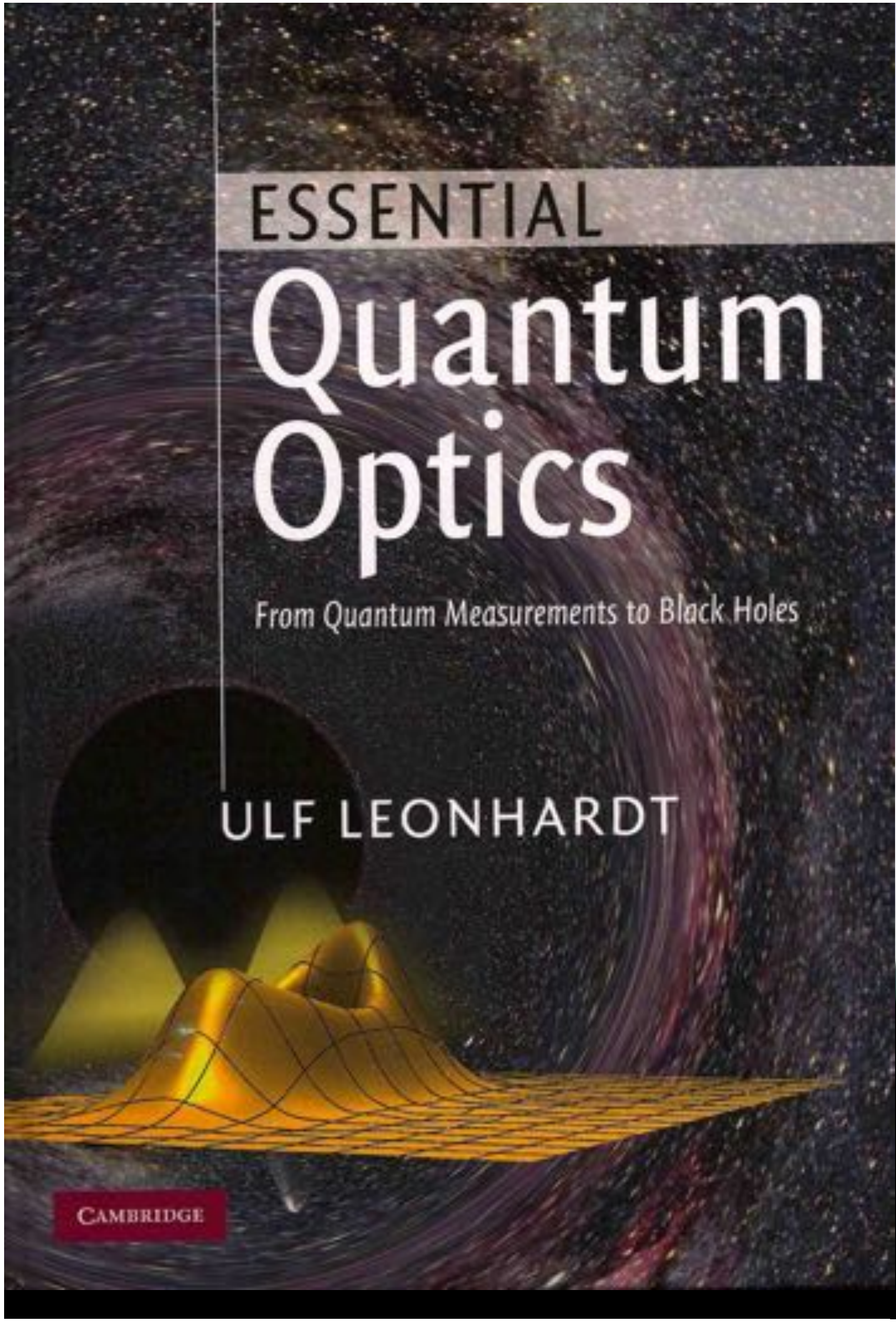
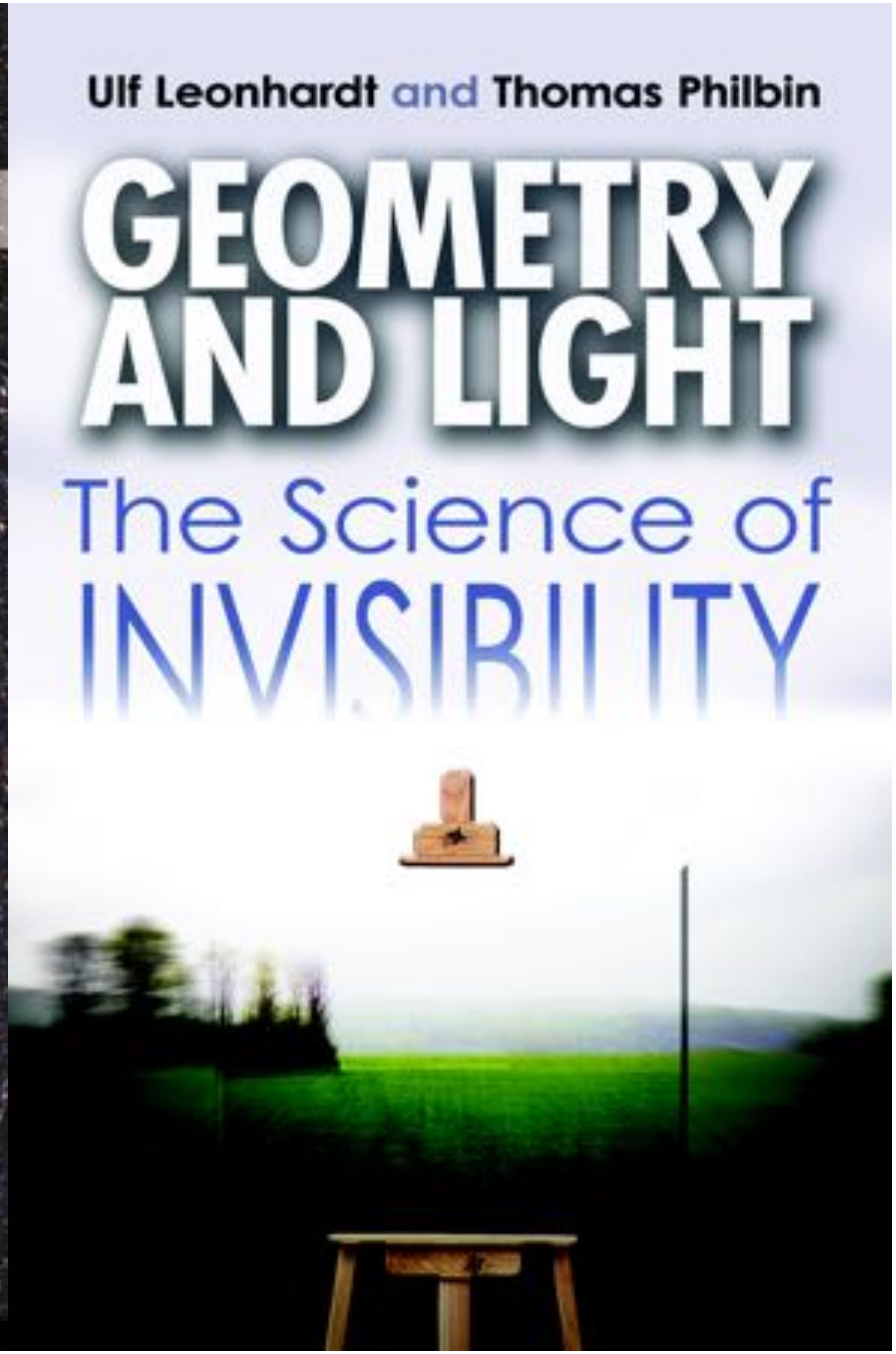
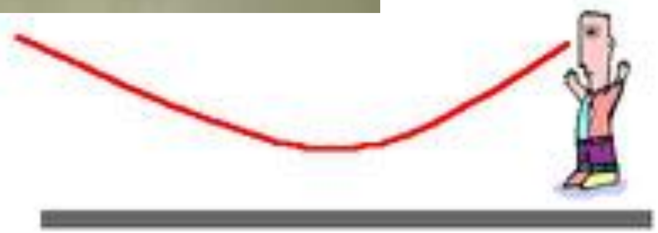
Transformation Optics

Ulf Leonhardt
Weizmann Institute of Science


ESSENTIAL
Quantum
Optics
From Quantum Measurements to Black Holes
ULF LEONHARDT
CAMBRIDGE

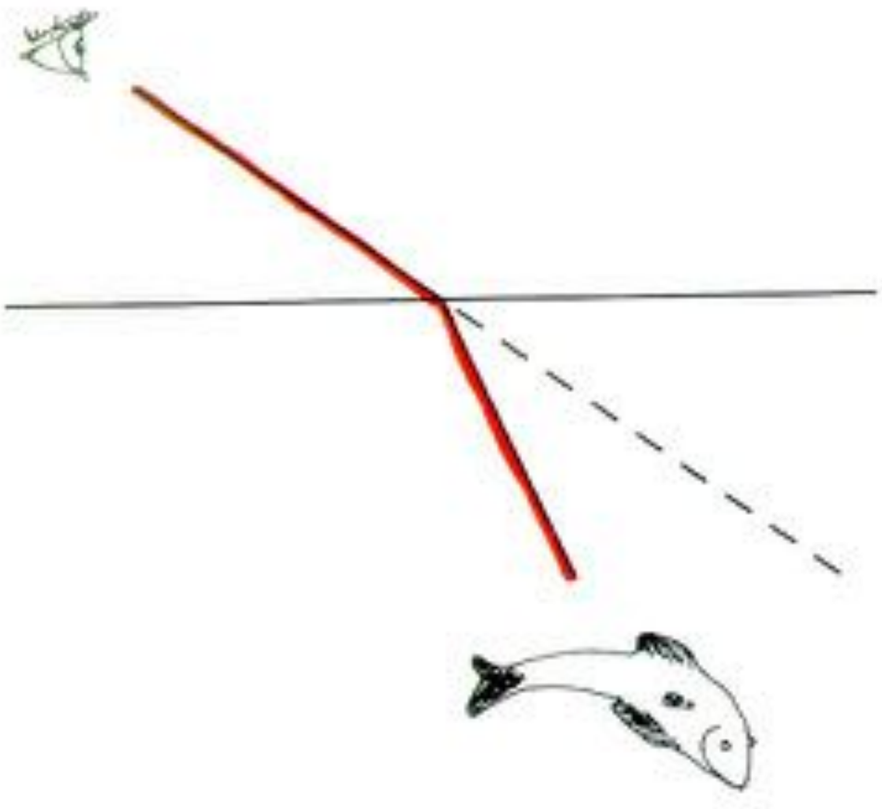

Ulf Leonhardt and Thomas Philbin
GEOMETRY
AND LIGHT
The Science of
INVISIBILITY

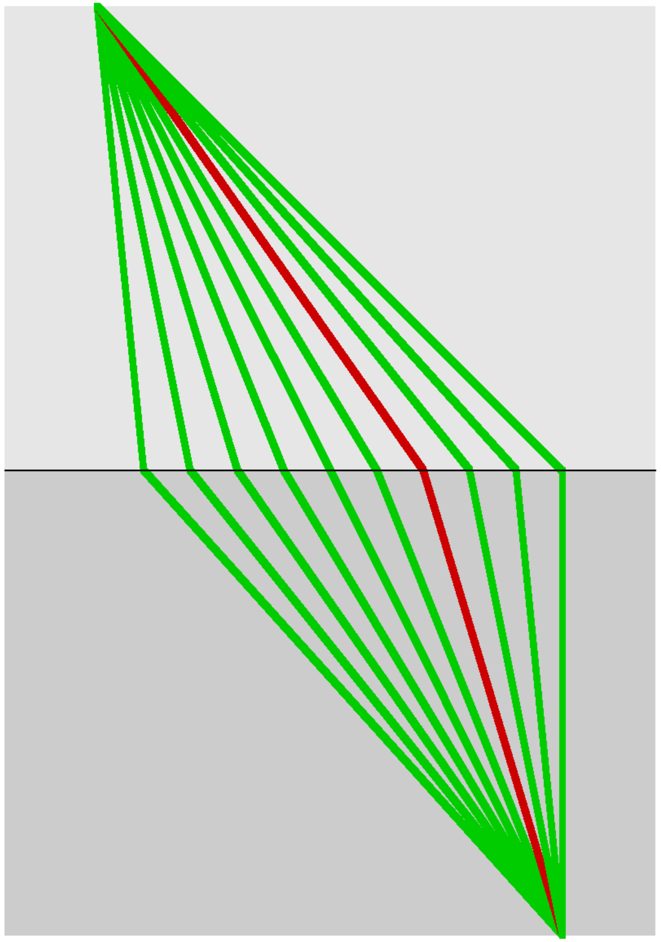
Mirage



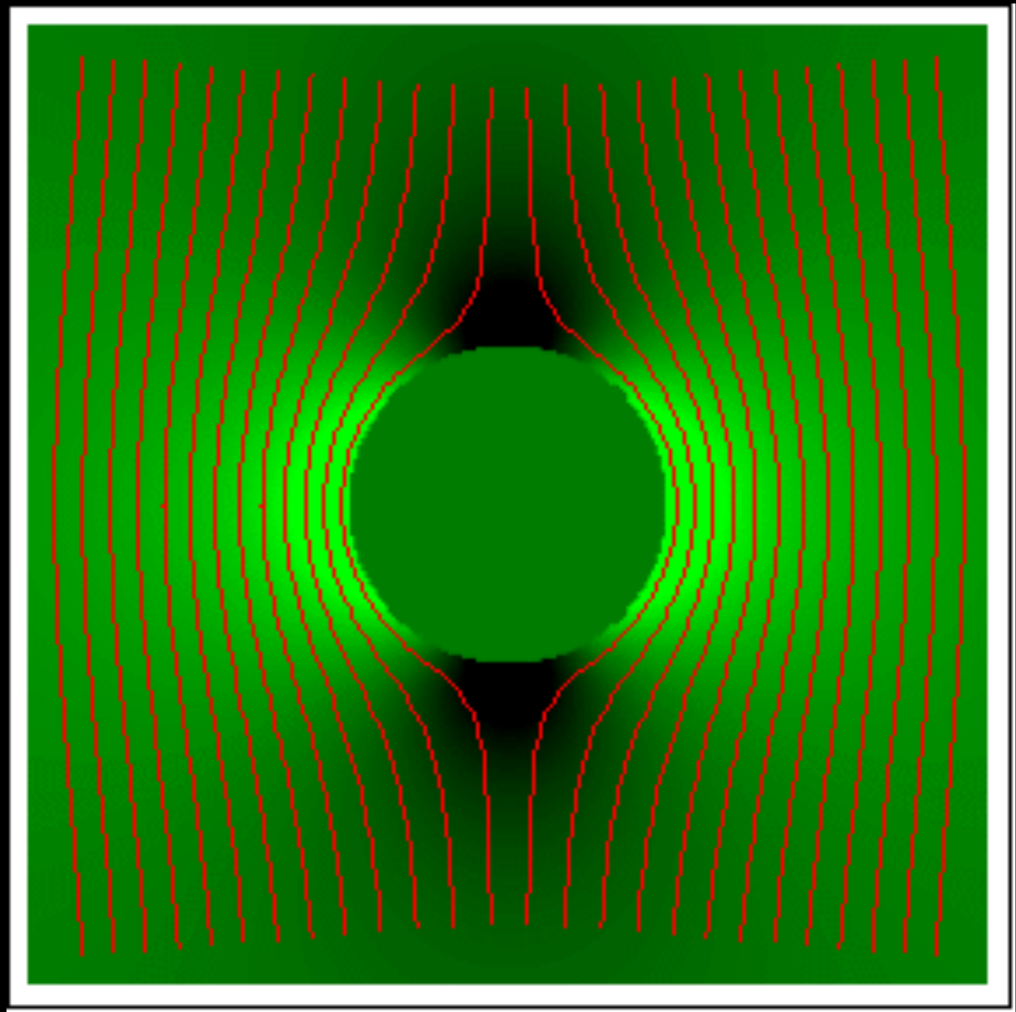
Fermat's Principle - the principle of the shortest optical path

$$s = \int n \, dl$$





Leonhardt 2002: Invisibility cloak?



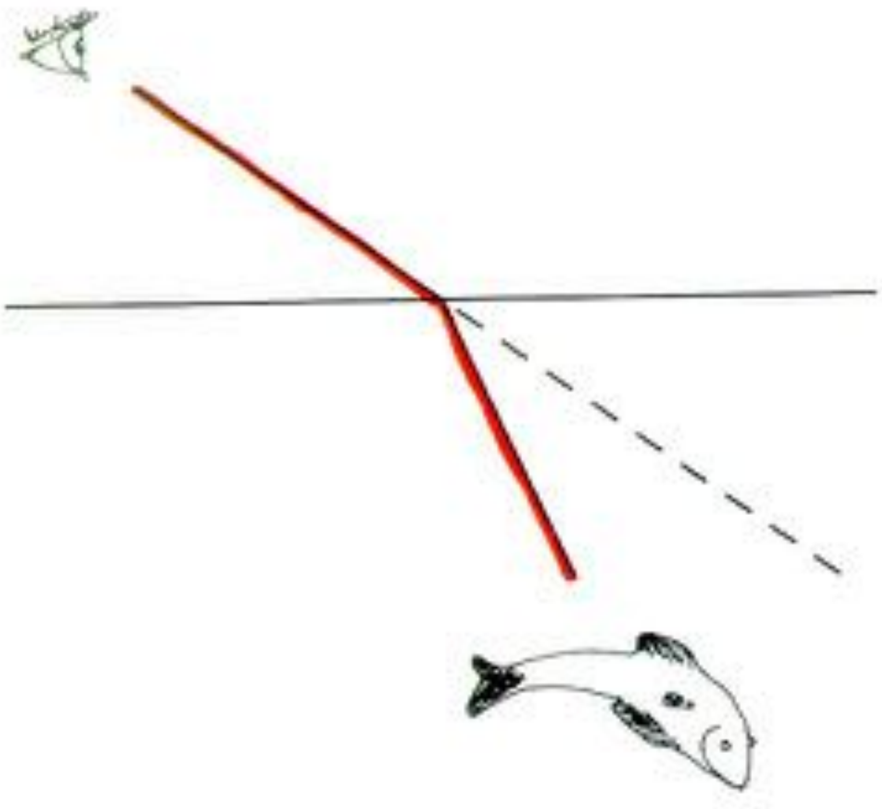
Invisibility: Invisible Man versus Invisible Woman

