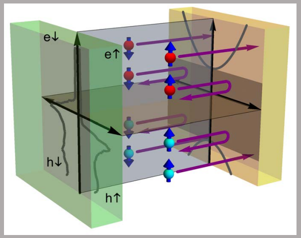
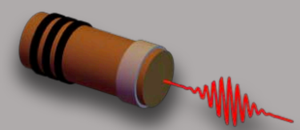
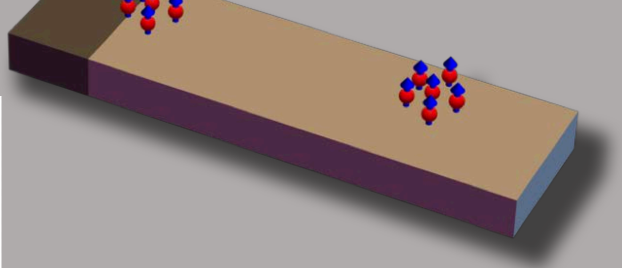
Towards THz spintronics: generation and transport of sub-picosecond spin current pulses

The non-trivial interplay of transport, thermalization and electromagnetism





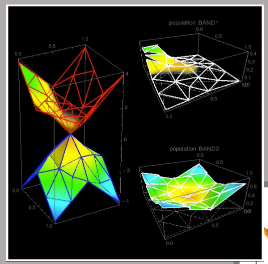


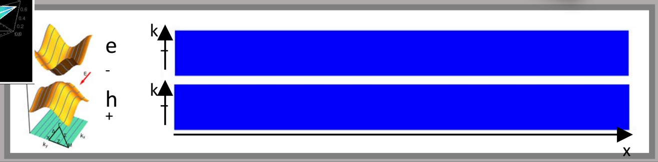
M. Battiato

Vienna University of Technology,
Vienna, Austria

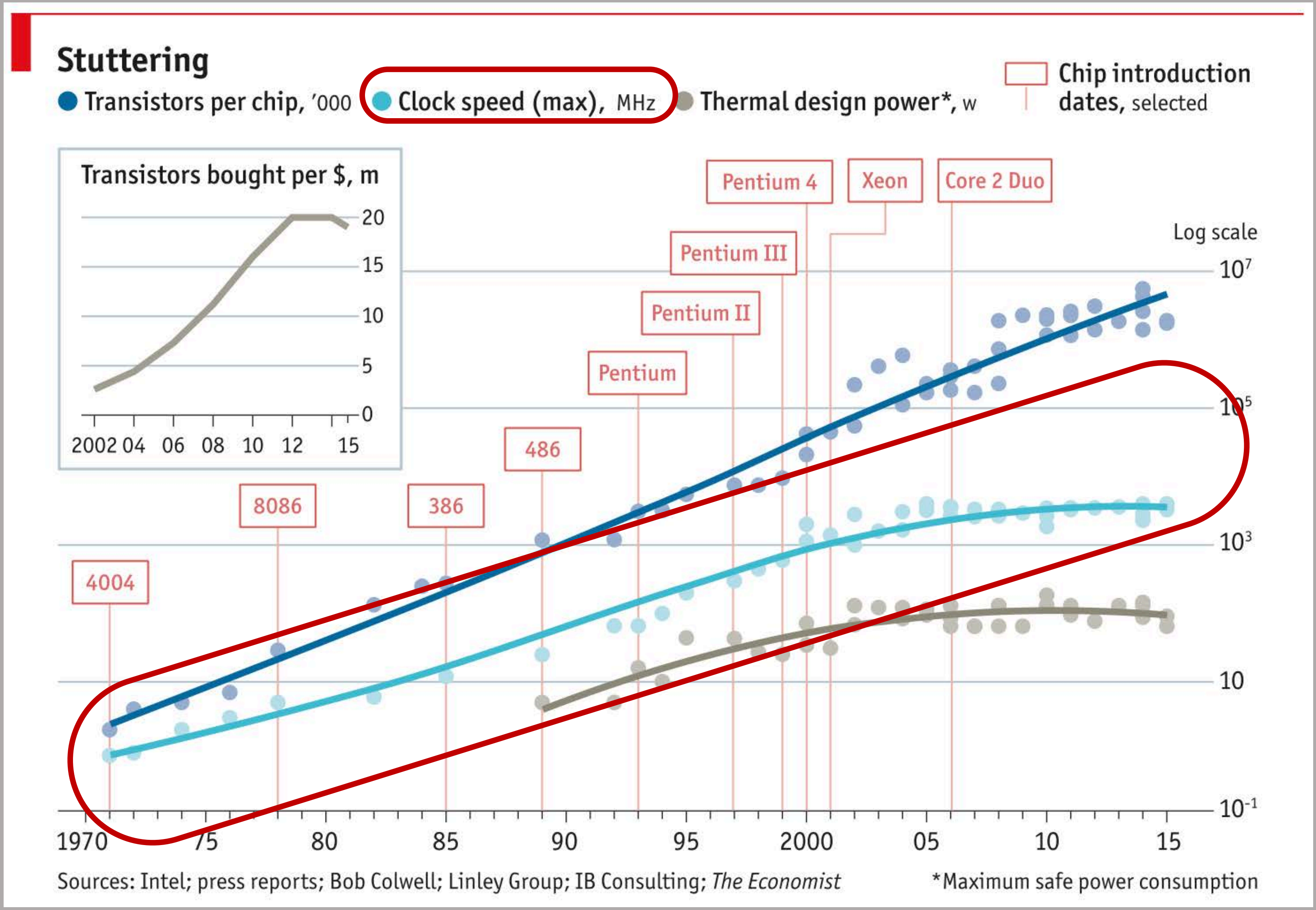
from the 1st of November at

Nanyang Technological University
Singapore, Singapore



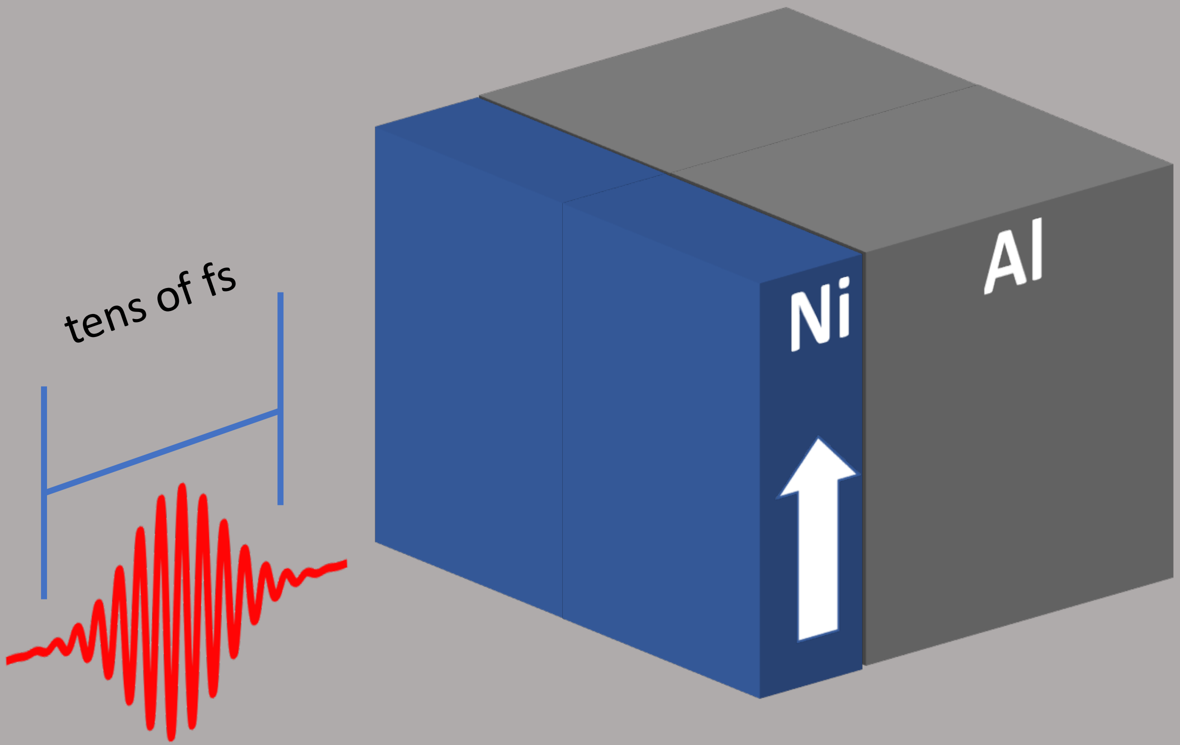


Moore speed?



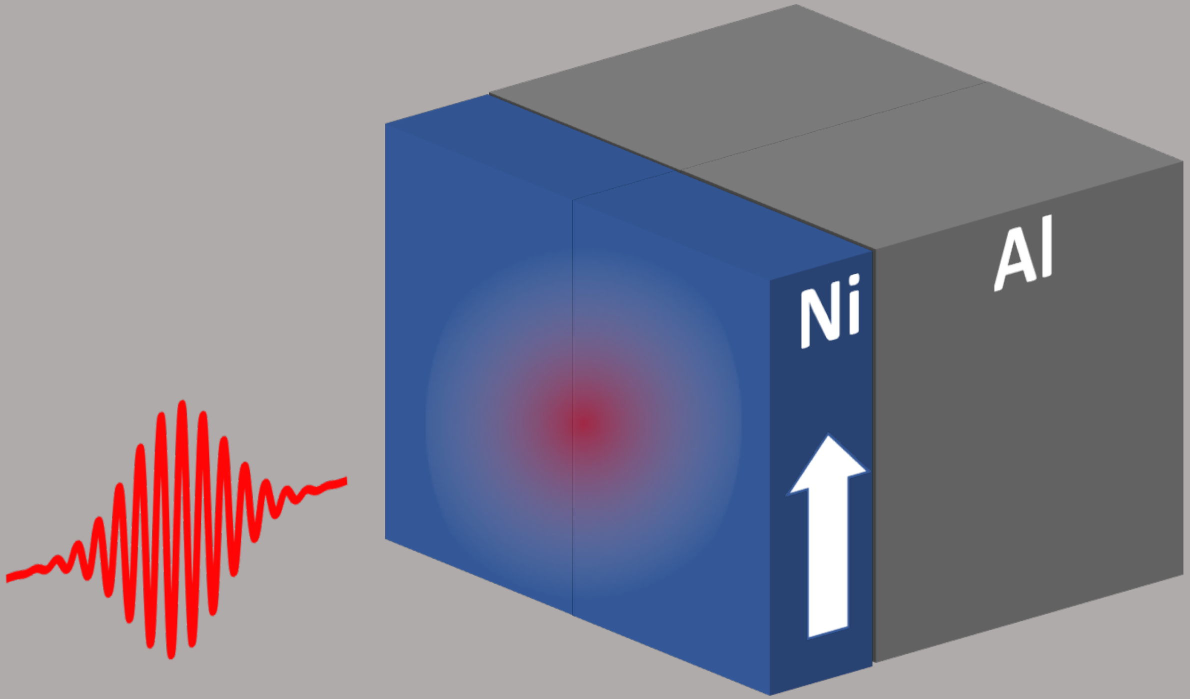
Stuttering
Transistors per chip, '000
Clock speed (max), MHz
Thermal design power*, w
Chip introduction dates, selected
Transistors bought per $, m
20
15
10
5
0
2002 04 06 08 10 12 15
Pentium 4
Xeon
Core 2 Duo
Pentium III
Pentium II
Pentium
486
386
8086
4004
Log scale
10^7
10^5
10^3
10
10^-1
1970 75 80 85 90 95 2000 05 10 15
Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; The Economist
*Maximum safe power consumption

Ultrafast demagnetization

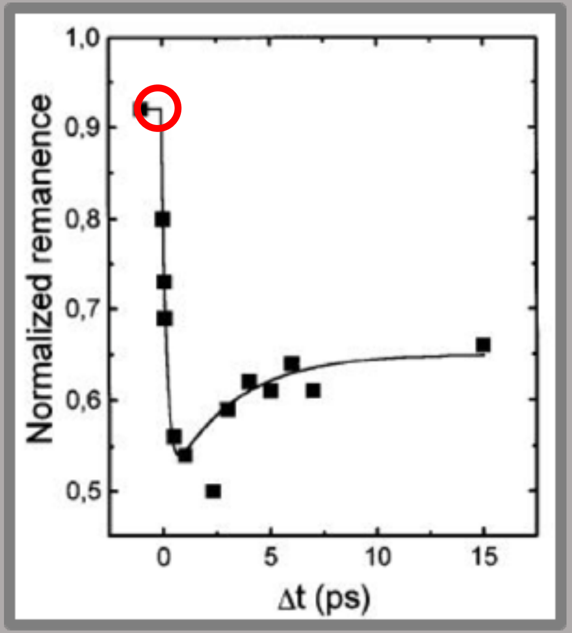


E. Beaurepaire et al., **Phys. Rev. Lett.** 76, 4250 (1996).

Ultrafast demagnetization

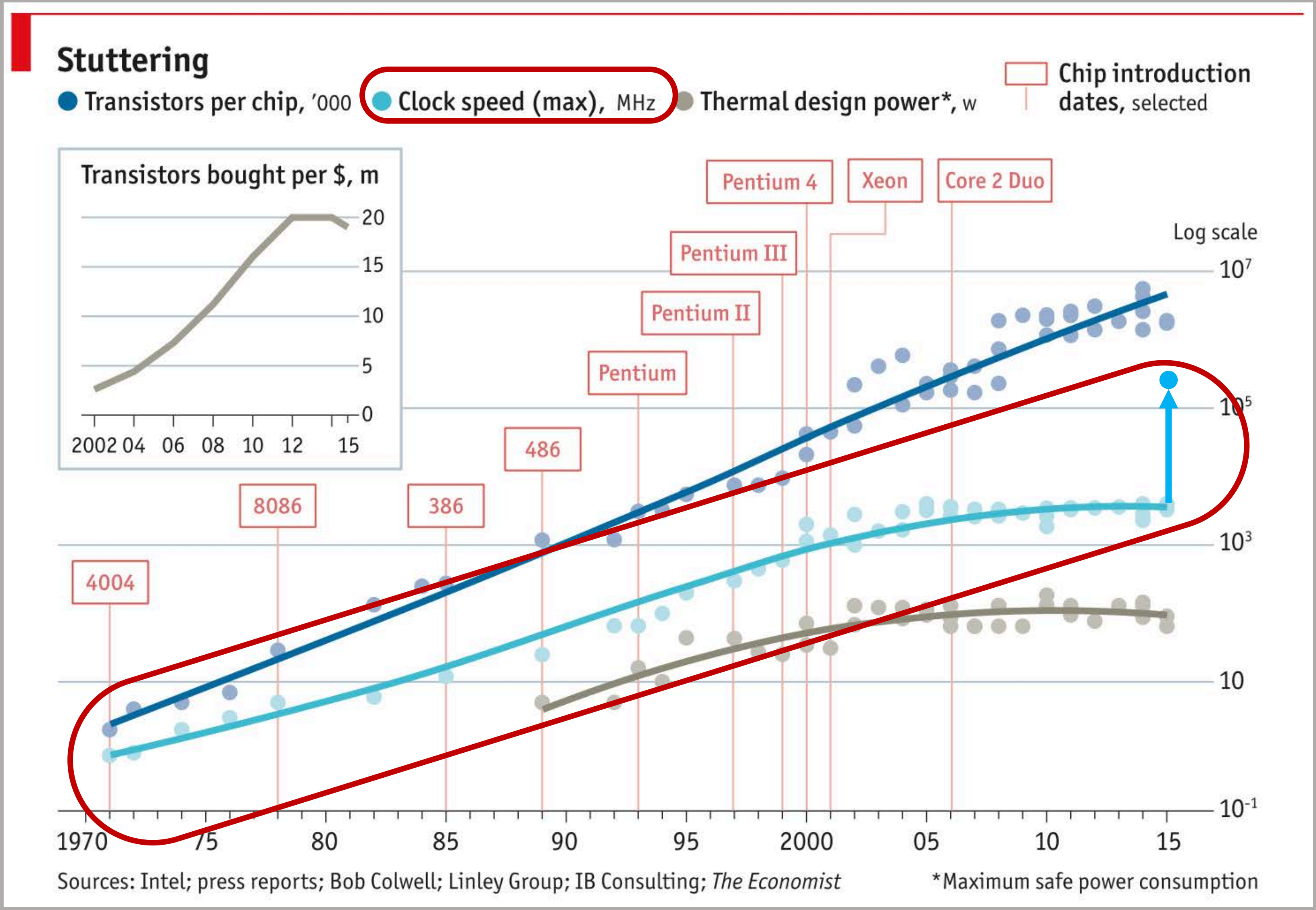


Few hundreds of fs!



