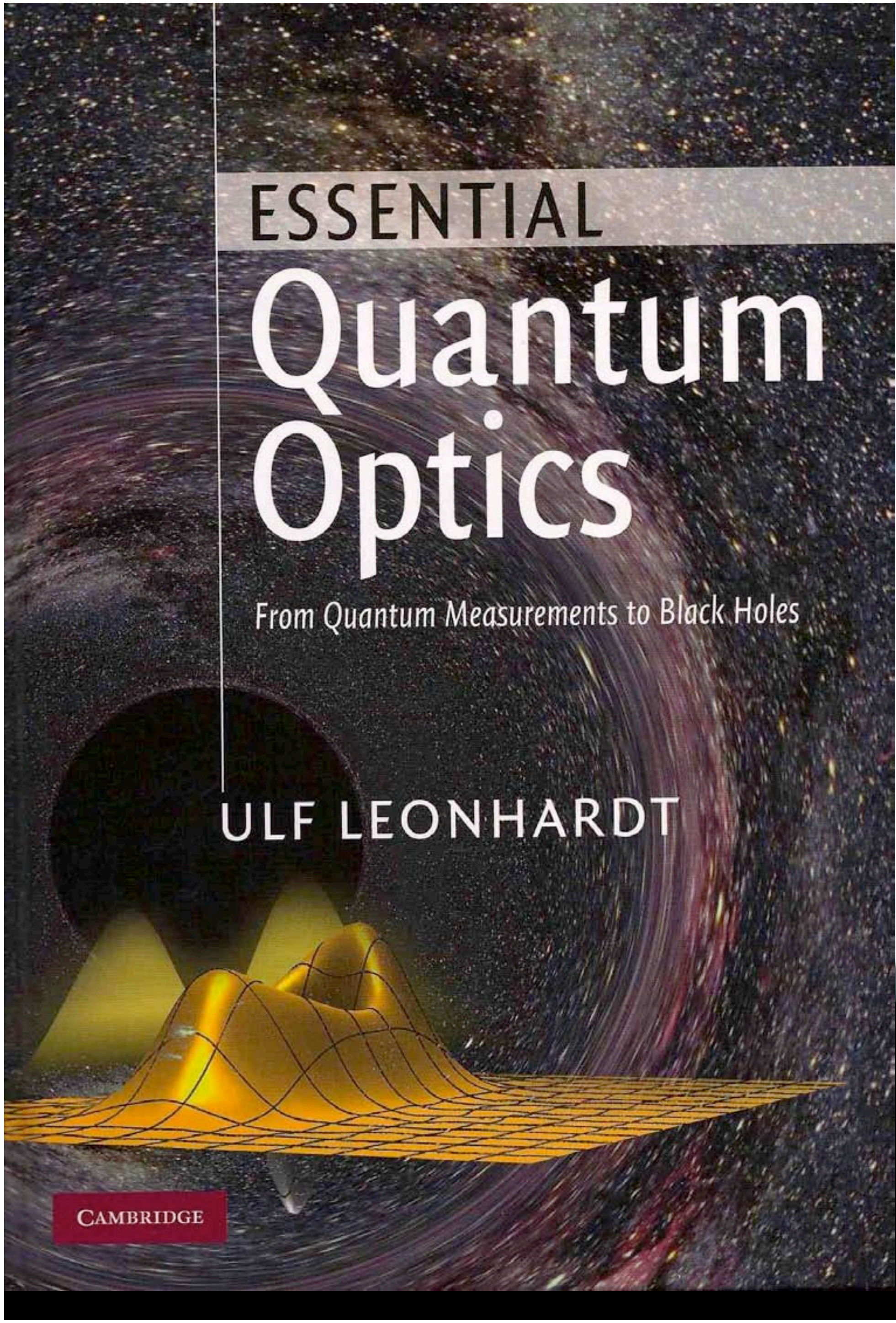
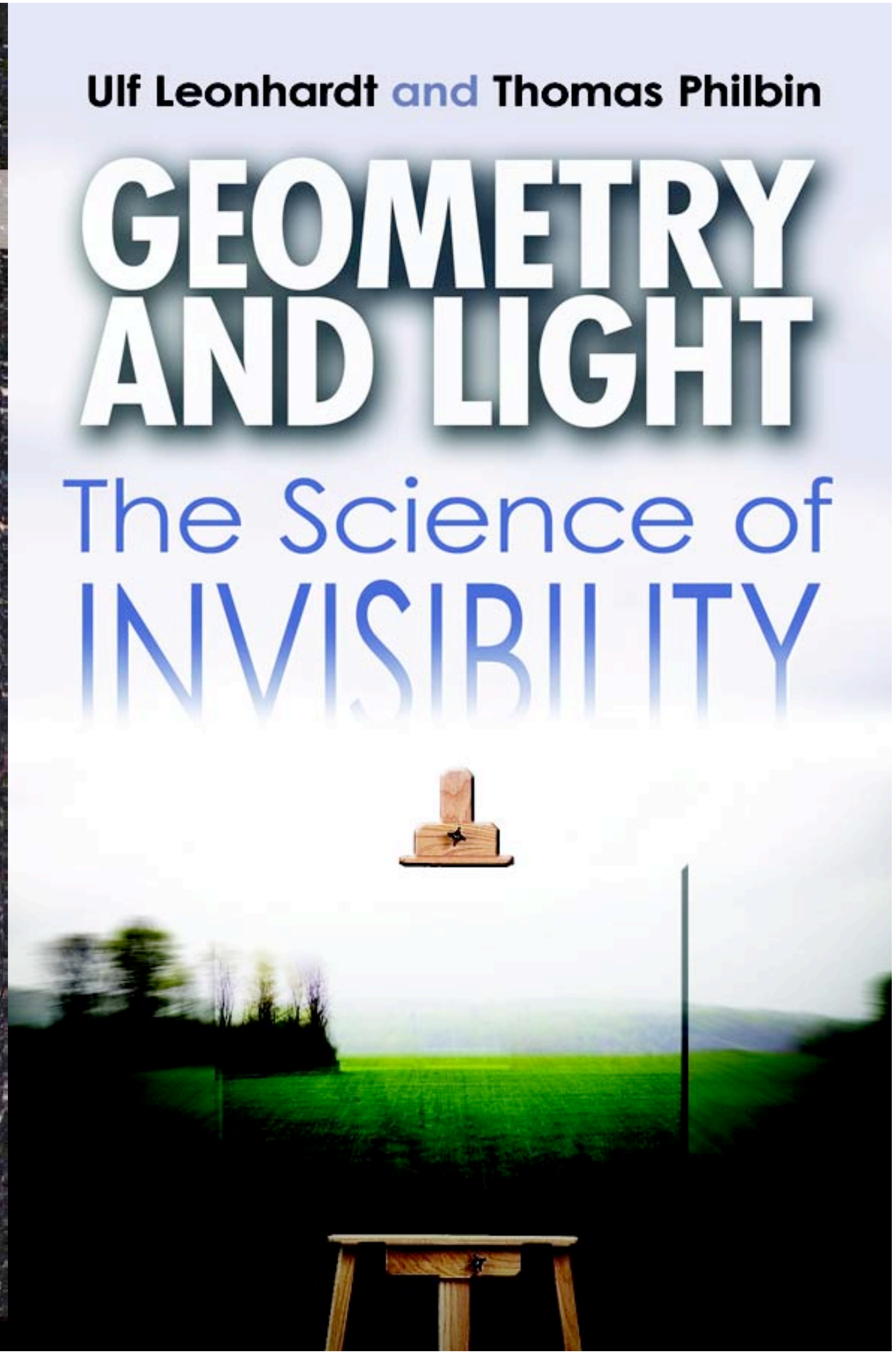
Invisibility Cloaking and Perfect Imaging

Ulf Leonhardt, University of St Andrews, UK

THE ROYAL SOCIETY
CELEBRATING 350 YEARS


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

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

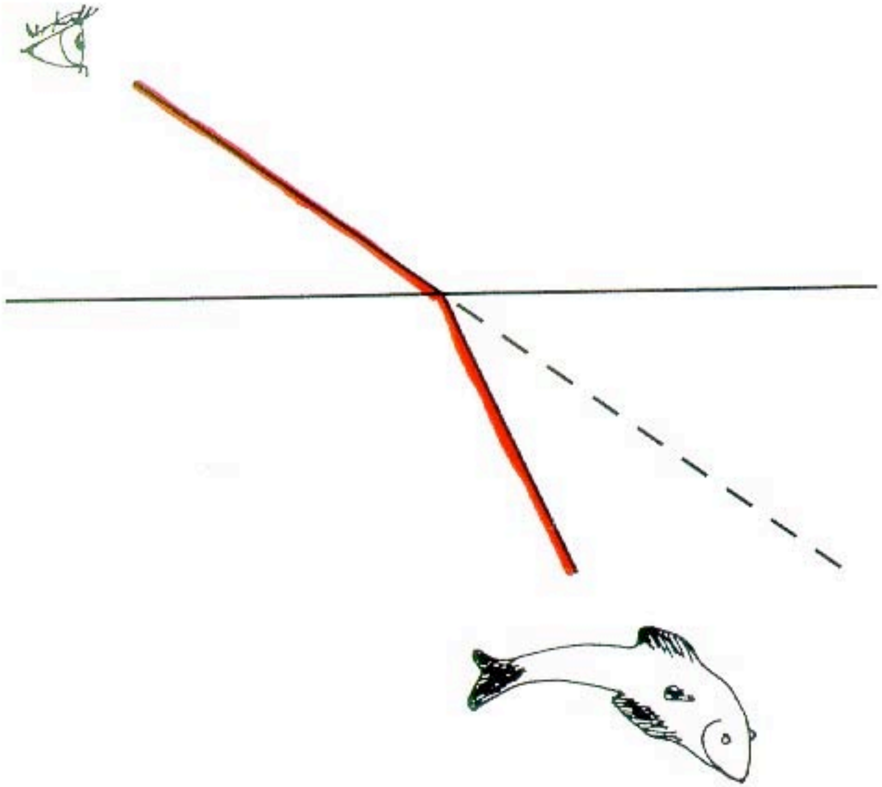
Invisibility: Invisible Man versus Invisible Woman

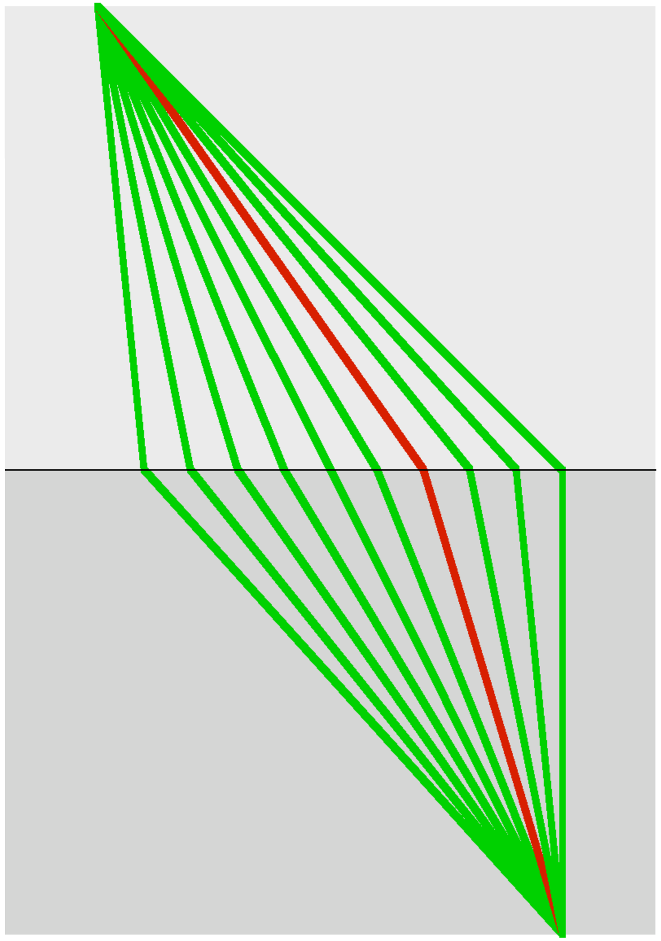
transparency

curved space

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

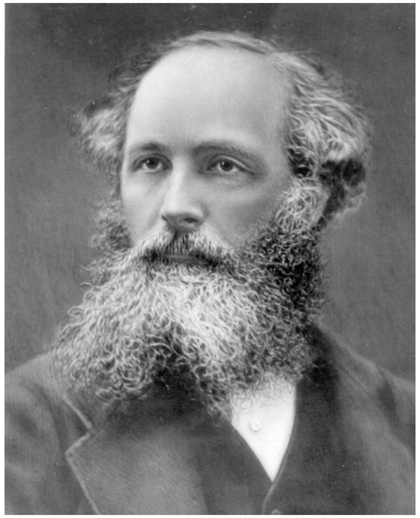
$$s = \int n \, dl$$





Maxwell's electromagnetism and Einstein's general relativity

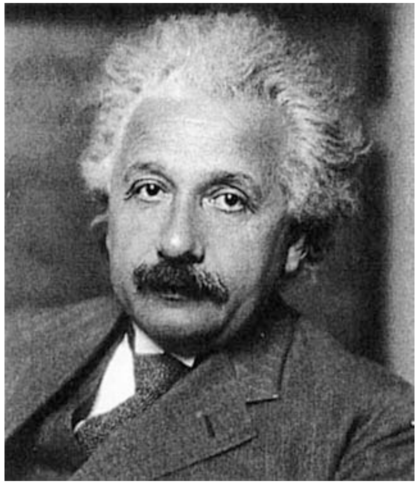
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}, \quad \nabla \cdot \vec{D} = \varrho$$



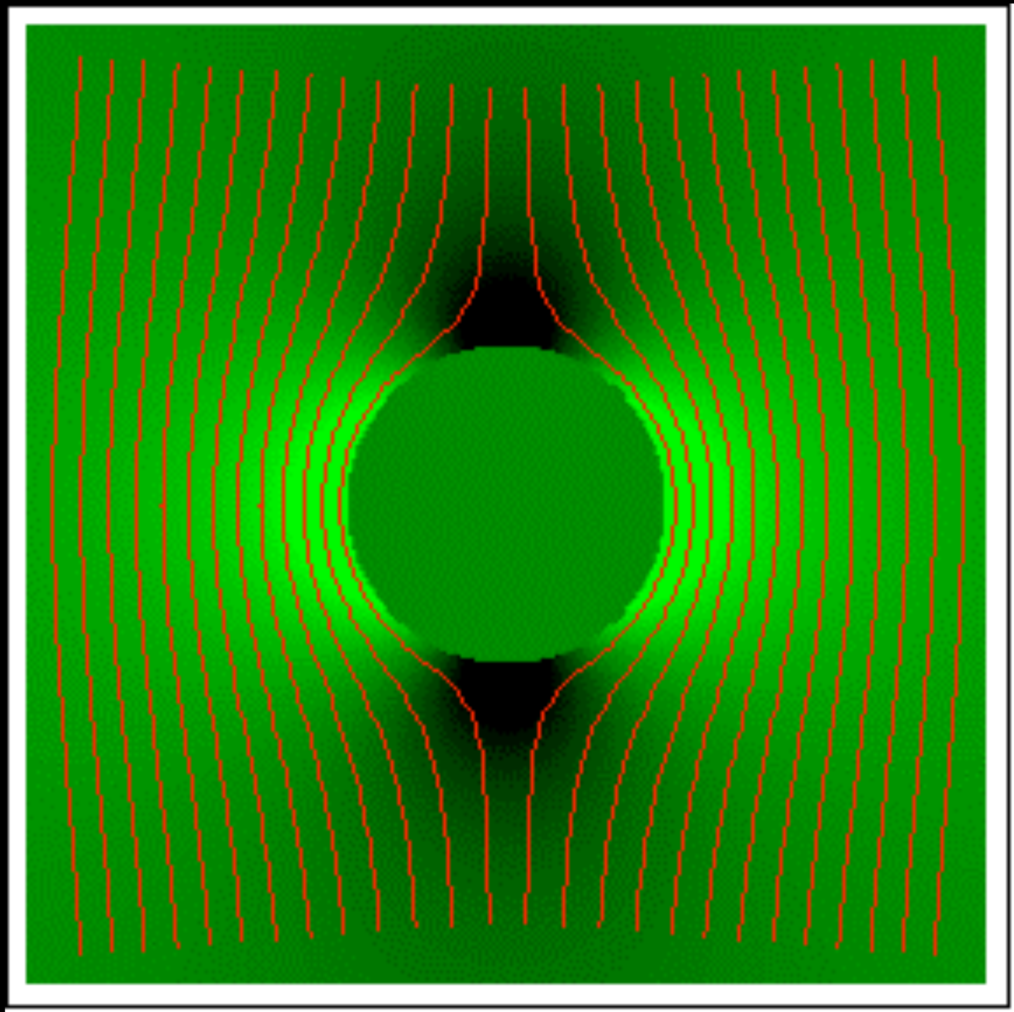
The covariant free-space Maxwell equations are equivalent to electromagnetism in a material medium
(Tamm, 1924; Plebanski, 1960).

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

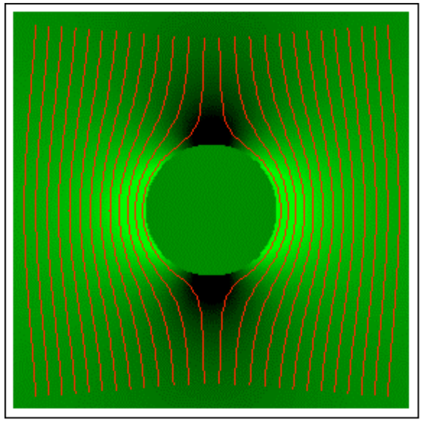
$$\varepsilon^{ij} = \mu^{ij} = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}, \quad w_i = \frac{g_{0i}}{g_{00}}$$



Leonhardt 2002: Invisibility cloak?

