GEOMETRY, LIGHT, AND A WEE BIT OF MAGIC

Ulf Leonhardt
University of St Andrews

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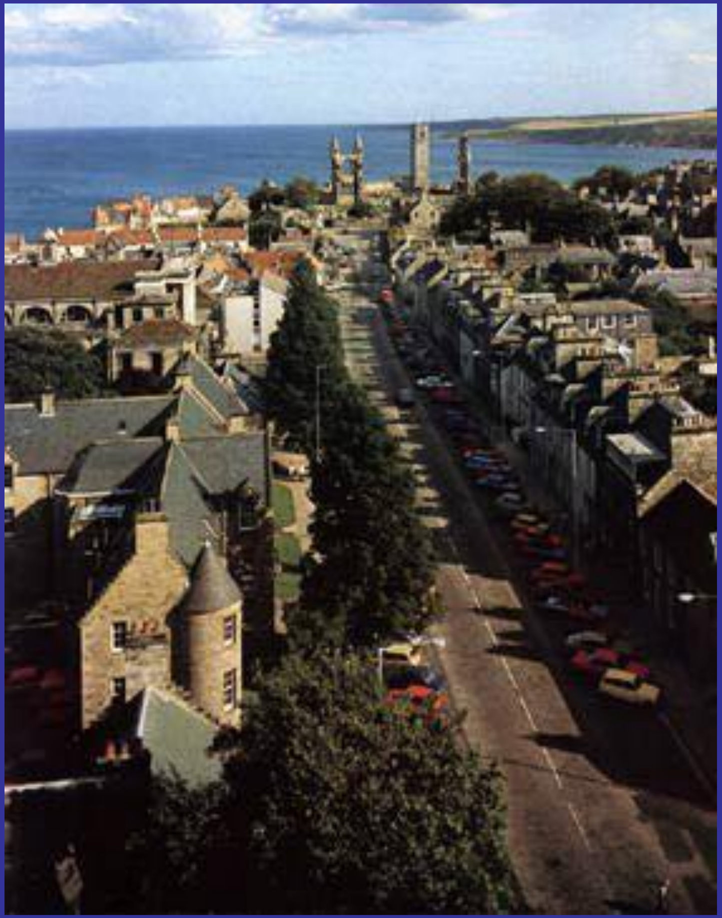
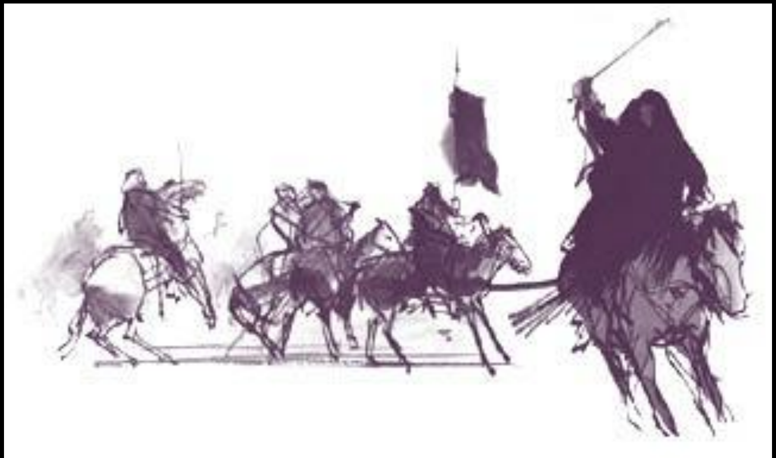
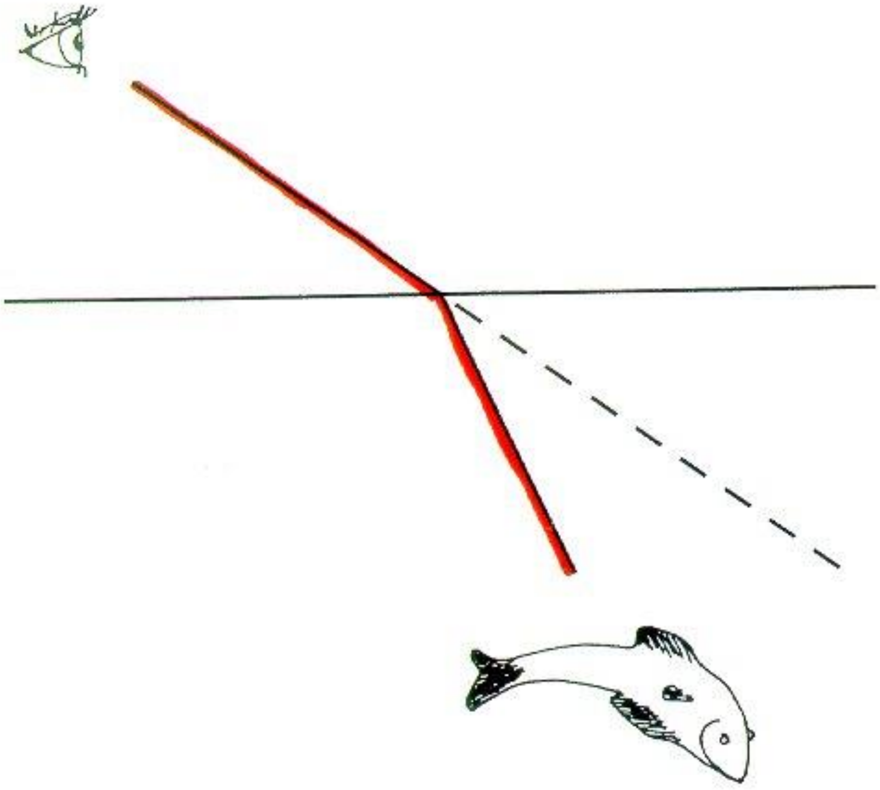


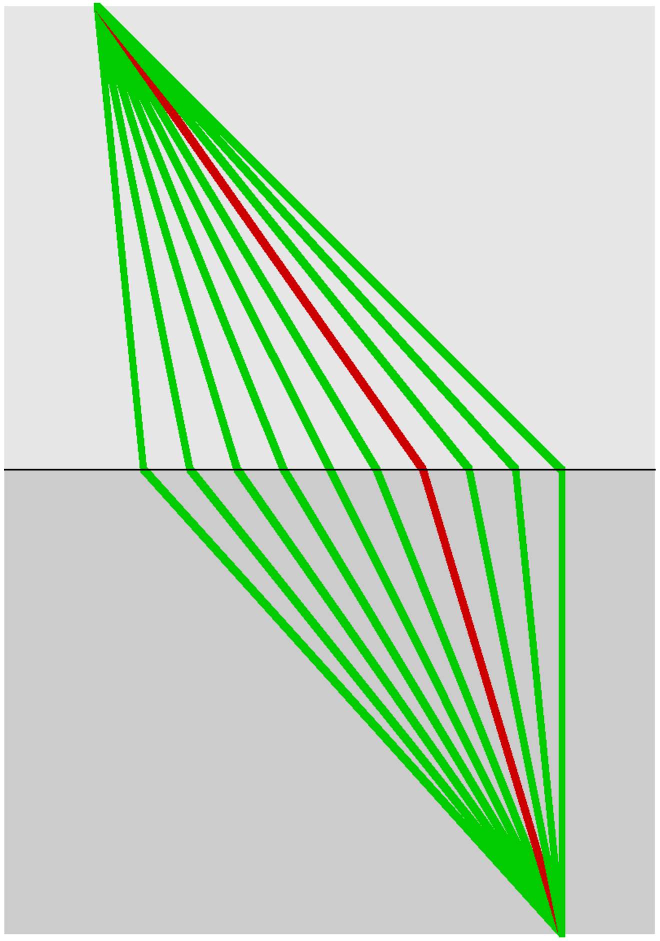


Mirage

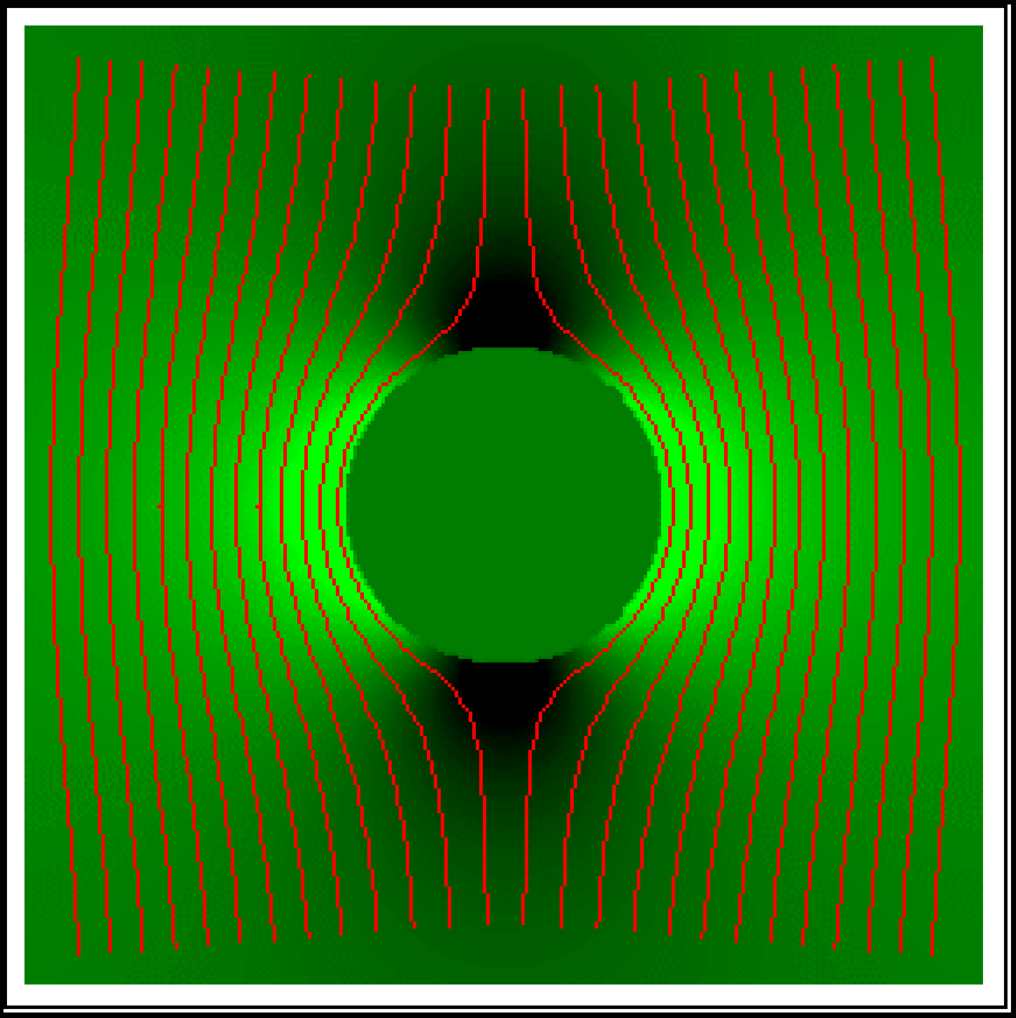
Fermat's Principle - the principle of the shortest optical path

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



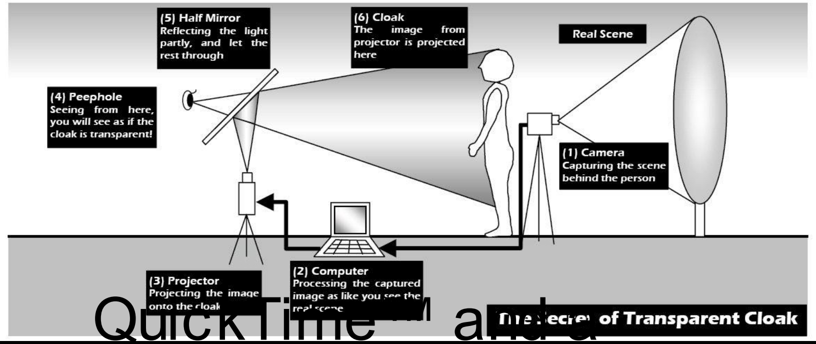


Invisibility cloak?

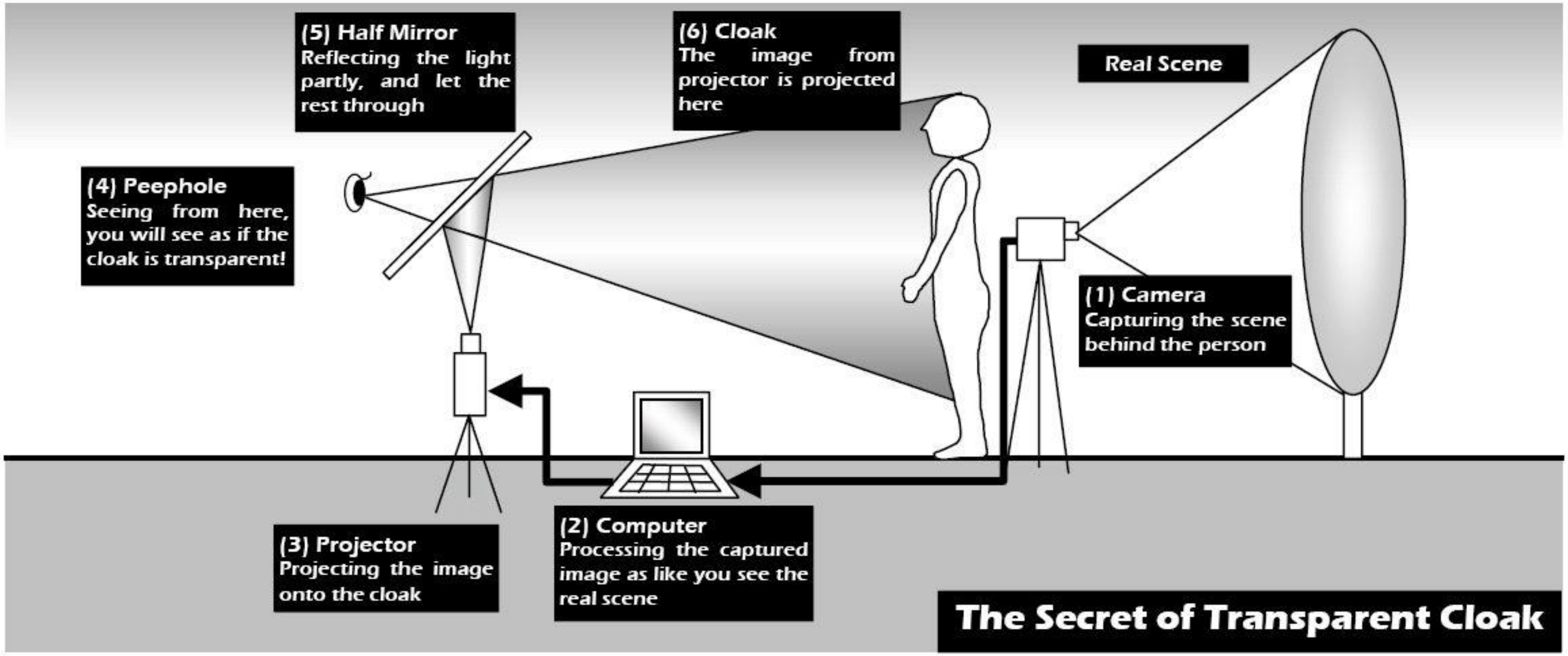


Stealth technology

Optical camoflage



The secret of optical camoflage



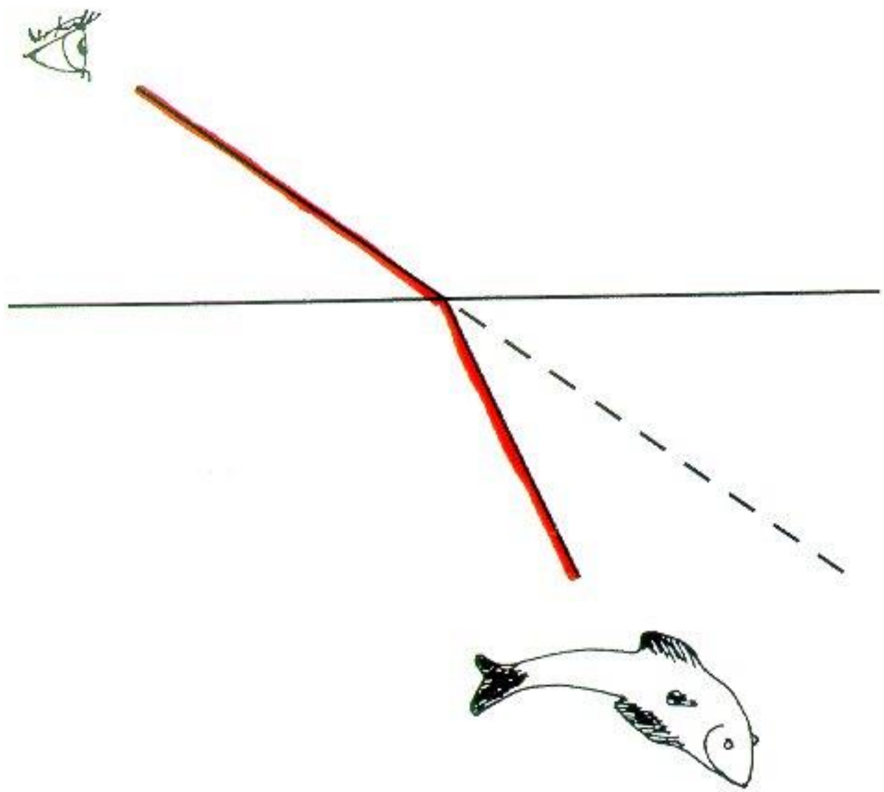
Invisibility: Invisible Man versus Invisible Woman

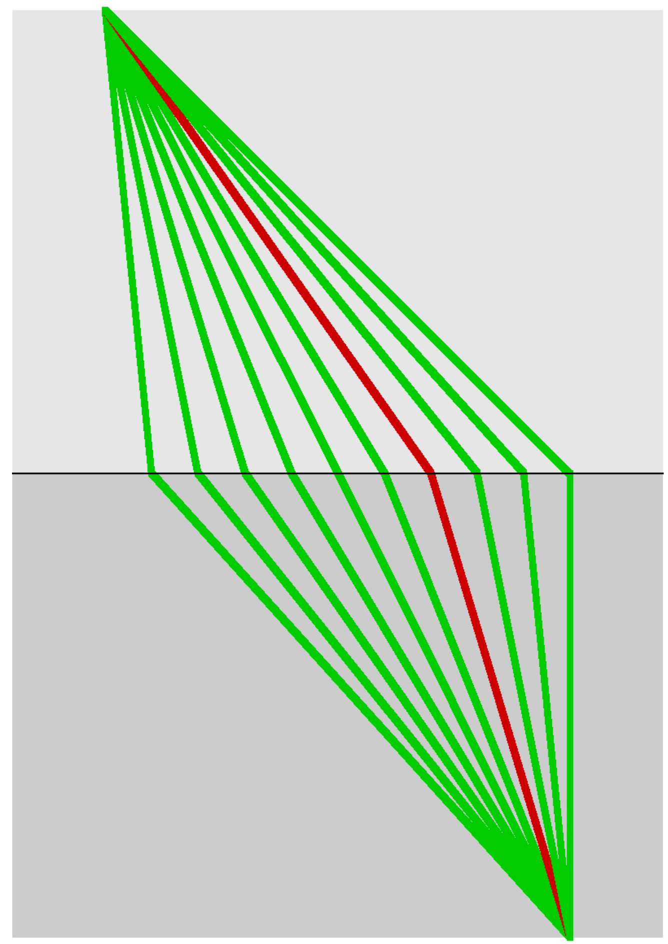
transparency

curved space

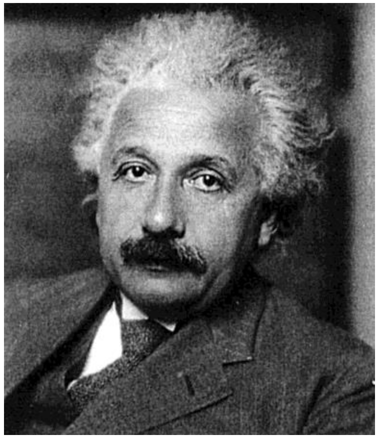
Fermat's Principle - the principle of the shortest optical path