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

Speed Moore



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Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*
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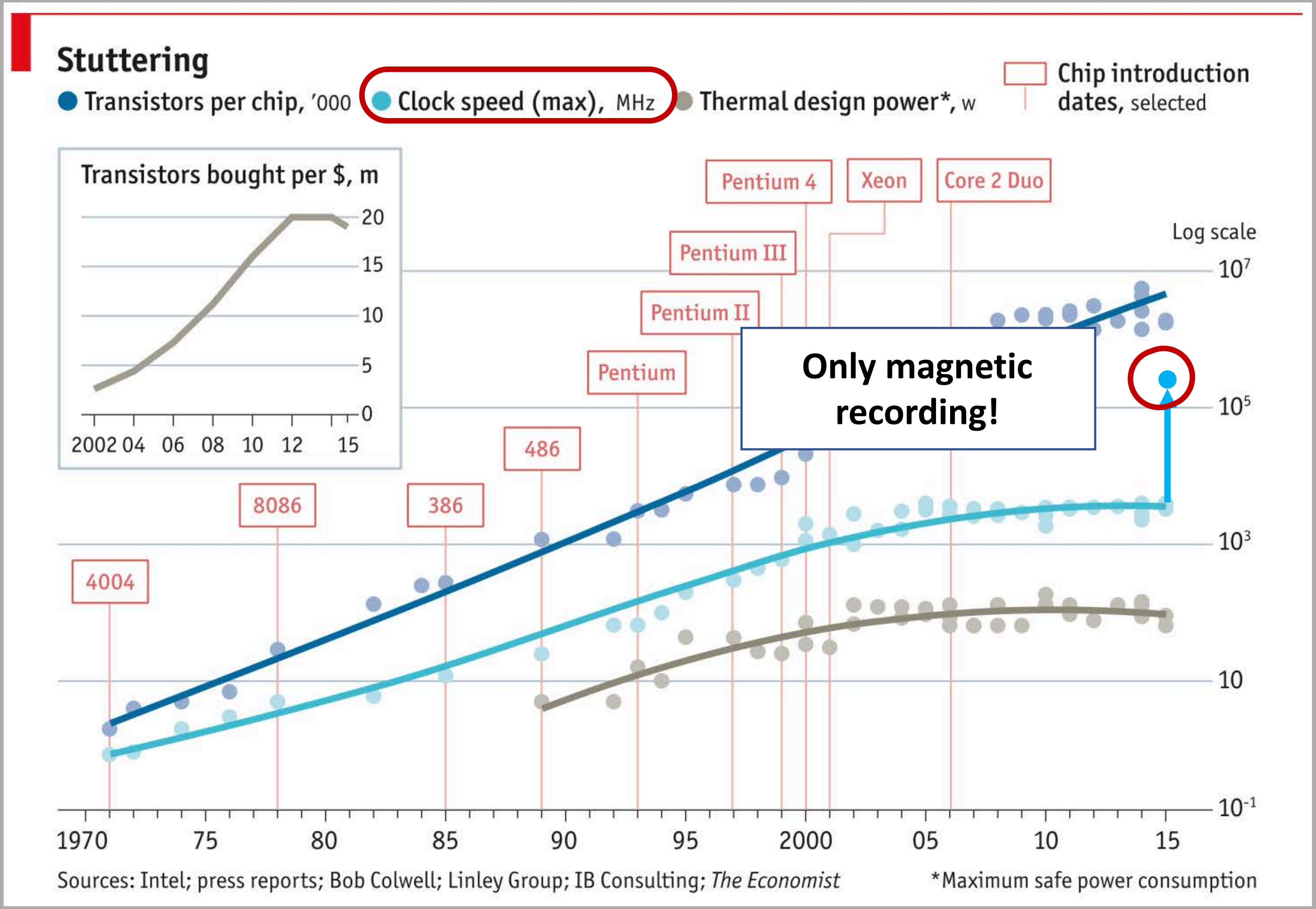
Speed Moore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4004
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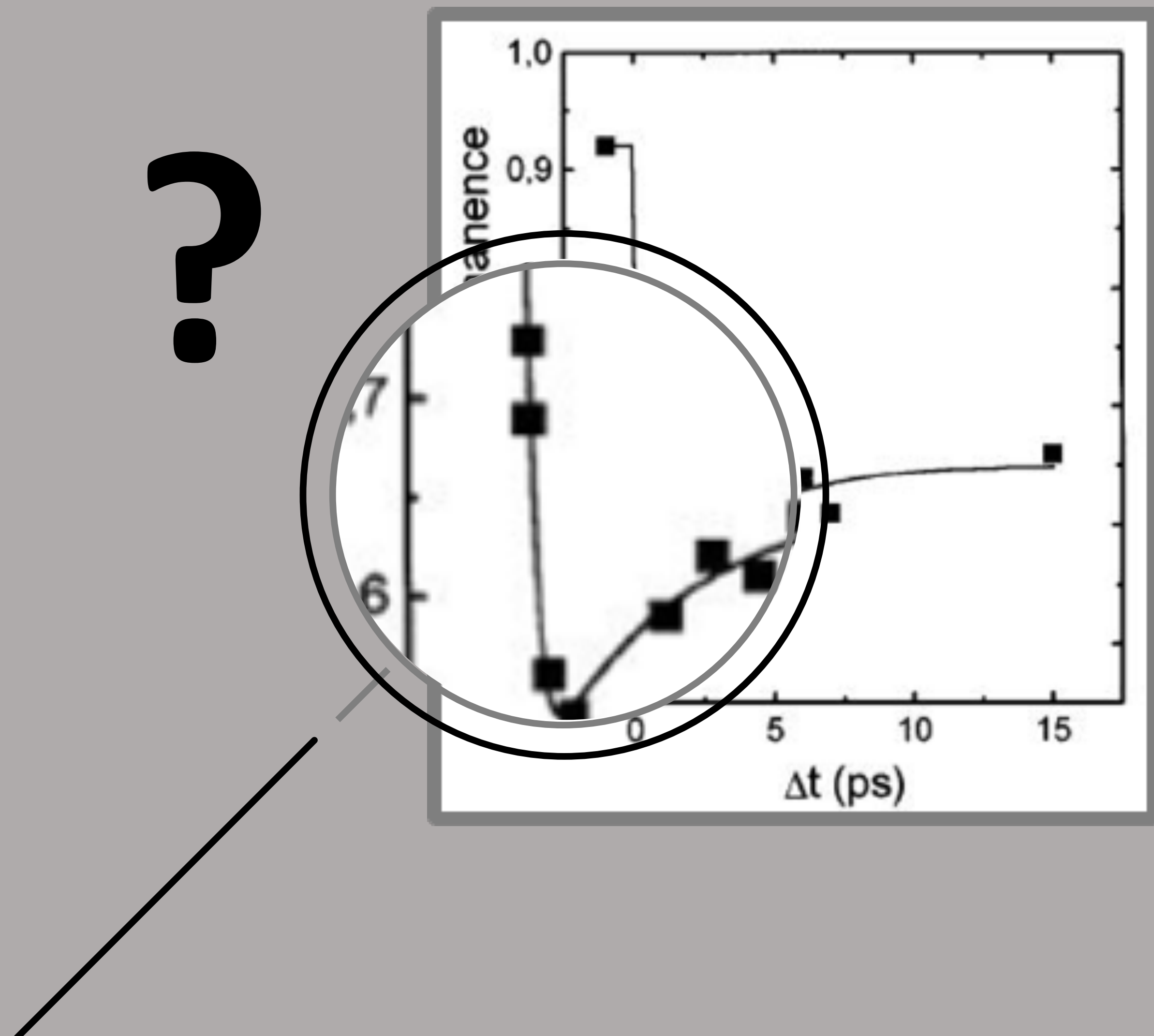
10^5
10^3
10
10^{-1}
1970 75 80 85 90 95 2000 05 10 15
Only magnetic recording!
Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*
*Maximum safe power consumption

The puzzle of the ultrafast demagnetization

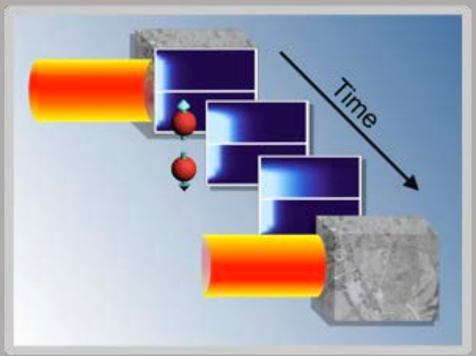


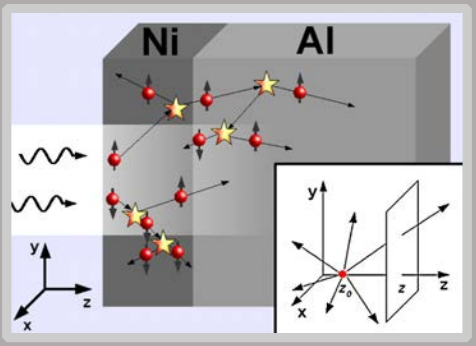
The puzzle of the ultrafast demagnetization

- Electron-phonon coupling
- Spin to orbital momentum conversion

The puzzle of the ultrafast demagnetization

- Electron-phonon coupling
- Spin to orbital momentum conversion
- Superdiffusive spin transport





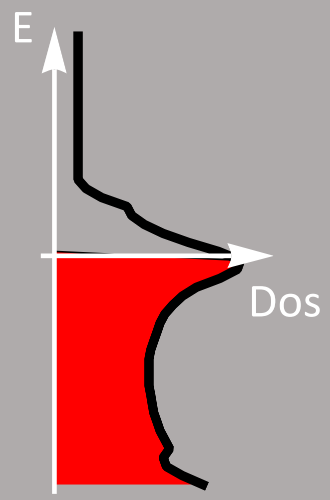
$$\frac{\partial n(\sigma,E,z,t)}{\partial t}+\frac{n(\sigma,E,z,t)}{\tau(\sigma,E,z)}=\left(-\frac{\partial}{\partial z}\hat{\Phi}+\hat{I}\right)S^{eff}(\sigma,E,z,t)$$

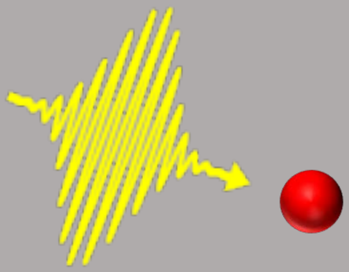
$$\widetilde{[\Delta t]}(z,z_0)=\int_{z_0}^{z}\frac{dz'}{v(z')} \quad ; \qquad \widetilde{[\Delta t/\tau]}(z,z_0)=\int_{z_0}^{z}\frac{dz'}{v(z')\,\tau(z')}$$

$$\hat{\Phi}S^{eff}=\int_{-\infty}^{+\infty}dz_0\int_{-\infty}^{t}dt_0\,S^{eff}(\sigma,E,z_0,t_0)\,\frac{\widetilde{[\Delta t]}}{2(t-t_0)^2}\,e^{-(t-t_0)\frac{\widetilde{[\Delta t/\tau]}}{\widetilde{[\Delta t]}}}\,\Theta\left[(t-t_0)-\left|\widetilde{[\Delta t]}\right|\right]$$

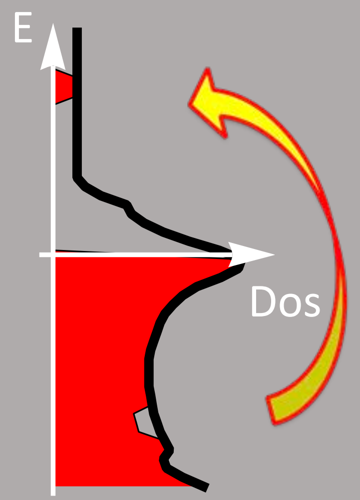
Battiato, Carva, Oppeneer, **Phys. Rev. Lett.** 105, 027203 (2010)

