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

  …an experimental point of view

- Experimental demonstrations of the QF of the EM field:

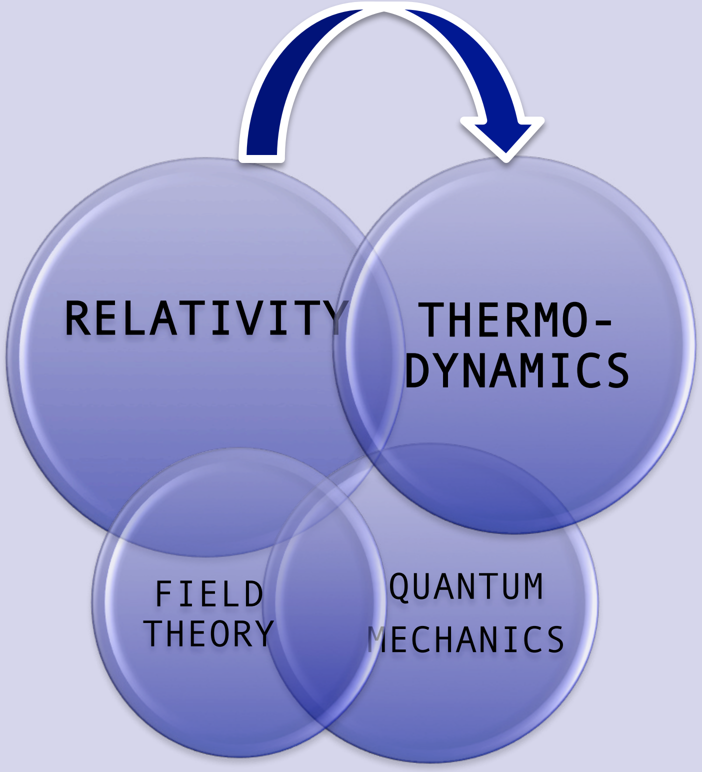
  - **static** scenario

    Casimir force, Lamb shift, spontaneous emission and liquid He

  - **dynamical** scenario

    DCE (cavity/waveguide), Unruh and Hawking radiation,
    the dynamical Casmir-Polder force

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*

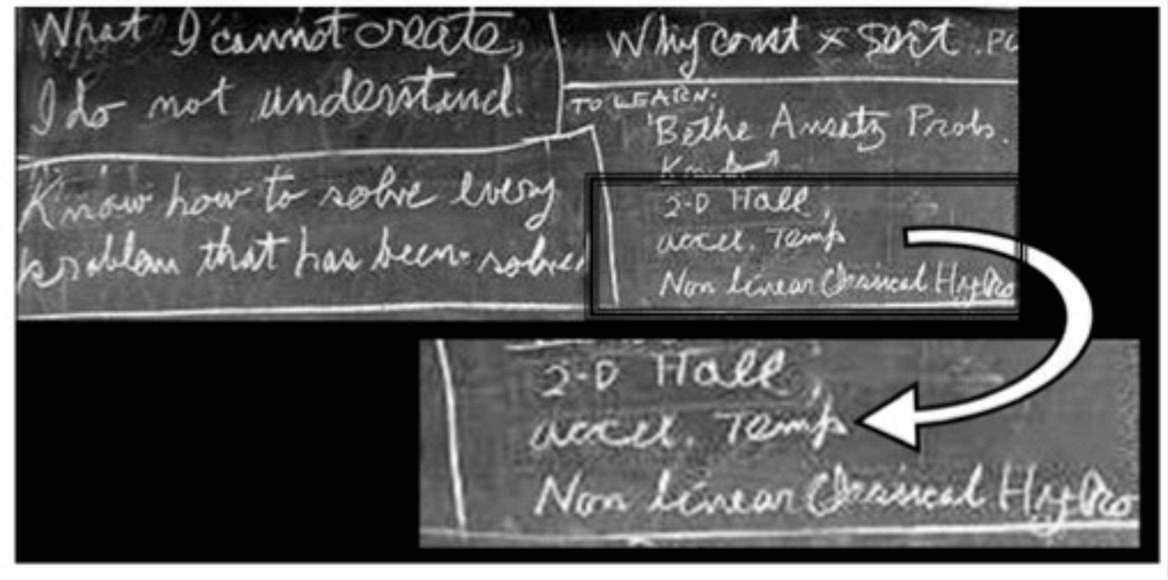
A harmonic oscillator *in acceleration* gains energy from the fluctuations of the ZP of the EM field in the vacuum.

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

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

Acceleration temperature

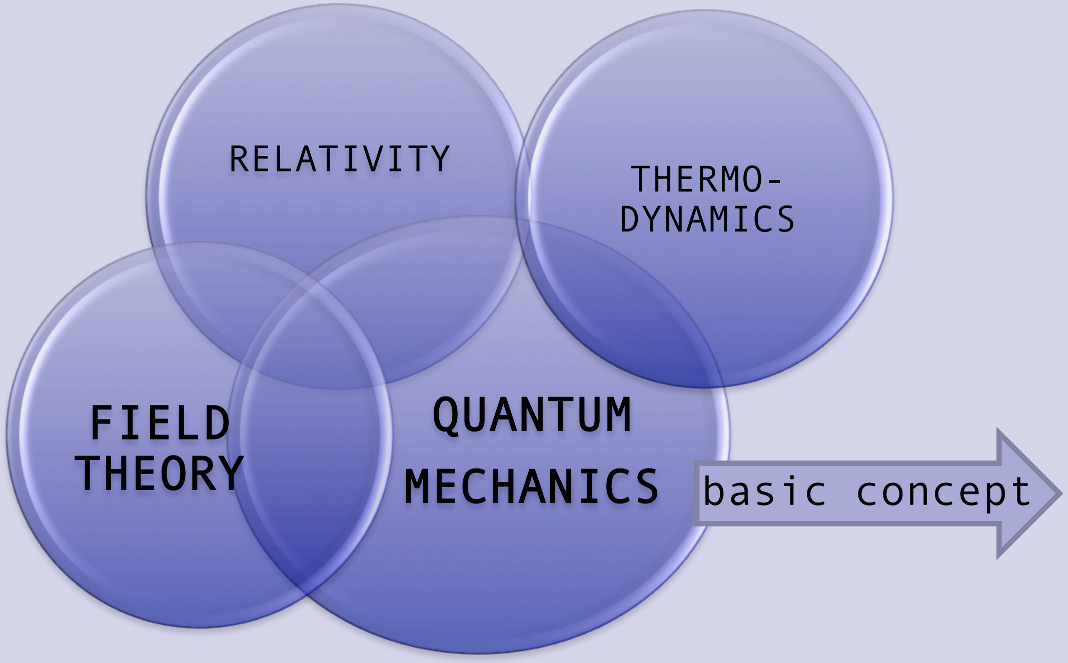
Part of Feynman’s blackboard at California Institute of Technology at the time of his death in 1988.



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

Framework

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



RELATIVITY

THERMO-DYNAMICS

FIELD THEORY

QUANTUM MECHANICS

basic concept

STATE of a SYSTEM
:= system of fields

Energy of the states of a system of fields?

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

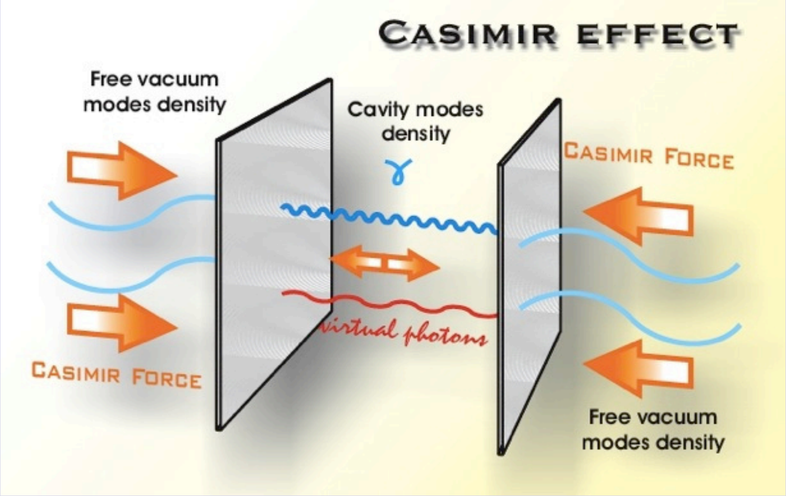
Essential point of view:
the Vacuum is not a substance, but a STATE,
precisely the ground state of the many field system.

VACUUM:= No excitation quanta – No particles

The excited states are the PARTICLE ASPECT of a field

QF STATIC manifestations

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



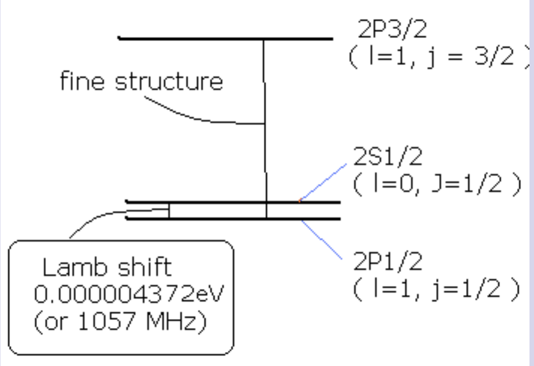
(frequency cut-off)

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

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

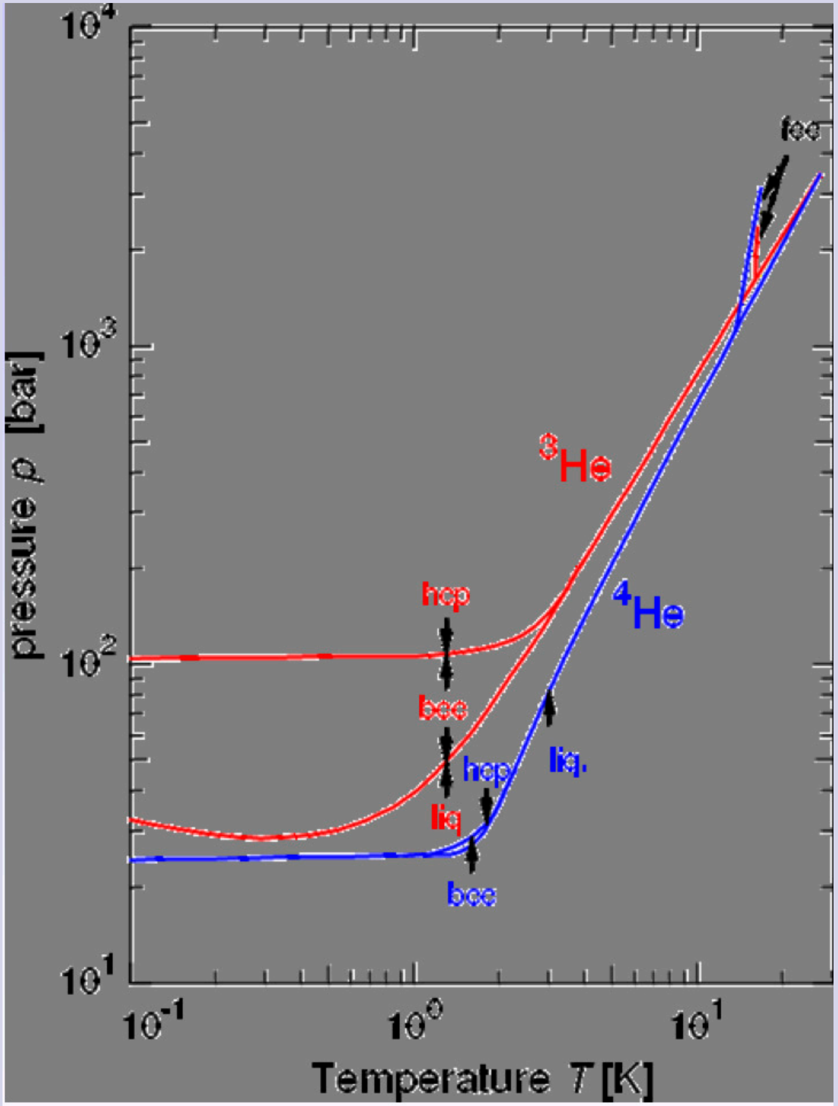
- spontaneous emission

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



QF STATIC manifestations

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



T_{eff}

- 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*

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

- 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 conditions*

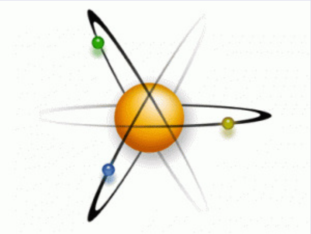
How to detect them in the laboratory?

