Ultra-high Anomalous Hall Conductivity in Fe(001) Films with High Conductivity

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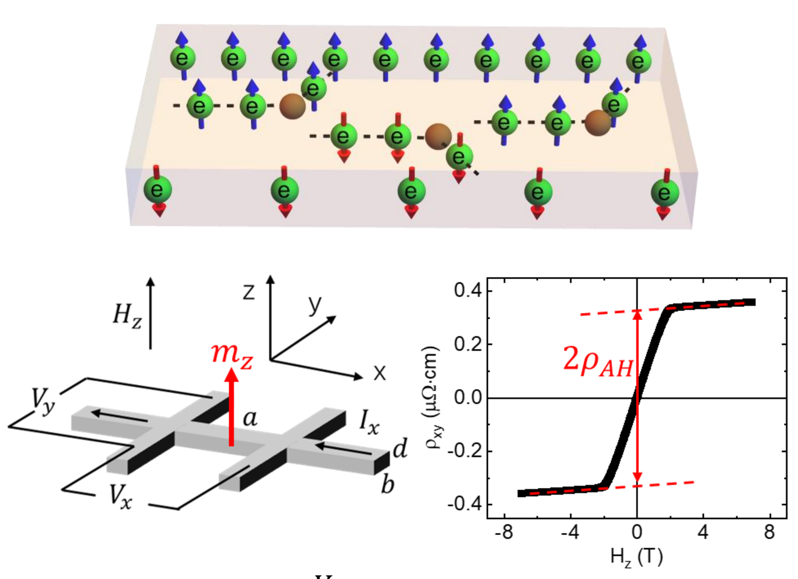
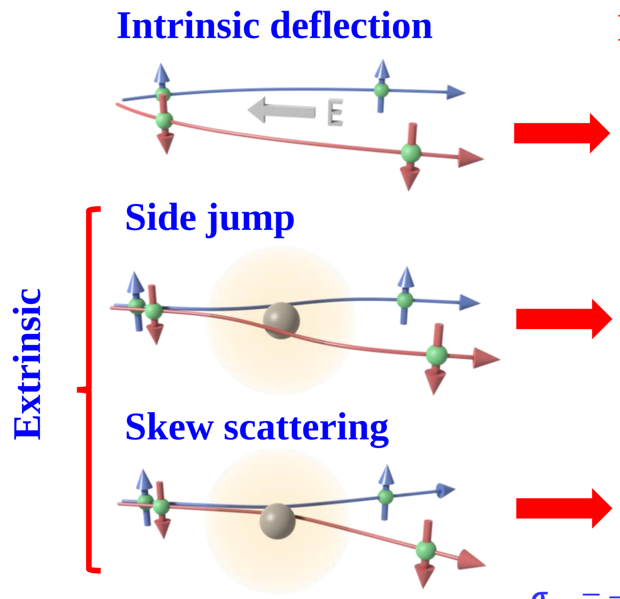
Motivation

Anomalous Hall effect (AHE):



$\rho_{xy} = \frac{V_y}{I_x} = R_H^0 H_z + \rho_{AH} m_z$

Mechanisms of AHE:



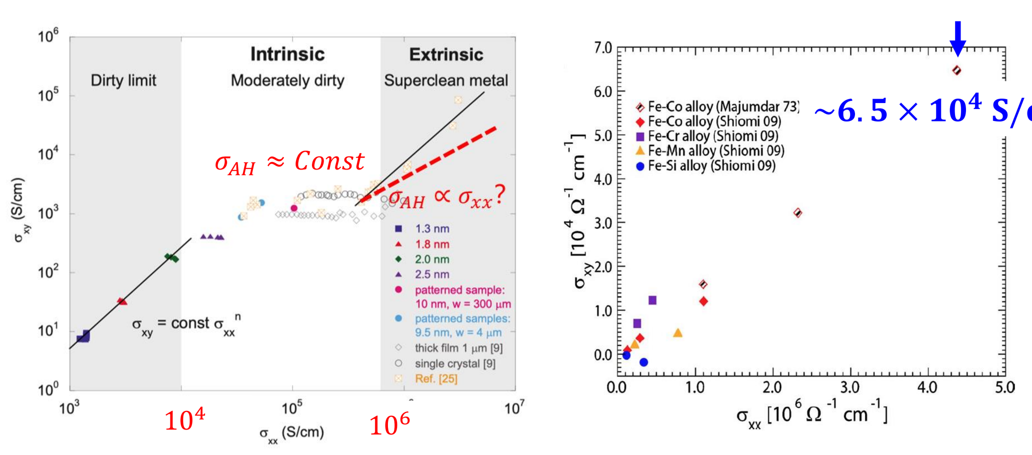
Intrinsic deflection — Different scaling: $\rho_{AH} \propto \rho_{xx}^2$, $\sigma_{AH} = Const$

