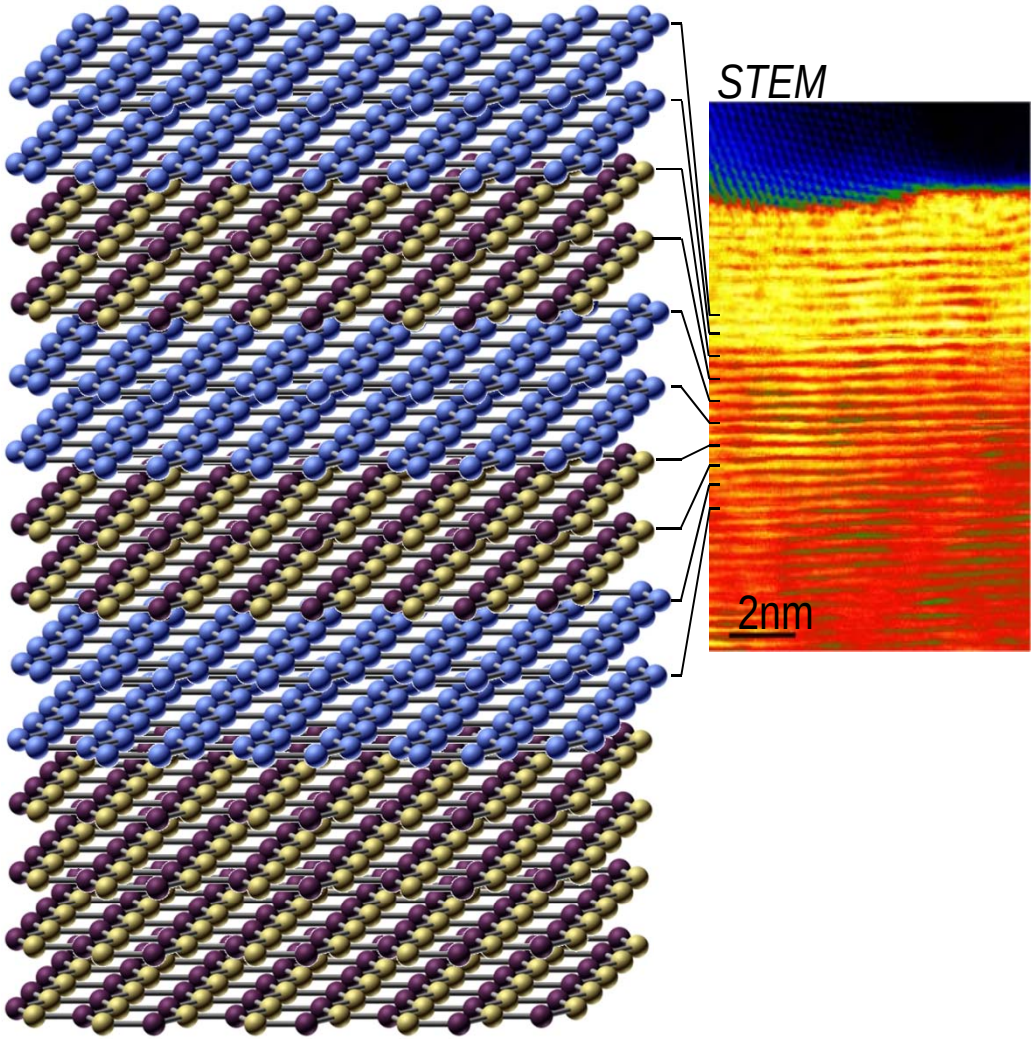
Ballistic G/hBN heterostructures: focusing and caustics in graphene devices

Vladimir Falko

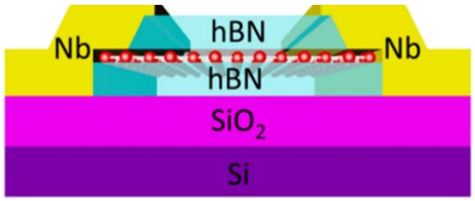
National Graphene Institute

Ballistic G/hBN heterostructures: focusing and caustics in graphene devices

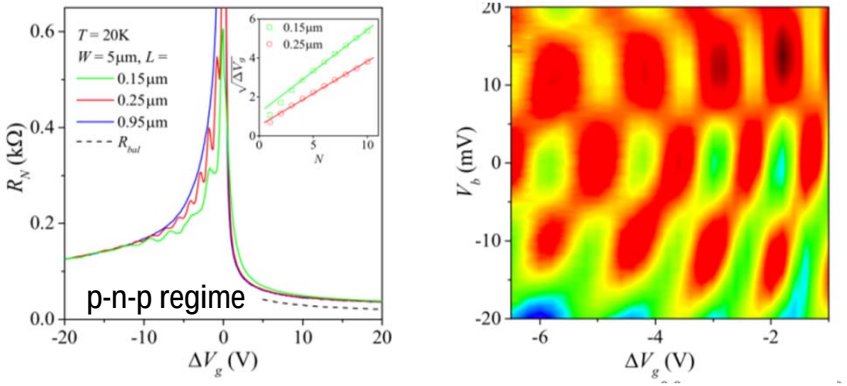


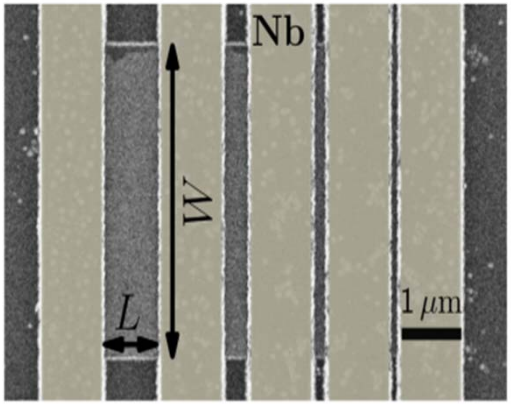
- Ballistic effects in G/hBN
- Electron focusing at p-n junction in graphene
- Caustics of snake orbits near p-n junction in graphene in magnetic field
- Magnetic focusing and caustics of electrons in moiré minibands in G/hBN heterostructures

hBN-encapsulated graphene: sample-length ballistic transport

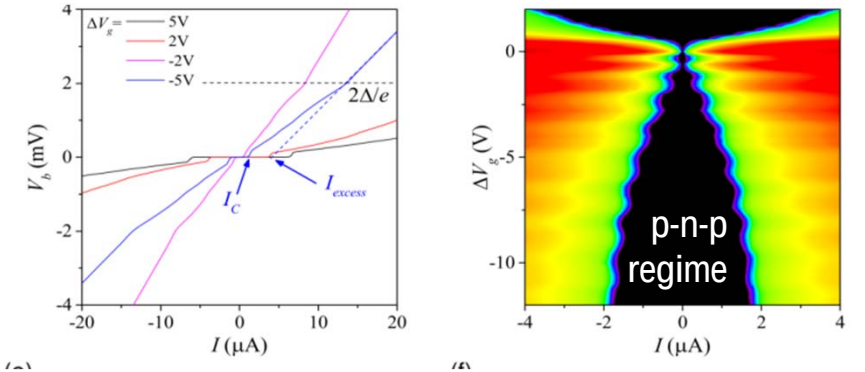


Ballistic graphene:
1μm mean free path
proven by Fabri-Perot
oscillations of *dI/dV*