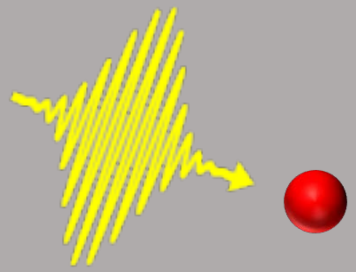
Superdiffusive spin transport



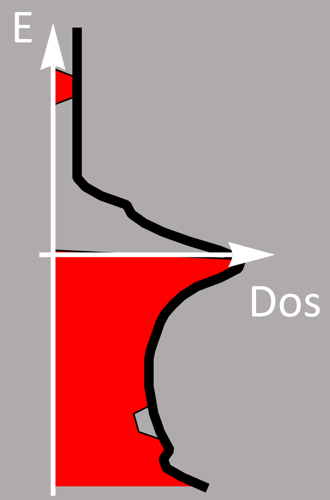


Superdiffusive spin transport

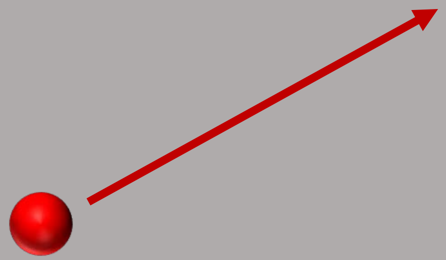




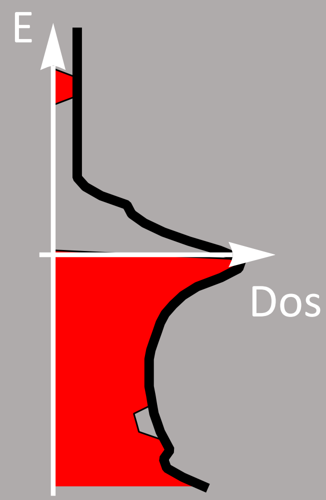
Superdiffusive spin transport



v ≈ 1nm/fs

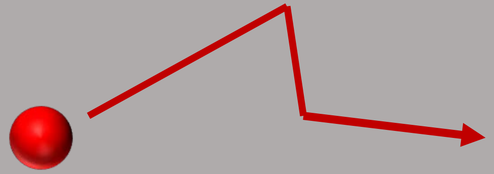


Superdiffusive spin transport

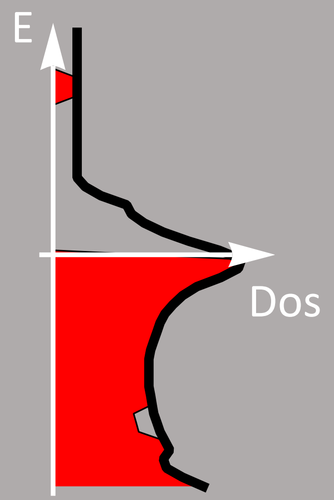


v ≈ 1nm/fs

τ ≈ tens of fs



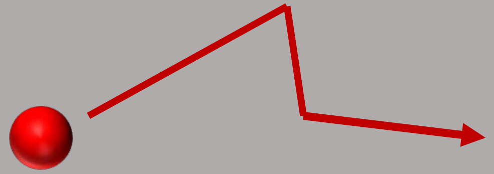
Superdiffusive spin transport



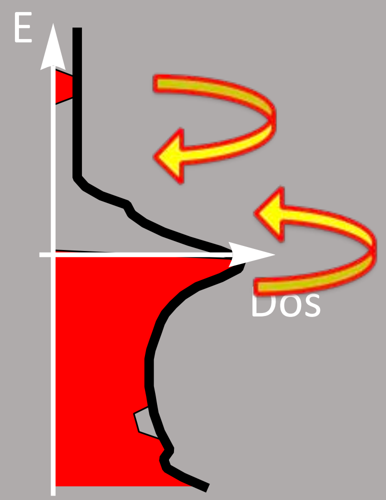
v ≈ 1nm/fs

τ ≈ tens of fs

λ ≈ tens of nm



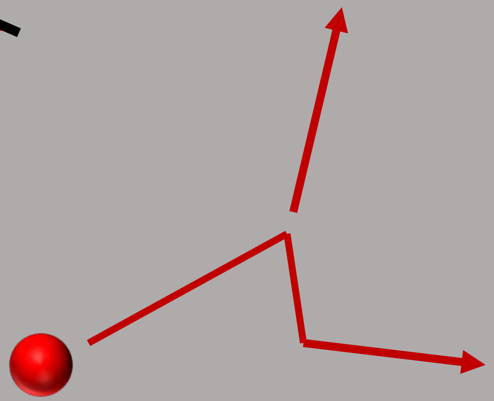
Superdiffusive spin transport



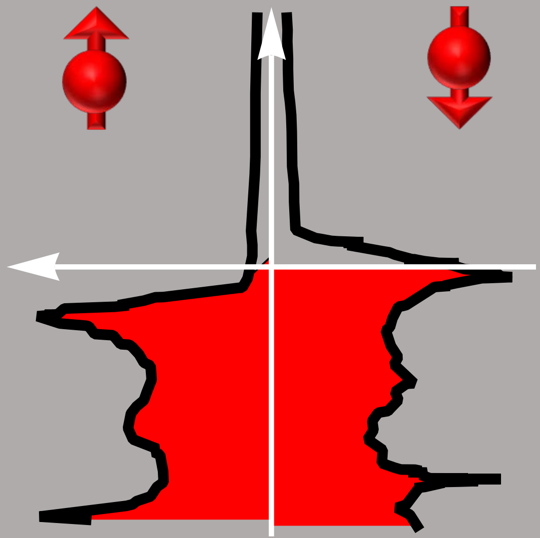
$v \approx$ 1nm/fs

$\tau \approx$ tens of fs

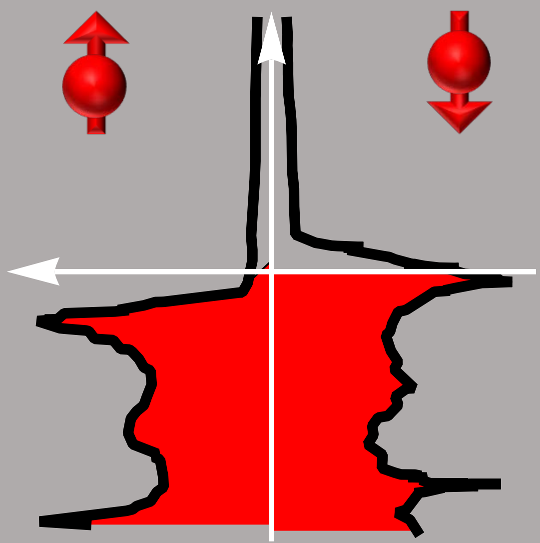
$\lambda \approx$ tens of nm

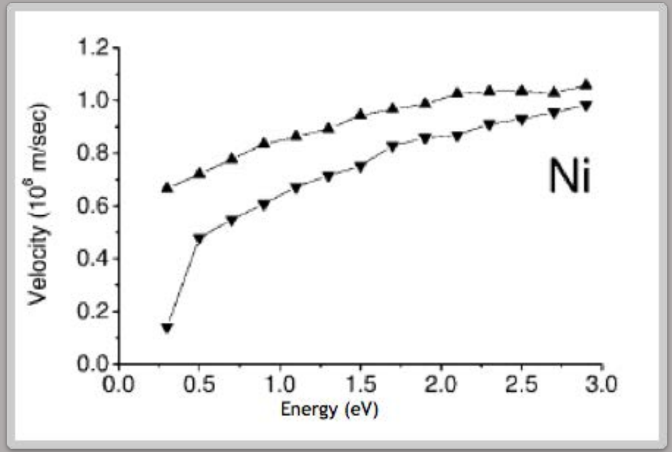


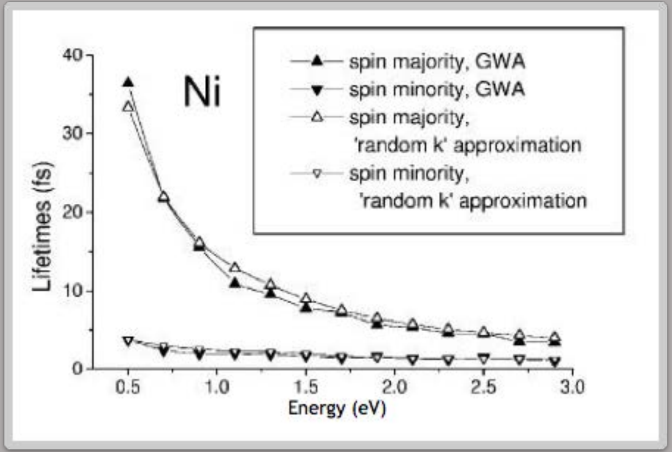
Superdiffusive spin transport



Superdiffusive spin transport

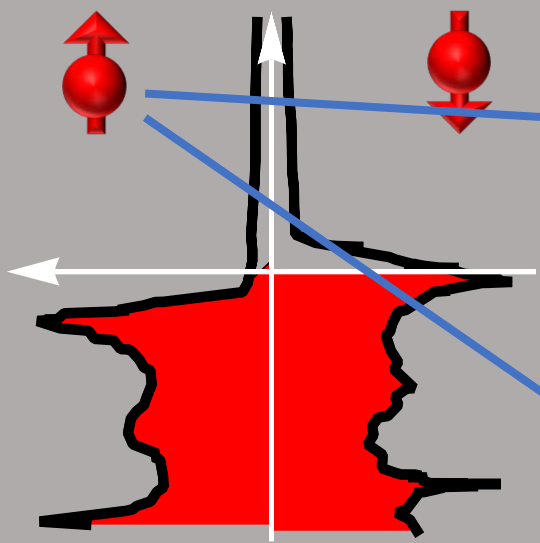


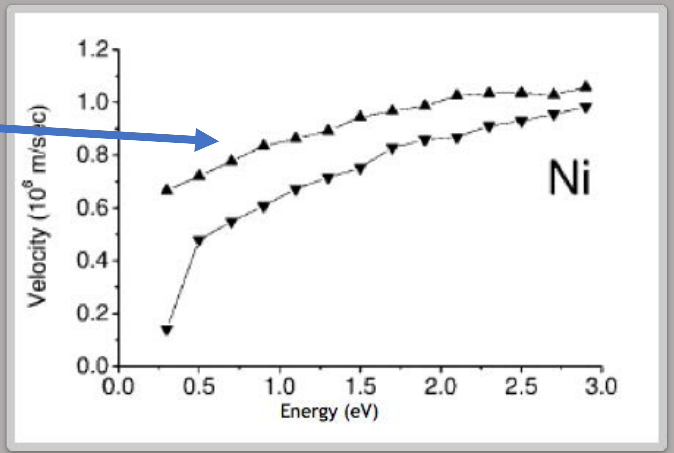


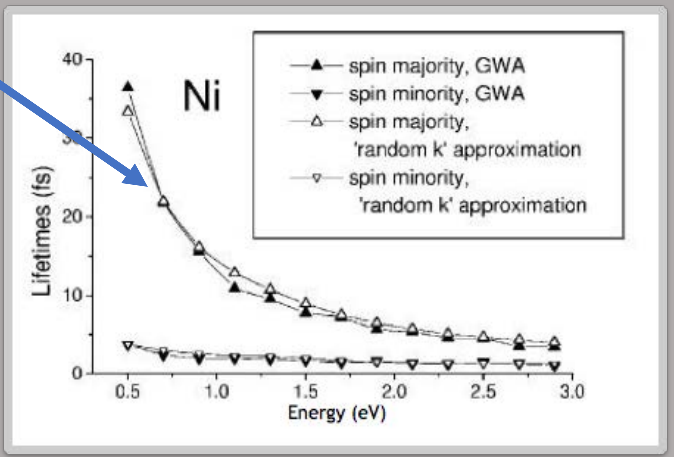


V. Zhukov, et al, Phys. Rev. B 73, 125105 (2006)

Superdiffusive spin transport







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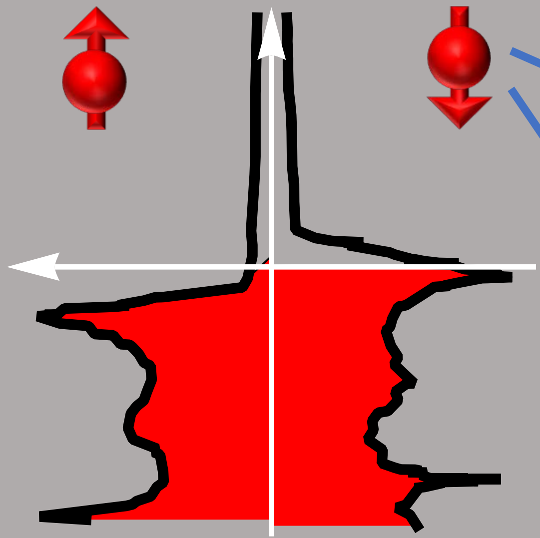

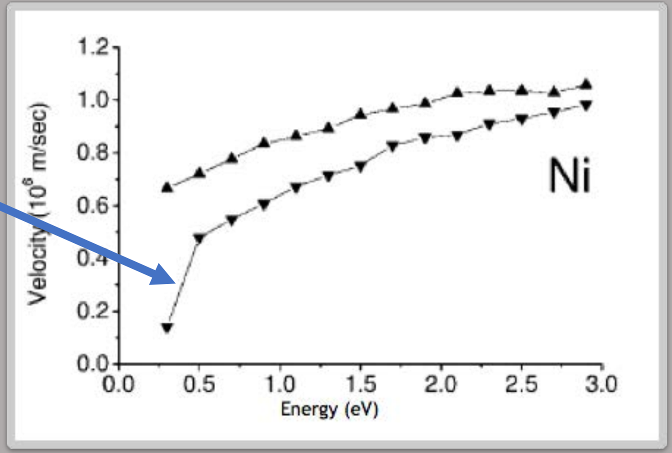

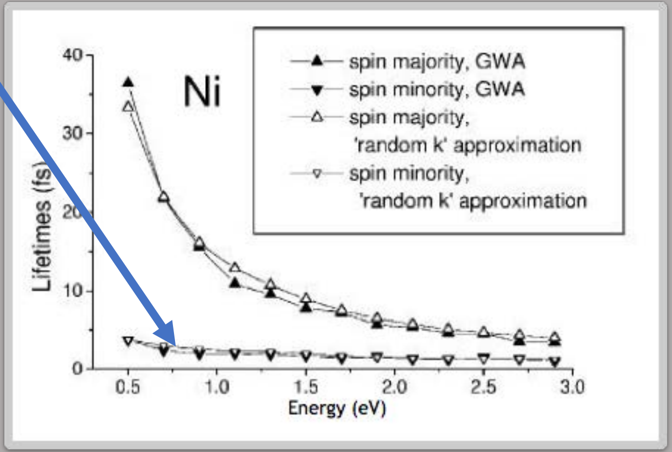

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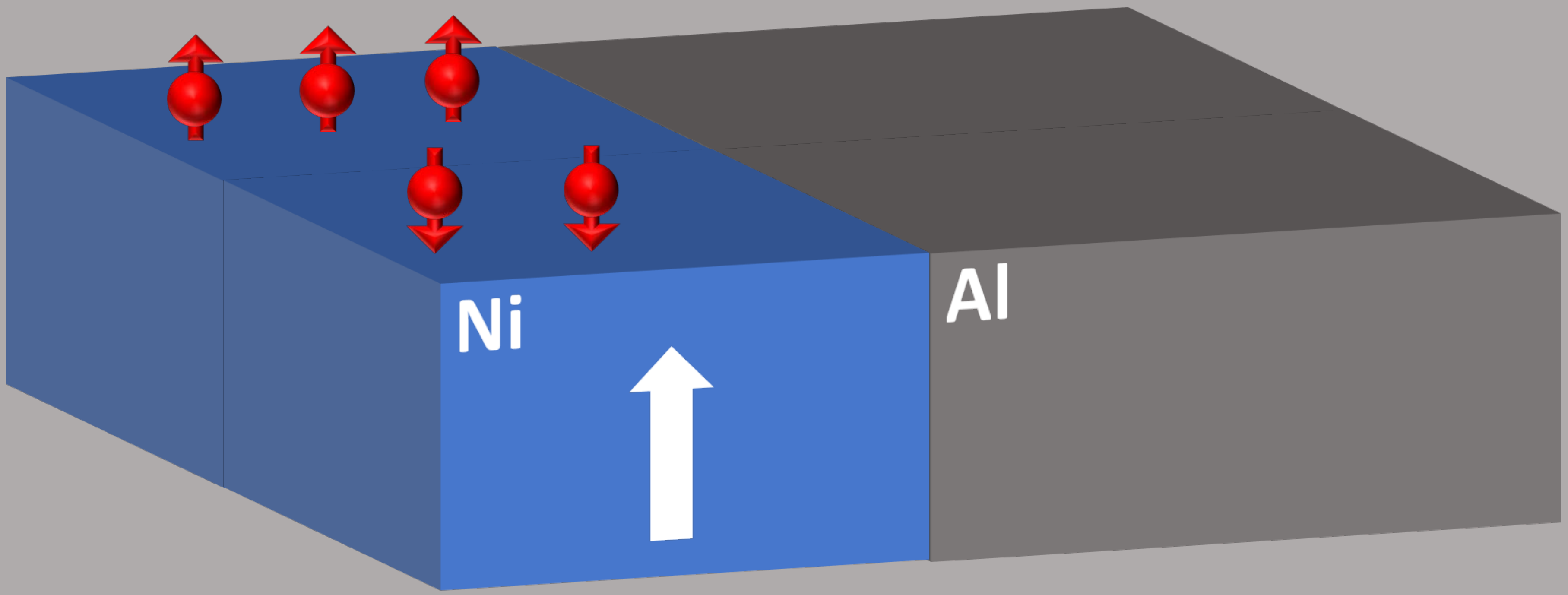
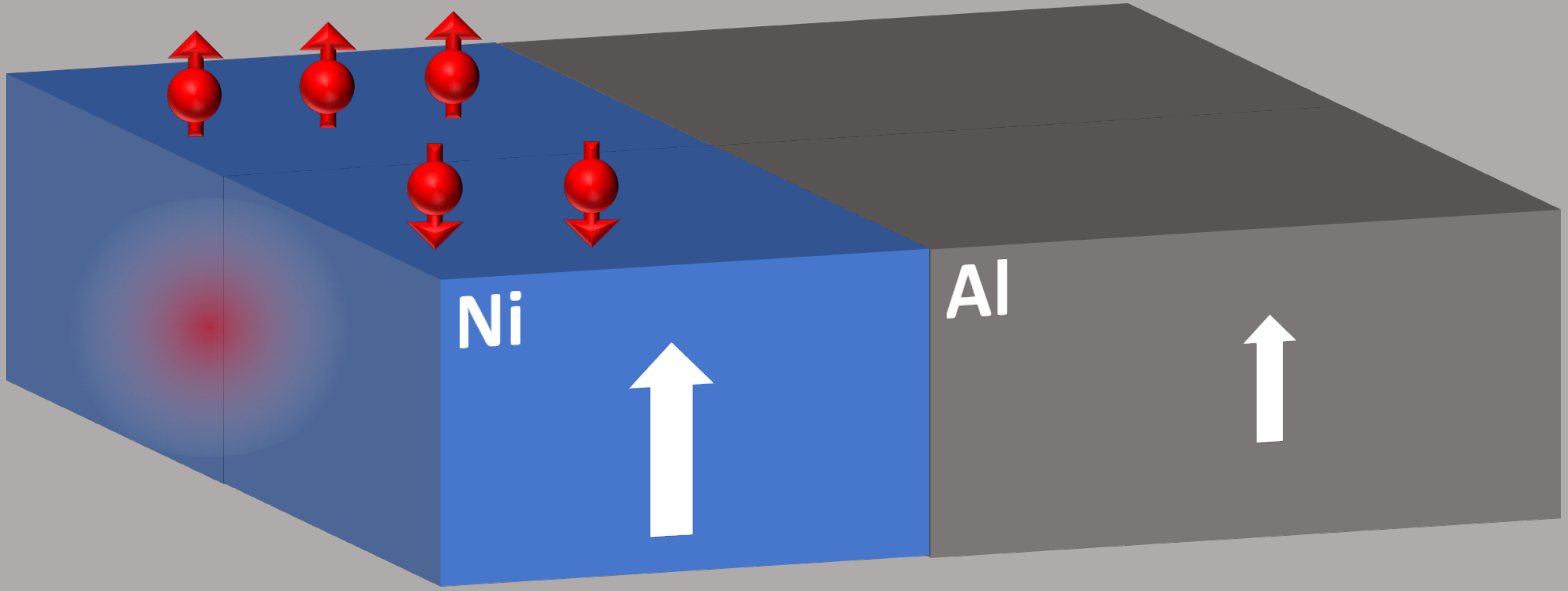
Superdiffusive spin transport



Superdiffusive spin transport



Superdiffusive spin transport

Boltzmann equation

$$\frac{\partial g}{\partial t} + \frac{1}{\hbar}\nabla_{\mathbf{r}} \cdot (g \nabla_{\mathbf{k}} \mathcal{E}) - \frac{e}{\hbar}\nabla_{\mathbf{k}} \cdot \left(g \left[\mathbf{E} + \frac{1}{e}\nabla_{\mathbf{r}} \mathcal{E} \right] \right) = \left(\frac{dg}{dt} \right)_{col} + \left(\frac{dg}{dt} \right)_{source}$$

- Small perturbation of equilibrium
- Perfect screening (perfect metal)
- Spherically symmetric band structure
- Breaking of momentum conservation

Superdiffusive spin transport model

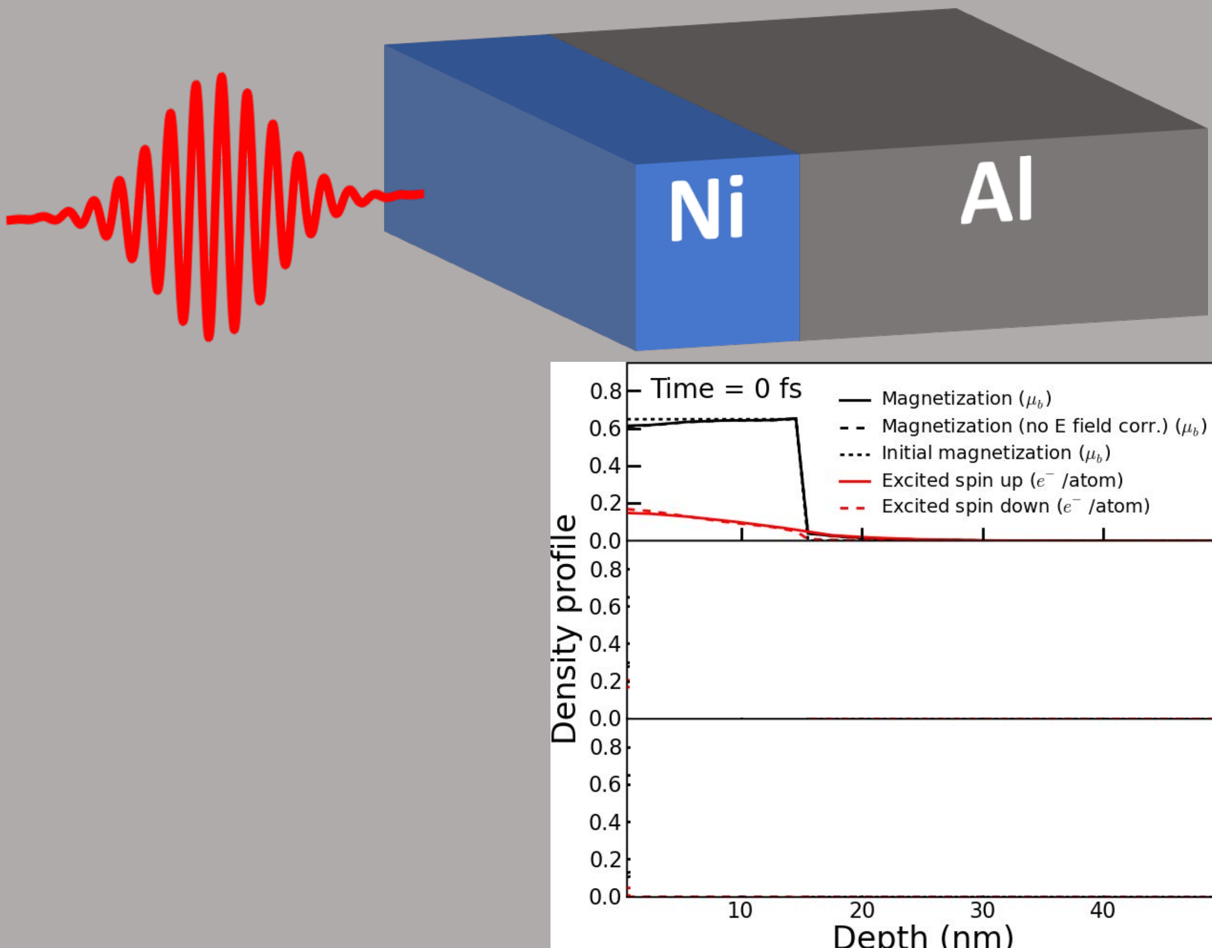
$$\frac{\partial n(\sigma, E, z, t)}{\partial t} + \frac{n(\sigma, E, z, t)}{\tau(\sigma, E, z)} = \left(-\frac{\partial}{\partial z}\hat{\Phi} + \hat{I} \right) S^{eff}(\sigma, E, z, t)$$

$$\widetilde{[\Delta t]}(z, z_0) = \int_{z_0}^{z} \frac{dz'}{v(z')} \quad ; \qquad \widetilde{[\Delta t/\tau]}(z, z_0) = \int_{z_0}^{z} \frac{dz'}{v(z')\,\tau(z')}$$

$$\hat{\Phi} S^{eff} = \int_{-\infty}^{+\infty} dz_0 \int_{-\infty}^{t} dt_0 S^{eff}(\sigma, E, z_0, t_0) \frac{\widetilde{[\Delta t]}}{2(t-t_0)^2} e^{-(t-t_0)\frac{\widetilde{[\Delta t/\tau]}}{\widetilde{[\Delta t]}}} \Theta\left[(t-t_0) - \left| \widetilde{[\Delta t]} \right| \right]$$

