Neutrinos from Supernova Remnants

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We provide elements for a discussion of the expected ν signal from Supernova Remnants (SNR). After recalling the reasons why SNR are thought to be interesting and recent relevant observations by H.E.S.S., we will describe a simple method to evaluate the ν fluxes. We get a flux of 5 (resp., 10-15) througoing muons per km^2 per year from RX J1713.7-3946 (resp., RX J0852.0-4652) in ANTARES location ($\phi = 42^\circ 50'$) and above $E_{th} = 50$ GeV.

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Contents

1 The cosmic ray/SNR connection

Supernovae are suspected to be the cosmic ray (CR) accelerators since '34 (Baade & Zwicky).

30 year later, Ginzburg & Syrovatsky remarked that if 10 % or so of the SNR kinetic energy $\mathcal{E}_{SN} \approx 10^{51}$ erg (=1 foe) goes in CR, the CR losses of the Milky Way are compensated:

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

where $V_{CR} = \pi R^2 H$ ($R = 15$ kpc, $H = 5$ kpc) and $\tau_{SN} = 30$ yr.

Based on Fermi ideas, a mechanism called 'diffusive shock wave acceleration' is being developed to understand CR acceleration in SNR.

The acceleration happens in the expanding SNR shock wave of size $R = u\ t$ ($u \sim$ 5,000 km/s), and it is mostly active in the first 1,000 years, as determined by $M_{ejecta} \sim {}^{4\pi}/_{3}\ R^3\ n_{ISM}$.

There are many open and possibly connected questions, e.g., Hillas '05:

- ○ How to "inject" e^-? *["diffusive shock acceleration" is incomplete?]*
- ○ Why isotropy? How $\Gamma = 2.1 \rightarrow 2.7$? *[imply propagation / reacceleration?]*
- ○ $E_{\max}$? *[limited by $R \sim D_{Bohm}/u$ but countered by Bell & Lucek]*
- We expected many point sources of hadronic VHE γ. Is this a real problem or expectations were too optimistic?
- How to firmly exclude a leptonic origin? Seeing ν?

Interesting shell-type SNR

Name	TeV γ obs.	decl. δ	distance	size	age
Vela Jr	< 10 TeV (HESS)	$-46^\circ 22'$	0.2 kpc	2°	680 yr
RX J1713-3946	< 40 TeV (HESS)	$-39^\circ 46'$	1 kpc	1°	1,600 yr
SN 1006	no (HESS close?)	$-41^\circ 53'$	2 kpc	$36'$	1,000 yr
Cas A	HEGRA (maybe)	$58^\circ 08'$	3 kpc	$6'$	320 yr

Some useful link:

. *Catalogue of SNR*, `www.mrao.cam.ac.uk/surveys/snrs/` [D. Green]

. *H.E.S.S. Source Catalogue*, `www.mpi-hd.mpg.de/hfm/HESS/` [W. Hofmann]

. Review on *Shell-type SNR*, `arXiv.org/astro-ph/0603502` [H.J. Völk]

