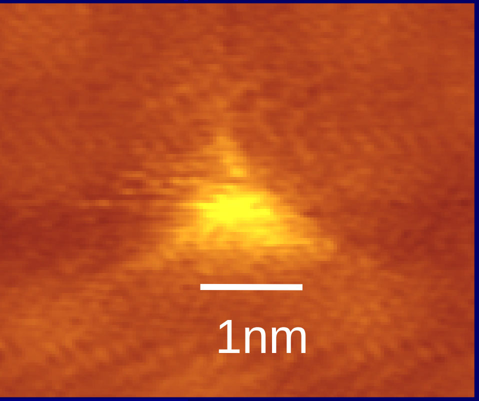
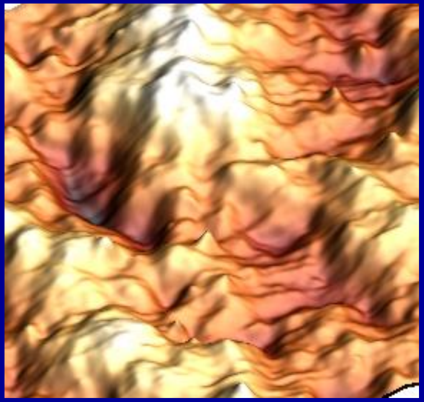
Kondo Screening of Moments in Imperfect Graphene

- Vacancy magnetic moment
- Kondo screening of magnetic moments
- Gate tunable magnetic moment
- Screening on a curved surface



Eva Y. Andrei

Rutgers University

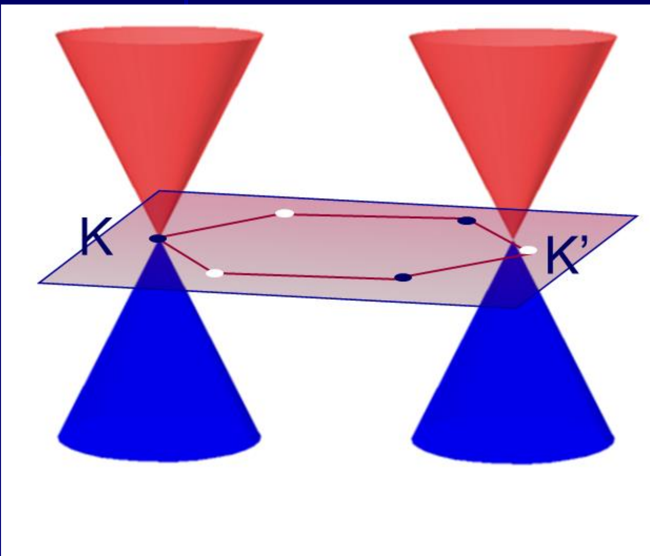


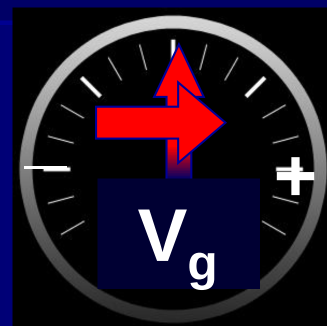
118th Statistical Mechanics Conference Rutgers Dec 2017

Honoring: Guenther, Cristina and Shelly

Perfect Graphene

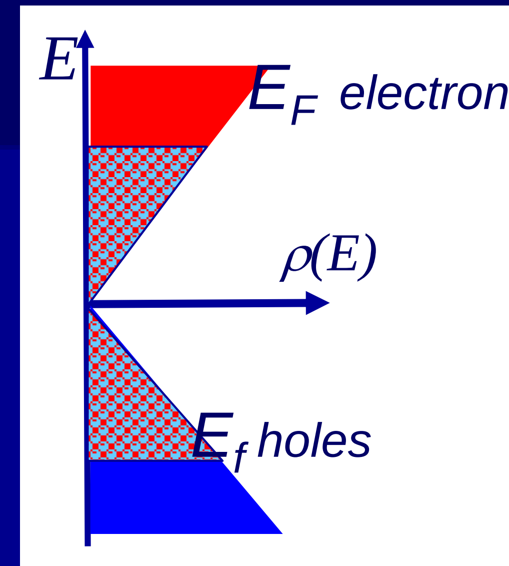
Band structure





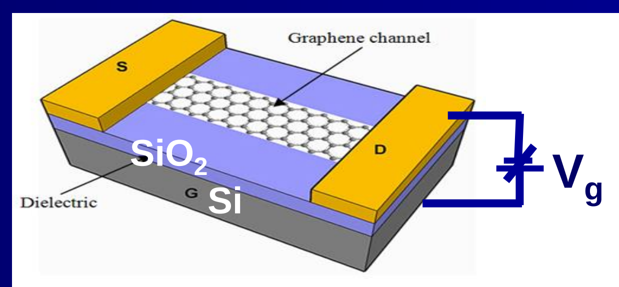
$1V \longmapsto 7x10^{10}\ cm^{-2}$

Density of states



Ingredients:

1. 2D
2. Honeycomb structure ● ●
3. Identical atoms



E.Y. Andrei

Magnetism and Perfect Graphene

VOLUME 62, NUMBER 10 PHYSICAL REVIEW LETTERS 6 MARCH 1989

Two Theorems on the Hubbard Model

Elliott H. Lieb
Departments of Physics and Mathematics, Princeton University, P. O. Box 708, Princeton, New Jersey 08544
(Received 12 December 1988)

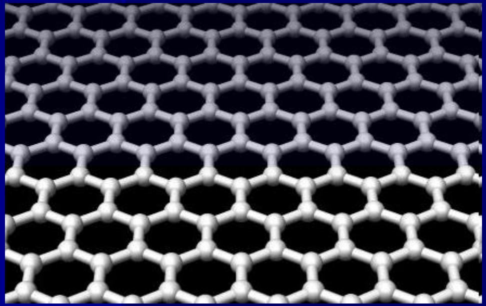
In the attractive Hubbard model (and some extended versions of it), the ground state is proved to have spin angular momentum $S=0$ for every (even) electron filling. In the repulsive case, and with a bipartite lattice and a half-filled band, the ground state has $S=\frac{1}{2}\,||B|-|A||$, where $|B|$ ($|A|$) is the number of sites in the B (A) sublattice. In both cases the ground state is unique. The second theorem confirms an old, unproved conjecture in the $|B|=|A|$ case and yields, with $|B|\neq|A|$, the first provable example of itinerant-electron ferromagnetism. The theorems hold in all dimensions without even the necessity of a periodic lattice structure.

