Cosmic rays and neutrinos from Supernova remnants

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OUTLINE

- Motivation: SNRs as galactic CR accelerators?
- Extracting the CR spectrum in SNRs from VHE γ-ray data
- Predicting the neutrino flux from SNRs from VHE γ-ray data
- Conclusions (and references)

(Phys.Rev.D76:125019,2007; Nucl.Instrum.Meth.A588:123-129,2008; arXiv:0807.4151)

SNRs: galactic CR accelerators?

Ginzburg and Syrovatskii → the Young SNRs are the origin of galactic CR

- The turbulent gas of a young SNR (t~1000 year) is a large reservoir of kinetic energy (E ~ 10^{51} erg).

- If SN inject 10^{51} erg of kinetic energy each 30 years, and 10% of this becomes CR, the losses of CR from the Milky Way are compensated.

$$\mathcal{L}_{\rm cr} = \frac{\rho_{\rm cr} V_{\rm cr}}{\tau_{\rm cr}} \simeq 0.1\,\frac{E_{\rm SN}}{\tau_{\rm SN}} = 0.1\,\mathcal{L}_{\rm SN}$$

- Diffusive shock wave acceleration should be able to produce the needed 10% factor of conversion of kinetic energy of the magnetized plasma into CR.

$$\frac{dN}{dE} \sim E^{-2.1} \cdot E^{-0.6} \sim E^{-2.7}$$

in source

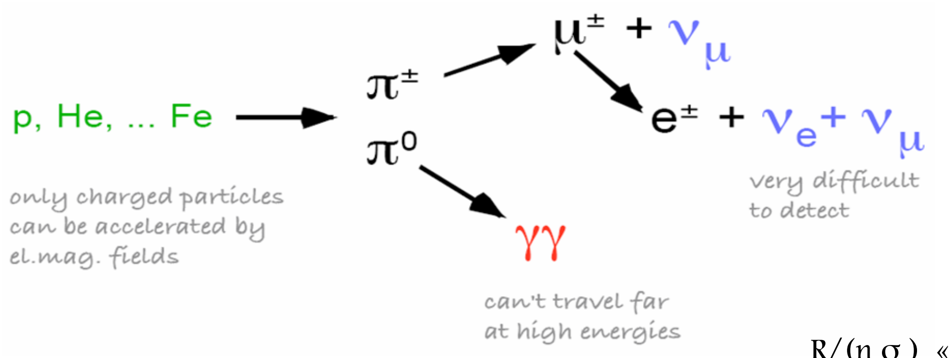
resident time in galaxy

at earth

Evidence of relativistic electrons in SNRs (synchrotron and Inv. Compton). No direct evidence of CR acceleration yet.

SNRs as cosmic beam dumps

CR can interact with the ambient medium (ISM or molecular clouds close to the source) → Cosmic beam dump



p, He, ... Fe → $\pi^\pm$, π^0

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$

$\mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu$

$\pi^0 \rightarrow \gamma\gamma$

only charged particles can be accelerated by el.mag. fields

very difficult to detect

can't travel far at high energies

γ and neutrinos points back to the source (CR are deflected by magnetic fields)

SNRs are γ-transparent:

$R/(n\,\sigma_\gamma) \ll 1$

R ~ few pc

n ~ 100 cm^{-3} (molecular cloud typ. density)

- Great progresses in γ–astronomy → observation of SNRs in the TeV–band.
- H.E.S.S. showed that few SNRs (RX J1713-3946 and Vela Jr) emit γ above 10 TeV

If we assume that the observed γ are produced by CR accelerated in the SNR:

1) What can we learn on CR in the SNR from the observed γ ray data?
2) How well can we predict the neutrinos flux from the SNR the observed γ ray data?

We answered to these questions in a simple, model-independent and accurate way

How to extract the primary CR spectrum in SNRs from very high energy γ–ray data?

Phys.Rev.D76:125019,2007

Extracting the CR spectrum

The mathematical problem is to invert the integral equation:

Adimentional distrib. function → describe the photon spectrum in pp interactions

$$\Phi_\gamma[E_\gamma] = \int_{E_\gamma}^{\infty} \frac{dE_{\rm p}}{E_{\rm p}}\, \Phi_{\rm p}[E_{\rm p}]\; F_\gamma\left[\frac{E_\gamma}{E_{\rm p}}, E_{\rm p}\right]$$

The CR and the target proton densities (n_p and n respectively) enter the CR effective flux:

$$\Phi_{\rm p}[E_{\rm p}] = \frac{c\,\sigma[E_{\rm p}]}{4\pi R^2} \int d^3r\; n[\mathbf{r}]\, \frac{dn_{\rm p}[\mathbf{r}, E_{\rm p}]}{dE_{\rm p}}$$

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

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

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

Extracting the CR spectrum

Writing E/(1 TeV) = exp[ε], assuming a scaling F function, we cast:

$$\Phi_\gamma[E_\gamma] = \int_{E_\gamma}^{\infty} \frac{dE_\mathrm{p}}{E_\mathrm{p}}\, \Phi_\mathrm{p}[E_\mathrm{p}]\, F_\gamma\left[\frac{E_\gamma}{E_\mathrm{p}}, E_\mathrm{p} = E_{\mathrm{p}0}\right]$$

