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Vacuum Fluctuations in Domains with Moving Boundaries and the Dark Energy Issue

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ICE/CSIC & IEEC, UAB, Barcelona

4th Dark Side of the Universe, BUE El Cairo, 1-5 June, 2008

Outline of this presentation

- The Casimir Effect: Theory, Experiments, Uses

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- Gravity Equations as Equations of State

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Even then: Has the final value real sense ?

The Casimir Effect

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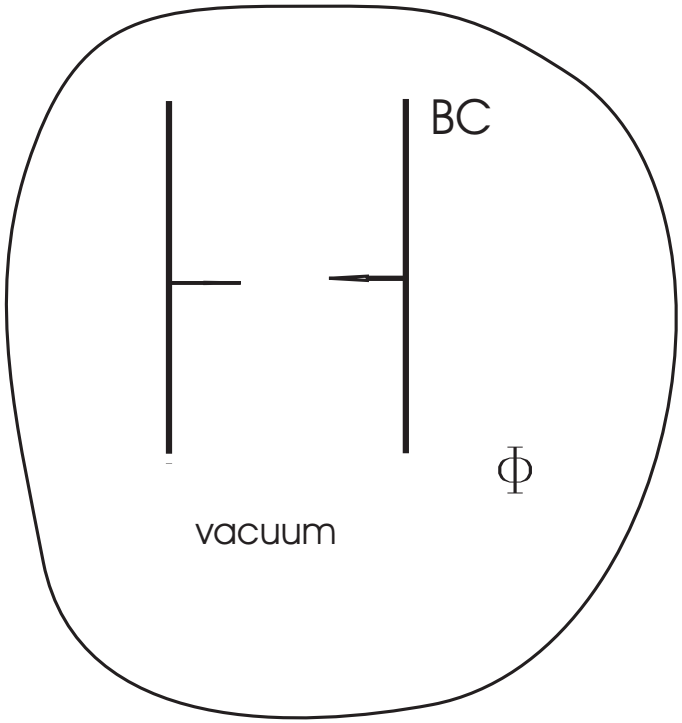

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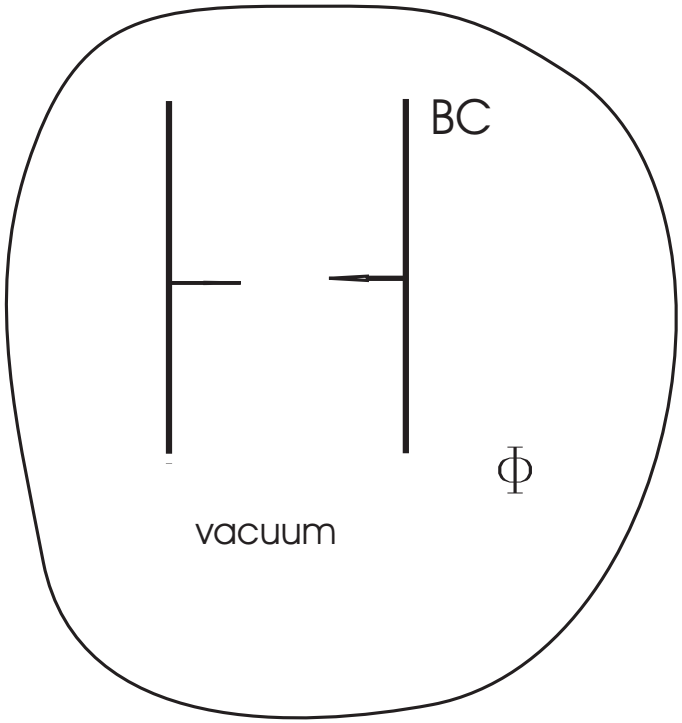

