Transport properties of diluted magnetic semiconductor ferromagnets

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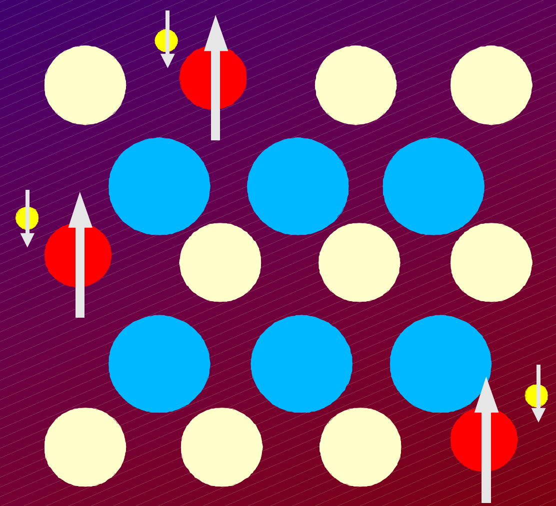
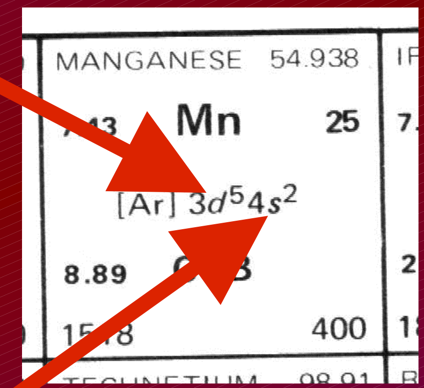
Hole-mediated ferromagnetism

Tomasz Dietl *et al.*:
(Phys. Rev. B '97)



- Analogy with (II,Mn)VI

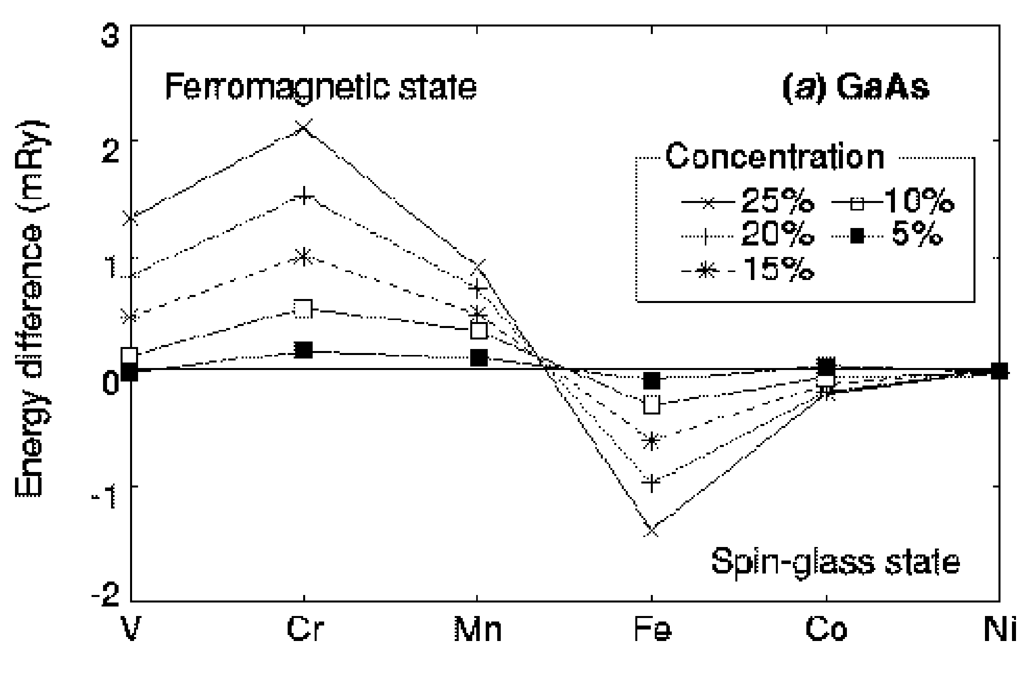
diluted magnetic semiconductors



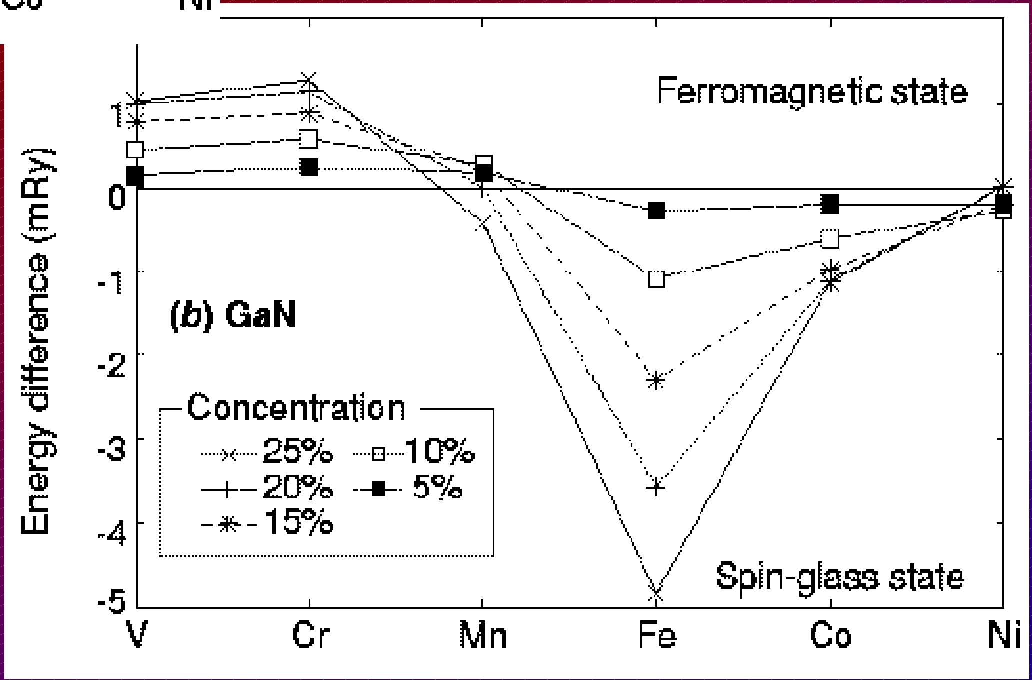
- Plus Mn is an acceptor in (III,Mn)V

ZINC 65.38 7.14 Zn 30 [Ar] $3d^{10}4s^2$ 2.66 HEX 1.856 693 234	GALLIUM 69.72 5.91 Ga 31 [Ar] $3d^{10}4s^2 4p^1$ 4.51 ORC 1.695 1.001 303 240	GERMANIUM 72.59 5.32 Ge 32 [Ar] $3d^{10}4s^2 4p^2$ 5.66 DIA 1211 360	ARSENIC 74.922 5.72 As 33 [Ar] $3d^{10}4s^2 4p^3$ 4.13 RHL 54°10′ 1090 285	SELENIUM 78.96 4.79 Se 34 [Ar] $3d^{10}4s^2 4p^4$ 4.36 HEX 1.136 490 150^{LT}
CADMIUM 112.40 8.65 Cd 48 [Kr] $4d^{10}5s^2$ 2.98 HEX 1.886 594 120	INDIUM 114.82 7.31 In 49 [Kr] $4d^{10}5s^2 5p^1$ 4.59 TET 1.076 429.8 129	TIN 118.69 7.30 Sn 50 [Kr] $4d^{10}5s^2 5p^2$ 5.82 TET 0.546 505 170	ANTIMONY 121.75 6.62 Sb 51 [Kr] $4d^{10}5s^2 5p^3$ 4.51 RHL 57°6′ 904 200	TELLURIUM 127.60 6.24 Te 52 [Kr] $4d^{10}5s^2 5p^4$ 4.45 HEX 1.330 723 139^{LT}

