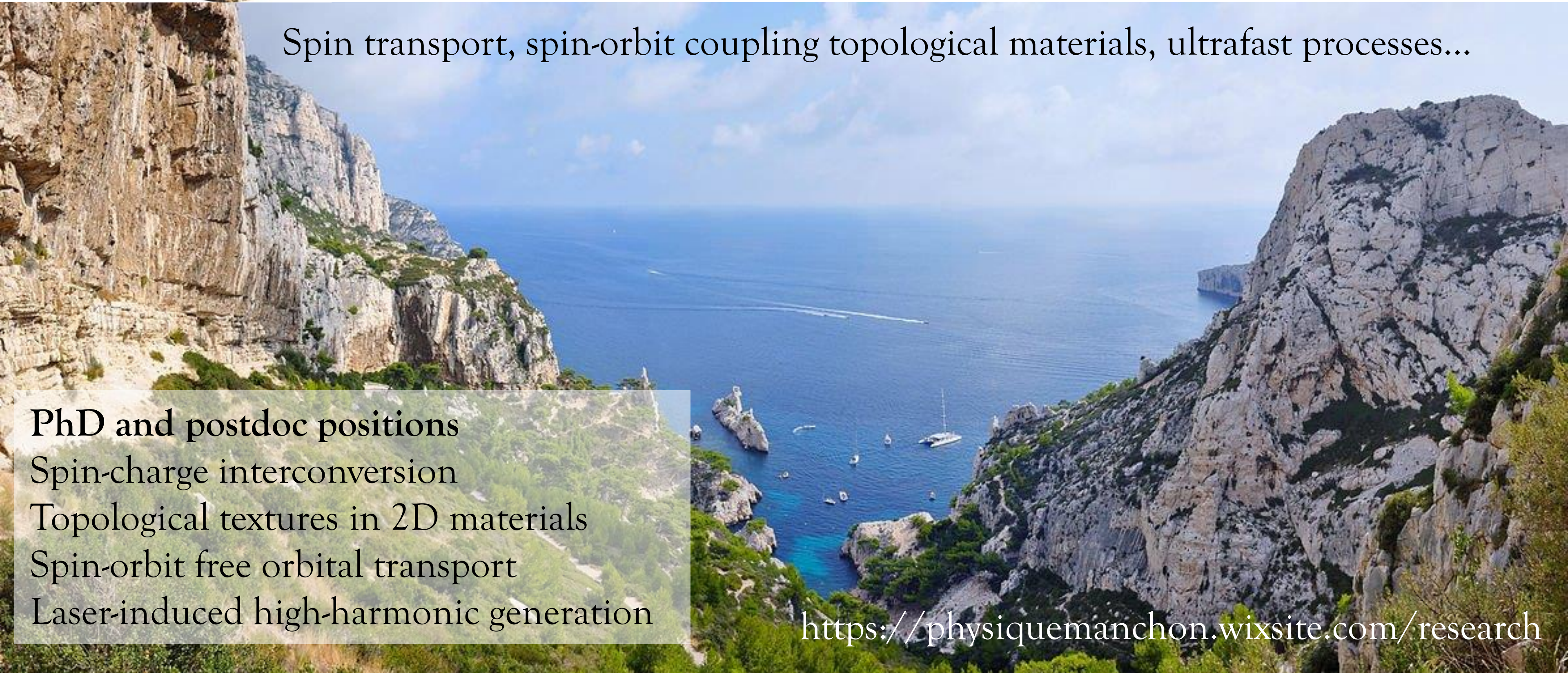
Spin Transport: GMR, TMR etc.

by Aurélien Manchon

physiquemanchon.wixsite.com

Center of Interdisciplinary Nanoscience of Marseille
Theory and Numerical Simulation Department
Aix-Marseille University

CINaM



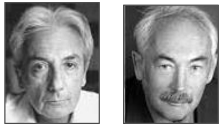
Spin transport, spin-orbit coupling topological materials, ultrafast processes…

PhD and postdoc positions

Spin-charge interconversion
Topological textures in 2D materials
Spin-orbit free orbital transport
Laser-induced high-harmonic generation

https://physiquemanchon.wixsite.com/research

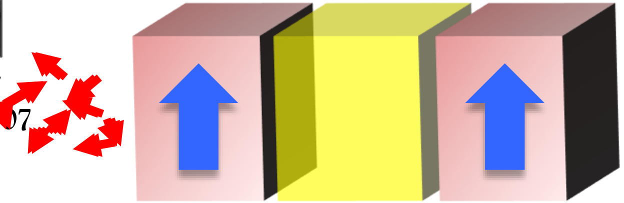
Spintronics: A history of revolutions



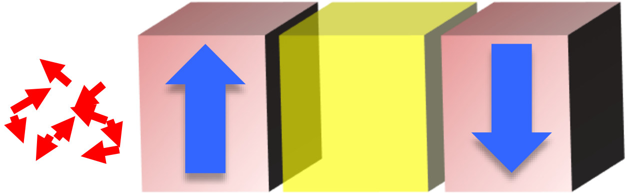
Fert & Grünberg

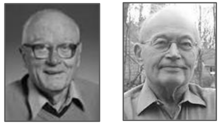
Nobel Laureates 2007

Giant magnetoresistance



Spin transfer torque



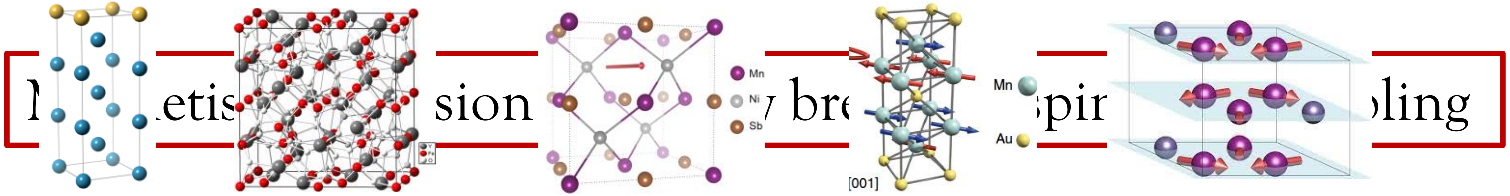


Berger & Slonczewski

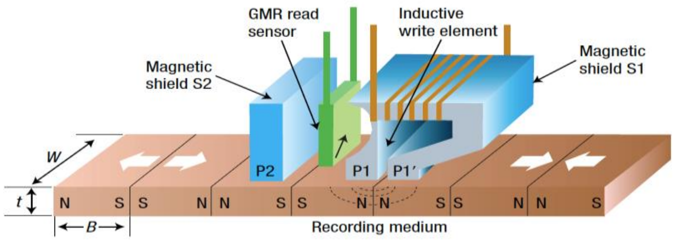
Buckley price 2013

Typically: Co/Cu/Co, CoFeB/MgO/CoFeB

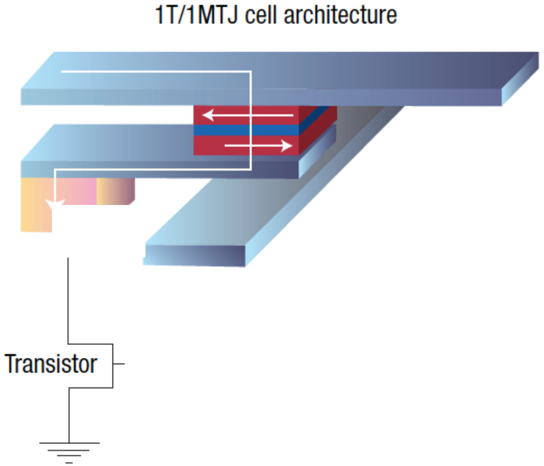
Typically: (Pt, Ta, W etc.)/Magnet

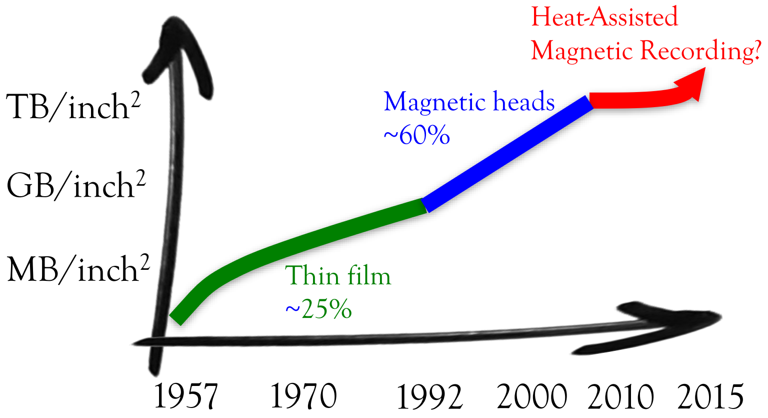


Spintronics: A history of revolutions

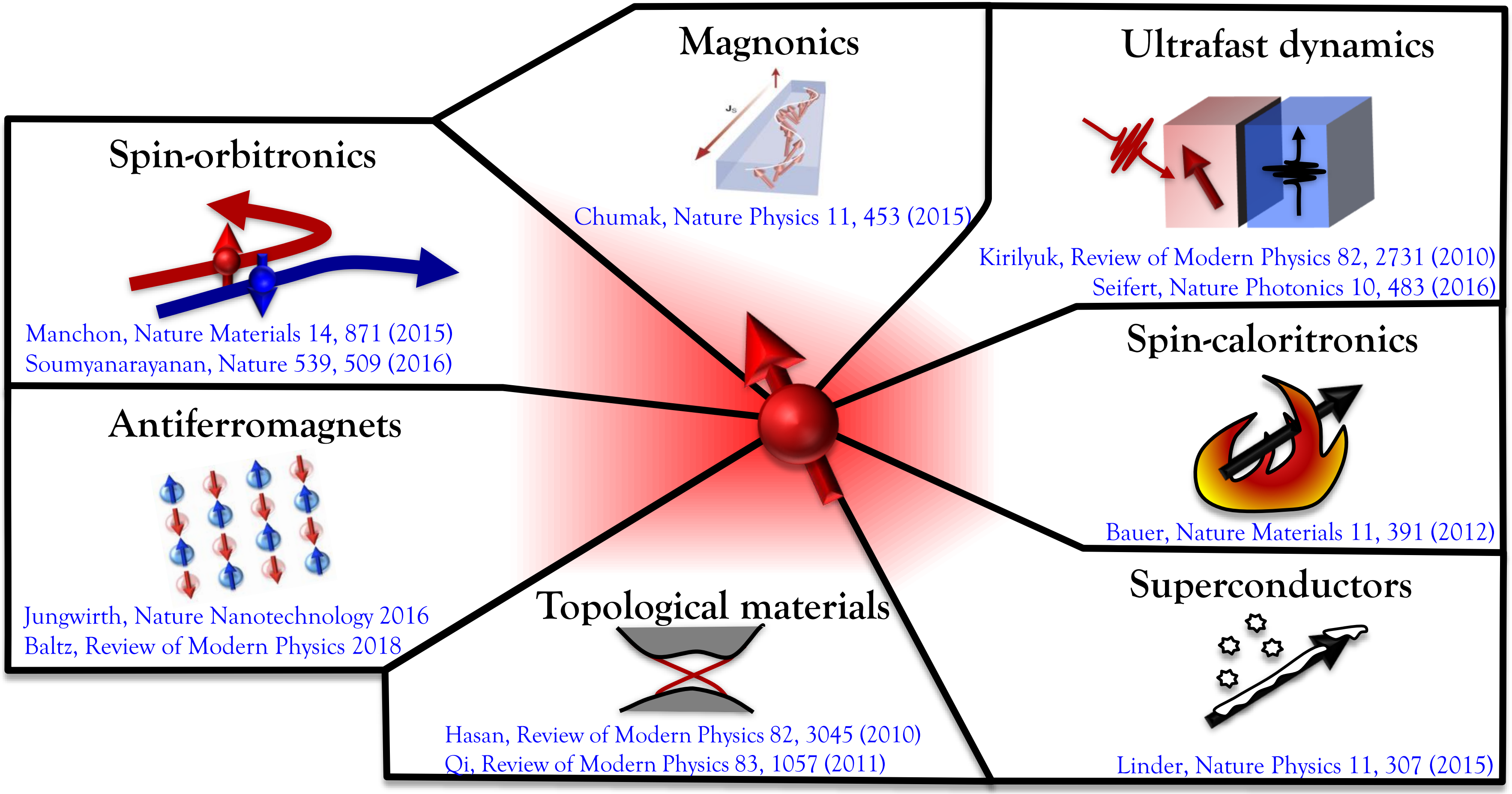


Chappert et al., Nature Materials 2007





Major semiconductor bigfoot: IBM, Samsung, Intel, Toshiba, Qualcom etc.



