Low-Dimensional Disordered Electronic Systems (Experimental Aspects)

Lecture II

Electron-Electron Interactions and Dephasing Processes in Disordered Conductors

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The State University of New Jersey
Rutgers
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Lecture 2: Electron-electron Interactions and Dephasing Processes in Disordered Conductors

- El.-el. interactions in disordered conductors: anomalous corrections to the DoS and conductivity
- Dephasing induced by interactions
- Dephasing at ultra-low temperatures: dephasing by Kondo impurities and high-frequency electromagnetic noise

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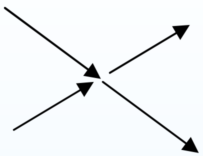
El.-El. Interactions in disorder-free conductors

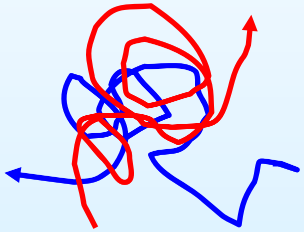
Collisions with large and ***T*-independent** momentum transfer $q \sim k_F$ $\qquad \tau_{ee}^{-1} \propto \dfrac{\varepsilon^2}{E_F}$



El.-el. interactions do renormalize electron parameters at a large energy scale (~ E_F), this renormalization does not result in anomalous low-T behavior of these parameters.

T^2 term in the resistivity, no anomalous corrections at low T

Interaction processes in disordered conductors:



$$L_\varepsilon = \sqrt{\frac{\hbar D}{\varepsilon}}$$

energy transfer

Electron scattering by impurities dramatically changes the situation at low energies (<< E_F). Because of the diffusive motion, processes with collisions with a ***small momentum transfer*** $q \sim [\max(T,\varepsilon)/D]^{1/2} \ll k_F$ becomes important.

Due to the diffusive motion, the renormalization of all electron parameters becomes ***T-dependent***, and all thermodynamic and transport quantities (including DoS, which is not affected by WL) acquire ***non-trivial T-dependent corrections***.

$$\Delta\sigma_{INT}(T) \longrightarrow L_T = \sqrt{\frac{\hbar D}{k_B T}}$$

the ***thermal dephasing*** length -

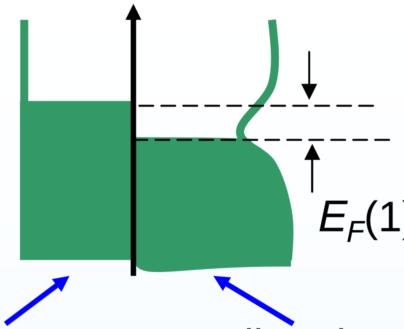
The dimensionality of a conductor:
$\boldsymbol{L \Leftrightarrow L_T(T)}$

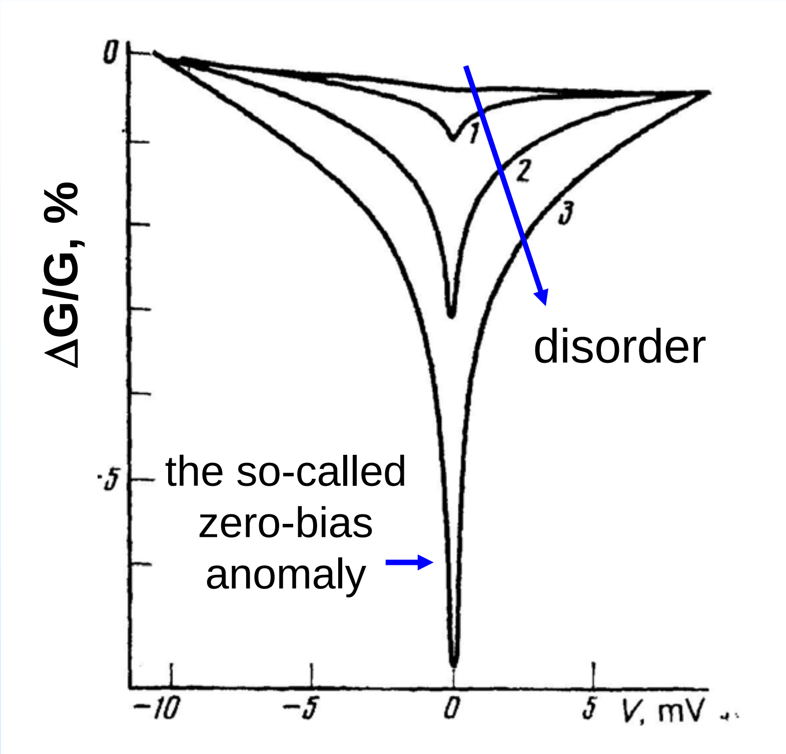
$l \ll L_T \leq L_\varphi$ - a large scale (D=10 cm^2/s, T=1K, L_T~0.1μm), ***non-locality*** and "***universality***" of INT effects, similar to the WL effects.

Because of a large characteristic length scale, the interaction corrections are "***non-local***" and "***universal***" (similar to the WL correction)

Corrections to the Tunneling DoS

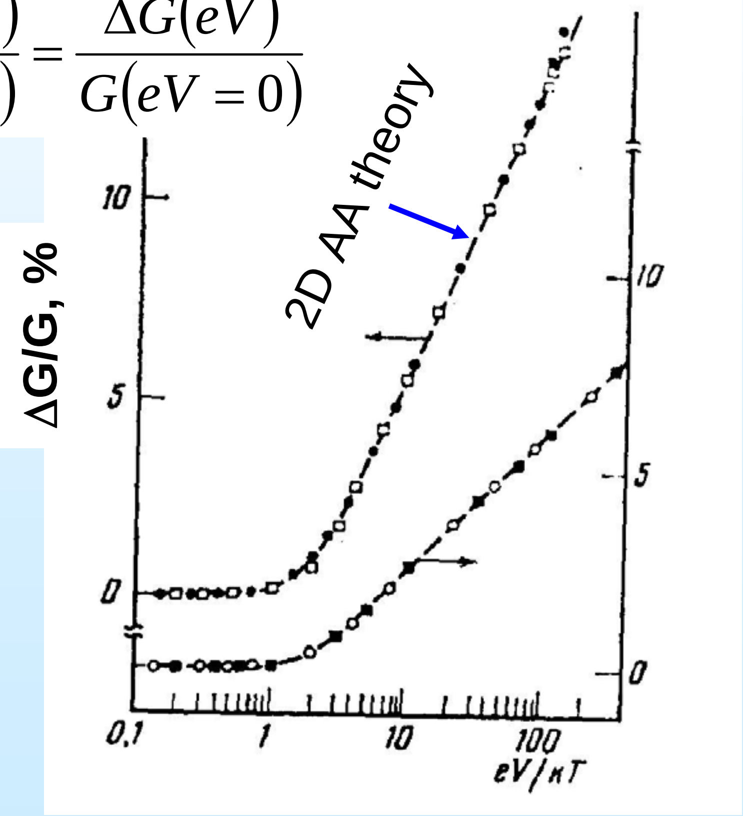
tunnel junctions (thin disordered) Al-Al_2O_3-Al
(magnetic field suppresses SC below T_C)





MG, Gubankov, Falei ('85,'86)

$$\frac{\Delta\nu(\varepsilon)}{\nu(E_F)} = \frac{\Delta G(eV)}{G(eV=0)}$$



The dimensionality of a conductor:

$L \Leftrightarrow L_\varepsilon \quad \varepsilon = \max[T, eV]$

With increasing disorder, the ZBA transforms into the Coulomb gap (the SL regime)

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Corrections to the Conductivity

The interaction correction to the conductivity - as a result of the interference between wavefunctions of different electrons propagating in a random scattering potential.

Two regimes: ***ballistic*** (**$T\tau$ > 1** or **L_T** ≤ ***l***) and ***diffusive*** (**$T\tau$ << 1 or L_T >>*l***)

Metals – mostly diffusive regime, semiconductor structures – both regimes (Lecture 3).

2D

$k_F l$ >> 1, all orders in interactions, the leading order in T.

Zala, Narozhny, & Aleiner ('01)

$$\Delta\sigma_{INT} = f(F_0^{\,a})\frac{T\tau}{\hbar} + g(F_0^{\,a})\ln\left(\frac{\hbar}{T\tau}\right)$$

ballistic regime — diffusive regime

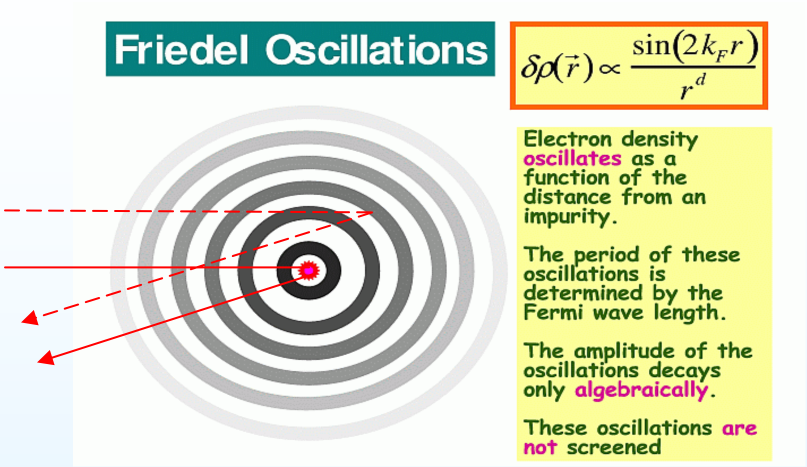
Altshuler-Aronov-Lee corrections

$$T << T_F\left(1+F_0^{\,\alpha}\right)^2$$

Functions ***f*** and ***g*** are combinations of the "charge" and "spin" terms, the latter depends on $\boldsymbol{F_0^{\alpha}}$ - the Fermi-liquid constant.

Some Comments

"***Elasticity***" of the processes that contribute to $\Delta\sigma_{INT}$ should be emphasized: they preserve the time reversal symmetry and do not cause phase breaking. An illustration: one of the contributions to the interaction corrections to the conductivity in the ballistic regime is due to the interference between the waves backscattered off an impurity (a short-range potential) "dressed" by Friedel oscillations. Other contributions, which involve virtual energy exchange processes at a scale $\varepsilon >> T$, also do not break the time reversal symmetry.



Sign of the corrections: depending of the value of $\boldsymbol{F_0^\alpha}$, the corrections could be either ***positive*** or ***negative***.

$$\Delta\sigma_{INT} = f(F_0^a)\frac{T\tau}{\hbar} + g(F_0^a)\ln\left(\frac{\hbar}{T\tau}\right)$$

$\boldsymbol{F_0^\alpha}$ can be found from independent measurements of ***g****, e.g., from the analysis of SdH oscillations in semiconductor structures, or from the ESR with mobile electrons in metals.

$$g^* = \frac{g}{1+F_0^\alpha}$$

Typically, $|F_0^\sigma| < 0.1$ in metals, and the interaction effects ***decrease*** the conductivity. In semiconductors, the abs. value of $\boldsymbol{F_0^\sigma}$ increases with the strength of interactions: e.g. $F_0^\sigma \cong -0.3$ in Si MOSFETs at low carrier densities (see Lecture 2 by Vladimir Pudalov). In the latter case, the conductivity is ***increased*** by the interaction effects. For the detailed discussion of the corrections to σ at large $|F_0^\alpha|$, see Lecture 3.

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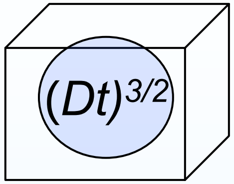
Metals: diffusive approximation, $F_0^\sigma \approx 0$

3D:

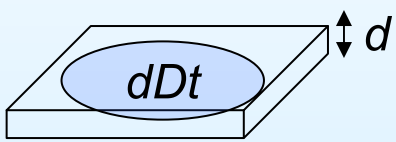


$$\Delta\sigma_{INT} \propto$$

$$\Delta\sigma_{INT}^{3D} \propto \frac{e^2}{h}\left[\frac{1}{L_T(T)} - const\right]$$

$$L_T < \text{all dimensions}, \xi$$

2D:

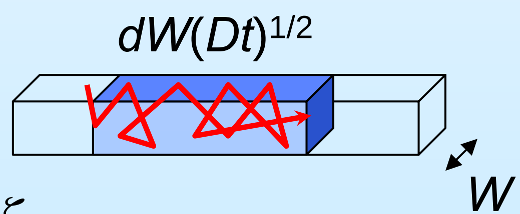


$$d < L_T << \xi$$

$$\Delta\sigma_{INT}^{2D} \propto -\frac{e^2}{h}\ln\left[\frac{L_T(T)}{l}\right]$$

$$\delta\sigma_C(T) = -\frac{e^2}{2\pi^2\hbar}\ln\left(\frac{\hbar}{T\tau}\right)$$

