Title: On the origin of high energy neutrinos observed by IceCube

Abstract: The discovery of a diffuse flux of high energy neutrinos made by IceCube, a neutrino telescope of 1 km$^3$ located in the South Pole, has opened a new era for neutrino astronomy. The observations of IceCube are compatible with the theoretical expectations for cosmic neutrinos. However many important questions, raised by these findings, are still unsolved: what is the source and the mechanism of production of the cosmic neutrinos seen by IceCube? Is it an astrophysical mechanism? Is their origin extragalactic or is there also a galactic population? How to use high energy neutrinos in the context of multi-messenger physics? The aim of this thesis is to investigate these questions.

The mechanisms of production and the sources in which these processes are likely to occur are discussed. The propagation of neutrinos is studied and their interaction with neutrino telescopes is examined.

The flavor composition is analyzed, both from a theoretical and an experimental point of view. We find that the flavor composition of the cosmic neutrinos detected by IceCube is compatible with any plausible mechanism of production of neutrinos, namely pions decay, neutrons decay and decay of heavy mesons containing the quark charm. Due to the low statistics it is not possible to rule out any of these mechanisms, but it is possible to rule out exotic scenarios, such as pure electronic or muonic composition at the Earth. Moreover, based on the flavor, we discuss also the exotic scenario of full neutrino decay, finding that this scenario is disfavored by the present data; particularly the normal hierarchy shows a tension of 2$\sigma$ whereas the inverted hierarchy shows a tension of 3$\sigma$. The analysis of the flavor composition and of the neutrino decay scenario are new results.

A topology of events that are expected but not yet observed is discussed. These are the double pulses, produced by very energetic tau neutrinos around PeV, and the Glashow resonance, produced by electron antineutrinos with energy of multi-PeV. Non-observation of these events does not represent an issue at present, being compatible with (but not far from) the current exposure and this represents a new result.

An interpretation of the flux of high energy neutrinos is proposed. The tension between the flux that comes from the Southern hemisphere (observed with the contained events) and the flux that come from the Northern hemisphere (observed with through-going muons) is discussed and addressed. We provide, for the first time, an estimation of the Galactic component, that could reconcile the observations. The results is that Galactic neutrinos from disk, distributed as $E^{-2.4}$ and giving a contribution especially below 100 TeV, is compatible with present data and is relevant for the above issue. The Galactic component should contribute to 6 ± 3 contained events of the 54 observed by IceCube, with a null Galactic component disfavored at 2$\sigma$. The presence of Galactic high energy neutrinos would be important not only from a theoretical point of view but also from the incoming KM3NeT experiment, that is expected to be able to measure (or rule out) this flux of neutrinos. We also analyzed the role of atmospheric prompt neutrinos, expected from a theoretical point of view but not yet detected.

The last part of the thesis is dedicated to the multi-messenger correlations, between high energy neutrinos and $\gamma$-rays or other known radiations, considering specific astrophysical assumptions.
We find that the Galactic center cannot produce events detectable in IceCube, although the Galactic center is very interesting for the $\gamma$-rays astronomy. Considering extragalactic sources we find, for the first time, that the BL Lacs shows a tensions of $3.7\sigma$ in the hypothesis that they are the main emitters of high energy neutrinos above 200 TeV. On the other side, starburst galaxies seem to have the necessary budget to explain IceCube neutrinos, but more observations are required to better constraint the scenario. A preliminary analysis is presented in this thesis.

Summarizing, high energy cosmic neutrinos have been observed with a significance of $6\sigma$. Up to now there no evidence of point sources was found. This is an unsatisfactory situation but, evidently, it is quite difficult to obtain definitive answers with only 29 through-going muons and 54 contained events. The incoming IceCube generation 2, with an exposure of 6-7 times larger, along with neutrino telescopes located in the Northern hemisphere, will have an essential role to progress in the study of the origin of high energy neutrinos.

Advisor: Francesco Vissani

External Referees :
Walter Winter
Fabrizio Tavecchio
Esteban Roulet
Candidate: Federica Agostini  
[Oct 23, presentation 14.00-14.00, then defence]  

Title: The XENON project: backgrounds and new results

Abstract: Experimental observations tell us that the biggest amount of mass constituting the universe does not absorb or emit electromagnetic radiation; that is the reason why it is called Dark Matter (DM). The evidences for the existence of DM are based on gravitational effects, such as anomalies in rotational curves of spiral galaxies, gravitational lensing, CMB anisotropies, etc. A consistent theoretical model of particles that includes DM has not been developed yet, thus a DM candidate is generally called Weakly Interacting Massive Particles (WIMP).

