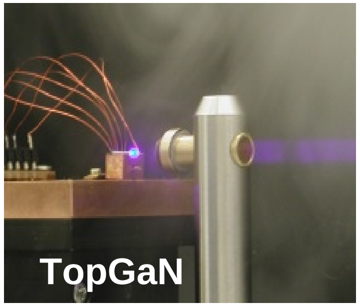
Spintronics -- materials aspect

Why to do not combine complementary resources of ferromagnets and semiconductors?



- **hybrid ferromagnetic-metal/semiconductor structures**

cf. B. Dieny

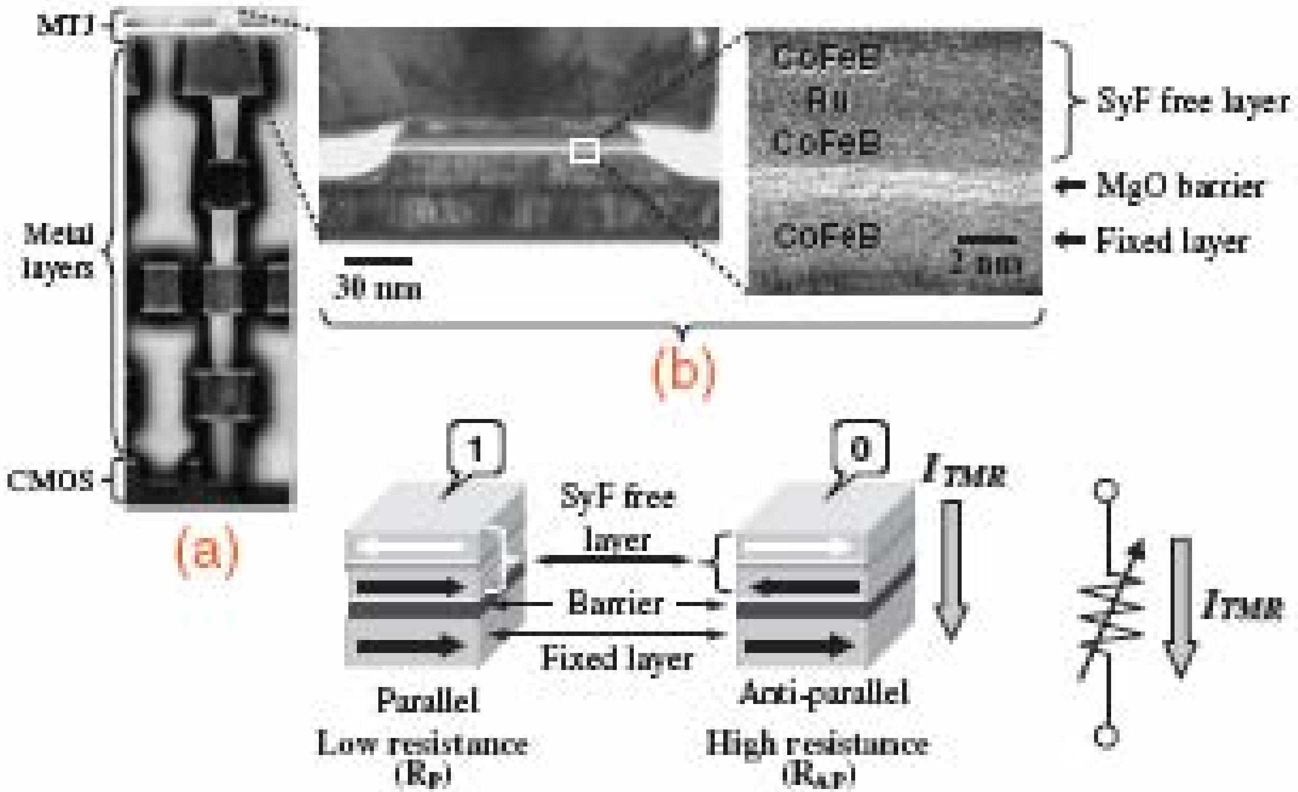
Hybrid structures – an example

low-power hybrid logic

(distributed non-volatile memory)

spintronics

electronics



Adder: 34 MOSs + 4 MTJs

S. Matsunaga et al.. (Tohoku) APEX'08

cf. B. Dieny

Spintronics -- materials aspect

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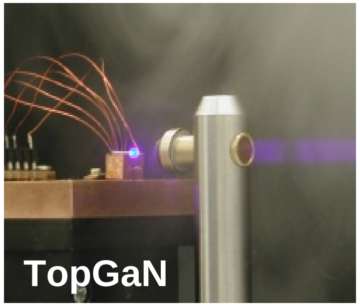


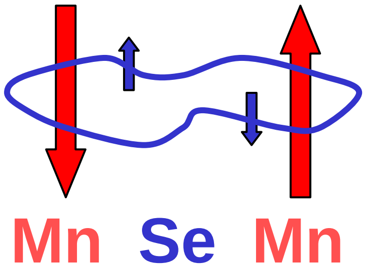
- **ferromagnetic semiconductors** – ***multifunctional materials***

Search for ferromagnetic semiconductors

- ***Antiferromagnetic*** **superexchange dominates in magnetic insulators and semiconductors**

➔ **no spontaneous magnetisation**

NiO, MnSe, EuTe, …



Search for ferromagnetic semiconductors

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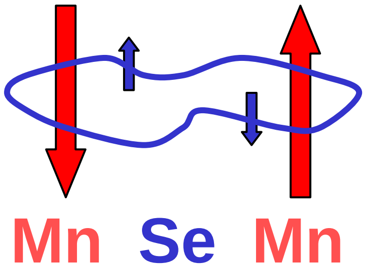
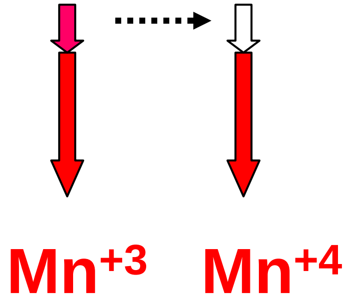
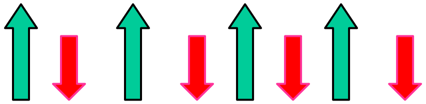


- **Exceptions**
  - **-- ferromagnetic superexchange dominates**
    EuO, $ZnCr_2Se_4$, … $T_C \approx 100$ K ***IBM, MIT, Tohoku, … '60-'70***
  - **-- double exchange (two charge states co-exist)**
    $LaMnO_3$ → $La_{1-x}Sr_xMnO_3$ (holes in d band)

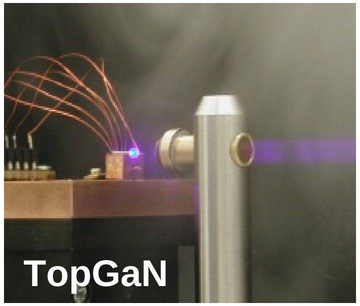


  - **-- ferrimagnets (two ions or two spin states co-exist)**
    Mn_4N, $NiO(Fe_2O_3)$, …



Spintronics -- materials aspect

Why to do not combine complementary resources of ferromagnets and semiconductors?



- **ferromagnetic semiconductors – *multifunctional materials***
  - **making good semiconductors of magnetic oxides**
  - **making good semiconductors magnetic**

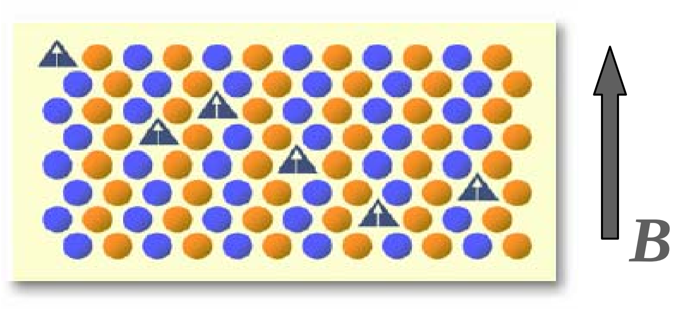
R.R. Gałązka et al. (Warsaw)'77- ; H. Ohno et al. (IBM, Tohoku) '89 -

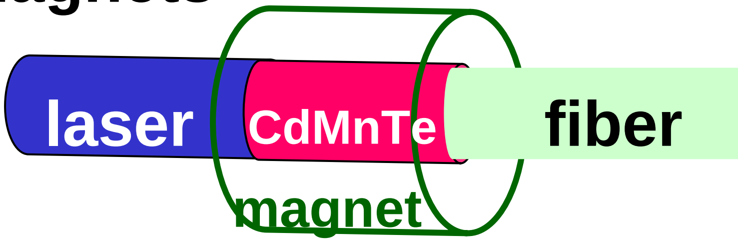
Making DMS ferromagnetic

- **Intrinsic DMS – random antiferromagnets**

$Cd_{1-x}Mn_xTe$

$Zn_{1-x}Co_xO$





optical isolator ***TOKIN***

Making DMS ferromagnetic

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$Cd_{1-x}Mn_xTe$

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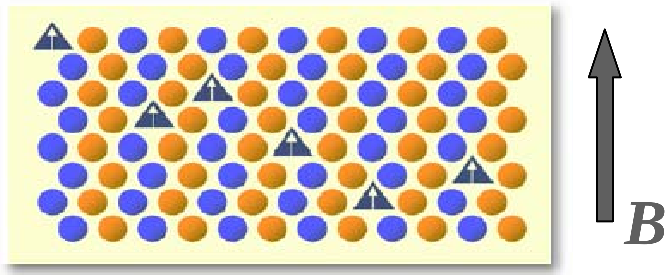
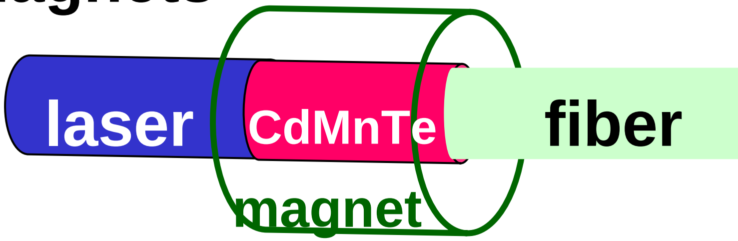




optical isolator ***TOKIN***

- **p⁺-type DMS - ferromagnets**

IV-VI: p-$Pb_{1-x-y-}Mn_xSn_yTe$ ***Story et al. (Warsaw, MIT) PRL'86***

p-$Ge_{1-x}Mn_xTe$ ***Lechner et al. (Linz)***

III-V: $In_{1-x-}Mn_xAs$ ***Ohno et al. (IBM) PRL'92***

$Ga_{1-x-}Mn_xAs$ ***Ohno et al. (Tohoku) APL'96*** **$T_C \approx$ 110 K for x = 0.05**

II-VI: $Cd_{1-x}Mn_xTe/Cd_{1-x-y}Zn_xMg_yTe$:N QW ***Haury et al.(Grenoble,Warsaw) PRL'97***

$Zn_{1-x}Mn_xTe$:N ***Ferrand et al. (Grenoble, Linz, Warsaw) Physica B'99, PRB'01***

quantum nanostructures and ferromagnetism combined

Transport in magnetic semiconductors and oxides

Lecture 4

Tomasz Dietl

1. Institute of Physics, Polish Academy of Sciences,
Laboratory for Cryogenic and Spintronic Research
2. Institute of Theoretical Physics, Warsaw University

support: ***FunDMS – ERC Advanced Grant***
SemiSpinNet **Maria Curie action**
SPINTRA – ESF; Humboldt Foundation

Dual character of description of carriers in solids

I. *Carriers reside in c/v band*

-- Boltzmann conductivity:

$1/\tau = 1/\tau_{ii} + 1/\tau_{ph}(T) + \ldots$

$\sigma(T) \rightarrow \sigma_o > 0$; $\rho(T) \rightarrow \rho_o < \infty$ for $T \rightarrow 0$

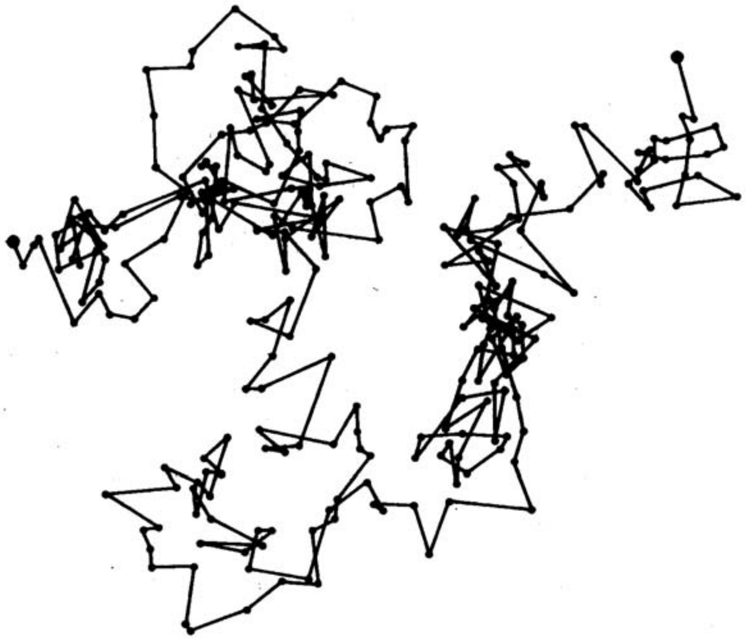
-- dielectric function

$\varepsilon(q) \rightarrow \infty$ for $q \rightarrow 0$

-- electron-electron interaction

unimportant

-- ….



II. Carriers reside on impurities

-- phonon-assisted hopping

$\sigma(T) \rightarrow 0$; $\rho(T) \rightarrow \infty$ for $T \rightarrow 0$

-- dielectric function

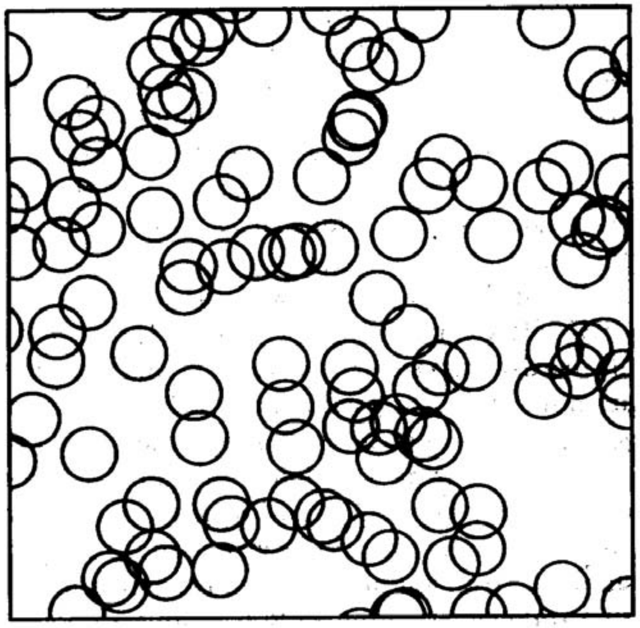
$\varepsilon(q) \rightarrow \varepsilon_s < \infty$ for $q \rightarrow 0$

-- electron-electron

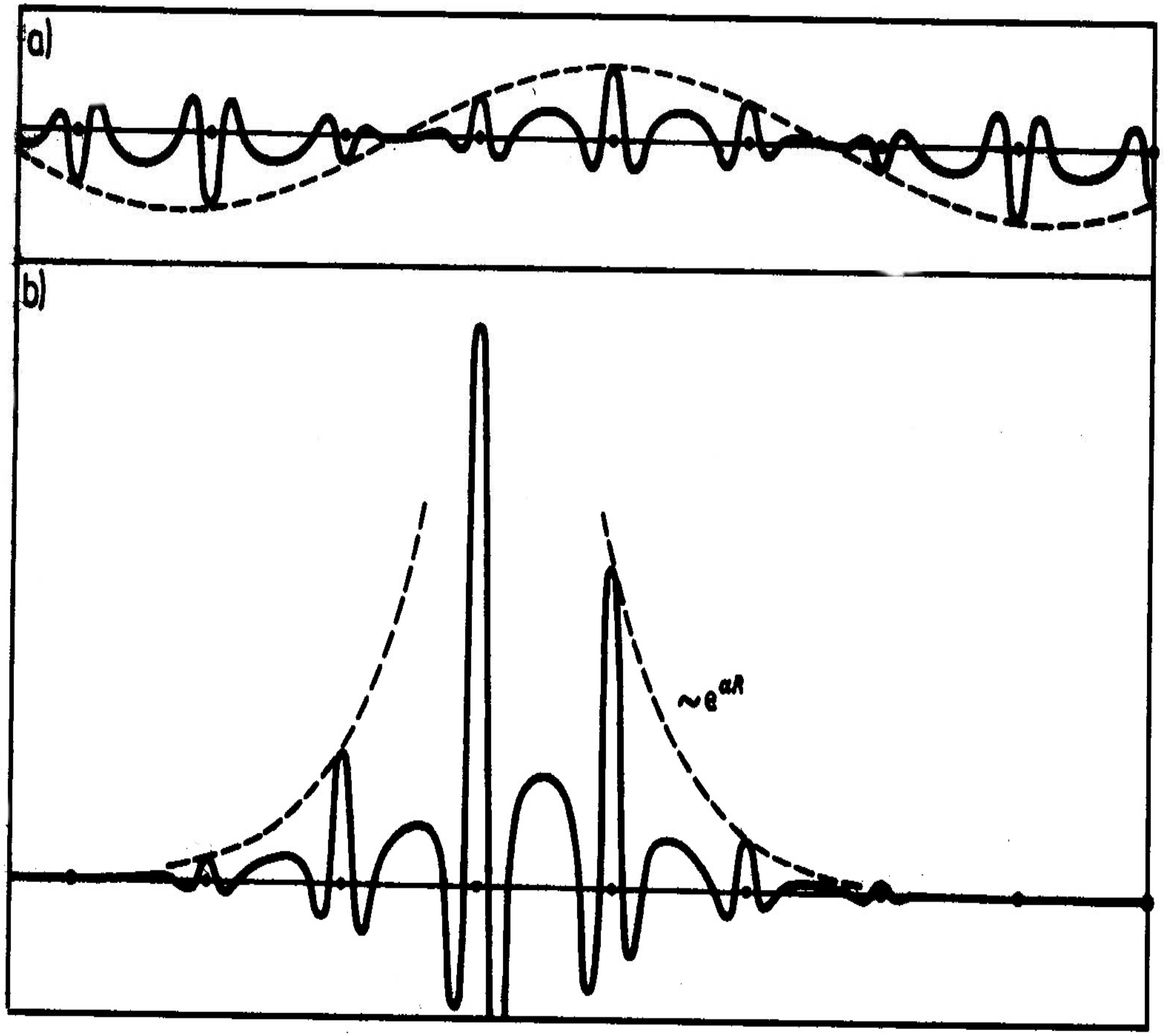
interaction important

(Coulomb gap in DOS, …)

-- ….



