IL NUOVO CIMENTO Vol. 37 C, N. 5 Settembre-Ottobre 2014
DOI 10.1393/ncc/i2014-11826-y

Colloquia: The Legacy of Bruno Pontecorvo

Edoardo Amaldi, Bruno Pontecorvo and the invisible light of stars

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Summary. — Two new astronomical windows are opening at the beginning of the third millennium, thanks to Observatories of very peculiar cosmic messengers: neutrinos and gravitational waves. Bruno Pontecorvo and Edoardo Amaldi, in different ways, have contributed to the advancement of these fields of research and have inspired the work of many physicists. I dedicate this contribution to the memories of these two scientists. Remembering my encounter with Bruno, I report here on the experimental search for gravitational waves, in Italy and worldwide, and on some aspects of the study of the simultaneous emission of gravitational waves and neutrinos by a supernova.

1. – Introduction

In the fall of 1992, Guido Pizzella accompanied Bruno Pontecorvo to visit the recent installation of the gravitational wave detector Nautilus in the INFN Frascati Laboratories. Sadly, his friend and colleague Edoardo Amaldi was not there, as he died three years before. Gravitational wave research was the main scientific interest of Amaldi during the last twenty years [1] and I think for Bruno that visit had the special meaning to see the last developments of the long scientific work of Edoardo.

He wanted to know everything about the state of the search for gravitational waves, and how the Nautilus detector worked. As many others who met Bruno for the first time, I was impressed by his extreme kindness and his gentle manner, I would say elegance. I was excited to know one of the major particle physicist of the XX century. A man whose ideas and proposals were in advance of the times. He realized that the detection of neutrinos was possible at a time in which the rest of the world thought that this was impossible. He suggested the use of the neutrino chlorine reaction that was then used in the Homestake experiment. He anticipated the existence of two type of neutrinos and the hypothesis of neutrino mixing and hence of oscillations.

The conversation drifted on neutrinos and on the implications of the simultaneous detection of gravitational wave and neutrinos from a Supernova. I was delighted by the conversation.

I dedicate my talk, on this natural source of visible and invisible light in the framework of the search for gravitational waves, to the memories of these two great scientists.

2. – Amaldi and the birth of the gravitational wave research in Italy

The first attempts to detect gravitational waves are due to Joseph Weber (1919–2000), one of the founders of laser and maser physics. His interest in general relativity led Weber to study with Wheeler in Princeton and to focus his interest on gravitational radiation at a time when the existence of gravitational waves was not widely accepted and the knowledge on possible powerful cosmic sources was very poor.

He developed the first gravitational wave detectors (Weber bars) in the 1960s, and began publishing papers with evidence that he had detected these waves [2]. Soon, in the course of the 1970s, his attempts to find gravitational waves with bar detectors were considered to have failed. But the flame of the passion for the detection and study of spacetime perturbations, voices from extreme cosmic sources, was already burning in several countries and laboratories.

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 [3] [4] [5].

During the sixties Amaldi tried to push Italian physicists in the direction of new researches in the birth phase: infrared background radiation (after Penzias & Wilson experiment) and gravitational waves (after Weber's experiments).

In the words of Amaldi, reported in an Internal Note of the Physics Institute of Rome: "*The idea of starting an experiment aiming to detect gravitational waves in Rome was stimulated by the Course on Experimental Tests of Gravitational Theories held in summer 1961 at the Scuola Internazionale Enrico Fermi in Varenna, where the problems was discussed by J. Weber. The program remained rather vague for practical reasons until 1968, when W. Fairbank spent a few months in Rome at the G. Careri low temperature laboratory. When Fairbank mentioned his intention of starting the development of a low temperature gravitational antenna, Careri who was informed for long time of the interest of E. Amaldi in the subject, suggested a direct contact. This was the beginning of the collaborations among the group of Stanford (W. Fairbank et al.), Louisiana State University (W. Hamilton et al.) and the Istituto di Fisica of Rome.*"

Every project needs a leader, and this man was Guido Pizzella. Amaldi assistant, he was just returning in Rome from Iowa city, where he had spent a few years doing research on cosmic rays and Van Allen radiation belts of the Earth (working with Van Allen). He wanted to change its activity from space research to a more fundamental field: he decided for gravitational waves (Francesco Melchiorri later choose the infrared background).

In the words of Guido [6]: "*On September 3, 1970, I said to Amaldi: Professor, I want to make an experiment for the search of gravitational waves. His eyes lighted and immediately we agreed to proceed.*"

But 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.

After various tests and prototype detectors, the efforts eventually resulted in the creation of a sophisticated cryogenic bar, Explorer, which operated at CERN from 1980 [7] [8]. Ten years later, the Rome group designed the first ultracryogenic bar detector, Nautilus at the INFN Frascati Lab [9] [10]. At the end of the 1980s, a new group led by Massimo Cerdonio, who was among the first members of the Rome group, realized at the INFN Legnaro Lab another detector of the same class, Auriga [11] [12].

