CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

Nanolight 2022

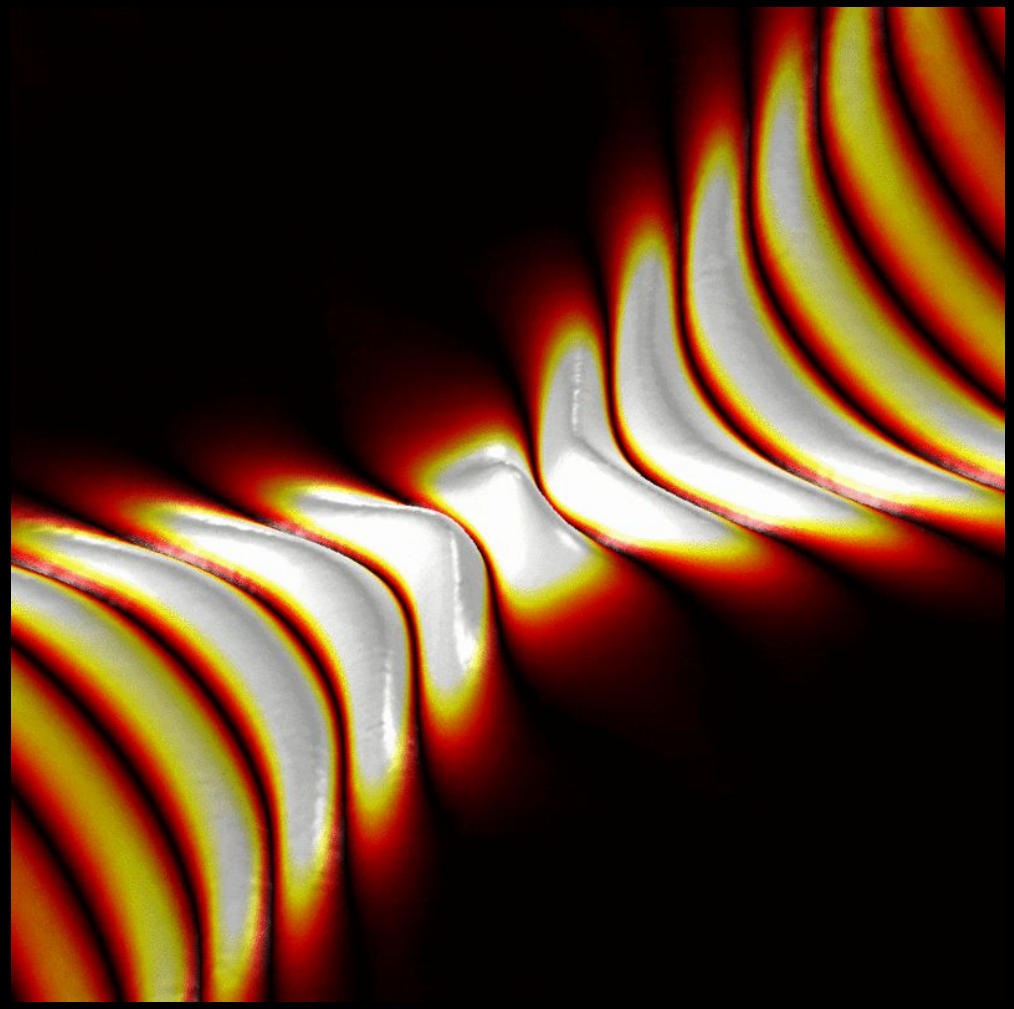
Twisted Nanoresonators for Hyperbolic Light

Kirill Voronin, Alexey Nikitin

Donostia International Physics Center

"la Caixa" Foundation

MIPT
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY



Science 359, 892 (2018)

Outline

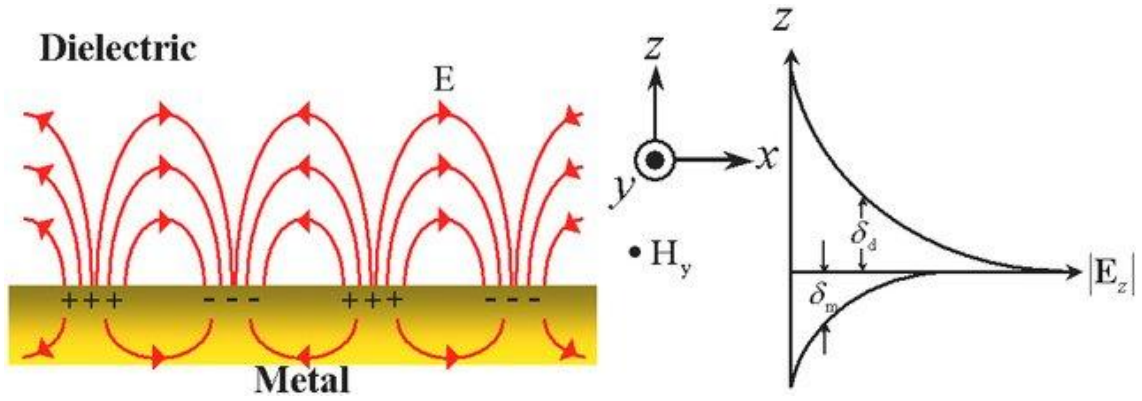
Introduction. Hyperbolic nanooptics with van der Waals crystals

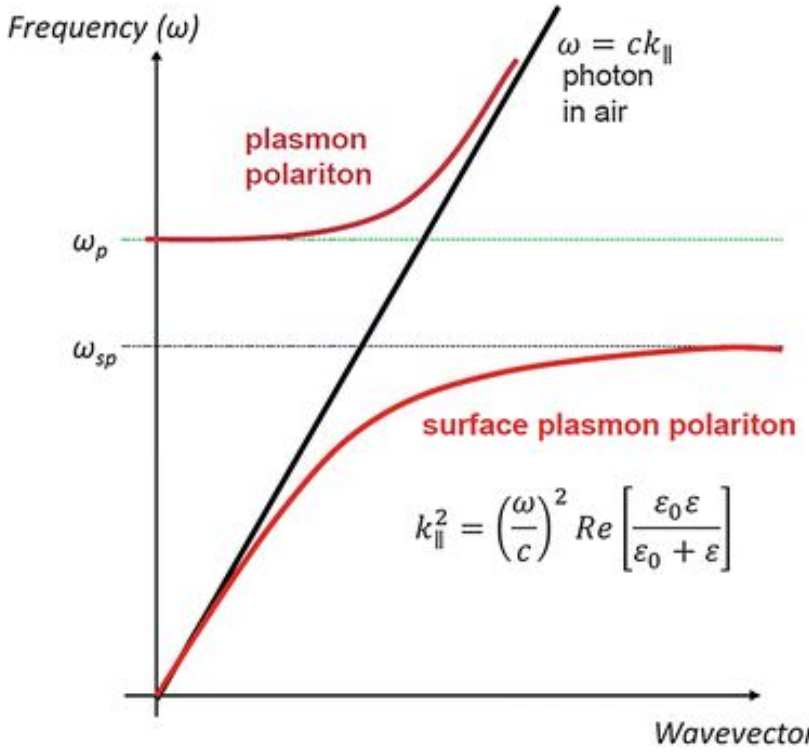
Elliptical and hyperbolic phonon-polaritons in α-MoO_3. Twisted nanooptics

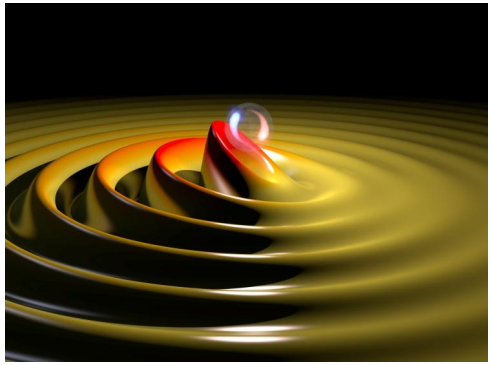
Far- and near-field measurements of resonances in rotated structures

Mapping of dispersion surface

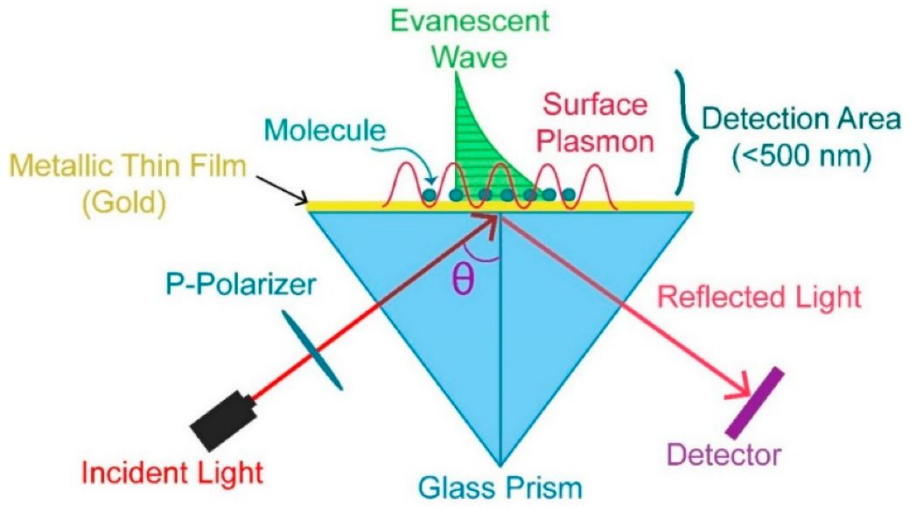
Plasmon polaritons



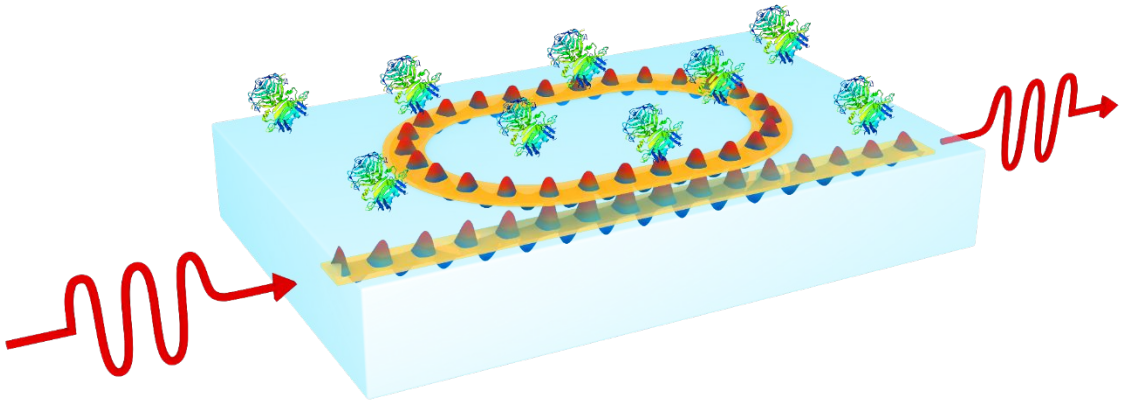




Science **340**, 328 (2013)

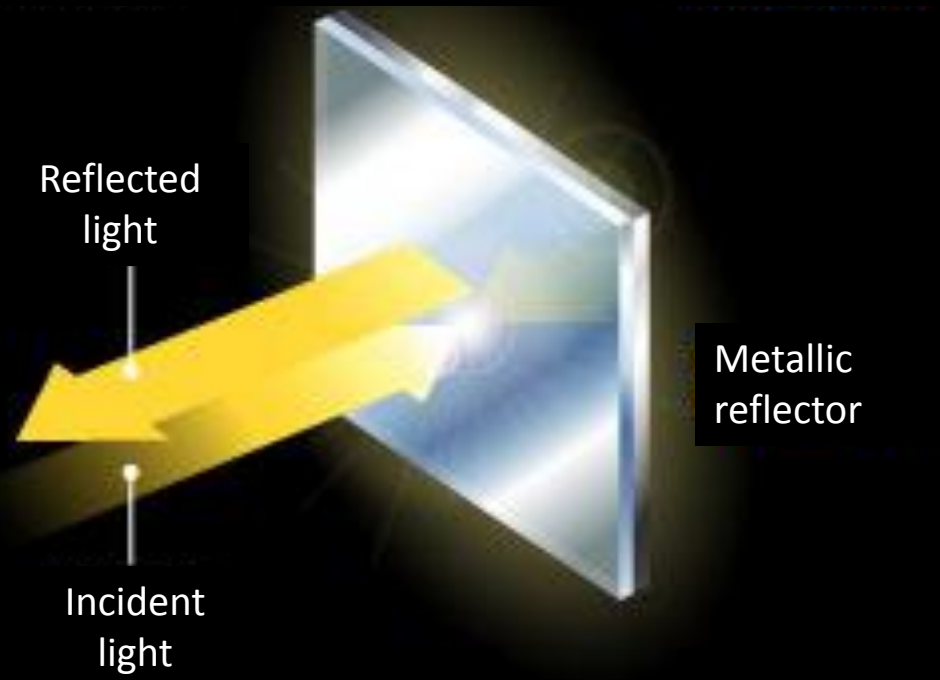


Molecules **2020**, *25*(12)