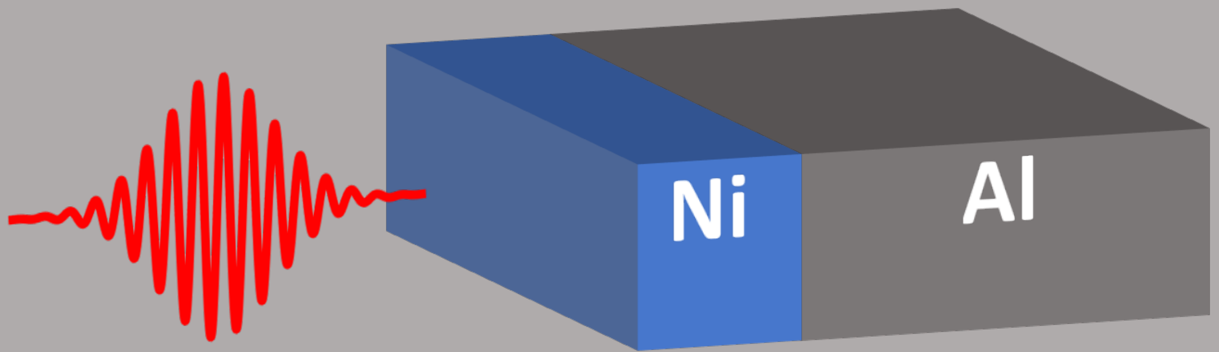
Battiato, Carva, Oppeneer, **Phys. Rev. Lett.** 105, 027203 (2010)

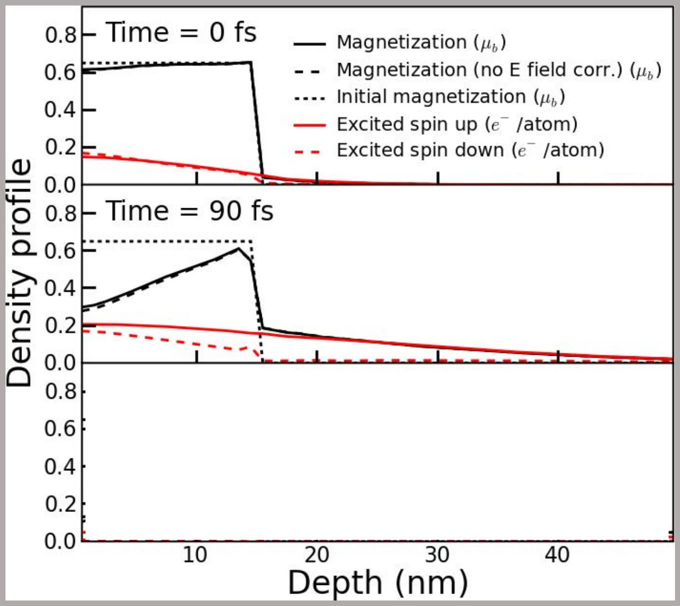
Superdiffusive spin transport



Battiato, Carva, Oppeneer, **Phys. Rev. Lett.** 105, 027203 (2010)

Superdiffusive spin transport





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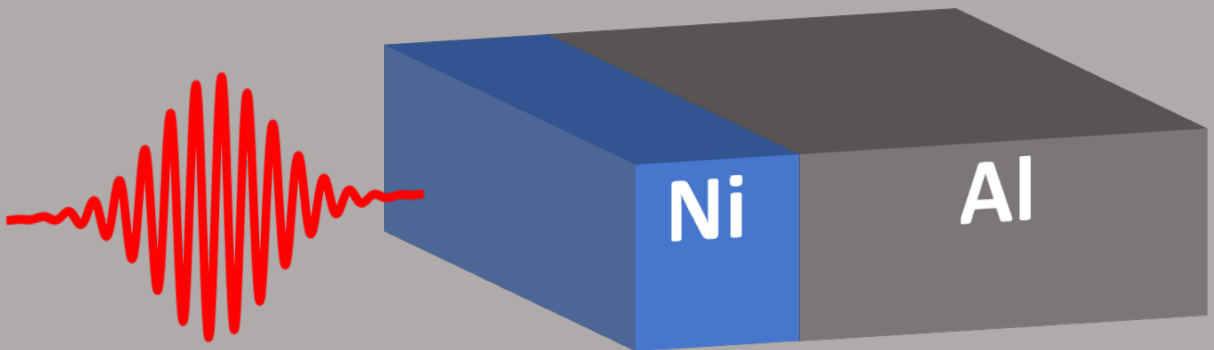
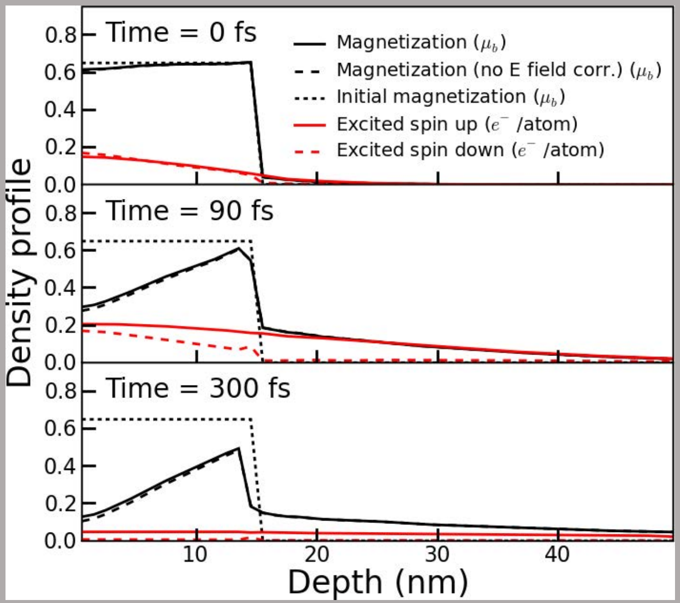
Superdiffusive spin transport





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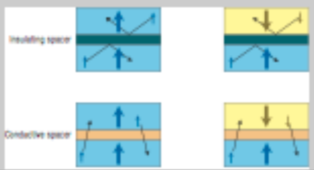
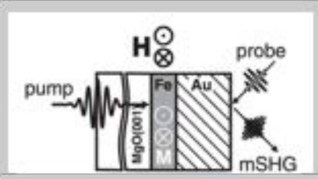
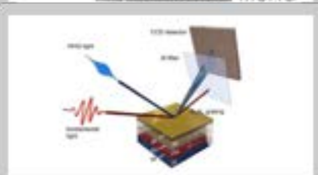
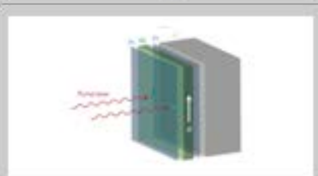
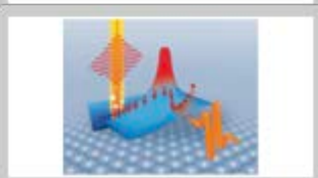
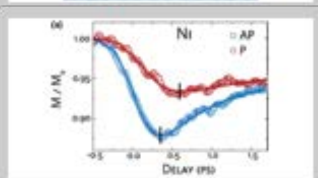



Malinowski et al. **Nature Phys**. 4, 855 (2008)

Melnikov et al. **Phys. Rev, Lett.** 107, 076601 (2011)

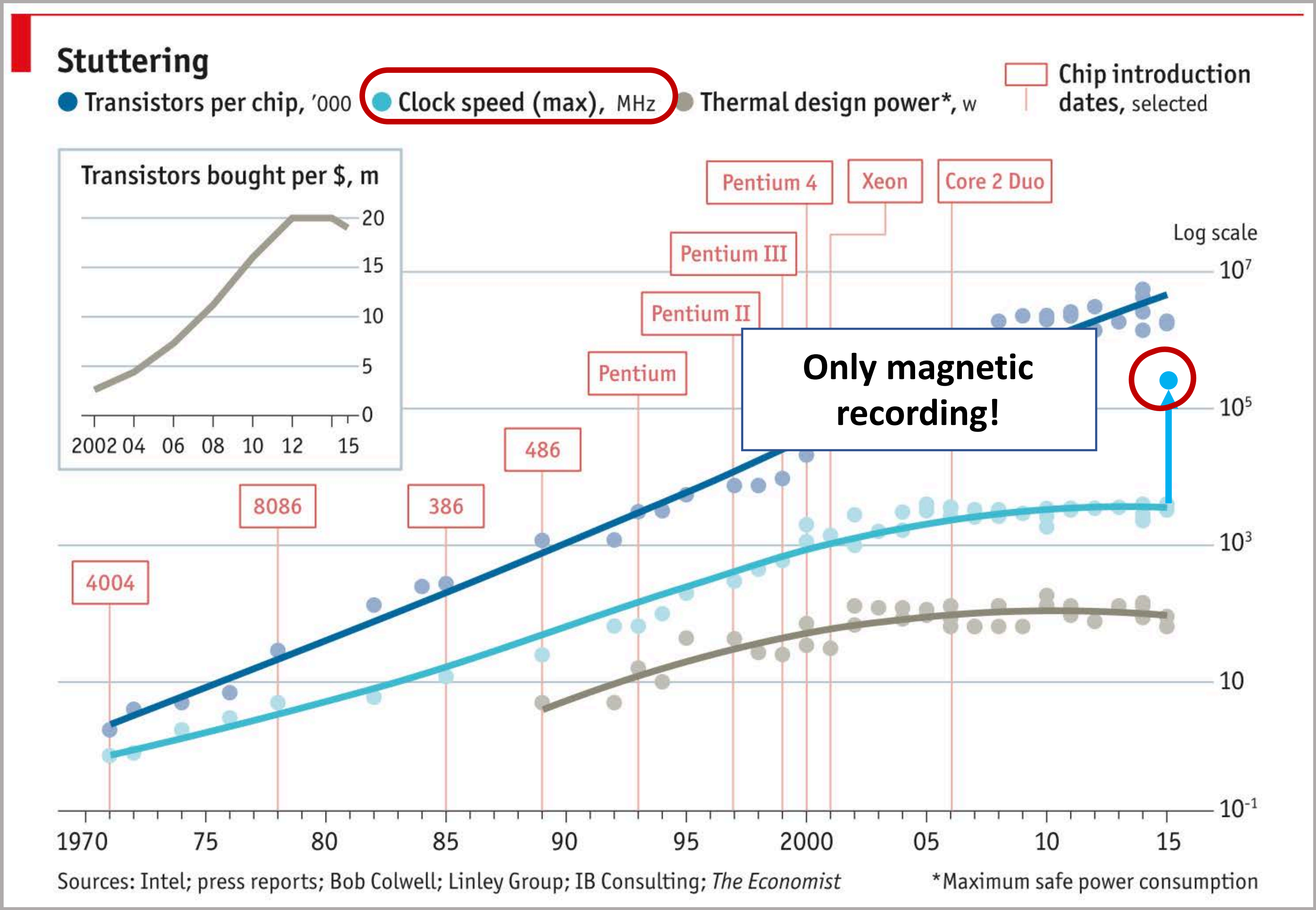
Rudolf, <u>Battiato</u> et al. **Nature Comm.** 3, 1038 (2012)

Eschenlohr, <u>Battiato</u> et al. **Nature Mater.** 12, 332 (2013)

Kampfrath, <u>Battiato</u> et al. **Nature Nanotech.** 8, 256 (2013)

Schellekens et al. **Phys. Rev. B** 90, 104429 (2014)

Speed Moore



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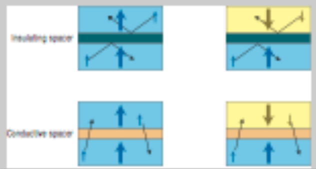
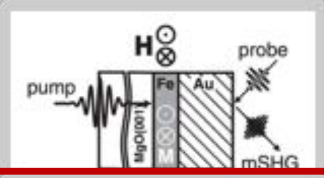
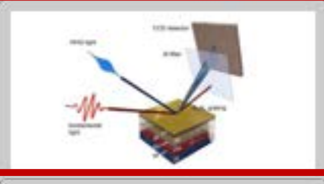
Superdiffusive spin transport



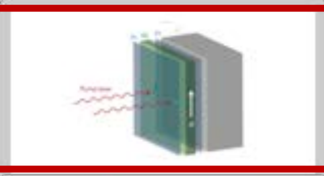
Malinowski et al. **Nature Phys**. 4, 855 (2008)



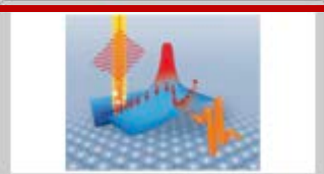
Melnikov et al. **Phys. Rev, Lett.** 107, 076601 (2011)



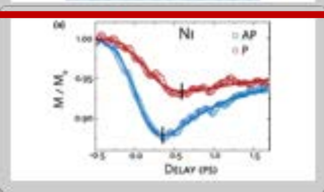
Rudolf, Battiato et al. **Nature Comm.** 3, 1038 (2012)



Eschenlohr, Battiato et al. **Nature Mater.** 12, 332 (2013)

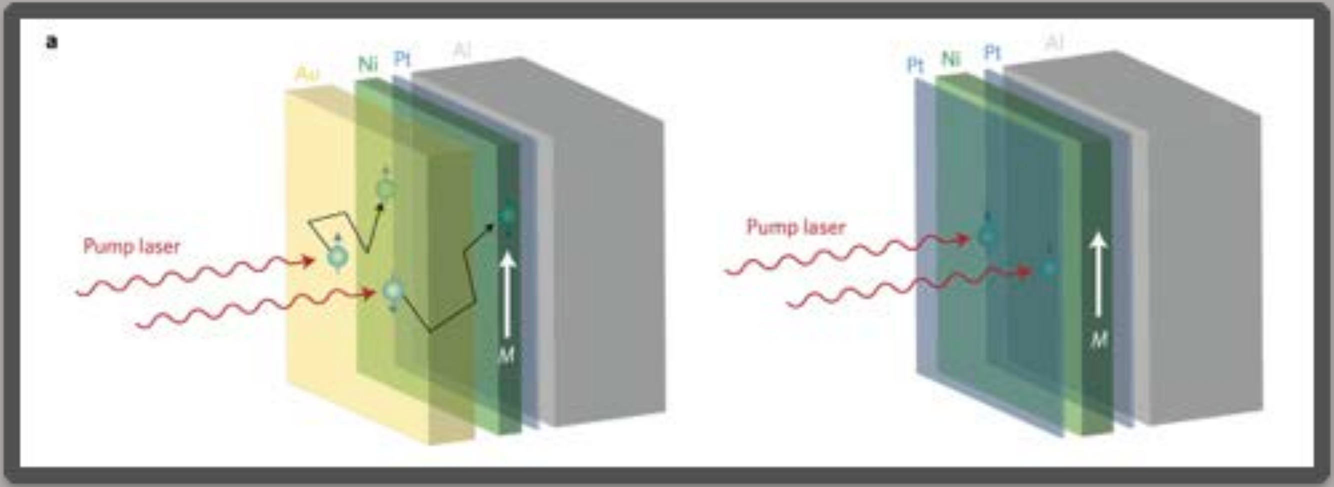


Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)



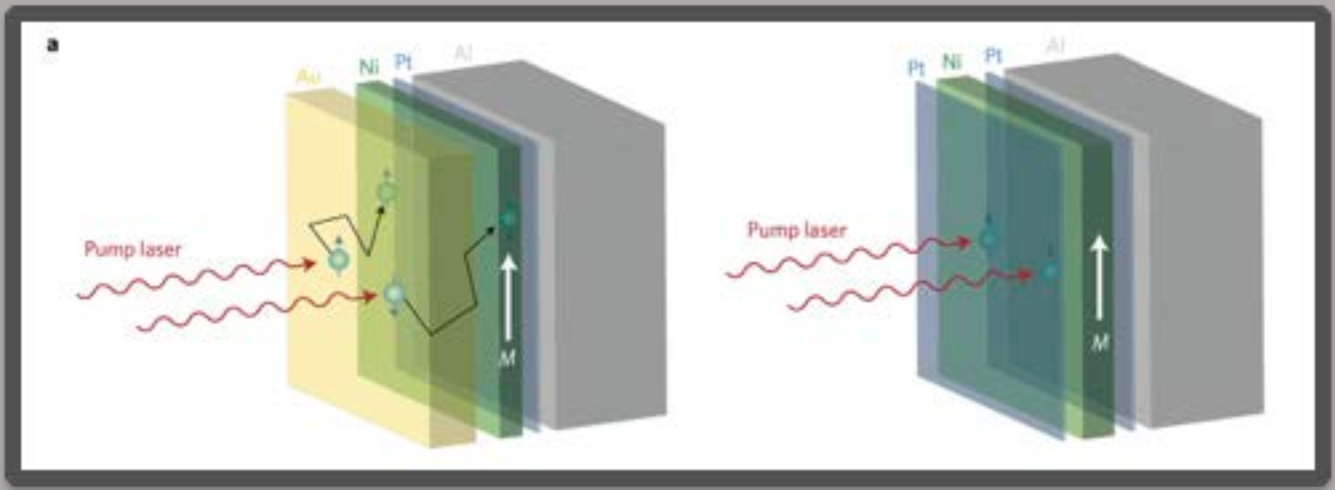
Schellekens et al. **Phys. Rev. B** 90, 104429 (2014)

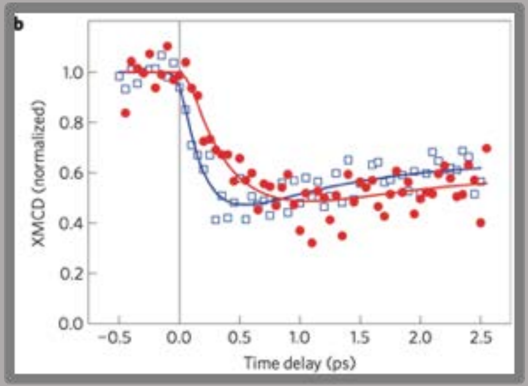
Demagnetisation without direct laser excitation



Eschenlor, Battiato et al, **Nature Mater** 12, 332 (2013).

