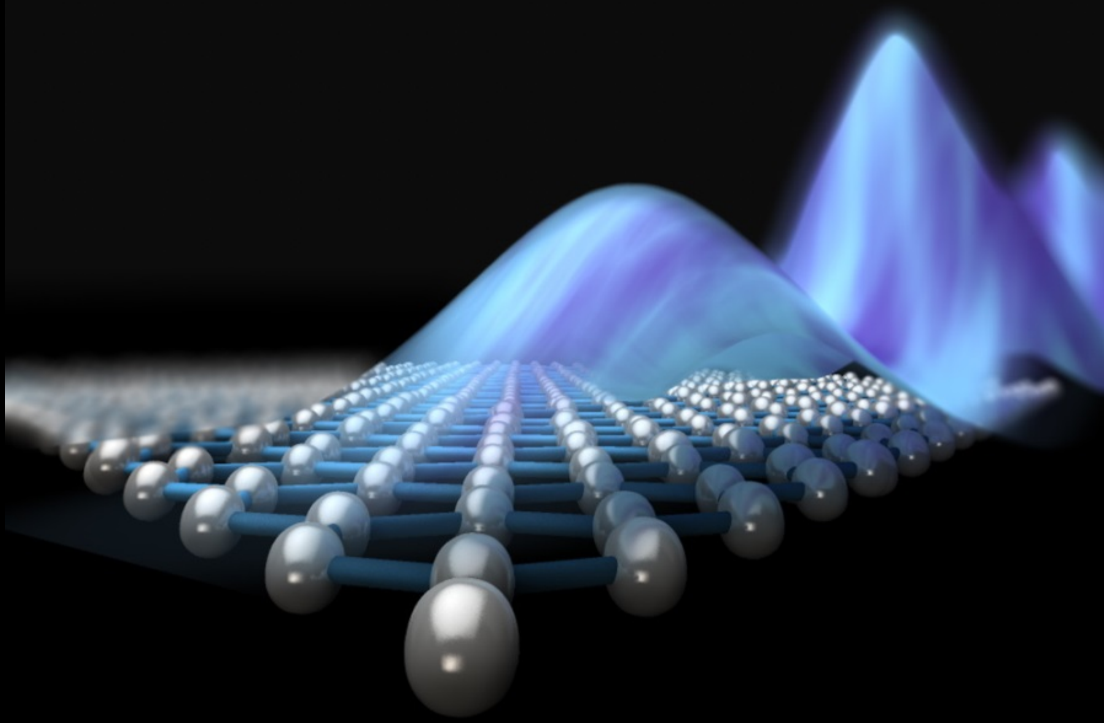
2D Nanophotonics



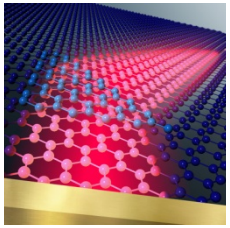
Alexey Nikitin

Donostia International Physics Center

ikerbasque
Basque Foundation for Science

CIC nanoGUNE
nanoscience cooperative research center

Outline of the presentation



- **Intro: Nanooptics of Van der Waals materials**

- **Launching graphene plasmons with metallic antennas**

- **Nanoimaging of hyperbolic polaritons**

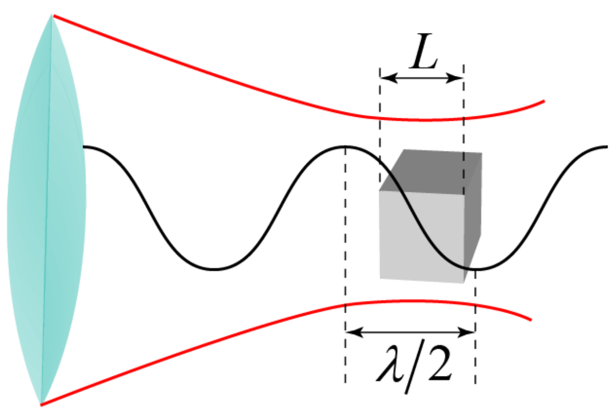
Diffraction limit

("Uncertainty principle")

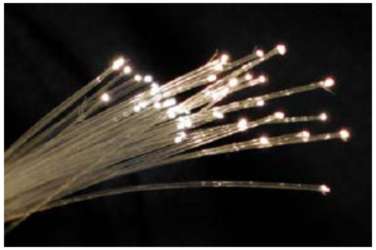
Propagating waves

$$E(x,y) \propto e^{ik_x x + ik_z z}$$

$$\Delta x \geq \frac{1}{2\Delta k_x} \qquad L \geq \frac{\lambda}{2}$$



Example: optical fibers

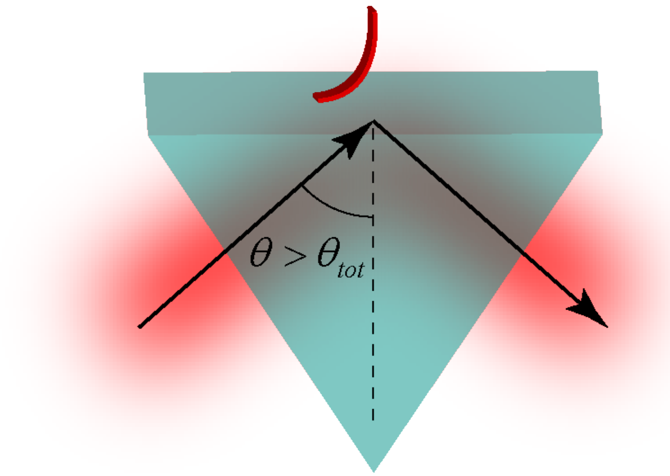


Evanescent waves

$$E(x,y) \propto e^{ik_x x - |k_z| z}$$

$$\Delta x < \frac{1}{2\Delta k_x}$$

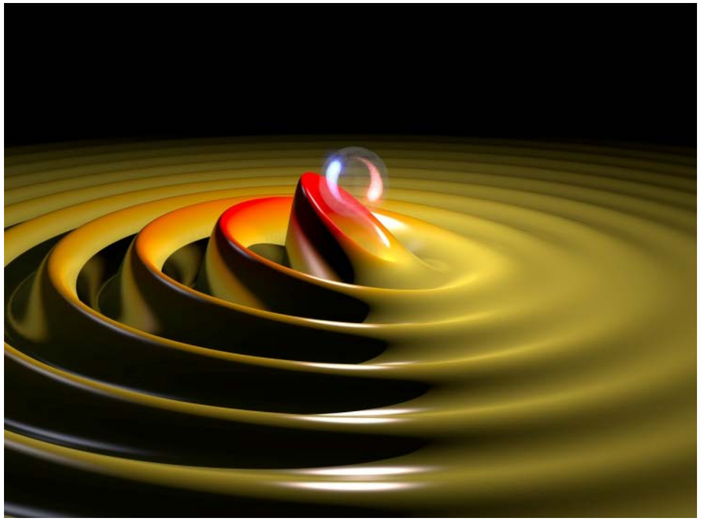
Example: total internal reflection



Surface waves: Plasmonics

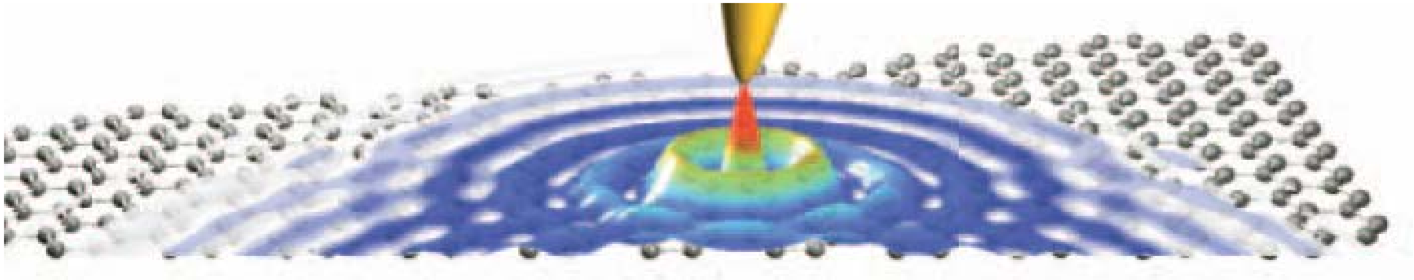
Gravity–capillary waves on a surface of water

Surface plasmons on metallic surfaces



Science **340**, 328 (2013)

Plasmons in graphene (one-atom-thick conductor)

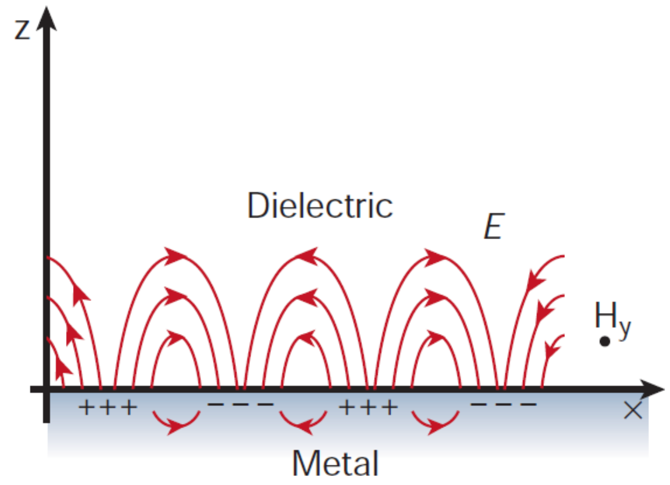


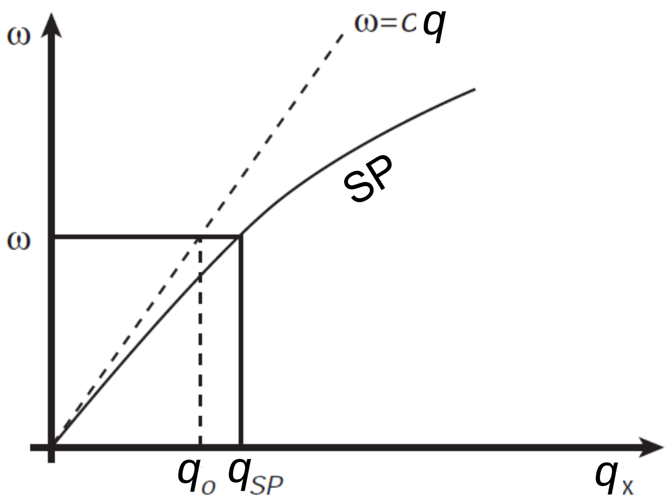
Nature **487**, 77 (2012)

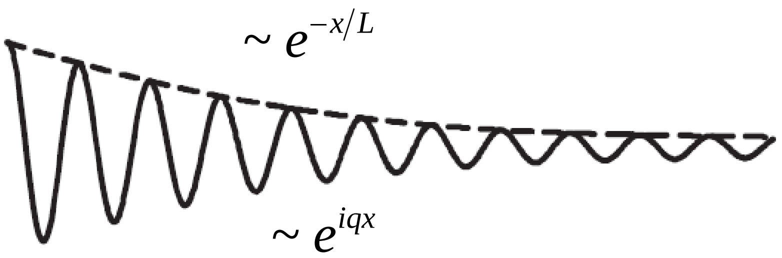
Surface plasmon-polaritons

Surface plasmon-polaritons on metallic surafces

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} > k_0$$



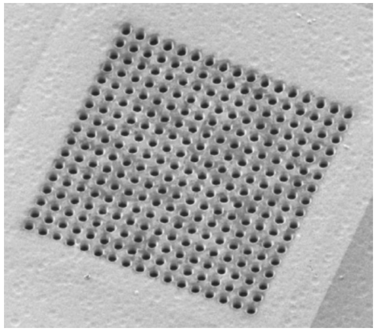


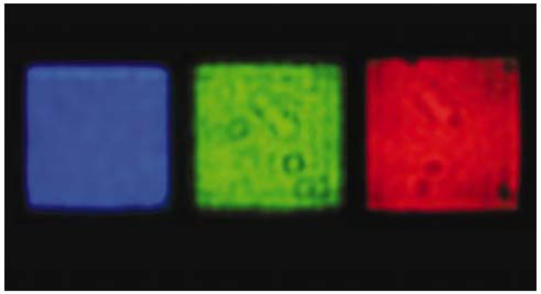


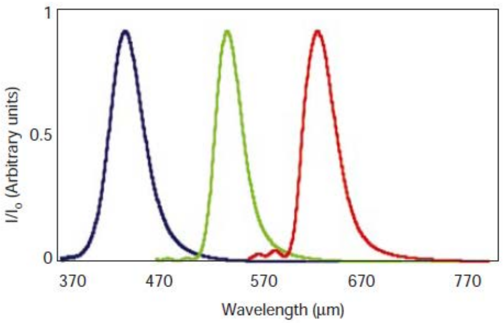
W. L. Barnes et al., Nature **424**, 824 (2003)

Plasmonics in the visible

Plasmonic sensing and filtering: hole arrays

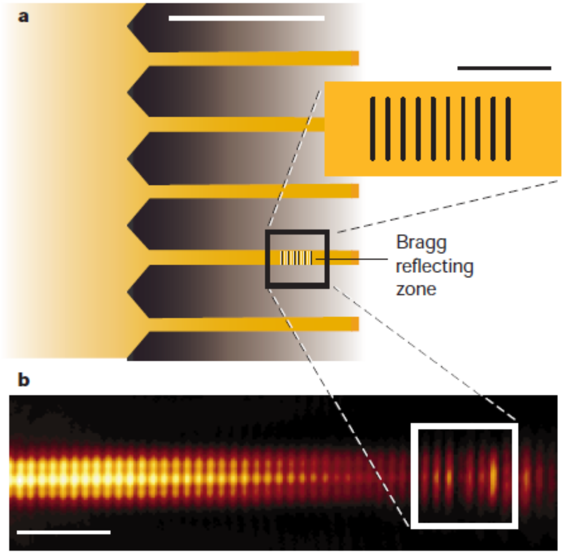




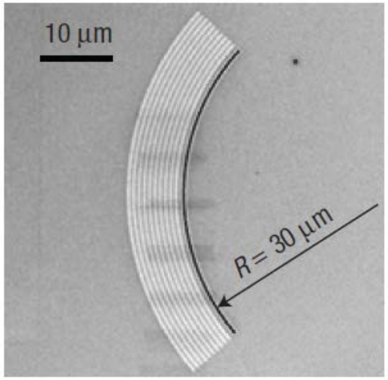


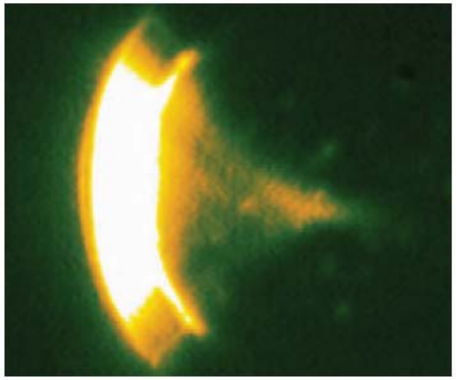
T. W. Ebbesen et al., Nature **391**, 667 (1998)

Plasmonic waveguiding and focusing



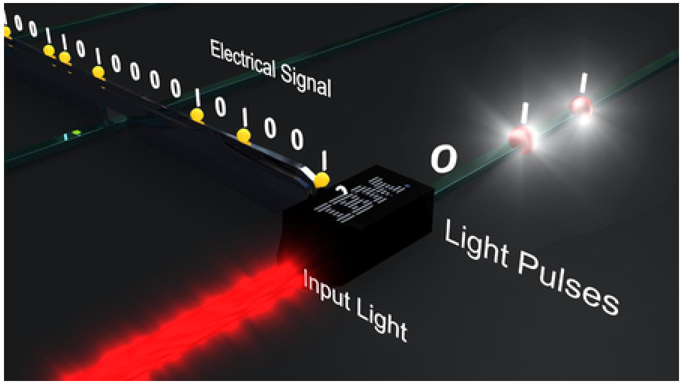
W. L. Barnes et al., Nature **424**, 824 (2003)



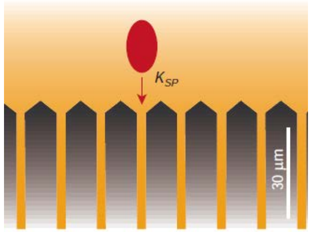


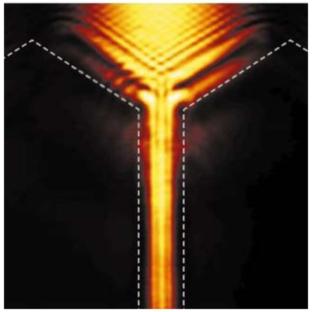
F. López-Tejeira et al., Nat. Phys. **3**, 324 (2007)

Optical solutions: possible future of Electronics?