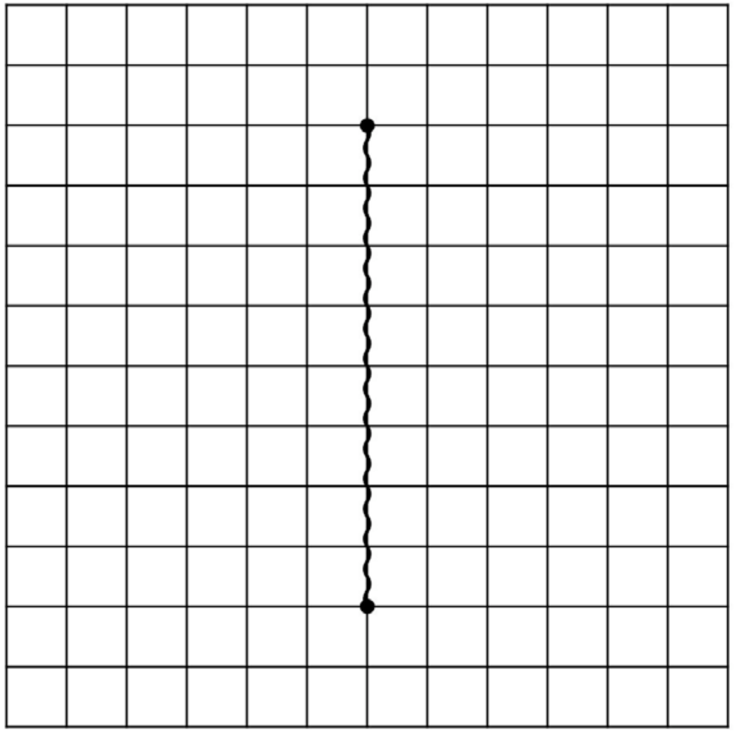


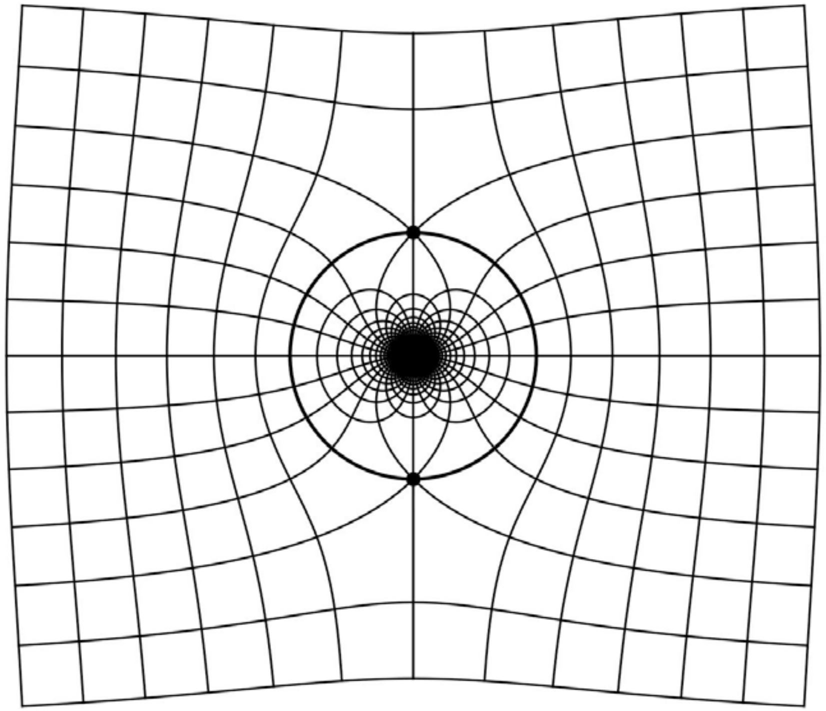
[Leonhardt, Science **312**, 1777 (2006)]



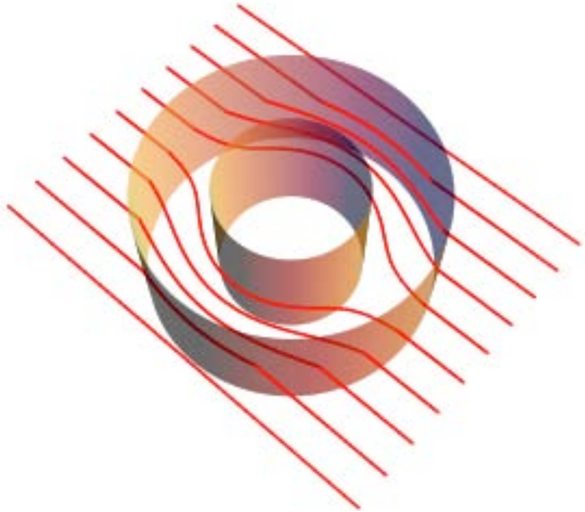
Virtual space

Physical space



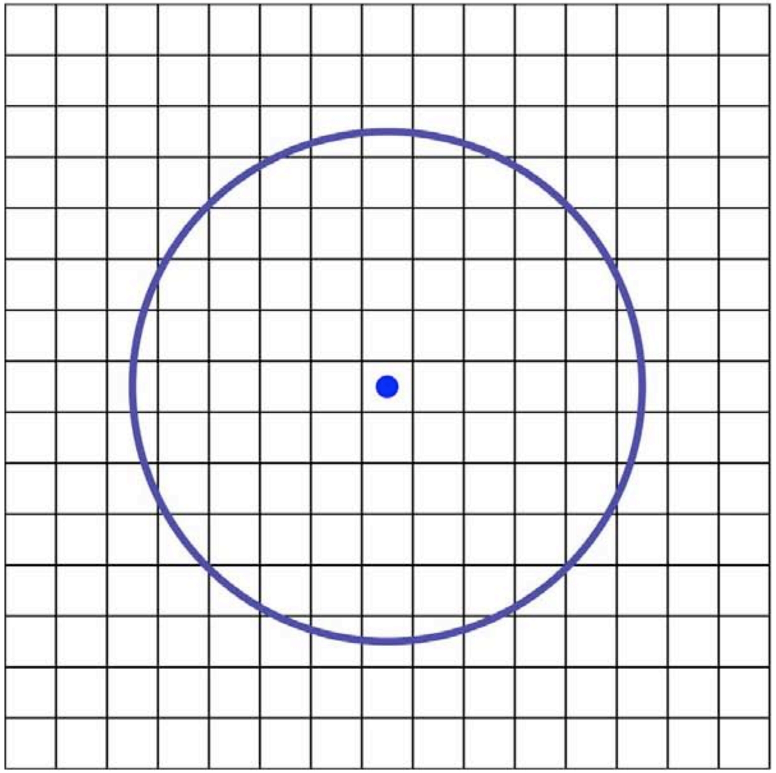


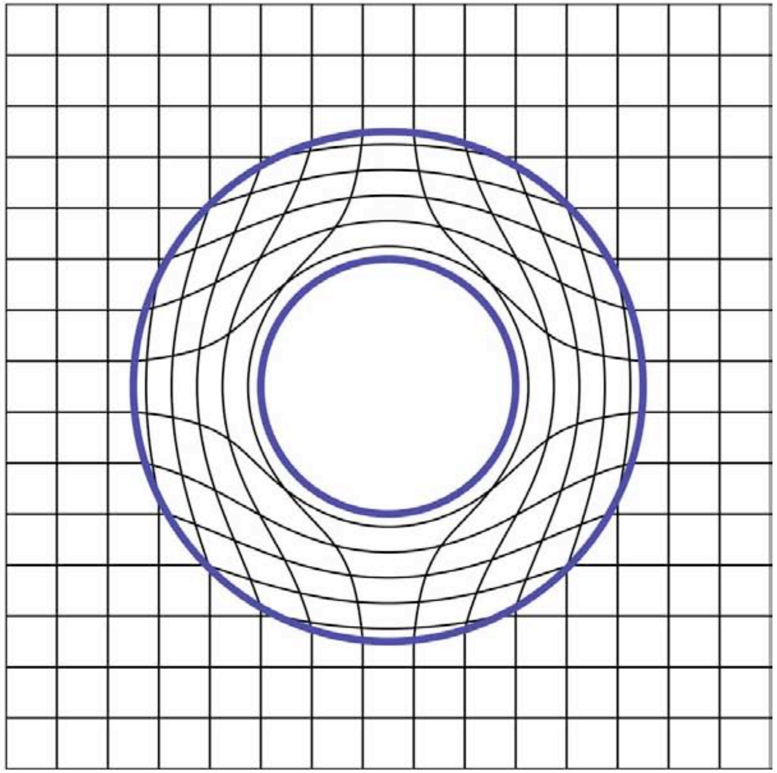
Pendry, Schurig and Smith,
Science **312**, 1780 (2006)]



Virtual space

Physical space





Maxwell's electromagnetism and Einstein's general relativity

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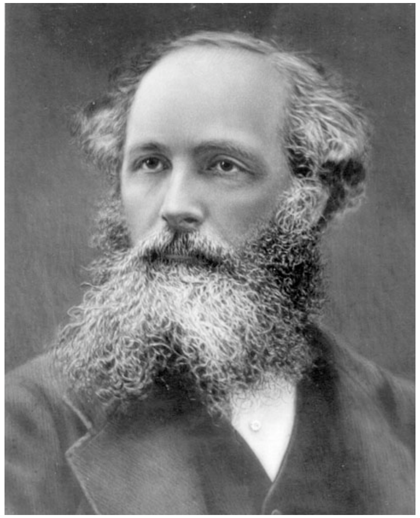

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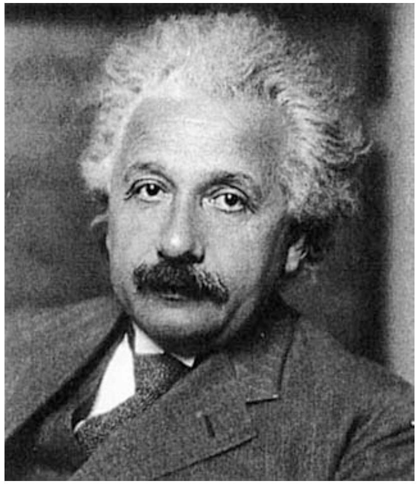

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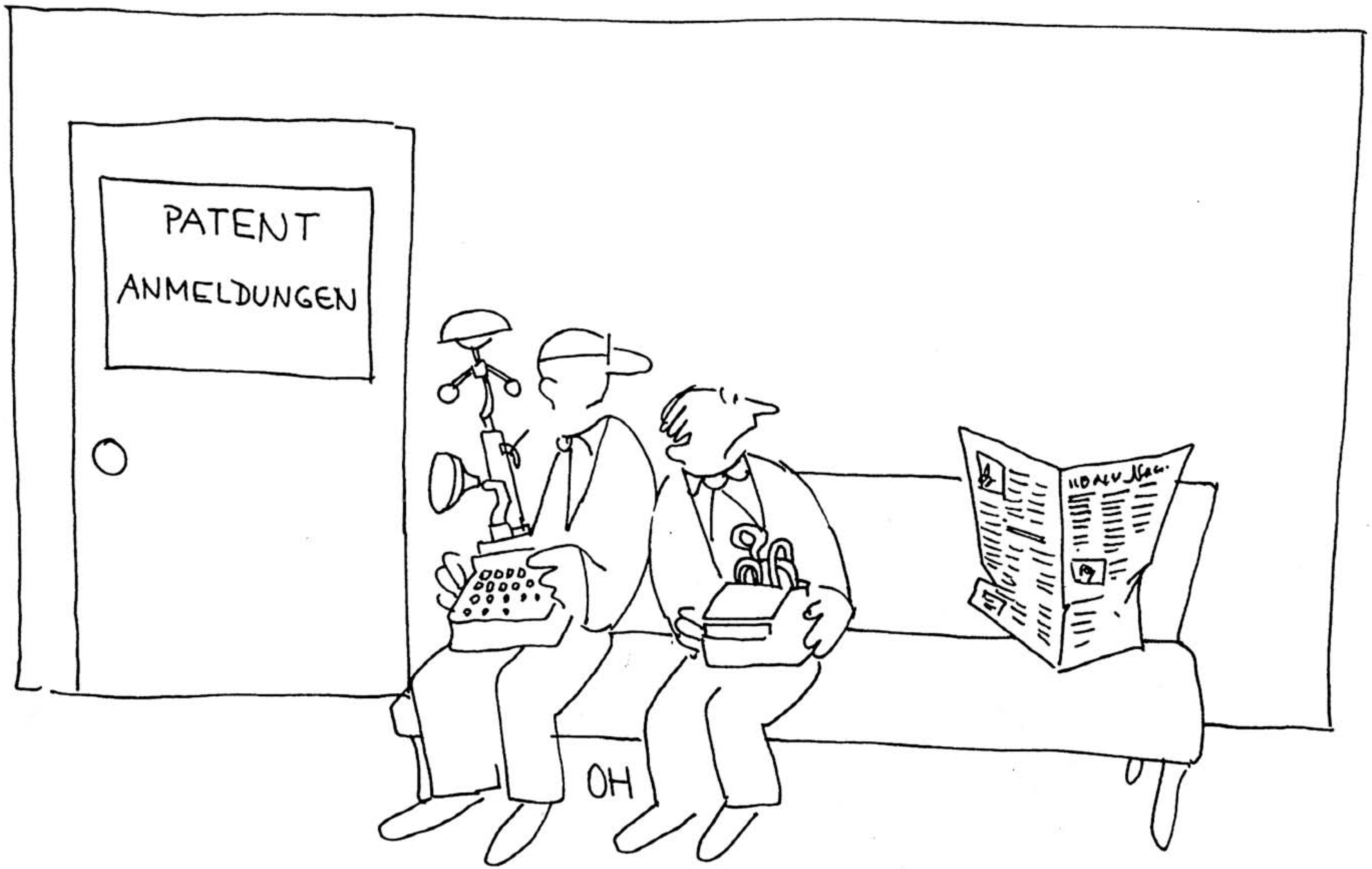
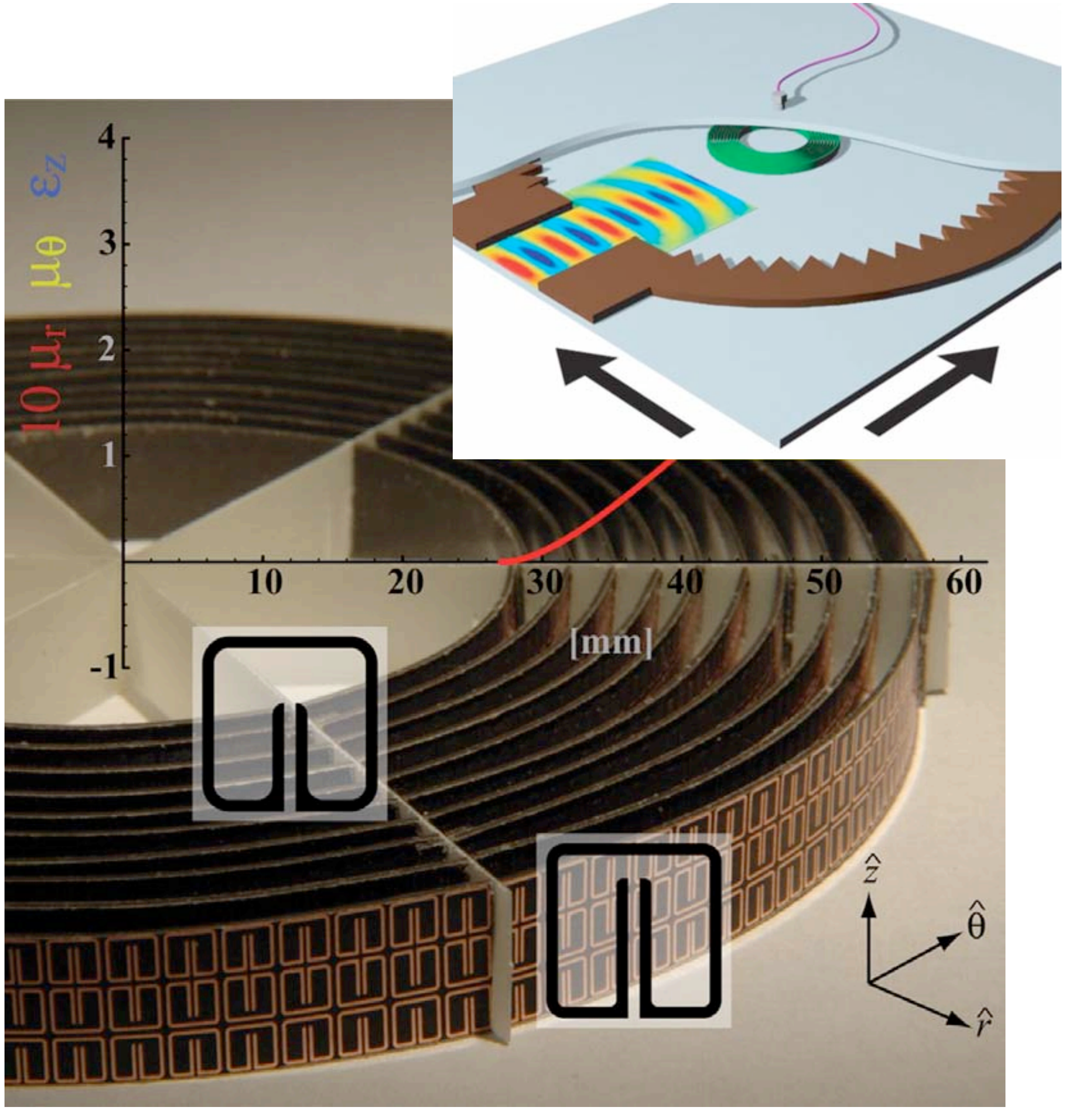
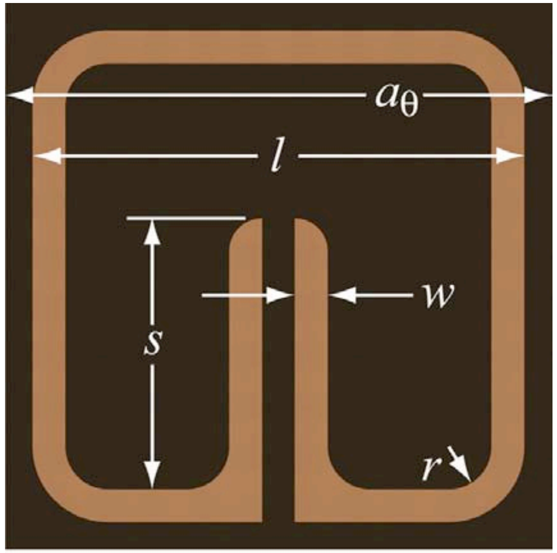
Patent office

