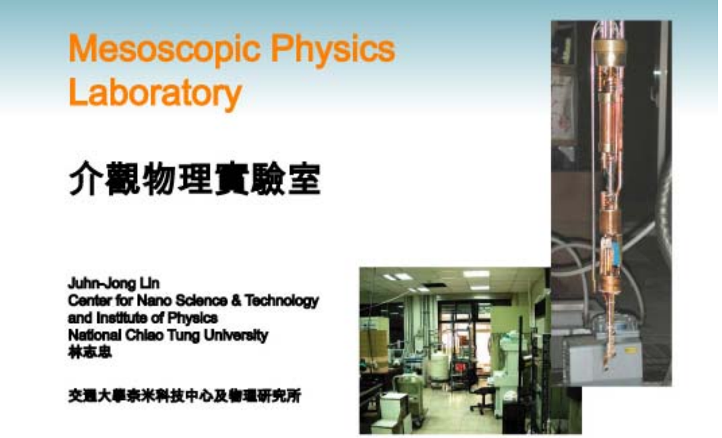

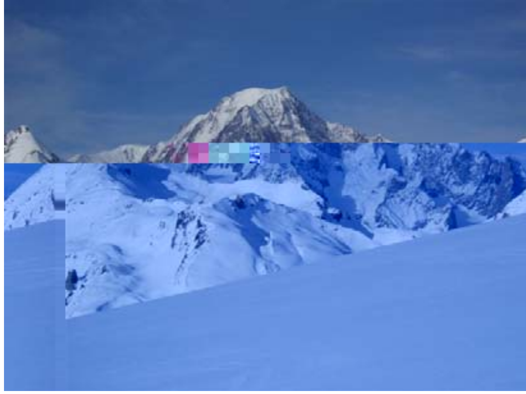

Moriond 2008

Strong Electron Dephasing in Highly Disordered $Cu_{93}Ge_{4}Au_{3}$ Thin Films and other Metal Alloys

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ELECTRON DEPHASING TIME
in highly disordered metals

Electron dephasing time from weak localization studies in highly disordered $Cu_{93}Ge_4Au_3$ thin films

Comparison with dilute Kondo magnetic impurity scattering time

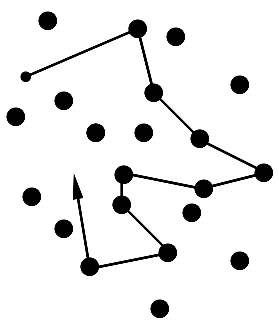
Nonmagnetic dephasing due to dynamical structural defects and/or other mechanisms

Nonmagnetic dephasing in highly disordered AuPd alloys and granular thick films

D ~ 10 cm^2/s, our samples

D ~ 100 cm^2/s, Grenoble, Saclay-Birge, Mohanty-Webb

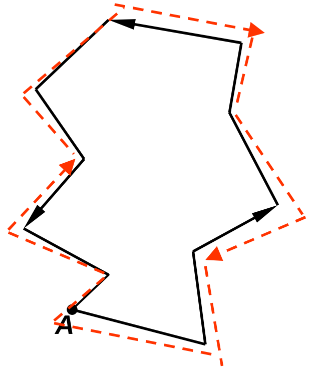
Weak Localization in Disordered Metals

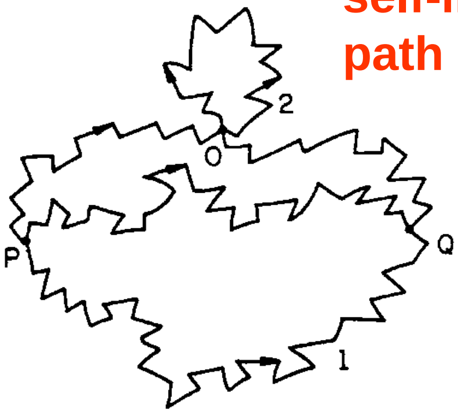


diffusive motion in disordered system

Weak localization results from the interference of two partial waves of the same electron. In real space the two partial waves propagate on a closed loop in opposite directions

Weak localization
(increased probability of finding the electron at the origin)





self-intersecting path

The two electron partial waves will maintain coherent quantum interference for a time scale called the electron dephasing time (which is often several hundreds to thousands times longer than the elastic scattering time)

Inelastic Magnetic Scattering

In recent years, the dephasing rate arising from scattering by magnetic Kondo impurities has been intensely studied, theoretical and experimental

It is widely argued that all real samples are contaminated by a **very low**, **undetectable** level of magnetic impurities

$$\frac{1}{\tau_{\varphi}(T)} = \frac{1}{\tau_{ep}(T)} + \frac{1}{\tau_{ee}(T)} + \frac{1}{\tau_{m}(T)}$$

$T \rightarrow 0$ K

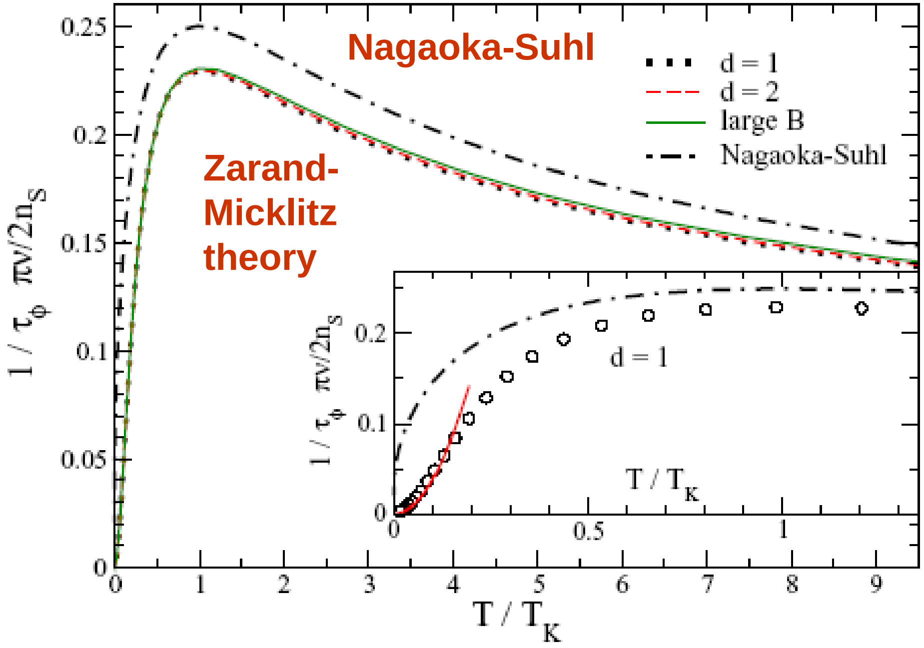
Extensive efforts have been focused on τ_{m}. But …

Dephasing rate due to diluted Kondo impurities

The inelastic scattering rate by Kondo impurities with ***S* = ½** has recently been recalculated in the case of clean metals

The new theory predicts a maximum dephasing rate $1/\tau_m$ at $T = T_K$, and a linear temperature dependence of $1/\tau_m$ in $0.05T_K < T < 0.5T_K$

