

Is the peculiar behavior of $1/f$ noise in graphene the result of the interplay between band-structure and inhomogeneities?

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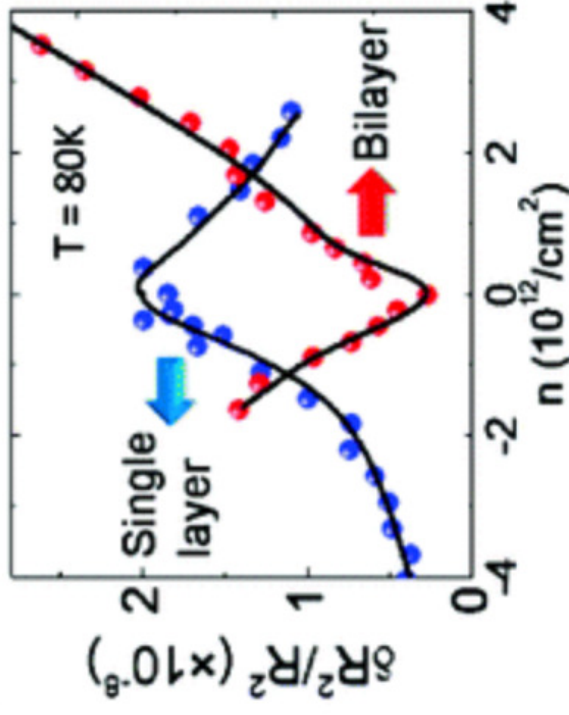


Summary

- Summary of main challenges involving flicker noise in graphene
- Overview of the models in the literature
- Derivation of an expression for the noise
- Evaluation of the noise amplitude for monolayer and bilayer graphene sheets and ribbons
- Comparison of noise factors for nanoribbons with experimental results
- Unsolved problem
- Conclusions



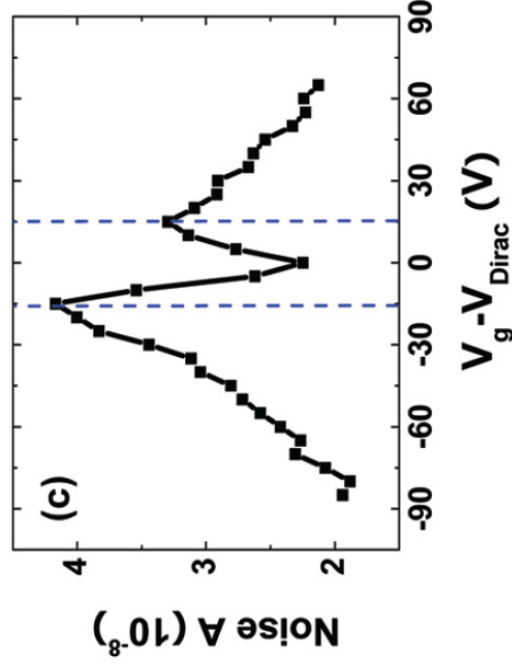
Behavior of flicker noise in graphene



A. N. Pal, ACS Nano 5, 2075 (2011)

Specifically, for monolayer graphene, shapes varying from the M to the Δ type have been observed, while for bilayer graphene a variation from the V to the M type has been reported

The amplitude of $1/f$ noise, intended as the power spectral density divided by the square of the average of the fluctuating quantity (and possibly multiplied by the frequency) exhibits characteristic features in monolayer and, particularly, bilayer graphene as a function of carrier density



G. Xu et al., Nano Letters, 10, 3312 (2010)



Theoretical attempts to explain the $1/f$ noise behavior in graphene (I)

- Xu et al. (Nano Letters 10, 3312) attribute the appearance of the M shape to the presence of charge inhomogeneities in the sample, and extend such an approach, coupled to the particular bandstructure, to explain also the noise behavior observed in bilayer graphene
- Pal et al. (ACS Nano, 5, 2075) have formulated an explanation based on the contribution from charge trapping and from a slow rearrangement of charges with their migration through the substrate or surface adsorbates. This theory is rather complex and is based on at least 4 fitting parameters.
- A. Rhaman et al. (Nano Letters, 14, 6621) attribute the particular behavior of $1/f$ noise in graphene mainly to short-range and long-range disorder, which are assumed to be varying in time



