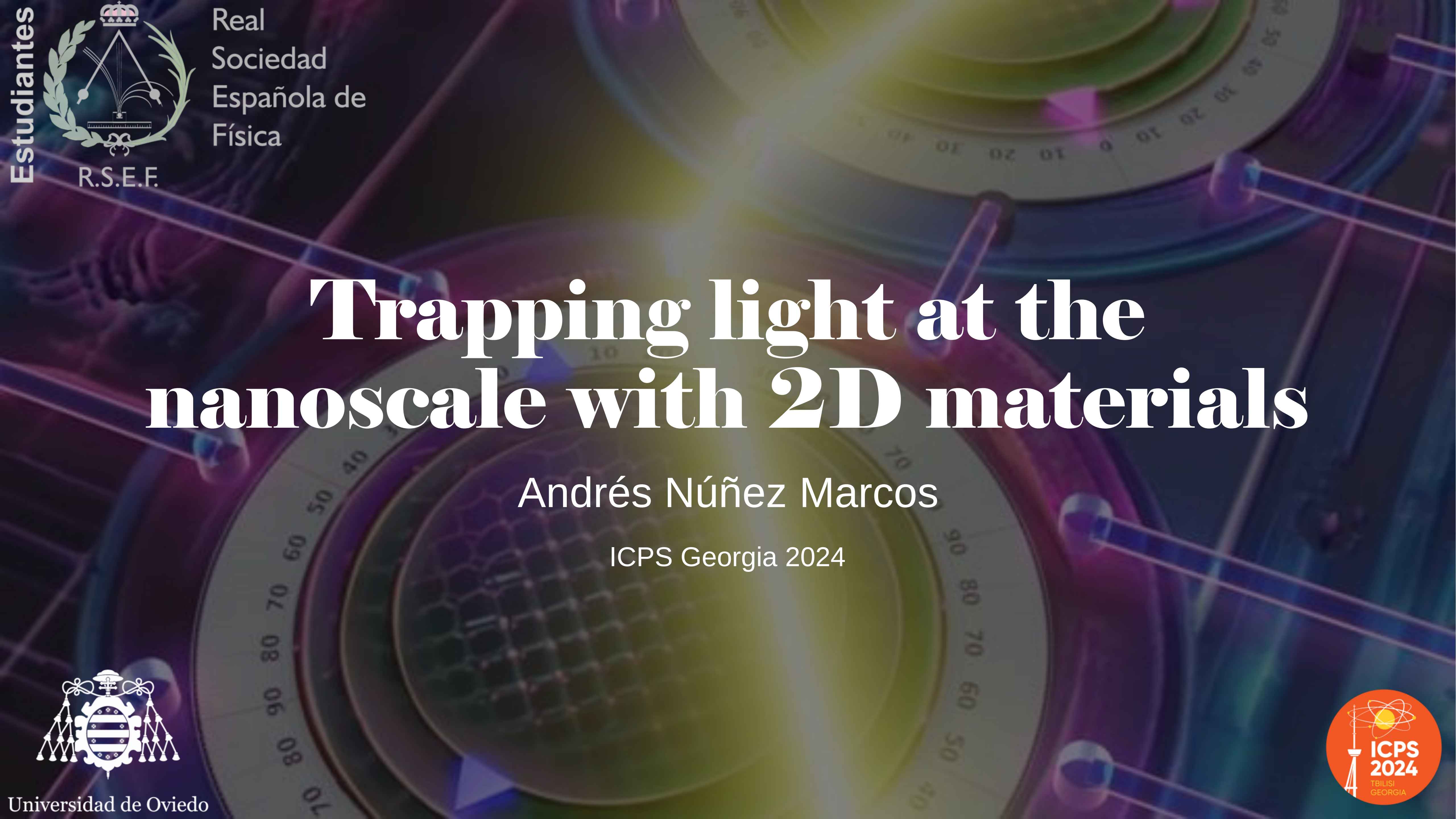
Estudiantes
Real
Sociedad
Española de
Física
R.S.E.F.