The new dephasing rate is slightly weaker than the Nagaoka-Suhl rate over a wide range of temperature attainable by the experiment



The maximum scattering rate occurs at $T = T_K$

$$\frac{1}{\tau_m} = \frac{n_m}{2\pi\hbar N(E_F)}$$

(Numerical renormalization group method)

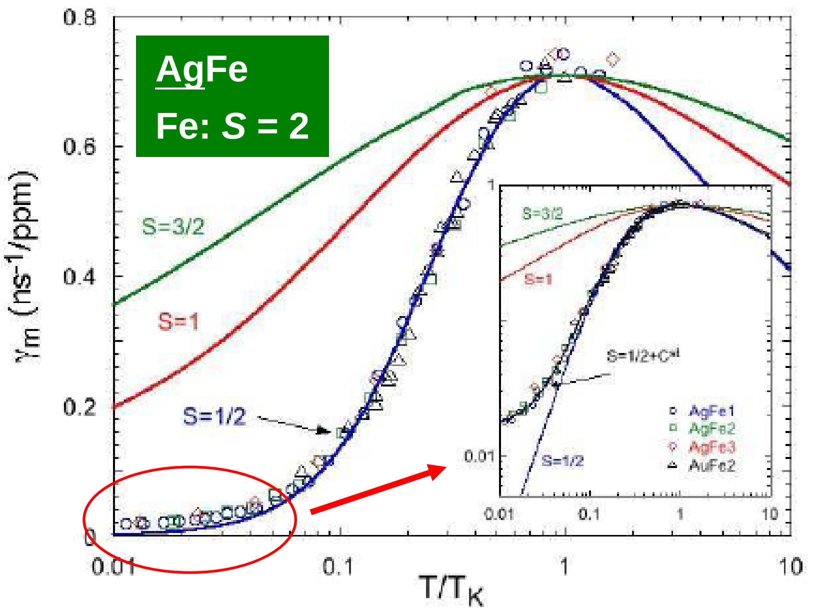
Zarand et al., PRL (2004)
Micklitz et al., PRL (2006)

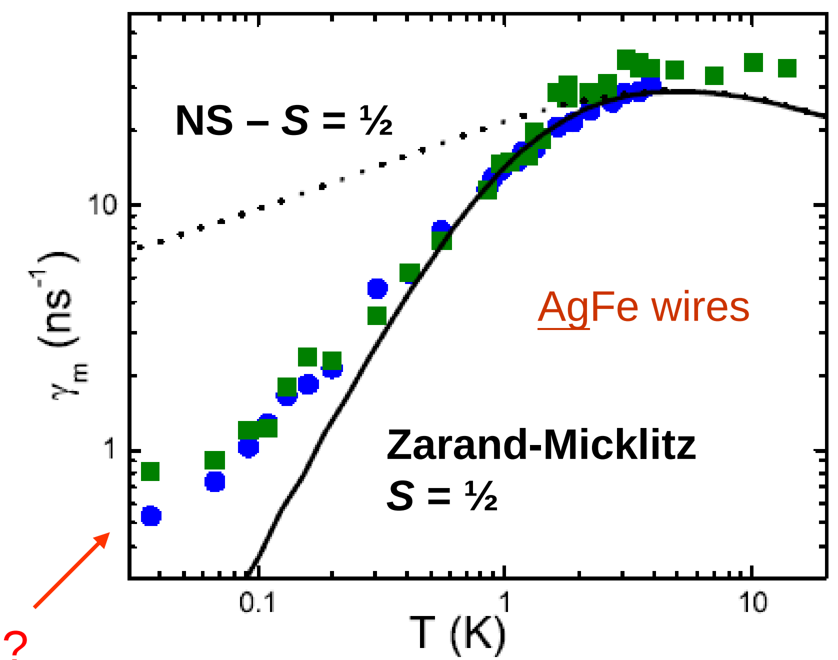
Magnetic scattering: comparison with experiment

For $T > 0.1T_K$, the measured dephasing rate is well described by the Zarand-Micklitz theory for $S = ½$ impurities

BUT, the experiment actually dealt with ***S* = 2** spins

At lower temperatures, **strong deviations** from the theory are found. The experimental rate is **significantly larger** than the theoretical value





Origin of this "residual" dephasing?

Mallet, Bauerle et al., PRL (2006)

Alzoubi & Birge, PRL (2006)

Magnetic Scattering or not?

Very often, when the measured dephasing times were ascribed to τ_m, extremely low levels of magnetic impurities (~ 0.002 – 0.02 ppm) and very low values of T_K (<< 1 K) had to be inferred

e.g., Pierre et al., Phys. Rev. B 68, 085413 (2003)

Saminadayar et al., Physica E 40 (2007) 12

$n_m \approx 0.08$ ppm, $T_K < 1$ mK (for their cleanest samples)

Our results can **NOT** be explained by the magnetic-impurity scattering theories of Zarand (clean metals), and Kettemann (disordered metals)

Questions:

Incomplete current understanding of the inelastic magnetic scattering by Kondo impurities?

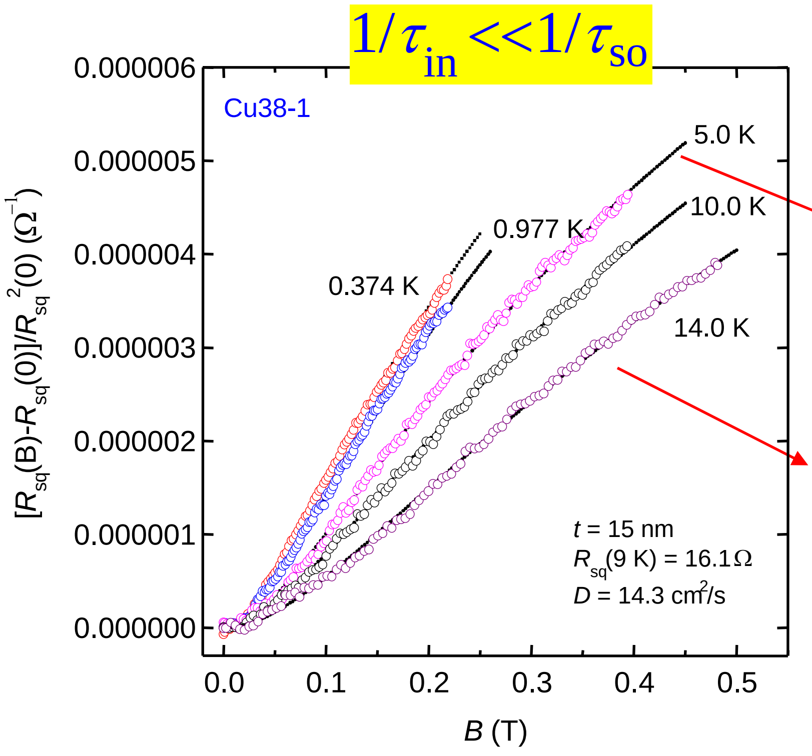
The role of magnetic scattering in dephasing is *overemphasized*?

