Investigating the Sea of Quantum Fluctuations:

Moving mirrors in the Vacuum

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IDPASC School Siena October 2013

What are we talking about?

Quantum Vacuum of Electromagnetic Field

Well tested at the **microscopic level** : road to development of QFT

- Lamb shift
- Anomalous magnetic moment

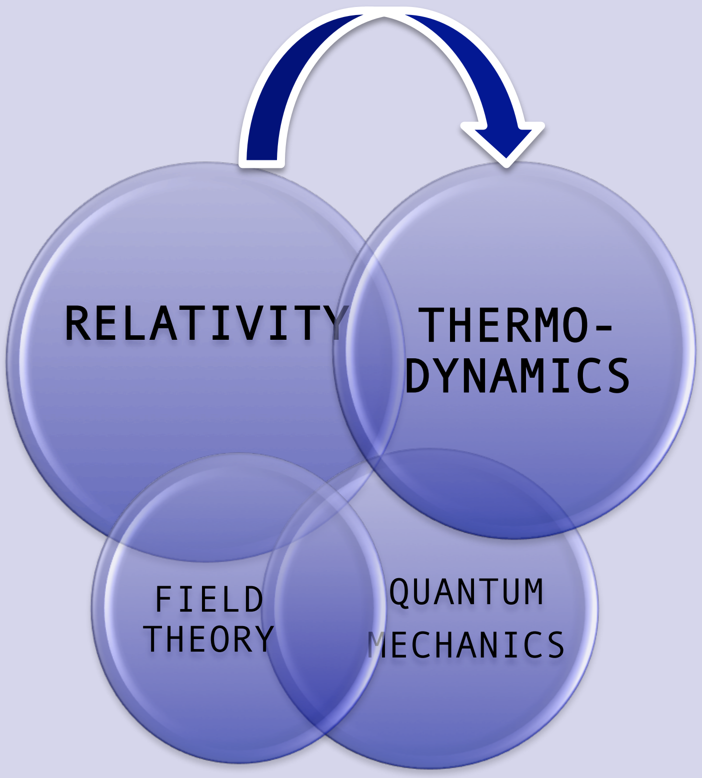
Manifestations at the **macroscopic level**: Static Scenario

- Vacuum birefringence
- Casimir effect: Modifications of the Vacuum State due to the presence of static boundaries

Dynamical scenario: Moving mirrors

- Schwinger Radiation (Dynamical Casimir Effect)
- Unruh – Hawking Radiation

Physics of the Vacuum as presently understood by
Relativistic Quantum Field theory



The distinction between *quantum fluctuations* and *thermal fluctuations* is not invariant but *depends on the observer motion*

A harmonic oscillator *in acceleration* gains energy from the fluctuations of the ZP of the EM field in the vacuum.

For a *uniformly accelerating* oscillator, the distribution of energy is *thermal*

velocity is constant → Lorentz invariance Casimir Effect
a = const → **Unruh effect** (detectors)
non-uniform a → **Dynamical Casimir effect** (mirrors)

Acceleration temperature

Part of Feynman's blackboard at California Institute of Technology at the time of his death in 1988.

At the right-hand side one can find "**accel. temp.**" as one of the issues to learn.

CASIMIR EFFECT

Casimir prediction dates back to 1948: two parallel conducting uncharged surfaces attract each other at close separation!

Casimir H B G 1948 *Proc. Kon. Ned. Akad. Wetenschap. Ser.* B **51** 793

$$\frac{F_c}{A} = \frac{\hbar c \pi^2}{240 d^4}$$

Theoretical work on Casimir effect far outweights experimental work

Force is extremely weak and experiments are very difficult

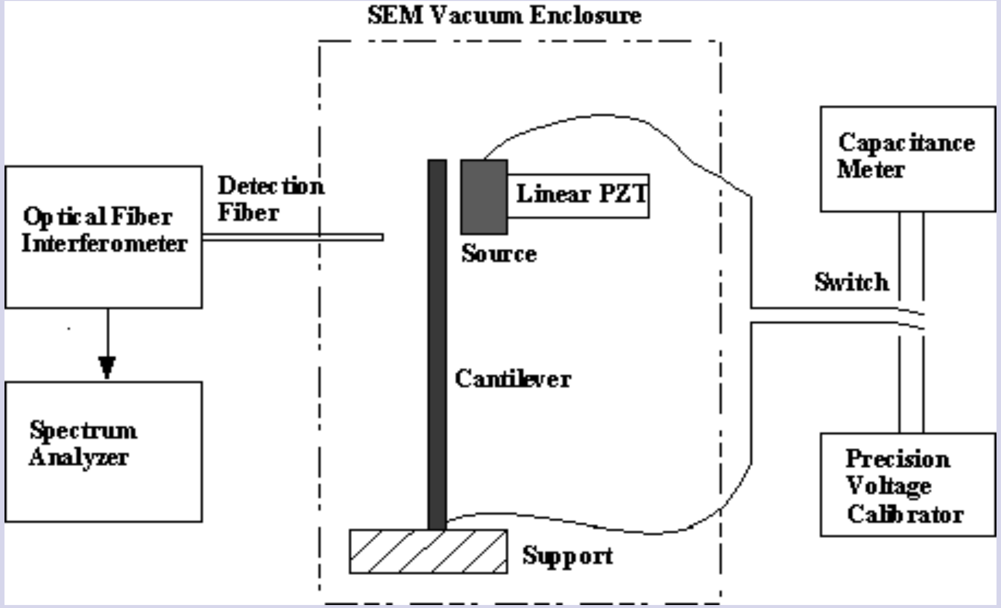
$F_c = 10^{-7}$ N

for 1 cm^2 @ 1 μm distance

Problems:

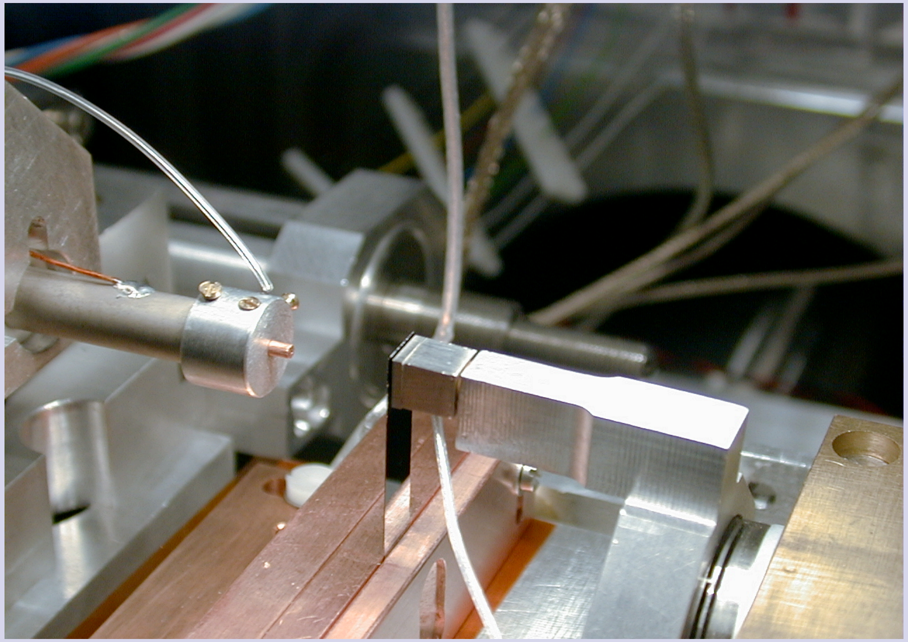
- parallelism between plates
- small separation
- background forces
- planarity
- rugosity, finite conductivity

Experimental Apparatus



- **Plane parallel** geometry
- **Silicon plates** with a 50 nm **chromium** deposit

- Apparatus inside **S**canning **E**lectron **M**icroscope (**SEM**) (pressure ~ 10^{-5} mbar)
- Mechanical decoupling between resonator and source
- SEM sitting on antivibration table
- System of actuators for parallelization
- Fiber-optic interferometer transducer
- SEM for final cleaning and parallelism monitoring
- Mechanical feedthroughs allow correct positioning of the apparatus in the electron beam
- Source approach to the cantilever using a linear PZT



Main Experimental Difficulties

Dust problem -- apparently only for distances below 2-3 microns

Presence of a **residual bias voltage** in the gap, to be determined precisely and cancelled

Control of **parallelism between surfaces**

Precise determination of **gap separation**

Stability of the resonance frequency

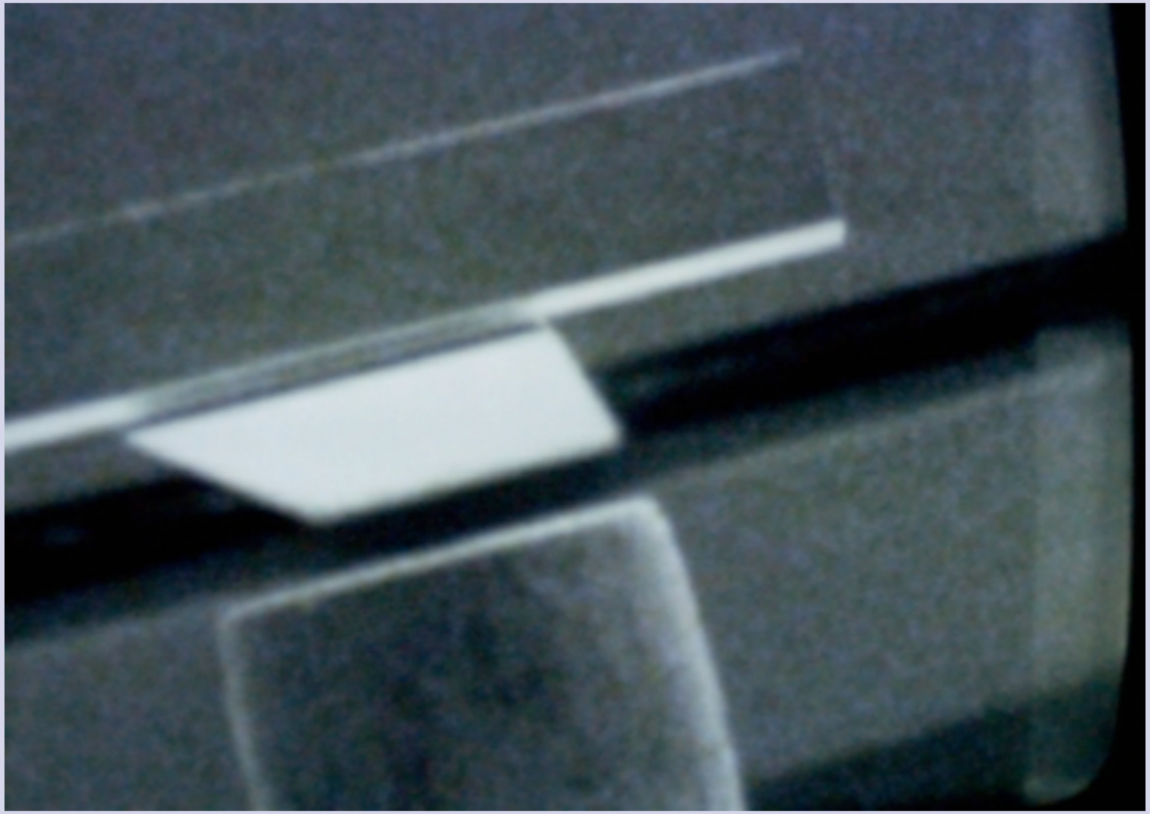
Limited sensitivity for the Casimir force at large separations due to the small area of the surfaces (1.2 x 1.2 mm^2)

The Cavity under SEM

Useful area **S = 1.2 x 1.2 mm^2**

Resonant cantilever:
1.9 cm x 1.2 mm x 47 μm
m = 11 mg
resonant frequency = 138.275 Hz
Source (Crossed with cantilever):
1.9 cm x 1.2 mm x 0.5 mm

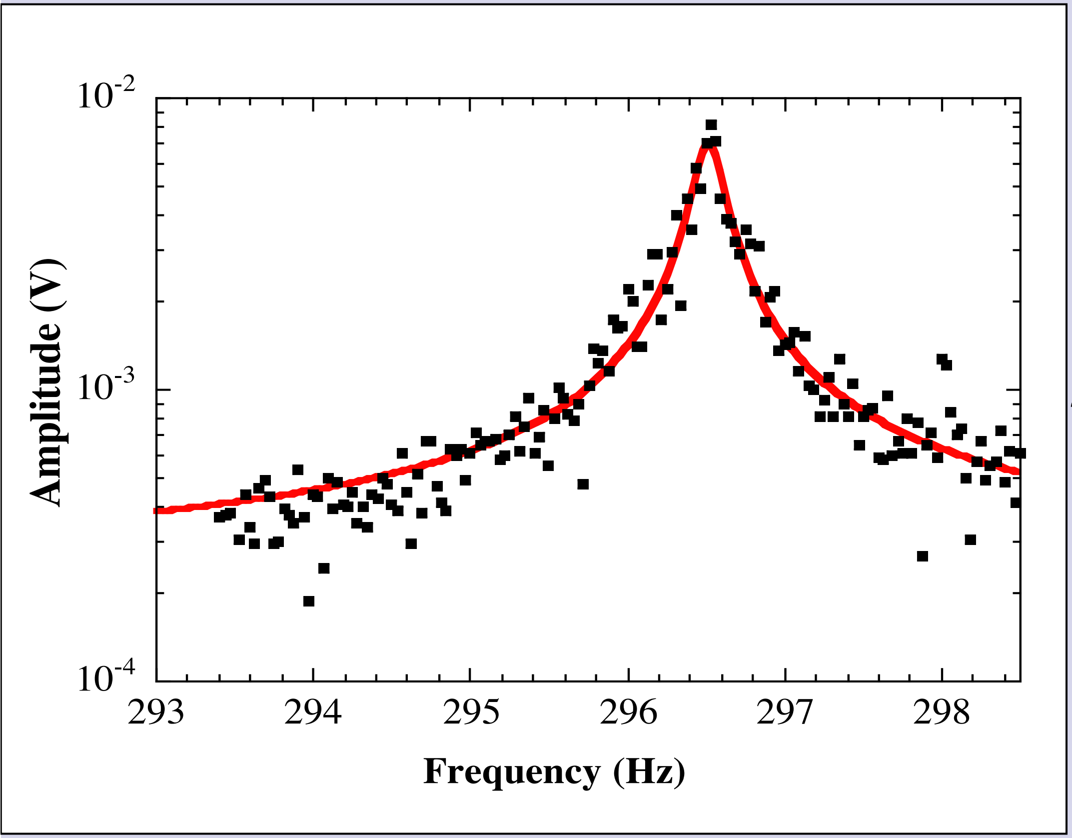
Surfaces roughness ~ 10 nm



Picture at SEM: field of view **3 mm x 2.3 mm**

Measurement : Frequency Shift Method

Measurement of the frequency of the first torsional mode of the cantilever by means of an FFT of the interferometer signal



