Galactic Sources of High Energy Neutrinos

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Outline

- *Nonthermal messengers*
- *Connection between gamma-ray and neutrino fluxes*
- *Limit on the gamma-ray flux:*

  (Vissani, Aharonian and Sahakyan, 2011- Astro. Phys)

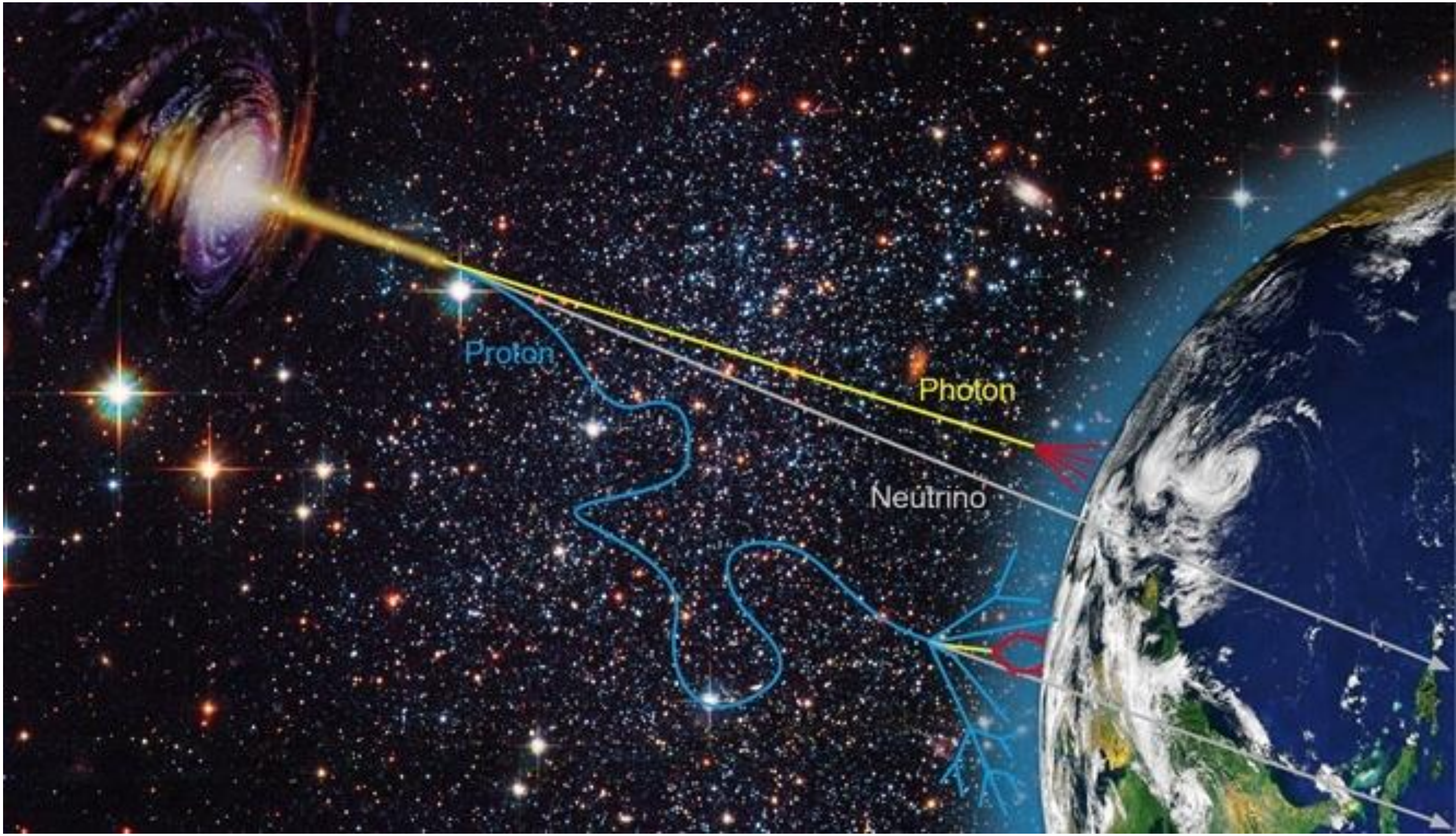
  @-20 TeV and @-1 TeV

- *Possible detection of HE neutrinos from SNRs and PWNe ?*
- *HE neutrinos from binary systems*
- *Hadronic gamma-rays and neutrinos from Cygnus X-3*

  (Sahakyan, Piano and Tavani 2014, ApJ)

- *Conclusion*

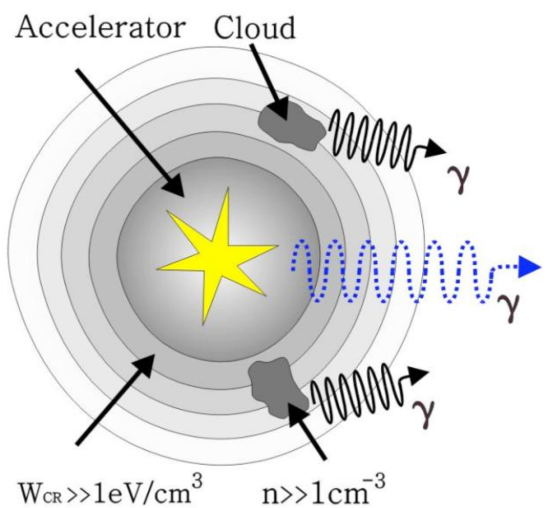
Nonthermal messengers



Neutrino production in cosmic accelerators

Proton acceleration $\propto E^{-\alpha}, \quad \alpha \geq 2$

1)



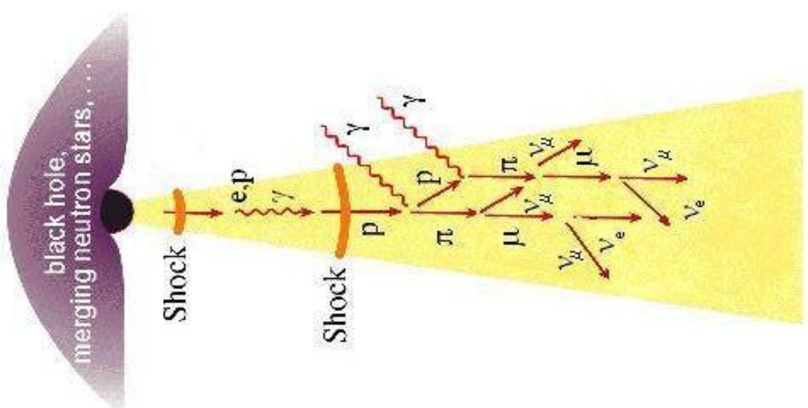
Dense target

p ⇒ p (SNR,X-Ray Binaries)