Trapping light at the nanoscale with 2D materials

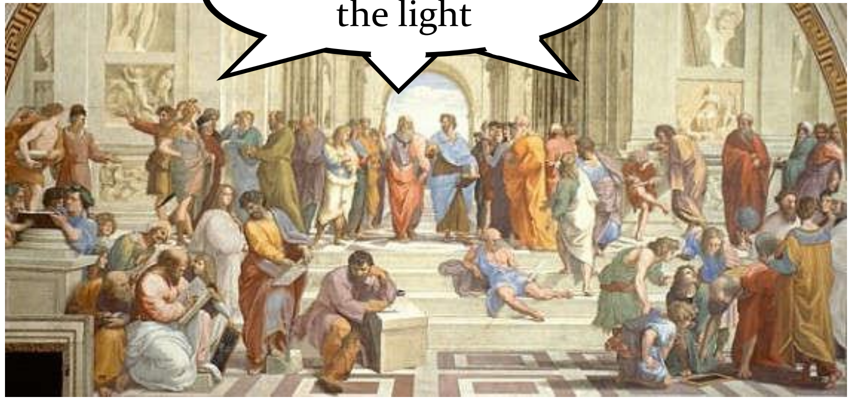
Andrés Núñez Marcos

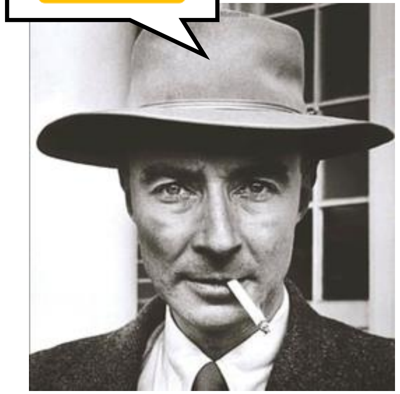
ICPS Georgia 2024

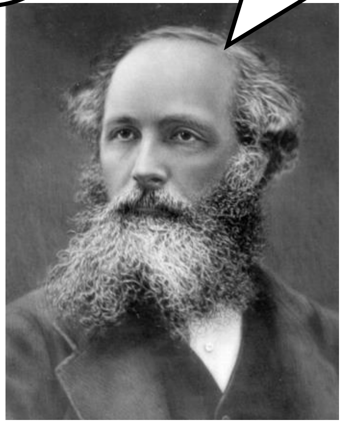
Universidad de Oviedo

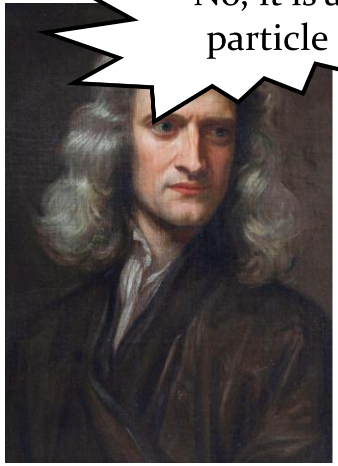
ICPS 2024
TBILISI
GEORGIA

Light is complicated



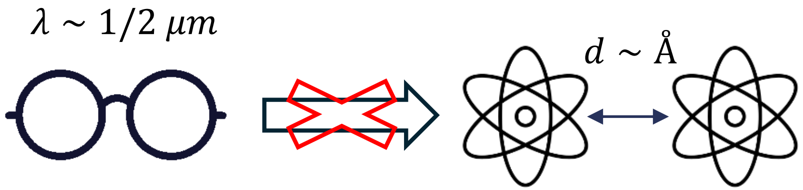


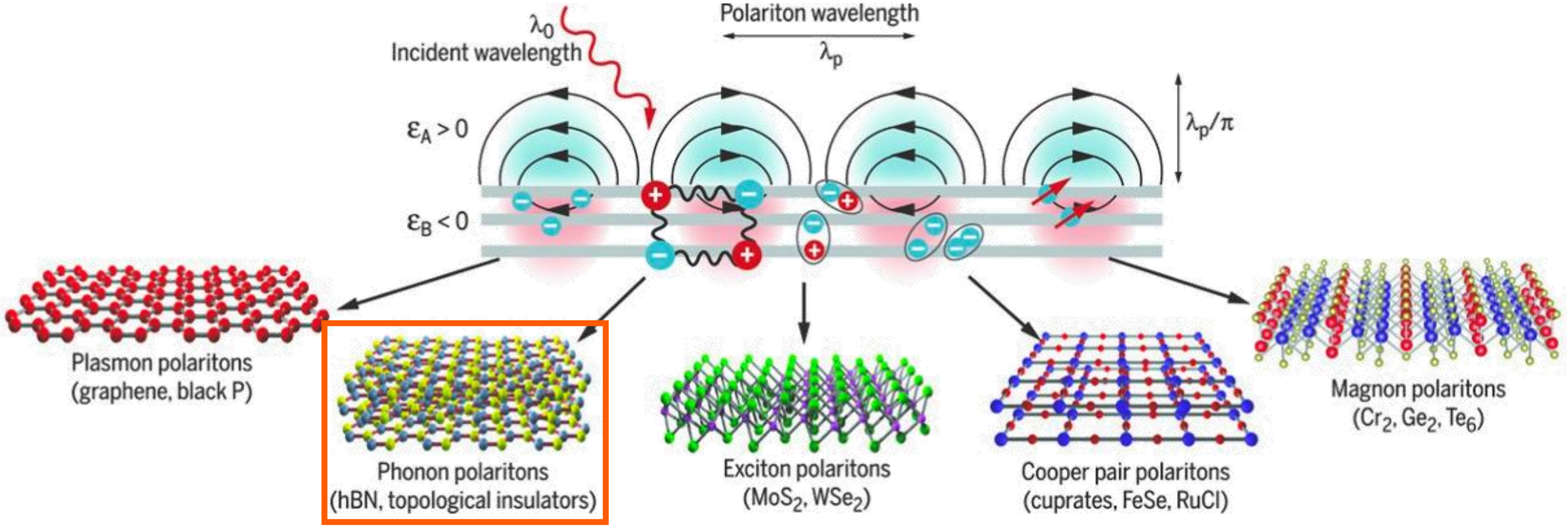




Light is brilliant

- Diffraction limit → $d \geq \lambda/2n$
- Ionizing lights are dangerous
- Light-matter interaction: **Polaritons**
- Although quantum, it can be explained through its classical wave nature

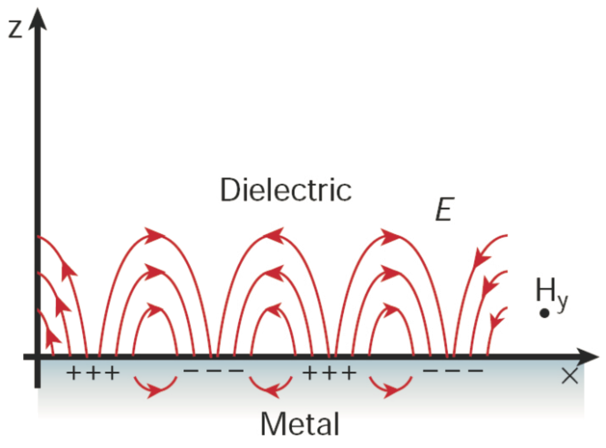




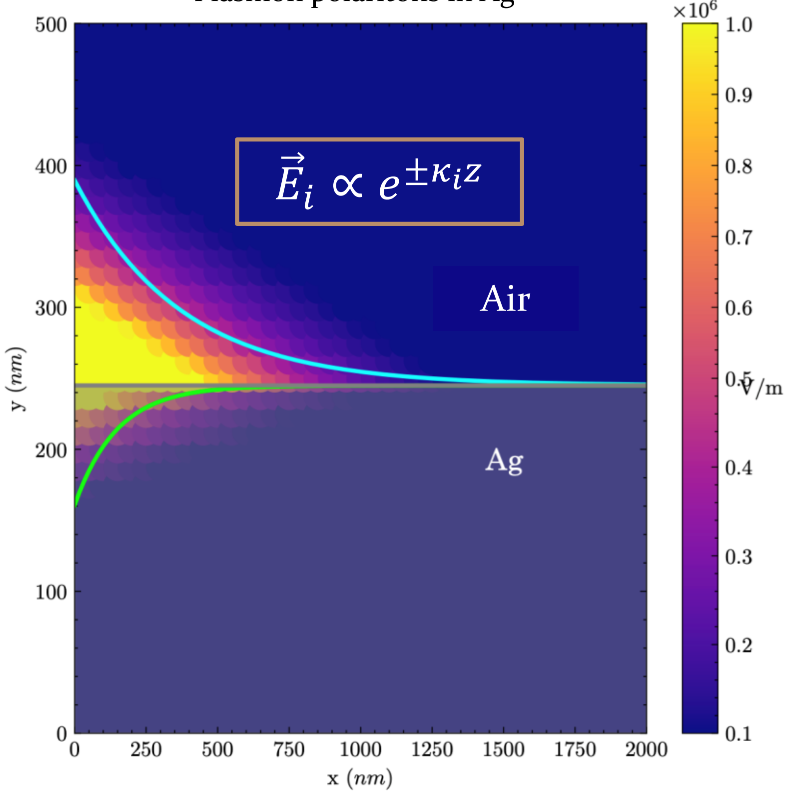
D N Basov et al., De Gruyter, Nanooptics 10, 2021 (10.1515/nanoph-2020-0449)