Magnonics

Chumak, Nature Physics 11, 453 (2015)

Ultrafast dynamics

Kirilyuk, Review of Modern Physics 82, 2731 (2010)
Seifert, Nature Photonics 10, 483 (2016)

Spin-orbitronics

Manchon, Nature Materials 14, 871 (2015)
Soumyanarayanan, Nature 539, 509 (2016)

Spin-caloritronics

Bauer, Nature Materials 11, 391 (2012)

Antiferromagnets

Jungwirth, Nature Nanotechnology 2016
Baltz, Review of Modern Physics 2018

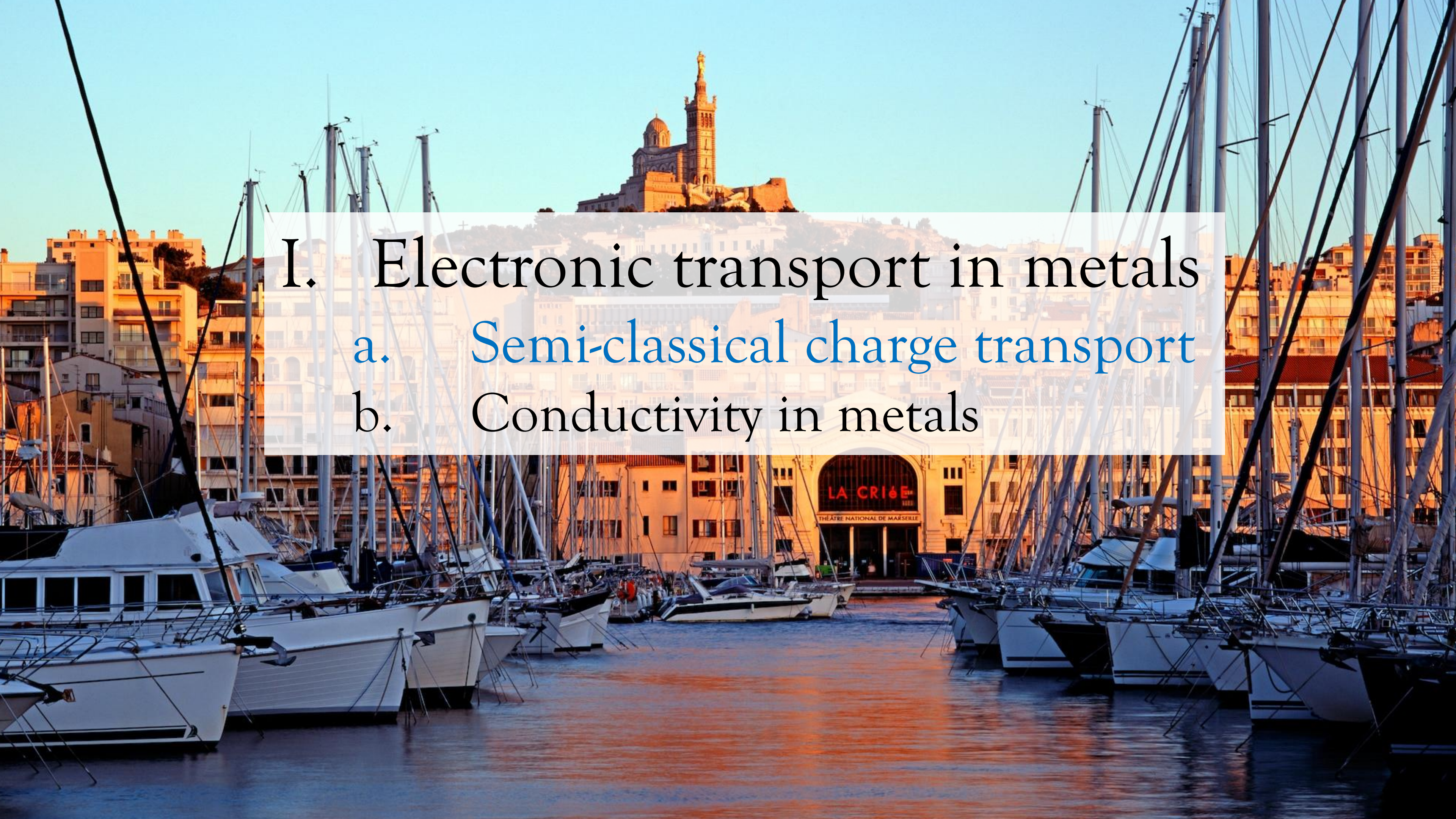
Superconductors

Linder, Nature Physics 11, 307 (2015)

Topological materials

Hasan, Review of Modern Physics 82, 3045 (2010)
Qi, Review of Modern Physics 83, 1057 (2011)

I. Electronic transport in metals
II. Spin transport in metals
III. Spin-dependent tunneling
IV. Antiferromagnets



I. Electronic transport in metals

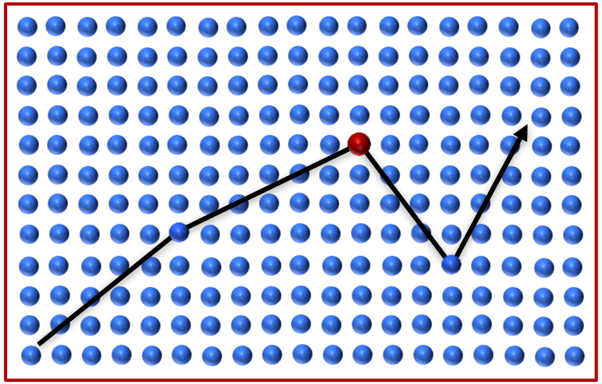
a. Semi-classical charge transport
b. Conductivity in metals

a. Semi-classical charge transport

Drude's model for charge conduction

The electron is described as a **classical free particle** colliding with the ions of the crystal

Actually, the electron is rather a **Bloch wave** scattering against the crystal's defects



Paul Drude

Newton's equation of motion

$$\frac{\partial \boldsymbol{p}}{\partial t} = -e\boldsymbol{E} - \frac{\boldsymbol{p}}{\tau} \quad e > 0$$

Electron's momentum

Electric field

Momentum relaxation

$$\boldsymbol{j}_c = -\frac{en}{m}\boldsymbol{p} = \boxed{\tau\frac{e^2n}{m}}\boldsymbol{E}$$

$$\sigma_c = \tau\frac{e^2n}{m}$$

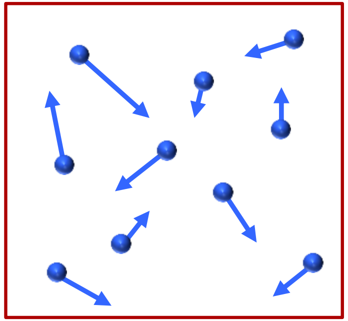
Drude conductivity

If the Fermi wavelength of the electronic wave is much shorter than the mean free path and the size of the system, $\lambda_F \ll \lambda, d \dots$
Drude's classical picture is acceptable

a. Semi-classical charge transport

Boltzmann transport equation

The semiclassical electron gas



The electron cloud is represented by a statistical distribution over the **position** and **velocity** $f = f(\boldsymbol{r}, \boldsymbol{v}, t)$

Ludwig Boltzmann

Cloud's dynamics $\dfrac{df}{dt} = \left.\dfrac{df}{dt}\right|_{\text{coll}}$ collision integral, relaxes *f* towards equilibrium

$$\frac{df}{dt} = \partial_t f + (\boldsymbol{v} \cdot \partial_{\boldsymbol{r}})f - (e\boldsymbol{E} \cdot \boldsymbol{v})\partial_\varepsilon f\, f$$

Electron's dynamics

velocity

acceleration=force

$$\left.\frac{df}{dt}\right|_{\text{coll}} = -\frac{f - f_0}{\tau}$$

a. Semi-classical charge transport

Boltzmann transport equation

$$\partial_t f + (\boldsymbol{v}\cdot\partial_{\boldsymbol{r}})f - (e\boldsymbol{E}\cdot\boldsymbol{v})\partial_\varepsilon f = -\frac{f-f_0}{\tau}$$

We now assume that $f = f_0 + \delta f$

δf → Non-equilibrium (linear in v)

f_0 → Equilibrium (Fermi-Dirac)

In steady state, we obtain $$\delta f = \underbrace{\tau(e\boldsymbol{E}\cdot\boldsymbol{v})\partial_\varepsilon f}_{\text{Drift}} - \underbrace{\tau(\boldsymbol{v}\cdot\partial_{\boldsymbol{r}})f}_{\text{Diffusion}}$$

By definition, the charge current reads $$\boldsymbol{J}_c = -2e\int\frac{d^3\boldsymbol{p}}{(2\pi)^3}\,\boldsymbol{v}\delta f$$

Drift-diffusion equation

$$\boxed{\begin{aligned}\boldsymbol{J}_c &= \sigma_c\boldsymbol{E} - D_c\partial_{\boldsymbol{r}}n\\ \partial_t n + \boldsymbol{\nabla}\cdot\boldsymbol{J}_c &= 0\end{aligned}}$$

Conductivity $$\sigma_c = \frac{1}{3}\tau e^2 v_F^2\mathcal{N}(\varepsilon_F)$$

Diffusion coefficient $$D_c = \frac{1}{3}\tau v_F^2$$

Einstein relation

$$\sigma_c = e^2\mathcal{N}(\varepsilon_F)D_c$$

a. Semi-classical charge transport

A few words on the collision integral

$$\left.\frac{df}{dt}\right|_{\text{coll}} = \frac{1}{\Omega}\int \frac{d^3\mathbf{p}'}{(2\pi)^3} W_{vv'}\left(f_{v'} - f_v\right)$$

Scattering against impurities

$$V_{imp} \approx \sum_i V_0 \delta(\mathbf{r} - \mathbf{R}_i)$$

In the limit of short-range impurities, the momentum relaxation time is independent of the momentum

$$\frac{1}{\tau} = n_i |V_0|^2 \mathcal{N}(\varepsilon_F)$$

Impurity concentration

Constant relaxation time approximation

Scattering against phonons

$$V_{e-ph} = \sum_i V\left(r - R_i - \delta R_i(t)\right)$$

It can be written in second quantization

$$V_{e-ph} = \sum_{\mathbf{k},\mathbf{q}} \left(B_{\mathbf{q}} c^\dagger_{\mathbf{k}+\mathbf{q}} c_{\mathbf{k}} b_{\mathbf{q}} + B_{-\mathbf{q}} c^\dagger_{\mathbf{k}-\mathbf{q}} c_{\mathbf{k}} b^\dagger_{\mathbf{q}}\right)$$

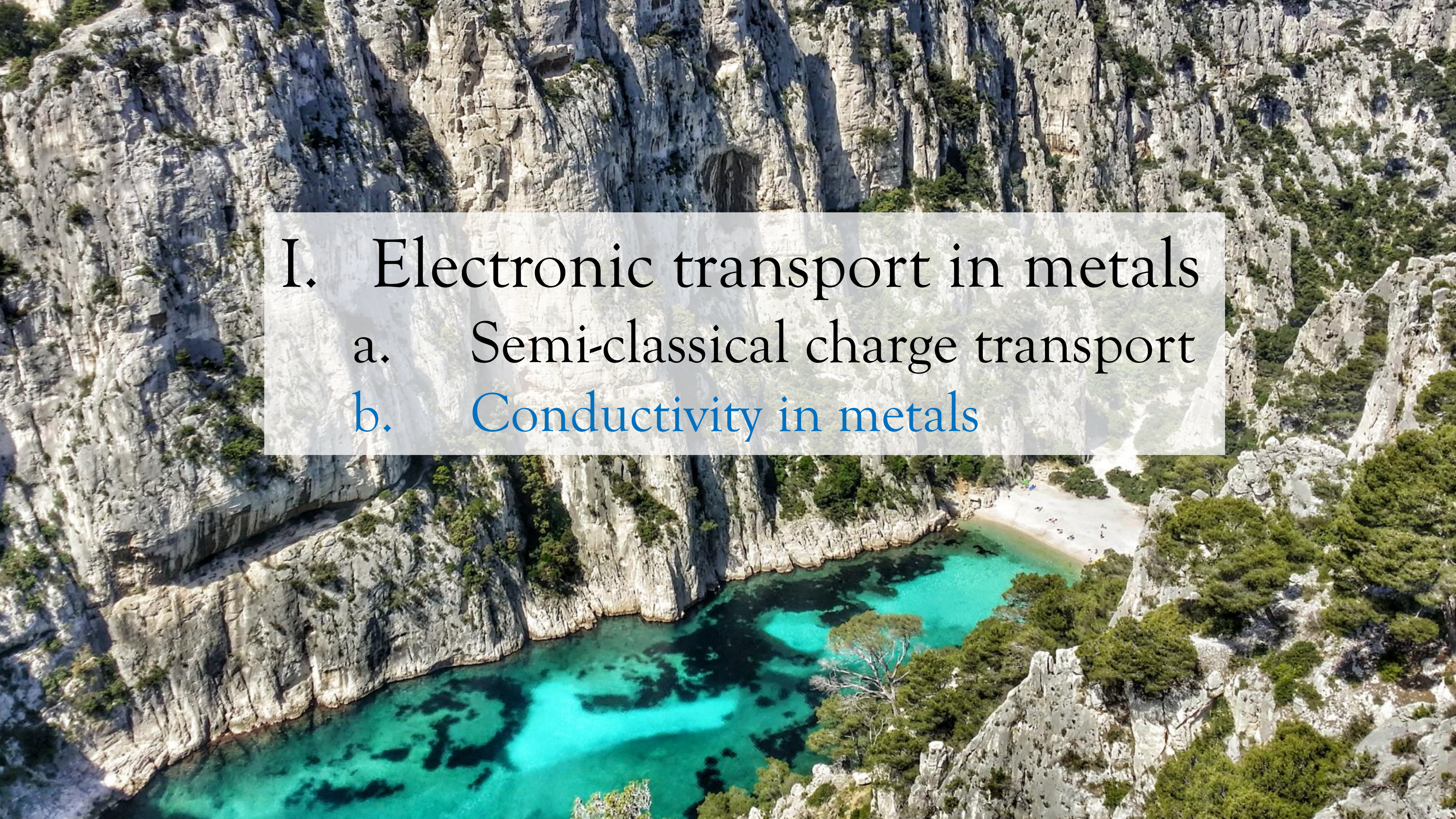
Phonon absorption

Phonon emission

$$\frac{1}{\tau} \sim T^5, T \ll \Theta \qquad \frac{1}{\tau} \sim T, T \gg \Theta$$

Debye temperature

The scattering time increases with temperature



I. Electronic transport in metals

a. Semi-classical charge transport

b. Conductivity in metals

b. Conductivity of metals

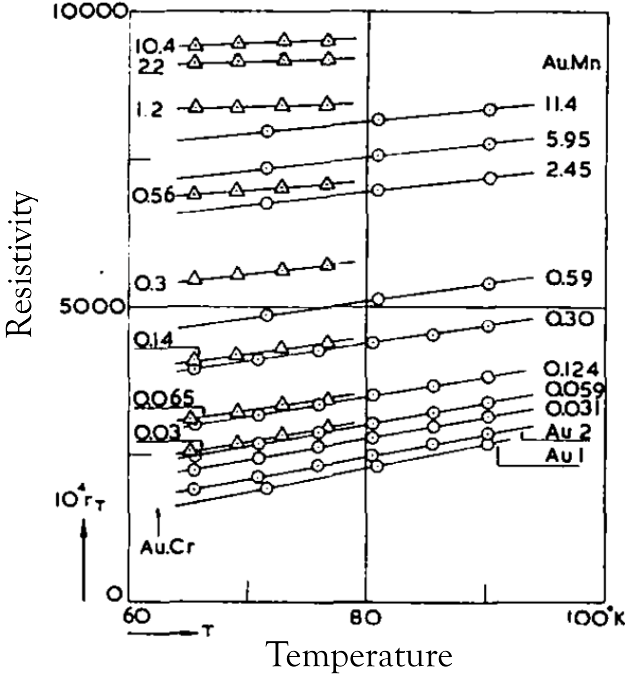
Matthiessen's rule (1862)

$$\rho = \rho_{th}(T) + \rho_r(x)$$

Phonons

Impurities

Mn and Cr impurities in Au

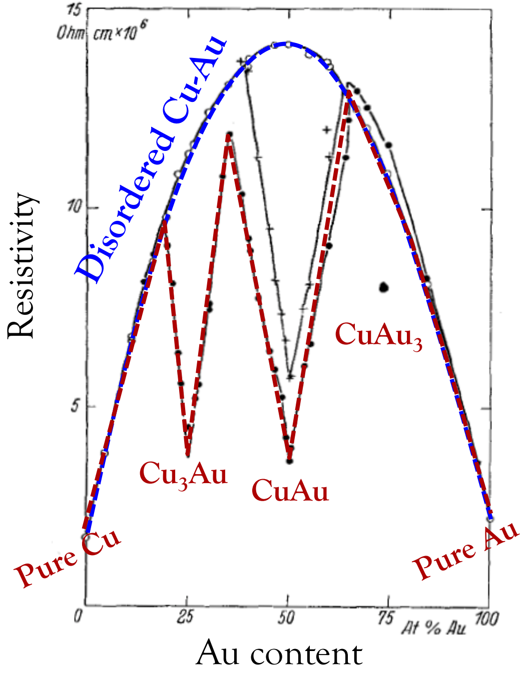


Gerritsen and Linde, Physica 18, 877 (1952)