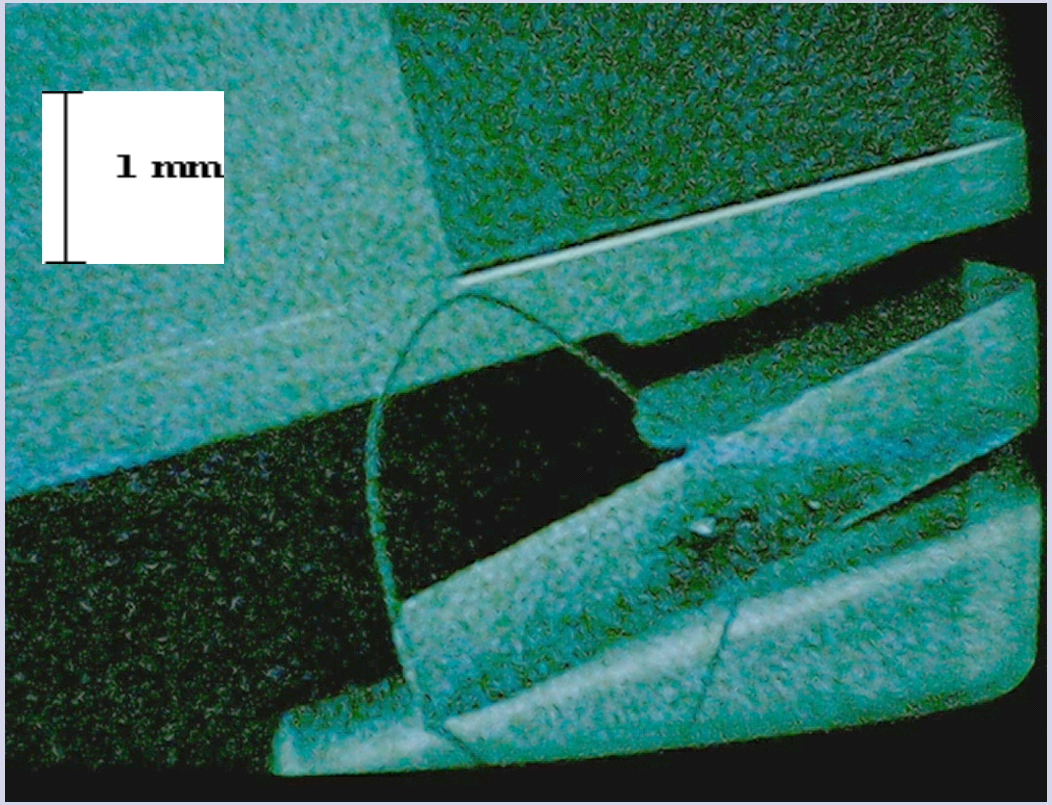
A power-law static force $F(d_0) = C / d_0^n$ exerted between source and cantilever, spaced by d_0, gives

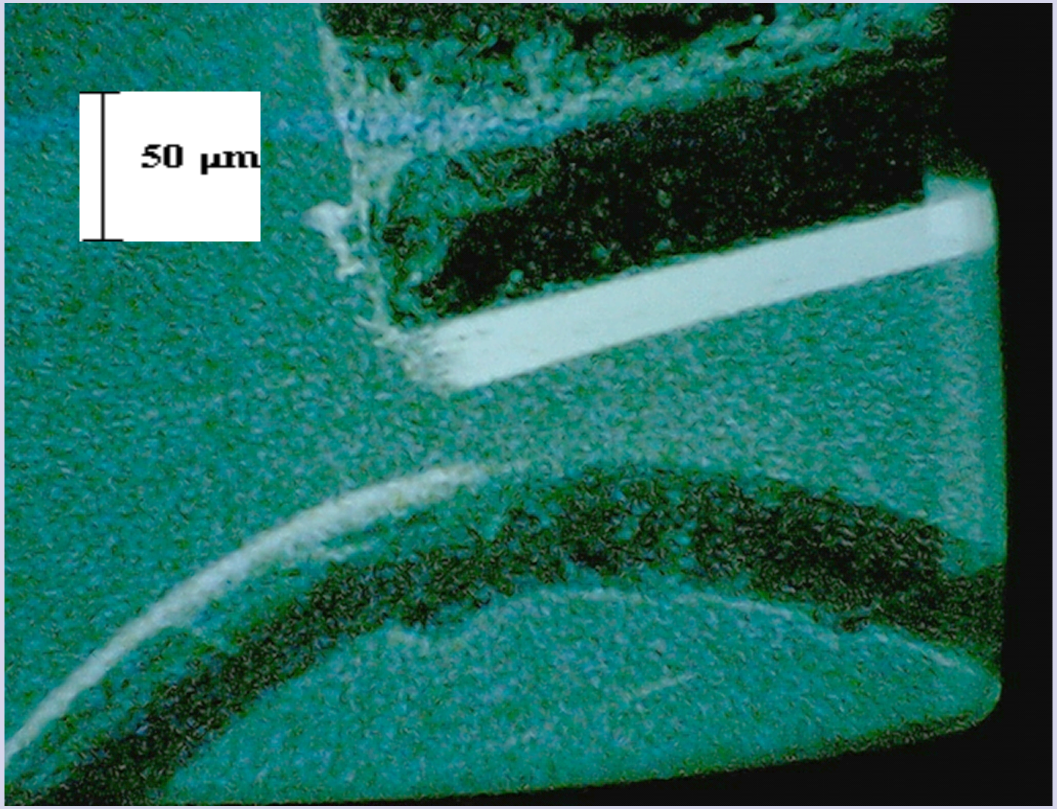
$$\nu^2 = \nu_r^2 - \frac{1}{4\pi^2 m}\frac{\partial F(x_r, x_p, d_0)}{\partial x_r} = \nu_r^2 + \frac{nC}{4\pi^2 m d_0^{n+1}}$$

- n=2 Coulomb force
- n=4 Casimir force

Cleaning Tool

Dust problem was a key issue in this experiment. Normally this was showing up for separations below 2-3 microns. Surfaces were reduced to lower the probability of large dust particles on them.





Results

VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

Measurement of the Casimir Force between Parallel Metallic Surfaces

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(Received 10 October 2001; published 15 January 2002)

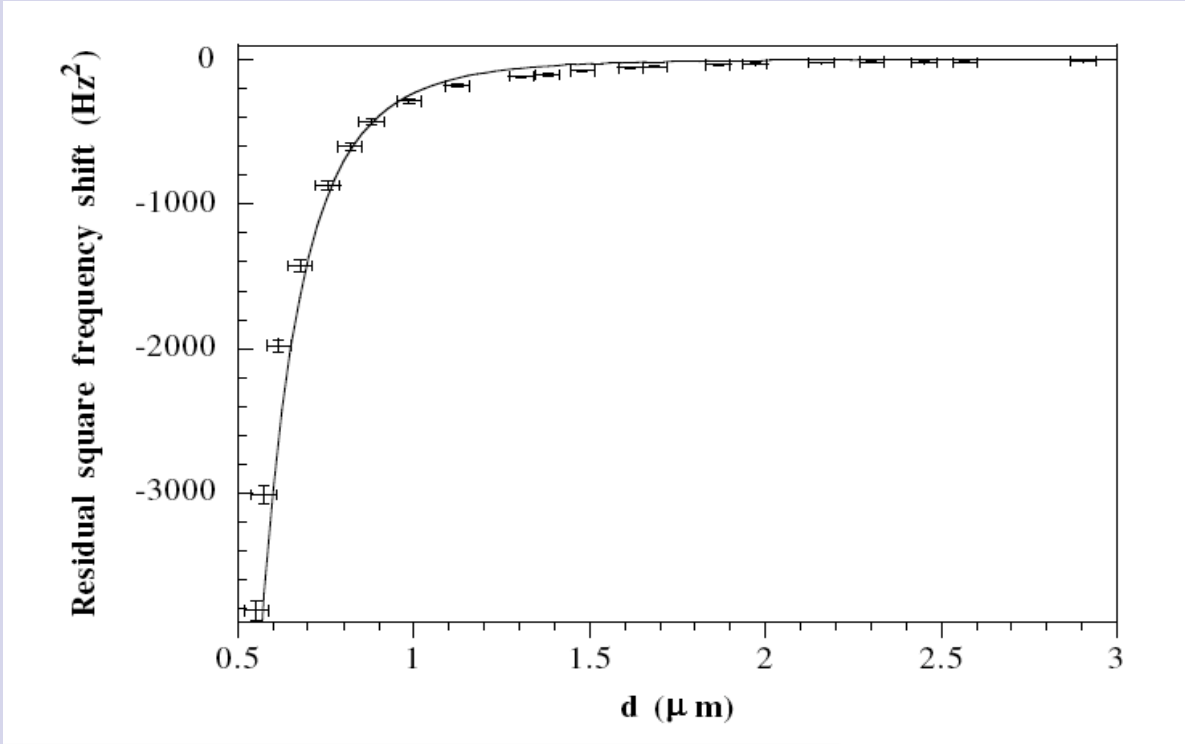
We report on the measurement of the Casimir force between conducting surfaces in a parallel configuration. The force is exerted between a silicon cantilever coated with chromium and a similar rigid surface and is detected by looking at the shifts induced in the cantilever frequency when the latter is approached. The scaling of the force with the distance between the surfaces was tested in the 0.5–3.0 μm range, and the related force coefficient was determined at the 15% precision level.

First measurement of the Casimir effect between parallel metallic surfaces

$$F = \frac{K_C}{d^4} S$$

$$\mathrm{K_C} = (1.22 \pm 0.18) \cdot 10^{-27}\ \ \mathrm{N\ m^2}$$

$$\mathrm{K}_C^{th} = \frac{\pi^2 \hbar c}{240} = 1.3 \cdot 10^{-27}\ \ \mathrm{N\ m^2}$$



Gravitational Like Forces

Search for new physics / test of theories

- probe gravity below 200 μm
- extra-dimensions
- forces mediated by new light particles

Possible form of the interaction potential:

$$V(r) = \frac{GM}{r}[1 + \alpha e^{-r/\lambda}]$$

The Casimir force is a background force in this type of measurement

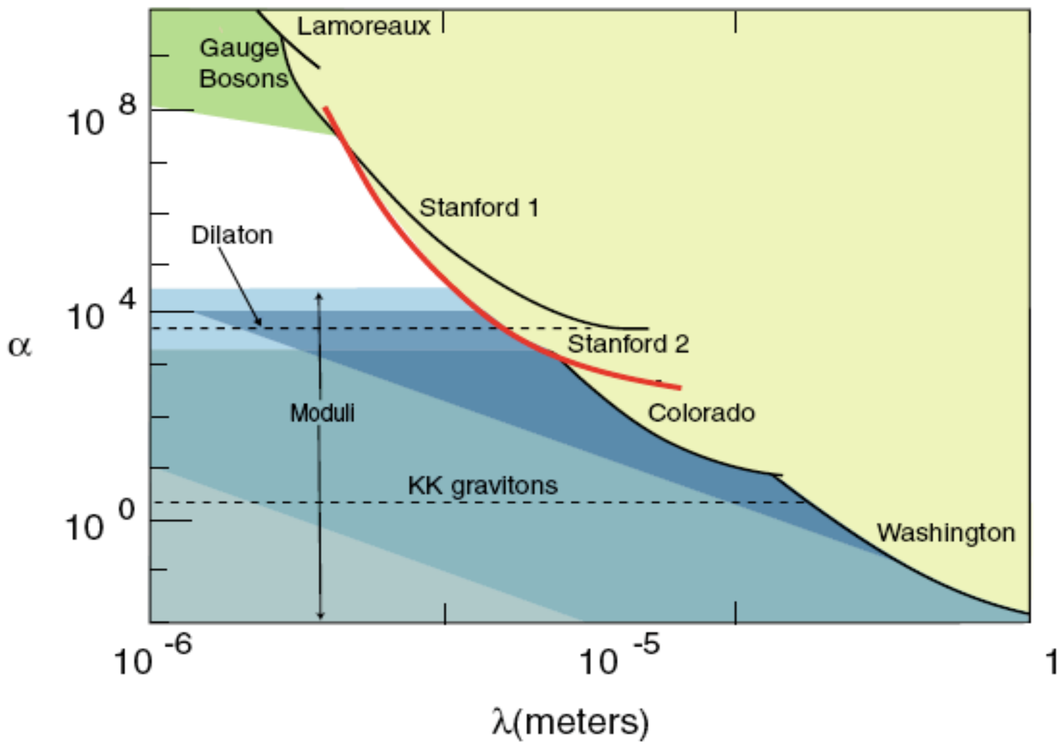


FIG. 1 (color online). Experimental results (solid lines) and theoretical predictions shown in α–λ space. The area to the upper right of the experimental lines (from Refs. [9,14–16,31] and our latest results from this paper) shows where Yukawa-type deviations from Newtonian gravity have been excluded. The line

S. J. SMULLIN *et al.*

PHYSICAL REVIEW D **72,** 122001 (2005)

Main mechanisms by which Vacuum Fluctuations are *amplified* into photons:

Fluctuation Dissipation Theorem vs Thermodynamics

- Schwinger Radiation or Dynamical Casimir effect: rapidly modulating the boundary conditions of the EM field, with peak velocities close to the speed of light
- Hawking radiation   not only a black hole!
- Unruh effect an observer accelerated to $10^{20}g$

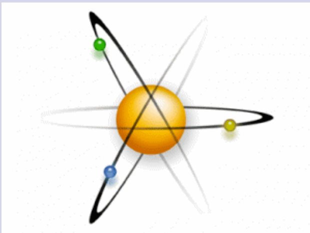
They become appreciable under *extreme condition!!!!*

How to detect them in the laboratory?