Theoretical attempts to explain the $1/f$ noise behavior in graphene (II)

- Sun et al. (J. Low. Temp. Phys. **172**, 202) explain the origin of the M and Λ shaped behaviors for single-layer graphene on the basis of an interplay between the gate voltage dependence of the normalized conductance and of the chemical potential (which has a dip in the charge neutrality point)
- Zhang et al. (ACS Nano **5**, 8124) have formulated a model based on Hooge's approach with a coefficient α_H that depends on mobility, which fits reasonably well experimental data for single layer graphene devices both on a SiO_2 substrate and suspended



Calculation of the noise power spectral density (I)

- An estimate of the instantaneous current through the device can be obtained with this expression, where n_c is the total surface carrier concentration (including electrons and holes)

$$I = \frac{1}{L} \int_A \mu n_c(x, y) E(x, y) dx dy$$

where we have defined $n_c = n_n + n_p$

- The relative fluctuation of the current as a function of the local relative fluctuation of the number of carriers, if we assume the mobility fluctuation due to the trapped charge to be negligible, can be written:

$$\frac{\Delta i}{I} = \frac{1}{A} \int_A \frac{\Delta n_c}{n_c} dx dy$$

B. Pellegrini, Eur. Phys. J. B **86**, 373 (2013)



Calculation of the noise power spectral density (II)

- We define also the density of negative charges $n=n_n-n_p$ and the derivatives, with respect to the potential energy

$$a_c = \frac{\partial n_c}{\partial U}; \quad a = \frac{\partial n}{\partial U}$$

- Then we have

$$\frac{\Delta i}{I} = \frac{1}{A} \int_{\delta A} \frac{a_c}{a n_c} \Delta n dx dy = -\frac{1}{A} \left(\frac{a_c}{a n_c} \right) \Delta \chi$$

- Since the fluctuation of the occupancy of each trap can be described as a random telegraph process, whose power spectral density is a Lorentzian, if we consider the effect of a distribution of traps with reasonably chosen time constants, a $1/f'$ spectrum is obtained (usually with $\gamma=1$):

$$\frac{S}{I^2} = \frac{n_t B}{A} \left(\frac{a_c}{a n_c} \right)^2 \frac{1}{f\gamma}$$

where n_t is the surface density of traps [B. Pellegrini, Microelectron. Reliab. **40**, 1775 (2000)]



Calculation of the noise power spectral density (III)

- In the presence of a spatial fluctuation of the potential U across the device, and defining $P(U)$ as the probability density function of U , assumed to be Gaussian, we get

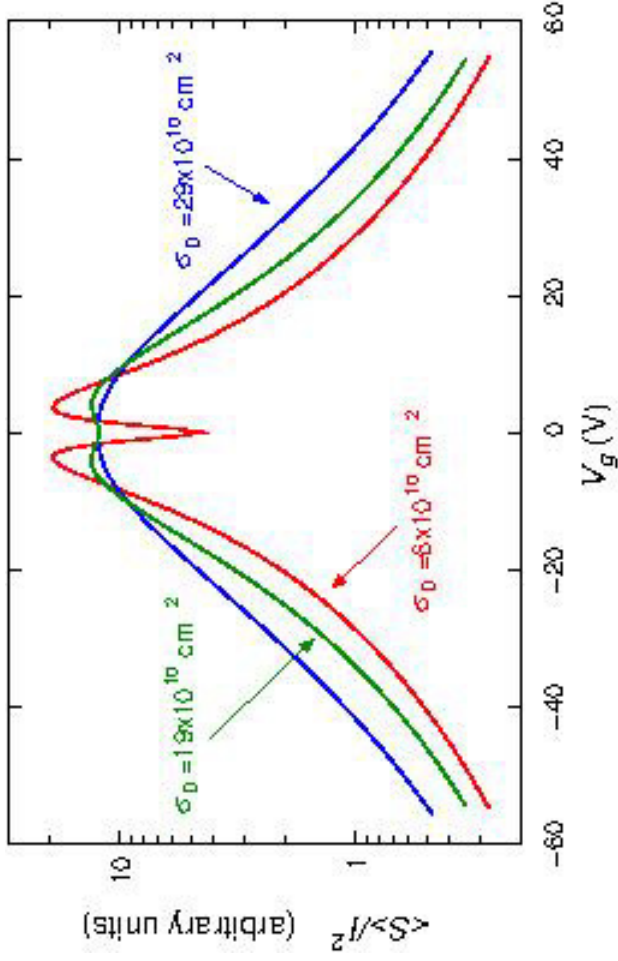
$$\frac{\langle S \rangle}{I^2} = \frac{\langle n_t \rangle}{A f \gamma} \int B \left(\frac{a_c}{a n_c} \right)^2 P(U) dU$$