Quasi-1D:



$$d, W < L_T << \xi$$

$$\Delta\sigma_{INT}^{1D} \propto -\frac{e^2}{h}L_T(T)$$

$$\delta\sigma_C(T) = -\frac{e^2}{\pi\hbar}\sqrt{\frac{\hbar D}{2\pi T}}\left(\frac{3\zeta(3/2)}{2}\right)$$

$$\varsigma(3/2) \cong 2.612$$

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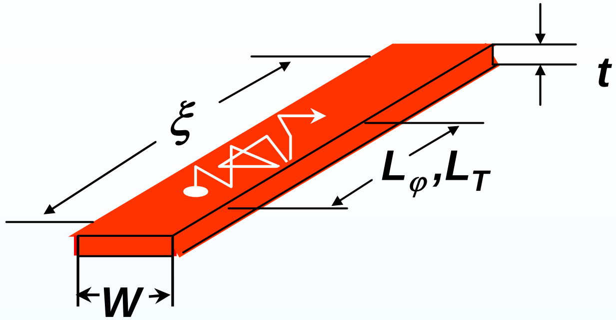
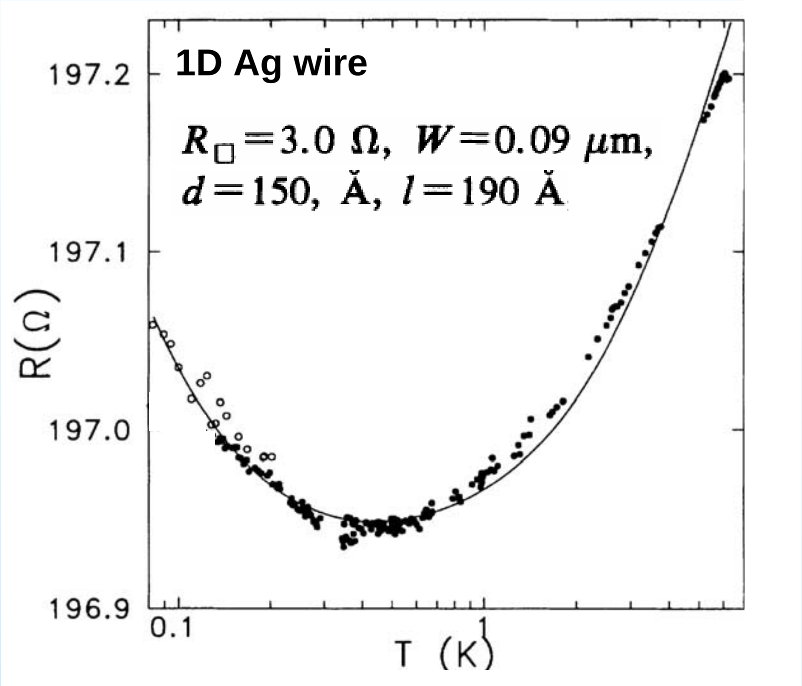
WL and INT corrections to the conductivity of quasi-1D conductors

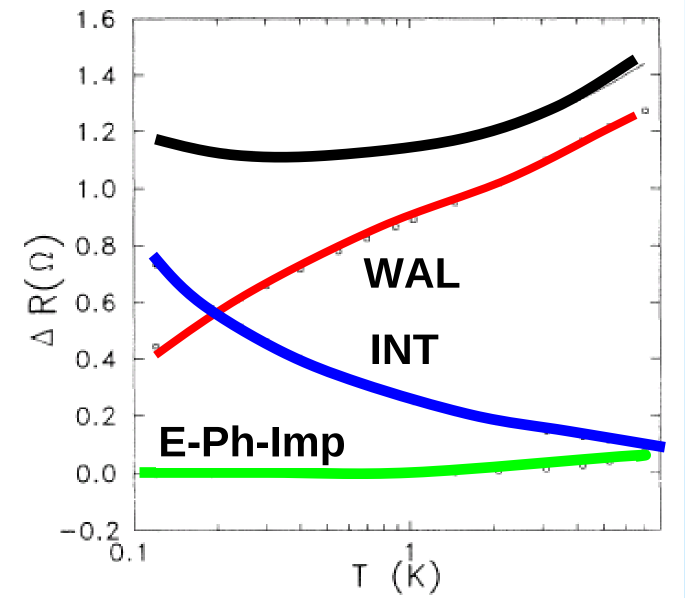


$$\lambda_F << \ell \leq W < L_\varphi, L_T << \xi_{1D}$$



Echternach, MG *et al*., *PRB* **50**, 5748 ('94)

$$\Delta\sigma_{WL}\left[\tau_\varphi(T)\right] + \Delta\sigma_{EEI}(T)$$



How to separate WL and INT corrections?

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Magnetic Field Effect

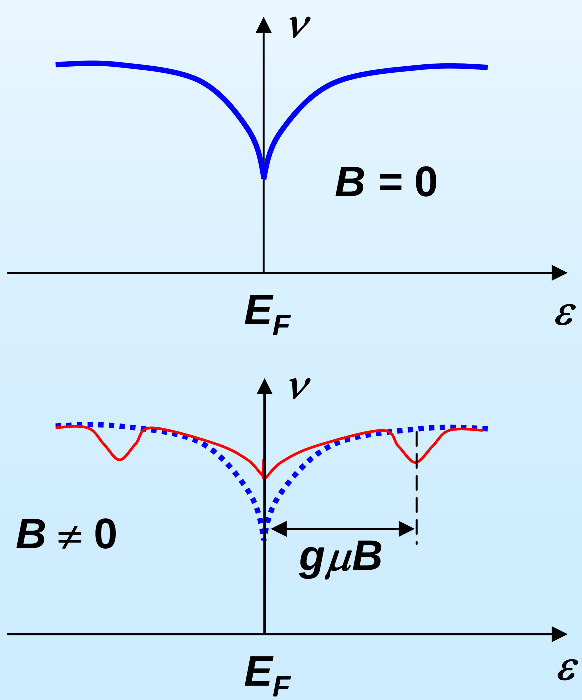
$$\Delta\sigma_{INT} = f(F_0^{\,a})\frac{T\tau}{\hbar} + g(F_0^{\,a})\ln\left(\frac{\hbar}{T\tau}\right)$$

ballistic regime diffusive regime

Functions ***f*** and ***g*** - combinations of the "charge" and "spin" terms.

"Charge" term isn't sensitive to the field at all, "spin" terms are affected by the field if the Zeeman energy ***gμB*** exceeds ***T***.

Sloppy analogy:



$$\Delta\sigma_{INT}^{diff}(2D) \propto -\left[1 + \frac{3}{2}F\right]\ln\left(\frac{\hbar}{T\tau}\right)$$

"charge" "spin"

Note: in a system with interactions, the corrections to the DoS and conductivity are not simply interrelated:

$$\sigma \neq e^2\nu\, D \quad \Longrightarrow \quad \sigma = e^2\frac{d\mu}{dn}D$$

When B is applied, two (of three) "triplet" contributions to the DoS are "shifted" in energy by ***gμ B*** with respect to the Fermi energy, and ***$\nu(E_F)$*** increases.

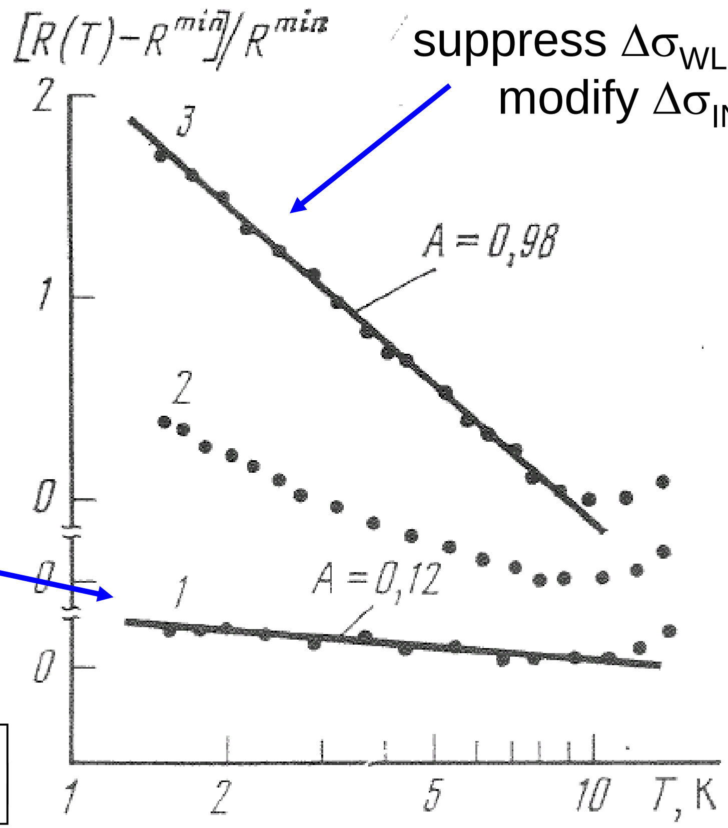
Experimental separation of WL and INT corrections

Let's apply a magnetic field which, on the one hand, sufficiently strong to suppress the ***T***-dependence of WL corrections [$L_H \ll L_\varphi(T)$], but, on the other hand, too weak to modify el.-el. interactions ($g\mu B \ll T$).

R(*T*) for a 4.2-nm-thick Ag film

MG *et al.,* JETP 83, 2348 ('82)

(in units $e^2 R_\square / 2\pi^2\hbar$):



B=1T is sufficiently strong to suppress $\Delta\sigma_{WL}(T)$ but too weak to modify $\Delta\sigma_{INT}(T)$: only INT

$$\Delta\sigma^{2D} = -\frac{e^2}{2\pi^2\hbar}\ln\left[\frac{L_T(T)}{l}\right]$$

B=0: INT + anti-WL

(almost compensate each other)

$$\Delta\sigma^{2D} = +\frac{e^2}{4\pi^2\hbar}\ln\left[\frac{L_\varphi(T)}{l}\right] - \frac{e^2}{2\pi^2\hbar}\ln\left[\frac{L_T(T)}{l}\right]$$

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INT corrections close to the WL-SL crossover

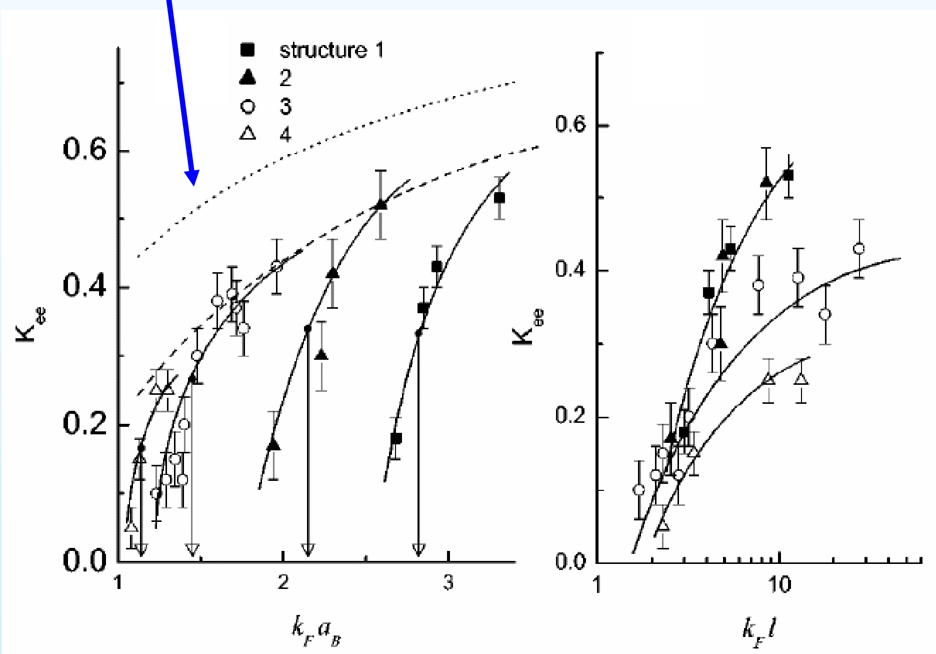
Gated δ-doped heterostructures $In_{0.2}Ga_{0.8}As/GaAs$, $n\sim1\times10^{12}cm^{-2}$, $\mu\sim2{,}000\ cm^2/Vs$

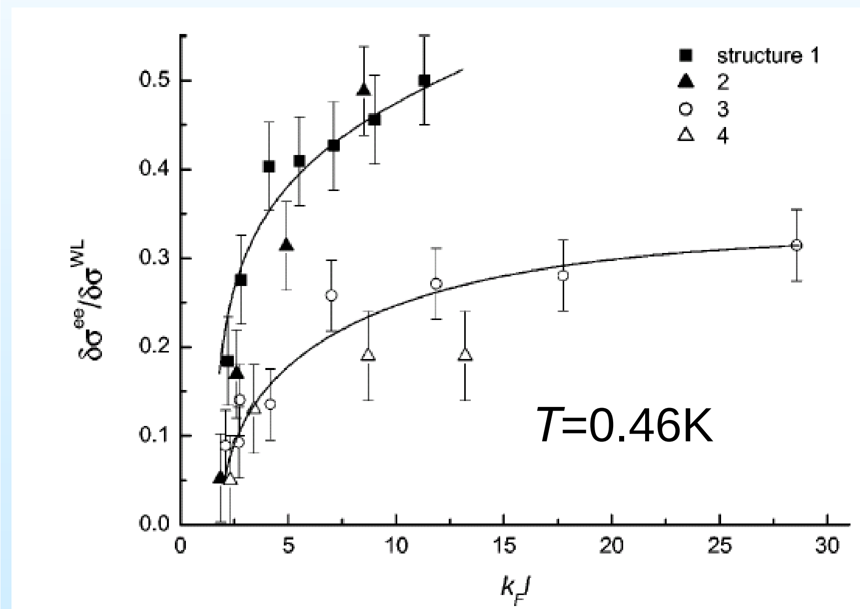
Minkov et al., *PRB* **67**, 205306 ('03)

$$\Delta\sigma^{2D}_{INT} = -K_{ee}\frac{e^2}{2\pi^2\hbar}\ln\left(\frac{\hbar}{k_B T\tau}\right)$$

$$K_{ee} = \left[1+3\left(1-\frac{\ln(1+F_0^\sigma)}{F_0^\sigma}\right)\right]$$

$$F_0^\sigma = -\frac{1}{2\pi}\frac{r_s}{\sqrt{2-r_s^2}}\ln\left(\frac{\sqrt{2}+\sqrt{2-r_s^2}}{\sqrt{2}-\sqrt{2-r_s^2}}\right), \quad r_s^2<2$$





Observation: INT corrections are suppressed well below the theoretical estimate when σ approaches e^2/h. (Qualitatively, similar behavior is observed in high-μ Si MOSFETs).

