ICE CSIC IEEC

Semi Transparent Mirrors; & the Fate of Gravity Equations as Equations of State

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ICE/CSIC & IEEC, UAB, Barcelona

Trento, October 24, 2008

Outline of the talk

- On the Casimir Effect

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- The Dynamical Casimir Effect (Davies-Fulling)

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- Future perspectives: η/s

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QFT vacuum to vacuum transition: $\langle 0|H|0\rangle$

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Even then: Has the final value real sense ?

Bohr $\longrightarrow$ Casimir $\longrightarrow$ Pauli ...

The Casimir Effect

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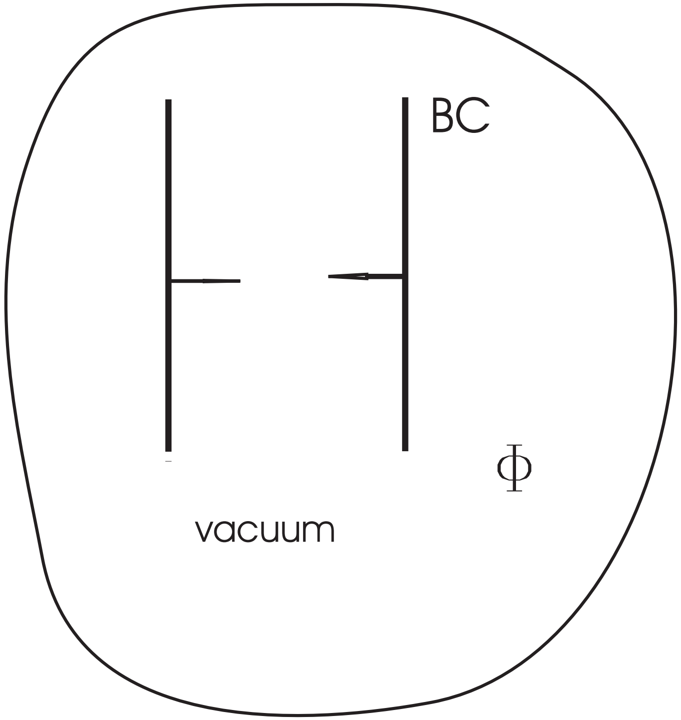

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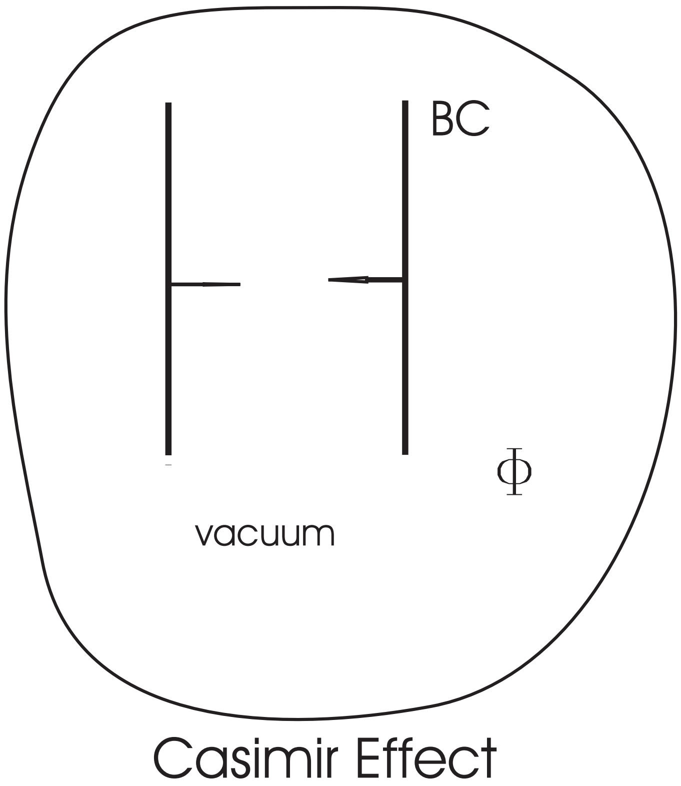

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$\Longrightarrow$ all kind of fields