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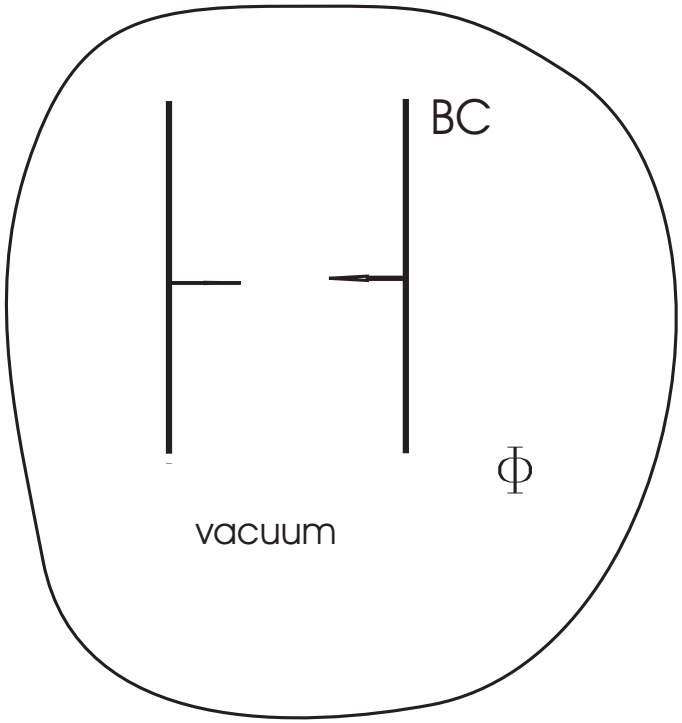

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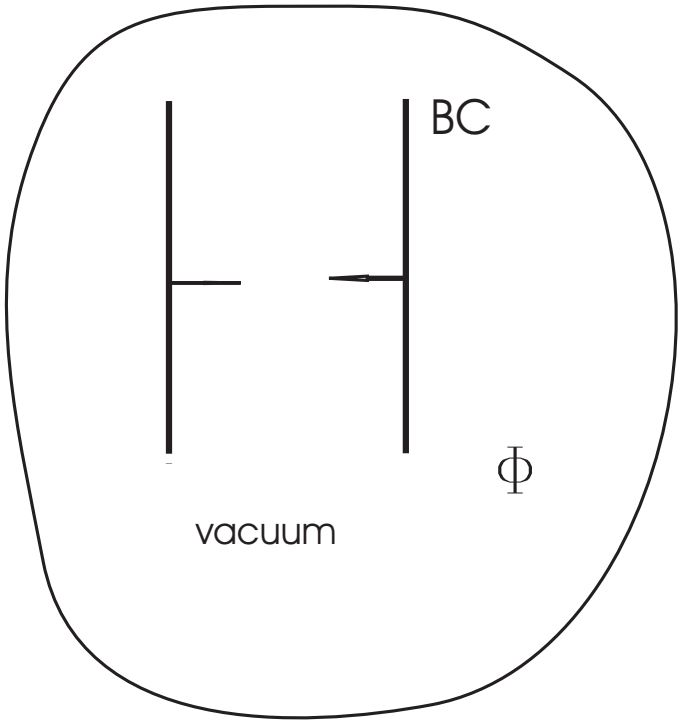

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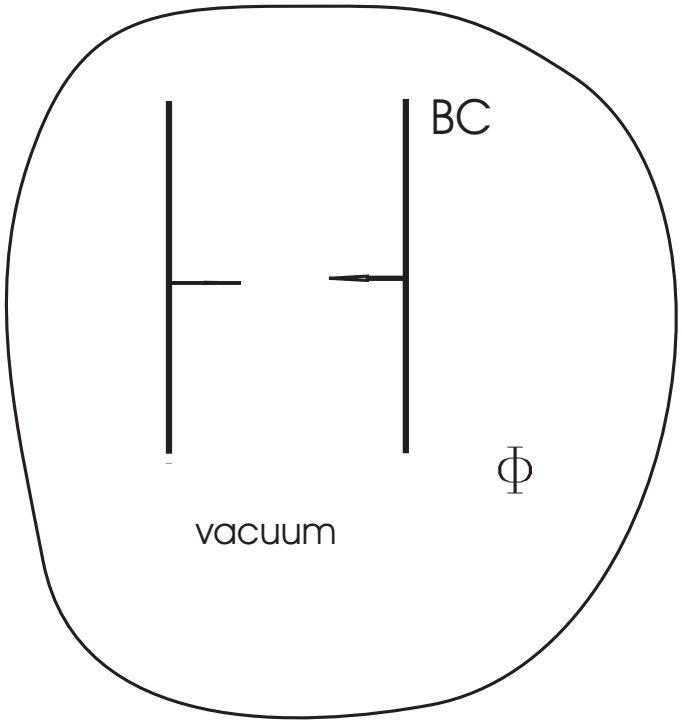

