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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

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On the detectability of high-energy galactic neutrino sources

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Expectations for Galactic High Energy ν Sources

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Cosmic νs above TeV are the dream of modern neutrino astronomy. Here discussed:

- Expectations for galactic sources, with emphasis on γ-ray-transparent ones.
- Connections with γ-ray astronomy and minimal intensities in γ-rays.
- Motivations for a specific class of SNR, with focus on RX J1713.7-3946.
- (Precise) upper bounds on expected neutrinos signals for various cases.

Approach is mostly phenomenological rather than theoretical.

With F. Aharonian, ML. Costantini, N. Sahakyan, F.L. Villante, C. Vissani

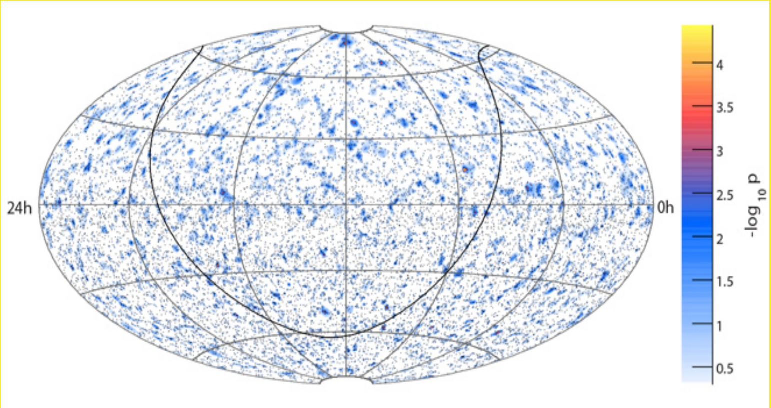
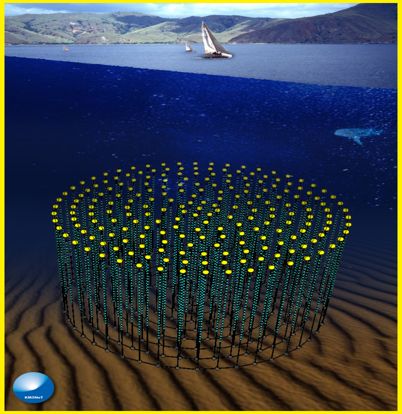


Figure 1: *IceCUBE is ready and producing physics results. Km3NET detector is being finalized in size and location.*



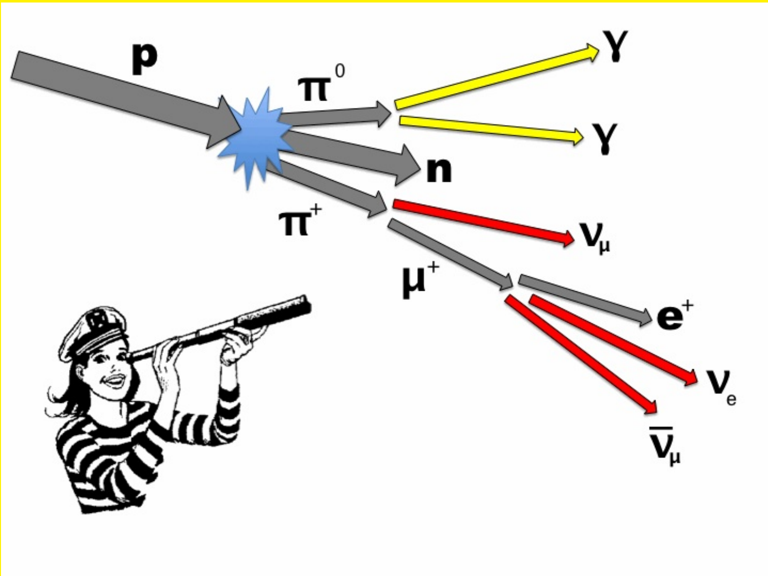


Figure 2: *Standard astrophysical view adopted in this talk: The observation of high-energy neutrinos is very difficult but perhaps possible and would amount to an unambiguous signal of cosmic ray collisions, and, hopefully, those in their source.*

The strict connection of γ and ν_μ produced in cosmic ray collisions can be tested, unless γ are absorbed/modified.

1 Introduction

Are expectations really needed?

Maybe not, since surprises are the rule for new astronomies: From Pulsars to most recent Fermi bubbles or Crab variability.

Are they useful?

Of course, yes. Good predictions are precious for experiments, but also reasonable expectations eventually contradicted are not useless.

Relevant precedents of expectations?

Solar neutrinos, predictions with errorbars since the 60's; Supernova neutrinos, some expectations before SN1987A; TeV γ-rays from Crab foreseen in 1965.

This talk: towards expectations by help of γ-ray observations, limiting the use of theory inputs but assuming transparency.

... if we know the gamma's, getting expectations is easy ...

Both neutrinos and unmodified, hadronic gamma are linear functions of the cosmic ray intensity. Thus they are linked by a linear relation:

$$\Phi_{\nu_\mu}(E) = 0.380\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.013\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_\mu(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

$$\Phi_{\bar\nu_\mu}(E) = 0.278\ \Phi_\gamma\left(\frac{E}{1-r_\pi}\right) + 0.009\ \Phi_\gamma\left(\frac{E}{1-r_K}\right) + \int_0^1 \frac{dx}{x} K_{\bar\mu}(x)\Phi_\gamma\left(\frac{E}{x}\right)$$

where the first and second contribution are due to direct mesons decay into neutrinos, $r_x = (m_\mu/m_x)^2$ with $x = \pi, K$ and the second to μ decay, e.g.:

$$K_\mu(x) = \begin{cases} x^2(15.34 - 28.93x) & 0 < x < r_K \\ 0.0165 + 0.1193x + 3.747x^2 - 3.981x^3 & r_K < x < r_\pi \\ (1-x)^2(-0.6698 + 6.588x) & r_\pi < x < 1 \end{cases}$$

and similarly for antineutrinos; oscillations included FV'06; Villante&FV'08.

... three flavor oscillations are well understood & relevant ...

