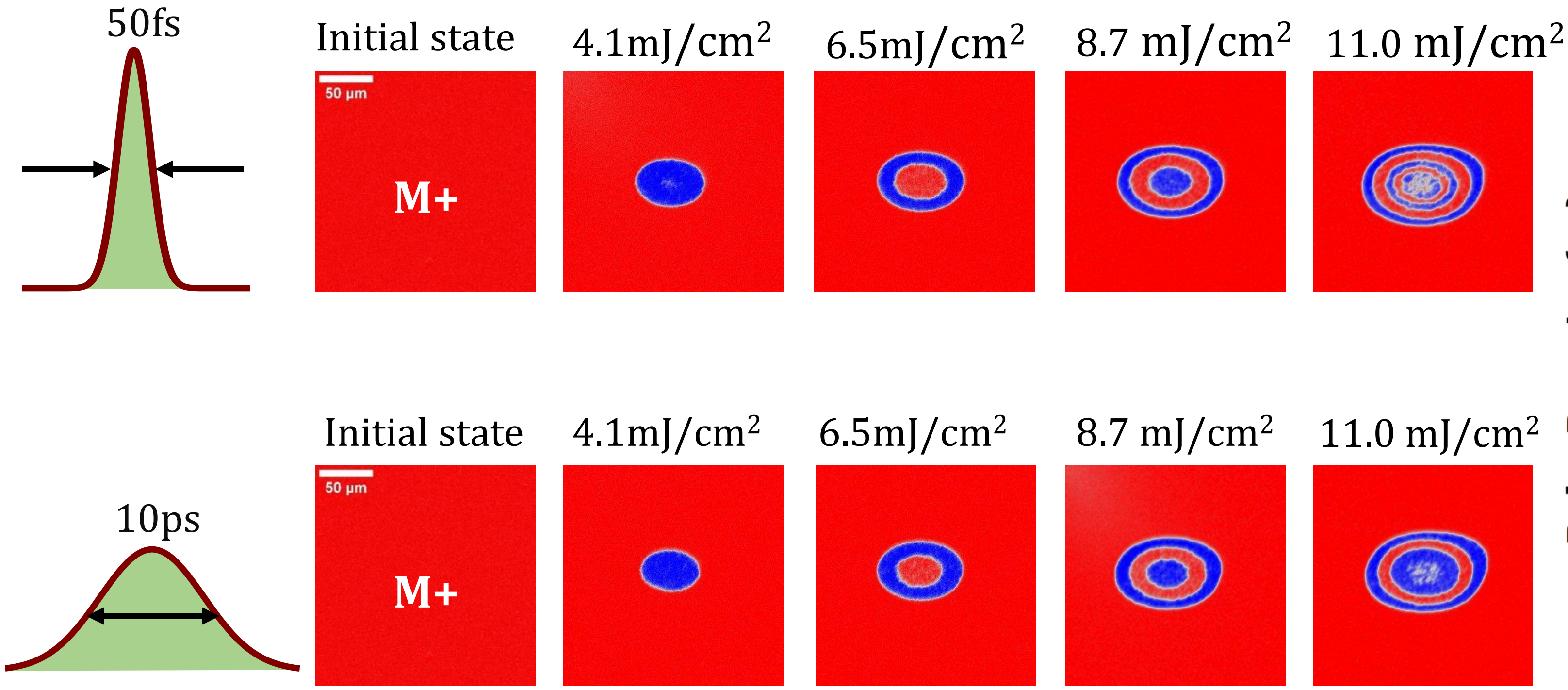
Domain wall motion by thermal gradient

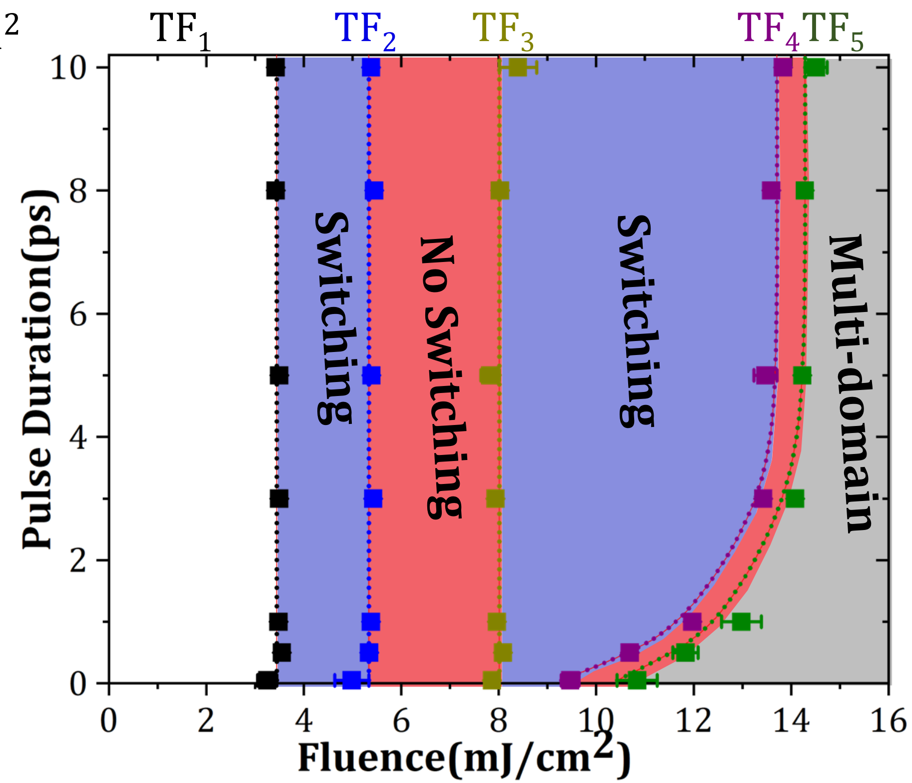
Y. Quessab et al Phys. Rev. B 97, 054419 (2018)

All Optical – Precessional switching

Characteristics

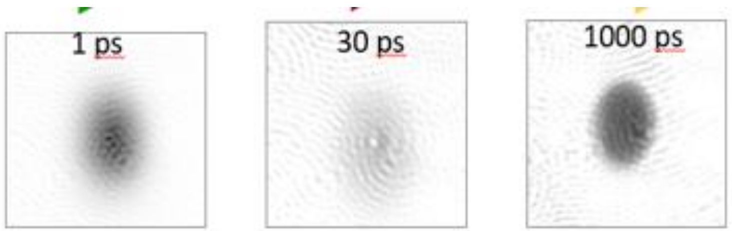
Single switching in [Tb/Co]$_5$ multilayer





Single pulse switching

Slow



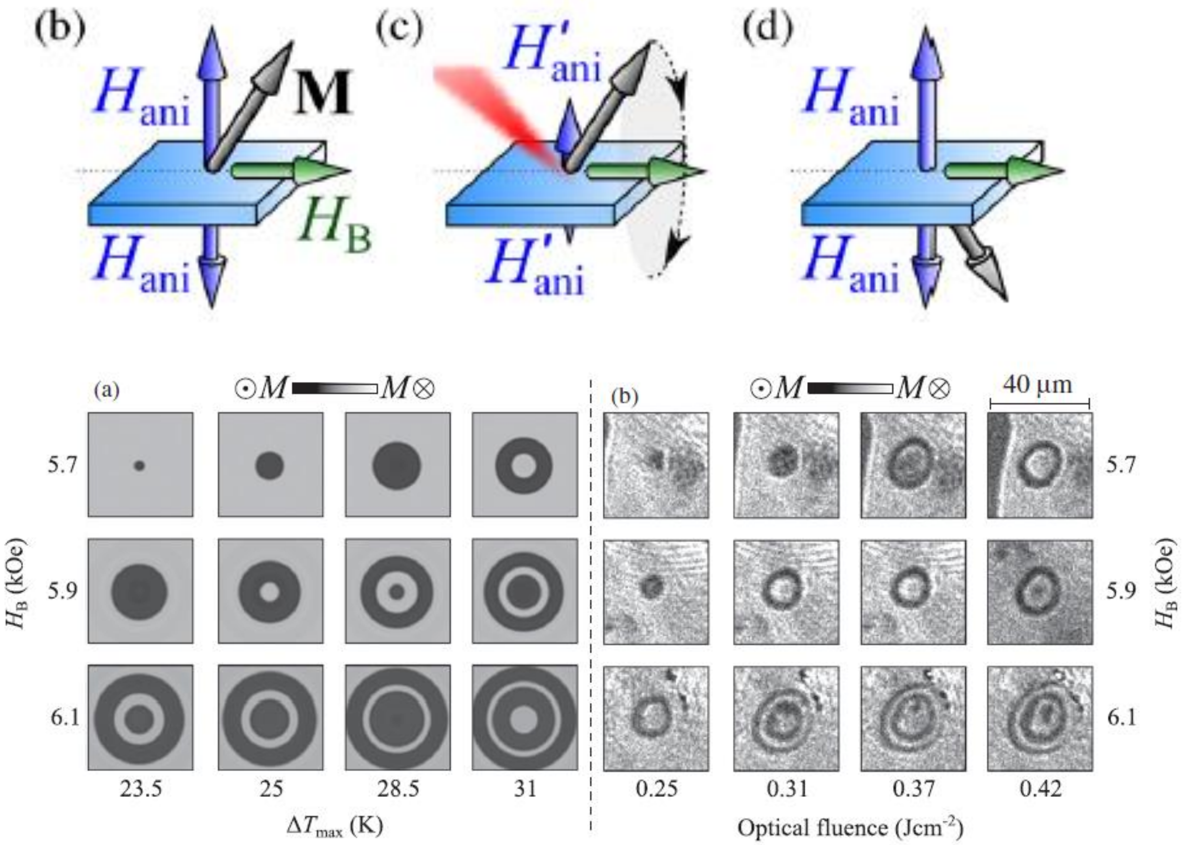
Characteristic State diagram

Peng , Y et al. Nature Com 14 (1) 5000 (2023)
Peng Y et al Appl Phys Lett **124**, 022405 (2024)

All Optical – Precessional switching

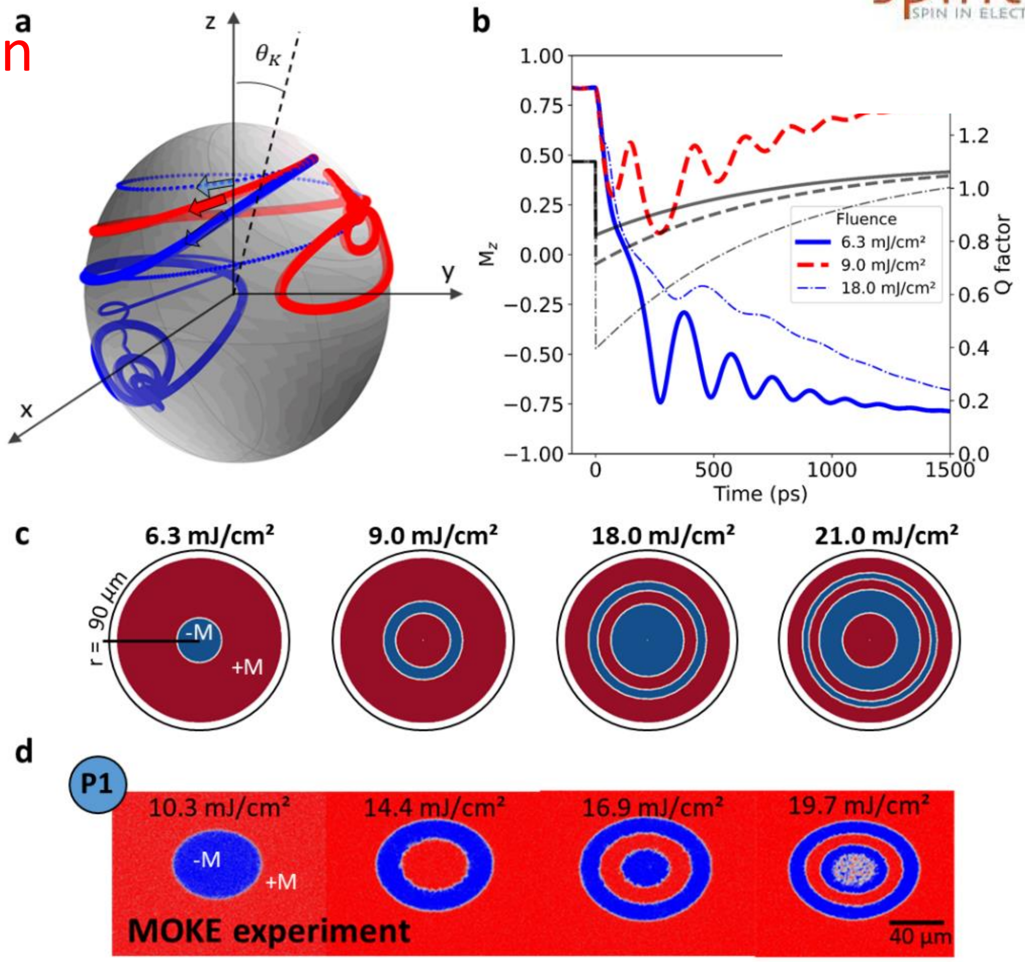
Mechanism

In plane reorientation



C. S. Davies et al, Phys. Rev. Lett. 122, 027202 (2019)

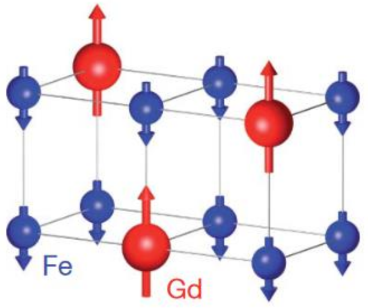
L. A. Shelukhin et al, Phys. Rev. B 97, 014422 (2018)

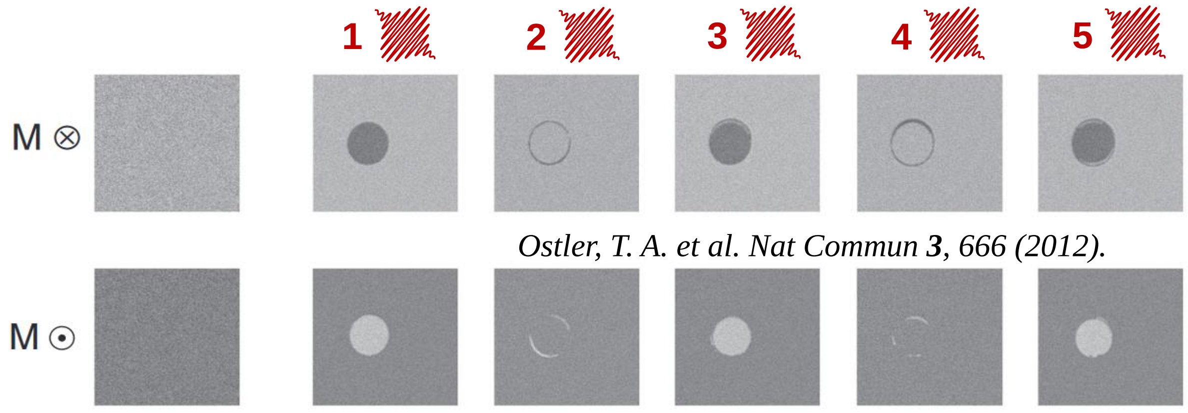


D. Salomoni, et. al, Phys. Rev. Applied 20, 034070 (2023)

All Optical – Helicity Independent switching

Characteristics





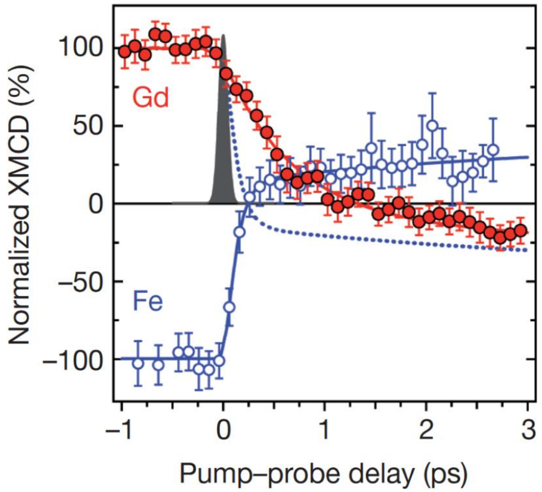
Ostler, T. A. et al. Nat Commun ***3****, 666 (2012).*

Single pulse & Fast

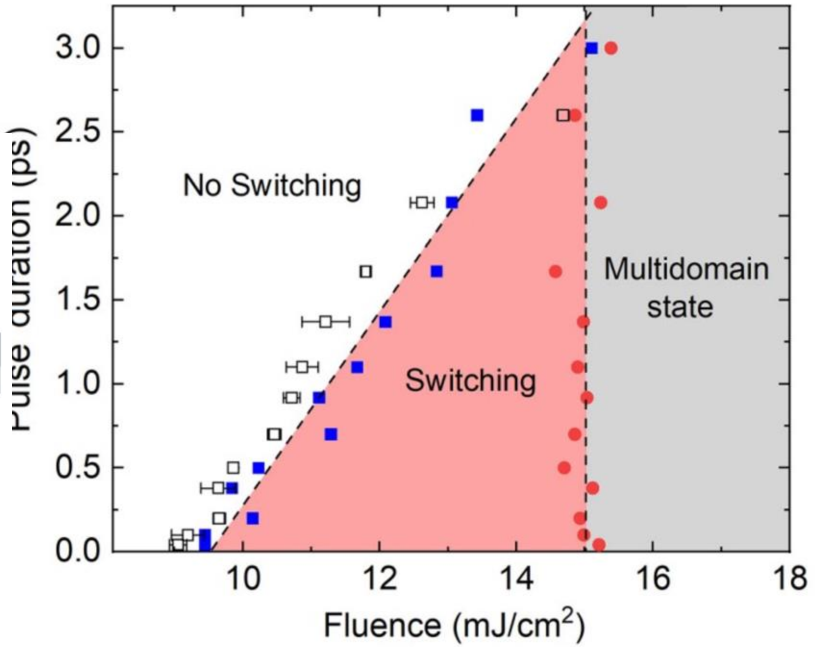
Specific materials

➡ Gd based Material

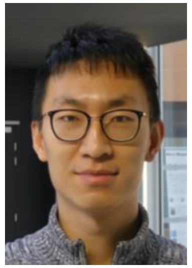
➡ MnRuGa



Radu, I. et al. Nature ***472****, 205–208 (2011).*



Characteristic State diagram



Wei, J. et al.
Phys Rev Applied 15, 054065 (2021).

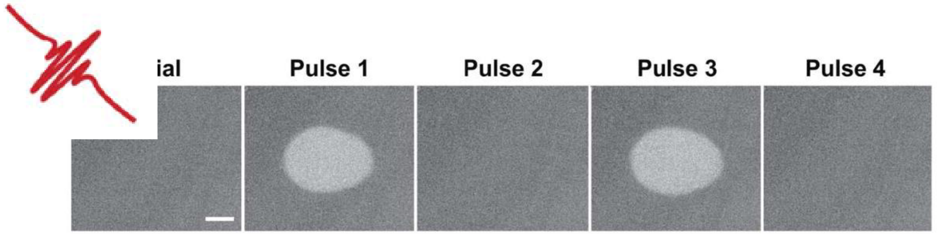
Jiaqi Wei

All Optical – Helicity Independent switching

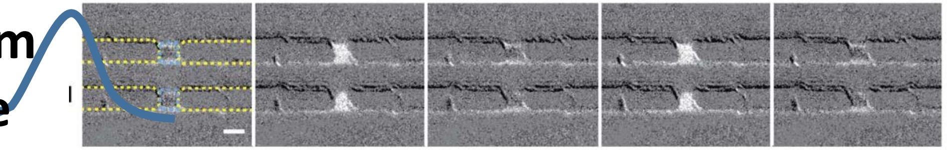
Mechanism

Heat assisted phenomena

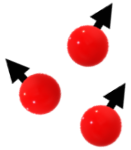
Optical Pulse



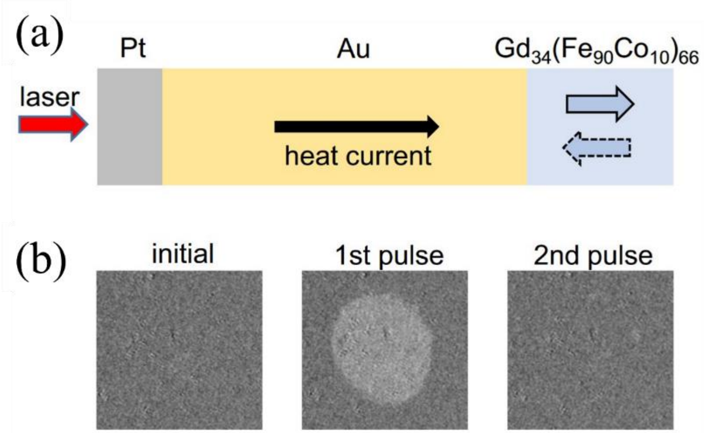
Heat Pulse from Electrical Pulse



Yang, Y. et al. Science Advances ***3****, e1603117 (2017).*



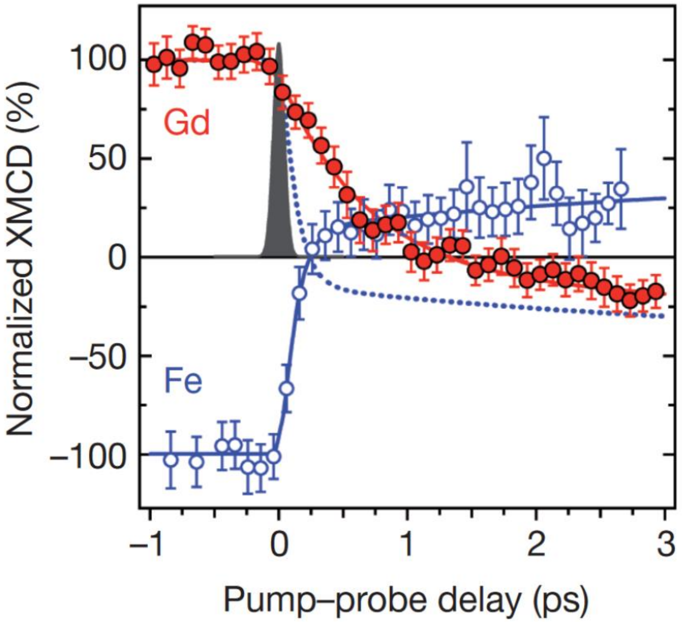
Hot Electron Pulse



N. Bergeard,et al , Phys. Rev. Lett. 117, 147203 (2016)
N Bergeard, et al APL 117 (22), 222408 (2020)

Wilson, R. B. et al. Physical Review B ***95****, 180409 (2017).*

Angular mt transfer between two sublattices



Recipe

- Demagnetize Fe
- Demagnetize Gd to generate angular mt transfer

$$Js = dM_{Gd}/dt$$

3 types of thermally assisted switching at different time scales

**All Optical –
Helicity dependent switching**

**All Optical –
Precessional switching**

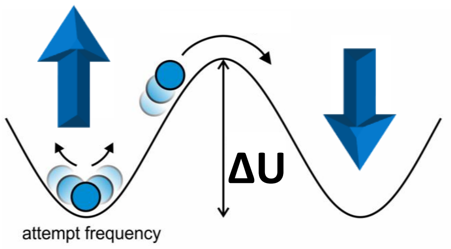
**All Optical –
Helicity Independent switching**

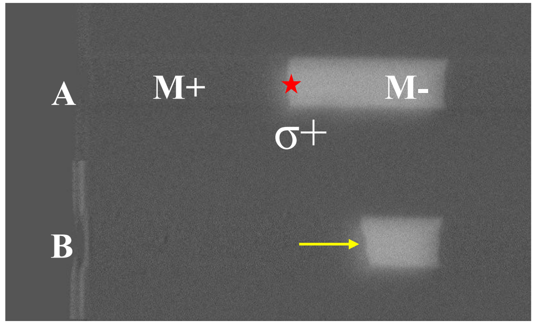
Different but all are thermally driven

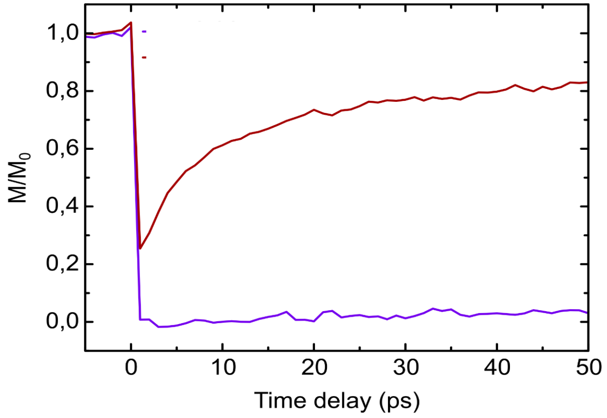
- Domain nucleation
  Domain wall propagation