(γ, ν)

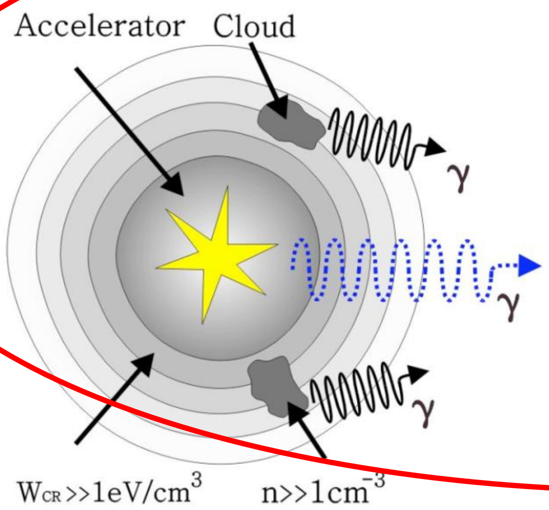
Photon field

2)



$p \Rightarrow \gamma$ (AGN, microQSO)

Neutrino production in cosmic accelerators



Proton acceleration $\propto E^{-\alpha}, \quad \alpha \geq 2$

1)

Dense target

p ⇒ p (SNR,X-Ray Binaries)

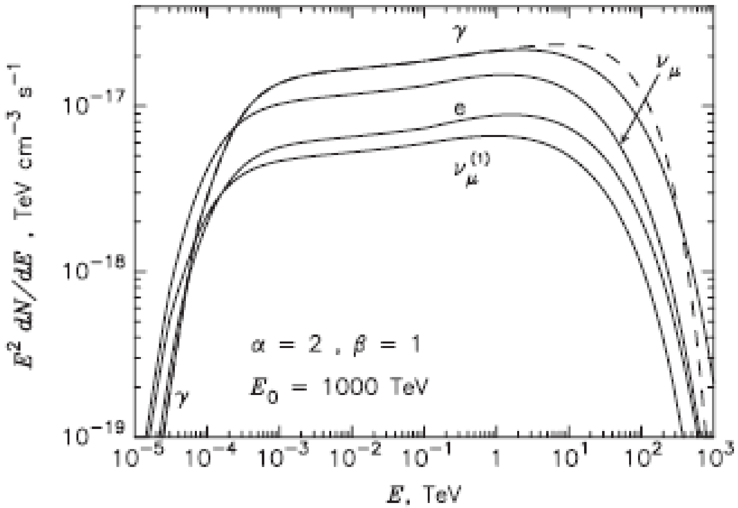
$$(\gamma, \nu)$$

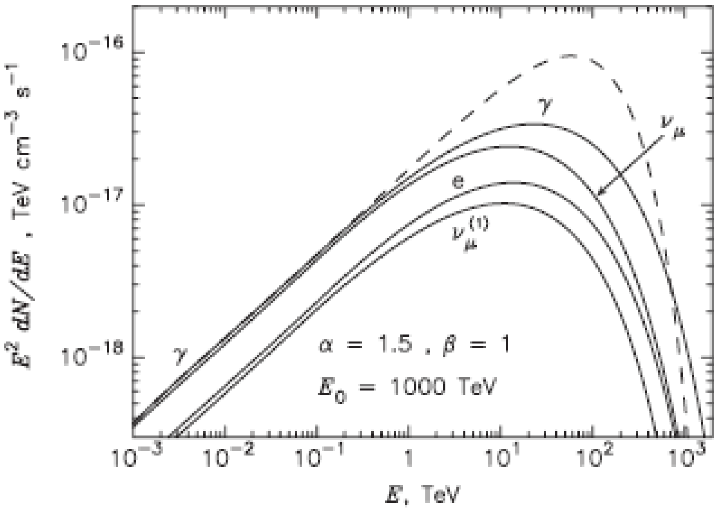
Proton-proton interaction

gamma-rays and neutrinos produced from *pp* interactions:

$$p + p \xrightarrow{\sigma_{pp}} \pi^0, \pi^{\pm} \quad \pi^0 \to 2\gamma, \; \pi^{\pm} \to \nu + \mu^{\pm}, \quad \mu^{\pm} \to e^{\pm} + \nu + \nu$$

For the proton distribution $J_p(E_p) = \frac{A}{E_p^{\alpha}} \exp\left[-\left(\frac{E_p}{E_0} \right)^{\beta} \right]$ (Kelner, Aharonian & Bugayov 2006)





connection between flux of primary protons and the flux of photons and neutrinos -> relation between fluxes of photons and neutrinos:

$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} K_\nu[E_\nu, E_\gamma] \Phi_\gamma(E_\gamma)$$

Gamma-ray flux

For proton distribution:

$$\frac{dN_p(E_p)}{dE_p} \propto \begin{cases} E_p^{-\alpha_p} \xrightarrow{pp} \dfrac{dN_\gamma(\varepsilon_\gamma)}{d\varepsilon_\gamma} \propto \varepsilon_\gamma^{-\alpha \approx \alpha_p} & \text{(Kelner, Aharonian \& Bugayov 2006)} \\ E_p^{-\alpha_p} Exp\left(-\dfrac{E_p}{E_c}\right) \xrightarrow{pp} \dfrac{dN_\gamma(\varepsilon_\gamma)}{d\varepsilon_\gamma} \propto \varepsilon_\gamma^{-\alpha \approx \alpha_p} Exp\left(-\sqrt{\dfrac{\varepsilon_\gamma}{\varepsilon_c}}\right) & \text{(Kappes et al. 2007)} \end{cases}$$

The gamma-ray spectrum from *pp* interaction can be characterized by:

$$I_\gamma(E_\gamma) = N_\gamma \times \left(\frac{E_\gamma}{1TeV}\right)^{-\alpha} \times Exp\left(-\sqrt{\frac{E}{E_c}}\right)$$