***Nonmagnetic* source for dephasing is responsible?**

Highly disordered $Cu_{93}Ge_4Au_3$ thin films: Nonmagnetic dephasing

The measured magnetoresistances are well described by the 2D weak localization theoretical predictions, with τ_φ as the **only** free parameter

15 – 20 nm thickness



Ge doping: increasing disorder

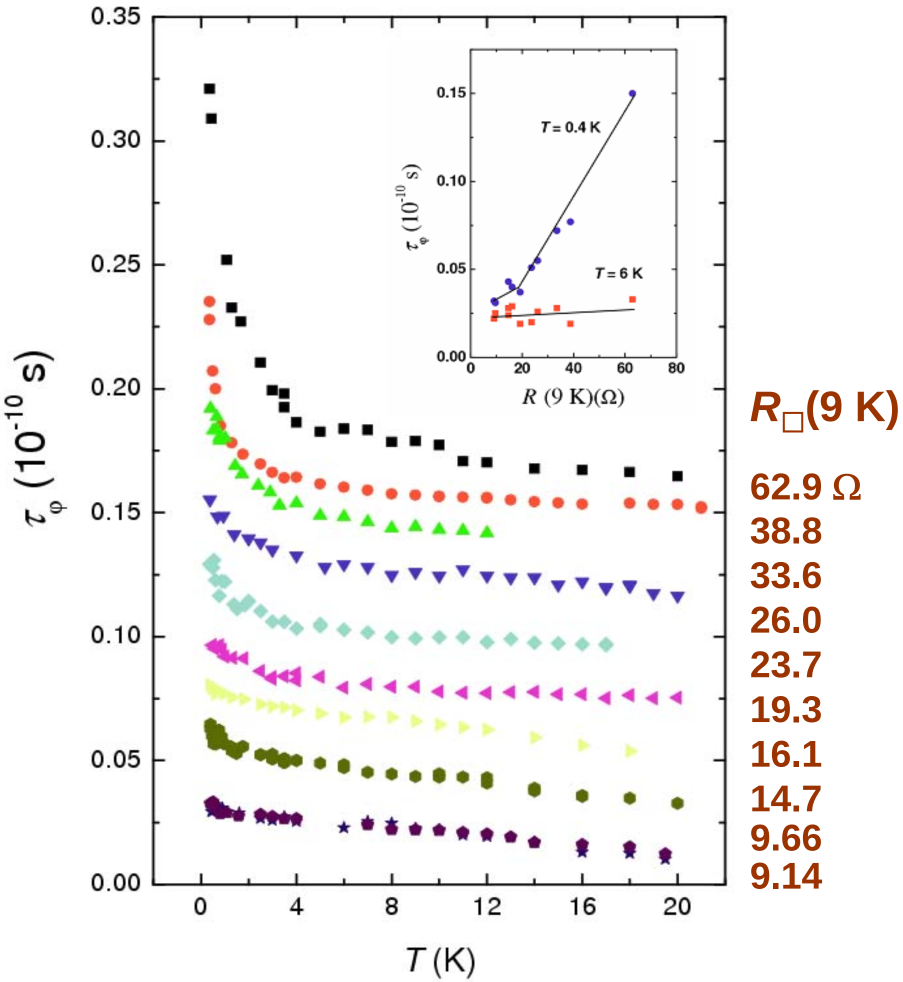
Au doping: enhancing spin-orbit scattering

Mohanty, Birge, Bauerle:
(*weakly* disordered)
***D* > 100 cm²/s**

Lin: (*highly* disordered)
***D* = 4 – 25 cm²/s**

Strong electron dephasing in CuGeAu films

$Cu_{93}Ge_4Au_3$ films



(The value of τ_φ for each film has been vertically shifted up for clarity)

A plateau in τ_φ around 6 K, followed by a slow upturn as the temperature is further reduced below 4 K

Very short and **similar** value of τ_φ(6 K) ≈ 2 – 3 ps. Two orders of magnitude shorter than $\tau_{ee}^{(2D)}$

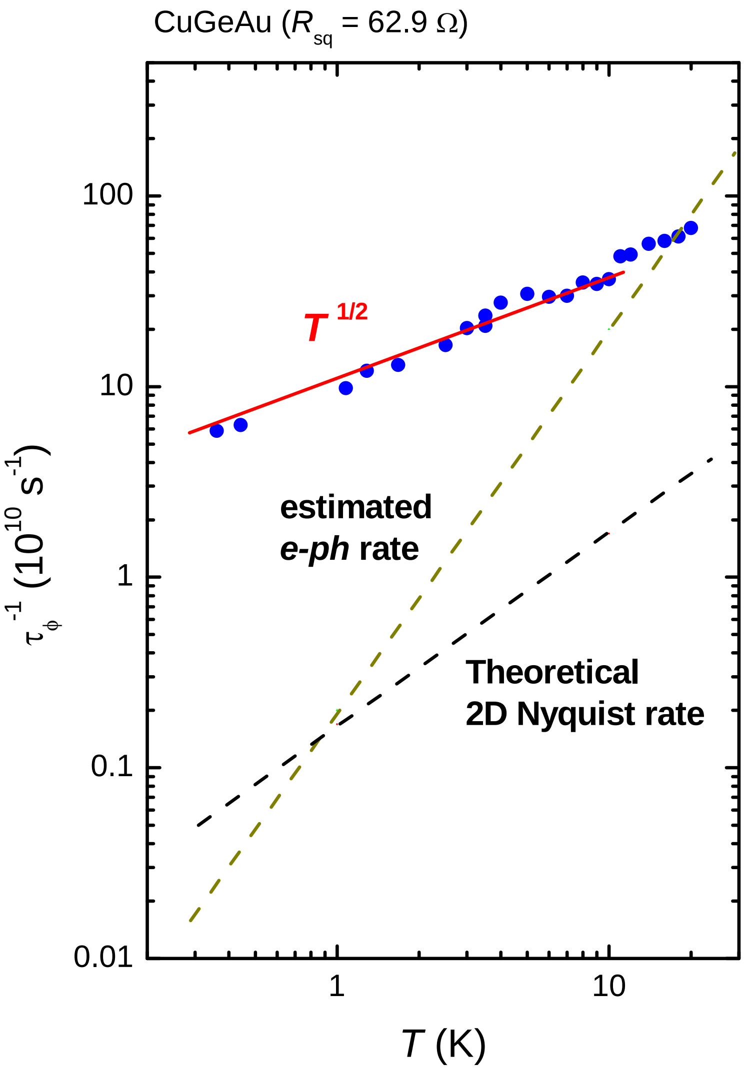
If the measured τ_φ(6 K) were all ascribed to magnetic scattering, one would need an **unrealistically high** level of n_m ≈ 200 – 300 ppm

$$\frac{1}{\tau_m} = \frac{n_m}{2\pi\hbar N(E_F)}$$

⇒ **Nonmagnetic dephasing !**

Huang et al., PRL 99, 046601 (2007)

