Expectations for Galactic Neutrino Sources

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Generic and specific expectations for the search for neutrinos above TeV are examined. The motivations for the search of galactic sources and, in particular, for a specific class of supernova remnants are recalled. The status of the expectations for one of these SNR, RX J1713.7-3946, is reviewed. The connections with gamma ray astronomy are emphasized.

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

1 Expectations?

Is this really needed?

Maybe not, since surprises are the rule for new astronomies: From Pulsars to most recent Fermi bubbles or Crab variability ... but we need people as Bruno Rossi ...

Is this useful?

Good predictions are precious for experiments! But also reasonable expectations eventually contradicted are not useless ... they mark where we are and allow progress.

Which precedents?

Solar neutrinos, predictions with errorbars since the 60's .... see Bahcall's book.

Supernova neutrinos, some expectations before SN1987A ... but, still, *work in progress.*

TeV γ-rays from Crab foreseen in 1965 ... detection method since 1985, detection 1989.

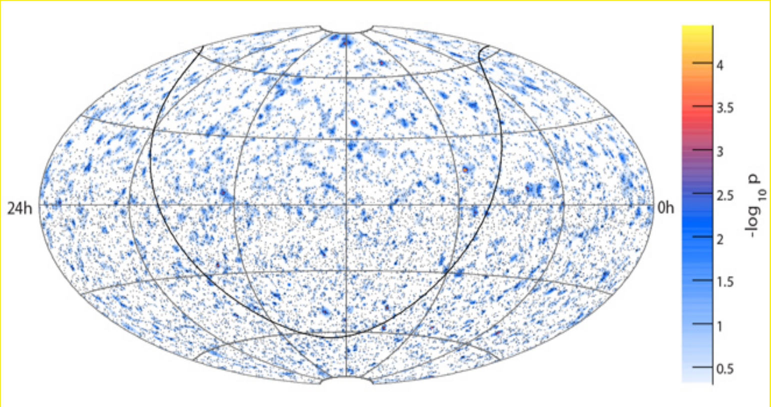
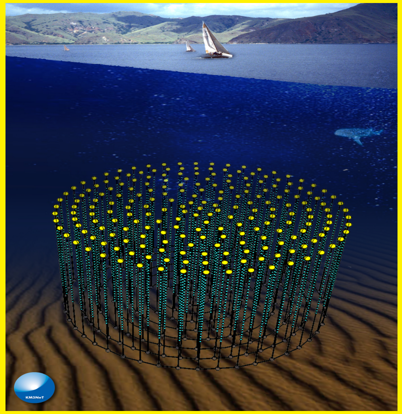


Figure 1: *IceCUBE is ready and producing physics results! Km3NET detector is being finalized in size and location.*



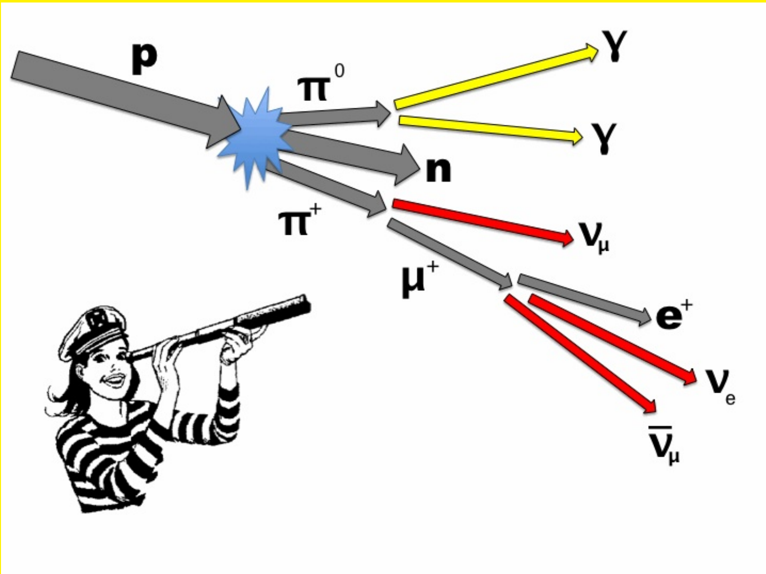


Figure 2: *The standard astrophysical point of view is taken here: The observation of high-energy neutrinos is very difficult but perhaps possible and would amount to an unambiguous signal of cosmic ray collisions; hopefully, those in their source.*

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

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

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; 3 flavor oscillations included FV 06; Villante FV '08.

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

After cosmic distances, the simplest regime–Pontecorvo formula–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 or antineutrinos becomes:

