Electric field dependence of the effective dielectric constant in graphene materials

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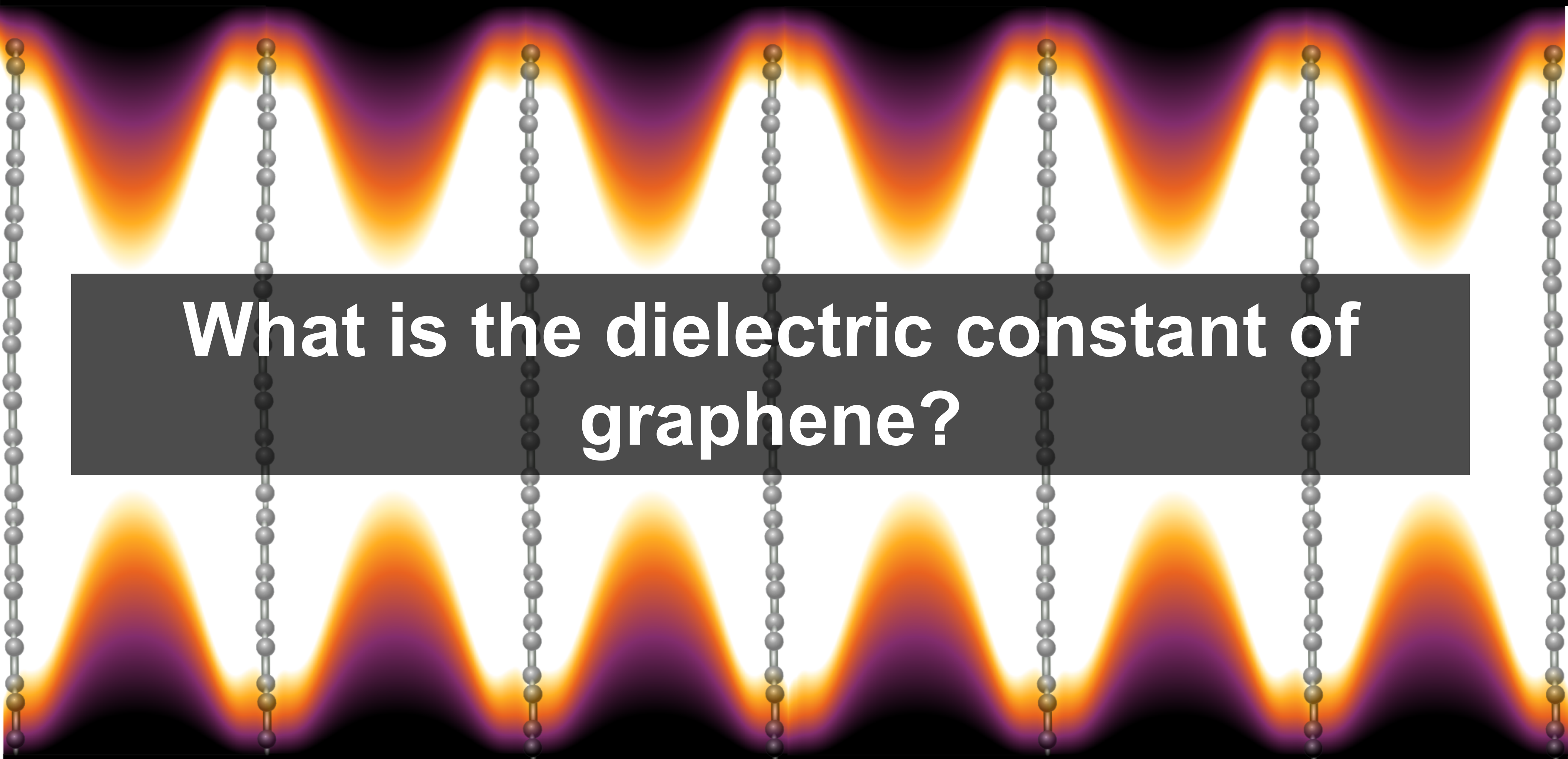
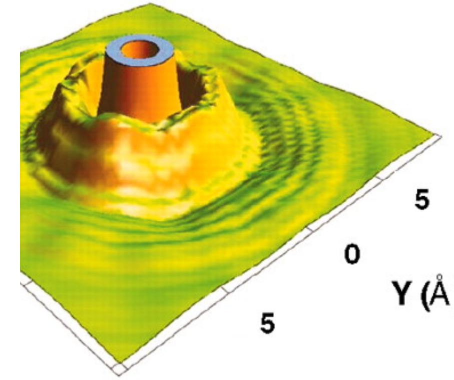

What is the dielectric constant of graphene?

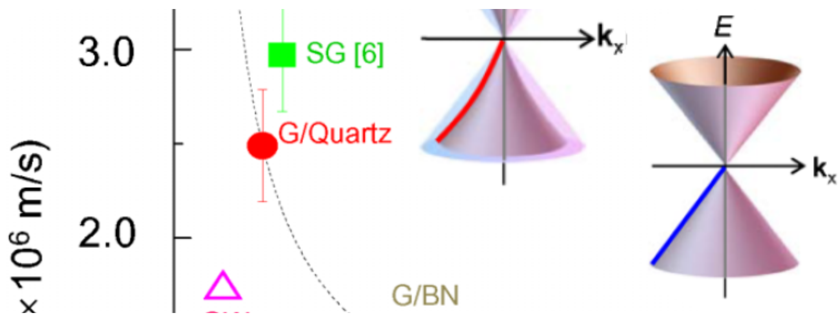
Debate in the literature

self-consistently, also within the random phase approximation. The value of ε_G has recently become a subject of considerable debate[23–27]. Our data clearly show no anomalous screening, contrary to the recent report[27] that suggested $\varepsilon_G \approx 15$, but in good agreement with measurements reported in ref. 28.

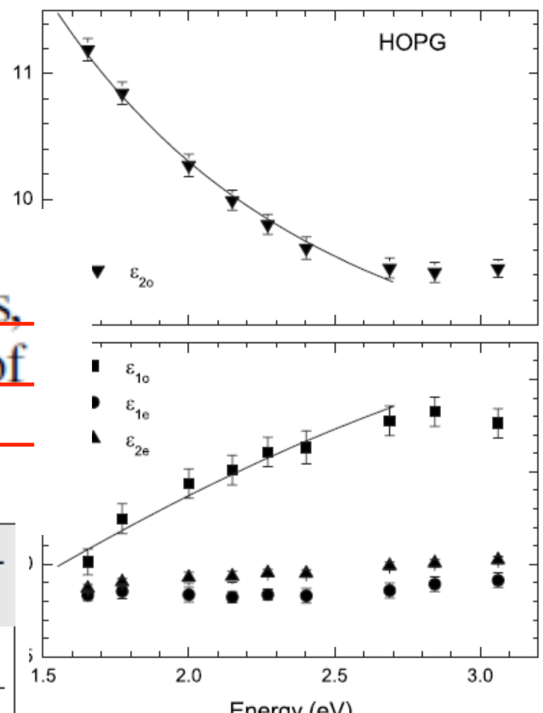


Reed et al. *Science* (2010) **330**, 805

Elias et al. *Nat. Physics,* (2011) **7**, 70



This value is of the same order of magnitude as previous studies, although the real dielectric constant of graphite is a source of controversy with measured values ranging from 2 to 13 (29).



High-resolution angle-resolved photoemission spectroscopy

ε~7.0

Table 1 | Fermi velocity (v_F), dielectric constant (ε), and fine structure constant (α) of graphene on each substrate

Substrate	$v_F \times 10^6$ m/s	ε	α
Metals (LDA)	0.85	∞	-
SiC(000-1)	1.15±0.02	7.26±0.02	0.35
h-BN	1.49±0.08	4.22±0.01	0.61
Quartz	2.49±0.30	1.80±0.02	1.43

Ellipsometric measurements

ε~2 - 13

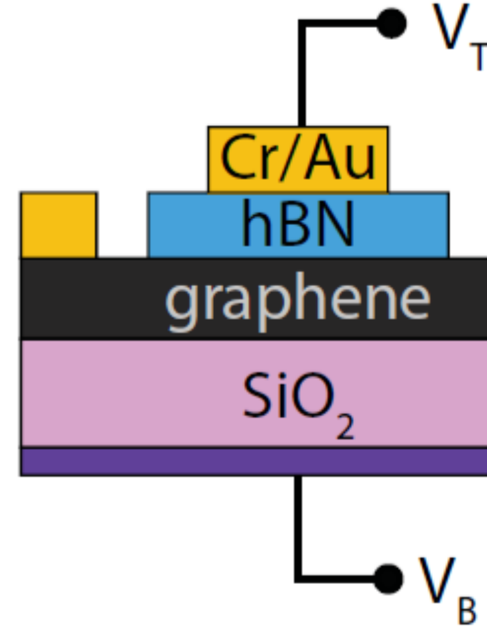
Siegel et al. *PNAS* (2011) pnas.1100242108

Hwang et al. Scient. Report (2012) **2**, 590

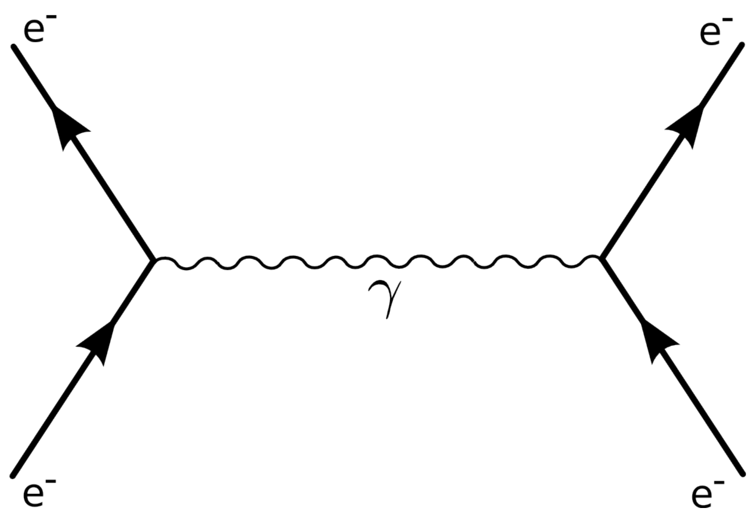
Jellison et al. PRB (2007) **76**, 205418

Dielectric constant is a fundamental quantity

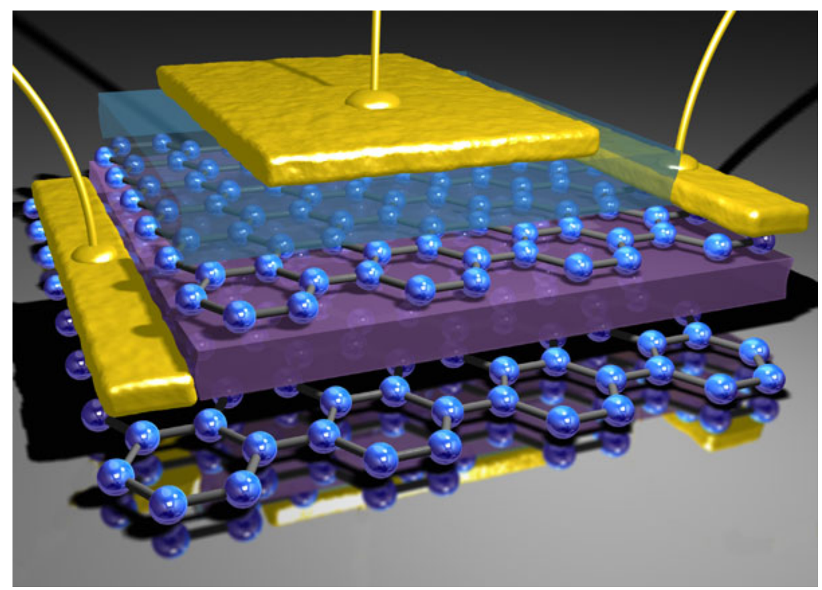
Capacitance, screening, electrical displacement, polarization, compressibility, etc.