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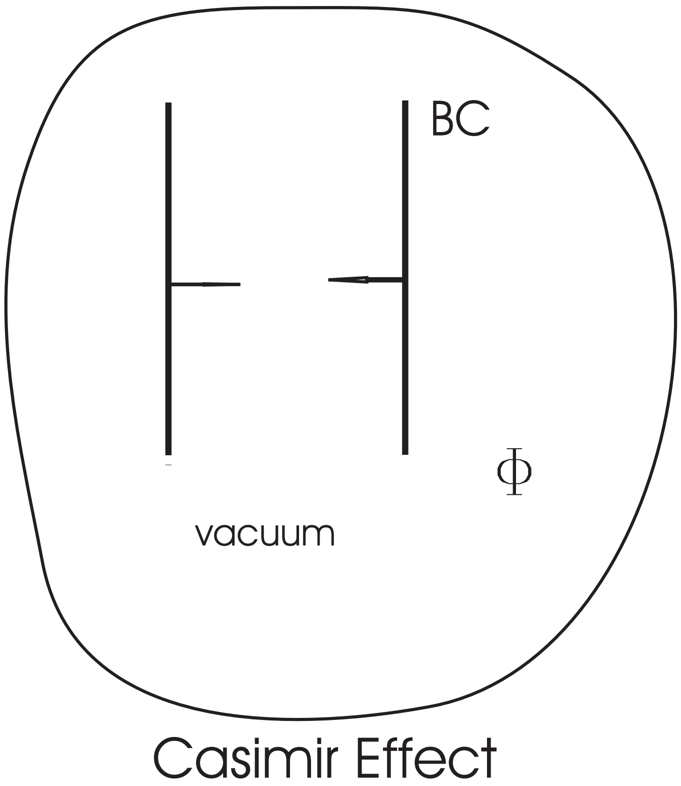

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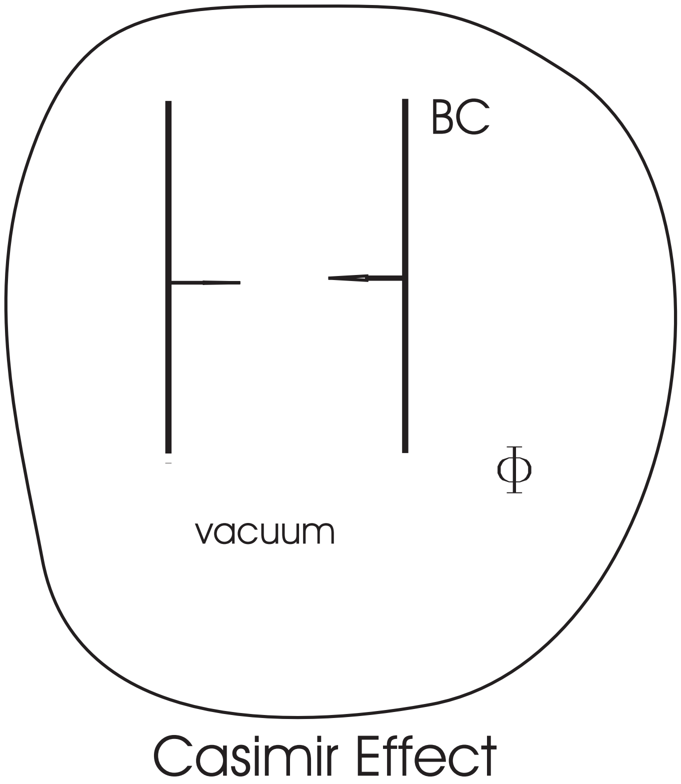

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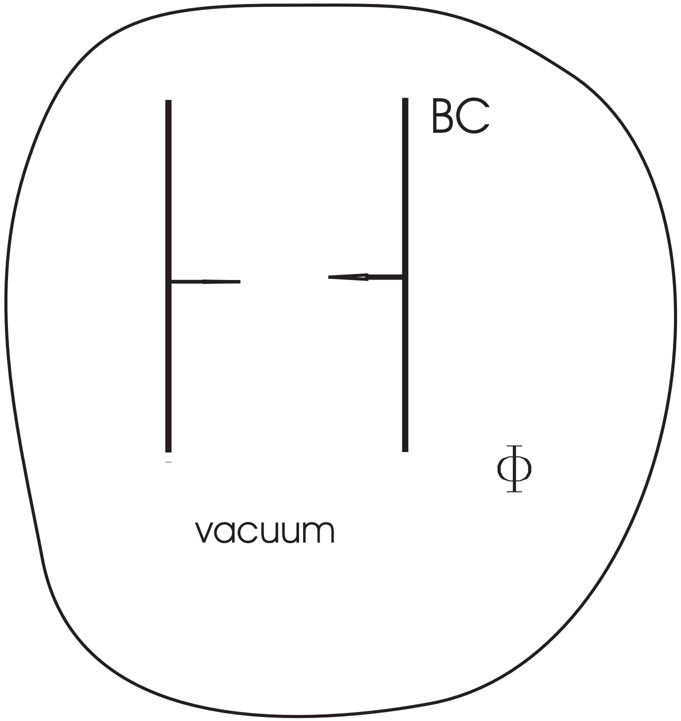
Universal process:

The Casimir Effect



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- Sonoluminiscence (Schwinger)
- Cond. matter (wetting ^{3}He alc.)
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- Direct experim. confirmation

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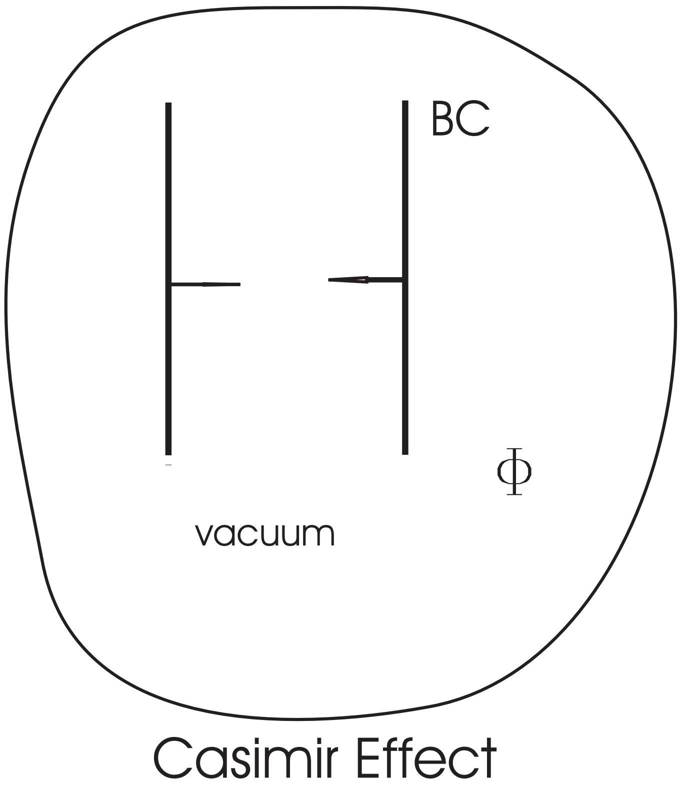

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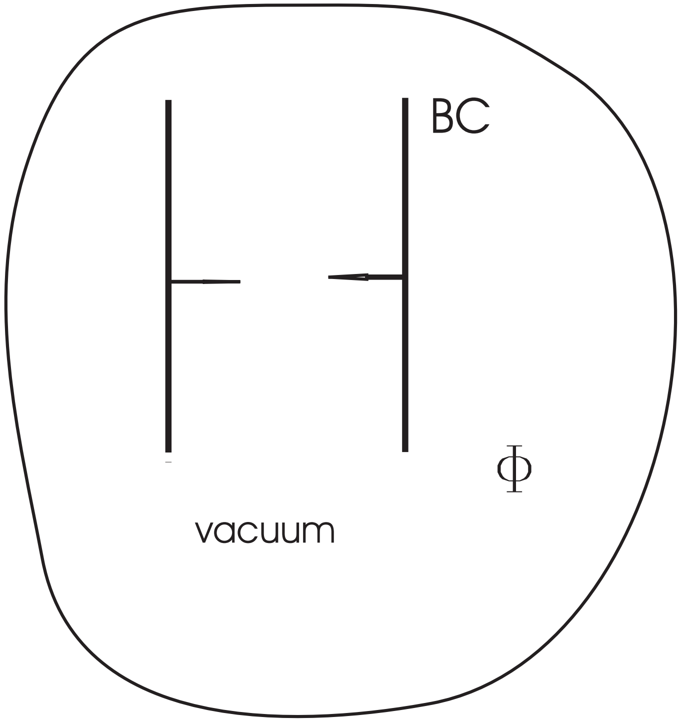

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Van der Waals, Lifschitz theory

- Dynamical CE $\Leftarrow$
- Lateral CE, piston, pistol, ...
- Extract energy from vacuum
- CE and the cosmological constant $\Leftarrow$

On the ‘reality’ of zero point fluctuations

- The Casimir effect gives no more nor less support for the “reality” of the vacuum fluctuations than other one-loop effects in QED (like vacuum polarization contribution to Lamb shift)

  [R. Jaffe, PRD72 (2005) 021301; hep-th/0503158]

