PROCEEDINGS OF SCIENCE

Concluding Remarks - III

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After a canonical disclaimer and some general remarks, I will make brief comments on two arbitrarily selected topics: gravitational waves and cosmic neutrinos. I will add a very brief comment on a third topic: cosmic rays. I will end with traditional acknowledgements and a call to show up at the next year Mondello (why not Vulcano?) meeting.

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1. Introduction

As stated above (see abstract), I have to start with a classical statement that the selection of topics for these concluding remarks is based on personal impressions and as such it has to be arbitrary. Next, I would like to note my observation that this year conference was definitely proceeding under the banner of multimessenger astronomy. On our very eyes the astronomy is opening new bold chapters of its research. The most striking case are, of course, gravitational waves which after only a few years since the first detection already enormously extended our knowledge of many astrophysical phenomena. The case of cosmic neutrinos is not as impressive but impact of the discoveries in this area is also enormous. The observations of solar neutrinos not only confirmed the theory of stellar structure and evolution but also led to a fundamental discovery in the area of elementary particles physics: the nonzero rest mass of neutrinos. The observations of neutrinos from SN1987 confirmed the theory of final stages of stellar evolution and the physics of core collapse supernovae. While both the gravitational waves and the cosmic neutrinos are undoubtedly two new powerful tools of astrophysical research, we have a third tool that is also a new messenger namely cosmic rays. This tool is used for more than a century by physicists but it is a new tool in the area of astrophysics. To manifest that it is indeed a new one, it is enough to say that in spite of great effort put in the construction of powerful instruments (like Auger Telescope) we still have to identify the first astrophysical source of cosmic rays.

2. Gravitational Waves

We got two nice reviews from Rosa Poggiani and Dorota Rosińska. The progress in this field is really breathtaking. During the first five years of observations we detected already 90 events (the statistics improves very fast). Among them about 84 sources were due to mergers of binary black holes, 2 were mergers of two neutron stars and about 4 were due to black holes - neutron stars mergers. The gravitational waves events (GWEs) could already be used for still new tests of the general relativity and so far no evidence of physics beyond the general relativity was found. GWEs were also used in cosmological analysis namely determination of the Hubble constant. The result (~ 70 km/sec/Mpc) is quite reasonable. The accuracy of this determination is still smaller than that from, say, microvave background radiation but there is a hope that with the increased statistics (and the number of the observed GWEs is growing very rapidly) the precision of this determination will improve.

Among the highlights in the area of GWEs we should mention the first black hole - neutron star mergers. We detected four such sources (one case is marginal). These are: GW200115-042309 (masses of the components 6.0+1.4 M_{sun}), GW191219-163120 (masses 31.1+1.2 M_{sun}), GW190917-114630, (masses 9.7+2.1 M_{sun}) and GW190814 (masses 23.3+2.6 M_{sun}, in this case the secondary could be a very low mass black hole but probably it was rather a heavy neutron star).

Another group of highlights are intermediate mass black holes (IMBHs) created as products of the mergers. Assuming that mass above 100 M_{sun} is sufficient criterion to include a black hole into IMBH class, we have at present four candidates: GW190403-051519 (masses 85.0+20.0 M_{sun}, mass of the final product 106.6 M_{sun}), GW200220 -061928 (masses 87+61 M_{sun}, the final mass 148 M_{sun}), GW190521 (masses 98.4+57.2 M_{sun}, the final mass 153.1 M_{sun}) and GW190426-190642 (masses 105.5+76.0 M_{sun}, the final mass 182.3 M_{sun}). One should remember, however, that the precision of the mass determination is, in some cases, rather poor so not necessarily in all of the above cases the mass of the final black hole is indeed larger than 100 M_{sun}.

Talking about the masses it is worth to mention the lightest (5.1 M_{sun}) black hole found so far in GWEs. This was in GW190924-021846 (masses 8.8+5.1 M_{sun}).