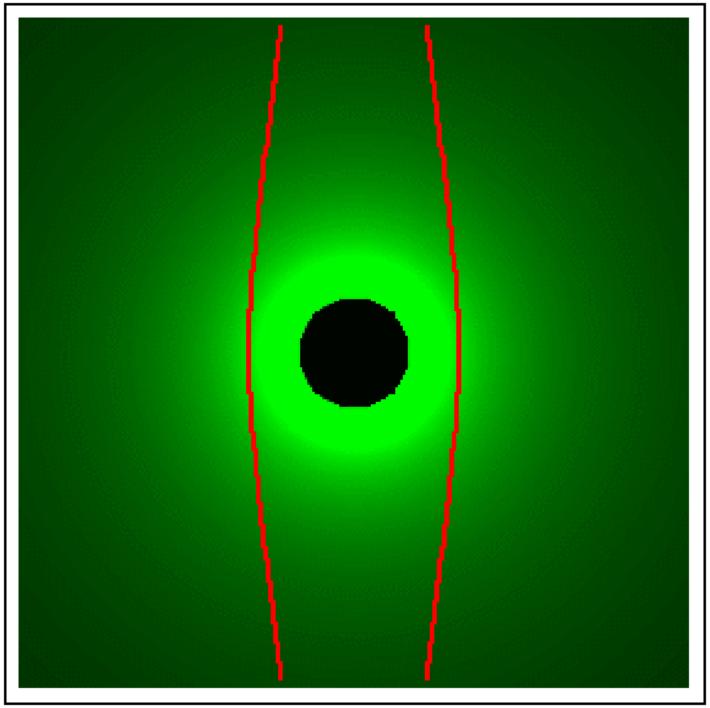
$$s = \int n\,dl$$

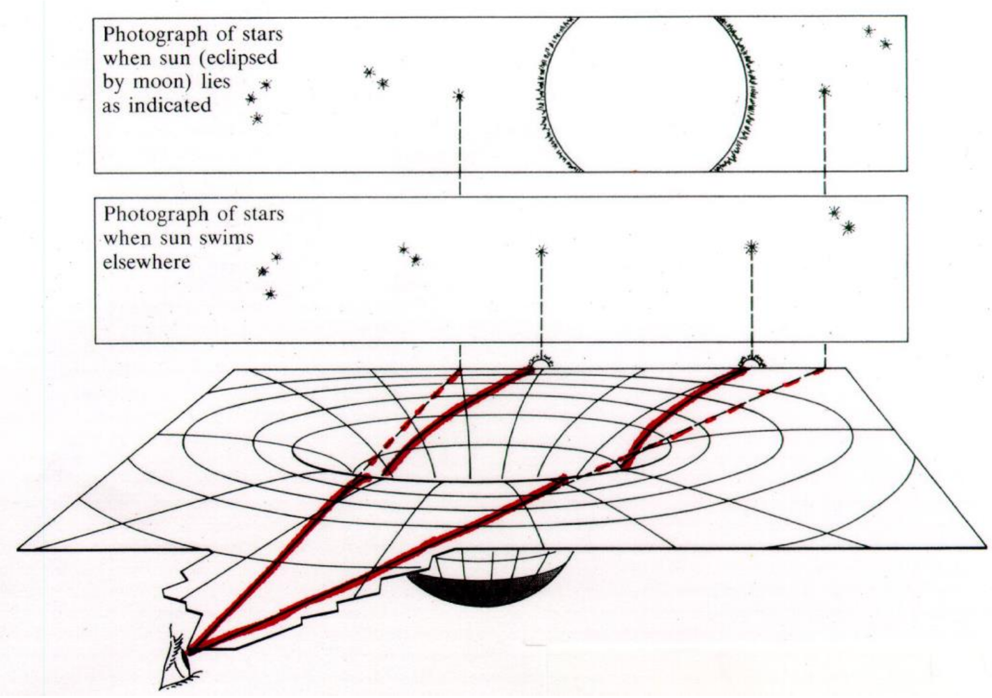




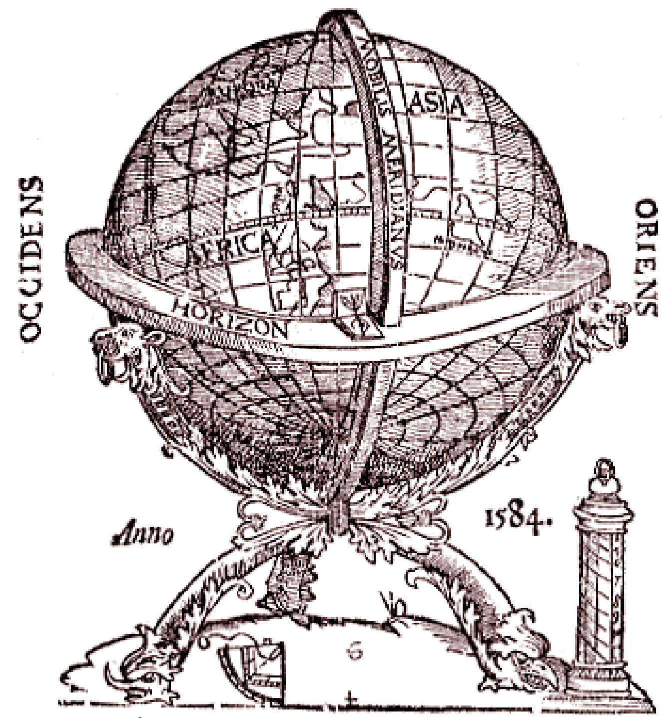
Gravitational lens







Conformal maps

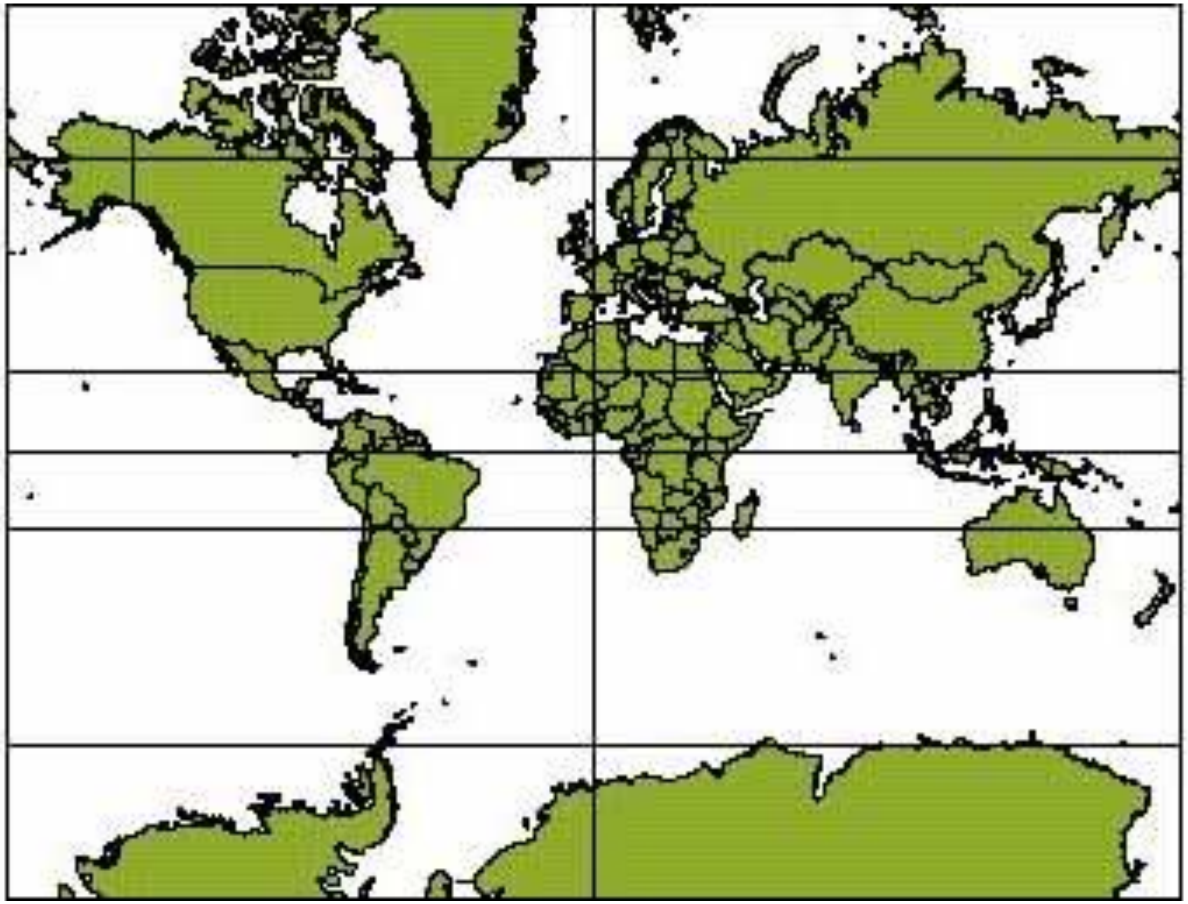


Coſmographia, ſiue Deſcriptio uniuerſi Orbis, Petri Apiani & Gemmæ Friſij, Mathematicorum inſignium, iam demùm integritati ſuæ reſtituta.

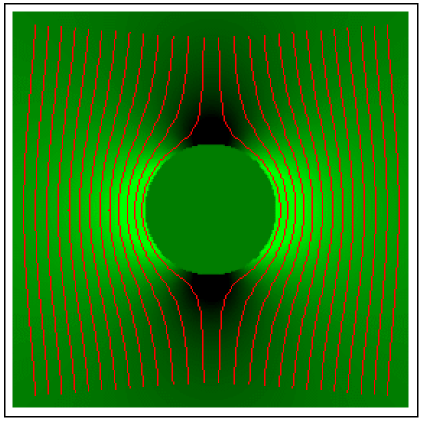
Adiecti ſunt alij, tum Gemmæ Friſij, tum aliorum Auctorum eius argumenti Tractatus ac Libelli varij, quorum ſeriem verſa pagina demonſtrat.

Antuerpiæ, ex Officina Ioannis VVithagij.

Mercator projection

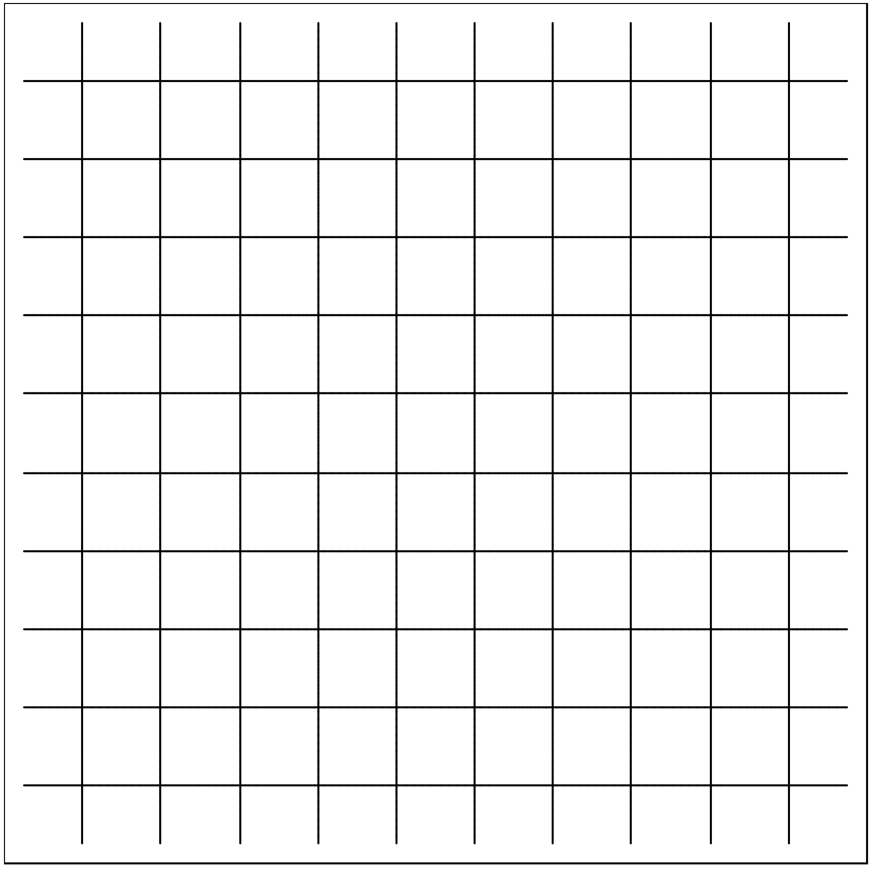


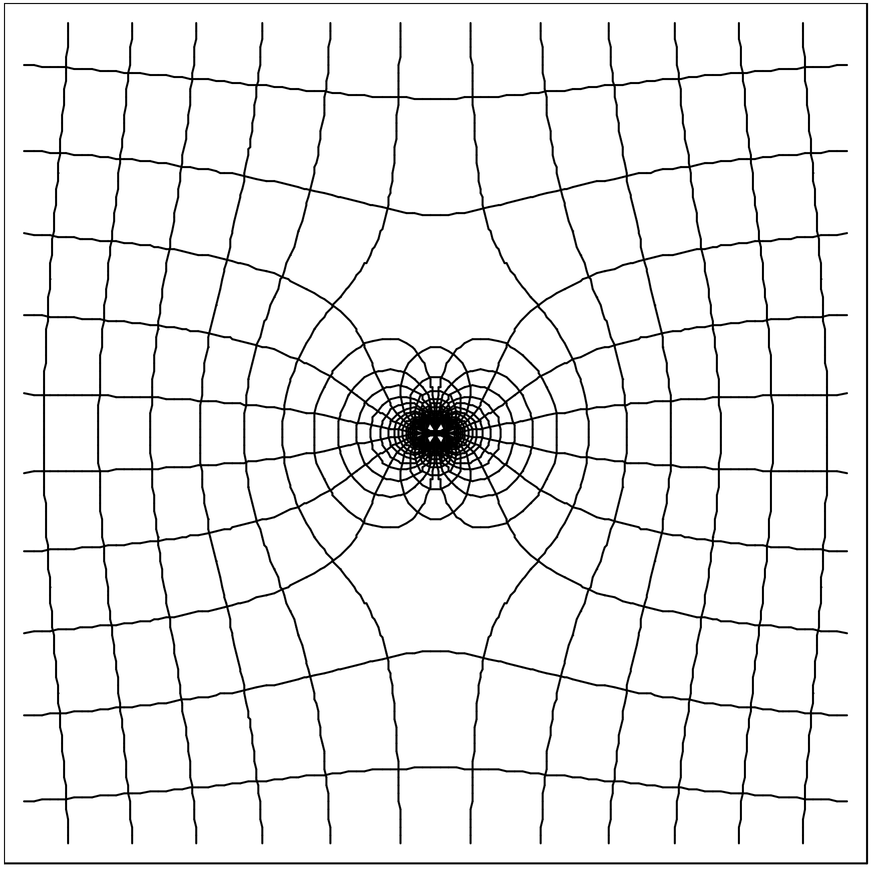
[Leonhardt, Science **312**, 1777 (2006)]



Virtual space

Physical space

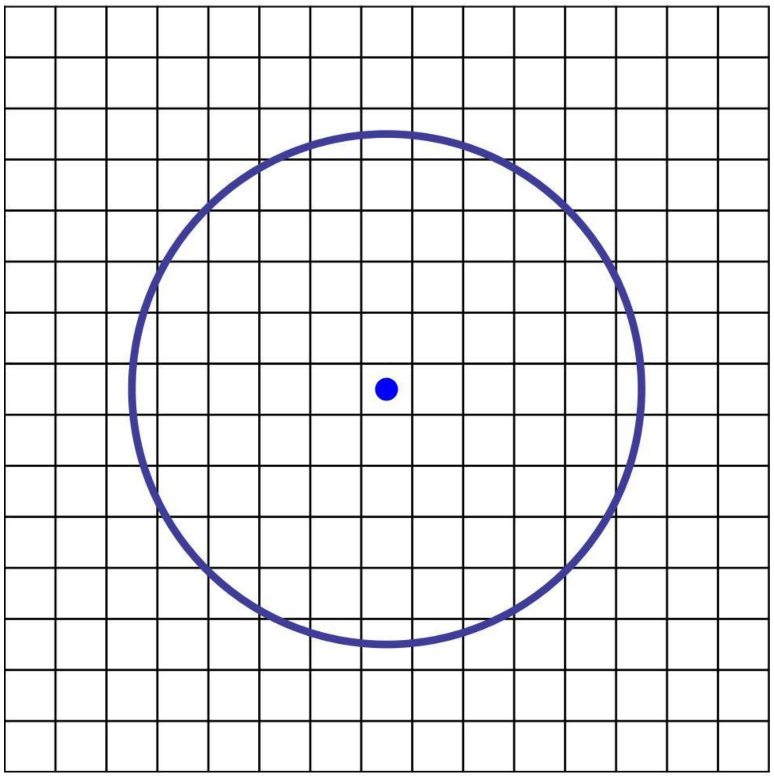


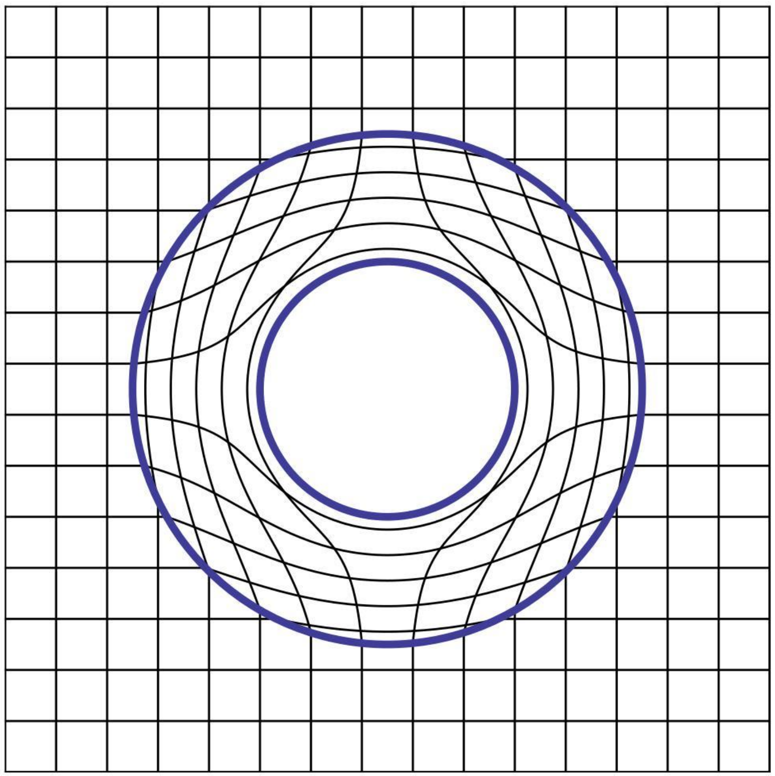


[Pendry, Schurig and Smith, Science **312**, 1780 (2006)]

Virtual space

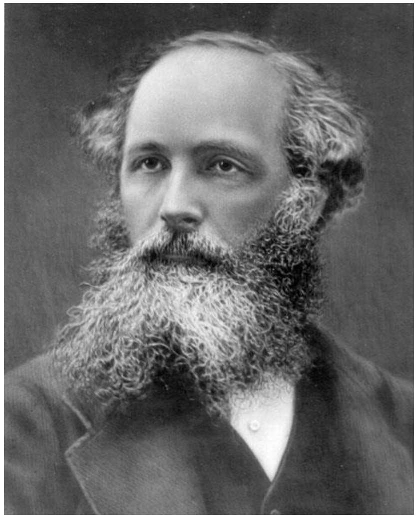
Physical space





Maxwell's electromagnetism and Einstein's general relativity

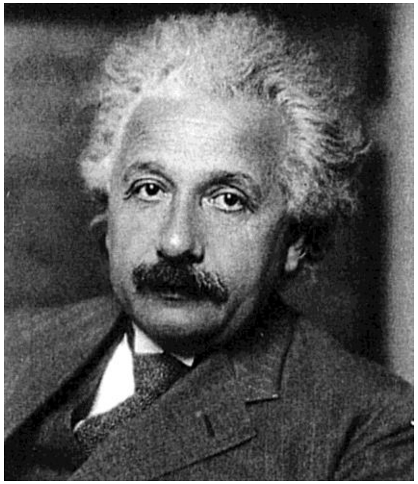
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}, \quad \nabla \cdot \vec{D} = \rho$$



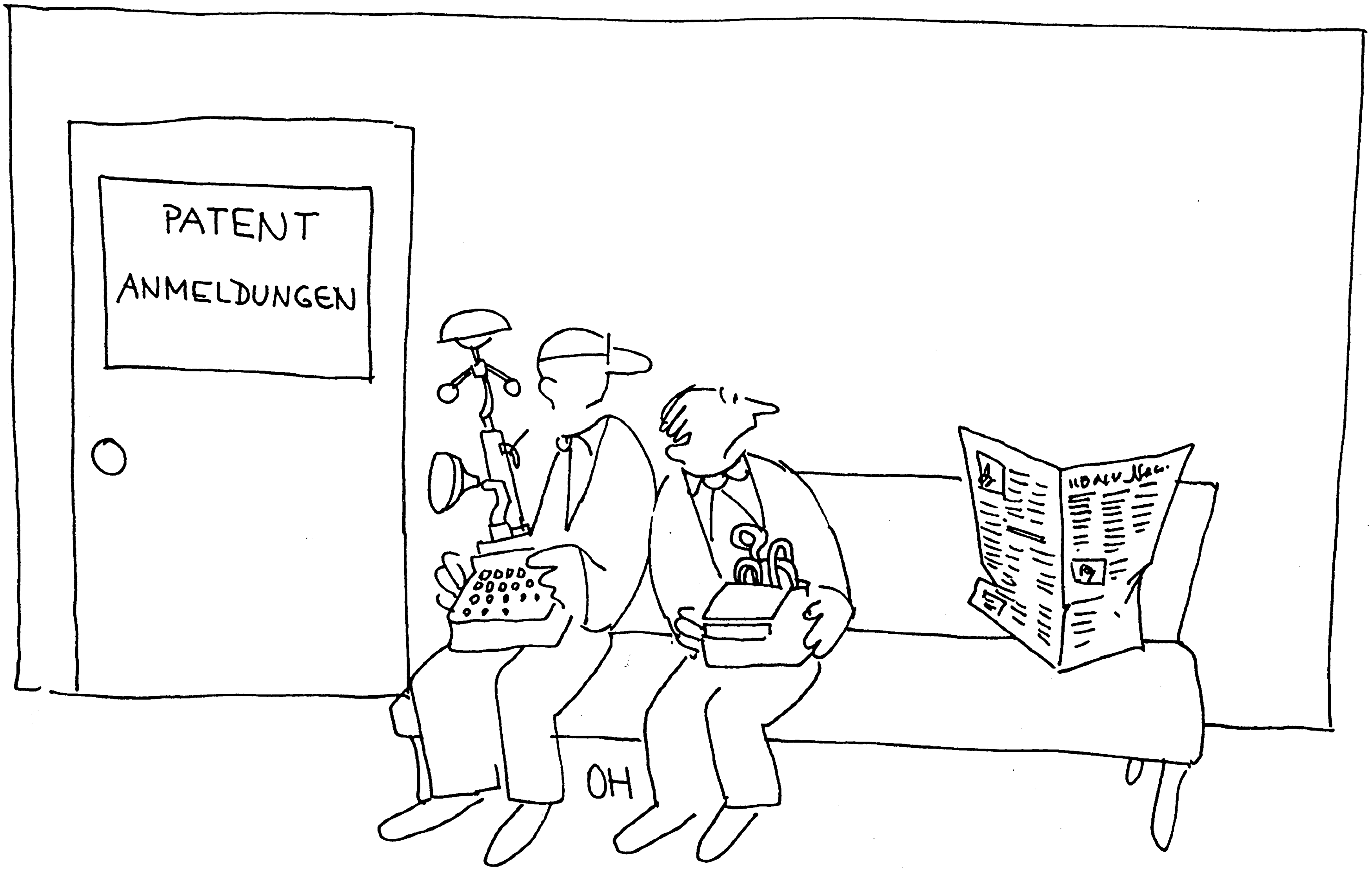
The covariant free-space Maxwell equations are equivalent to electromagnetism in a material medium (Tamm, 1924; Plebanski, 1960).