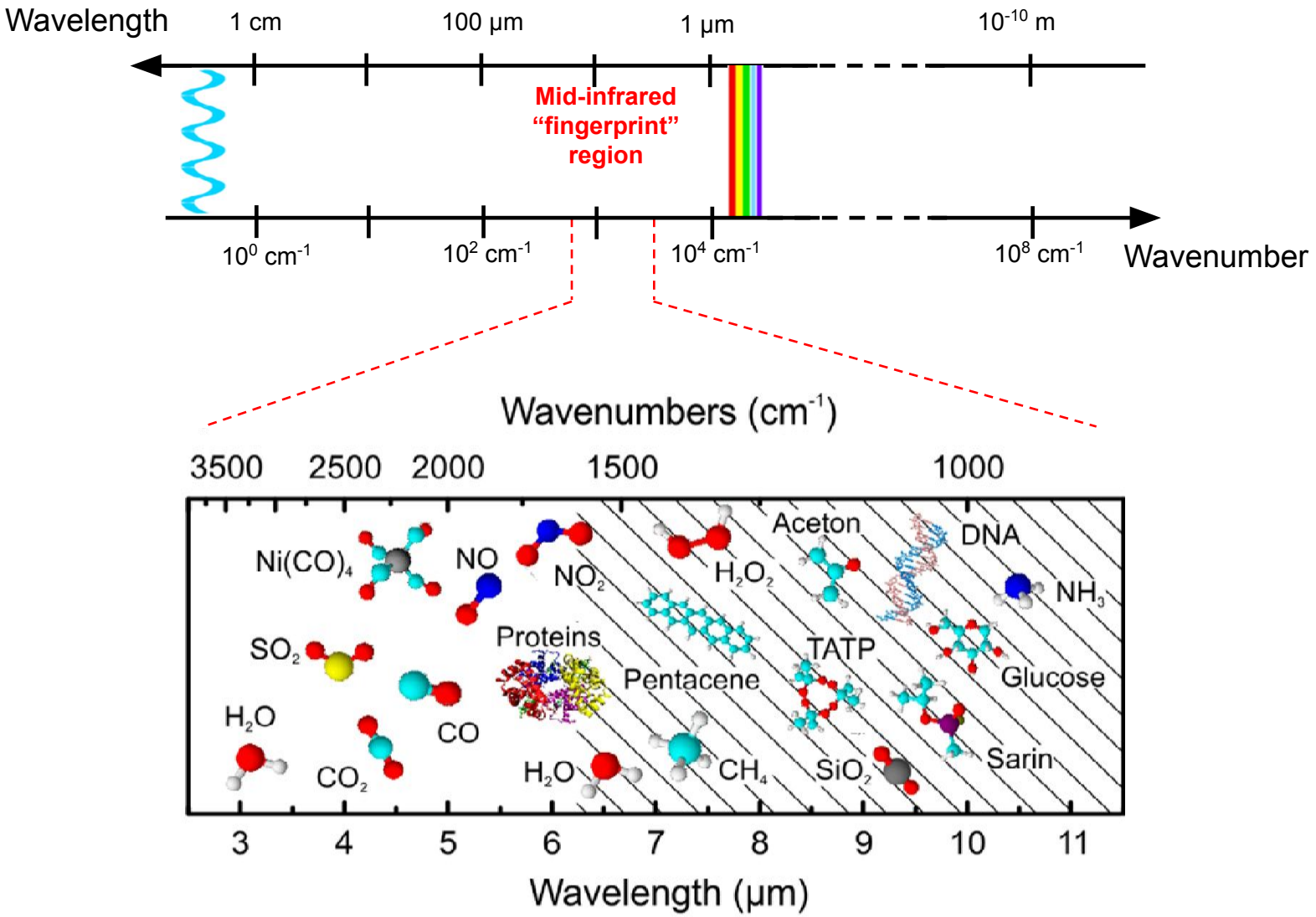


Sensors **2020**, *20*(1), 203

Metals at mid-IR frequencies behave like mirrors

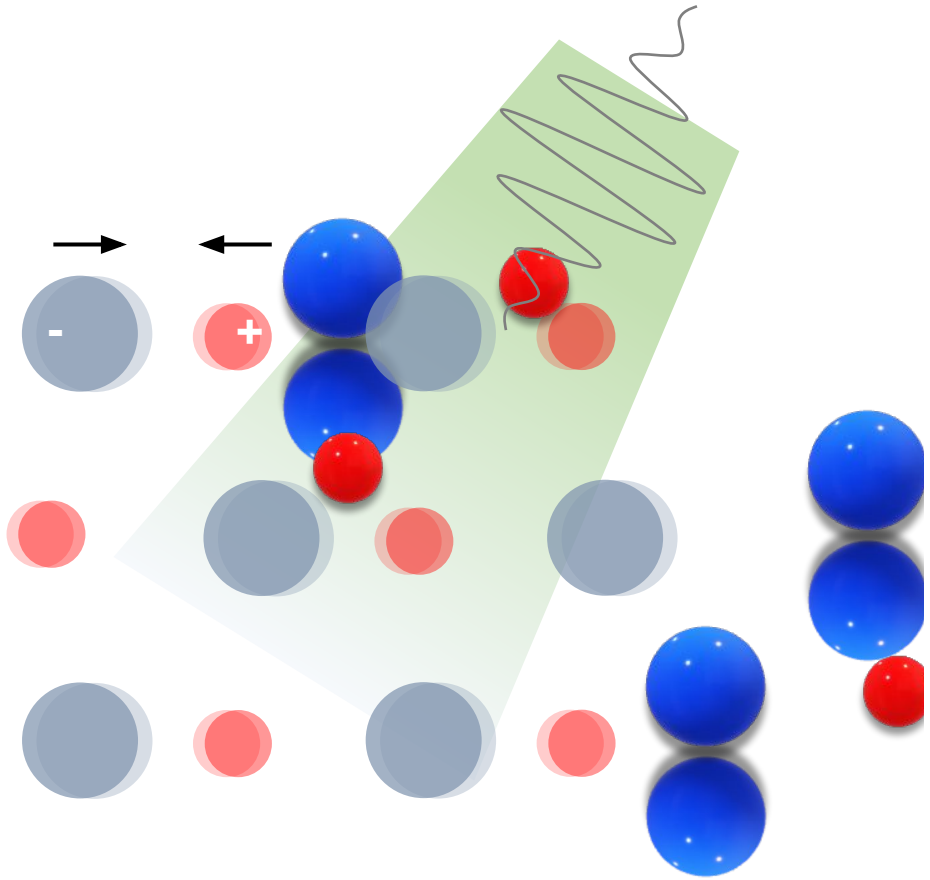


Mid-IR molecular spectroscopy

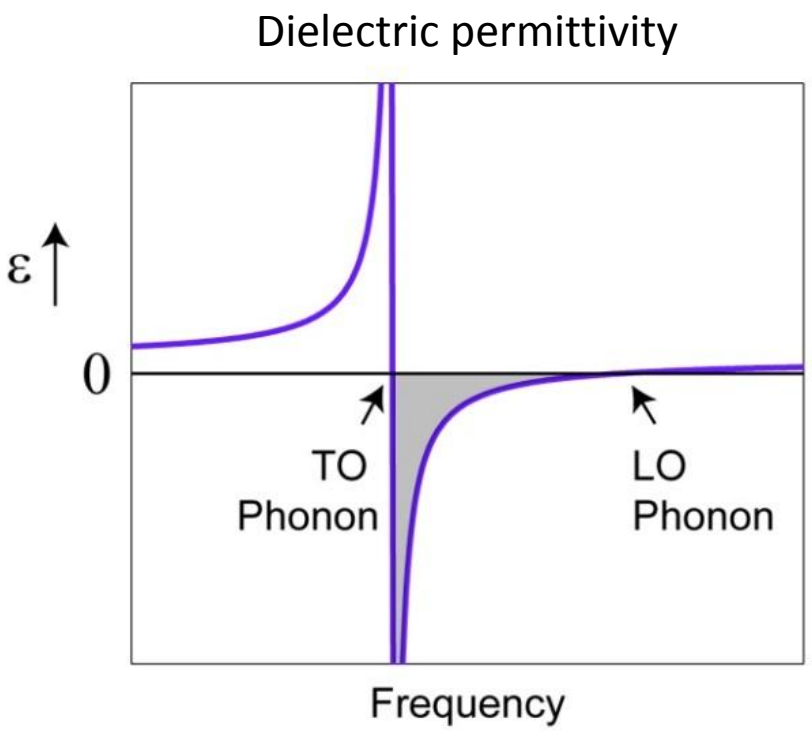


F. Neubrech et al., Chem. Rev. **117**, 5110 (2017)

Phonon polaritons



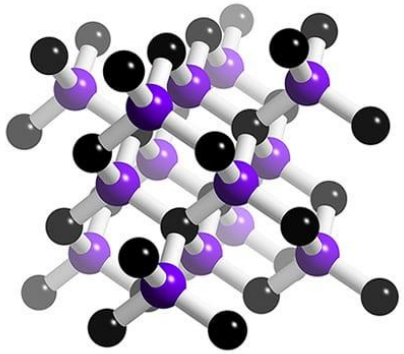
Lattice vibrations (phonons)



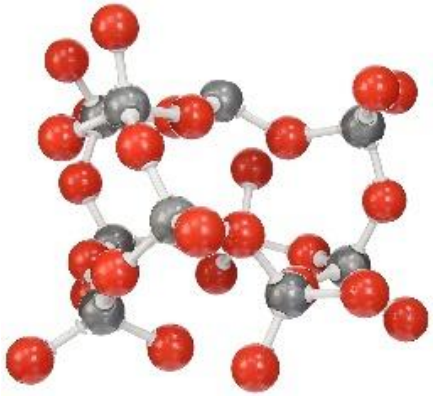
R. Hillenbrand, et al. , Nature **418,** 159, (2002)
J. Caldwell, et al. Nanophotonics **4,** 44 (2015)

Polar bulk crystals

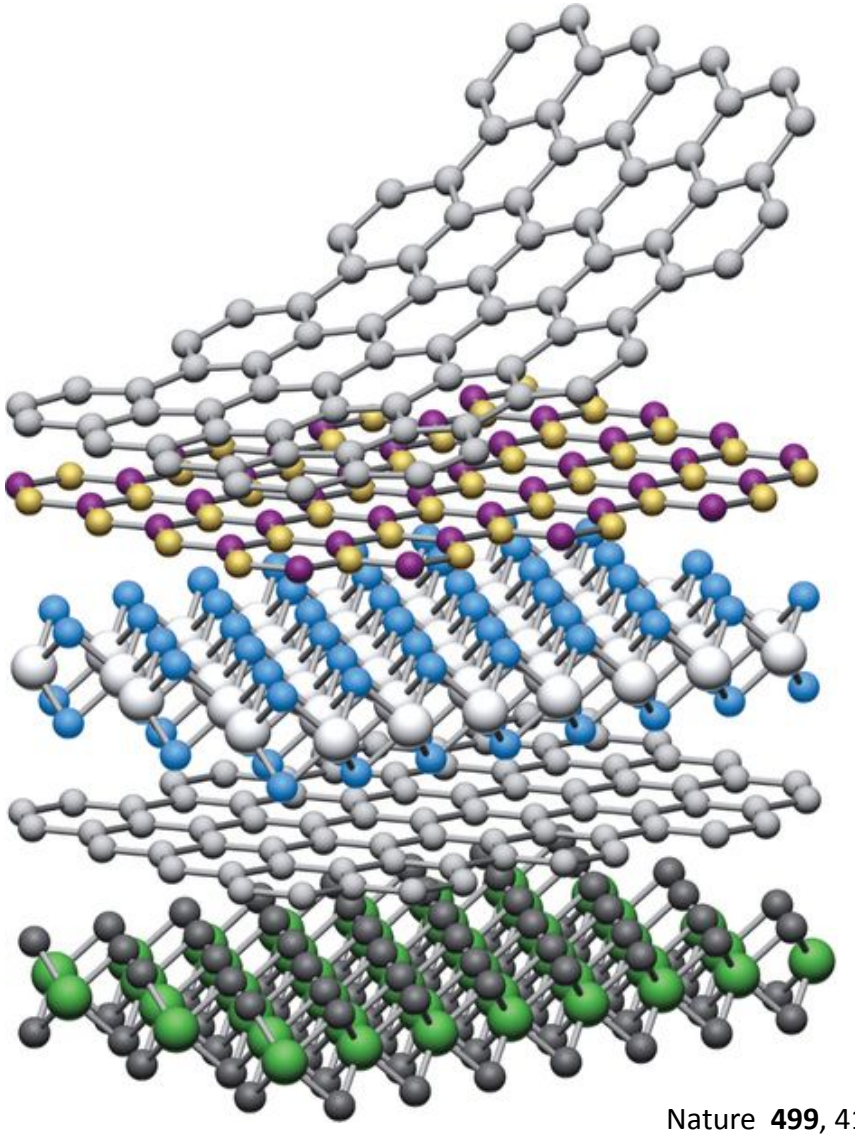
SiC



SiO_2

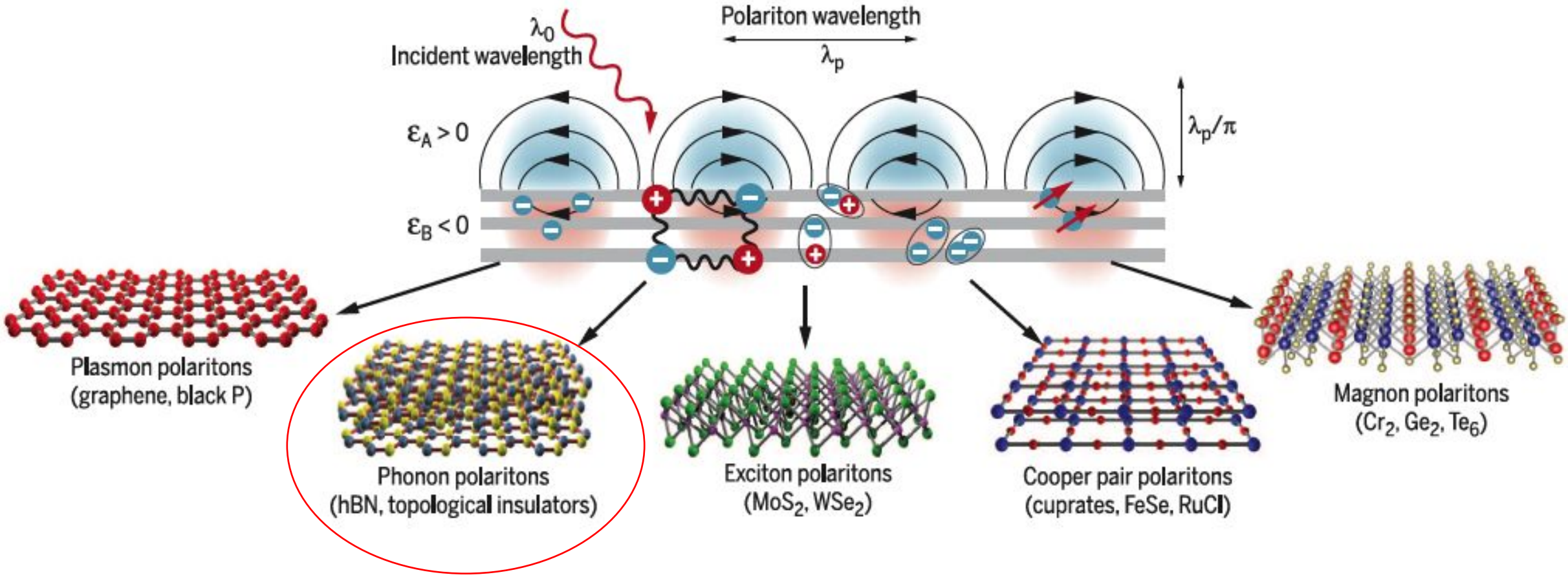


Van der Waals materials



Nature **499**, 419 (2013)

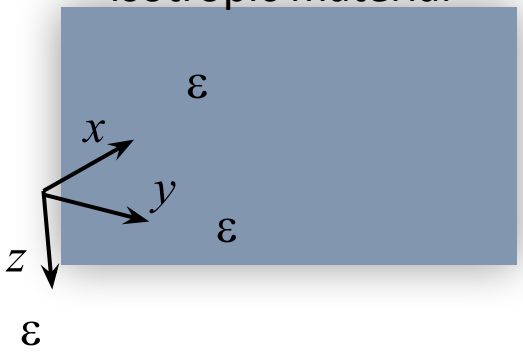
Polaritons in van der Waals materials



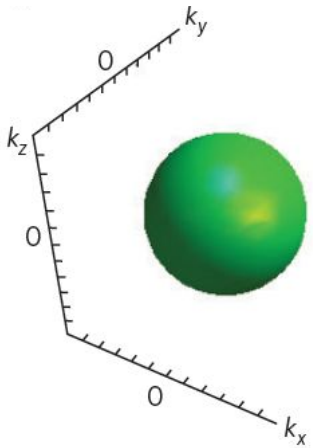
Science **354**, 1992 (2016)
Nature Mat. **16**, 182 (2017)

Dispersion of poilaritons in hyperbolic media

Isotropic material



Uniaxial hyperbolic crystal



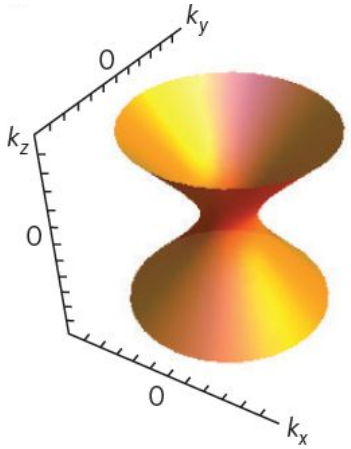
Isofrequency surface spheroid

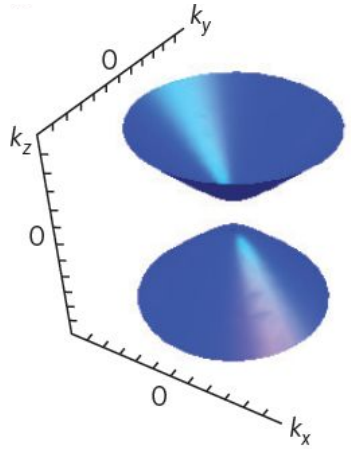
$$\frac{k_x^2}{\varepsilon}+\frac{k_y^2}{\varepsilon}+\frac{k_z^2}{\varepsilon}=\frac{\omega^2}{c^2}$$

Type II

$\varepsilon_\perp < 0$

$\varepsilon_\parallel > 0$





Type I

$\varepsilon_\perp > 0$

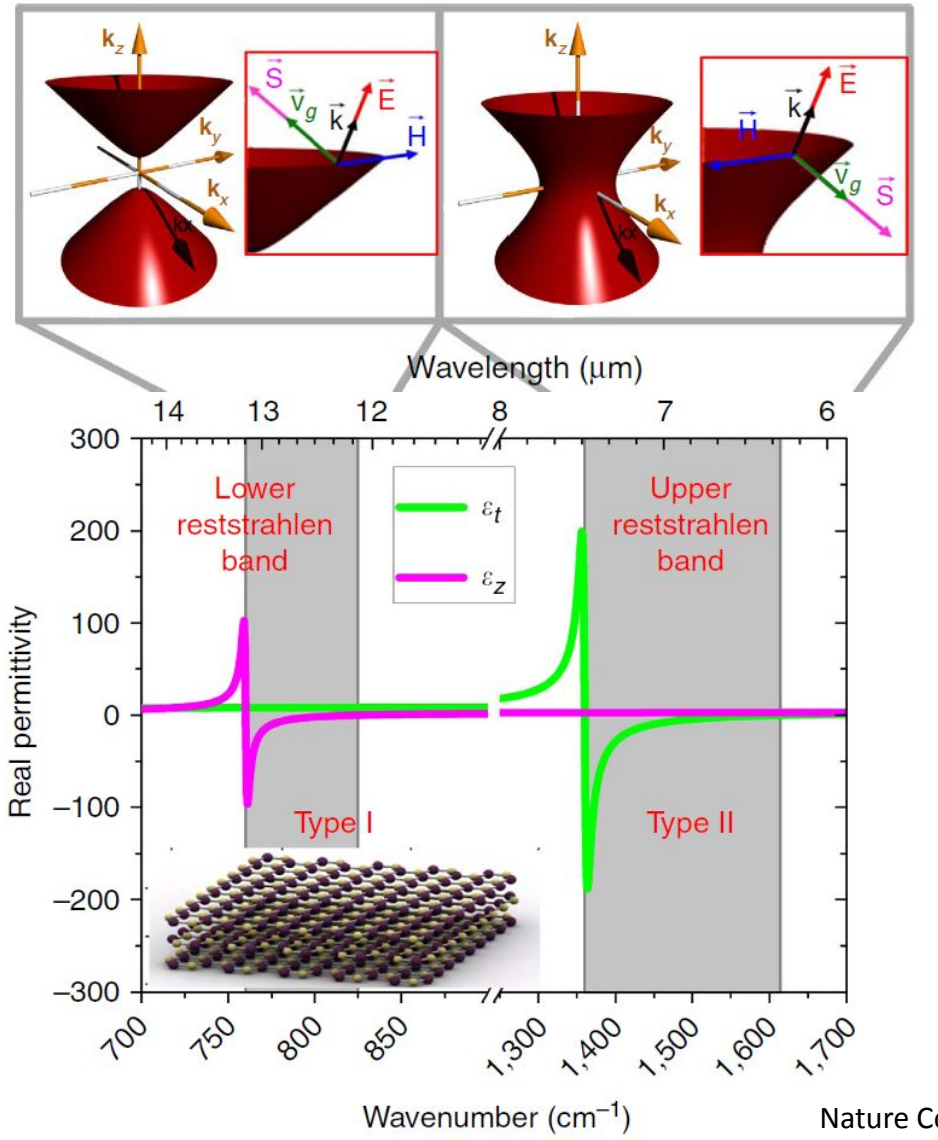
$\varepsilon_\parallel < 0$

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)

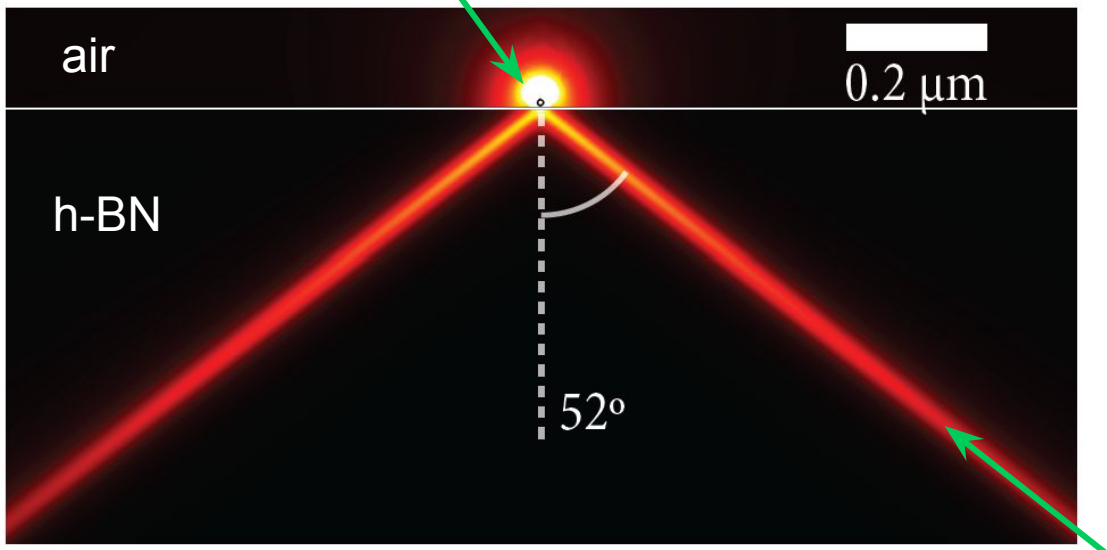
h-BN: a natural hyperbolic material



Nature Commun. **5**, 5221 (2014)