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- Milonni has reformulated all of QED from the point of view of ZPF

The standard approach

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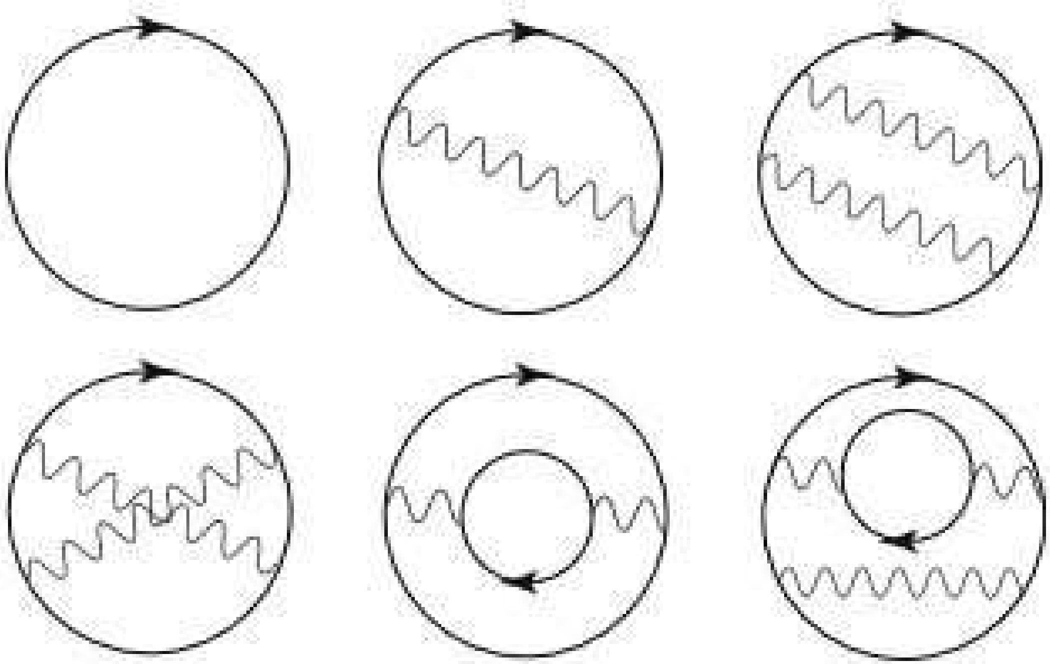

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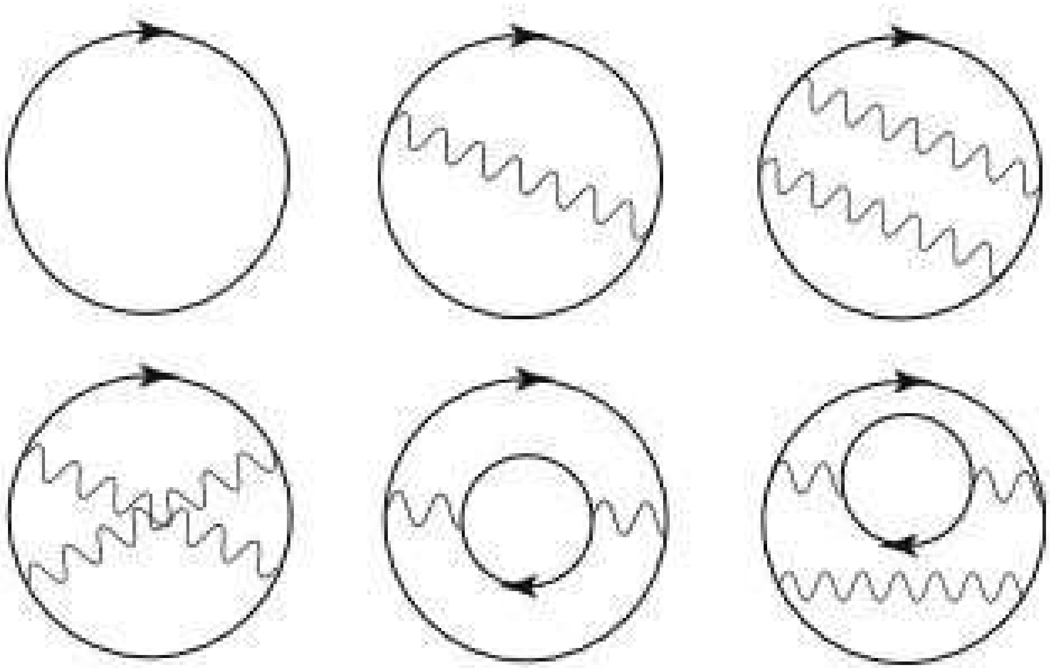