For transparent sources, the simplest regime – Pontecorvo's – applies:

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

and the flux of muon neutrinos/antineutrinos becomes:

$$\Phi_{\nu_\mu} = P_{\mu\mu}\ \Phi^0_{\nu_\mu} + P_{e\mu}\ \Phi^0_{\nu_e} = \Phi^{\rm tot}_\nu \times (P_{\mu\mu} + \psi \times P_{e\mu})/(1+\psi)$$

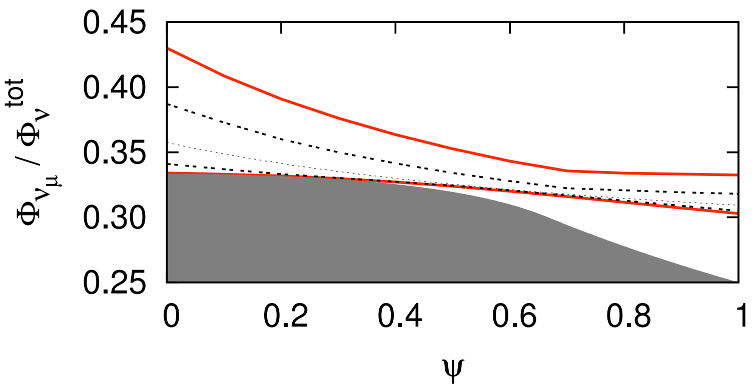


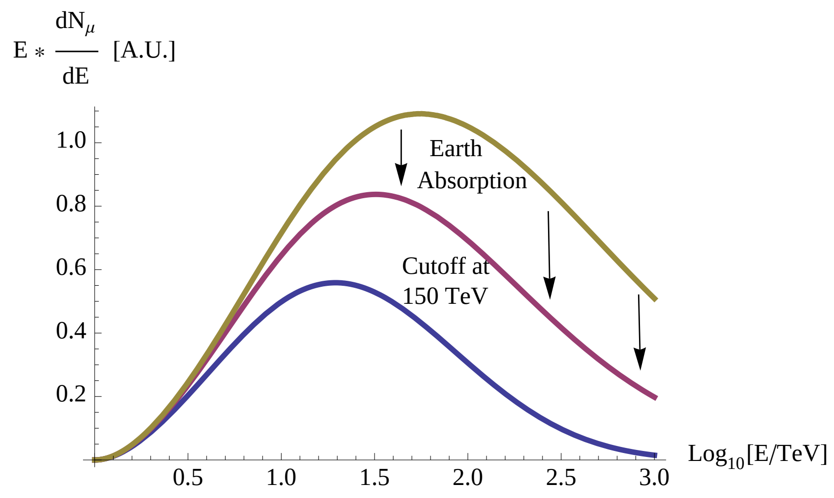
Figure 3: *Value $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu$ as a function of $\psi = \Phi^0_{\nu_e}/\Phi^0_{\nu_\mu}$ (gray region forbidden). Uncertainty is small; $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu = 0.33 - 0.35$ at 2σ when $\psi = 0.5$.*

... and calculating the muon signal is standard.

$$P_{\nu_\mu\to\mu} = \int_{E_{th}}^{E} dE_\mu \frac{d\sigma_{cc}}{dE_\mu} R_\mu/m_n \qquad [\text{say, } 10^{-35}\ \text{cm}^2 \times N_A/\beta \sim 10^{-6}]$$

$$A_{\nu_\mu} = A_\mu(\theta) \times P_{\nu_\mu\to\mu}(E,\theta) \times e^{-\sigma\ z/m_n} \quad [\text{say, } 1\ \text{km}^2 \times 10^{-6} \sim 1\ \text{m}^2]$$

Figure 4: *Distribution of ν_μ leading to muons, assuming E^{-2} primary spectrum (sienna); then, including Earth absorption, for a source at $\delta = -39^\circ$ as seen from Antares (purple); then with a spectrum $E^{-2}e^{-\sqrt{E/150\ \text{TeV}}}$ (blue), i.e., with primaries cutoffed at $\sim$3 PeV.*



Recall that when $E \sim 10$ TeV, $s \sim 2m_n E \sim Q^2 > M_W^2$, then xsec decreases.

Absorption for $E \sim$ few $\cdot$ 100 TeV, when $\sigma(E) \sim m_n/(R_\oplus \bar\rho_\oplus) \sim 5\cdot 10^{-34}$ cm^2.

2 Potential neutrino sources and γ-rays

Potential neutrino sources are characterized by their hadronic γ-rays $\langle$`distributed as` $I_\gamma \propto E_\gamma^{-\alpha} \cdot e^{-\sqrt{E_\gamma/E_c}}$, `with` $\alpha = 1.8 - 2.2$ `and` $E_c =$ `TeV`$-$ `PeV`$\rangle$ for π^0 and $\pi^\pm$ are produced together.

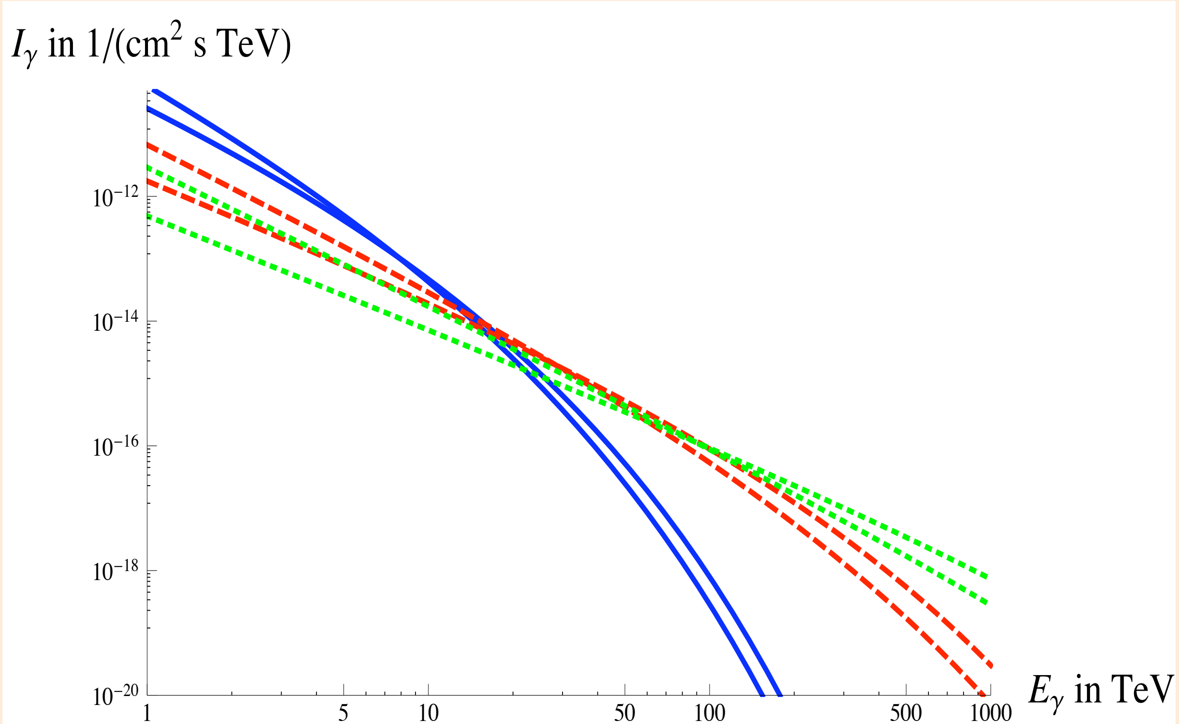


Figure 5: *γ-ray intensities corresponding to a signal of 1 muon/km^{2}yr above 1 TeV, evaluated assuming that the sources are transparent to their gamma rays.*

Note that:

Similar intensities $10-50$ TeV; all fluxes are in a narrow range:

$$I_\gamma(>10\ \text{TeV}) = (1-2)\times 10^{-13}/(\text{cm}^2\ \text{s})$$

To collect $\geq 100\gamma$'s in a reasonable time, km^2 area needed:

$$\textbf{Exposure} = L^2\times T \sim 2\times\ \text{km}^2\times 10\ \text{h}$$

e.g., a 10×10 Cherenkov telescopes array, or one dedicated EAS array.

