Geminga and Tycho' SNR viewed in TeV gamma rays.

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***Abstract*— The gamma-quantum spectra produced by the electronic and hadronic components of cosmic rays have similar shapes at the energies from 1 GeV to 1 TeV due to the synchrotron losses of the electrons. So, the only observational possibility to discriminate between leptonic and hadronic contributions is to measure the gamma-quantum spectrum at energies higher than 1 TeV, where these two spectra are expected to be essentially different. According to the theoretical prediction the gamma-quantum emitting objects in our Galaxy are the supernova remnants and binary. It is expected that about 20 Supernova Remnants should be visible in the TeV gamma-rays whereas only two were detected up to now by SHALON in northern hemisphere, namely Tycho's SNR and Geminga. The expected π^o-decay gamma-ray flux from Tycho Brage $F_\gamma \sim E_\gamma^{-1}$ extends up to > 30 TeV, whereas the inverse Compton gamma-ray flux has a cutoff above a few TeV. Hence, the detection of gamma-rays at energies 10 - 40 TeV by SHALON provides an evidence of their hadronic origin. Geminga is one of the brightest sources of MeV - GeV gamma-ray, but the only known pulsar that is radio-quiet. Geminga has been the object for study at TeV energies with upper limits being reported by three experiments Whipple'93, Tata'93 and Durham'93.The images of gamma-ray emission from Geminga by SHALON telescope are presented. The value Geminga flux obtained by SHALON is lower than the upper limits published before. Its integral gamma-ray flux is found to be $(4.8 \pm 0.7) \times 10^{-12} cm^{-2} s^{-1}$ at energies of > 0.8 TeV. Within the range 0.8 - 5 TeV, the integral energy spectrum is well described by the single power law $I(> E_\gamma) \propto E_\gamma^{-0.58 \pm 0.11}$. The energy spectrum of supernova remnant Geminga $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum.**

I. Introduction

TeV energies gamma-rays, measurable by the imaging Cherenkov technique, are the most interesting for searching

TABLE I
THE SHALON CATALOGUE OF GALACTIC GAMMA-QUANTUM SOURCES WITH ENERGY > 0.8 TEV

Sources	Observable flux ($\times 10^{-12} cm^{-2} s^{-1}$)	Distance (kpc)
Crab Nebula (SNR)	(1.70 ± 0.13)	2
Cygnus X-3 (binary)	(0.68 ± 0.07)	10
Geminga (radioweak pulsar)	(0.48 ± 0.17)	0.25
Tycho' SNR	(0.52 ± 0.09)	2.3
2129+47XR (binary)	(0.19 ± 0.09)	6

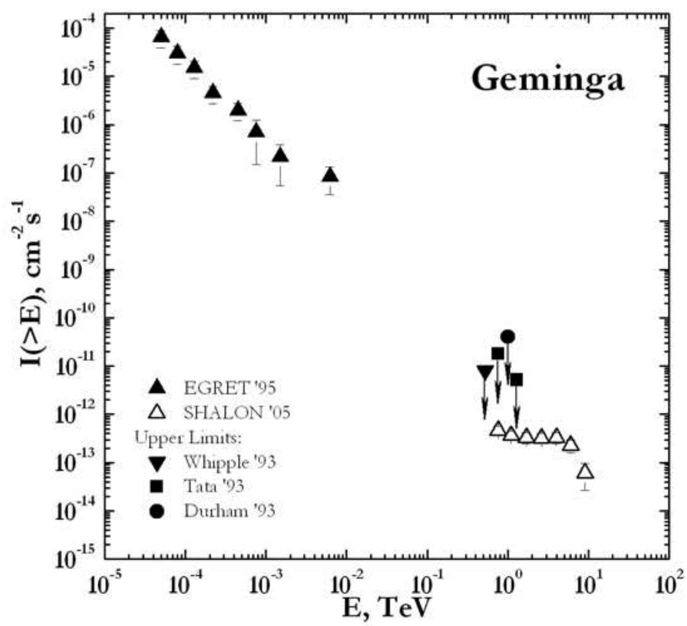

Fig. 1. The Geminga gamma - quantum ($E > 0.8$ TeV) integral spectrum by SHALON in comparison with other experiments: Whipple'93 [7], Tata'93 [8] and Durham'93 [9]