- Anisotropy reorientation
  Magnetization Precession

- Ultra-fast Demagnetization
  Angular Momentum transfer



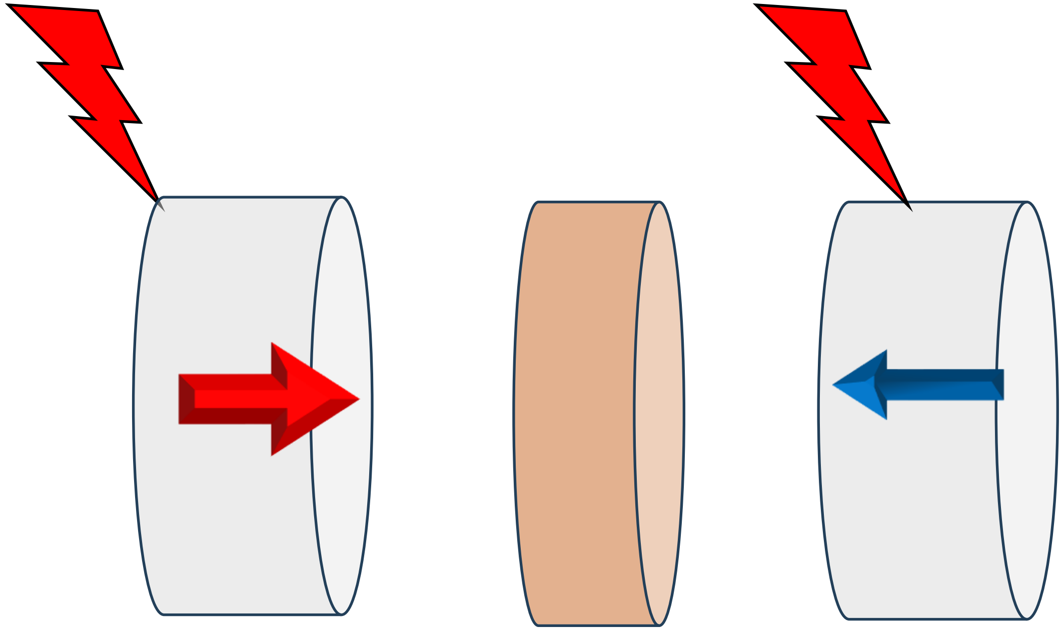




μs → ns → ps → fs

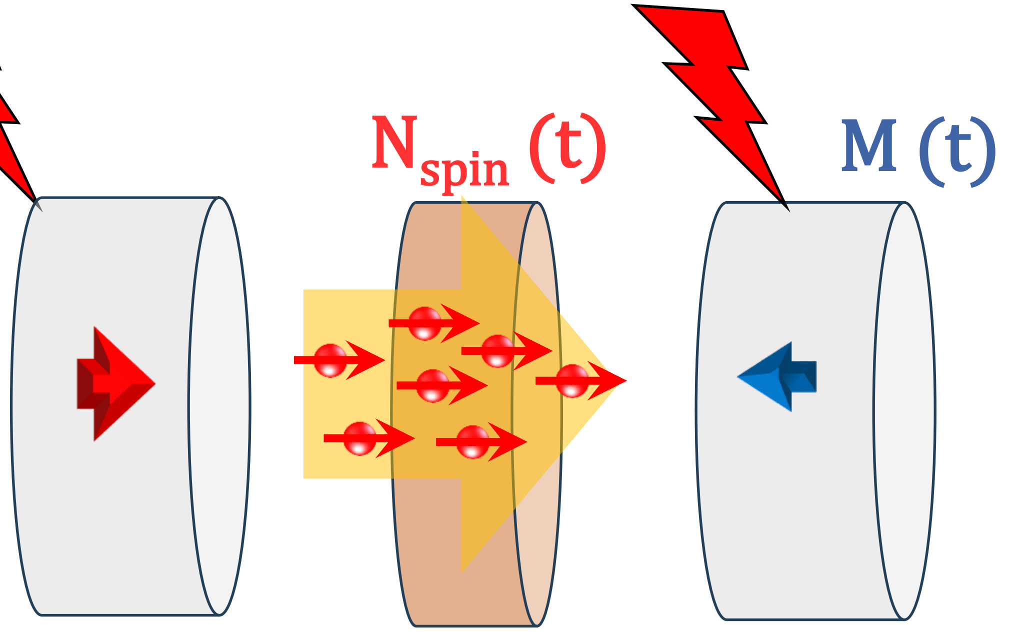
Light induced switching

Ultra-fast Optical switching From **AP state** to P state



Light induced switching

Ultra-fast Optical switching From **AP state** to P state

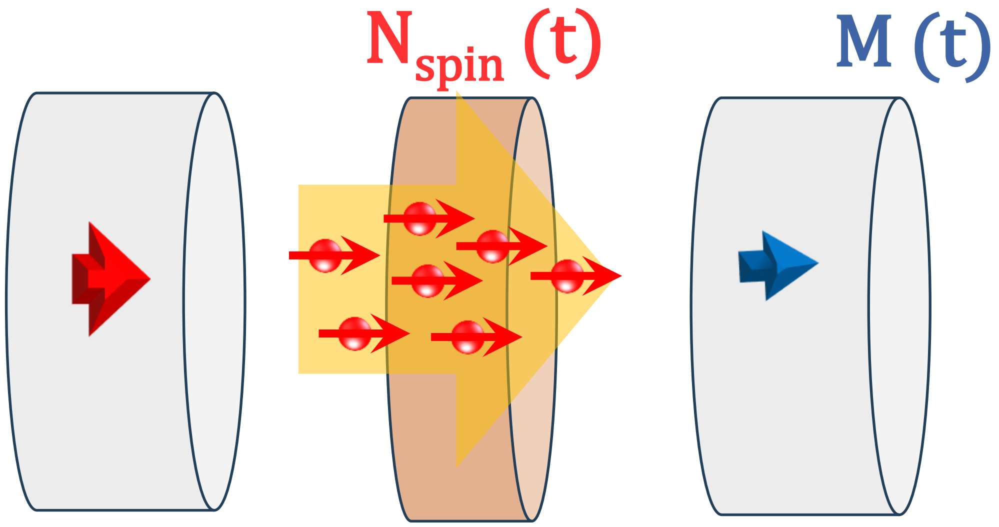


Ultra-fast spin pumping by ultra-fast demagnetization

Ultra-fast demagnetization

Light induced switching

Ultra-fast Optical switching From **AP state** to P state



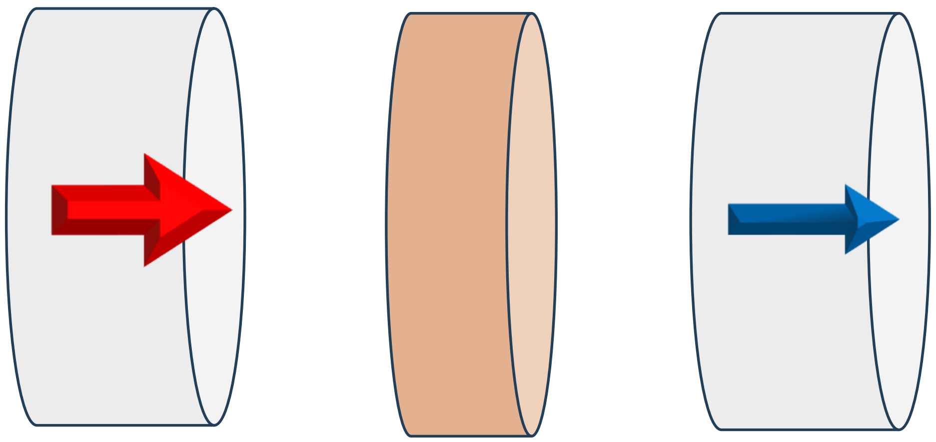
Criteria:

Synchronization

$N_{spin}(t) > \Delta M(t)$

Light induced switching

Ultra-fast Optical switching From **AP state** to **P state**



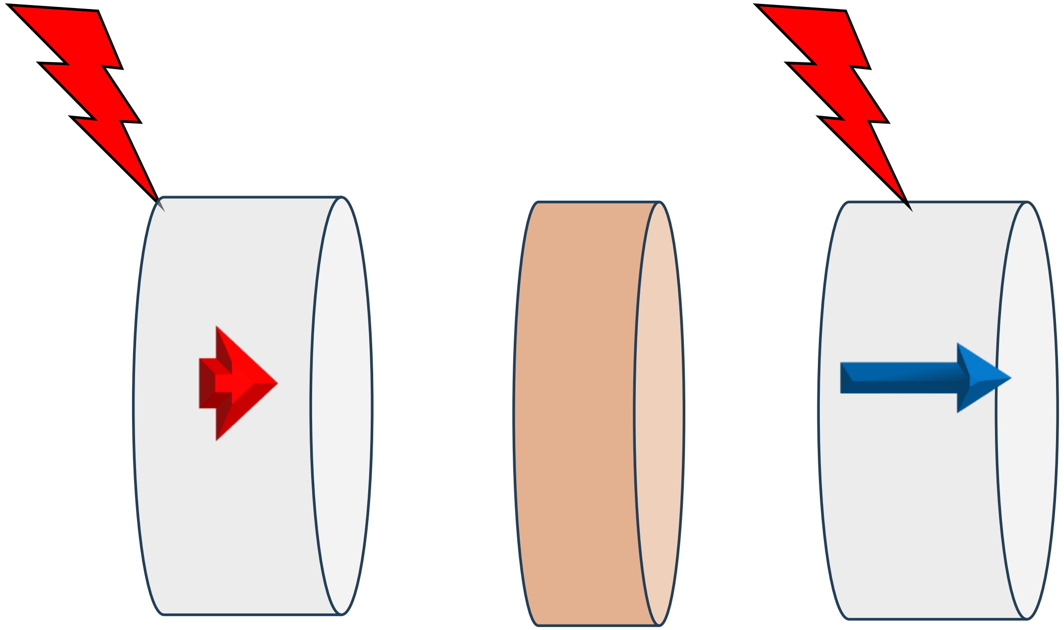
Criteria:

Synchronization

$N_{spin}(t) > \Delta M\ (t)$

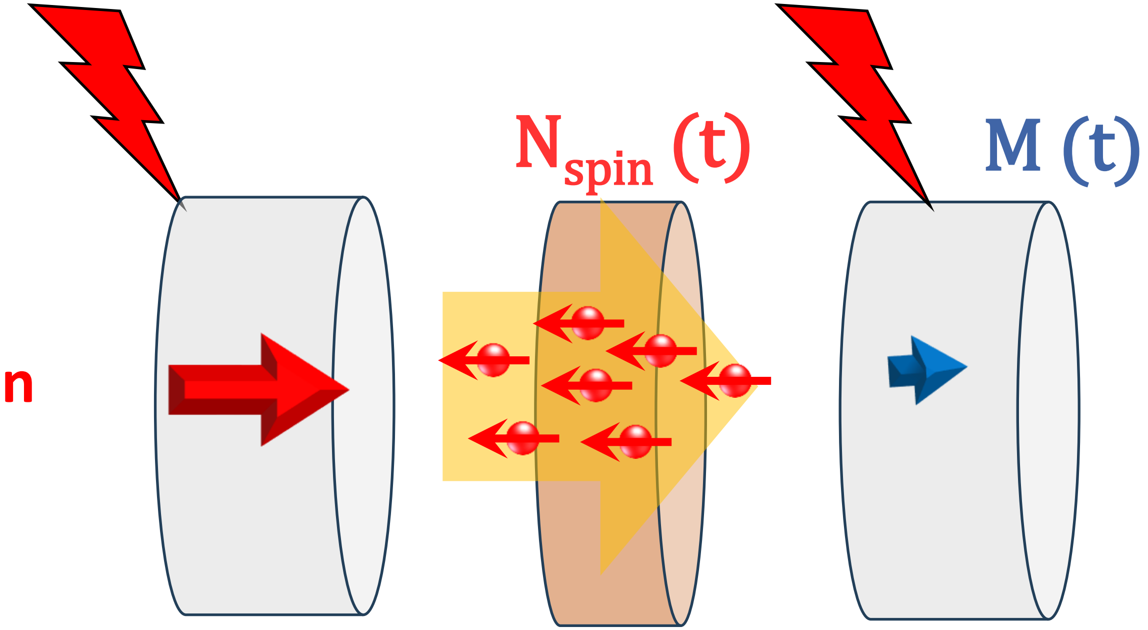
Light induced switching

Ultra-fast Optical switching From **P state** to **AP state**



Light induced switching

Ultra-fast Optical switching From **P state** to **AP state**

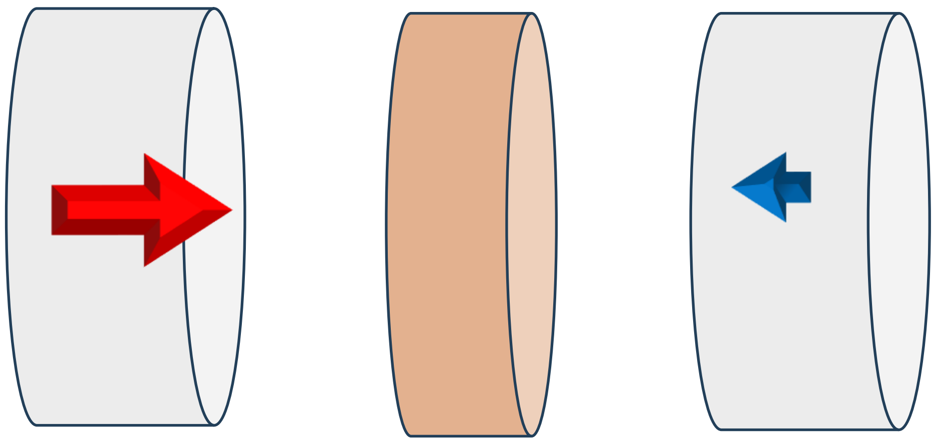


spin pumping
by fast **remagnetization**

ultra-fast demagnetization

Light induced switching

Ultra-fast Optical switching From **P state** to **AP state**



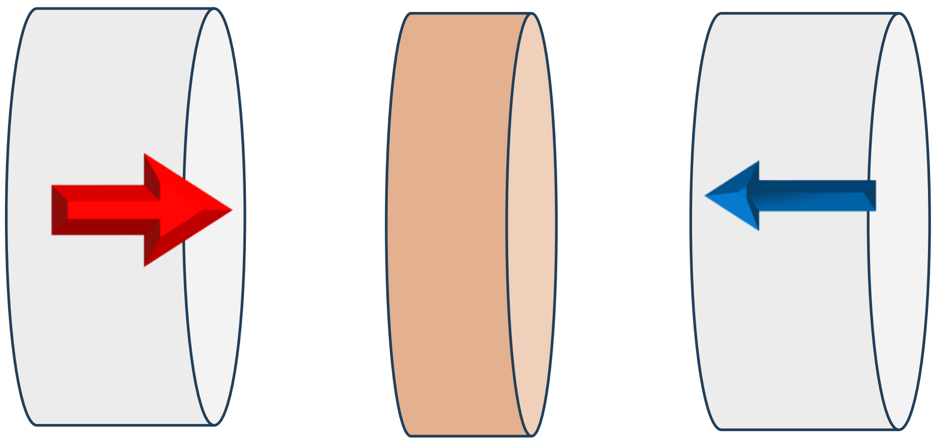
Criteria:

Synchronization

$N_{spin}(t) > \Delta M\ (t)$

Light induced switching

Ultra-fast Optical switching From **P state** to **AP state**



Criteria:

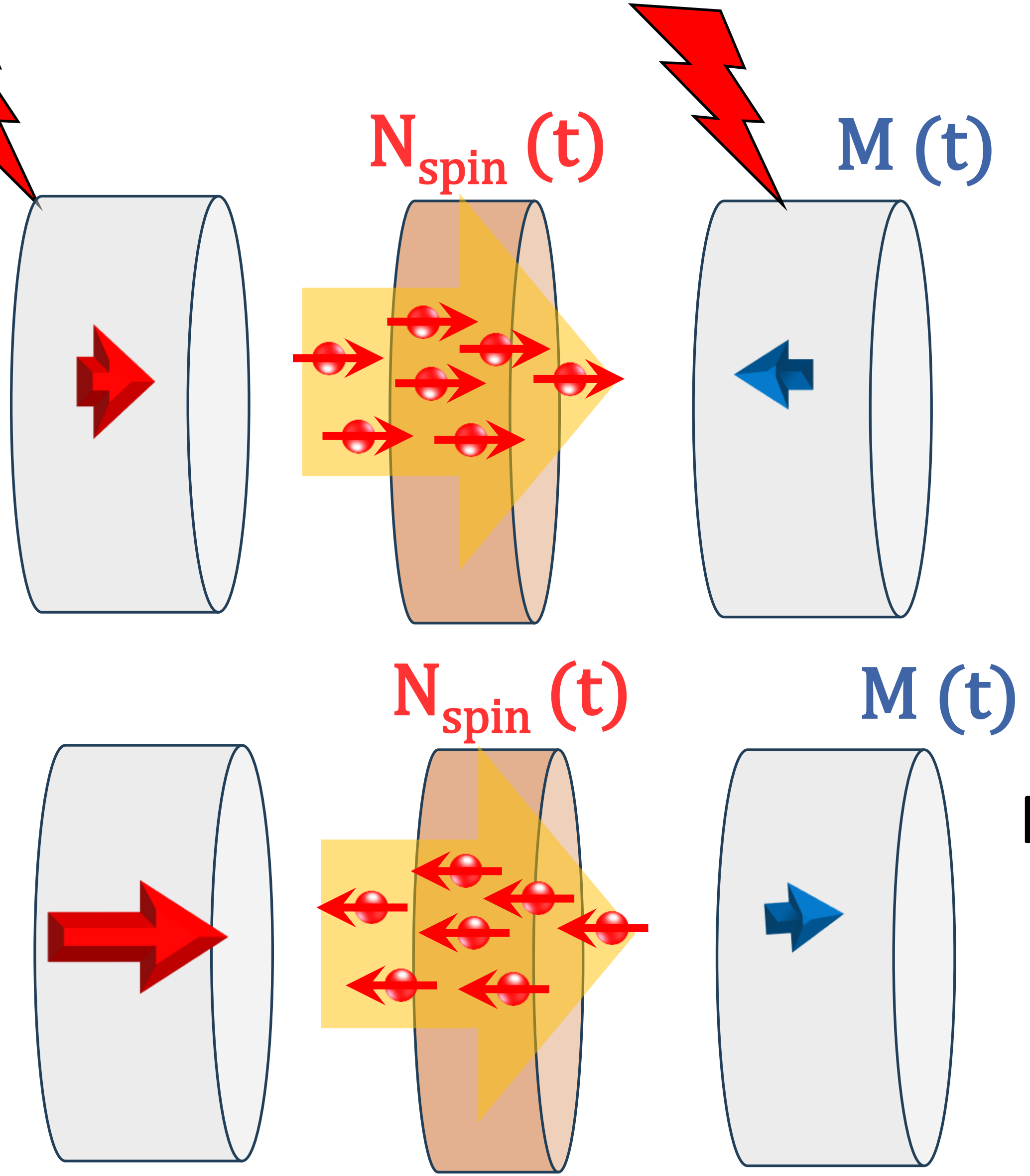
Synchronization

$N_{spin}(t) > \Delta M\ (t)$

Light induced switching

Ultra-fast Optical switching

Ultra-fast spin pumping
by ultra-fast demagnetization



spin pumping
by fast **remagnetization**

From **AP state**

to **P state**

Ultra-fast demagnetization

Synchronization

$$N_{spin}(t) > \Delta M(t)$$

From **P state**

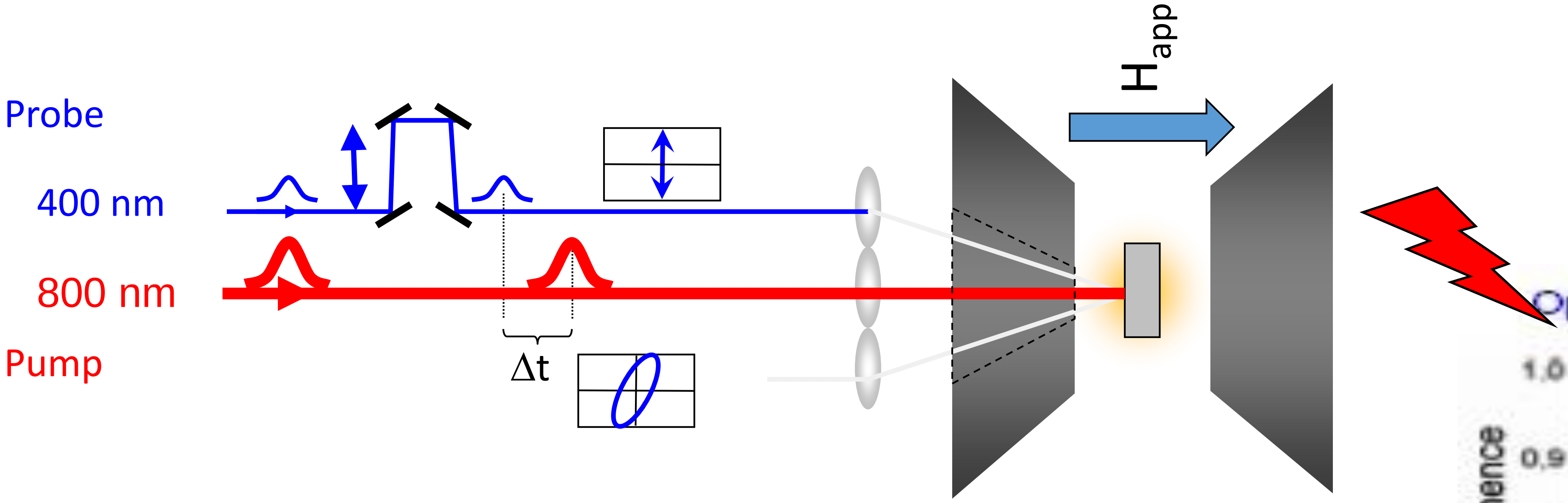
To **AP state**

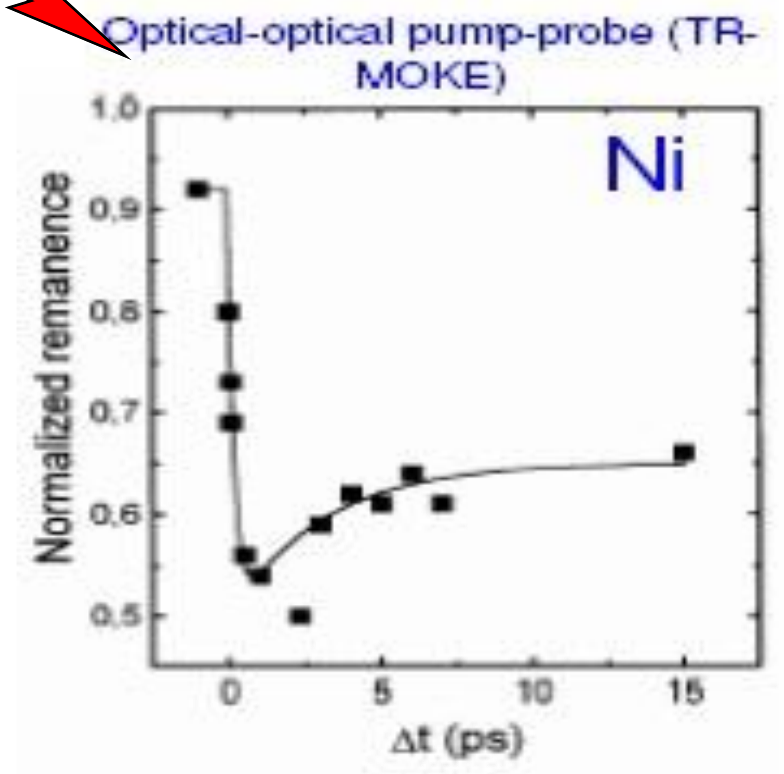
ultra-fast demagnetization

Oulines

- Current Vs Light Induced switching
- Light Induced switching : demagnetization driven switching
- Experimental results showing:
  single pulse – ultra-fast – deterministic –low energy switching
- Conclusions

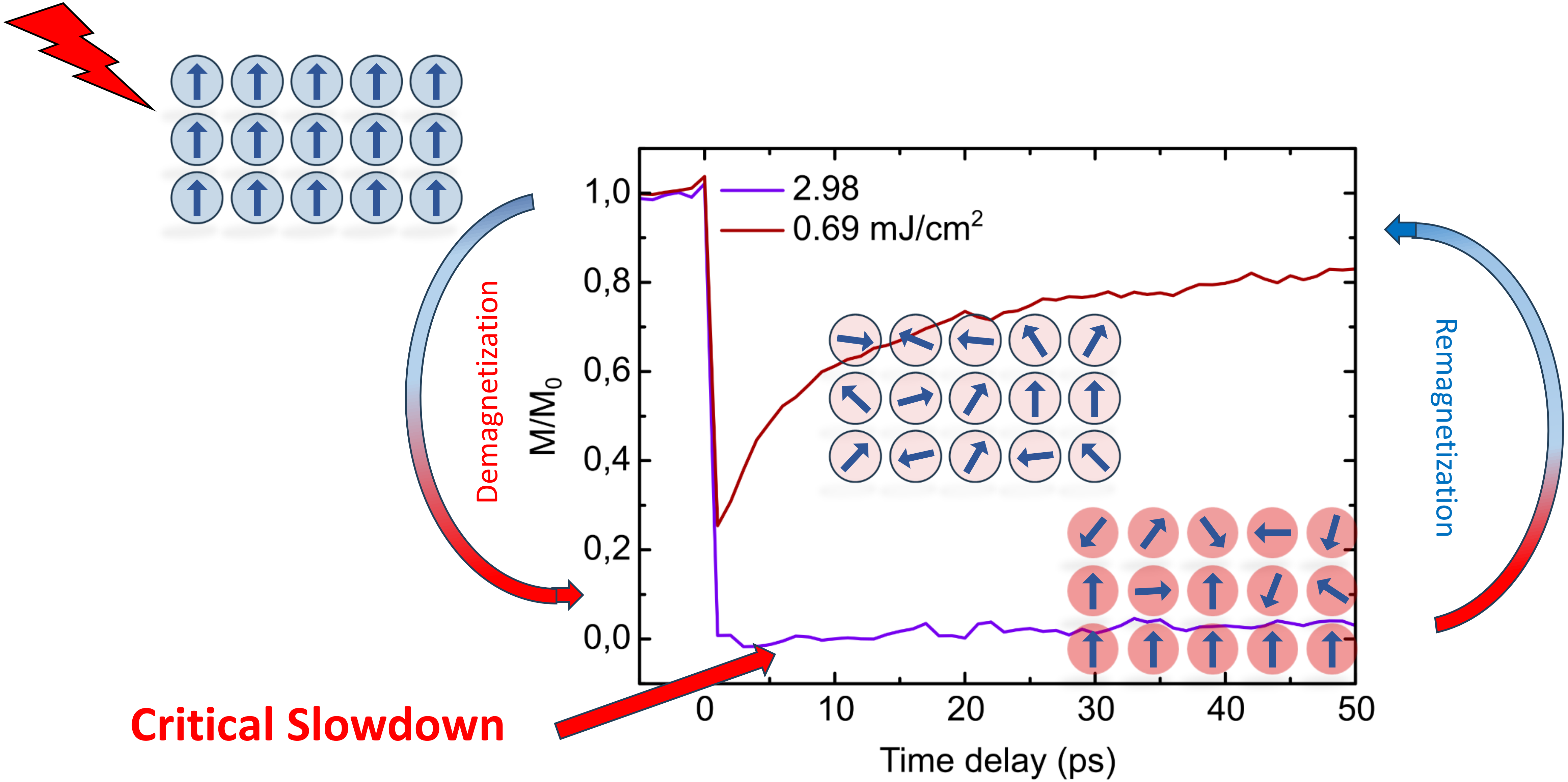
Ultrafast demagnetization





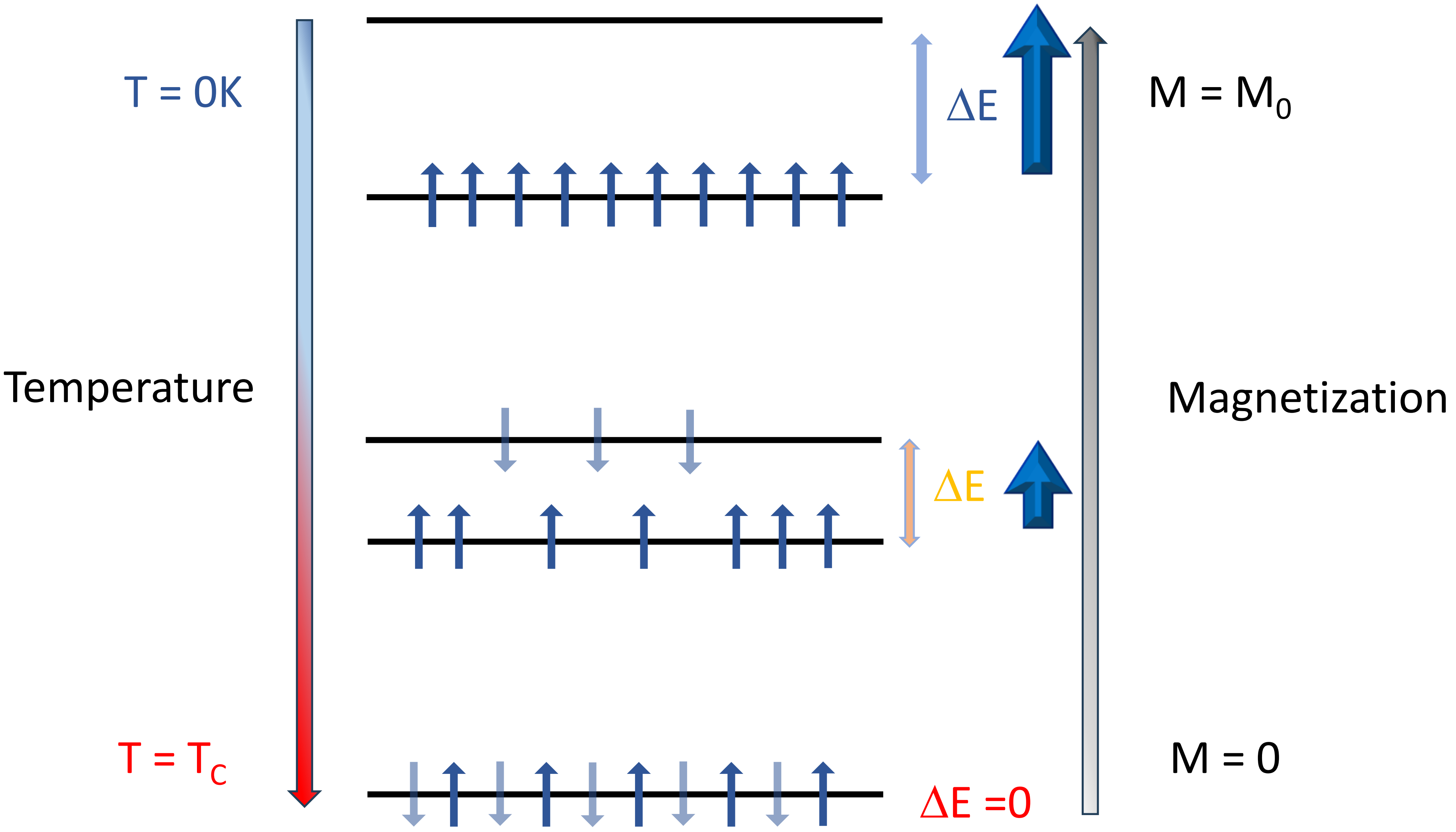
E. Beaurepaire, et al Phys. Rev. Lett. 76, 4250 (1996)

