

Applicazioni Fotonica1: Propagazione

Propagazione

$$\vec{v}_p = \frac{\omega}{k} \hat{k} \quad \text{velocità di fase}$$

$$\vec{v}_g = \vec{\nabla}_{\vec{k}} \omega(\vec{k}) \quad \text{velocità di gruppo;}$$

$$\vec{v}_e \equiv \frac{\vec{S}}{U_{em}} \quad \text{velocità energia}$$

$$\vec{S} \quad \text{vettore di Poynting} \quad U_{em} \quad \text{densità energia}$$

$$\boxed{\vec{v}_e = \vec{v}_g}$$

Negative v_g
Strong dispersion

- *Mirrors*
- *Cavities (defects)*
- *Waveguides*

Slow light

Figure 5: The photonic band structure for the lowest bands of Yablonovite (inset, from

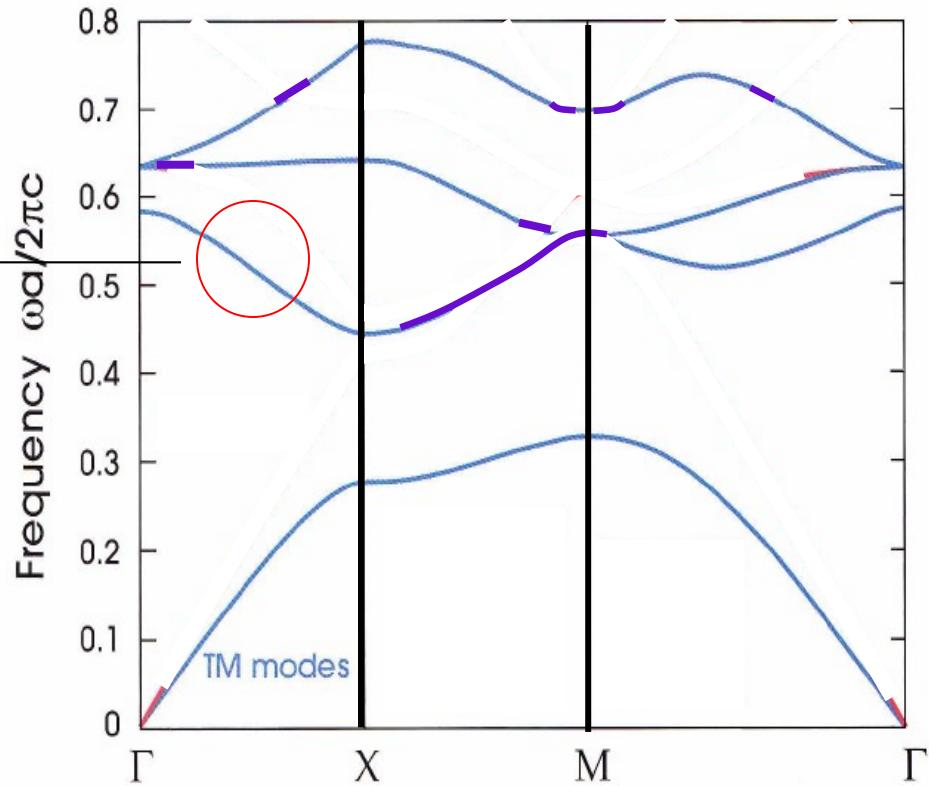
Propagazione in PhC

$$v_g = \frac{d\omega}{dk} < 0$$

$$\vec{v}_g \cdot \vec{k} < 0$$

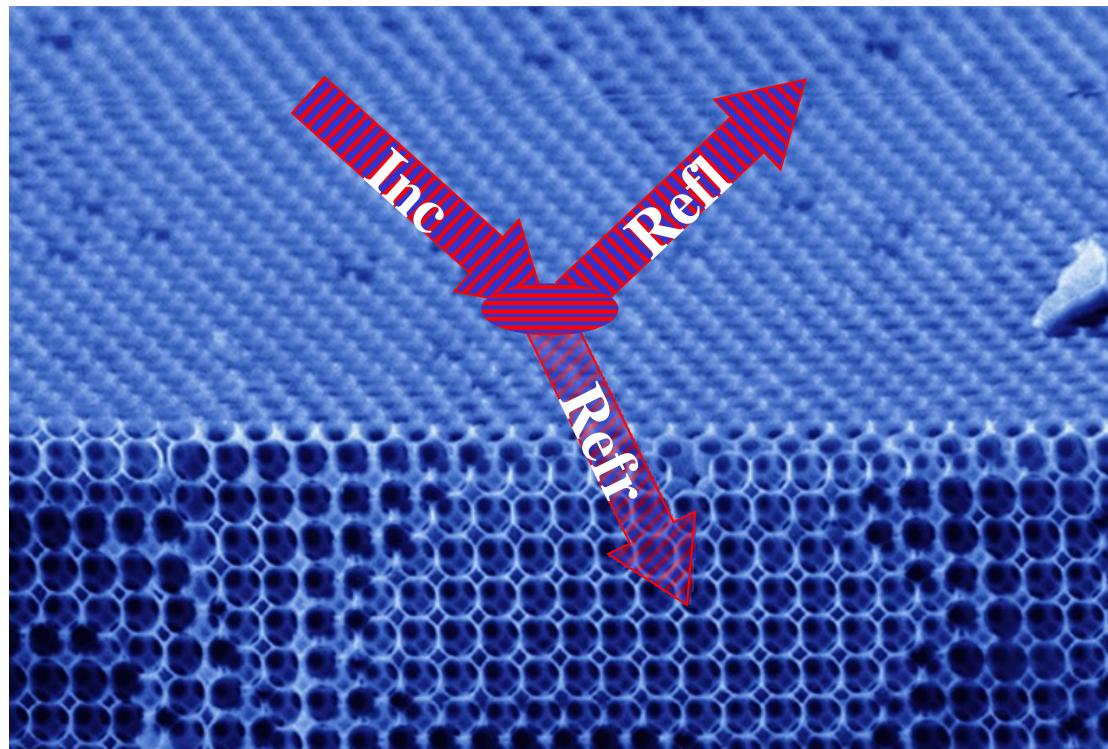


$$0 > \vec{S} \cdot \vec{k} = (\vec{E} \times \vec{H}) \cdot \vec{k}$$



Left handed materials

Accoppiamento con luce esterna



Riflessione

$$k_{refl} = k_{in}$$

Riflessione
&
Diffrazione

$$k_{refl,/\!/} = k_{in,/\!/} + \ell \frac{2\pi}{\Lambda}$$

ℓ = ordine diffrattivo

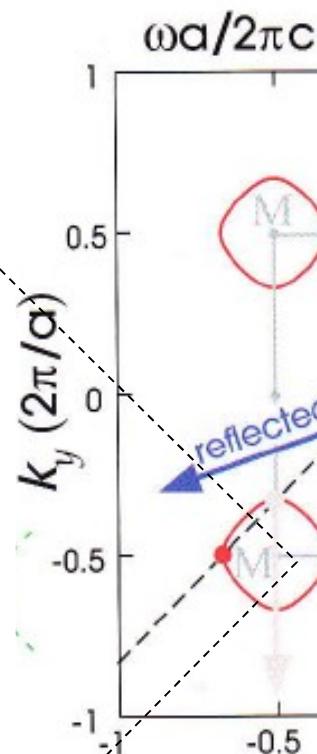


Figure 14: Left: Schematic of reflection (blue) and refraction (red) on a square lattice of dielectric rods (green) in air, for an inter-

Riflessione & Diffrazione

$$k_{refl,/\!/} = k_{inc,/\!/} + \ell \frac{2\pi}{\Lambda}$$

$$\vec{k}_{refl} = (k_{refl,/\!/}, k_{refl,\perp})$$

$$k_{refl,/\!/}^2 + k_{refl,\perp}^2 = \frac{\omega^2}{c^2}$$

$$\rightarrow k_{refl,\perp} = - \sqrt{\frac{\omega^2}{c^2} - \left(k_{inc,/\!/} + \ell \frac{2\pi}{\Lambda} \right)^2}$$

$$\ell = 0 \rightarrow k_{refl,\perp} = -k_{inc,\perp}$$

Riflessione è sempre presente

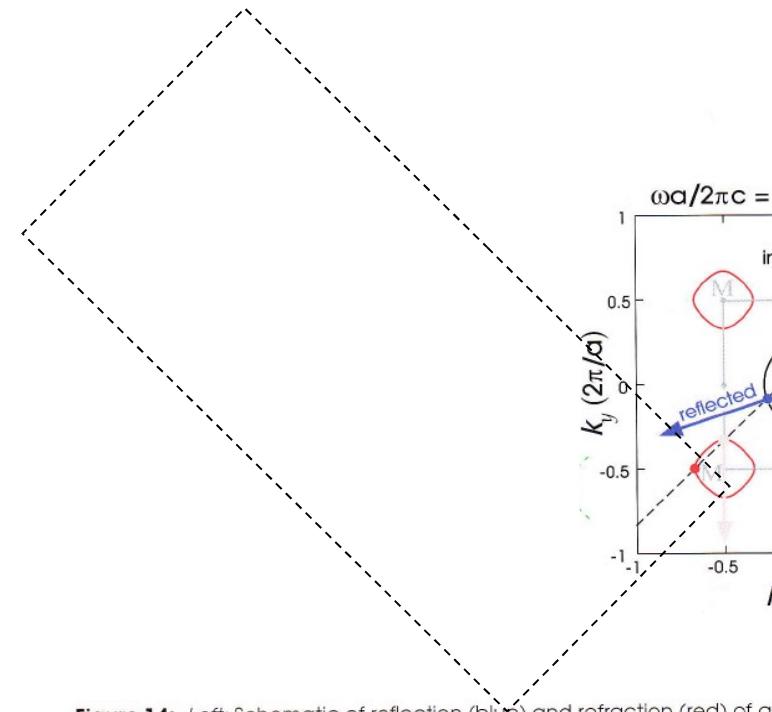


Figure 14: Left: Schematic of reflection (blue) and refraction (red) of a wave (black) on a square lattice of dielectric rods (green) in air, for an interface $\Lambda = a\sqrt{2}$ in the diagonal (110) direction. Depending on the frequency, there are additional reflected and/or refracted waves due to Bragg diffraction. Right: contours in \mathbf{k} space at $\omega a / 2\pi c = 0.276$ for air (black circle) and crystal (gray shaded region). The group velocity direction at various \mathbf{k} points (black/blue/red for incident/reflected/refracted waves). Because the wave vector component parallel to the interface is conserved, all reflected and refracted waves (black/blue/red dots) must lie along the dashed line (running perpendicular to the interface).

Riflessione & Diffrazione

$$k_{refl,\perp} = - \sqrt{\frac{\omega^2}{c^2} - \left(k_{inc,\parallel} + \ell \frac{2\pi}{\Lambda} \right)^2}$$

$$\rightarrow \left| k_{inc,\parallel} + \ell \frac{2\pi}{\Lambda} \right| \leq \frac{\omega}{c}$$

Limite $\lambda > \Lambda \rightarrow \ell = -1$ primo

$$\frac{2\pi}{\Lambda} < \frac{\omega}{c} (1 + \sin \theta)$$

$$\frac{\omega \Lambda}{2\pi c} = \frac{\Lambda}{\lambda} > \frac{1}{(1 + \sin \theta)} \geq 0.5$$

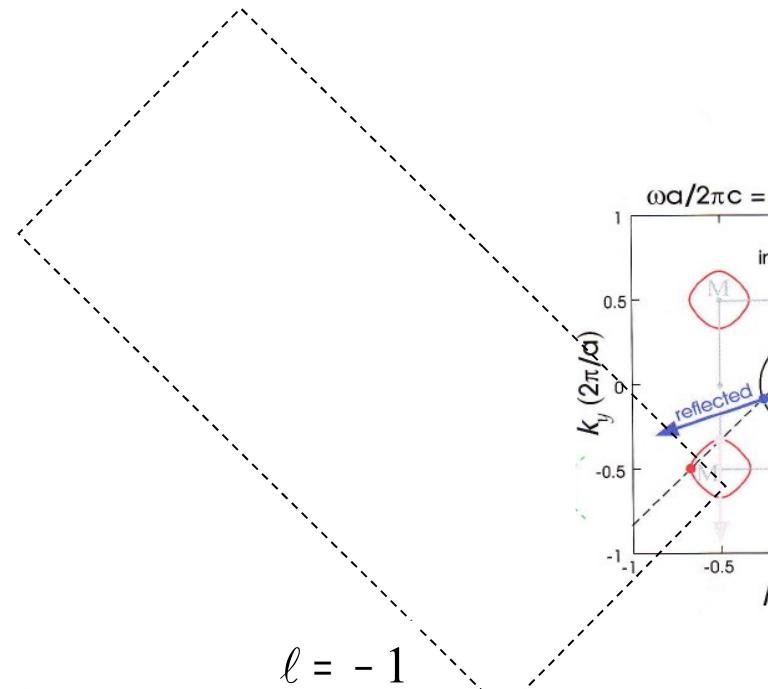


Figure 14: Left: Schematic of reflection (blue) and refraction (red) of a wave on a square lattice of dielectric rods (green) in air, for an interface $\Lambda = a\sqrt{2}$ in the diagonal (110) direction. Depending on the frequency, there are additional reflected and/or refracted waves due to Bragg diffraction. Right: Plot of $k_y (2\pi/a)$ vs $\omega a / 2\pi c = \omega / v_g$ showing contours in \mathbf{k} space at $\omega a / 2\pi c = 0.276$ for air (black circle) and crystal (red circle). The gray shaded region represents the Brillouin zone in \mathbf{k} -space. The group velocity direction at various \mathbf{k} points (black/blue/red for incident/reflected/refracted waves) are shown as dots. Because the component parallel to the interface is conserved, all reflected and refracted (red dots) must lie along the dashed line (running perpendicular to the interface).

