Ondes en Milieu Complexe

UMR 5493

GDR 2253

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Grenoble

Waves in Complex Media

Novel Media

- **Band Gap Materials**
  opening and control of gap?
- **Strongly Disordered Media**
  Anderson Localization?
- **Cold Atomic Gazes**
  Mesoscopic
  quantum light scattering?
- **Left-Handed Materials**
  Super-lenses?
- **Random Laser/NL Disorder**
  Origin of Feedback?
  Instability?

Broken Symmetry

- **Magnetic Fields/Vortices**
  Photon Hall Effect?
  Acoustic AB effect?
- **Liquid Crystals**
  Anisotropic Diffusion?
- **Chiral (Random) Media**
  Polarization?
  Chiral Band Gaps
- **Non-spherical Particles**
  Relevance to Aerosols,
  Interstellar dust?
- **Chaotic media**
  Heisenberg time?
  "Quantum" chaos?

Natural Media

- **Biological Tissue**
  Smart Medical Imaging?
- **Planetary Atmospheres**
  Coherent Backscattering?
- **The Earth**
  Imaging without source?
  ?
- **Granular media?**
  Scattering mechanism?
- **Vacuum**
  Diverging energy?
  Momentum transfer?

Waves in Complex Media

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  Origin of Feedback?
  Instability?
- **Bose-Einstein Condensate**
  What scatters from what?
- **Acoustic (random) laser**
  Time-resolved inversion?

Broken Symmetry

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- **Chaotic media**
  Heisenberg time?
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- **Magneto-Chiral Media**
  Origin of life &
  chirality ?

Natural Media

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  ?
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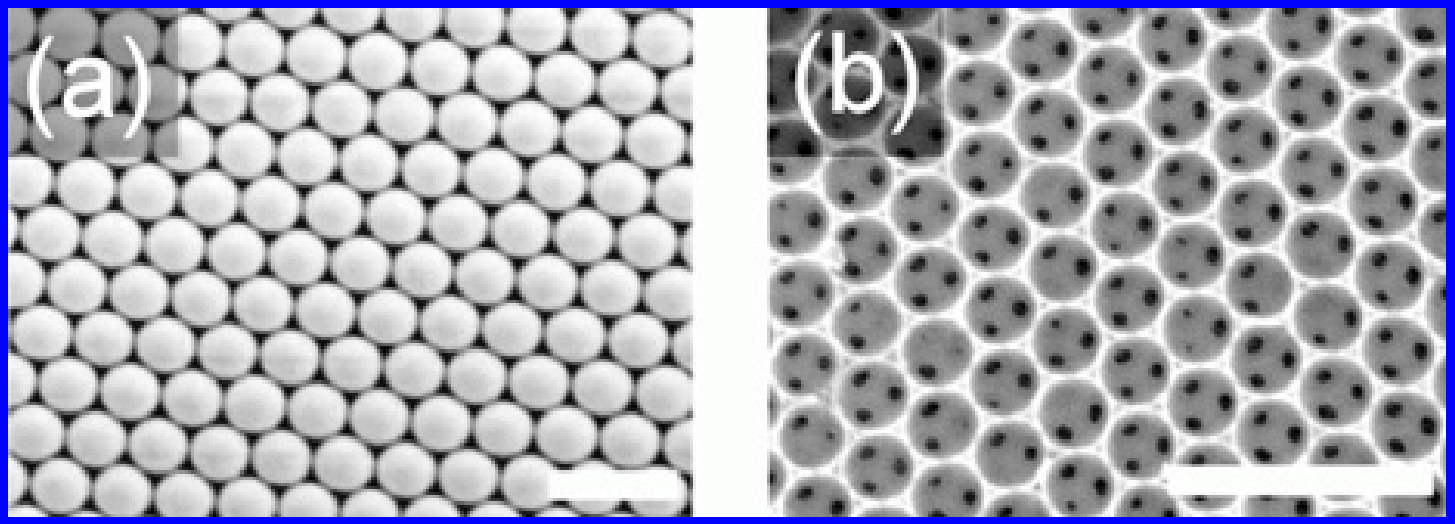
- **Vacuum**
  Diverging energy?
  Momentum transfer?
- **The Universe**
  Scattering of
  Gravitational Waves?
- **New York City**
  Communication by Portable
  Telephone?

Les nouveaux matériaux: les cristaux « photoniques »