hadronic CRs in SNRs because they provide the information about CRs of highest possible energies $10^{13} - 10^{14}$ eV. Direct information about high-energy CR population in SNRs can be obtained from gamma-ray observation. The gamma-quantum spectra produced by the electronic and hadronic components of cosmic rays have similar shapes at the energies from 1GeV to 1 TeV due to the synchrotron losses of the electrons. So, the only observational possibility to discriminate between leptonic and hadronic contributions is to measure the gamma-quantum spectrum at energies higher than 1 TeV, where these two spectra are expected to be essentially different. High-energy gamma-rays are produced by electronic and hadronic CR components in the inverse Compton (IC) scattering and in the hadronic collisions leading to pion production and subsequent decay respectively. The gamma-quantum emitting objects in our Galaxy are the supernova remnants and binary. SNe of type Ib and II are more numerous in our Galaxy. According to the theoretical prediction about 20 SNRs should be visible

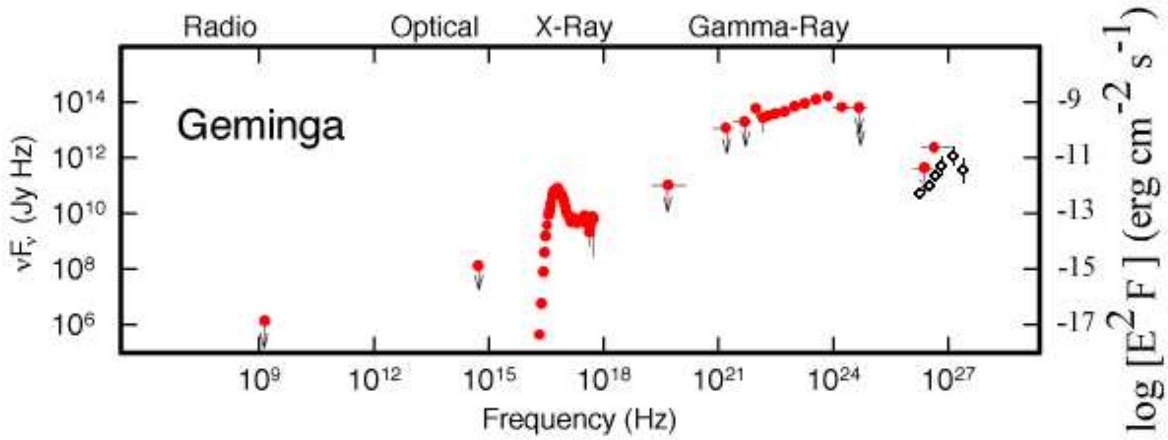

Fig. 2. The broadband energy spectrum of Geminga. Upper limits correspond to that of pulsed flux whereas the data points represent the total flux [18]. Open circles are SHALON data.