QF DYNAMIC manifestations

An apparently innocent, “einsteinian” question:

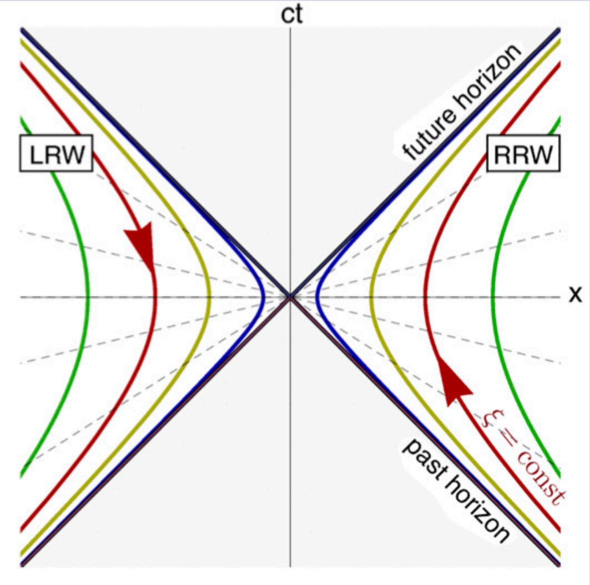
how are the QF perceived by an observer in acceleration?

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~~).



A QUBIT

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

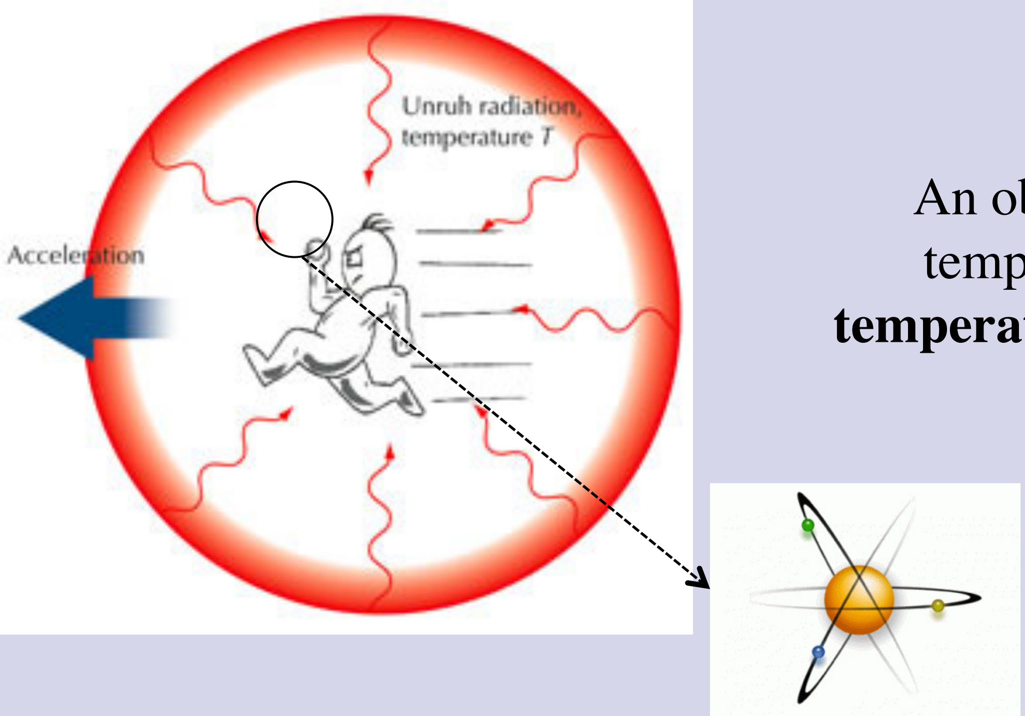


Unruh effect

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.

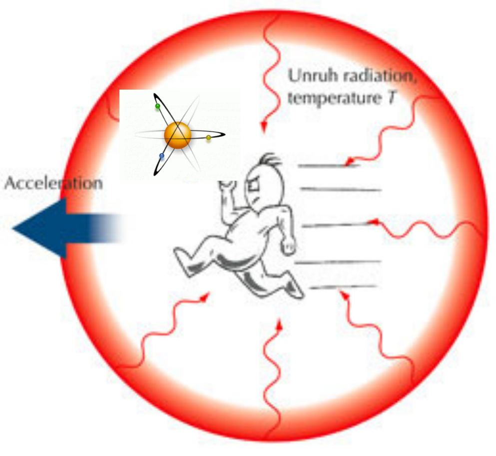
Unruh (Phys. Rev. D14, 870 (1976))



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

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

Unruh effect



“accel. radiation” is exceedingly small!

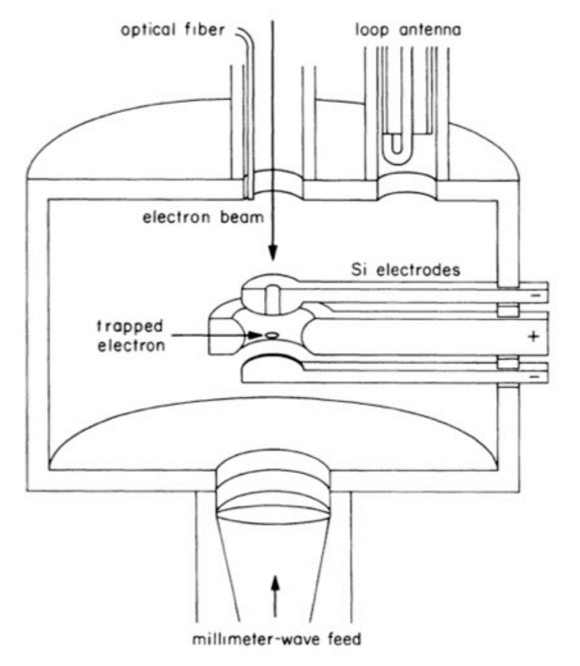
$$T_U = \frac{\hbar}{2\pi c k_B} a \approx 4 \cdot 10^{23} a$$

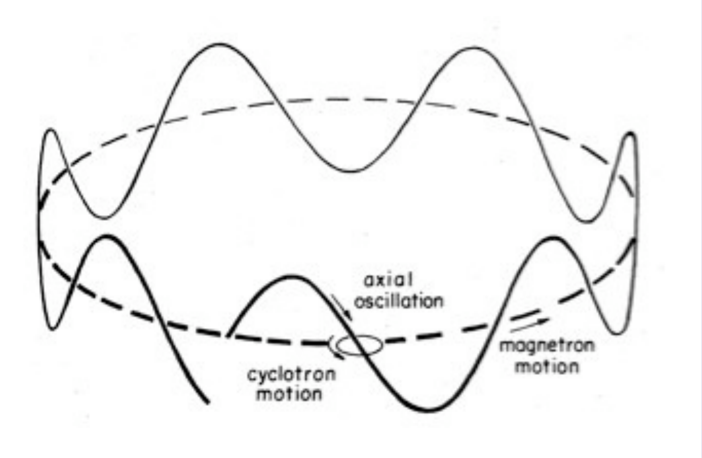
$$\Rightarrow \; a \geq 10^{20} g, \; g \text{ mean gravity acceleration on Earth}$$

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)



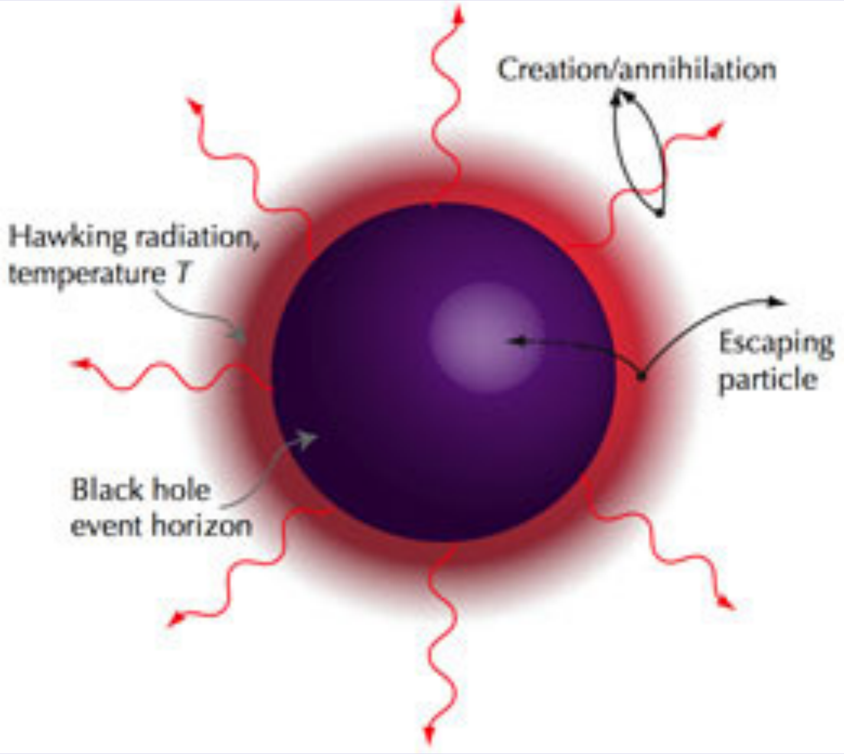


the electron accelerates centripetally in the trap's magnetic field, the vacuum radiation excites its motion along the trap axis (ω_a)

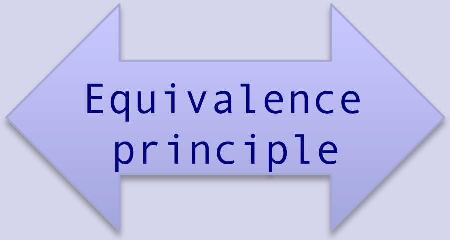
- detector:= relativistic ***e***$^-$ confined into a Penning trap (“Geonium atom”)
- ***e***$^-$ path is a combination of three components: ω_m, ω_c and ω_a
- B = 150 kG → $a \approx 10^{22}$ cm/s^2 corresponding to T_U=2.4 K
- cavity surrounding the Penning trap

Hawking radiation

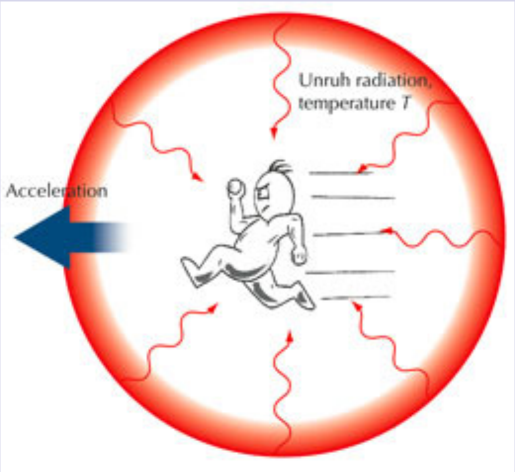
Hawking (Nature 248, 30-31 (1974))