...repulsive Hubbard with **bipartite lattice** and **half-filled** band:

- spin of ground state with N_A, N_B populated sites:

$$S = 1/2(N_A - N_B)$$

Pristine graphene (graphite) $N_A = N_B \rightarrow S=0$



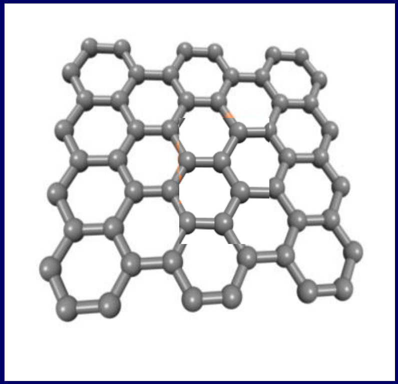
Perfect graphene
Non-Magnetic!

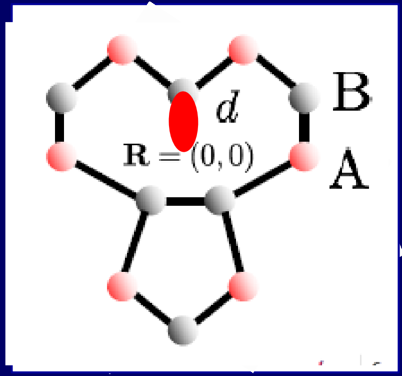
- *T. L. Makarova, et al Nature 413, 716 (2001) (RT ferromagnetism in C60)*
- *D. P. Esquinazi, et al Phys. Rev. B (2002). (Ferromagnetism in graphite)*
- *R. A. Wood, et al J. Phys. Condens. Matter (2002) (Ferromagnetic fullerines)*
- *J. M. D. Coey et al, Nature 420, 156 (2002). (Extra-terrestrial graphite)*

Vacancies in graphene $\rightarrow N_A > N_B \mapsto$ magnetic moment $> 1\mu_B$

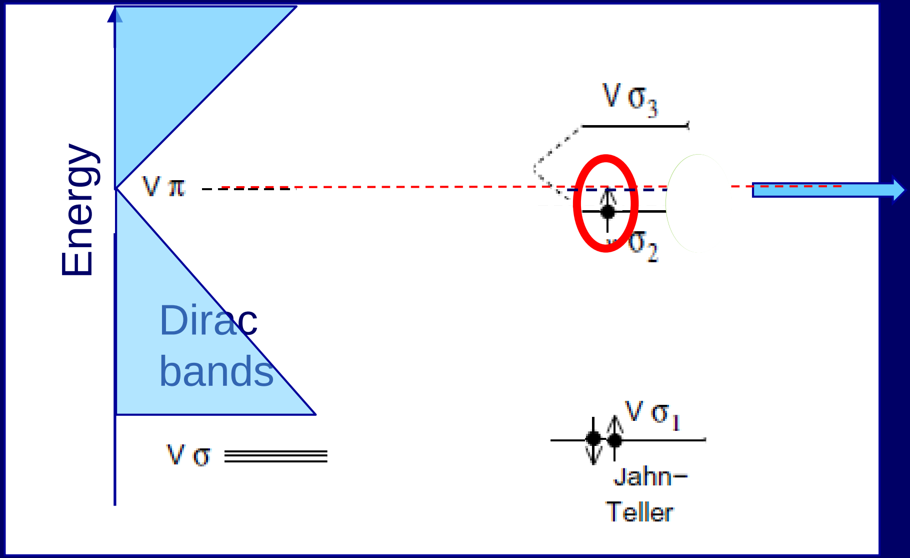
A.H. Castro Neto et al. Solid State Commun. (2009).
T. Wehling,. Phys. Lett. (2009)
O. Yazyev, et al Rep. Prog. (2010).
M. Vojta *et.al*, EPL, 90 (2010) 27006
T. O. Wehling, Phys. Rev. B 81, 115427(2010)
J. O. Sofo, et al Phys. Rev. B 85, 115405 (2012)

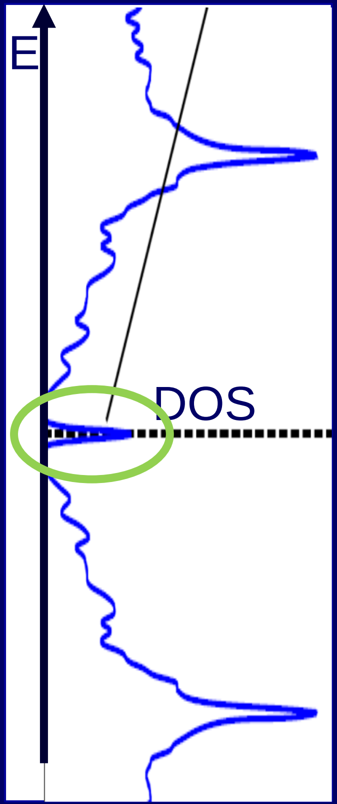
Imperfect Graphene - Vacancy





Yazyev & Helm (2007),
Popovi'c, Nanda, Satpathy (2012)





Broken
AB
symmetry

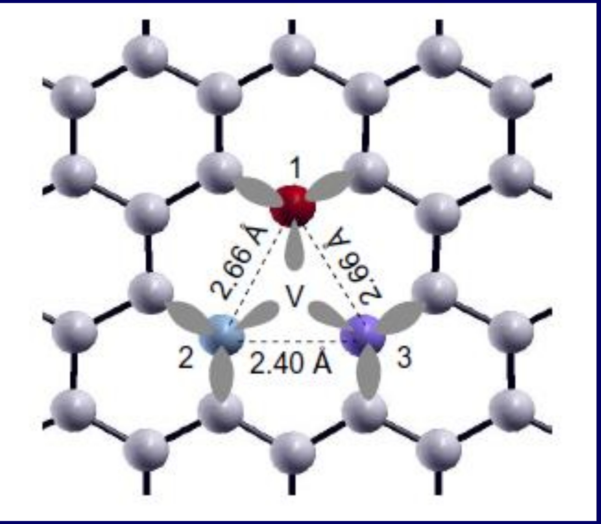
σ Dangling bond $\mapsto$ localized state $\mapsto 1\mu_B$

$p_z \mapsto$ quasi-localized state on other sublattice $\mapsto \sim 0.5\text{-}0.7\mu_B$