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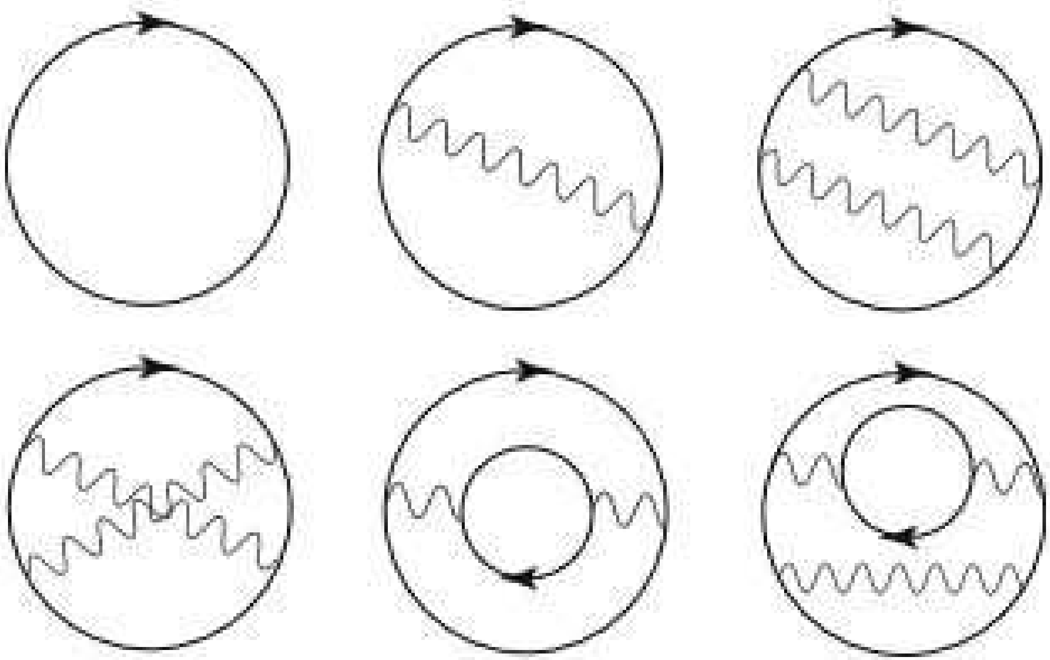

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In modern language the Casimir energy can be expressed in terms of the trace of the Greens function for the fluctuating field in the background of interest (conducting plates)

$$\mathcal{E} = \frac{\hbar}{2\pi} \mathrm{Im} \int d\omega\omega \; \mathrm{Tr} \int d^3x \left[\mathcal{G}(x,x,\omega+i\epsilon) - \mathcal{G}_0(x,x,\omega+i\epsilon) \right]$$

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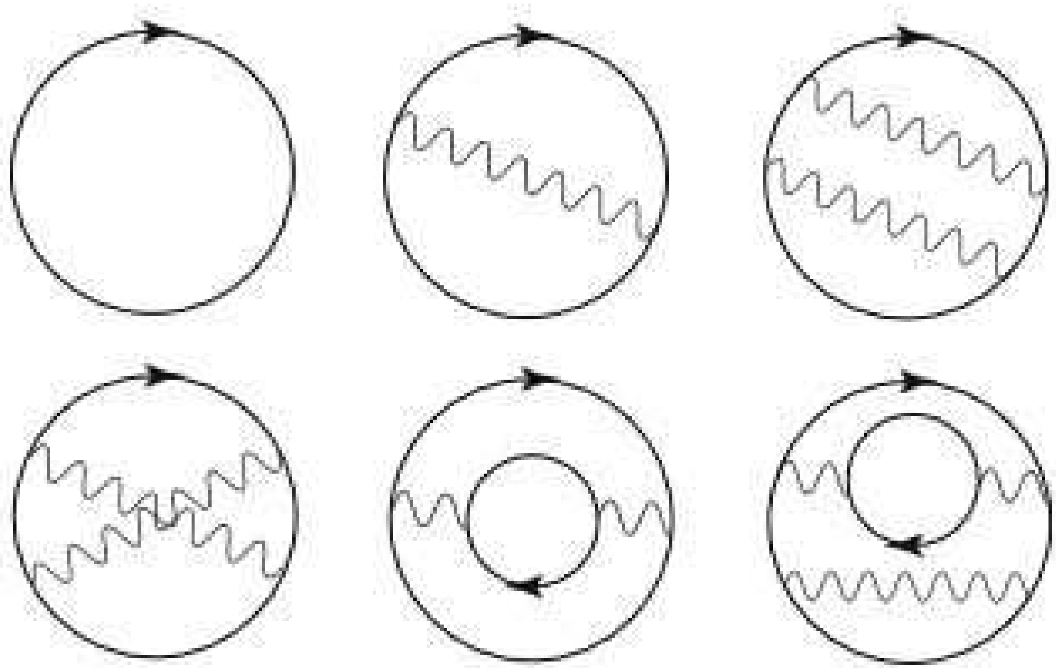