Another group was formed in Pisa by Adalberto Giazotto on the ambitious design of a large laser interferometer, which soon became the French-Italian Virgo project [13].

Italy has been since the beginning a top player in this field of research.

3. – The large interferometer network

Since the pioneering work of Weber, the quest for the detection of gravitational waves (GW) has progressed at higher and higher levels of ingenuity and effort.

The first decade of the XXI century has seen a shift in the technologies used in GW searches as the first generation of large interferometers has begun operation at their design sensitivities, taking up the baton from the bar detectors.

LIGO [14], Virgo [15], and GEO 600 [16] are a network of interferometric detectors aiming to make the first direct observations of GWs. They consist of two experimental sites in the US (Hanford, WA and Livingston, LA) and two in Europe (Hannover, Germany and Cascina, Italy). An additional experimental site to host an underground cryogenic detector named KAGRA is under construction in Japan [17] while a proposal to build a third LIGO site in India is currently being evaluated [18].

These detectors use kilometer-scale Michelson interferometry to measure the fractional differential change dL/L in the distances of two orthogonally positioned pairs of masses. Such changes are expected to occur upon the passage of a GW. The fractional distance change dL/L between two such pairs of perpendicularly arranged masses defines $h(t)$, the GW strain as measured by the detectors. This is a direct measure of the strength of the local spacetime distortions (which is the GW itself) folded with coefficients of order unity that depend on the direction of the wave source and the orientation of the interferometer.

The network of GW detectors is currently (2013) undergoing upgrades which are expected to produce a factor of about 10 improvement in sensitivity [22]. These will be the advanced LIGO and advanced Virgo detectors and are expected to come online, between 2015 and 2016.

We are then on the threshold of a new era of GW astrophysics. First generation interferometers have broken new ground in sensitivity and have proven technique, second generation detectors are starting installation and will expand the "Science" (astrophysics) by a factor of 1000.

Data from GW detectors are searched for many types of possible signals. In particular signals from compact binary coalescences (CBC), including Binary Star systems. The gravitational waveform from a binary neutron star coalescence is well modelled and matched filtering can be used to search for signals and measure the system parameters. In the era of advanced detectors, the LSC and Virgo will search in near real-time for CBC and burst signals for the purpose of rapidly identifying event candidates. It is likely that the first detected signal will be from a CBC.

However, there is another potential source that cannot be underestimated: a core collapse supernova. Much can be understood by a simultaneous detection of the GW and neutrino bursts. Let me discuss the scientific relevance for a joint analysis of GWs and low-energy neutrino data to probe the processes powering a supernova explosion [20].

4. – Supernova

A supernova is an explosion of a massive supergiant star. No events in nature surpasses its raw power: about 10^{53} erg/s is released as neutrinos from a core-collapse supernova, which is as much instantaneous power as all the rest of the luminous, visible Universe combined. They give birth to the most exotic states of matter known: neutron stars and black holes. Supernovae have been at the forefront of astronomical research for the better part of a century, and yet no one is sure how they work.

Several mechanisms in a core-collapse supernova can give rise to GW bursts. Signals may last from milliseconds to seconds in the instruments' band. While the astrophysical motivation for expecting GWs to accompany core-collapse supernovae is strong, the expected rate, GW strength and waveform morphology are uncertain [21]. The expected energy going into GWs would be $10^{-10} - 10^{-4}$ $\mathrm{M}_{\odot}\, c^2$ (or $2 \times 10^{44} - 2 \times 10^{50}$ erg).

This is only a small fraction of the energy liberated in neutrinos: the core collapse of a massive star is expected to produce a huge flux of neutrinos. Actually nearly all (about 99%) of the binding energy $\mathrm{O}(10^{53}$ erg) of the resulting neutron star (or black hole) ends up in neutrinos escaping on a short timescale (a few tens of seconds). The neutrinos (and antineutrinos) produced are of all flavours, and have energies in the few to tens of MeV range. The burst of neutrinos from SN1987A in the Large Magellanic Cloud, detected by various neutrino detectors, confirmed the baseline model of stellar collapse. On the contrary, the estimates of GW bursts associated with supernova rely on models. Most such models are not yet three-dimensional, do not incorporate the entire set of possibly relevant physics, and do not predict robust supernova explosions as observed in the electromagnetic universe. So, despite the availability of multiple potential explosion mechanisms and their associated multi-dimensional dynamics and GW signatures, the current picture is unlikely to be complete.

It is well worth to study the supernova signals with GWs and neutrino detectors with a multi-messenger approach.

The first important point is that GWs and neutrinos from core-collapse supernovae are emitted in the inner-most, high density region of the supernova core which cannot be probed electromagnetically. GWs and neutrinos thus are the only messengers that can carry live dynamical information from deep inside a dying massive star and constrain the detailed, yet unknown, mechanism driving the core-collapse supernova explosion.