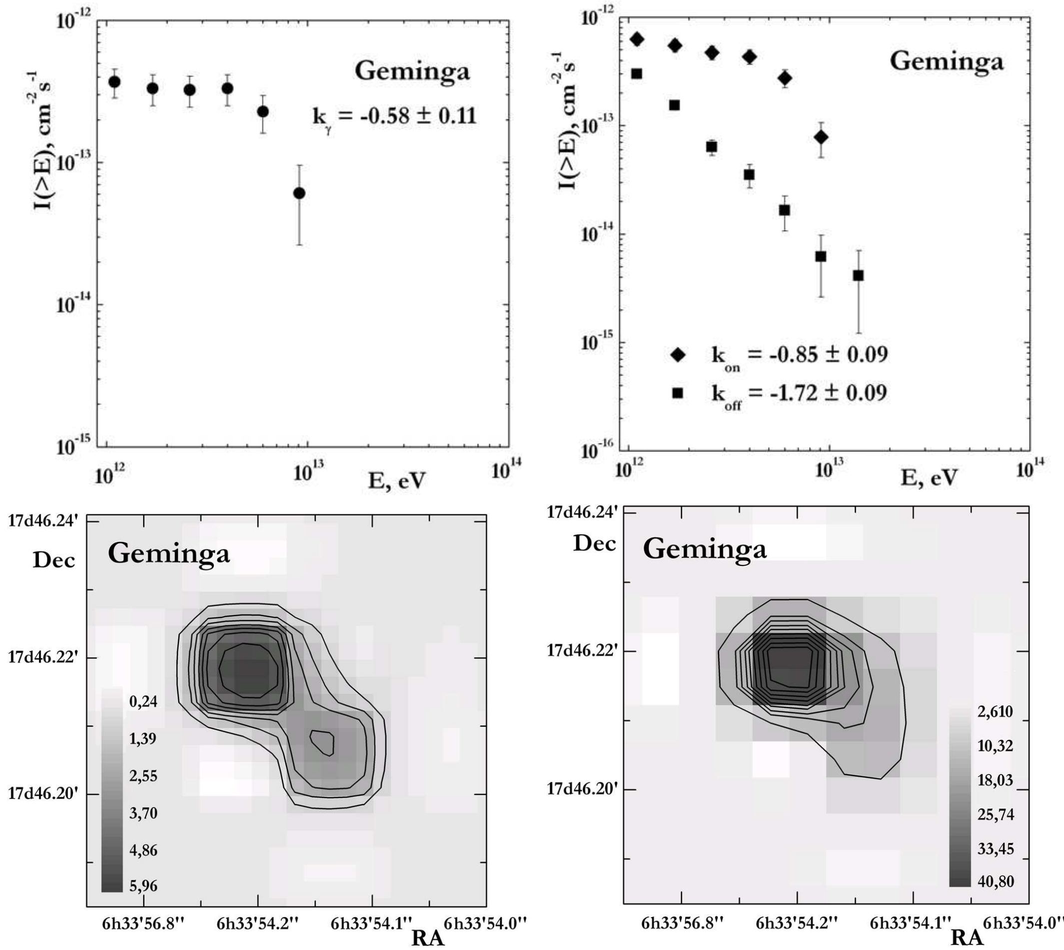

Fig. 3. **Top. left:** The Geminga gamma-quantum integral spectrum with power index of $k_\gamma = -0.58 \pm 0.11$; **right:** The event spectrum from Geminga with background with index of $k_{ON} = -0.85 \pm 0.09$ and spectrum of background events observed simultaneously with Geminga with index $k_{OFF} = -1.72 \pm 0.09$; **Bottom. left:** The image of gamma-ray emission from Geminga; **right:** The energy image (TeV units) of Geminga by SHALON

in the TeV gamma-rays whereas only two were detected up to now by SHALON, namely Tycho's SNR and Geminga. The observations on Tien-Shan high-mountain station with SHALON had been carried out since 1992 year [1], [2], [3], [4]. During this period 12 metagalactic and galactic sources have been observed. Among them are galactic sources Crab Nebula (supernova remnant), Cygnus X-3 (binary), Tycho's SNR (supernova remnant), Geminga (radioweak pulsar) and