Extended vs. localized states



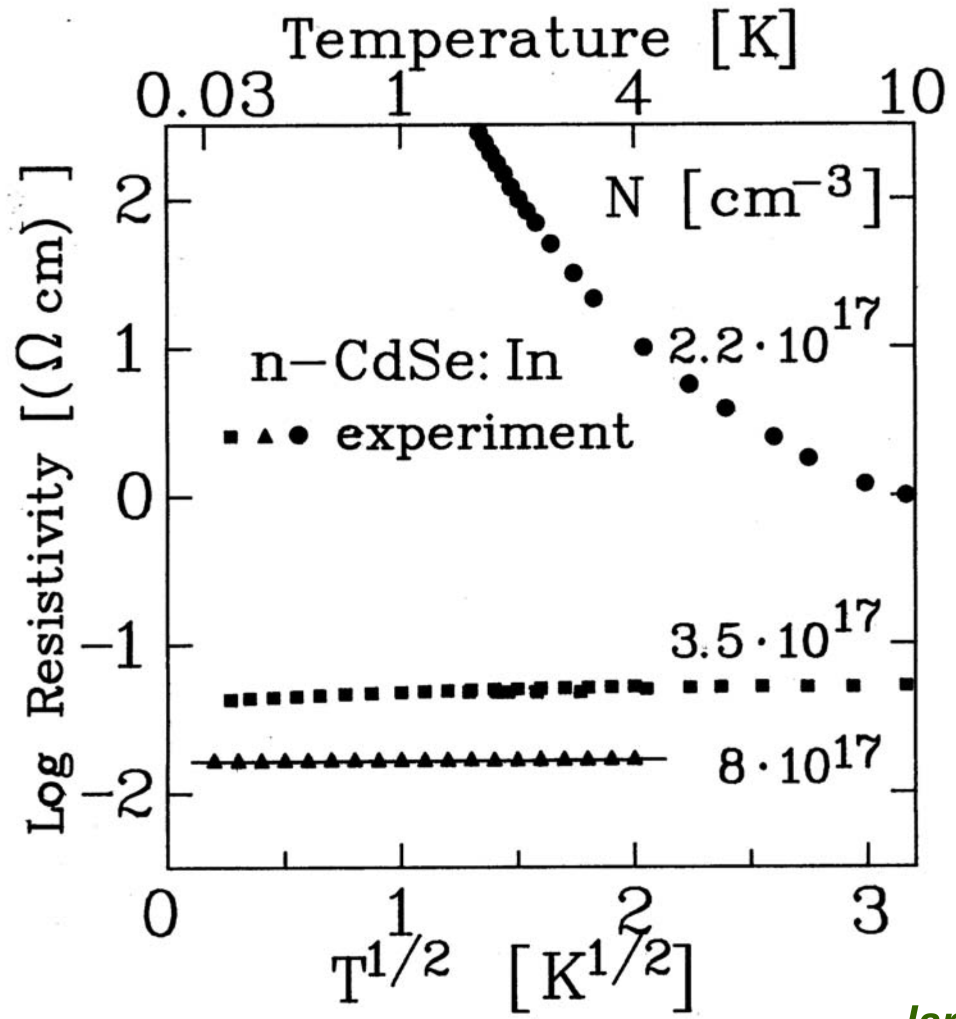
Sensitive to boundary conditions

Insensitive to boundary conditions

Examples of metal-insulator transition (MIT)

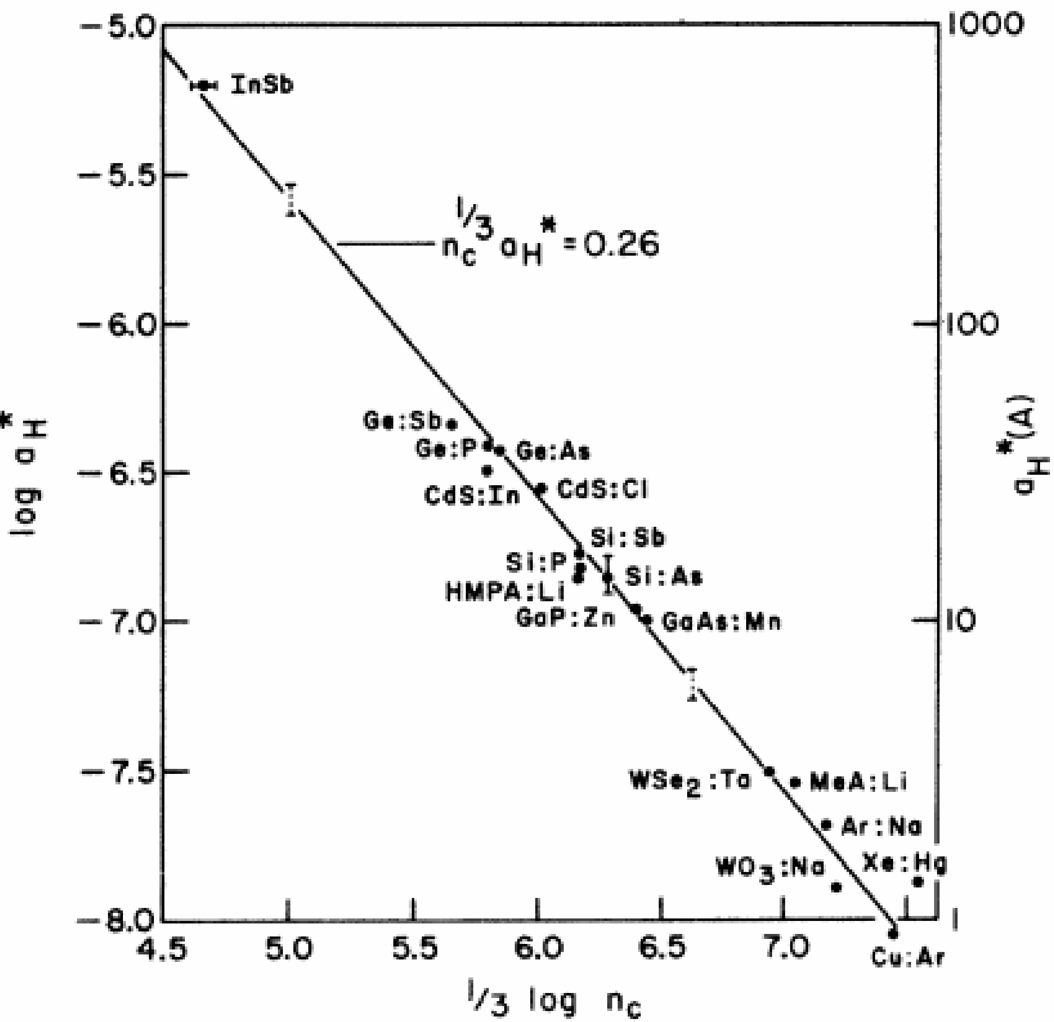
cf. J. Spałek

MIT in doped semiconductors



Jaroszynski … T.D..'83

MIT in various materials



Edwards, Sienko (Cornell) PRB'78

MIT occurs for: $n_c^{*1/3} a_B \approx 0.25$

$r_s/a_B^* = [3/(4\pi n_c)^{1/3}]/a_B \approx 2.5$

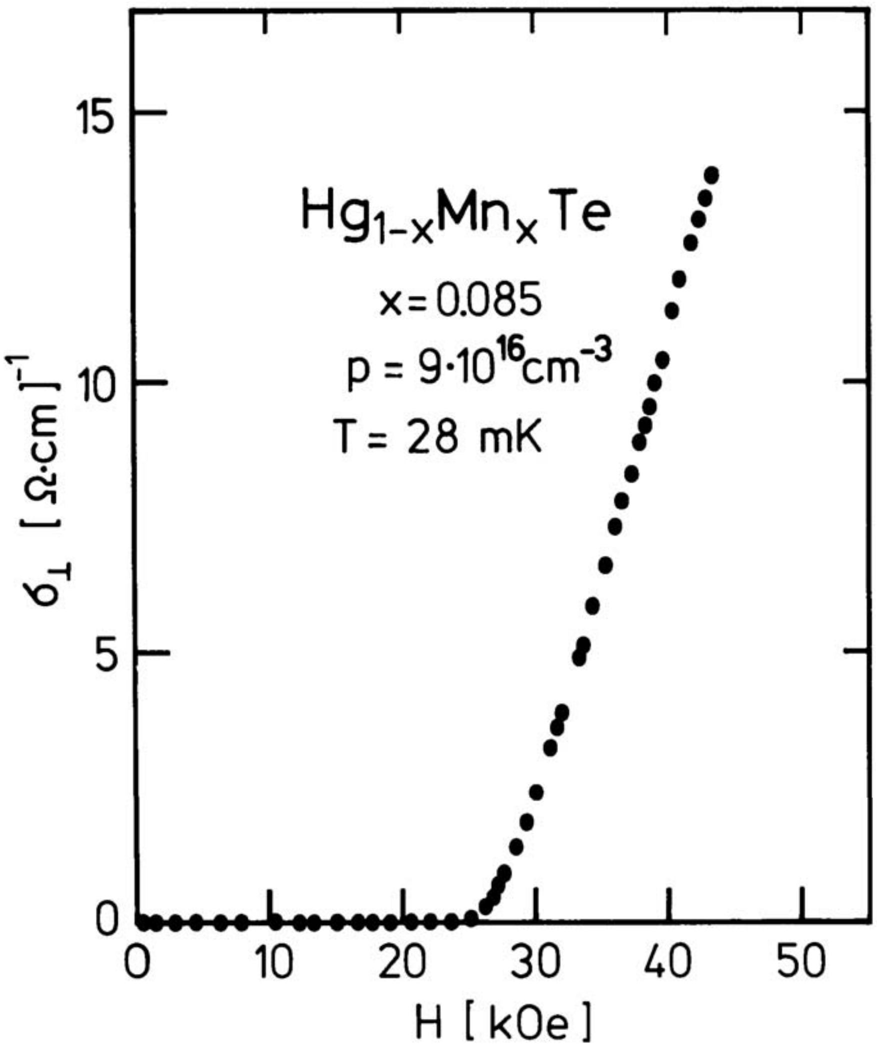
For hydrogenic-like donors:

$a_B^* = a_B\, \varepsilon_s/(m^*/m_o)$

More general:

$a_B^* = \hbar/(2E_I m^*)^{1/2}$

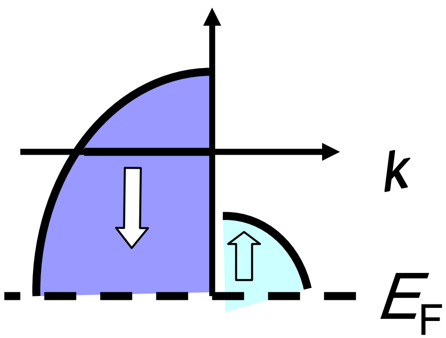
MIT in p-(Hg,Mn)Te -- disorder (scattering by Mn spins) reduced by the magnetic field

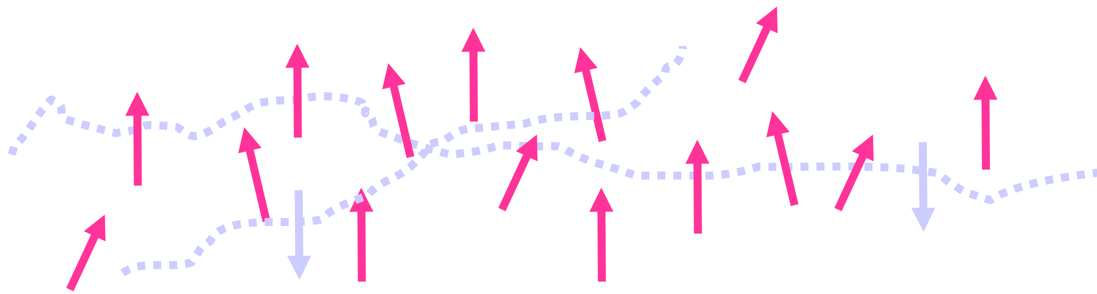


Wojtowicz … TD
PRL'86

Spin/charge transport on the metallic side of the Anderson-Mott MIT

p-d Zener model of hole-mediated ferromagnetism in DMS



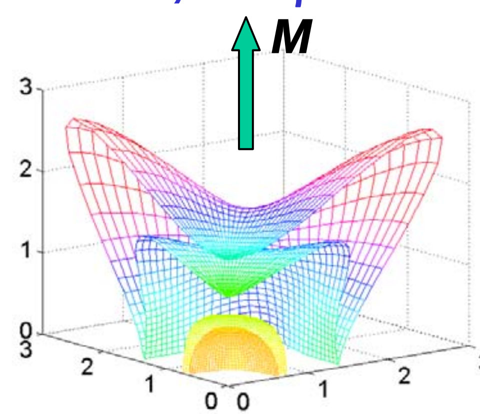


Driving force:

lowering of the hole energy due to redistribution between hole spin subbands split by p-d exchange interaction, $\Delta \sim \beta M$

Essential ingredient:

Complexity of the valence band structure has to be taken into account



No adjustable parameters

$T_C \sim \beta^2 \rho^{(s)}_{DOS}$

T.D. et al.,'97-
MacDonald et al. (Austin/Prague) '99-

p-d Zener model + Luttinger-Kohn *kp* theory of carrier-mediated ferromagnetism in DMS

- **p-d Zener model + 6x6 (or 8x8) *kp* theory describes *quantitatively* or *semi-quantitatively*:**

  -- thermodynamic [T_C, $M(T,H)$]

  -- micromagnetic

  (magnetic anisotropy, magnetic stiffness, magnetic domains)

  -- dc and ac charge and spin transport

  (AHE, AMR, PHE, $\sigma(\omega)$, ESR)

  -- optical properties (MCD)

  Warsaw/Tohoku 1999-, Austin/Prague 2001-

  → **bases for magnetization manipulation**

  Tohoku/ Warsaw/Grenoble/Wuerzburg/Orsay/Hitachi/Prague

a recent example

Vol 455 | 25 September 2008 | doi:10.1038/nature07318 nature

Magnetization vector manipulation by electric fields

D. Chiba[1,2], M. Sawicki[2,3], Y. Nishitani[2], Y. Nakatani[4], F. Matsukura[2,1] & H. Ohno[2,1]

[1]Semiconductor Spintronics Project, Exploratory Research for Advanced Technology, Japan Science and Technology Agency, Sanban-cho 5, Chiyoda-ku, Tokyo 102-0075, Japan. [2]Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan. [3]Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02668, Warszawa, Poland. [4]University of Electro-communications, Chofugaoka 1-5-1, Chofu, Tokyo 182-8585, Japan.

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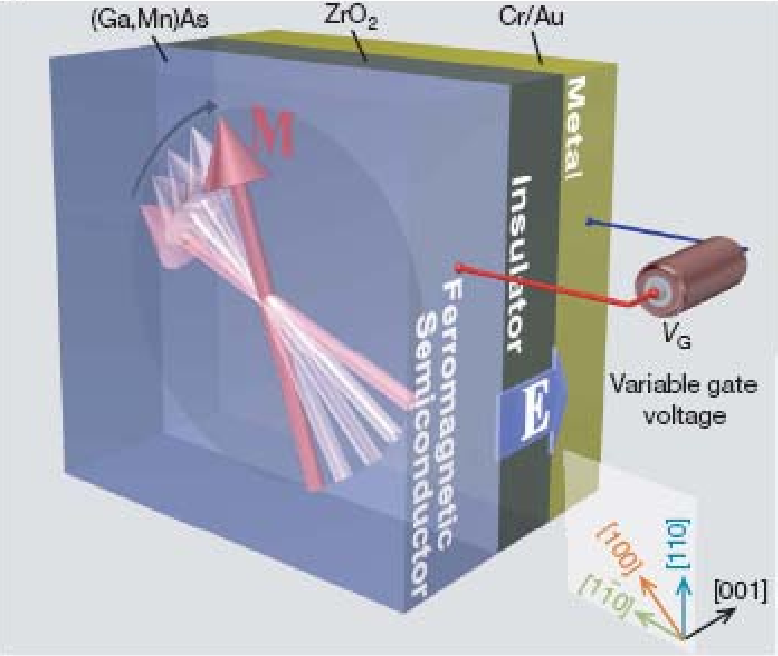
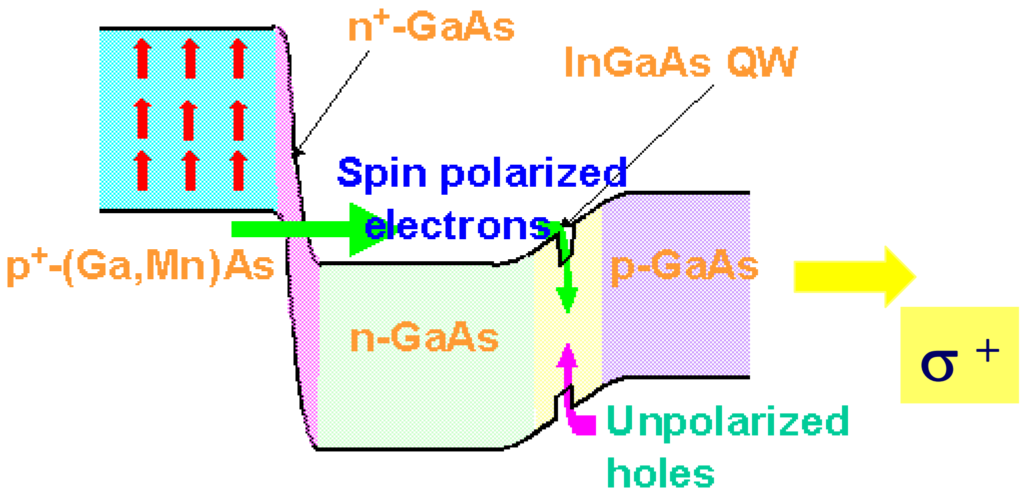


Spin Esaki-Zener Diode

How to change *spin polarization of holes* into *spin polarized electrons*

Spin Esaki-Zener diode



Recent experimental results:

Polarization of electrons P_j up to 70%

Tohoku, St. Barbara, IMEC, Regensburg,...