Fabri-Perot oscillations
of critical supercurrent in
S-G-S devices

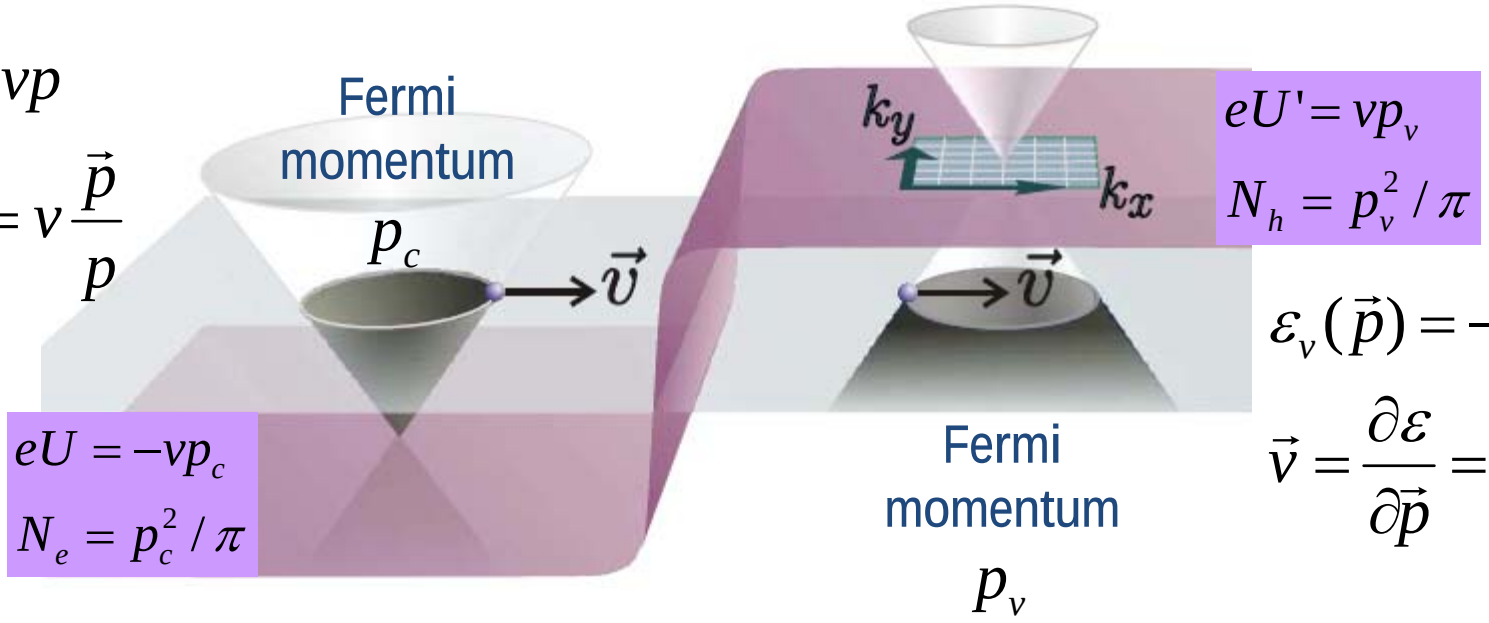


Ben-Shalom, Zhu, VF, Mishchenko, Kretinin, Novoselov, Woods, Watanabe, Taniguchi, Geim, Prance - arXiv:1504.03286

Negative refraction of electrons at p-n interface

$$\varepsilon_c(\vec{p}) = vp$$

$$\vec{v} = \frac{\partial \varepsilon}{\partial \vec{p}} = v\frac{\vec{p}}{p}$$



$$\varepsilon_v(\vec{p}) = -vp$$

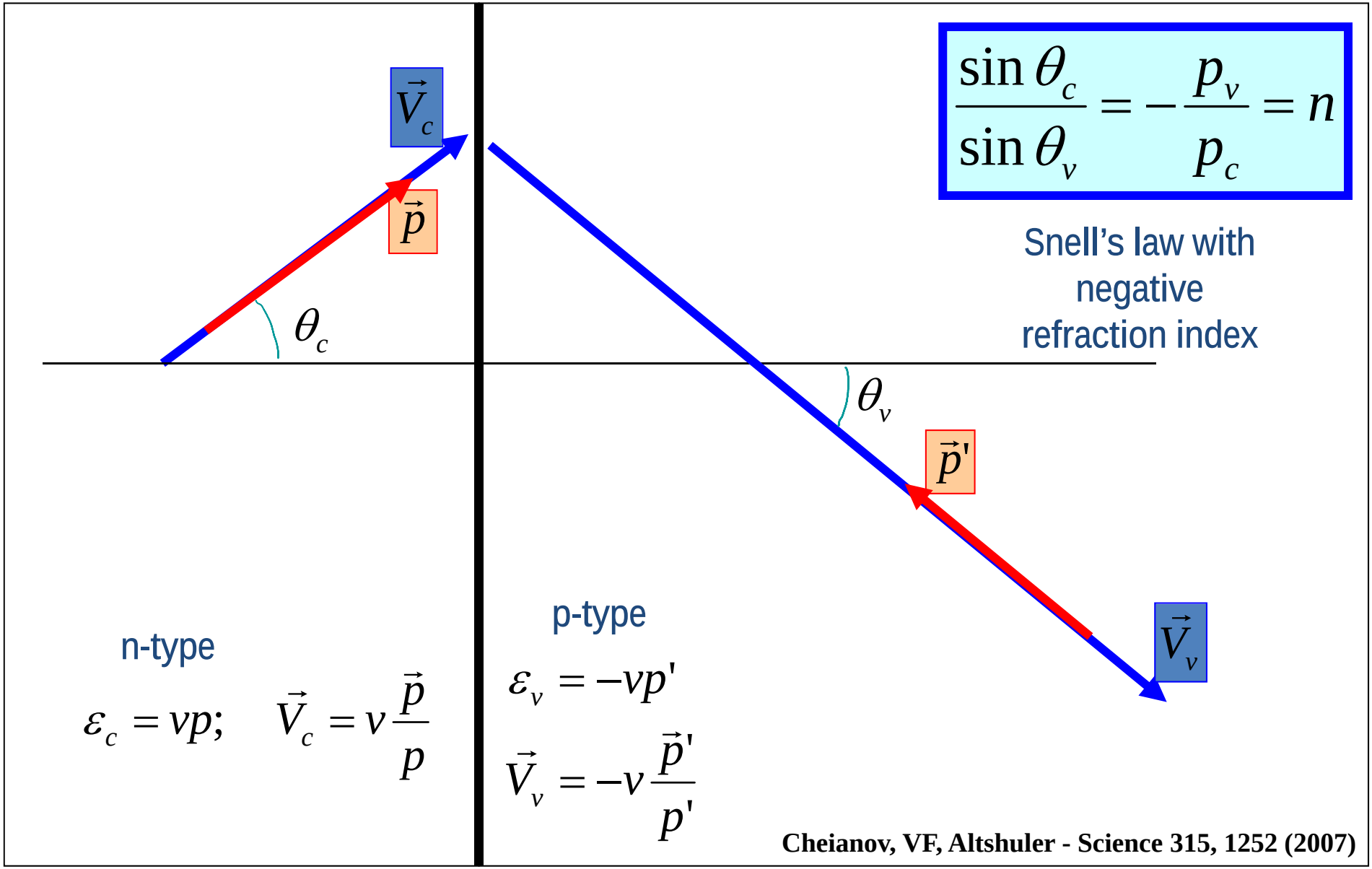
$$\vec{v} = \frac{\partial \varepsilon}{\partial \vec{p}} = -v\frac{\vec{p}}{p}$$

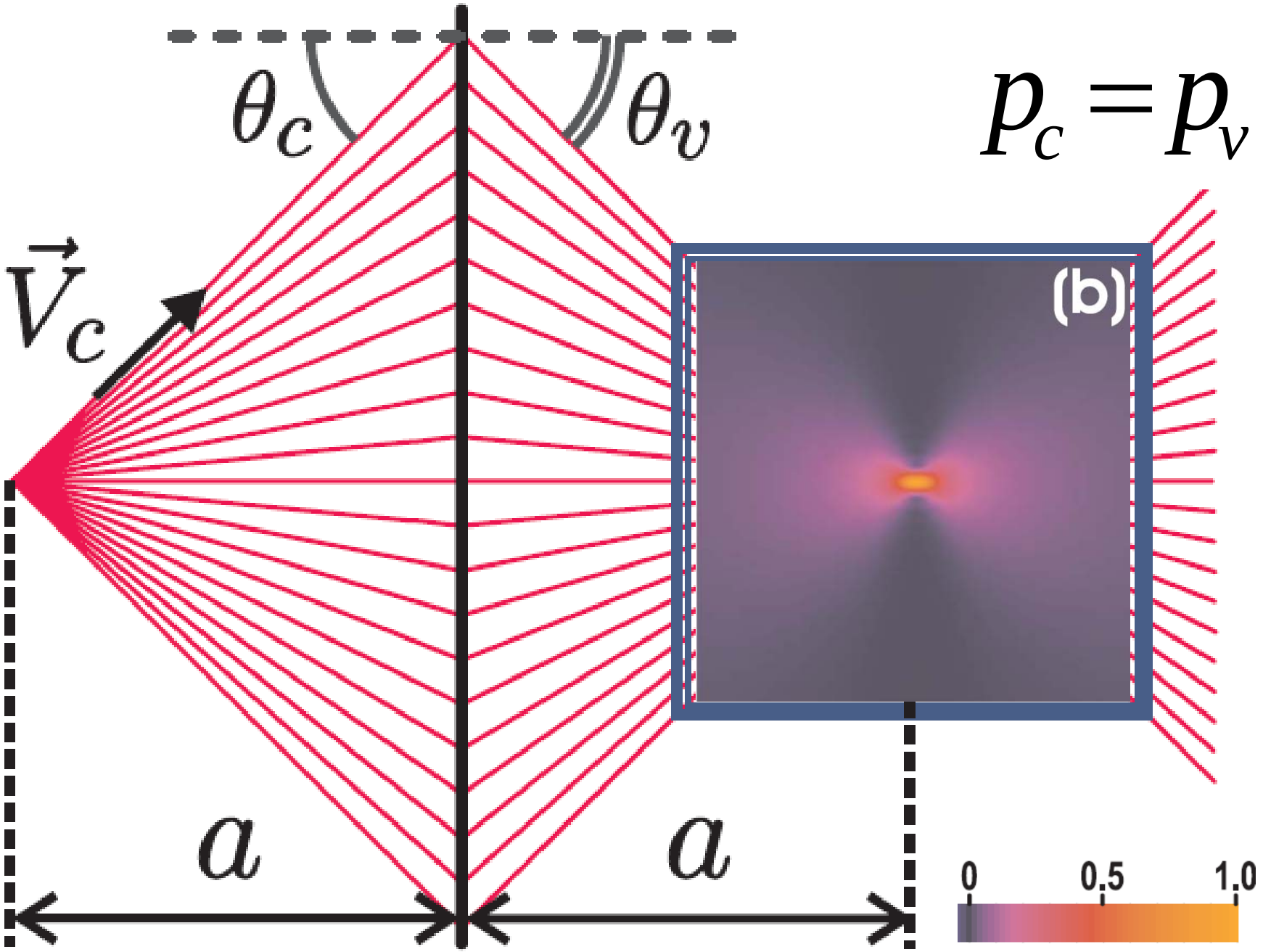
The effect would be the strongest in sharp PN junction, with $d \sim \lambda_F$, which is possible to achieve in hBN-encapsulated graphene.