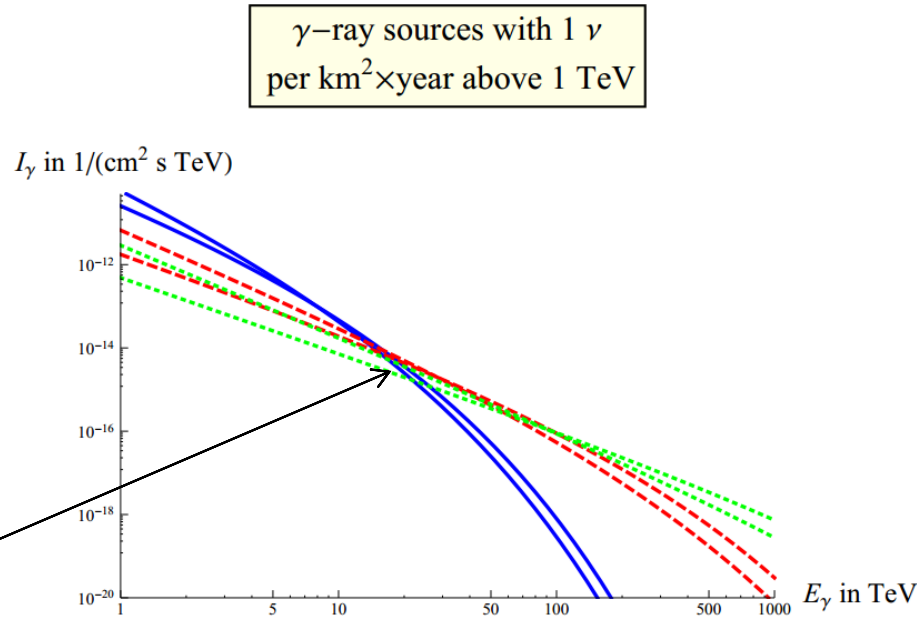
We consider: $\alpha = 1.8 - 2.2$ and energy cutoff $E_c = 1TeV - 1PeV$. Unknown parameter- N_γ

(Vissani, Aharonian and NS, 2011, Astro. Phys 34, 778)

Characteristic flux of gamma-rays

The normalization of gamma-ray flux is calculated assuming : the neutrino telescope detects 1 muon or antimuon per km x km per year above 1TeV

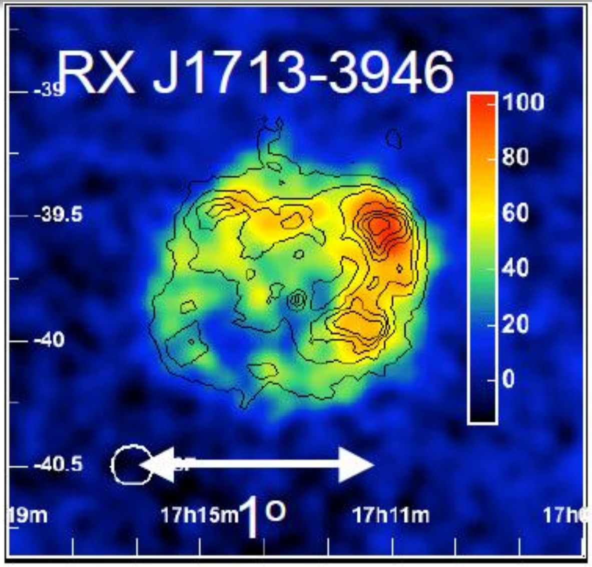
N_γ		$E_c =$						
		10^0	$10^{0.5}$	10^1	$10^{1.5}$	10^2	$10^{2.5}$	10^3
	1.8	70	16	4.9	2.1	1.1	0.7	0.5
	1.9	86	20	6.7	3.0	1.7	1.1	0.8
$\alpha =$	2.0	110	25	9.0	4.2	2.5	1.7	1.3
	2.1	130	32	12	5.9	3.5	2.5	2.0
	2.2	160	41	16	8.0	5.0	3.6	3.0



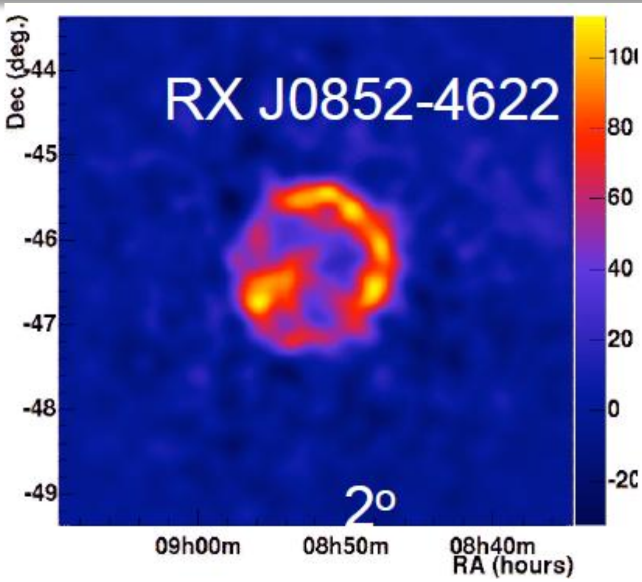
The flux $I_\gamma(20\,TeV) = (2-6)\times10^{-15}\ ph/(cm^2\,s\,TeV)$ characterizes the region of energies and of intensities where the gamma-ray observations are more relevant for the HE neutrino detectors.

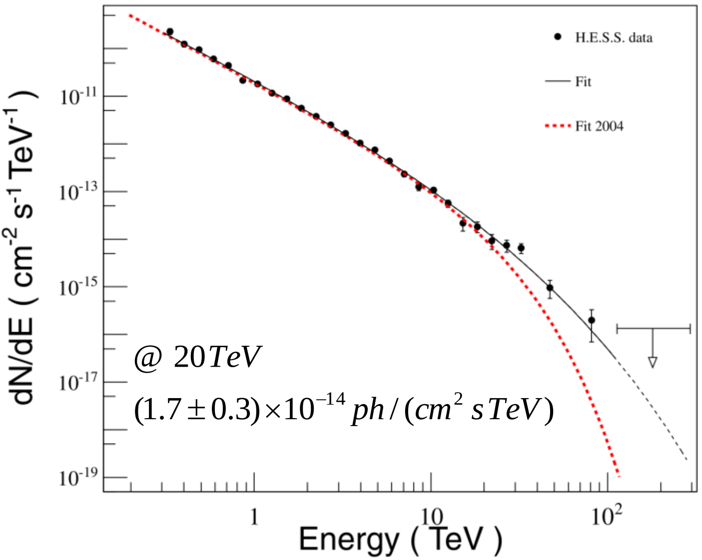
(Vissani, Aharonian and NS, 2011, Astro. Phys 34, 778)

