High Energy Neutrino Astronomy: Highlights

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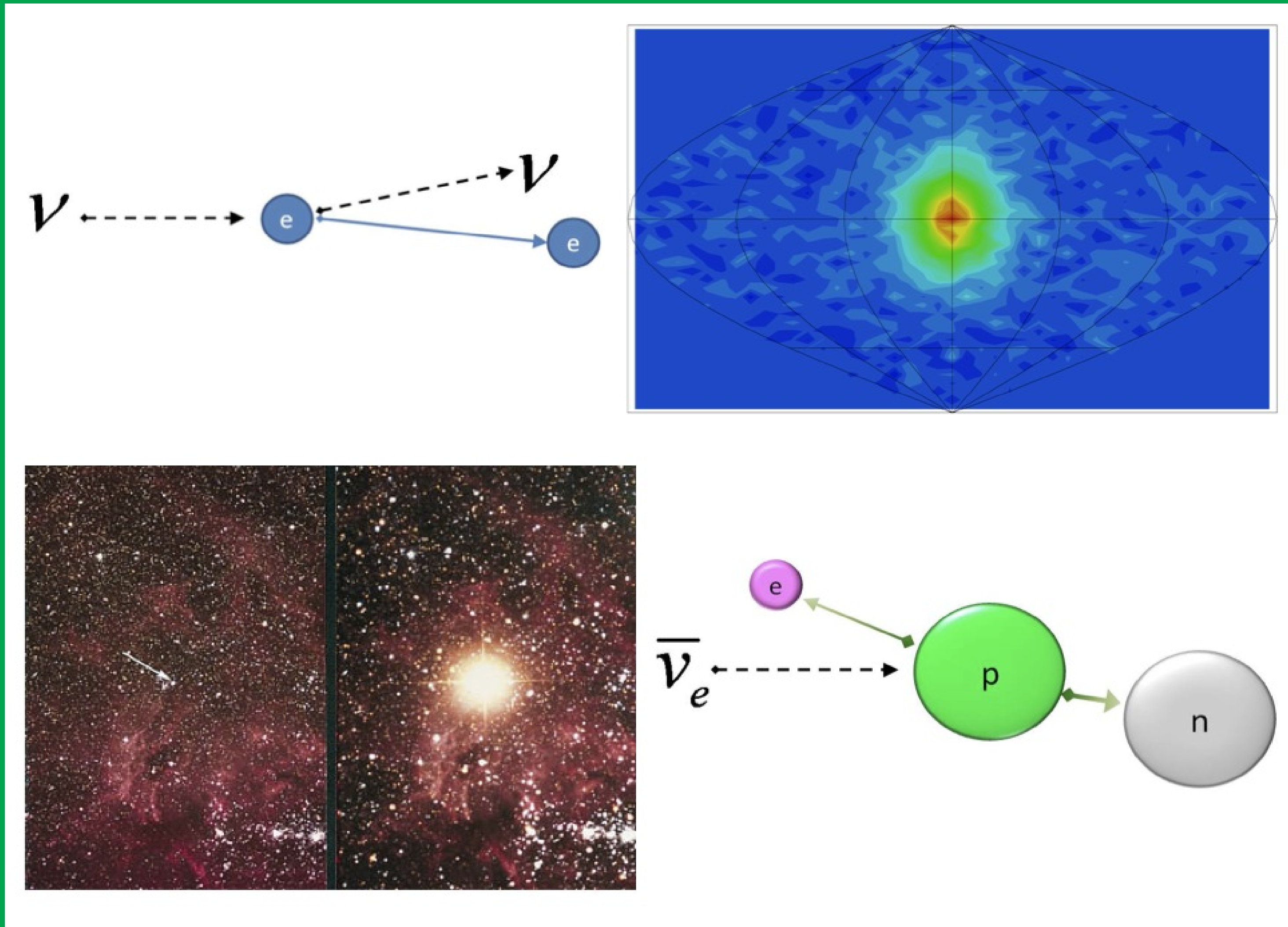
The detection of cosmic neutrinos with energy above TeV is the dream of the modern neutrino astronomy. The first results of IceCUBE have significantly probed the high energy neutrino sky. This has began an important exploration, especially of extra-galactic sources, making more clear the goals but also revealing the difficulties of such an enterprise. We review the main sources of high-energy neutrinos, emphasizing the interest in studying the galactic sources. We stress the importance of progressing further with complementary observations, and eventually, with theory.

NEUTRINO ASTRONOMY

A recognized discipline – Nobel Prize 2002

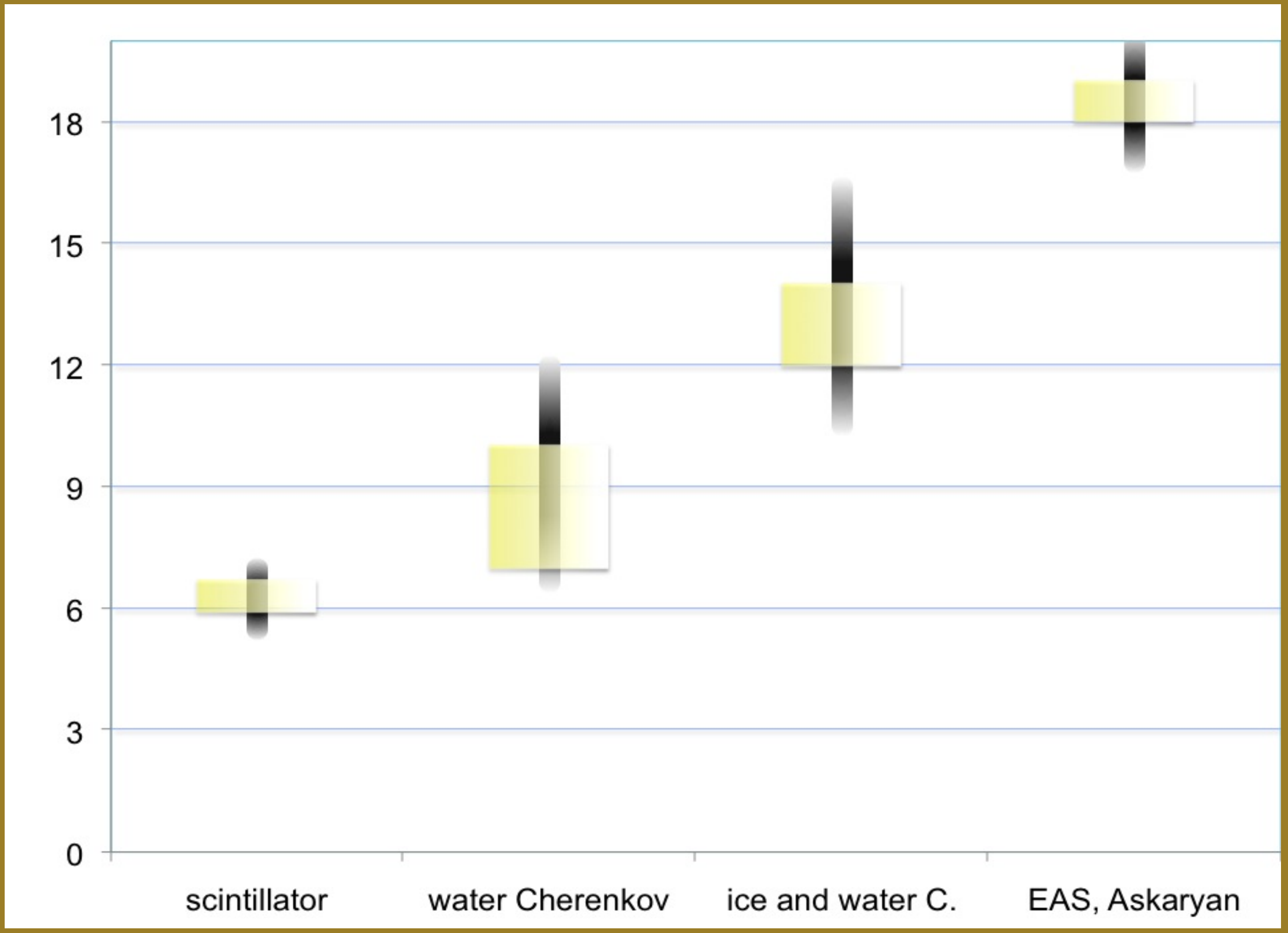


The investigations concerned astrophysical processes of the ‘classical’ nuclear regime $E < 100$ MeV, therefore connected with relatively low energy neutrinos.

They led us to various achievements, also on basic neutrino properties, and have still important possibilites to progress, e.g., with geoneutrinos and solar (CNO) neutrinos, and even more with supernova neutrinos.

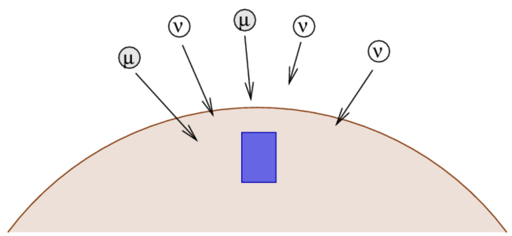
The obtained knowledge and the increased confidence motivate us to continue, widening scope and field of investigation.

We are now monitoring a huge range of energies!

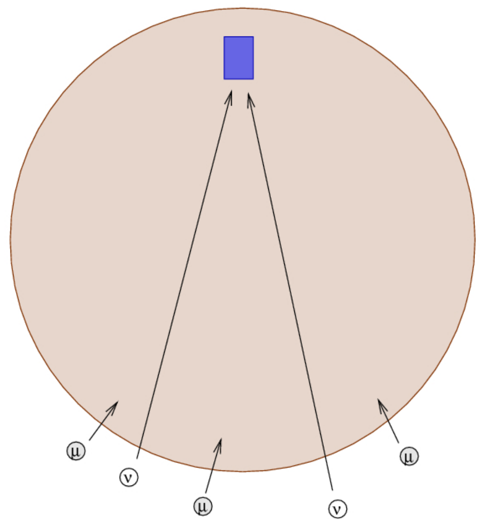


HIGH ENERGY NEUTRINOS

High energy neutrinos telescopes – the beginning



Induced μ's are the main practical way to cope with atmospheric μ's and probe high energy neutrinos, as understood by Markov end of 50's.