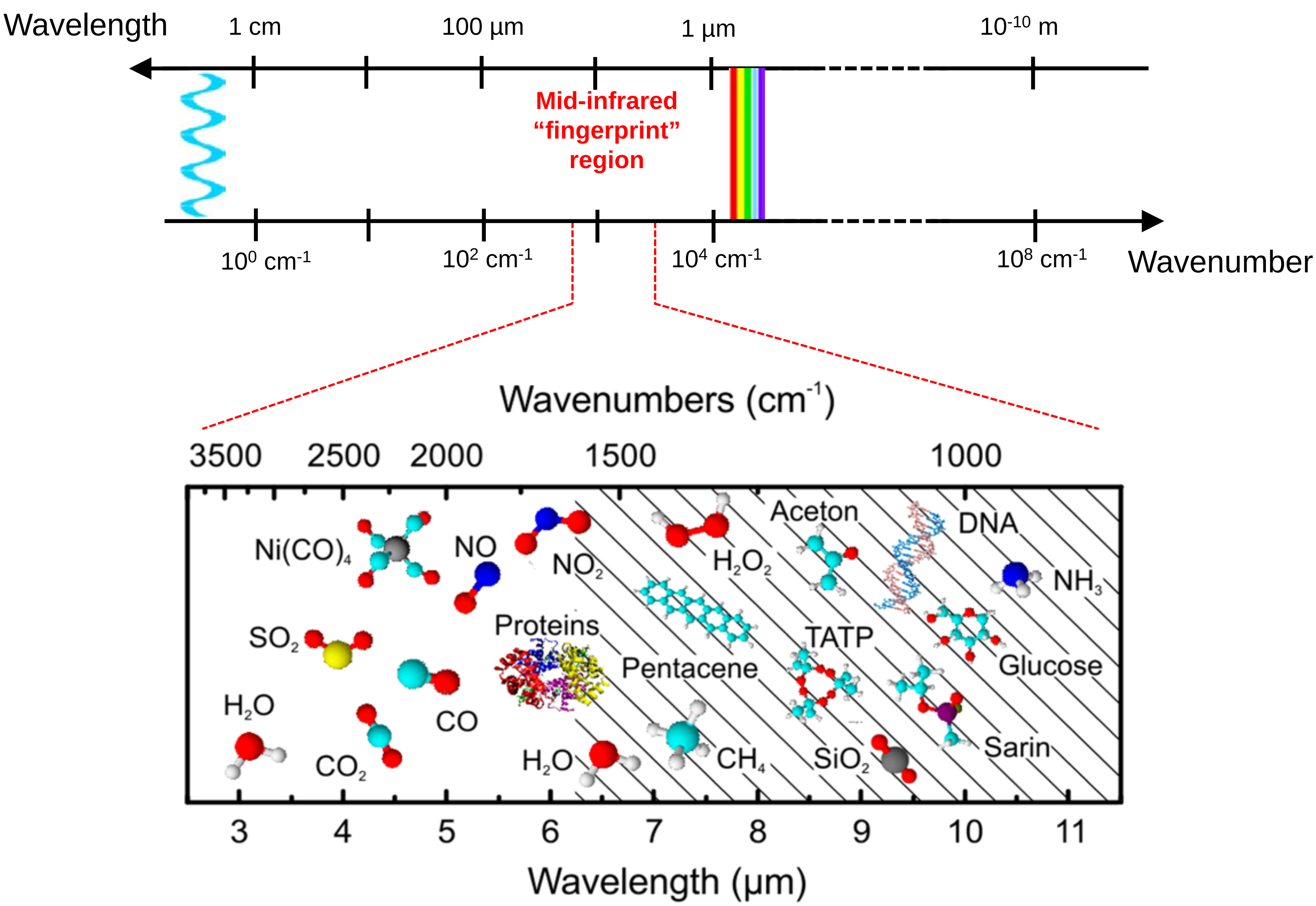


Thin metallic optical interconnectors





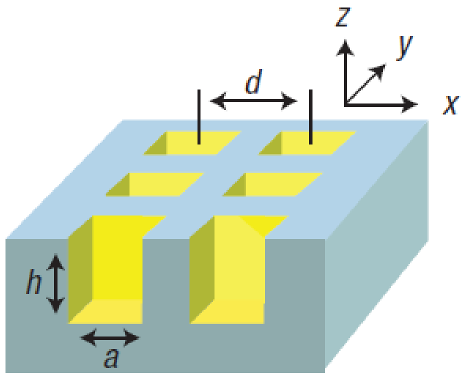
mid-IR molecular spectroscopy

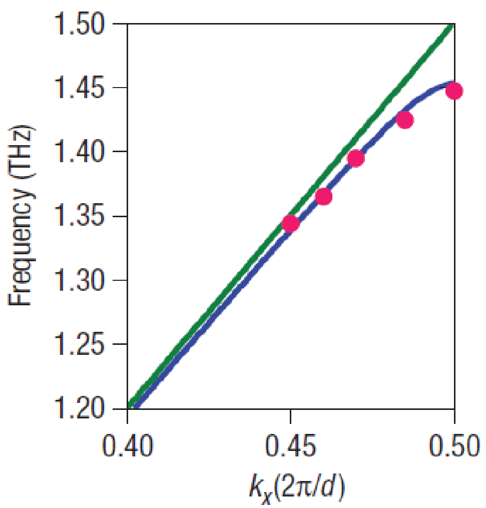


F. Neubrech et al., Chem. Rev. **117**, 5110 (2017)

Plasmonics in mid-IR and THz

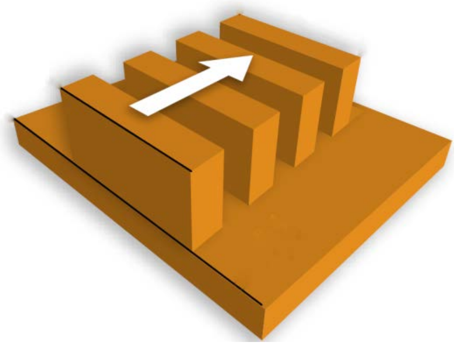
Spoof plasmons

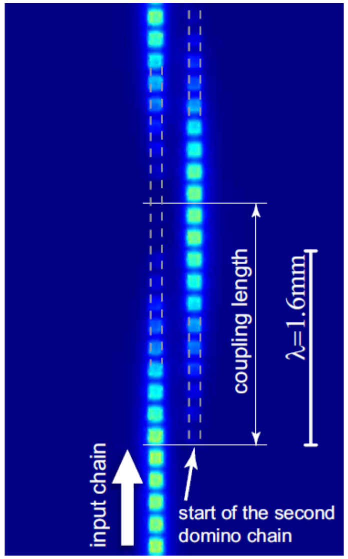




Science **305**, 847 (2004)
Nature Photon. **2**, 175 (2008)

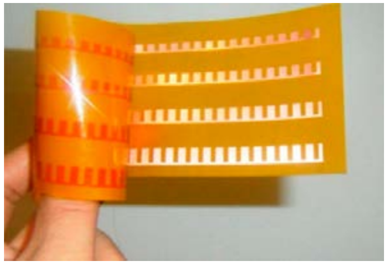
Domino plasmons

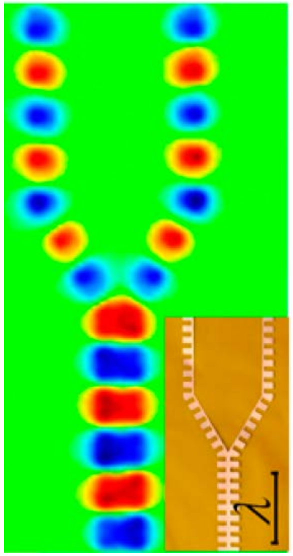




Opt. Express **18**, 754 (2010)

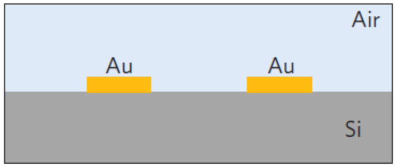
Conformal plasmons

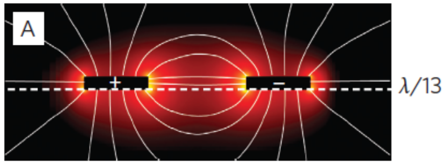




PNAS **110**, 40 (2013)

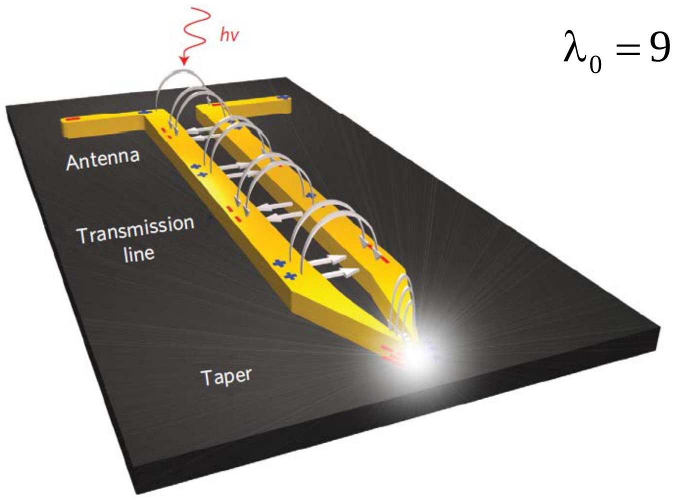
Transmission lines

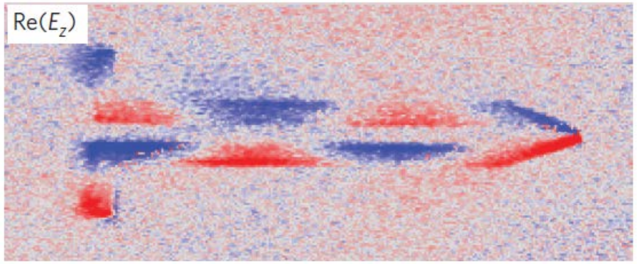


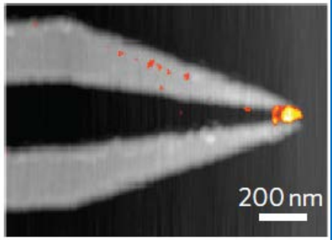


Tapering the transmission line

$$\lambda_0 = 9.3\,\mu m$$

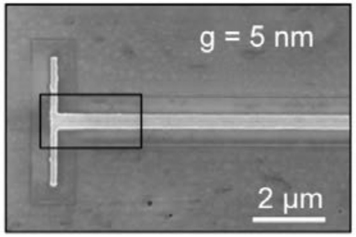


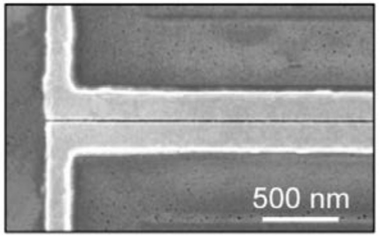


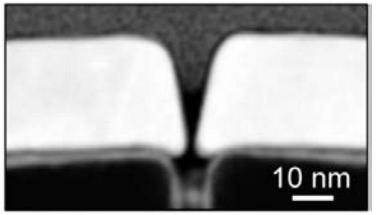


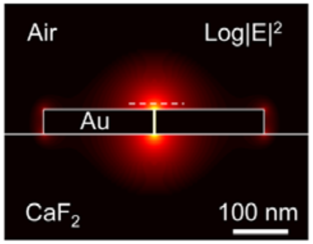
M. Schnell et al. Nat. Photon. **5**, 283 (2011)

