A Física dos metamateriais: da refração negativa aos mantos da invisibilidade

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Outline

- What is Negative Refraction (NR) ?
- What are the main consequences of NR?
  - Electromagnetic properties of NR media.
- What are the applications of NR and metameterials ?
  - Perfect lens
  - Cloaking
- How to achieve NR ?
- Alternative routes to NR ?
  - The chiral route to NR.

What is negative refraction ?

Left-Handed materials

Wave equation

$$\nabla^2 \mathbf{E} - \frac{\varepsilon\mu}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0$$

Plane wave

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 \exp(\mathbf{k}\cdot\mathbf{r} - \omega t)$$

$$\left[k^2 - \varepsilon\mu\frac{\omega^2}{c^2}\right]\mathbf{E} = 0$$

Propagation occurs if

$$\varepsilon > 0, \mu > 0$$

OR

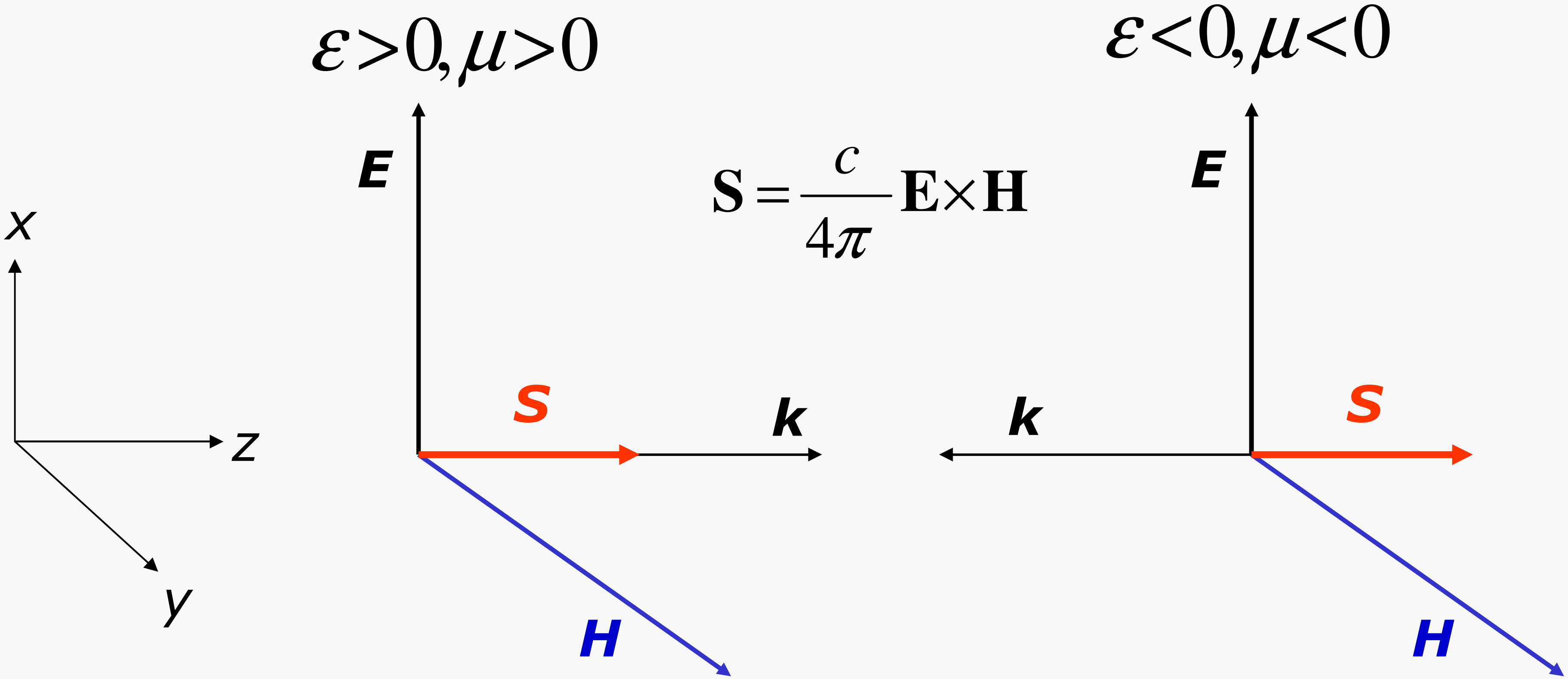
$$\varepsilon < 0, \mu < 0$$

If $\varepsilon < 0, \mu < 0$

$$\mathbf{k}\times\mathbf{E} = -\frac{|\mu|\omega}{c}\mathbf{H} \qquad \mathbf{k}\times\mathbf{H} = +\frac{|\varepsilon|\omega}{c}\mathbf{E}$$

What is negative refraction ?

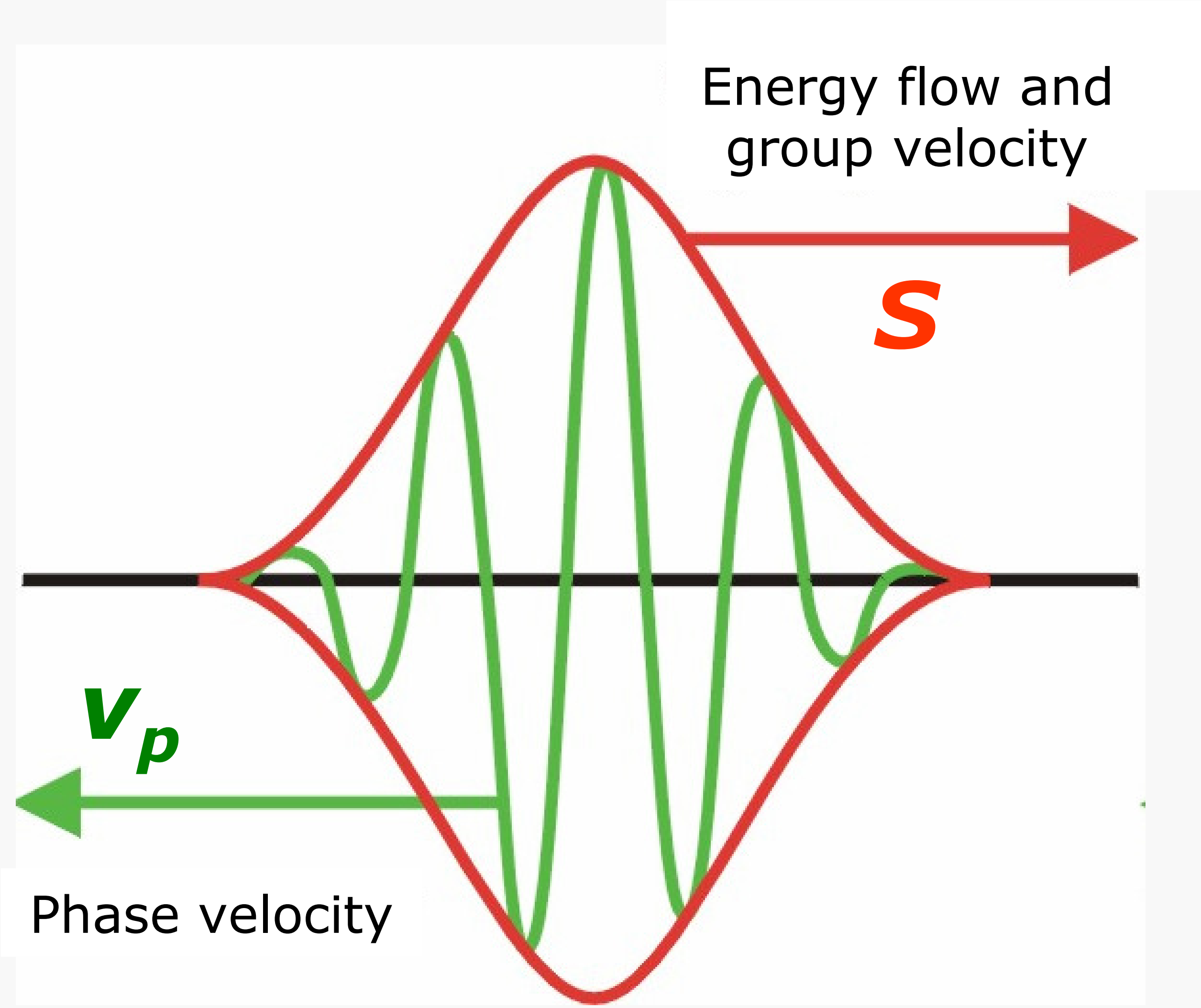
Left-Handed materials



$$\mathbf{S} = \frac{c}{4\pi} \mathbf{E} \times \mathbf{H}$$

Phase velocity $v_p = \omega / k$ is opposite to the direction of electromagnetic propagation (group velocity)!

What is negative refraction ?



What is negative refraction ?

Left-Handed materials: Dispersion

Electromagnetic energy $U = \frac{1}{8\pi}\left\{\frac{\partial(\varepsilon\omega)}{\partial\omega}E^2 + \frac{\partial(\mu\omega)}{\partial\omega}H^2\right\} > 0$

In LH media, ϵ and μ *must* depend on the frequency !

Otherwise $U = \frac{1}{8\pi}\left\{\varepsilon E^2 + \mu H^2\right\} < 0$

$\frac{\partial\omega\varepsilon(\omega)}{\partial\omega} > 0 \quad \frac{\partial\omega\mu(\omega)}{\partial\omega} > 0$ **Kramers-Kronig relations**

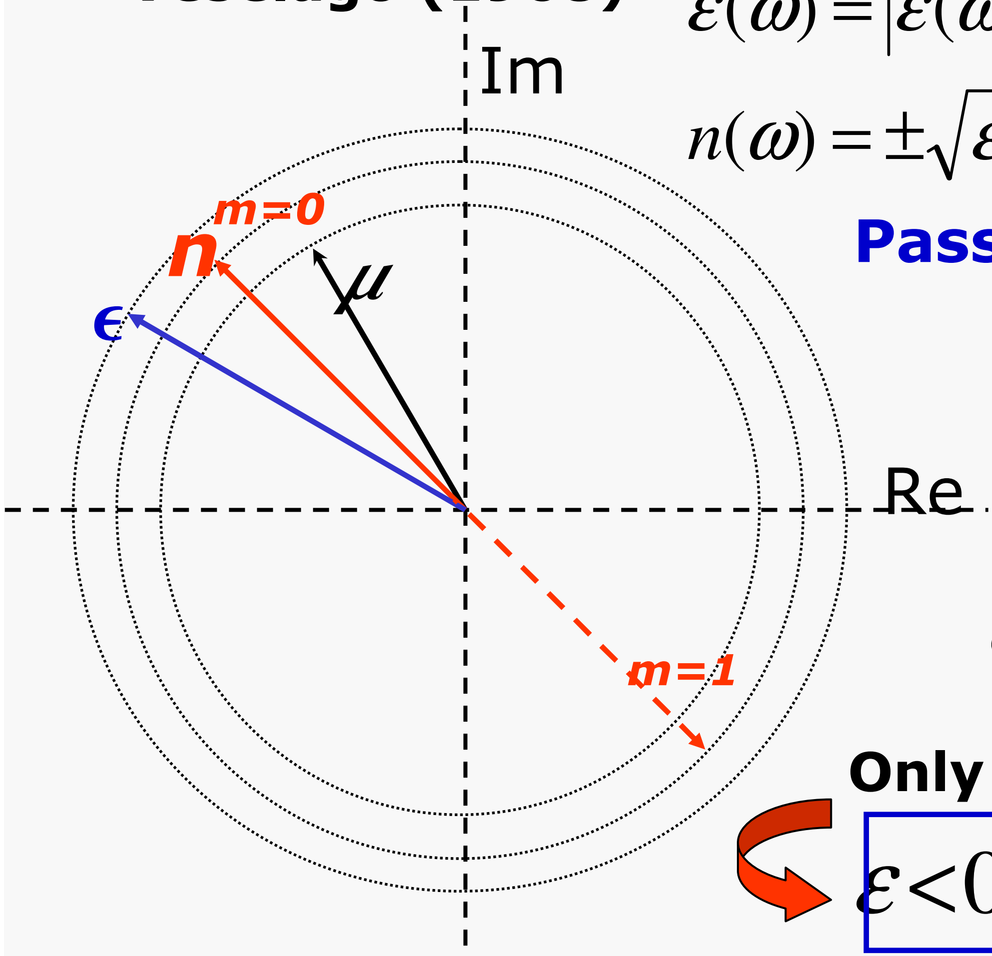
Complex

$\varepsilon(\omega) \quad \mu(\omega)$

What is negative refraction ?