where B is a proper coefficient

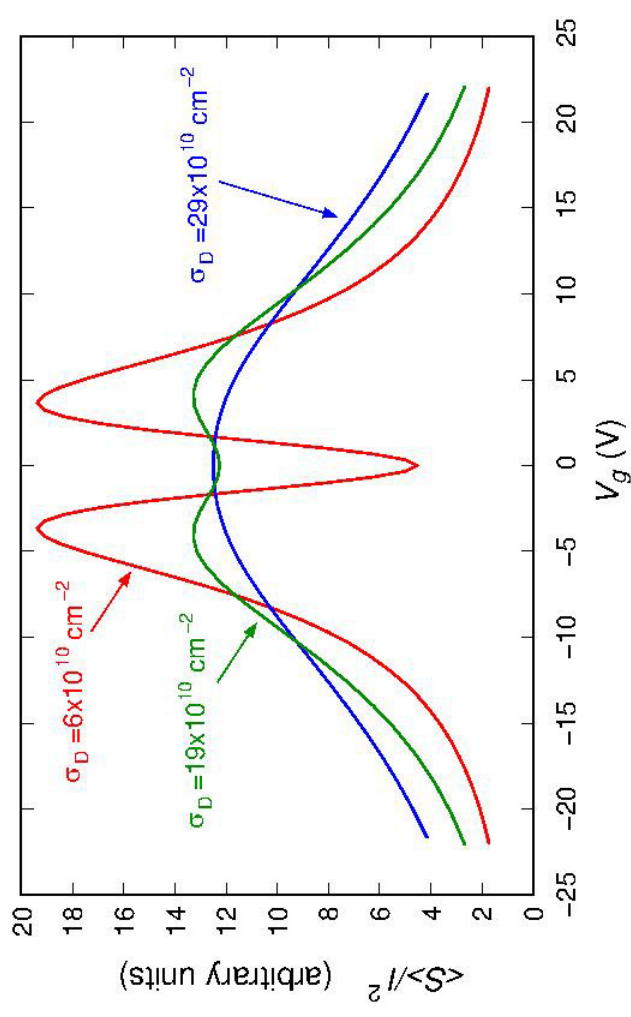
- The functional dependence of a , a_c , n , and n_c on the potential U and on the applied gate voltage depends on the bandstructure of the graphene sample being considered, therefore on whether it is monolayer or bilayer, and whether it is an indefinite sheet or confined in one or both spatial directions
- We have performed calculations for monolayer and bilayer sheets and ribbons, computing the above integral for the corresponding bandstructures