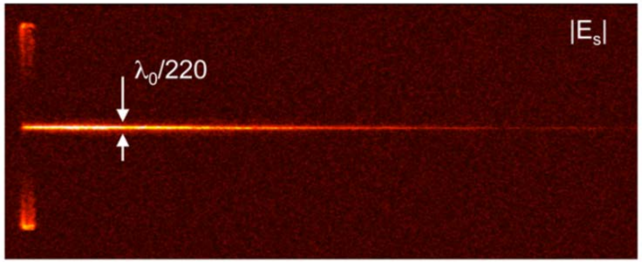
Ultra-narrow gap transmission lines









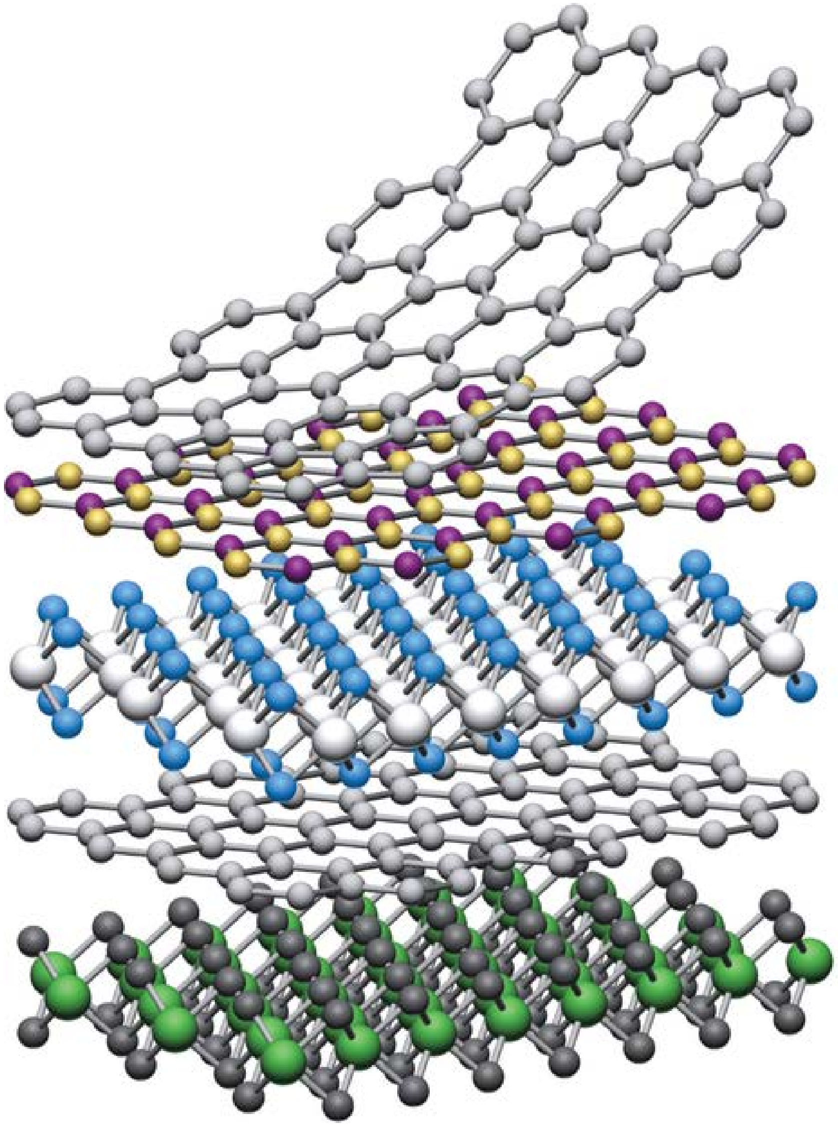


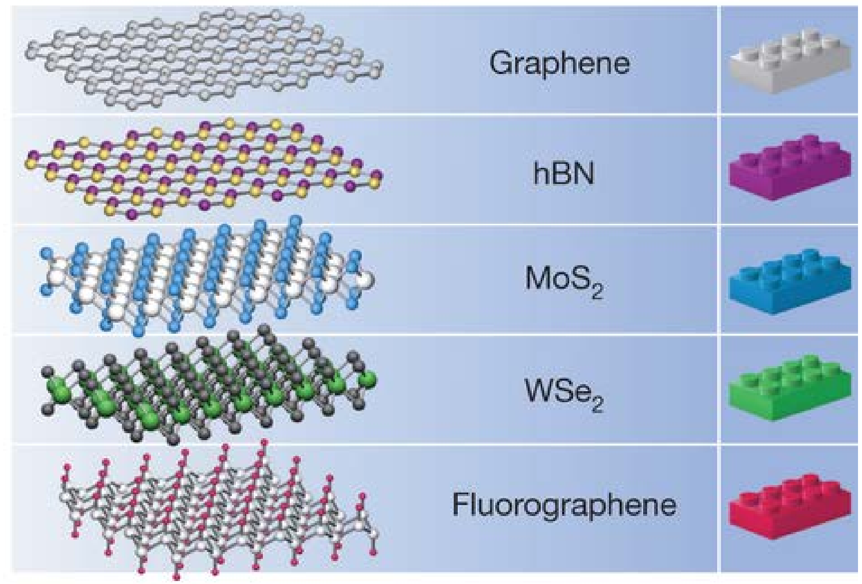
P. Sarriugarte et al. ACS Photonics **1**, 604 (2014)

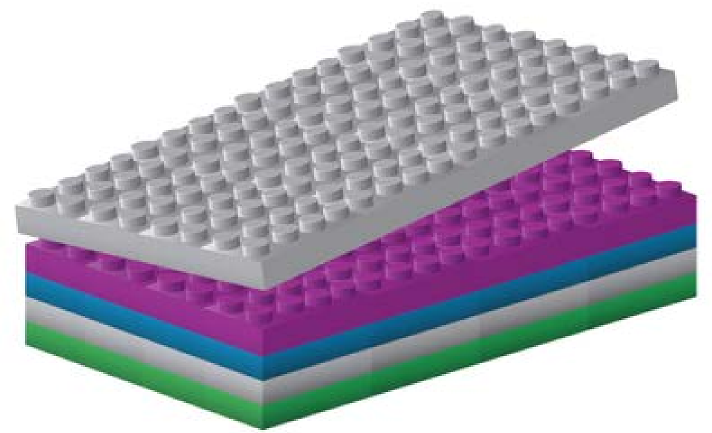
Van der Waals forces

Geckos can stick to walls and ceilings because of Van der Waals forces

Van der Waals heterostructures: “Lego concept”

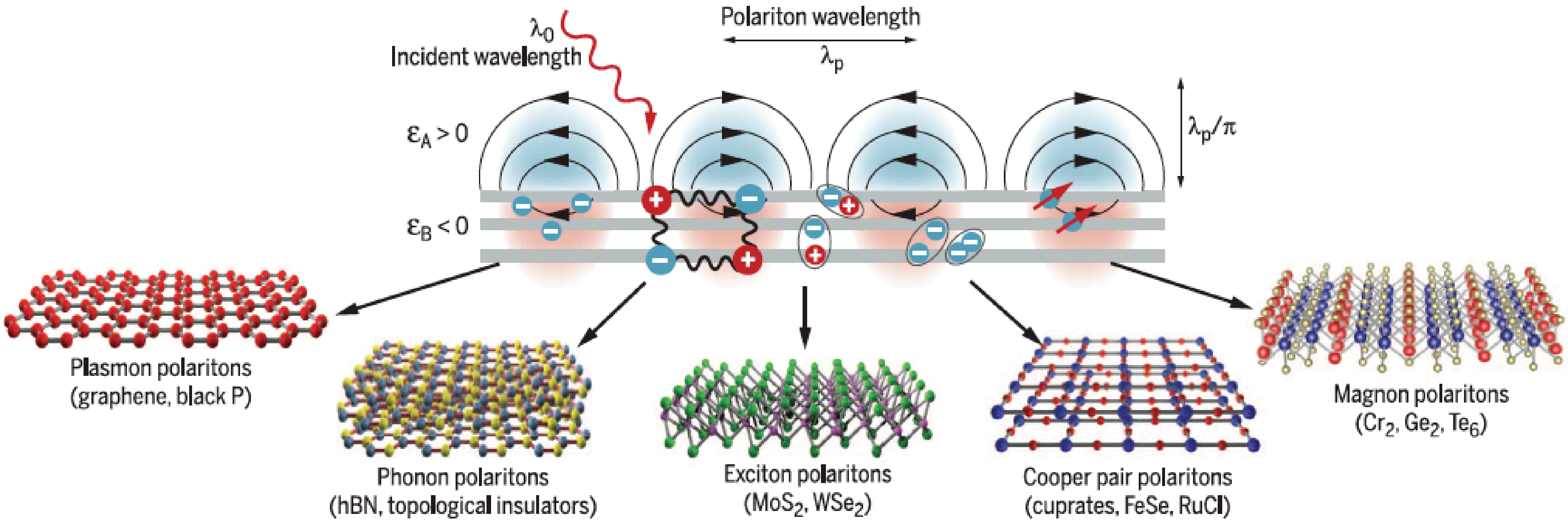






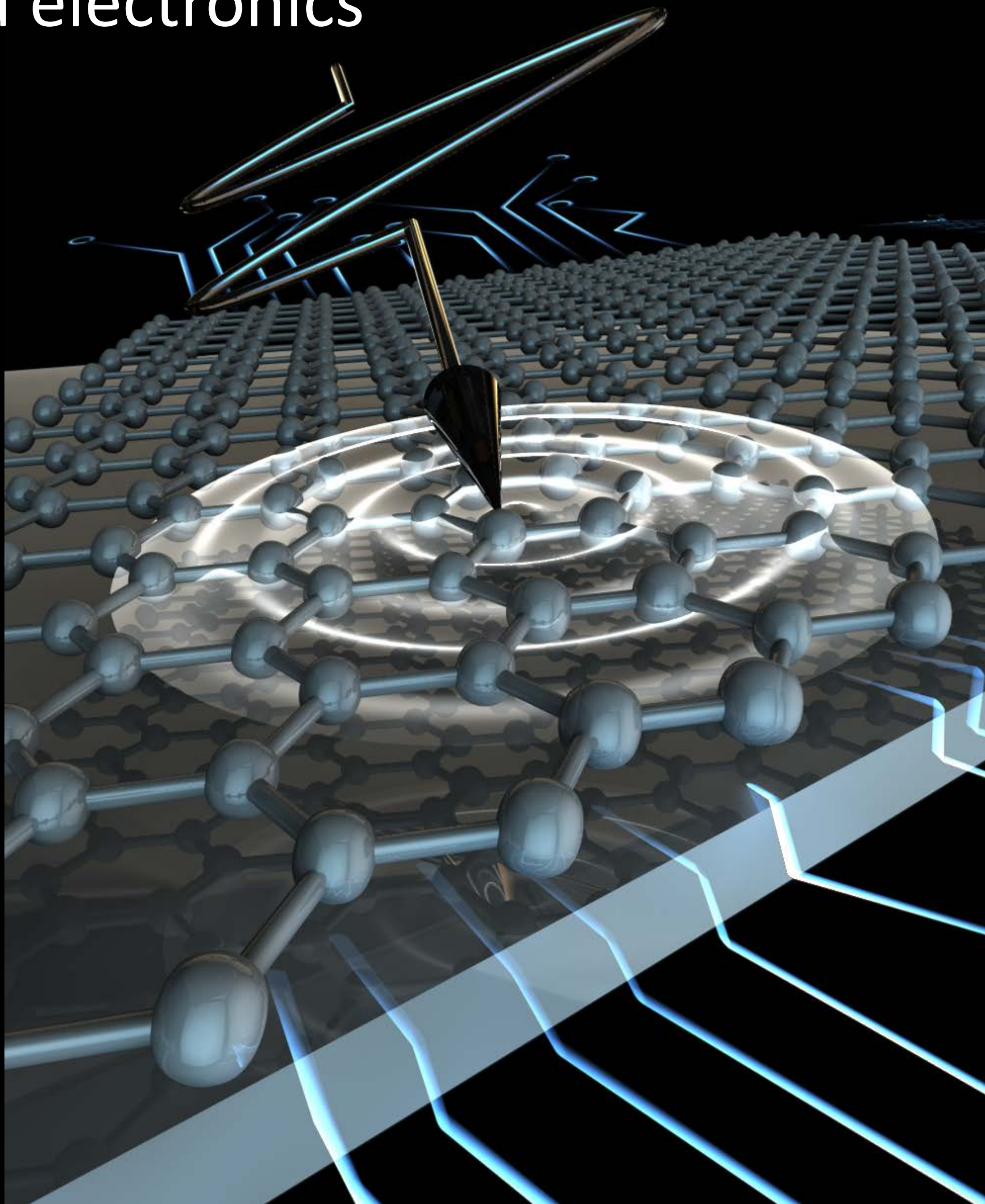
Nature **499**, 419 (2013)

Polaritons in van der Waals materials



Science **354**, 1992 (2016)
Nature Mat. **16**, 182 (2017)

Merging photonics and electronics



Photodetection with graphene

– *in THz*: Nat. Nanotechnol. **12**, 31 (2017)

– *in mid-IR*: Nat. Mater. 16 204 (2017)

– *the review:* Nature Nanotechnol. 9, 780 (2014)

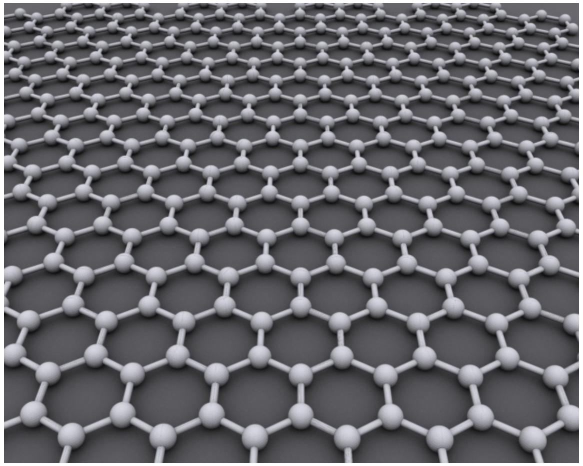
– *see works of Victor Ryzhii & Dmitry Svintsov*

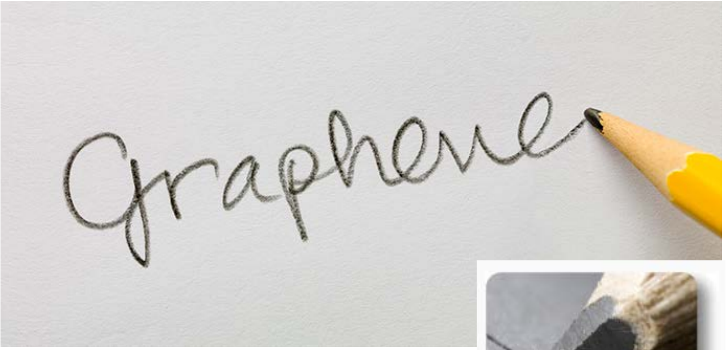
Graphene: Nobel Prize in Physics

2010

Andre Geim

Konstantin Novoselov

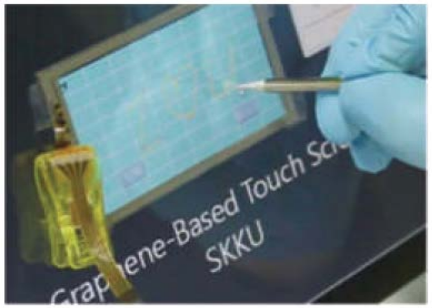




Science 306, 666 (2004)

Graphene-based optoelectronics

Touch screen



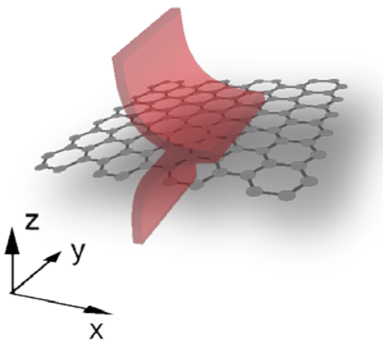
Flexible smart window

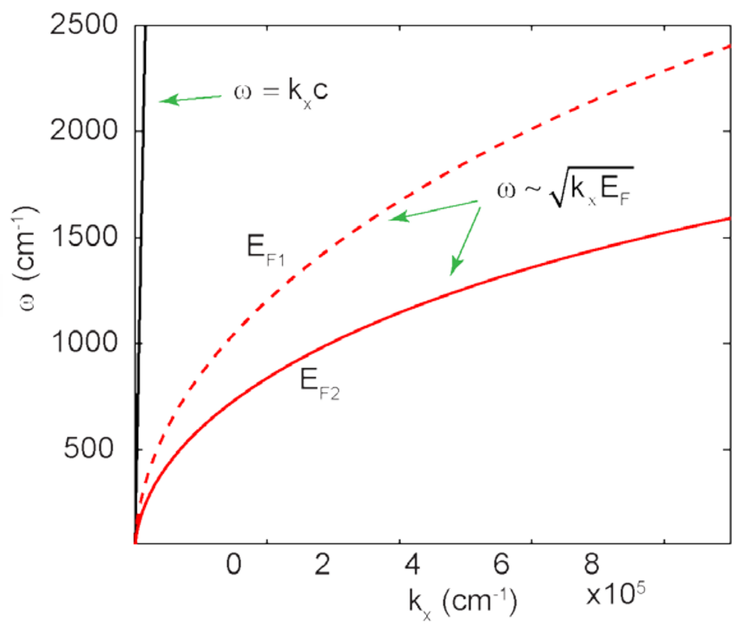
F. Bonaccorso et al., *Nature Phot.* **4**, 611 (2010)