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$\mathcal{G}$ full Greens function for the fluctuating field

$\mathcal{G}_0$ free Greens function   Trace is over spin

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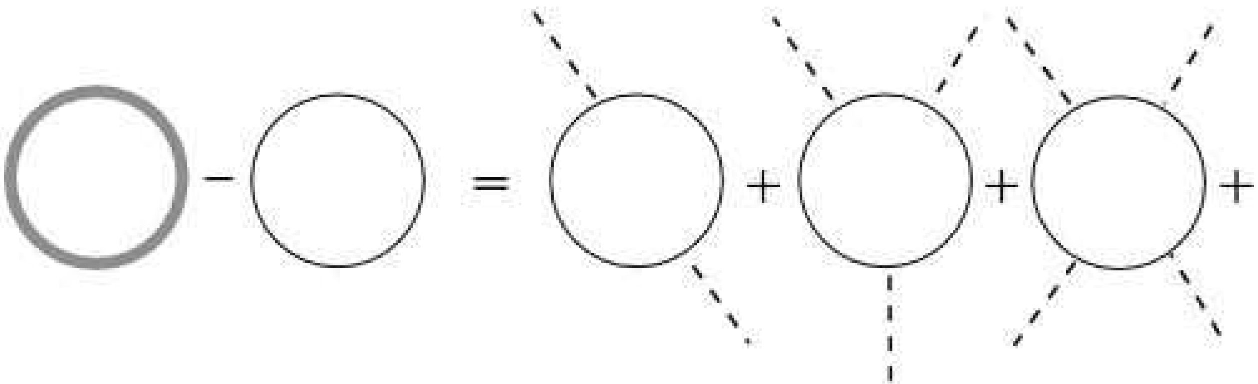

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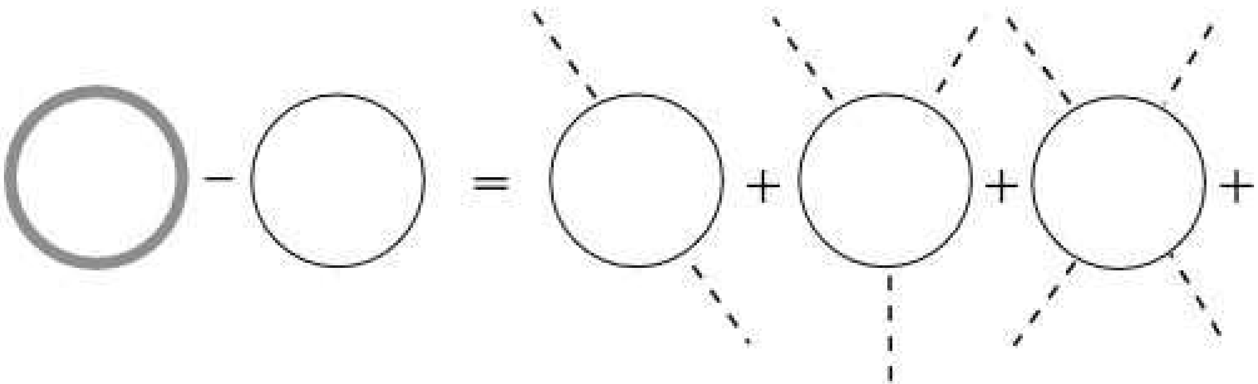

$\Longrightarrow$ Experimental confirmation of the Casimir effect does not establish the reality of zero point fluctuations

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Moore; Razavy, Terning; Johnston, Sarkar; Dodonov et al; Plunien et al; Barton, Eberlein, Calogeracos; Jaeckel, Reynaud, Lambrecht; Ford, Vilenkin; Brevik, Milton et al; Dalvit, Maia-Neto et al; Law; Parentani, ...

