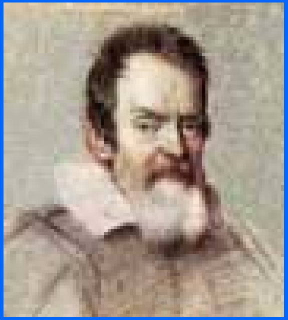
Towards experimental test of the dynamical Casimir effect

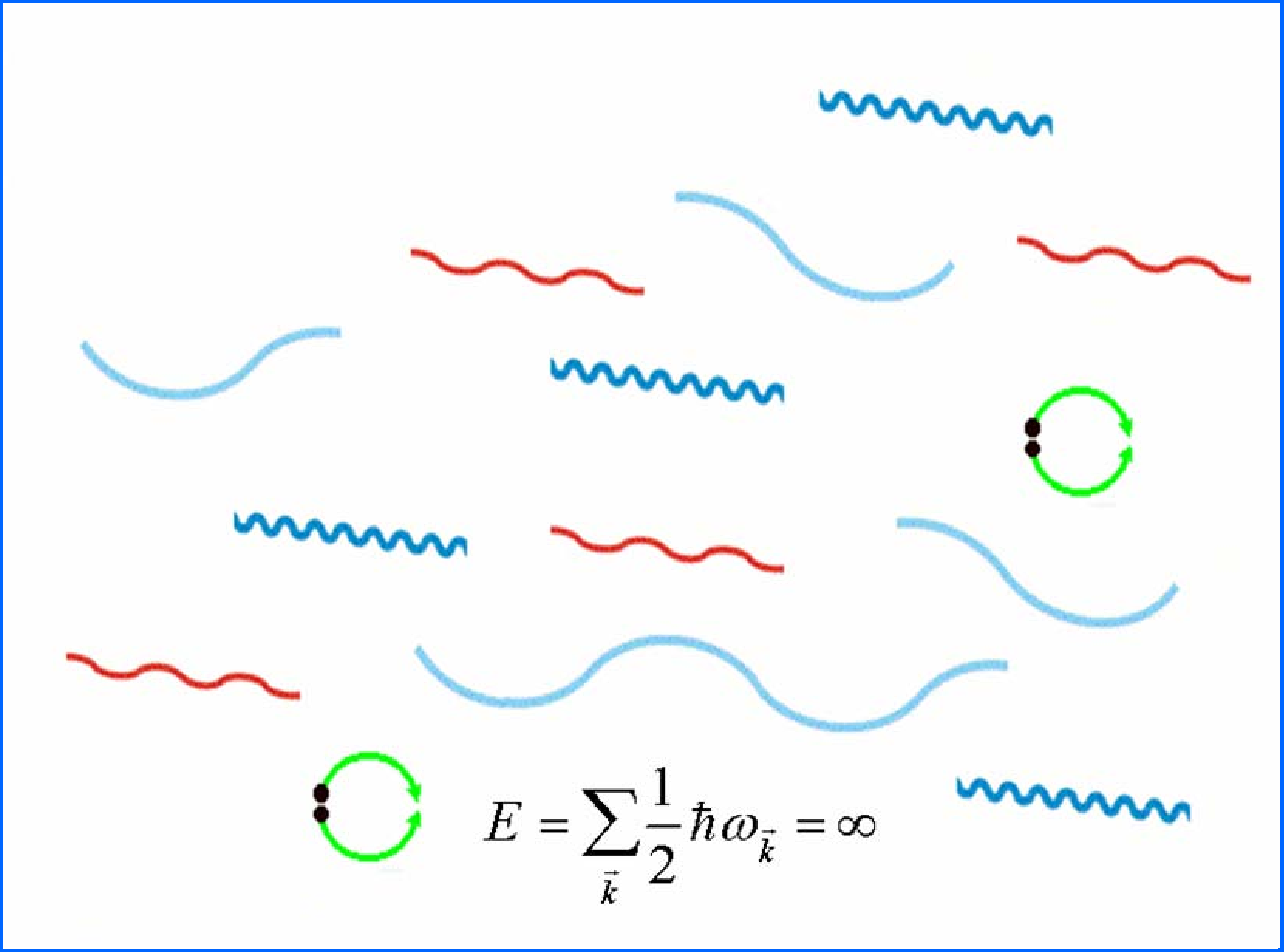


Roberto Onofrio

Department of Physics “Galileo Galilei”, University of Padova
Department of Physics and Astronomy, Dartmouth College

KITP, UCSB, Santa Barbara, 11/20/2008

Quantum vacuum is a non-trivial medium: polarization, dispersion, dissipation



$$E = \sum_{\vec{k}} \frac{1}{2} \hbar \omega_{\vec{k}} = \infty$$

QUANTUM VACUUM IS A VISCOUS MEDIUM

A mirror moving in quantum vacuum with *non-uniform* acceleration will experience a damping force

(compare to a body in a fluid, which will experience a damping force if in motion)

Asymptotic motional states are the ones at most with constant acceleration

(compare to asymptotic motional states in an ordinary fluid are the ones at constant velocity)

From this perspective, quantum vacuum appears as a sort of “ether” or privileged frame of reference with respect to which accelerated motions should be absolute: if motion is nonuniformly accelerated with respect to quantum vacuum then dissipation occurs

(Moore; Fulling & Davies; Dodonov, Jaekel, Lambrecht & Reynaud)

Dynamical Casimir Effect

- Time-dependent boundary conditions
- This generates a dissipative force
- Observable through motion-induced photon emission
- Virtual photons promoted to real photons via phonon-photon interaction
- Use of parametric resonance and a high finesse electromagnetic cavity (Q)

- **Essential to be in a high finesse cavity (Lambrecht *et al.*,1996)**
- **Yablonovitch, Lozovik *et al.* , Braggio *et al.* (2005)**
- **Proposal using Rydberg atoms in cavities (Dodonov *et al.*, 1996)**
- **Use of nanoresonators and hyperfine states (R.O., *QFTEX'03*)**