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

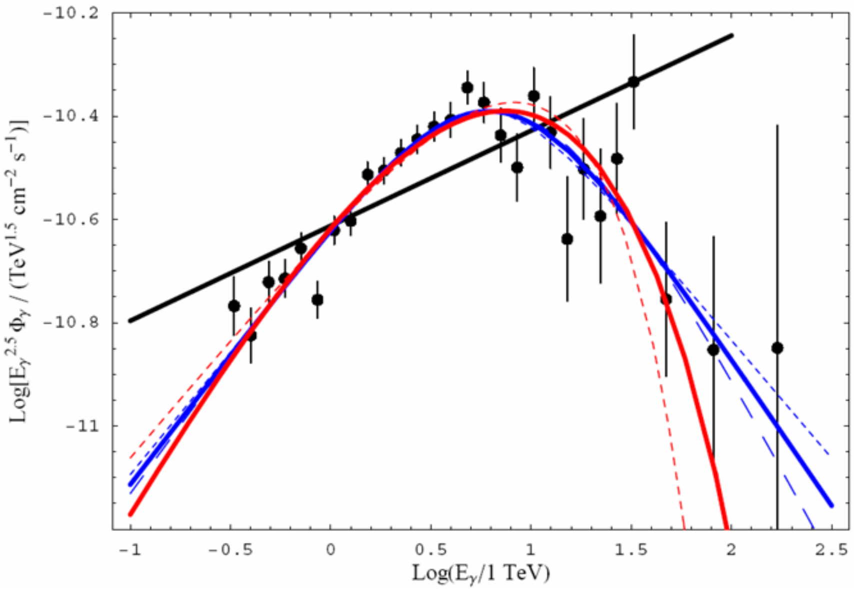
$$\Phi_\mathrm{p}[E] = \sum_{n=0}^{5} a_n \left(E\frac{d}{dE}\right)^n \Phi_\gamma[E]$$

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 %.

The SNR RX J1713.7-3946: a good opportunity to test the paradigm

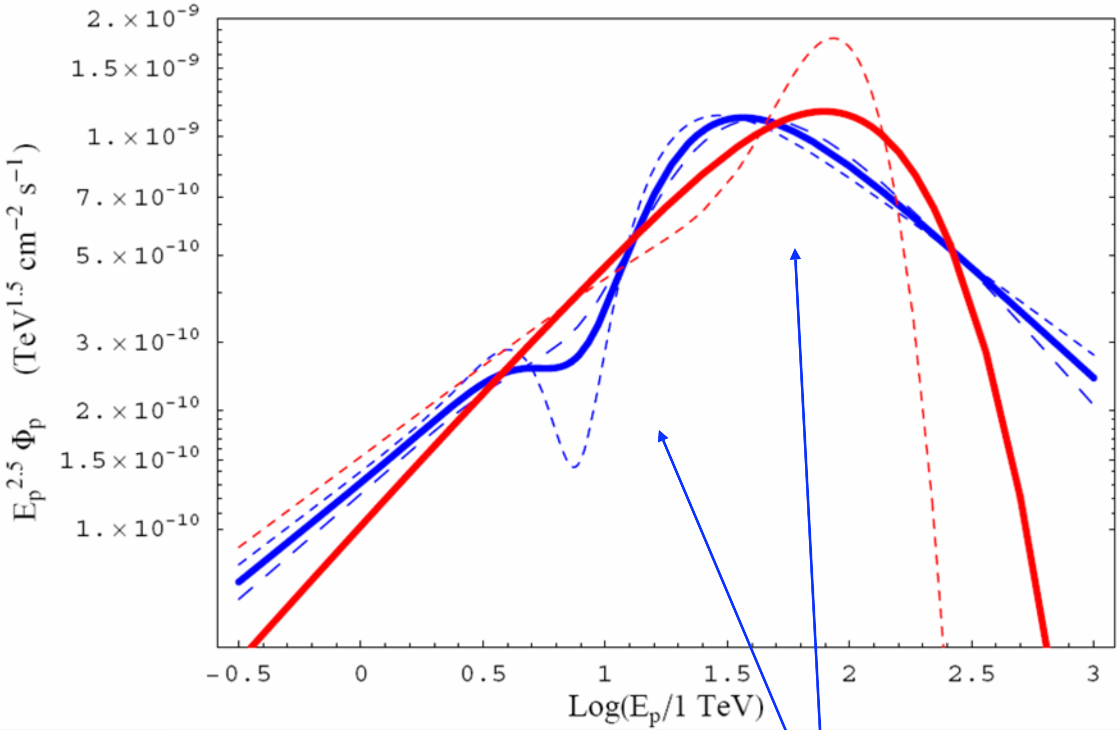
- ~1000 years old, distance ~1kpc, ~1° angular dimension in the sky
- First TeV γ ray SNR, first resolved image. Bright γ ray source.
- γ ray spectrum well determined by H.E.S.S. between 0.3–300 TeV



- Evidence for deviation from a pure power law behaviour (black line, Γ~ 2.3)
- Well fitted by broken power law (blue lines: Γ_{LE} – 2, Γ_{HE} ~ 3) or power law with exponential cut-off (red lines: Γ ~ 2, E_{cut} ~ 5 – 30 TeV)
- Cut-off/Transition may be more or less sharp (dash/dotted lines)
- Spectral shape disfavour IC emission

