Sidereal time analysis as a tool for detection of gravitational and neutrino signals from the core-collapse SN explosions in the inhomogeneous Local Universe

Yu. V. Baryshev [1,*], G. Paturel [2], V. V. Sokolov [3]

[1]*Astronomical Department, Saint Petersburg State University, Saint-Petersburg, Russia;*
[*]*yubaryshevl@mail.ru*
[2]*CRAL-Observatory de Lyon, Saint-Genis Laval, France*
[3]*Special Astrophysical Observatory of RAS, Nizhnij Arkhyz, Russia*

Abstract The core-collapse supernova explosion produces both neutrino and gravitational wave (tensor-transversal plus possible scalar-longitudinal) bursts. In the case of GW detectors, which have low angular resolution, the method of sidereal time analysis of output signals was applied for extraction of GW signals from high level noise. This method was suggested by Joseph Weber in 1970 for analysis of signals from his bar detector and later was developed for existing bar and interferometric GW detectors. The same sidereal time approach can be also used for low energy neutrino detectors which have many years of observational time (e.g. Super-Kamiokande, LVD, Baksan). This method is based on: 1) difference between sidereal and mean solar time (which help to delete noises related to day-night solar time), 2) directivity diagram (antenna pattern) of a detector (which chooses a particular sky region in a particular sidereal time), and 3) known position on the sky of spatial inhomogeneities of GW and neutrino sources in the Local Universe (distances less than 100 Mpc), such as the Galactic plane, the Galaxy center, closest galaxies, the Virgo galaxy cluster, the Super-galactic plane, the Great Attractor.

Keywords: Core-Collapse Supernova Explosion, Gravitational Waves, Neutrino Detectors, Methods of Analysis

1. Introduction

Observations of the SN 1987A explosion marked the beginning of both the neutrino and gravitational wave extragalactic astronomy [1 – 5]. From neutrino observations there was evidence for rather complex behavior of a collapsing stellar core during formation of a proto neutron star. Actually it was detected two neutrino bursts of several seconds duration and 4.5 hours' time interval between them.

The first neutrino burst was observed at 2h 52m U.T. on 23 February 1987 by the LSD detector located in the Mont-Blanc laboratory. The second neutrino burst was found at 7h 36m of the same day in the data of Kamiokande, IMB and Baksan. The occurrence of two neutrino bursts, with time distance of about four and half hours, appeared surprising because the most accepted theories predicted that a star should collapse in a very short time, in the range of a few seconds or even less.

The first neutrino burst coincides with the GW burst detected by the room temperature bar detector GEOGRAV in Rome [3, 4] (Fig.1). Also, smaller additional coincident pulses in a period of 2 hours during the rapid evolutionary phase of supernova 1987A were detected by the Weber's bar gravitational antenna in Maryland [5].