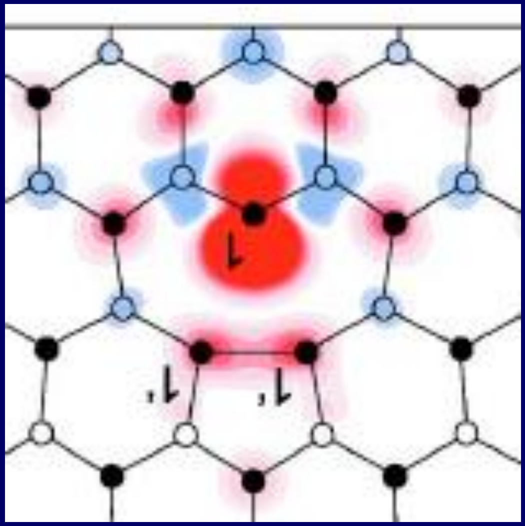
Zero mode peak at ~Dirac Point

Imperfect Graphene - Vacancy

Magnetic moment ~ 1.7μ_B



Magnetic Moment



Yazyev & Helm (2007)

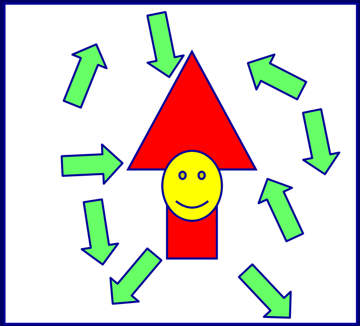
Interaction of ultra-relativistic electrons with Local magnetic moment?

Kondo Screening of Impurity Moments in Metals

Impurity spin in metal

$T>T_K$

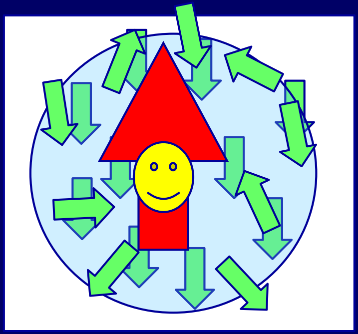
Unscreened



J antiferromagnetic coupling to electron bath

$T<T_K$

Screened



$$T_K \propto \exp(-1/\rho J)$$

ρ ***density of states at*** $\boldsymbol{E_F}$

$\rho(E_F) > 0$, $J>0 \mapsto T_K > 0$

- Normal metals $\quad \rho(E_F) \sim \mathit{finite};\ J \neq 0 \quad \mapsto T_K > 0$
- Insulators $\quad \rho(E_F) = 0 \quad$ No Kondo screening

What happens in a pseudogap system?

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Kondo Screening in pseudo-gap systems

- Pseudo- gap systems $\rho(E) \propto E^r$ screening suppressed.
  - r = 1 (graphene, high T_c superconductors)

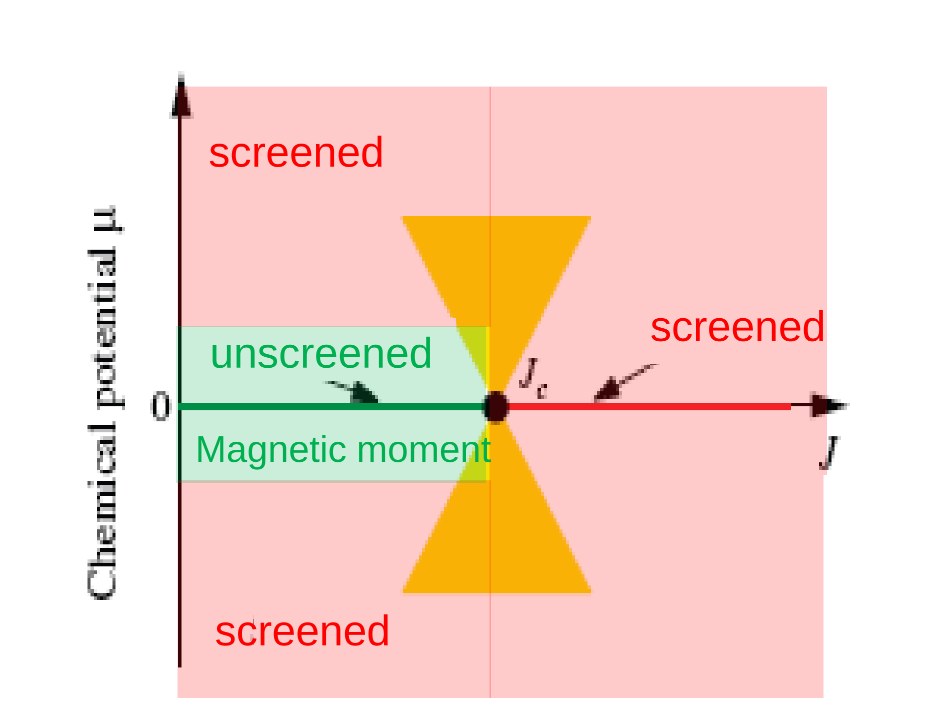
μ~0 (undoped)

•Kondo screening only for J>Jc

•J_c finite only for asymmetric DOS

|μ|>>0 doped

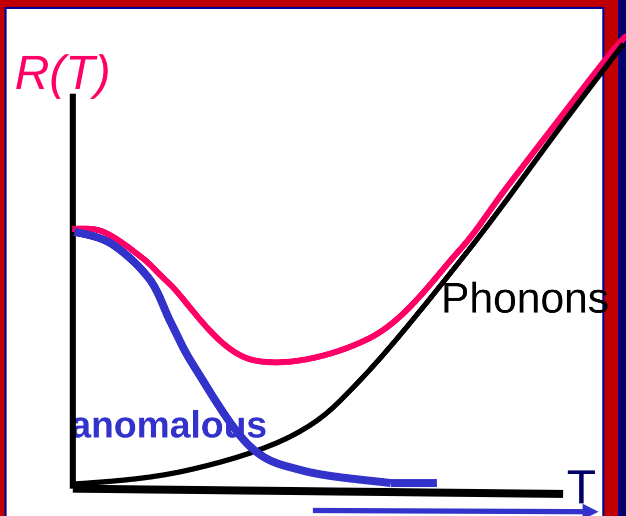
- Normal Kondo screening



- D. Withoff and E. Fradkin, Phys. Rev. Lett. 64, 1835(1990)
- K. Chen and C. Jayaprakash, J. Phys L491 (1995)
- K. Ingersent, Phys. Rev. B54, 11936 (1996)
- C. Cassanello and E. Fradkin , (1996)
- R. Bulla, T. Pruschke, and A. C. Hewson, (1998)
- Polkovnikov A., Phys. Rev. B, 65 (2002) 064503
- Vojta M. and Fritz L., Phys. Rev. B, 70 (2004) 094502.
- Vojta, Fritz, Bulla EPL (2010)
- PW Lo, GY Guo, F. Anders, arXiv:1402.0040