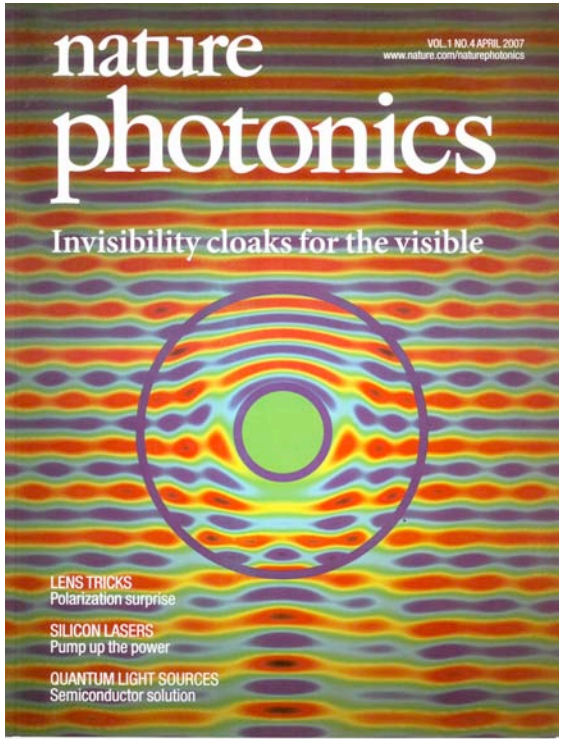


Cloaking device for electromagnetic microwaves

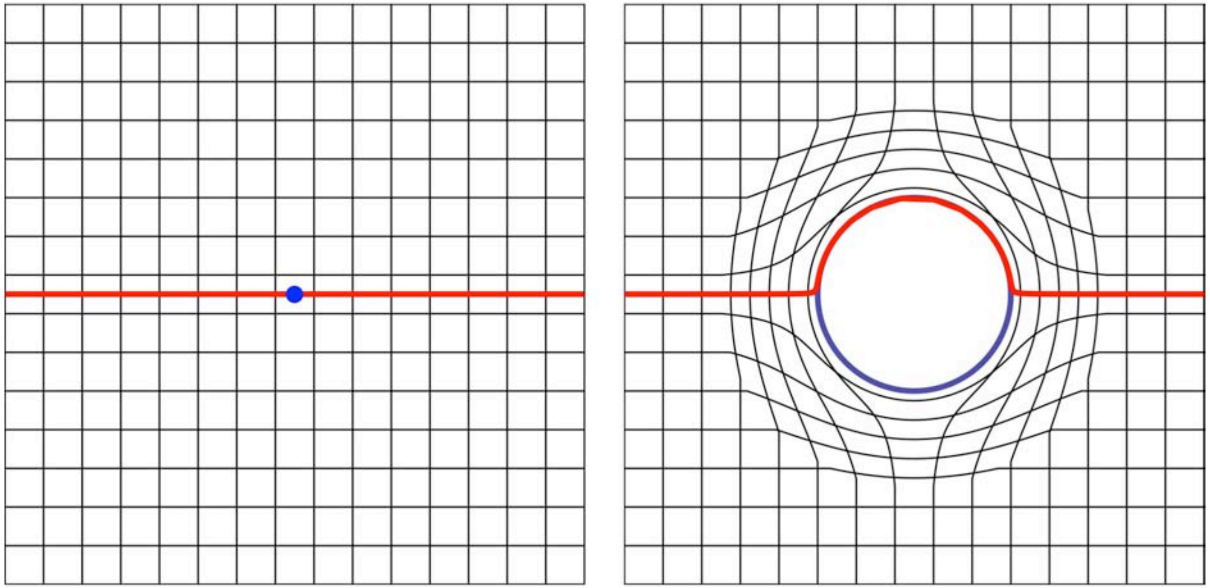




cyl.	r	s	μ_r
1	0.260	1.654	0.003
2	0.254	1.677	0.023
3	0.245	1.718	0.052
4	0.230	1.771	0.085
5	0.208	1.825	0.120
6	0.190	1.886	0.154
7	0.173	1.951	0.188
8	0.148	2.027	0.220
9	0.129	2.110	0.250
10	0.116	2.199	0.279



Challenge: Broadband invisibility



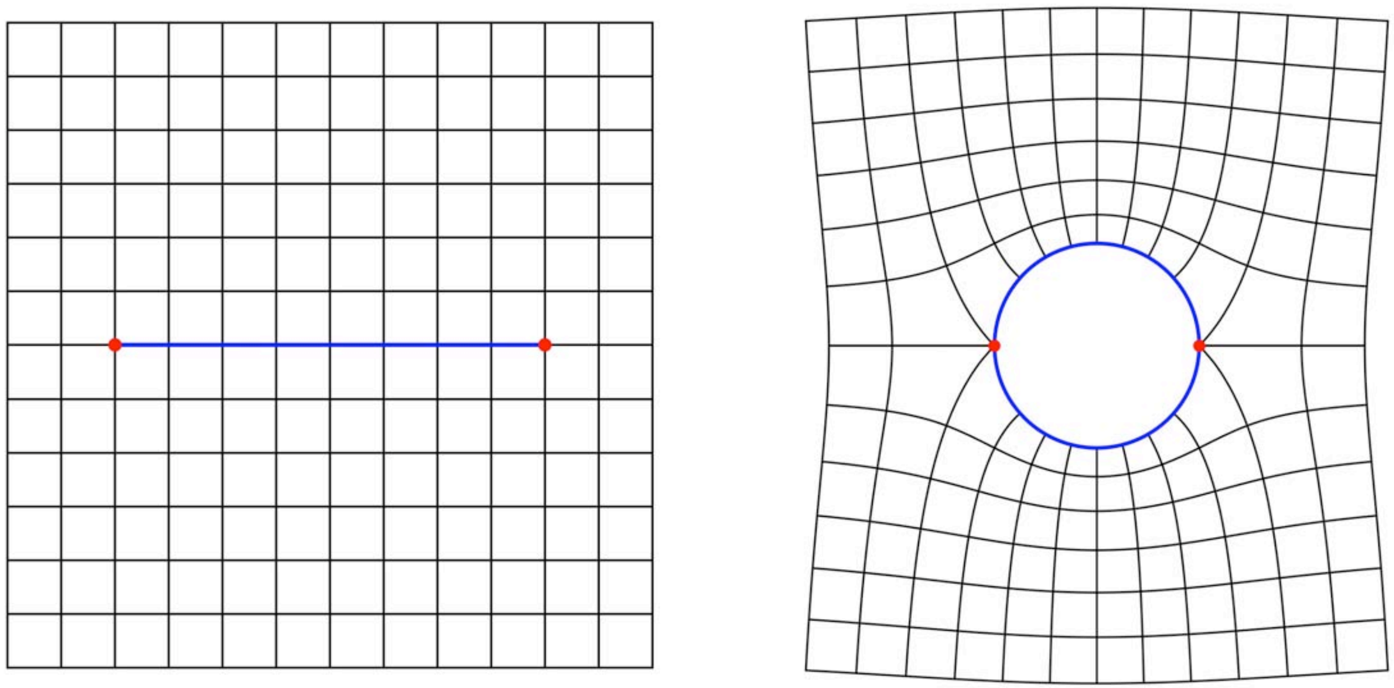
Problems: * anomalous dispersion,
* infinite phase velocity at inner lining
[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]
* zero group velocity
[H. Chen, C.T. Chan, J. Appl. Phys. **104**, 033113 (2008)]

Hiding under the Carpet: A New Strategy for Cloaking

Jensen Li and J. B. Pendry
Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
(Received 10 June 2008; revised manuscript received 7 August 2008; published 10 November 2008)

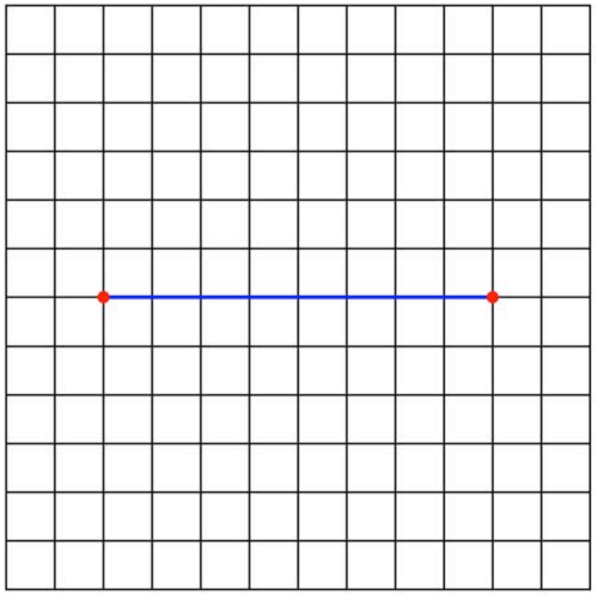
A new type of cloak is discussed: one that gives all cloaked objects the appearance of a flat conducting sheet. It has the advantage that none of the parameters of the cloak is singular and can in fact be made isotropic. It makes broadband cloaking in the optical frequencies one step closer.

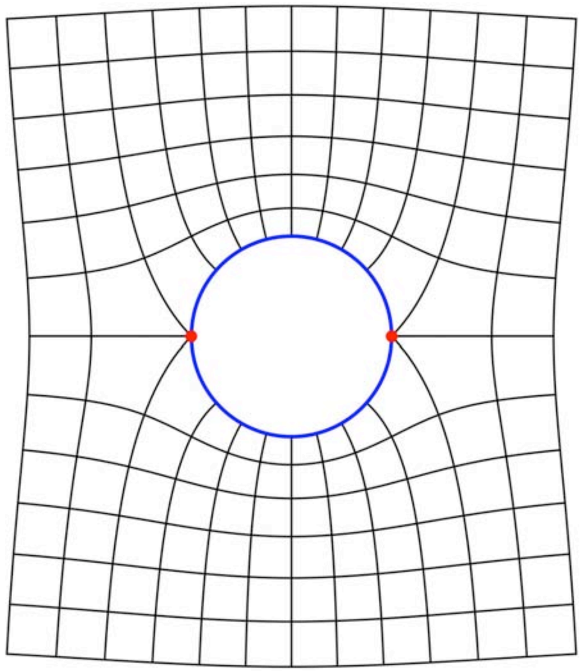
DOI: 10.1103/PhysRevLett.101.203901 PACS numbers: 42.79.−e, 02.40.−k, 41.20.−q



[Leonhardt, Science **312**, 1777 (2006); Tyc and Leonhardt, New J. Phys. **10**, 115038 (2008)]

From fugu to flatfish





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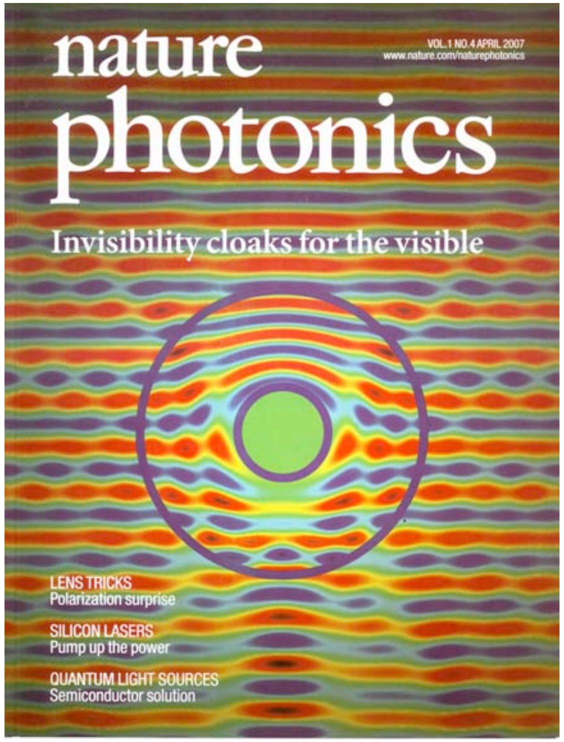