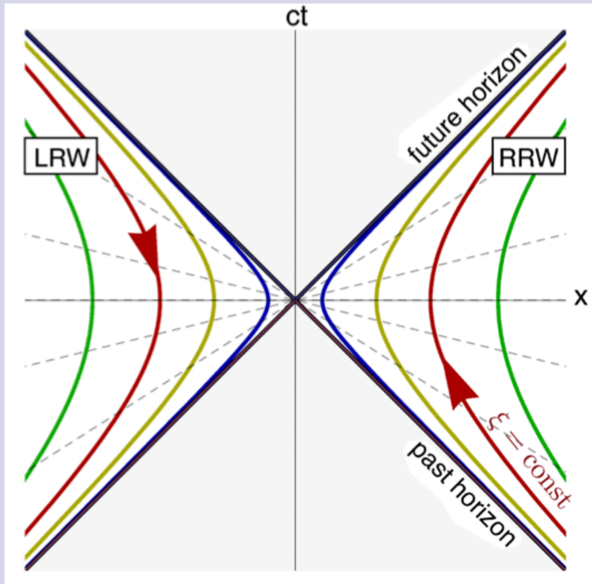
An apparently innocent, “einsteinian” question:

how are perceived the Quantum Fluctuation by an observer in acceleration?

oscillator (particle detector)



→ its QF noise power is the same
… BUT
this is no more true for the noise power of the field, to be calculated for the oscillator universe line (~~geodetic~~).

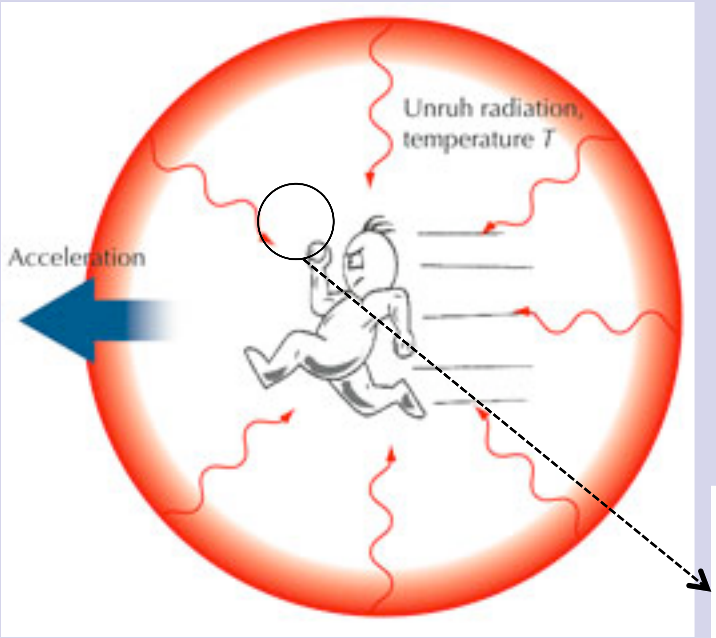


In Minkowsky coordinates (ct,x) the paths of observers with constant acceleration are hyperbolas in spacetime

In order to describe the Minkovski vacuum as seen by the accelerating observer, the mode functions and their associated vacuum states are found for a scalar and quantum field in both the Minkovski and Rindler spacetimes.

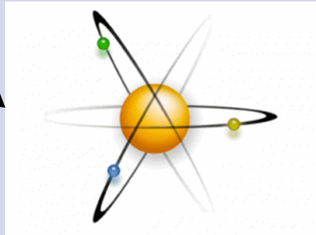
Bogoliubov transformations linking the M and R creation and annihilation operators are found, and the quantum state seen by a RRW observer is described.

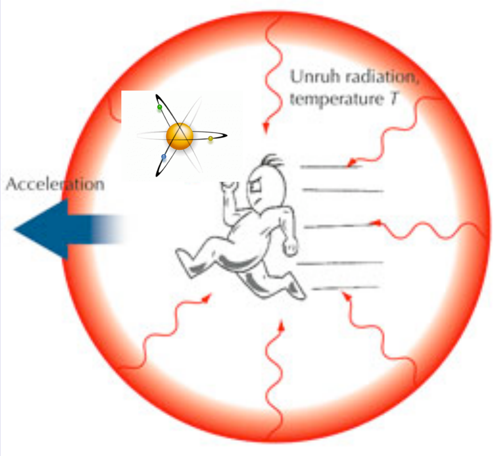
Unruh (Phys. Rev. D14, 870 (1976))



$$T_U = \frac{\hbar}{2\pi c k_B} a$$

An observer would measure a nonzero temperature T_U with respect to **a zero temperature vacuum** in the laboratory frame.





"accel. radiation" is exceedingly small!

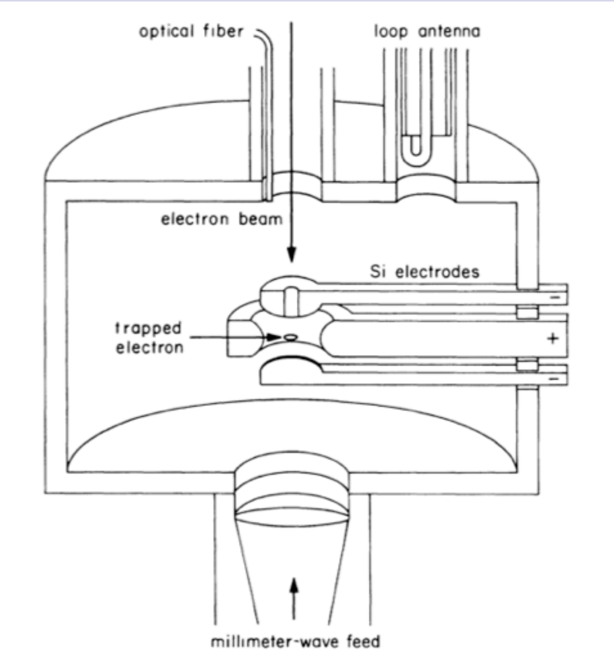
$$T_U = \frac{\hbar}{2\pi c k_B} a \approx 4 \cdot 10^{23} a$$

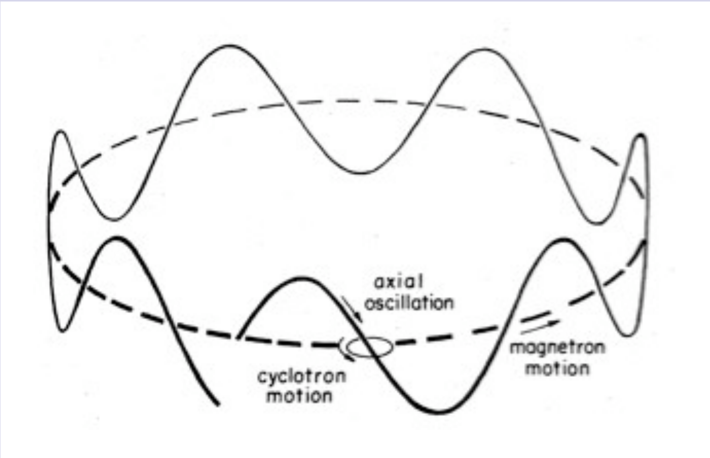
$$\Rightarrow\ a \geq 10^{20} g,\ g \text{ mean gravity acceleration on Earth}$$

is required in order to have a heat bath quantum vacuum at the level of only one Kelvin!

An experimental proposal to study the acceleration temperature

Rogers, Phys Rev. Lett. 61, 2118 (1988)

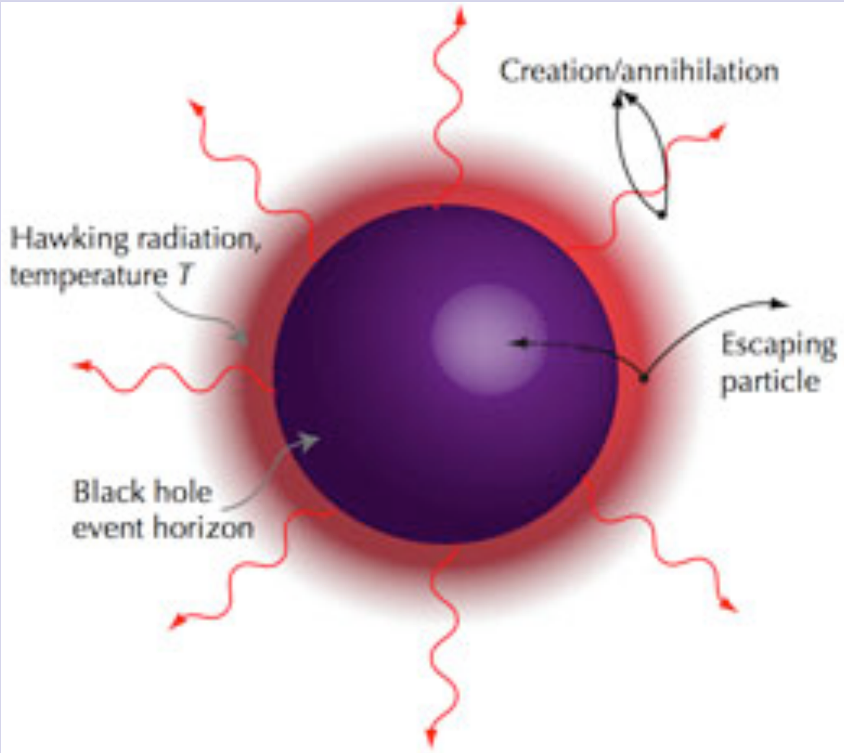




the electron accelerates centripetally in the trap's magnetic field, the vacuum radiation excites its motion along the trap axis (ω_a)

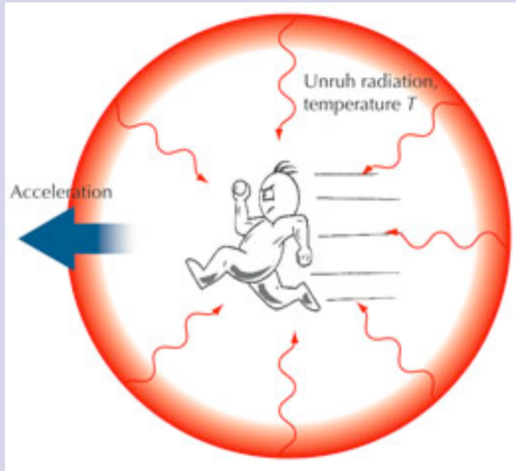
- detector:= relativistic ***e***$^-$ confined into a Penning trap ("Geonium atom")
- ***e***$^-$ path is a combination of three components: ω_m, ω_c and ω_a
- B = 150 kG → $a \approx 10^{22}$ cm/s^2 corresponding to T_U=2.4 K
- cavity surrounding the Penning trap

Hawking (Nature 248, 30-31 (1974))



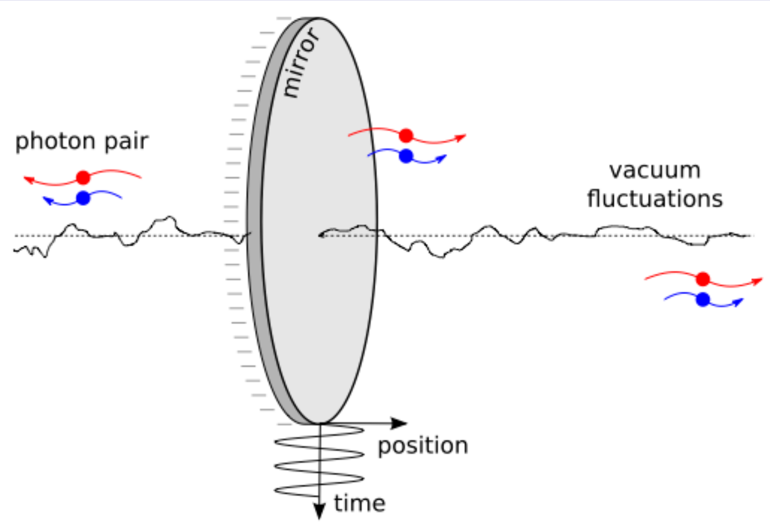
$$T_H = \frac{\hbar}{2\pi c k_B} g$$

Equivalence principle



$$T_U = \frac{\hbar}{2\pi c k_B} a$$

Single-mirror DCE

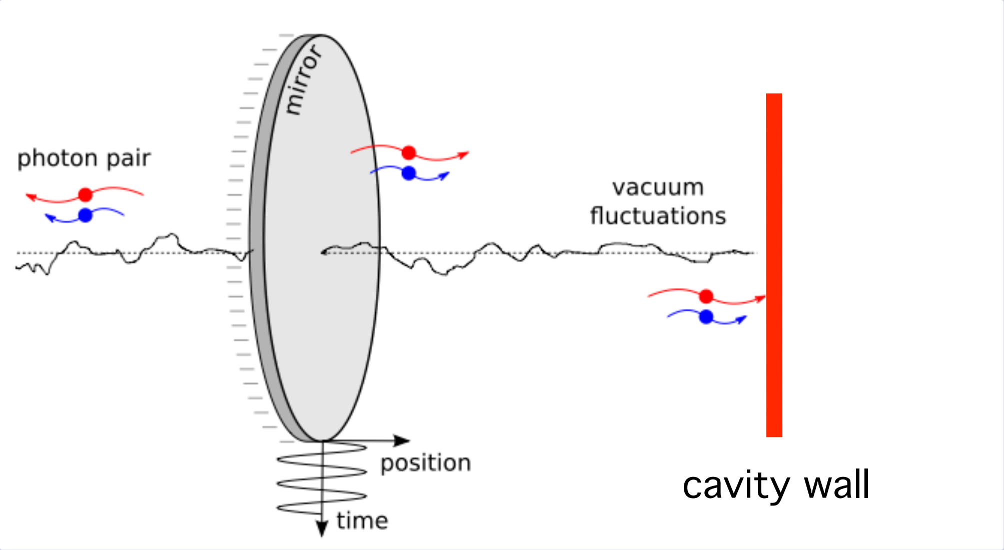


Broadband photons generation

CM Wilson *et al. Nature* **479**, 376-379 (2011)