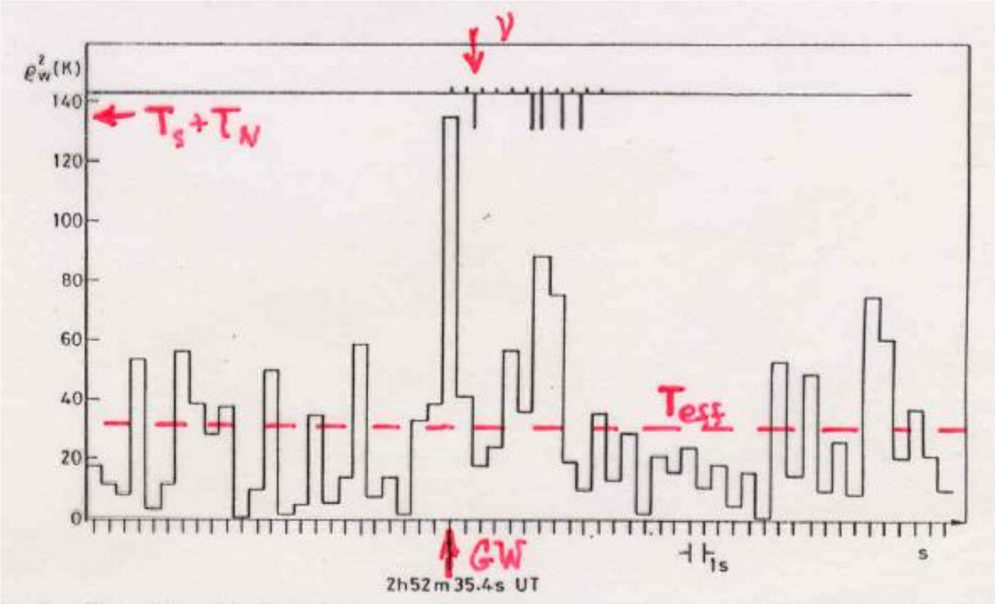

Fig1. *Gravitational signal (the continuous curve) from Rome room temperature GEOGRAV detector (signal + noise) and the five neutrino events of the first neutrino burst from Mont Blanc LSD detector at 2h 52m 35s UT [3].*

Though the majority of publications on the SN1987A core-collapse observations were dedicated only to analysis of the second neutrino burst (at 7h 36m), there are also attempts to explain the full actually observed phenomena including two neutrino and gravitational busts [5] – [13].

In this report we discuss some problems of theoretical analysis of the massive core-collapse SN explosion and their influence on the strategy of observations which led to discovery of corresponding gravitational and neutrino signals. The method of sidereal time analysis is suggested for detection of gravitational and neutrino signals hidden in the detectors' high level noises.

2. The problem of core-collapse SN explosion

Adam Burrows in his review "Perspectives on Core-Collapse Supernova Theory" [14] emphasized that one of the most important, yet frustrating, astronomical question is "What is the mechanism of core-collapse supernova explosions?" Fifty-year history of CCSN theory, which uses advanced hydrodynamics and shock physics, convection theory, radiative transfer, nuclear physics, neutrino physics, particle physics, statistical physics, thermodynamics and **gravitational physics** have not answered this question definitively. Intriguingly up to now there is no theoretical understanding of how to extract such energy from relativistic collapse of an iron core and produce the observed kinetic energy of an expanding stellar envelope [14] – [15].

2.1. The riddle of "bounce" in the SN gravitational core-collapse

According to the review [14], for all trustworthy models of core-collapse SNe (CCSN) the explosion energy is never higher than a few tenths of Bethe (1 Bethe = 10^{51} ergs), which is not enough to overcome the gravitational binding energy of a "canonical" neutron star of mass ~1.5 $M_{\odot}$. Many years theorists have been presented with a stalled accretion shock at a radius near ~100-200 km and have been trying to revive it (see [14] for a review of the literature). This bounce shock should be the CCSN explosion. However, both simple theory and detailed numerical simulations universally indicate that the neutrino burst and photodissociation of the in-falling nuclei debilitate the shock wave into accretion within ~5 milliseconds of bounce. What is more, if the shock is not revived and continues to accrete, all cores will collapse to black holes, which contradicts to observations of NSs in SN remnants.

Rapid rotation with magnetic fields (e.g. [16]) and 3D MGD simulations taking into account different instabilities need to be studied more carefully in future. The true model should explain also such observational properties of the CCSN as two-stage collapse and gravitational signals. However, though many different revival mechanisms were considered, up to now there is no successful model yet, because the problem of CCSN explosion exists at a very fundamental level.

2.2. The long time interval between two neutrino bursts

To overcome the theoretical difficulty of the standard one-pulse neutrino burst from a CCSN explosion, in a number of publications ([11] – [13]) the "two stage collapse" scenario was suggested. The key point in this scenario is the presence of rotation in the stellar core that is about to collapse. This mechanism of the SN explosion is based on the rotational instability and develops through several stages. The inclusion of rotation effects can help to solve the problem of transformation of the original collapse of an iron core to explosion of an SN shell with the energy release on a scale of 10^{51} ergs. The collapse in itself leads to the birth of a neutron star emitting neutrino and gravitational radiation signals of large intensity, whose total energy significantly (by a factor of hundreds) exceeds the SN burst energy.

In the framework of the model [11] – [13] for rotational mechanism of the CCSN explosion there is a two-stage collapse with a phase difference of $\sim$5 h and neutrino signal duration of several seconds. This gives an interpretation of the events in underground neutrino signals from the supernova SN 1987A. However within this scenario there are several phenomenological gaps which should be developed and tested in a future theory.