LDA ground-state



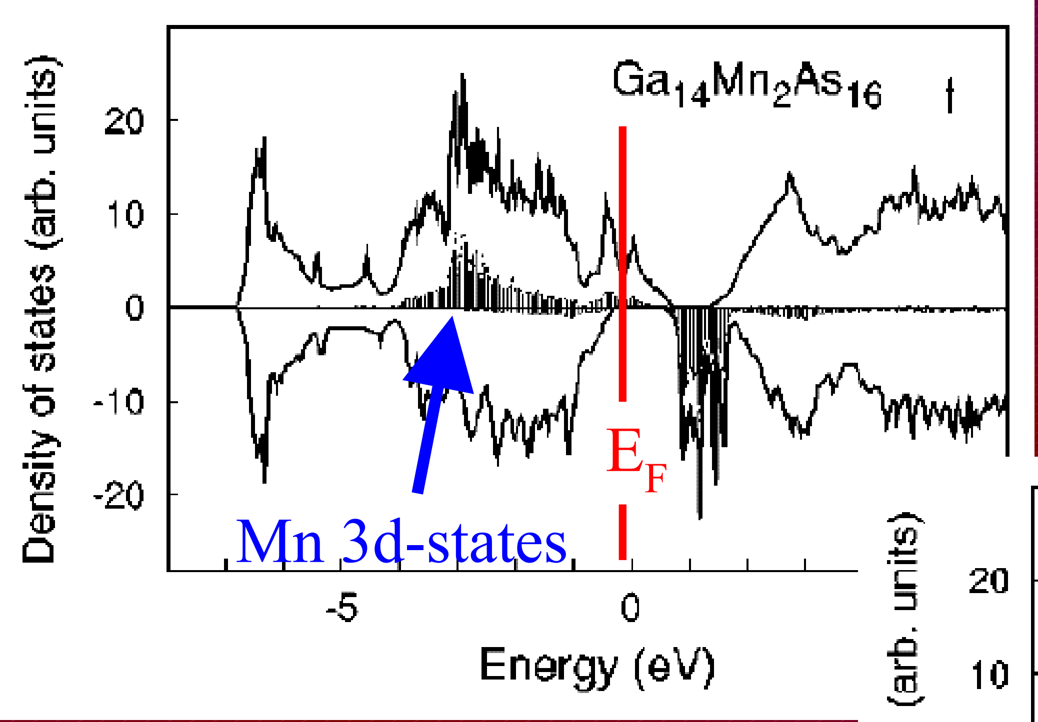
ferromagnet
vs
spin-glass



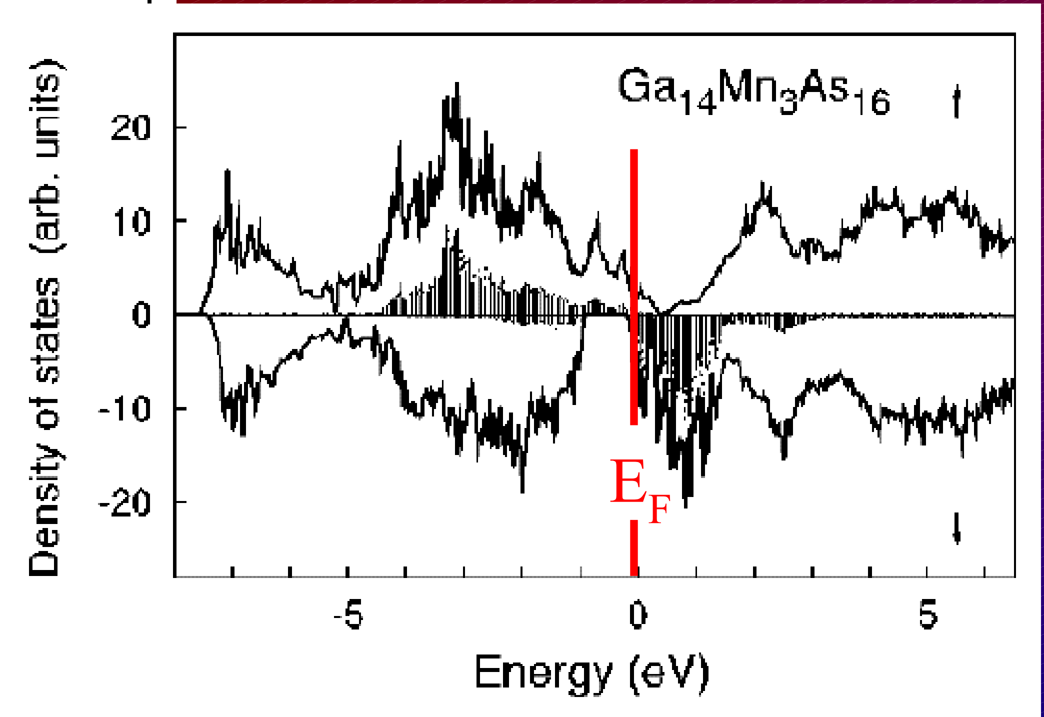
(K. Sato and H. Katayama-Yoshida, Semicond. Sci. and Technol. '02)

Electronic structure

2 substitutional Mn ions

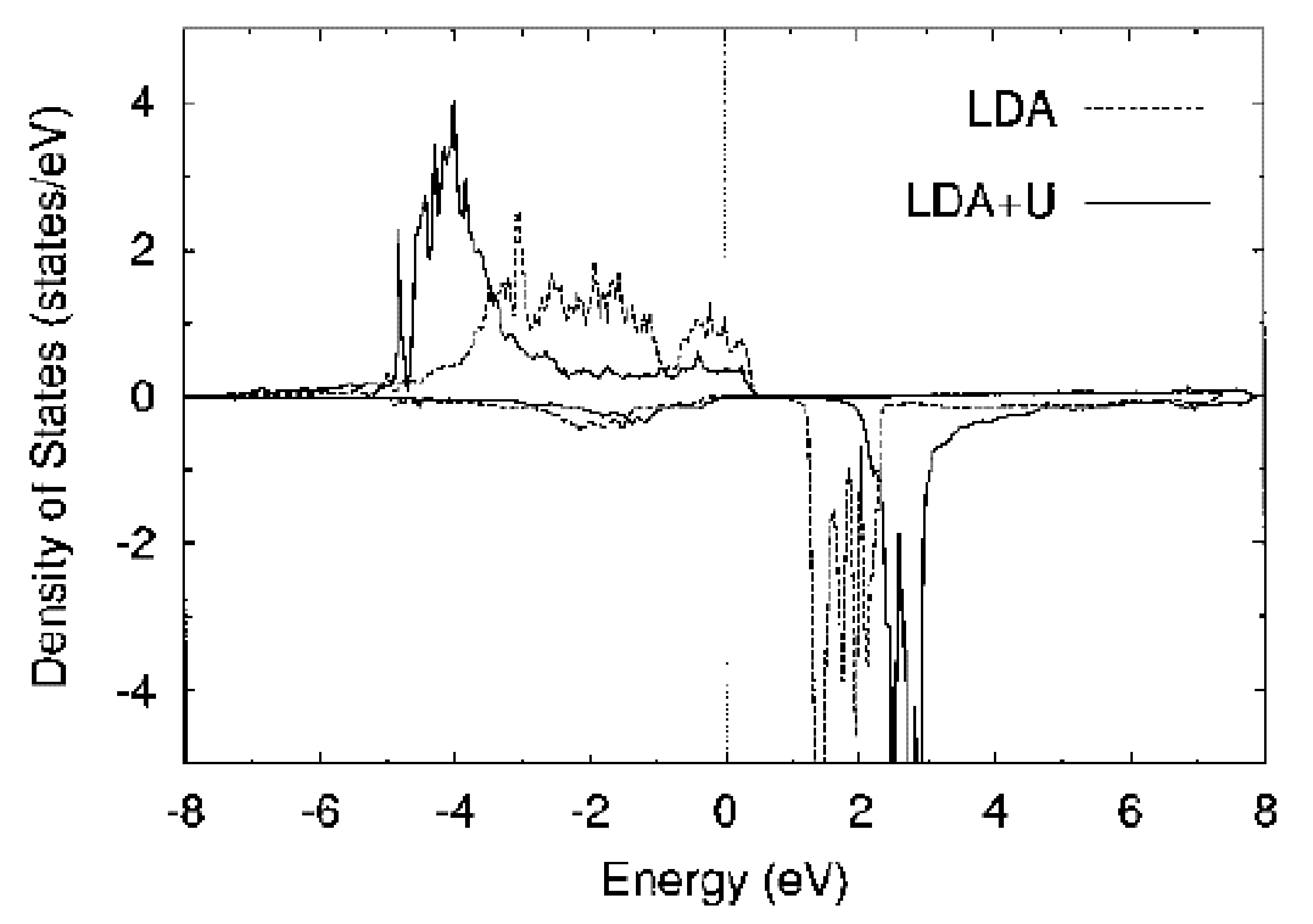


2 substitutional and
1 interstitial Mn



(F. Máca and J. Mašek PRB '02)