A. F. Young et al. *PRB* (2012), **85**, 235458

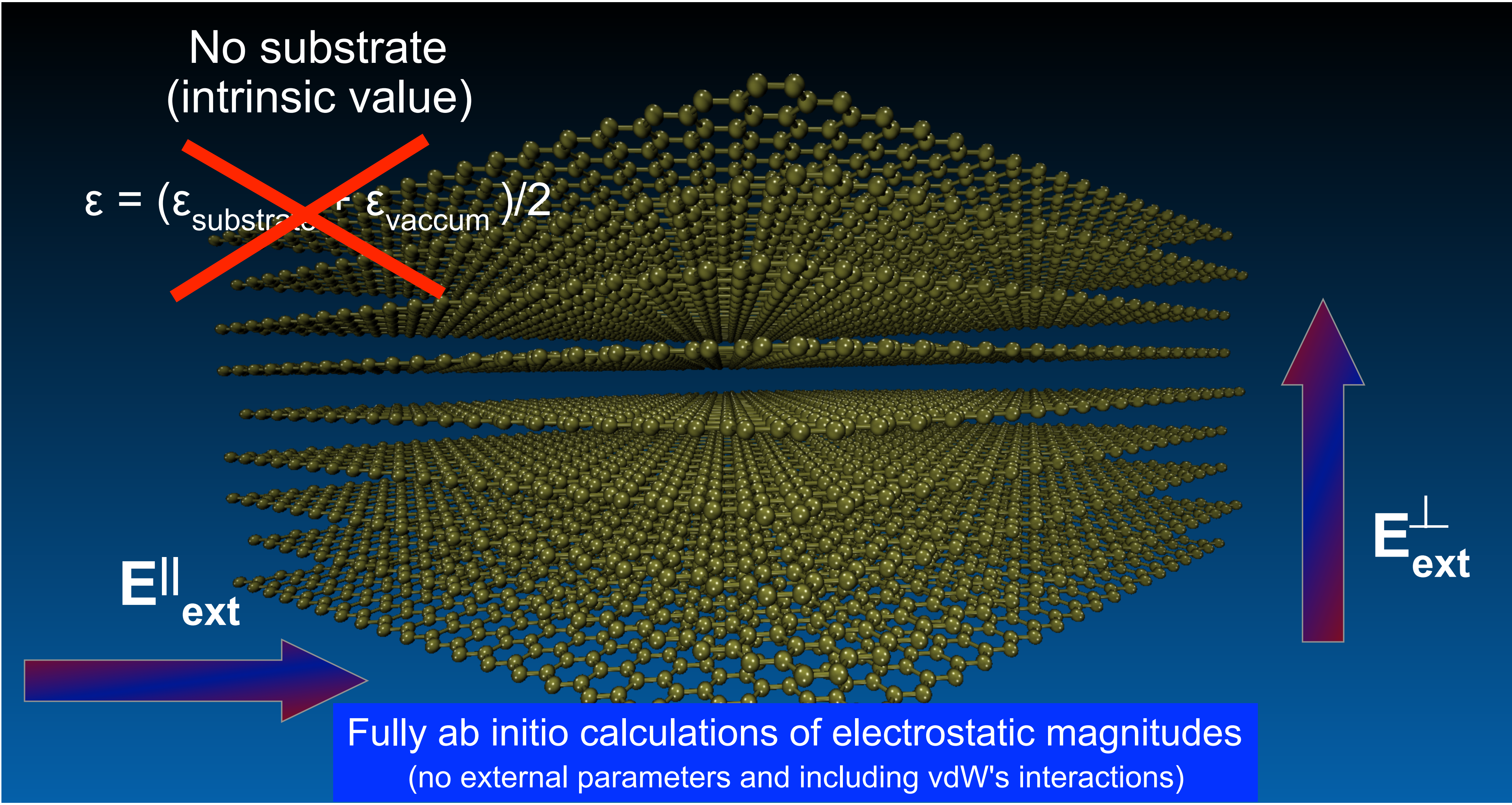


Electron-electron interactions



L. Britnell et al. *Science* (2012) **335**, 947

Our approach: capacitor model

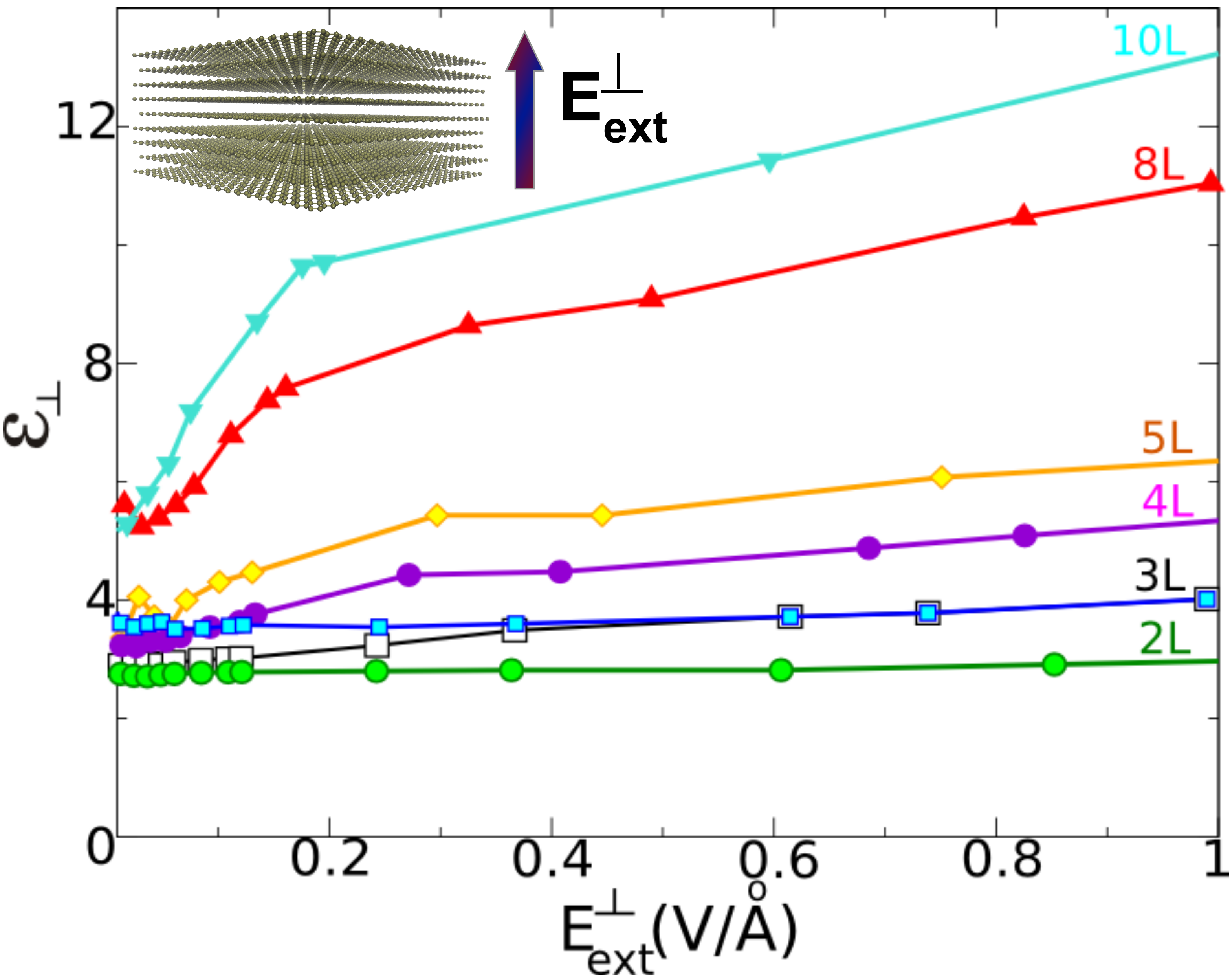


Dielectric constant, $\varepsilon(\mathbf{k},\omega)$ → Effective dielectric constant, ε_G

Fine-structure constant, $\alpha(\mathbf{k},\omega)$ → Effective fine-structure constant, $\alpha_G = U/K = e^2/\varepsilon_G \hbar \upsilon_F \sim 2.2/\varepsilon_G$