Using parameterized γ ray data

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



Low energy (E < 10 TeV):
Power law with spectral index
Γ_{LE} ~ 1.8 – 2.1

High energy (E < 10 TeV):
Cutoff in the spectrum at
E_p ~ 30 –100 TeV

A plausibility criterion for testing the hadronic origin assumption:

Dilution of spectral features in hadronic cascades → No sharp features in γ spectrum if it is originated by hadrons → sharp features in γ spectrum may correspond to unphysical or "strange" features in proton spectrum

The cutoff shape contains the physical informations → at present, too low statistics

How precisely ν emission from SNRs can be constrained by VHE γ–ray data?

arXiv:0807.4151; Nucl.Instrum.Meth.A588:123-129,2008

Predicting the ν spectrum

- If the VHE γ–rays originate from π_0 , we can deduce the π_0 flux:

$$\Phi_\gamma[E_\gamma] = \int_{E_\gamma}^{\infty} \frac{dE}{E}\,\Phi_{\pi^0}[E] \quad \Longrightarrow \quad \Phi_{\pi^0}[E] = -\,\frac{E}{2}\,\frac{d\Phi_\gamma[E]}{dE}$$

- For large number of emitted pions, isospin invariance implies:

$$\Phi_{\pi_0} \simeq \Phi_{\pi^+} \simeq \Phi_{\pi^-}$$

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

$$\Phi_\nu[E_\nu] = \int_{E_\nu}^{\infty} \frac{dE_\gamma}{E_\gamma}\, K_\nu\,[E_\nu/E_\gamma]\;\Phi_\gamma[E_\gamma] \quad \longrightarrow \quad K_\nu[x] = -\frac{1}{2}\sum_{i=\pi^\pm} \frac{d\omega_{i\nu}[x]}{d\ln x}$$

$w_{i\nu}[x]\,dx =$ spectrum of a neutrino ν in the decay chain of the i meson.

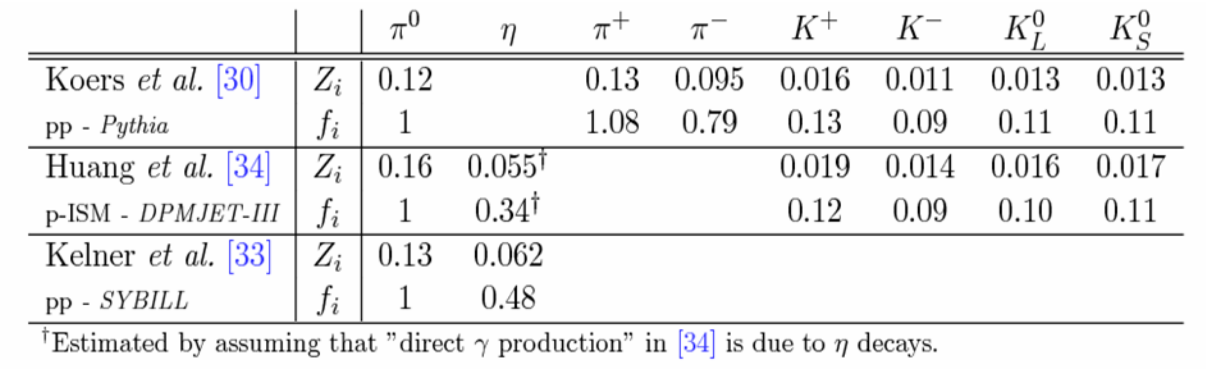
Completing the framework

We estimate the relative meson production rates at a fixed energy from hadronic interaction models, assuming a power–law primary spectrum with spectral index $\alpha = 2$:

$$\boxed{f_{\mathrm{i}} = \frac{R_{\mathrm{i}}}{R_{\pi_0}}}$$

We take into account:

- Deviation from isospin invariance: $f_{\pi^+} \simeq 1.08 \qquad f_{\pi^-} \simeq 0.79$
- η contribution to γ production: $f_\eta \simeq 0.48 \qquad (B.R. = 0.394)$
- K^+ and K^- contribution to ν production: $f_{K^+} \simeq 0.13;\ f_{K^-} \simeq 0.09 \qquad (B.R. = 0.635)$