On Mn-site correlations



(J.H. Park, S.K. Kwon, and B.I. Min, Physica B '00)

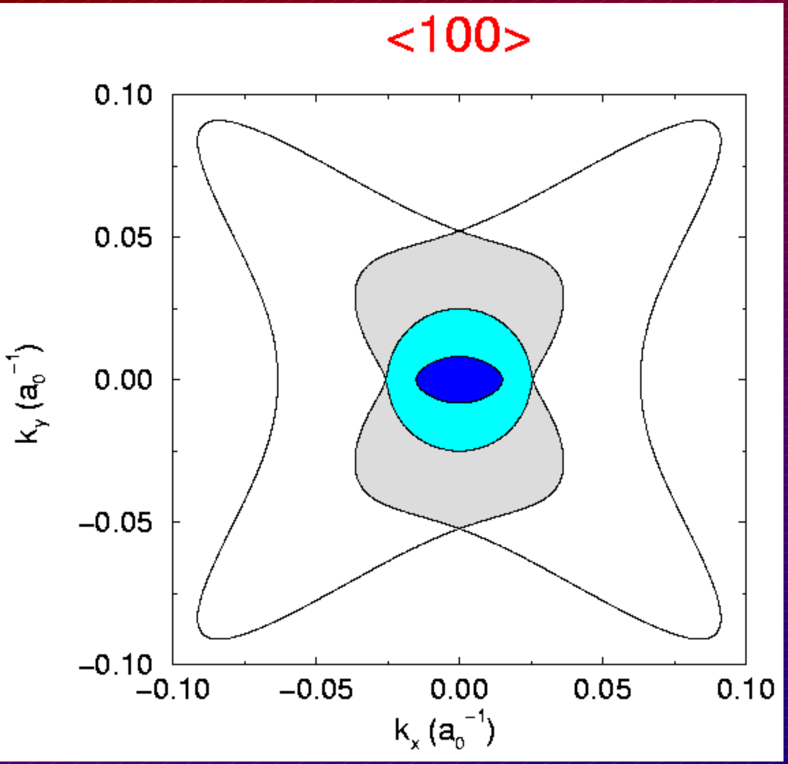
Effective Hamiltonian theories

- Semi-phenomenological Kohn-Luttinger model for heavy, light, and spin-orbit split-off band holes

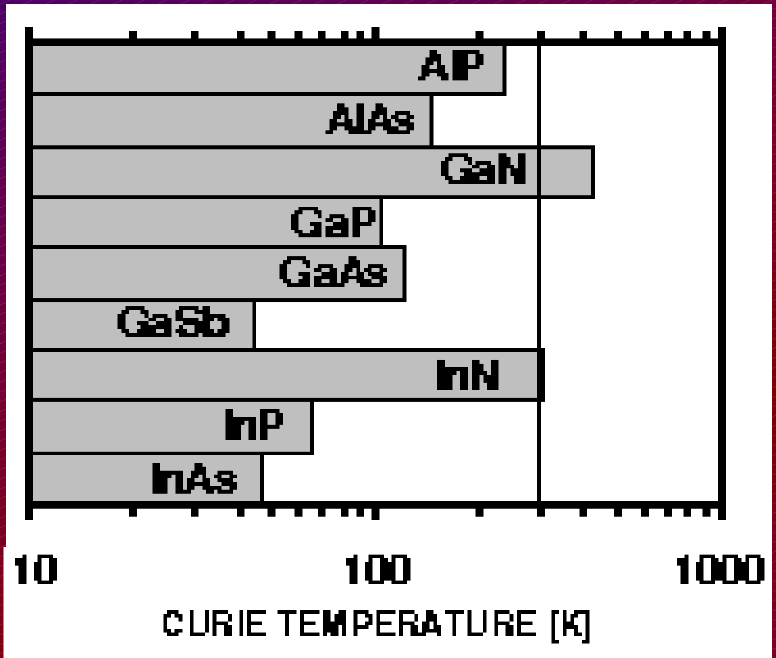
- Kondo spin Hamiltonian:
  $\Sigma_i J_{pd} \boldsymbol{S}_i \cdot \boldsymbol{s}$; Mn: S=5/2; valence-band hole: s=1/2; $J_{pd} > 0$

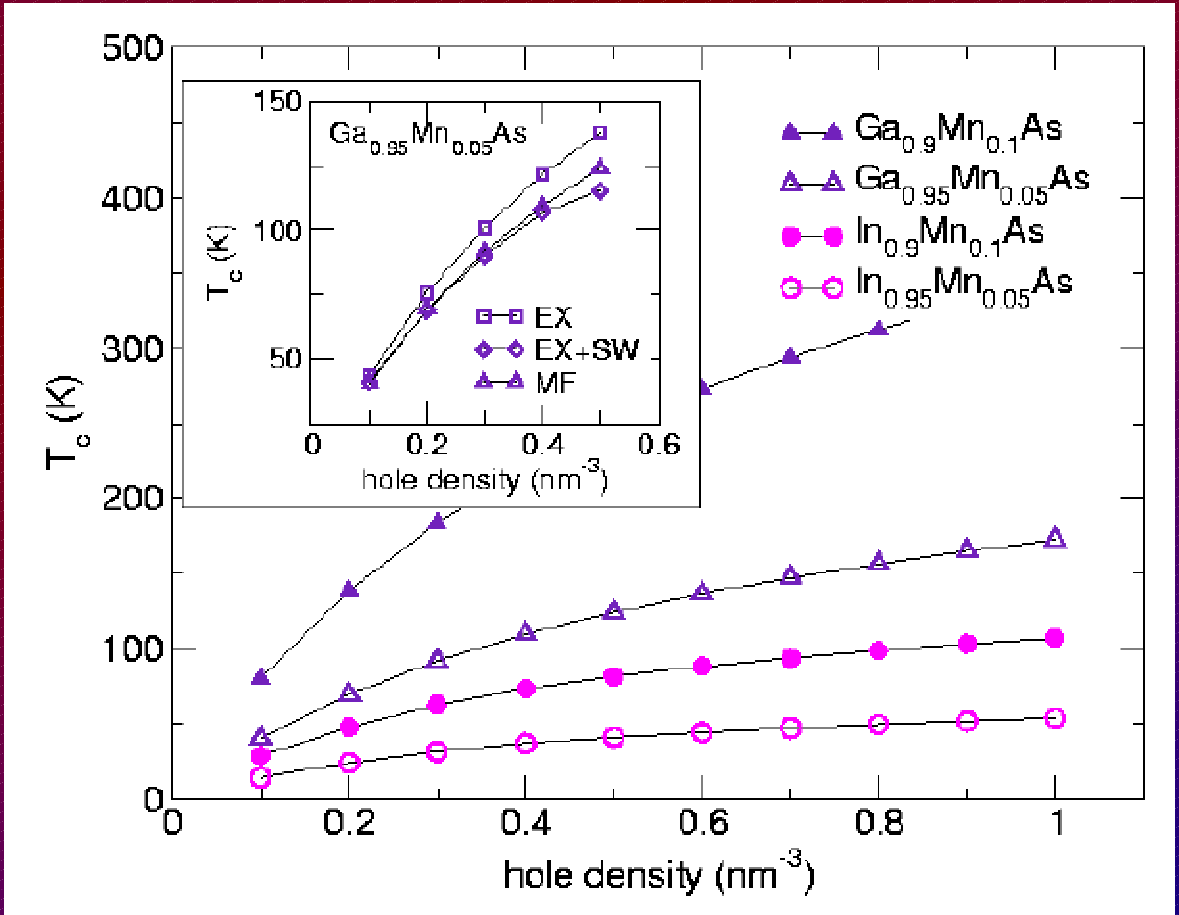
- Mean-field theory

(T. Jungwirth et al. Phys. Rev.B'99; T.Dietl et al., Science '00)