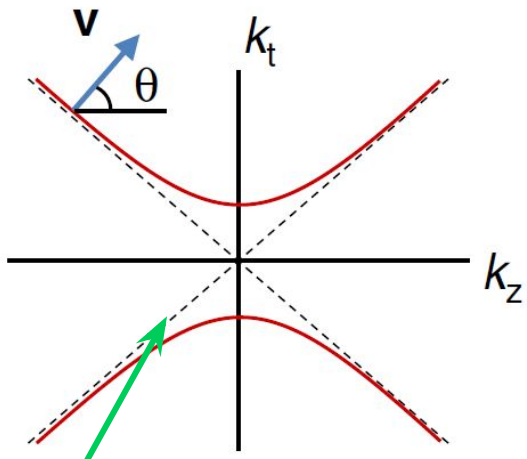
Polaritons in hyperboilc media

A point source (dipole)



Simulations by Javier Alfaro

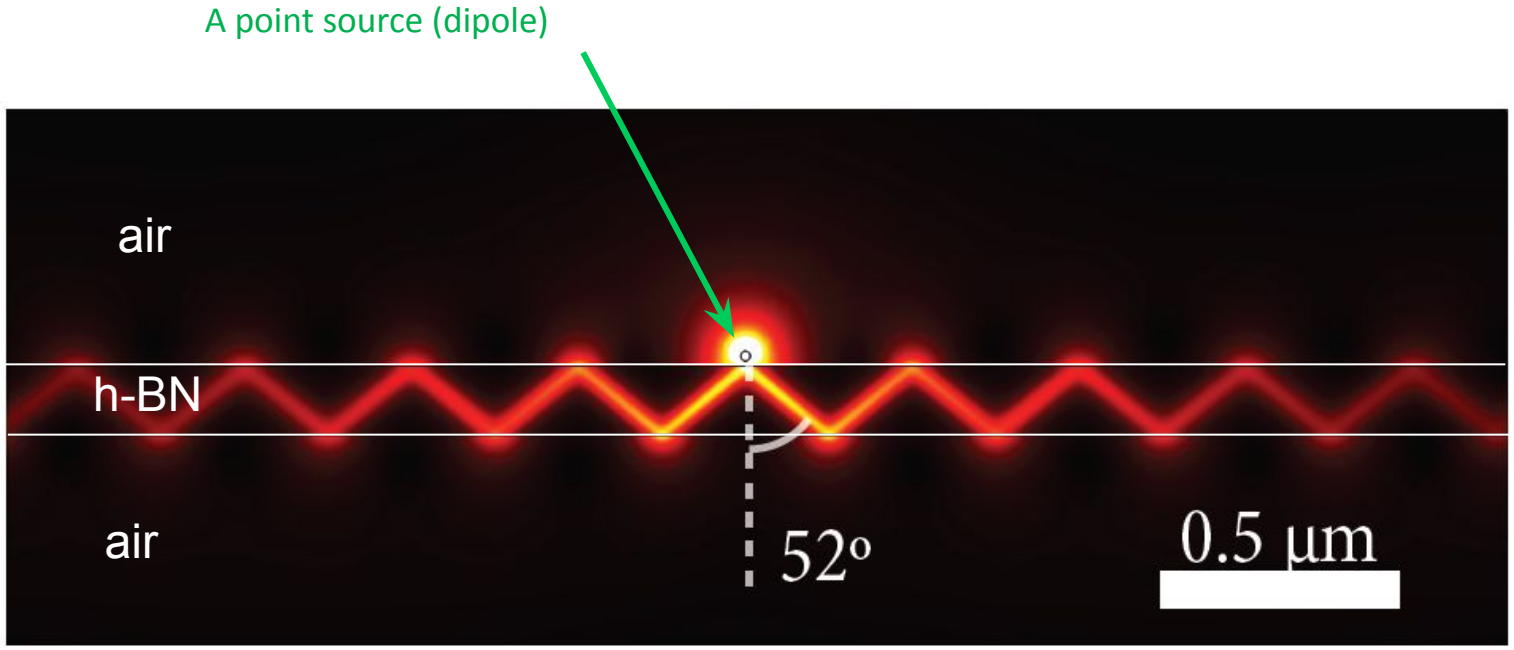
Isofrequency surface (Type II)



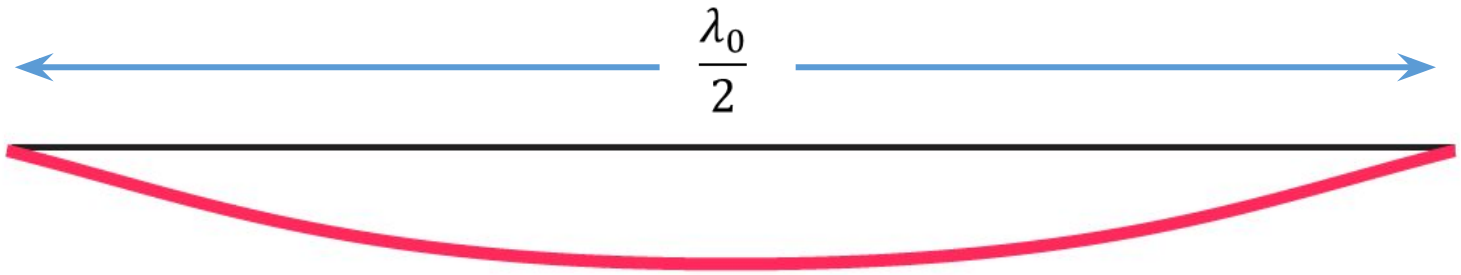
The origin of the rays is asymptotic straight lines

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

Polaritons in thin hyperboilc slabs

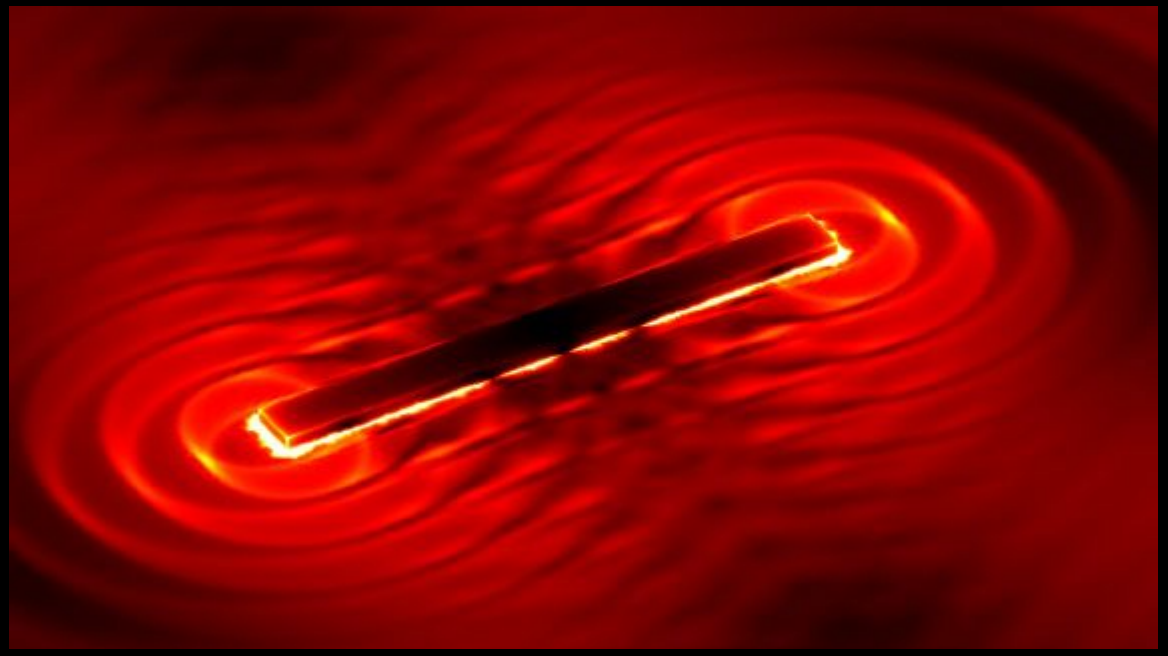


Simulations by Javier Alfaro

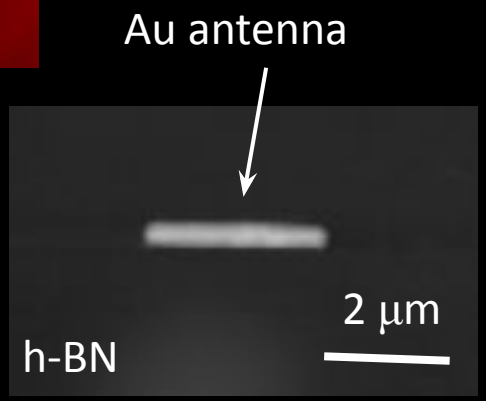


When a h-BN crystal has a finite thickness (slab), the rays reflect from the faces of the slab forming the subwavelength zig-zag pattern

Hyperbolic polaritons launched by an Au antenna



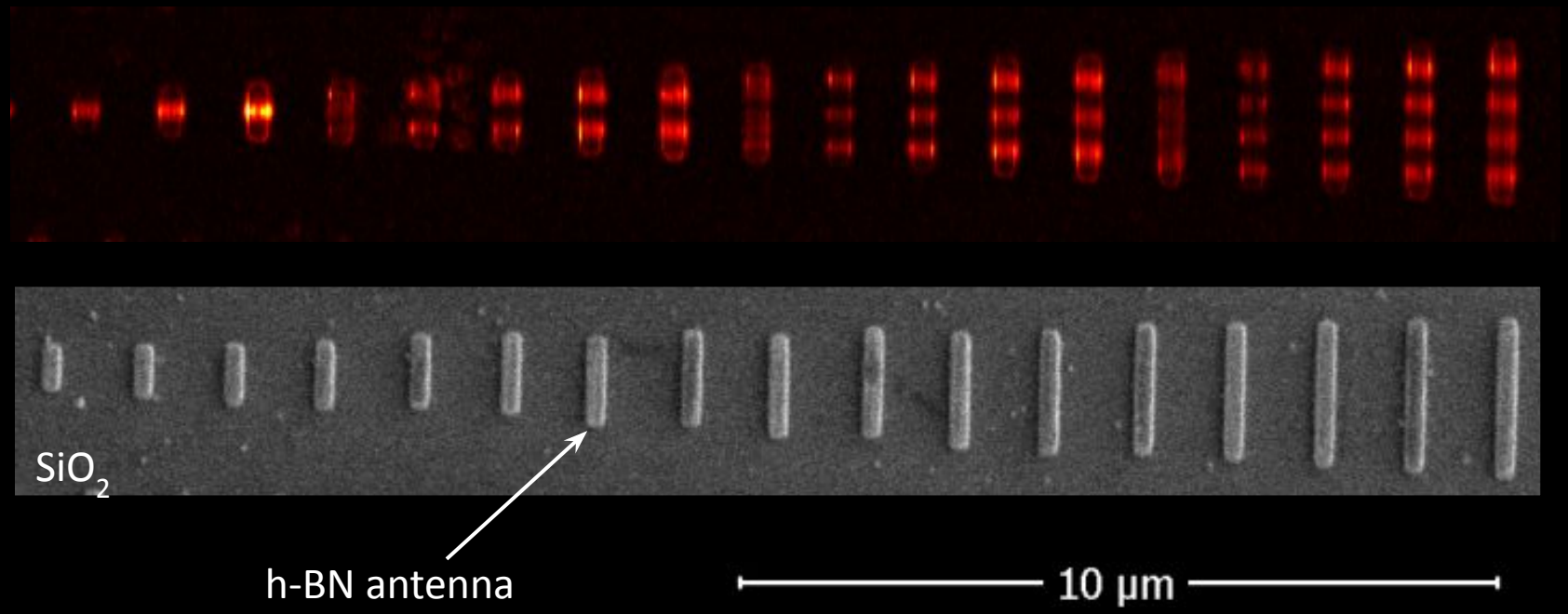
Simulations by Pablo Pons



P. Pons et al, Nature Commun. 10, 3242 (2019)

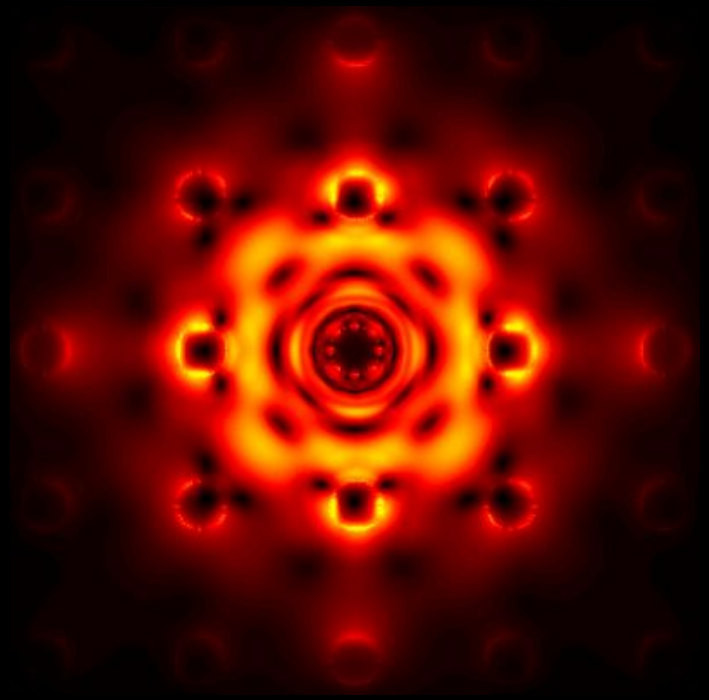
Localized hyperbolic polaritons

Experiments by Javier Alfaro



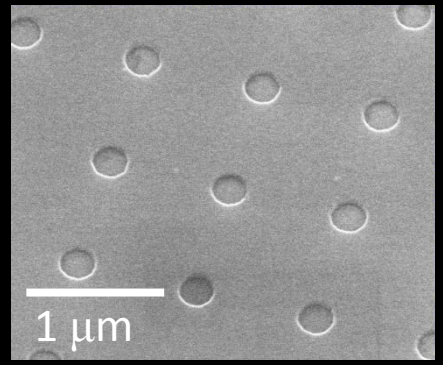
J. Alfaro et al, Nature Commun. 8, 15624 (2017)

Hyperbolic polaritons in h-BN photonic crystal



Simulations by Sergio Gutierrez

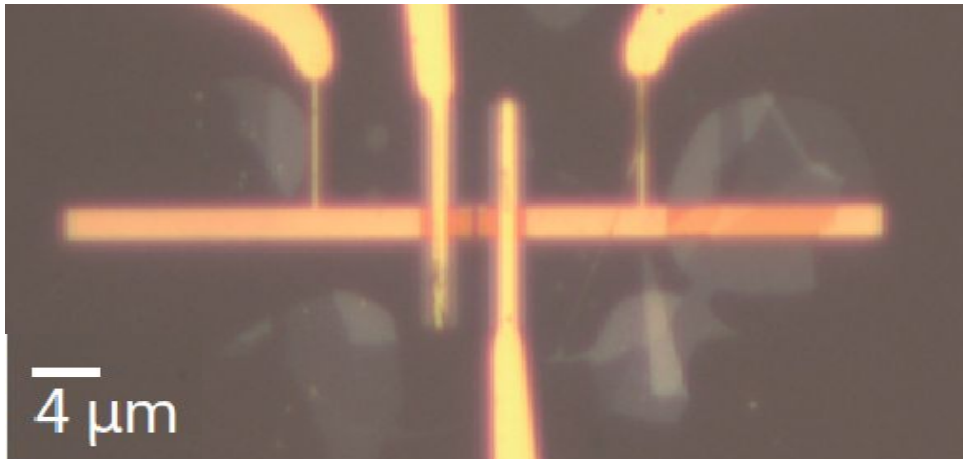
See poster by Nathaniel Capote



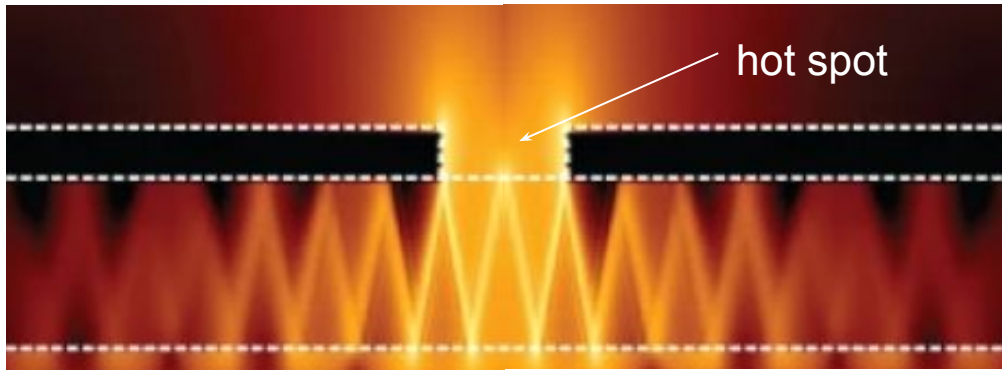
J. Alfaro et al, Nature Commun. 10, 42 (2019)

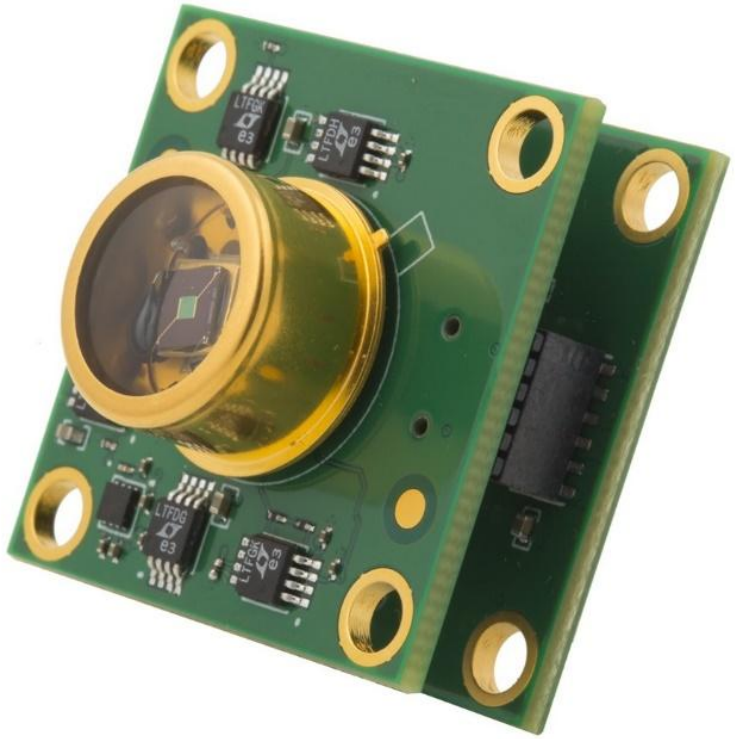
Antenna-integrated graphene photodetector

Top view



Side view (zoom-in)