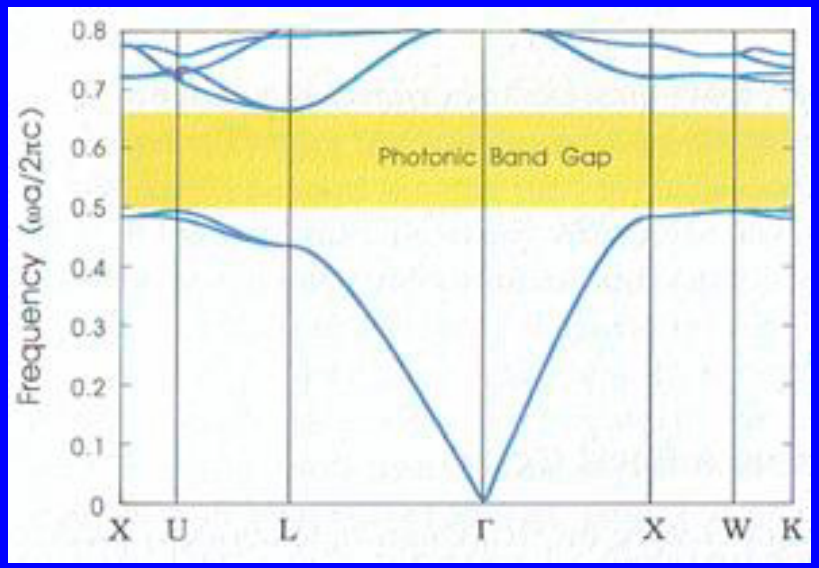
2 µm ↔ ℓ

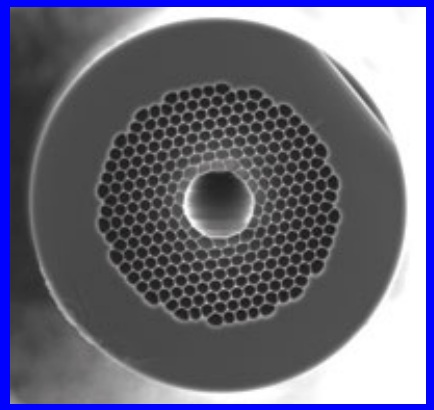


Les semi-conducteurs optiques

Willem Vos

Bande interdite



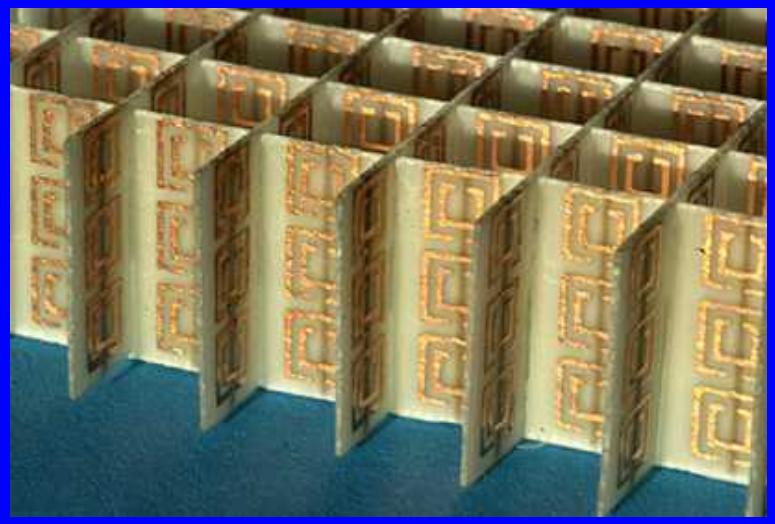


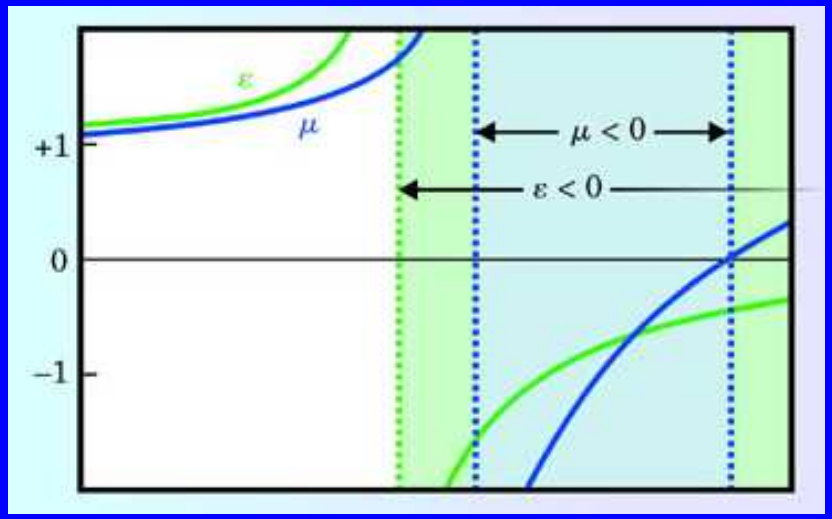
Guider les photons

Les nouveaux matériaux: les cristaux « phononiques »

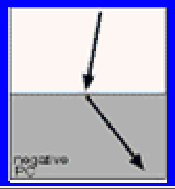
Materials Science Institute de Madrid

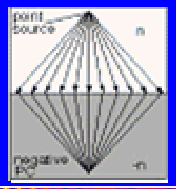
Les nouveaux matériaux: les matériaux « gauchers »



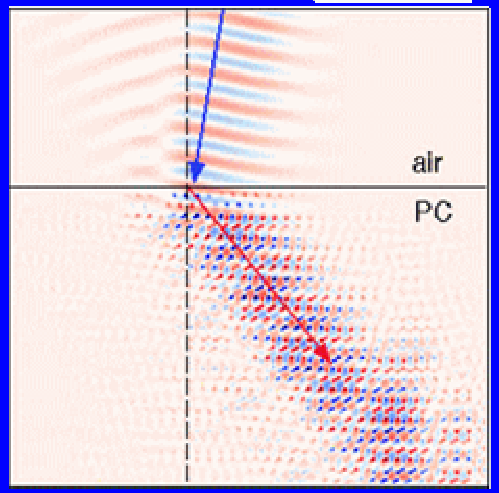


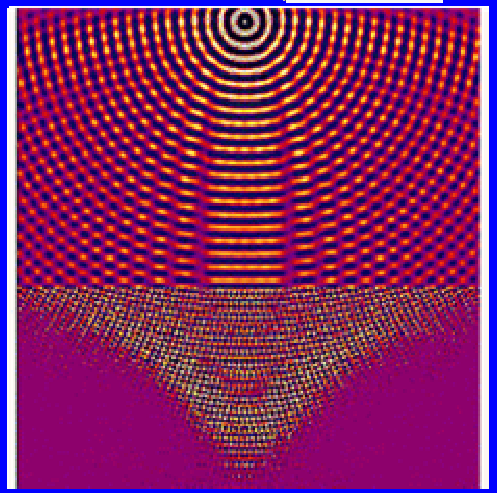
John Pendry (2001)





Réfraction négative



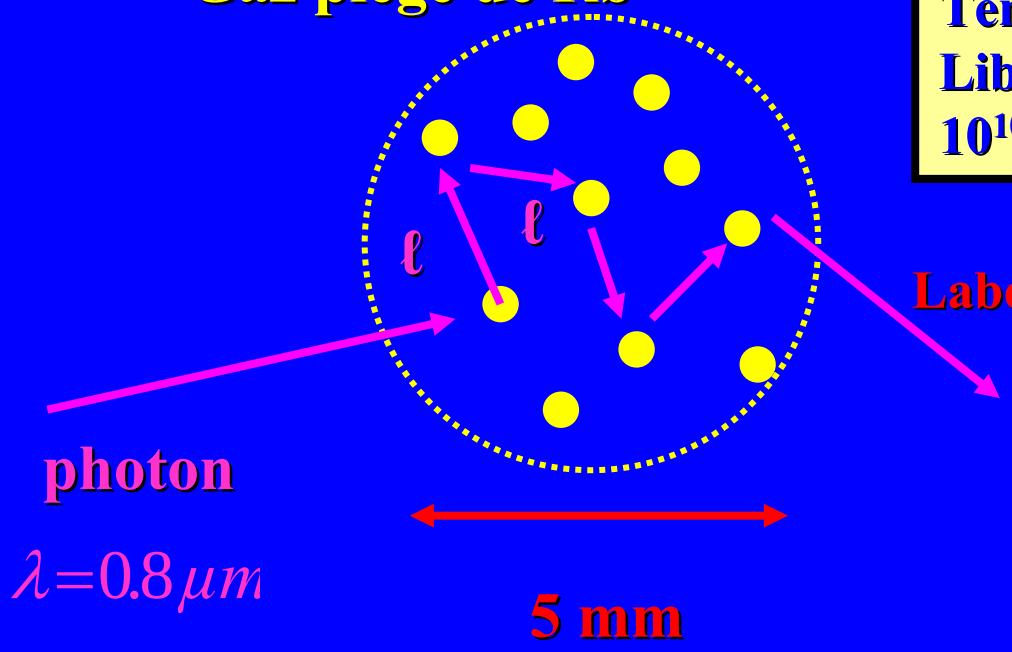


lentille parfaite

Les nouveaux matériaux: les atomes ultrafroids

Gaz piégé de Rb^{85}

Température T = 0,0001 K (v=15 cm/s)
Libre parcours moyen ℓ = 0.3 mm
10^{10} atomes



