# Spin Transport: GMR, TMR etc.



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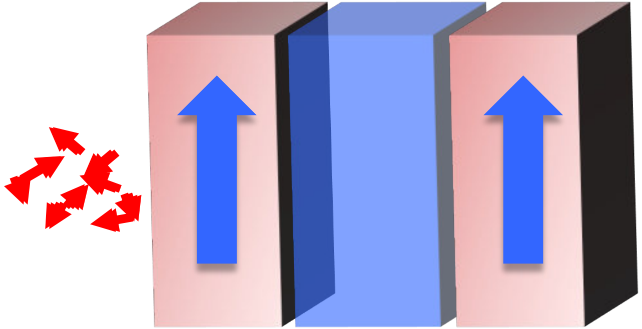
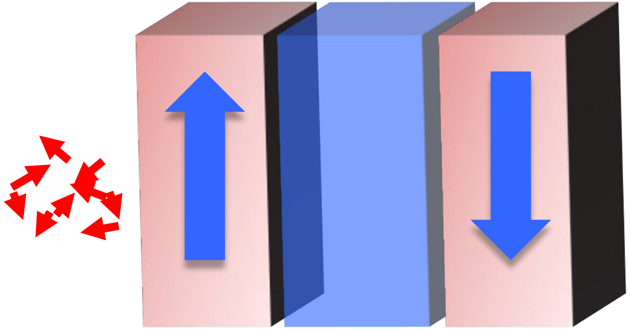
# Spintronics: a success story



Giant magnetoresistance - 1988

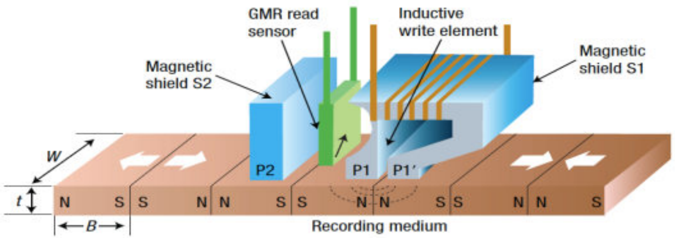
Fert & Grünberg
**Nobel Laureates 2007**



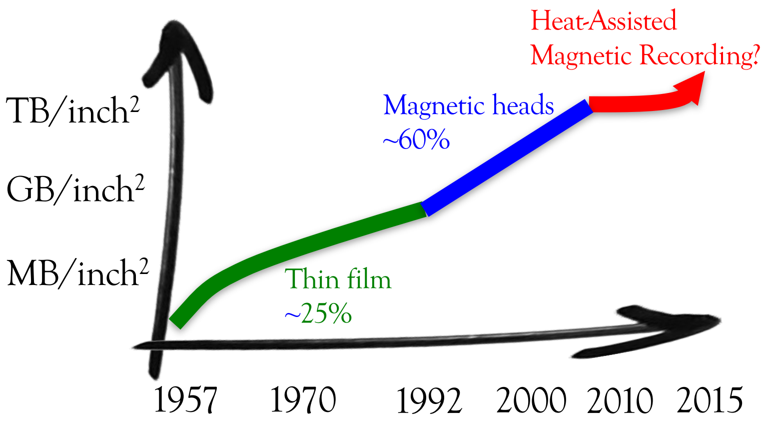
Spin transfer torque - 1996

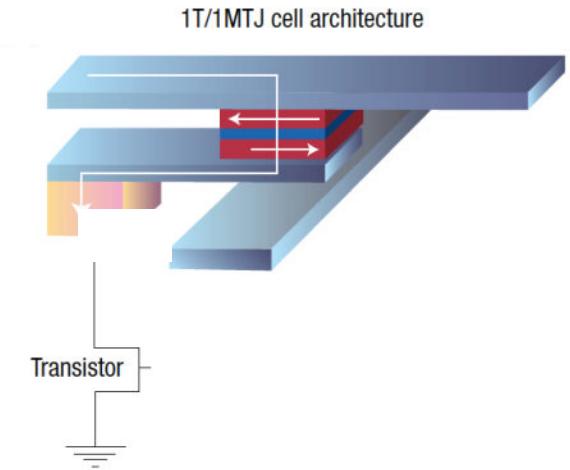
Berger &
Slonczewski
**Buckley price 2013**