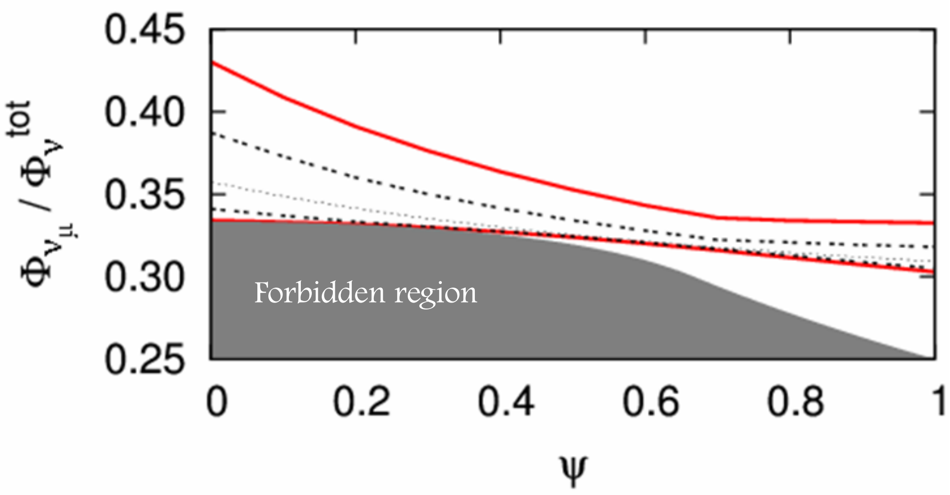


		π^0	η	π^+	π^-	K^+	K^-	K^0_L	K^0_S
Koers *et al.* [30]	Z_i	0.12		0.13	0.095	0.016	0.011	0.013	0.013
pp - *Pythia*	f_i	1		1.08	0.79	0.13	0.09	0.11	0.11
Huang *et al.* [34]	Z_i	0.16	$0.055^\dagger$			0.019	0.014	0.016	0.017
p-ISM - *DPMJET-III*	f_i	1	$0.34^\dagger$			0.12	0.09	0.10	0.11
Kelner *et al.* [33]	Z_i	0.13	0.062						
pp - *SYBILL*	f_i	1	0.48						

†Estimated by assuming that "direct γ production" in [34] is due to η decays.

Considering the approximation implicit in our method (constant f_i factors, neglected prod. channels, etc.) and uncertainty in hadronic modeling, we estimate that the γ–ν relation is affected by 20% systematic uncertainty

The effect of ν–oscillations



The flux of neutrinos from meson decays are modified:

$$\begin{aligned}\Phi_{\nu_\mu} &\rightarrow P_{\mu\mu}\Phi^0_{\nu_\mu} + P_{e\mu}\Phi^0_{\nu_e}\\ \Phi_{\overline{\nu}_\mu} &\rightarrow P_{\mu\mu}\Phi^0_{\overline{\nu}_\mu} + P_{e\mu}\Phi^0_{\overline{\nu}_e}\end{aligned}$$

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

$$P_{lh} = \textstyle\sum_{i=1}^{3} \left|U^2_{li}\right| \left|U^2_{hi}\right| \qquad \text{with} \qquad l, h = e, \mu\tau$$

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

By propagating uncertainties of ν oscill. parameters, we obtain:

For $\Psi = \frac{\Phi^0_{\nu_e}}{\Phi^0_{\nu_\mu}} \simeq 0.5$ → $\frac{\Phi_{\nu_\mu}}{\Phi^{\rm tot}_\nu} = (0.33 - 0.35)$ 2σ range

Small uncertainty → results from partial cancellation of $P_{\mu\mu}$ an $P_{e\mu}$ anticorrelated error

The final result and its application to SNR RX J1713.7-3946

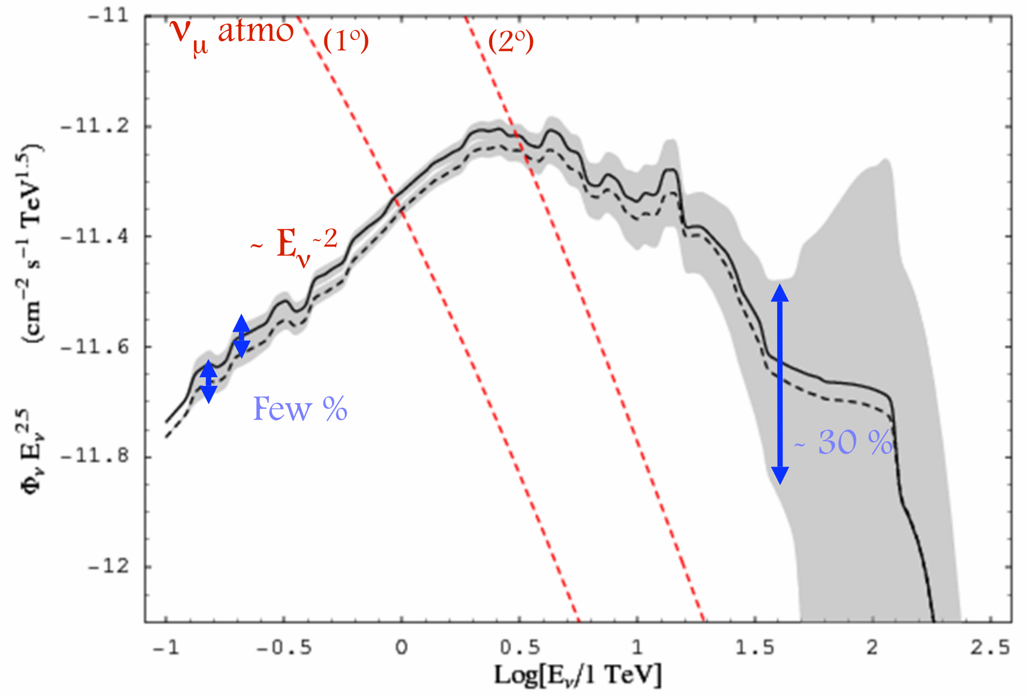
As final result, we obtain the simple expressions:

$$\Phi_{\nu_\mu}[E] = 0.380\,\Phi_\gamma[E/(1-r_\pi)] + 0.0130\,\Phi_\gamma[E/(1-r_K)] + \int_0^1 \frac{dx}{x}\, k_{\nu_\mu}[x]\,\Phi_\gamma[E/x]$$