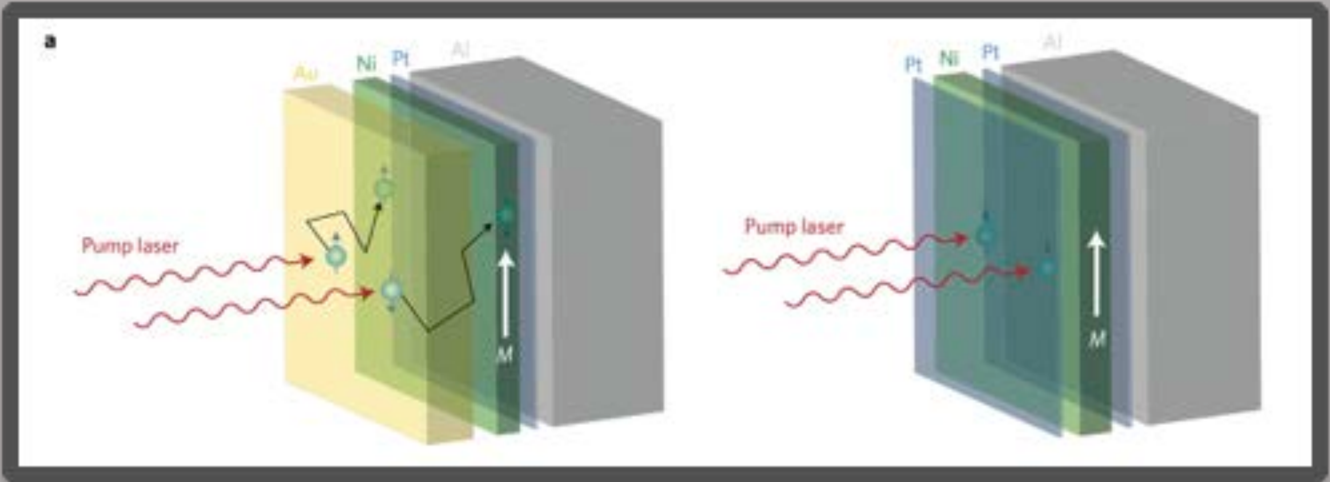
Demagnetisation without direct laser excitation

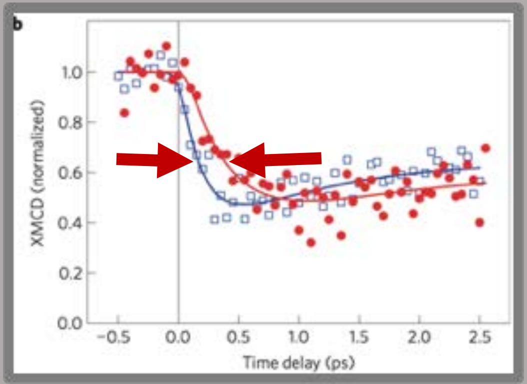




Eschenlor, Battiato et al, **Nature Mater** 12, 332 (2013).

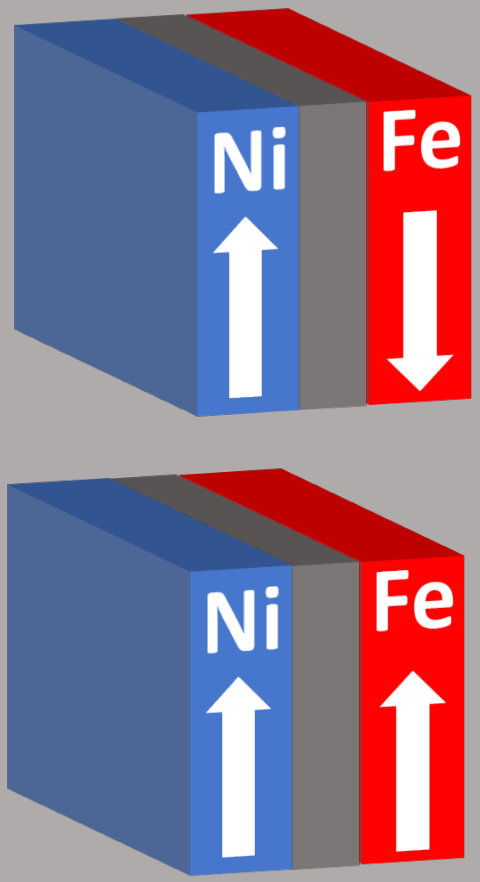
Demagnetisation without direct laser excitation





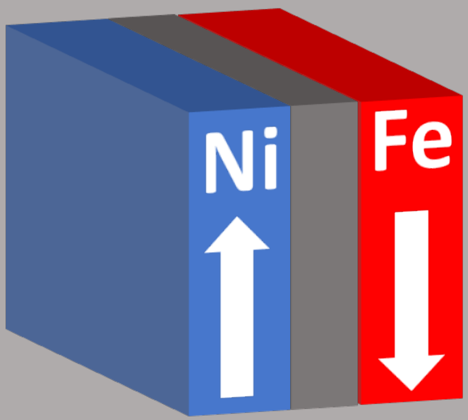
Eschenlor, Battiato et al, **Nature Mater** 12, 332 (2013).

Ultrafast increase of magnetization

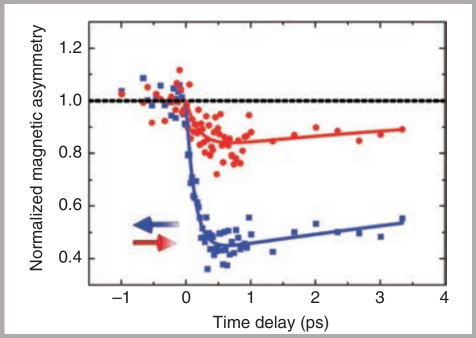


Rudolf, Battiato et al. **Nature Comm.** 3, 1038 (2012)

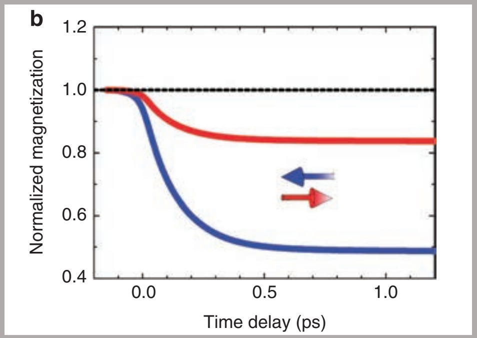
Ultrafast increase of magnetization

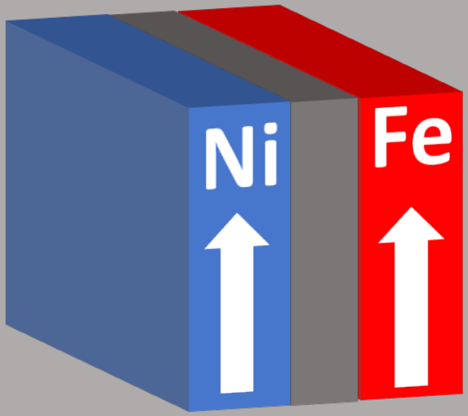


Experiments



Theory



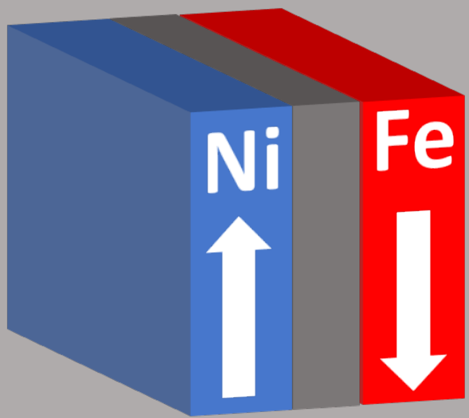


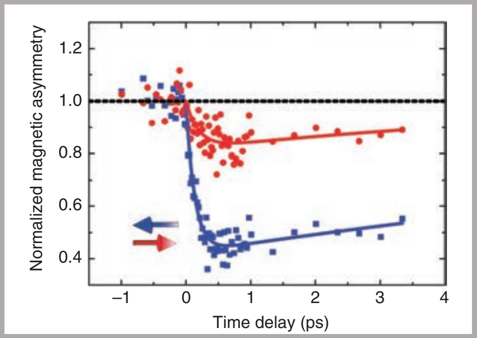
Rudolf, Battiato et al. **Nature Comm.** 3, 1038 (2012)

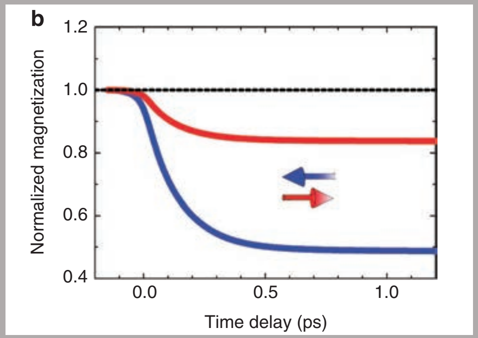
Ultrafast increase of magnetization

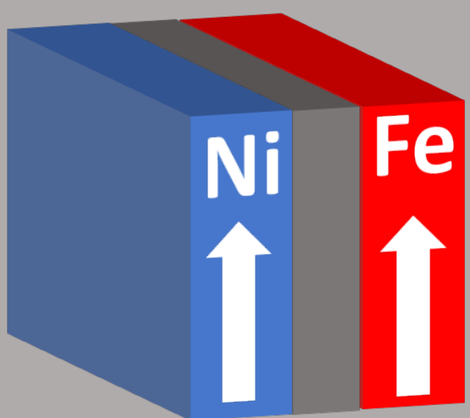
Experiments

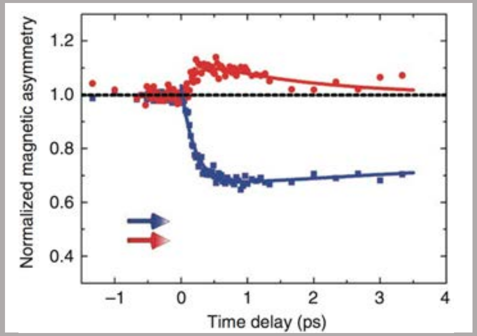
Theory

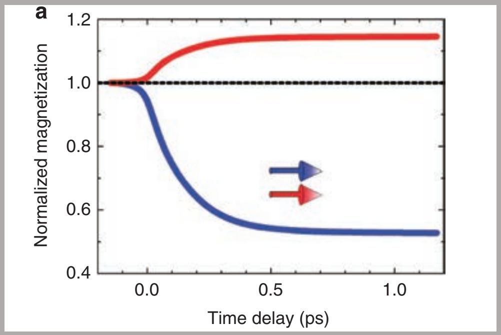








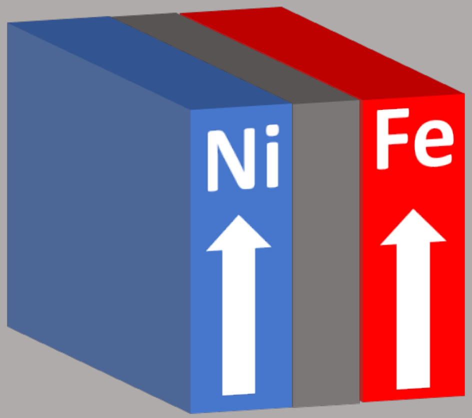


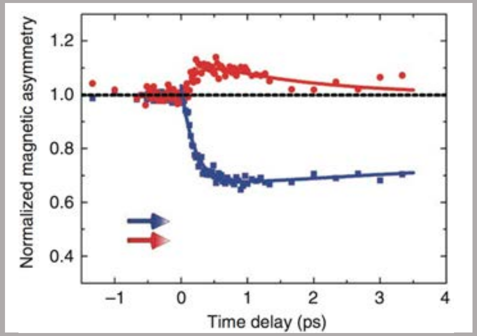


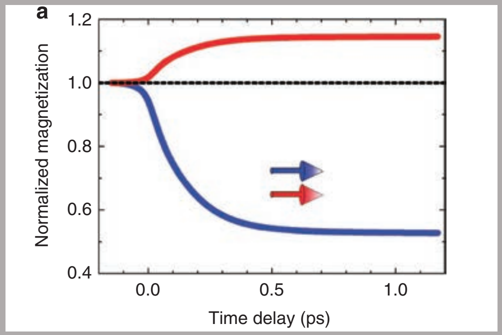
Rudolf, Battiato et al. **Nature Comm.** 3, 1038 (2012)

Ultrafast increase of magnetization

- Strong confirmation of ultrafast spin diffusion
- First observation of the ultrafast magnetization increase







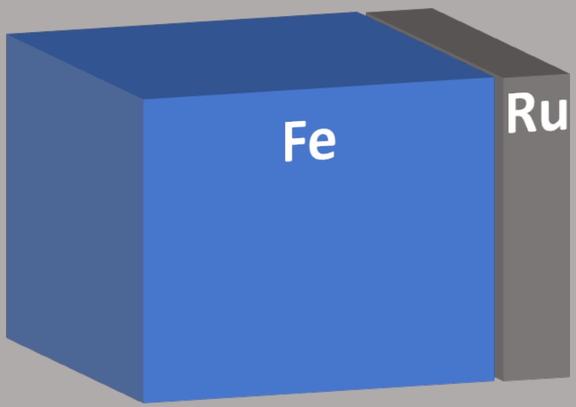
Rudolf, Battiato et al. **Nature Comm.** 3, 1038 (2012)

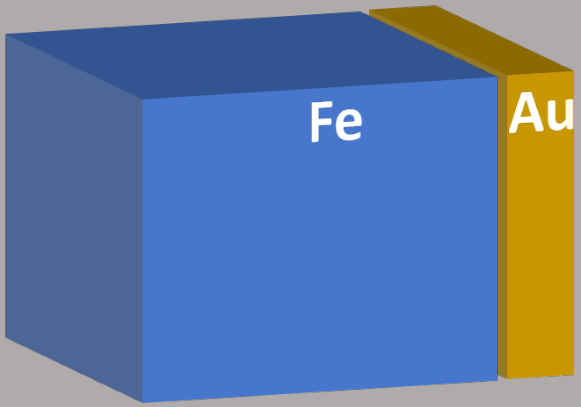
Spin current pulses shaping

Can we control these ultrafast spin currents?

Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

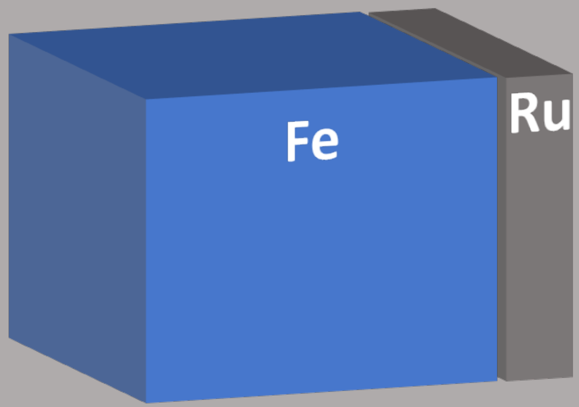
Spin current pulses shaping

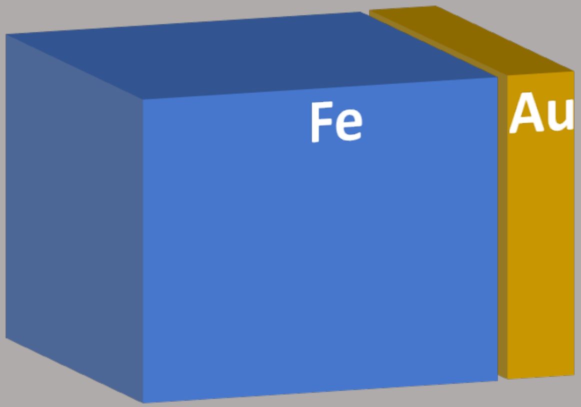


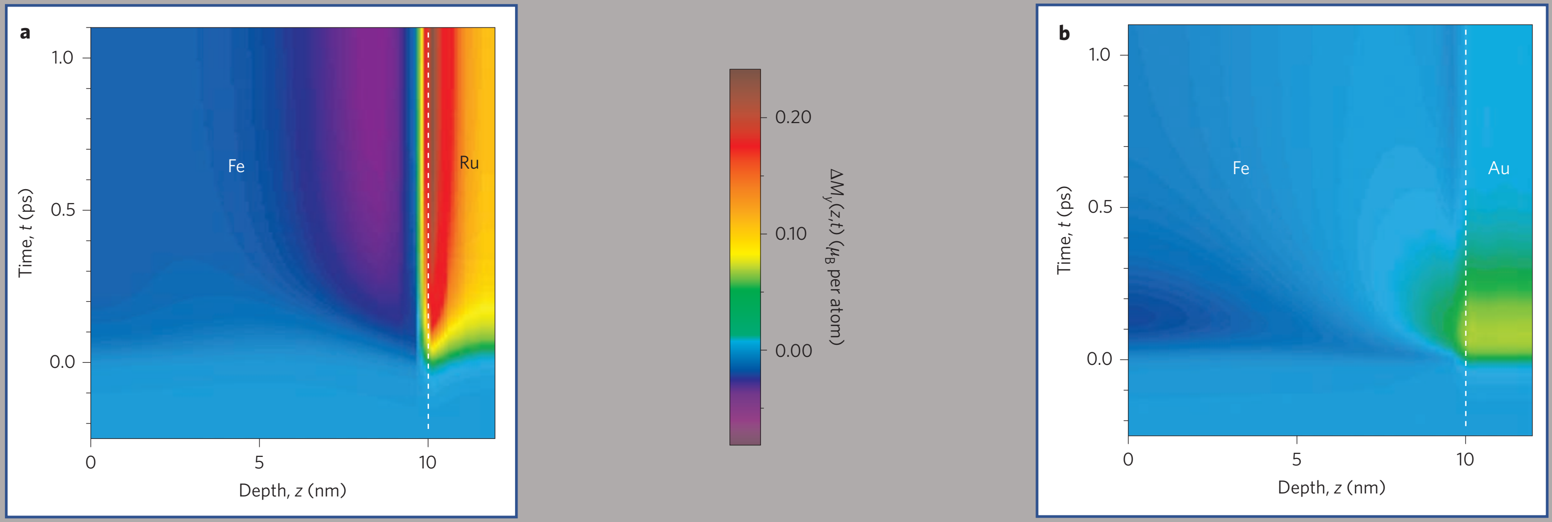


Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

Spin current pulses shaping







Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

Spin current pulses shaping

Detection ultrashort spin currents

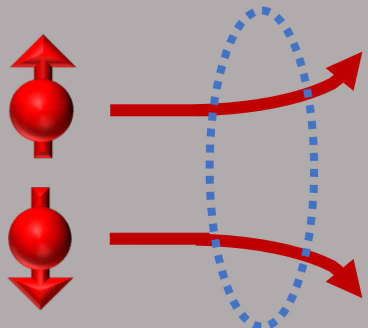
Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