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

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

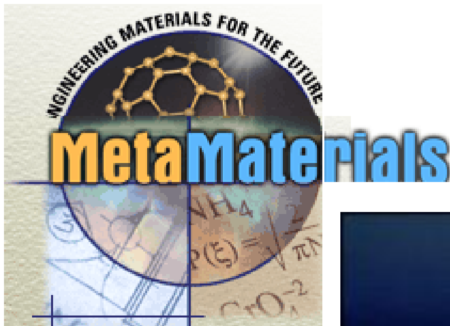


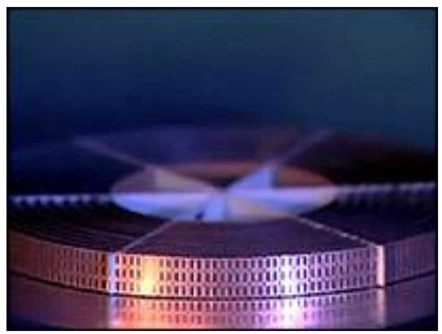
Patent office



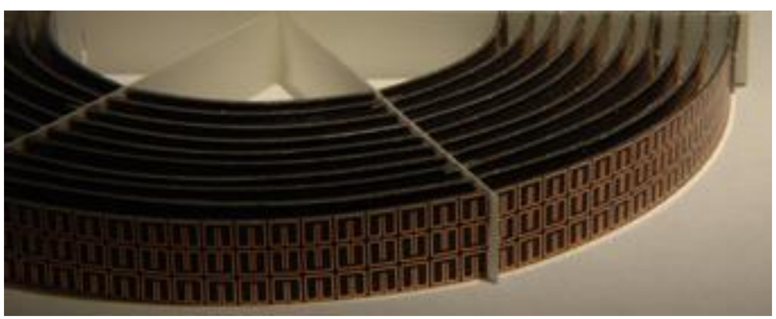
Practical demonstrations

[Schurig et al., Science Express, October 19th (2006)]



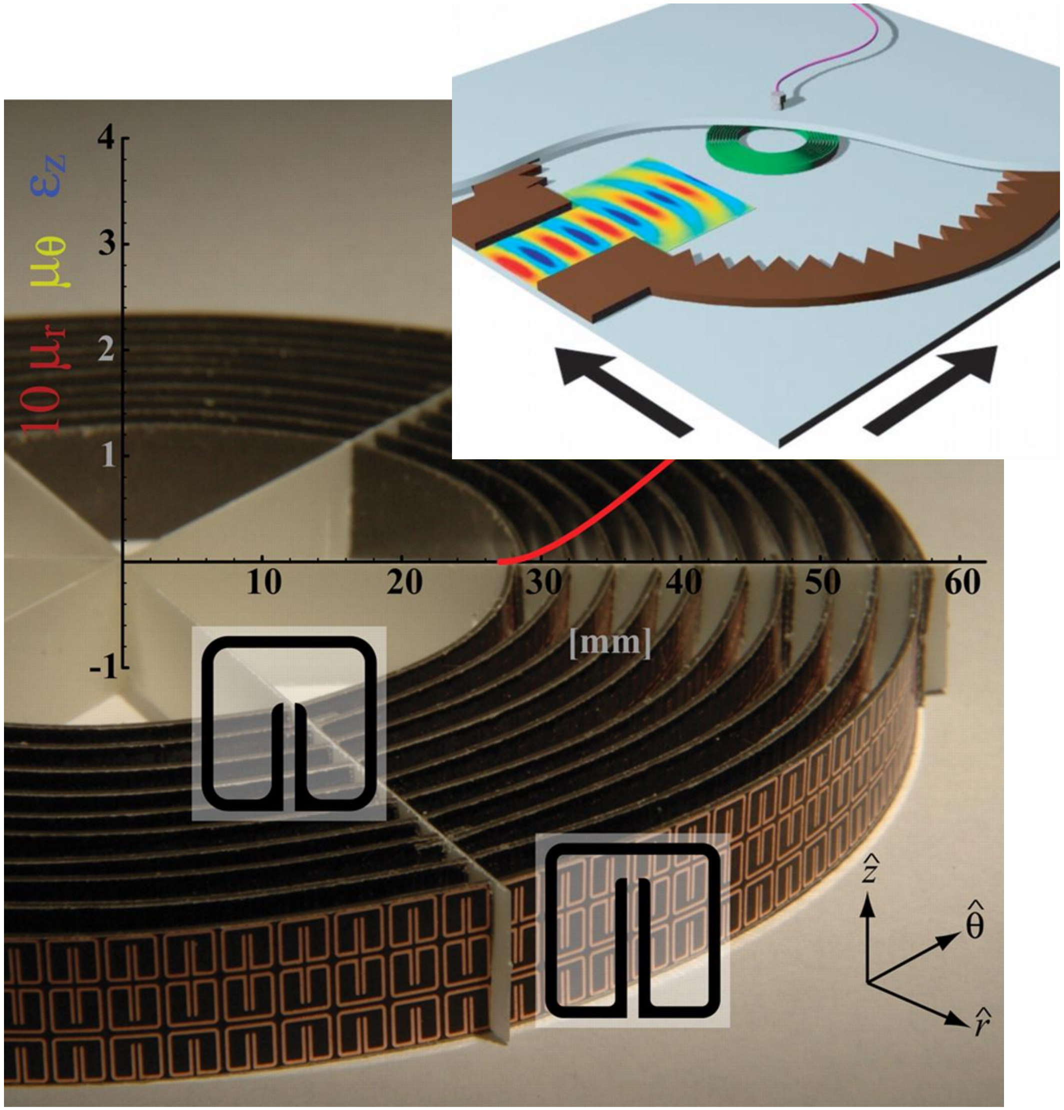


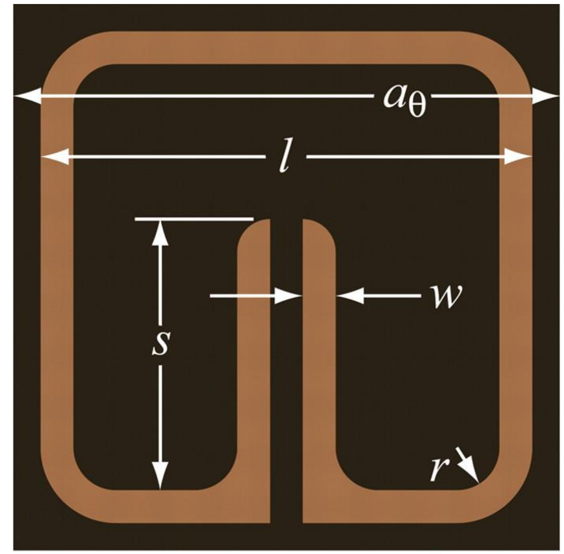
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Wegener, Linden @ Karlsruhe

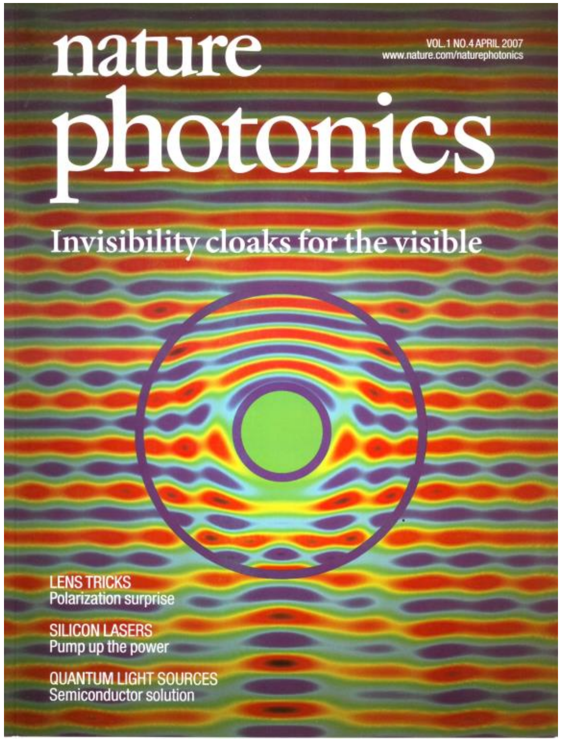
Cloaking device for electromagnetic microwaves

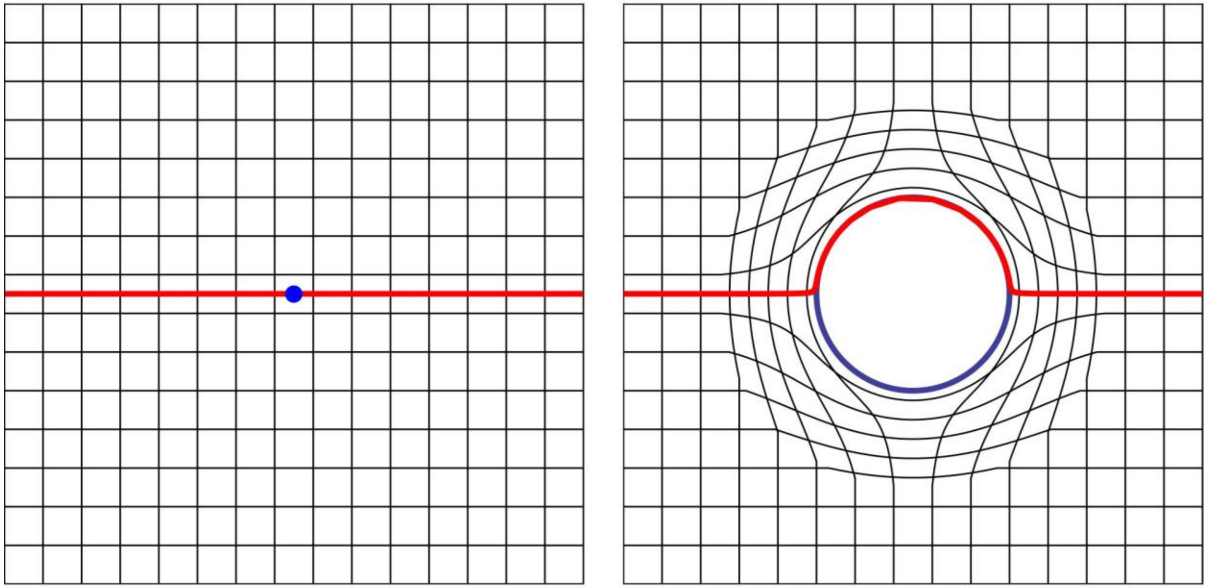


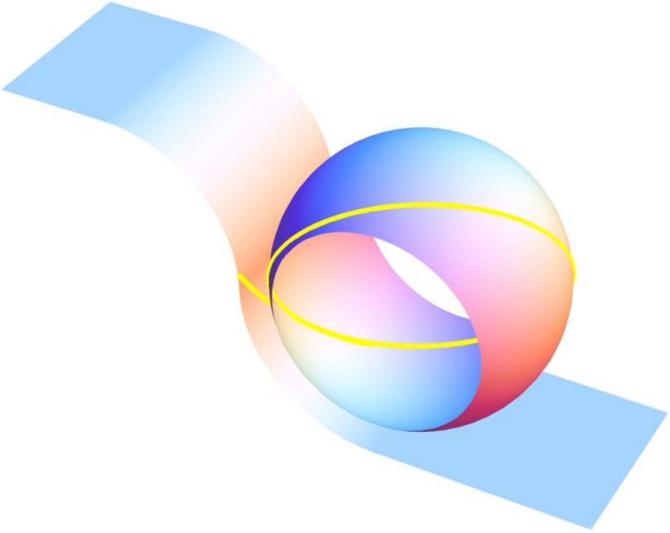


cyl.	r	s	μ_r
1	0.260	1.654	0.003
2	0.254	1.677	0.023
3	0.245	1.718	0.052
4	0.230	1.771	0.085
5	0.208	1.825	0.120
6	0.190	1.886	0.154
7	0.173	1.951	0.188
8	0.148	2.027	0.220
9	0.129	2.110	0.250
10	0.116	2.199	0.279

Challenge: Broadband invisibility



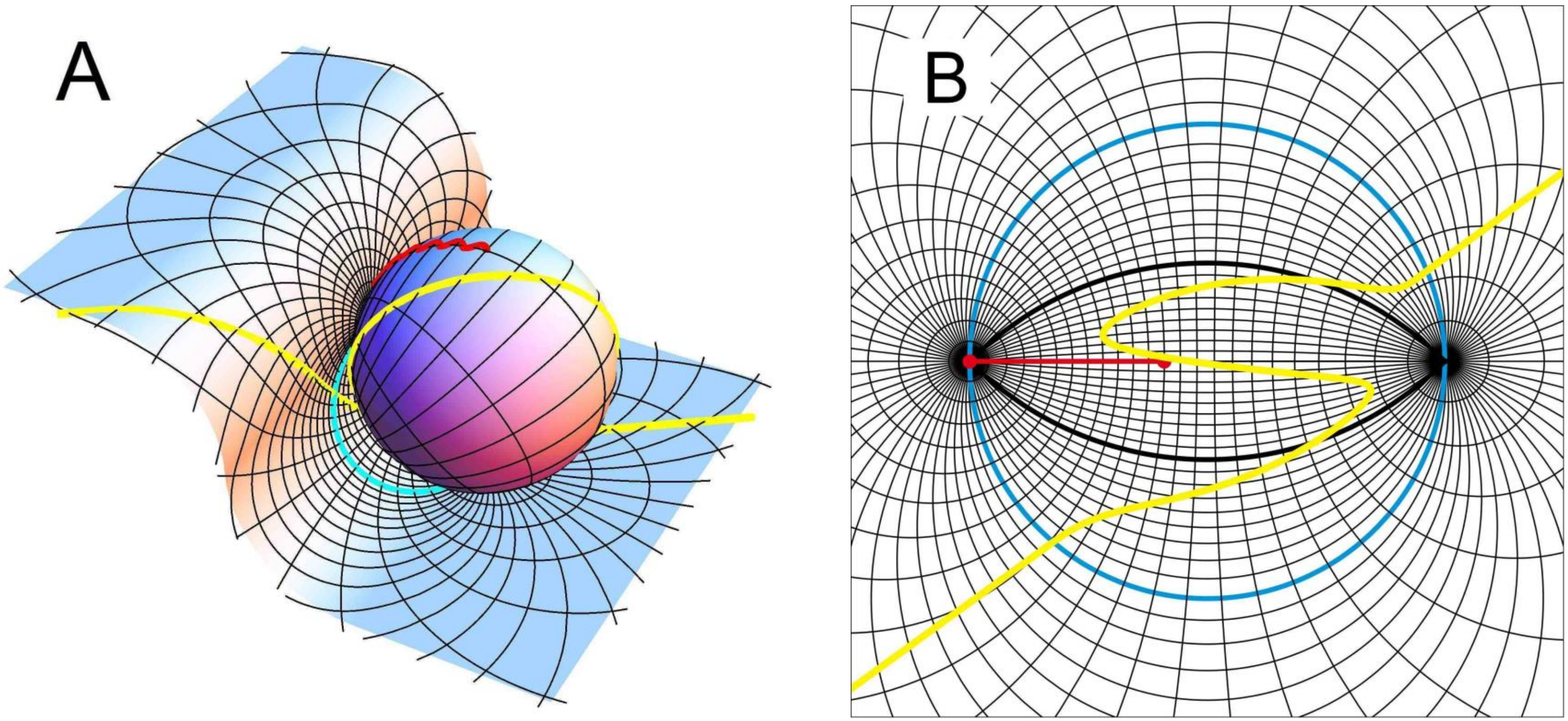




Problems: * anomalous dispersion,
* infinite speed of light at inner lining
[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)].

Ideas from Non-Euclidean Geometry

The idea



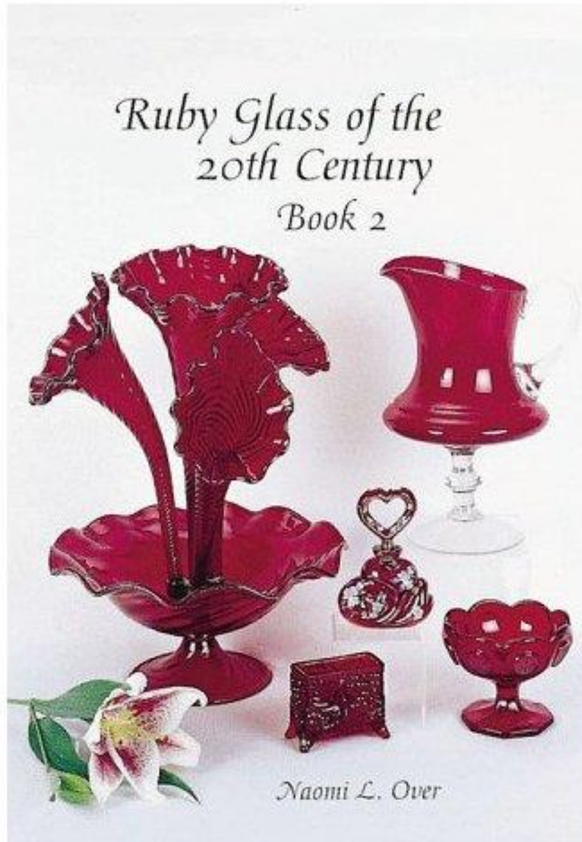
Sciencexpress Report

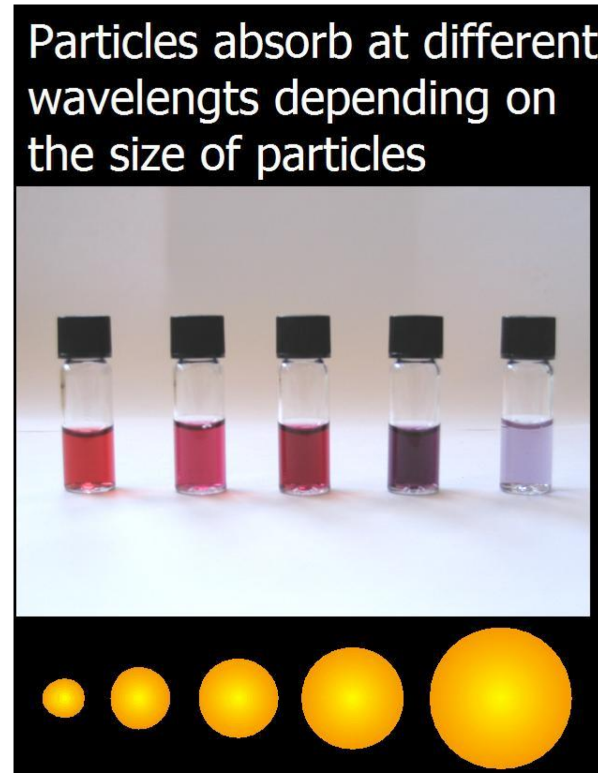
Broadband Invisibility by Non-Euclidean Cloaking