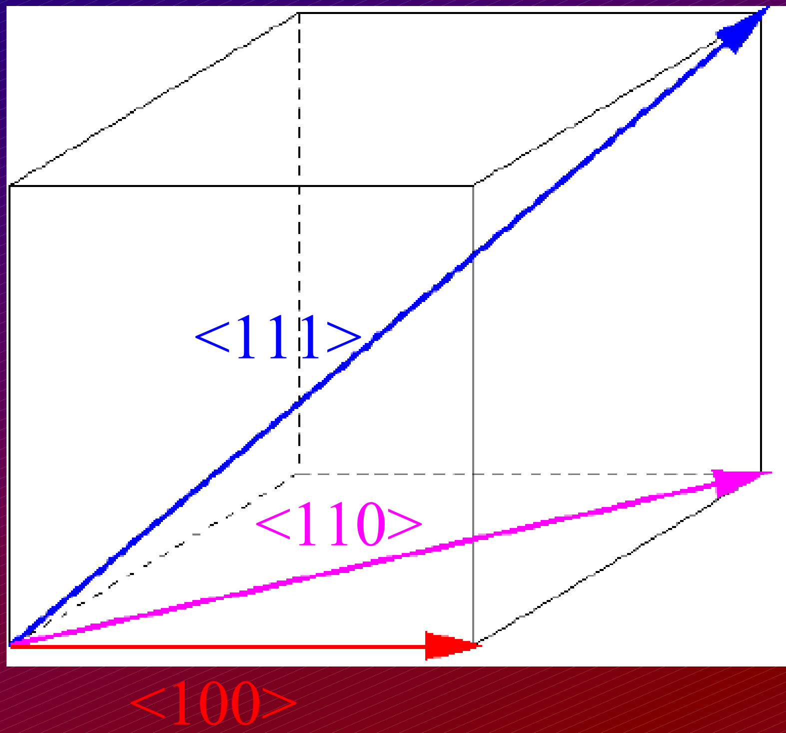
Ferromagnetic transition temperature

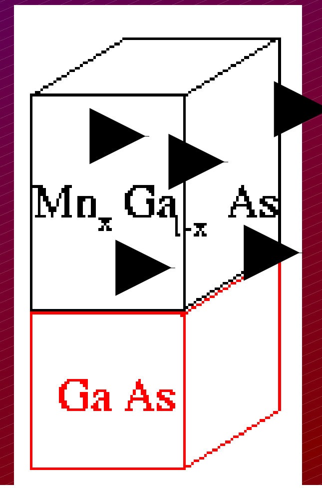


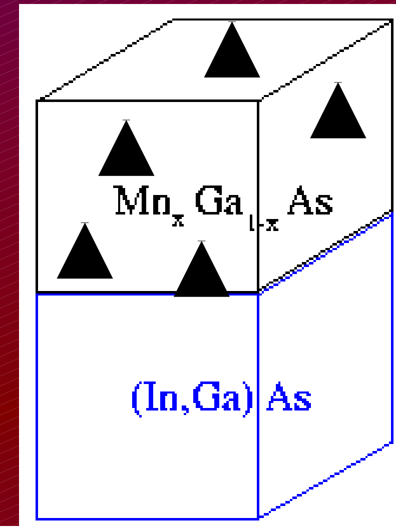


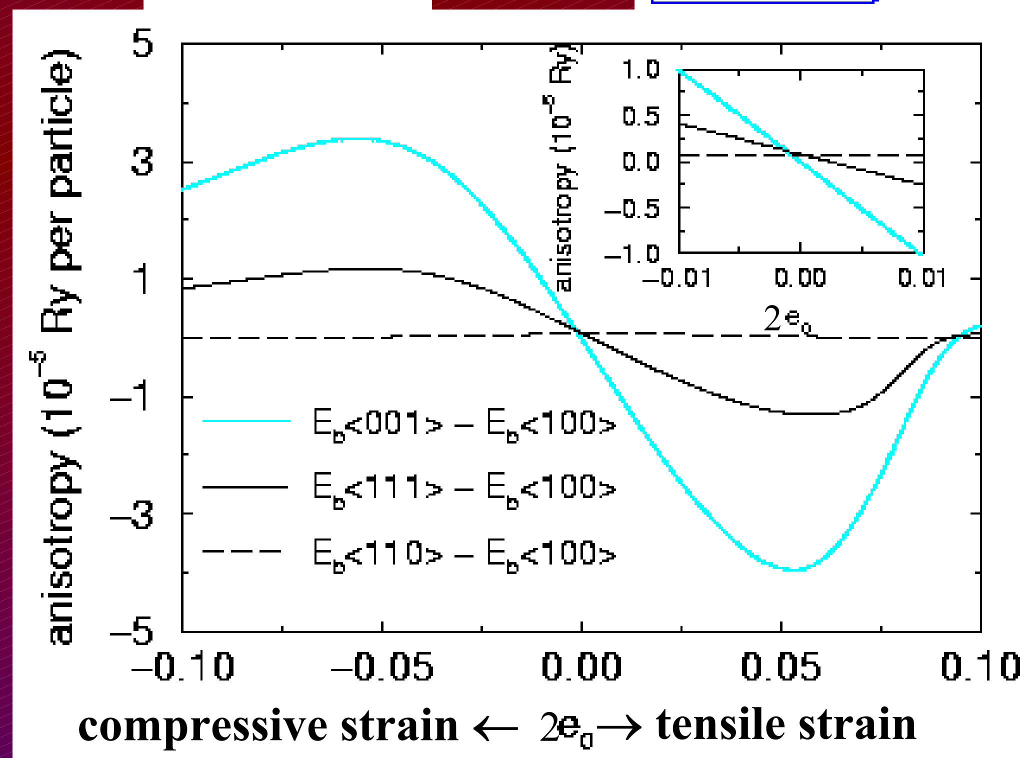
(T. Dietl, H. Ohno, T. Matsukura, Phys. Rev. B '01; T. Jungwirth et al. Phys. Rev. B '99; '02)