Magnitudes of the 2D Nyquist e-e scattering, e-ph scattering, and the measured dephasing rates



The 2D Nyquist e-e scattering time is **~ 2 orders of magnitude longer** than our measured values of τ_φ

Theoretical *e-e* scattering time:

$$\frac{1}{\tau_{ee}^{(2D)}} = \frac{e^2 R_\square}{2\pi\hbar^2} k_B T \ln\left(\frac{\pi\hbar}{e^2 R_\square}\right)$$

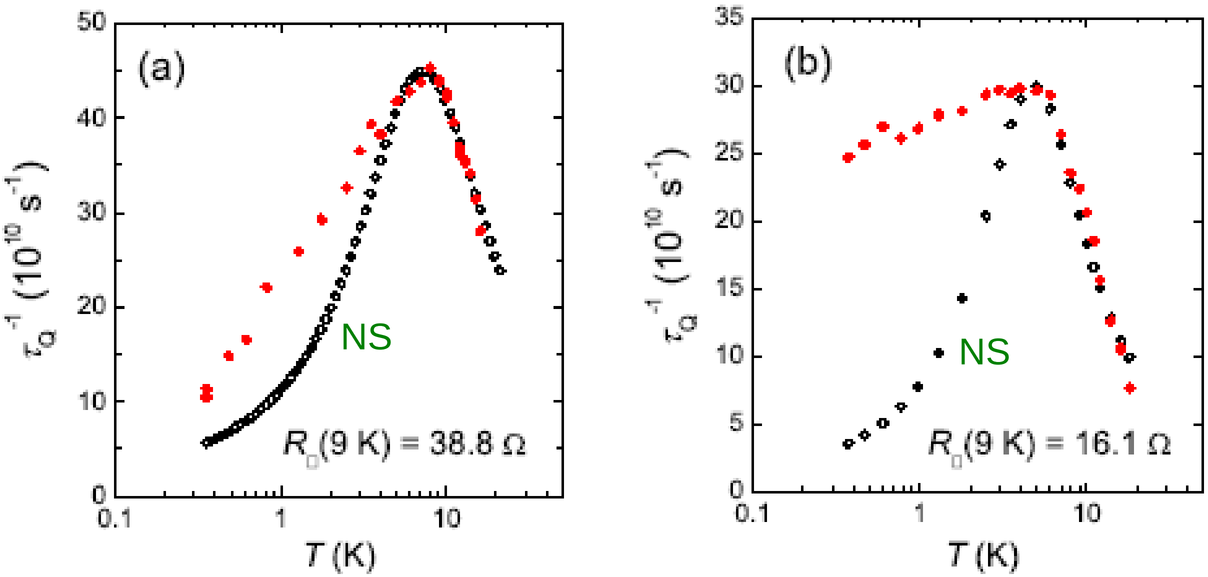
$$\tau_{ee}^{(2D)} \approx 2.8\ T^{-1}\ \text{ns} \quad \text{for} \quad R_\square = 10\ \Omega$$

$$\approx 4.7\times10^{-10}\ \text{s} \quad @ \quad 6\ \text{K}$$

Assume the maximum magnetic scattering rate occurs at a ‘characteristic temperature’ T_K*

Adjust n_m and S so that the theory reproduces the experiment around and above T_K* $\Rightarrow$ The values of the parameters thus obtained are unrealistic: n_m is extremely large (≈ 200 – 300 ppm) while S is unusually small (≈ 0.05 – 0.12)

Far below T_K*, significant discrepancies are observed

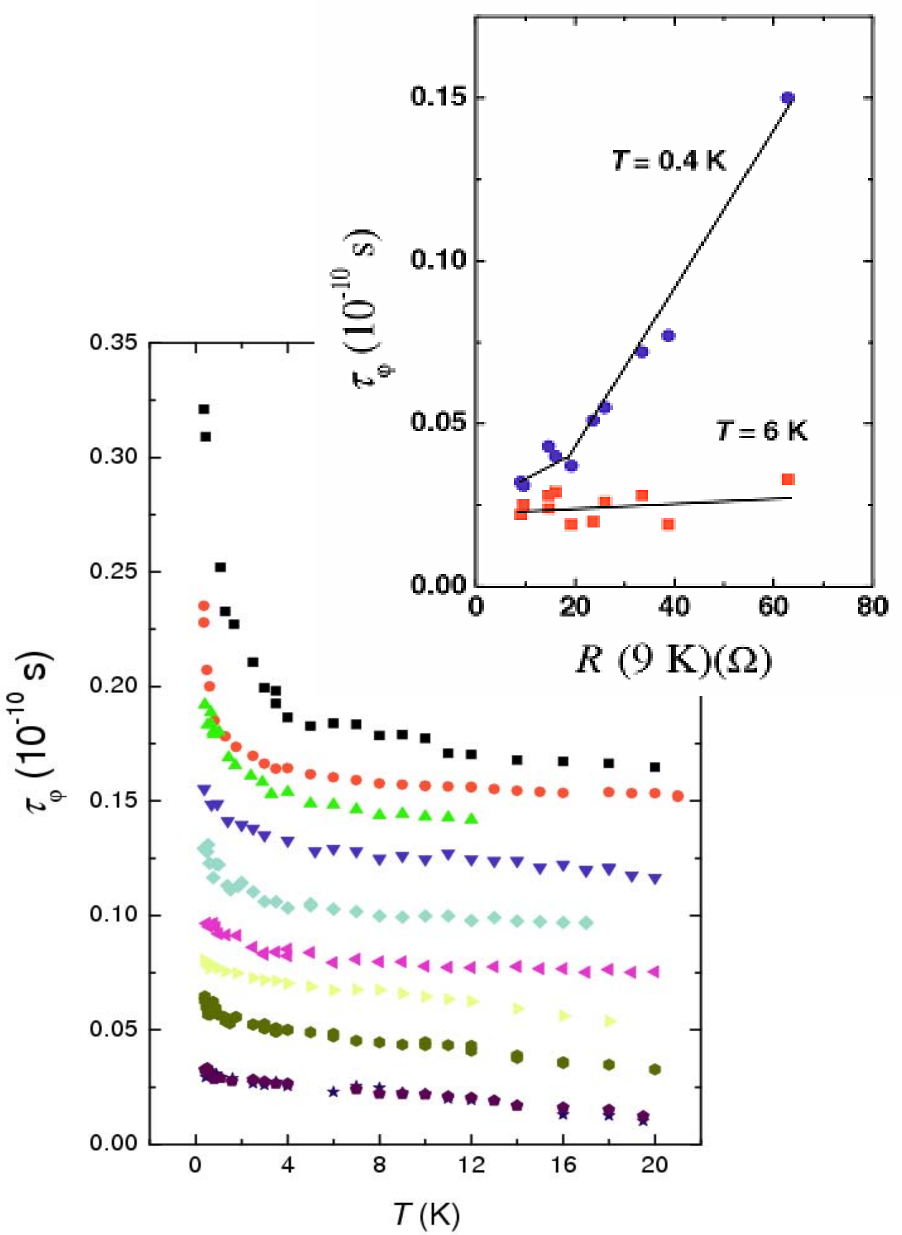


$$\frac{1}{\tau_Q} = \frac{1}{\tau_\varphi} - A_{ep} T^2$$

At $T = T_K$,

$$\frac{1}{\tau_m} = \frac{n_m}{2\pi\hbar N(E_F)}$$

Huang et al., PRL (2007)



(The value of τ_φ for each film has been shifted vertically for clarity)

There is a **slow upturn** in τ_φ below about 4 K

$$\tau_\varphi \propto T^{-p}, \ \mathbf{0 \le \mathit{p} \le 0.6}$$

The upturn in τ_φ is more pronounced in more disordered films

Approximate scaling behavior:

$$\tau_\varphi(0.4\ \mathrm{K}) \propto R_\square$$

The reason why:

metallurgical effect, dynamic defects?

a broad distribution of T_K due to strong disorder?

electron-electron interactions?