EJGS and E. Kaxiras, *Nano Letters* (2013) **13**, 898

Graphene dielectric constant is electric field dependent

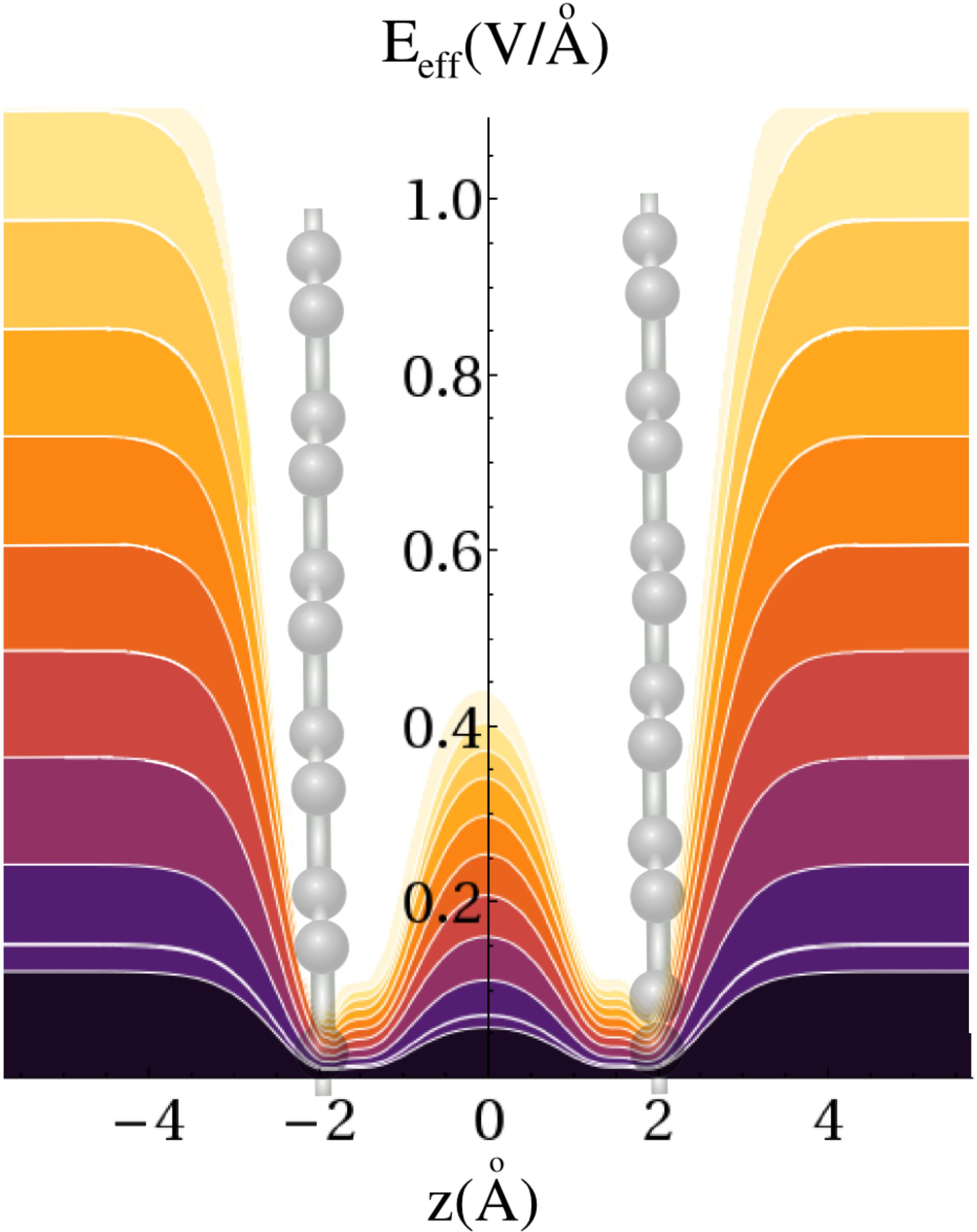


The thicker the structure (more layers) the stronger is the modulation

Modifications even at low fields <0.10 V/Angs.

Implications on other quantities, e.g. fine-structure constant α ~2.2/ε_G

Interlayer electric field is not constant

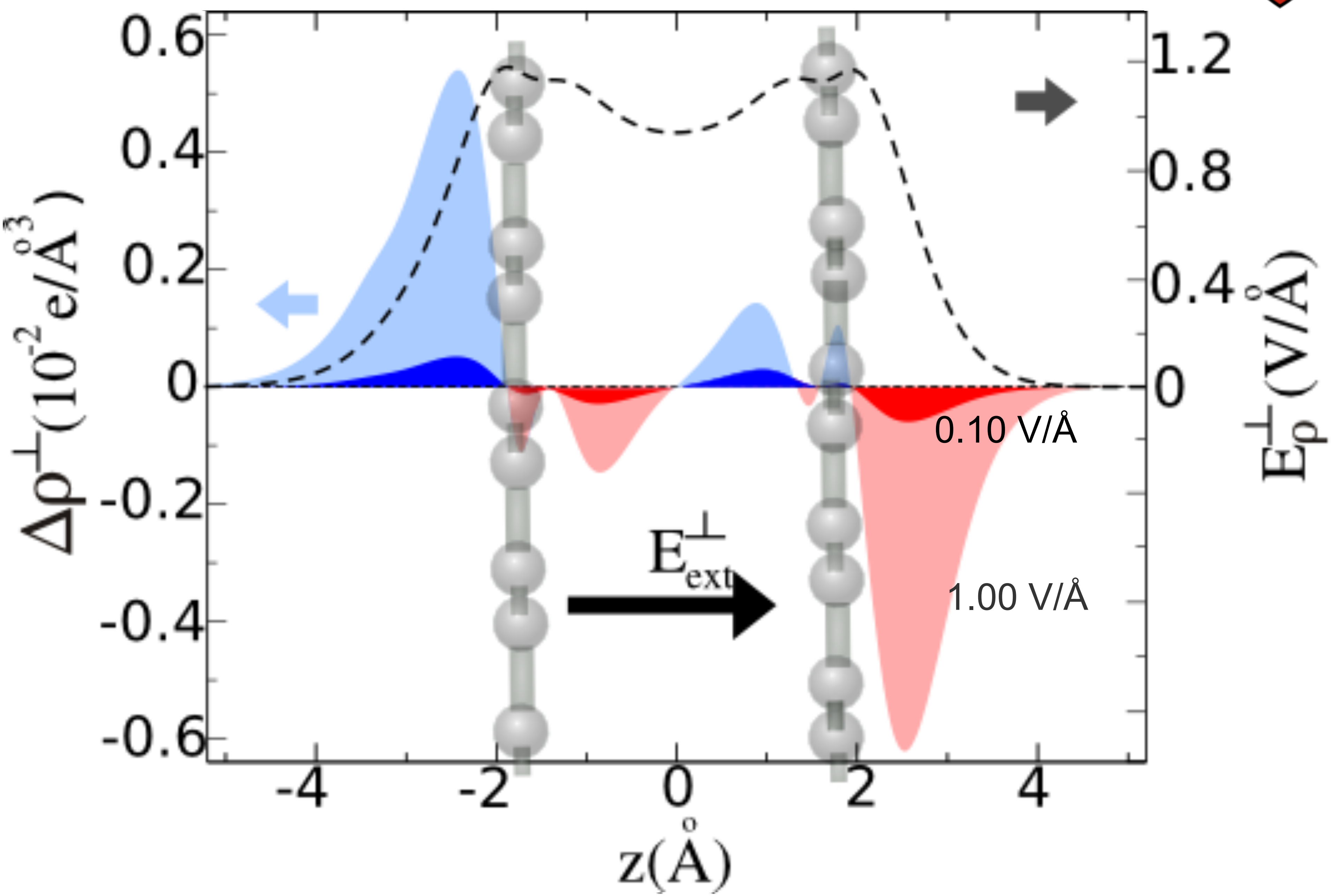


Position-dependent interlayer electric field (maximum and minimal values)

Screening is not perfect: not a metal, not a semiconductor

Also apply for multilayer graphene

Polarization charge is field dependent



EJGS and E. Kaxiras, *Nano Letters* (2013) **13**, 898

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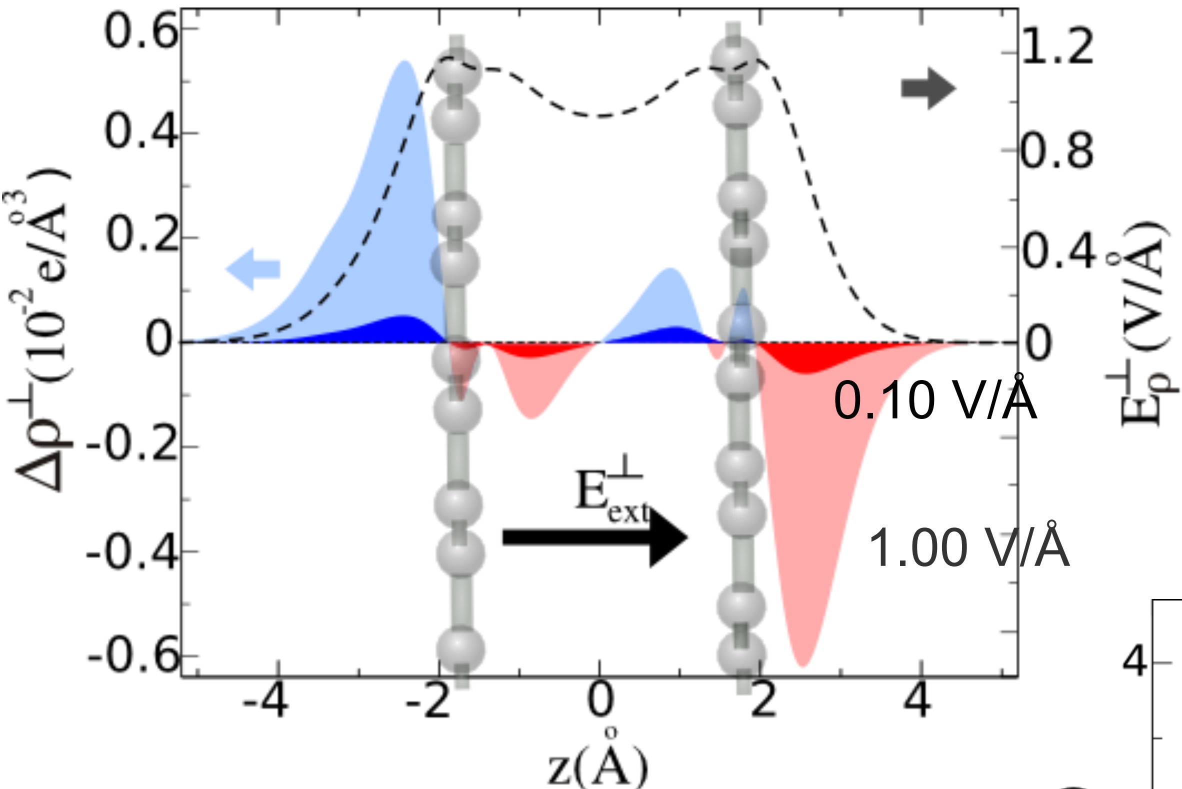
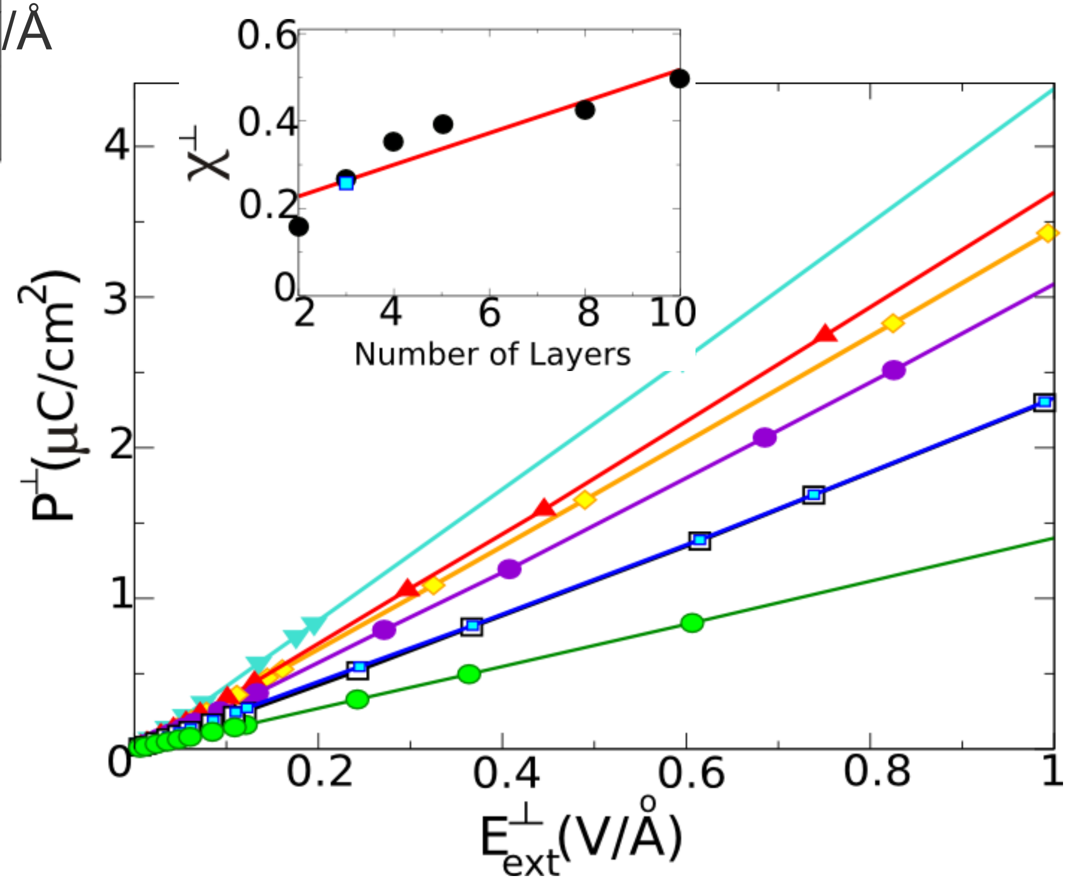