Riflessione
&
Diffrazione



Riflessione



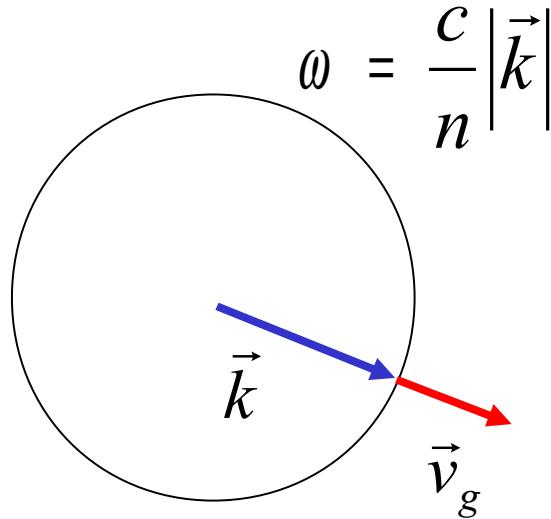
Figure 5: The photonic band structure for the lowest bands of Yablonovite (inset, from

Velocità gruppo

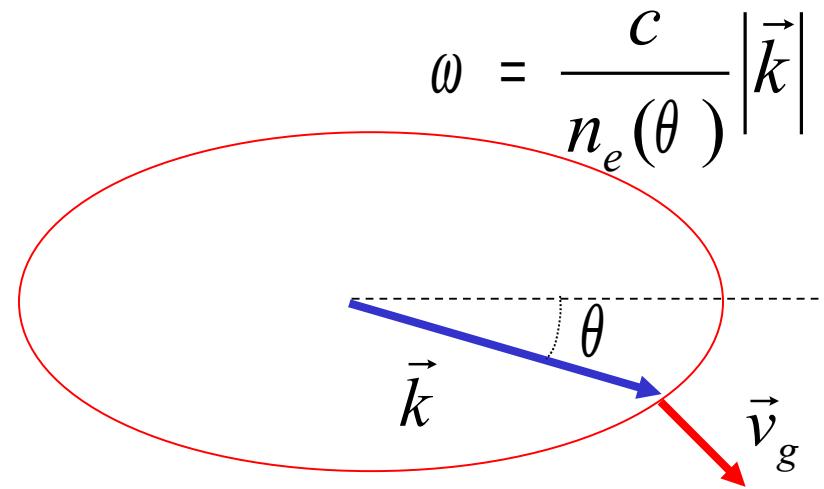
$$\omega = \omega(\vec{k})$$

Superficie di isofrequenza

Dielettrico isotropo



Dielettrico anisotropo



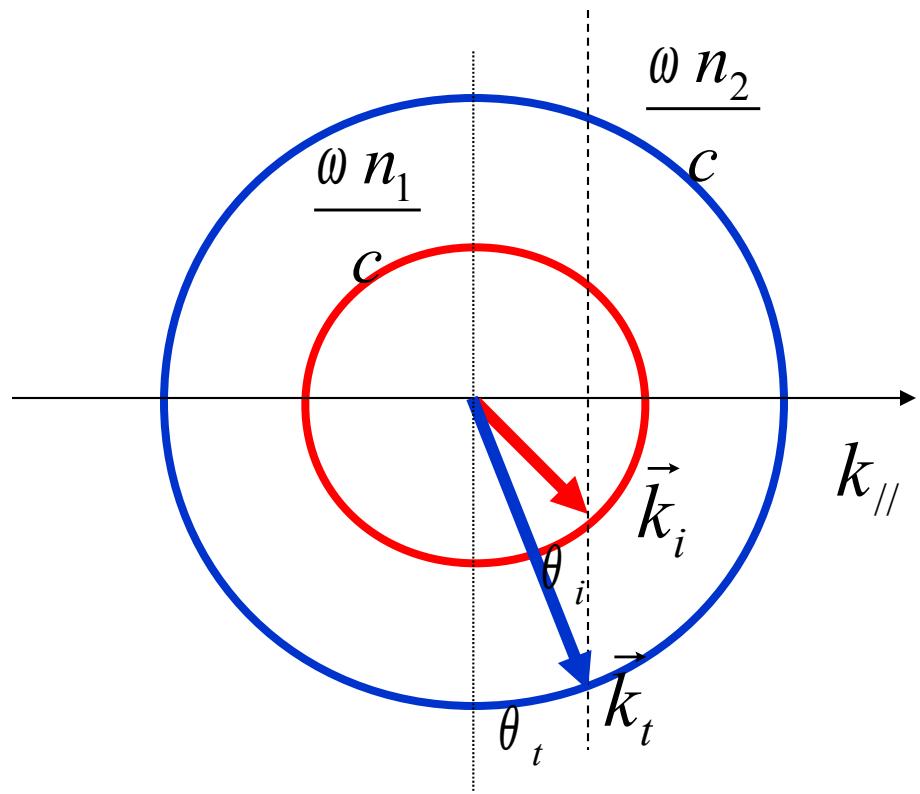
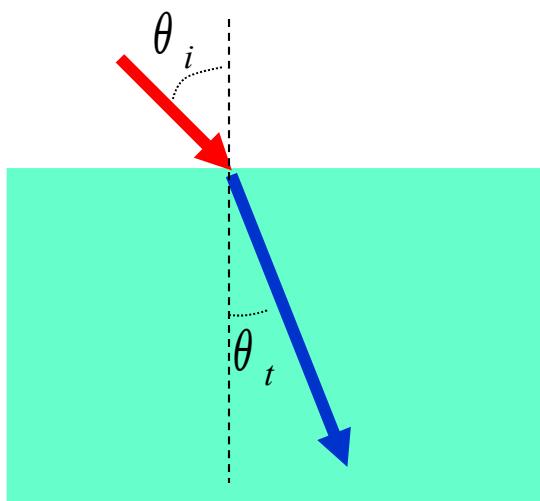
Metodo grafico per rifrazione

$$n_2 > n_1$$

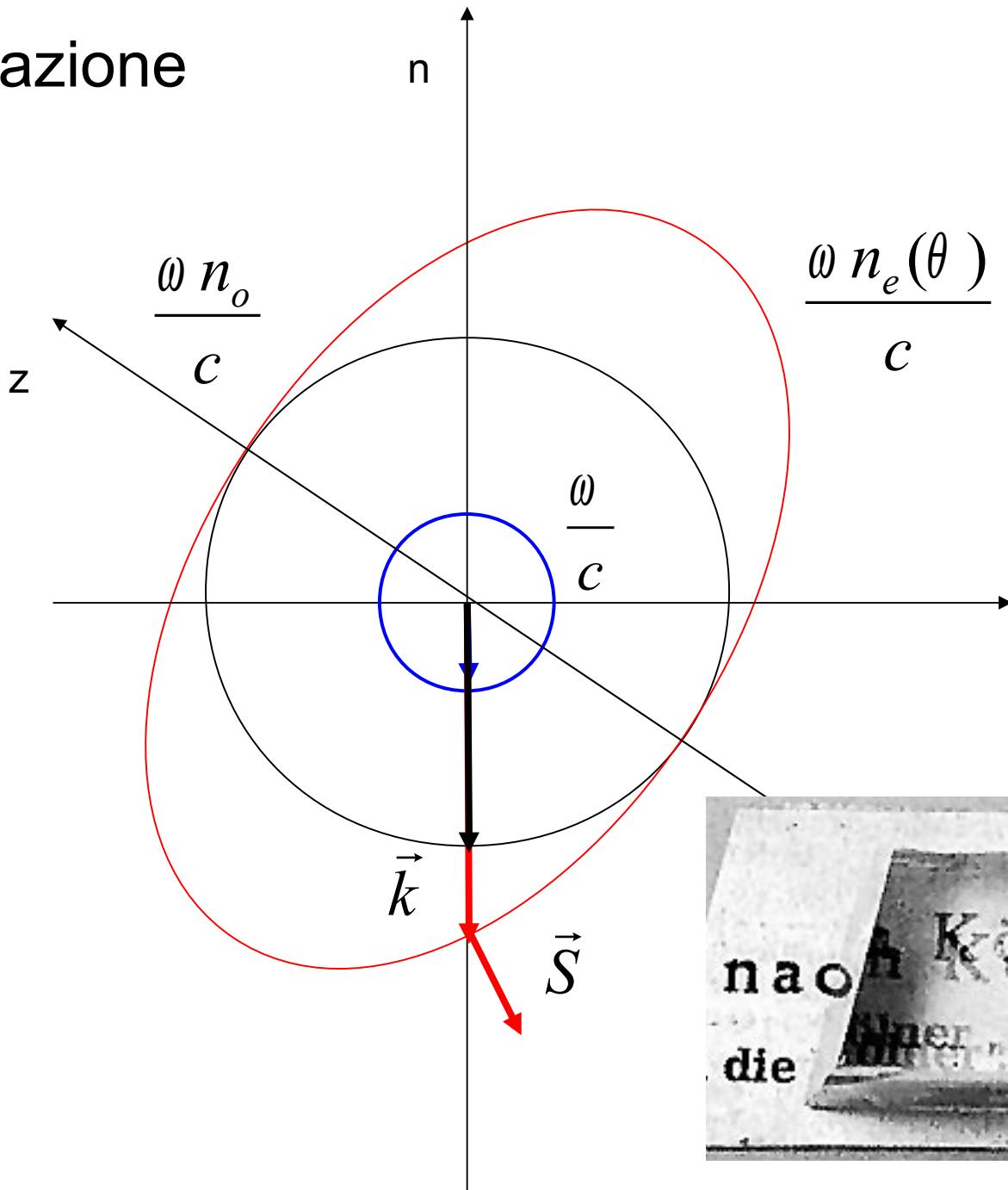
$$\omega_i = \omega_r = \omega_t \equiv \omega$$

$$\vec{k}_{i,\parallel} = \vec{k}_{r,\parallel} = \vec{k}_{t,\parallel}$$

$$n_1 \sin \theta_i = n_2 \sin \theta_t$$



Doppia rifrazione



Struttura a bande

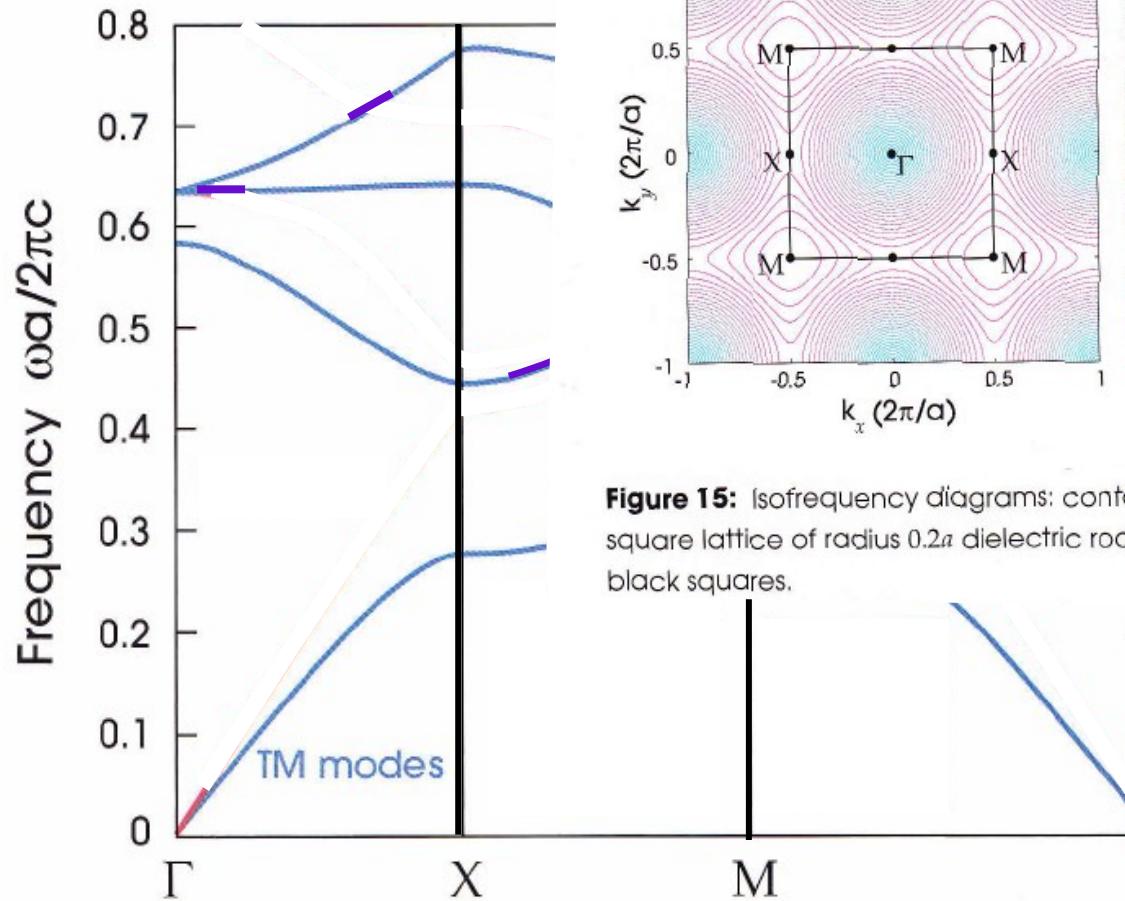


Figure 2: The photonic band structure for a square array of dielectric columns with $r=0.2a$. The blue bands represent TM modes and the red bands represent TE mode. Left inset shows the Brillouin zone, with the irreducible zone shaded light blue. The right inset shows a cross-sectional view of the dielectric function. The columns ($\epsilon=8.9$, as for c) are embedded in air ($\epsilon=1$).

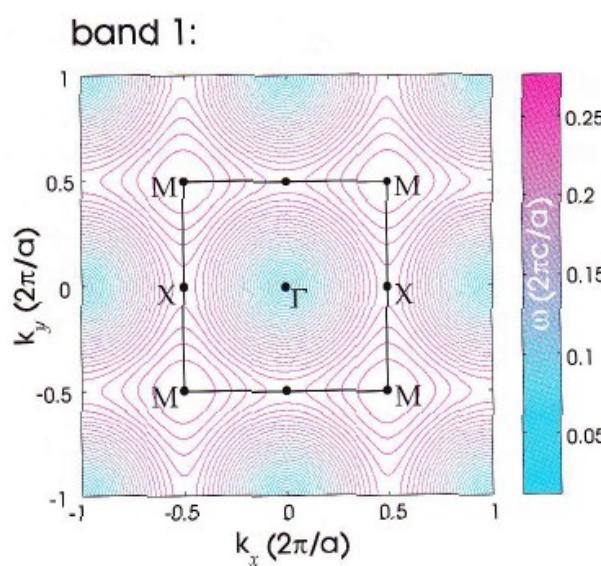


Figure 15: Isofrequency diagrams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a square lattice of radius $0.2a$ dielectric rods (black squares).

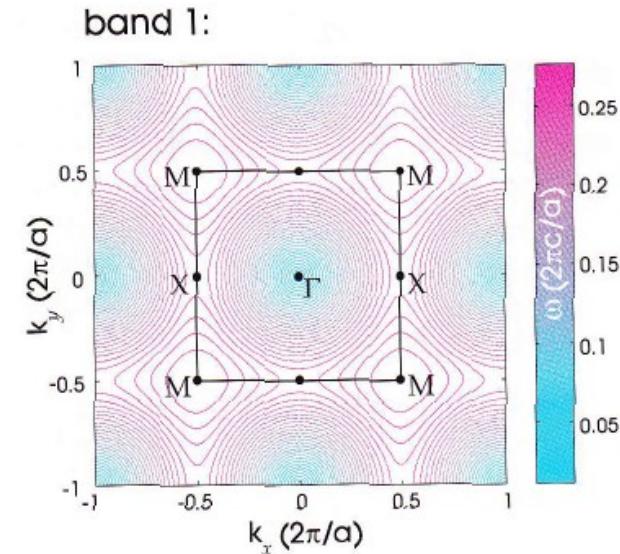


Figure 15: Isofrequency diagrams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a square lattice of radius $0.2a$ dielectric rods ($\epsilon=1$) (black squares).

Struttura a bande

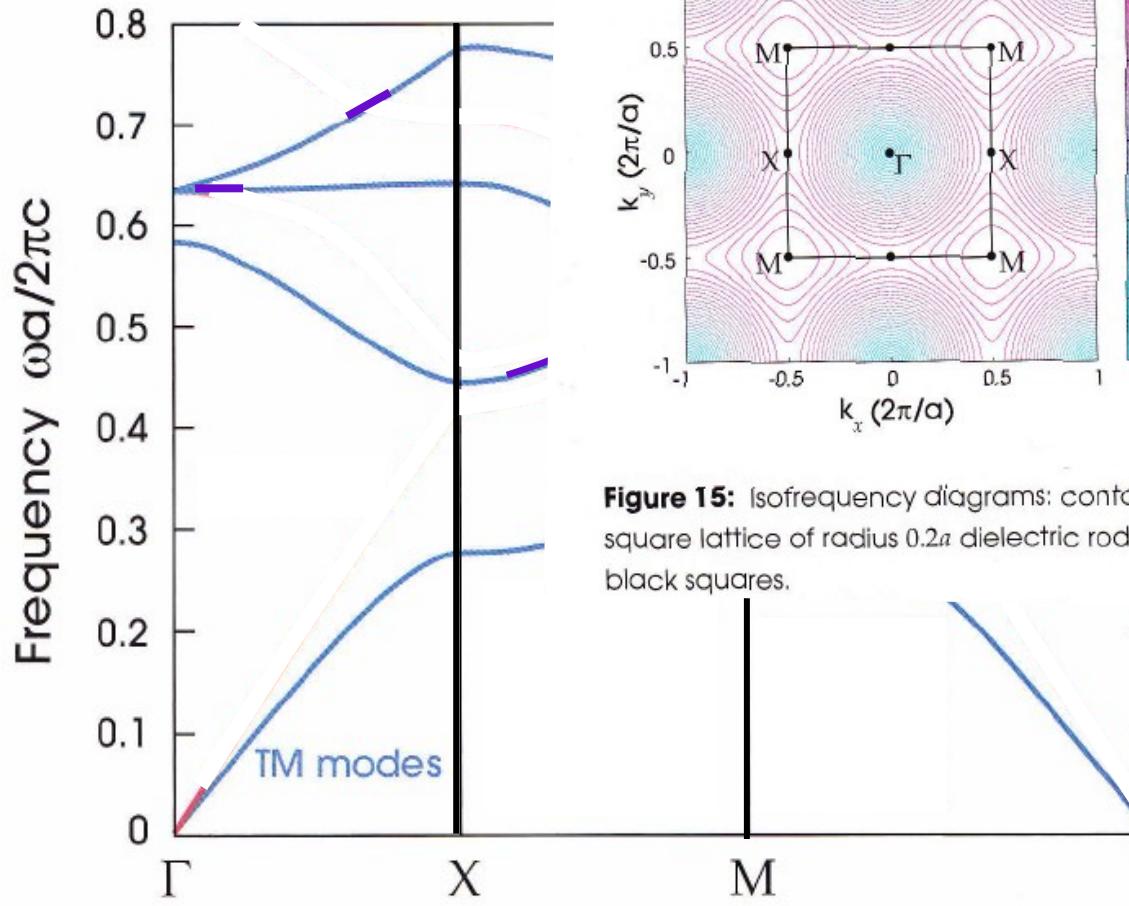


Figure 2: The photonic band structure for a square array of dielectric columns with $r=0.2a$. The blue bands represent TM modes and the red bands represent TE mode. Left inset shows the Brillouin zone, with the irreducible zone shaded light blue. The right inset shows a cross-sectional view of the dielectric function. The columns ($\epsilon=8.9$, as for c) are embedded in air ($\epsilon=1$).

