Neutrinos (and Cosmic Rays) from Supernova Remnants

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Supernova remnants are likely to be the accelerators of galactic CRs. Assuming the correctness of this hypothesis, we analyze the quantitative connection between the observed VHE gamma radiation and the potentially observable VHE muon-neutrino radiation, and discuss what we learn on the primary spectrum.

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1 Motivation

The conjecture of Ginzburg & Syrovatskii is that the young SNR are the origin of galactic CR:

$$\frac{V_{CR}\ \rho_{CR}}{\tau_{CR}} \approx 0.1 \times \frac{\mathcal{E}_{SN}}{\tau_{SN}}$$

I.e.: if SN inject 1 foe each 30 years of kinetic energy, and 10% of this becomes CR, the losses of CR from the Milky Way are compensated ($V_{CR} = 4,000$ kpc^3, $\tau_{CR} = 50$ million years).

The mechanism of acceleration in the shock wave should be able to produce the needed $\sim 10\%$ factor of conversion of kinetic energy of the gas into CR, as discussed by Blasi.

HESS showed that the young SNR RX J1713-3946 and RX J0852-4666 emit γ ray above 10 TeV (see talk of Puehlhofer).

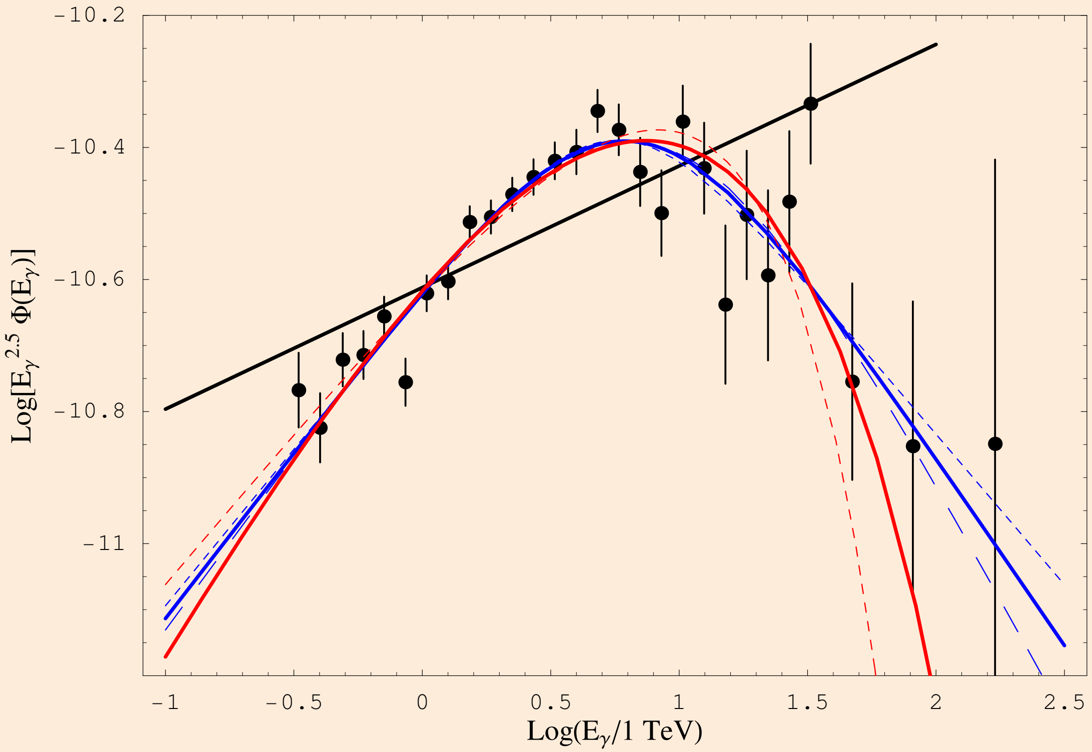
> In the context of Ginzburg and Syrovatskii hypothesis, it is natural to postulate that CR interact with the ambient matter and produce π^0. Maybe, the time when HESS met Ginzburg and Syrovatskii for the first time is NOW.