Ultrafast demagnetization

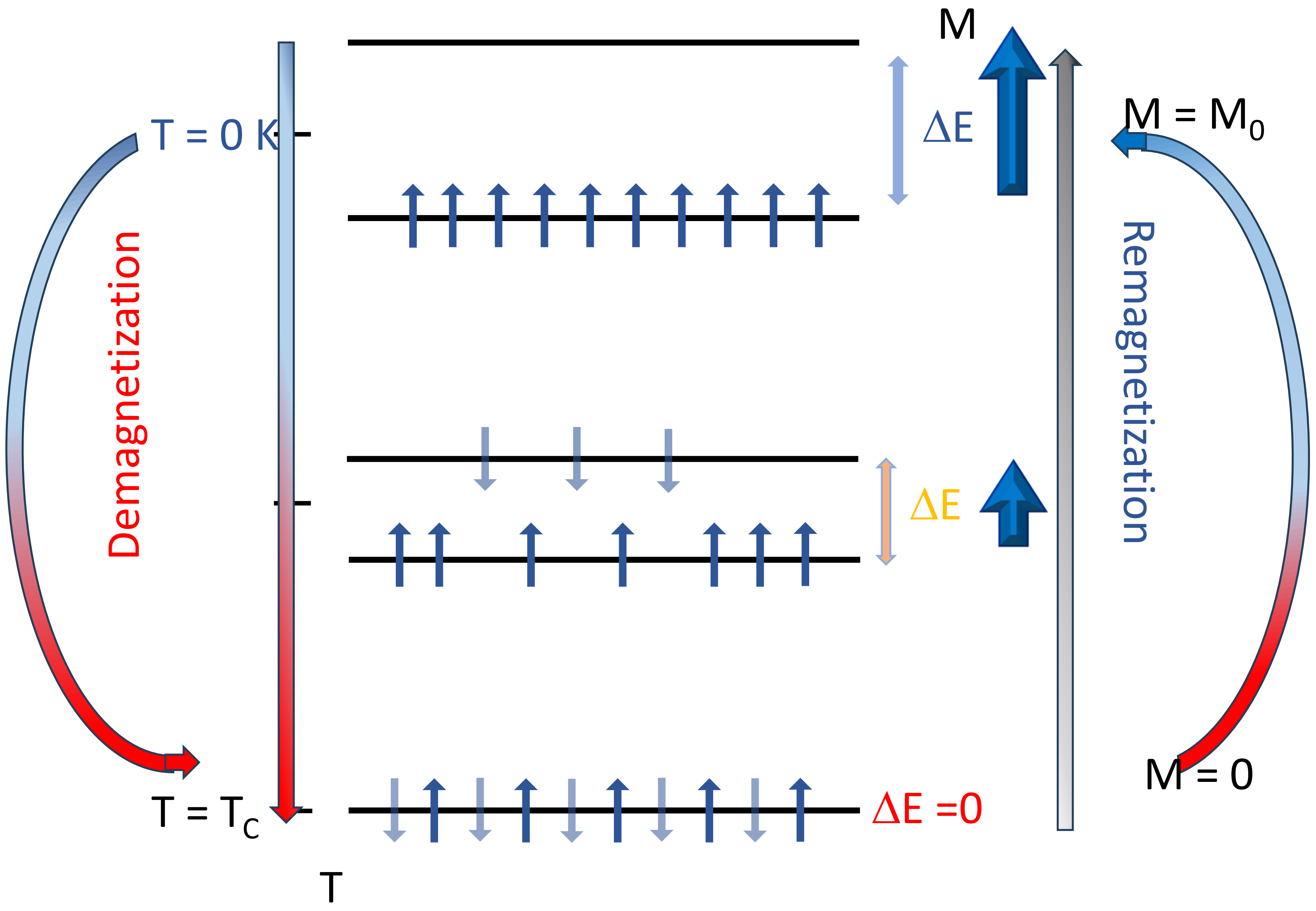


E. Beaurepaire et al Phys. Rev. Lett. **76**, 4250–4253 (1996).
M. Scheffer, et al. Nature 461, 53–59 (2009).

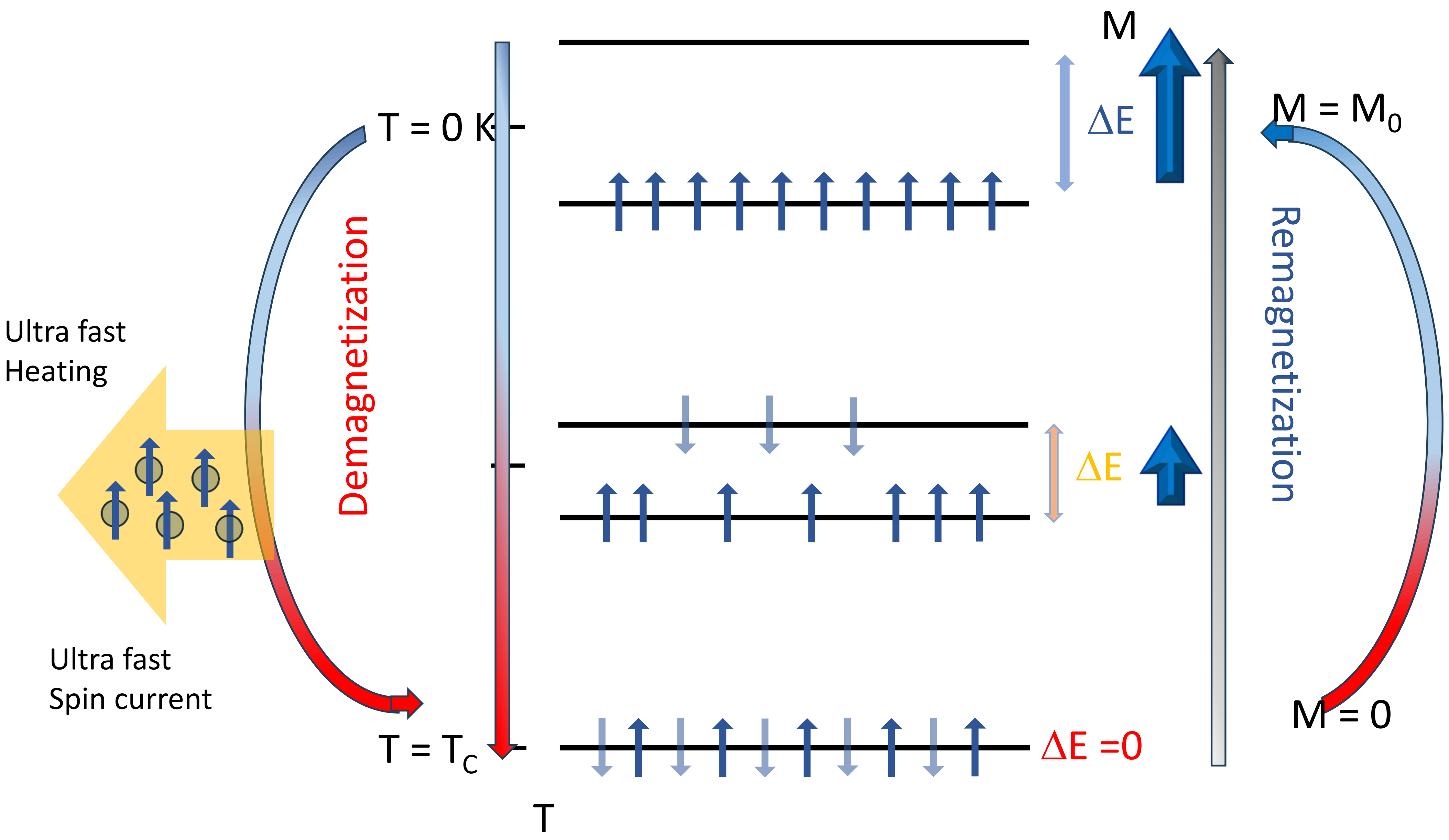
Ultrafast demagnetization : 2 level model



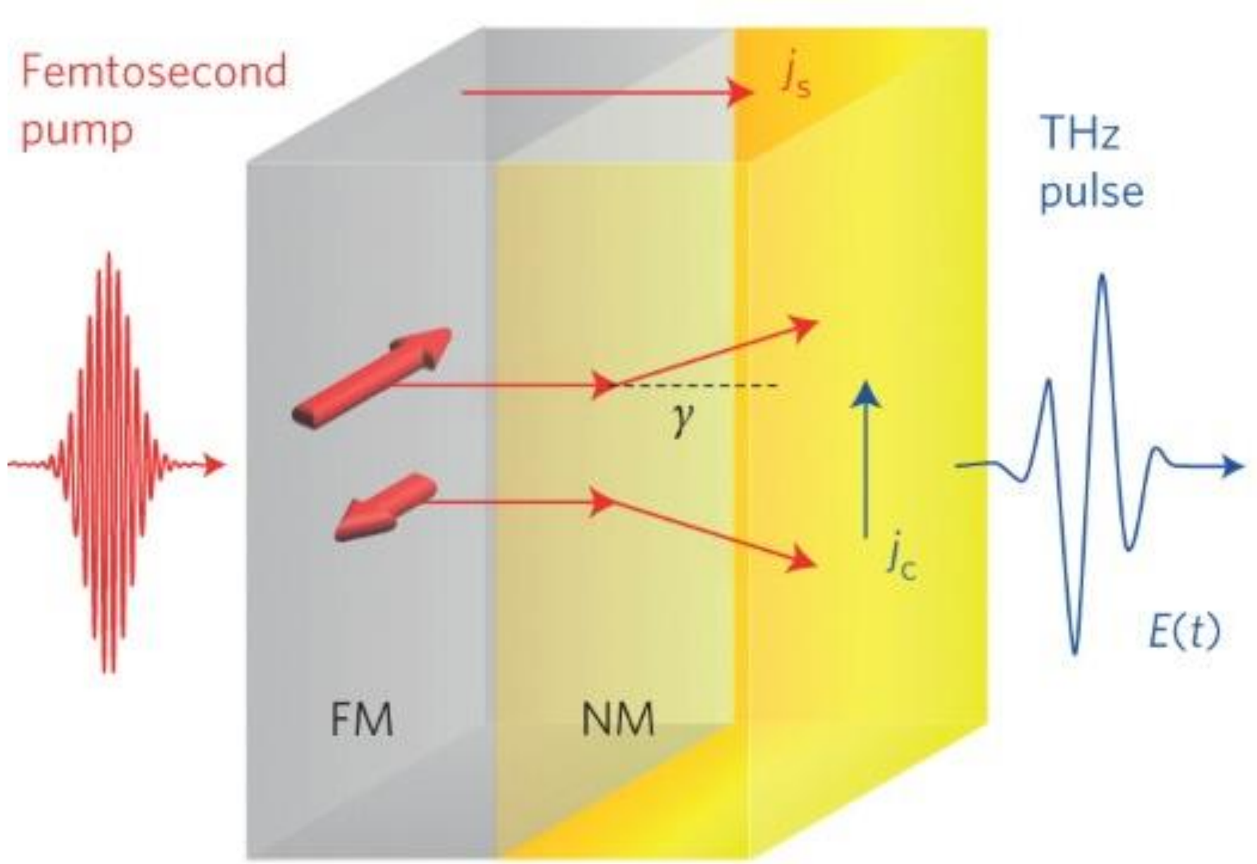
Ultrafast demagnetization : 2 level model



Ultrafast demagnetization : 2 level model



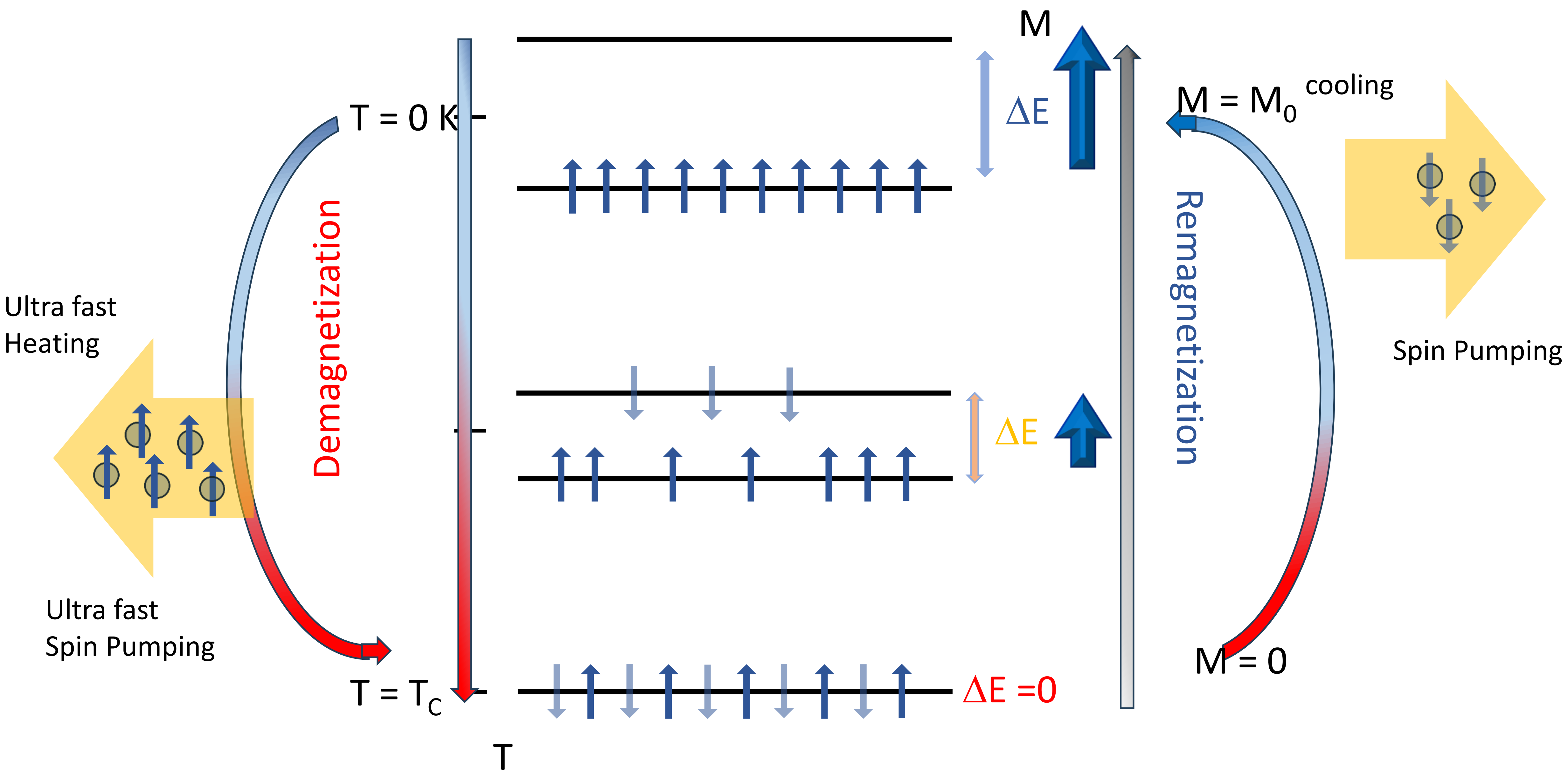
Ultrafast demagnetization : Ultrafast spin current - Ultrafast spin pumping



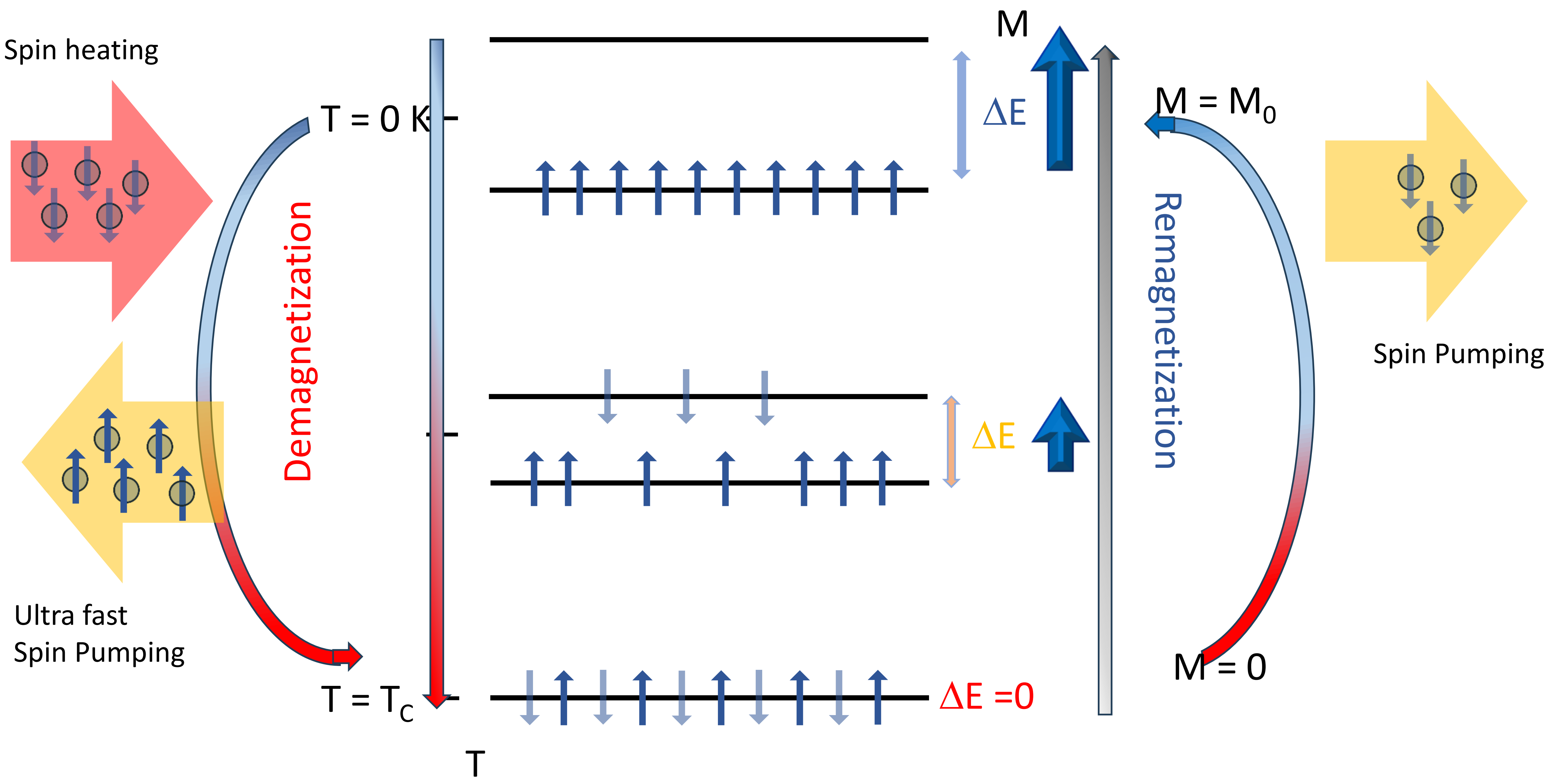
T. Seifert Nature Photonics ***10****, 483–488 (2016)*

T. Kampfrath et al. Nat. Photon. 5, 31 (2011)

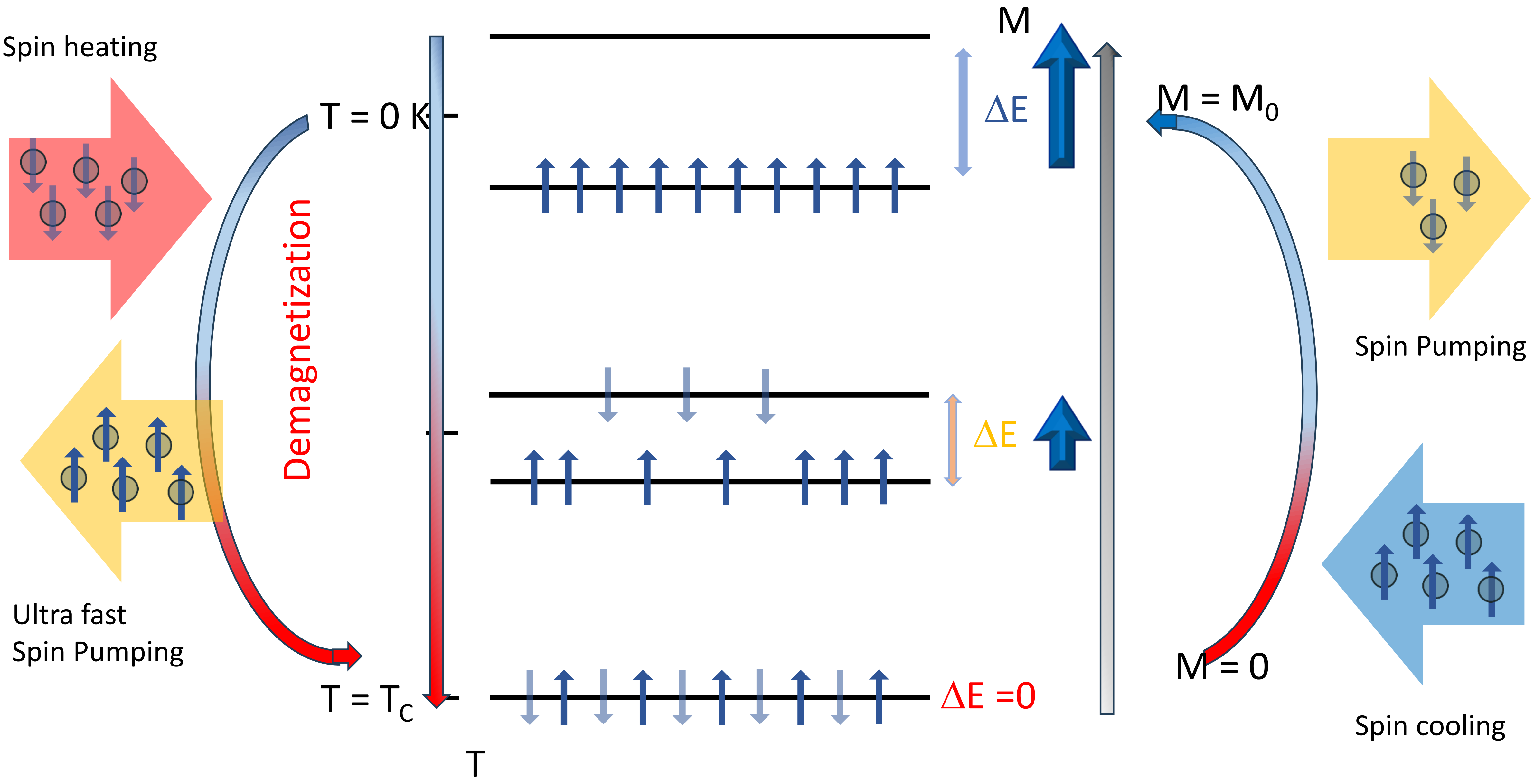
Ultrafast demagnetization : 2 level model



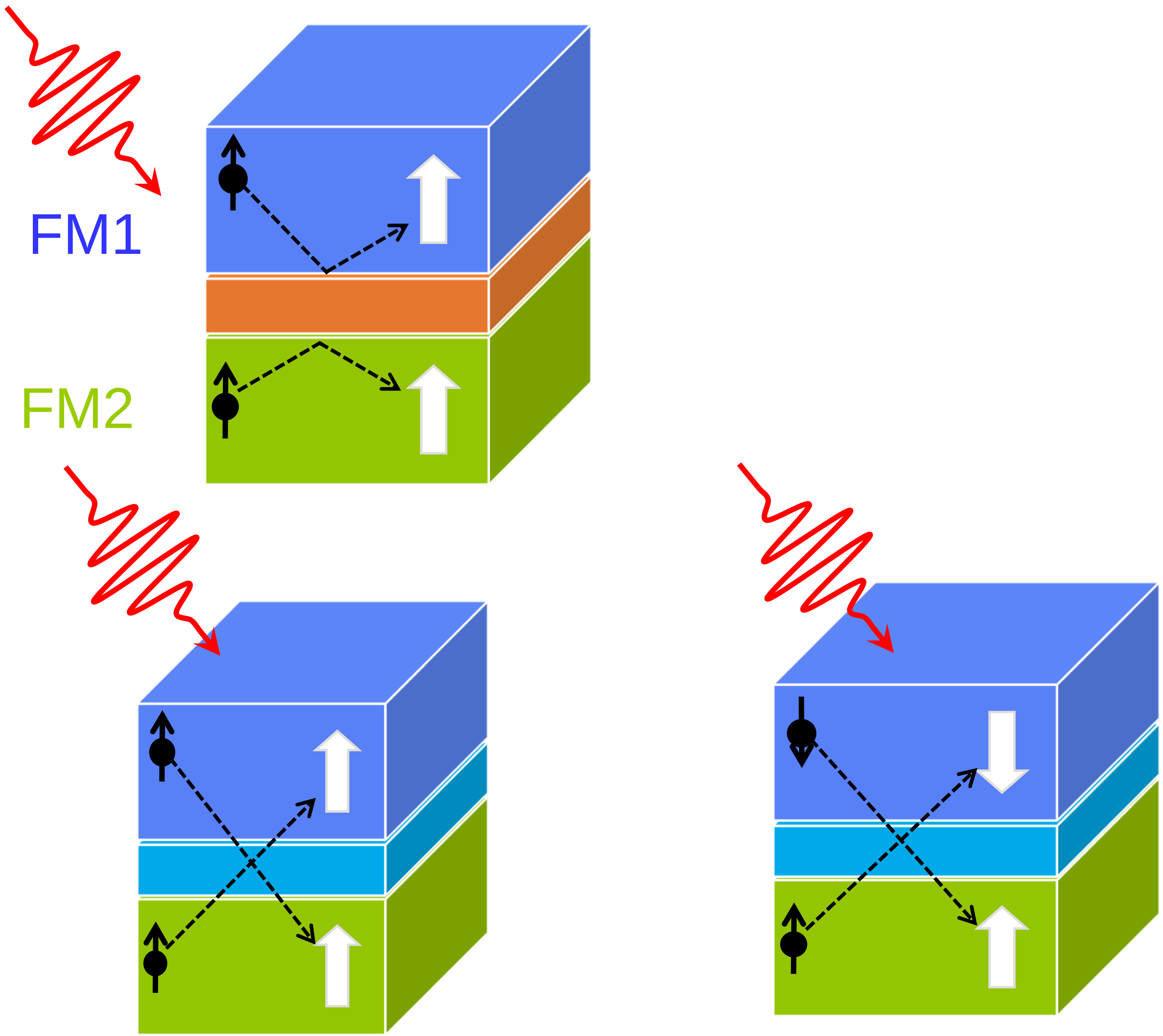
Ultrafast demagnetization : 2 level model