Nordheim's rule (1931)

$$\rho_r(x) \propto x(1 - x)$$

Cu-Au alloy



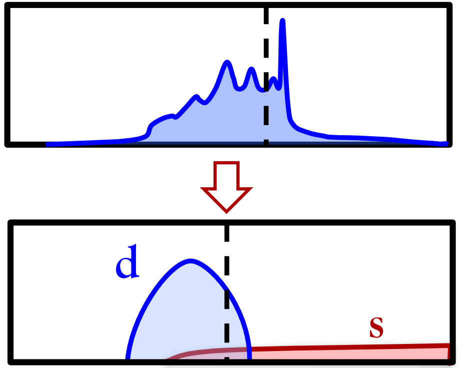
Johansson and Linde, Annel der Physics 5, 1 (1936)

b. Conductivity of transition metals

The s-d model in transition metals (Mott 1935)

Nevill F. Mott

Typical density of states of a transition metal



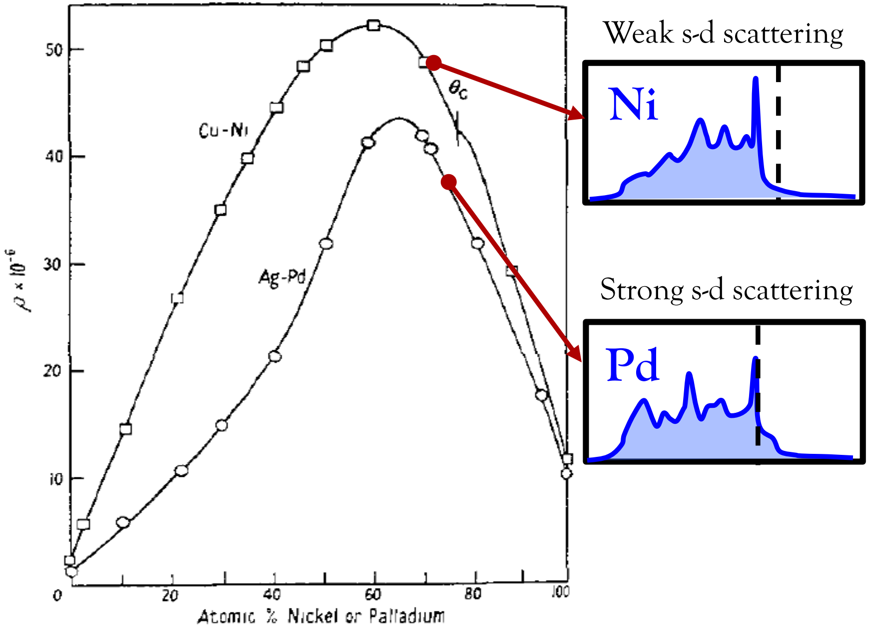
$$v_s \gg v_d$$

$$\mathcal{N}_d(\varepsilon_F) \gg \mathcal{N}_s(\varepsilon_F)$$

Transport is dominated by s-electrons
But…s-d scattering is quite strong!

$$\frac{1}{\tau_s} = \frac{1}{\tau_{ss}} + \frac{1}{\tau_{sd}}$$

Deviation from Nordheim's rule



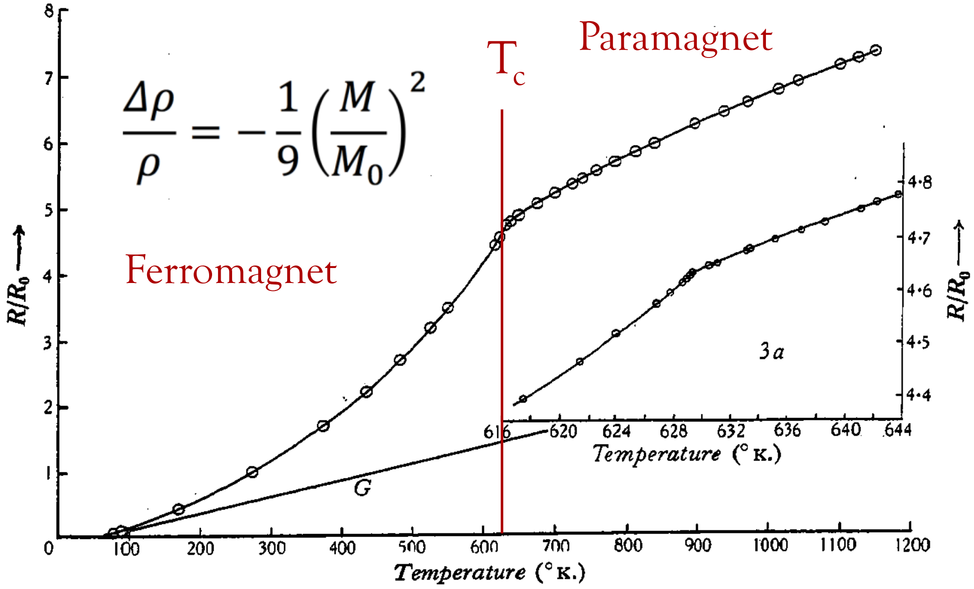
Weak s-d scattering

Strong s-d scattering

Coles, Proc. Phys. Soc. B 65 221 (1952)

b. Conductivity of transition metals

Conductivity enhancement in magnetic transition metals



$$\frac{\Delta\rho}{\rho} = -\frac{1}{9}\left(\frac{M}{M_0}\right)^2$$

Figure 3. Resistance of nickel as a function of temperature.

Figure 3a. The neighbourhood of the Curie point.

H. Potter, Proc. Phys. Soc. 49, 671 (1937)

We remember that $\sigma_c \sim \mathcal{N}(\varepsilon_F)$

In a free electron model

$$\mathcal{N}_\sigma(\varepsilon_F) \sim \sqrt{\varepsilon_F} \sim (n_F^\sigma)^{1/3}$$

One can define

Average density per spin

$$P = \frac{n_F^\uparrow - n_F^\downarrow}{n_F^\uparrow + n_F^\downarrow} \Rightarrow n_F^{\uparrow,\downarrow} = \bar{n}_F(1 \pm P)$$

Spin polarization at Fermi level

Assuming $P \approx \dfrac{M(T)}{M_0}$ we get

$$\rho = \rho_{ss} + \frac{\rho_{sd}}{2}\left(\left(1 - \frac{M}{M_0}\right)^{1/3} + \left(1 + \frac{M}{M_0}\right)^{1/3}\right)$$

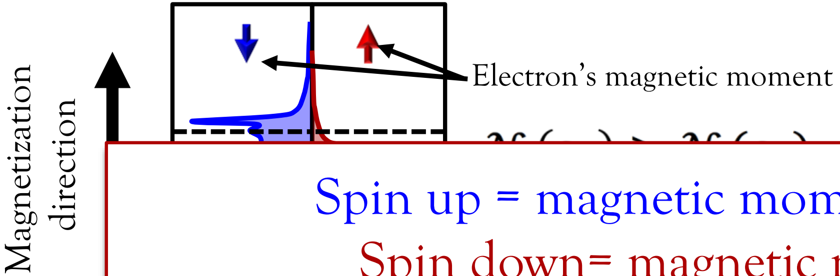
II. Spin transport in metals

a. The two-channel model

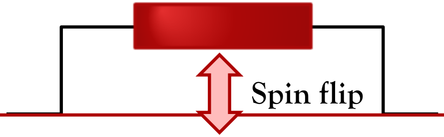
b. Spin diffusion and magnetoresistance

The two-channel model

Density of states in a ferromagnet



Equivalent circuit



Spin up = magnetic moment down = down electron

Spin down= magnetic moment up= up electron

Spin dependent scattering

$$\frac{1}{\tau_\downarrow} > \frac{1}{\tau_\uparrow}, \lambda_\uparrow > \lambda_\downarrow$$

Spin-dependent mean free path

Spin relaxation

$$\lambda_{sf}^{\sigma} = \sqrt{\frac{1}{3} v_\sigma \lambda_\sigma \tau_{\uparrow\downarrow}}$$

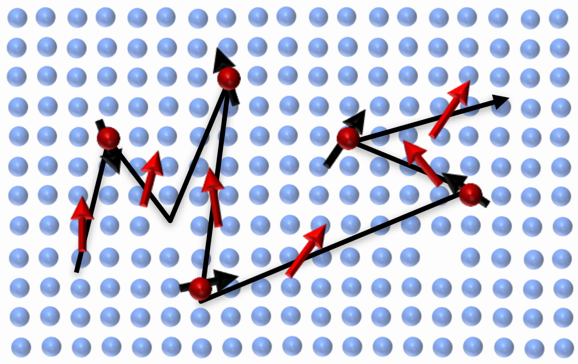
Spin relaxation time

Spin relaxation length
Spin diffusion length

$$\frac{1}{\lambda_{sf}} = \frac{1}{\sqrt{\left(\lambda_{sf}^{\uparrow}\right)^2 + \left(\lambda_{sf}^{\downarrow}\right)^2}}$$

Spin relaxation

Magnetic impurities

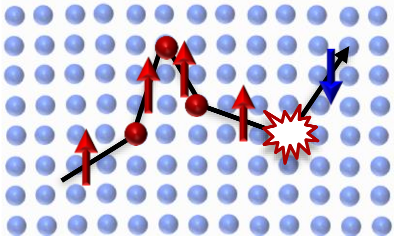


Isolated magnetic impurities acts like a random field, spatially distributed

$$\frac{1}{\tau_{sf}^{m}} = \frac{8\pi}{3} n_m N_0 S(S+1) v_{sm}^2$$

The stronger the scattering,
the faster the spin relaxation

Elliott-Yafet scattering



The itinerant spin precesses around the spin-orbit field

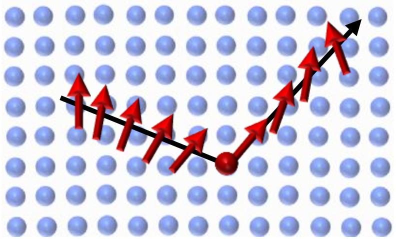
$$H_{so} = \xi_{so}\boldsymbol{\sigma}\cdot\boldsymbol{L} \propto \xi_{so}\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{k}')$$

The precession occurs upon scattering (phonons or impurities)

$$\frac{1}{\tau_{sf}^{so}} = \frac{8}{9}\frac{\xi_{so}^2}{\tau}$$

The fast the scattering,
the faster the spin relaxation

Dyakonov-Perel' relaxation



The itinerant spin precesses continuously around the spin-orbit field of the crystal

$$H_R = -\alpha\boldsymbol{\sigma}\cdot(\boldsymbol{z}\times\boldsymbol{k})$$

The precession occurs during propagation

It leads to anisotropic relaxation times

$$\frac{1}{\tau_{sf}^{R,||}} = \frac{2\alpha^2 k_F^2}{\hbar^2}\tau \qquad \frac{1}{\tau_{sf}^{R,z}} = \frac{4\alpha^2 k_F^2}{\hbar^2}\tau$$

The fast the scattering,
the slower the spin relaxation

The two-channel model

We start from Boltzmann transport equation

$$\int \frac{d^3\boldsymbol{p}}{(2\pi)^3} \quad \boldsymbol{v}\times \qquad -(e\boldsymbol{E}\cdot\boldsymbol{v})\partial_\varepsilon f = -\frac{f_\downarrow - f_0}{\tau_\downarrow} + \frac{f_\uparrow - f_\downarrow}{\tau_{\uparrow\downarrow}}$$

$-(e\boldsymbol{E}\cdot\boldsymbol{v})\partial_\varepsilon f = -$

$$-(e\boldsymbol{E}\cdot\boldsymbol{v})\partial_\varepsilon f = -\frac{f_\uparrow - f_0}{\tau_\uparrow} - \frac{f_\uparrow - f_\downarrow}{\tau_{\uparrow\downarrow}}$$

Spin relaxation time

Spin-dependent scattering time

Weak spin relaxation: decoupled spin channels

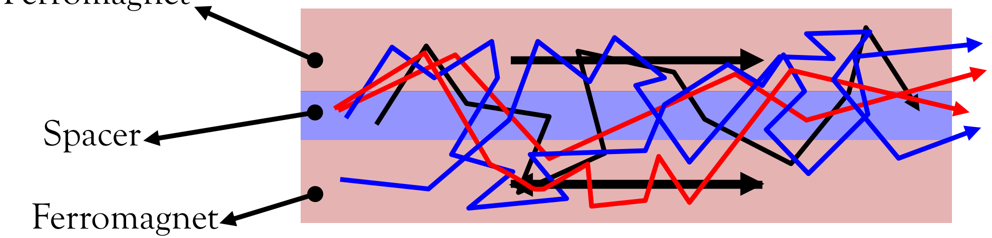
$$\frac{1}{\tau_\uparrow}, \frac{1}{\tau_\uparrow} \gg \frac{1}{\tau_{\uparrow\downarrow}} \Rightarrow \begin{cases} \sigma_\downarrow = \tau_\downarrow \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \\ \sigma_\uparrow = \tau_\uparrow \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \end{cases}$$

Strong spin relaxation: no spin-dependence

$$\frac{1}{\tau_{\uparrow\downarrow}} \gg \frac{1}{\tau_\uparrow}, \frac{1}{\tau_\uparrow} \Rightarrow \begin{cases} \sigma_\downarrow = \dfrac{2\tau_\uparrow\tau_\downarrow}{(\tau_\uparrow + \tau_\downarrow)} \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \\ \sigma_\uparrow = \dfrac{2\tau_\uparrow\tau_\downarrow}{(\tau_\uparrow + \tau_\downarrow)} \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \end{cases}$$

Current-in-plane Giant Magnetoresistance

Knudsen regime $\lambda \sim d$



Ferromagnet

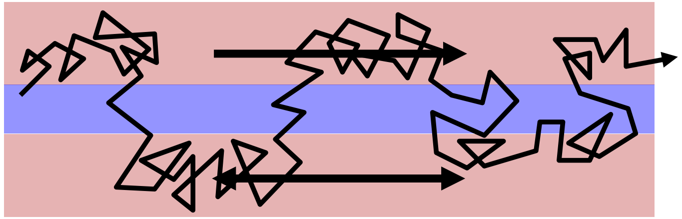
Spacer

Ferromagnet

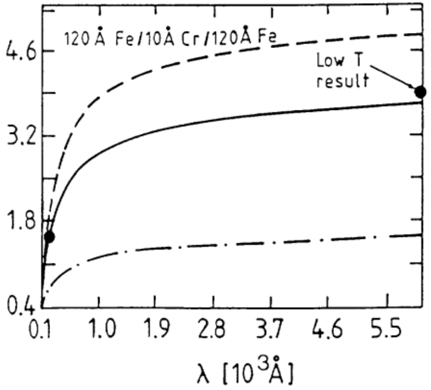
Parallel $\sigma_c^{\uparrow} > \sigma_c^{\downarrow}$

Antiparallel $\sigma_c^{\uparrow} \sim \sigma_c^{\downarrow}$

Diffusive regime $d \gg \lambda$



The electron doesn't "remember"
where it comes from!



