Neutrino Spectra From Supernova Remnants

DESY Summer Student Programme 2016

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Abstract

A modification in a PYTHON code that solves the transport equation of particles in SNRs has been introduced with the aim of developing a model for neutrino flux. Furthermore, results from these simulations applied to SNR RX J1713.7-3946 have been checked with analytic expressions and simplified approximations in order to test their veracity, as well as with previous carried out works for this precise SNR. According to our results, we have concluded that the estimated neutrino spectra expected from RX J1713.7-3946 will be below the flux of atmospheric neutrinos.

About the Summer Student and Motivation

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- End Date: August 26th 2016

Collaborating Group

I did my internship at the Deutsches Elektronen-Synchrotron (DESY) placed in Zeuthen, a Research Centre of the Helmholtz Association, enrolled as Summer Student in the programme of 2016. Its orientation is mainly the research on basic science, whose more important research lines are Theory in Particle Physics and Astroparticles, and experiments based on gamma-ray and neutrino astronomy with the observatories CTA, HESS, MAGIC, VERITAS, and Fermi LAT and IceCube.

Concretely, the Astroparticle Physics Theory Group (THAT) studies very energetic particles that make of Cosmic Rays (CR), neutrinos, and gamma-rays. They keep on the theoretical description of physical systems in which particle acceleration is believed to take place, for instance in Supernova Remnants (SNRs), Active Galactic Nuclei (AGN), and Gamma-Ray Bursts (GRB). Different methods are used to model the behaviour of those particles such as hydrodynamical simulations, kinetic models following the individual particles, and global radiation models. I joined this group at DESY, specifically working under Shan Gao's and Robert Brose's advice.

Purpose of the Internship

In this report, my tasks as a summer student at DESY (Zeuthen) are explained, as well as the most important results derived from the summer project. I accomplished my tasks by the end of the internship, improving my learning in Neutrino Physics from a point of view close to research.

I carried out my internship in the fields of Astroparticle Physics, focusing on modelling astroparticles acceleration in Supernova Remnants (SNRs) in order to obtain neutrino spectra. I decided to carry out an internship at DESY in order to get experience in a research group and to learn how science is performed nowadays in other pioneered countries such as Germany. Furthermore, I expected this internship to open me the possibility of going into a new research line, as it is Astroparticles Physics, unknown for me until this very moment. The opportunity of working in a physics department together with a research group made me learn how modelling in astroparticles could be a suitable research line to get enrolled in a PhD program in the future.

Contents

1. Introduction

It is believed that supernova remnants (SNRs) are the sources of galactic cosmic rays (CR). Although this premise is still unproven, it has received strong support thanks to the detection of TeV-range photons from some SNR. One of the most well-known model to explain the origin of CR is the one based on diffusive shock acceleration of particles in expanding SNR shells. Nevertheless, in spite of the fact a large number of astrophysicists agree with this this model, there are still several dilemma related to the SNR hypothesis.

For this reason, the development in γ-ray astronomy gives a way to solve the problem of the origin of galactic CR. Mostly two mechanisms are argued for the production of γ-rays. They are expected to be consequences of, on the one hand, the acceleration of CR at SNR shock waves where photons gain energy due to Inverse Compton process (IC) (leptonic origin) and, on the other hand, during their subsequent propagation in the interstellar medium (ISM) where CR may collide with other protons (hadronic origin), producing secondary decays. Hence, although many SNRs at TeV energies nicely fit with the above mentioned models, this does not guarantee a conclusive proof of itself, as it is extremely difficult to disengage the hadronic and leptonic contributions to the observed γ-ray emission.

According to hadronic origin of CR, they interact with the ISM protons producing γ-rays and secondary leptons by inelastic collisions which may decay into secondary lepton particles, most of them being π^0 and η. Both of theses particles decay into γ-rays in their main channels. However, during the interaction of CR with ISM, charged mesons such as $\pi^{\pm}$ and other secondaries may produce high-energy neutrinos and other electrons and positrons. In fact, protons that compose the ISM may interact with other protons in the ISM producing secondary leptons, neutrinos among them. The abundance of cosmic-ray neutrinos will be determined by the amount of particles that composed the CR and the production cross sections of the parents particles, that can be $\pi^{\pm}, K^{\pm}, K_S^0, K_L^0, \Sigma^{\pm}, \Sigma^0, \Lambda, \bar{\Lambda}$.