Pion decay   kaon decay   muon decay

$$\Phi_{\overline{\nu}_\mu}[E] = 0.278\,\Phi_\gamma[E/(1-r_\pi)] + 0.0090\,\Phi_\gamma[E/(1-r_K)] + \int_0^1 \frac{dx}{x}\, k_{\overline{\nu}_\mu}[x]\,\Phi_\gamma[E/x]$$

which can be applied directly to observational data:



Solid line: ν_μ flux at earth

Dotted line: anti–ν_μ flux at earth

Shaded areas: obtained propagating observational errors

Red dotted lines: atmospheric ν flux (vertical flux, integrated over 1 and 2 ang. diameter window)

Events in neutrino telescopes

The number of events expected in an ideal ν telescope:

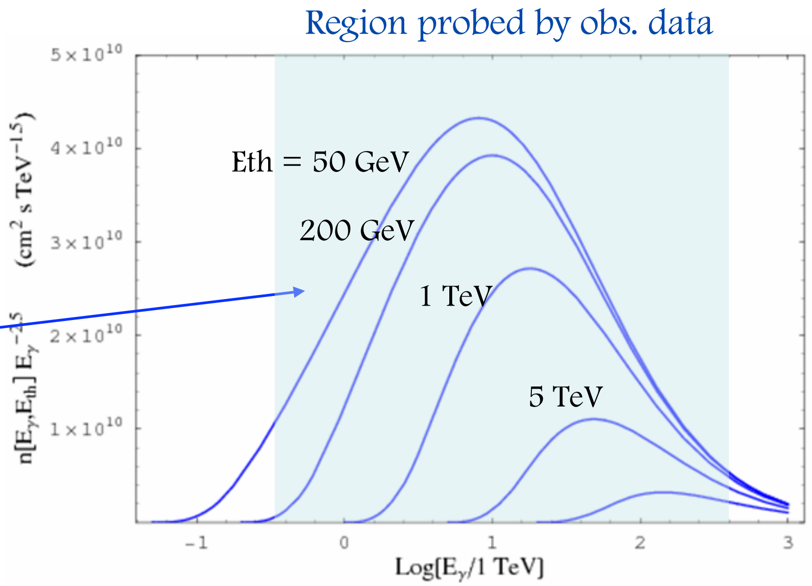
$$N_{\mu+\overline{\mu}} = f_{\rm liv} \cdot A \cdot T \cdot \int_{E_{\rm th}}^{\infty} dE\, \Phi_{\nu_\mu}[E] \times Y_\mu[E, E_{\rm th}](1 - \overline{a}_{\nu_\mu}[E]) + (\nu_\mu \rightarrow \overline{\nu}_\mu)$$

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

- A = 1 km² and T = 1 solar year.
- Eth = threshold for muon detection.
- source is below the horizion for f_{liv}=0.78 (Antares).
- The muon range (in the yield Yμ) is calculated for water.
- The neutrino absorption coefficient a_μ, averaged over the daily location of the source, is calculated for standard rock.

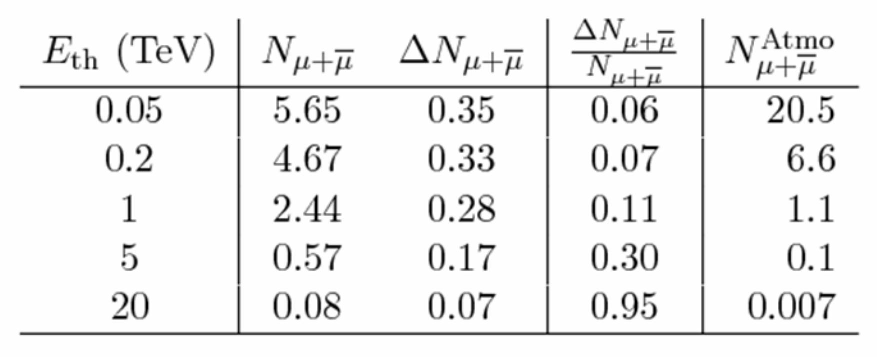
By exploiting the γ–ν relation, one recast:

$$N_{\mu+\overline{\mu}} = \int_{E_{\rm th}}^{\infty} \frac{dE_\gamma}{E_\gamma} \boxed{n[E_\gamma, E_{\rm th}]\Phi_\gamma[E_\gamma]}$$



Expected number of events from RX J1713.7-3946

For 1km² year exposure in ANTARES location:



E_{th} (TeV)	$N_{\mu+\bar{\mu}}$	$\Delta N_{\mu+\bar{\mu}}$	$\frac{\Delta N_{\mu+\bar{\mu}}}{N_{\mu+\bar{\mu}}}$	$N^{\mathrm{Atmo}}_{\mu+\bar{\mu}}$
0.05	5.65	0.35	0.06	20.5
0.2	4.67	0.33	0.07	6.6
1	2.44	0.28	0.11	1.1
5	0.57	0.17	0.30	0.1
20	0.08	0.07	0.95	0.007