Camley, Physical Review Letters 63, 664 (1989)

II. Spin transport in metals

a. The two-channel model

b. Spin diffusion and magnetoresistance

Spin transport in metals

Remember that in a metal, charge transport is governed by

Charge current density $\boldsymbol{J}_c = \sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\mu)$ Flow of charge per unit area

Charge density $\partial_t n + \boldsymbol{\nabla} \cdot \boldsymbol{J}_c = 0$ Number of charge per unit volume

Chemical potential $\mu = \dfrac{n}{e\mathcal{N}(\varepsilon_F)}$

Total charge density (C/m^3) $n = n_\uparrow + n_\downarrow$

Total spin density $((eV.s)/m^3)$ $s = \left(\dfrac{\hbar}{2e}\right)(n_\uparrow - n_\downarrow)$

Magnetic moment (μ_B/m^3) $m = -\left(\dfrac{\mu_B}{e}\right)(n_\uparrow - n_\downarrow)$

$\bar{\mu} = \dfrac{1}{2}(\mu_\uparrow + \mu_\downarrow)$ Spin-independent chemical potential

$\mu_s = \dfrac{1}{2}(\mu_\uparrow - \mu_\downarrow)$ Spin-dependent chemical potential

Spin diffusion equation

Charge current $\boldsymbol{J}_c = \sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\mu)$

Charge conservation $\partial_t n + \boldsymbol{\nabla} \cdot \boldsymbol{J}_c = 0$

Ohm's law $J_c = g(\mu_R - \mu_L)$

Chemical potential $\mu = \dfrac{n}{e\mathcal{N}(\varepsilon_F)}$

$$\boldsymbol{J}_c^\sigma = \sigma_c^\sigma(\boldsymbol{E} - \boldsymbol{\nabla}\mu_\sigma)$$

$$\partial_t n_\sigma + \boldsymbol{\nabla} \cdot \boldsymbol{J}_c^\sigma = 0$$

$$J_c^\sigma = g_\sigma(\mu_R^\sigma - \mu_L^\sigma)$$

$$\mu_\sigma = \frac{n_\sigma}{e\mathcal{N}(\varepsilon_F)}$$

Valet and Fert, Physical Review B 48, 7099 (1993)

Charge and spin current definitions

$$\boldsymbol{J}_c = \boldsymbol{J}_c = \sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\bar{\mu}) - \beta\sigma_c\boldsymbol{\nabla}\mu_s \;)\boldsymbol{\nabla}\mu_s$$

$$\frac{2e}{\hbar}\boldsymbol{J}_s \frac{2e}{\hbar}\boldsymbol{J}_s = \beta\sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\bar{\mu}) - \sigma_c\boldsymbol{\nabla}\mu_s{}_c^\downarrow)\boldsymbol{\nabla}\mu_s$$

Total conductivity $\sigma_c = \sigma_c^\uparrow + \sigma_c^\downarrow$

Current polarization $\beta = \dfrac{\sigma_c^\uparrow - \sigma_c^\downarrow}{\sigma_c^\uparrow + \sigma_c^\downarrow}$

Charge and spin conservation

$$\partial_t n + \boldsymbol{\nabla} \cdot \boldsymbol{J}_c = 0$$

$$\partial_t s + \boldsymbol{\nabla} \cdot \boldsymbol{J}_s = -\frac{s}{\tau_{sf}}$$

Spin relaxation

In steady state $\dfrac{2e}{\hbar\sigma_c}\boldsymbol{\nabla} \cdot \boldsymbol{J}_s \approx -\dfrac{\mu_s}{\lambda_{sf}^2}$

$$\lambda_{sf}^2 = D_c\tau_{sf}$$

Spin accumulation

The concept of spin accumulation

Charge

$$\boldsymbol{J}_c = \sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\bar{\mu}) - \boxed{\beta\sigma_c\boldsymbol{\nabla}\mu_s}$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{J}_c = 0$$

Spin

$$\boldsymbol{J}_s = \beta\sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\bar{\mu}) - \sigma_c\boldsymbol{\nabla}\mu_s$$

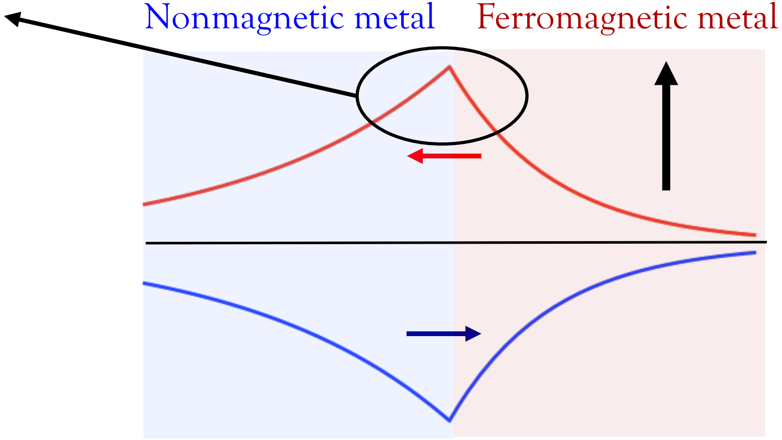
$$\frac{1}{\sigma_c}\boldsymbol{\nabla}\cdot\boldsymbol{J}_s = -\frac{\mu_s}{\lambda_{sf}^2}$$

$$\bar{\mu} = -\beta\mu_s + Ax + B$$

$$\mu_s = Ce^{x/\lambda_{sf}^*} + De^{-x/\lambda_{sf}^*}$$

$$\lambda_{sf}^{*2} = (1-\beta^2)\lambda_{sf}^2$$

Spin accumulation



Spin accumulation profile

$$\mu_{s,N}(x) = -J_c\frac{\beta e^{x/\lambda_N}}{\frac{\sigma_F}{\lambda_F}+\frac{\sigma_N}{\lambda_N}}$$

$$\mu_{s,F}(x) = -J_c\frac{\beta e^{-x/\lambda_F}}{\frac{\sigma_F}{\lambda_F}+\frac{\sigma_N}{\lambda_N}}$$

Ferromagnet

$\beta > 0, \lambda_{sf} = \lambda_F$

Nonmagnetic metal

$\beta = 0, \lambda_{sf} = \lambda_N$

Interfacial Matching Conditions

Spin density continuous ➔ no interfacial resistance

Spin current continuous ➔ no spin flip

Chemical potential drop

$$\frac{\Delta\mu}{J_c} = \frac{\beta^2}{\frac{\sigma_F}{\lambda_F}+\frac{\sigma_N}{\lambda_N}}$$

Additional interfacial resistance!!

van Son et al., Physical Review Letters 58, 2271 (1987)

Johnson and Silsbee, Physical Review B 35, 4959 (1987)

Spin current

Ohm’s law

$$J_c = g_I \Delta\mu \quad \Rightarrow \quad \begin{aligned} J_c &= g_I \Delta\bar{\mu} + \gamma g_I \Delta\mu_s \\ J_s &= \gamma g_I \Delta\bar{\mu} + g_I \Delta\mu_s \end{aligned}$$

The spin current in the ferromagnet reads

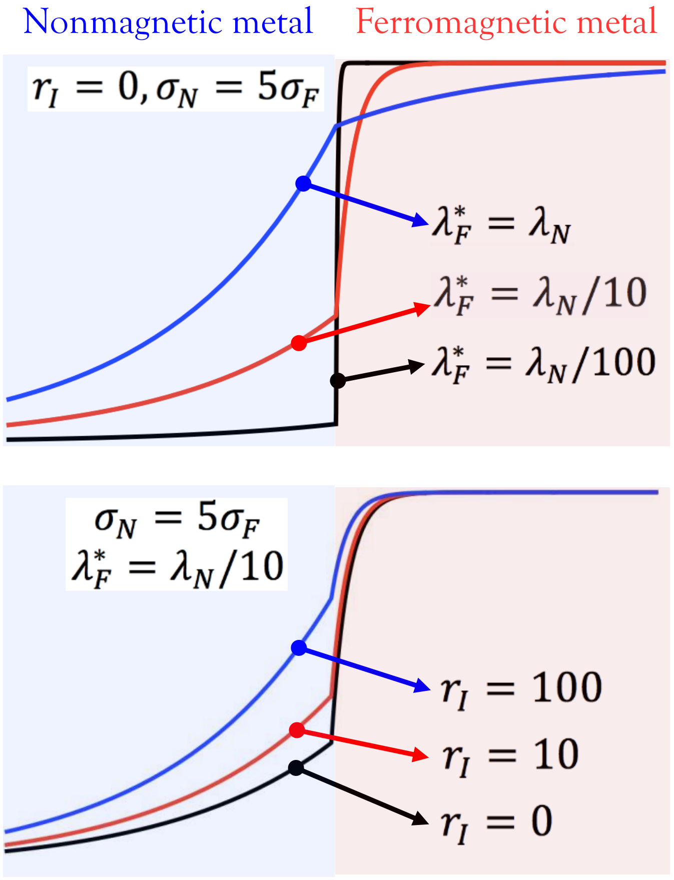
$$\frac{J_{s,F}}{J_c} = \beta - \frac{(\beta-\gamma) r_I + \beta r_N^s}{r_I + r_F^s + r_N^s} e^{-x/\lambda_F^*}$$

Spin diffusion length of the ferromagnet

Interfacial resistance $r_I = (1-\gamma^2)/g_I$

“spin” resistance $r_N^s = \frac{\lambda_N}{\sigma_N}, r_F^s = \frac{\lambda_F}{\sigma_F}$

The shorter the spin diffusion length, the smaller the spin resistance

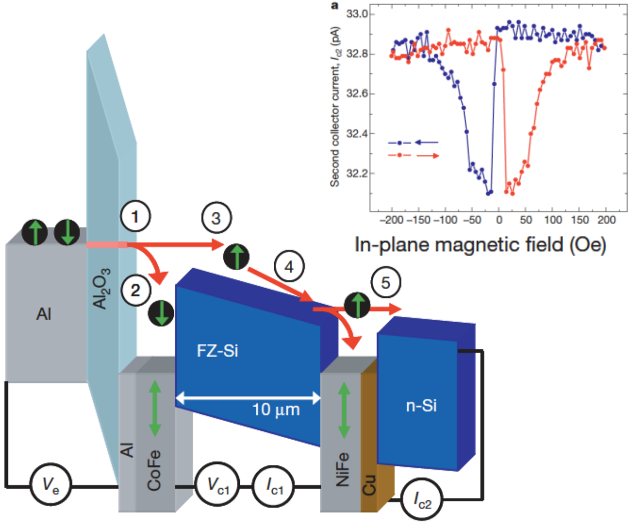


Spin injection

Take Home Message: Contradiction between *high* injection and *long-range* propagation

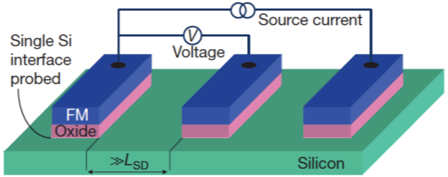
Appelbaum et al., Nature 447, 295 (2007)

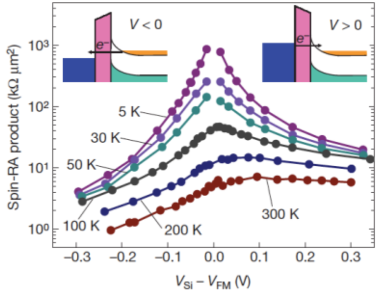
Hot electron injection



Dash et al., Nature 462, 491 (2009)

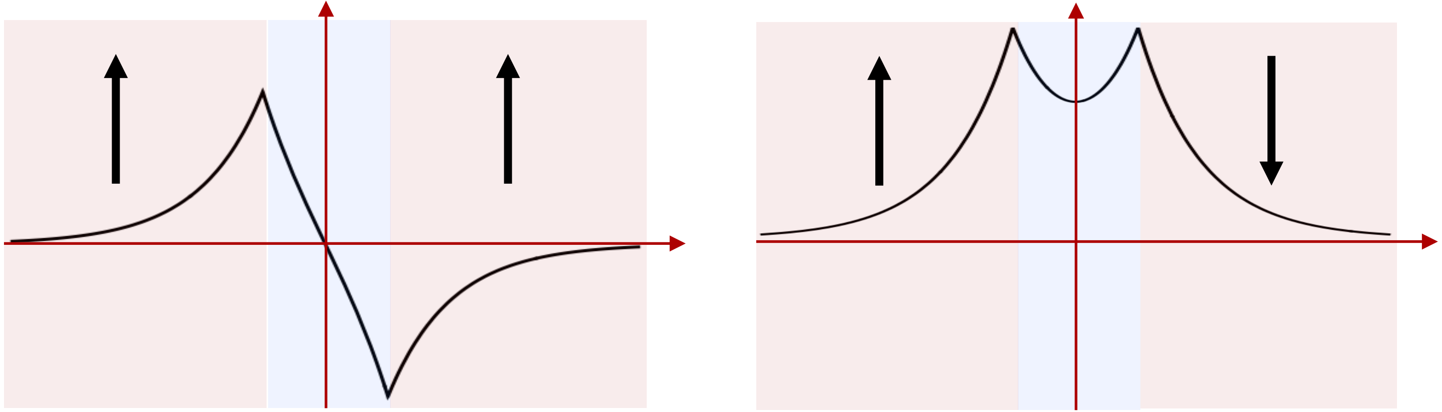
Non-local tunneling injection





Giant Magnetoresistance

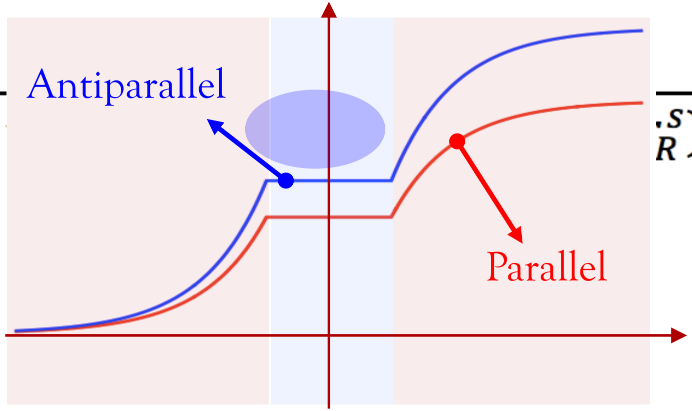
Spin accumulation profile in a metallic spin-valve