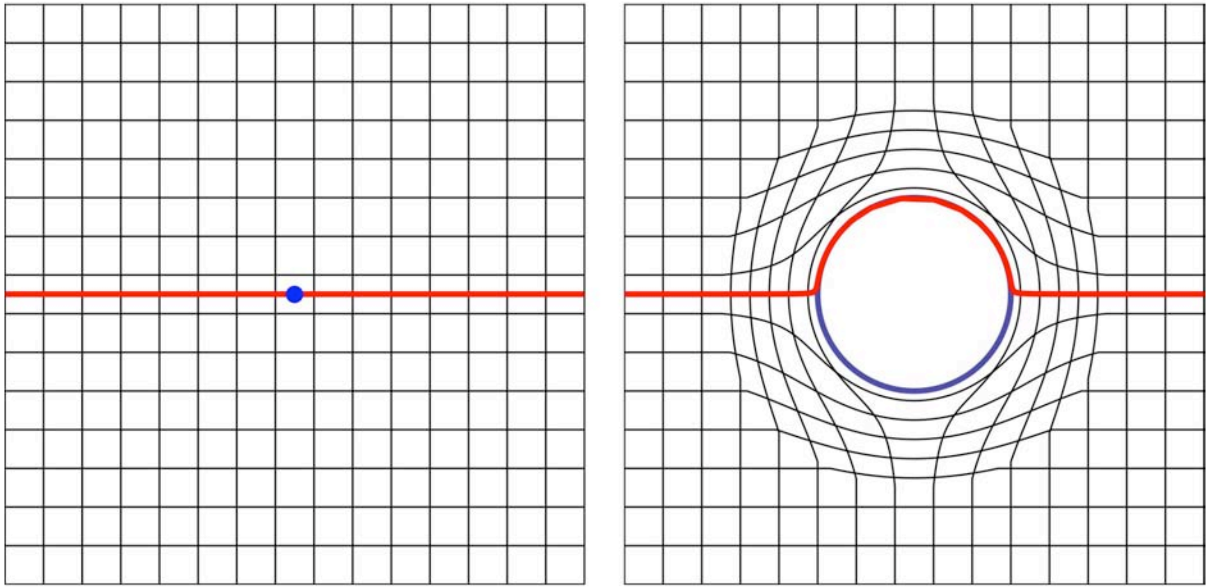

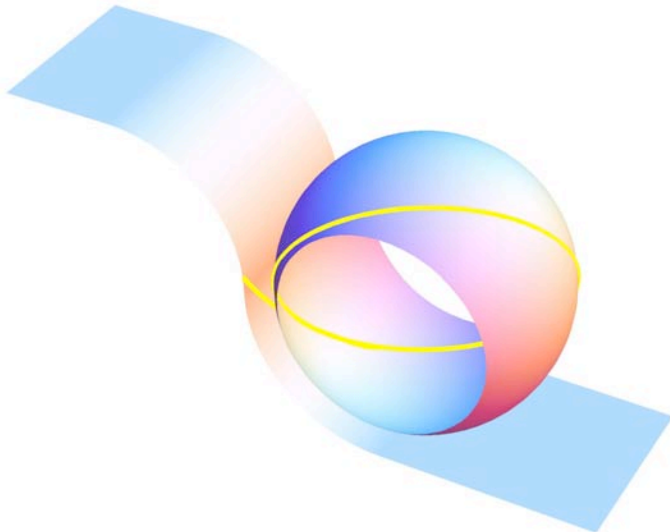

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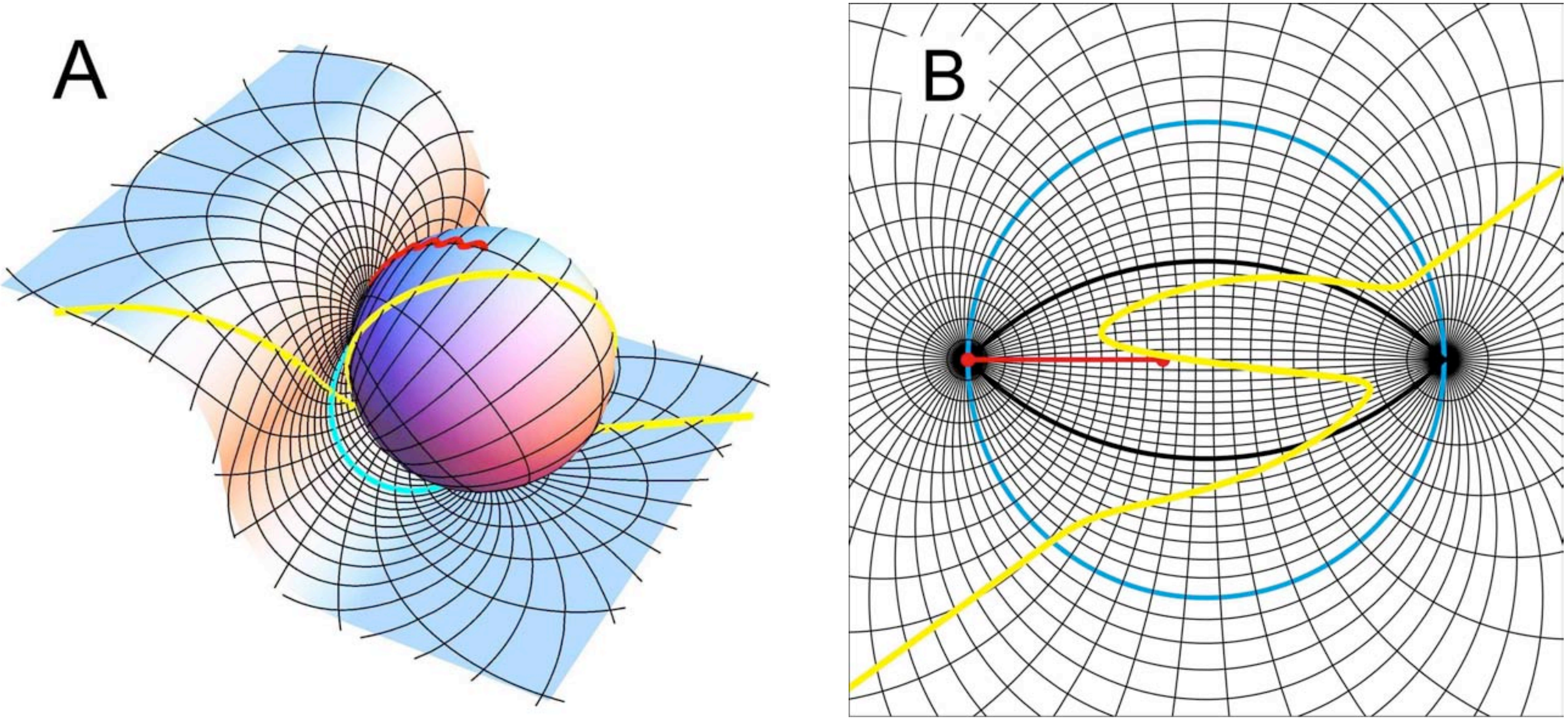
[H. Chen, C.T. Chan, J. Appl. Phys. **104**, 033113 (2008)]

Ideas from Non-Euclidean Geometry

The idea

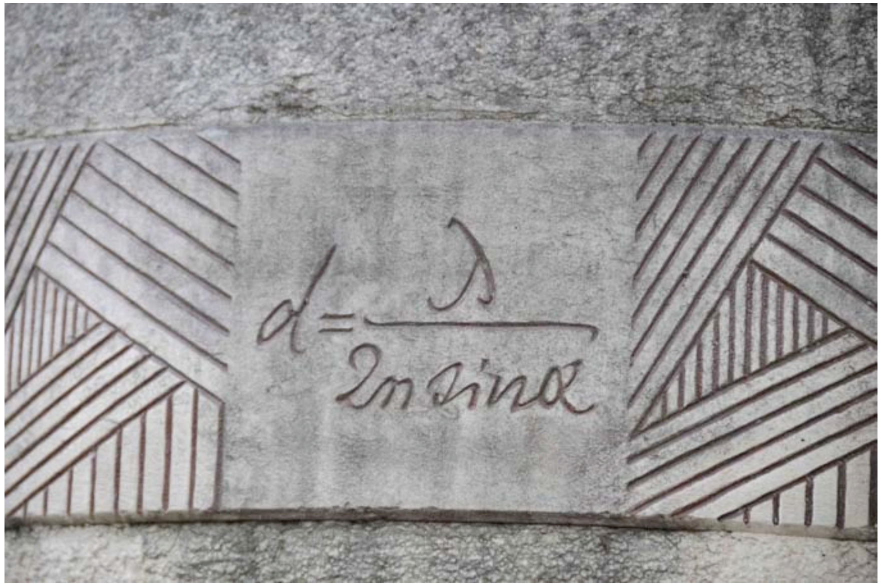


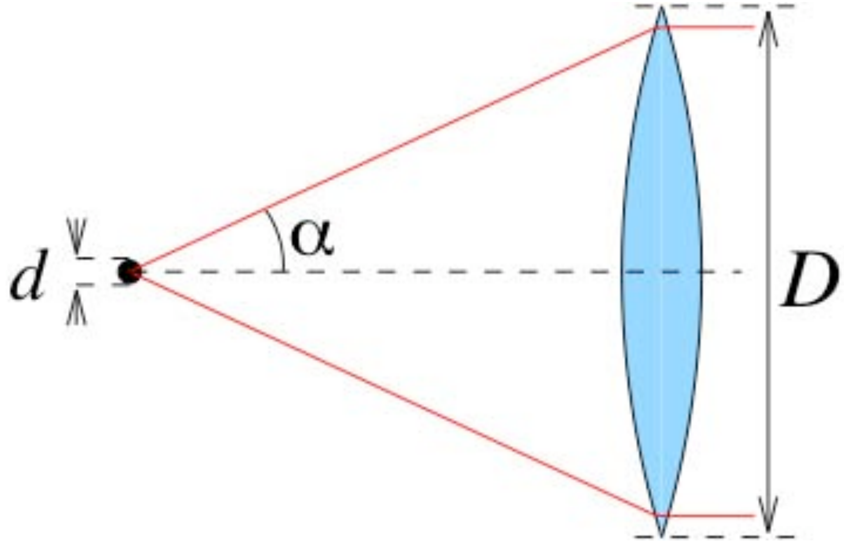
Sciencexpress Report

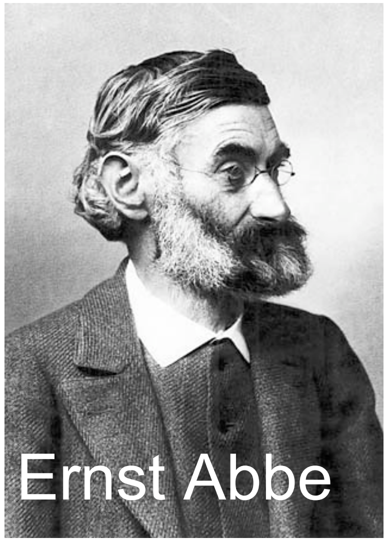
Broadband Invisibility by Non-Euclidean Cloaking

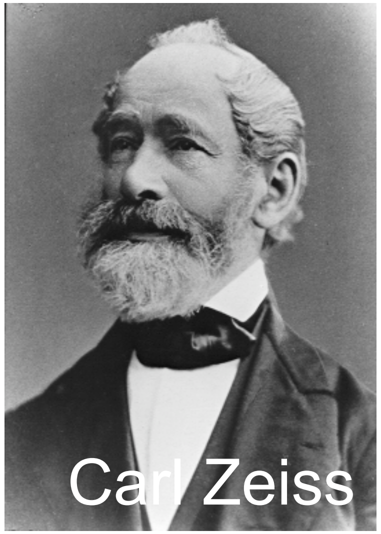
Ulf Leonhardt[1,2]* and Tomás Tyc[2,3]

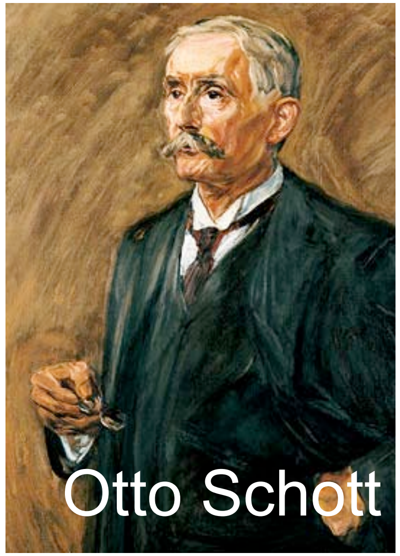
The resolution limit of imaging, established around 1870











VOLUME 85, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 2000

Negative Refraction Makes a Perfect Lens

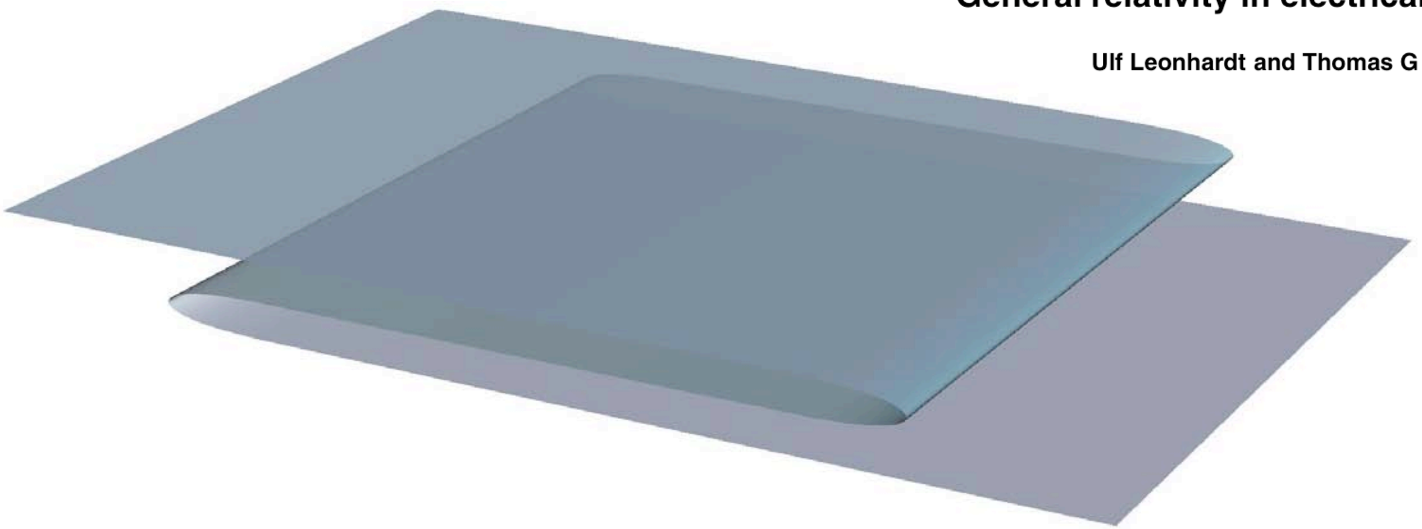
J. B. Pendry
Condensed Matter Theory Group, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
(Received 25 April 2000)

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.

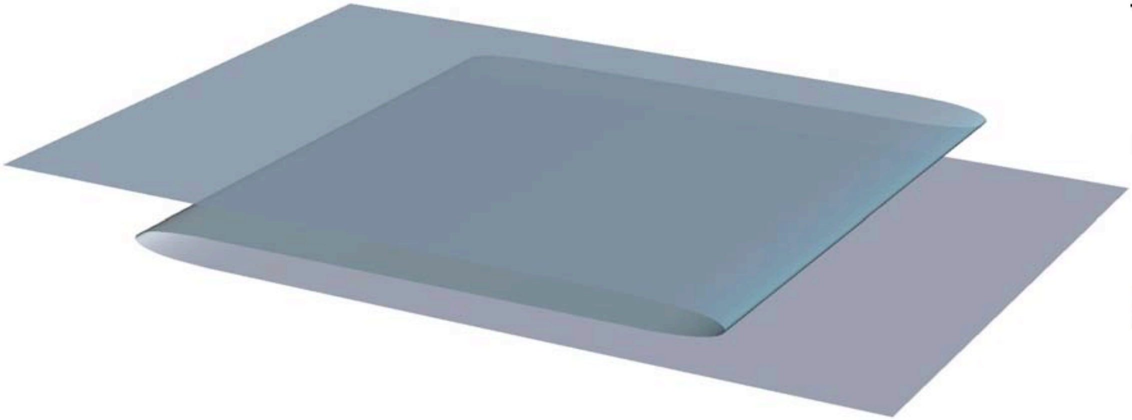
New Journal of Physics
The open-access journal for physics

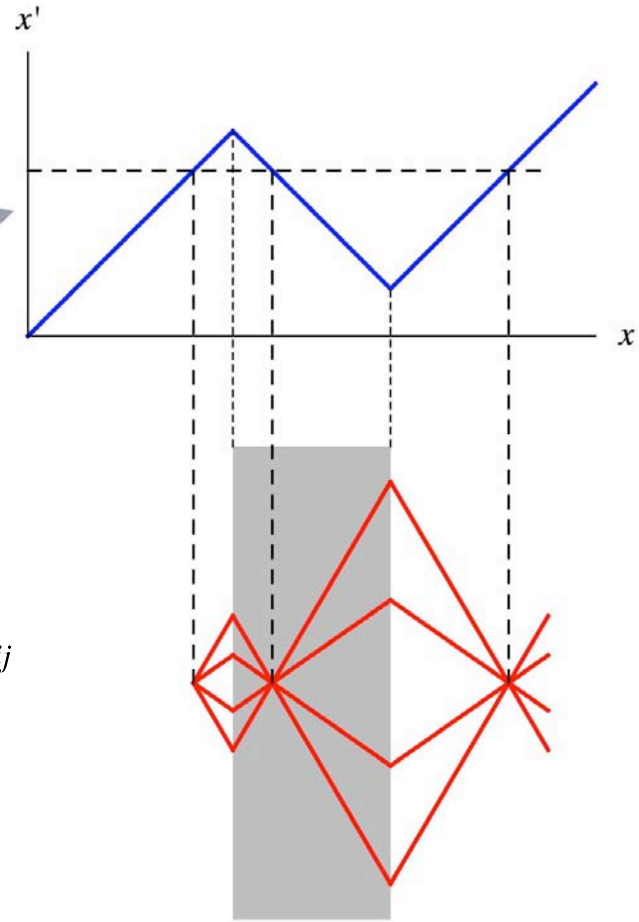
General relativity in electrical engineering

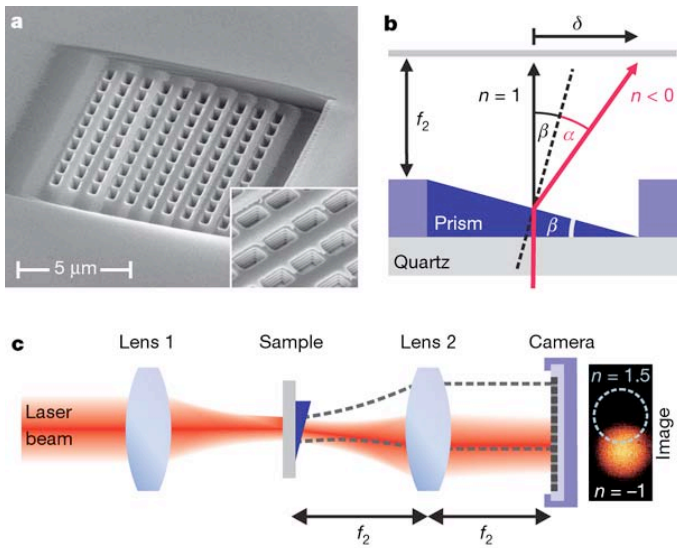
Ulf Leonhardt and Thomas G Philbin



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)]