Dephasing in disordered conductors

"Clean" conductors: $\tau_\varphi^{-1} \sim \frac{T^3}{\Theta_D^2} + \frac{T^2}{E_F}$ - e-e term dominates at low ***T***

e-ph e-e

"Disordered" conductors: static disorder strongly enhances/modifies the *e-e* inelasic processes (while the *e-ph* scattering rate can be even reduced, e.g., in the case of "vibrating" impurities).

In 1D and 2D, the main contribution to the dephasing rate comes from ***quasi-elastic collisions*** with a ***small energy transfer*** $\Delta\varepsilon \sim \tau_\varphi^{-1} << T$. These processes govern the phase relaxation at low temperatures.

$$\frac{\hbar}{\tau_\varphi} \propto \frac{T}{g(L_\varphi)}$$

$$g(L_\varphi) \equiv \frac{h}{e^2 R(L_\varphi)} \propto L_\varphi^{d-2}$$

– dimensionless conductance at a scale L_φ, $R(L_\varphi)$ - the resistance of a sample of the length L_φ (1D) or area L_φ^2 (2D)

$$L_\varphi \propto T^{-1/(4-d)}$$

$$\tau_\varphi \propto T^{-2/(4-d)} \propto \begin{cases} T^{-1} & 2D \\ T^{-2/3} & 1D \end{cases}$$

Interactions-induced Dephasing

3D Collisions with the small momentum transfer $q \sim L_T^{-1}$ and energy transfer $\Delta\varepsilon \sim T$ dominate, ***the dephasing and energy relaxation rates are similar***:

Schmid, '74; Altshuler and Aronov, '79

$$\tau_\varphi^{-1} \approx \tau_{ee}^{-1} = \frac{\sqrt{2}}{12\pi^2\hbar\ \nu}\left(\frac{T}{\hbar D}\right)^{3/2}$$

1D & 2D ***the dephasing and energy relaxation rates are different***. In phase relaxation, the collisions with the energy transfer $\Delta\varepsilon \sim \tau_\varphi^{-1}$ dominate. These collisions are equivalent to the interaction of an electron with the fluctuating *e.-m.* field produced by all other electrons (dephasing by Nyquist noise).

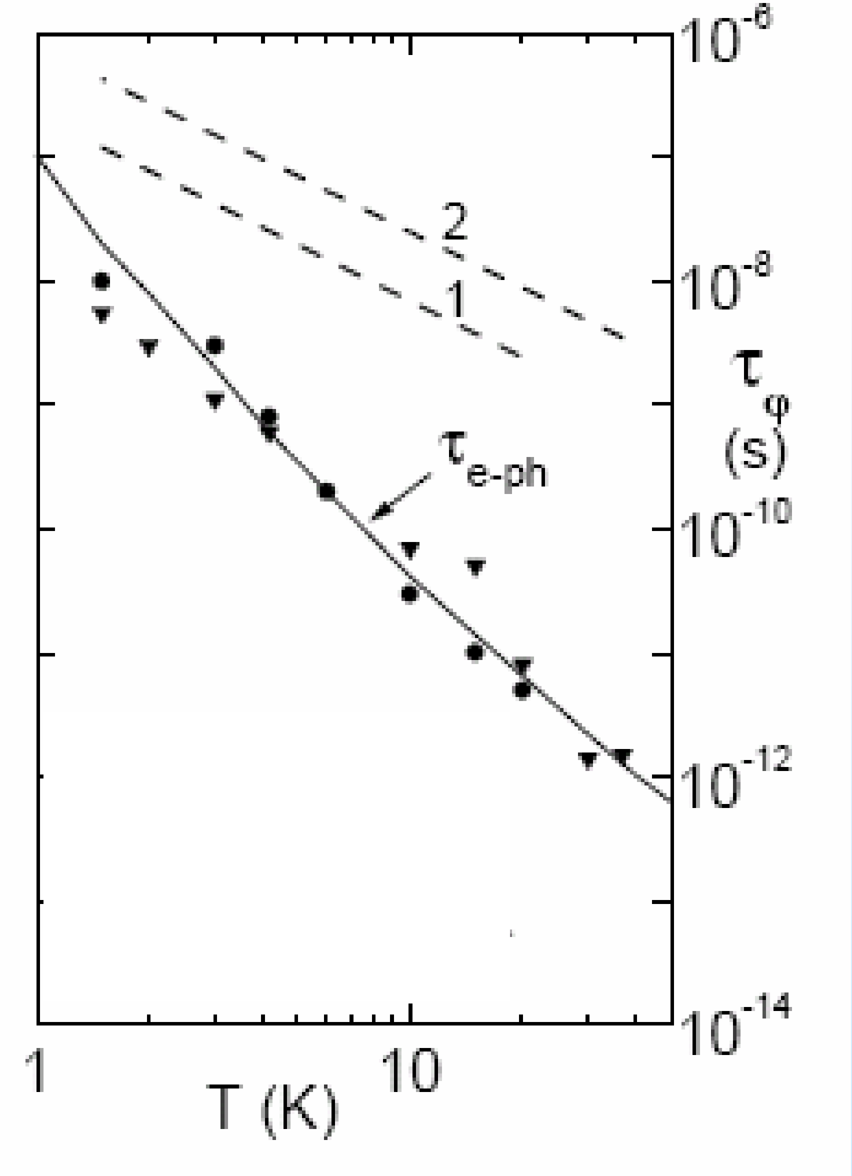
(Altshuler, Aronov, and Khmelnitskii '82).

2D $$\frac{1}{\tau_\varphi} = \frac{T}{g}\ln g + \frac{\pi}{4}\frac{T^2}{E_F}\ln\left(E_F\tau\right),$$ where $$g = \frac{h}{e^2}\sigma_{2D}$$

The first (diffusive) term becomes comparable to the second (ballistic) term when $T\tau \sim 1$

1D $$\frac{1}{\tau_\varphi} = \left(\frac{e^2\sqrt{D}}{\hbar\sigma_1}\frac{k_B T}{\hbar}\right)^{2/3}$$

3D disordered metals



Thick disordered metal films, including metal glasses, and heavily doped semiconductors

● - 1μm-thick Cu films $\rho=6\times10^{-5}\ \Omega$ cm
(Aronov, MG, Zhuravlev, '84)

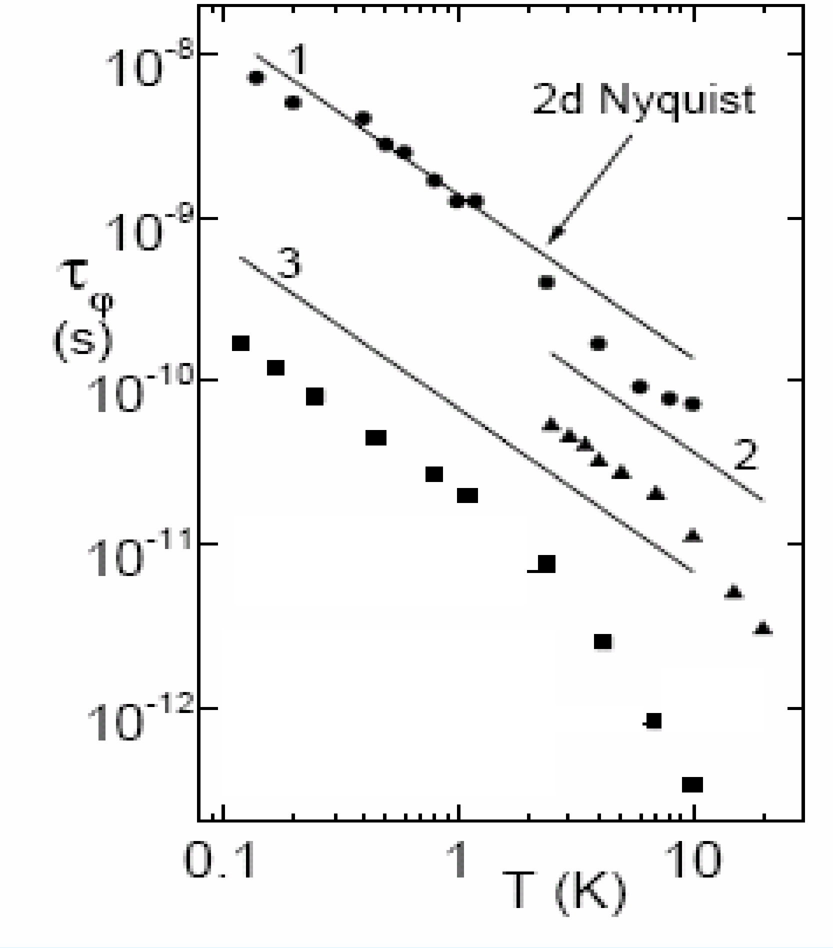
▼ - $Cu_{0.9}Ge_{0.1}$ $\rho=2.8\times10^{-5}\ \Omega$ cm
(Eschner *et al.*, '84)

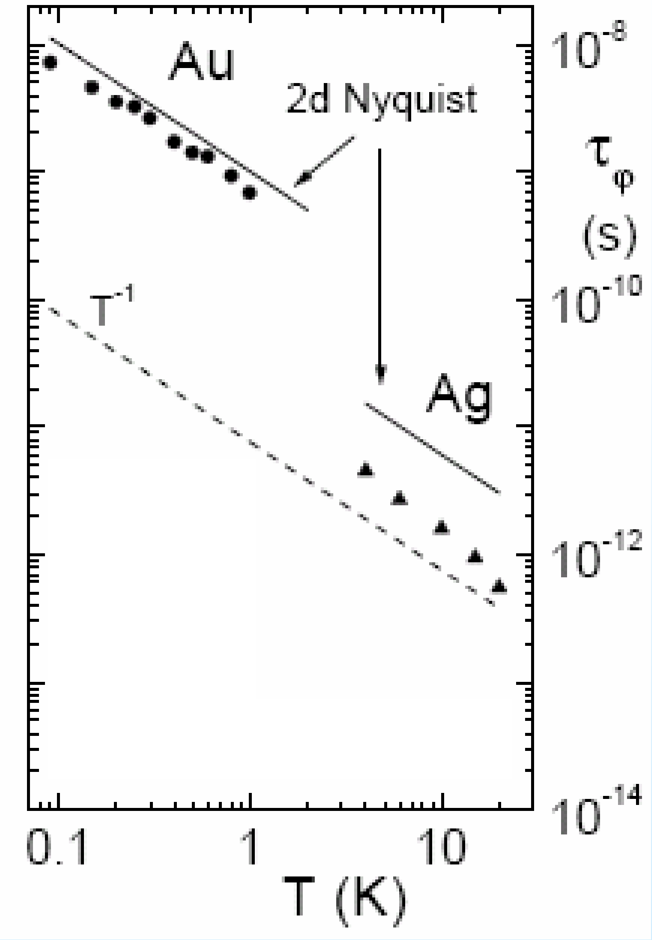
solid curve – dephasing due to e-ph collisions in disordered conductors (D =10 cm^2/s)

dashed lines – dephasing due to e-e collisions with small momentum transfer

$$\tau_\varphi^{-1} = \frac{\sqrt{2}}{12\pi^2\hbar\nu}\left(\frac{k_B T}{\hbar D}\right)^{3/2}$$

2D metal films





● - Mg film, $R_\square$= 22.3 Ω (White *et al*., '84)

▲ - Al film, $R_\square$= 112 Ω (MG *et al*., '83)

■ - Bi film, $R_\square$= 630 Ω (Komori *et al*., '83)

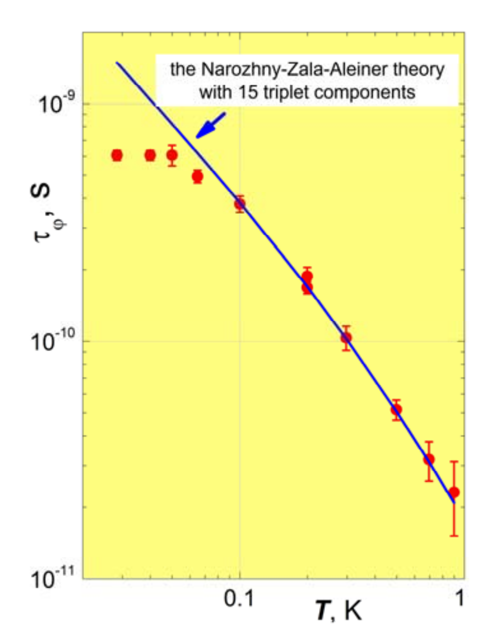
● - Au film, $R_\square$= 32.7 Ω (Aronov *et al*., '84)