The easiest way to encounter this problem is to suppose that during proton-proton collisions the same number of charged and neutral pions are created so that

$$p + p \to \pi^{\pm}. \tag{1}$$

The main decay branches of $\pi^{\pm}$ are the following,

$$\pi^+ \to \mu^+ + \nu_\mu \tag{2}$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu, \tag{3}$$

and consequently, muons and antimuons decay into secondary leptons as,

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \tag{4}$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu. \tag{5}$$

Therefore, detecting high energy neutrinos that may be produced during secondary lepton decays will bound the origin of CR to be hadronic, bringing to light the problem itself.

2. Strategy

The main aim of this work is to explain several methods to model neutrino spectra. In this report, the most relevant methods to describe neutrino spectra are briefly summarized, and then they are applied to a concrete SNR example so that a final solution of the problem of CR origin can be discussed. We start with a simplified theoretical approximation that obtains the neutrino flux as of γ-ray. Then, we follow different analytic works that explain empirically the production rate of secondary leptons in hadronic decays. Finally, we modify a complex computing software that models particle acceleration within SNR in order to include secondary lepton production by means of matrix that explain neutrino production rate obtained in Monte Carlo Simulations. These three mechanisms are also applied to a concrete SNR, RX J1713.7-3946, comparing our results with previous attempts of modelling it by other scientists.

3. Simplified Approximation

It is possible to set up a basic approximation for neutrino spectra starting by the γ-ray spectra itself. This approach starts by setting that γ-ray spectra is mainly formed by photons coming from neutral pion decays as,

$$\pi^0 \to \gamma\gamma. \tag{6}$$

If we suppose that the number of charged pions $\pi^\pm$ is going to be equal to the number of neutral pions π^0, we can stablish that the flux of neutral pions is going to be equal to the flux of charged pions. Moreover, the energy associated to neutral pions would be the double of that assigned to photons, and therefore, the energy associated to charged pions would be also the double. As charged pions decay according to Eqs. (2) and (3), we may suppose that the energy associated to the parent particle may be equally distributed for both the neutrino and muon (daughter particles). At the same time, we may suppose the energy associated to the muon will be equally divided in three parts when it decays into two neutrinos and one electron.

With these conditions, a starting approximation of the neutrino spectra derived from γ-ray spectra can be obtained. However, these premises are not correct, due to the fact that the difference between muon, electron and neutrinos mass is too large. Consequently, another approximation is required so that the mass of the outcoming particles as well as the energy of the parent particles are taken into account.

4. Analytic Approximation

We discuss simplified models for production of secondary particles in high energy hadrons collisions so that the theoretical neutrino production rate in these decays is defined as a function of the mass of the incoming and outcoming particles and the energy of the parent particles. For this purpose, we have followed previous works that attempt to explain the production rate of secondary lepton production.

According to *A. H. Hillas* [2], proton to proton collisions will produce a number n of charged pions (see Eq. (1)) following a production rate energy profile $\frac{dn}{dx_{\pi^\pm}}$ defined as,

$$\frac{dn}{dx_{\pi^\pm}} = \frac{1}{x_{\pi^\pm}} \times \left[1.22\,(1-x_{\pi^\pm})^{3.5} + 0.98e^{18x_{\pi^\pm}} \times \left(1 + \frac{0.4}{E_p x_{\pi^\pm} - 0.14}\right)^{-1}\right], \tag{7}$$

where $x_{\pi^\pm} = E_{\pi^\pm}/E_p$ is a change of variable defined as the energy of the outgoing particle (charged pions) divided by the energy of the parent particle (protons). Consequently, charged pions would decay into muons, according to Eqs. (2) and (3), following a production rate energy profile defined by *S. Hümmer et al.* [5] to be as,

$$\frac{dn}{dx_{\mu^\pm}} = \frac{1}{(1 - r_{\mu^\pm})} H(x_{\mu^\pm} - r_{\mu^\pm}), \tag{8}$$

where $x_{\mu^\pm} = E_{\mu^\pm}/E_{\pi^\pm}$, $r_{\mu^\pm} = (m_{\mu^\pm}/m_{\pi^\pm})^2$ being $m_{\mu^\pm}$ and $m_{\pi^\pm}$ the masses of charged muons and pions respectively, and H the Heaviside function[1]. We set that the production rate profile that defines the first muon-neutrino spectra (index I) from Eqs. (2) and (3) will be the complementary of Eq. (8) such as,