Kondo Screening Experimental Signatures

Resistance minimum



$$R \xrightarrow[T>T_K]{} \frac{1}{\log^2(T/T_K)}$$

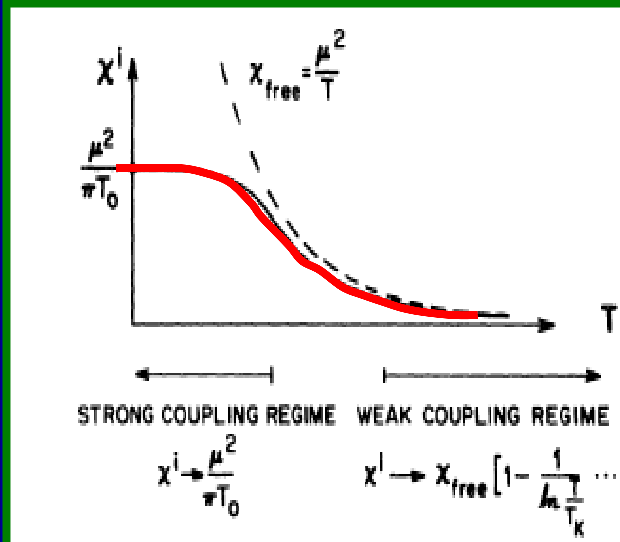
nature physics | LETTER
PUBLISHED ONLINE: 3 APRIL 2011 | DOI:10.1038/NPHYS1

Tunable Kondo effect in graphene with defects

Jian-Hao Chen[1,2†], Liang Li[2], William G. Cullen[1,2], Ellen D. Williams[1,2] and Michael S. Fuhrer[1,2*]

Measures:
scattering off Kondo cloud

Magnetization saturation



$\chi_{free} = \frac{\mu^2}{T}$

$\chi^i \rightarrow \frac{\mu^2}{\pi T_0}$ $\quad$ $\chi^i \rightarrow \chi_{free}\left[1 - \frac{1}{\ln \frac{T}{T_K}} \cdots\right]$

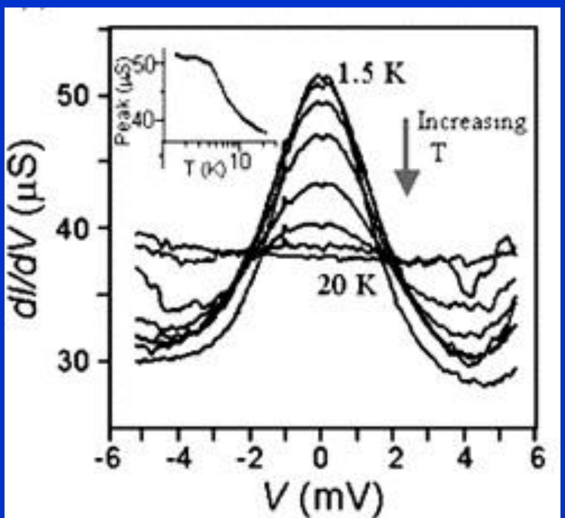
nature physics | LETTERS
PUBLISHED ONLINE: 10 JANUARY 2012 | DOI:10.1038/NPHYS218

Spin-half paramagnetism in graphene induced by point defects

R. R. Nair[1], M. Sepioni[1], I-Ling Tsai[1], O. Lehtinen[2], J. Keinonen[2], A. V. Krasheninnikov[2,3], T. Thomson
A. K. Geim[1] and I. V. Grigorieva[1*]

Measures:
Unscreened moment

DOS – Kondo Peak



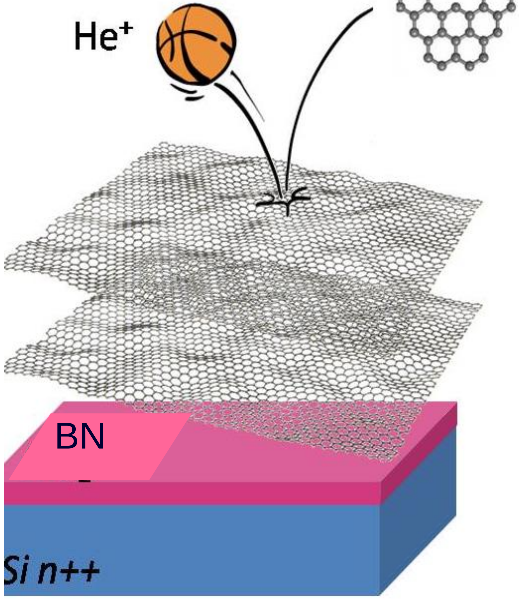
- Kondo Peak at E_F
- Appears at $T \sim T_K$
- Low T linewidth Γ