Cheianov, VF, Altshuler - Science 315, 1252 (2007)

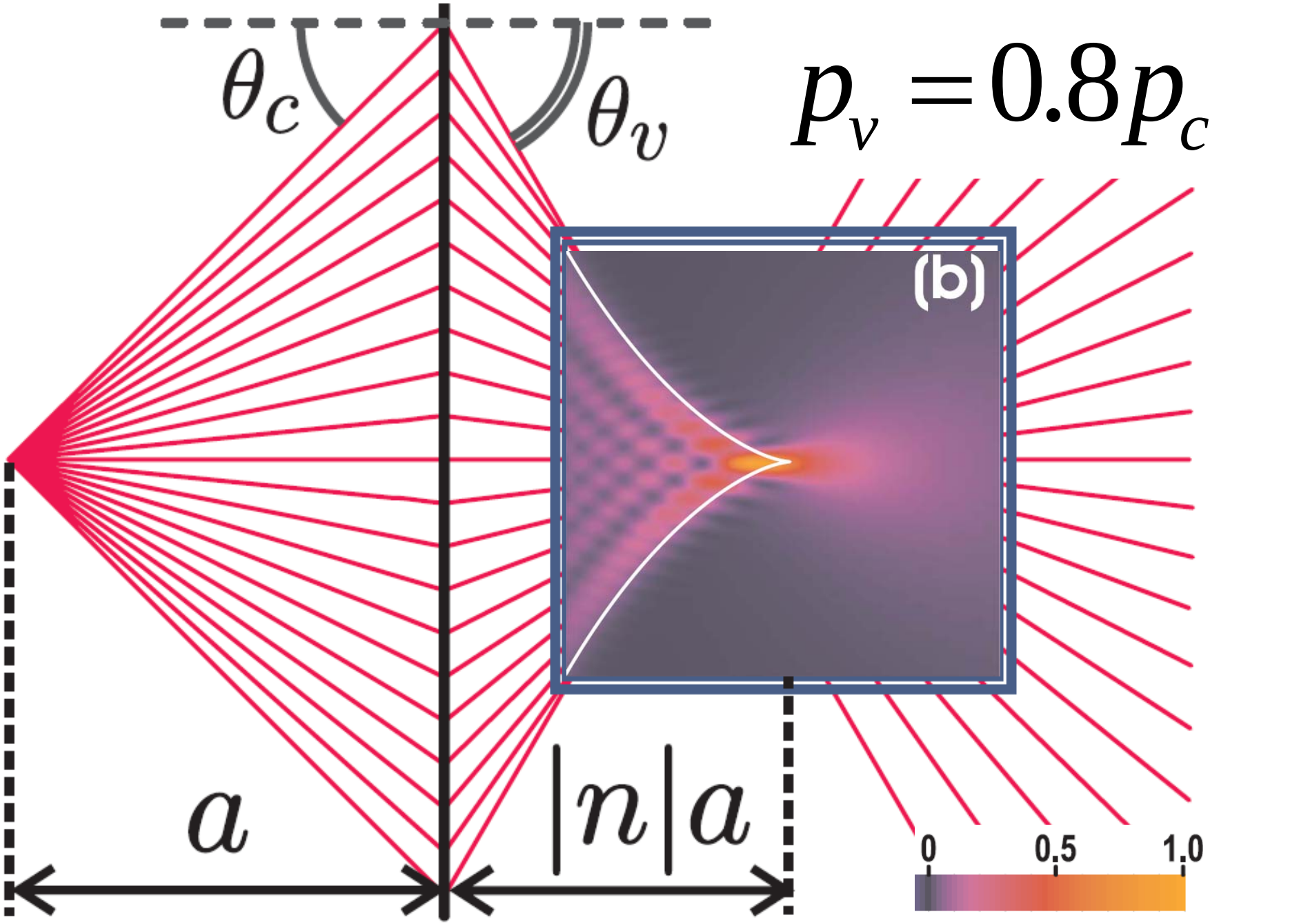
$$p_y = p_y' \;\Rightarrow\; p_c \sin\theta_c = -p_v \sin\theta_v$$

p-n junction



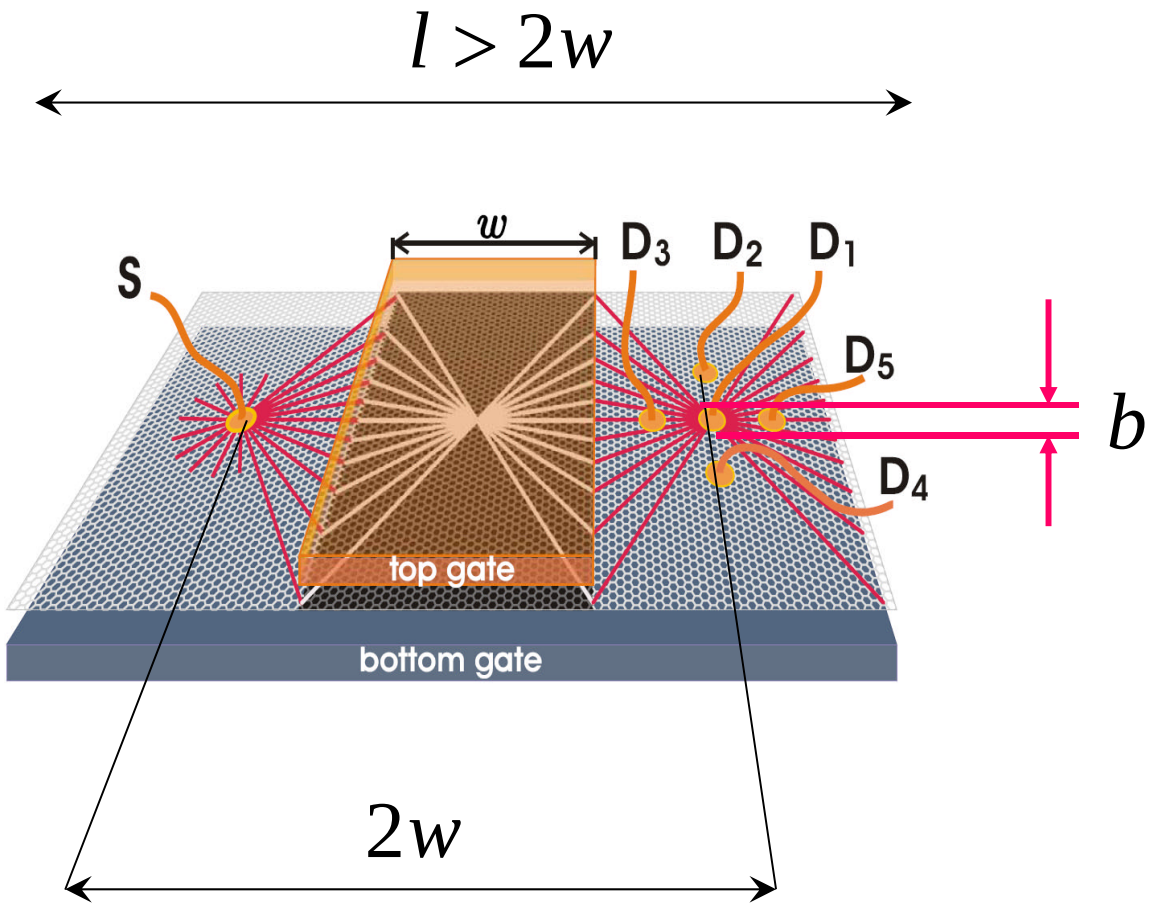


Cheianov, VF, Altshuler - Science 315, 1252 (2007)



Cheianov, VF, Altshuler - Science 315, 1252 (2007)

Veselago lens for electrons in ballistic graphene



$$kT < \frac{b}{w}\varepsilon_F$$

Cheianov, VF, Altshuler - Science 315, 1252 (2007)

Cheianov, Fal'ko, Altshuler - Science 315, 1252 (2007)