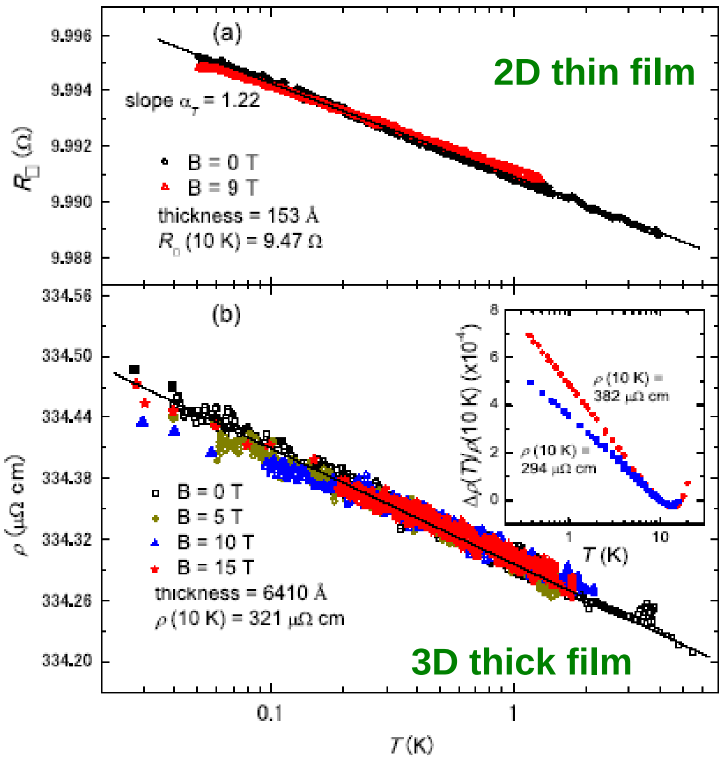
……

Non-Magnetic Origin in CuGeAu Films

In both 2D and 3D films, the resistance obeys a strict **ln*T*** dependence from 30 mK up to above 10 K, and is **insensitive** to high magnetic fields

⇒ Nonmagnetic origin in CuGeAu

⇒ Dynamical structural defects seem responsible (?!)



slope ≈ (1.33±0.13) $\dfrac{e^2}{2\pi^2\hbar}$

WL + e-e interaction effects predict a slope ≤ 1

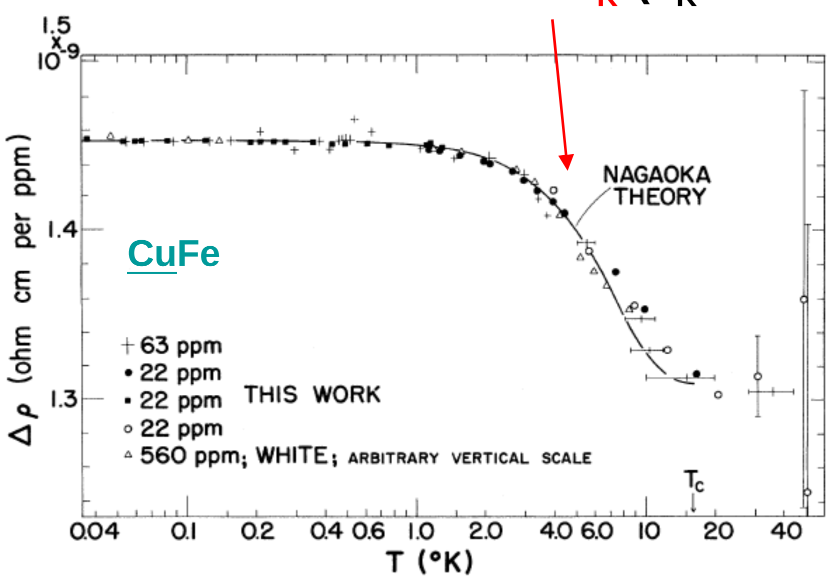
No square-root-*T* dependence, as would be expected for 3D e-e interaction effect

Huang et al., PRL (2007)

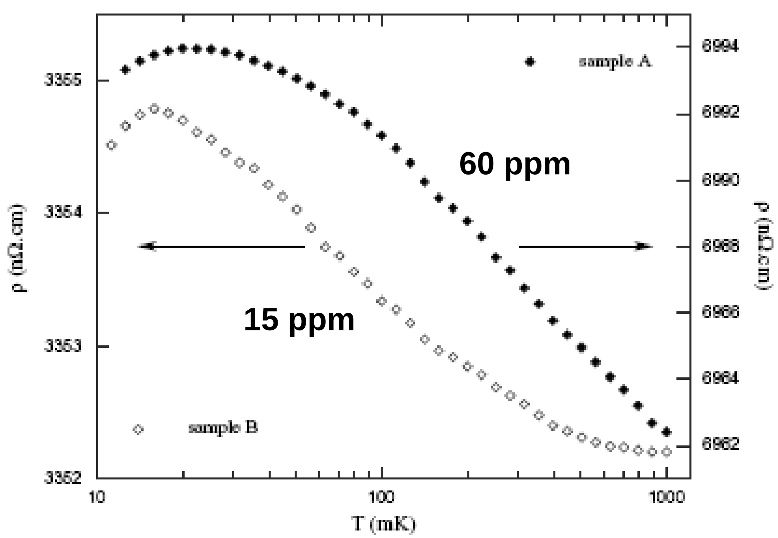
Nonmagnetic Origin in CuGeAu Films

If there existed a high magnetic impurity concentration of **200–300 ppm**, one should have observed Kondo-like and/or spin-glass-like behavior in the temperature behavior of resistance

$0.3T_K$ (T_K = 16 K)



$0.07T_K$ (T_K = 300 mK)



The unitary limit: high T_K and low magnetic impurity concentration (Daybell, Steyert, PRL 18 (1967) 398)

A resistance maximum is seen, signifying spin-glass behavior and RKKY interactions between local moments (Schopfer et al., Solid State Phys., vol. 43 (2003))