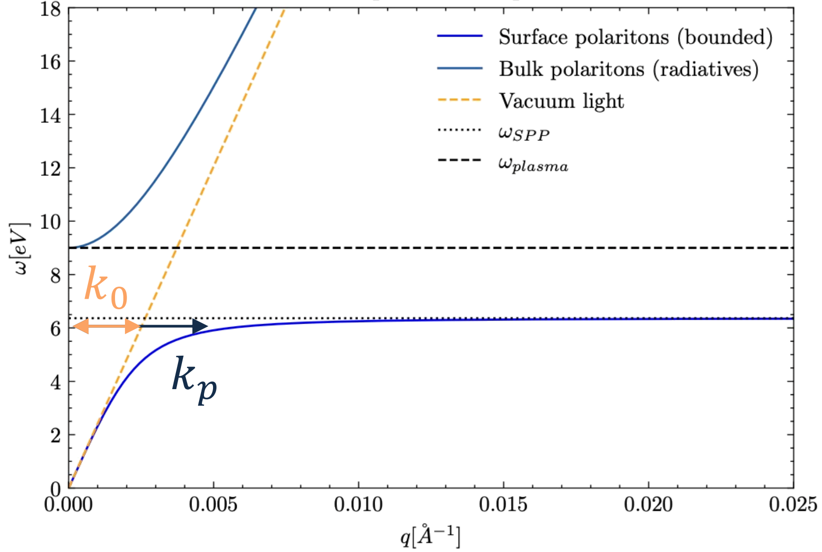
Main properties of polaritons

- Two mediums with opposite sign in electric permittivity
- Evanescent waves – exponential decay in the perpendicular propagation direction
- High confined waves that can not be excited only with natural light



Barnes W et al., Nature, 2003 (10.1038/nature01937)

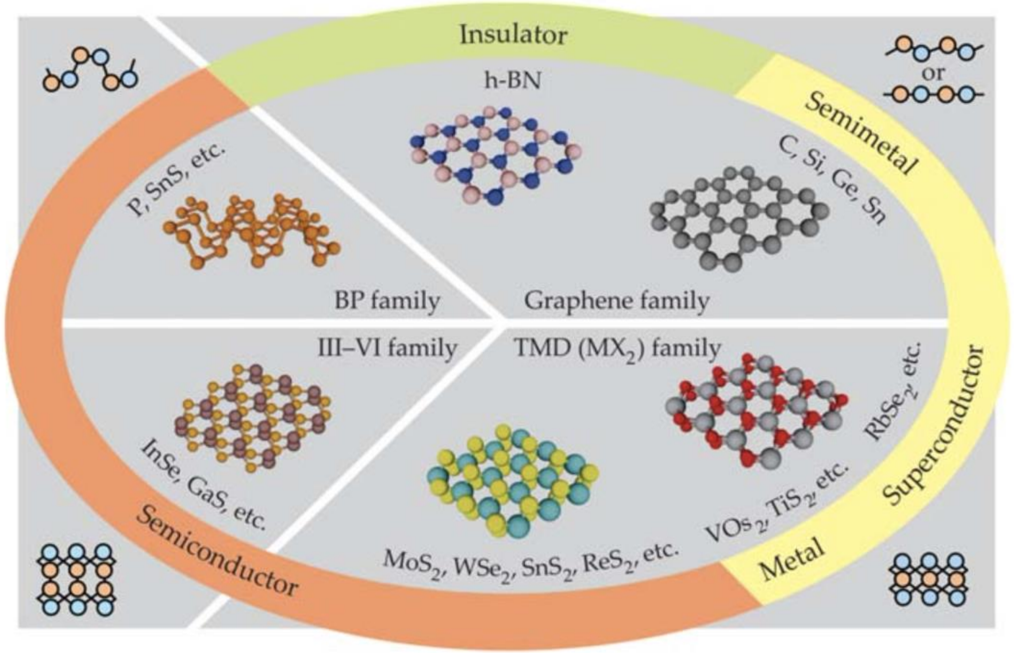

Plasmon polaritons in Ag


Plasmon polariton dispersion

$$\boxed{k \propto \frac{2\pi}{\lambda} \rightarrow \lambda_p \ll \lambda_0}$$

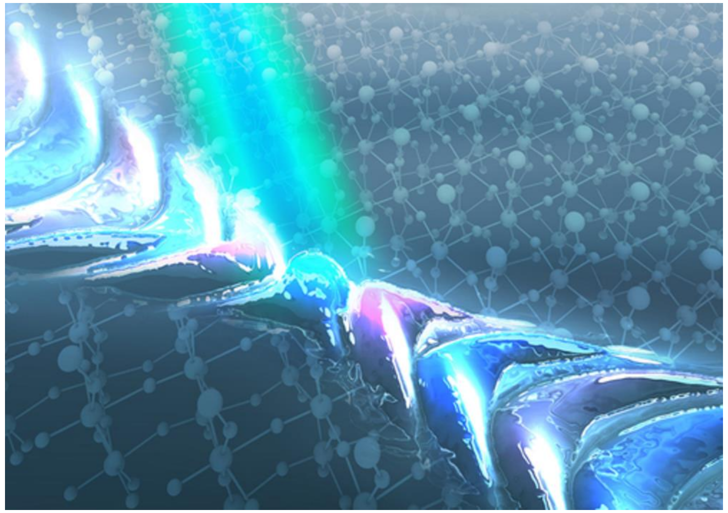
van der Waals (2D) materials

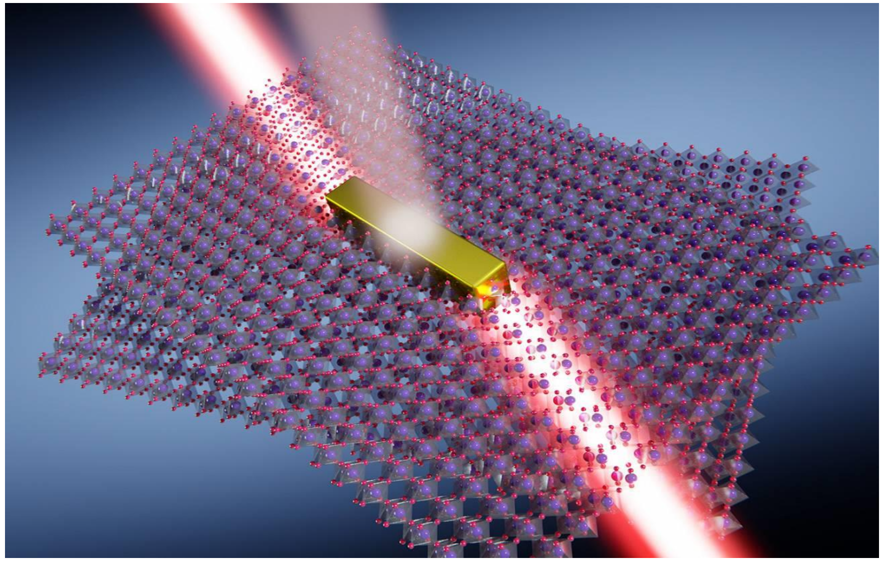
- Strong (covalent) forces in atomic plane and weak (vdW) forces between planes
- First kind discovered (unexpectedly) was graphene
- All types of properties and structures
- Polaritons have greater coupling in 2D materials thanks to reduced electrical screening