▼ - ultra-thin Ag film, $R_\square$= 1.5 kΩ

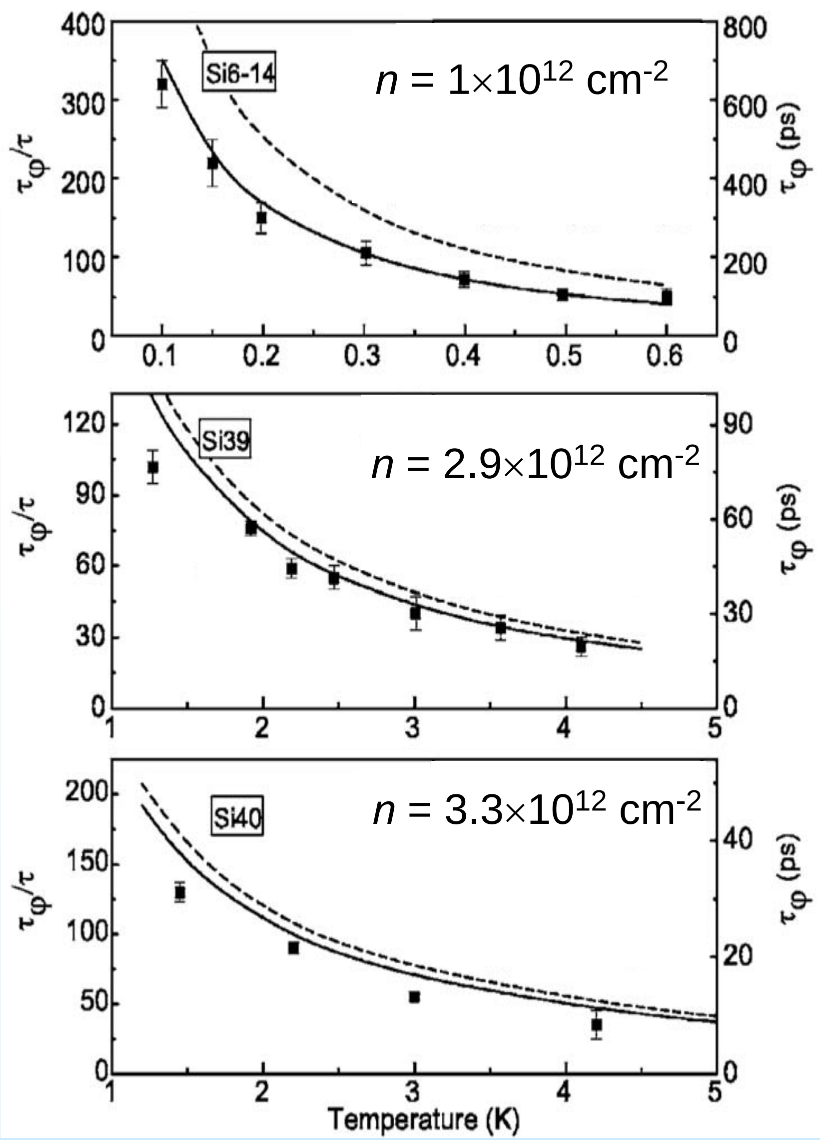
Dephasing in Si MOSFETs

The dephasing rate due to both singlet and triplet channels (2D):
Narozhny, Zala, Aleiner, '02

$$\frac{1}{\tau_\varphi} = \left[1 + \frac{15(F_0^\sigma)^2}{(1+F_0^\sigma)(2+F_0^\sigma)}\right]\frac{T}{g}\ln\left[g(1+F_0^\sigma)\right] +$$
$$\frac{\pi}{4}\left[1 + \frac{15(F_0^\sigma)^2}{(1+F_0^\sigma)^2}\right]\frac{T^2}{E_F}\ln\left(E_F\tau\right)$$



Solid lines – 15 triplet components (two degenerate valleys)
Dashed lines – 3 triplet components (single valley)



Despite strong interactions, still a Fermi-liquid system

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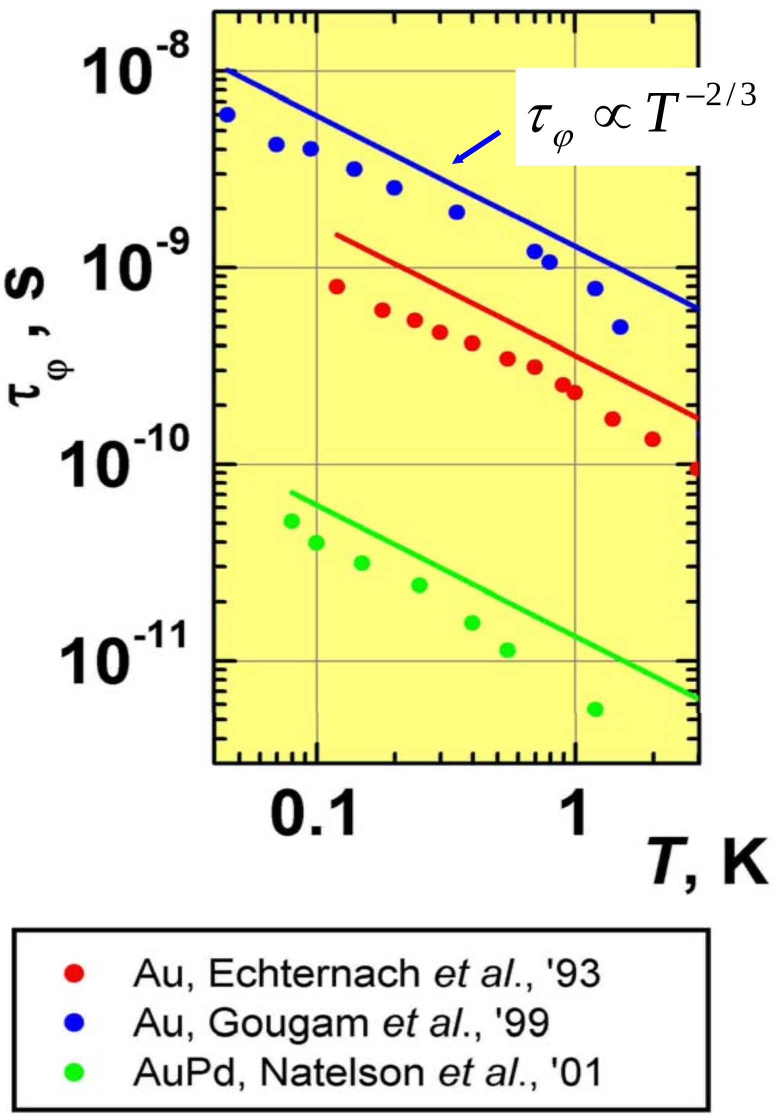

		d, nm	*W*, nm	*L*, μm	*R*, Ω
Au	'93	15	90	100	4100
Au	'99	45	90	176	1080
AuPd	'01	7.5	5	1.5	28800

1D wires

1D:

$$\tau_\varphi = \left(\frac{\hbar^2}{e^2 R_1 \sqrt{D}\, k_B T} \right)^{2/3}$$

Altshuler, Aronov, and Khmelnitskii, ’82; Aleiner et al., ‘99

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Validity of the Fermi-liquid approach

Fermi liquid approximation holds (single-particle excitations are well defined)

provided that

$$T\frac{\tau_\varphi(T)}{\hbar} = g(L_\varphi) > 1$$

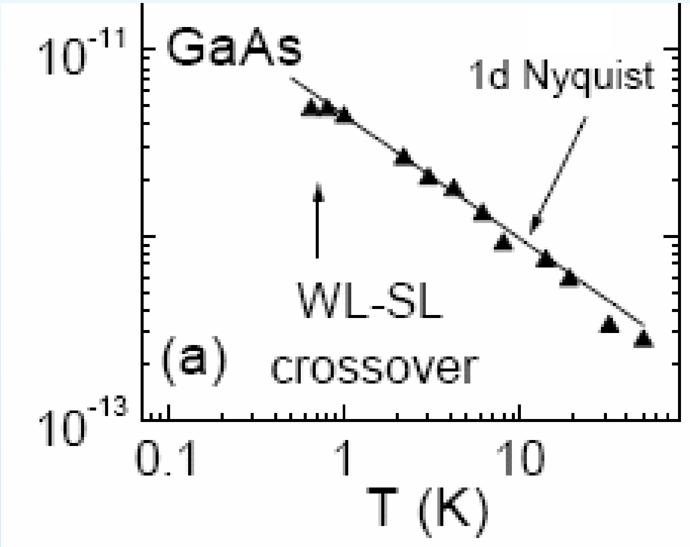
On the "metallic" side of the WL-SL crossover ($L_\varphi << \xi$) $g(L_\varphi) << g(\xi) \sim 1$

Both quasi-1D and 2D conductors behave as Fermi liquids

At the crossover $g(L_\varphi) \sim 1$

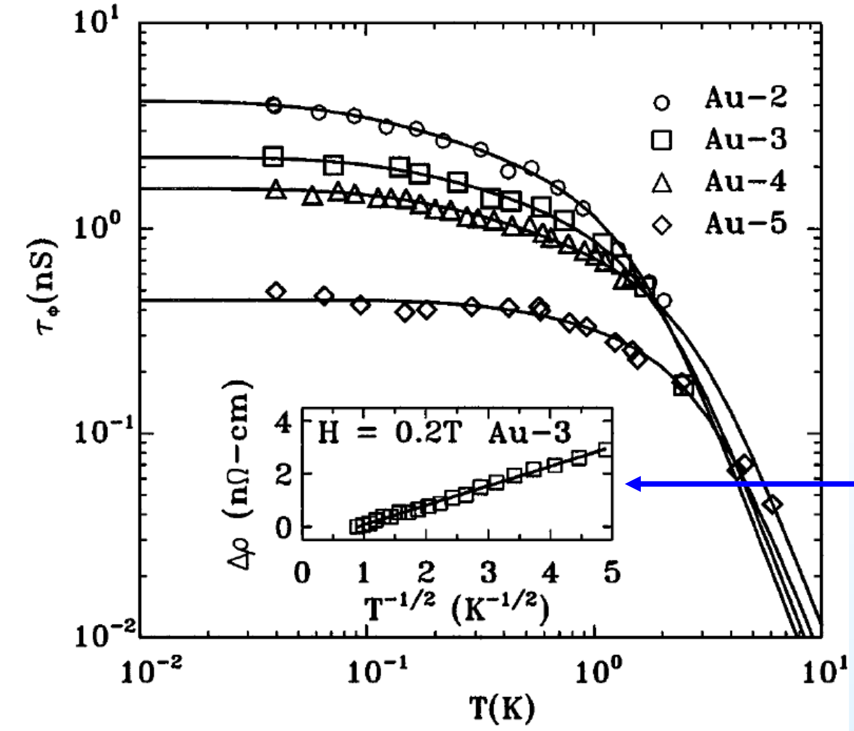
The upper limit on τ_φ:

$$\tau_\varphi(T) < \frac{\xi^2}{D}$$



δ-doped GaAs wires (W=50nm, $R_\square$= 1 kΩ)
Khavin, MG, Bogdanov, '98

Puzzle of Low-*T* Saturation of $\tau_\varphi(T)$



Mohanty, Jariwala, and Webb ('97)

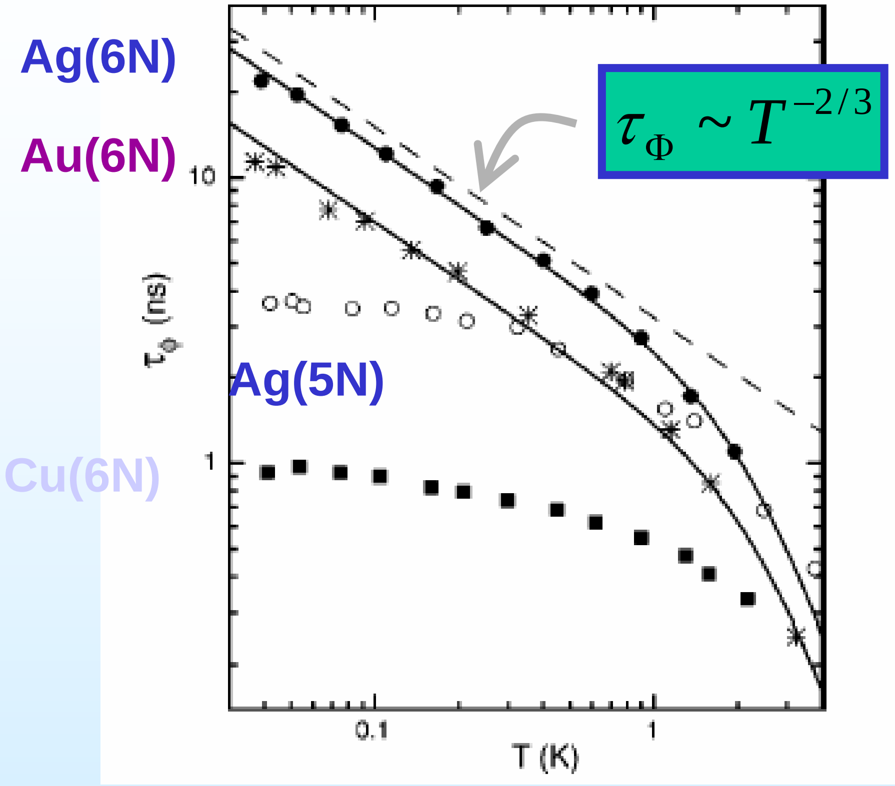
Saturation of $\tau_\varphi(T)$ at low temperatures was observed in many (but not all!) experiments. A trivial cause – overheating by measuring current – has been ruled out.

What causes the apparent low-T saturation of τ_φ :

- at least in some cases, the saturation can be attributed to the presence of ***paramagnetic impurities*** in a small concentration undetectable by analytical methods (Michigan + Saclay collaboration, '02-'07, Bauerle *et al*., '05, etc.):

- dephasing by an ***external high-frequency electromagnetic noise***. This effect has not received the deserved attention though it was proposed as an explanation of Webb's results right after the publication of MJW paper [Khavin, MG, Bogdanov, *Phys. Rev. Lett*. **81**, 1066 ('98)].