Spin current pulses shaping

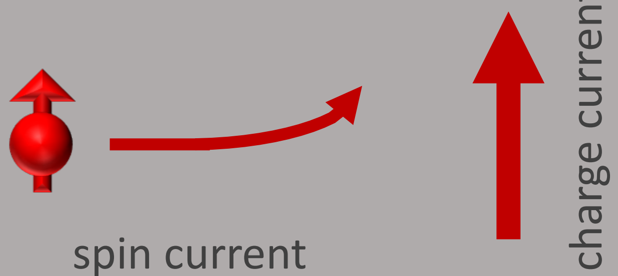
Detection ultrashort spin currents

- Conversion spin current to charge current

Spin Hall effect



Inverse Spin Hall effect

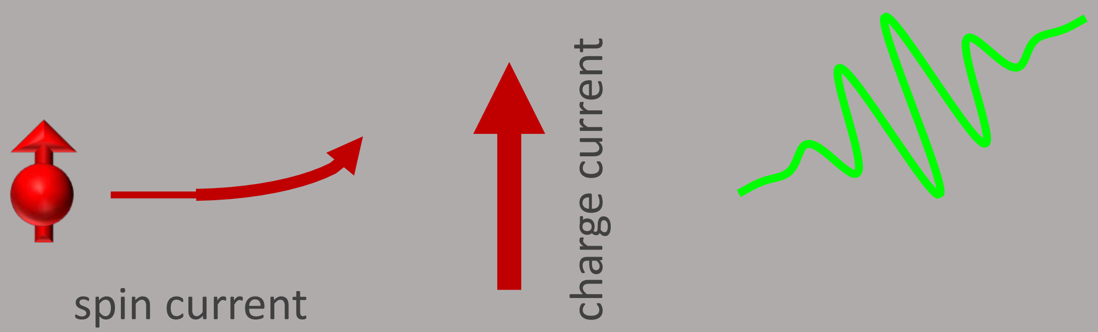


Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

Spin current pulses shaping

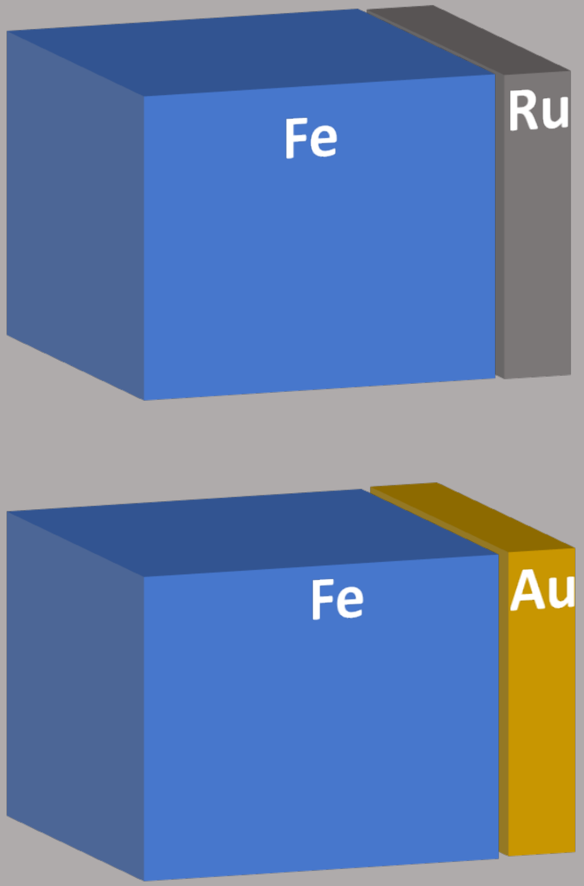
Detection spin currents

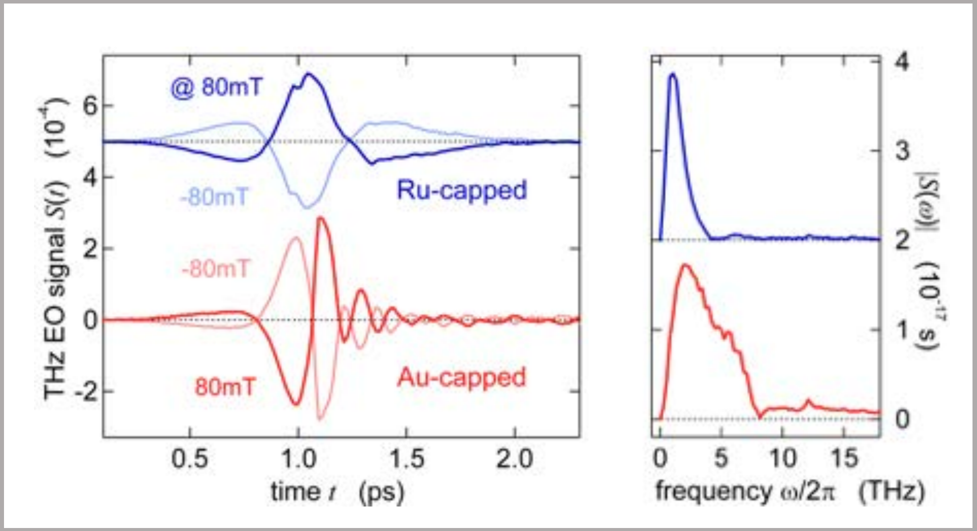
- Conversion spin current to charge current
- Conversion charge current to THz radiation



Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

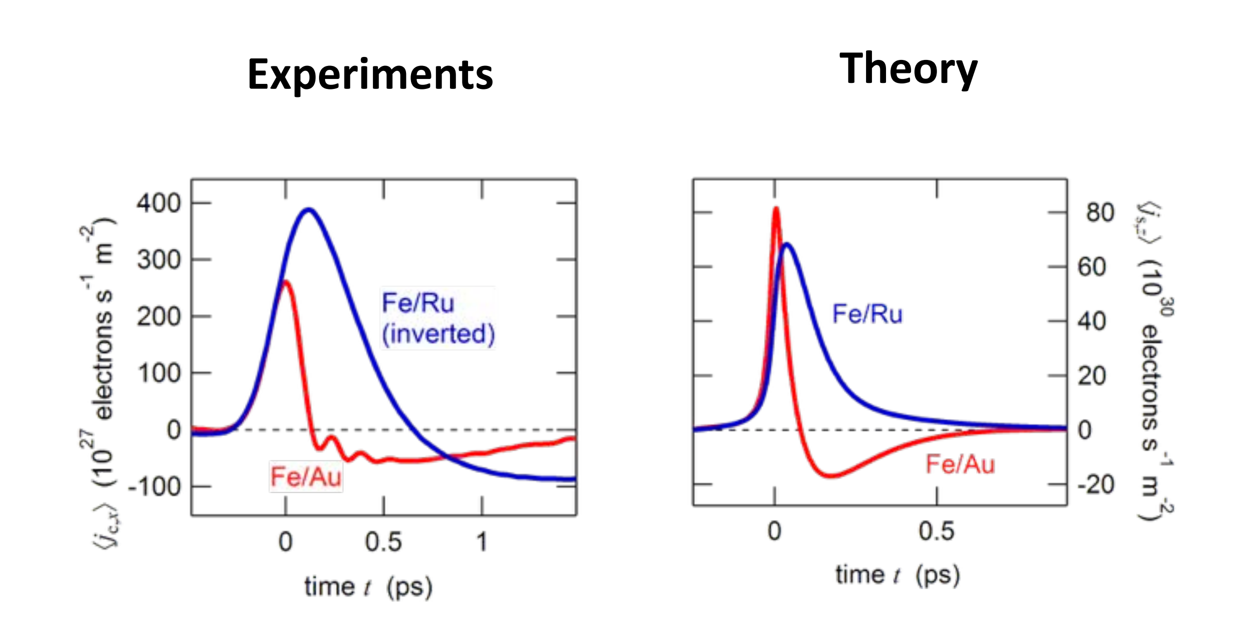
Spin current pulses shaping





Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

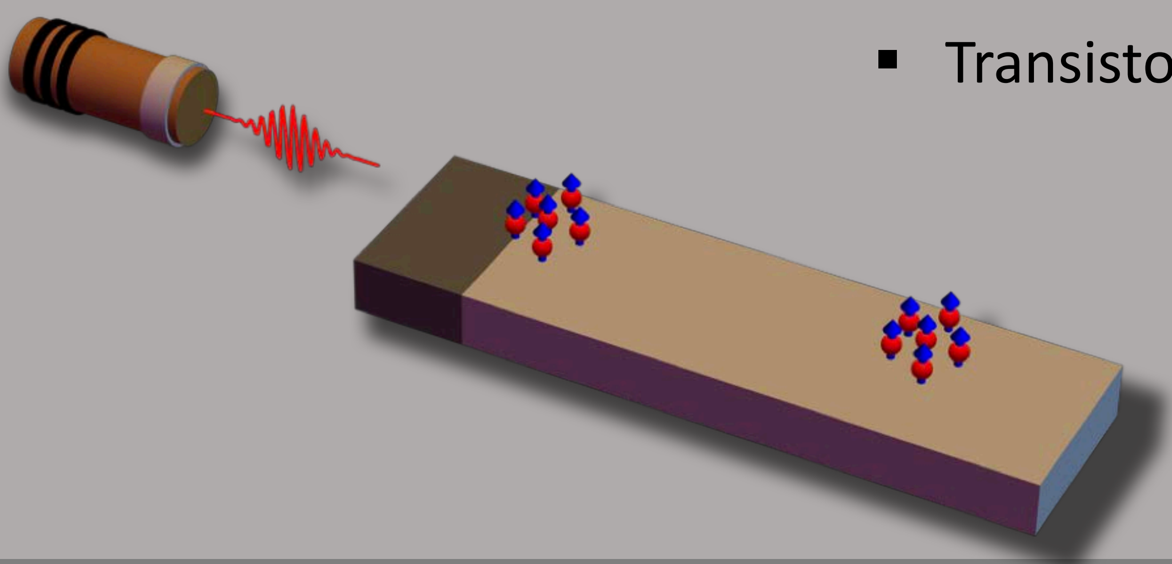
Spin current pulses shaping



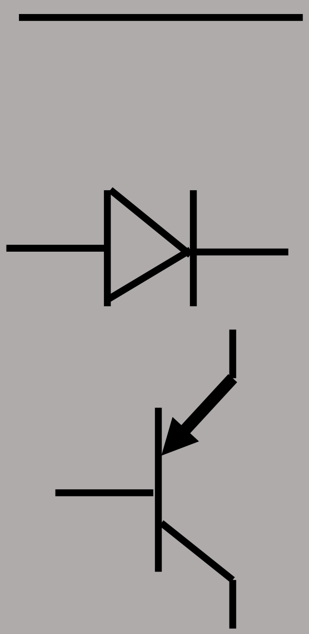
- Control of ultrafast spin currents shape
- Identification mechanism of THz emission in UD
- Ultrafast spin Ampere-meter
- Broadband THz emitter (covering gap 5-10 THz)

Kampfrath, Battiato et al. **Nature Nanotech.** 8, 256 (2013)

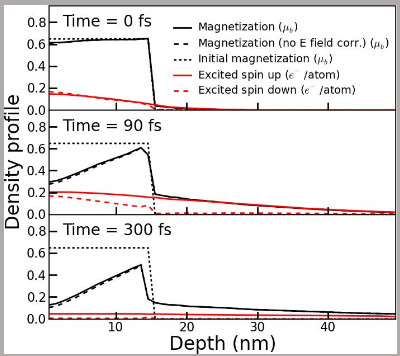
Ultrafast spintronics



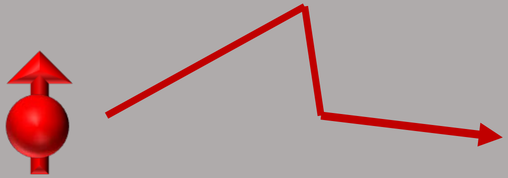
- Wire
- Diode
- Transistor



Wires: ultrafast spin injection in semiconductors

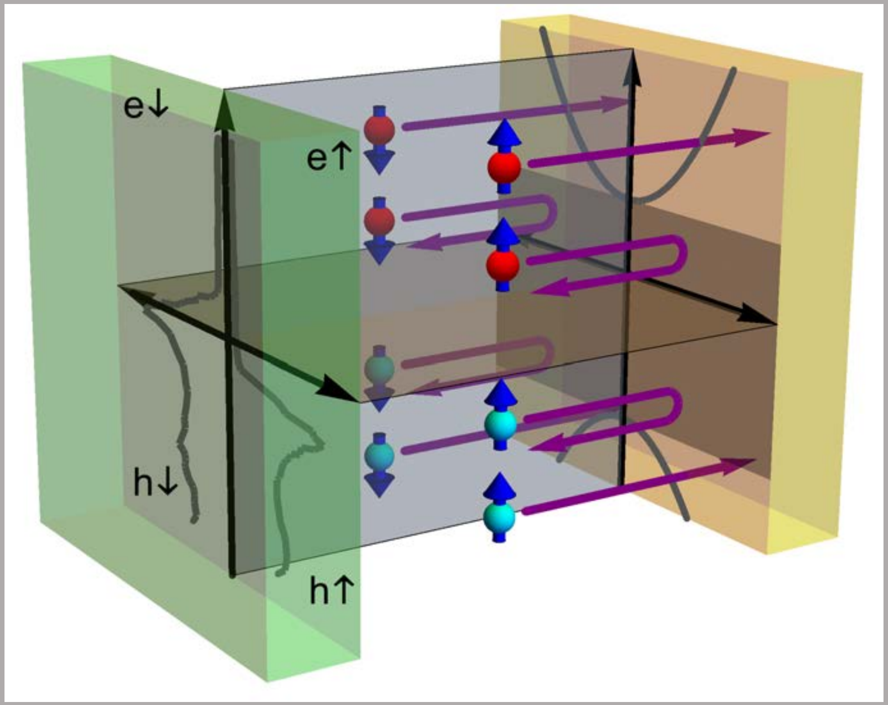


Ultrashort spin pulses diffuse in metals only up to few hundreds of nm



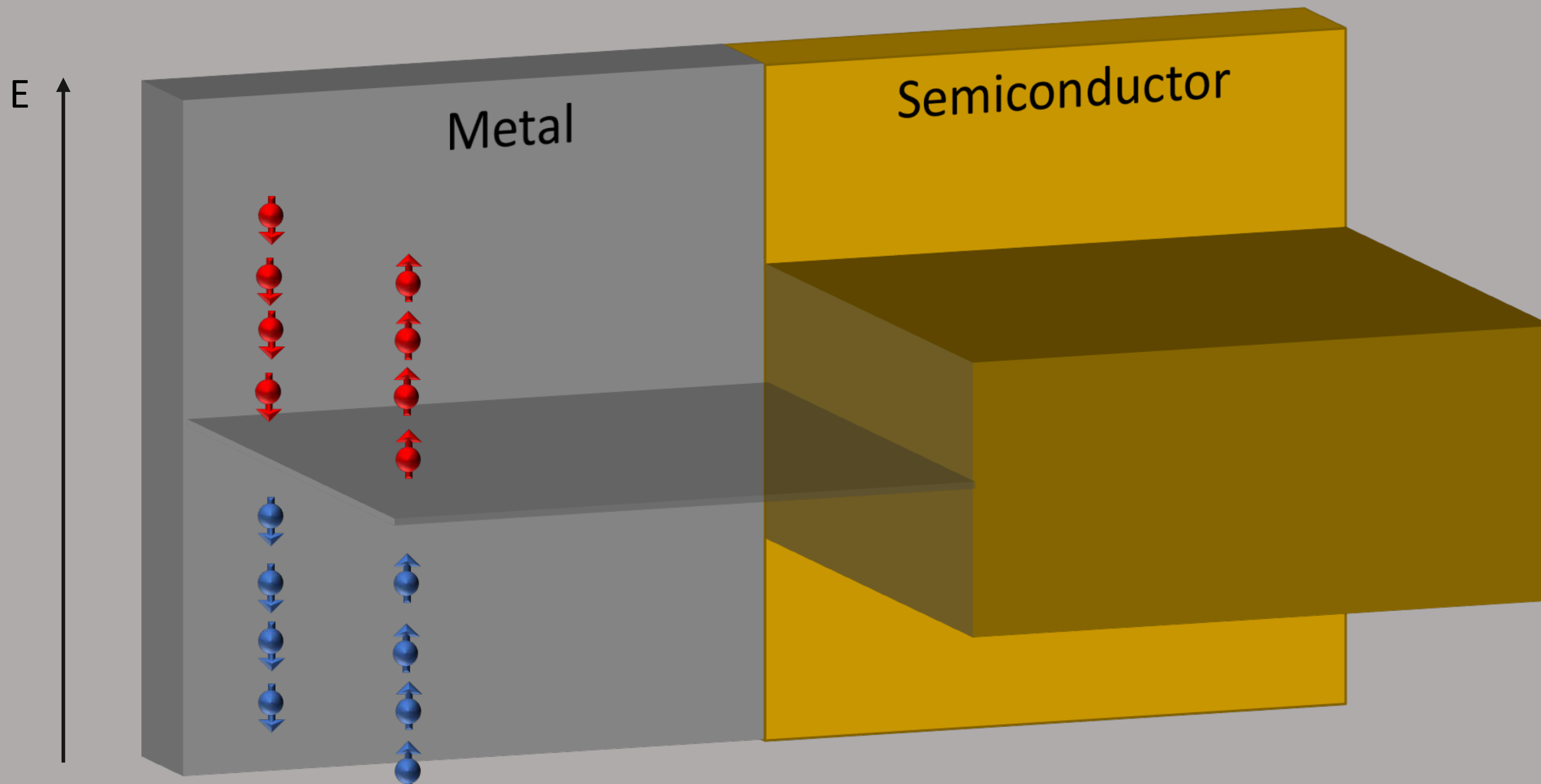
short mean free path

Wires: ultrafast spin injection in semiconductors



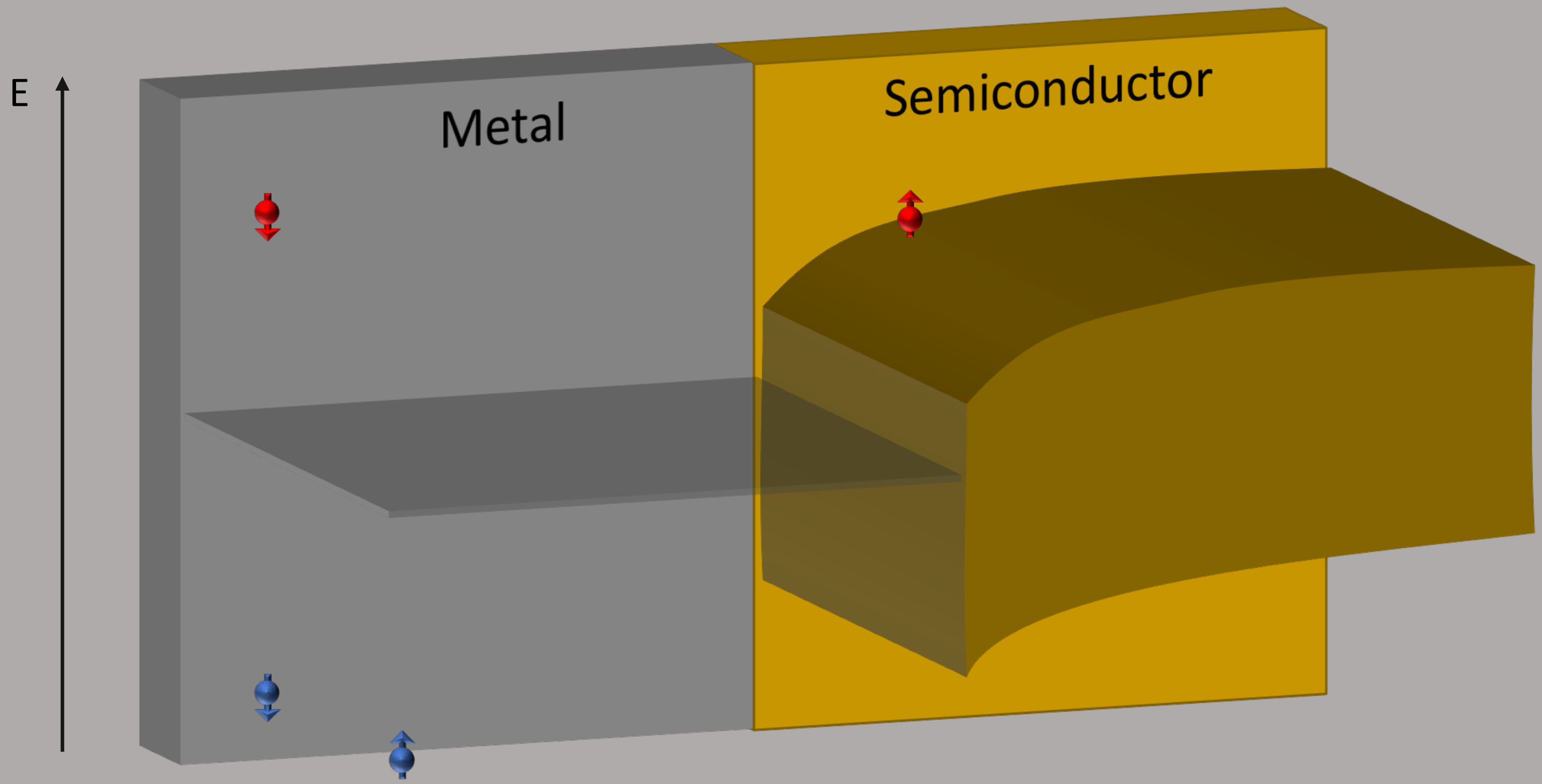
Battiato, Held, **Phys. Rev. Lett.** 116, 196601 (2016)