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



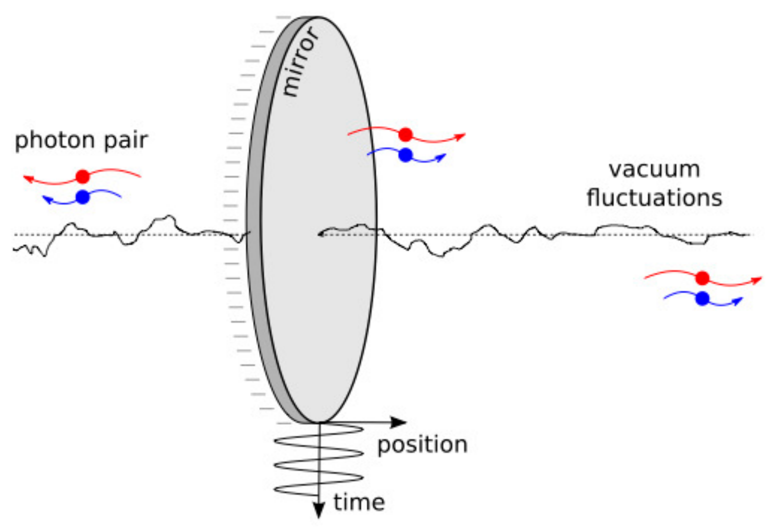
Equivalence principle



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

DCE: a definition

Single-mirror DCE

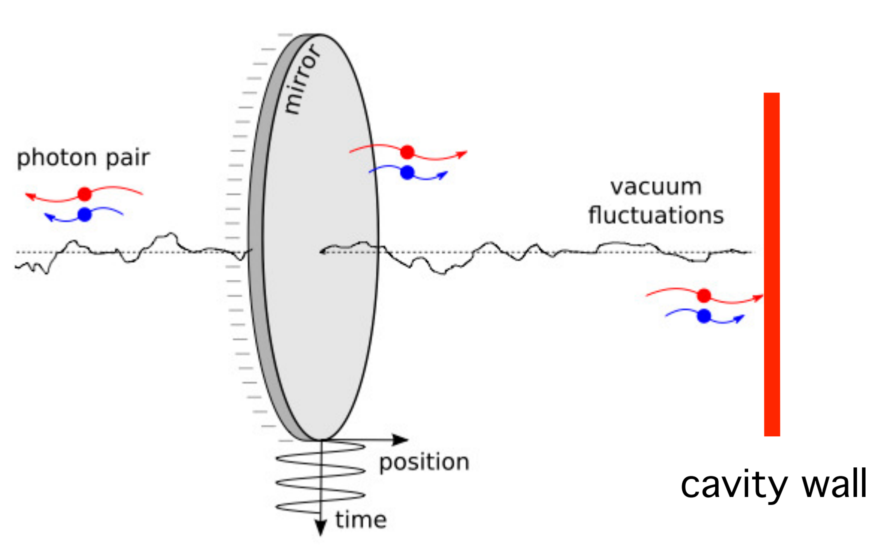


Broadband photons generation

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

IN THE MATTER

Cavity DCE



Basic mechanism is
parametric amplification

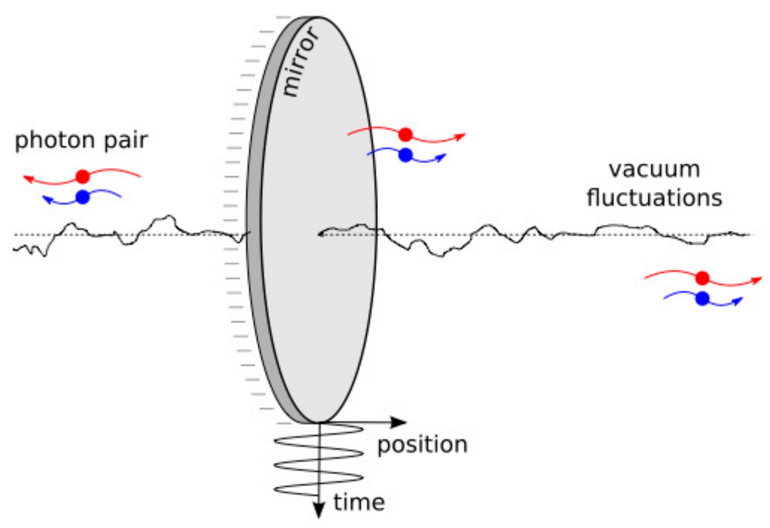
$$\nu_{\text{excitation}} = 2\nu_0$$

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

IN THE VACUUM

DCE: a definition

Single-mirror DCE



Broadband photons generation

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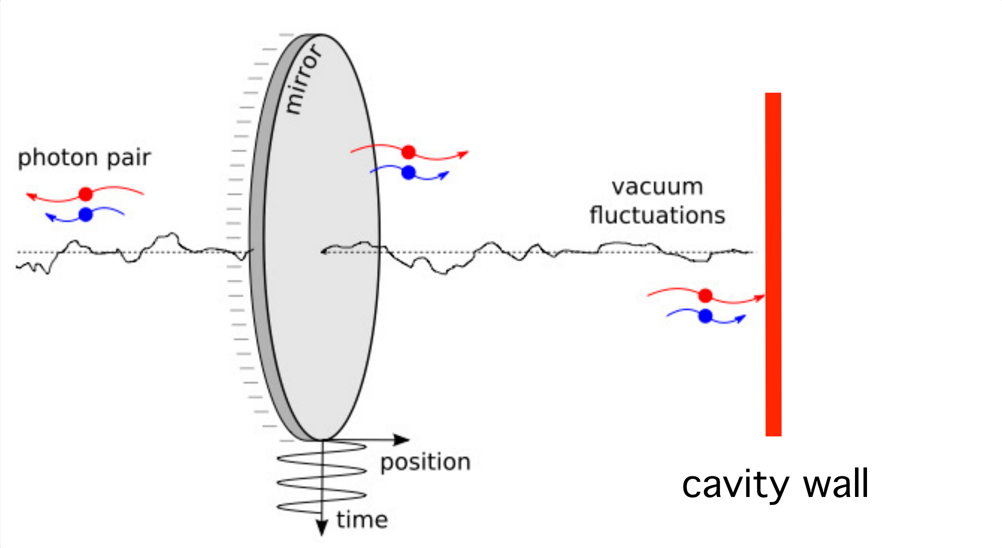
Cavity DCE

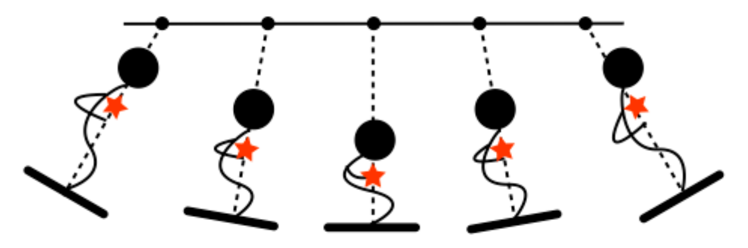


Basic mechanism is
parametric amplification
$\nu_{excitation} = 2\nu_0$

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

Cavity DCE and parametric amplification

A representative example: a child standing on a swing



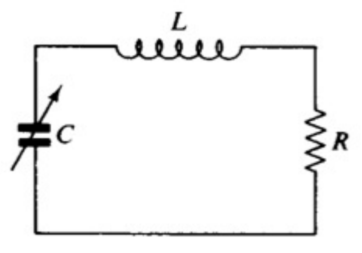
The amplification is driven by changing the center of mass, and thus effective length, of the pendulum at twice the frequency of the unperturbed swing.

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

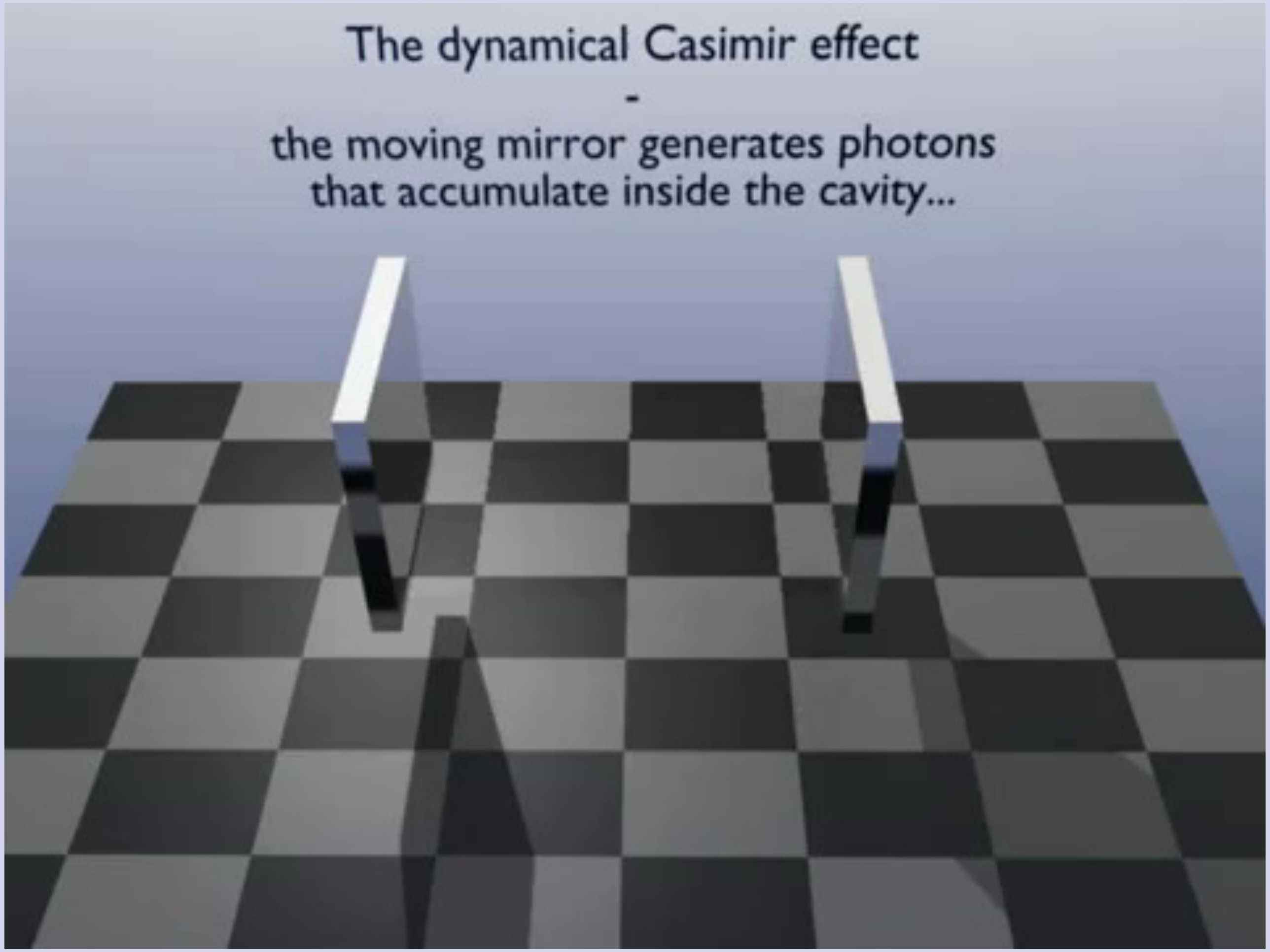
$$\boxed{\omega_{\rm cm} = 2\omega_s,} \quad \theta(t) = \theta(0) e^{\epsilon t/2}\cos(\omega_s t) + \frac{L(0)}{m\omega_s l} e^{-\epsilon t/2}\sin(\omega_s t).$$

exponential growth!