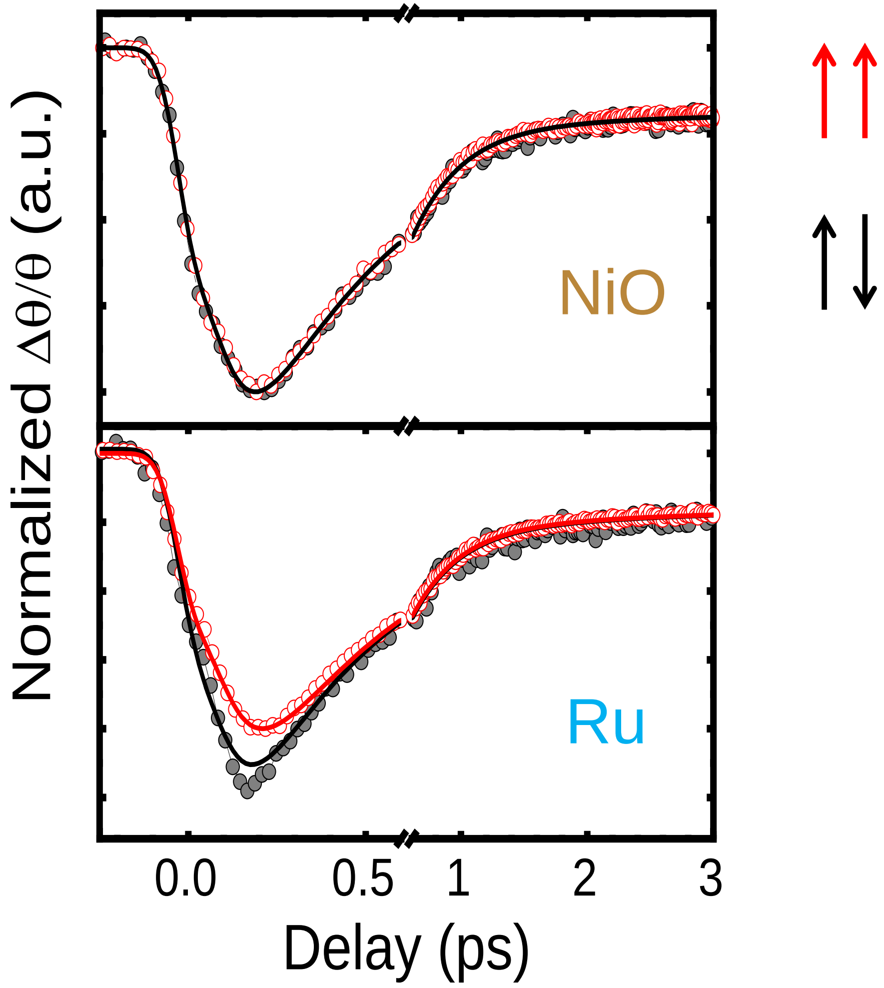


Ultrafast demagnetization : 2 level model



Ultra-fast spin current affect demagnetization





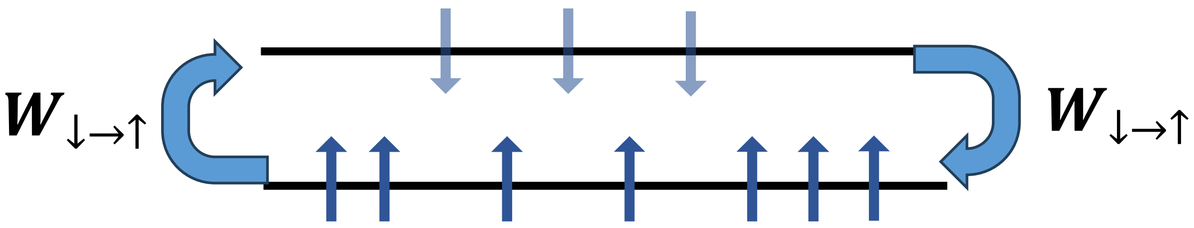
G. Malinowski et al. Nature Physics ***4****, 855 (2008)*

Modeling – Spin pumping

- Spin temperature/magnetization changes:

$$\frac{dm}{dt} = 2(W_{\uparrow\to\downarrow} n_{\uparrow} - W_{\downarrow\to\uparrow} n_{\downarrow})$$

$$\frac{W_{\downarrow\to\uparrow}}{W_{\uparrow\to\downarrow}} = e^{-\frac{\Delta E}{k_B T_e}}$$



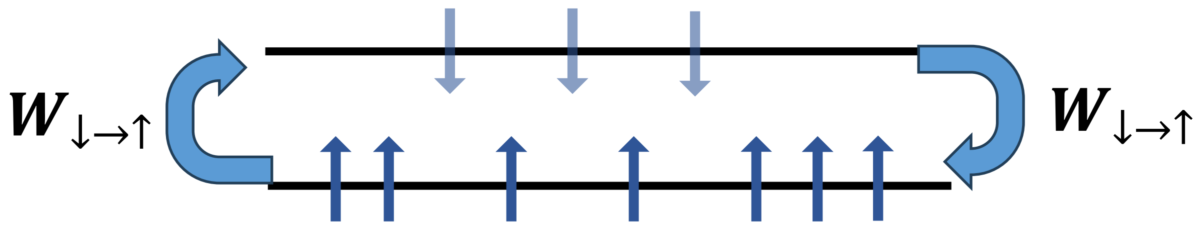
*K. Blum, K.. **64**, (Springer Berlin Heidelberg, 2012).*
*Cywiński, Ł. & Sham, L. J. Phys. Rev. B **76**, 045205 (2007).*
*J.-H. Shim, et al. Nat. Com. **8**, 796 (2017).*
Q. Remy et al, Nature Com **14** 445 (2023)

Modeling – Spin pumping

- Spin temperature/magnetization changes:

$$\frac{dm}{dt} = 2(W_{\uparrow\to\downarrow} n_\uparrow - W_{\downarrow\to\uparrow} n_\downarrow)$$

$$\frac{W_{\downarrow\to\uparrow}}{W_{\uparrow\to\downarrow}} = e^{-\frac{\Delta E}{k_B T_e}} = e^{-\frac{2mk_B T_C - \Delta\mu}{k_B T_e}}$$



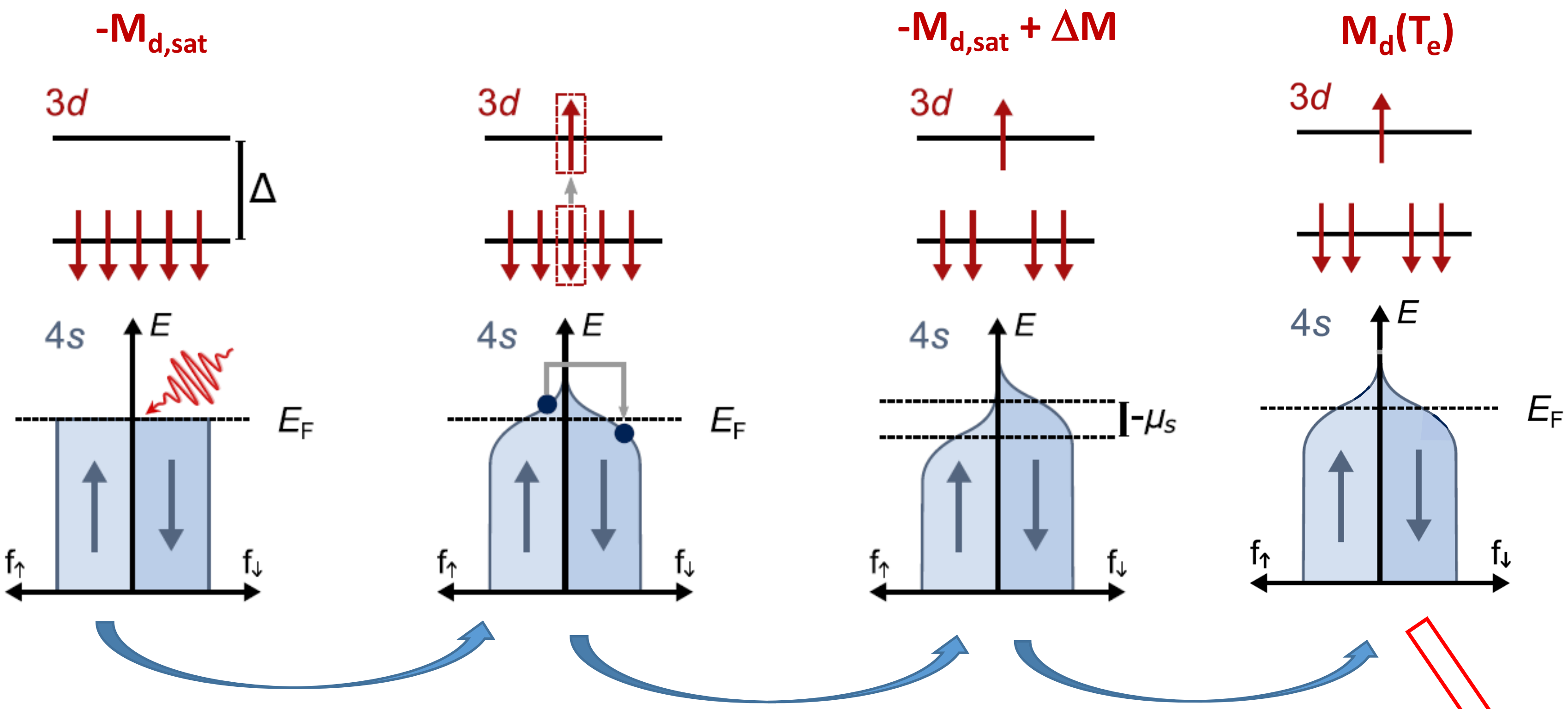
- m: self consistency/ mean field : $\Delta\mu = m = 0 \Rightarrow dm/dt = 0$
- T_e: cooling/heating
  Hard to control.
- $\Delta\mu$: Spin cooling/Spin heating
  Controlled by changing external spin polarization.

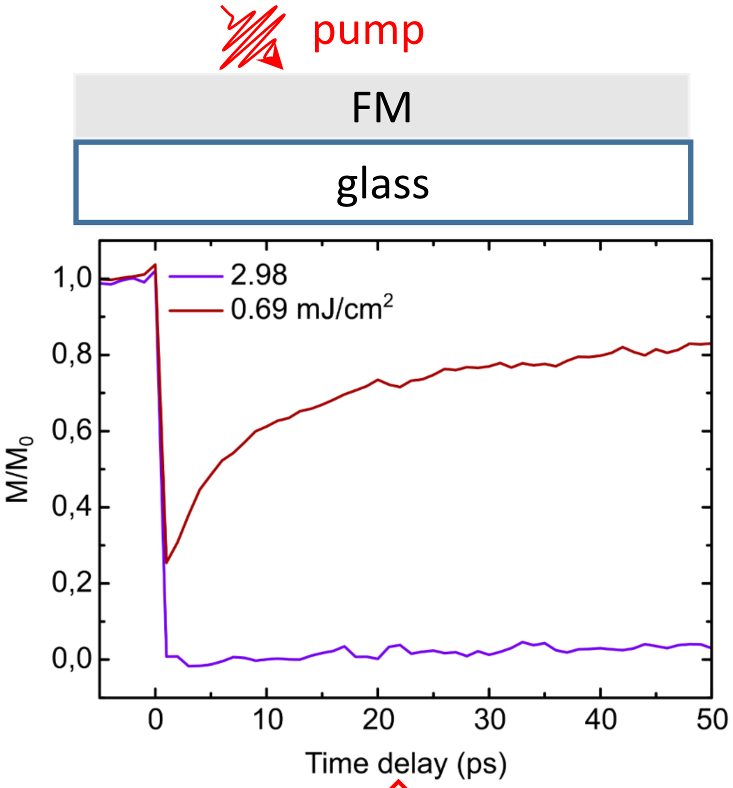
CSD!

$$\frac{\mathrm{dm}}{\mathrm{dt}}_{|m=0} = \frac{-\Delta\mu}{2\tau k_B T_C}$$

*K. Blum, K.. **64**, (Springer Berlin Heidelberg, 2012).*
*Cywiński, Ł. & Sham, L. J. Phys. Rev. B **76**, 045205 (2007).*
*J.-H. Shim, et al. Nat. Com. **8**, 796 (2017).*
*Q. Remy et al, Nature Com **14** 445 (2023)*

Modeling – Spin pumping (3d-4s) model





Heating
s-electrons

Angular momentum
transfer d -> s
(sd-exchange)

Decay of μ_s
via e ph scattering

$$\frac{dm_d}{dt} = \frac{1}{\tau_{sd}}\left(m_d - \frac{\mu_s}{2k_B T_C}\right)\left[1 - m_d \coth\left(\frac{2m_d k_B T_C - \mu_s}{2k_B T_e}\right)\right]$$

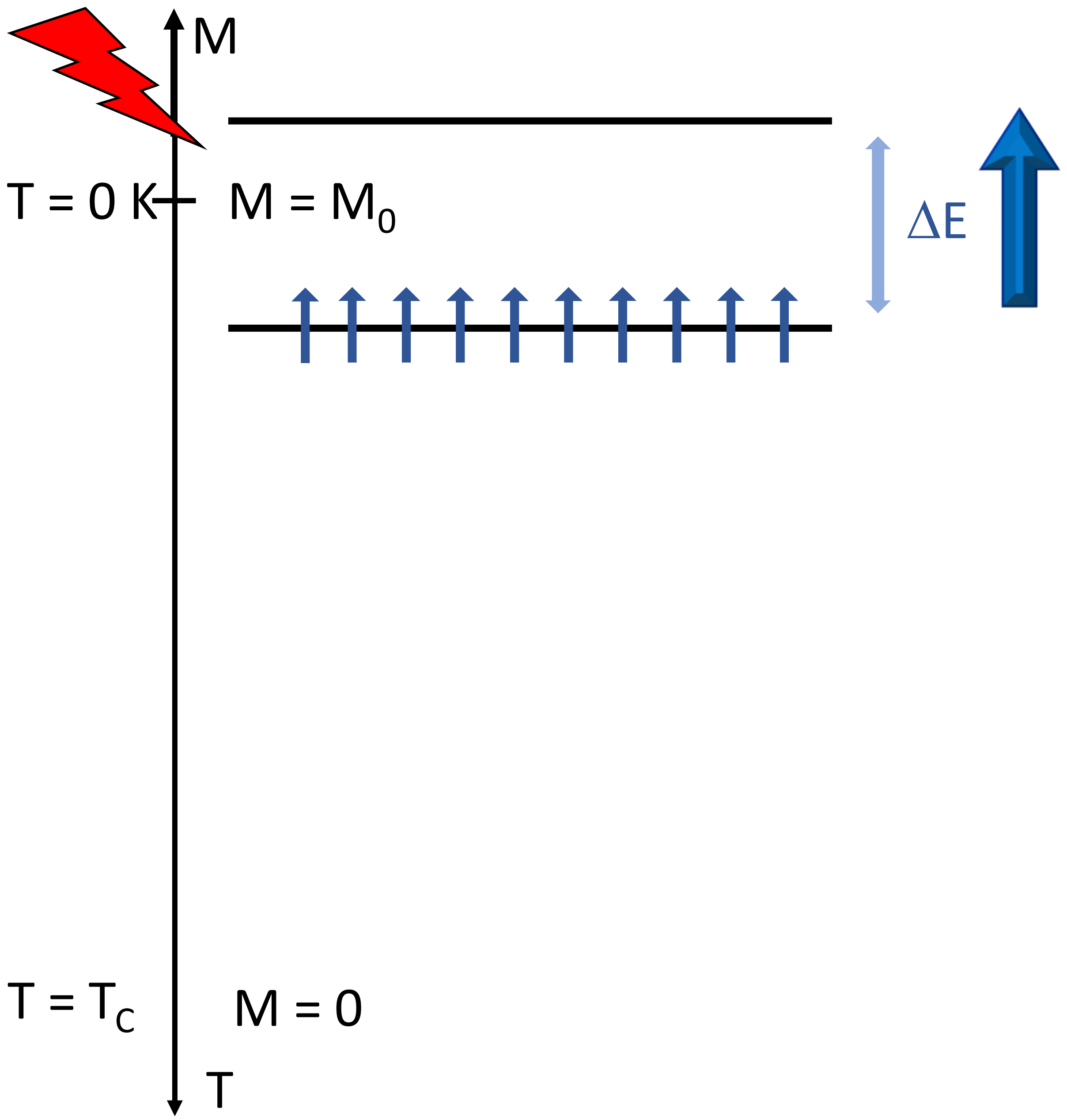
$$\frac{d\mu_s}{dt} = \rho_{sd}\frac{dm_d}{dt} - \frac{\mu_s}{\tau_s}$$

Js = dM/dt

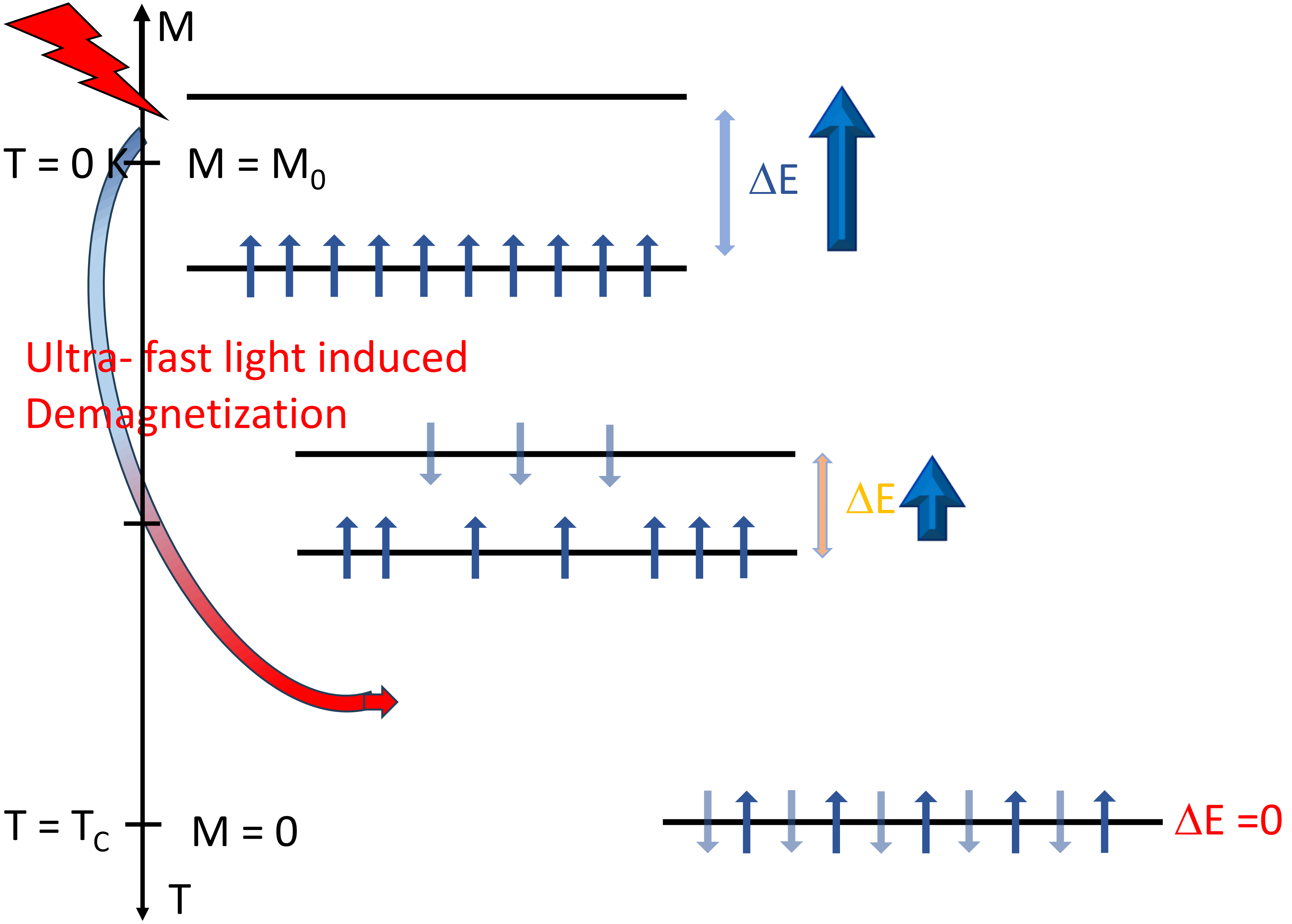
*M. Beens et al., Phys. Rev. B **102**, 054442 (2020)*

*Q. Remy Phys. Rev. B **107**, 174431 (2023)*

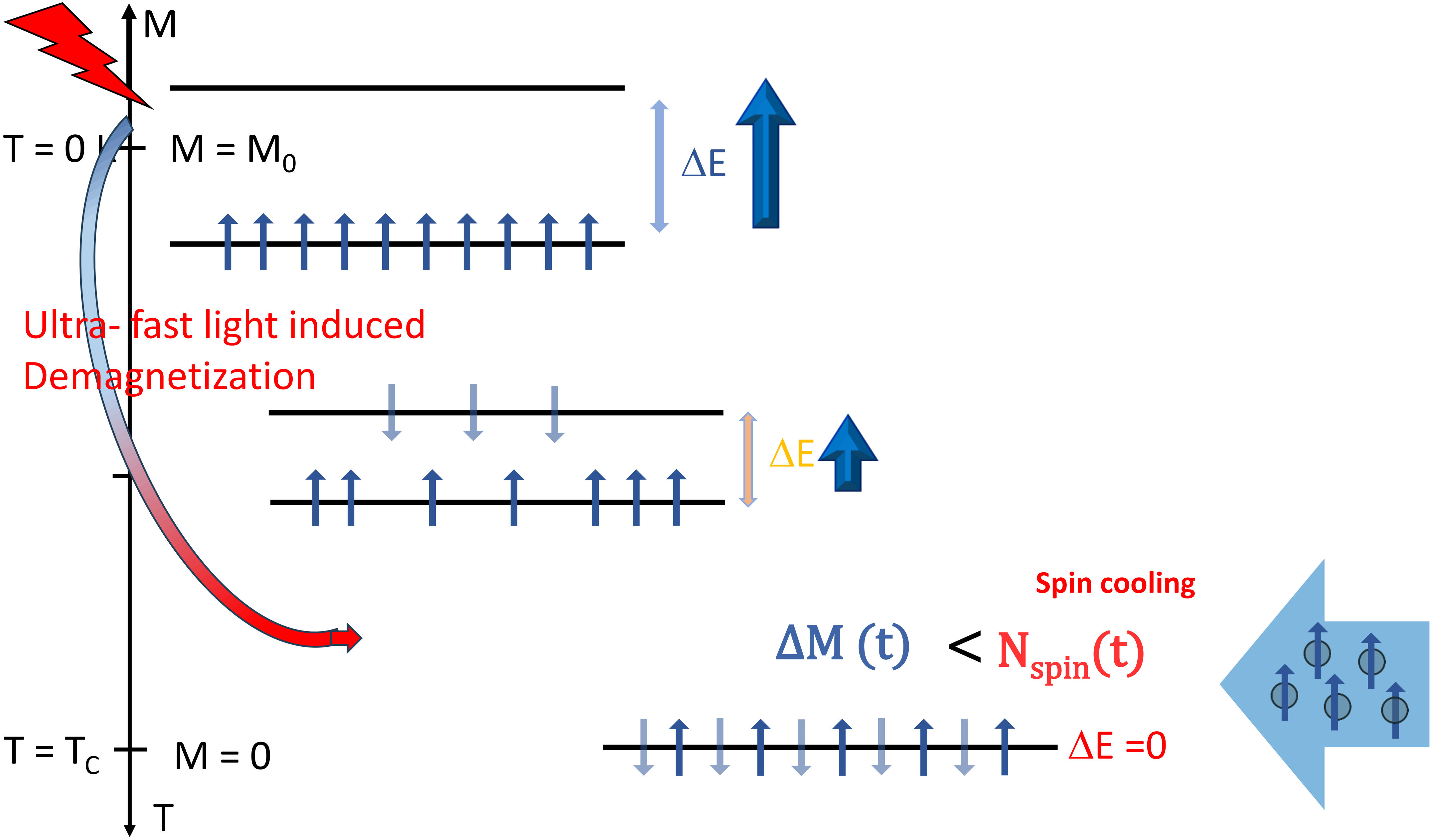
Ultrafast switching = demagnetization + remagnetisation