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- The dissipative part we obtain agrees with the other methods. But those have problems with the reactive part, which in general yields a non-positive energy $\Longrightarrow$ EXPERIMENT

SOME DETAILS OF THE METHOD

- Hamiltonian method for neutral Klein-Gordon field in a cavity Ω_t, with boundaries moving at a certain speed $v << c$, $\epsilon = v/c$

(of order 10^{-8} in Kim, Brownell, Onofrio, PRL 96 (2006) 200402)

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- Hamiltonian. Transform moving boundary into fixed one by (non-conformal) change of coordinates

$$\mathcal{R} : (\bar{t}, \mathbf{y}) \rightarrow (t(\bar{t}, \mathbf{y}), \mathbf{x}(\bar{t}, \mathbf{y})) = (\bar{t}, \mathbf{R}(\bar{t}, \mathbf{y}))$$

transform Ω_t into a fixed domain $\widetilde{\Omega}$

$\widetilde{\Omega}$: $(t(\bar{t}, \mathbf{y}), \mathbf{x}(\bar{t}, \mathbf{y})) = \mathcal{R}(\bar{t}, \mathbf{y}) = (\bar{t}, \mathbf{R}(\bar{t}, \mathbf{y}))$

(with $\bar{t}$ the new time)

CASE OF A SINGLE, PARTIALLY TRANSMITTING MIRROR

Case of a single, partially transmitting mirror

Seminal Davis-Fulling model [PRSL A348 (1976) 393] renormalized energy is negative: while the mirror moves, the renormalized energy cannot be considered as the energy of the produced particles at time t [cf. paragraph after Eq. (4.5)]

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Trajectory $(t, \epsilon g(t))$. When mirror at rest, scattering described by matrix

$$S(\omega) = \begin{pmatrix} s(\omega) & r(\omega)e^{-2i\omega L} \\ r(\omega)e^{2i\omega L} & s(\omega) \end{pmatrix}$$

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$\rightarrow$ Real in the temporal domain: $S(-\omega) = S^*(\omega)$

$\rightarrow$ Causal: $S(\omega)$ is analytic for Im $(\omega) > 0$

$\rightarrow$ Unitary: $S(\omega)S^\dagger(\omega) = \text{Id}$

$\rightarrow$ The identity at high frequencies: $S(\omega) \rightarrow \text{Id}$, when $|\omega| \rightarrow \infty$

$s(\omega)$ and $r(\omega)$ meromorphic (cut-off) functions (material's permitivity and resistivity)

RESULTS ARE REWARDING:

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In our Hamiltonian approach

$$\langle \hat{F}_{Ha}(t) \rangle = -\frac{\epsilon}{2\pi^2} \int_0^\infty \int_0^\infty \frac{d\omega d\omega' \omega\omega'}{\omega + \omega'} \text{Re}\left[e^{-i(\omega+\omega')t} \, \widehat{\dot{g}\theta_t}(\omega + \omega') \right]$$
$$\times \left[|r(\omega) + r^*(\omega')|^2 + |s(\omega) - s^*(\omega')|^2 \right] + \mathcal{O}(\epsilon^2)$$

Note this integral diverges for a perfect mirror ($r \equiv -1$, $s \equiv 0$, ideal case), but nicely converges for our partially transmitting (physical) one where $r(\omega) \to 0$, $s(\omega) \to 1$, as $\omega \to \infty$

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Energy conservation is fulfilled: the dynamical energy at any time t equals, with the opposite sign, the work performed by the reaction force up to that time t

$$\langle \hat{E}(t)\rangle = -\epsilon\int_0^t \langle \hat{F}_{Ha}(\tau)\rangle \dot{g}(\tau)d\tau$$

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- Calculate the radiation emitted by the mirror from its back (right) side
- As is well-known, a perfect mirror that follows this kind of trajectory produces a thermal emission of scalar massless particles obeying Bose-Einstein statistics:
  for $1 \ll \omega'/k \ll e^{ku_0}$ and $1 \ll \omega'/\omega \ll e^{ku_0}$, one has

$$\left|\beta^{R,R}_{\omega,\omega'}\right|^2 \equiv \left|(\phi^{out\ *}_{\omega,R};\phi^{in}_{\omega',R})\right|^2 \cong \frac{1}{2\pi\omega' k}\left(e^{2\pi\omega/k} - 1\right)^{-1}$$