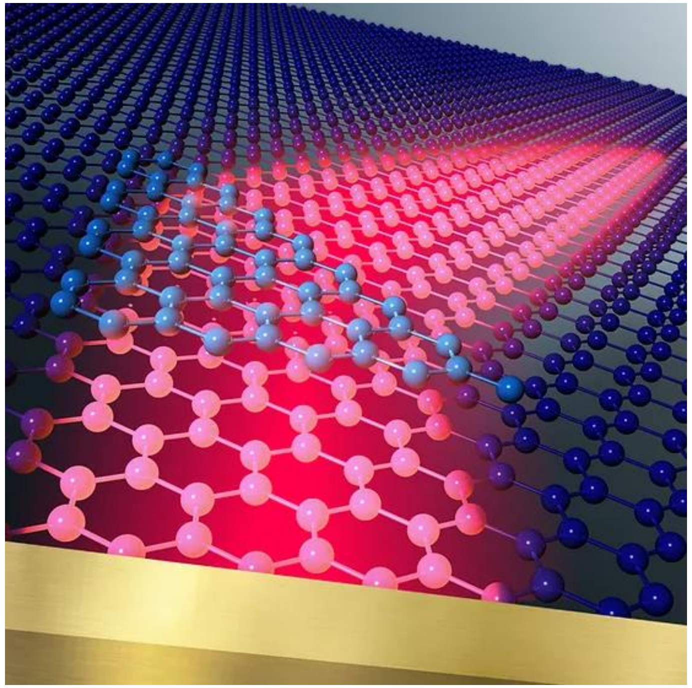


P. Ajayan y col., Physics Today 69, 38-44 (2016)

Counterintuitive phenomena

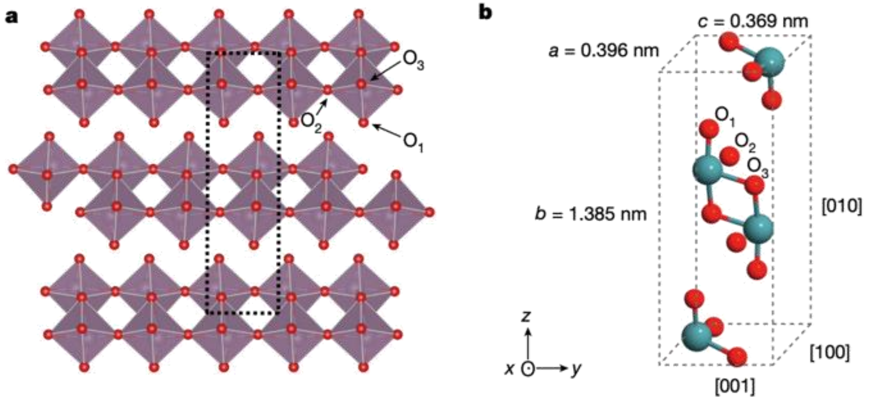






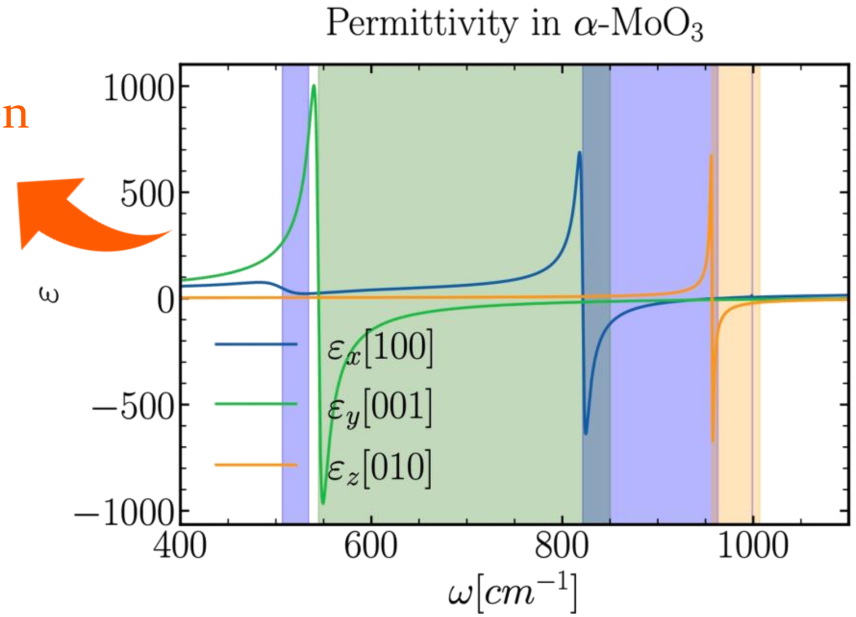
Hyperbolic light-matter propagation

- Molybdenum trioxide in alpha phase ($\alpha\text{-}MoO_3$)



Weiliang Ma; P. Alonso-González et al., Springer Nature, 2018 (10.1038/s41586-018-0618-9)

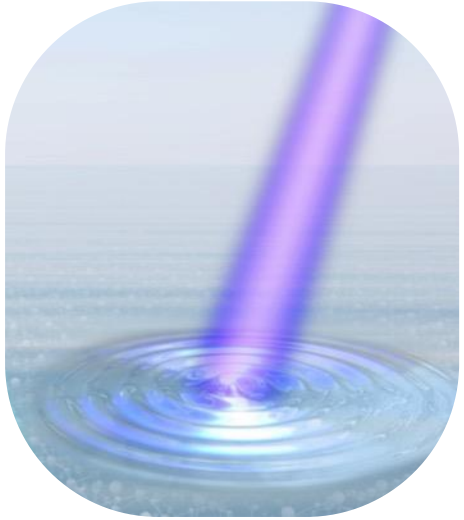
Multiple Reststrahlen bands ($\varepsilon_i < 0$)