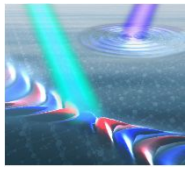


http://www.emberion.com

S. Castilla et. al, Nano Lett. **19**, 2765 (2019)

Outline

Introduction. Hyperbolic nanooptics with van der Waals crystals

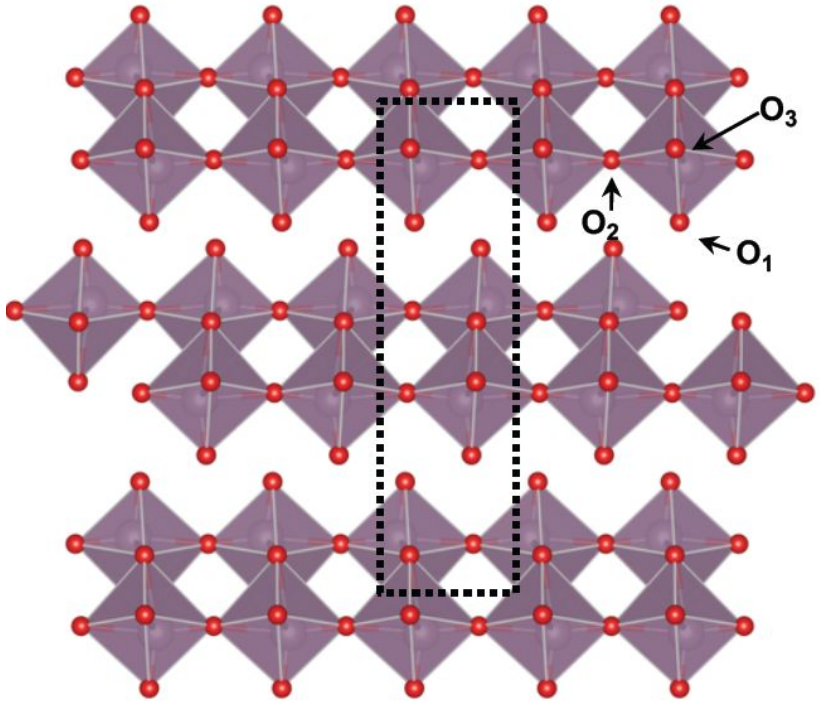


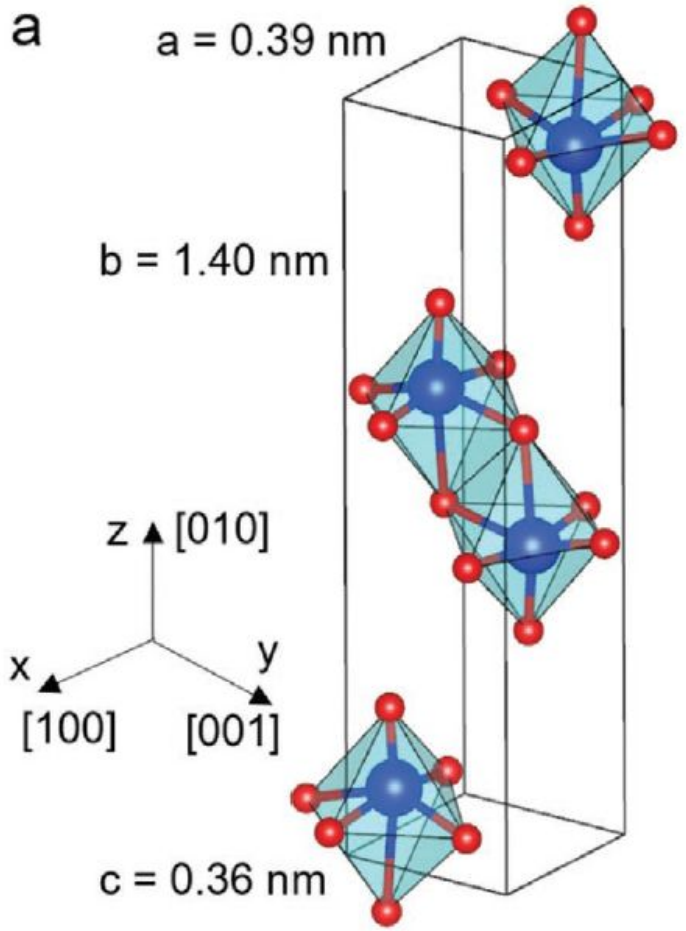
Elliptical and hyperbolic phonon-polaritons in α-MoO_3. Twisted nanooptics

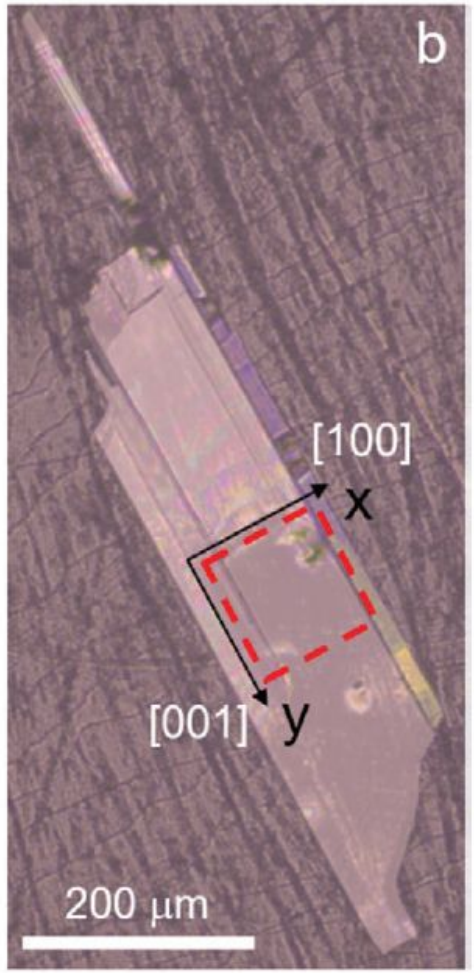
Far- and near-field measurements of resonances in rotated structures

Mapping of dispersion surface

Biaxial van der Waals crystal, α-MoO_3





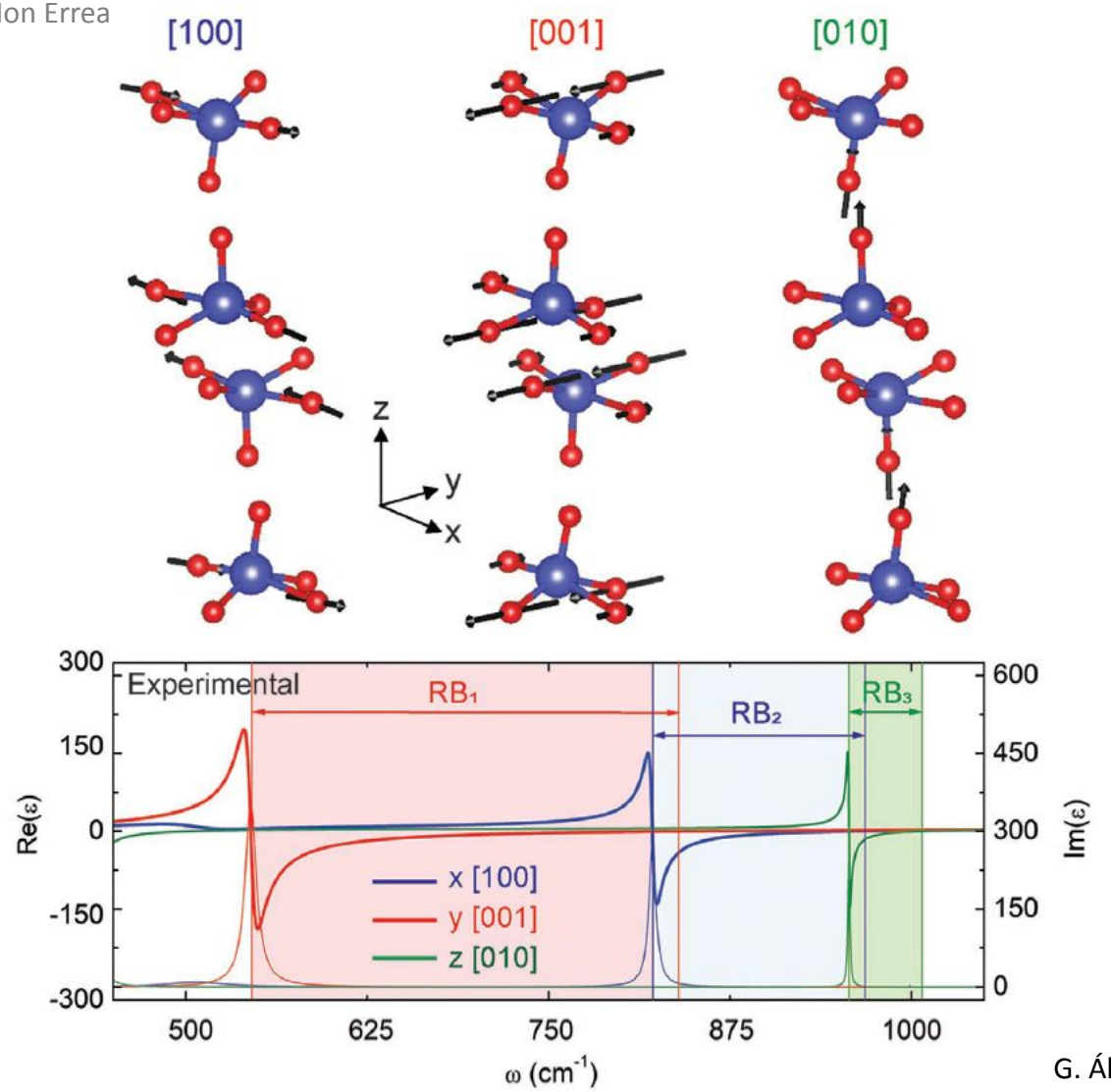


α−MoO_3 crystals are anisotropic due to their molecular structure. They show a strong narrow-band phononic responce

W. Ma et al., Nature **562**, 557 (2018)
Z. Zheng et al., Adv. Mat. **32**, 1705318 (2018)
Z. Zheng et al., Science Adv.. **5**, eaav8690 (2019)
G. Álvarez-Pérez et al., Adv. Mat. **32**, 1908176 (2020)

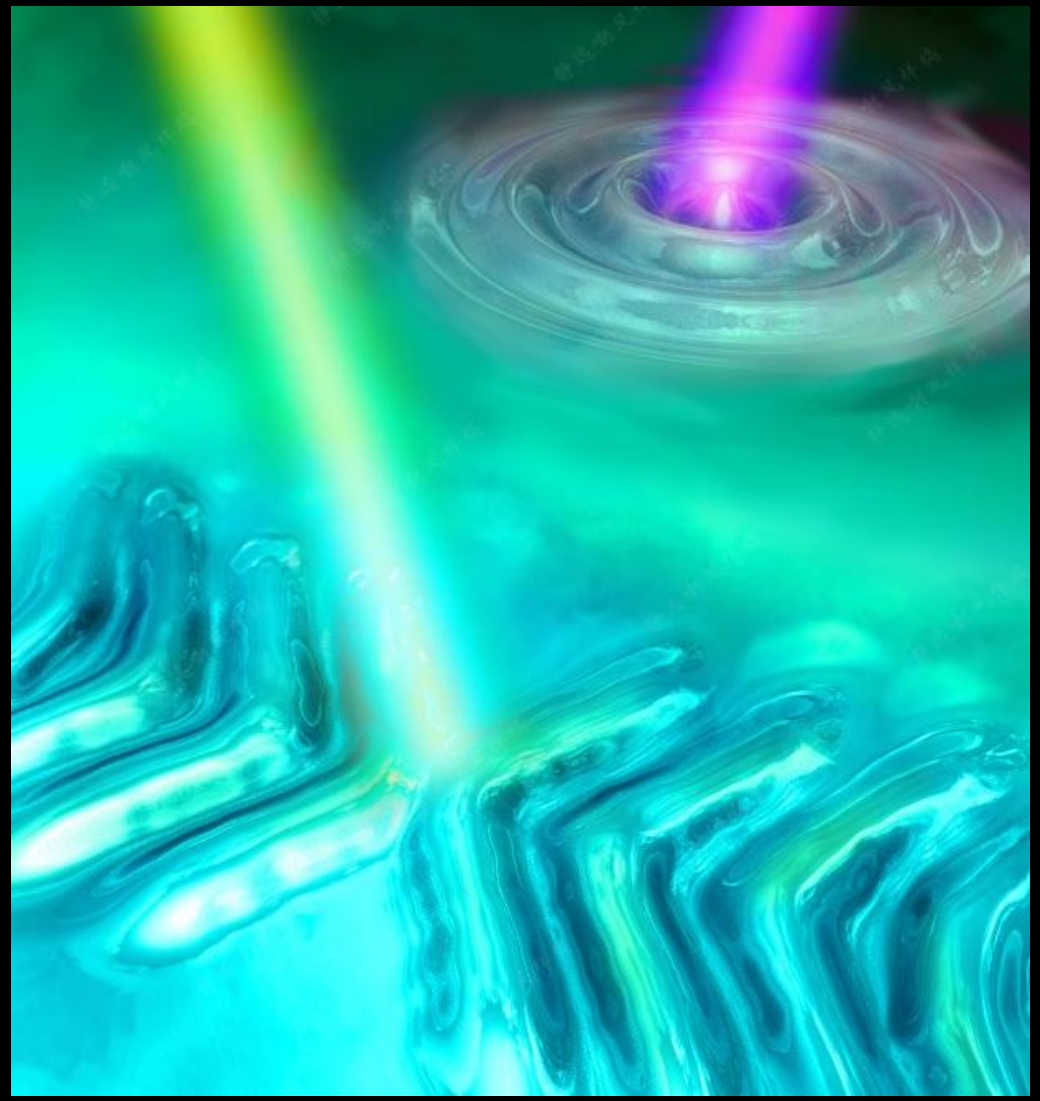
Dielectric permittivity tensor of α-MoO_3

DFT by Ion Errea

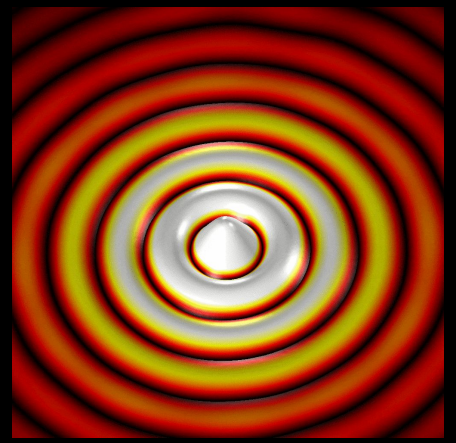


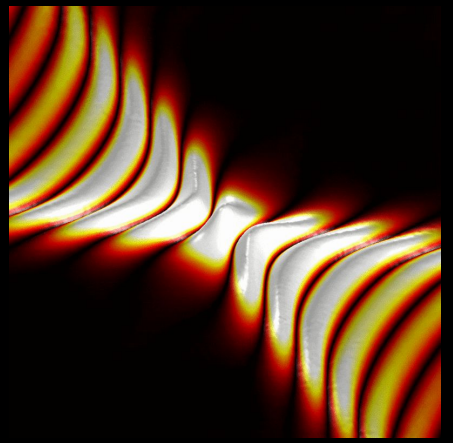
G. Álvarez-Pérez et al., Adv. Mat. **32**, 1908176 (2020)

Hyperbolic and elliptic polaritons coexist



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





Simulations by Peining Li

Twisted bilayer graphene

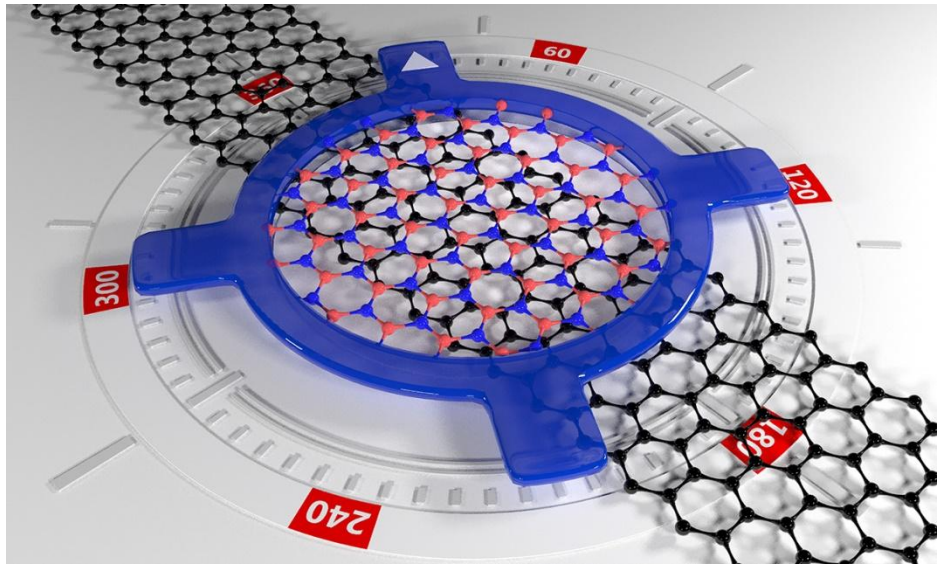
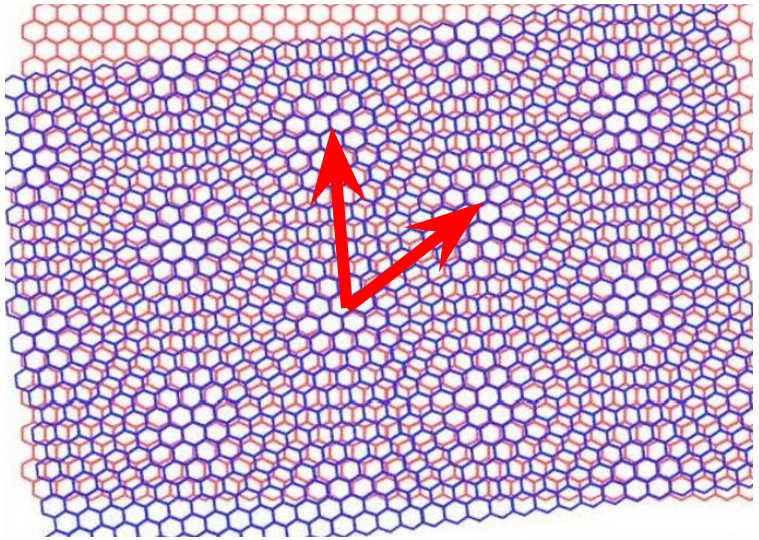