$$x_{\nu_\mu^I} = 1 - x_{\mu^\pm} = E_{\nu_\mu^I}/E_{\pi^\pm}. \tag{9}$$

Finally, also according to *S. Hümmer et al.* [5], the rate profiles for the second muon-neutrino (index II) and electron-neutrino from Eqs. (4) and (5) are defined as,

$$\frac{dn}{dx_{\nu_\mu^{II}}} = 2\left(\frac{5}{3} - 3x^2_{\nu_\mu^{II}} + \frac{4}{3}x^3_{\nu_\mu^{II}}\right) \tag{10}$$

$$\frac{dn}{dx_{\nu_e}} = 2\left(2 - 6x^2_{\nu_e} + 4x^3_{\nu_e}\right), \tag{11}$$

where $x_{\nu_\mu^{II}} = E_{\nu_\mu^{II}}/E_{\mu^\pm}$ and $x_{\nu_e} = E_{\nu_e}/E_{\mu^\pm}$. Therefore, the number of particles produced at each step need to be integrated all over the range of energy of the parent particles, and then, taken into account for the production of the outcoming particles at the end.

5. Detailed Modelling

The acceleration of CR at supernova shock waves can be described by the *linear theory of diffusive shock acceleration*. We consider the system formed by a core-collapse SNR and a shell of dense gas located just outside the remnant. Hence, the main goal is to study how the evolution of shock waves from SNR moving out in the medium created by the progenitor stars state the high-energy emission of these celestial objects.

In order to do that, the first step is to model the SN expansion into the ambient medium. It is necessary to know the nature of the ISM itself, as it will proportionate different elements and several amounts of future-to-be parent particles in collisions and decays. Thus, in general, ISM are studied according to the different type of SN that took place to produce the SNR [9].

The particles from in the ISM accelerate depending on the magnetic field in the SNR, concretely in the upstream and downstream vicinities of the shocks, emitting radiation. Therefore, the second step is to parametrize the MF inside the remnant following either pressure or density distributions. Several approximations has been tested, and even hydrodynamic solutions for the MF in SNR has been numerically encountered.

[1] Several definitions of the Heaviside function has been used along the history. In this case, we have used $H(x) = 0$ if $x < 0$ and $H(x) = 1$ if $x \geq 0$.

Finally, the last step is to solve time-depended kinetic calculations based on the convection-diffusion equation for the momentum-space distribution function N that describe the acceleration of particles in SNR, in the test-particle limit. In this limit, CR pressure can be neglected and insufficient to modify the shock structure. Once that the momentum-space distribution function N is found, is used to carry out several γ-ray spectra taking into account the different mechanisms of radiation production.

5.1. Computing Software

The Particle Acceleration Transport Radiation Object-orieNted PYthon Code, also known as PATRON, is a computing software developed by some members of the Theoretical Astroparticles Group in DESY. It has been written mainly by I. Telezhinsky [9].

PATRON solves the full transport equation for the differential particle number density N on a grid co-moving with the shock wave and in spherically symmetric geometry [7], using transformation of coordinates for the position and momentum. This grid extends from the SNR centre to several SNR radii ahead of the forward first shock. These hydrodynamical simulations describe the evolution of the SNR. The transport equation is,

$$\frac{\partial N(p,r)}{\partial t} - \frac{1}{r_s}\frac{\partial}{\partial r}\left[r^2 D(p,r)\frac{\partial N(p,r)}{\partial t} - r^2 V(r) N(p,r)\right] + d_E N(p,r) = Q(p,r) \tag{12}$$

where d_E is the differential energy operator, $V(r)$ is the shock wave velocity that is characterized by the profile of the ISM, Q are the CR sources, and D is the diffusion parameter, which is characterized by the magnetic field. Once that the differential particle number density $N(p,r)$ in every point has been calculated, PATRON transforms that information into physical energetic meaning. Then, the contribution of γ-ray by neutral pions decays, Inverse Compton, Synchrotron and Bremsstrahlung radiation is obtained.