Description of spin transport effects in ferromagnetic structures

- two spin channels characterized by $f_\uparrow$ and $f_\downarrow$

-- spin diffusion equation

-- continuity conditions

-- boundary conditions

Aronov et al. ’76-- ; Silsbee et al. ’80-- ; Fert et al. ’93-- , Schmidt et al. ’00—

cf. B. Dieny

spin accumulation, resistance mismatch, ...

Description of spin transport effects in ferromagnetic structures

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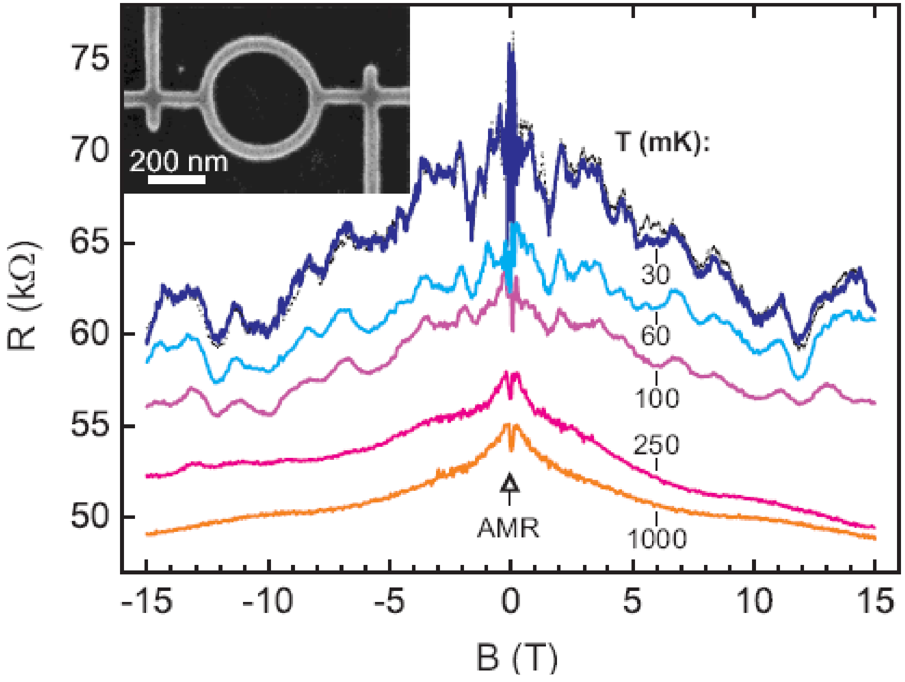
cf. B. Dieny

➔ **spin accumulation, resistance mismatch, ...**

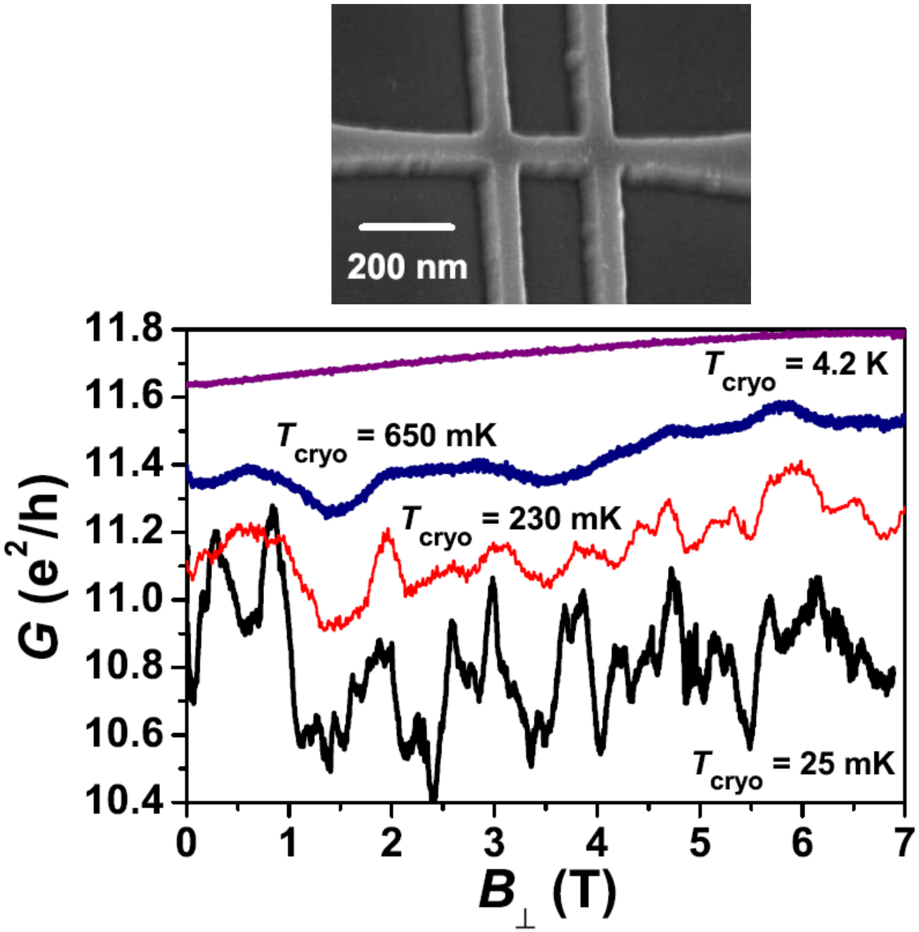
-- Implicit assumption: $L_s \gg L_\varphi$

is it valid in (Ga,Mn)As?

(Ga,Mn)As: universal conductance fluctuations



Wagner et al. (Regensburg) PRL'06



Vila et al. (Marcoussis, Grenoble) PRL'07

$L_\varphi(T) \approx$ 100 nm at 4 K from WLR and UCF

Description of spin transport in modulated structures of (Ga,Mn)As

- **in (Ga,Mn)As type materials:**

  -- four channels strongly mixed by spin-orbit interaction

  $L_s \leq L_\varphi(T) \approx$ 30 nm at 4 K from WLR and UCF

Description of spin transport in modulated structures of (Ga,Mn)As

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$$L_s \leq L_\varphi(T) \approx 30 \text{ nm at 4 K from WLR and UCF}$$

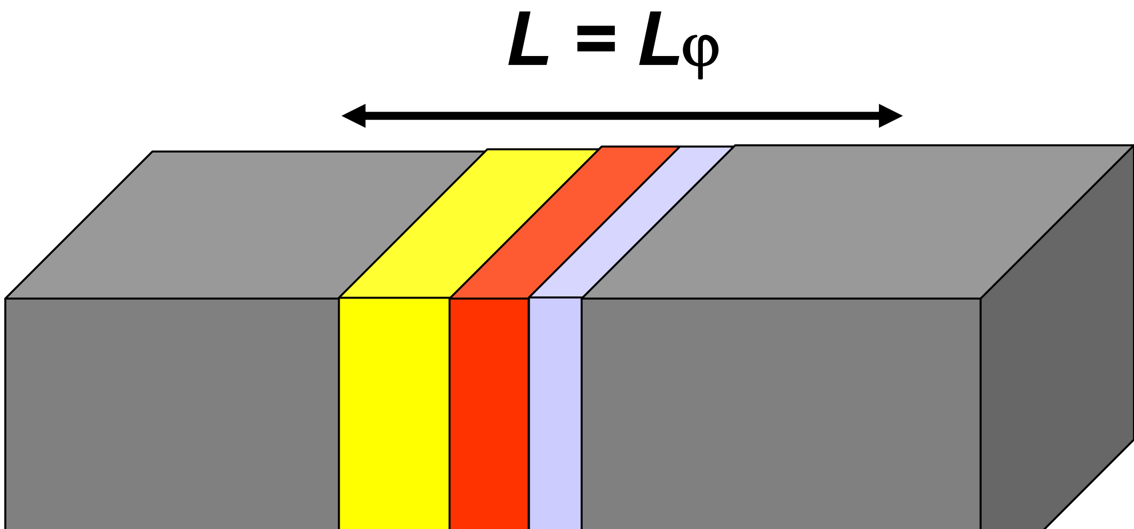
➔ quantum Landauer-Buettiker formalism

implementation for semiconductor layered structures, see A. Di Carlo, SST'03

-- uniform and infinite in 2D (k_x, k_y good quantum numbers)

-- modulation in 1D

-- simulation length $L \approx L_\varphi$



Description of semiconductor band structure

kp **method:** RTD *Petukhov et al., PRL'02*

TMR *Brey, APL'04, Jeffres '06*

DWR *Nguyen et al., PRL'06*

Description of semiconductor band structure

***kp* method:** RTD *Petukhov et al., PRL'02*
TMR *Brey, APL'04, Jeffres '06*
DWR *Nguyen et al., PRL'06*

Standard *kp* formalism disregards effects important for spin transport and spin tunneling:

- Rashba and Dresselhaus terms
- spin filtering at interfaces cf. Fe/MgO *cf. A. Bonanni*
- spin-mixing conductance *Brataas et al. '01*
- band extrema away from the center of the Brillouin zone

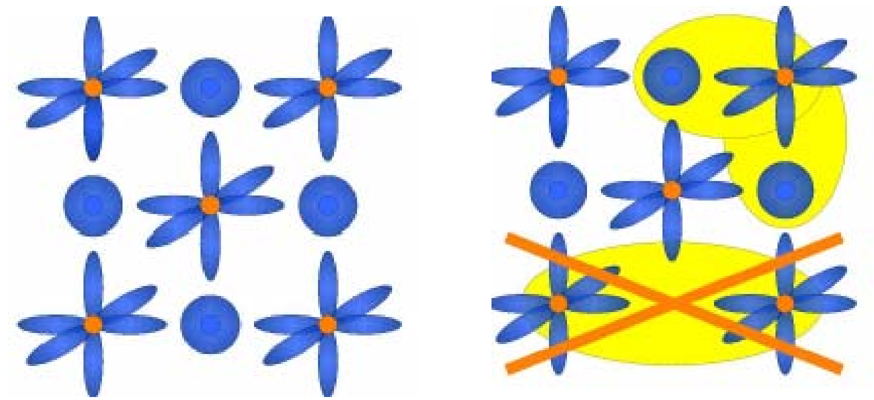
These can be taken into account within empirical tight-binding approach

Tight-binding model

GaAs: $sp^3d^5s^*$:

- nn coupling
- Ga and As atoms: 20 orbitals
- parametrization:

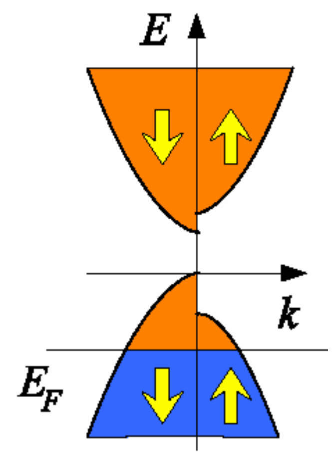
M.-J. Jancu et al., PRB'98



(Ga,Mn)As: GaAs + spin splitting

- VCA, MFA
- $\Delta_c = \alpha N_o x\langle S_z\rangle$, $\Delta_v = \beta N_o x\langle S_z\rangle$,

  $\alpha N_o = 0.2$ eV, $\beta N_o = -1.2$ eV



no adjustable parameters

Landauer-Büttiker + tight-binding model for (Ga,Mn)As-based structures -- summary

- The model describes
  - -- magnitude and anisotropy of P_j and TMR
  - -- decay of P_j and TMR with V
  - -- crystalline anisotropy of P_j and TMR

  P. Sankowski… T.D., PRB'05, 07

- LLG eq. + adiabatic spin torque describes:
  - -- current-induced domain-wall velocity

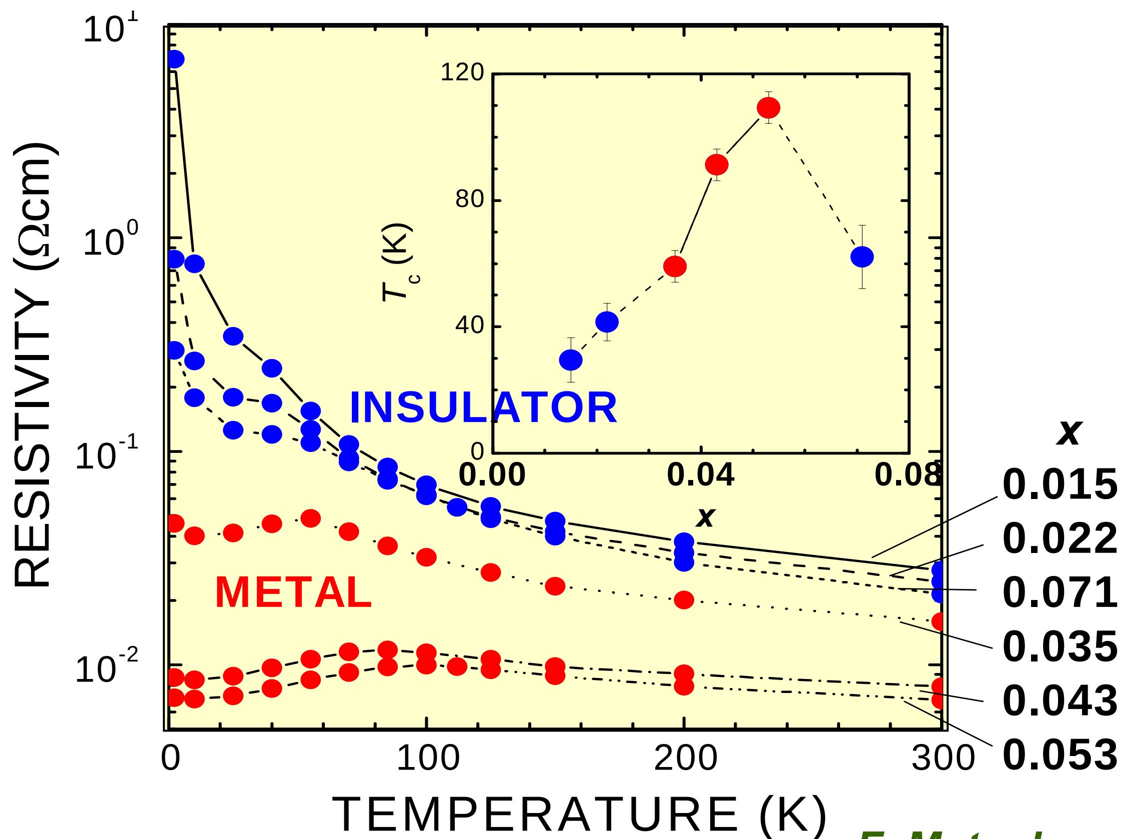
  D. Chiba… T.D. … PRL'06

- The model does *not* describe:
  - -- domain-wall resistance → disorder essential