2.3. "Gravitational roots" of the core-collapse SN explosion problem

In the understanding of the physics of core-collapse supernovae explosion the crucial role belongs to a correct description of gravitational interaction because CCSNs are gravitationally powered. The nuclear burning during explosive nucleosynthesis of the outer mantle after explosion might contribute at most ~10% of the blast energy.

A possibility to revive the bounce shock essentially depends on the gravity force acting within a pre-neutron star (pre-NS), where at least post-Newtonian relativistic gravity effects should be taken into account.

In modern theoretical physics there are two alternative descriptions of gravitational interaction. The first description is the Einstein's geometrical approach - General Relativity Theory (GRT), which is developed in many aspects, but is still really tested in the weak field approximation. GRT is based on curvature of the Riemannian space and has not such physical concepts as gravity force and energy of gravitational field [17].

The second description is the Feynman's field gravity approach (the field gravity theory – FGT) which is based on consideration of material relativistic quantum physical field in the Minkowski space [18] – [23]. According to the Feynman's approach the theory of gravitational interaction must be relativistic (gravidynamics – GD) and quantum (quantum gravidynamics – QGD), as well as in the theory of electromagnetic interaction we have electrodynamics (ED) and quantum electrodynamics (QED).

Within FGT all general physical concepts are working as in other theories of fundamental physical interactions, so the gravity force and positive energy density of gravitational field exist inside and outside of a massive body. An important new element of FGT is the principal role of the scalar part ψ of the symmetric tensor field ψ^{ik} , which is its trace $\psi = \eta_{ik}\psi^{ik}$ and actually presents the repulsive force, which was missed in [17], [18]. The unique role of the scalar field in FGT was discovered in [20] (see also [21] – [23] and references therein).

The CCSN explosion within FGT has an essentially different scenario than in GRT. The post-Newtonian equations of relativistic hydrodynamics in the context of FGT were derived in [24], according to which the gravity force essentially depends on the value and direction of gas flow. This gives a possibility for pulsation of the inner core of a pre-NS star and formation of a jet-like outflow along the rotation axis.

The quantum consideration of the macroscopic limiting high-density quark-gluon bag gives self-gravitating configurations with the preferred mass 6.7 $M_{\odot}$ and radius 10 km [21]. So, gravidynamics predicts two peaks in the mass distribution of relativistic compact objects (RCO): 1.4 $M_{\odot}$ for neutron stars and 6.7 $M_{\odot}$ for quark stars, which can be tested by observations of close binary systems [21].

2.4. Surprises from observations of black hole candidates and possible revival mechanisms in FGT

As was noted above, in the framework of geometrical GRT all cores of massive SNe will collapse to black holes, if the shock is not revived and continues to accrete. However, up to now the problem of "the mechanism of CCSN explosion" is not solved [14], and so the absence of many black holes in remnants of massive SN is a puzzling observational fact.

Other surprising observational facts come from the studies of BH candidates. As was emphasized recently in [25] – [28], the inner 20 gravitational radii around the black hole candidates at the center of luminous Active Galactic Nuclei and stellar mass Black Hole Binaries are now being routinely mapped by X-ray spectral-timing techniques including observations of the iron K_{α} line profiles. An amazing result of such observations is that the estimated radius of the inner edge (R_{in}) of accretion disk around central relativistic compact objects (RCO) is always less than the Schwarzschild radius of corresponding central mass. This points to a suspicion that in the nature there is no Schwarzschild black holes, and this explains why in literature they use now the term "a gravitational radius" (R_g) instead of "the Schwarzschild radius" (R_{Sch}), which relates to each other as:

$$R_g = \frac{GM}{c^2} \qquad \text{instead of} \qquad R_{Sch} = \frac{2GM}{c^2}$$

The factor "2" is essential, because in the case of the Kerr BH the horizon radius is given by the relation:

$$R_H = R_g\,(1 + \sqrt{1 - a^2})$$

where $= J_{bh}/J_{max}$ $(a \leq 1)$ is a normalized spin parameter of the Kerr metrics, which is equal to the ratio of angular momentum of a rotating BH to that of maximally rotating (with the velocity of light c) black hole. We should note that the radius of the ergosphere, where the time $dt = 0$, is always equal to the Schwarzschild radius R_{Sch} in the equatorial plane.