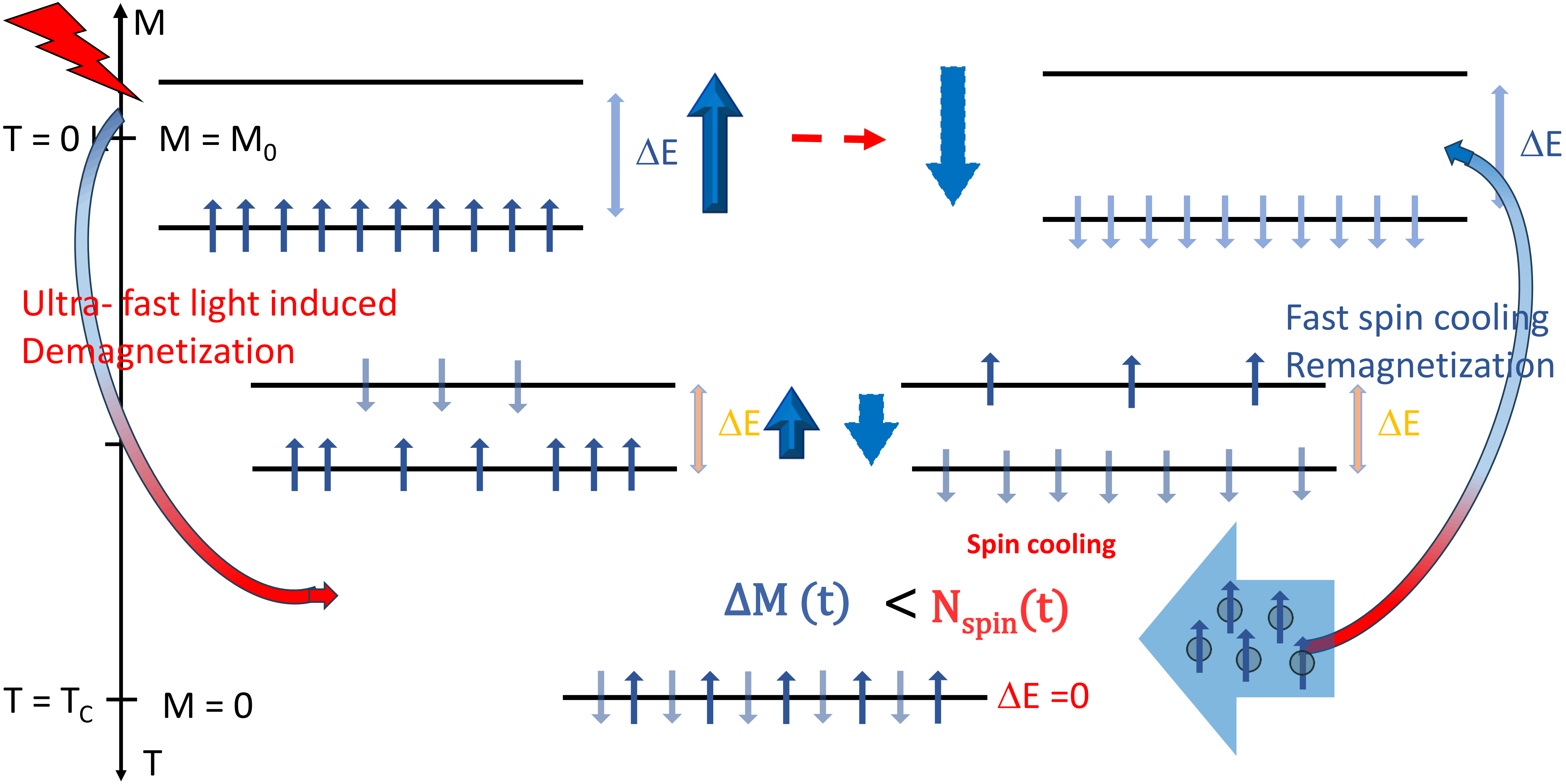
Ultrafast switching = demagnetization + remagnetisation



Ultrafast switching = demagnetization + remagnetisation



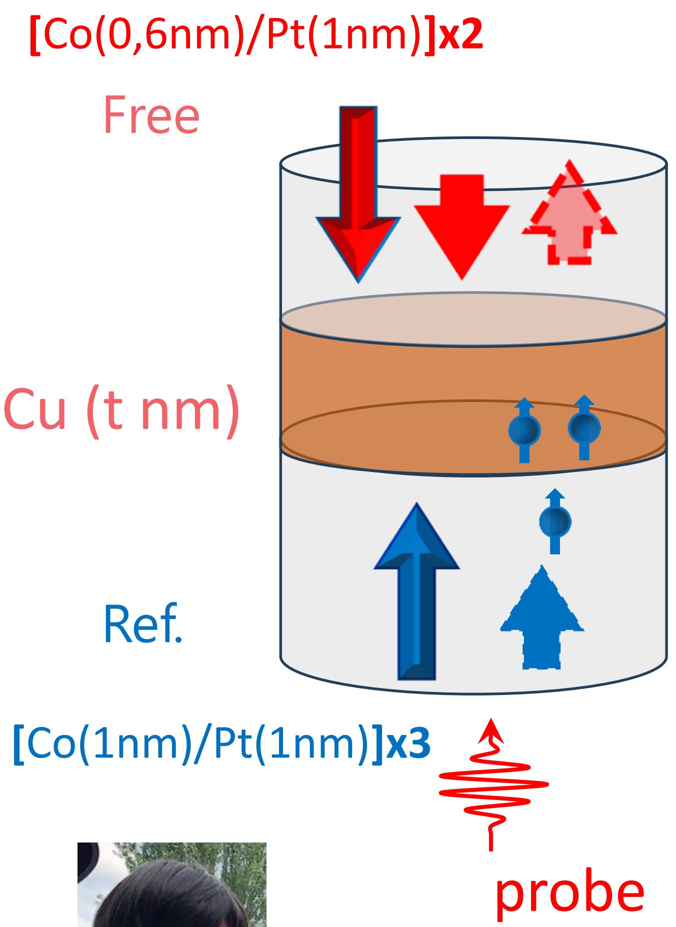
Ultrafast switching = demagnetization + remagnetisation

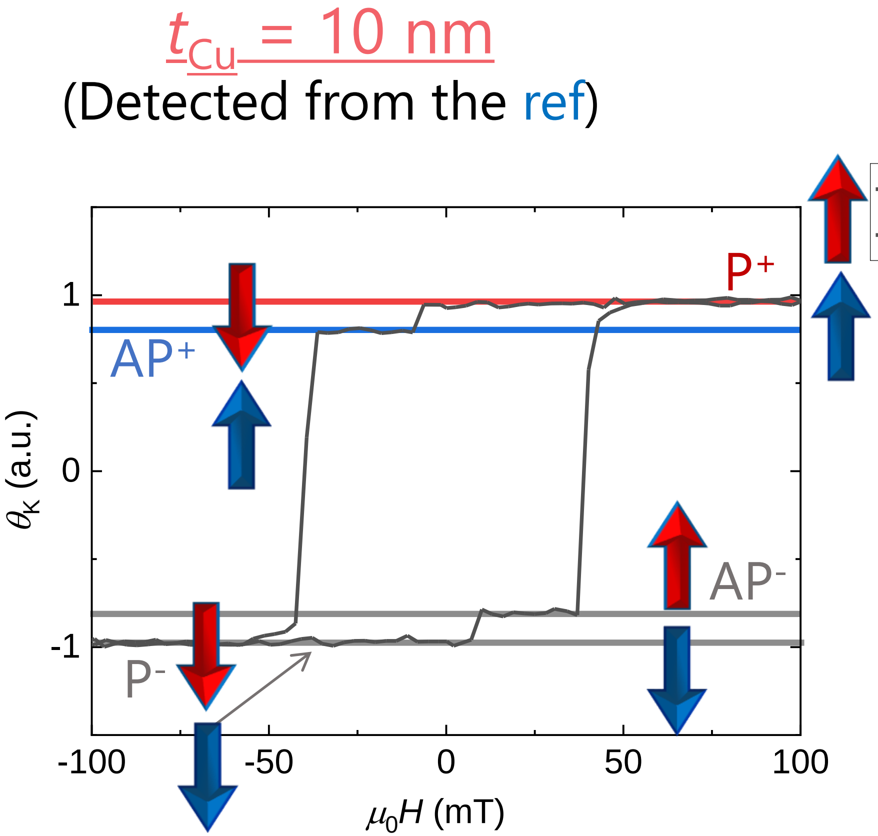


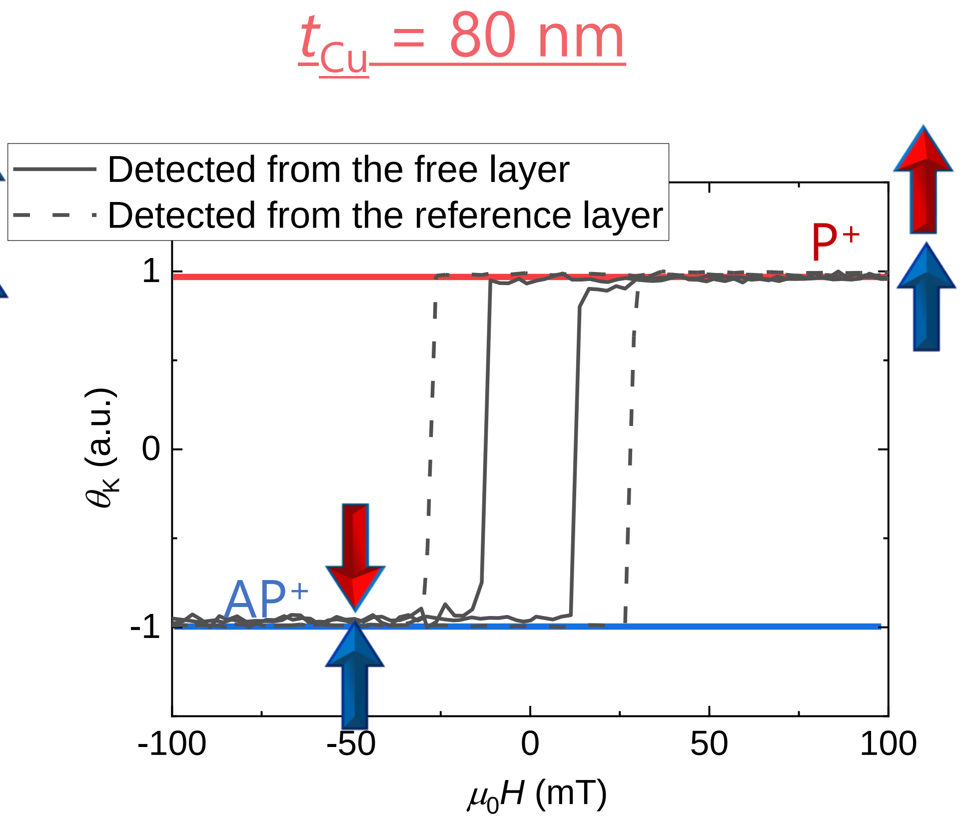
Oulines

- Current Vs Light Induced switching
- Light Induced switching : demagnetization driven switching
- Experimental results showing:
  single pulse – ultra-fast – deterministic –low energy switching
- Conclusions

[Co/Pt] /Cu(t nm) /[Co/Pt]



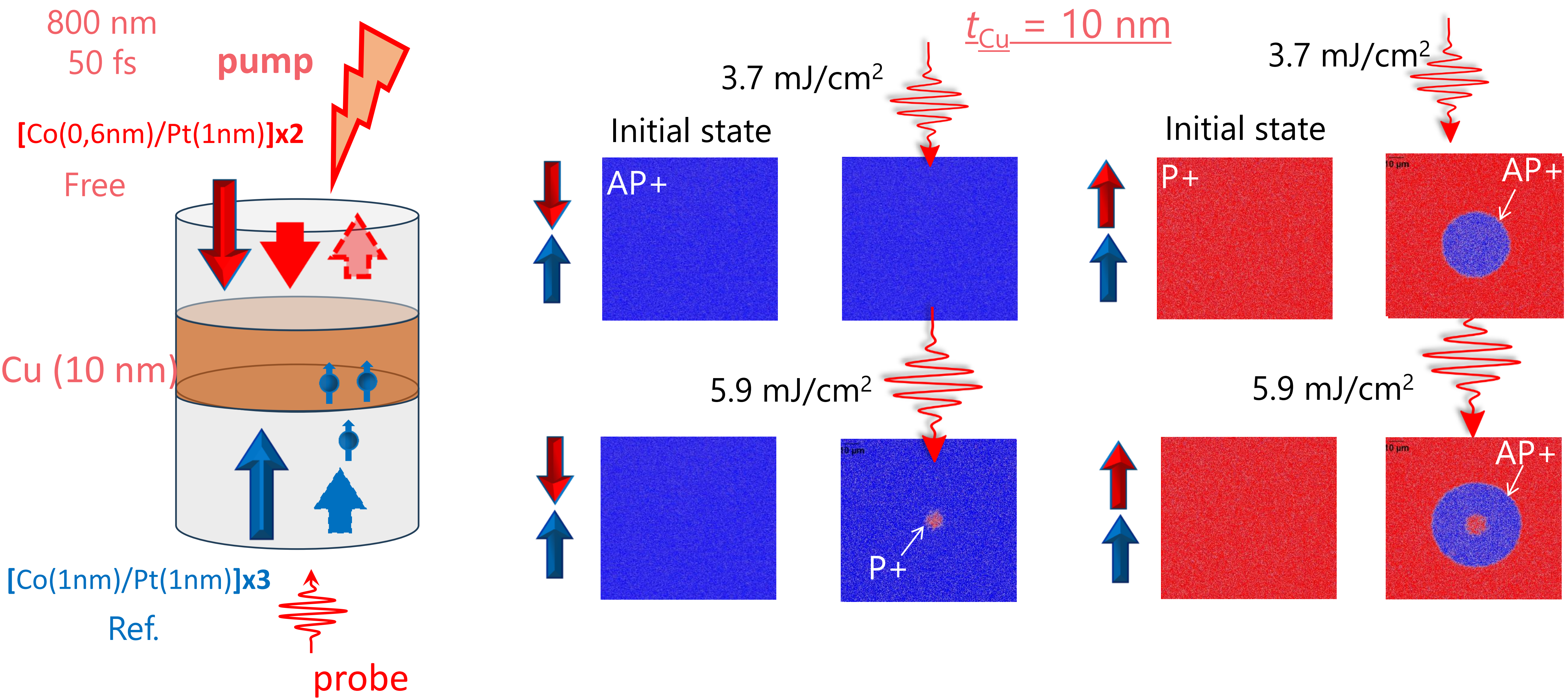




Junta Igarashi
AIST

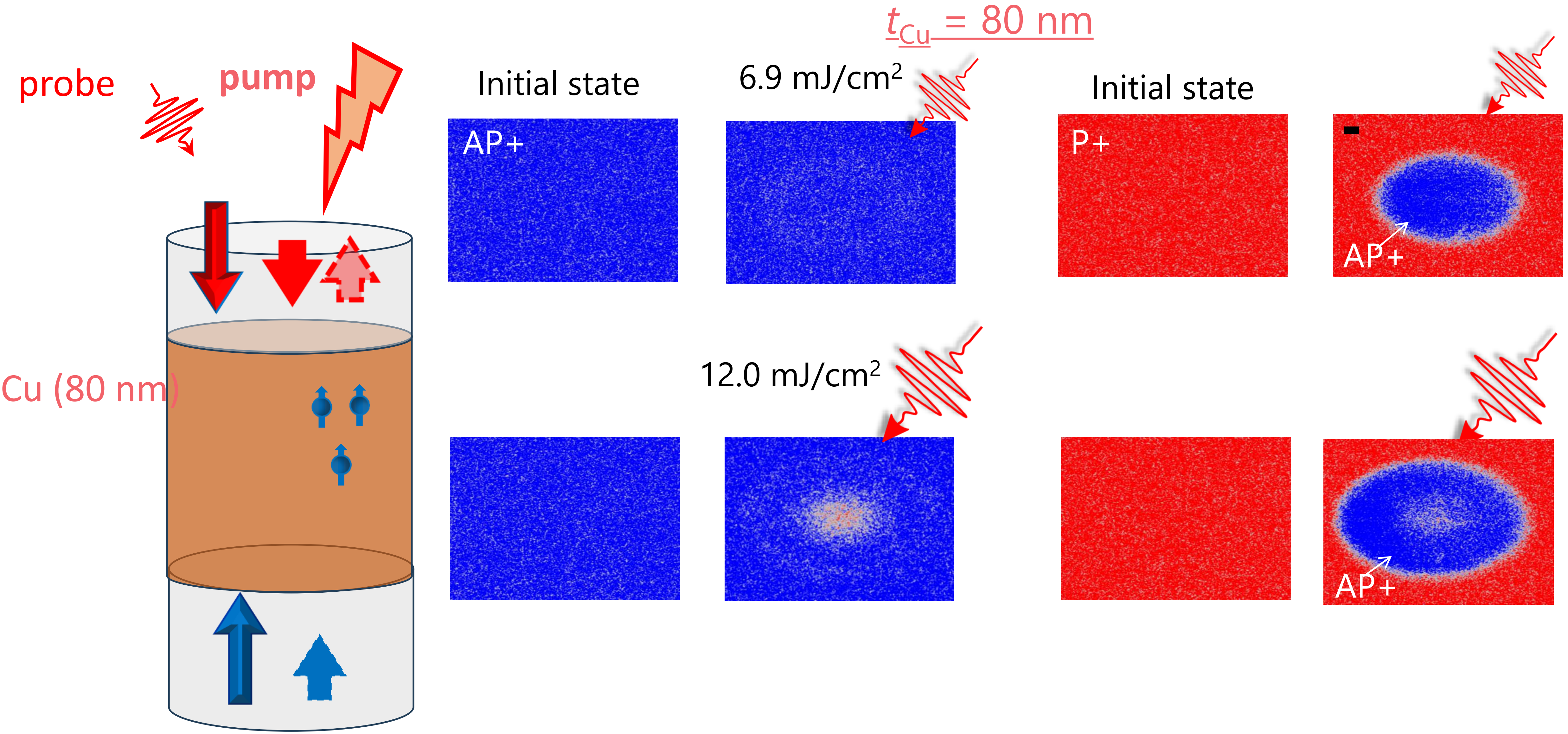
J. Igarashi, et al Nature Mat, **114** 36 (2023)

[Co/Pt] /Cu(t nm) /[Co/Pt]



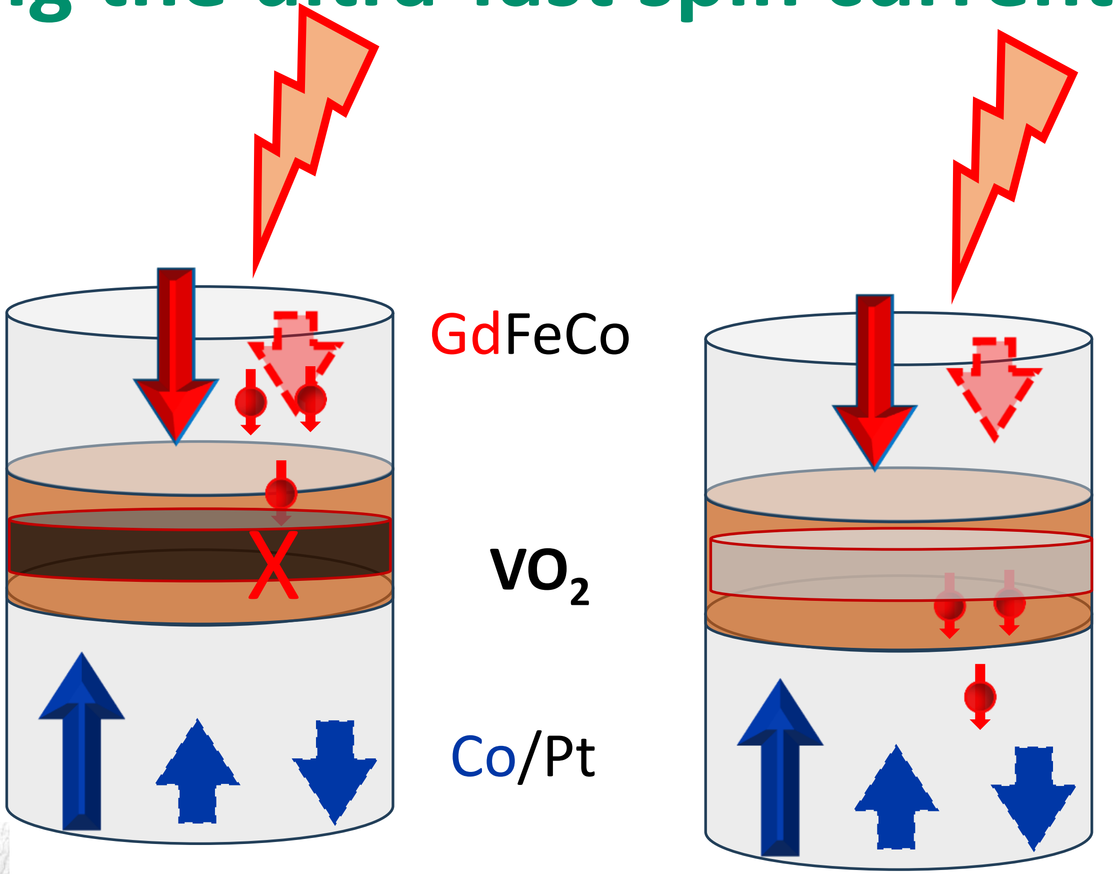
J. Igarashi, et al Nature Mat, **114** 36 (2023)

A [Co/Pt] /Cu(t nm) /[Co/Pt]



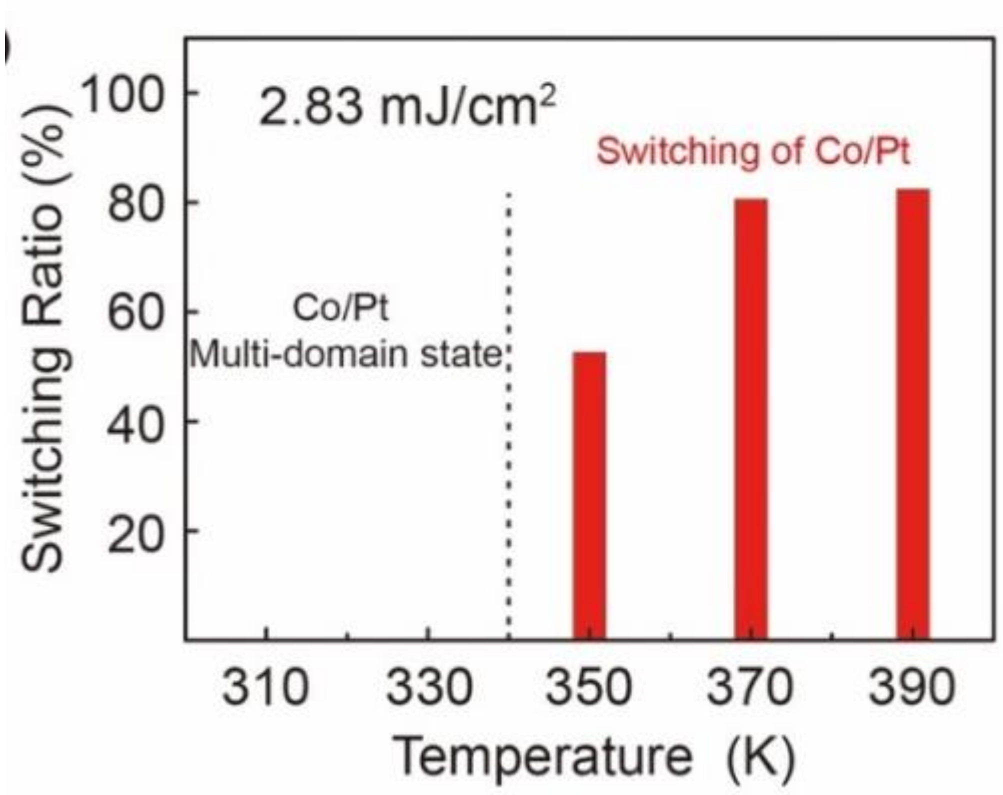
J. Igarashi, et al Nature Mat, **114** 36 (2023)