For example…

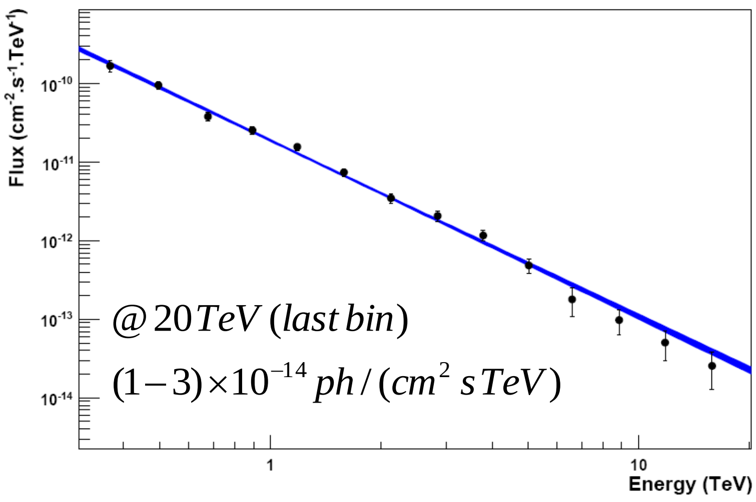


Two bright shell type SNRs



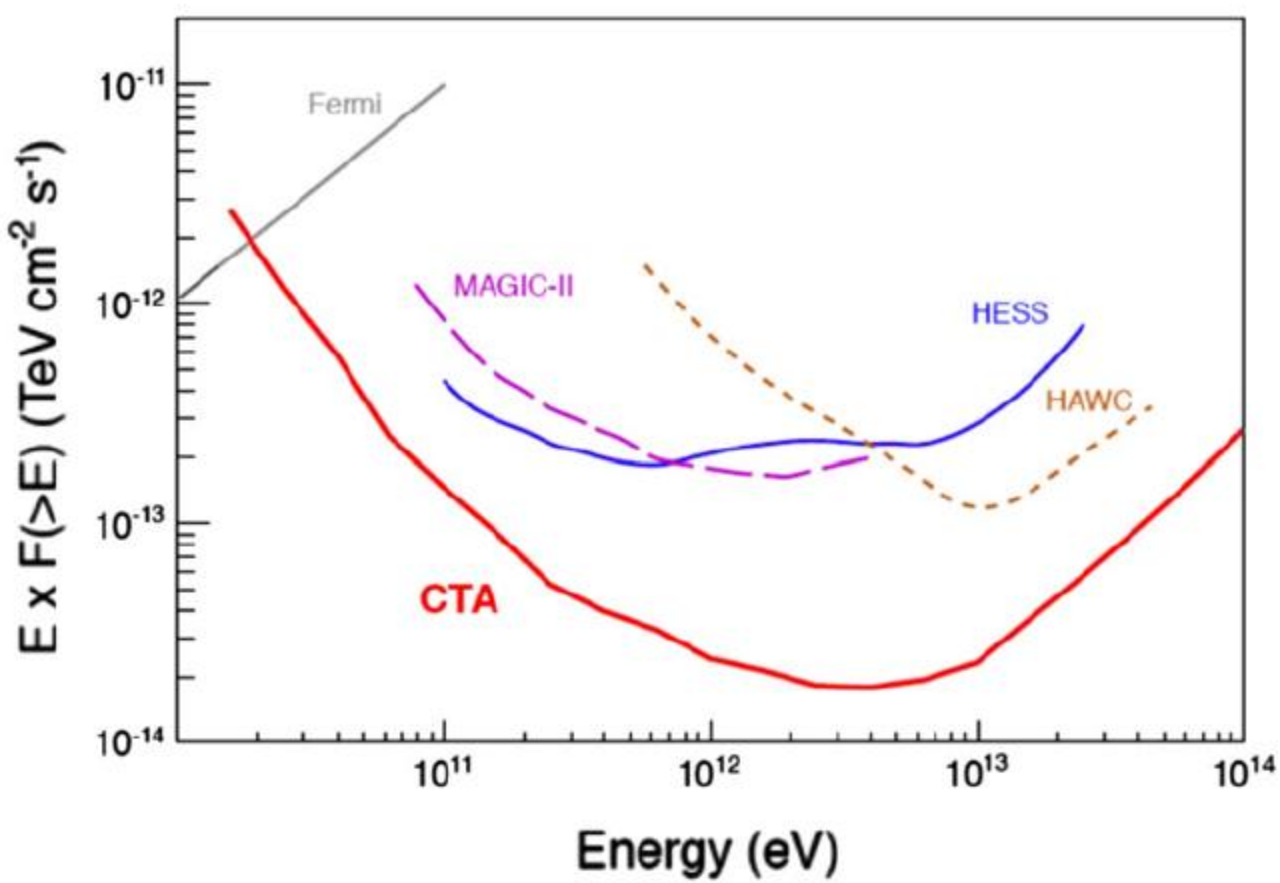


Possible sources of HE neutrinos



Problems with obtained limit ?

For now YES: this limit requires data of the flux @ 20 TeV- which is not well studied, yet!



The future gamma-ray measurements in the region 10–100 TeV –by the CTA instrument–will have an important impact on the expectations of HE neutrinos.

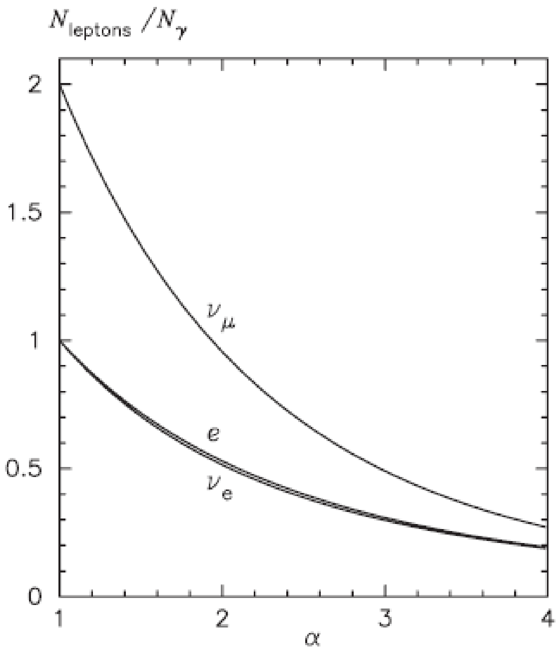
Limit at lower energies ?