Magnetic anisotropy







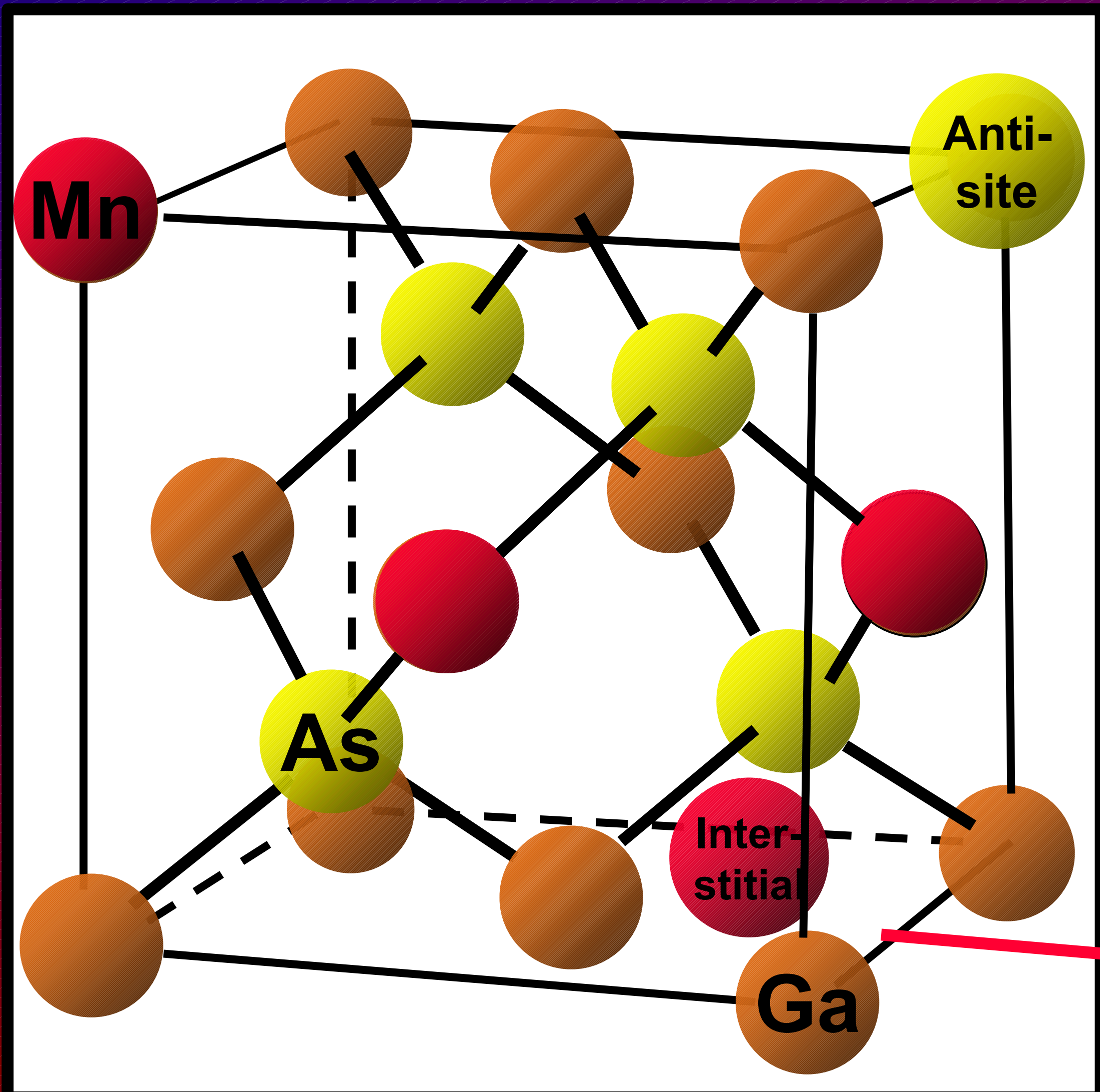


Condensation energy depends on magnetization orientation

(T. Dietl, H. Ohno, F. Matsukura, PRB '01; M. Abolfath, T. Jungwirth, J. Brum, A.H. MacDonald, Phys. Rev. B '01)

Low Temperature MBE

Disorder

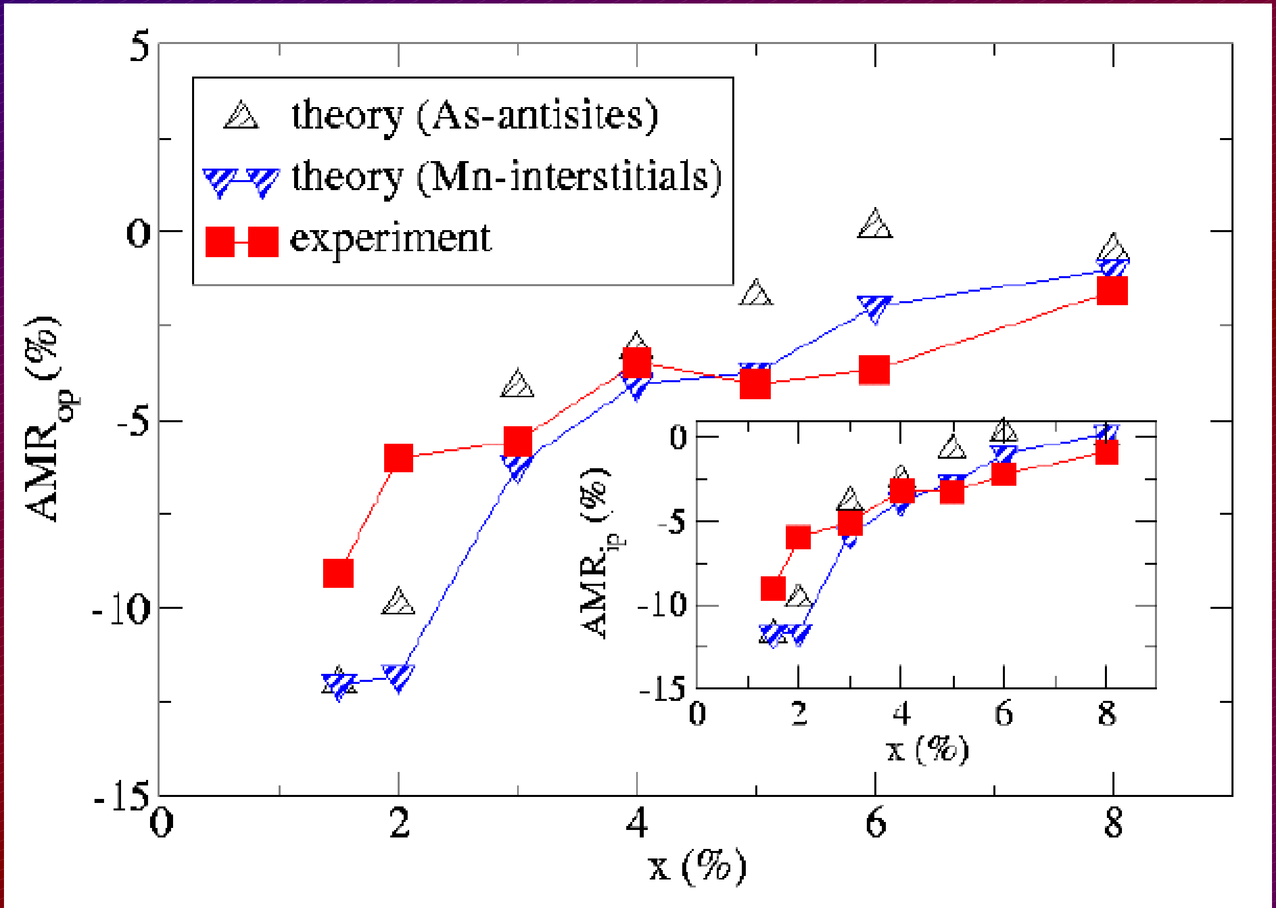


As anti-site deffect:
Q=+2e
Coulomb potential

Substitutioanl Mn:
Q=+e and local5/2 moment
Coulomb and exchange potentials

Interstitial Mn:
Q=+2e
Coulomb potential

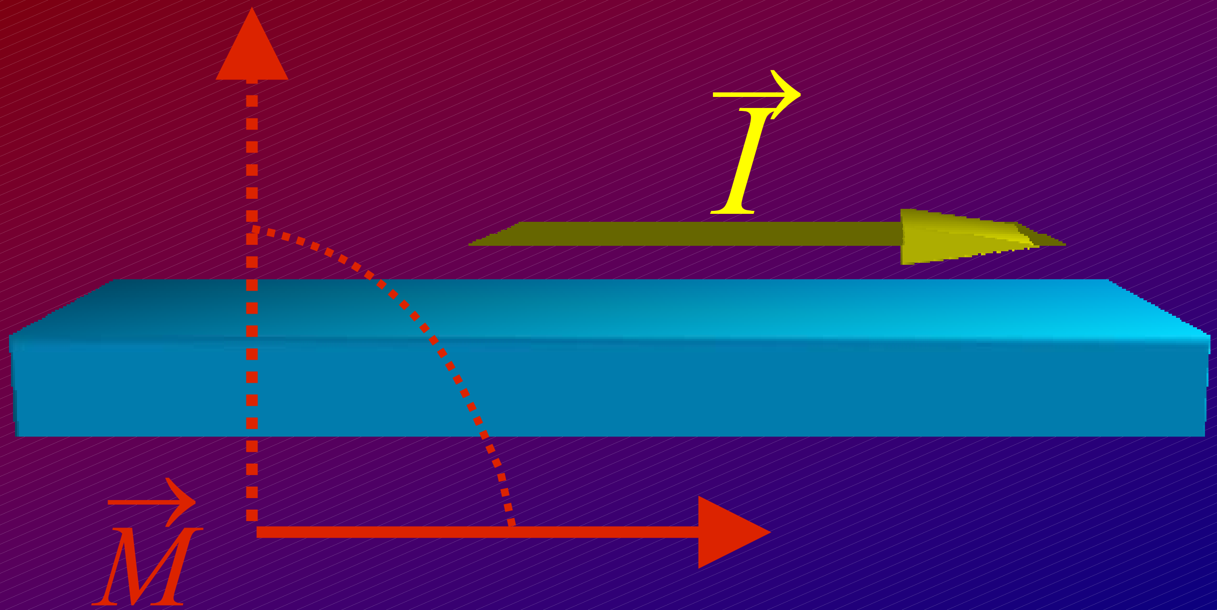
Anisotropic magnetoresistance



Born approximation
(finite quasiparticle lifetimes)