Left-Handed materials: Index of refraction

Veselago (1968)



$$\varepsilon(\omega) = |\varepsilon(\omega)| \exp(i\phi_\varepsilon) \quad \mu(\omega) = |\mu(\omega)| \exp(i\phi_\mu)$$

$$n(\omega) = \pm\sqrt{\varepsilon(\omega)\mu(\omega)} \quad n(\omega) = |n(\omega)| \exp(i\phi_n)$$

Passive materials $\Rightarrow$ $n_i(\omega) > 0$

$$0 \le \phi_\varepsilon, \phi_\mu, \phi_n \le \pi$$

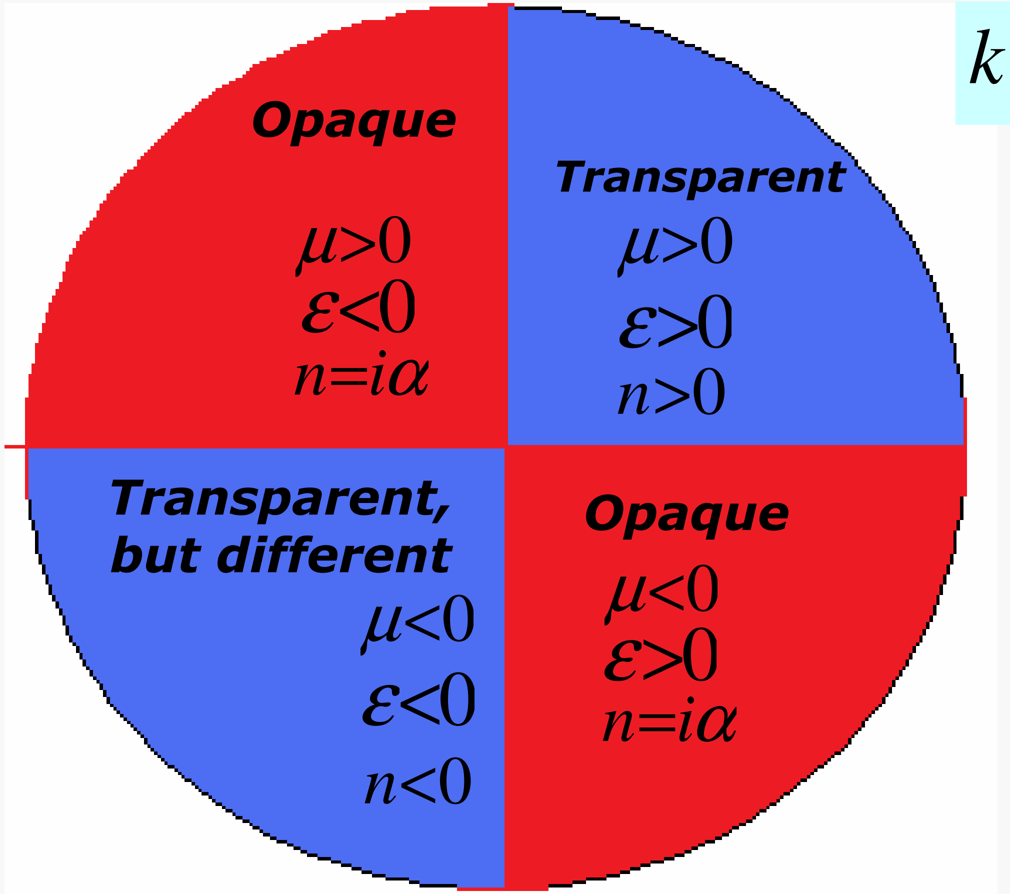
$$|n(\omega)| = \sqrt{|\varepsilon(\omega)\mu(\omega)|}$$

$$\phi_n = \frac{1}{2}\left(\phi_\varepsilon + \phi_\mu + 2\pi m\right) \quad m = 0,1$$

Only *m=0* is physical $\Rightarrow$ $n_i(\omega) > 0$

$\varepsilon < 0$ **and** $\mu < 0$ **means** $n_r(\omega) < 0$

What is negative refraction ?



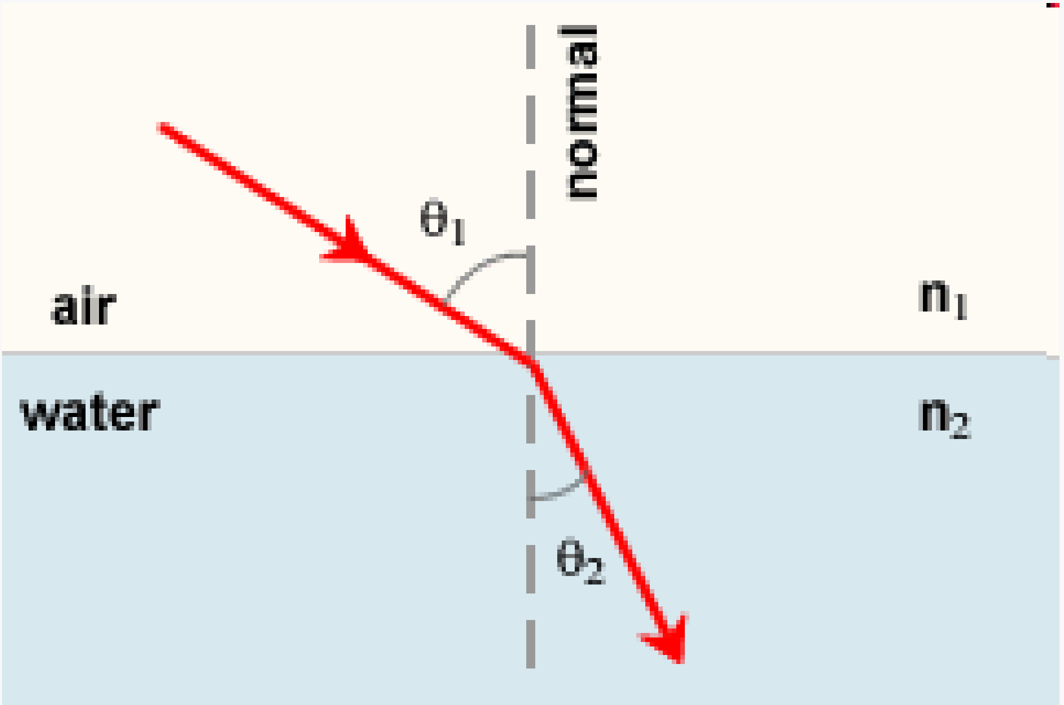
$k=(\omega/c_o)\times n$

$\varepsilon<0$ **and** $\mu<0$ **means** $n_r(\omega)<0$

What is negative refraction ?

Normal refraction

Snell-Descartes Law (1621)

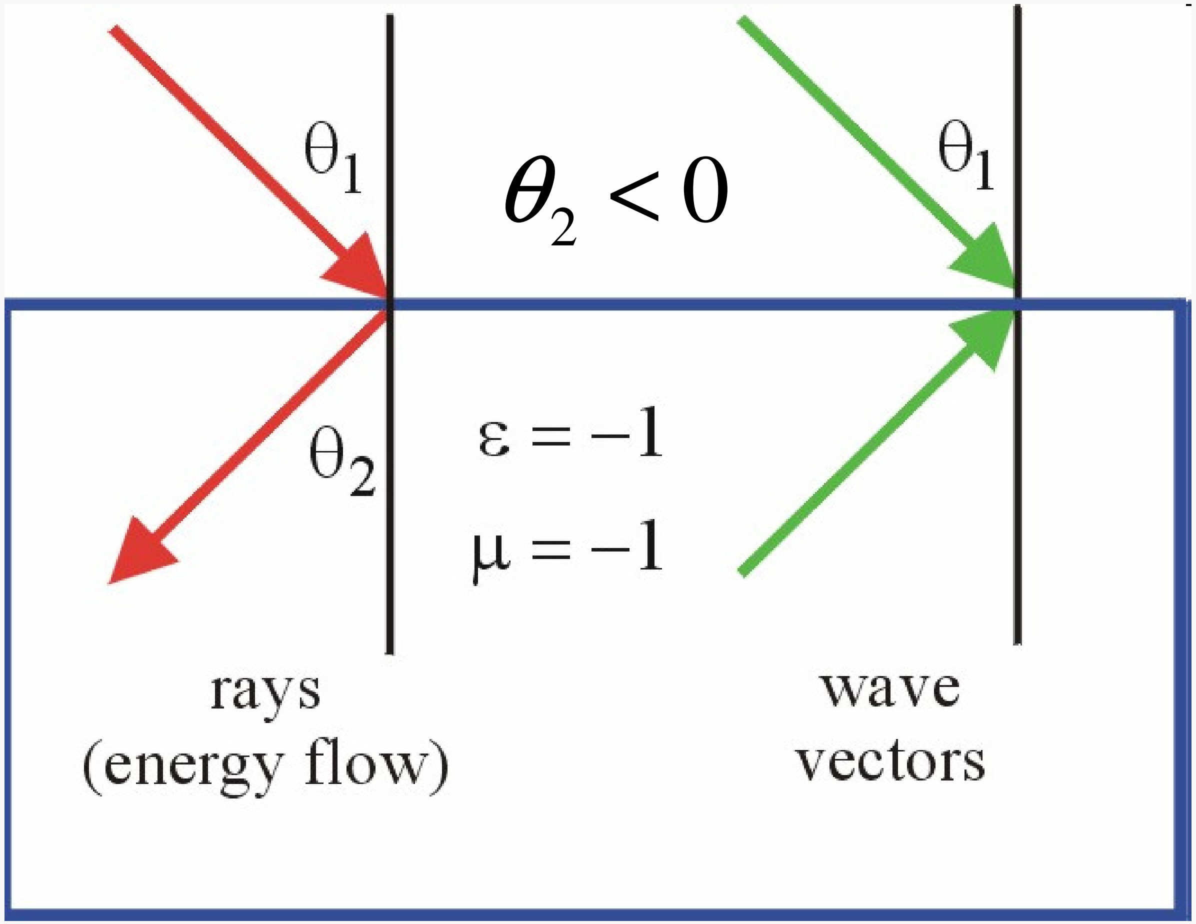


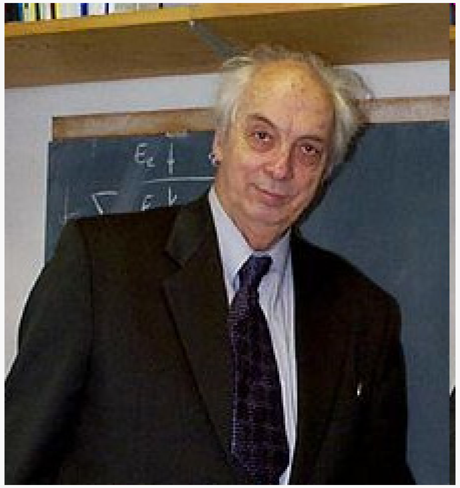
Willebrord Snell van Roijen
(or Snellius) (1580- 1626)

$$n_1 sen\ \theta_1 = n_2 sen\ \theta_2$$

$$n = \sqrt{\varepsilon\mu}$$

What is negative refraction ?





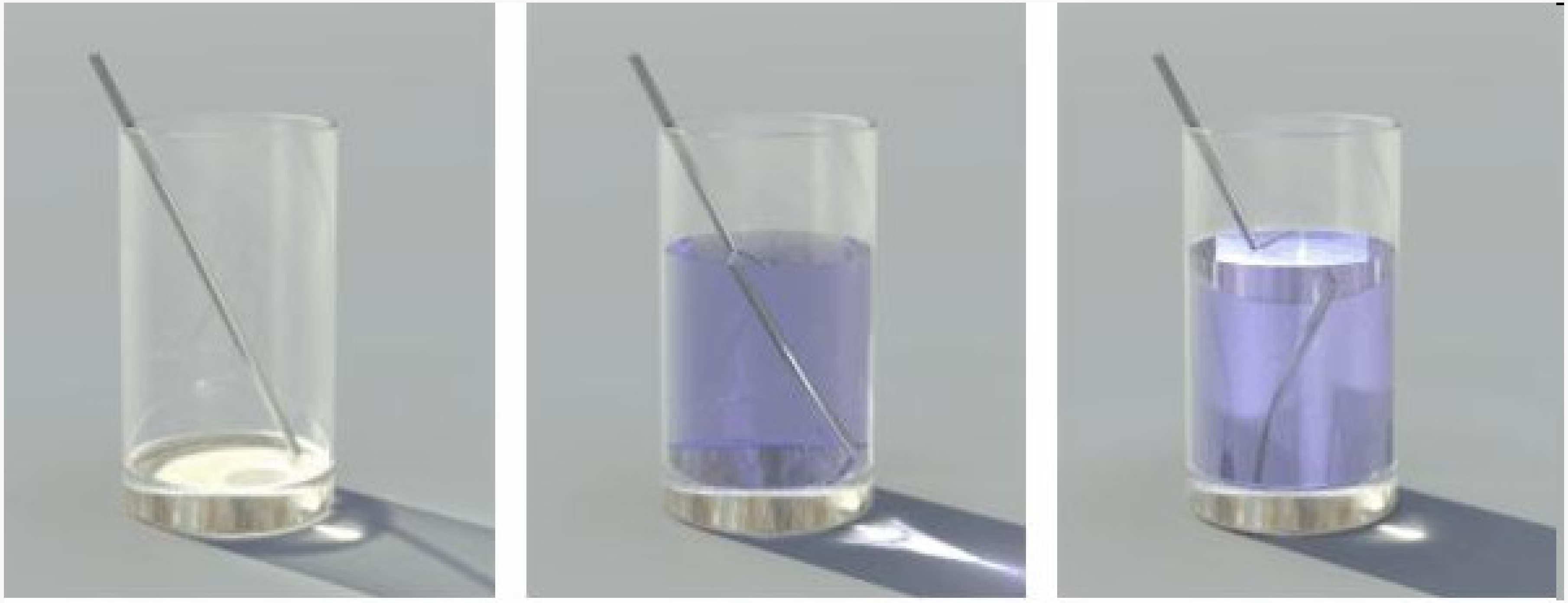
V. Veselago

$$n = -\sqrt{\varepsilon\mu}$$

What is negative refraction ?

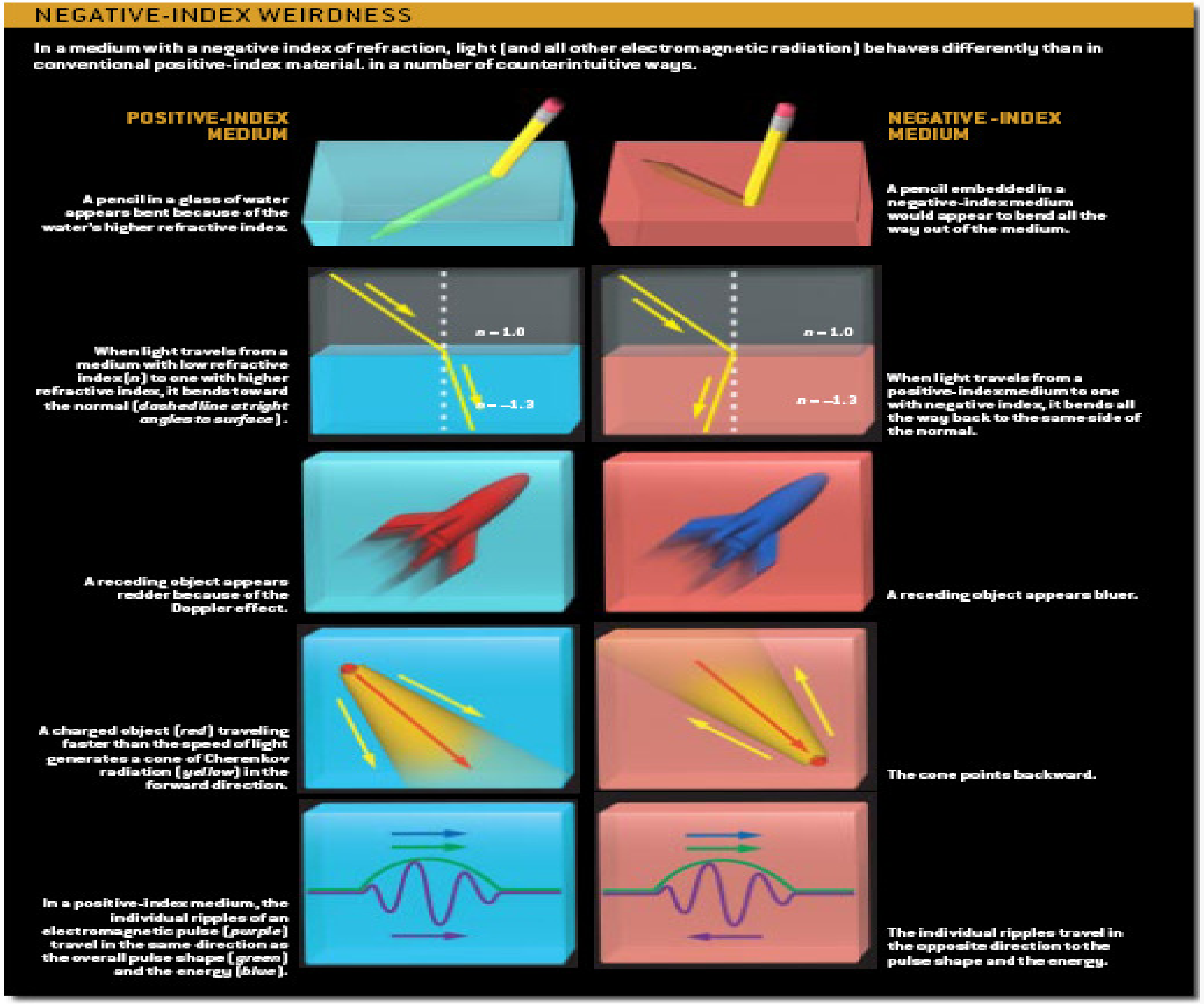
Normal refraction

Negative refraction



(a) (b) (c)

What are the main consequences of NR?