  R. Oszwaldowski … T.D. PRB'06

Spin/charge transport near the Anderson-Mott MIT

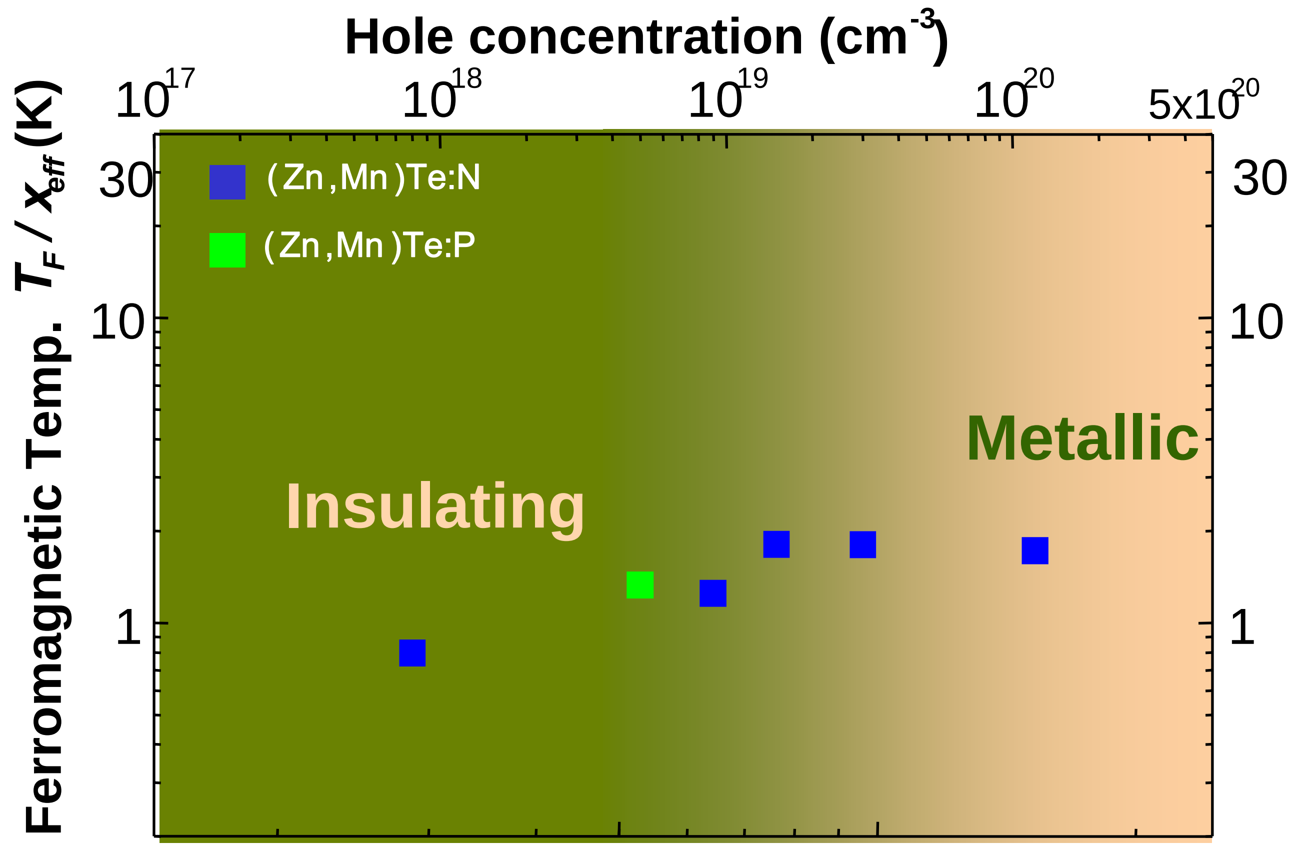
$Ga_{1-x}Mn_xAs$: resistance vs. temperature and Curie temperature vs. x



F. Matsukura et al. (Tohoku) PRB'98

- **ferromagnetism on both sides of metal-insulator transitions**
- **ferromagnetism disappears in the absence of holes**

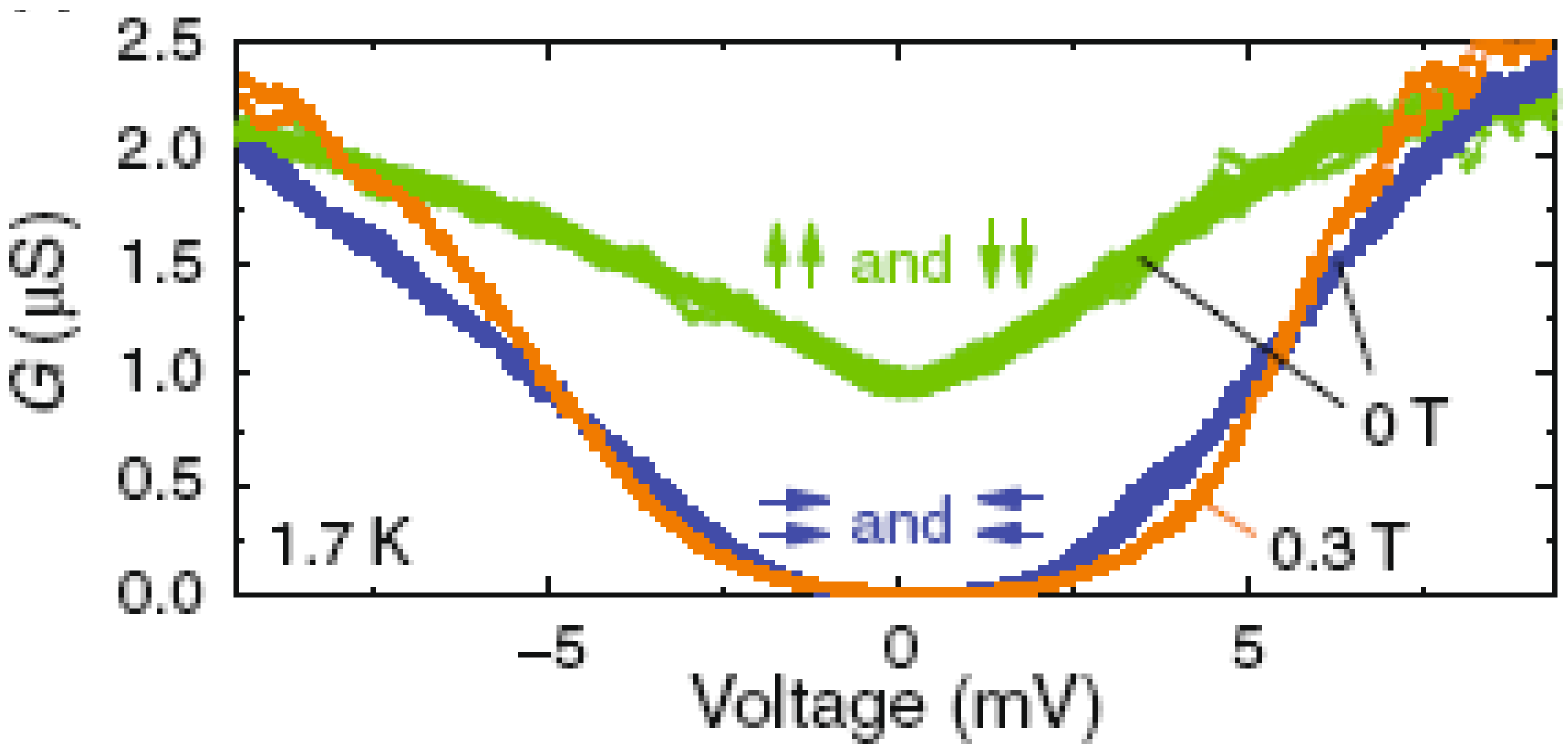
Ferromagnetic temperature in p-(Zn,Mn)Te



- **ferromagnetism disappears in the absence of holes**
- **ferromagnetism on both sides of metal-insulator transition**

D. Ferrand et al. (Grenoble, Warsaw) PRB'01
M. Sawicki et al. (Warsaw) pss'02

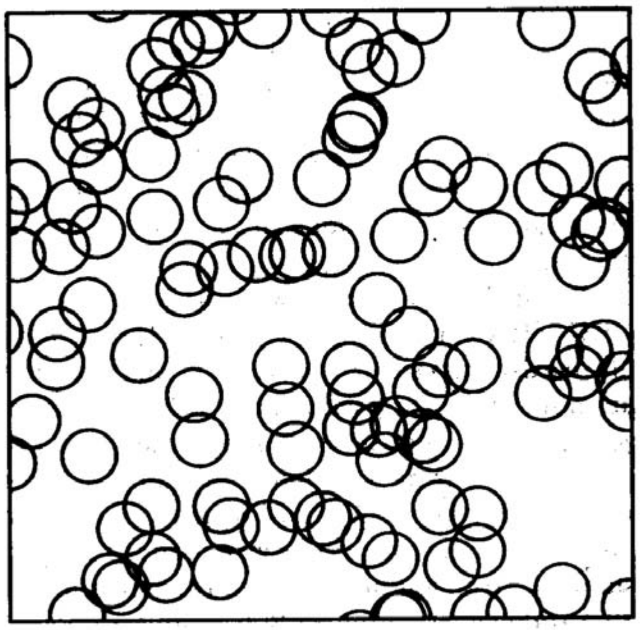
Conductance vs. bias in a TMR structure of (Ga,Mn)As - evidence for a Coulomb gap and TAMR

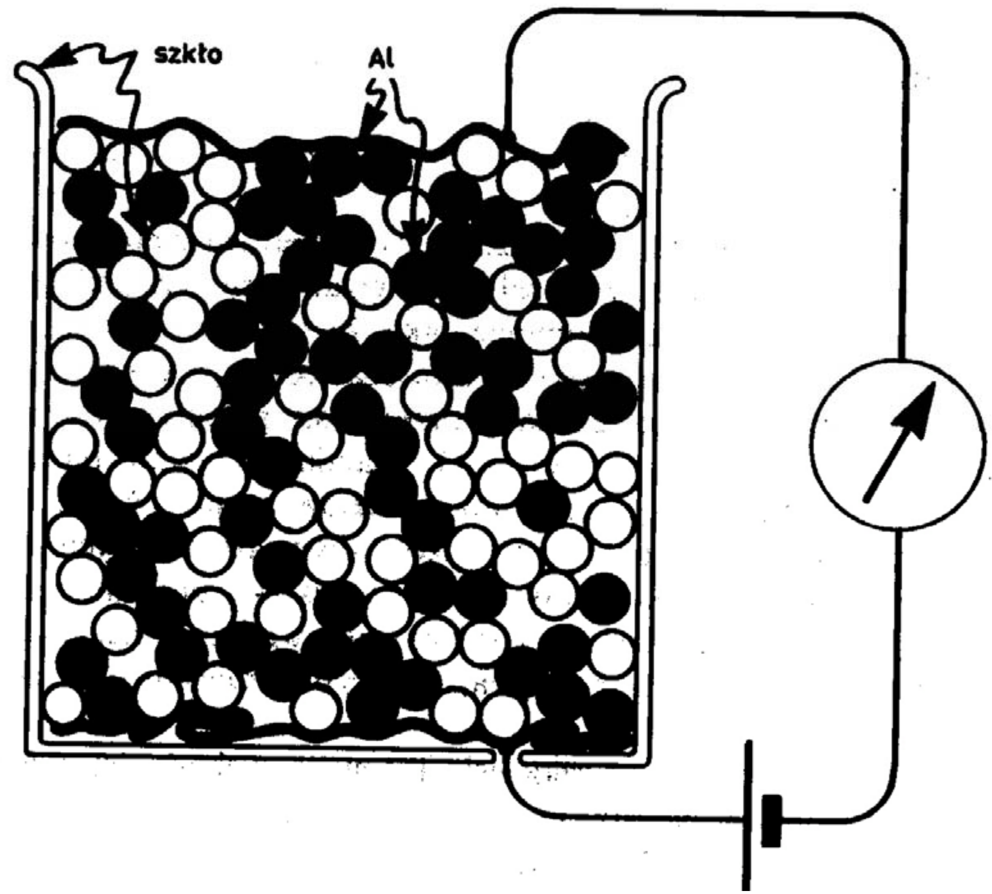


Pappert et al. (Wuerzburg) PRL'06

(Classical) percolation theory of MIT

Conductive/nonconductive composites



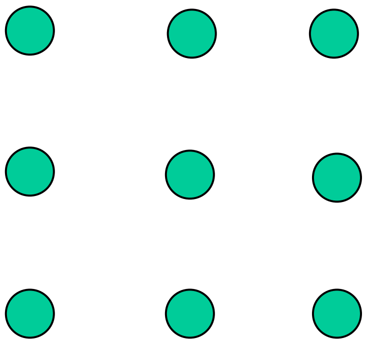


(Quantum) Anderson localization

Particle/wave propagation in solids

Crystals

(periodic potential)

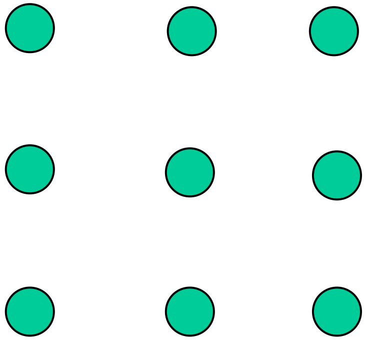


Classical particles: channeling

(e.g., Rutherford back scattering of α particles)

Particle/wave propagation in solids

Crystals
(periodic potential)

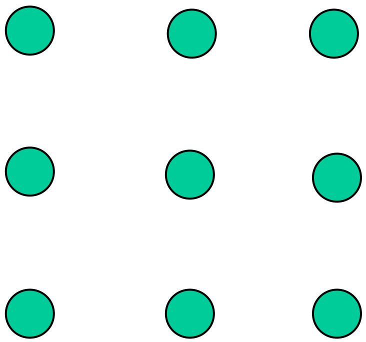


Classical particles: channeling
(e.g., Rutherford back scattering of α particles)

Quantum particles: (electrons, photons,...)
Energy bands: quasi-free (ballistic) propagation
Energy gaps: regions of evanescent waves

Particle/wave propagation in solids

Crystals
(periodic potential)



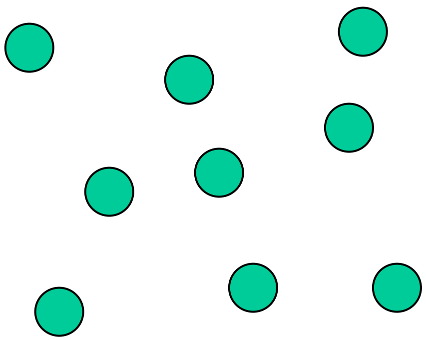
Classical particles: channeling
(e.g., Rutherford back scattering of α particles)

Quantum particles: (electrons, photons,...)
Energy bands: quasi-free (ballistic) propagation
Energy gaps: regions of evanescent waves

Disordered solids

Classical particles:
diffusion above percolation threshold

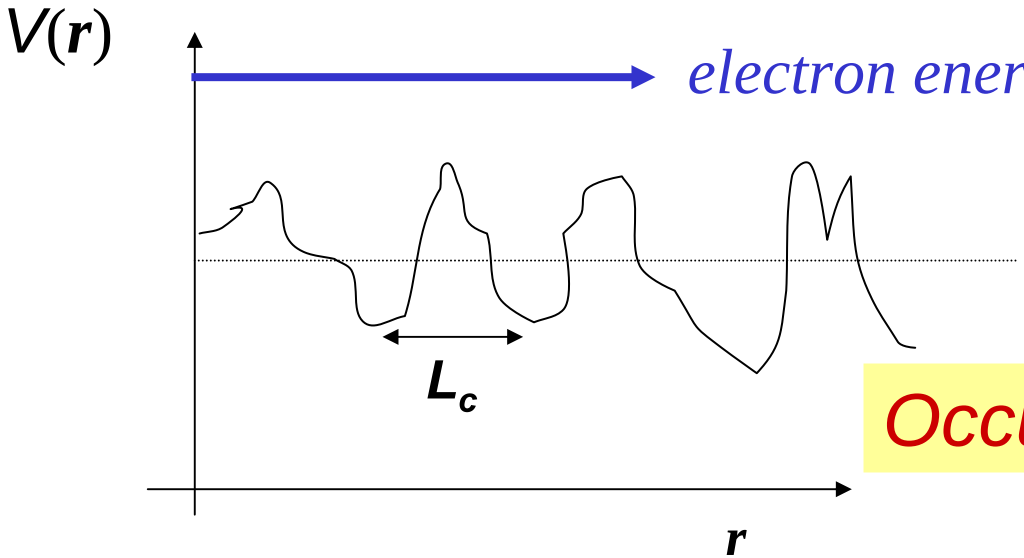
$$(\langle r^2(t) \rangle)^{1/2} = \sqrt{2tDd} \rightarrow \infty \text{ for } t \rightarrow \infty$$



Anderson localization

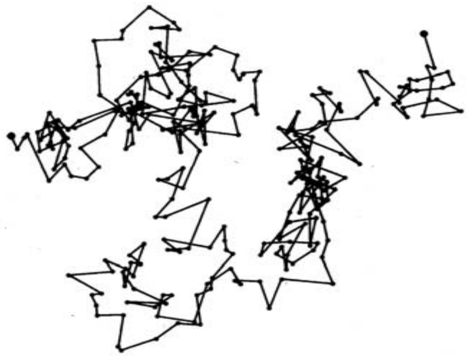
Quantum localization by scattering

1. Contradicts classical percolation picture



Occurs even if $E > V_{max}$

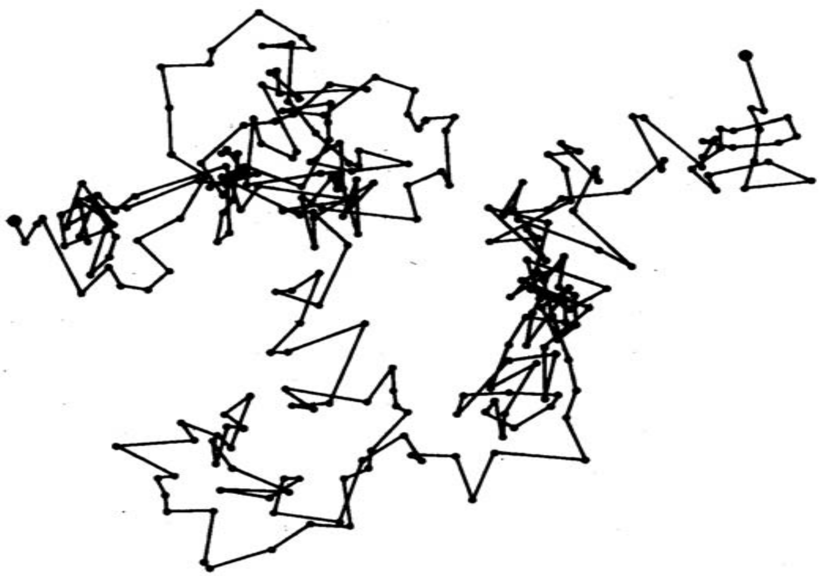
2. Contradicts classical diffusion equation