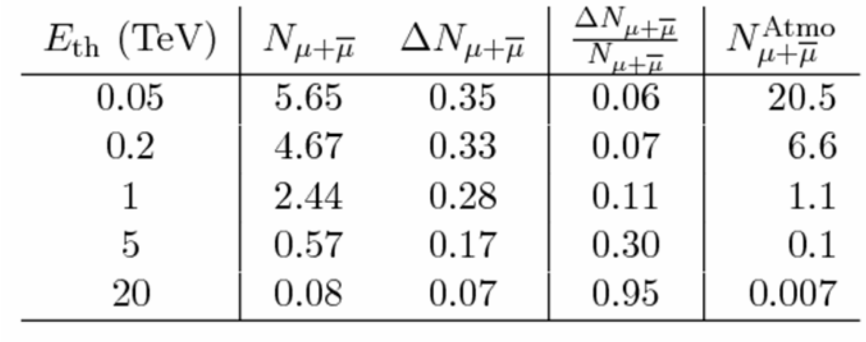
Note that:

- rates calculated directly from raw data (no γ–parameterization assumed)
- we neglect a possible "leptonic" contamination in the observed γ–ray flux
- ideal detector was assumed
- atmospheric background estimated by integrating the vertical flux from Lipari '08 over a 2° angular diameter window
- Uncertainties obtained by propagating obs. errors in the γ ray flux.
- Comparable syst. uncertainty (~ 20%) arise from the assumed hadronic int. model

This result can be compared with the 6 events of Vissani '06, the 9 events in Costantini & Vissani '04 (power law $\Phi \sim E^{-2.2}$ extended till 1 PeV) and the 40 events in Alvarez-Muniz & Halzen '02 ($\Phi \sim E^{-2}$, oscillations, livetime and absorption ignored)

Conclusions

SNR RX J1713.7–3946 – 1km^2 year exposure – Antares location



$E_{\rm th}$ (TeV)	$N_{\mu+\bar{\mu}}$	$\Delta N_{\mu+\bar{\mu}}$	$\frac{\Delta N_{\mu+\bar{\mu}}}{N_{\mu+\bar{\mu}}}$	$N^{\rm Atmo}_{\mu+\bar{\mu}}$
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- The ν–γ ratio is a rather solid prediction which should not be affected by large syst. uncertainties.

- The present, successful program of observations of VHE γ–rays from SNRs covers the right energy region to derive expectations for the forthcoming neutrino telescopes.

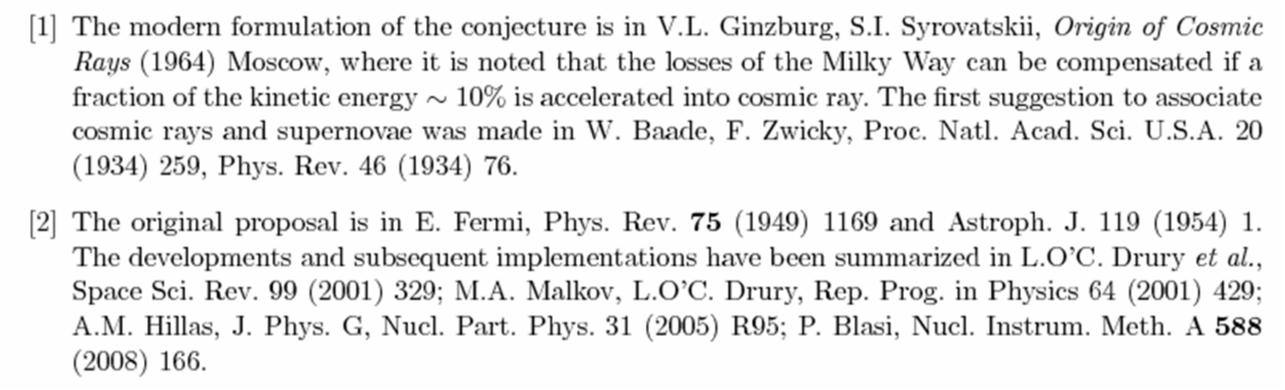
- SNR RX J1713.7–3946 → could be possible to detect a neutrino signal with exposures of the order of few km2 years, if the detection threshold in future ν–telescopes will be lower than about 1TeV.

- Due to the presence of the atmospheric neutrino background, it does not seem really much useful to lower the threshold for neutrino observation much below the TeV region.

- Another promising (better?) young SNR is Vela Jr, whose higher part of gamma ray spectrum (above 20 TeV) is still to be studied.

(Incomplete) list of references [1]

SNRs-CR association and FERMI mechanism



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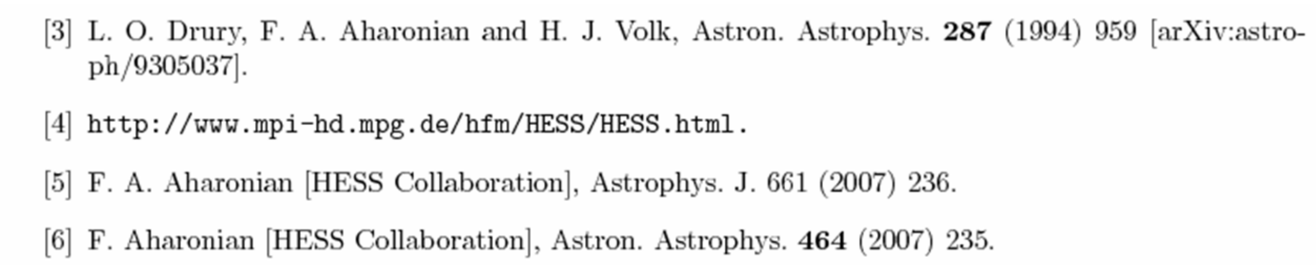
VHE gamma ray emission from SNRs – Proposal of detection and results from H.E.S.S.



