The Lasting Contribution of Acoustic Bar Detectors

Eugenio Coccia

Gran Sasso Science Institute and INFN, Italy

Amaldi 12, Pasadena 13 July 2017

References

Harry Collins

- Gravity's Shadow

The University of Chicago Press

C. B. De Witt and D. Rickles (eds.)

Conference on the role of gravitation in physics. In: Proceedings of conference at Chapel Hill, North Carolina, January 18–23, 1957. Wright Air Development Center (WADC) technical report 57–216, United States Air Force, Wright-Patterson air force base, Ohio (1957))

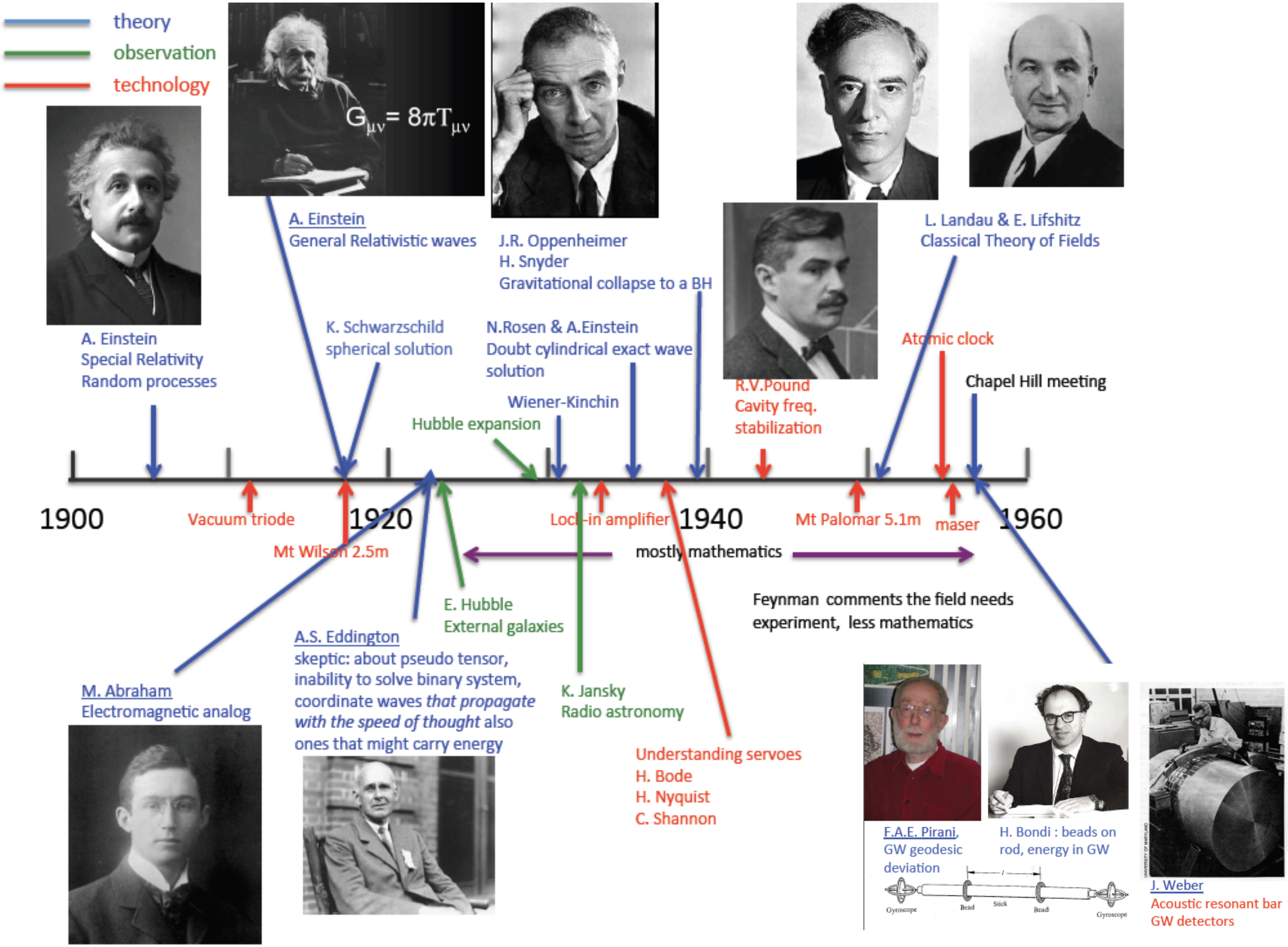
Peter R. Saulson

- Josh Goldberg and the physical reality of gravitational waves

  Gen Relativ Gravit (2011) 43:3289–3299

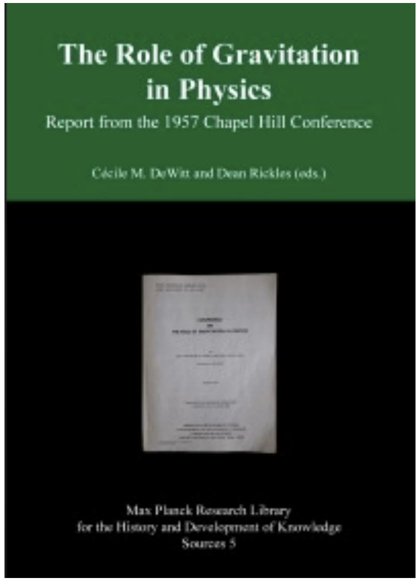
Ugo Amaldi

- “Renaissance man”, Physics World, September 2008.

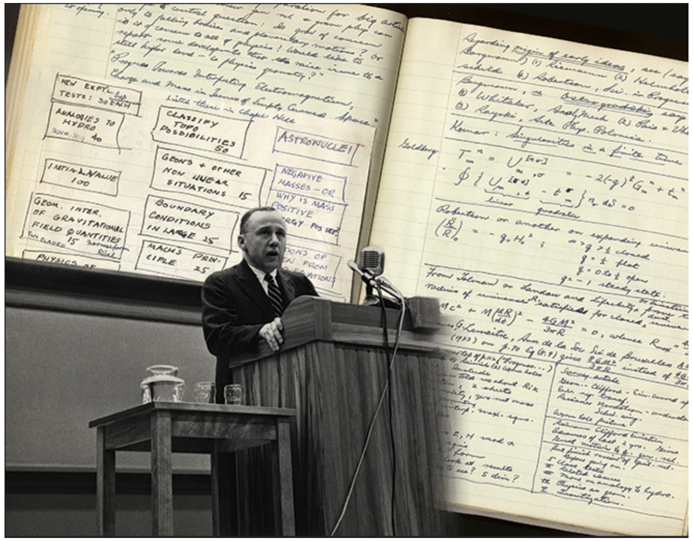


Credit: Ray Weiss

A debate was raging in the '50s: whether gravitational waves even existed as a true physical effect as opposed to a coordinate effect only. Almost incredibly to us today, Einstein often found himself in the anti-gravitational wave camp.



The turning point: the 1957 Chapel Hill Meeting, "Conference on the role of gravitation in physics"



There was no discussion of black holes or neutron stars; those objects had been just barely imagined, but were not known in any astrophysical context.

Attention devoted to the physical reality of gravitational waves, and in particular focused on the question of whether gravitational waves could be understood to interact in a physically meaningful way with a detection device.

Chapter 14
Measurement of Classical Gravitation Fields

Felix Pirani

Because of the principle of equivalence, one cannot ascribe a direct physical interpretation to the gravitational field insofar as it is characterized by Christoffel symbols $\Gamma^{\mu}_{\nu\rho}$. One can, however, give an invariant interpretation to the variations of the gravitational field. These variations are described by the Riemann tensor; therefore, measurements of the relative acceleration of neighboring free particles, which yield information about the variation of the field, will also yield information about the Riemann tensor.

Now the relative motion of free particles is given by the equation of geodesic deviation

$$\frac{\partial^2 \eta^\mu}{\partial \tau^2} + R^{\mu}_{\nu\rho\sigma} v^\nu \eta^\rho v^\sigma = 0 \quad (\mu,\nu,\rho,\sigma = 1,2,3,4) \tag{14.1}$$

Here η^μ is the infinitesimal orthogonal displacement from the (geodesic) worldline ζ of a free particle to that of a neighboring similar particle. v^ν is the 4-velocity of the first particle, and τ the proper time along ζ. If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (14.1) becomes

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + R^{a}_{0b0} \eta^b = 0 \quad (a,b = 1,2,3,) \tag{14.2}$$

Here η^a are the physical components of the infinitesimal displacement and R^a_{0b0} some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One

can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

Now the Newtonian equation corresponding to (14.2) is

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + \frac{\partial^2 v}{\partial x^a \partial x^b} \eta^b = 0 \tag{14.3}$$

It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence $R^a_{0b0} \sim \frac{\partial^2 v}{\partial x^a \partial x^b}$ between equations (14.2) and (14.3), for the respective empty-space equations may be written $R^a_{0a0} = 0$ and $\frac{\partial^2 v}{\partial x^a \partial x^b} = 0$. (Details of this work are in the course of publication in *Acta Physica Polonica.*)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

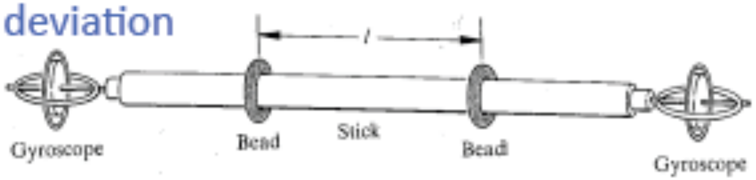
PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

LICHNEROWICZ: Is it possible to study stability problems for η?

PIRANI: It is the same as the stability problem in classical mechanics, but I haven't tried to see for which kind of Riemann tensor it would blow up.

F.A.E. Pirani, GW geodesic deviation

H. Bondi : beads on rod, energy in GW



Felix Pirani points out the transparent connection between the equation of geodesic deviation and Newton's Second Law, as long as one identifies $\mathbf{R}_{a0b0}$ with the second derivative of the Newtonian potential (i.e., as the tidal field.)

The main point was that it is relative accelerations of neighboring free particles that are the physically meaningful (i.e.,measurable) ways to observe gravitational effects

To make sure everyone sees how important and simple this is, he remarks, "By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor".

from: P. Saulson, Gen Relativ Gravit (2011) 43:3289–3299

Bondi saw immediately the importance of Pirani's argument. After the formal presentation of Pirani's paper in the Proceedings, there is recorded a brief exchange between Bondi and Pirani.

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\mathbf{d}\eta/\mathbf{d}\tau$ term, to learn what part of the Riemann tensor would be the energy-producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring". You can invent a system with such a term quite easily.

Joe Weber was then a U. of Maryland professor, on sabbatical in 1956-57 with John Wheeler at Princeton.

At the Chapel Hill conference, Wheeler and Weber heard the key talk by Pirani. They understood the message: GW's were real, because they could (in principle) be detected.

