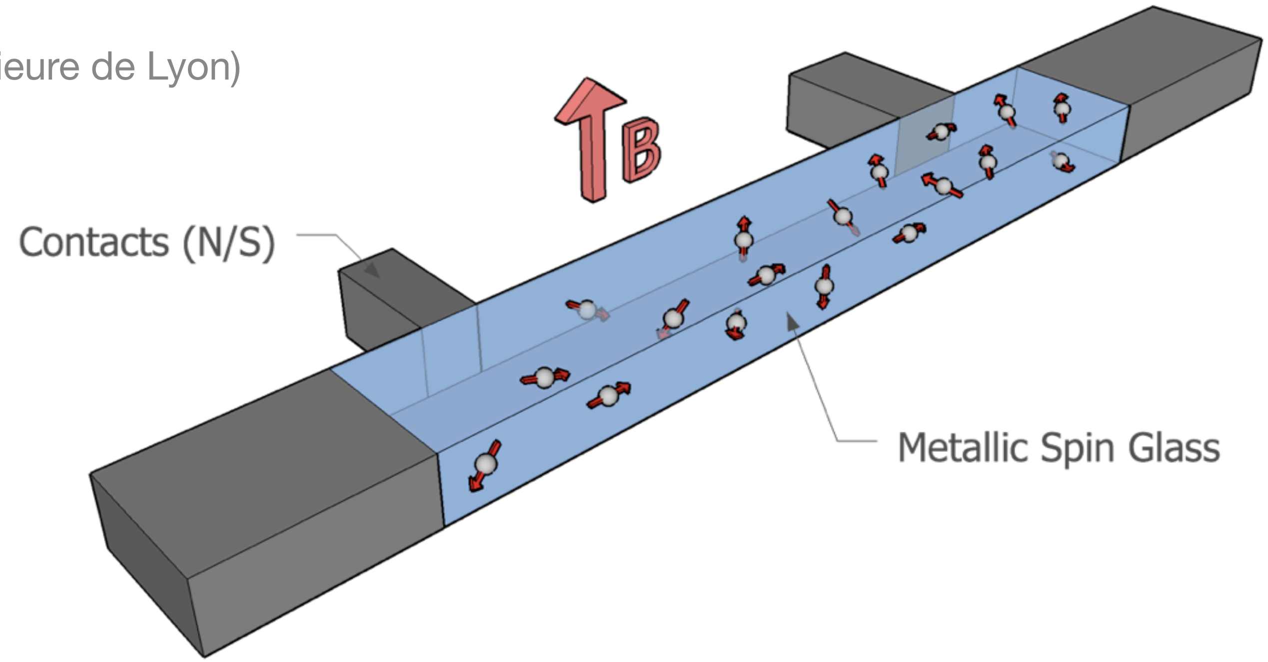
Probing a Metallic Spin Glass Nanowire via Coherent Electronic Waves Diffusion

D. Carpentier,
(Ecole Normale Supérieure de Lyon)



- Theory :

A. Fedorenko, E. Orignac, **G. Paulin** (PhD)
(Ecole Normale Supérieure de Lyon)

- Experiments :

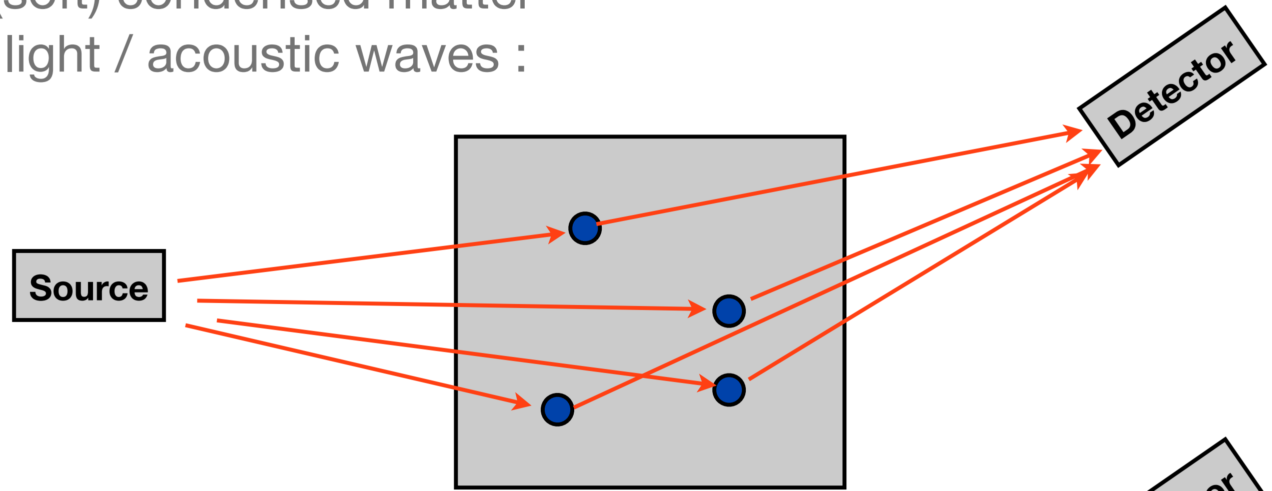
C. Bäuerle, **T. Capron** (PhD), L. Lévy, T. Meunier, L. Saminadayar
(Quantum Coherence Group, Institut Néel, Grenoble)

Support : CNRS, Computing center of ENS-Lyon (PSMN) and ANR MesoGlass

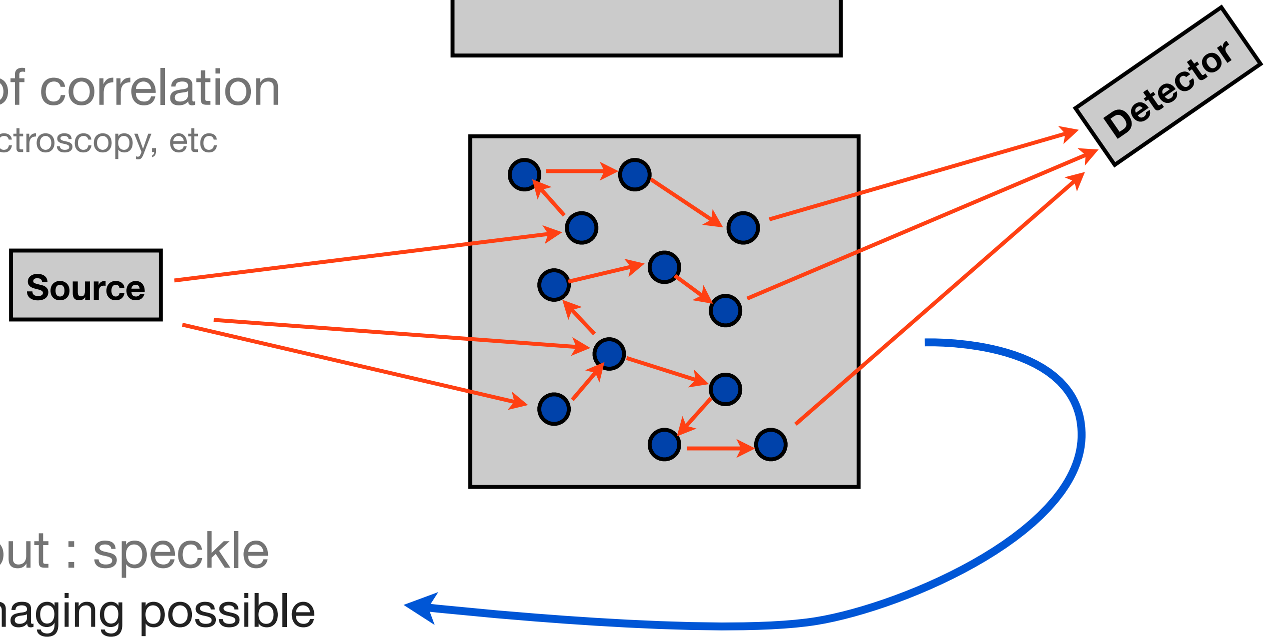
Using waves to probe matter

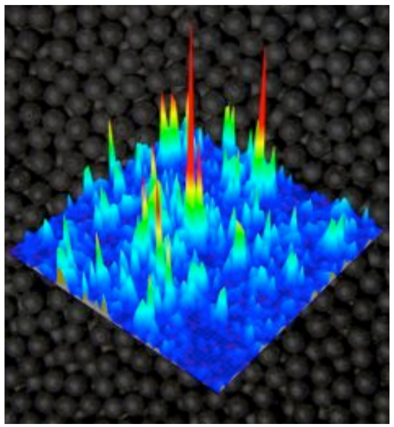
Various methods to probe (soft) condensed matter using coherent diffusion of light / acoustic waves :

- Simple diffusion
  (radar, seismic detector, doppler velocimetry, etc)



- **Multiple diffusion** : use of correlation
  Diffusion (acoustic) / coda wave spectroscopy, etc