Extrinsic:

- Side jump: $\rho_{AH} \propto \rho_{xx}^2$, $\sigma_{AH} = Const$
- Skew scattering: $\rho_{AH} \propto \rho_{xx}$, $\sigma_{AH} \propto \sigma_{xx}$

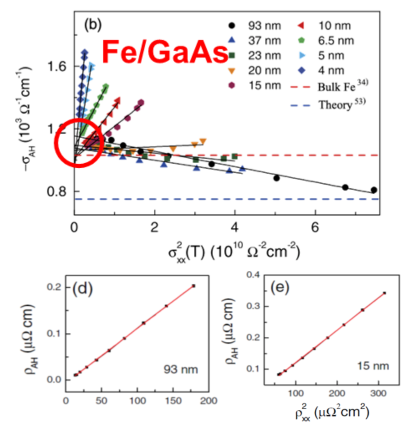
$\sigma_{xx} = \frac{1}{\rho_{xx}}$ $\quad \sigma_{AH} = \frac{\rho_{AH}}{\rho_{xx}^2 + \rho_{AH}^2}$

Three regions of AHE in conventional understanding



S. Sangiao *et al.*, Phys. Rev. B (2009), N. Nagaosa *et al.*, Rev. Mod. Phys. (2010)

In magnetic thin film



$\sigma_{AH} = -(\alpha\sigma_{xx0}^{-1} + \beta\sigma_{xx0}^{-2})\sigma_{xx}^2 - b$

$\rho_{AH} = (\alpha\rho_{xx0} + \beta\rho_{xx0}^2) + b\rho_{xx}^2$

Impurity scattering — Intrinsic

TYJ model — Y. Tian *et al.*, PRL (2009)

AHE scaling in ultra-clean region of magnetic thin film?

High quality samples

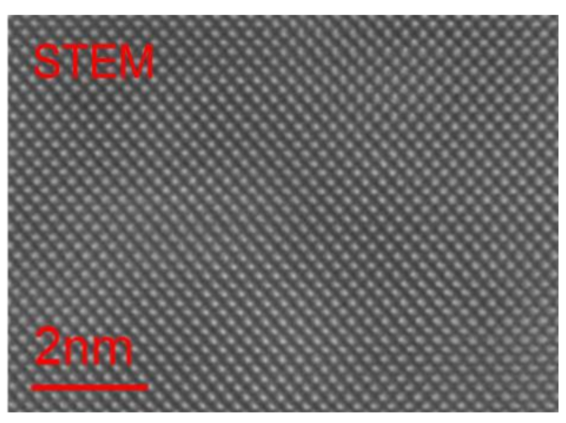
Fe/MgAl₂O₄(001)