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

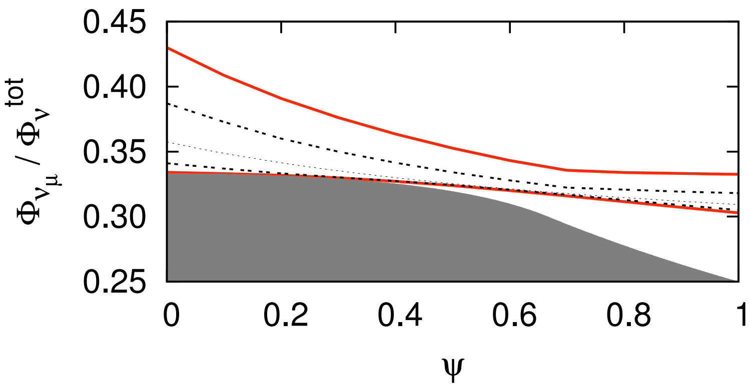


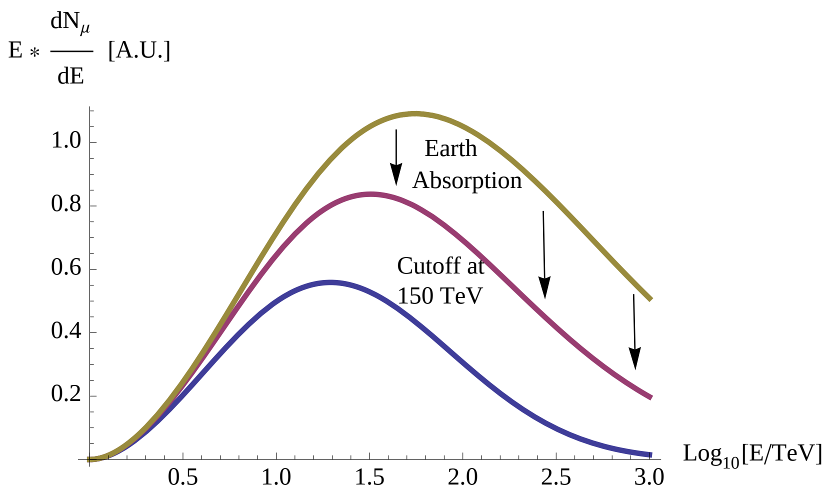
Figure 3: *Value $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu$ as a function of $\psi = \Phi^0_{\nu_e}/\Phi^0_{\nu_\mu}$ (gray region forbidden). The uncertainty is generally small; when $\psi = 0.5$, $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu = 0.33 - 0.35$ at 2σ.*

… 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, as for RXJ1317 seen from Antares (purple); then using a spectrum behaving as $E^{-2}e^{-\sqrt{E/150\ \text{TeV}}}$ (blue), i.e., with primaries cutoffed at ∼3 PeV.*



Recall that when $E \sim 10$ TeV, $s \sim 2m_nE \sim Q^2 > M_W^2$, 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.

1.1 Synergy of gamma and neutrino search

We characterize the potential neutrino sources, using the fact that π^0 and $\pi^\pm$ come together, by mean of their hadronic γ-rays, distributed as $I_\gamma \propto E_\gamma^{-\alpha} \times e^{-\sqrt{E_\gamma/E_c}}$, with $\alpha = 1.8 - 2.2$ and $E_c = 1$ TeV-1 PeV.

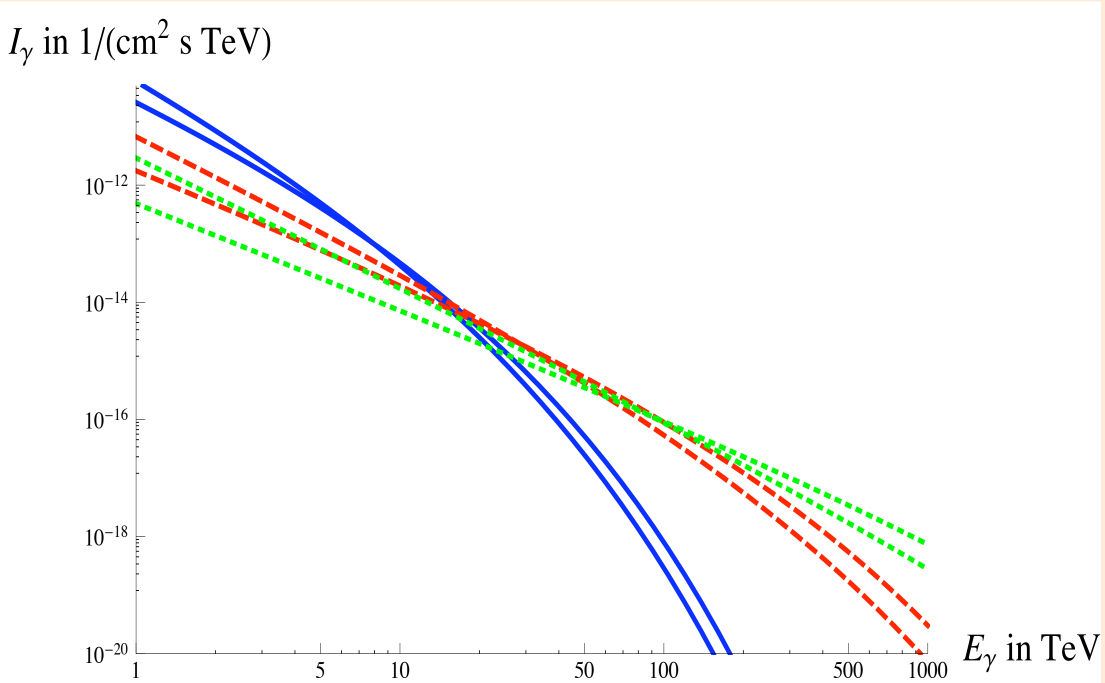


Figure 5: *γ-ray intensities corresponding to a signal of 1 muon/km^{2}yr above 1 TeV, evaluated assuming that the sources are transparent to their gamma rays.*

Intensities are similar between 10 to 50 TeV.

Is it possible to detect these γ-ray fluxes? Note that:

They all lay in a narrow range:

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

If we want 100-200 γ's in a reasonable time, we need large area:

$$\text{exposure} = L^2 \times T = (5/3\ \text{km})^2 \times 10\ \text{h}$$

E.g., a square network of 100 Cherenkov telescopes, one each 170 m; or a km^2 dedicated EAS array.

These fluxes should be within the reach of high energy facility of CTA, or, of an *ad hoc* instrument built to support $\overset{(-)}{\nu}_\mu$ search.