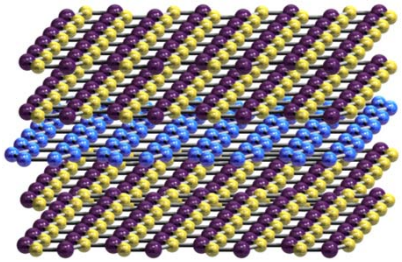
nature physics

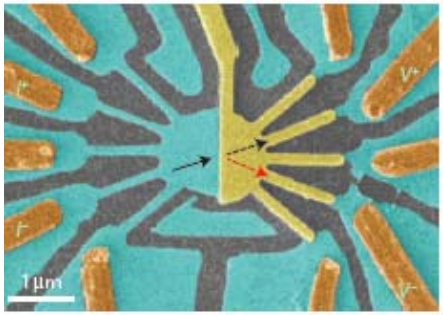
LETTERS

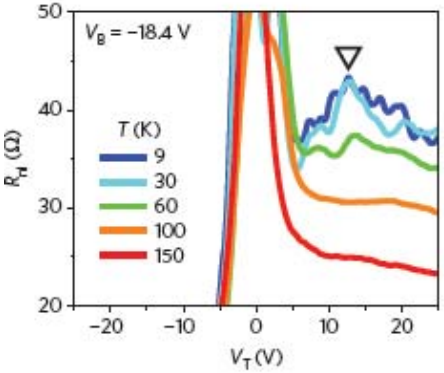
PUBLISHED ONLINE: 14 SEPTEMBER 2015 | DOI: 10.1038/NPHYS3460

Observation of negative refraction of Dirac fermions in graphene

Gil-Ho Lee†, Geon-Hyoung Park and Hu-Jong Lee*







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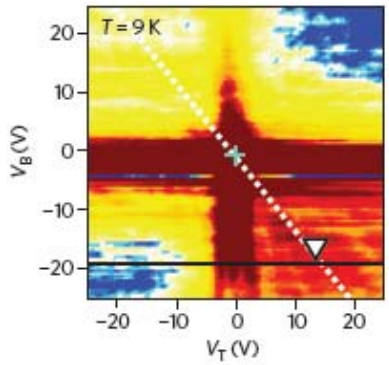

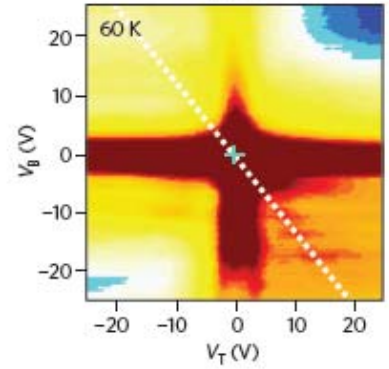

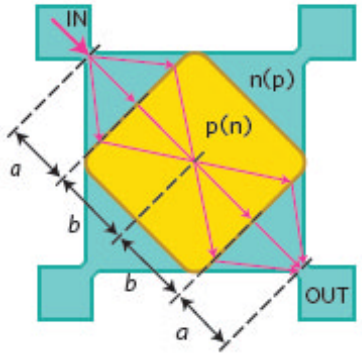

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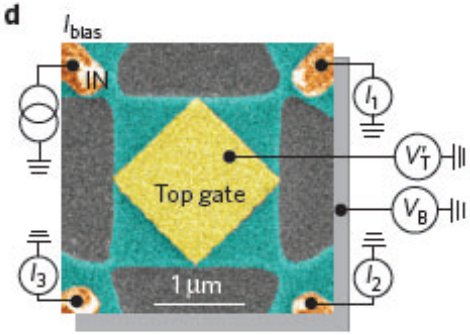
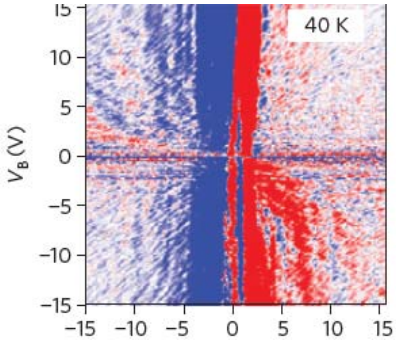
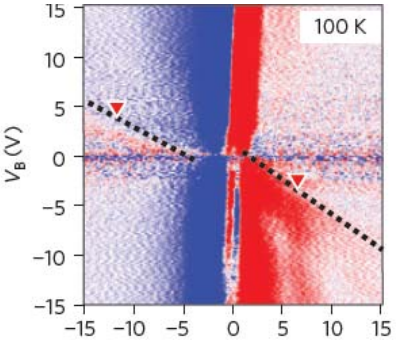
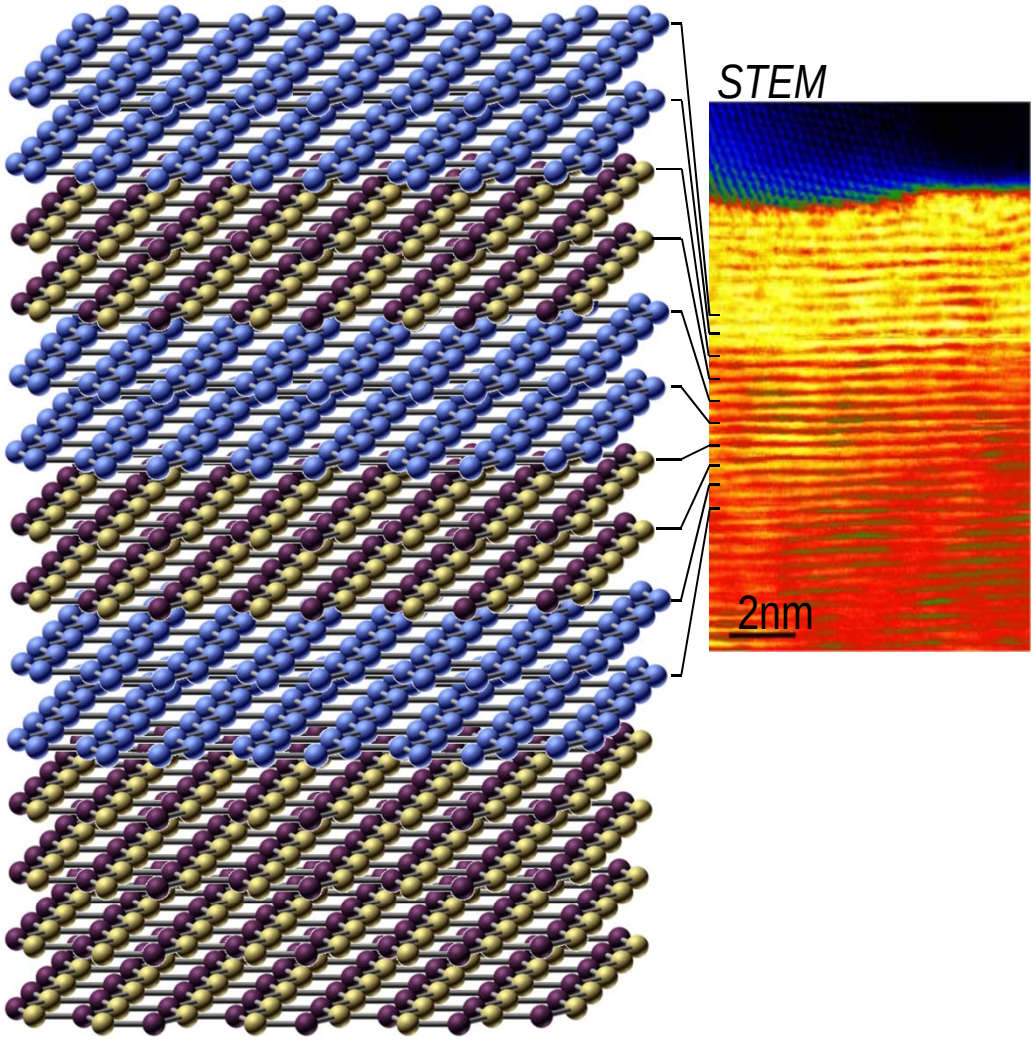