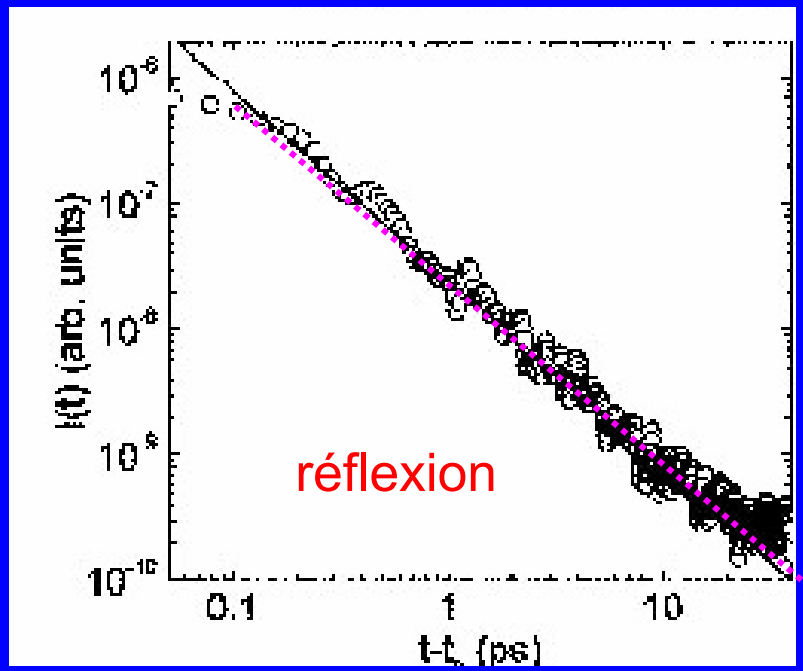
Labeyrie, Miniatura, Kaiser (Nice, 2002))

Mouvement Brownien des photons

$$\frac{\langle r^2(t)\rangle}{6t} \rightarrow D = \tfrac{1}{3} v_E \ell$$

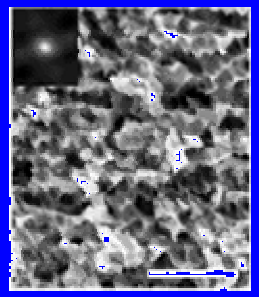
$v_E = \ldots\ldots\ldots \quad 0.00003\, c_0$

Les nouveaux matériaux:
le brouillard le plus épais au monde



$1/t^{3/2}$

Mouvement Brownien



3 µm

GaP poreux

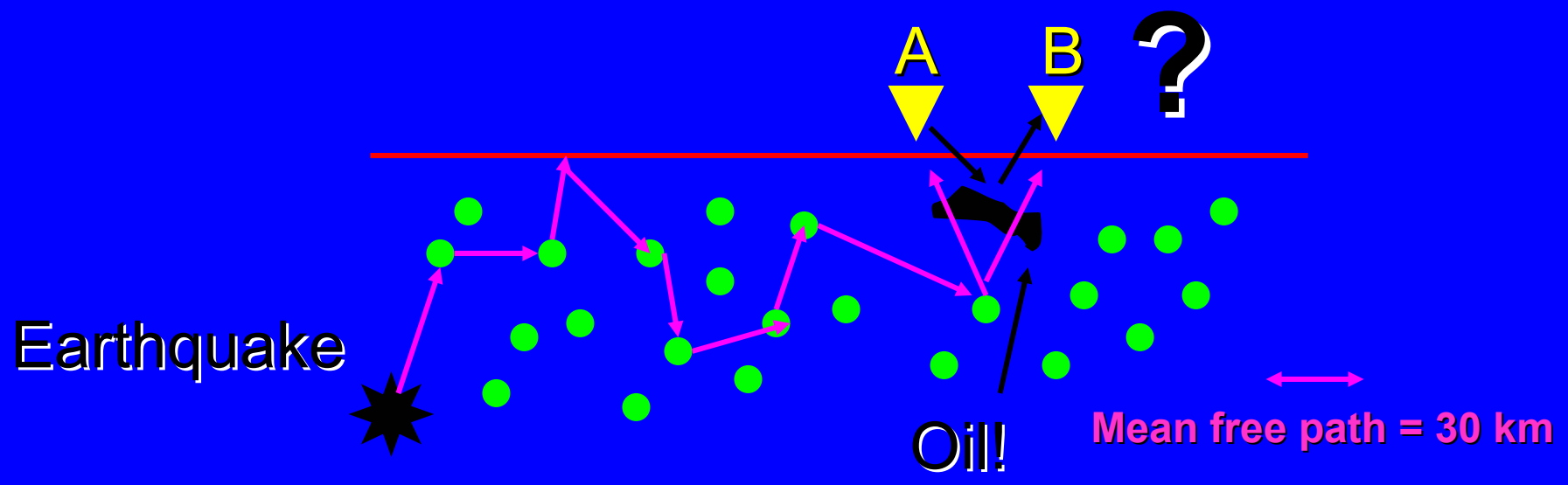
Lagendijk etal, 2003

Le mouvement Brownien des photons, ça marche toujours!

$$\lambda = 739 \ nm$$

$$\ell = 250 \ nm$$

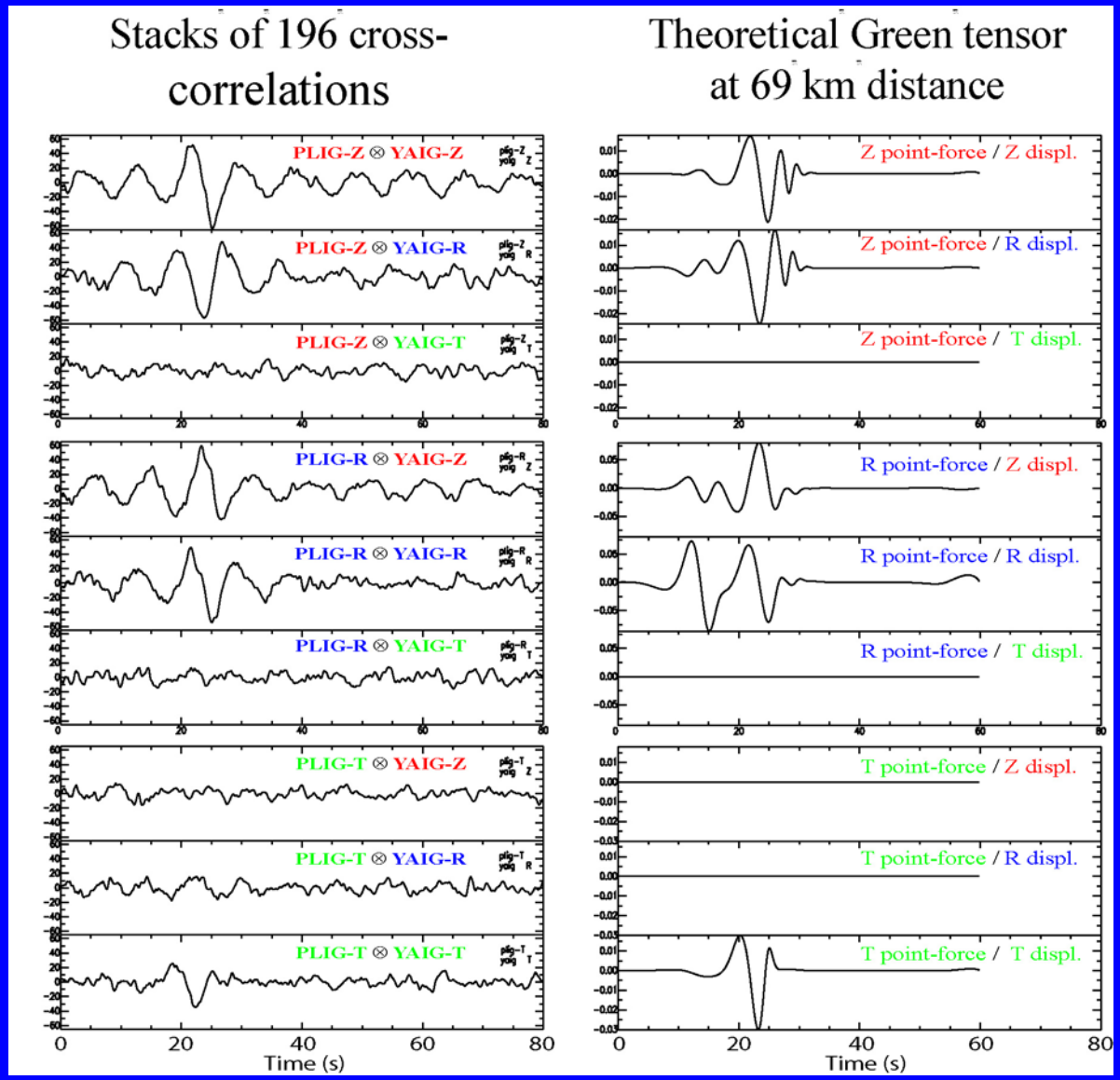
Les milieux naturels: l'imagerie sismique sans source