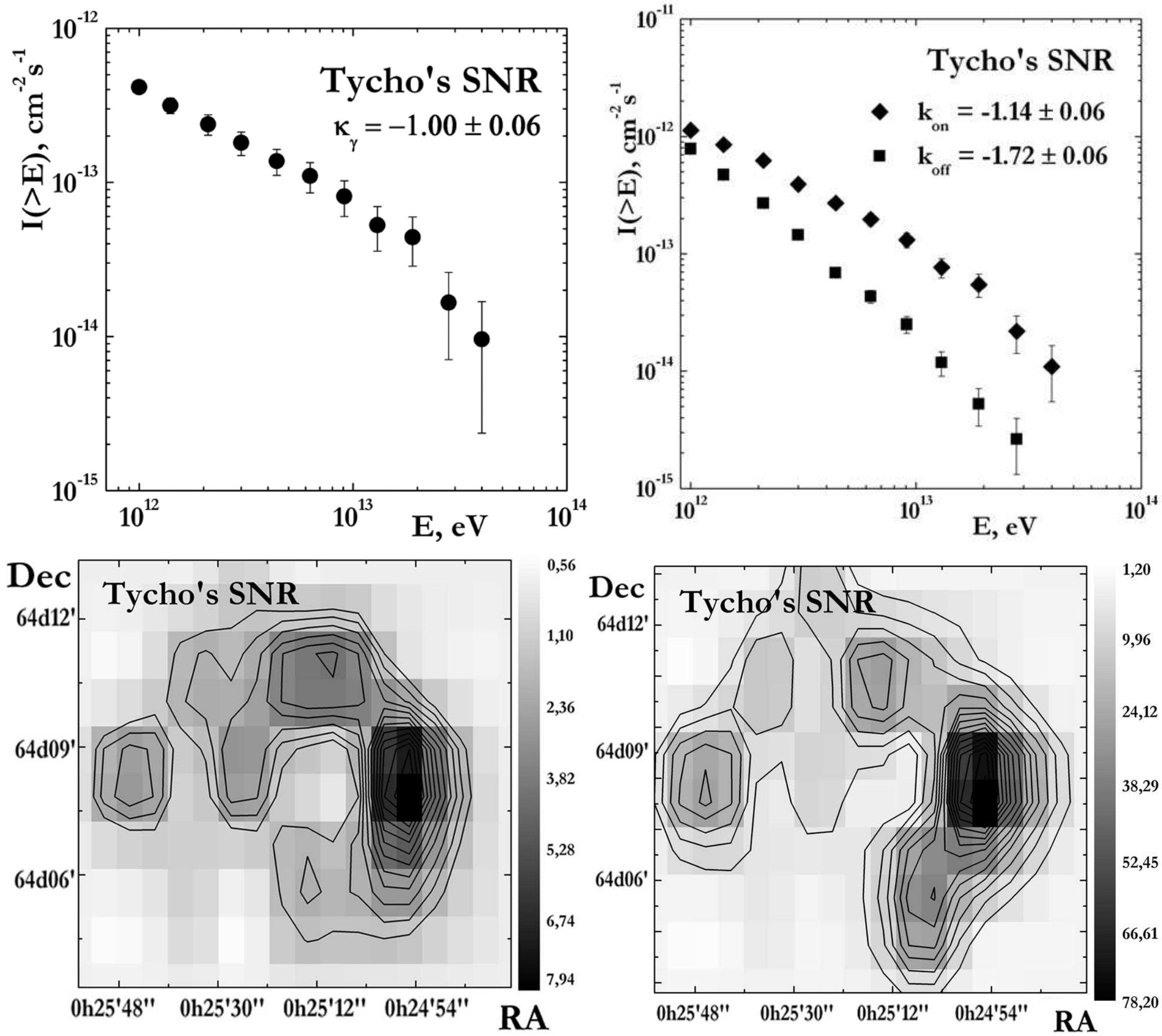

Fig. 4. **Top. left:** The Tycho's SNR gamma-quantum integral spectrum with power index of $k_\gamma = -1.00 \pm 0.06$; **right:** The event spectrum from Tycho' SNR with background with index of $k_{ON} = -1.14 \pm 0.06$ and spectrum of background events observed simultaneously with Tycho's SNR with index $k_{OFF} = -1.72 \pm 0.06$. **Bottom. left:** The SHALON image of gamma-ray emission from Tycho's SNR and; **right:** The energy image (TeV units) of Tycho's SNR by SHALON;

2129+47 (binary) [1 – 18] and table I. The results of observation data analysis for the each source are integral spectra of events coming from source - k_{ON}, and background events, coming simultaneously with source observation - k_{OFF}, temporal analysis of these two kind events and the source images. At Figs. 1, 2, 3, 5, 6, the observation results of Galaxy gamma-sources are showed.

II. Geminga

A neutron star in the constellation Gemini is the second brightest source of high-energy gamma-rays in the sky, discovered in 1972, by the SAS-2 satellite. For nearly 20 years, the nature of Geminga was unknown, since it didn't seem to show up at any other wavelengths. In 1991, an regular periodicity of 0.237 second was detected by the ROSAT satellite in soft X-ray emission, indicating that Geminga is almost certainly a pulsar. Geminga is the closest known pulsar to Earth. Figure 2 presents broadband energy spectrum of Geminga. Upper limits correspond to that of pulsed flux whereas the data points represent the total flux [18]. Black points are SHALON data for steady flux.

Geminga is one of the brightest source of MeV - GeV gamma-ray, but the only known pulsar that is radio-quiet. Geminga has been the object for study at TeV energies with upper limits being reported by three experiments Whipple'93 [7], Tata'93 [8] and Durham'93 [9]. Figures 1 and 3 show the SHALON results for this gamma-source. An image of gamma-ray emission from Geminga by SHALON telescope is shown in Fig. 3. As is seen from fig.1 the value Geminga flux obtained by SHALON is lower than the upper limits published before. Its integral gamma-ray flux is found to be $(0.48 \pm 0.17) \times 10^{-12}$ at energies of > 0.8 TeV. Within the range 0.8 - 5 TeV, the integral energy spectrum is well described by the single power law