The muon range, dictated by e.m. interactions

$$R(E_\mu, E_{th}) \approx \textbf{2.5 km w.e.} \times \log \left[\frac{1 + \frac{E_\mu}{0.5 \text{ TeV}}}{1 + \frac{E_{th}}{0.5 \text{ TeV}}} \right]$$

already indicates the size of ~ 1 km of ideal HE neutrino detectors.

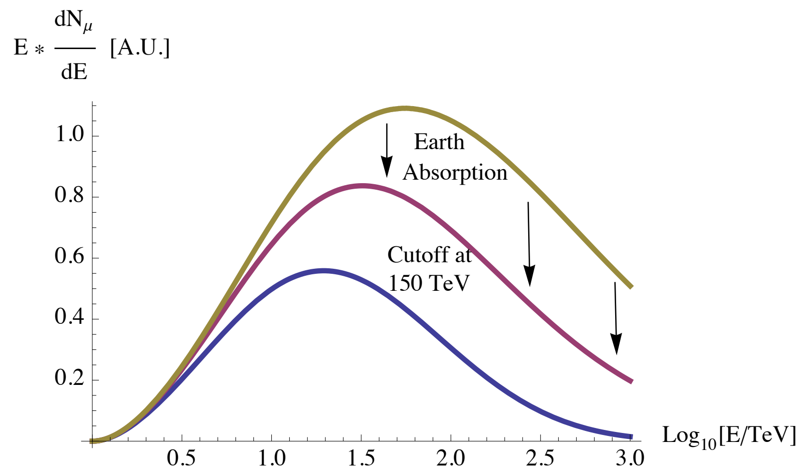
The most relevant energy range

1. $E_{th} > 1$ TeV: threshold to overcome atmospheric bkgr [e.g., Lipari 06].
2. $E_\nu \sim 10$ TeV: where $\sigma_{\nu N}$ starts to grow less $[2 m_N E_\nu \sim M_W^2]$.
3. $E_\gamma^{max}/2 \sim 10$ TeV: typical extent of observed γ energies.
4. $E_p^{knee} x_{p\to\nu} \sim 150$ TeV: cutoff of Galactic CR $[x_{p\to\nu} \sim 1/20]$.
5. few 100 TeV: cut due to Earth absorption $[R_\oplus \sim m_N/(\rho_\oplus \sigma_{\nu N})]$.

To be taken in mind for the expected main signal induced μ, with some fine prints: few γ sources observed at higher energies; contained events or Earth skimming ones may extend in energies; same for extragalactic sources; etc.

Illustration of the impact of the high-energy cuts

Distribution of ν_μ leading to muons, assuming E^{-2} primary spectrum (sienna); then, including Earth absorption, for a source at $\delta = -39°$ 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.



The shape of the spectrum is based on the assumption that the primaries have an exponential cutoff (Ke'lner 06; Kappes 07)

The interest in searching for cosmic sources of high energy neutrinos has also a long history–beginning, again, in Markov's group.

In the thesis of Zheleznykh (1958) we read,

1. from new star's shell as Crab *"the flux could equal the atmospheric one"*
2. from old CR population as GC *"could be large if attenuation is essential"*
3. *"γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos"*
4. *"worth searching especially if HE γ beyond atmosphere were found"*

These points maintain their validity: note, in particular, the outlined link with high energy γ rays and with (galactic) cosmic rays.

HE neutrino sources

Many cases are possible, in particular,

1. Galactic / Extragalactic.
2. Continuous / sporadic (bursting).
3. Point source / diffuse.
4. Transparent to γ rays / opaque.
5. Transparent to cosmic rays / hidden accelerator.
6. Individual / generic.

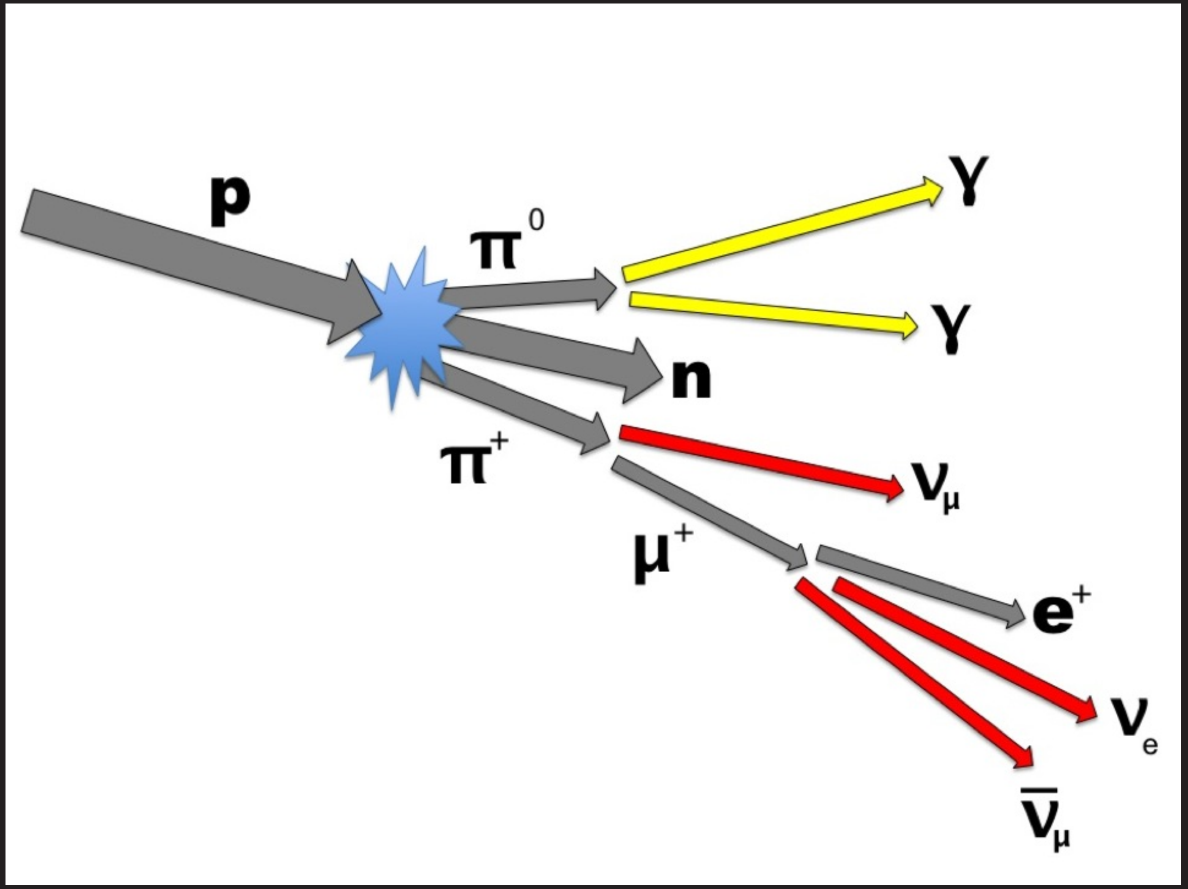
Some of these cases are better understood and theoretically motivated than other ones.

Several interesting possibilities from astronomy

(Young) supernova remnants.
Dense molecular clouds illuminated by CR.
Star forming regions.
Compact stars.
Microquasars.
Gamma rays bursts.
Active galactic nuclei (jet, core and/or halo).
Cosmogenic neutrinos.
Galactic center.
RX J1713.7-3946, Vela Jr, Vela X.
CEN-A.
The next nearest GRB.
....

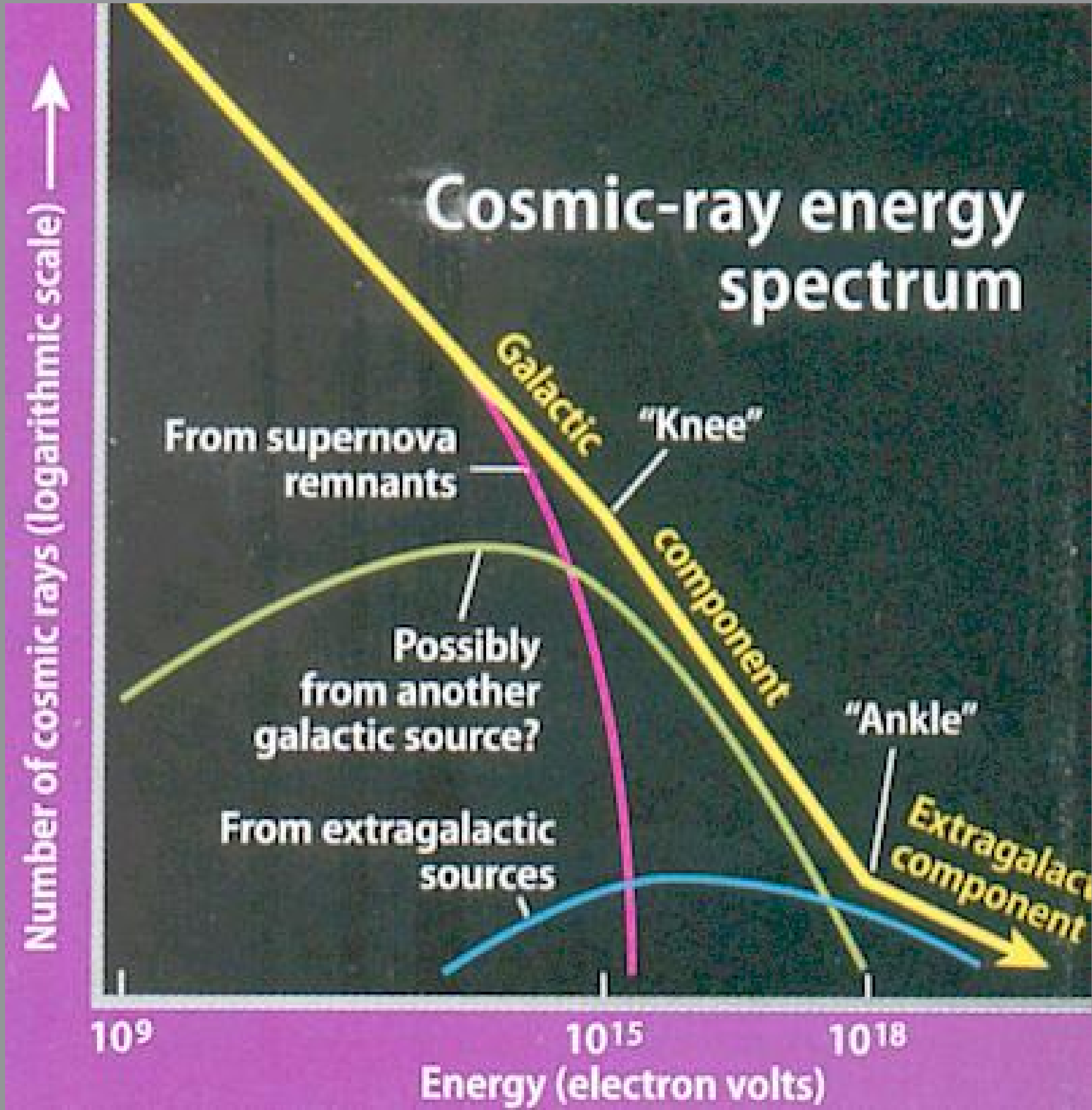
(plus particle physics candidates, such as dark matter annihilation, neutrinos from mirror world, topological defects, superheavy decaying particles, *etc)*