A large area γ apparatus, such as CTA or a custom instrument, would be invaluable for ν community and would cost $\sim 3\%$ of a ν-telescopes.

3 Complementary views in γ and ν_μ

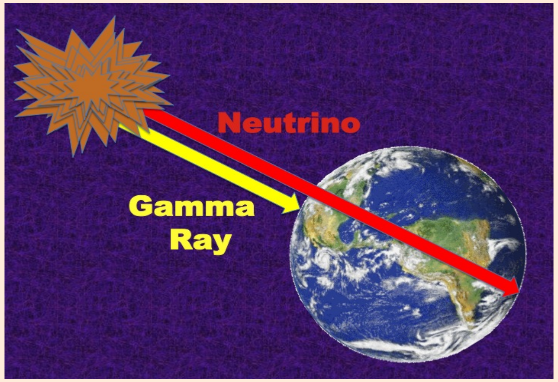


Figure 6: *Neutrino telescopes look downward! Due to atmospheric μ background, ν_μ from cosmic sources are preferentially detected from below (Zheleznykh '58)*

γ and ν_μ views are complementary; maximal complementarity for antipodal locations.

A steady source at declination δ, is seen from a detector at latitude ϕ for a fraction of time: $f_\gamma = \mathrm{Re}[\cos^{-1}(-\tan\delta\tan\phi)]/\pi$; the fraction of time for neutrinos is just $f_{\nu_\mu} = 1 - f_\gamma$.

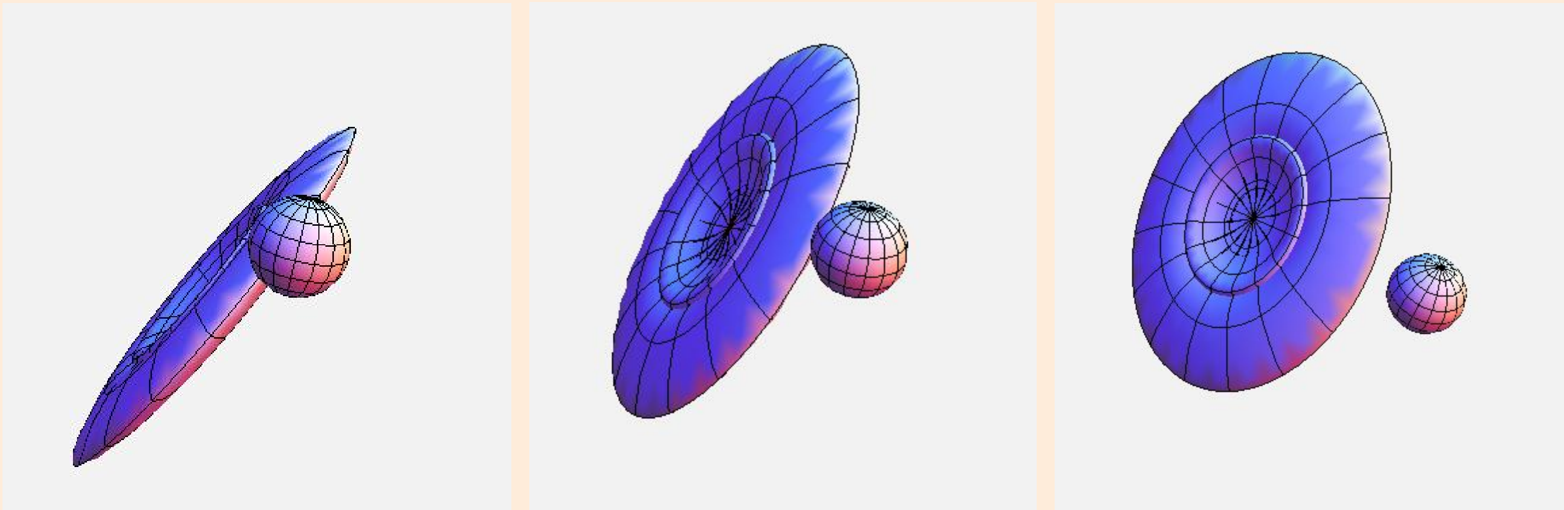
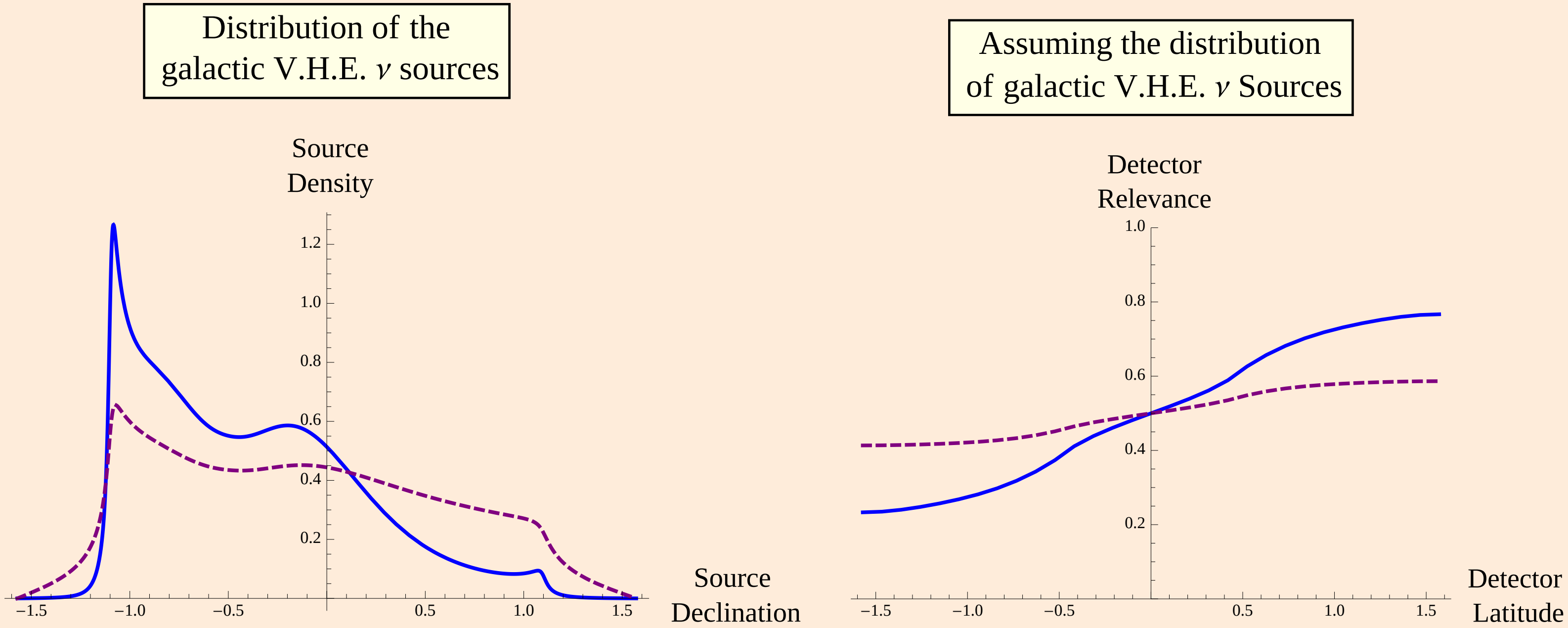