5.2. Modifications to include Neutrino Spectra

PATRON has been modified in order to include neutrino spectra from secondary leptonic decays by means of the differential particle number density $N(p,r)$. For that, production matrix for each stable neutrino in p-induced interaction have been linked to PATRON. These matrix, developed by *C.Y. Huang* [3], describe the production rate of neutrinos taking into account the incident total energy until to 10^8 GeV, using a parametric model for $E < 10$ GeV and the Monte Carlo high-energy event generator DPMJET-III for $E > 10$ GeV. Moreover, the matrix also take into account more secondary lepton decays that include neutrinos apart from charged pions, such as n, $\Sigma^{\pm}$, Σ^0, Γ, K and τ (for further information about all channel decays the reader is kindly referred to [3]).

In order to calculate neutrino spectra, the same procedure that *C.Y. Huang et al.* [4] applied to γ-ray spectra has been used. We calculate the number of neutrinos $Q_v(E_i)$ as a function of the energy according to the following expression.

$$Q_v(E_i) = \sum_j n_{ISM} \Delta E_j N_{CR}(E_j) c \beta_j \sigma_j M_{ij} \tag{13}$$

where n_{ISM} in the density of the interstellar medium, ΔE_j is the energy binning to perform the sum, c is the speed of light, $N_{CR}(E_j)$ is the production rate profile of the parent protons as a function of the energy, β is the relativistic factor, σ_j is the cross-section depending on the energy, and M_{ij} the production rate matrix. Once that $Q_\nu(E_i)$ is obtained, it is transformed into flux magnitude accordingly.

6. Results for RX J1713.7-3946

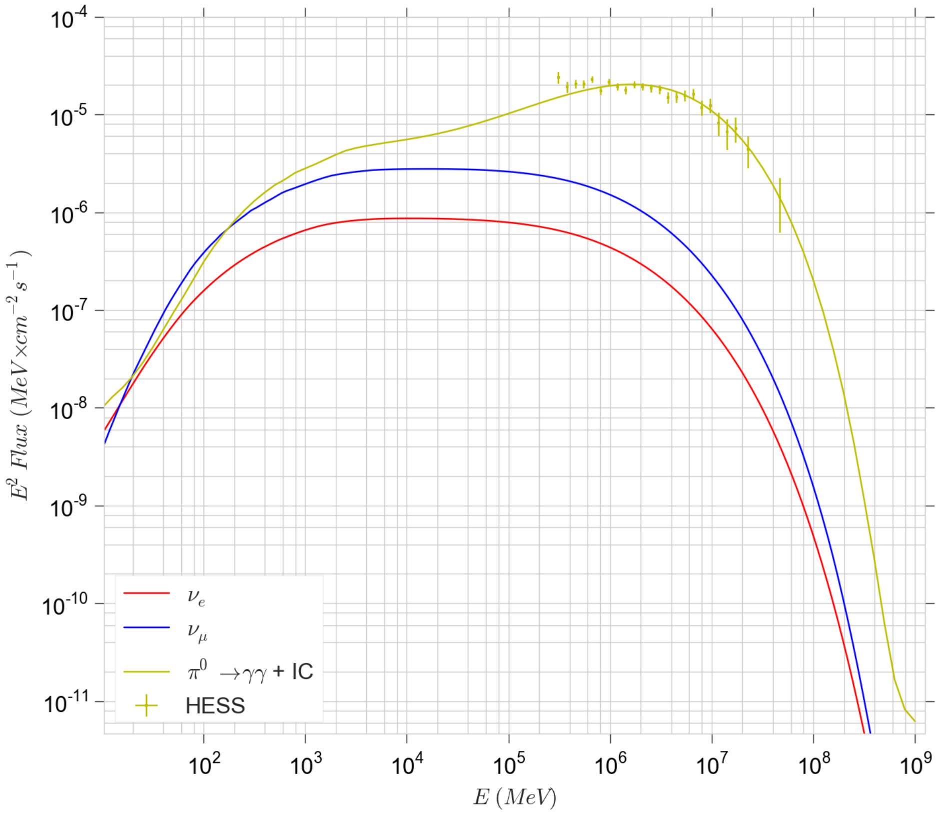
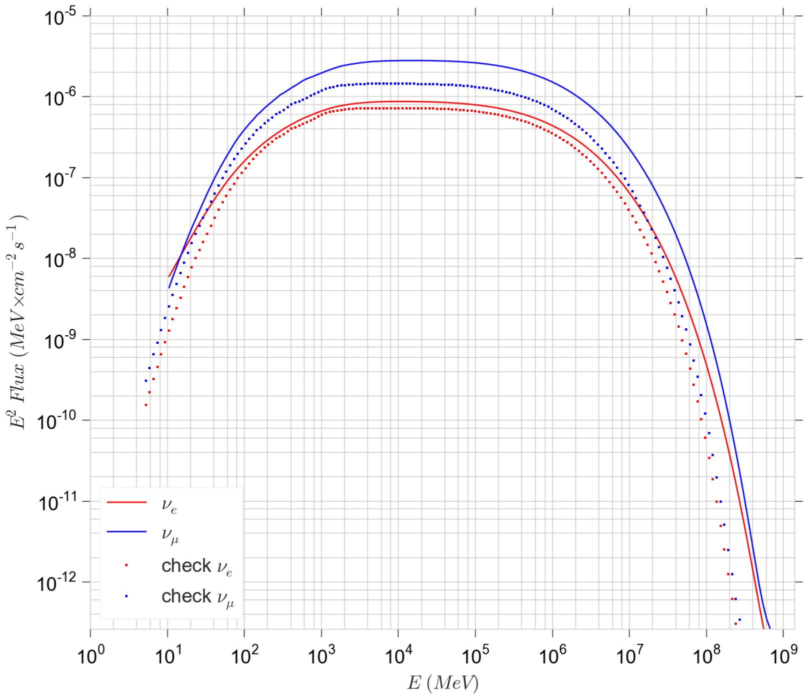