Such an apparatus should be much cheaper than nu telescopes; it could be a good investment also for nu community.

To be sure, just remind that...

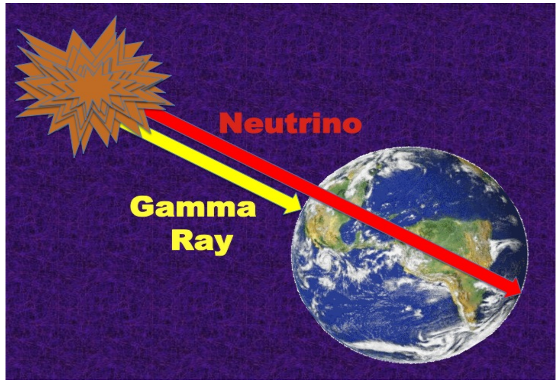


Figure 6: *Neutrino telescopes look downward! Due to atmospheric μ background, ν_μ from cosmic sources are preferentially detected from below* *(Zheleznykh '58)*

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 $f_{\nu_\mu} = 1 - f_\gamma$.

1.2 South & North

Popular arguments for the search of high energy galactic neutrinos:

- Most of cosmic rays with energies as large as several PeV, the knee seen in EAS arrays, are supposedly of galactic origin.
- We should/could search for galactic point sources using high energy neutrinos from hadronic collisions.
- We can presume that neutrino sources are distributed similarly to the matter of the Milky Way.

On these pretty general bases, some conclusion can already be drawn.

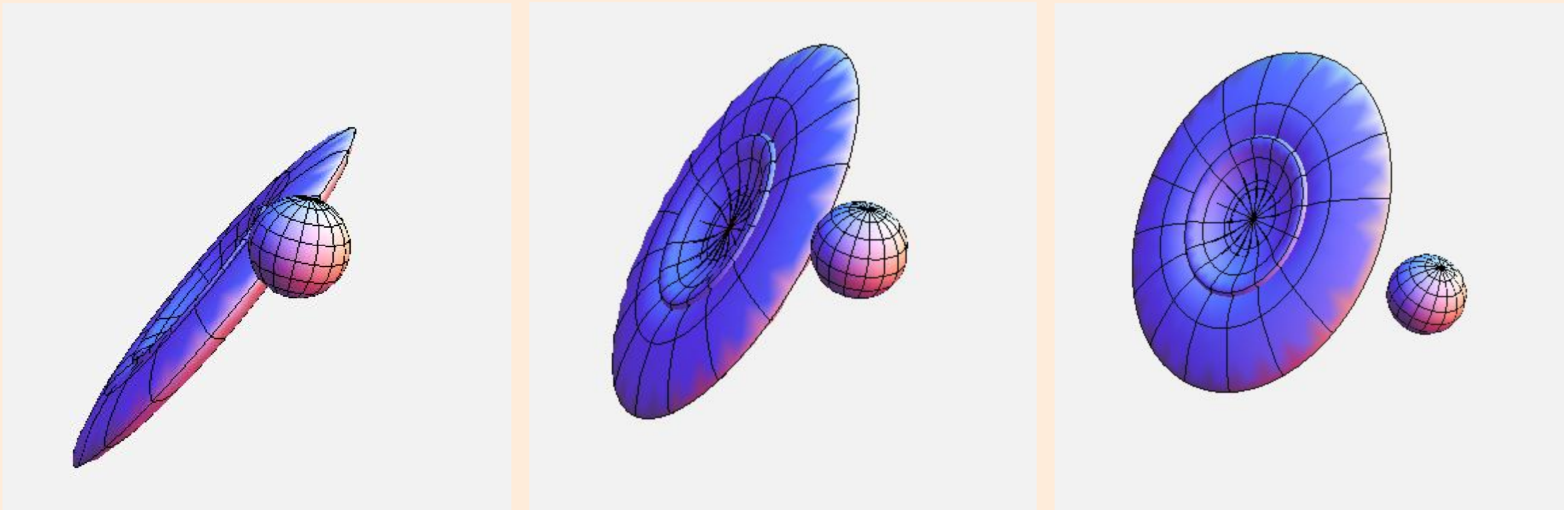
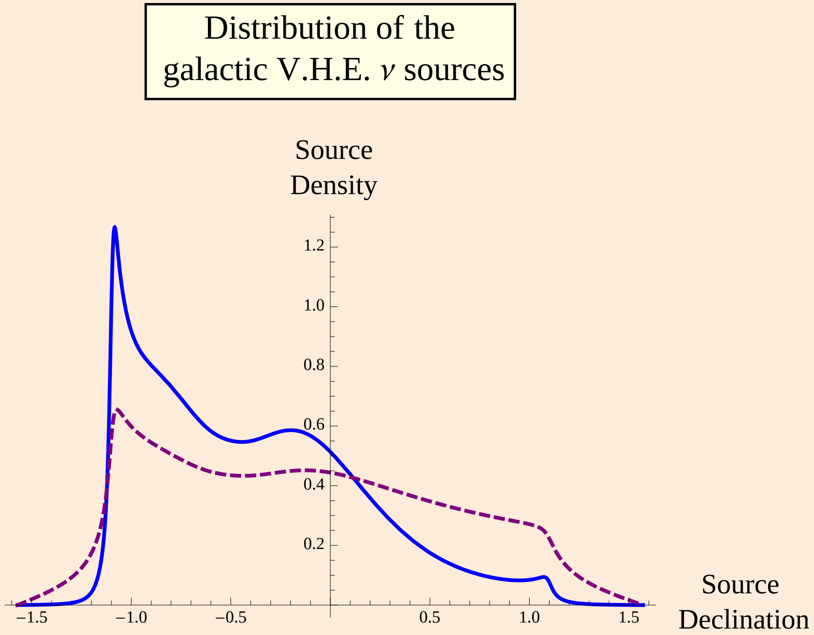
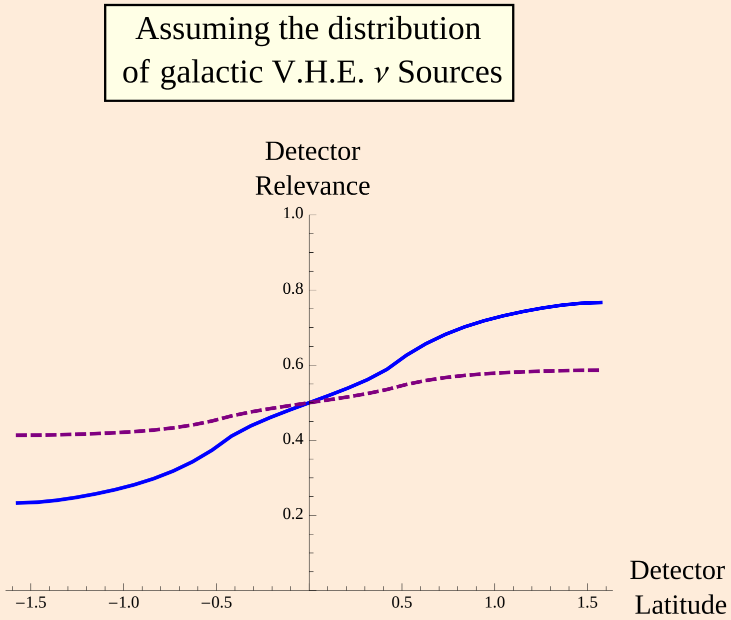