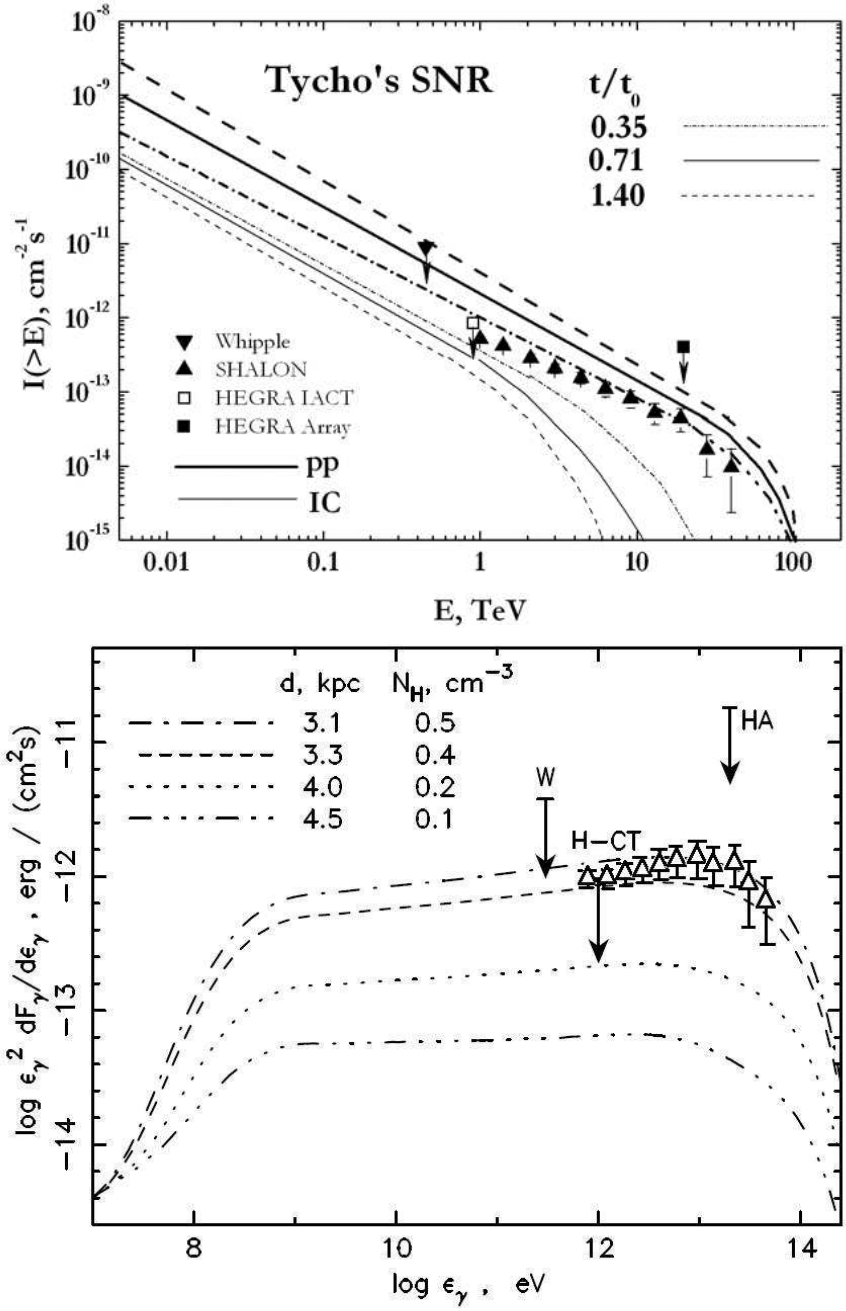

Fig. 5. **top:** The Tycho's SNR gamma-quantum integral spectrum by SHALON in comparison with other experiments: the observed upper limits Whipple, HEGRA IACT system, HEGRA AIROBICC and calculations: IC emission (thin lines), π° - decay (thick lines) [6]. **bottom:** L. T. Ksenofontov, H.J. Vöek, E.G. Berezhko in The Multi-Messenger Approach to High Energy Gamma-ray Sources, Barcelona, July 4-7, 2006 and [16]

$I(> E_{\gamma}) \propto E_{\gamma}^{-0.58\pm0.11}$(Fig. 3). The energy spectrum of supernova remnant Geminga $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum.

III. Tycho's SNR

Tycho Brage supernova remnant has been observed by SHALON atmospheric Cherenkov telescope of Tien-Shan high-mountain observatory. This object has long been considered as a candidate to cosmic ray hadrons source in Northern Hemisphere, although it seemed that the sensitivity of the present generation of Imaging Atmospheric Cherenkov System's too small for Tycho's detection. Tycho's SNR has been detected by SHALON at TeV energies. The integral gamma-ray flux above 0.8 TeV was estimated as $(0.52 \pm 0.09) \times 10^{-12}$ (Fig. 5).