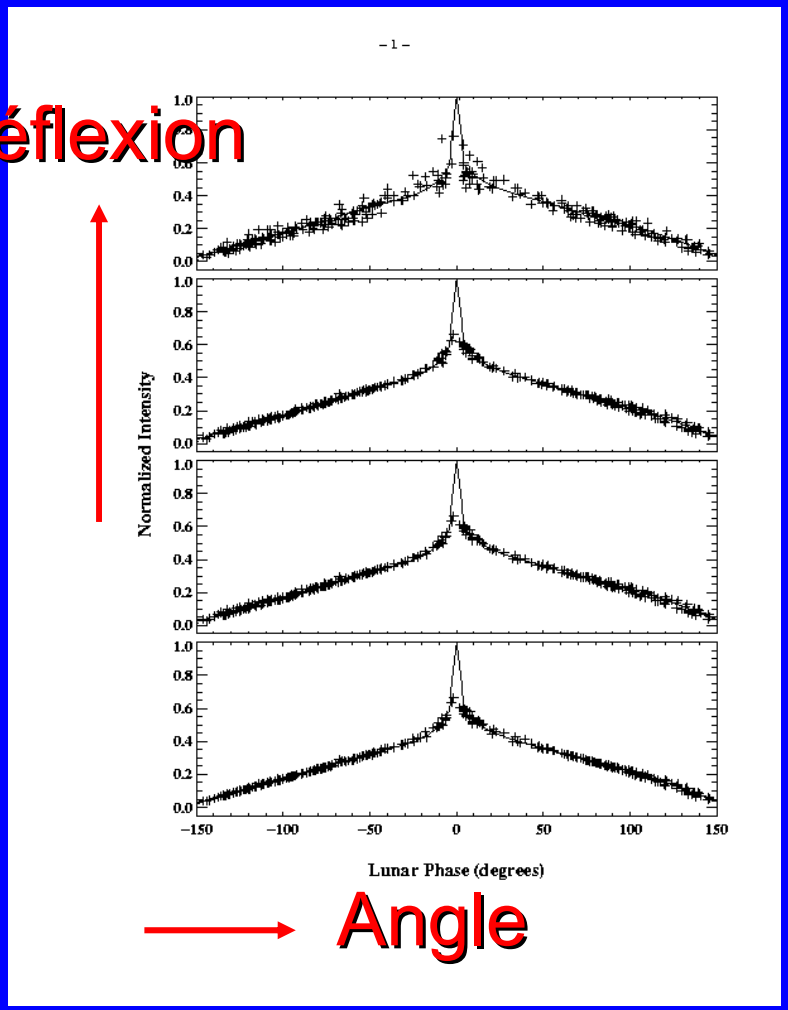
$$\int dt \quad A(t-\tau) \quad B(t+\tau) \; = G_{AB}(\tau) \; + \; G_{BA}(-\tau)$$

Coda sismique au Mexique

Campillo & Paul
Science, Janvier 2003



Retrodiffusion cohérente des photons (Akkermans, Maynard 1986)