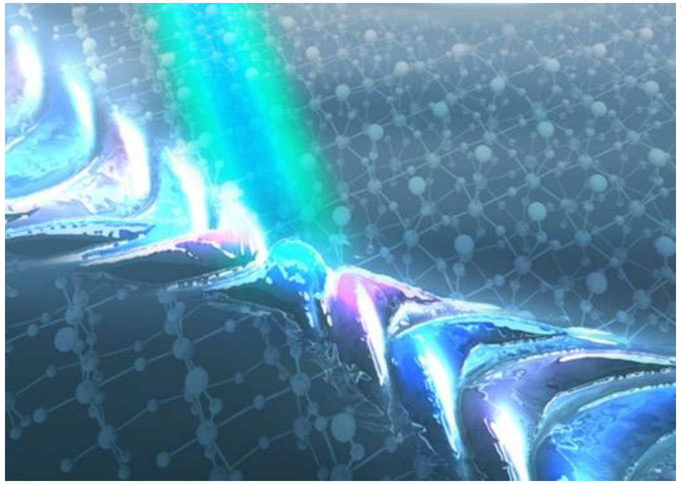


- Light-matter hyperbolic propagation in the plane

$$\varepsilon = \varepsilon_0$$

- Scalar





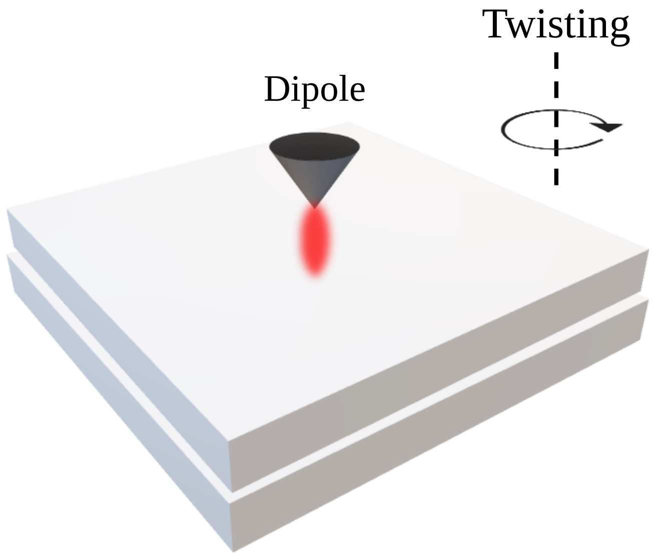
$$\varepsilon = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

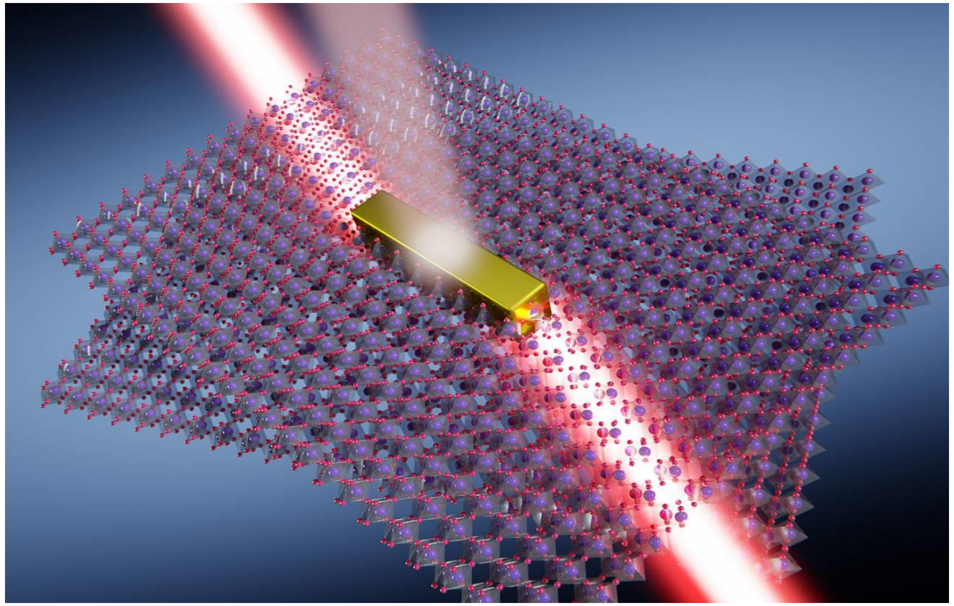
- Tensor

G. Álvarez Pérez, PhD Thesis, Universidad de Oviedo, 2023

Light natural canalization

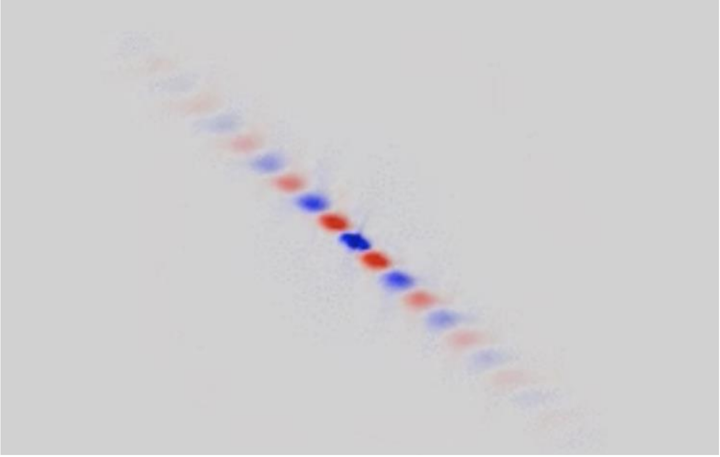
- **Twistoptics** → Light-matter interaction in rotated 2D materials
- Phonon polaritons’ (PhPs) propagation can be modified from open (hyperbolic) curve to close (circular) curve
- Light natural canalization
- “Diffraction-less” propagation





Jiahua Duan et al., Nano Letters, 2020 (10.1021/acs. nanolett.0c01673)