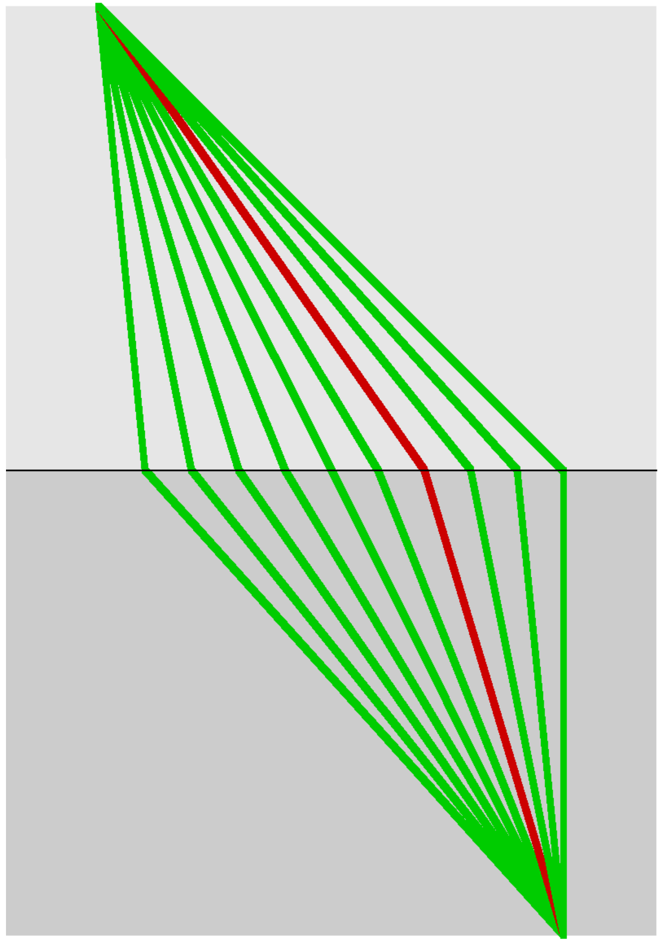
transparency

curved space

Fermat's Principle - the principle of the shortest optical path

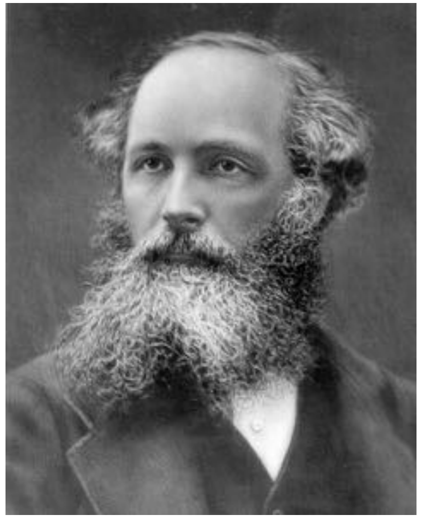
$$s = \int n\, dl$$





Maxwell's electromagnetism and Einstein's general relativity

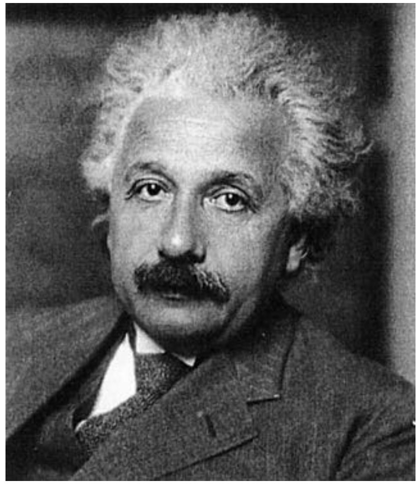
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}, \quad \nabla \cdot \vec{D} = \rho$$



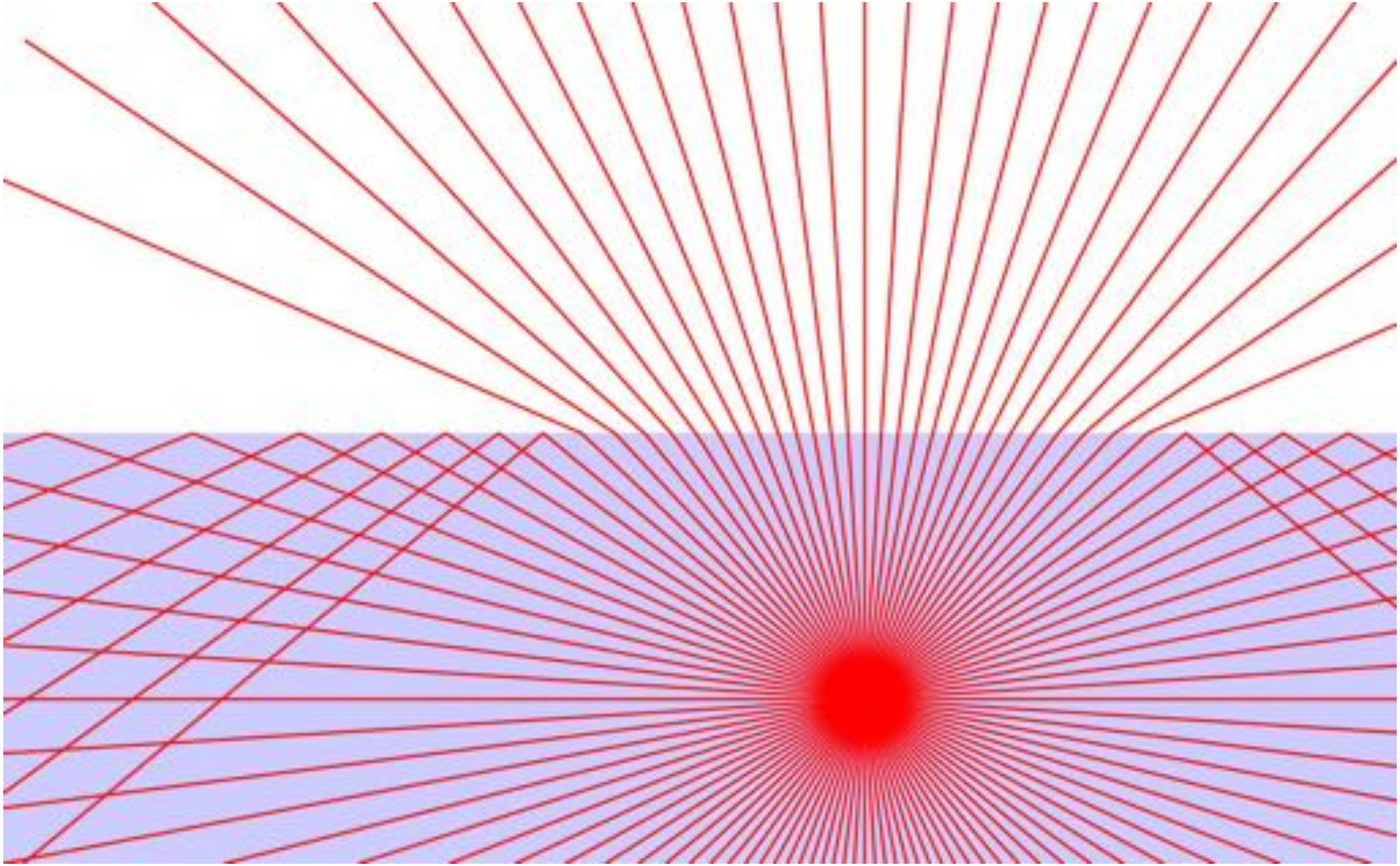
The covariant free-space Maxwell equations are equivalent to electromagnetism in a material medium
(Tamm, 1924; Plebanski, 1960).

$$\vec{D} = \varepsilon_0 \varepsilon \vec{E} + \frac{\vec{w}}{c} \times \vec{H}, \quad \vec{B} = \frac{\mu}{\varepsilon_0 c^2} \vec{H} - \frac{\vec{w}}{c} \times \vec{E}$$

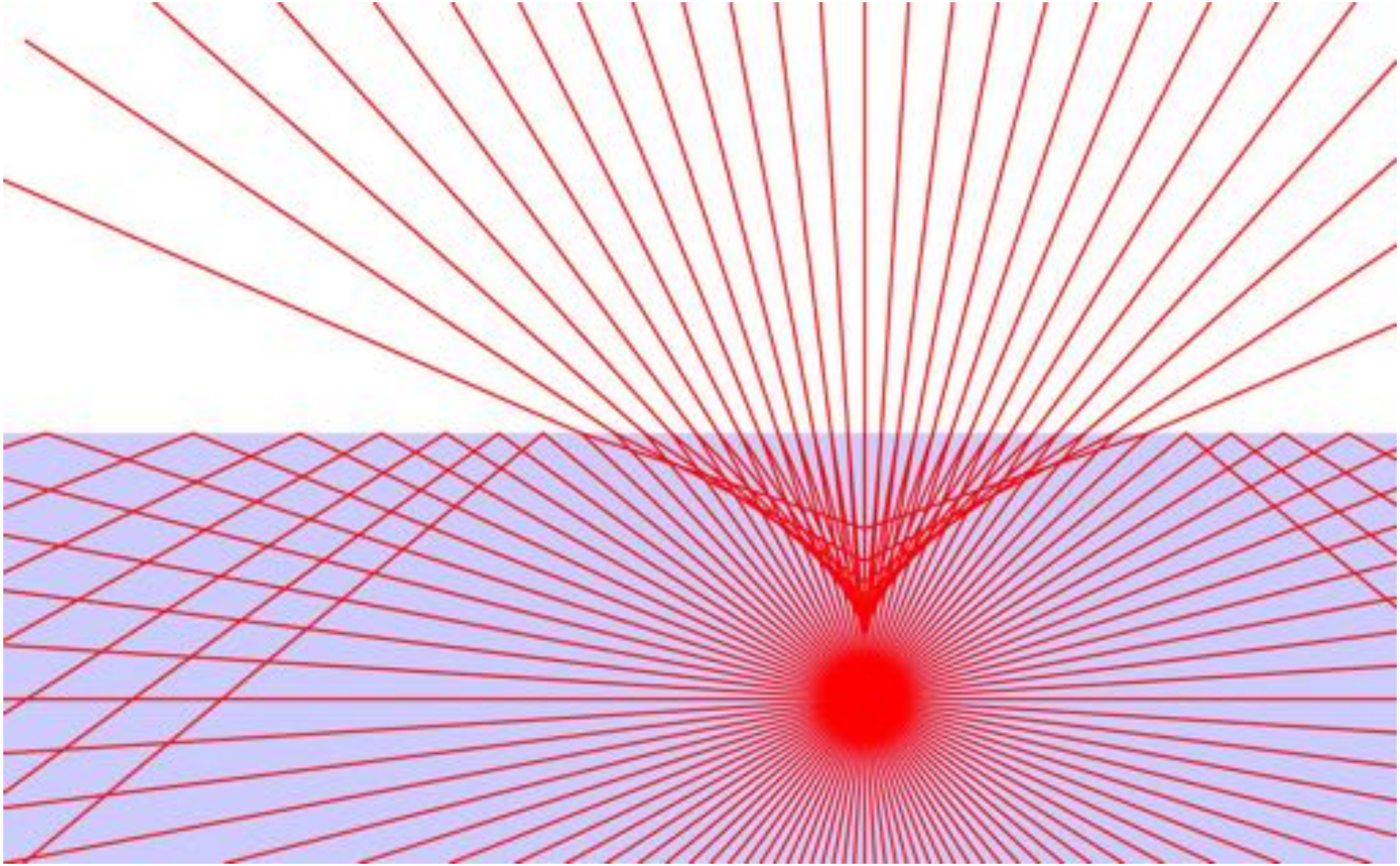
$$\varepsilon^{ij} = \mu^{ij} = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}, \quad w_i = \frac{g_{0i}}{g_{00}}$$



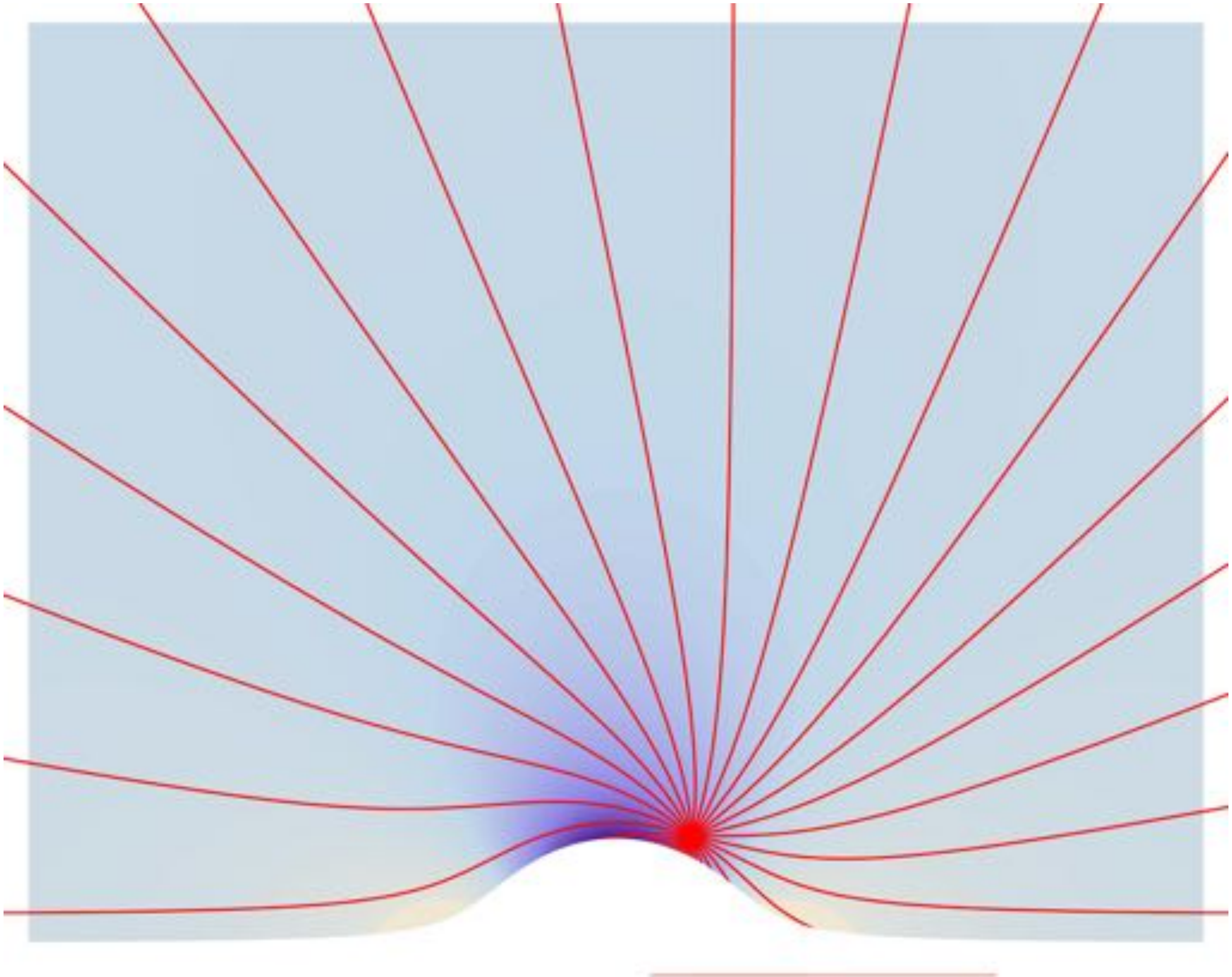
Refraction in ordinary medium



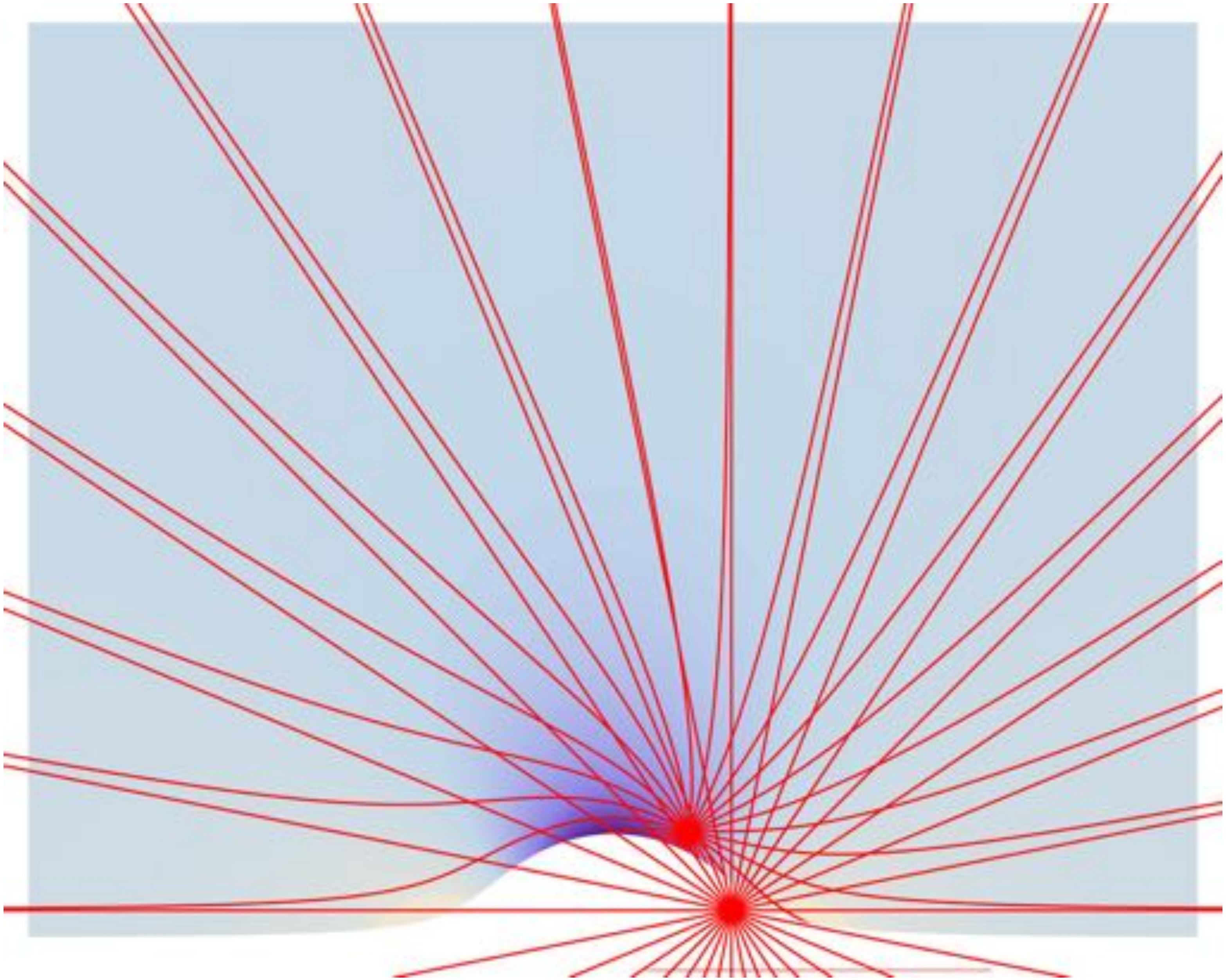
Refraction in ordinary medium:
virtual image depends on viewpoint