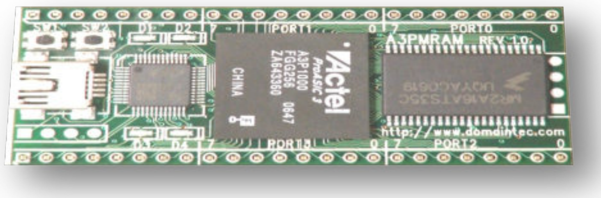
# Spintronics: a success story



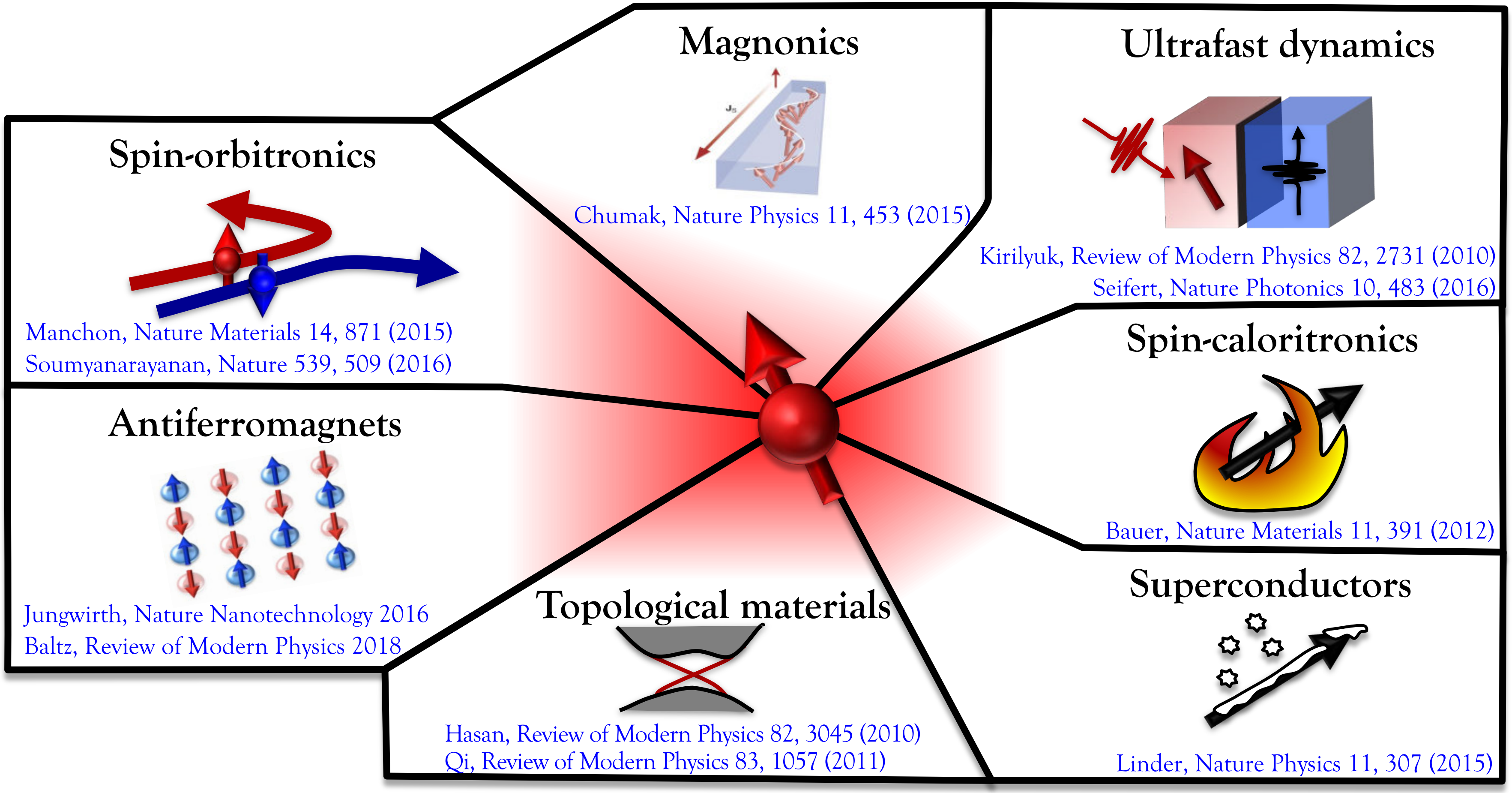

Chappert et al., Nature Materials 2007

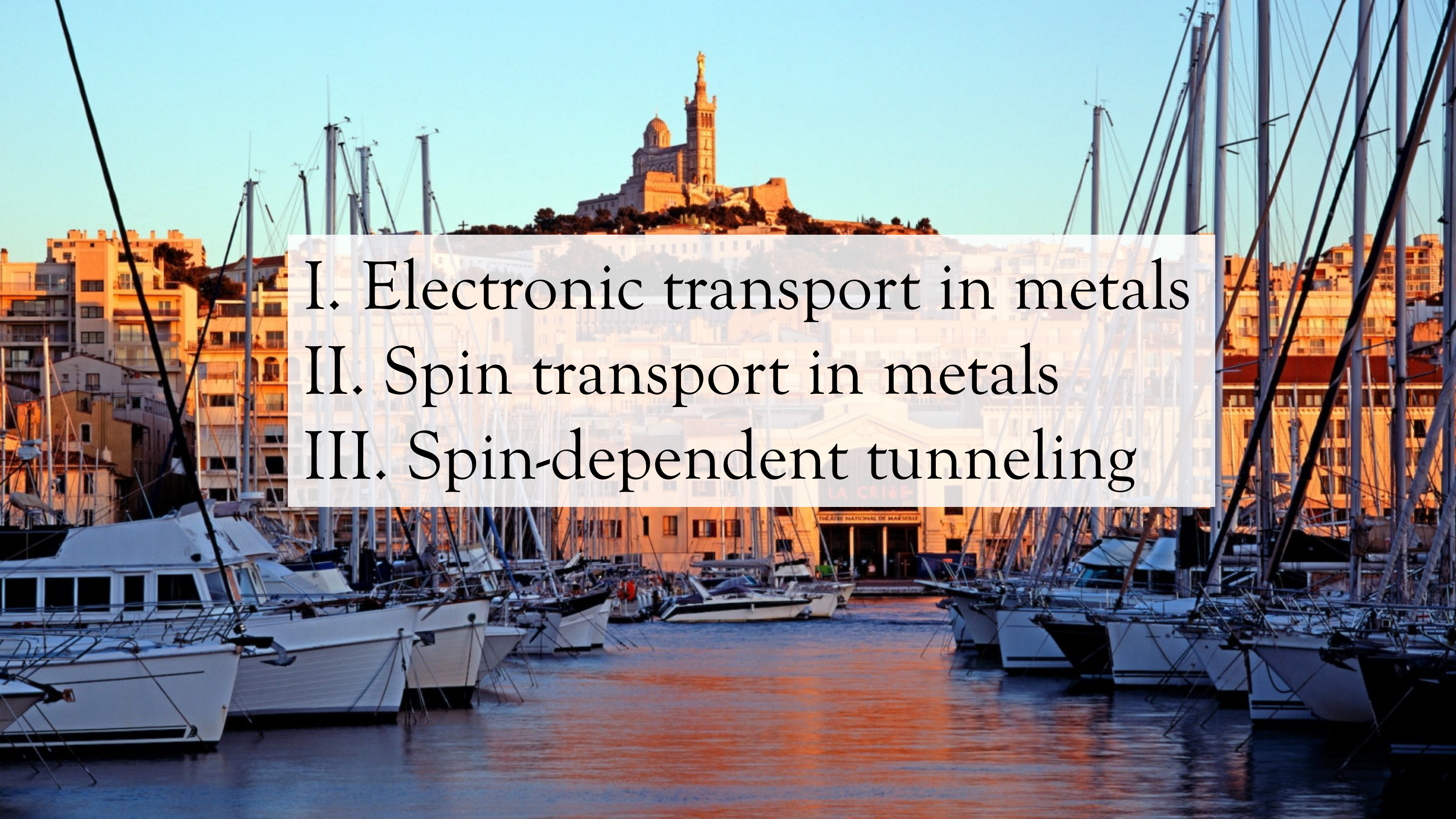


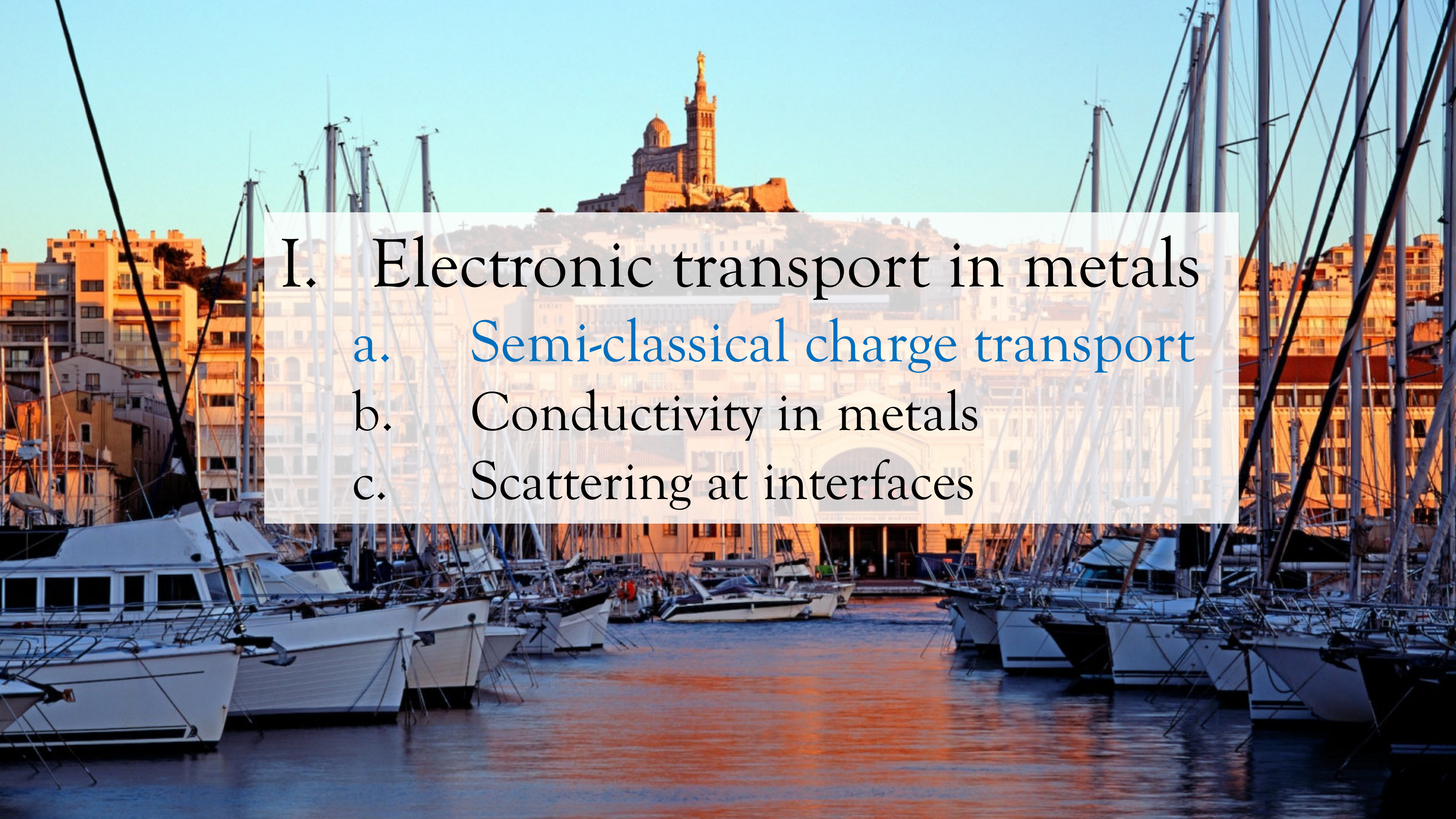



Major semiconductor bigfoot: IBM, Samsung, Intel, Toshiba, Qualcom etc.


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
Topological materials
Hasan, Review of Modern Physics 82, 3045 (2010)
Qi, Review of Modern Physics 83, 1057 (2011)
Superconductors
Linder, Nature Physics 11, 307 (2015)




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



# I. Electronic transport in metals

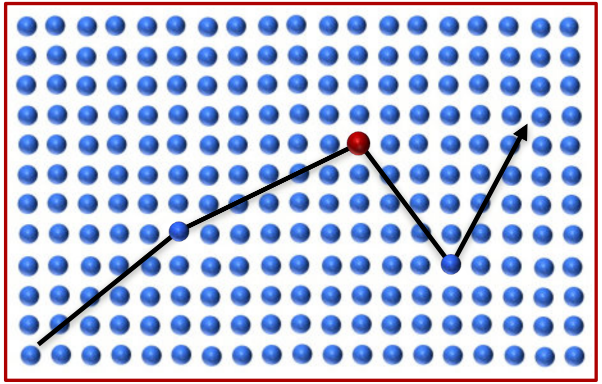
a. Semi-classical charge transport
b. Conductivity in metals
c. Scattering at interfaces

# 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



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

Paul Drude

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

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

Drude conductivity

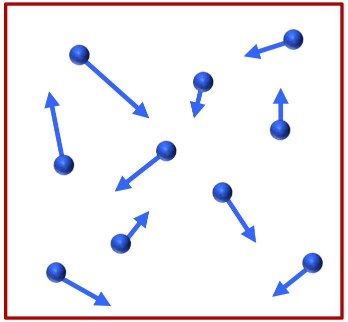
If the Fermi wavelength of the electronic wave is much shorter than the mean free path and the size of the system, $\lambda_F \ll \lambda, d$ ...
Drude's classical picture is acceptable

# a. Semi-classical charge transport

## Boltzmann transport equation

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

The semiclassical electron gas



Ludwig Boltzmann

Cloud's dynamics $\dfrac{df}{dt} = \left.\dfrac{df}{dt}\right|_{\mathrm{coll}}$ 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

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

# 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 $f = f_0 + \delta f$

Non-equilibrium (linear in v)

Equilibrium (Fermi-Dirac)

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

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

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

### Scattering against impurities

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

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

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

It can be written in second quantization

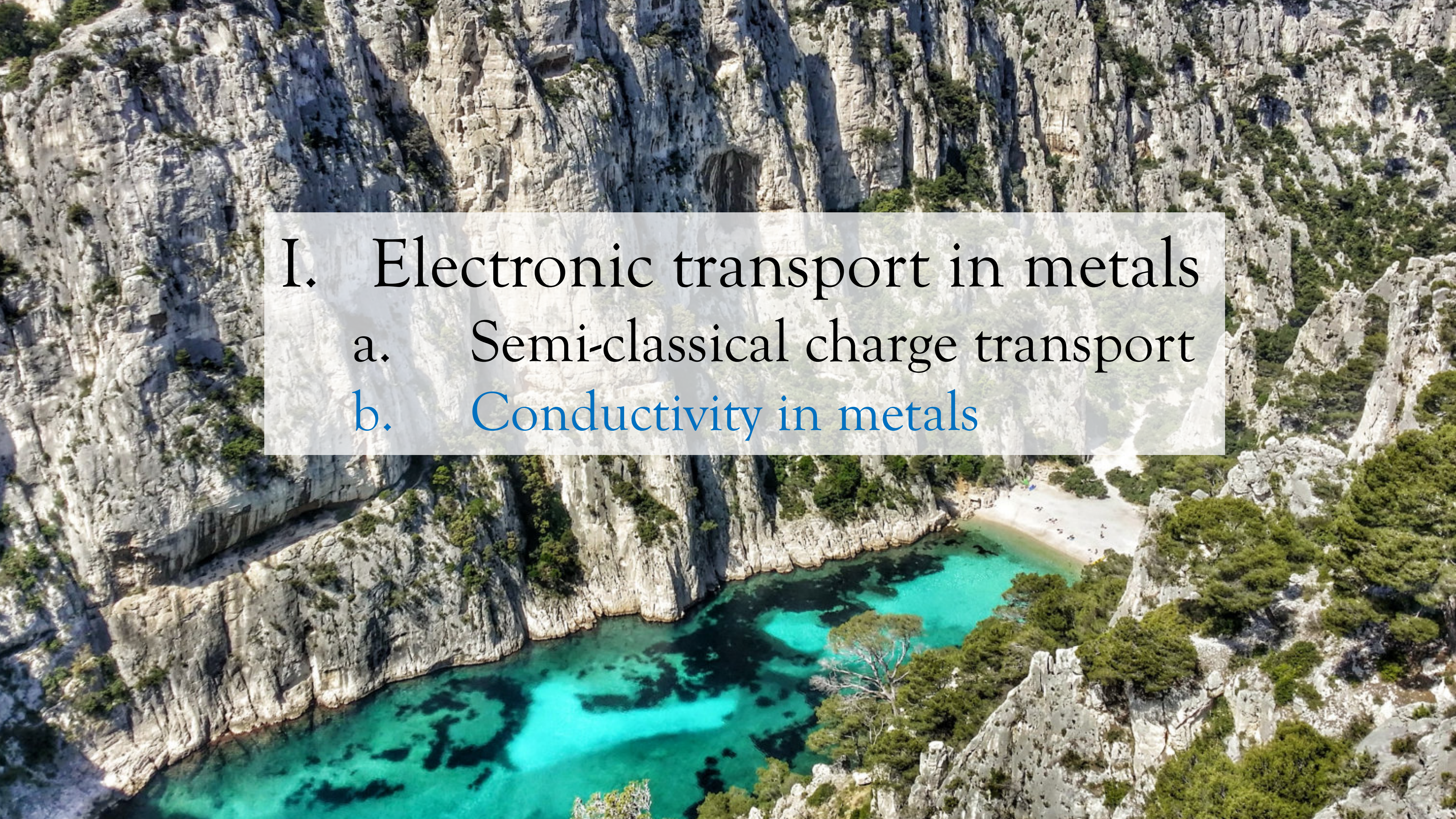
$$V_{e-ph} = \sum_{\boldsymbol{k},\boldsymbol{q}} \left(B_{\boldsymbol{q}} c^\dagger_{\boldsymbol{k}+\boldsymbol{q}} c_{\boldsymbol{k}} b_{\boldsymbol{q}} + B_{-\boldsymbol{q}} c^\dagger_{\boldsymbol{k}-\boldsymbol{q}} c_{\boldsymbol{k}} b^\dagger_{\boldsymbol{q}}\right)$$

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

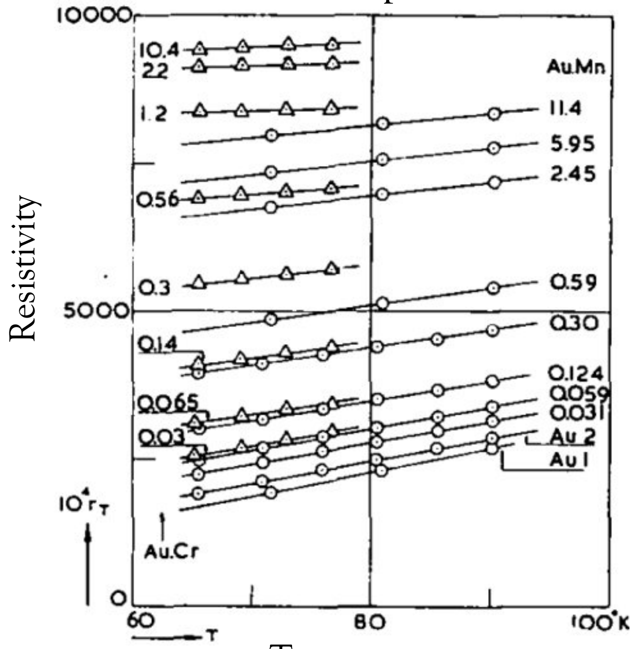
**Matthiessen's rule (1862)**

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

Phonons

Impurities

Mn and Cr impurities in Au

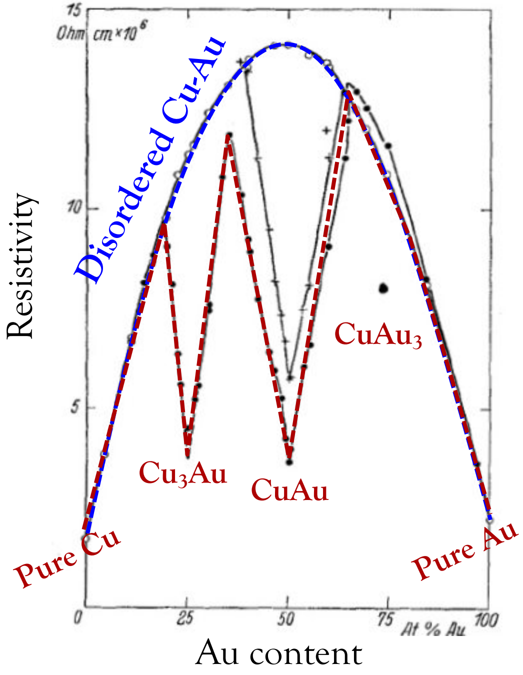



Gerritsen and Linde, Physica 18, 877 (1952)

**Nordheim's rule (1931)**

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

Cu-Au alloy



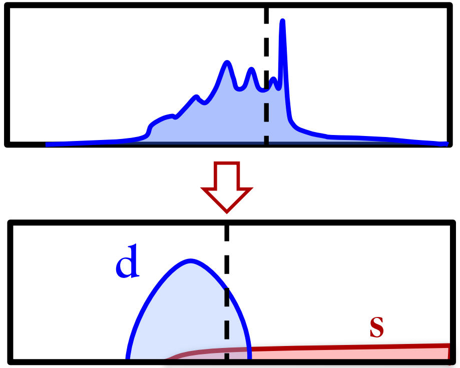

Johansson and Linde, Annel der Physics 5, 1 (1936)