Figure 7: *Relative orientation of Earth and Milky Way.*

Thus, 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 $1/r^2$.

1.3 Doubts and warnings against vague arguments

If there are only few intense neutrino sources–the closest? or special sources?– fluctuations are essential; average matter distribution could be misleading.

Gamma transparency: is it a reliable hypothesis?

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?

Search for γ above 10 TeV helps ν astronomy, 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?

2 Firmer expectations

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

1. *Fermi* *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:

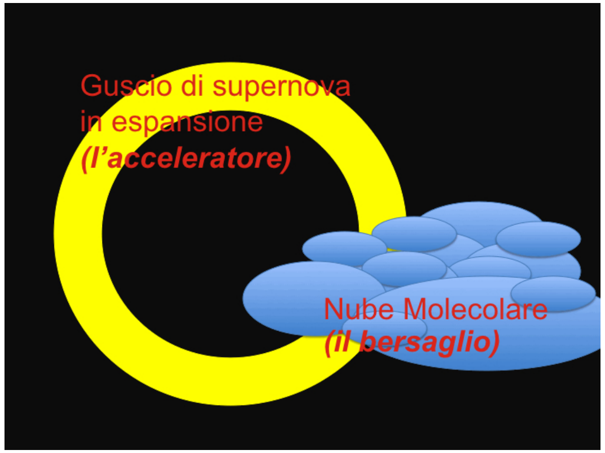


Figure 8: *Sketch of the association between a shell-type SNR and a molecular cloud. The first acts as a cosmic ray accelerator the second as a target (in Italian, "l'acceleratore" and "il bersaglio"). In particle physics parlance, it is a classical "beam dump" configuration.*

2.1 SNR+MC paradigm, pros and cons

⋆ **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...