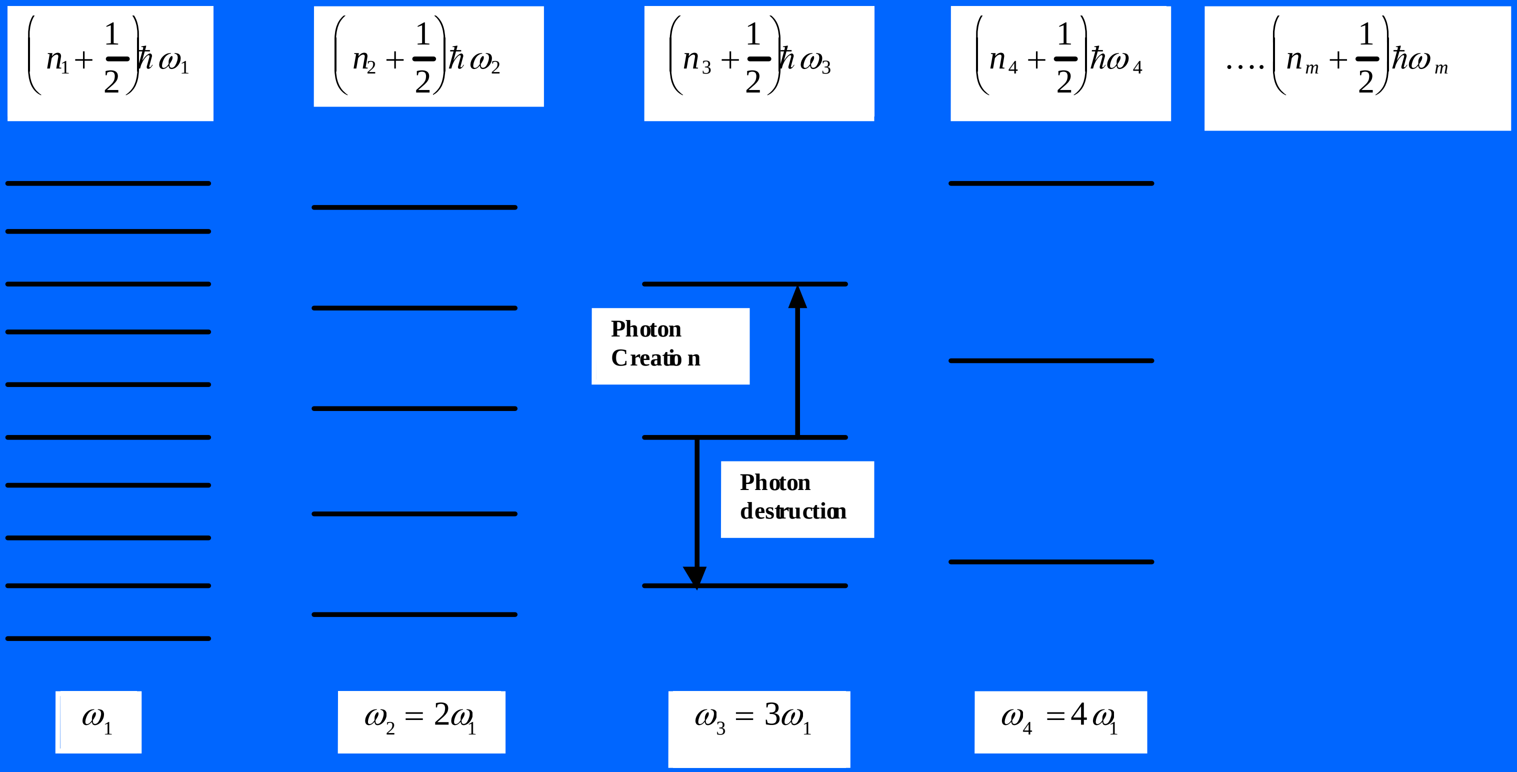
Mechanical creation of photons

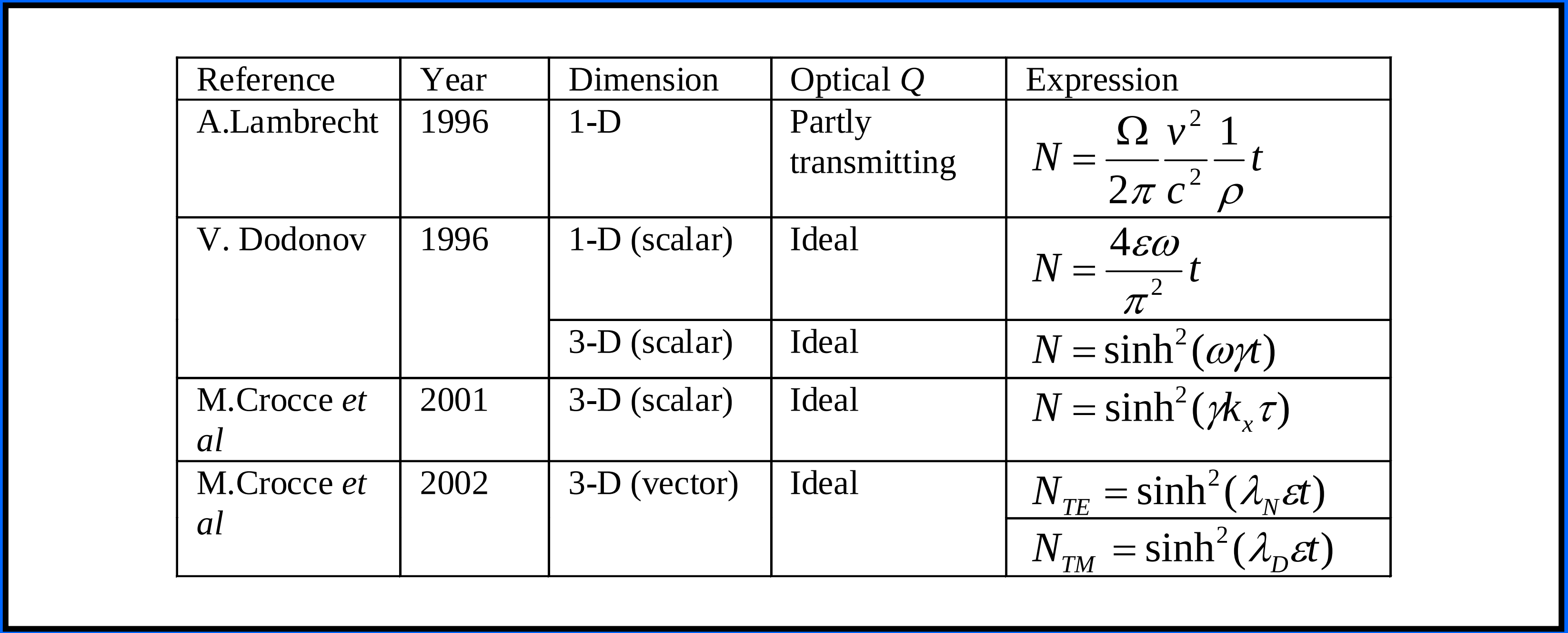
(from MIR experiment, D. Zanello *et al*., INFN)