Wires: ultrafast spin injection in semiconductors



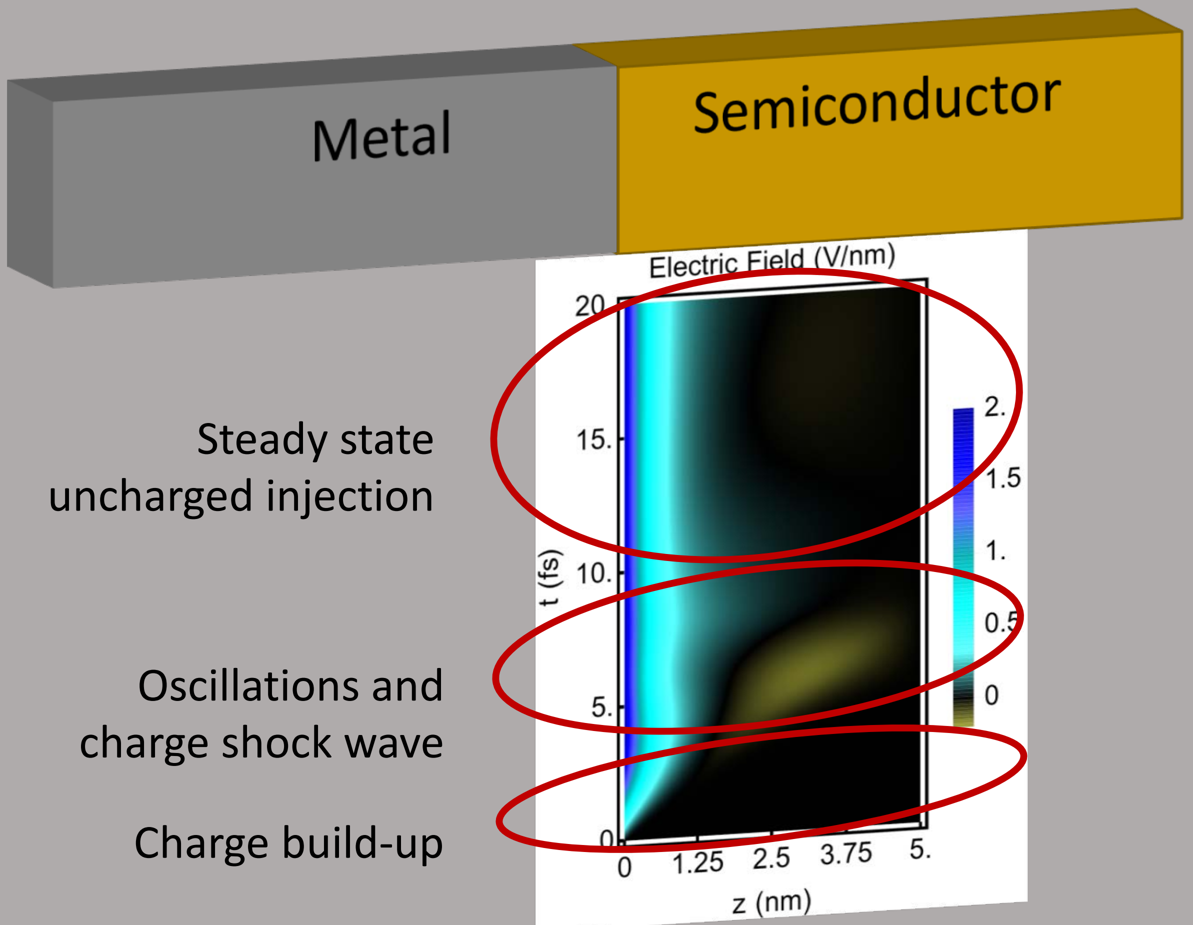
Battiato, Held, **Phys. Rev. Lett.** 116, 196601 (2016)

Ultrafast spin injection in semiconductors



Battiato, Held, **Phys. Rev. Lett.** 116, 196601 (2016)

Ultrafast spin injection in semiconductors



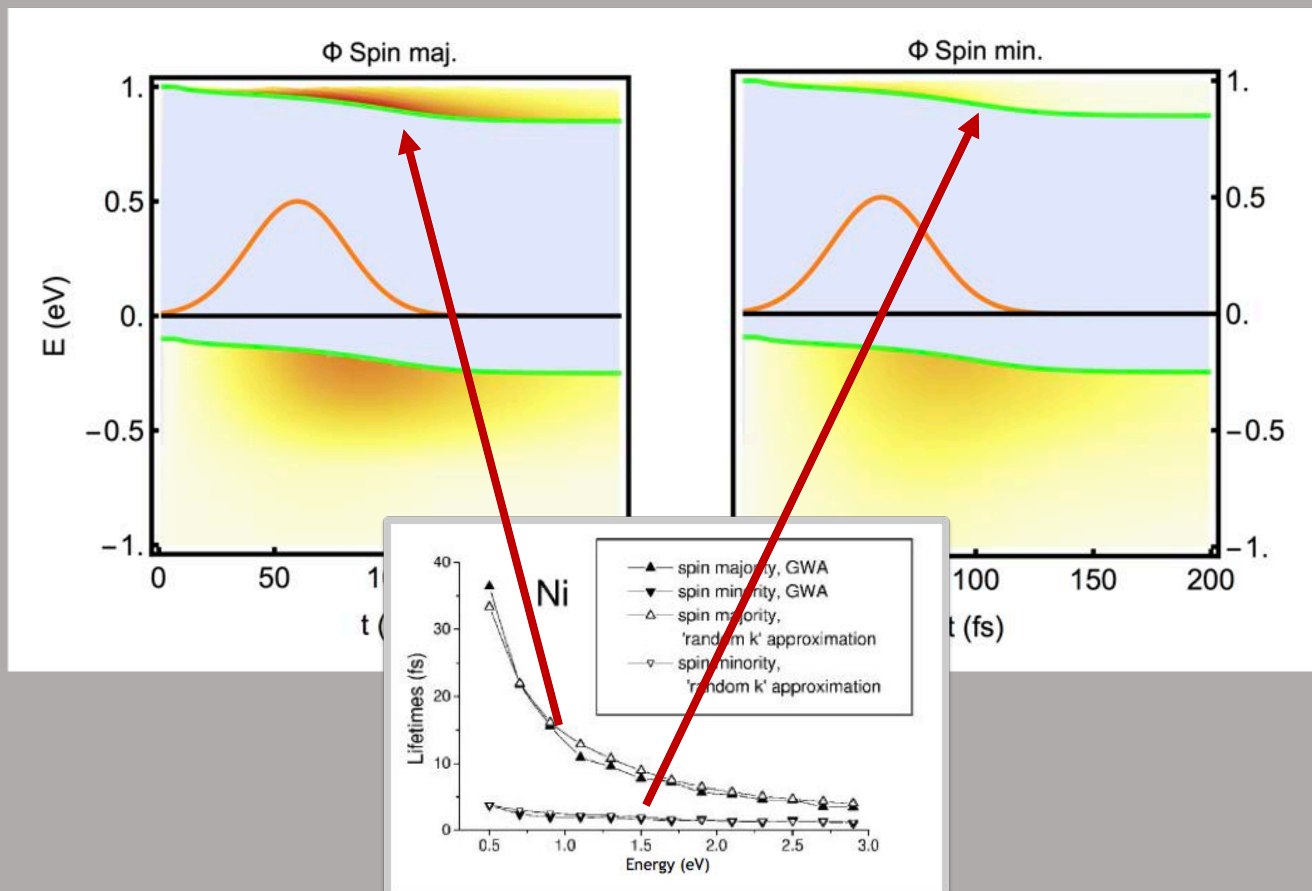
Steady state
uncharged injection

Oscillations and
charge shock wave

Charge build-up

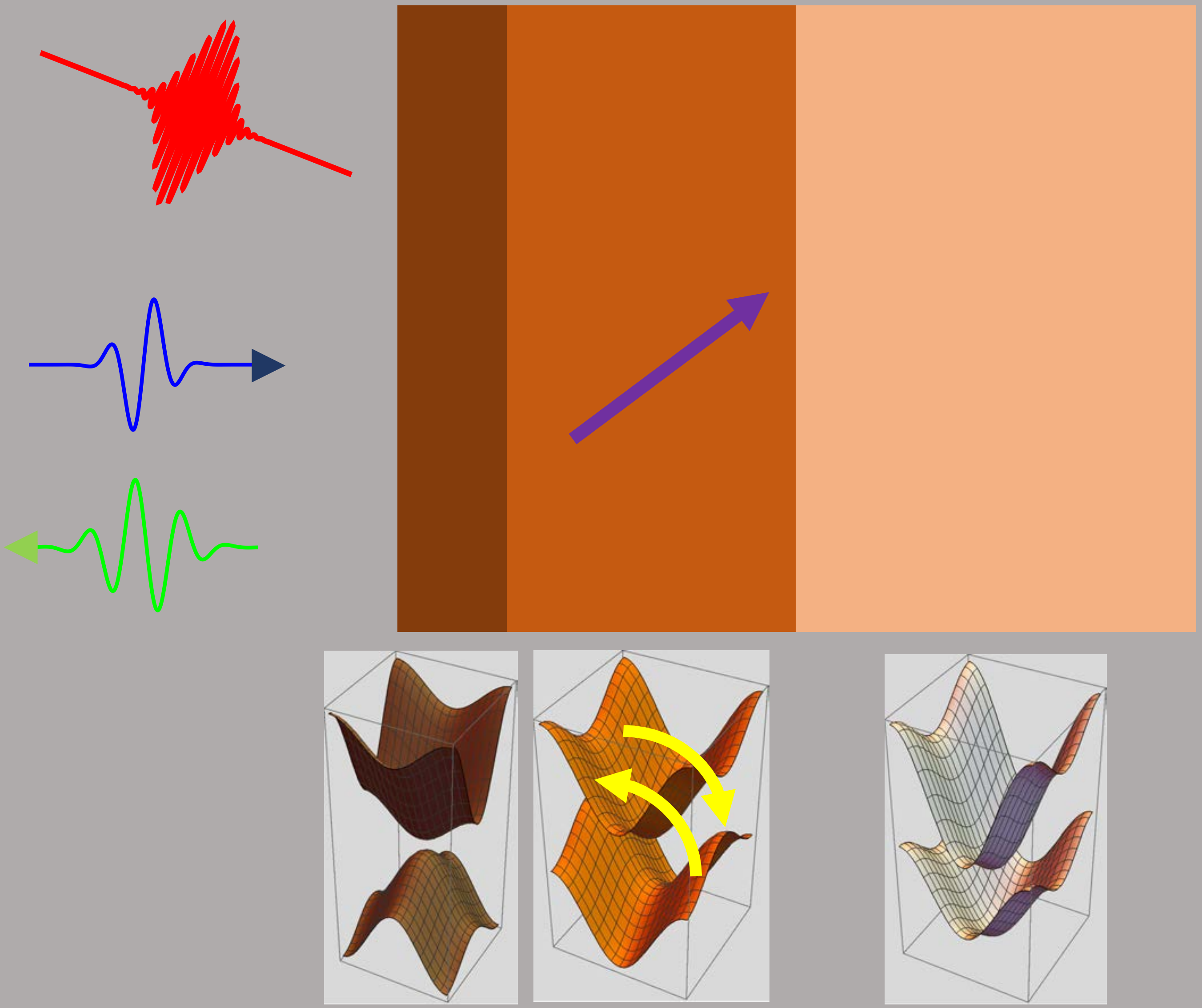
Battiato, Held, **Phys. Rev. Lett.** 116, 196601 (2016)

Ultrafast spin injection in semiconductors



Battiato, Held, **Phys. Rev. Lett.** 116, 196601 (2016)

Boltzmann + Maxwell system



Boltzmann + Maxwell system

Electronic population $f[t, \mathbf{x}, \mathbf{k}]$

Electromagnetic field $\mathbf{E}[t, \mathbf{x}] \quad \mathbf{B}[t, \mathbf{x}]$

$$\frac{\partial f}{\partial t} + \frac{1}{\hbar}\nabla_{\mathbf{k}}\mathcal{E}\cdot\nabla_{\mathbf{x}} f + \frac{e}{\hbar}\mathbf{E}\cdot\nabla_{\mathbf{k}} f - \left(\frac{\partial f}{\partial t}\right)_{\mathrm{sc}} - \left(\frac{\partial f}{\partial t}\right)_{\mathrm{ex}} = 0$$

$$\nabla\cdot\epsilon\mathbf{E} = \rho$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\times\frac{\mathbf{B}}{\mu} = \mathbf{j} + \frac{\partial\epsilon\mathbf{E}}{\partial t}$$

$$\rho[t, \mathbf{x}] = -\frac{e}{(2\pi)^3}\int f[t, \mathbf{x}, \mathbf{k}]d\mathbf{k}$$

$$\mathbf{j}[t, \mathbf{x}] = -\frac{e}{(2\pi)^3\hbar}\int \frac{\partial\mathcal{E}}{\partial\mathbf{k}} f[t, \mathbf{x}, \mathbf{k}]d\mathbf{k}$$

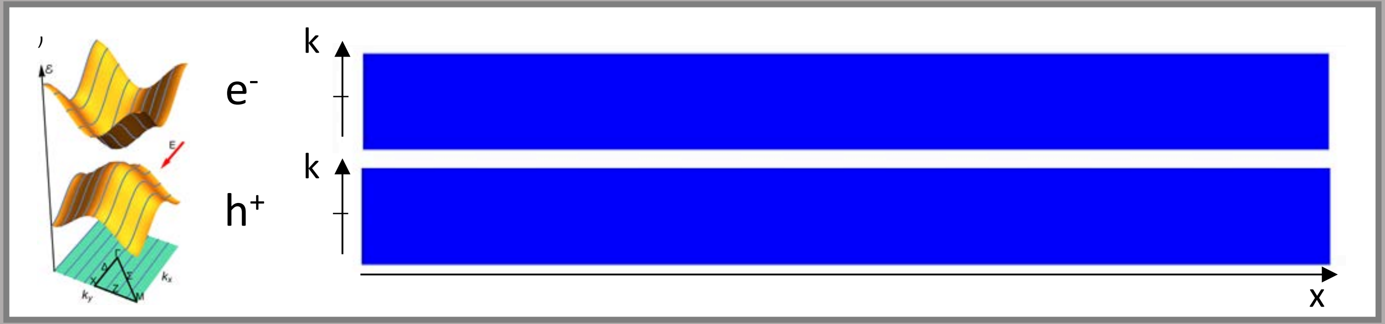
Boltzmann equation

$$\frac{\partial f}{\partial t}+\boxed{\frac{1}{\hbar}\nabla_{\mathbf{k}}\mathcal{E}\cdot\nabla_{\mathbf{x}}f+\frac{e}{\hbar}\mathbf{E}\cdot\nabla_{\mathbf{k}}f}-\left(\frac{\partial f}{\partial t}\right)_{\mathrm{sc}}-\left(\frac{\partial f}{\partial t}\right)_{\mathrm{ex}}=0$$

1+1+3 dimensional problem: not cheap, but can be handled

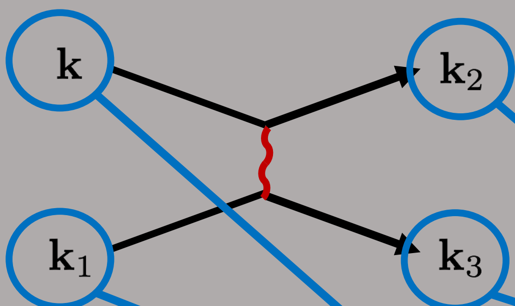
Runge Kutta Discontinuous Galerkin

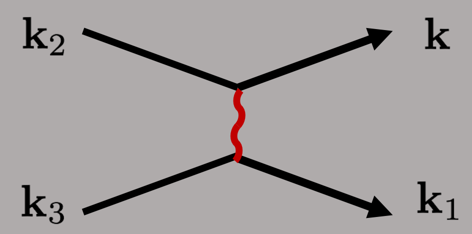
- Unstructured meshes
- Arbitrarily high order of convergence (depending on max polynomial power)
- Mass, energy and momentum conserving
- High stability in presence of shocks