# 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




$$v_s \gg v_d$$

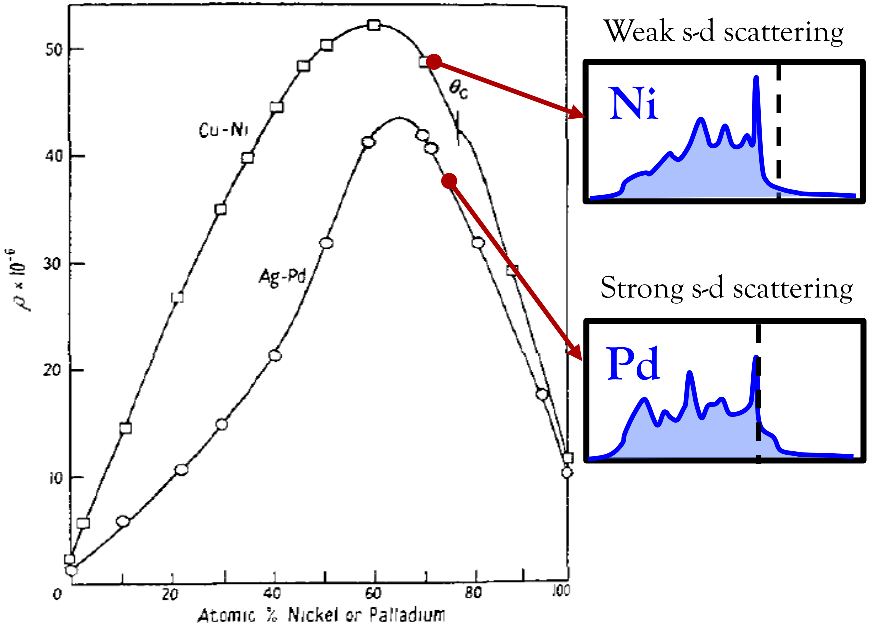
$$\mathcal{N}_d(\varepsilon_F) \gg \mathcal{N}_s(\varepsilon_F)$$

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




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

# b. Conductivity of transition metals

## Conductivity enhancement in magnetic transition metals

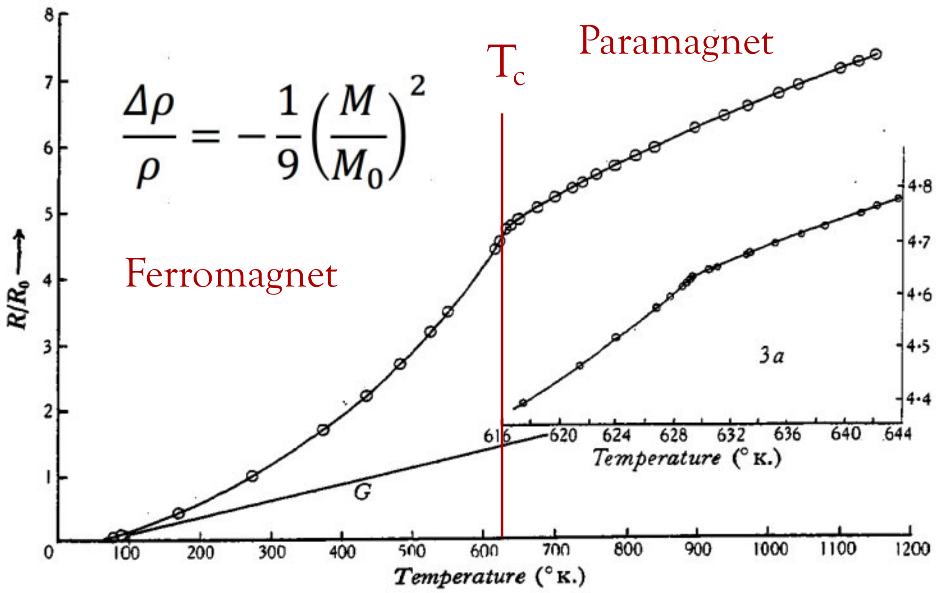



Figure 3. Resistance of nickel as a function of temperature.
Figure 3a. The neighbourhood of the Curie point.

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

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

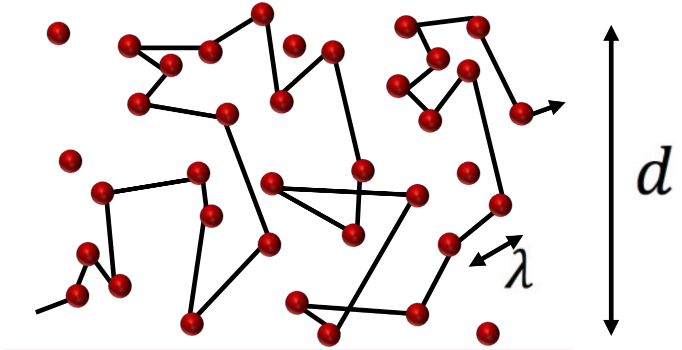
Spin polarization at Fermi level

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

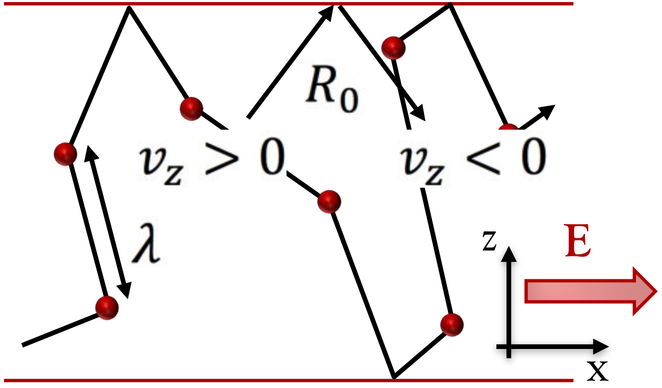
$$\rho = \rho_{ss} + \frac{\rho_{sd}}{2}\left(\left(1 - \frac{M}{M_0}\right)^{1/3} + \left(1 + \frac{M}{M_0}\right)^{1/3}\right)$$

# Size effect in thin films: Fuchs-Sondheimer theory

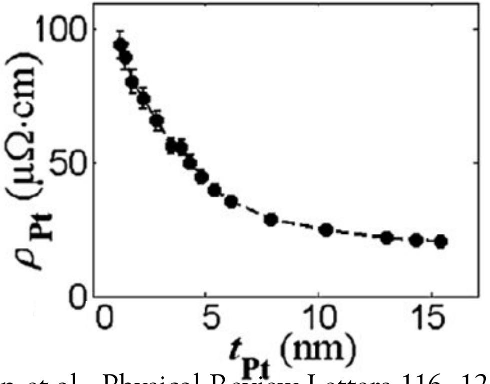
Diffusive regime $\lambda \ll d$




Knudsen regime $\lambda \sim d$

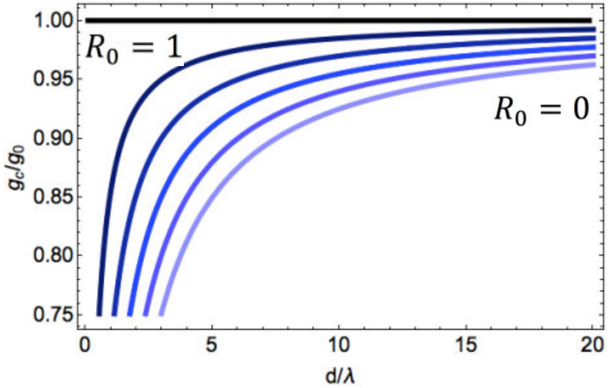


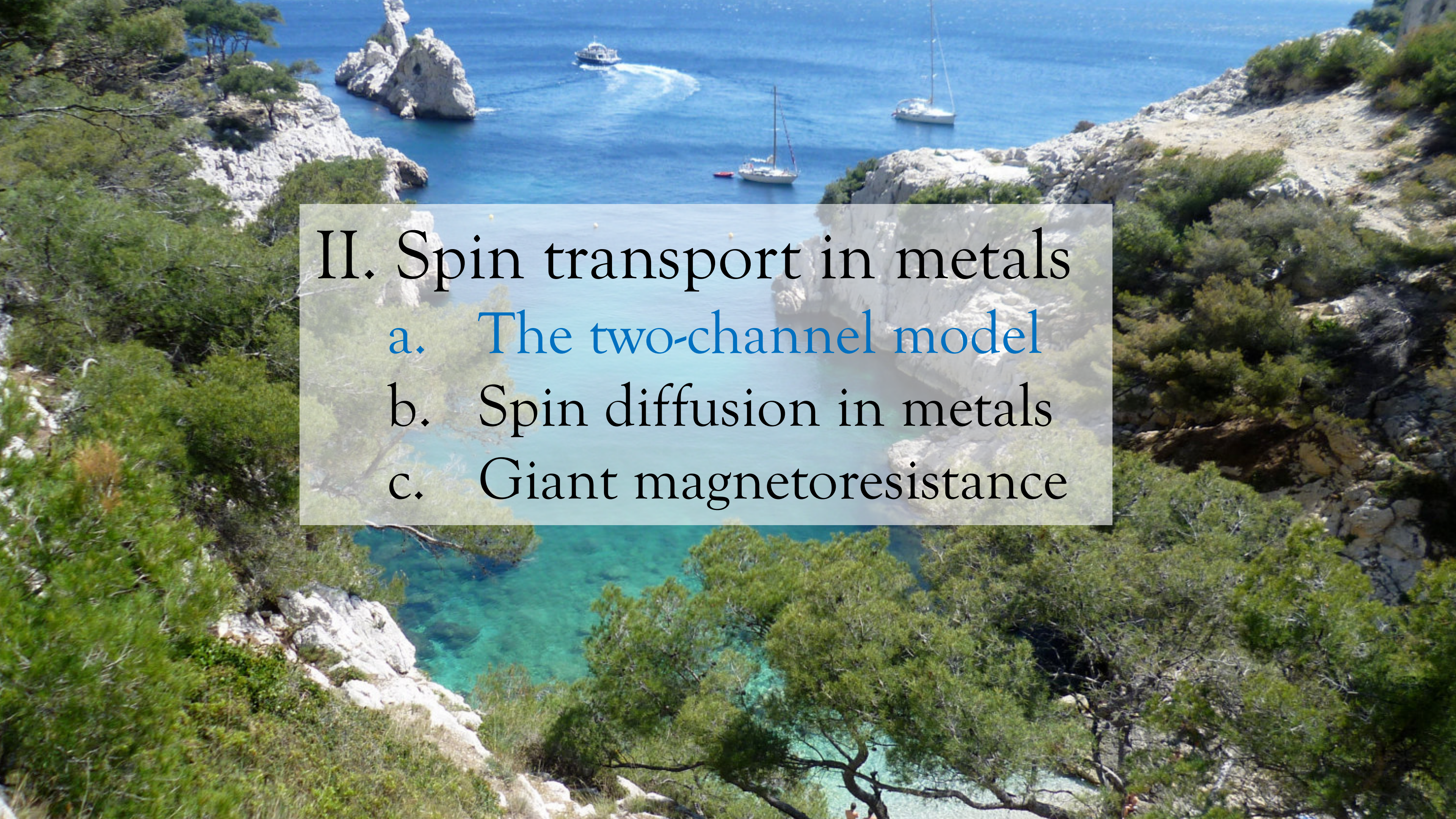

Resistivity of Pt thin film




Nguyen et al., Physical Review Letters 116, 126601 (2016)

Total conductivity



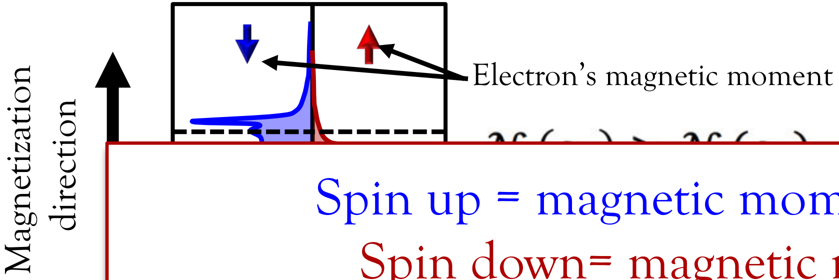


# II. Spin transport in metals

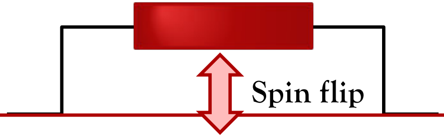
a. The two-channel model
b. Spin diffusion in metals
c. Giant magnetoresistance