The best known spectrum: RX J1713.7-3946

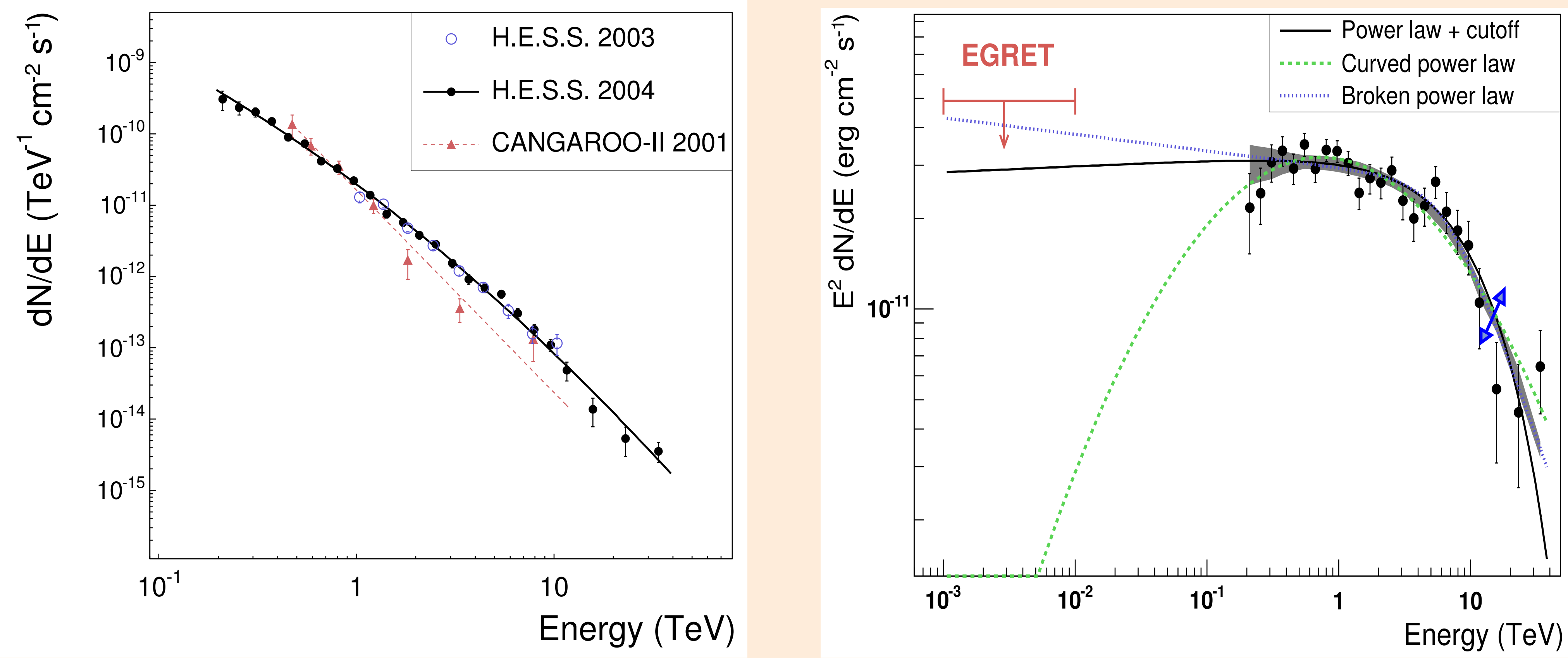

Figure 1: *Determination of VHE γ spectrum by the H.E.S.S. IACT array*

(a partial summary, remarks and end of introduction)

The hypothesis that shell-type young SNR accelerate CR (perhaps till the knee) seems to be still valid and is actively debated. For 2 SNR observed in VHE γ, the "hadronic" hypothesis looks plausible.

> Specific models for CR acceleration in RX J1713.7-3946: 1) Malkov, Diamond, Sagdeev '05 suggest that the nearby molecular cloud has a main role for CR interactions; 2) Berezhko & Völk '06 fit H.E.S.S. observations starting from the opposite view.

Future observations of H.E.S.S. (and of VERITAS and MAGIC) will provide more data permitting more crucial tests.

2 TeV neutrinos from SNR

Motivated by the (shell-type, young) SNR / CR connection and by the existing plans for large neutrino telescopes, we calculated the flux of TeV neutrinos from the SNR with known VHE γ*-ray spectrum.*

> Indeed, during CR acceleration the SNR are transparent to their γ radiation. Thus, we can convert the measured γ ray flux (from π^0) into an expectation for the neutrino flux (from $\pi^\pm$ and $K^\pm$) under the hypothesis that the radiation is of hadronic origin.

We begin by discussing flavor oscillations, then describe the γ/ν *connection and finally estimate the rate of events in neutrino telescopes.*

2.1 Oscillations

The flux of neutrinos from meson decays are modified:

$$F_{\nu_\mu} = F^0_{\nu_\mu} P_{\mu\mu} + F^0_{\nu_e} P_{e\mu}$$

where the oscillation probabilities takes the simplest form, Gribov-Pontecorvo's (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.*

Sophistications

We performed a more detailed analysis

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

where θ=measured parameters (from Strumia & V '05). 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 (Costantini & V '04):

$$P_{\mu\mu} \simeq {}^1\!/_2 - {}^x\!/_2 - y \text{ and } P_{e\mu} \simeq {}^x\!/_2 + y,$$

$$\text{where} \quad \begin{aligned} x &= \sin^2 2\theta_{12}, \\ y &= \cos 2\theta_{23}\ {}^x\!/_4 + \theta_{13}\ \cos\delta_{\rm CP}\ \sqrt{x(1-x)}/2. \end{aligned}$$