It can also be seen as a parametric conversion of real phonons into real photons via quantum vacuum (compare to an acousto-optical modulator)

- 1D case: Strong intermode interaction due to equidistant mode levels. The number of photons in each mode grows as t, whereas the total energy grows exponentially

- 3D case: Mode levels are not equidistant, hence no intermode interaction. The growth is directed in a particular resonant mode in which number of photons grows exponentially





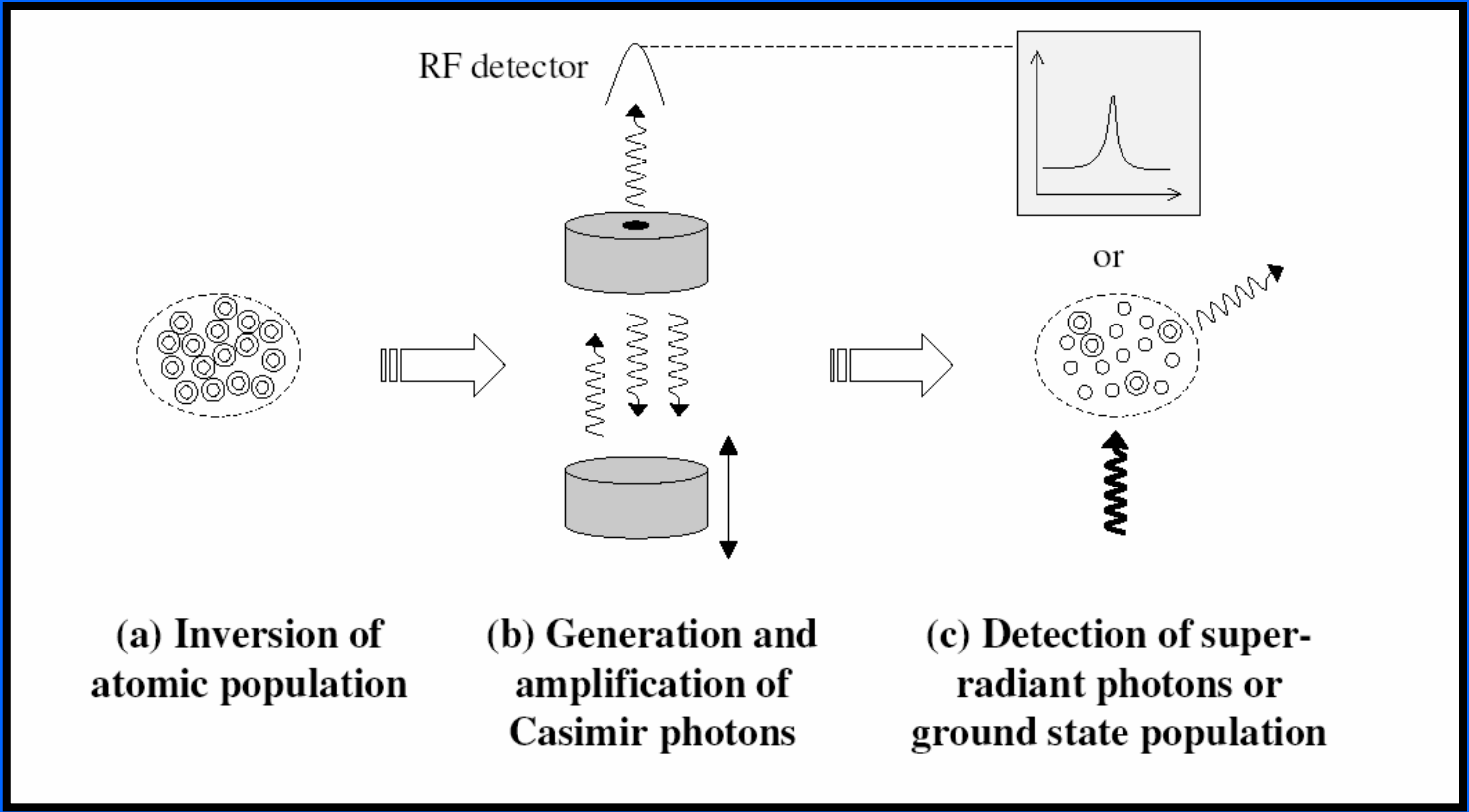
Reference	Year	Dimension	Optical *Q*	Expression
A.Lambrecht	1996	1-D	Partly transmitting	$N = \frac{\Omega}{2\pi}\frac{v^2}{c^2}\frac{1}{\rho}t$
V. Dodonov	1996	1-D (scalar)	Ideal	$N = \frac{4\varepsilon\omega}{\pi^2}t$
		3-D (scalar)	Ideal	$N = \sinh^2(\omega\gamma t)$
M.Crocce *et al*	2001	3-D (scalar)	Ideal	$N = \sinh^2(\gamma k_x \tau)$
M.Crocce *et al*	2002	3-D (vector)	Ideal	$N_{TE} = \sinh^2(\lambda_N \varepsilon t)$
				$N_{TM} = \sinh^2(\lambda_D \varepsilon t)$

$$\boxed{N \cong N_0 \sinh^2(\Omega\varepsilon t) \xrightarrow{\tau=\frac{Q}{\omega}} N_0 \sinh^2(2Q\varepsilon)}$$

- - Number of photons depends on the product $Q\varepsilon$ (squeezing parameter, with $\varepsilon = v/c$) and very sensitive to its variations, $Q\varepsilon$ = 0.5, 1, 2 gives N=1.4, 13, 740.
- For a direct measurements at $Q\varepsilon$ =1, the expected power is quite small

$$\boxed{P = N_{Cas}^{Sat}\frac{\hbar\omega}{\tau} \approx 10^{-22} W}$$

Experimental Scheme



I. Preparation of atoms
II. Generation of photons
III. Interaction of atoms-photons via superradiance

Preparation: Selection of atomic species

- Currently feasible frequency of mechanical resonator: up to a few GHz
- Use hyperfine splitting of alkali atoms as two-level systems, such as Li (228 MHz), Na (1.77 GHz), Rb (6.83 GHz), and Cs (9.19 GHz)
- Lifetime of the excited level is important