Illustration: Philip Krantz/Krantz NanoArt

Moiré patterns



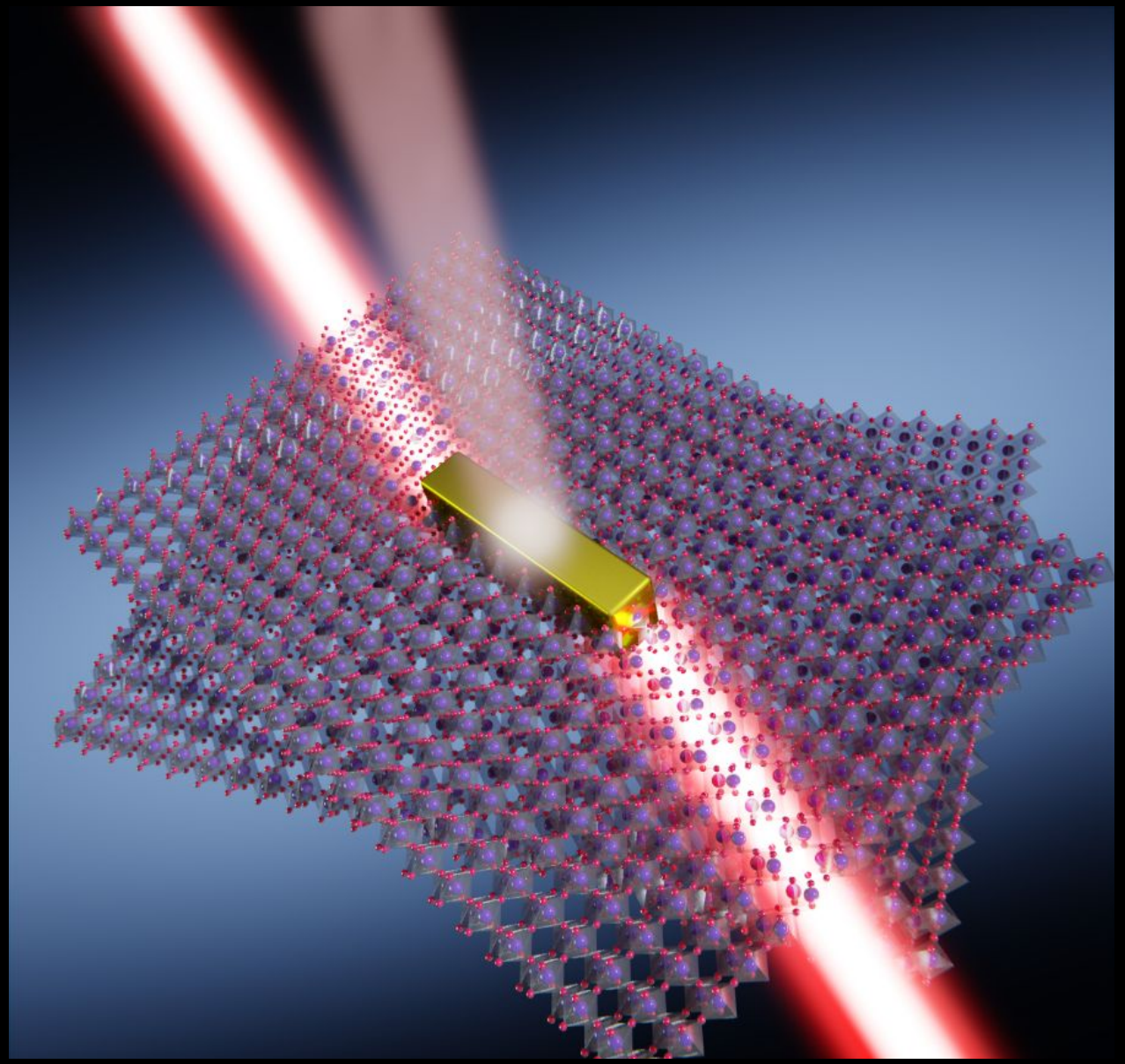
Superconductivity

Y. Cao et al., Nature **556**, 43, (2018)
Y. Cao et al., Nature **556**, 80, (2018)

Photonic crystal

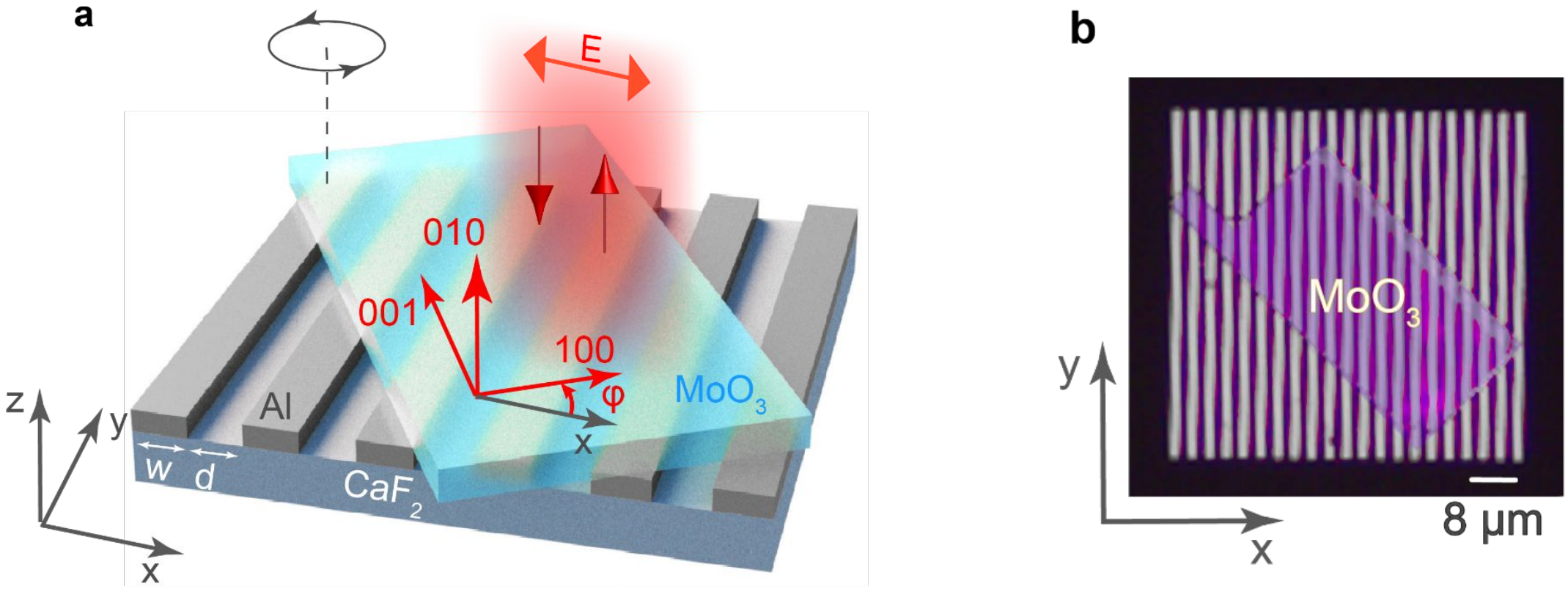
S.S. Sunkuet al., Science **362**, 1153, (2018)

Twisted Nano-Optics



J. Duan, el al Nano Lett. **20**, 5323 (2020)
G. Hu Et al. Nature **582**, 209 (2020)
M. Chen, et al. Nature Mat. (2020)
Z. Zheng et al. Nano Lett. **20** 5301 (2020)

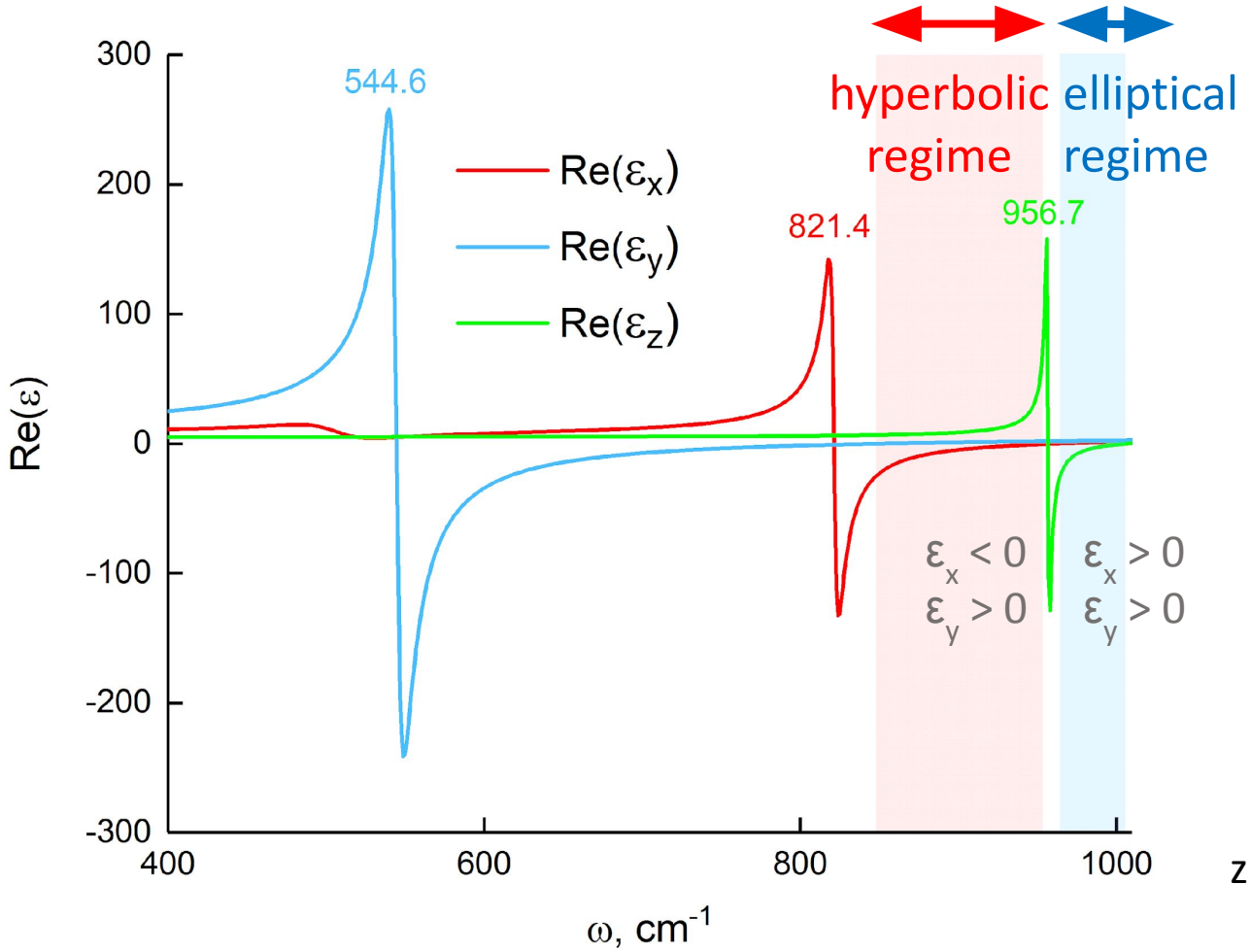
Twisted nanoresonators for hyperbolic polaritons



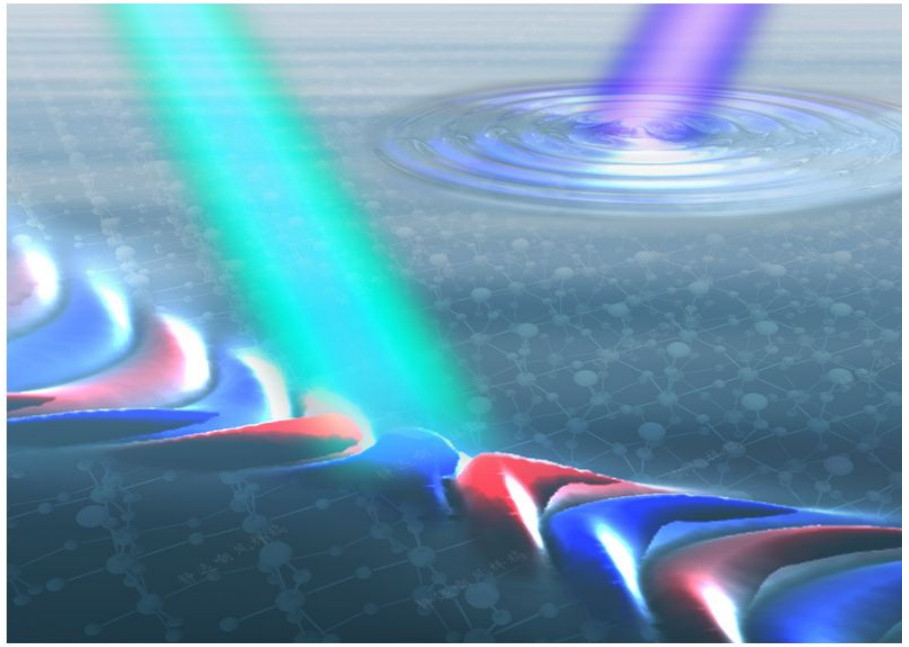
Nanoresonators are formed by α-MoO_3 placed above metallic ribbons

Elliptic and hyperbolic regimes of phonon-polaritons in α-MoO_3

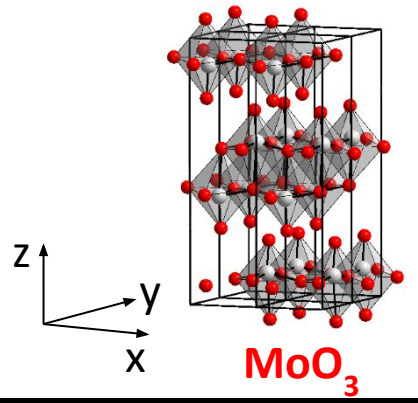
We consider both elliptic and hyperbolic polaritons in α-MoO_3



Álvarez-Pérez, G. et al., Adv. Mater. (2020)

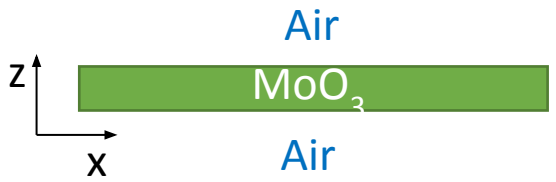


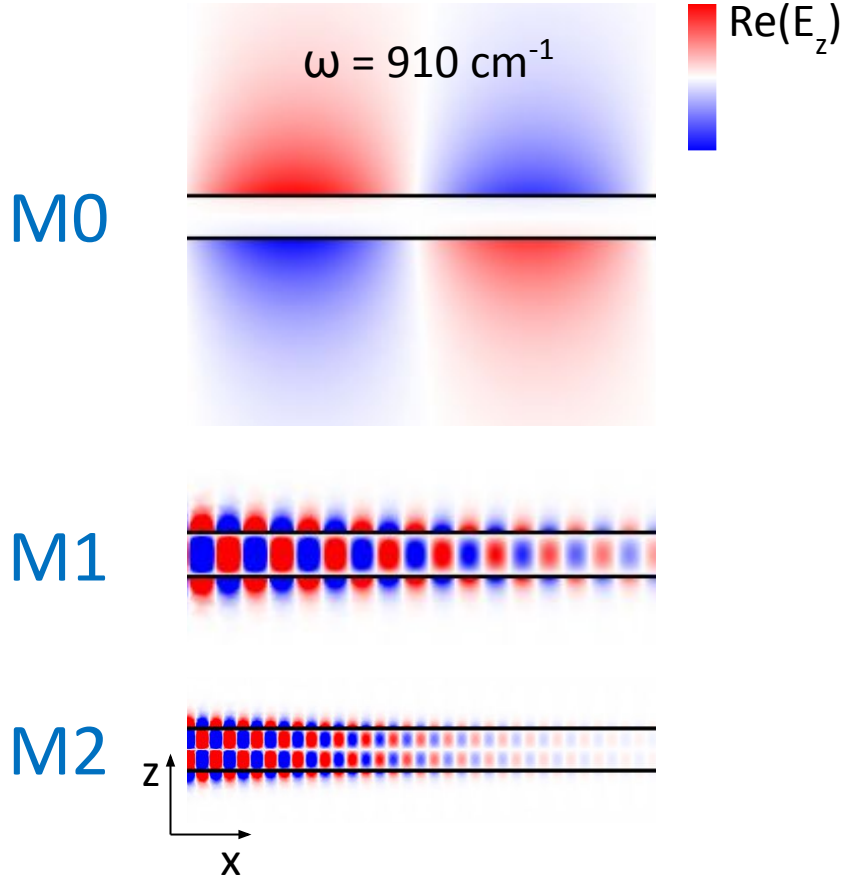
W. Ma et al., Nature **562**, 557 (2018)

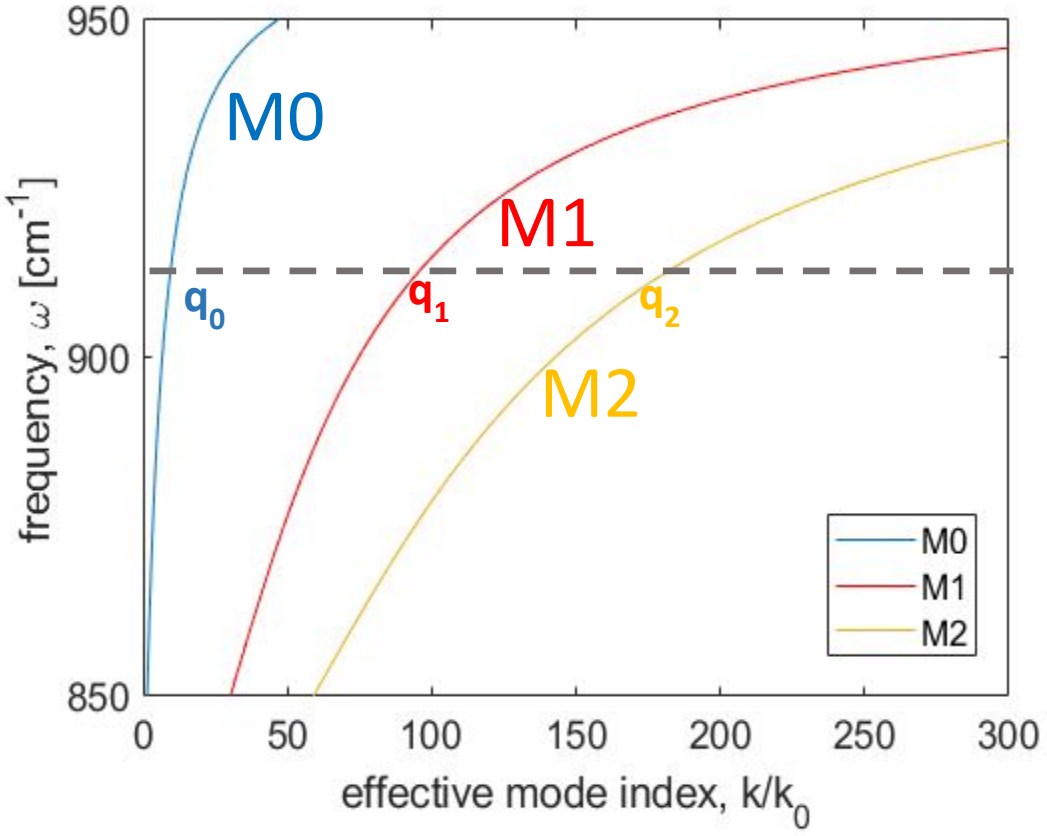


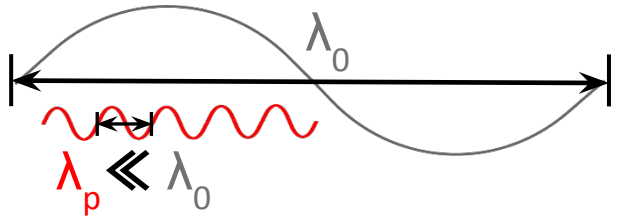
$$\hat{\varepsilon}(\omega) = \begin{pmatrix} \varepsilon_x(\omega) & 0 & 0 \\ 0 & \varepsilon_y(\omega) & 0 \\ 0 & 0 & \varepsilon_z(\omega) \end{pmatrix}$$