Chemical potential profile

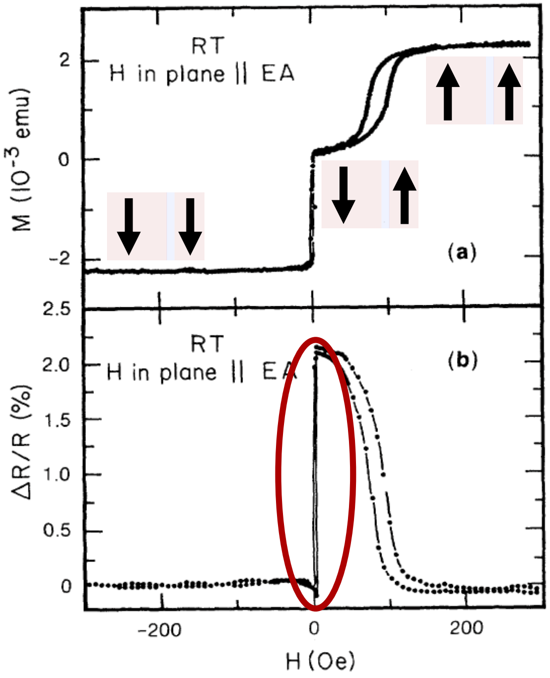
$\Delta r =$ $+$ $_R^S)\cosh(d/\lambda_{sf})$

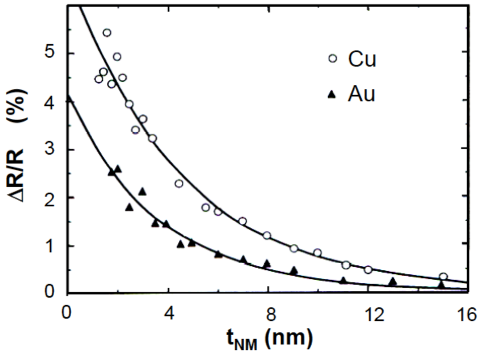
$$r = \frac{\bar{\mu}_{-\infty} - \bar{\mu}_{+\infty}}{J_c}$$

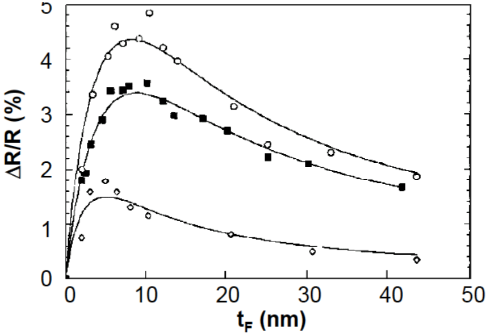


Giant Magnetoresistance

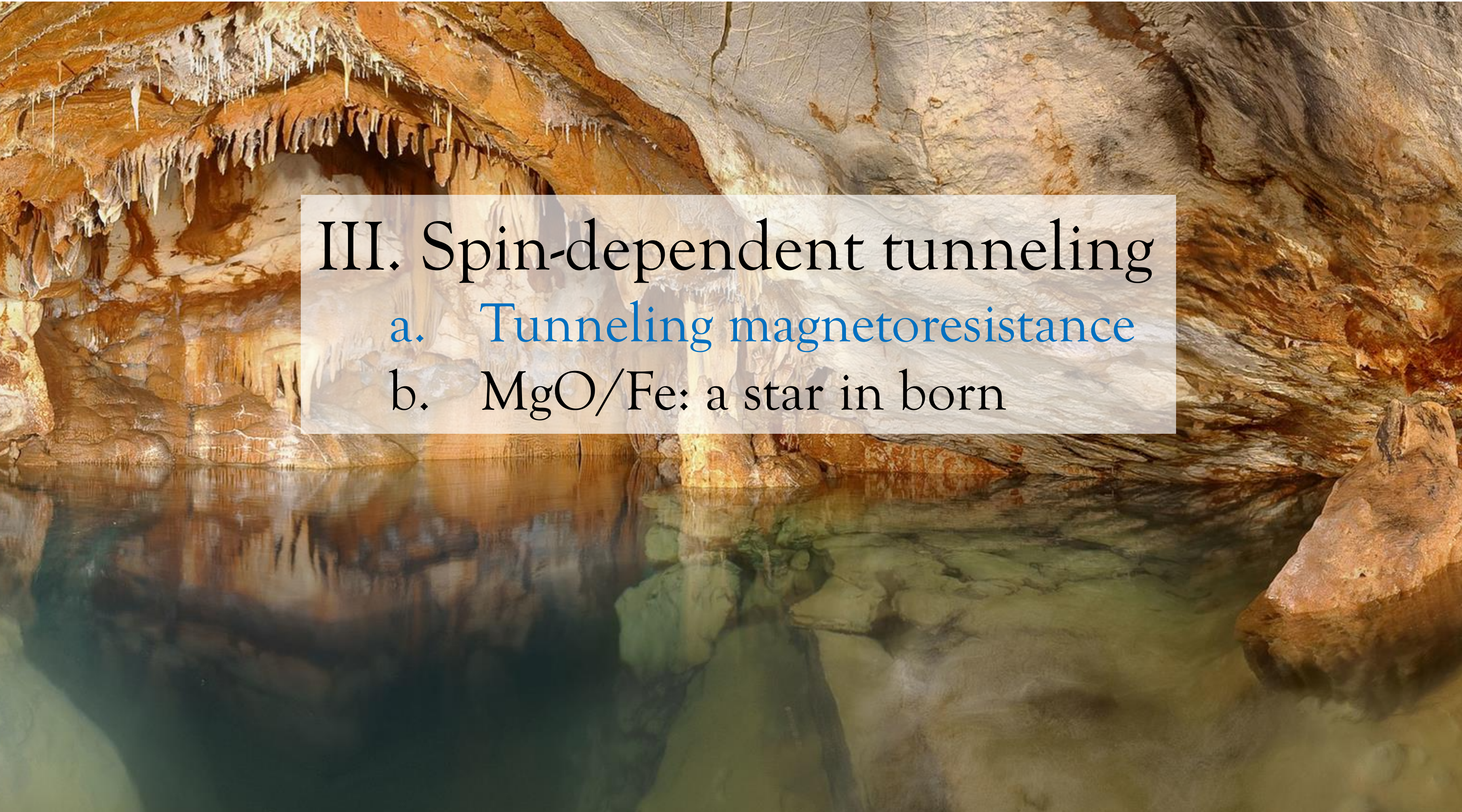
$$\Delta r = \frac{4\beta_L\beta_R r_L^s r_R^s r_N^s}{(r_N^{s2} + r_L^s r_R^s)\sinh(d/\lambda_{sf}) + r_N^s(r_L^s + r_R^s)\cosh(d/\lambda_{sf})}$$







Dieny et al., Physical Review B 43, 1297 (1991)
Dieny et al., Journal of Applied Physics 69, 4774 (1991)



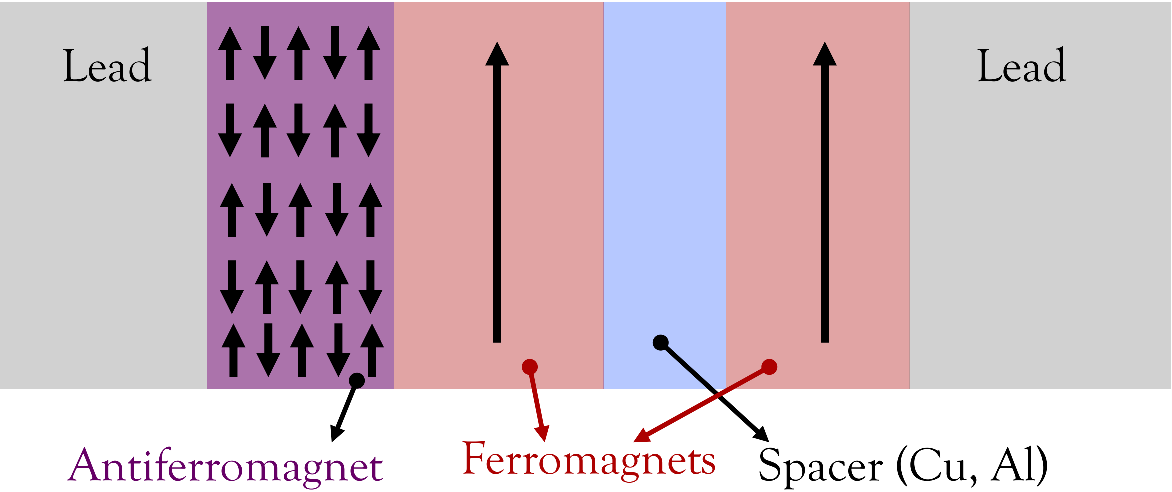
III. Spin-dependent tunneling

a. Tunneling magnetoresistance

b. MgO/Fe: a star in born

Giant versus tunneling magnetoresistance

The problem with giant magnetoresistance



Lead

Lead

Antiferromagnet

Ferromagnets

Spacer (Cu, Al)

$$\Delta r \approx 4\beta_L\beta_R \frac{r_L^s r_R^s}{r_L^s + r_R^s}$$

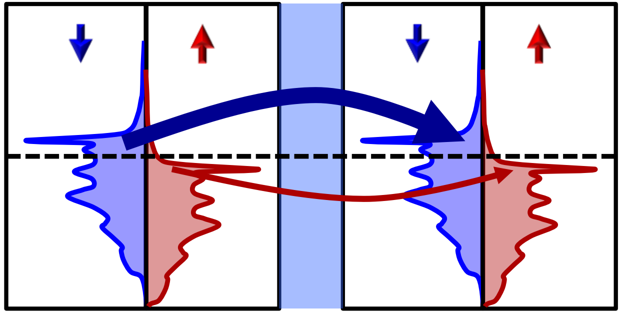
The addition resistances in series quench the GMR ratio $\frac{\Delta r}{r} \sim \%$

Solution: use a tunnel barrier!

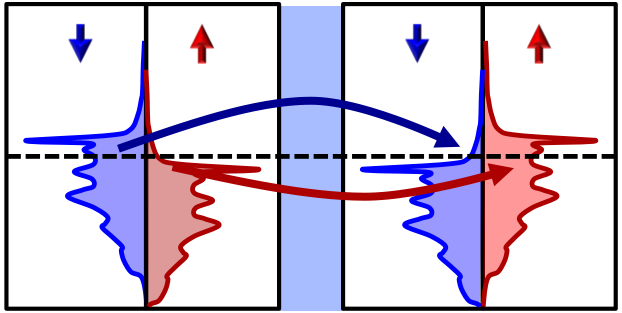
Spin-dependent tunneling

Basics of spin-dependent tunneling

Parallel configuration



Antiparallel configuration



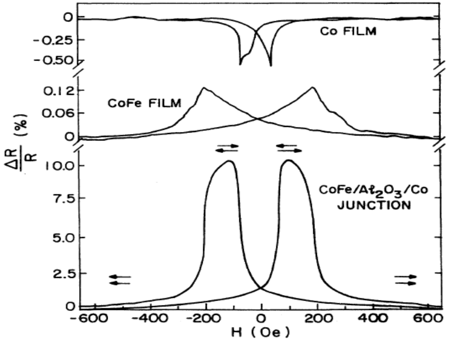
In parallel configuration

The transport is dominated by electrons with down electrons (up spin)

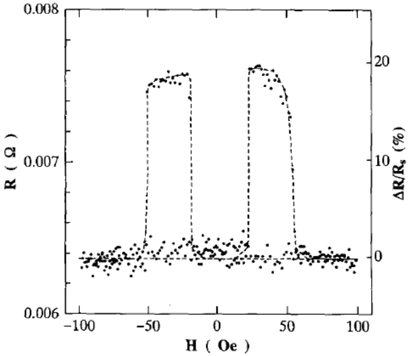
In antiparallel configuration

Both up and down electrons contribute equally

CoFe/Al_2O_3/Co



Fe/Al_2O_3/Fe

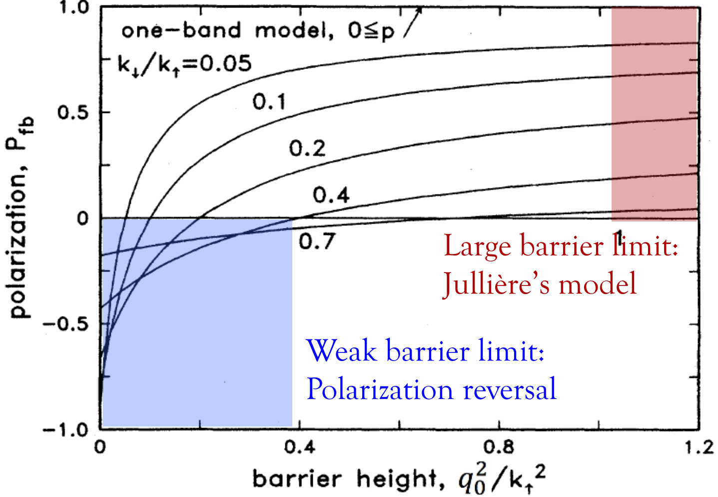


Moodera et al., Physical Review Letters 74, 3273 (1995)
Miyazaki, Tezuka, JMMM 139, L231 (1995)

Spin-dependent tunneling

Free electron model for spin-dependent tunneling

$$P = \frac{(k_\uparrow - k_\downarrow)(q_0^2 - k_\uparrow k_\downarrow)}{(k_\uparrow + k_\downarrow)(q_0^2 + k_\uparrow k_\downarrow)}$$

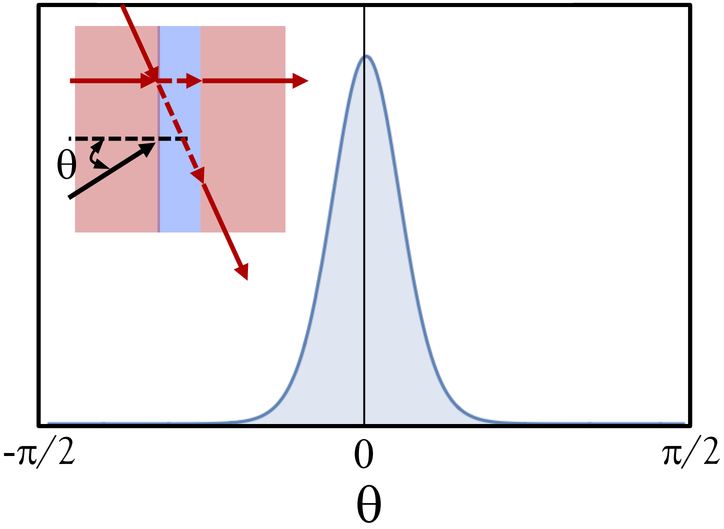


Large barrier limit: Jullière's model

Weak barrier limit: Polarization reversal

Slonczewski, Physical Review B 39, 6995 (1989)

$$T(\kappa) = \frac{16q^2 k_L k_R e^{-2qd}}{(q^2 + k_L^2)(q^2 + k_R^2)}$$



$$U_{\mathrm{MgO}} \approx 1 - 2\ eV, U_{\mathrm{AlO_x}} \approx 3\ eV$$

$$k_F^\uparrow \approx 1.09\ \mathrm{A^\circ}^{-1}, k_F^\downarrow \approx 0.42\ \mathrm{A^\circ}^{-1}$$