- **GWs are detectable in principle**

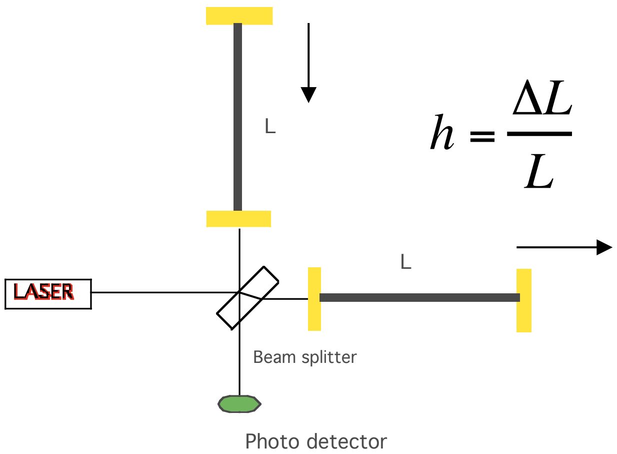
  The equation for geodetic deviation is the basis for all experimental attempts to detect GWs:

$$\frac{d^2 \delta l^j}{dt^2} = -R_{joko} l^k = \frac{1}{2} \frac{\partial^2 h_{jk}}{\partial t^2} l^k$$

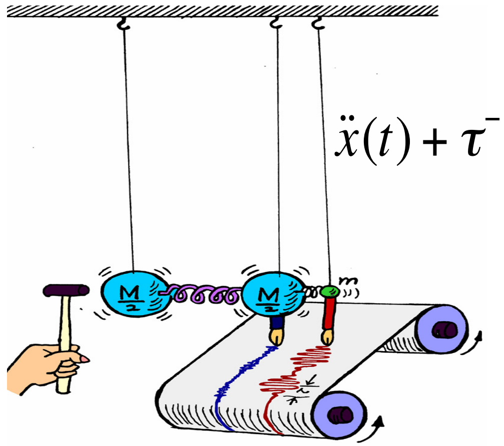
- **GWs change (δl) the distance (l) between freely-moving particles in empty space.**

  They change the proper time taken by light to pass to and fro fixed points in space

  In a system of particles linked by non gravitational (ex.: elastic) forces, GWs perform work and deposit energy in the system

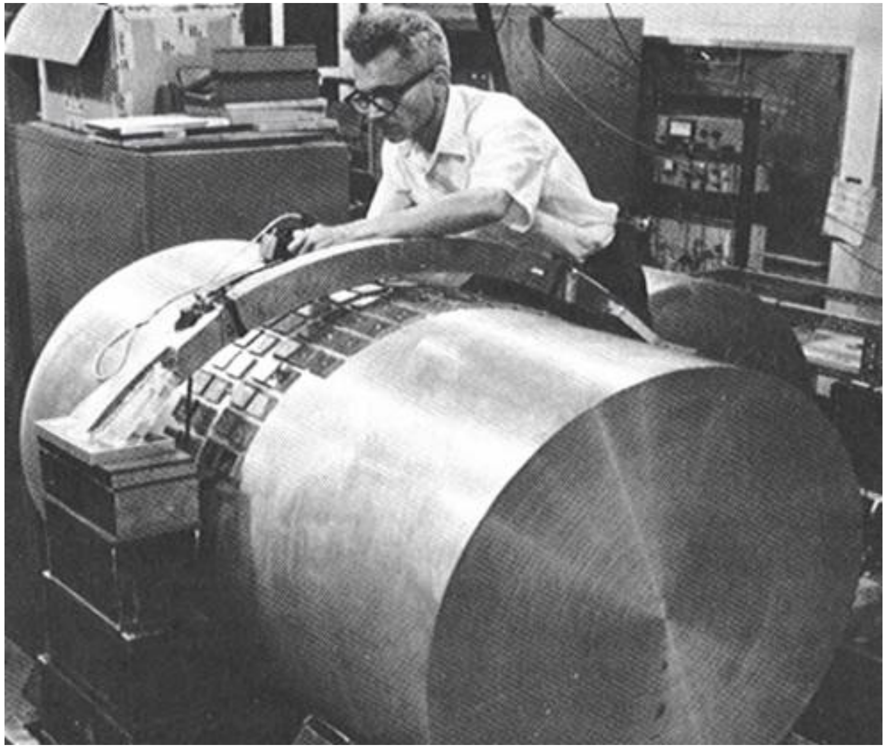


$$h = \frac{\Delta L}{L}$$



$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{l}{2}\ddot{h}(t)$$

It was an act of genius (and/or madness) to transform the *gendankenexperiment* of Pirani into a working apparatus and an observing program. *(P. Saulson)*



Weber's detector was a cylinder of aluminum, each end of which is like a test mass, while the center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

In 1969, Weber made his first (of many) announcements that he was seeing coincident excitations of two detectors.

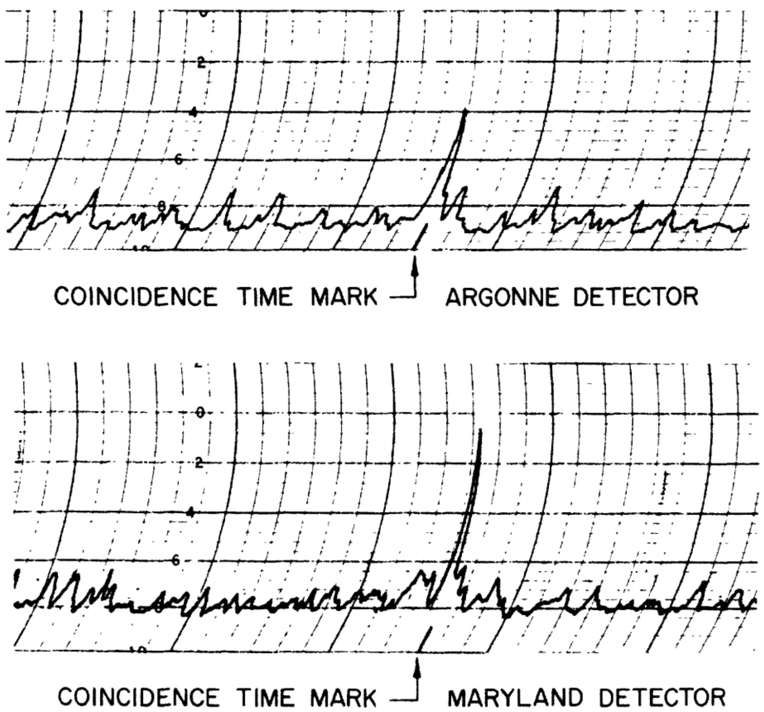
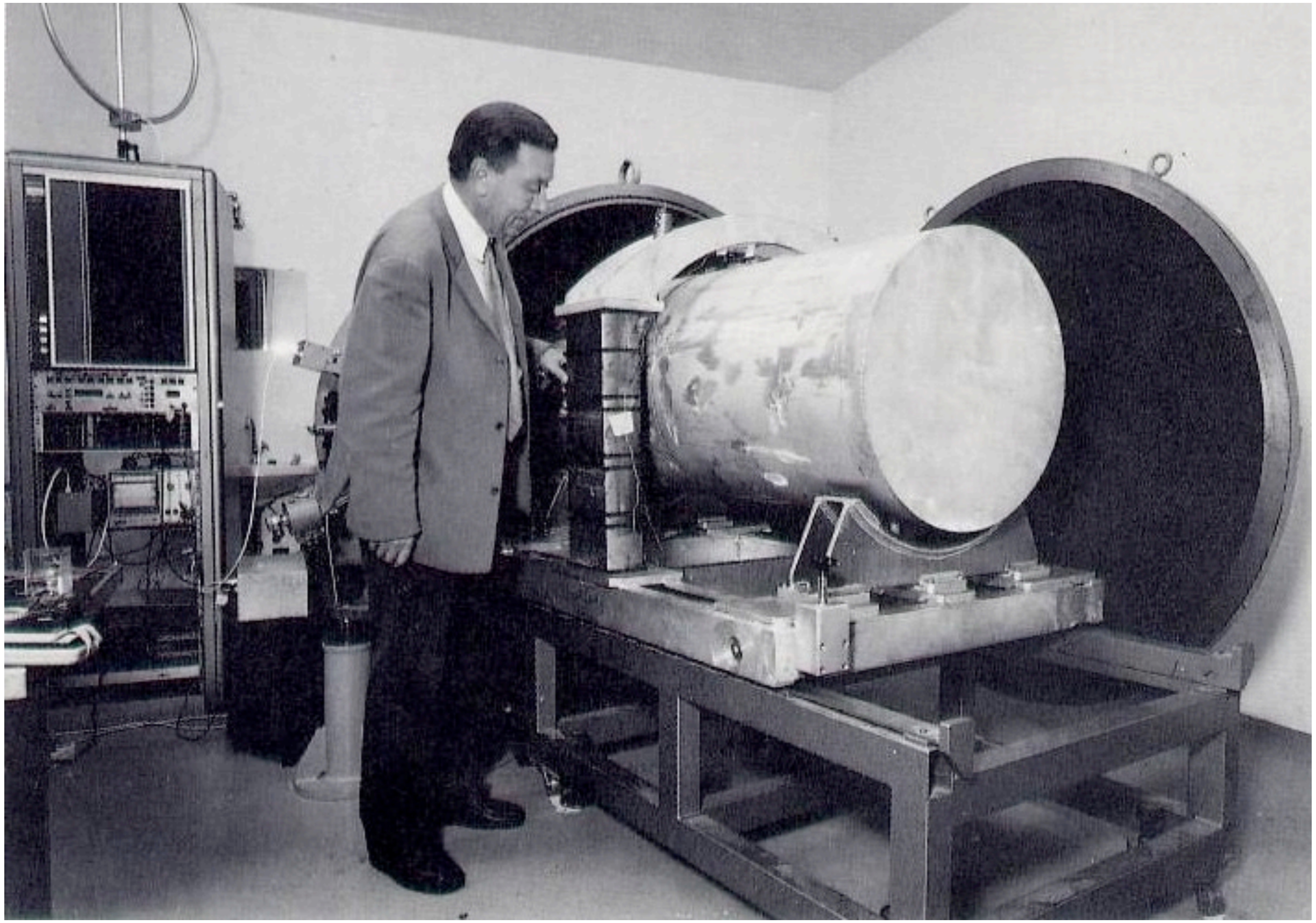


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

The flame of the passion for the detection and study of spacetime perturbations burned in several countries and Laboratories.

But soon it became clear that Weber's signals weren't real.

Billing and the bar at Munich



Ron Drever

Jim Hough

R. Garwin

W. Fairbank

E. Amaldi

1965-1975
Room T bars

Bell Labs
Frascati
Glasgow
IBM
Rochester
Max Planck
Rome

1975-1990+
Cryogenic bars

Geneva
Frascati ; Legnaro
Louisiana
Moscow
Perth
Rochester
Stanford

2000 ->
Spherical cryogenic detectors

Brazil
Netherlands

A. Tyson

W. Hamilton

P. Michelson

Credit: Ray Weiss

Edoardo Amaldi

This was the atmosphere in the Institute of Physics of the University of Rome in 1970, where the most influential Italian physicist worked.

Edoardo Amaldi (1908 – 1989), worked in nuclear physics in the Fermi group before the Second World War and, afterwards, he rebuilt the Italian physics, giving fundamental contributions to particle and astroparticle physics. He also played a key role in the setting up of CERN and the European Space Agency, and in promoting arms control.

The beginning:
I ragazzi di via Panisperna

They took their name, the boys from Panisperna Street, from the street in central Rome where the Physics Institute at which Fermi and his collaborators worked from 1926 to 1937 was located.
It was there that at the beginning of 1934 they made the historic discovery that new radioactive isotopes were produced when elements were bombarded by neutrons.

Rome 1934. I ragazzi di via Panisperna
From left: Oscar D'Agostino, Emilio Segrè, Edoardo Amaldi,Franco Rasetti,and Enrico Fermi (on the top: Bruno Pontecorvo and Ettore Majorana)

E. Amaldi F. Rasetti E. Segrè

The physicists organized themselves by dividing the responsibilities, sharing the work and enjoying vacations together. Indeed, the US science historian Gerald Holton has said that this was the first real science Group.