Modes in thin slab of α-MoO_3

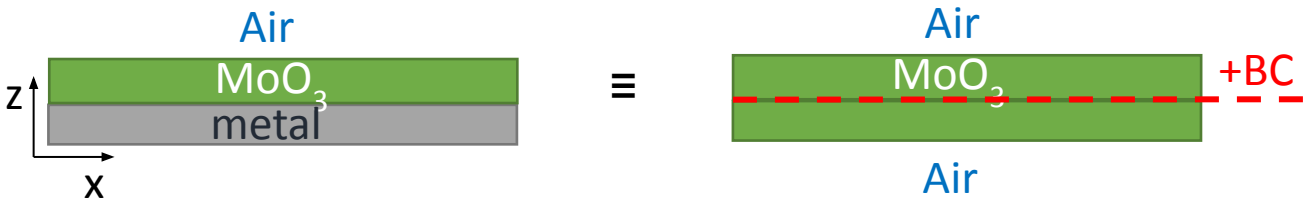




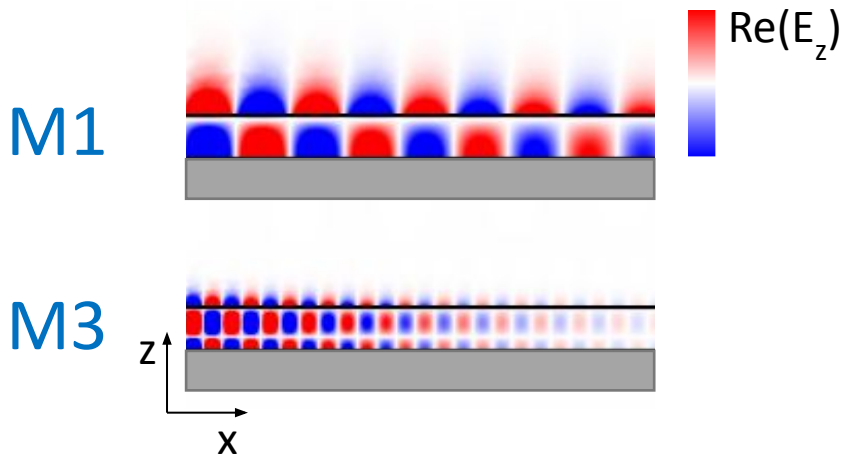




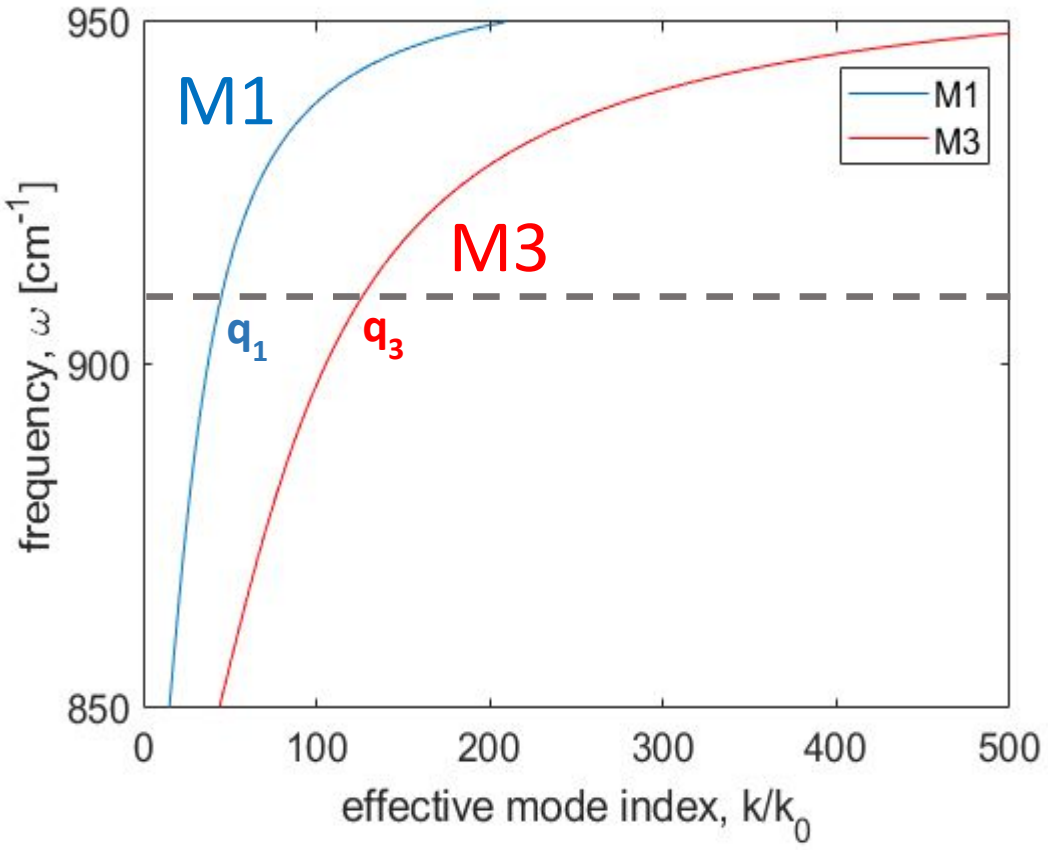
Modes in thin slab of α-MoO_3 above metal

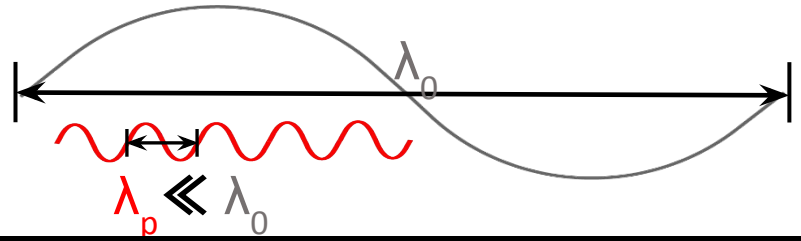


ω = 910 cm^{-1}



odd modes only

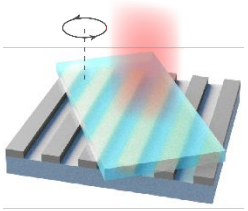




Outline

Introduction. Hyperbolic nanooptics with van der Waals crystals

Elliptical and hyperbolic phonon-polaritons in MoO3. Twisted nanooptics

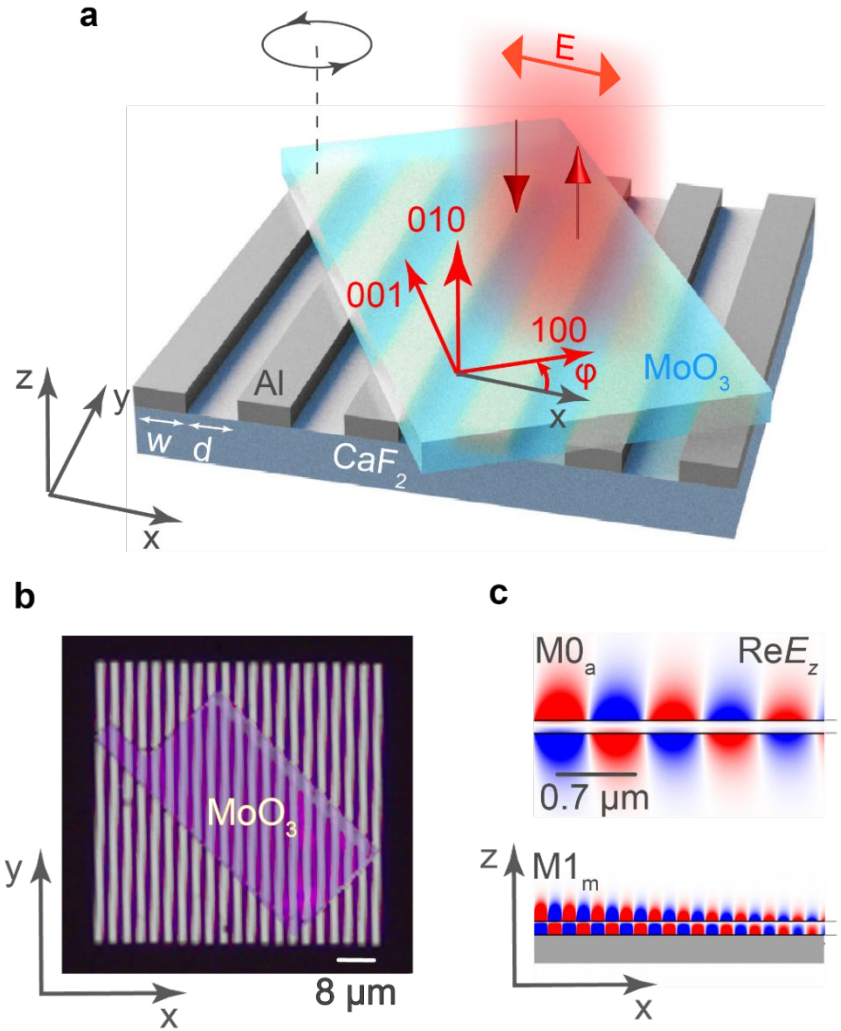


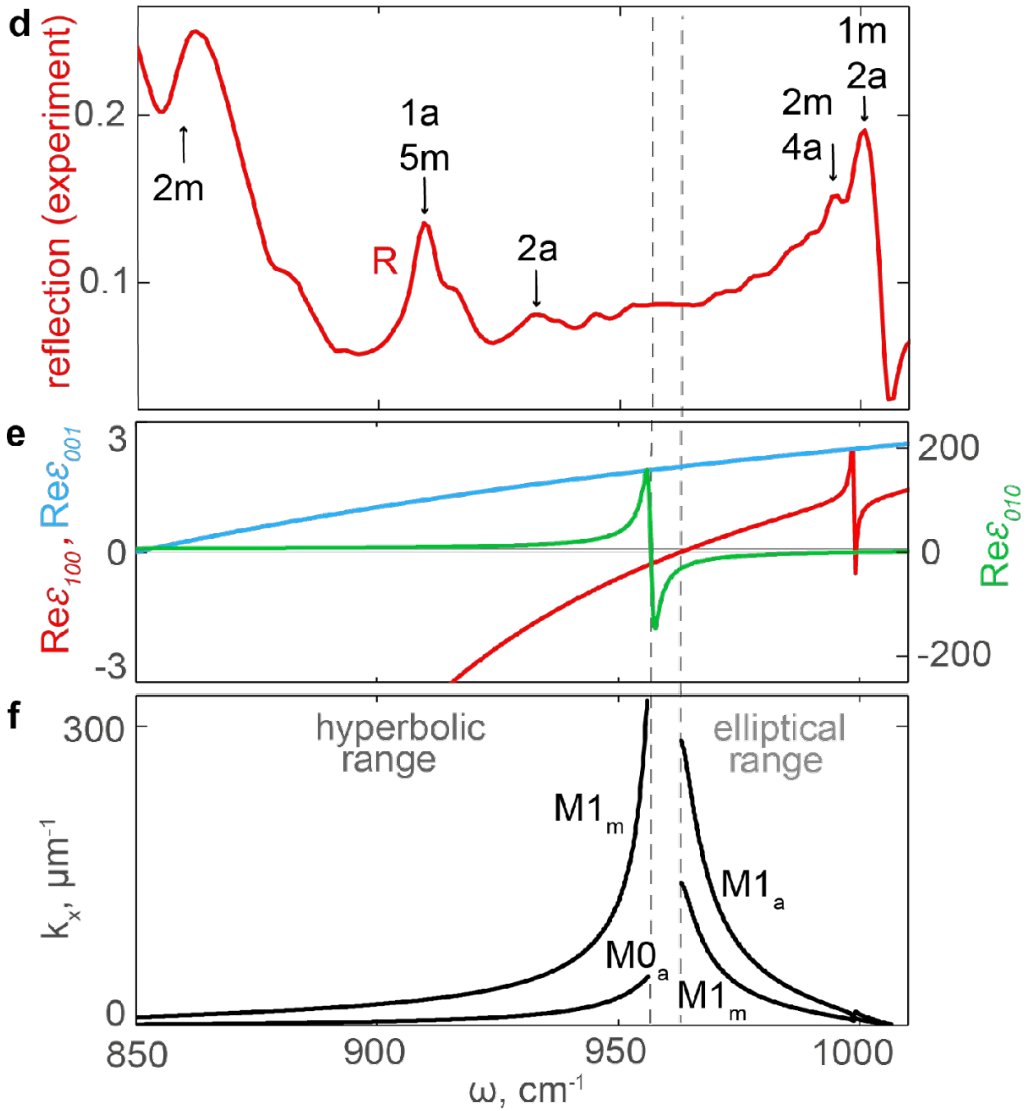
Far- and near-field measurements of resonances in rotated structures

Mapping of dispersion surface

Far-field measurements of resonances in twisted structures

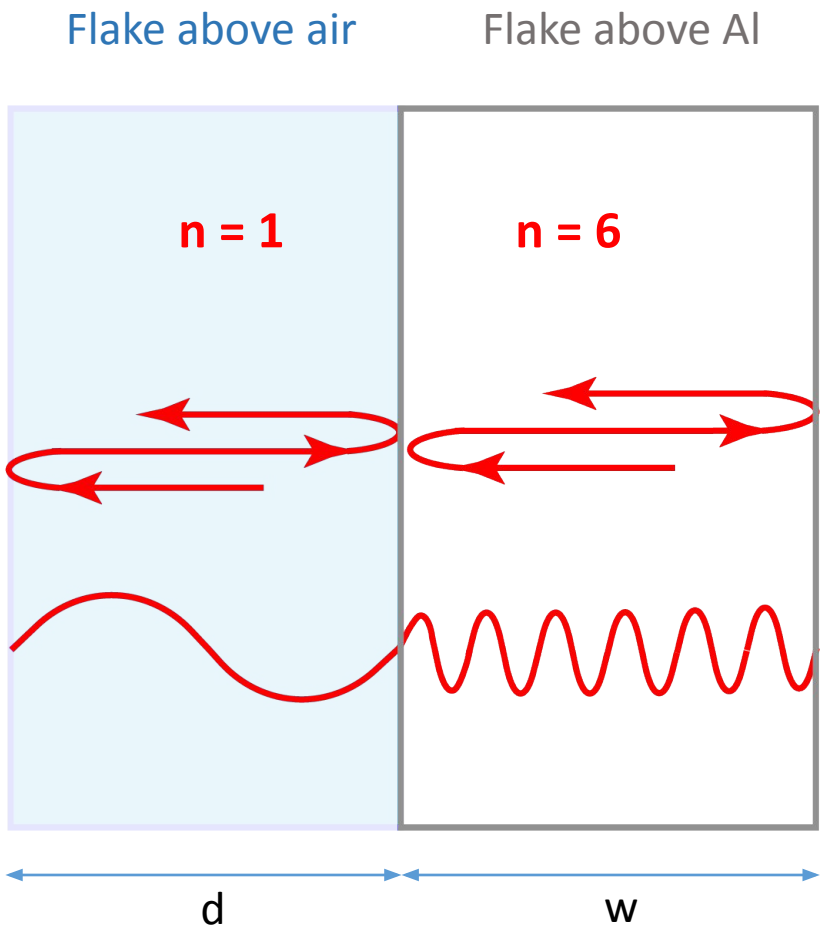
α-MoO_3 above air and α-MoO_3 above metal supports modes with significantly different wavevectors forming two types of Fabry-Perot resonators





Model of resonances

We assume the structure to be equivalent to two independent Fabry-Perot resonators



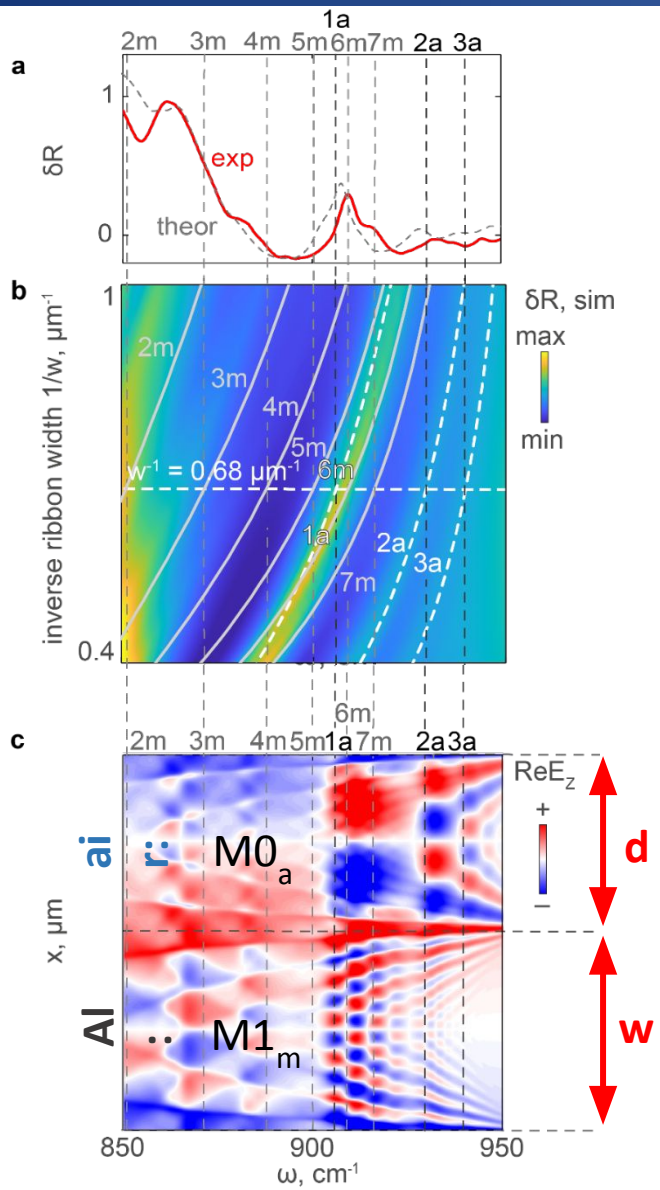
phase matching:

air: $2kd + 2\Phi_a = 2\pi n$

Al: $2kw + 2\Phi_m = 2\pi m$

Simulation of resonances in twisted structures

$\varphi = 0$, period of lattice changes (d/w = const)