Magnetic dipole transition giving a natural, free-space lifetime of thousands of years

$$\boxed{T_1^{free} = \frac{3\pi\varepsilon_o \hbar c^5}{\mu_B^2 \omega^3}}$$

$$\Downarrow$$

For $Q = 10^8$, the natural lifetime in a cavity is reduced on the order of $10^3 - 10^5$ seconds.

$$\boxed{T_1^{Cav} = \frac{4\pi^2}{3Q_{opt}} \frac{V}{\lambda^3} T_1^{free}}$$

$$\Downarrow$$

Superradiance helps to speed-up the decay which is assisted/stimulated by photons

$$\boxed{T_{SR} = \frac{T_1^{Cav}}{N_{at}}}$$

$$\boxed{P_{SR} = N_{at}\frac{\hbar\omega}{T_{SR}} = 10^{-13}W}$$

This is now detectable with either micro-bolometers with sensitivity $10^{-16}W/\sqrt{Hz}$ or sub-fW RF power spectrum analyzer of KHz bandwidth

[A. D Turner et al., Applied Optics **40**, 4921 (2001)]

Competition between superfluorescence (spontaneous triggering) and superradiance (Casimir triggering)

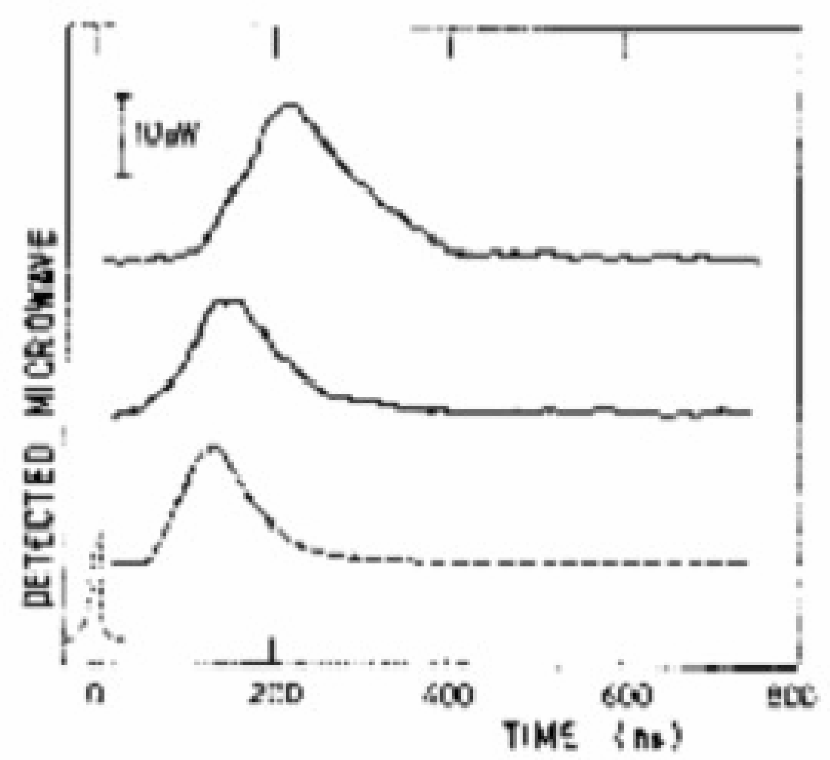
$$\boxed{T_D = T_{SR}\ln\left[\frac{N_{at}}{1+N_{ph}}\right]}$$

The delay time reveals the number of initial Casimir photons
[P. Goy, J. M. Raimond, M. Gross, and S. Haroche, PRL **50**, 1903 (1983)]

Alternatively, move the atoms out of cavity with an optical tweezer technique *before* the expected superfluorescence and *after* the superradiance
[T. L Gustavson *et al*., PRL **88**, 020401 (2002)]

SR delay time measurements

- Rydberg atom maser at 108 GHz
- Atomic beam through a gaussian cavity
- Triggering by external radiation evidenced by decrease in emission delay
- Possibility of a single photon detector