Figure 7: *Relative orientation of Earth and Milky Way.*

E.g.: a hypothetical ν_μ (resp., γ) emission from Galactic Center is visible from North (resp., South) Pole.



- The Galactic Center is at about $\delta = -30^\circ$: Thus, matter is mostly located in the region $\delta < 0$, i.e., below the celestial equator.
- A telescope at the latitude of NEMO has a priori 2.9 (1.4) better chances to see galactic neutrino sources than IceCUBE.

The continuous line considers just the matter distribution; the dashed one weights it with $1/r^2$.

4 Questions and doubts

Gamma transparency: is it a reliable hypothesis?

Use of average matter distribution is doubtful, since the HESS scans shows only few intense sources. Fluctuations are essential, individual object matters.

Are we sure of the 'point source' hypothesis? Similar as asking: is $\ll 1^\circ$ pointing really important for very high energy gamma and/or neutrino telescopes?

That γ above 10 TeV would help ν astronomy is reasonable, and would be a natural direction of progress, but which are guaranteed aims of such a search?

Eventually, the true question is: How to tell leptonic from hadronic gamma's? Neutrino identify CR collisions, but is this the only way to proceed?

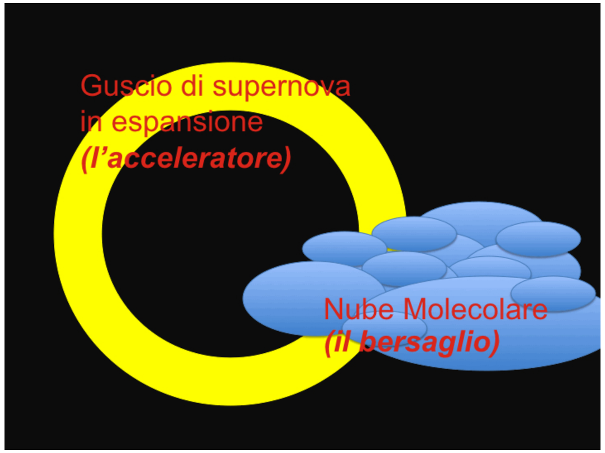
5 The SNR+MC paradigm

From Baade & Zwicky's insight, to the modern paradigm of CR origin:

1. *Fermi* $_{\textit{and many more}}$*: kinetic energy of gas transforms into CR;*
2. *Ginzburg & Syrovatskii: energy injected by SNR$\simeq 10\times$ CR losses;*
3. *Aharonian, O'Drury, Völk: SNR+mol.clouds $\Rightarrow$ hadronic ν & γ;*

as further illustrated in the following funny plot:

Figure 8: *Sketch of the association between a shell-type SNR and a molecular cloud. The first acts as a cosmic ray accelerator the second as a target (in Italian, "l'acceleratore" and "il bersaglio"). In particle physics parlance, it is a classical "beam dump" configuration.*



Pros & cons of SNR+MC paradigm

⋆ **Some support from GeV γ's from relatively old SNR.**

... e.g, the SNRs W28 and W44.

⋆ **Gamma transparency usually holds.**

... as we'll check a special case later.

⋆ **Young ($\sim$ 1000 y) SNR should have protons till 100 TeV.**

... the closest should be at about 1 kpc since we have 1 new SN each 30 yr.

⋆ **Acceleration above 100 TeV is an open theoretical problem.**

... that can be approach observationally measuring gammas above 10 TeV.

⋆ **Concrete cases require theoretical modeling anyway.**

... plus as many multiwavelength observations as possible...