The dependance of the reflection coefficient on ribbon width and frequency. Comparison of the numerical simulation with the experimental results

phase matching:

air: $2kd + 2\Phi_a = 2\pi n$

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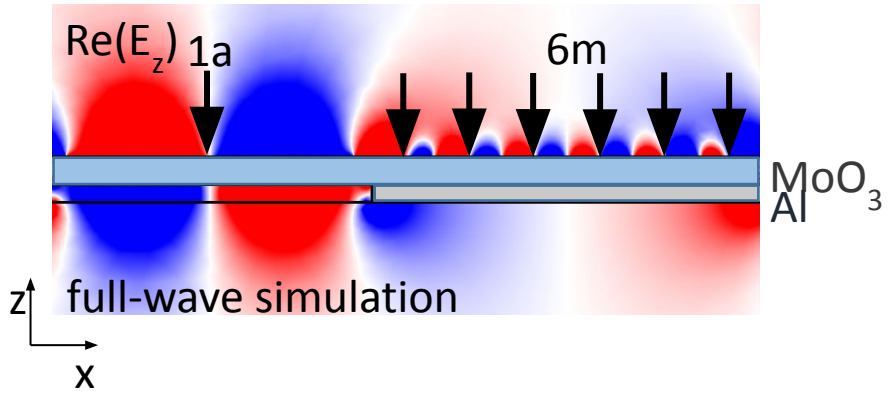
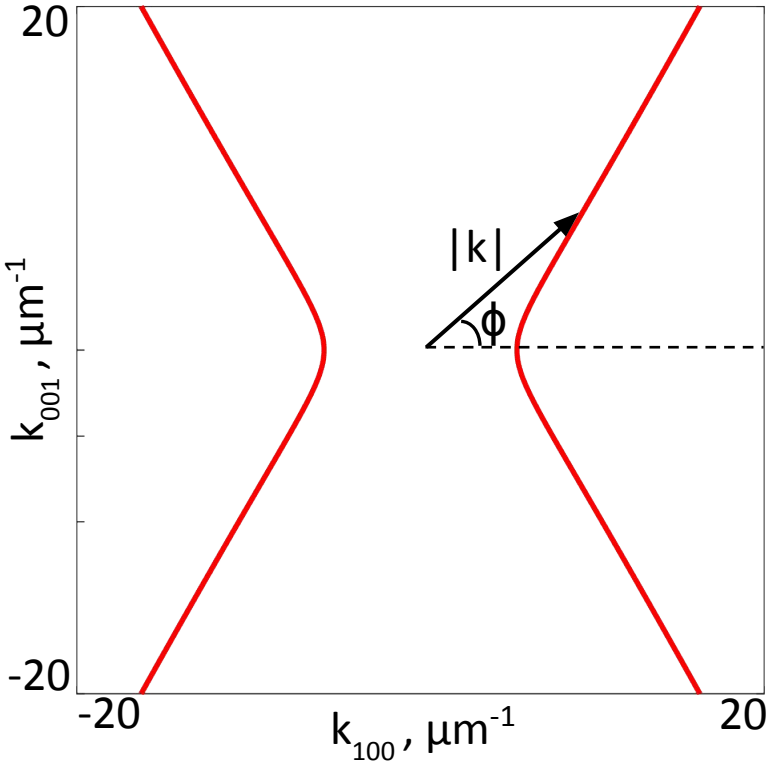
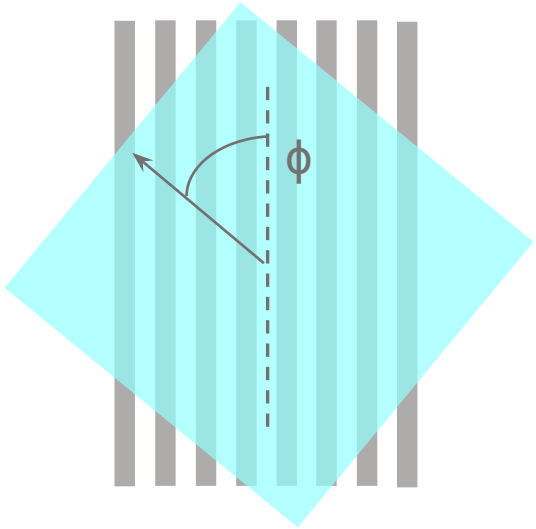


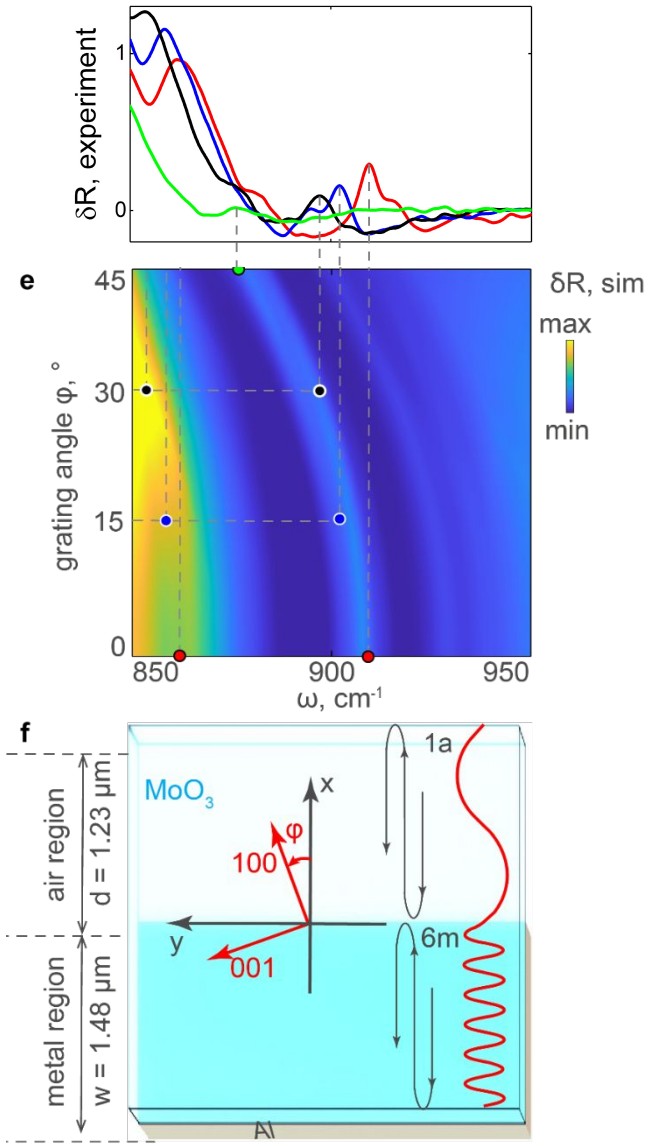
Far-field measurements for different angles

The dependance of the reflection coefficient on frequency and the angle between main axes of the biaxial slab and ribbons direction. Comparison of the numerical simulation with the experimental results



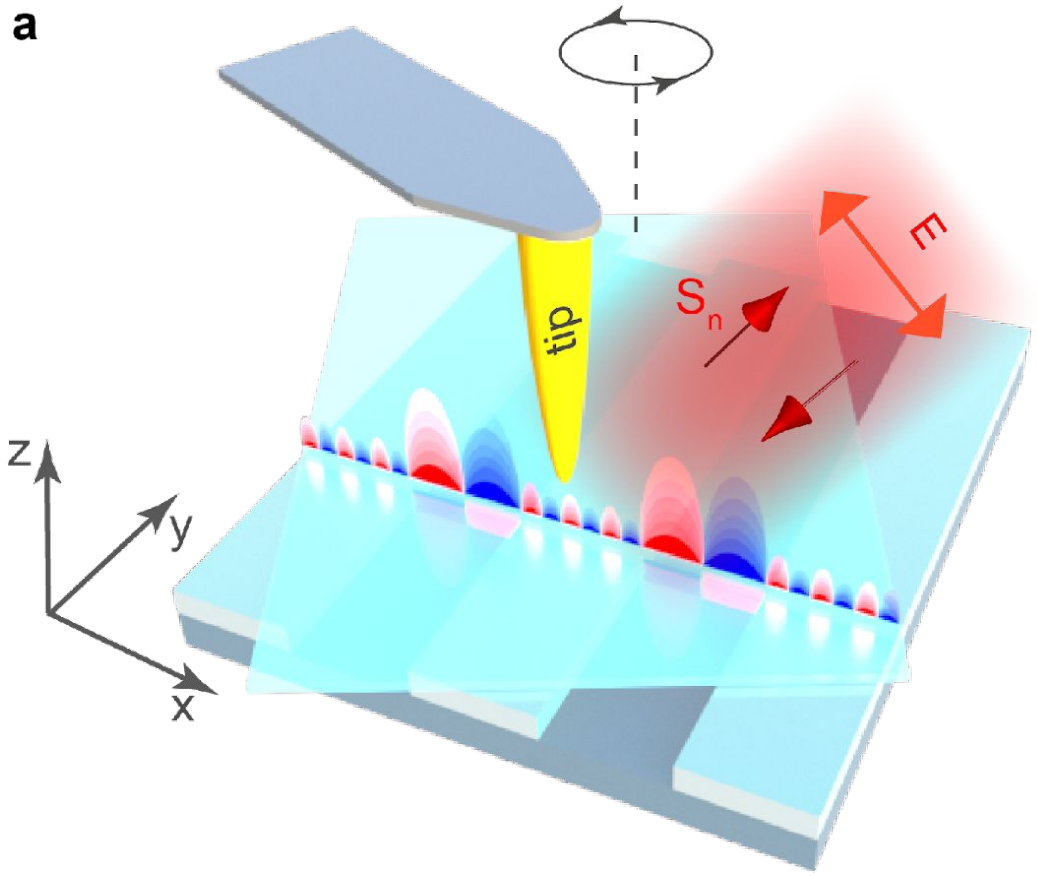
Period of lattice is fixed, φ changes





s-SNOM measurements

s-SNOM measurements verify our assumption about resonances in α-MoO_3 film



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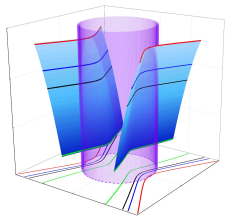
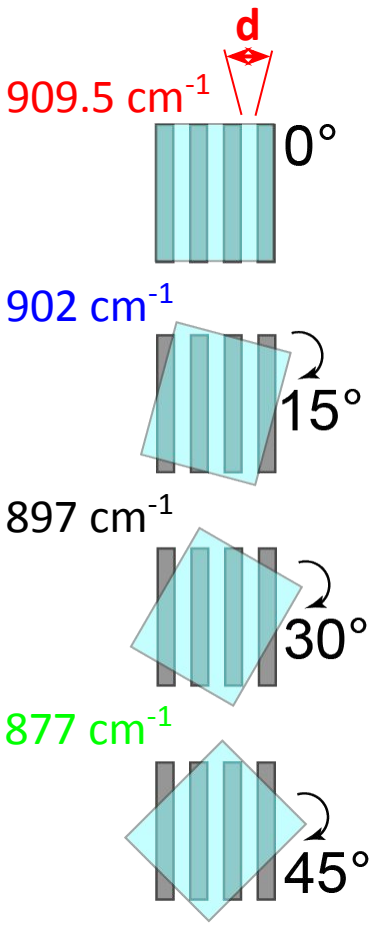


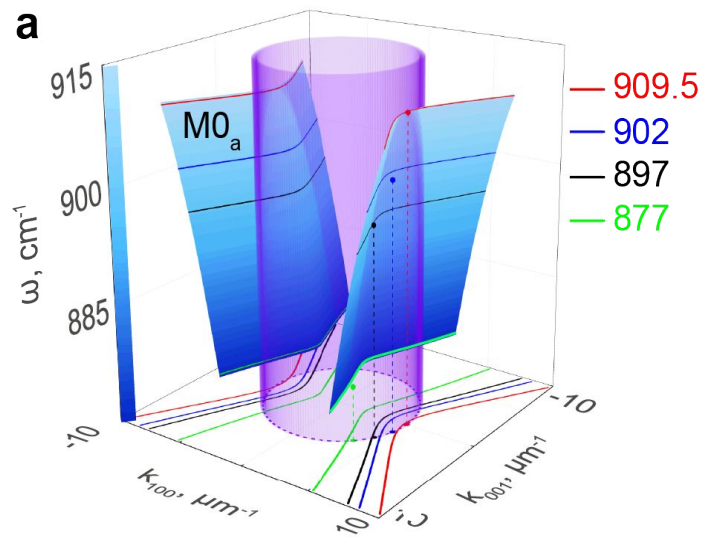
Mapping of dispersion surface

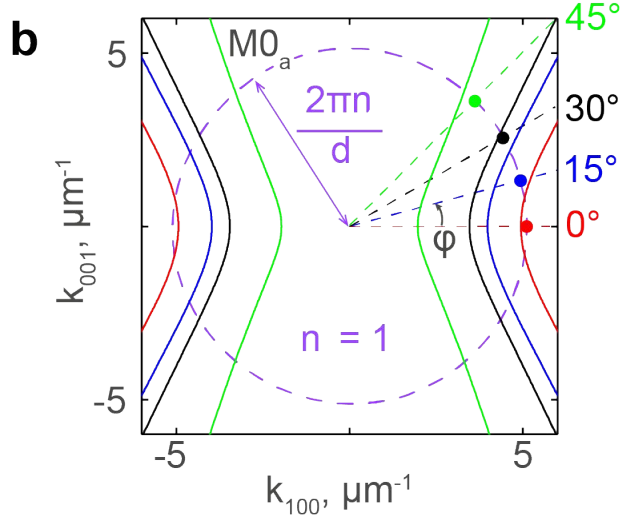
Mapping of dispersion surface

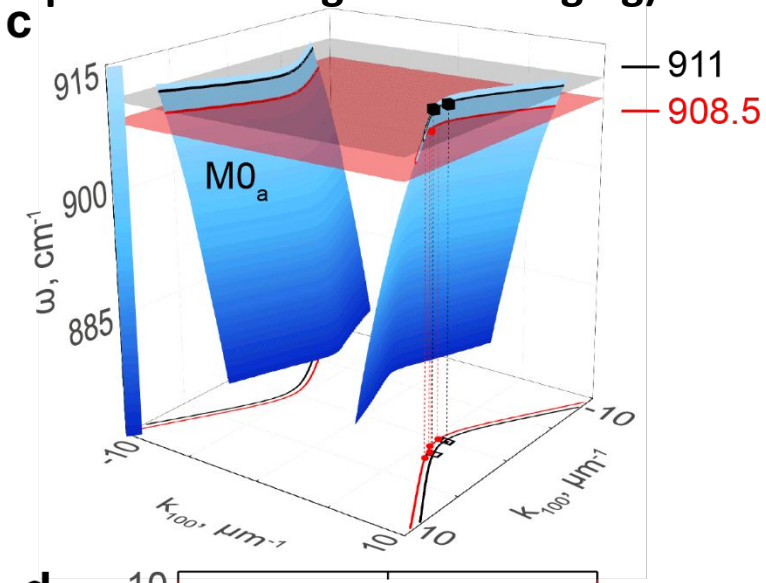
cut in momentum (period is constant, frequency and angle are changing)

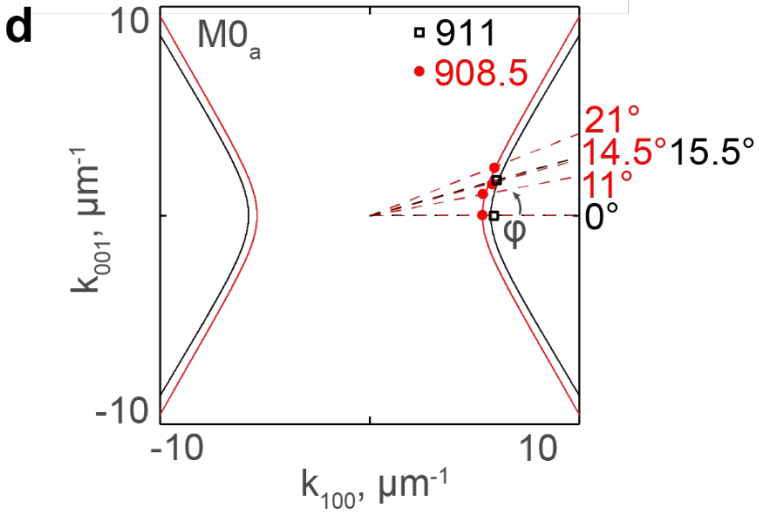
cut in frequency (frequency is constant, period and angle are changing)

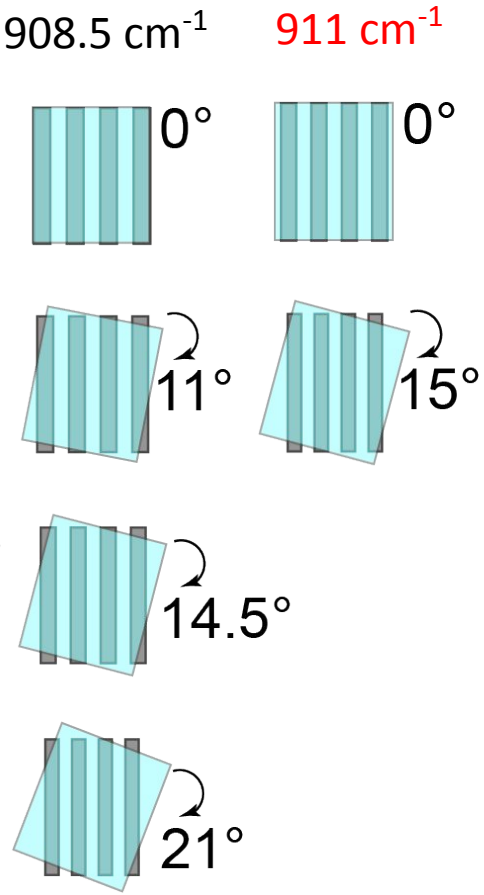












Take-home messages

- **High-quality (Q ≈ 200) resonances** of surface PhPs identified by far- and near-field measurements
- Unique **tunability** of resonators **by a rotation** of the crystal slab with respect to the grating
- Experimental **dispersion surface mapping**
- **Applications to** tunable strong coupling of PhP with organic molecules, **tunable** infrared **sensors** and photodetectors

2D Nanophotonics group

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Gonzalo Alvarez Olga Matveeva Nathaniel Capote

Kirill Voronin

"la Caixa" Foundation

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Thank you for your attention!