$$k_B T_K \sim \Gamma/2$$

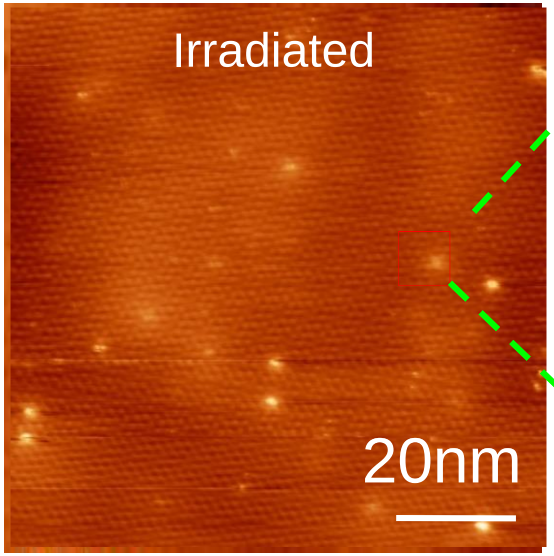
DOS enhancement at E_F

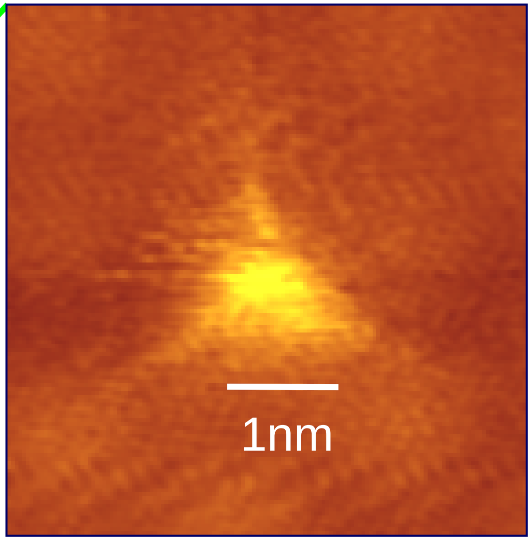
Creating Vacancies

Sputtering with 100eV He$^+$ ions



STM Topography

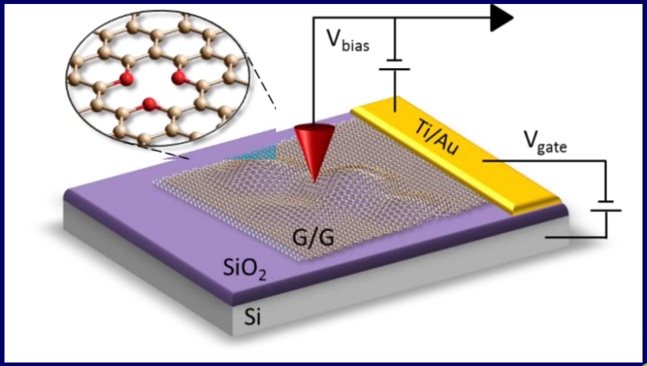


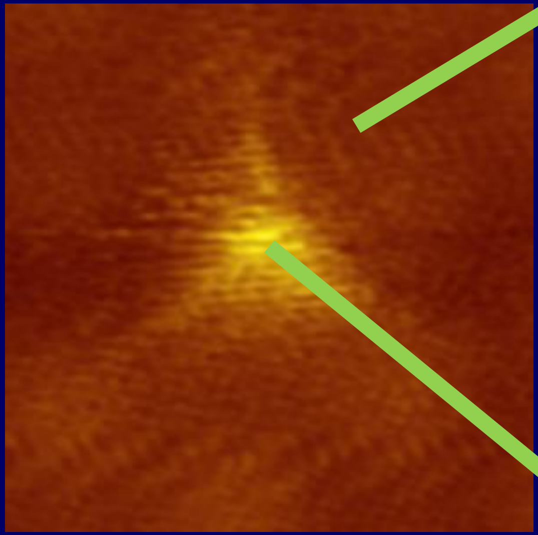


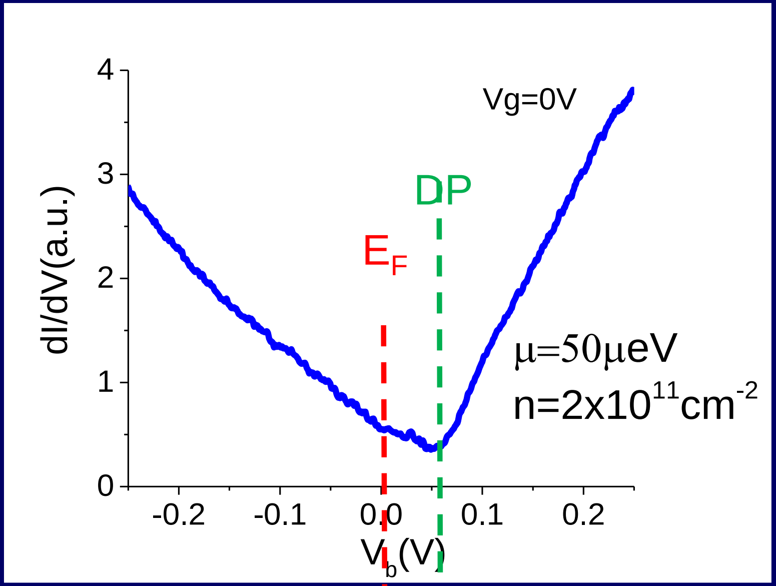
Single atom vacancy → triangular structure.

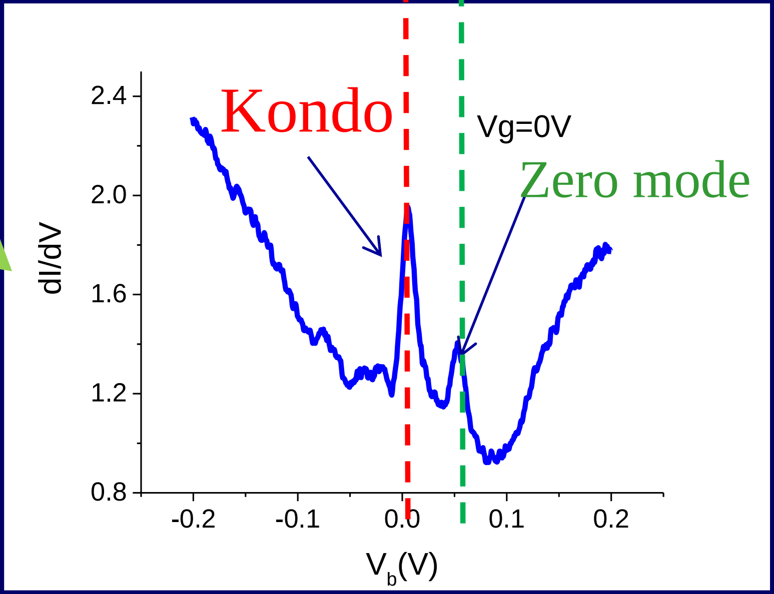
M. M. Ugeda, *et al* PRL 104, 196804 (2010).