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

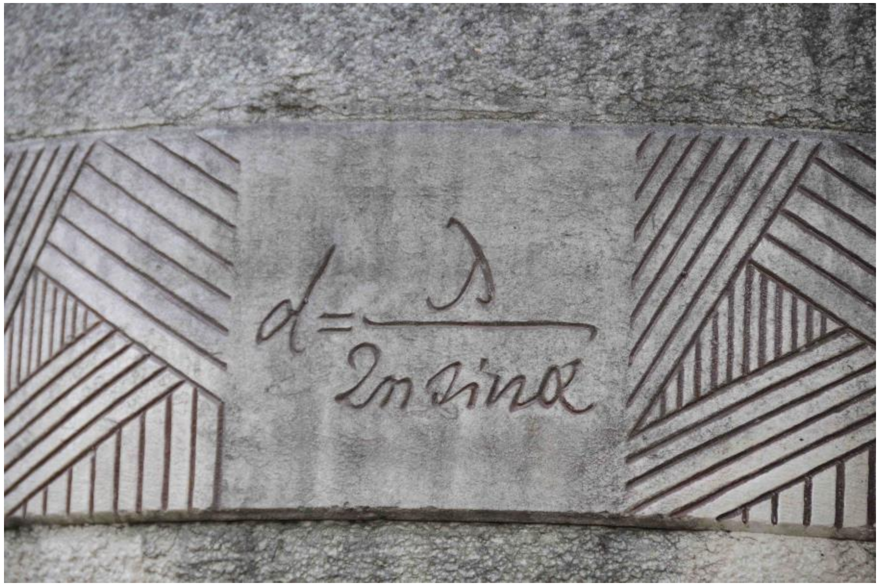
Ruby glass

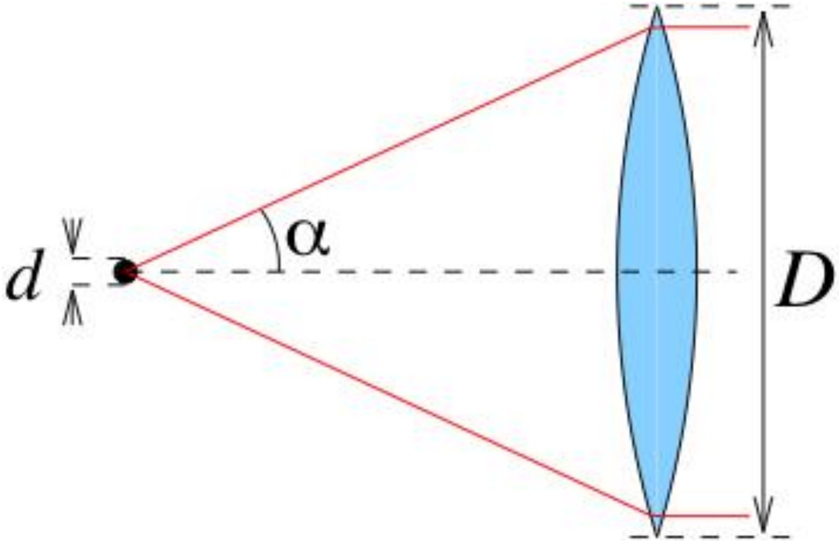
Lycurgus Cup
Roman, 4th century AD

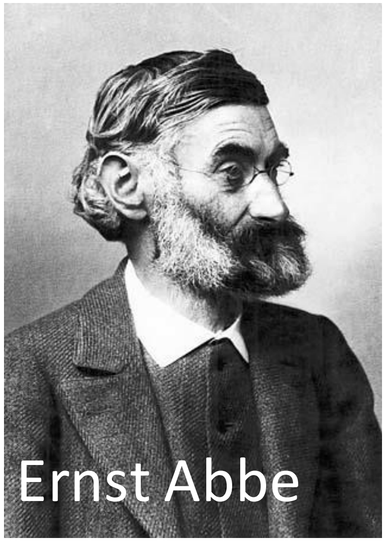




The resolution limit of imaging, established around 1870

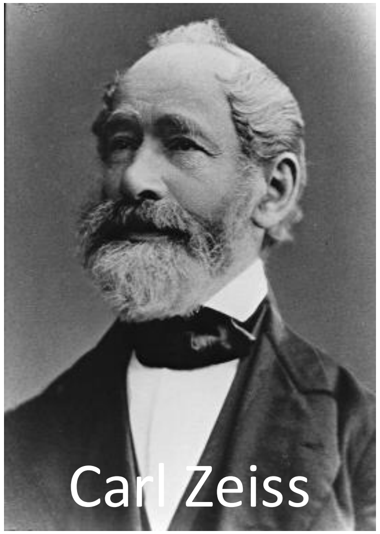


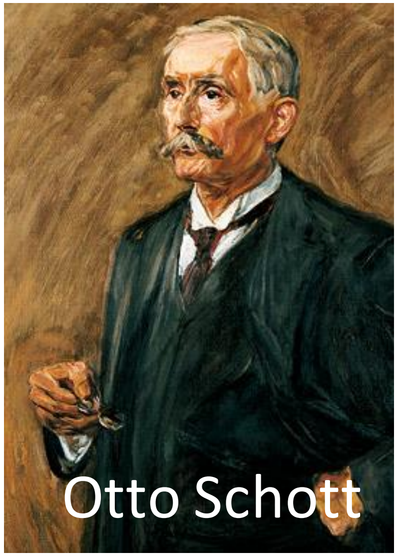




ZEISS

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
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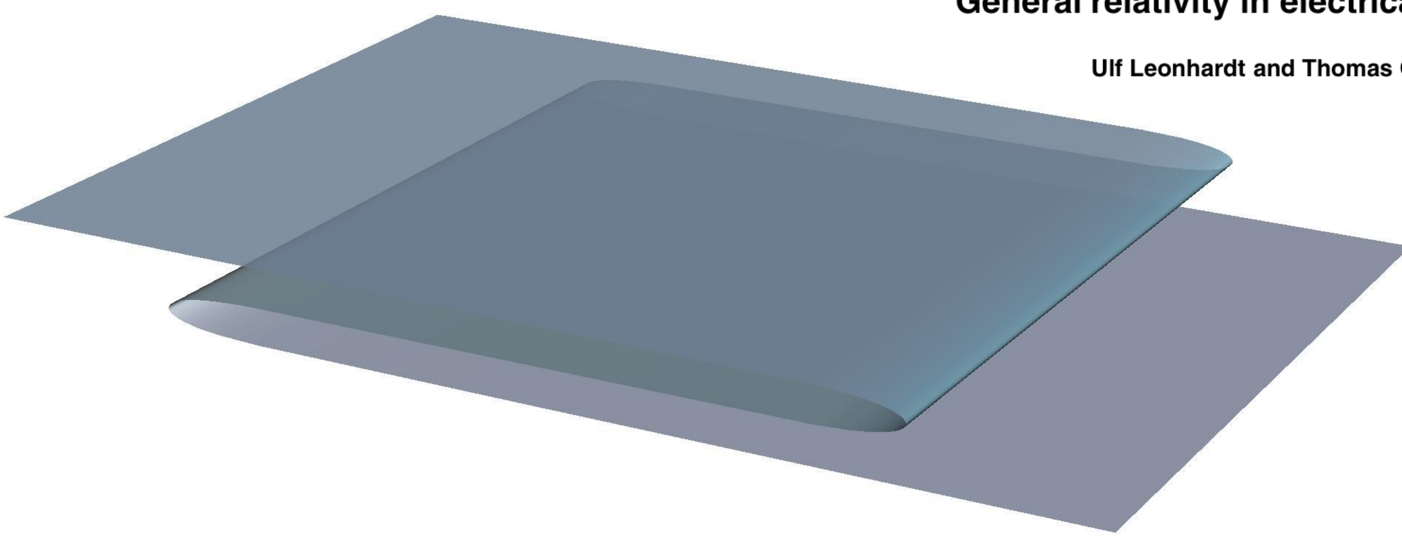
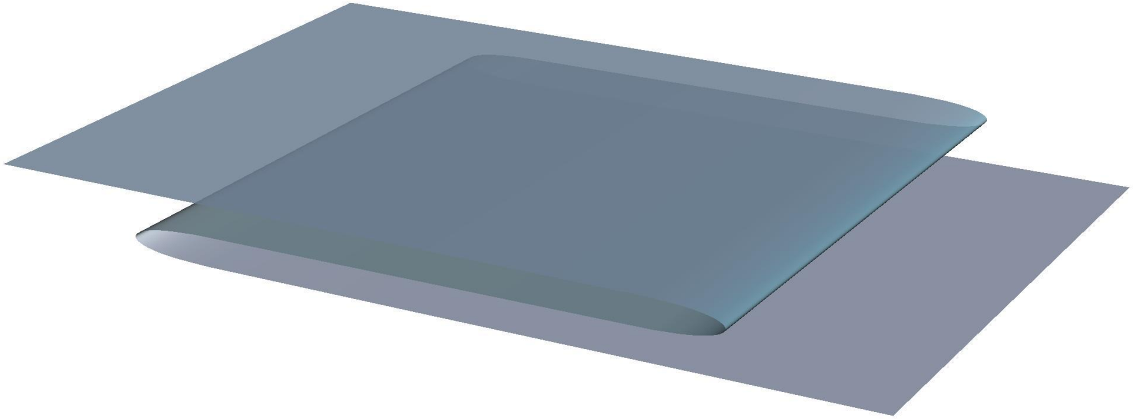
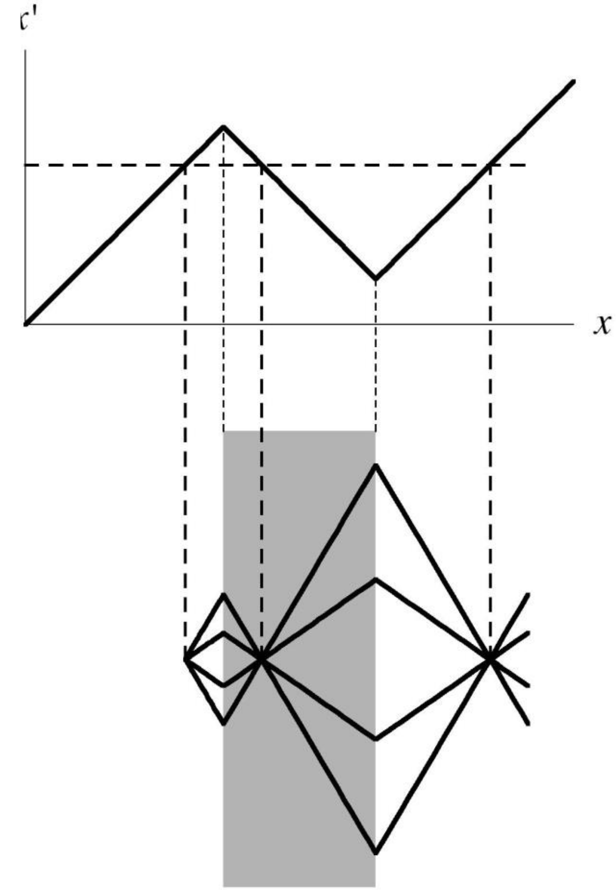
General relativity in electrical engineering

Ulf Leonhardt and Thomas G Philbin



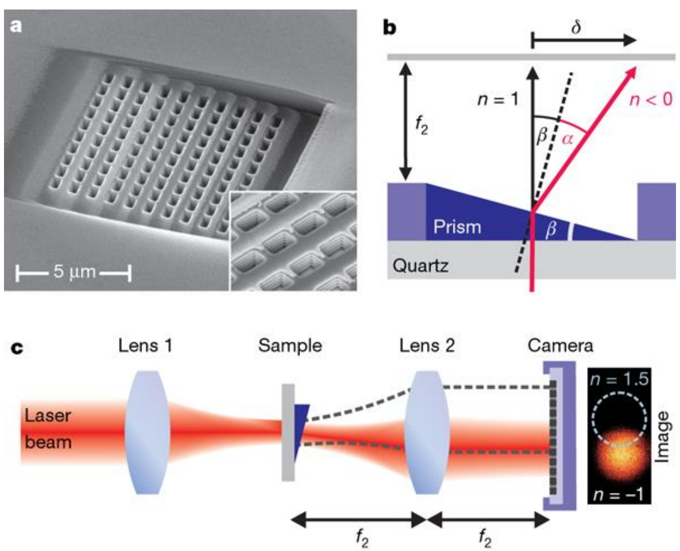
Negative refraction and perfect lens





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

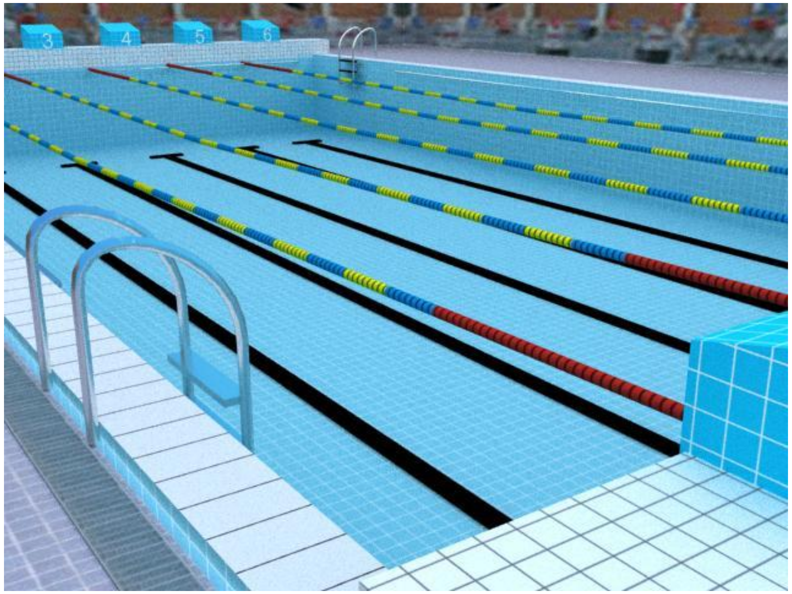
$\varepsilon = \mu = 1$ $\varepsilon = \mu = -1$ $\varepsilon = \mu = 1$

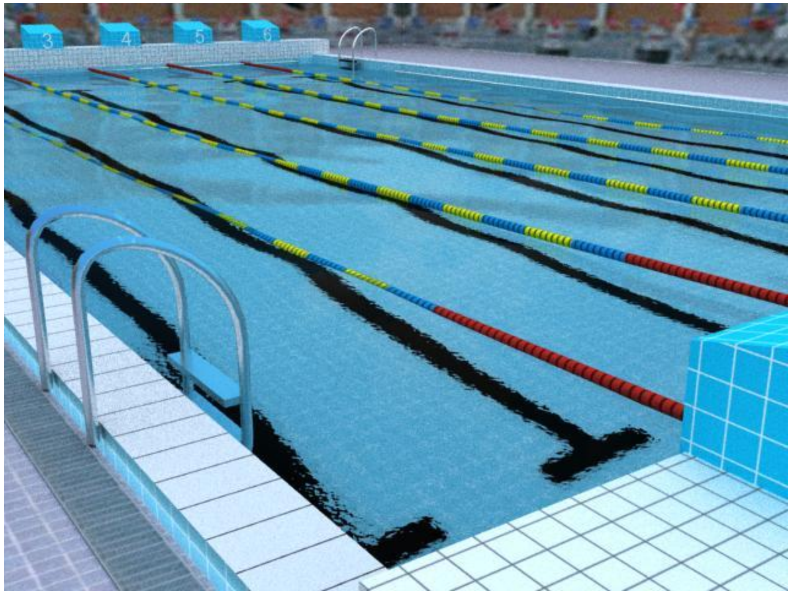


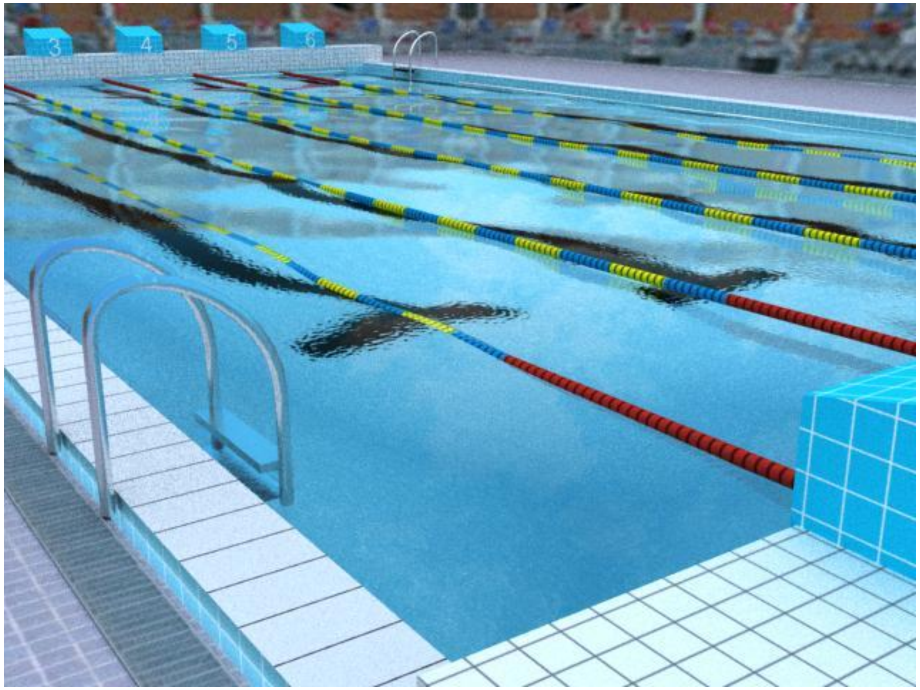
Xiang Zhang et al.
@ Berkeley

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

Negatively refracting water







$n = -1.33$

[Aaron Danner, Singapore]

Casimir effect

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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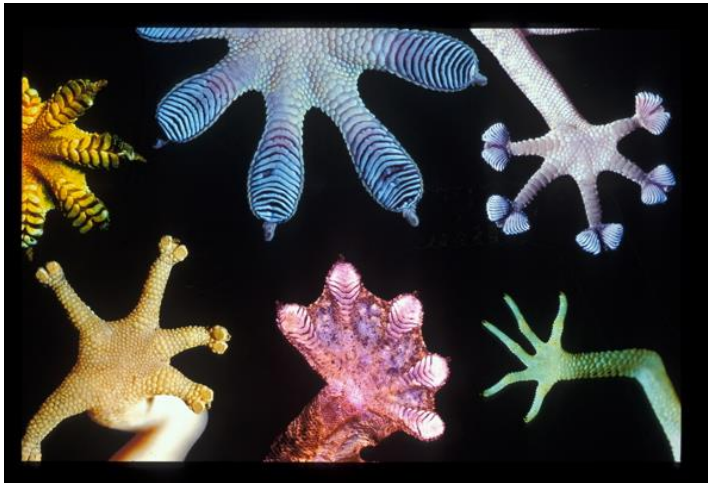
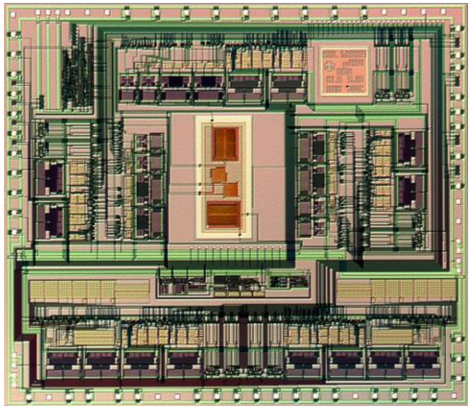
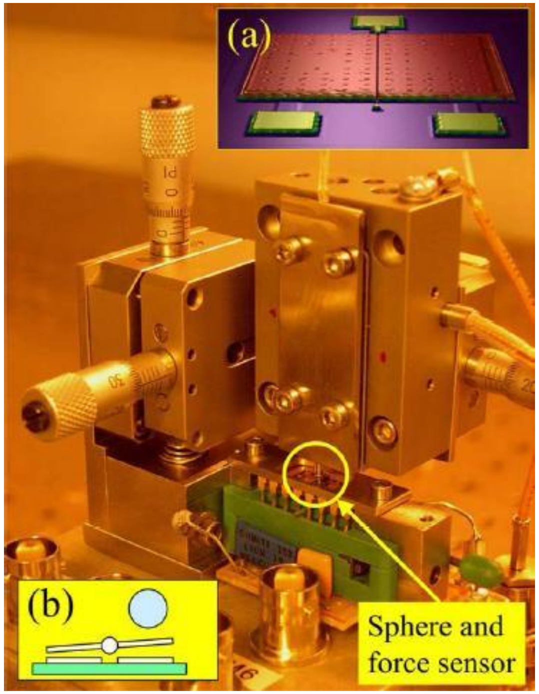
Casimir

Capasso

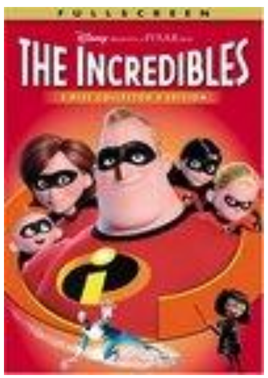
Theory: Casimir 1948
Precision experiment: Lamoreaux, PRL **78**, 5 (1997)

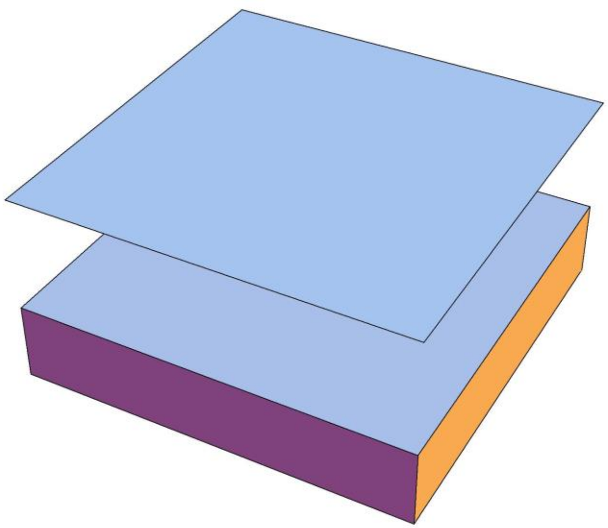


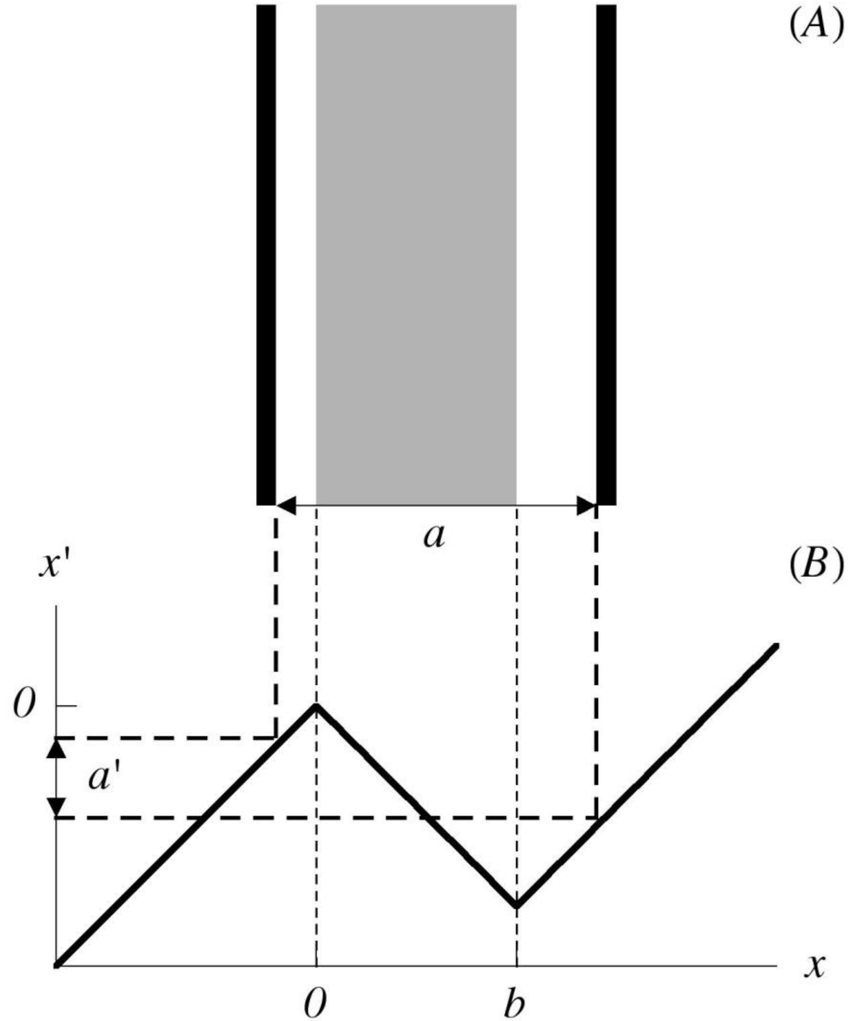




Quantum levitation







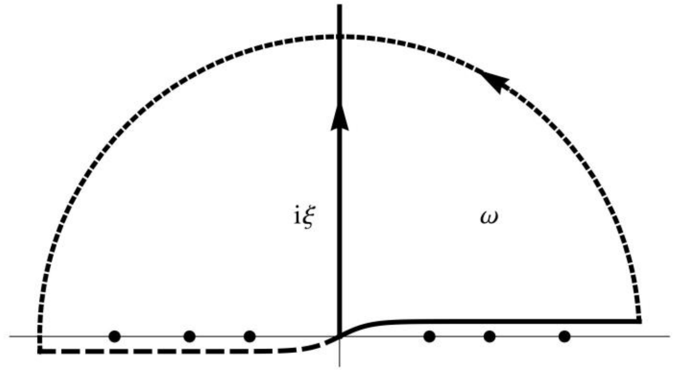
[Leonhardt and Philbin, New J. Phys. **9**, 254 (2007)]