And if this is the case, we should address the quantitative question:

What we learn on CR and ν from the observed VHE γ's?

This is particularly urgent in view of the forecoming, large ν telescopes.

Figure 1: The VHE γ ray data from RX J1713-3946 *are known precisely*. They can be described well by a broken-power-law or by introducing a modified-exponential-cut, but not by a simple power-law.



The γ ray data admit a more or less 'sharp' transition / cutoff (dashed lines).

2 Direct calculation of neutrinos

We begin by describing a physically transparent and direct procedure that permits to calculate the muon neutrino fluxes:

⋆ If the VHE γ rays originate from $\pi^0 \to \gamma\gamma$, we can deduce the π^0 flux:

$$\Phi_\gamma[E] = \int_E^\infty dE' \, \frac{2\Phi_{\pi^0}[E']}{E'} \;\Rightarrow\; \Phi_{\pi^0}[E] = -\frac{E}{2}\,\frac{d\Phi_\gamma}{dE}$$

⋆ For large number of emitted pions, isospin invariance implies

$$\Phi_{\pi^0} \approx \Phi_{\pi^-} \approx \Phi_{\pi^+}$$

⋆ The rest of the job is kinematics of $\pi^\pm$ and $\mu^\pm$ decay (Lipari '88).

The gamma flux has to be reduced by $f_\eta \approx 0.25$ and the semileptonic decays of $K^\pm$ ($f_K \approx 0.20$, BR=0.635) can easily be included.

Oscillations

The flux of neutrinos from meson decays are modified:

$$\Phi_{\nu_\mu} = \Phi^0_{\nu_\mu} P_{\mu\mu} + \Phi^0_{\nu_e} P_{e\mu}$$

where the oscillation probabilities takes the simple Gribov-Pontecorvo's form (namely, the one of low energy solar neutrinos):

$$P_{\ell\ell'} = \sum_{i=1}^{3} |U^2_{\ell i}|\ |U^2_{\ell' i}| \quad \text{with } \ell, \ell' = e, \mu, \tau$$

There is no MSW effect, for matter term is negligible close to the SNR and too large in the Earth

With central values of the mixing elements $U_{\ell i}$ we get $P_{\mu\mu} \sim 0.4$ and $P_{e\mu} \sim 0.2$; that is, $1/2$ of the original ν_μ and $\bar{\nu}_\mu$ fluxes reach the detector.

A more sophisticated analysis:

$$\mathcal{L}(P_{\mu\mu}) \propto \max{}_{\theta} \left[e^{-\frac{(P_{\mu\mu}-P_{\mu\mu}(\theta))^2}{2\sigma^2}} \times \mathcal{L}(\theta) \right] \text{ with } \sigma \to 0$$

where θ=measured parameters. We get $P_{\mu\mu} = 0.39 \pm 0.05$ and $P_{e\mu} = 0.22 \mp 0.05$ where most of the error (0.04) is due to θ_{23}.

To understand the uncertainty budget, use an expansion in the small parameters:

$$P_{\mu\mu} \simeq {}^{1}\!/_{2} - {}^{x}\!/_{2} - y \text{ and } P_{e\mu} \simeq {}^{x}\!/_{2} + y,$$

$$\text{where } \begin{cases} x = \sin^2 2\theta_{12} \sim 0.86, \\ y = \cos 2\theta_{23}\ {}^{x}\!/_{4} + \theta_{13}\ \cos\delta_{\rm CP}\ \sqrt{x(1-x)}/2 \lesssim 0.05. \end{cases}$$

The adequacy of the simple-minded treatment is confirmed.