STS: DOS Peak at E_F









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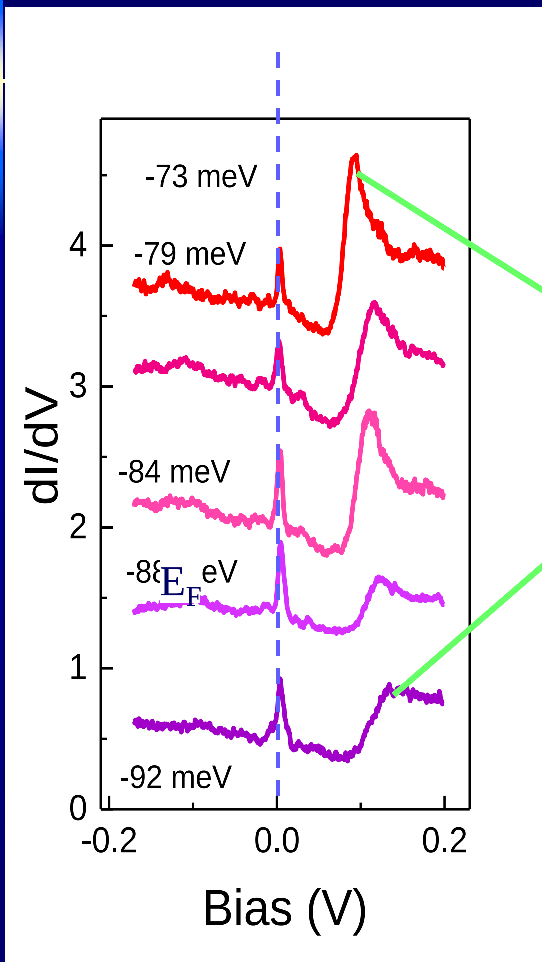
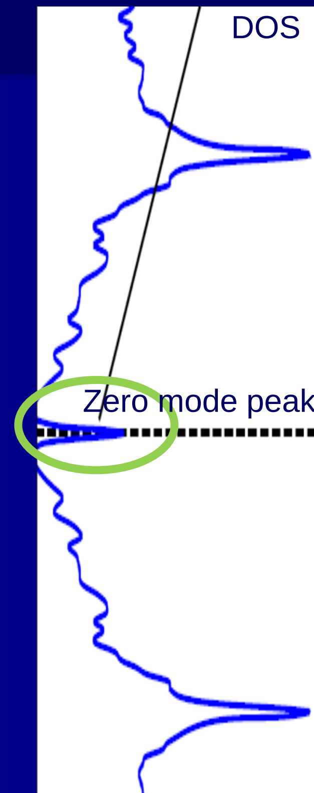
Gate Dependence