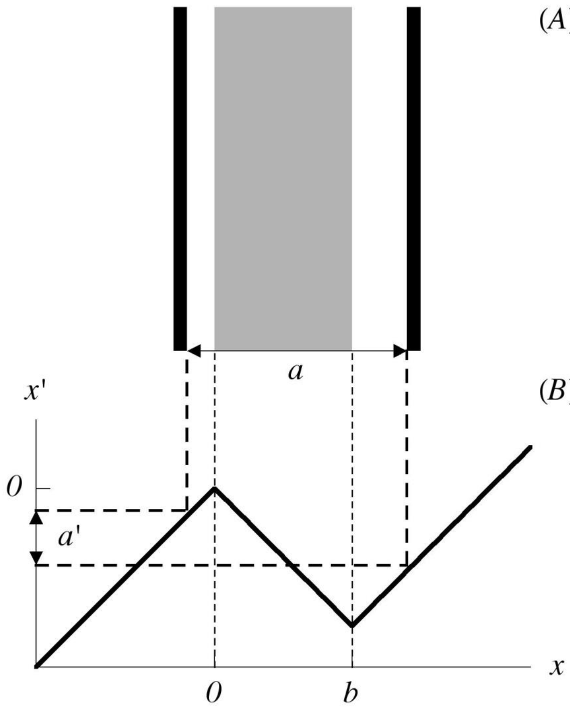
Challenge: intuition versus Lifshitz theory

$$\vec{f} = \nabla\cdot\sigma \;,\quad \sigma(\vec{r},\vec{r}\,') = \tau(\vec{r},\vec{r}\,') - \tfrac{1}{2}\mathrm{Tr}(\vec{r},\vec{r}\,')\,\mathbb{1}$$

$$\tau(\vec{r},\vec{r}\,') = \varepsilon_0 \langle 0|\hat{\vec{E}}(\vec{r})\otimes\hat{\vec{E}}(\vec{r}\,') + c^2\hat{\vec{B}}(\vec{r})\otimes\hat{\vec{B}}(\vec{r}\,')|0\rangle$$

$$\sigma = \lim_{\vec{r}\to\vec{r}\,'}\Big(\sigma(\vec{r},\vec{r}\,') - \sigma_\infty(\vec{r},\vec{r}\,')\Big),\quad \nabla\cdot\sigma_\infty = 0$$





(A) $$\langle 0|\hat{\vec{E}}(\vec{r})\otimes\hat{\vec{E}}(\vec{r}\,')|0\rangle = -\frac{\hbar}{\varepsilon_0 c^2\pi}\int_0^\infty \xi^2\, G(\vec{r},\vec{r}\,',i\xi)\,d\xi$$

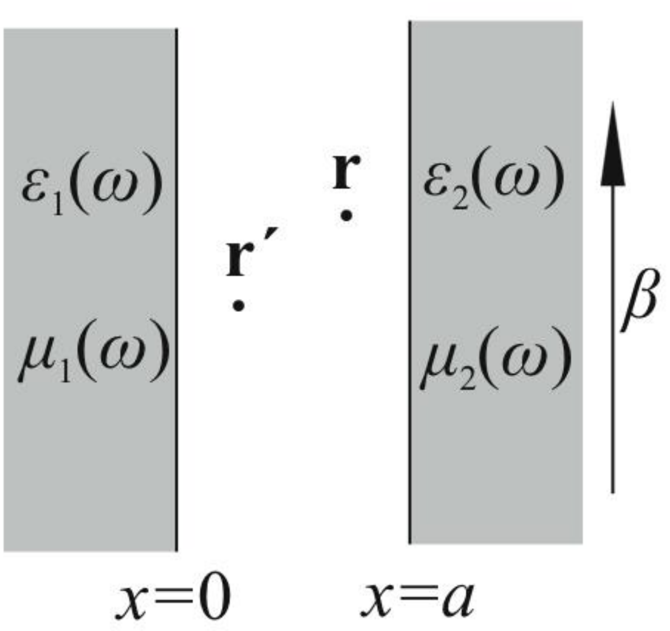
$$\langle 0|\hat{\vec{B}}(\vec{r})\otimes\hat{\vec{B}}(\vec{r}\,')|0\rangle = \frac{\hbar}{\varepsilon_0 c^2\pi}\int_0^\infty \nabla\times G(\vec{r},\vec{r}\,',i\xi)\times\overleftarrow{\nabla}'\,d\xi$$

G : GREEN'S FUNCTION

(B) $$\sigma_{xx} = \frac{\hbar}{\pi^2}\int_0^\infty\!\!\int_0^\infty \frac{wu}{e^{2a'w}-1}\,du\,d\xi \;,\quad w^2 = u^2 + \frac{\xi^2}{c^2}$$

$$\frac{wu}{e^{2a'w}-1} = -\frac{wu}{e^{-2a'w}-1} - wu \quad \text{REPULSION}$$

Challenge: theory of nanomachines

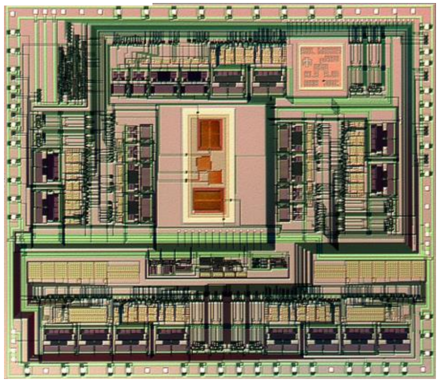


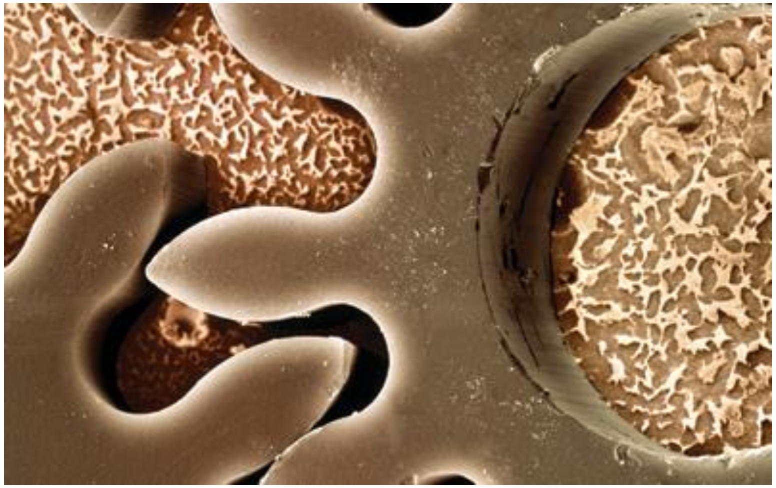
Static Casimir effect: Lifshitz 1955

Motion: Philbin and Leonhardt, New J. Phys. **11**, 033035 (2009).

No quantum friction between moving plates

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.





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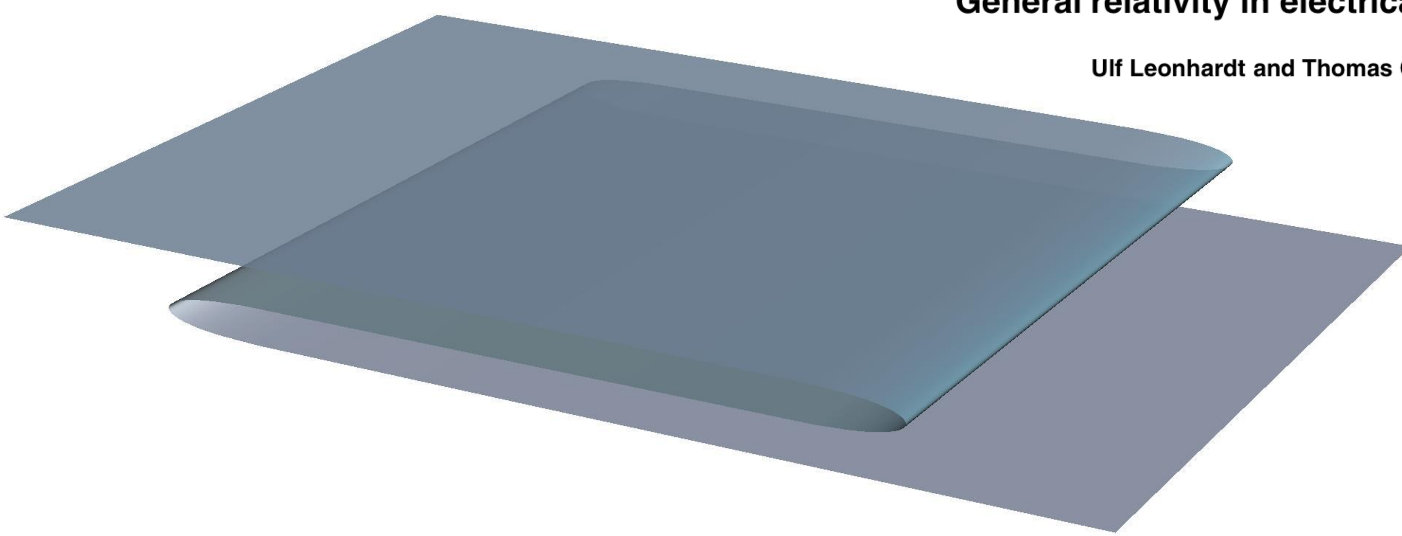
General relativity in electrical engineering

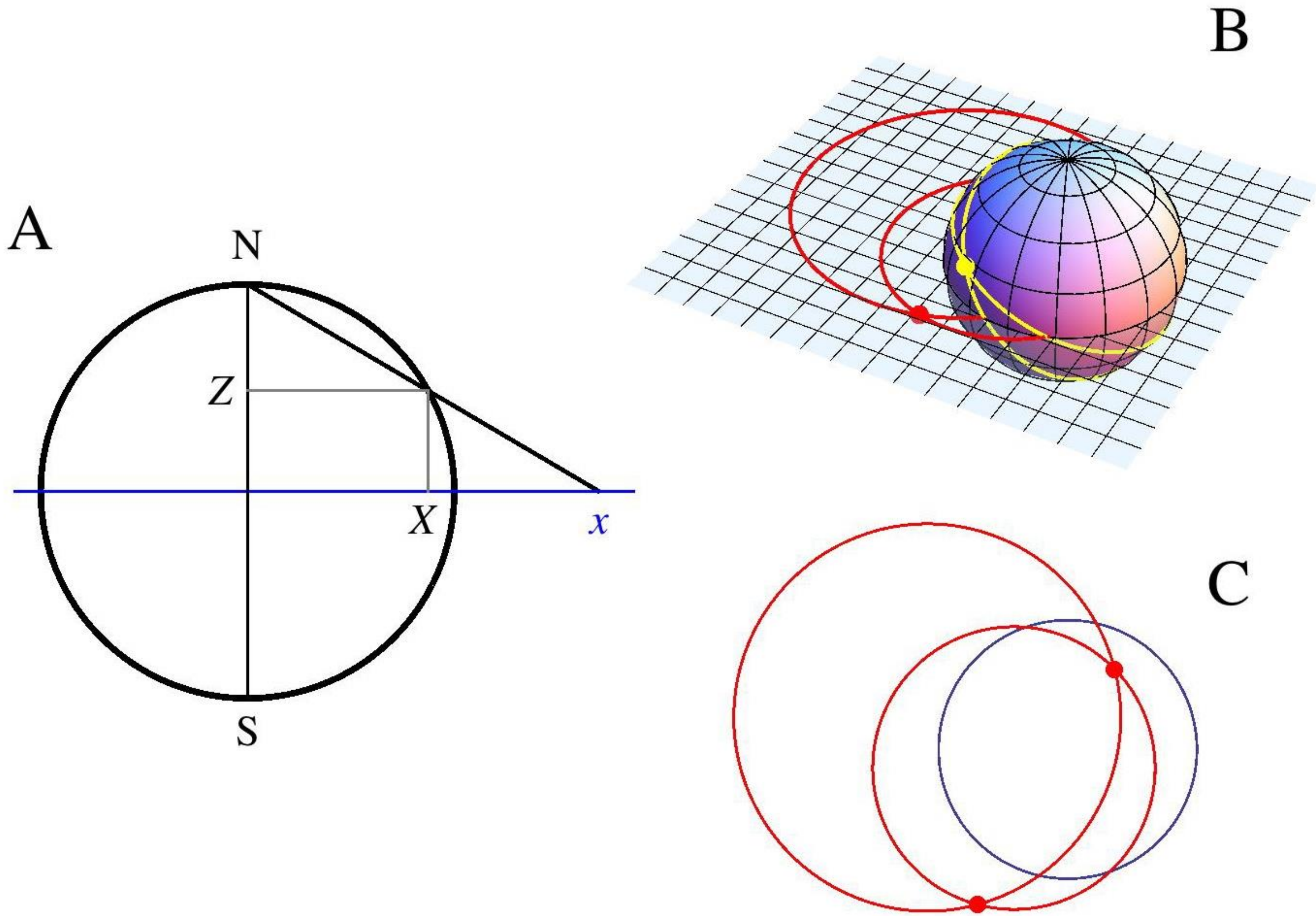
Ulf Leonhardt and Thomas G Philbin



Maxwell's fish eye makes a perfect lens

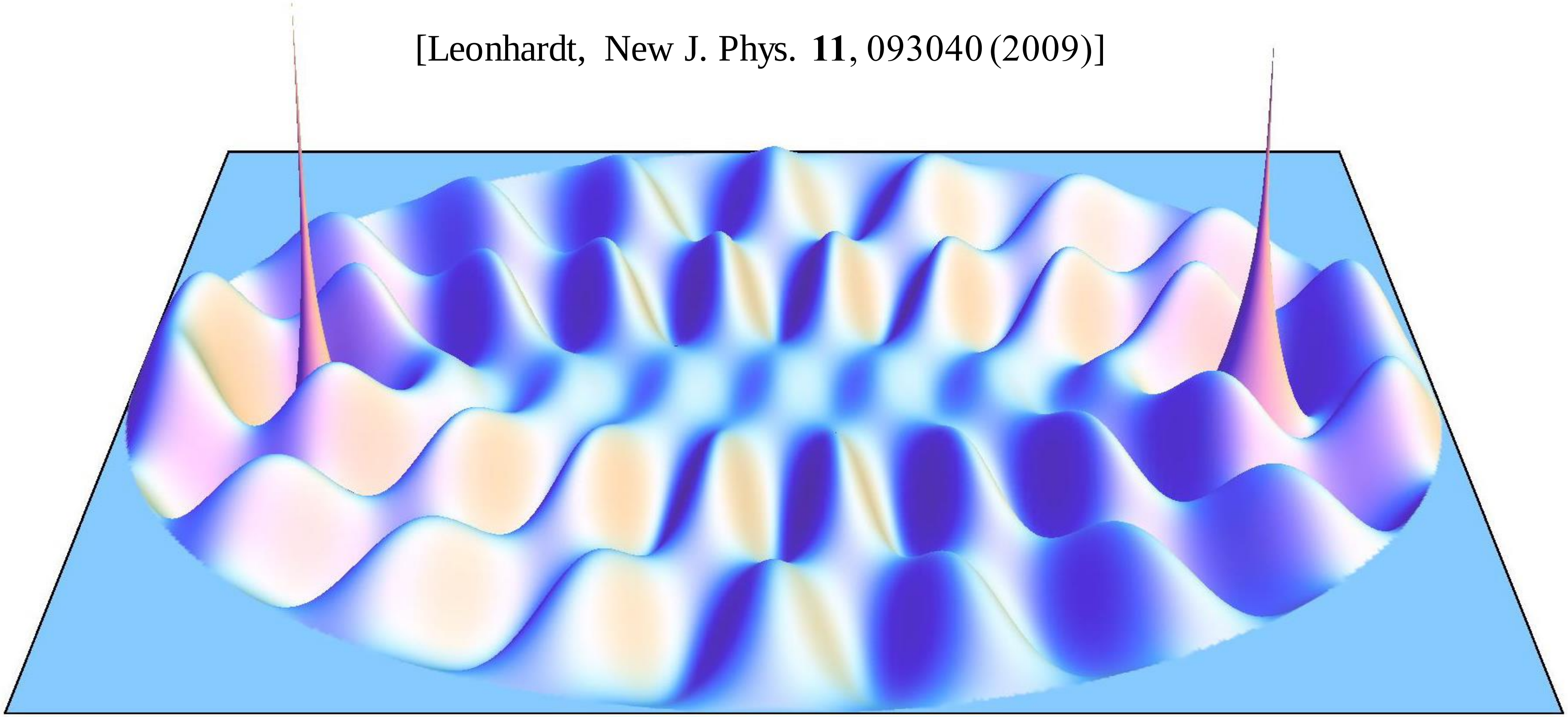
Maxwell 1854

Luneburg 1944: Stereographic projection



Perfect imaging without negative refraction

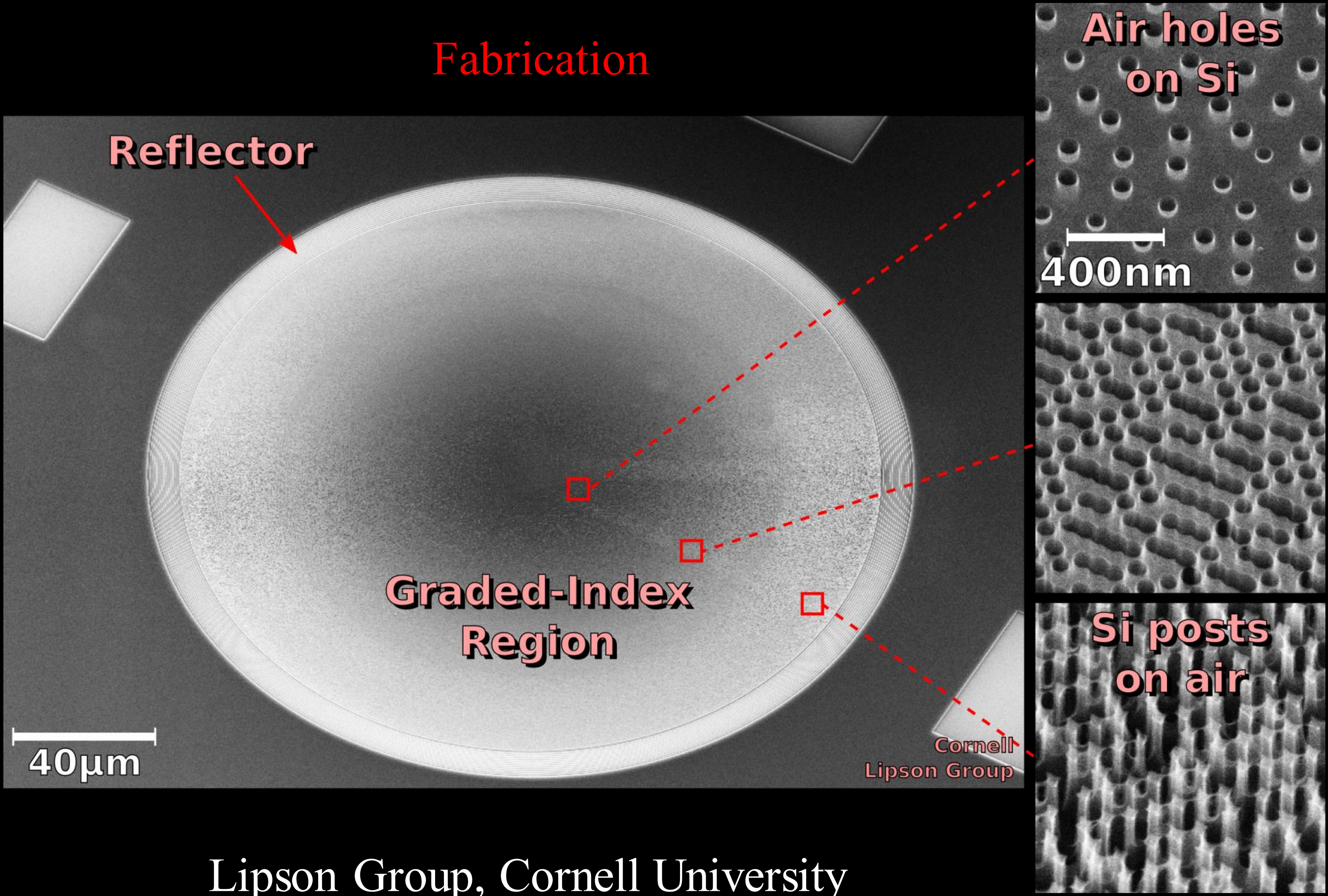
[Leonhardt, New J. Phys. **11**, 093040 (2009)]



