# Sub-THz Photons in the Universe and in my life.

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**Abstract.**
Keep our eyes open. This could be my maxim, especially in 2015, international year of LIGHT. We have natural photons detectors. However, there are not simple spectrum detectors. Three orders of magnitude frequency below these visible photons are the THz and sub-THz photons, the main topics of this conference series. They played also a fundamental role all along my life, and recently for everybody when understanding the evolution of the Universe as a whole, or in the amazing single photon quantum games.

## I. THE VISIBLE PHOTONS.

After Newton who discovered the white light splitting in its spectrum (rainbow colors), physicists thought everything is understood for human vision.
The German genius Goethe established with careful experiments the basic triangle of "primary colors" red-green-blue (creating all human color sensations, for instance with any computer or TV screen), and the complementary colors cyan-magenta-yellow, which are the inks necessary (on white paper background) for all printers, as shown in the cartoon below, published a week before the three cartoonists were killed by terrorists on 2015 JAN 7th. Black is added for the texts.

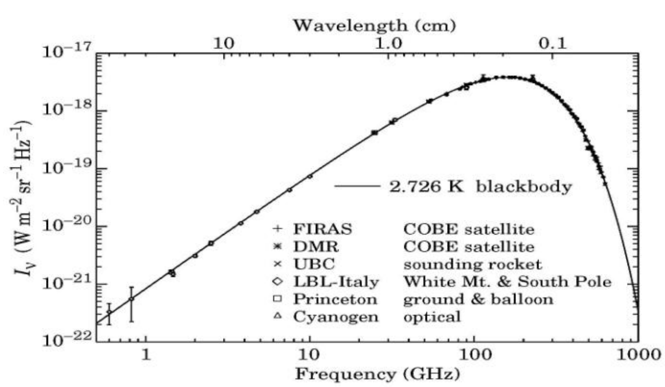

Detail of former French Pt Sarkozy by famous cartoonist Cabu, where dots are quite visible, the trick of the American painter Roy Lichtenstein.
For color movie pictures, Technicolor was created in the thirties at Hollywood. It is very simple to take a color movie, using three black-and-white films, if the natural image is split through primary filters: red, green and blue. I used these filters to make the portrait of my wife in the early eighties. There are successively three exposures, with the white mask on the face moved from bottom to top. Meanwhile, the black hair is moved against the white background, so that appear the complementary colors cyan (no red), magenta (no green) and yellow (no blue). Naturally are also observed the sums cyan+yellow=green, magenta+yellow=red…

## II. THE DOMINANT SUB-THz PHOTONS.

Ken BUTTON had the genius to understand, forty years ago, how fruitful could be the exploration of the less known electromagnetic domain, between microwaves and infrared. I must say how much I owe to him. His remarkable organization, during decades, for obtaining the "collisions" of scientists from extremely various branches of Physics around the famous "THz technology gap", surpassed the critical reaction mass!

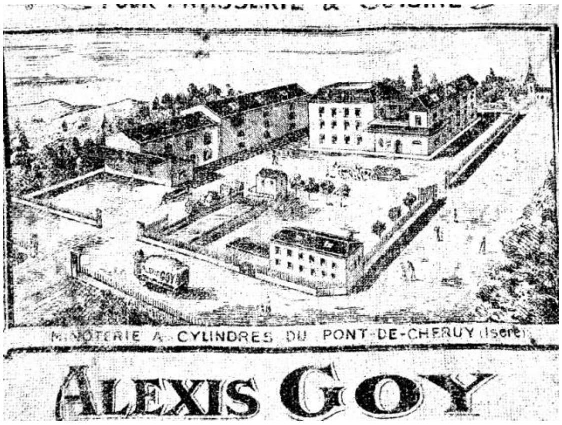
In particular, the splendid recent complete sky survey by Planck satellite improves the "Big Bang" theory.

It is remarkable that the 2.726 K blackbody cosmic radiation (see figure below) contributes to 95% in power of all the observed radiations from the radiofrequencies to the gamma-rays. I have been involved, by an early choice, exactly in this sub-THz frequency domain. This "massive" observation is a great satisfaction to me.



## III. HOW I BECAME A SUB-THz ADDICT.

The engraving below shows my birth place, a mill close to Lyon, France. The square at right of the truck is the visible part of a water canal going subterranean below the mill. A 3.5m high 2m3/s water fall produces 70 kW AC-DC electricity, so that my grand-father Alexis was the first, in the village, to have electricity light at home.




My father still improved this installation, and built a 100% electricity powered truck in 1937. This was very wise, since Germans occupying the village in the years 1940-1944 took all gas for their war purposes. Nevertheless my father could deliver flour to bakeries.