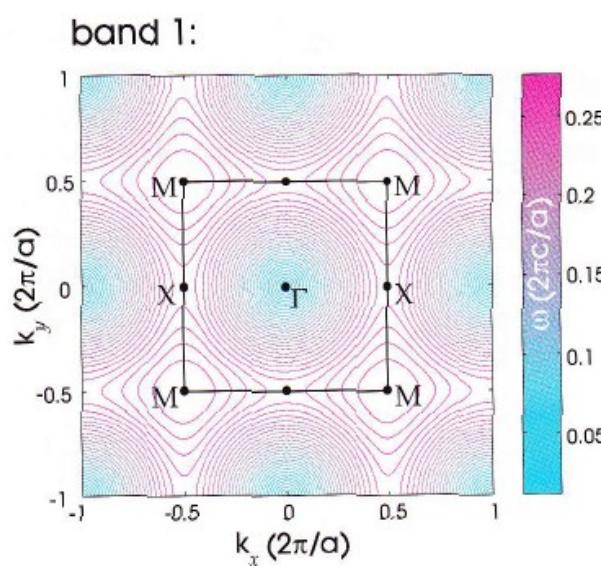


Figure 15: Isofrequency diagrams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a square lattice of radius $0.2a$ dielectric rods (black squares).

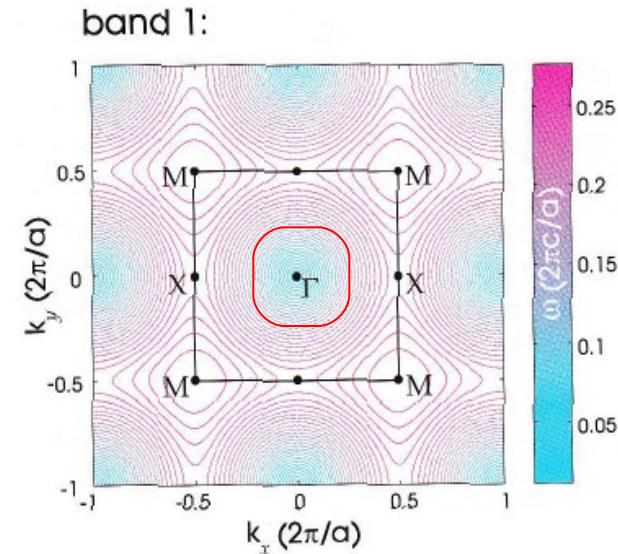
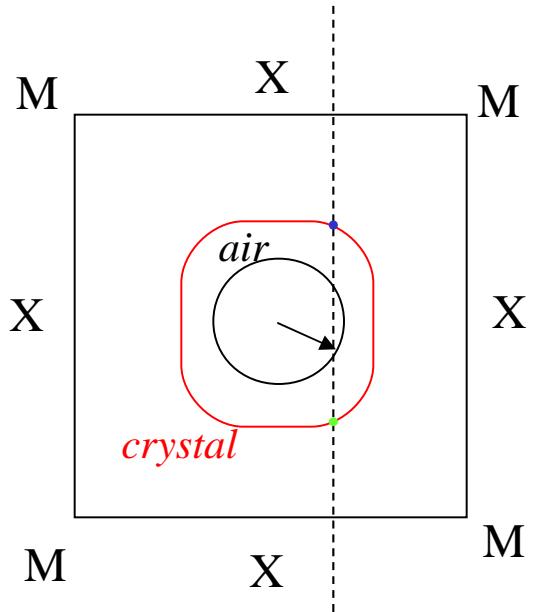
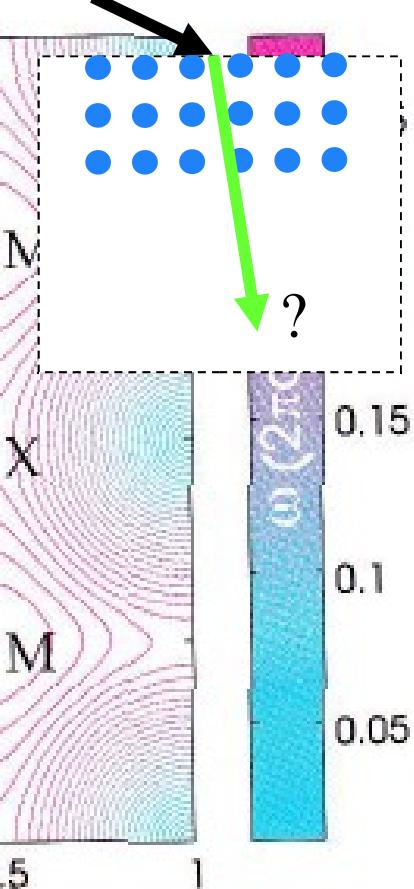


Figure 15: Isofrequency diagrams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a square lattice of radius $0.2a$ dielectric rods ($\epsilon=1$) (black squares).

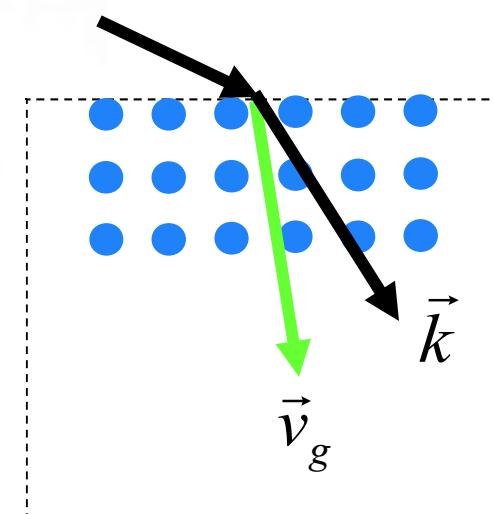
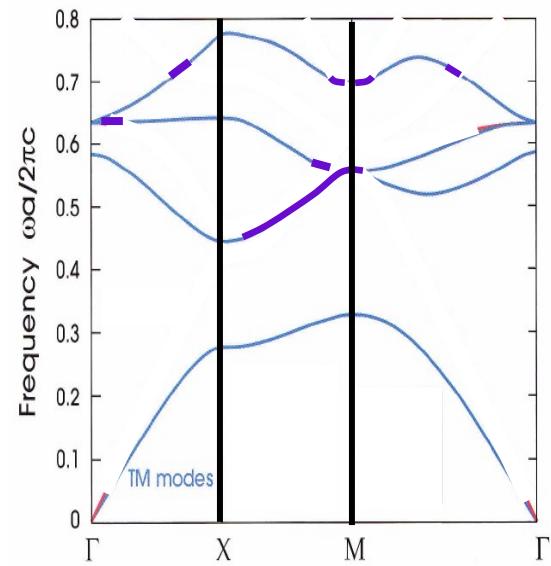
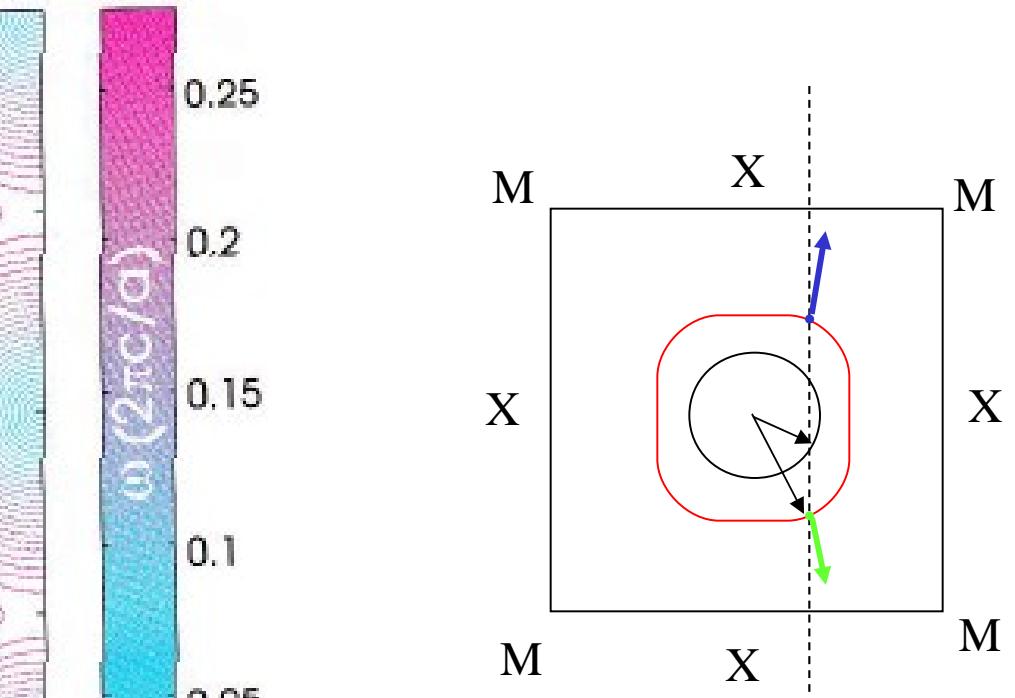
Rifrazione in PhC



ams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a

Rifrazione in PhC

Band 1: Γ è un minimo

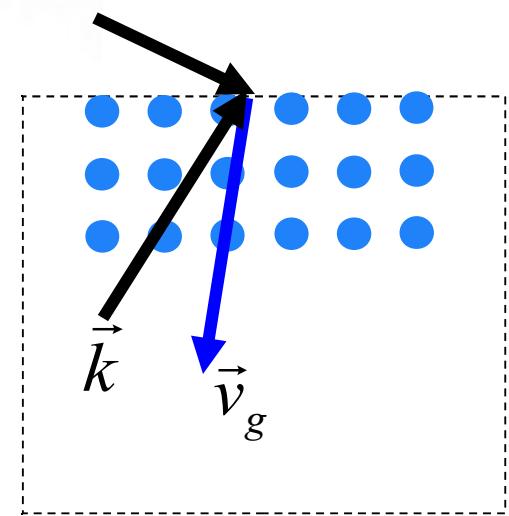
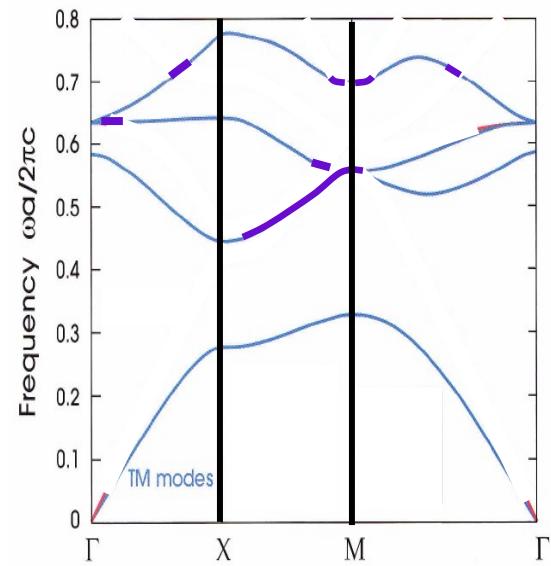
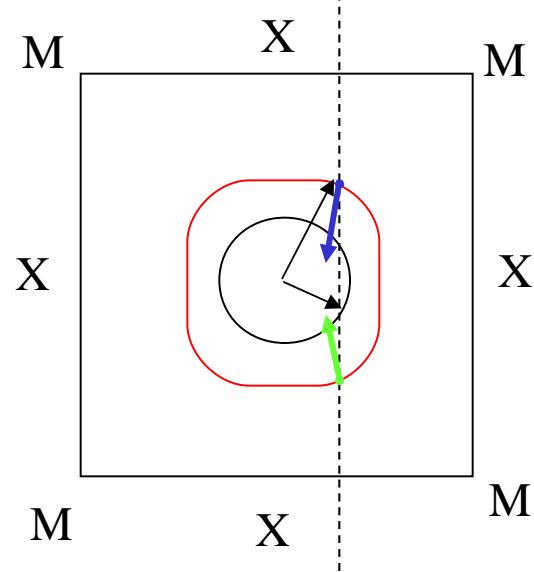
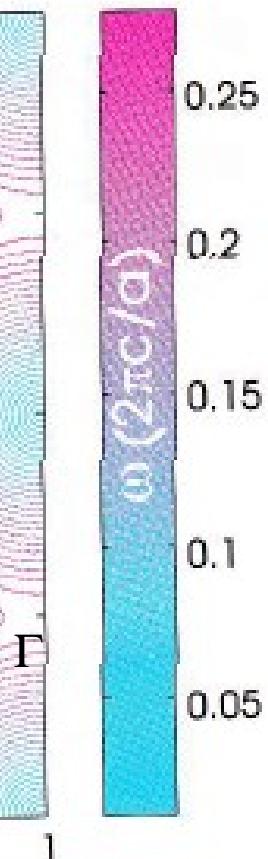