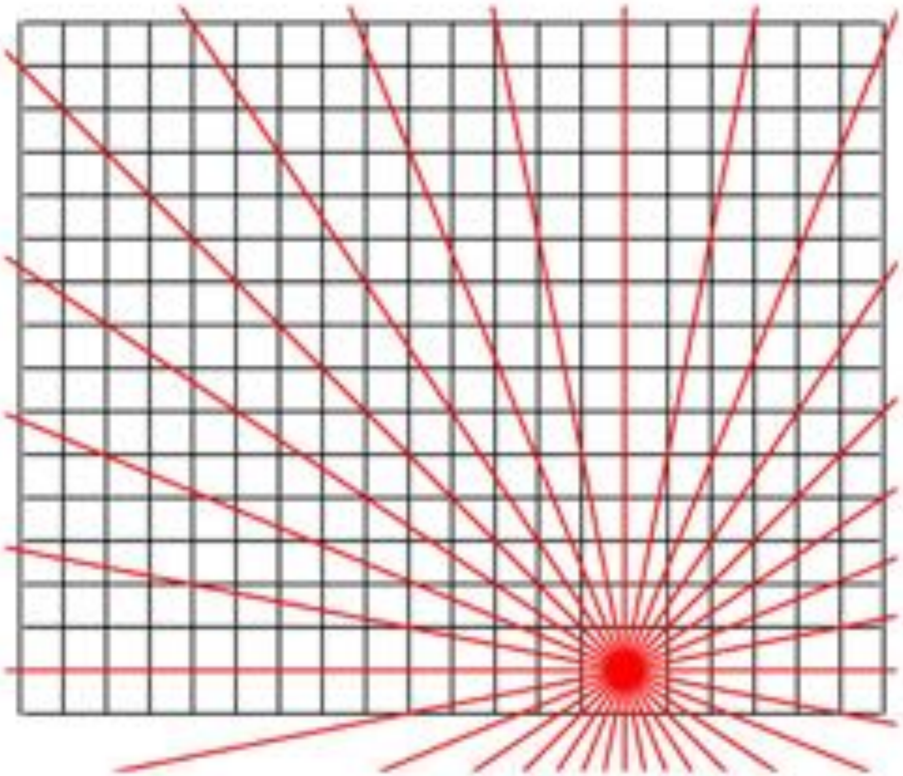
Transformation medium

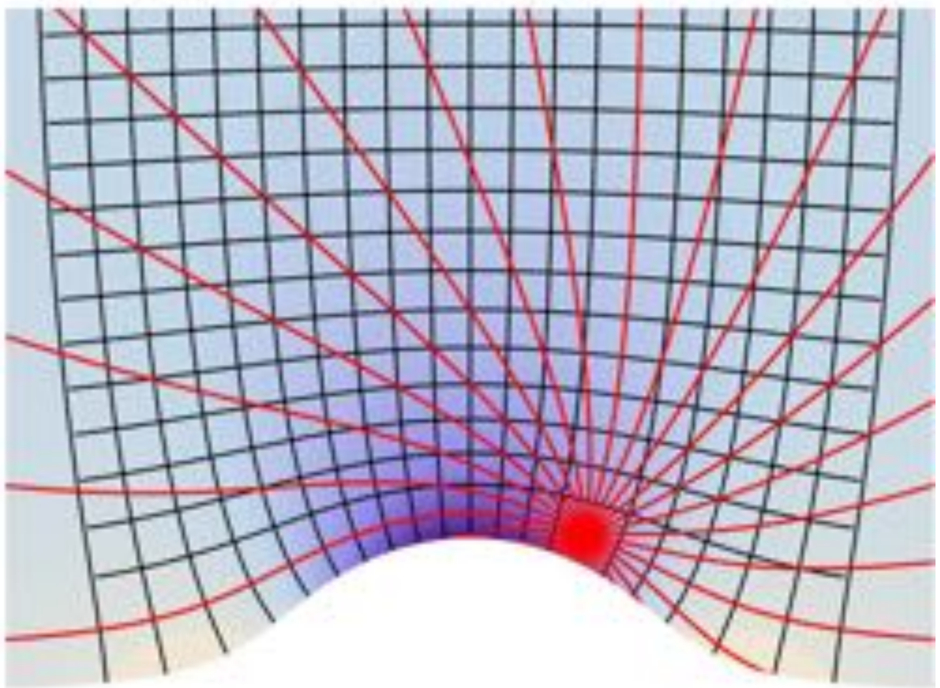


Transformation medium: definite virtual image



Transformation medium

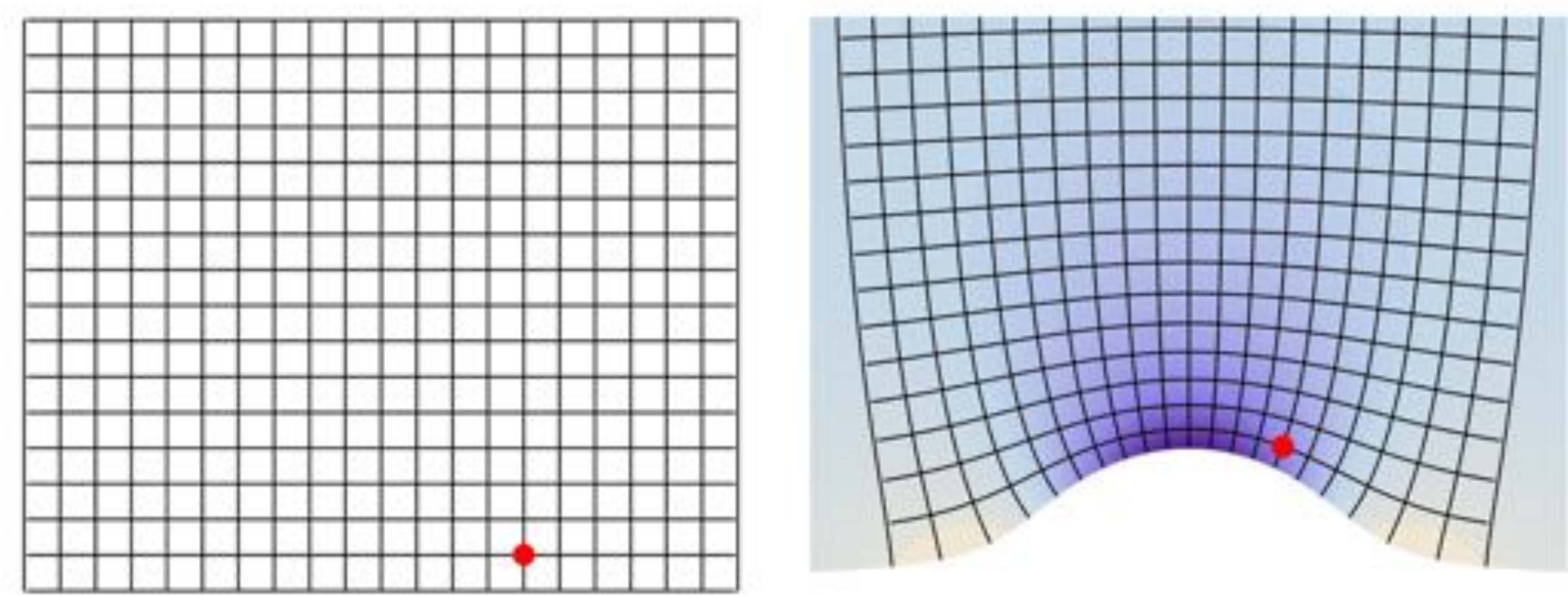




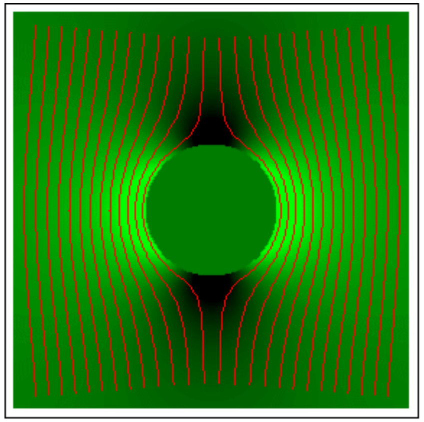
Transformation medium

Virtual space

Physical space

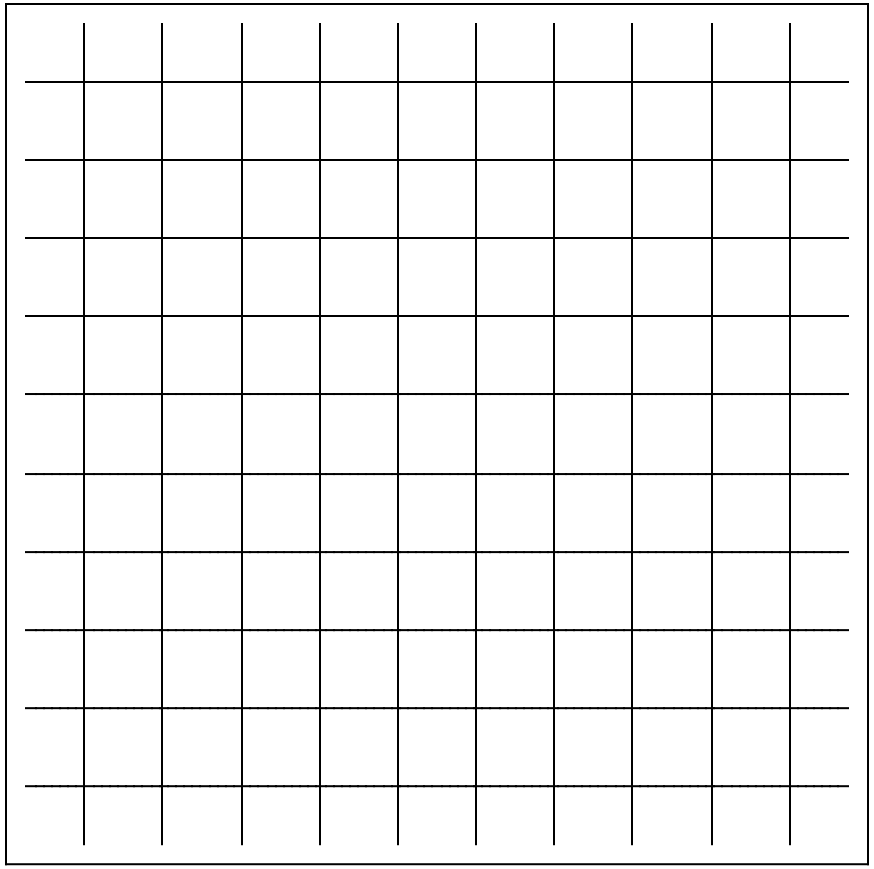


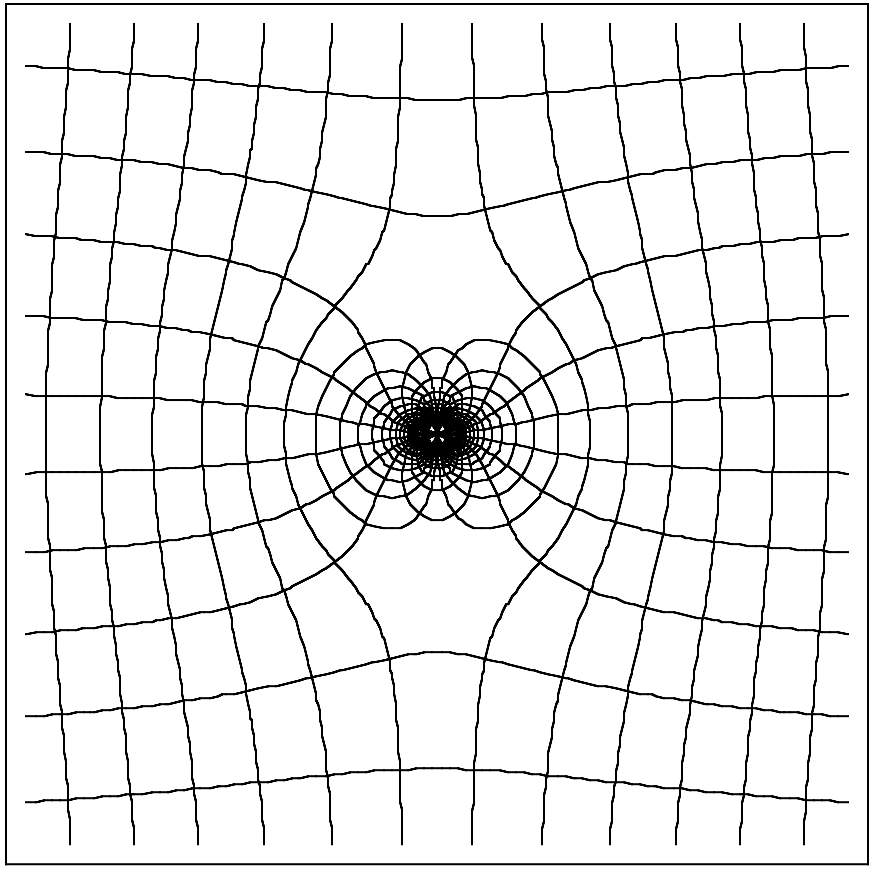
[Leonhardt, Science **312**, 1777 (2006)]



Virtual space

Physical space

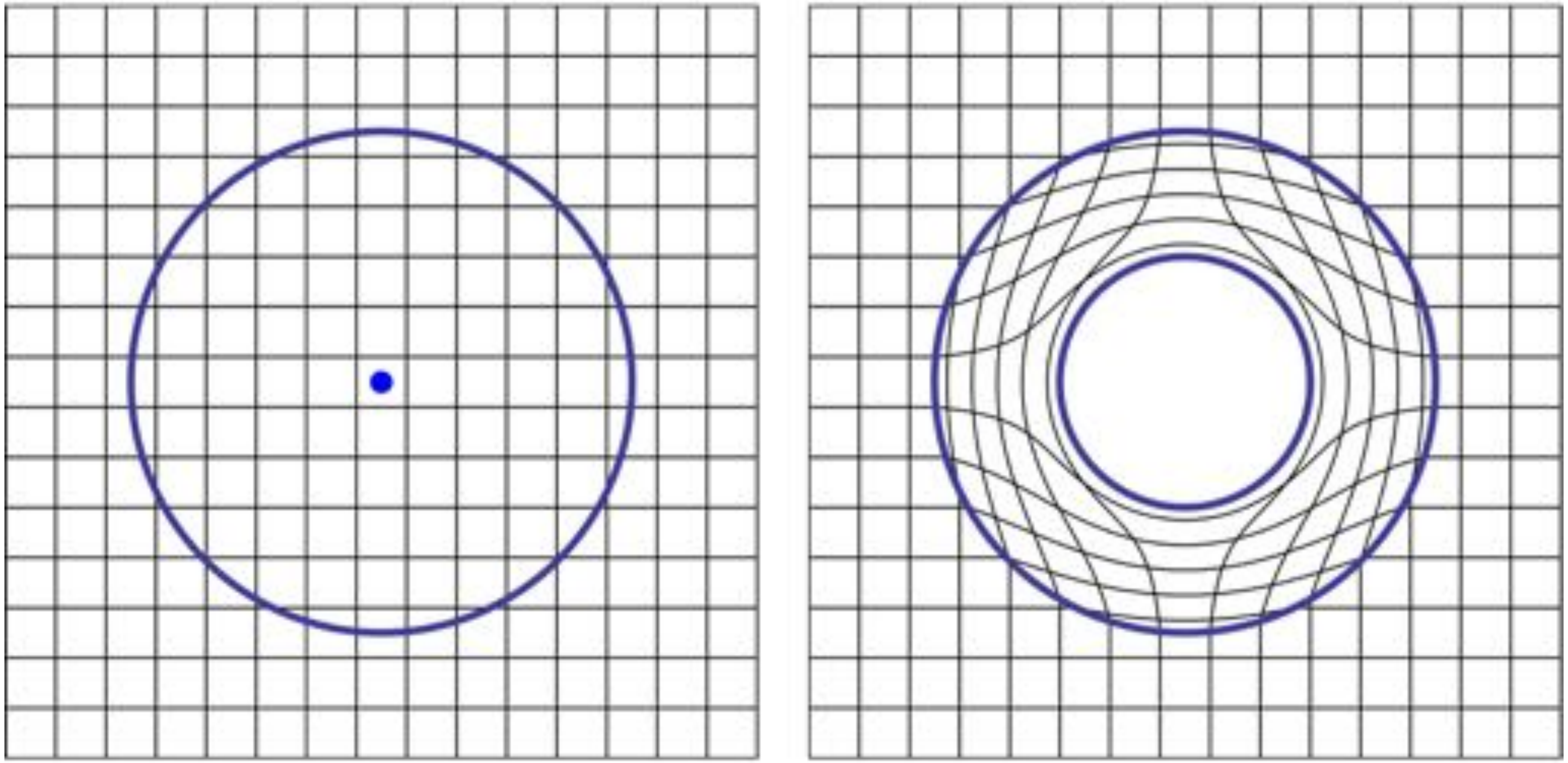




[Pendry, Schurig and Smith, Science **312**, 1780 (2006)]

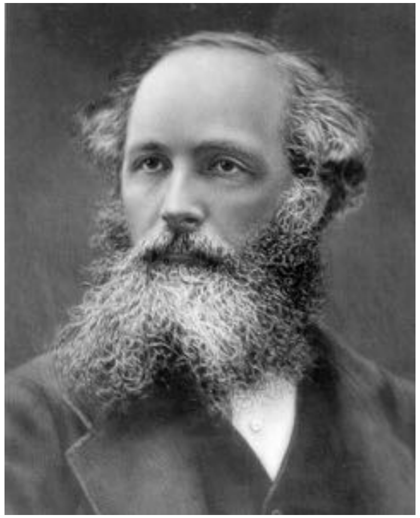
Virtual space

Physical space



Maxwell's electromagnetism and Einstein's general relativity

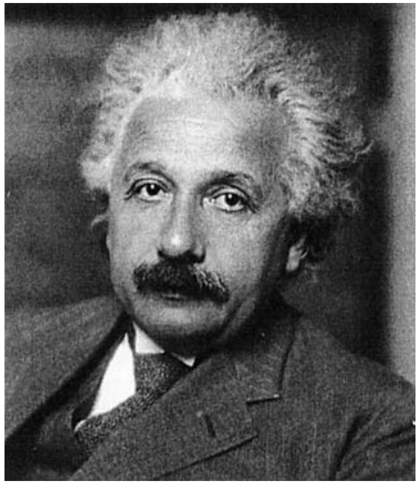
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}, \quad \nabla \cdot \vec{D} = \rho$$



The covariant free-space Maxwell equations are equivalent to electromagnetism in a material medium
(Tamm, 1924; Plebanski, 1960).