We need hadronic collisions

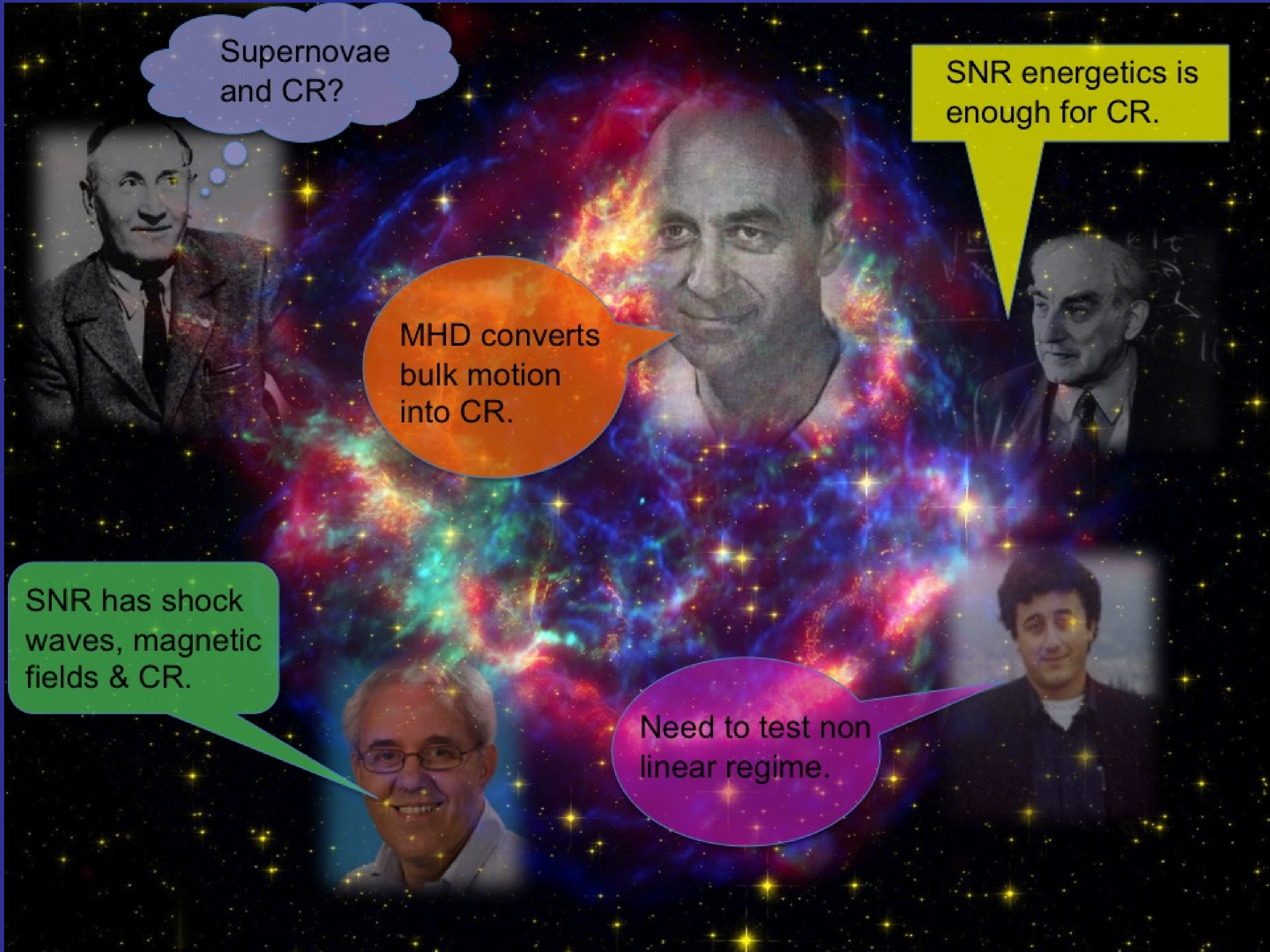


As recalled, one can imagine hidden (coconed, shrouded, dark, opaque, ...) CR sources; in this way, however, motivations and predictivity usually weaken.

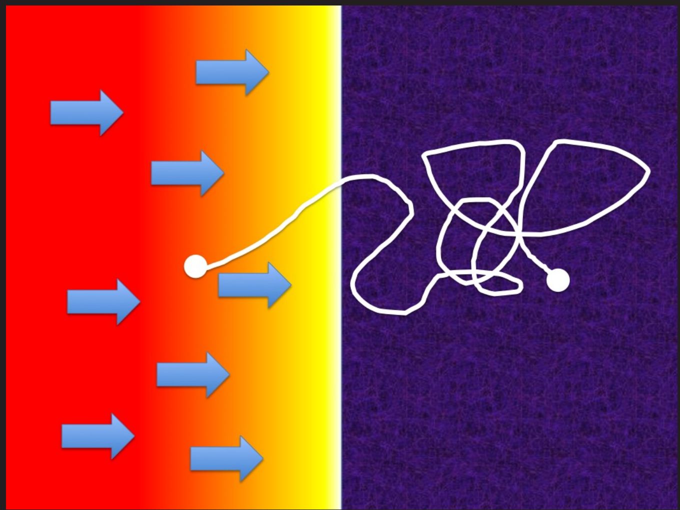
SOME FACTS
ON COSMIC RAYS

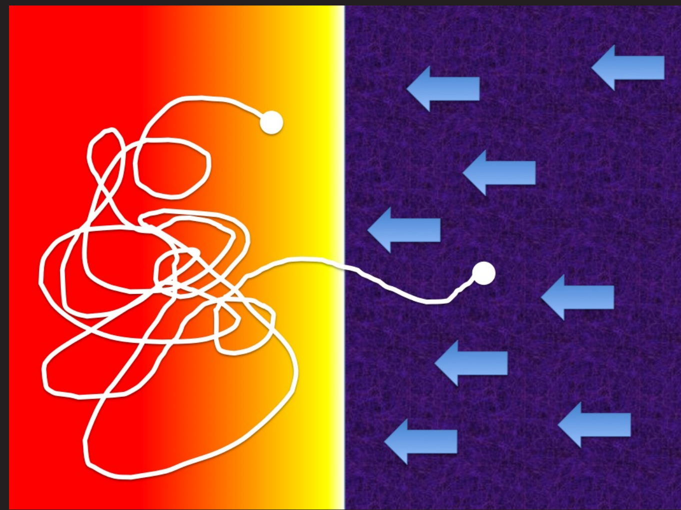


Cosmic-ray energy spectrum
Galactic component
"Knee"
From supernova remnants
Possibly from another galactic source?
"Ankle"
From extragalactic sources
Extragalact component
Number of cosmic rays (logarithmic scale)
10^9
10^15
10^18
Energy (electron volts)


Supernovae
and CR?
SNR energetics is
enough for CR.
MHD converts
bulk motion
into CR.
SNR has shock
waves, magnetic
fields & CR.
Need to test non
linear regime.

High energy particles gain kinetic energy from collective motions as they cross the shock front. Also, they amplify the magnetic field that modify their trajectories, making the problem non-linear–and thus difficult.





A charged particle, with given energy, wanders in the interstellar space due to irregular magnetic fields. Then, it enters a shocked region (left). In the rest frame of the shock, its energy is larger. The particle wanders again, and then it exits from the shocked region (right). In the rest frame, its energy is larger *(etc)*.

Supernova remnants and cosmic rays

The young SNR are the accelerators of the galactic CR

$$\frac{V_{\mathsf{CR}}\rho_{\mathsf{CR}}}{\tau_{\mathsf{CR}}} = 0.1 \times \frac{\mathcal{E}_{\mathsf{SN}}}{T_{\mathsf{SN}}}$$

I.e., the losses of CR from the Milky Way are compensated ($\tau_{\mathsf{CR}} = 50$ Myr and $V_{\mathsf{CR}} = \pi R^2 H$ with $R = 15$ kpc, $H = 5$ kpc) if each SN injects 1 foe of kinetic energy every $T_{\mathsf{SN}} = 30$ yr, and 10% of them become CR.

It agrees with Fermi-LAT observations of SNR W44 and W28–that, however, being relatively old, have lost the highest energy CR already.

Still we need a full non linear theory of SNR and CR, and to know the the extent of (and in particular the maximum) CR energies.

Anything similar for UHECR?

The observed energy above 1 EeV, $\rho_{\text{UHECR}} = 3 \times 10^{-19} \frac{\text{erg}}{\text{cm}^3}$, gives

$$R = \frac{\rho_{\text{UHECR}}}{T_H} = 9 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{ yr}}$$

with $T_H = 10$ billion years. This can be saturated by

$$\frac{900 \text{ GRB}}{\text{Gpc}^3 \text{ yr}} = \frac{R}{10^{51} \text{ erg}} \quad \textbf{.OR.} \quad \frac{150 \text{ AGN}}{\text{Gpc}^3} = \frac{R}{2 \times 10^{44} \text{ erg/s}}$$

The denominators are set to the typical e.m. energy outputs.