IN THE MATTER

Cavity DCE



Basic mechanism is
parametric amplification

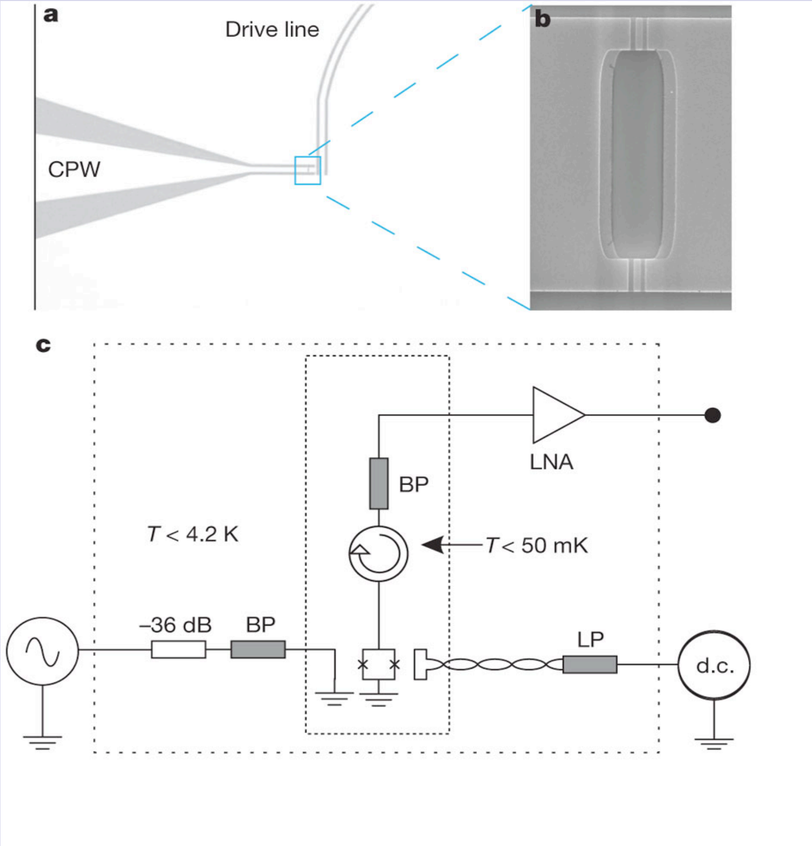
$$\nu_{excitation} = 2\nu_0$$

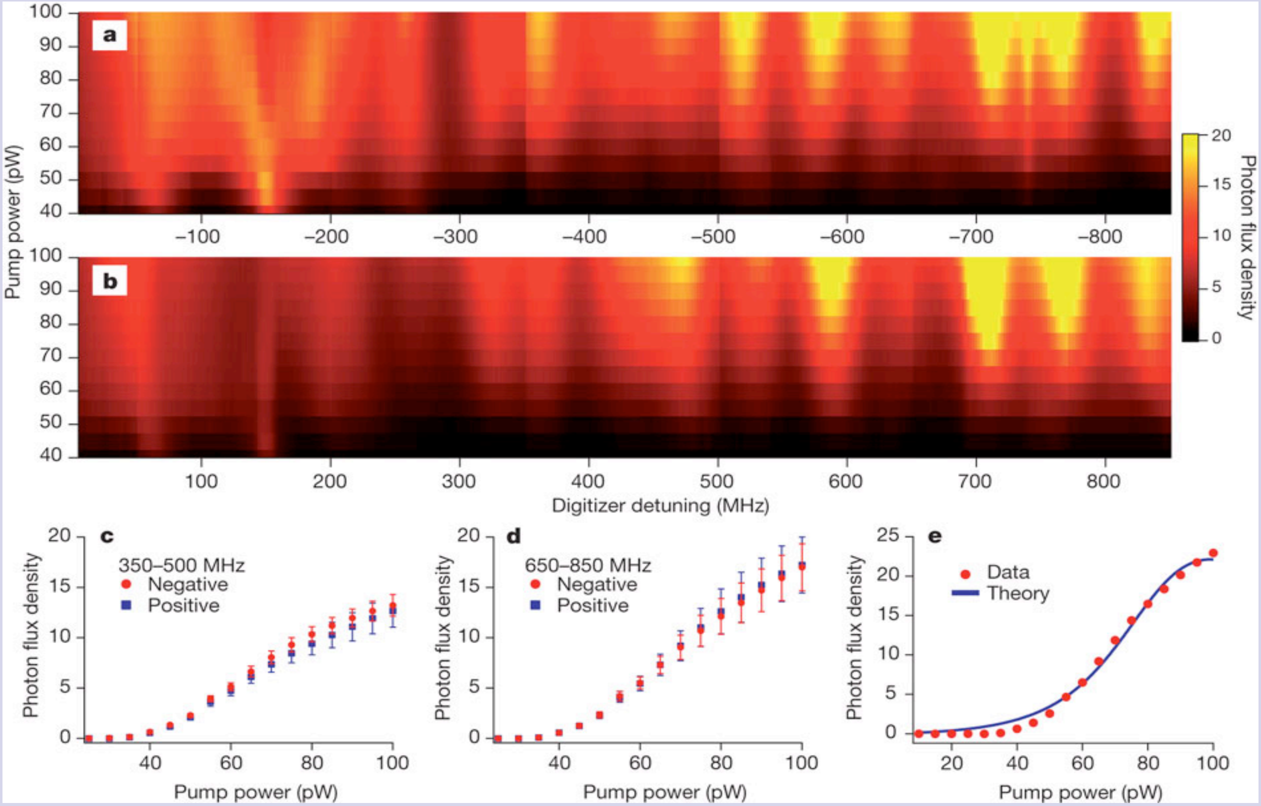
C. Braggio *et al. EPL* 70 , pp. 754–760 (2005)

IN THE VACUUM

Single-mirror DCE

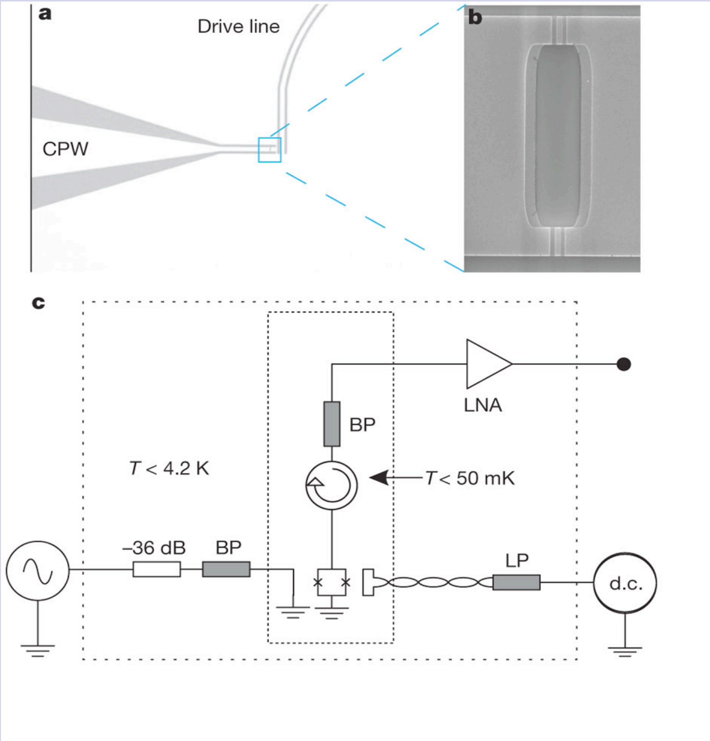
CM Wilson *et al*. *Nature* **479**, 376-379 (2011)

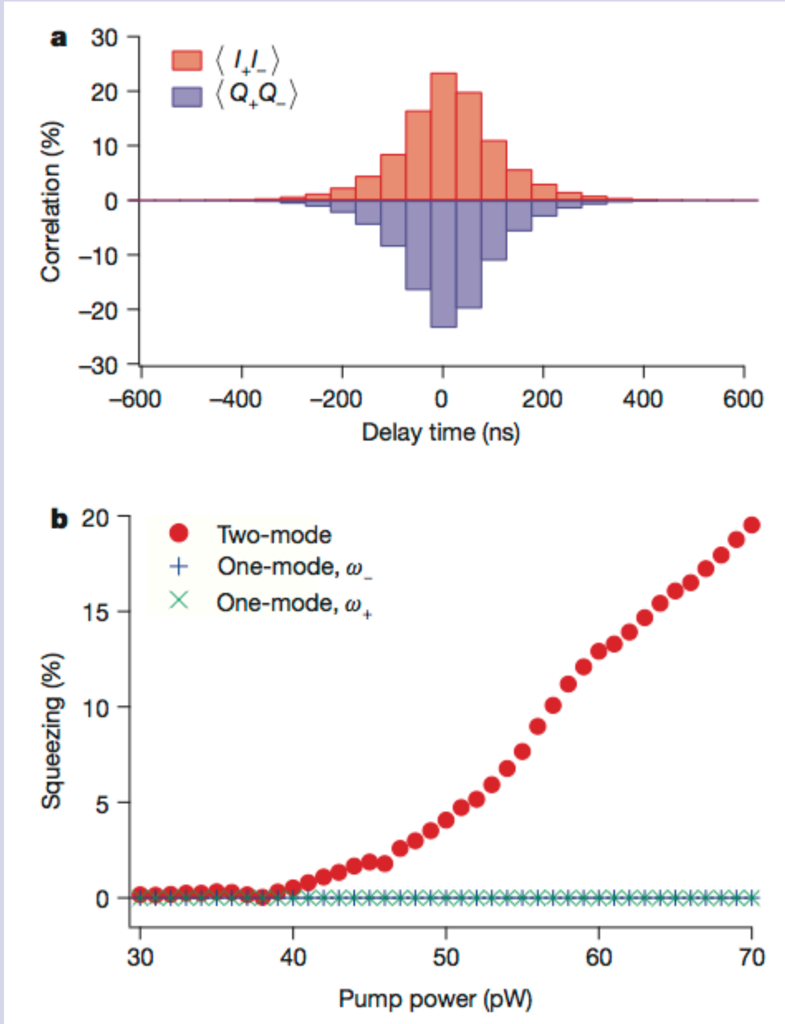




Single-mirror DCE

CM Wilson *et al.* *Nature* **479**, 376-379 (2011)



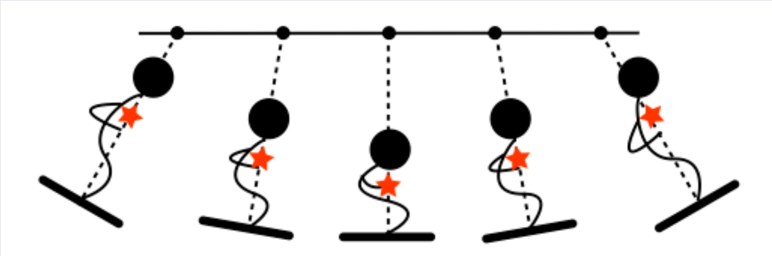


CORRELATION
at sideband frequencies

Photons are produced in pairs such that their frequencies sum to the drive frequency

$$\omega_d = \omega_+ + \omega_-$$

A representative example: a child standing on a swing



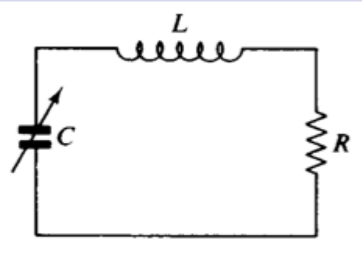
The amplification is driven by changing the center of mass, and thus effective length, of the pendulum at twice the frequency of the unperturbed swing.

$$\theta(t) = \theta(0)\cos(\omega_s t) + \frac{L(0)}{m\omega_s l}\sin(\omega_s t), \quad \omega_s(t) = \omega_s(0) + \epsilon \sin(\omega_{\rm cm} t),$$

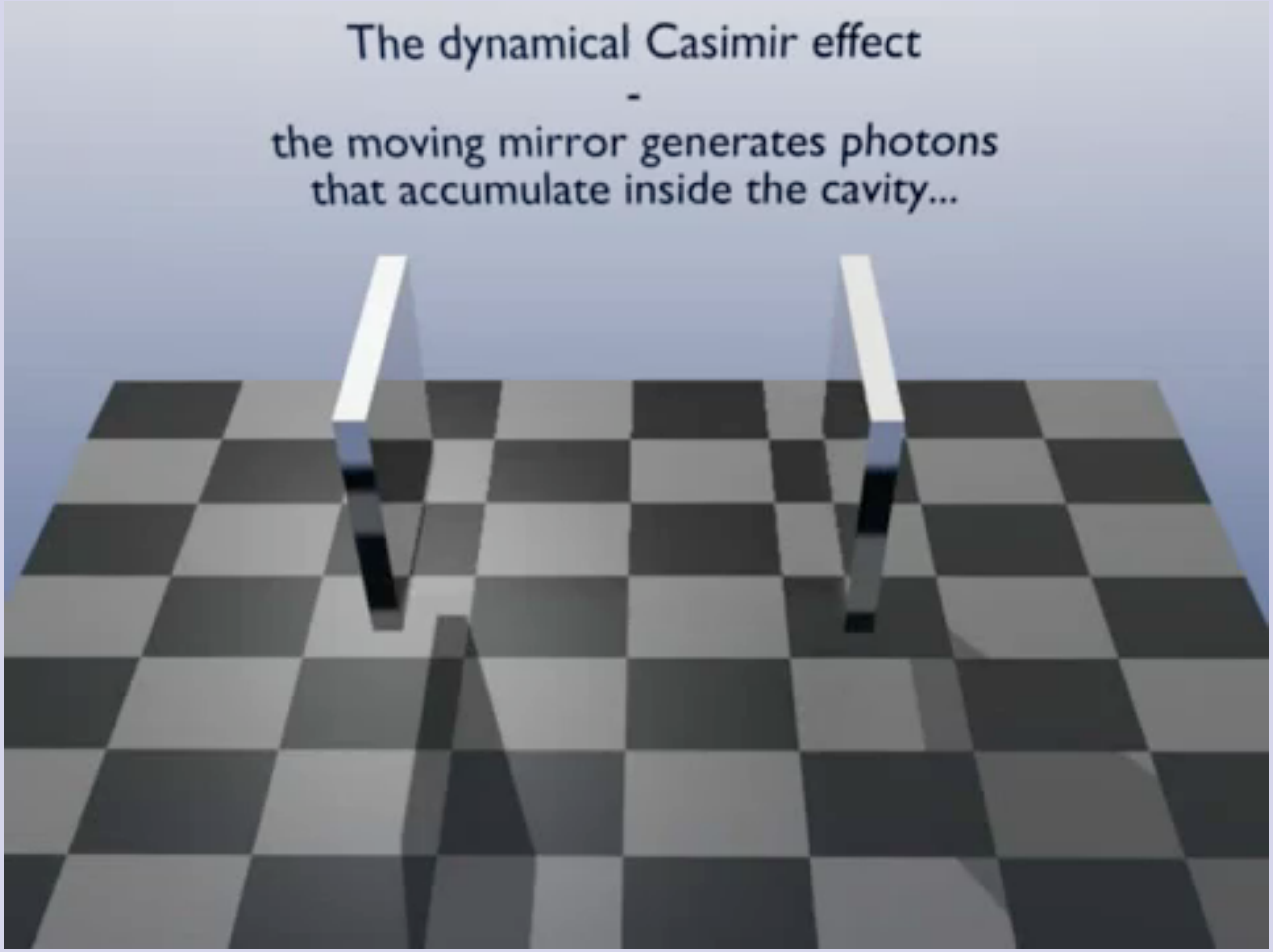
$$\boxed{\omega_{\rm cm} = 2\omega_s,} \quad \theta(t) = \theta(0) e^{\epsilon t/2}\cos(\omega_s t) + \frac{L(0)}{m\omega_s l} e^{-\epsilon t/2}\sin(\omega_s t).$$

exponential growth!