Parametrically excited resonant circuit



DCE: Casimir radiation stored in the cavity mode

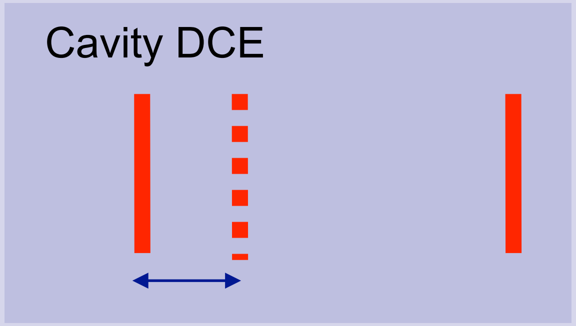


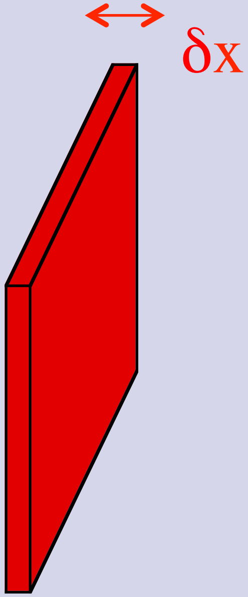
The dynamical Casimir effect

-

the moving mirror generates photons
that accumulate inside the cavity...

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

Limit of a mechanical approach

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.

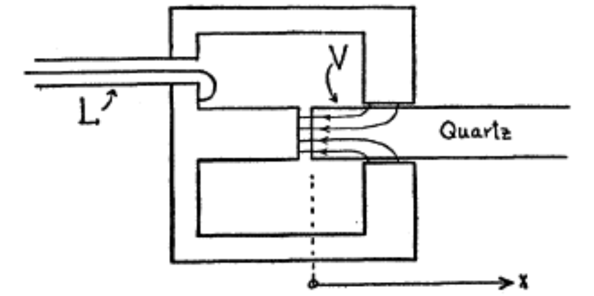
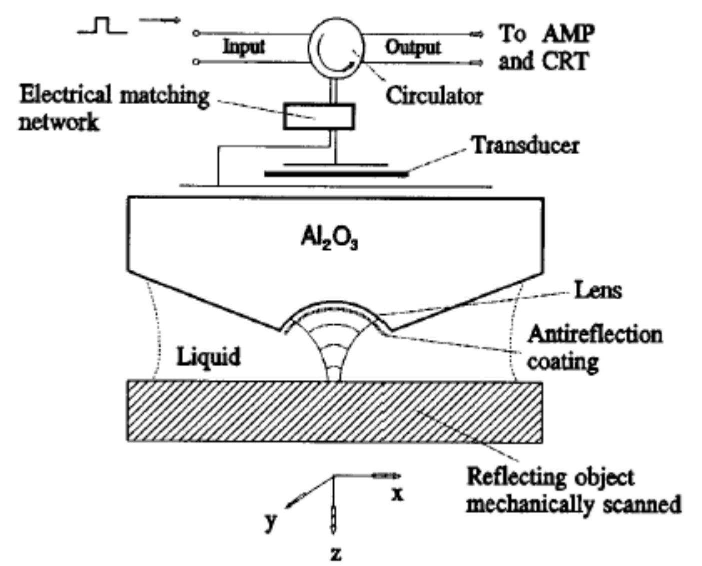


FIG. 1. Cavity with quartz rod, the volume V of which is exposed to the electric field. Lead L critically coupled to cavity.



ii) Acoustic microscopes

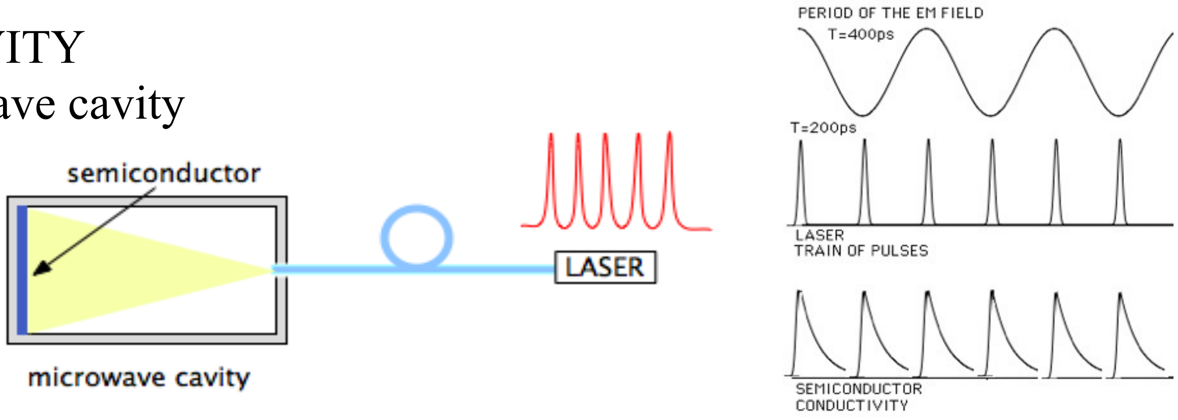
Excitation of resonant modes in sapphire blocks (typical frequency 3 GHz)

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

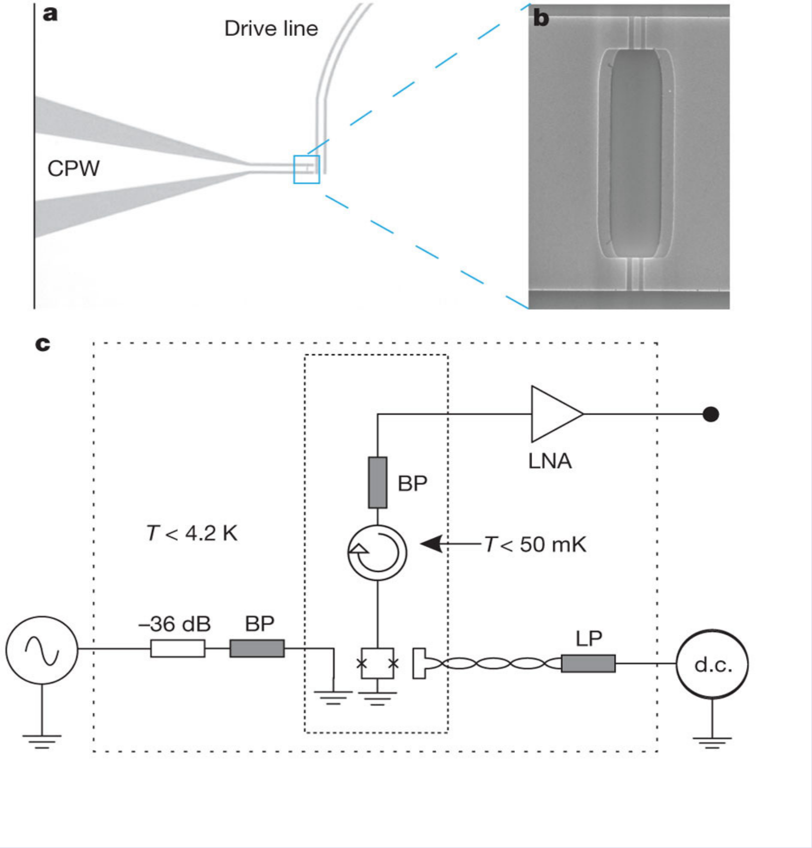
Accelerating reference frame for electromagnetic waves in a rapidly growing plasma: Unruh-Davies-De Witt radiation and the nonadiabatic Casimir effect
E. Yablonovitch *Phys. Rev. Lett. Vol. 62, 1989*

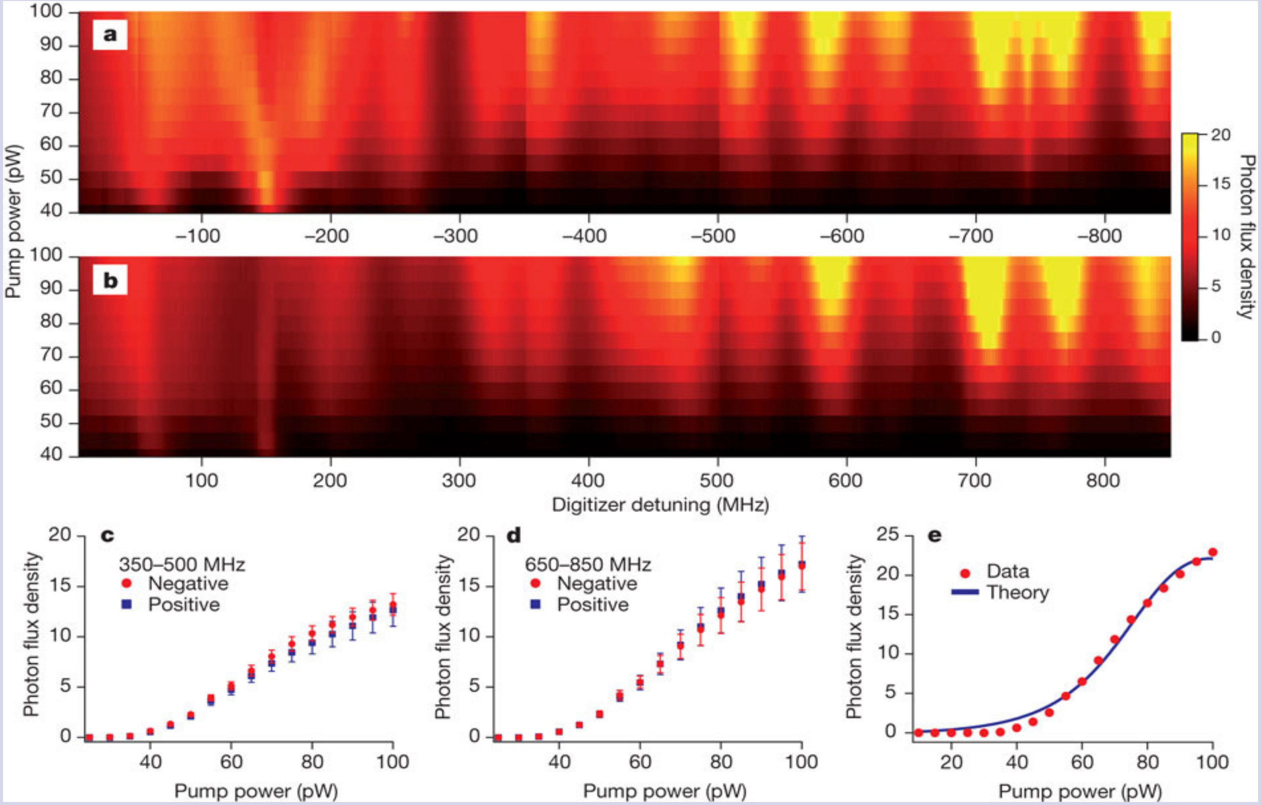
Parametric excitation of vacuum by use of femtosecond pulses
Y. E. Lozovik, V.G. Tsvetus and E. A. Vinogradov *Physica Scripta Vol. 52, 1995*