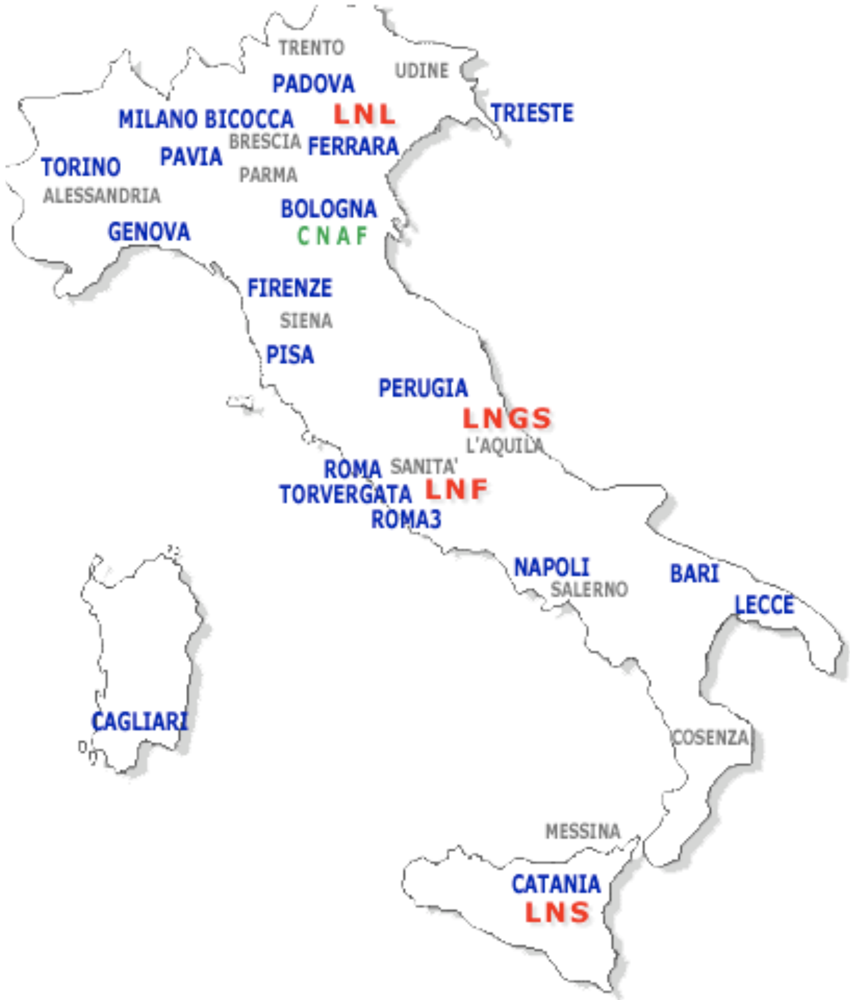
Between 1948 and 1950 the idea of an international laboratory devoted to accelerator physics was being discussed independently in many European circles. Amaldi was particularly worried by the increasing gap between US and European research, and by the brain drain that had already seen many of the best European scientists emigrating to the US after the war.
He discussed the idea with Bernardini, who by then was at Columbia University in the US and thus had the opportunity to stimulate the interest of Isidor Isaac Rabi, the European-born chair of Columbia's physics department, and with Pierre Auger, UNESCO Science Director.

Pierre Auger, Edoardo Amaldi and Lew Kowarski, 6 February 1952

From these discussions, actions where taken and at the beginning of 1951 first Italy, under pressure of Amaldi, and then France and Belgium, put at his disposal funds to act. In February 1952 an agreement was signed and Amaldi was nominated as the founding secretary general of the provisional CERN organization. The Geneva site was chosen in February 1953.

First meeting of the CERN Council, Sir Ben Lockspeiser, Amaldi, Bloch, Kowarski, Bakker, Niels Bohr 15 february 1954

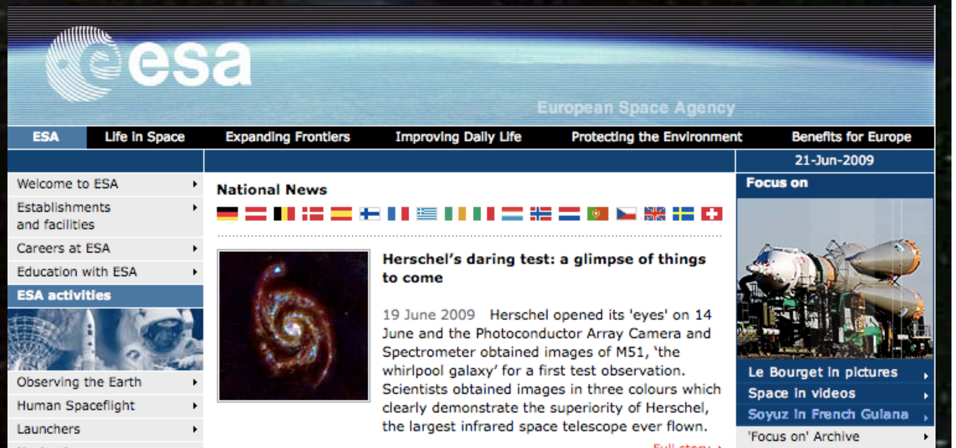
In parallel, Amaldi, Bernardini and colleagues in the Rome group joined with others doing similar work in Milan, Padua and Turin to become the nucleus of the INFN, which still coordinates Italian nuclear, particle and astroparticle physics.
In 1960 Amaldi succeeded Bernardini as president of that organization.



Amaldi also played a crucial role in initiating the European collaboration in space research.

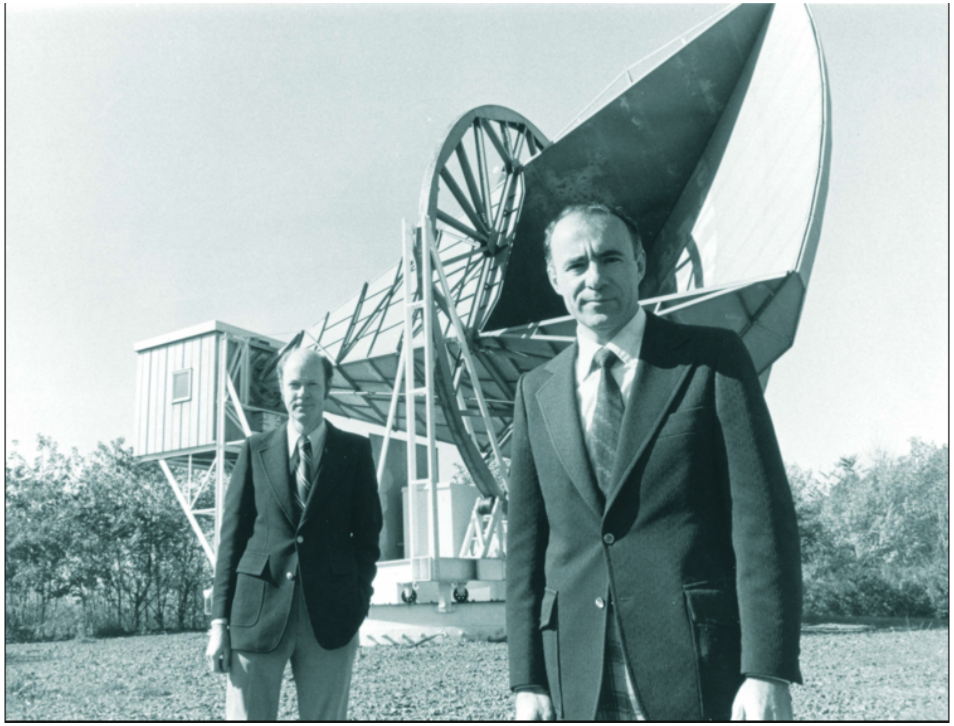
After the Soviet Union launched the Sputnik satellite, in 1958, he wrote a letter to a group of prominent European scientists and science managers, which was published in "L' Expansion de la Recherche Scientifique" in December 1959 under the title "Let us create a European Organisation for Space Research".

Within a year, a conference on the idea was held at CERN and by 1961 a commission had begun working on the European space programme that would eventually become today's European Space Agency (ESA).



During the sixties Amaldi tried to push the Italian physicists in the direction of new researches in the birth phase:

Infrared Background radiation and Gravitational Waves (after Penzias & Wilson and Weber’s experiments).



The research activity in GW detection in Rome started officially in September 1970. Guido Pizzella, Edoardo Amaldi's assistant, had just come back from the USA, where he had been working at the University of Iowa with James Van Allen, when he proposed to Amaldi to begin an experiment in this field.

What kind of experiment?

In January 1971 Amaldi received the Stanford and Louisiana proposal for a detector consisting in a 5 ton aluminum bar cooled to very low temperature (0.003 K) employing a dcSQUID amplifier coupled to a resonant transducer.

It was clear to Amaldi and Pizzella that this was the kind of experiment they should have aimed to realize.

Bill Fairbank

Bill Hamilton

Astron. Astrophys. 216, 325–332 (1989)

ASTRONOMY AND ASTROPHYSICS

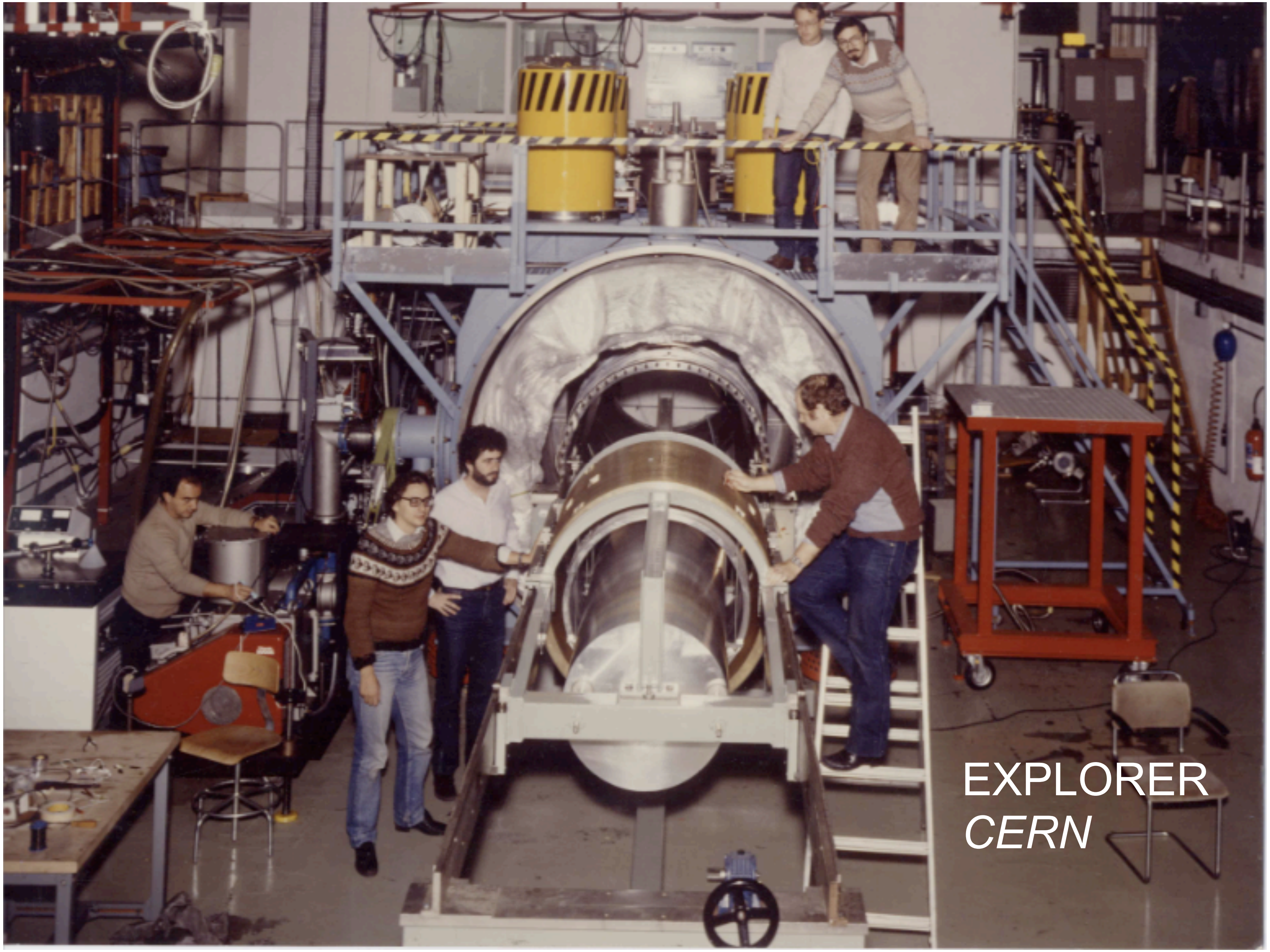
First gravity wave coincidence experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford

E. Amaldi[1,3], O. Aguiar[9], M. Bassan[2,8], P. Bonifazi[3,4], P. Carelli[1,5], M.G. Castellano[3,4], G. Cavallari[7], E. Coccia[2,3], C. Cosmelli[1,3], W.M. Fairbank[8], S. Frasca[1,3], V. Foglietti[3,5], R. Habel[1,6], W.O. Hamilton[9], J. Henderson[8], W. Johnson[9], K.R. Lane[8], A.G. Mann[9], M.S. McAshan[8], P.F. Michelson[8], I. Modena[2,3], G.V. Pallottino[1,3], G. Pizzella[1,3], J.C. Price[8], R. Rapagnani[1,3], F. Ricci[1,3], N. Solomonson[9], T.R. Stevenson[8], R.C. Taber[8], and B.-X. Xu[9]