Kondo-related Dephasing



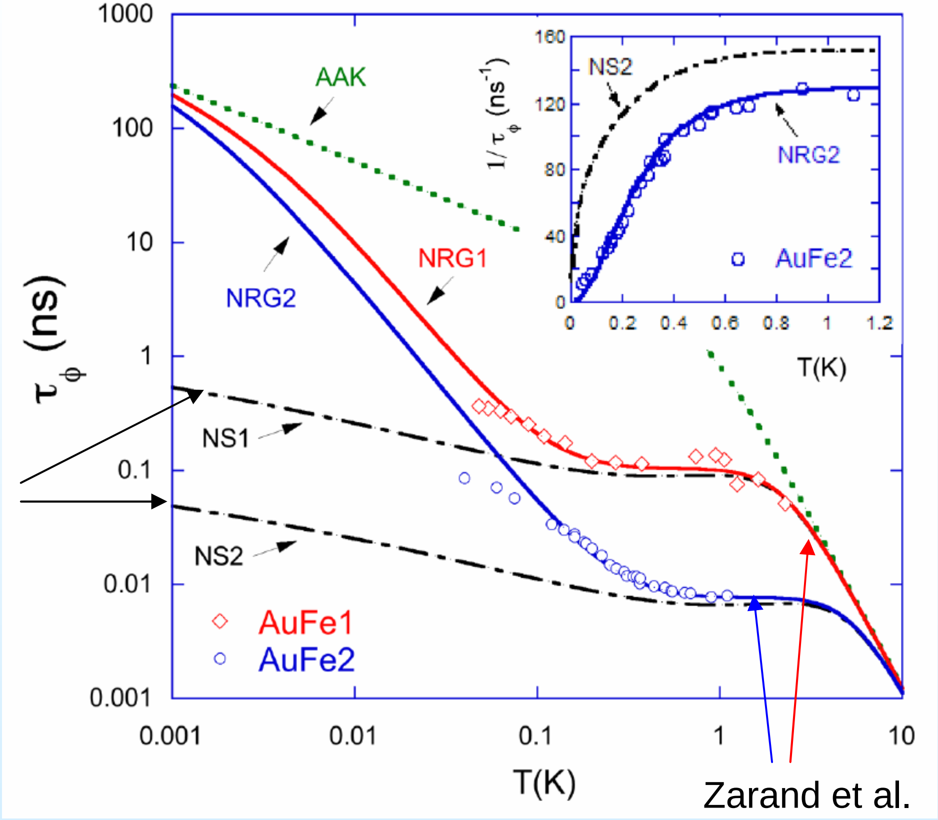
With an increase of the dephasing length, the dephasing rate might be affected by magnetic impurities even if their concentration is very low :

L_φ~10μm $\Rightarrow$ volume $L_\varphi^2 d$ contains
~3 impurities
at the concentration 1 ppm.

Pierre *et al.* ('03)

Experimental Test of the NRG Theory for Dephasing by Magnetic Impurities

Suhl-Nagaoka



The theoretical expression for the *T*-dependence of the dephasing rate, calculated on the basis of the Numerical Renormalization Group (NRG) bridges the gap between the low-*T* Fermi liquid theory and the high-*T* Suhl-Nagaoka expansion.

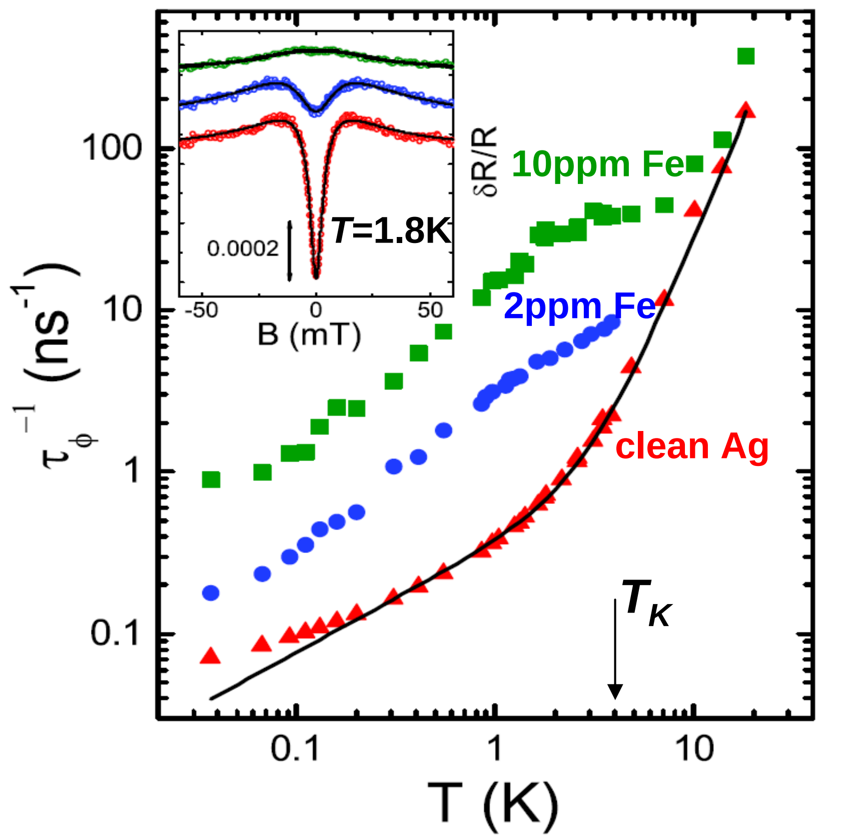
Zarand *et al*., *PRL* **93**, 107204 ('04)

Micklitz *et al*., *PRL* **96**, 226601 ('06)

C. Bauerle, F. Mallet, F. D. Mailly, G. Eska, and L. Saminadayar, *PRL* **95,** 266805 ('05)

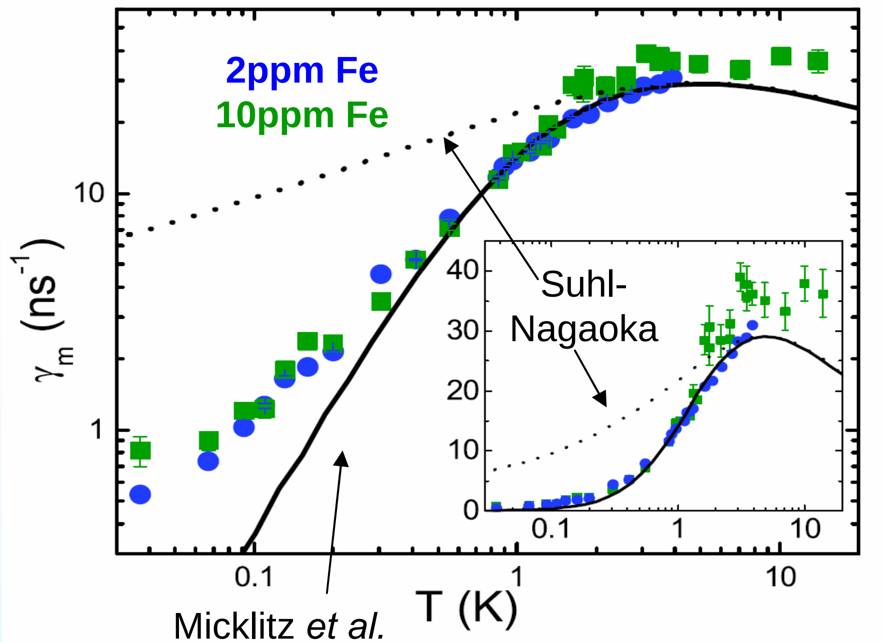
The "quadratically vanishing" dephasing rate appears only well below T_K.

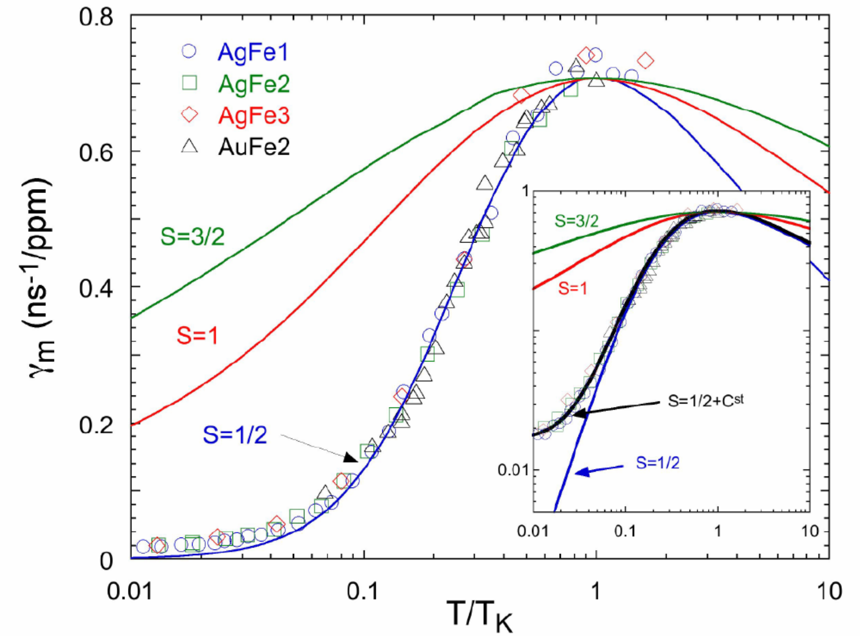
Experimental Test of the NRG Theory for Dephasing by Magnetic Impurities



Alzoubi and Birge, *PRL* **97**, 266803 ('06)

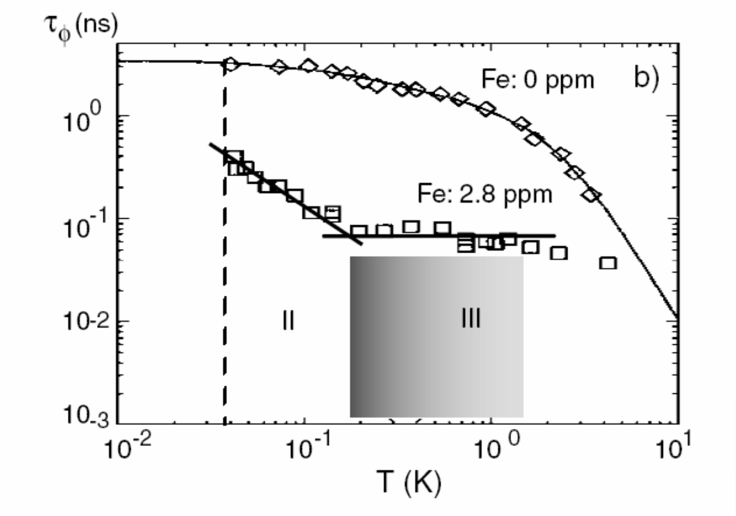
$$\tau_\varphi^{-1} = \tau_{in}^{-1} + \gamma_m$$





Mallet et al., *PRL* **97**, 266804 ('06)

Dephasing by external noise?

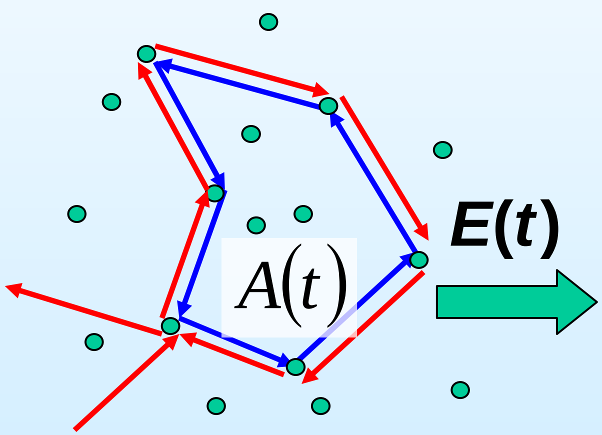


Mohanty & Webb, '03

Though controlling magnetic impurities at a level of a few *ppm* is a challenge, there were claims that at least in some samples, the observed saturation had nothing to do with magnetic impurities…

One of the suspects – dephasing by ***external high-frequency electromagnetic*** noise ***without overheating***.

Altshuler, Aronov, and Khmelnitsky, *SSC* **39**, 619 ('81)



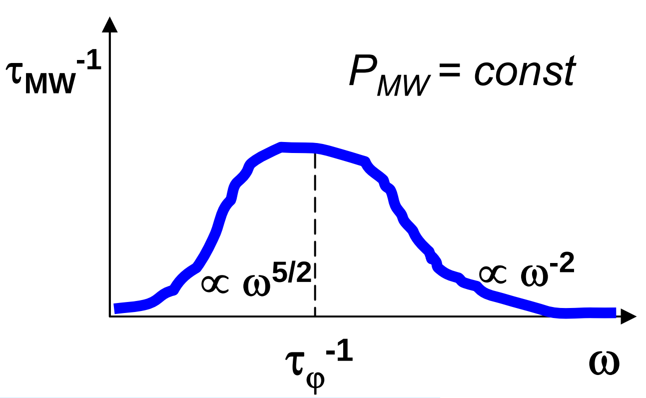
time-dependent E induces dephasing.