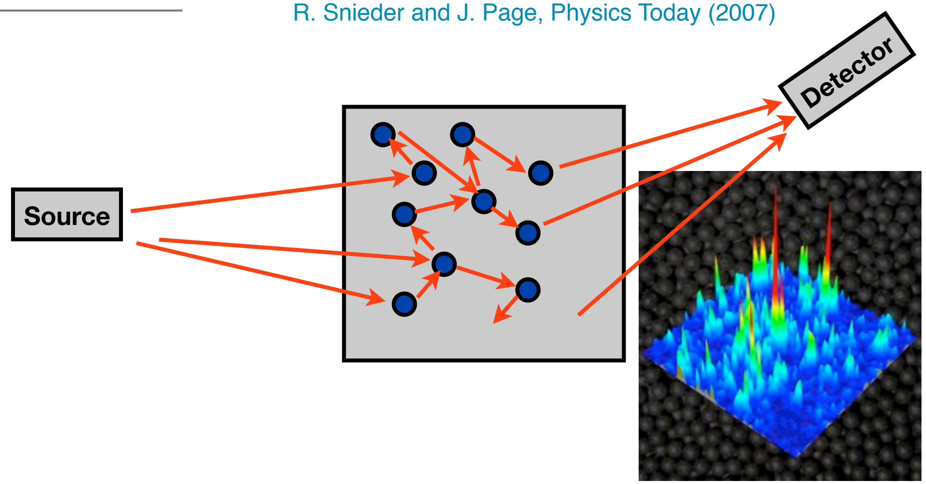


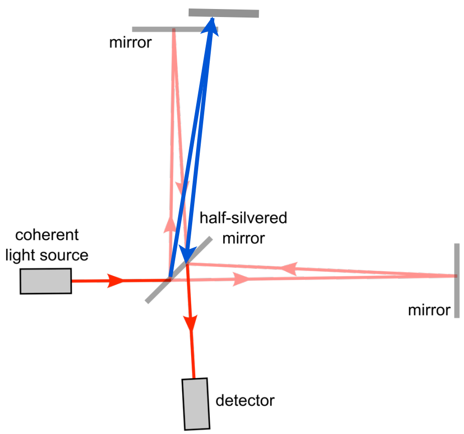
Output : speckle
no imaging possible

Coherent mult. diffusion : acoustic wave spectroscopy

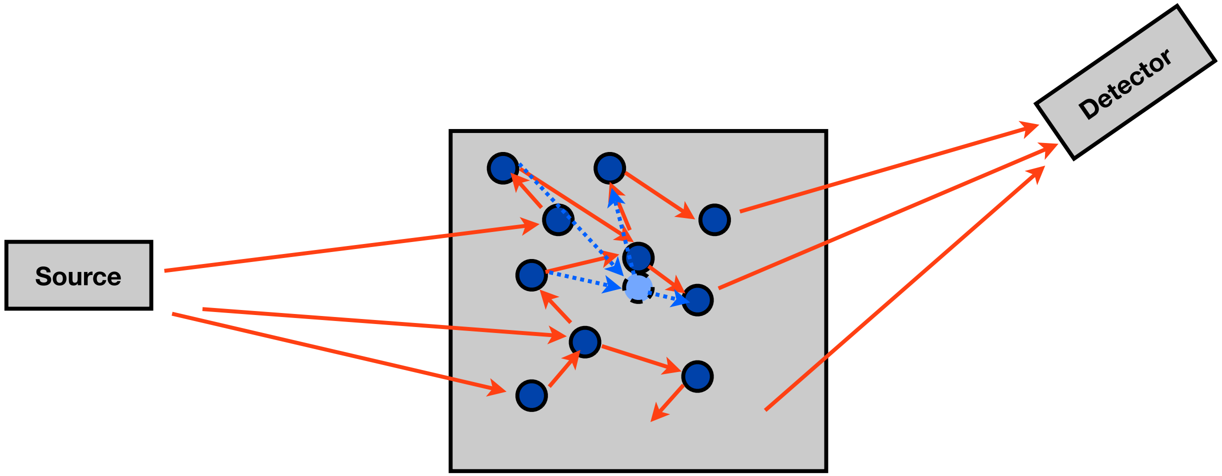
R. Snieder and J. Page, Physics Today (2007)

- Output : speckle
➡ too difficult to analyze / use to probe
- Idea : analyze change of output when the diffusing medium is modified





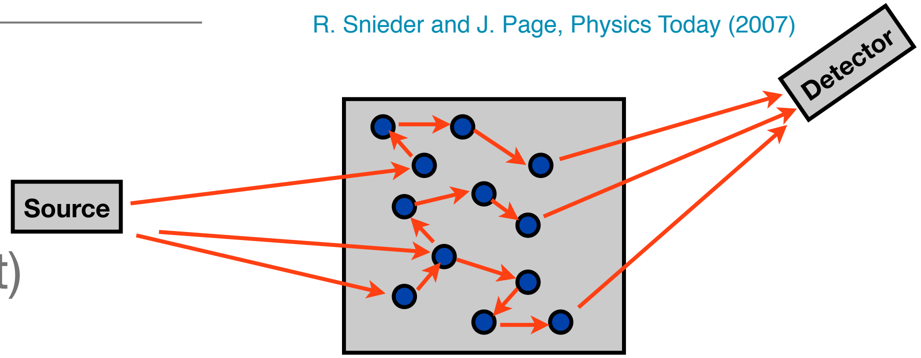
~ Interferometer



Intensity modified by small variations of diffusion medium
➡good sensitivity

Coherent mult. diffusion : acoustic wave spectroscopy

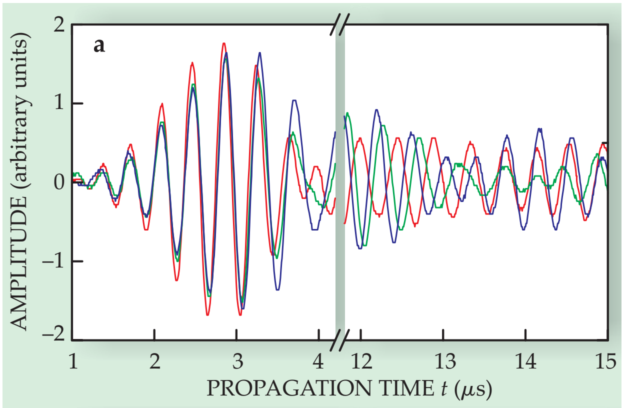
R. Snieder and J. Page, Physics Today (2007)



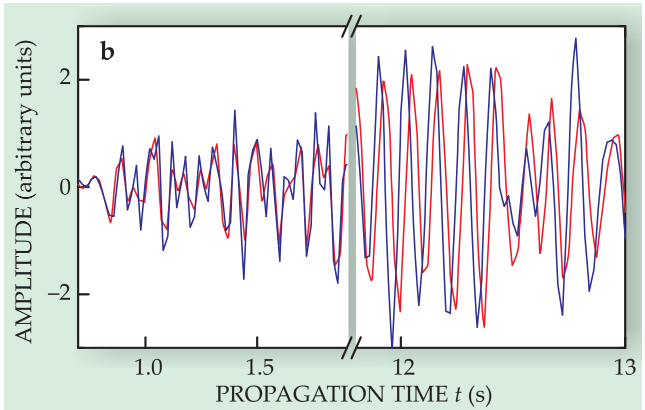
- Procedure :

1. At time T_1 : send a pulse
2. Record the transmitted amplitude $\psi(T_1,t)$ as a function of time
3. Repeat another trace $\psi(T_2,t)$ at time $T_2 = T_1+\Delta T$
4. etc

- Correlation between traces : mean relative displacement in the medium $g(\Delta T) \approx \int \psi(T,t)\, \psi^*(T+\Delta T,t)\, dT \approx \exp(-\, N(t)k^2 \langle \Delta r^2(\Delta T)\rangle)$



ultrasonic pulse in particulate suspension



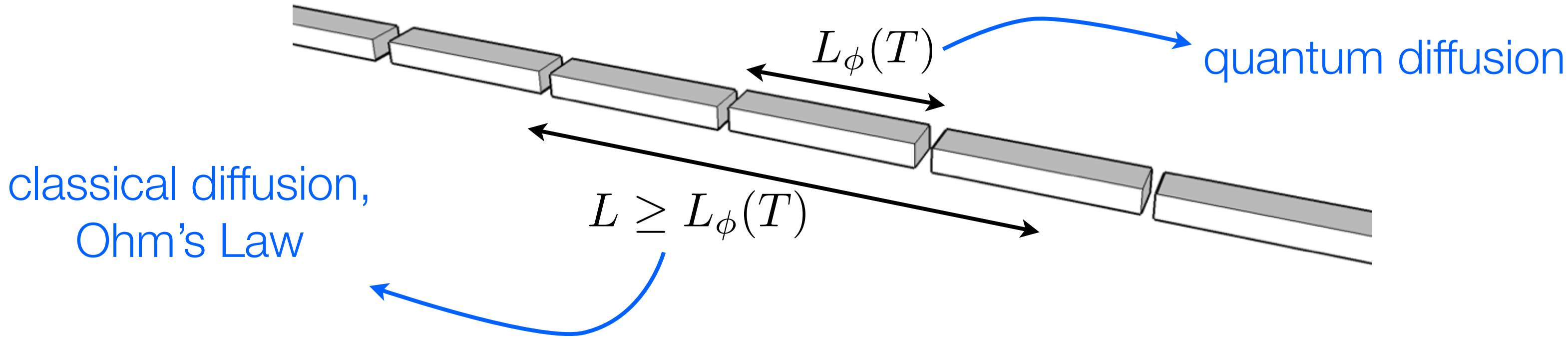
sismographic wave transmitted near Mount Merapi

from R. Snieder and J. Page, Physics Today (2007)

What about electronic waves ?

- waves diffusion : necessity to be phase coherent
  - electrons interact with environment (phonons, other electrons, impurities)
  - randomization of its phase
  - “looses memory of its phase” over coherence length $L_\phi(T)$

➡ electronic transport is classical in “standard situations” (Ohm’s law)
but quantum at low T (fewer phonons), and small length (few µm)



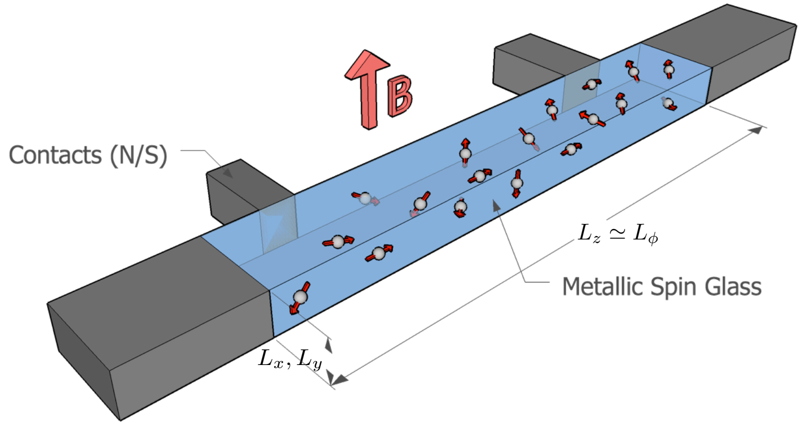
- only total flux (current) detected : no angle information, no speckle
- advantages : charge (sensitive to magnetic flux), spin (use it here).