There are mainly two dark matter detection techniques: indirect search, based on tagging the particles produced by the decay of self-annihilation of WIMPs, and direct search, which consists in identifying elastic scatterings of WIMPs off target nuclei. The XENON project is a DM direct search detector, located at the Gran Sasso National Laboratories. The experiment is based on a xenon dual-phase (Liquid/Gas) Time Projection Chamber (TPC), exploiting both scintillation and ionization signals to identify and discriminate impinging WIMP particles from background. XENON100, operating up to 2016, published in 2012 the best exclusion limit, at that time, for spin-independent WIMP-nucleon elastic interactions, with a minimum cross section of $2.0 \times 10^{-45}$ cm$^2$ for a WIMP mass of 55 GeV/c$^2$, at 90% confidence level. Moreover, from a combined analysis over three runs, a long period of 477 live days of data has improved the sensitivity by almost a factor 2. The subsequent experiment XENON1T is the first multi-ton scale dark matter direct search detector to date, and, on May 18th 2017, the Collaboration released the results from the first science run, setting the limit for spin-independent WIMP-nucleon elastic scattering, to $7.7 \times 10^{-47}$ cm$^2$ cross section for a 35 GeV/c$^2$ WIMP mass at 90% confidence level. This limit is, at the moment, the best one.

The work of this thesis is based both on XENON100 and XENON1T experiments. In XENON100 a study on the electromagnetic background, due to electrons or gammas scattering off xenon electrons, has been developed. The calibration data from Xe activation lines by neutron inelastic scattering, $^{232}$Th and CH$_3$T sources have been compared with the Monte Carlo (MC) simulations. The model used to predict the number of photons, or light yield and electrons, or charged yield emitted by a particle interacting with the detector is called Noble Element Simulation Technique (NEST). It consists in a phenomenological description of the xenon response to an ionizing radiation, through a collection of target-related parameters obtained by fitting up-to-date experimental results. A refined matching between MC and measured data has been achieved within a Bayesian statistical approach. For this purpose, the light and charge yield obtained by NEST have been improved by using the data from tritium calibration as input. That topic is of fundamental importance for XENON1T, where the large self-shielding power of the liquid xenon does not allow to reach the inner fiducial volume through usual calibration sources located outside the TPC.

In the case of XENON1T, an active Muon Veto (MV) has been employed in order to reduce the muon-induced neutron background. It consists of a cylindrical tank, containing the TPC, filled with water and equipped with 84 photomultiplier tubes (PMTs), to tag the Cerenkov light emitted from a muon, or its daughters, crossing the water tank. I took care of the MV system since the very beginning, from the installation of the PMTs inside the water tank to its operation in the final state. Moreover, a muon analysis to tag neutron-induced muon events over the first
science run of data is object of this work. 63 single scatterings off xenon nuclei inside 1 ton fiducial volume have been found in the low energy region, that is of interest for WIMP search; no one of them has been vetoed by MV, but they have been discriminated as electromagnetic background.

**Advisors:** Gabriella Sartorelli

*External Referees:*
- Emanuela Meroni
- Vitaly Kuryavtsev
- Carlo Broggini
Candidate: Gang Wang
[Oct 23, presentation 16.00-17.00, then defence]

Title: Implementing a Tidal Template Bank for Binary Neutron Star Search and Multi-Messenger Perspectives for the Coalescences

Abstract:

The success of the Advanced LIGO and Advanced Virgo observing runs opened the gravitational wave (GW) astronomy era and made multi-messenger astronomy enter an unprecedented new epoch. Until now, four unambiguous GW detections, GW150914, GW151226, GW170104 and GW170814, were identified as binary black holes coalescences. On August 17, 2017 the Advanced LIGO and Advanced Virgo gravitational-wave detector network detected a GW signal from binary neutron stars (BNS) inspiral for their first time. In the current matched-filtering search for BNS inspiral, the GW template bank is using the aligned-spin waveform without considering the tidal effects depending on the equation of state (EoS). However, the deformation of the NS could become significant in the late inspiral stage. The differences of GW waveforms between the non-tidal and tidal could make the signal-to-noise ratio for BNS search decrease. We build a BNS template bank including the tidal parameters to explore the improvement in the BNS search sensitivity. Using our tidal template bank, we show an improvement in the sensitive time-volume to the strong tidal effect of ∼6% compared to current point-particle aligned-spin BNS banks.

The joint observation of GW and electromagnetic (EM) radiations from BNS inspiral and coalescences can boost our understanding of the astrophysics, dense matter, gravitation and cosmology. We simulate the GW and fiducial short GRB joint search with current/forthcoming GW detector network, Hanford-Livingston-Virgo-KAGRA-India, and high-energy EM telescopes, Fermi-GBM, Swift-BAT, EinsteinProbe-WXT, SVOM-ECLAIRs and SVOM-GRM. Also, a proposed GRB-less X-ray emission from BNS merger with respect to the different EoSs are investigated in our simulation. Our results show that, among five γ-ray and X-ray detectors, Fermi-GBM has the most promising capability to achieve the joint detection with GW detectors and could find 70% of associated short-GRBs. Our simulations show that the short-GRB-less X-ray transients can be a promising candidate for seeking the high-energy EM counterpart from BNS coalescence for some specific EoSs. The wide field of view (FoV) X-ray telescopes, Einstein Probe (EP), SVOM-ECLAIR and Swift-BAT, could give good contributions to search X-ray counterpart from the BNS merger.

Advisors: Giancarlo Cella, Massimiliano Razzano

Tutor: Walter Del Pozzo, Alexander Nitz

External Referees:
Eric Chassande-Mottin
Szabolcs Marka
Samaya Nissanke