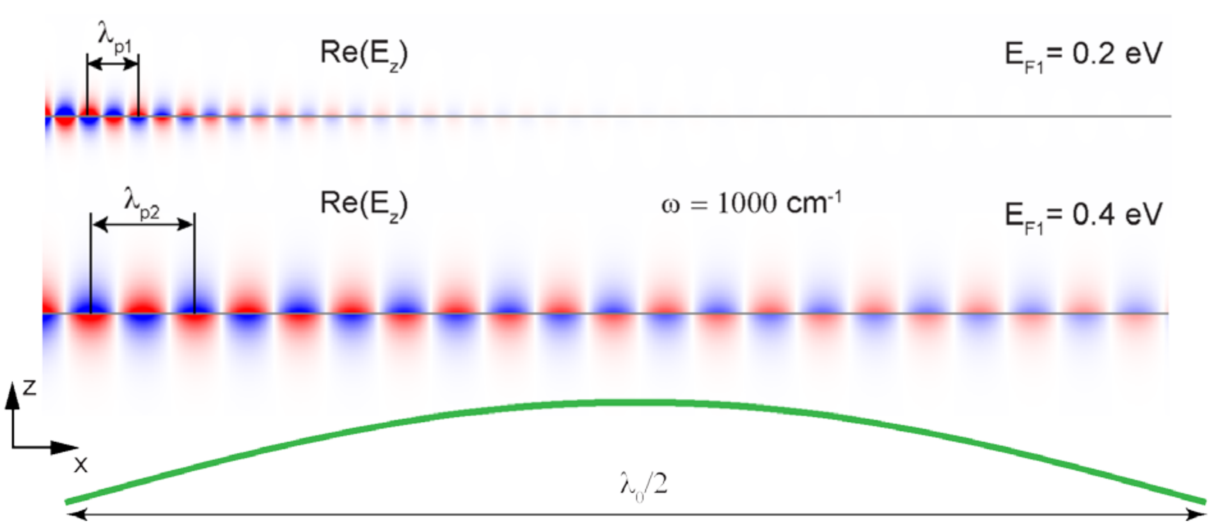
Ultrathin flexible technologies

http://graphenewholesale.com/graphene-uses/

Plasmons in graphene







Important properties

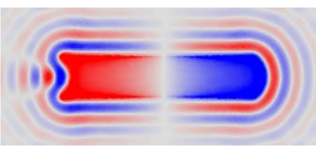
- Tunable
- Extremely short-wavelength
- Ultra-confined
- Very sensitive to environment

Relevant applications

- Strong light-matter interaction
- (Bio)Sensing
- Photocurrent detection and generation
- Nonlinear optics
- Nanophotonic circuits (light manipulation, modulation)

Nikitin in "*Handbook of Metamaterials and Plasmonics*", World Scientific (2017)

- Intro: Nanooptics of Van der Waals materials

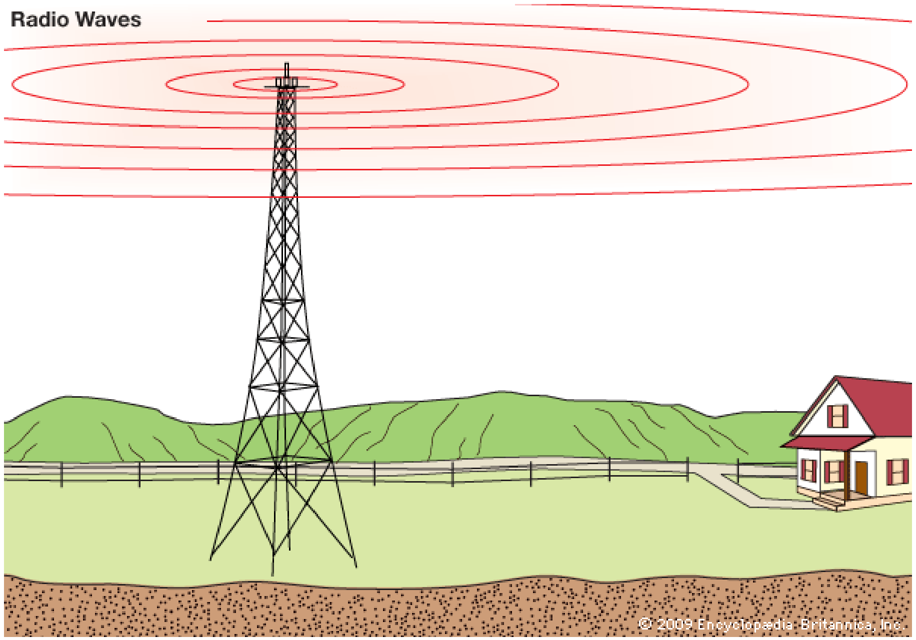


- **Launching graphene plasmons with metallic antennas**

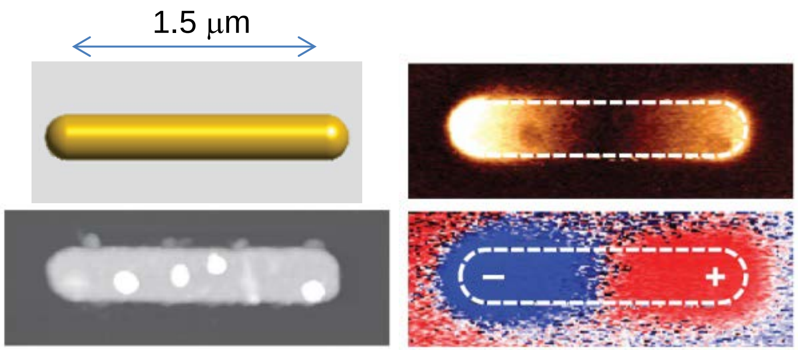
- Nanoimaging of hyperbolic polaritons

Radio-wave and optical antennas

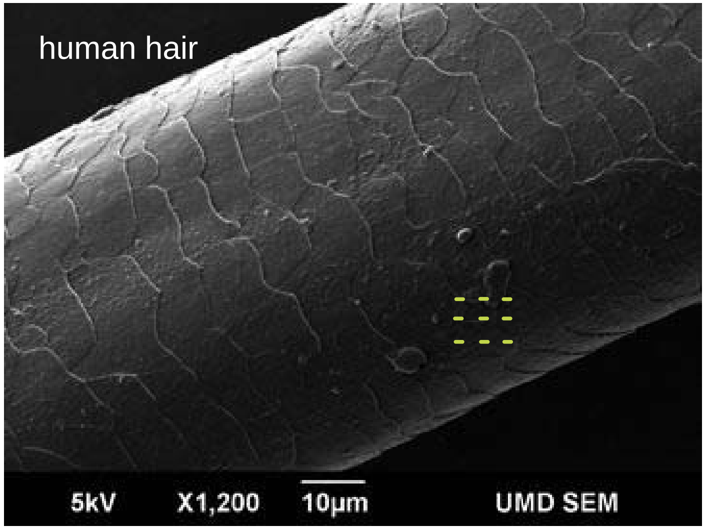
Radio-wave antenna



Infra-red antenna

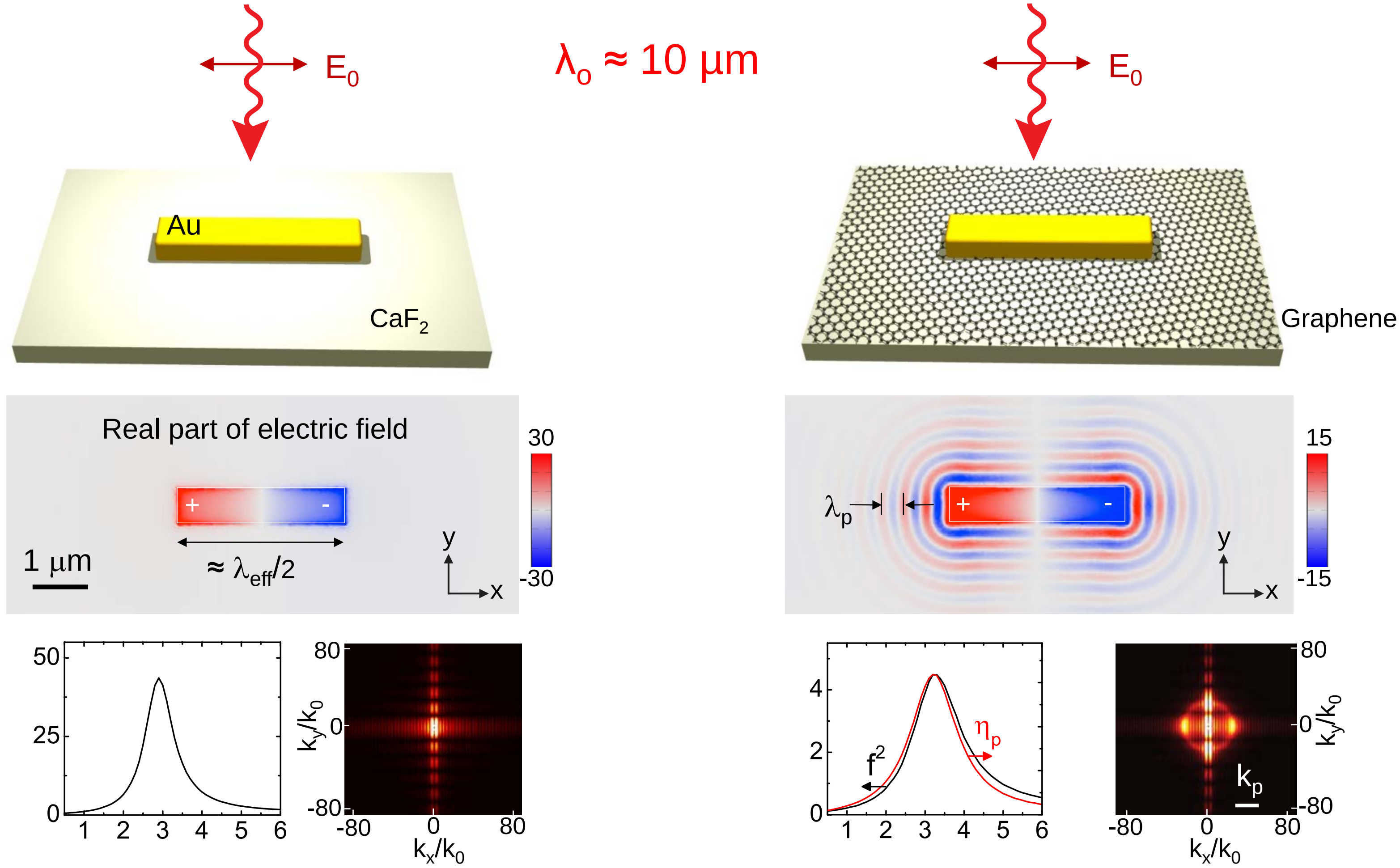


Nature Photonics 3, p.287 (2009)



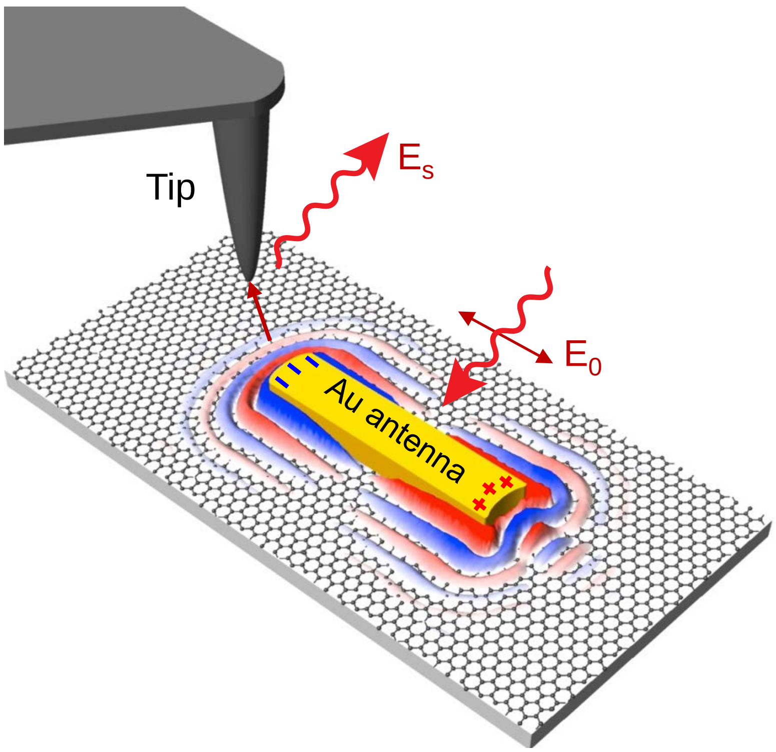
Scanning Electron Microscopy © 2010 University of Minnesota Duluth

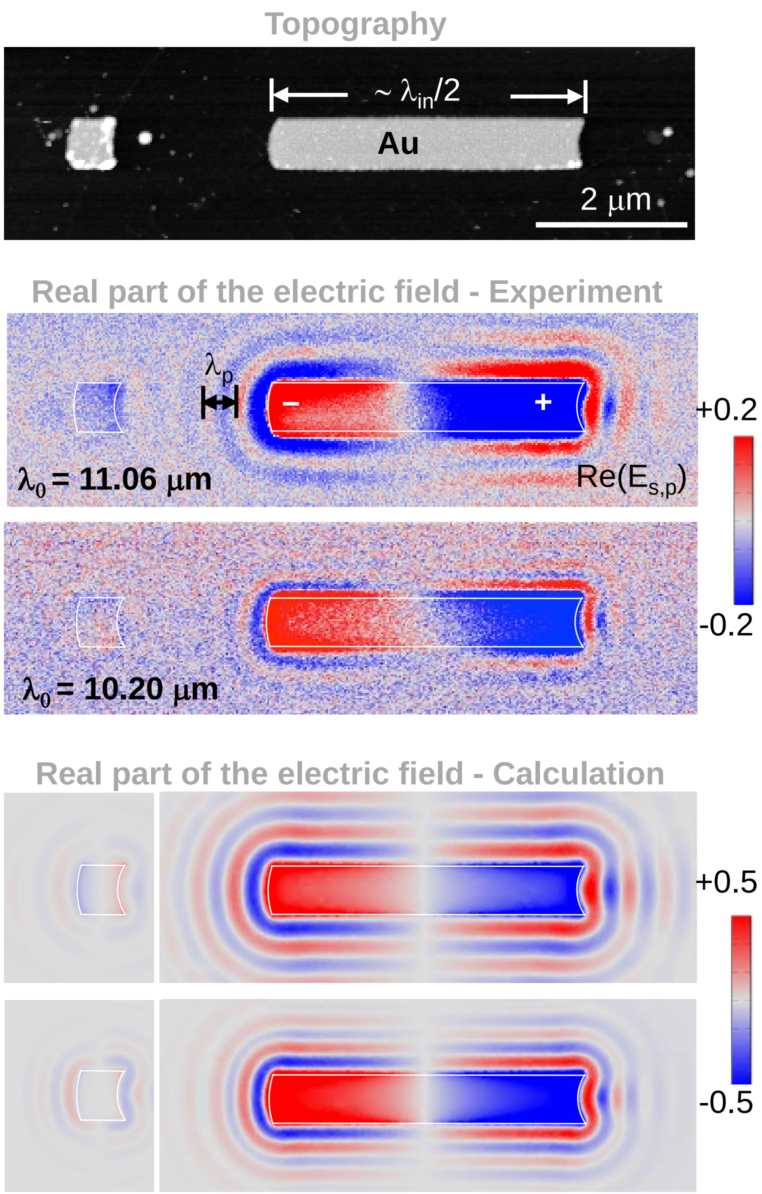
Graphene plasmons can be launched by metal antennas



Alonso Gonzalez, et al., Science **344**, 1369 (2014)

We can image graphene plasmon wavefronts



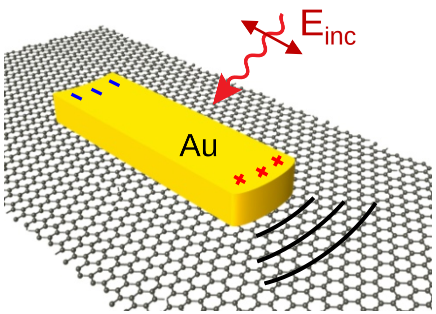


- Plasmon field amplitude scales with antenna field
- Plasmon phase follows the antenna phase