L'effet opposition des annaux de Saturne

Lyot, 1929

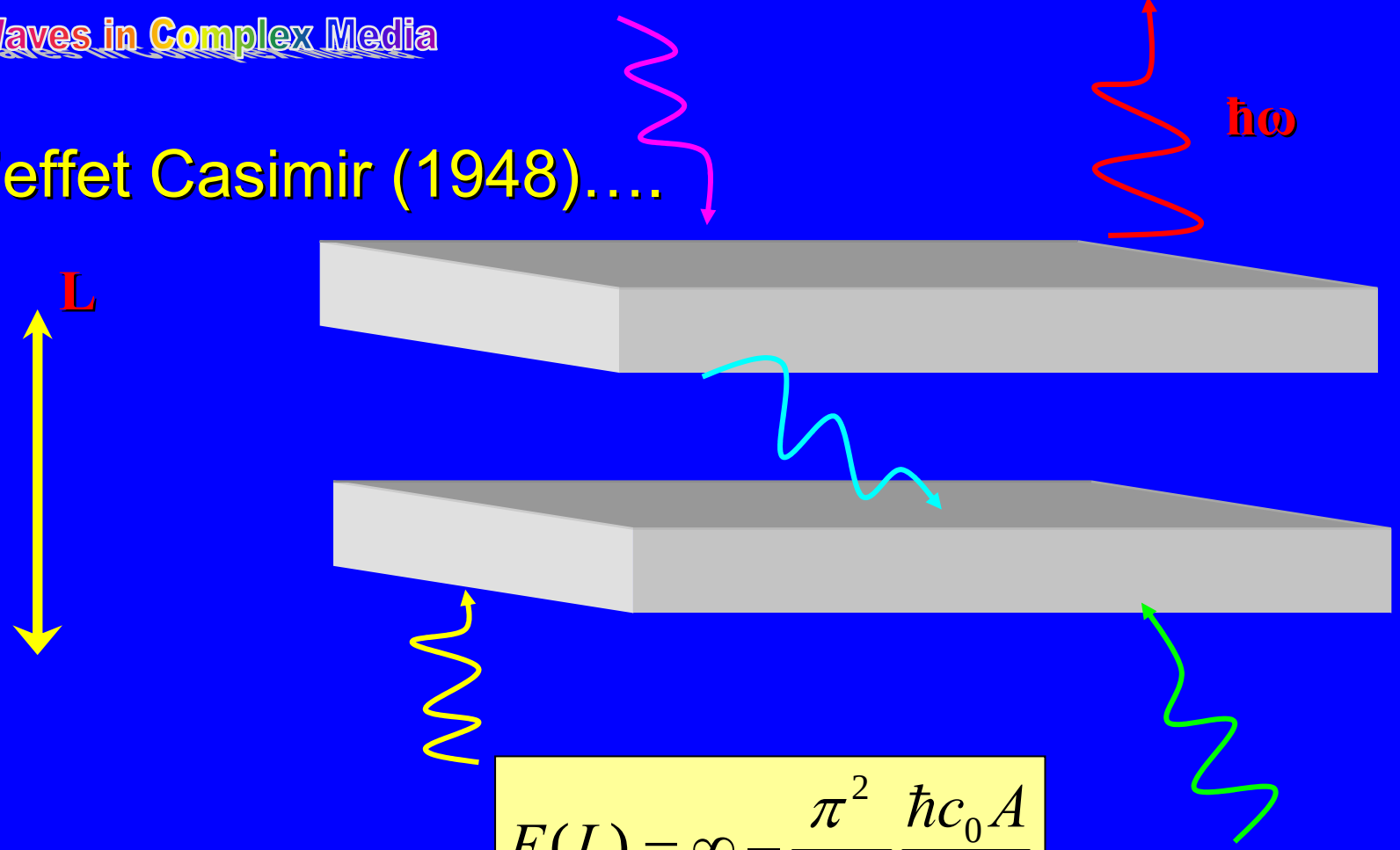
Mischenko 1992

Quantité de mouvement du Vide induite par l'effet magnétoélectrique optique

Quantité de mouvement de nulle part?

Collaborateurs:
Geert Rikken et Vojislav Krstic (LCMP Toulouse)

L'effet Casimir (1948)….



$$E(L) = \infty - \frac{\pi^2}{720}\frac{\hbar c_0 A}{L^3}$$

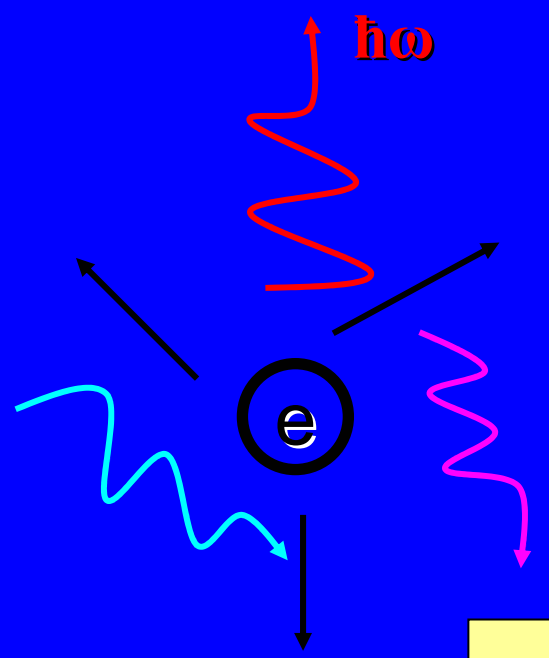
$$\mathbf{F}(L) = -\frac{\partial E}{\partial \mathbf{L}} = -\frac{\pi^2}{240}\frac{\hbar c_0 A}{L^4}\hat{\mathbf{L}}$$

Pression négative

Conservation de quantité de mouvement des plaques

Et encore une idée brillante (Casimir 1956)

L'électron est-t-il stable grâce aux fluctuations du vide?



$$F_{\text{vide}} = -(\cdots)\frac{\hbar c_0 A}{r_e^4} = -(\cdots)\frac{4\pi\hbar c_0}{r_e^2}$$

$$F_{\text{vide}} + F_{\text{coulomb}} = 0 \Rightarrow \frac{e^2}{\hbar c_0} = 4\pi \times (\cdots)$$

$$F_{\text{Coulomb}} = +\frac{e^2}{r_e^2}$$

$$F = +0.045\frac{\hbar c_0}{r_e^2}$$

répulsive

(Barton, 1968)

VOLUME 92, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2004

Quantum Vacuum Contribution to the Momentum of Dielectric Media

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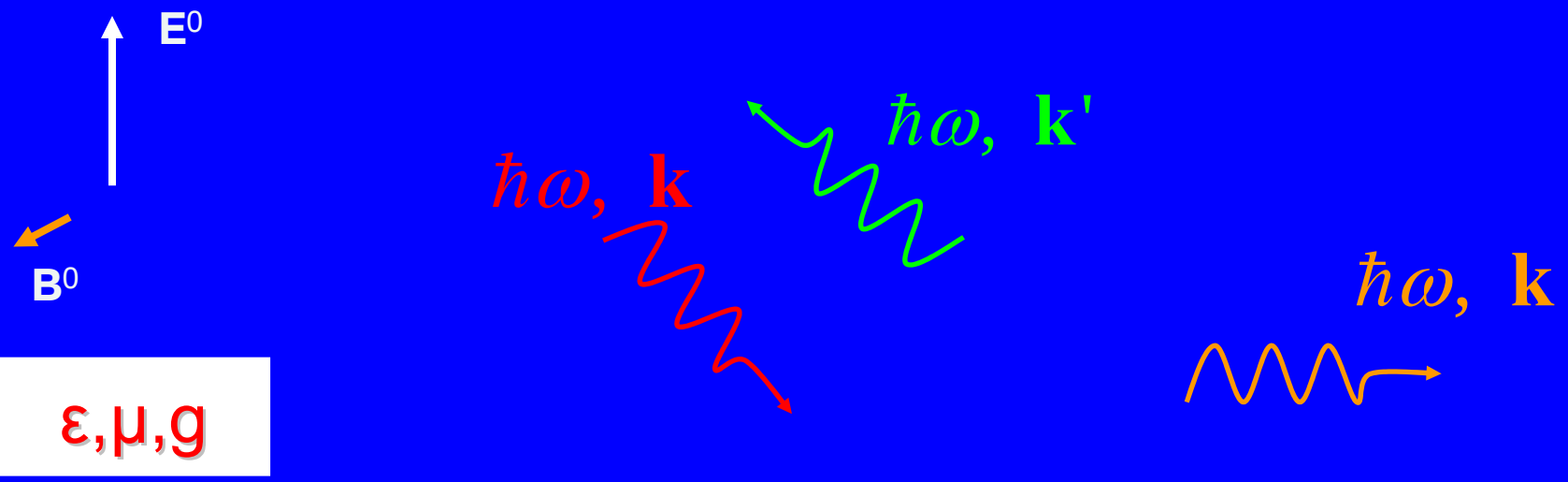
(Received 3 February 2003; published 16 January 2004)

Momentum transfer between matter and electromagnetic field is analyzed. The related equations of motion and conservation laws are derived using relativistic formalism. Their correspondence to various, at first sight self-contradicting, experimental data (the so-called Abraham-Minkowski controversy) is demonstrated. A new, Casimir-like, quantum phenomenon is predicted: contribution of vacuum fluctuations to the motion of dielectric liquids in crossed electric and magnetic fields. Velocities of about can be expected due to the contribution of high frequency vacuum modes. The proposed phenomenon could be used in the future as an investigating tool for zero fluctuations. Other possible applications lie in fields of microfluidics or precise positioning of micro-objects, e.g., cold atoms or molecules.