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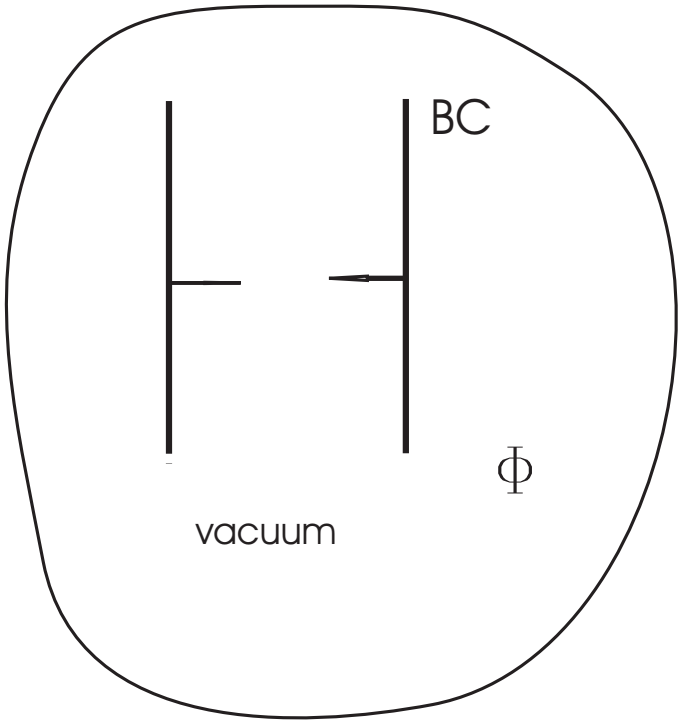

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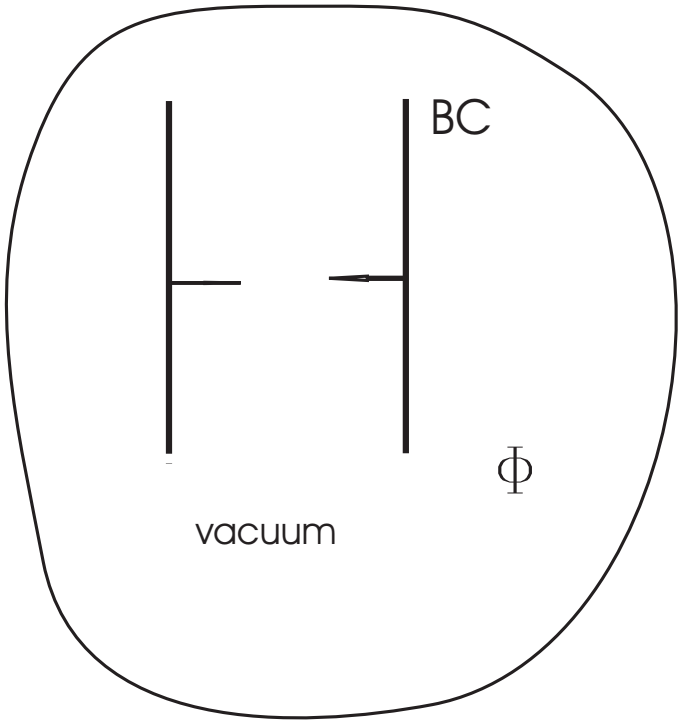

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- Dynamical CE $\Leftarrow$
- Lateral CE
- Extract energy from vacuum
- CE and the cosmological constant $\Leftarrow$

