Veselago lensing in Dirac materials

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LOMA, Université de Bordeaux

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Outline

I will talk about **Veselago lenses** (or **negative refraction**) for :

1) **The electromagnetic field** (photons)

↓

2) **Electrons** in graphene pn junctions

3) **Electrons and holes** at graphene/superconductor interfaces

4) **Chiral electrons** in 3D Weyl semimetals

I) Veselago lensing with photons

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 4 JANUARY-FEBRUARY 1968

538.30

THE ELECTRODYNAMICS OF SUBSTANCES WITH SIMULTANEOUSLY NEGATIVE VALUES OF ϵ AND μ

V. G. VESELAGO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Usp. Fiz. Nauk 92, 517–526 (July, 1964)

Electromagnetic waves in matter

Dispersion of an electromagnetic wave:

$$\mathbf{k}^2 = \frac{\omega^2}{c^2}\,\epsilon_r \mu_r$$

Optical index $$n^2 = \epsilon_r \mu_r$$

Veselago (1968) considered an hypothetical material where both dielectric constant and magnetic permeability are negative (in some frequency window)

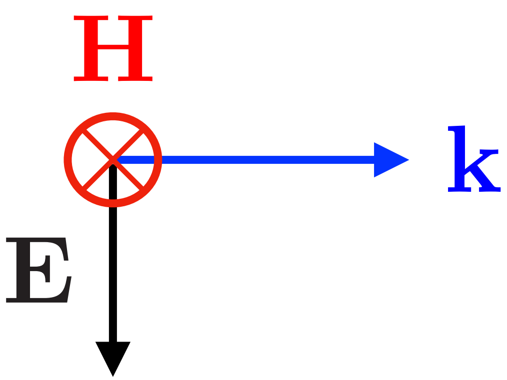
Veselago electrodynamics

$$\mathbf{k} \wedge \mathbf{E} = \omega\, \mu_0 \mu_r\, \mathbf{H}$$

$$\mathbf{k} \wedge \mathbf{H} = -\omega\, \epsilon_0 \epsilon_r\, \mathbf{E}$$

Standard situation :

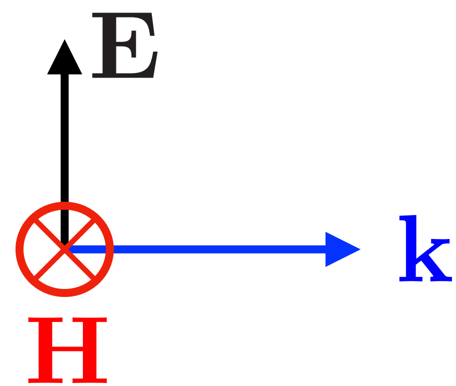
$\epsilon_r > 0 \quad \mu_r > 0$



(k,E,H) direct

Veselago situation :

$\epsilon_r < 0 \qquad \mu_r < 0$



(k,E,H) indirect

Veselago electrodynamics

$$\mathbf{k} \wedge \mathbf{E} = \omega\, \mu_0 \mu_r\, \mathbf{H}$$

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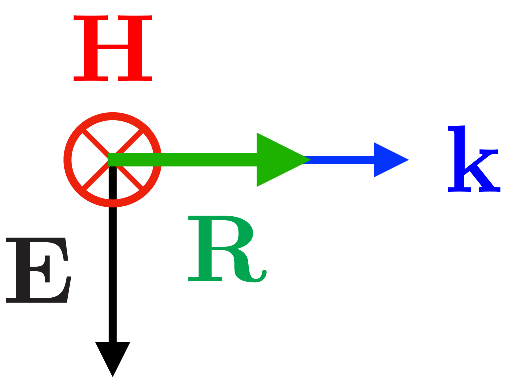
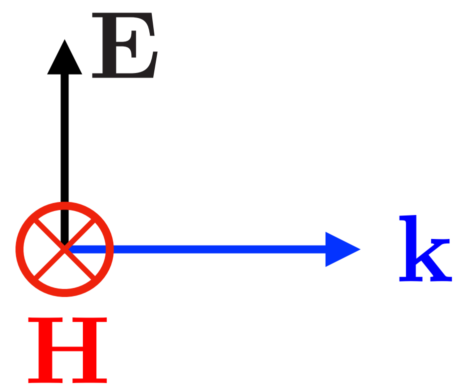


$$\mathbf{R} = \mathbf{E} \wedge \mathbf{H}$$

Veselago situation :

$\epsilon_r < 0 \qquad \mu_r < 0$



Poynting vector oriented as : $\mathbf{k}$

Veselago electrodynamics

$$\mathbf{k} \wedge \mathbf{E} = \omega\, \mu_0 \mu_r\, \mathbf{H}$$

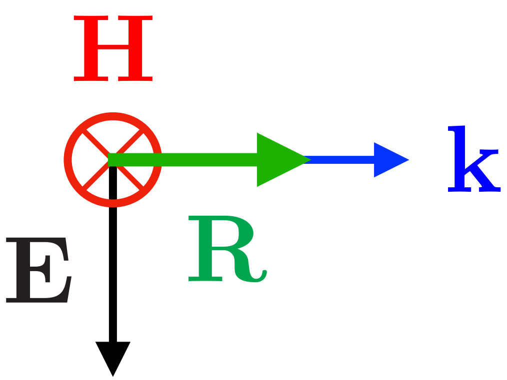
$$\mathbf{k} \wedge \mathbf{H} = -\omega\, \epsilon_0 \epsilon_r\, \mathbf{E}$$

Standard situation :

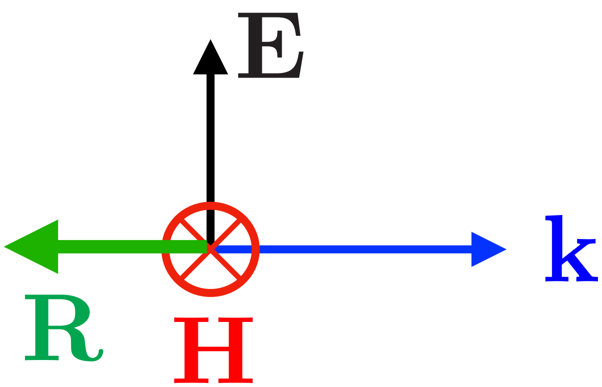
$\epsilon_r > 0 \quad \mu_r > 0$

Veselago situation :

$\epsilon_r < 0 \qquad \mu_r < 0$



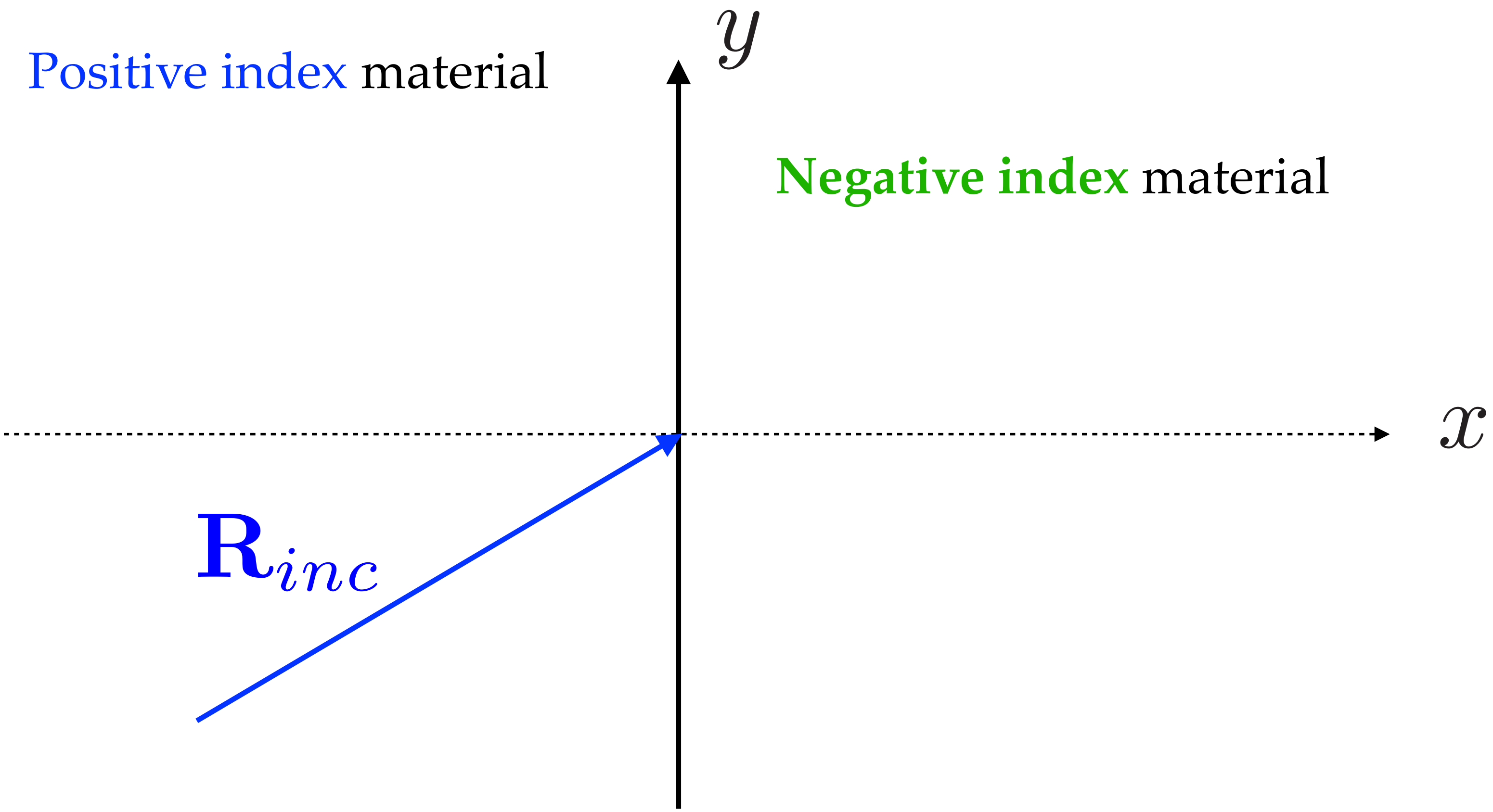
$$\mathbf{R} = \mathbf{E} \wedge \mathbf{H}$$



Poynting vector oriented as : $\mathbf{k}$

Poynting vector oriented as : $-\mathbf{k}$

Negative refraction of rays



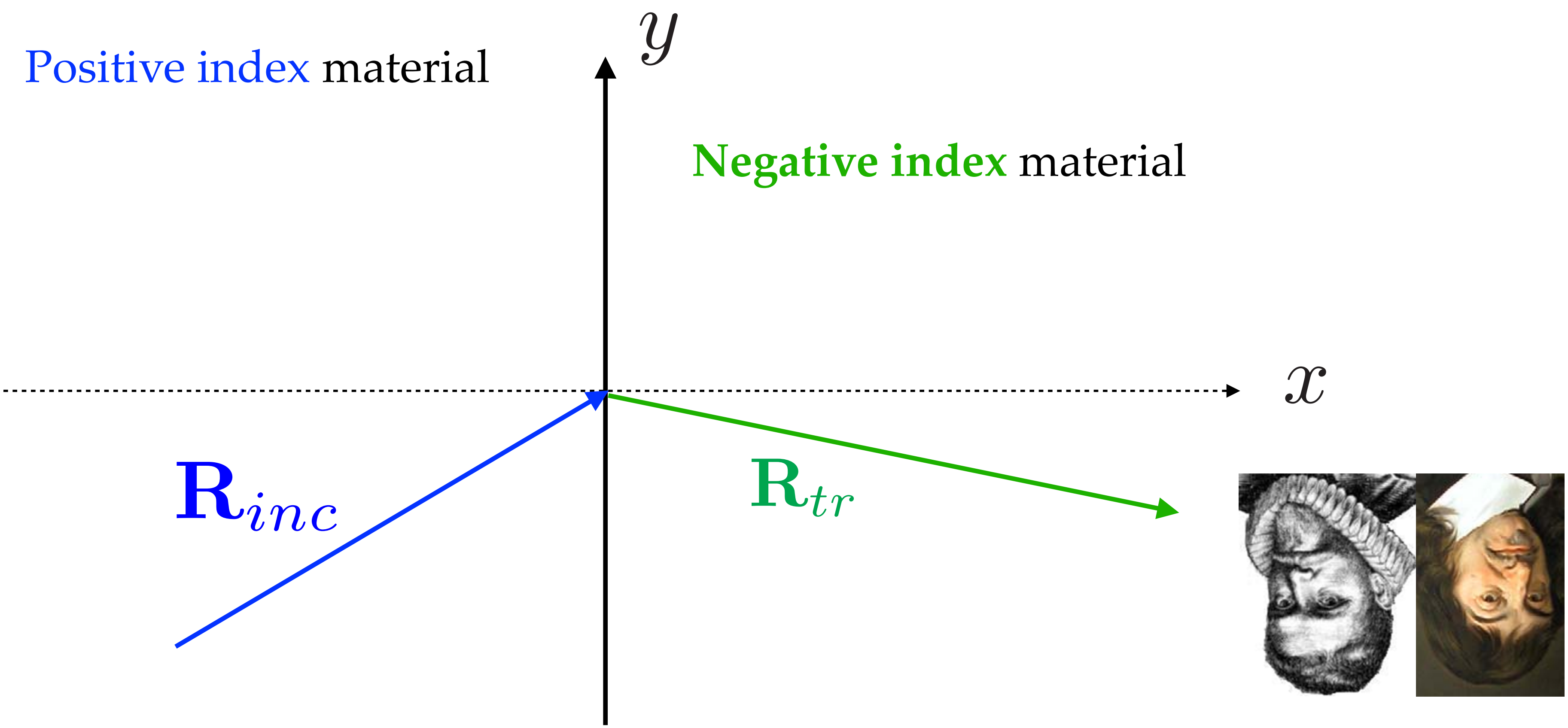
Conservation of interfacial wave vector

$$\mathbf{e}_y \cdot \mathbf{k}_{inc} = \mathbf{e}_y \cdot \mathbf{k}_{tr} > 0$$

Outgoing-wave

$$\mathbf{e}_x \cdot \mathbf{R}_{tr} > 0$$

Negative refraction of rays



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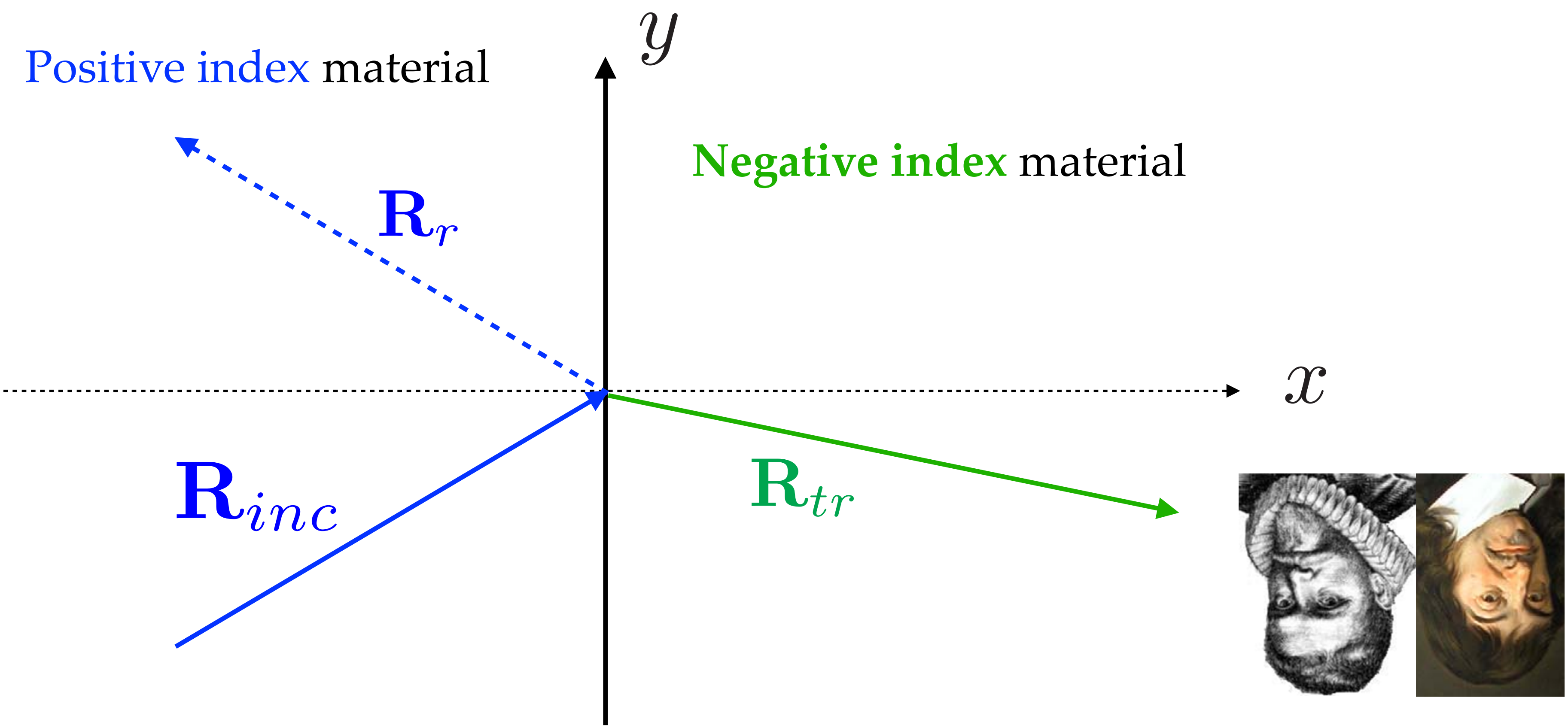