6 SNR RX J1713.7-3946: a case study

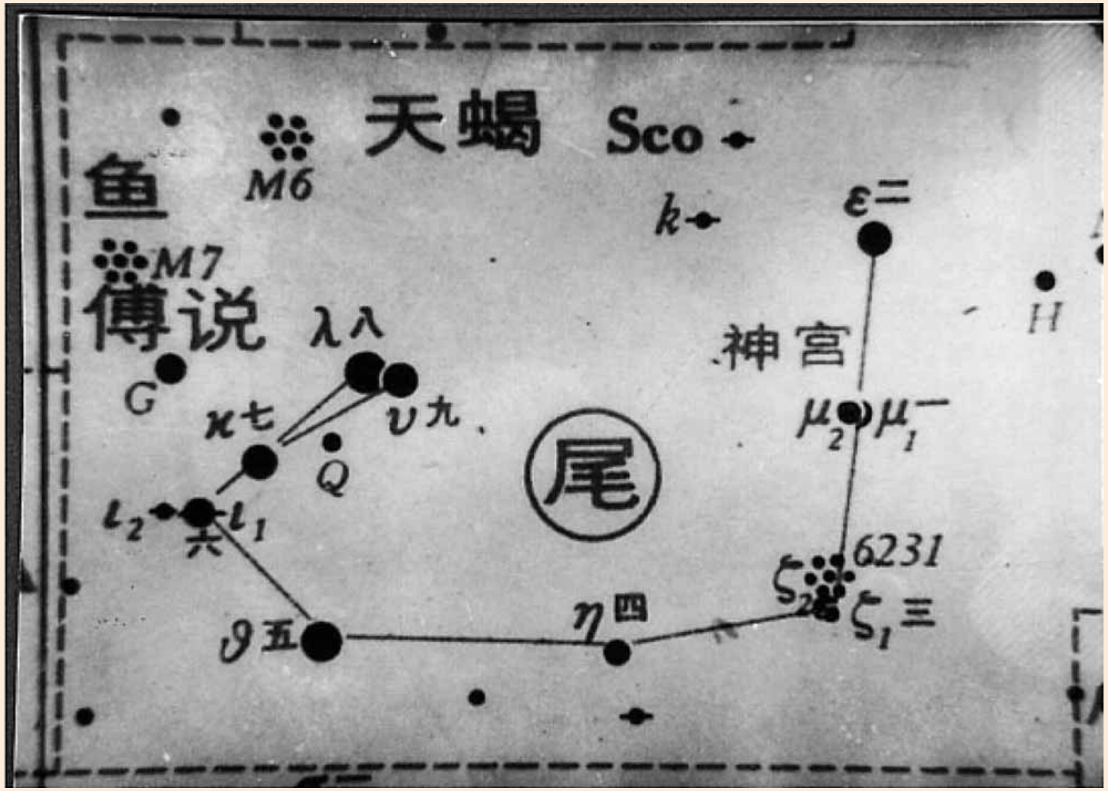
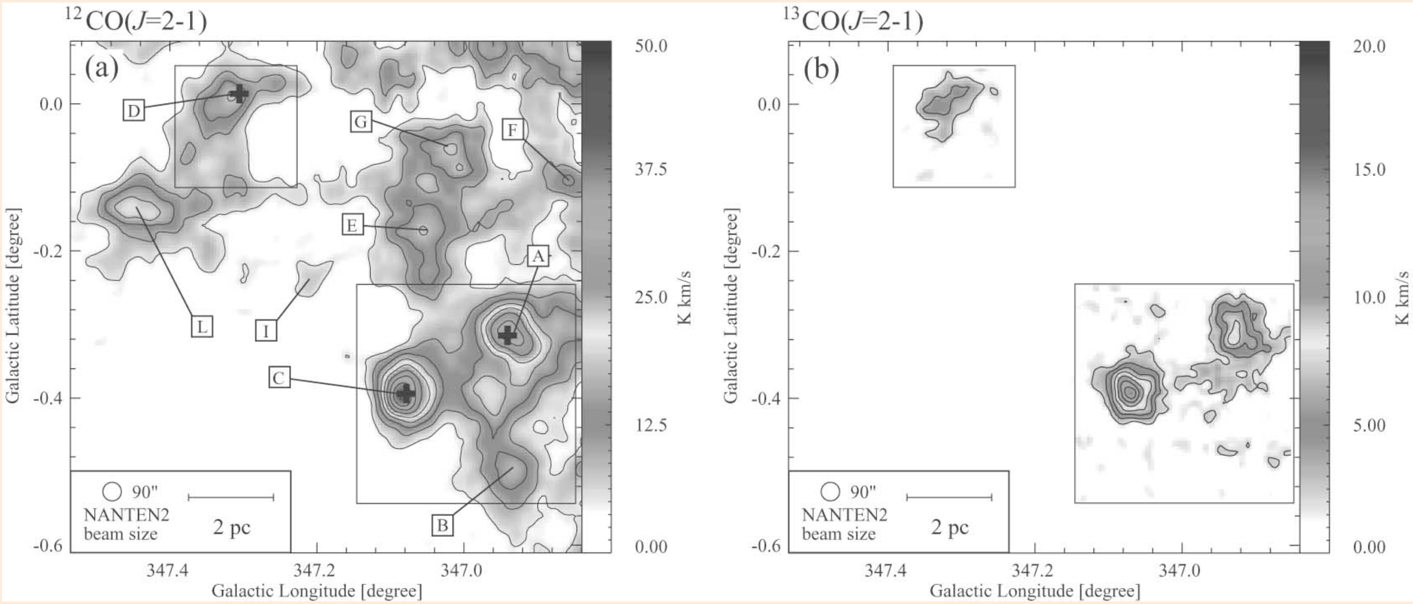


Figure 9: *Wang et al.: 393AD guest star=progenitor of RX J1713.7-3946.*

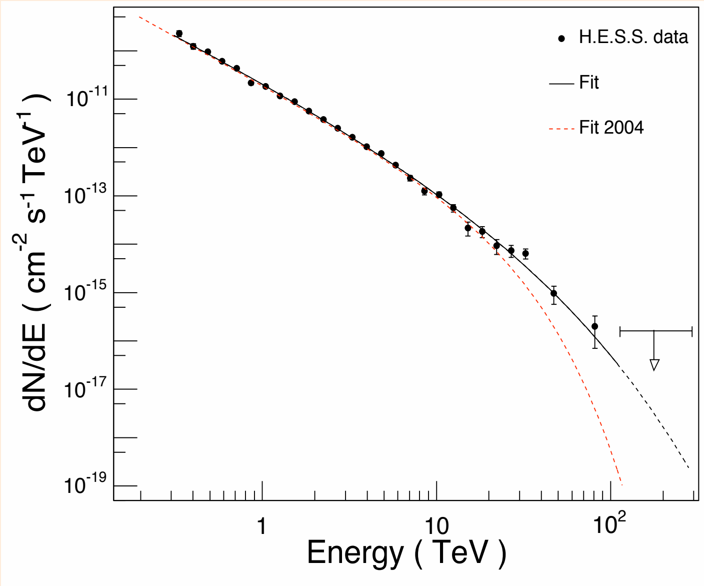
Molecular clouds *are* present

Figure 10: *NANTEN (Sato et al., 2010) has observed the molecular clouds associated with RX J1713.7-3946 studying the CO emissions, correlated with IR and anti-correlated with X ray emissions. The overdensities are named: peak A,B,C,D...*



Plausibly: overdensities formed by SN explosion and interacting with the shock wave. A,C,D most prominent. Peak C estimated mass is 400 $M_\odot$; with 1 pc size ($\sim 0.1^\circ$ angular size) it has the column density of $20\ \mu$m of Lead.