The standard approach

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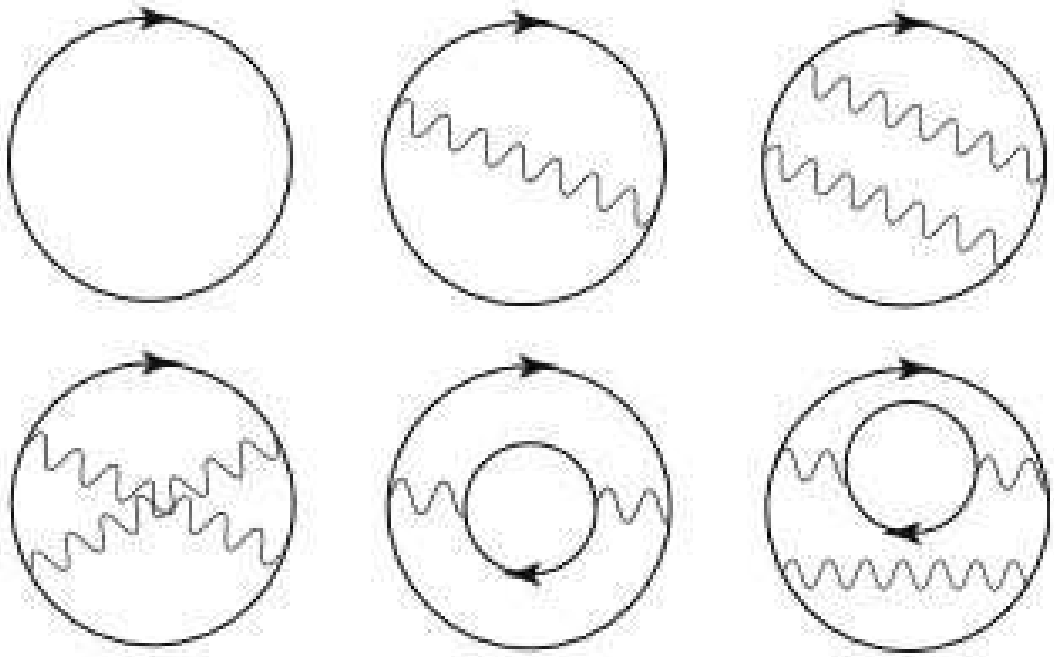

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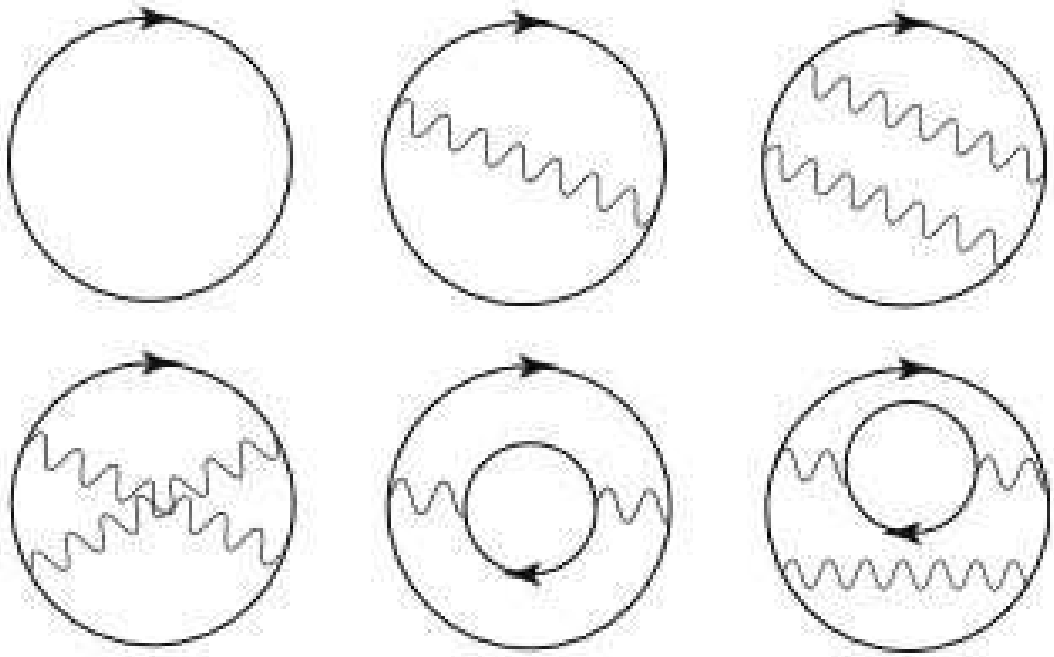