# 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**

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

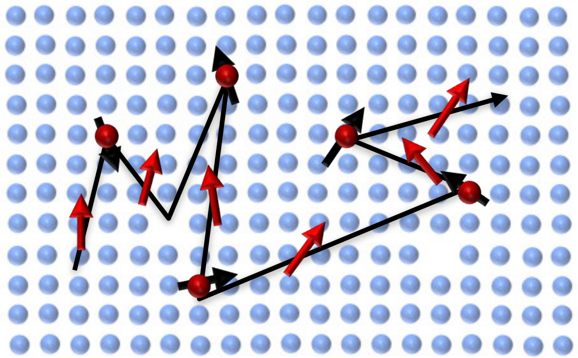
Spin relaxation time

Spin relaxation length
Spin diffusion length

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

# Spin relaxation

## Magnetic impurities

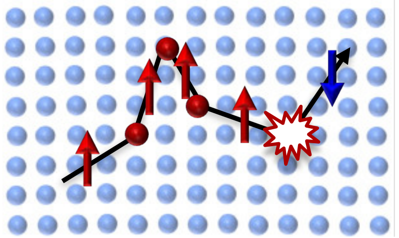


Isolated magnetic impurities acts like a random field, spatially distributed

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

The stronger the scattering,
the faster the spin relaxation

## Elliott-Yafet scattering



The itinerant spin precesses around the spin-orbit field

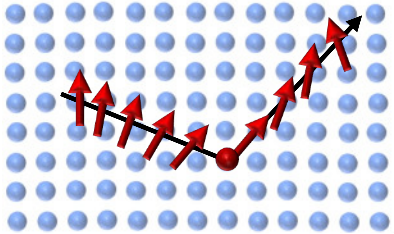
$$H_{so} = \xi_{so} \boldsymbol{\sigma} \cdot \boldsymbol{L} \propto \xi_{so} \boldsymbol{\sigma} \cdot (\boldsymbol{k} \times \boldsymbol{k}')$$

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

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

Spin relaxation time

Spin-dependent scattering time

Weak spin relaxation: decoupled spin channels

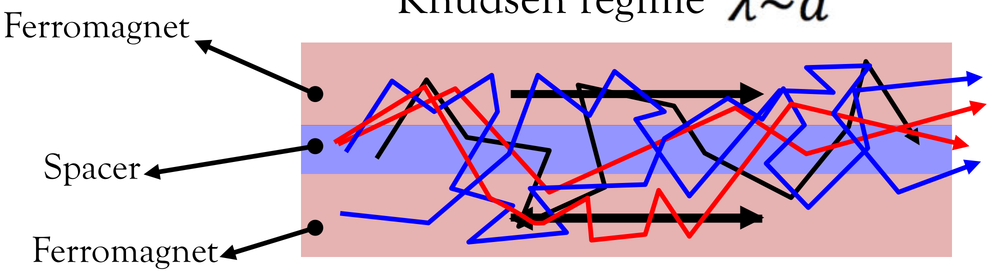
$$\frac{1}{\tau_\uparrow}, \frac{1}{\tau_\uparrow} \gg \frac{1}{\tau_{\uparrow\downarrow}} \Rightarrow \begin{cases} \sigma_\downarrow = \tau_\downarrow \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \\ \sigma_\uparrow = \tau_\uparrow \dfrac{e^2 v_F^2}{3} \mathcal{N}(\varepsilon_F) \end{cases}$$

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

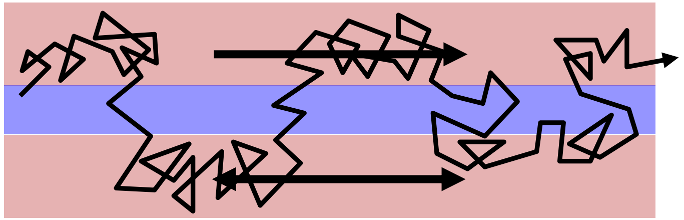
Knudsen regime $\lambda \sim d$



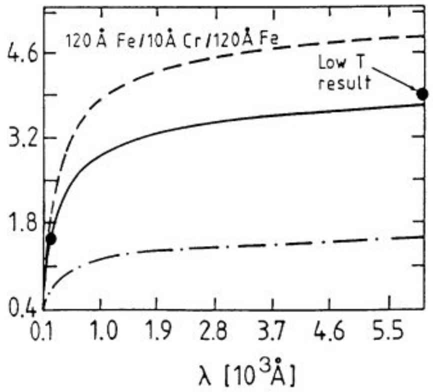

Parallel $\sigma_c^{\uparrow} > \sigma_c^{\downarrow}$

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 in metals (Tutorial!)

c. Giant 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 ($\mu_B$/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 | $\boldsymbol{J}_c = \sigma_c(\boldsymbol{E} - \boldsymbol{\nabla}\mu)$ | $\boldsymbol{J}_c^\sigma = \sigma_c^\sigma(\boldsymbol{E} - \boldsymbol{\nabla}\mu_\sigma)$ |
| Charge conservation | $\partial_t n + \boldsymbol{\nabla}\cdot\boldsymbol{J}_c = 0$ | $\partial_t n_\sigma + \boldsymbol{\nabla}\cdot\boldsymbol{J}_c^\sigma = 0$ |
| Ohm's law | $J_c = g(\mu_R - \mu_L)$ | $J_c^\sigma = g_\sigma(\mu_R^\sigma - \mu_L^\sigma)$ |
| Chemical potential | $\mu = \dfrac{n}{e\mathcal{N}(\varepsilon_F)}$ | $\mu_\sigma = \dfrac{n_\sigma}{e\mathcal{N}_\sigma(\varepsilon_F)}$ |

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

## Charge and spin current definitions

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

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

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

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

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

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

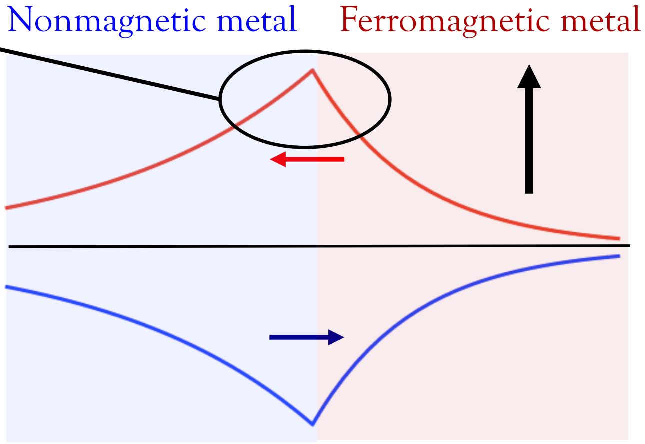
# Spin accumulation

## The concept of spin accumulation

Charge
$$\begin{cases} J_c = \sigma_c(E - \nabla\bar{\mu}) - \beta\sigma_c\nabla\mu_s \\ \nabla\cdot J_c = 0 \\ J_s = \beta\sigma_c(E - \nabla\bar{\mu}) - \sigma_c\nabla\mu_s \\ \dfrac{1}{\sigma_c}\nabla\cdot J_s = -\dfrac{\mu_s}{\lambda_{sf}^2} \end{cases}$$
Spin

$$\bar{\mu} = -\beta\mu_s + Ax + B$$
$$\mu_s = Ce^{x/\lambda_{sf}^*} + De^{-x/\lambda_{sf}^*}$$
$$\lambda_{sf}^{*2} = (1-\beta^2)\lambda_{sf}^2$$

Spin accumulation




**Spin accumulation profile**

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

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

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

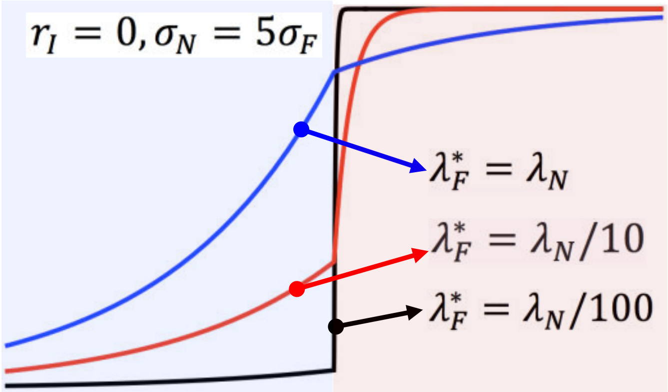
Spin diffusion length of the ferromagnet

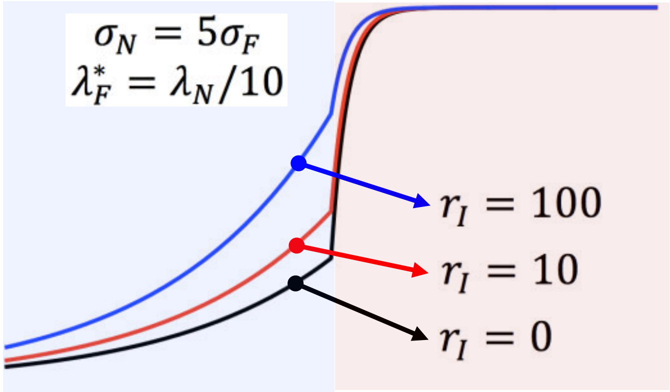
Interfacial resistance $r_I = (1-\gamma^2)/g_I$

"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

Nonmagnetic metal Ferromagnetic metal

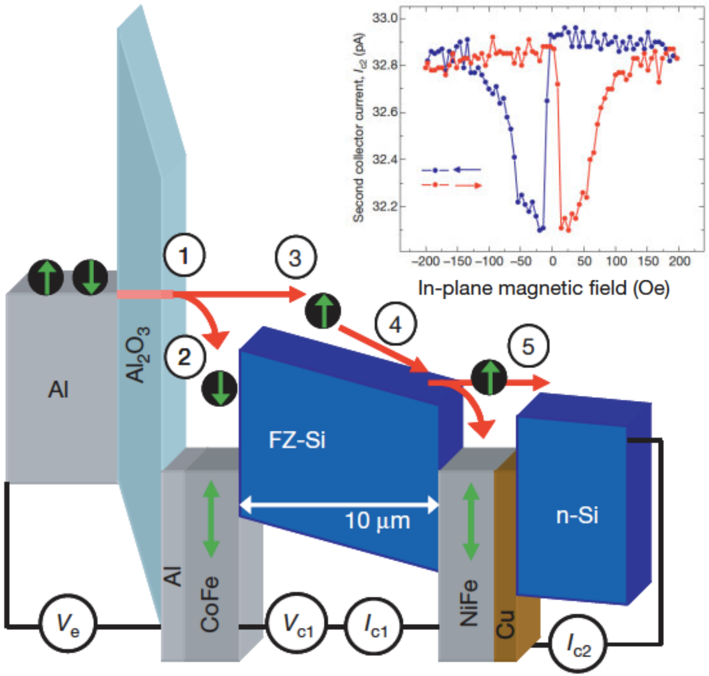


# Spin injection

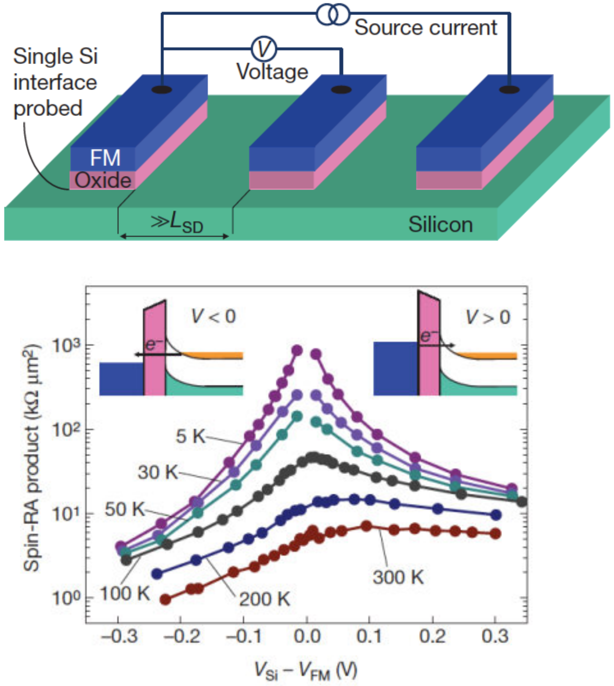
**Appelbaum et al., Nature 447, 295 (2007)**