Rifrazione anisotropa

contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a

Rifrazione in PhC

Band 2: Γ è un massimo

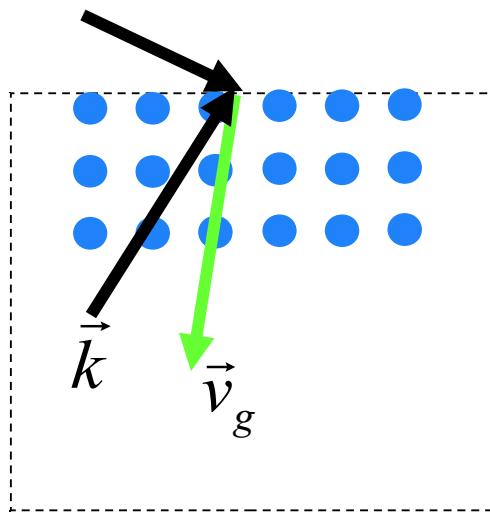


Rifrazione negativa

contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a

Rifrazione negativa

Legge di Snell



$$\sin \theta_i = n_2 \sin \theta_t$$

$$n_2 > 0 \rightarrow \theta_t > 0$$



$$\theta_t < 0$$

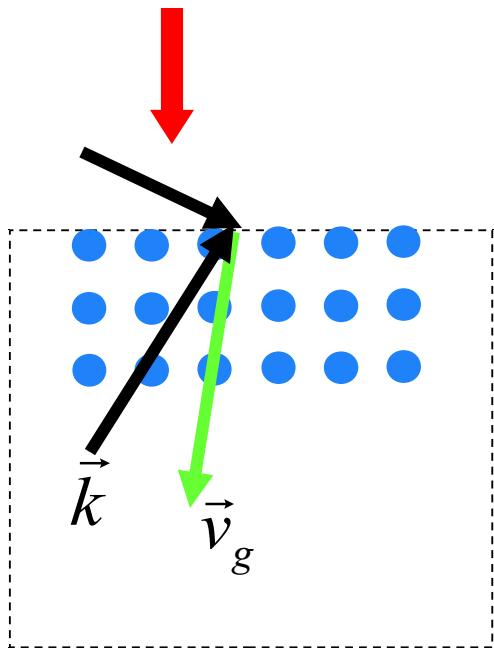
$$\sin \theta_i = n_2 \sin \theta_t$$

$$n_2 < 0$$

Rifrazione negativa

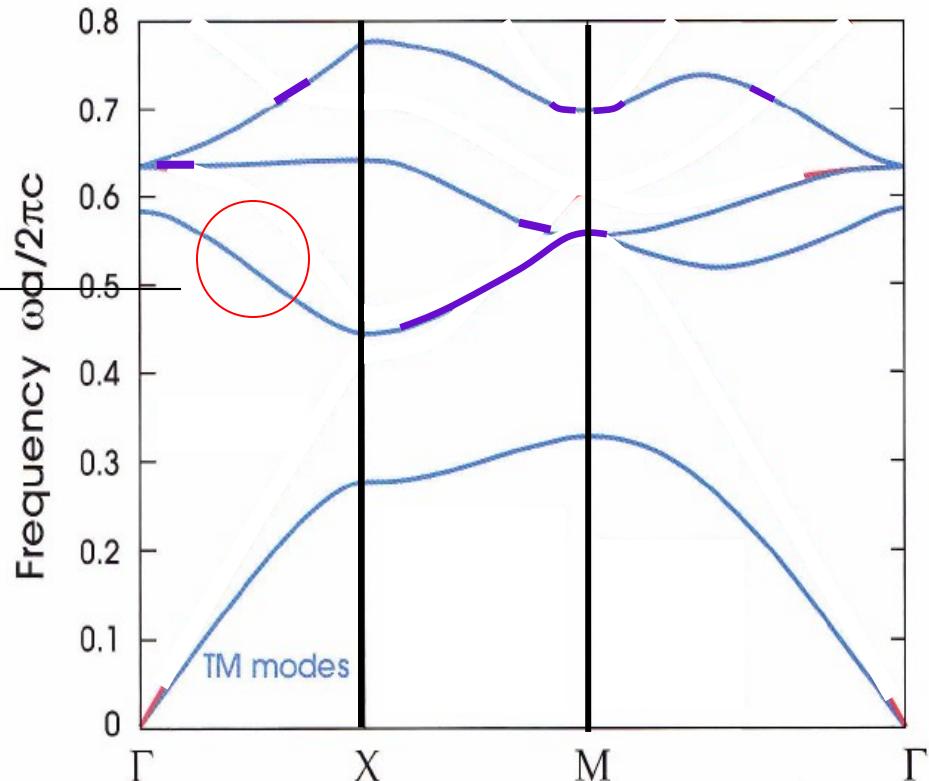
$$v_g = \frac{d\omega}{dk} < 0$$

$$\vec{v}_g \cdot \vec{k} < 0$$



$$\vec{v}_p = \frac{c}{n} \hat{k} \Rightarrow \vec{v}_{p,in} \cdot \vec{v}_{p,refr} < 0$$

come se $n < 0$



Velocità di gruppo, propagazione "normale"

$$\vec{v}_p = \frac{\omega}{k} \hat{k} \quad \text{velocità di fase}$$

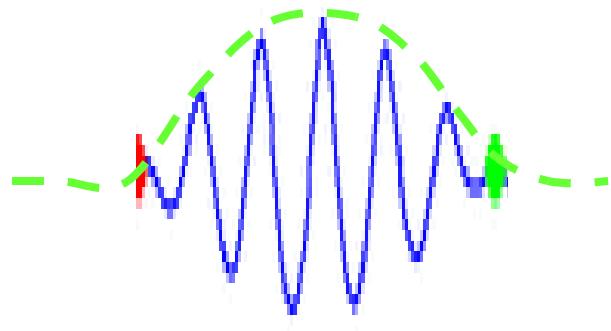
$$\vec{v}_g = \vec{\nabla}_{\vec{k}} \omega(\vec{k}) \quad \text{velocità di gruppo;}$$

$$\vec{v}_p \neq \vec{v}_g \quad \vec{v}_p \cdot \vec{v}_g > 0$$

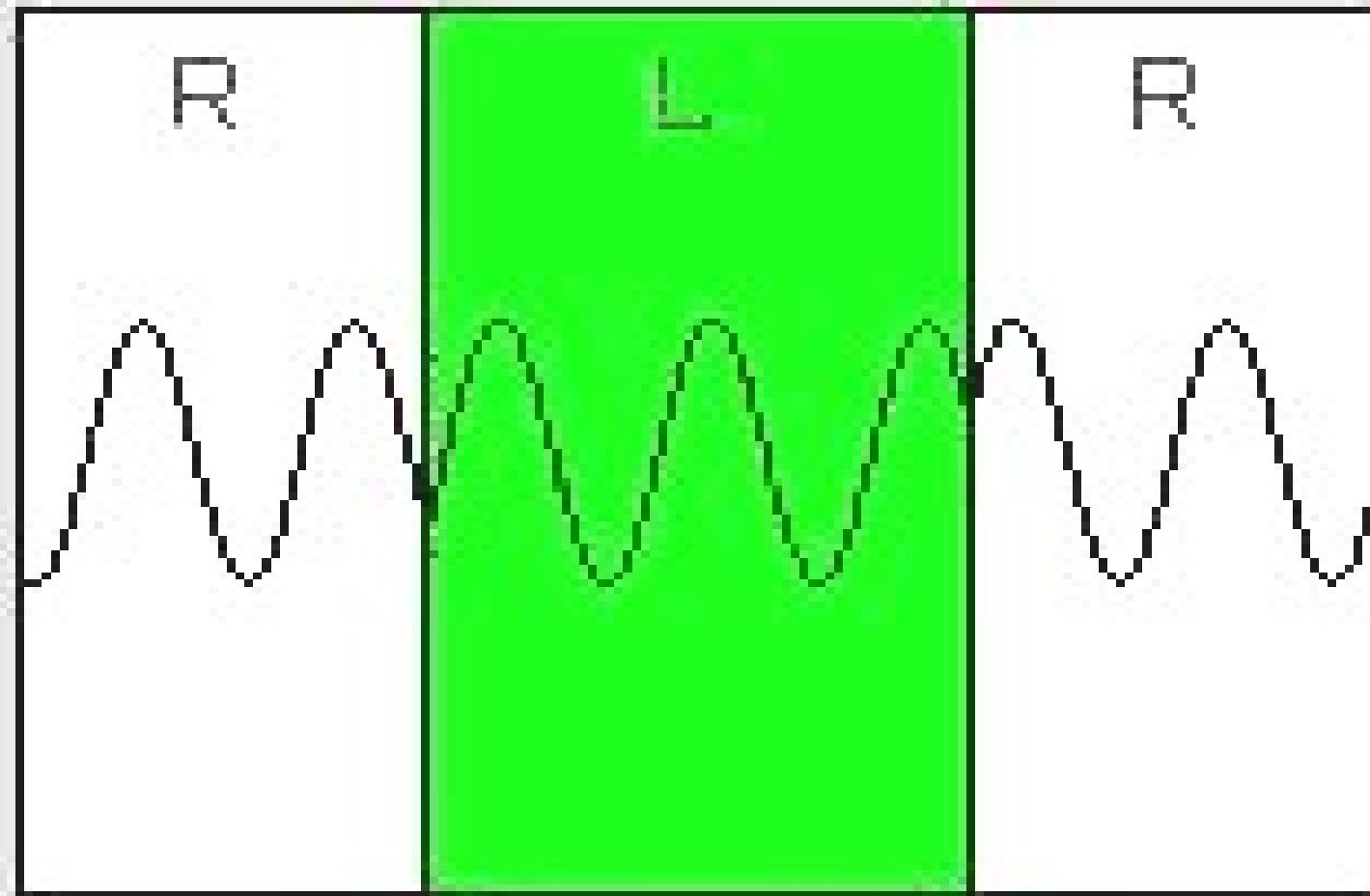
Velocità di gruppo, propagazione "normale"

$$\vec{v}_p > \vec{v}_g$$

$$\vec{v}_p \cdot \vec{v}_g > 0$$

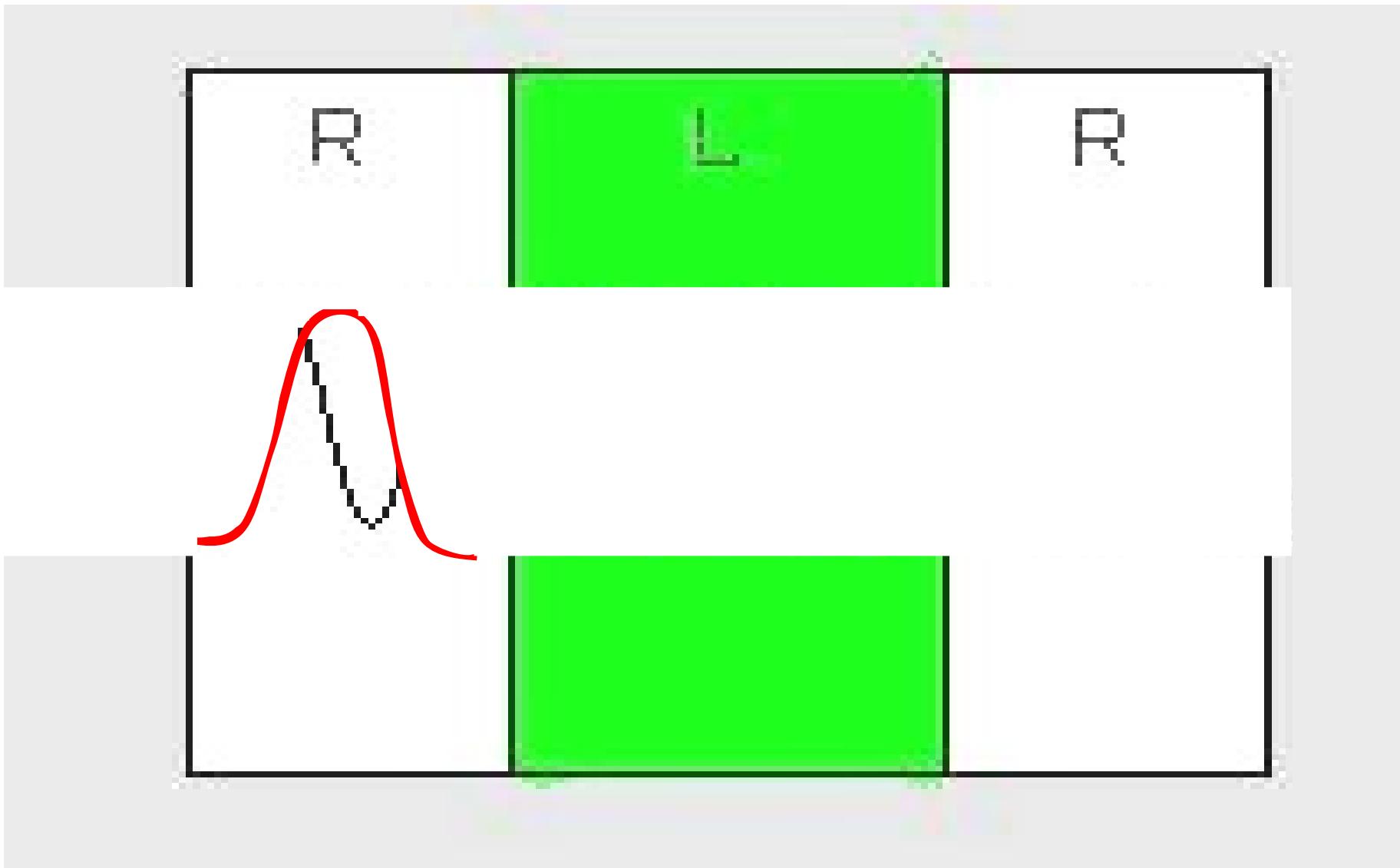


Propagazione "anormale" ($n < 0$) $\vec{v}_p \cdot \vec{v}_g < 0$



$$\vec{v}_p \cdot \vec{v}_g < 0$$

Propagazione "anormale" ($n<0$)