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

Index contrast: factor of 2

Fabrication

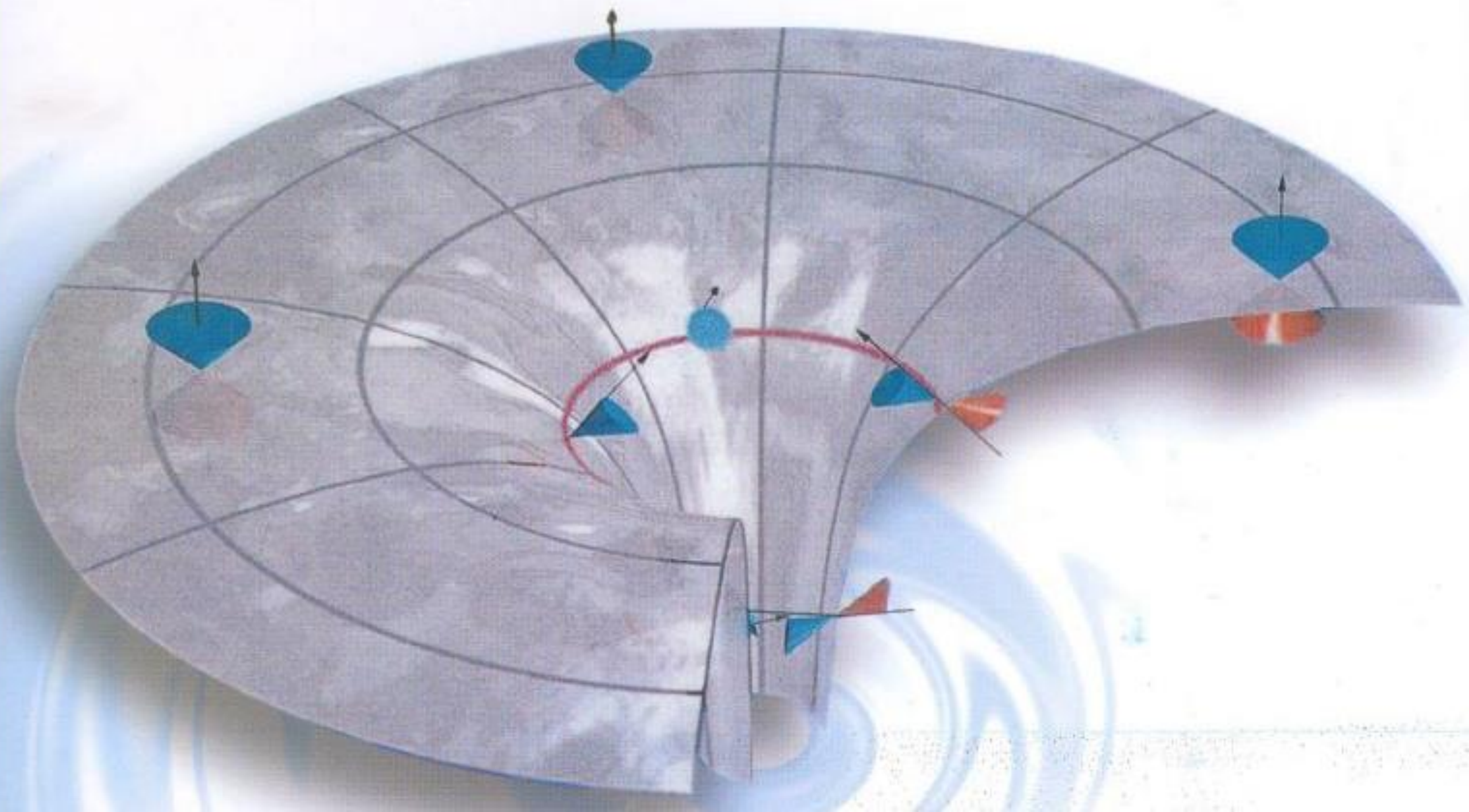


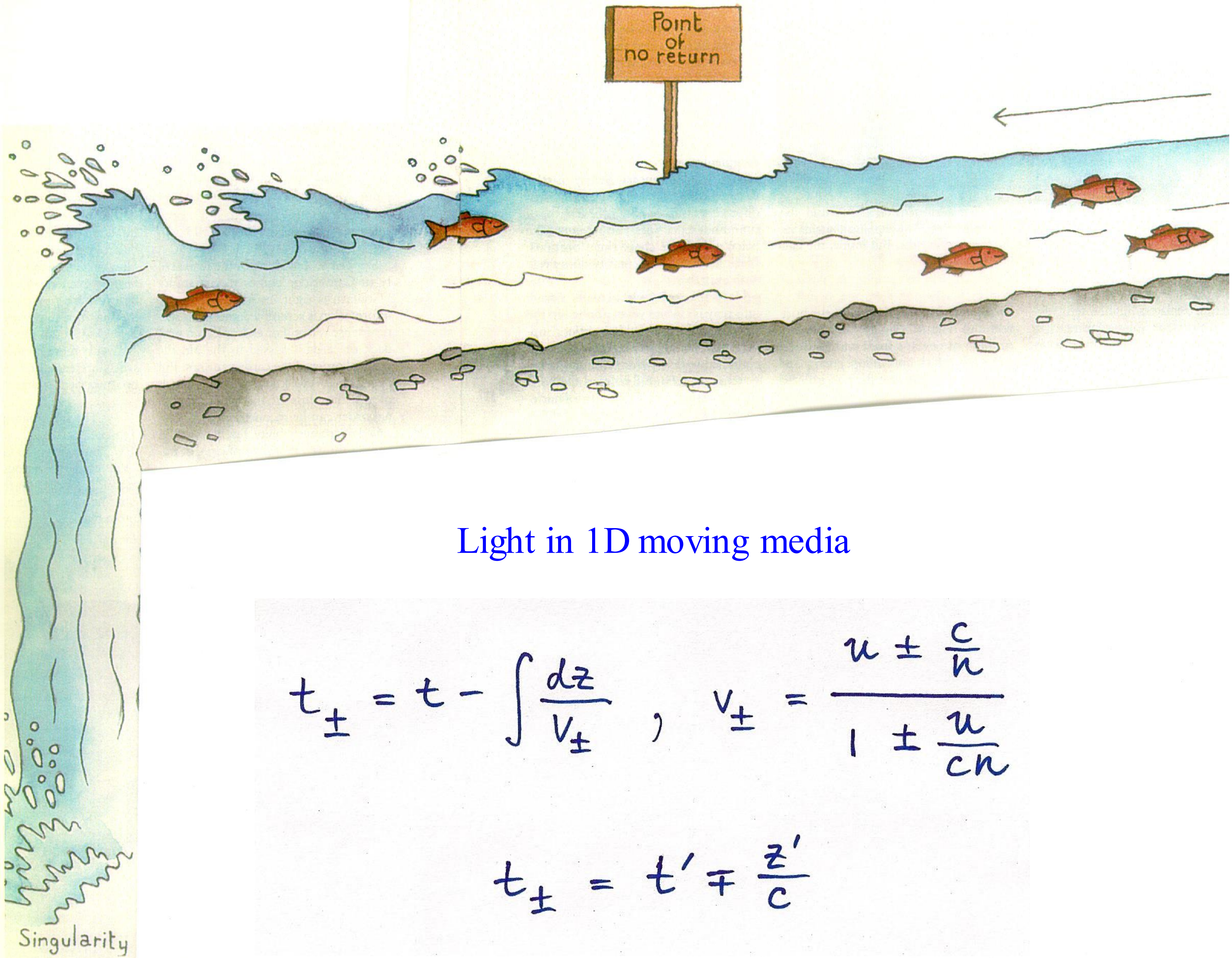
Lipson Group, Cornell University

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

ARTIFICIAL

BLACK HOLES





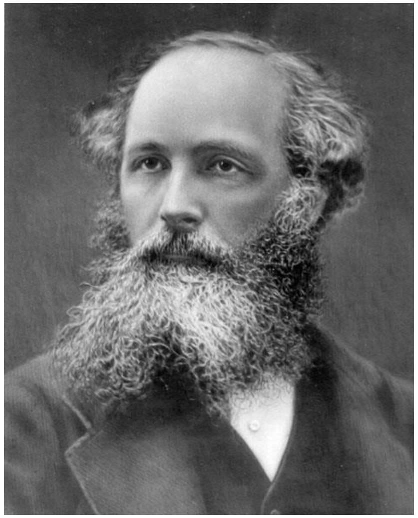
Light in 1D moving media

$$t_\pm = t - \int \frac{dz}{V_\pm}\,, \quad V_\pm = \frac{u \pm \frac{c}{n}}{1 \pm \frac{u}{cn}}$$

$$t_\pm = t' \mp \frac{z'}{c}$$

Space-time transformations: moving media

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

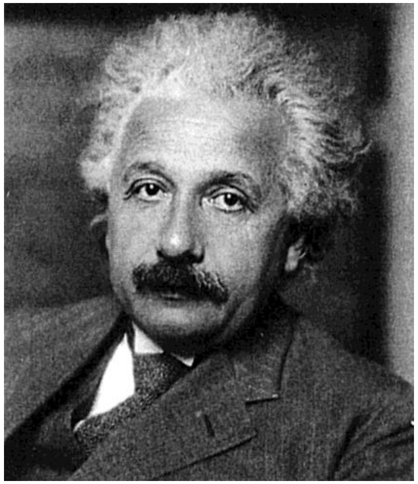


Constitutive equations of electromagnetism
in a space-time geometry:

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

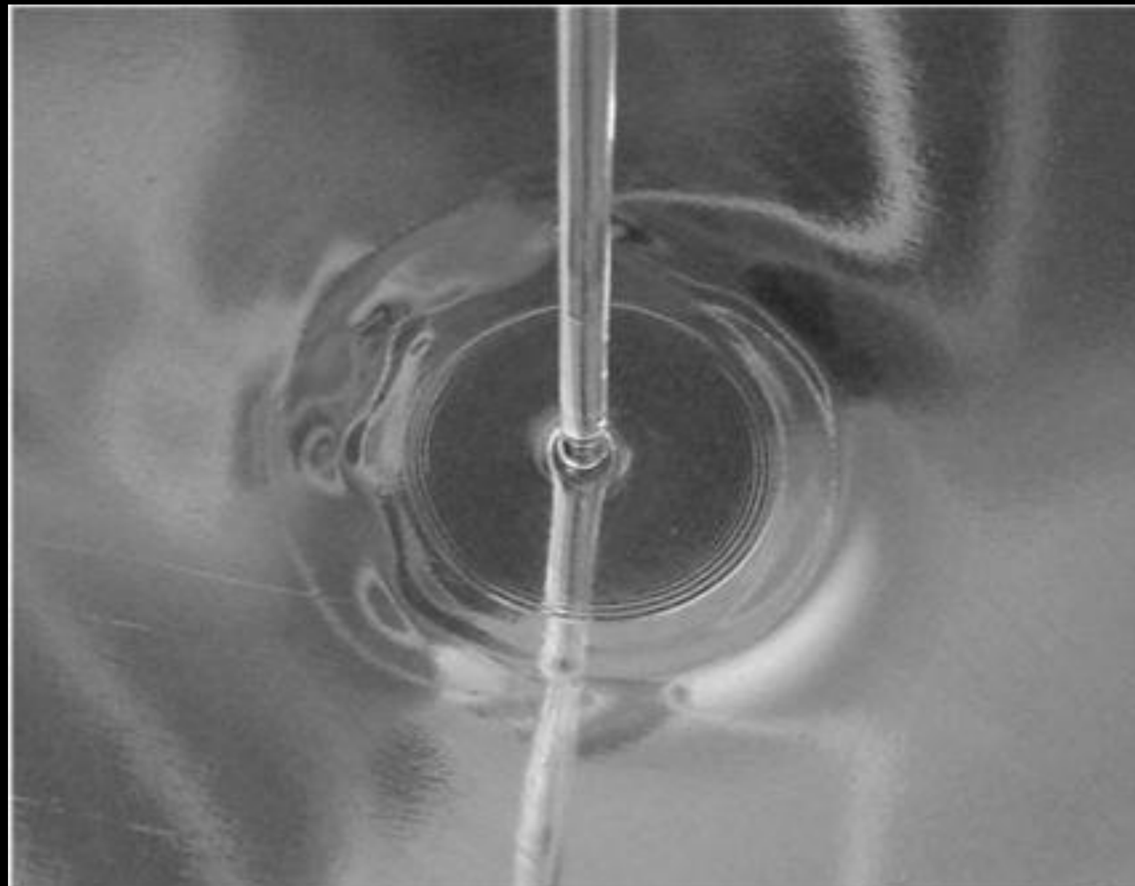
$$\varepsilon^{ij} = \mu^{ij} = \mp \frac{\sqrt{-g}}{g_{00}} g^{ij}, \quad w_i = \frac{g_{0i}}{g_{00}}$$

$$w_i = \frac{n^2 - 1}{1 - u^2 n^2 / c^2} u_i$$



Moving media

Artificial event horizons



Piotr Pieranski

Hawking radiation of black holes

they must produce a response in the scintillator comparable with that produced by a conventional charged particle. As mentioned earlier, the EAS studied by Ramana Murthy were almost two orders of magnitude less energetic than those used by us and also a much smaller time range was examined. Since the peak in our distribution occurs after the 18 μs time interval investigated by Ramana Murthy, the results cannot be directly compared. But a statistical examination of his published data using David's technique indicates that there is less than 5% probability that the data is from a uniform distribution. We note that, subjectively, the observed distribution seems to rise in the period prior to 13 μs before the shower arrival. This is not inconsistent with our observations.

It is possible than an explanation may be found for these results without invoking the existence of tachyons. A. G. Gregory has pointed out to us that fission or spallation in the interstellar medium or production of associated particles at the source might account for the correlated arrival of cosmic rays. We note, however, that unless particles are produced with closely similar rigidity and velocity vectors they are unlikely to remain associated for long in the interstellar or source magnetic fields. A closely related problem has been discussed by Weekes[8] in connection with pulsar periodicities in cosmic-ray arrival times.

We conclude that we have observed non-random events preceding the arrival of an extensive air shower. Being unable to explain this result in a more conventional manner, we suggest that this is the result of a particle travelling with an apparent velocity greater than that of light.

We thank Dr A. G. Gregory and Professors C. A. Hurst and J. R. Prescott for comments, Mr K. W. Morris for advice on statistical analysis, and Ms J. M. Taylor for chart reading. One of us (R.W.C.) holds a Queen Elizabeth Fellowship. The University of Calgary is thanked for the loan of equipment.

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Black hole explosions?

Quantum gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of spacetime outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s. The purpose of this letter is to show that this indeed may be the case: it seems that any black hole will create and emit particles such as neutrinos or photons at just the rate that one would expect if the black hole was a body with a temperature of $(\kappa/2\pi)(\hbar/2k) \approx 10^{-6}\,(M_\odot/M)K$ where κ is the surface gravity of the black hole[1]. As a black hole emits this thermal radiation one would expect it to lose mass. This in turn would increase the surface gravity and so increase the rate of emission. The black hole would therefore have a finite life of the order of $10^{71}\,(M_\odot/M)^{-3}$ s. For a black hole of solar mass this is much longer than the age of the Universe. There might, however, be much smaller black holes which were formed by fluctuations in the early Universe[2]. Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.

To see how this thermal emission arises, consider (for simplicity) a massless Hermitean scalar field ϕ which obeys the covariant wave equation $\phi_{;ab}g^{ab} = 0$ in an asymptotically flat space time containing a star which collapses to produce a black hole. The Heisenberg operator ϕ can be expressed as

$$\phi = \sum_i \{f_i a_i + \bar{f}_i a_i^+\}$$

where the f_i are a complete orthonormal family of complex valued solutions of the wave equation $f_{i;ab}g^{ab} = 0$ which are asymptotically ingoing and positive frequency—they contain only positive frequencies on past null infinity I^- [3,4,5]. The position-independent operators a_i and a_i^+ are interpreted as annihilation and creation operators respectively for incoming scalar particles. Thus the initial vacuum state, the state containing no incoming scalar particles, is defined by $a_i|0_-\rangle = 0$ for all i. The operator ϕ can also be expressed in terms of solutions which represent outgoing waves and waves crossing the event horizon:

$$\phi = \sum_i \{p_i b_i + \bar{p}_i b_i^+ + q_i c_i + \bar{q}_i c_i^+\}$$

where the p_i are solutions of the wave equation which are zero on the event horizon and are asymptotically outgoing positive frequency waves (positive frequency on future null infinity I^+) and the q_i are solutions which contain no outgoing component (they are zero on I^+). For the present purposes it is not necessary that the q_i are positive frequency on the horizon even if that could be defined. Because fields of zero rest mass are completely determined by their values on I^-, the p_i and the q_i can be expressed as linear combinations of the f_i and the $\bar{f}_i$:

$$p_i = \sum_j \{\alpha_{ij} f_j + \beta_{ij} \bar{f}_j\} \quad \text{and so on}$$

The β_{ij} will not be zero because the time dependence of the metric during the collapse will cause a certain amount of mixing of positive and negative frequencies. Equating the two expressions for ϕ, one finds that the b_i, which are the annihilation operators for outgoing scalar particles, can be expressed as a linear combination of the ingoing annihilation and creation operators a_i and a_i^+

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

Thus when there are no incoming particles the expectation value of the number operator $b_i^+ b_i$ of the ith outgoing state is

$$< 0_- |b_i^+ b_i| 0_- > = \sum_j |\beta_{ij}|^2$$

The number of particles created and emitted to infinity in a gravitational collapse can therefore be determined by calculating the coefficients β_{ij}. Consider a simple example in which the collapse is spherically symmetric. The angular dependence of the solution of the wave equation can then be expressed in terms of the spherical harmonics Y_{lm} and the dependence on retarded or advanced time u, v can be taken to have the form $\omega^{-1/2}$ *exp* $(i\omega u)$ (here the continuum normalisation is used). Outgoing solutions $p_{lm\omega}$ will now be expressed as an integral over incoming fields with the same l and m:

$$p_\omega = \int \{\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} \bar{f}_{\omega'}\}\, d\omega'$$

(The lm suffixes have been dropped.) To calculate $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ consider a wave which has a positive frequency ω on I^+ propagating backwards through spacetime with nothing crossing the event horizon. Part of this wave will be scattered by the curvature of the static Schwarzschild solution outside the black hole and will end up on I^- with the same frequency ω. This will give a $\delta(\omega - \omega')$ behaviour in $\alpha_{\omega\omega'}$. Another part of the wave will propagate backwards into the star, through the origin and out again onto I^-. These waves will have a very large blue shift and will reach I^- with asymptotic form

$$C\omega^{-1/2} \exp\{-i\omega\kappa^{-1}\log(v_0 - v) + i\omega v\}\ \textit{for}\ v < v_0$$

and zero for $v \geq v_0$, where v_0 is the last advanced time at which a particle can leave I^-, pass through the origin and escape to I^+. Taking Fourier transforms, one finds that for large ω', $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ have the form:

$$\alpha_{\omega\omega'} \approx C \exp[i(\omega - \omega)v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/\kappa)[-i(\omega - \omega')]^{-1+i\omega/\kappa}$$

$$\beta_{\omega\omega'} \approx C \exp[i(\omega + \omega)v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/\kappa)[-i(\omega + \omega')]^{-1+i\omega/\kappa}.$$

The total number of outgoing particles created in the frequency range $\omega \rightarrow \omega + d\omega$ is $d\omega\int_0^\infty|\beta_{\omega\omega'}|^2 d\omega'$. From the above expression it can be seen that this is infinite. By considering outgoing wave packets which are peaked at a frequency ω and at late retarded times one can see that this infinite number of particles corresponds to a steady rate of emission at late retarded times. One can estimate this rate in the following way. The part of the wave from I^+ which enters the star at late retarded times is almost the same as the part that would have crossed the past event horizon of the Schwarzschild solution had it existed. The probability flux in a wave packet peaked at ω is roughly proportional to $\int_{\omega_1'}^{\omega_2'}\{|\alpha_{\omega\omega'}|^2 - |\beta_{\omega\omega'}|^2\}\, d\omega$ where $\omega_2' \gg \omega_1' \gg 0$. In the expressions given above for $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ there is a logarithmic singularity in the factors $[-i(\omega - \omega')]^{-1+i\omega/\kappa}$ and $[-i(\omega + \omega')]^{-1+i\omega/\kappa}$. Value of the expressions on different sheets differ by factors of $\exp(2\pi n\omega\kappa^{-1})$. To obtain the correct ratio of $\alpha_{\omega\omega'}$ to $\beta_{\omega\omega'}$ one has to continue $[-i(\omega + \omega')]^{-1+i\omega/\kappa}$ in the upper half ω' plane round the singularity and then replace ω' by $-\omega'$. This means that, for large ω',

$$|\alpha_{\omega\omega'}| = \exp(\pi\omega/\kappa)\, |\beta_{\omega\omega'}|$$

From this it follows that the number of particles emitted in this wave packet mode is $(\exp(2\pi\omega/\kappa) - 1)^{-1}$ times the number of particles that would have been absorbed from a similar wave packet incident on the black hole from I^-. But this is just the relation between absorption and emission cross sections that one would expect from a body with a temperature in geometric units of $\kappa/2\pi$. Similar results hold for massless fields of any integer spin. For half integer spin one again gets a similar result except that the emission cross section is $(\exp(2\pi\omega/\kappa) + 1)^{-1}$ times the absorption cross section as one would expect for thermal emission of fermions. These results do not seem to depend on the assumption of exact spherical symmetry which merely simplifies the calculation.

Beckenstein[6] suggested on thermodynamic grounds that some multiple of κ should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this. Of course this calculation ignores the back reaction of the particles on the metric, and quantum fluctuations on the metric. These might alter the picture.

Further details of this work will be published elsewhere. The author is very grateful to G. W. Gibbons for discussions and help.

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University of Cambridge

Received January 17, 1974.