Ballistic G/hBN heterostructures: focusing and caustics in graphene devices



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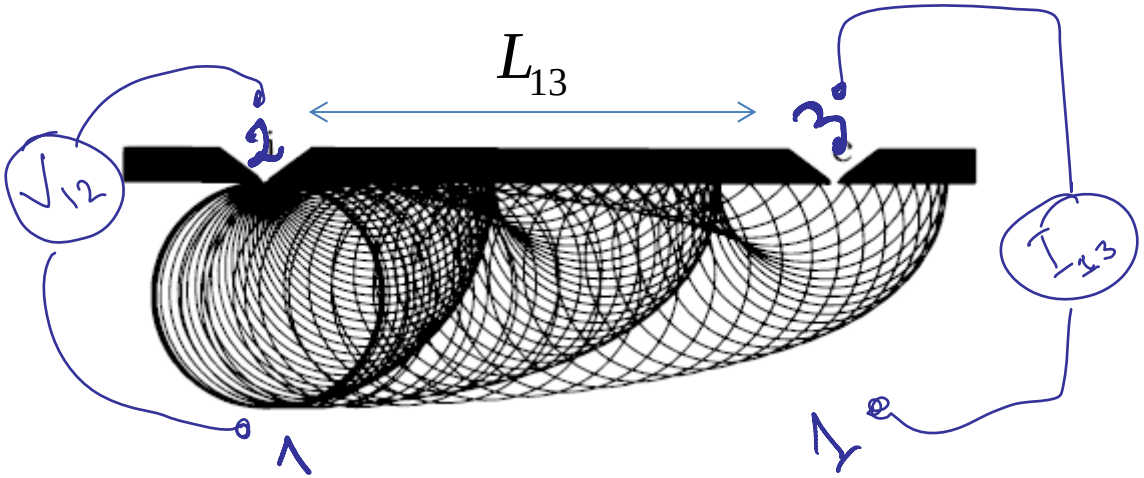
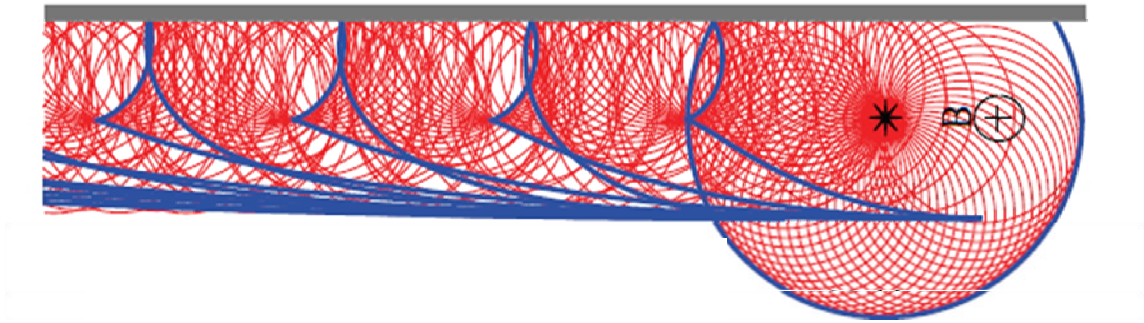
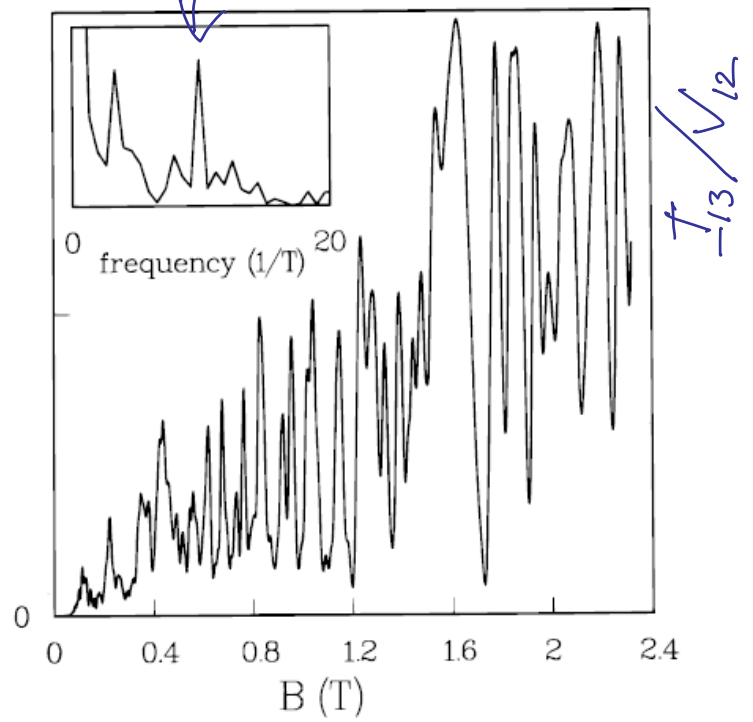
Caustics in the electron skipping motion



$$R_c = \frac{p_F}{eB}$$



corresponds to $NR_c \simeq L_{13}$



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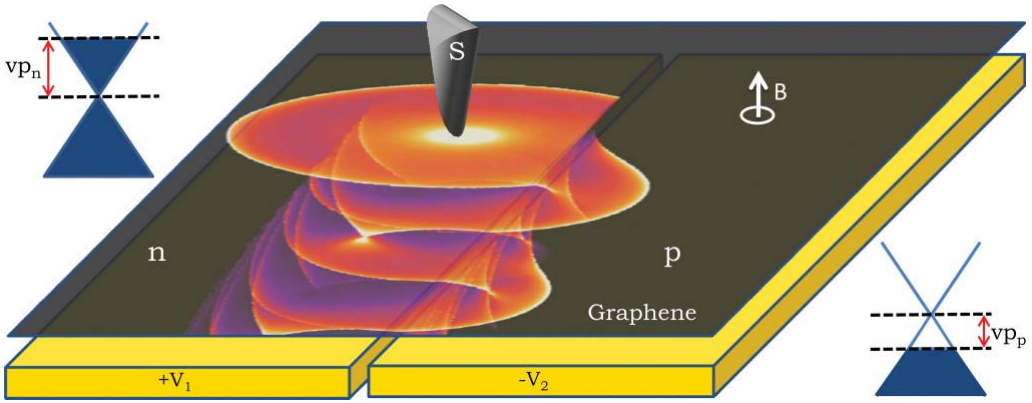
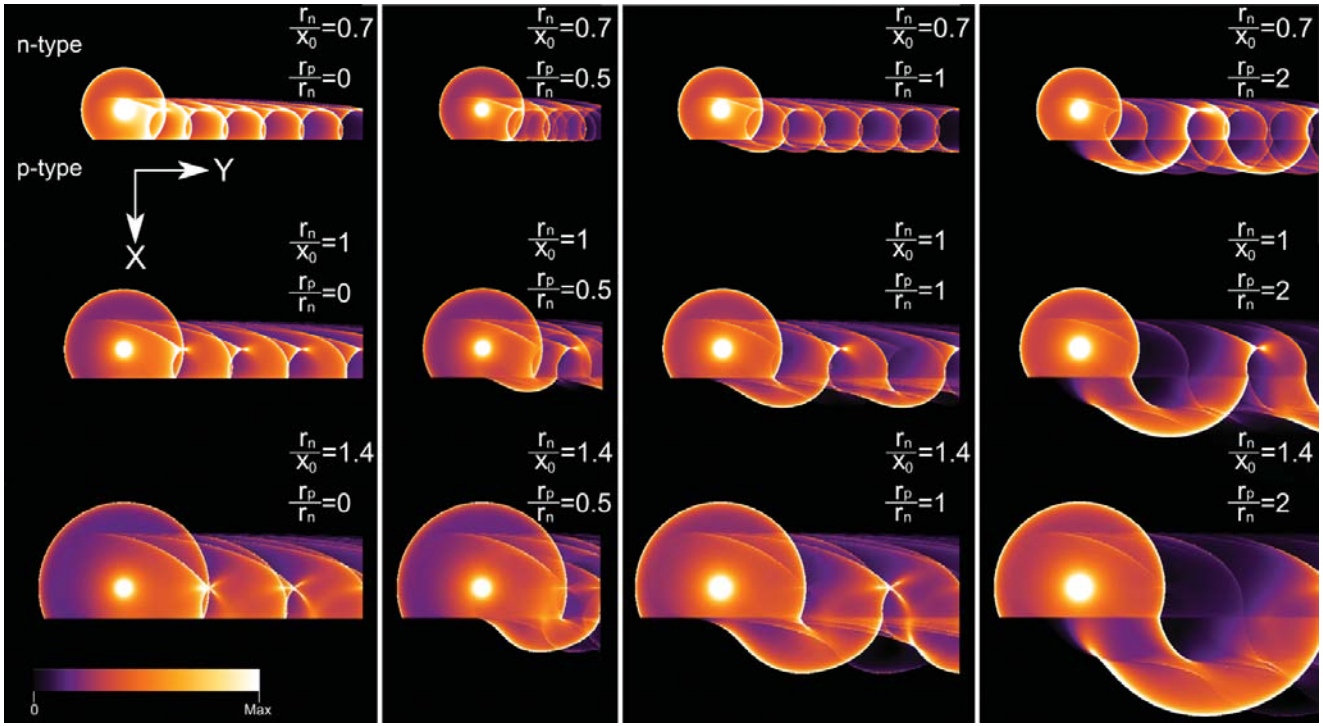
Davies, Patel, Cortijo, Cheianov, Guinea, VF - B 85, 155433 (2012)

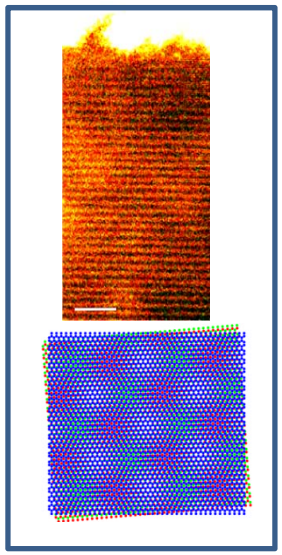
Caustics of electron snake orbits near p-n junction