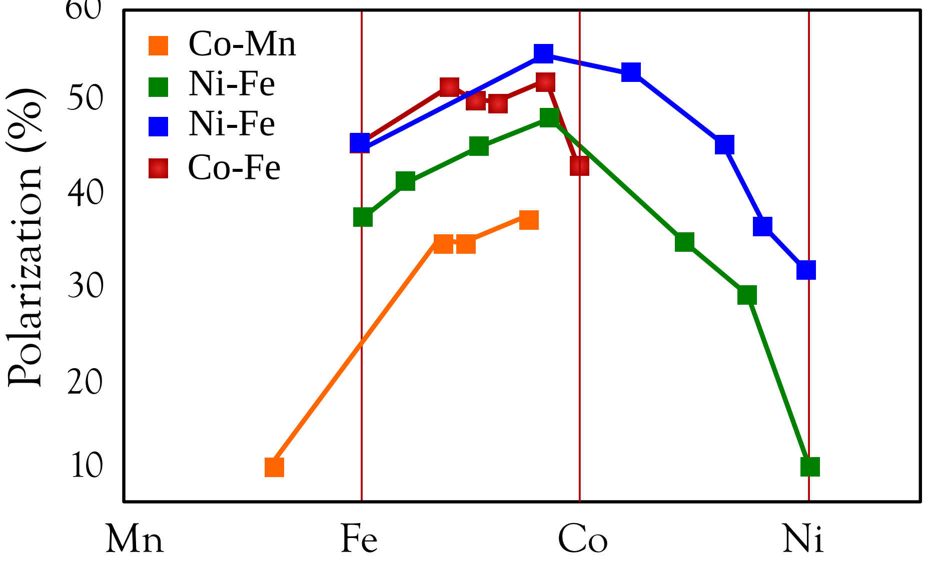
$$m^* \approx 0.4\, m_e$$

Spin-dependent tunneling

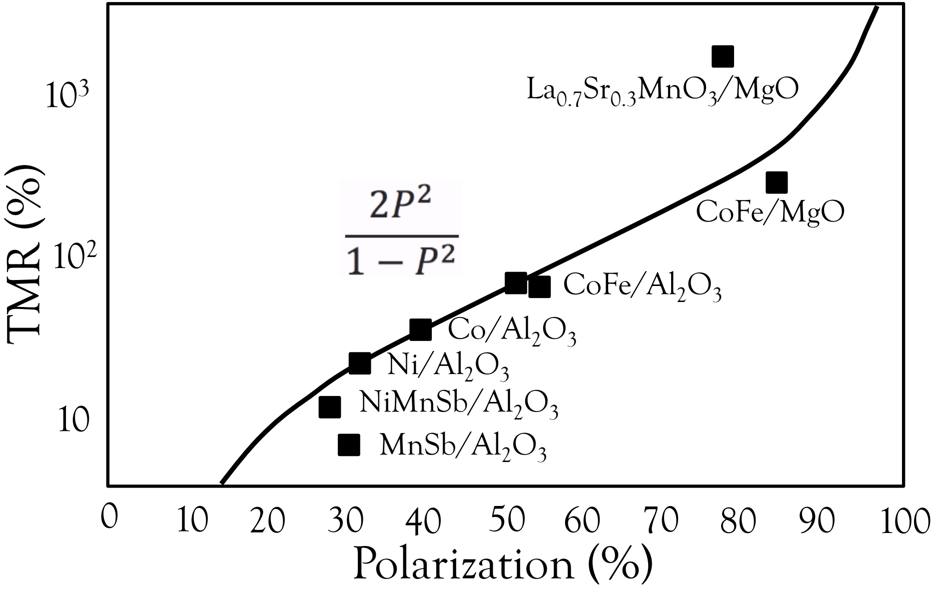
Jullière formula (see Tutorial!)

$$\frac{G_P - G_{AP}}{G_{AP}} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_L P_R}{1 - P_L P_R}$$

Data from Meservey, Parkin, Moodera



Data collected by H. Swagten



III. Spin-dependent tunneling

a. Tunneling magnetoresistance

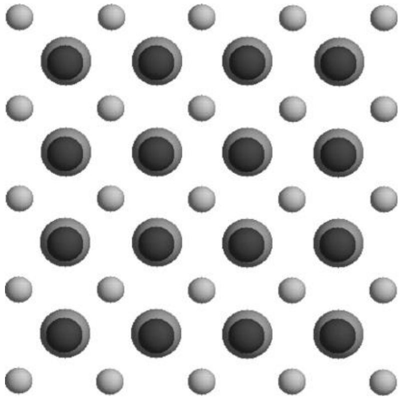
b. MgO/Fe: a star in born

MgO/Fe interfaces

Why shall we expect remarkable tunneling magnetoresistance?

Crystal structure

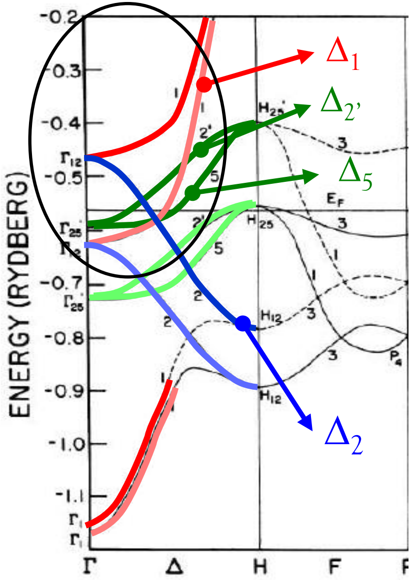
Fe and MgO have both bcc structure with very small lattice mismatch



Butler, Physical Review B 63, 054416 (2001)

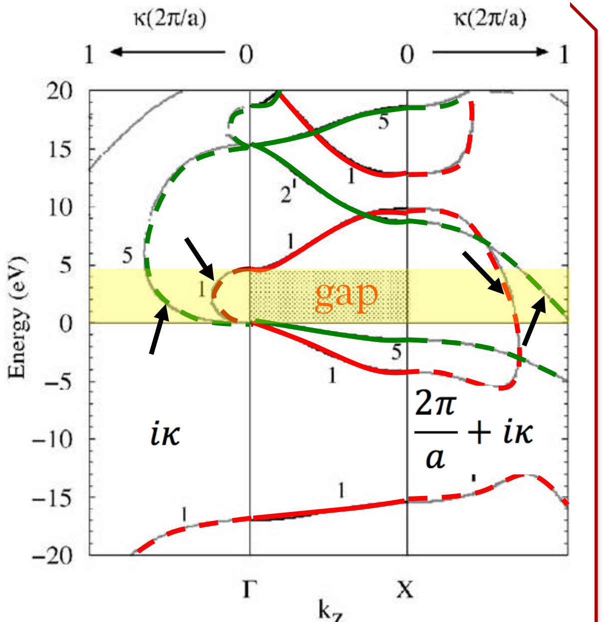
Their Bloch states adopt the same symmetries

Fe band structure



Fe is a half metal for Δ_1

MgO complex band structure

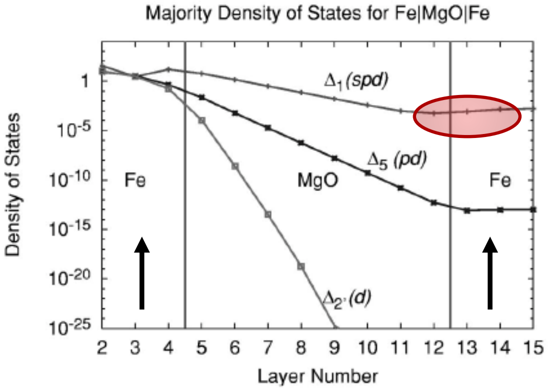


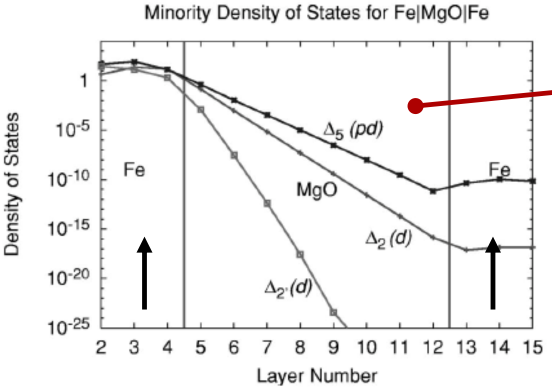
Dederichs et al., JMMM 240, 108 (2002)

MgO filters Δ_1 Bloch states!

MgO/Fe interfaces

Bloch state filtering in Fe/MgO/Fe tunnel junction



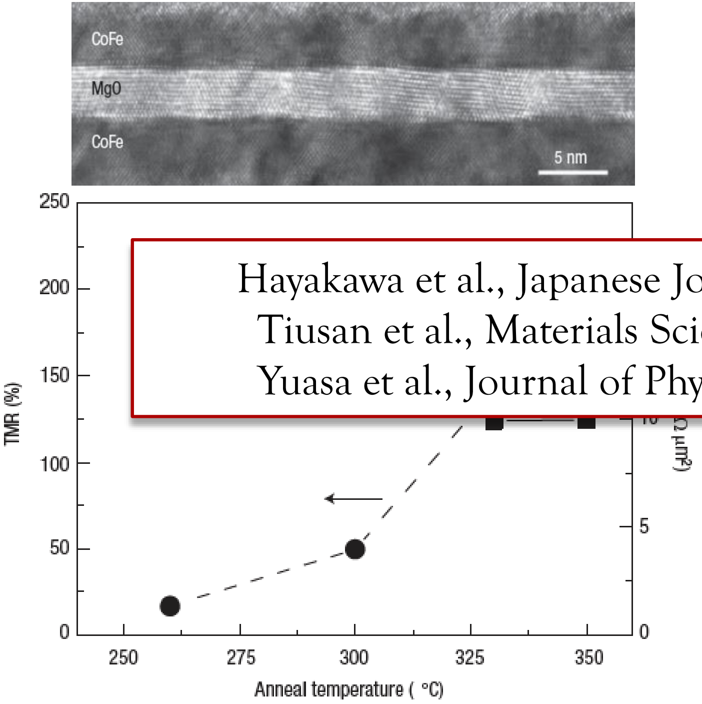


No Δ_1 at all!

Butler et al., Physical Review B 63, 054416 (2001)

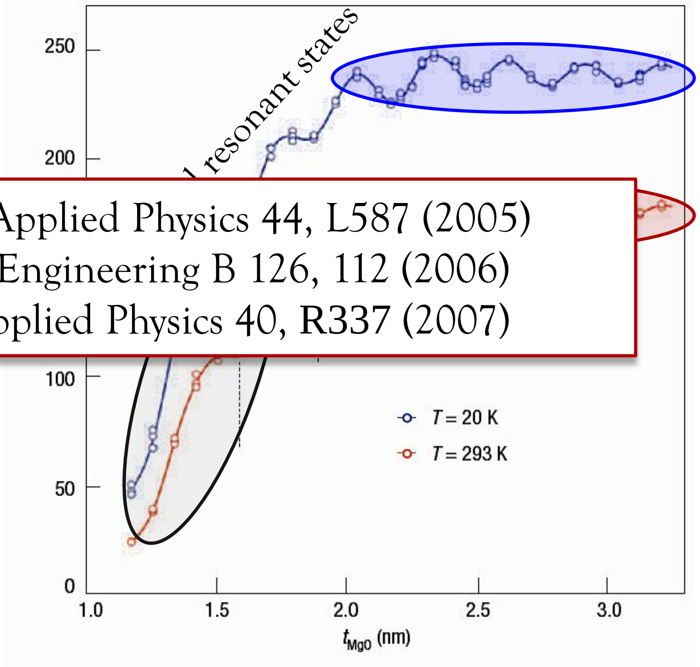
MgO/Fe interfaces

Epitaxial deposition of Fe/MgO/Fe junctions



Parkin et al, Nature Materials 3, 862 (2004)

Thickness dependence of TMR



Yuasa et al., Nature Materials 3, 868 (2004)

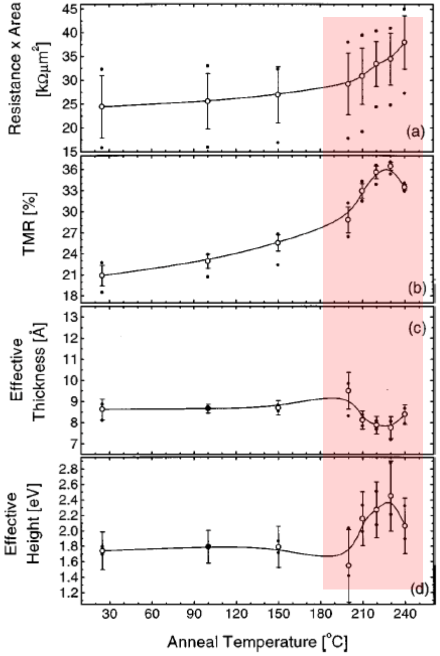
Hayakawa et al., Japanese Journal of Applied Physics 44, L587 (2005)
Tiusan et al., Materials Science and Engineering B 126, 112 (2006)
Yuasa et al., Journal of Physics D: Applied Physics 40, R337 (2007)

Designing efficient magnetic tunnel junctions

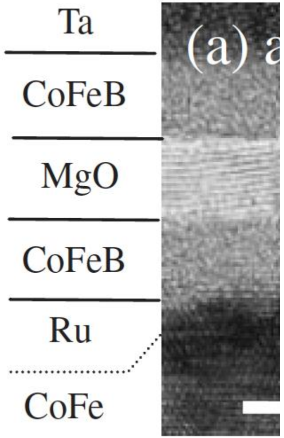
- High TMR (>100%)
- Low resistance-area ($\Omega.\mu m^2$)
- Optimal magnetic properties

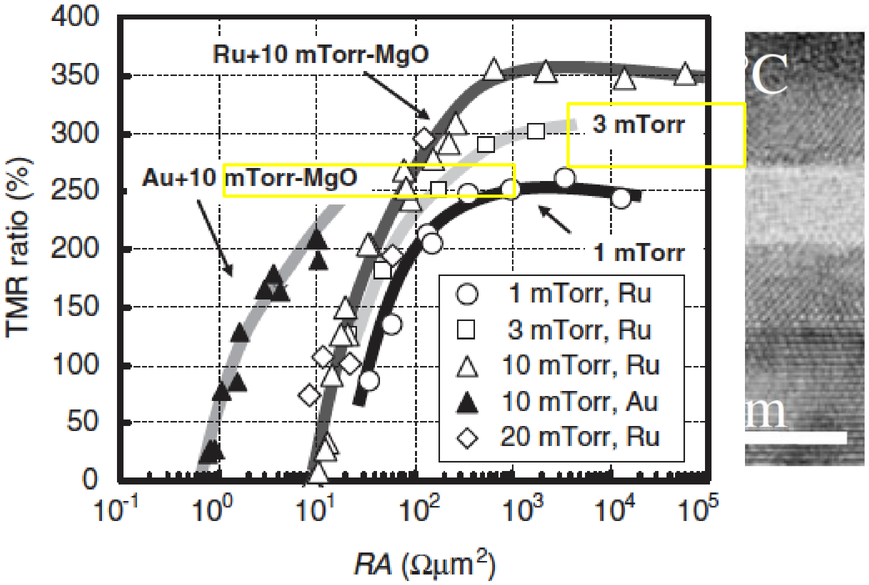
- Material growth (texture, roughness)
- Barrier quality (pinholes, defects)
- Atomic diffusion (Mn, Ru, B etc.)