$a_{Fe} = 0.287$ nm

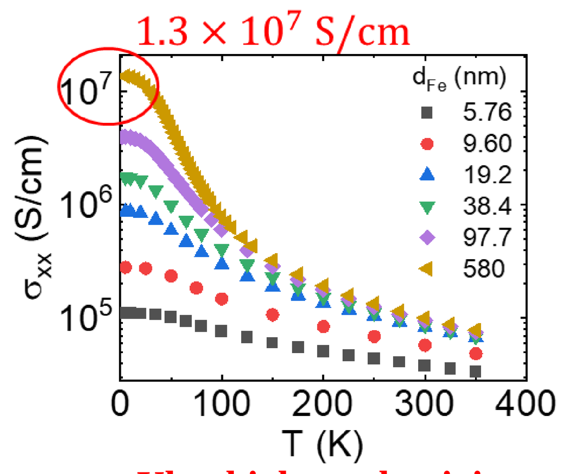
$\frac{a_{MAO}}{2\sqrt{2}} = 0.286$ nm

0.4% mismatch

B. Khodadadi *et al.*, Phys. Rev. Lett. (2020)



High quality epitaxial growth

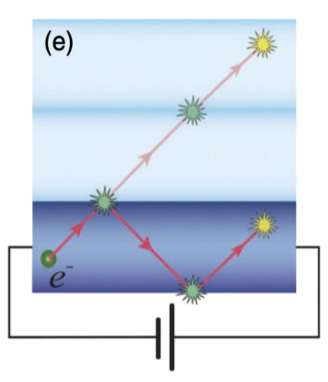


Ultrahigh conductivity

Scaling in thin films

Low temperature: Electron-impurity scattering dominates

Conventional

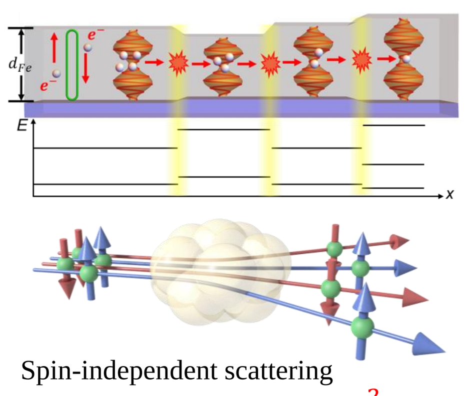


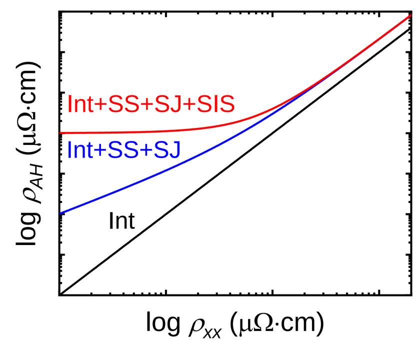
$\sigma_{AH} = \alpha_I\sigma_{xx0} + \beta_I + b$

$\rho_{AH} = \alpha_I\rho_{xx0} + (\beta_I + b)\rho_{xx0}^2$

D. Hou *et al.*, JPCM (2012)

Quantum confinement effect





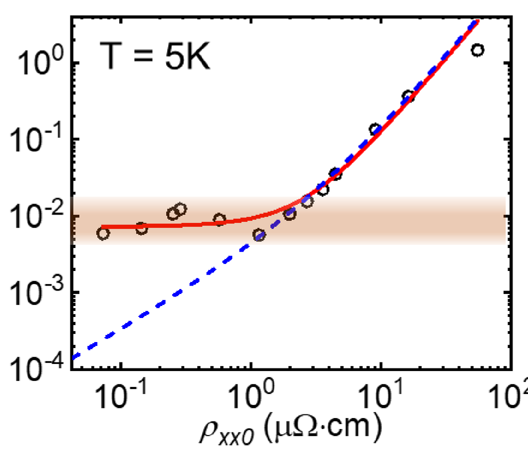
$\sigma_{AH} = \alpha_I \frac{\sigma_{xx0}^2}{\sigma_I} + \beta_I \frac{\sigma_{xx0}}{\sigma_I} + b$

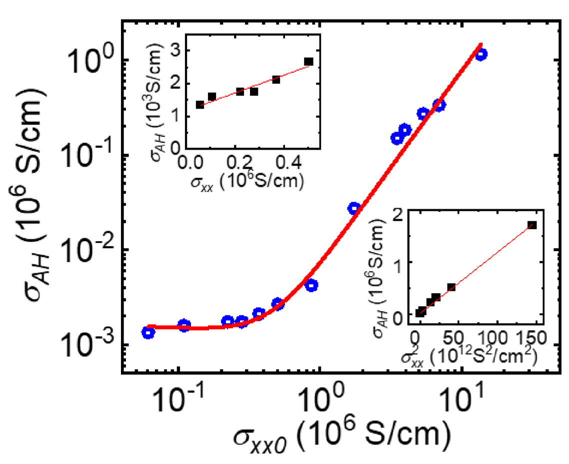
$\rho_{AH} = \alpha_I\rho_I + \beta_I\rho_{xx0}\rho_I + b\rho_{xx0}^2$