Parametrically excited resonant circuit



DCE: Casimir radiation stored in the cavity mode



i) Acoustic waves in solids
In the 60's Bömmel-Dransfeld produced GHz acoustic waves in quartz using piezo excitation, but exciting all modes.
- Motion of a single mode dx << 1 nm.
- Large microwave power.

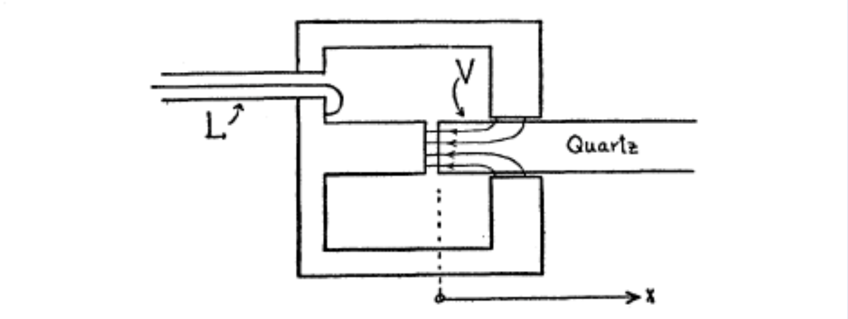
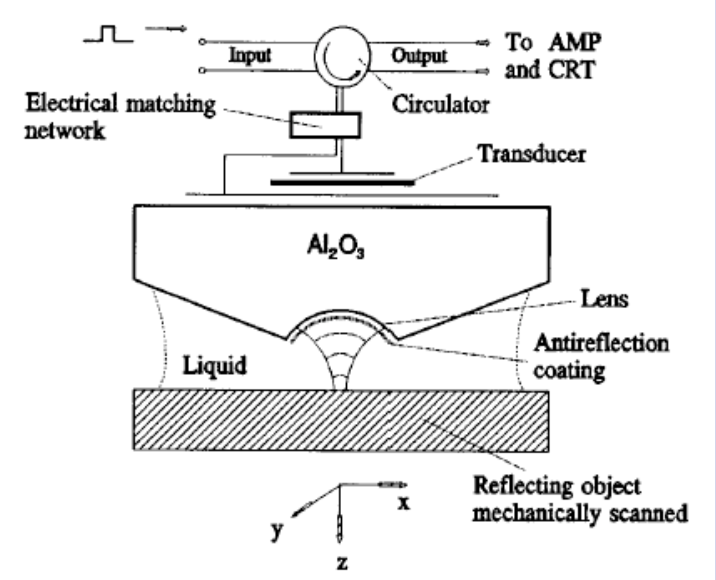


FIG. 1. Cavity with quartz rod, the volume V of which is exposed to the electric field. Lead L critically coupled to cavity.



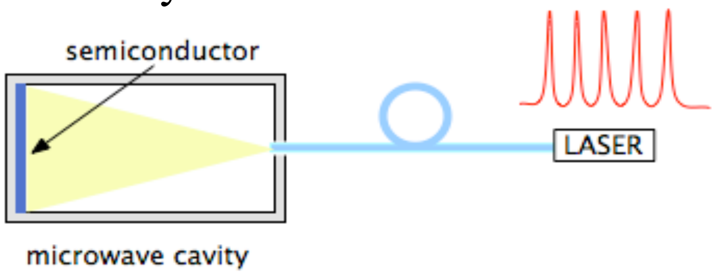
ii) Acoustic microscopes
Excitation of resonant modes in sapphire blocks (typical frequency 3 GHz)

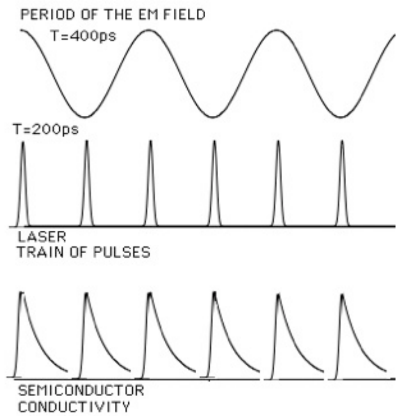
High Q reduces power requests, in fact for sapphire Q f ~ 10^{12}, i.e. for f ~ 10^9 follows Q ~ 10^3.
Same amplitude with P/1000.
But again dx ~ 10^{-10} m and small area

MIR experimental scheme

What is a MIRROR for the EM field? … a good conductor
is a plasma ($n_e \approx 10^{16}$ cm^{-3}) on a semiconductor a good conductor at microwave frequency?
C. Braggio *et al* *Rev. Sci. Inst. Vol. 70, 2005*

Modulation of the surface CONDUCTIVITY
of a semiconductor slab inside a microwave cavity





C. Braggio *et al*
Europhys. Lett. Vol. 70, 2005

Accelerating reference frame for electromagnetic waves in a rapidly growing plasma: Unruh-Davies-De Witt radiation and the nonadiabatic Casimir effect
E. Yablonovitch *Phys. Rev. Lett. Vol. 62, 1989*

Parametric excitation of vacuum by use of femtosecond pulses
Y. E. Lozovik, V.G. Tsvetus and E. A. Vinogradov *Physica Scripta Vol. 52, 1995*

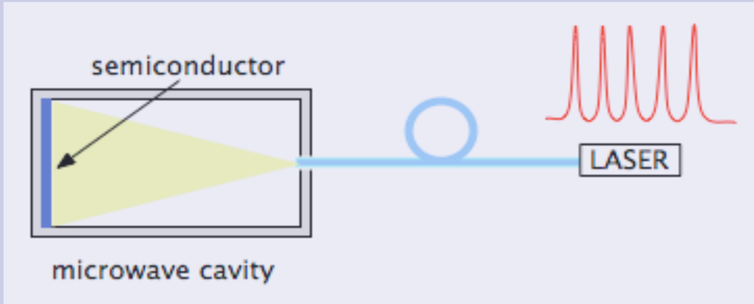
Quantum phenomena in nonstationary media
V. V. Dodonov, A B Klimov, D Nikonov *Phys. Rev. A. Vol. 47, 1993*

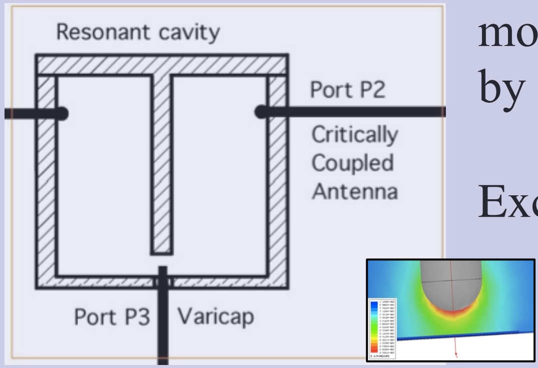
Alternative approaches

The key requirement is to modulate the boundaries to the EM field

modulation of the conductivity

Excitation source: laser



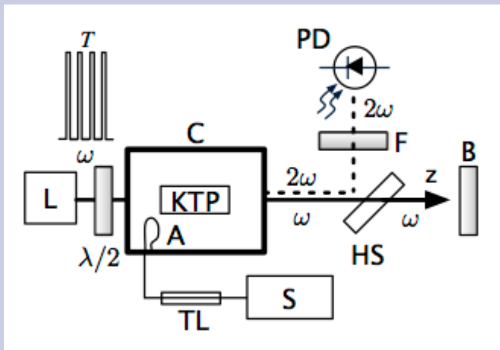


modulation of the cavity gap capacitance
by means of a VARICAP

Excitation source: a radiofrequency generator

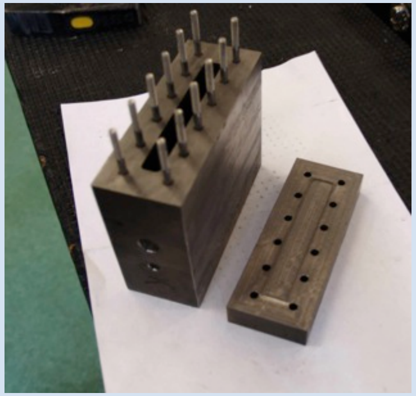
modulation of the index of refraction
in a NONLINEAR CRYSTAL

Excitation Source: laser

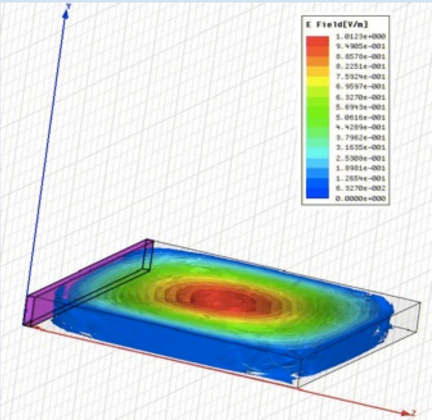


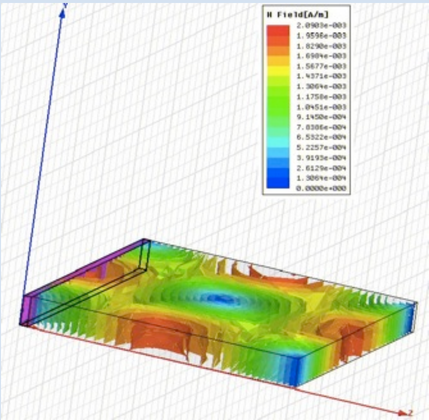
Nb superconducting cavity

(80 x 90 x 9) mm^3



E, H field profiles

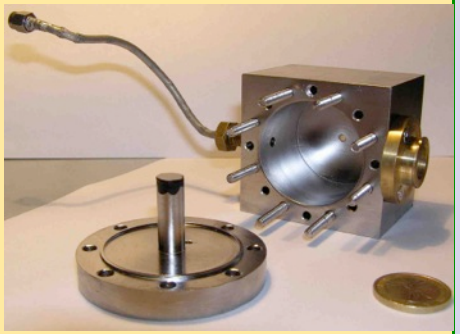




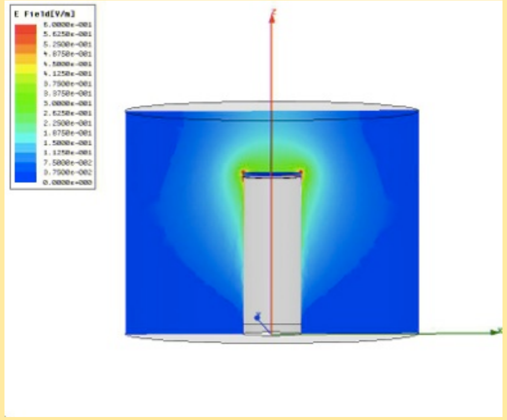
Cylindrical reentrant cavity

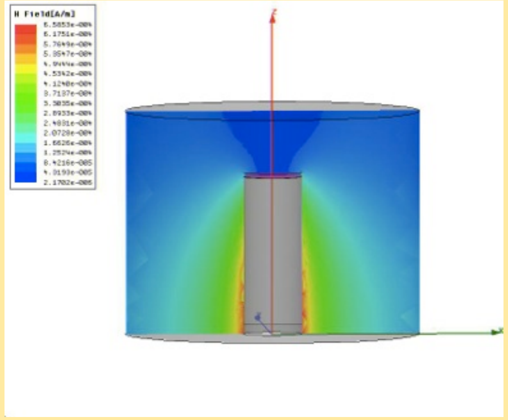
($\Phi_{cav} = 42$ mm, $h = 34$ mm, $\Phi_{GaAs} = 8$ mm, $d = 10$ mm)