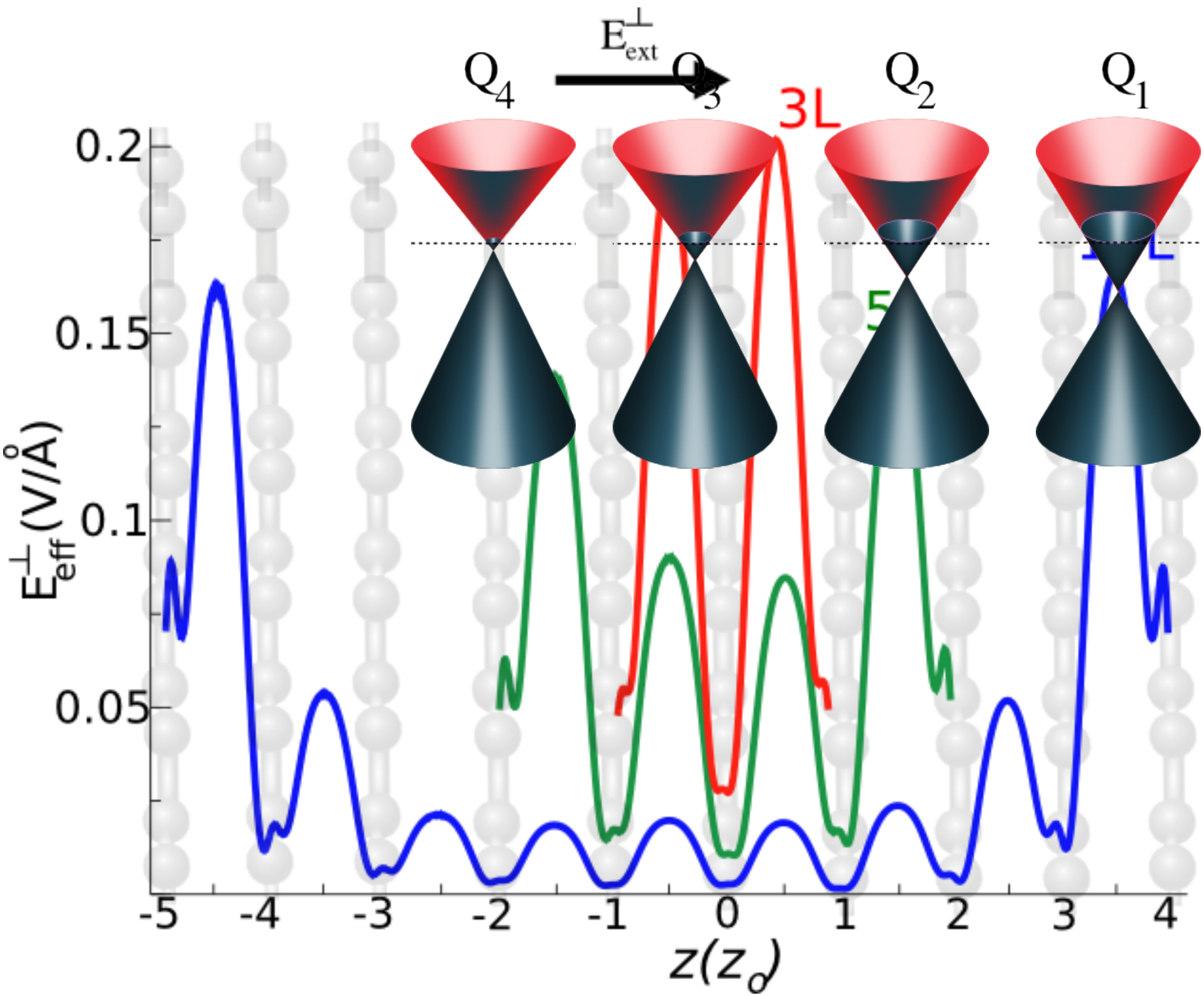
Charge accumulation/depletion at graphene layer generates the response field.



The response electric field E_ρ screens the external field E_{ext} as in:

$$E_{tot} = E_{ext} - E_\rho$$

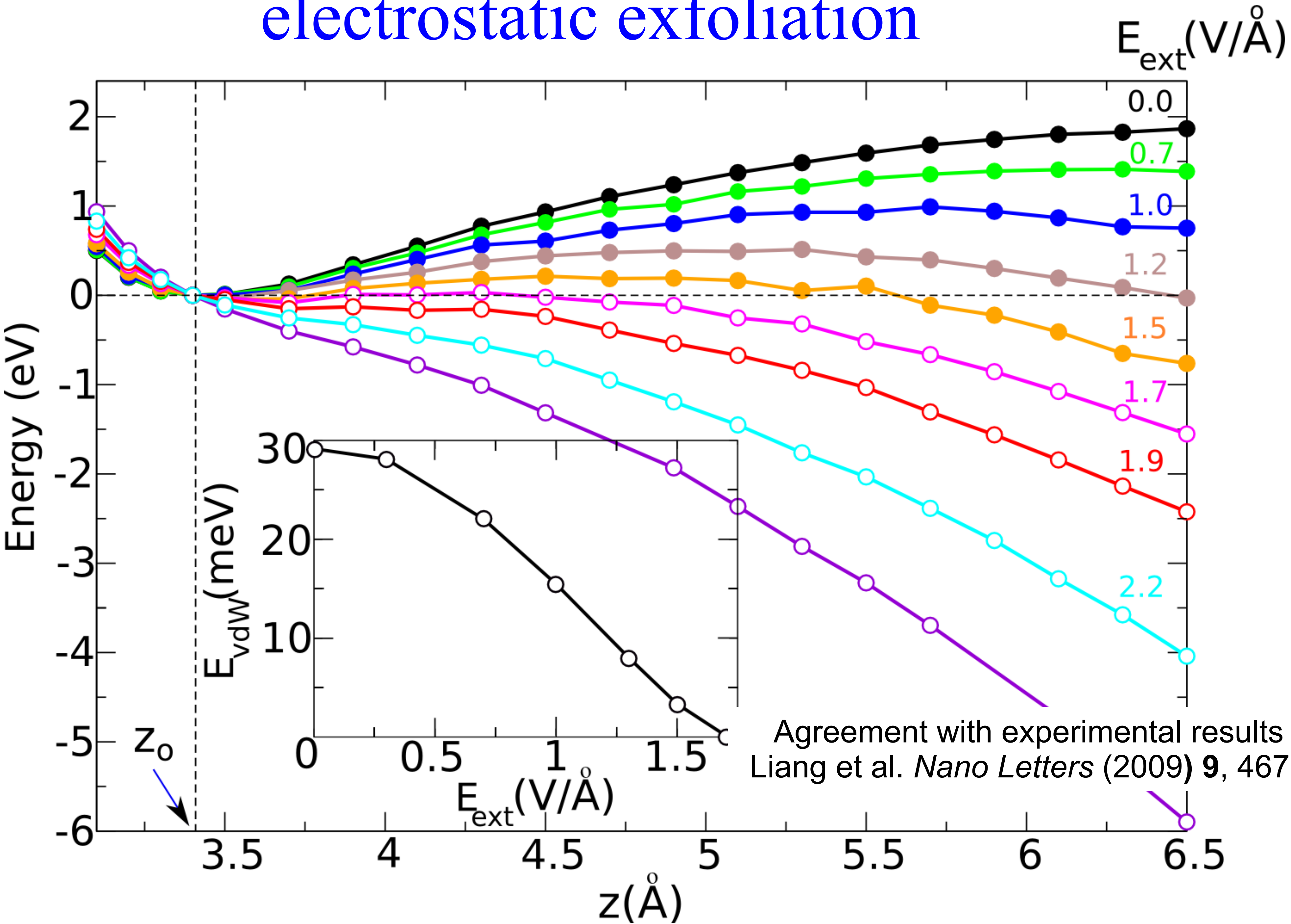
Non-linear screening is the main effect behind of electric-driven tuning of ε