CoFe/Al_2O_3/CoFe



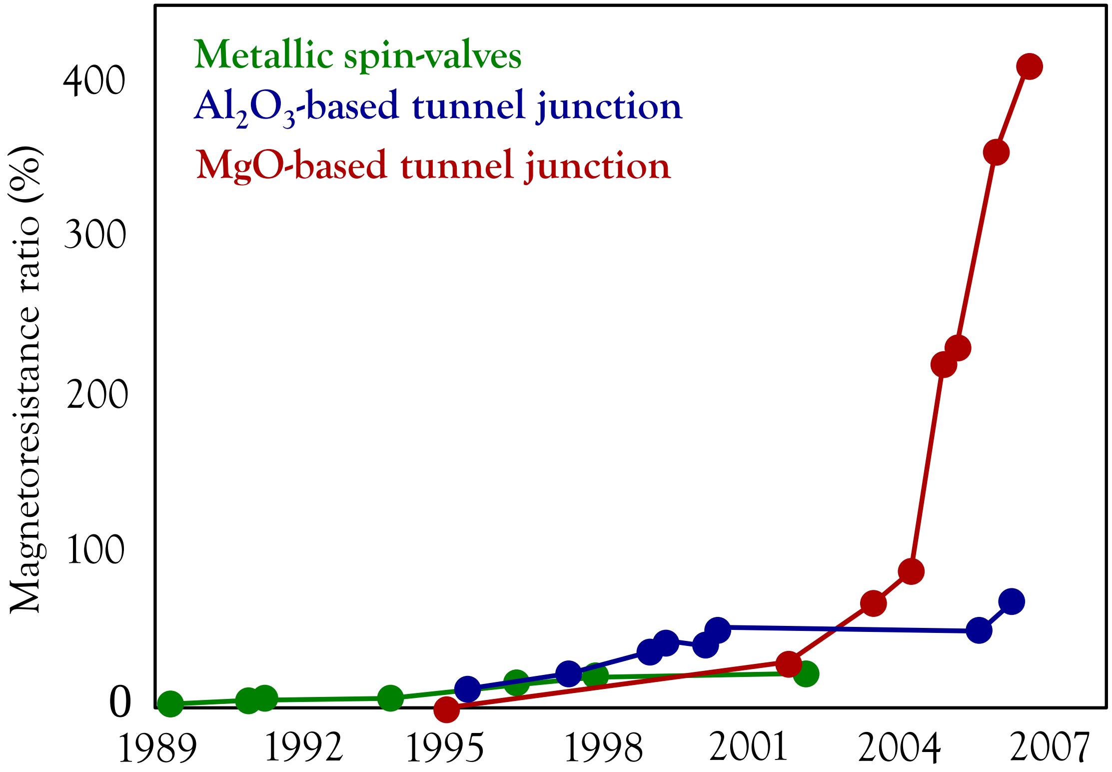
Sousa et al., Applied Physics Letters 73, 3288 (1998)





Hayakawa, Jap. Jour. Appl. Phys. 44, L587 (2005)

Tunneling versus “giant” magnetoresistance



~1000% at low T

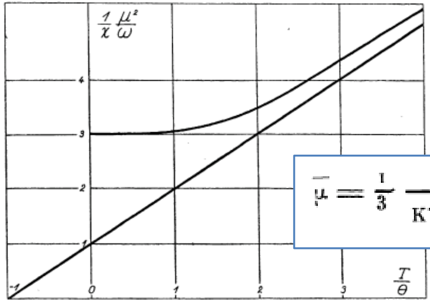
Heiliger and Mertig, Materials Today **9**, 46 (2006)
Ikeda et al., IEEE Trans. Elec. Dev. **54**, 991 (2007)

IV. Antiferromagnets: the new frontier

a. Collinear antiferromagnets
b. Noncollinear antiferromagnets

Why “antiferromagnets”?

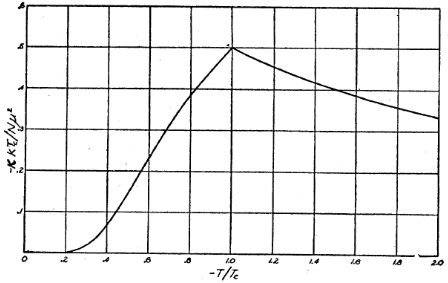
1932 “Constant paramagnetism”



$$\bar{\mu} = \frac{1}{3}\,\frac{\mu^2 H}{KT + \frac{\omega}{3}}$$

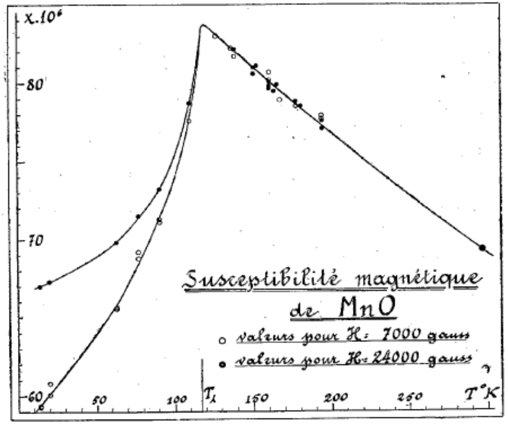
Neel, PhD Thesis 1932
Comptes Rendus 203, 304 (1936)

1938 “Antiferromagnetism”



Bitter, Physical Review 54, 79 (1938)
Van Vleck, The Journal of Chemical Physics 9 , 85 (1941)

1938 First observation of antiferromagnetism

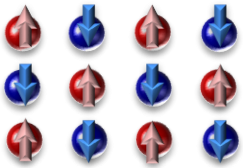


Bizette, Comptes Rendus 207, 449 (1938)

Why do we care ?

Ferromagnets

Antiferromagnets

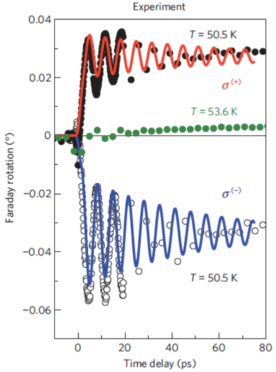


$$\omega_F = \gamma\mu_0\sqrt{H_z(H_z + H_K)} \quad \omega_{AF} = \gamma\mu_0 H_z \pm \gamma\mu_0\sqrt{H_K(2H_E + H_K)}$$

Advantages
- No stray field
- Ultrafast dynamics
- AMR, SMR etc.

Ultrafast dynamics

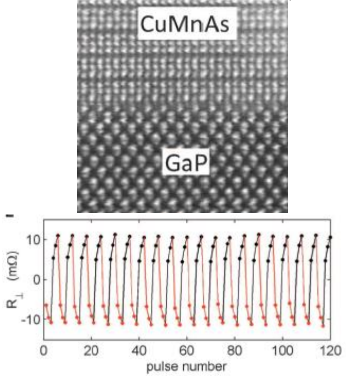
NiO, $HoFeO_3$, Tm FeO_3



Kimel Nature 429, 850 (2004)
Kimel Nature Physic 5, 727 (2009)
Satoh, PRL 105, 077402 (2010)

Spin-orbit torque

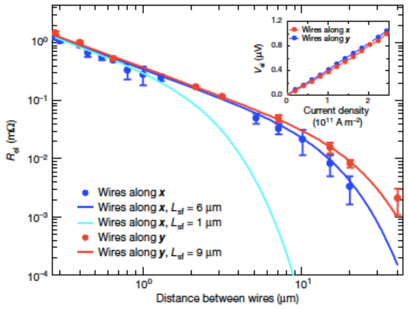
CuMnAs, Mn2Au, NiO, etc.



Zelezny PRL113, 157201 (2014)
Wadley Science 351, 587 (2015)
Chen PRL 120, 207204 (2018)

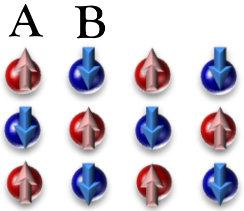
Spin wave transmission

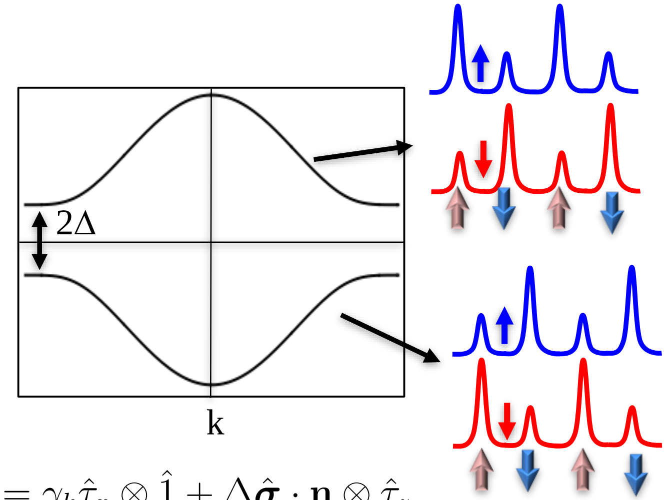
NiO, a-Fe_2O_3



Wang PRL 113, 097202 (2014).
Hahn 108, 57005 (2014)
Lebrun Nature 222, 561 (2018)

Toy model of the g-type antiferromagnet

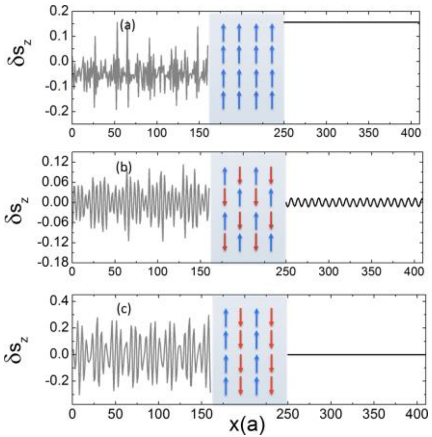




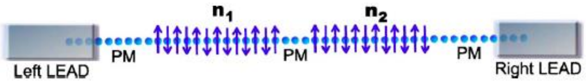
$$\tilde{H} = \gamma_k \hat{\tau}_x \otimes \hat{1} + \Delta \hat{\boldsymbol{\sigma}} \cdot \mathbf{n} \otimes \hat{\tau}_z$$

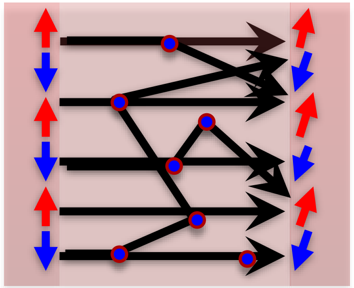
$$\psi^h_{s,s} = \frac{1}{\sqrt{2}}\left(\sqrt{1+s\frac{\Delta}{\varepsilon_{k,s}}}|A\rangle + s\sqrt{1- s\frac{\Delta}{\varepsilon_{k,s}}}|B\rangle\right)\otimes|s\rangle, \varepsilon_{k,s} = s\sqrt{\gamma_k^2+\Delta^2}$$

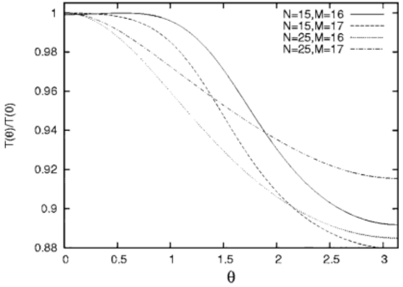
Polarization of the local density of states, but no spin current out of an antiferromagnet!!



Saidaoui, Manchon, Waintal PRB 89, 174430 (2014)

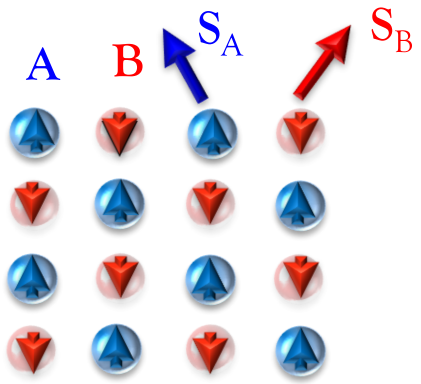






Nunez, Duine, McDonald PRB 73, 214426 (2006)

Spin diffusion in conventional collinear antiferromagnets



S_A+S_B: uniform spin accumulation
S_A-S_B: staggered spin accumulation

Drift-diffusion equation for the **uniform spin density**

$$\partial_t(n_A+n_B) = -\partial_i j_{c,i},\ j_{c,i} = -\mathcal{D}^{\parallel}\partial_i(n_A+n_B),$$

$$\mathbf{J}_i^s = -\mathcal{D}^{\parallel}\partial_i[(\mathbf{S}_A+\mathbf{S}_B)\cdot\mathbf{n}]\mathbf{n} - \mathcal{D}^{\perp}\mathbf{n}\times[\partial_i(\mathbf{S}_A+\mathbf{S}_B)\times\mathbf{n}],$$

$$\partial_t(\mathbf{S}_A+\mathbf{S}_B) + \frac{1}{\tau_\varphi}\underbrace{\mathbf{n}\times[(\mathbf{S}_A+\mathbf{S}_B)\times\mathbf{n}]}_{\text{dephasing}} + \frac{1}{\tau_{\text{sf}}}\underbrace{(\mathbf{S}_A+\mathbf{S}_B)}_{\text{relaxation}} = -\partial_i\mathbf{J}_i^s,$$

Relation between uniform and staggered spin accumulation

$$\mathbf{S}_A-\mathbf{S}_B = \frac{\tau^*}{\tau_\Delta}\underbrace{\mathbf{n}\times(\mathbf{S}_A+\mathbf{S}_B),}_{\text{Lifetime/precession time}}$$

In the diffusive regime, an antiferromagnet behaves like an **anisotropic normal metal**

Manchon, Journal of Physics: Condensed Matter 29, 104002 (2017)

Spin splitting and texture in momentum space

What are the conditions for spin splitting?