Boltzmann equation

$$\frac{\partial f}{\partial t} + \frac{1}{\hbar}\nabla_{\mathbf{k}}\mathcal{E}\cdot\nabla_{\mathbf{x}} f + \frac{e}{\hbar}\mathbf{E}\cdot\nabla_{\mathbf{k}} f - \boxed{\left(\frac{\partial f}{\partial t}\right)_{\mathrm{sc}}} - \left(\frac{\partial f}{\partial t}\right)_{\mathrm{ex}} = 0$$





$$\left(\frac{\partial f}{\partial t}\right)_{col}(t,\mathbf{x},\mathbf{k}) =$$

$$\boxed{\int d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3}\ \boxed{W(\mathbf{x},\mathbf{k},\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)}\Big[\boxed{(1-f(t,\mathbf{x},\mathbf{k}))\,(1-f(t,\mathbf{x},\mathbf{k}_1))\,f(t,\mathbf{x},\mathbf{k}_2)f(t,\mathbf{x},\mathbf{k}_3)+}$$

$$\boxed{-\boxed{f(t,\mathbf{x},\mathbf{k})}\boxed{f(t,\mathbf{x},\mathbf{k}_1)}\boxed{(1-f(t,\mathbf{x},\mathbf{k}_2))}\boxed{(1-f(t,\mathbf{x},\mathbf{k}_3))}}\Big]$$

$$W(\mathbf{x},\mathbf{k},\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) =$$

$$= \sum_{\mathbf{G}} w(\mathbf{x},\mathbf{k},\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)\ \underline{\delta(\mathbf{k}+\mathbf{k}_1-\mathbf{k}_2-\mathbf{k}_3+\mathbf{G})}\ \underline{\delta(\mathcal{E}(\mathbf{k})+\mathcal{E}(\mathbf{k}_1)-\mathcal{E}(\mathbf{k}_2)-\mathcal{E}(\mathbf{k}_3))}$$

k-conservation
(umklapp)

energy-conservation

Scattering term

$$S_{ijklm} = \sum_{\mathbf{G}} \int d\mathbf{k} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3$$

$$\Big(w(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \cdot$$

$$\delta(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 + \mathbf{G})\ \delta(\mathcal{E}(\mathbf{k}) + \mathcal{E}(\mathbf{k}_1) - \mathcal{E}(\mathbf{k}_2) - \mathcal{E}(\mathbf{k}_3)) \cdot$$

$$b_i(\mathbf{k}) b_j(\mathbf{k}) b_k(\mathbf{k}_1) b_l(\mathbf{k}_2) b_m(\mathbf{k}_3) \Big)$$

Scattering term

$$S_{\boxed{ijklm}} = \sum_{\mathbf{G}} \int d\mathbf{k} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3$$
$$\Big(w(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \cdot$$
$$\delta(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 + \mathbf{G})\ \delta(\mathcal{E}(\mathbf{k}) + \mathcal{E}(\mathbf{k}_1) - \mathcal{E}(\mathbf{k}_2) - \mathcal{E}(\mathbf{k}_3)) \cdot$$
$$b_i(\mathbf{k}) b_j(\mathbf{k}) b_k(\mathbf{k}_1) b_l(\mathbf{k}_2) b_m(\mathbf{k}_3) \Big)$$

- 5 dimensional tensor: number of entries is N^5
  (400 basis functions -> 10^{13} integrals to calculate and 10TB to store)

Scattering term

$$S_{ijklm} = \sum_{\mathbf{G}} \int \boxed{d\mathbf{k} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3}$$
$$\Big(w(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \cdot$$
$$\delta(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 + \mathbf{G}) \; \delta(\mathcal{E}(\mathbf{k}) + \mathcal{E}(\mathbf{k}_1) - \mathcal{E}(\mathbf{k}_2) - \mathcal{E}(\mathbf{k}_3)) \cdot$$
$$b_i(\mathbf{k}) b_j(\mathbf{k}) b_k(\mathbf{k}_1) b_l(\mathbf{k}_2) b_m(\mathbf{k}_3) \Big)$$

- 5 dimensional tensor: number of entries is N^5
  (400 basis functions -> 10^{13} integrals to calculate and 10TB to store)
- 12 dimensional integral

Scattering term

$$S_{ijklm} = \sum_{\mathbf{G}} \int d\mathbf{k} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3$$

$$\Big(w(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \cdot$$

$$\boxed{\delta(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 + \mathbf{G})\ \delta(\mathcal{E}(\mathbf{k}) + \mathcal{E}(\mathbf{k}_1) - \mathcal{E}(\mathbf{k}_2) - \mathcal{E}(\mathbf{k}_3)) \cdot}$$

$$b_i(\mathbf{k}) b_j(\mathbf{k}) b_k(\mathbf{k}_1) b_l(\mathbf{k}_2) b_m(\mathbf{k}_3) \Big)$$

- 5 dimensional tensor: number of entries is N^5
  (400 basis functions -> 10^{13} integrals to calculate and 10TB to store)
- 12 dimensional integral
- Dirac deltas inside the integral

Scattering term

$$S_{ijklm} = \sum_{\mathbf{G}} \int d\mathbf{k} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3$$

$$\Big(w(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \cdot$$

$$\delta(\mathbf{k} + \mathbf{k}_1 - \mathbf{k}_2 - \mathbf{k}_3 + \mathbf{G})\ \delta(\mathcal{E}(\mathbf{k}) + \mathcal{E}(\mathbf{k}_1) - \mathcal{E}(\mathbf{k}_2) - \mathcal{E}(\mathbf{k}_3)) \cdot$$

$$b_i(\mathbf{k}) b_j(\mathbf{k}) b_k(\mathbf{k}_1) b_l(\mathbf{k}_2) b_m(\mathbf{k}_3) \Big)$$

- 5 dimensional tensor: number of entries is N^5 (400 basis functions -> 10^{13} integrals to calculate and 10TB to store)
- 12 dimensional integral
- Dirac deltas inside the integral
- Failure to integrate to extreme precision leads to breaking of particle, energy and momentum conservation

Thermalization in real band structures

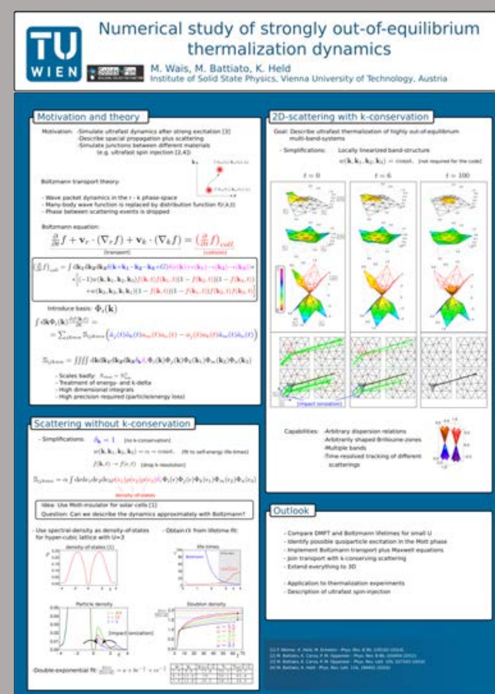
$$\left(\frac{\partial f}{\partial t}\right)_{col}(t,\mathbf{x},\mathbf{k}) =$$

$$\int d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3\, W(\mathbf{x},\mathbf{k},\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)\Big[\left(1-f(t,\mathbf{x},\mathbf{k})\right)\left(1-f(t,\mathbf{x},\mathbf{k}_1)\right)f(t,\mathbf{x},\mathbf{k}_2)f(t,\mathbf{x},\mathbf{k}_3)+$$

$$-f(t,\mathbf{x},\mathbf{k})f(t,\mathbf{x},\mathbf{k}_1)\left(1-f(t,\mathbf{x},\mathbf{k}_2)\right)\left(1-f(t,\mathbf{x},\mathbf{k}_3)\right)\Big]$$

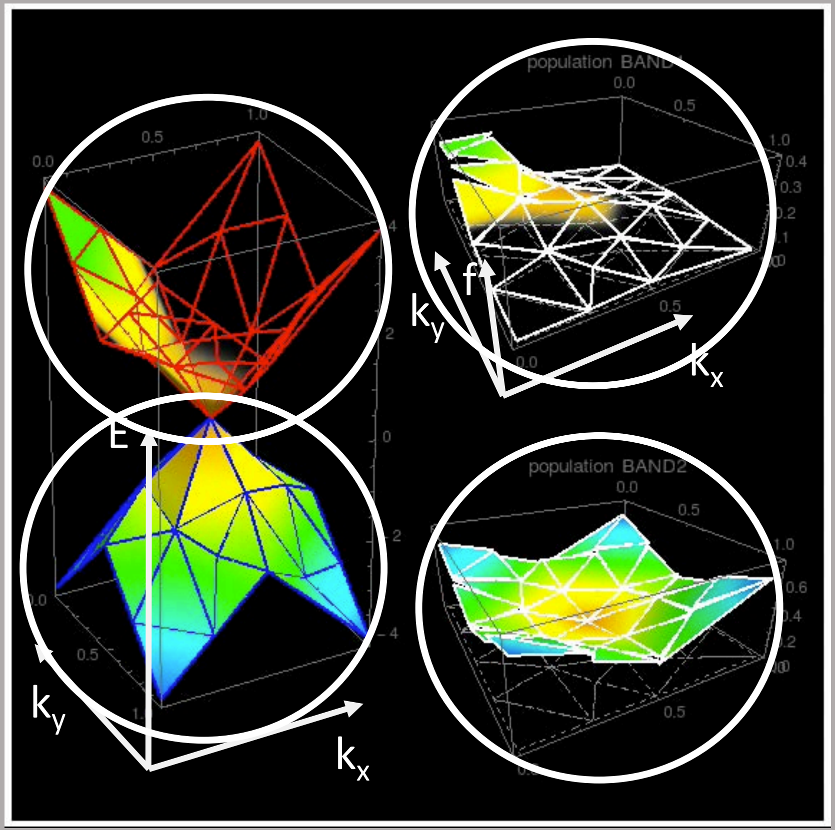
Michael Wais

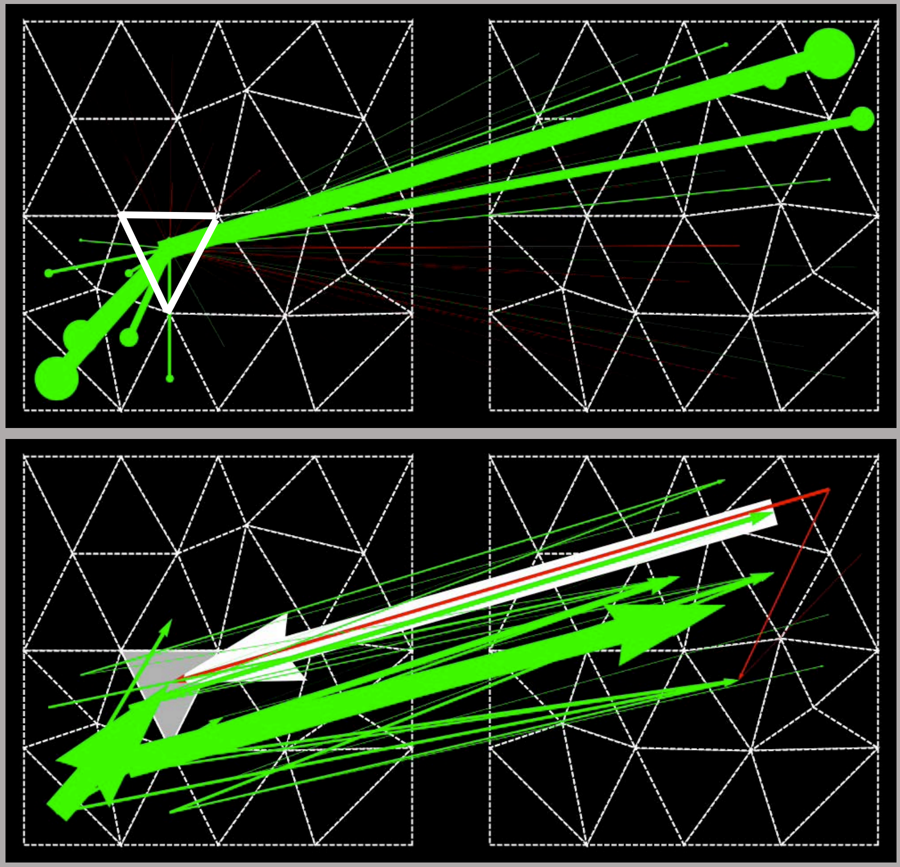
Check his poster out!!!



Thermalization in real band structures

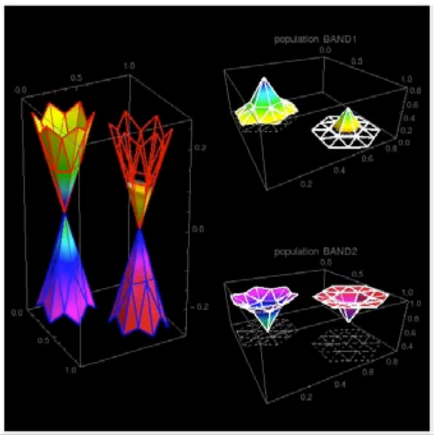
$$\left(\frac{\partial f}{\partial t}\right)_{col}(t,\mathbf{x},\mathbf{k}) =$$
$$\int d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3 \, W(\mathbf{x},\mathbf{k},\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)\big[\,(1-f(t,\mathbf{x},\mathbf{k}))\,(1-f(t,\mathbf{x},\mathbf{k}_1))\,f(t,\mathbf{x},\mathbf{k}_2)f(t,\mathbf{x},\mathbf{k}_3)+$$
$$-\,f(t,\mathbf{x},\mathbf{k})f(t,\mathbf{x},\mathbf{k}_1)\,(1-f(t,\mathbf{x},\mathbf{k}_2))\,(1-f(t,\mathbf{x},\mathbf{k}_3))\,\big]$$





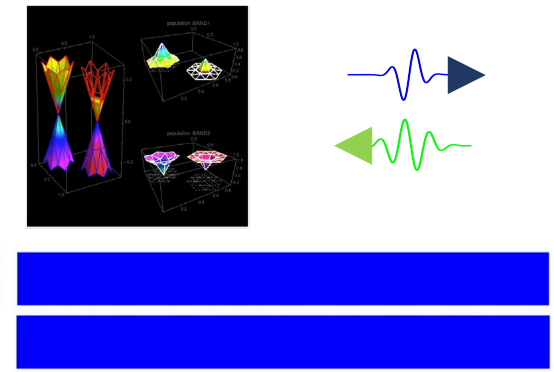
Future plans / Areas of interest

2D/3D thermalisation



2D/3D thermalisation + transport + Poisson

2D/3D thermalisation + transport + Maxwell



Thermalisation in real band struct

- Impact ionization
- Timescales of thermal.
- Momentum conserv.
- Thermal bottlenecks

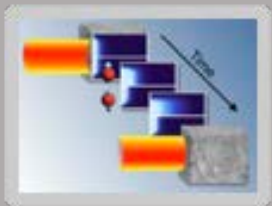
Out of equilibrium transport

- Spin diffusion
- Spin injection
- Charging of interfaces
- Transport blockade

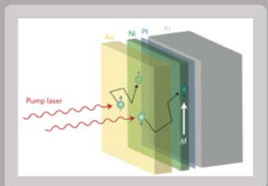
THz radiation

- THz emission
- THz absirption

THANKS TO



P. Maldonado
K. Carva
P. M. Oppeneer



A.Eschenlohr
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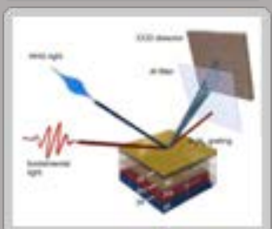
R. Mitzner
A. Föhlisch

C. Stamm



D. Rudolf
C. La-O-Vorakiat
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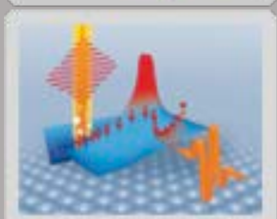
M. Aeschlimann

H. C. Kapteyn
M. M. Murnane
C. M. Schneider

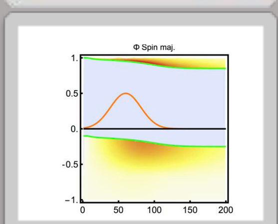


T. Kampfrath
G. Eilers
J. Nötzold

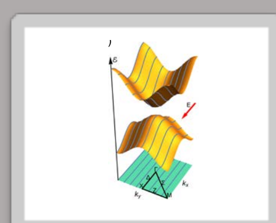
S. Mährlein
V. Zbarsky
F. Freimuth

Y. Mokrousov
S. Blügel
M. Wolf

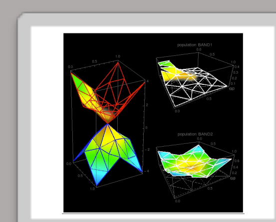
I. Radu
M. Münzenberg



K. Held



M. Wais
G. Kitzler
J. Schöberl



M. Wais
K. Held

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FWF
Der Wissenschaftsfonds.

THANK YOU

Multiple PhD and PostDoc positions

Starting dates
PhD: Aug 2018 / Jan 2019
PostDoc: Nov 2017

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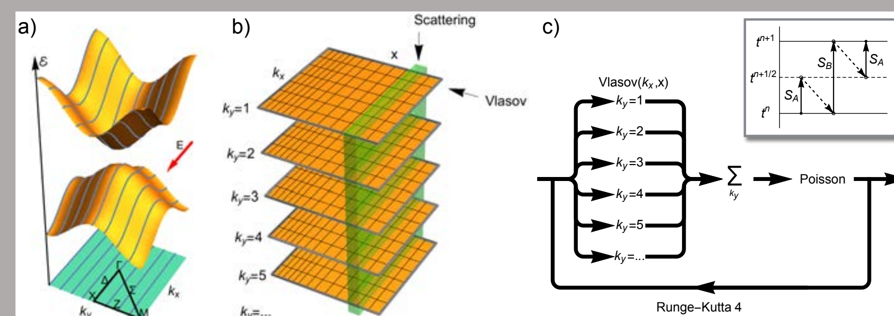
NAP Award (1M S$ + PhD's)

- Physics (theory)
- Mathematics
- Electronics

NANYANG TECHNOLOGICAL UNIVERSITY



- Ultrafast dynamics
- Ab initio methods
- Boltzmann equation
- Discontinuous Galerkin

QS World ranking

11th World Ranking
3rd Engineering and Technology
7th Materials Science