Calculated muon neutrino flux

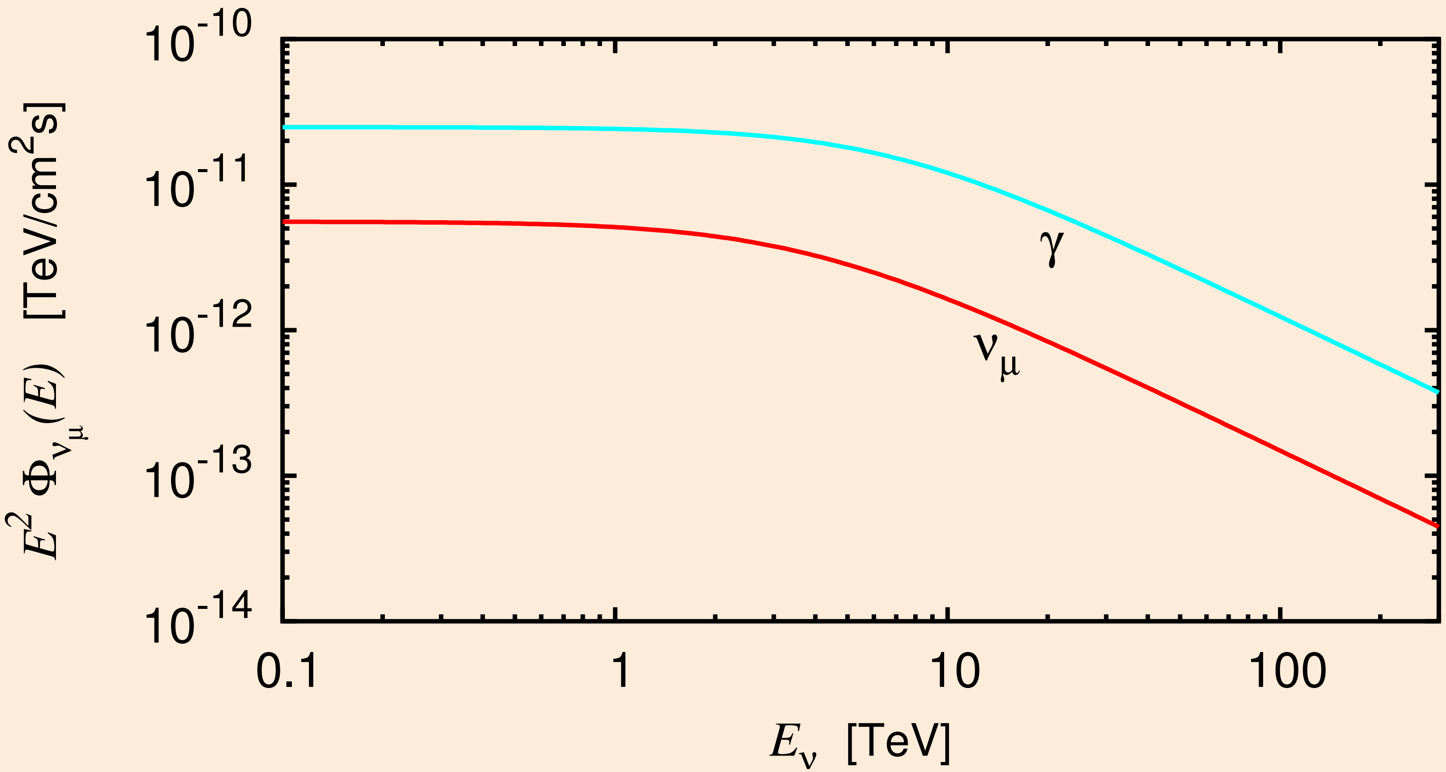


Figure 2: ν_μ flux expected from RX J1713-3946 (approximately equal to $\bar{\nu}_\mu$ flux), for the best fit, broken-power-law γ-ray spectrum. Includes the most recent HESS data and oscillations. $f_\eta = 25\%$ and $f_K = 20\%$.