1. Smaller amount of E_{pulse}
2. Simplified optical scheme for uniform illumination of the semiconductor



E, H field profiles

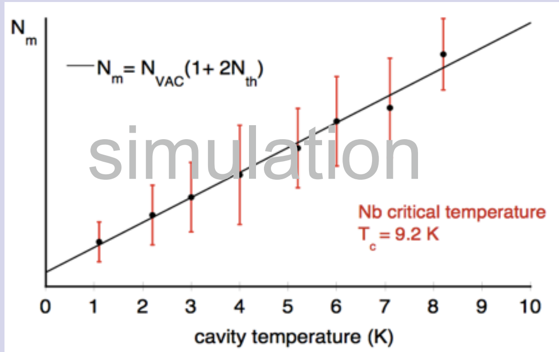




MIR experimental scheme

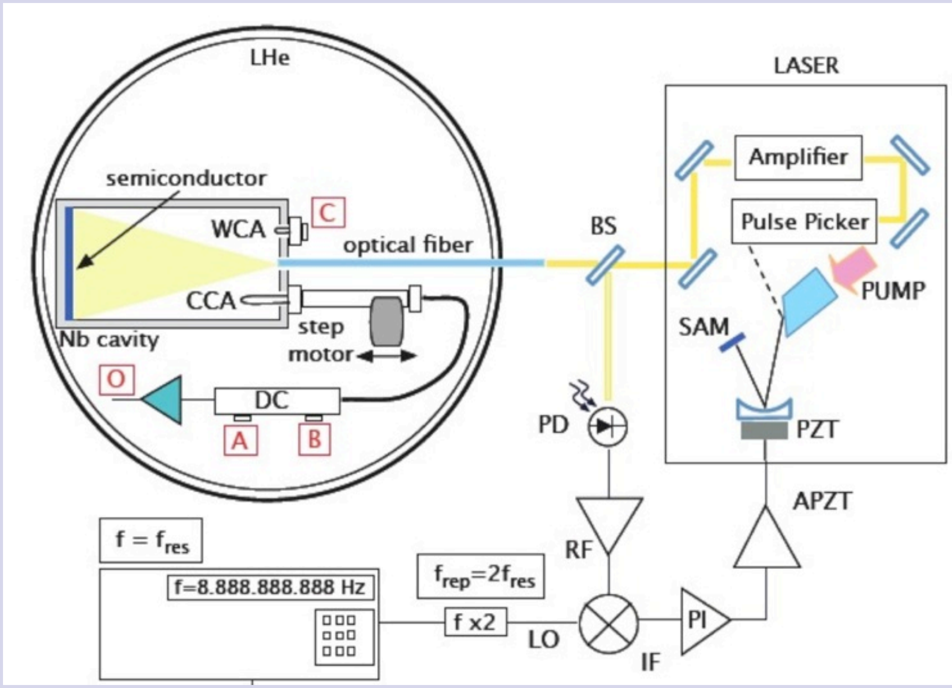
parametrically excited photons could initially be seeded by thermal fluctuations instead of vacuum fluctuations…

cryogenic environment

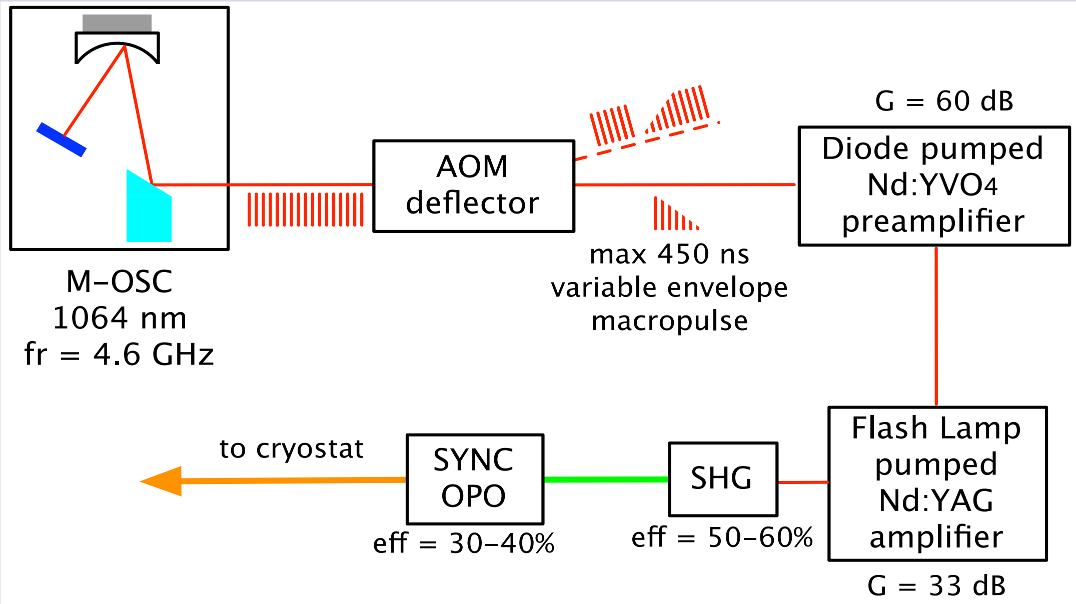


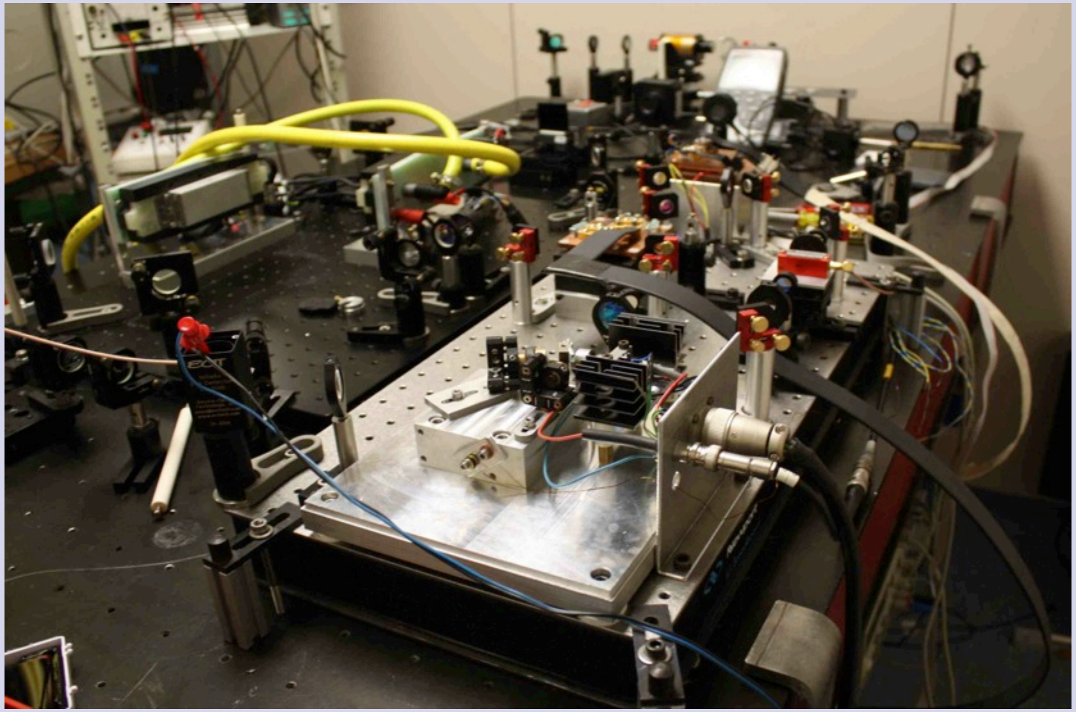
80 l LHe vessel, $T = (0.8 \div 9)$ K

30 l



Laser system - 1





Oscillation is performed for a finite interval of time

$E_{pulse} \approx 10$ μJ;
since the average power of a CW mode-locked laser having this value of energy per pulse would be too high, we developed a laser delivering a macropulse up to of $\Delta T = 450$ ns duration (~ 2000 pulses).

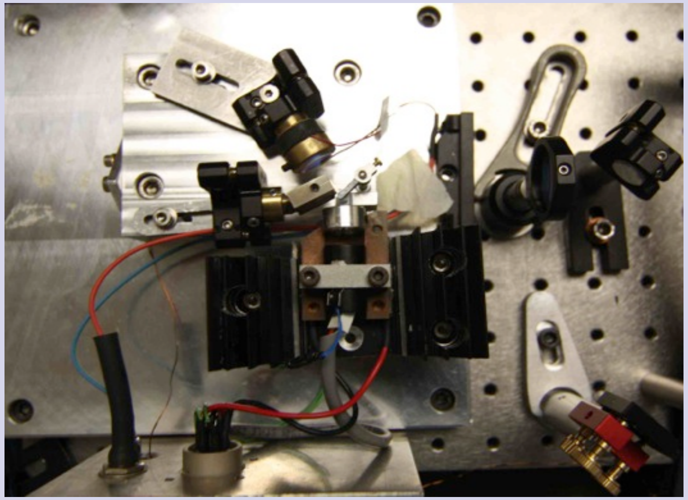
Total macropulse energy is a few millijoules

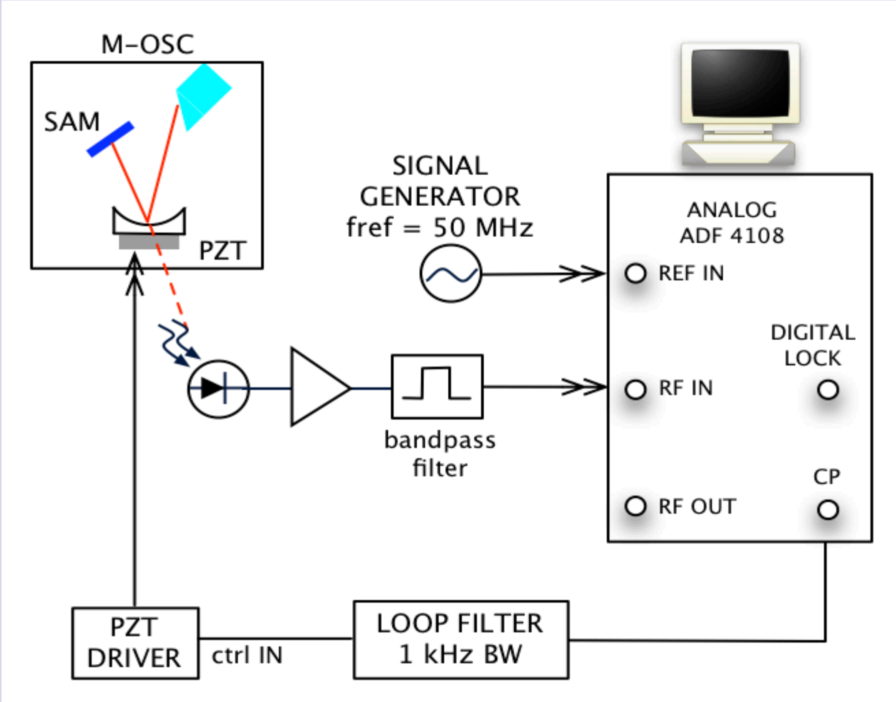
FINAL SPECS
- high frequency repetition rate ($f_{rep} \approx$ 5 GHz, stability better than the cavity BW 1 kHz),
- tunable f_{rep},
- 10 ps pulses duration,
- $E_{pulse} \approx$ few microjoules,
- 780 – 820 nm output wavelength

Optics Express **13**, 5302 (2005)
Optics Express **14**, 9244 (2006)
Optics Express **16**, 15811 (2008)

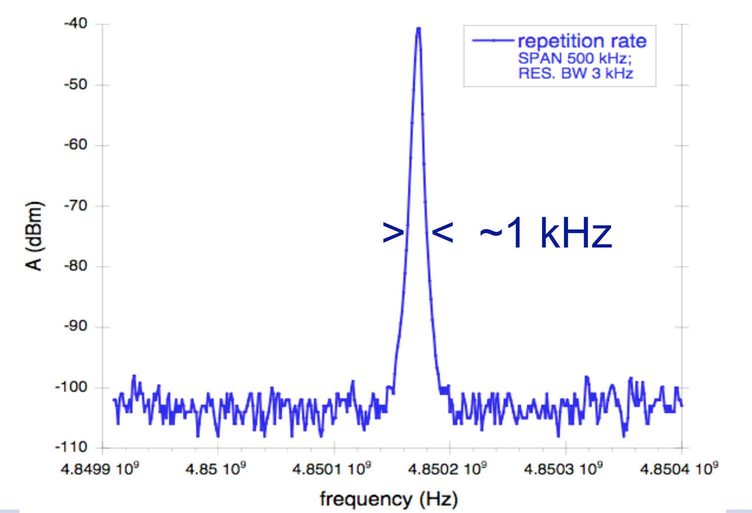
LASER repetition rate stability and tuning

Active control of the Master Oscillator length:
the feedback system locks the repetition frequency
of the laser to a reference microwave generator

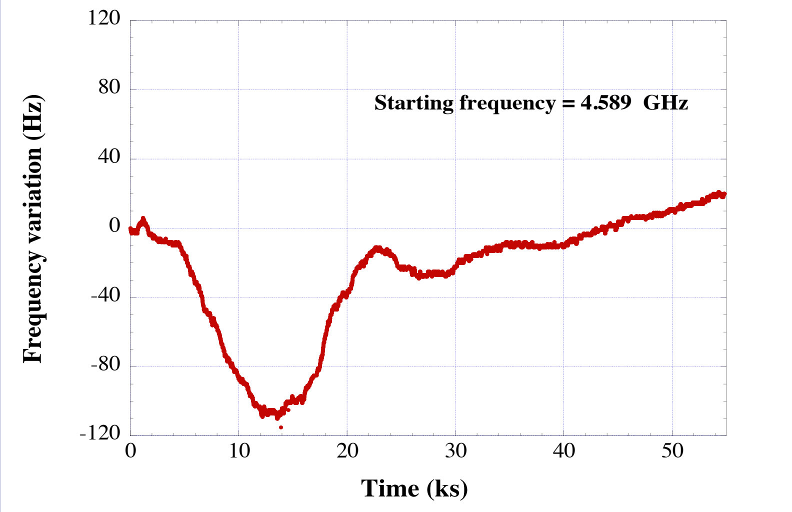




SHORT TERM STABILITY



LONG TERM STABILITY



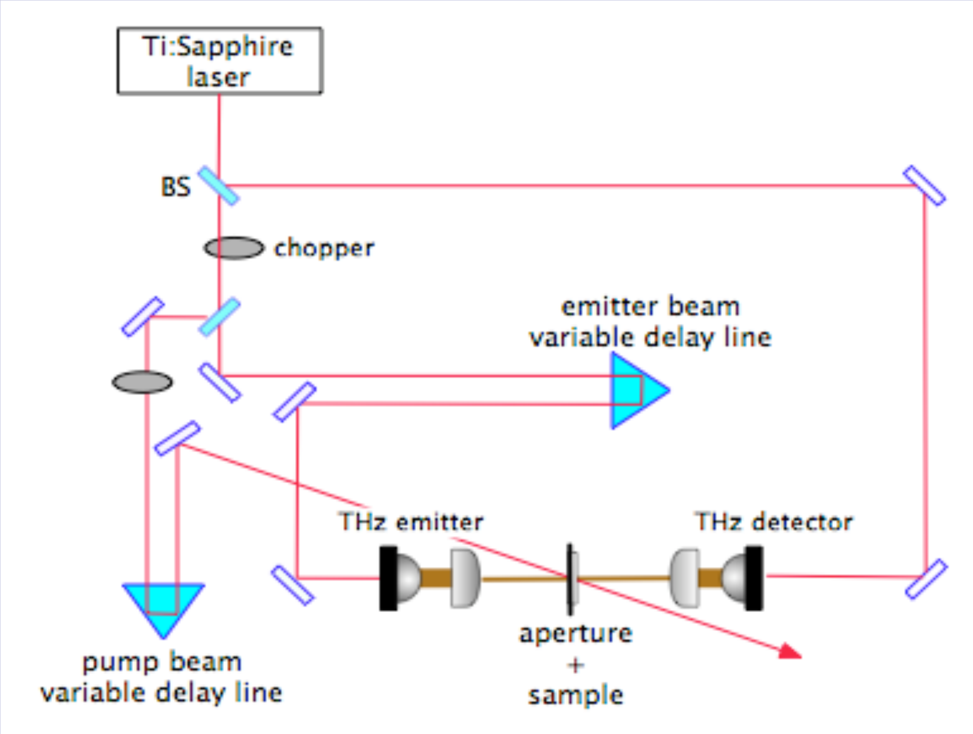
Requirements: high mobility (1 $m^2/V\ s$)
short recombination time (a few picoseconds)