2.2 The connection between γ and ν

For RX J1713.7-3946 there are 2 calculations in the literature:

1. Alvarez-Muñiz & Halzen '02 use $F_\gamma \propto E^{-2}$ suggested by CANGAROO results and obtain $F_{\nu_\mu} = F^0_{\nu_\mu} \propto F_\gamma$ by

$$\int_{E_p^{\min}/12}^{E_p^{\max}/12} dE_\nu \; E_\nu F_\nu(E_\nu) = \int_{E_p^{\min}/6}^{E_p^{\max}/6} dE_\gamma \; E_\gamma F_\gamma(E_\gamma)$$

2. Costantini & V '04 use $F_\gamma \propto E^{-2.2}$ as extrapolated from early H.E.S.S. results and adopt standard techniques (e.g., Gaisser '90)

$$F_\gamma = \frac{\Delta X}{\lambda_p} \frac{2 Z_{p\pi^0}}{\Gamma} F_p \quad \text{and similarly for } F_\nu$$

Both methods are tailored for power law spectra.

New evaluation, elaborating on Lipari '88

From $F_\gamma(E) = \int_E^\infty dE' \; 2 \; F_{\pi^0}(E')/E'$ valid for VHE γ-rays we find:

$$F_{\pi^0}(E) = -\frac{E}{2} \; \frac{dF_\gamma}{dE} \tag{1}$$

Due to the approximate isospin-invariant distribution of pions, $F_\pi \equiv F_{\pi^0} \approx F_{\pi^+} \approx F_{\pi^-}$, we find for the neutrino from $\pi^+ \to \mu^+ \nu_\mu$:

$$F_{\nu_\mu}(E) = \int_{E/(1-r)}^\infty \frac{dE'}{1-r} \; \frac{F_\pi(E')}{E'} = \frac{F_\gamma(E/(1-r))}{2(1-r)} \tag{2}$$

where $r = (m_\mu/m_\pi)^2$. The neutrinos $\nu = \bar{\nu}_\mu, \nu_e$ from μ^+ decay are:

$$F_\nu(E_\nu) = \int_0^1 \frac{dy}{y} \; F_\mu(E_\mu) \; [g_0(y) - \bar{P}_\mu(E_\mu) \; g_1(y)] \text{ where } E_\mu = \frac{E_\nu}{y} \tag{3}$$

g_i are polynomials, F_μ and $\overline{P}_\mu$ (=polarization averaged over π distribution) also known. $K \to \mu\nu$ described in the same manner but weighted by 0.635×0.12.