Hot electron injection




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

Non-local tunneling injection



# II. Spin transport in metals

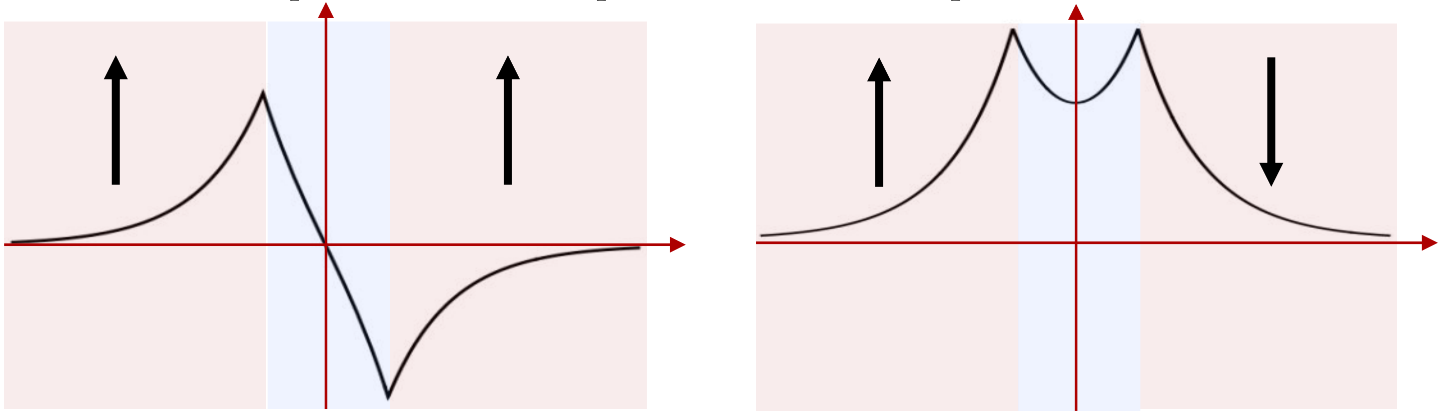
a. The two-channel model

b. Spin diffusion in metals

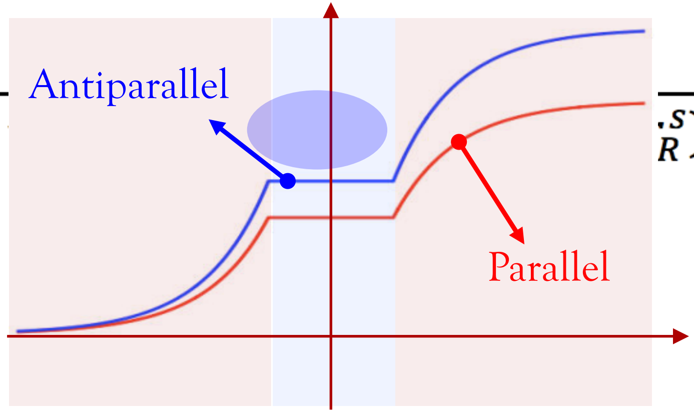
c. Giant magnetoresistance

# Magnetoresistance

Spin accumulation profile in a metallic spin-valve



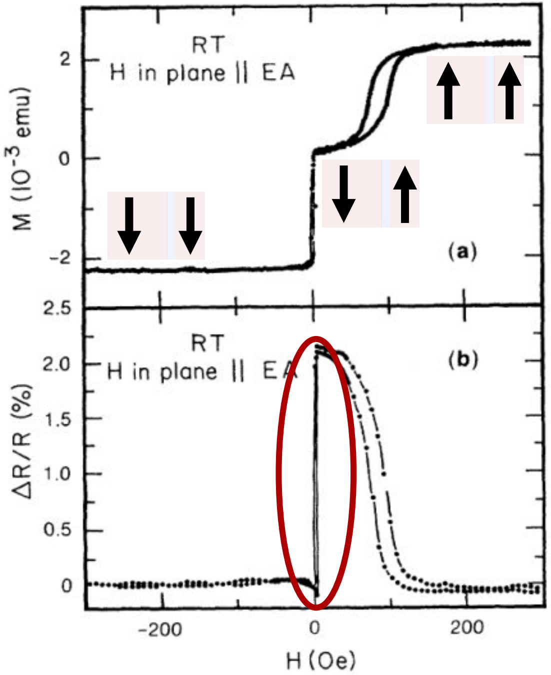
Chemical potential profile

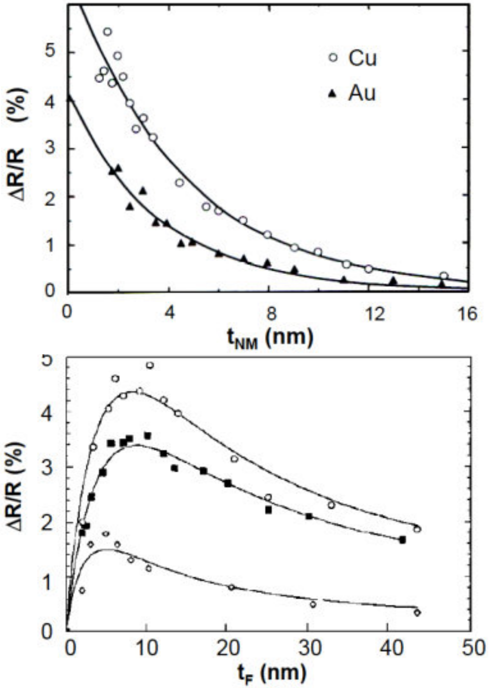



$$r = \frac{\bar{\mu}_{-\infty} - \bar{\mu}_{+\infty}}{J_c}$$

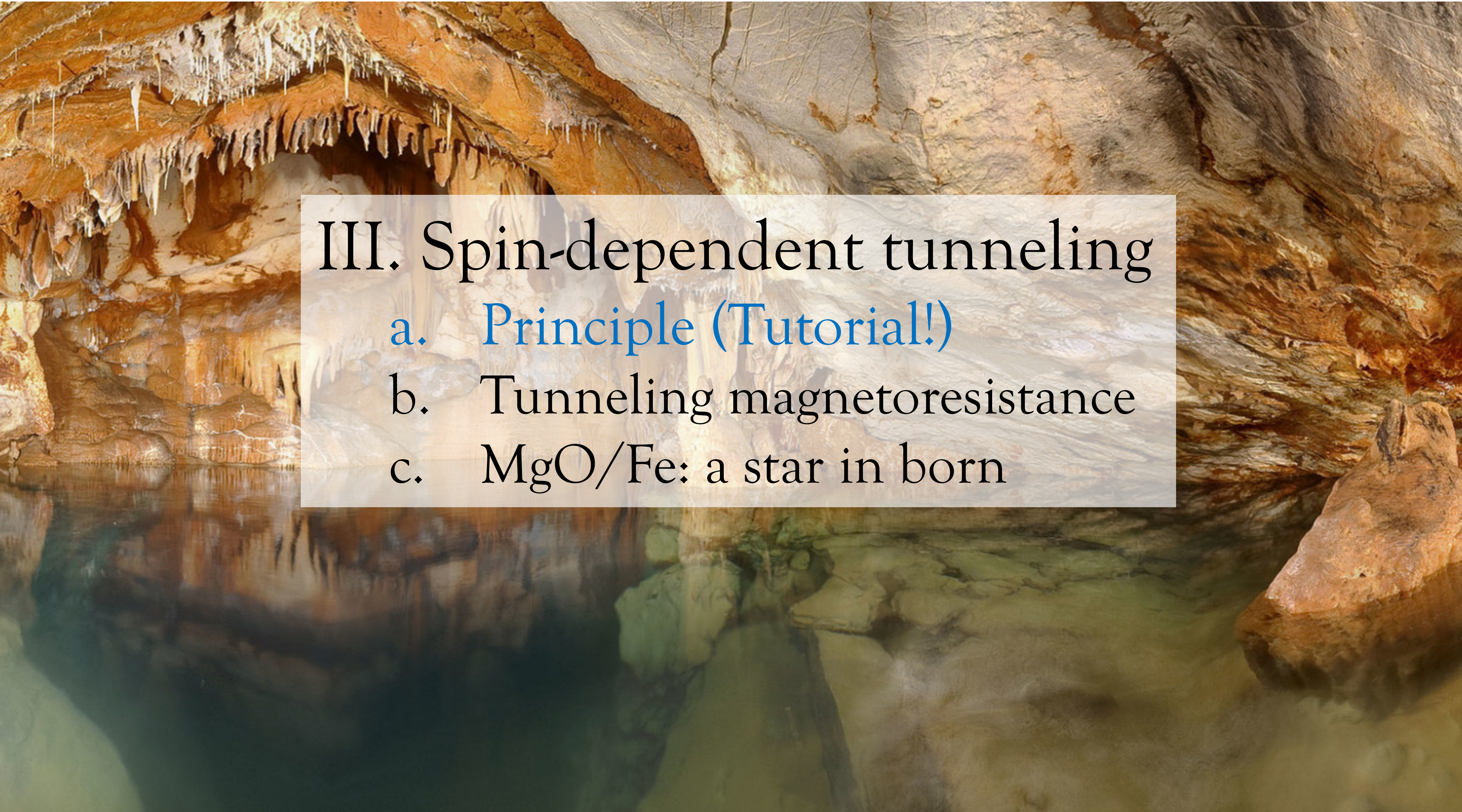
# Magnetoresistance

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




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

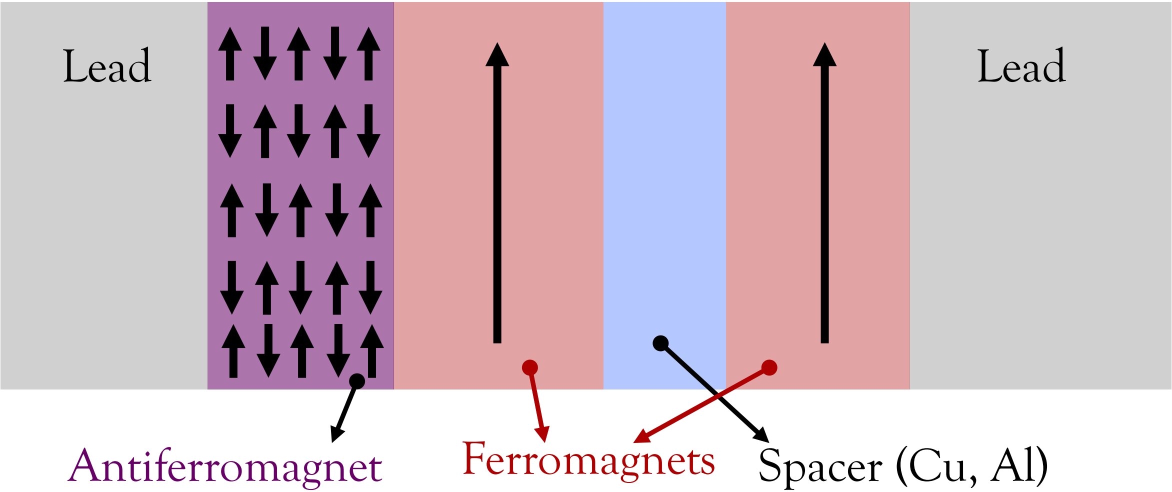


# III. Spin-dependent tunneling

a. Principle (Tutorial!)
b. Tunneling magnetoresistance
c. MgO/Fe: a star in born

# Giant versus tunneling magnetoresistance

The problem with giant magnetoresistance

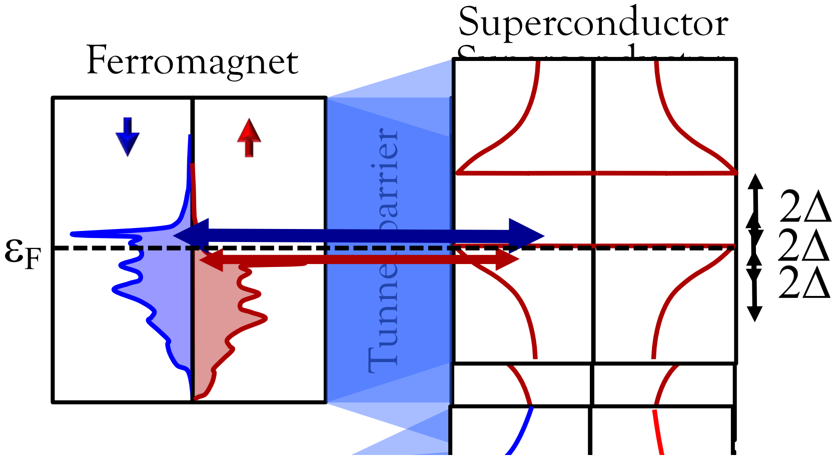


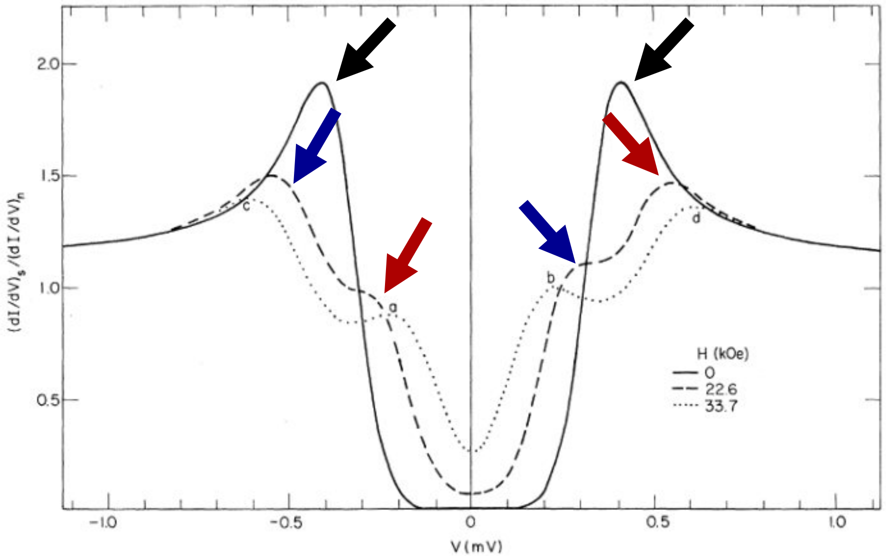

$$\Delta r \approx 4\beta_L\beta_R \frac{r_L^s r_R^s}{r_L^s + r_R^s}$$

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

Solution: use a tunnel barrier!