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

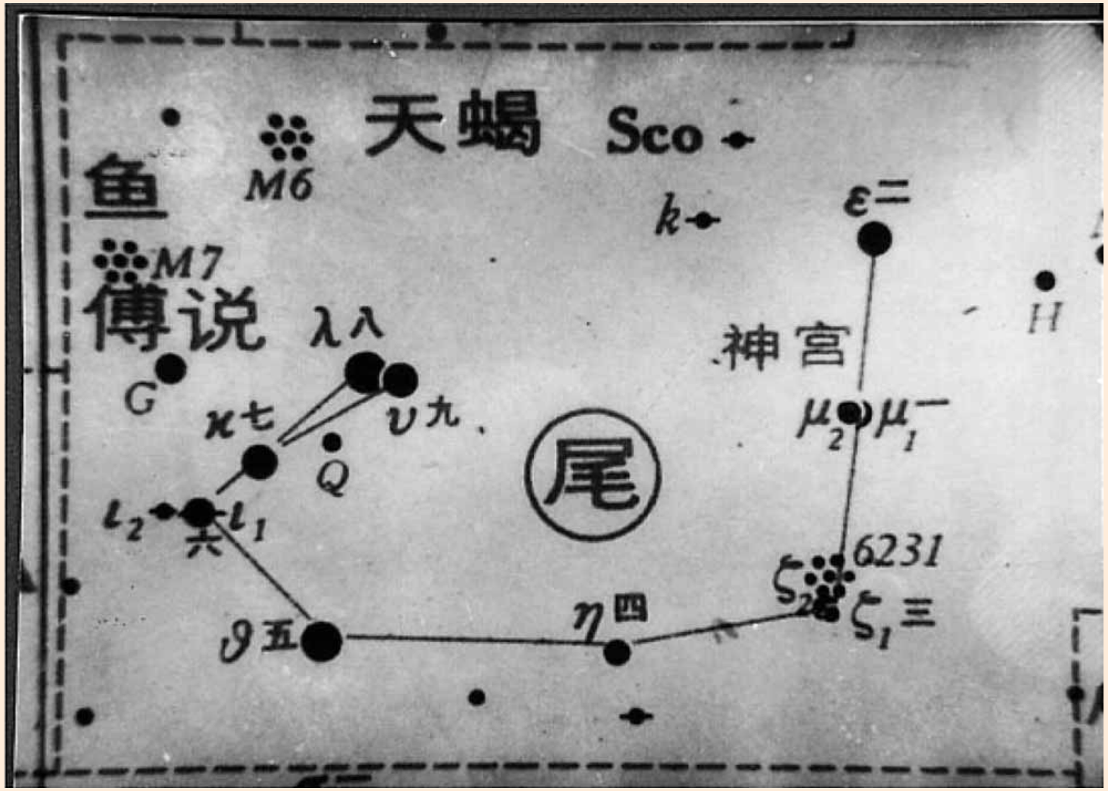
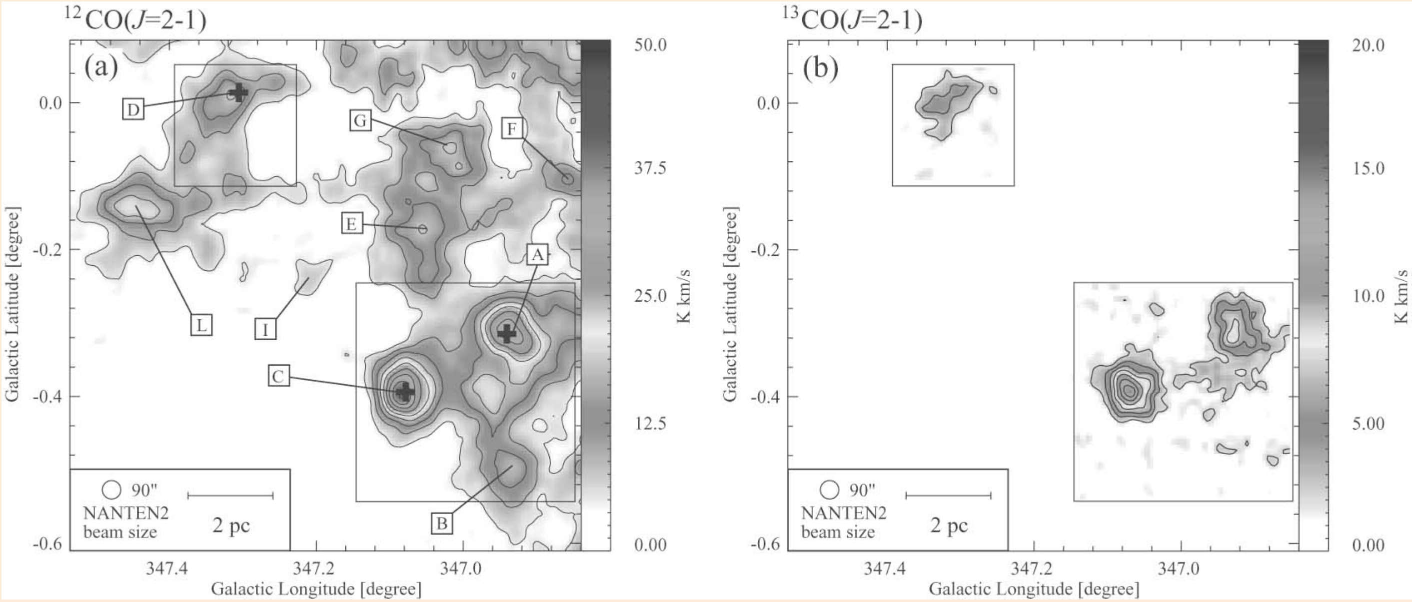


Figure 9: *Wang et al.: 393AD guest star=progenitor of RX J1713.7-3946.*

3.1 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.

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

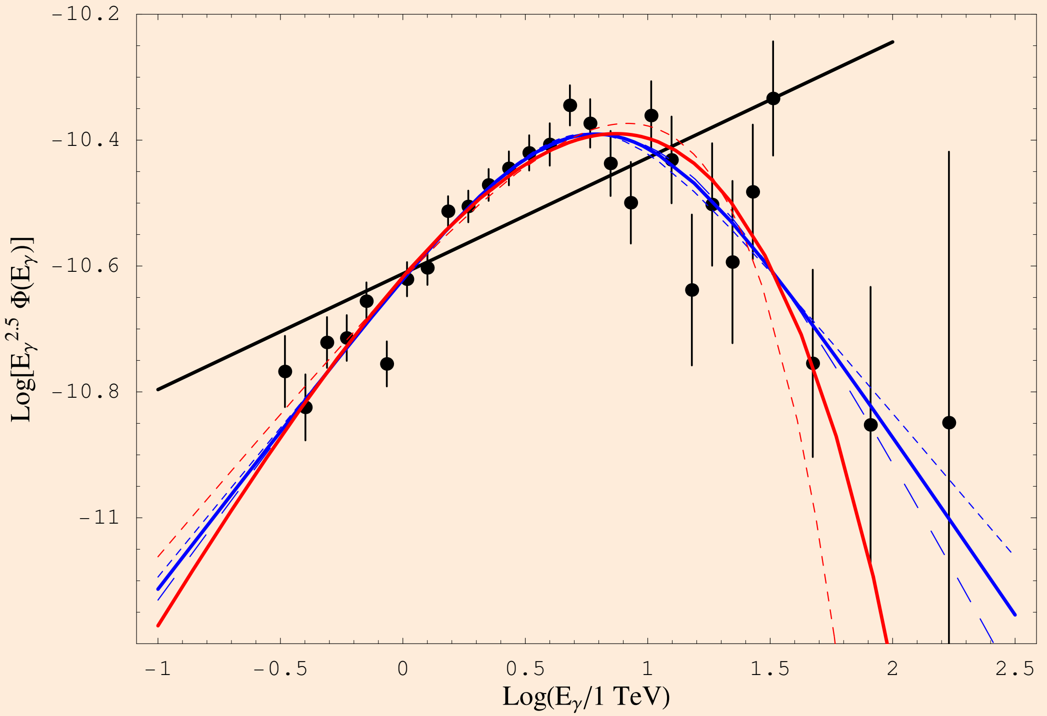


Figure 11: *Thanks to HESS, γ rays up to 100 TeV are measured. Spectrum is well described by a broken-power-law or by a modified-exponential-cut.*

About 500 events above 30 TeV, though 70% is background, sadly.