$$d_1 = d_2 = 200\ nm \ \rightarrow \theta = 63°$$

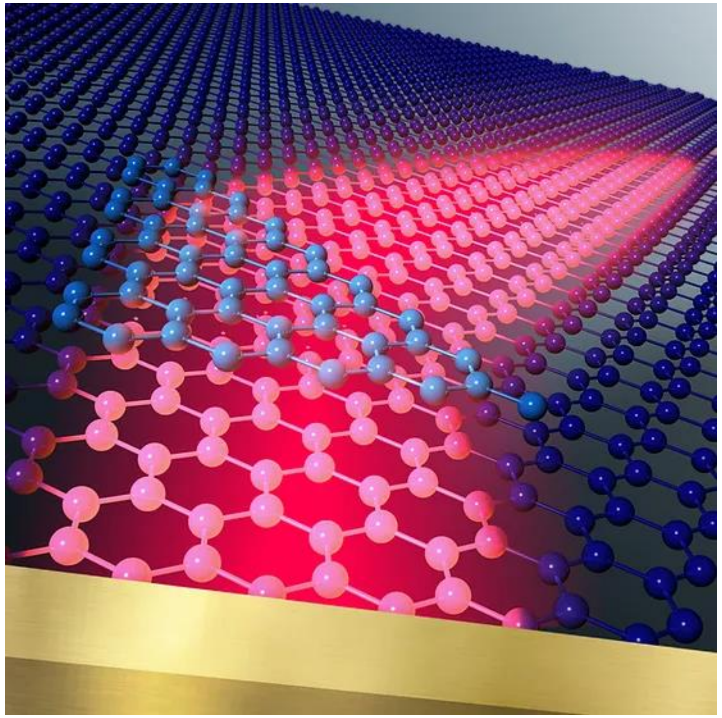


Negative and back reflection

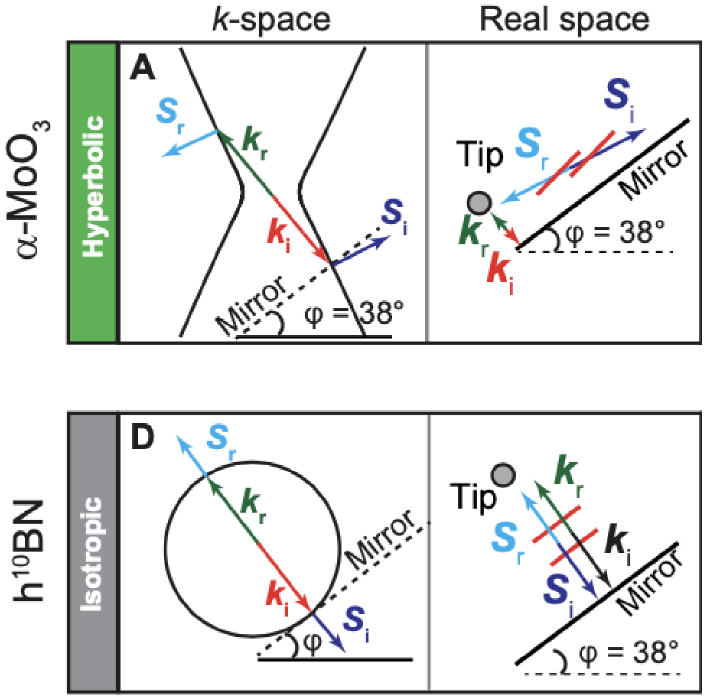
- Back reflection → Light reflects in same direction and opposite sign as incident light

$$\Delta\vec{k} \equiv \vec{k}_{\parallel}^{r} - \vec{k}_{\parallel}^{i} = 0 \quad \rightarrow \quad |\vec{k}_r| \sin\theta_r = |\vec{k}_i| \sin\theta_i$$

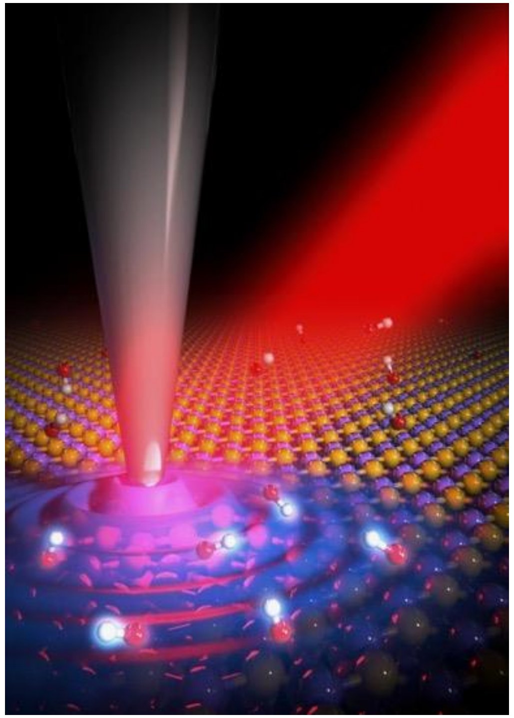
- Usually demonstrated in artificially engineered interfaces, such as metasurfaces
- Recently visualized in high anisotropic materials in atomic plane



Reflection of phonon polaritons (by courtesy of Quantum Nano-optics Lab at the University of Oviedo)



G. Álvarez-Pérez et al., Science Advances 8, 2022 (10.1126/sciadv.abp8486)

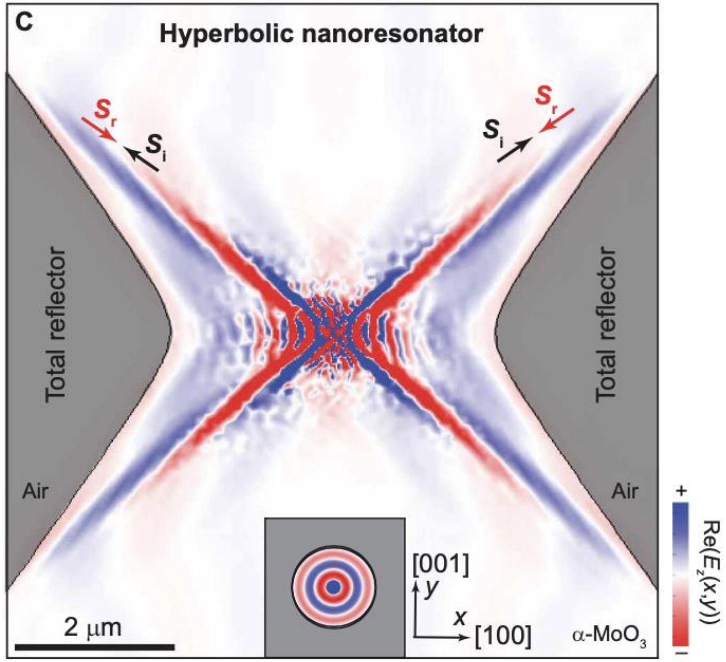


Nature, Volume 15 Issue 3, March 2021

Applications

Nanochemistry → Hyperbolic mirror

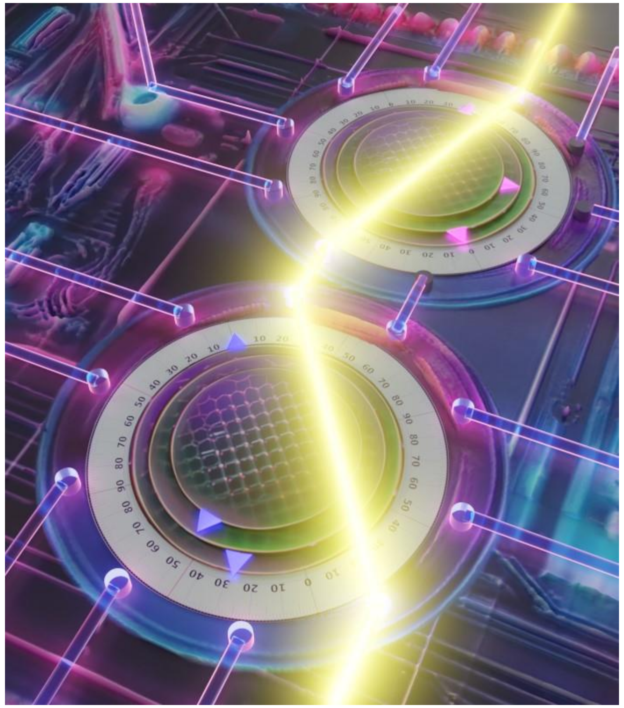
- Reflecting all incident phonon polaritons back to their source
- Intensity and, in principle, temperature increasement
- Experimental research in progress