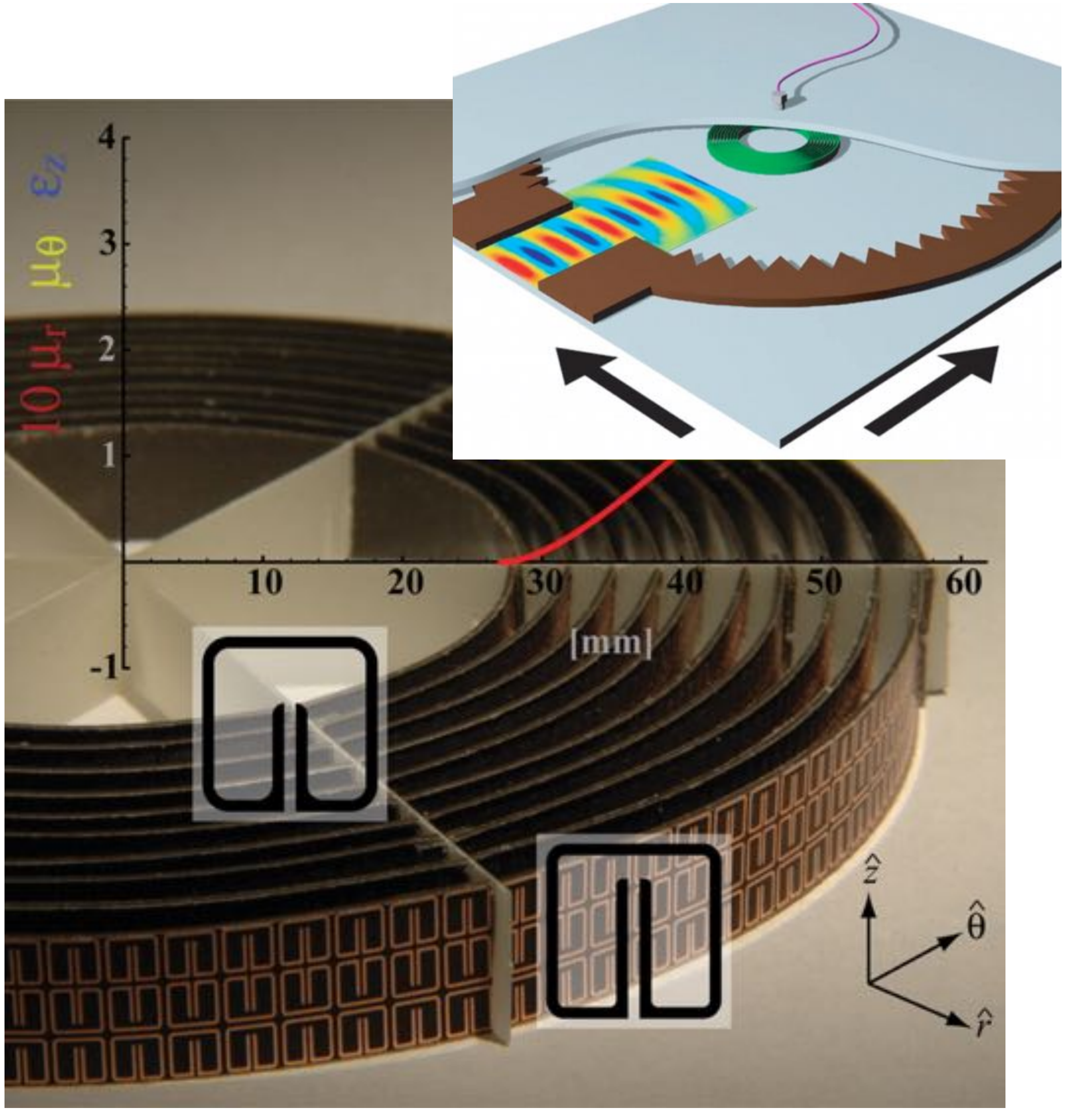
$$\vec{D} = \varepsilon_0 \varepsilon \vec{E} + \frac{\vec{w}}{c} \times \vec{H}, \quad \vec{B} = \frac{\mu}{\varepsilon_0 c^2} \vec{H} - \frac{\vec{w}}{c} \times \vec{E}$$

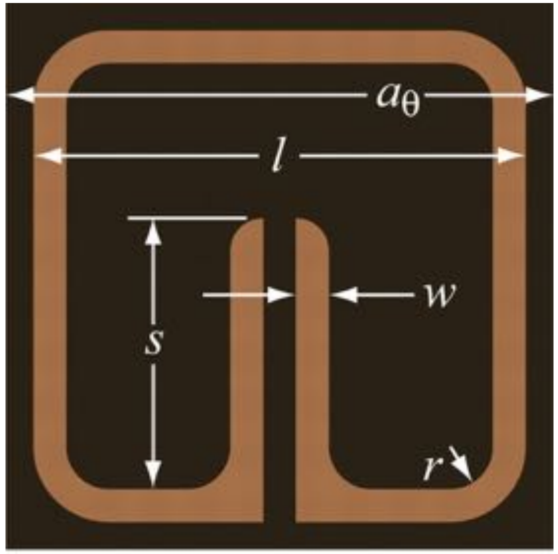
$$\varepsilon^{ij} = \mu^{ij} = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}, \quad w_i = \frac{g_{0i}}{g_{00}}$$



Patent office

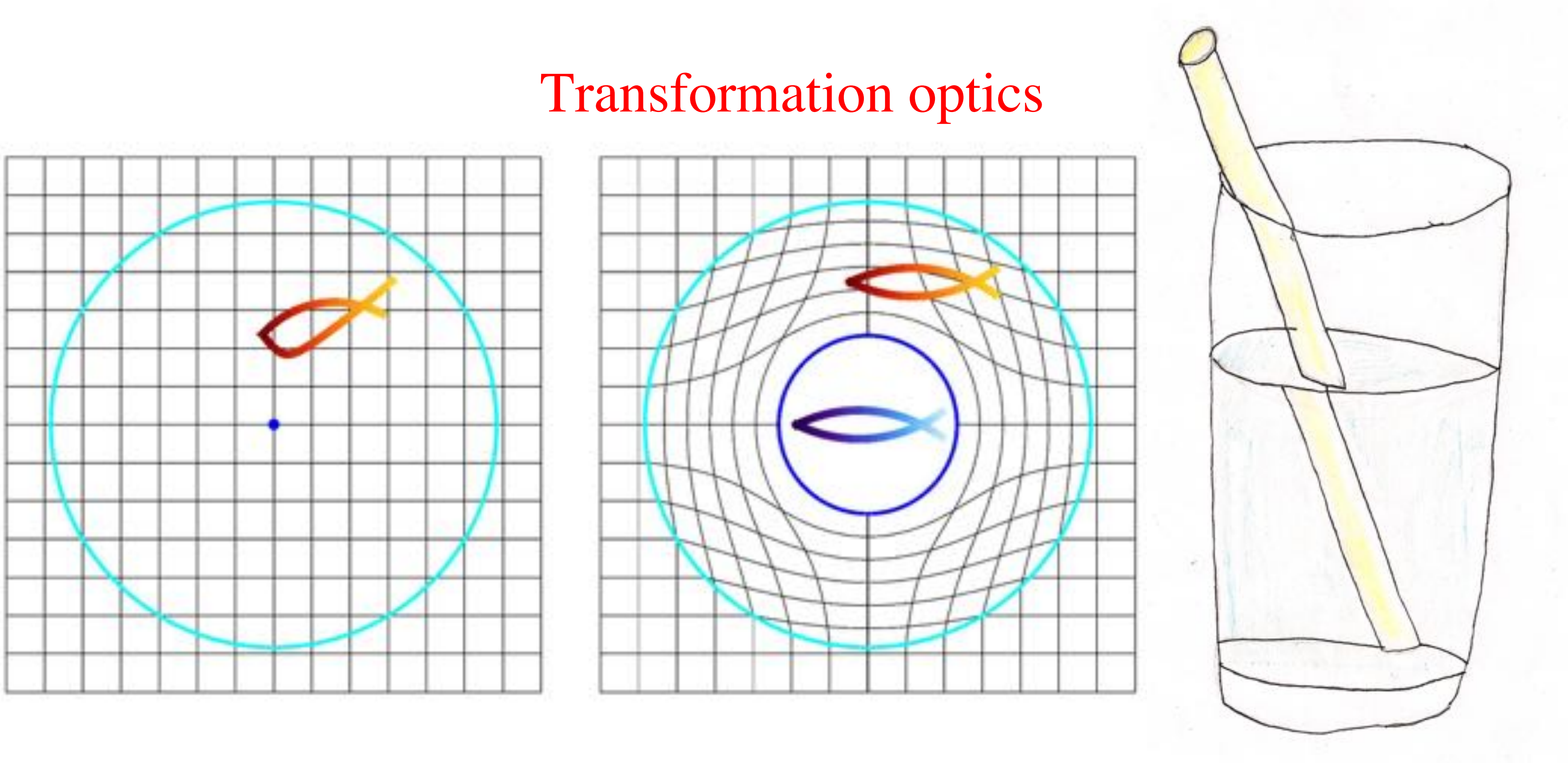
Cloaking device for electromagnetic microwaves





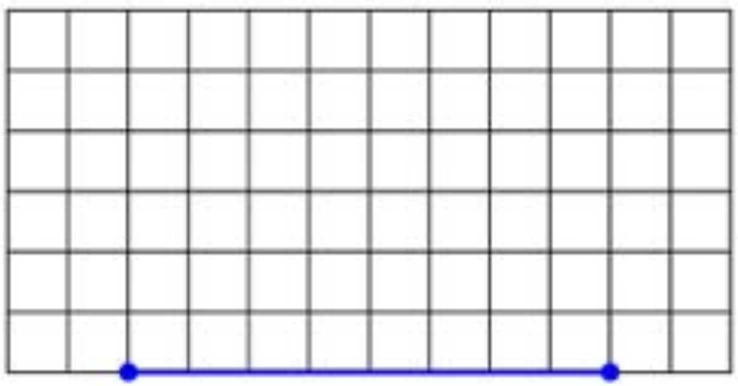
cyl.	r	s	μ_r
1	0.260	1.654	0.003
2	0.254	1.677	0.023
3	0.245	1.718	0.052
4	0.230	1.771	0.085
5	0.208	1.825	0.120
6	0.190	1.886	0.154
7	0.173	1.951	0.188
8	0.148	2.027	0.220
9	0.129	2.110	0.250
10	0.116	2.199	0.279

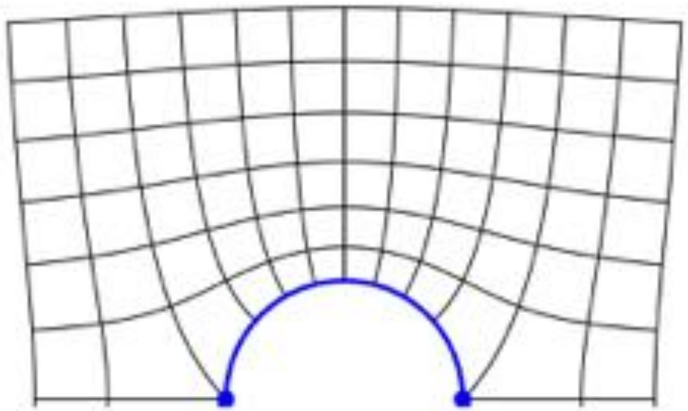
Transformation optics



[Greenleaf, Lassas and Uhlmann, Math. Res. Lett. **10**, 685 (2003) electrostatics;
Leonhardt, Science **312**, 1777 (2006) conformal transformations;
Pendry, Schurig and Smith, Science **312**, 1780 (2006) spatial transformations;
Leonhardt and Philbin, NJP **8**, 247 (2006)] space-time & negative refraction]

Turning a fugu into a flatfish





Credit: Maria Leonhardt

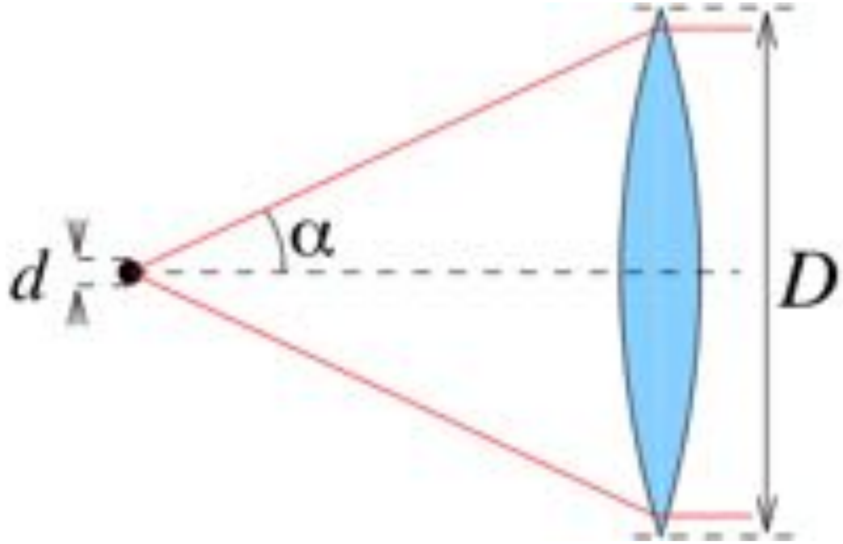
A new fish-eye lens based on an idea of James Clark Maxwell.

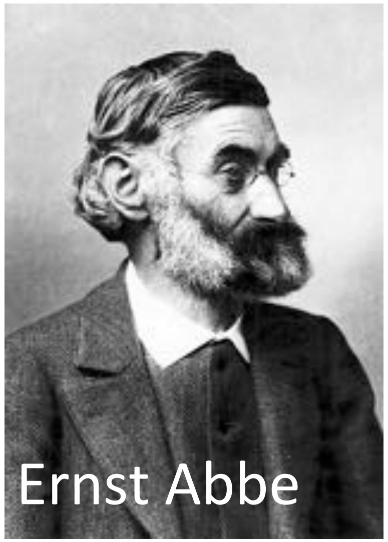
To invisibility and beyond

Combining Maxwell's equations with Einstein's general relativity promises perfect images and cloaking devices, explains **Ulf Leonhardt**.

[Leonhardt, Nature **471,** 292 (2011)]

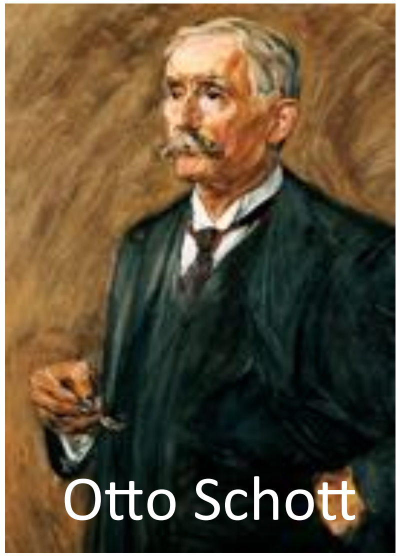
The resolution limit of imaging, established around 1870





ZEISS

SCHOTT 125 YEARS



Negative Refraction Makes a Perfect Lens

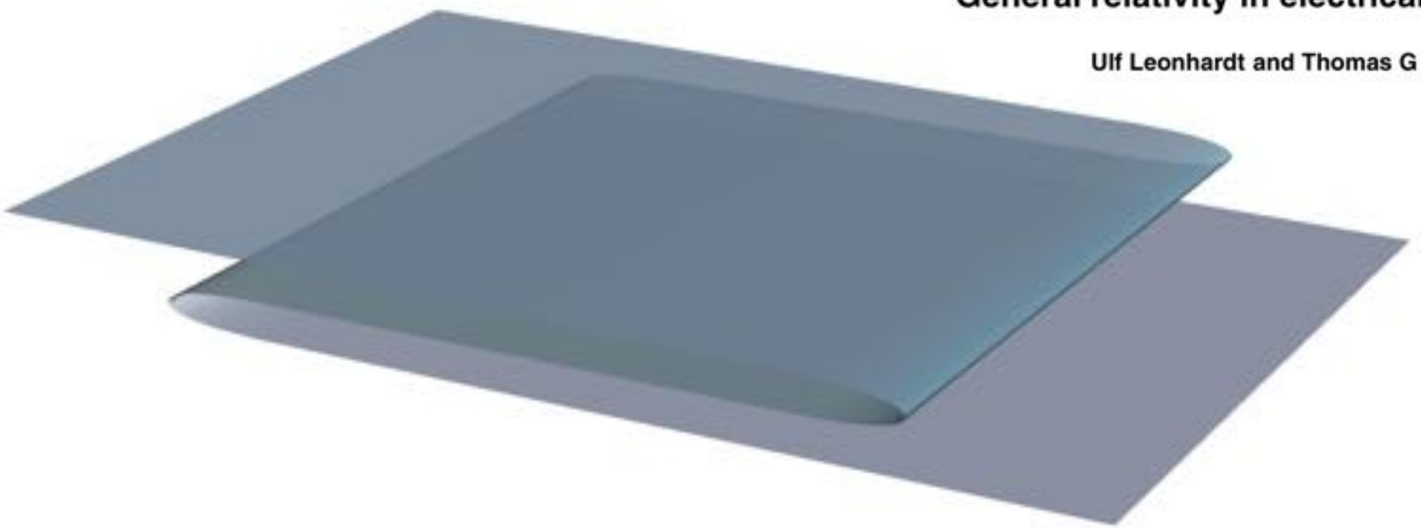
J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

With a conventional lens sharpness of the image is always limited by the wavelength of light. An unconventional alternative to a lens, a slab of negative refractive index material, has the power to focus all Fourier components of a 2D image, even those that do not propagate in a radiative manner. Such "superlenses" can be realized in the microwave band with current technology. Our simulations show that a version of the lens operating at the frequency of visible light can be realized in the form of a thin slab of silver. This optical version resolves objects only a few nanometers across.

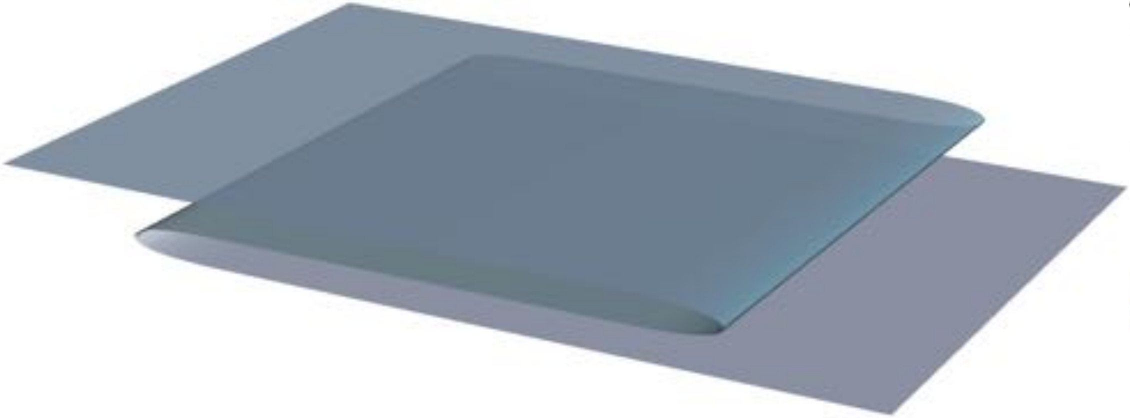
New Journal of Physics
The open-access journal for physics

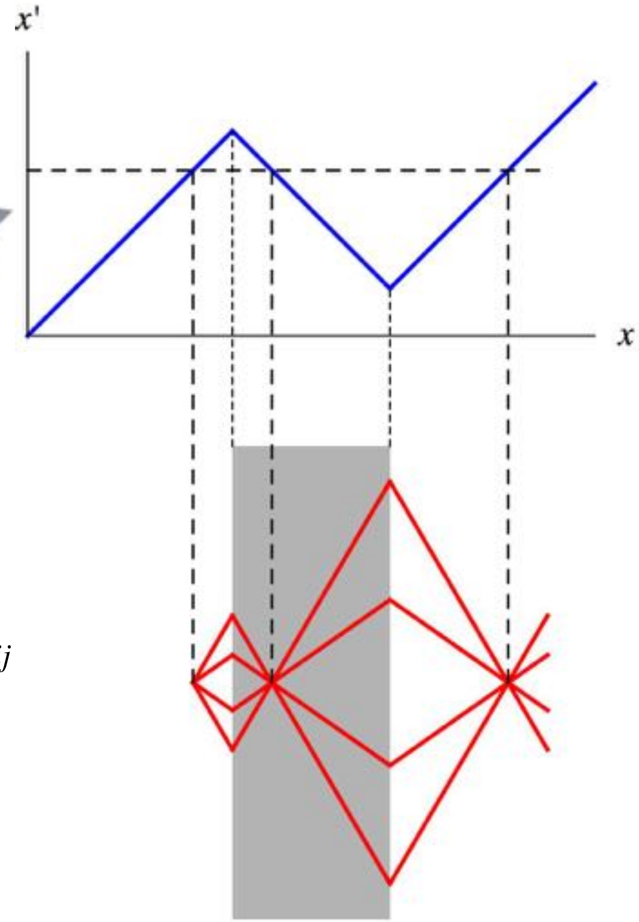
General relativity in electrical engineering

Ulf Leonhardt and Thomas G Philbin



Negative refraction and perfect lens



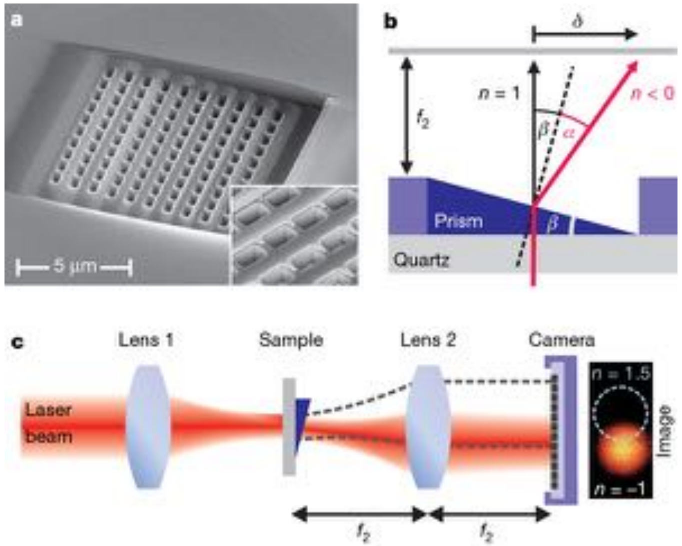


$$\varepsilon = \mu = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}$$

$\varepsilon = \mu = 1$

$\varepsilon = \mu = -1$

$\varepsilon = \mu = 1$



Xiang Zhang et al.
@ Berkeley

[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]

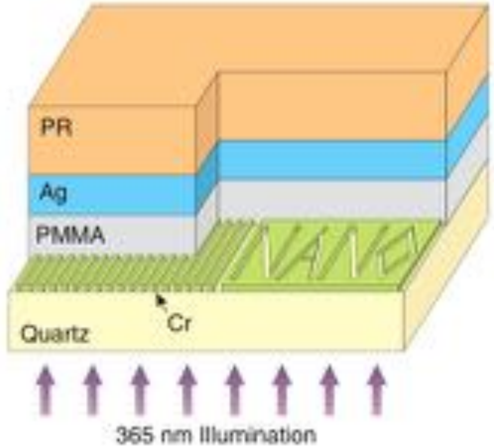
“Poor man’s perfect lens” [Science. **308**, 534 (2005)]

REPORTS

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 opto-electronic devices.