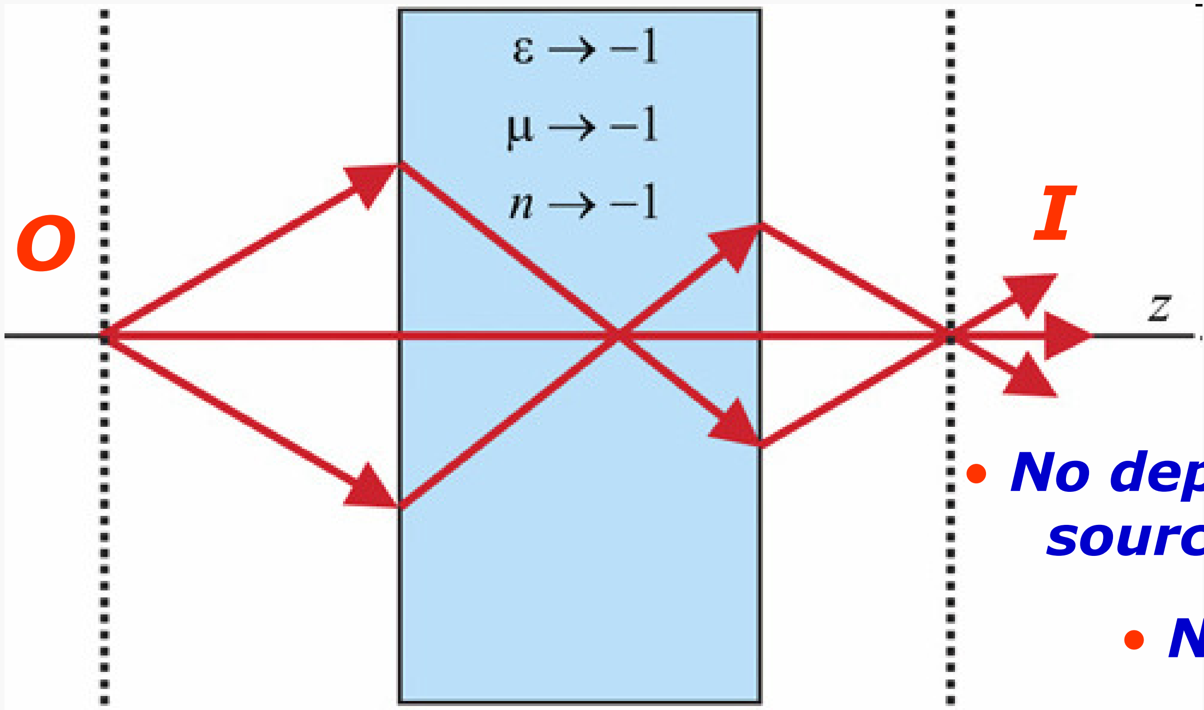


J. Pendry,
D. Smith,
Sci. Am. 7/2006

What are the applications of NR ?

Perfect lens: Snell's law

J. Pendry, PRL **85**, 3966 (2000)



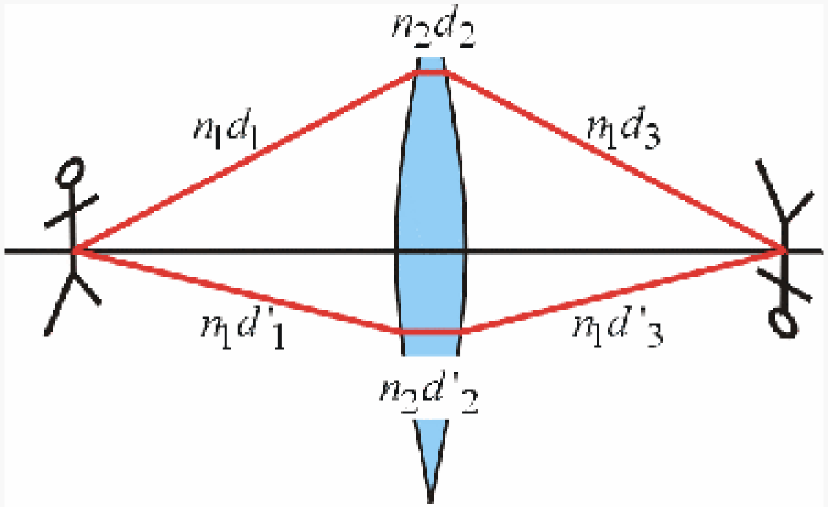
- Focusing
- No dephasing between point source and image (n=-1)
- No reflection (n=-1)

$$k_{2z} = -k_{1z}$$

Applications: Perfect lens

The Fermat's principle

"Light takes the shortest optical path between two points."



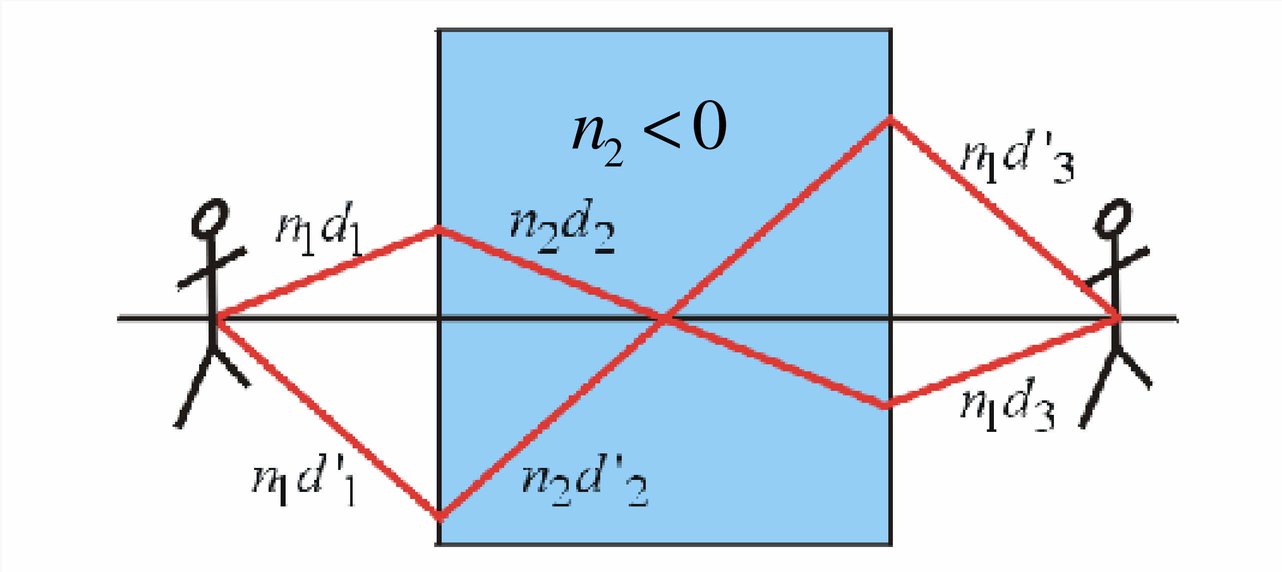
For a lens, the shortest optical path between object and image is:

$$n_1d_1 + n_2d_2 + n_1d_3 = n_1d'_1 + n_2d'_2 + n_1d'_3$$

Both paths converge at the same point because both correspond to a minimum.

Applications: Perfect lens

The Fermat's principle for negative refraction



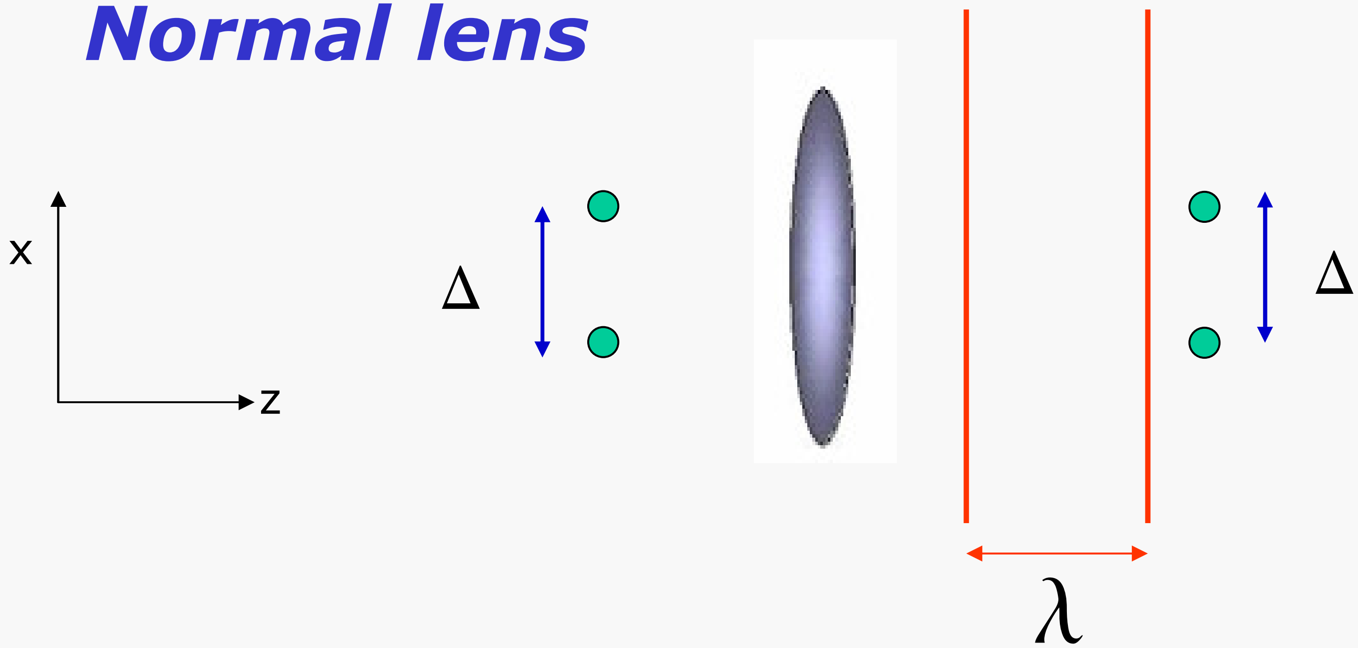
- For a perfect lens *(n2= −n1)* the shortest optical path between object and image is *zero.*

$$0 = n_1 d_1 + n_2 d_2 + n_1 d_3 = n_1 d'_1 + n_2 d'_2 + n_1 d'_3$$

For a perfect lens the image *is* the object !

Applications: Perfect lens

Normal lens



To resolve two points at distance Δ $\Rightarrow$ $k_x > 2\pi/\Delta$

$$k_x^2 + k_z^2 = \frac{\omega^2}{c^2} \qquad k_x < k_x^{\max} = \frac{\omega}{c} = \frac{2\pi}{\lambda} \qquad k_x > k_x^{\max} \Rightarrow \text{Decay exponentially}$$

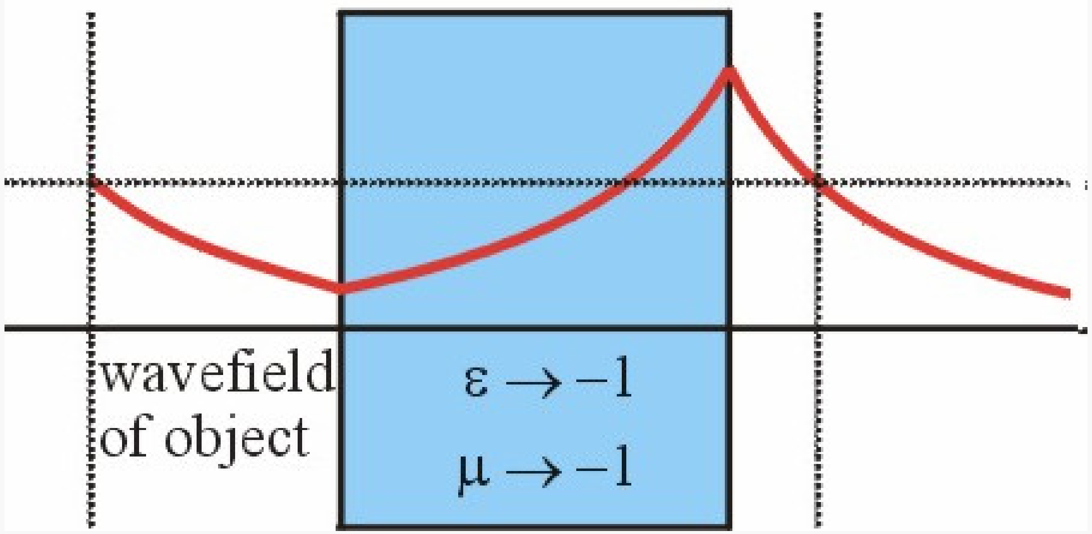
Resolution: $$\Delta = \frac{2\pi}{k_x^{\max}} = \lambda$$

Difraction limit !