Both review speakers presented the prospects for future GWEs observations. The future of such observations looks very bright. The existing detectors (LIGO, VIRGO, Kagra and, in further perspective, LIGO-India) will constantly improve their sensitivity. As a result in about 5 years perspective the volume of the observable part of the Universe will increase by more than an order of magnitude. This means that instead of 100 we will have 1000 detections which will be already a big progress. Moreover, in $\sim$ 10 years perspective we will get three new third generation instruments which will be much more powerful than the present ones. The first of them will be Einstein Telescope (project of ESA). It will be a laser interferometer similar to the present detectors but with three arms of 10 km length that will form a triangular shape. The instrument will be put underground to minimize the seismic noise. Its sensitivity will be so high that it will be able to detect all GWEs within the presently observable Universe (up to redshift $\sim$ 100) The second new generation instrument will be Cosmic Explorer (project of NASA). It will be traditional L shape interferometer with arms of 40 and 20 km. Both Einstein Telescope and Cosmic Explorer will be able to detect mergers of stellar mass binary black holes. The third new generation instrument LISA (project of ESA) will be sensitive to much lower frequency of the merger signal which will permit to register the mergers of supermassive black holes. LISA will be again a triangular shape detector (similarly as Einstein Telescope) but this time with the arms 2.5 $\times 10^6$ km long. With this size (200 greater than the size of our planet) the instrument will have to be located in the outer space. To summarize all this, the future of GWEs observations looks indeed very bright.

3. Cosmic Neutrinos

The review was given by our regular cosmic neutrino reviewer Todor Stanev. Then Rosa Poggiani and Paolo Padovani discussed possible coincidences between the directions of arrival of high energy neutrinos and the positions of the known electromagnetic radiation sources. Unfortunately, the arrival direction of the incoming neutrino is determined only very approximately (error one to ten degrees). Therefore, we are looking also for time coincidences (electromagnetic radiation close to the time of high energy neutrino arrival). The search is not easy and the progress is relatively slow. However, there is some progress. The first object that was identified as an undoubtful source of high energy ($\geq$ 0.3 PeV) neutrinos was blazar TXS 0506+056. Further searches discovered a couple of more possible sources of neutrinos: NGC1068, TXS 9596, PKS1424+240 and GB9. NGC 1068 (4.2 σ identification) is an active galaxy from which IceCube has detected 79 +/-20 high energy neutrinos between 2011 and 2020. The error of 20 events is due to the fact that the exact direction of the different neutrino events are not determined equally well. Other sources are $\sim 3\sigma$ identifications. Todor summarized the identification status of high energy neutrino sources as follows: One of the most recent IceCube papers shows a list of 275 high energy events. About one third to about half of them are probably astrophysical. To make more determined statement we have to wait for the advanced version (enlargement) of the IceCube telescope. Then we might expect not 10-20 but 100-200 interesting events per year. At present, we have to remain with the statement that we observe ~ 5 sources with firm identifications and ~ 100 unidentified sources that are probably of astrophysical nature.

Clearly, the neutrino astronomy is just at the beginning of its spectacular rise. It promises to provide a new window on very high-energy astrophysics (blazar jet physics) at energies forever inaccessible with photons. The future looks bright.

4. High Energy Cosmic Rays

To be more precise, we should specify that we are talking here about Ultra High Energy Cosmic Rays (UHECRs) or particles with energies ≥ 0.1 EeV. We listened to two nice reviews of this field given by Chiara Righi and Daniele Fargion. The situation with the sources identification is even more embarrassing than in the case of cosmic neutrinos. At present, we list exactly zero (!) of identified sources. The culprit of this embarrassing situation is bending of the travel trajectories of the cosmic rays in the galactic and intergalactic magnetic fields. We know quite a lot about UHECRs but it is mostly a circumstantial evidence. There is an evidence that the composition of CR becomes lighter as the energy increases toward the so called "ankle" (until around 2 EeV) and then becomes heavier again when approaching UHE. We suspect that the sources of the UHECRs are some active galaxies. Prime suspects are Cen A, M82 and NGC253 but they are only suspects. Also an abundant class of weak radio galaxies known as FR 0 galaxies is mentioned as a possible suspect. The situation is challenging and the future of the field looks very interesting.

5. Other Topics

There is no chance to discuss the other highly interesting topics of our conference but I would like at least to mention some of them together with the names of the speakers (again unfair selection). I believe that I should name:

- Gamma Ray Bursts (L. Amati)
- Dark Matter (D. Malyshev)
- Ultra Luminous X-Ray Sources (M. Bachetti)
- Supergiant Fast X-Ray Transients (E. Bozzo)
- Binaries at gamma-rays (P. Bordas)
- Intermediate Mass Black Holes (I. Zaw)
- Supermassive Black Holes Binaries (P. Severgnini)

6. Acknowledgements

Finally, I would like to thank Franco, all organizers and all participants and express the hope that all of us will meet next year at Mondello (and perhaps finally at Vulcano?)