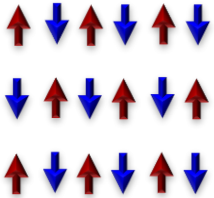
$\mathcal{T}$	Time reversal
$\mathcal{P}$	Inversion
$\mathcal{S}$	Spin rotation
τ_s	Sublattice translation

Transformations that ensure spin degeneracy

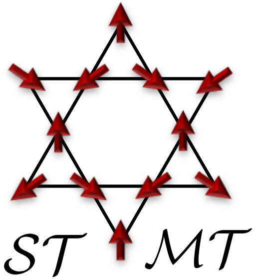
Nonmagnetic materials $\mathcal{PT}$ (Kramers theorem)
If $\mathcal{P}$ is broken => spin splitting in momentum (Rashba)

Magnetic materials $\mathcal{T}$ is broken

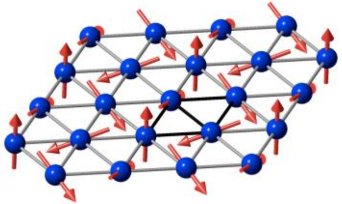
If there exists a symmetry $\mathcal{O}$ operation such that is $\mathcal{OT}$ preserved, then spin degeneracy is enforced



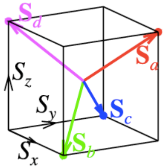
$\mathcal{T}\tau_s$ $\mathcal{S}\tau_s$



$\mathcal{ST}$ $\mathcal{MT}$



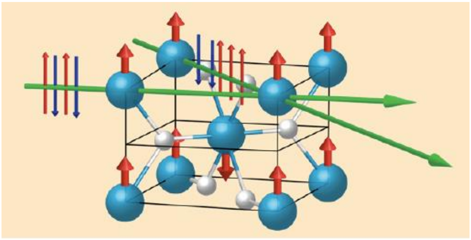
$\mathcal{S}$

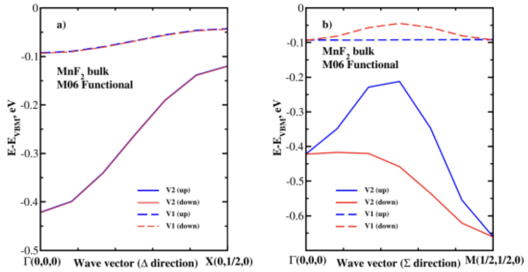


Discussion in Manchon & Zelezny, Physics 13, 112 (2020)

Antiferromagnets with spin splitting

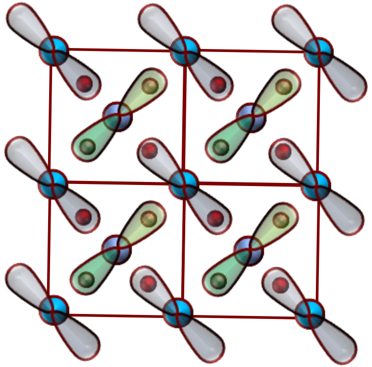
Chemically equivalent magnetic sublattices but **anisotropic** orbital overlap



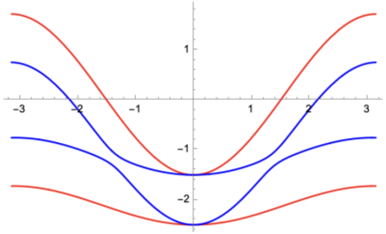


Egorov and Evarestov, J. Phys. Chem. Lett. 2021, 12, 2363–2369

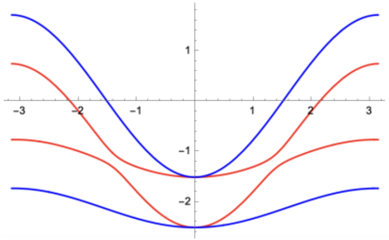
Toy model for spin split AF

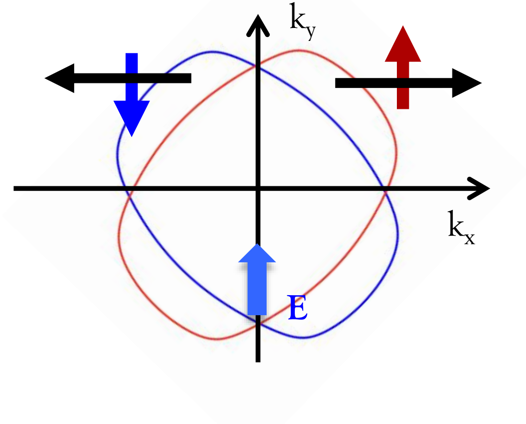


Along (110)



Along (-110)





Hayami et al. Journal of the Physical Society of Japan 88, 123702 (2019)
Yuan et al. Physical Review B 102, 014422 (2020)
Smejkal et al. Science Advances 6, eaaz8809 (2020); PRX 12, 031042 (2022)

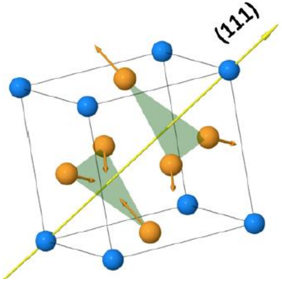
González-Hernández et al.,
Physical Review Letters 126, 127701 (2021)

IV. Antiferromagnets: the new frontier

a. Collinear antiferromagnets
b. Noncollinear antiferromagnets

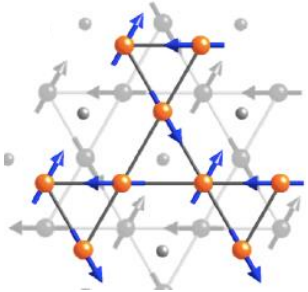
Why non-collinear?

Mn_3Ir, Mn_3Pt



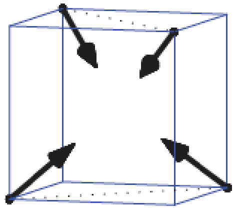
Ekholm PRB 10, 104423 (2011)

Mn_3Ge, Mn_3Sn



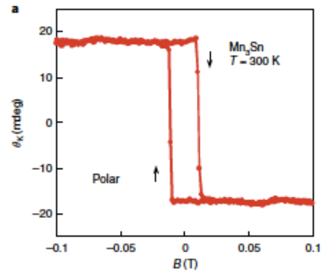
Ekholm PRB 10, 104423 (2011)

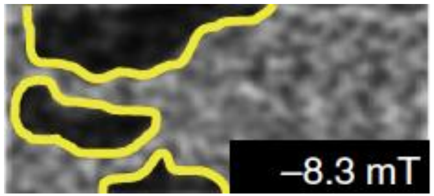
γ-MnX



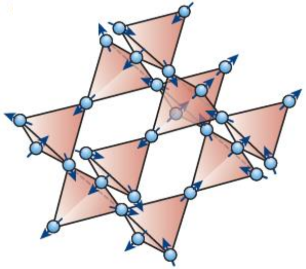
Ekholm PRB 10, 104423 (2011)

Spin-orbit coupling ➔ spin Hall effect
Mirror symmetry breaking ➔ "breaks TRS"
Anomalous Hall and MO Kerr effects



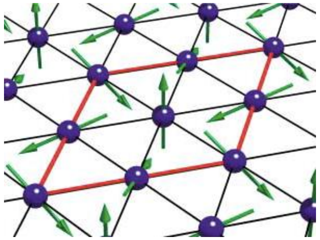


$Nd_2Ir_2O_7$, $Eu_2Ir_2O_7$, $Cd_2Os_2O_7$, $Sm_2Ir_2O_7$



Gardner RMP 82,53 (2010)

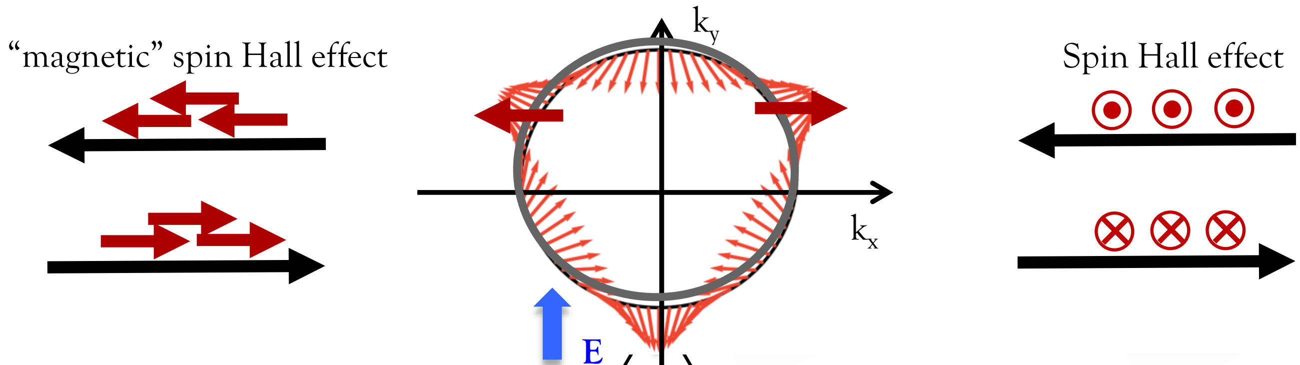
Mn/Cu(111), $Na_{0.5}CoO_2$



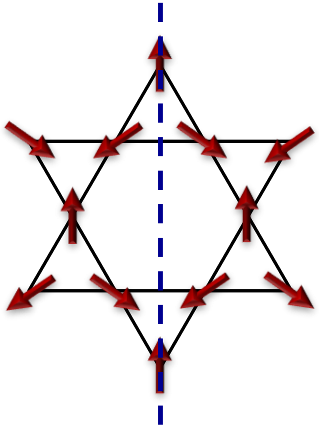
Kurz PRL 86, 1106 (2003)
Kato, PRL 105, 266405 (2010).

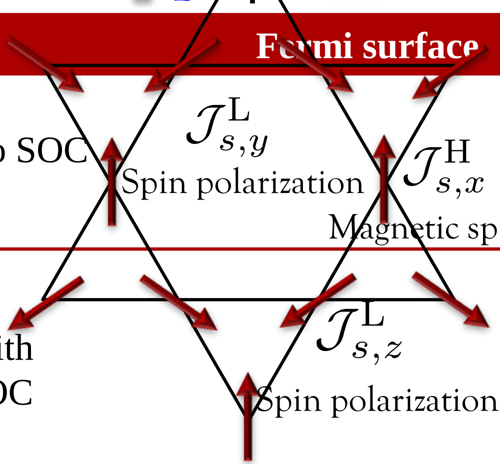
Nakatsuji, Nature; Higo Nature Physics
Nayak et al. Sci. Adv. 2016; 2 : e1501870,
Shindou, Nagaosa, PRL 87, 116801 (2001).
Chen, Niu, McDonald, PRL 112, 017205 (2014).
J. Kübler, C. Felser, EPL 108, 67001 (2014).

Spin texture and anomalous transport



Magnetic group: 2’/m’



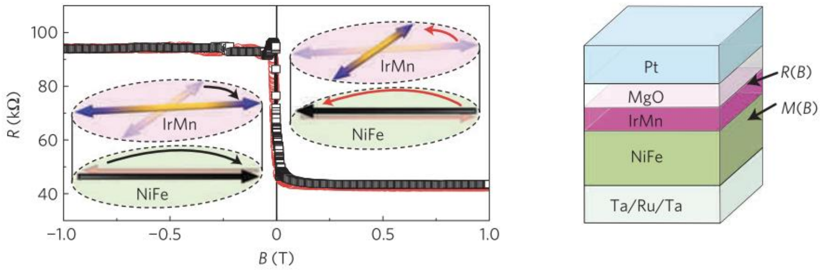


	Fermi surface		Fermi sea
No SOC	$\mathcal{J}^{\mathrm{L}}_{s,y}$ Spin polarization	$\mathcal{J}^{\mathrm{H}}_{s,x}$ Magnetic spin Hall	$\mathcal{J}^{\mathrm{H}}_{s,z}$ Spin Hall
With SOC	$\mathcal{J}^{\mathrm{L}}_{s,z}$ Spin polarization		$\mathcal{J}^{\mathrm{H}}_{s,y}$ $\mathcal{J}^{\mathrm{L}}_{s,x}$ Spin Hall, polarization $\mathbf{J}^{\mathrm{H}}_{c}$ Anomalous Hall

Zelezny et al. PRL 119, 187204 (2017); Bonbien and Manchon, PRB 102, 085113 (2020)

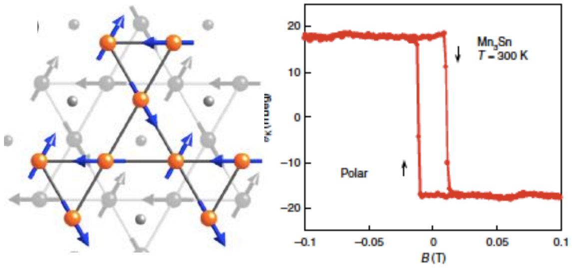
Some notable experimental results

Tunneling anisotropic magnetoresistance



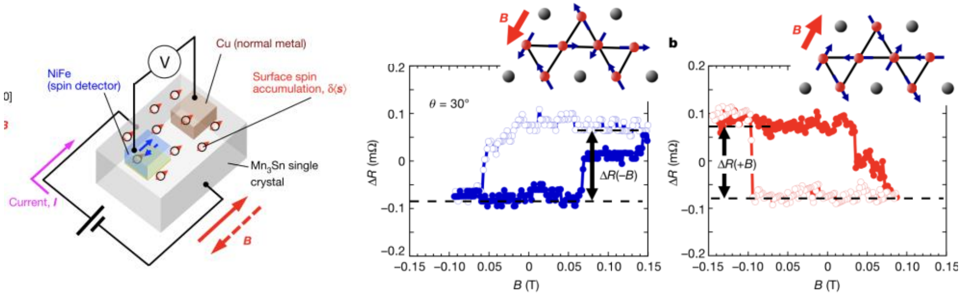
Park et al. Nature Materials 10, 347 (2011)

Anomalous Hall effect



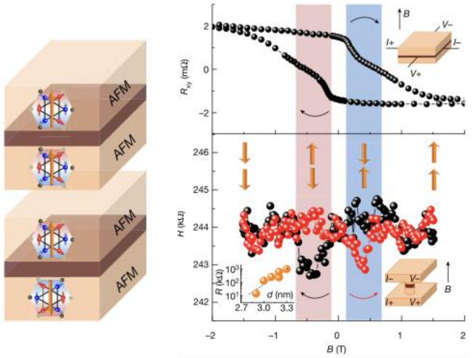
Nakatsuji, Nature 527, 212–215 (2015).
Nayak et al. Science Advances 2, e1501870 (2016)

Magnetic spin Hall effect



Higo et al. Nature 565, 627 (2023)

Tunneling magnetoresistance



Chen et al. Nature 613, 490 (2023)


That's all Folks!