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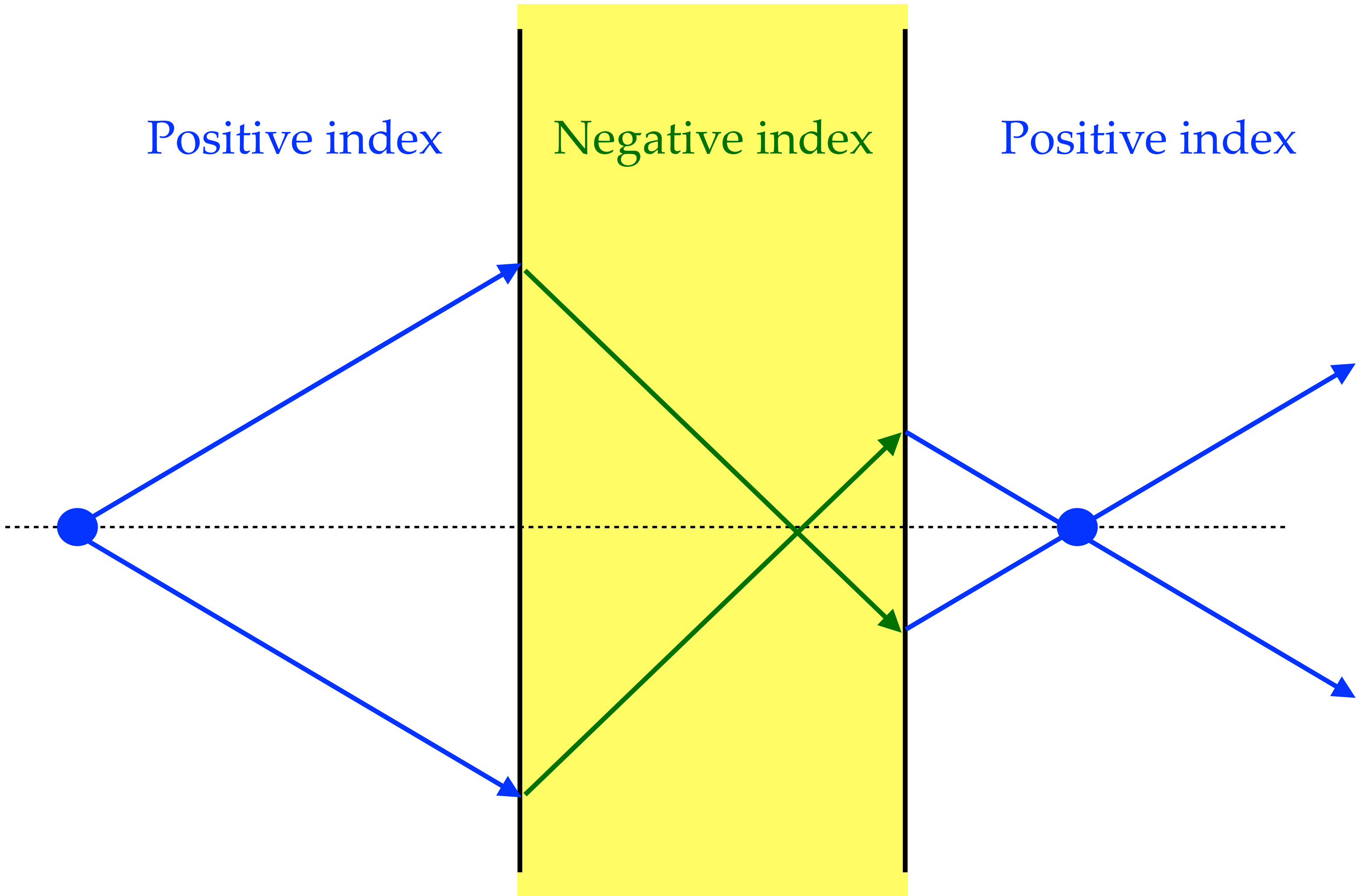
Outgoing-wave

$$\mathbf{e}_x \cdot \mathbf{R}_{tr} > 0$$

Flat lens focusing

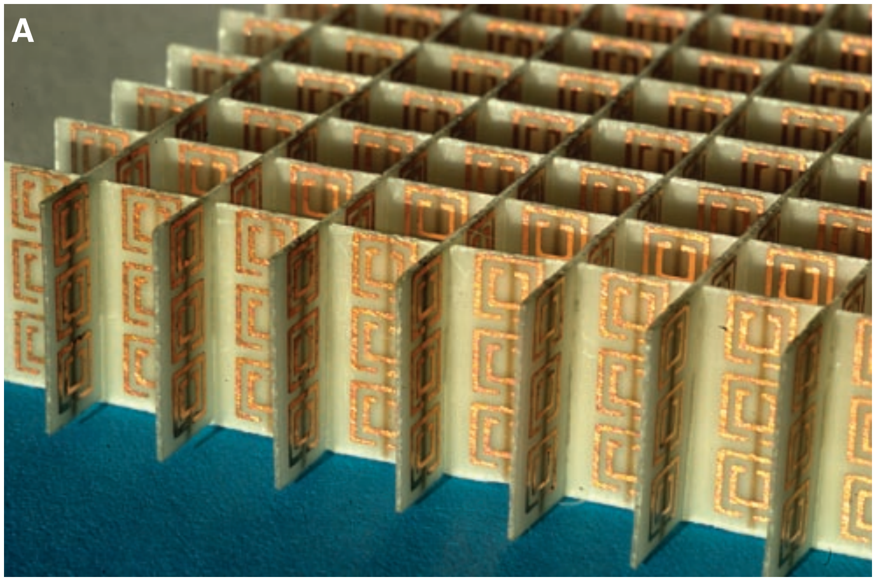


Even a single interface can focus a beam

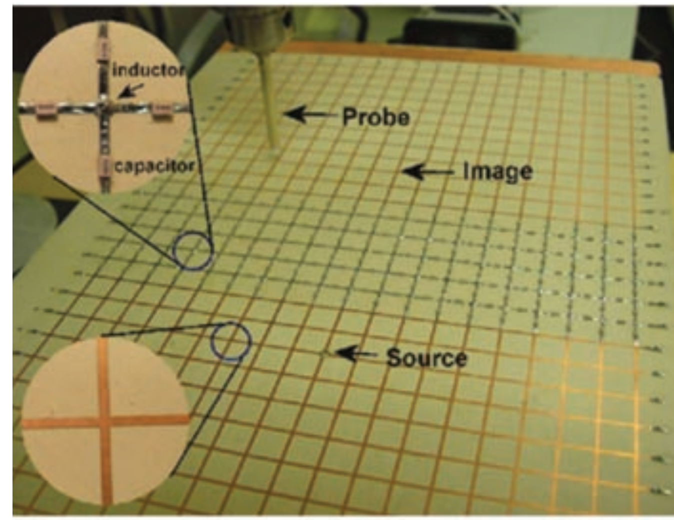
Experiments: metamaterials

Artificial materials with subwavelengths structures

1 cm



3D metamaterial
Smith (UC San Diego)



2D version of a flat lens

Elementary blocks = metallic resonators

D.R. Smith, J.B. Pendry and M.C.K. Wiltshire, Science 2004

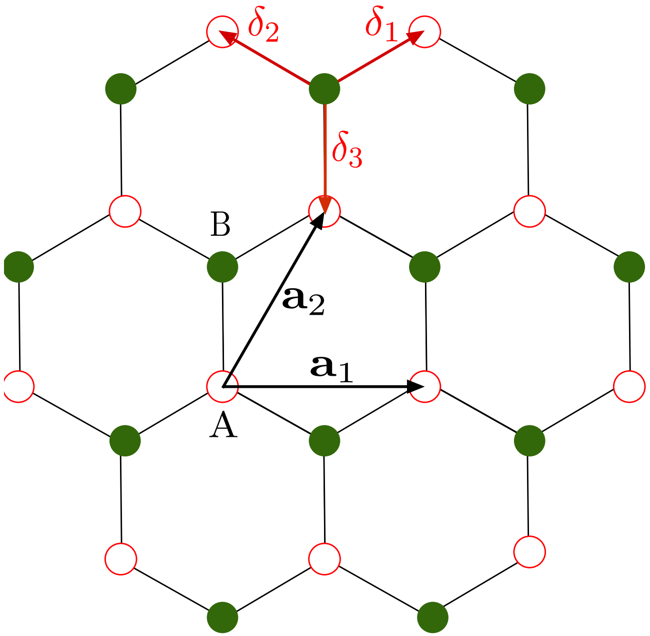
Optics with electrons

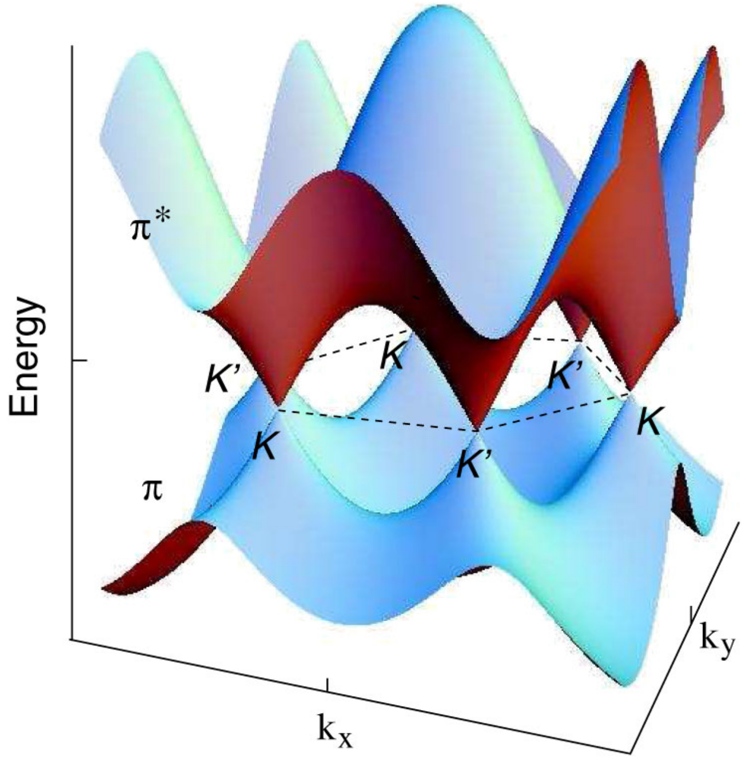
Photons	Electrons in ballistic regime
Dispersion	Electronic band structure
Maxwell equations	Schrödinger equation
Poynting vector	Group velocity
Optical rays	Semiclassical trajectories of electrons
Massless bosons	Massive fermions with charge e
Non interacting	e-e interactions
3D	Quasiparticles : 3D, 2D, 1D
Polarizations	Spin

Suitable devices : Electronic lenses, beamsplitters, interferometers for electrons