&

Linear-response theory



Anomalous Hall effect

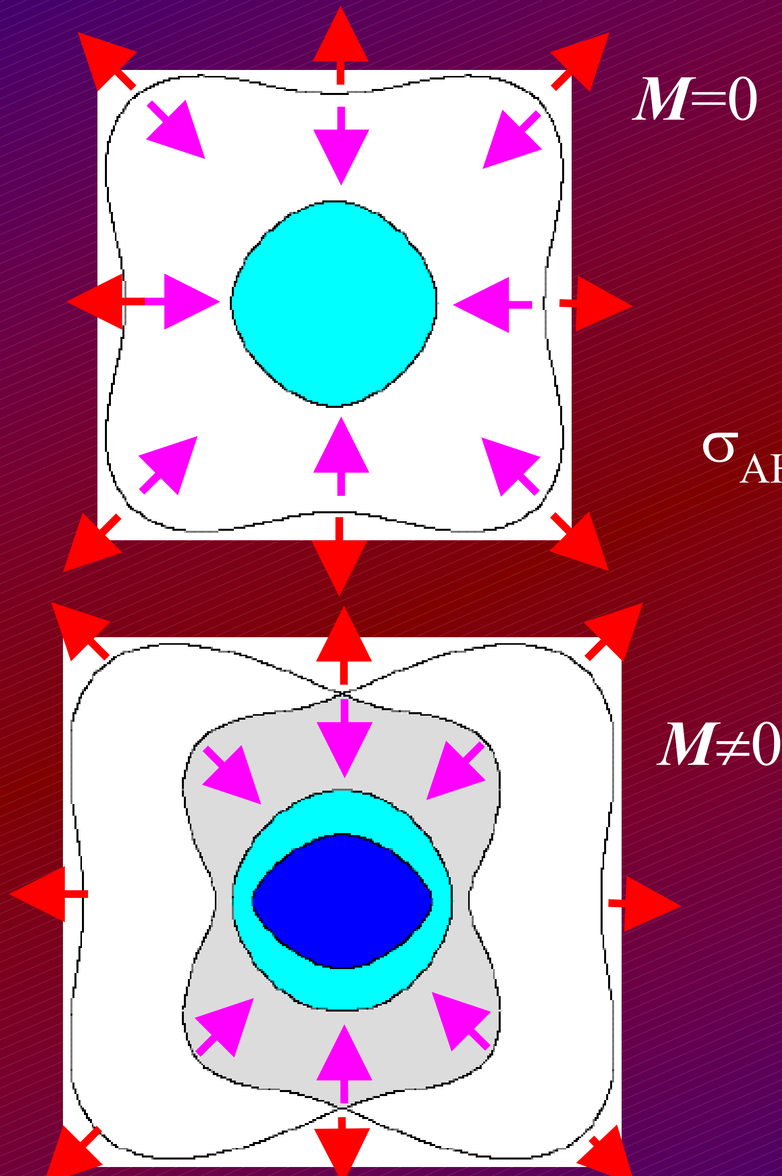
- Traditional approach: spin-orbit coupling in the scattering term
  skew scattering-> $\rho_{AH} \sim \rho$ and side-jump scattering-> $\rho_{AH} \sim \rho^2$
  (L. Berger, Phys. Rev. B '70)

- First and latest theories: band Hamiltonian with spin-orbit coupling
  non-zero *intrinsic* σ_{AH}
  (R. Karplus, J. Luttinger, Phys. Rev '54;
  M. Onoda, N. Nagaosa, J. Phys. Soc. Jpn. '02;
  T. Jungwirth, Q. Niu, A.H. MacDonald, PRL '02)

- Semiclassical anomalous velocity

  $\boldsymbol{v} = \partial E_k / h\, \partial \boldsymbol{k} + (e/h)\, \boldsymbol{E} \times \boldsymbol{F}$

  Berry phase (F): $\sigma_{AH} \sim \mathrm{Im}\langle \partial u_n / \partial k_x | \partial u_n / \partial k_y \rangle$



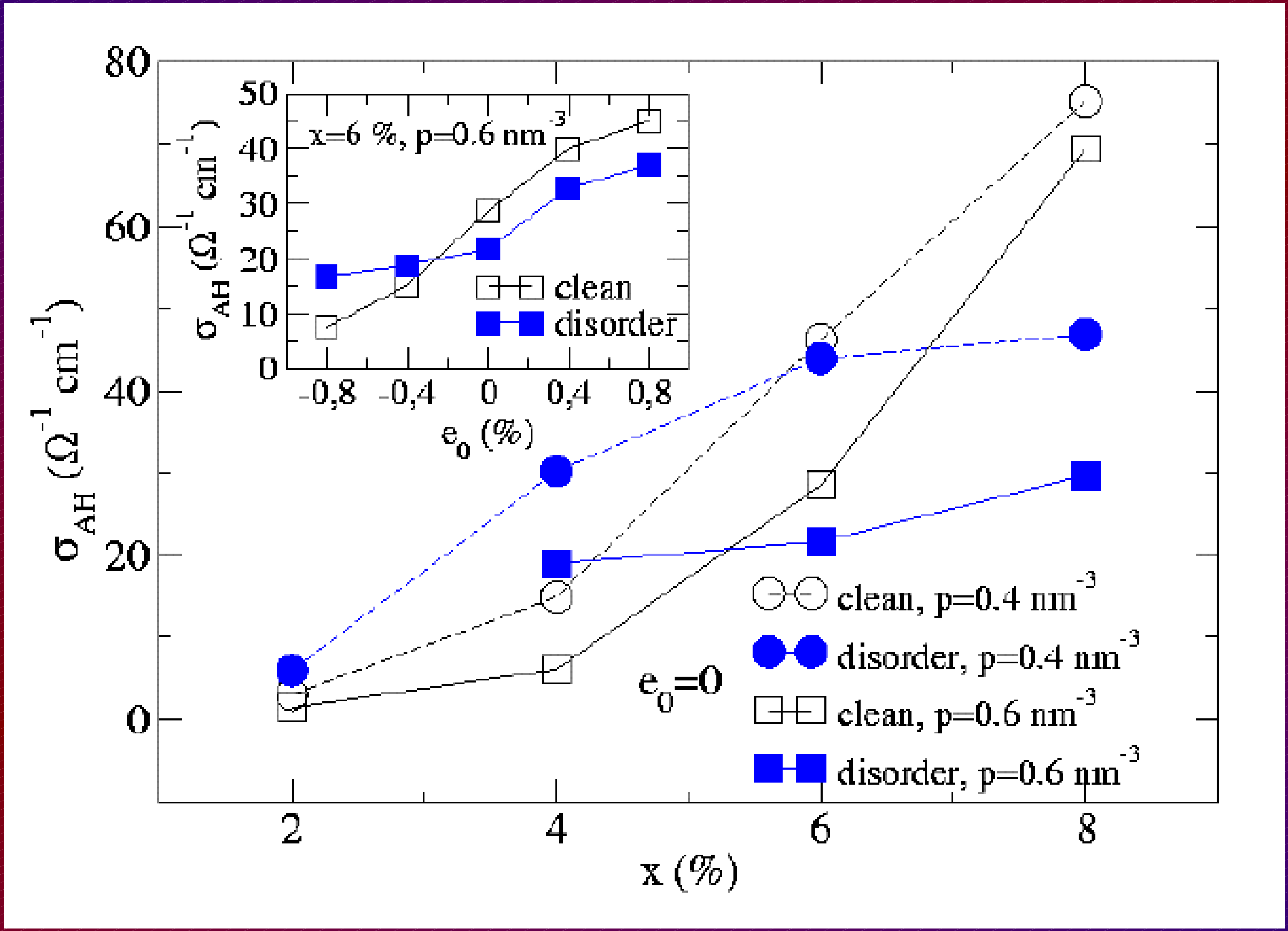
- Quantum Kubo formula

$$\sigma_{AH} \sim \mathrm{Im}[\langle n',\mathbf{k}|p_x|n,\mathbf{k}\rangle\langle n,\mathbf{k}|p_y|n',\mathbf{k}\rangle]/(E_{n,\mathbf{k}} - E_{n',\mathbf{k}})^2$$