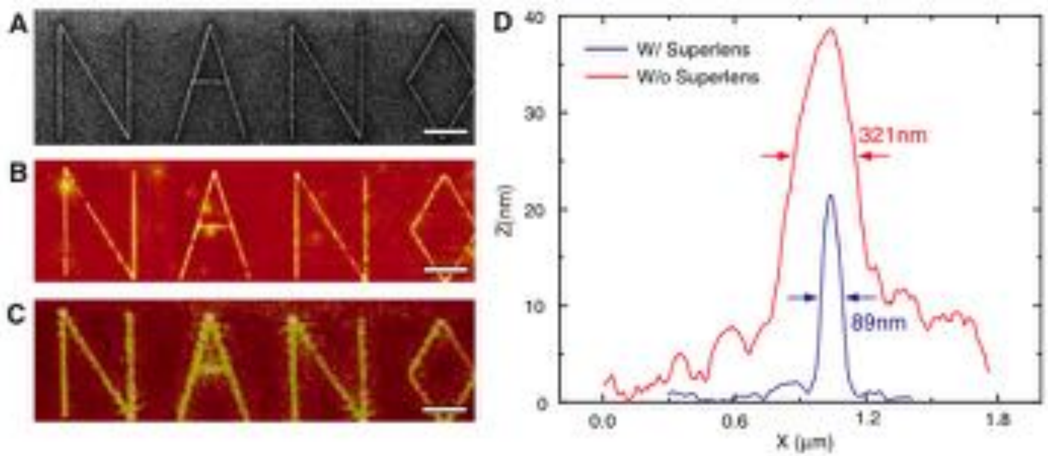


Fig. 4. An arbitrary object “NANO” was imaged by silver superlens. (A) FIB image of the object. The linewidth of the “NANO” object was 40 nm. Scale bar in (A) to (C), 2 μm. (B) AFM of the developed image on photoresist with a silver superlens. (C) AFM of the developed image on photoresist when the 35-nm-thick layer of silver was replaced by PMMA spacer as a control experiment. (D) The averaged cross section of letter “A” shows an exposed line width of 89 nm (blue line), whereas in the control experiment, we measured a diffraction-limited full width at half-maximum line width of 321 ± 10 nm (red line).

Invisibility: Invisible Man versus Invisible Woman

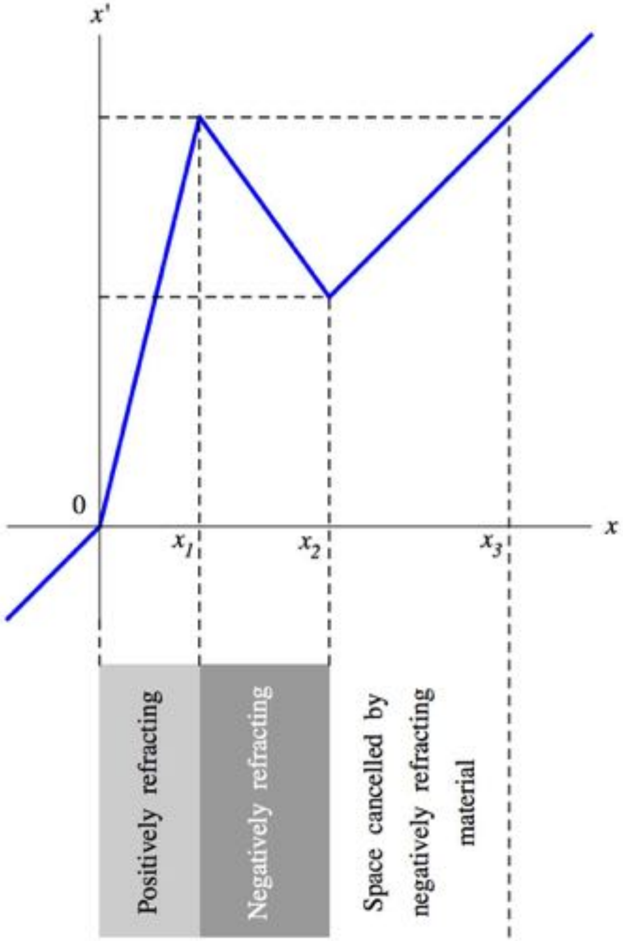
transparency

curved space

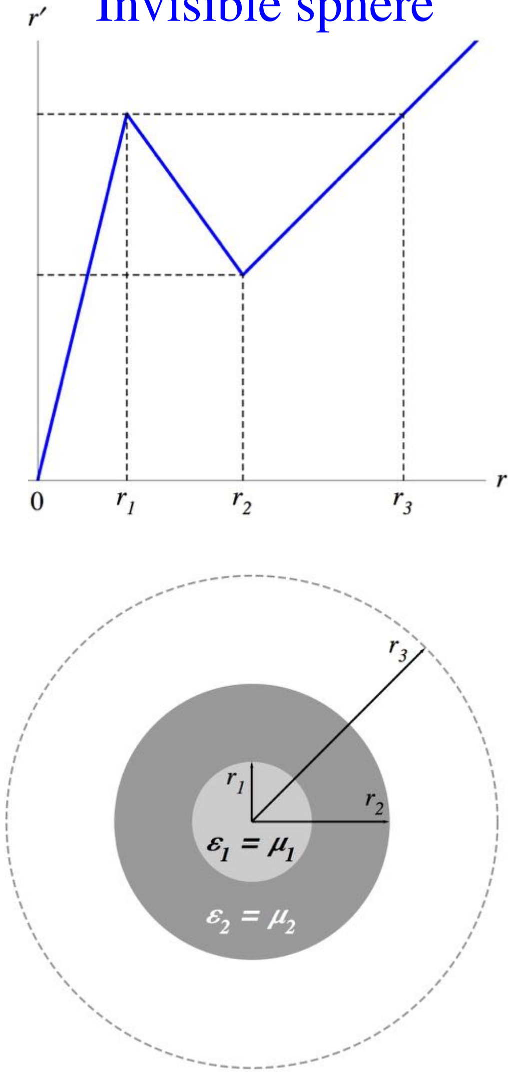
Cloaking at a distance

[Lai, Chen, Zhang and Chan, Phys. Rev. Lett. **102**, 093901 (2009)]

Invisible slab

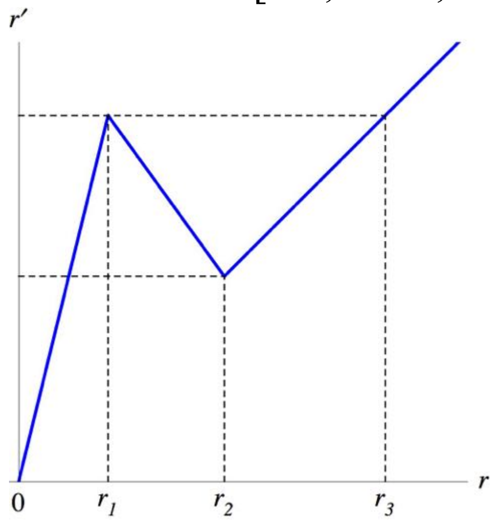


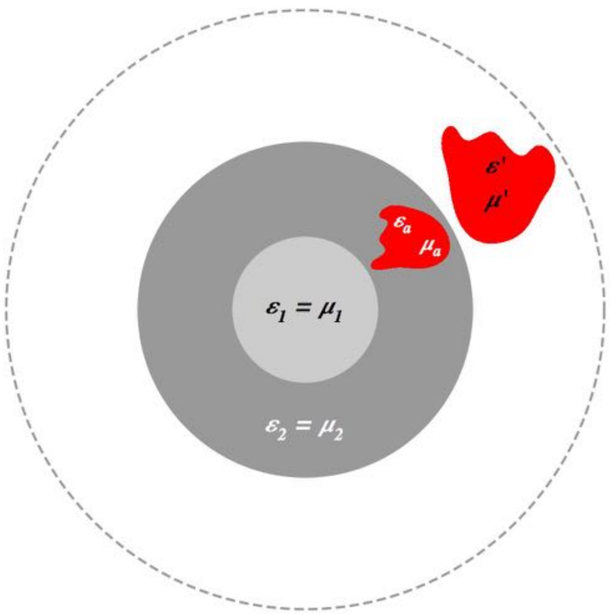
Invisible sphere

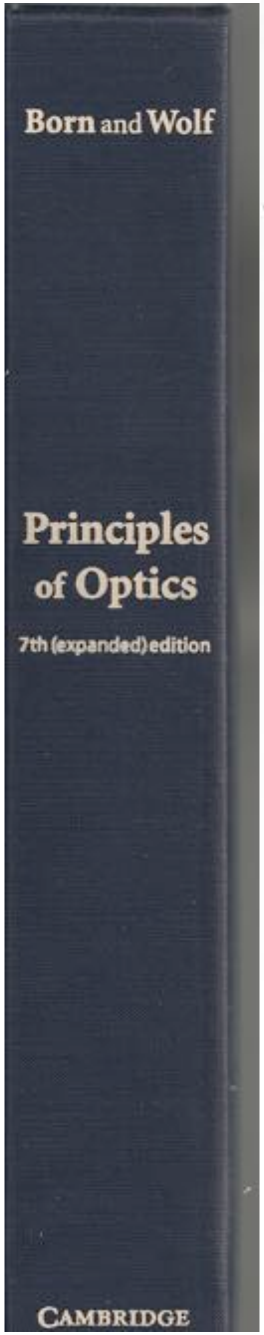


The Invisible Man - cloaking at a distance

[Lai, Chen, Zhang and Chan, Phys. Rev. Lett. **102**, 093901 (2009)]







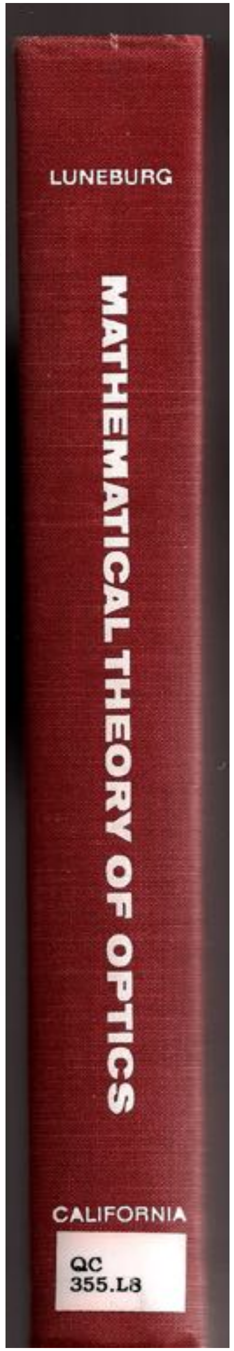
Principles of optics

Electromagnetic theory of propagation, interference and diffraction of light

MAX BORN
MA, Dr Phil, FRS
Nobel Laureate
Formerly Professor at the Universities of Göttingen and Edinburgh

and

EMIL WOLF
PhD, DSc
Wilson Professor of Optical Physics, University of Rochester, NY



Section "Perfect imaging"

THE SCIENTIFIC PAPERS OF

JAMES CLERK MAXWELL

MATHEMATICAL THEORY OF OPTICS

by

R. K. LUNEBURG

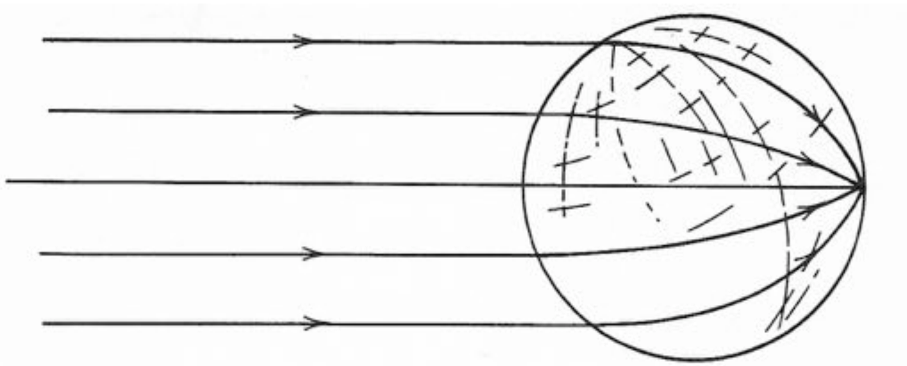
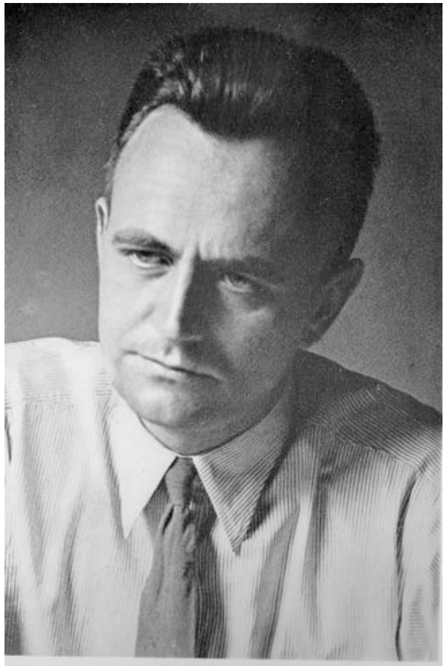
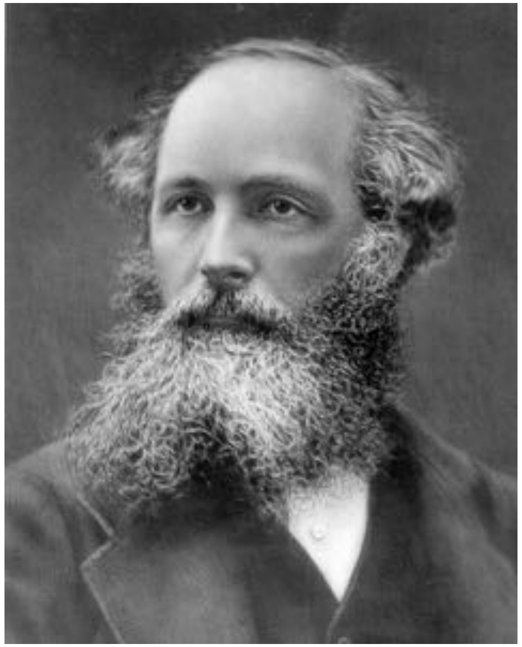