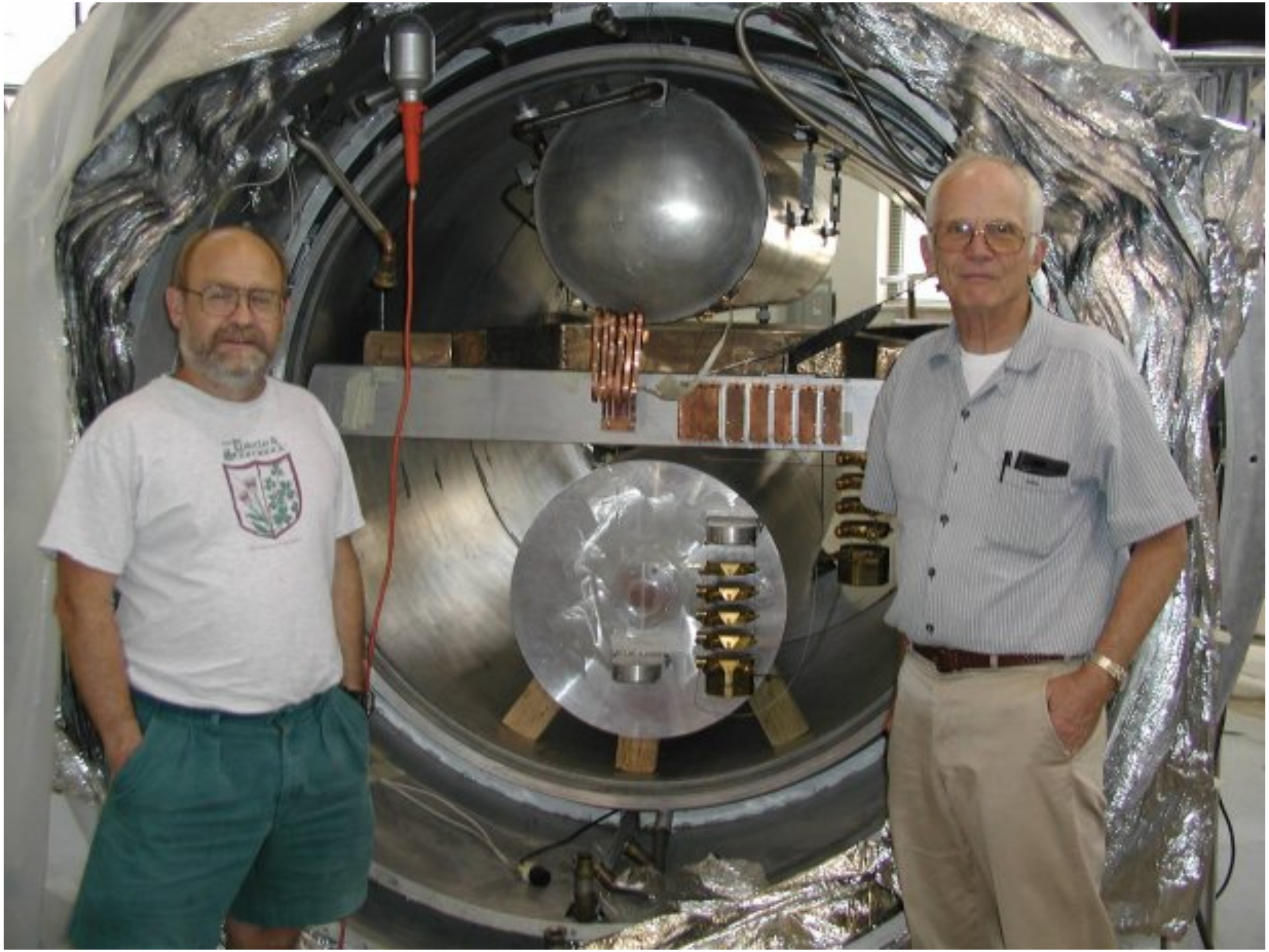
[1] Dipartimento di Fisica dell'Universita 'La Sapienza', Piazza Aldo Moro, 2, I-00185 Roma, Italy
[2] Dipartimento di Fisica dell'Universita 'Tor Vergata', Roma, Italy
[3] Istituto Nazionale di Fisica Nucleare, Roma, Italy
[4] Istituto di Fisica dello Spazio Interplanetario del CNR, Frascati (Roma), Italy
[5] Istituto di Elettronica dello Stato Solido del CNR, Roma, Italy
[6] ENEA, Centro Ricerche Energia, Frascati (Roma), Italy
[7] CERN, European Organization for Nuclear Research, Geneva, Switzerland
[8] Department of Physics, Stanford University, Stanford, CA 94305, USA
[9] Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803-4001, USA

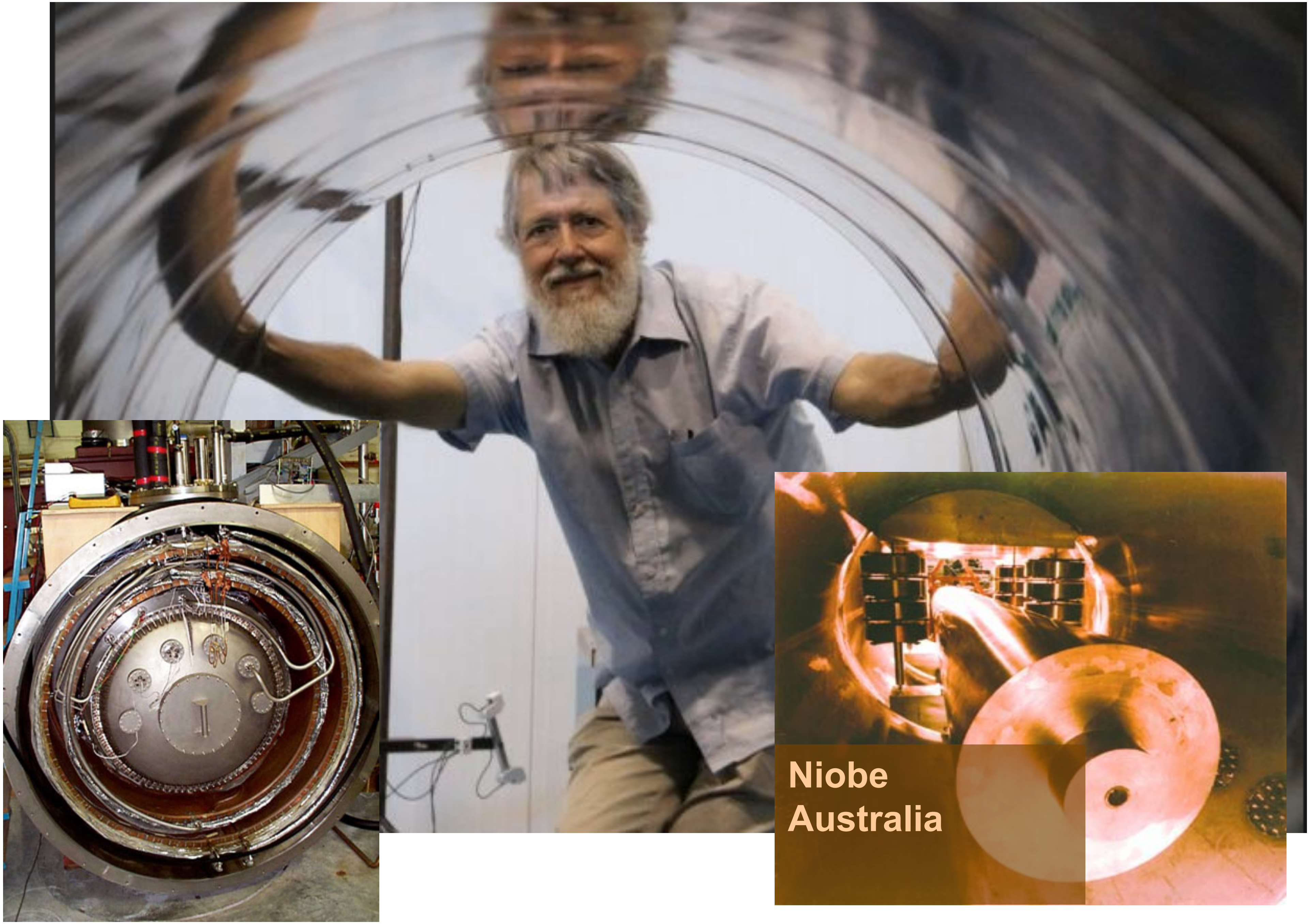
Received August 8, accepted November

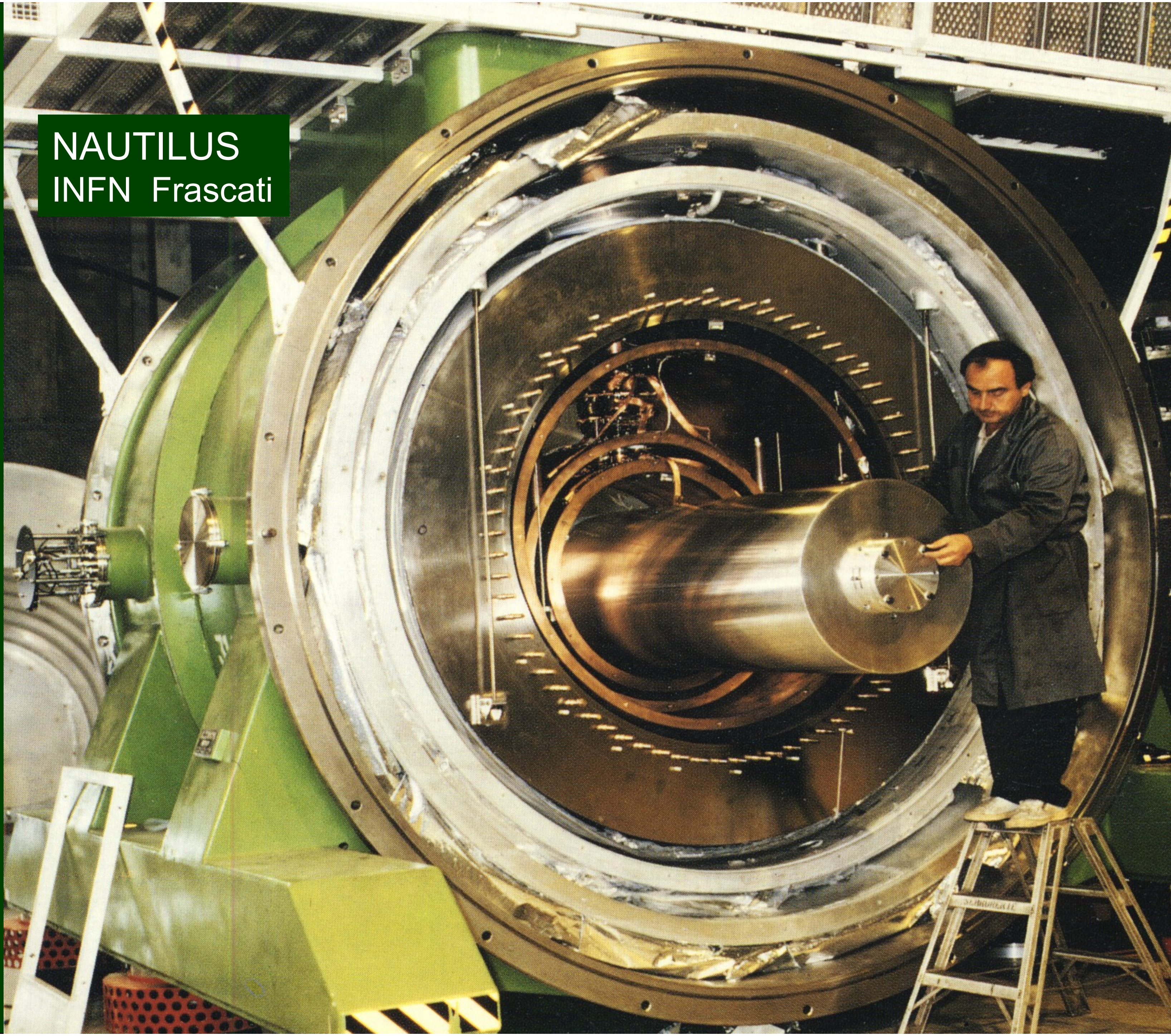
Summary. The results of a coincidence search for short bursts of gravitational radiation with cryogenic resonant-mass detectors are reported. No significant excess of coincidences at zero time delay were found. The data have been used to set an improved observational upper limit on the flux of impulsive gravitational waves that may be impinging on the Earth.