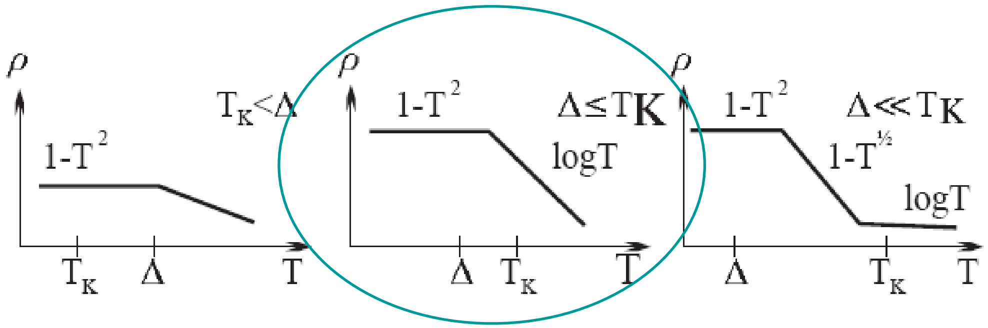
DYNAMICAL STRUCTURAL DEFECTS
(Defects with degenerate degrees of freedom)

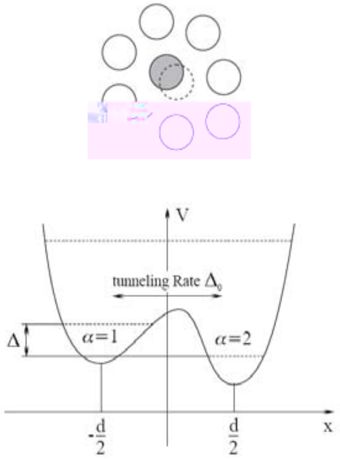
Zawadowski and coworkers, JPSJ (2005):

The experimental situation concerning the role of structural defects in dephasing in metallic glasses and strongly disordered systems is still a subject of debates

Thermal annealing studies indicate that the measured dephasing time is very sensitive to the metallurgical properties of the samples

Lin & Giordano, PRB 1987; Lin et al., Europhys. Lett. 2002





Cox & Zawadowski, Adv. Phys. 47 (1998) 604

Possible dephasing by dynamical structural defects

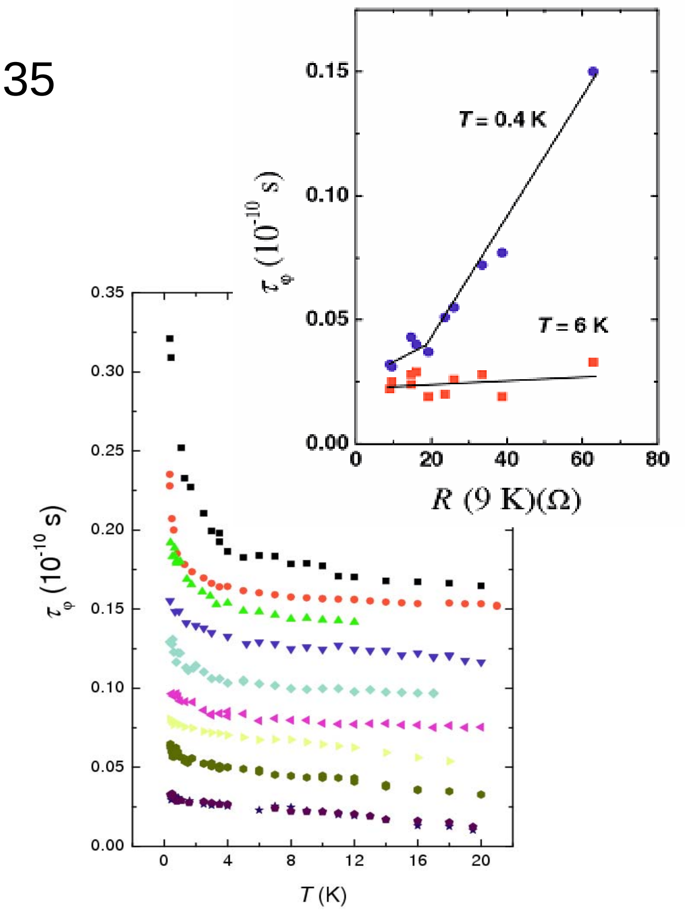
In strongly disordered systems, the dephasing time may possess a **very weak** temperature dependence in a certain temperature interval and then cross over to a **slow increase** with decreasing *T*

Imry,Ovadyahu, Schiller, arXiv:cond-mat/0312135

Galperin, Kozub, Vinokur, PRB (2004)

In the "plateau" regime, the theory of Galperin *et al*., predicts:

$$\frac{1}{\tau_\varphi} \propto D$$



This model qualitatively explained our results on highly disordered CuGeAu thin films and AuPd alloys

Electron Dephasing Time in **AuPd** Revisited

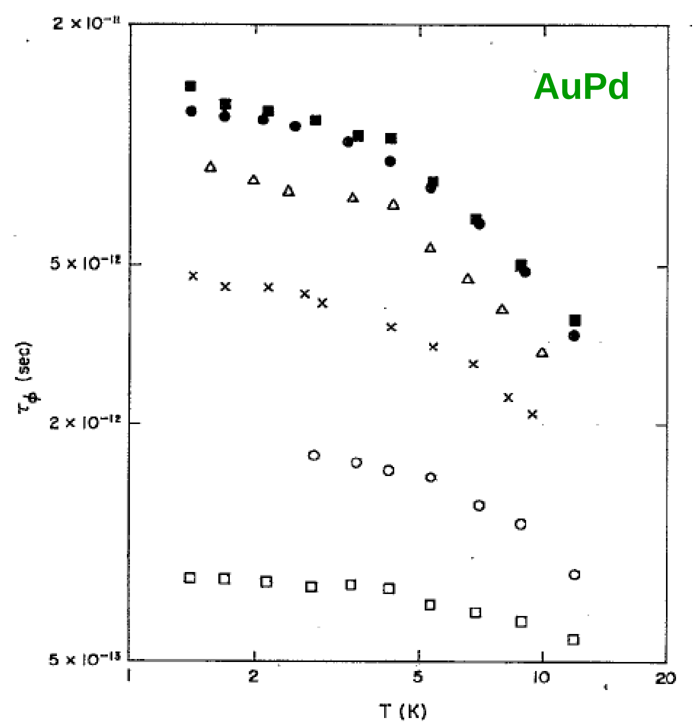
The electron dephasing time in AuPd alloys often reveals a very weak temperature dependence already at a *relatively high* temperature of 1–4 K

The dephasing time is very short:
~ 0.002 – 0.1 ns

It would need a very high level of magnetic impurities to account for such a short dephasing time

Low-temperature thermopower measurements indicate no contribution from Kondo impurity scattering: $\boldsymbol{S} \propto \boldsymbol{T}$

Evaporated and sputtered films



Lin & Giordano, PRB 35, 1071 (1987)

Electron Dephasing Time in **AuPd** Revisited

The dephasing times in AuPd and AgPd alloys measured in different experiments reveal a **strong correlation** with the electron diffusion constant *D*