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Absorption and emission by interstellar CH at 9 cm

Rydbeck, Ellder and Irvine[1] have recently detected the 9-cm lines of the $^2\Pi_{1/2}$, $J = \frac{1}{2}\Lambda$ doublet of interstellar CH. The $F = 1 \rightarrow 1$ transition at 3,335.475 MHz was observed in emission in a wide range of galactic sources ranging from dark clouds to the spiral arms in front of Cassiopea A. The two satellite transitions $F = 0 \rightarrow 1$ (at 3,263.788 MHz) and $F = 1 \rightarrow 0$ (at 3,349.185 MHz) were also observed in emission in several sources.

We have observed the 3,335.475 MHz transition of CH in several southern galactic sources. In RCW38 this line is seen in absorption, while the two satellite lines are seen in emission. In several sources the distribution of CH is found to be extended.

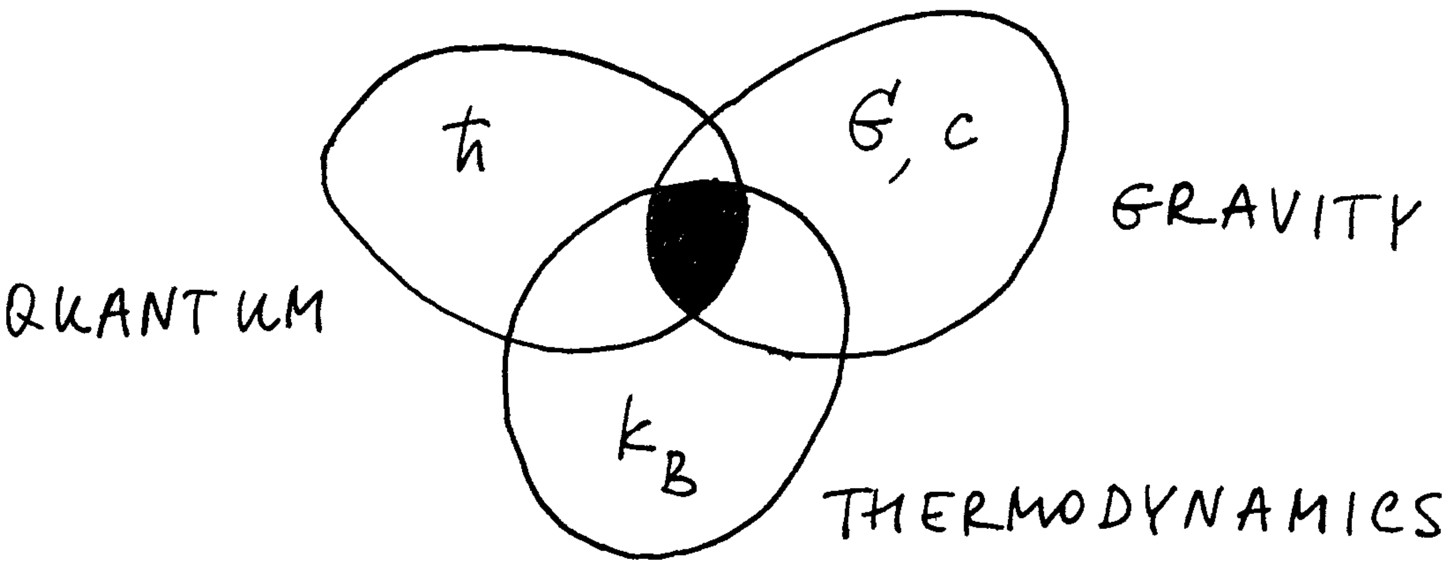
The observations were made on December 10 and 11, 1973, with the Parkes 64-m telescope equipped with a 9-cm parametric amplifier having a noise temperature of 150 K. The telescope beam at 9 cm is 6 arc min. The receiver output was analysed by a 512-channel digital correlator producing a spectral resolution of 19.5 kHz.

The Onsala observations[1] of CH emission at 3,335.475 MHz from Cloud 2 and W12 were confirmed. In Cloud 2 we measured an antenna temperature similar to that found with the Onsala 25-m telescope. For W12 it was 0.23 K, about 50% greater than the Onsala value of 0.15 K; however, at a position 5 arc min south (where the continuum intensity had fallen to one seventh of its peak value) the line signal had decreased by only 30%. A similar situation occurred in RCW36. Thus the CH distribution is considerably more extended than the continuum for these HII regions; in Cloud 2 it must be comparable with the 16 arc min beam of the Onsala 25-m telescope.

Hawking radiation: connections

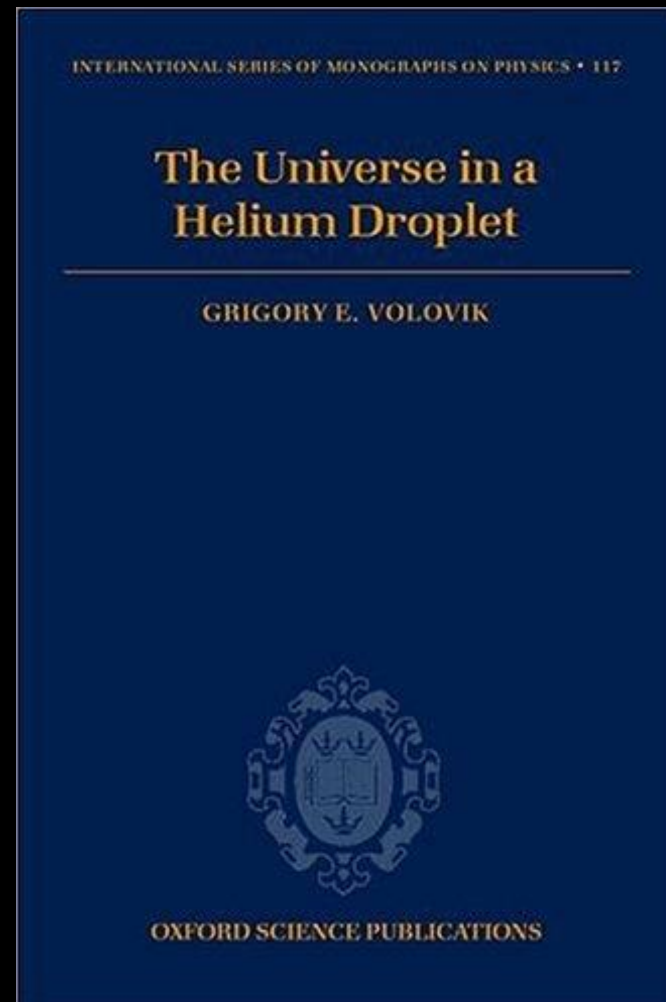
$$k_B T = \frac{\hbar \alpha}{2\pi}, \quad \alpha = \frac{c^3}{4GM} = \frac{c}{2R}$$

M: MASS, R: SCHWARZSCHILD RADIUS



Artificial event horizons in superfluid Helium-3

Kylmälaboratorio
Lågtemperaturlaboratoriet
Low Temperature Laboratory



Artificial event horizons in optical fibers (St Andrews project)

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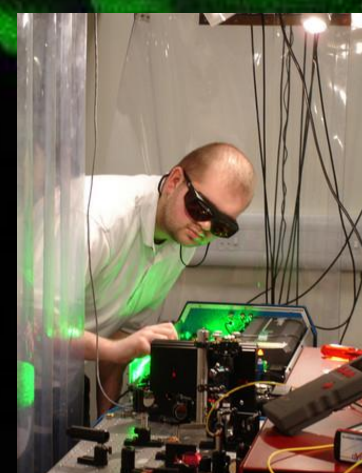
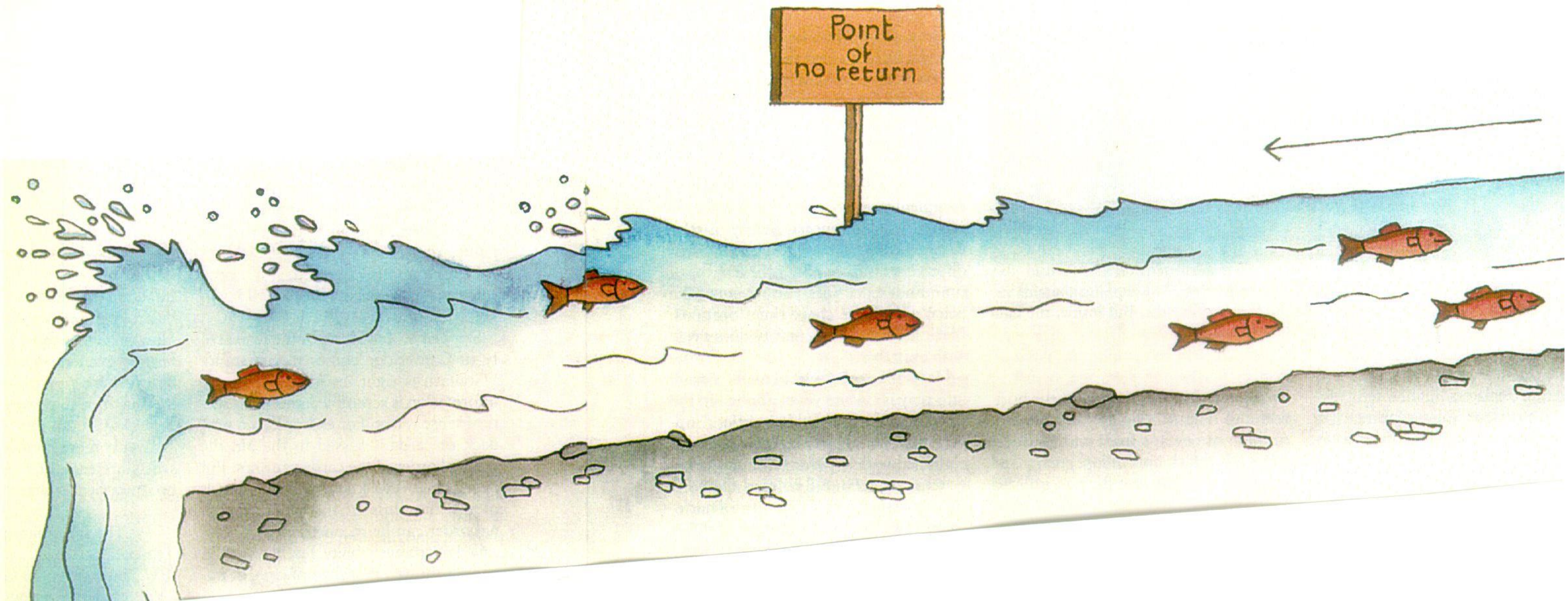
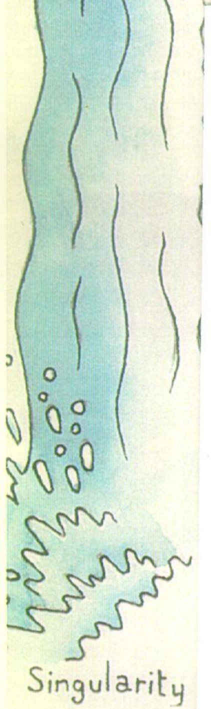


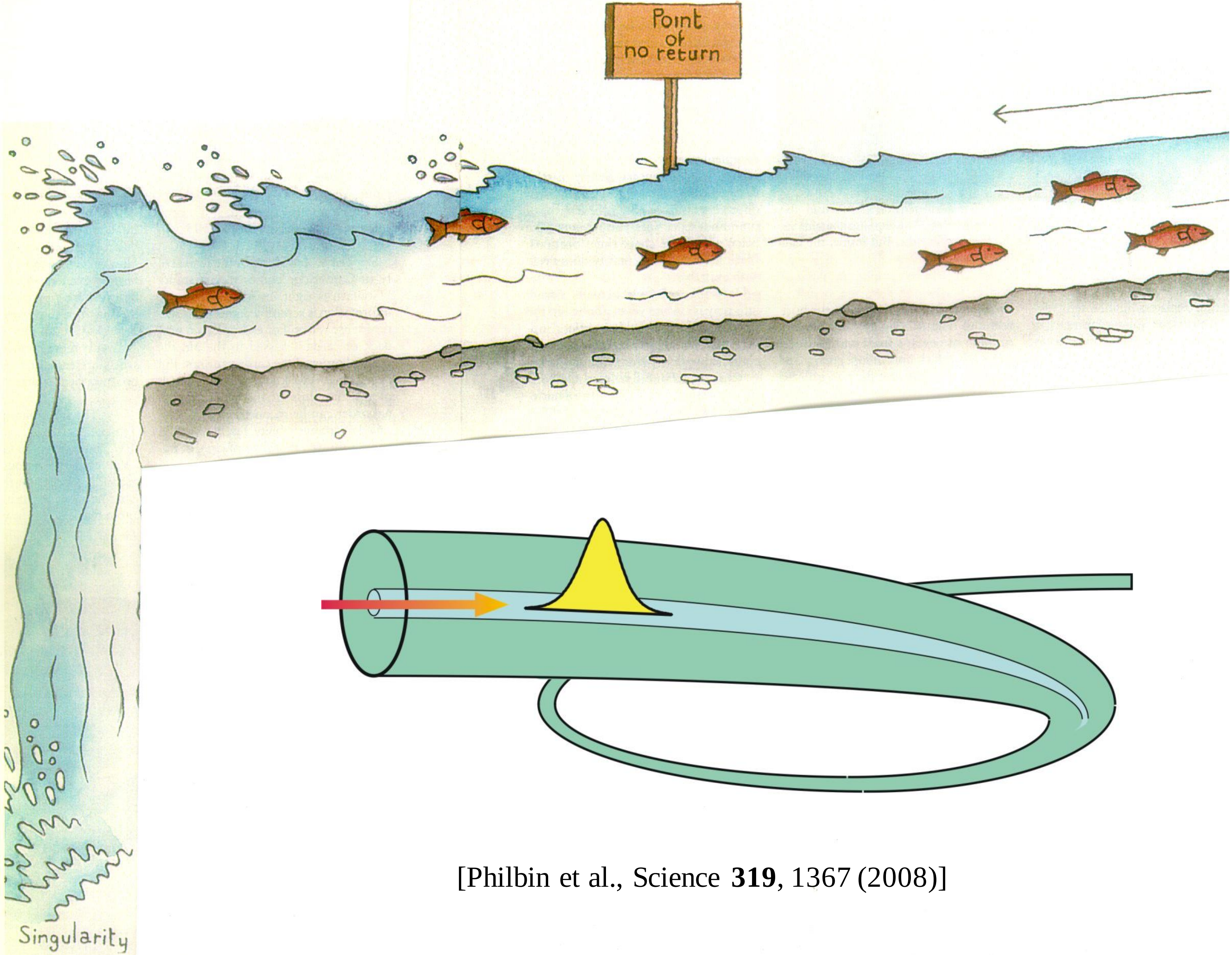




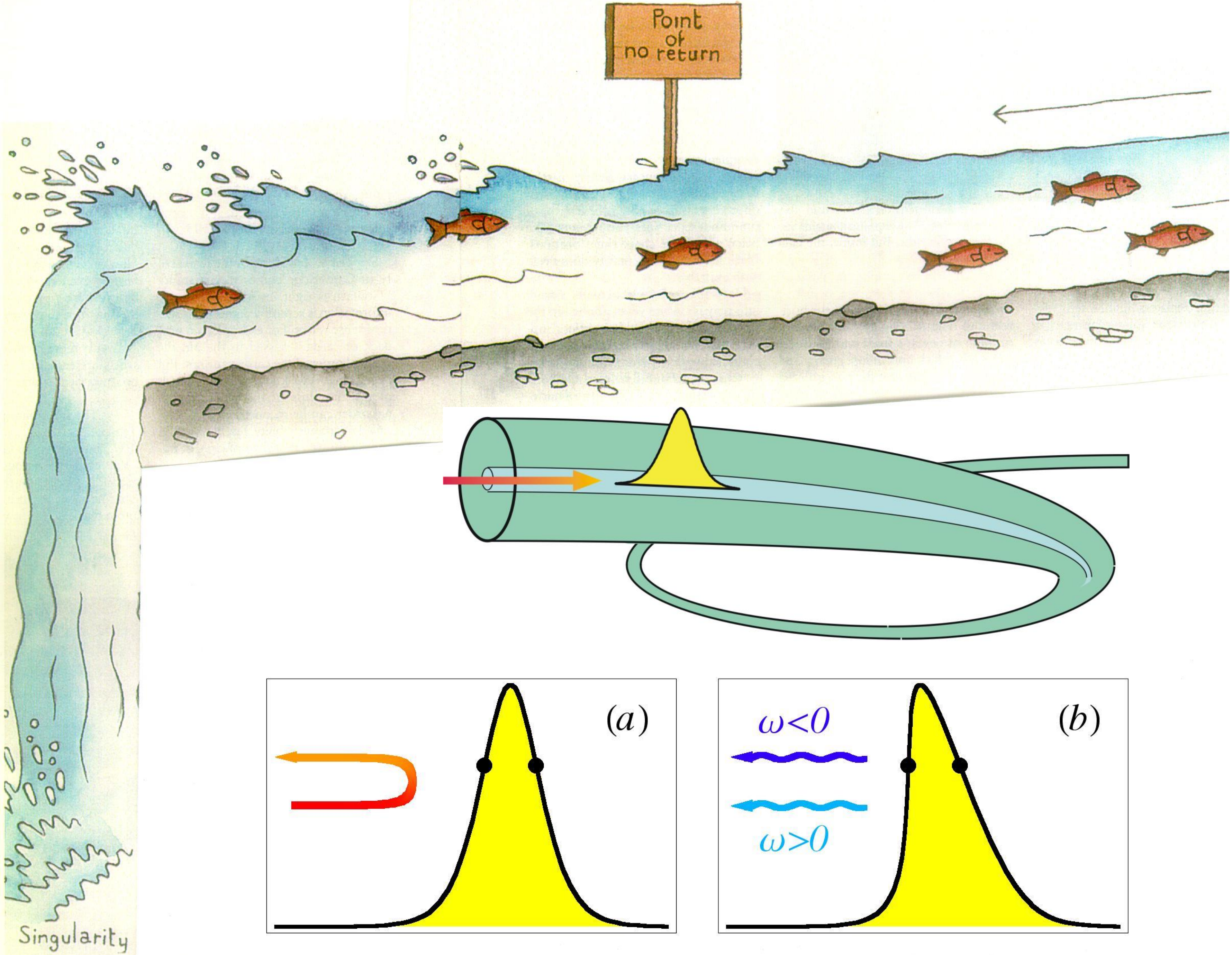
Light in 1D moving media

$$t_\pm = t - \int \frac{dz}{v_\pm}\,, \quad v_\pm = \frac{u \pm \frac{c}{n}}{1 \pm \frac{u}{cn}}$$

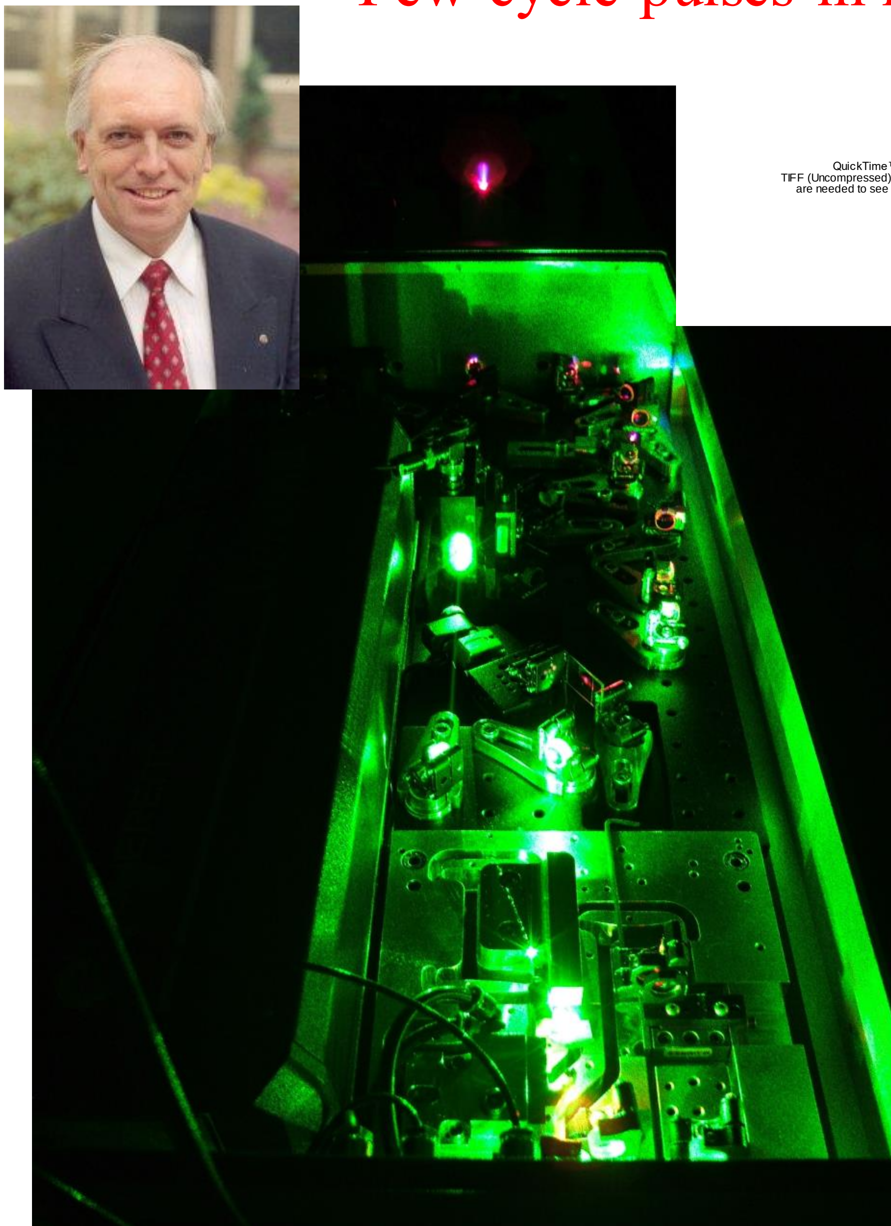
$$t_\pm = t' \mp \frac{z'}{c}$$



[Philbin et al., Science **319**, 1367 (2008)]