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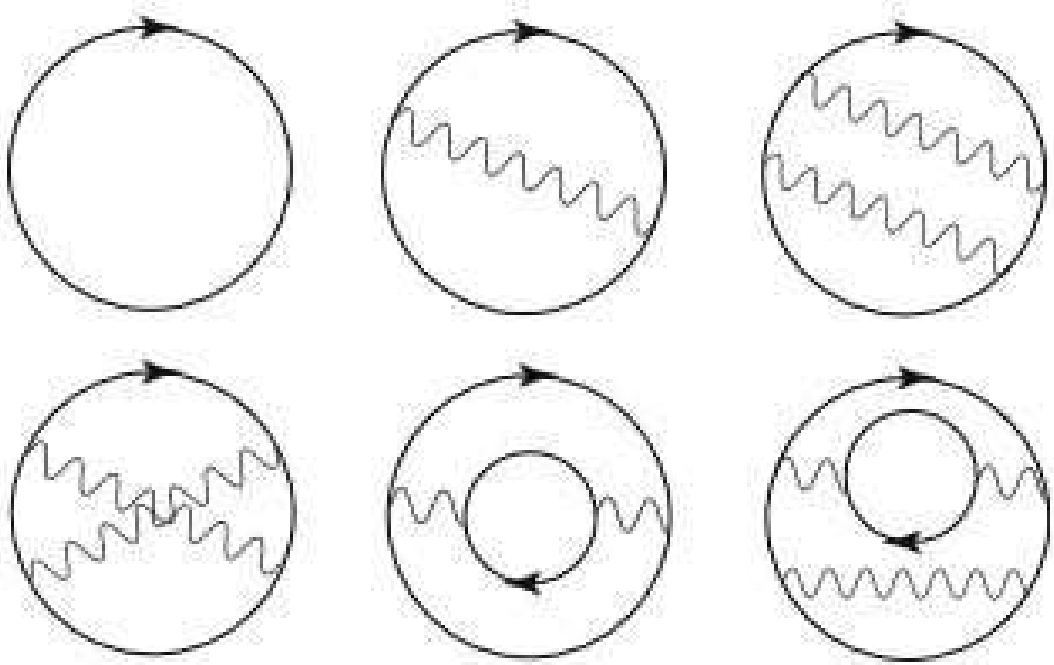

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$$\mathcal{E} = \frac{\hbar}{2\pi}\mathrm{Im}\int d\omega\omega\ \mathrm{Tr}\int d^3x\,[\mathcal{G}(x,x,\omega+i\epsilon) - \mathcal{G}_0(x,x,\omega+i\epsilon)]$$