TeV γ-ray emission *is* measured up to 100 TeV



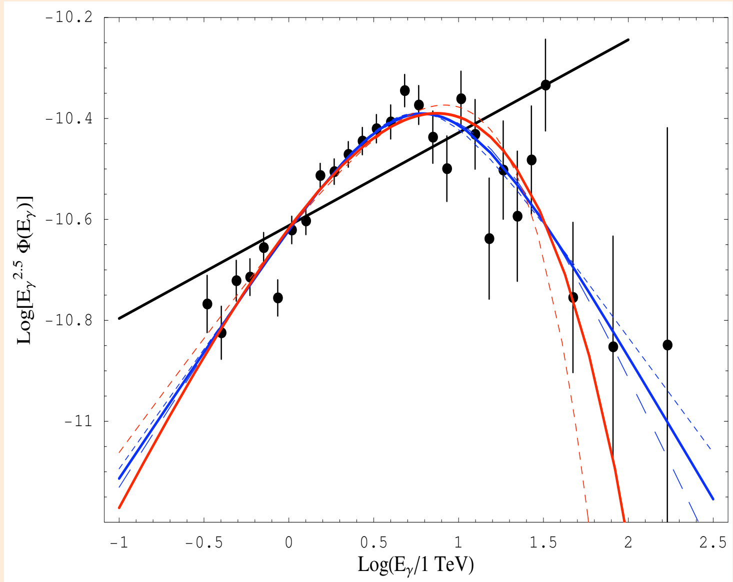
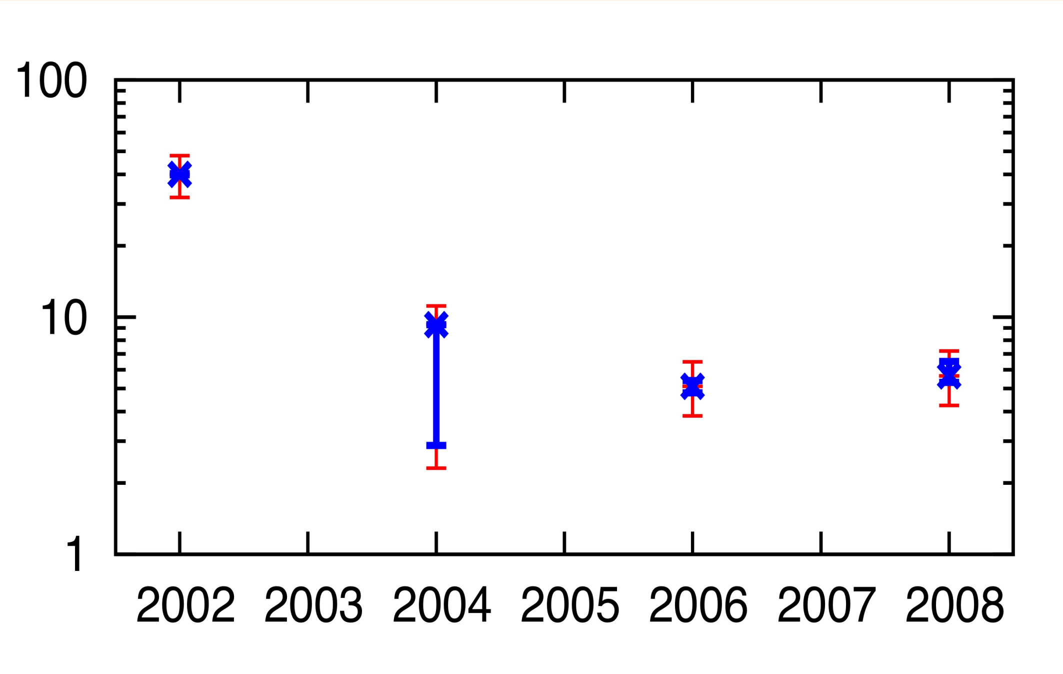


Figure 11: *Thanks to HESS we know that the spectrum is non-trivial: it is well described by a broken-power-law or by a modified-exponential-cut.*

Power spectrum with 1.79 ± 0.06 and $E_c = 3.7 \pm 1$ TeV (Villante & FV '07)

Upper bound on neutrino *has become* precise

Figure 12: *Expected muon flux per km$^2\times$yr and above 50 GeV. In blue, the error deduced from 4 publications, in red, 20% systematic error.*



Why the changes: 1 $\to$ 2: oscillations, absorption, livetime. 2 $\to$ 3: cutoffed HESS spectrum. 3 $\to$ 4: latest theoretical and observational improvements.

Indeed, the latest HESS data, with the hadronic hypothesis, permit us to evaluate the expected fluxes precisely enough to obtain reliable expectations (or more precisely, upper bounds):

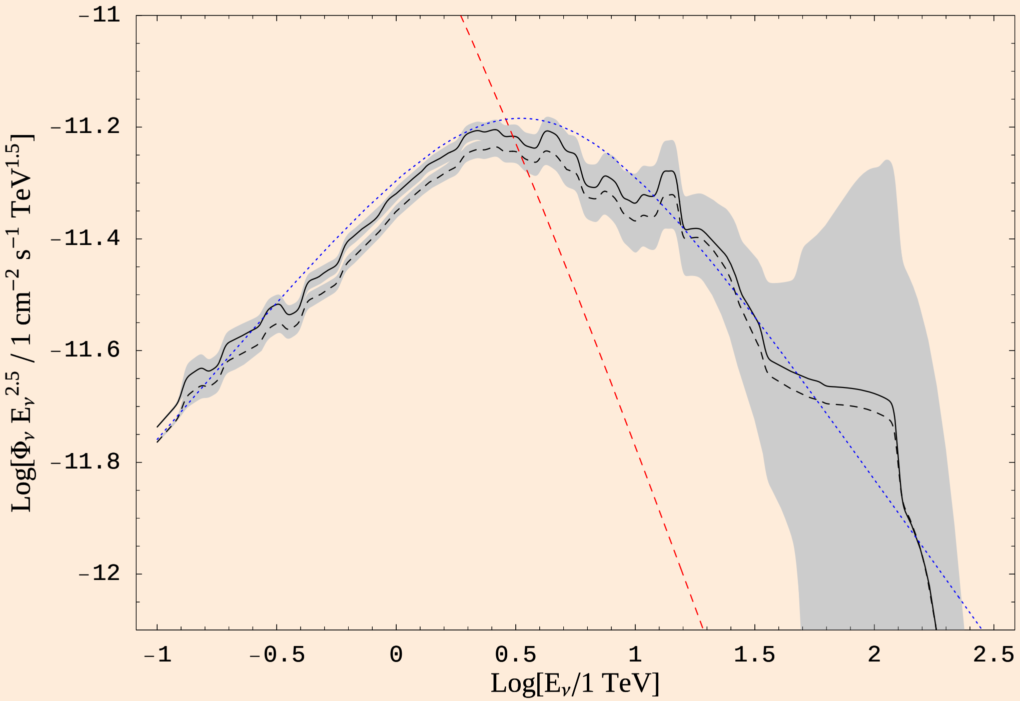


Figure 13: *ν_μ and $\bar{\nu}_\mu$ fluxes deduced from latest HESS data, assuming a hadronic γ-ray emission* (*Villante & FV '08*). *The corresponding number of events above 1 TeV is:*
$I_{\mu+\bar{\mu}} = 2.4 \pm 0.3 \pm 0.5/km^2\ yr$

Threshold	Expected signal	1σ error	Atm. background
50 GeV	5.7	6%	21
200 GeV	4.7	7%	7
1 TeV	2.4	10%	1
5 TeV	0.6	30%	0.1
20 TeV	0.1	100%	0.0