The sensitivity of IceCube detector –

$$@1TeV - F_{\nu} = 1.7\times10^{-11} TeV^{-1} cm^{-2} s^{-1} \ (1\, year)$$

$$@1TeV - F_{\nu} = 4.9\times10^{-12} TeV^{-1} cm^{-2} s^{-1} \ (5\, year)$$

The ratio between gamma-ray and neutrino fluxes:



(Kelner, Aharonian & Bugayov 2006)

For the power-law index in the range of (1.5-3.5) this ratio:

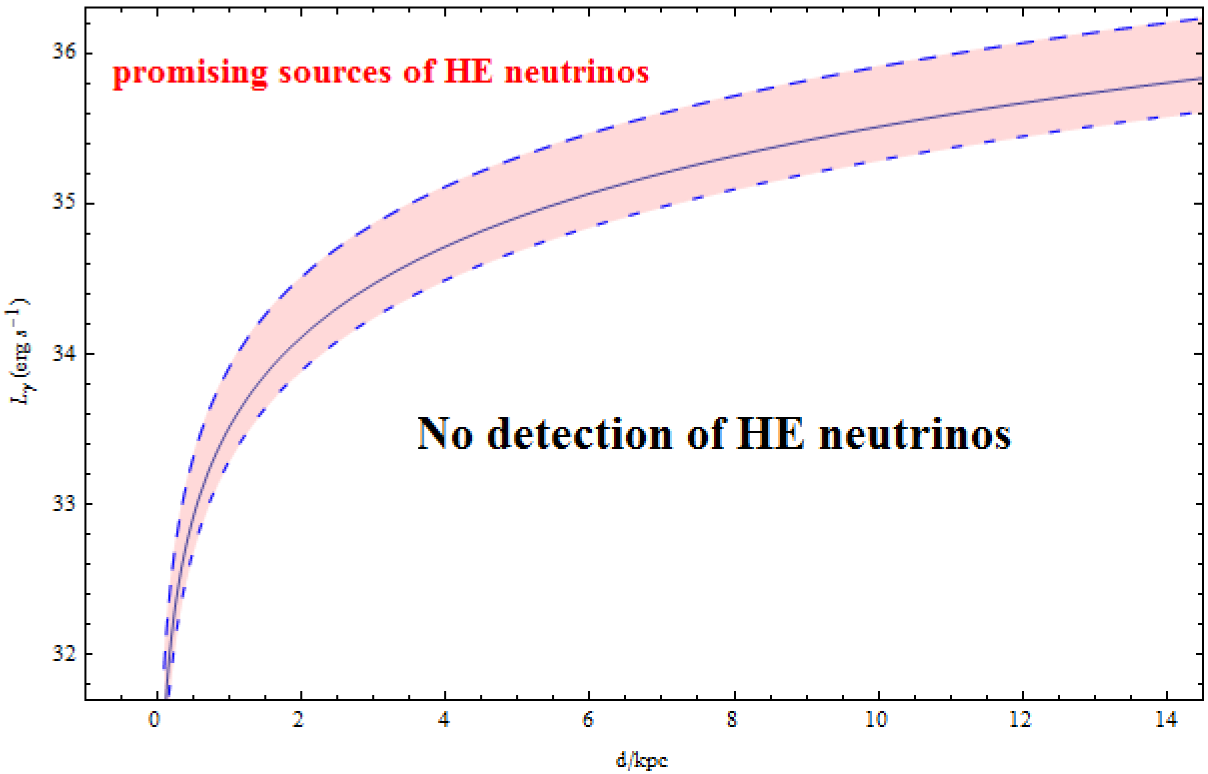
$$\frac{F_{\gamma}}{F_{\nu}} \approx (0.6 \div 2.5)$$

Therefore corresponding gamma-ray flux can be calculated: transferring to isotropic luminosity

$$@1TeV - L_{\gamma} = (1.95 \div 8.13)\times10^{33}\left(\frac{d}{1kpc}\right)^2 erg\, s^{-1} \ (1\, year)$$

$$@1TeV - L_{\gamma} = (5.6 \div 23.3)\times10^{32}\left(\frac{d}{1kpc}\right)^2 erg\, s^{-1} \ (5\, year)$$

Isotropic luminosity @ 1 TeV

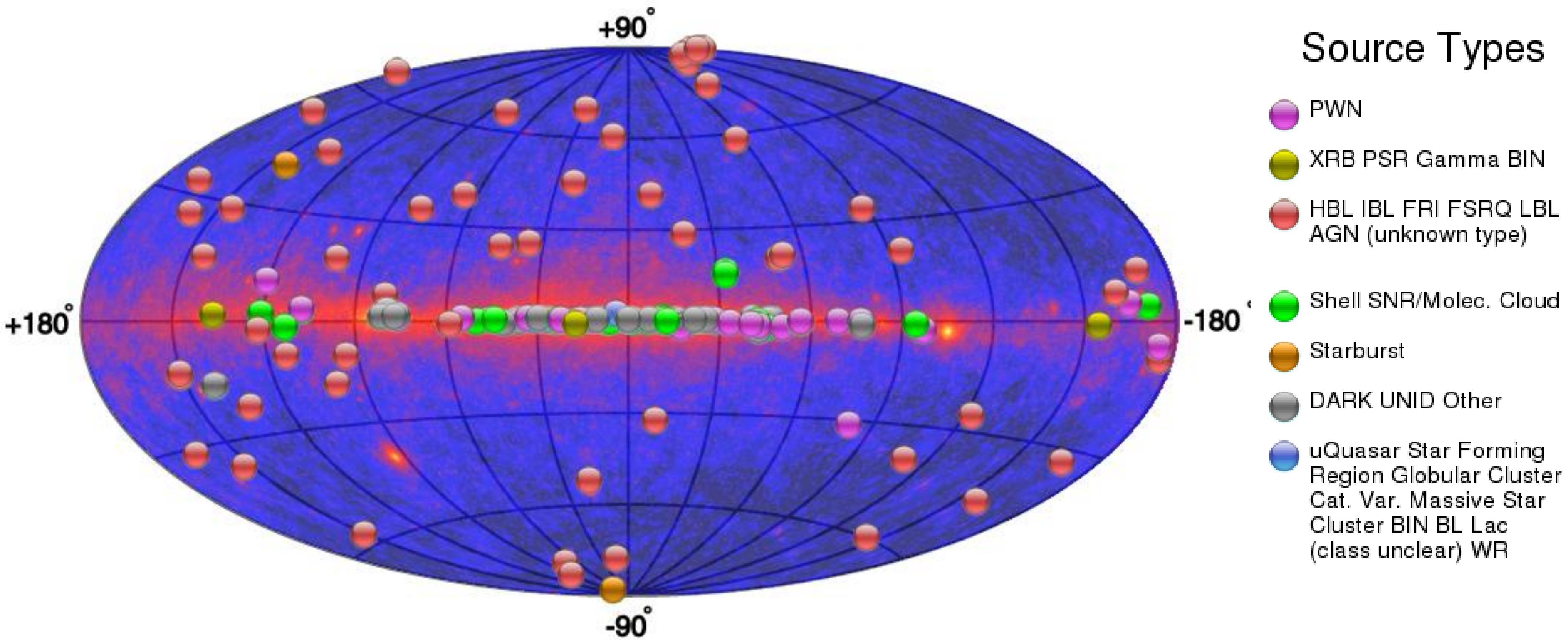


@ 1TeV complete information on the fluxes and neutrinos are confined within an angle less than one degree.