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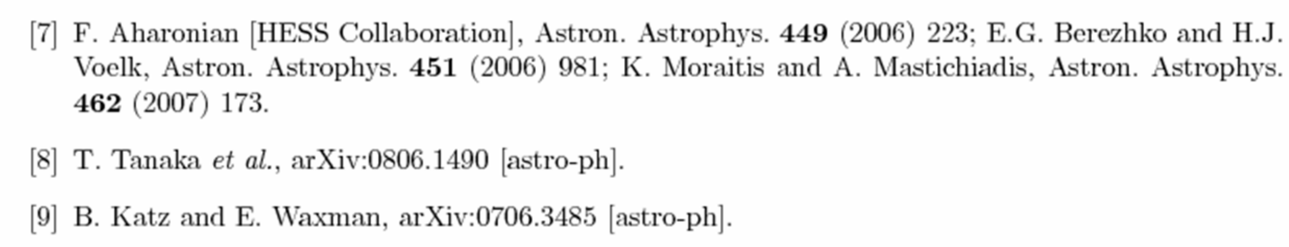
Interpretations of SNRs VHE gamma-ray data



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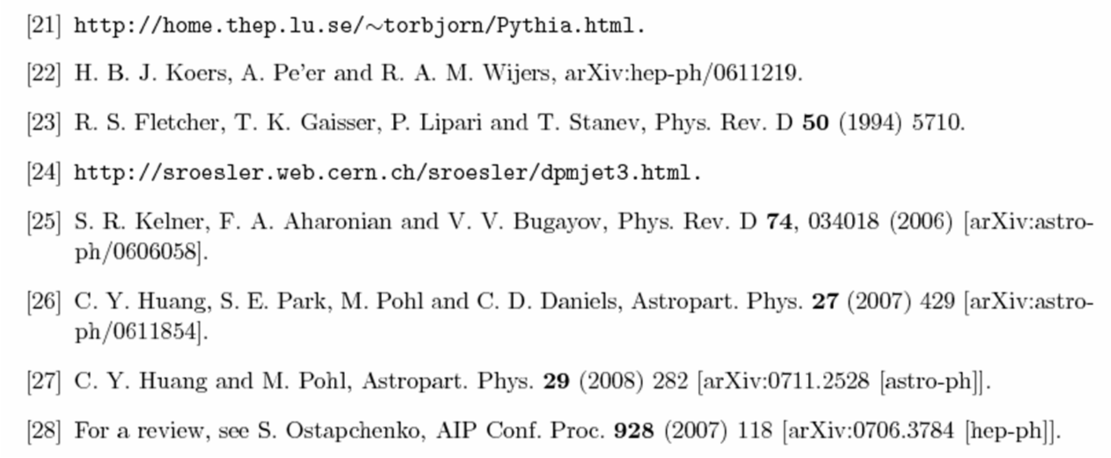

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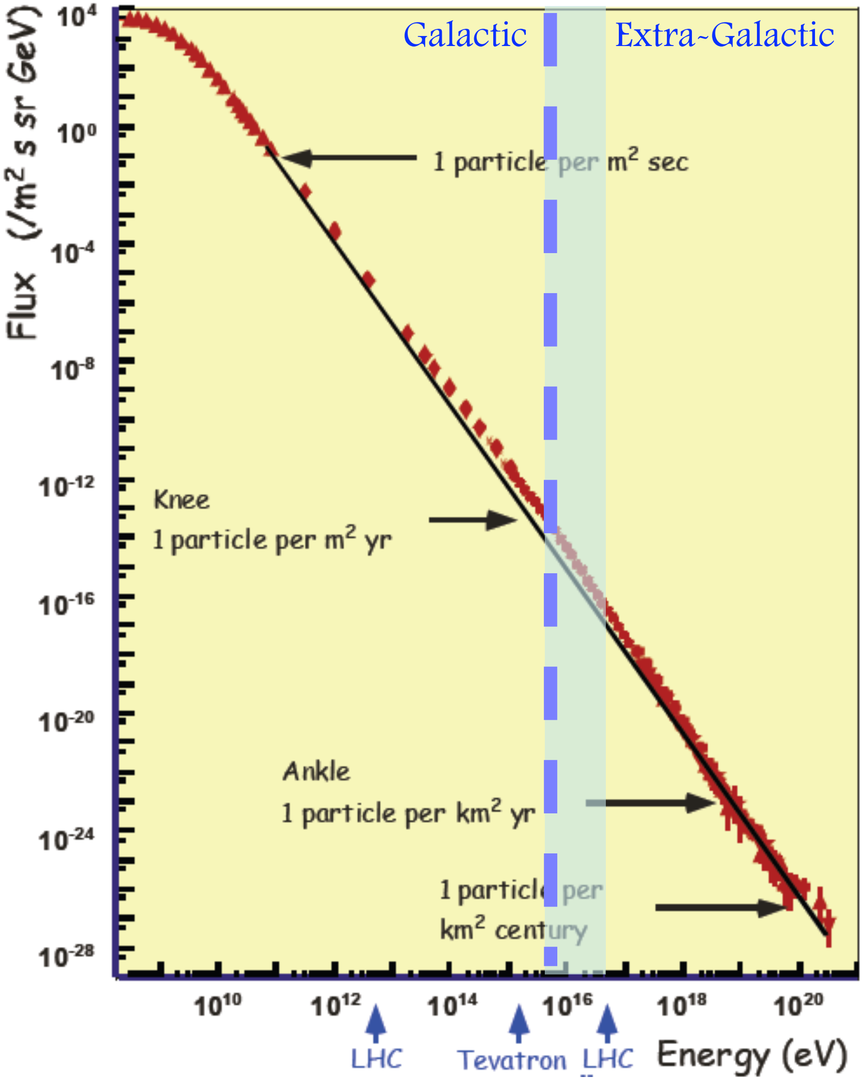
Additional Slides