The errors increase at high energies, but the flux is small there.

3.3 Upper bound on neutrino *is* precise

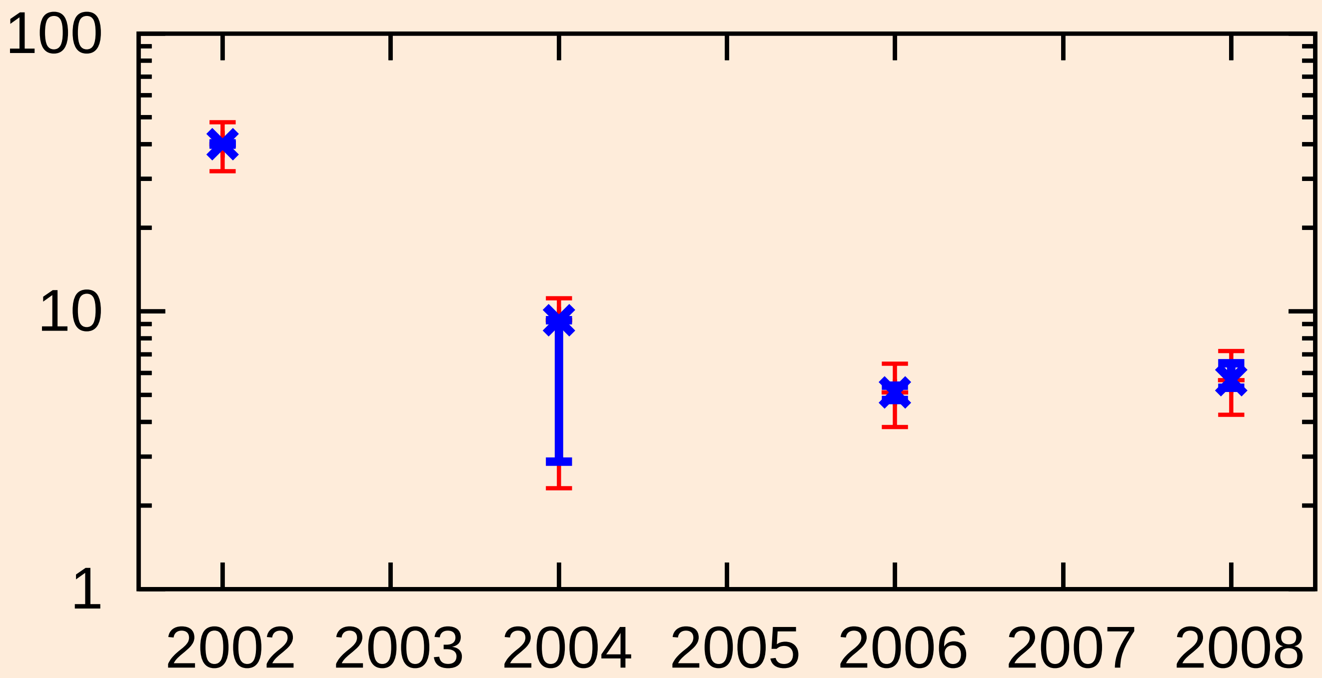


Figure 12: *Muon per km^2 per year above 50 GeV expected from RX J1713.7-3946. In blue, the error deduced from 4 publications, in red, 20% systematic error. Reason of change: 1 → 2: oscillations, absorption, livetime. 2 → 3: cutoffed HESS spectrum. 3 → 4: latest theoretical and observational improvements.*

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):