Invisibility: Invisible Man versus Invisible Woman

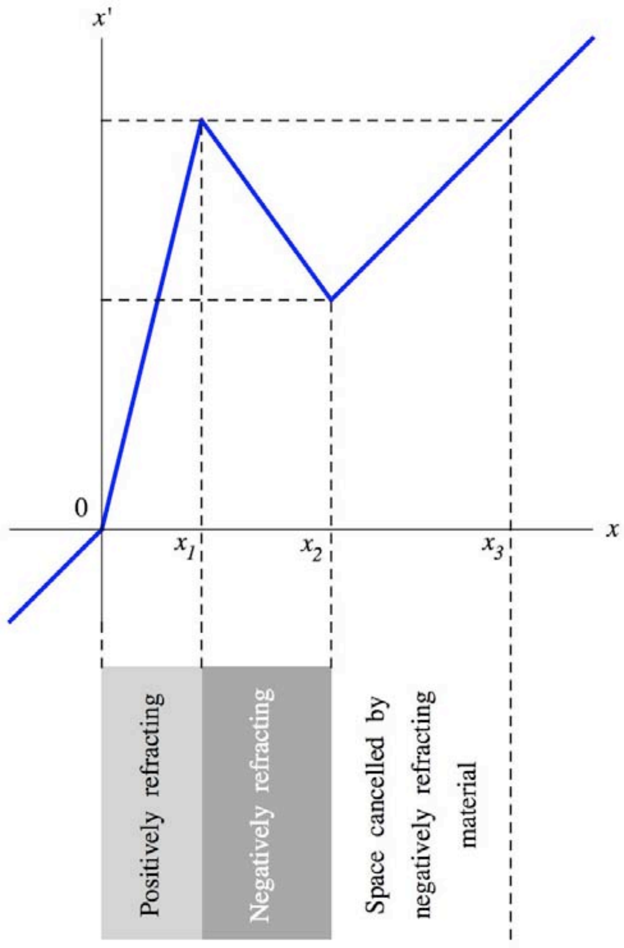
transparency

curved space

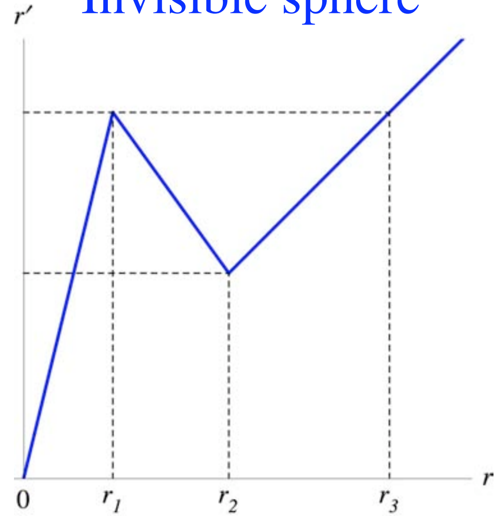
Cloaking at a distance

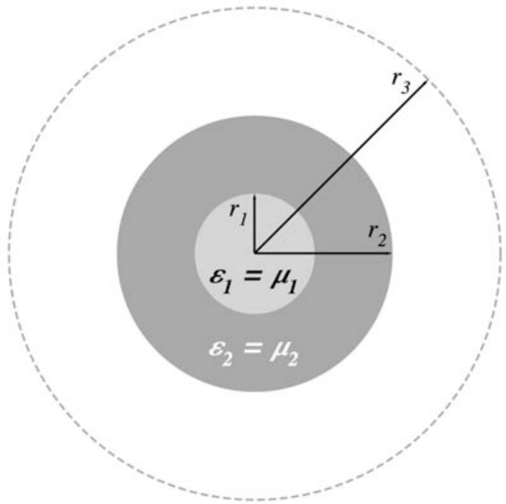
[Lai, Chen, Zhang and Chan, Phys. Rev. Lett. **102**, 093901 (2009)]

Invisible slab



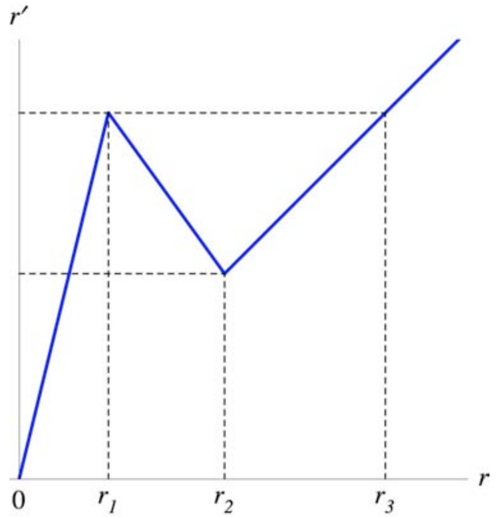
Invisible sphere

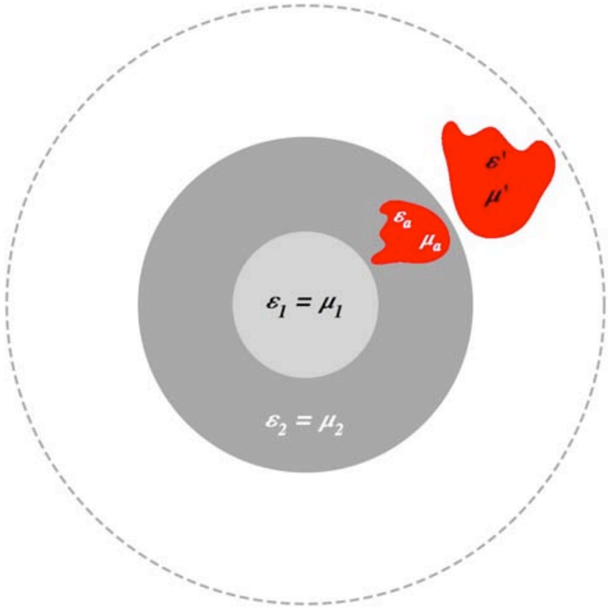




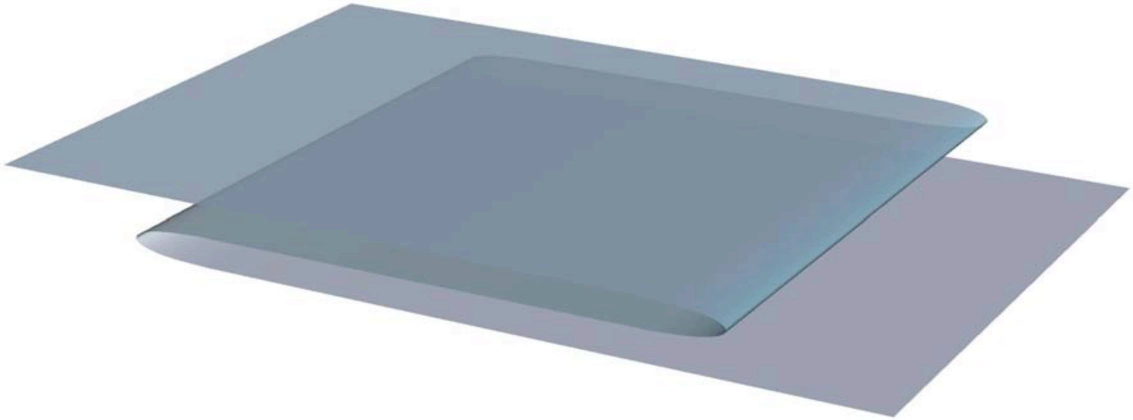
The Invisible Man - cloaking at a distance

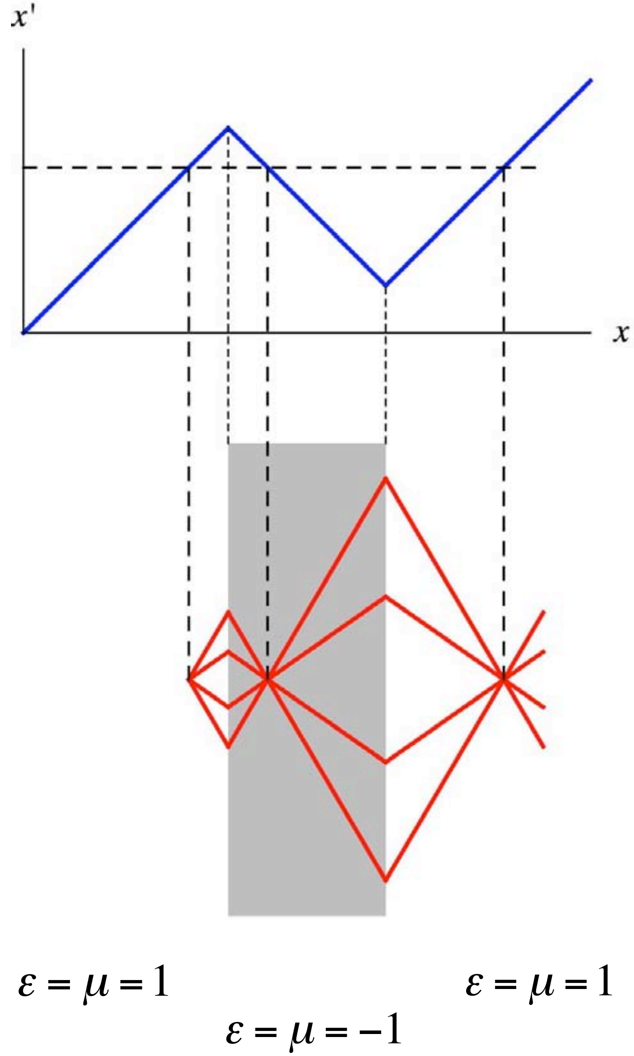
[Lai, Chen, Zhang and Chan, Phys. Rev. Lett. **102**, 093901 (2009)]

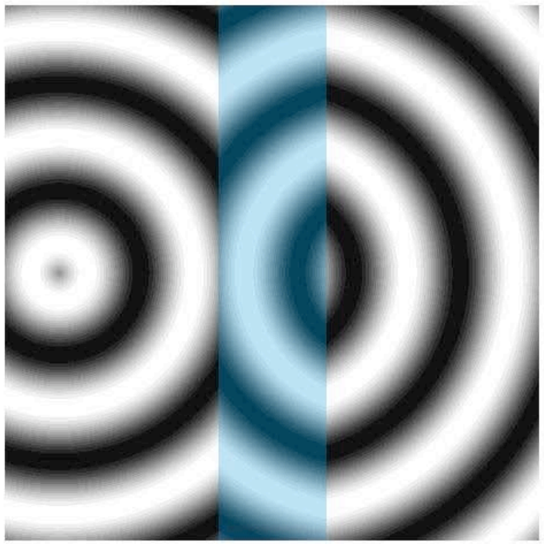


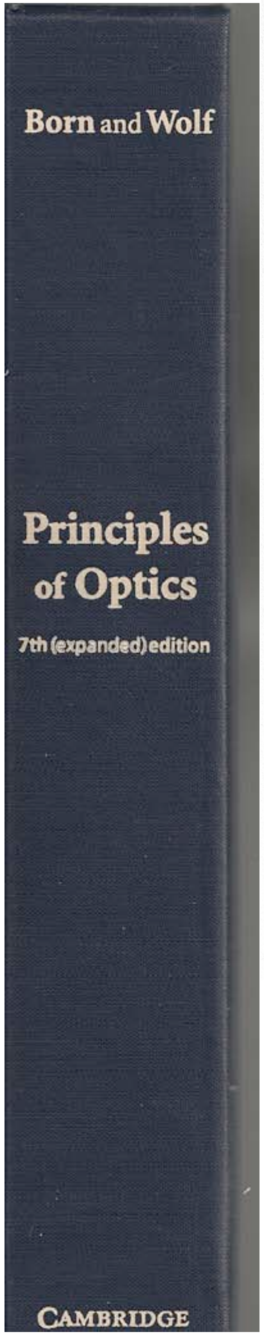


Problems of negative refraction









Principles of optics

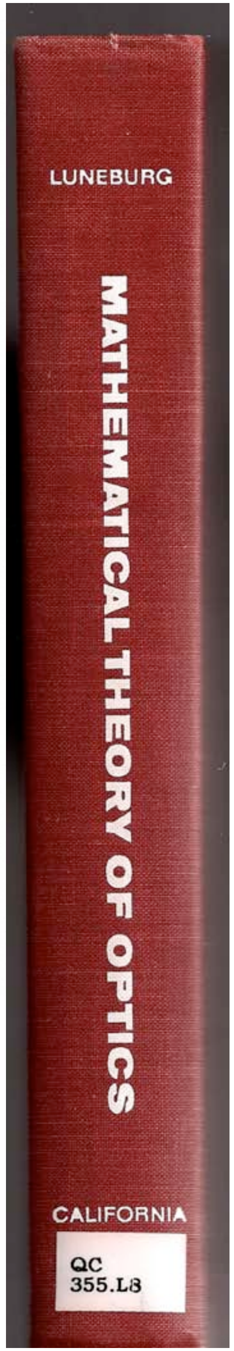
Electromagnetic theory of propagation, interference and diffraction of light

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

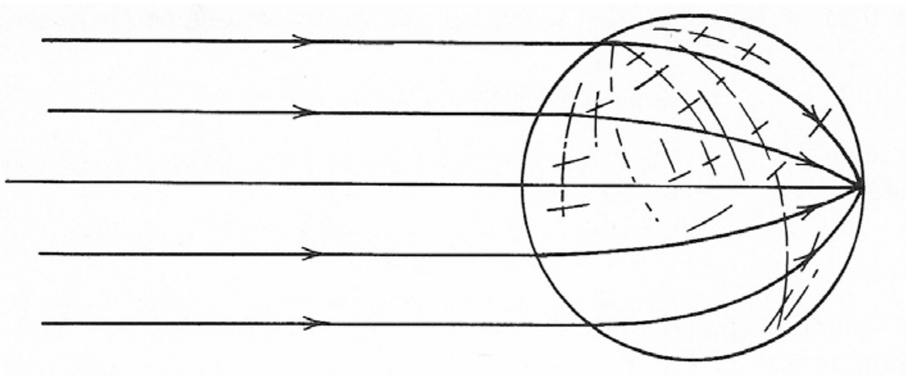
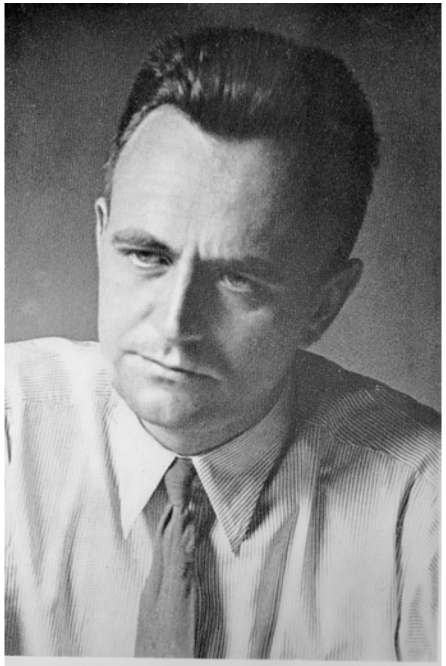
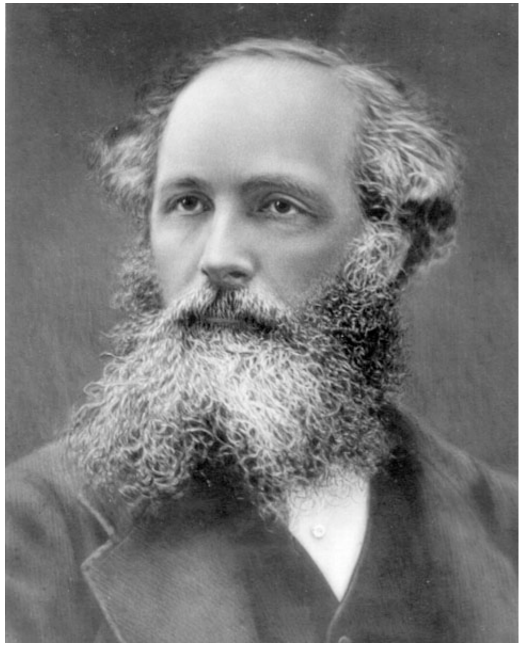


Figure 114



R. K. Luneburg



Conformal maps

Coſmographia, ſiue Deſcriptio vniuerſi Orbis, Petri Apiani & Gemmæ Friſij, Mathematicorum inſignium, iam demùm integritati ſuæ reſtituta.

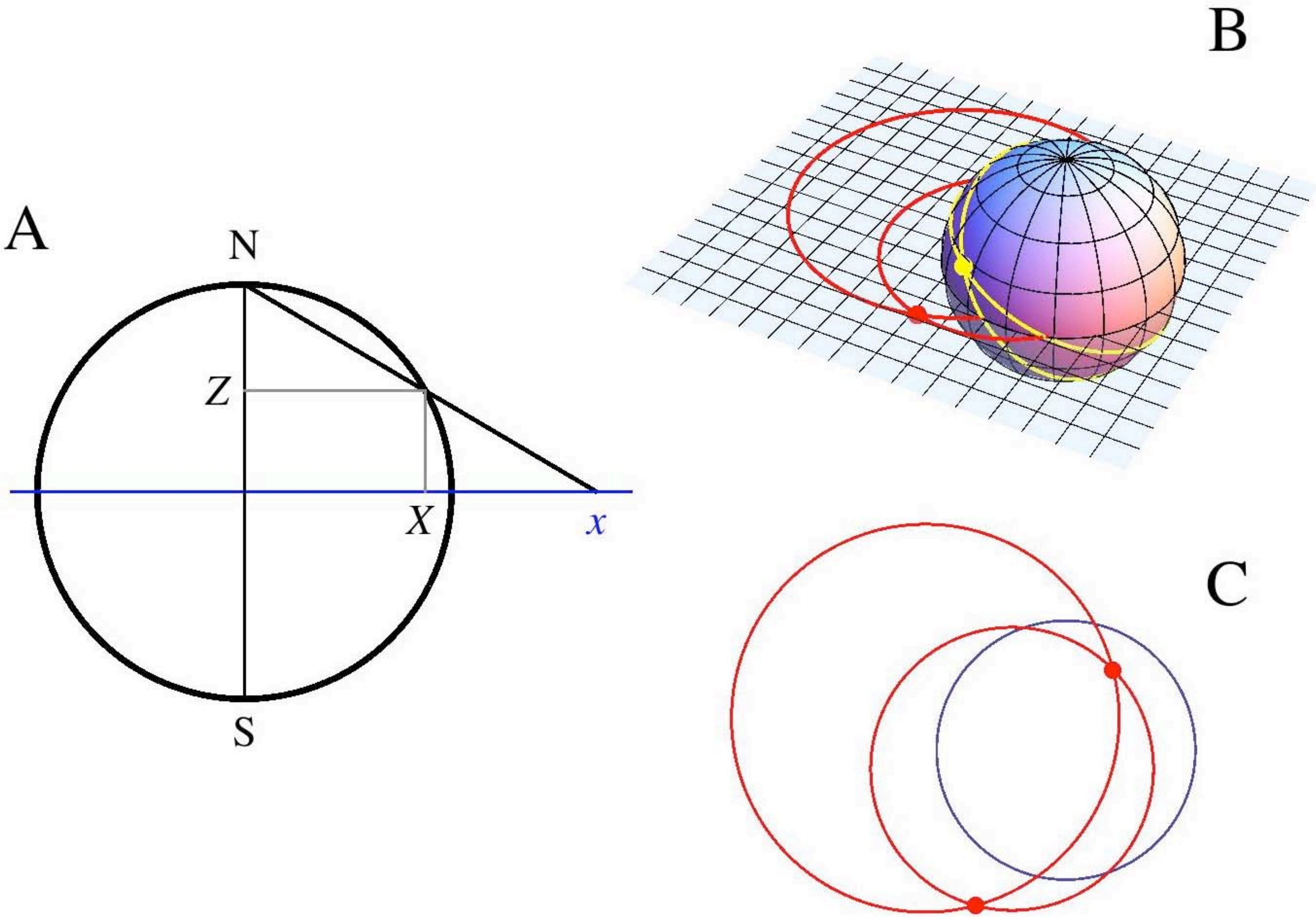
Adiecti ſunt alij, tum Gemmæ Friſij, tum aliorum Auctorum eius argumenti Tractatus ac Libelli varij, quorum ſeriem verſa pagina demonſtrat.