II) Veselago lensing with massless electrons in 2D graphene

Graphene band structure

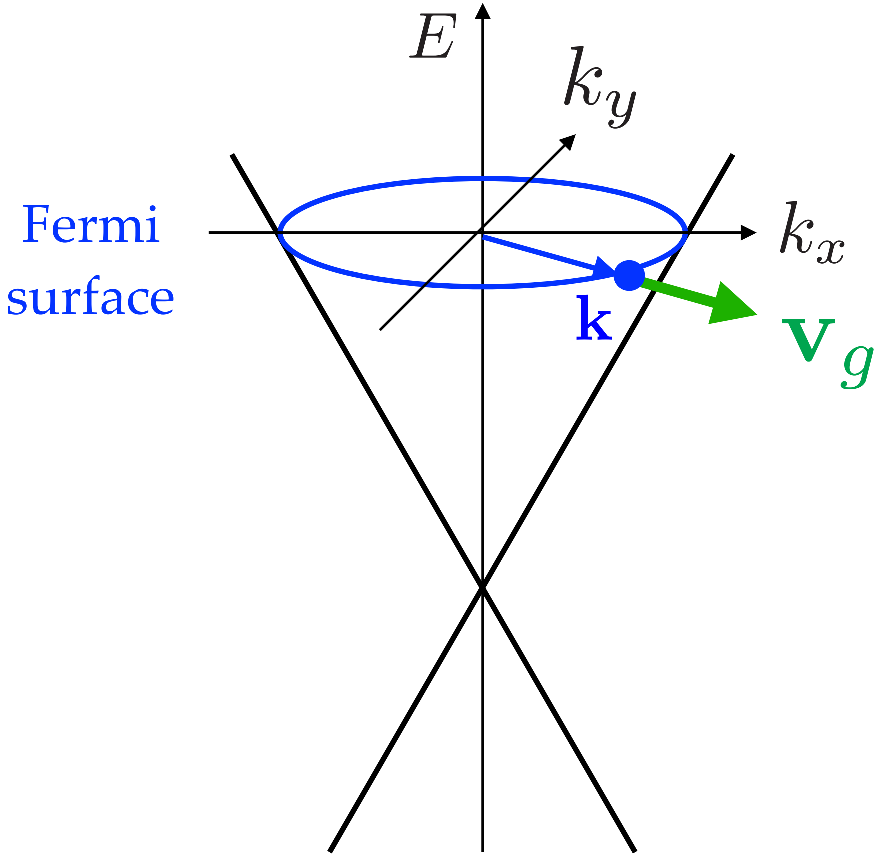


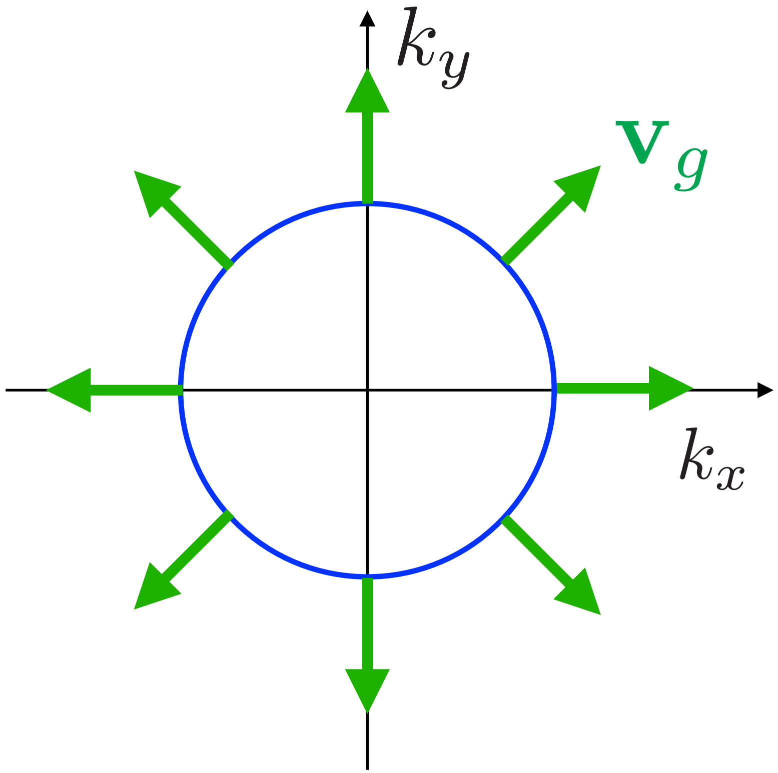


$$\mathbf{v}_g = \frac{1}{\hbar}\nabla_{\mathbf{k}} E(\mathbf{k})$$

The group velocity is the gradient of the (rich) dispersion relation

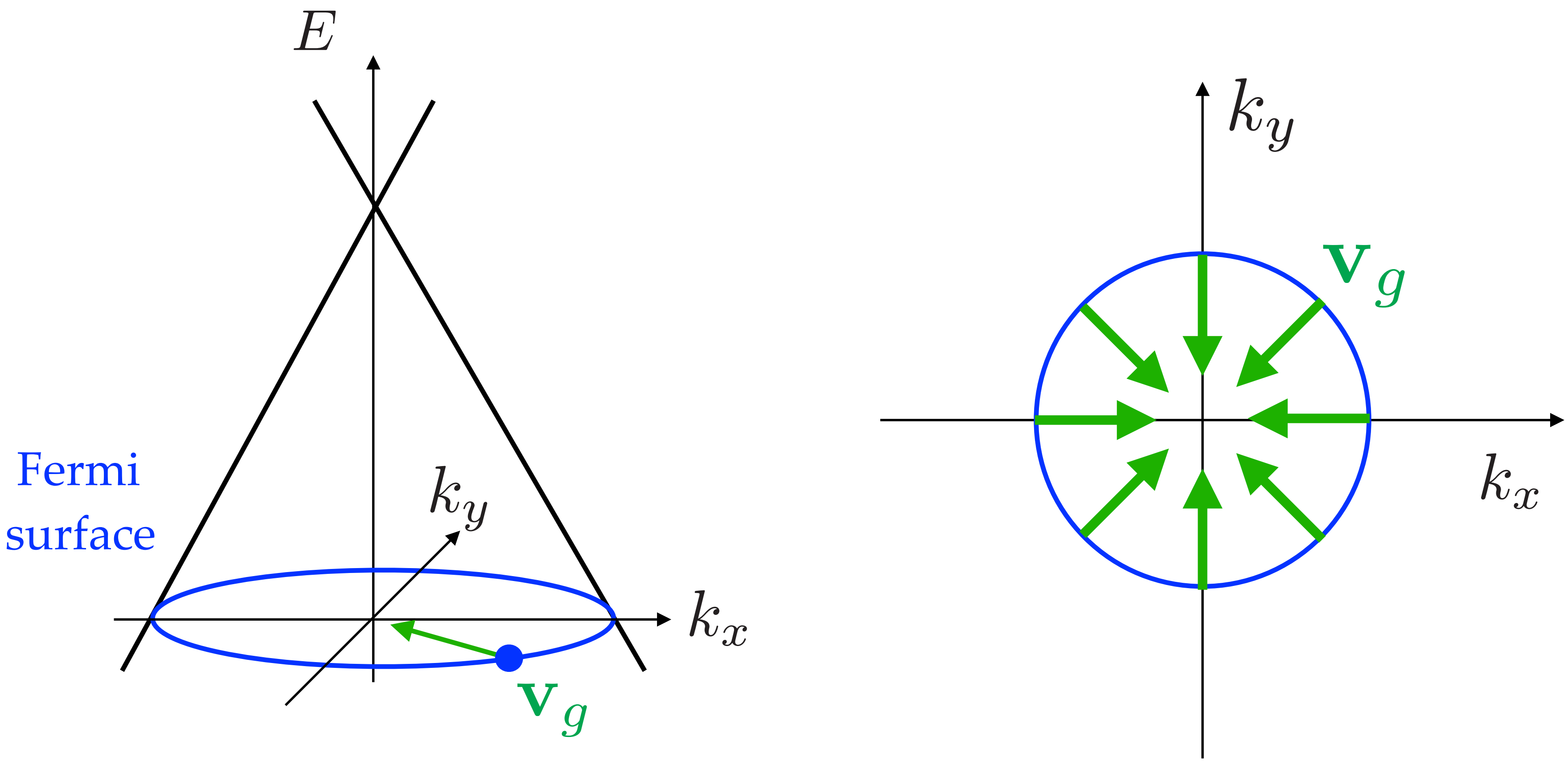
n-doped graphene





In n-doped graphene, the group velocity and the wave-vector like points **in the same direction.**

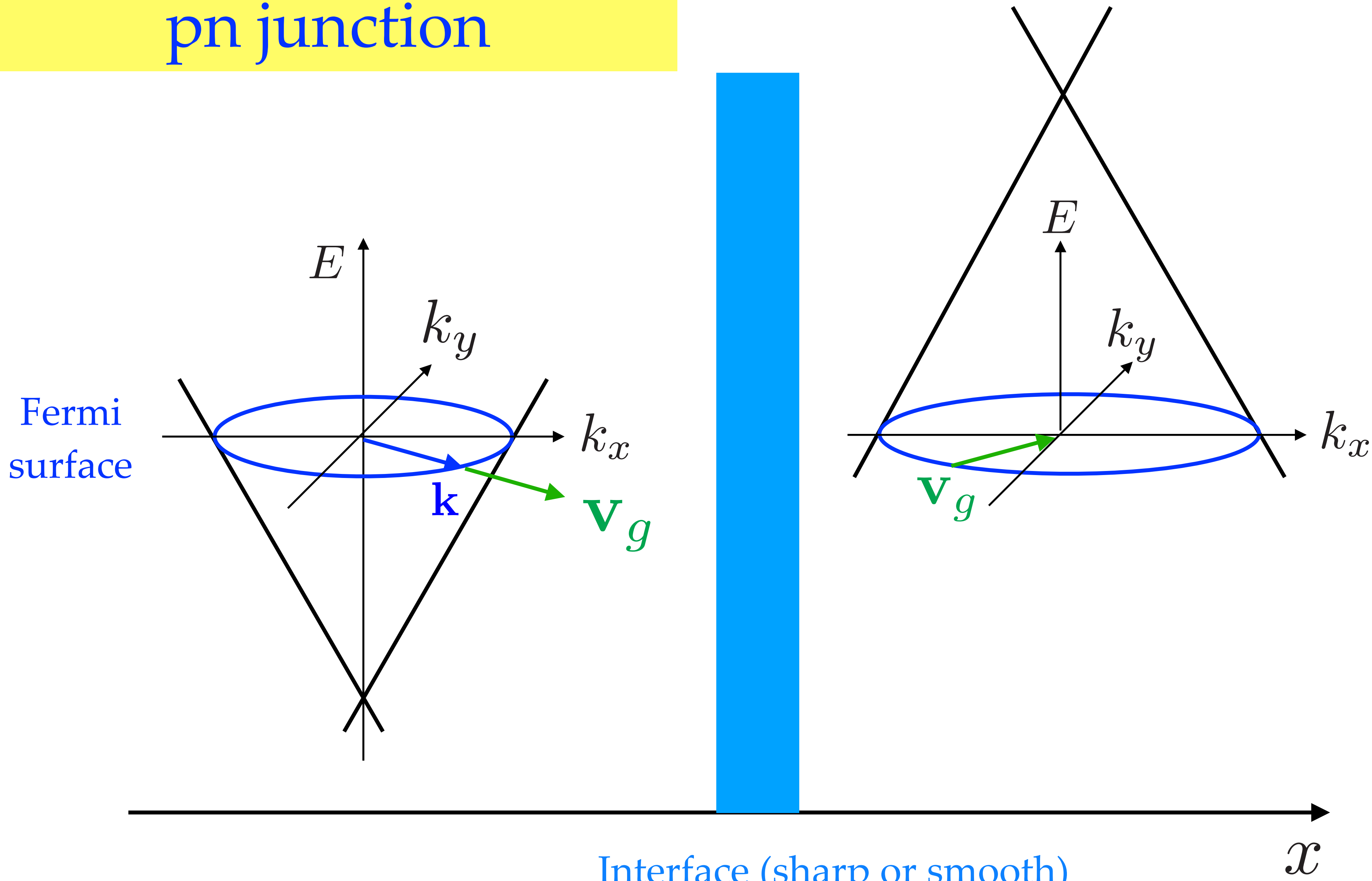
p-doped graphene



In p-doped graphene, the group velocity and the wave-vector like points in **opposite directions**, like in a negative index medium

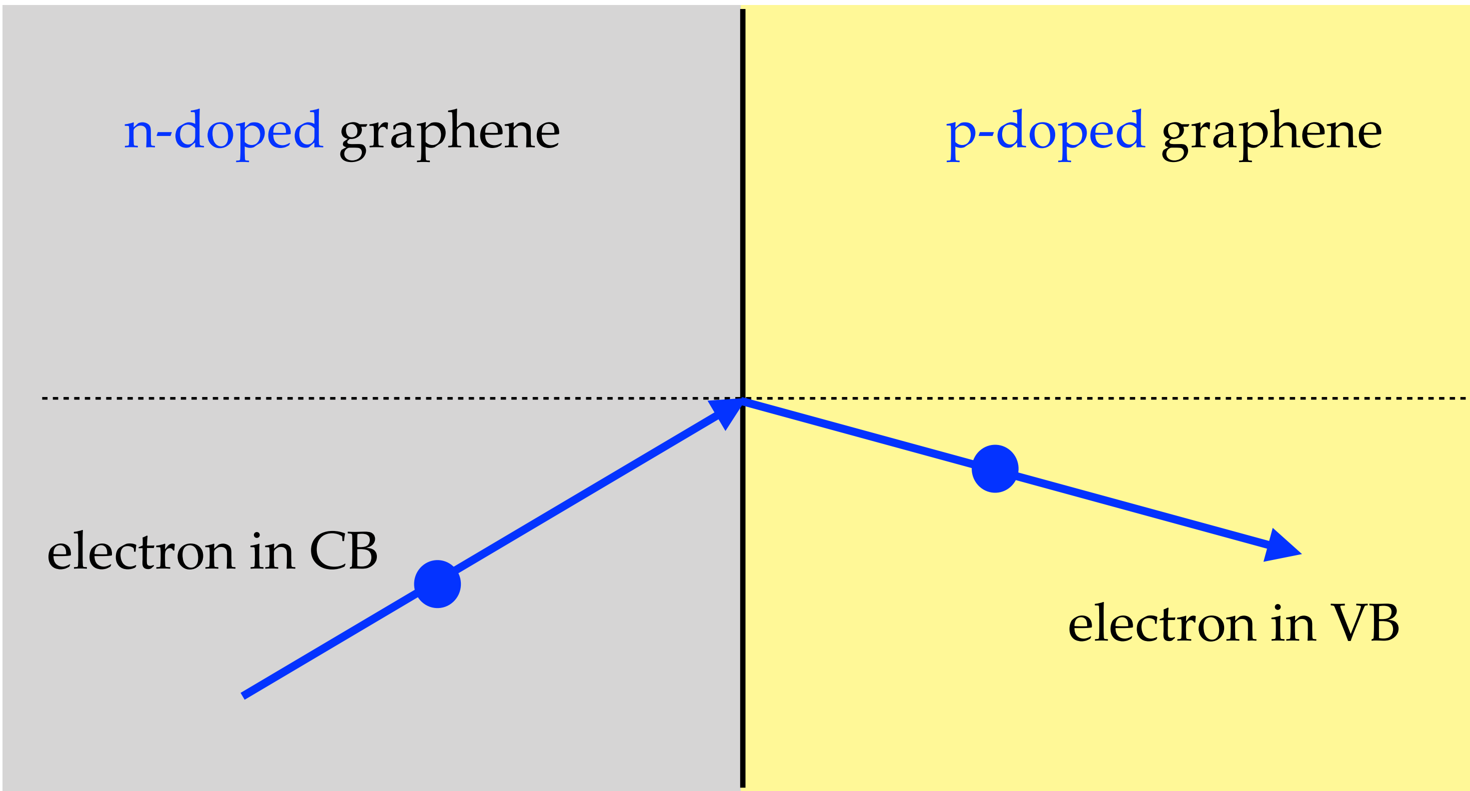
(The same in any negatively-dispersing band)

pn junction



Interface (sharp or smooth)
obtained by electrostatic GATING

Veselago lensing with electrons in graphene

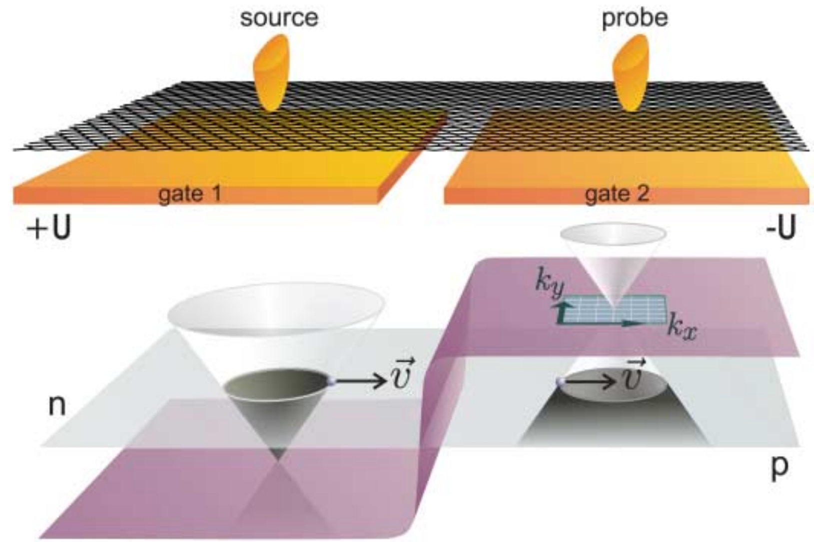


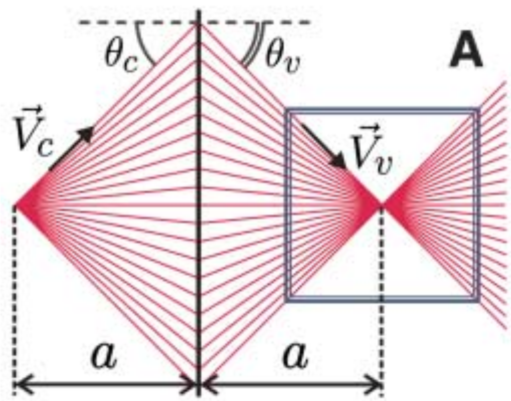
Arrows represent group velocities / semiclassical trajectories

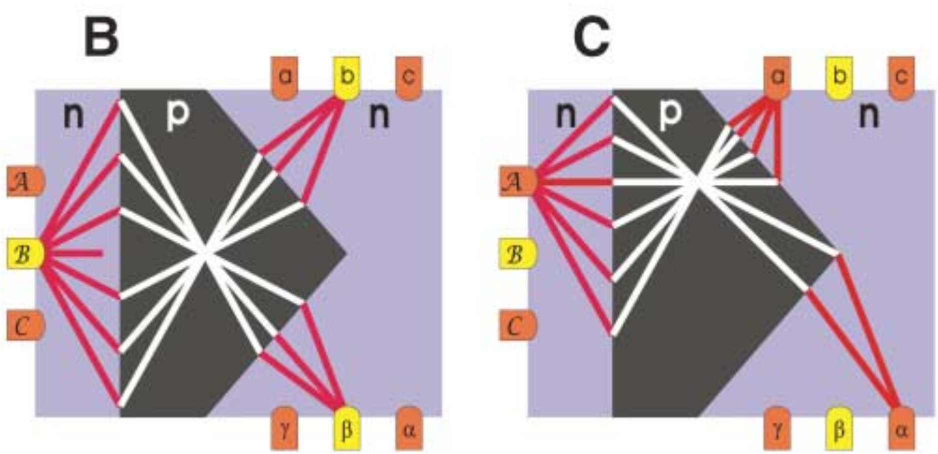
The Focusing of Electron Flow and a Veselago Lens in Graphene *p-n* Junctions

Vadim V. Cheianov,[1*] Vladimir Fal'ko,[1] B. L. Altshuler[2,3]