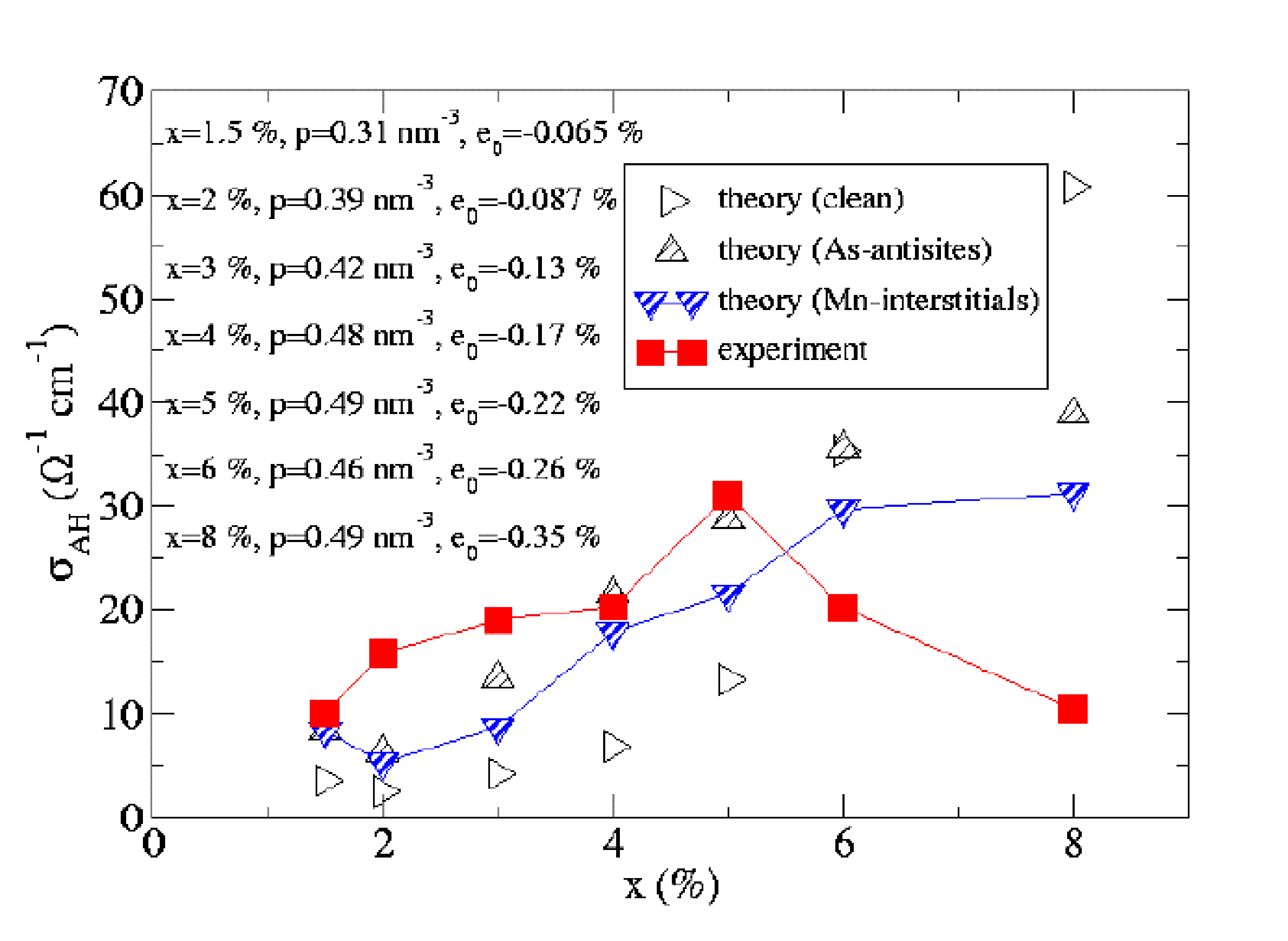
finite quasiparticle lifetimes

Analytic expression for the clean limit, small polarization, and strong spin-orbit coupling

Doping and strain dependent AHE



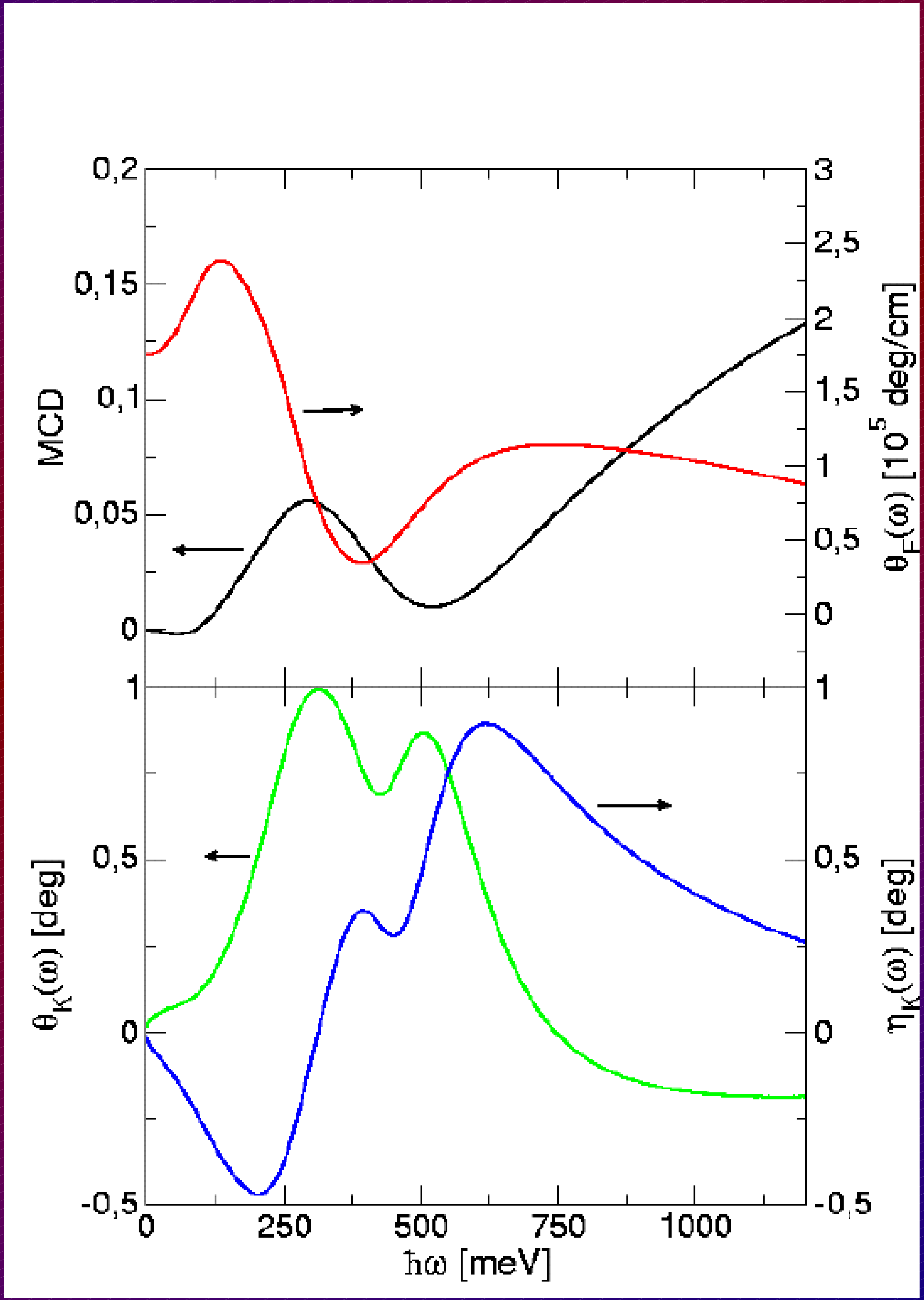
Theory vs. experiment



(T. Jungwirth, K.W. Edmonds, J. Sinova, B. L. Gallagher, A.H. MacDonald, unpublished)

Infared magneto-optics

- Finite-frequency Kubo formula
- Born approximation quasiparticle lifetimes



Large MO effects

(J. Sinova, B. T. Jungwirth, A.H. MacDonald, unpublished)

Effective Hamiltonian (MF) and weak scattering theories
(no free parameters)