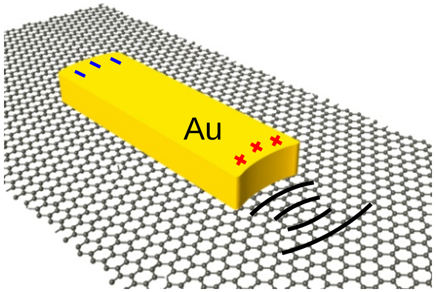
Alonso Gonzalez, et al., Science **344**, 1369 (2014)

Graphene plasmons can be focused by tailoring the antenna geometry

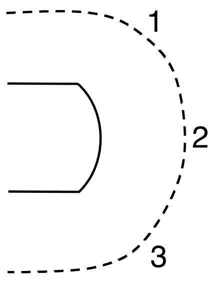
Topography | Experiment | Calculation

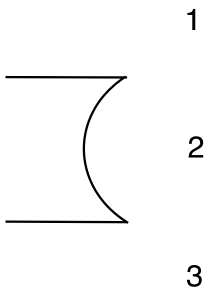


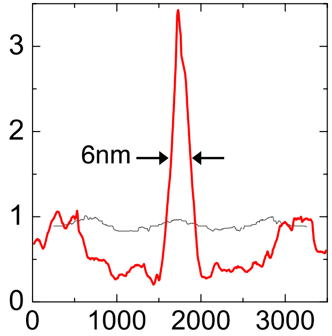
convex



concave

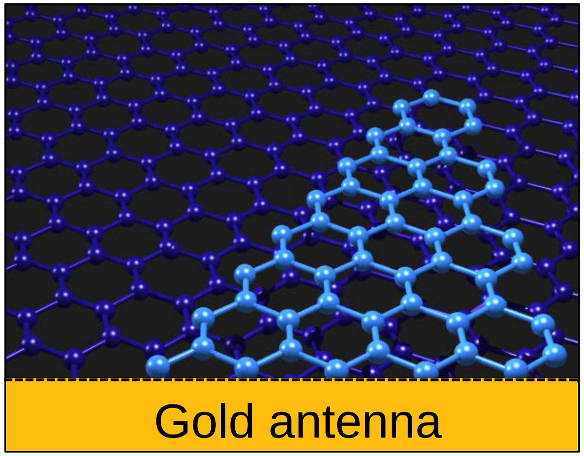


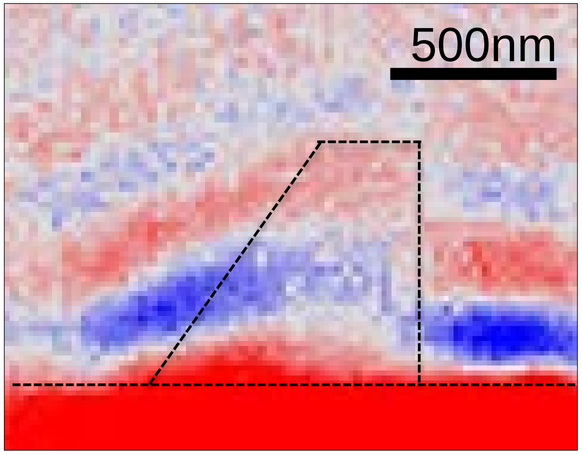




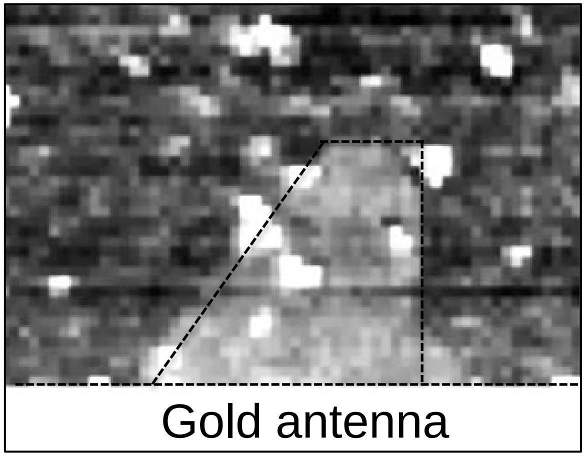
Alonso Gonzalez, et al., Science **344**, 1369 (2014)

Graphene plasmons refract when passing through a double layer





Topography



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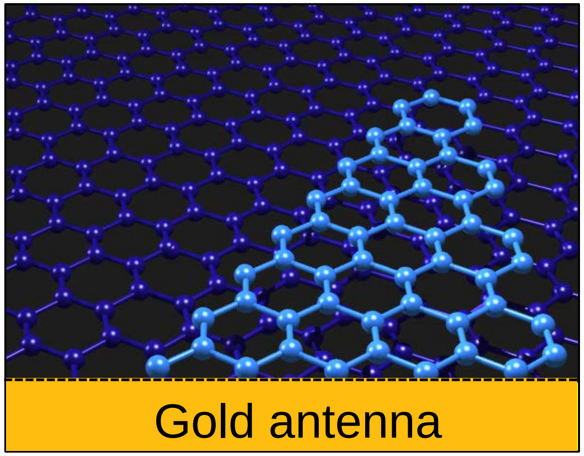
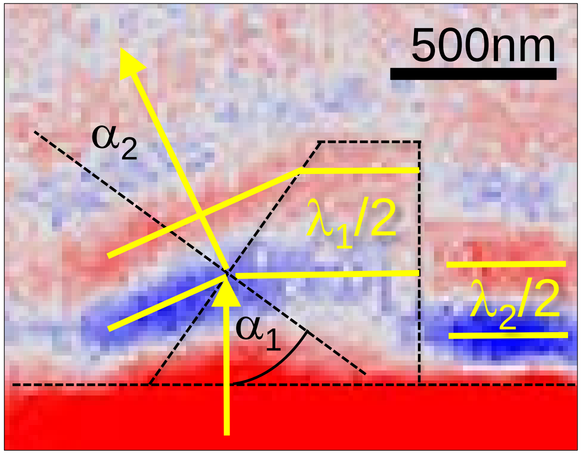




Graphene plasmons follow qualitatively Snell´s law

$$\frac{sin\alpha_1}{sin\alpha_2} = \frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$$

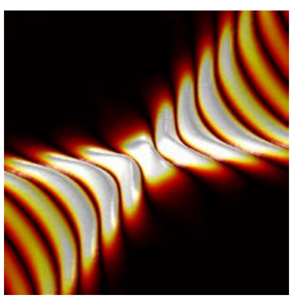
$\lambda_{p,}/\ \lambda_p = 1.4$

$sin\alpha_1/sin\alpha_2 = 1.75$

Alonso Gonzalez, et al., Science **344**, 1369 (2014)

- Intro: Nanooptics of Van der Waals materials

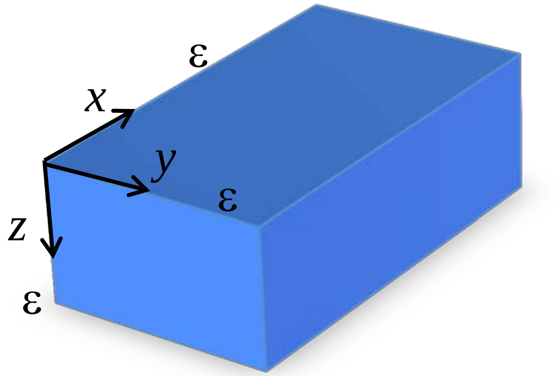
- Launching graphene plasmons with metallic antennas

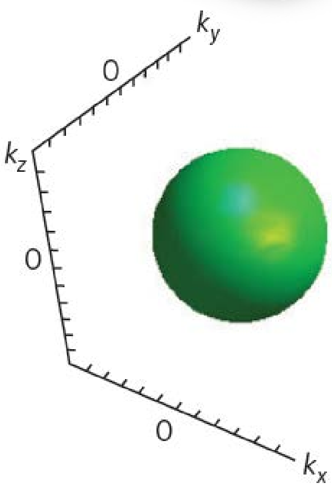


- **Nanoimaging of hyperbolic polaritons**

Dispersion of waves in hyperbolic media

Isotropic material

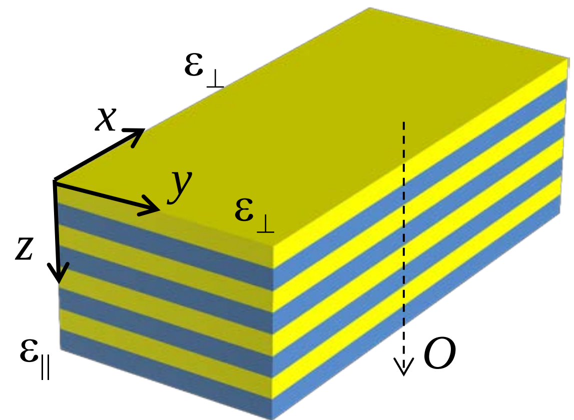




Isofrequency surface spheroid

$$\frac{k_x^2}{\varepsilon}+\frac{k_y^2}{\varepsilon}+\frac{k_z^2}{\varepsilon}=\frac{\omega^2}{c^2}$$

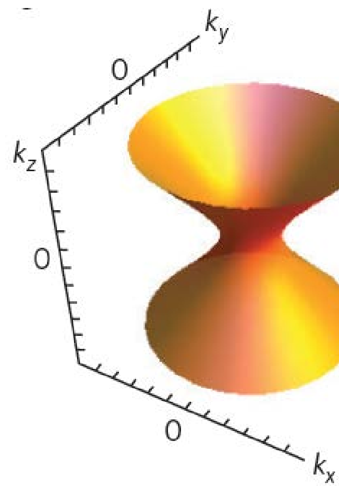
Uniaxial crystal

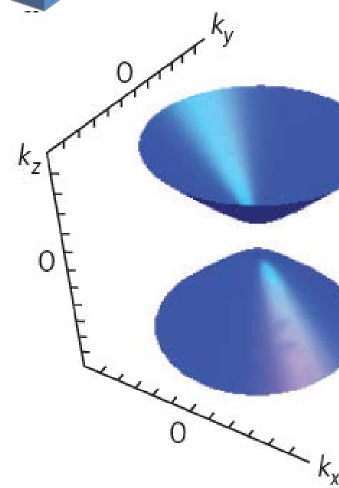


Type II

$\varepsilon_\perp < 0$

$\varepsilon_\parallel > 0$





Type I

$\varepsilon_\perp > 0$

$\varepsilon_\parallel < 0$

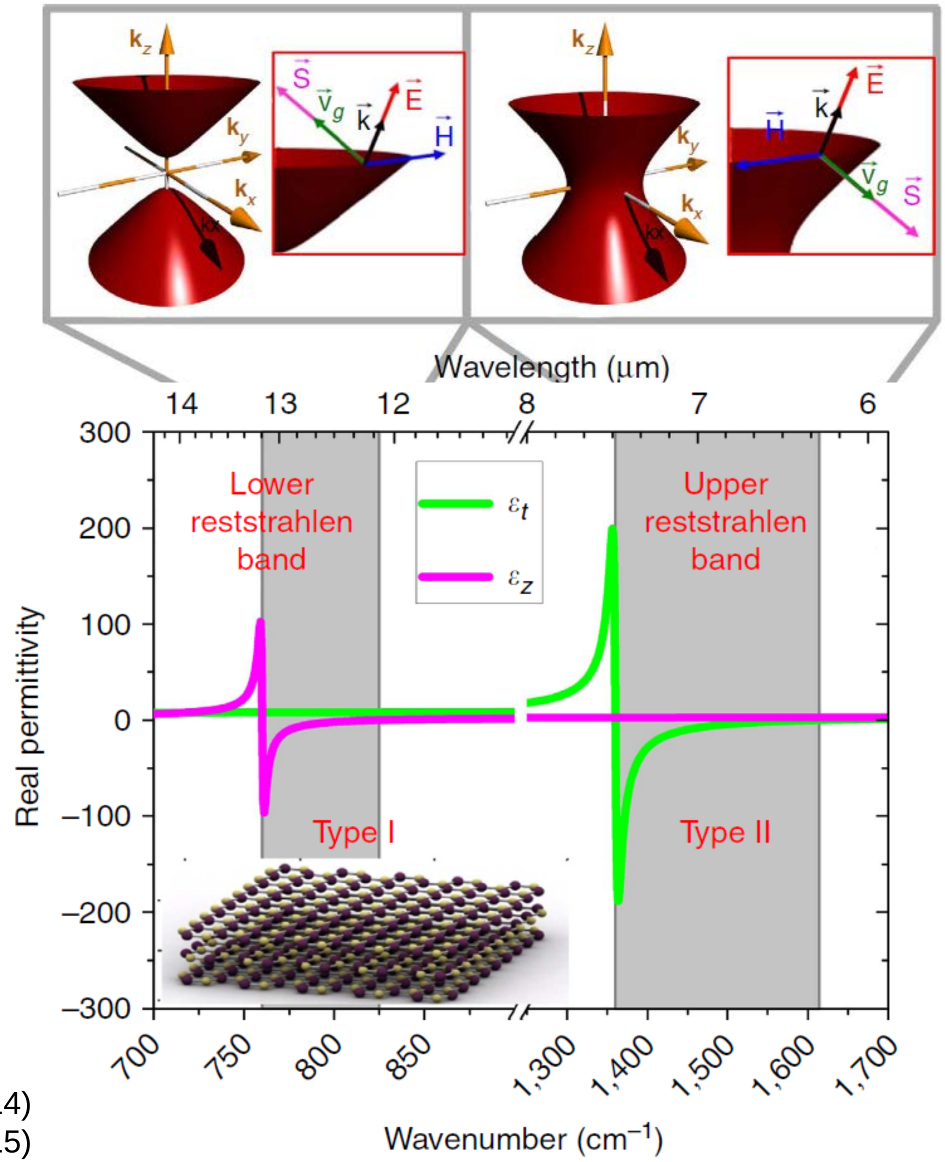
Isofrequency surface hyperboloid

$$\frac{k_z^2}{\varepsilon_\perp}+\frac{k_x^2+k_y^2}{\varepsilon_\parallel}=\frac{\omega^2}{c^2}$$

Nature Photon. **9**, 214 (2015)

h-BN: a natural hyperbolic material

The figures are taken from Nature Commun. **5**, 5221 (2014)

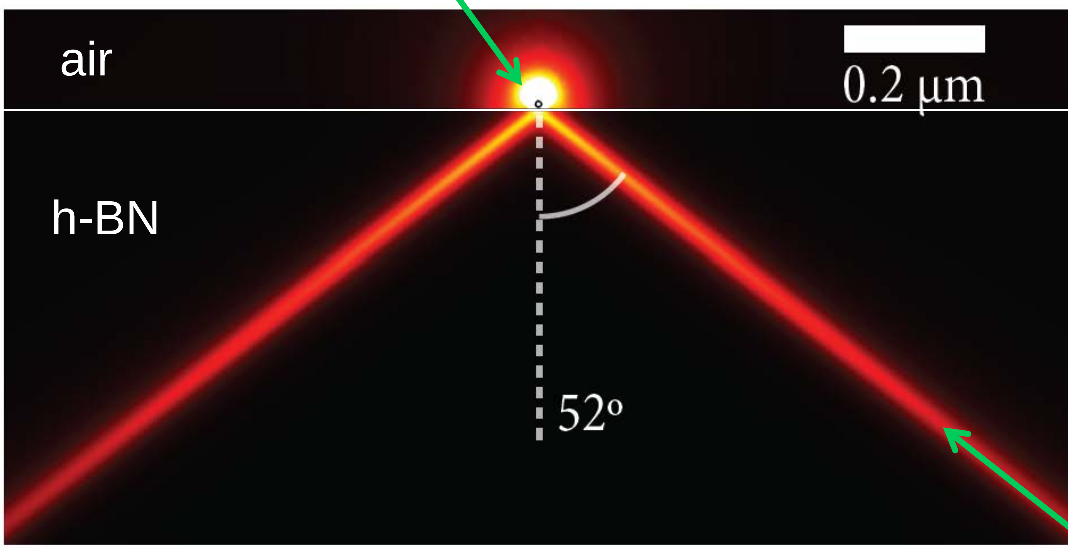


Science **343**, 1125 (2014)
Nature Commun. **5**, 5221 (2014)
Nature Commun. **6**, 6993 (2015)
Nature Photonics **9**, 674 (2015)