2 MARCH 2007 VOL 315 SCIENCE

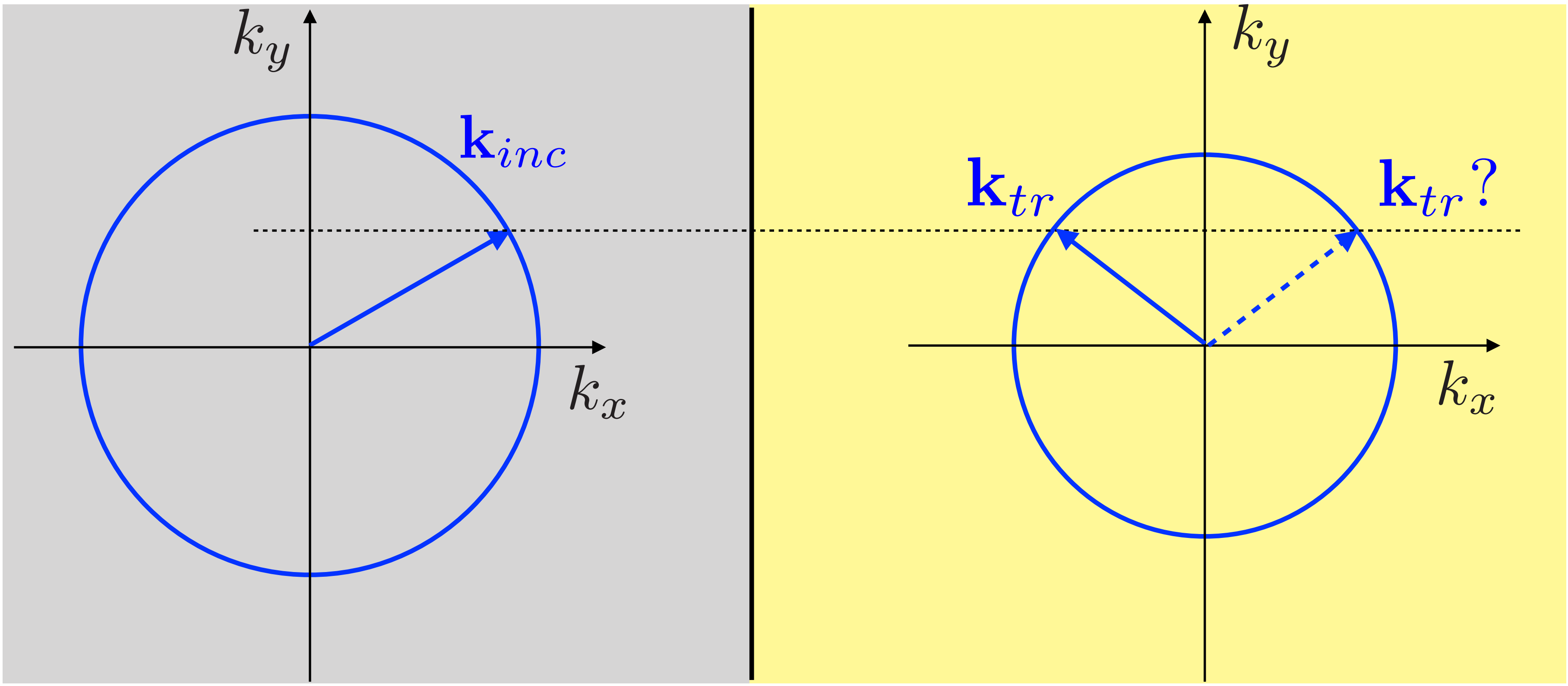






Experimental realization
Quentin Wilmart (LPENS, ex-LPA

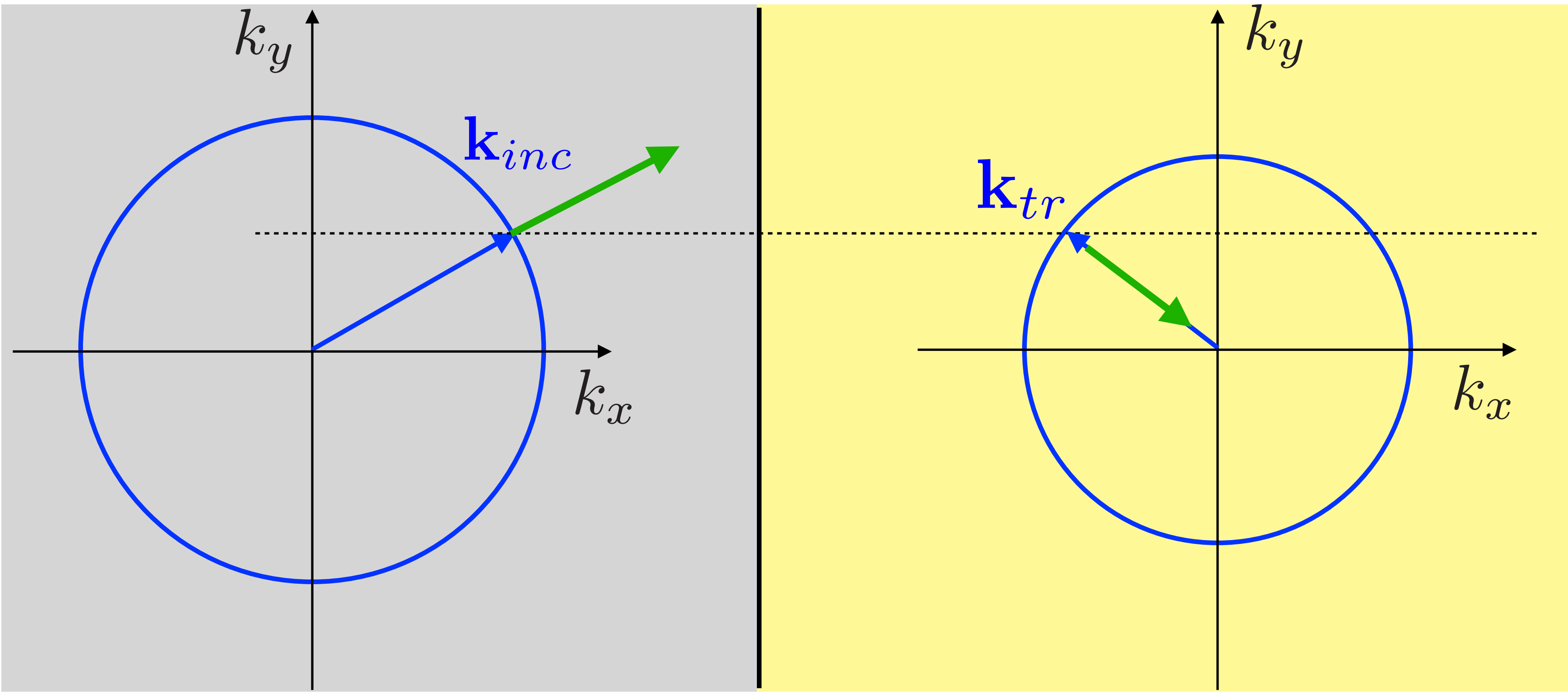
Origin of negative refraction



n-doped graphene

p-doped graphene

Origin of negative refraction



n-doped graphene p-doped graphene

Transmission through pn junction

Perfect transmission at **normal incidence**

Sharp interface : $k_F d \ll 1$

$\lambda_F \simeq \ 10 - 100 nm$

$$T(\phi) = \cos^2 \phi$$

Smooth interface : $k_F d \gg 1$

$$T(\phi) = e^{-\pi k_F d \sin^2 \phi}$$

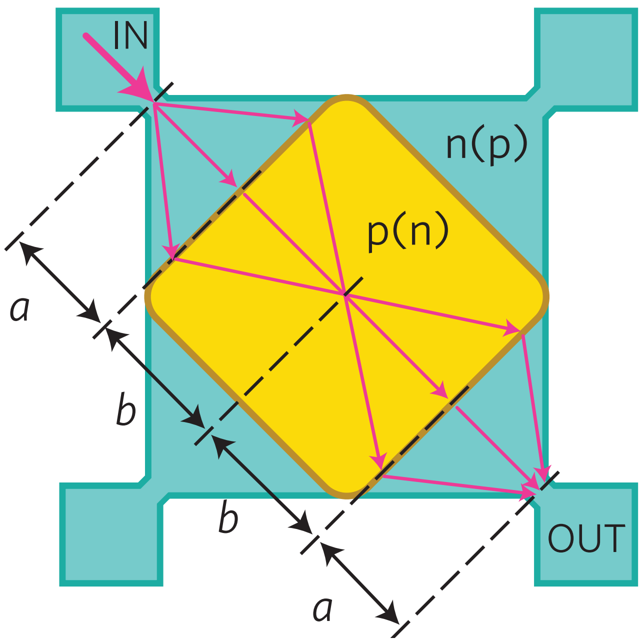
Collimation

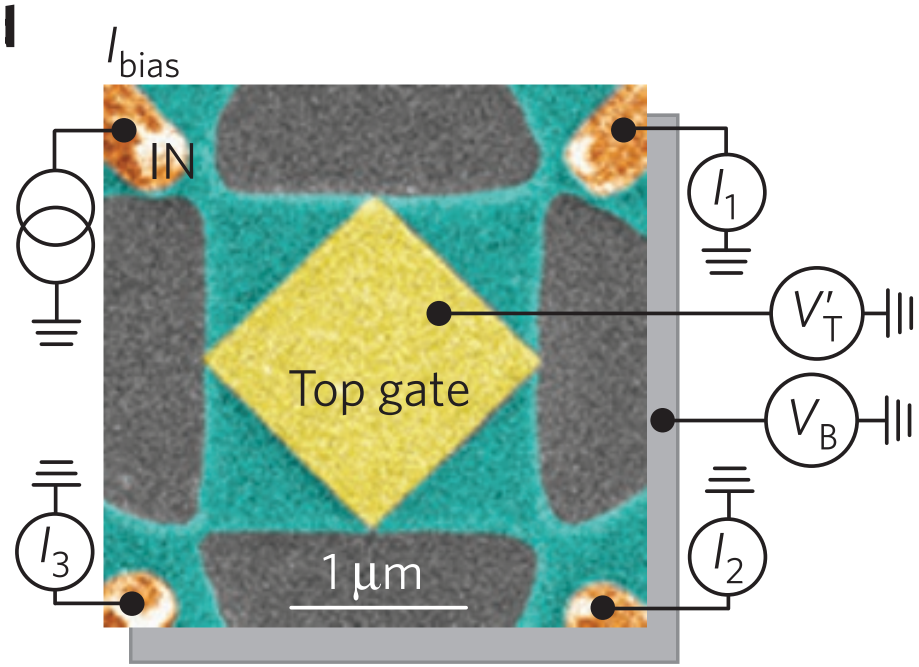
Experiments in ballistic regime (2015)

nature physics
LETTERS
PUBLISHED ONLINE: 14 SEPTEMBER 2015 | DOI: 10.1038/NPHYS3460

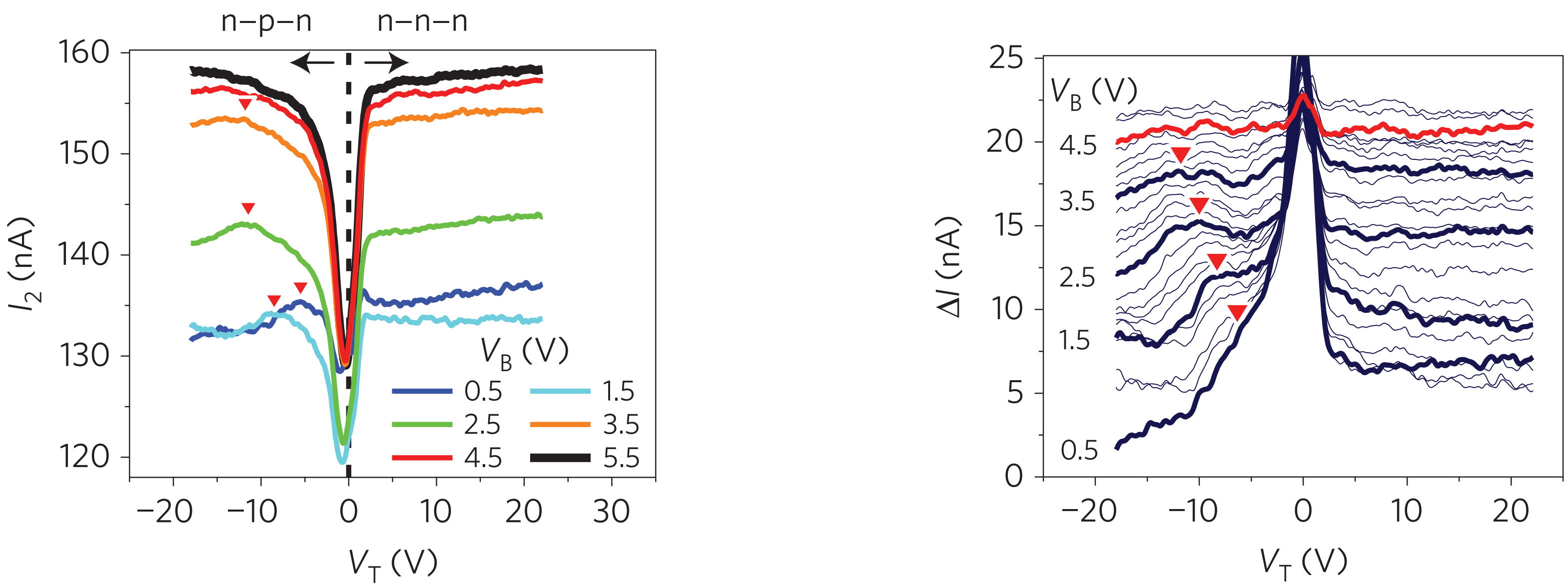
Observation of negative refraction of Dirac fermions in graphene

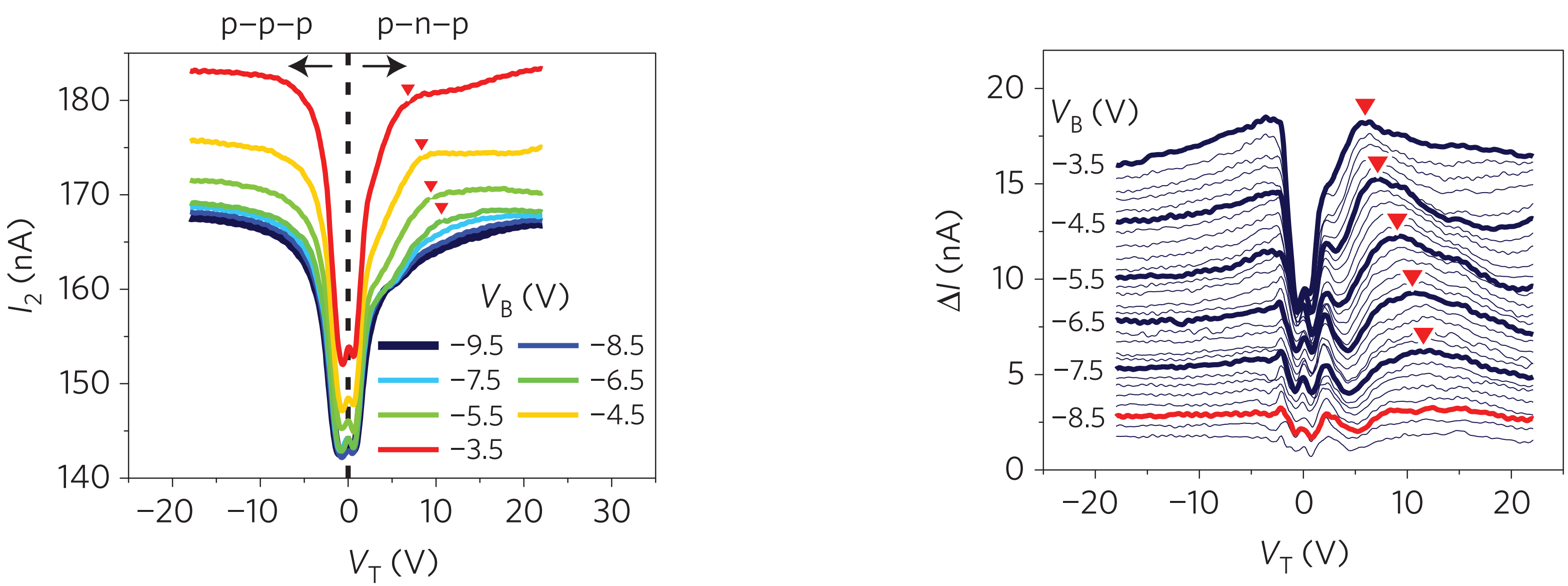
Gil-Ho Lee†, Geon-Hyoung Park and Hu-Jong Lee*





Focused peaks…





Experiments in ballistic regime (2016)

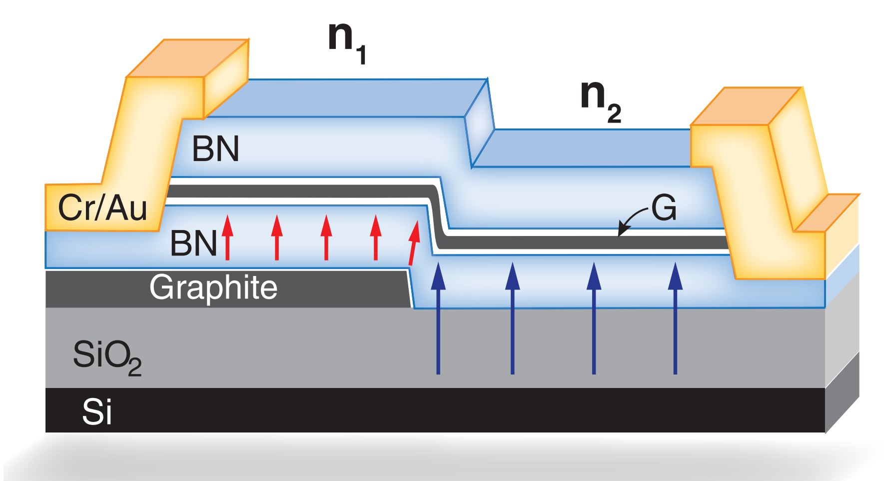
RESEARCH | *REPORTS*

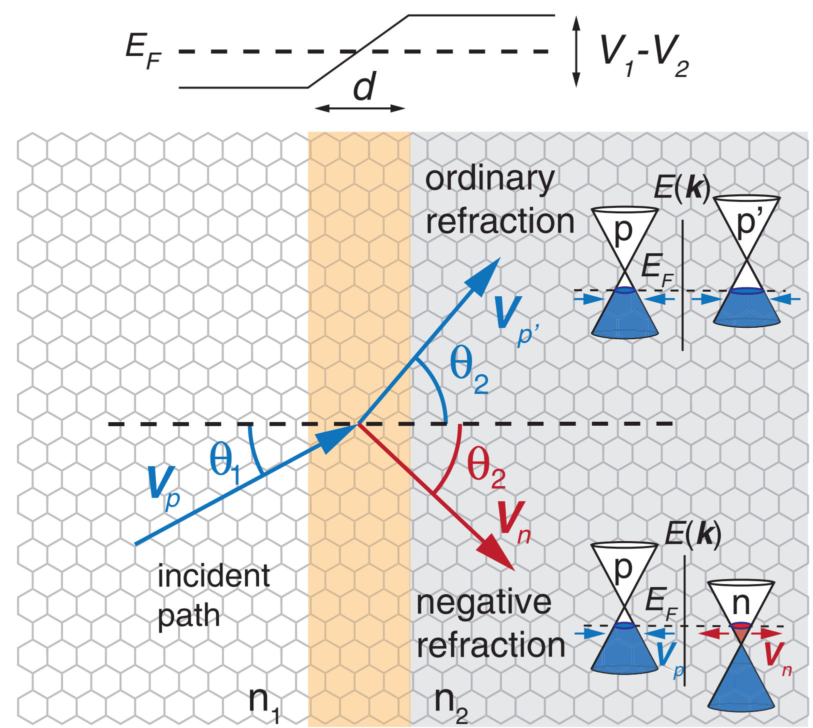
GRAPHENE

Electron optics with p-n junctions in ballistic graphene

Shaowen Chen,[1,2*] Zheng Han,[1,7*] Mirza M. Elahi,[3] K. M. Masum Habib,[3†] Lei Wang,[4] Bo Wen,[1,8] Yuanda Gao,[5] Takashi Taniguchi,[6] Kenji Watanabe,[6] James Hone,[5] Avik W. Ghosh,[3] Cory R. Dean[1‡]