From the fitting of the observed Fe K_{α} line profiles it follows that the radius of the inner edge of accretion disc is about (1.2 – 1.4) R_g which demands that BH is rotating with a velocity about 0.998c. So, according to GRT, the ordinary observed BHs must be maximally rotating ones, because $R_{in} < R_{Sch}$, which is impossible within GRT. For example, in the case of Seyfert 1 galaxy Mrk335 $R_{in} \approx 1.23\ R_g$ and the emissivity profile sharply increases to a smaller radius of disk [25].

Another kind of observations of super-massive BH candidates comes from the mm- wavelength VLBI Event Horizon Telescope, which has been designed to answer the crucial questions: Does General

Relativity hold in the strong field regime? Is there an Event Horizon? Can we estimate Black Hole spin by resolving orbits near the Event Horizon? How do Black Holes accrete matter and create powerful jets? [29] – [33].

Event-horizon-scale structure in the super-massive black hole candidate at the Galactic Centre (SgrA*) and M*87 can be achievable directly with the sub-mm EHT in the near future and this will give a possibility to test relativistic and quantum gravity theories at the gravitational radius [32], [33] for the first time. The first results of EHT observations at 1.3mm surprisingly demonstrate that for a RCO in SgrA* there is no light ring expected for BH at radius $5.2R_{Sch}$ [30], [32]. These observations have opened a new page in the study of RCO.

Beside surprising observational data there are several severe paradoxes in the very basis of the theory of black holes (see discussions in [34] – [36]). For example, there is a paradox of the infinite time formation of a black hole (in the coordinates of a distant observer, so for us) and the finite time of BH evaporation – a BH should evaporate before its formation [36].

The situation is so confusing, that even the father of black holes Stephen Hawking claimed in [34] that though there is no escape from a black hole in the classical theory, but in the quantum theory, however, energy and information can escape from a black hole. An explanation of the process requires a theory that successfully merges gravity with other fundamental forces of nature.

Such a way for constructing gravity theory, based on the same principles as other theories of fundamental physical interactions, already exists and it is the Feynman's Field Gravity Approach (GD and QGD – see [18] – [24] and their references). Within FGT the size of a limited self-gravitating RCO is about the gravitational radius $R_g \approx GM/c^2$, which directly follows from the positive energy density of gravitational field distributed around a massive body. The concept of the gravitational radius in FGT is analogous to the classical radius of electron $R_e = e^2 / m_e c^2$. Thus, black holes and singularities are excluded by existence of positive energy density of gravitational field considered in the framework of FGT.

New possibilities for revival mechanisms in the theory of CCSNe are opened by a difference in behavior of the gravity force in GRT and FGT, as we already have discussed in Section 2.3. In the framework of FGT a subsonic inner core and shocked mantle together can execute a long-time coherent harmonic oscillation with a period of ~1 millisecond. Also the core rotation will lead to a jet-like flow due to strong dependence of the gravity force on direction of velocity of particles. All these facts demonstrate that the choice of the certain direction in the physical description of gravitational interaction has important consequences for analysis of the structure and stability of relativistic astrophysical objects.

2.5. A gravitational burst during a CCSN explosion

There is a long-standing problem within the General Relativity Theory (GRT) related to existence and non-localizability of the energy density of gravitational field. It is known as the "pseudo-tensor of energy-momentum" problem [17], which is caused by the geometrical nature of gravity in GRT (see a review in [21]).

However, discovery and observations of a binary system with a pulsar PSR 1913+16 and the loss of its orbital energy via positive energy of gravitational radiation, stopped all discussions about existence of energy density of gravitational field. In fact the Nobel Prize in physics-1993 was given to Hulse & Taylor for discovery of a process of gravitational radiation of positive energy density.

In the case of SN 1987A the puzzling problem in interpretation of a gravitational signal detected by the room temperature GEOGRAV is a too large amount of energy of gravitational wave needed for explanation of the ~30K signal. Indeed, the mass of a progenitor star is about 20 $M_{\odot}$, while in the framework of General Relativity Theory the burst of GW should have a form of one-millisecond pulse with the total energy about 2000 $c^2 M_{\odot}$ [3] (and even more due to an additional small quantity – the asphericity of core-collapse).