General Idea of this work

P. de Vegvar, L. Lévy, and T. Fulton, Phys. Rev. Lett. **66**, 2380 (1991)
D.C. and E. Orignac, Phys. Rev. Lett. 100 (2008)

- How to measure correlations between different spin configurations ?

- Our proposal : use coherent electronic transport to probe of a spin configuration :
  correlation of spin configurations ⇔
  correlation of transport properties



L. Lévy et al. : 1000ppm Cu:Mn,
$(d_{SS} \simeq 23\text{Å}), L \simeq 1\mu m, L_\phi \simeq 0.5\mu m,$
$L_y \simeq 900\text{Å}, N^{\perp}_{spins} \simeq 40$

Quantity analogous to Speckle ?

- Coherent transport regime : transport on distances L_z comparable with the coherence length scale $L_\phi(T)$: small wires ($L_z \simeq \mu m$)

- $L_\phi(T)$ is limited by inelastic scattering :
  - phonons ⇒ low temperatures (T~ 100 mK)
  - inelastic magnetic scattering : reduced in spin glass !!!

  $L_\phi(T)$ increases in the Spin Glass phase

- Transport in a wire : $L_x, L_y \ll L_z, L_\phi$

Transport probe : Classical ≠ Quantum Diffusion

E. Akkermans and G. Montambaux, Mesoscopic Physics of electrons and photons, 2007

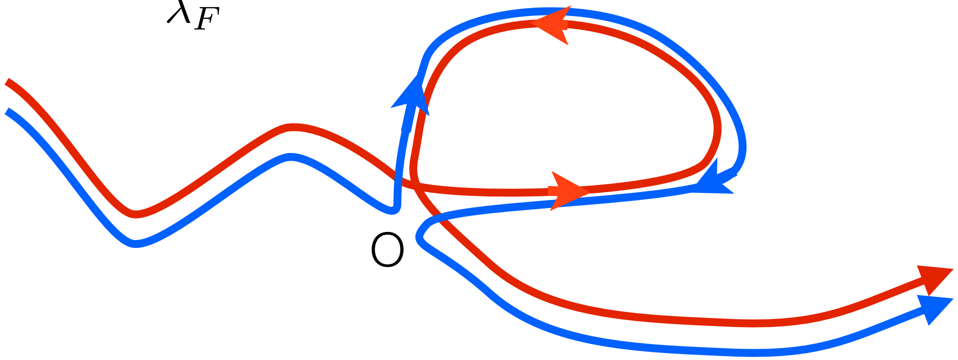
- Probability to diffuse from $\vec{r}$ to $\vec{r}'$

Classical

Interferences

$$P(\vec{r} \to \vec{r}') \propto \left| \sum_{path\ \mathcal{C}_{\vec{r} \to \vec{r}'}} A_{\mathcal{C}} \right|^2 = \sum_{\mathcal{C}} |A_{\mathcal{C}}|^2 + \sum_{\mathcal{C} \neq \mathcal{C}'} A_{\mathcal{C}} A^*_{\mathcal{C}'}$$

- Phase variation along a diffusion path : $\delta\phi_{\mathcal{C}} = 2\pi \frac{L_{\mathcal{C}}}{\lambda_F}$ $\Rightarrow$ random in a metal
- Average interferences vanish, except if "$\mathcal{C} = \mathcal{C}'$" (reversed ring)



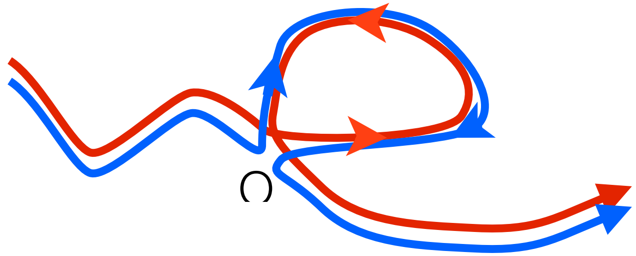
➡Quantum correction : loop contributions

(weak localization : first signs of Anderson Localization of waves)

Transport probe : Magnetic field effects

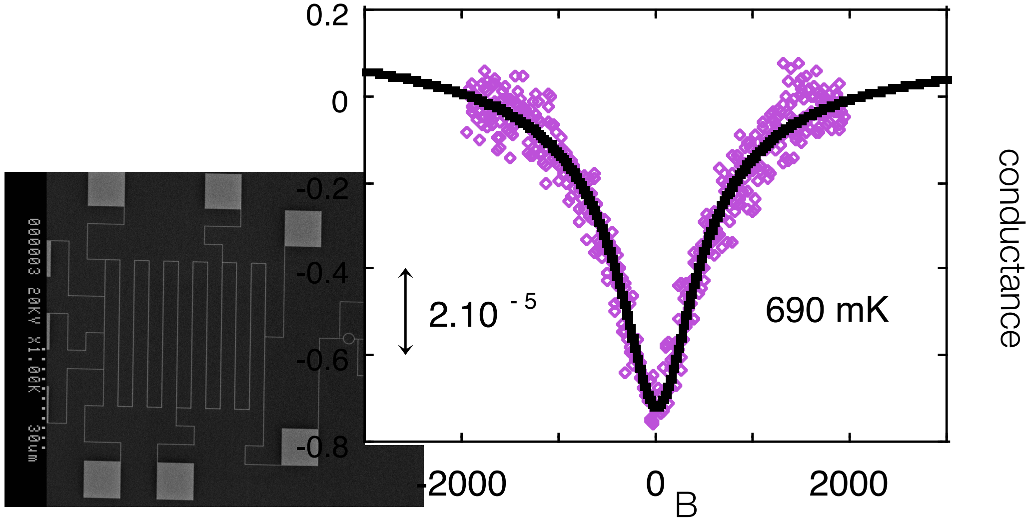
E. Akkermans and G. Montambaux, Mesoscopic Physics of electrons and photons, 2007

Application of a magnetic field : dephase path with respect to each other : $\delta\phi_{\mathcal{C},\mathcal{C}'} = 2\pi\Phi_{\mathcal{C},\mathcal{C}'}/\Phi_0$

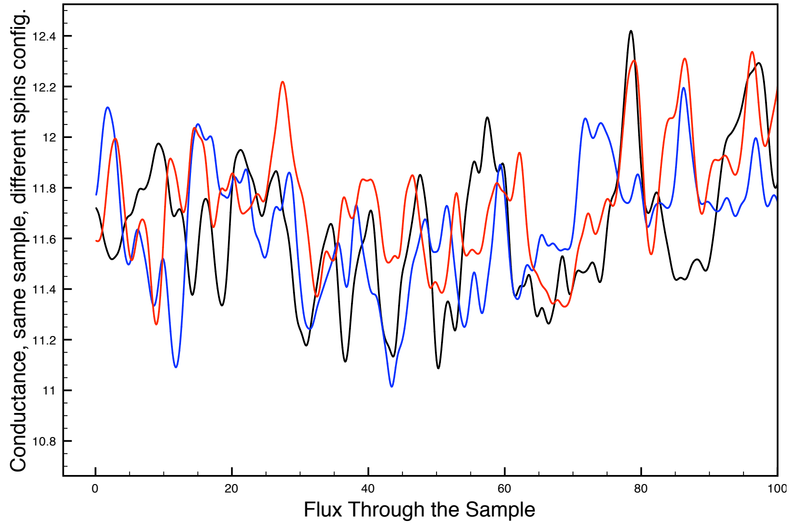


➡ quantum corrections affected with 2 consequences :

weak localization (long wires)



universal conductance fluctuations : fingerprint of disorder configurations



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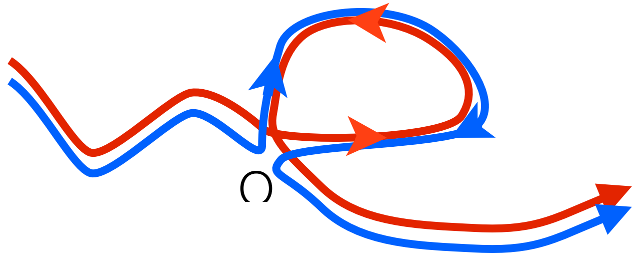
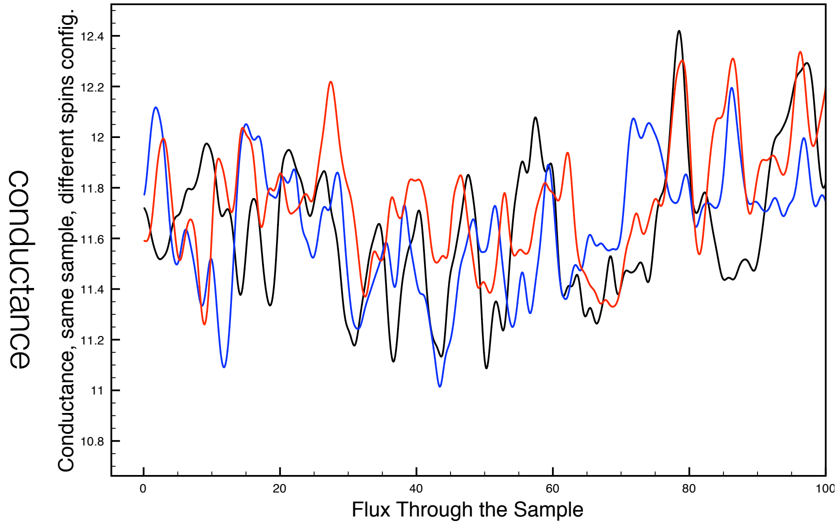