1522 30 SEPTEMBER 2016 • VOL 353 ISSUE 6307





Encapsulated graphene (between BN layers)

GRAPHENE

Electron optics with p-n junctions in ballistic graphene

Shaowen Chen,[1,2*] Zheng Han,[1,7*] Mirza M. Elahi,[3] K. M. Masum Habib,[3†] Lei Wang,[4]
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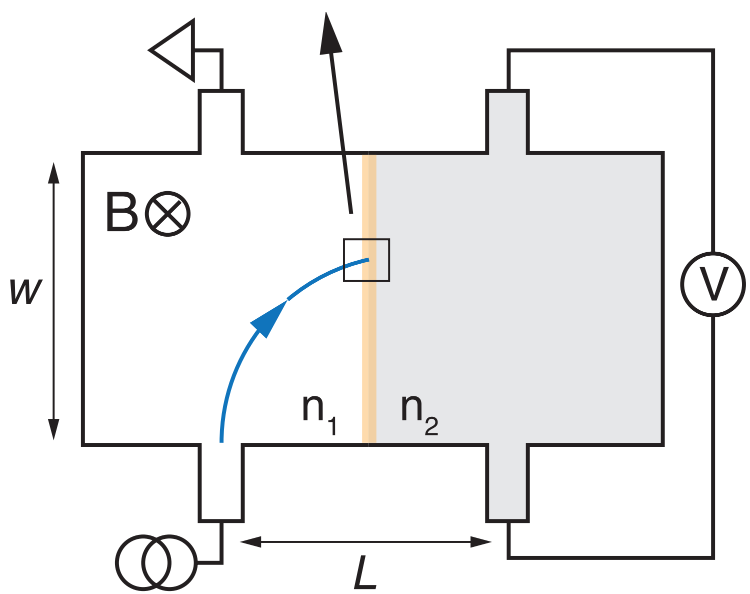
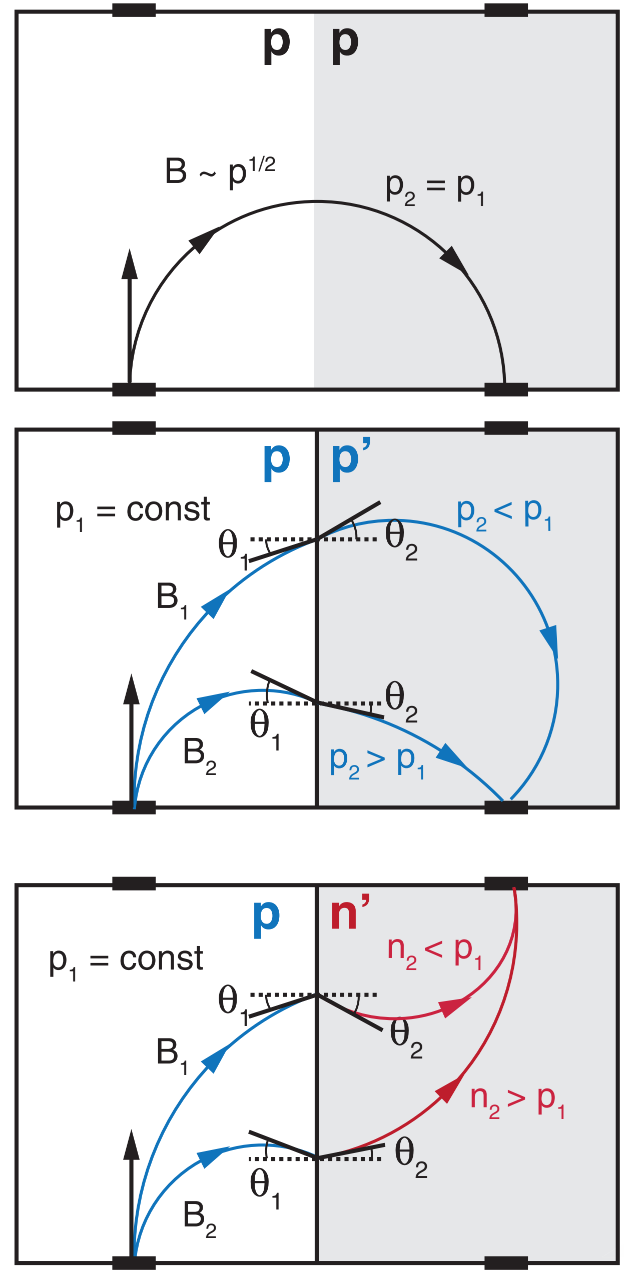
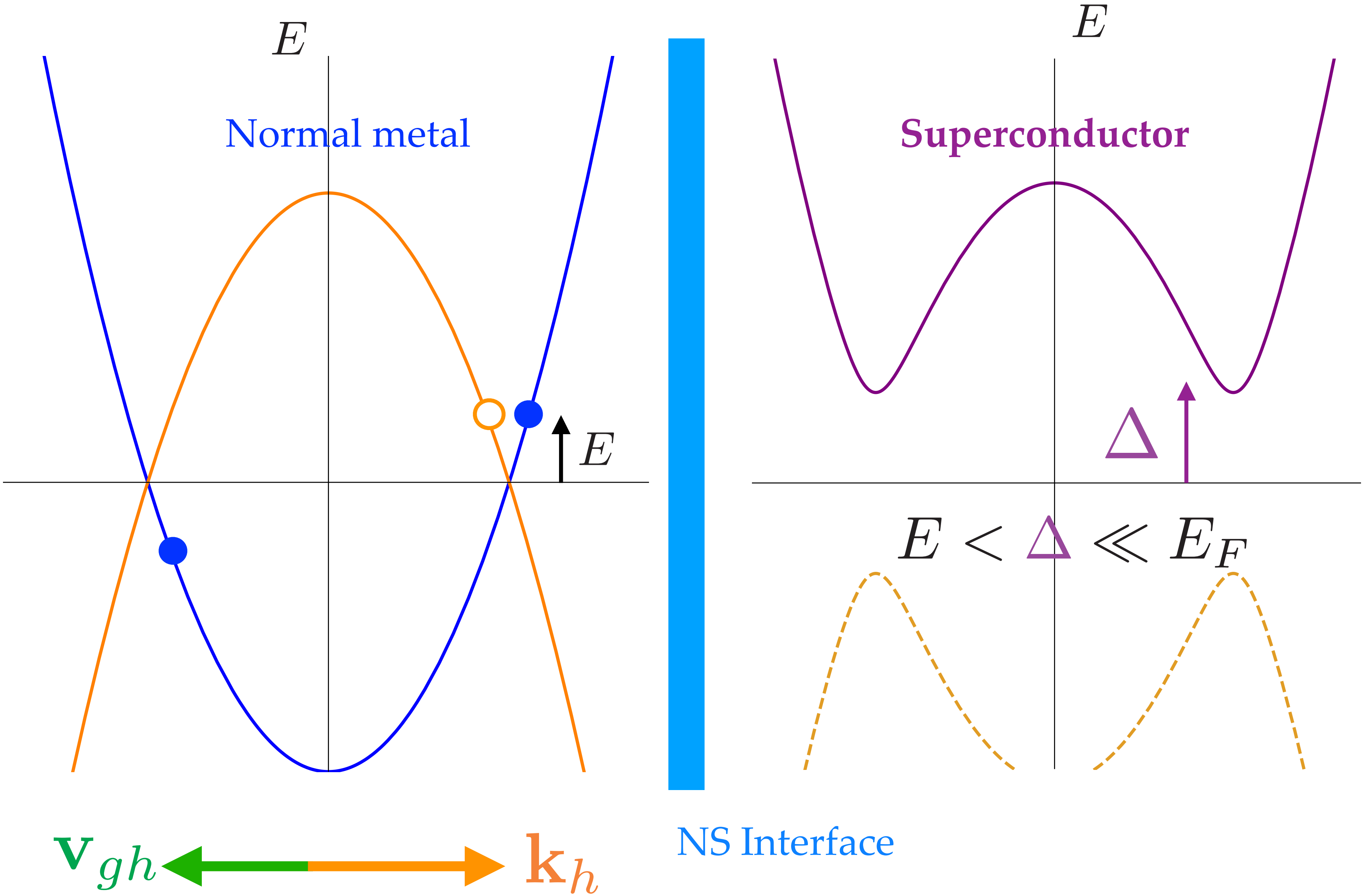
Negative refraction and cyclotron focusing