# Spin-dependent tunneling



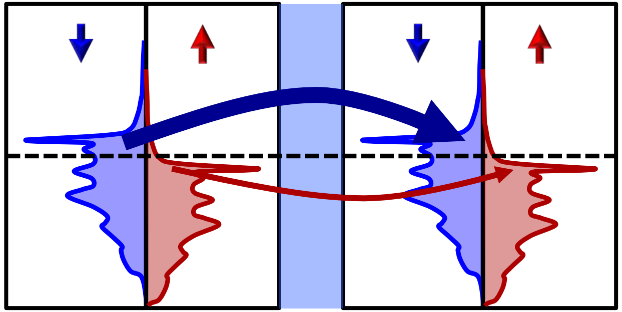

Tedrow and Meservey, Physical Review Letters 26, 192 (1971)

$Al/Al_2O_3/Ni$: P=29%
$Al/Al_2O_3/Co$: P=38%
$Al/Al_2O_3/CoFe$: P=48%

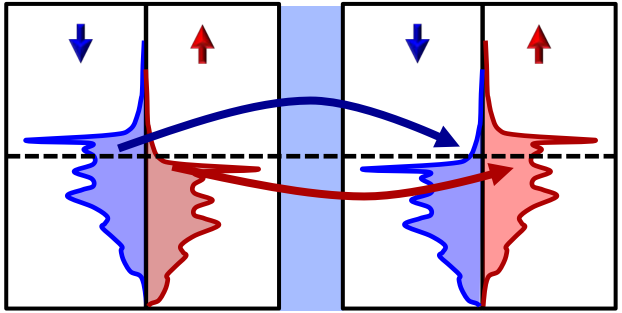
# Spin-dependent tunneling

## Basics of spin-dependent tunneling

Parallel configuration



Antiparallel configuration



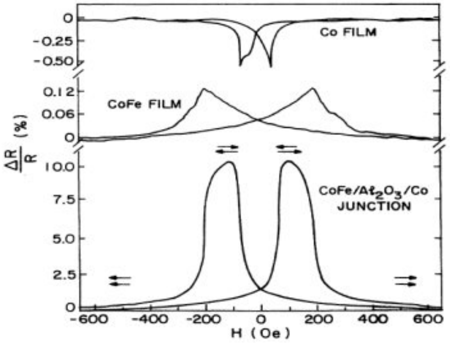
**In parallel configuration**

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

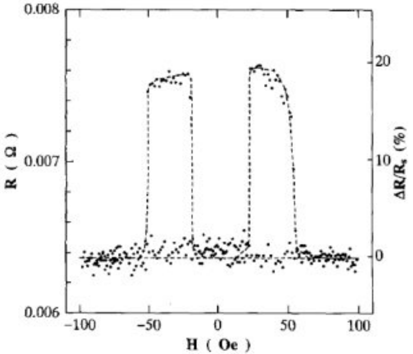
**In antiparallel configuration**

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)

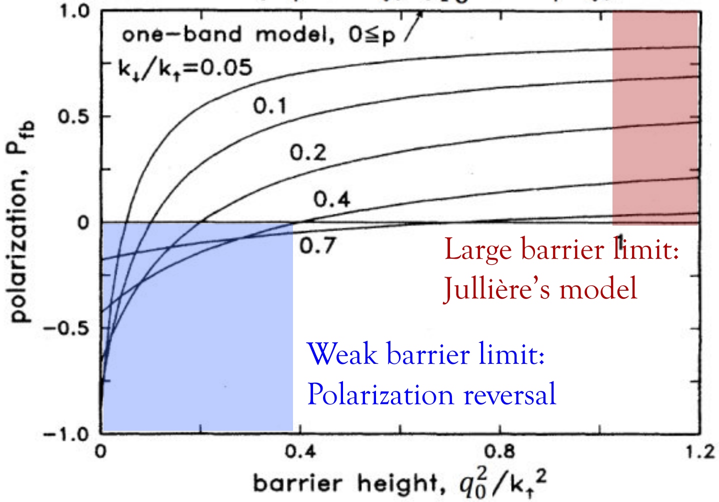
Miyazaki, Tezuka, JMMM 139, L231 (1995)

# Spin-dependent tunneling

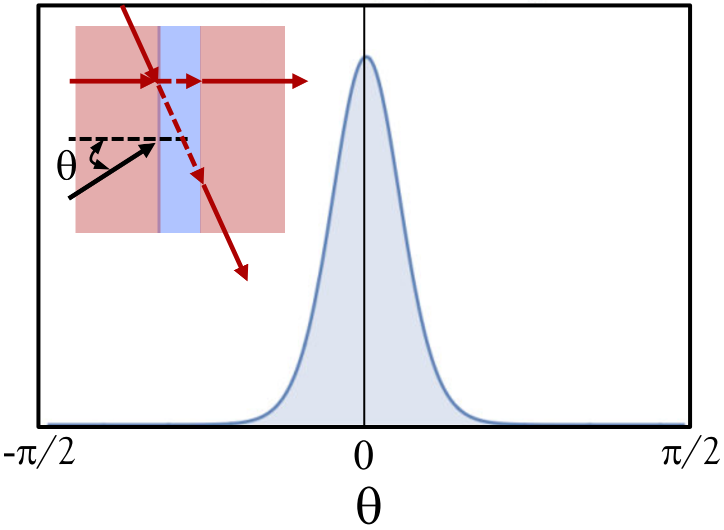
Free electron model for spin-dependent tunneling

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

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




Slonczewski, Physical Review B 39, 6995 (1989)



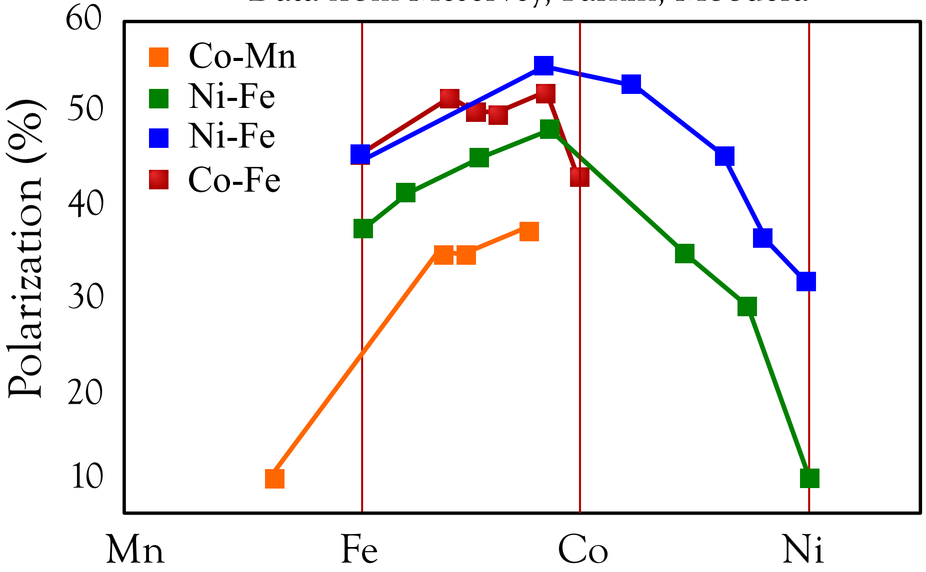

$$U_{\mathrm{MgO}} \approx 1 - 2\ eV,\ U_{\mathrm{AlO_x}} \approx 3\ eV$$
$$k_F^\uparrow \approx 1.09\ \mathrm{A}^{\circ -1},\ k_F^\downarrow \approx 0.42\ \mathrm{A}^{\circ -1}$$
$$m^* \approx 0.4\ m_e$$

# Spin-dependent tunneling

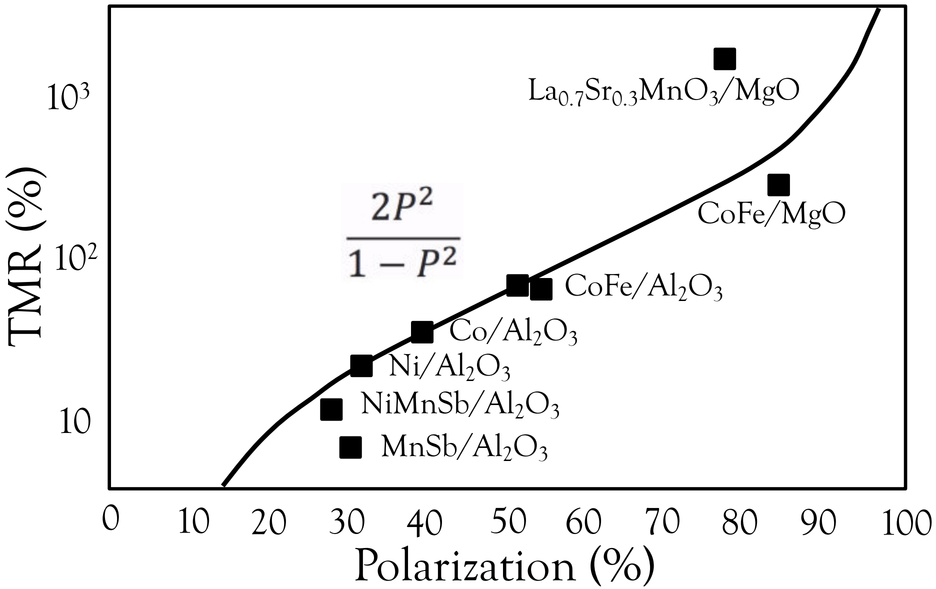
Jullière formula (see Tutorial!)

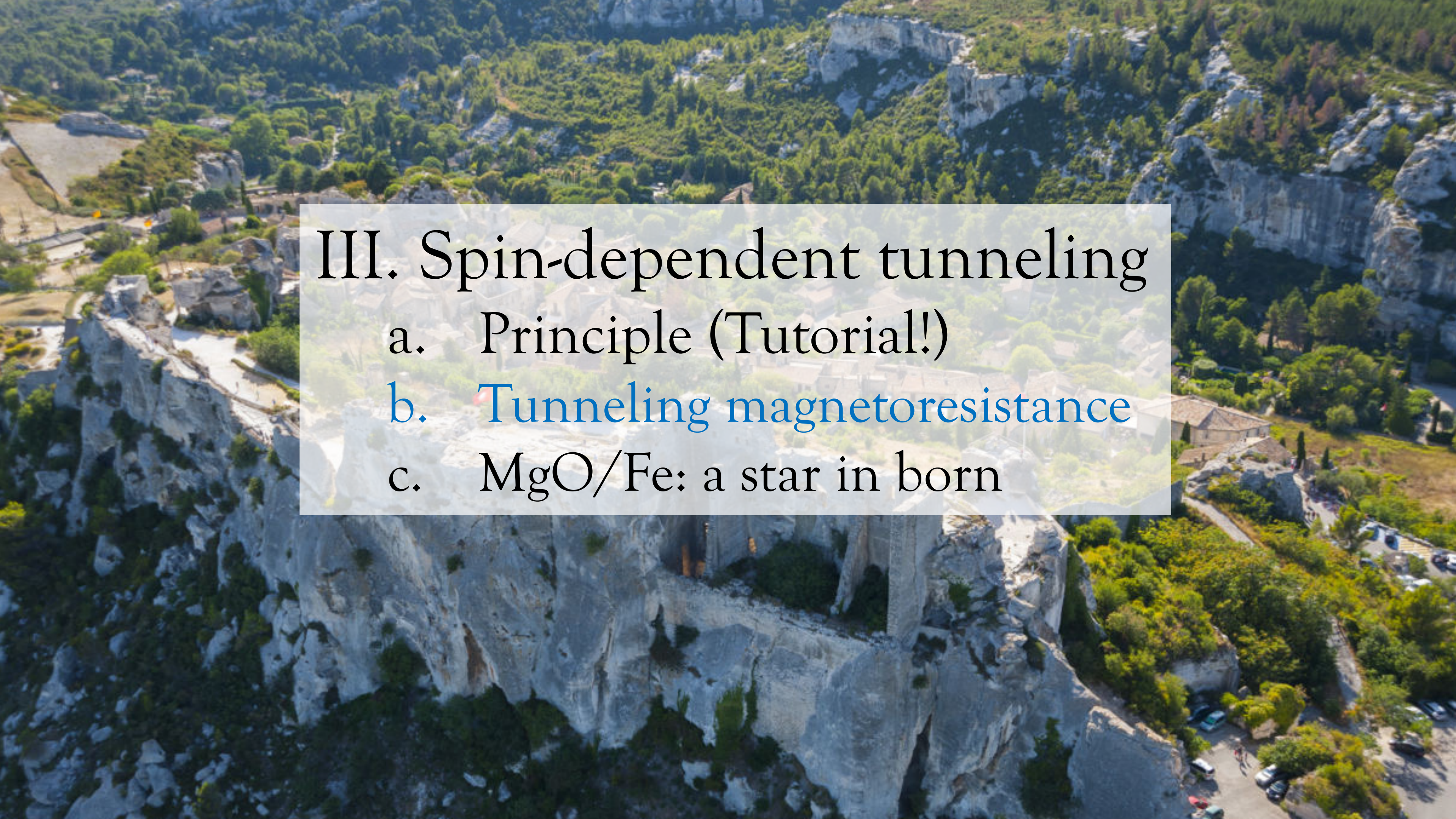
$$\frac{G_P - G_{AP}}{G_{AP}} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_L P_R}{1 - P_L P_R}$$