Results for monolayer sheets



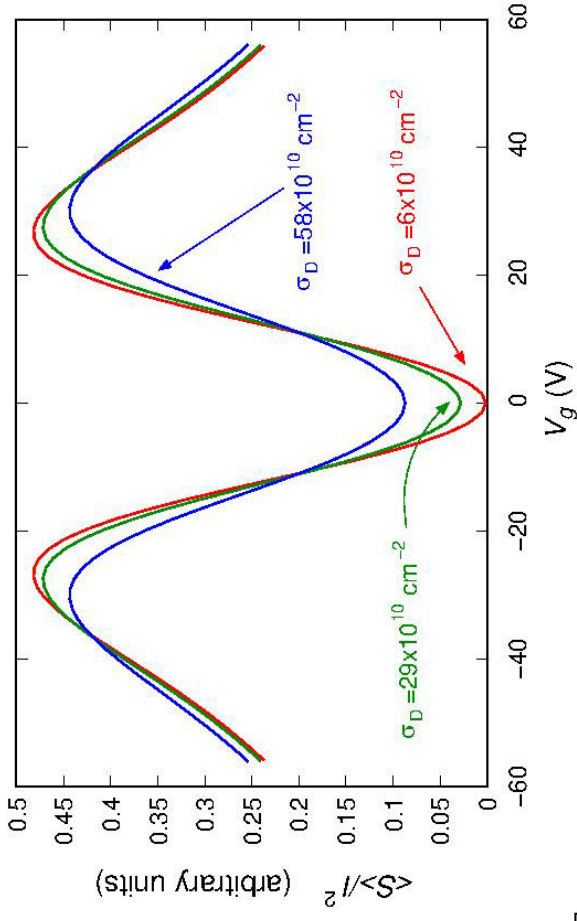
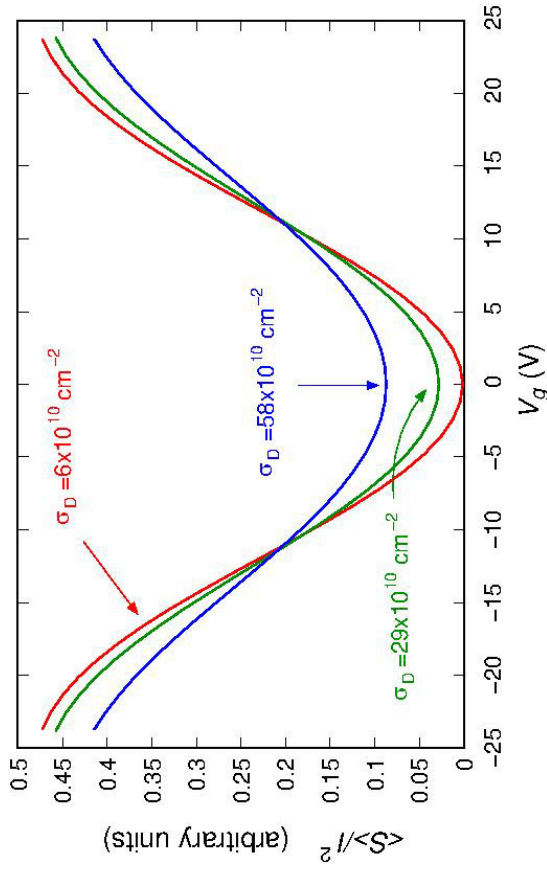
Considering the linear dispersion relationship of monolayer graphene an M shape is obtained, which turns into a Λ shape as the variance of the potential fluctuations is increased



Over an expanded gate voltage scale the transition from the M shape to the Λ shape is more apparent