A thicker structure screens with shorter screening length than a thinner structure

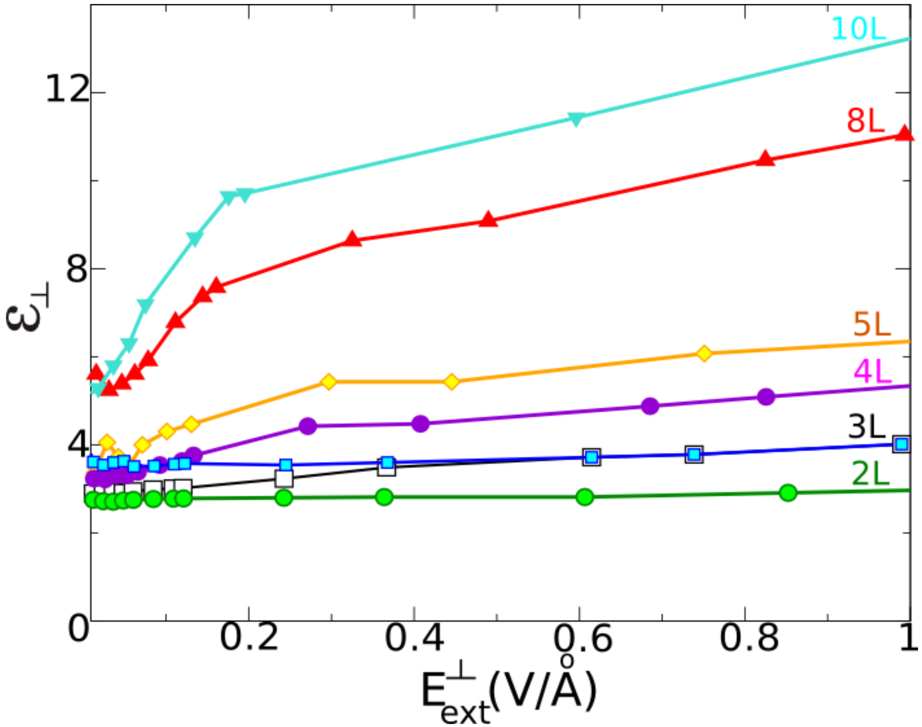
The electric field is screened by the charge Qi accumulated at each layer.

Limits on the applied electric field: electrostatic exfoliation



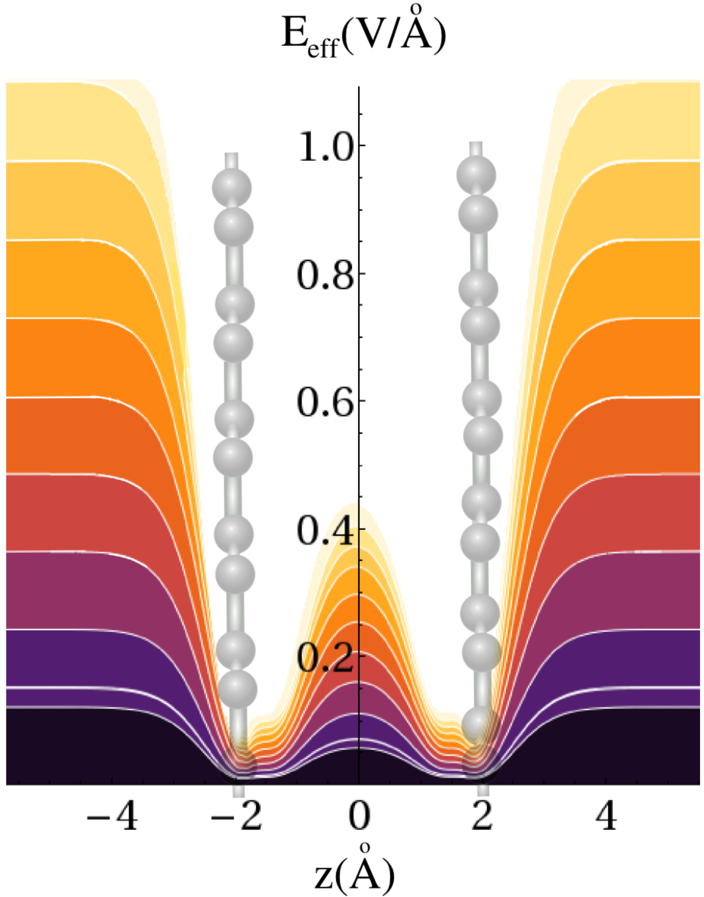
Agreement with experimental results
Liang et al. *Nano Letters* (2009) **9**, 467.

Messages to take home



The dielectric constant of graphene is electric-field dependent

The thicker the structure (more layers) the stronger is the modulation



The non-linear screening effect is the main reason behind of the electric tuning

Electrostatic exfoliation is also possible using a bias

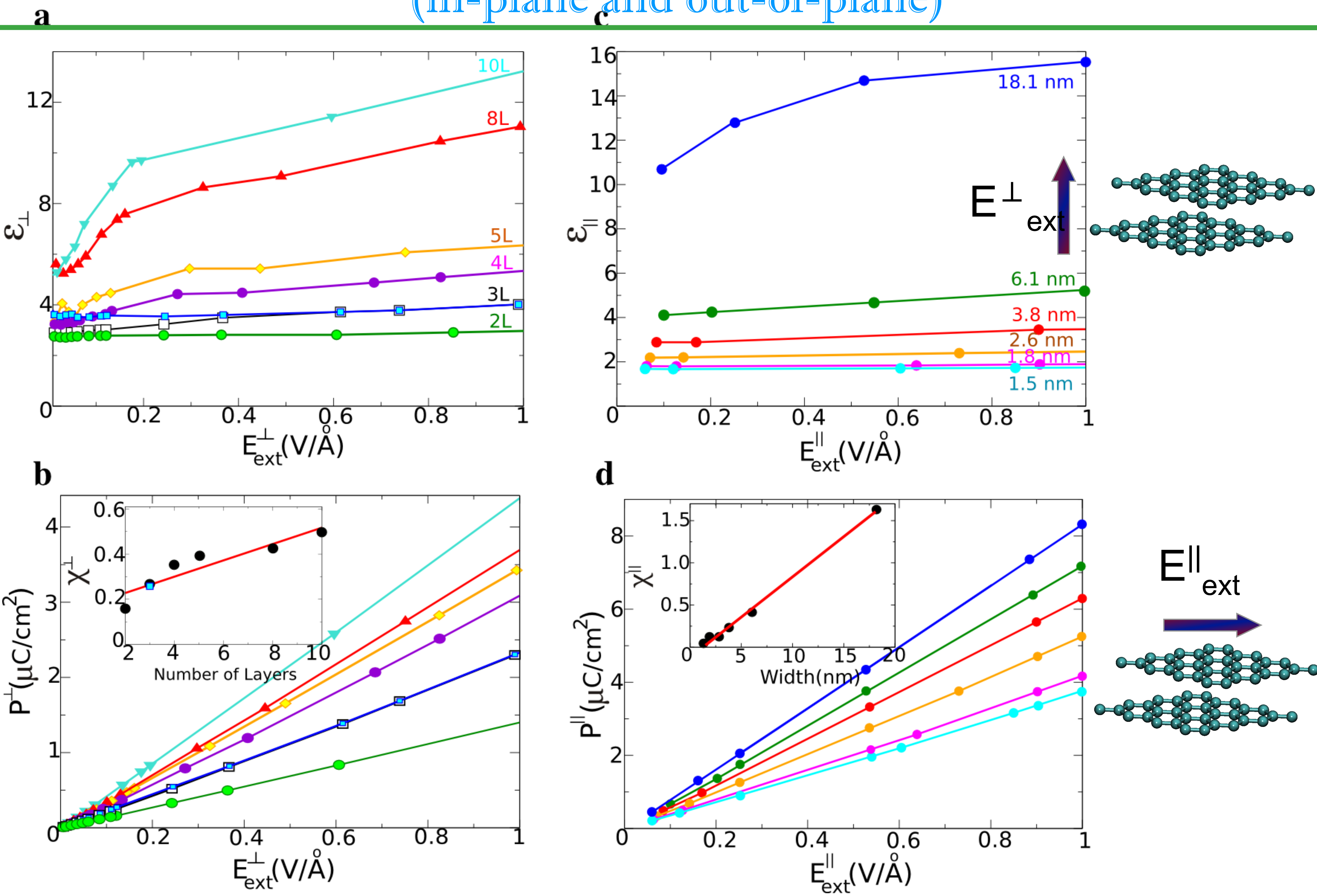
Other 2D-crystals, e,g, MoS_2, also show similar behavior

EJGS and E. Kaxiras, *Nano Letters* (2013) **13**, 898

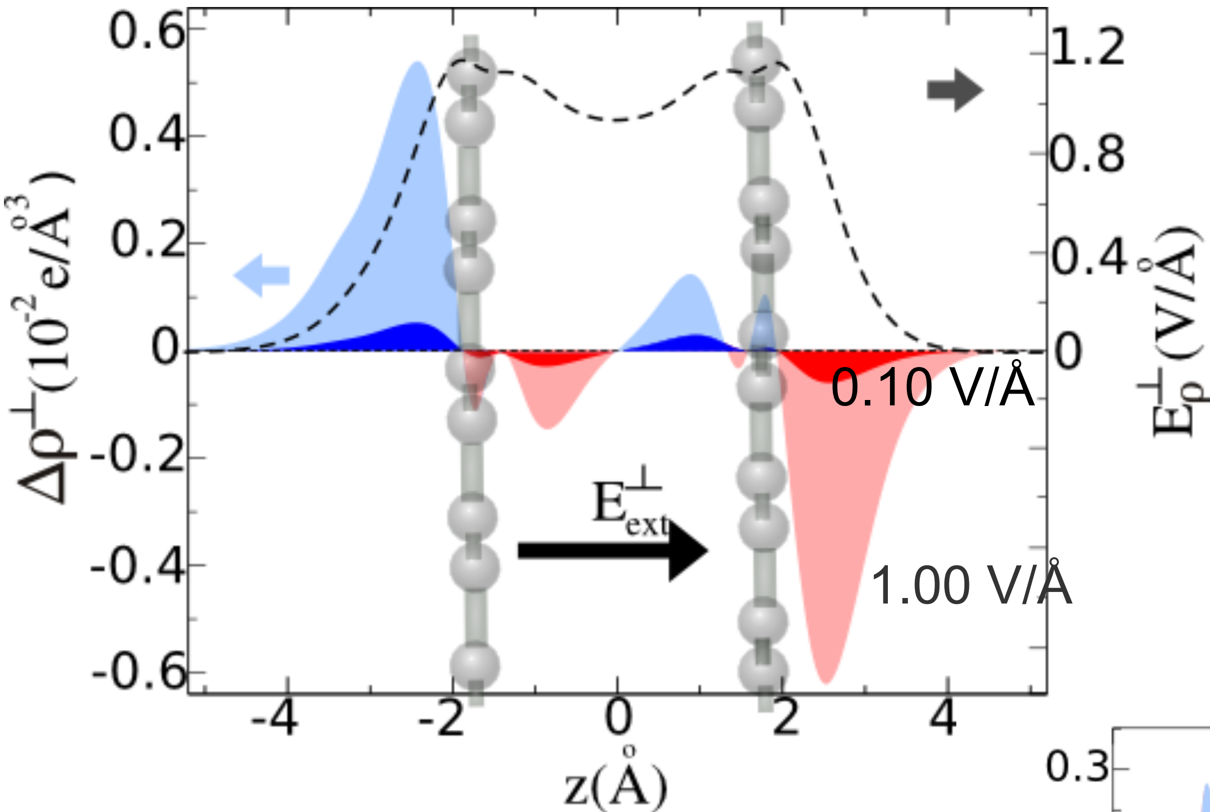
Thank you for your attention!