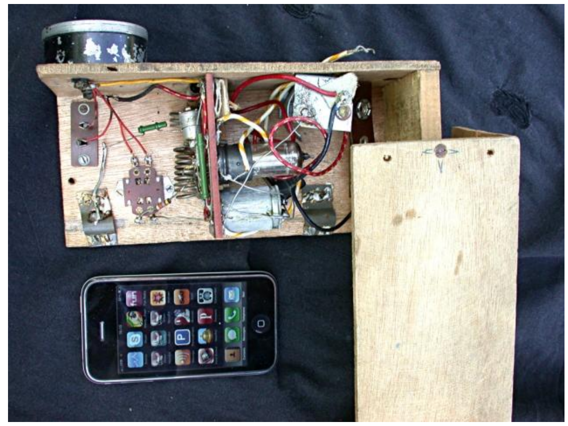
This 100% electric powered vehicle was the very first I ever drove in my life, as a child.

My father introduced me into the radiofrequency techniques, with old vacuum tubes receivers. I started to have my soldering iron hot for all week-ends.

He told me once the decisive sentence:

"You know, my son, wavelength below 10 m are very difficult."

What a challenge! After receivers and emitters in the several MHz range (including a very nice French bomber 2kW all-bands emitter, which was completely forbidden to use, however so fun!), I built walkie-talkies at 144 and 72 MHz with tubes (French transistors of the fifties were very bad at "high" frequencies), see picture thereafter.



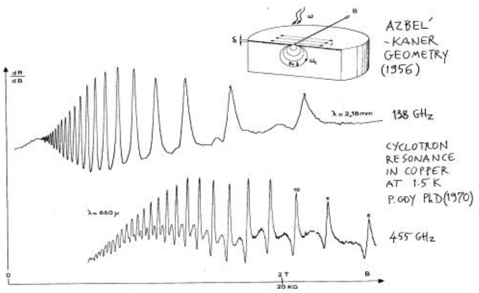
The smartphone gives the scale. From the RF point of view, the frequency is now 20 times higher. That permits a small antenna instead of the (removed) 1 m-long antenna. I could talk to somebody I knew, within 1 km, at a given time said in advance. Today's mobile phones have about the same RF power and primary distance range. They allow you to call anybody in the world, at any time. This is due to digital treatments and dense network of relays.

As a student I entered the "Ecole Normale Superieure" (ENS) which selects good pupils all over France in all domains: literature, history, philosophy, science and mathematics. I have chosen the experimental physics way. Visiting the laboratories at the ENS Physics Department, I saw the exceptional equipment of BWOs sources, made in France under the name "carcinotron", covering the 30-700 GHz frequency domain with >10 mW powers already in the sixties (see below). That's the future! I said to myself.

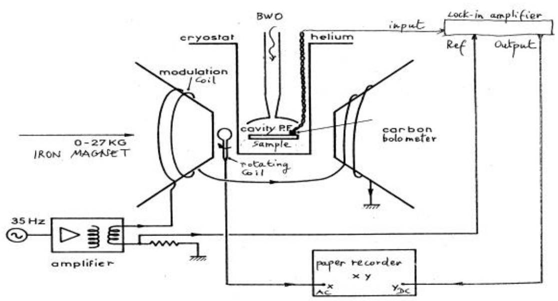
## IV. SOLID-STATE PHYSICS RESEARCH.

My PhD (defense: Paris University 1970) was "Millimeter-Submillimeter-Waves Cyclotron Resonance in Metals".

When placed in a magnetic field B, the electron of effective mass m* rotates at the cyclotron frequency $\varpi$=eB/m*. Matching the BWOs frequencies with magnetic fields was out of range of available magnets of that time. However, the researchers Azbel' and Kaner invented, in Soviet Union, the geometry in which the field B is placed quite parallel to the surface of the metal crystal sample.




In this condition, the electron sees the microwave penetrating only in a very thin skin depth, and can be in phase with it after an integer number of periods of the microwave. At fixed microwave frequency and sweeping the magnetic field, the resonance condition becomes Bn=Bc/n, and is fullfilled even with moderate magnetic field maximum like mine (2.7T).




I worked with a Fabry-Perot cavity, the polished copper spherical mirror, at top, with a coupling hole for the microwave entrance, and the plane single crystal sample, with a detection by a carbon bolomerter sticked on the side of it.