Antuerpiæ, ex Officina Ioannis VVithagij.

Maxwell's fish eye makes a perfect lens

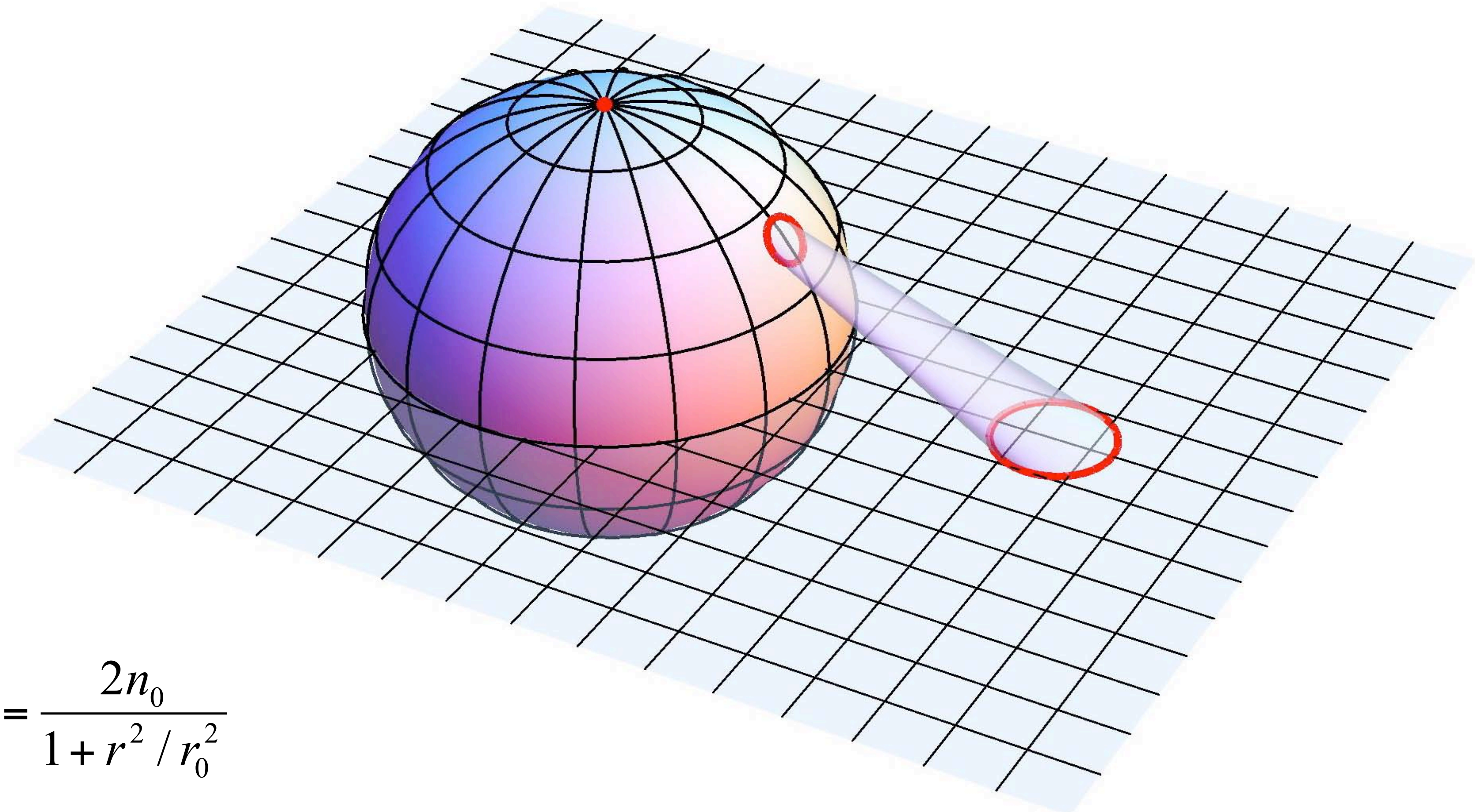
Maxwell 1854

Luneburg 1944: Stereographic projection



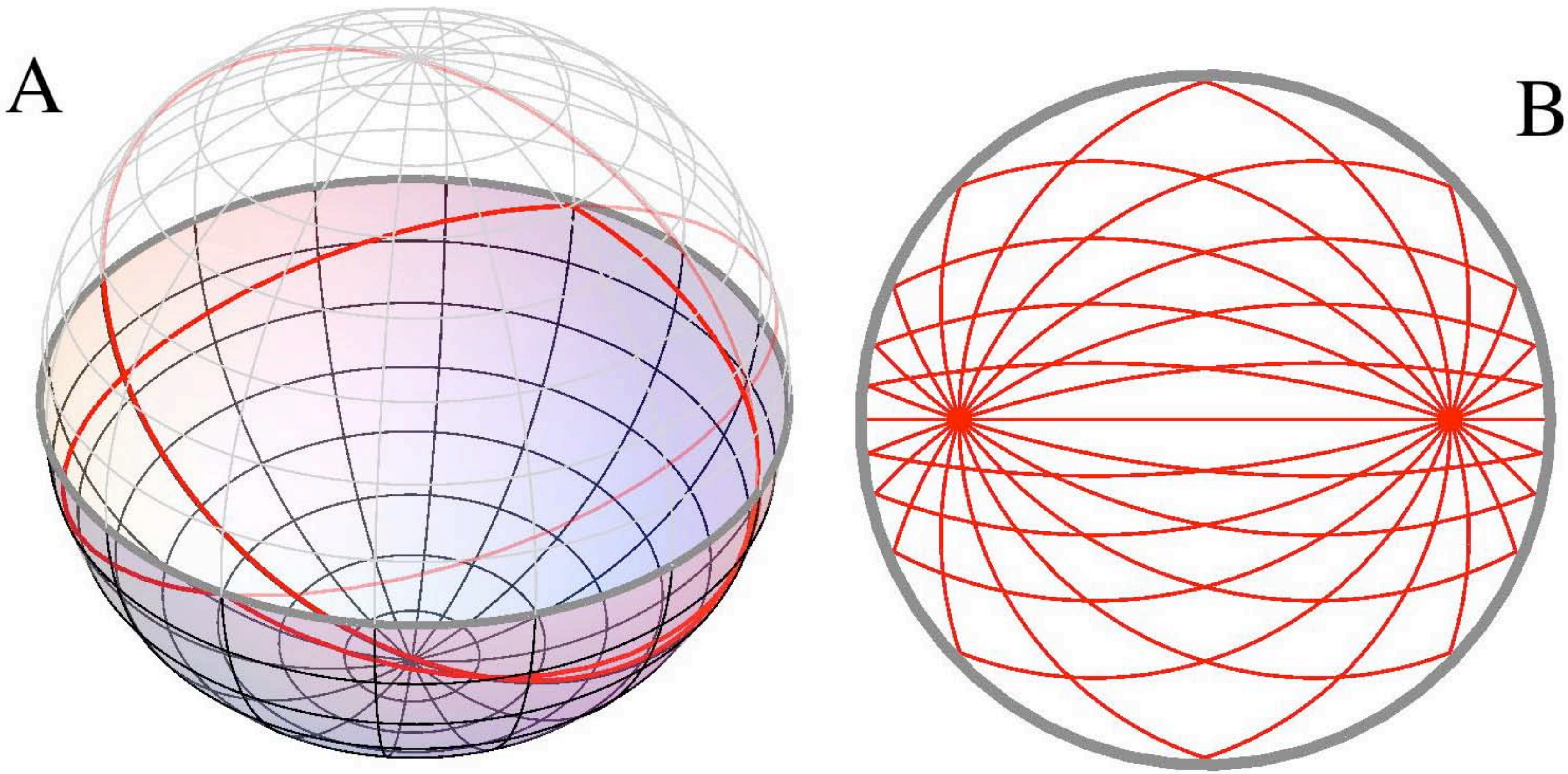
Refractive index

n = virtual length/ real length



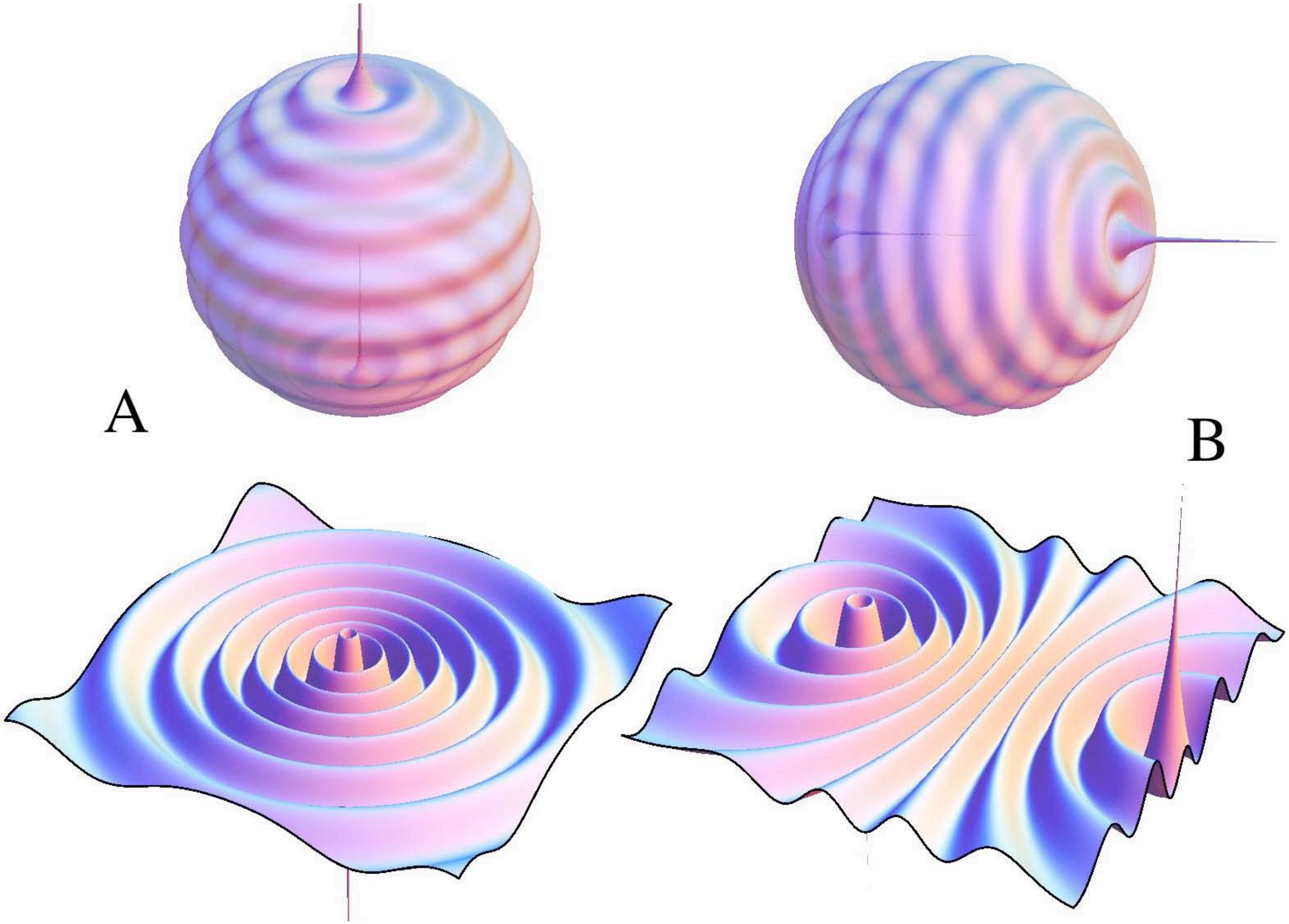
$$n = \frac{2n_0}{1 + r^2 / r_0^2}$$

Fish-eye mirror



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

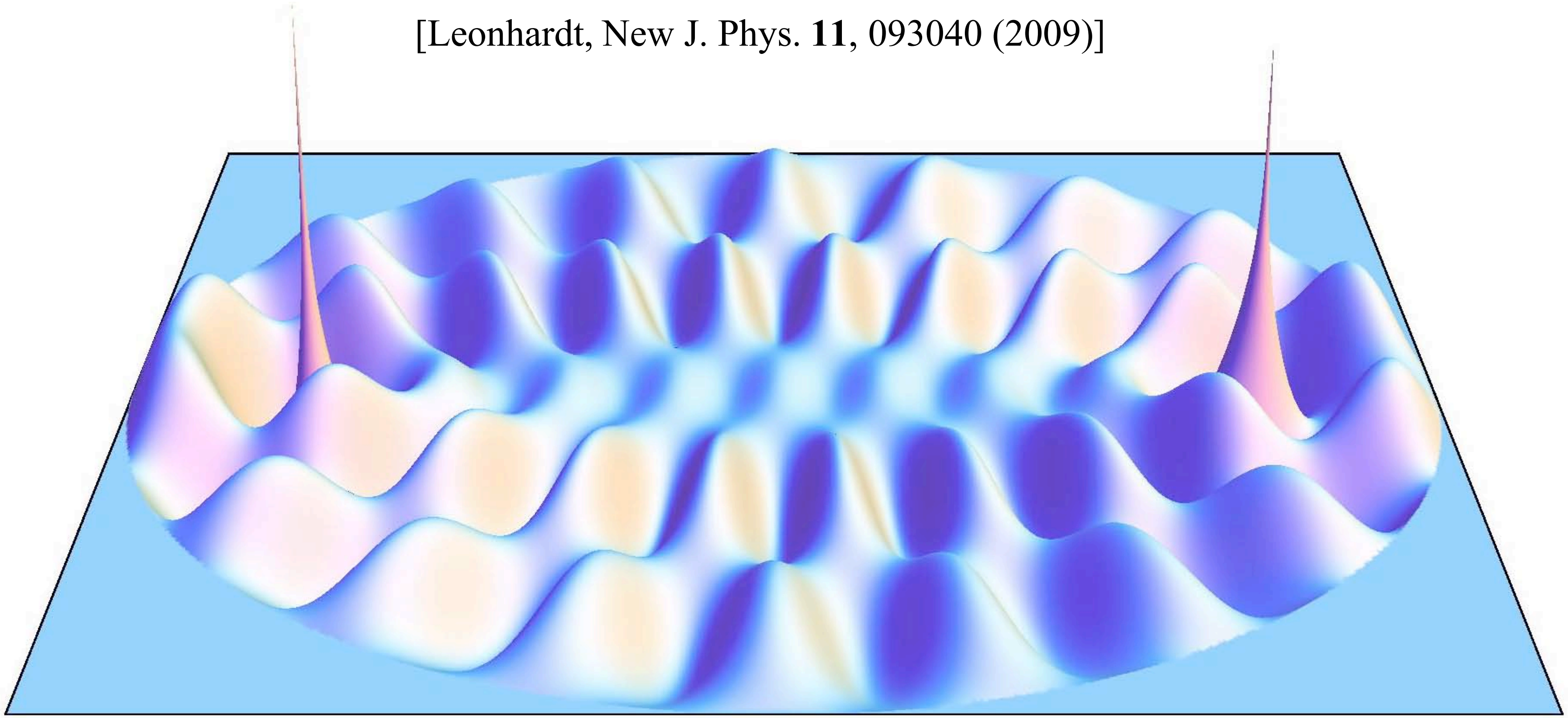
What about waves?