There are attempts to reconsider the value of the cross-section of metallic bar detectors for gravitational waves within GRT by adding quantum mechanics calculations [5], [7] – [10]. Such study is still a controversial subject, though the amplification factor about $10^4 - 10^6$ was claimed.

In the frame of FGT, natural reasons exist for essential increase of sensitivity of the Amaldi-Weber metallic bar detectors and so for explanation of a GW signal from SN 1987A [6]. The first one is the ordinary physical concept of the energy-momentum tensor of gravitational field exists, according to which the GW is localizable and has a positive energy density. Second, the core-collapse can be of pulsating character with a slowly changing frequency, hence at some time when it coincides with a resonance of a bar antenna, the amplification will be high. Also, the cross-section for scalar GW can be much larger due to special features of its interaction with a metallic detector.

3. Sidereal time analysis of gravitational and neutrino signals

The core-collapse of massive stars produces both neutrino and gravitational wave (a tensor plus a possible scalar) bursts. In the case of GW detectors, which have low angular resolution, the method of sidereal time analysis of output signals was applied for extraction of GW signals from a high-level noise. This method was suggested by Joseph Weber (1970) [37] for analysis of signals from his metallic bar detector and later was developed for existing bar and interferometric GW detectors [38] – [42].

The sidereal time approach can be also used for low energy neutrino detectors which have many years of observational time (e.g. LVD [43], Super-Kamiokande [44], Baksan). This method is based on: 1) a difference between sidereal and mean solar time (which helps to delete noises related to the day-night solar time), 2) a directivity diagram (antenna pattern) of a detector (which chooses a particular sky region in a particular sidereal time), and 3) a known position of spatial inhomogeneities of GW and neutrino sources in the Local Universe (distances less than 100 Mpc) on the sky, such as the Galactic plane, the Galaxy center, closest galaxies, the Virgo galaxy cluster, the Super-galactic plane, the Great Attractor.

3.1. Universal time vs. Sidereal Time

The Universal Time (UT) is measured by reference to the Sun direction as seen from the Earth. Because the Earth moves around the Sun, this time is not properly "universal". It is convenient only to define a same time for all inhabitants of the planet. On the opposite, the Sidereal Time (ST) is related to the true Earth rotation and refers to the position of the gamma-point, γ (vernal equinox) in the sky. There is no bright star in this direction, but γ behaves as a virtual star with null declination, obeying the same apparent diurnal motion. More precisely, γ is on the intersection of two planes: the plane of the Sun orbit (ecliptic) and the plane of the terrestrial equator. By convention, γ is in the direction where the Sun crosses the equator from the south to the north (the ascendant node). Because of precession the γ point is not rigorously fixed. Nevertheless, for our purpose this will be perfectly convenient, owing to the small angular resolution of GW and neutrino detectors and to the slow displacement of the γ point.

We should emphasize three characteristics of ST: 1) Contrarily to the UT, the ST is not the same for different places on the Earth, because it takes into account the difference in geographic longitudes of different places. 2) The pace of ST is not identical to the pace of UT. A solar day is longer than a sidereal day (see Figure 2). In other words, the ST runs faster by about 4 minutes per day, i.e. 24h per year. 3) The ST is the hour angle of the gamma point (an angle between the direction of the observer's meridian and the gamma point counted positively towards West (clockwise).

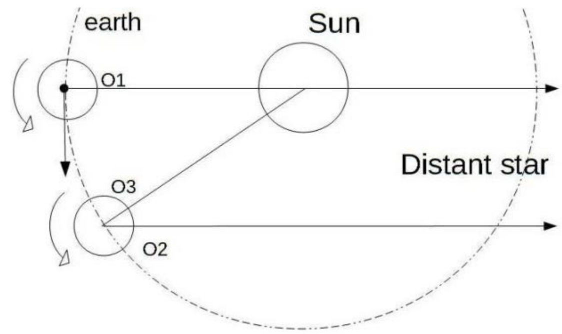

Fig2. *Difference in definition of UT and ST. An observer in O1 will see first a distant star in O2 after 24 hours of ST and 4 minutes later the Sun in O3 after 24 hours of UT. This means that one Earth's revolution is equal to ~23h 56m 04s of mean solar day.*

The merit of the sidereal time analysis can be understood easily. Imagine that many galaxies in a given cluster emit regularly light/neutrino/gw bursts observed with a fixed telescope crossing each day the cluster because of the Earth rotation. If one plots the time of bursts between 0-24h UT, the positions of bursts will be spread all along the axis of time, because they come from an apparent direction that changes regularly due to the displacement of the Earth around the Sun.