Results for bilayer sheets

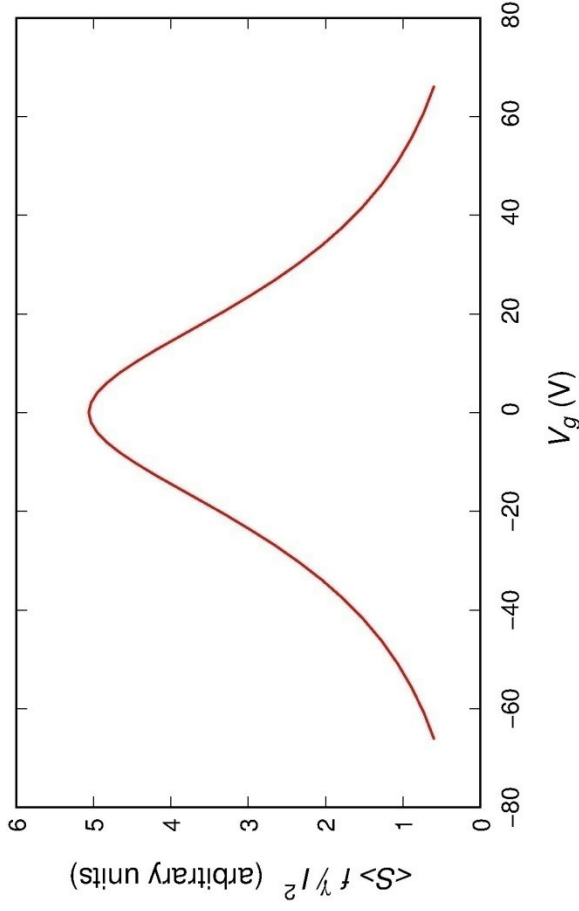
Also for bilayer graphene an *M* shape is obtained, which is however much smoother and wider than for the monolayer case, with a much weaker dependence on the variance of the potential



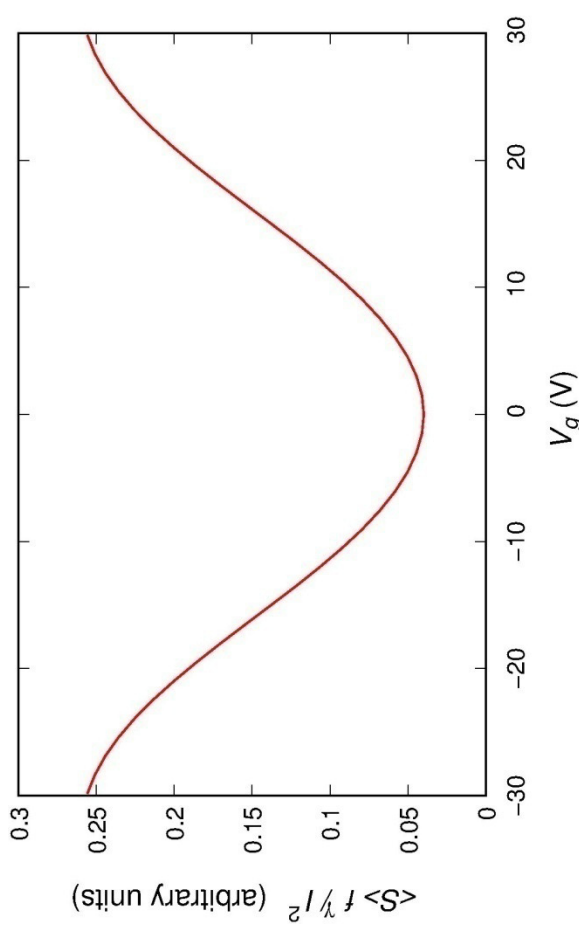
Over a limited gate voltage range the behavior appears of *V* type



Results for nanoribbons (I)