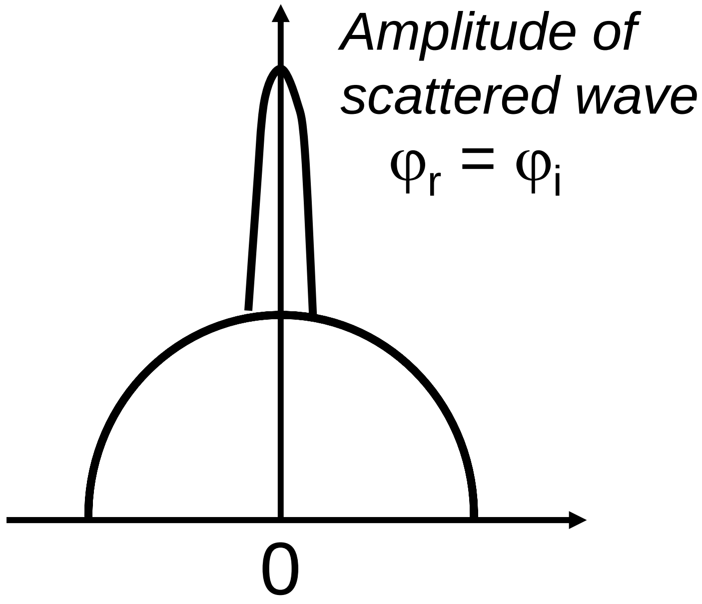


$$(< r^2(t) >)^{1/2} = \sqrt{2tDd} \rightarrow \infty \text{ for } t \rightarrow \infty$$

Cannot be described by CPA,…

Enhanced backscattering





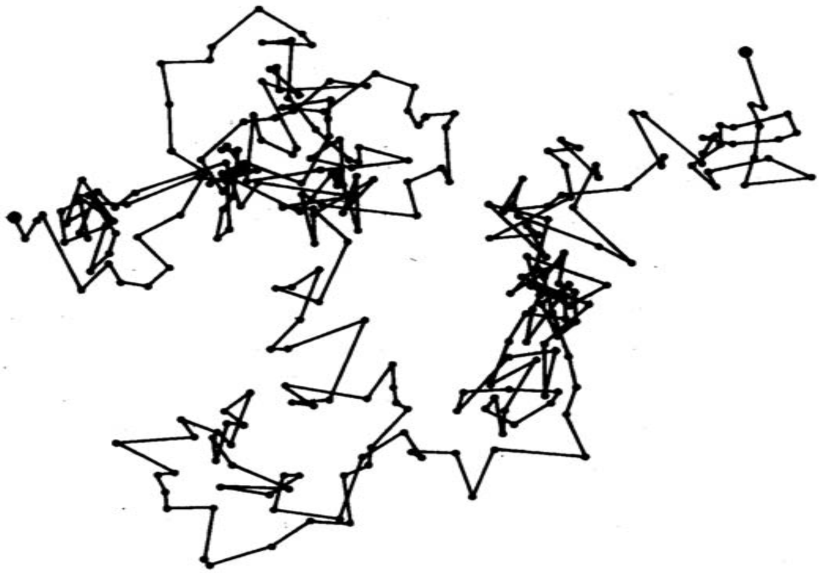
$$T_{\mathbf{return}} = T_{\mathbf{r}} + T_{\mathbf{l}} + 2|T_{\mathbf{r}}T_{\mathbf{l}}|^{1/2}\cos(\varphi_r - \varphi_l)$$

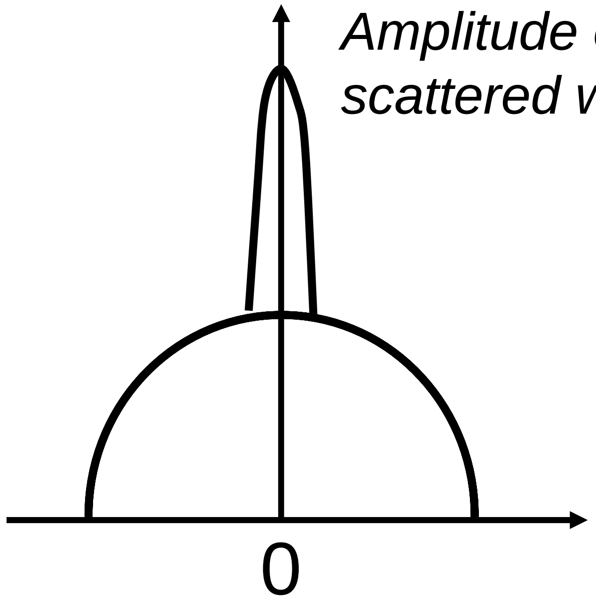
$\varphi_r - \varphi_l = 0$ if no magnetic field and spin scattering
Factor of two enhancement over classical value

Experimental evidence for backscattering:
oscillations in rings and magnetoresistance in films

Khmelnitskii, Larkin, Hikami, ….

Enhanced backscattering



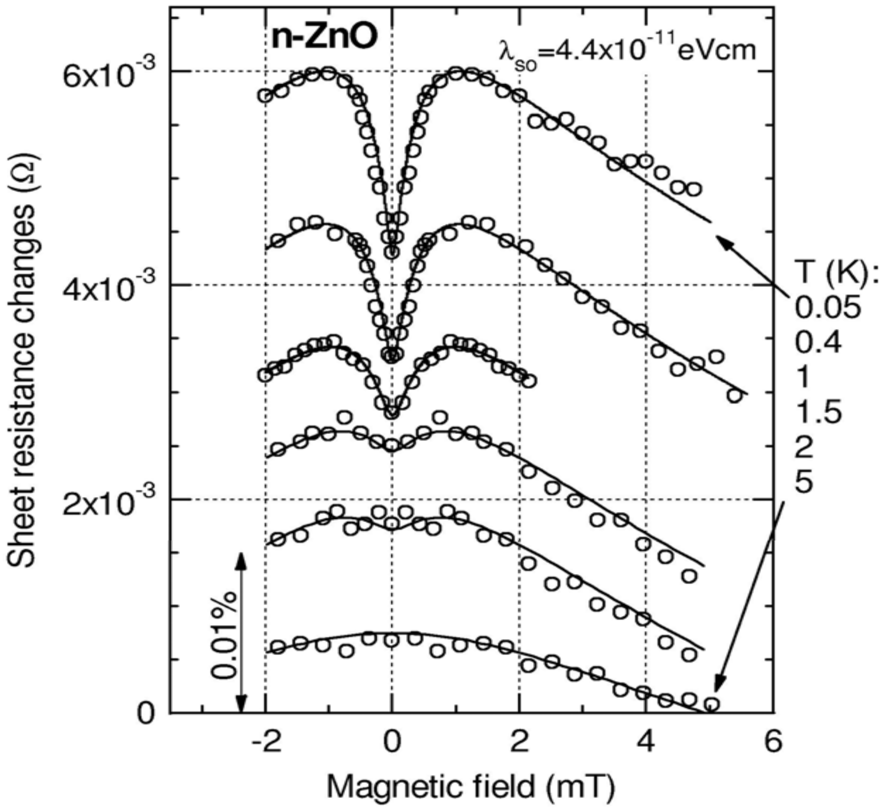


$$T_{\mathbf{return}} = T_{\mathbf{r}} + T_{\mathbf{l}} + 2|T_{\mathbf{r}}T_{\mathbf{l}}|^{1/2}\cos(\varphi_r - \varphi_l)$$

$\varphi_r - \varphi_l = 0$ if no magnetic field and inelastic scattering
Factor of two enhancement over classical value

➔ magnetic field and temperature *enhance* diffusion

Quantum localisation magnetoresistance in *n*-wz ZnO



T. Andrearczyk, …, T.D., PRB'05

$H_{so} = \lambda_{so}\hat{\boldsymbol{c}}(\boldsymbol{s}\times\boldsymbol{k})$

$\tau_{sox}^{-1} = \lambda_{so}^2 k_F^2 \tau/12$

$B_m \approx 1.6\ \alpha_{so}^2 m^{*2}$

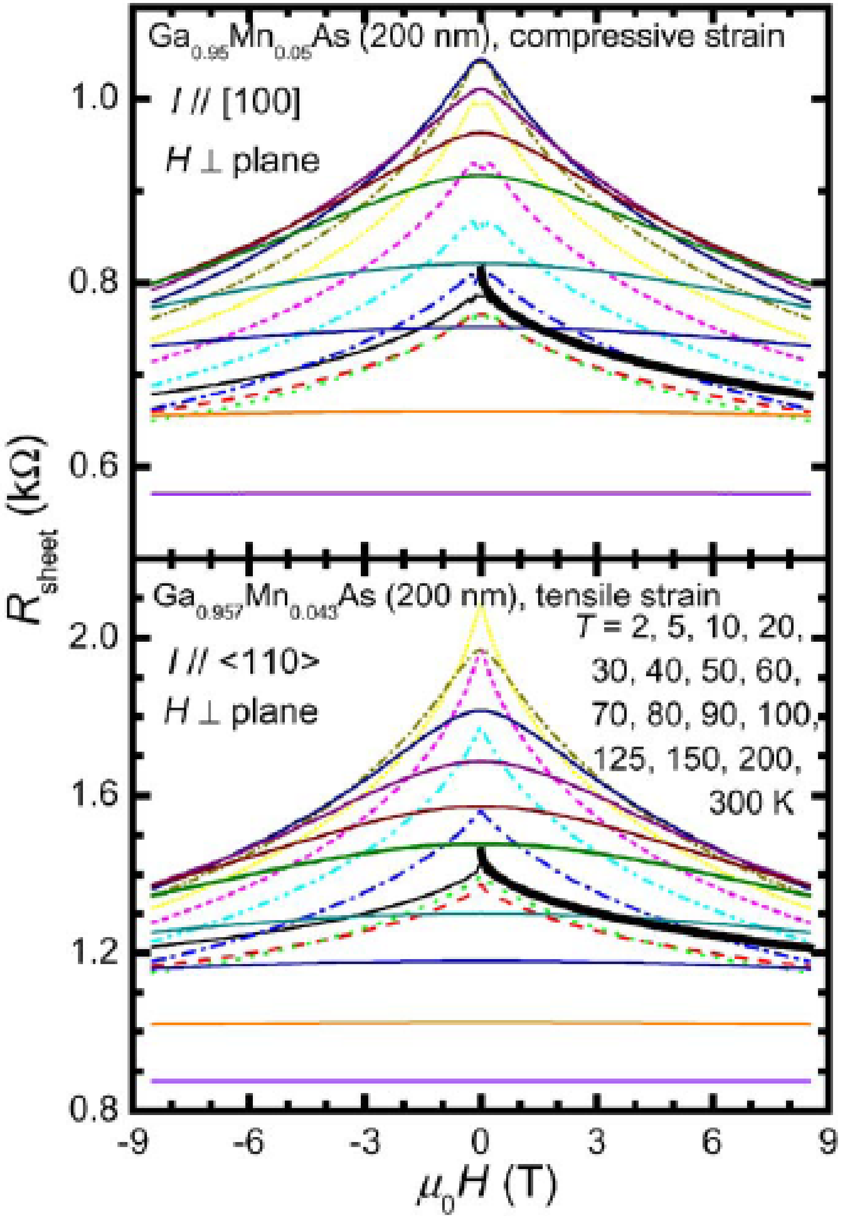
Dyakonov-Perel; Fukuyama, Hoshino

λ_{so}[meVÅ]	CdSe	ZnO
WLR	50±10	4.4±0.4
LMTO-LSD*	30	2.2

T_2 = 10 ns

****Voon et al. (Stuttgart, Aarhus) PRB'96***

(Ga,Mn)As: low temperature negative magnetoresistance



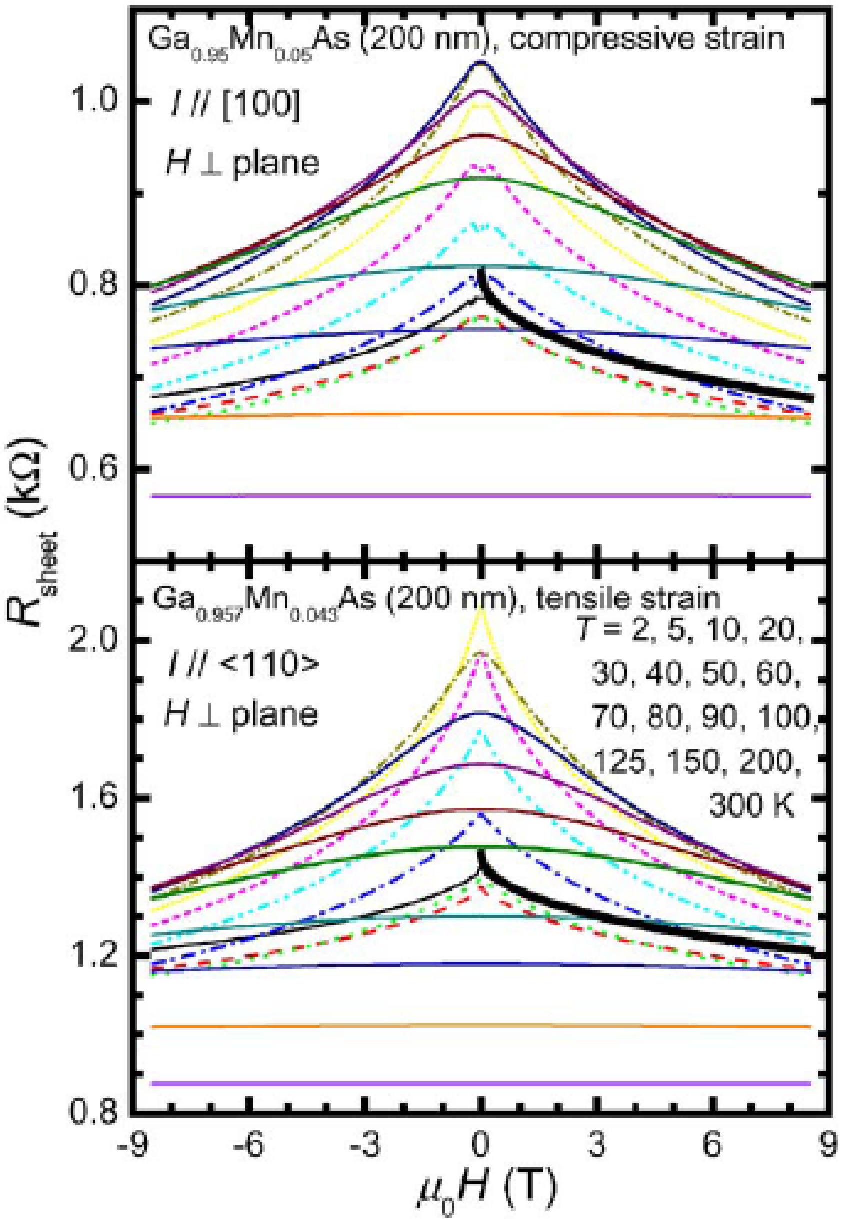
theory

$$\Delta\rho/\rho = -n_v e^2 C_o \rho (eB/\hbar)^{1/2}/(2\pi^2\hbar).$$

A. Kawabata'80

F. Matsukura … T.D. (Warsaw, Tohoku)'04

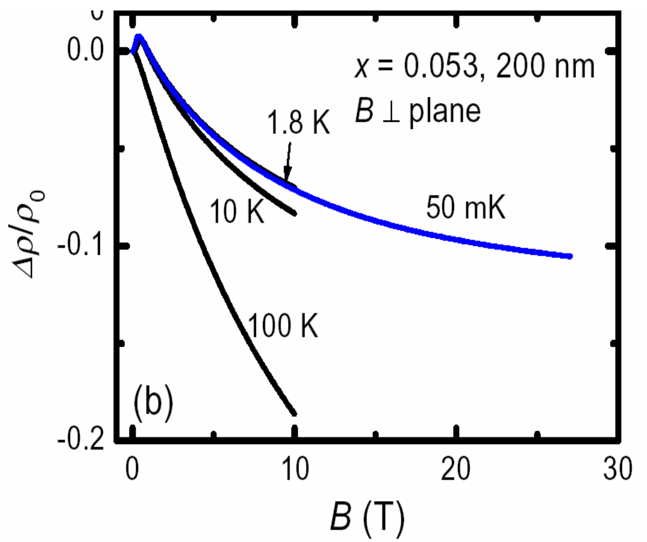
(Ga,Mn)As: low temperature negative magnetoresistance