Applications: Perfect lens

n<0 $\Rightarrow$ ***Amplification of evanescent waves !***

k_z can be imaginary and $k_x > k_x^{\max} = \omega / c$ possible



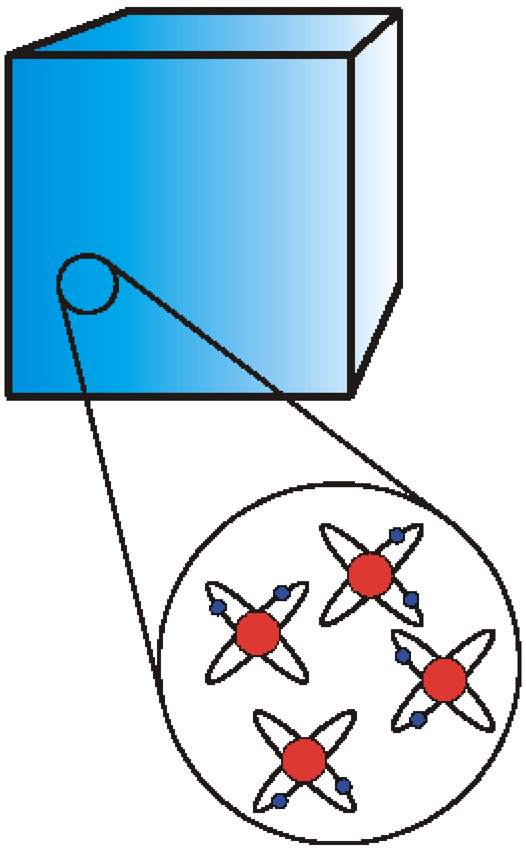
No resolution limit !

Sub-wavelength imaging possible

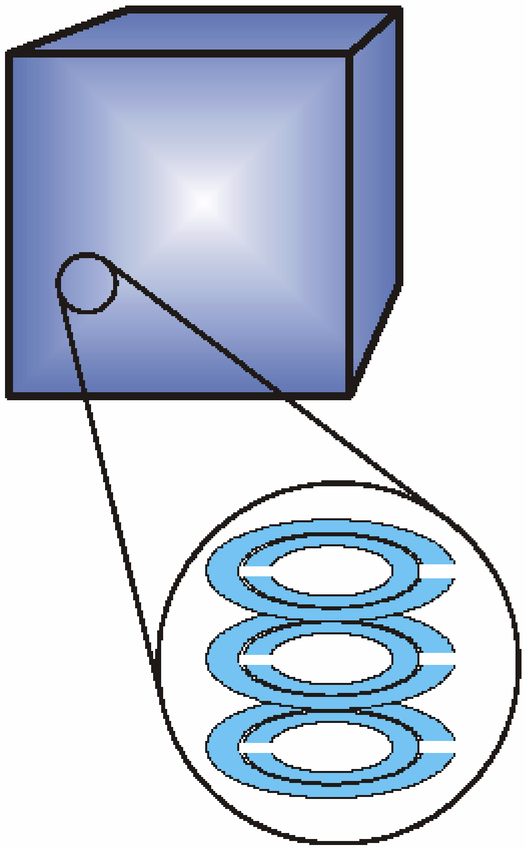
How to achieve NR ?

What is a Metamaterial?

Conventional materials:
properties derive from their constituent *atoms.*



Metamaterials:
properties derive from their constituent *units*. These units can be engineered.

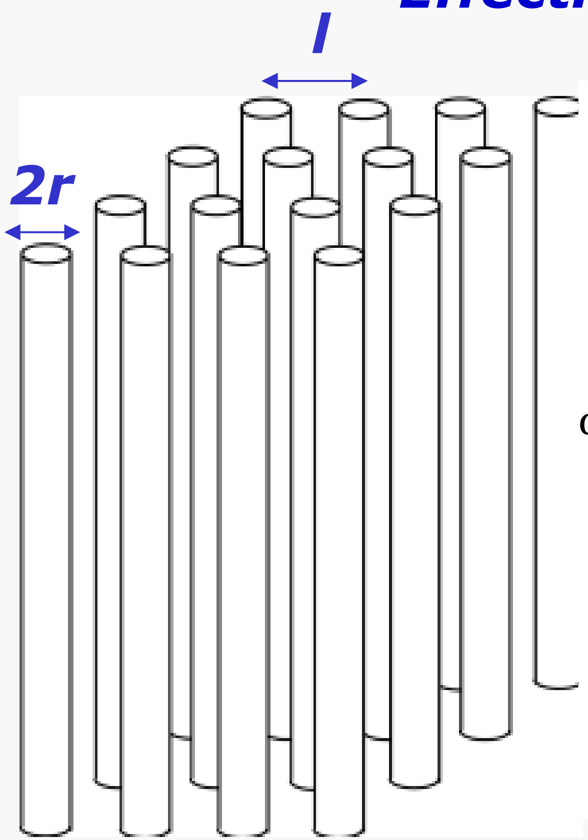


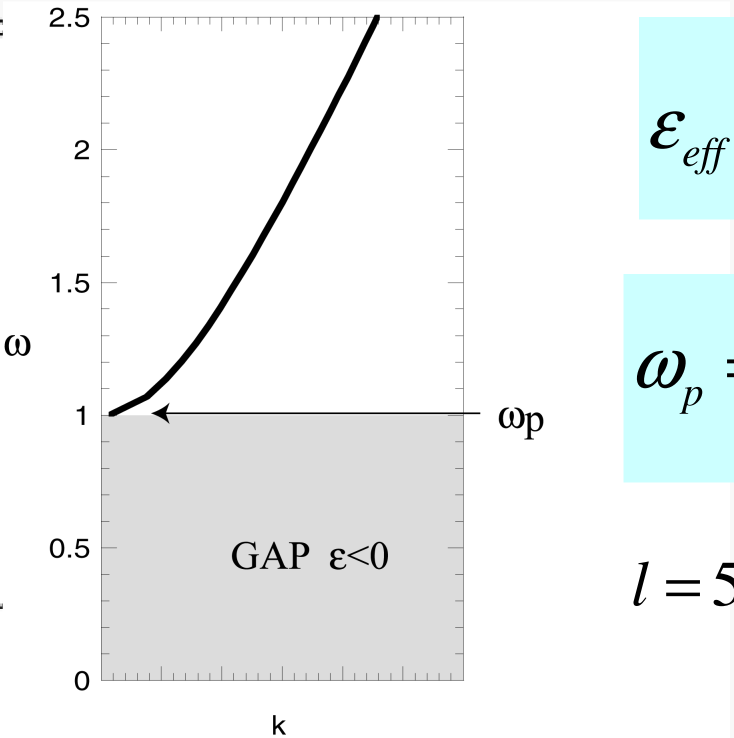
How to achieve NR ?

Metamaterials

Electric response: negative ϵ Arrays of thin metallic wires

Effective parameters $\Rightarrow$ $\lambda >> l, r$





$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\omega_p = \frac{2\pi c}{l\sqrt{2\pi \ln(l/r)}}$$

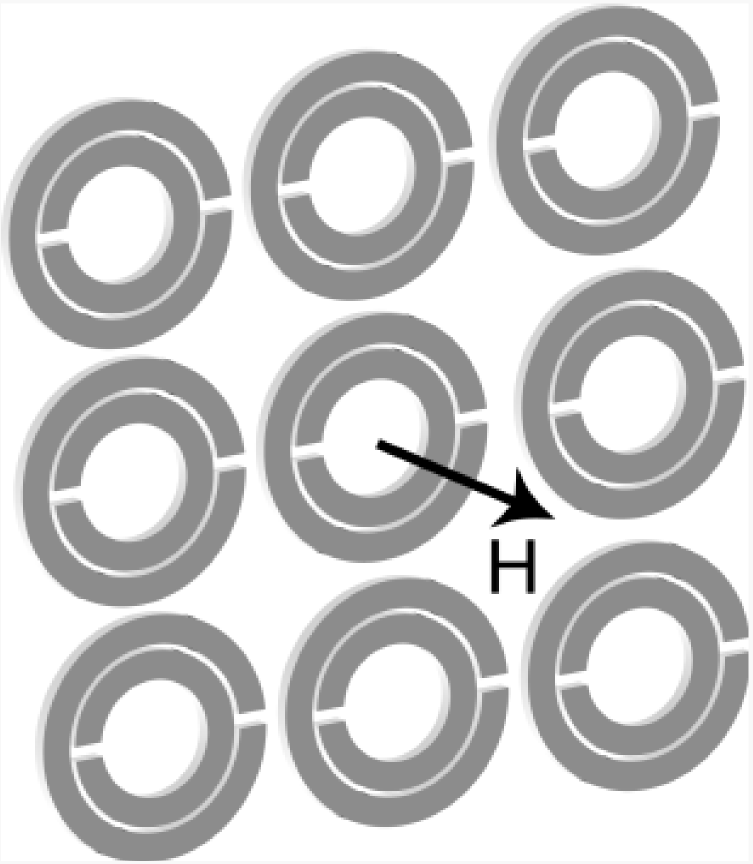
$l = 5mm \quad r = 0.003l$

$\omega_p \approx 66.6GHz$

How to achieve NR ?

Metamaterials

Magnetic response: negative μ Split Ring Resonators



$$\mu_{eff}(\omega) = 1 + \frac{F\omega^2}{\omega_{LC}^2 - \omega^2}$$

$$\omega_{LC} \approx GHz$$

inner radius = 2.0mm

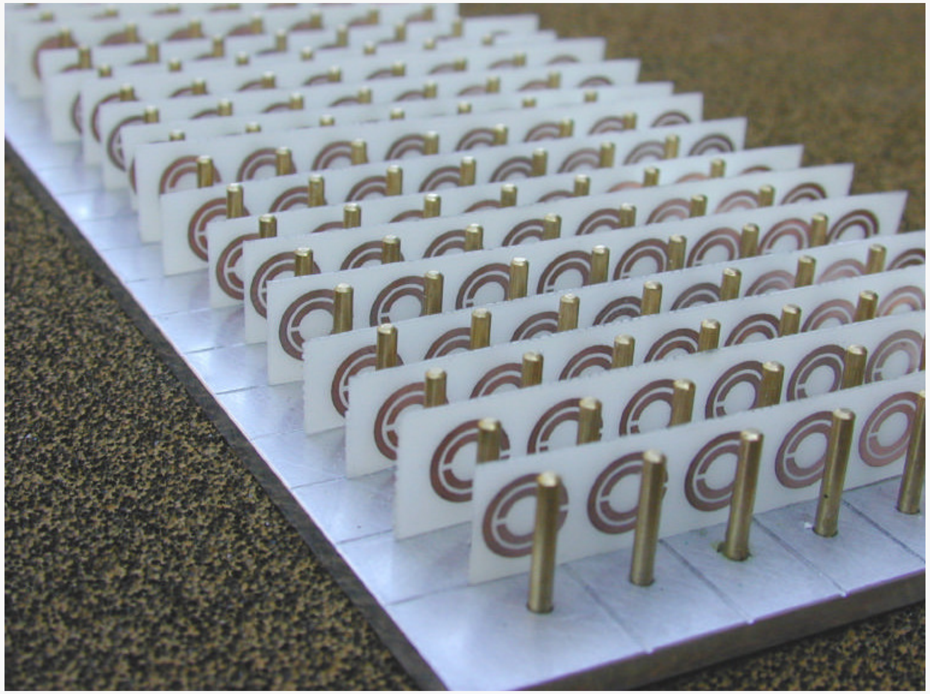
width of each ring = 1.0mm

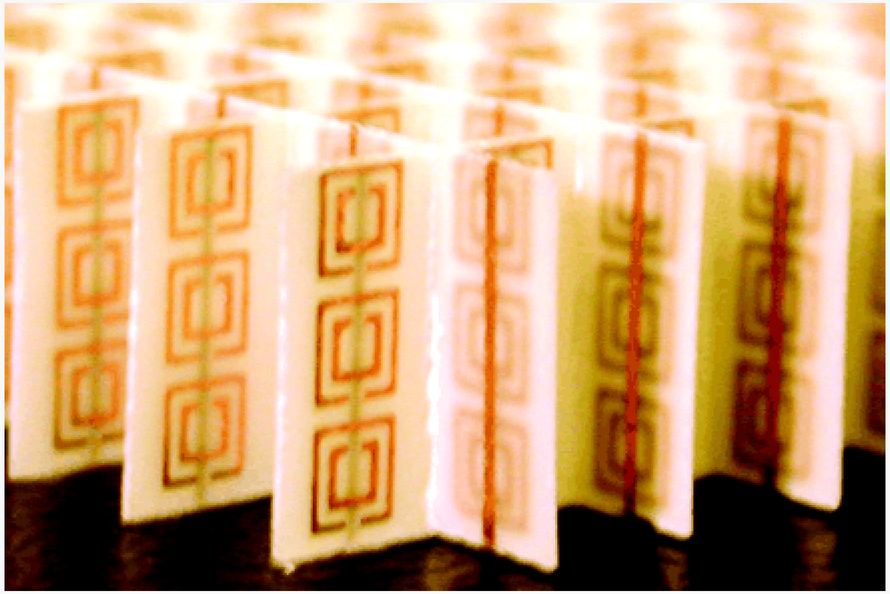
spacing between ring edges = 0.1mm

lattice constant = 10.0mm

How to achieve NR ?