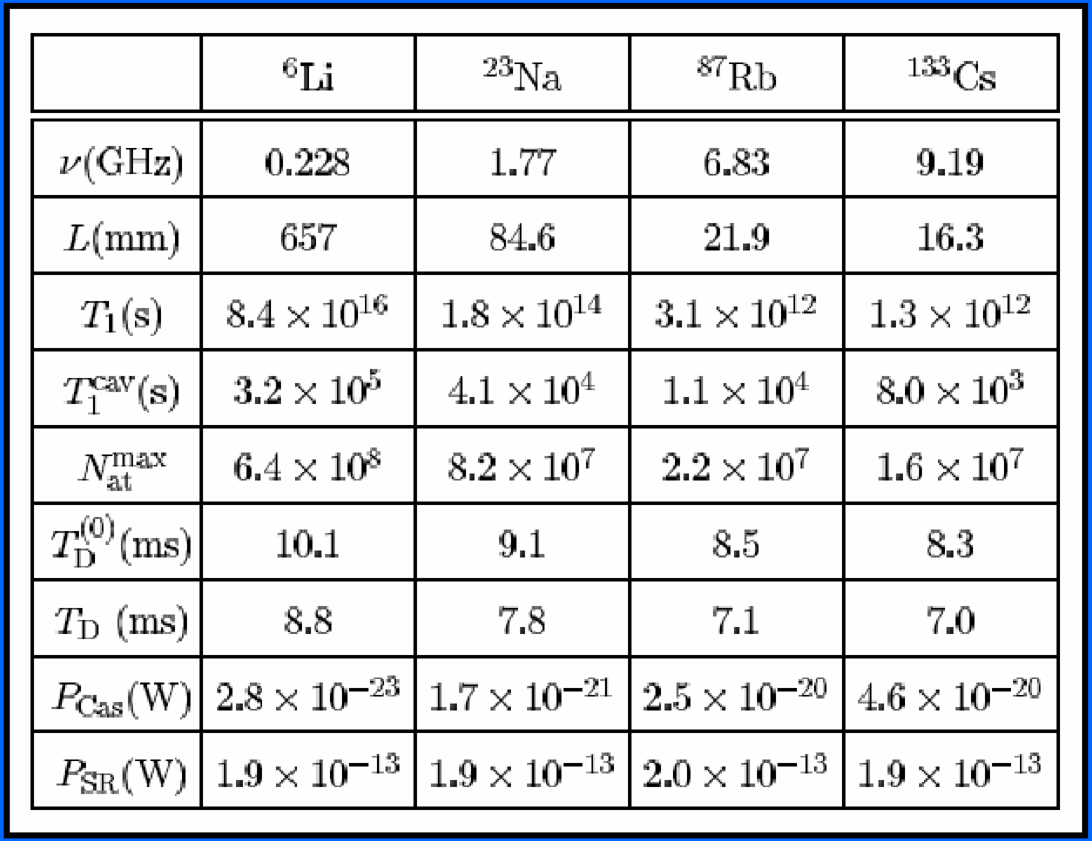


L. Moi *et al.*, Phys. Rev. A **26**, 2043 (1982)
P. Goy *et al.*, Phys. Rev. A **27**, 2065 (1982)

Alternatively, use of Rydberg states, recently used to detect the blackbody radiation in the microwave range with single photon resolution

[Tada *et al.*, Phys. Lett. A 349, 488 (2006)]

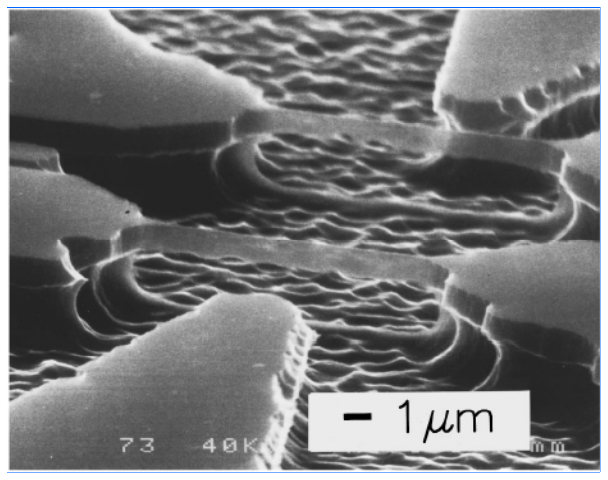
Possible candidates

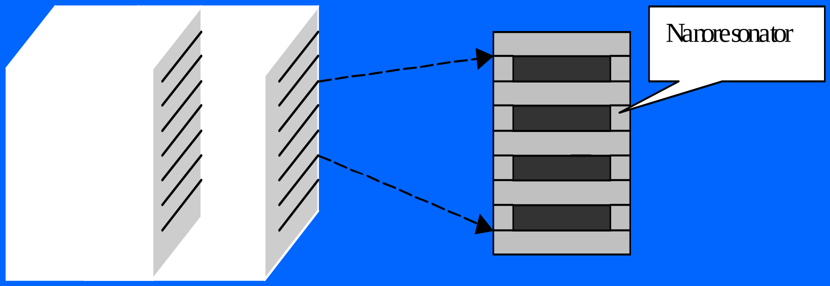


	^{6}Li	^{23}Na	^{87}Rb	^{133}Cs
ν(GHz)	0.228	1.77	6.83	9.19
L(mm)	657	84.6	21.9	16.3
T_1(s)	8.4×10^{16}	1.8×10^{14}	3.1×10^{12}	1.3×10^{12}
T_1^{cav}(s)	3.2×10^{5}	4.1×10^{4}	1.1×10^{4}	8.0×10^{3}
$N_{\mathrm{at}}^{\mathrm{max}}$	6.4×10^{8}	8.2×10^{7}	2.2×10^{7}	1.6×10^{7}
$T_{\mathrm{D}}^{(0)}$(ms)	10.1	9.1	8.5	8.3
T_{D} (ms)	8.8	7.8	7.1	7.0
P_{Cas}(W)	2.8×10^{-23}	1.7×10^{-21}	2.5×10^{-20}	4.6×10^{-20}
P_{SR}(W)	1.9×10^{-13}	1.9×10^{-13}	2.0×10^{-13}	1.9×10^{-13}

- Sodium seems to be the most promising candidate
- Maximum amount of 10^{8} atoms have been trapped
- RF hyperfine transition have been intentionally driven
- Superradiance has also been observed
- $\Omega=2\omega$ is feasible with FBARs

Nanoelectromechanical (NEMS) resonators





- Two-dimensional array of resonators.
- Frequency of 1.5 GHz has been achieved
- Relatively high *Q* and routine productions
- Possibility to synchronize their motions in a coherent fashion

A. Cleland, M. Pophristic, and I. Ferguson, APL **79**, 2070 (2002)
A. Gaidarzhy *et al.*, PRL **94**, 030402 (2005)

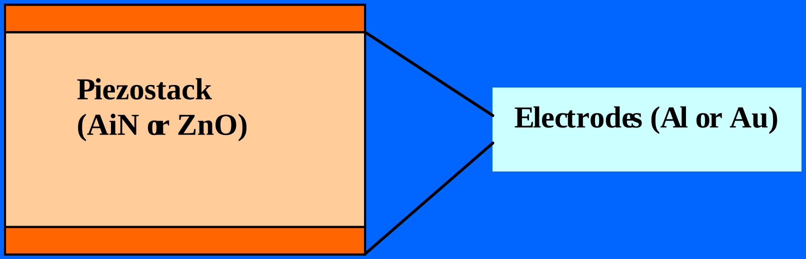
Drawbacks of NEMS resonators

- Reproducibility
- Reduced Q-factor due to near-surface effect
- Large magnetic fields (8T), which may destroys critical fields of superconducting cavity (around 100-900 gauss)
- Electronic components in cryogenic environment
- Reduced area of vibration