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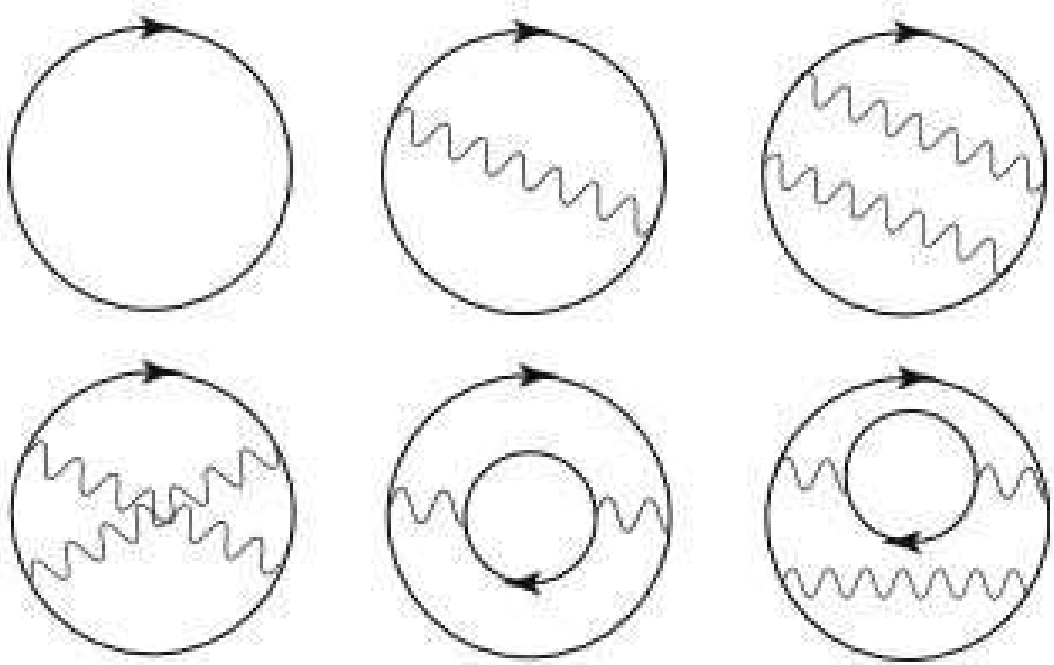

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$\mathcal{G}$ full Greens function for the fluctuating field

$\mathcal{G}_0$ free Greens function

Trace is over spin

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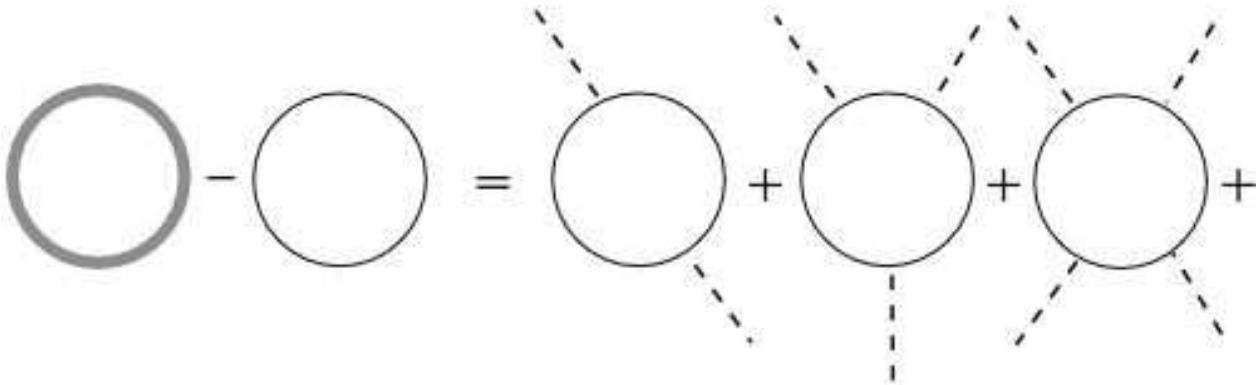

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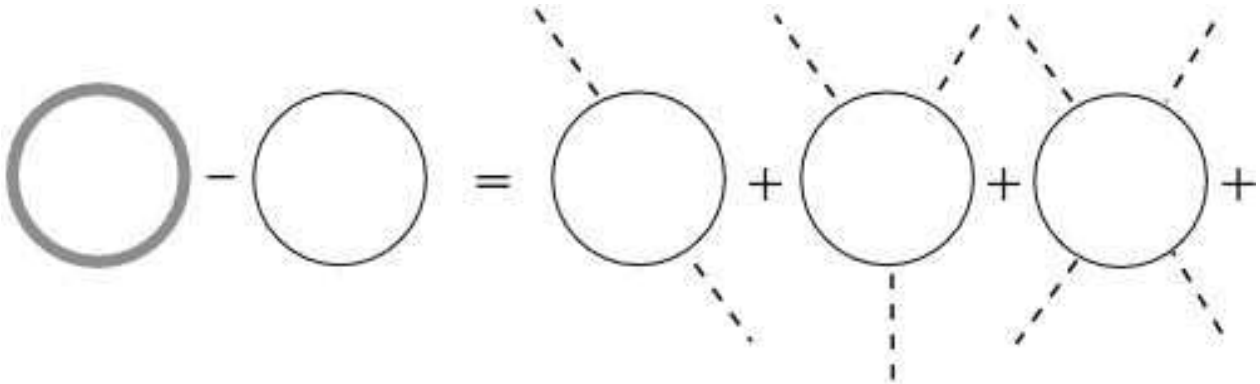