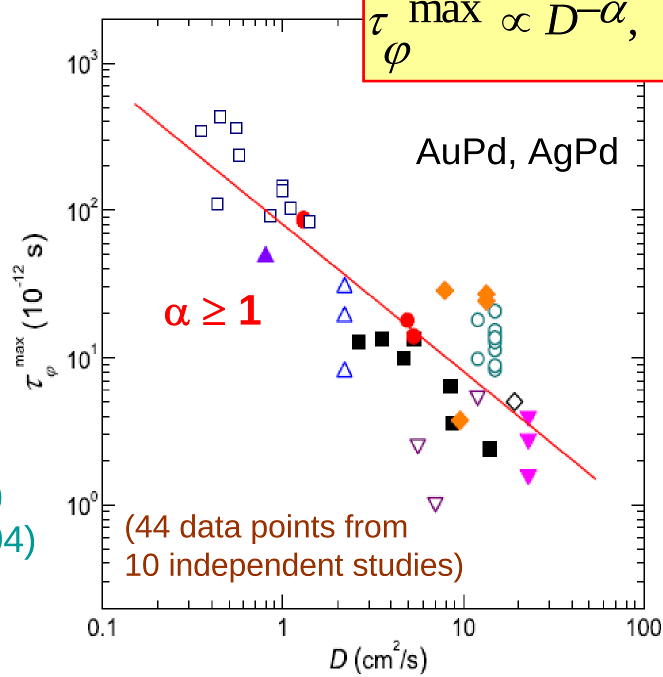
Unintentional magnetic impurity contaminations should lead to **randomly** distributed values of $\tau_\varphi^{\max}$

The measured values of $\tau_\varphi^{\max}$ varied by ~ 2 orders of magnitude

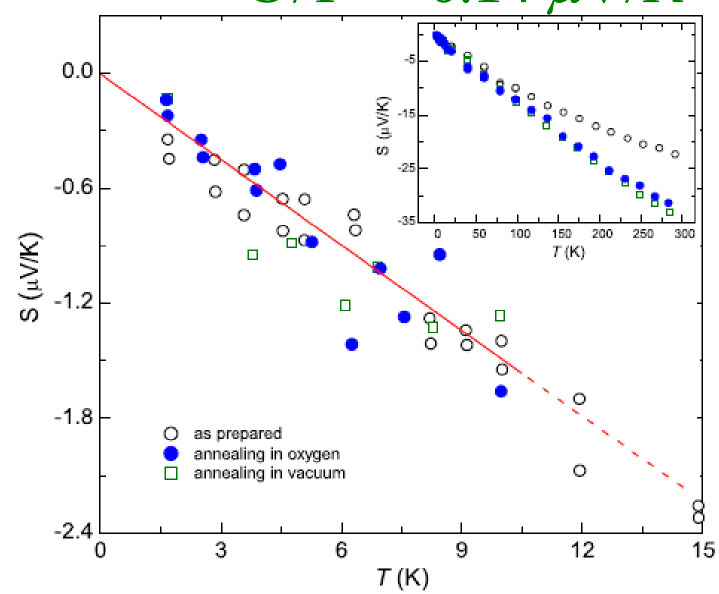
⇒ Need magnetic concentration varying by ~ 2 orders of magnitude !

Data taken from:
Zhong, Lin (1998)
Lin et al. (2002)
Lin, Kao (2001)
Lin, Giordano (1987)
Webb et al. (1998)
Natelson et al. (2001)
Trionfi, Natelson (2004)
Heraud et al. (1987)

$$\tau_\varphi^{\max} \propto D^{-\alpha}, \quad \alpha \geq 1$$



$$S/T = -0.14\ \mu\text{V/K}$$



Lin et al., Physica E 40, 25 (2007)

Dephasing Length in $Cu_x(SiO_2)_{1-x}$ Granular Films

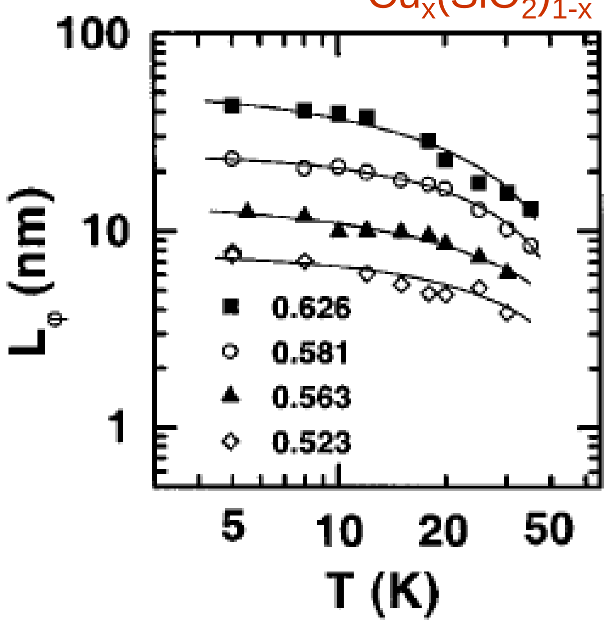
The dephasing length is short (~ tens nm) and only weakly temperature dependent

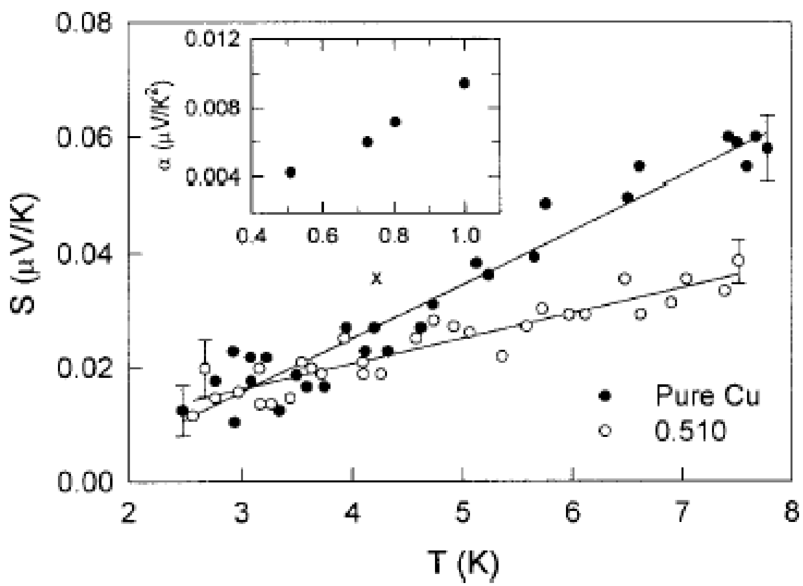
Low-temperature thermoelectric powers indicate no sign of contribution from dilute Kondo magnetic impurity

Cu, SiO_2 grains ~ a few nm

S/T ~ 0.006 $\mu V/K^2$, very small !