Reference	Frequency	*Q*-factor	Dimension ($l*w*t$) μm	Material	Operating Condition	Driving method	Year
A.Cleland *et al*	70.72 MHz	20000	7.7*0.8*0.33	Si	4.2 K	Lorentz/ EMF	1996
E.Buks *et al*	179.3 KHz	2000~ 10000	270*1*0.25	SiN	Not known	Not known	2002
H.Huang *et al*	1.014 GHz	500	1.1*0.12*0.075	SiC	4.2 K	Lorentz/ EMF	2003
R. Knobel *et al*	116 MHz	1700	3*0.25*0.2	GaAs	30mK	Lorentz/ EMF	2003
H.Hussin *et al*	105.3 MHz	8500	1.3 *0.043 (radius)	Pt	4 K	Lorentz/ EMF	2004
V.Sazonova *et al*	55 MHz	80	1.2 *0,004 (radius)	CNT	300 K	Capacitive	2004
A.Gaidarzhy *et al*	1.5 GHz	150	10.7* 0.4 *0.245	Si	1K	Lorentz/EMF	2005
H. Peng *et al*	1.3 GHz	440	0.3*0.0035(radius)	CNT	300K	Capacitive	2006

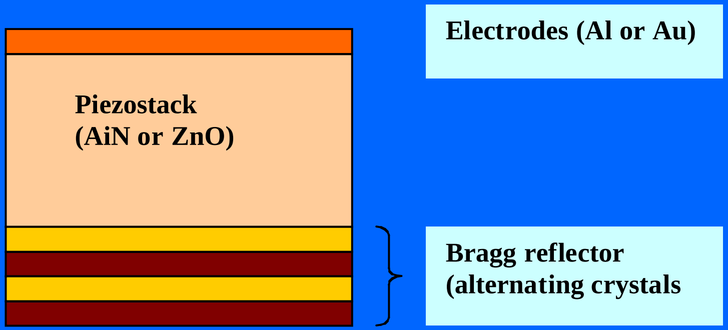
FBAR Technology

- FBAR- Film Bulk Acoustic Resonator
- Al N- Aluminum Nitride expands and contract with an alternating potential
- Mechanical quality factor up to 3500 in liquid nitrogen
- Frequencies up to 8.0 GHz has been achieved
- Dissipated power of a few Watts



Piezostack
(AiN or ZnO)

Electrodes (Al or Au)



Electrodes (Al or Au)

Piezostack
(AiN or ZnO)

Bragg reflector
(alternating crystals

Mass sensor for DNA and proteins in biophysics

- Greater sensitivity achieved through higher resonance frequencies
- Exceeds 50 times that of a typical quartz crystal microbalance (QCM)

PCS duplexer in wireless communication

- Needs of small bandwidth/ high Q-factor due to guard band requirement (20 MHz)
- Power handling capabilities (order of 1 W)

Year	Frequency	Q-Factor	Material	Application	Reference
1980	0.5 GHz	2600	ZnO	Filter	T.Grudkowski
1999	1.9 GHz	300	AlN	Duplexer	R. Ruby
2004	1.8 GHz	3500 (4.2K)	AlN	Qubits	A. Cleland
2004	2.0 GHz	330-440	ZnO	Sensor	R. Gabl
2006	5.3 GHz	30	AlN	Filter	Y.D Kim
2006	1.0 GHz	1200-48000	ZnO	HBAR	H. Zhang
2006	8.0 GHz	200-350	AIN	Sensor	Rey-Mermet

Progress in this technology is measured in one semester timescale

Summary of technical challenges

- Reproducibility and internal defects, such as pinhole breakdown of FBAR---> limited area of active vibration
- Small size of FBAR 500 μm^2 (possible to scale up to cm^2?)
- Cavity wall as mechanical antenna through dipole radiation, although this does not directly affect the resonant mode
- Maintaining the optimal cavity quality factor in the presence of various electronic and mechanical components, such as detector, FBAR, atomic pathways and ports
- All of these should be placed in a cryogenic environment (around 10 mK where $N_{thermal} << N_{Casimir}$)

[W.-J. Kim, J. H. Brownell, and R. O., PRL **96**, 200402 (2006)]