V. L. Grigoryan *et al.*, Phys. Rev. B (2017)

$\rho_{xx0}(\sigma_{xx0})$: total resistivity(conductivity); $\rho_I(\sigma_I)$: impurity resistivity(conductivity) in bulk; α_I: impurity skew scattering; β_I: impurity side jump

New results from high quality Fe films:





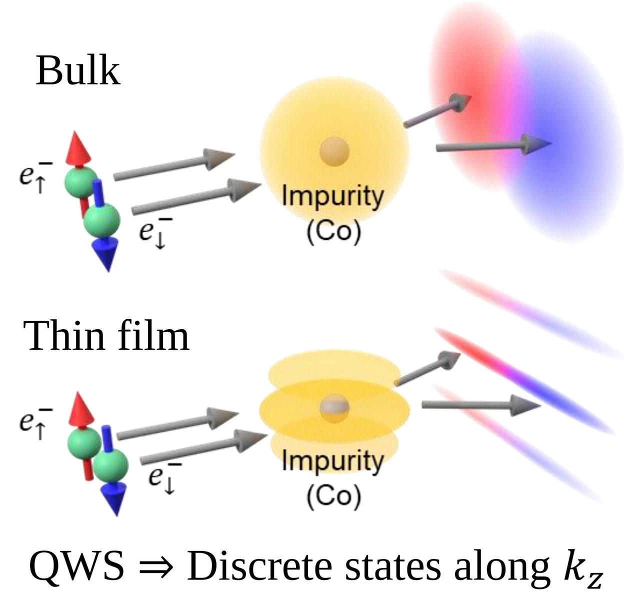
- Low σ (High ρ): $\rho_{AH} \propto \rho_{xx0}, \sigma_{AH} \propto \sigma_{xx0}$ Conventional
- High σ (Low ρ): $\rho_{AH} \approx Const, \sigma_{AH} \propto \sigma_{xx0}^2$

Maximum AHE conductivity

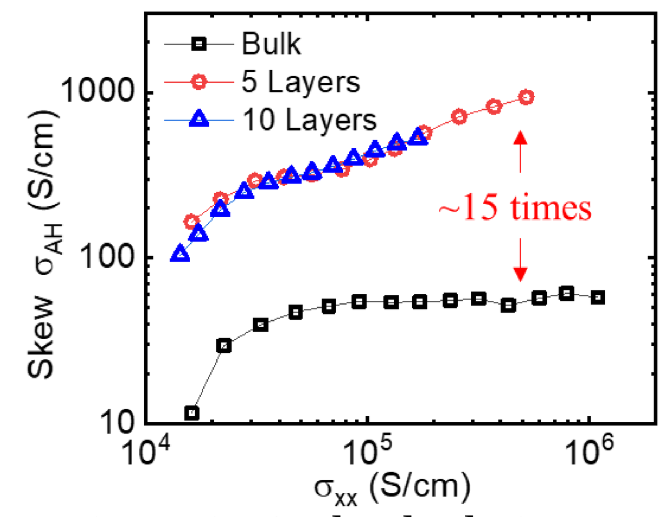
$\sigma_{AH} \sim 1.15 \times 10^6$ S/cm