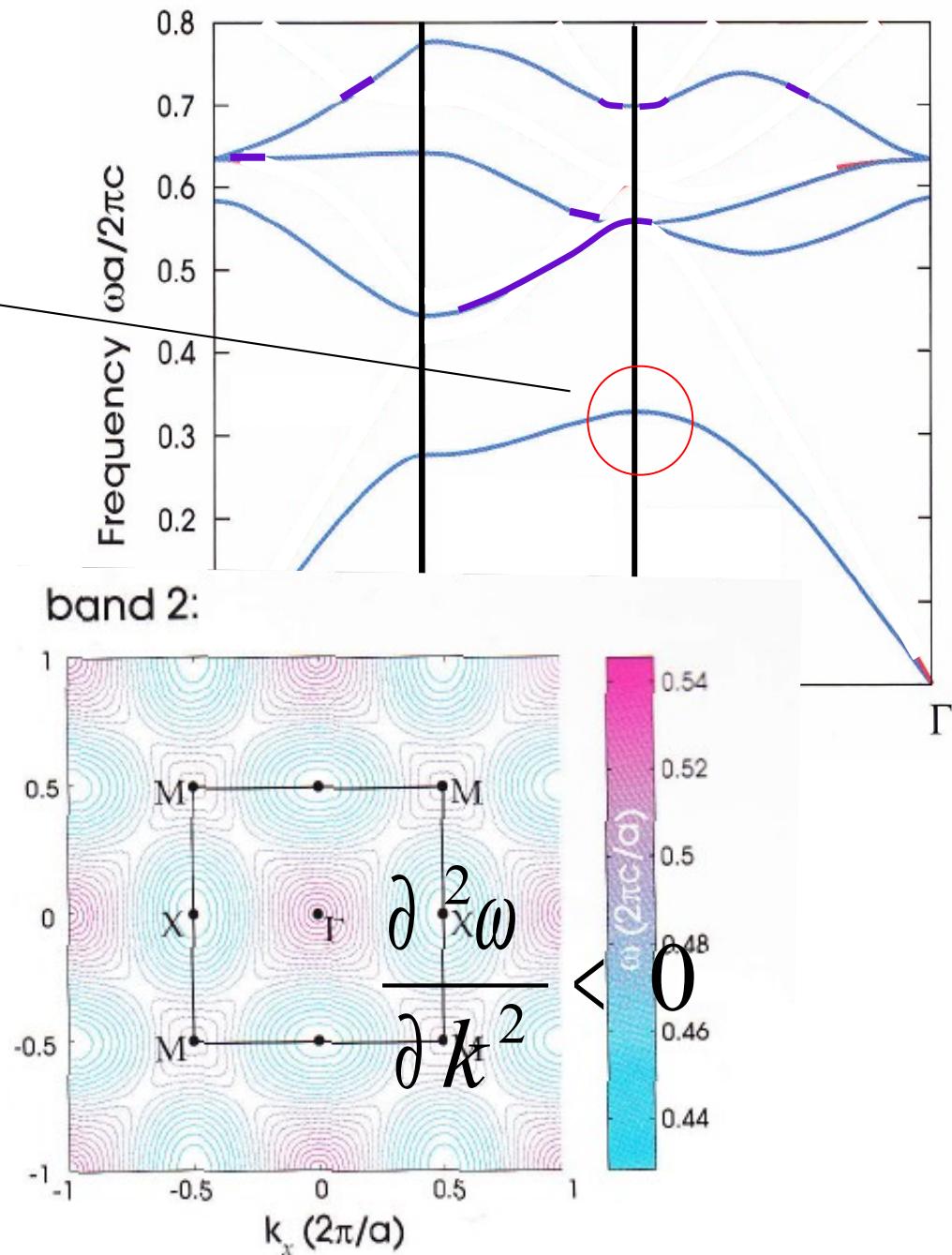


Altro punto particolare

$$v_g = \frac{d\omega}{dk} \rightarrow 0$$

$$\vec{v}_g \cdot \vec{k} > 0$$

$v / (2\pi/a)$

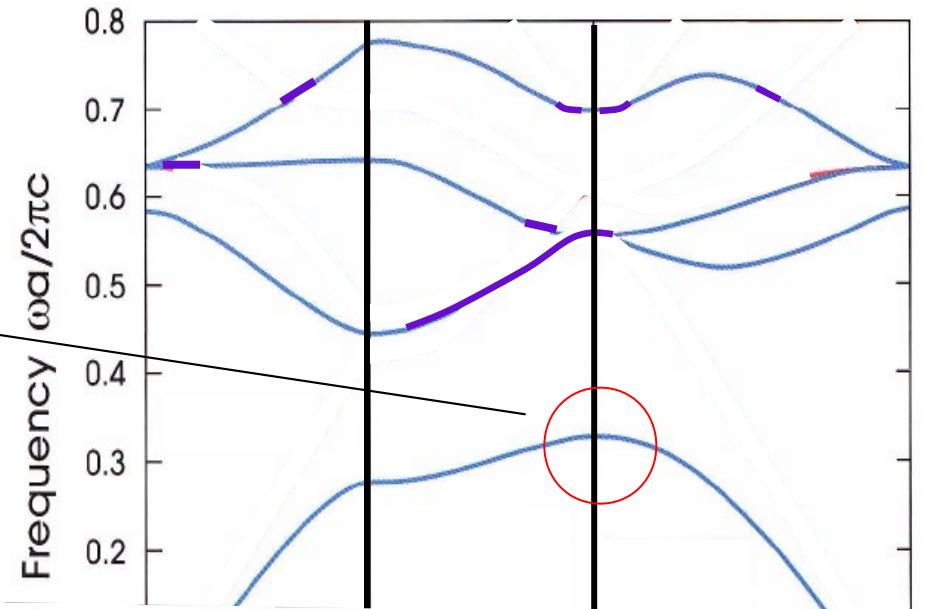


Altro punto particolare

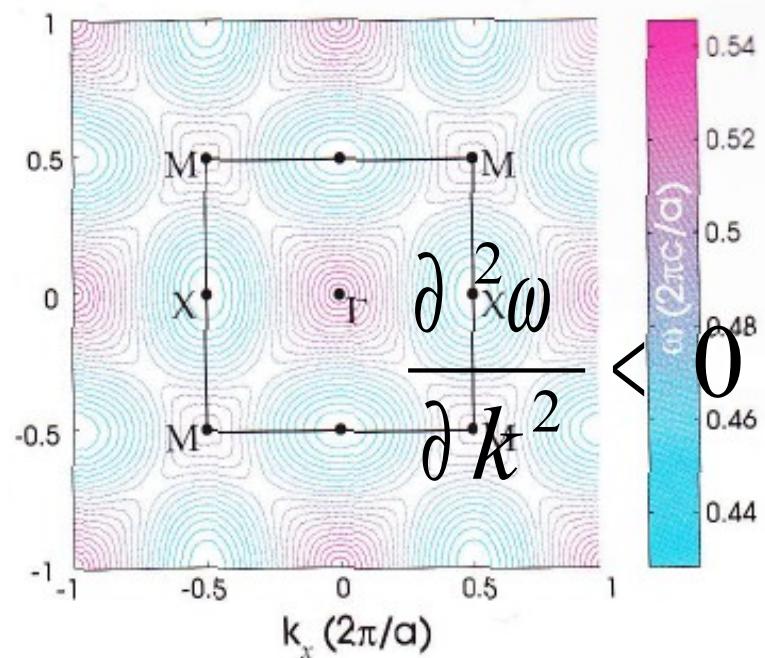
$$v_g = \frac{d\omega}{dk} \rightarrow 0$$

$$\vec{v}_g \cdot \vec{k} > 0$$

$v / (2\pi/a)$

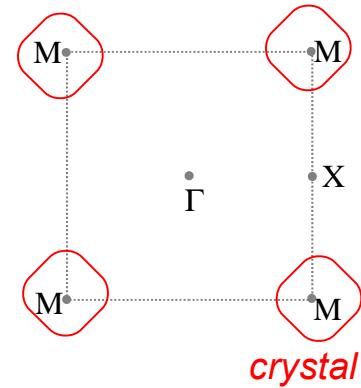


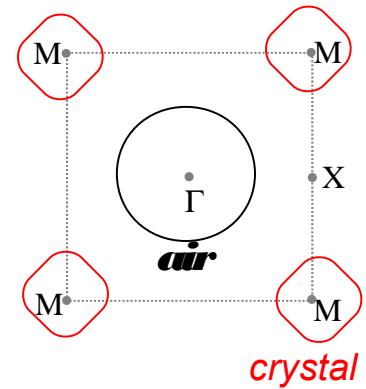
band 2:

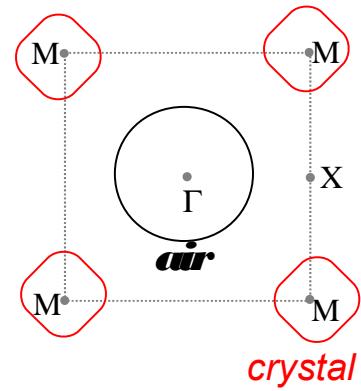


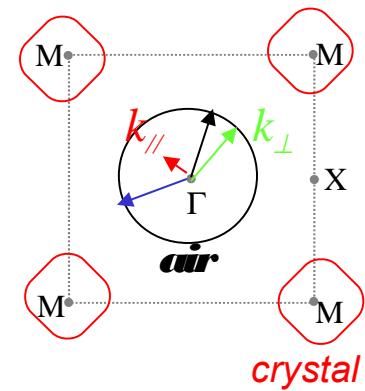
Γ

Superficie con normale lungo (11)

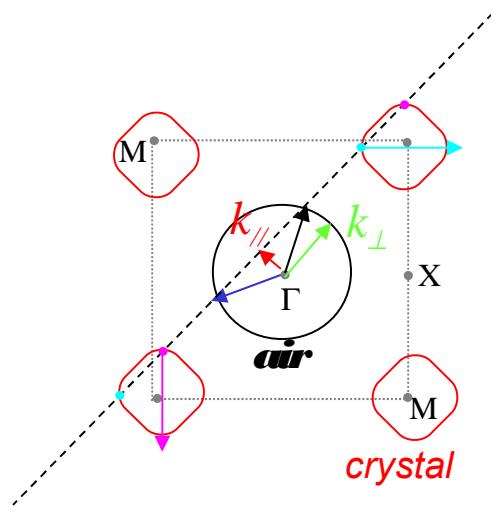




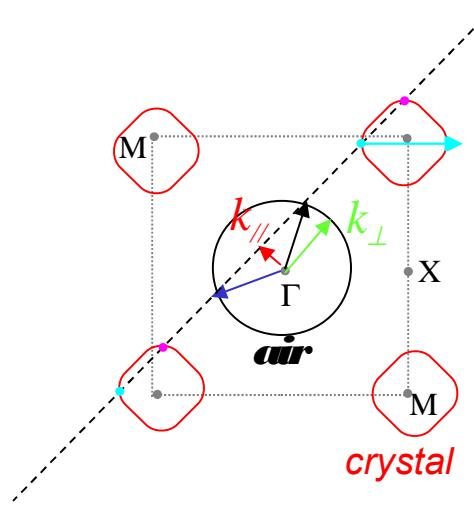




crystal



Negative refraction



Negative refraction

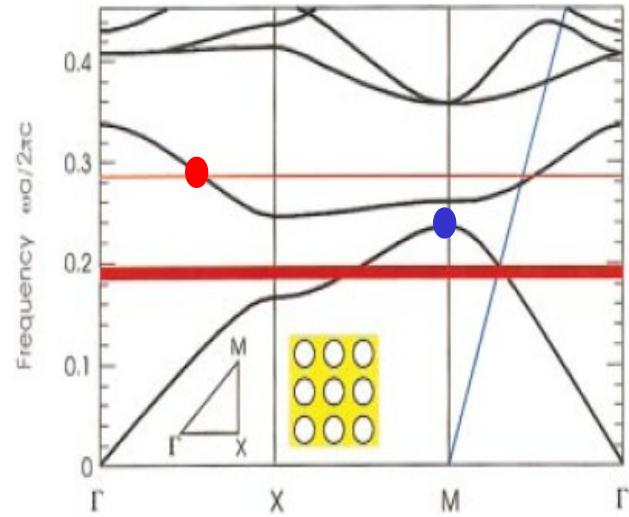
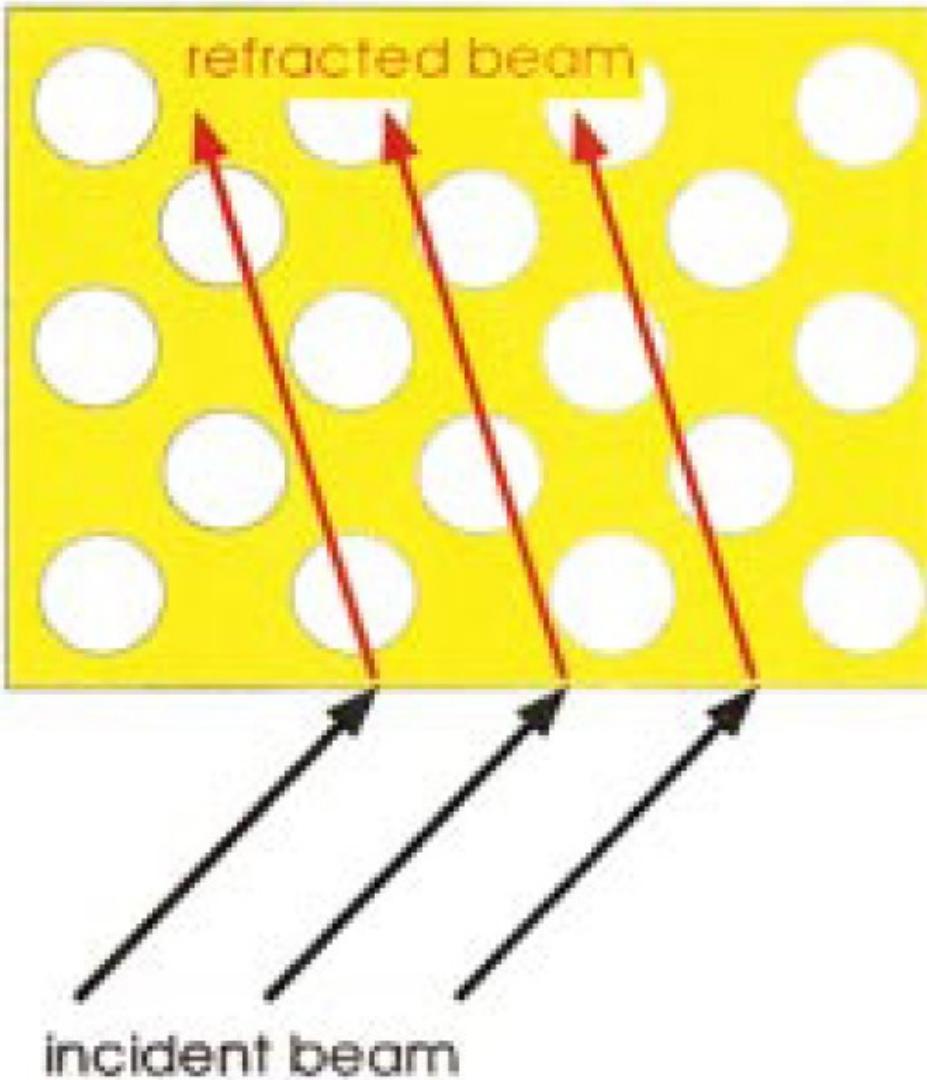
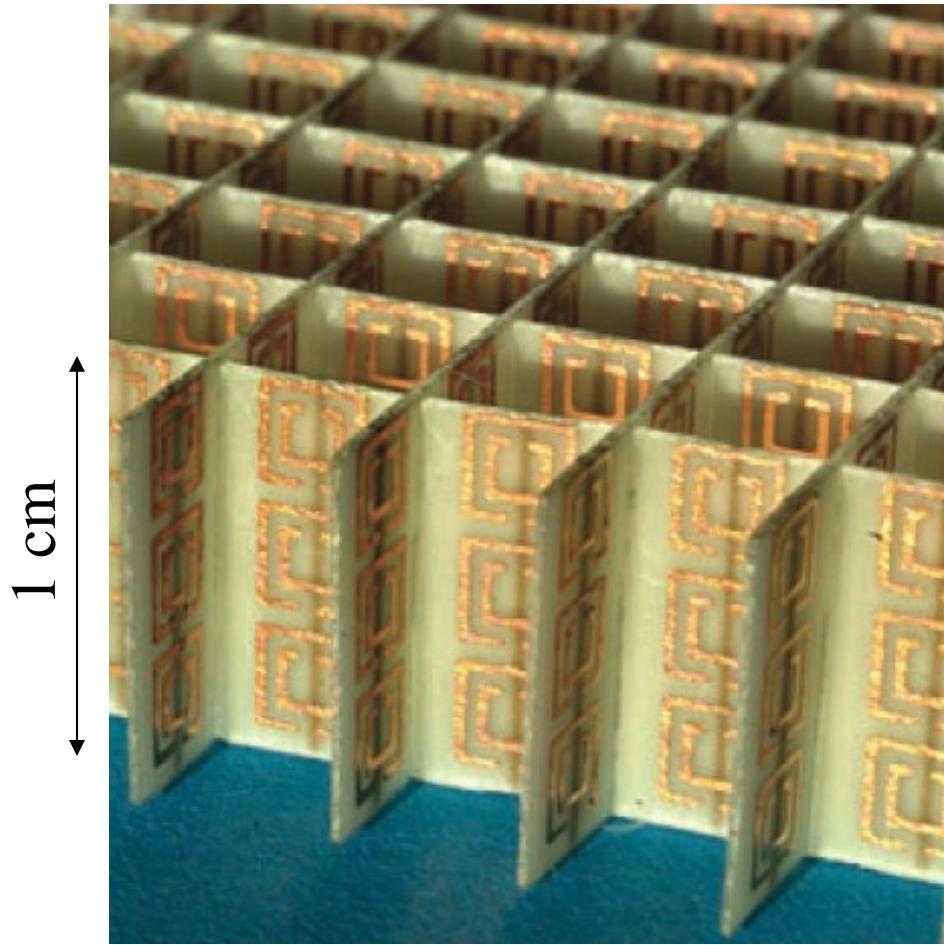


FIG. 3. (Color) The AANR frequency ranges are highlighted in red in the band structure. The light line shifted to M is shown in blue.