The most efficient dephasing: $\omega \approx \tau_\varphi^{-1}$

(typically, τ_φ ~ 1 ns, thus f_{MW} in the GHz range)

For an optimal ω, the MW-induced dephasing rate $\tau_{MW}^{-1} \sim \tau_{\varphi 0}^{-1}$ at

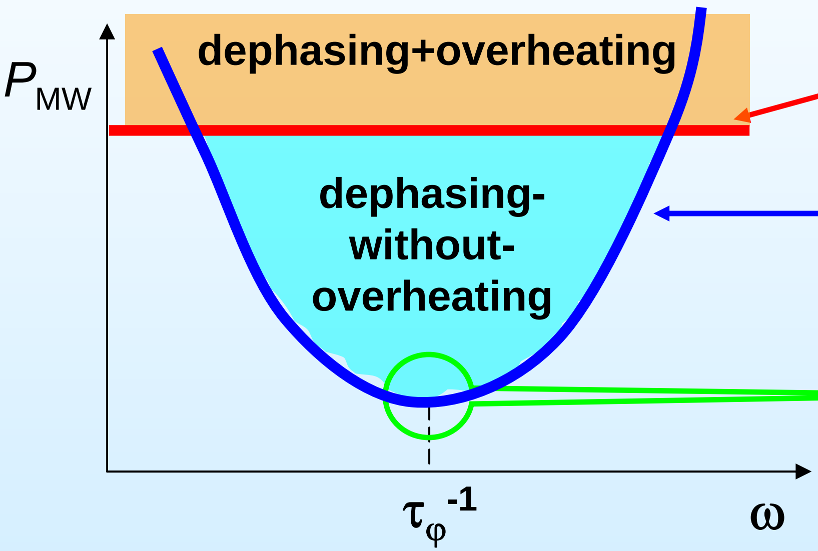
$$eE_{MW}\sqrt{D\tau_\varphi} \sim \frac{\hbar}{\tau_\varphi}$$



Experimental Challenge: MW Dephasing-w/o-Overheating

- ***dephasing***
- ***heating*** (also causes a decrease of τ_φ)

to separate ***E*(*t*)**–induced dephasing from trivial heating, the ***electron cooling*** should be optimized.



Electron heating becomes significant

MW-induced dephasing rate τ_{MW}^{-1} becomes comparable with $\tau_{\varphi 0}^{-1}$.

$$eE_{MW}\sqrt{D\tau_\varphi} \sim \frac{\hbar}{\tau_\varphi}$$

$$P_{MW} \propto \tau_{\varphi 0}^{-3}$$

For observation of the "MW dephasing-without-overheating":

- ***the lower T, the better*** **:** at ***T*** **> 1K**, dephasing in metal films is mostly due to the el.-ph. scattering ($\tau_\varphi \sim T^{-3}$) and $P_{MW} \sim T^{9}$ grows with ***T*** much faster than the thermal conductivity (~ T^{5}).
- ***1D is better than 2D***

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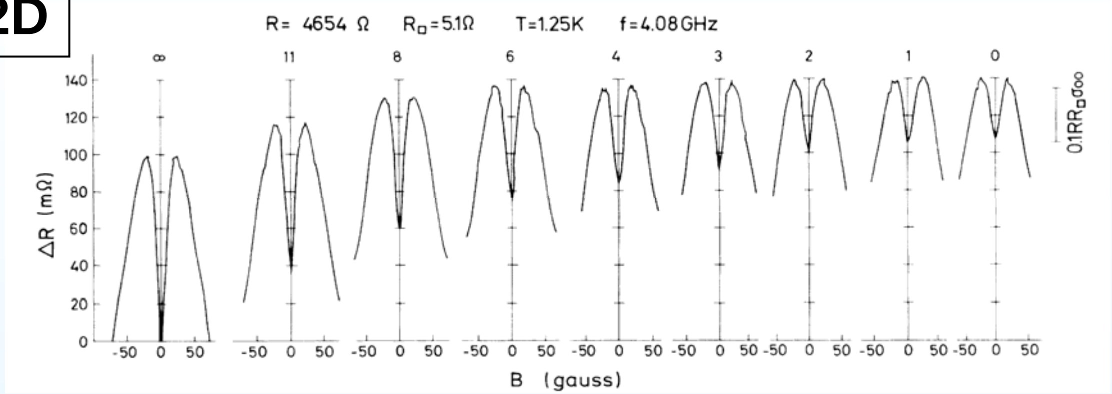
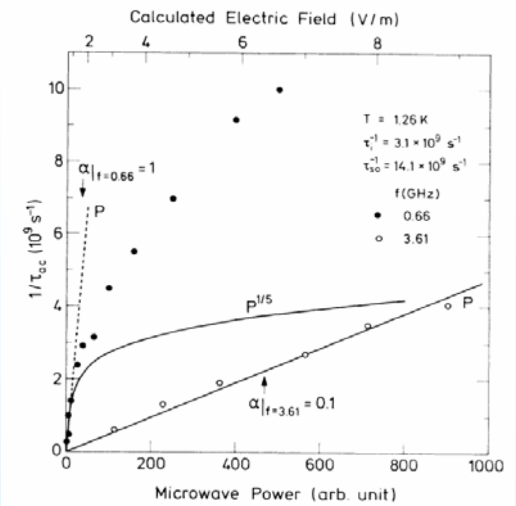
Prior Experiments on MW-induced Dephasing

2D





Wang and Lindelof, 1987 – Mg films

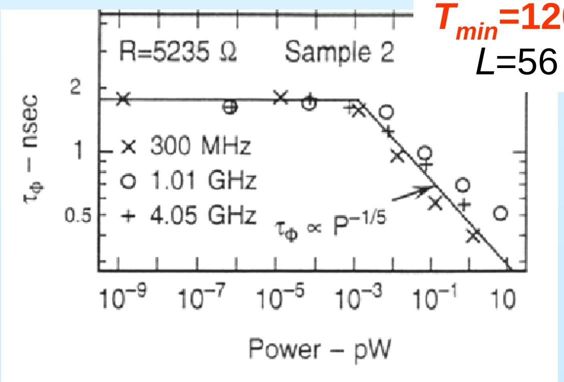
Vitkalov *et al*., 1988 – Si MOSFETs

In both experiments, the range of P_{MW} for "dephasing-without-overheating" was very narrow (if any).

1D

"We find that up to 26 GHz this external environment does not cause decoherence without a concomitant increase in the energy relaxation rate"

Webb *et al*., *in "Quantum Coherence and Decoherence"* (Elsevier 1999)



T_{min}=120 mK
L=56 μm

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Optimization of Sample Geometry

1D wires, ultra-low T

$$P_{MW}^{\varphi}\left(\propto \tau_{\varphi 0}^{-3}\right) = R\left(\frac{ek_B T}{\hbar}\right)^2$$

the MW power that results in $\tau_{MW} \sim \tau_{\varphi}$ (at optimal f_{MW})

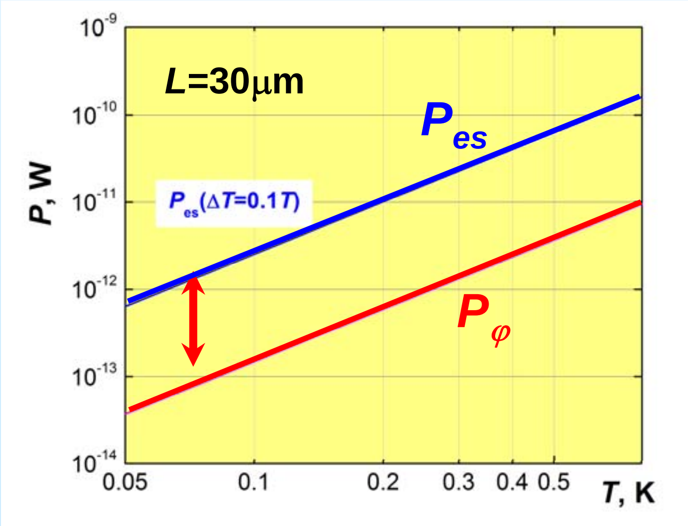
$$P_{es} \approx \left(\frac{2\pi k_B}{e}\right)^2 \frac{T\Delta T}{R}$$

cooling due to outdiffusion of hot electrons

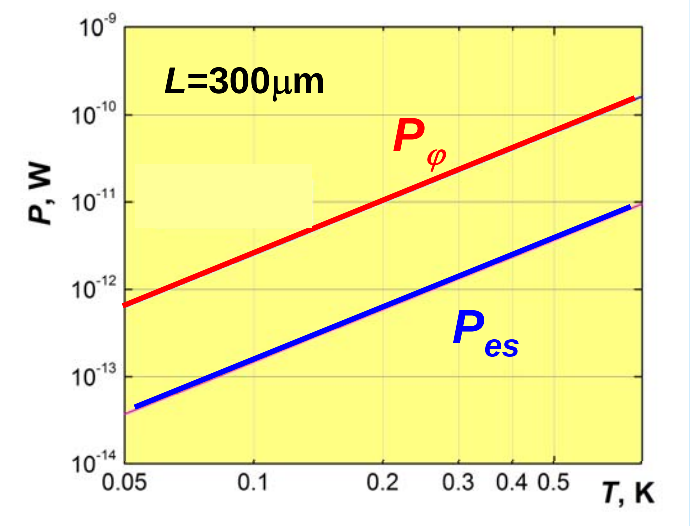
$$\frac{P_{es}}{P_{MW}^{\varphi}} \approx \left(\frac{h/e^2}{R}\right)^2 \frac{\Delta T}{T}$$

R – the total resistance of a wire

Short wires: "dephasing – ***without*** – overheating"



Long wires: "dephasing – ***with*** – overheating"



ideal samples for probing the intrinsic dephasing mechanisms

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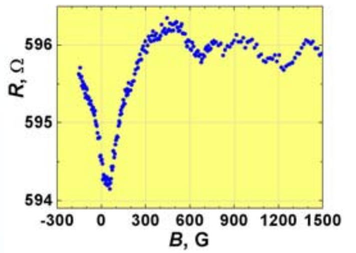
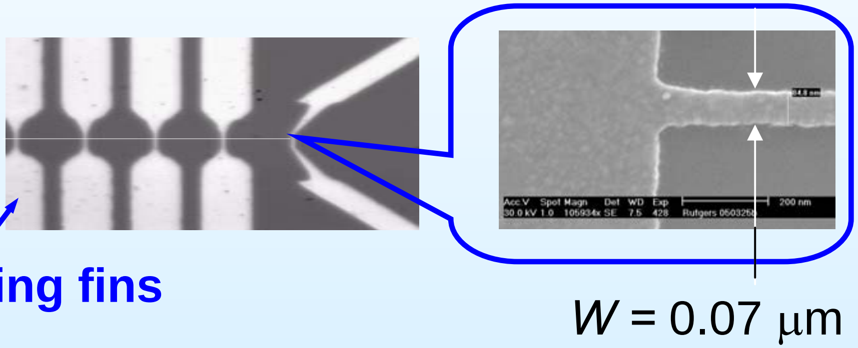
Sample Design

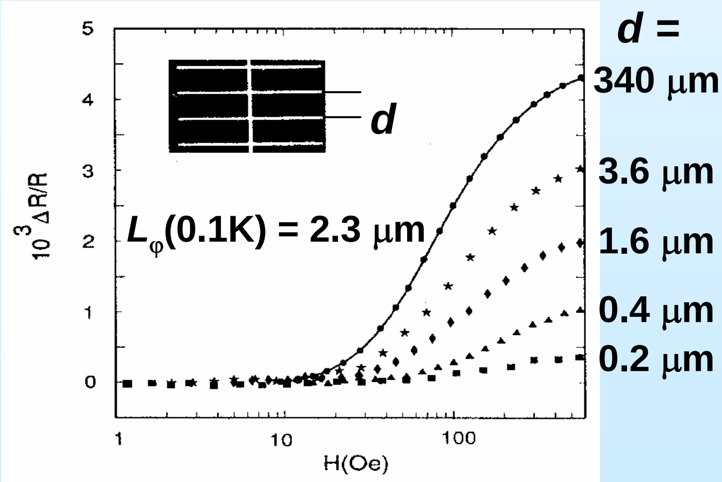


Short wires:
- **+** efficient outdiffusion cooling
- **-** poor UCF averaging, ***susceptible to the external noise***

Long wires:
- **+** better UCF averaging, less susceptible to external noise
- **-** only e-ph cooling, very inefficient at $T < 1$K

Solution: long wires with periodically spaced cooling fins.





Distance between cooling fins d = 30 μm, the total length – 1200 μm

One can neglect the effect of cooling fins on $\Delta\sigma_{WL}$ if $d > 10\ L_\varphi(T)$.