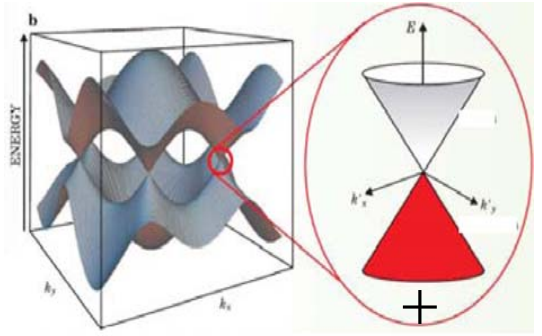
$$\rho = \int \delta(\mathbf{r} - \mathbf{r}_n) d\varphi d\theta$$



Patel, Davies, Cheianov, VF
Phys Rev B 86, 081413 (2012)



Phenomenological low-energy 'Dirac theory' for electrons in G/hBN moiré superlattices



Wallbank, Patel, Mucha-Kruczynski, Geim, VF - PRB 87, 245408 (2013)

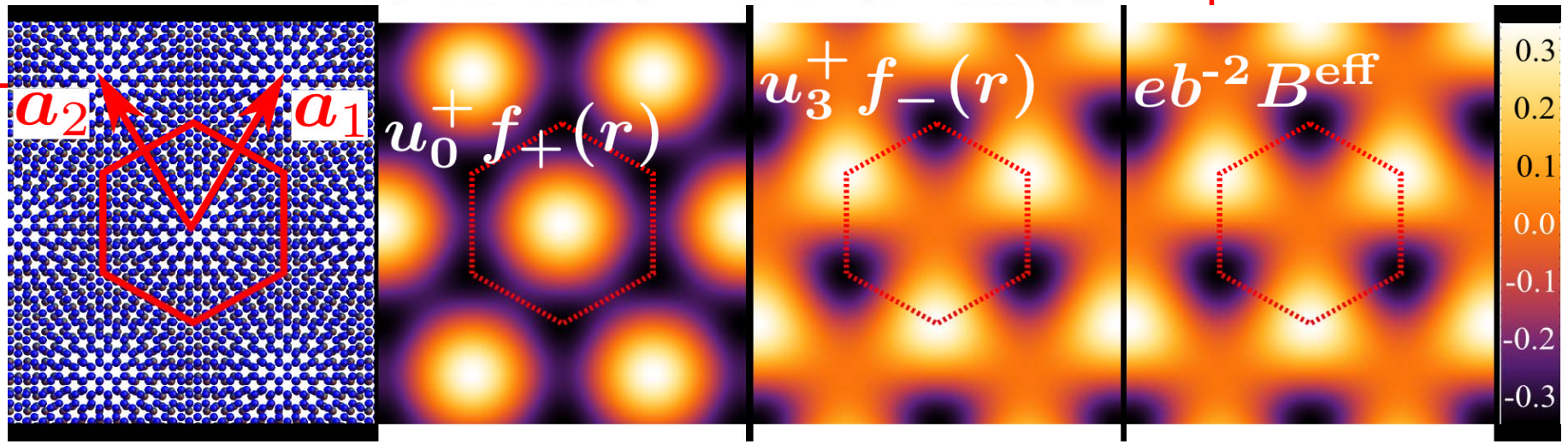
δH_{moire}

graphene sublattice

graphene valley

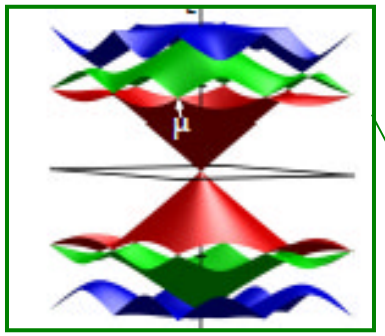
$$\hat{H} = vp \cdot \boldsymbol{\sigma} + u_0 vb f_1(r) + u_3 vb f_2(r) \sigma_3 \tau_3 + u_1 v \left[l_z \times \nabla f_2(r) \right] \cdot \boldsymbol{\sigma} \tau_3$$