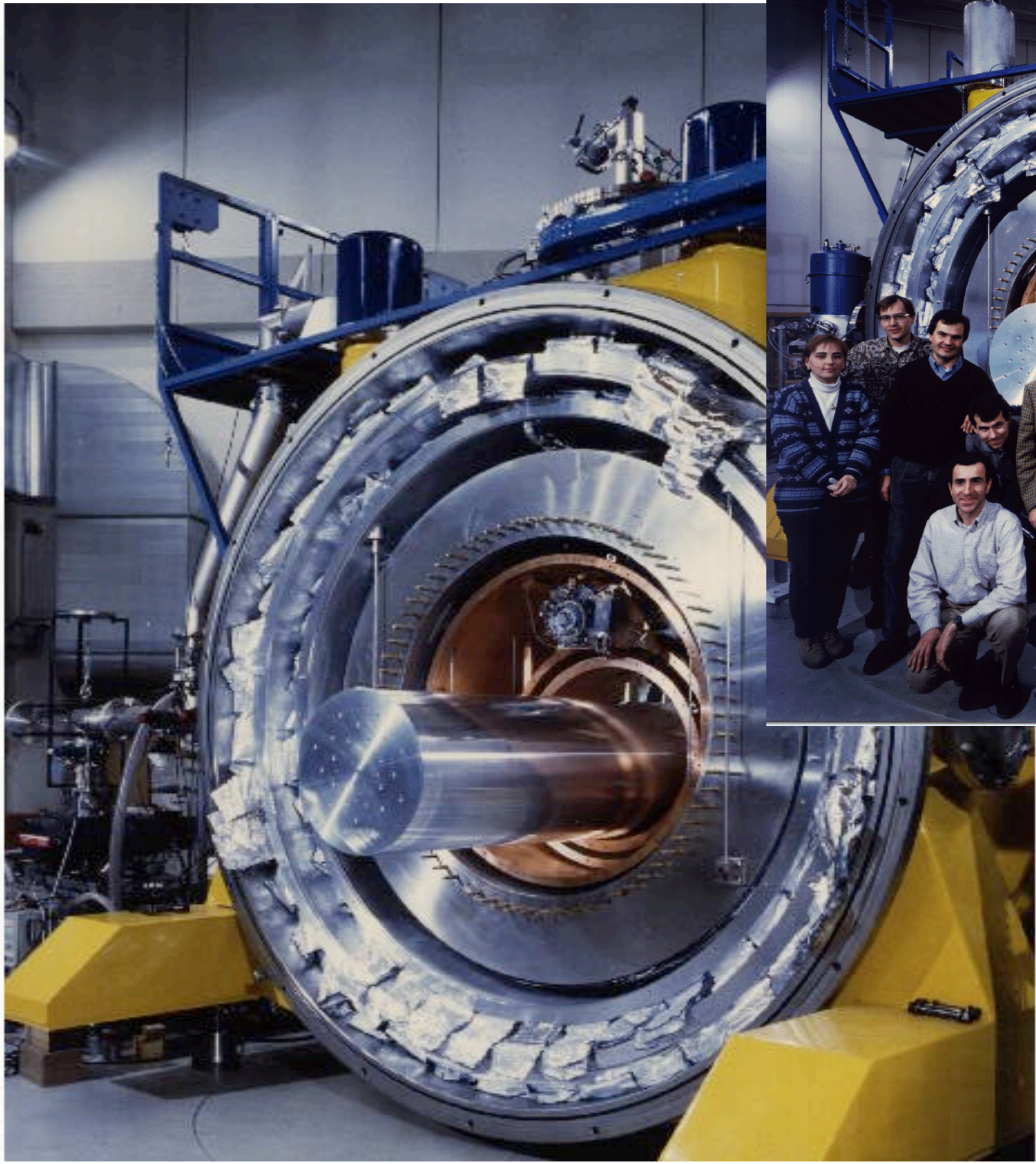

EXPLORER
CERN

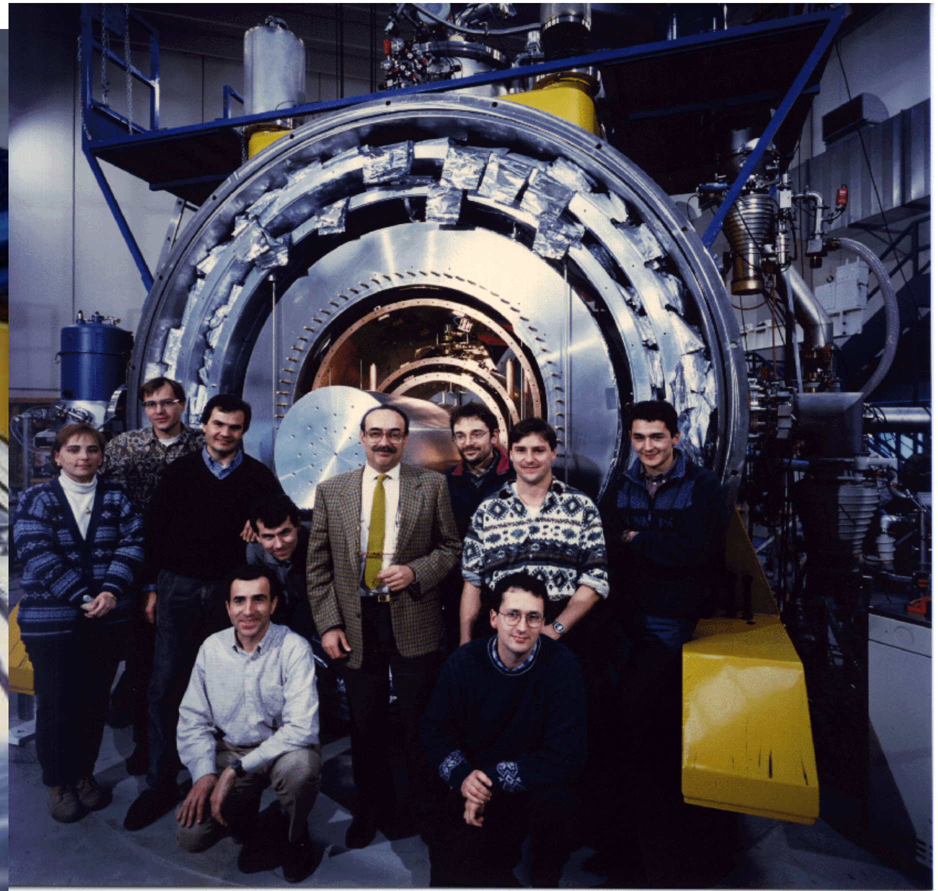
ALLEGRO, LSU




Niobe
Australia

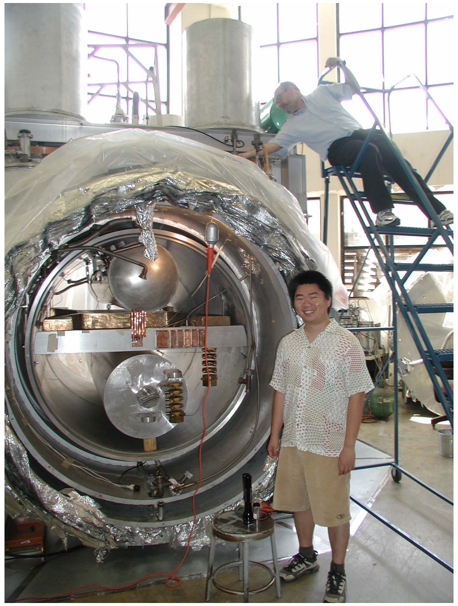

NAUTILUS
INFN Frascati

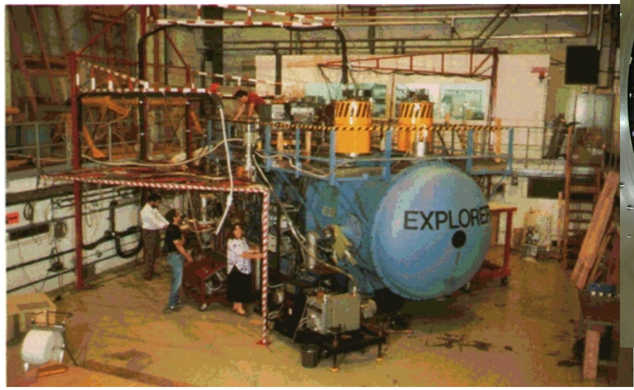


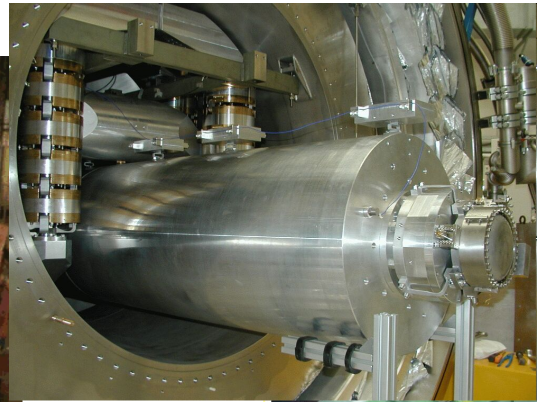


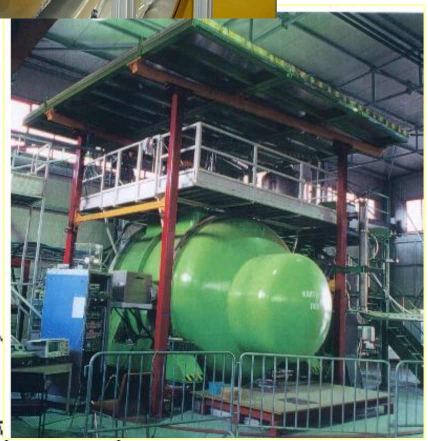
AURIGA
INFN Legnaro

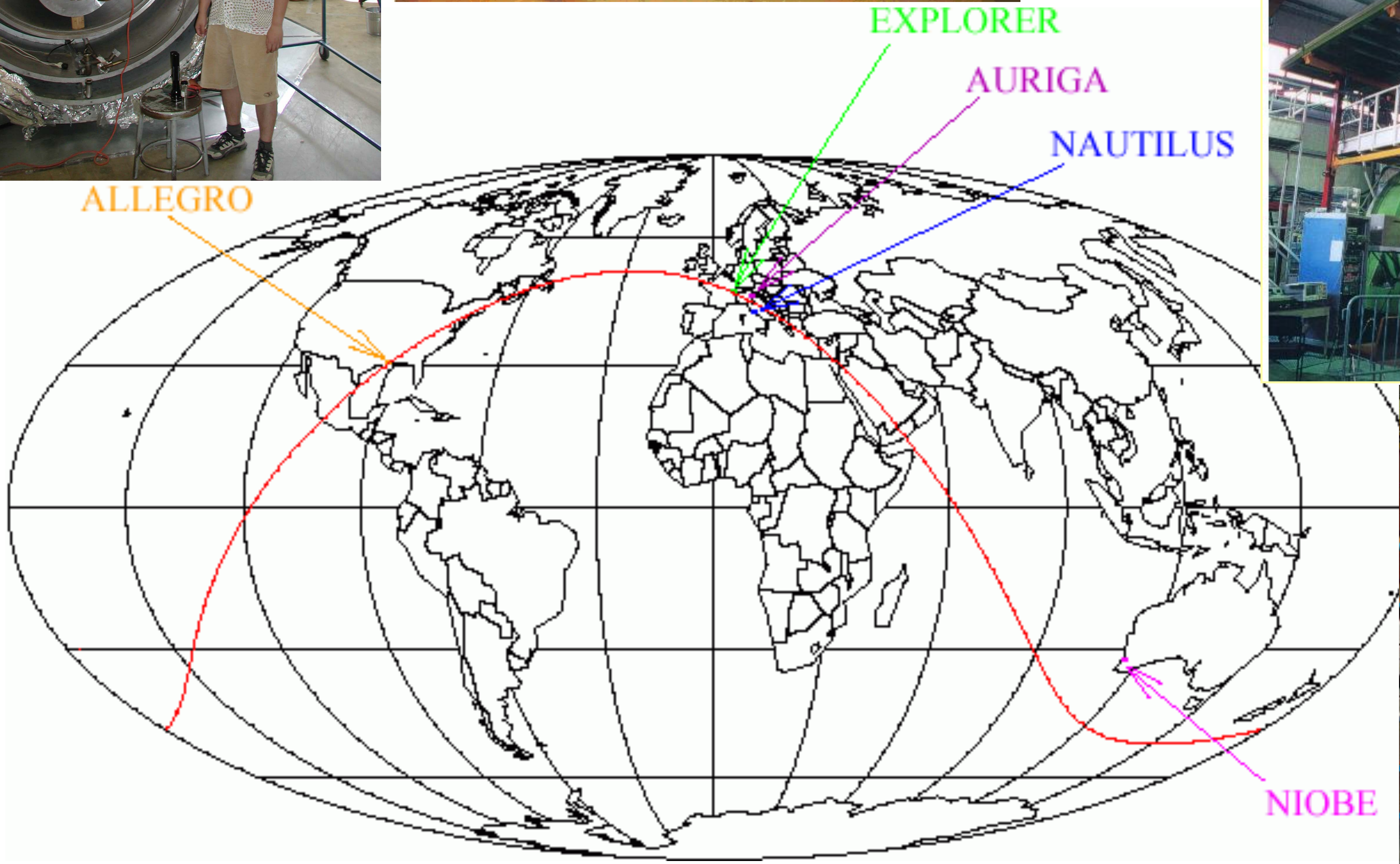
Bar Network

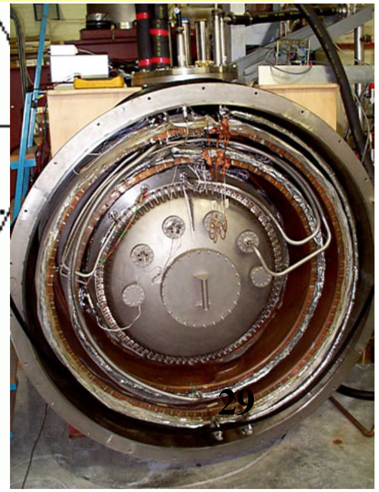


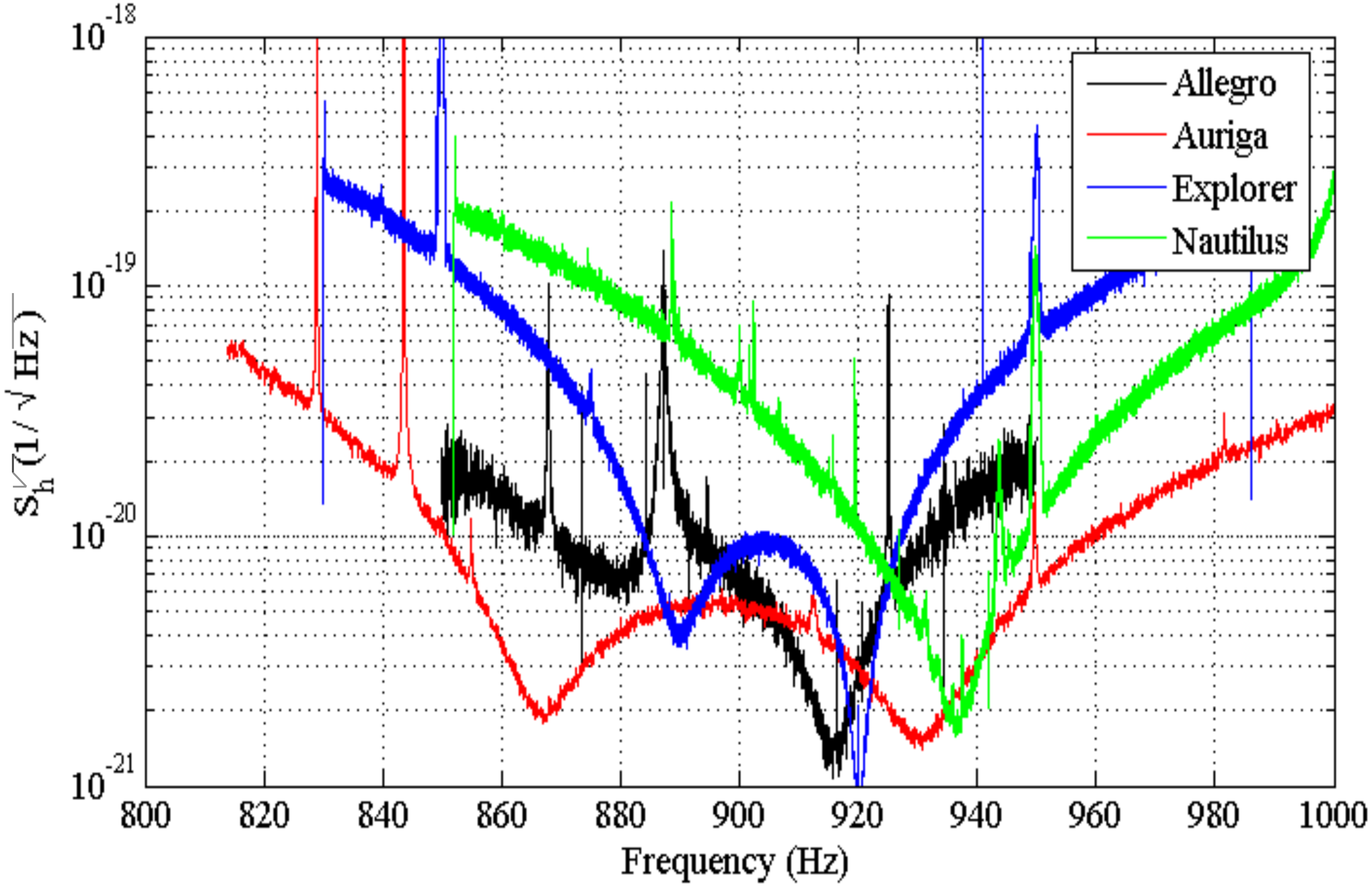








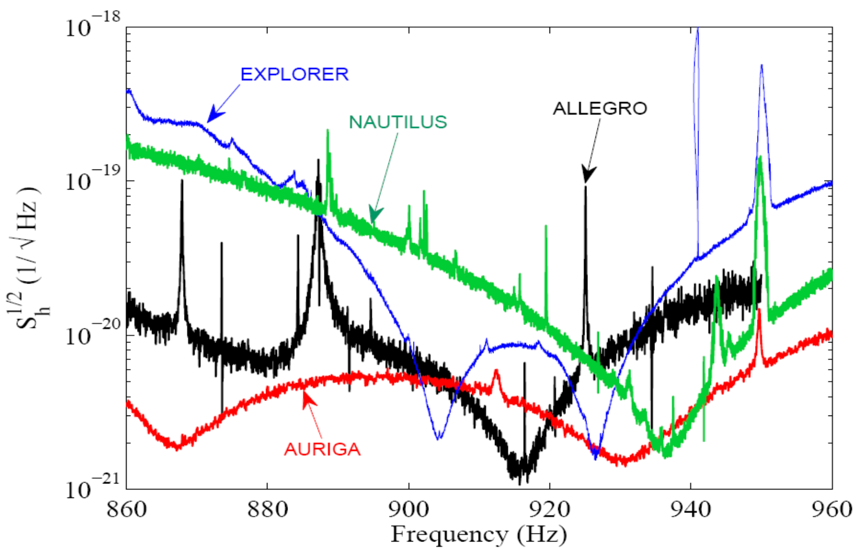



Allegro
Auriga
Explorer
Nautilus
10^{-18}
10^{-19}
10^{-20}
10^{-21}
S_h (1 / √ Hz)
800
820
840
860
880
900
920
940
960
980
1000
Frequency (Hz)

ALLEGRO (LSU) - AURIGA (LNL) – EXPLORER (CERN) – NAUTILUS (LNF)