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

Single-mirror DCE

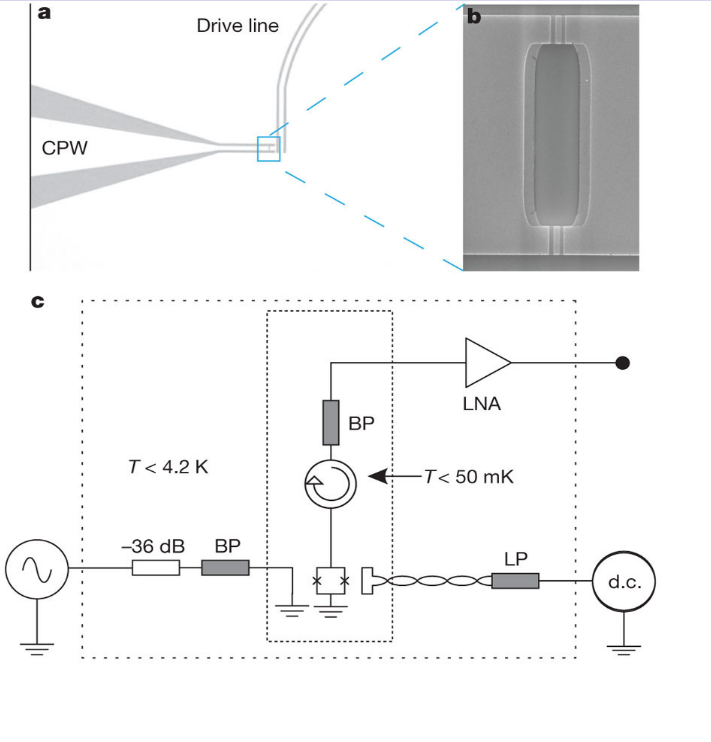
CM Wilson *et al*. *Nature* **479**, 376-379 (2011)

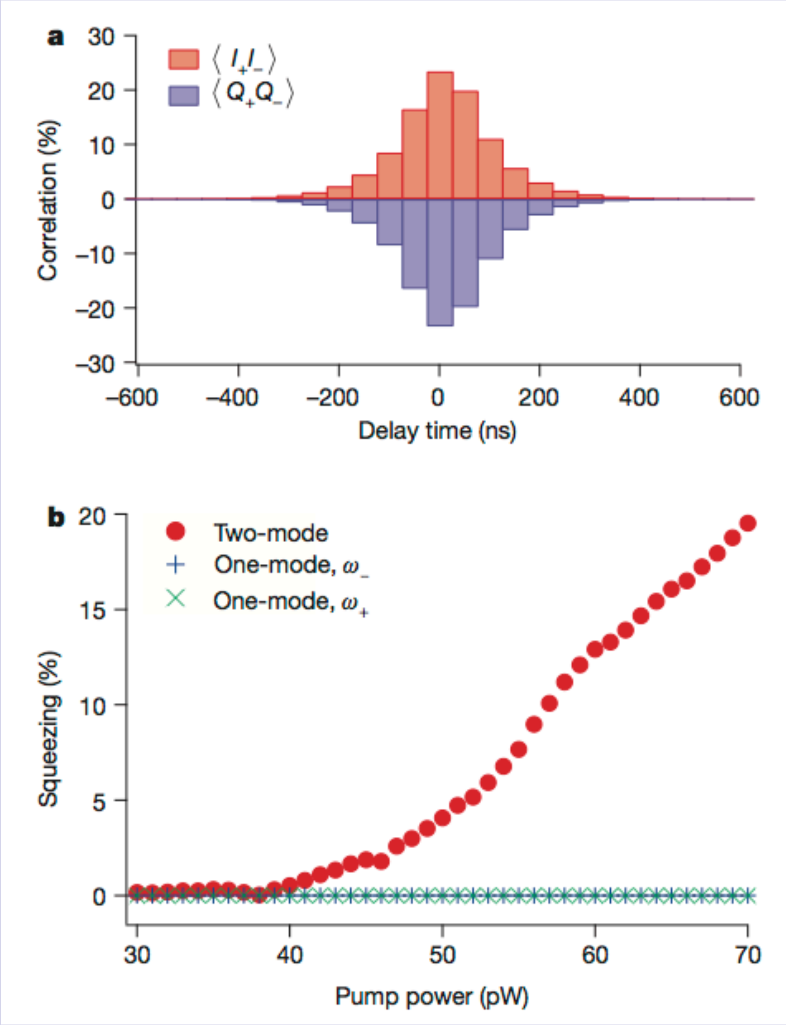




Single-mirror DCE

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

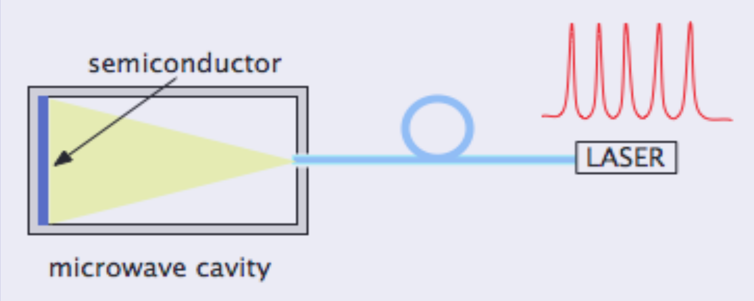
$$\omega_d = \omega_+ + \omega_-$$

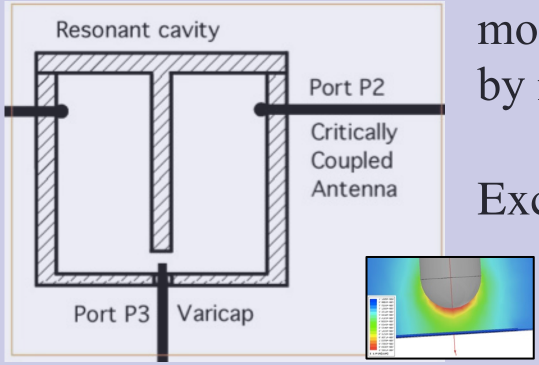
Alternative approaches

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

modulation of the conductivity

Excitation source: laser



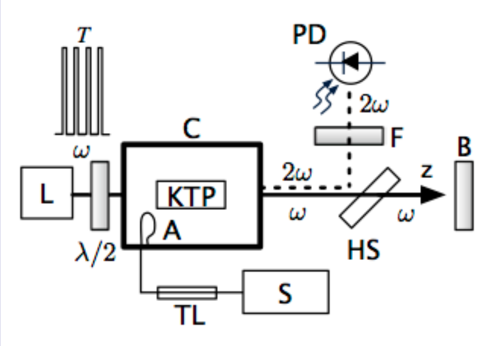


modulation of the cavity gap capacitance
by means of a VARICAP

Excitation source: a radiofrequency generator

modulation of the index of refraction
in a NONLINEAR CRYSTAL

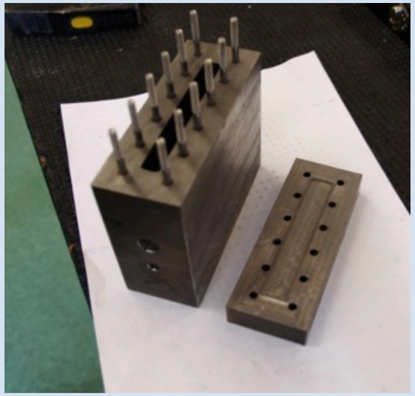
Excitation Source: laser



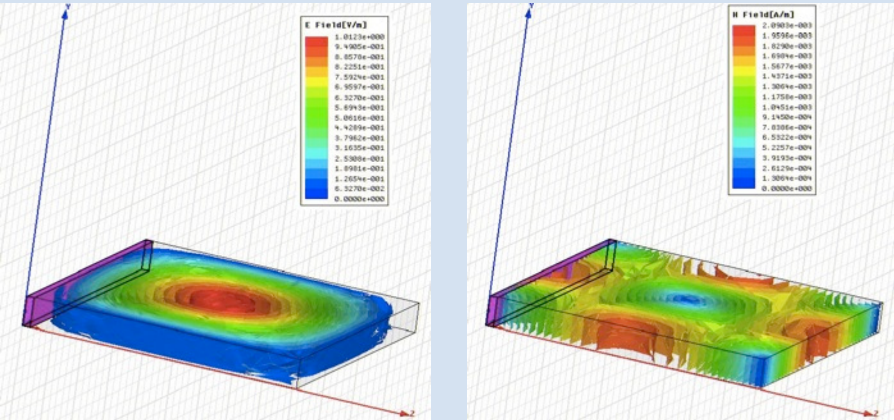
Microwave Cavity

Nb superconducting cavity

(80 x 90 x 9) mm^3



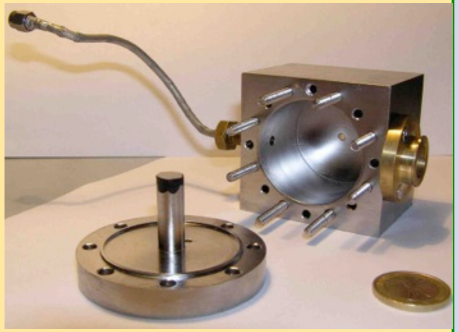
E, H field profiles



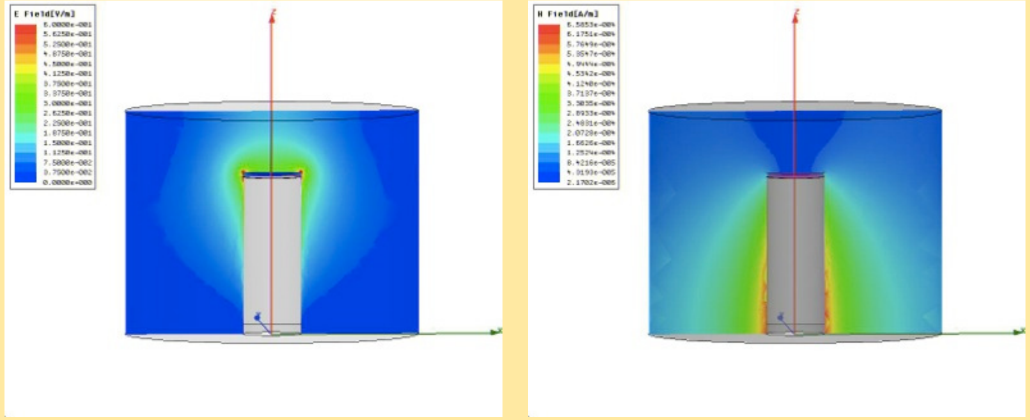
Cylindrical reentrant cavity

($\Phi_{cav} = 42$ 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



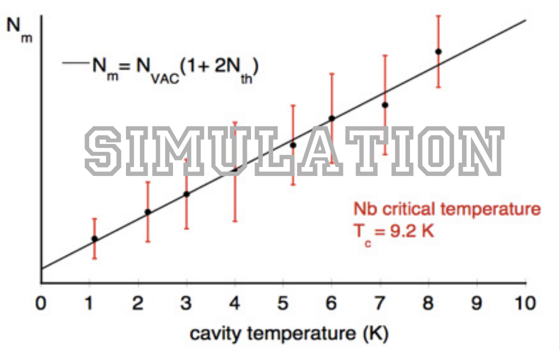
E, H field profiles



MIR experimental scheme

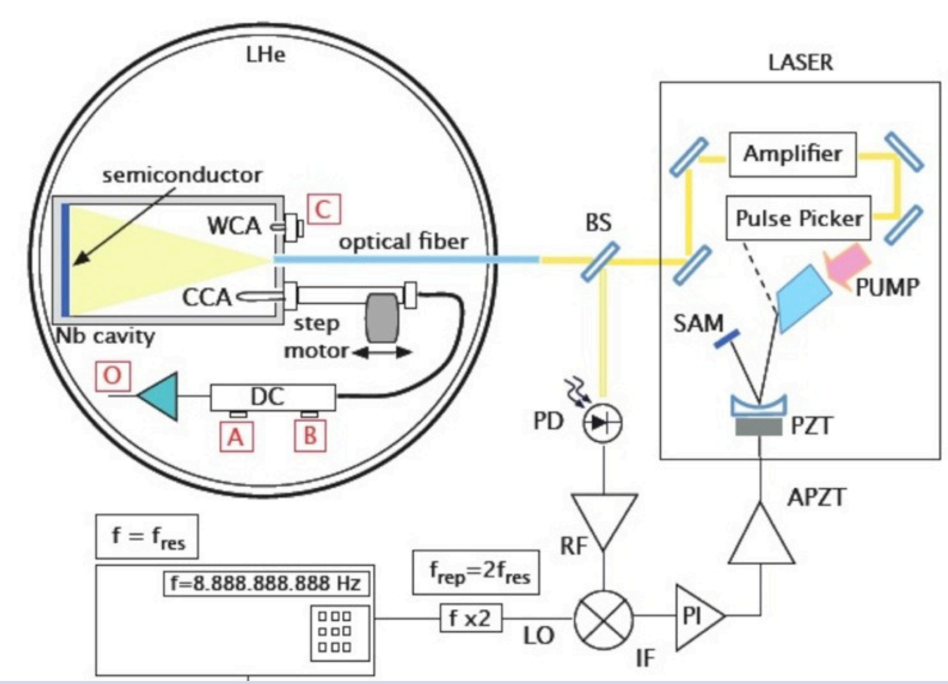
parametrically excited photons could initially be seeded by thermal fluctuations instead of vacuum fluctuations…