DOI: 10.1103/PhysRevLett.92.020404 PACS numbers: 03.50.De, 42.50.Nn, 42.50.Vk



Théorie de Feigel

$$\langle 0|\rho\,\mathbf{v}|0\rangle \propto \frac{1}{c_0}\int d^3\mathbf{k}\,\frac{1}{2}\hbar\omega_k \times (1+\varepsilon)\,g\;\mathbf{E}_0\times\mathbf{B}_0 \propto \hbar\omega_c^4\,g\,\mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d\mathbf{r}}{dt}\propto \mathbf{E}_0\times\mathbf{B}_0$$

$$\langle 0|\rho\,\mathbf{v}|0\rangle \propto \frac{1}{c_0}\int d^3\mathbf{k}\,\frac{1}{2}\hbar\omega_k \times (1+\varepsilon)\,g\;\mathbf{E}_0\times\mathbf{B}_0 \propto \hbar\omega_c^4\,g\,\mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d\mathbf{r}}{dt} \propto \mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d-\mathbf{r}}{dt} \propto -\mathbf{E}_0\times\mathbf{B}_0$$

Parité = OK

$$\langle 0|\rho\,\mathbf{v}|0\rangle \propto \frac{1}{c_0}\int d^3\mathbf{k}\,\frac{1}{2}\hbar\omega_k \times (1+\varepsilon)\,g\;\mathbf{E}_0\times\mathbf{B}_0$$

$$\propto \hbar\omega_c^4\,g\,\mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d\mathbf{r}}{dt}\propto \mathbf{E}_0\times\mathbf{B}_0$$

Parité = OK

Renversement du temps = OK

$$m\frac{d\mathbf{r}}{d-t}\propto \mathbf{E}_0\times -\mathbf{B}_0$$

$$\langle 0|\rho\,\mathbf{v}|0\rangle \propto \frac{1}{c_0}\int d^3\mathbf{k}\,\frac{1}{2}\hbar\omega_k \times (1+\varepsilon)\,g\;\mathbf{E}_0\times\mathbf{B}_0$$

$$\propto \hbar\omega_c^4\,g\,\mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d\mathbf{r}}{dt}\propto \mathbf{E}_0\times\mathbf{B}_0$$

Parité = OK

Renversement du temps = OK

Conjugaison de charge = OK

$$m\frac{d\mathbf{r}}{dt}\propto -\mathbf{E}_0\times -\mathbf{B}_0$$

$$\langle 0|\rho\,\mathbf{v}|0\rangle \propto \frac{1}{c_0}\int d^3\mathbf{k}\,\frac{1}{2}\hbar\omega_k \times (1+\varepsilon)\,g\;\mathbf{E}_0\times\mathbf{B}_0 \propto \hbar\omega_c^4\,g\,\mathbf{E}_0\times\mathbf{B}_0$$

$$m\frac{d\mathbf{r}}{dt} \propto \mathbf{E}_0\times\mathbf{B}_0$$

Parité = OK

Renversement du temps = OK

Conjugaison de charge = OK

$$m\frac{d\mathbf{r}}{dt} \propto -\mathbf{E}_0\times-\mathbf{B}_0$$

Symétrie de Lorentz = OK ? $FeGaO_3$: 78 m/s

Couper les fluctuations du vide…..

……brise la symétrie de Lorentz

……nous introduit de façon *ad hoc* à une nouvelle longueur

……n'affecte pas la force (observée) de Casimir

……souffre déjà d'une une controverse pour expliquer la sonoluminescence, initiée par Schwinger (>1980)

$$E(\text{bulle}) \approx \tfrac{4}{3}\pi\, a^3 \int d^3\mathbf{k}\, \frac{1}{2}\hbar k c_0 \left(1 - \frac{1}{\sqrt{\varepsilon}}\right) \propto a^3 \omega_c^4 \ldots$$

= 10 Mev
Sonoluminescence?
Schwinger 1980,

$$\int \frac{d^d\mathbf{k}}{(2\pi)^d} (x^2 + k^2)^{-p/2} = \frac{x^{d-p}\Gamma\left(\frac{p-d}{2}\right)}{(4\pi)^d \Gamma\left(\frac{p}{2}\right)} \quad (p > d)$$

$$E(\text{bulle}) \xrightarrow[\substack{x=0 \\ d=3 \\ p=-1}]{} 0$$

Milton & Ng 1997

$$\int_{x<a} d^3\mathbf{x} \int_{y<a} d^3\mathbf{y}\, \frac{-23\alpha^2 N^2}{4\pi|\mathbf{x}-\mathbf{y}|^7} \xrightarrow[\substack{d=3 \\ \gamma=7}]{} + \frac{23(\varepsilon-1)^2}{1536\, a}$$

(- ∞)

$$\int_{x<1} d^d\mathbf{x} \int_{y<1} d^d\mathbf{y}\, \frac{1}{|\mathbf{x}-\mathbf{y}|^\gamma} = \frac{\pi^{d-1/2} 2^{d-\gamma} \Gamma\left(\frac{d-\gamma+1}{2}\right)}{(d-\gamma)\Gamma(d/2)\Gamma(d+1-\gamma/2)} \quad (d > \gamma/2)$$

énergie de Casimir avec N dipôles dans la sphère (Brevik, 1999; Barton 1998)
Un transfert ME en milieu infini ?????

Milieux bi anisotropes

$$\mathbf{D} = \varepsilon \mathbf{E} + \boldsymbol{\chi} \cdot \mathbf{H}$$

$$\mathbf{B} = \mathbf{H} + \boldsymbol{\chi}^{*} \cdot \mathbf{E}$$

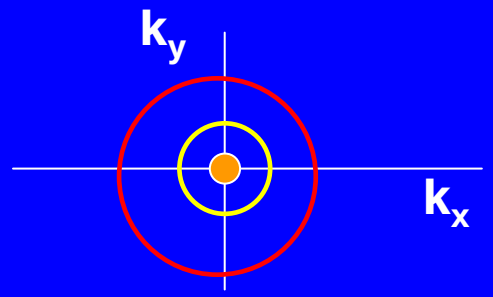
loi Fresnel pour la dispersion

$$\det\left(\varepsilon\omega^2 - p^2 + \mathbf{pp} + \omega\,\boldsymbol{\chi}\cdot\boldsymbol{\Phi}_{\mathbf{p}} + \omega\,\boldsymbol{\Phi}_{\mathbf{p}}\cdot\boldsymbol{\chi}^{*}\right) = 0$$

$$\left(\Phi_{\mathbf{p}}\right)_{inm} = i\varepsilon_{nml}\,p_l$$

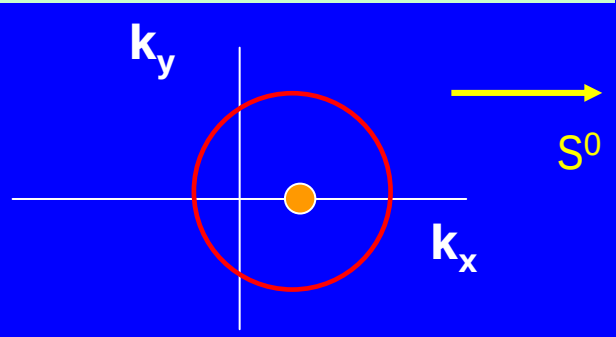
Pouvoir rotatoire

$$\chi_{ij}(\omega) = i\omega\, g\,\delta_{ij}$$



Optique Magnétoélectrique

$$\chi_{ij}(\omega) = g\left(E_i^0 B_j^0 - B_i^0 E_j^0\right)$$



Conservation de quantité de mouvement champ EM + matière

Macro-Maxwell

$$\partial_t\left(\frac{1}{4\pi}\mathbf{D}\times\mathbf{B}\right)+\nabla\cdot\mathbf{T}=\mathbf{f}$$