Figure 114



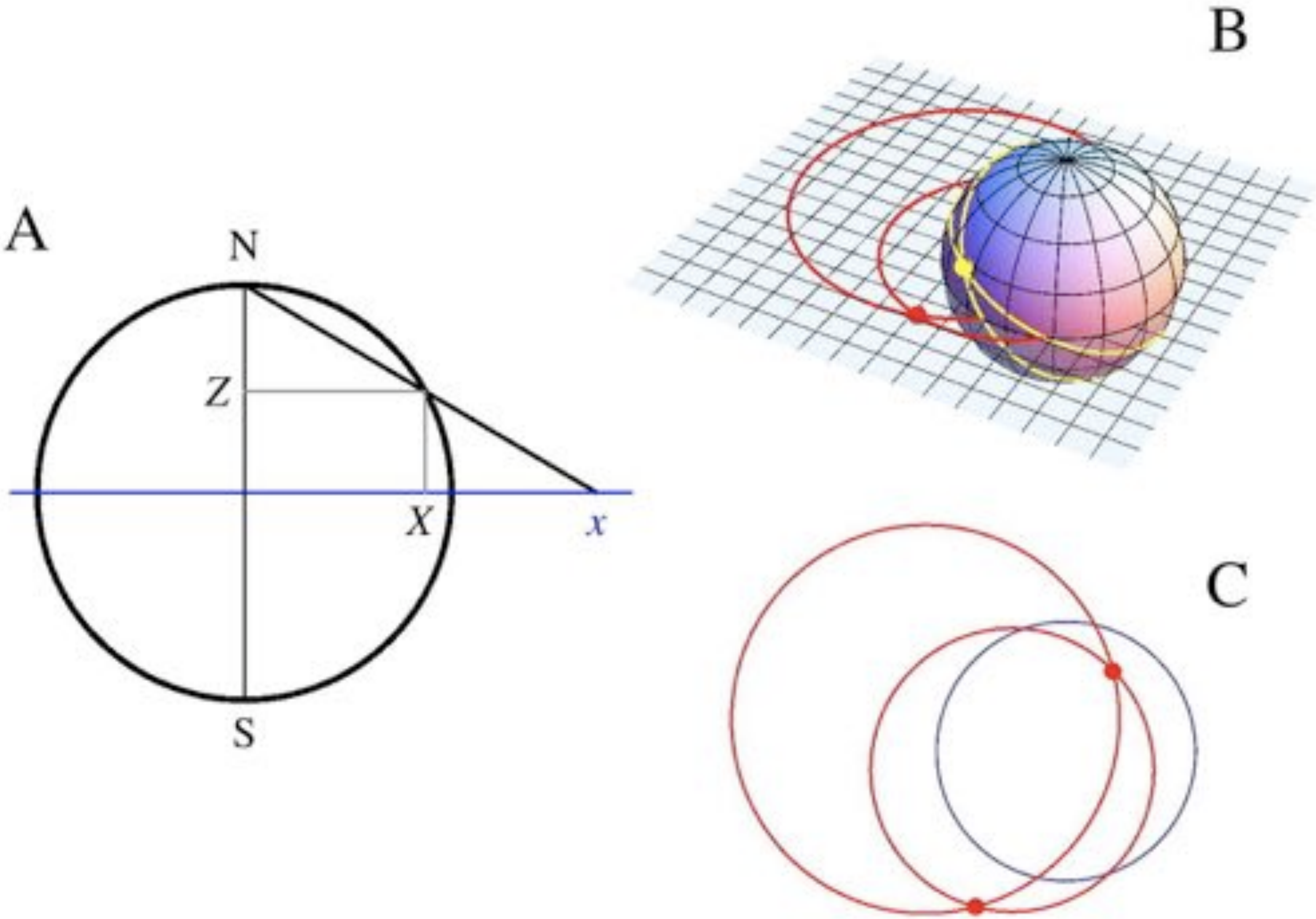
R. K. Luneburg



Maxwell’s fish eye makes a perfect lens

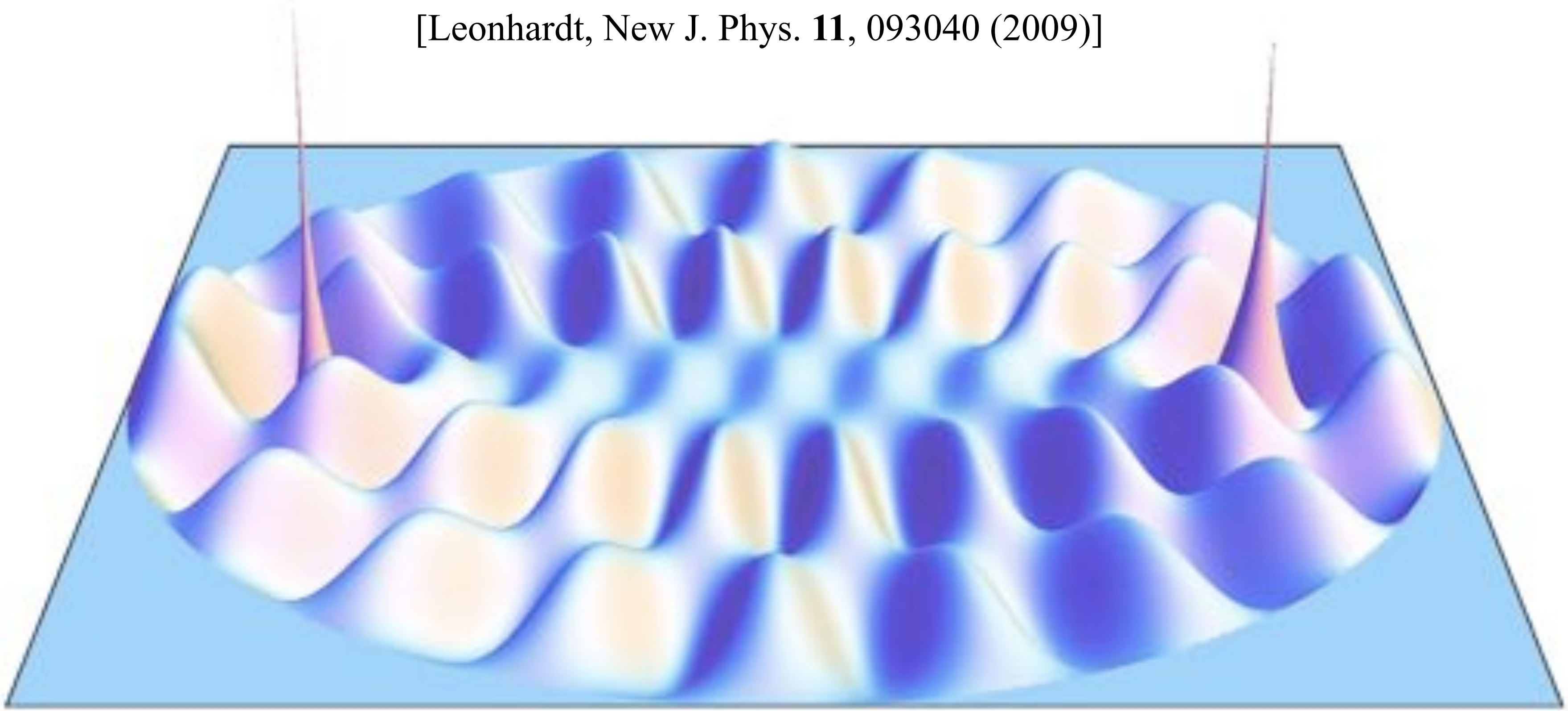
Maxwell 1854

Luneburg 1944: Stereographic projection



Perfect imaging without negative refraction

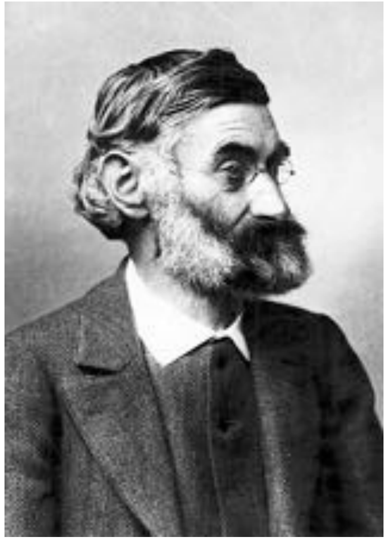
[Leonhardt, New J. Phys. **11**, 093040 (2009)]

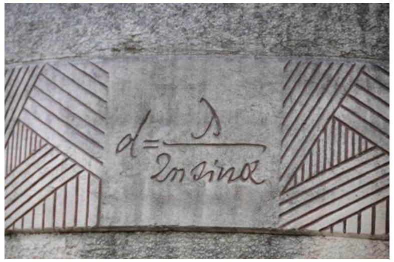


$$n = \frac{2n_0}{1 + r^2 / r_0^2}$$

Index contrast: factor of 2

Feynman's objection to the diffraction limit

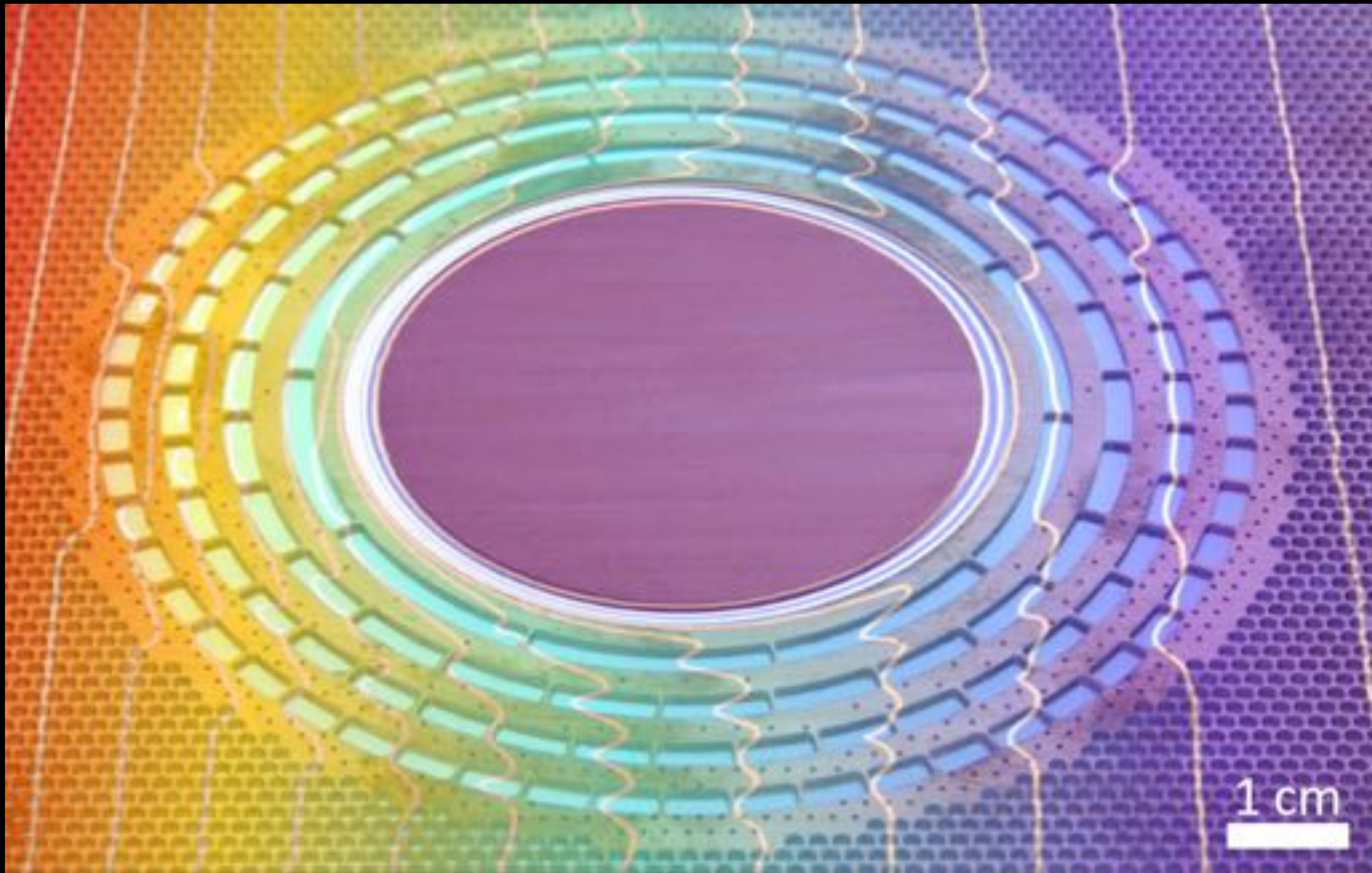




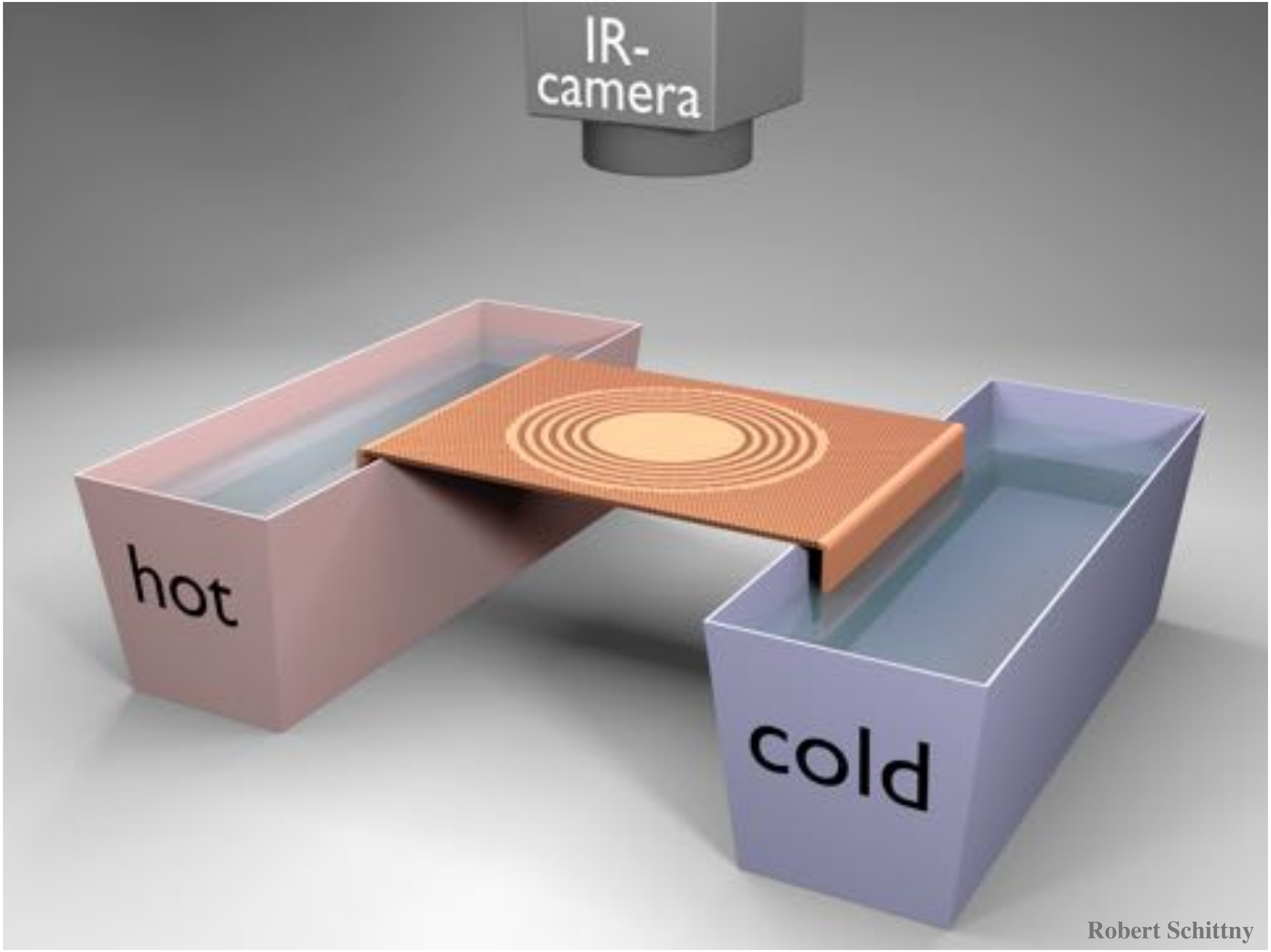
Maxwell's equations are time-reversible!
But you have to inverse the source, too.

Thermal cloaking

Thermal Cloaking



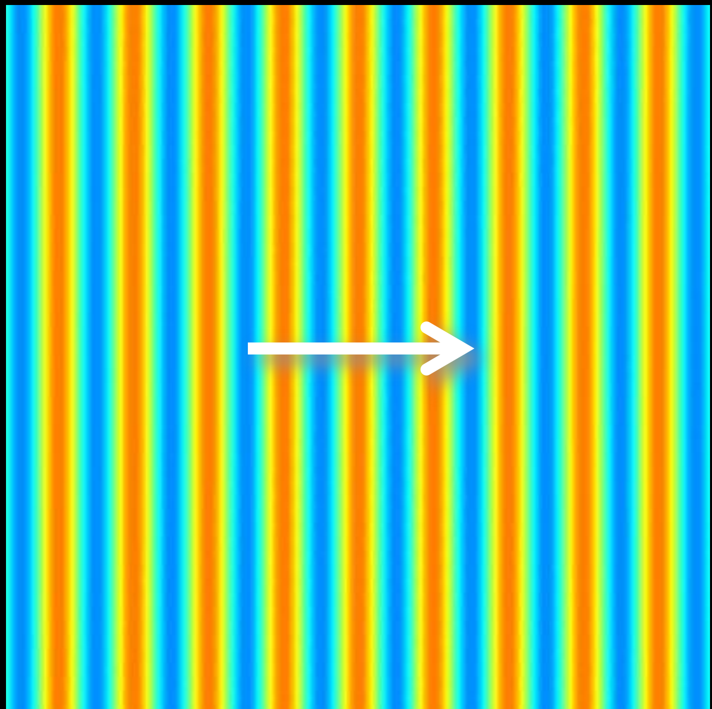
R. Schittny et al., Phys. Rev. Lett. 110, 195901 (2013)


IR-
camera
hot
cold
Robert Schittny

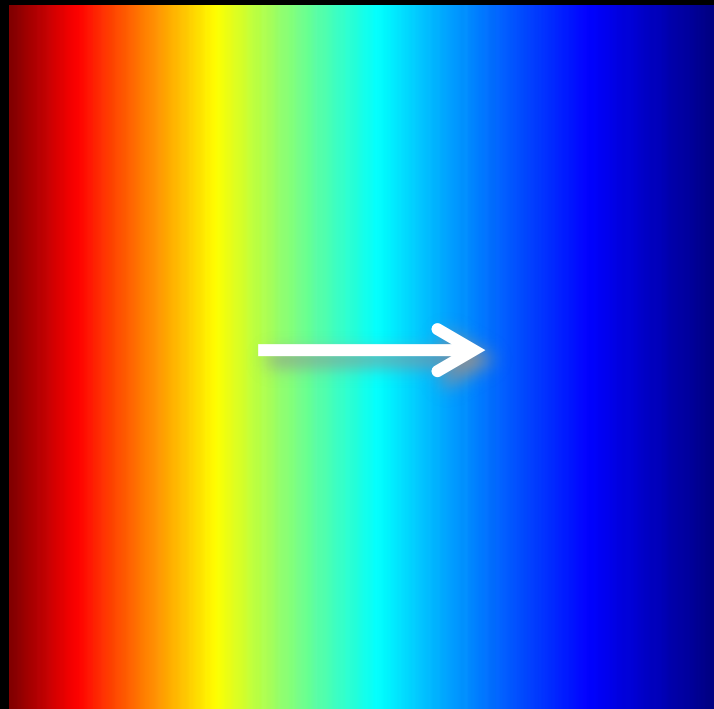
Thermal cloaking is not just thermal isolation

“Free Space”