$Cu_x(SiO_2)_{1-x}$

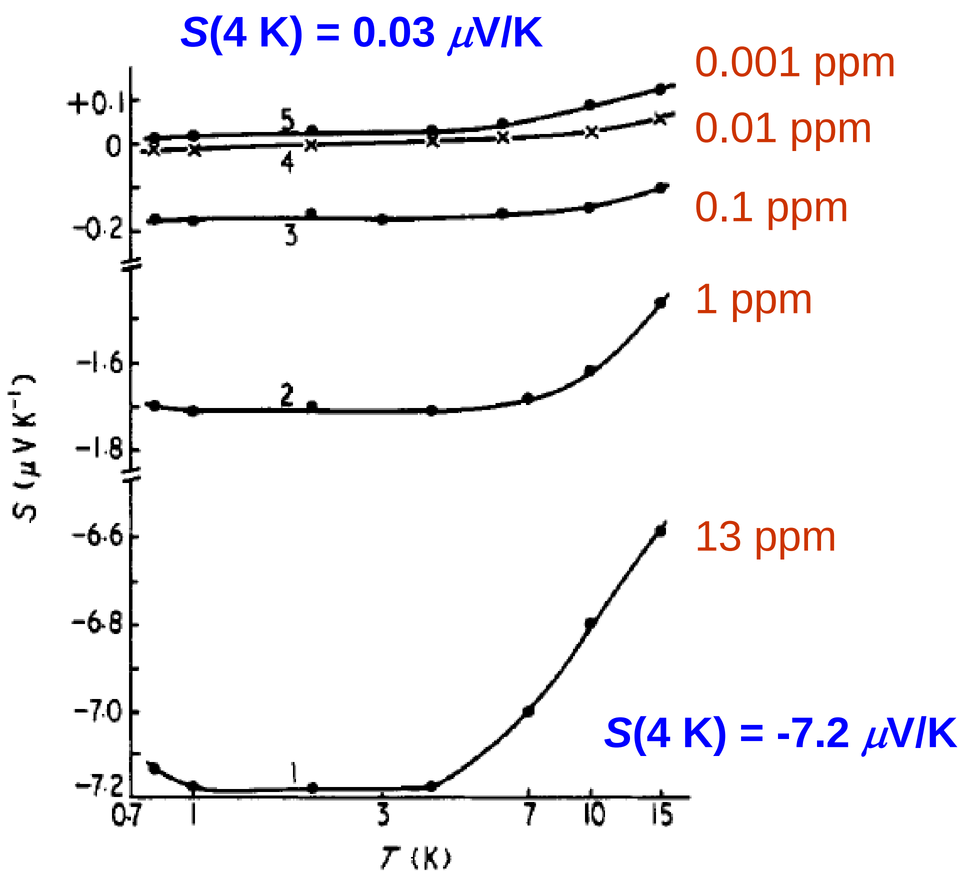




Zhang *et al*., PRL (2001)

Chen *et al*., Appl. Phys. Lett. 81, 523 (2002)

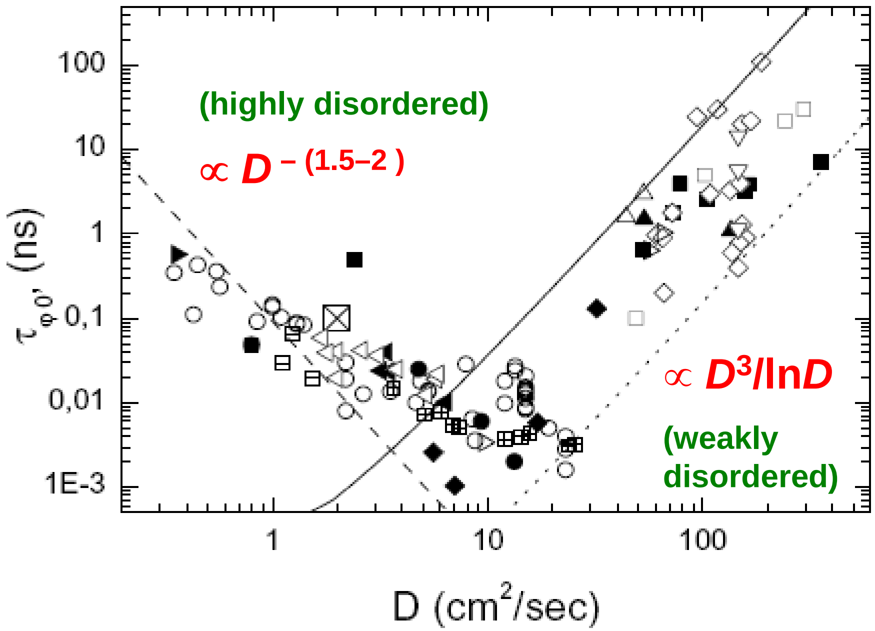
Thermoelectric power of 80-μm diameter AuFe alloy



Kopp, J Phys F 5, 1211 (1975)

Electron-electron interactions in disordered systems

A recent theory has proposed that electron-electron interaction in the presence of disorder **always** causes a saturated dephasing time which depends **strongly** and **non-monotonously** on disorder, while being insensitive to sample dimensionality



A universal formula for all cases of (1) weakly disordered conductors, (2) highly disordered conductors, and (3) quantum dots

$$\tau_\varphi^0 \sim g\tau_D/\ln(E_c/\delta)$$

e-e interactions + disorder
$\Rightarrow$ **intrinsic** saturation

~ 130 metallic samples from ~ 30 publications, ~ 3 decades of electron diffusion constant

Golubev & Zaikin, Physica E (2007)

Conclusion

In addition to Kondo-impurity scattering, an additional nonmagnetic scattering must be present

high-field $R(T)$
disorder dependence
Thermopower $S(T)$

In very weakly disordered samples, $1/\tau_Q$ could dominate over $1/\tau_m$ only at extremely low T

$$\frac{1}{\tau_\varphi} = \frac{1}{\tau_{ep}} + \frac{1}{\tau_{Nyquist}} + \frac{1}{\tau_m} + \frac{1}{\tau_Q} + \ldots\ldots$$

as $T \to 0$

Nonmagnetic $1/\tau_Q$ is more pronounced in more disordered samples

2D and 3D samples, deposited and measured, no lithographic processes

Stronger contrast between inelastic $\tau_\varphi \propto T^{-p}$ ($p \geq 1$) and, if any, saturated τ_φ^0

Magnetic scattering is important for dephasing.
Nonmagnetic scattering can be even more important !

Lin & Giordano, PRB 1987:

The results suggest that either the spin-spin scattering process is more complicated than considered by current theories, or that perhaps there is *another source* of electron scattering which leads to a temperature-independent scattering time

Mohanty & Webb (1997)

Lin & Bird, JPCM 2002:

These measurements have demonstrated that hot-electron effects, external microwave noise, and very dilute magnetic impurities can *at most* play a *subdominant* role in the finite dephasing of τ_φ as $T \to 0$

Huang et al., PRL 2007:

We report the observation of a strong electron dephasing in disordered CuGeAu thin films. This dephasing is much stronger than any known inelastic electron scattering process. This dephasing must be *nonmagnetic* in origin