$\Longrightarrow$ "Experimental confirmation of the Casimir effect does not establish the reality of zero point fluctuations" [R. Jaffe et. al.]

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

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- Such force is split into two parts: a dissipative force whose work equals minus the energy of the particles that remain & a reactive force vanishing when the mirrors return to rest
- 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 $v << c$, $\epsilon = v/c$

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

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

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

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

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

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Seminal Davis-Fulling model [PRSL A348 (1976) 393]

renormalized energy negative while the mirror moves:

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[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: $S(\omega)S^\dagger(\omega) = \mathrm{Id}$

$\rightarrow$ The identity at high frequencies: $S(\omega) \rightarrow \mathrm{Id}$, 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

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

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

$\Longrightarrow$ Two mirrors; higher dimensions; fields of any kind

Quantum Vacuum Fluct's & the CC

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- Recent observations: M. Tegmark et al. [SDSS Collab.] PRD 2004

$$\Lambda \; = \; (2.14 \pm 0.13 \times 10^{-3} \text{ eV})^4 \quad \sim \; 4.32 \times 10^{-9} \text{ erg/cm}^3$$

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- Casimir stress tensor between pair of parallel perfectly conducting plates, at distance a, transverse dimensions $L >> a$

[Brown and Maclay, Phys. Rev. 184 (1969) 1272]

$$\langle T_{\mu\nu} \rangle = \frac{\mathcal{E}_{\mathcal{C}}}{a} \, \text{diag}(1, -1, -1, 3)$$

third spatial direction is normal to plates, $\mathcal{E}_{\mathcal{C}}$ Casimir energy per unit area

$$\mathcal{E}_{\mathcal{C}} = -\frac{\pi \hbar c}{720 a^3}$$

Outside the plates, $\langle T_{\mu\nu} \rangle = 0$

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- Gravitational interaction of the Casimir apparatus: use gravitational definition of the energy-momentum tensor as variation of matter part of action:

$$\delta W_m = \frac{1}{2} \int \sqrt{-g} \, \delta g_{\mu\nu} \, T^{\mu\nu} \qquad (*)$$

Following Schwinger (note the factor 2 in the definition), for a weak field Fulling et al define: $g_{\mu\nu} = \eta_{\mu\nu} + 2 h_{\mu\nu}$

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  energy-momentum tensor of the phys sys must be conserved, so include a physical mechanism holding the plates apart against the Casimir force
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- BUT: the renormalized total $T^{\mu\nu}$ must be conserved in curved s-t (gauge inv!)

CC PROBLEM

- Relativistic field: collection of harmonic oscill's (scalar field)

$$E_0 \;=\; \frac{\hbar\, c}{2}\sum_n \omega_n, \qquad \omega = k^2 + m^2/\hbar^2, \;\; k = 2\pi/\lambda$$

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- What we do consider —with relative success in some different approaches— is the additional contribution to the cc coming from the non-trivial topology of space or from specific boundary conditions imposed on braneworld models:

$\Longrightarrow$ kind of cosmological Casimir effect

Cosmolog Imprint of the Casimir Eff't?

- Assuming one will be able to prove (in the future) that the ground value of the cc is zero (as many had suspected until recently), we will be left with this incremental value coming from the topology or BCs

  * L. Parker & A. Raval, VCDM, vacuum energy density

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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 (personal discussions)

- Jacobson's argum non-trivially extended to $f(R)$ gravity field eqs, as EoS of local space-time thermodynamics
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