Table 1: *Dependence on the threshold of the number of signal muons from RX J1713.7-3946, assuming the hadronic hypothesis. Also quoted the estimated error from HESS statistics and the estimated background.*

Fermi view at *GeV* and above

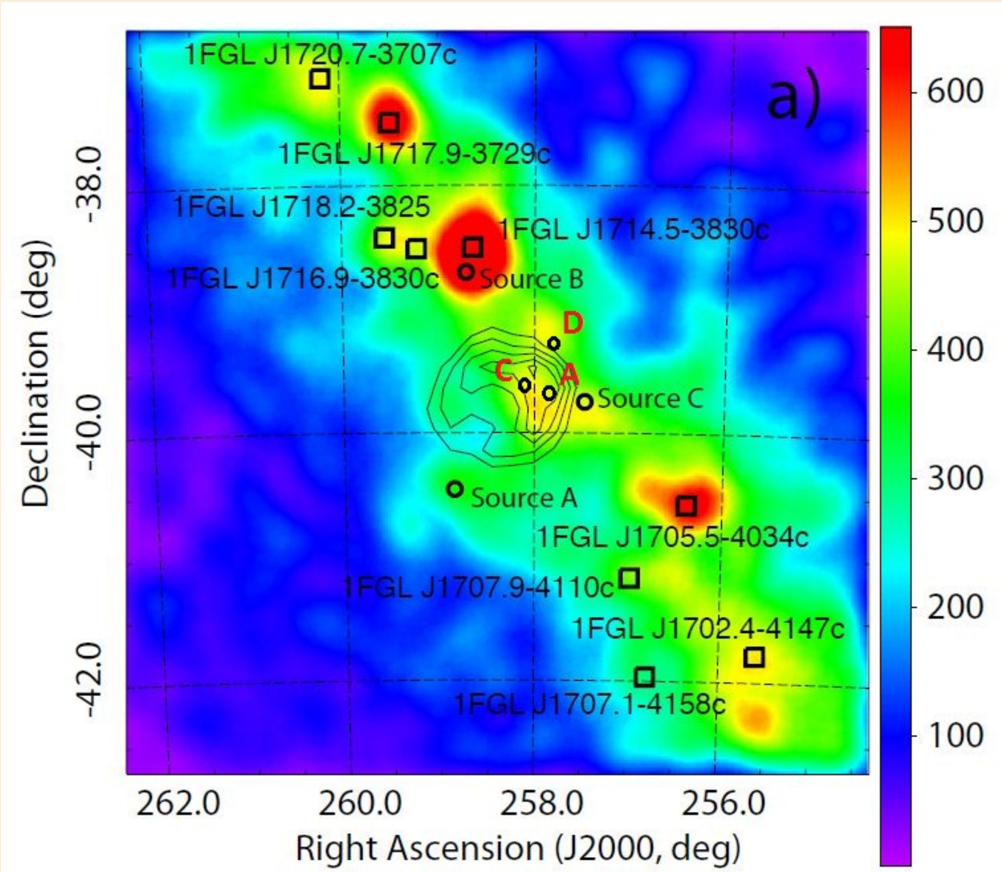


Figure 14: *Counts* > 3 GeV *given by Fermi collaboration, claiming: a* **wide** *source in SNR location with spectrum* $\approx E_\gamma^{-1.5}$ *from upper bound on* γ *of 0.5-5 GeV and measurements above; several* **point** *sources, including one sloping as* $\approx E_\gamma^{-2.45}$*, outshining the wide source at GeV;* **diffuse** *background from the Milky Way.*

We superimposed the molecular clouds A, C, D of NANTEN.

An important result deserves comments and discussion:

- Wide emission could be IC with $\gamma \approx 2$: $E_e^{-\gamma} \Rightarrow E_\gamma^{-(\gamma+1)/2}$.
- As claimed in Katz & Waxman '08 based on lack of thermal X-ray emission.
- $E_\gamma^{-1.7}$ not excluded firmly, that would fit hadronic emission and very efficient acceleration.
- Important to understand the nature of the emission below 5 GeV.

We expect progresses from GeV in close future: Wait and see!