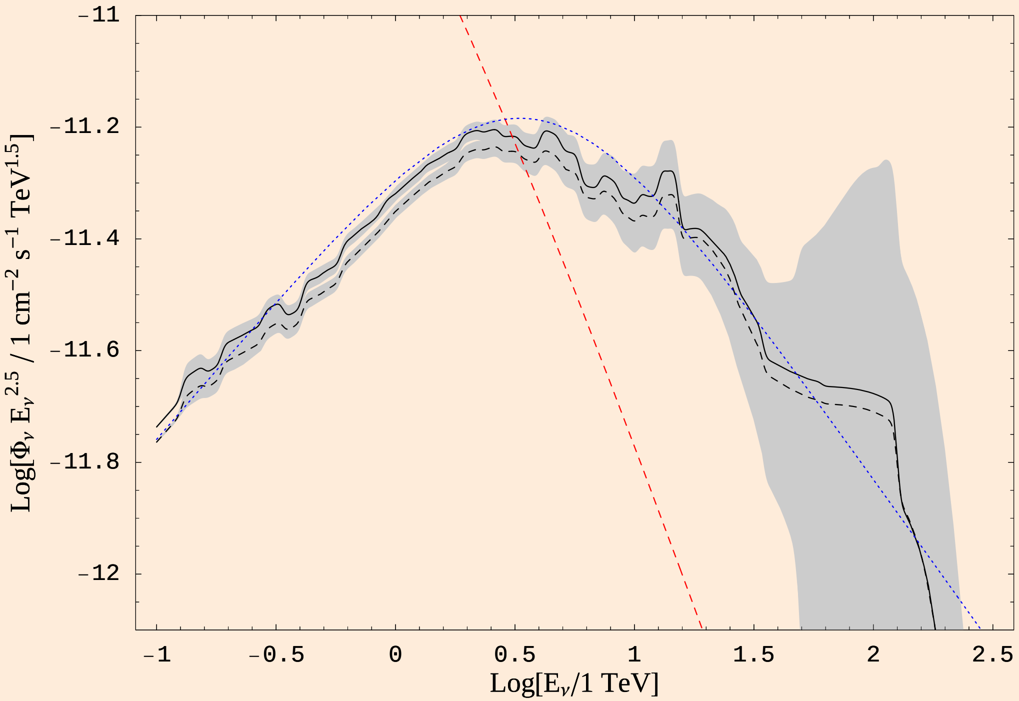


Figure 13: *ν_μ and $\bar{\nu}_\mu$ fluxes deduced from latest HESS data, assuming a hadronic γ-ray emission (Villante & FV '08). The corresponding number of events above 1 TeV is:* $I_{\mu+\bar{\mu}} = 2.4 \pm 0.3 \pm 0.5/km^2\ yr$

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.*

3.4 News from *GeV* region

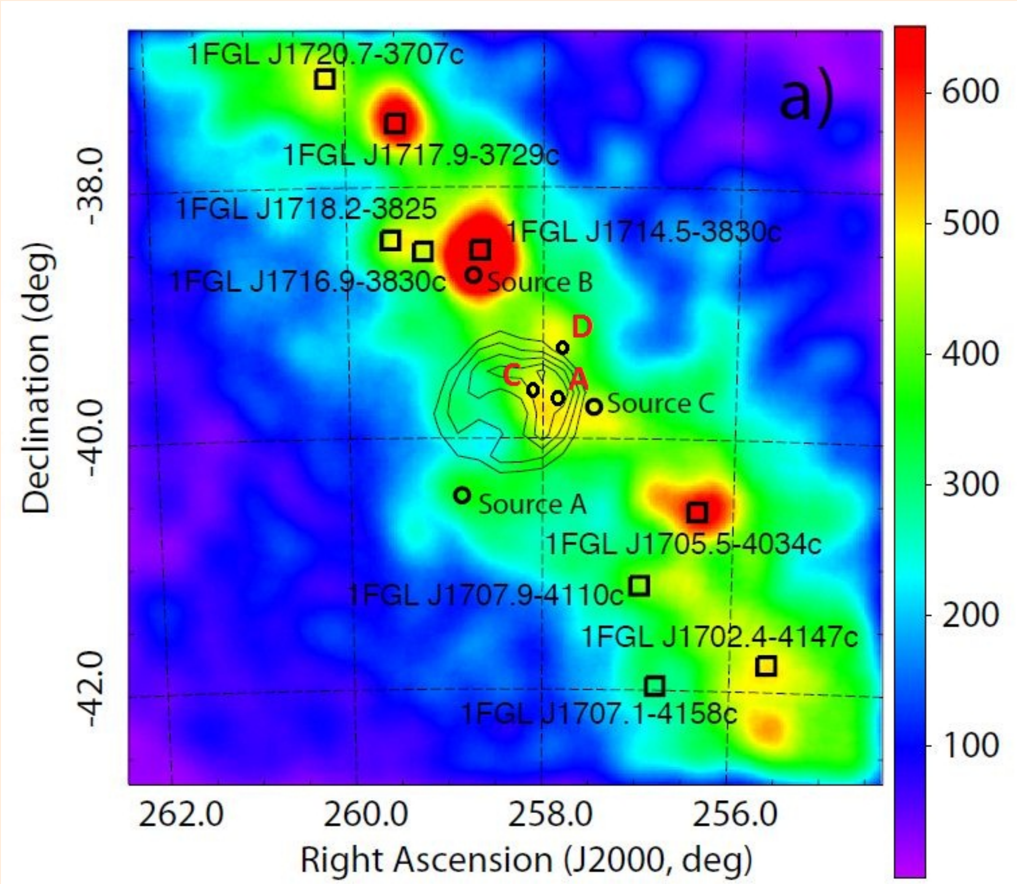


Figure 14: *Counts* > 3 GeV *given by Fermi collaboration, claiming: a* **wide** *source in SNR location with spectrum* $\approx E_\gamma^{-1.5}$ *from upper bound on* γ *of 0.5-5 GeV and measurements above; several* **point** *sources, including one sloping as* $\approx E_\gamma^{-2.45}$*, outshining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