If one plots the bursts in sidereal time between 0-24h ST, all the bursts will appear concentrated in the same sidereal time domain. The detection of this emitting region will be easy to identify. Even if some bursts come from some other regions, the cluster will be seen as a bump of events. This means that the ST plot reflects the density of potential sources. This can help to confirm the reality of detection. The summation of all output signals within one Earth's revolution (~23h 56m 04s of mean solar day) during several years of observations will reveal a certain structure at predicted sidereal hours (by using directivity pattern of a detector), so the detection has a statistical sense.

3.2 Calculation of signals within an antenna pattern

For GW detectors, different geometries exist, from a simple bar detector, with only one main axis, to an interferometer with two arms. The orientation with respect to the main direction to the Earth must be taken into account. For instance, in our paper [38], the main axis OX of the detector lies in the local horizontal plane, making an angle Φo with the direction of the north (in the opposite direction of the observer's meridian) and is counted in the direct sense over the range 0-2π. This axis (OX) together with the zenith axis (OZ) and the third direct axis (OY) define a reference system in which we have to express the sensitivity pattern (lobe antenna) using the proper angles with respect to direction of a source.

The relevant angles for expressing the relative sensitivity pattern of antenna are: the azimuth Φ of the source measured with respect to the OX axis and the zenith distance ζ measured with respect to the OZ axis (see Figure 3).

At each sidereal time and for each latitude, Φ and ζ primarily depend on the equatorial coordinates (α, δ) of a source. However, the detailed expression depends on how the signal acts on the detector (a tensor GW is transversal while a scalar wave is longitudinal). In some cases, a polarization angle has to be used to define the action of the signal [38].

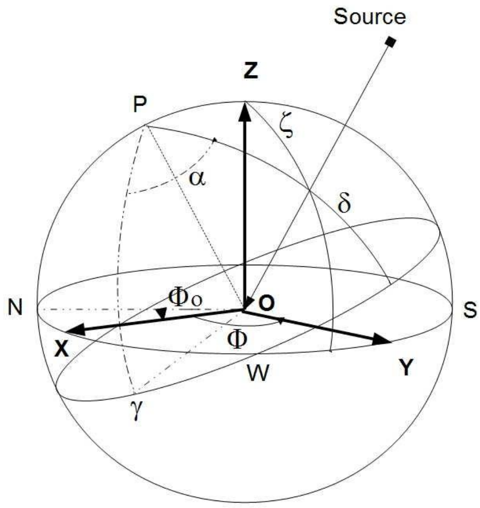

Fig3. *Geometry of the system. The antenna pattern must be expressed in the {OXYZ} coordinates, OX being often used as the main axis of a GW detector, by expressing the two angles Φ and ζ in function of characteristics of a source (equatorial coordinates and mode of action on a detector).*

3.3. Application of ST analysis for GW detectors

Real spatial and projected on the sky galaxy distribution of the Local Universe is very inhomogeneous (see Fig.4 [38]). Many thousands of galaxies can be concentrated in special directions at the sky (the Super-galactic plane, the Virgo cluster, the Great Attractor), and this lead to the expected rate of CCSN events ~ 1/(3days).