theory

$$\Delta\rho/\rho = -n_v e^2 C_o \rho (eB/\hbar)^{1/2}/(2\pi^2\hbar).$$

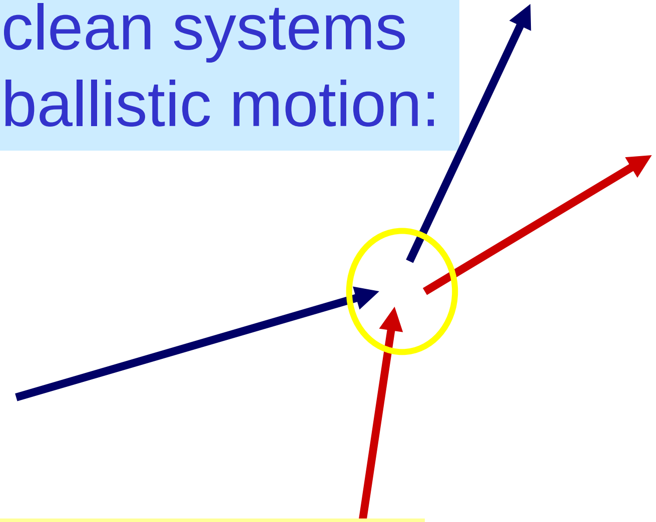
A. Kawabata'80



F. Matsukura … T.D. (Warsaw, Tohoku)'04

Electron-electron scattering

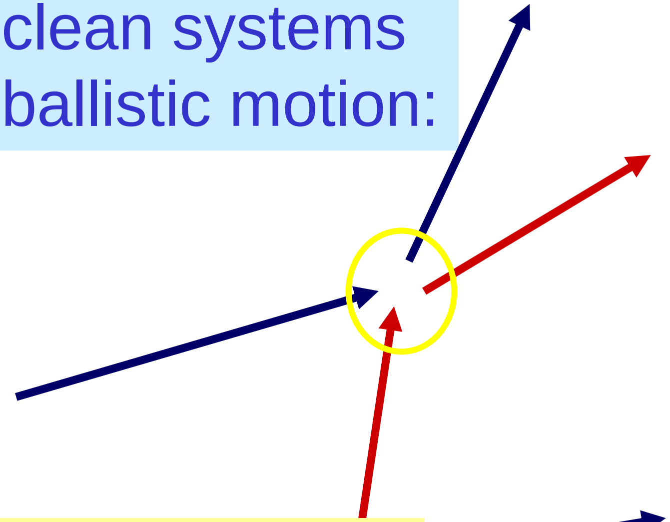
clean systems
ballistic motion:



electrons never
meet again…

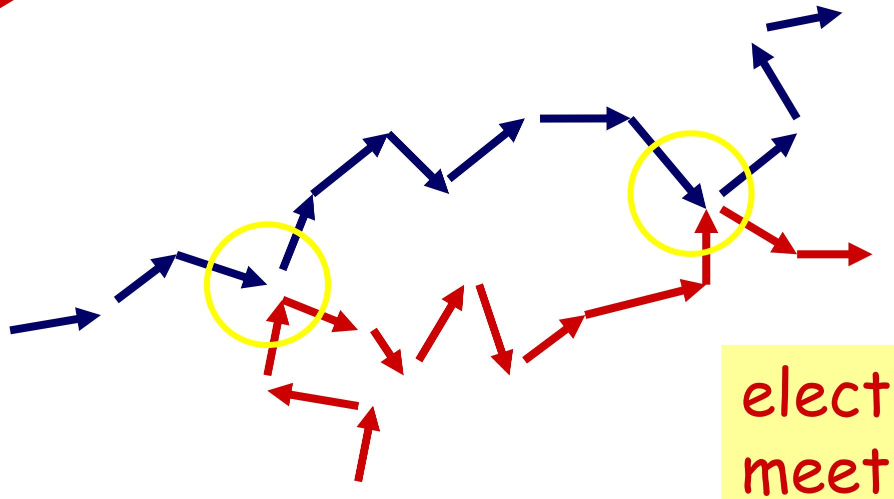
Electron-electron scattering

clean systems
ballistic motion:



electrons never
meet again…

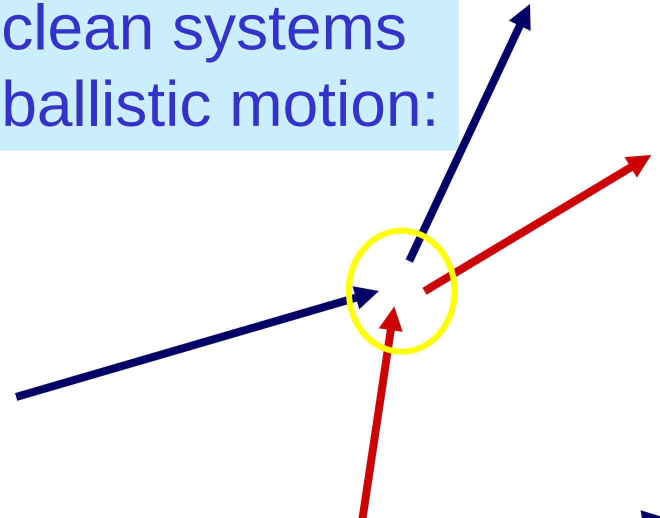
disordered systems
diffusive motion:



electrons can
meet again…

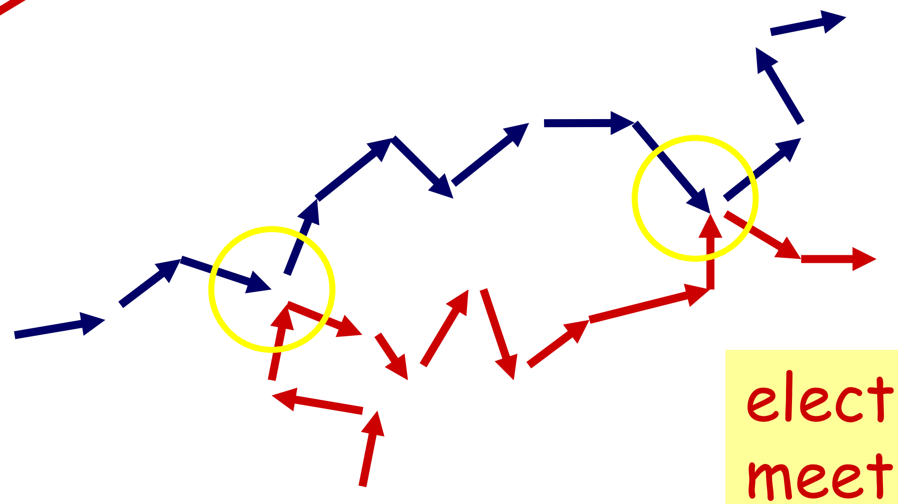
Electron-electron scattering

clean systems
ballistic motion:



electrons never meet again…

disordered systems
diffusive motion:



electrons can meet again…

interference of scattering amplitudes

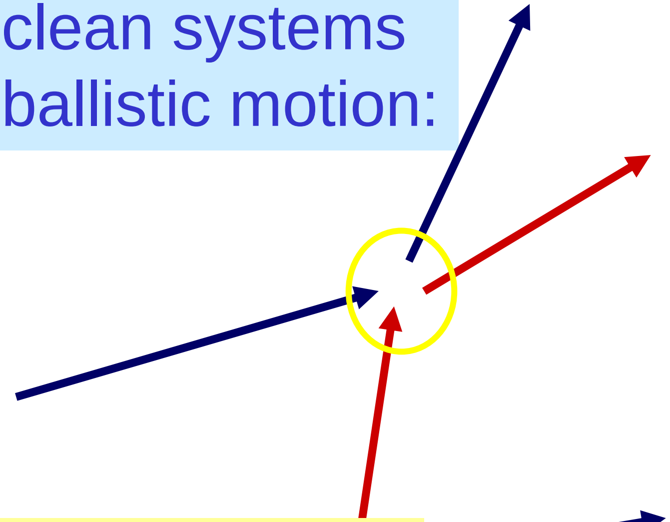
$$T_{\sigma\sigma'} = T_{\sigma} + T_{\sigma'} + 2|T_{\sigma}T_{\sigma'}|^{1/2}\cos(\varphi_{\sigma} - \varphi_{\sigma'})$$

depending of spins (triplet vs. singlet):
diffusion reduced/enhanced
Coulomb anomaly at E_F

Altshuler, Aronov, Fukuyama, Lee, Ramakrishnan, …

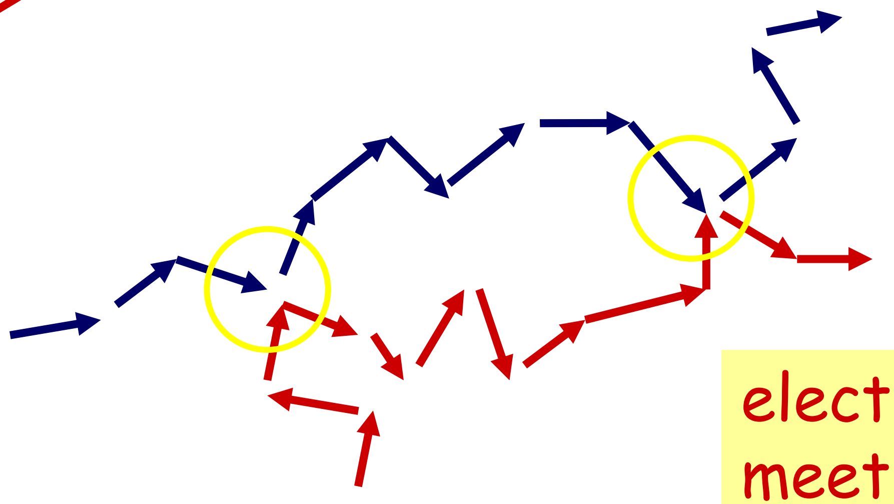
Electron-electron scattering

clean systems
ballistic motion:



electrons never
meet again…

disordered systems
diffusive motion:



electrons can
meet again…

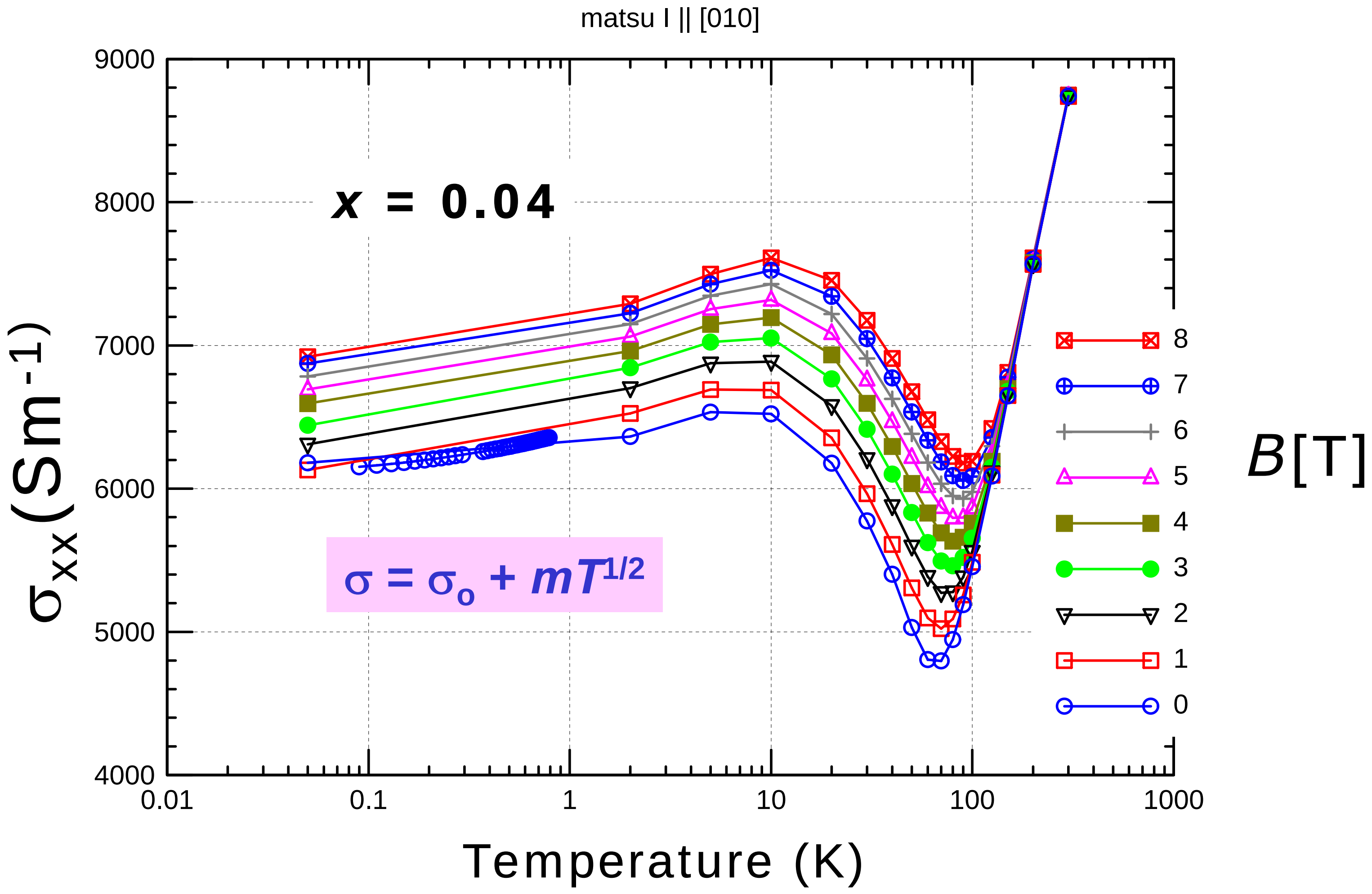
interference of scattering amplitudes

$$T_{\sigma\sigma'} = T_{\sigma} + T_{\sigma'} + 2|T_{\sigma}T_{\sigma'}|^{1/2}\cos(\varphi_{\sigma} - \varphi_{\sigma'})$$

same spins: diffusion reduced
opposite spins: diffusion enhances

➔ spin splitting and spin scattering *reduce* diffusion

Temperature dependence of conductance in various magnetic fields in (Ga,Mn)As



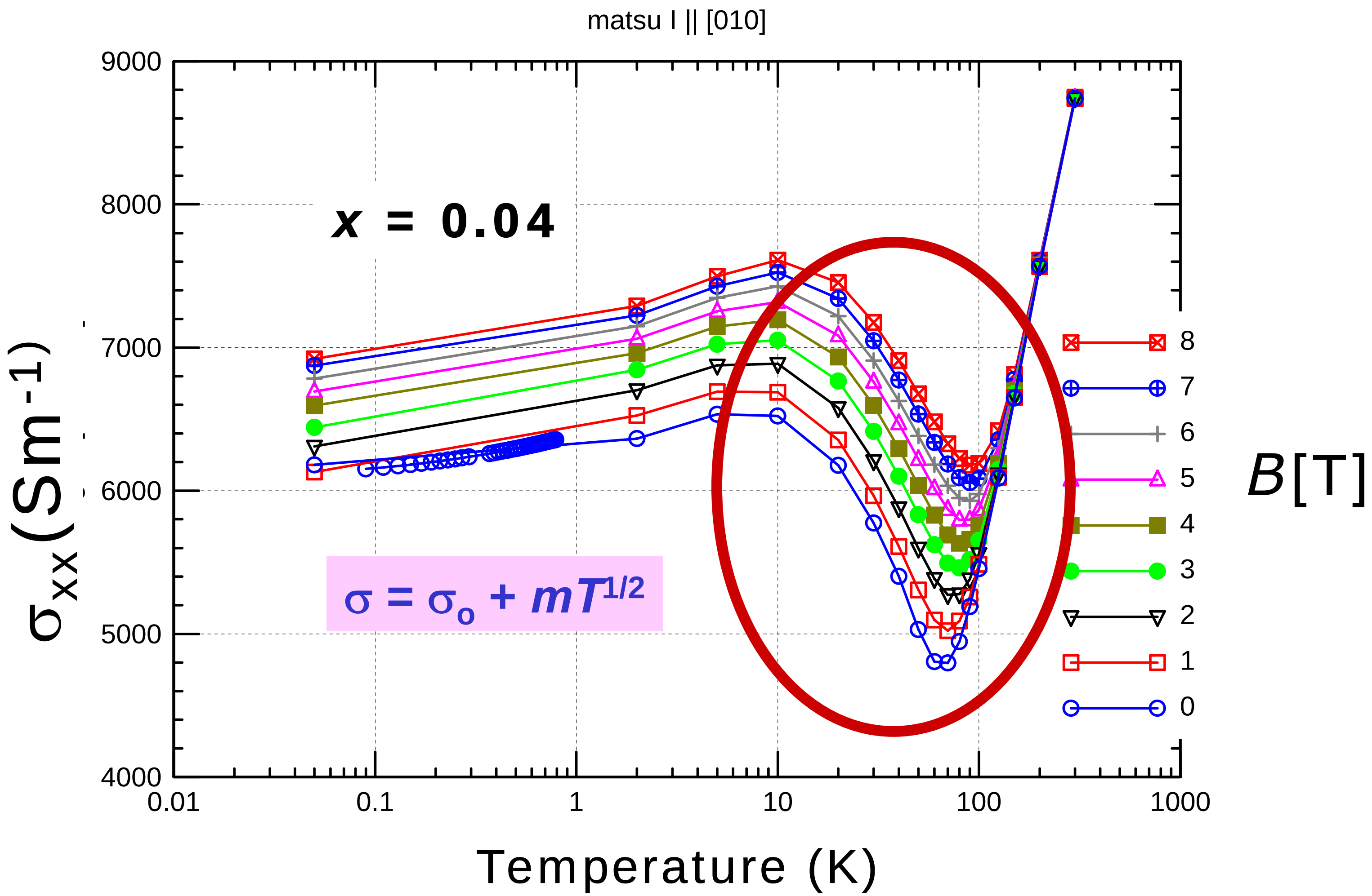
F. Matsukura et al. (Warsaw, Tohoku)'04,'05, D. Neumaier et al. (Regensburg)' 08'09

we do not understand

- critical scattering at T_C
  (at $T \rightarrow 0$ in paramagnets)