➡quantum corrections affected with 2 consequences :

$$P(\vec{r} \to \vec{r}') \propto \left| \sum_{path\ \mathcal{C}_{\vec{r}\to\vec{r}'}} A_{\mathcal{C}} \right|^2 = \sum_{\mathcal{C}} |A_{\mathcal{C}}|^2 + \sum_{\mathcal{C}\neq\mathcal{C}'} A_{\mathcal{C}} A^*_{\mathcal{C}'}$$

universal conductance fluctuations :
fingerprint of disorder configurations



Quantity analogous to Speckle

Ergodic Hypothesis :

Changing random potential (length of paths) or applying B : similar statistical dephasing

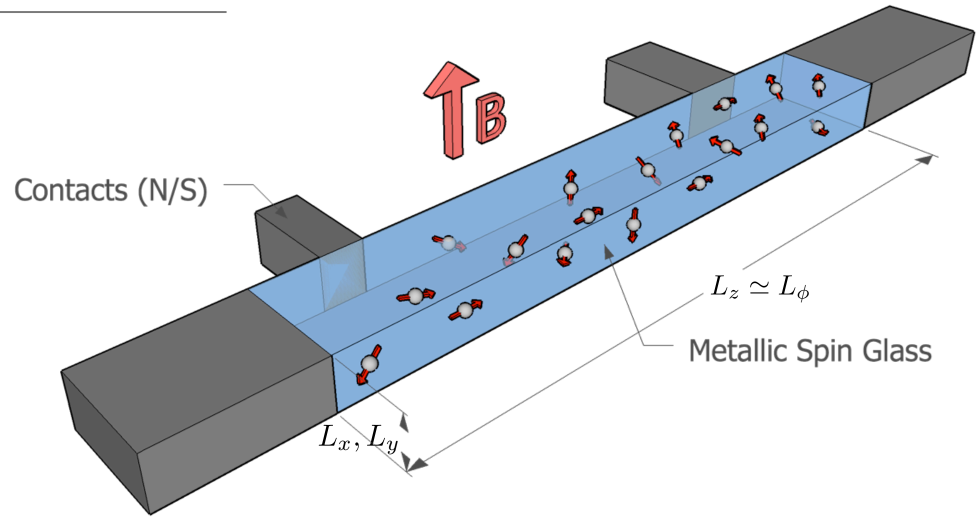
➡averaging over B or V equivalent

$$\langle(\delta G(B,V))^2\rangle_B = \langle(\delta G(B,V))^2\rangle_V = c\frac{e^2}{h}$$

Crucial for theoretician

General Idea of this work (2)

D.C. and E. Orignac, Phys. Rev. Lett. 100 (2008)



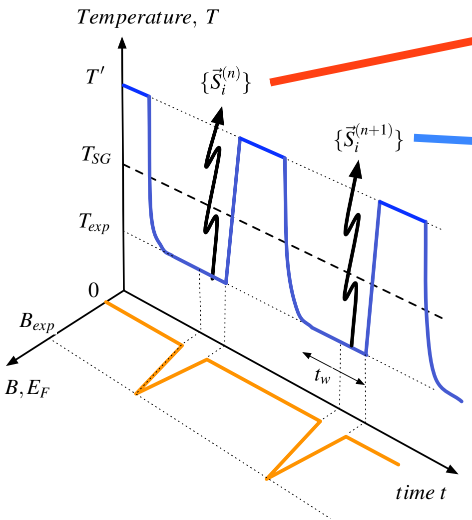
correlation of spin configurations ⇔

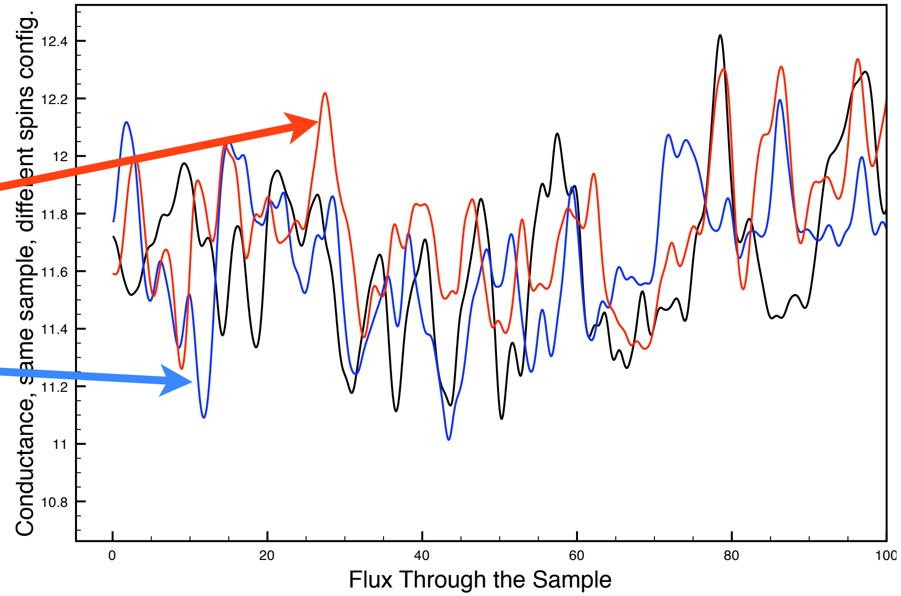
correlation of transport properties

- Measure traces G(B) in 1 sample, but for 2 spin configurations $G\left(B,\{S_j^{(1)}\}\right), G\left(B,\{S_j^{(2)}\}\right)$

- Consider average correlation between the two traces : $\left\langle \delta G\left(B,\{S_j^{(1)}\}\right)\delta G\left(B,\{S_j^{(2)}\}\right)\right\rangle_B$

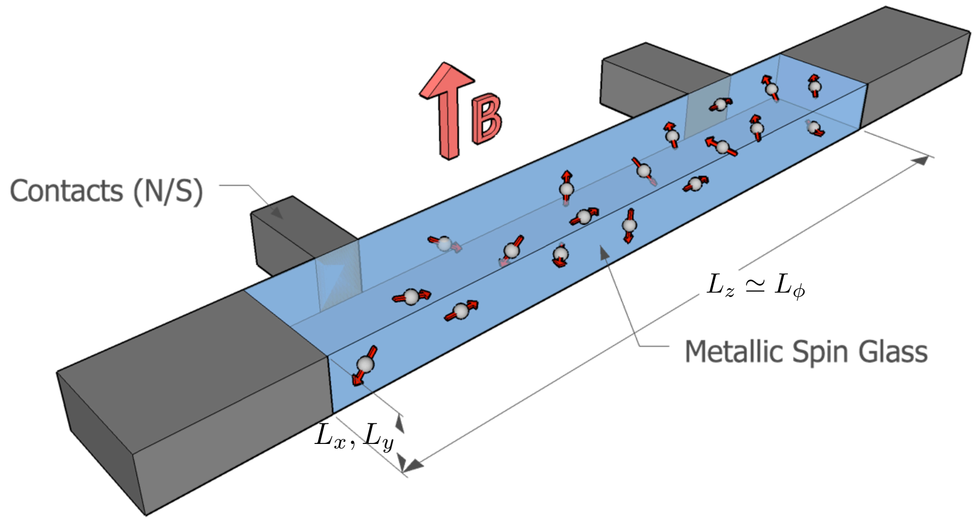
➡ Provides a measure of correlation between the spin configurations ?





1D Diffusion but 3D Spin Glass !

- In theory : no Spin Glass phase in d=1,2 (Ising SG)
- Typical number of spins in a section : $N_\perp \simeq 40$
- putative overlap / equilibration length for a 3D spin glass $N_{eq}^{(3D)}(t)$
- Evaluation of $N_{eq}^{(3D)}(t)$ from field change experiments and recent simulations (Ising SG) : $N_{eq}^{(3D)}(t_w = 1000s) \simeq 30 - 50 spins$



- Depending on concentration :
  - Probing a 3D spin glass through 1D coherent electronic diffusion ($N_\perp \geq N_{eq}^{(3D)}(t_w)$)
  - Probing 1D/3D cross-over through 1D coherent electronic diffusion

J.-P. Bouchaud, V. Dupuis, J. Hammann, and E. Vincent, Phys. Rev. B 65, 024439 (2001)
S. Jimenez, V. Martin-Mayor, and S. Perez-Gaviro, Phys. Rev. B 72, 054417 (2005).

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Brief history

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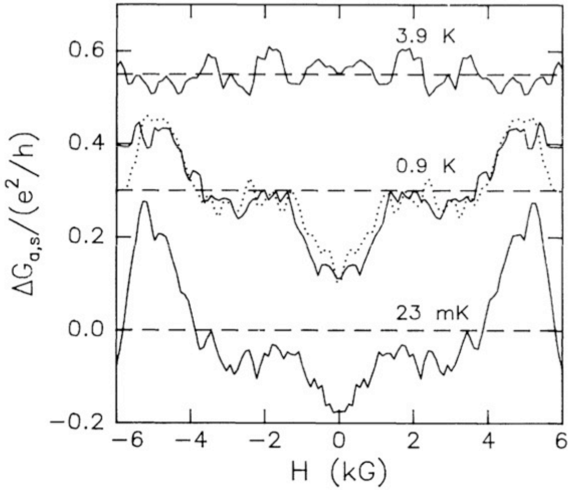
N. Israeloff, et al. , Phys. Rev. Lett. 63, 794 (1989).
G. Alers, M. Weissman, and N. Israeloff, Phys. Rev. B 46, 507 (1992).
J. Jaroszynski, et al. Phys. Rev. Lett. 80, 5635 (1998)
G. Neuttiens, et al. , Phys. Rev. B 62, 3905 (2000).