inversion symmetric

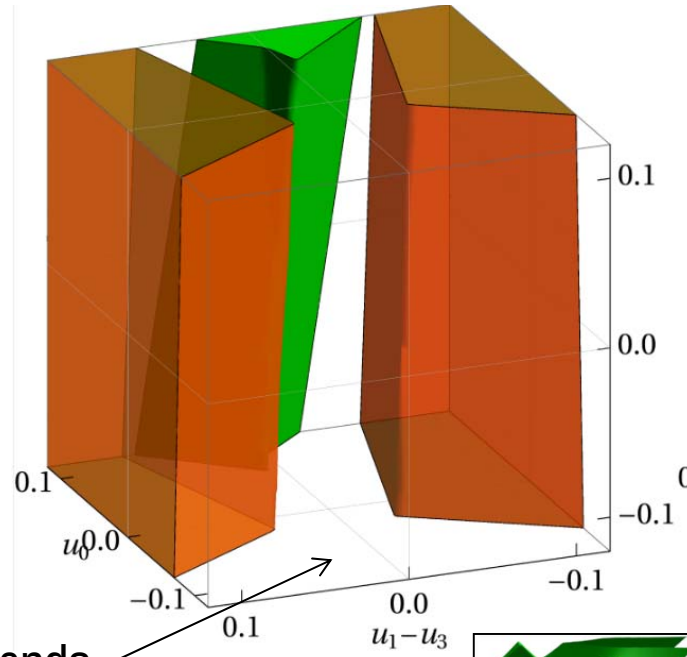


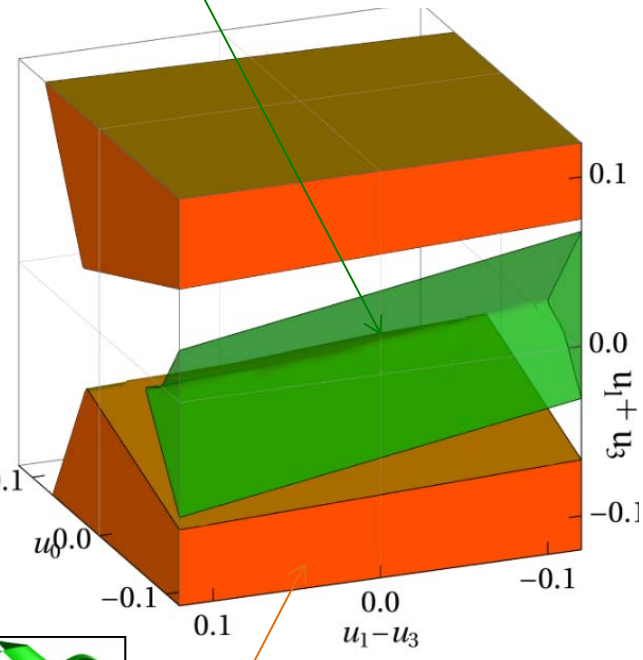
characteristic moiré miniband regimes

Three mini-DPs at the edge of 1st miniband



conduction band

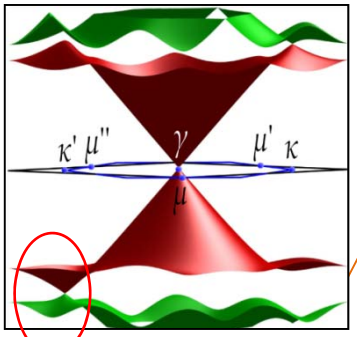




valence band

Overlapping bands hiding mini-DPs of moire minibands

vb

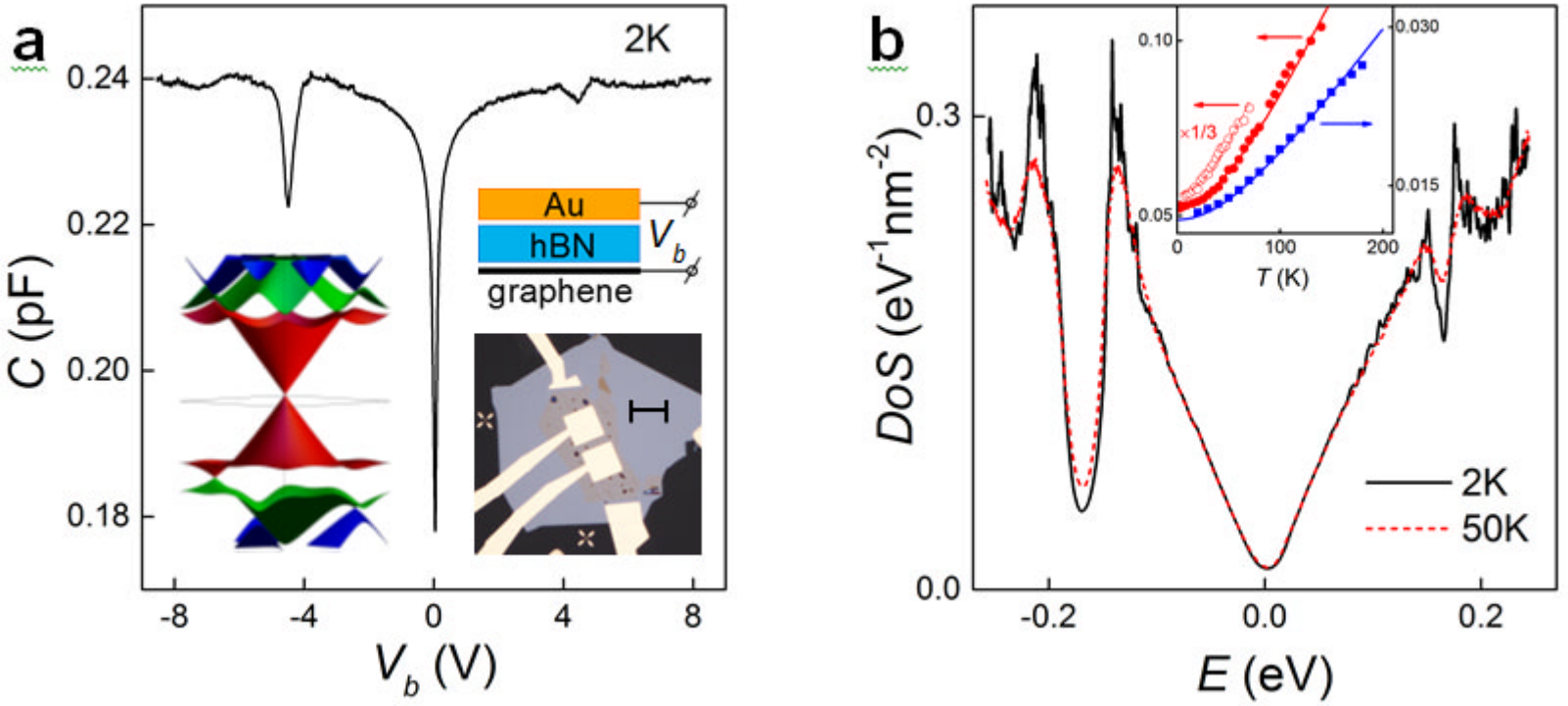


single mini-DP at the edge of 1st miniband

$$\nu_{mDP} \approx \frac{1}{2}\nu$$

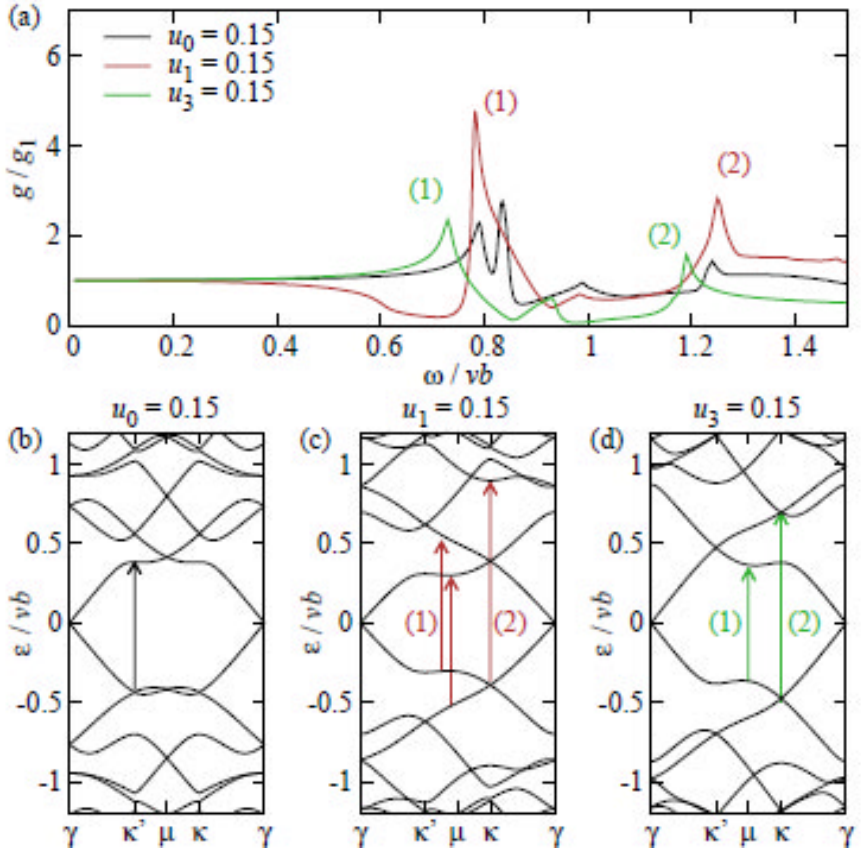
Wallbank, Patel, Mucha-Kruczynski, Geim, VF - PRB 87, 245408 (2013)

Capacitance spectroscopy of moiré minibands in G-hBN heterostructures

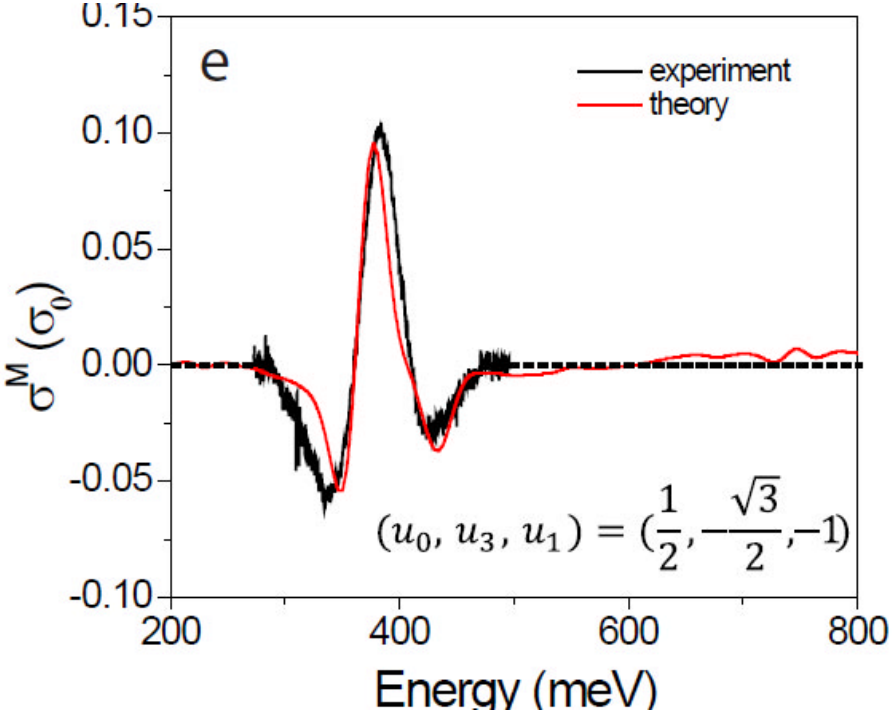


Yu, Gorbachev, Tu, Kretinin, Cao, Jalil, Withers, Ponomarenko, Chen, Piot, Potemski, Elias, Watanabe, Taniguchi, Grigorieva, Novoselov, VF, Geim, Mishchenko - Nature Physics 10, 525 (2014)