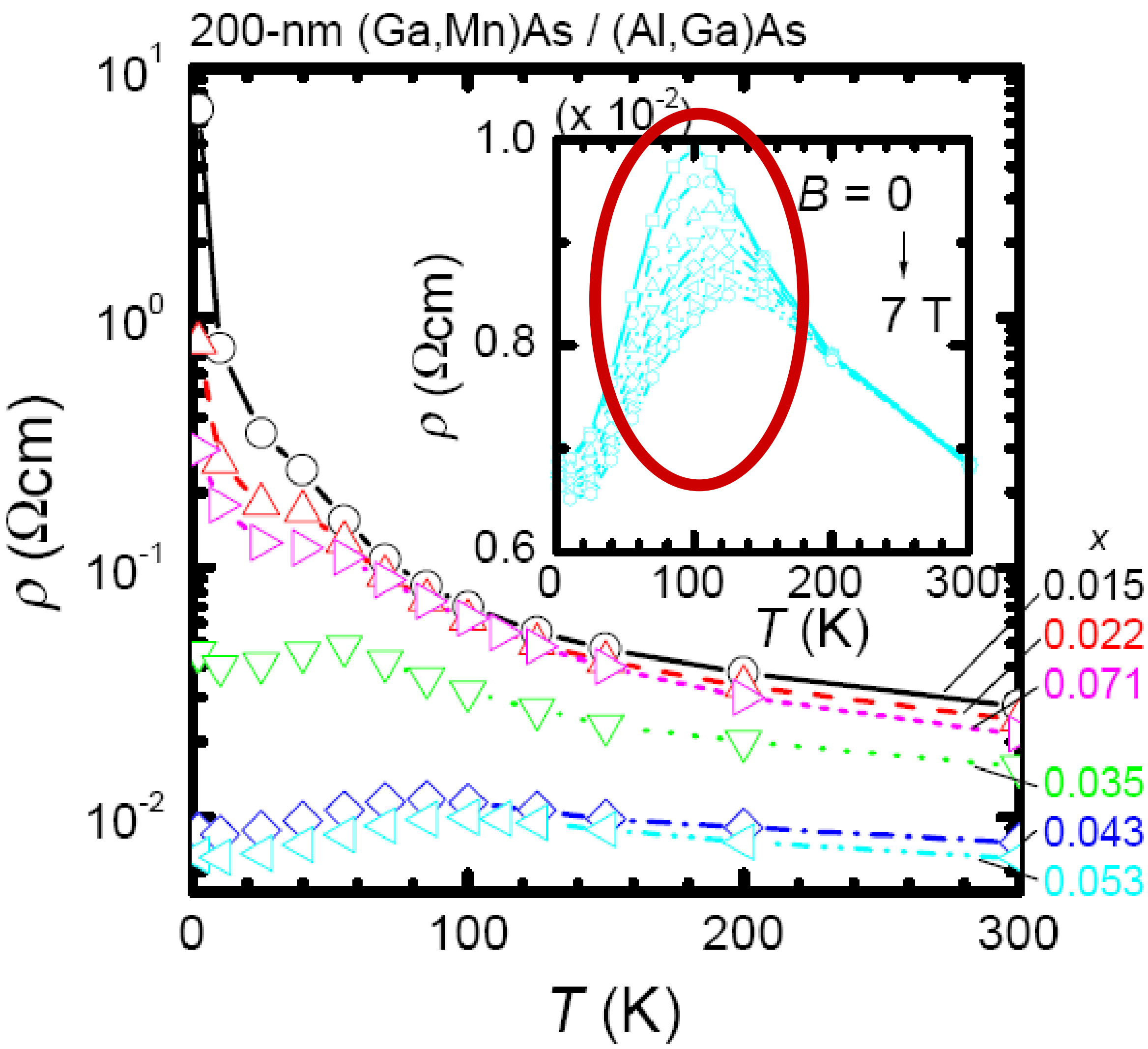
- CMR

Temperature dependence of conductivity in various magnetic fields in (Ga,Mn)As



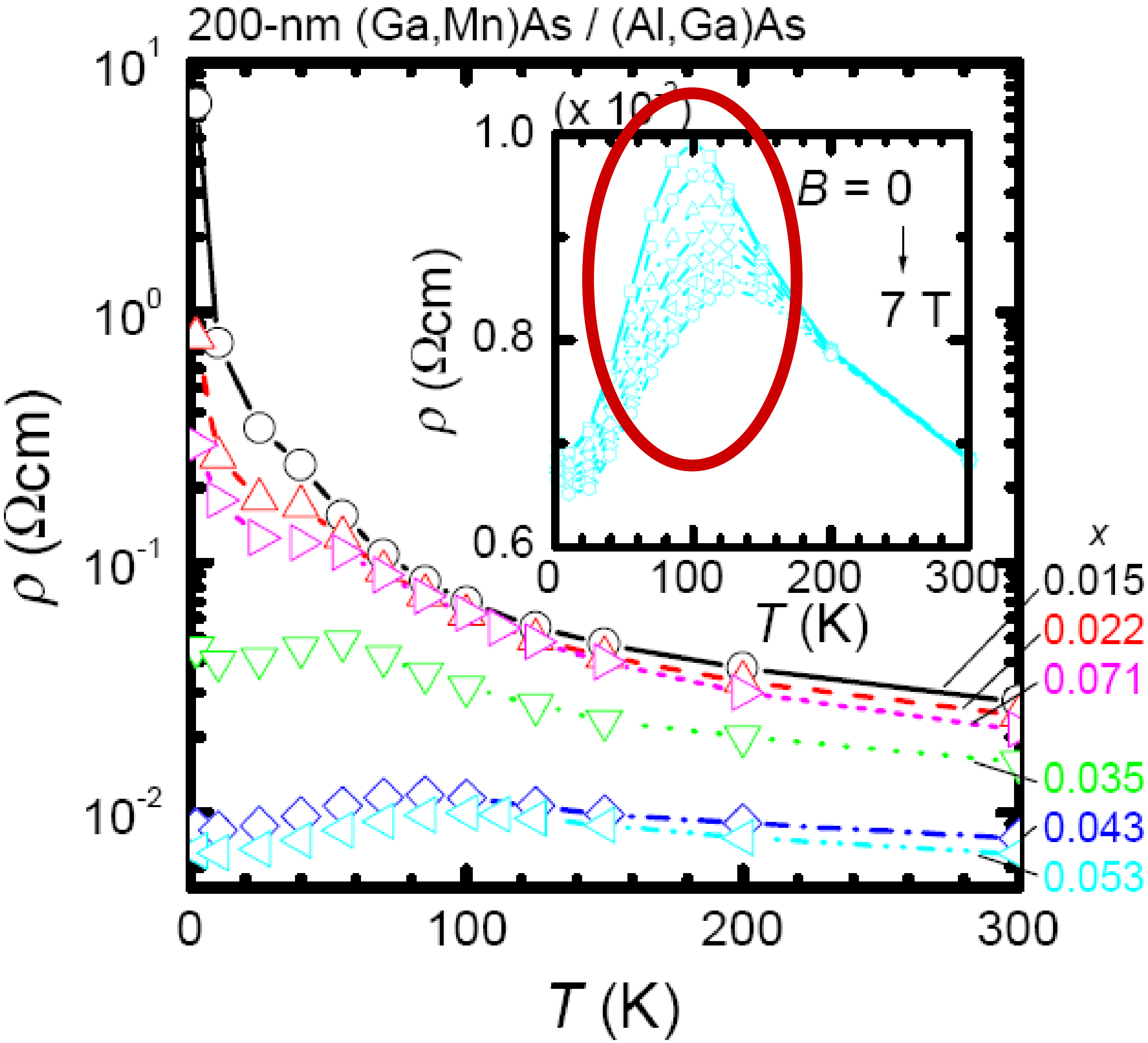
F. Matsukura …T. D. (Warsaw, Tohoku)'04,'05, Neumaier et al. (Regensburg)',08

Temperature dependence of resistivity in various magnetic fields in (Ga,Mn)As



F. Matsukura et al., PRB'98

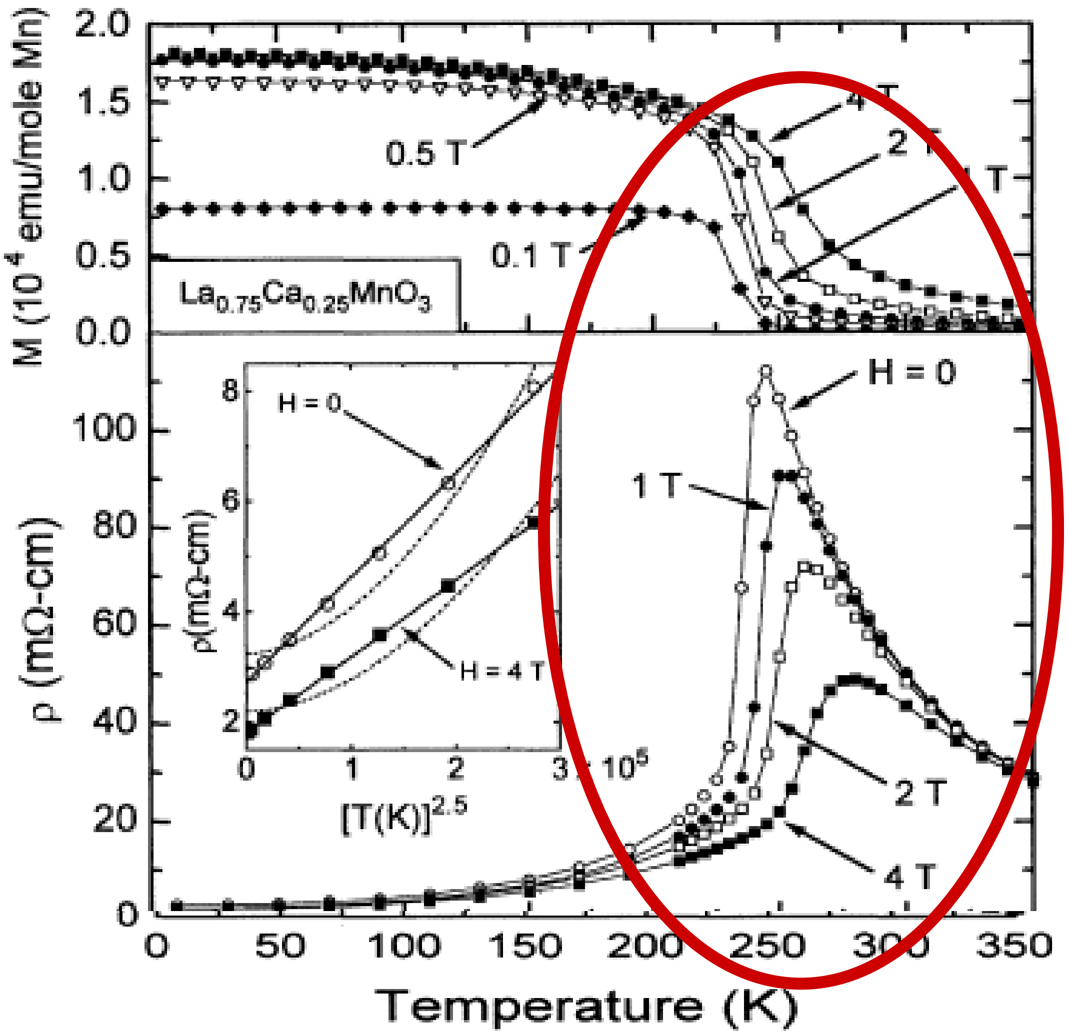
Temperature dependence of resistivity in various magnetic fields in (Ga,Mn)As