cryogenic environment

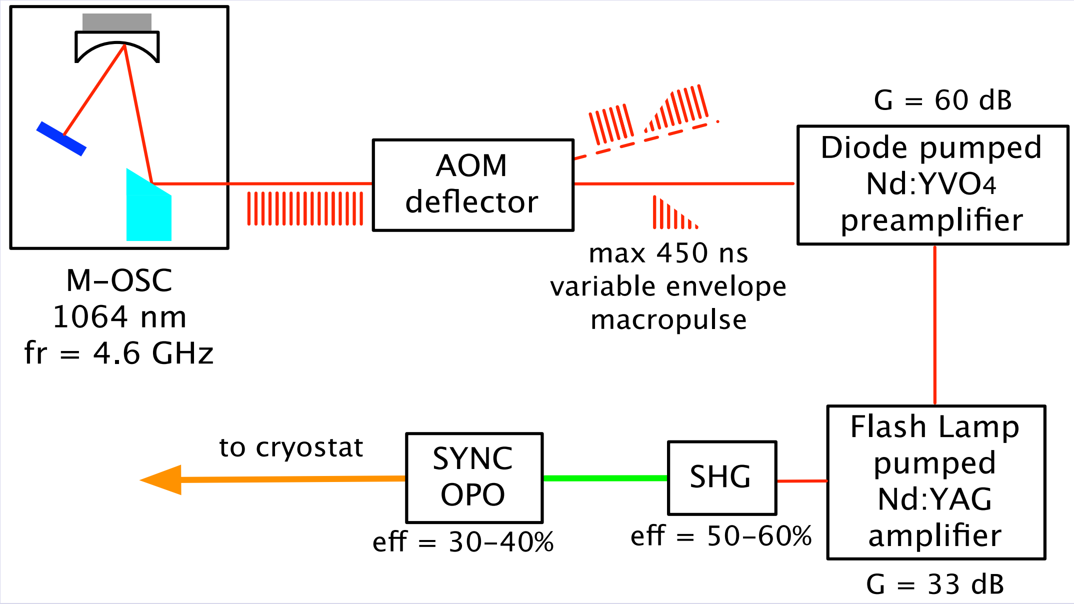


30 l

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



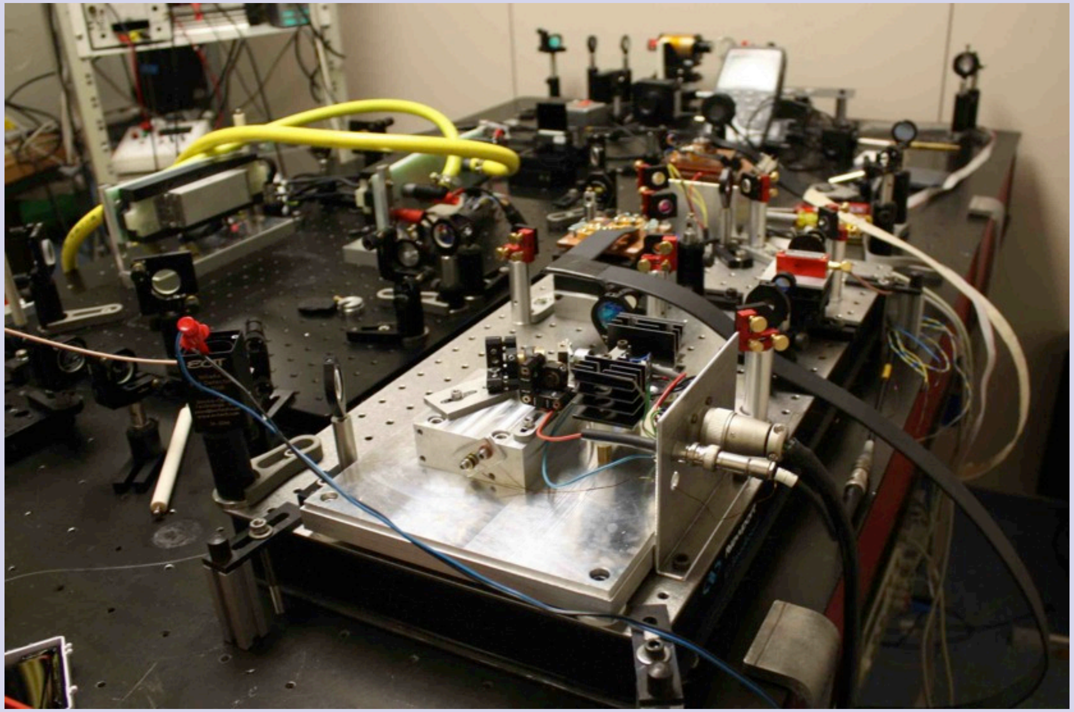
Laser system - 1



Oscillation is performed for a finite interval of time

$E_{\text{pulse}} \approx 10\ \mu\text{J}$;
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



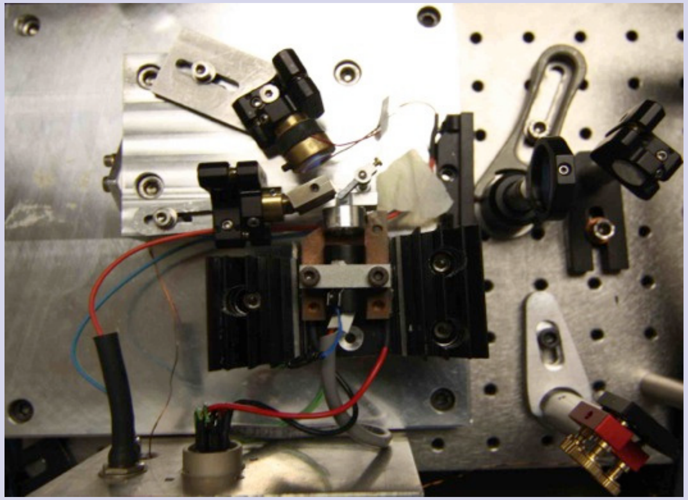
FINAL SPECS
- high frequency repetition rate ($f_{rep} \approx 5$ GHz, stability better than the cavity BW 1 kHz),
- tunable f_{rep},
- 10 ps pulses duration,
- $E_{\text{pulse}} \approx$ few microjoules,
- 780 – 820 nm output wavelength

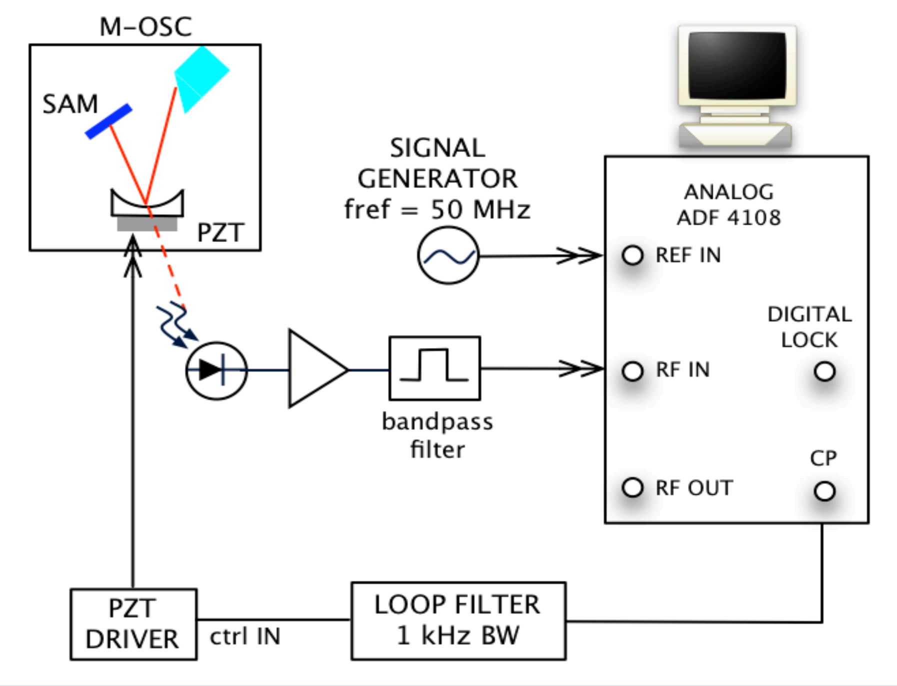
Optics Express **13**, 5302 (2005)
Optics Express **14**, 9244 (2006)
Optics Express **16**, 15811 (2008)

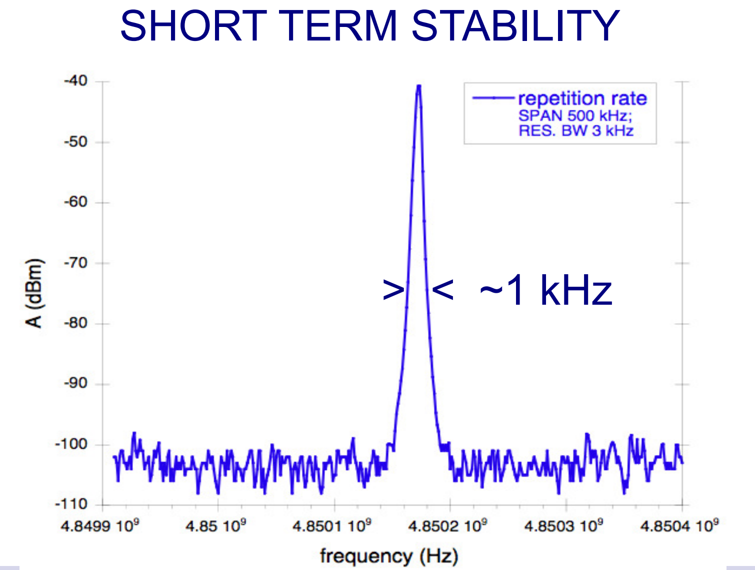
Laser system - 2

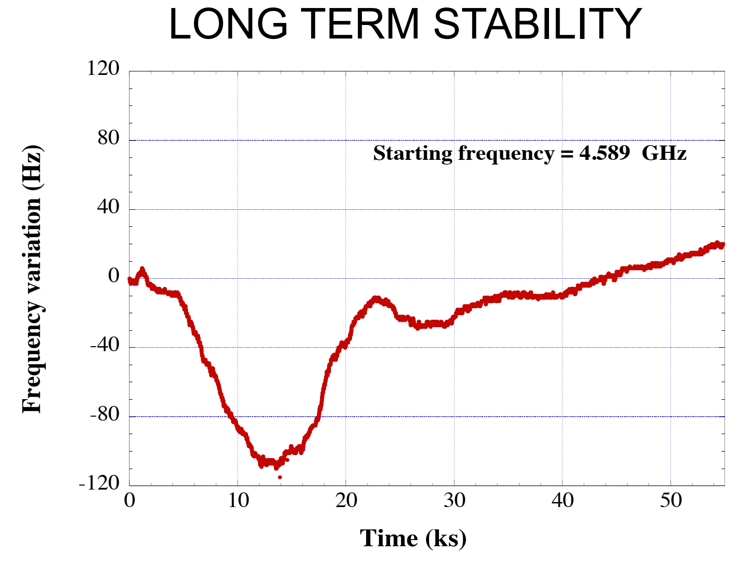
LASER repetition rate stability and tuning