Data from Meservey, Parkin, Moodera




Data collected by H. Swagten





# III. Spin-dependent tunneling

a. Principle (Tutorial!)

b. Tunneling magnetoresistance

c. MgO/Fe: a star in born

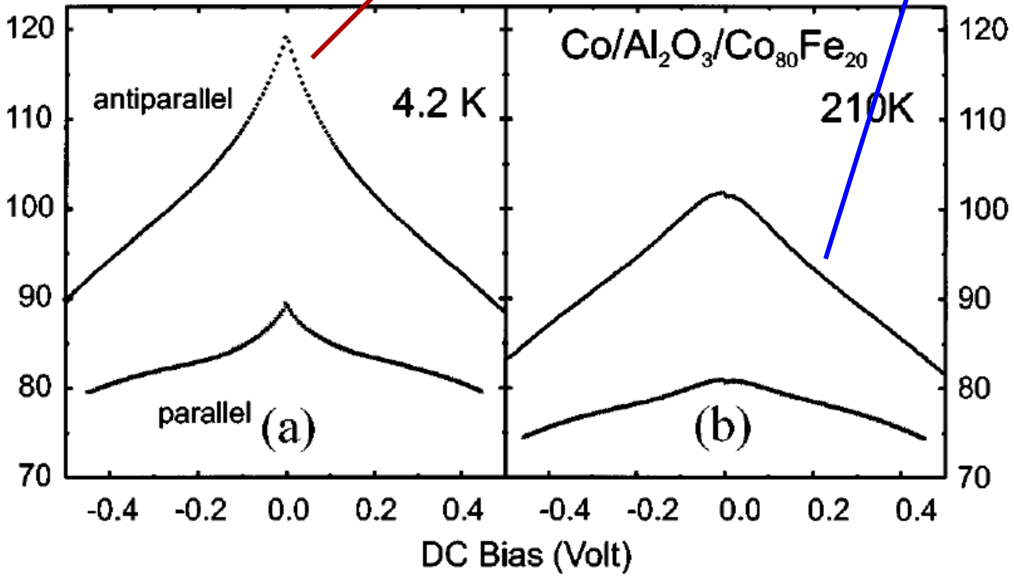
# Bias voltage of spin tunneling

Tunneling magnetoresistance has been studied with many barriers: AlOx, TaOx, MgOx, ZrOx etc.

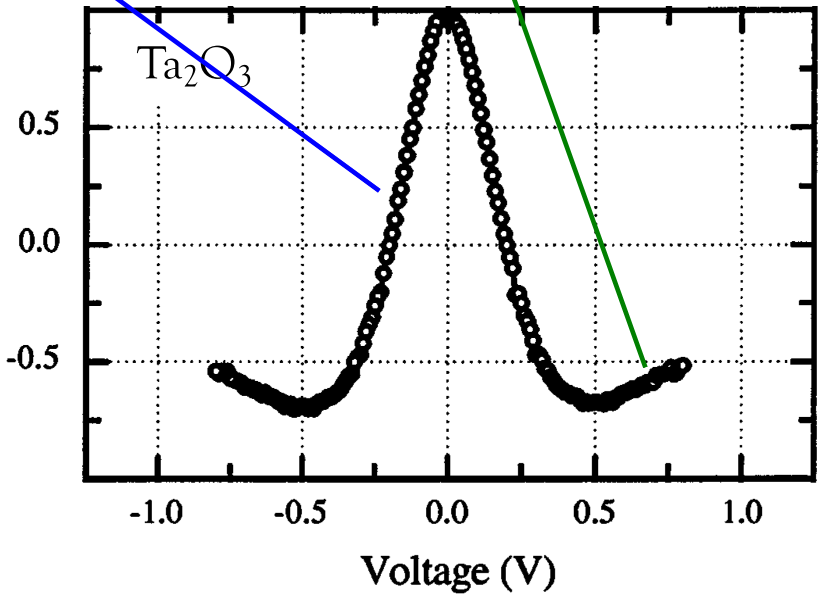
Zero-bias anomalous at low T

Systematic decrease of the TMR

Even sign reversal !



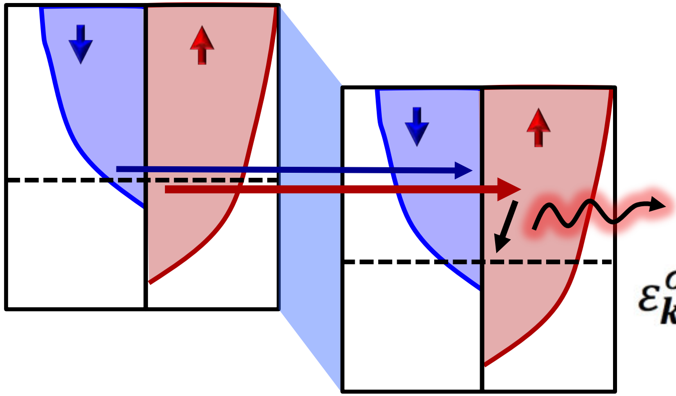

Zhang et al., Physical Review Letters 79, 3744 (1997)




Sharma et al., Physical Review Letters 82, 616 (1999)

# Spin-dependent tunneling

Hot electron tunneling: magnons and phonons

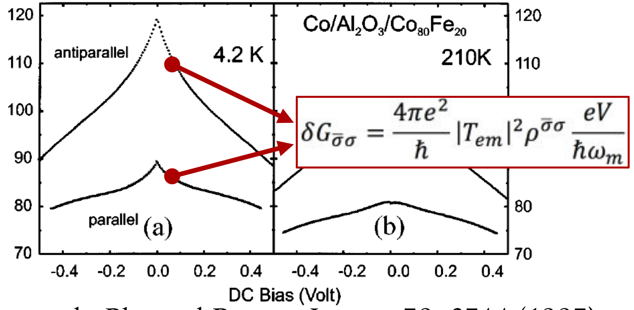


Phonon emission

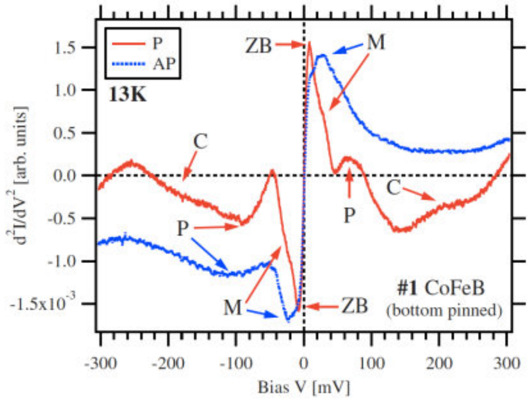
$$\varepsilon_{\boldsymbol{k}}^{\sigma} \rightarrow \varepsilon_{\boldsymbol{k-q}}^{\sigma} - \hbar\omega_{\boldsymbol{q}}$$

Magnon emission

$$\varepsilon_{\boldsymbol{k}}^{\downarrow} \rightarrow \varepsilon_{\boldsymbol{k-q}}^{\uparrow} - \hbar\omega_{\boldsymbol{q}}$$




Zhang et al., Physical Review Letters 79, 3744 (1997)




Drewello et al., Physical Review B 79, 174417 (2009)

# III. Spin-dependent tunneling

a. Principle (Tutorial!)

b. Tunneling magnetoresistance

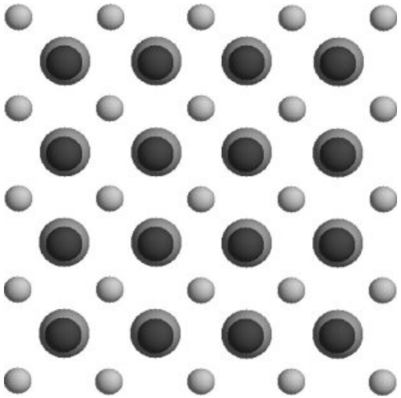
c. MgO/Fe: a star in born

# MgO/Fe interfaces

Why shall we expect remarkable tunneling magnetoresistance?

## Crystal structure

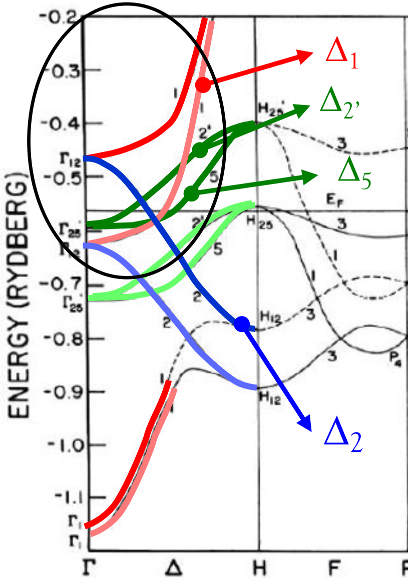
Fe and MgO have both bcc structure with very small lattice mismatch



Butler, Physical Review B 63, 054416 (2001)

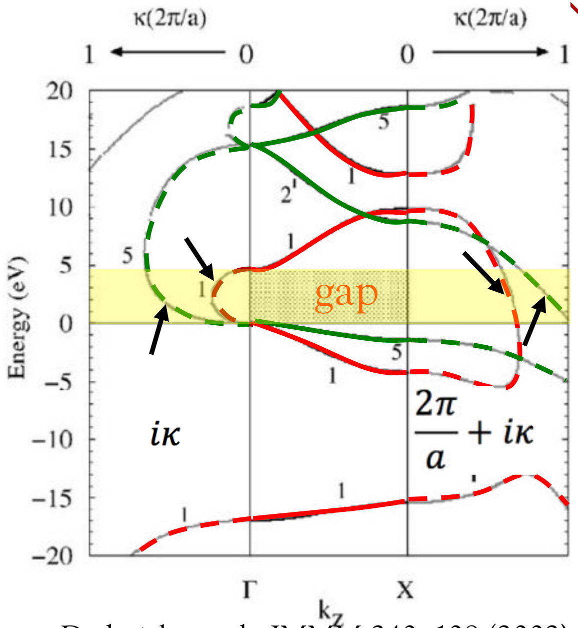
Their Bloch states adopt the same symmetries

## Fe band structure




Fe is a half metal for $\Delta_1$

## MgO complex band structure

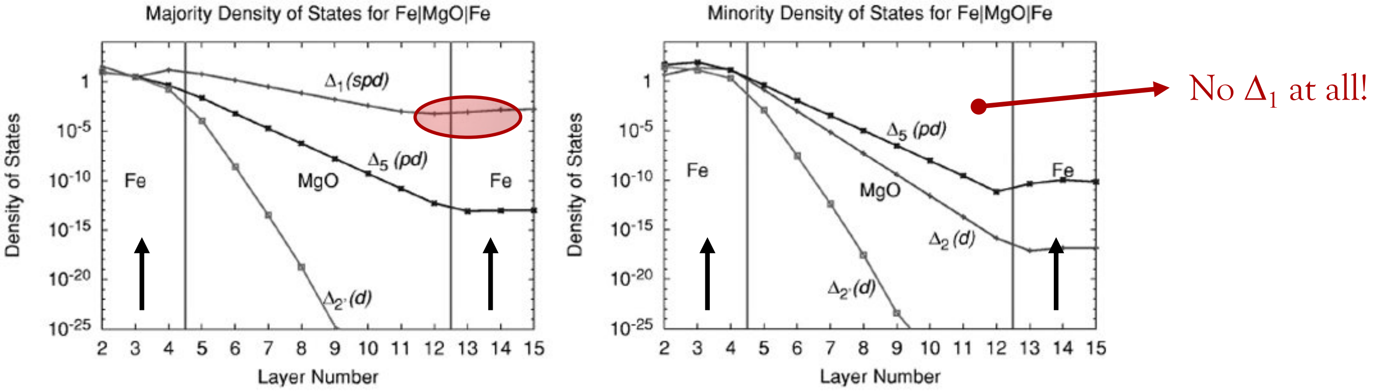



Dederichs et al., JMMM 240, 108 (2002)

MgO filters $\Delta_1$ Bloch states!