Zirakashvili-Aharonian *theoretical* model

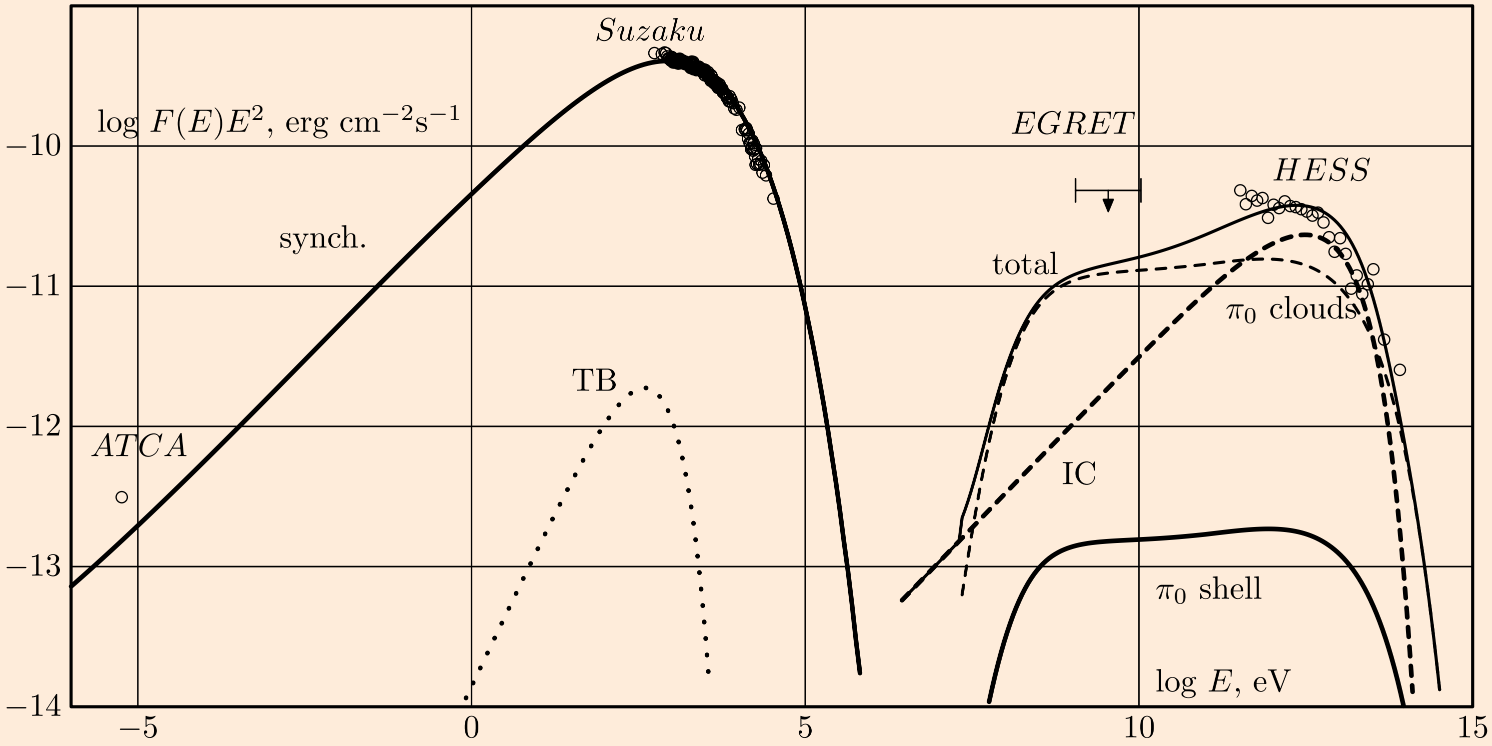


Figure 15: *For the first time, emphasis on the need to quantify hadronic and leptonic γ emission, rather than excluding one model in favor of the other one.*

Further progresses with VHE gammas?

Assume that spectrum is mixed. Beside spectrum,

We need to know arrival directions of γ's to test correlation with molecular clouds. This is especially important for γ's at 10 TeV and above, directly linked to TeV neutrinos!

What about HESS? They have about 500 events above 30 TeV, though 70% is cosmic ray background (i.e., noise), sadly.

Then... we should wait for CTA or for an equivalent km^2 class γ-ray telescope, sensitive above 10 TeV, and with good angular pointing!

7 Three *other* possible galactic sources

(1) Above the bound necessary to have more than 1 $\mu/(\text{km}^2\times\text{yr})$,

$$I_\gamma(20\ \text{TeV}) = (2-6)\times 10^{-15}/\text{cm}^2\ \text{s TeV}$$

there are 2 more young SNR, Vela Jr and Vela X, observed by HESS.

The first one, also known as RX J0852-4622, is shell type SNR, with estimated age of 660-1400 yr, distance 0.26-0.50 kpc, angular size 2°. Its slope is about 2 measured and the cutoff still uknown.

It is more intense than RX J1713.7-3946 in γ-rays:

$$I_\gamma(20\ \text{TeV}) = (1-3)\times 10^{-14}/\text{cm}^2\ \text{s TeV}$$

but 20 TeV is the last point presently measured by HESS.

(2) Star forming region of $100,000 M_\odot$ mass at 1.7 kpc from us in Cygnus. Includes sources of TeV γ-rays and possibly of ν visible from IceCUBE:

MGRO 2019+37 still unidentified. No correlation to matter excess, ARGO & Veritas do not see it. If $\phi_\gamma = 10^{-11} \times E^{-2.2} \times e^{-\sqrt{E/E_c}}$ with $E_c = 45$ TeV, up to 1.5 muon events per km^2 year above 1 TeV.

MGRO 1908+06 seen also by ARGO≈Milagro>HESS; a pulsar found by Fermi. Using $\phi_\gamma = 2 \times 10^{-11} \times E^{-2.3} \times e^{-\sqrt{E/E_c}}$ with $E_c = 30$ TeV, up to 2.5 muon events per km^2 year above 1 TeV.

MORE REMARKS:

1) MGRO 2032+41 slightly weaker in gamma.
2) Photons intensity ϕ_γ per TeV per cm^2 per sec.
3) CASA-MIA bounds at 100 TeV accounted by the cutoff.
4) Weaker theoretical case, but at least, target material is present.

(3) Possible (outstanding) diffuse sources could be *Fermi bubbles.*

Are they a reservoire of galactic cosmic rays? If so, they could be also promising neutrino sources! (Crocker, Aharonian, 2011)

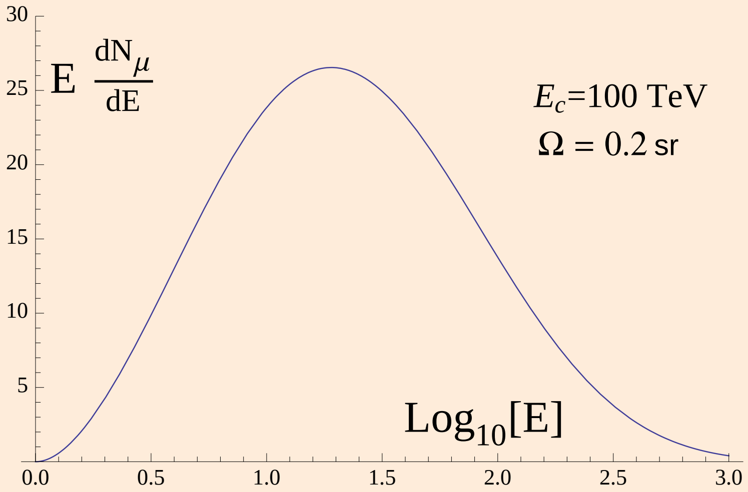


Figure 16: $\phi_\gamma(E) = \Omega\ 10^{-9} e^{-\sqrt{E/E_c}}/E^2$ *with* E_c *=100 TeV meaning a cut at 1 PeV in CR spectrum;* $\Omega = 0.2$ sr $\approx \pi \times (15°)^2$.

Corresponds to a signal of about 100 muons a year for 1 km^2 detector area.

It could be observable in Km3NET as a diffuse flux

8 Summary

The above considerations suggest that the search for γ-ray transparent, galactic sources of high energy neutrinos will be difficult.

- **Only few TeV γ-bright sources known – individual objects matter.**
- **Neat expectations only assuming hadronic gamma-ray emission.**
- **Even if all TeV γ are hadronic, strong neutrino signals are not expected.**

Multiwavelength observations and theory help to progress.

Sub degree pointing with gamma is important to further test SNR+MC.

RXJ1713 demonstrates at least that we can proceed toward expectations.

Promising galactic neutrino sources tied to γ's above 10 TeV.

Many thanks for the attention!

9 This talk is based...

The main reference is:

On the detectability of high-energy galactic neutrino sources
FV, Felix Aharonian, Narek Sahakyan.
Published in **Astropart.Phys. 34 (2011) 778**
e-Print: **arXiv:1101.4842 [astro-ph.HE]**

Expectations of Sect.6 are taken from:

How precisely neutrino emission from supernova remnants can be constrained by gamma ray observations?
Francesco Lorenzo Villante, FV.
Published in **Phys.Rev. D78 (2008) 103007**
e-Print: **arXiv:0807.4151 [astro-ph]**

+ experimental results, papers quoted in the previous 2, and many precious discussions with colleagues & collaborators.

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