Metamaterials



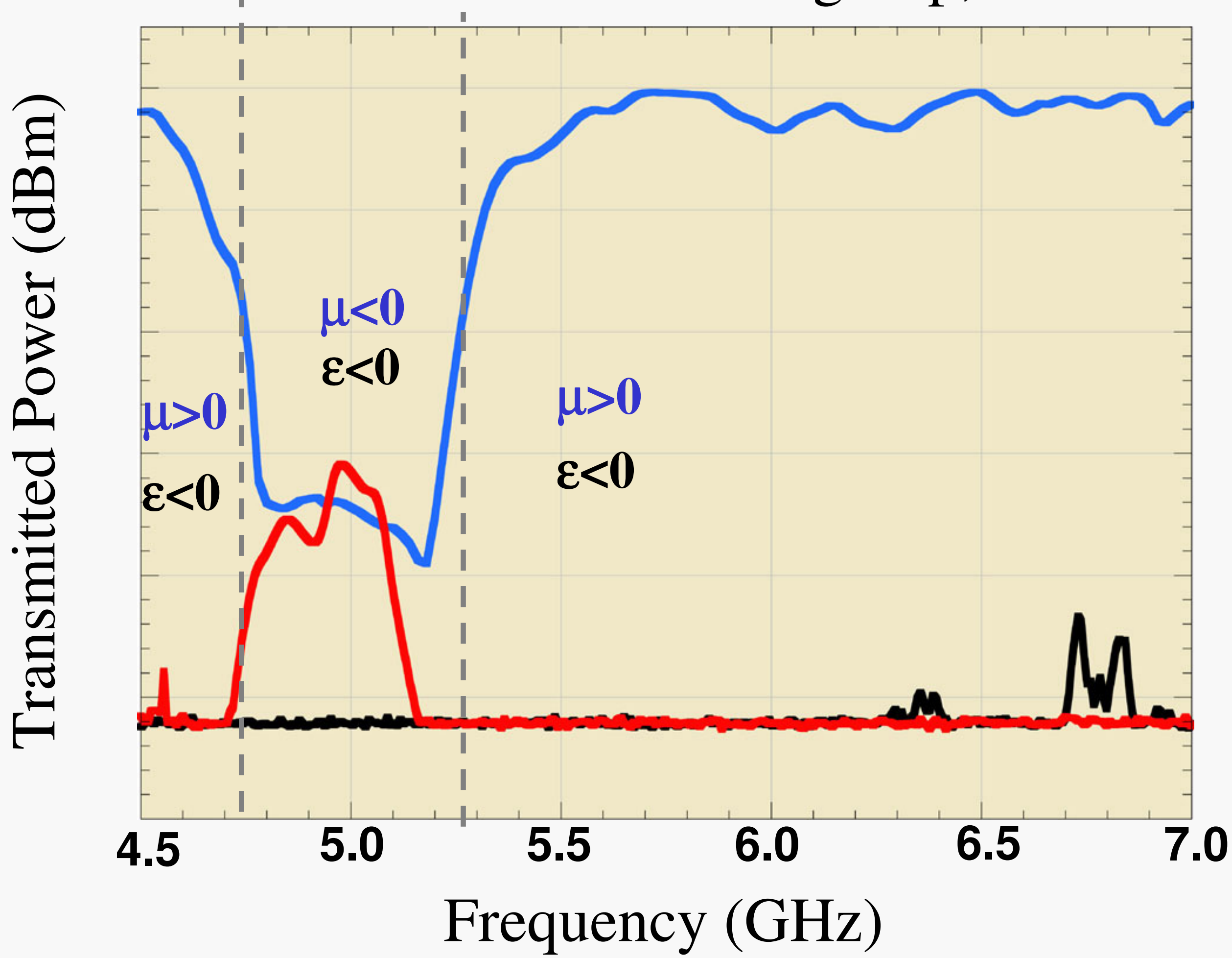


David Smith and Shelly Schultz, UCSD

How to achieve NR ?

Transmission measurements

D. Smith and S. Schultz group, UCSD



Further experimental evidence of NR

After many criticisms, intense debate…

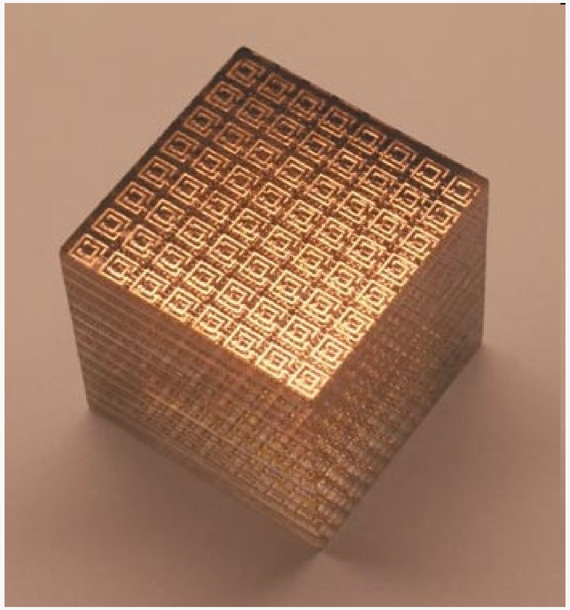
P.M. Valanju, et al., PRL. **88**,187401 (2002).

N. Garcia and M. Nieto-Verperinas, PRL **88**, 207403 (2002).

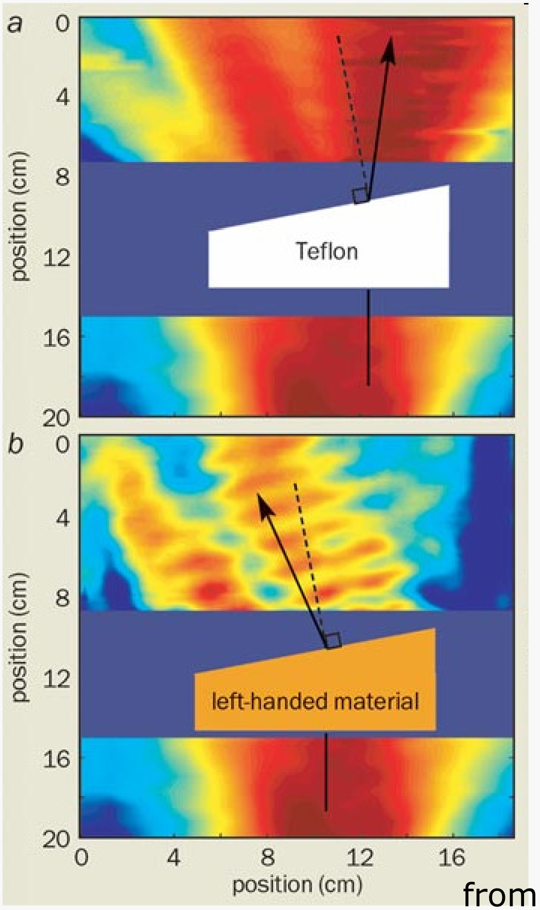
Observation of Snell's law for LHM

1) A. Houck et al.,PRL **90** 137401 (2003)

Microwave regime



2) C.G. Parazzoli et al., PRL 90, 107401 (2003)



from Ref.1

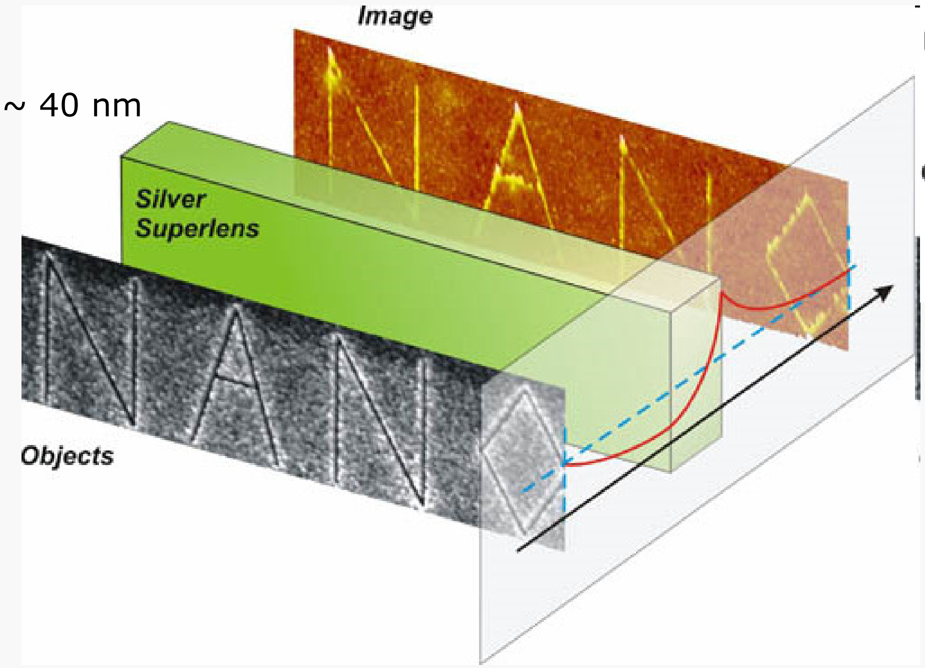
Applications of NR

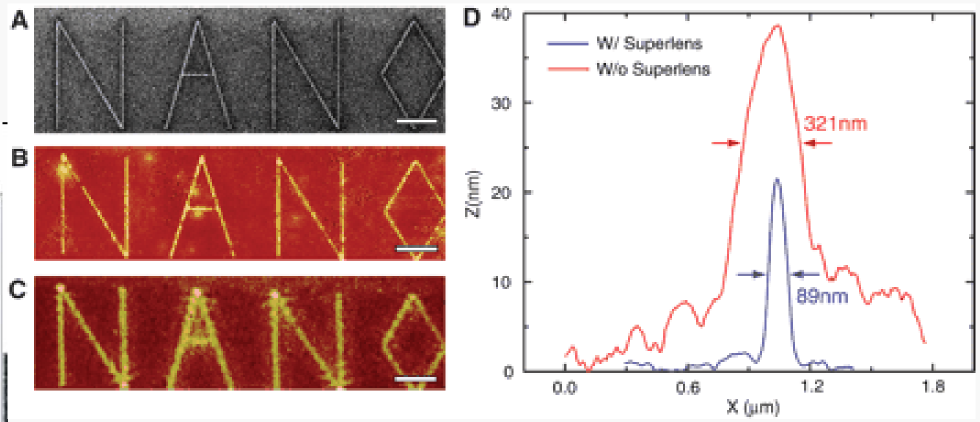
"Perfect" lens

Fang, N., Lee, H., Sun, C., Zhang, X., "Sub-diffraction-limited optical imaging with a silver superlens", Science **308,** 534 (2005)

Recovery evanescent waves in an image via the excitation of surface plasmons in a silver slab

~ 40 nm





60-nm resolution: 1/6 of illuminating λ !

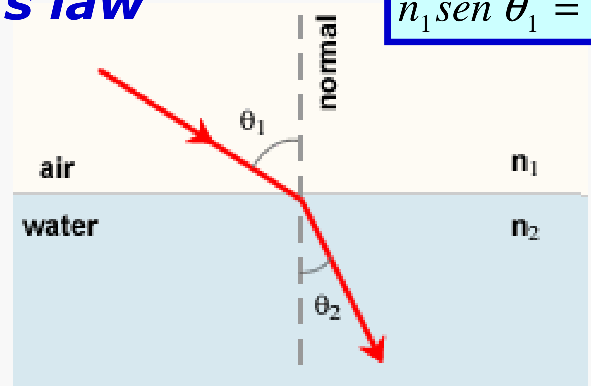
Applications of metamaterials: Electromagnetic cloaking

How to bend light ?

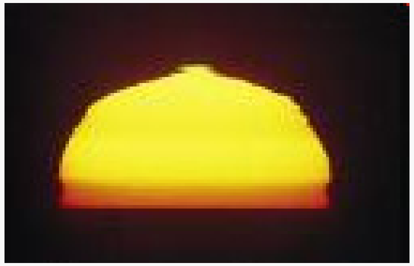
A simple example: refraction at a surface

Snell's law

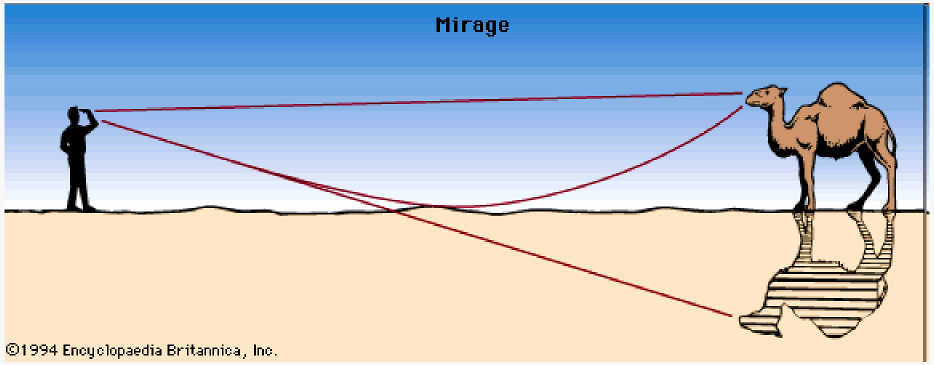
$$n_1 sen\,\theta_1 = n_2 sen\,\theta_2$$



Atmospheric seeing



Mirage ⇒ the *refractive index* varies continuously near the surface



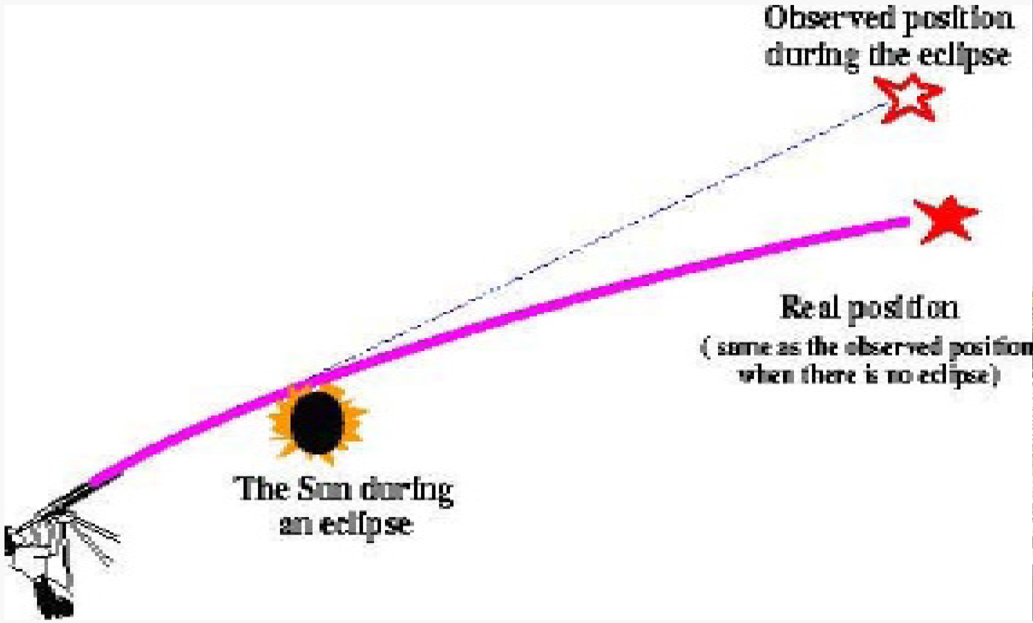
How to bend light ?