Stopping the ultra-fast spin current



VO_2 (insulator)
Low temperature

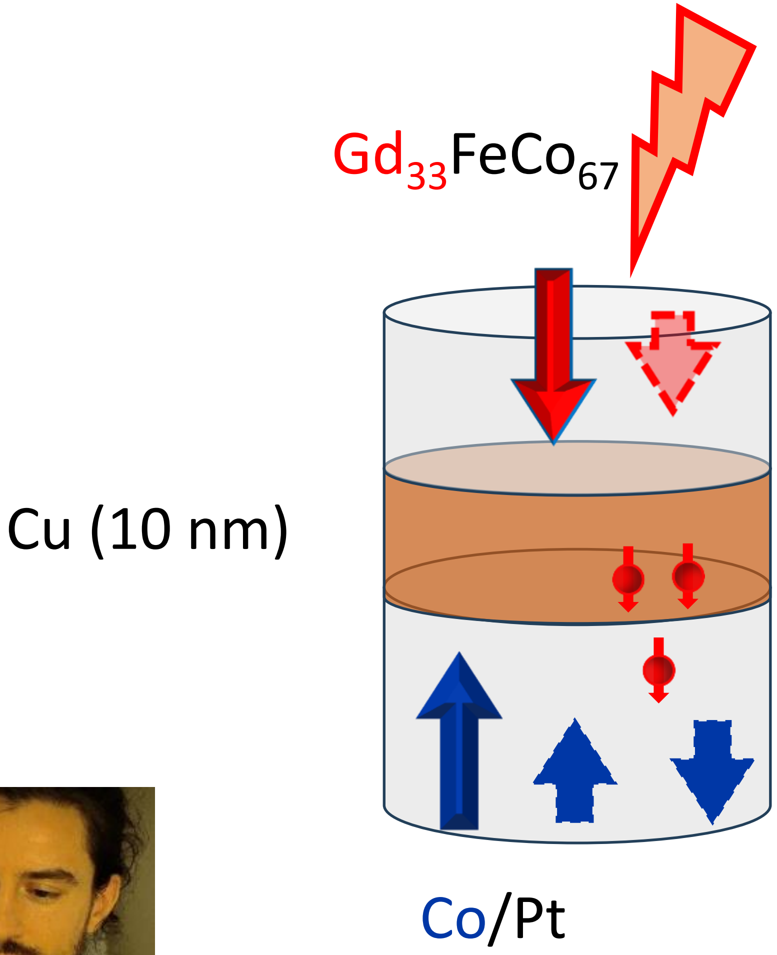
VO_2 (conductor)
High temperature



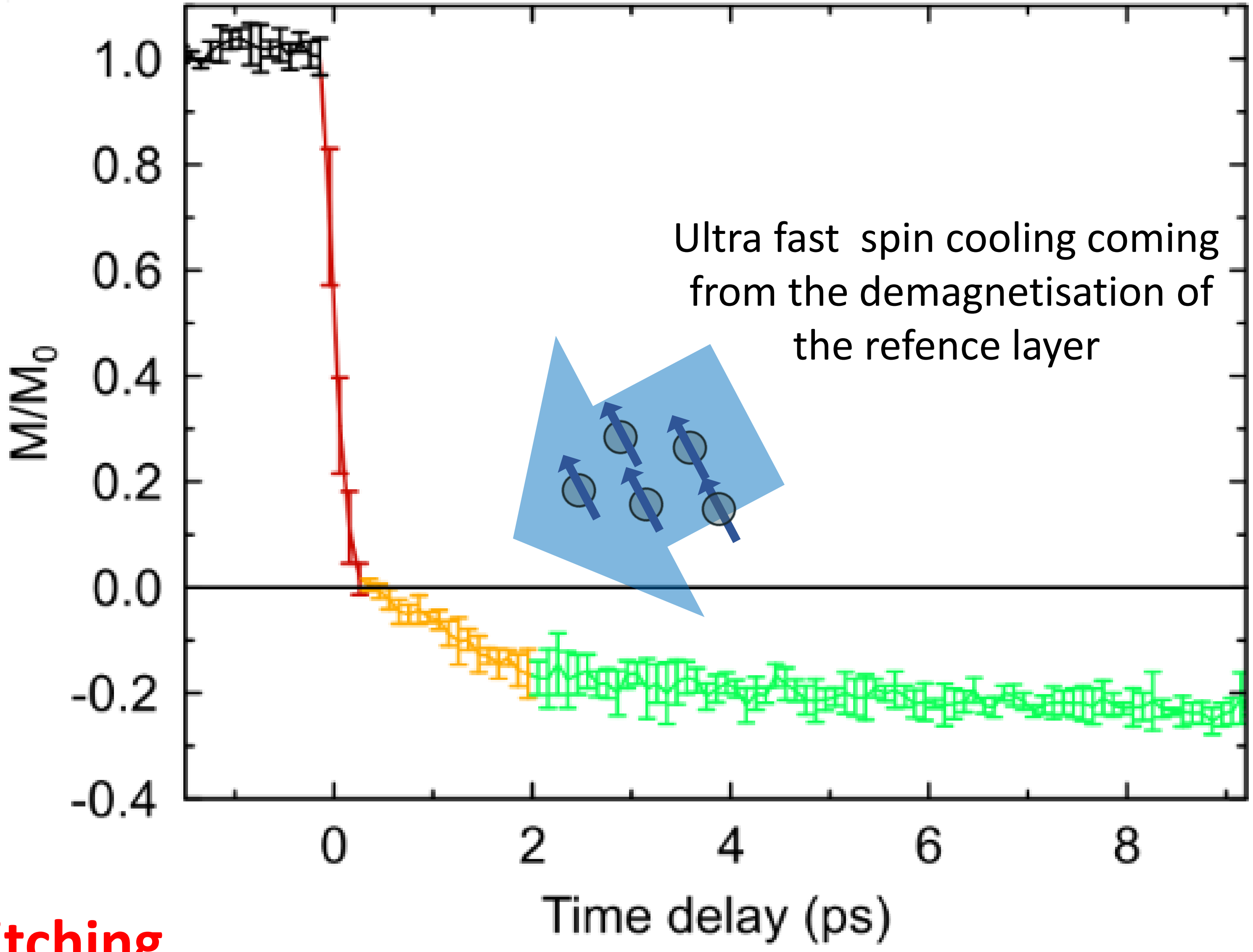
Xiaofei Fan
Beihang University

X. Fan et al Advanced Electronic Materials 8 (10), 2200114 *(2022)*

Ultra-fast magnetisation switching AP to P



Quentin Remy
Frei Universitat Berlin

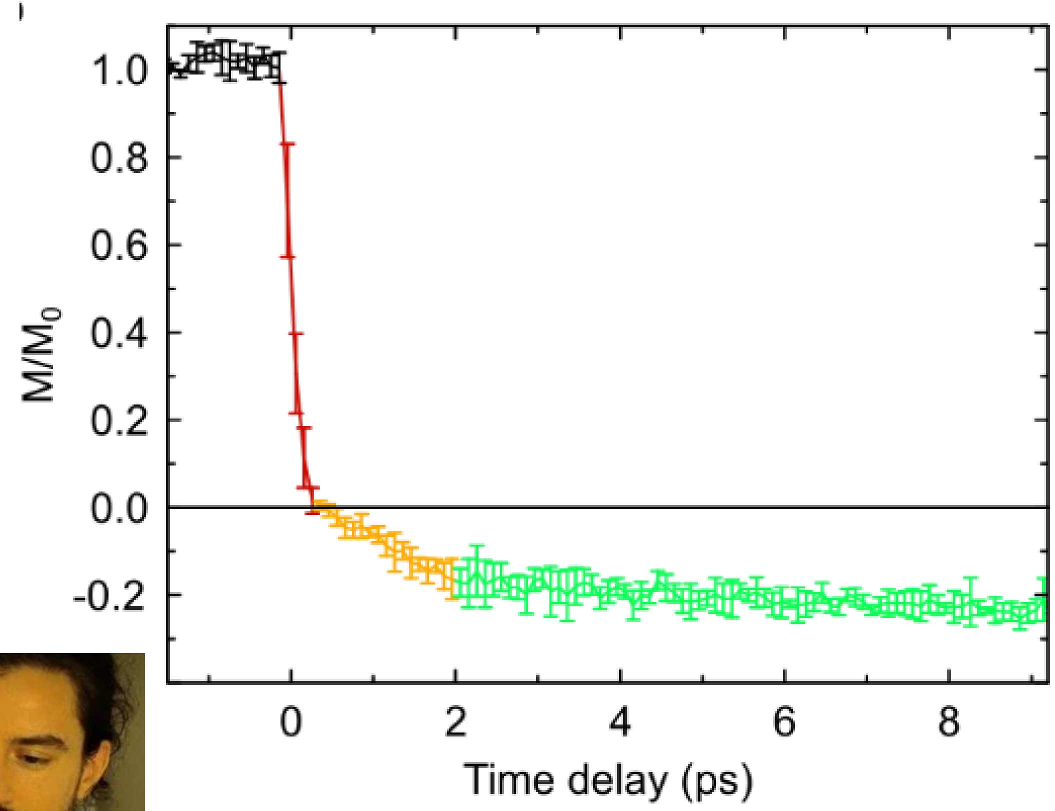


Ultra-fast switching

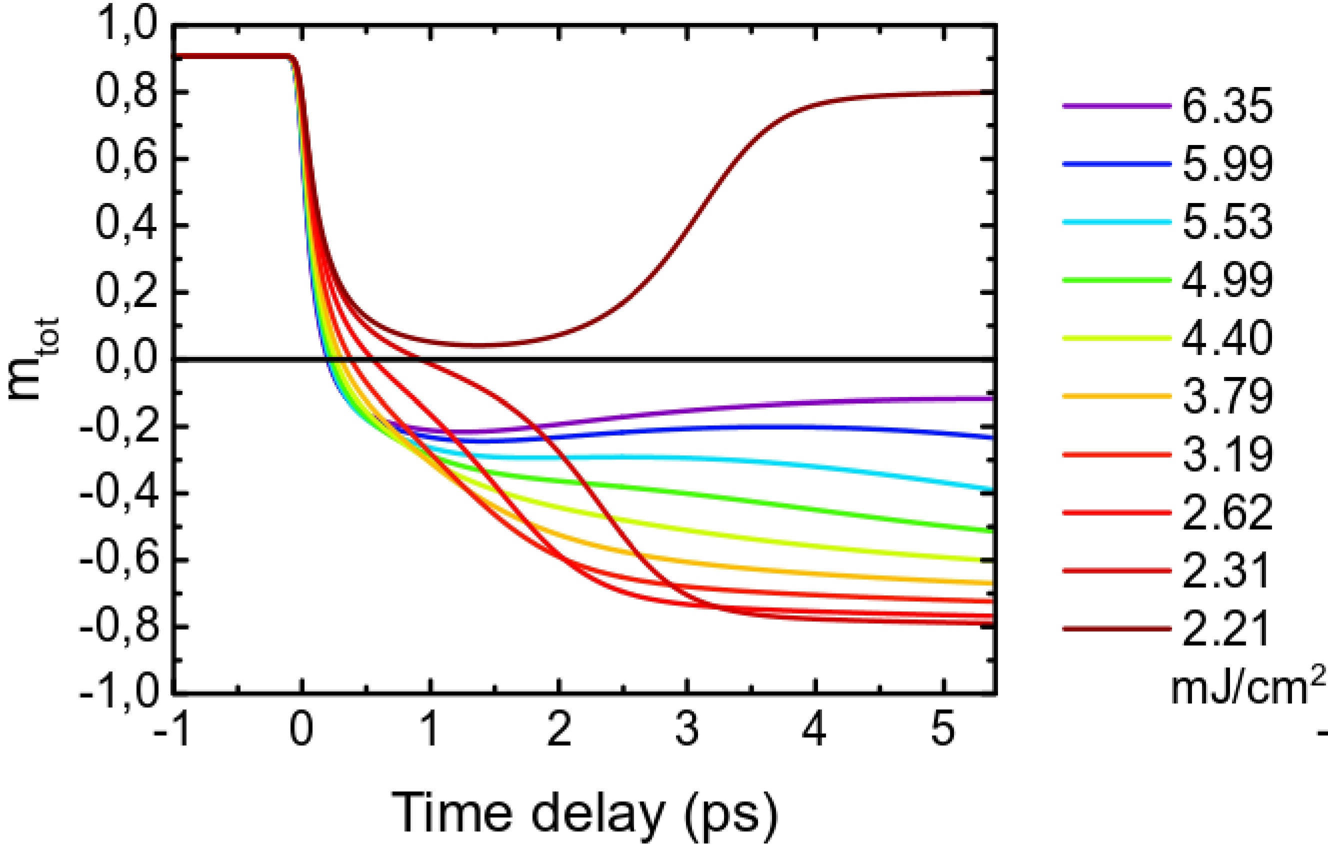
Q. Remy et al Nature Com 14 (1), 445 (2023)

Ultra-fast magnetisation switching

Experiment



Theory

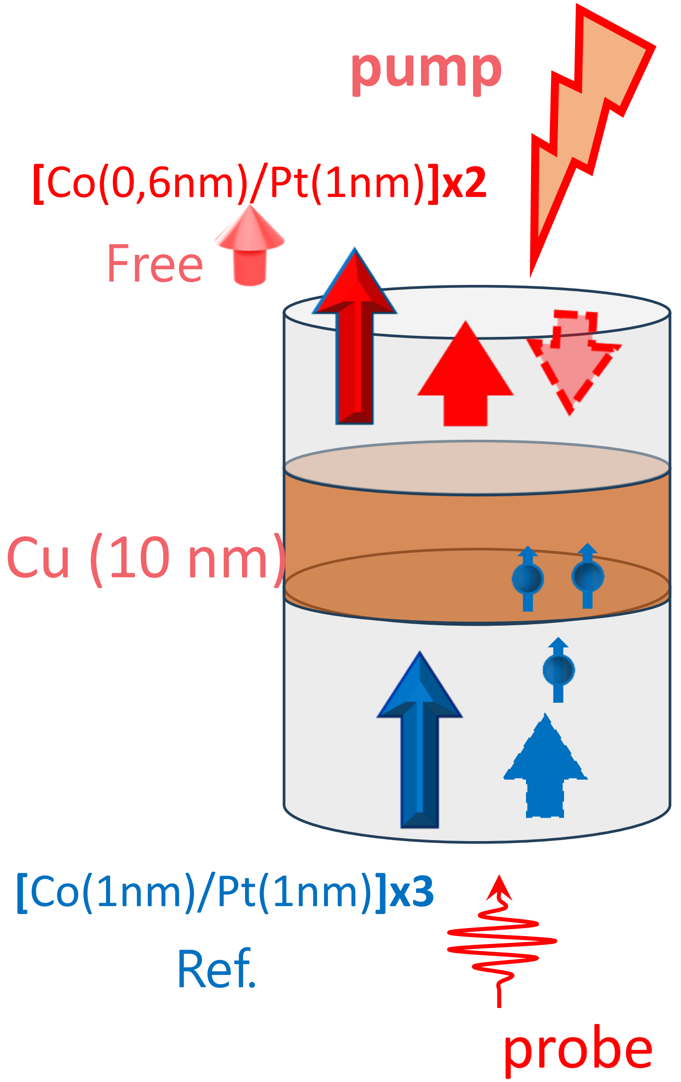


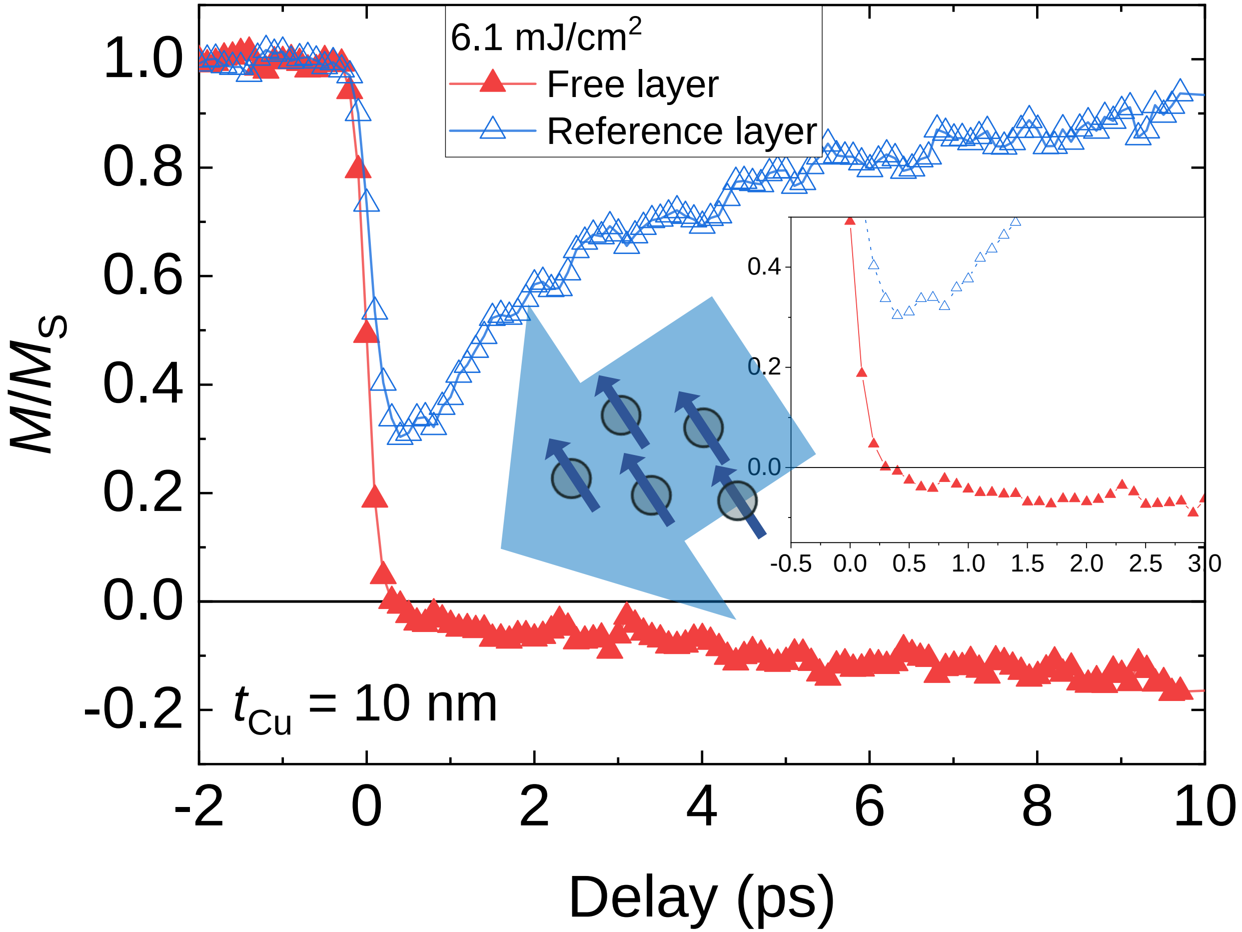
Quentin Remy
Frei Universitat Berlin

Q. Remy et al Nature Com 14 (1), 445 (2023)

Ultra-fast magnetisation switching P to AP

Ultra fast spin cooling coming from the remagnetisation of the refence layer

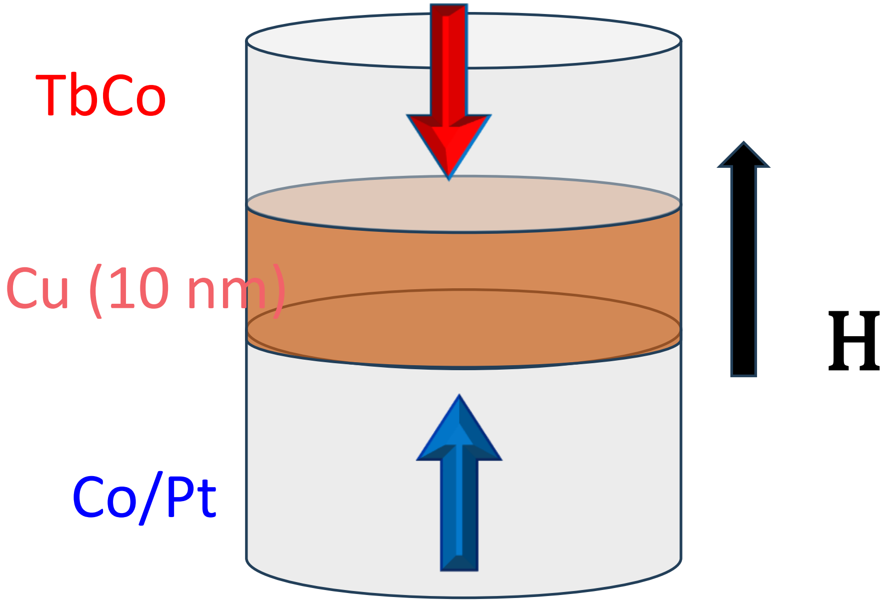


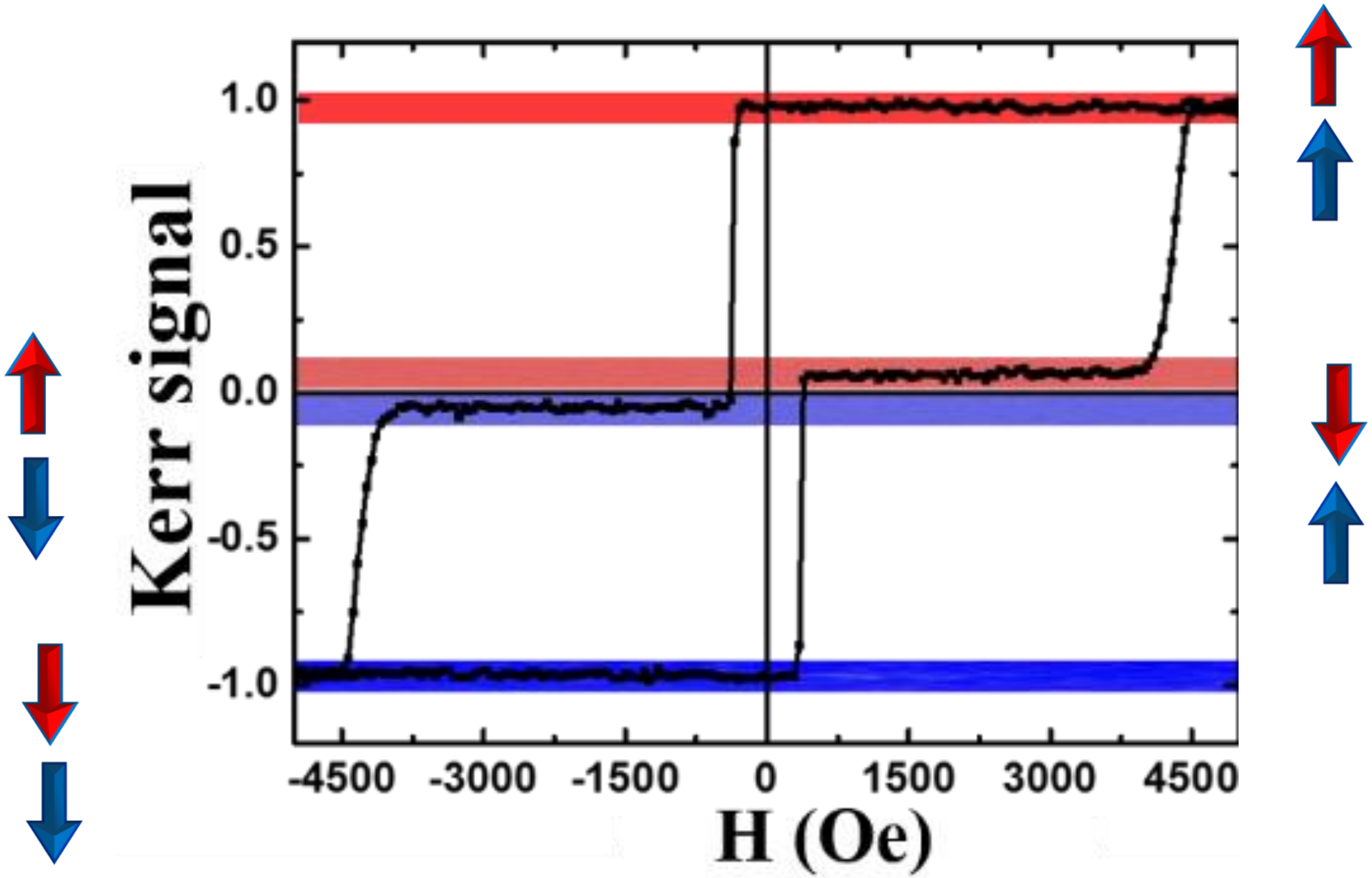


J. Igarashi, et al Nature Mat, **114** 36 (2023)

H. Singh et al to be published

Deterministic Switching in TbCo/Cu/[Co/Pt]





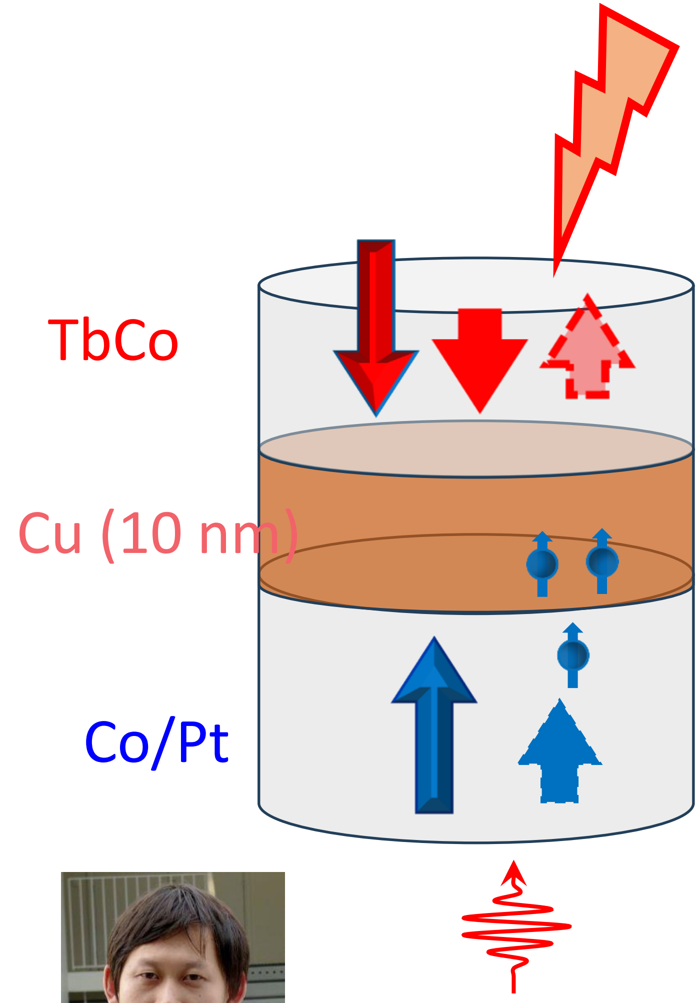
$H_{TbCo} >> H_{Co/Pt}$

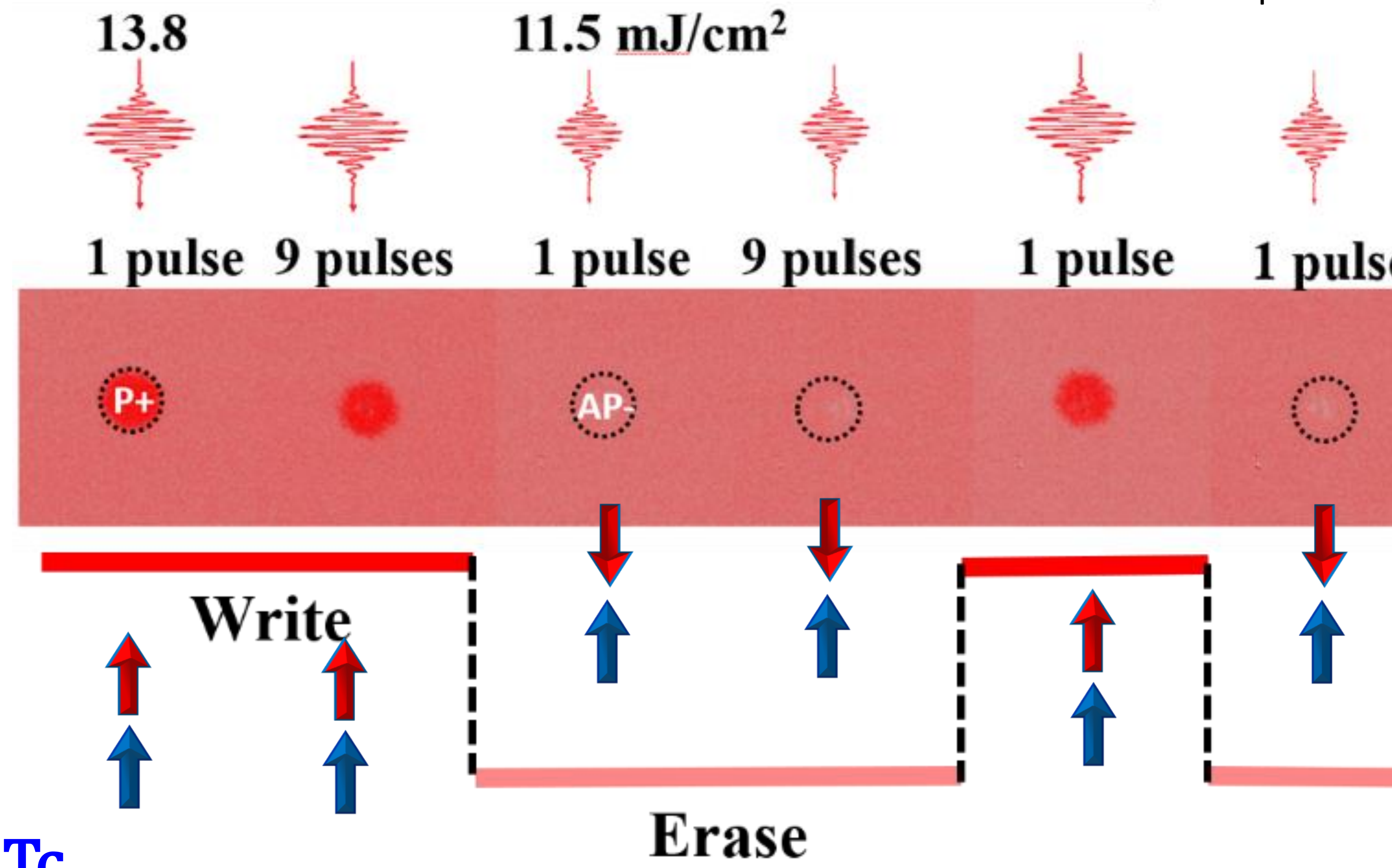
Wei Zhang
Beihang University

W. Zhang et al submitted

Deterministic Switching in TbCo/Cu/[Co/Pt]