Acknowledgements: Xsede, supported by NSF grant numbers
TG-DMR120073, TG-DMR120049 and TG-PHY120021

Electric Field Dependence of the Effective Dielectric Constant (in-plane and out-of-plane)



Polarization charge is field dependent



Charge accumulation/depletion at graphene layer generates the response field.

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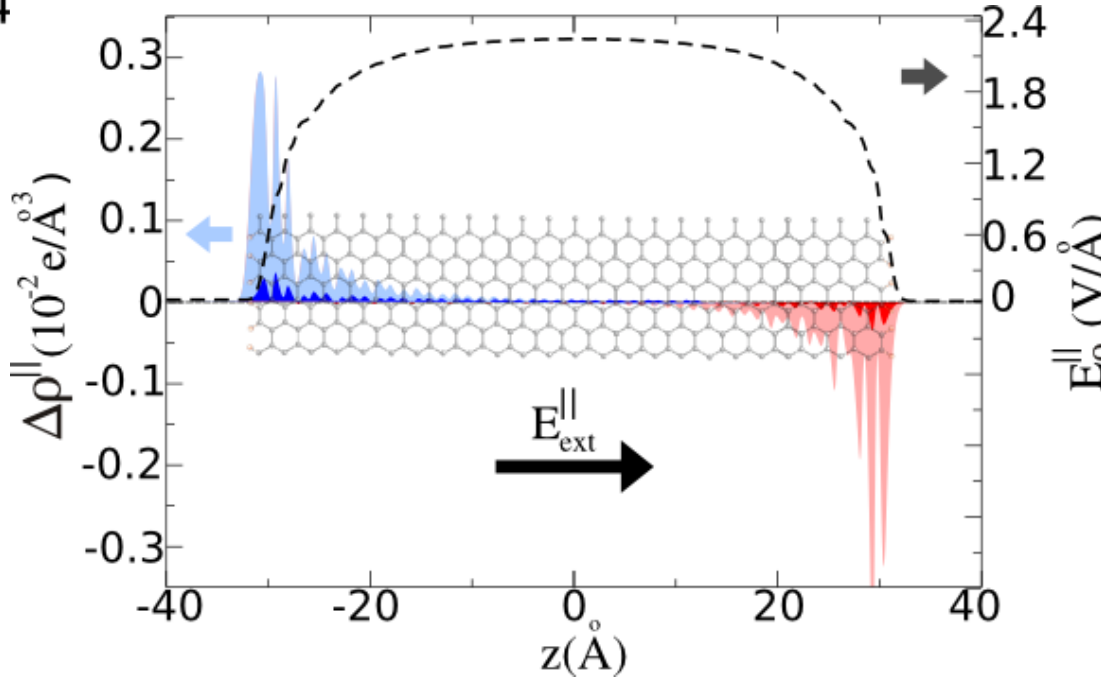
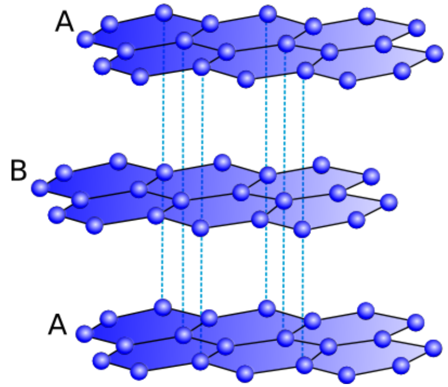


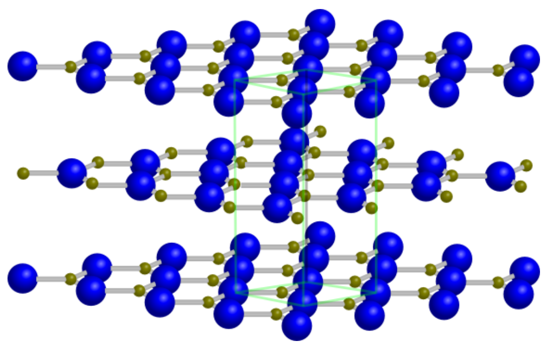
What about other 2D-materials?

Graphene



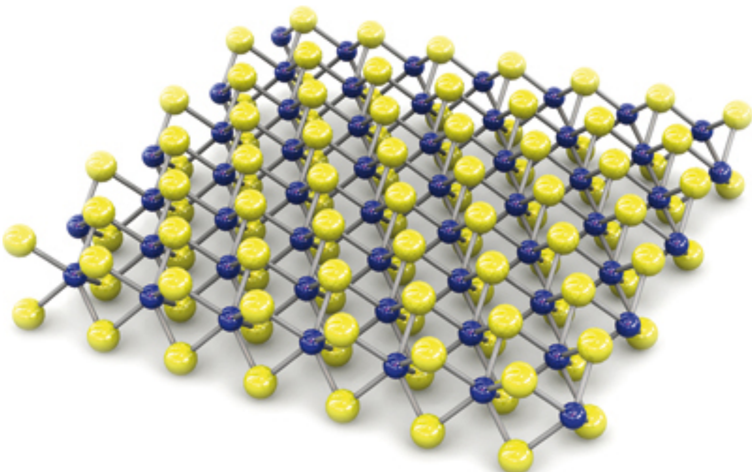
Novoselov et al. *Nature* (2005) **438**, 197.
Zhang et al. *Nature* (2005) **438**, 201.

h-BN



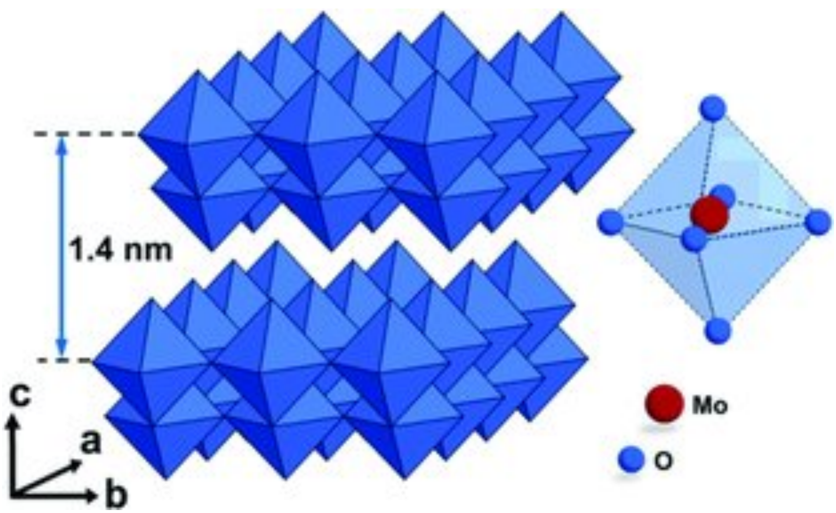
Dean et al. *Nat. Nanotech,* (2010) **5**, 722

Metal dichalcogenide (WS_2, TiS_2, ZrS_2, $MoSe_2$, MoS_2, ...)



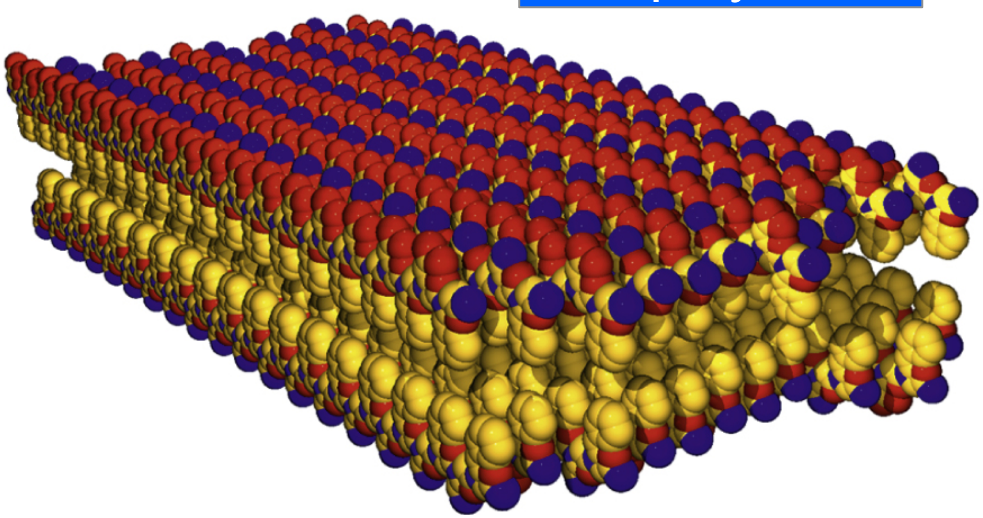
Radisavljevic et al. *Nat. Nanotech.* (2011) **6**, 147
Kim et al. Nat. Communications (2012) 3:1011