Events in neutrino telescopes

We can calculate $N_\mu + N_{\bar{\mu}}$ for an ideal detector using:

$$N_\mu = A \cdot T \cdot f_{liv} \cdot \int_{E_{th}}^{\infty} dE_\nu \, \Phi_{\nu_\mu}(E_\nu) Y_\mu(E_\nu, E_{th})(1 - \overline{a}_{\nu_\mu}(E_\nu))$$

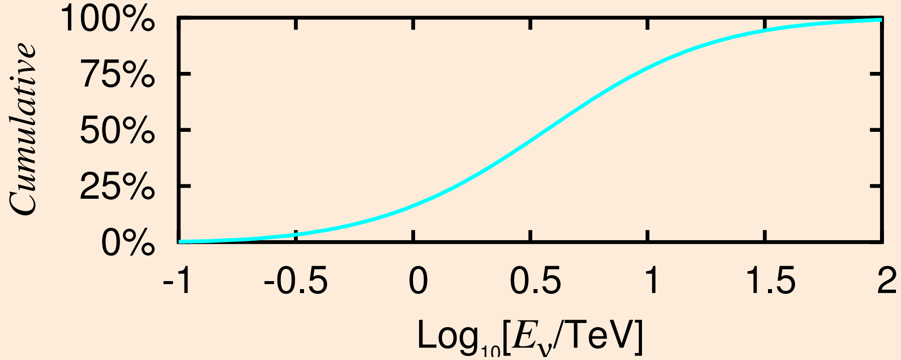
where E_ν is the neutrino energy before the interaction point and:

- *A=1 km^2 and T=1 solar year.*
- *Source is below horizon for $f_{liv} = 78$ % (ANTARES).*
- *The muon range (in the yield Y_μ) is calculated for water.*
- *The neutrino absorption coefficient a_{ν_μ}, averaged over the daily location of the source, is calculated for standard rock.*
- *The threshold for muon detection is $E_{th} = 50$ GeV.*

The role of the background, and realistic values of the threshold are discussed by Lipari '06.

Number of events from RX J1713.7-3946

A last warning: the effects of detection efficiency are not included but they are likely to be important, since the median energy is $E_\nu = 3.7$ TeV.



In summary, the number of events for the ideal detector is:

$$N_\mu + N_{\bar{\mu}} = 6.2$$

This can be compared with the 5 events of V '06, the 9 events in Costantini & V '04 (power law $F_\gamma \propto E^{-2.2}$ extended till 1 PeV) and the 40 events in Alvarez-Muñiz & Halzen '02 ($F_\gamma \propto E^{-2}$, oscillations, livetime and absorption ignored)

3 Extracting proton spectra, then neutrinos

The mathematical problem is to invert an integral equation:

$$\Phi_\gamma[E_\gamma] = \int_{E_\gamma}^{\infty} \frac{dE_p}{E_p}\ \Psi_p[E_p] \times F\left[\frac{E_\gamma}{E_p}, E_p\right]$$

The cosmic ray and the target densities, n_p and n_{H} enter the CR 'flux':

$$\Psi_p[E_p] = \frac{c\ \sigma_{\text{inel.}}[E_p]}{4\pi R^2} \int d^3\vec{r}\ n_{\text{H}}[\vec{r}]\ \frac{dn_p}{dE_p}[E_p, \vec{r}]$$

For $F[x, E] = (1-x)^4/x$, this can be inverted:

$$\Psi_p[E] = -\frac{E^4}{24}\ \frac{d^5}{dE^5}[\ E\ \Phi_\gamma[E]\ ]$$

But also for the actual kernel F (we use the one of Kelner et al, *2007) a similar, simple formula can be obtained!*

Writing $E/(1\ \text{TeV}) = \exp[\epsilon]$, assuming a scaling F function, we cast

$$\Phi_\gamma[E_\gamma] = \int_{E_\gamma}^{\infty} \frac{dE_p}{E_p}\ \Psi_p[E_p] \times F\left[\frac{E_\gamma}{E_p}\ ,\ E_p = E_p^0\right]$$

in the form of a convolution integral. The inverse of the Fourier transform of the kernel can be approximated by a polynomial, thus:

$$\boxed{\Psi_p[E] = \sum_{n=0}^{5} a_n \left(E\frac{d}{dE}\right)^n \Phi_\gamma[E_p]}$$

The effects of scaling violations are small (several %) but can be anyway included by using the approximate solution perturbatively.