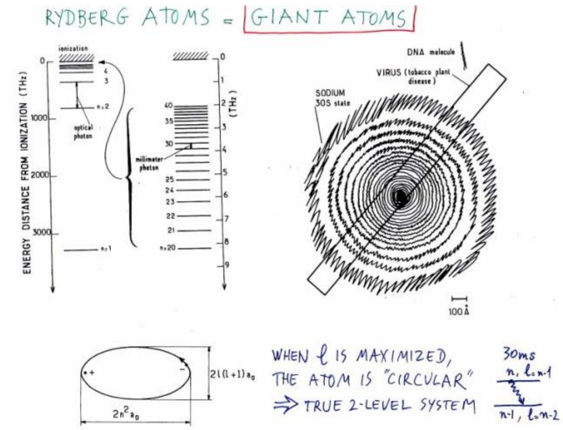
I made studies mostly on large electron-phonon interaction metals (in the frame of superconductivity understanding), in which the phonon energies could be approached by our photon energies (a few meV): Hg, Pb, In, Cd, Nb, and also in a magnetic material Ni, for which the Fermi surface is split.

### V. ATOMIC PHYSICS RESEARCH

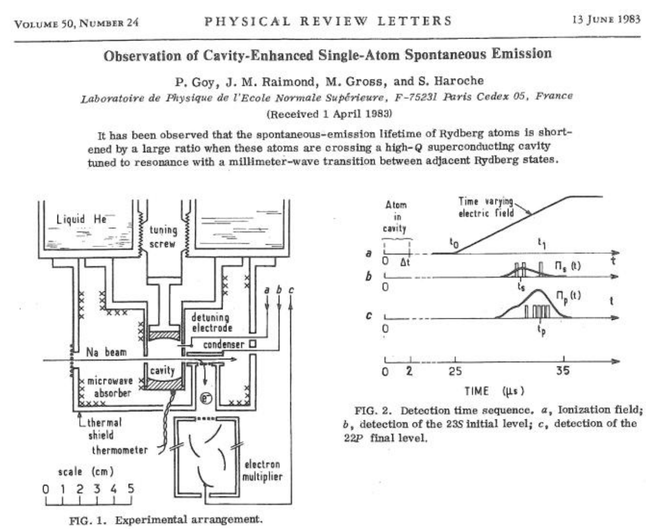
Next door from my room at the ENS Physics Department was an exceptionnally talented physicist Serge Haroche, at right, creating (in 1975, the picture being 38 years later) a five-person group for studying Rydberg atoms.

From left to right: Michel Gross, Jean-Michel Raimond, Claude Fabre, myself and Serge Haroche.

The Rydberg atoms are obtained with alkalis with their valence electron excited, by tunable lasers, close to the ionization threshold. They become "Giant Atoms" and show an incredible sensitivity to mm-smm photons inducing transitions between excited states (that was my job, among all these lasers specialists).




I adapted my Fabry-Perot setup for studying Rydberg atoms.When the population inversion in an atomic transition between levels is enough, one observes the maser (or laser) coherent emission.



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**Observation of Cavity-Enhanced Single-Atom Spontaneous Emission**

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It has been observed that the spontaneous-emission lifetime of Rydberg atoms is shortened by a large ratio when these atoms are crossing a high-Q superconducting cavity tuned to resonance with a millimeter-wave transition between adjacent Rydberg states.

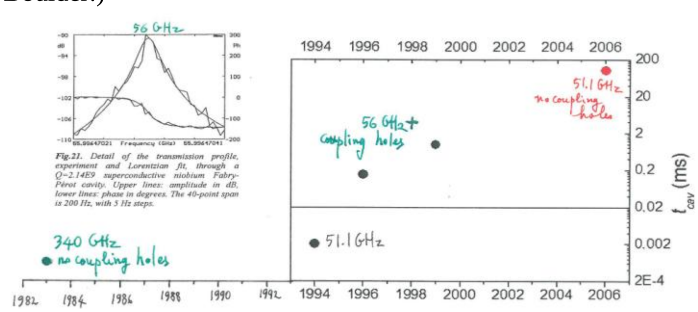


FIG. 1. Experimental arrangement.

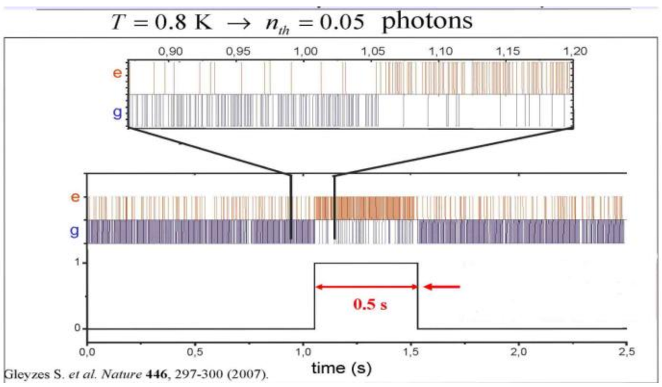
FIG. 2. Detection time sequence. *a*, Ionization field; *b*, detection of the 23S initial level; *c*, detection of the 22P final level.