Figure 1: Broadband γ-ray and ν flux spectra of RX J1713.7-3946 as measured with HESS (yellow points), compared to calculated γ-ray and Inverse Compton contribution at the age of 1600 years (solid yellow line), electron neutrino spectra (red solid line) and muon neutrino contribution (blue line).

We have applied the above mentioned methods to obtain the neutrino spectra associated to the SNR RX J1713.7-3946 (also known as G347.3-0.5). This is a shell-type Supernova Remnant placed at the galactic place in the tail of the constellation of Scorpius.

This SNR is likely to be placed at 1 kpc in distance and the implied age is about 1600 years [3]. The remnant is described by a serie of parameters such as the magnetic field (the magnetic field of the precursor region is set to be $B_p = 23\mu G$ and the downstream field $B_d = 75\mu G$), the density of the interstellar medium, the radius $R \approx 8.65$ pc and the shock speed $V_{sh} \approx 4200$ km/s. The dense gas shell radially extends from 8.75 pc until 9.05 pc of the SNR.



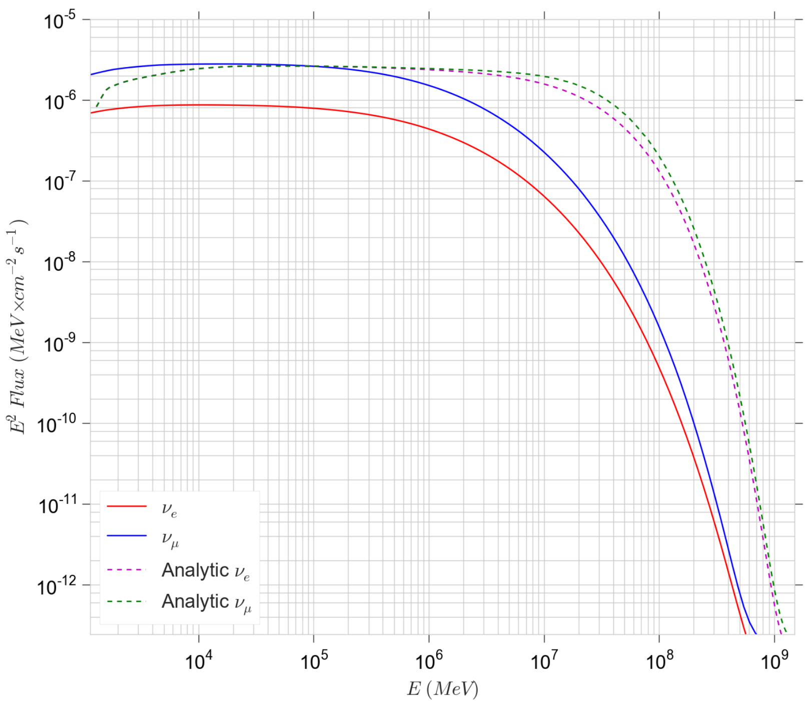


Figure 2: Simulated fluxes of neutrinos ν (plus anti-neutrinos) from RX J1713.7-3946 compared to the results from the simplified approximation (above, dotted lines) and the analytic approximation (below, dashed lines). Both electronic and muonic neutrino contributions are shown in both check tests.