The numerical precision is a fraction of %.

Using the parameterized γ ray data

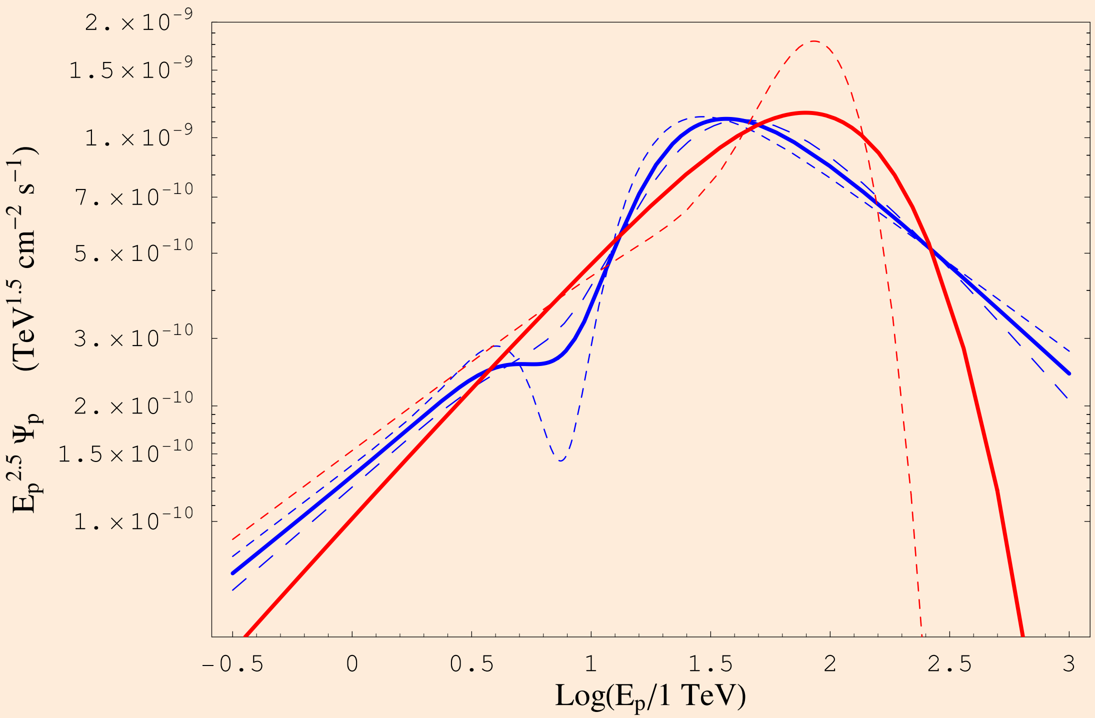


Figure 3: The CR spectra extracted from the VHE gamma ray spectra, parameterized as broken-power-law and modified-exponential-cut (with various 'sharpness' factors).