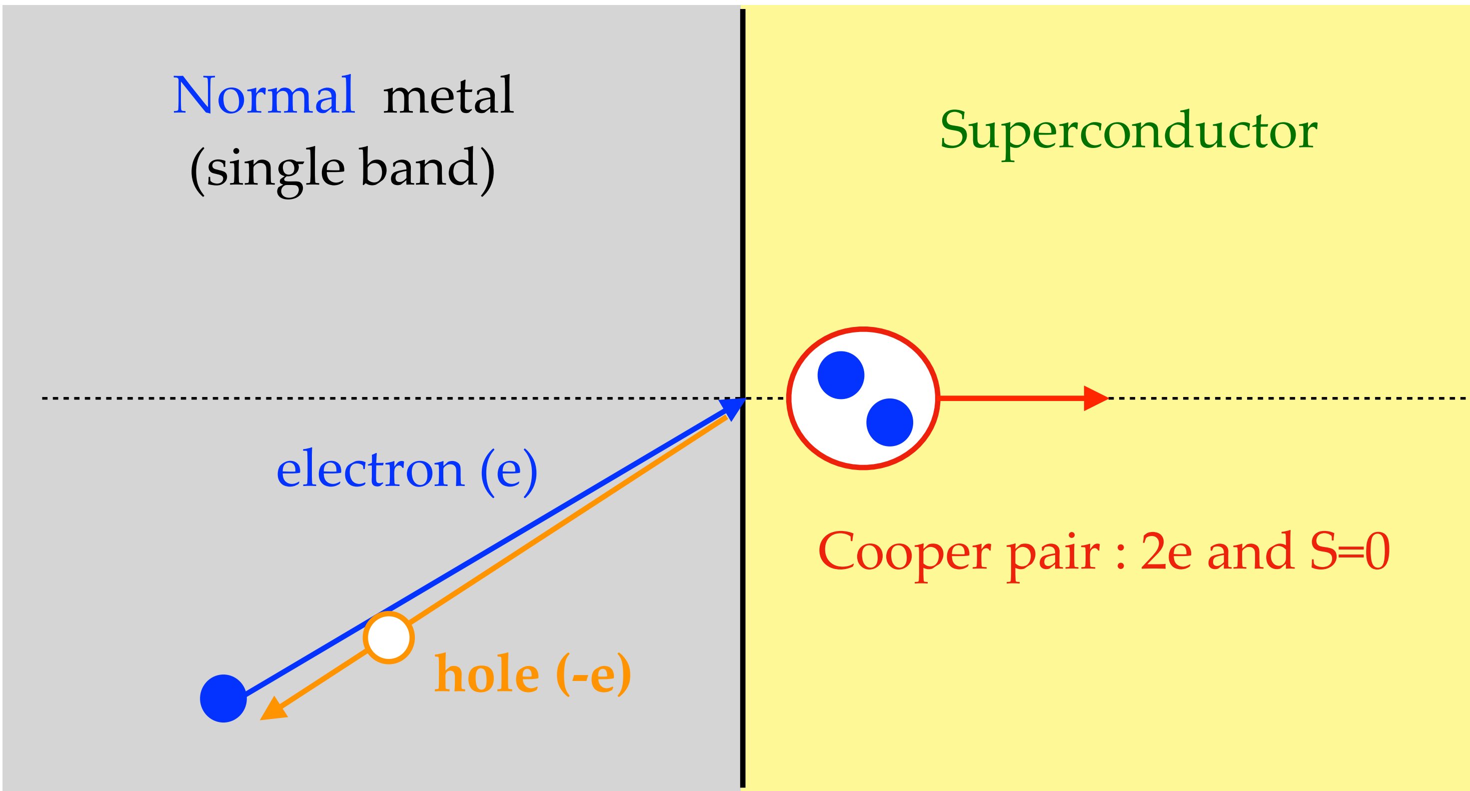


III) Andreev reflection at graphene/ superconductor interface

Andreev reflection at NS interface

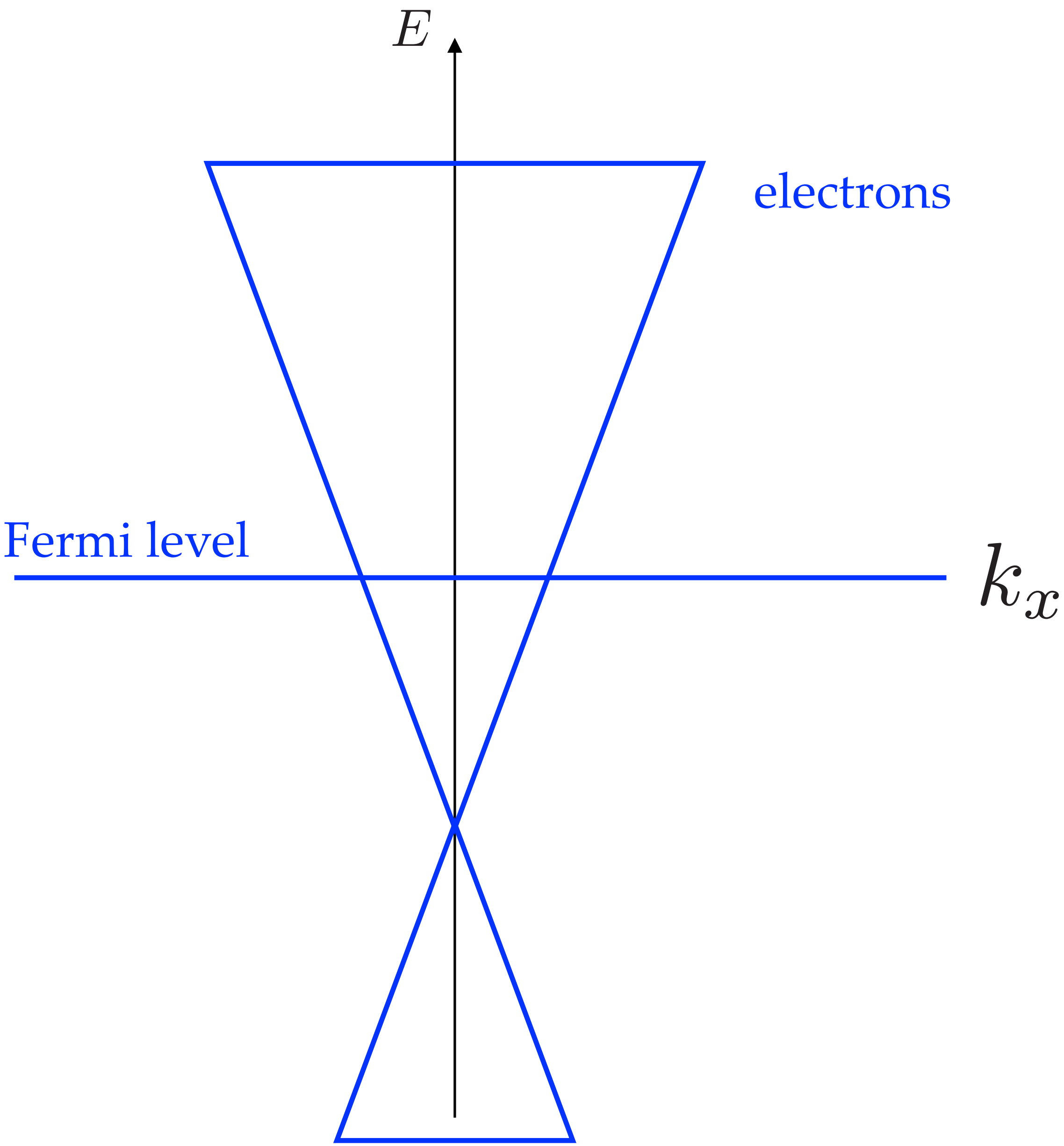


Andreev reflection in standard metals

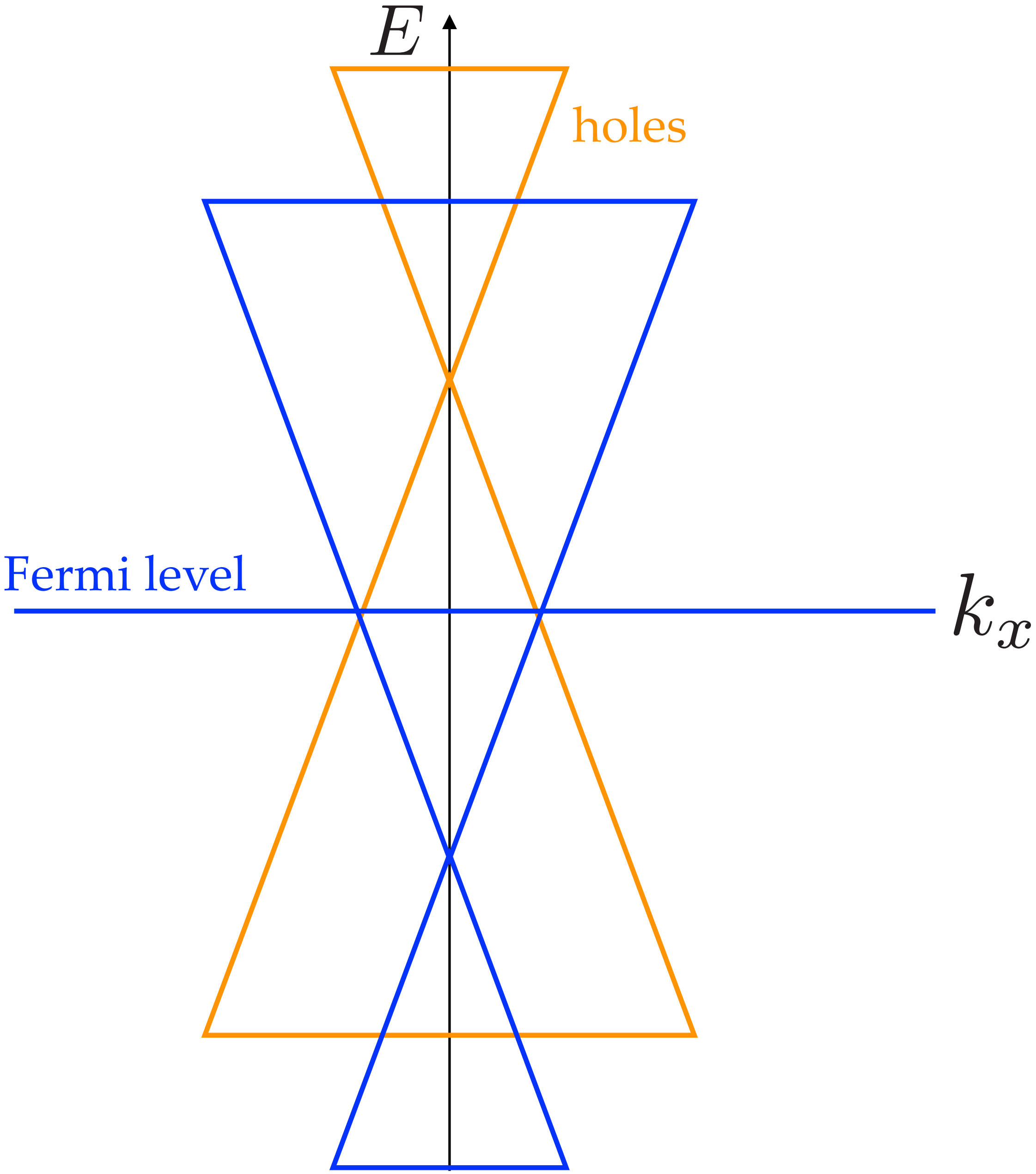


Retro-reflection (with a tiny mismatch angle)

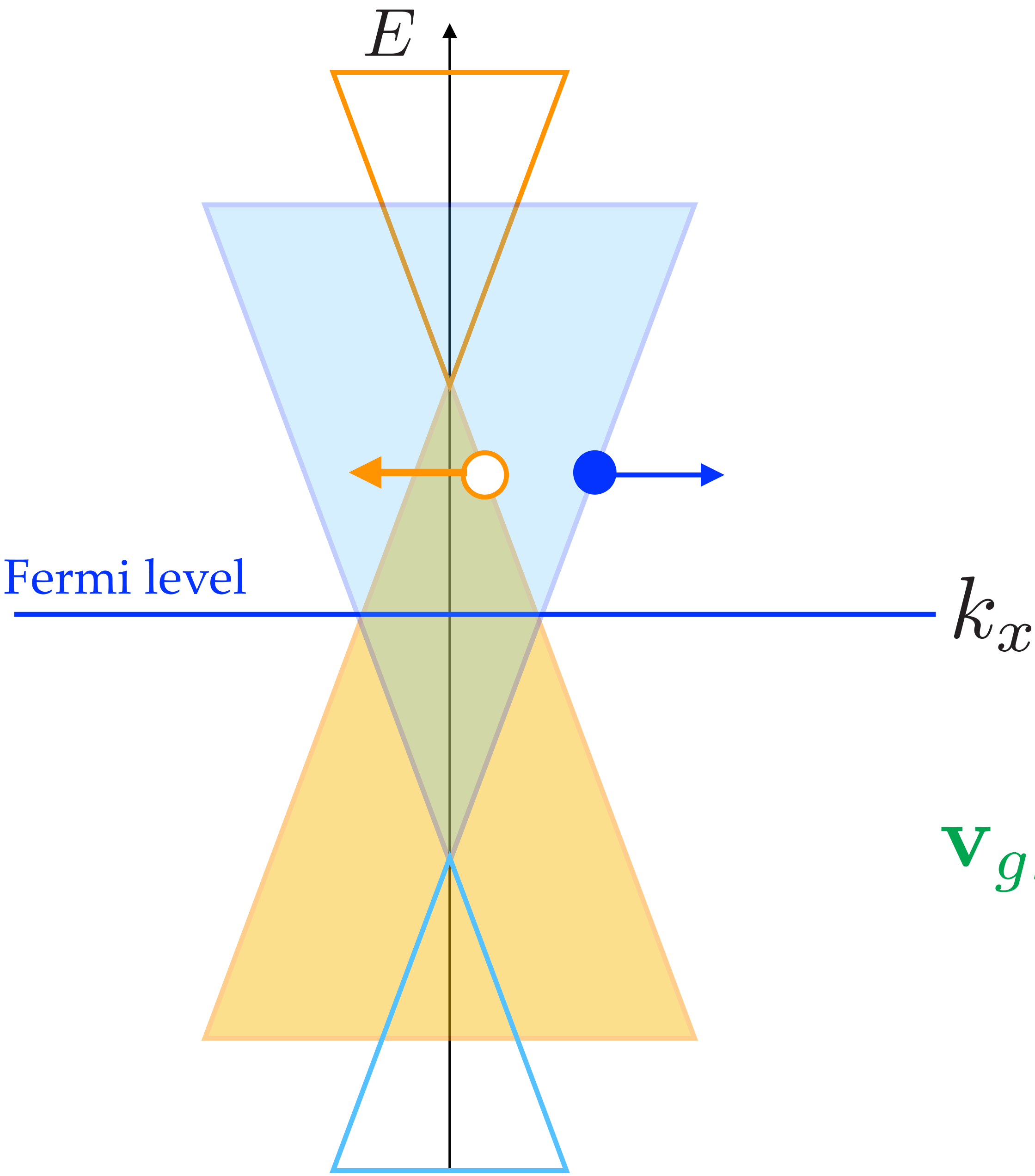
Andreev reflection in a Dirac cone (2 bands)



Andreev reflection in a Dirac cone



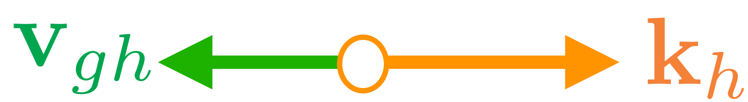
Andreev-Dirac reflection : intraband case



$$E < E_F$$

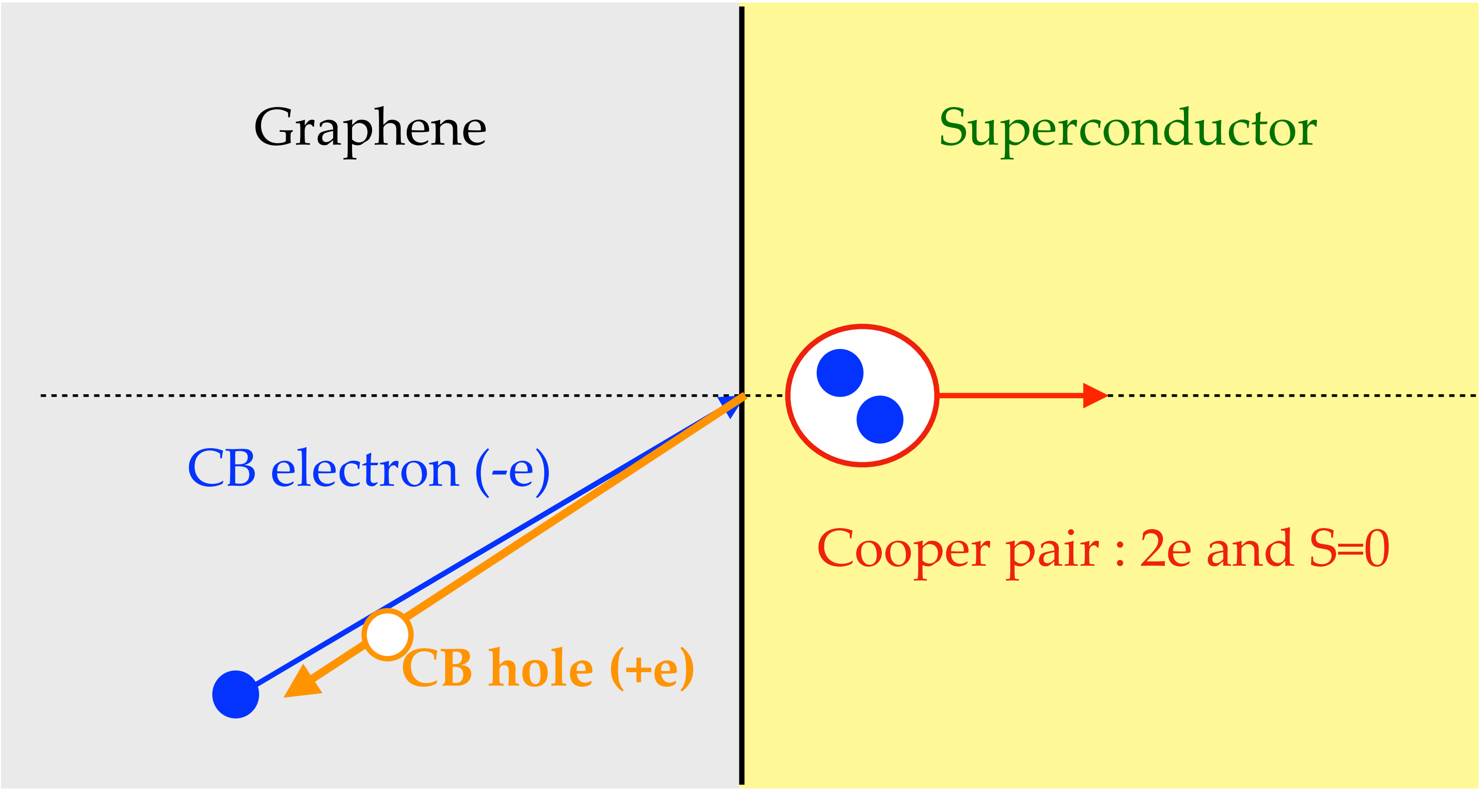
The hole also belongs to the conduction band

Intraband AR
Ret-reflection



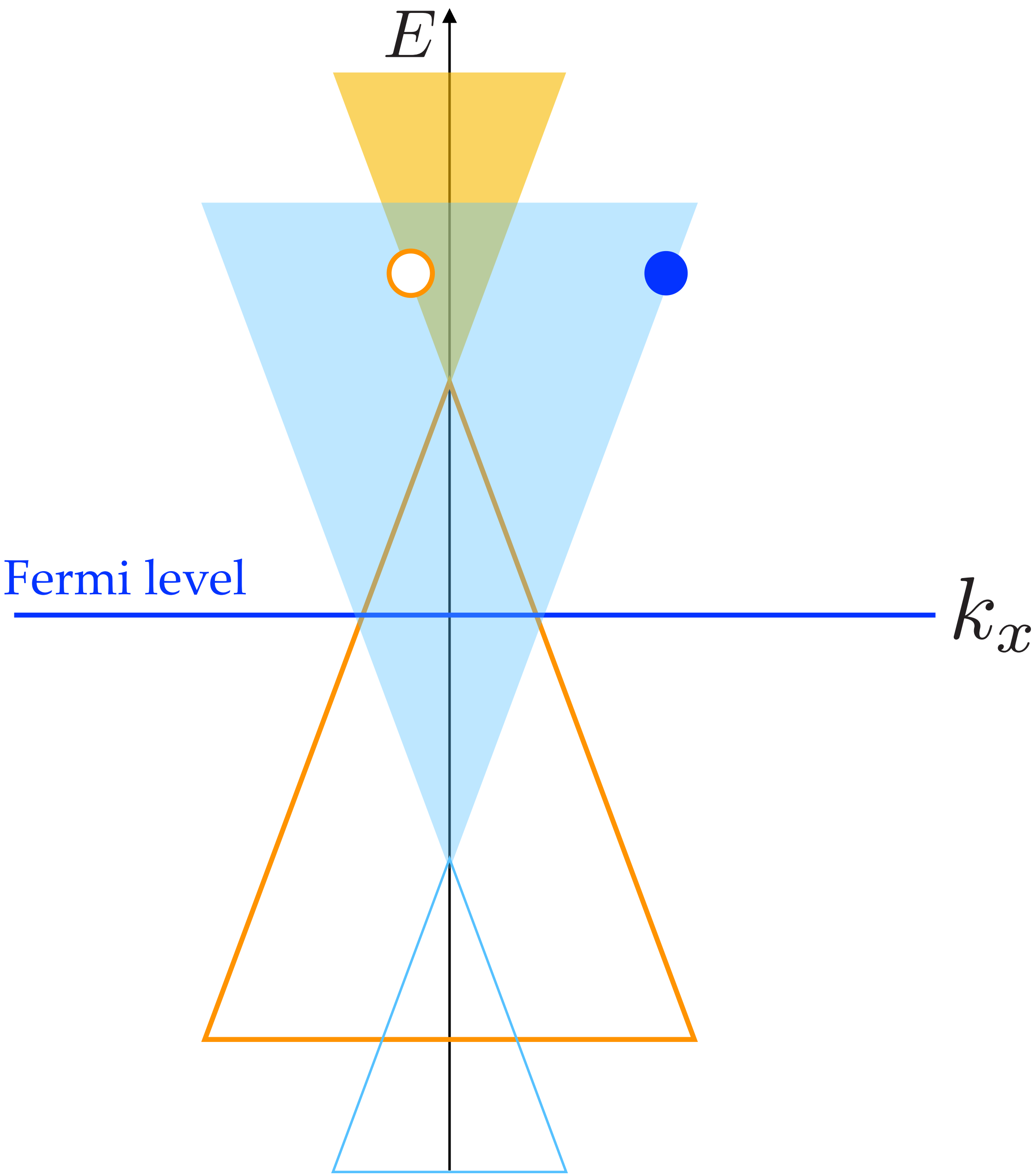
Andreev-Dirac reflection : intraband case

Intraband



Retro-reflection (with a tiny mismatch angle)