Pioneering work of L. Lévy et al.:

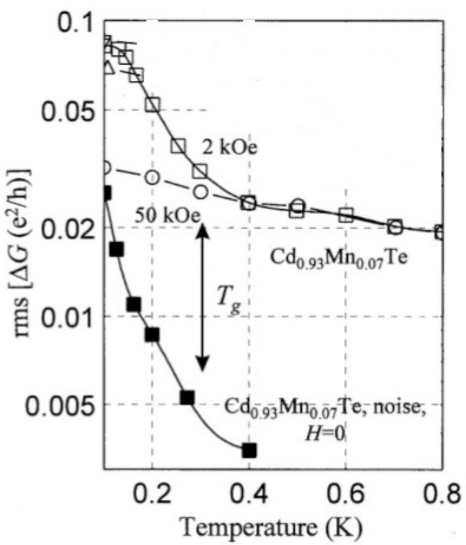
➡ Coupling between SG freezing and electronic transport

➡ Electron's transport is coherent

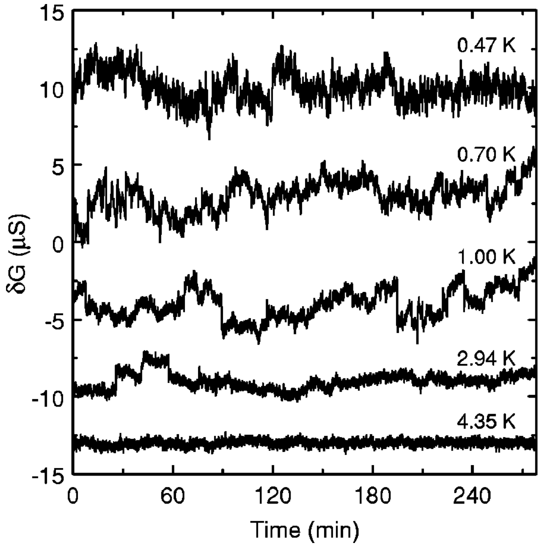
de Vegvar et al. PRL (1991)



1000ppm Cu:Mn



diluted magn. semicond. $Cd_{0,93}$ $Mn_{0,07}Te$
Jaroszynski et al., PRL (1998)



AuFe wires @ 5% at.
Neuttiens et al. PRB (2000)

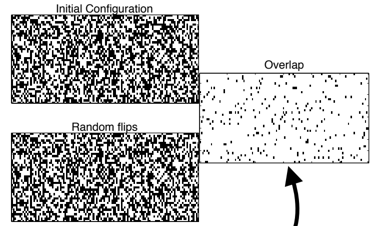
- But most focused electronic (1/f) noise
- Signature of slow relaxation of SG ? but difficult to interpret (see M. Weissman RMP (1993))

Here focus on correlations !

Theoretical Model

B. Al'tshuler and B. Spivak, JETP Lett. 42, 447 (1985)
M. G. Vavilov, L. I. Glazman, and A. I. Larkin, Phys. Rev. B 68, 075119 (2003)
D.C. and E. Orignac, Phys. Rev. Lett. 100 (2008)

$$H = \sum_{<i,j>} t\ c_i^\dagger c_j + h.c. + \sum_i v_i c_i^\dagger c_i + \sum_i J\ c_i^\dagger \vec{\sigma} c_i . \vec{S}_i$$



- Spins assumed randomly frozen ➡ Anderson model + Spins
  - scalar disorder $v_i \in [-W/2, +W/2]$ (characterizes a sample)
  - Frozen spins : randomly oriented, but correlated between configurations (characterizes a Spin Glass state)

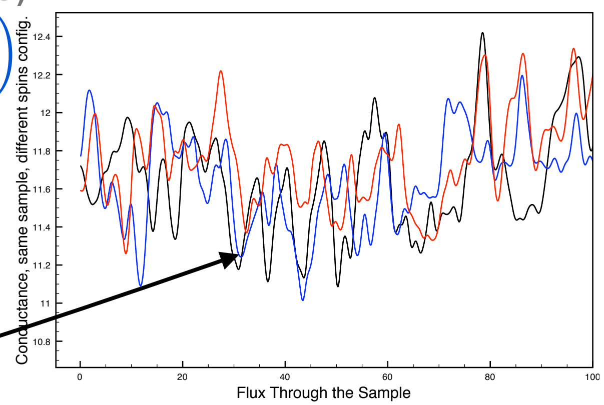
- Spins of magnetic impurities : dephasing of electrons ➡ new length $L_m(J)$

  diffuson/Cooperon : reduction of UCF

- General idea here :
  - consider a given sample : $\{v_i\}$
  - 2 spin config. $\{\vec{S}_i^{(1)}\}$ and $\{\vec{S}_i^{(2)}\}$ (2 Spin Glass states)

➡Study correlation between $G\left(V, \{S_j^{(1)}\}\right)$ and $G\left(V, \{S_j^{(2)}\}\right)$

- Ergodic Hypothesis : corresponds to correlation between magnetoconductance traces in 2 Spin Glass states $G\left(\phi, \{S_j^{(1)}\}\right)$ and $G\left(\phi, \{S_j^{(2)}\}\right)$



Techniques

$$H = \sum_{<i,j>} t\ c_i^\dagger c_j + h.c. + \sum_i v_i c_i^\dagger c_i + \sum_i J\ c_i^\dagger \vec{\sigma} c_i . \vec{S}_i$$

- Spins assumed randomly frozen ➡ Anderson model + Spins
  - scalar disorder $v_i \in [-W/2, +W/2]$ (characterizes a sample)
  - Frozen spins : randomly oriented, but correlated between configurations (characterizes a Spin Glass state)

- Quantitative conductance correlations in a spin glass :
  - ✓ Weak localization diagrammatic (perturb.) (D.C. and E. Orignac, Phys. Rev. Lett. 100 (2008))

    magnetic dephasing of the “cooperons” and “diffusons”
  - ✓ Field Theory (non-linear Sigma) (A.A. Fedorenko and D.C., arXiv:0904.1011, EPL 2010)

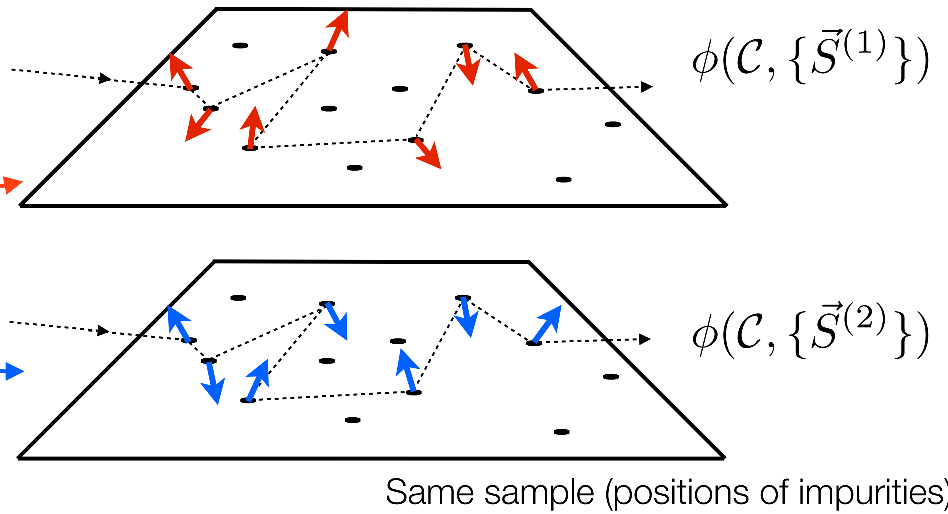
    study crossover between orthogonal and unitary classes, extend to calculations of conductance correlations
  - ✓ Numerical Landauer method (G. Paulin and D.C., arXiv:0910.4341)

Flavor of diagrammatic... (or why this idea can work)

D.C. and E. Orignac, Phys. Rev. Lett. 100 (2008)

- We consider the correlation

$$\left\langle \delta G\left(V,\{S_j^{(1)}\}\right)\delta G\left(V,\{S_j^{(2)}\}\right)\right\rangle_V$$



- The 2 components of propagating Diffuson / Cooperon see different spin configurations

- If two spin configurations similar : weak relative dephasing
- if two spin configurations different : strong relative dephasing

- Along a diffusion path : $\prod_j e^{i(JS)\hat{S}_j^{(1)}.\vec{\sigma}^{(1)}} e^{\pm i(JS)\hat{S}_j^{(2)}.\vec{\sigma}^{(2)}}$ + work to lower order in J

➡ different dephasing rate/length for singlet / triplet component of the Diffuson / Cooperon :

$$L^{(D,S)} = L_m/\sqrt{1-Q_{12}}, \qquad L^{(D,T)} = L_m/\sqrt{1+Q_{12}/2} \quad L_m^{-2} = 2\pi\rho_0 n_{imp} D^{-1} J^2 \langle S^2\rangle$$

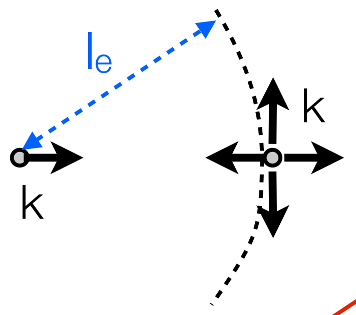
➡ dependance on the overlap $Q_{12} = \dfrac{1}{N_{imp}}\displaystyle\sum_{i=1}^{N_{imp}} \vec{S}_i^{(1)}.\vec{S}_i^{(2)}$