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









Semiconductor

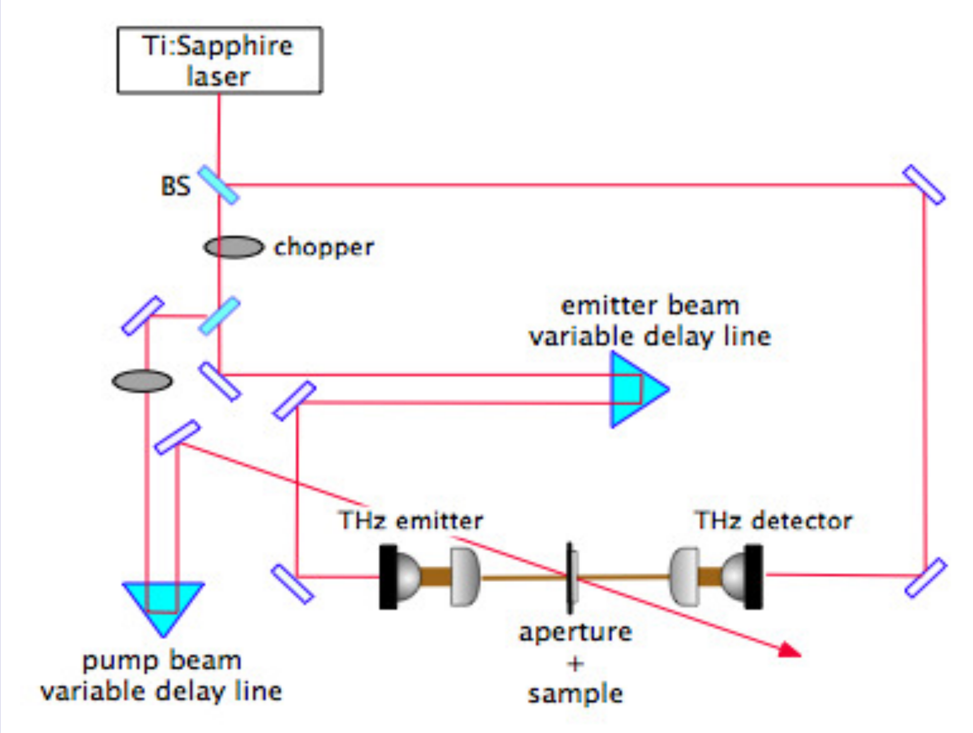
Requirements: high mobility (1 $m^2/V\ s$)
short recombination time (a few picoseconds)

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

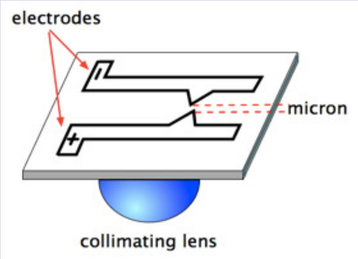
SI GaAs irradiated with thermal neutrons (Italy, USA)	Foulon *et al.* 2000, *J. Appl. Phys.* **88**, 3634
SI GaAs irradiated with Au, Br ions (Tandem accel. in LNL)	Mangeney *et al.* 2002, *Appl. Phys. Lett.* **80**, 4711
SI GaAs irradiated with 1-5 MeV protons (CN accel. in LNL)	Mangeney *et al.* 2000,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

Measurement of the recombination time and mobility of the irradiated samples

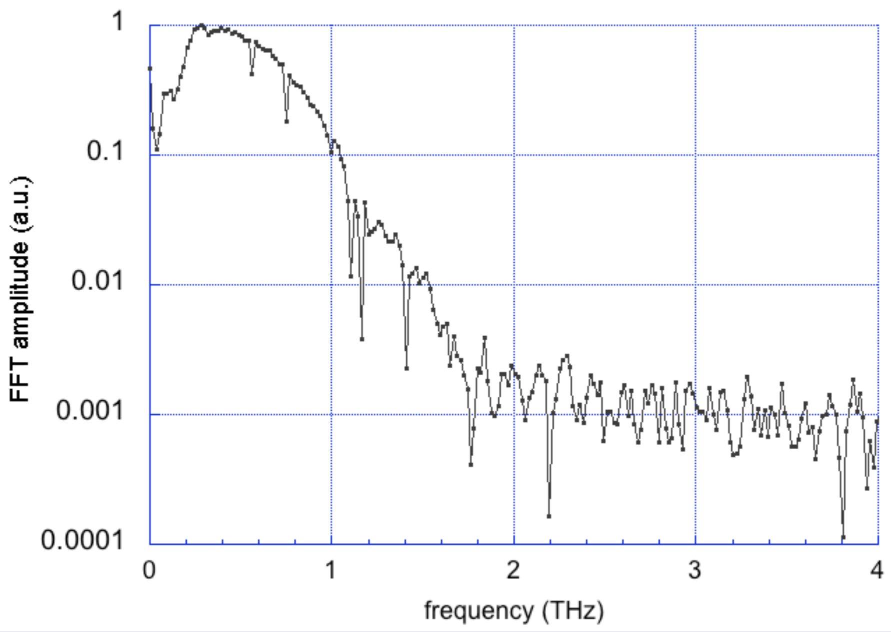
Optical-pump terahertz-probe setup

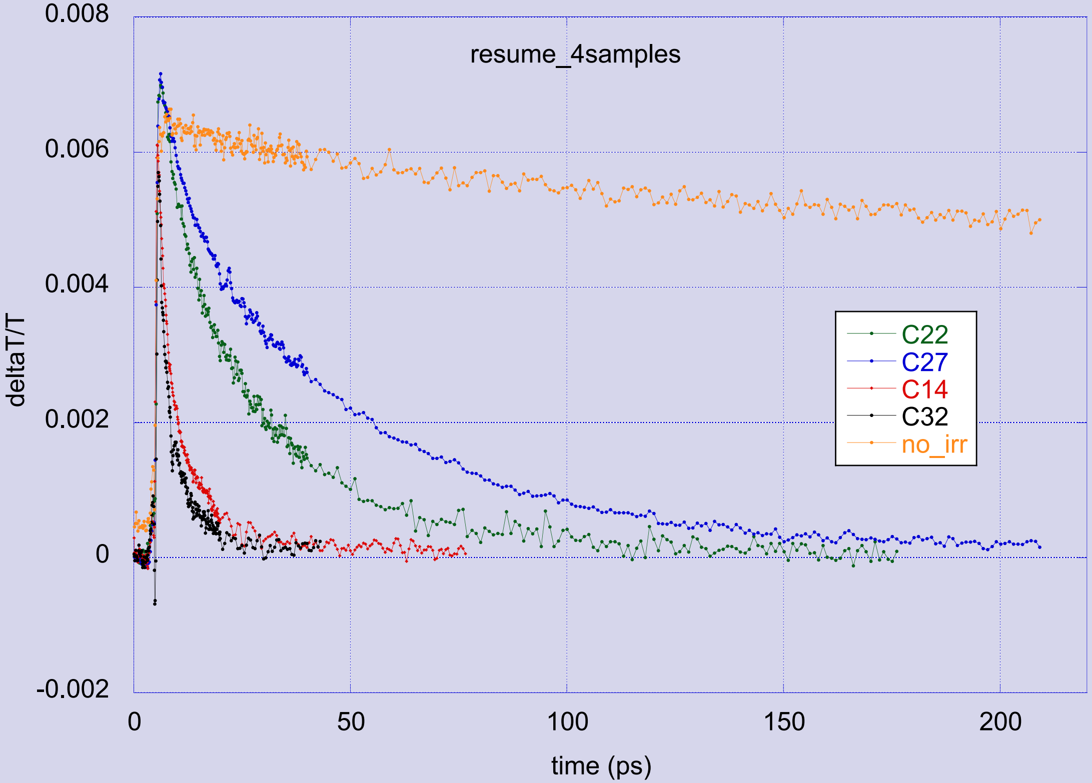


1. Same concentration of free carriers produced as in the plasma mirror ($n \approx 10^{17}\ cm^{-3}$);
2. Measurements are conducted at different temperatures in the range 300 – 10 K in a cryocooler