In order to explain UHECR, we need a reasonable number of hypothetical accelerators and an efficient acceleration mechanism.

THE NEUTRINO SKY TODAY

The neutrino sky is 'cloudy': At the moment we do not see anything else than atmospheric neutrinos – that should be very well understood for the next steps anyway, and that are all but uninteresting (e.g., large scale anisotropies revealed; charm contribution still searched).

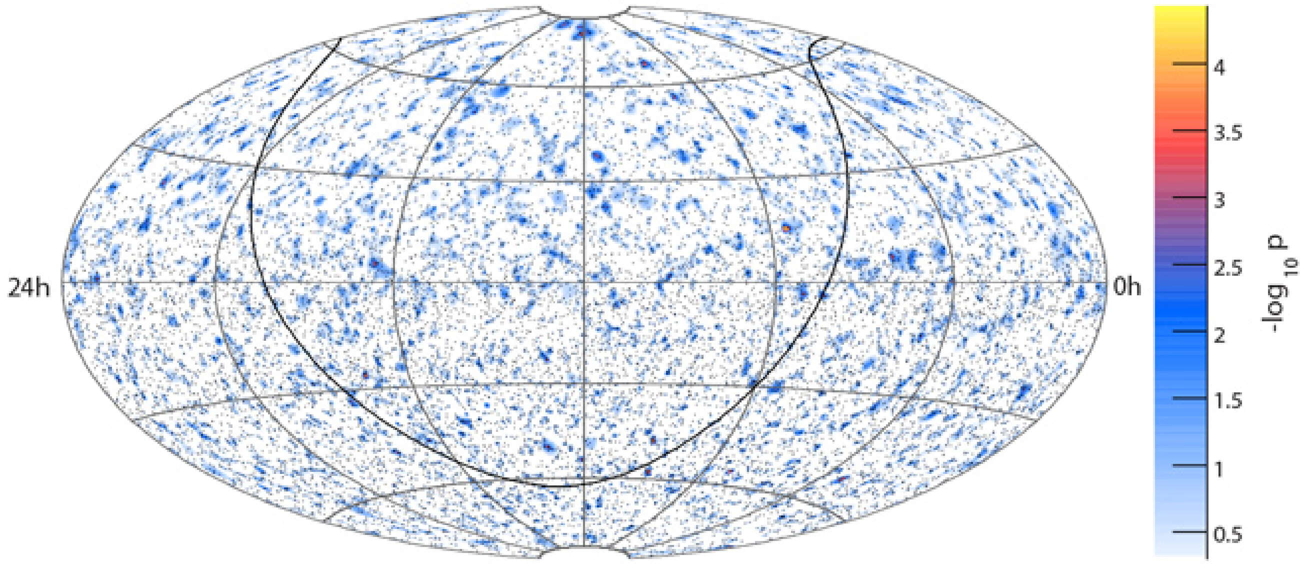


Figure 1: *A significance skymap of IceCube (from high energy muon events) in Galactic coordinates, assuming that the spectra of the neutrino sources is E^{-2}.*

Waxman-Bahcall bound

The Waxman-Bahcall bound assesses that the UHECR observed energy should be more than the one in secondary particles. In essence, it amounts to the the statement that the accelerators are not hidden.

Also calculations are uncomplicated

differential rate of UHECR production=`1E44` erg/Mpc^3 yr $=R$
energy density=$R \times T_H$=`1E54` erg/Mpc^3 =`6E56` GeV/Mpc^3 $=\rho$
flux $= \rho \times c/4\pi =$`.5E42` GeV/Mpc^2 s=`.5E-7` GeV/cm^2 s=F_p
bound=$F_p/4$=`1.2E-8` GeV/cm^2 s $> F_\nu$

HP-1: slope $\alpha = 2$ at production (Fermi acceleration)
HP-2: universal accelerators.
HP-3: observed UHECR=average UHECR;
HP-4: losses=gains.

WB bound, contd

Published bound and expected GRB signal (losses are calculable, $\sim 15\%$):

$$E^2 dN/dE < 2 \times 10^{-8} \mathrm{GeV/cm^2 s\ sr}$$

$$E^2 dN/dE_{\mathrm{GRB}} \sim 0.3 \times 10^{-8} \mathrm{GeV/cm^2 s\ sr}$$

We are below the bound, but it is difficult to continue since we should rely on the knowledge atmospheric neutrinos where it is not well known.

However, such a flux should be isotropic, while atmospheric events are not; moreover, the atmospheric spectrum at high energies should be, to a certain extent, calculable. Presumably, muons should also help.

GRB neutrinos

The hypothesis that GRB's are UHECR accelerators permits to estimate neutrino emission (Waxman '95, WB '97).

IceCube monitored about 100 GRB in the window of time when neutrinos were expected. Expected 0.1 background plus 3 signal events, saw none – that leaves a wide margin for further searching.

Theoretical uncertainties are at least a factor of 2 (Guetta).

UHE neutrinos

Scattering of neutrinos above EeV causes impulsive radio emission, due to Cherenkov radiation from the subsequent bunch of negative particles (Askaryan effect).

ANITA experiment expected 1 background plus 0.3-30 signal events and saw 1 – thus proceeding much farther won't be easy.

The key hypothesis, that UHE cosmic rays are protons (Berezinsky, Zatsepin) is however called into cause by the recent studies of composition of Pierre Auger Observatory.

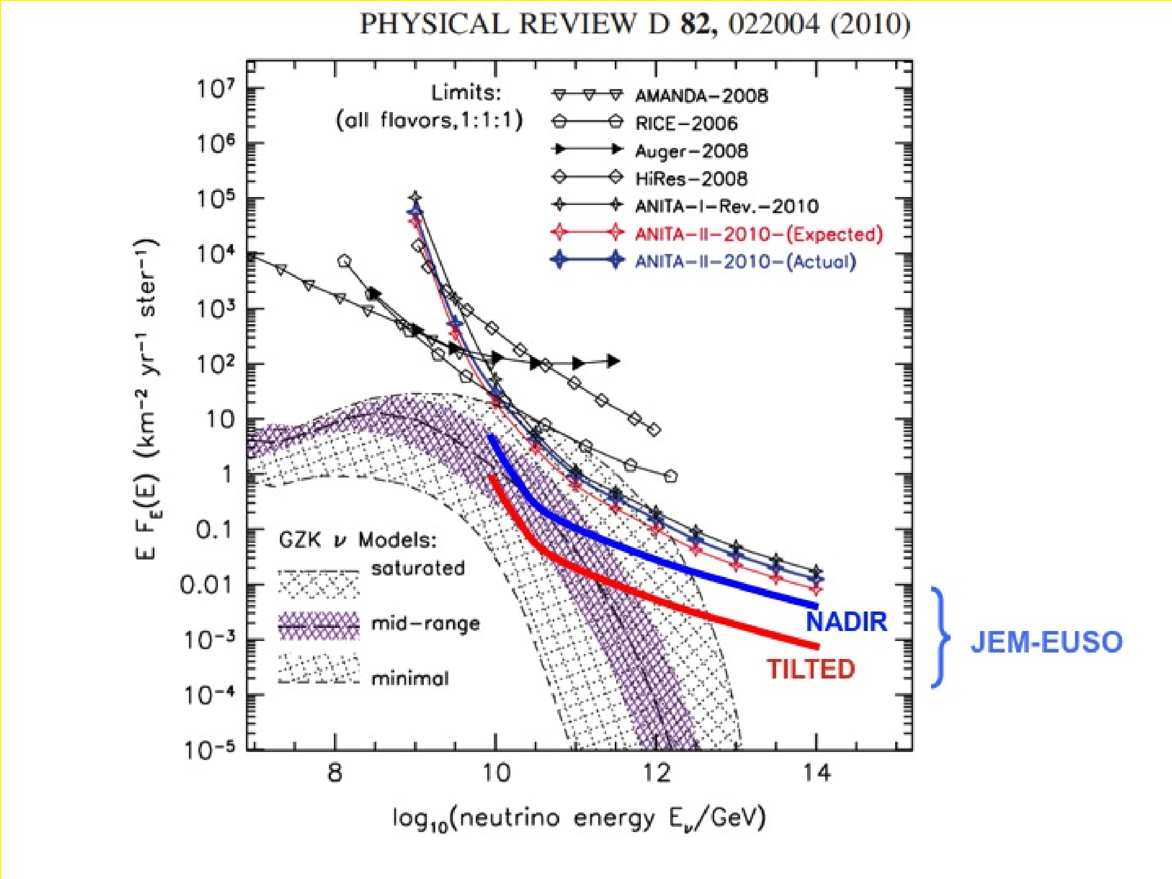


Figure 2: *Limits obtained by ANITA and RICE, by Amanda and by the UHECR observatories. The theoretical curves assume that UHECR are protons. In the future, JEM-EUSO could contribute to the search (curves drawn by Medina-Tanco).*

NEUTRINOS AND GAMMA RAYS

We already illustrated the tight relation between gamma and neutrinos at the production.

Now we show how to **quantify** the relation, in the hypotheses that:
(1) the sources are transparent to the gamma rays;
(2) the CR collide with protons;
that are reasonable hypotheses for certain galactic sources, such as SNR.

We show an important application of this technique, and comment on the connection between gamma and neutrino **detectors**. Then we come back on the discussion of galactic sources, beginning with RX J1713.7-3946.

How to derive a precise upper bounds when γ's are measured

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

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

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

The first and second contributions are due to direct mesons decay into neutrinos, $r_x = (m_\mu/m_x)^2$ with $x = \pi, K$ and the third 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.