$L_m(J)$: cross-over length scale

G. Paulin and D.C., *unpublished*

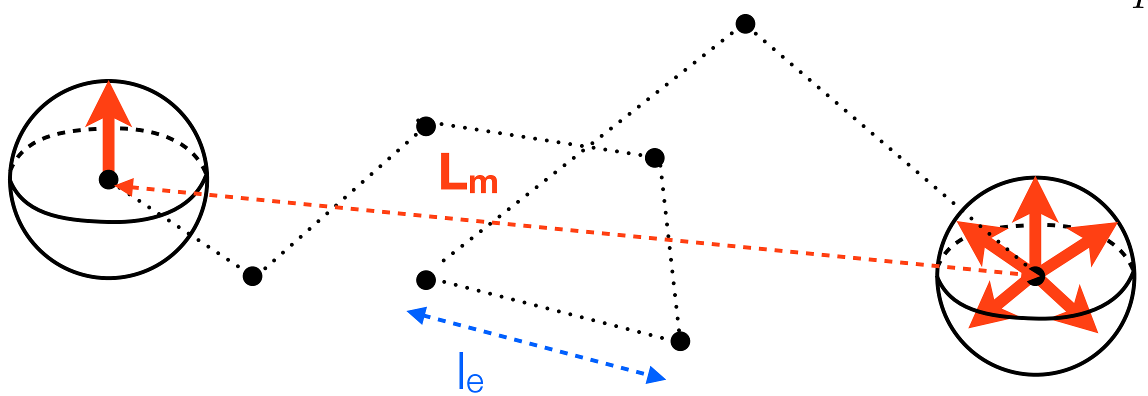
$$H = \sum_{<i,j>} t\, c_i^\dagger c_j + h.c. + \sum_i v_i c_i^\dagger c_i + \sum_i J\, c_i^\dagger \vec{\sigma} c_i . \vec{S}_i$$

Elastic scattering time : $\tau_e = \dfrac{1}{2\pi \rho_0 n_i v_0^2} \longrightarrow l_e = v_F \tau_e,\ \xi_{loc} \simeq N_\perp l_e$



Elastic scattering time : $\tau_m = \dfrac{1}{2\pi \rho_0 n_i J^2 \langle S^2 \rangle} \xrightarrow{\text{weak J}} L_m = \sqrt{D\tau_m}$

$$D = v_F^2 \left(\frac{1}{\tau_e} + \frac{1}{\tau_m} \right)^{-1}$$



$L_m(J)$: cross-over length scale

G. Paulin and D.C., *unpublished*

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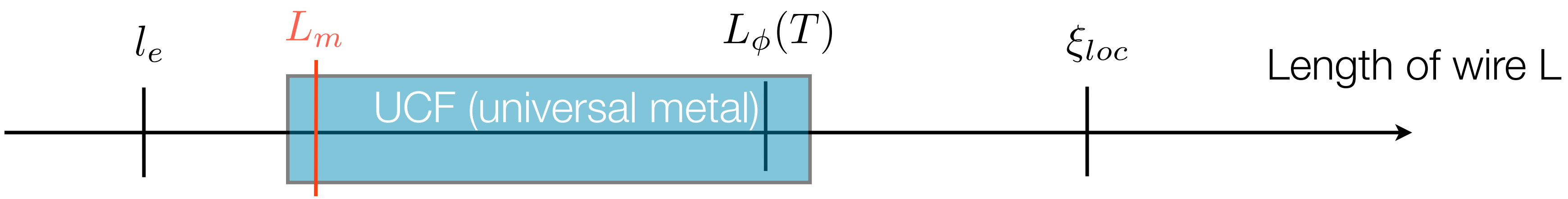

Strong magnetic disorder : Unitary Class
Sensitive to few spin flips

$L_m(J)$: cross-over length scale

G. Paulin and D.C., *unpublished*

$$H = \sum_{<i,j>} t\, c_i^\dagger c_j + h.c. + \sum_i v_i c_i^\dagger c_i + \sum_i J\, c_i^\dagger \vec{\sigma} c_i . \vec{S}_i$$

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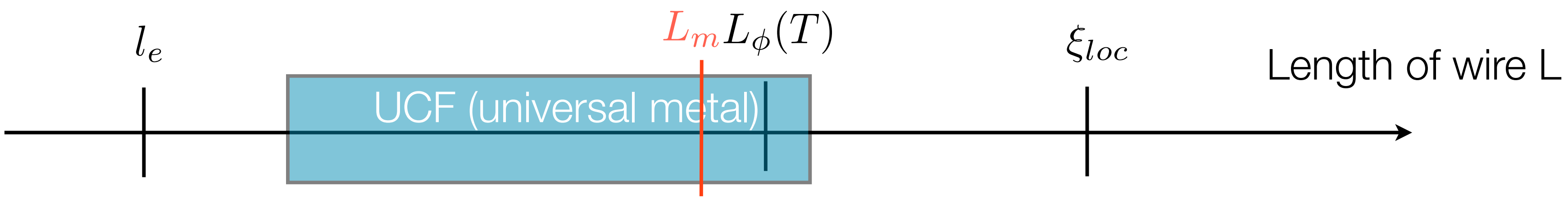

Very Weak magnetic disorder : Orthogonal Class
Not Sensitive to spins

$L_m(J)$: cross-over length scale

G. Paulin and D.C., *unpublished*

$$H = \sum_{<i,j>} t\ c_i^\dagger c_j + h.c. + \sum_i v_i c_i^\dagger c_i + \sum_i J\ c_i^\dagger \vec{\sigma} c_i . \vec{S}_i$$

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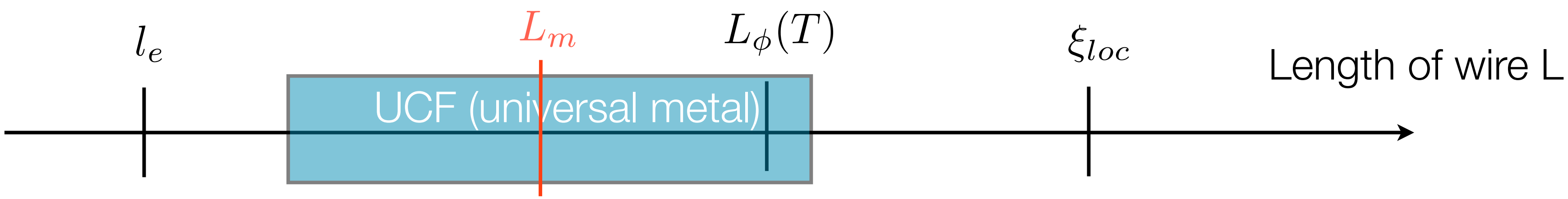


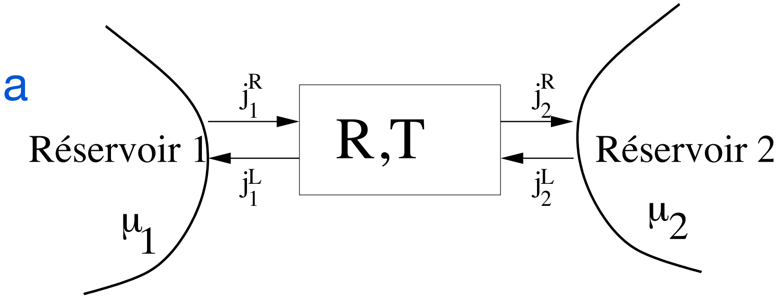
Weak magnetic disorder : Cross-over
Sensitive to rearrangement of config. of spins

Numerical Landauer Method

G. Paulin and D.C., arXiv:0910.4341
G. Paulin and D.C., arXiv:0910.4270

- Transport in Nanowires : Landauer formula

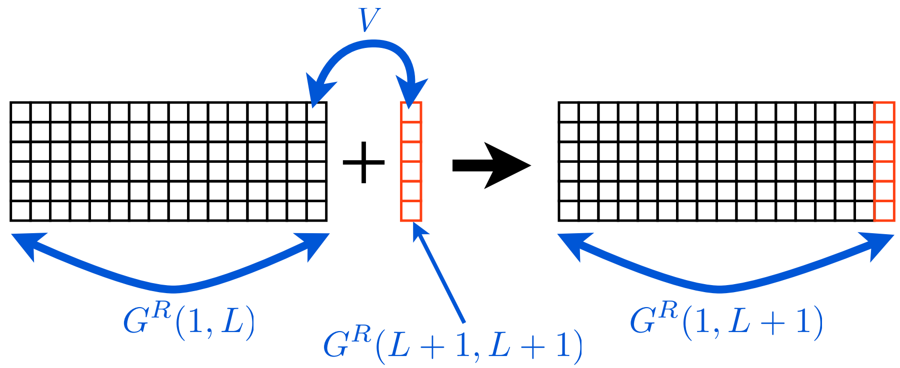
$$g = \frac{e^2}{h} \sum_{modes\ \alpha,\beta} T_{\alpha\beta}$$



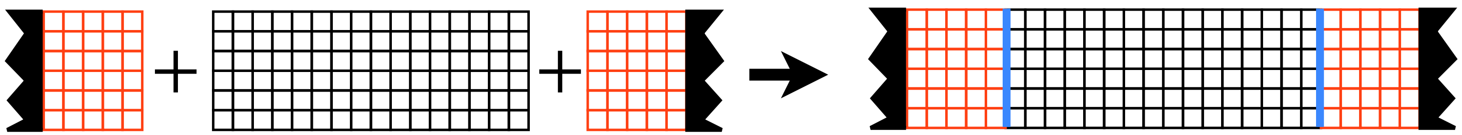
- Scattering Matrix S obtained through the Fisher-Lee relations :
  - wave function $\phi_\alpha(y,x)$ of mode α , velocity v_α
  - transmission coefficient (G^R electronic Green's function) :

$$t_{\alpha\beta} = i\hbar\sqrt{v_\alpha v_\beta} \int\int dy_\alpha dy_\beta\ \phi_\alpha(y_\alpha, x=0) G^R(y_\alpha, x=0 | y_\beta, x=L) \phi_\beta(y_\beta, x=L)$$

- Green's function : recursive method
  - Dyson eq. : $G^R = G_0^R + G_0^R V G$
  - Build wire row by row