We have solved numerically the time-dependent transport equation (Eq. (12)) for RX J1713.7-3946 using PATRON introducing the above mentioned parameters, as it was already carried out by *Federici et al.* [1]. Then, we have calculated the emission spectra fir 1600 years (see Fig. 1) including γ-ray from neutral pion decay, inverse Compton (IC) and neutrino production from charged pion decay for both flavours. We observe how HESS data can be only explained if the model we use is a mixed one: the radiation has an hadronic and leptonic origin.

Next, we have compared the simulated neutrino spectra with the simplified approximation and the analytic expressions described above (see above and bottom of Fig. 2). See how the simplified approximation fails to explain the modelled neutrino spectra obtained by PATRON. In spite of the fact that it follows the same shape, the simplified test predicts a less flux of muon neutrinos. On the contrary, the analytic expressions predicts a higher flux of neutrinos at higher energies than found with PATRON neutrino spectra.

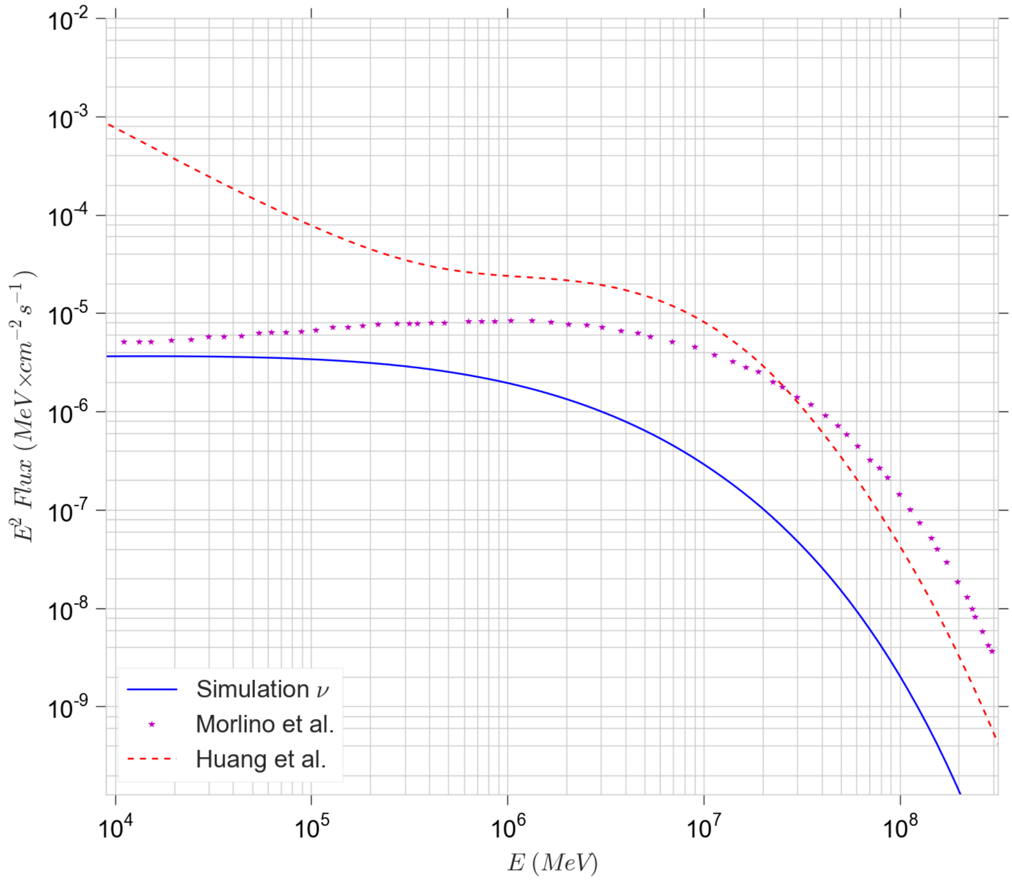


Figure 3: Broadband of simulated ν flux spectra (blue line) of RX J1713.7-3946 compared to previous works carried out by *Huang et al.* [3] (red dashed line) and by *Morlino et al.* [6] (pink stars). In this case, both electron and muon neutrino contribution are summed up.