optics



thermodynamics



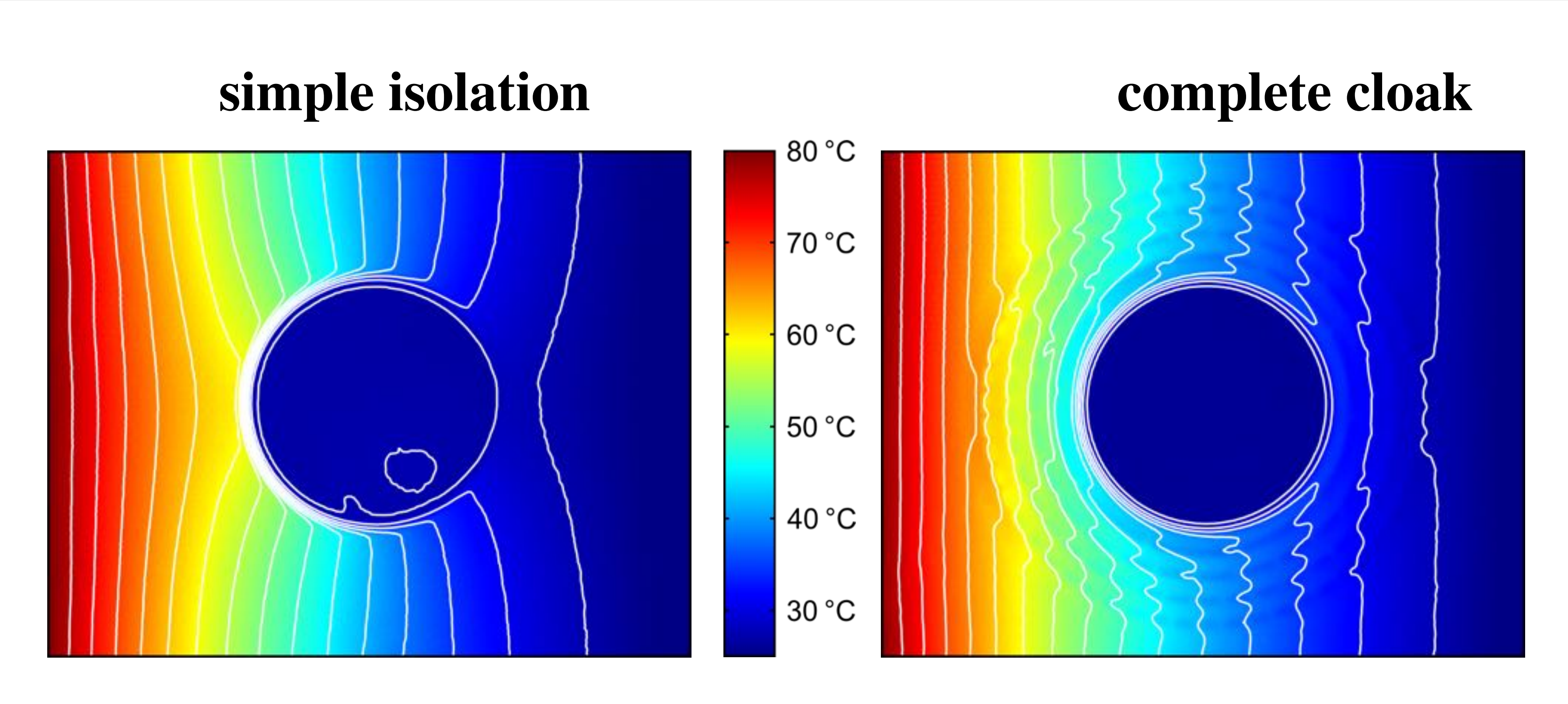
Robert Schittny

Simple Isolation

optics

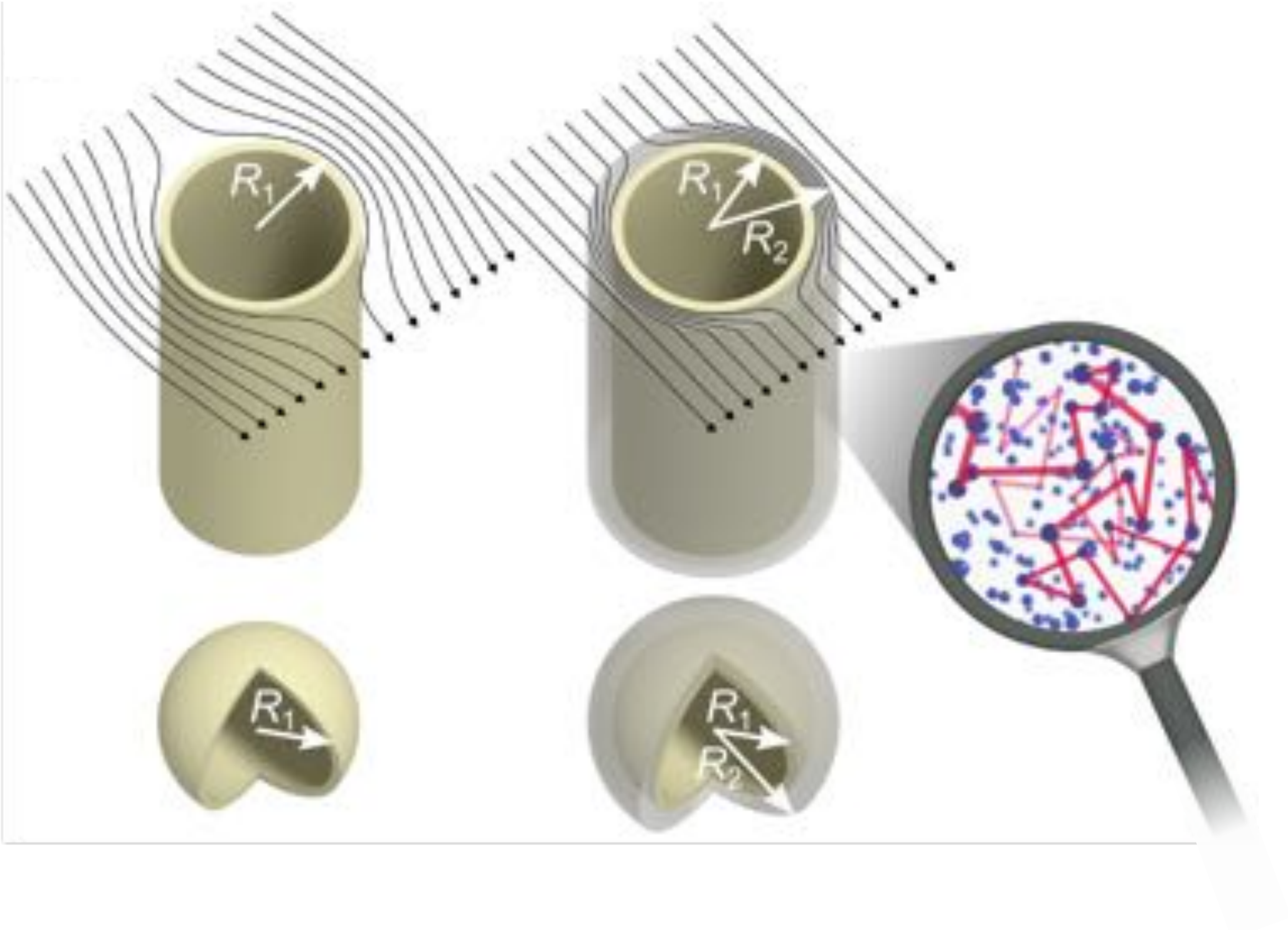
thermodynamics

Robert Schittny



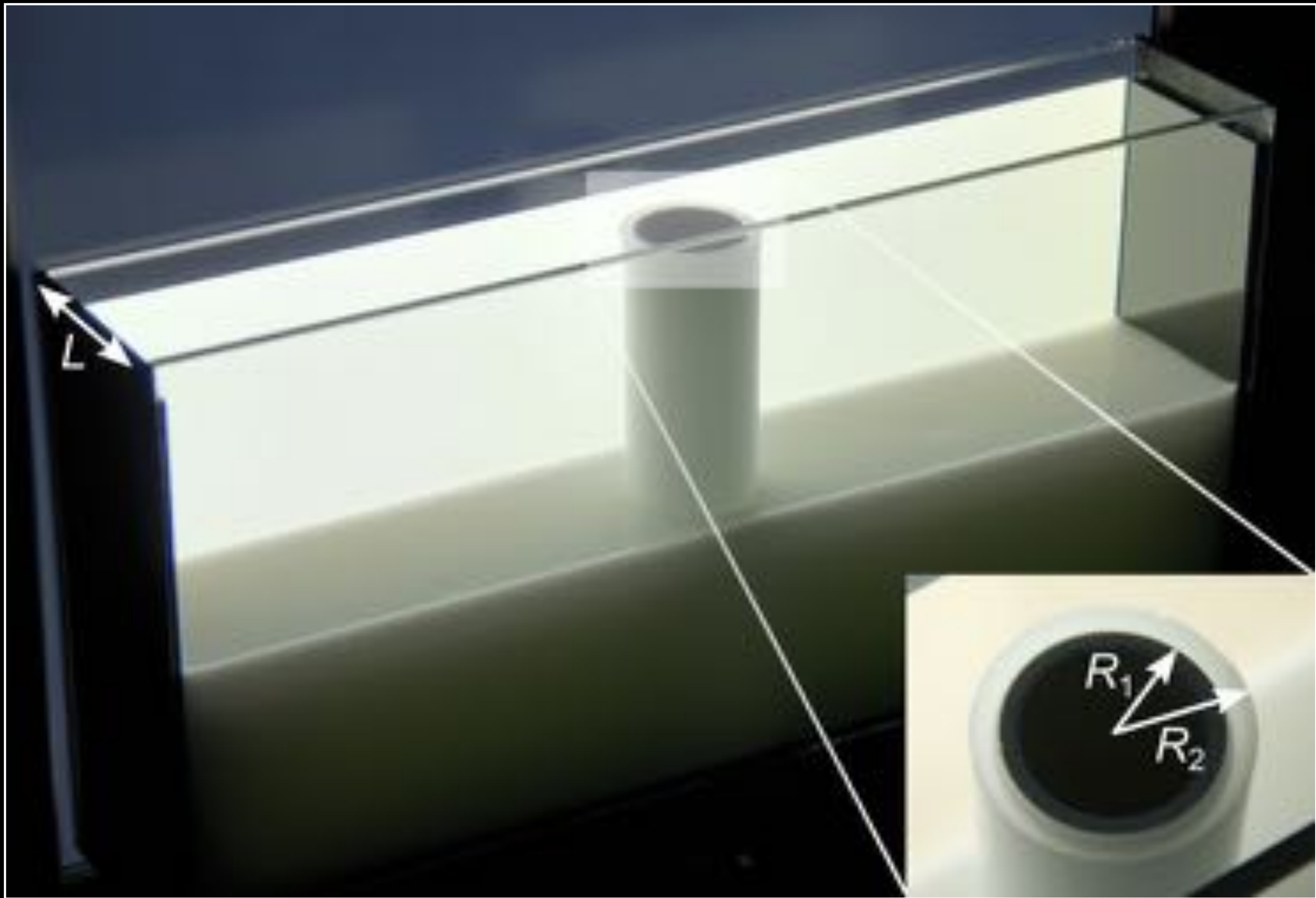
R. Schittny et al., Phys. Rev. Lett. 110, 195901 (2013)

Invisible for Diffusive Light

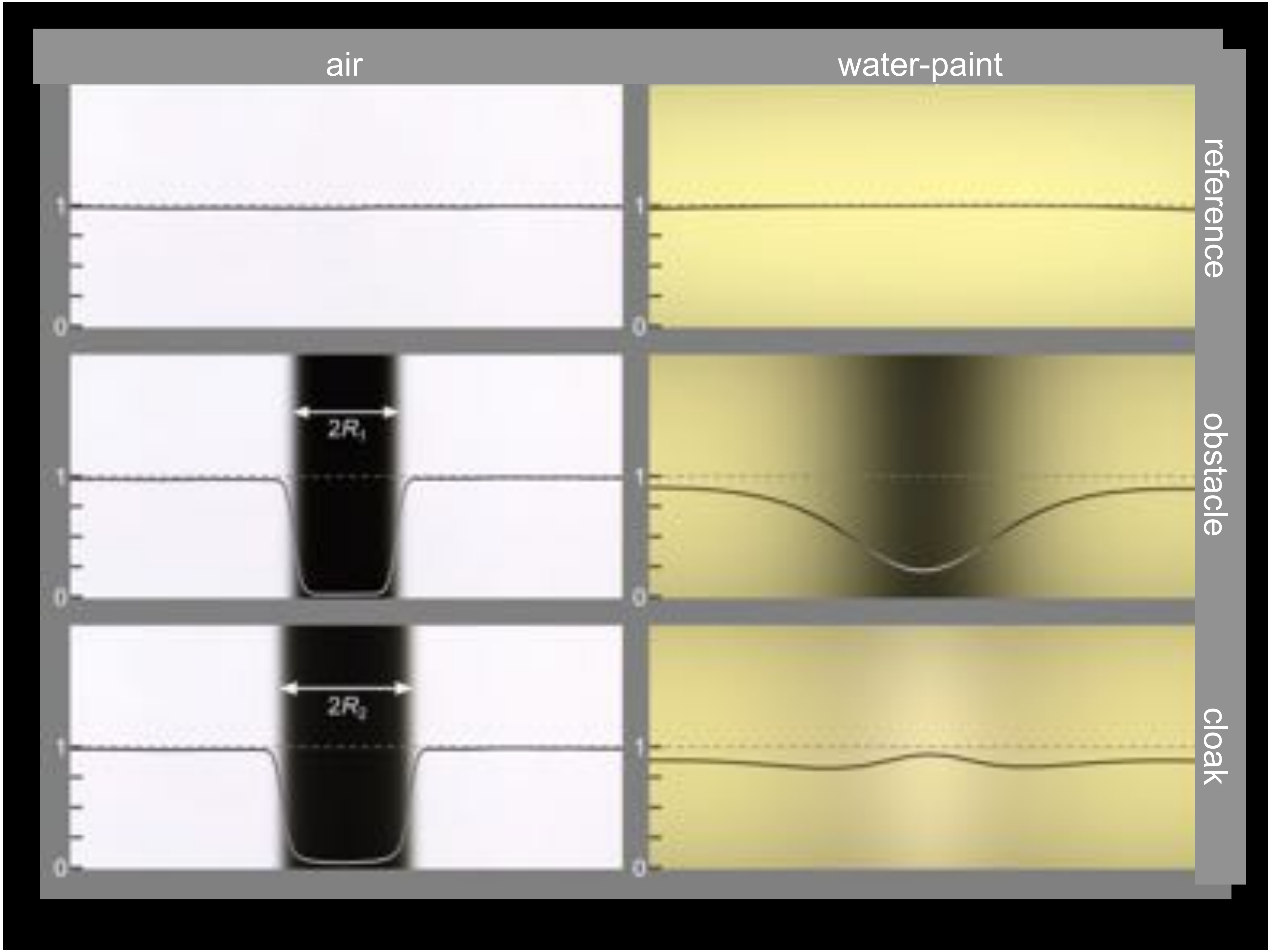


R. Schittny et al., Science 345, 427 (2014)

Experimental Setup



$L = 6.0\,\mathrm{cm}$, $2R_1 = 3.2\,\mathrm{cm}$, $2R_2 = 4.0\,\mathrm{cm}$



air
water-paint
reference
obstacle
cloak
$2R_1$
$2R_2$
1
0

Sound waves and sonar

The deep sea

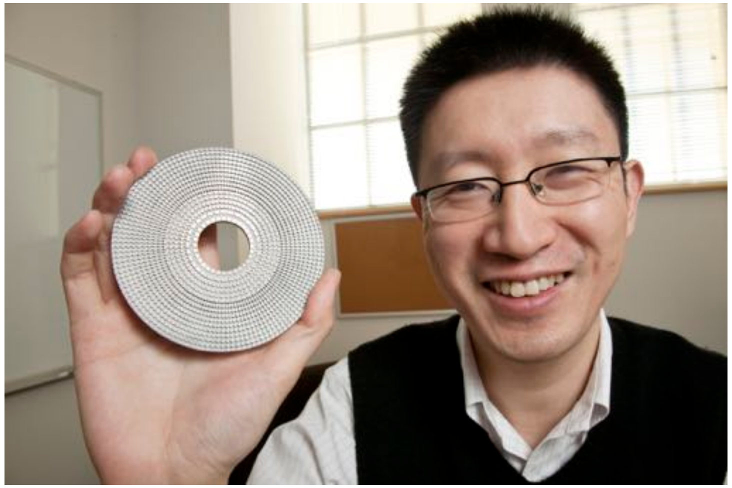
Sound waves and sonar

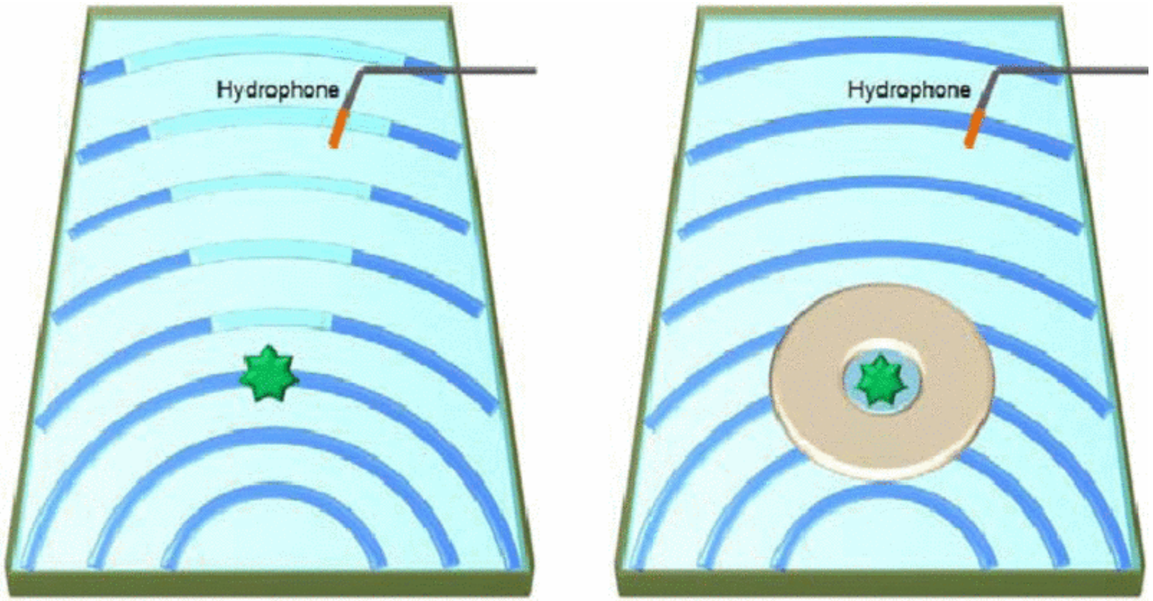
Sound waves and sonar

Cloaking against sound waves

Nicholas Fang,
MIT

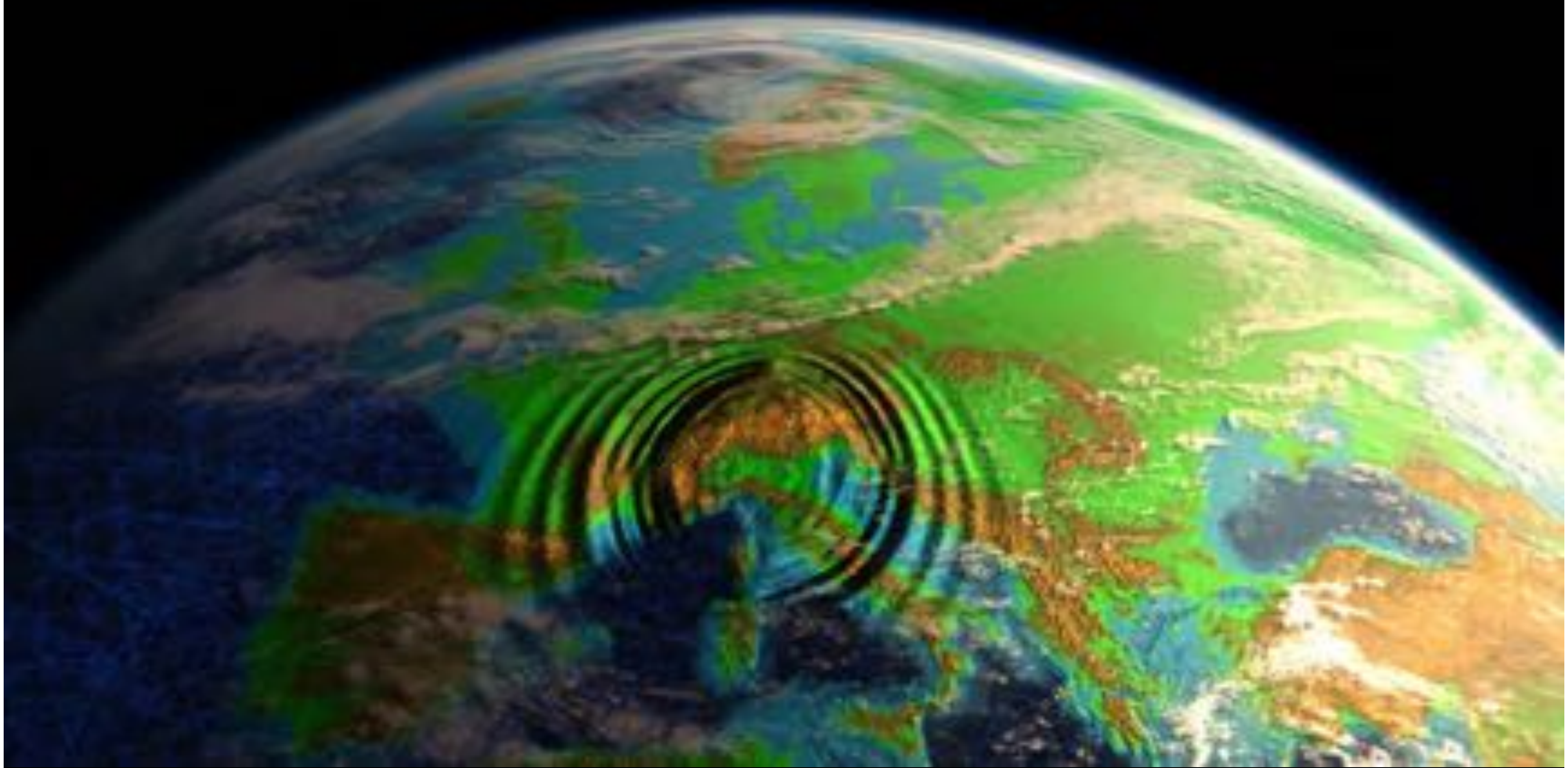
Photo: L. Brain
Stauffer





(a) (b)