- Negative photonic mass
- $\vec{v}_g \cdot \vec{k} < 0$ (LHM)
- [Veselago, 1968 negative ϵ, μ] (metamateriali,)

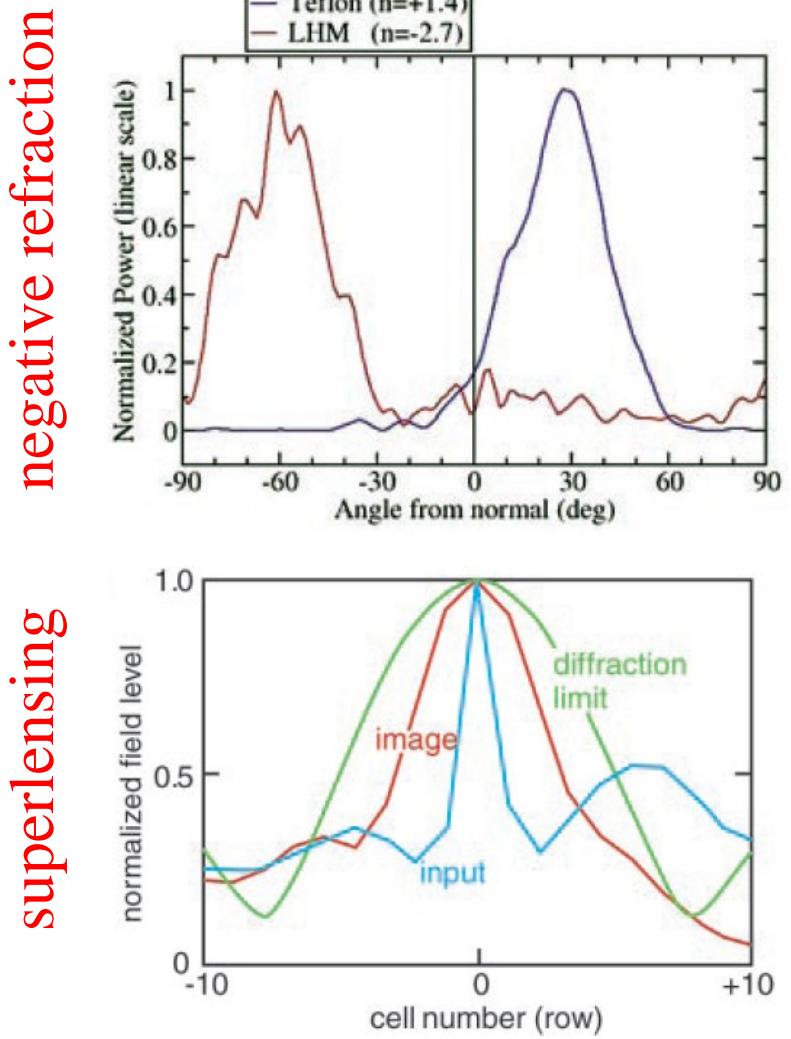
Metamateriali

Microwave negative refraction



Magnetic (ring) + Electric (strip) resonances

[D. R. Smith, J. B. Pendry, M. C. K. Wiltshire, *Science* **305**, 788 (2004)]



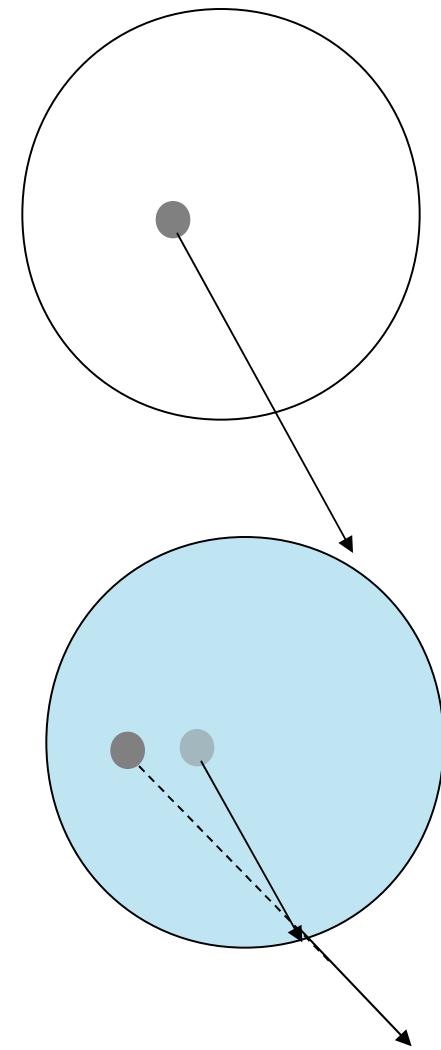
A metal rod in an empty drinking glass



Fill the glass with blueberry juice ($n = 1.3$)...



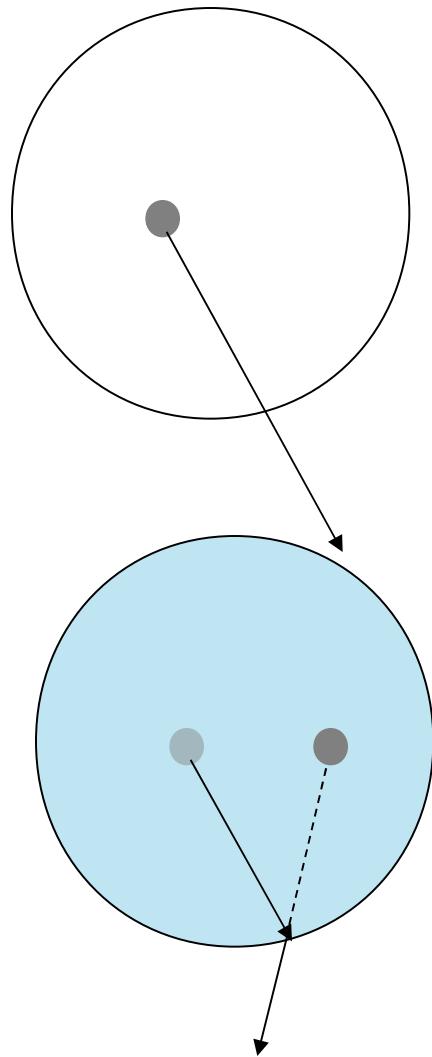
Rifrazione normale



A metal rod in an empty drinking glass



Rifrazione negativa



Now try the new recipe:
negative refraction



A metal rod in an empty drinking glass



Fill the glass with blueberry juice ($n = 1.3$)...



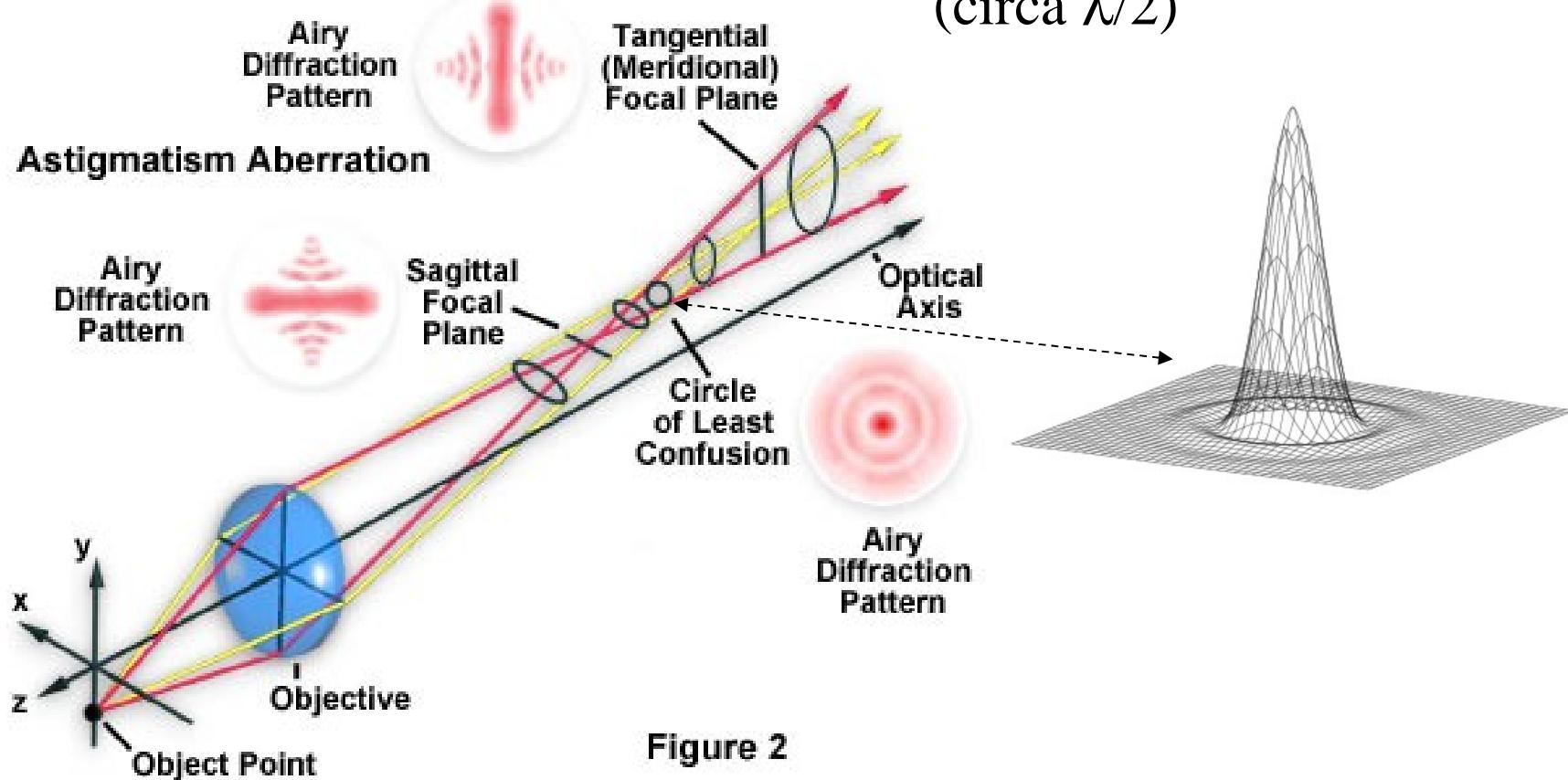
Now try the new recipe:
negative refraction



These pictures are NOT quoted from science fictions; they are computer simulations published in renowned peer-reviewed scientific journals!

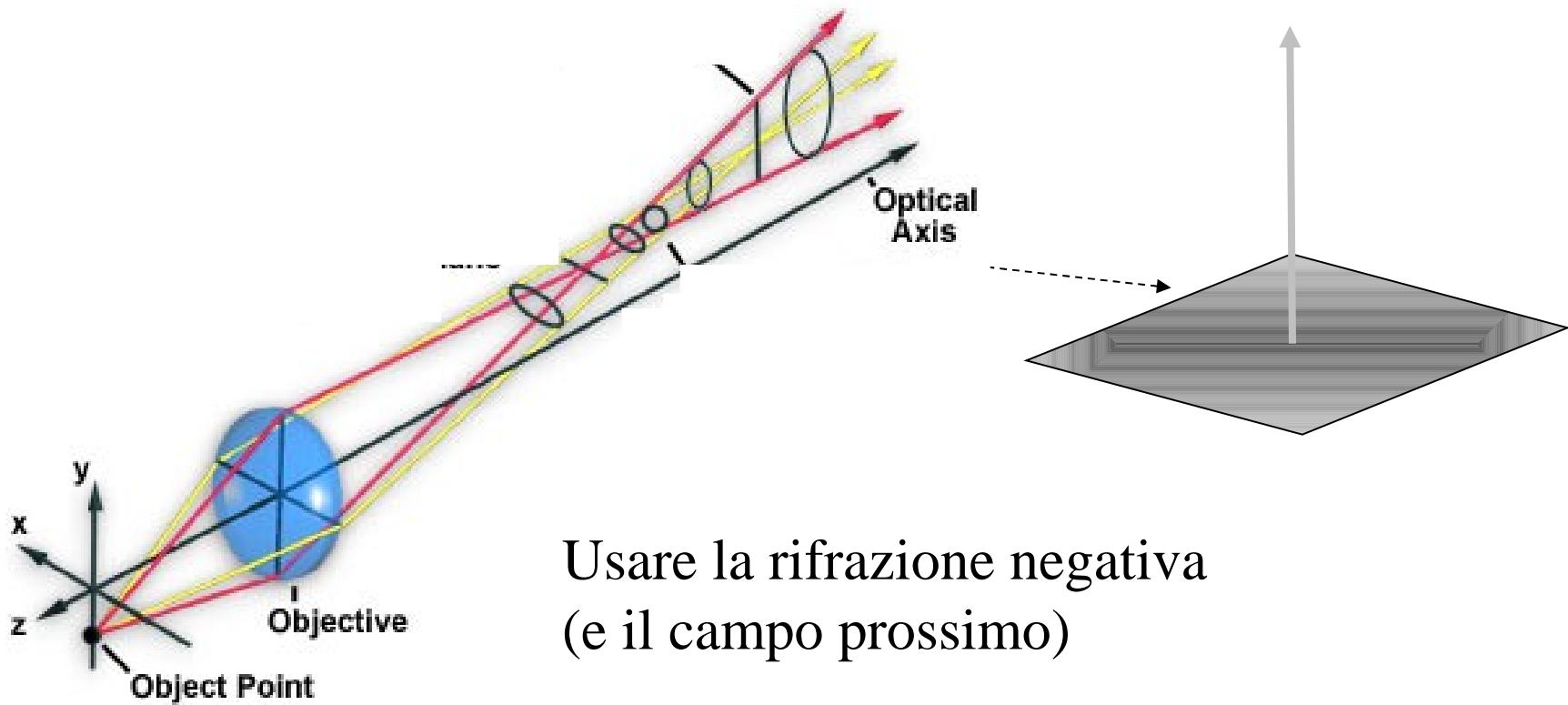
G. Dolling, et al., "Photorealistic images of objects in effective negative-index materials," Opt. Express **14**, 1842-1849 (2006).