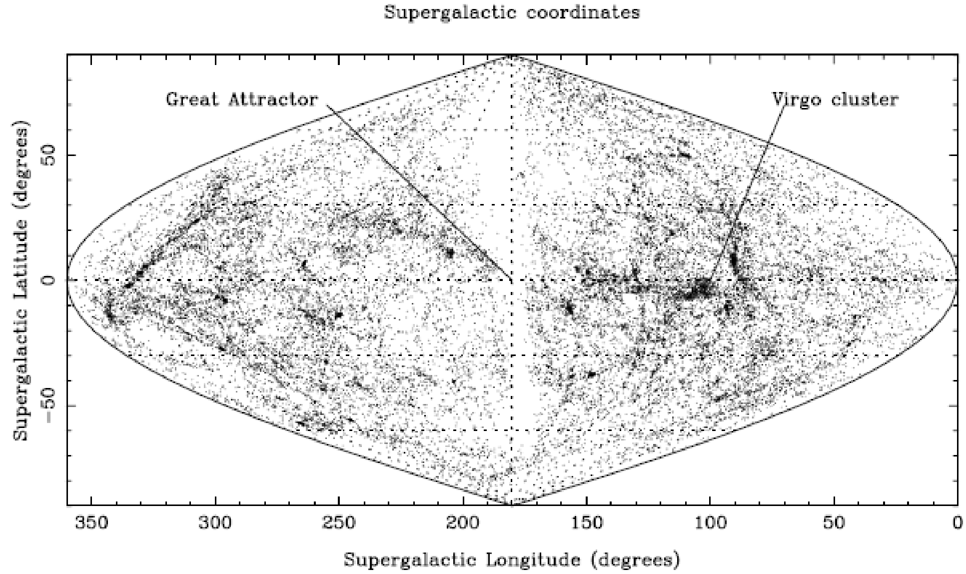

Fig4. *Sky distribution of the Local Universe galaxies (distance < 100 Mpc) in the super-galactic coordinates. Interesting observational fact is that the Super-galactic plane is almost orthogonal to the Galactic plane (from [38]).*

In order to test the calculation we made the calculation for data produced by the Galactic Center (which is similar to the Galactic Plane), that Weber thought to have detected (Fig.5a [37]). We also made the same for two series of observations by the ROG group in Rome [39]. The result (Fig. 5 b,c) is interesting. Unfortunately, the theoretical GRT prediction does not permit such detection [42].

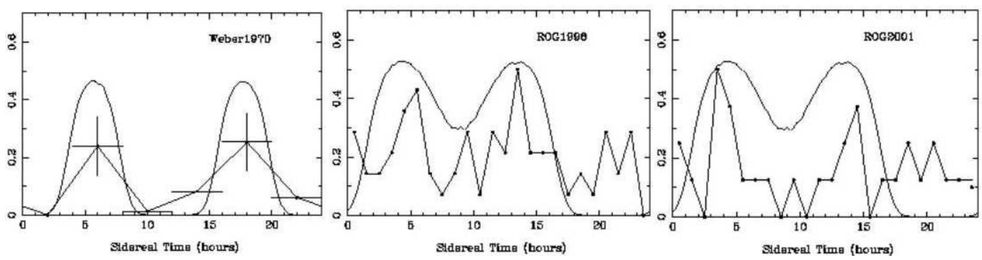

Fig5. a, b, c: *Distribution of the relative event counts in sidereal time for bar detectors and sources of tensor (transversal) GW from the Galactic Center/Plane for the cases respectively: 1970 Weber's data (left)[37] and ROG group data from the Explorer detector in 1998 and 2001 (middle and left) [39].*

A possibility to explain the GW detections (Fig.5) in principle exists in the framework of FGT, if one takes into account pulsate character of the CCSN explosion and specific properties of generation and detection of the scalar GW.

4. Conclusion

The sidereal time analysis could provide us with a high confidence confirmation of detection of both GW and neutrino coming from SN explosions. The most spectacular result would be the detection of a correlation between GW and neutrino signals as it possibly happened in the case of SN1987A (Fig. 1). The goal of the ST analysis is to get statistical evidence of the extragalactic origin of tiny signals in a large noise.

As explained in this paper, spatial inhomogeneities of GW and neutrino sources in the Local Universe (distances less than 100 Mpc) will produce bumps at given ST hours, for both GW and neutrino events. Each coincidence at the right place (after a proper shift in longitude) would be a strong evidence that the detections are real. To apply the ST analysis to neutrino detection, it is important to determine the directivity diagram of neutrino detectors (LVD, Super-Kamiokande, Baksan). This makes us to dream and gives us a hope to explore the Galactic plane, the Galaxy center, the closest galaxies, the Virgo galaxy cluster, the Super-galactic plane, the Great Attractor by using existing and forthcoming GW and neutrino detectors.

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