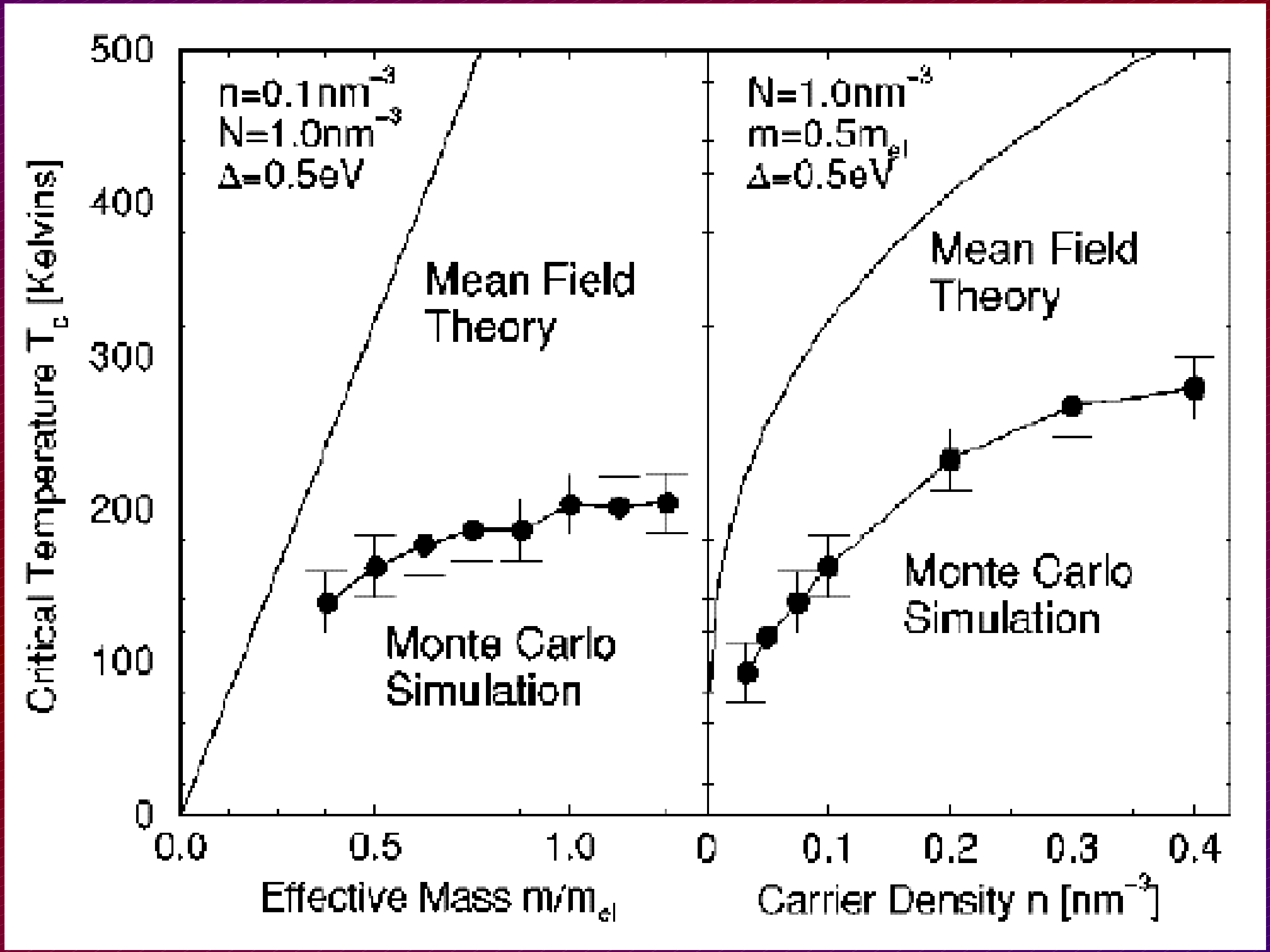
- Ferromagnetic transition temperature √
- Magneto-crystalline anisotropy and coercivity √
- Domain structure √
- Anisotropic magnetoresistance √
- Anomalous Hall effect √
- MCD in the visible range √
- Non-Drude peak in longitudinal ac-conductivity √

- Infrared and visible range magneto-optics
- Ferromagnetic resonance
- Heterostructures and multilayers (spin-transfer, TMR, etc.)
- . . .

Extras ...

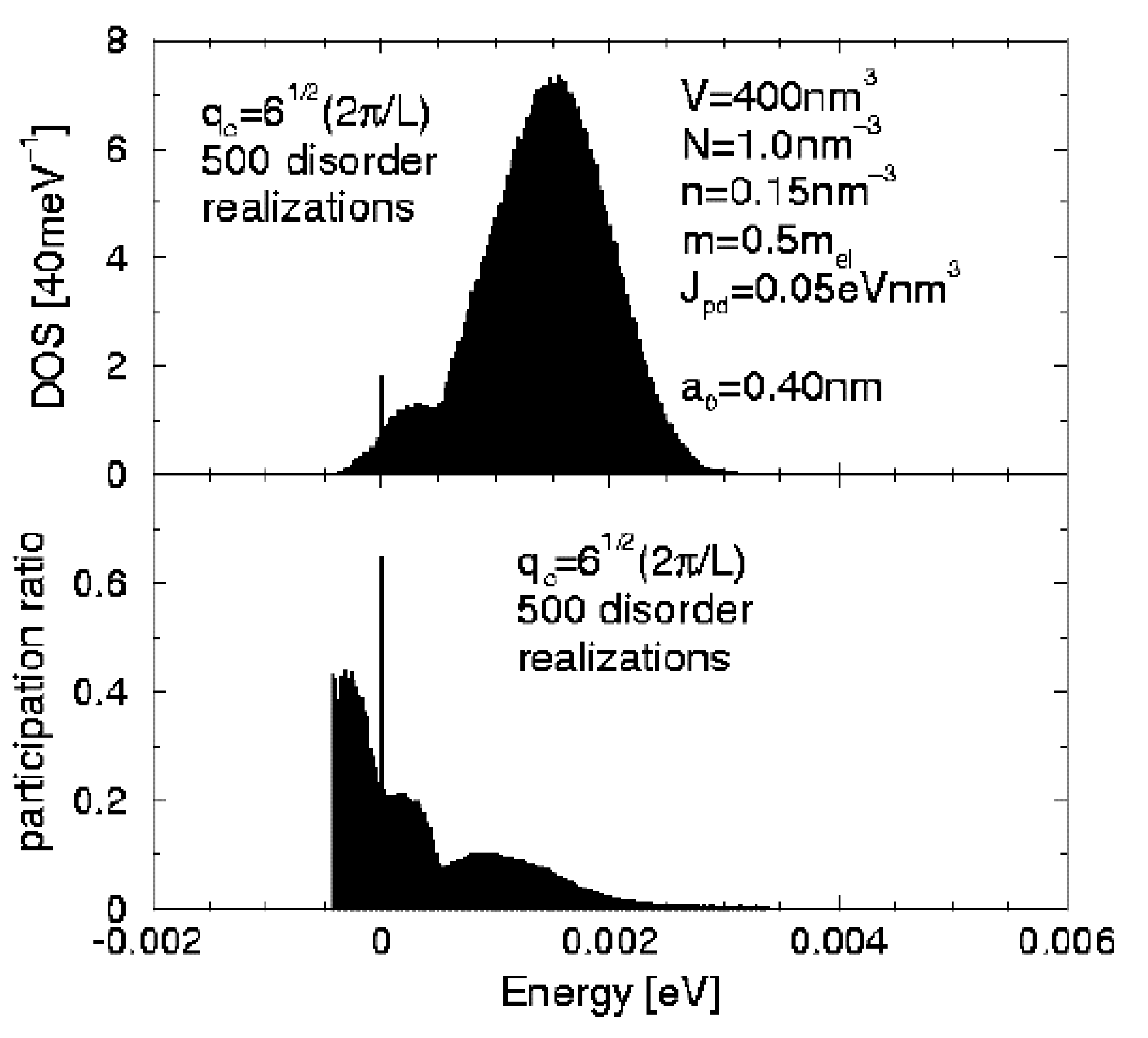
Disorder effects beyond Born approximation

Suppresion of T_c due to spin fluctuations and disorder



(J. Schliemann, J. König, and A.H. MacDonald, PRB '01)

Non-collinear ground states



(J. Schliemann and A.H. MacDonald, PRL '02; also G. Zerand and B. Janko, PRL '02)

Metal-insulator transition at ~1% Mn

(S.-R. Eric Young and A.H. MacDonald, cond-mat/0202021;
C. Timm, F. Schäfer and F. von Oppen, PRL'02)

Enhanced T_c due to disorder in the insulating phase

(R.N. Bhatt, M. Berciu, M.P. Kennett, and X.Wan, Journal of Superconductivity '02)