Normal Lens

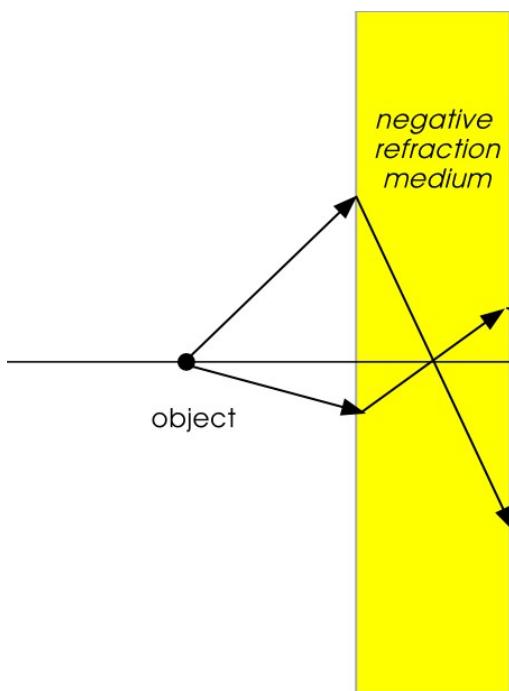


SuperLens

Immagine di una sorgente puntiforme ha dimensioni nulle

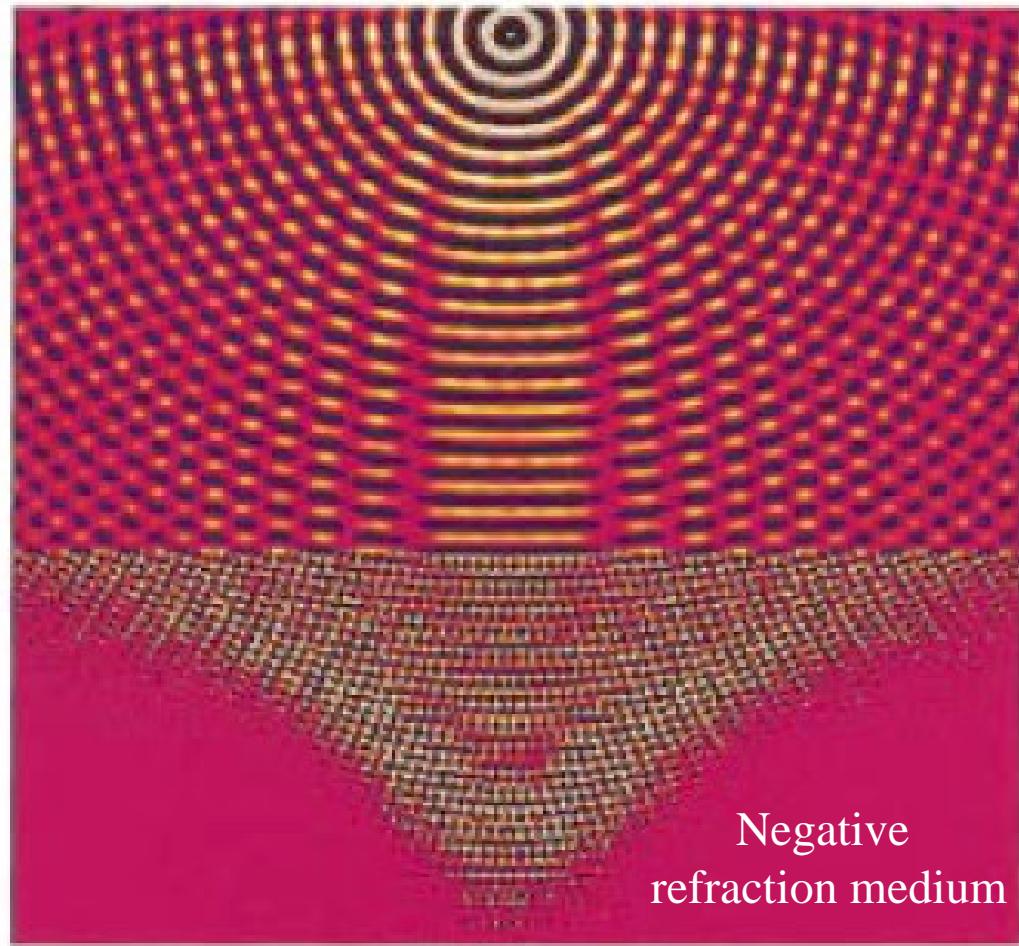


Negative-refraction can focus light



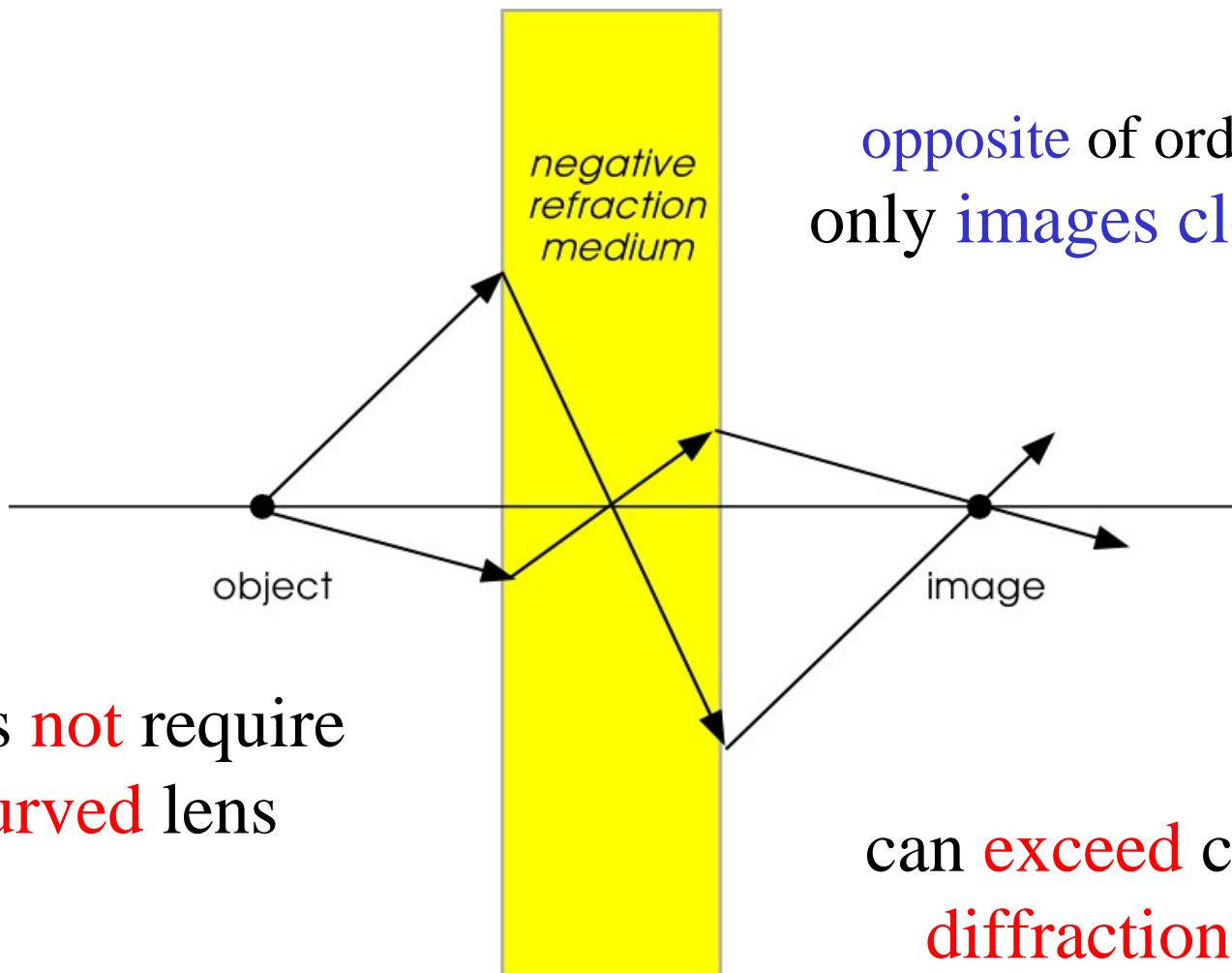
focussing

Ultra-refraction



[M. Notomi, *PRB* **62**, 10696 (2000).]

Negative Refraction Superlens

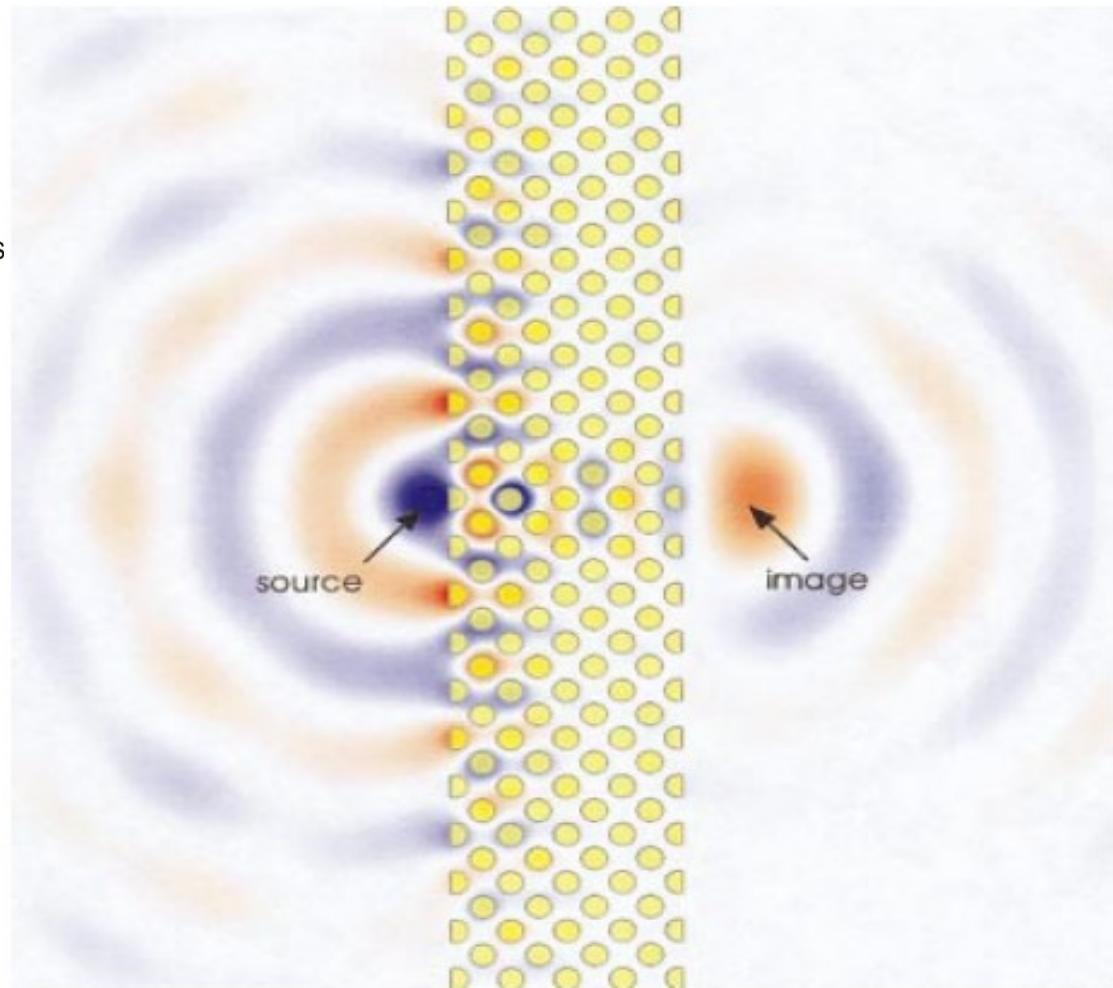
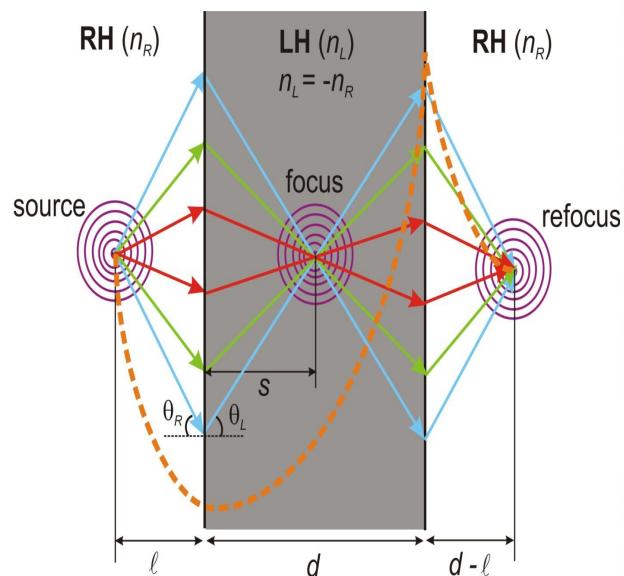


opposite of ordinary lens:
only images close objects

does **not** require
curved lens

can **exceed** classical
diffraction limit

PhC Super Lens

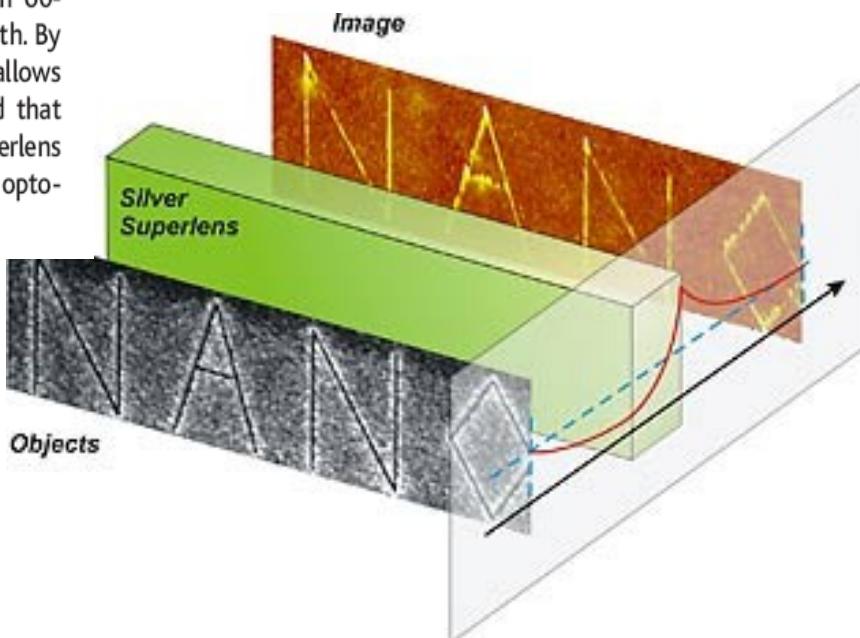


Usare la rifrazione negativa (e il campo prossimo)

Sub-Diffraction-Limited Optical Imaging with a Silver Superlens

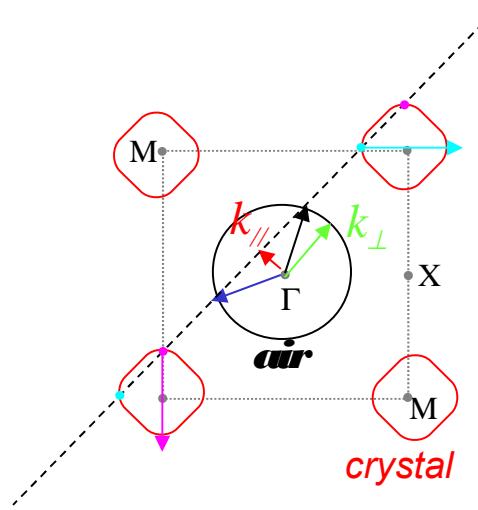
Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang*

Recent theory has predicted a superlens that is capable of producing sub-diffraction-limited images. This superlens would allow the recovery of evanescent waves in an image via the excitation of surface plasmons. Using silver as a natural optical superlens, we demonstrated sub-diffraction-limited imaging with 60-nanometer half-pitch resolution, or one-sixth of the illumination wavelength. By proper design of the working wavelength and the thickness of silver that allows access to a broad spectrum of subwavelength features, we also showed that arbitrary nanostructures can be imaged with good fidelity. The optical superlens promises exciting avenues to nanoscale optical imaging and ultrasmall optoelectronic devices.