Pulse duration of 2 ps

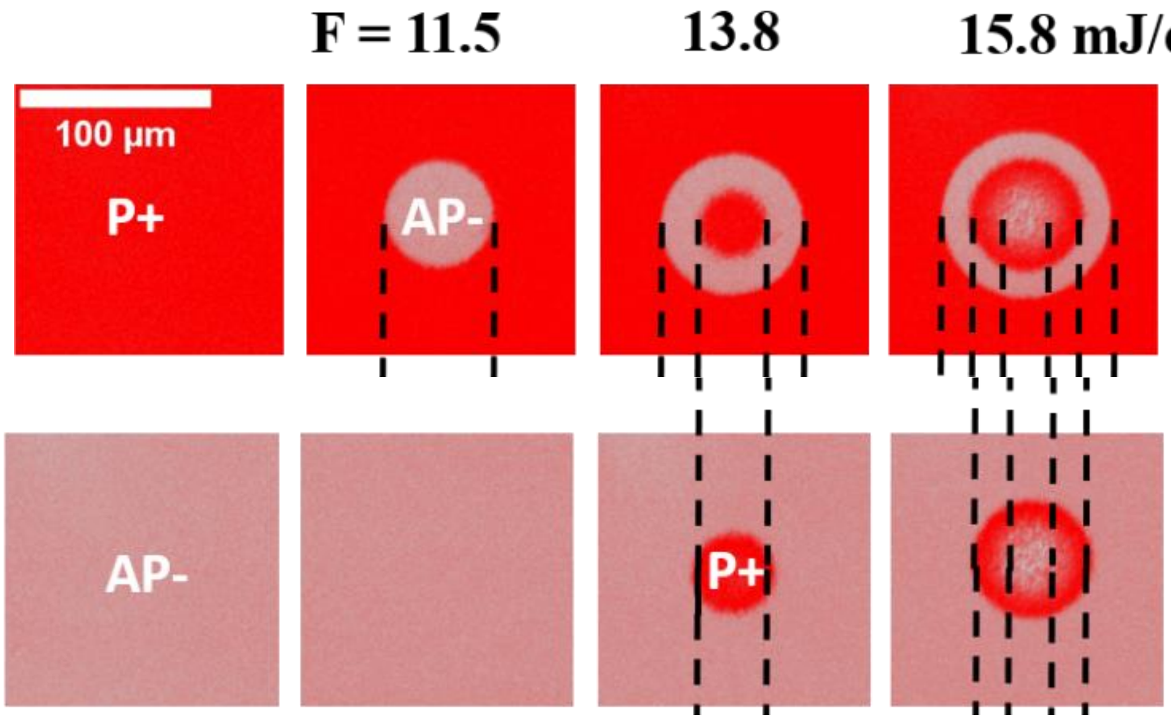


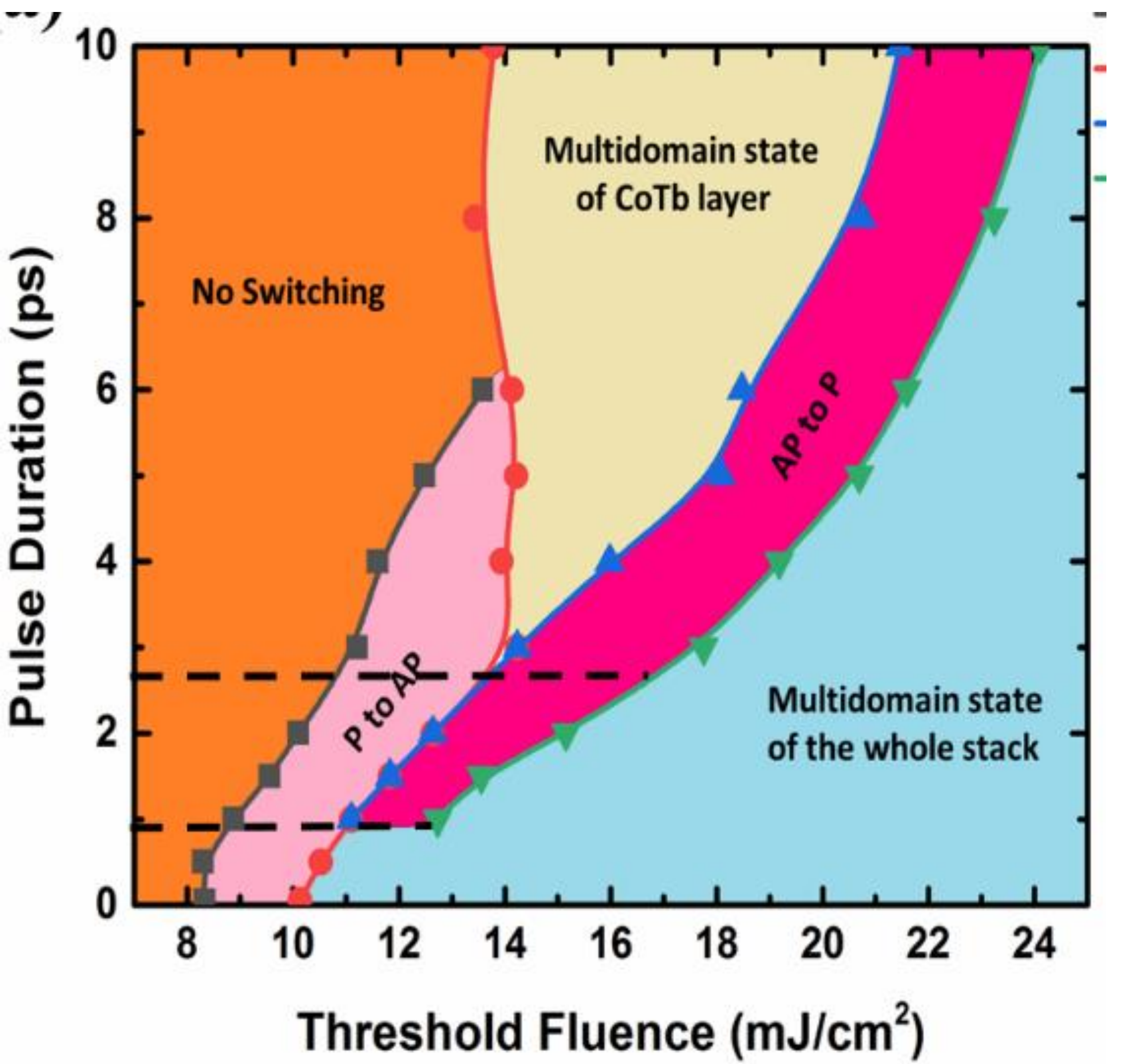


$Tc_{TbCo} < Tc_{Co/Pt}$

Deterministic Switching in TbCo/Cu/[Co/Pt]

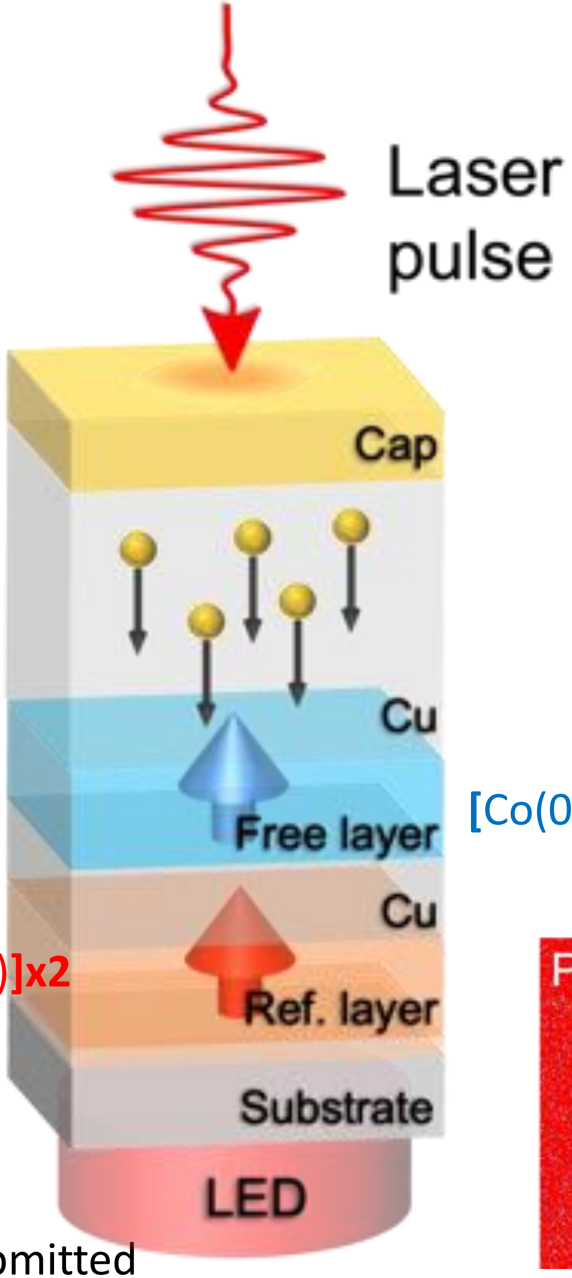
Pulse duration of 2 ps





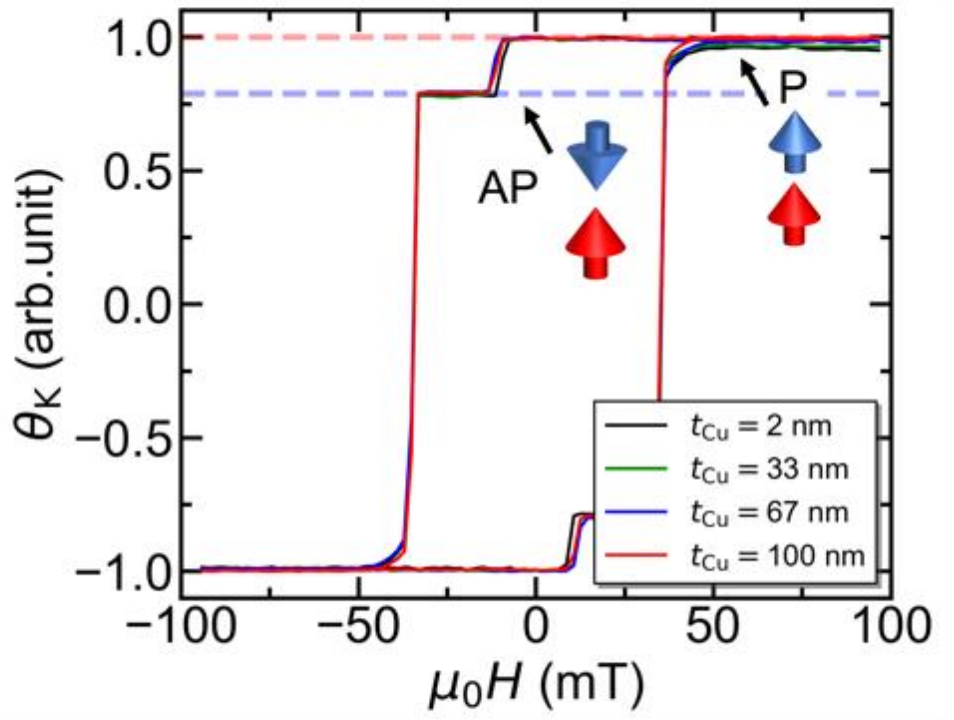
Light induced switching ?

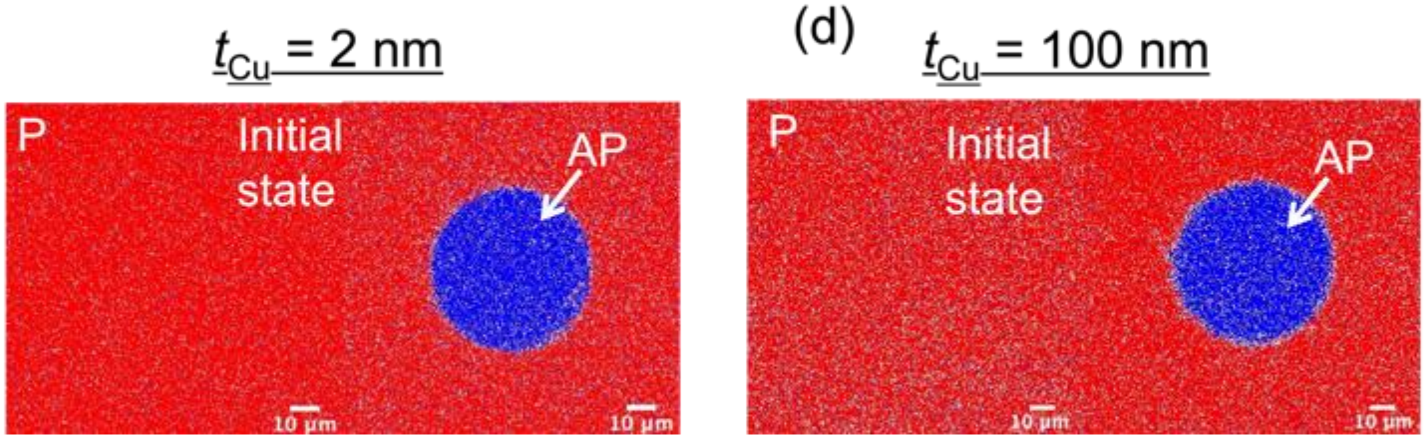
Kazuaki Ishibashi



[Co(0,6nm)/Pt(1nm)]**x2**

[Co(0.6nm)/Pt(1nm)]**x2**

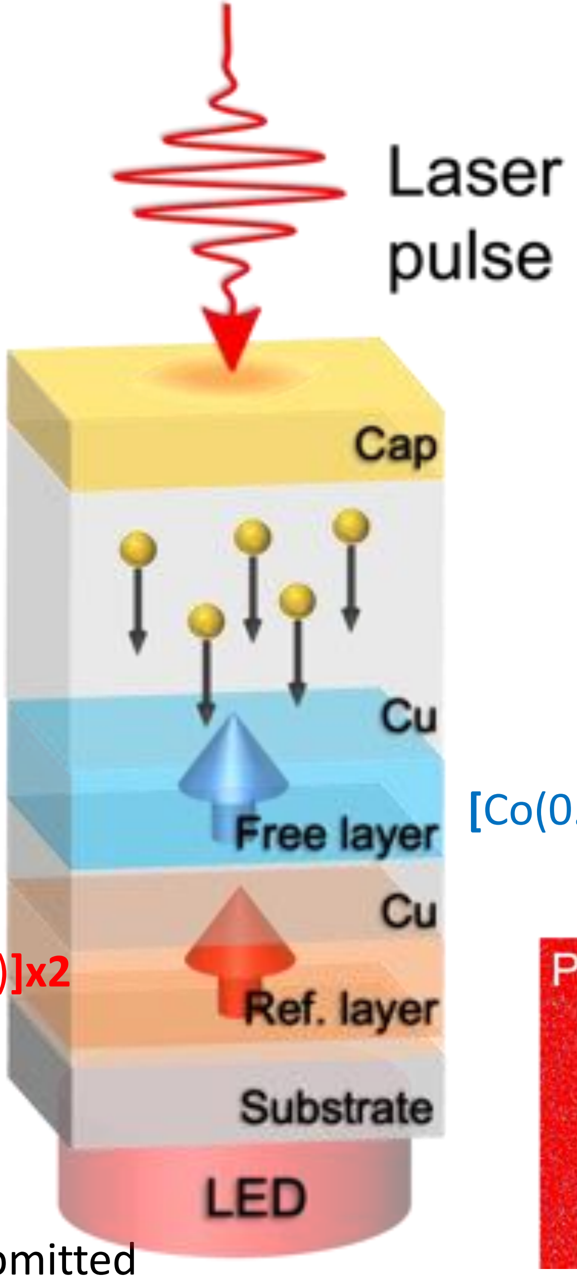




K. Ishibashi et al submitted

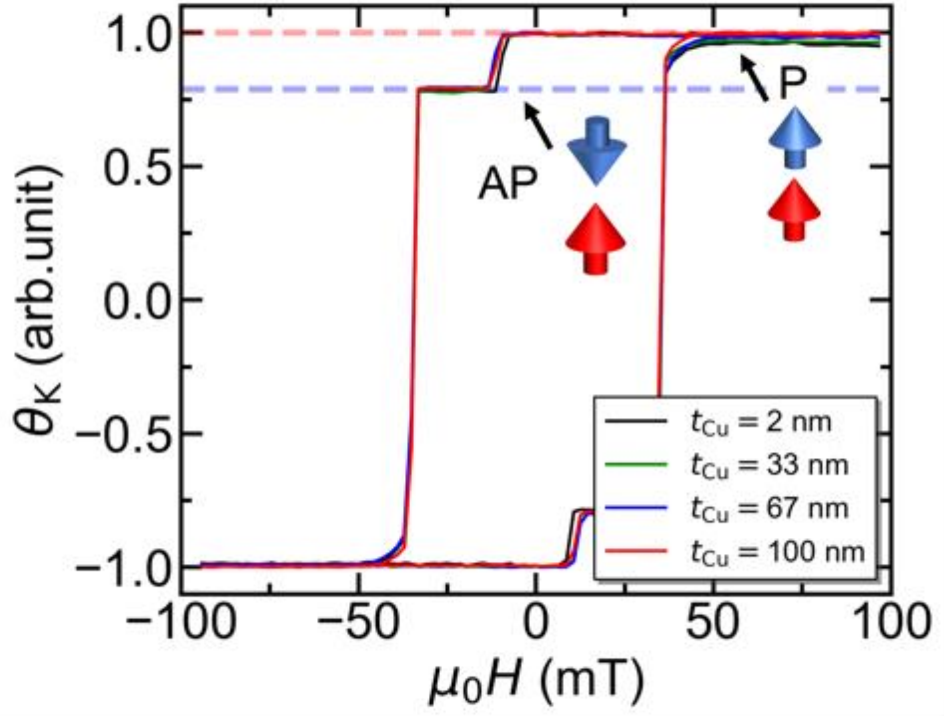
Light induced switching : heat induced switching

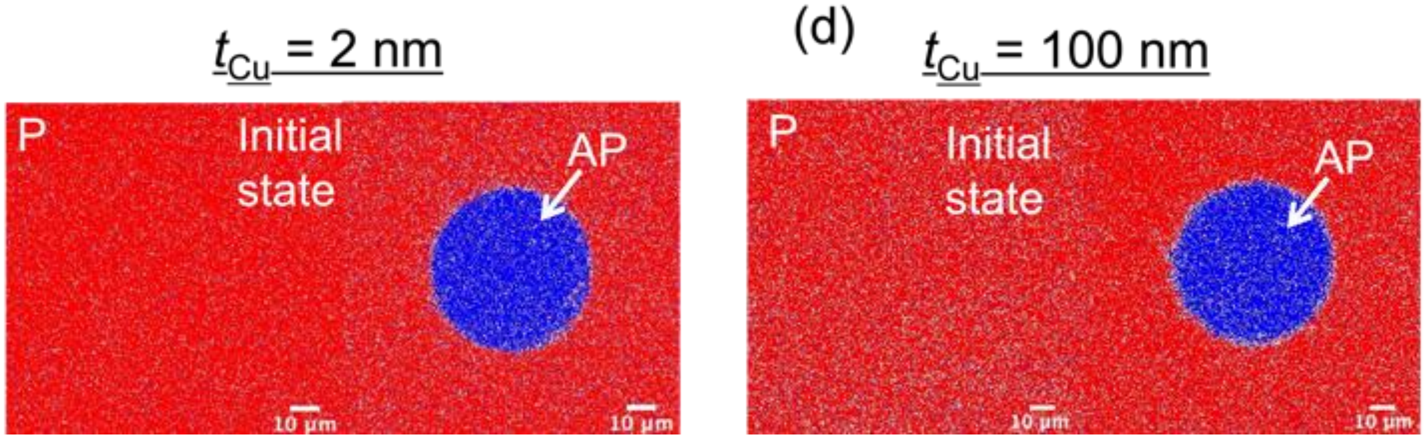
Kazuaki Ishibashi



[Co(0.6nm)/Pt(1nm)]x2

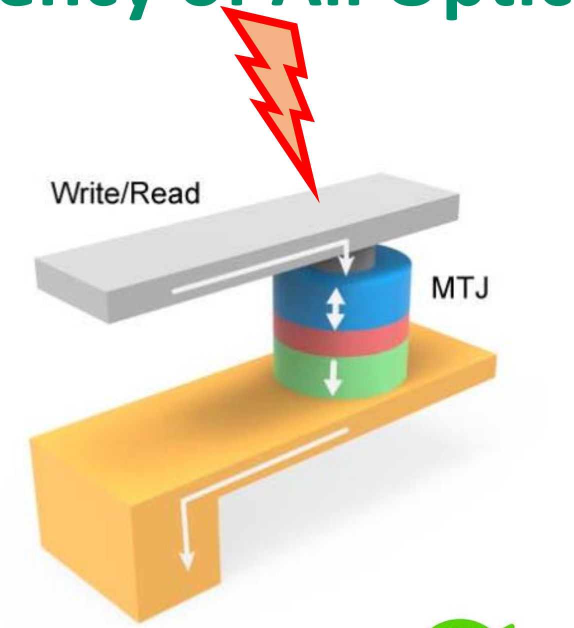
[Co(0,6nm)/Pt(1nm)]x2





K. Ishibashi et al submitted

Efficiency of All Optical Switching M-RAM



Switching time: 1ps ✓

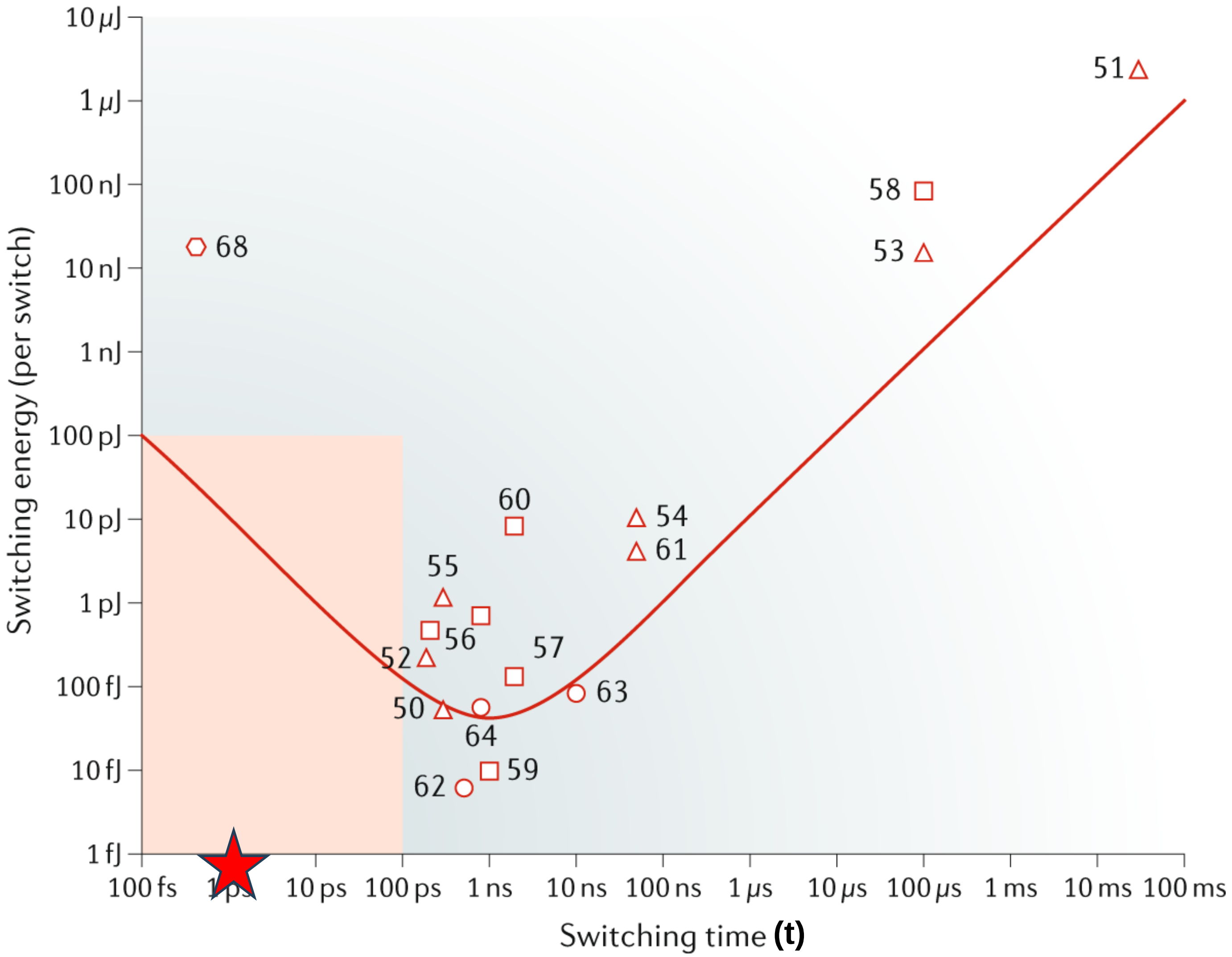
Fluence = 10 mJ/cm^2

Device area = 10 nm × 10 nm = 10^{-10} cm^2

Energy = 1fJ/bit ✓

Threshold Fluence : Tc ✓

Thermal Stability : ΔU ✓

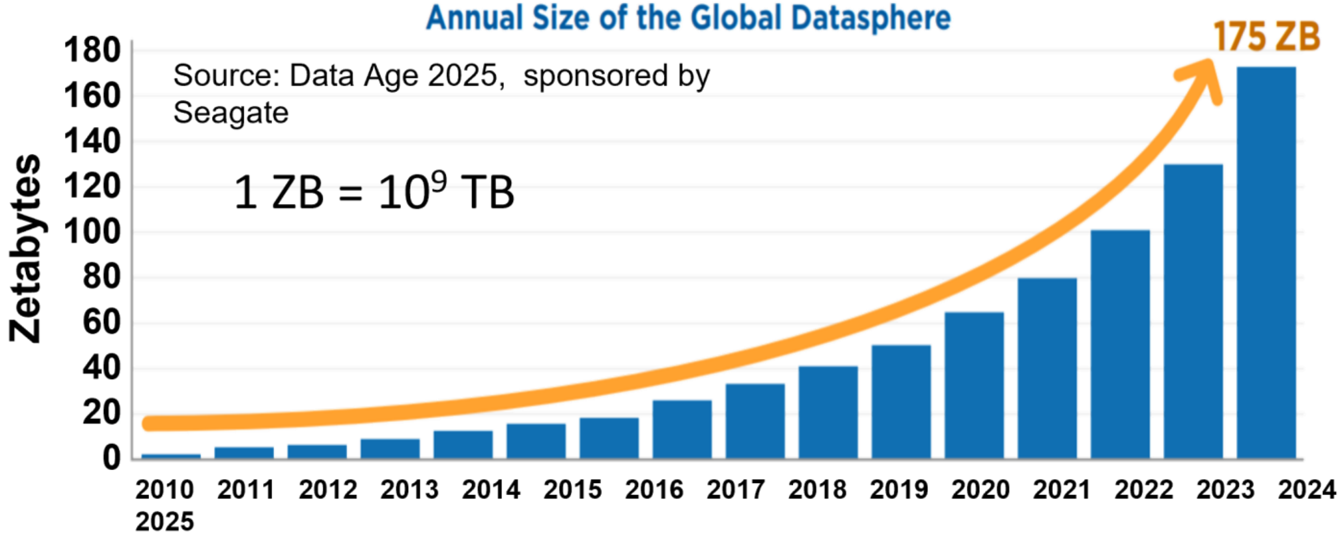


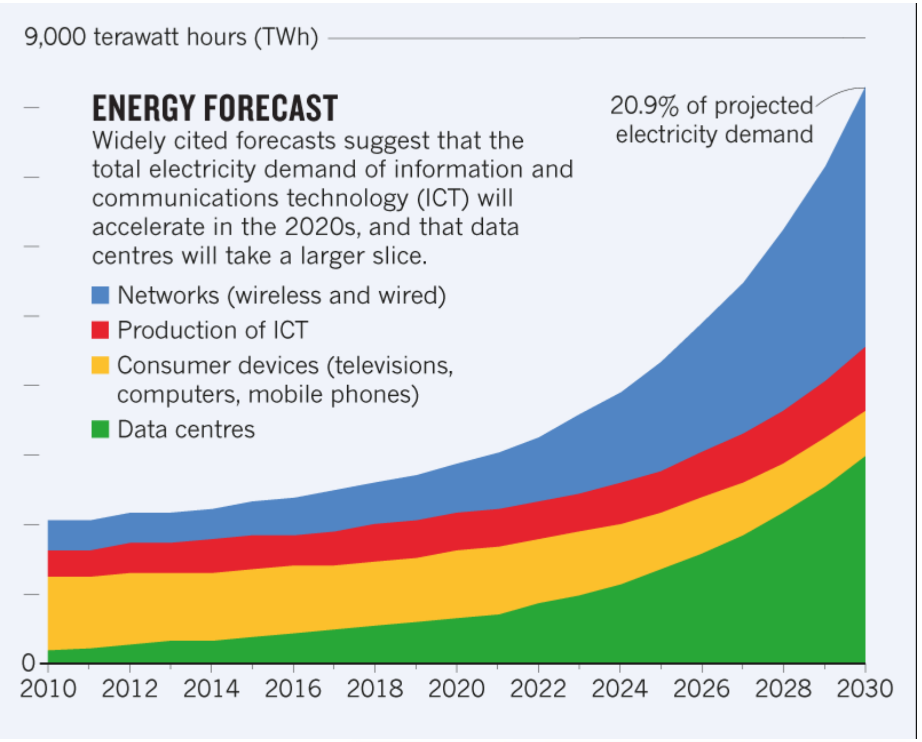
Will it work for small devices ?