Search for TeV sources

TeV gamma-ray sources are grouped in TeVcat- @ www.tevcat.uchicago.edu

TevCat



Total- 145 sources

Sample selection

Supernovae remnants (SNRs)

- acceleration of particles (above 100 TeV); possible hadronic origin.

In total 23 SNRs are included in TeVCat, including:

i) 13- shell type

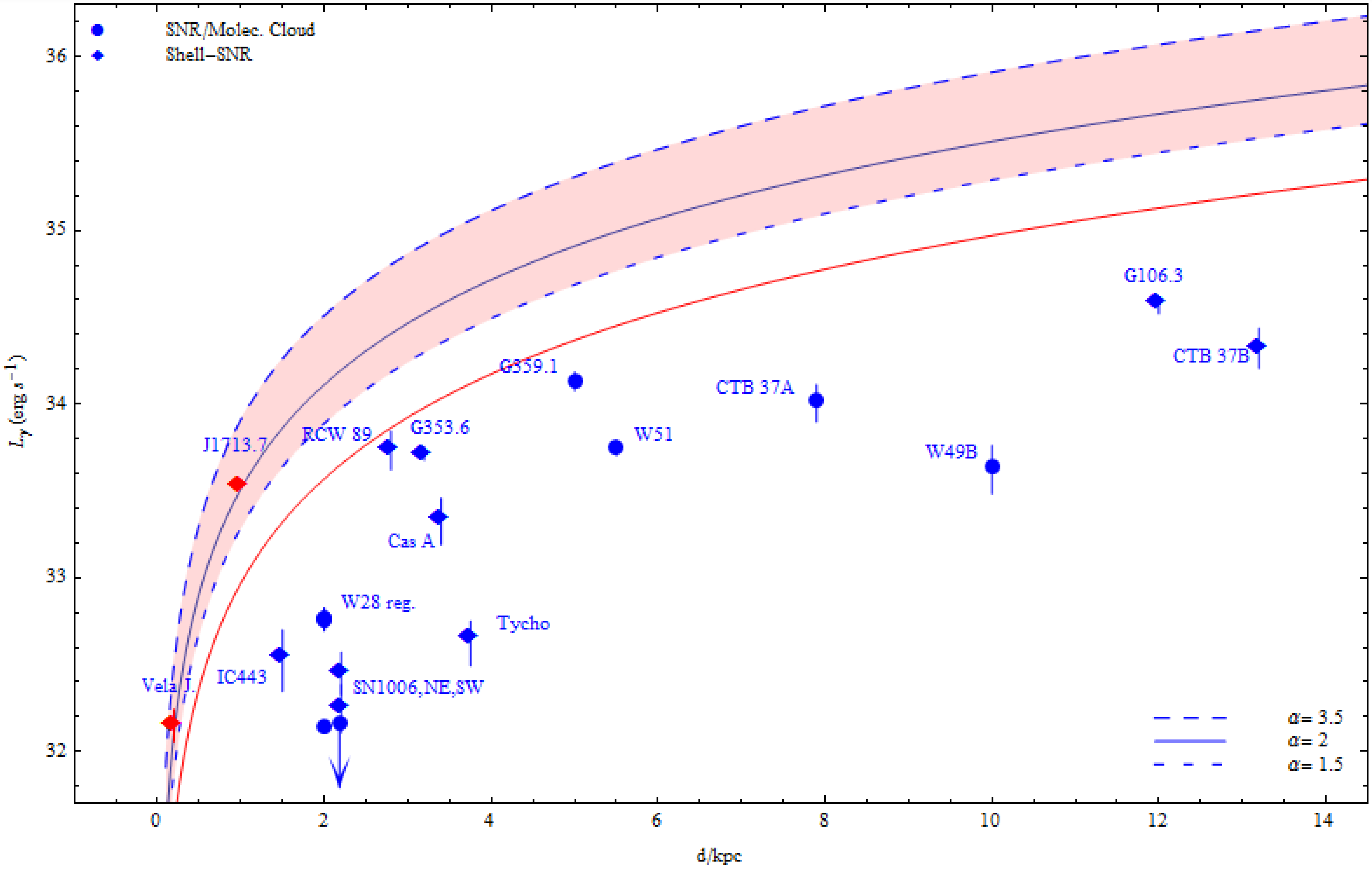
ii) 10 SNRs interaction with molecular clouds

Pulsar wind nebula (PWN)

- acceleration of particles (up to 100 TeV); possible hadronic origin.

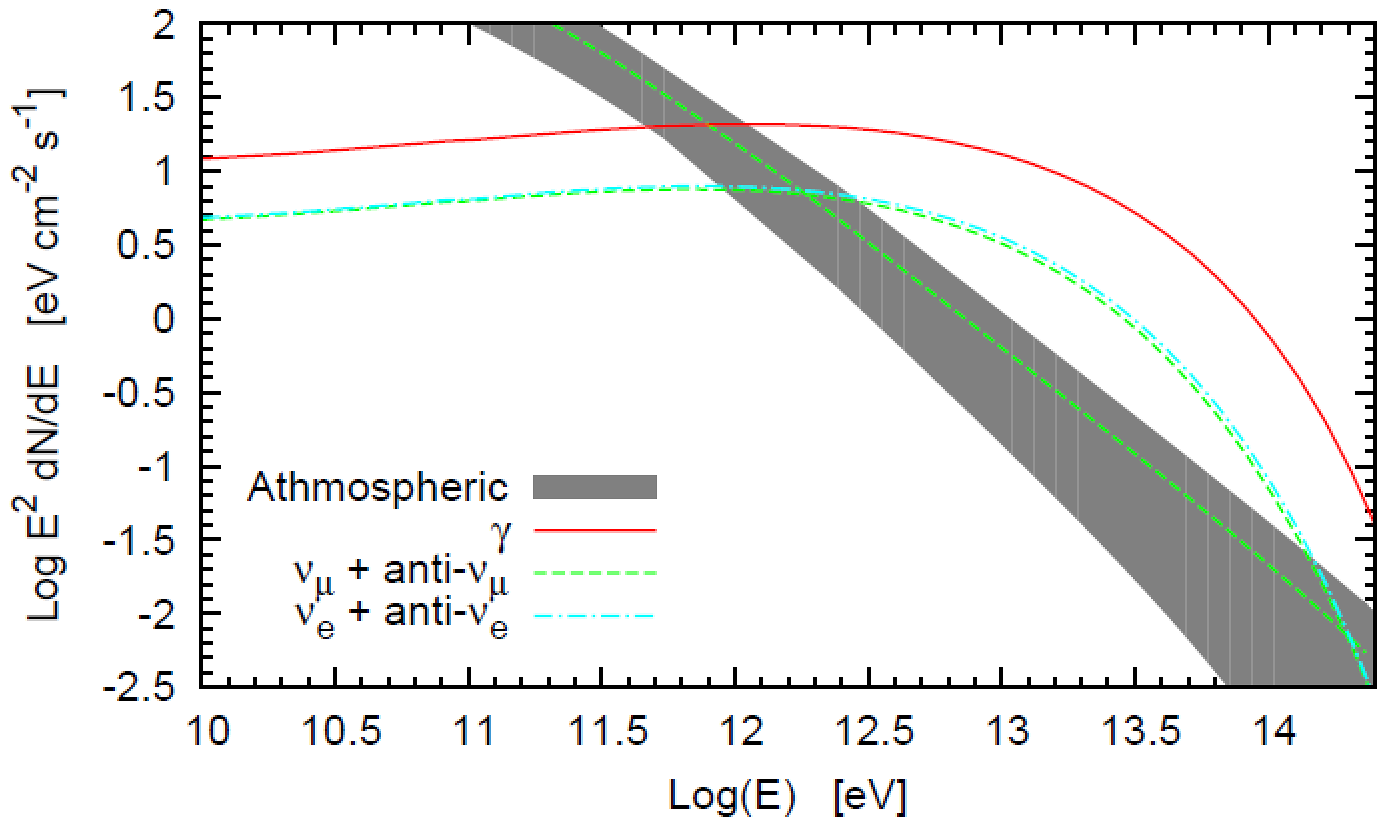
In total 35 PWNe are included in TeVCat, for some of them missing data (only upper limits).