α-MoO_3



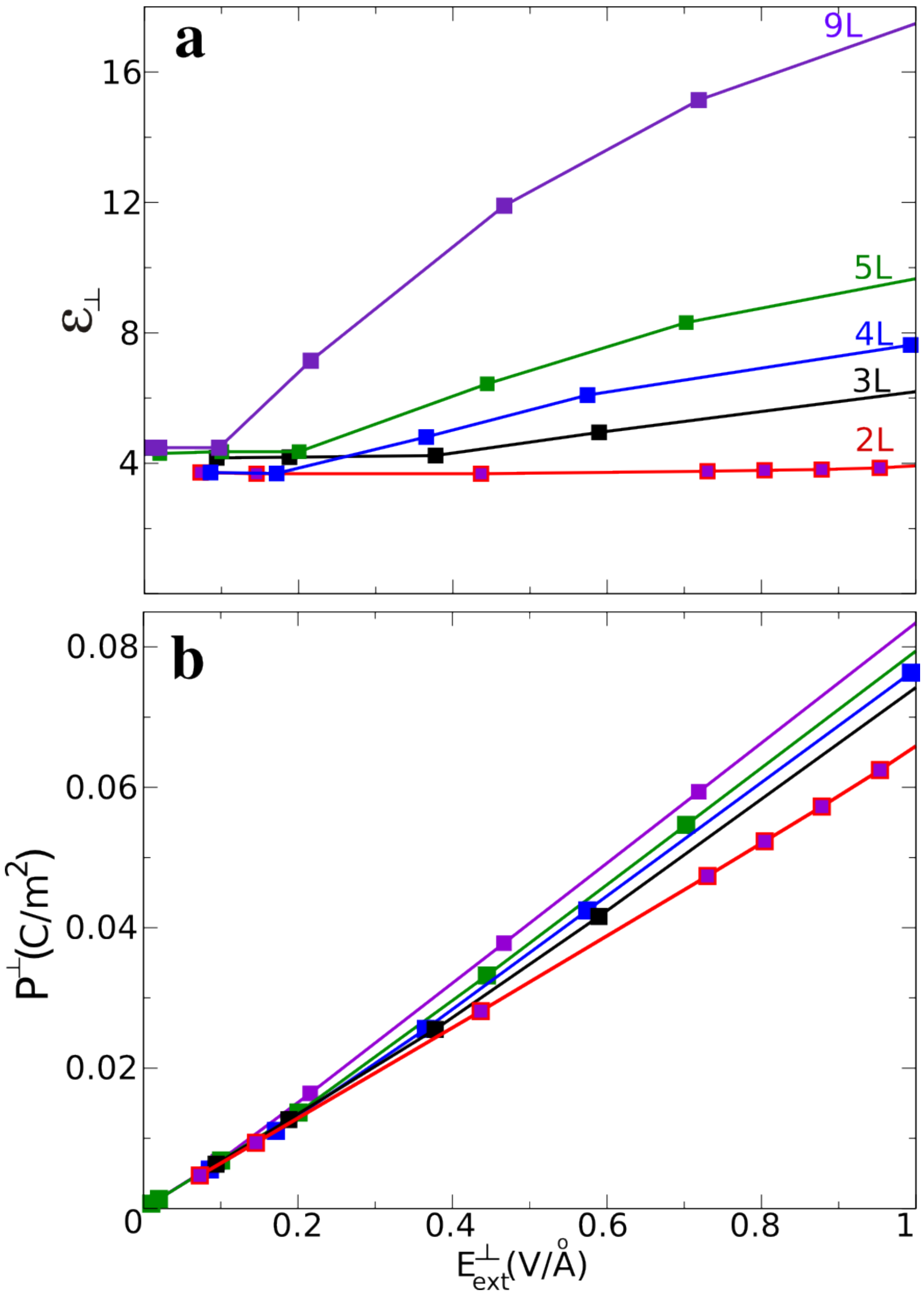
Balendhran et al. *Adv. Materials* (2013) **25**, 108

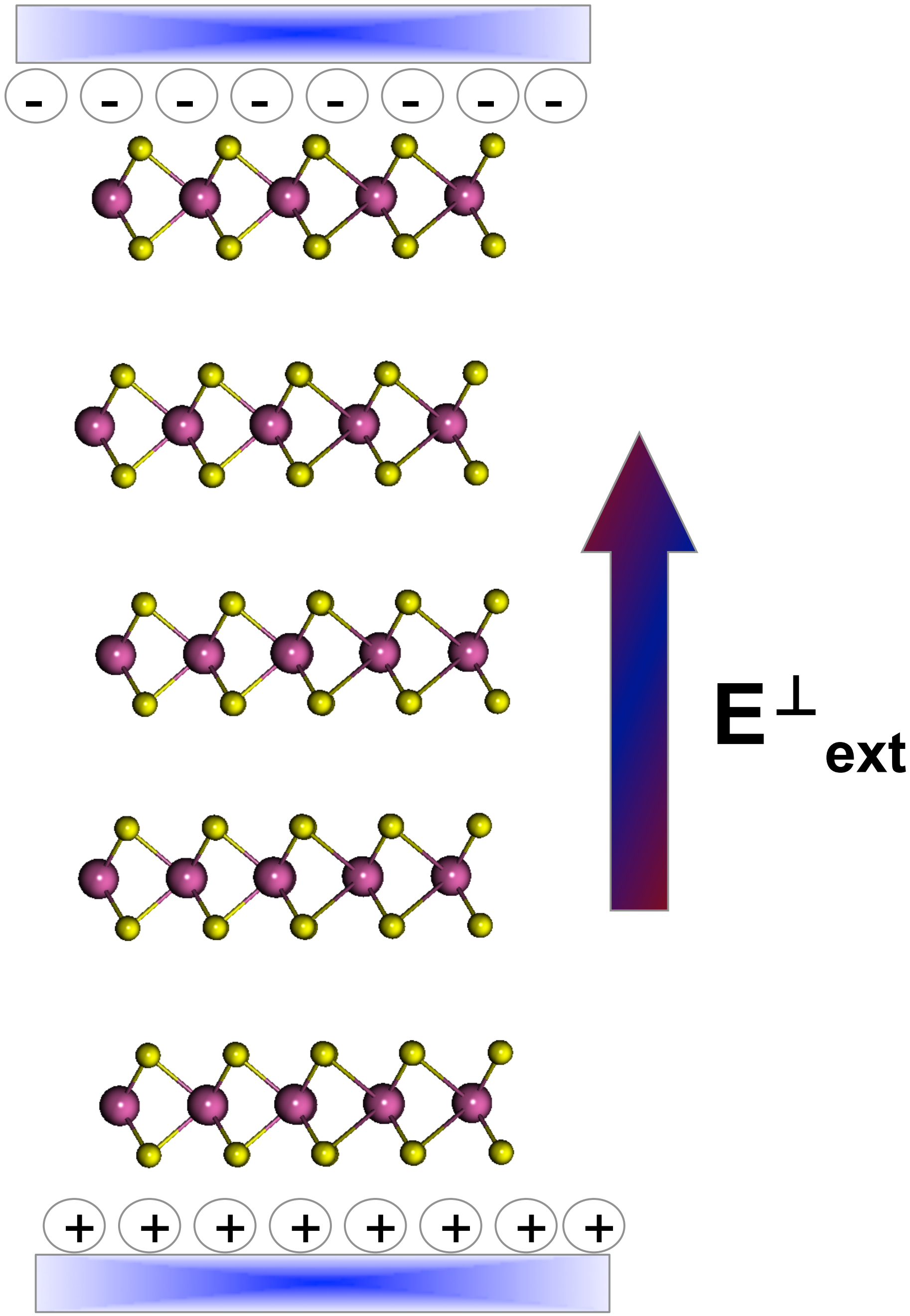
2D-polymers



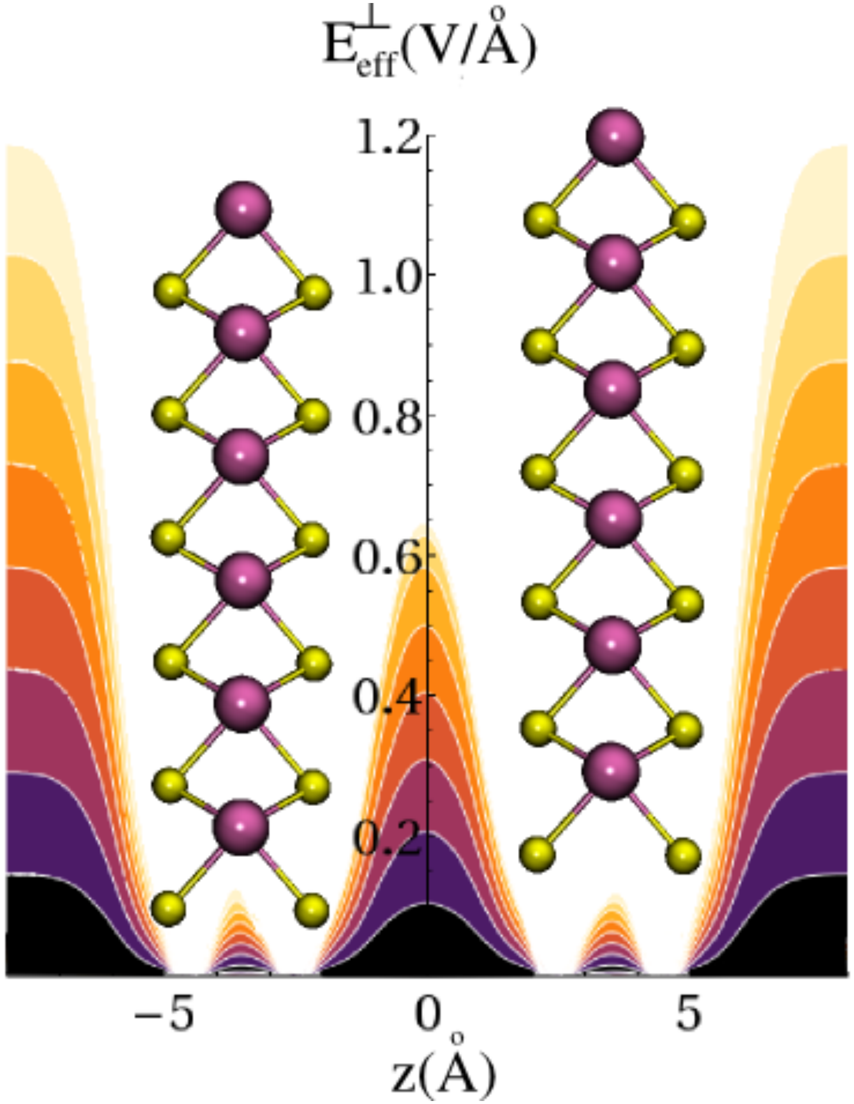
Nam et al. *Nat. Materials* (2010) **9**, 454