R&D on a new material, starting from semi-insulating (SI) GaAs

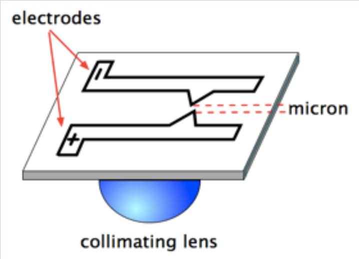
SI GaAs irradiated with thermal neutrons (Italy, USA) — Foulon *et al.* 2000, *J. Appl. Phys.* **88**, 3634
SI GaAs irradiated with Au, Br ions (Tandem accel. in LNL) — Mangeney *et al.* 2002, *Appl. Phys. Lett.* **80**, 4711
SI GaAs irradiated with 1-5 MeV protons (CN accel. in LNL) — Mangeney *et al.* 2000, *Appl. Phys. Lett.* **76**, 40

Measurement of the recombination time and mobility of the irradiated samples

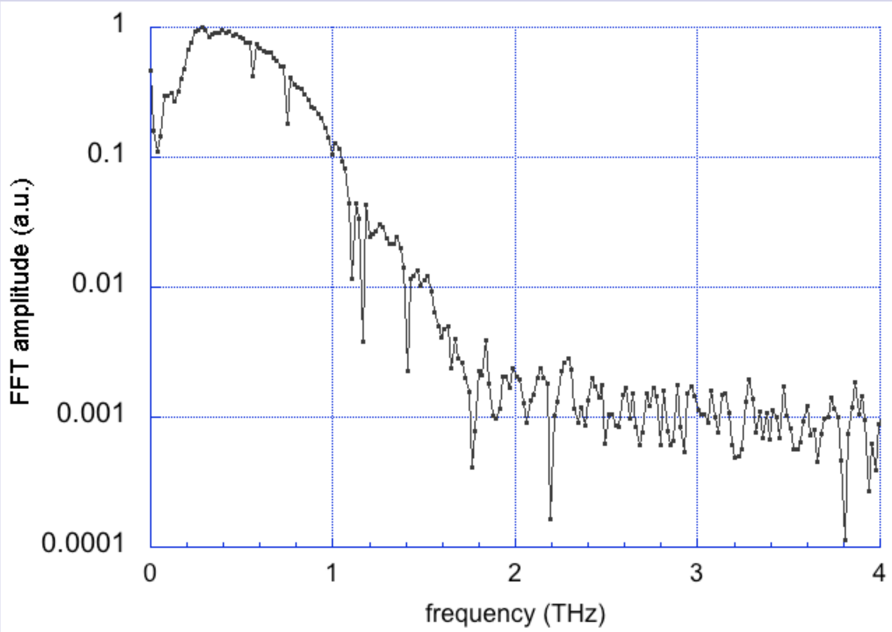
Optical-pump terahertz-probe setup

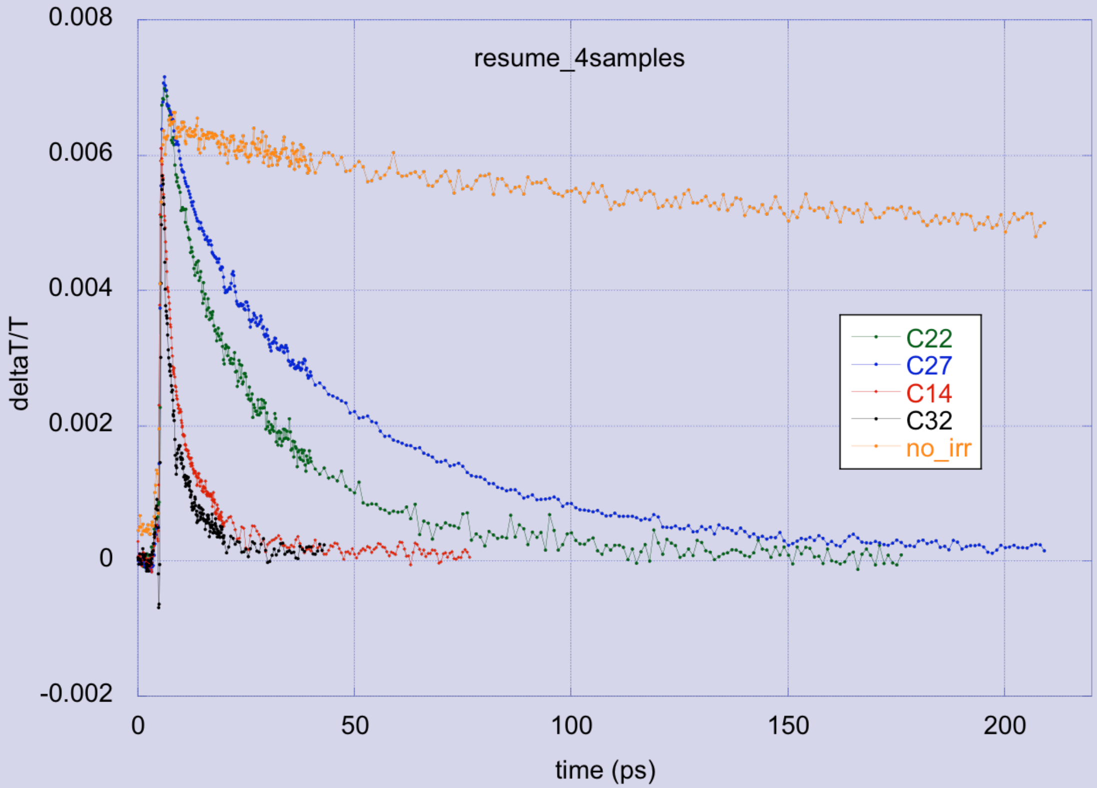


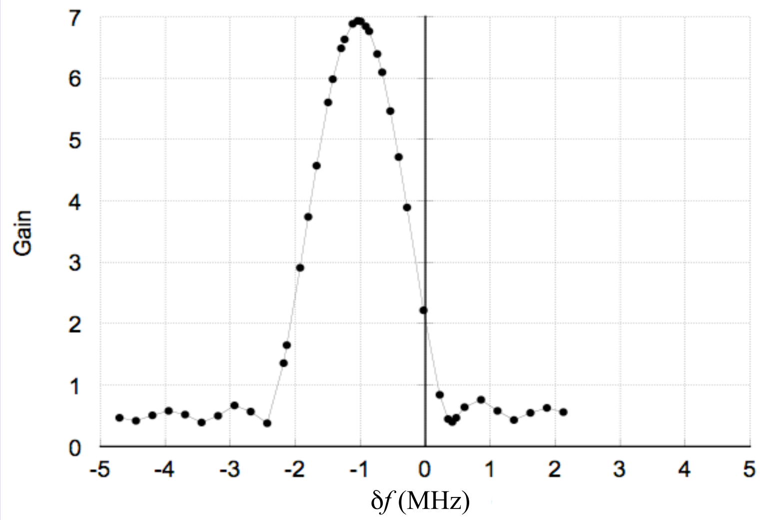
1. Same concentration of free carriers produced as in the plasma mirror ($n \approx 10^{17}$ cm^{-3});
2. Measurements are conducted at different temperatures in the range 300 – 10 K in a cryocooler

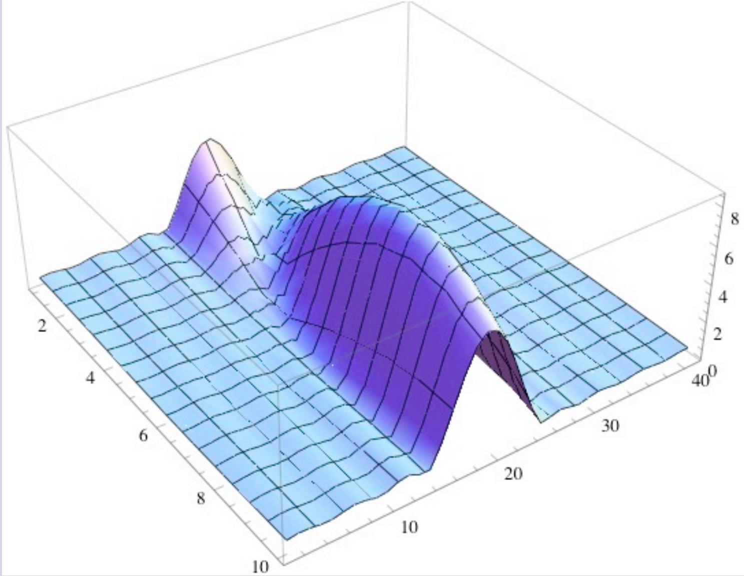


Semiconductor



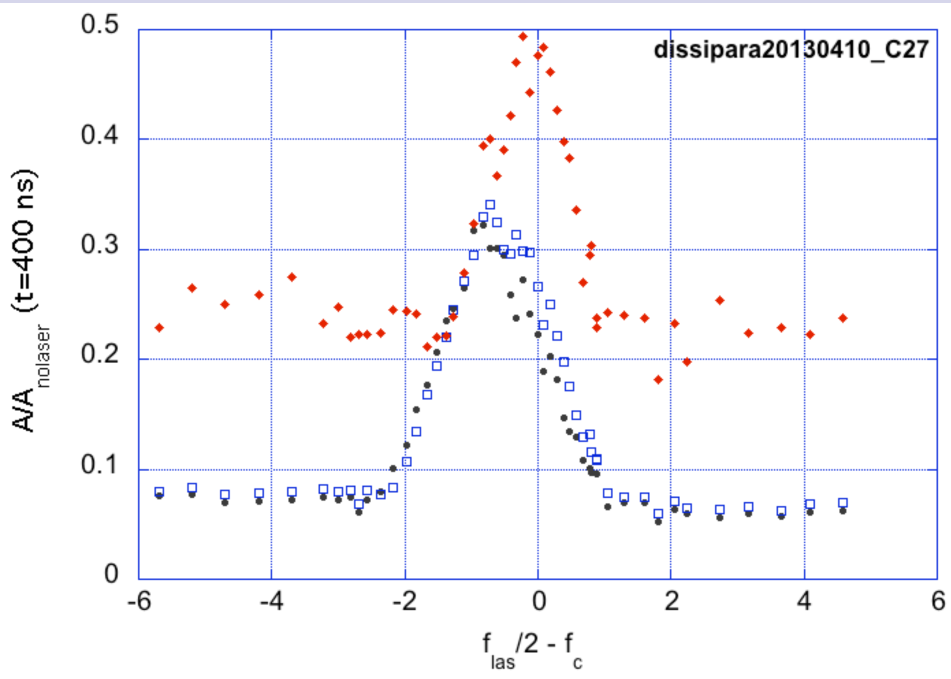




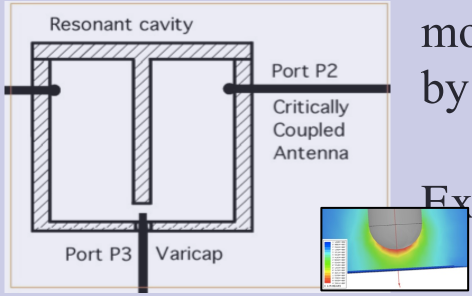


1. exponential growth at the parametric resonance; decaying oscillations when detuned
2. higher order maxima in the gain vs. δf plot are observed
3. the maximum of the amplification is found at $f_{rep}=2\,f_0+\delta f$ (in our experiment the excitation is not a pure harmonic signal);
4. If the phase between the excitation and the field in the cavity varies, at each laser shot a different gain is observed;

- a pre-charged field (external generator) is used to study of the parametric response (detuning curve)
- make sure that the modulator is not the source of the searched photons
- compare results from NG Spice simulations and theory (V. Dodonov)
- thermal field
- DCE field at cryogenic temperatures



The DCE with the '*semiconductor approach*' is not detectable due to inherent dissipative phenomena in the parametric amplification process.