Neutrinos from SNRs ?



only 1 potential source: RX J1713.7-3946 and a source at limit of detection- Vela junior

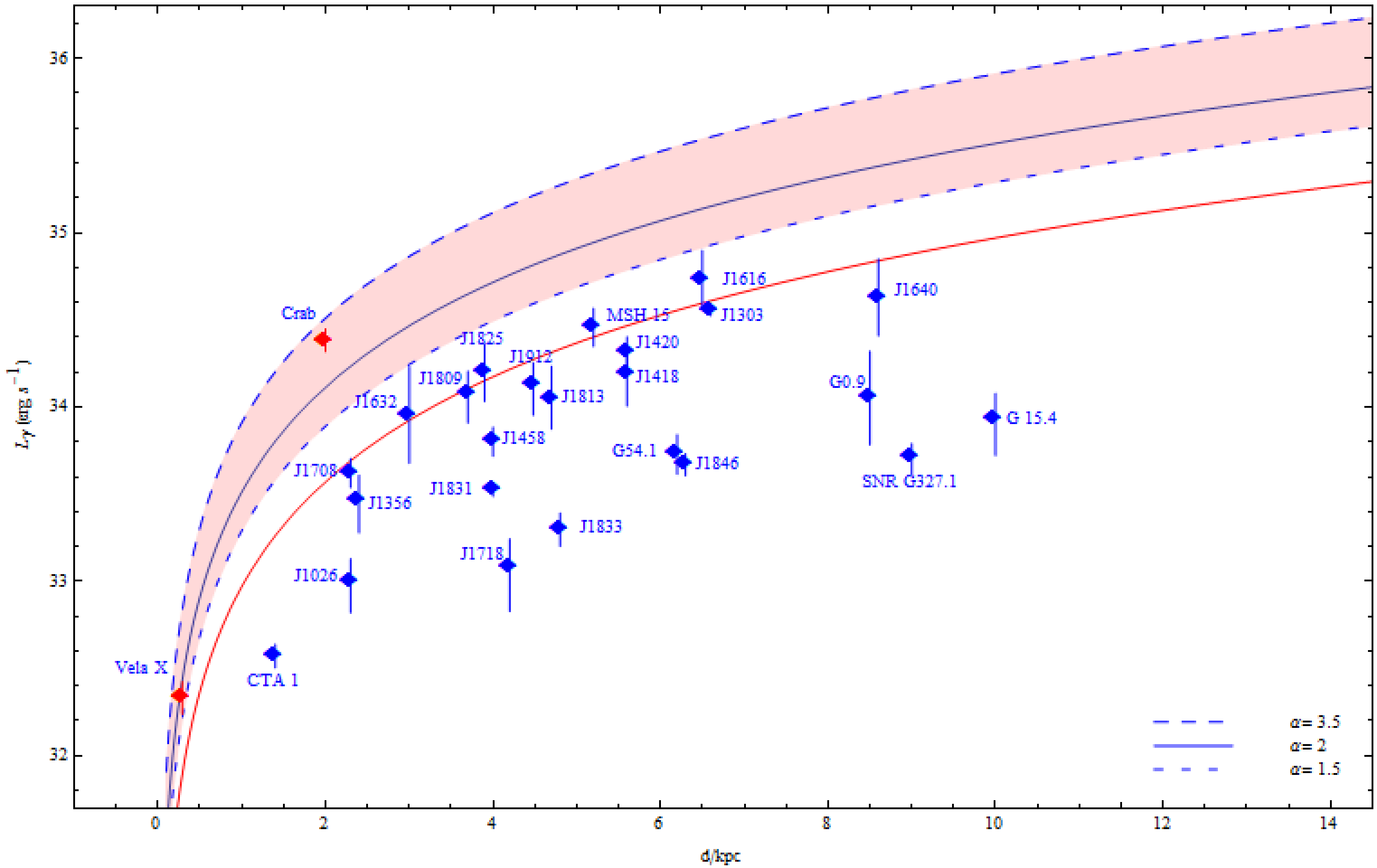
Neutrinos from RX J1713.7-3946



(Morlino, Blasi & Amato 2009)

Can be detected by KM3Net detector

Neutrinos from PWNe ?