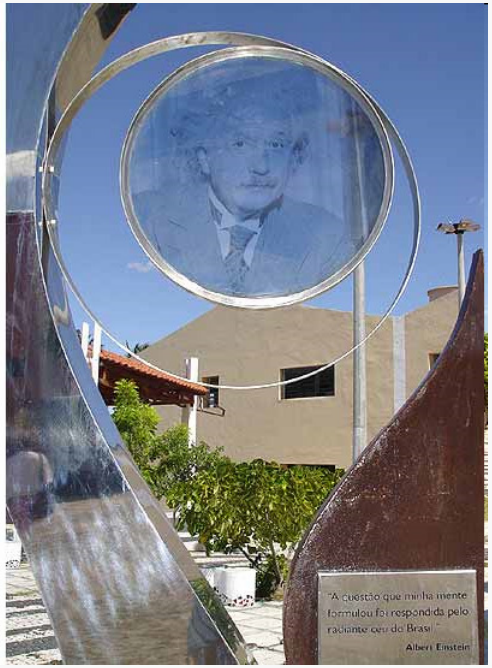
Einstein's general theory of relativity

Gravity changes geometry

Thus gravity should bend light

Sobral eclipse (1919)

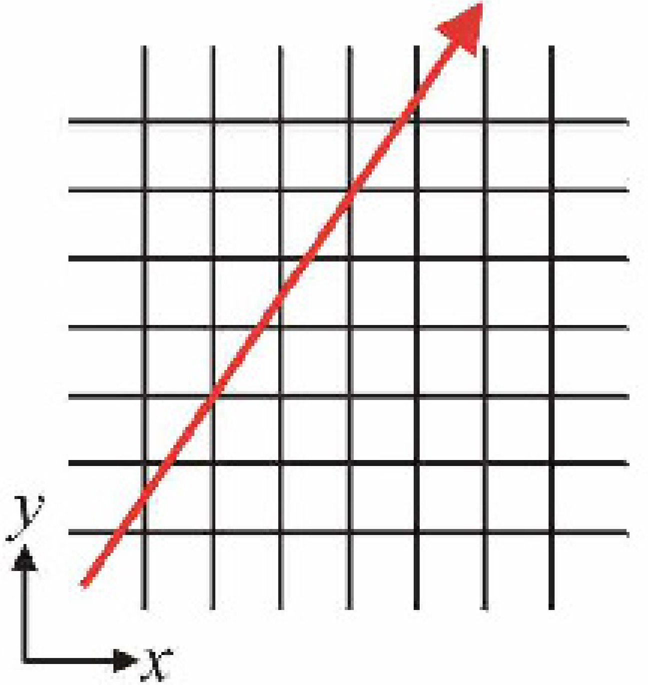




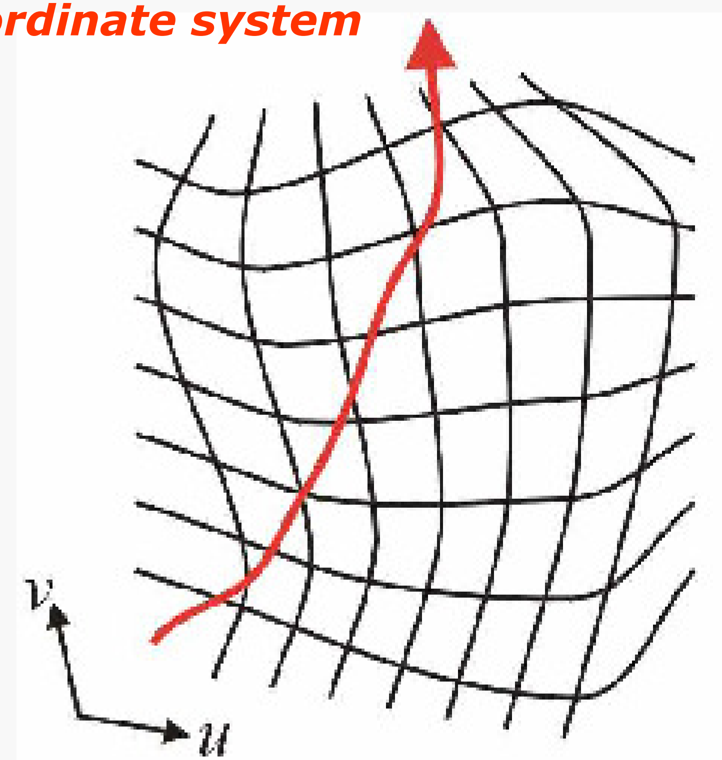
How to bend light ?

General relativity ⟺ Transformation optics

Maxwell's equations are invariant upon changing the coordinate system



No gravitational fields

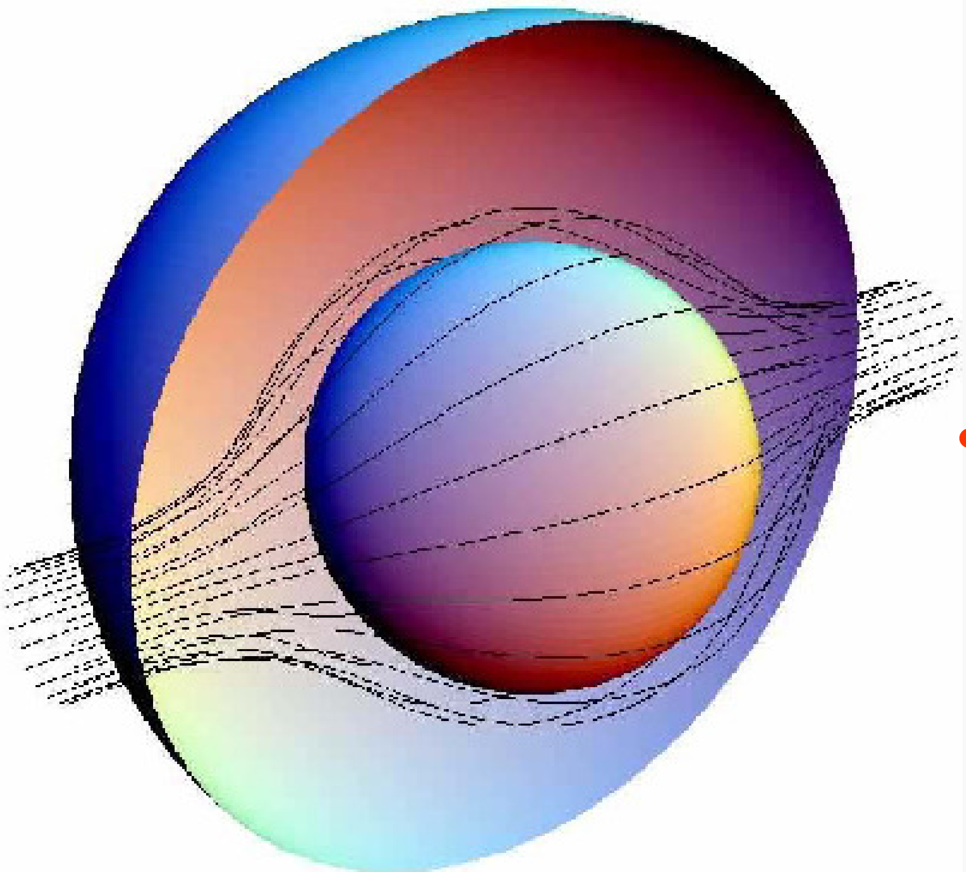


Massive objects distorts space and thus light rays ⇒ *Metric g*

Einstein's metric has exactly the same effect on light as a refractive index

How to bend light ?

Maxwell's equations are invariant upon changing the coordinate system but with scaled ϵ and μ

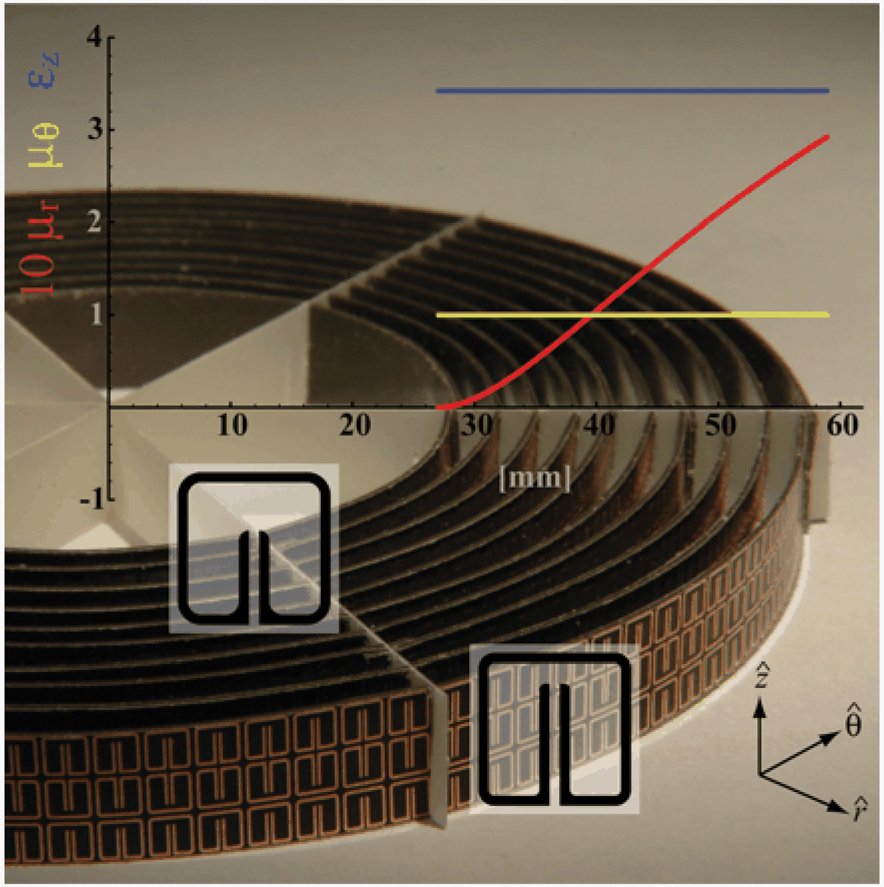


Electromagnetic cloak

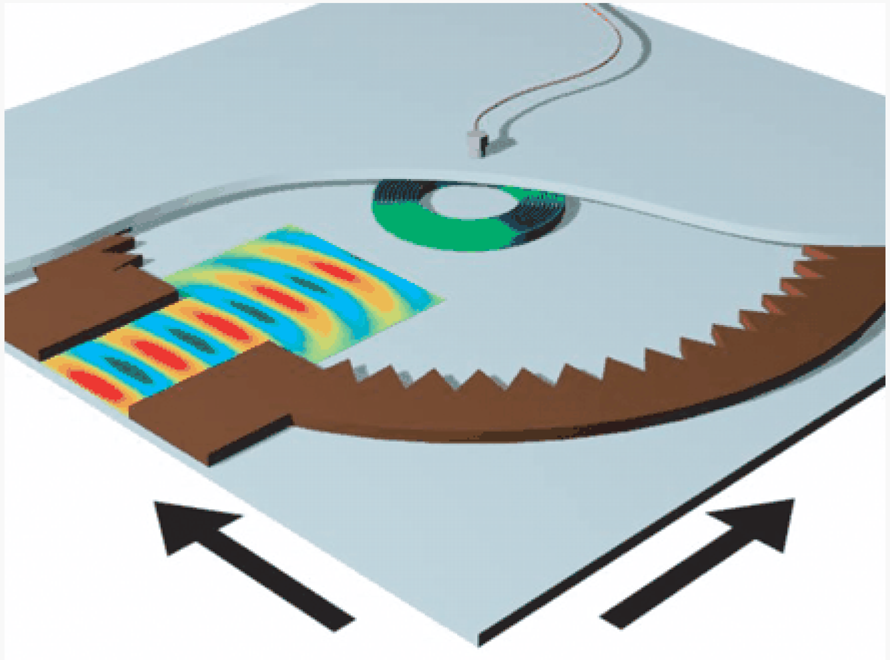
- Hide the object by bending light around the object (*mirage effect*).
- Grading the index of refraction in the cloak using *metamaterials*.

J.B. Pendry, D. Schurig, D.R. Smith, Science **312**, 1780 (2006)

Electromagnetic cloak



Metamaterial cloak
for microwaves



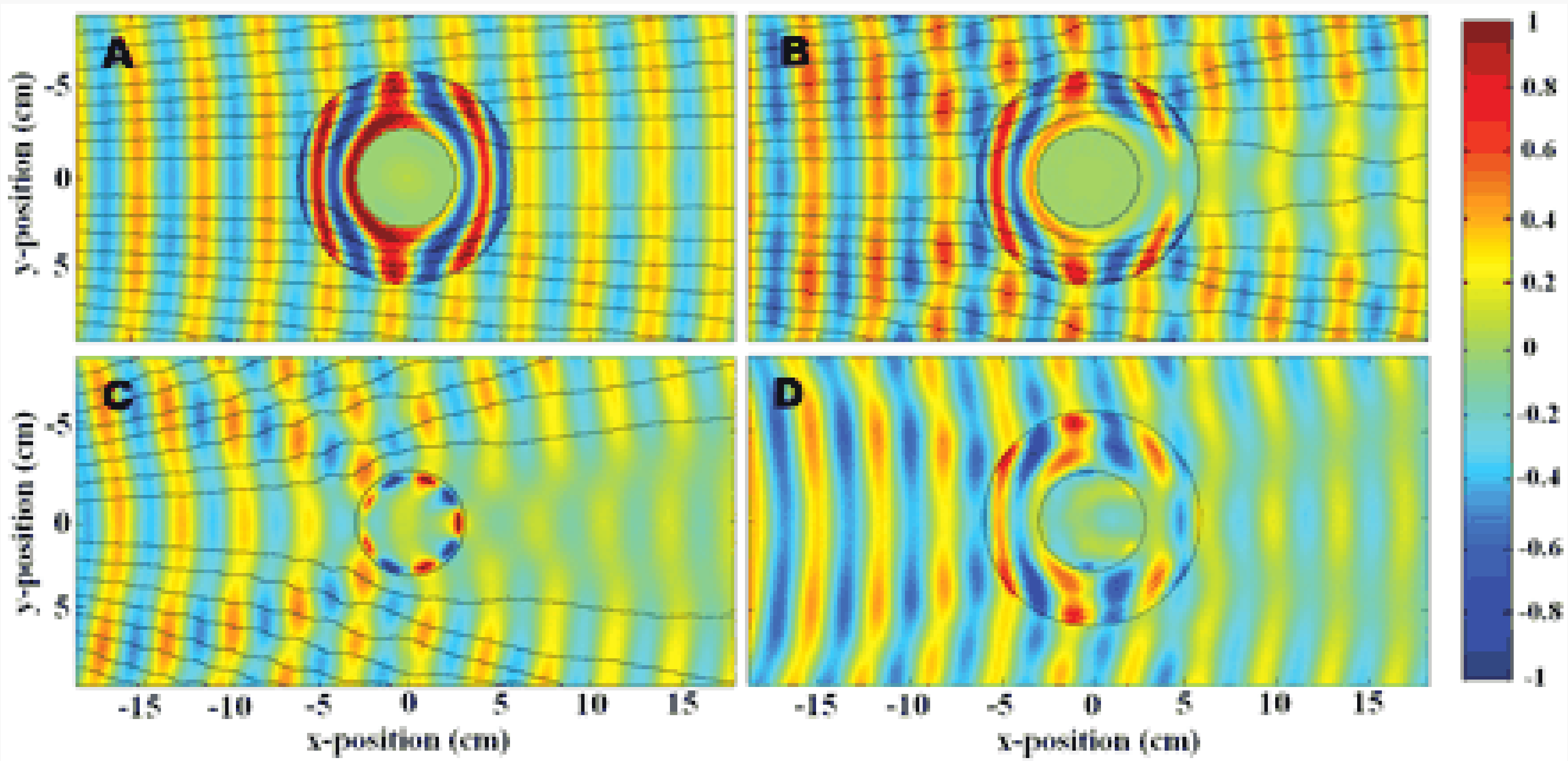
D. Schurig *et al*. Science **314**, 977 (2006)

Electromagnetic cloak

D. Schurig *et al*. Science **314**, 977 (2006)

Sim.