Reminiscent to CMR oxides

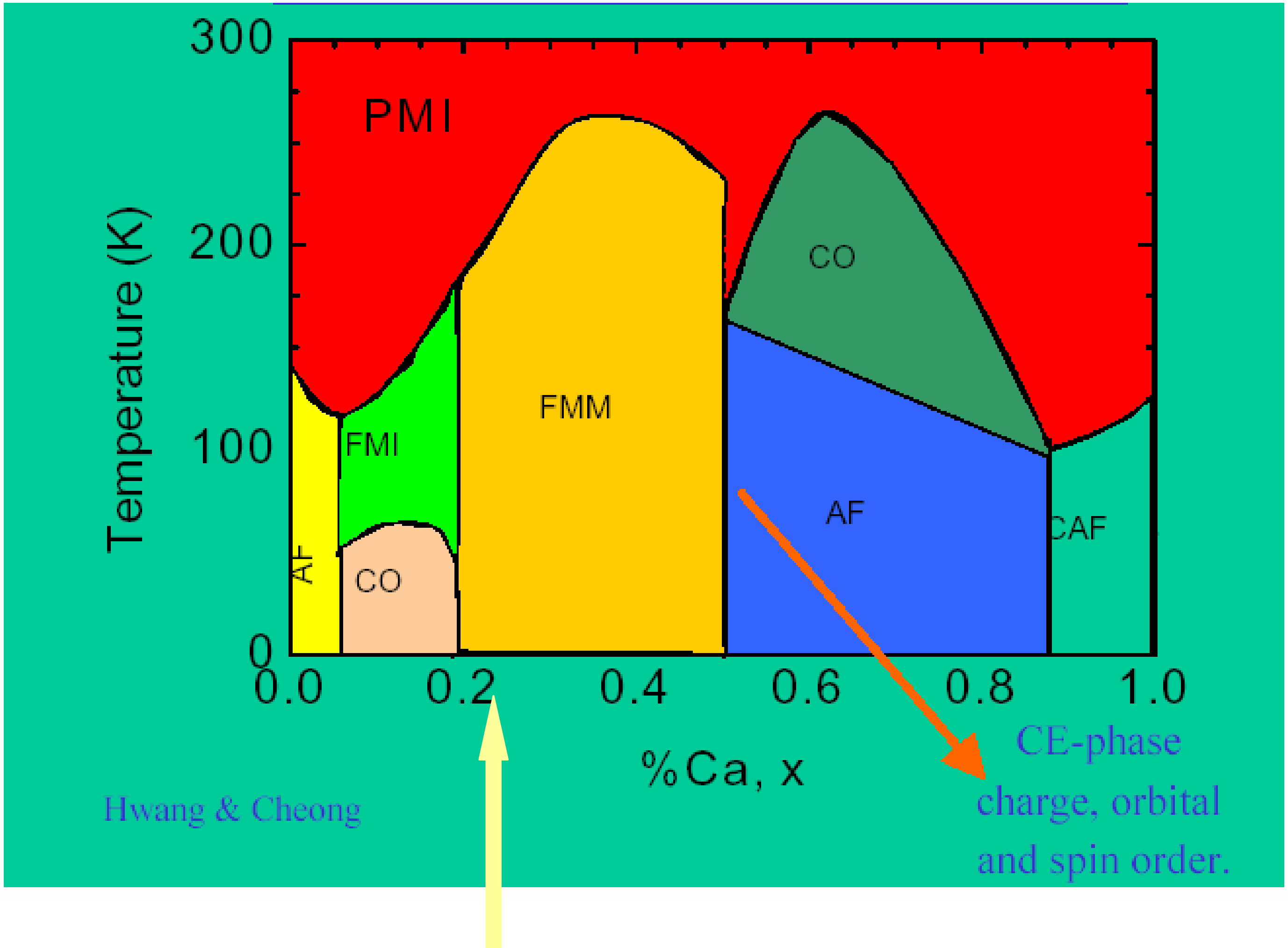
F. Matsukura et al., PRB'98

Magnetization and resistivity in $(La,Ca)MnO_3$



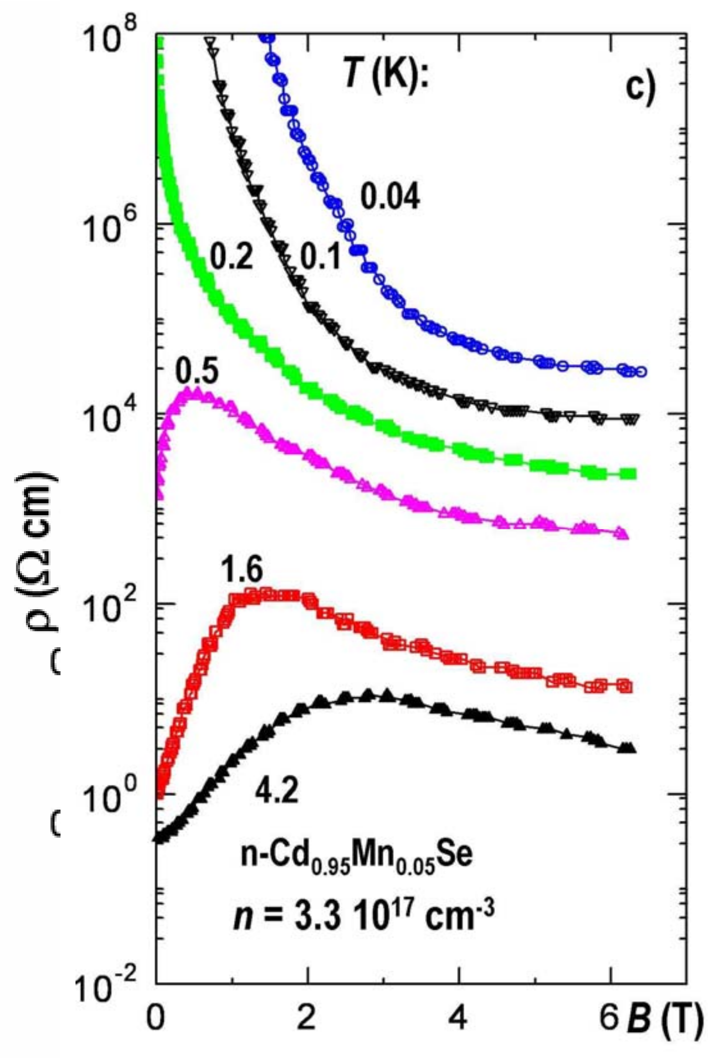
P. Schiffer et al. (PSU), PRL'95

Phase diagram of $La_{1-x}Ca_xMnO_3$



CMR near MIT

CMR in n-(Cd,Mn)Se

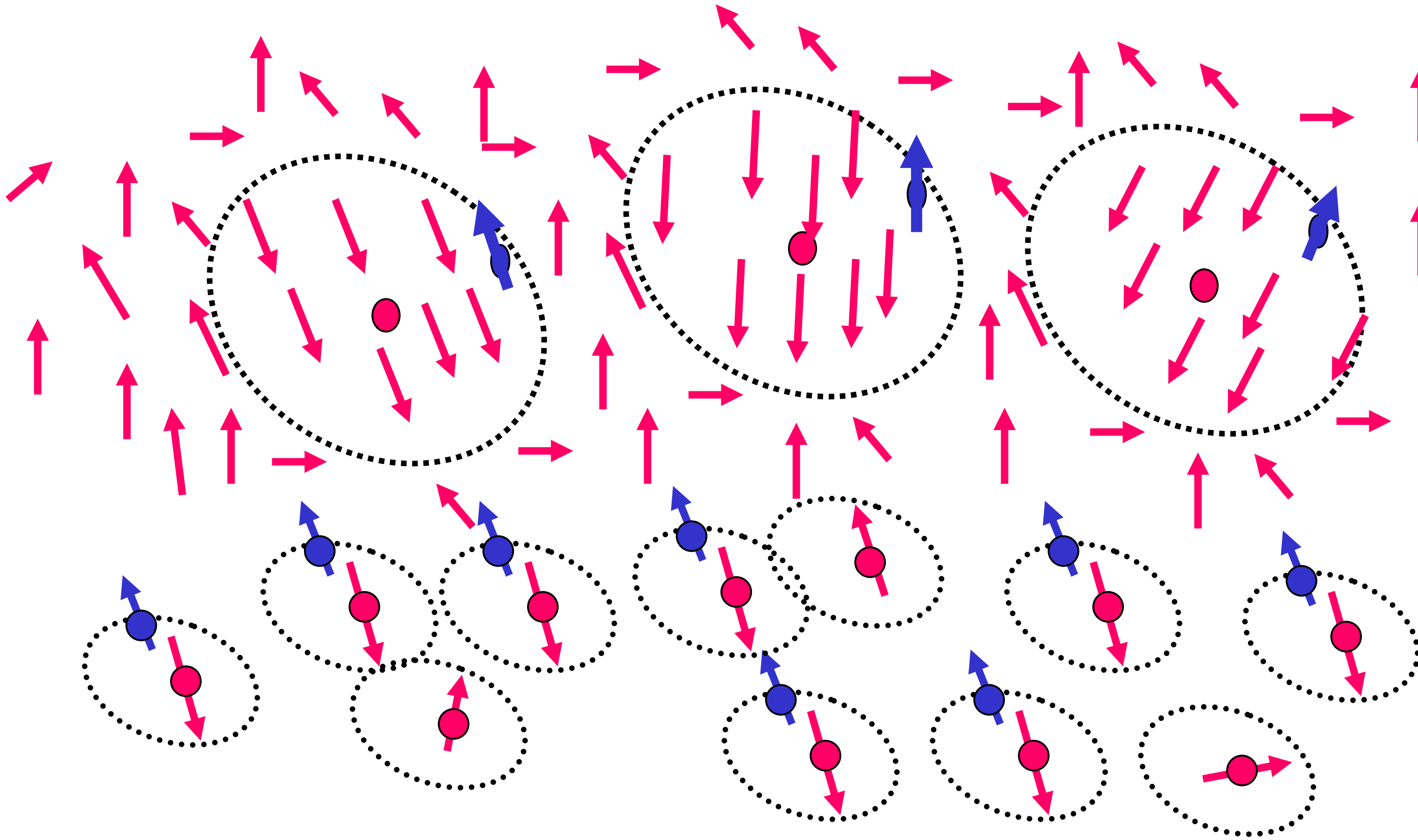


M. Sawicki, TD et al. (Warsaw) PRL'86, Physica B'93

Possible model: enhancement of localization by bound magnetic polaron formation

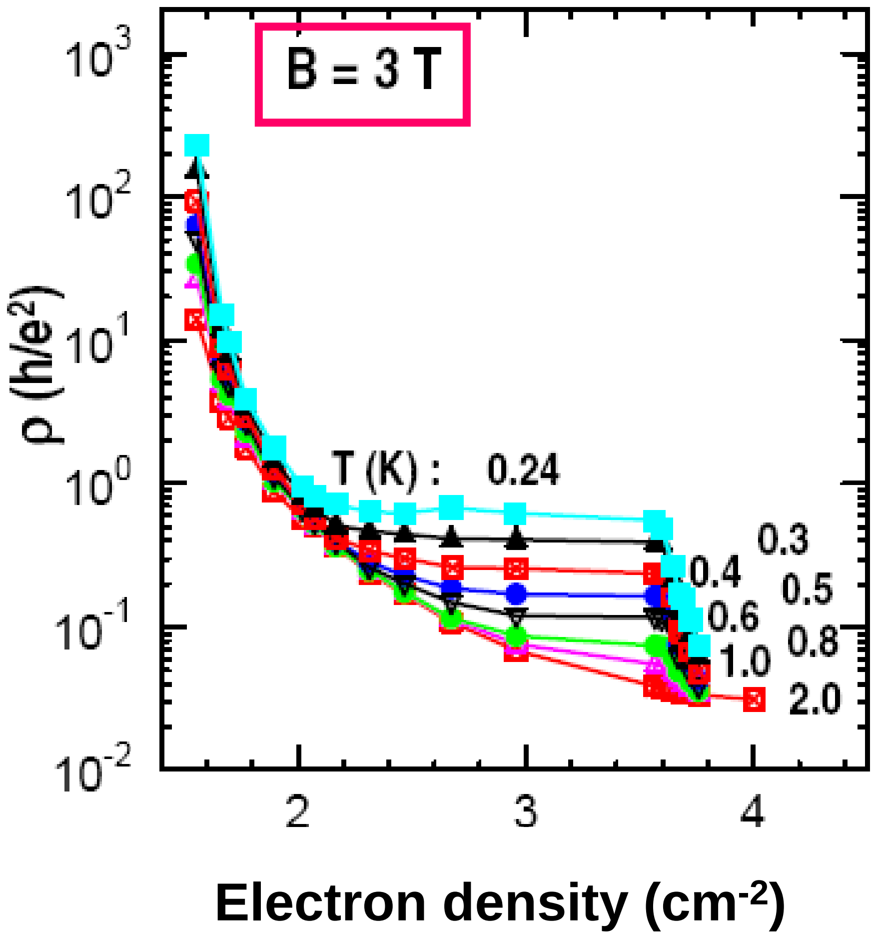
p-type (II,Mn)VI

(III,Mn)V



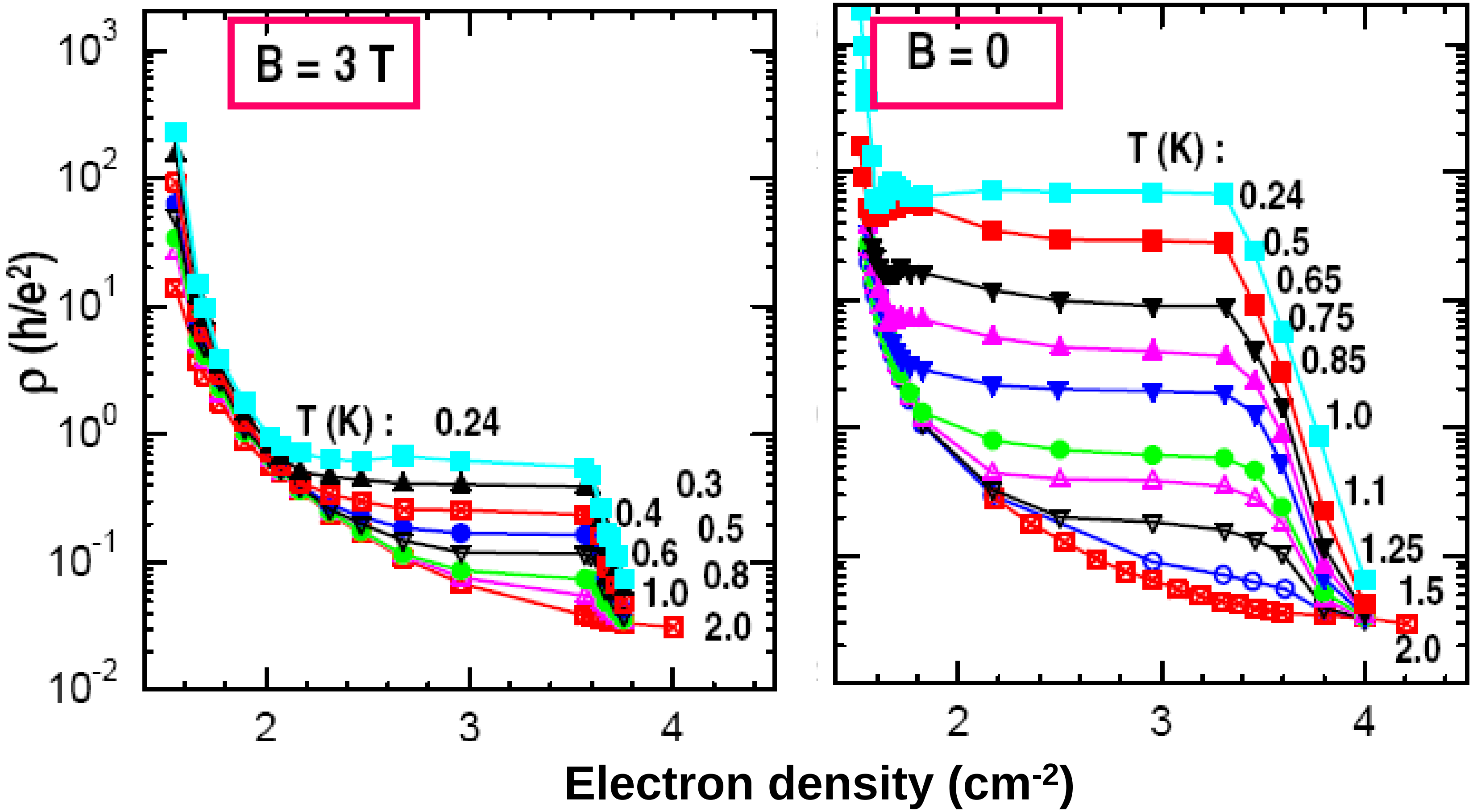
BMP binding energy ~ $\chi(T)$

Resistivity vs. carrier density at various *T* in (Cd,Mn)Te/(Cd,Mg)Te:I quantum well



J. Jaroszynski , TD et al. (Warsaw, NHMFL) PRB'07

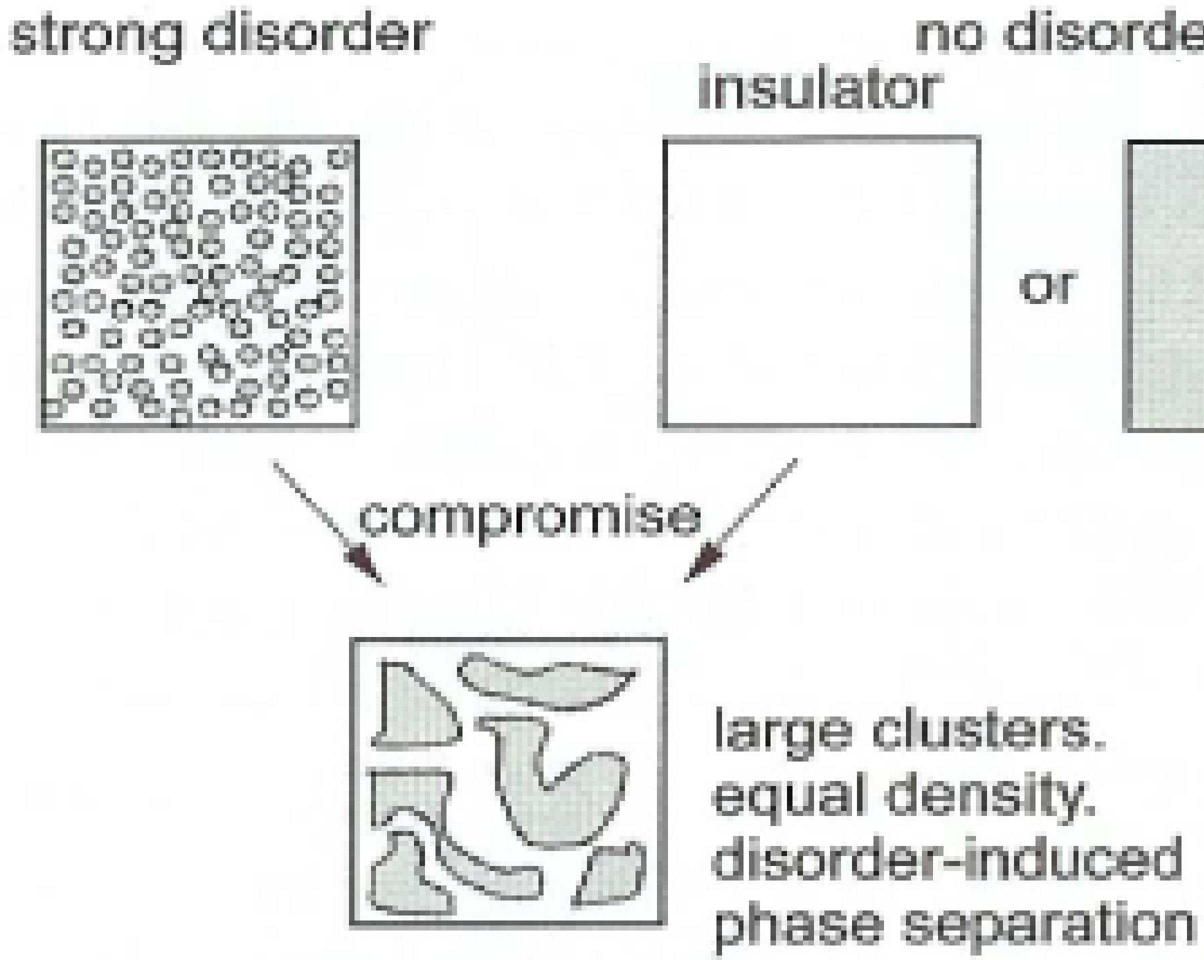
Resistivity vs. carrier density at various *T* in (Cd,Mn)Te/(Cd,Mg)Te:I quantum well



no BMP but critical scattering and CMR!

J. Jaroszynski , TD et al. (Warsaw, NHMFL) PRB'07

Pictorial representation of states near MIT



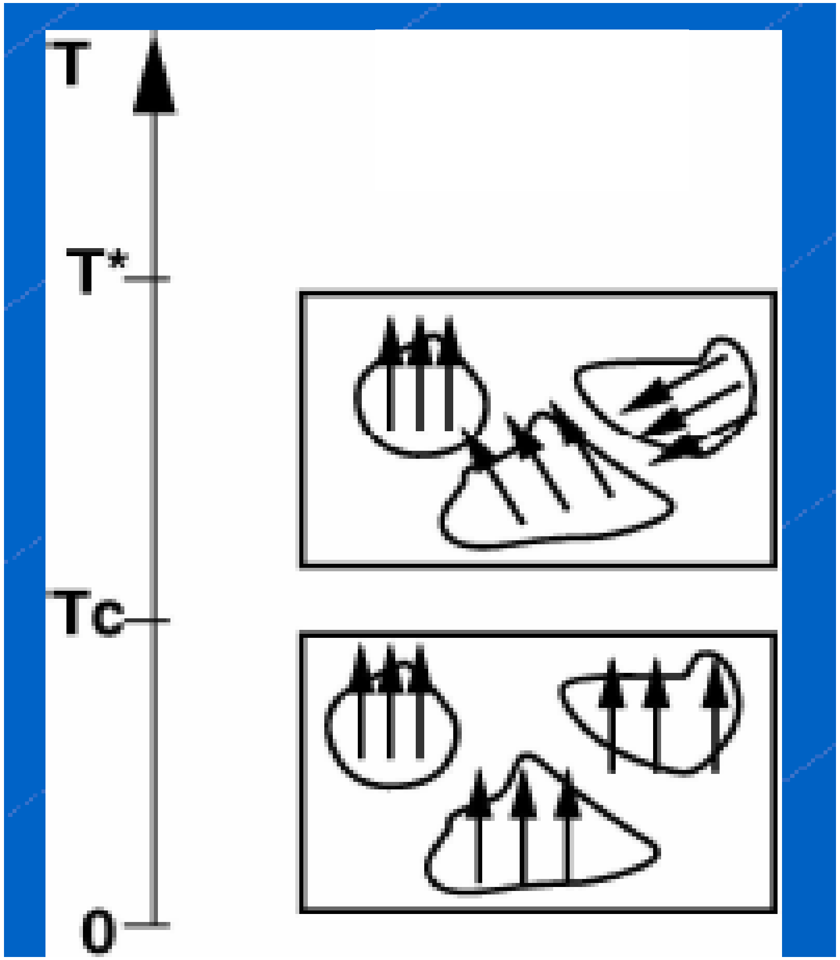
cf. A. Moreo et al. Science'99
Nagaev'85

white = para grey = ferro (mesoscopic scale)

Nanoscale electronic phase separation

$T_C > 0$ in
p-type DMS

$T_C \cong 0$ in
n-type DMS



strong-spin dependent scattering and CMR

SUMMARY

Quantum effects essential at the Anderson-Mott transition

Leads to:

- Coulomb anomaly of DOS at E_F
- specific dependence $\sigma(T,H)$
- nanoscale phase separation into para and ferro regions

  ➔ colossal negative magnetoresistance

  ➔ much enhanced critical scattering

END