Point of no return
Singularity
(a)
(b)
$\omega<0$
$\omega>0$

Few-cycle pulses in microstructured fibres



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TIFF (Uncompressed) decompressor
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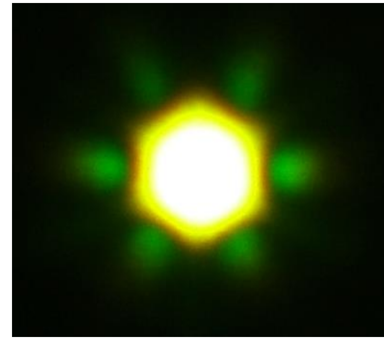

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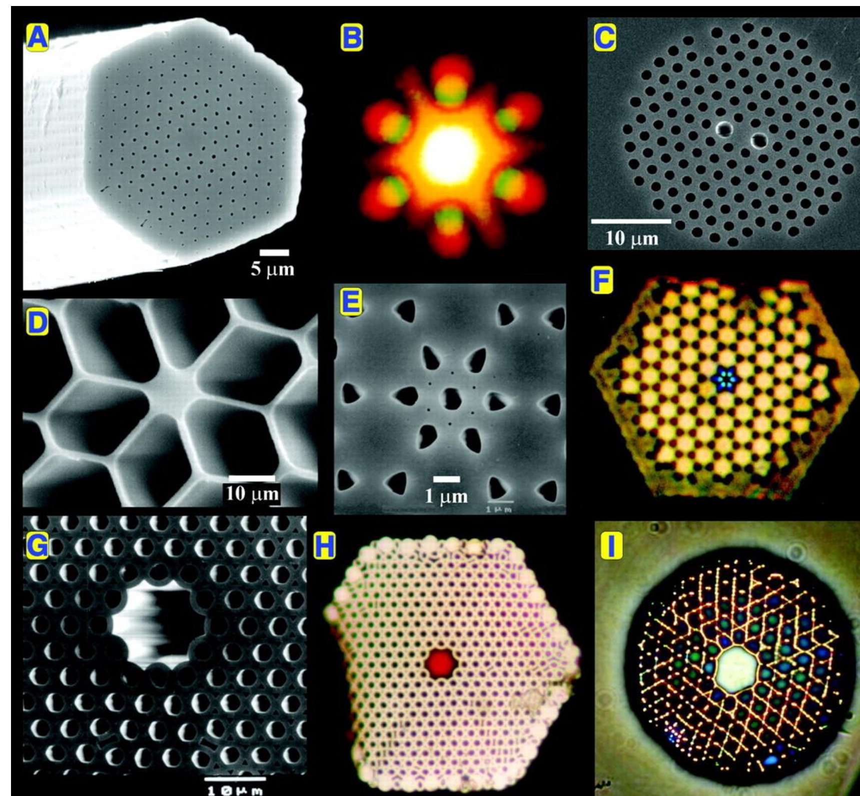
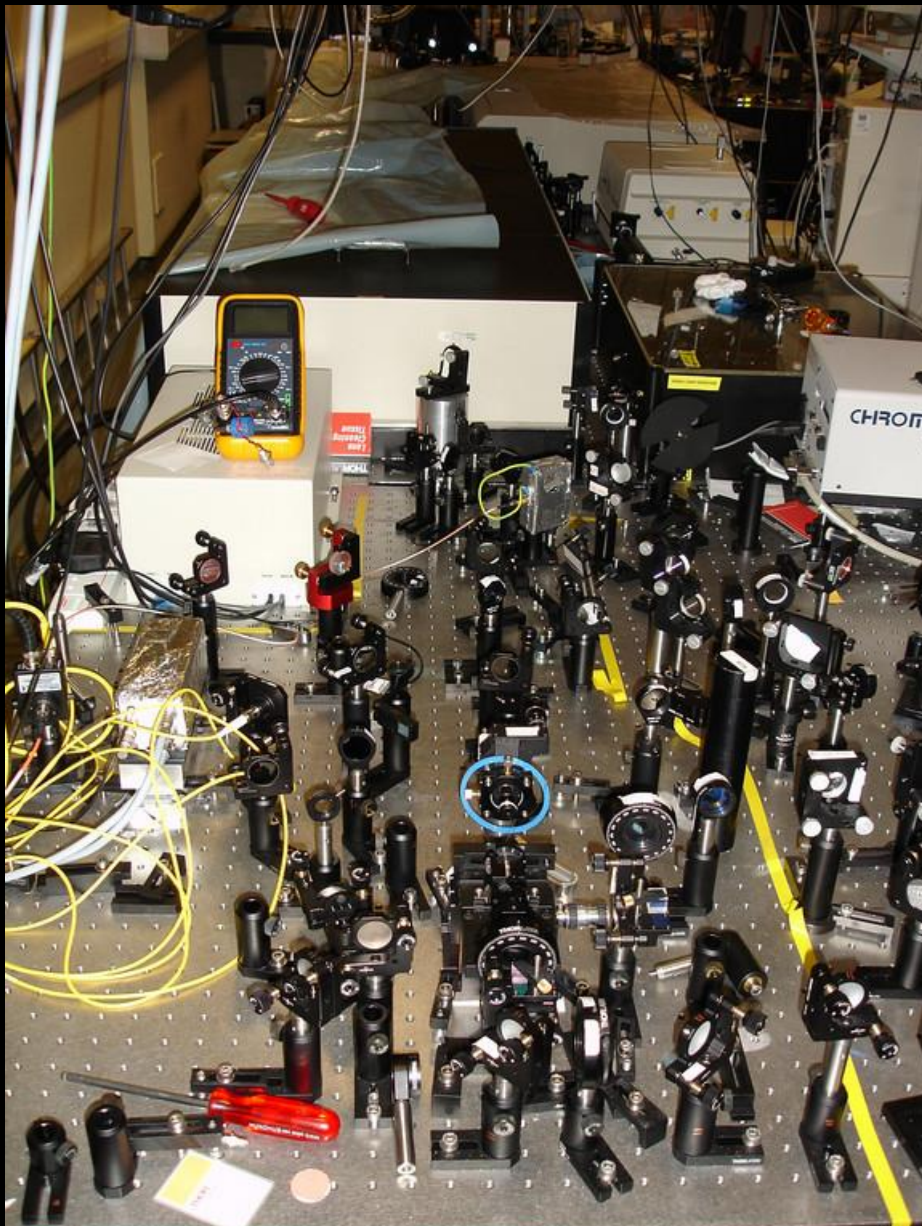
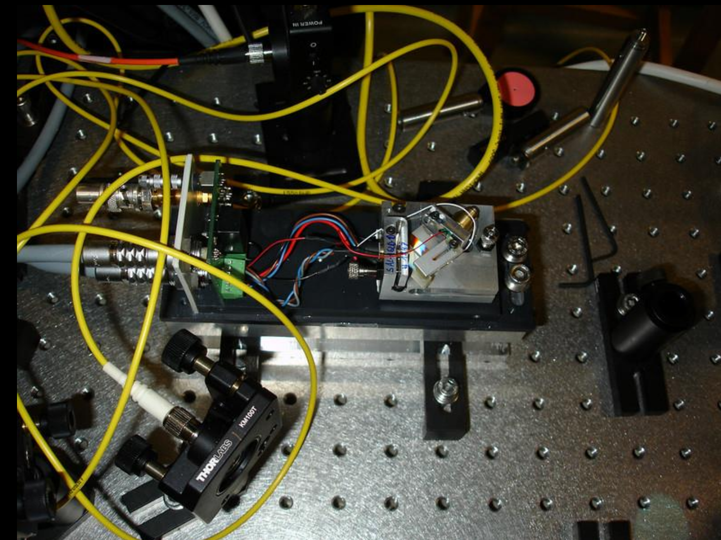


Experiment





Probe laser

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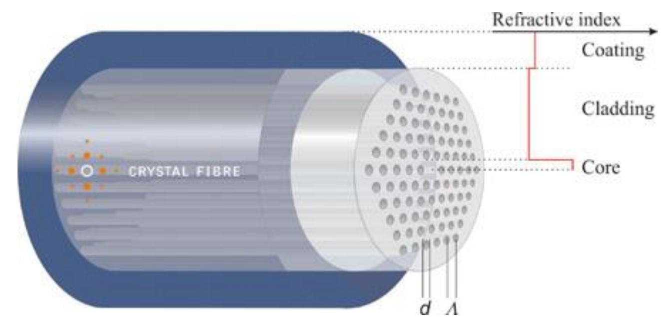
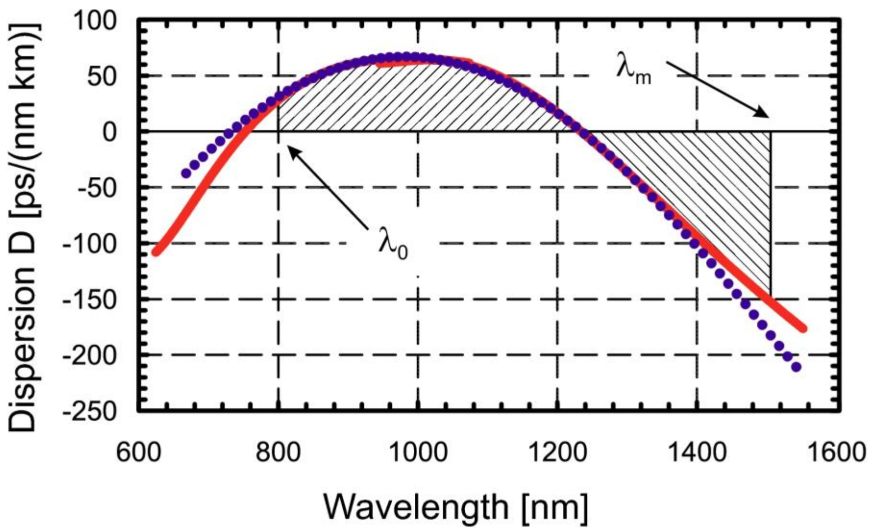
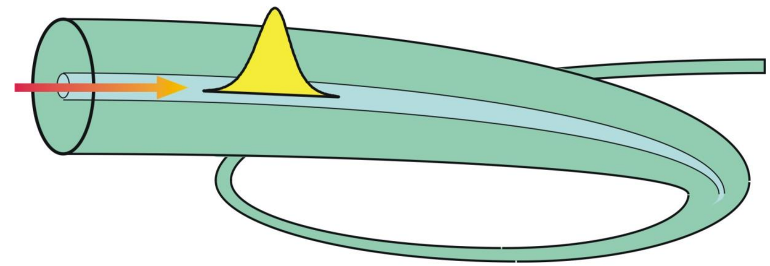
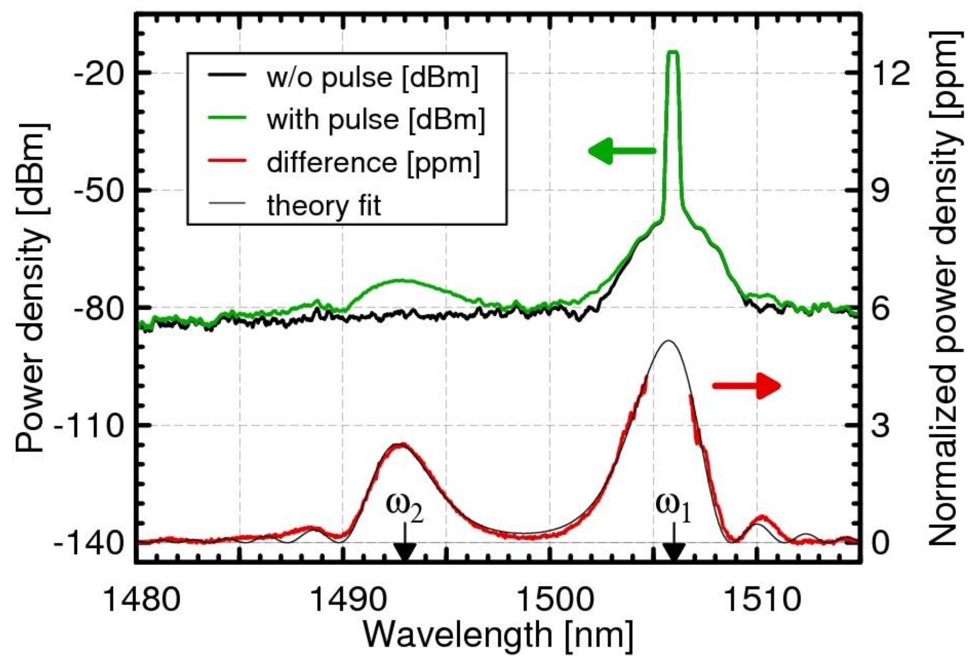
Experiment: blue-shifting

[Philbin et al., Science **319**, 1367 (2008)]







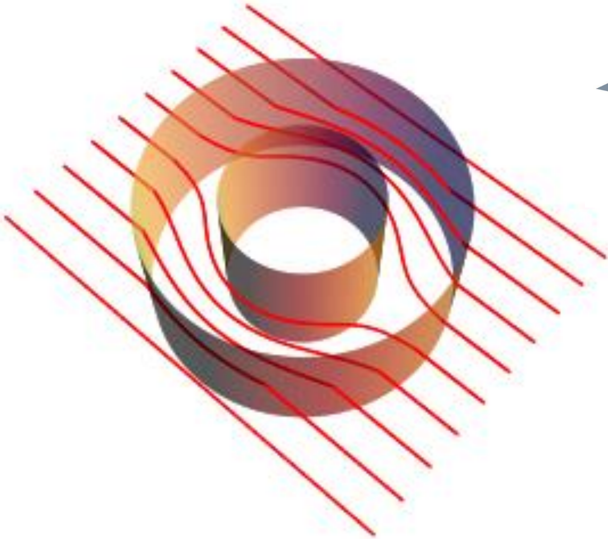


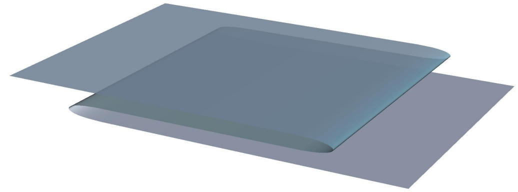
$$D = \frac{\partial^2 \beta}{\partial \omega \partial \lambda} \quad , \quad v_g = \frac{\partial \omega}{\partial \beta}$$

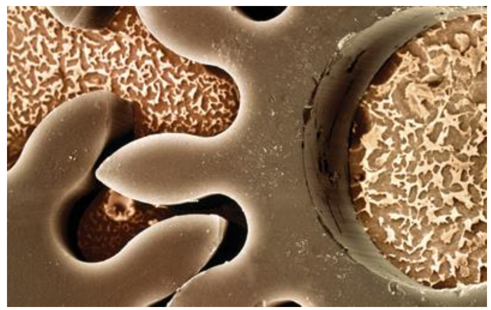
$$\int_{\lambda_0}^{\lambda_1} D \, d\lambda = 0$$

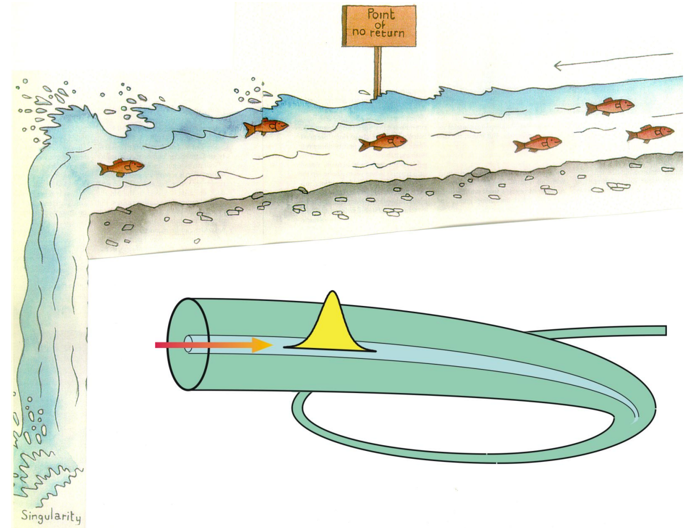
General relativity in electrical engineering

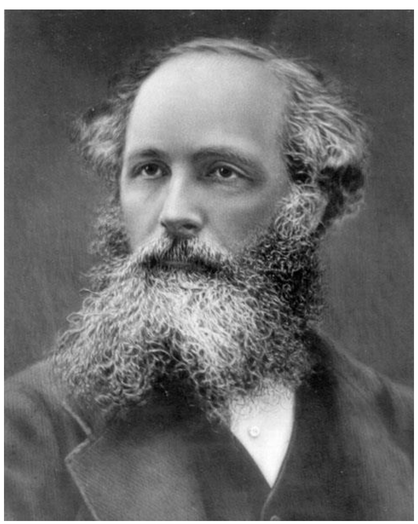
[Leonhardt and Philbin, New J. Phys. **8**, 247 (2006)]

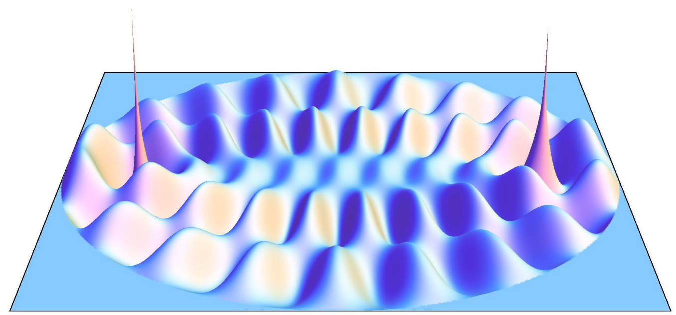


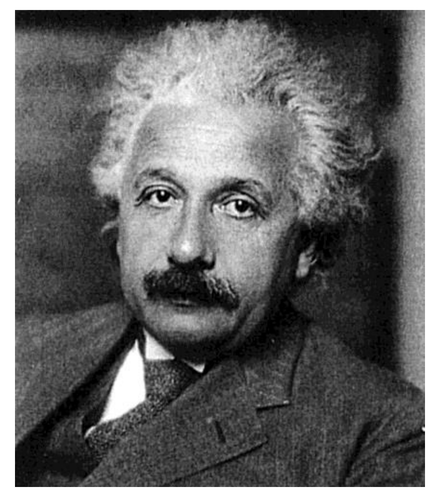












Einwell and Maxstein

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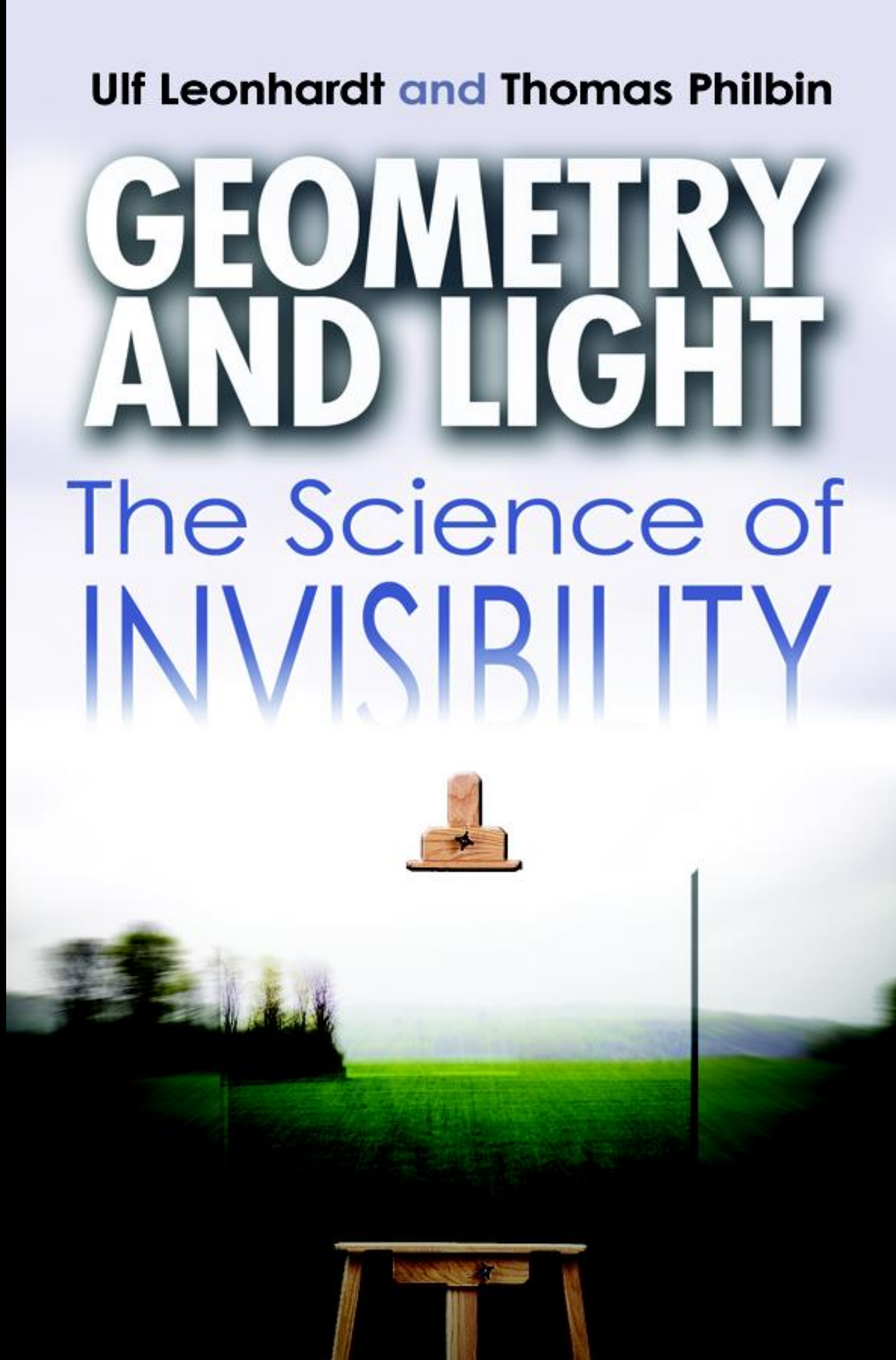
decompressor
are needed to see this picture.


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