Exp.



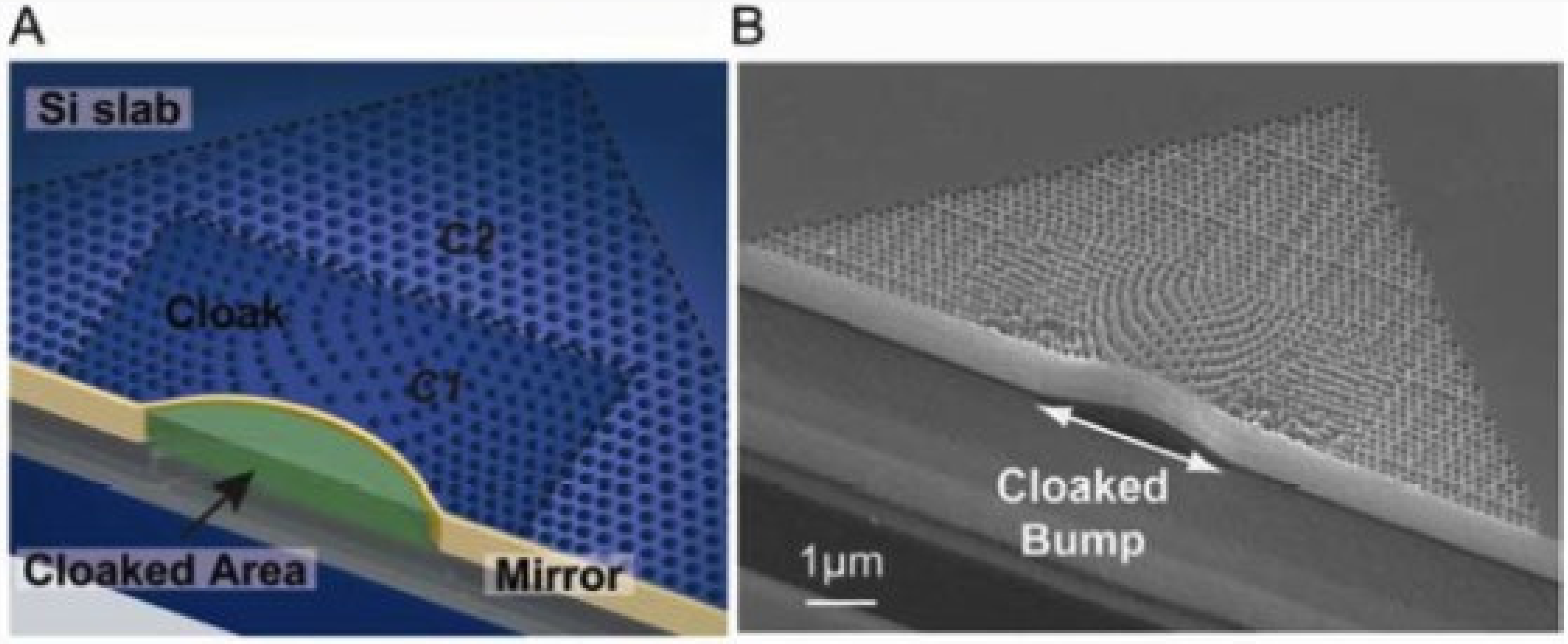
A cloaking experiment at 8.5GHz.

Electromagnetic cloak

Towards the visible...the carpet cloak!

Idea: J. Li and J. B. Pendry, PRL **101**, 203901 (2008).

Experiment: J. Valentine *et al*., Nature Materials (2009)
L. Gabrielli *et al*., cond-mat 0904.3508 (2009)



U.C. Berkeley (2009)

Felipe Pinheiro, Ciência Hoje junho (2009)

Electromagnetic cloak

Towards the visible
...the carpet cloak!

Near Infrared

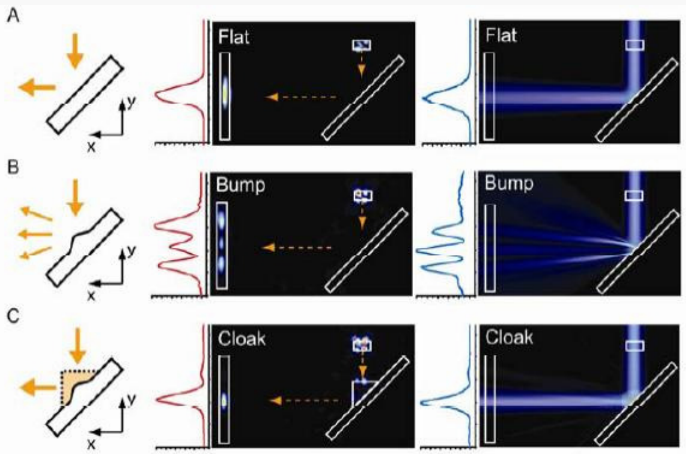
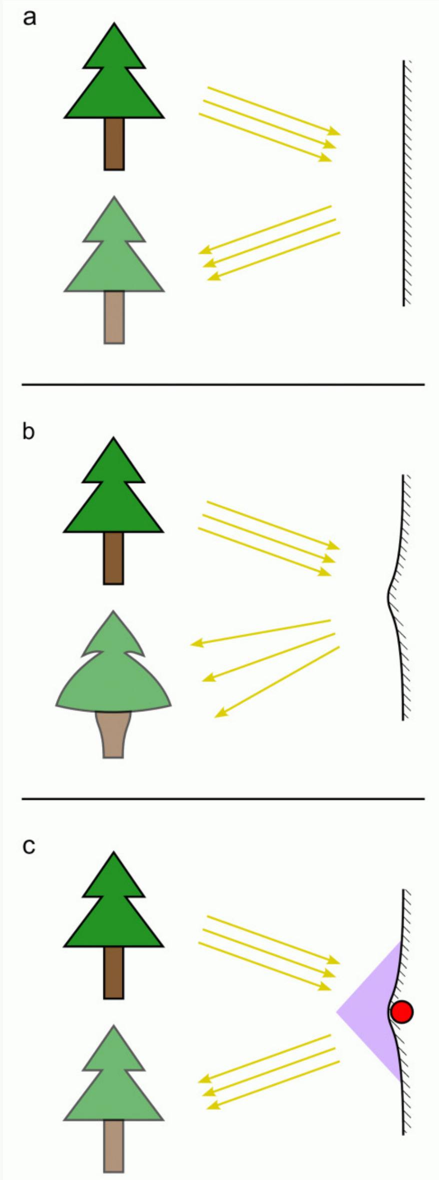


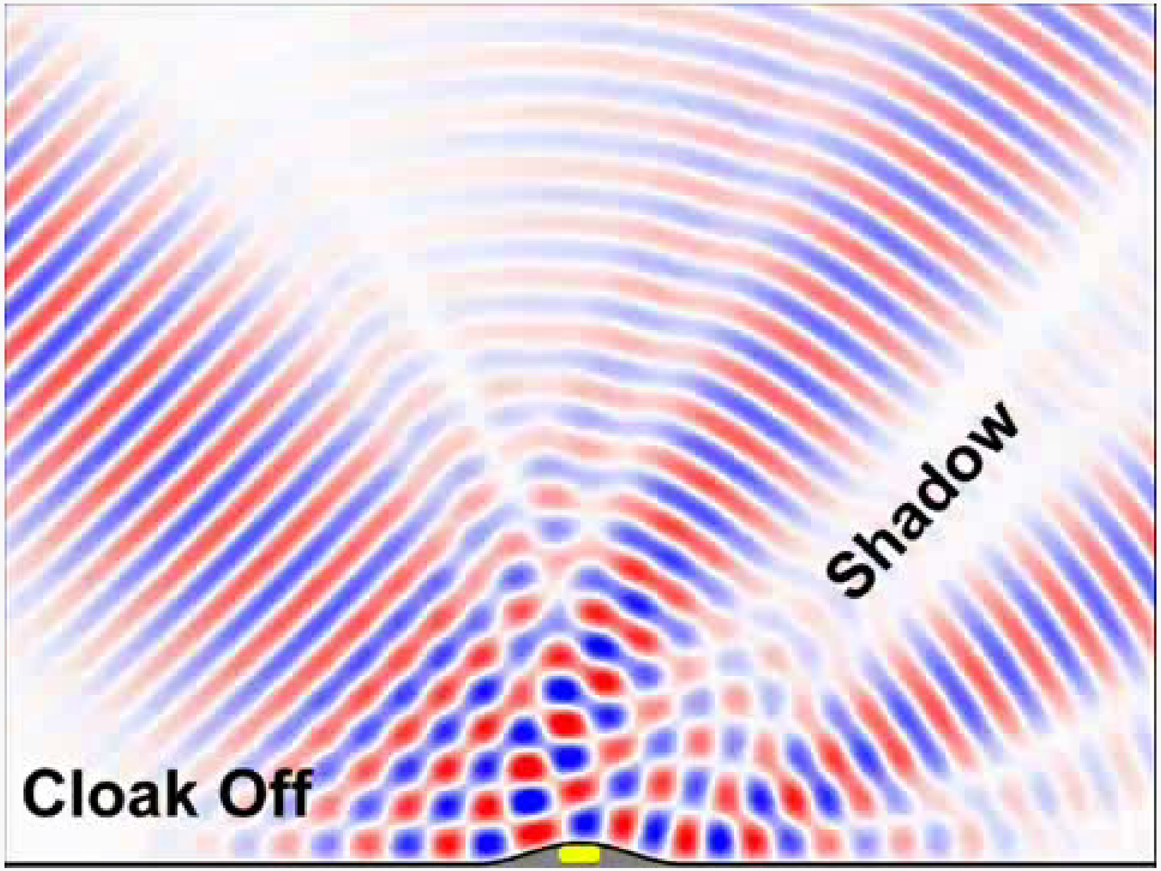
Fig. 3. Optical carpet cloaking at a wavelength of 1540 nm. The results for a Gaussian beam reflected from (**A**) a flat surface (**B**) a curved (without cloak) surface, and (**C**) the same curved reflecting surface with cloak. The left panel shows the schematics. The middle panel shows the optical microscope images and normalized intensity along the output grating position. The curved surface scatters the incident beam into three separate lobes while the cloaked curved surface maintains the original profile, similar to reflection from a flat surface. The experimental intensity profile agrees well with the intensity profile ($|E_z|^2$) from 2D simulations (right panel).

U.C. Berkeley (2009)



Electromagnetic cloak

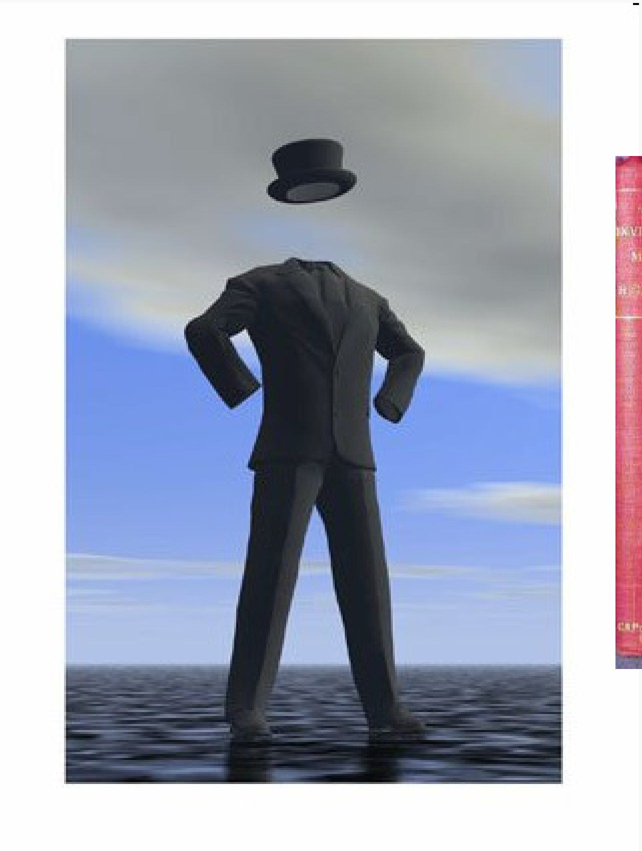
U.C. Berkeley (2009)