Optical signature of moiré minibands

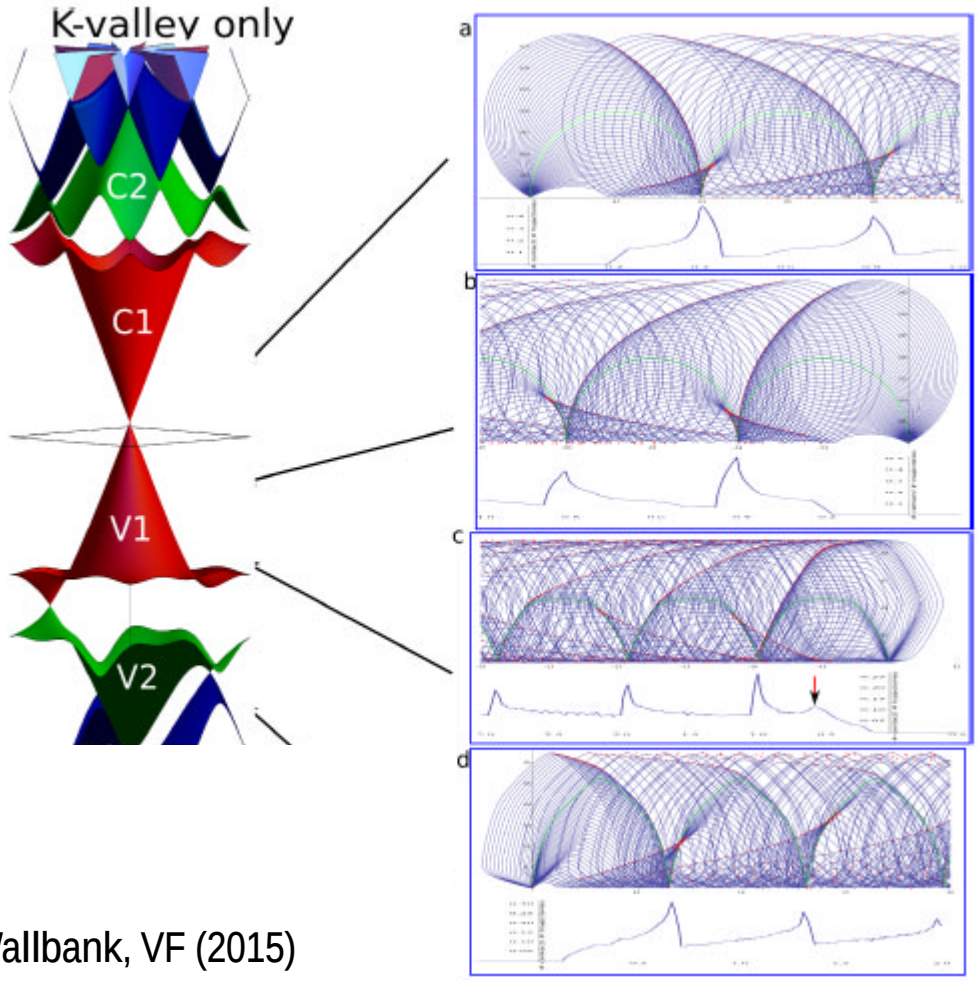


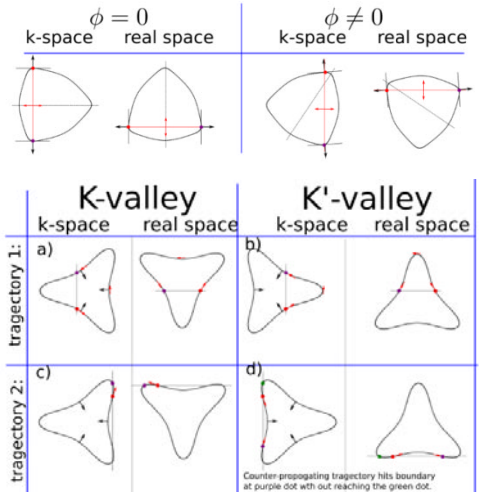
Abergel, Wallbank, Chen, Mucha-Kruczynski, VF
New J Phys 15, 123009 (2013)



Shi, Jin, Yang, Ju, Horng, Lu, Bechtel, Martin, Fu, Wu,
Watanabe, Taniguchi, Zhang, Bai, Wang, Zhang, Wang
arXiv:1405.2032

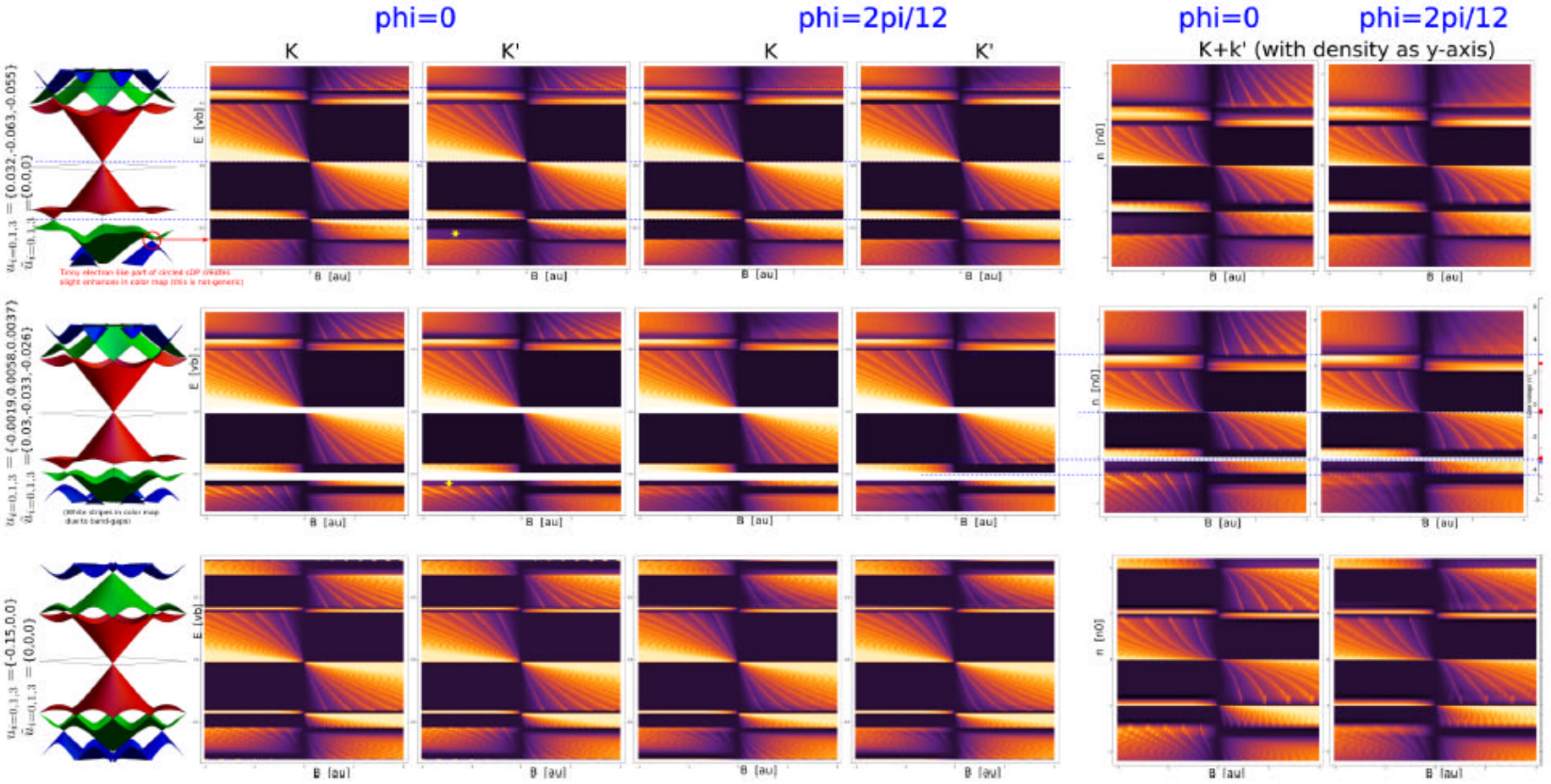
Focusing of electrons in moiré minibands in G-hBN heterostructures





Wallbank, VF (2015)

Focusing of electrons in moiré minibands in G-hBN heterostructures



Wallbank, VF (2015)

Ballistic G/hBN heterostructures: focusing and caustics in graphene devices

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- ✓ Magnetic focusing and caustics of electrons in moiré minibands in G/hBN heterostructures

in collaboration with

John Wallbank (NGI Manchester)

Aavishkar Patel (Harvard), Nathan Davis (BAE), Paco Guinea (Madrid)

Boris Altshuler (Columbia NY), Vadim Cheianov (Lorentz Inst Leiden)

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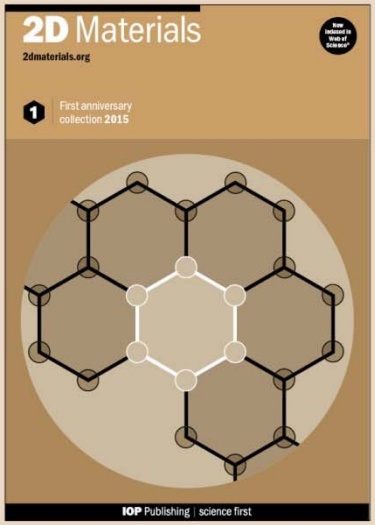

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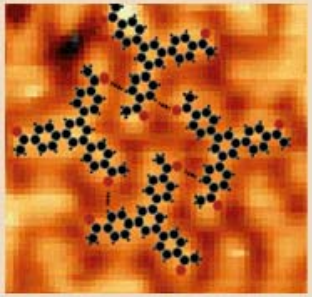

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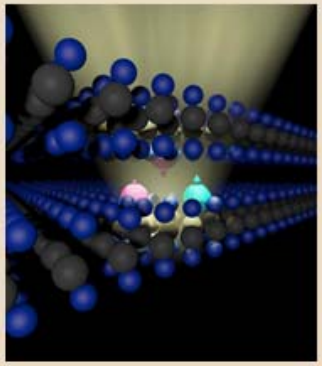

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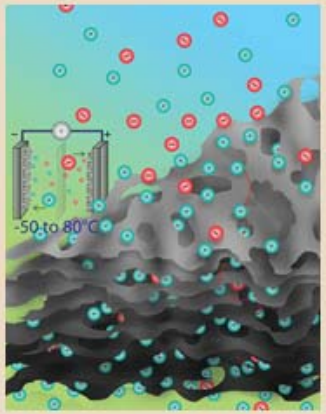

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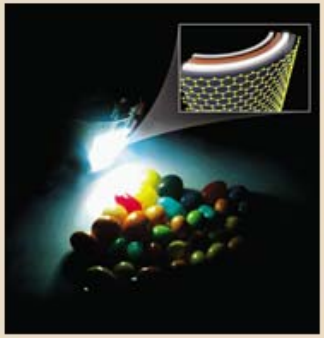

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