Newton-Lorentz

$$\partial_t\left(\rho\,\mathbf{v}-\mathbf{P}\times\mathbf{B}\right)+\nabla\cdot\mathbf{U}=-\mathbf{f}$$

$$f_j=\frac{1}{8\pi}\left[\mathbf{E}^2\left(\nabla\boldsymbol{\varepsilon}\right)+\mathbf{H}^2\left(\nabla\boldsymbol{\mu}\right)\right]$$

$$\partial_t\left(\rho\,\mathbf{v}+\frac{1}{4\pi}\mathbf{E}\times\mathbf{B}\right)+\nabla\cdot\mathbf{T}^0=0$$

$$T^0_{ij}=\frac{1}{8\pi}\left(\mathbf{E}^2+\mathbf{B}^2\right)\delta_{ij}-\frac{1}{4\pi}\left(E_i\,E_j+B_i\,B_j\right)$$

$$\int d^3\mathbf{r}\left(\rho\,\mathbf{v}+\frac{1}{4\pi}\mathbf{E}\times\mathbf{B}\right)=\text{conservé}$$

Calcul de perturbation de E x B du vide

$$\left\langle 0 \middle| E_i(\mathbf{r},\omega) E^*{}_j(\mathbf{r}',\omega) \middle| 0 \right\rangle = -2\hbar\omega^2 \,\mathrm{Im}\, G_{ij}(\mathbf{r},\mathbf{r}',\omega)$$

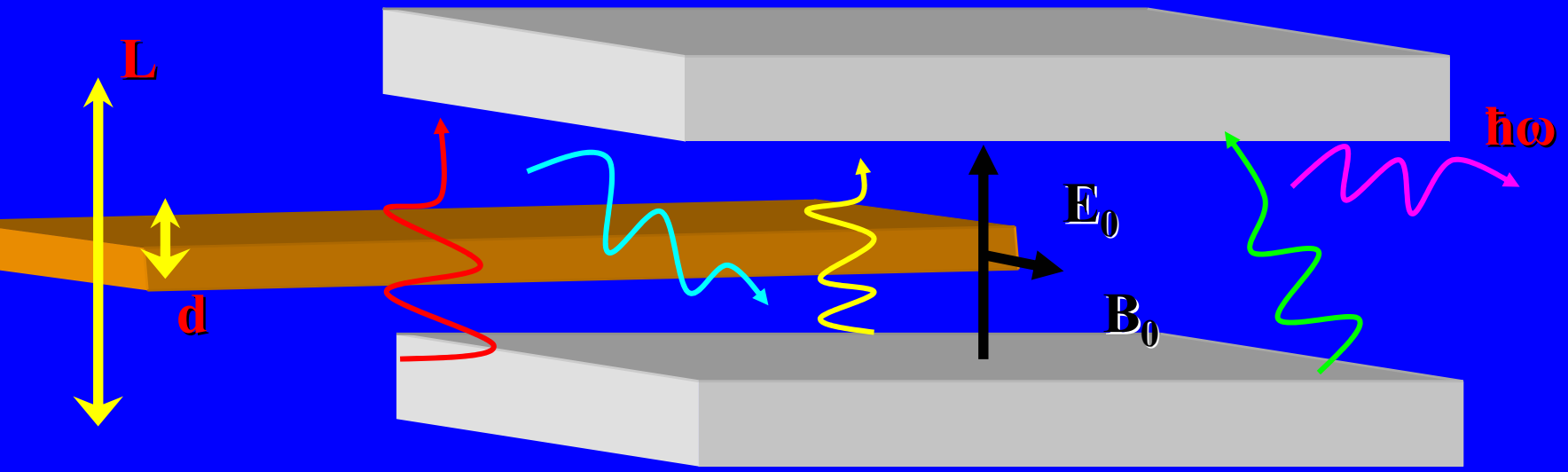
$$\int d^3\mathbf{r} \left\langle 0 \middle| (E(\mathbf{r}) \times B(\mathbf{r})_i \middle| 0 \right\rangle$$

$$= -\frac{\hbar}{\pi} \int_0^\infty d\omega\, \omega \sum_{\mathbf{k}} \left\{ k_i \,\mathrm{Im}\, G_{jj}(\mathbf{k},\mathbf{k},\omega) - k_j \,\mathrm{Im}\, G_{ij}(\mathbf{k},\mathbf{k},\omega) \right\}$$

$$\mathbf{G}(\omega) = \mathbf{G}_0(\omega) + \mathbf{G}_0(\omega)\cdot\mathbf{V}(\omega)\cdot\mathbf{G}_0(\omega) + \mathbf{G}_0(\omega)\cdot\mathbf{V}(\omega)\cdot\mathbf{G}_0(\omega)\cdot\mathbf{V}(\omega)\cdot\mathbf{G}_0(\omega) + \cdots$$

Van Tiggelen, Rikken, Krstic, PRL, 2006

L'effet « Feigel » dans la géométrie de Casimir



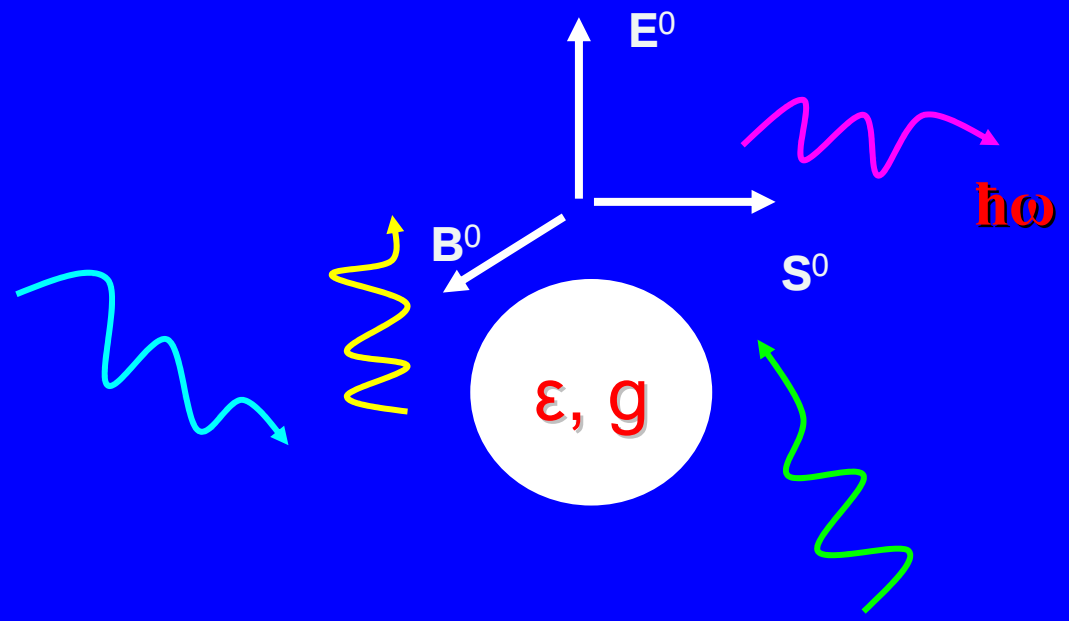
$$\langle 0|m\mathbf{v}|0\rangle = \infty - \frac{\pi\hbar}{24}\frac{A}{L^3}\frac{\sin\frac{\pi d}{2L}}{\cos^3\frac{\pi d}{2L}} \times g\,\mathbf{E}_0 \times \mathbf{B}_0$$