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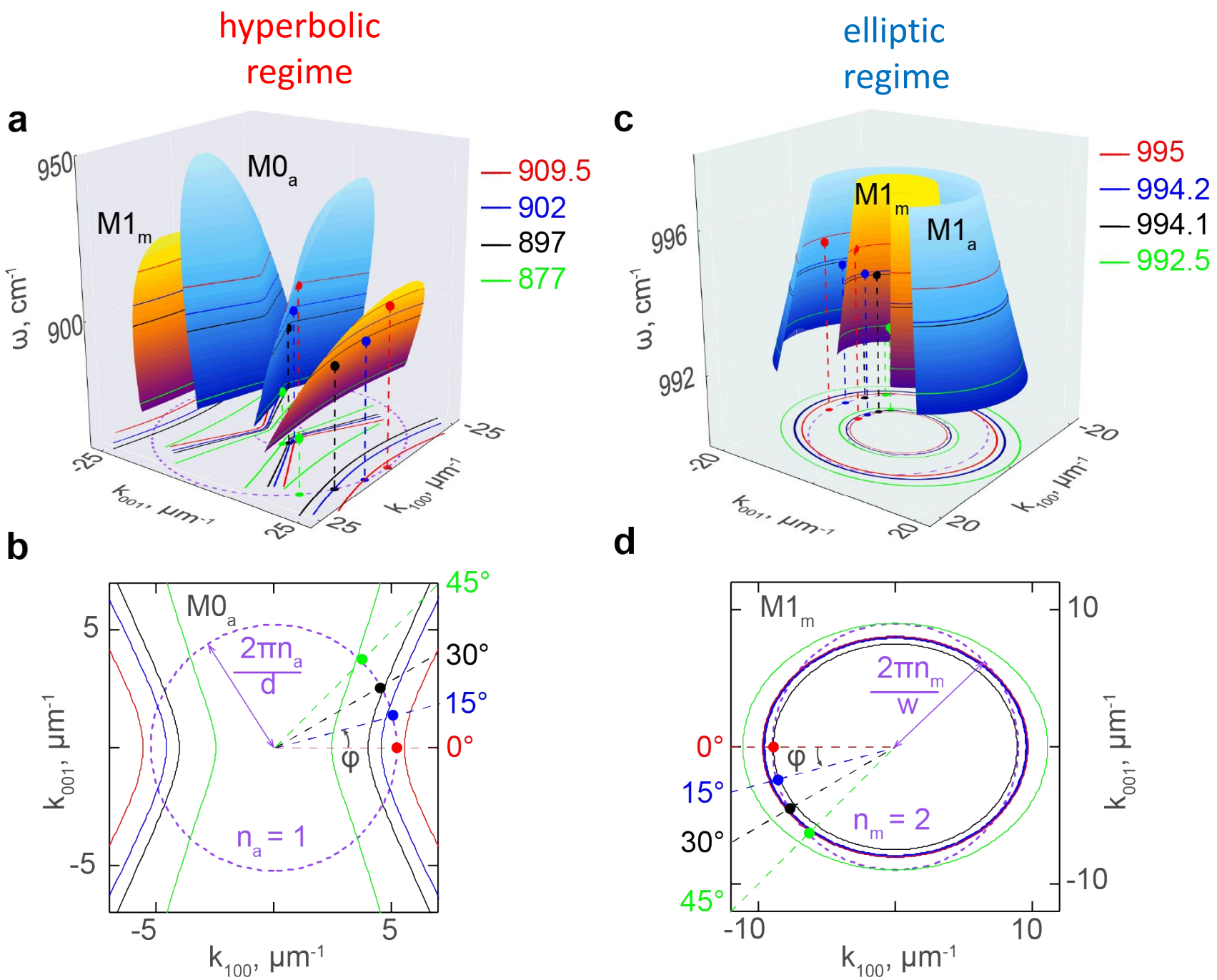
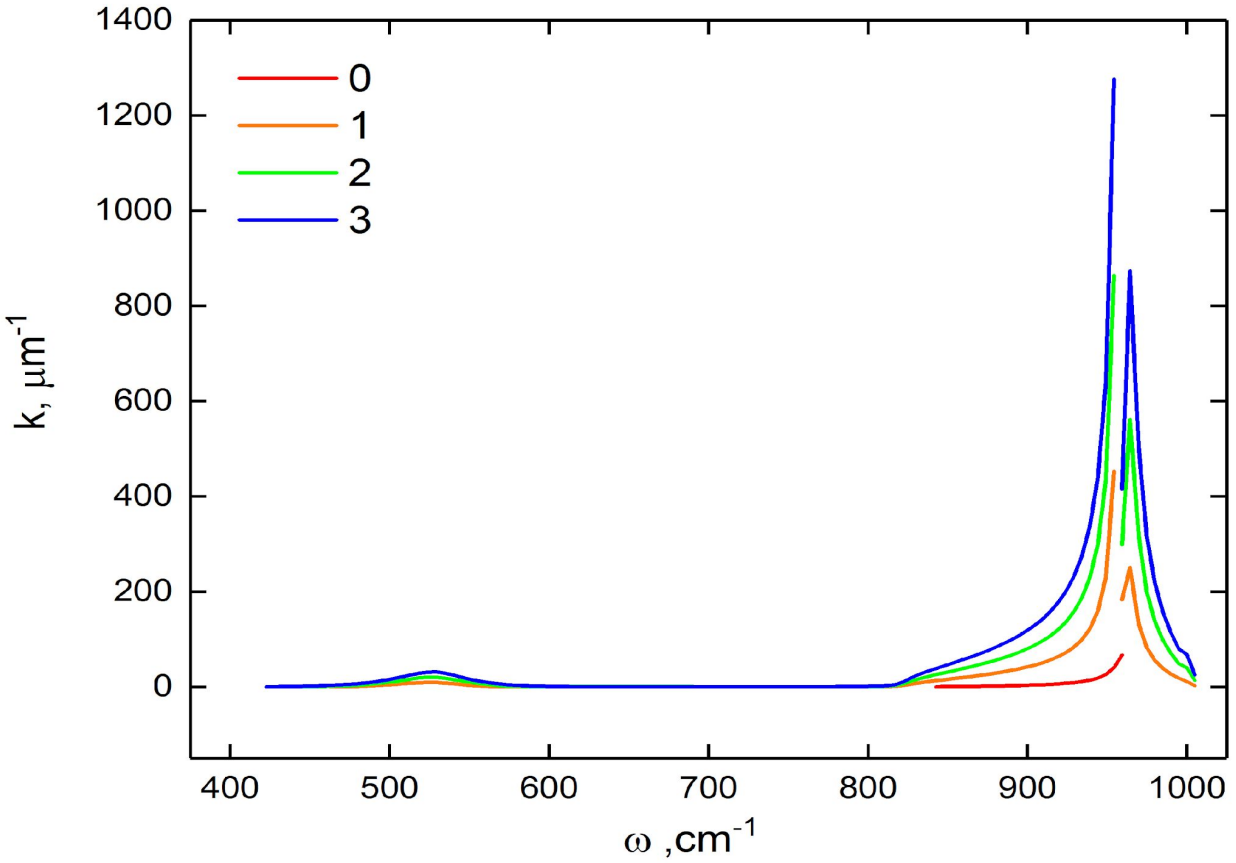
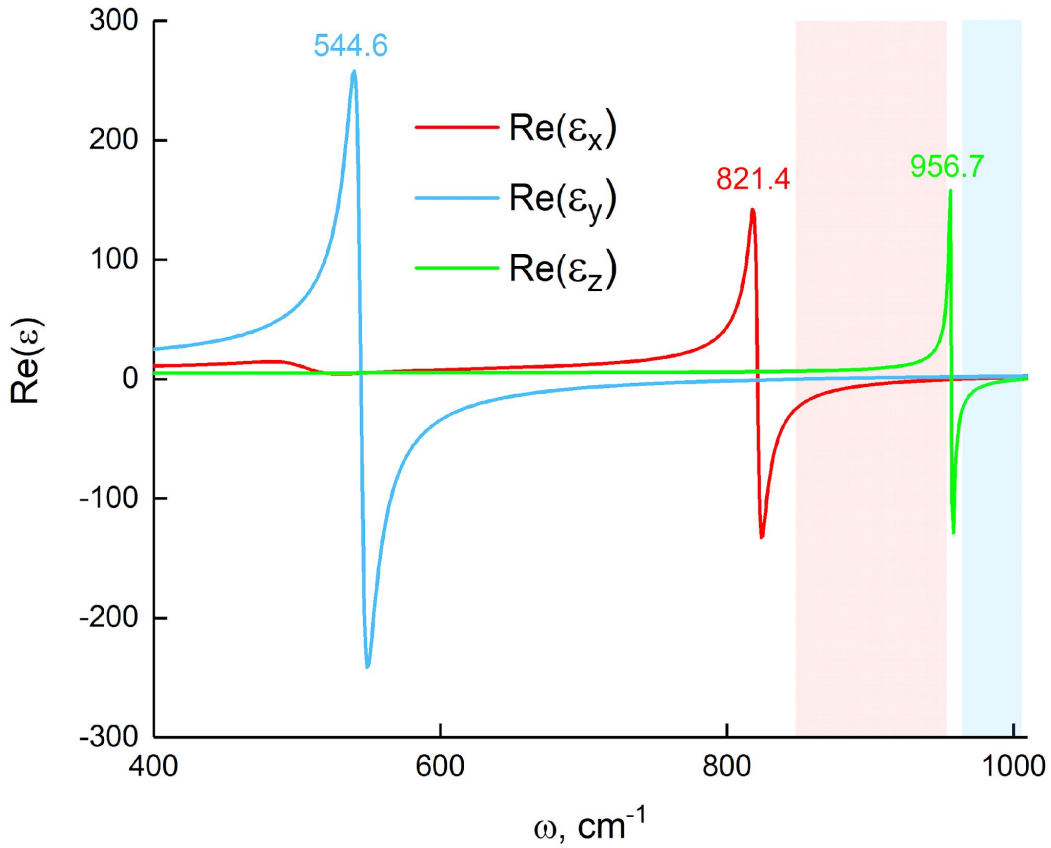
Supplementary slides

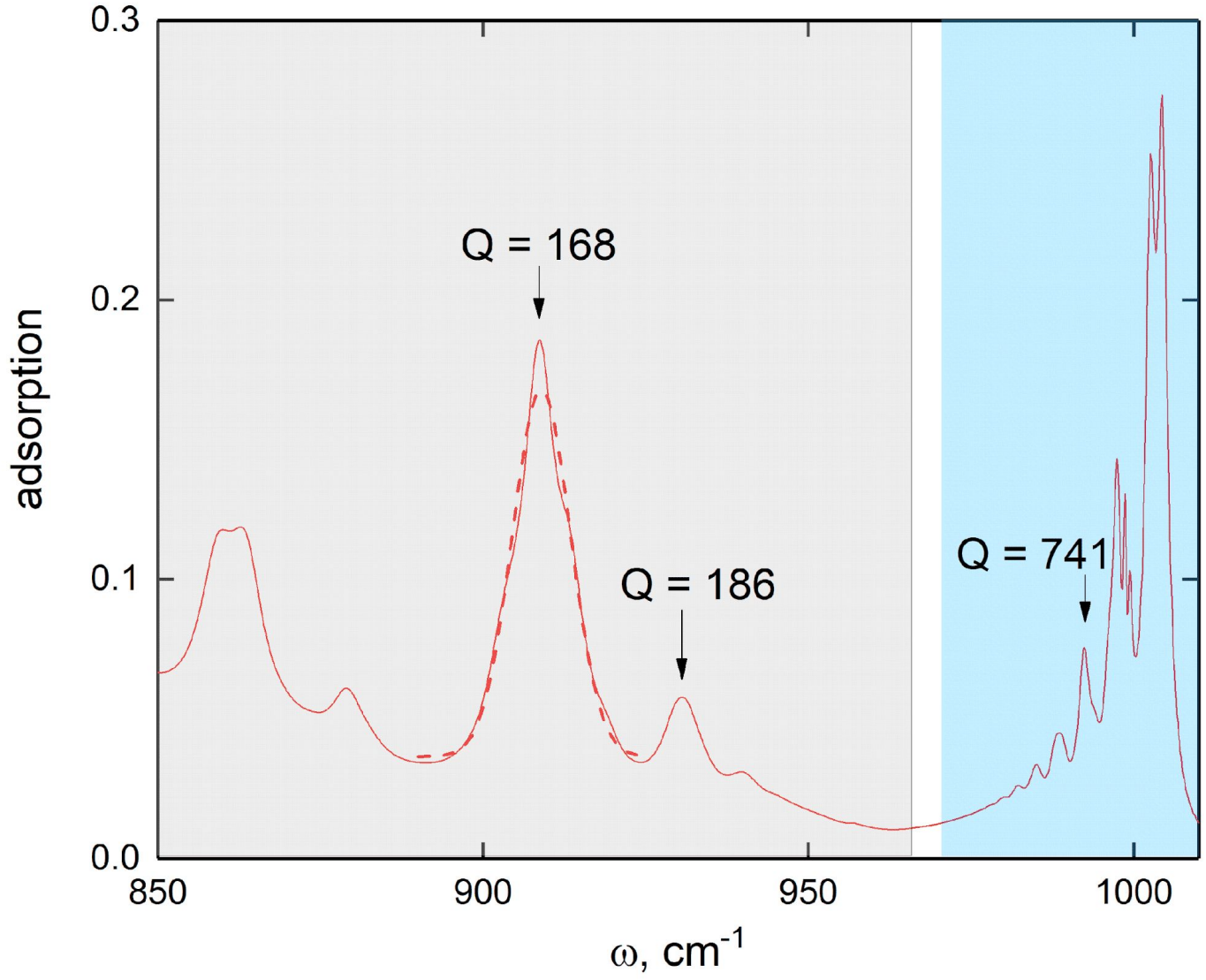

hyperbolic regime
elliptic regime
a
c
b
d
M0a
M1m
M1a
909.5
902
897
877
995
994.2
994.1
992.5
ω, cm-1
950
900
996
992
k001, μm-1
k100, μm-1
25
-25
20
-20
2πna/d
2πnm/w
φ
na = 1
nm = 2
45°
30°
15°
0°
5
-5
10
-10

Dispersion of modes



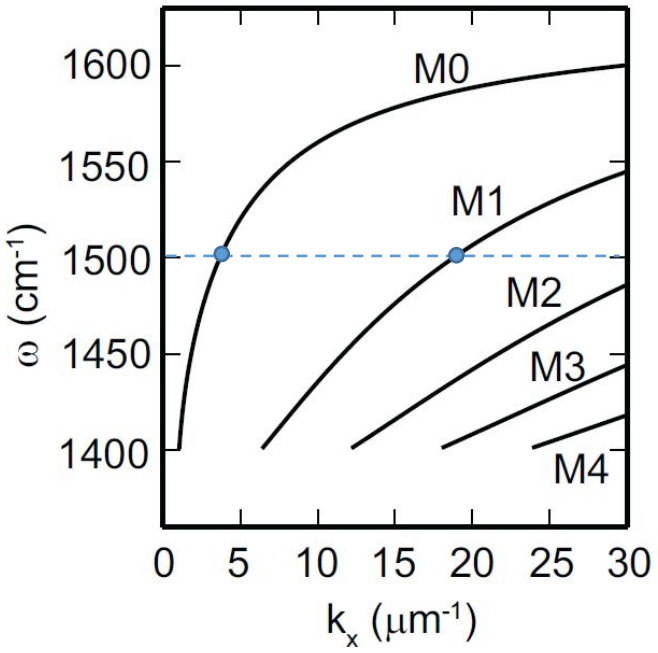


resonance quality factor

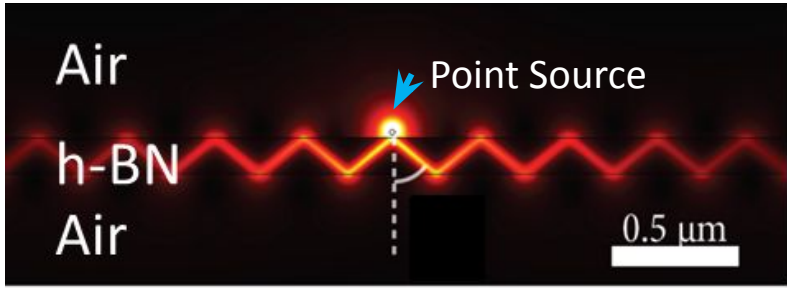


Hyperbolic volume modes in h-BN slabs

Dispersion curves of the modes



The zig-zag pattern can be seen as a superposition of the HPP waveguiding modes.



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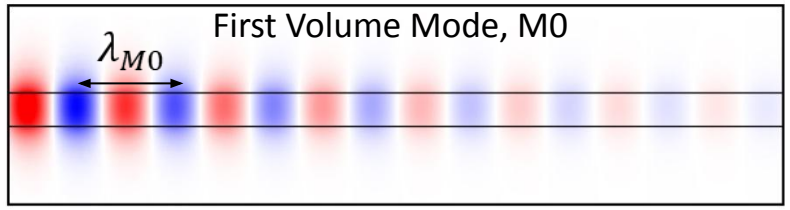

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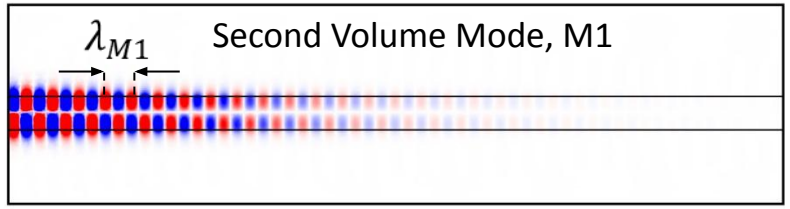

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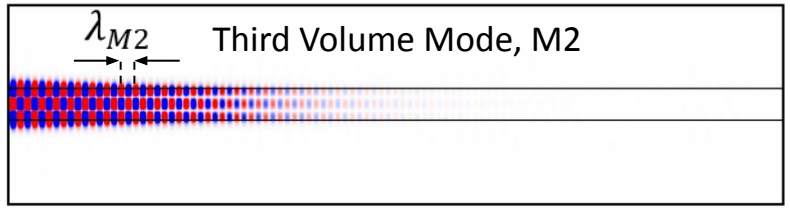

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Higher order Modes