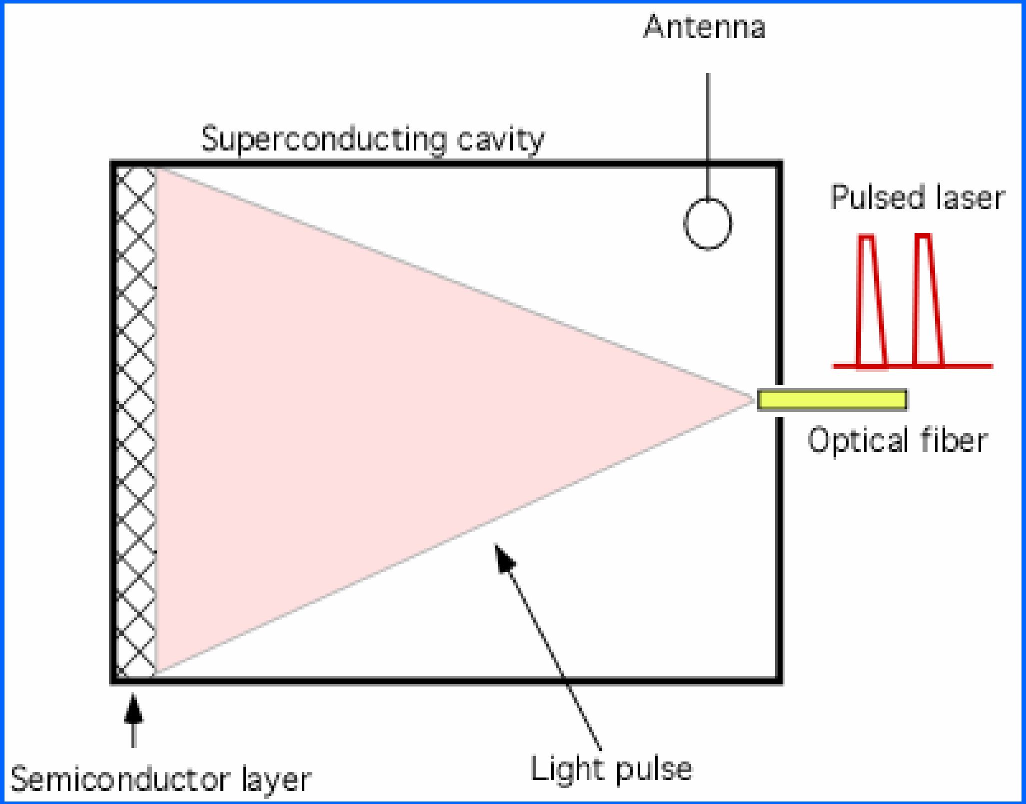
An alternative experimental scheme

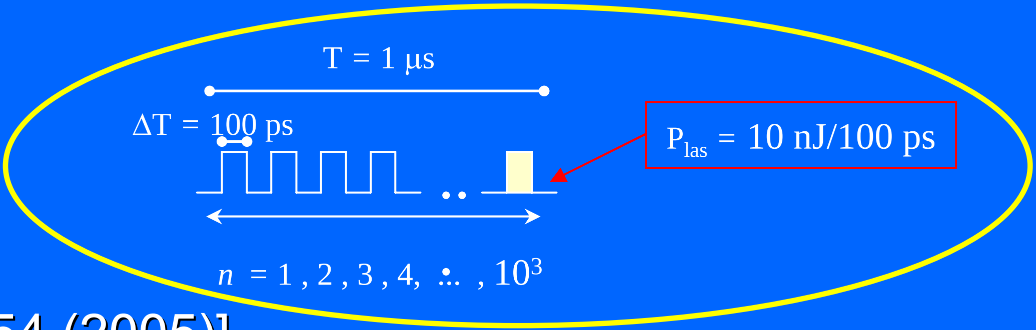
A semiconductor layer (thickness ~ 1 mm) is placed on one end of a niobium super-conducting cavity. Cavity resonance ν_r.

Using an amplitude modulated (at frequency f) laser light the semiconductor switches from transparency to reflection, thus producing an effective motion. $f = 2\,\nu_r$

Photons detected by the antenna

With this set-up the amplitude of the motion is very large (mm), thus providing a large effective velocity





[Braggio *et al.*,

RSI 75, 4967 (2004)], EPL 70, 754 (2005)]

Potential bottlenecks

a) Blackbody photons: the experiment will run at 4.2 K, at 3 GHz about 20 photons in a thermal state each ½ photon of the quantum ground state/mode. If operated at 10 mK thermal photons are negligible, but with reduced mobility carriers in the semiconductor cannot follow high-frequency switches

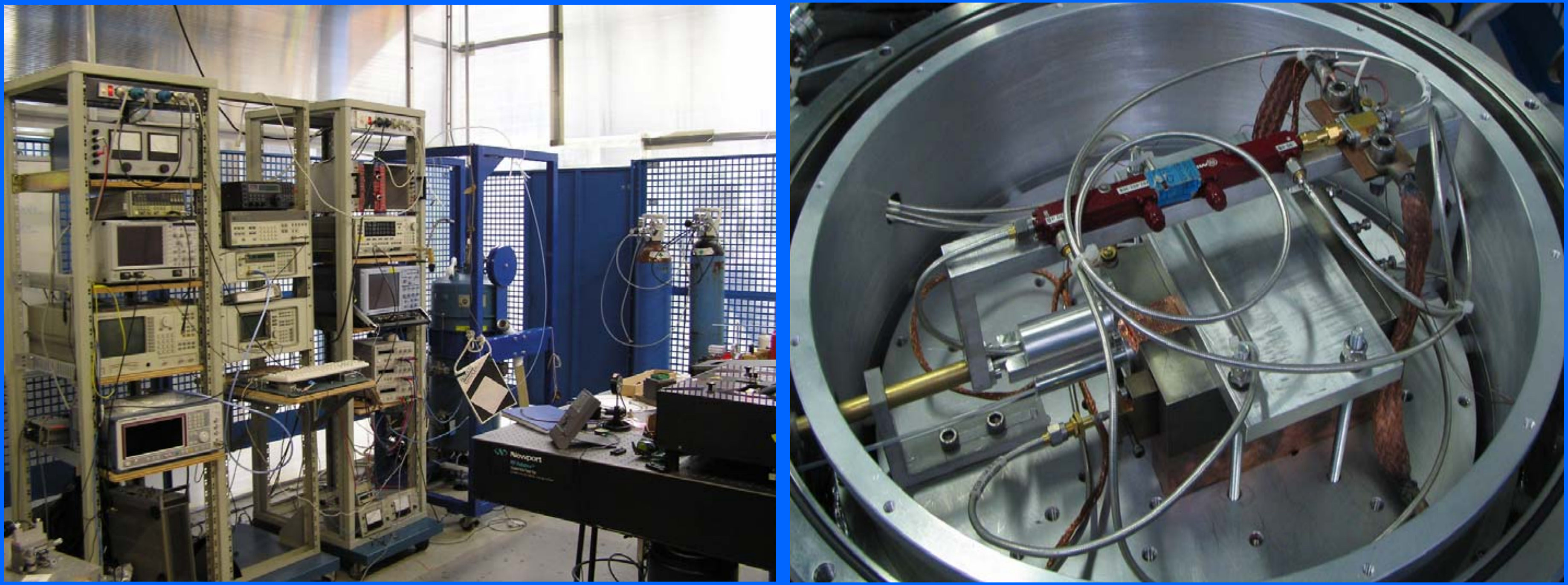
b) Parametric down-conversion of photons from optical to THz and below may originate a background not well controllable (not seen so far)

c) Possible solutions based on shifting the resonance frequency will affect both the ½ vacuum photon and the BB photons in the same way: photons are indistinguishable, likewise hard to integrate signals starting from a small SNR

d) Even if successful, this will test the *photon* production in vacuum via *plasmon* excitations, rather then via genuine *phonon* excitations

Nevertheless, it is important to pursue this approach

Actual experiment ongoing, and unique experiment worldwide



[Agnesi *et al*., JPA 41, 164024 (2008)]

Physics runs expected to take place next year

Further thoughts

Mechanical parametric excitation seems to be an inefficient way to excite (and interrogate) quantum vacuum

Similar informations can also be obtained by studying quantum vacuum effects in strong fields, boundary conditions may be seen as strong fields

A plethora of possible phenomena, for instance:

a) Photon-photon scattering;

b) Photon splitting and harmonic generation;

c) Electric and magnetic birefringence;

d) Creation of electron-positron pairs (Schwinger effect).

High power laser intensities and strong magnetic fields makes now these studies within reach.

In astrophysics, strong magnetic fields already exists (magnetars).