After polishing Niobium spherical mirrors cooled at Helium temperature, I obtained a quality factor ca 10+6 at 341 GHz, so that the tuning of the cavity made a visible downwards transfer of a single Na atom.

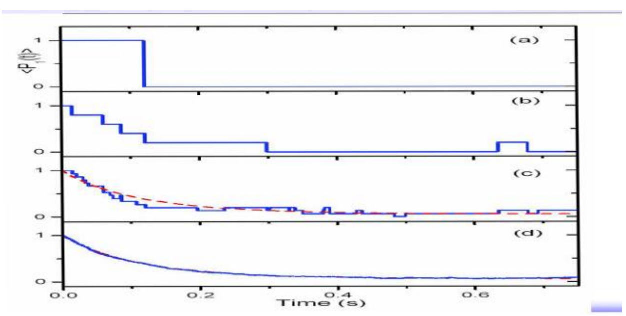
That first experiment was the beginning of a long path to the spectacular control of the very basic quantum situation of a single atom interacting with a single photon (2012 Nobel prize to Serge Haroche, shared with David Wineland of NIST, Boulder.)



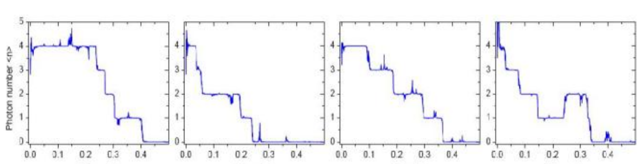
In the previous figure is shown the 23-year improvement of the Nb superconductive cavity, which became, finally, the best open cavity in the world (any frequency). The single photon is captured in this cage for 0.13s, the time necessary to make one turn around the earth! (mine in 1983 made only140 m).




With the last cavity, Quantum Non Demolition measurements are realized by atoms exploring the presence, or not, of the photons inside the cavity. The field of the photons changes the phase of circular Rydberg levels, submitted to another microwave at the cavity entrance and at the cavity output in a Ramsey fringes setup. In the figure above is detected a thermal photon lasting for an exceptional duration (0.5s, i.e. go-and-back for 150,000 km bteween mirrors).




A single photon, injected at time zero, disappears due to finite reflection of mirrors, at a random instant. Top a): experiment with a single photon, b) 5 experiments averaged, c) 15 experiments averaged, d) 900 experiments averaged. Quantum mechanics cannot predict the precise decay time, only the average of many single realizations, which is, by the way, the same as the classical energy decay with time in a finite quality factor cavity.




After injecting 4 photons in the cavity, one observes, thanks to the Rydberg atoms exploring the cavity field (QND), their natural decay, photon per photon. In the last sequence, a thermal photon comes suddendly, moving the total number of photons from 1 to 2, then both disappear quasi-simultaneously.

## VI. INSTRUMENTATION.

The characterization of high-Q cavities needed a specific instrument that I made with a Schottky multiplier HG and a Schottky mixer HM, each working with a centimeter L.O. The HG L.O. at frequency F1 is called "master", and the HM L.O. at frequency F2 "slave". There is a PLL control of the slave versus the master, so that F2=F1–f. I have chosen f=3MHz at the beginning, so that a short-wave amateur radio could select the desired harmonic N among the comb of equally spaced harmonics, for instance N=4, then receiver tuned at 12 MHz. The millimeter frequency Fmm detected is simply the HG frequency F1 read on an ordinary counter, multiplied by N. For instance F1=12.775 GHz for the selected transition between "circular states" of 85Rb: 51c-50c=51.1GHz (Rb is finally chosen for creating Rydberg states, the first excitation steps being performed by infrared solid-state diode lasers).

In december 1985, we went to CERN Geneva, for making our first Nb cavities, characterized by this setup with the short-wave radio, giving a « blop » sound at the loudspeaker, when crossing the very sharp resonance.
Keeping the same "synthesized frequency difference" (not absolute), Michel Gross and myself developed the vector measurement, with a vector receiver in which all downconversions are synchronized by the same quartz as for the f=F1-F2 PLL control. This new setup was patented. The so-called MVNA-8-350 Vector Analyzer was shown for the 1st time at the IRMMW Würzburg conference in 1989, Michael von Ortenberg being the chairman, as well as my vigourous help for installing the heavy system. The 1 THz vector measurement was reached as soon as 1995, and the sart-up AB MILLIMETRE could install its MVNAs, see numbers below, all around the world, for many branches of sub-THz research.