MG, P. Echternach *et al.*, *PRB* **51**,19256 (1995)

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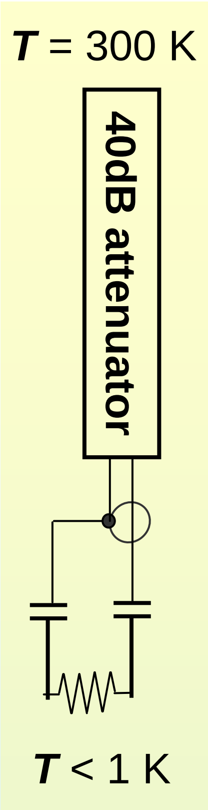
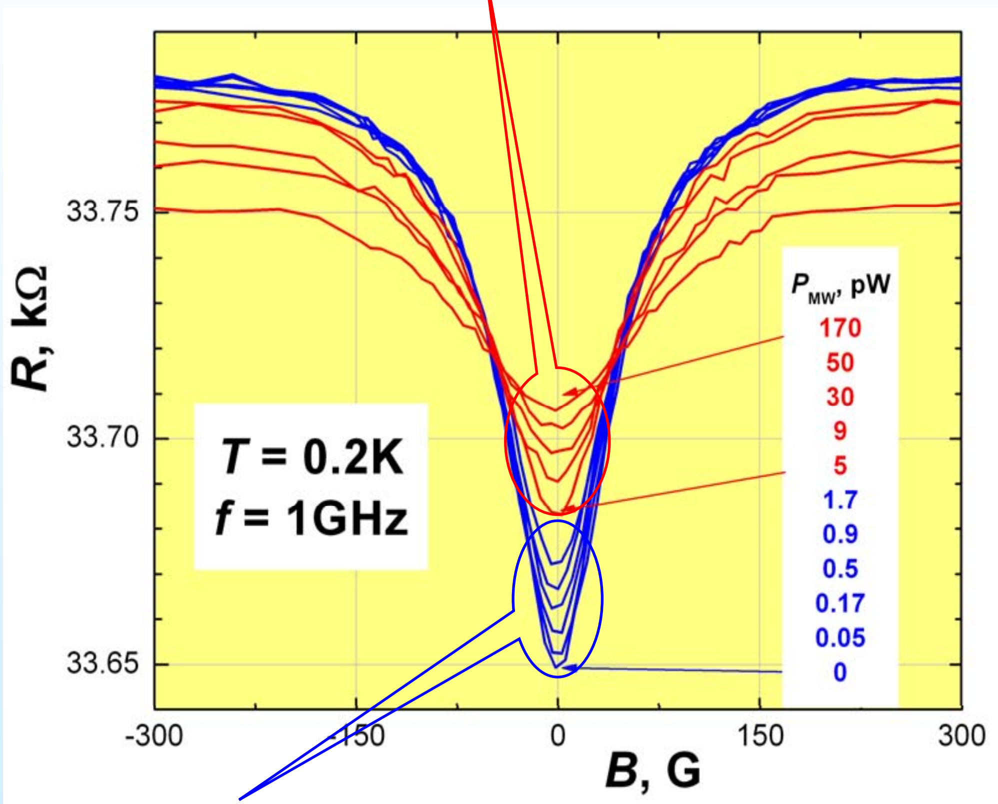
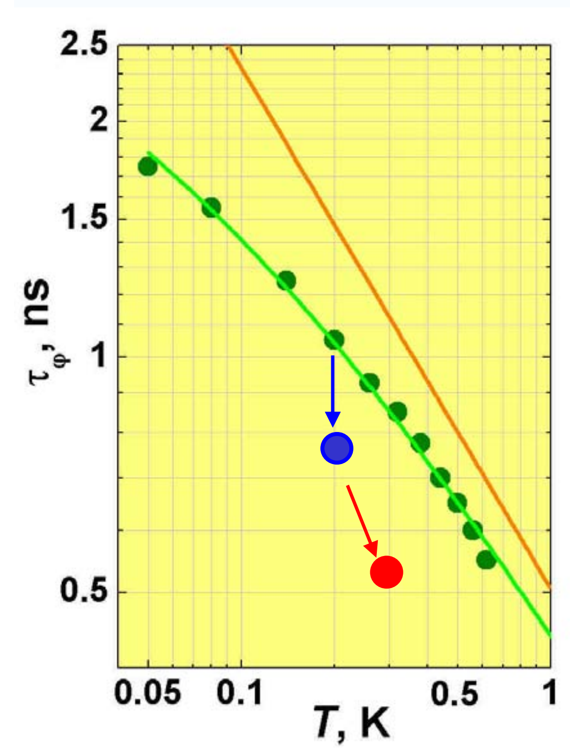
Effect of Microwave Radiation on the WL MR



MW dephasing + overheating



MW dephasing ***without*** overheating



Overheating at P_{MW} =170pW

Wei Jian, Pereverzev, MG, PRL. **96**, 086801 (2006)

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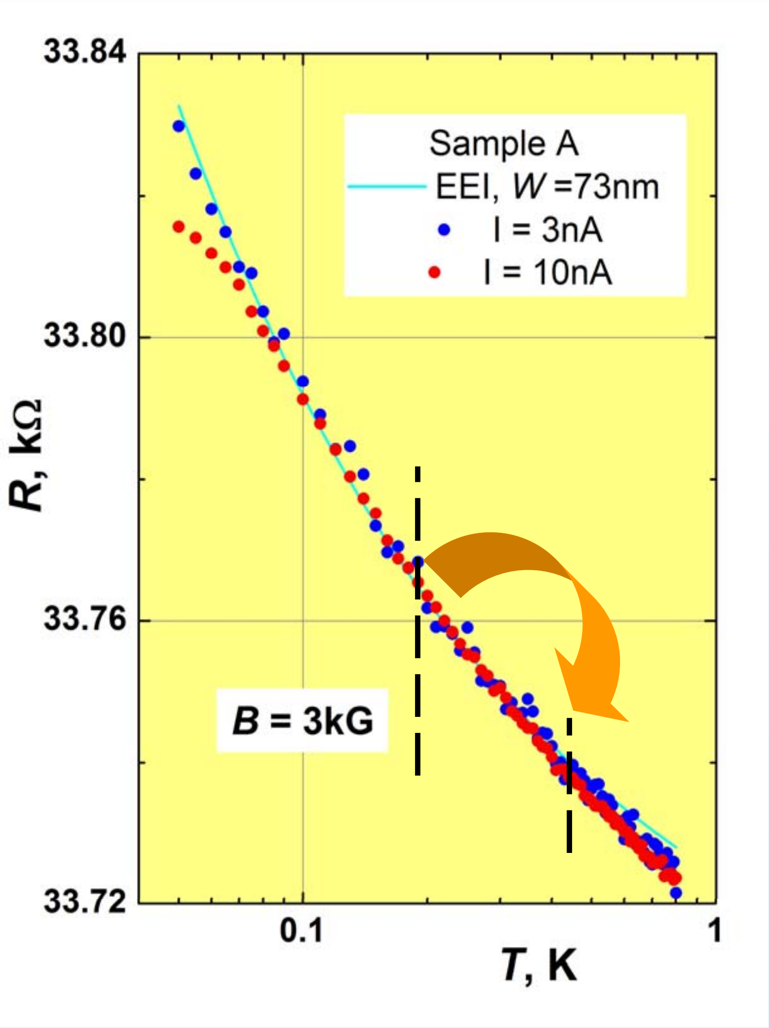
To compare our experiment with the AAK theory:

$$eE_{MW}\sqrt{D\tau_\varphi} \sim \frac{\hbar}{\tau_\varphi}$$

- $\tau_\varphi(T)$, $\tau_\varphi(T,P_{MW})$ - from the WL magnetoresistance at $P_{MW}=0$ and at $P_{MW}\neq 0$
- E_{MW} (or P_{MW} dissipated in the sample) – by comparing the DC and MW heating
- T_e – from the interaction corrections in strong magnetic fields ($L_H \ll L_\varphi$)

Interaction Corrections as a Built-in Thermometer



In strong magnetic fields ($L_H << L_\varphi$), $R(T)$ is determined solely by the interaction corrections $\Delta\sigma_{EEI}(T_e)$.

The measurements of ***R*** in strong ***B*** have been used for the direct measurement of T_e and calibration of the MW power dissipated in the sample, P_{MW}.

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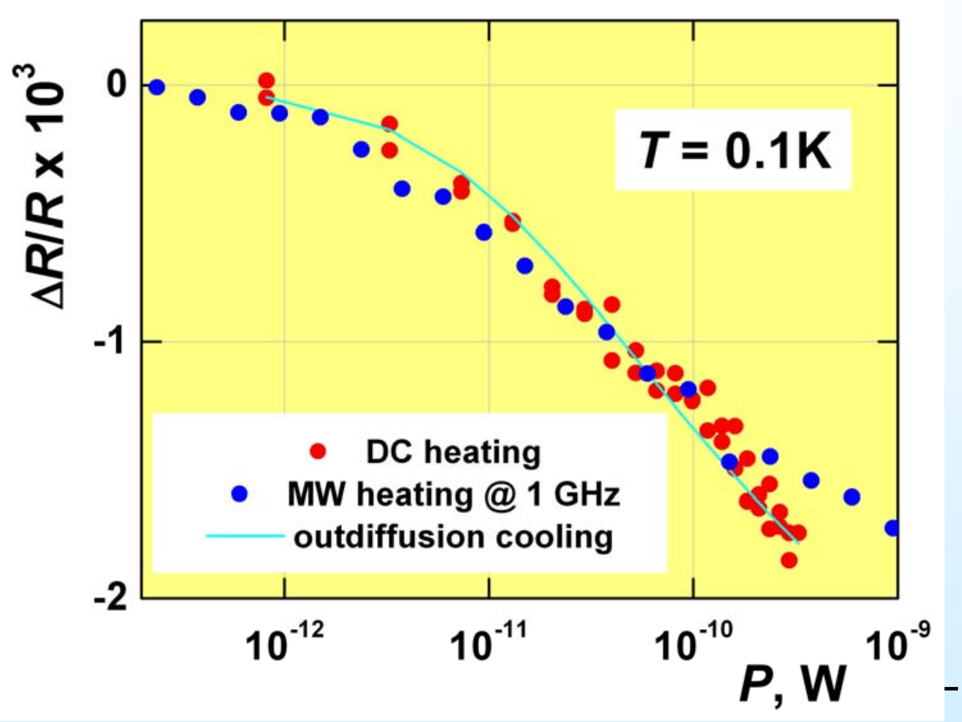
Calibration of MW power



- the MW power ***dissipated*** in a wire

Assumption:

dc current heating ≡ MW heating (ω **<< 1/**τ**,** τ - the momentum relaxation time)

At ***T*** = 0.1K, $\boldsymbol{P}_{MW}$ < 1 pW is sufficient to overheat the electrons in a 1.2 mm-long nanowire with cooling fins. For a typical 1D wire (***L*** ≤100 μm) , this power is in the ***fW*** range.

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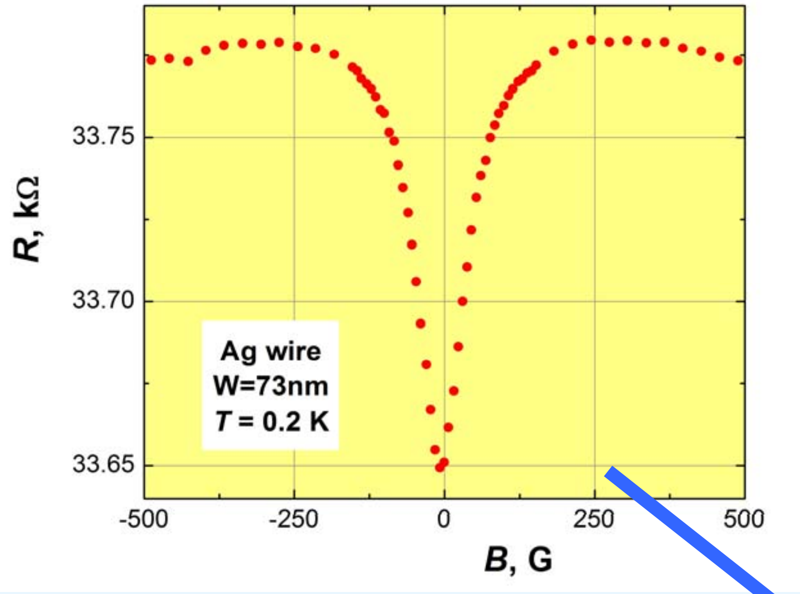
$\tau_\varphi(T)$ at $P_{MW} = 0$

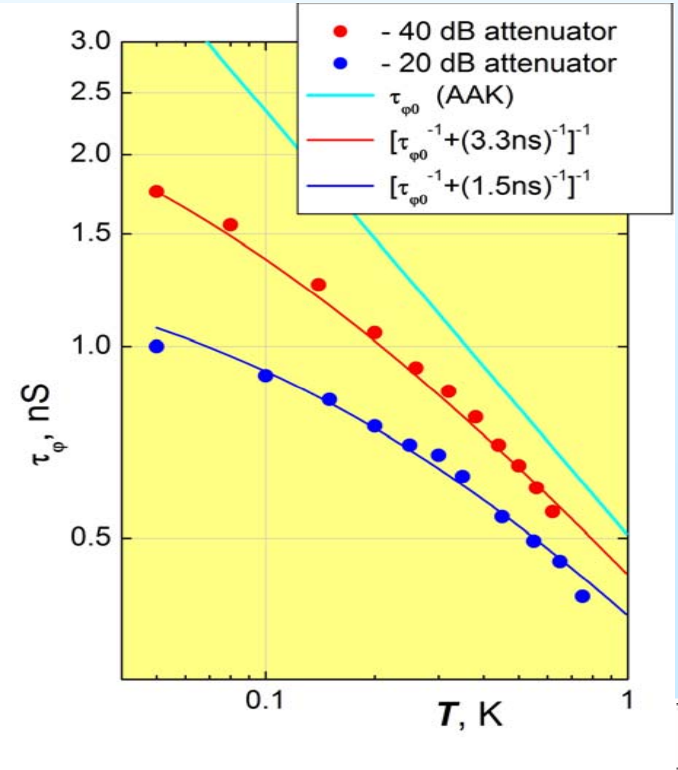


$$\Delta\sigma_1 = \frac{e^2 L_\varphi}{\pi\hbar}\frac{Ai\left(\tau_\varphi/\tau_H\right)}{\left[Ai\left(\tau_\varphi/\tau_H\right)\right]'}$$

modified for the case of strong spin-orbit interaction

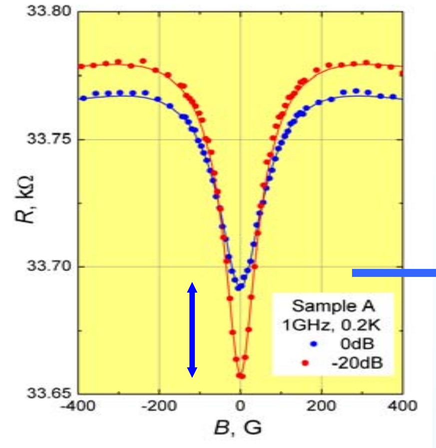
$$\tau_H = \frac{12L_H^4}{DW^2}$$

- dephasing by magnetic field



- $\tau_\varphi(T)$ "saturates" below $T \sim 0.1$ K
- $\tau_\varphi(T)$ depends on the coupling of a sample to its "environment"