Neutrinos from RX J1713.7-3946

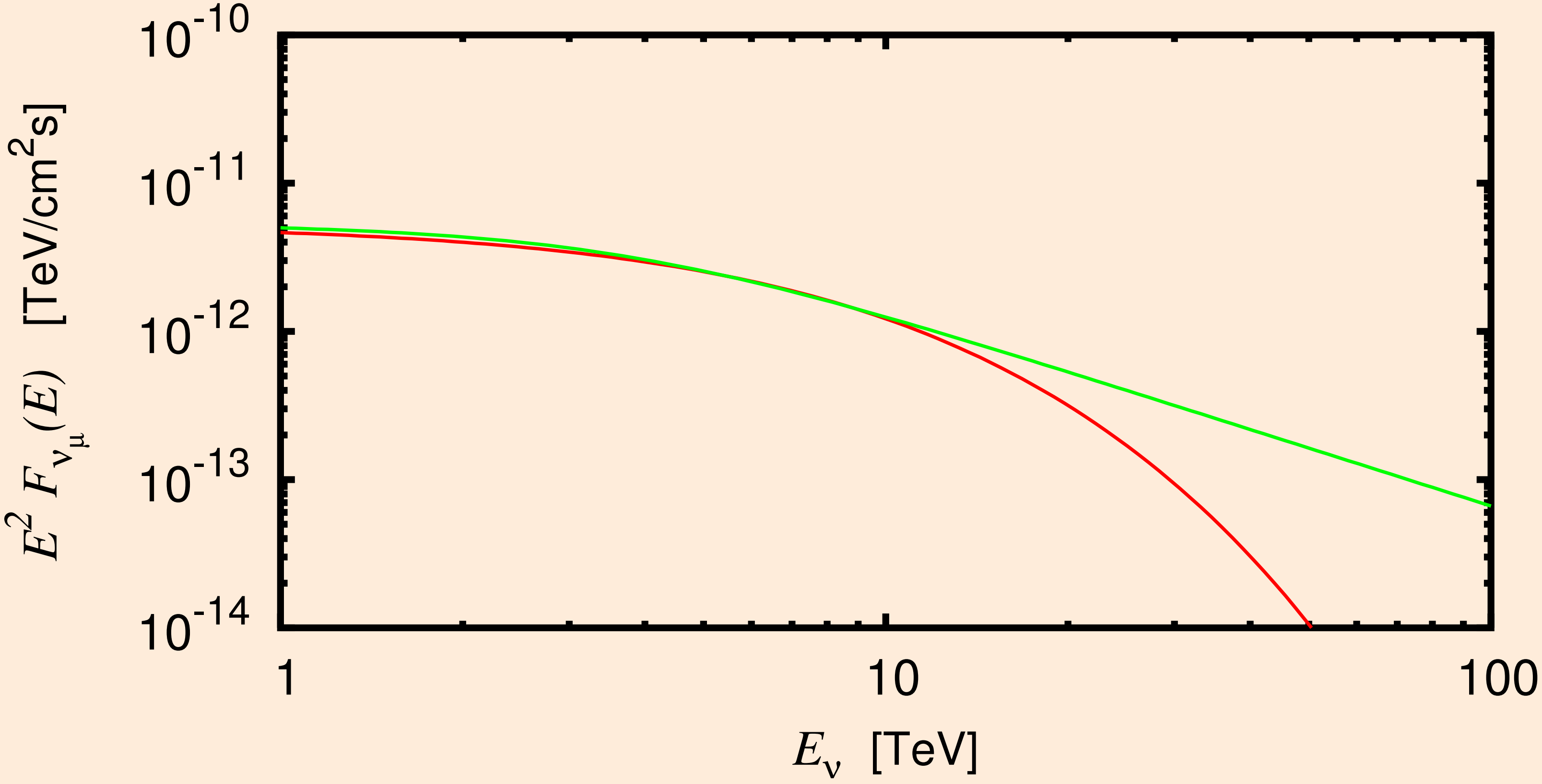

Figure 2: ν_μ *spectra, corresponding to 2 (out of 3) fits of the H.E.S.S. VHE* γ*-rays: a broken power law and a power law with exponential cutoff (the curved power law was discarded, since it increases before 40 GeV).*

2.3 Events in neutrino telescopes

Now we can calculate $N_\mu + N_{\bar{\mu}}$ using e.g.:

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

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

- *A=1 km^2 and T=1 solar year.*
- *Source is below ANTARES horizon (=visible) for $f_{liv} = 78$ %.*
- *The threshold for muon detection is $E_{th} = 50$ GeV.*
- *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.*

Number of events from RX J1713.7-3946

We find that the number of events does not depend crucially on the extrapolation:

$$N_\mu + N_{\bar\mu} = \begin{cases} 4.8 \text{ per km}^2 \text{ per year} & \text{[exponential cutoff]} \\ 5.3 \text{ per km}^2 \text{ per year} & \text{[broken power law]} \end{cases}$$

This can be compared with 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)

> *The effects of detection efficiency are not included (ideal detector); they are likely to be important since the median energy is $E_\nu = 3$ TeV.*

3 Discussion and perspectives

$\star$ *In this talk we discussed the expected neutrino flux from γ-transparent accelerators of cosmic rays, and emphasized the case of young SNR.*
We showed that for RX J1713.7-3946 the expectations are stable.

$\star$ *In the close future we should know more on RX J0852.0-4652 (Vela Jr) that has $F_\gamma = 6.5$ million γ-rays $E^{-2.1}/(TeV\,km^2 yr)$ below 10 TeV.*
We get $N_\mu + N_{\bar\mu} = 10\ (15)/(km^2 yr)$ in ANTARES location and above $E_{th} = 50$ GeV if the exponential cutoff is at $E_{\gamma\mathrm{cut}} = 50\ (150)\ TeV$.

$\star$ *For discussions of the background, of S/B, and of performance of real detectors, see tomorrow talks of P. Lipari and F. Lucarelli.*

Thanks for the attention!