We have also compared the simulated neutrino spectra with previous works carried out for RX J1713.7-3946 by *Huang et al.*, who attempted to estimate the neutrino flux from this SNR building on the assumption of a power law approximation for the gamma ray spectrum and simple scaling relations between the gamma ray and neutrino spectra (their approximation is valid for energies larger than 10^6 MeV), and *Morlino et al.* [6], who calculated the neutrino spectra by applying the theory of non-linear particle acceleration. PATRON neutrino flux follows the shape obtained by *Huang et al.* and *Morlino et al.*. However, both works predicts a larger flux than obtained with PATRON.

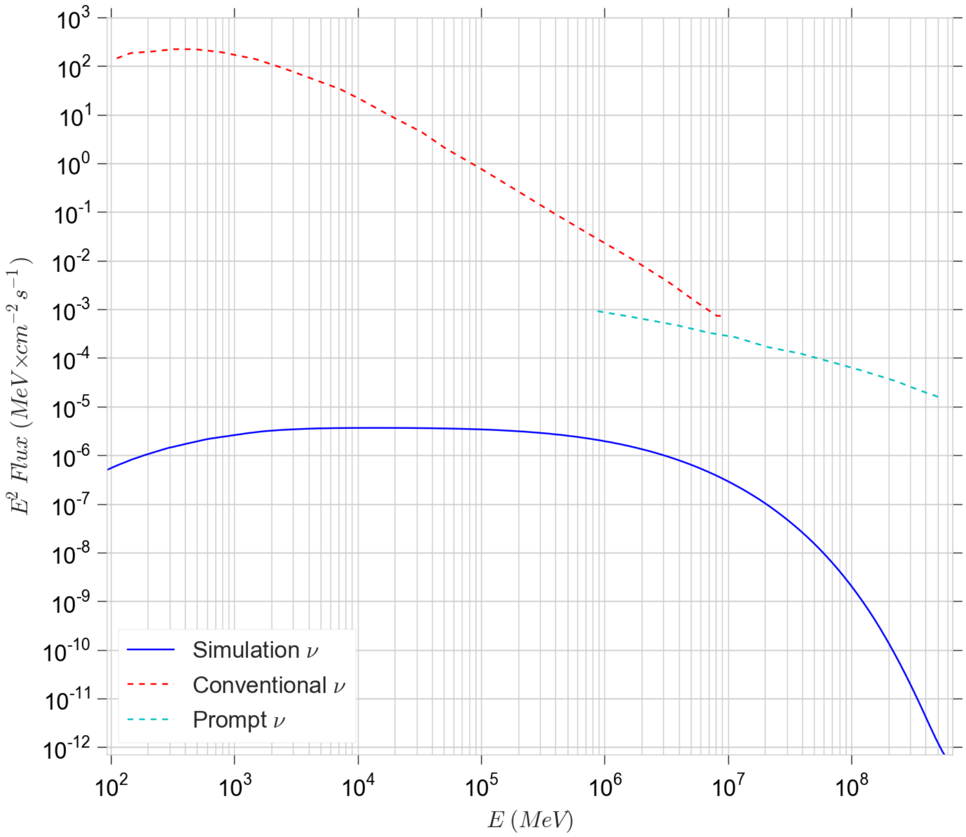


Figure 4: Broadband of simulated ν flux spectrum (blue line) of RX J1713.7-3946 compared to atmospheric prompt neutrino spectrum (light blue dashed line) and conventional neutrino spectrum (red dashed line). Both electronic and muonic neutrino contribution are summed up.

Finally, we have checked whether any neutrino could be detected by experiments such as IceCube. For that, we compare in Fig. 4 estimated neutrino flux from simulations with neutrino spectra coming from the atmosphere (conventional and prompt). Atmospheric neutrinos are produced in air showers, when CR interact with with the atmosphere. The conventional neutrino flux, dominating in the GeV to TeV range, is produced by the decay of charged pions and kaons. Prompt atmospheric neutrinos are produced by the decay of heavier mesons typically containing a charm quark. Their production is strongly suppressed, but they are expected to exhibit a harder energy spectrum, dominating at energies above 100 TeV [8]. Although prompt neutrinos have not yet been observed, if they result to actually exist, neutrino spectra from RX J1713.7-3946 will be covered by that from the atmosphere.