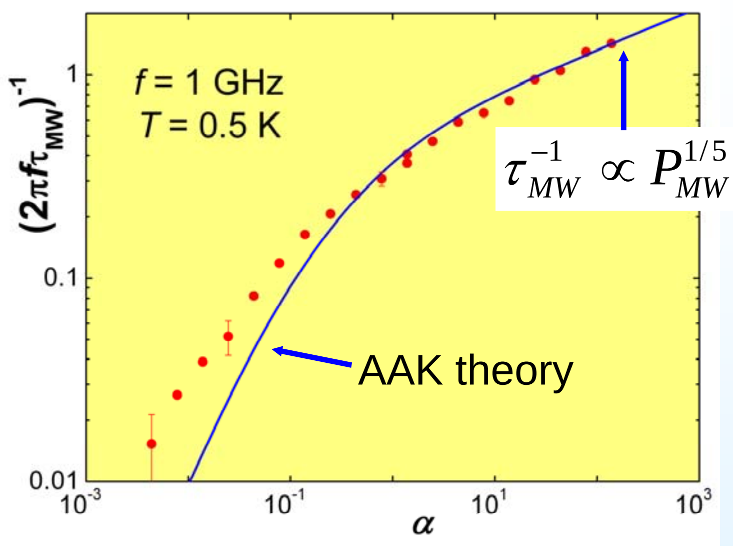
MW-induced Dephasing



The total dephasing rate:

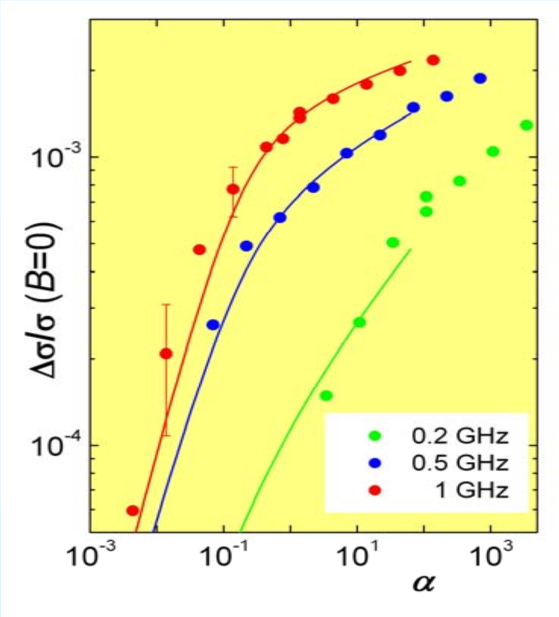
$$\tau_\varphi^{-1}(\omega, P_{MW})$$
$$= \tau_{\varphi 0}^{-1}(P_{MW} = 0) + \tau_{MW}^{-1}(\omega, P_{MW})$$

τ_{MW}^{-1} – the MW- induced dephasing rate



$$\alpha \equiv \frac{2e^2 D E_{MW}^2}{\hbar^2 \omega^3}$$ - the normalized MW power

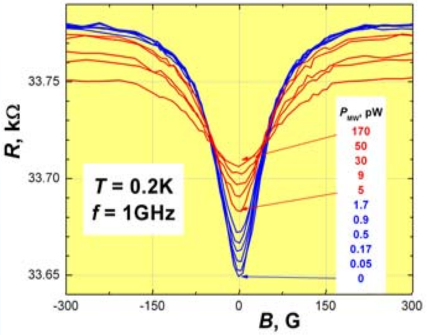
$\Delta\sigma_{WL}(B = 0, P_{MW})$



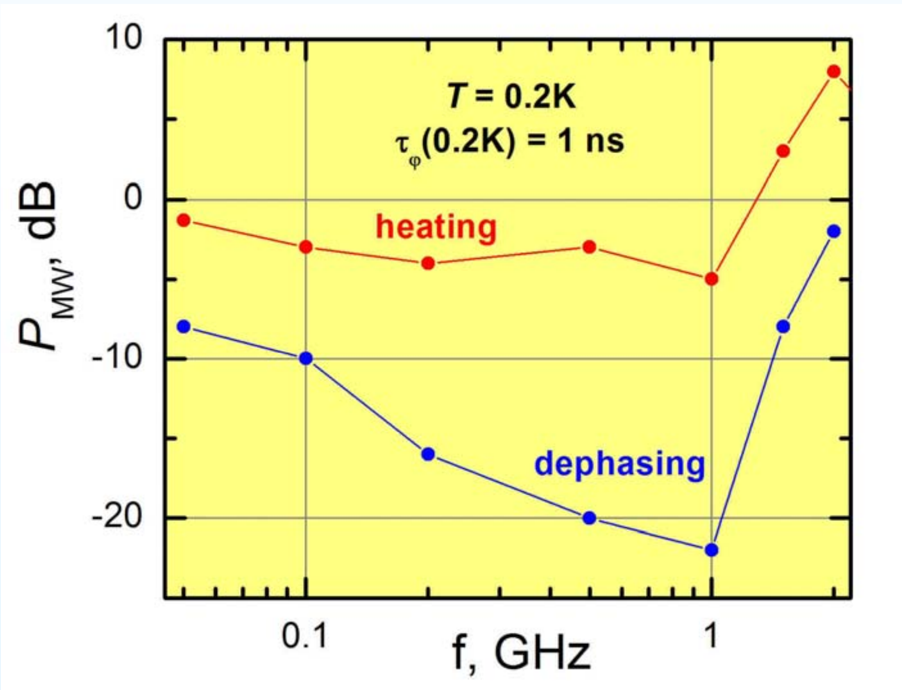
Wei Jian, Pereverzev, MG, PRL **96**, 086801 ('06)

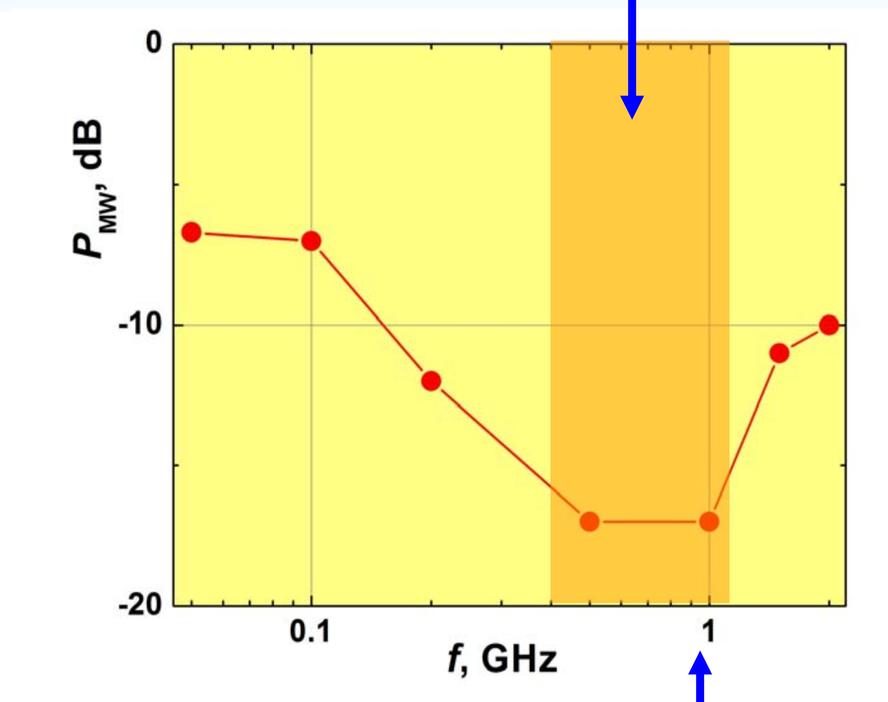
All experimental results are in good agreement with the AAK theory ***(no fitting parameters!)***

MW-induced Dephasing (cont.)



the most efficient
"MW dephasing-
without-overheating"





$f = 1/\tau_\varphi(0.2K)$

$$\Delta R(B=0) = +5\Omega$$

$$\Delta R(B=3kG) = -5\Omega$$

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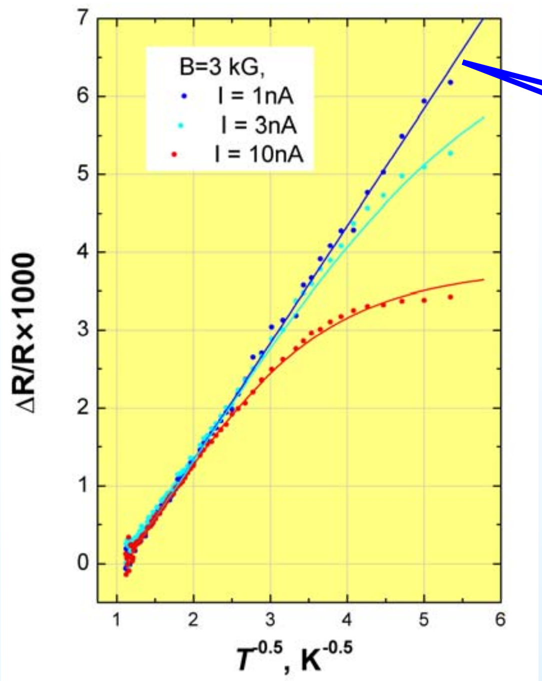
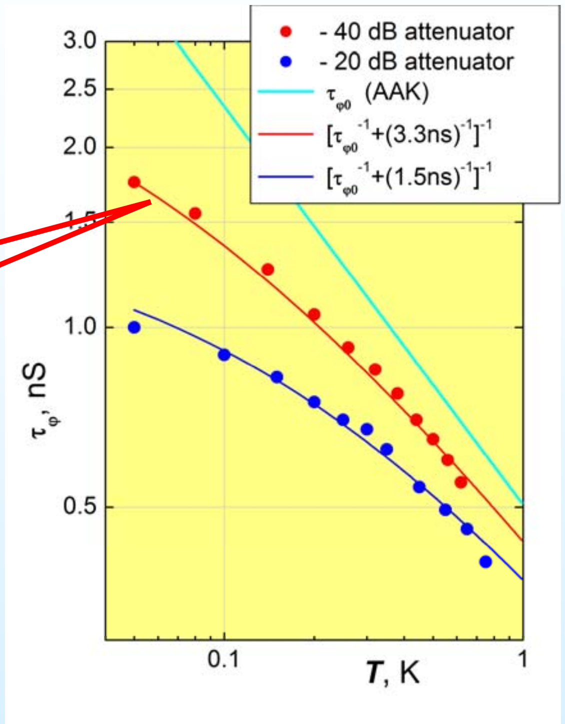
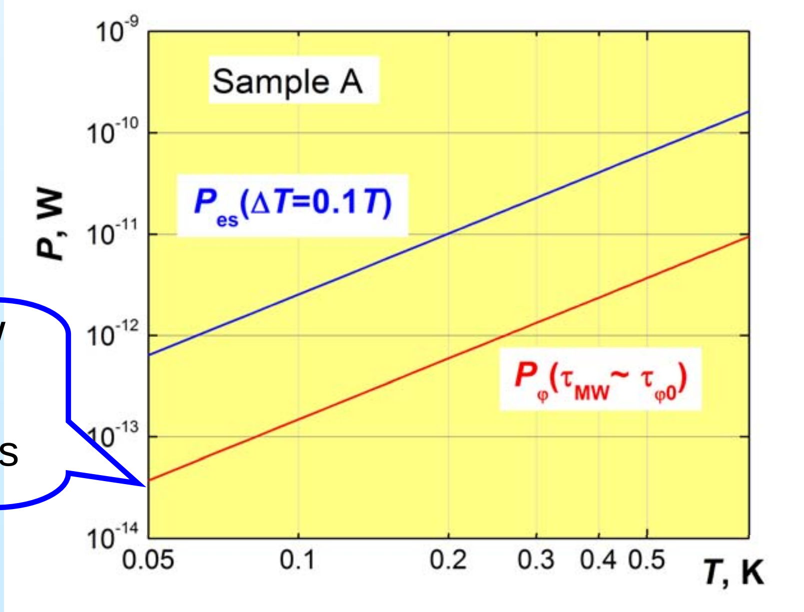
Low-*T* saturation of τ_φ



the upper bound on the external noise power ~ $3 \cdot 10^{-14}$ W



$$\tau_\varphi^{-1}(T) = \tau_{\varphi 0}^{-1}(T) + (3.3\text{ ns})^{-1}$$



$P_{MW} = 3 \cdot 10^{-14}$ W leads to $\tau_{MW} \sim \tau_\varphi$(50 mK)=3.7 ns

Conclusion: in our experiment, the saturation of $\tau_\varphi(T)$ may be caused by the external electromagnetic noise

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Summary

- Interaction effects in disordered conductors produce quantum corrections to the conductivity, DoS, and other electron parameters.

- Dephasing in 1D and 2D conductors at low T is governed by interaction effects

- The observed saturation of $\tau_{\varphi}(T)$ at $T < 0.1$K - most likely due to scattering by paramagnetic impurities and dephasing by high-frequency electromagnetic noise.

Lecture 3: Quantum Corrections to the Conductivity of High-Mobility Si MOSFETs

- Intro: quantum corrections in Si MOSFETs (the most ubiquitous 2D structure) $\Rightarrow$ 25-year-old mystery and the work is still in progress

- Ingredients essential for better understanding of interaction effects in Si MOSFETs:

  - interaction parameters in high-mobility Si MOSFETs
  - valley splitting and inter-valley scattering

- Analysis of $\Delta\sigma(T,B)$

- The crossover from "metallic" to "insulating" conductivity: role of inhomogeneity?