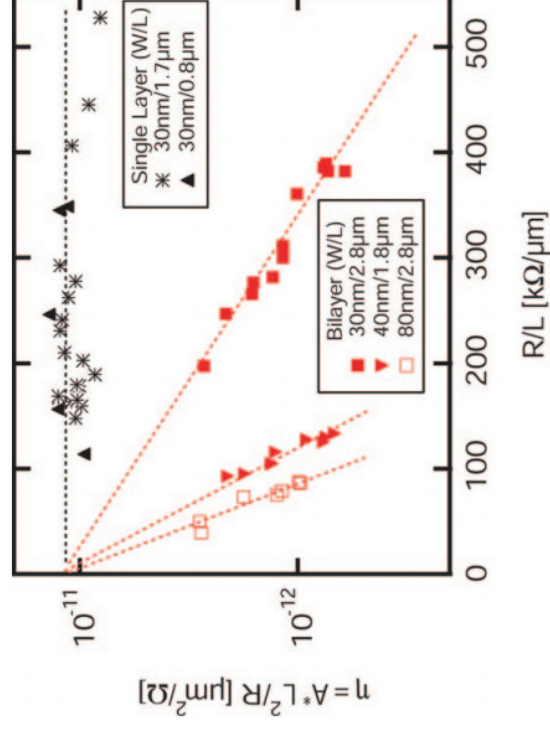
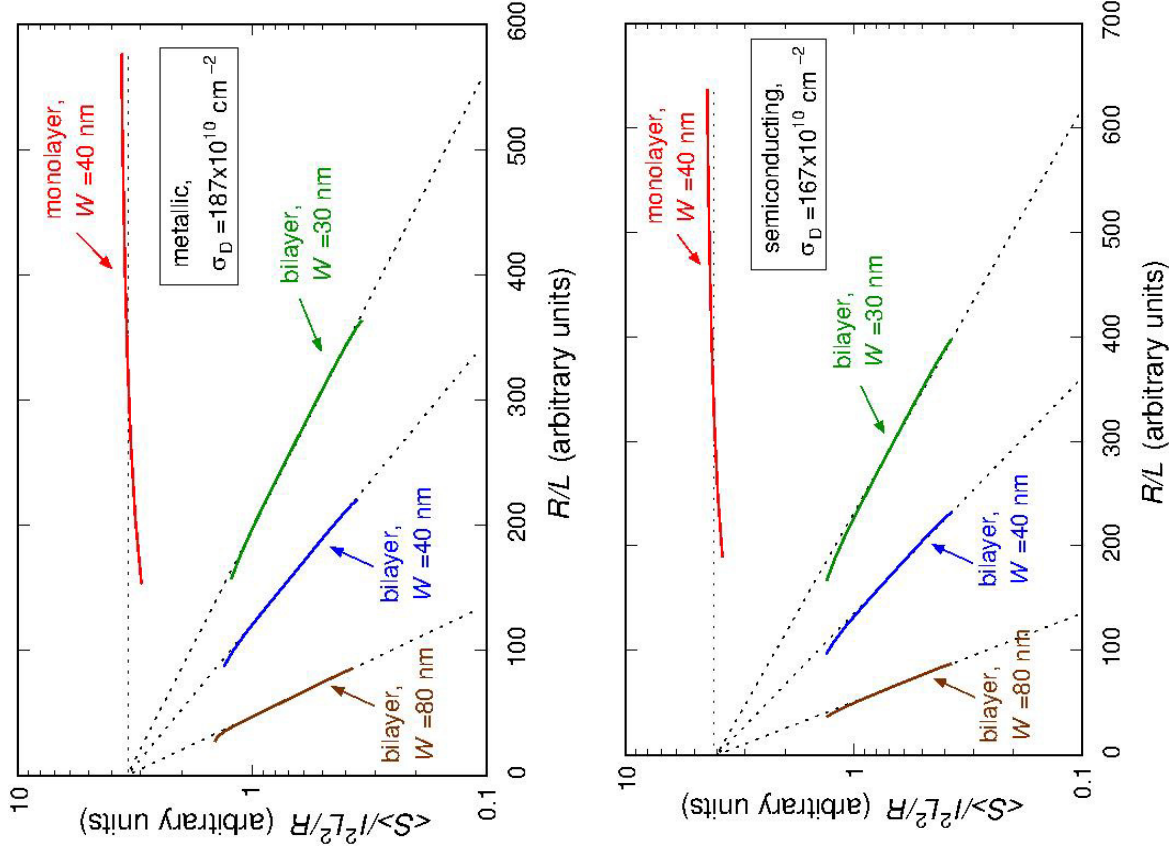
For a 30 nm wide armchair monolayer graphene nanoribbon, we observe a clear Λ shape for the noise amplitude as a function of gate voltage or, equivalently, of carrier concentration



For a 30 nm wide armchair bilayer graphene nanoribbon the noise amplitude has instead a V shape