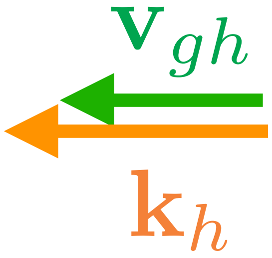
Andreev-Dirac reflection : interband case



$$E > E_F$$

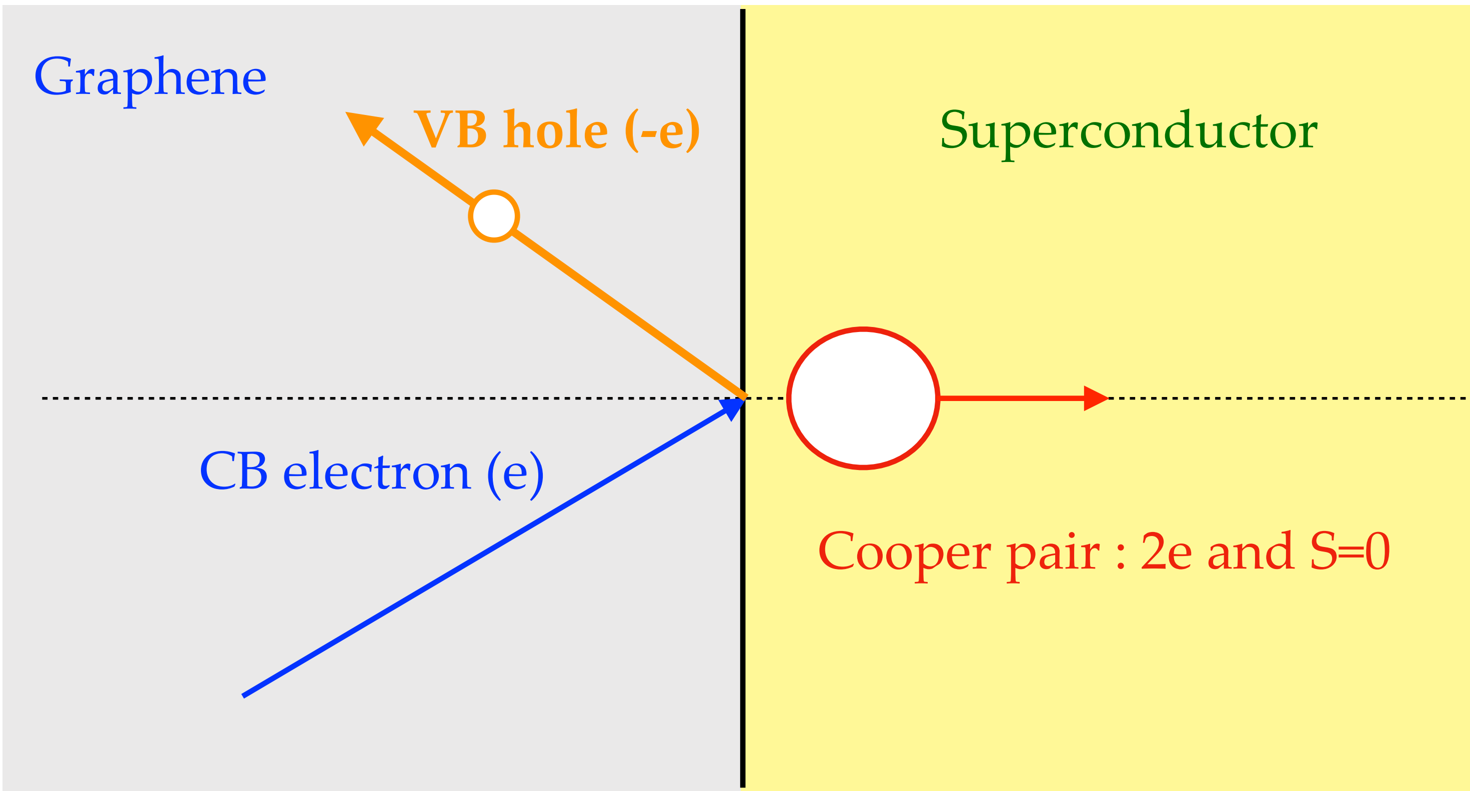
The hole also belongs to the valence band

Interband AR
Retro-reflection



Andreev-Dirac reflection : interband case

Interband

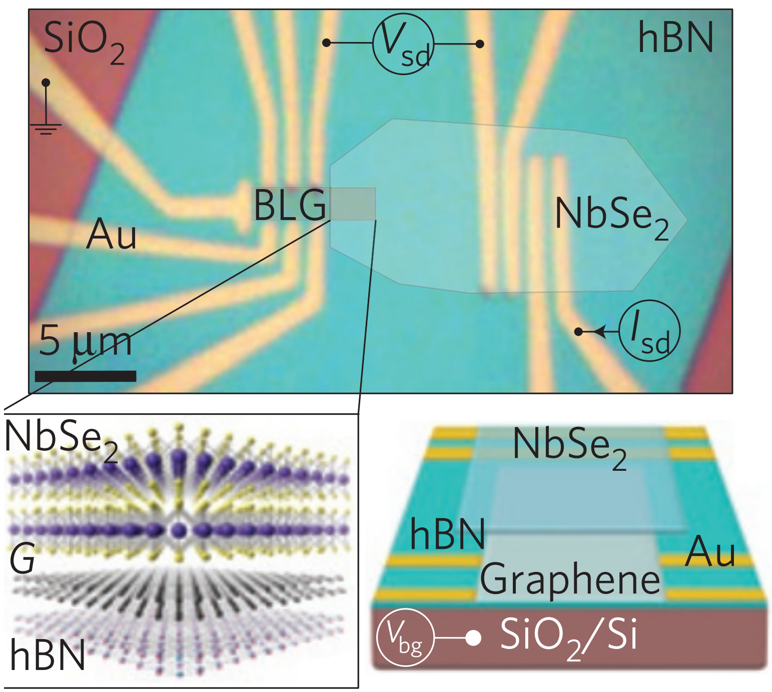


Specular-reflection (with a tiny mismatch angle)

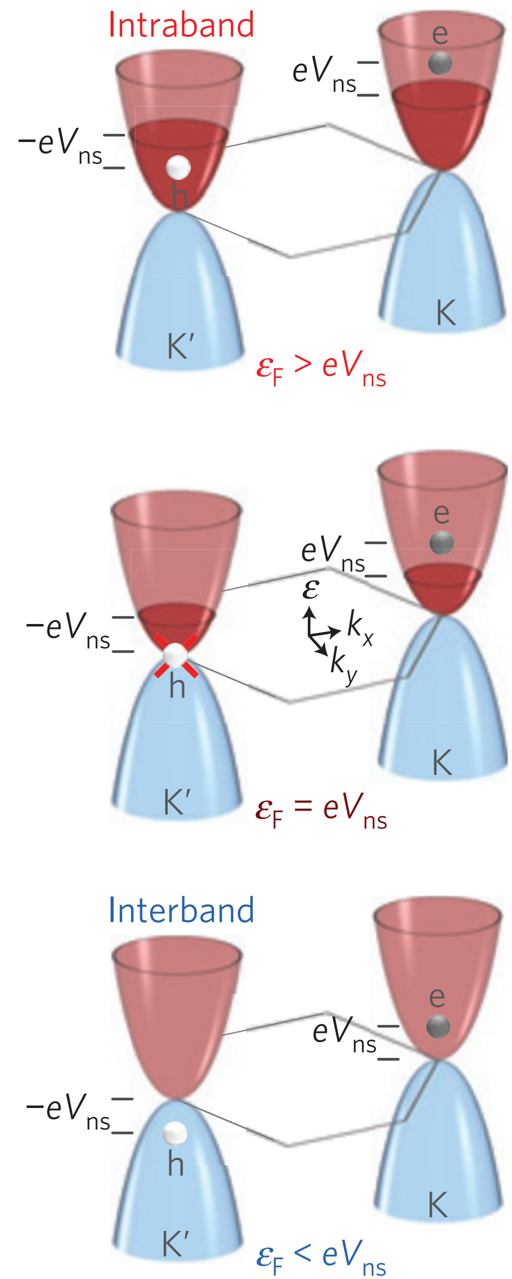
LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NPHYS3583
nature physics

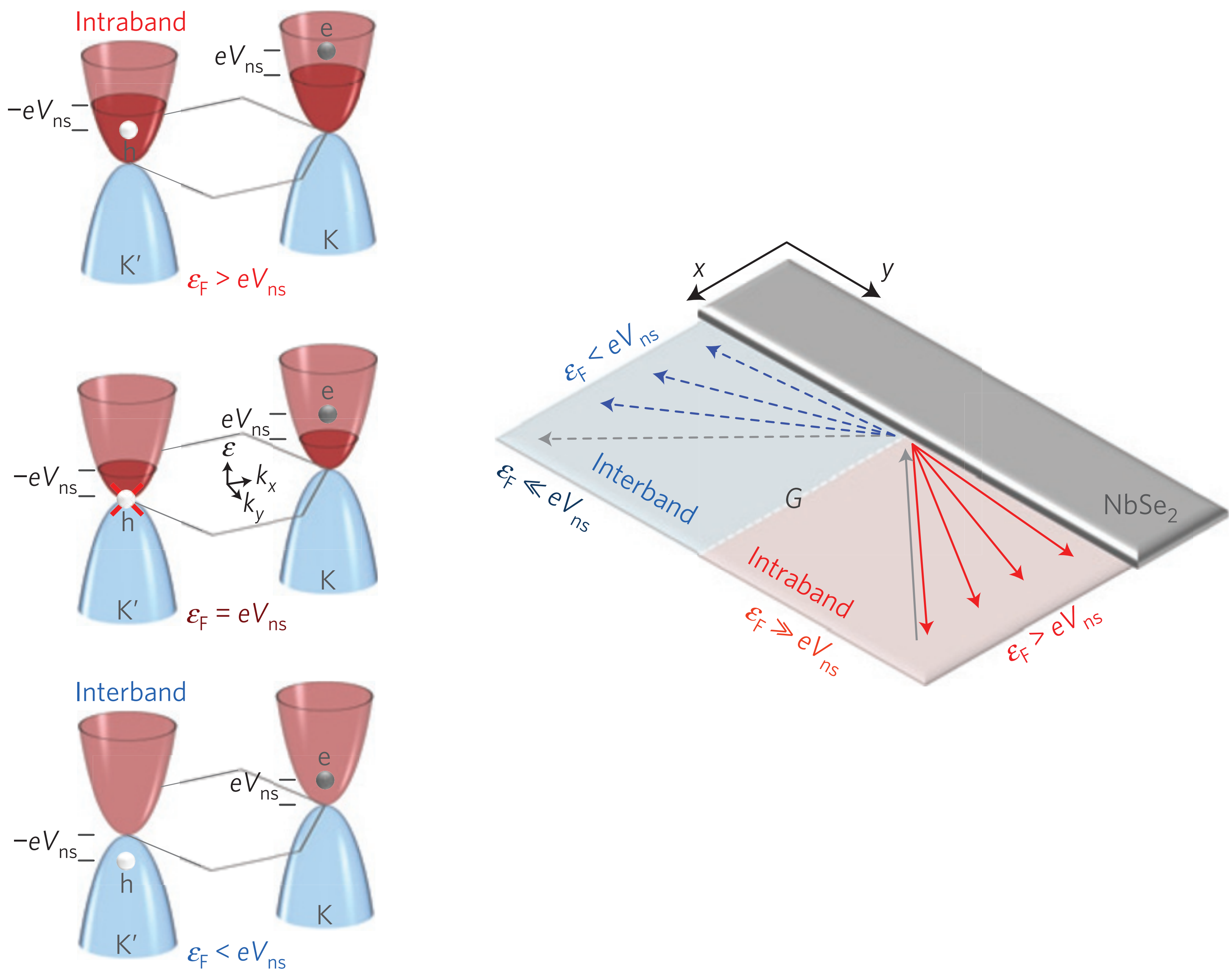
Specular interband Andreev reflections at van der Waals interfaces between graphene and $NbSe_2$

D. K. Efetov[1*], L. Wang[2], C. Handschin[1], K. B. Efetov[3,4], J. Shuang[5], R. Cava[5], T. Taniguchi[6], K. Watanabe[6], J. Hone[2], C. R. Dean[1] and P. Kim[1*]



Bilayer Graphene





Intraband
eV_{ns}
$-eV_{ns}$
e
h
K′
K
$\varepsilon_F > eV_{ns}$
eV_{ns}
$-eV_{ns}$
ε
k_x
k_y
$\varepsilon_F = eV_{ns}$
Interband
$\varepsilon_F < eV_{ns}$
x
y
$\varepsilon_F < eV_{ns}$
$\varepsilon_F \ll eV_{ns}$
Interband
G
$NbSe_2$
Intraband
$\varepsilon_F \gg eV_{ns}$
$\varepsilon_F > eV_{ns}$

Internal degrees of freedom

Veselago lensing is useful because it allows focusing by a planar interface, but at this stage it is spin/chirality insensitive

In devices using electronic optics, it would be interesting to design lenses that **focus a specific eigenvalue** of spin or chirality.

Spintronics

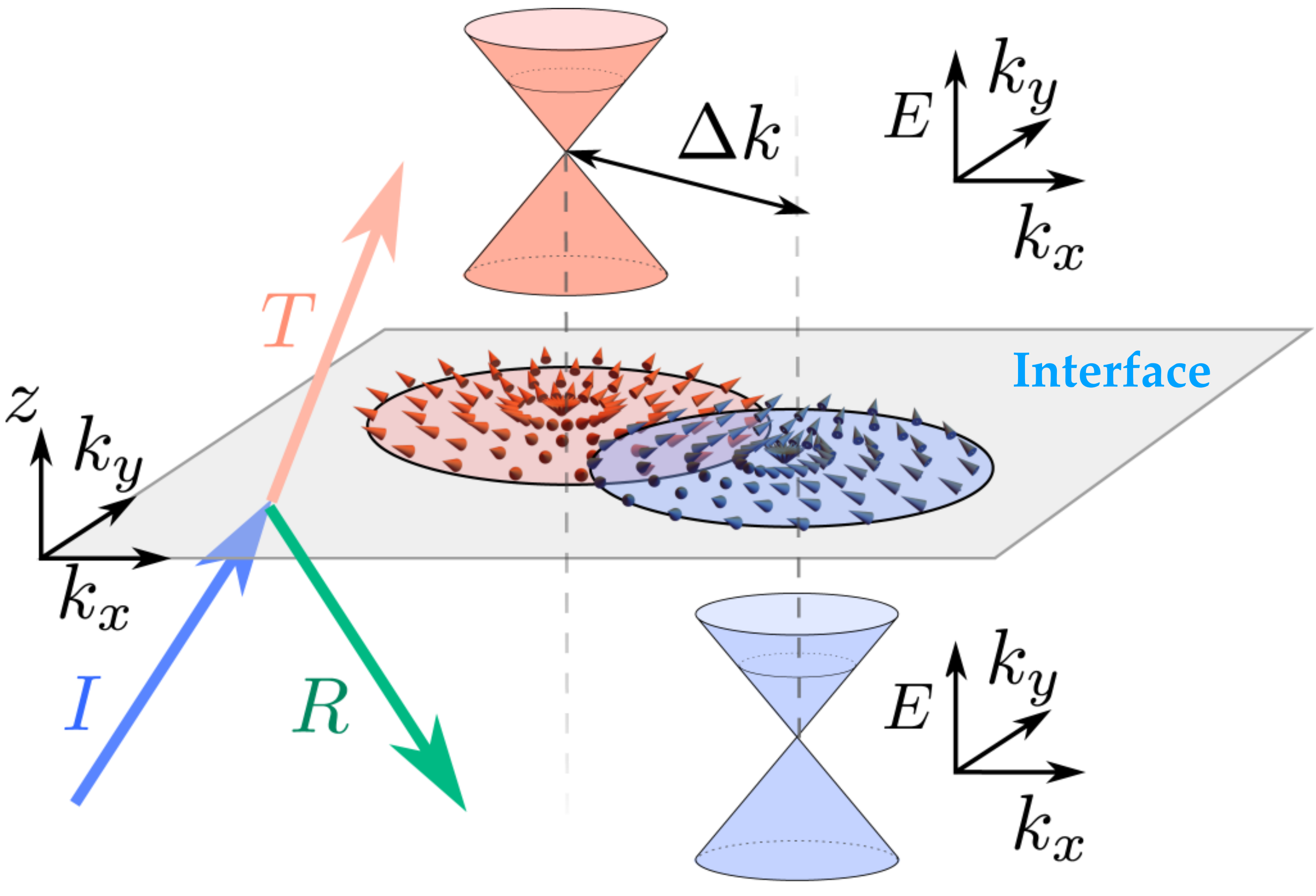
Valleytronics

Chirality?