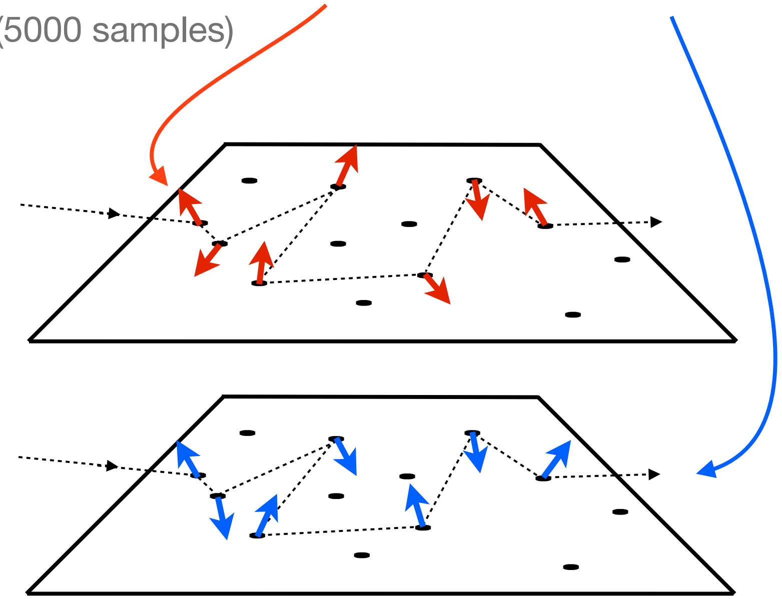
  - Connect the reservoirs



Distribution of Correlations

G. Paulin and D.C., *unpublished*

Distribution of $G(\{v_i, \vec{S}_i^{(1)}\}) - G(\{v_i, \vec{S}_i^{(2)}\})$ when $V = \{v_i\}$ varies (5000 samples)



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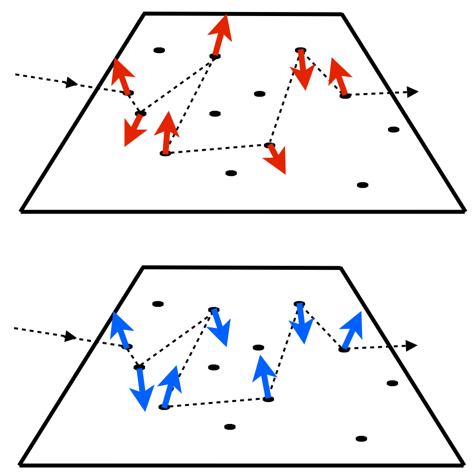
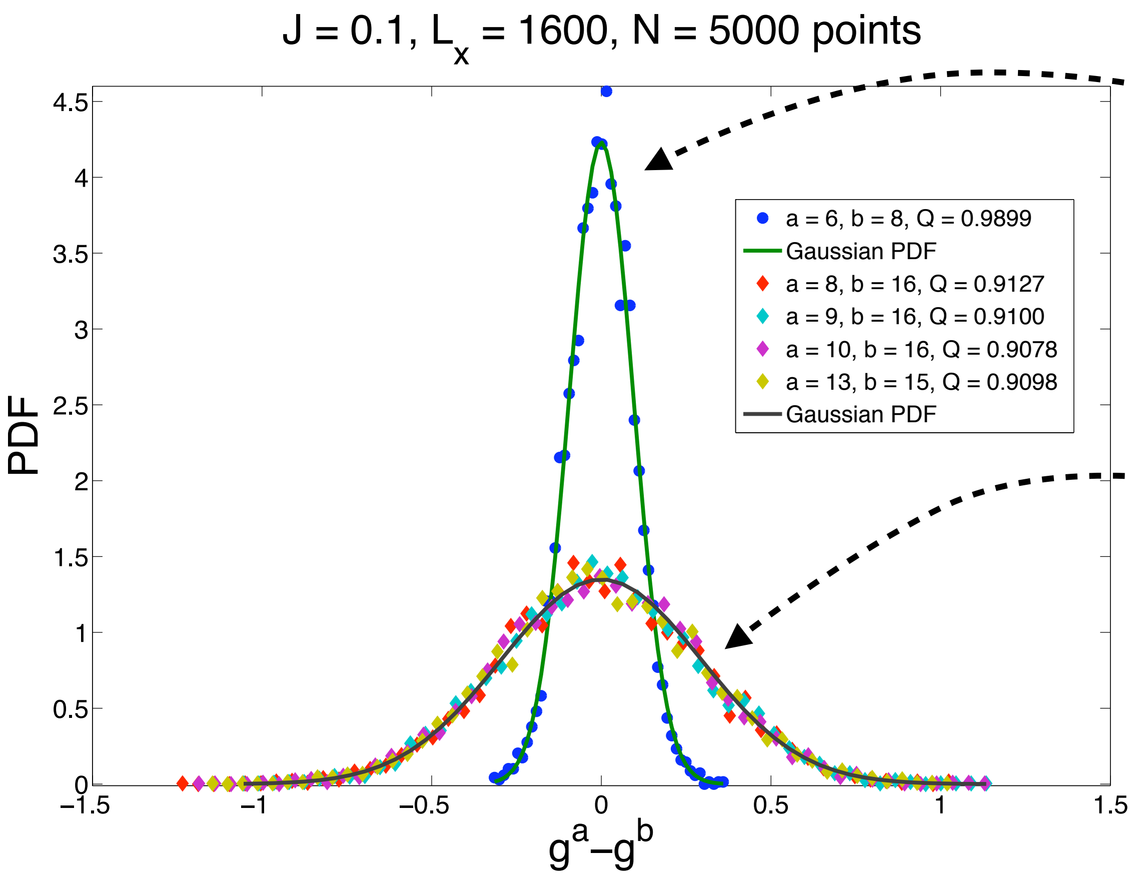
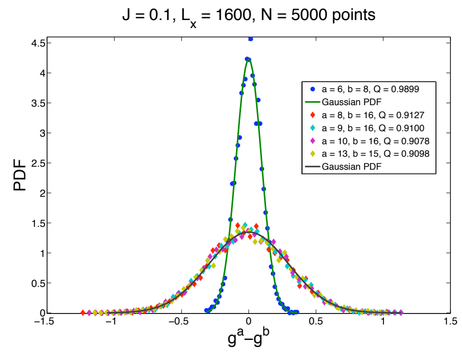




1 pair of config. with correlation Q1

1 pair of config. with correlation Q2

Distribution of Correlations



G. Paulin and D.C., *unpublished*

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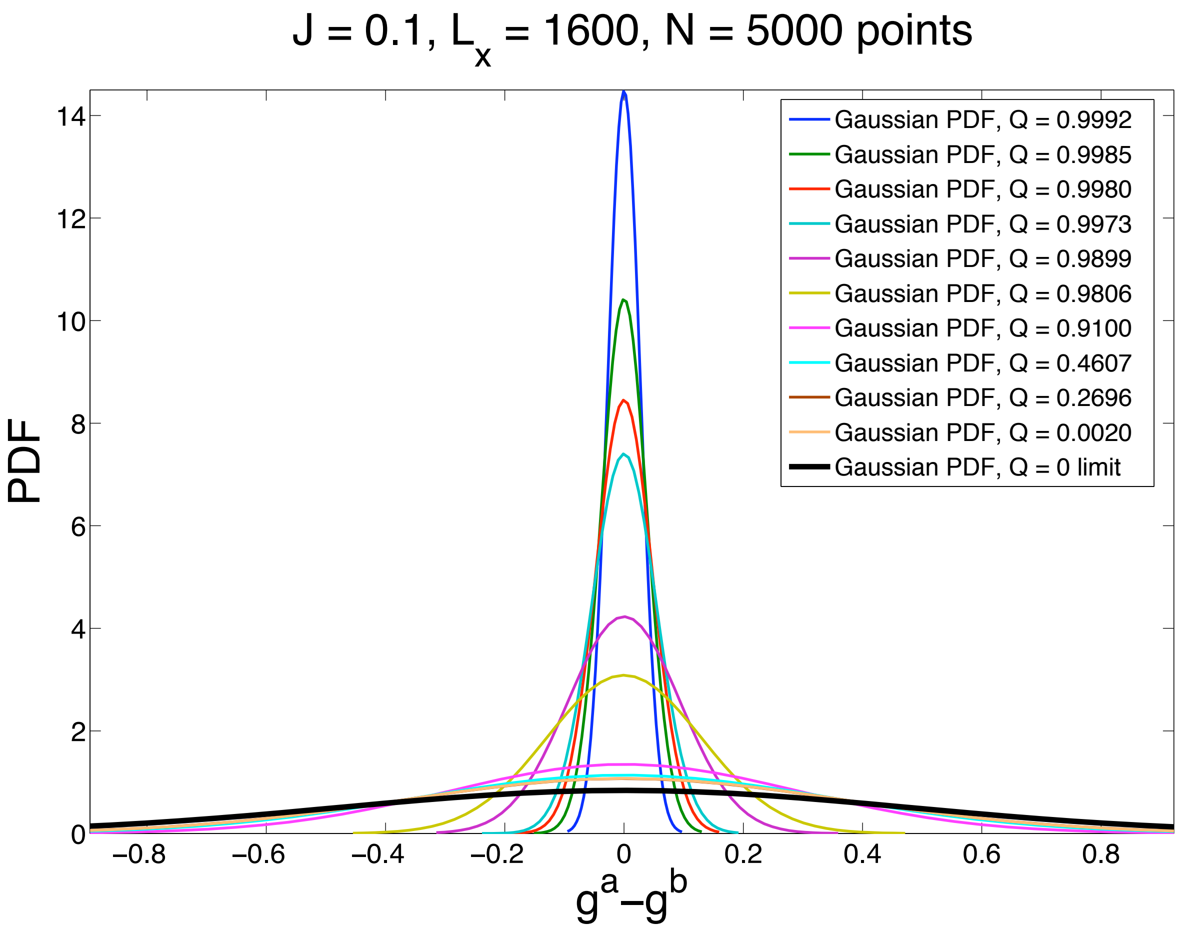