60 nm di risoluzione

Superifrazione



Superfrazione

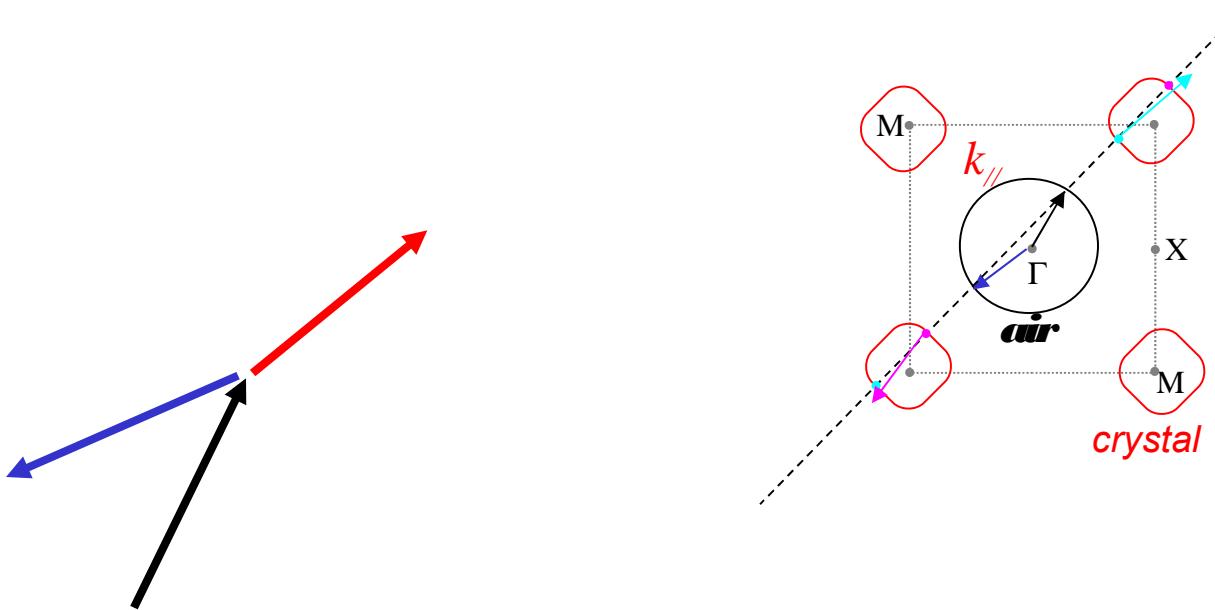


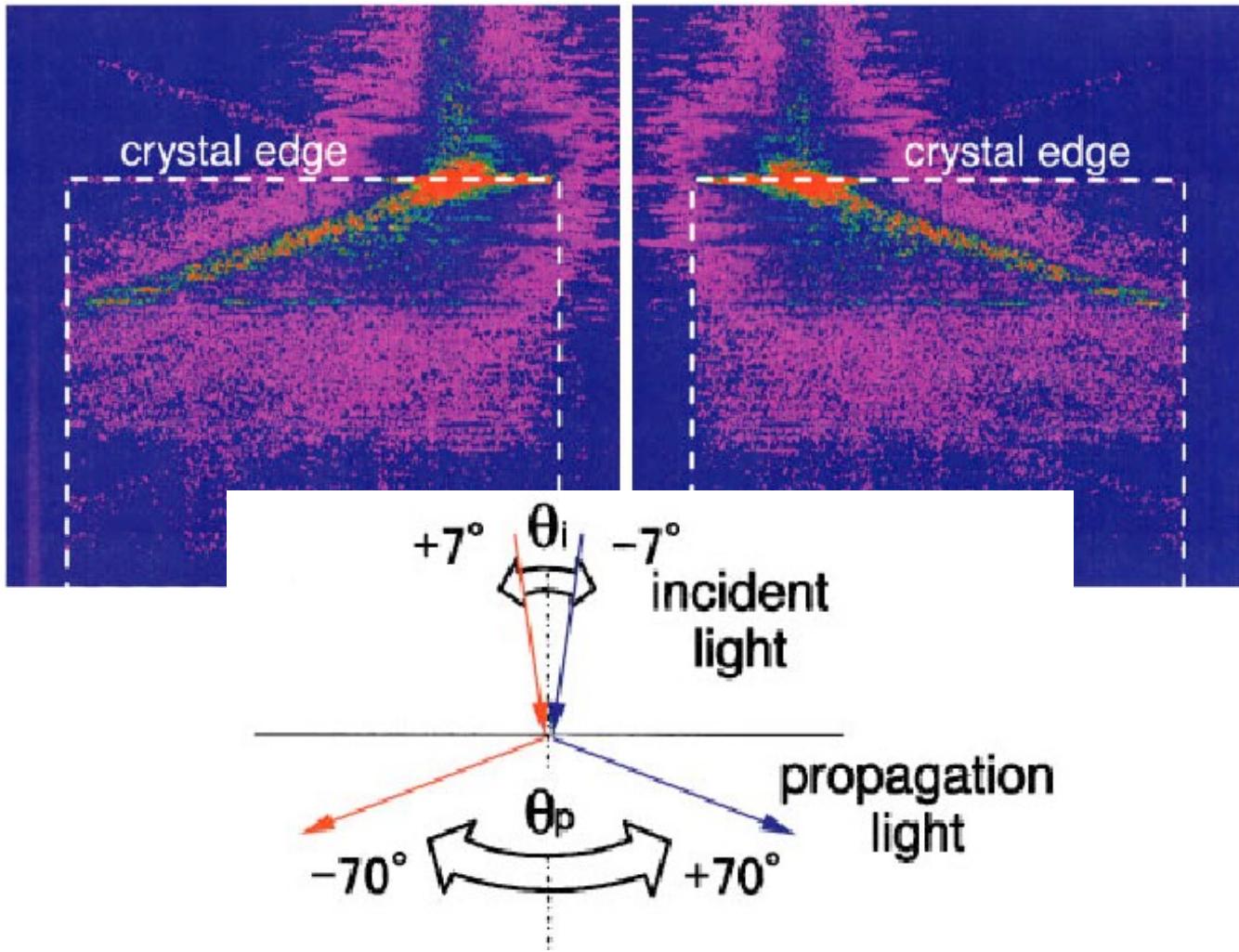
Figure 14: *Left:* Schematic of reflection (blue) and refraction (red) of a plane wave incident (black) on a square lattice of dielectric rods (green) in air, for an interface with period $\Lambda = a\sqrt{2}$ in the diagonal (110) direction. Depending on the frequency, there may also be additional reflected and/or refracted waves due to Bragg diffraction. *Right:* Isofrequency contours in k -space at $\omega/\omega_c = 0.70$ for air (black circle) and crystal (red circle), with the Brillouin zone in gray. The group velocity direction at various k points is shown as arrows (black/blue/red for incident/reflected/refracted waves). Because the wave vector component parallel to the interface is conserved, all reflected and refracted solutions (blue and red dots) must lie along the dashed line (running perpendicular to the interface).

**Piccolo cambiamento di angolo di incidenza,
grande variazione angolo rifrazione**

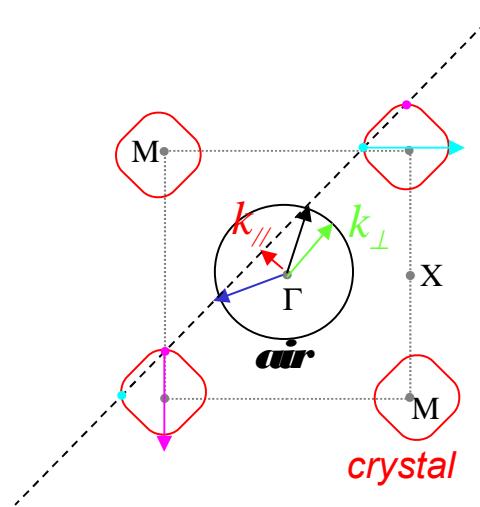
Superrifrazione

from divergent dispersion (band curvature)

[Kosaka, *PRB* **58**, R10096 (1998).]



Superifrazione



Superifrazione

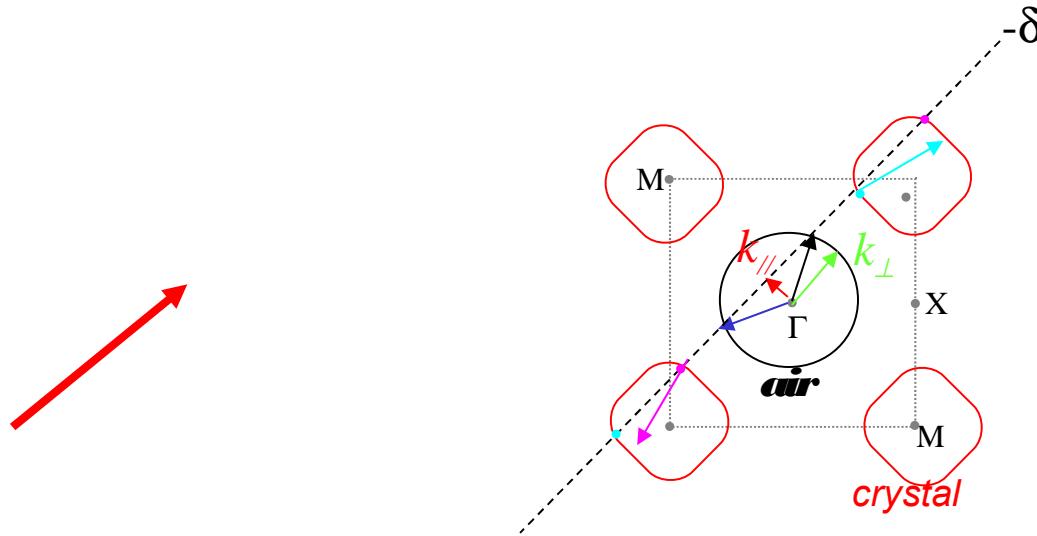
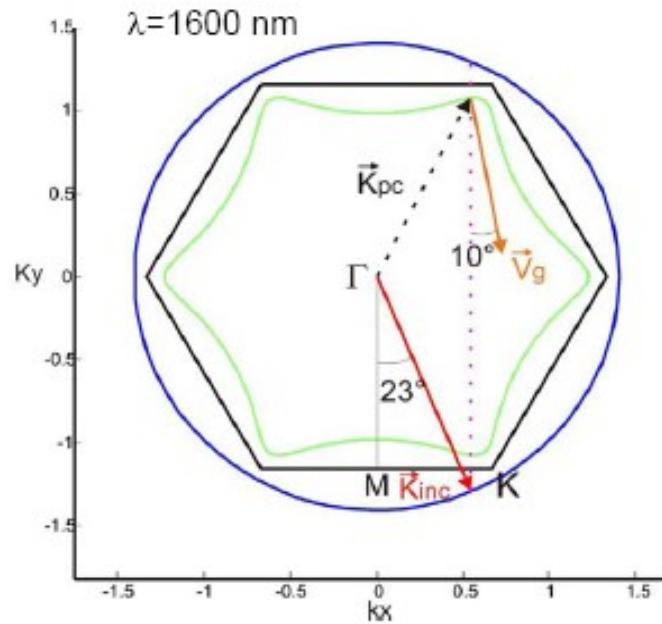
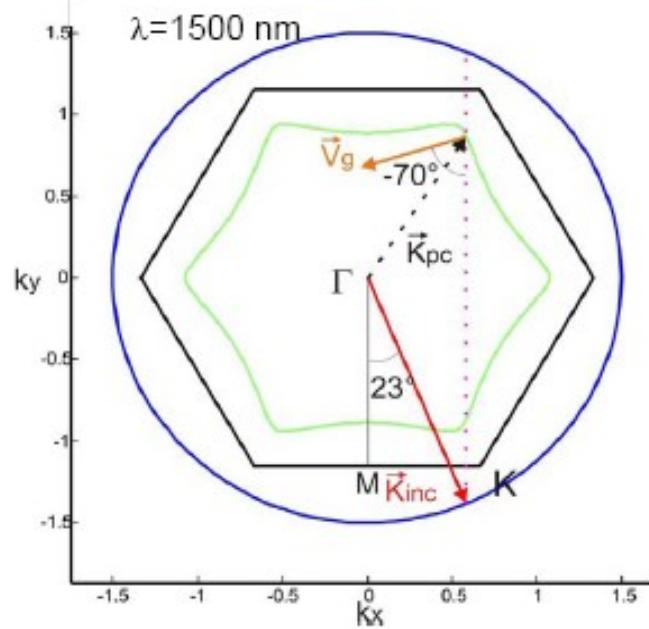


Figure 14: Left: Schematic of reflection (blue) and refraction (red) of a plane wave incident (black) on a square lattice of dielectric rods (green) in air, for an interface with period $\Lambda = a\sqrt{2}$ in the diagonal (110) direction. Depending on the frequency, there may also be additional reflected and/or refracted waves due to Bragg diffraction. Right: Isofrequency contours in k -space at $\omega/\omega_c = 0.50$ for air (black circles) and crystal (red contours), with the Brillouin zone in gray. The group velocity direction at various k points is shown as arrows (black/blue/red for incident/reflected/refracted waves). Because the wave vector component parallel to the interface is conserved, all reflected and refracted solutions (blue and red dots) must lie along the dashed line (running perpendicular to the interface).

**Piccolo cambiamento di frequenza,
grande variazione angolo rifrazione**

Superifrazione

Light direction propagation in the PC for different wavelengths ($\lambda=1500\text{nm}$ and $\lambda=1600\text{nm}$) f
 $n=2.143$ and $\theta_{\text{inc}}=23^\circ$.



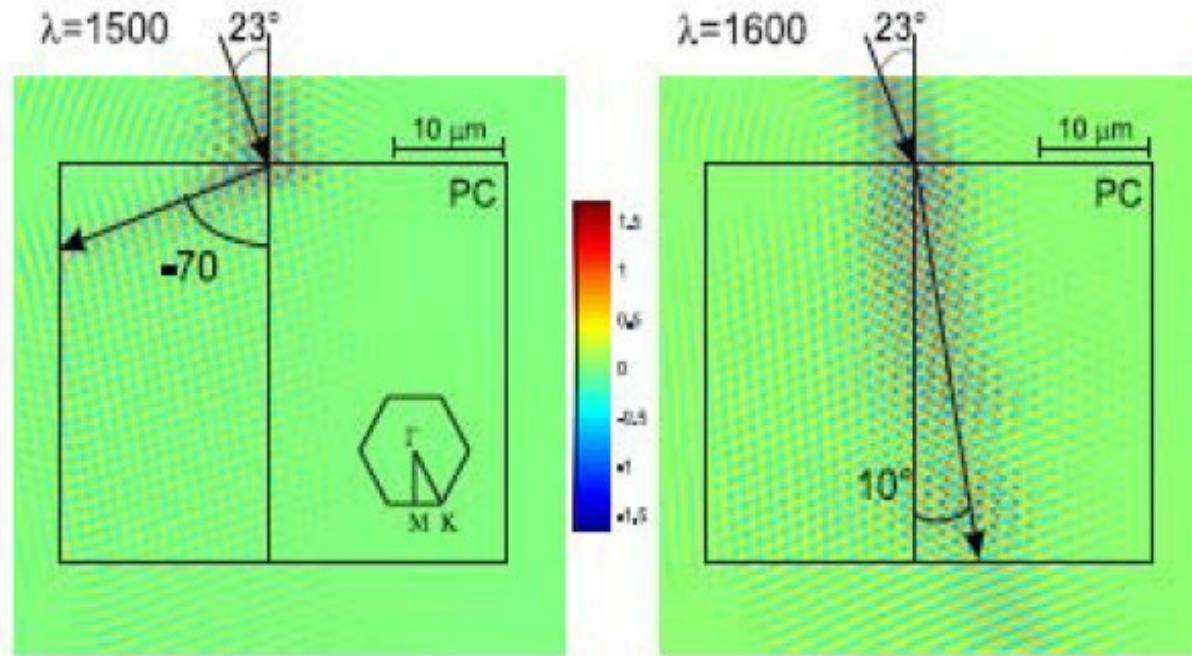
Analysis of CFDS (PWE)

$$\lambda=1500\text{ nm} \quad \theta_{\text{PC}}=-70^\circ$$

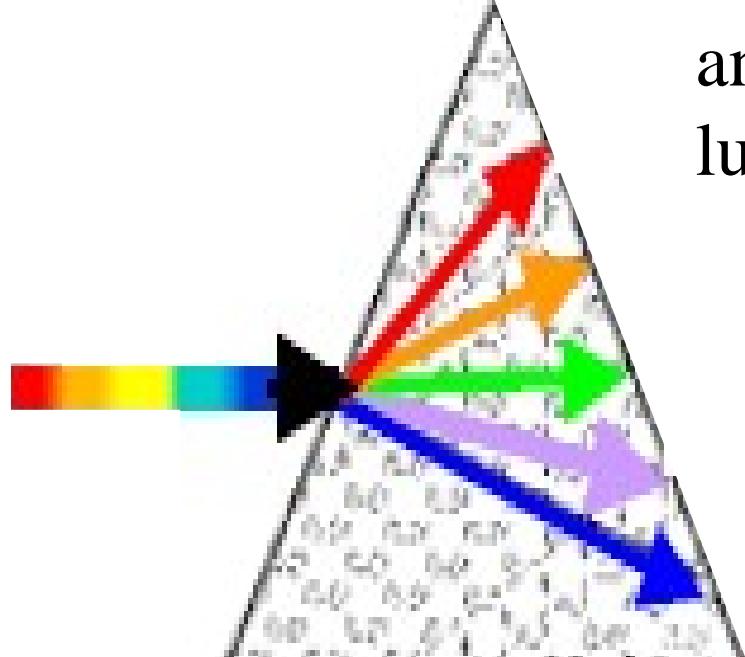
$$\lambda=1600\text{ nm} \quad \theta_{\text{PC}}=10^\circ$$

Superifrazione

Light direction propagation in the PC for different wavelength ($\lambda=1500\text{nm}$ and $\lambda=1600\text{nm}$) for $n=2.143$ and $\theta_{\text{inc}}=23^\circ$.



SuperPrism



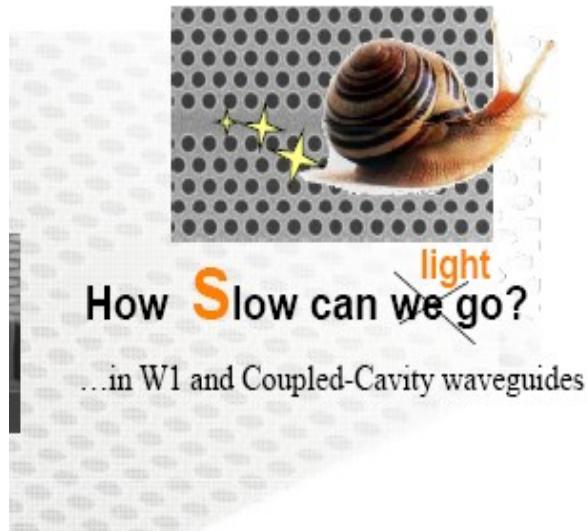
Prism

Grande separazione
angolare delle diverse
lunghezze d'onda

structures

made lasers

in PhC structures



...in W1 and Coupled-Cavity waveguides