Quantum confinement effect ⇒ New AHE scaling

Enhancement of skew scattering



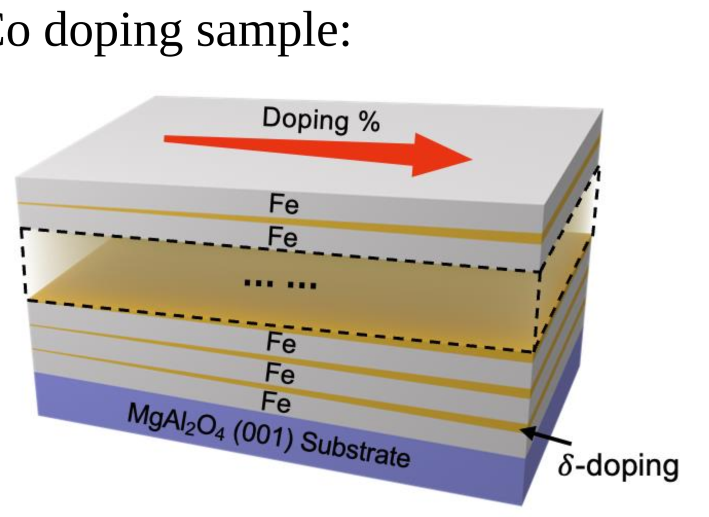
QWS ⇒ Discrete states along k_z

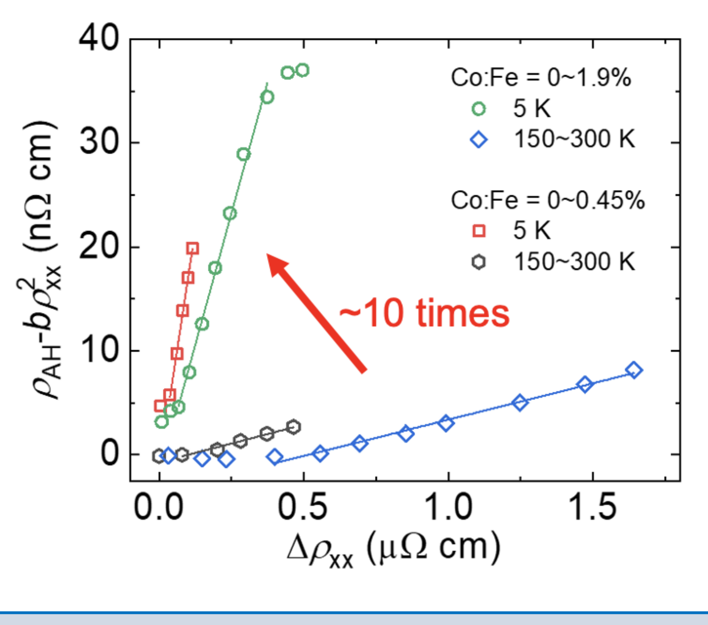


First principal calculation

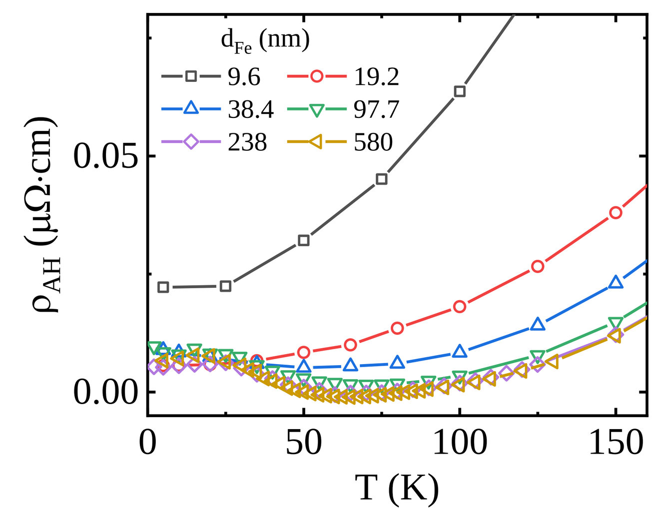
⇒ **Enhanced skew scattering in thin films**

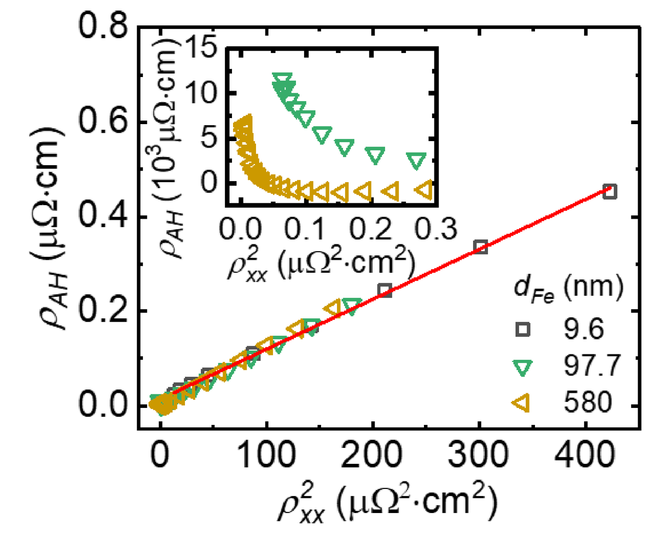
Co doping sample:



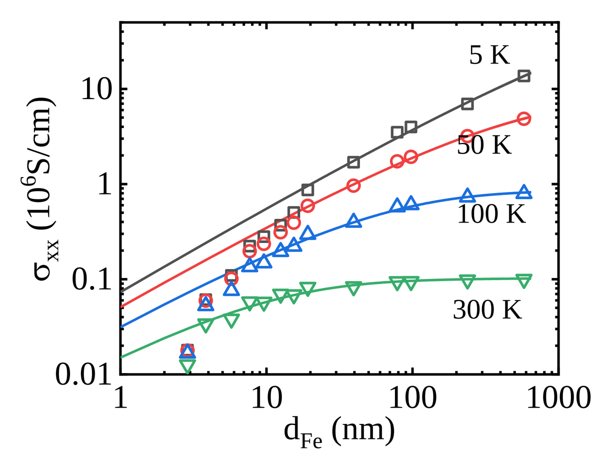


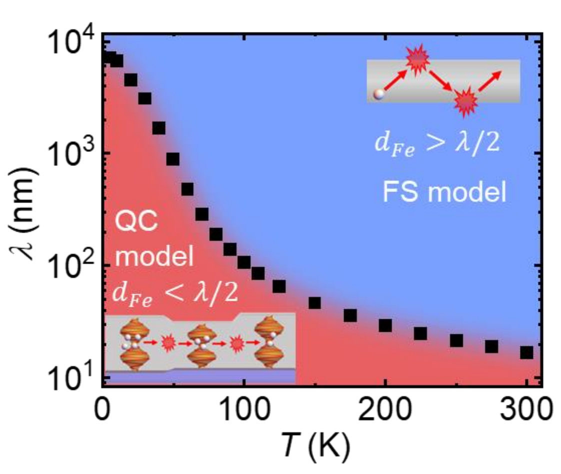
Nonmonotonic $\rho_{AH}(T)$ dependence

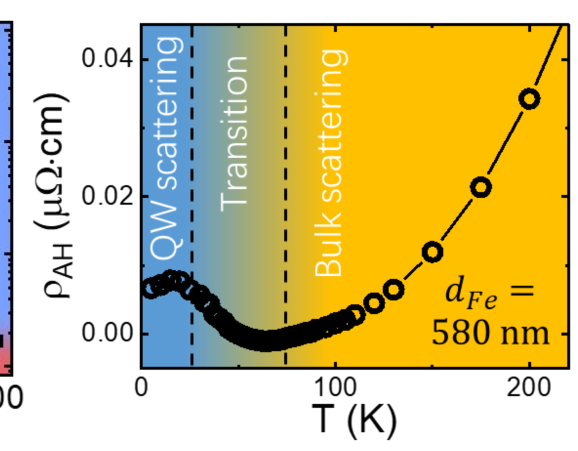




Nonmonotonic $\rho_{AH} \sim T$ dependence in $d_{Fe} > 30$ nm films







Fitted by Fuchs-Sondheimer(FS) model:

$\sigma(d) = \sigma_0 - \frac{3\lambda}{2d}\sigma_0(1-p)\int_1^\infty \left(\frac{1}{t^3} - \frac{1}{t^5}\right)\frac{1-e^{-\frac{d}{\lambda}t}}{1-pe^{-\frac{d}{\lambda}t}}dt$

⇒ mean free path λ(T)