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

Perfect imaging without negative refraction

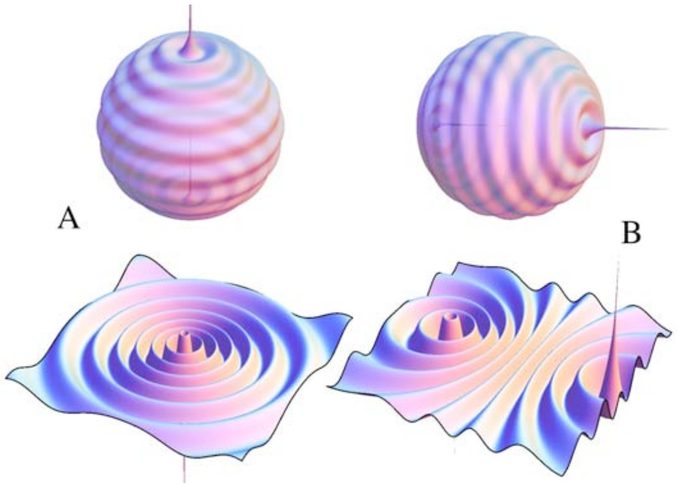
[Leonhardt, New J. Phys. **11**, 093040 (2009)]

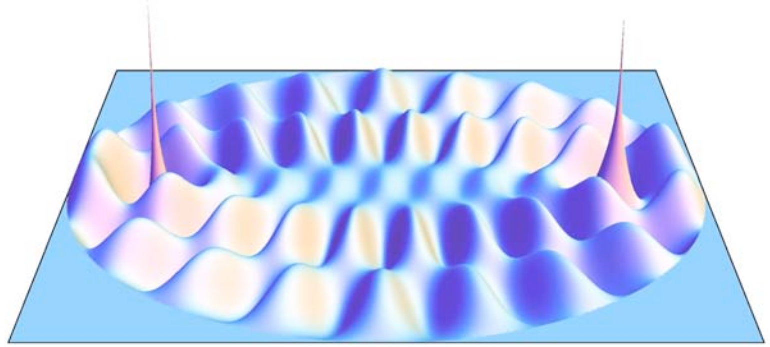


$$n = \frac{2n_0}{1 + r^2 / r_0^2}$$

Index contrast: factor of 2

Geometry of light: reason for perfect imaging





TE: $$0 = \frac{1}{n^2}\nabla^2 E + k^2 E = \frac{1}{\sqrt{g}}\,\partial_A \sqrt{g}\, g^{AB}\,\partial_B E + k^2 E$$

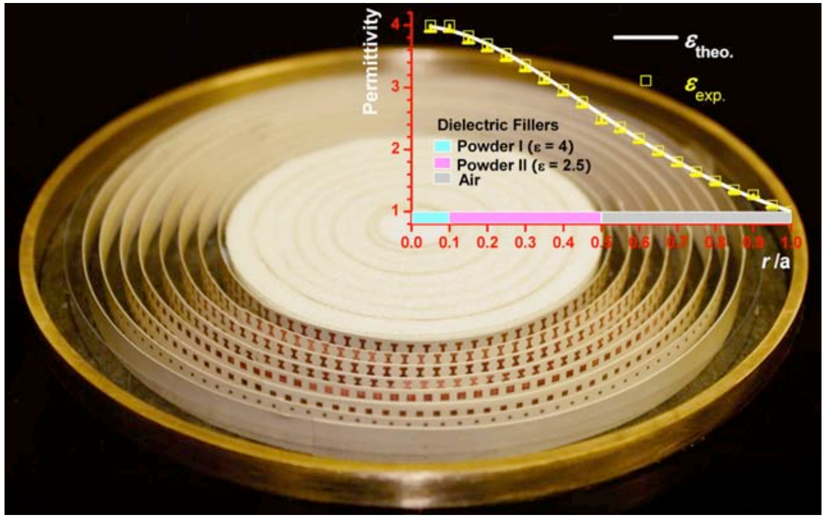
$$g_{AB} = n^2\,\mathbb{1}\,, \quad g = n^4\,, \quad g^{AB} = n^{-2}\,\mathbb{1}$$

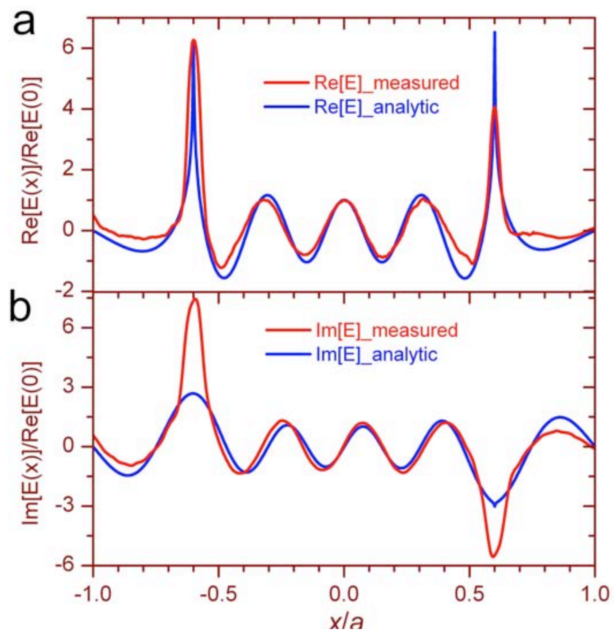
TM: $$\nabla\cdot\frac{1}{n^2}\nabla H + k^2 H = 0$$ No perfect imaging

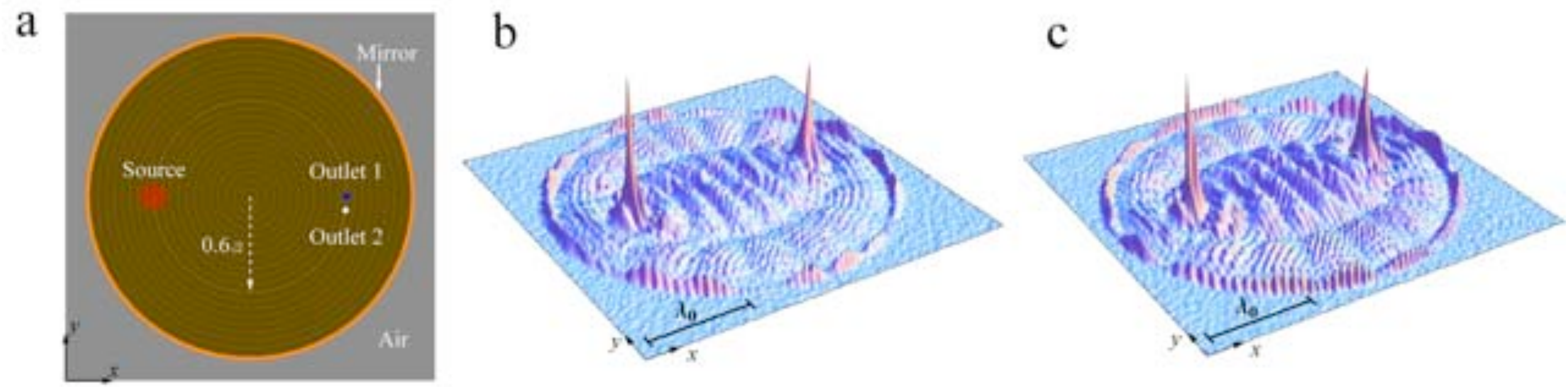
3D: Impedance matching necessary for perfect imaging

Perfect imaging without negative refraction for microwaves

[Yungui Ma, Singapore]

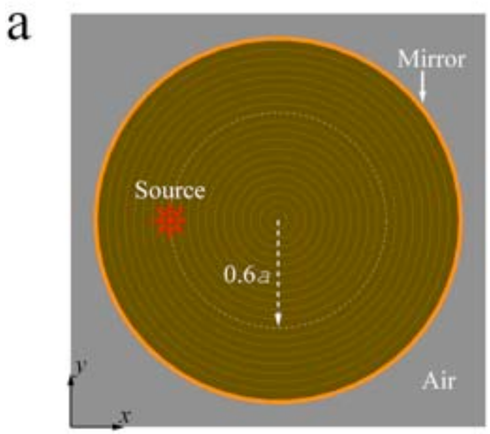


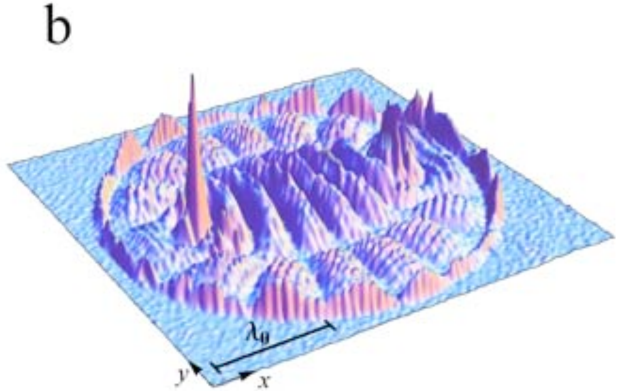


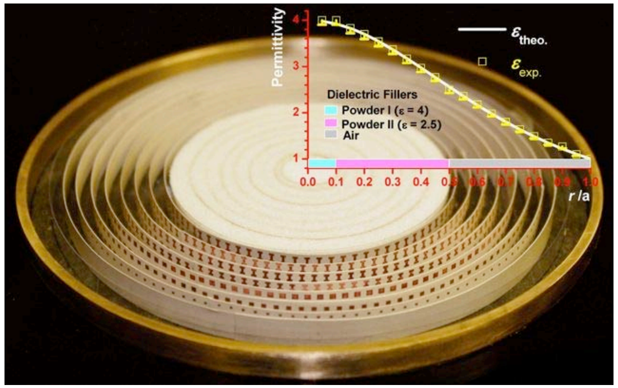


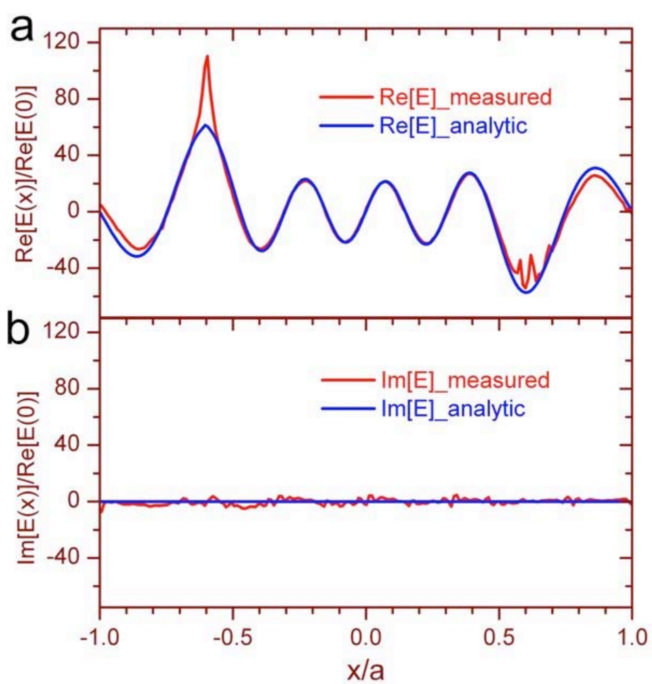
No outlet, no running wave, no perfect image

[Yungui Ma, Singapore]

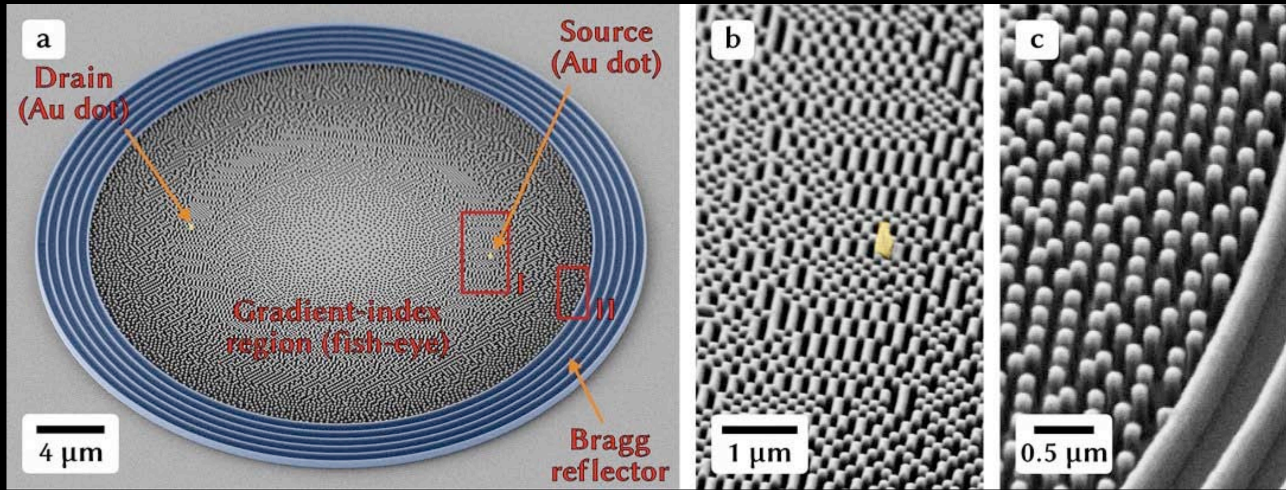


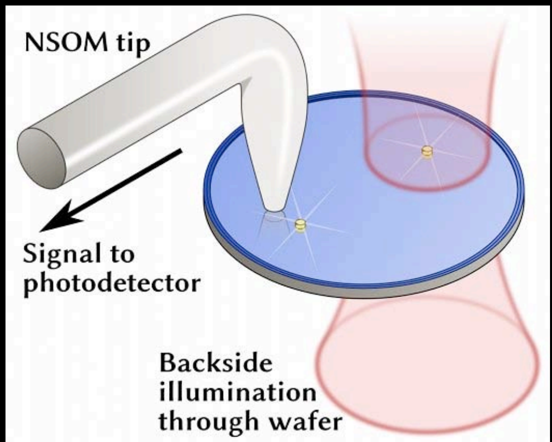


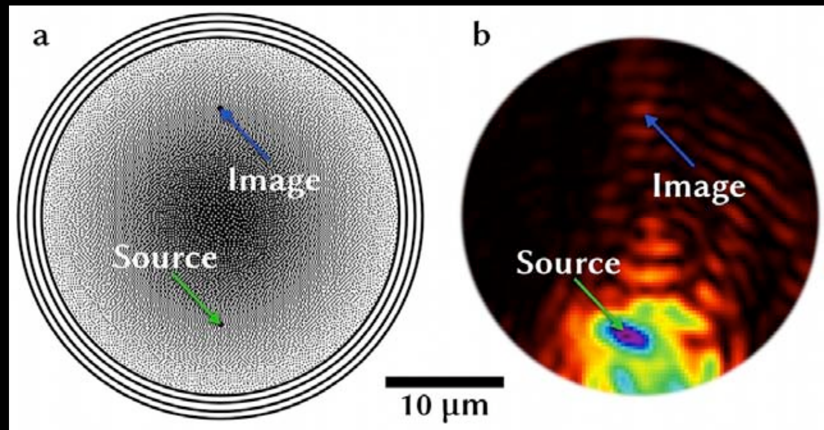




Perfect imaging without negative refraction in silicon photonics





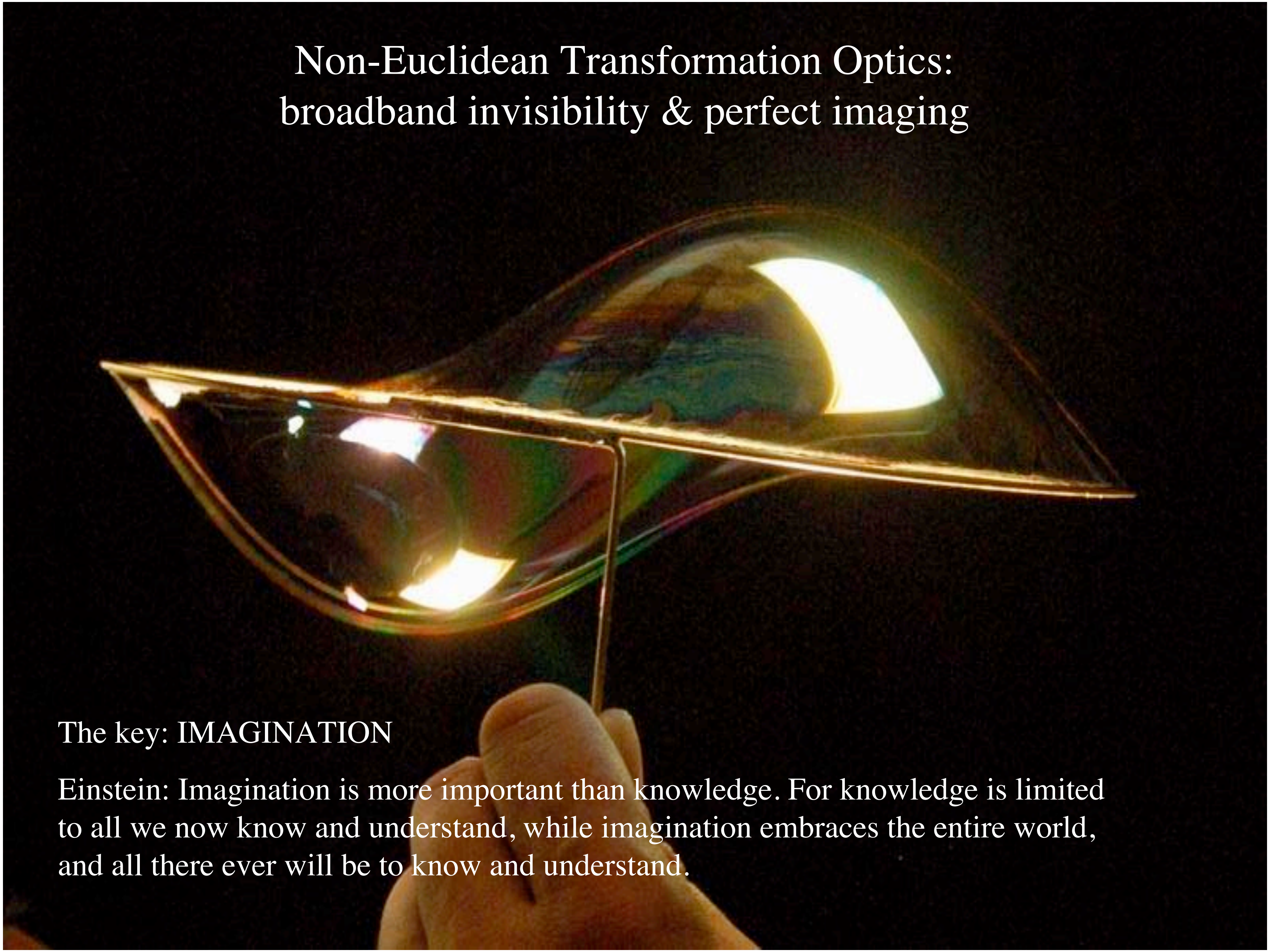


Lipson Group, Cornell University

Similar to carpet cloaking

[LH. Gabrielli, J. Cardenas, C.B. Poitras, and M. Lipson, Nature Photonics 3, 461 (2009)]