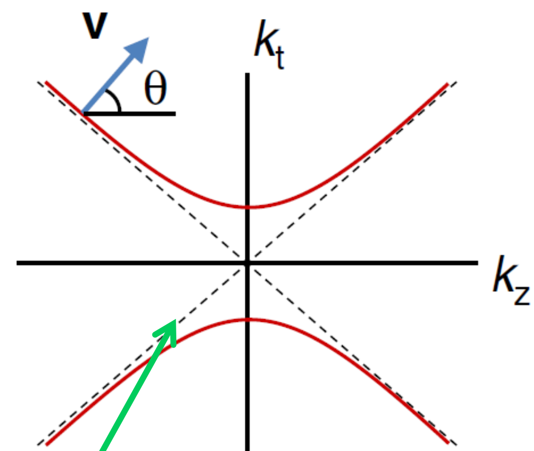
Hyperboilc rays in h-BN

A point source (dipole)

Isofrequency surface (Type II)



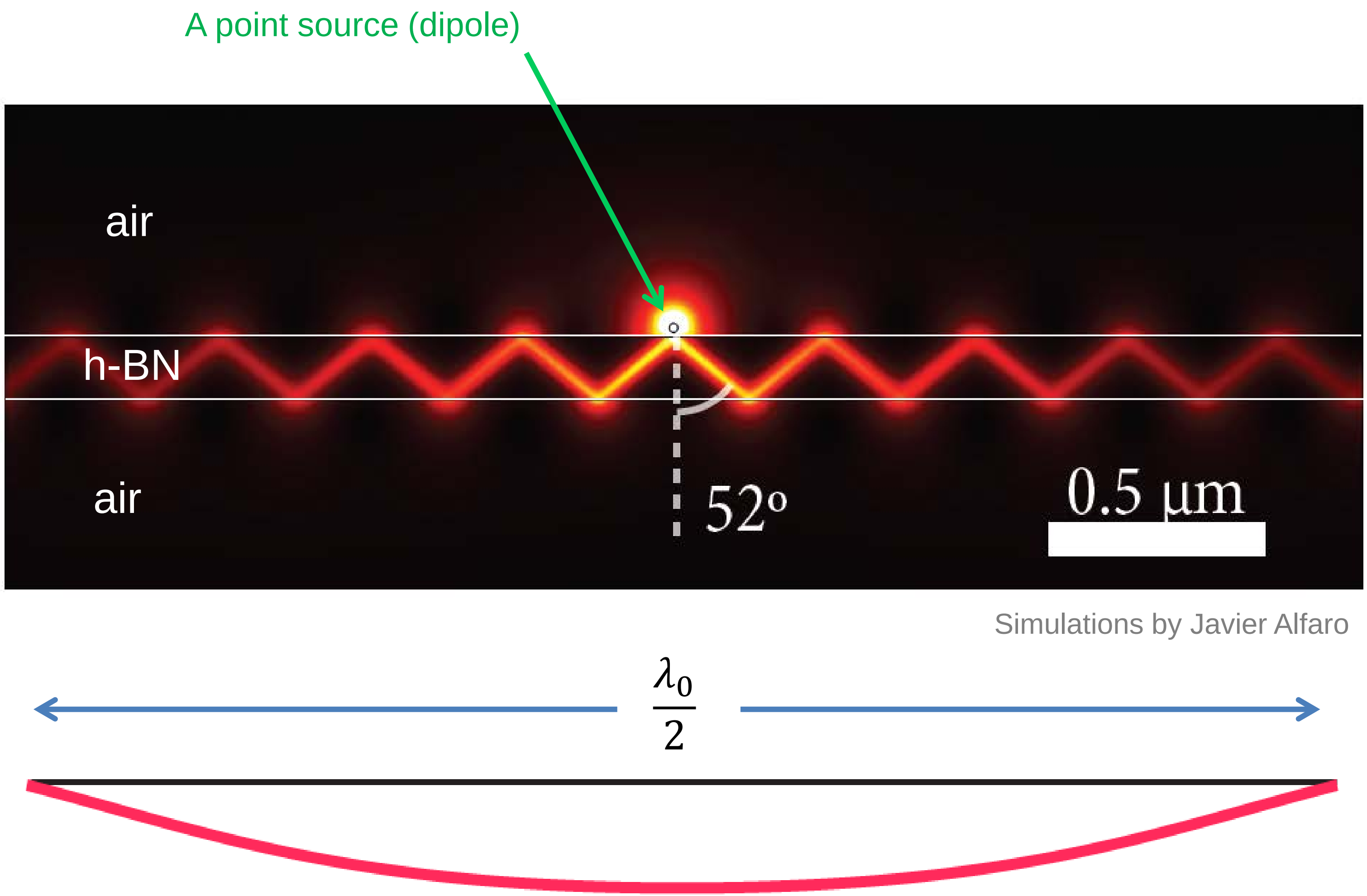
Simulations by Javier Alfaro



The origin of the rays is asymptotic straight lines

Due to the hyperbolic dispersion, the waves travelling inside h-BN crystals form "rays"

Hyperbolic rays in h-BN slabs

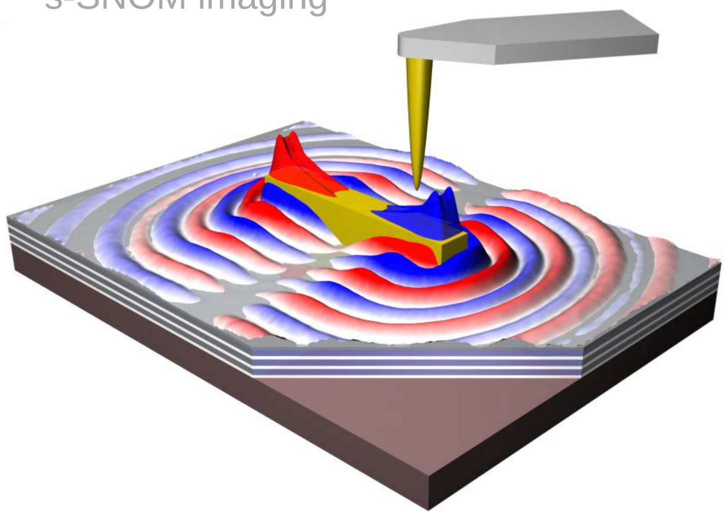


Simulations by Javier Alfaro

When a h-BN crystal has a finite thickness (slab), the rays reflect from the faces of the slab forming the subwavelength zig-zag pattern

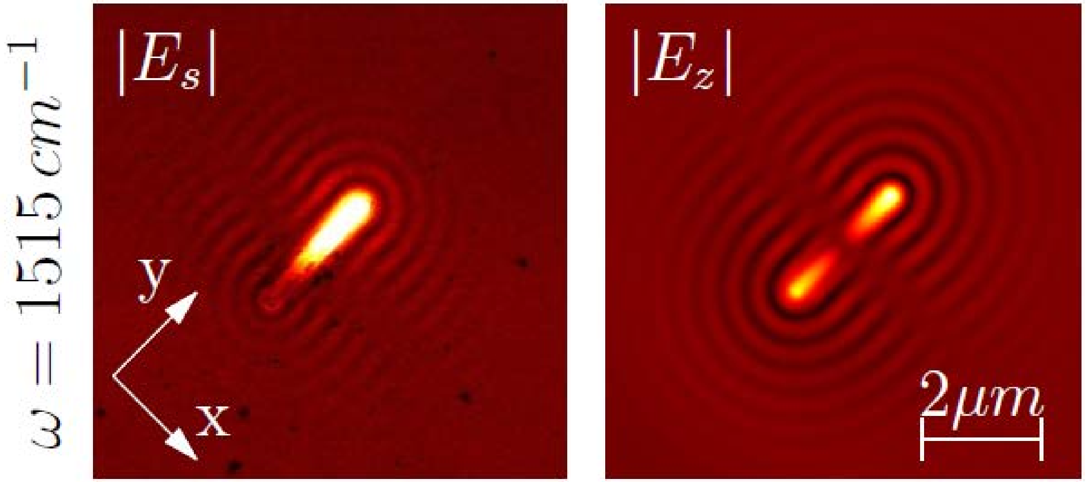
Imaging of hyperbolic polaritons launched by Au antenna

s-SNOM imaging



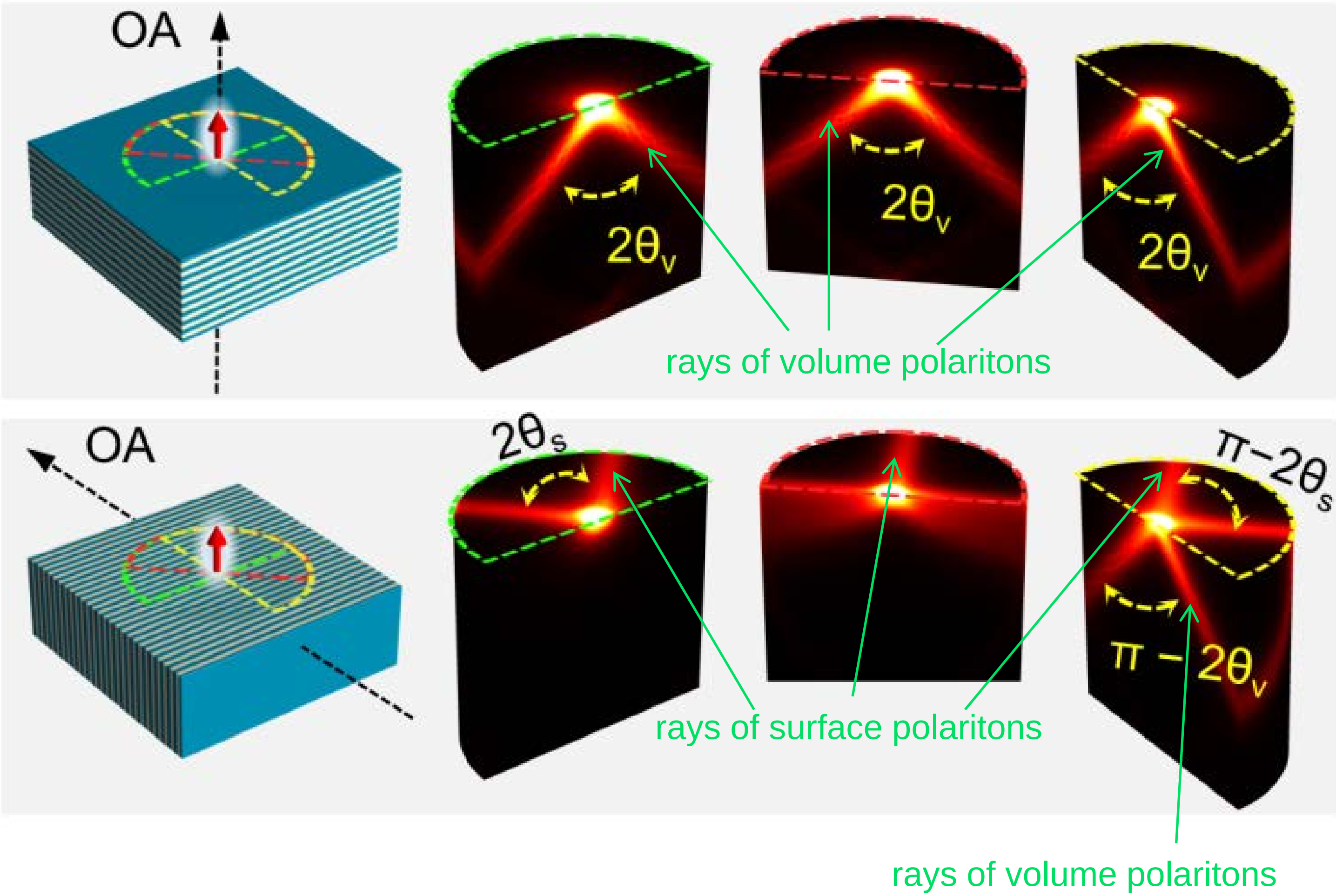
Experiment

Simulation



P. Pons Valencia et al, in preparation

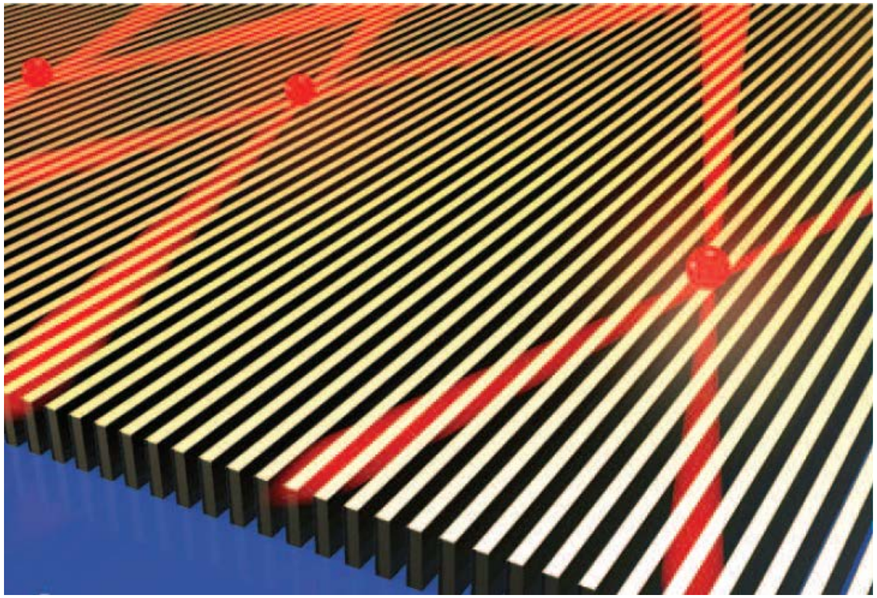
Vain dreams: imaging of the hyperbolic ray in-plane



P. Li, et al, Nano Lett. **17**, 228 (2017)

Metal gratings act as in-plane hyperbolic metasurface

Metallic hyperbolic metasurface



- A plasmonic grating can act as a hyperbolic metasurface in the visible

Science **339**, 1232009 (2013)
Appl. Phys. Lett. **103**, 141101 (2013)
Nature **522**, 192 (2015)
ACS Photonics **3**, 2211 (2016)

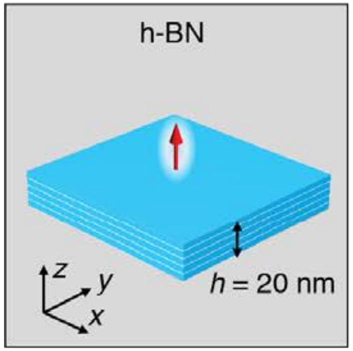
- In the mid-IR hyperbolic waves have been found, but they are too lossy…

ACS Photonics ***4***, 2899 (2017)
ACS Appl. Nano Mater. **1**, 1212 (2018)
by Andrei Laverinenko & Osamu Takayama

Can we do a hyperbolic metasurface with h-BN in the **mid-IR**?