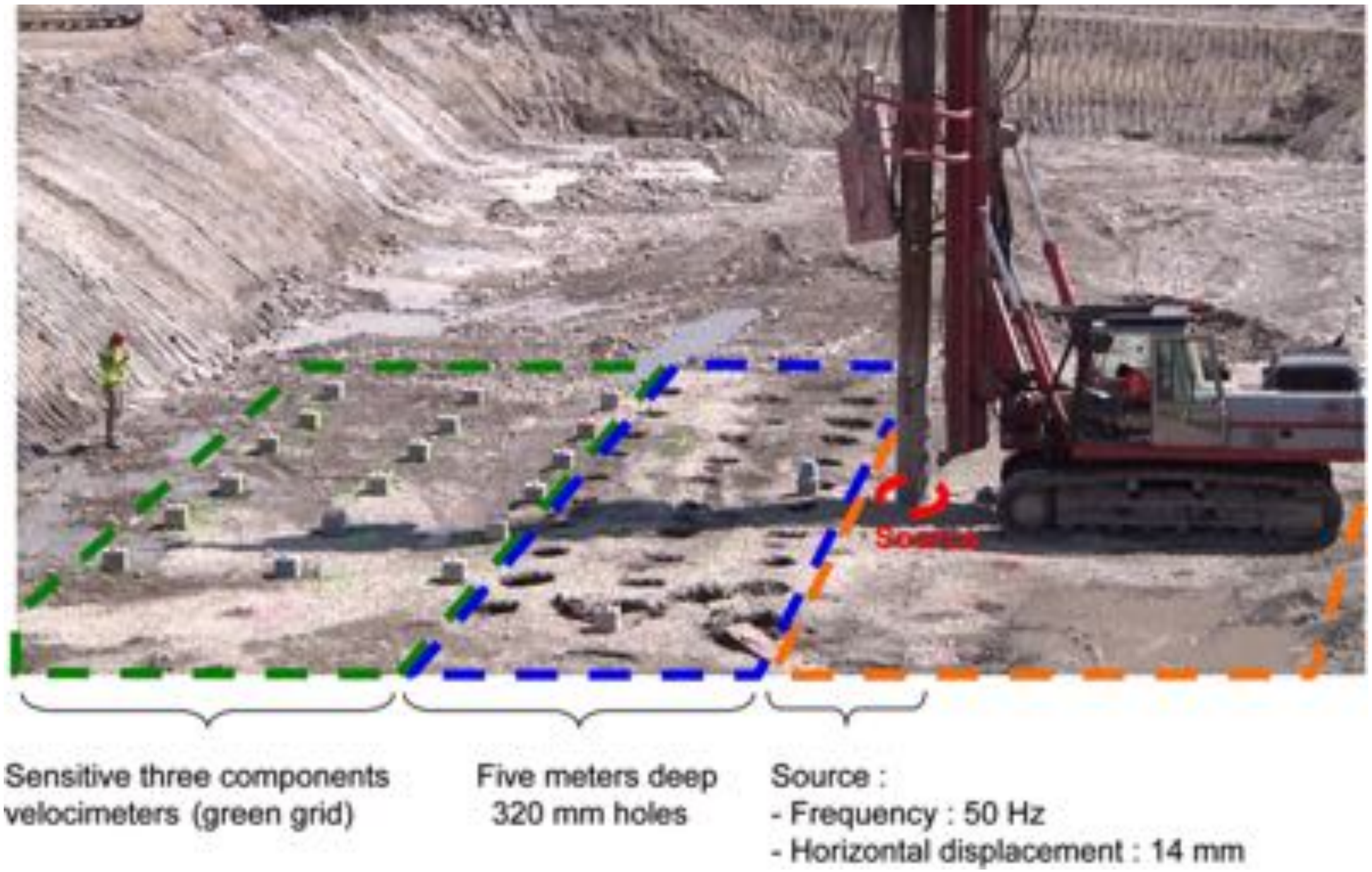
Earthquakes



Selected for a Viewpoint in *Physics*
PRL **112,** 133901 (2014) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2014

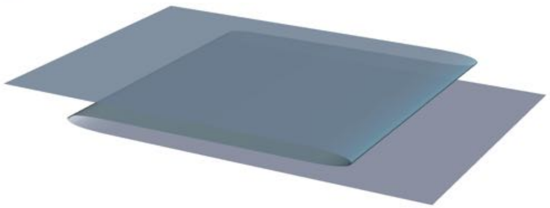
Experiments on Seismic Metamaterials: Molding Surface Waves

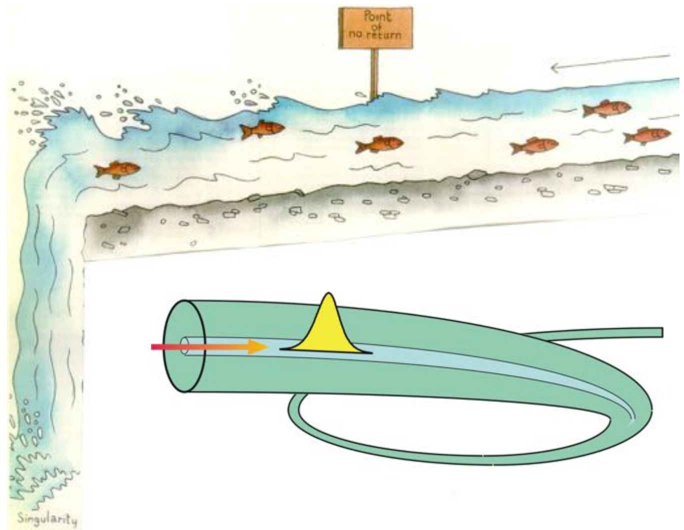
S. Brûlé,[1] E. H. Javelaud,[1] S. Enoch,[2] and S. Guenneau[2]
[1]*Ménard, 91 620 Nozay, France*
[2]*Aix-Marseille Université, CNRS, Centrale Marseille, Institut Fresnel, UMR 7249, 13013 Marseille, France*
(Received 18 May 2013; published 31 March 2014)

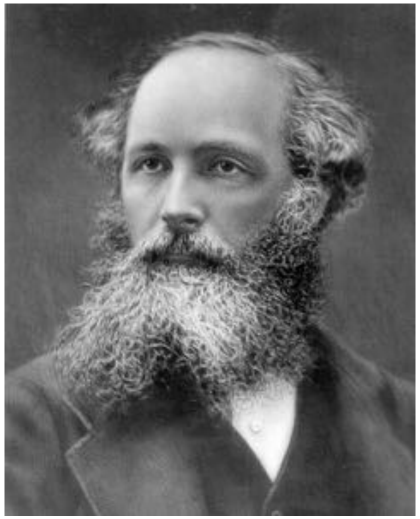


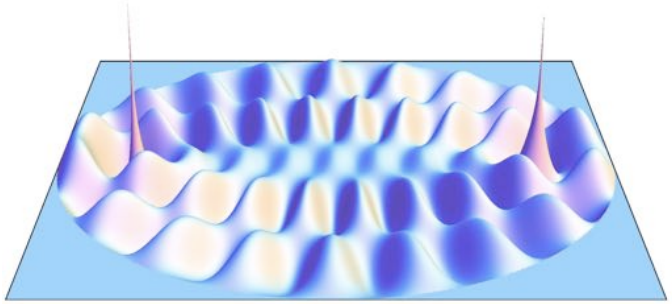
General relativity in electrical engineering

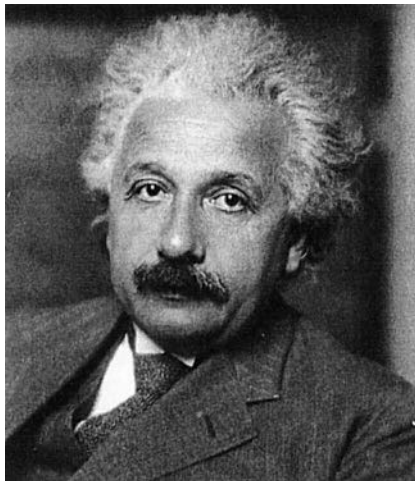
[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]



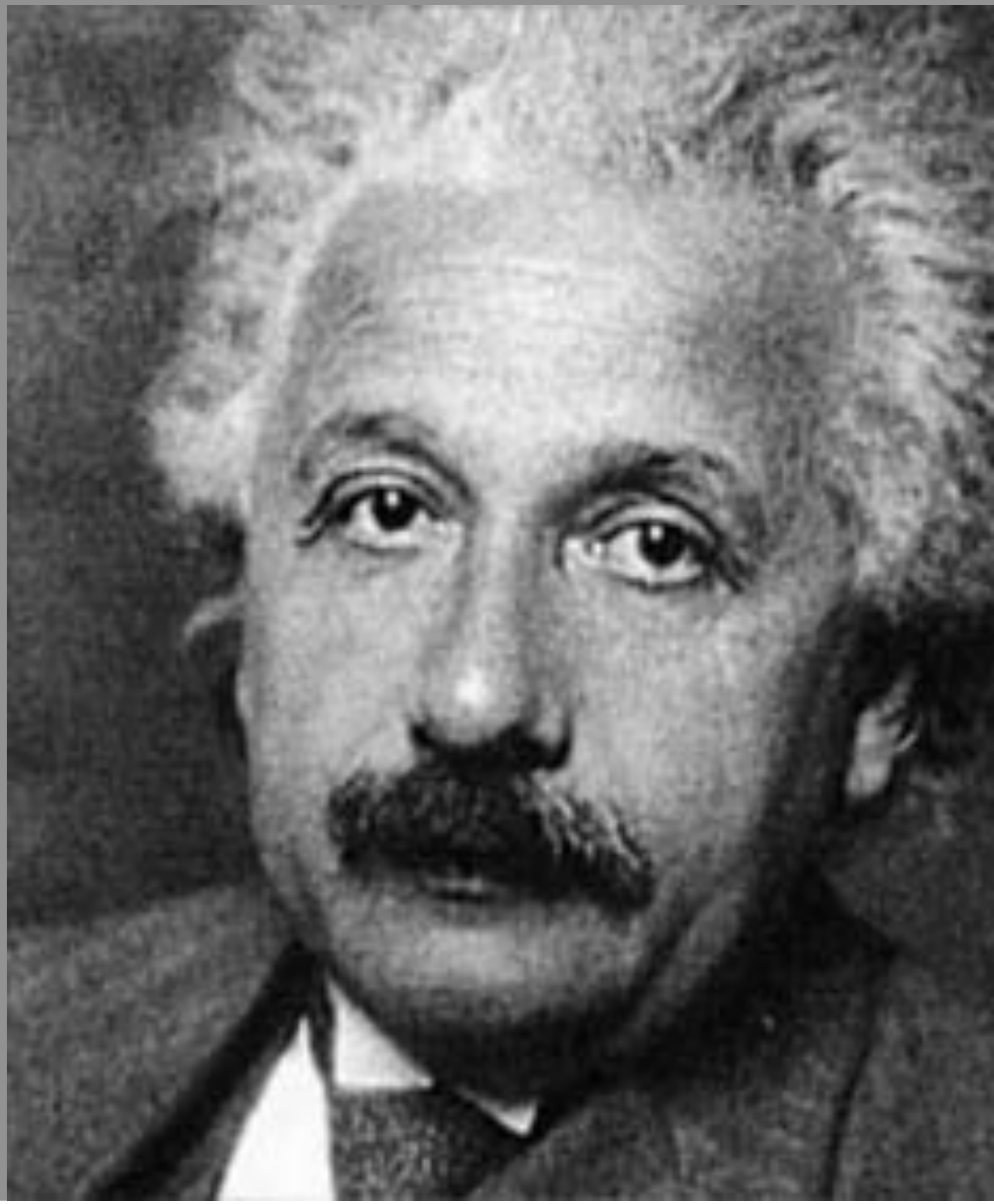


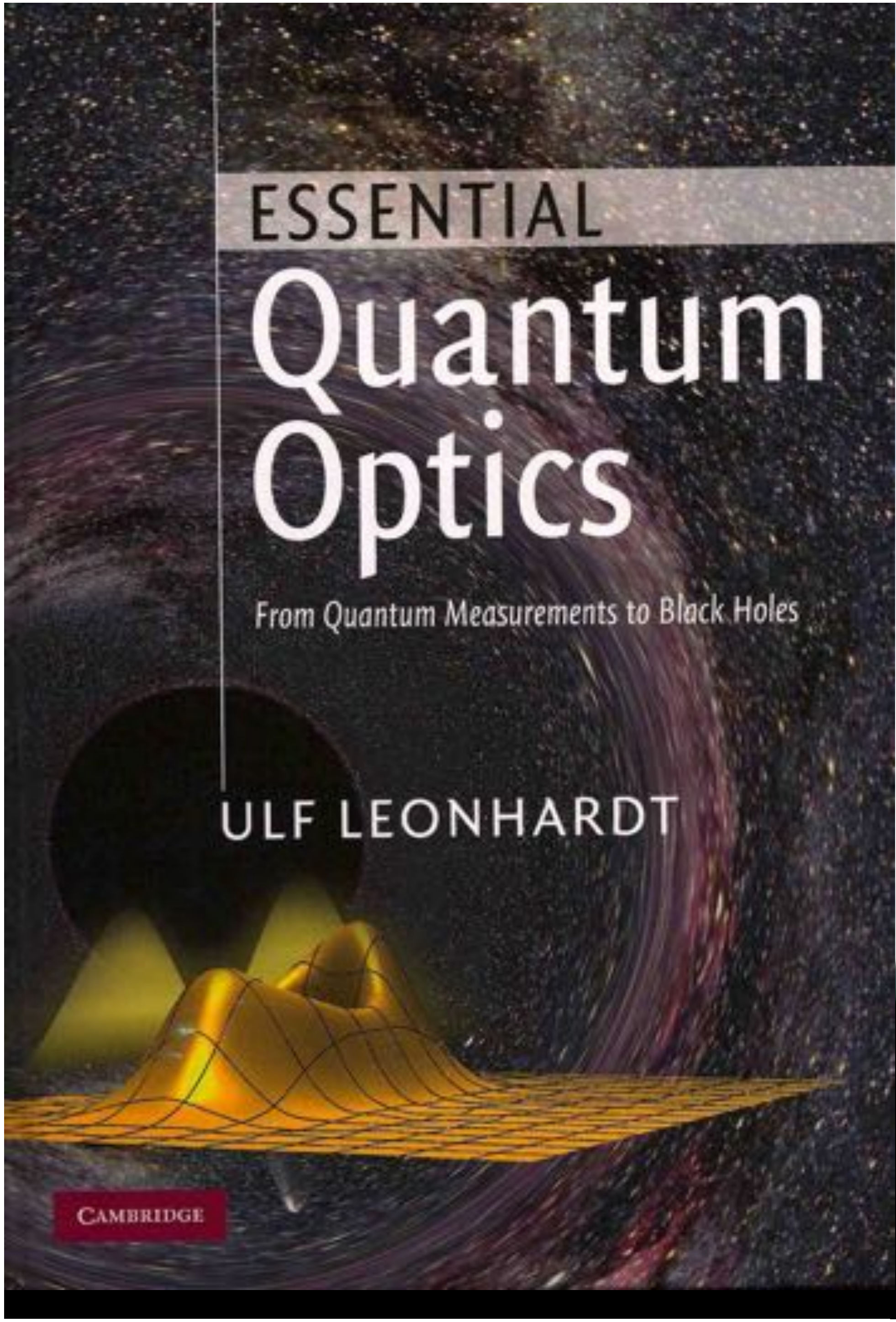


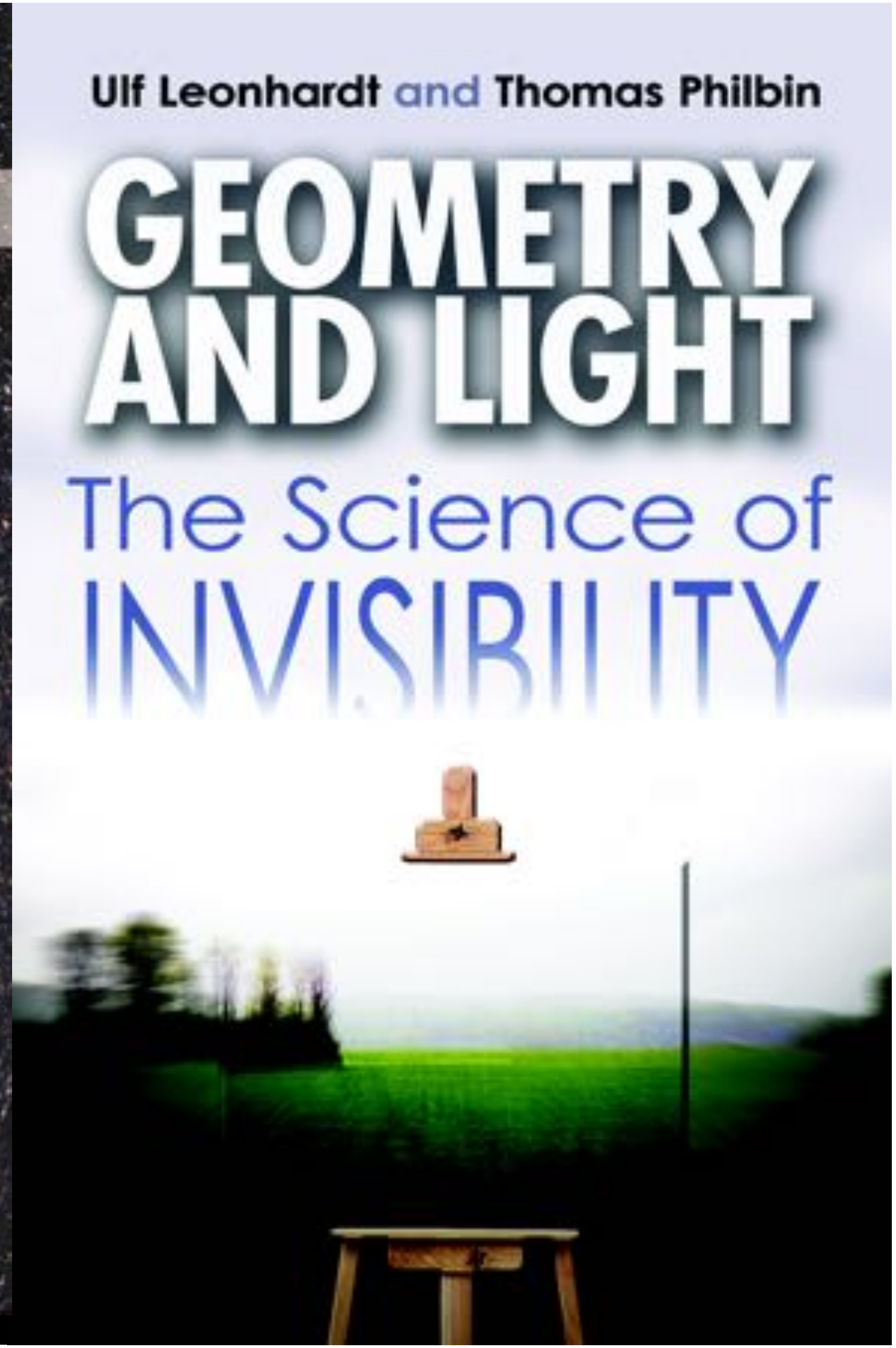




Einwell and Maxstein




ESSENTIAL
Quantum
Optics
From Quantum Measurements to Black Holes
ULF LEONHARDT
CAMBRIDGE


Ulf Leonhardt and Thomas Philbin
GEOMETRY
AND LIGHT
The Science of
INVISIBILITY