Another point is that both GWs and neutrinos leave the core-collapse event on approximately the same time scale (seconds) in contrast to electromagnetic radiation, which can take hours or days to become visible to astronomers. Moreover, a visible supernova near the edge of sensitivity may be a rather poor tag of core collapse for both GW and neutrino detectors separately, in the presence of detector background, given what will likely be a large uncertainty on the occurrence itself of a collapse and on its timing [23].

Let me develop these considerations.

Several of the world's present neutrino detectors are sensitive to a neutrino burst from a galactic supernova. Super-K, a 50-kton water Cherenkov detector in Japan, would observe some 8000 events for a core collapse at the center of the Milky Way, about 8.5 kpc away [24]. The LVD and Borexino scintillation detectors at Gran Sasso in Italy, and KamLAND in Japan, would observe hundreds of interactions. The IceCube detector at the South Pole, although nominally a multi-GeV neutrino detector, would observe a coincident increase in count rate in its phototubes due to a diffuse burst of Cherenkov photons in the ice, and has sensitivity to a galactic supernova. The Super-K, LVD, IceCube and Borexino detectors are also operating as part of the SNEWS (SuperNova

Early Warning System) network [25], which has the aim of providing a prompt alert to astronomers in the case of a coincident supernova neutrino burst. Uncertainties on the rate of supernovae in the nearby universe are significant. According to current rate estimates, there is about one supernova every 40 years in the galaxy, 3 or 4 supernovae per century in the local group (at a distance of about 1 Mpc), about one supernova every other year between 5 Mpc, with an integral rate of one supernova per year out to the Virgo cluster. These rates are more likely to be lower than upper bounds. A significant fraction of galactic or very close extragalactic supernovae (within 1 Mpc) could be optically silent, not only because of no or very weak explosions, but also because of dust extinction of the electromagnetic (optical) emission. We can use GWs and neutrinos to identify such core-collapse events that do not lead to a strong electromagnetic display. A neutrino and GW coincidence, in the absence of a strong prompt electromagnetic signal, would provide smoking-gun evidence for this weak or failing supernova scenario. It is worth noting that the rate of such events may be comparable to the rate of supernovae with optical signals. An example is SN 2008iz that exploded in M82 in late January 2008, but was discovered serendipitously in the electromagnetic spectrum (through radio observations) only more than a year later. Combining GW data with neutrino observations would enhance the ability to find electromagnetically dark or obscured supernovae in our nearby universe.

There is an assured improvement offered to the core-collapse supernova reach by the joint analysis of the GW and neutrino detectors. This is due to the possibility of a tighter search window and lower background rate. Estimates have been done and are in progress in order to quantify this improvement [20].

5. – The perspectives of the GW field

Let me end with the perspectives on the evolution of the GW detectors field.

The laser interferometers are evolving toward their second generation: the advanced (Virgo and LIGO) detectors. According to the current GW sources modelling, when these apparatuses will be near to their nominal sensitivity, the detection of the GW seems probable in few months of data taking. But the sensitivity needed to test the Einstein's gravity in strong field condition or to realize precision GW astronomy goes beyond the expected performances of the advanced detectors.

The fundamental limitations at low frequency of the sensitivity of the 2nd generation detectors are given by the seismic noise, the related gravitational gradient noise (so-called Newtonian noise) and the thermal noise of the suspension of the test masses. To circumvent these limitations new infrastructures are necessary: an underground site for the detector, to limit the effect of the seismic noise, and, likely, cryogenic facilities to cool down the mirrors to directly reduce the thermal vibration of the test masses. ET (Einstein Telescope http://www.et-gw.eu/) is a project for a future European third generation GW detector to be realized underground [26].

The realization of the ET research infrastructure, allowing operations for many decades, will be triggered by the first GW detection with the start of the site preparation beginning as early as 2018 and with scientific data being available in the following decade. Similarly, there will be the possibility for a high-sensitivity large-bandwidth observatory to be built in other continents.

The low-frequency range, below 1 Hz, includes a large and diverse population of strong GW sources that can only be observed at these frequencies. Detection technologies are diverse and range from polarization measurements of the cosmic microwave background and pulsar timing to spacecraft tracking and large baseline laser interferometry. All of these technologies will eventually be used to observe the complete GW spectrum covering more than 20 orders of magnitude in frequency. The scientific objectives of space-based and groundbased instruments are complementary in the same way that optical and x-ray astronomy are complementary and have provided information about different types of astrophysical objects and phenomena.

eLISA, a space-based interferometer will open the low-frequency GW window from 0.1 mHz to 0.01 Hz. eLISA is the GW community's highest priority for a space-based mission. The goal of a launch of eLISA in, say, 2025 is technologically feasible and entirely timely, considering that the technology precursor mission, LISA Pathfinder, will be launched in 2015.

Also worth to be mentioned are the growing efforts to use radio astronomy for the detection of gravitational waves in the nanohertz frequency band, with the formation of the International Pulsar Timing Array (IPTA) collaboration. These efforts are complementary to those of the ground- and space-based laser interferometric projects and could well lead to observation of gravitational radiation from supermassive black hole binaries or from a stochastic background in this band at the end of this decade.

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