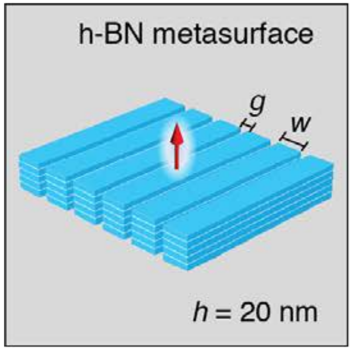
h-BN grating acts as a hyperbolic metasurface

$\varepsilon_{\text{eff},\,x} < 0$
$\varepsilon_{\text{eff},\,y} < 0$



$\varepsilon_{\text{eff},\,x} > 0$
$\varepsilon_{\text{eff},\,y} < 0$

In-plane hyperbolic



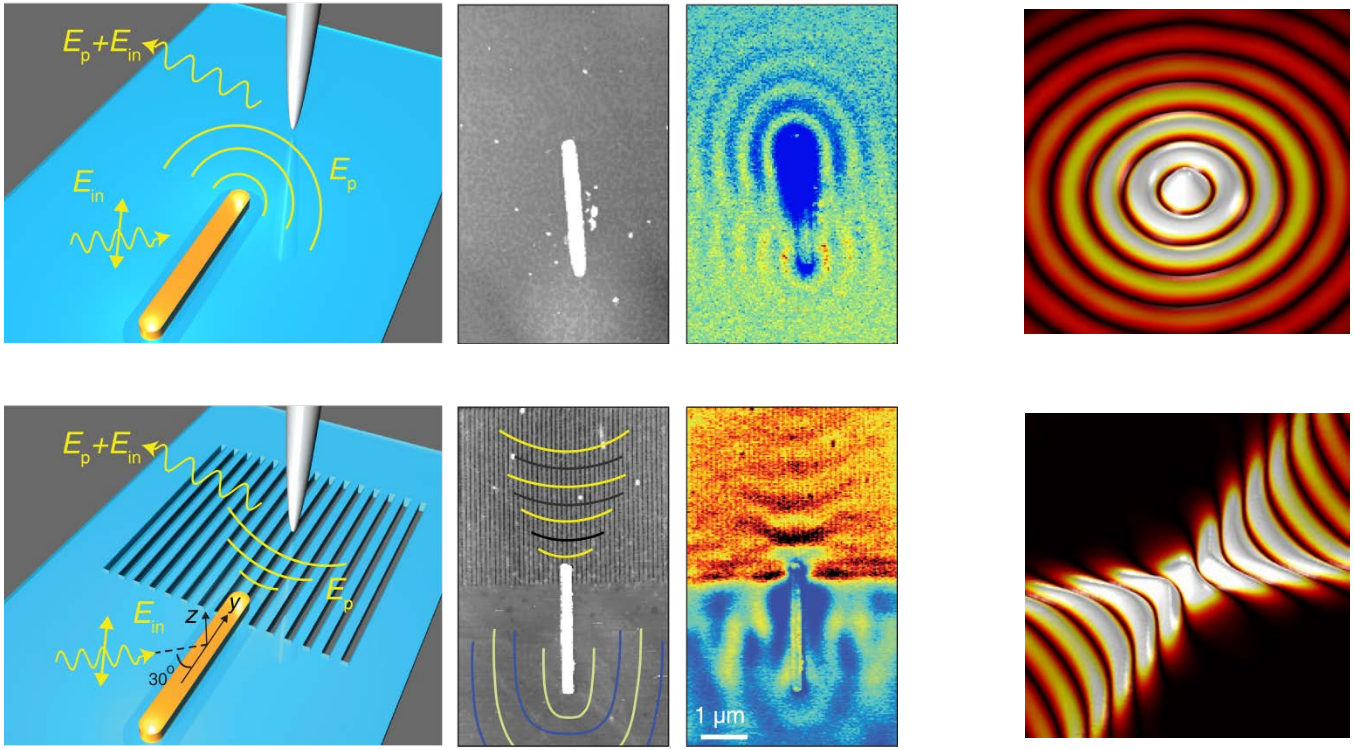
The in-plane propagation of out-of-plane hyperbolic h-BN phonon polaritons

➡ On bare h-BN: isotropic with radial convex wavefronts

➡ On structured h-BN: anisotropic with diverging concave wavefronts and increased *k*

P. Li, I. Dolado, et al., Science **359**, 892 (2018)

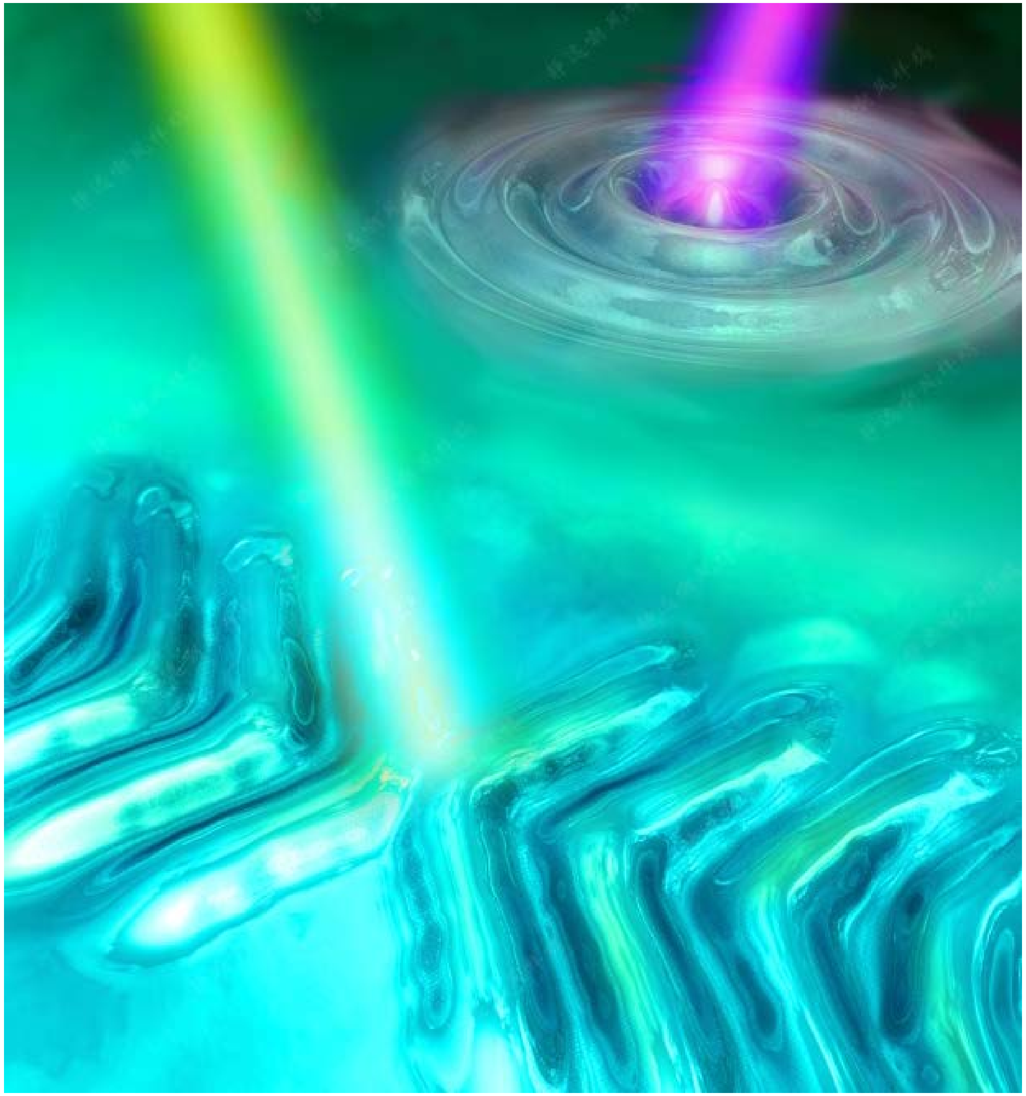
Wavefront mapping of antenna-launched polaritons in h-BN grating



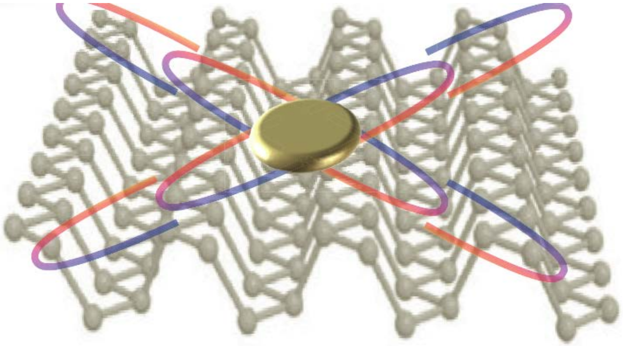
- Developed: hyperbolic metasurface (grating) based on a van der Waals material
- Imaged: anomalous wavefronts of deeply confined polaritons on HMS
- Imaging scheme (antenna launching and s-SNOM imaging) could be used for other anisotropic materials

P. Li, I. Dolado, et al., Science **359**, 892 (2018)

Are there natural materials supporting the in-plane hyperbolic polaritons?



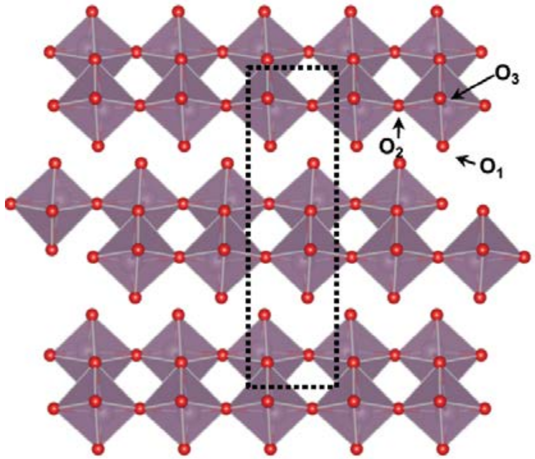
Black Phosphorus?

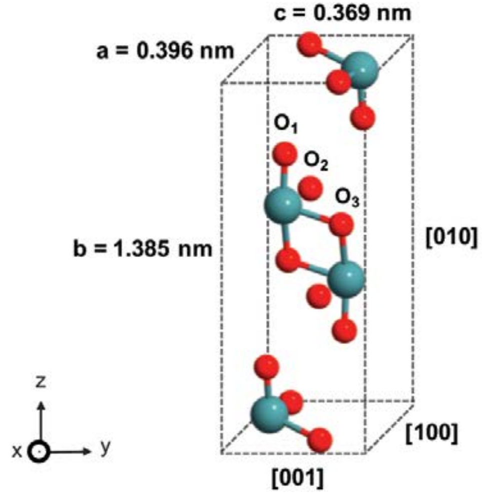


Nature Mat. **16**, 182 (2017)
Nature Nanotechnol.**12**, 207 (2017)

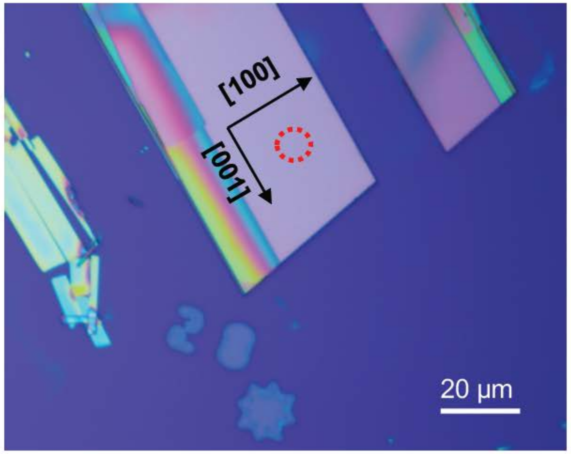
too lossy…

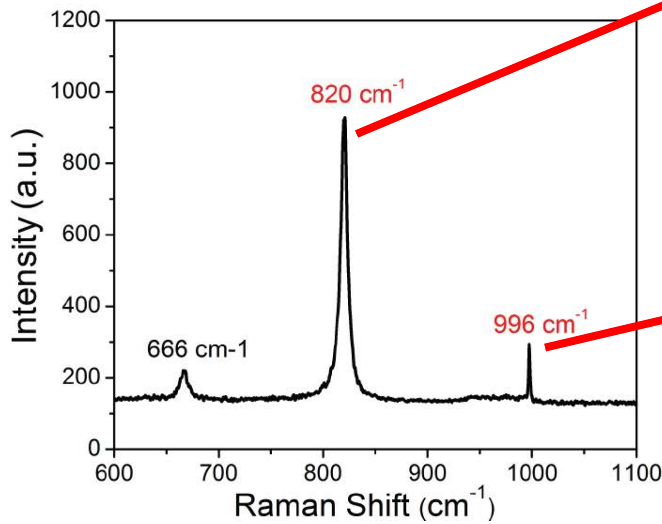
Again phonon-polaritons, now in a biaxial Van der Waals crystal

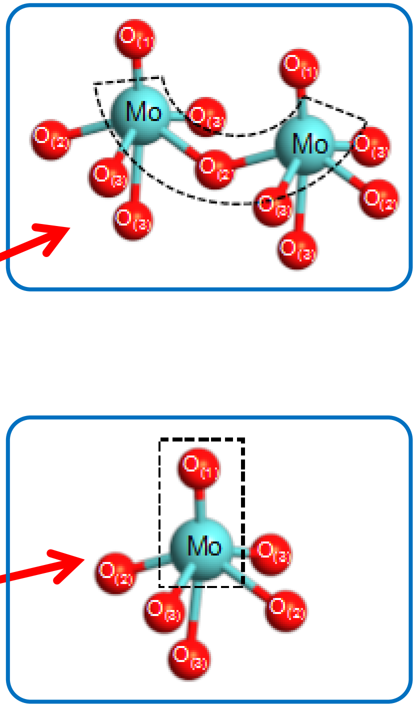




α–MoO_3





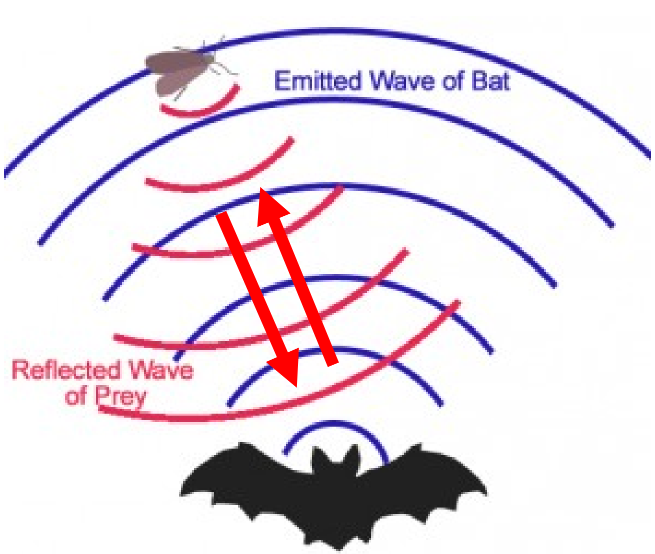


α–MoO_3 crystals are anisotropic due to their molecular structure.
They show a strong narrow-band phononic responce