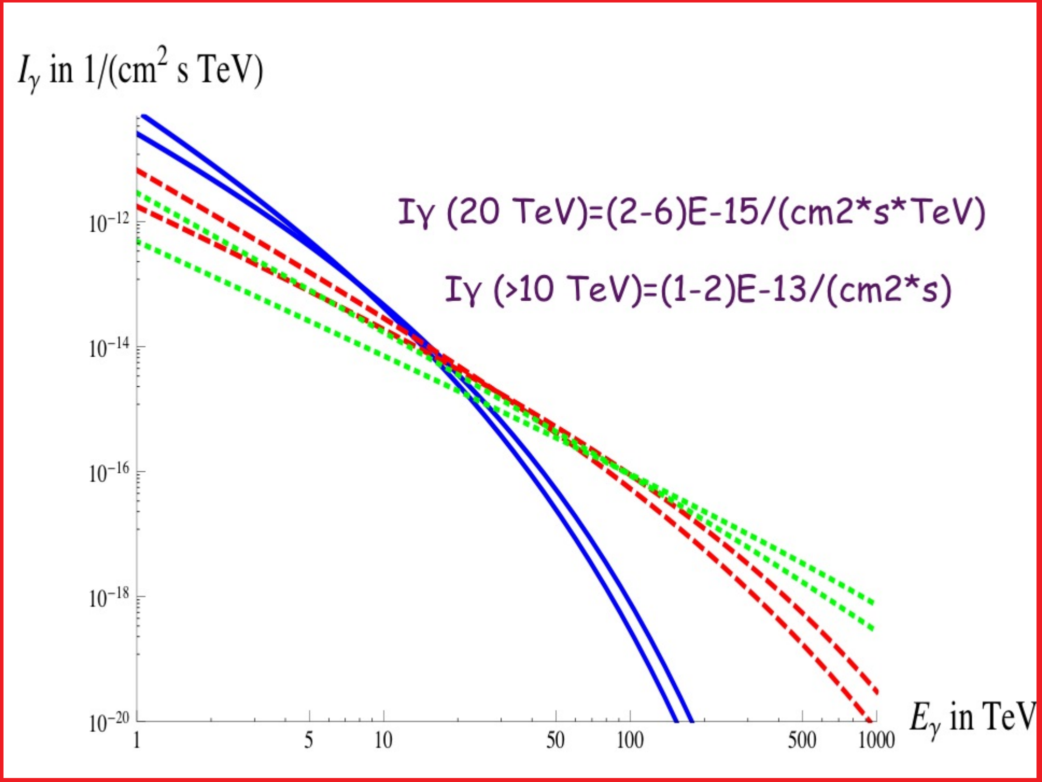
Application: which potential neutrino sources?

They are characterized by their hadronic γ-rays, distributed as

$$I_\gamma \propto E_\gamma^{-\alpha} \ \exp[-\sqrt{E_\gamma/E_c}]$$

with $\alpha = 1.8 - 2.2$ and $E_c =$ TeV$-$ PeV.

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.



In other words, we can say that all the potential neutrinos sources have γ-rays intensities above

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

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 the high energy array in CTA or a custom instrument, would be invaluable for ν community.

Complementary views in γ and ν_μ

Two detectors in the same latitude φ won't see the same event in the same time.

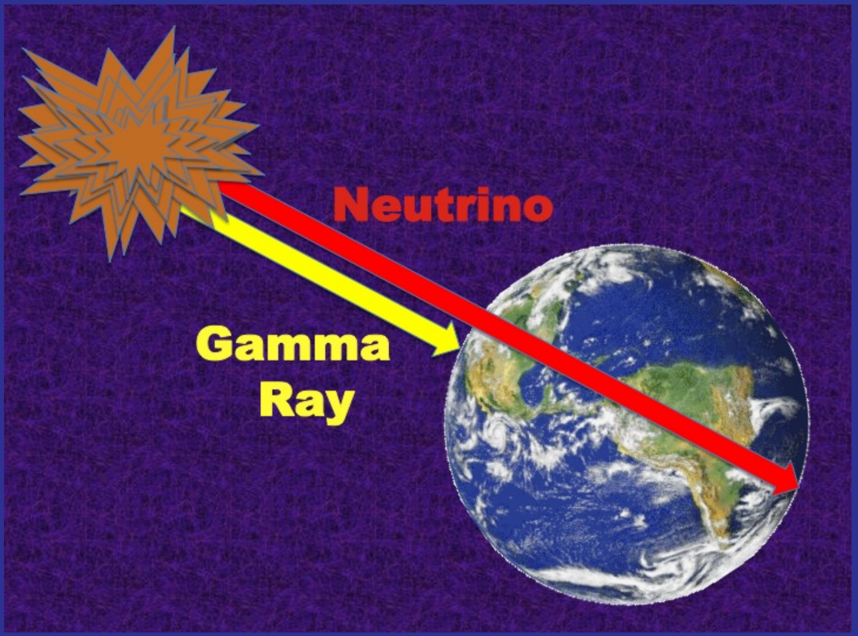
A steady source at δ is seen for

$$f_\gamma = \arccos[-\tan\delta \tan\varphi]/\pi$$

by a γ-ray detector and

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

by a neutrino detector.



Antipodal location means maximum complementarity.

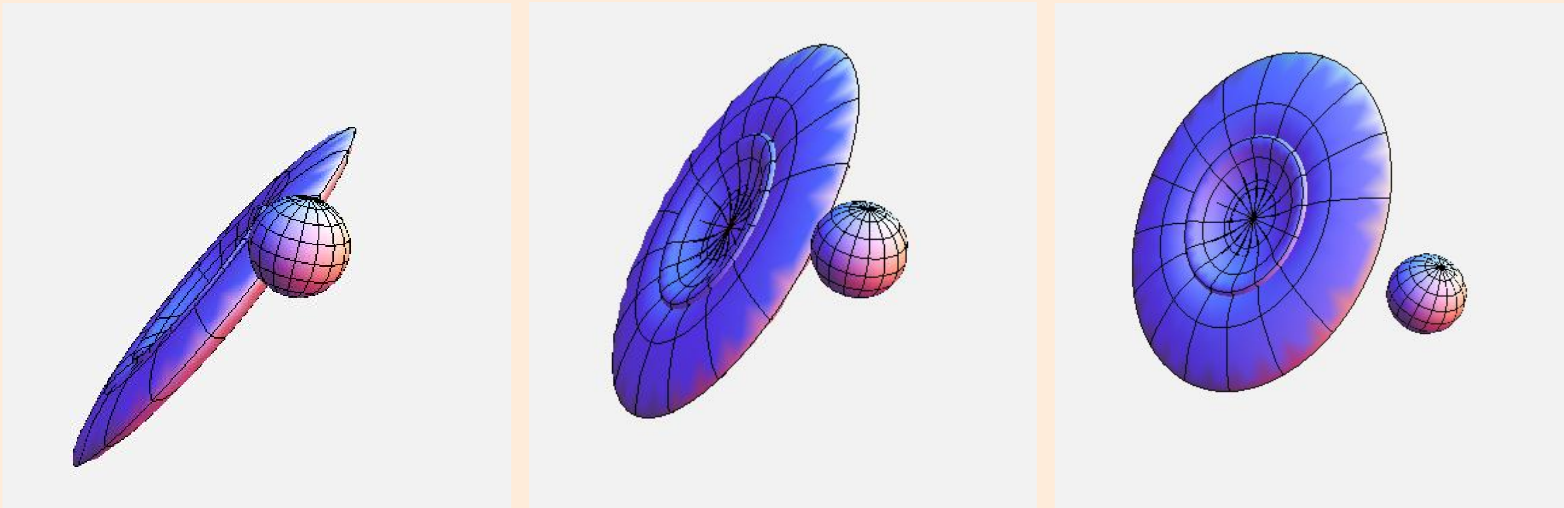
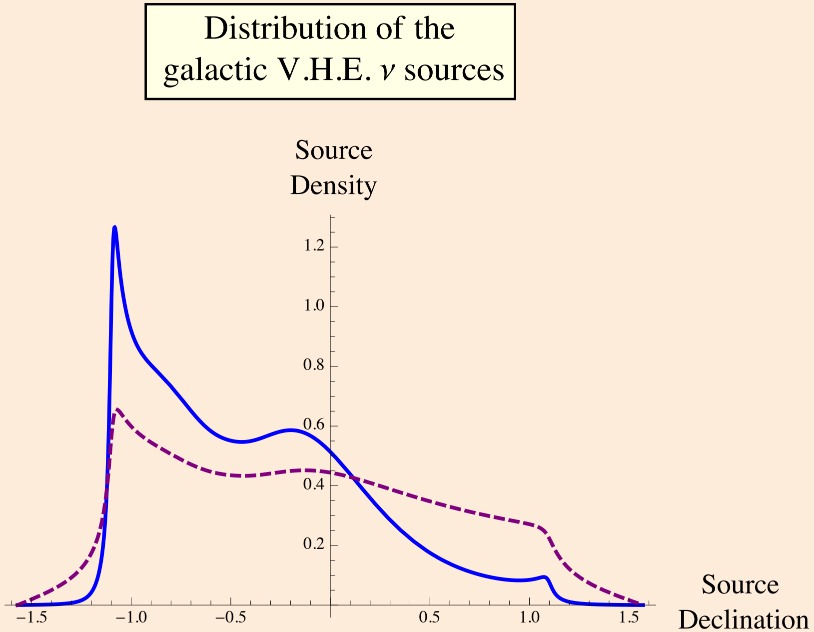
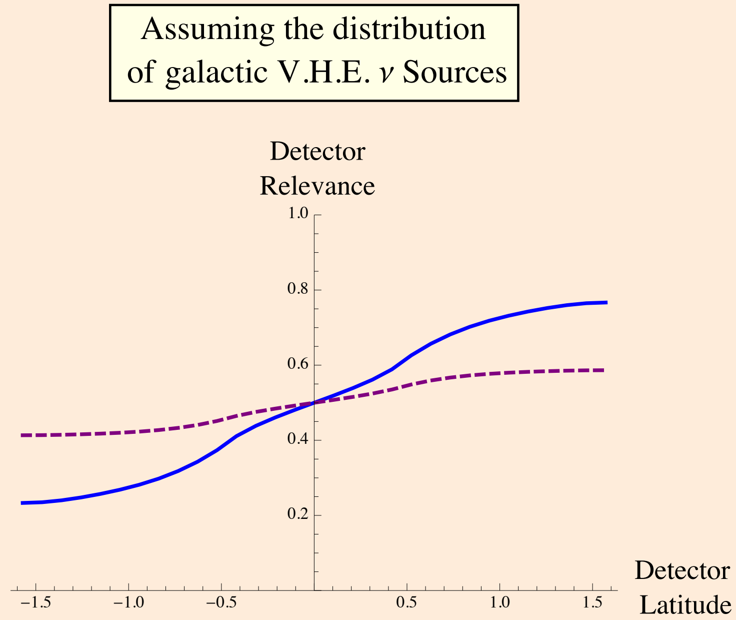


Figure 3: *Relative orientation of Earth and Milky Way.*

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.