Work undergoing at CfA Harvard/Smithsonian (sponsored by JSF)

Casimir effects: some final remarks (facts + personal opinions)

1) The force is not tiny, it is substantial on the microscopic scale

2) Casimir is not strictly relevant in nanotechnology

(since retardation effects in 10 nm range are negligible)

3) At the level of demonstrations, the current situation may be considered satisfactory, but of somewhat limited relevance unless useful tools will be designed to enable some new technology

4) At the level of experiments, the current situation is quite unsatisfactory

5) We need more experiments in the parallel plane configuration

(only Legnaro group is further pursuing this route, see NJP 2006)

6) Careful check of the use of PFA versus exact approaches for other than surface related forces

7) Explicit declaration of various issues with the sphere-plane geometry (and curved geometries in general) are emerging during 2008

8) Reanalysis of Yukawian limits after recent findings. Final outcome of the Casimir measurement in terms of the measure of the product
$\hbar c = (3.16152636 \pm 0.00000054) \times 10^{-26} Jm$ regardless of the geometry

9) Establish a link between equilibrium thermal corrections in Casimir force and nonequilibrium thermal corrections in Casimir-Polder forces

10) Nobody land between the dynamical Casimir effect and strong

field physics to be filled (both deal with creation of particles in vacuum)

11) Metamaterials can be used to create layers of Casimir plane cavities, which could result in anisotropic inertial masses. Together with a torsional balance, this could also test the “free fall” of quantum vacuum + applications

12) Important to corroborate the claimed sensitivity with the experimental evidence that the apparatus is actually sensitive to tiny effects

-Minimum detectable magnetic field, Wang *et al.*, PRA 73, 042103 (2006)

-Minimum detectable difference in thin films thickness,

Lisanti *et al*., PNAS 102, 11981 (2005)

13) Need for independent calibrations for instance using radiation pressure or viscous forces (see Petrov and Capasso groups)

14) Important to share data as in other scientific communities

15) Important to follow short communications with long, unlimited accounts of the experiments and data analysis

16) Important to have plenary workshops with all the experimental groups equally represented

17) A more sober approach in the claims will help interested people to put in a more realistic/less confusing perspective experimental work

18) Close cooperation among demonstrationalist, experimentalists, and theorists with *skeptical and critical* skills is fundamental

-Quantum vacuum studies still contain potential for growth and bridging with many other subfields

-Sustainable, small scale both for calculations and measurements, ideal for undergraduate and graduate research projects, highly interdisciplinary

- Let us make an effort to put aside unnecessary controversies also for the future of younger researchers in the subfield

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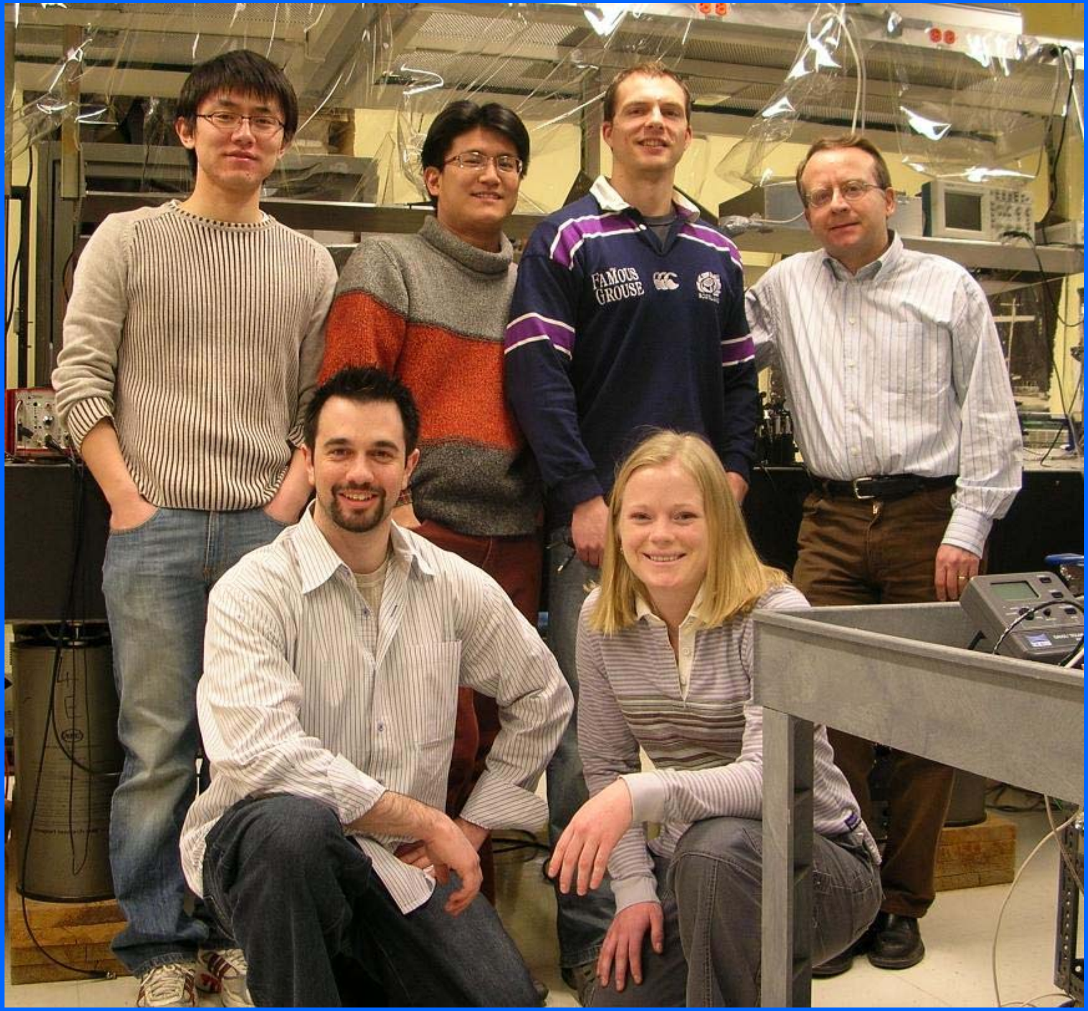

http://www.dartmouth.edu/~ongroup/

For a recent review: Special Issue on Casimir Forces,

New J. Phys. (October 2006) **www.njp.org** **(free access)**