This result agrees with the fact that after 6 years of measuring data by IceCube, the expected neutrinos by *Huang et al.* and *Morlino et al.* have not been detected yet.

7. Conclusion

To sum up, the safest way to prove or reject whether the acceleration of hadrons takes place in SNR is to seek for neutrinos produced in the decays of charged pions. In this work, we have applied a PYTHON code that solves the time-dependent transport equation for RX J1713.7-3946. In order to calculate the expected neutrino flux from this remnant, we have modified PATRON to include decays of charged pions by means of their production rate, previously calculated using Monte Carlo simulations from [3]. Furthermore, we have checked the simulated neutrino spectra with previous works and with analytic expressions. Finally, we have concluded that the estimated neutrino flux would be hardly detected as it will be covered by neutrino from the atmosphere.

8. Acknowledges

First, I would like to thank my enjoyable supervisors *Shan Gao and Robert Brose*, for their advices and motivation in the whole process. I extend my gratitude also to *Alina Willem*, who always had time to explain me some concepts at the office. All of them gave me the possibility of going into the exciting world of Neutrino Physics and Supernova Remnants. Furthermore, special thanks goes to the DESY, for making possible my stay at their emplacement during the whole summer. Moreover, I have appreciated the scientific atmosphere of the Astroparticle Theory Group. Finally, I have to say that I feel nothing but gratitude for all summer students kindness, as I became friend of wonderful people.

References

[1] S. Federici et al. "Analysis of GeV-band γ-ray emission from supernova remnant RX J1713.7-3946". In: *Astronomy and Astrophysics* 577, A12 (May 2015), A12. DOI: 10.1051/0004-6361/201424947. arXiv: 1502.06355 [astro-ph.HE].

[2] A. M. Hillas. "Inclusive Cross-Sections for Production of Secondary Particles in High Energy Hadron Collisions". In: *International Cosmic Ray Conference* 6 (1979), p. 13.

[3] C.-Y. Huang. "User's Note: Hadronic Interaction by Using DPMJET and Production Matrix Part II: Leptons". In: Dec. 2007. URL: http://cherenkov.physics.iastate.edu/lepton-prod/note.lepton.pdf.

[4] C.-Y. Huang et al. "Gamma-Rays Produced in Cosmic-Ray Interactions and the TeV-band Spectrum of RX J1713.7-3946". In: *The First GLAST Symposium*. Ed. by S. Ritz, P. Michelson, and C. A. Meegan. Vol. 921. American Institute of Physics Conference Series. July 2007, pp. 169–171. DOI: 10.1063/1.2757294. arXiv: 0706.0509.

[5] S. Hümmer et al. "Simplified Models for Photohadronic Interactions in Cosmic Accelerators". In: *The Astrophysical Journal* 721 (Sept. 2010), pp. 630–652. DOI: 10.1088/0004-637X/721/1/630. arXiv: 1002.1310 [astro-ph.HE].

[6] G. Morlino, P. Blasi, and E. Amato. "Gamma rays and neutrinos from SNR RX J1713.7-3946". In: *Astroparticle Physics* 31 (June 2009), pp. 376–382. DOI: 10.1016/j.astropartphys.2009.03.007. arXiv: 0903.4565 [astro-ph.HE].

[7] Stephen P. Reynolds. "Supernova Remnants at High Energy". In: *Annu. Rev. Astron. AStrophysics* (2008).

[8] A. Schukraft. "A view of prompt atmospheric neutrinos with IceCube". In: *Nuclear Physics B Proceedings Supplements* 237 (Apr. 2013), pp. 266–268. DOI: 10.1016/j.nuclphysbps.2013.04.105. arXiv: 1302.0127 [astro-ph.HE].

[9] I. Telezhinsky, V. V. Dwarkadas, and M. Pohl. "Acceleration of cosmic rays by young core-collapse supernova remnants". In: *Astronomy and Astrophysics* 552, A102 (Apr. 2013), A102. DOI: 10.1051/0004-6361/201220740. arXiv: 1211.3627 [astro-ph.HE].