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- Obtain the 'in' modes on the rhs of the mirror when the reflection and transmission coeffs are

$$r(w) = \frac{-i\alpha}{\omega + i\alpha}, \qquad s(w) = \frac{\omega}{\omega + i\alpha}$$

with $\alpha \geq 0$, that is, when the Lagrangian density is

$$\mathcal{L} = \frac{1}{2}[(\partial_t \phi)^2 - (\partial_x \phi)^2] - \alpha\sqrt{1 - \dot{g}^2(t)}\phi^2\delta(x - g(t))$$

being $x = g(t)$ the trajectory in the (t, x) coordinates

The Main Results

Some of them quite remarkable indeed

(for $1 \ll \omega'/k \ll e^{ku_0}$ and $1 \ll \omega'/\omega \ll e^{ku_0}$)

- In the perfectly reflecting case, i.e., when $\omega' \ll \alpha$, we obtain

$$\left|\beta^{R,R}_{\omega,\omega'}\right|^2 = \frac{1}{2\pi\omega' k} \cong \left(e^{2\pi\omega/k} - 1\right)^{-1}, \qquad \left|\beta^{R,L}_{\omega,\omega'}\right|^2 \cong 0$$

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- In the physically more realistic case of a partially transmitting mirror (transparent to high enough frequencies, i.e., when $\alpha \ll \omega'$, what we obtain is

$$\left|\beta^{R,R}_{\omega,\omega'}\right|^2 \cong \frac{1}{2\pi\omega k}\left(\frac{\alpha}{\omega'}\right)^2 \left(e^{2\pi\omega/k}+1\right)^{-1}$$

$$\left|\beta^{R,L}_{\omega,\omega'}\right|^2 \sim \frac{1}{\omega\omega'}\mathcal{O}\left[\left(\frac{\alpha}{\omega'}\right)^2\right]$$

- And, since $\left|\beta^{R,L}_{\omega,\omega'}\right| \ll \left|\beta^{R,R}_{\omega,\omega'}\right|$, we conclude quite surprisingly that a semitransparent mirror emits a thermal radiation of scalar massless particles obeying Fermi-Dirac statistics

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- An additional calculation on a bidimensional fermionic model for massless particles seems to show that the reverse change of statistics may happen: the Fermi-Dirac statistics for the completely reflecting case will turn into the Bose-Einstein statistics for the partially reflecting mirror
- The physical reason of the remarkable change of statistics that takes place remains, as of now, a mystery. It might well find application in other situations, including perhaps black hole physics

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- C. Eling, R. Guedens, T. Jacobson [PRL2006]: extension to polynomial $f(R)$ gravity but as non-equilibrium thermodyn.
  Also Erik Verlinde (private discussions)

- Jacobson's argument: basic thermodynamic relation

$$\delta Q = T\delta S$$

  - entropy proport to variation of the horizon area: $\delta S = \eta\, \delta \mathcal{A}$
  - local temperature T defined as Unruh temp: $T = \hbar k/2\pi$
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- Key point in our generalization: the definition of the local entropy (Iyer+Wald 93: local boost inv, Noether charge)

$$S = -2\pi \int_{\Sigma} E_R^{pqrs} \epsilon_{pq}\epsilon_{rs}, \qquad \delta S = \delta\left(\eta_e A\right)$$

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- Case of $\mathbf{f}(R)$ gravities: $\mathbf{L} = \mathbf{f}(R, \nabla^n R)$

- Also the concept of an effective Newton constant for graviton exchange (effective propagator)

$$\begin{aligned}\frac{1}{8\pi G_{eff}} &= E_R^{pqrs}\epsilon_{pq}\epsilon_{rs} = \frac{\partial \mathbf{f}}{\partial R}(g^{pr}g^{qs} - g^{qr}g^{ps})\epsilon_{pq}\epsilon_{rs} \\ &= \frac{\partial \mathbf{f}}{\partial R} = \frac{\eta_e}{2\pi}, \qquad S = \frac{A}{4\,G_{eff}}\end{aligned}$$

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- Final result, for $\mathbf{f}(R)$ gravities:
  the local field equations can be thought of as an equation of state of equilibrium thermodynamics (as in the GR case)

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- S-F Wu, G-H Yang, P-M Zhang, arXiv:0805.4044, direct extension of our results to Brans-Dicke and scalar-tensor gravities
  T Zhu, Ji-R Ren and S-F Mo, arXiv:0805.1162 [gr-qc];
  C Eling, arXiv:0806.3165 [hep-th]; R-G Cai, L-M Cao and Y-P Hu, arXiv:0807.1232 [hep-th] & arXiv:0809.1554 [hep-th]

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Grazie Mille!