Electric-field control of the dielectric constant of MoS_2 materials



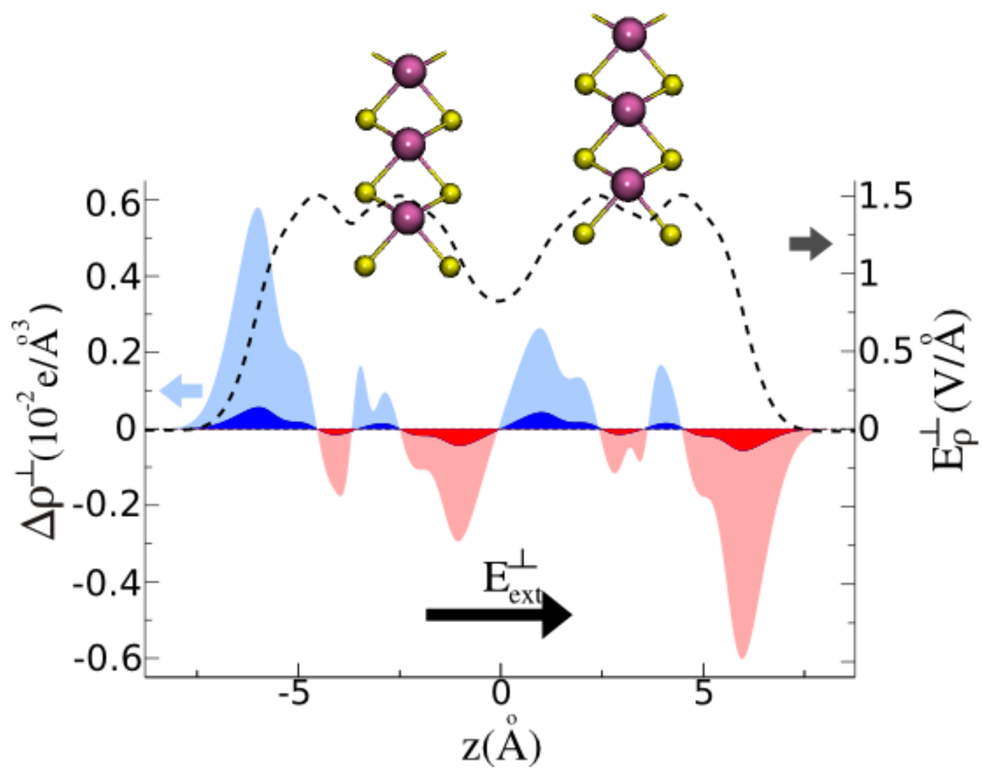


Similar behaviour as seen for multilayer graphene



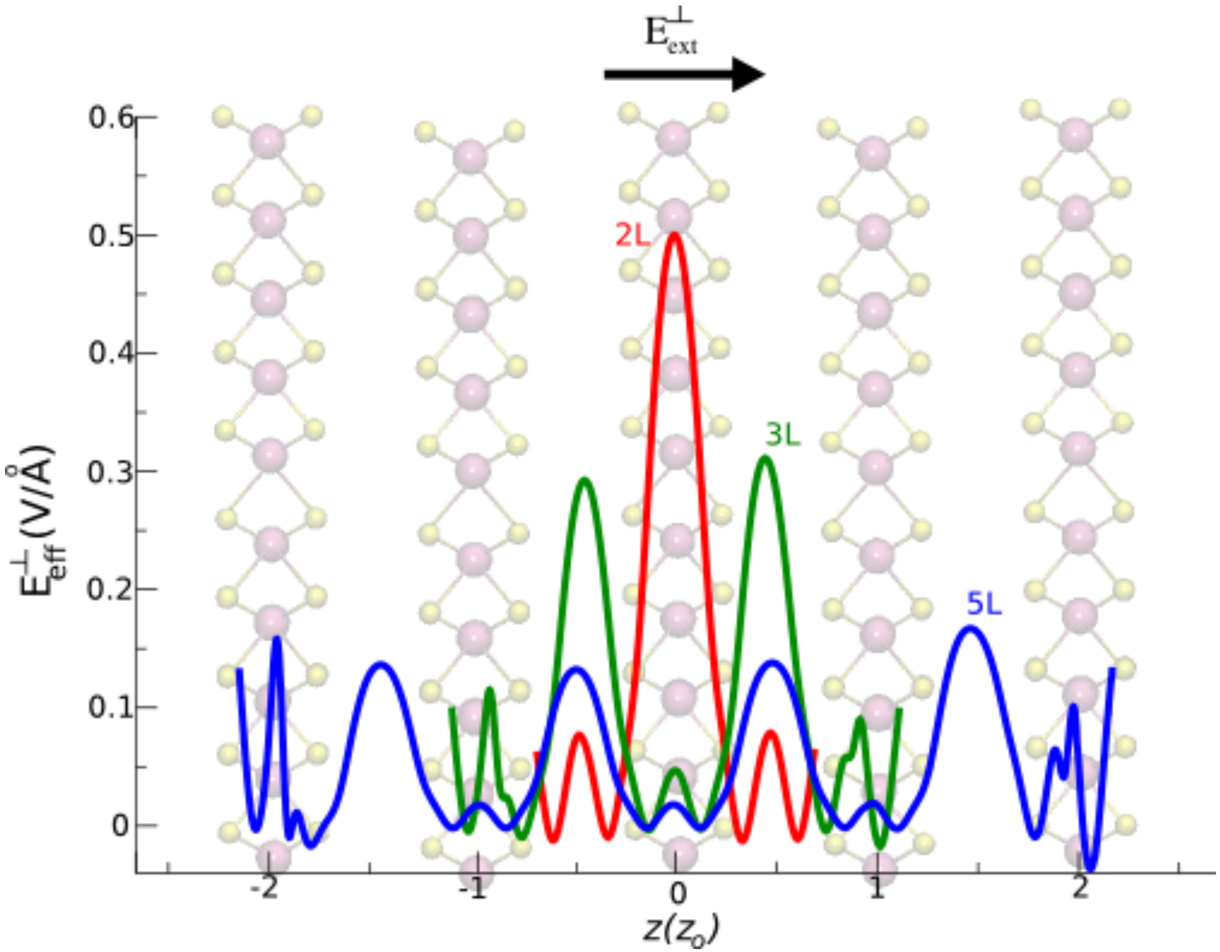
The polarization charge as well as the response field are bias dependent.

Only for small fields (<0.10 V/Å) the static dielectric constant is really constant.



Many similarities with graphene are recovered.

Non-linear screening in multilayer MoS_2

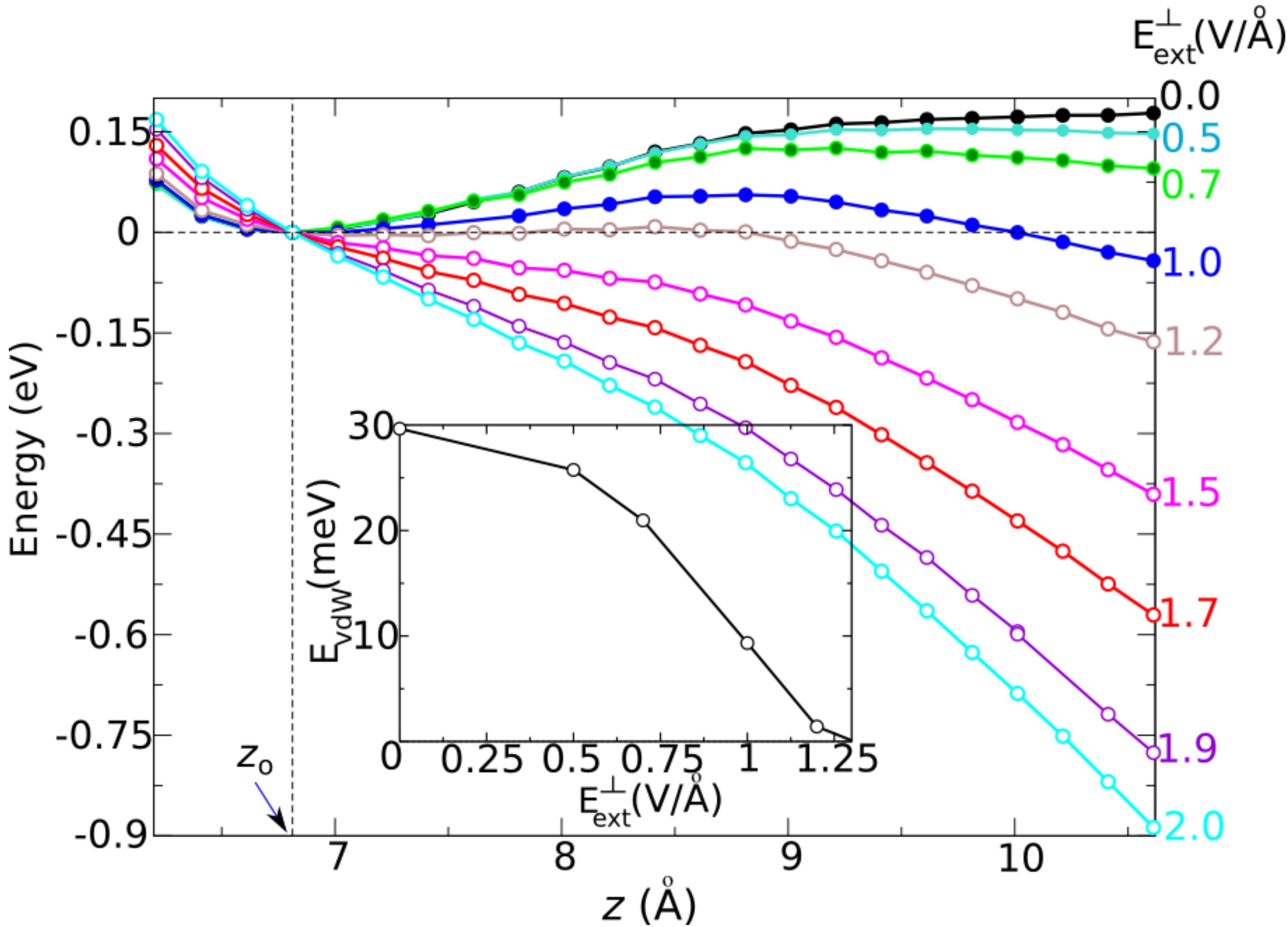


The electric field inside of the material decreases as a function of the number of layers.

The thicker the structure (more layers) the larger the value of ε

Oscillations are observed in-between S-Mo-S layer

Electrostatic exfoliation is also possible with MoS_2 at lower fields in comparison to Graphene



Questions? Comments?