G. Álvarez-Pérez et al., Science Advances 8, 2022 (10.1126/sciadv.abp8486)

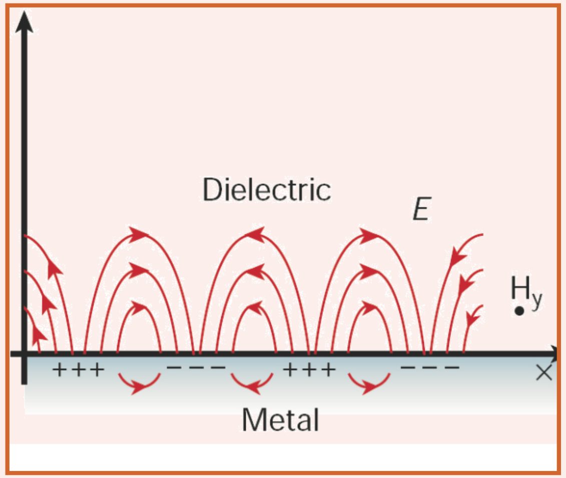
Quantum computing → Light propagation direction

- Programmed in-plane canalization direction
- Demonstrated both analytically and experimentally with systems of three layers
- Entanglement of quantum emitters



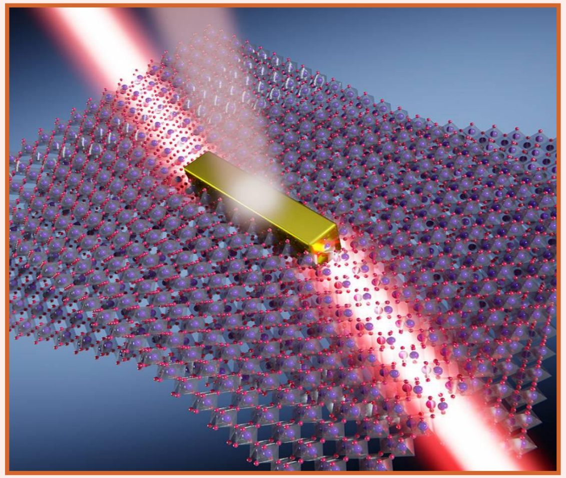
Light manipulation concept (by courtesy of Quantum Nano-optics Lab at the University of Oviedo)