- Phys. Rev. D82 (2010) 022003.
- Phys.Rev. D76 (2007) 102001.
- Phys.Rev. D68 (2003) 022001.
- Phys.Rev.Lett. 85 (2000) 5046-5050.

- **Last paper: 515 days of observation. from 16 November 2005 to 14 Aprile 2007. Search for coincidences. No coincidences with a background of 1 event / century**
- **in spite of the lower sensitivity respect to interferometers, the “IGEC” limit to the presence of big GW bursts (h_{rss}>10^{-19} $Hz^{-1/2}$) is better of a factor of 2.**

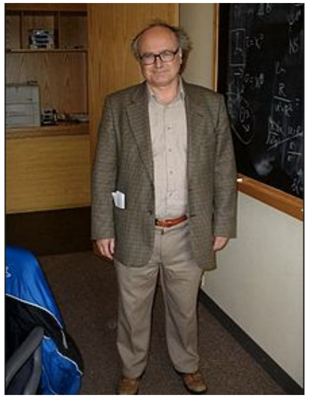


Complete coverage

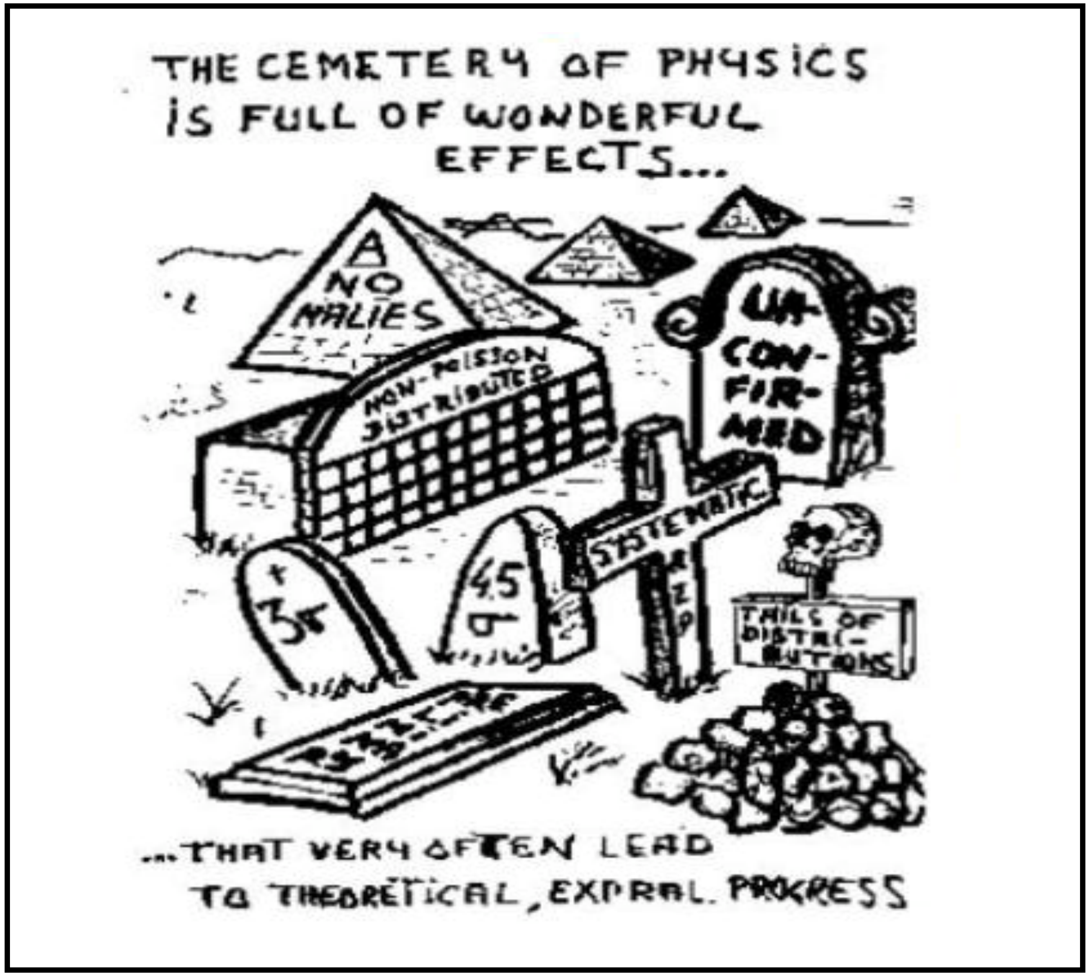
Configuration	Time of operation (days)
0 detector	0
1 detectors	1.633
2 detectors	30.998
3 detectors	188.837
4 detectors	293.532