# MgO/Fe interfaces

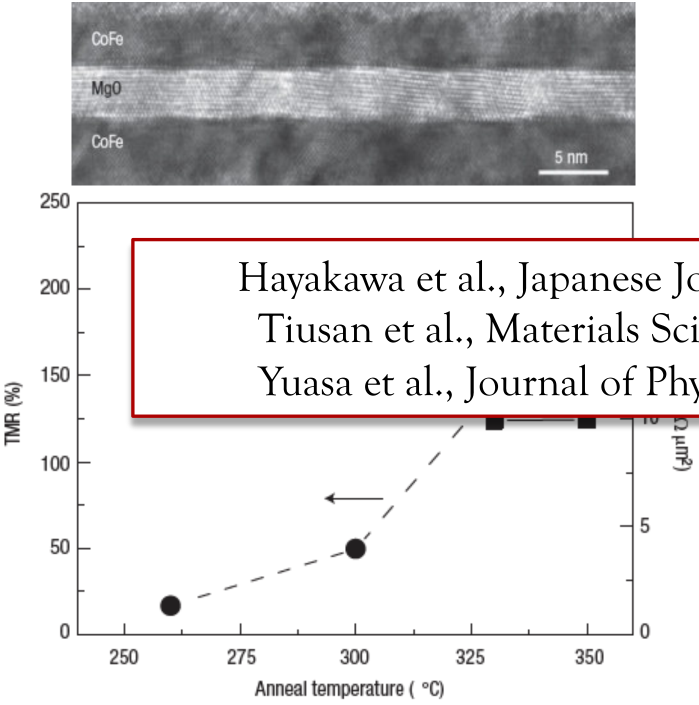
Bloch state filtering in Fe/MgO/Fe tunnel junction




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

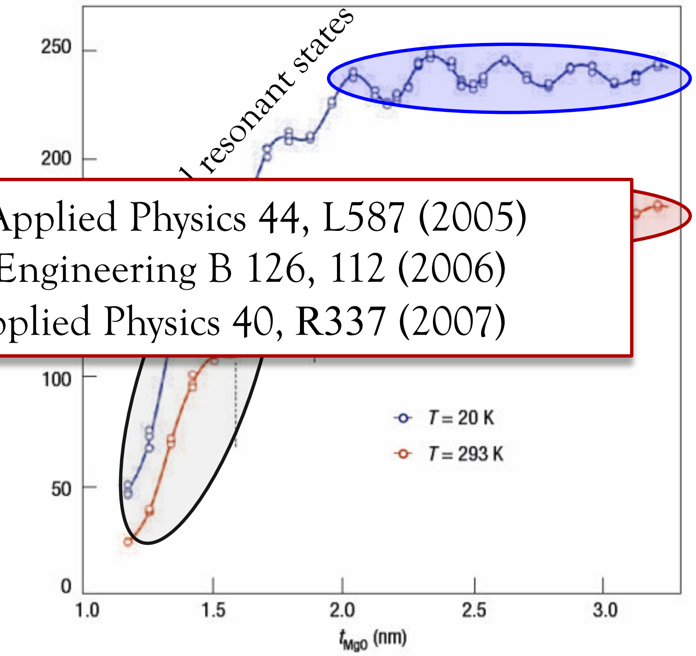
# MgO/Fe interfaces

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)

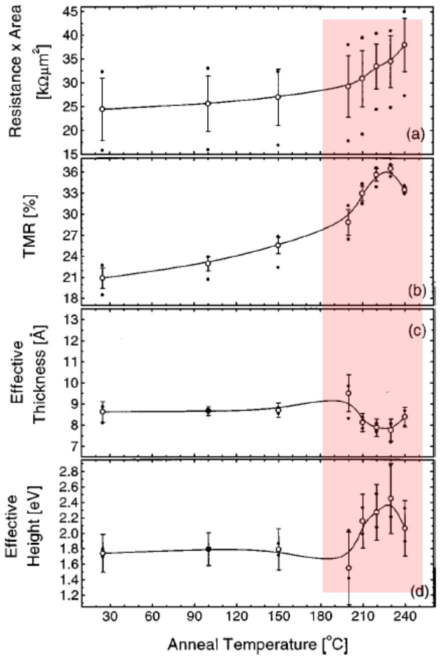
Hayakawa et al., Japanese Journal of Applied Physics 44, L587 (2005)
Tiusan et al., Materials Science and Engineering B 126, 112 (2006)
Yuasa et al., Journal of Physics D: Applied Physics 40, R337 (2007)

# Designing efficient magnetic tunnel junctions

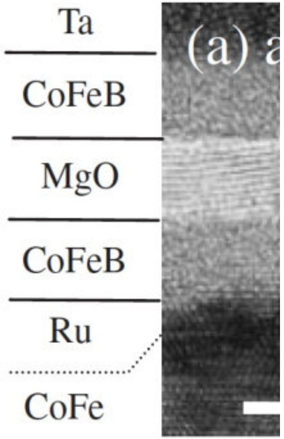
- High TMR (>100%)
- Low resistance-area ($\Omega.\mu m^2$)
- Optimal magnetic properties

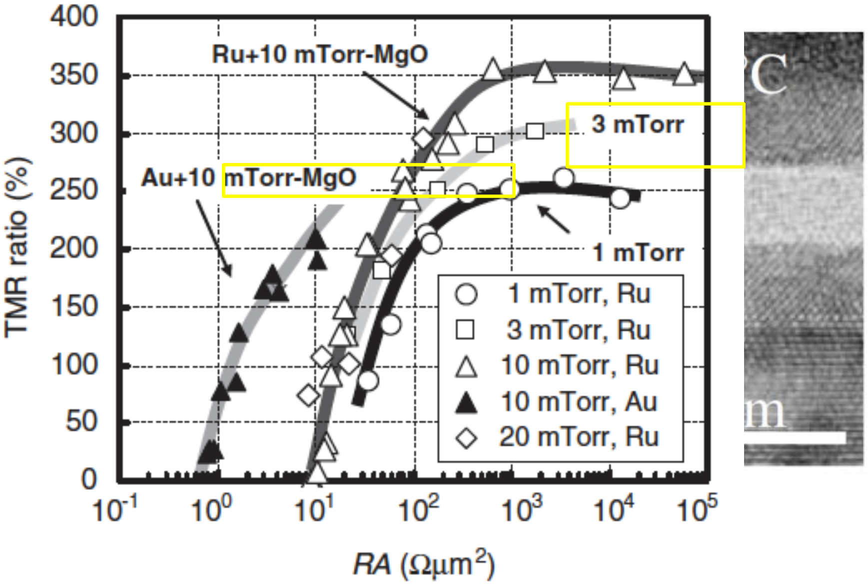
- Material growth (texture, roughness)
- Barrier quality (pinholes, defects)
- Atomic diffusion (Mn, Ru, B etc.)

$CoFe/Al_2O_3/CoFe$



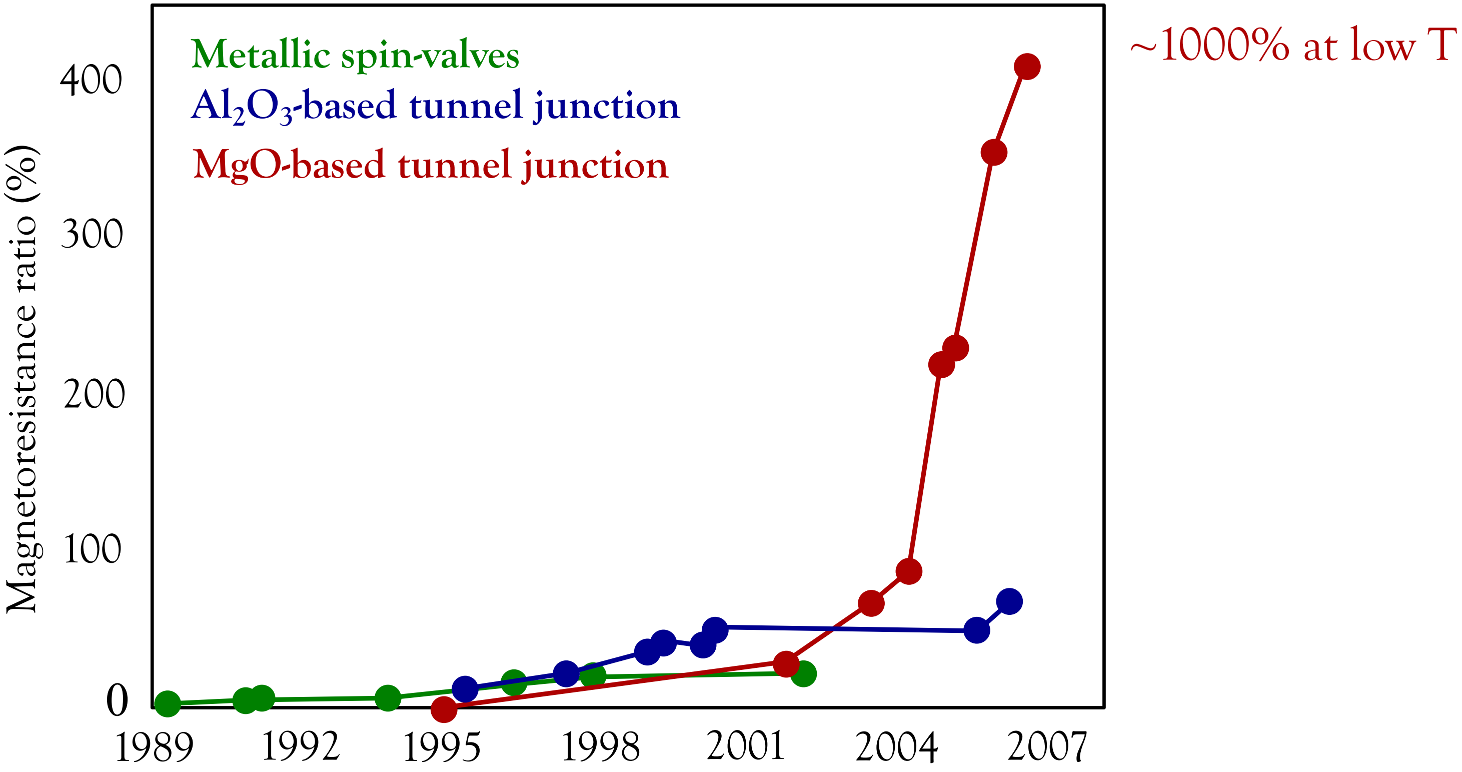

Sousa et al., Applied Physics Letters 73, 3288 (1998)




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

# Tunneling versus "giant" magnetoresistance




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

BONUS !


BONUS !

# A tale of spinning balls

# A tale of spinning balls

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New Journal of Physics
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## The spinning ball spiral

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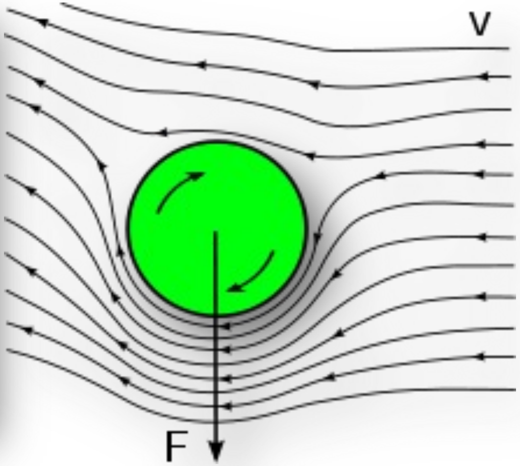
*New Journal of Physics* **12** (2010) 093004 (12pp)

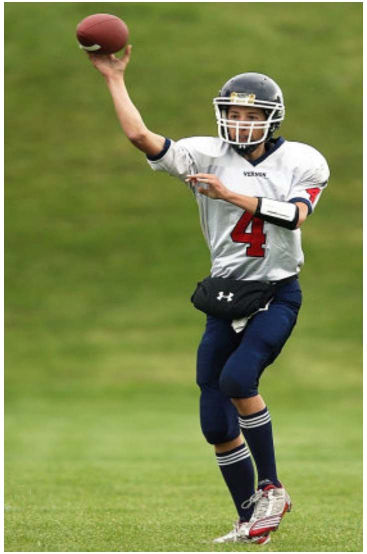
**Table 1.** Specifications for different sports. The first three sports are dominated by aerodynamic effects ($\mathcal{L} \ll U_0^2/g$). For the last two sports, gravity dominates aerodynamics ($\mathcal{L} \gg U_0^2/g$). In between, we identify sports for which both gravity and aerodynamics can be used to control the ball's trajectory. In this table, $L$ is the size of the field except for baseball, where it stands for the distance between the pitcher and the batter.

| Sport | $2R$ (cm) | $\rho_s/\rho$ | $U_0$ ($\mathrm{m\,s^{-1}}$) | $S = R\omega_0/U_0$ | $L$ (m) | $\mathcal{L}$ (m) | $U_0^2/g$ (m) | $d$ (m) |
|---|---|---|---|---|---|---|---|---|
| Table tennis | 4.0 | 67 | 50 | 0.36 | 2.7 | 9.3 | 255 | 1 |
| Golf | 4.2 | 967 | 90 | 0.09 | 200 | 141 | 826 | 7 |
| Tennis | 6.5 | 330 | 70 | 0.19 | 24 | 73 | 499 | 5 |
| Soccer | 21 | 74 | 30 | 0.21 | 100 | 54 | 92 | 7 |
| Baseball | 7.0 | 654 | 40 | 0.17 | 18 | 160 | 163 | 7 |
| Volleyball | 21 | 49 | 20 | 0.21 | 18 | 35 | 41 | 5 |
| Basketball | 24 | 72 | 10 | | 28 | 60 | 10 | |
| Handball | 19 | 108 | 20 | | 40 | 71 | 40 | |

# A tale of spinning balls

Heinrich Magnus
1802-1870





J.W.M. Bush, The aerodynamics of the beautiful game, 2013.
In *Sports Physics*, Ed. C. Clanet, Les Editions de l'Ecole Polytechnique, p.171-192.