IV) Veselago lensing
in 3D Weyl semi-metals

S. Tchoumakov, J. Cayssol, and A.G. Grushin, PRB 105, 075309 (2022)

Chirality filtering



First idea : shifting the Weyl nodes in momentum space

3D Veselago lensing

Recipe : Replace graphene by a 3D Weyl/Dirac semimetal

3 Issues :

1) Large carrier density but hard to tune it by gating

2) Bad interfaces because 2 different materials (disorder)

3) Insensitivity to internal degree of freedom : spin or chirality

Solution :

Use **the chiral anomaly** to create selectively a pn junction for one chirality only

Chirality of a Weyl fermion

Chirality : projection of spin along momentum

$$H_R = v\sigma \cdot (\mathbf{p} - \mathbf{K})$$

Positive chirality

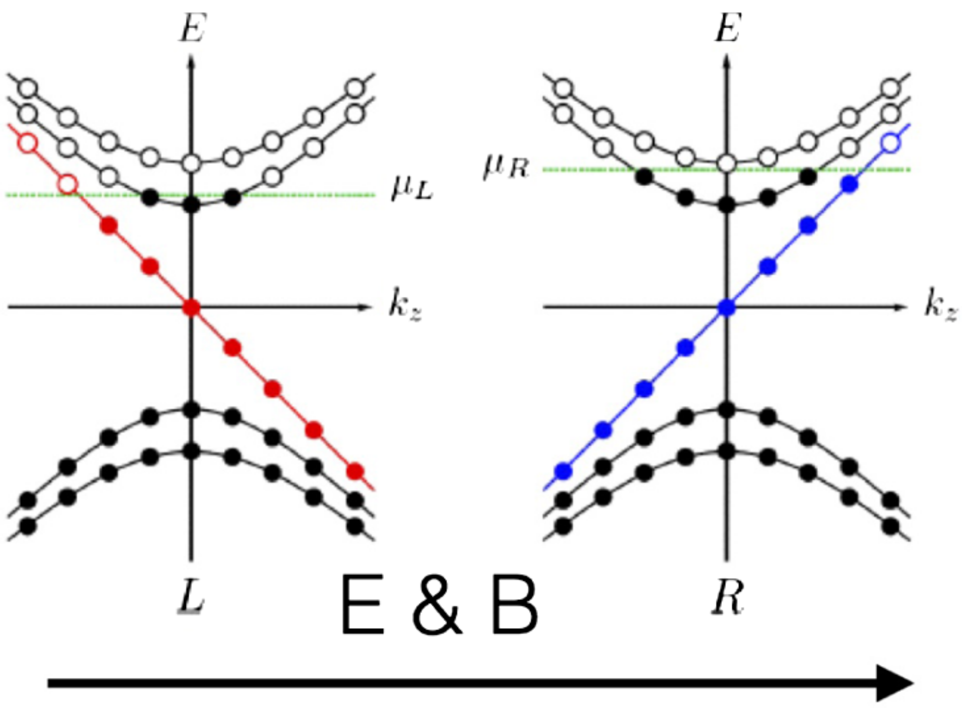
$$H_L = -v\sigma \cdot (\mathbf{p} + \mathbf{K})$$

Negative chirality

Total chirality is zero : even number of Weyl nodes (Nielsen-Ninomiya)

Chiral anomaly

Simplest case : two Weyl nodes of opposite chiralities



Landau levels (3D)

$$\frac{dn^{3D}_{R/L}}{dt} = \pm \frac{e^2}{h^2} \mathbf{E} \cdot \mathbf{B}$$

Nielsen-Ninomiya (1983)

Effect of B : disperse along the B field direction only

Effect of E : push/pump electrons from one node to the other

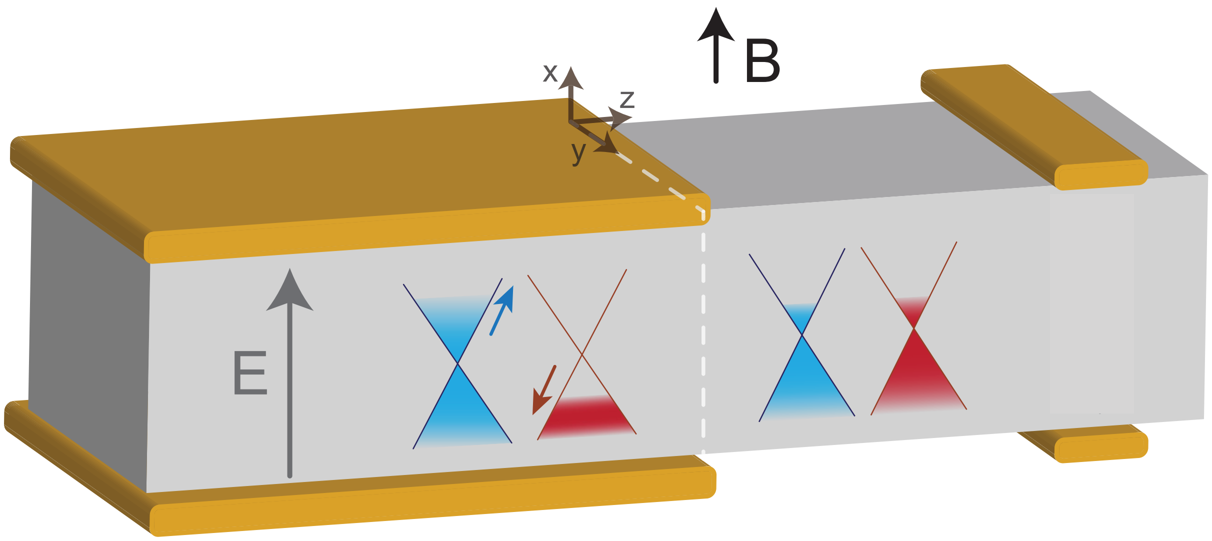
Interface and chiral anomaly

$$\Delta n = \frac{\tau e^2}{2\pi^2\hbar^2}\mathbf{E}\cdot\mathbf{B}$$

Interface : two Weyl nodes of opposite chiralities

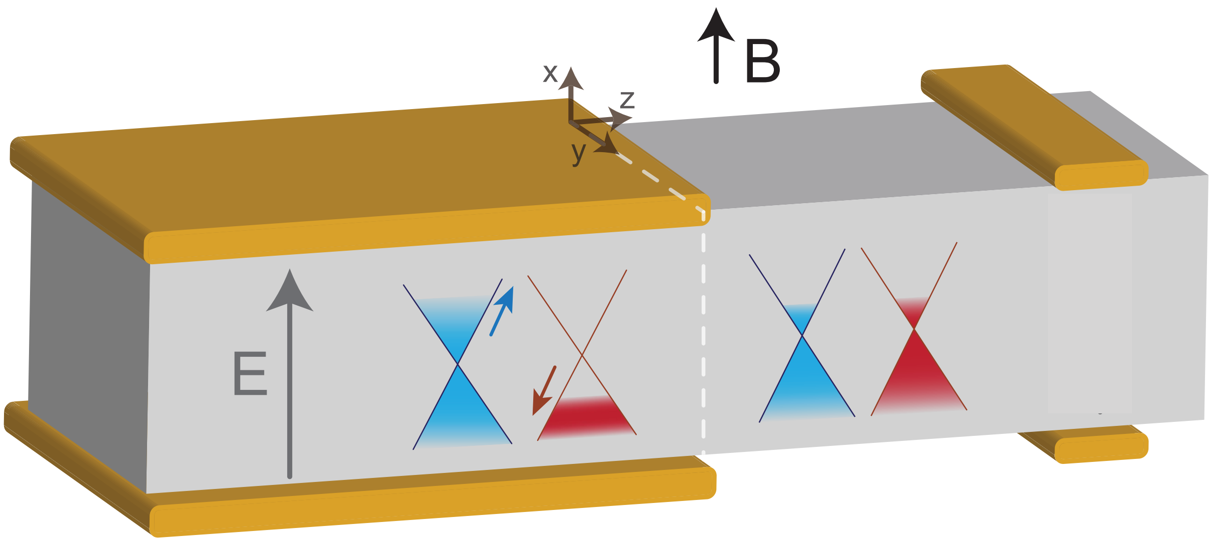
Magnetic field is applied homogeneously

Same material (clean interface)



pn junction when the magnetic field exceeds a critical value (of order 1 Tesla)

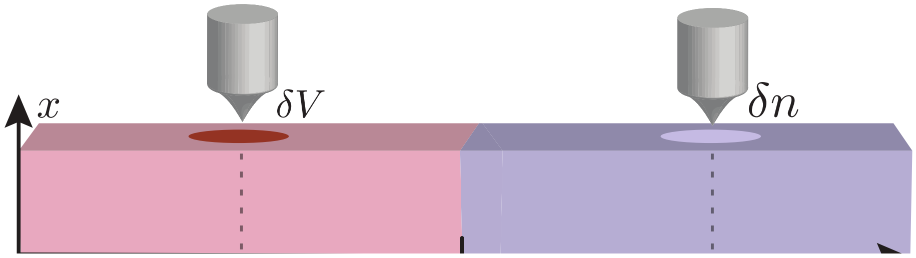
Interface and chiral anomaly



pn junction : the red chirality is Veselago focused by the interface

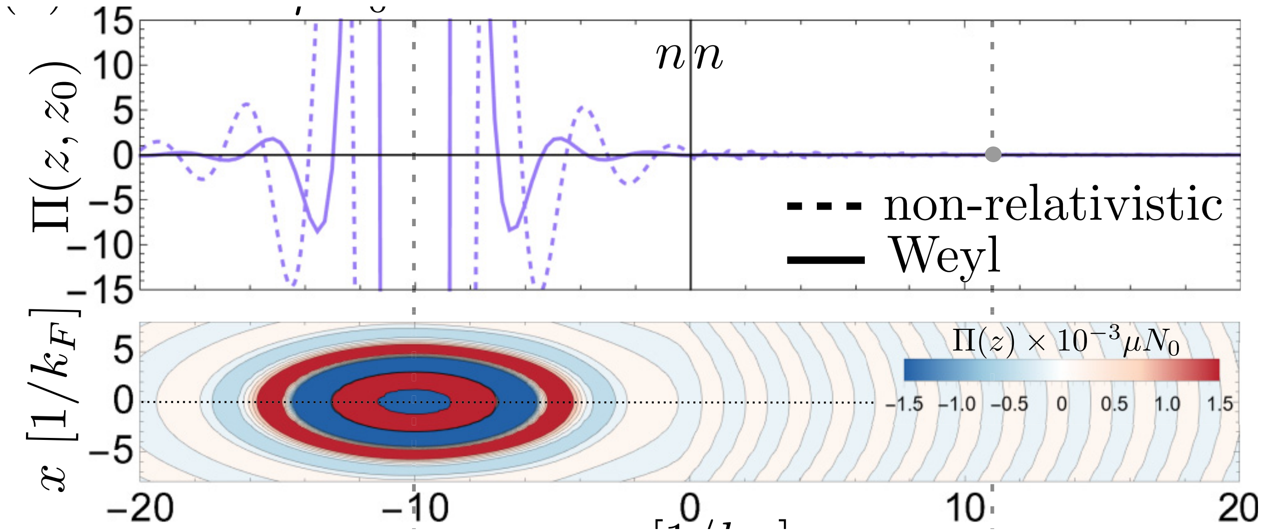
nn′ junction : the blue chirality is not

Polarizability and STM experiments



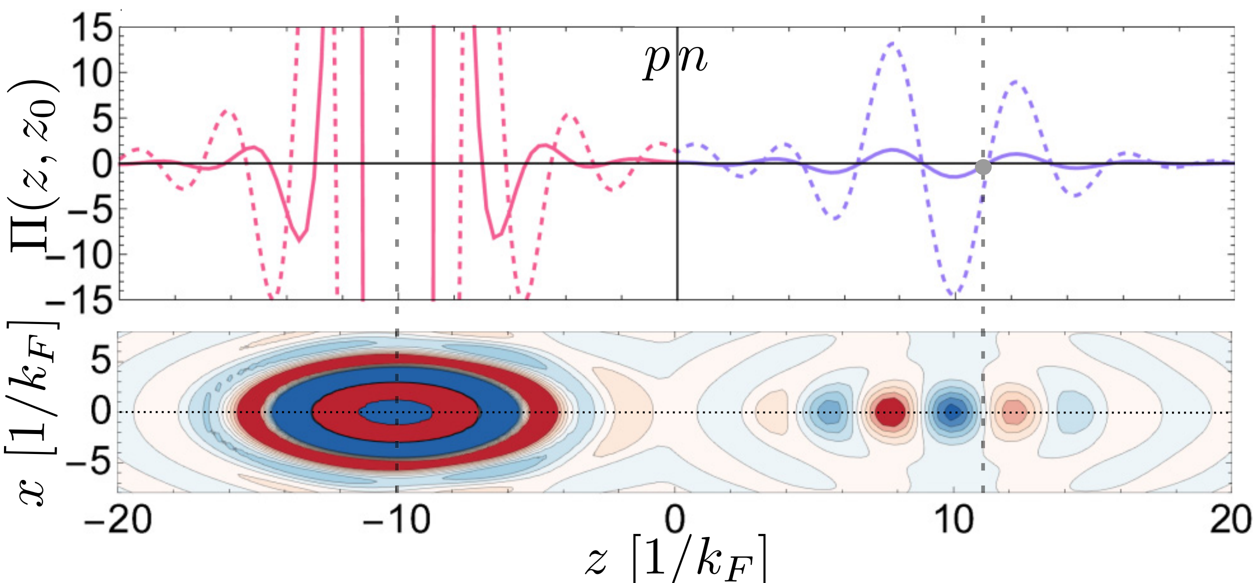
$$\Pi(z,z') = -\frac{1}{2\pi}\int d\omega\, \mathrm{Tr}\left[\hat{G}(z,z')\hat{G}(z',z)\right]$$

Polarizability results



nn junction

Damped Friedel oscillations



np junction

Formation of a (charge) image

Conclusion

Veselago effect allows focalisation of a beam by a single flat interface between materials with « opposite » dispersions. This is implemented by pn junctions in Dirac materials

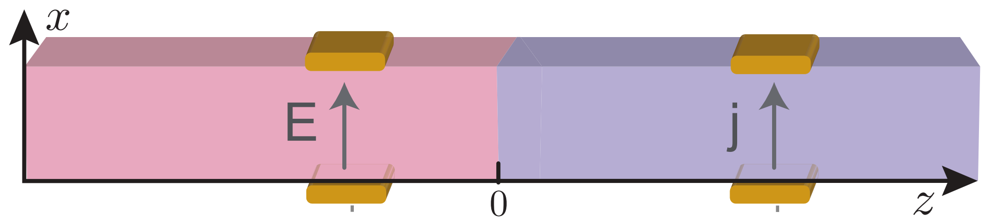
Graphene and Weyl : Zero gap allows transparent interfaces

Those pn junctions can be created either by :

- electrostatic doping (2D)
- the chiral anomaly pumping. In this case, the focusing is also chirality sensitive

Thank you !

Nonlocal transport



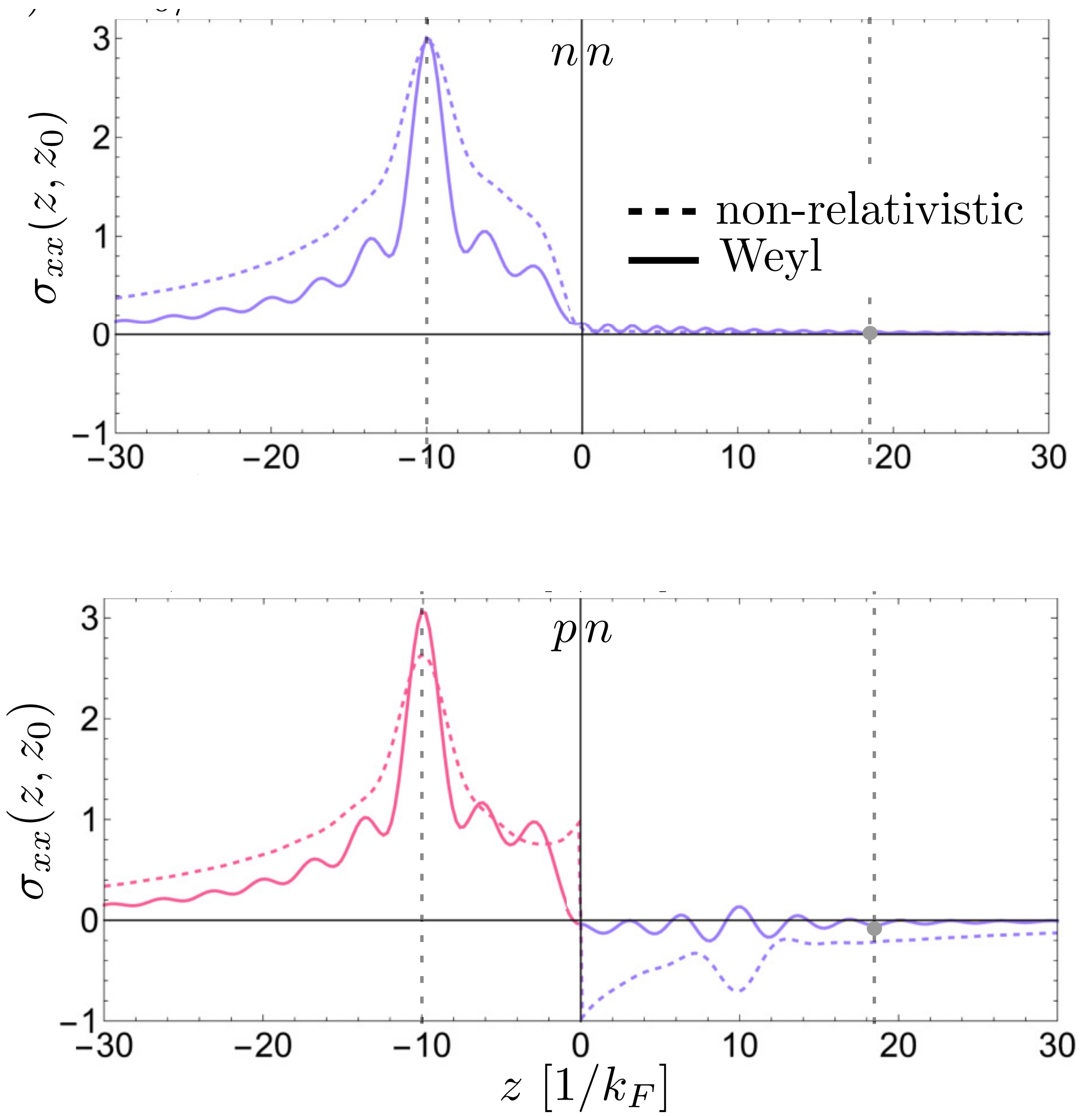
Magnetic field applied homogeneously and beyond a critical field (necessary to generate the pn junction)

Voltage only on one side of the junction

Nonlocal conductivity

$$\sigma_{\mu\nu}(z, z') = \int \frac{dS_z dS_{z'}}{\pi \mathcal{A}} \mathrm{Tr}\big[\hat{j}_\mu \,\mathrm{Im}\, \hat{G}(z, z') \hat{j}_\nu \,\mathrm{Im}\, \hat{G}(z, z')\big]$$

Nonlocal conductivity results



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Quantum interference and Klein tunnelling in graphene heterojunctions

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