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

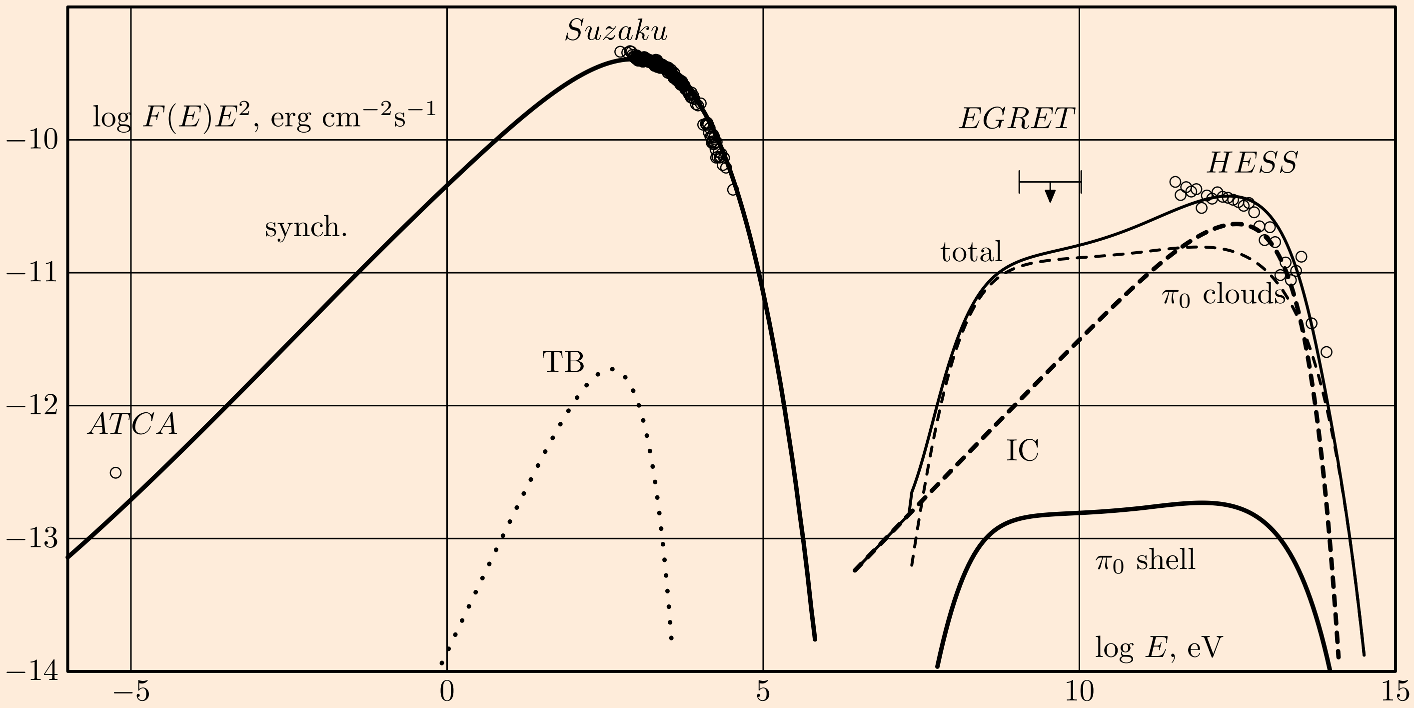
An important result deserves comments and discussion:

- *Wide emission could be IC* $E_e^{-\gamma} \Rightarrow E_\gamma^{-(\gamma+1)/2}$ *with* $\gamma \approx 2$ *as for 'canonical' leptonic emission.*
- *Dominance of IC claimed in Katz & Waxman 2008 on the basis of absence of thermal X-ray emission.*
- *But* $E_\gamma^{-1.7}$ *is not excluded firmly and this could indicate hadronic emission and a very efficient acceleration coefficient.*
- *Moreover, it would be important to understand the nature of the unidentified point sources and of the emission below 5 GeV.*

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

3.5 Zirakashvili Aharonian *theoretical* model

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



Beside spectrum, we'd need **pointing** at 10-100 GeV to test the correlation with molecular clouds; this is even more important at 10 TeV and above!

4 *Other* possible galactic sources

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 ON GAMMAS:

1) MGRO 2032+41 slightly weaker.
2) Photons intensity ϕ_γ per TeV per cm^2 per sec.
3) CASA-MIA bounds at 100 TeV accounted by the cutoff.

4.1 A possible (outstanding) diffuse source

Are **Fermi bubbles** a reservoir of galactic cosmic rays? If so, they are also promising neutrino sources! (Crocker, Aharonian, 2011)

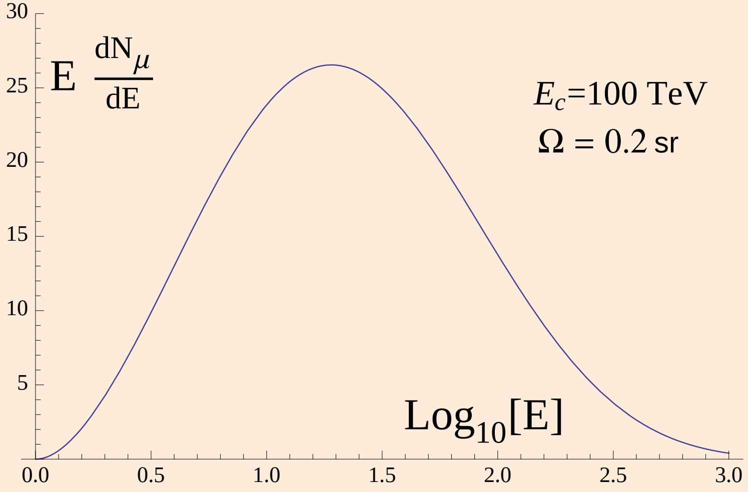


Figure 16: $\phi_\gamma(E) = \Omega\ 10^{-9} e^{-\sqrt{E/E_c}}/E^2$ *with* E_c *=100 TeV meaning a cut at 1 PeV in CR spectrum;* $\Omega = 0.2\ \mathsf{sr} \approx \pi \times (15^\circ)^2$.

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

5 Summary

The above considerations suggest that the search for (a class of) galactic sources of high energy neutrinos will be difficult and not devoid from risks.

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

Multiwavelength observations and theory are apparently helping us to separate hadronic from leptonic emissions.

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!

6 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. (But, as usual, errors are mine.)

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