Increasing μ

Kondo peak

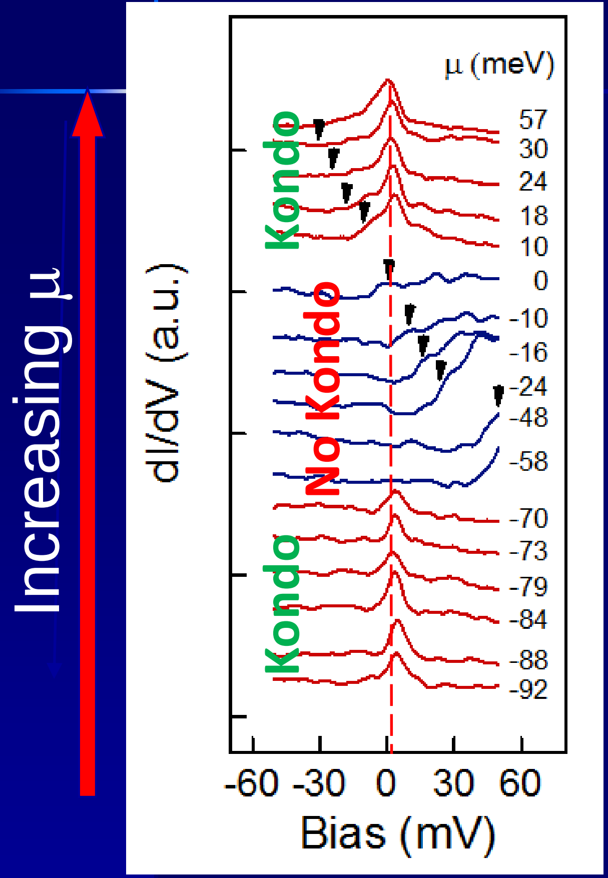


Zero mode

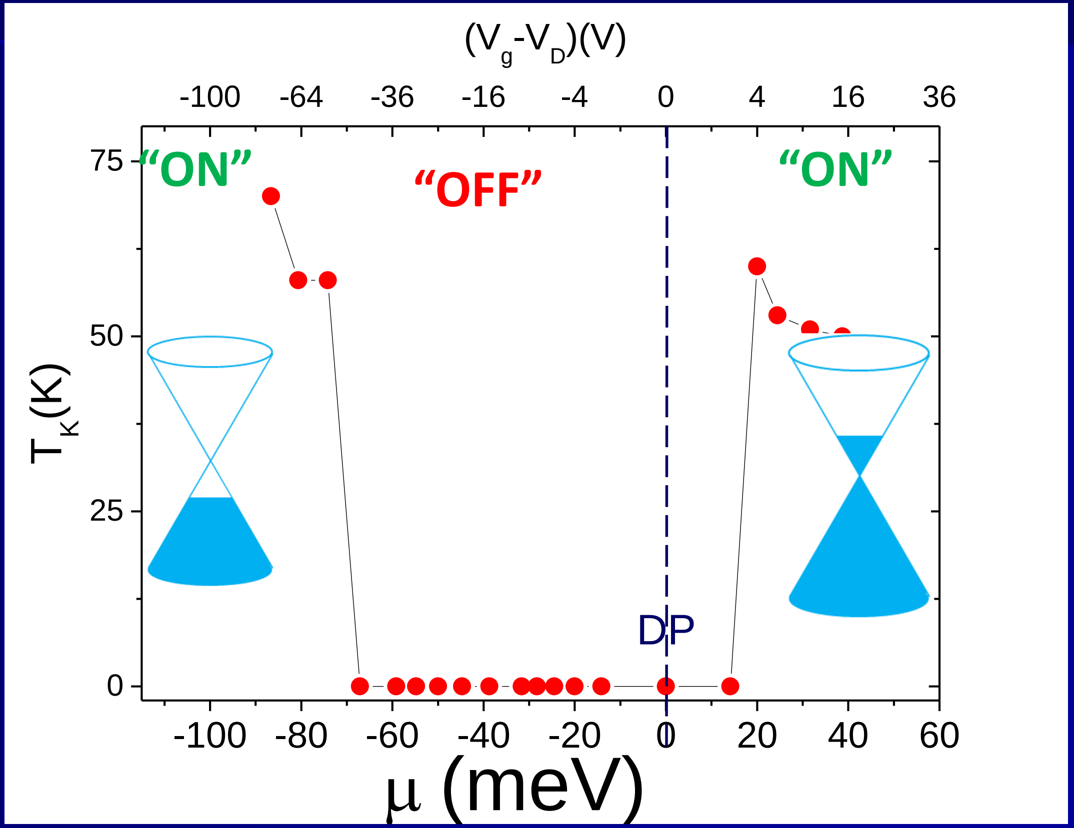


Pinned to E_F

Reentrant Kondo Screening



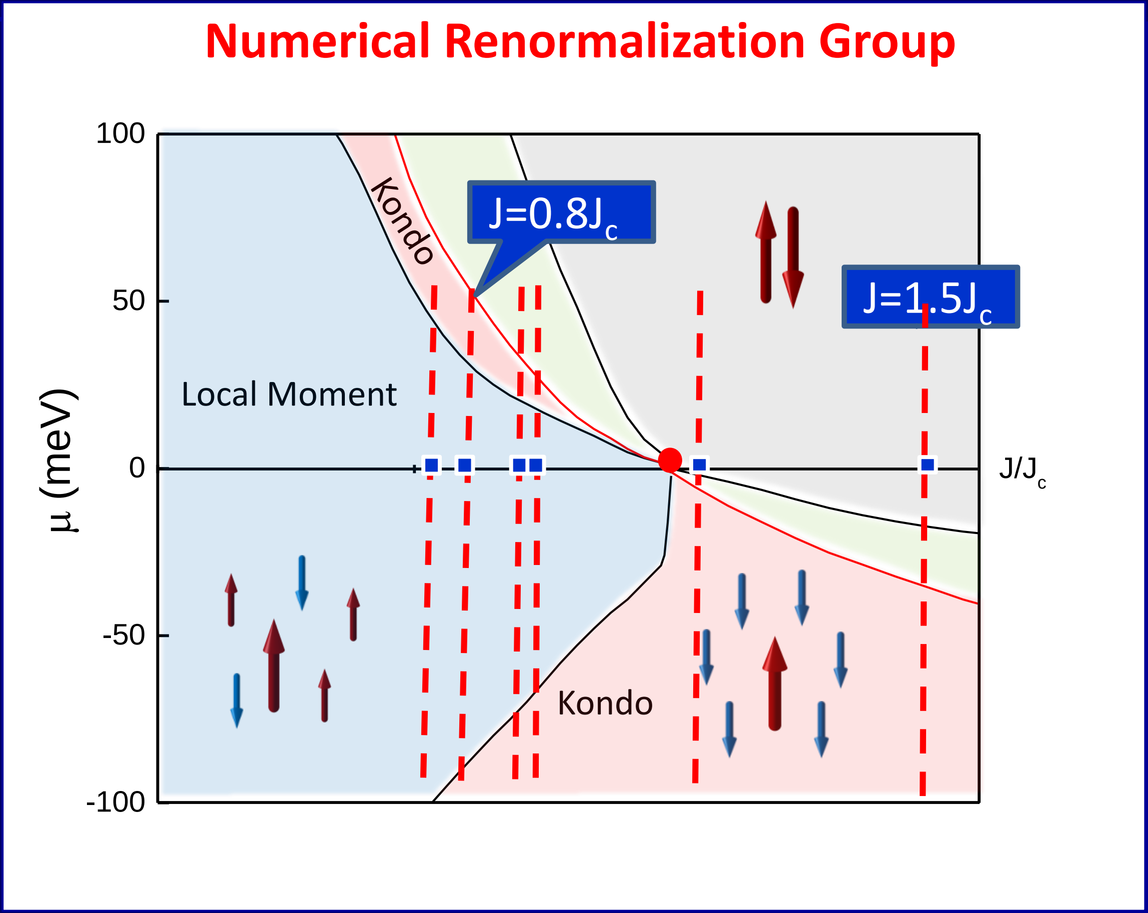
$J<J_c$



Electrically tunable magnetic moment

E.Y. Andrei

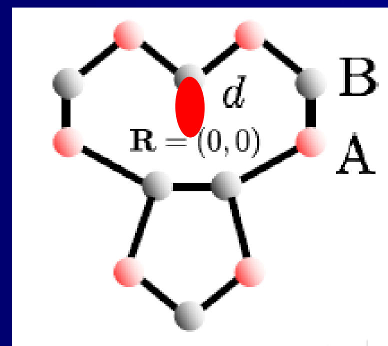
Kondo Screening Phase Diagram

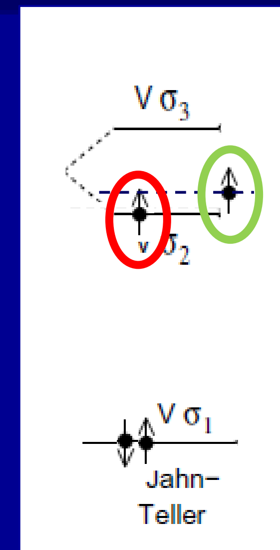


P.W Lo, GY Guo, F. Anders

What is the value of J?

- σ Dangling bond $\mapsto$ localized state $\mapsto$ $1\mu_B$
- p_z $\mapsto$ quasi-localized state on other sublattice $\mapsto$ ~0.5-$0.7\mu_B$





➢ σ state (in plane) – orthogonal to π conduction electrons $\mapsto$J=0

➢ p_z state – Ferromagnetic coupling $\mapsto$ J=0

J=0 $\mapsto$ NO KONDO SCREENING

Hentschel, M. & Guinea, F*Phys Rev B* **76**, 115407 (200)7
Haase, P., Fuchs, S., Pruschke, T., Ochoa, H. & Guinea, F (2011)
Cazalilla, M. A. I., A.; Guinea, F.; Castro Neto, A. H (2012)

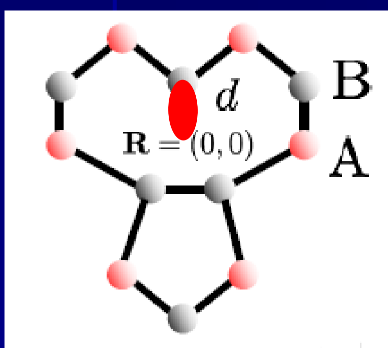
What determines J

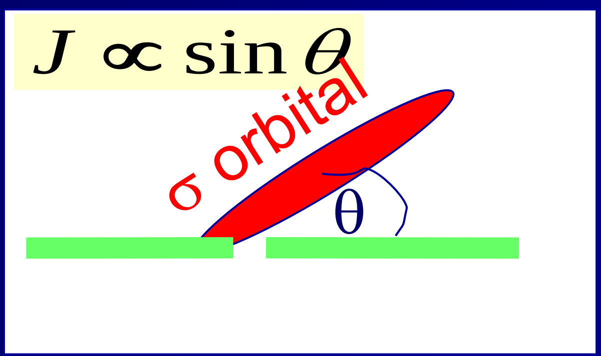
Local Moment Formation and Kondo Effect in Defective Graphene