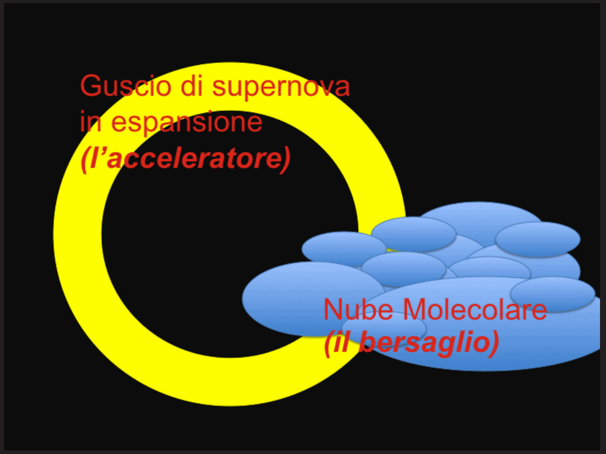
The continuous line considers just the matter distribution; the dashed one weights it with $1/r^2$.

THE CASE OF RX J1713.7-3946

An ideal SNR should...

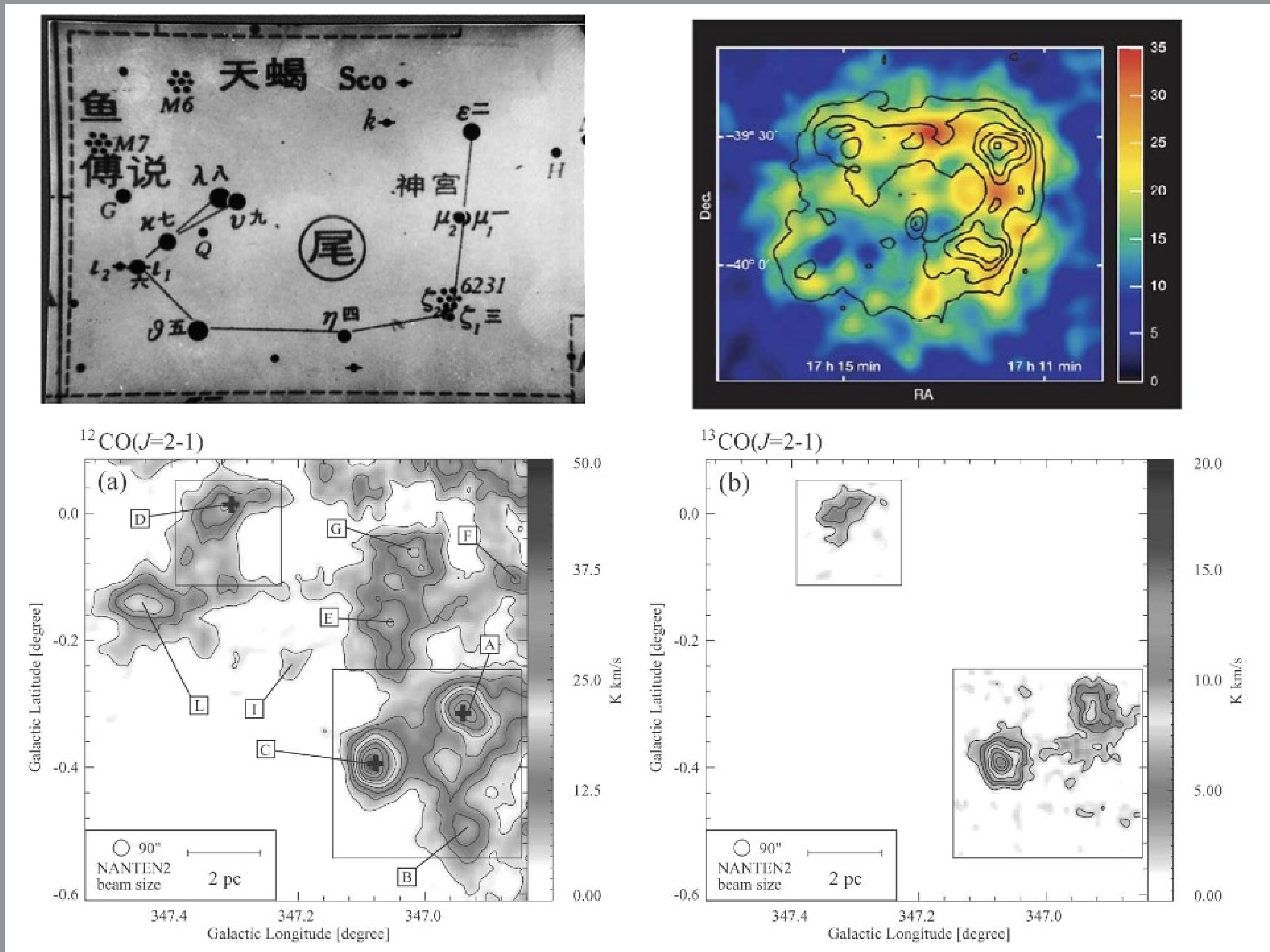
1. Contain very high energy cosmic rays;
2. Have an efficient neutrino-converter;
3. Be close to us.

Scheme of an association between a shell SNR and a molecular cloud. The first acts as an accelerator, the second as a target.
Aharonian, O'Drury, Völk 94.



Evidences of hadronic emission are at low energy, from old objects. What is relevant for neutrinos detection, is whether we have such a hadronic emitter in our cosmic backyard *and* young, ~ 1000 yr.

The best candidate: the SNR RX J1713.7-3946



TeV γ-ray emission is measured up to 100 TeV

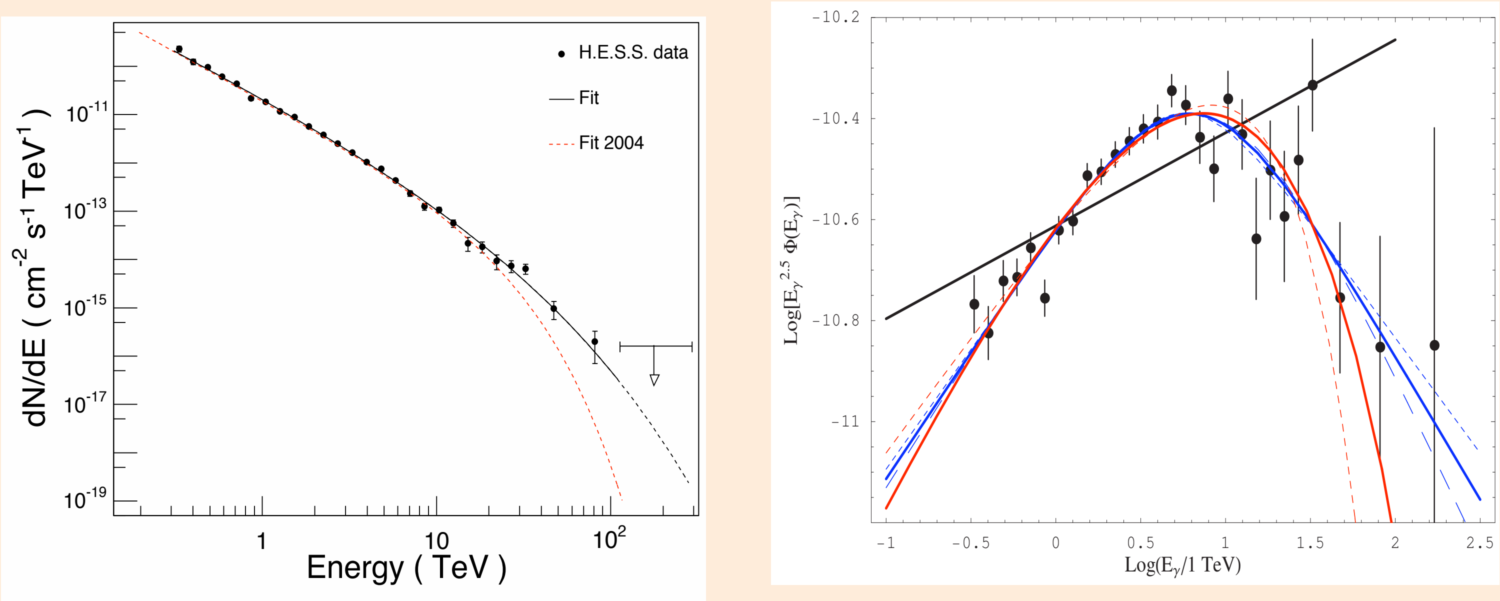
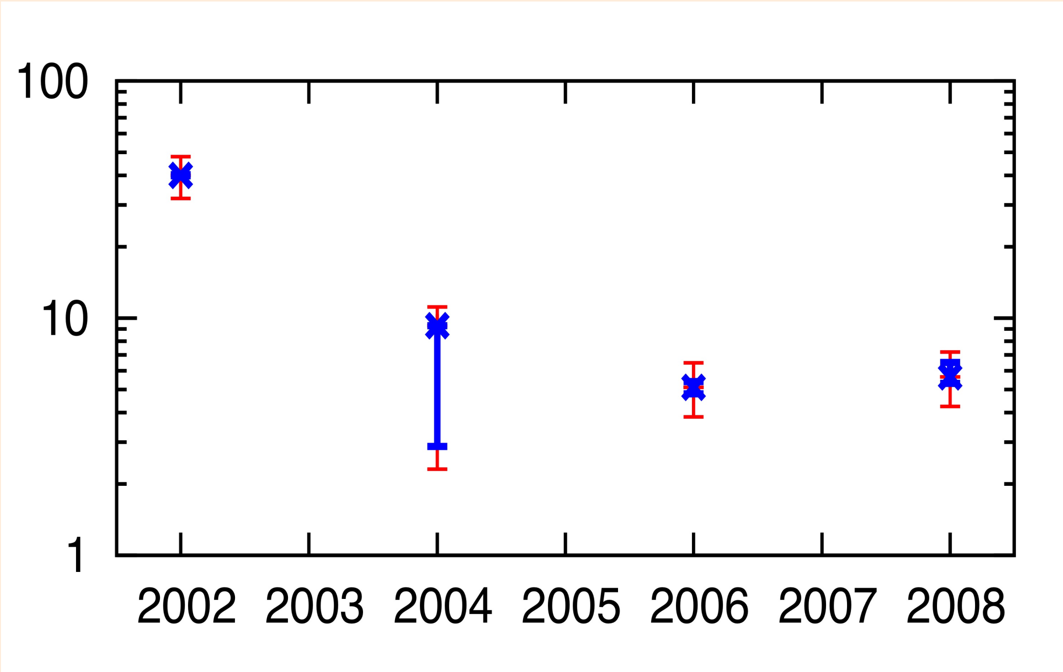