modulation of the cavity gap capacitance
by means of a VARICAP

Excitation source: a radiofrequency generator

C. Braggio *et al*. New J. Phys. 15 013044 (2013)

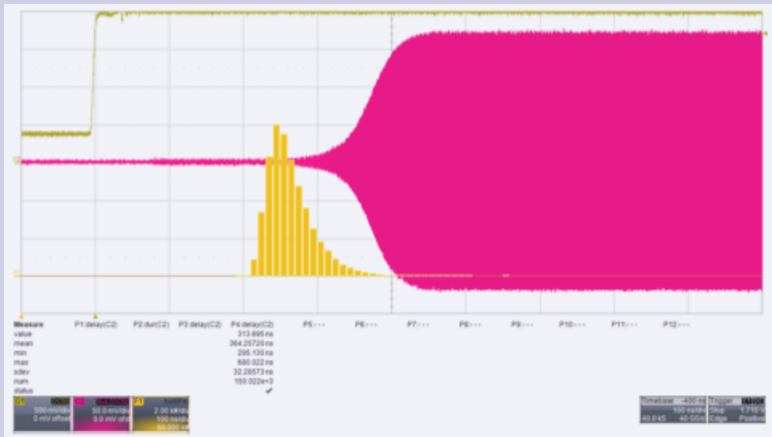
$$P_\nu(n) = \frac{1}{\bar{n}+1}\left(\frac{\bar{n}}{\bar{n}+1}\right)^n$$

$$\bar{n} = [\exp(h\nu_r / kT) - 1]^{-1}$$

It is a parametric amplifier

$$P_{out}(t) \approx P_{out}(0) e^{2(s-\lambda)t} g(\theta)$$

$$t_T = \tau_p \left[\ln \frac{P_T}{P_{out}(0)} - \ln g(\theta) \right]$$

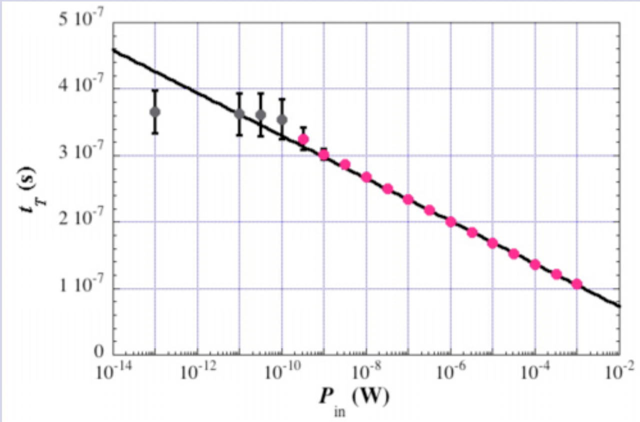


exponential growth of the signal seeded by
external/thermal photons at T=300 K

$$P_{out}(t) \approx P_{out}(0)e^{2(s-\lambda)t}g(\theta)$$

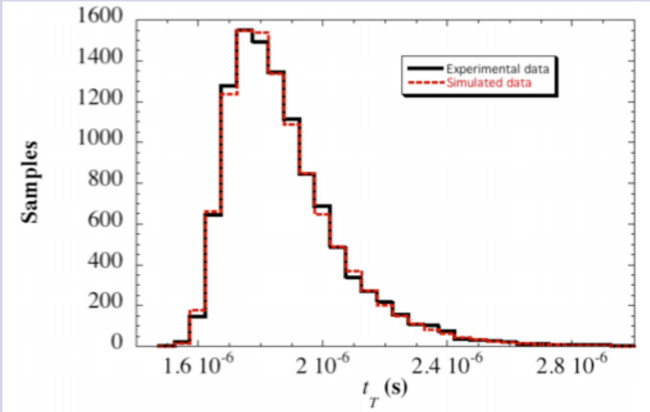
$$t_T = \tau_p\left[\ln\frac{P_T}{P_{out}(0)} - \ln g(\theta)\right]$$

The time constant of the amplification process is measured and plotted as a function of the pre-charged field



There is a source that cannot be switched off

MC- simulation of the parametric process: generate values of the time delays assuming that the energy present in the cavity at the starting trigger follows a B-E probability distribution



Calibration of the apparatus with a **pre-charged field** or with **thermal photons**

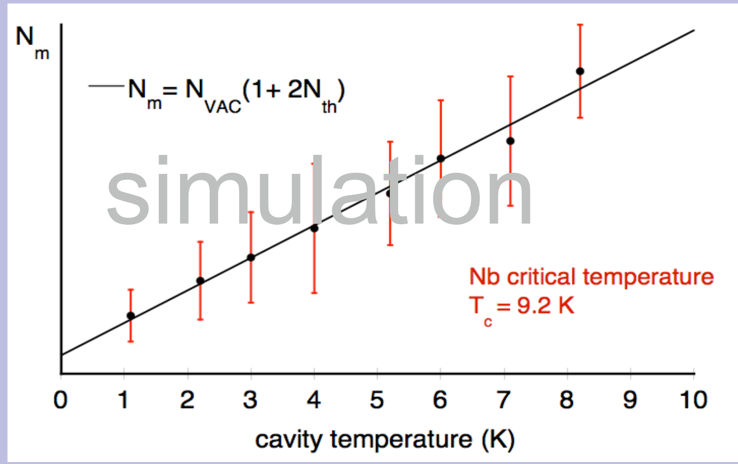
E_0 thermal or external field

$$N_{ph}(n) \propto E_0 e^{2|\chi_{\max}|F(A_0)n}$$

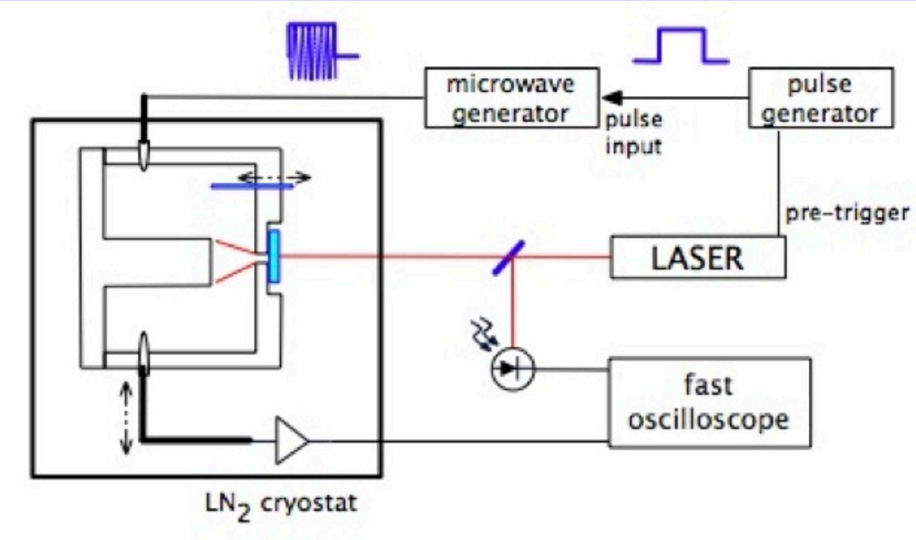
n number of pulses

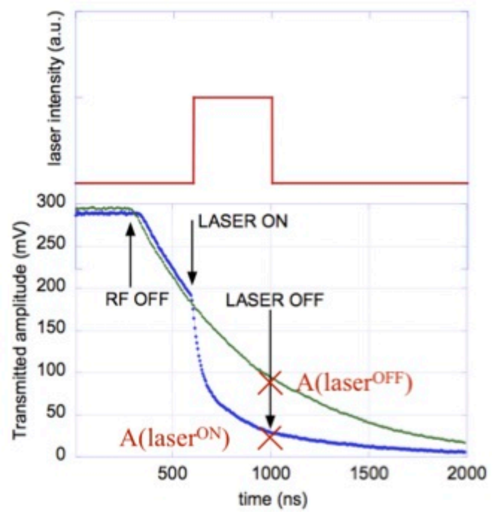
$F(A_0)$ gain coefficient

$|\chi_{\max}|$ increases with stationary frequency shift $\Delta f = f_{ill} - f_0$



To run this test we arranged a simplified experimental condition:
T = 77 K and charged field from an external radiofrequency generator





1. the cavity is pre-charged
2. the radiofrequency at f_0 is switched off (EM field starts to decay with decay time τ_0 : free oscillations);
3. ~100 ns after switching off the external generator, the laser train of pulses impinges on the semiconductor surface

Conclusions:

Many problems still to be solved :

1) Dissipation in Quantum Mechanics: Particle Production
2) Role of Vacuum Fluctuations at large accelleration
3) Zero Point Energy in QFT and Cosmological Constant Term
4) Casimir Forces and Technological Handling MEMS Devices
5) Thermodynamics of ZPE Fluctuations in the Matter
6) Instrumental developments to get extreme conditions

New Quantum Limited devices now start to be available

Framework

Energy of the states of a system of fields?

GROUND STATE
state of MIN energy
stability state

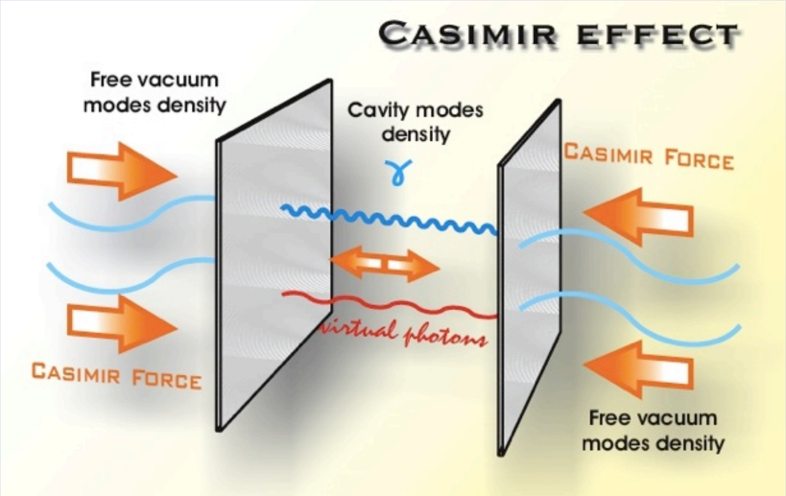
EXCITED STATES
containing
elementary quanta
of excitation

Essential point of view:
the Vacuum is not a substance, but a STATE,
precisely the ground state of the many field system.

VACUUM = No excitation quanta – No particles

The excited states are the PARTICLE ASPECT of a field

- Casimir effect (PRL 88, 041804 (2002) in Padova)



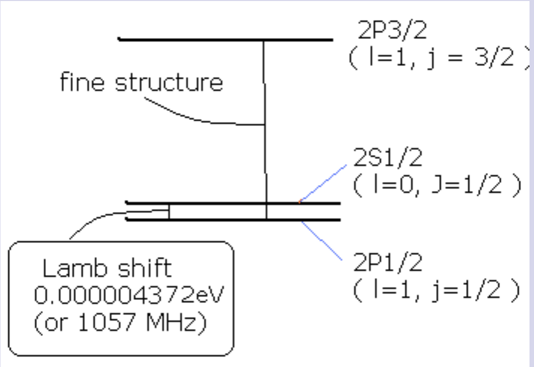
(frequency cut-off)

$$\frac{\Delta E_0(d)}{L^2} = -\frac{\pi^2}{720}\frac{\hbar c}{d^3}$$

- failure of liquid ^{4}He to solidify at normal pressures as T → absolute 0

- spontaneous emission

- Lamb shift (Lamb, Retherford 1947) measurement; (Bethe 1947) calculation



- The Vacuum in modern quantum field theory: nothing's plenty

  …an experimental point of view

- Experimental demonstrations of the QF of the EM field:

  - **static** scenario

    Casimir force, Lamb shift, spontaneous emission and LHe…

  - **dynamical** scenario

    DCE, Unruh and Hawking radiation, Schwinger process

- A new QED effect possibly to be explored…

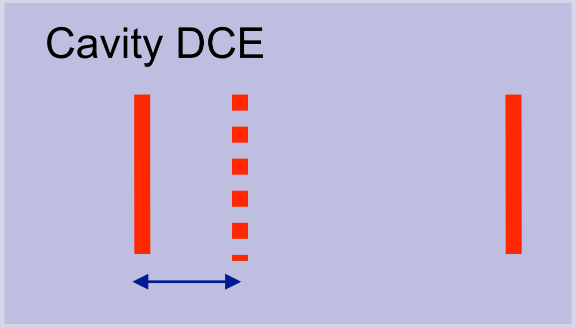
  the dynamical Casimir-Polder effect

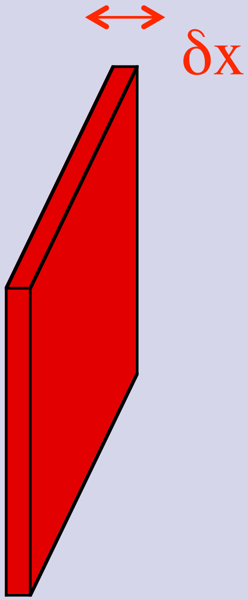
Main mechanisms by which vacuum fluctuations are *amplified* into photons:

- Dynamical Casimir effect
- Hawking radiation
- Unruh effect

They become appreciable under *extreme conditions*

How to perform the required wall oscillation?





$$E = \frac{1}{2}\rho V \omega^2 \delta x^2$$

$\omega / 2\pi = 10$ GHz

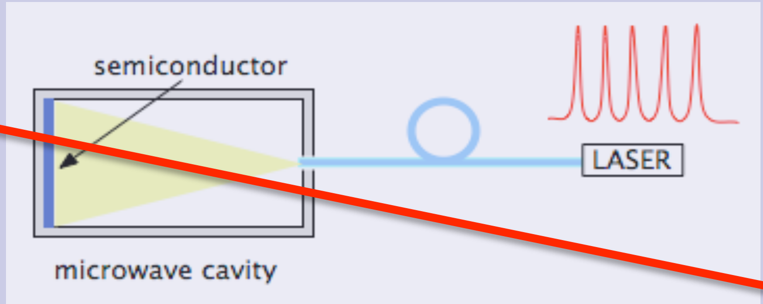
$\delta x = 1$ nm

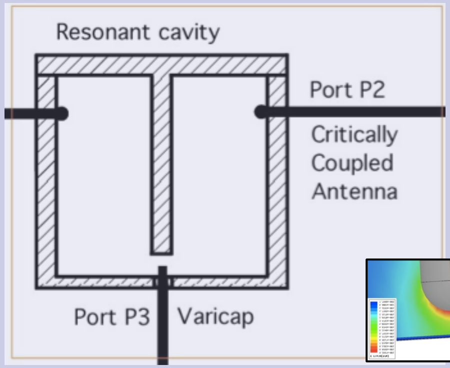
Required mechanical power
P ~ kW - MW
With Q factor = 100
P = 10 W – 10 KW

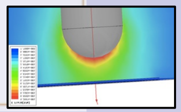
The key requirement is to modulate the boundaries to the EM field

modulation of the conductivity

Excitation source: laser







modulation of the cavity gap capacitance
by means of a VARICAP

Excitation source: a radiofrequency generator

modulation of the index of refraction
in a NONLINEAR CRYSTAL

Excitation Source: laser