$$\mathbf{F}_{\text{vide}} = \frac{d}{dt}\langle 0|m\mathbf{v}|0\rangle$$

L= 10 µm, d=5 µm:

22 ordres de grandeur plus faible que le résultat « coupé »

L'effet « Feigel » pour une sphère magnétoélectrique



1e Born → 0

2e Born: $$\langle 0 | m\,\mathbf{v} | 0 \rangle \rightarrow -\frac{\beta}{4\pi^4} \times \Lambda(a) \times \hbar(\varepsilon - 1)\, g\ \mathbf{E}_0 \times \mathbf{B}_0$$

$$\Lambda(a) = \int_{x<a} d^3\mathbf{x} \int_{y<a} d^3\mathbf{y} \frac{1}{|\mathbf{x}-\mathbf{y}|^7} \rightarrow \infty - \frac{\pi^2}{12\,a}$$

Le calcul de β…… (Polarisation des photons)

$$\beta = \beta_1 + \ldots + \beta_{10}$$

$$\beta_1 = \int_0^\infty dx \int_0^\infty dy \; x^4 y^2 \frac{(x+2y)}{(x+y)^2} j_0(x)\, j_0(y) \times e^{-\varepsilon(x+y)}$$

$$= -12 \int_0^{\pi/2} d\theta \; \cos(5\theta) \sin^4(\theta) \cos(\theta) = -0.589..$$

⋮

$$\beta = 1.0714...$$

$$\langle 0 | m\,\mathbf{v} | 0 \rangle \rightarrow -0.0158 \frac{\hbar(\varepsilon - 1)}{a}\, g\ \mathbf{E}_0 \times \mathbf{B}_0$$

$FeGa0_3$.: a=10 µm, $gE_0B_0 = 10^{-4}$ → v = 10^{-15} nm/s

(immesurable)

a=1 nm **→ v = 10^{-3} nm/s**

(1 molécule) **(80 nm en une journée)**

Coupure: $FeGaO_3$: 78 m/s

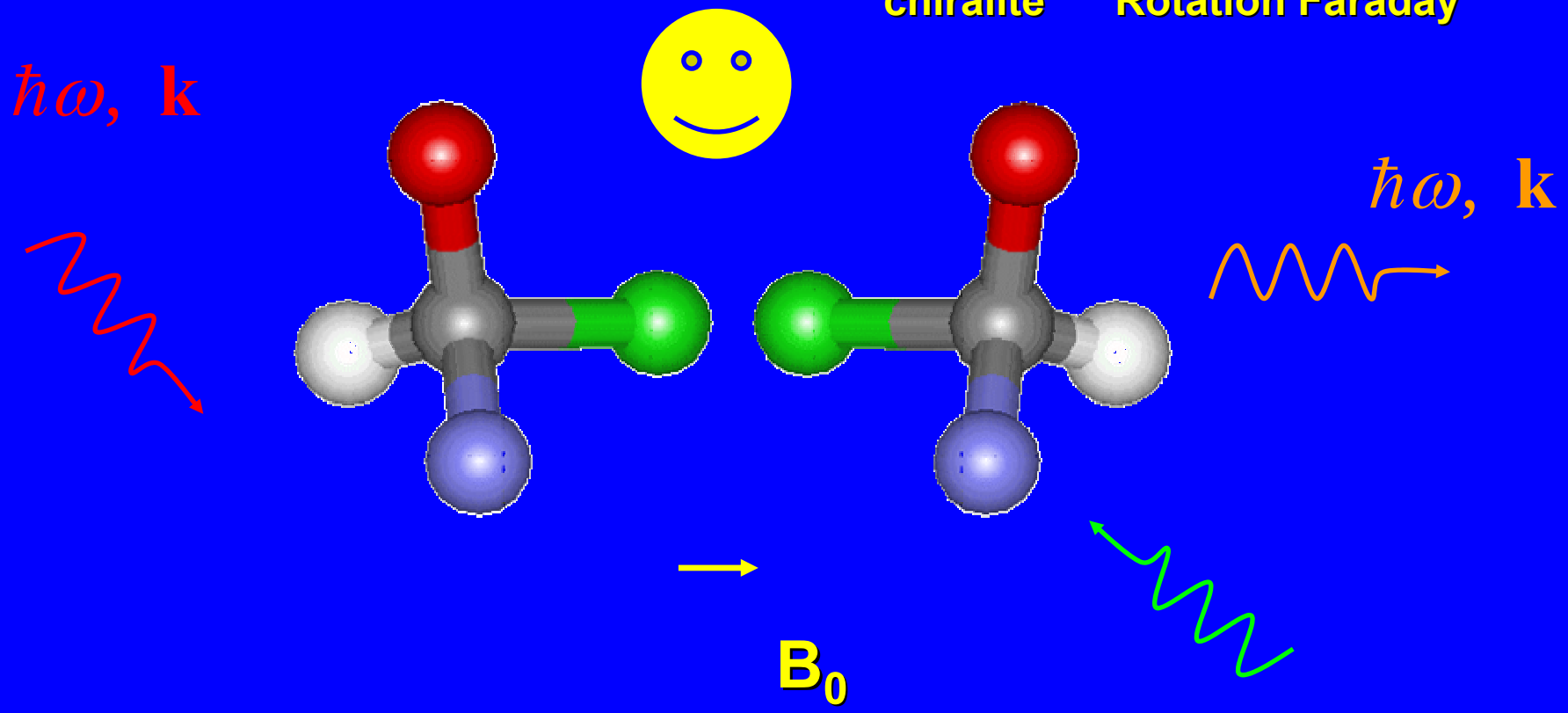
Conclusions

1. Transfert de la quantité de mouvement du « vide » à la matière, gérable par des champs électromagnétiques externes
2. L'effet est beaucoup plus faible que la première estimation

Perspectives

1. Théorie quantique pour la matière?

2. un rêve de Pasteur pourrait enfin se réaliser…

$$\langle 0 | m\,\mathbf{v} | 0 \rangle \rightarrow (??) \times \frac{\hbar}{a^3} g\; V\, \mathbf{B}_0$$

chiralité Rotation Faraday