Using the "raw" γ ray data

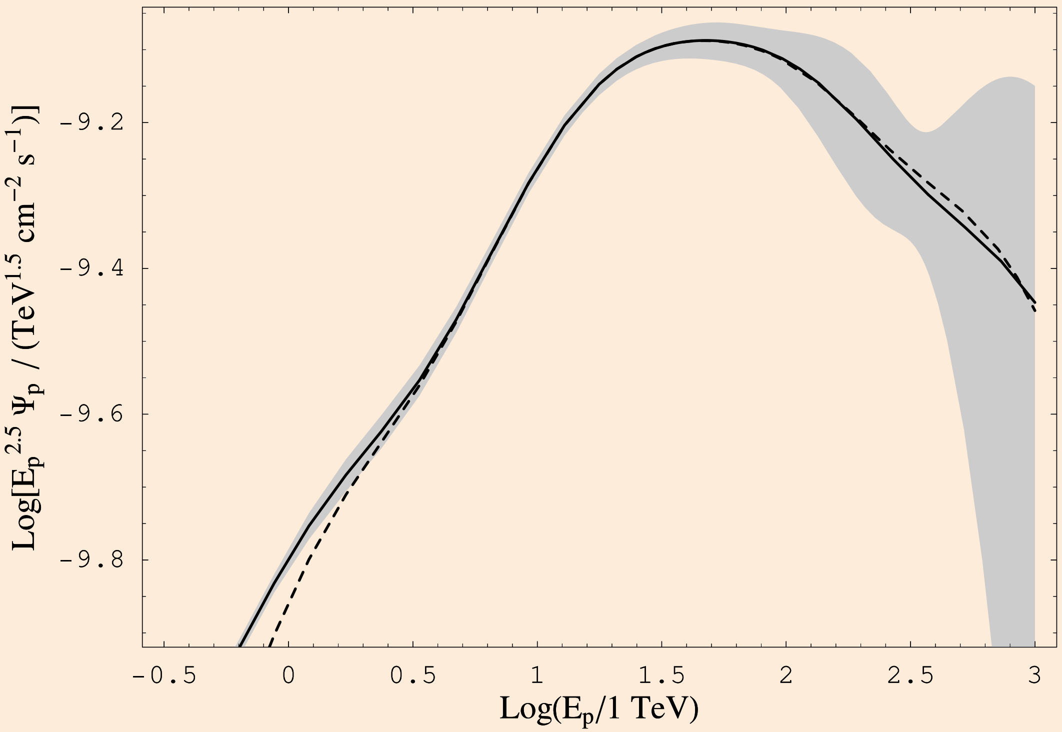


Figure 4: The CR spectra obtained directly from the VHE gamma ray data filtered by a Gaussian kernel; broken-power-law and modified-exponential-cut distributions are used to extrapolate at low and high energies. *Shaded region obtained by propagating observational errors.*

Finally, the neutrinos!

Now it is straightforward to calculate the ν_μs from the obtained proton flux. As an example, we adopt a broken-power-law, gamma-ray flux:

$$\Phi_\gamma[E] = E^{-\Gamma_1}\left(1+\left(\frac{E}{E_c}\right)^{1/S}\right)^{-S(\Gamma_1-\Gamma_2)}$$

(best fit values) and include the effects of scaling violation, too. We get:

E [TeV]	1	3	10	30	100	300
new calculation (using p)	1.7E-1	1.4E-2	5.5E-4	2.1E-5	5.1E-7	1.8E-8
old one ($f_\eta = 0.25,\ f_K = 0$)	1.8E-1	1.4E-2	5.4E-4	2.0E-5	4.8E-7	1.6E-8
old one ($f_\eta = 0.25,\ f_K = 0.2$)	2.1E-1	1.7E-2	6.6E-4	2.4E-5	6.0E-7	2.0E-8

The two independent calculations agree pretty well.

4 Summary

Motivated by the SNR/CR connection we addressed the question:

What can we learn from the observed SNR γ ray data?

We developed techniques of calculations that permitted us to obtain:

⋆ Reliable prediction on neutrinos from SNR.

⋆ Valuable information on cosmic rays flux in the SNR.

the most crucial role being played by the highest energy γs (100 TeV).

We applied these techniques to the best studied SNR and found that large detectors are needed to observe the neutrinos from RX J1713-3946. At present, Vela Jr. seems to be the most promising source of SNR neutrinos.

I conclude with the wish that HESS will continue to meet and talk with Ginzburg and Syrovatskii in the future: it was great till now!