Non-Euclidean Transformation Optics:
broadband invisibility & perfect imaging

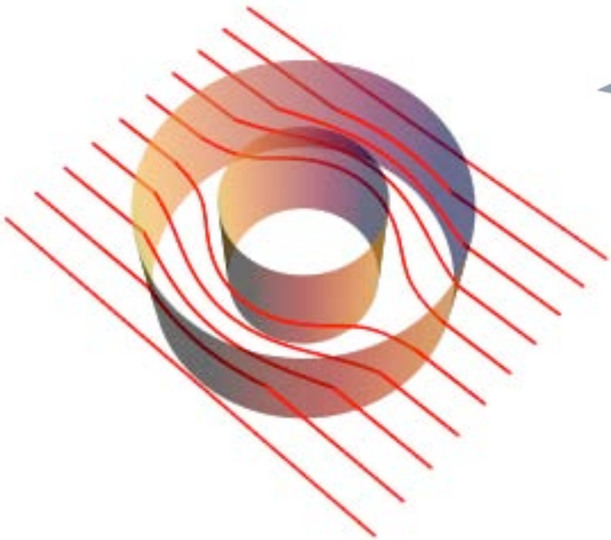


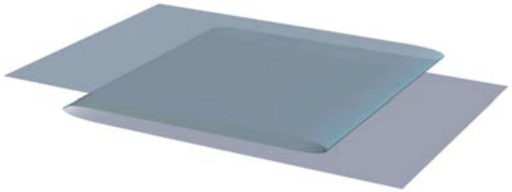
The key: IMAGINATION

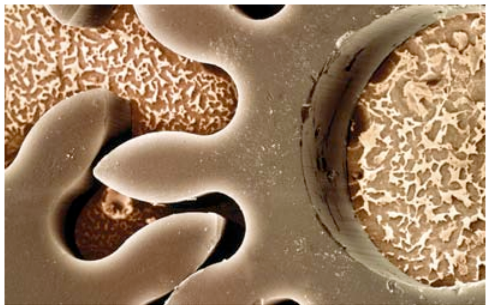
Einstein: Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand.

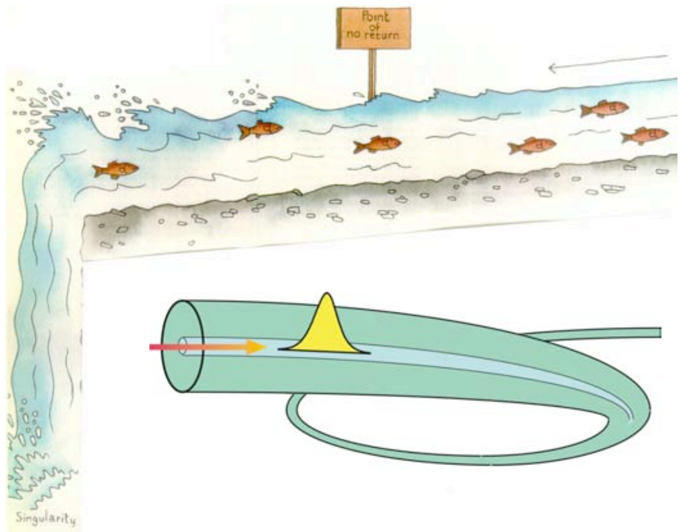
General relativity in electrical engineering

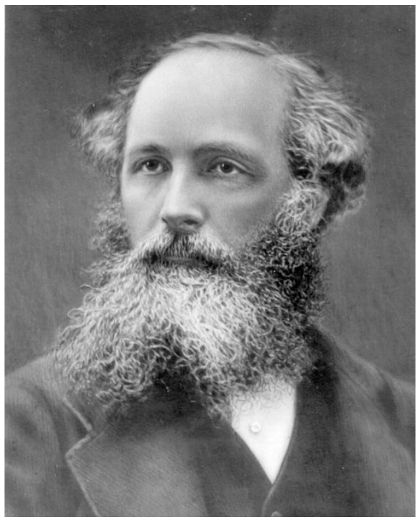
[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]

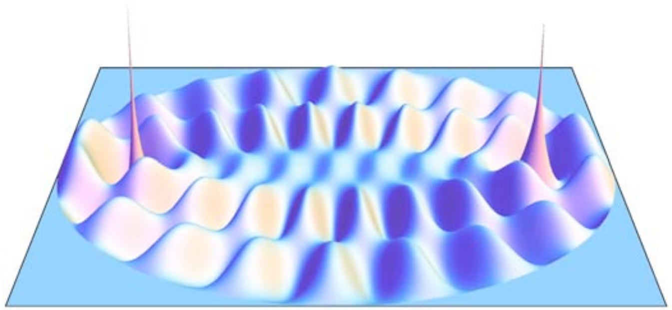


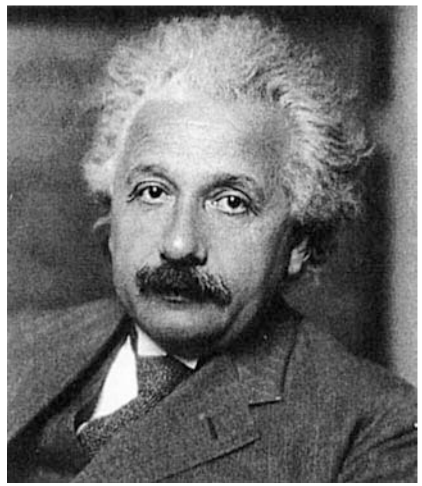




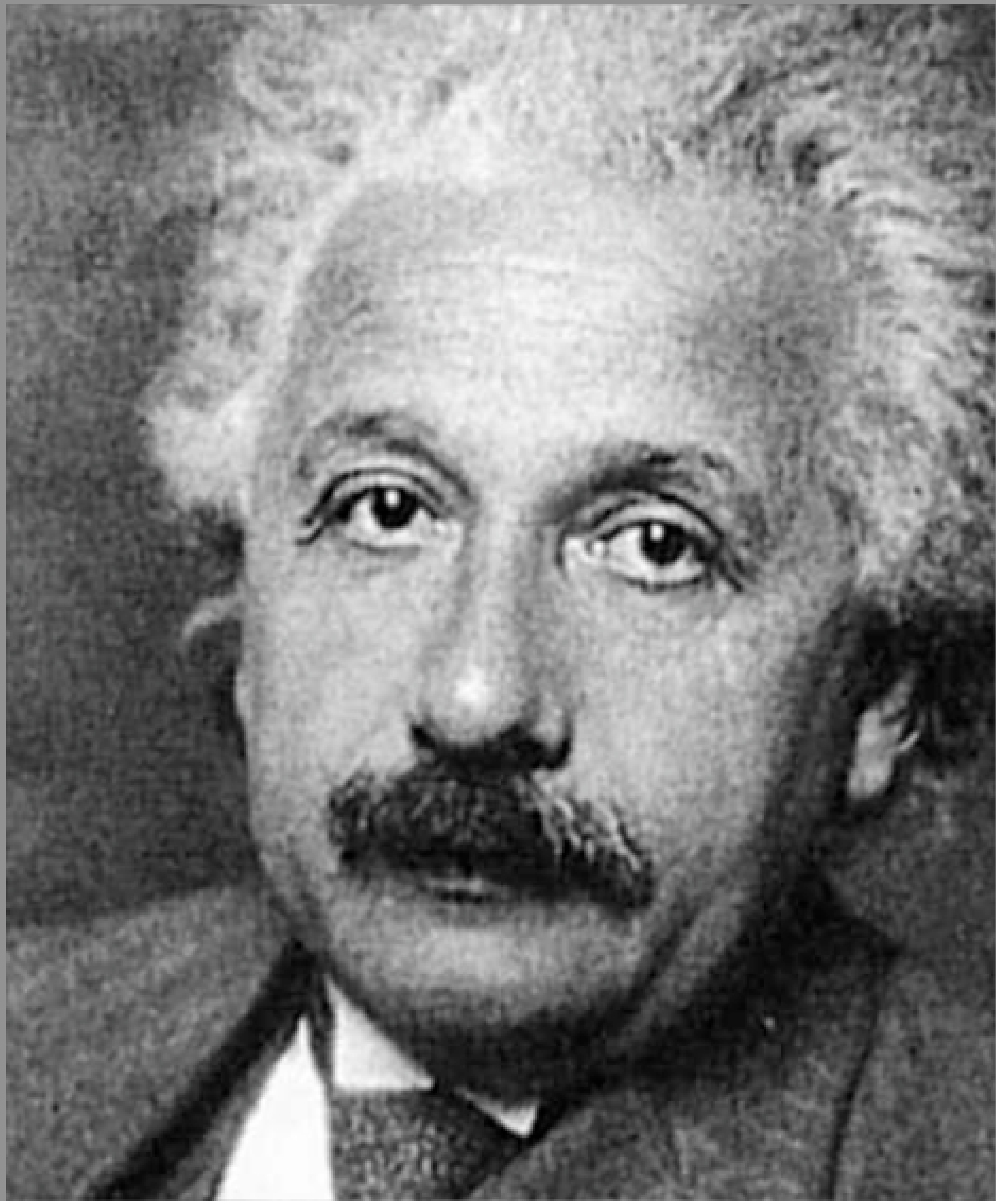


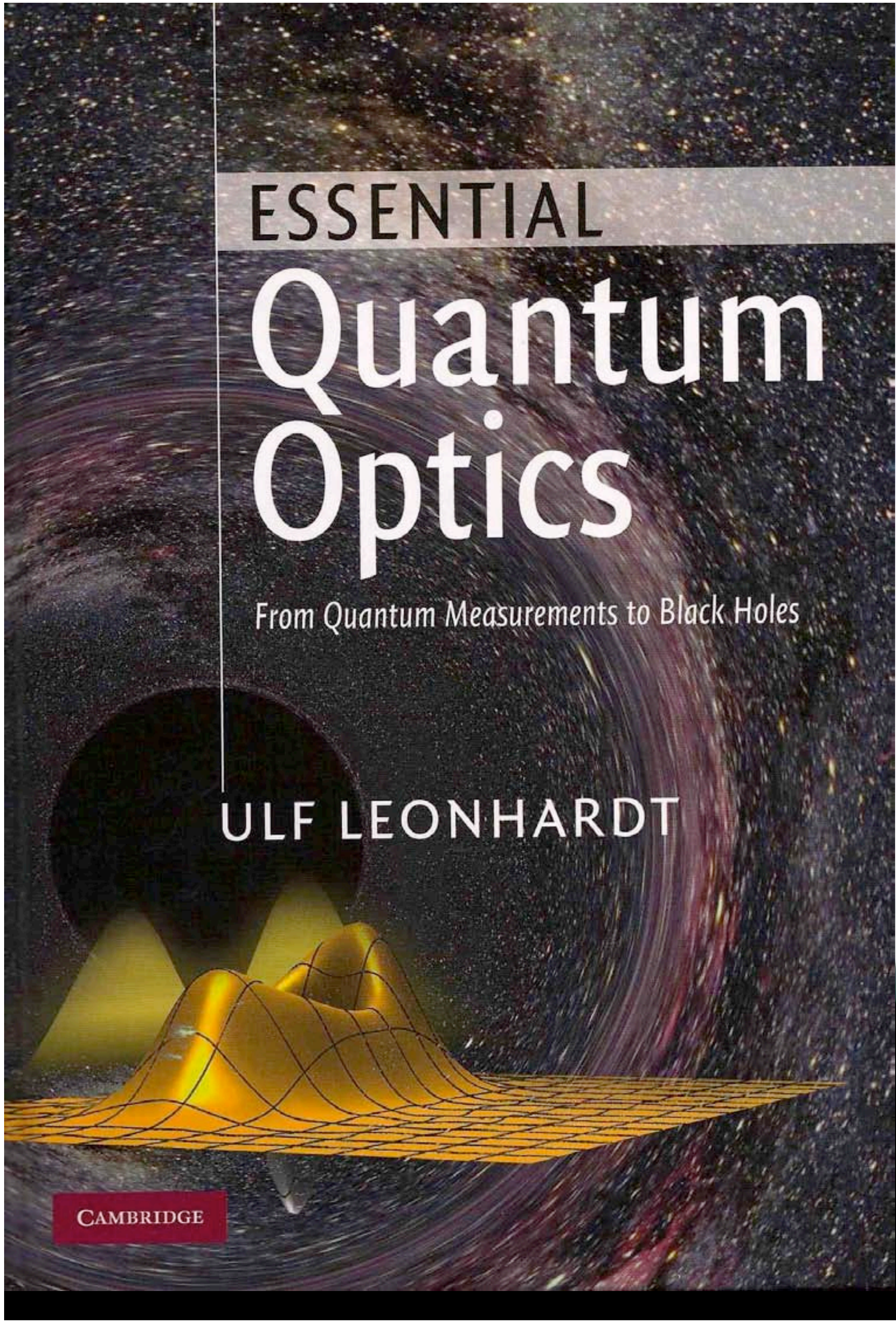






Einwell and Maxstein

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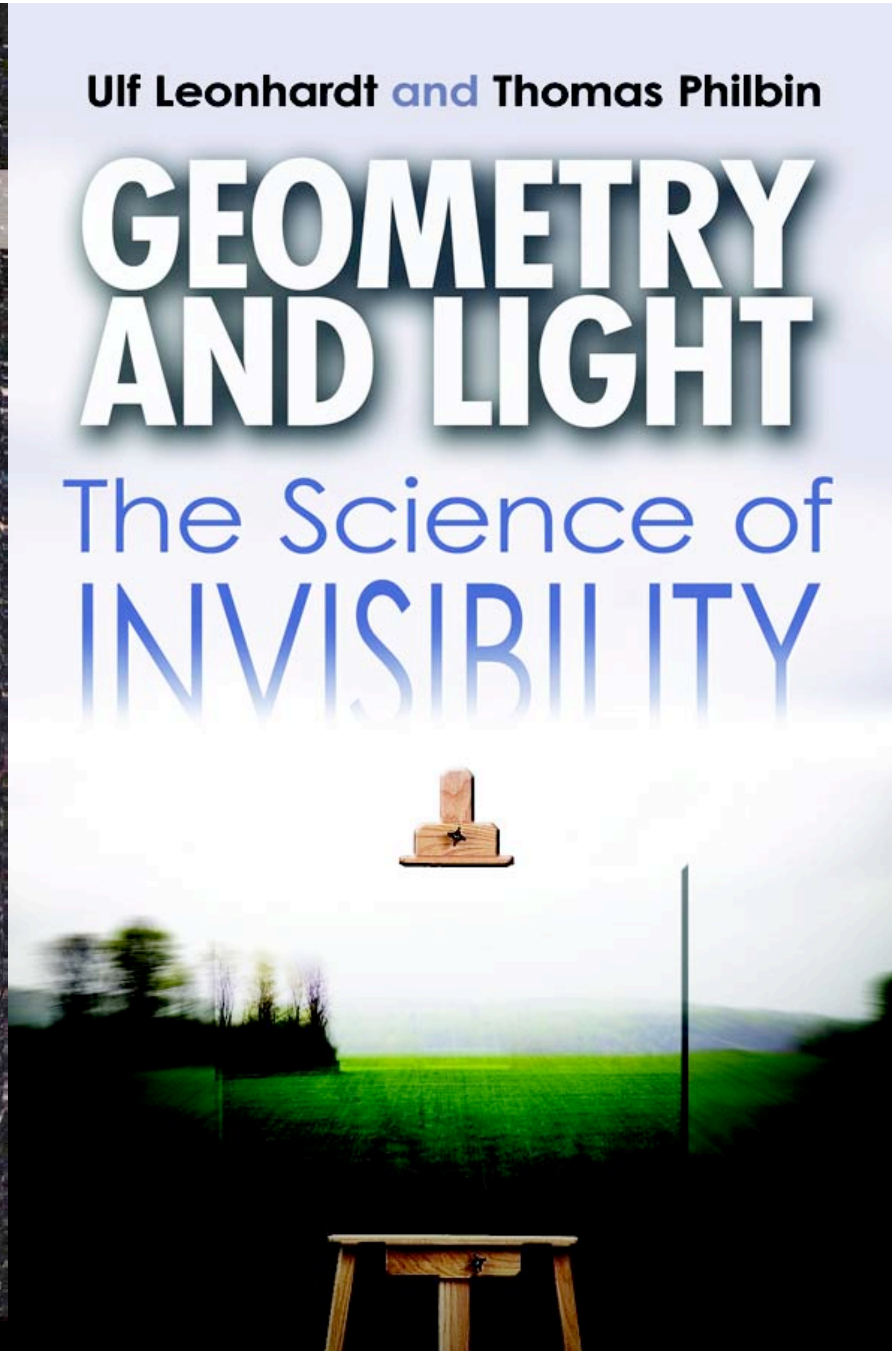
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