The cosmic ray flux



- Relativistic charged particles
- Power law spectrum with almost no structure

$$\frac{dn}{dE} \propto E^{-2.7}$$

- Energy emitted in CR from our Galaxy:

$$\mathcal{L}_{\rm cr} \simeq \frac{E_{\rm cr}}{\tau_{\rm cr}} \simeq 5 \times 10^{40}\,\mathrm{erg\,s^{-1}}$$

where:

Energy density: $\rho_{\rm cr} \simeq 1\ \ \mathrm{eV\,cm^{-3}}$

Total energy: $E_{\rm cr} \simeq \rho_{\rm cr} V_{\rm cr} \simeq 10^{55}\,\mathrm{erg}$

$$V_{\rm cr} \simeq \pi R^2 H$$

$$R = 15\mathrm{kpc}$$

$$H = 2\mathrm{kpc}$$

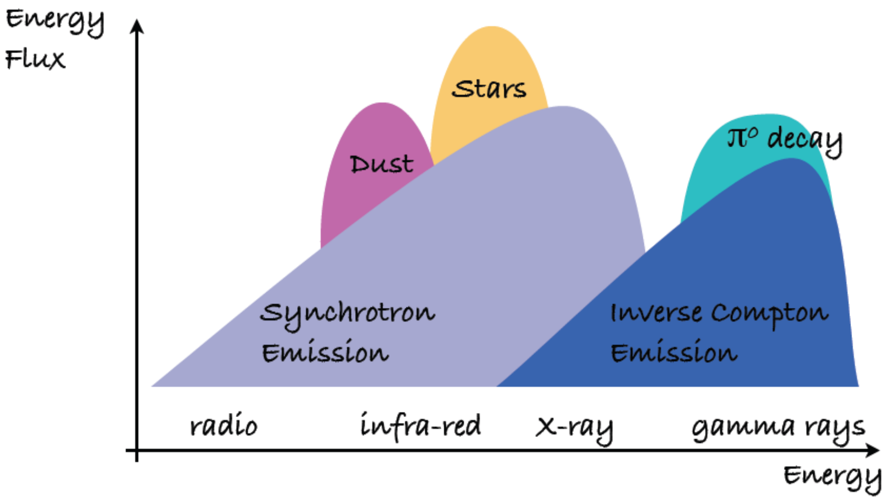
Confinement time: $\tau_{\rm cr} \simeq 6 \times 10^{6}\mathrm{years}$

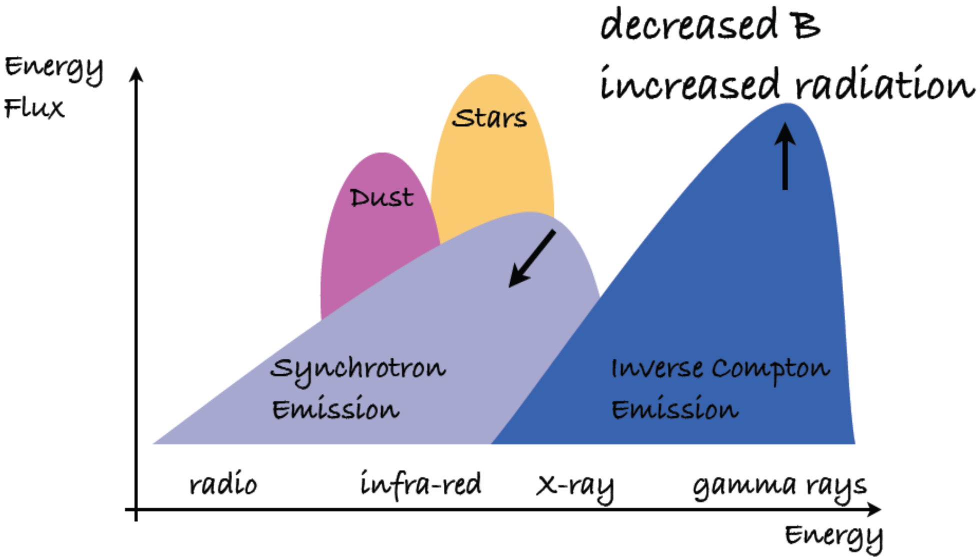
Creation of γ rays:

π_0 decays → Hadronic primaries

Synchrotron emission in magnetic fields
Inverse Compton effect
} → Leptonic primaries

γ rays production can be dominated by hadronic or leptonic mechanisms depending on local conditions:





Using the “raw” γ ray data

The CR spectra can obtained directly from the VHE gamma ray data

To apply our method to noisy data, we filtered them by a Gaussian kernel → only main features of the CR spectrum are obtained.

Broken power law (solid) and modified exponentialcut (dotted) distributions are used to extrapolate at low and high energies.

Shaded region are obtained by propagating observational errors.