Figure 4: *Thanks to HESS we know that the spectrum is non-trivial: it is well described by a broken-power-law or by a modified-exponential-cut.*

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 5: *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: $1 \rightarrow 2$: oscillations, absorption, livetime. $2 \rightarrow 3$: cutoffed HESS spectrum. $3 \rightarrow 4$: 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):

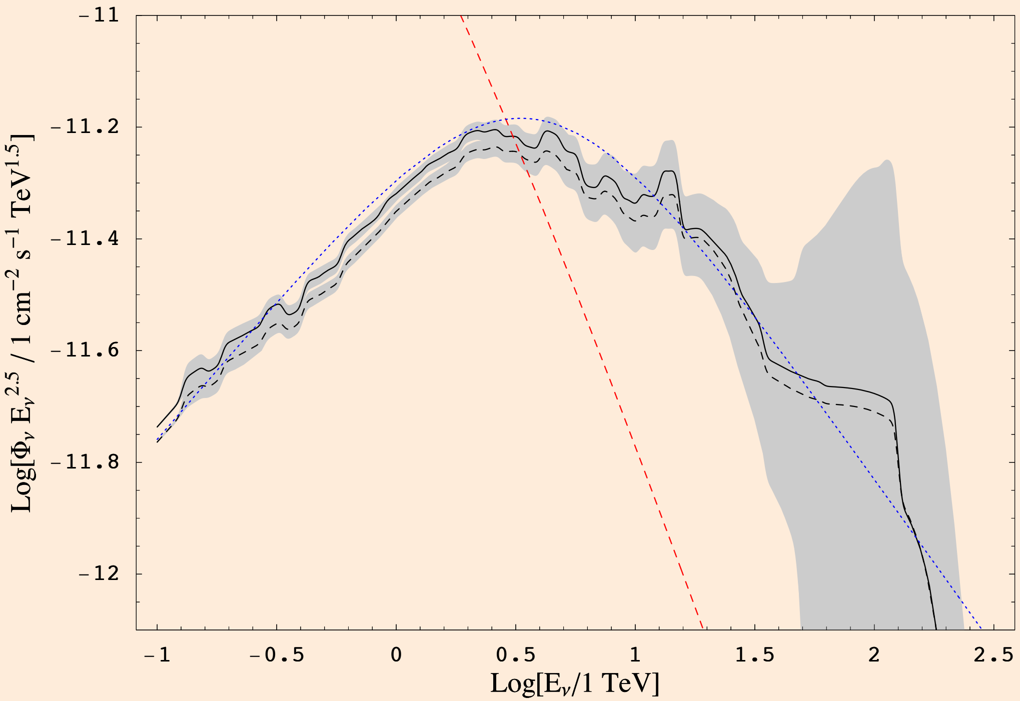
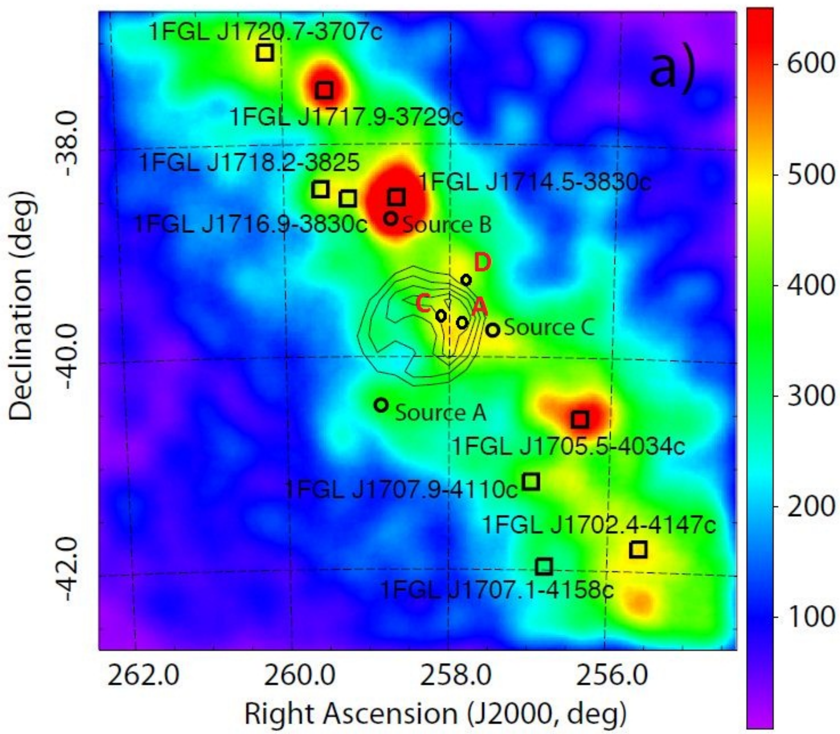


Figure 6: *ν_μ and $\bar{\nu}_\mu$ fluxes deduced from latest HESS data, assuming a hadronic γ-ray emission (Villante & FV '08). The corresponding number of events above 1 TeV is:* $I_{\mu+\bar{\mu}} = 2.4 \pm 0.3 \pm 0.5/km^2\ yr$

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



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 that deserves comments and discussion:

- $E_\gamma^{-1.7}$ would fit well HESS and it is not excluded firmly by Fermi, could still agree (?) with hadronic emission and very efficient acceleration.
- Even a spectrum $E_\gamma^{-1.5}$ can be leptonic $(E_e^{-\gamma} \Rightarrow E_\gamma^{-\frac{\gamma+1}{2}})$ or hadronic, with energy dependent penetration $(E_p^{-\gamma} \Rightarrow E_\gamma^{-\gamma+\frac{1}{2}})$ and $\gamma \approx 2$ (Fukui '11).
- Lack of thermal X-rays: uniform medium+leptonic (Ellison '10) or very non-uniform medium (Fukui '11).
- It would be important to understand better the emission below 5 GeV in the region of SNR.

We expect progresses in this region: Wait and see!

MORE GALACTIC SOURCES

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

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

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

First one, also known as RX J0852-4622, is a shell type SNR with angular size 2°. HESS spectrum $\propto E^{-2.1}$, whereas Fermi's $\propto E^{-1.9}$ (a a bad sign?).

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

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

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)

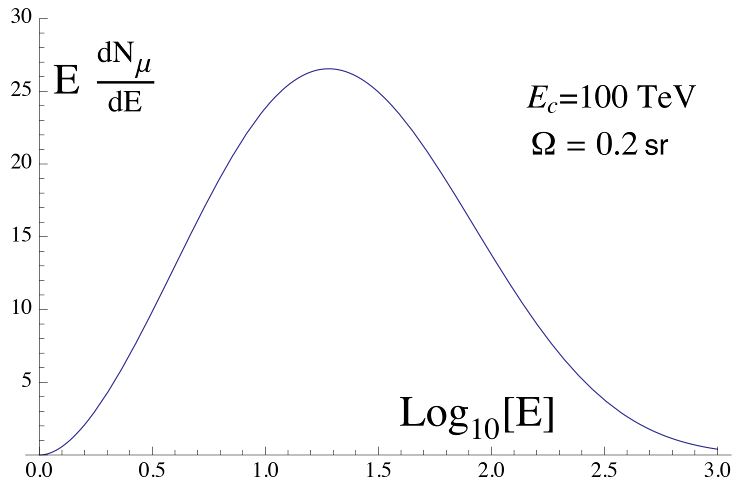


Figure 7: $\Omega \approx \pi \times (15°)^2$ *and* $\phi_\gamma(E) = \Omega \times 10^{-9} e^{-\sqrt{E/E_c}}/E^2$ *with* E_c *=100 TeV: we extrapolate at high energies assuming a CR spectrum cut at 1 PeV.*

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

NOT QUITE A CONCLUSION

After a long phase of preparation, the search for HE neutrinos is at a turning point.

IceCube, Antares, Rice, Anita ... KM3NeT!

This generation of experiments has true chances of making discoveries. Galactic neutrinos are of greatest interest and still largely unexplored.

Theory

Inspiring and imaginative works does not miss. Upper bounds are known. Predictions with errorbars and more input from astronomers is desirable.

Cosmic rays gamma rays and all that.

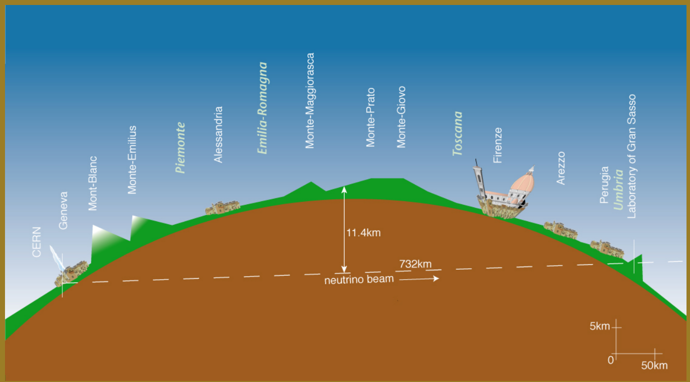
A lot of relevant information is being collected. It will surely help us to proceed in the understanding, we are going to assist to a global attack to the problem.

This is a beautiful moment, we can use it to reinforce astroparticle culture and collaboration... and let us hope in good luck!

BACKUP SLIDES

Superluminal neutrinos and GRB?

Autiero *et al.* '11 suggested that we could have missed the neutrinos from GRB, for they travel faster than the light, as claimed by OPERA '12.