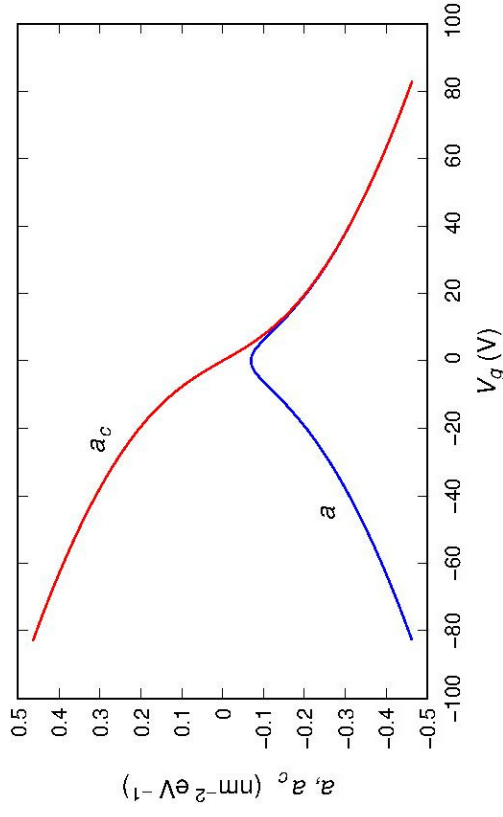
Results for nanoribbons (II)

For nanoribbons an interesting quantity is the noise factor $\langle S \rangle / I^2 L^2 / R$ that has been measured by Lin and Avouris (Nano Letters **8**, 2119)

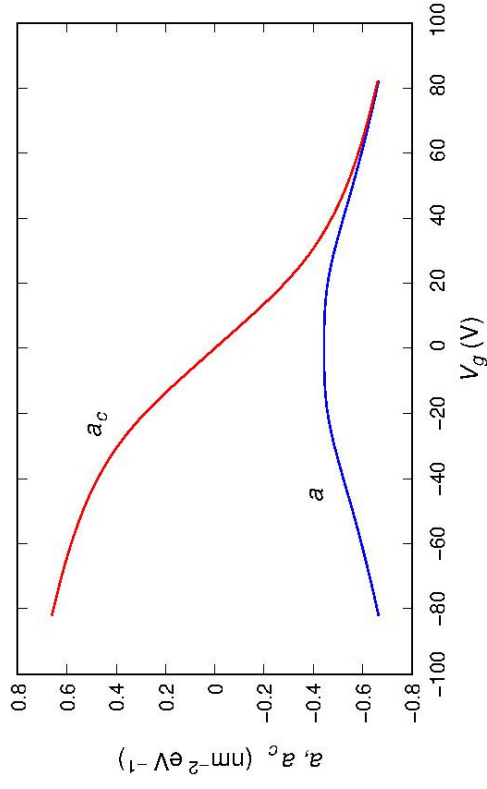


There is however an unsolved problem!

- We have computed the variation of the total carrier density from the perturbation of the potential determined by a trapping event
- This leads to a behavior of the a and a_c coefficients as follows



monolayer graphene



bilayer graphene

- It is apparent that both for monolayer and bilayer graphene a_c vanishes in the Dirac point, which implies that trapping of a charge should not have any effect on the current at the Dirac point



Unsolved problem

- At the Dirac point, when an electron gets trapped, according to this interpretation, it is screened by the disappearance of half an electron and the appearance of half a hole, which give the correct charge of $+e$, but zero variation of the number of charge carriers
- On the other hand, one could reason that, when an electron gets trapped close to the graphene sheet, it is lost for conduction (therefore there is one less mobile electron), but nothing else happens, because screening is performed just by the lack of such electron
- In graphical terms:



- The first interpretation supports all the results shown, the second would require updating some of the results



Conclusions

- An expression for the noise amplitude, i.e. the ratio of the noise power spectral density to the square of the average of the fluctuating quantity has been derived for a generic graphene device in the presence of a random potential
- Such an expression has been evaluated, as a function of the gate bias voltage (or equivalently of the carrier density) for monolayer and bilayer sheets and nanoribbons
- The results appear to be in good agreement with the existing experimental literature, although the actual perturbation of the number of carriers resulting from charge trapping is an unsolved problem