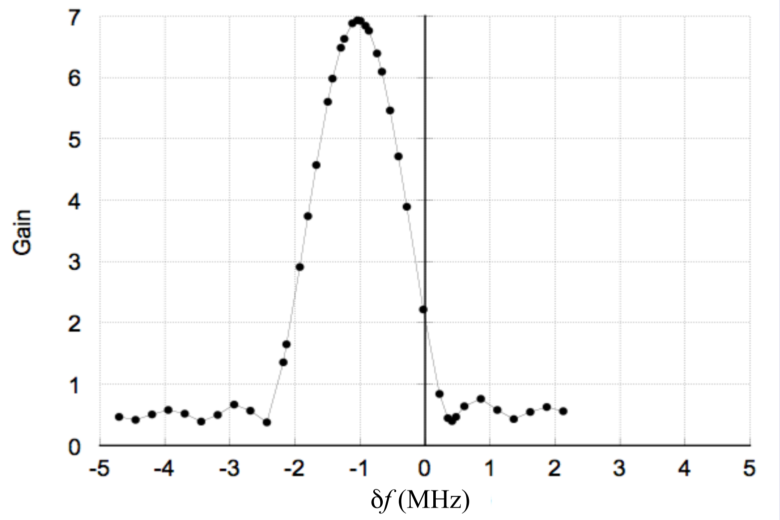


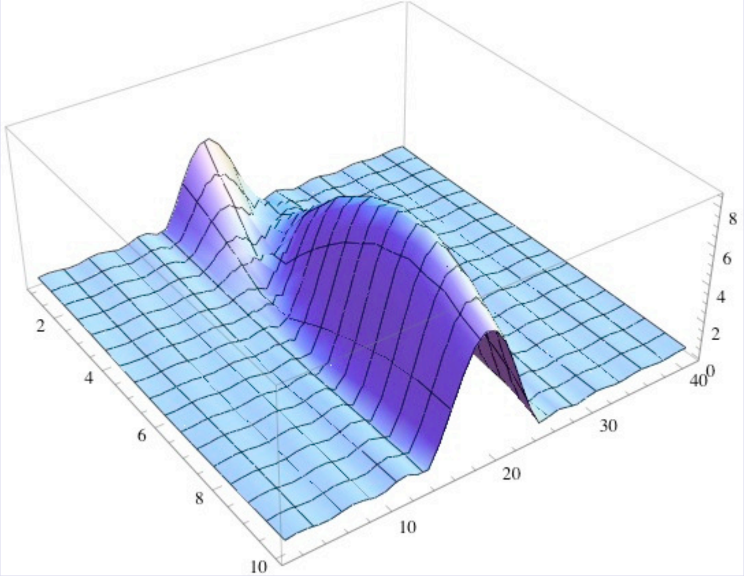
Semiconductor





Experiment simulation: RLC circuit

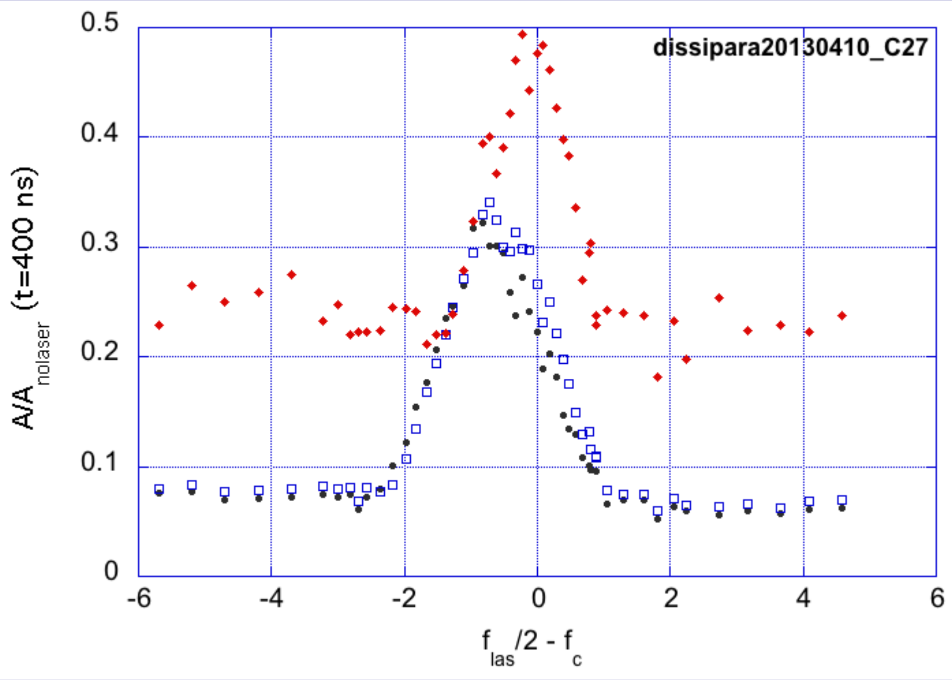




1. exponential growth at the parametric resonance; decaying oscillations when detuned
2. higher order maxima in the gain vs. δf plot are observed
3. the maximum of the amplification is found at $f_{\mathrm{rep}}=2\,f_0+\delta f$ (in our experiment the excitation is not a pure harmonic signal);
4. If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

How to test a cavity parametric amplifier for DCE

- 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



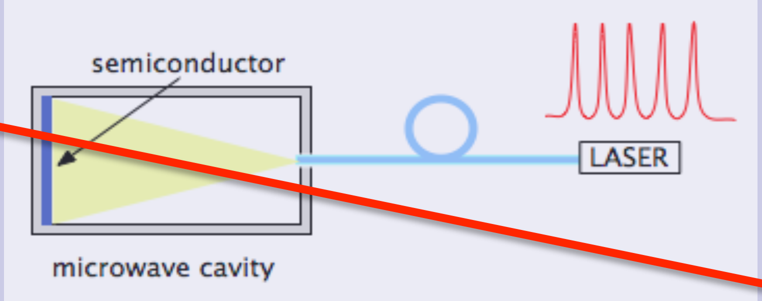
The DCE with the '*semiconductor approach*' is not detectable due to inherent dissipative phenomena in the parametric amplification process.

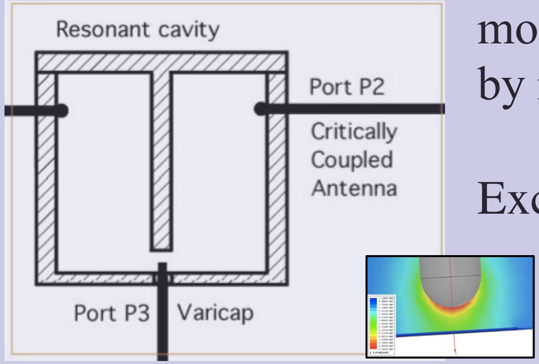
Alternative approaches

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

~~modulation of the conductivity~~

Excitation source: laser



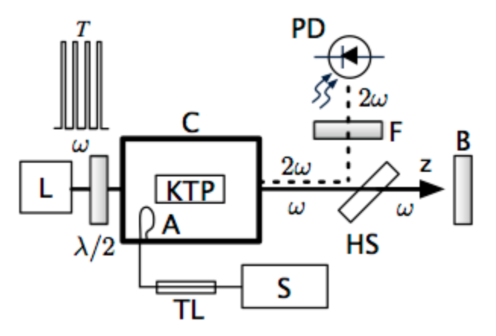


modulation of the cavity gap capacitance
by means of a VARICAP

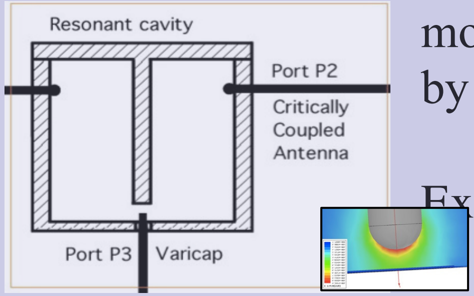
Excitation source: a radiofrequency generator

modulation of the index of refraction
in a NONLINEAR CRYSTAL

Excitation Source: laser



Study of a single-mode thermal field



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)

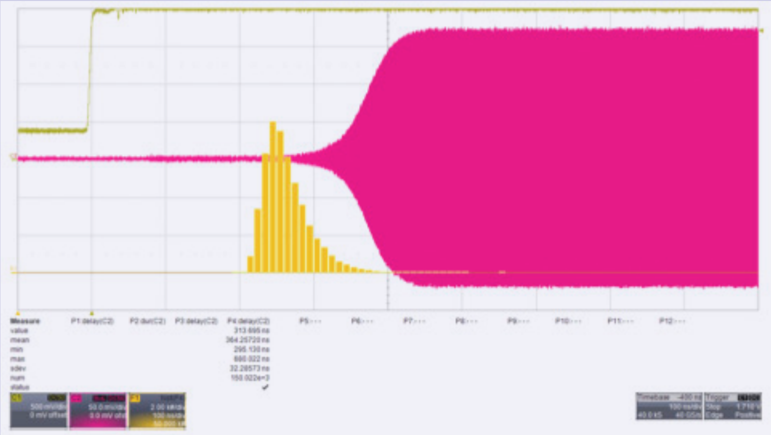
$$P_\nu(n) = \frac{1}{\bar{n}+1}\left(\frac{\bar{n}}{\bar{n}+1}\right)^n$$

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

It is a parametric amplifier

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

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

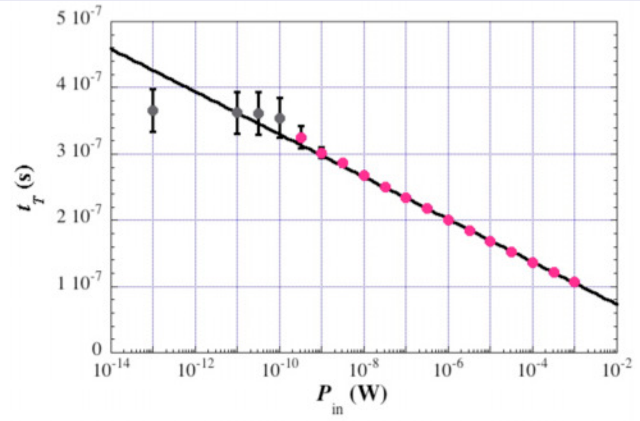


exponential growth of the signal seeded by
external/thermal photons at T=300 K

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

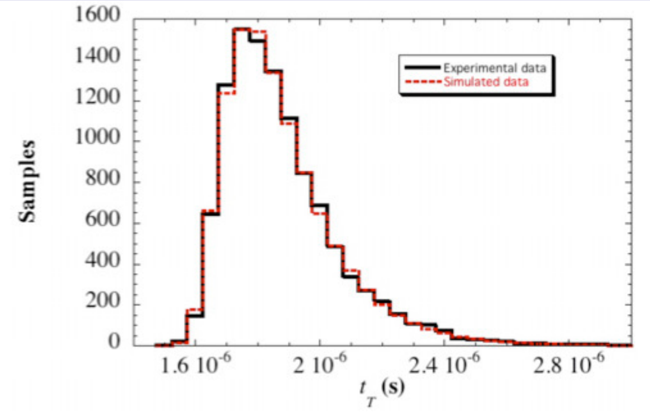
$$t_T = \tau_p \left[\ln \frac{P_T}{P_{out}(0)} - \ln g(\theta) \right]$$

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



Fundamental test of the cavity par. amp.

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

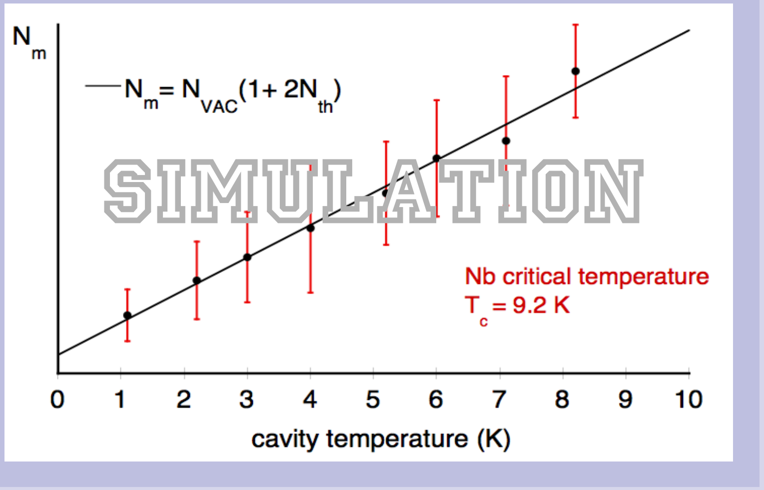
E_0 thermal or external field

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

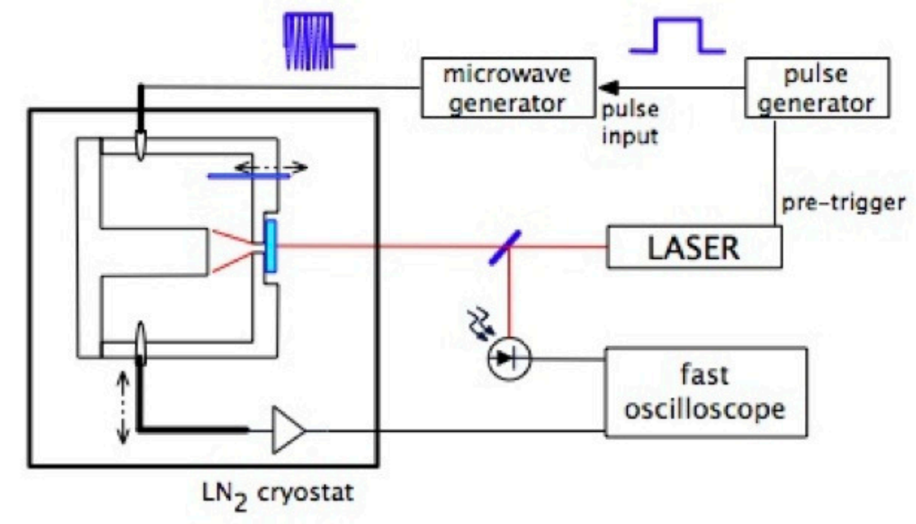
n number of pulses

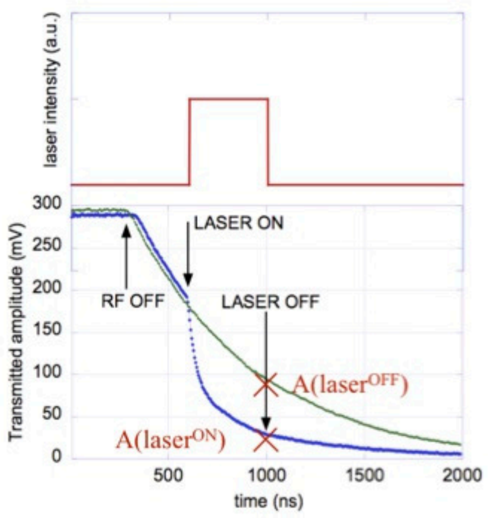
$F(A_0)$ gain coefficient

$|\chi_{\max}|$ 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