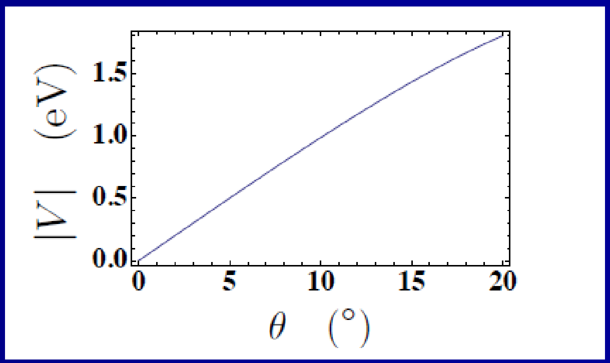
M. A. Cazalilla,[1,2] A. Iucci,[3] F. Guinea,[4] and A. H. Castro Neto[2]

- Out of plane distortion of dangling bond

$\mapsto$ Finite AF coupling with conduction electrons $\mapsto$ Kondo screening







Need Corrugated Substrate

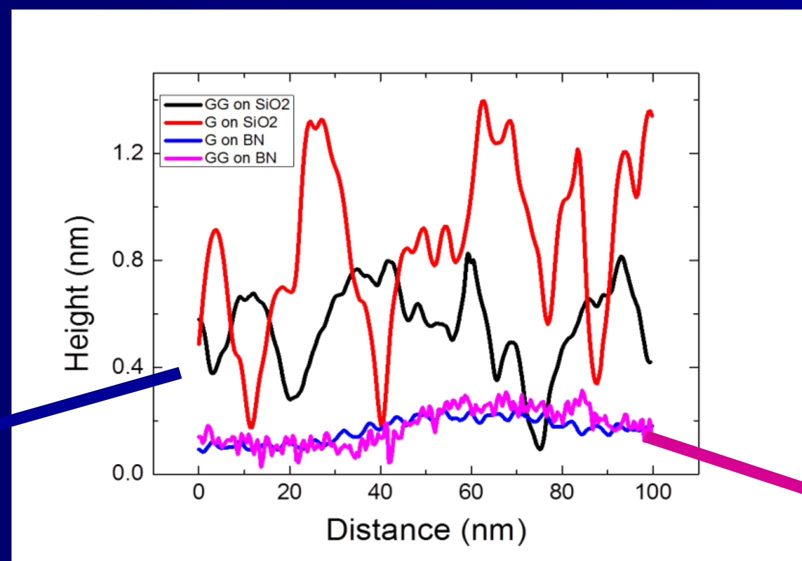
J strongly depends on Local curvature

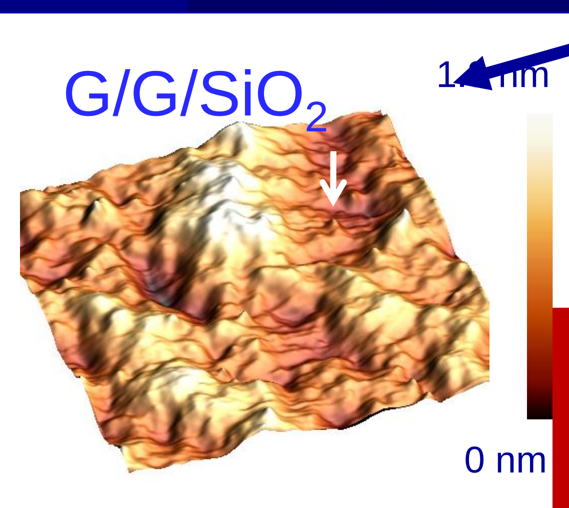
$\mapsto$ not all moments screened

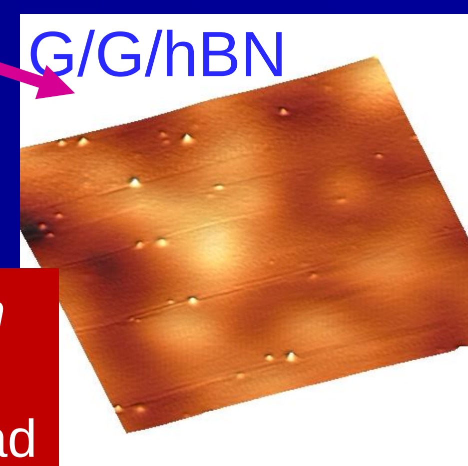
$\mapsto$ Need local measurement to observe Kondo screening

Substrate corrugation and Kondo screening

G/SiO_2	$G/G/SiO_2$	G/hBN	G/G/hBN







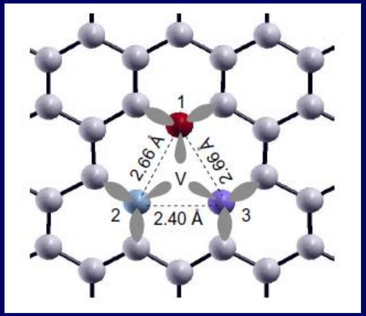
J depends on Local corrugation

↦ not all moments screened

↦ Global measurements can mislead

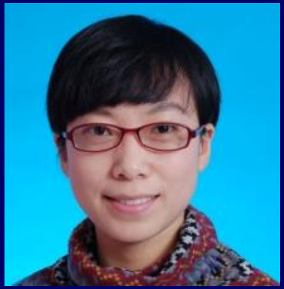
Summary

- Vacancy moment and Kondo screening
  - Screening depends on local corrugation $\mapsto$ not all moments screened
    - Magnetization: only sensitive to unscreened moments
    - Transport and STM: only sensitive to screened moments
  - Global measurements of randomly distributed moments are misleading!
  - Electrostatic control of vacancy moment

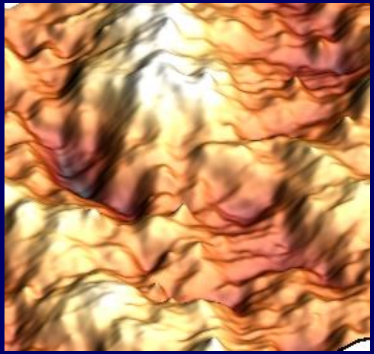


Guohong Li

Jinhai Mao



Yuhang Jiang



Theory: (Kondo)
- D. May, F. Anders
- GY Guo, P.W Lo

Substrates: (hBN)
- T. Taniguchi
- K. Watanabe

J. Mao et al arXiv:1711.06942
Quantum Critical Transition and Kondo Screening of Magnetic Moments in Graphene

E.Y. Andrei