Conclusions

- single pulse – Ultra-fast – deterministic –low energy switching
- Switching driven by fast demagnetization or remagnetization
- Synchronization $N_{spin}(t) > \Delta M\,(t)$
-

Digital world : A growing energy cost

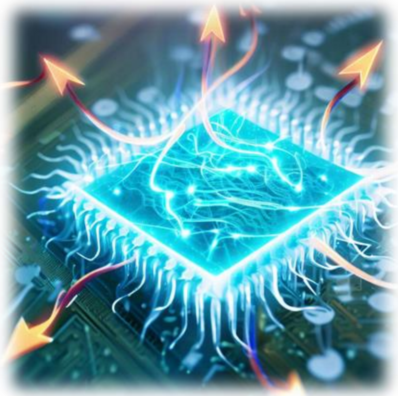




Artificial Intelligence

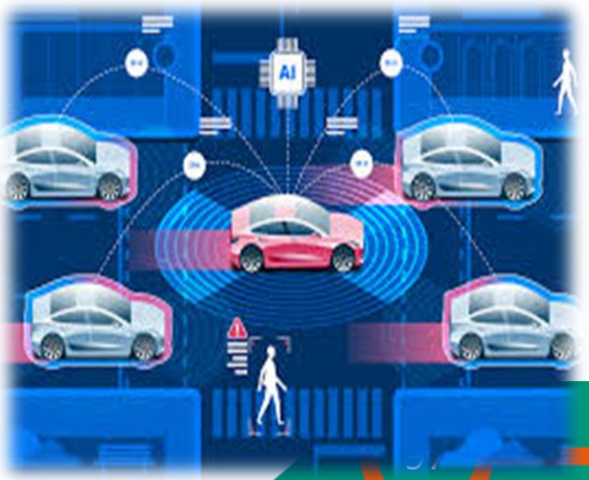
Creating an image with AI: a few Wh vs 40 Wh (laptop battery).

Training Google PALM: 3.5 GWh ≈ 20,000 years of human brain activity.



Autonomous vehicle

If 95% of the car fleet will be autonomous by 2050, the efficiency of digital components will need to double every 18 months to maintain carbon emissions at the current level.



Non volatile

Non Volatile **MRAM**

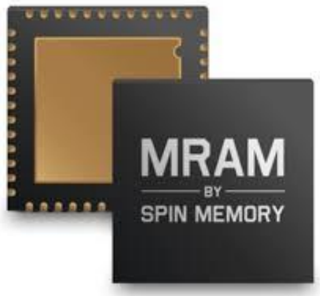
Needs NO Energy to be maintain

Volatile **DRAM SRAM**

Needs Energy to be maintain

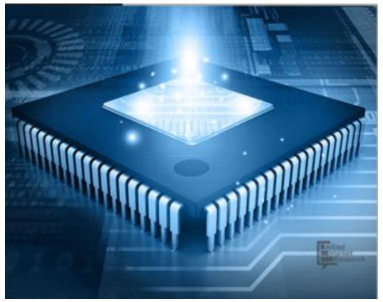
Memory

Hard disk



Magnetic Random Access Memory

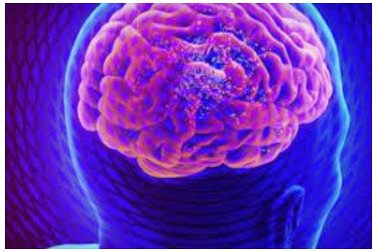
Logic



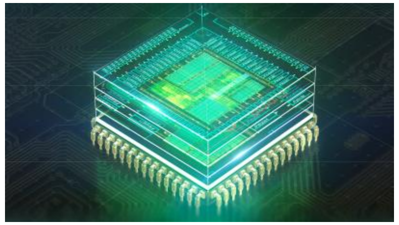
Magnetic logic

Sensors

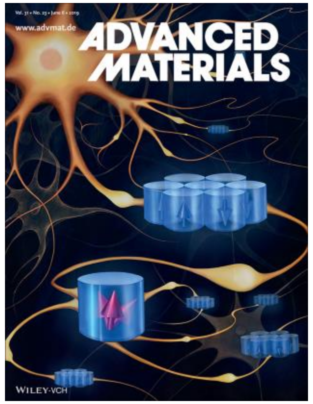
Magnetic sensors



Computing

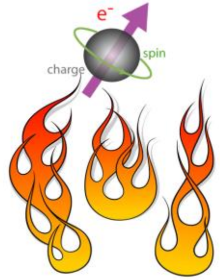


Probabilistic Computing

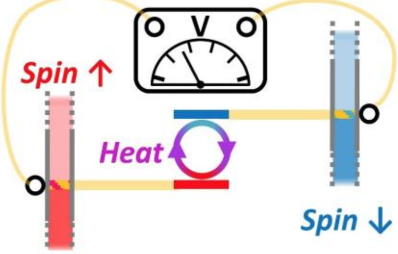


Neuromorphic computing

Energy

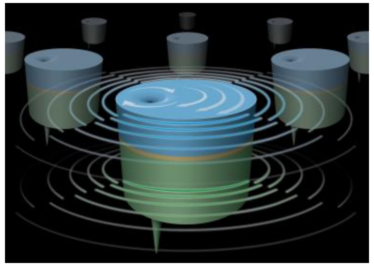


Spin caloritronic



Spin driven electrical power generation

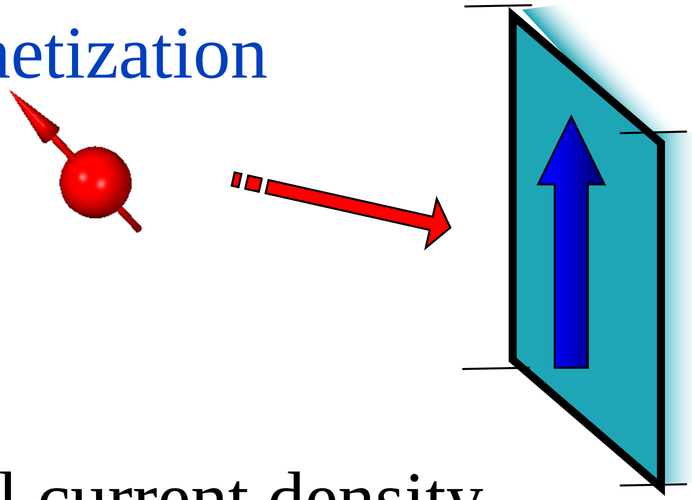
RF devices



Magnetic nano-oscillators

Spintronic

Interaction between : Electron Spin ⟷ magnetization



Influence of magnetization on electron spin

GMR TMR Spin precession

Small current density

Influence of electron spin on magnetization

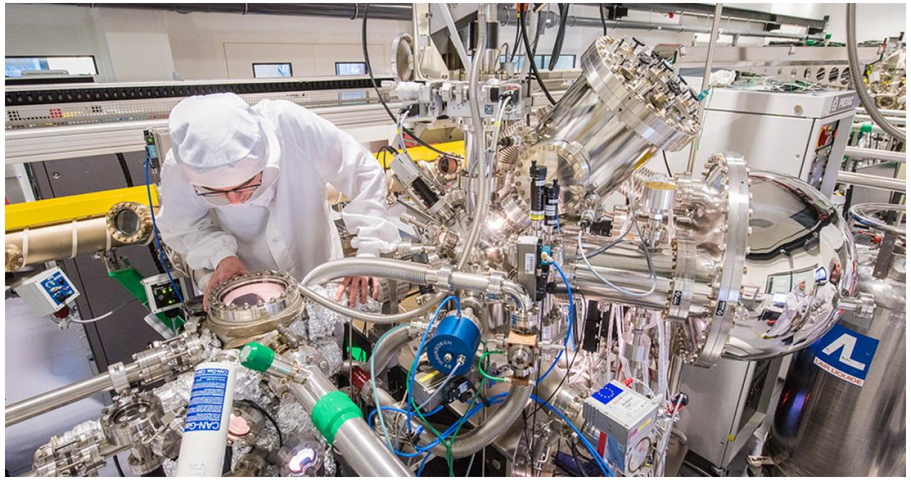
STT SOT

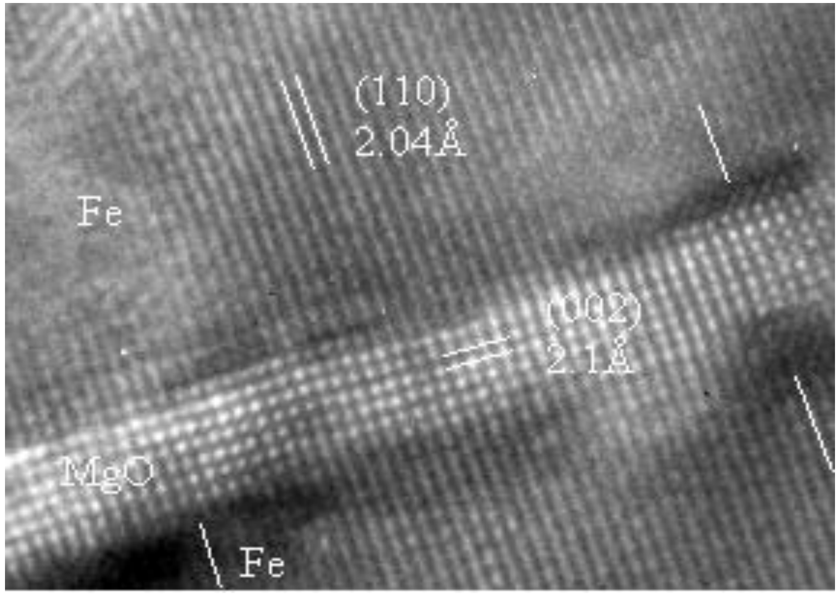
Large current density

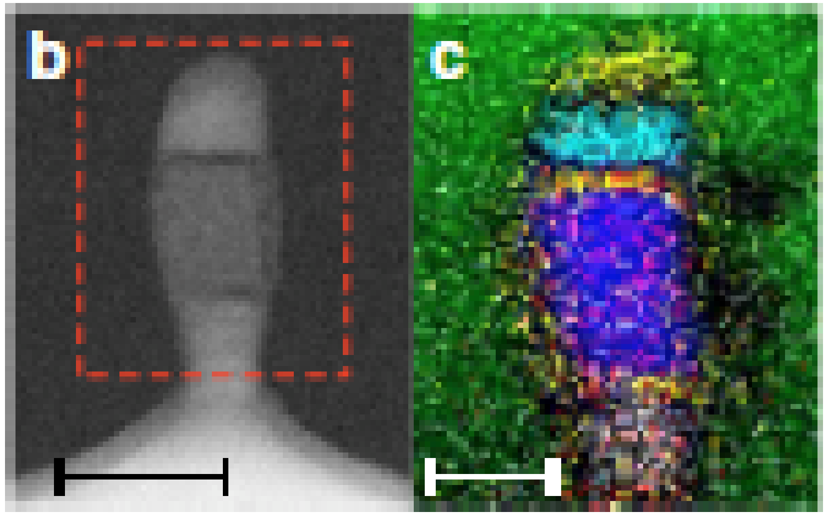
Need to understand the transfer of angular momentum

$$\frac{dL_M}{dt} \Leftrightarrow \frac{dL_S}{dt}$$

Requires nano-technologies







20 nm

20 nm

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Classical approach

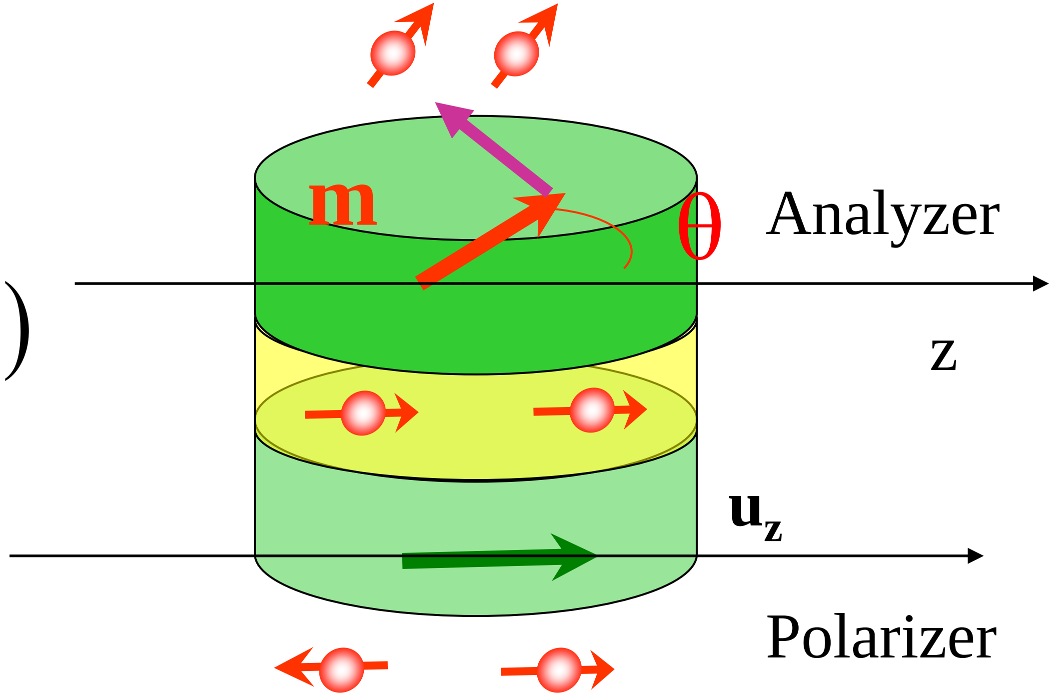
$$N = \frac{Idt}{e}$$

$$\Delta m_e^{\perp} = P_i g \mu_B (\sin\theta)$$

$$-\Delta L_e = \frac{1}{\gamma_0}\frac{Idt}{e} P_i g \mu_B (\sin\theta)$$

Newton second law

$$\mathbf{\Gamma} = \frac{d\mathbf{L}}{dt}$$

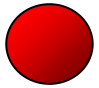


$$\mathbf{\Gamma} = \frac{d\mathbf{L}_e}{dt} = -\frac{1}{\gamma_0}\frac{IP_i g \mu_B}{e}\left(m \wedge (m \wedge u_z)\right)$$

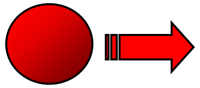
Quantum Mechanic approach

Number

$$n = \mathrm{Re}\sum_{i\sigma} \psi^{*}_{i\sigma}\,\psi_{i\sigma}$$



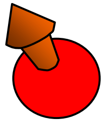
$$\mathbf{j} = \mathrm{Re}\sum_{i\sigma} \psi^{*}_{i\sigma}\,[\hat{\mathbf{v}}]\,\psi_{i\sigma}$$



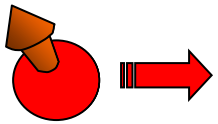
$$\frac{\partial \mathrm{n}}{\partial \mathrm{t}} = -\mathrm{j}$$

Spin

$$\mathbf{m} = \mathrm{Re}\sum_{i\sigma\sigma'} \psi^{*}_{i\sigma}\left[\mathbf{s}_{\sigma,\sigma'}\right]\psi_{i\sigma'}$$



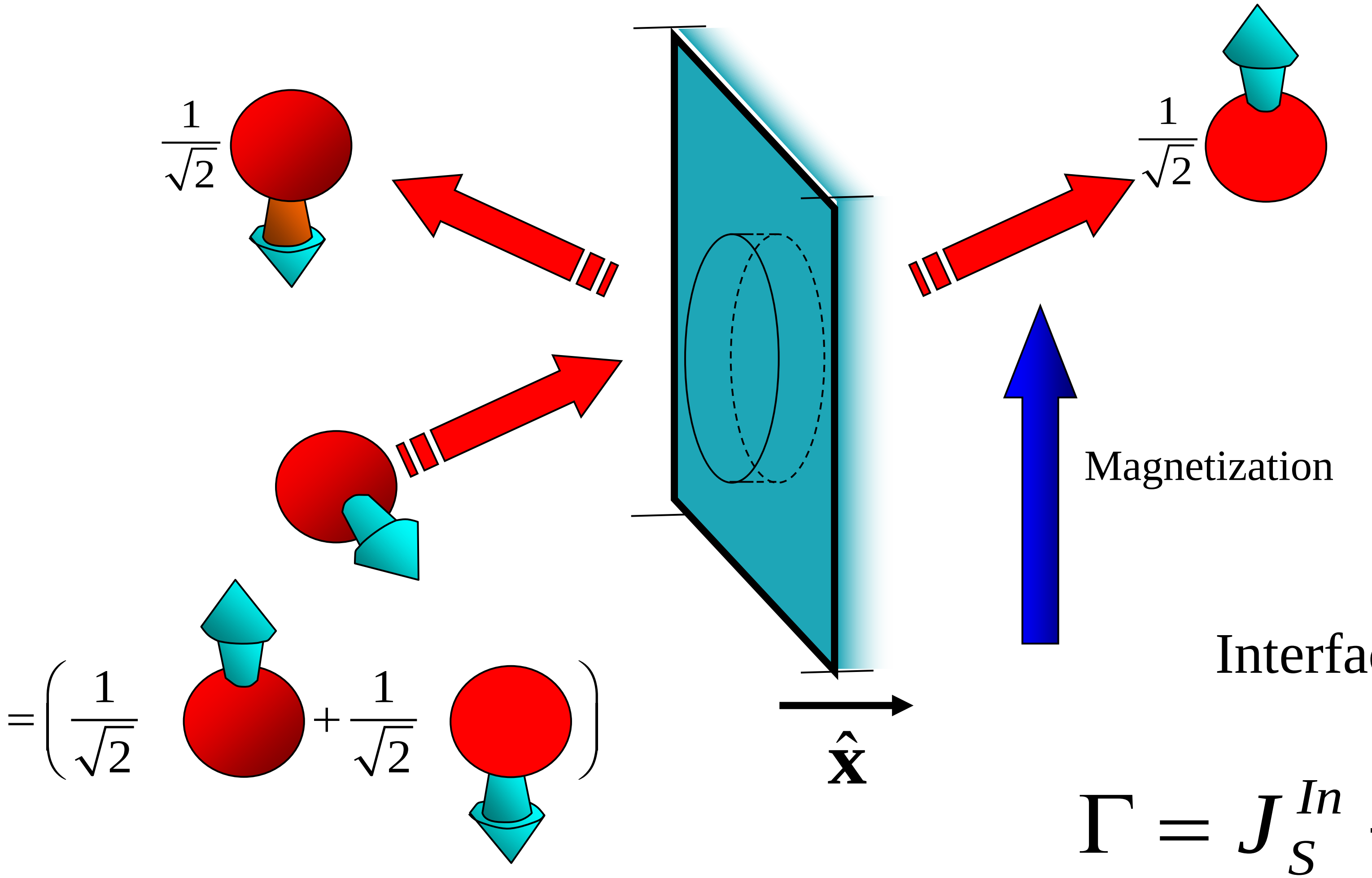
$$\mathrm{J_S} = Re\sum_{\mathrm{i}\sigma\sigma'} \psi^{*}_{\mathrm{i}\sigma}\left[\mathrm{s}_{\sigma,\sigma'} \otimes \hat{\mathrm{v}}\right]\psi_{\mathrm{i}\sigma}$$



$$\frac{\partial \mathbf{m}}{\partial \mathrm{t}} = -\mathrm{J_S}$$

$$\frac{\partial \mathbf{m}}{\partial \mathrm{t}} = -\mathrm{J_S} + \mathbf{m} \times \mathbf{B}_{\mathrm{eff}} + \mathrm{damping}$$

Absorption of tranverse angular mt



Simple limit

$|R_{\downarrow}|^2 = 1$

$|R_{\uparrow}|^2 = 0$

Interfacial torque

$$\Gamma = J_S^{In} - J_S^{Tr} + J_S^{ref}$$

$$\Rightarrow \quad \Gamma \approx J_{S\,\perp}^{In}$$

Spin transfer Torque

Approximately:

- Interfacial
- Complete absorption of transverse spin current

For one dimension

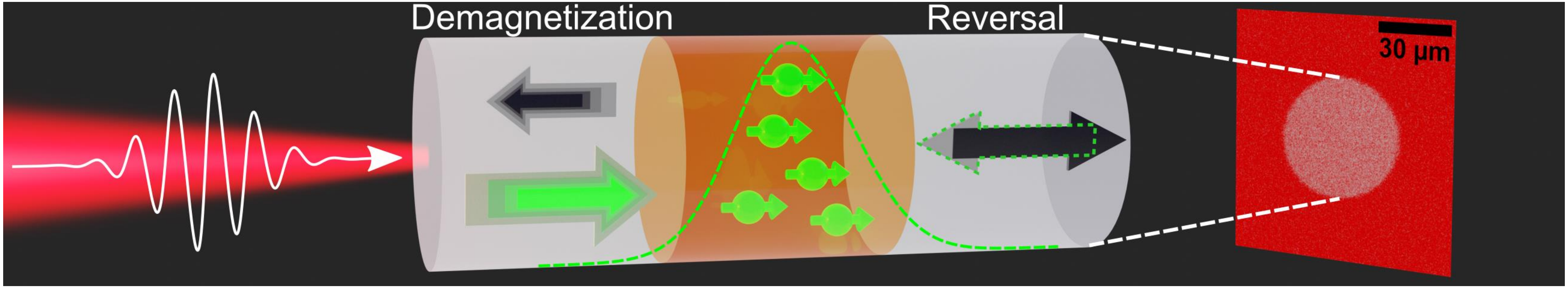
$$J_s = \frac{\hbar}{2} P \hat{\mathbf{s}} \otimes \mathbf{j}$$

$$J_{s\perp} = \frac{\hbar I}{2e} P\left[\hat{\mathbf{m}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{m}}\right)\right]$$

$$\Gamma = \frac{\hbar I}{2e} P\left[\hat{\mathbf{m}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{m}}\right)\right]$$

Review: Stiles and Miltat, Spin Dyn.in Confined Magn. Struct. III, Springer 2005

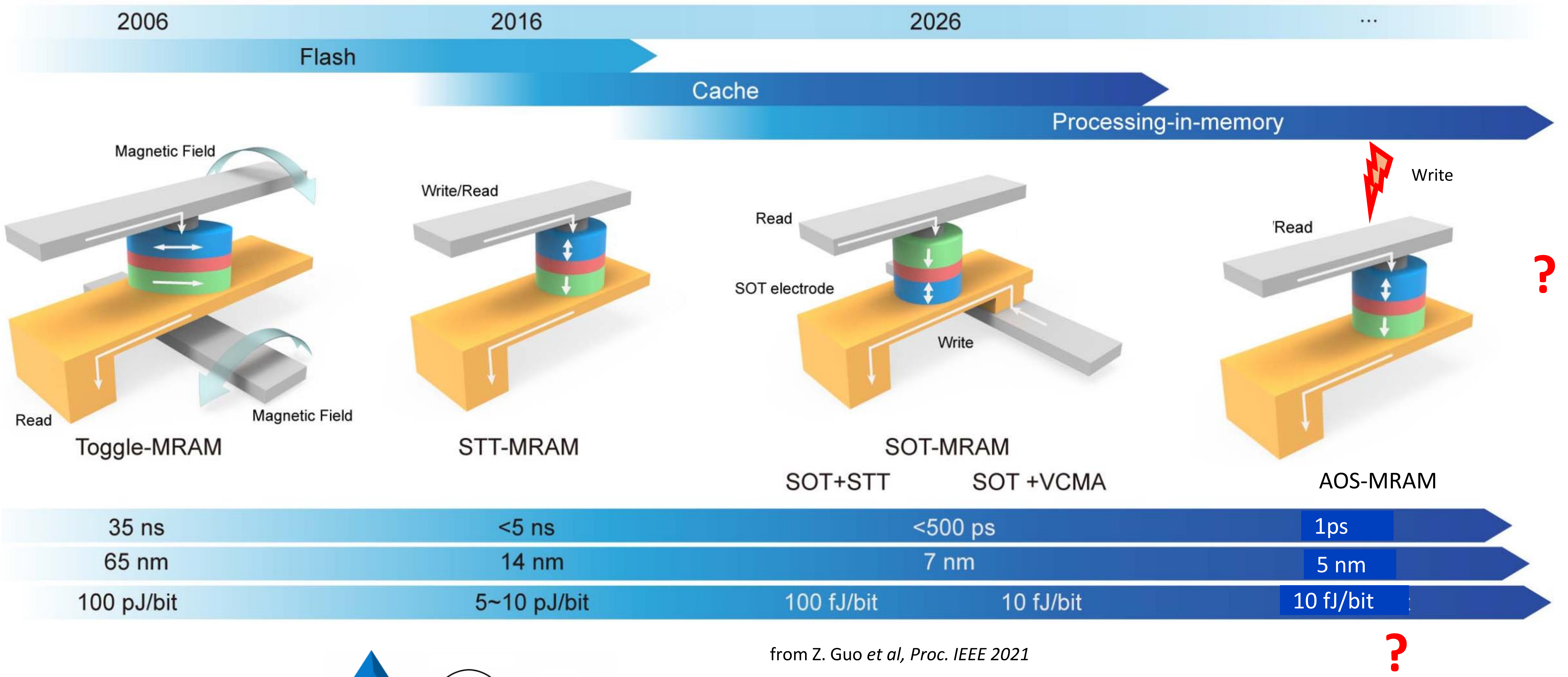
Ultra-fast AOS in spintronic devices



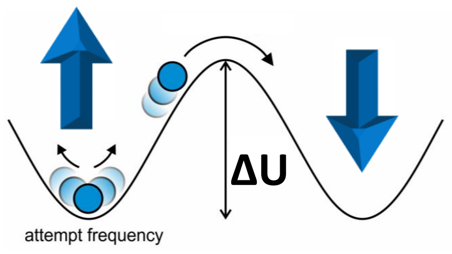
- 1 single ultra-short light pulse (50fs)
- Ultra-fast switching in less than 0.5 ps
- Deterministic and Controlled switching
- Energy efficient
- AP to P and P to AP switching
- Works for a large range of Materials

S. Iihama et al. Adv. Mater. **30**, 1804004 (2018)
Q. Remy et al Nature Com 14 (1), 445 (2023)

Toward AOS- MRAM ?



from Z. Guo *et al, Proc. IEEE 2021*



Thermal Stability given by $\Delta U = KV$

SAVE *the* DATE

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