Lights

- Sensitivity calculation and noise analysis
- Seismic isolation
- Thermal noise minimization by high Q
- Measurements of jumps in phase space (Gibbons & Hawking)
- Quantum technologies for reducing thermal and electronic noise (Fairbank)
- Back action noise and the Standard Quantum Limit (Braginski, Giffard), QND
- Coincidence for background rejection
- Time slides for background estimation
- Inverse False Alarm Rate detection statistic
- First collaborative efforts: Louisiana-Rome-Stanford and IGEC

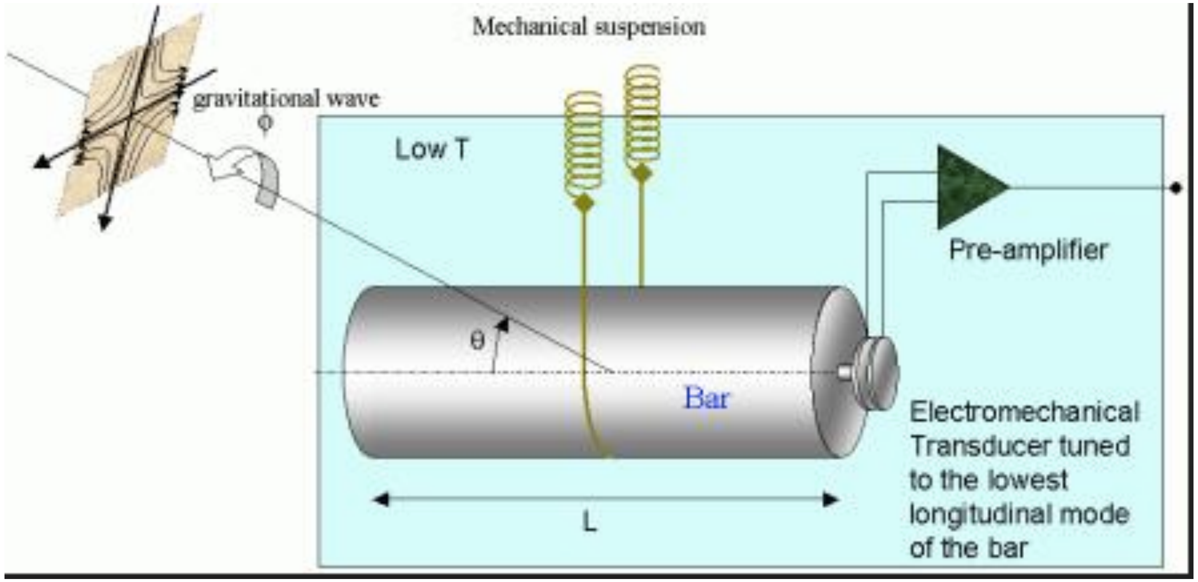


Shadows



Experimental obituary
(courtesy of A. De Rujula)

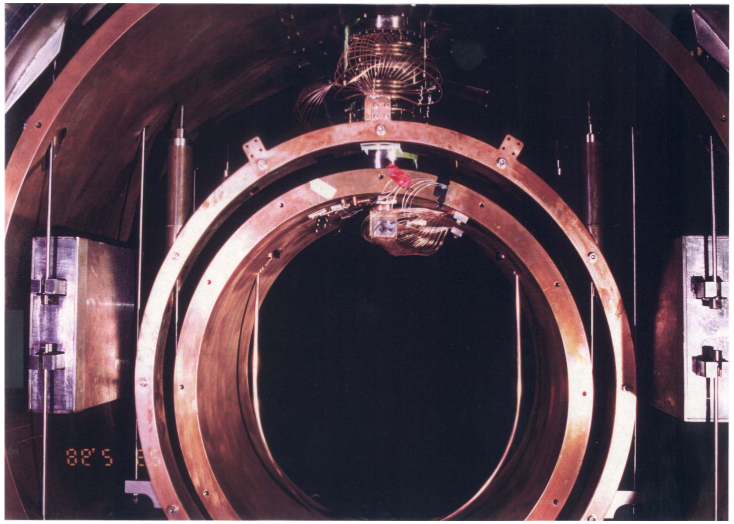
More lights



- Energy sensitivity = $10^2 - 10^4$ hν (Auriga and Nautilus)
- Detector calibrated with a dynamic gravitational field (Explorer)
- Coldest cubic meter in the Universe (Nautilus and Auriga)
- Acoustic detection of cosmic rays (Nautilus)
- Limits on quark nuggets and dark matter candidates (Nautilus)
- Limits on Planck scale physics (Auriga)
- Limits on Ultralight Scalar Dark Matter Candidate (Auriga)

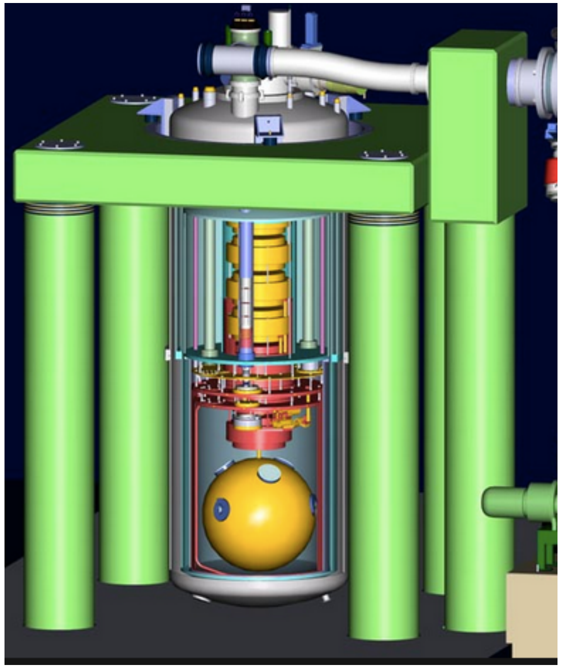
Inspiring the design of cryogenic detectors of gw and rare events

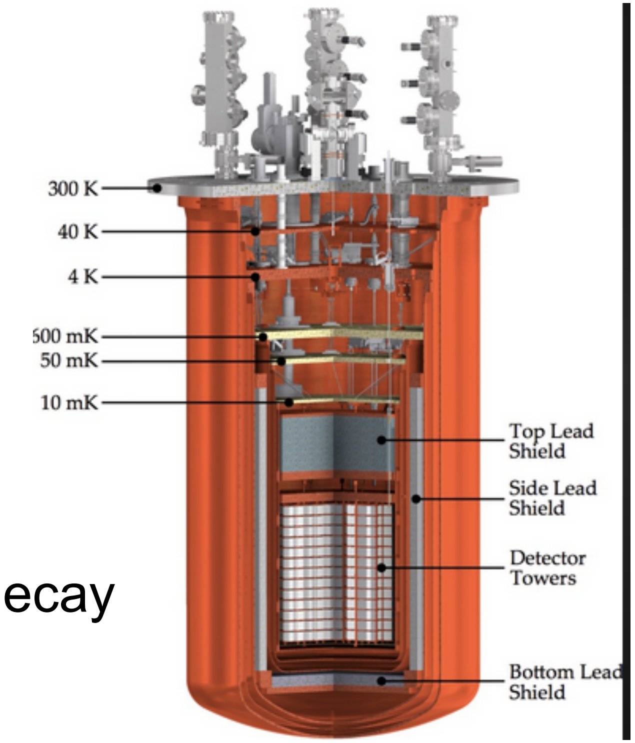
Silent mixing chamber
Cryogenic vessels decoupled from the detector
Soft thermal switches



Nautilus

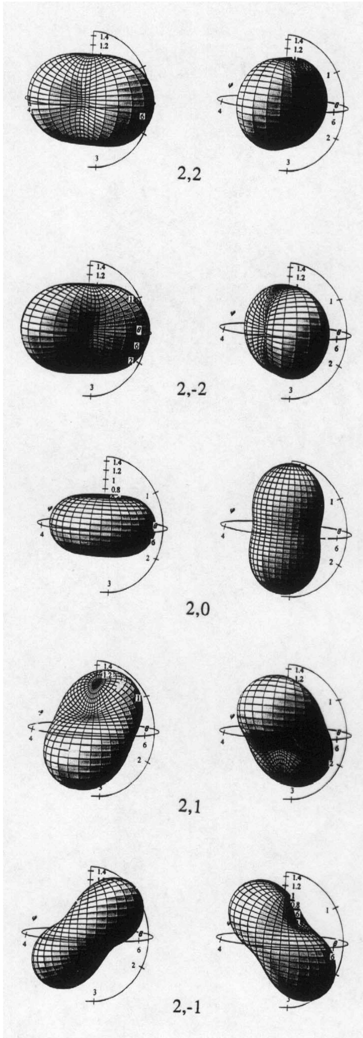
MiniGrail





CUORE, detector of neutrinoless double beta decay at the INFN Gran Sasso Lab.

Exploiting the resonant-mass detector technique: the spherical detector

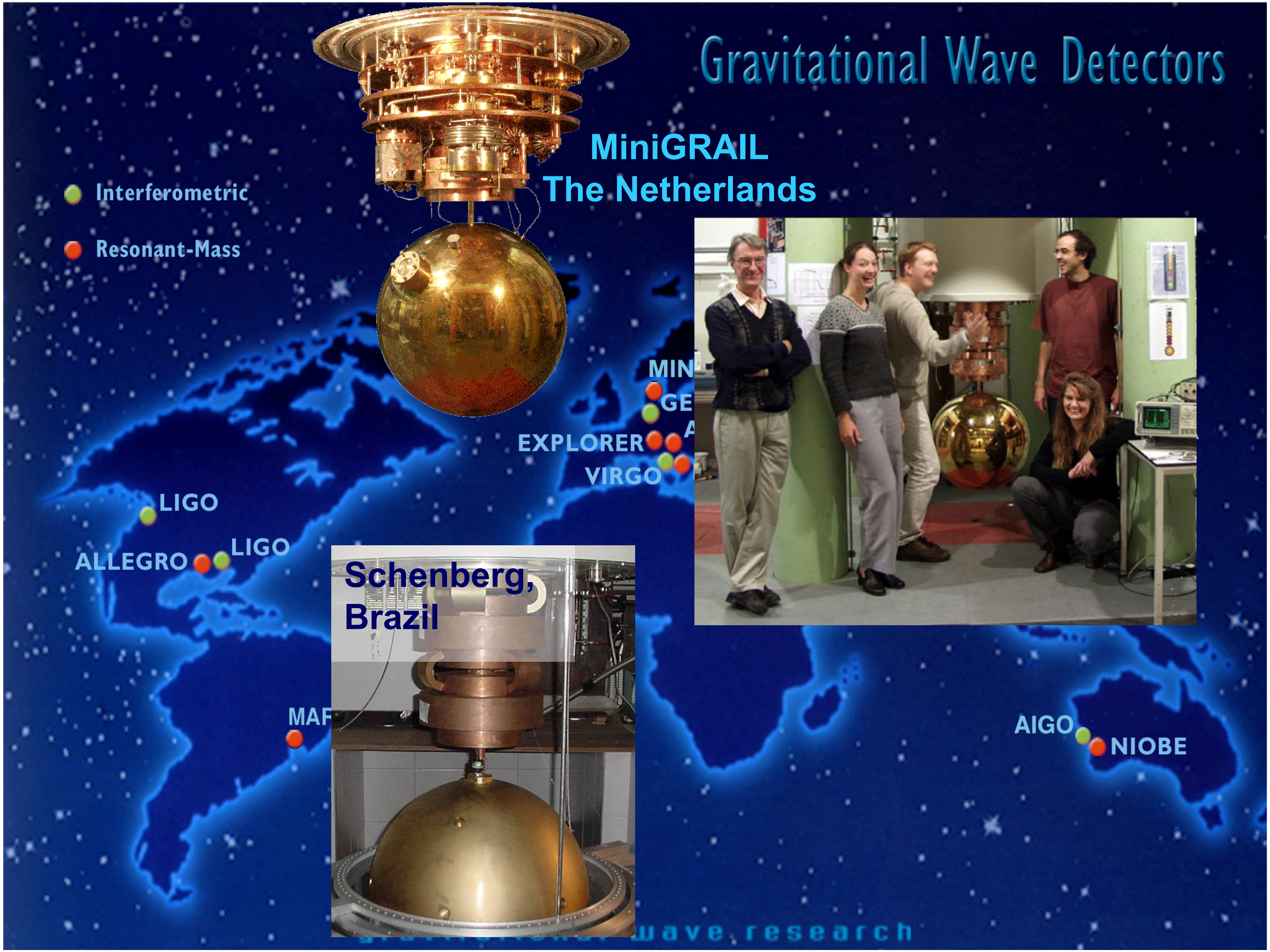


- 5 quadrupole modes
- Source direction
- Wave polarization

M = 1-100 tons
Sensitivity:
10^{-23} - 10^{-24} Hz$^{-1/2}$;
h ~ 10^{-21} - 10^{-22}