A very exciting possibility, but faces various questions (1) why SN1987A neutrinos did not arrive 4 years in advance; (2) why the pion decay tunnel of OPERA works as predicted by Einstein; (3) why neutrinos do not loose energy by pair emission.

Do we really need expectations? A discussion.

Are expectations useful?

Of course, yes. Good predictions are precious to optimize the experiments; also reasonable expectations eventually contradicted are not useless.

Do we have any relevant precedent?

Solar neutrinos, predictions with errorbars since the 60's; Supernova neutrinos, some expectations before SN1987A; γ-ray sources foreseen in fifties.

Are really high expectations needed?

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

We can proceed towards with the help of γ-ray observations, limiting the use of theory inputs.

... 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:

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

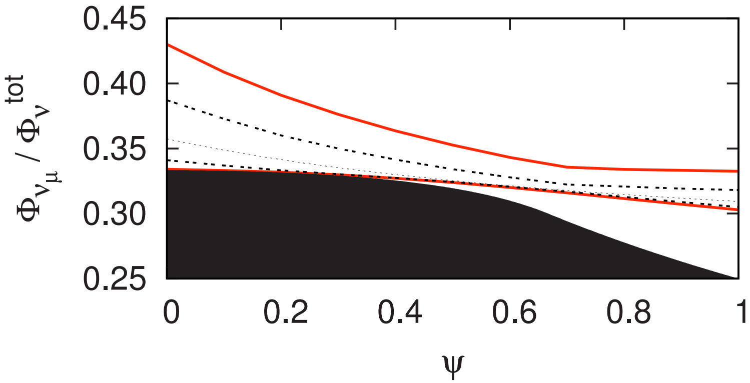


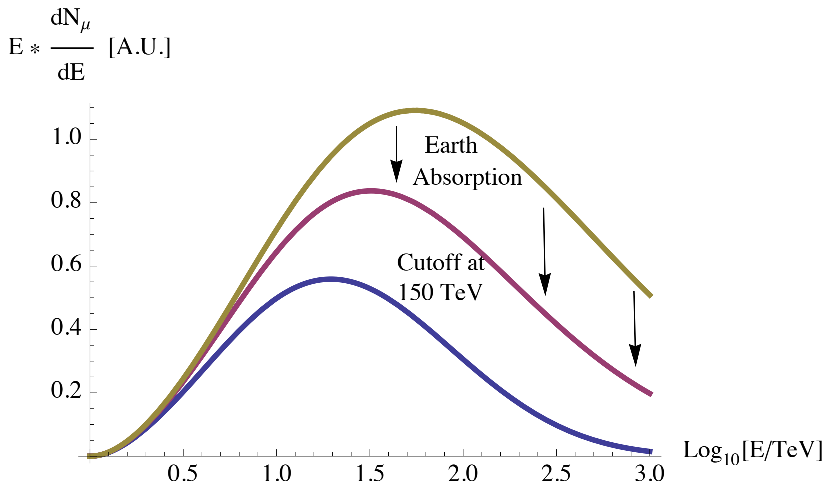
Figure 8: Value $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu$ as a function of $\psi = \Phi^0_{\nu_e}/\Phi^0_{\nu_\mu}$ (gray region forbidden). Uncertainty is small; $\Phi_{\nu_\mu}/\Phi^{\rm tot}_\nu = 0.33 - 0.35$ at 2σ when $\psi = 0.5$.

... and calculating the muon signal is standard.

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

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

Figure 9: **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.

Che succede con un grande θ_{13}?

Le oscillazioni agiscono semplicemente come costanti:

$$F_\mu = P_{\mu\mu} F_\mu^0 + P_{e\mu} F_e^0 \equiv P_{\text{eff}}\ F_\mu^0$$

Le variazioni sono anticorrelate (Costantini&FV 04) **così se pure** $P_{\mu\mu} = 0.37^{+0.05}_{-0.03}$ **e** $P_{e\mu} = 0.25^{+0.04}_{-0.05}$, **per i pioni,** $F_\mu^0 \sim 2F_e^0$, **vale** $P_{\text{eff}} = 0.32 - 0.36$ **a 2** σ**.**

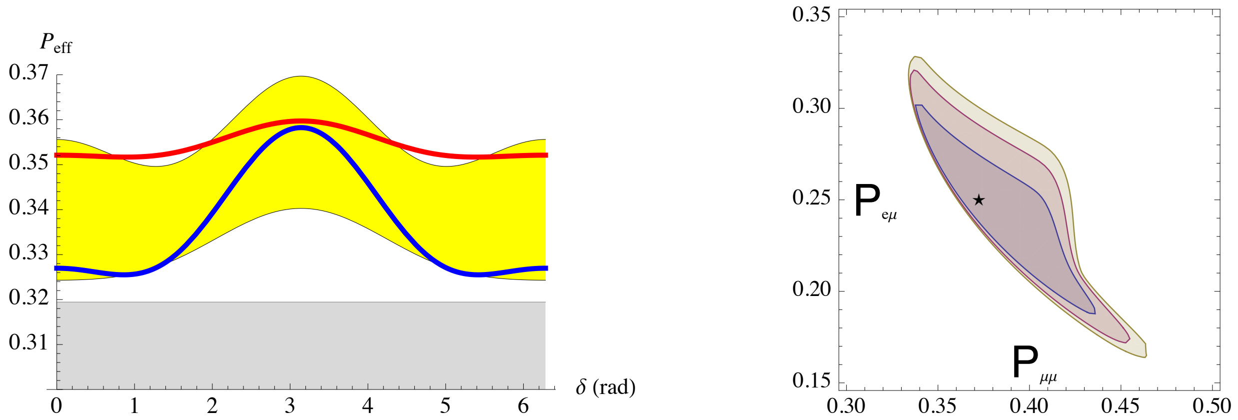


Figure 10: **Dipendenza dalla fase di CP e regione bidimensionale delle probabilità.**

La speranza di vedere qualche sorgente cosmica

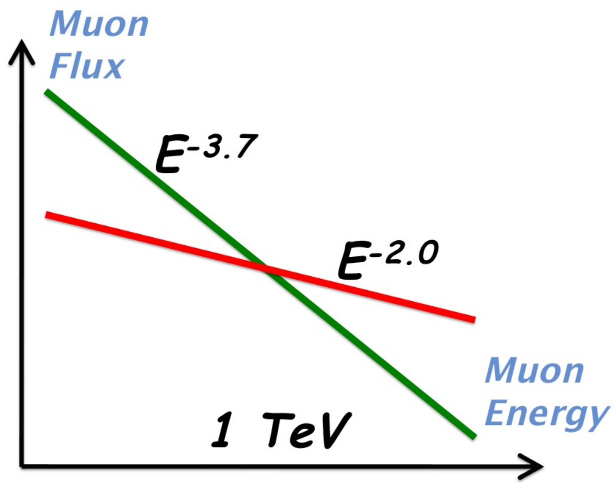


Figure 11: Se i raggi cosmici sono prodotti alla Fermi, quelli di loro che interagiscono producono neutrini. Questi spettri di neutrino ricalcherebbero quelli dei primari, e dunque, dovrebbero essere molto più duri di quello dei neutrini atmosferici.

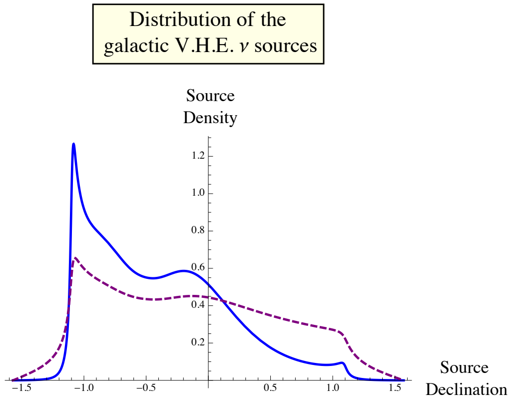
Ricordiamo un paio di numeri importanti:

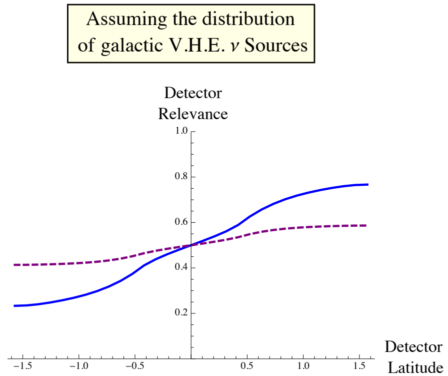
Al TeV, il flusso di ν_μ *atmosferici è depresso, come si capisce da* $d_\pi = c\tau_\pi \times \gamma = 55\text{km} \times \frac{E_\pi}{1\text{ TeV}}$; *inoltre, a quelle energie il cammino dei* μ *in acqua è intorno al km:* $R_\mu(E_\mu, E_{th}) \sim 2.5\text{km} \; \times \log\left[\frac{E_\mu + 0.5\text{ TeV}}{E_{th} + 0.5\text{ TeV}}\right]$.

Presente e futuro del campo

IceCUBE sperava di identificare qualcuno degli ipotetici acceleratori di raggi cosmici extragalattici, come gli AGN o i GRB, dai neutrini prodotti. Ma questo non è avvenuto: non c'è ancora alcuna sorgente identificata.

Essendo al Polo Sud, IceCUBE ha poca sensibilità alle sorgenti galattiche.





Se queste tracciano la massa, nel Mediterraneo abbiamo chances 3 volte più alte *a priori* — o solo il 50% in più, tenendo conto di $1/r^2$ che modula l'intensità. Ma... quanto si procede sulla sola base di un argomento del genere?

Do not ask us The Word [adapted from a poetry of Montale]

Do not ask us for the word that irradiates
neutrinos from the skys and in letters of fire
depicts its source, like a crocus
lost in the middle of a dusty field.

Neutrino sources at some level are there for sure.
The gamma- and cosmic-ray experiments
relieve our thirst of knowledge just a bit
but not the lust of finding them in future!

Do not ask us for the formula that opens up new worlds,
just gnarled syllables and dry as a branch.
Some theorist and IceCUBE whispered so
neutrino signals are low and nothing more we know.