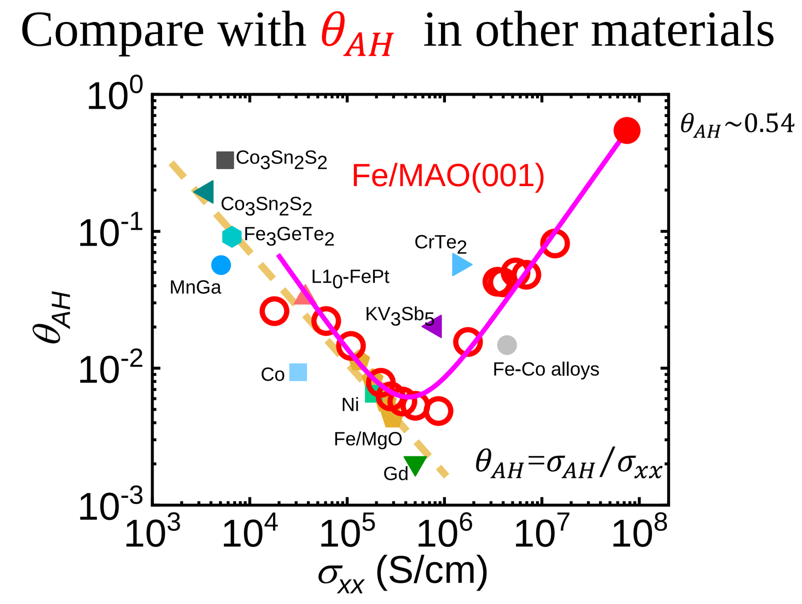
Transition from classic scattering to quantum confinement effect

⇒ Enhancement of ρ_{AH} at low temperature

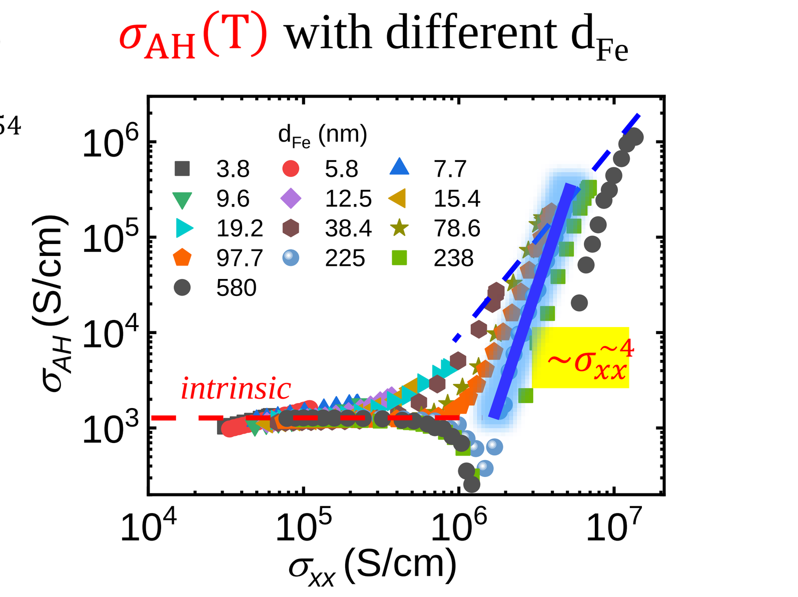
Skew scattering at low T is stronger than at high T

Ultra high anomalous Hall angle

Compare with θ_{AH} in other materials



σ_{AH}(T) with different d_{Fe}



- $10^4 < \sigma_{xx} < 10^6$ S/cm
  Intrinsic mechanism dominants, $\sigma_{AH} \approx 1.2 \times 10^3$ S/cm, $\theta_{AH} \propto \sigma_{xx}^{-1}$
- $\sigma_{xx} > 10^6$ S/cm (ultra-clean)
  Skew scattering dominants, $\theta_{AH} \propto \sigma_{xx}$, $\sigma_{AH} \sim 1.15 \times 10^6$ S/cm $\theta_{AH} \sim 8.6\%$
- Transition region at T ~ 50 K Unusual scaling: $\sigma_{AH} \propto \sigma_{xx}^{\sim 4}$

Summary

AHE measurement in high quality Fe(001) films

- Ultra-high conductivity $\sigma_{xx} \sim 1.3 \times 10^7$ S/cm.
- Ultra-high anomalous Hall conductivity $\sigma_{AH} \sim 1.15 \times 10^6$ S/cm.
- High Hall angle $\theta_{AH} \sim 8.6\%$.
- $\sigma_{AH} \propto \sigma_{xx0}^2$ at low T in skew scattering dominating region.
- Nonmonotonic $\rho_{AH}(T)$ dependence for $d > 30$ nm films.