- 3 kHz spheres

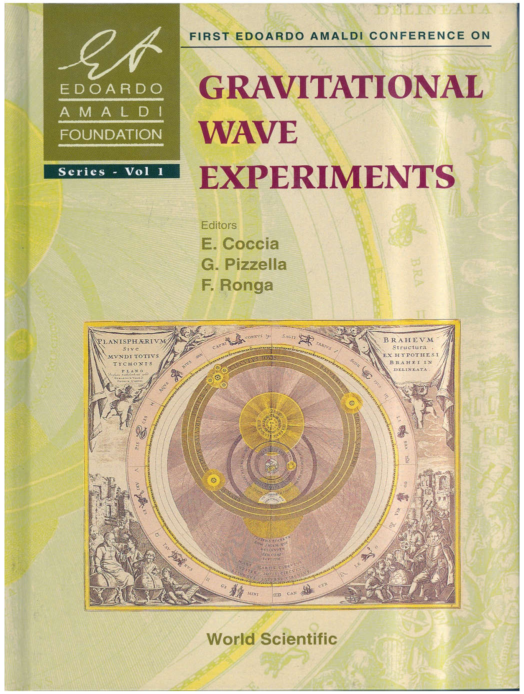
MiniGrail (Leiden, NL)
Sfera (Frascati, I)
Shenberg (Sao Paulo, B)

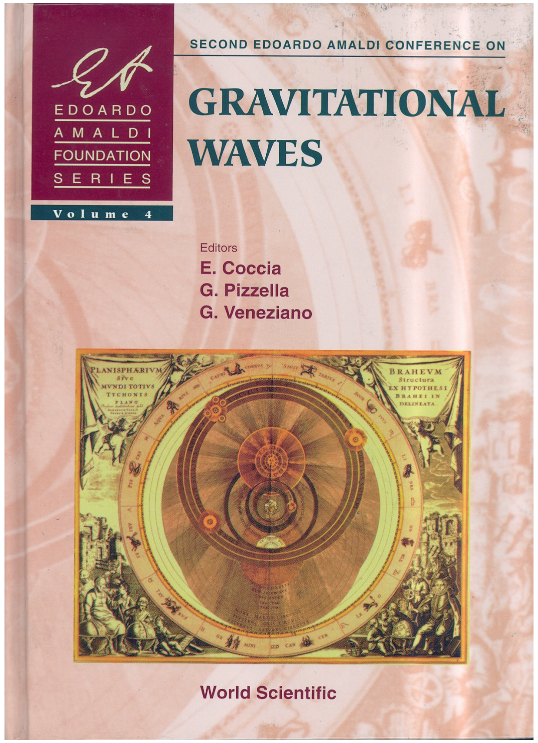


Gravitational Wave Detectors
MiniGRAIL
The Netherlands
Interferometric
Resonant-Mass
EXPLORER
VIRGO
LIGO
ALLEGRO
LIGO
Schenberg,
Brazil
AIGO
NIOBE
wave research

The Edoardo Amaldi Conference series on Gravitational Waves

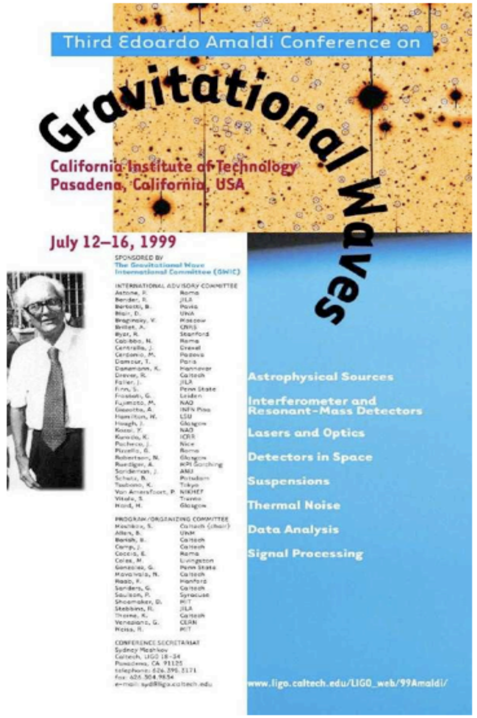
In 1993 Nautilus, the first ultracryogenic bar detector, started operating at the INFN Frascati Lab. It seemed natural to me to organize a new conference on GW experiments in Frascati, and to dedicate it to Amaldi. The idea was that this conference could be the first of a series. So the first EA conference was held in Frascati in 1994, with 120 participants from 13 countries.





The second edition was held at CERN in 1997, with a massive participation of the GW community. During the conference, the Gravitational-Wave International Committee (GWIC) was formed, under the chairmanship of Barry Barish. Barry agreed to organize the third edition in the US.

Since then, Caltech 1999, EAC is biennial and coordinated by GWIC as the cornerstone conference for the GW community worldwide.



GWIC
Gravitational Wave International Committee

An IUPAP Working group (WG11)

https://gwic.ligo.org/

- Home
- News
- GWIC Roadmap
- Thesis Prizes
- Statements
- Conferences
- GWIC meetings
- Reports to IUPAP
- Simulation Programs
- GWIC By-laws
- Members
- Related Links

The Gravitational Wave International Committee:

GWIC, the Gravitational Wave International Committee, was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. It is associated with the International Union of Pure and Applied Physics as its Working Group WG.11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC).

GWIC's Goals:

- Promote international cooperation in all phases of construction and scientific exploitation of gravitational-wave detectors;
- Coordinate and support long-range planning for new instrument proposals, or proposals for instrument upgrades;
- Promote the development of gravitational-wave detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics;
- Organize regular, world-inclusive meetings and workshops for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and foster research and development of new technology;
- Represent the gravitational-wave detection community internationally, acting as its advocate;
- Provide a forum for project leaders to regularly meet, discuss, and jointly plan the operations and direction of their detectors and experimental gravitational-wave physics generally.

More about GWIC:

GWIC - Ten Years on (PDF) reprinted from Matters of Gravity (Fall 2007),
the newsletter of the Topical Group on Gravitation of the American Physical Society.

The Chairpersons

Message from Massimo

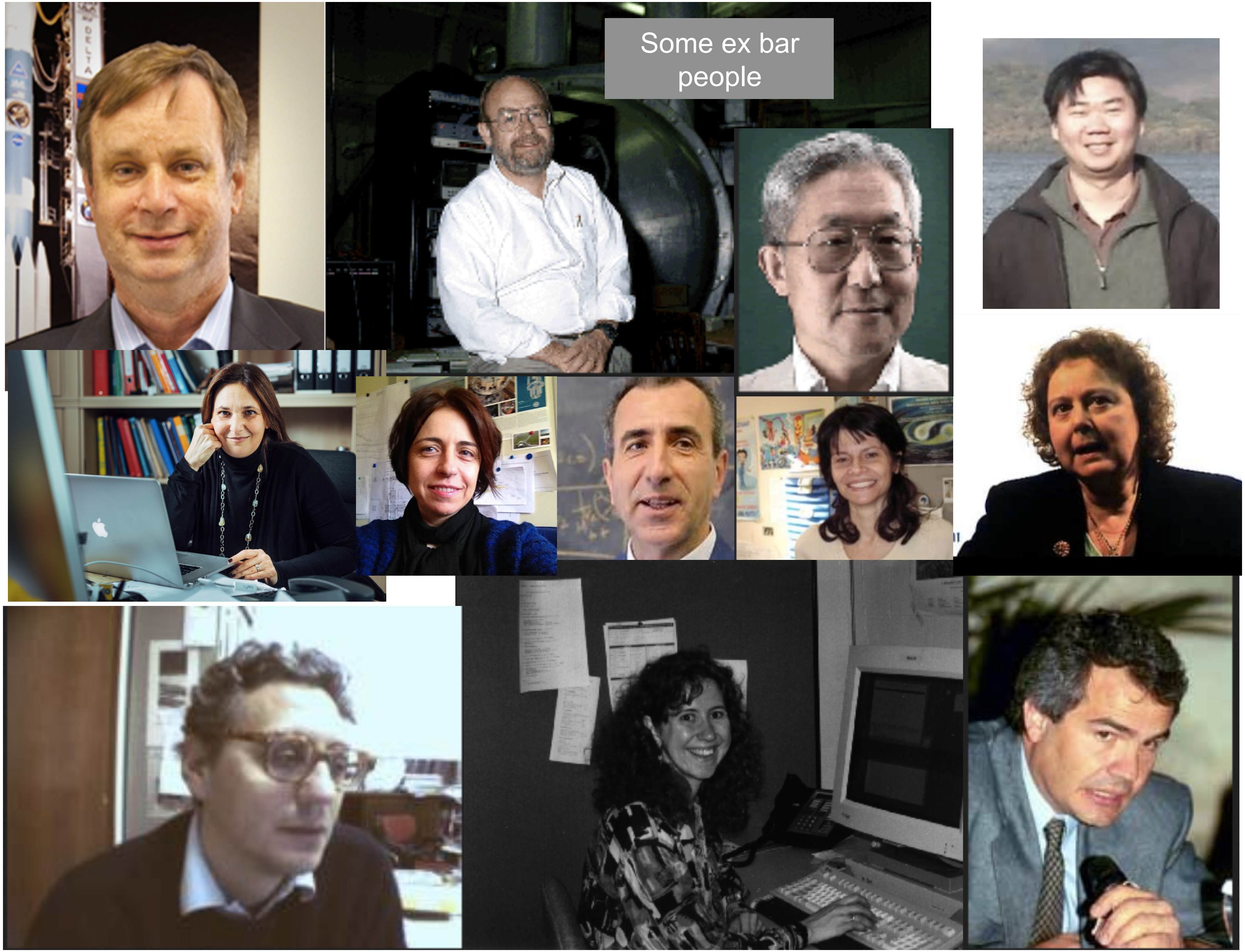
I had a sense of elation in seeing Fig 1 of the discovery paper. Then I felt proud that Giovanni, Gabriele and Marc had a relevant role and for Stefano's success with LPF – they all started with AURIGA on GWs searches.

best of luck to my friends and colleagues, who gave birth definitively to gravitational wave **astronomy**

cheers from my desk at home
and from Algarve

Casimir effects are not an experimental demonstration that free vacuum gravitates: connections to the Cosmological Constant Problem. M.C&C.Rovelli
Honorable Mention - Essay for the Gravity Research Foundation 2015 Awards
published in a selection of Mentions in Int.J.Mod.Phys. D24 1544020 (2015)

Some ex bar people



Lessons learned
from the bar detectors experience

- Cleverness may be more important than brute force.
- Skepticism is important to the progress of science.

  If you get in love with your result, you are in big trouble.

  Carry out carefully documented blind analyses.

  Make your data available and your procedures transparent to others.

- Let collaboration prevail over competition.

  Competition is an important boost and if it occurs in a collaborative framework leads to a win win game.

and Try to get fun from your work!