Evolution of PDF
of correlations of g
when
correlation of spins Q varies

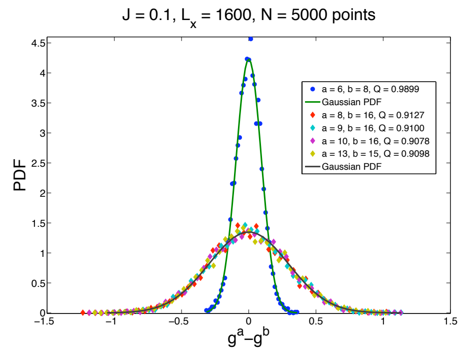
Distribution of Correlations

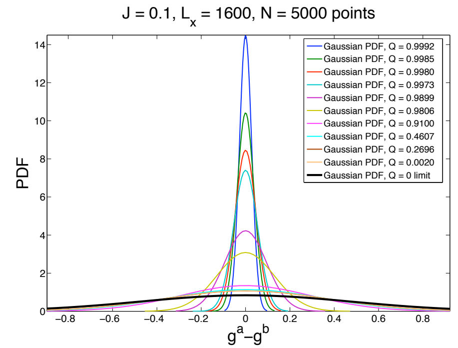
G. Paulin and D.C., *unpublished*

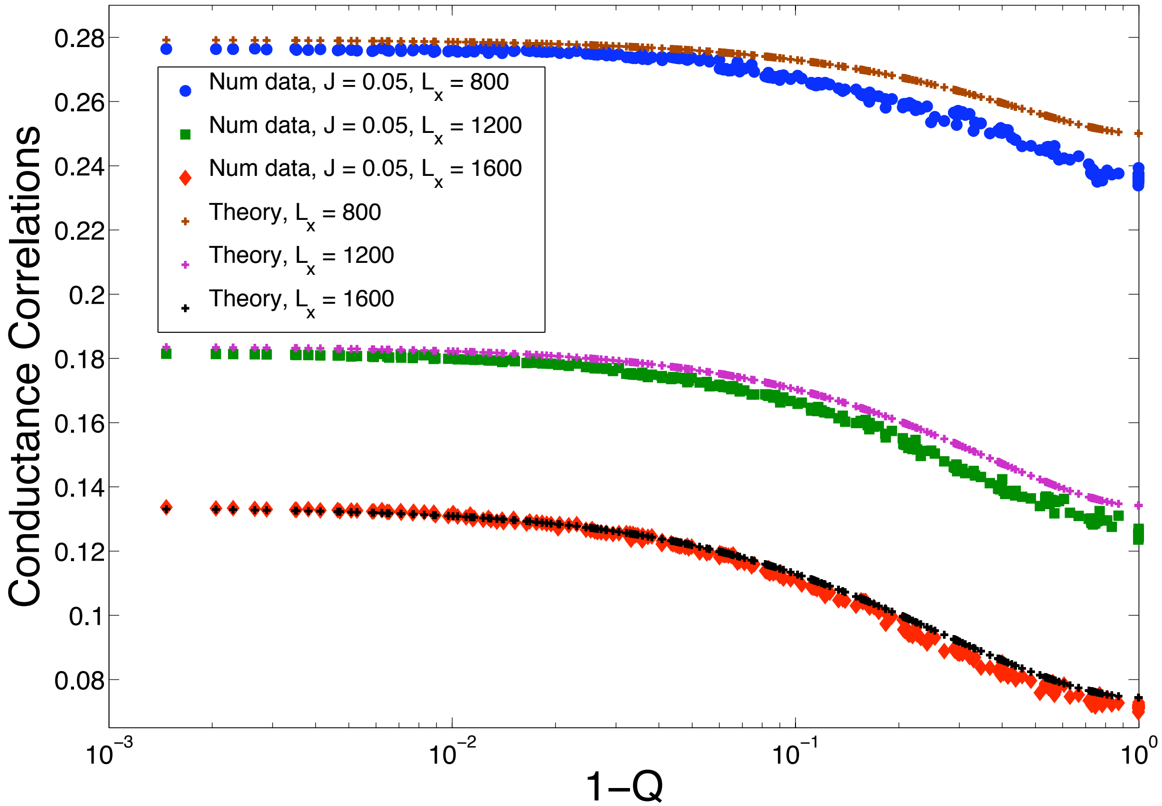
Distribution of $G(\{v_i,\vec{S}_i^{(1)}\})-G(\{v_i,\vec{S}_i^{(2)}\})$ when $V=\{v_i\})$ varies (5000 samples)

Variance : $\left\langle \delta G\left(V,\{S_j^{(1)}\}\right)\delta G\left(V,\{S_j^{(2)}\}\right)\right\rangle_V = \tilde{F}(L/L_m,Q)$

➡ Probe of overlap $Q=\frac{1}{N}\sum_i \vec{S}_i^{(1)}.\vec{S}_i^{(2)}$







Distribution of Correlations

G. Paulin and D.C., *unpublished*

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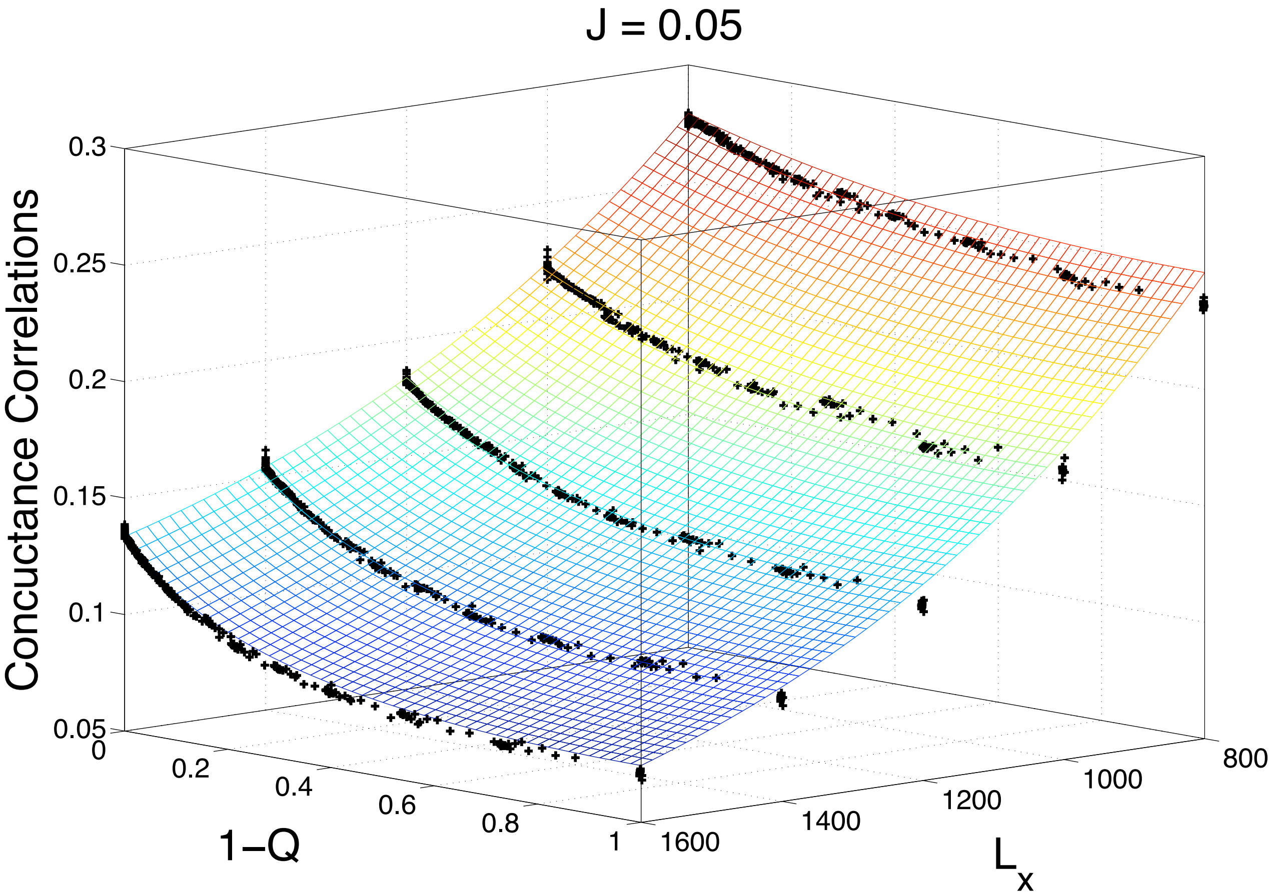

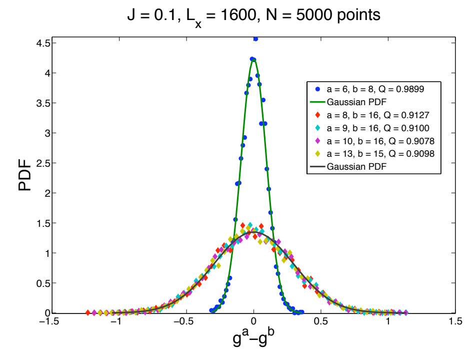

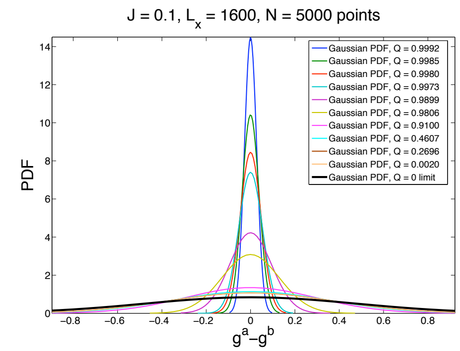

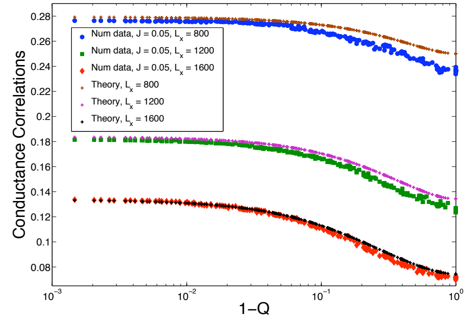

Perspectives

- Specificities a spin glass nanowire :
  - dimensional cross-over of dynamics ?
  - Effects of short range correlations between spins (T>Tg)
  - new type of material (spins implanted in pure metal)
- Perspectives :
  - characterization of T-chaos, aging, comparison between successives quenches
  - magnetoconductance at lower fields B
  - dynamics at low T (<Tg/10) and high fields (AT line ?)

Thank You !