Conclusions



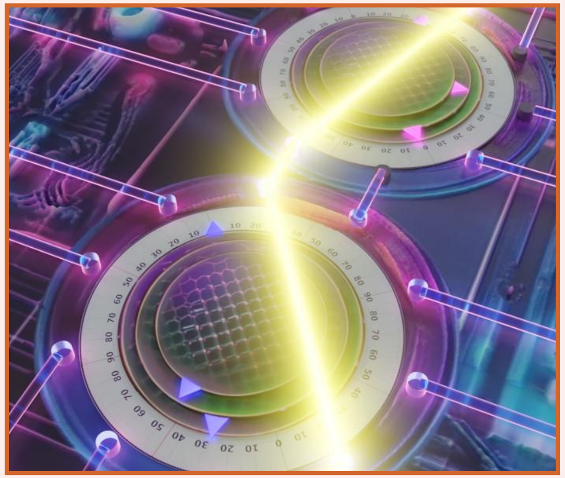
Polaritons

Phonon polaritons
2D materials



Nanoscale phenomena

Hyperbolic propagation
Light canalization
Back reflection



Applications

Nanochemistry
Quantum computing

QnanoOPTICS

Dr. Pablo Alonso González

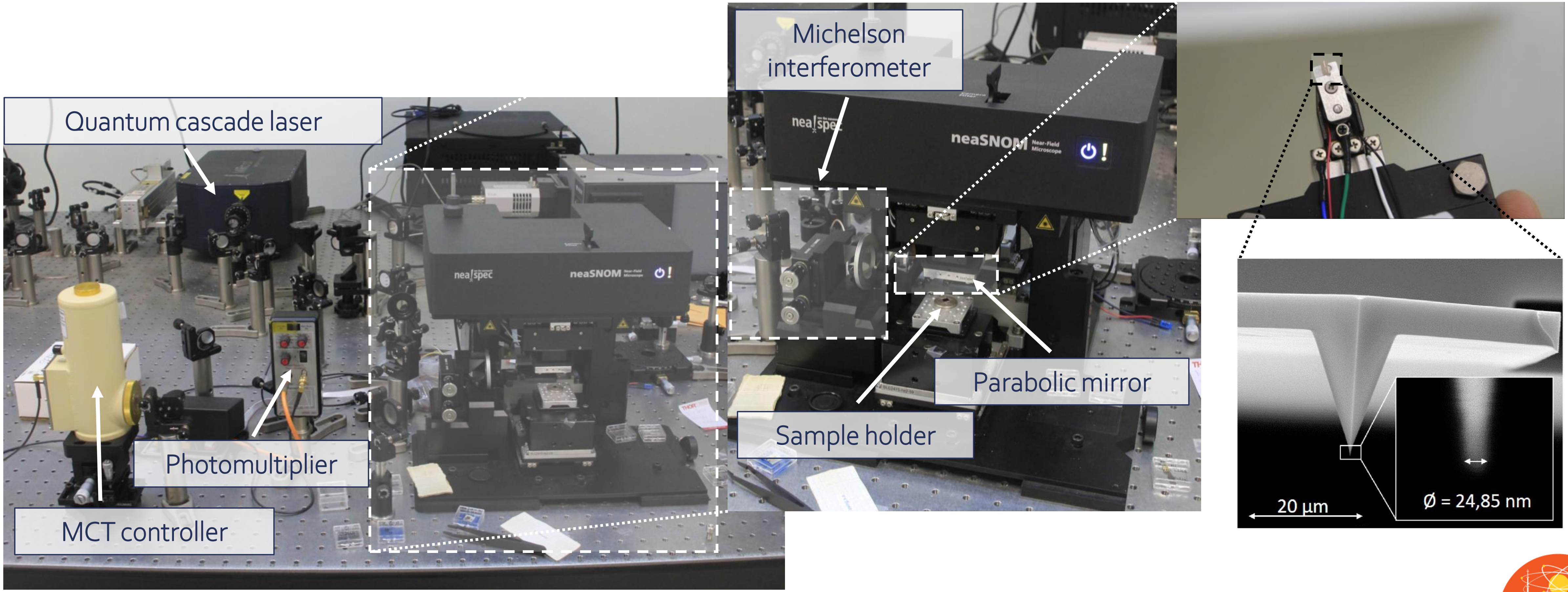
Post-PhD Aitana Tarazaga Martín-Luengo

ICPS 2024 TBILISI GEORGIA

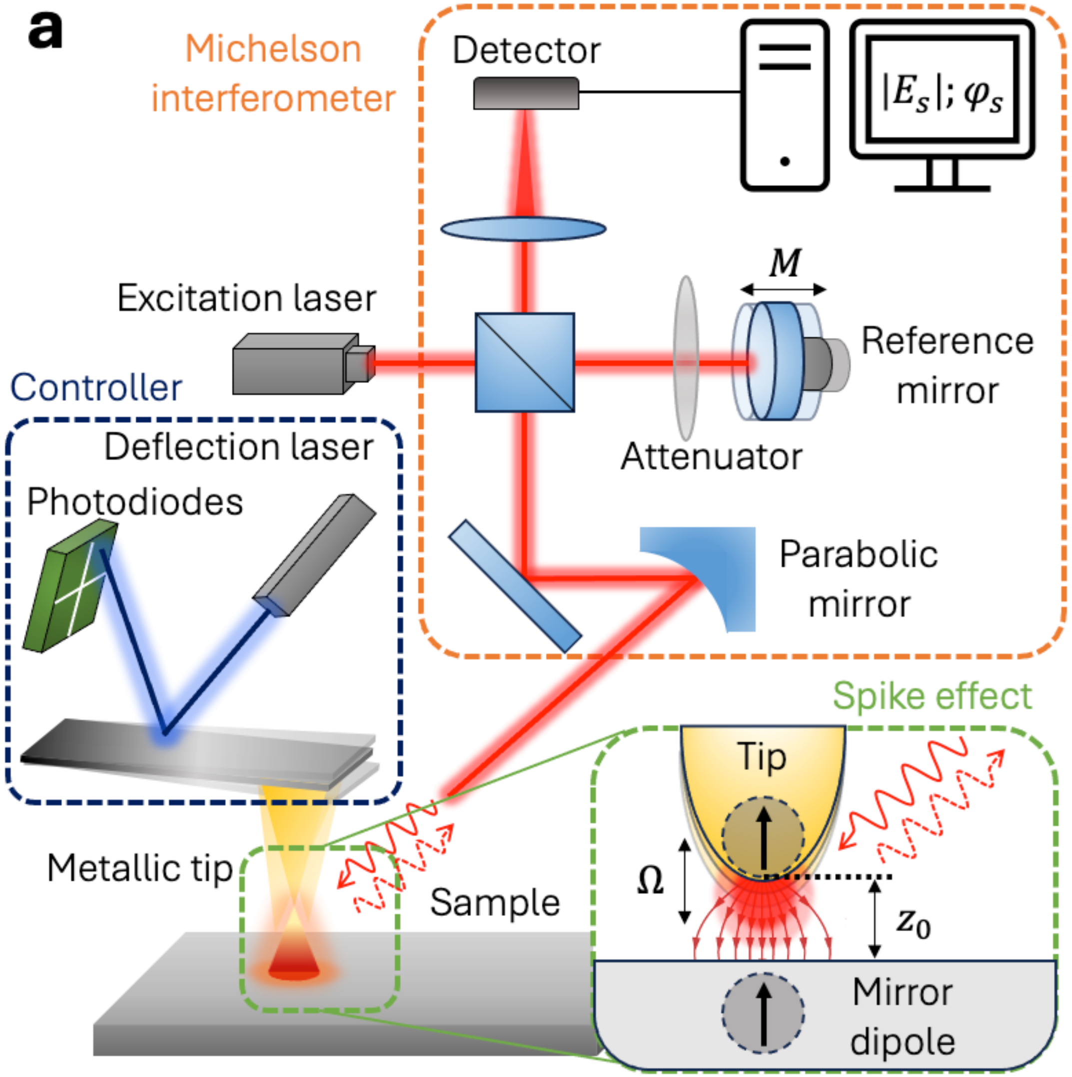
Thank you for your attention

Appendix

sSNOM: the nanometer viewer



Appendix



sSNOM: the nanometer viewer

- **Spike effect** → Field enhancement
- **Controller** → Responsible for tip contact
- **Michelson (asymmetrical) interferometer** → Background field + Near-field signal + Reference beam + Noise (uncertainty)

$$I = \boxed{|E_{nf}|^2} + 2|E_{nf}||E_{bg}|\cos(\varphi_{nf} - \varphi_{bg}) + 2|E_{nf}||E_{ref}|\cos(\varphi_{nf} - \varphi_{ref}) + E_{noise}^2$$

- *Tapping* method oscillates the tip vertically
- Reference field also oscillates harmonically to modulate signal phase
- Signal demodulation gives us the harmonic orders of our desired contribution (preferably 3rd and 4th harmonic orders)

Appendix

Polariton’s derivation from Maxwell’s equations

Maxwell’s equations

$$\begin{cases} \nabla \cdot \vec{D} = 4\pi\rho \qquad \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{E} = -\dfrac{1}{c}\dfrac{\partial \vec{B}}{\partial t} \qquad \nabla \cdot \vec{H} = -\dfrac{4\pi}{c}\vec{J} + \dfrac{1}{c}\dfrac{\partial \vec{D}}{\partial t} \end{cases}$$

$\longrightarrow$ Homogeneous materials

Constitutional equations

$$\begin{cases} \vec{J} = \sigma\vec{E} \\ \vec{D} = \varepsilon\vec{E} \\ \vec{B} = \mu\vec{H} \end{cases}$$

$\longrightarrow$ Non-magnetic materials

Electric permittivity

$$\vec{B} = \vec{H}$$

$$D_i = \varepsilon_{ij}E_j$$

$$\varepsilon = \mathrm{Re}\big(\varepsilon(\omega)\big) + i\mathrm{Im}\big(\varepsilon(\omega)\big)$$

$$\vec{n} = c\vec{k}/\omega$$

Fresnel’s momentum equation

$$\vec{k}^2\left(\varepsilon_x k_x^2 + \varepsilon_y k_y^2 + \varepsilon_z k_z^2\right) - \frac{\omega^2}{c^2}\left[k_x^2\varepsilon_x\left(\varepsilon_y + \varepsilon_z\right) + k_y^2\varepsilon_y(\varepsilon_x + \varepsilon_z) + k_z^2\varepsilon_z\left(\varepsilon_x + \varepsilon_y\right)\right] + \frac{\omega^4}{c^4}\varepsilon_x\varepsilon_y\varepsilon_z = 0$$

Boundary conditions

$$D_{1;z} = D_{2;z} \;\; ; \;\; E_{1;xy} = E_{2;xy}$$

TE propagation mode not possible!

$\longrightarrow$ Light plane wave TM mode

$$\overrightarrow{E_i} = \left(E_{i;x}; 0; \pm E_{i;z}\right)e^{i\left(\vec{k}_i\vec{r} - i\omega t\right)}$$

$$\overrightarrow{H_i} = \left(0; H_{i;y}; 0\right)e^{i\left(\vec{k}_i\vec{r} - i\omega t\right)}$$

$\longrightarrow$

$$ik_{i;z}H_{i;y} = \frac{\omega}{c}\varepsilon_i E_{i;x}$$

$$\frac{k_{1;z}}{\varepsilon_1} = -\frac{k_{2;z}}{\varepsilon_2}$$

$\downarrow$ Drude-Lorentz’s model

$$\varepsilon(\omega) = \varepsilon_\infty\left(1 + \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - i\gamma\omega}\right)$$

$\longleftarrow$ Continuous wave condition

Dispersion relation

$$\boldsymbol{k_{SPhP} \equiv k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon(\omega)}{1 + \varepsilon(\omega)}}}$$