Figures 5, 6 show the observational results for the Tycho's SNR. An image of gamma-ray emission from Tycho's SNR by SHALON telescope is shown in Fig. 6. It coincides with spot of the maximum intensity in north-east part of rim viewed in X-ray by ROSAT [17]. The energy spectrum of Tycho's

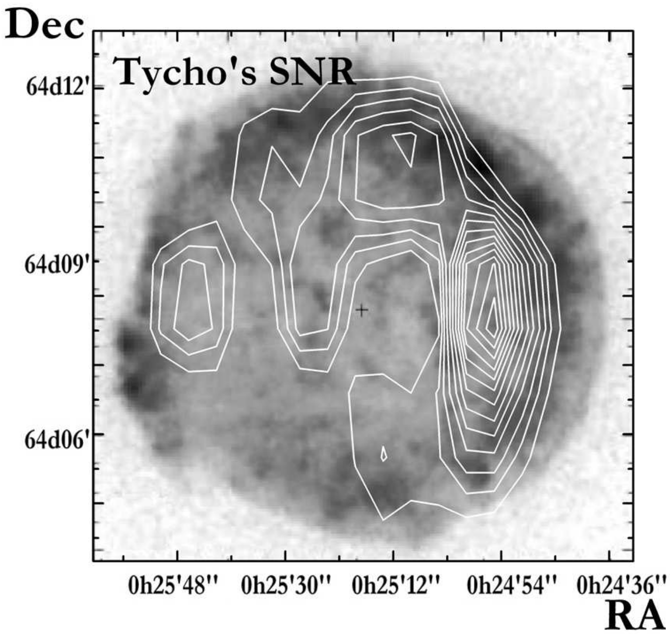

Fig. 6. contour - The SHALON image of gamma-ray emission from Tycho's SNR and grey scale image - ROSAT HRI [17] image of Tycho's SNR

SNR at $0.8 - 20$ TeV can be approximated by the power law $F(> E_O) \propto E^{k_\gamma}$, with $k_\gamma = -1.00 \pm 0.06$. The integral spectral indices of k_{ON} and k_{OFF} are shown in Figures 6. The energy spectrum of supernova remnant Tycho's SNR $F(E_O > 0.8TeV) \propto E^k$ is harder than Crab spectrum.

A nonlinear kinetic model of cosmic ray acceleration in supernova remnants is used in [6] (Fig. 5), to describe the properties of Tycho's SNR. The kinetic nonlinear model for cosmic ray acceleration in SNR has been applied to Tycho's SNR in order to compare model results with recently found very low observational upper limits on TeV energy range. In fact, HEGRA didn't detect Tycho's SNR, but established a very low upper limit at energies > 1 TeV. This value is consistent with that previously published by Whipple collaboration, being a factor of 4 lower (the spectral index of -1.1 for this comparison [6]). The π^O-decay gamma-quantum flux turns out to be some greater than inverse Compton flux at 1 TeV becomes strongly dominating at 10 TeV. The predicted gamma-quanta flux is in consistent with upper limits published by Whipple [10], [11] and HEGRA [12].

Figure 5 presents spectral energy distribution of the gamma-ray emission from Tychos SNR, as a function of gamma-ray energy ϵ_γ , for a mechanical SN explosion energy of $E_{SN} = 1.2 \times 10^{51}$ erg and four different distances d and corresponding values of the interstellar medium number densities N_H. All cases have dominant hadronic gamma-ray flux [L. T. Ksenofontov, H.J. Vöek, E.G. Berezhko in The Multi-Messenger Approach to High Energy Gamma-ray Sources, Barcelona, July 4-7, 2006]. The additional information about parameters of Tycho's SNR can be predicted in frame of nonlinear kinetic model [6], [16] if the TeV gamma- quantum spectrum of SHALON telescope is taken into account: a source distance 3.1 - 3.3 kpc and an ambient density NH $0.5 - 0.4$ cm^3 and the expected π^O-decay gamma-ray energy spectrum extends up to about 100 TeV.

IV. Conclusion

Since the expected flux of gamma-quanta from π^O-decay, $F_\gamma \propto E_\gamma^{-1}$, extends up to ~ 30 TeV, while the flux of gamma-rays originated from the Inverse Compton scattering has a sharp cutoff above the few TeV we may conclude that the detection of gamma-rays with energies of ~ 10 to 40 TeV by SHALON is an indication of their hadronic origin [6], [16].

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