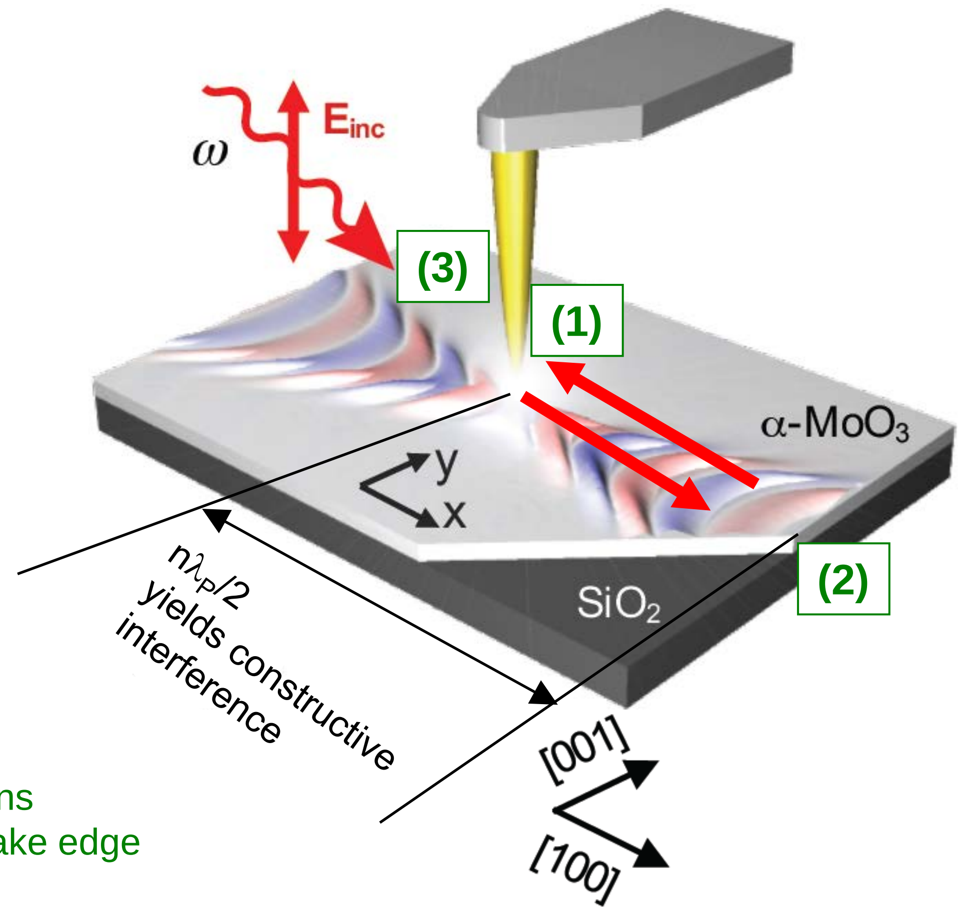
W. Ma et al., Nature **562**, 557 (2018)

s-SNOM: “echo” detection of hyperbolic polaritons

a hunting bat



polariton interferometry with s-SNOM

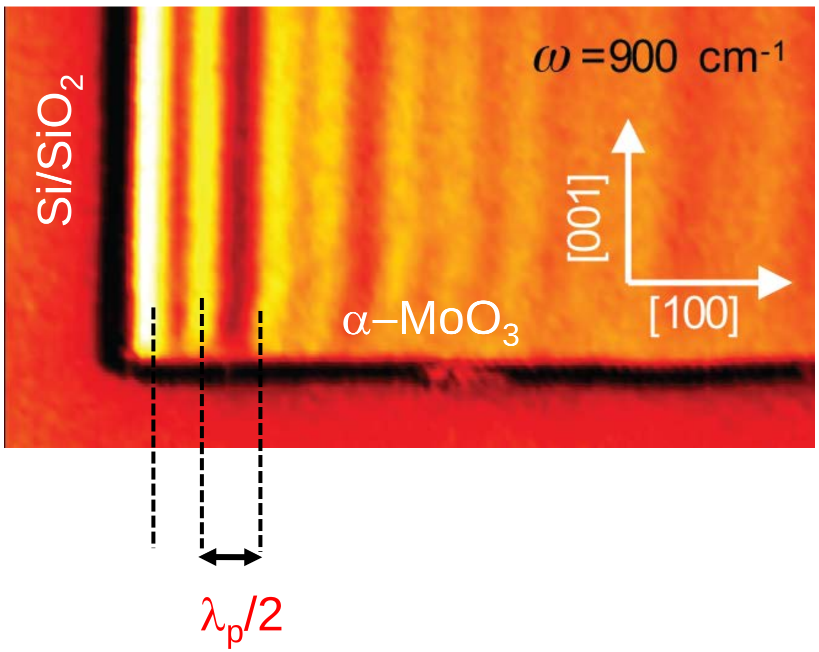


(1) near-field at tip apex excites phonon-polaritons
(2) phonon-polaritons are backreflected at the flake edge
(3) tip scatters interfering fields at its apex

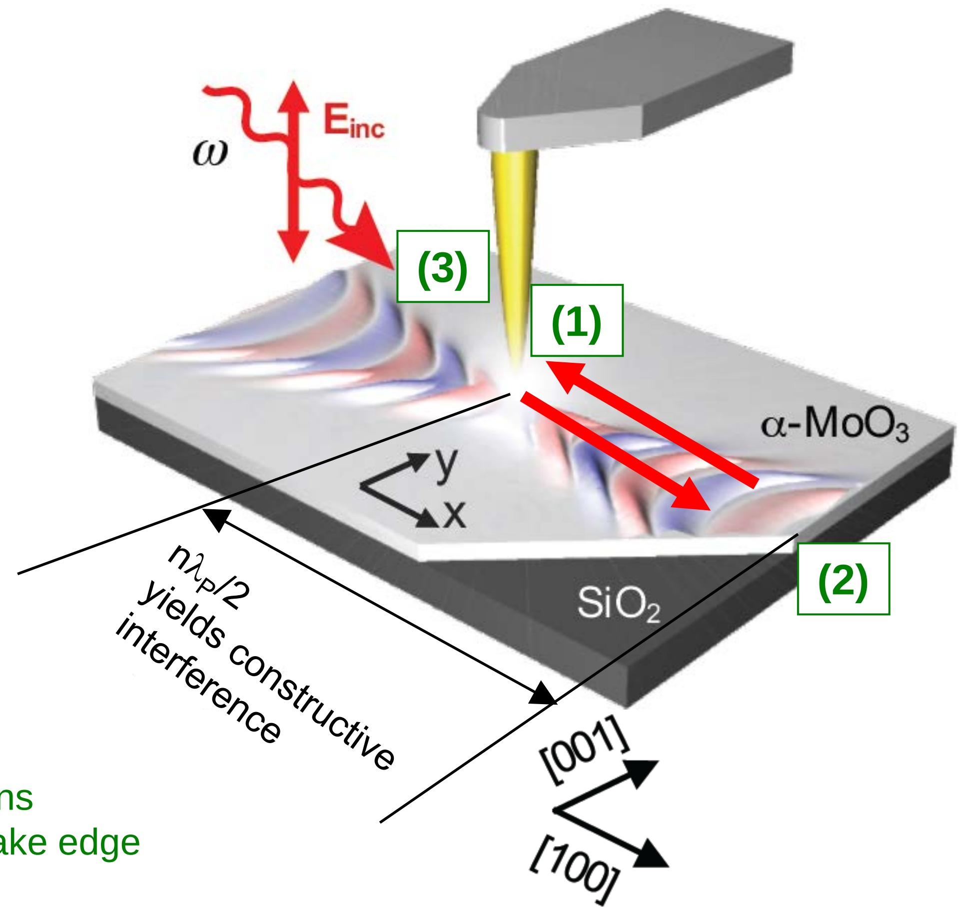
W. Ma et al., Nature **562**, 557 (2018)

s-SNOM: “echo” detection of hyperbolic polaritons

s-SNOM image



polariton interferometry with s-SNOM



(1) near-field at tip apex excites phonon-polaritons
(2) phonon-polaritons are backreflected at the flake edge
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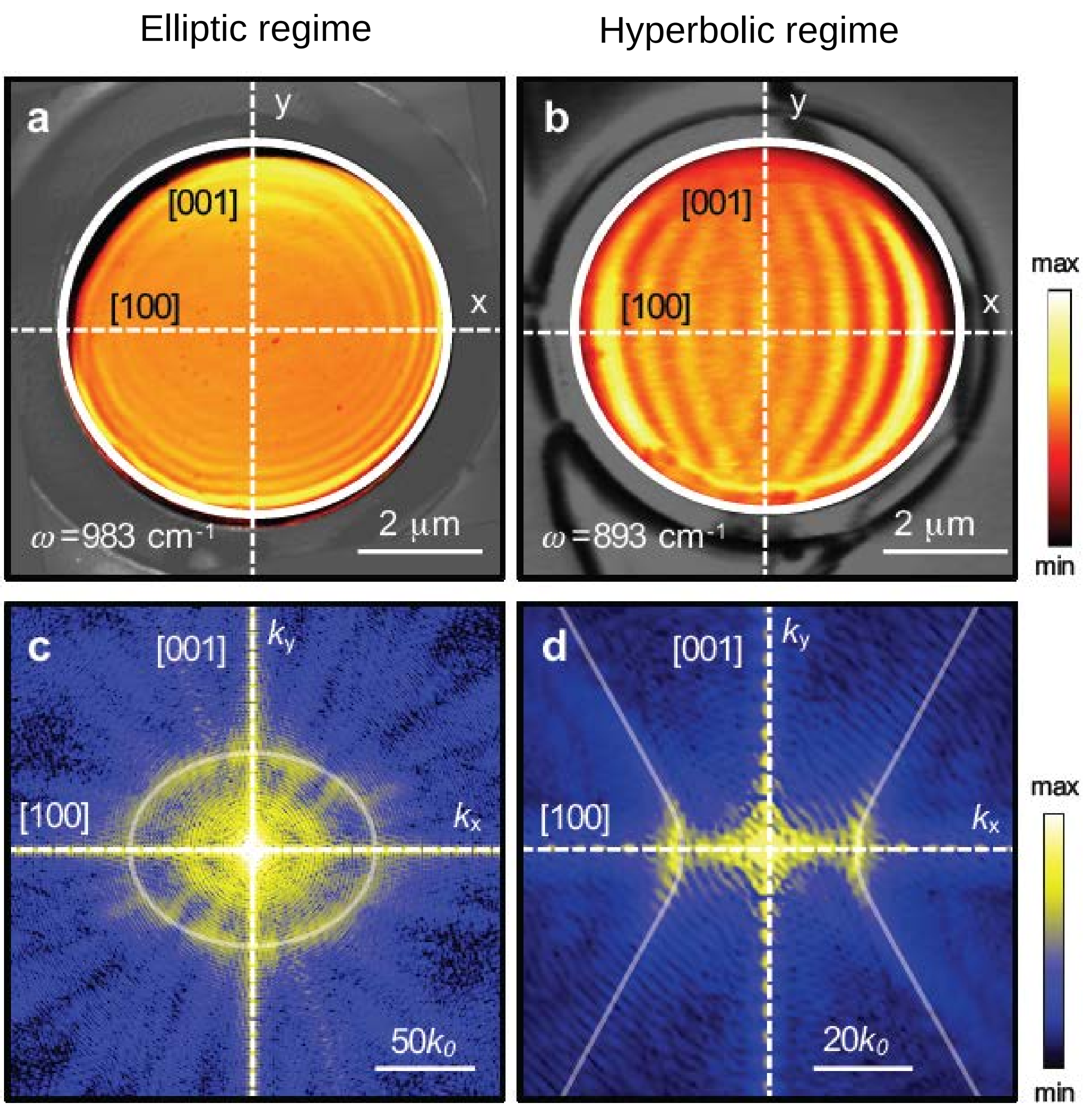
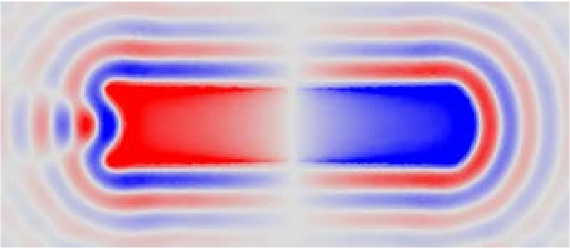
W. Ma et al., Nature **562**, 557 (2018)

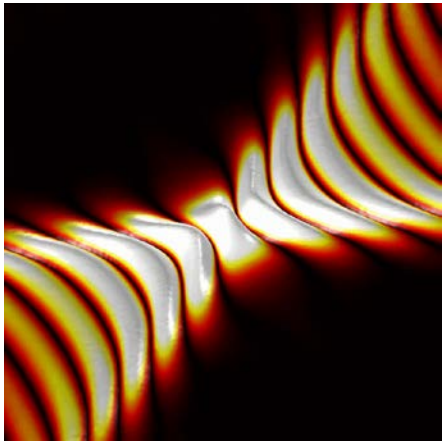
FT of the images of the disks prove the anisotropy of the phonon-polaritons in α–MoO_3

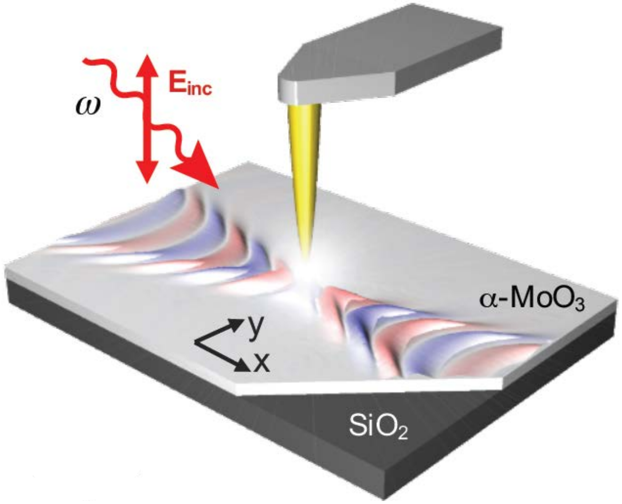


W. Ma et al., Nature **562**, 557 (2018)

Take-home messages







- We have managed to couple to polaritons in 2D Van der Waals materials, as well as to mantipulate them, with resonant Au antennas
- We have designed a h-BN hyperbolic metasurface and imaged in-plane hyperbolic phonon-polaritons
- We have found a natural anisotropic metamaterial (VdW biaxial crystal): α-MoO_3 and imaged long-lived elliptic and hyperbolic phonons-polaritons

Acknowledgements

CIC nanoGUNE — nanoscience cooperative research center

Nanooptics:
- Javier Alfaro
- Irene Dolado
- Peining Li
- Matthias Marco Wiecha
- Vladimir Biloek
- Rainer Hillenbrand

Nanodevices:
- Saül Vélez
- Federico Golmar
- Felix Casanova
- Luis Hueso

Universidad de Oviedo — La Universidad de Asturias

Pablo Alonso-González
Javier Martín-Sánchez
Javier Taboada-Gutiérrez

Universidad Zaragoza

Pablo Pons Valencia
Luis Martín-Moreno

ICFO

Frank Koppens
Gabriele Navickaite

Graphenea

Alba Centeno
Amaia Pesquera
Amaia Zurutuza

Monash University

Qiaoliang Bao
Zhigao Dai
Yupeng Zhang

RMIT University

Sharath Sriram
Kourosh Kalantar-Zadeh

Soochow University

Weiliang Ma
Shaojuan Li
Jian Yuan
Shuit-Tong Lee

Kansas State University

Song Liu
James H. Edgar

Gobierno de España — Ministerio de Economía y Competitividad

Graphene Flagship