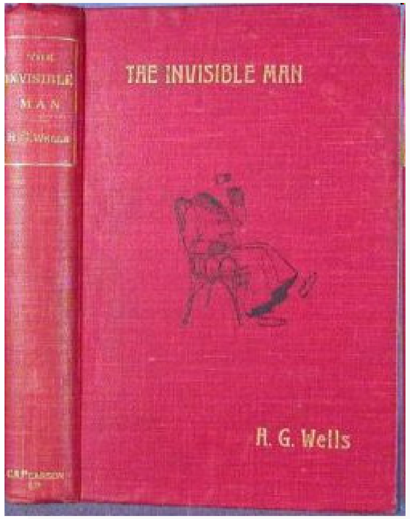


Electromagnetic cloak

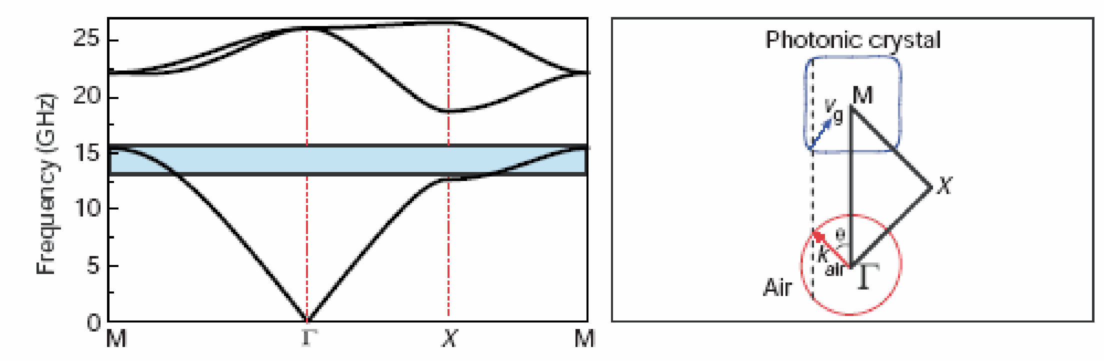
Perspectives for the future…

Herbert G. Wells (1897)



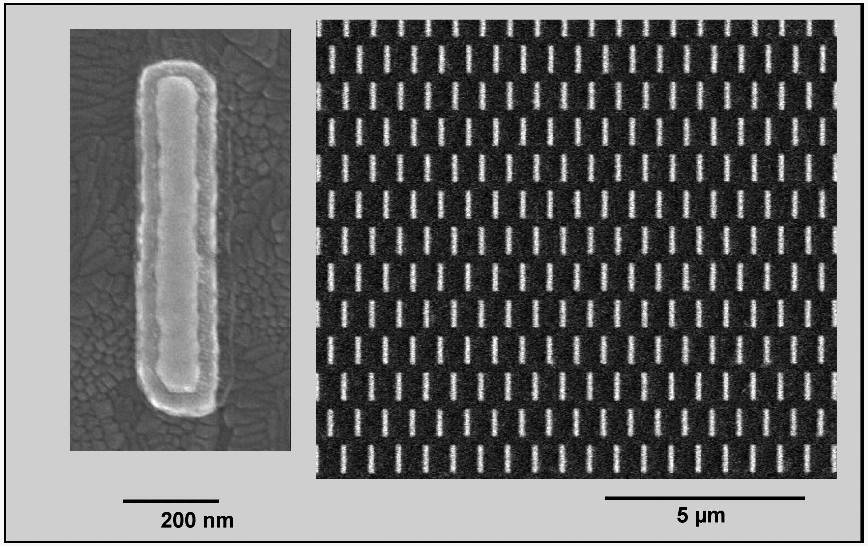


Alternative routes to NR ?



Soukoulis group (Iowa)

NR at the interface
air-photonic crystals
(square array of alumina
rods in the air)



Shalaev group (Purdue)

Parallel "nanorods" of gold
that conduct
plasmons in the near-infrared.

Alternative routes to NR ?

The chiral route to NR

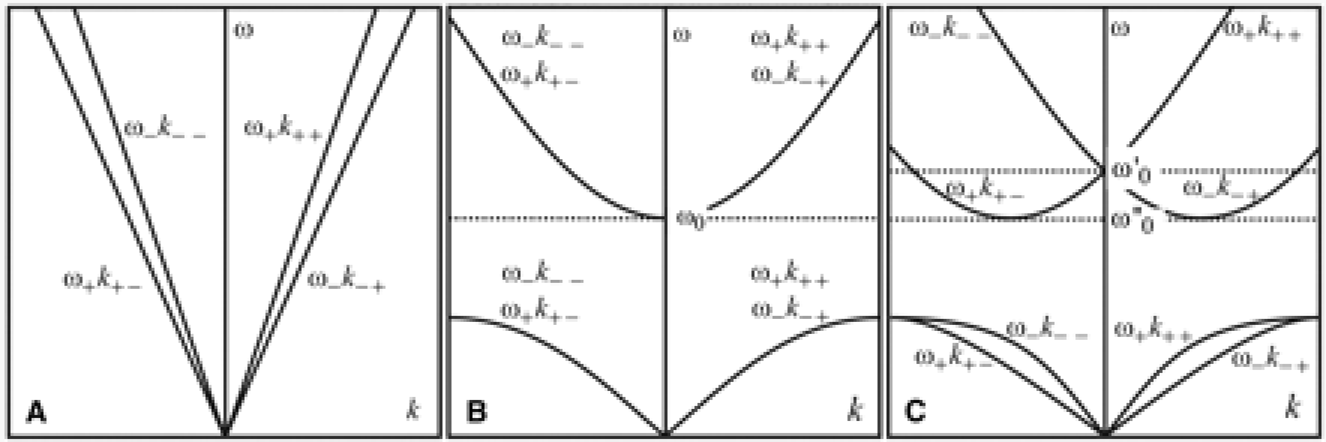
J. B. Pendry, Science **306**, 1353 (2004)

Isotropic chiral media $k_{\pm} = (n \pm \kappa)\dfrac{\omega}{c_0}$

If the chirality parameter $|\kappa| > n \Rightarrow v_p$ opposite to energy flow (NR)
for one polarization state

Ingredients $\Rightarrow$ ***Resonance + Chirality***

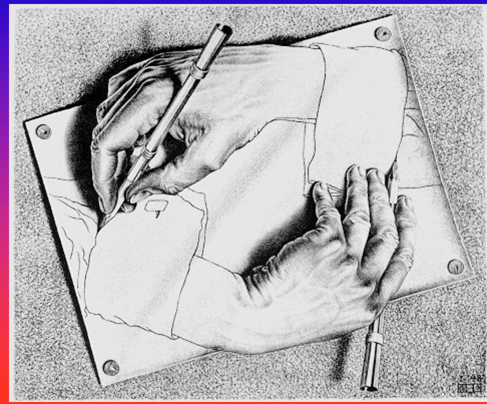
Homogeneous chiral medium | *Homogeneous achiral medium with resonant dipoles* | *Homogeneous chiral medium with resonant dipoles*



NRB

What is

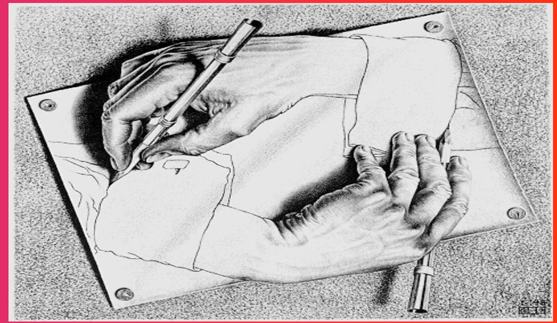
¿ Chirality Chirality ?



"I call any geometrical figure, or group of points, *chiral*, and say that it has *chirality*, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself ".

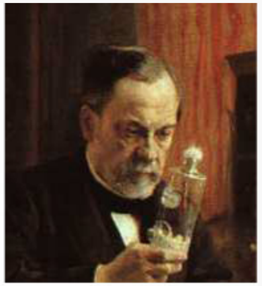
Lord Kelvin, Baltimore Lectures, 1884

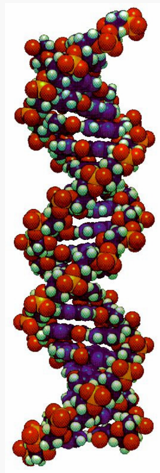
Some Manifestations of Chirality in Nature



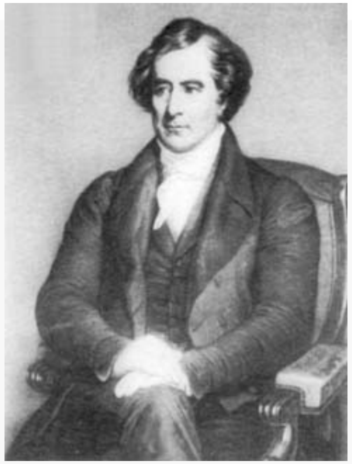
"I am inclined to think that life, as manifested to us, must be a function of the dissymmetry of the universe and of the consequences it produces.... Life is dominated by dissymmetrical actions. I can even foresee that all living species are primordially, in their structure, in their external forms, functions of cosmic dissymmetry."

-Louis Pasteur (c. 1850, Vallery-Radot)





The DNA (1953)

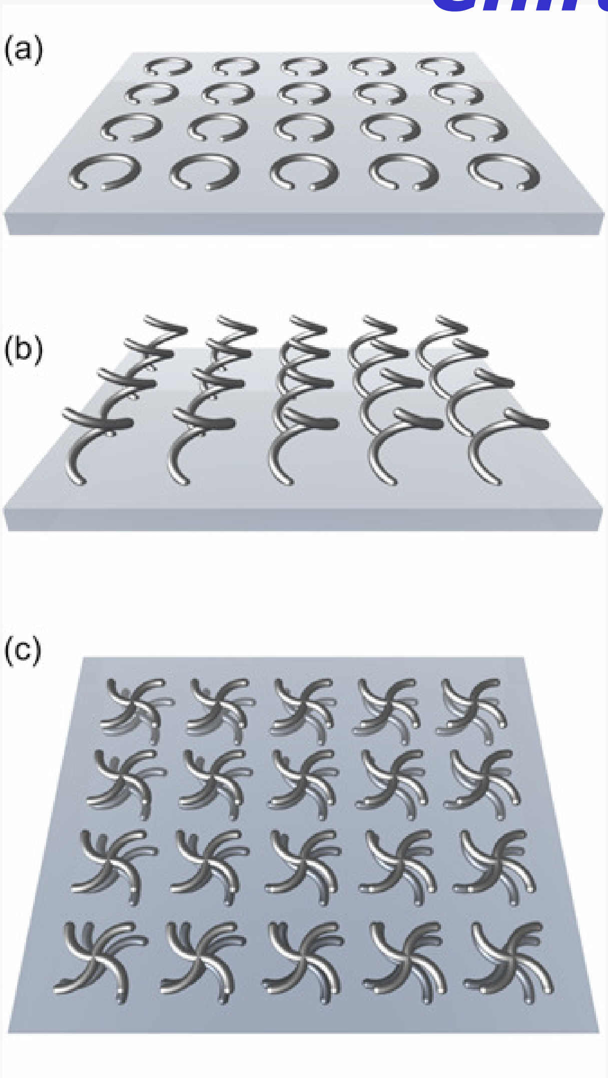


Discovery of the optical rotatory power of light by Arago (1811).

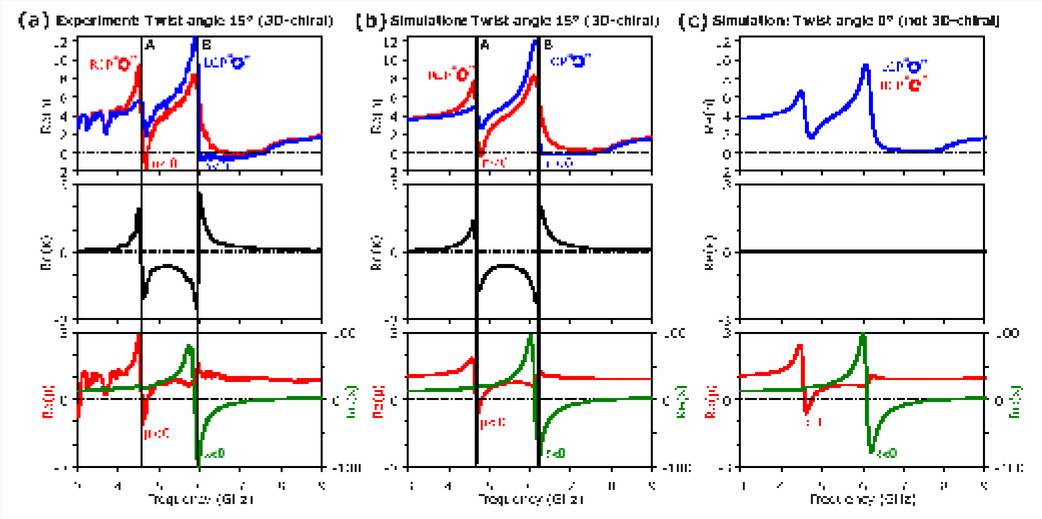
Parity violating "vector-axial vector" theory of the weak interaction by Feynman, Gell-Mann, Marshak and Sudarshan (1958).

The chiral route to NR

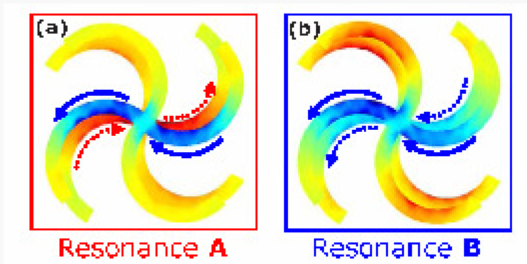
Chiral planar metamaterials

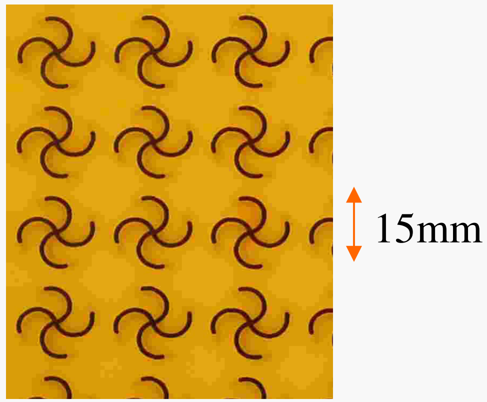


Huge optical activity and NR



Nature Photonics **3**, 133 (2009)
PRB **79**, 035407 (2009)
Viewpoint in Physics **2**, 3 (2009)





N. Zheludev group, Southampton, UK

Conclusions

- Metamaterials offer an enormous potential for new physics and applications.
- Super lens ⇒ Overcomes the diffraction limit
- Emerging field ⇒ ***Transformation optics***
- Cloaking at visible frequencies.
- New chapters should be added to textbooks on Electrodynamics.
- Nice example of a contemporary research topic that can be presented to high-school students.
- Old and well-established concepts of physics can be the subject of a lively debate.