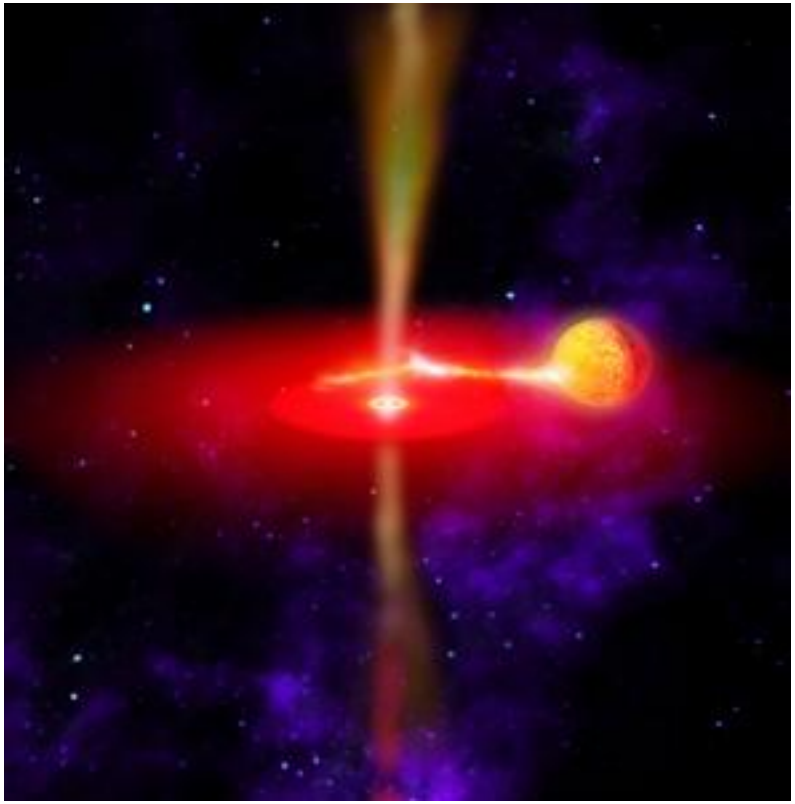
Only the intensity of Crab satisfies the condition. However, the gamma-rays seem to have leptonic origin.

From the sample of 23 SNRs and 35 PWNe $\Longrightarrow$ only 1 SNR (RX J1713.7-3946) possible candidate - detected by current generation of instruments .

other Galactic sources to be detected ?

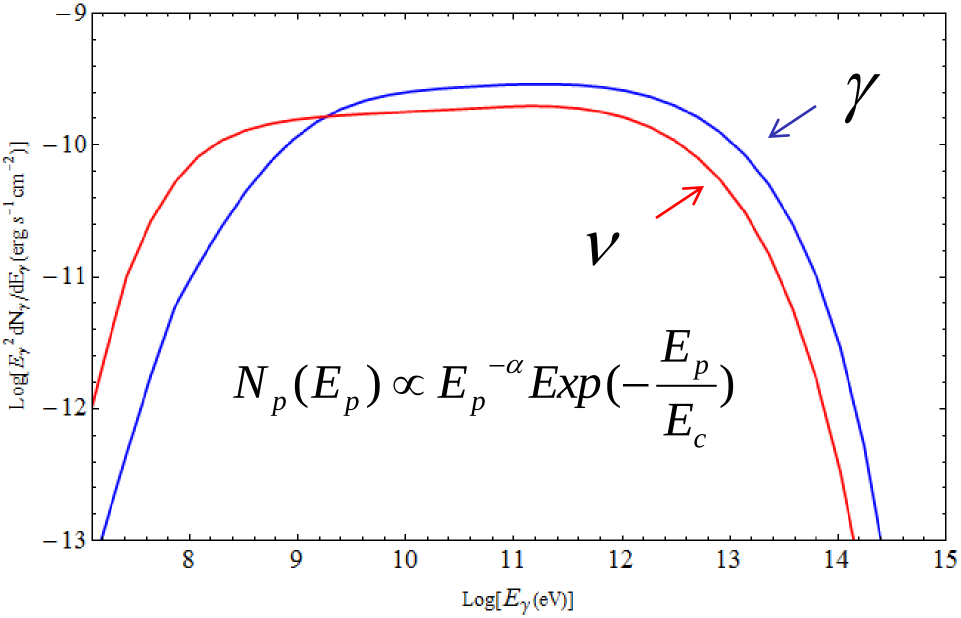
Search of other powerful galactic accelerators ?

The detections of TeV gamma-rays from two binary systems (called microquasars) – LS 5039 and LSI 61 303 clearly demonstrate that the galactic binaries systems containing a luminous optical star and a compact object (a black hole or a pulsar/neutron star), are sites of effective acceleration of particles (electrons and/or protons) to multi-TeV energies.



Binary systems vs SNRs, PWNe

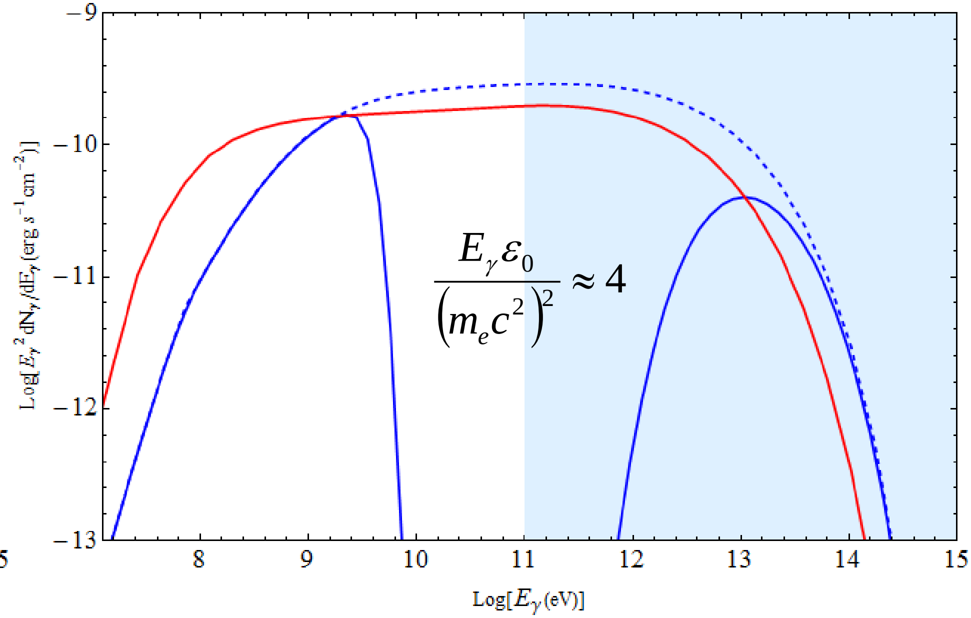
no absorption



$$\frac{F_\gamma}{F_\nu} \approx (0.6 \div 2.5)$$

- a chance to predict F_ν

absorption $\tau_\gamma(E_\gamma, r) = \int_r^\infty \int_{\epsilon_{min}}^\infty n(\epsilon_0, r')\sigma_{\gamma\gamma}(\epsilon_0, E_\gamma) d\epsilon_0\, dr'$



$$\frac{F_\gamma}{F_\nu} - ?$$

- unknown F_ν

Maybe surprising high flux of HE neutrinos

An example of the powerful accelerator is Cygnus X-3

nature   Vol 462|3 December 2009|**doi:10.1038/nature08578**

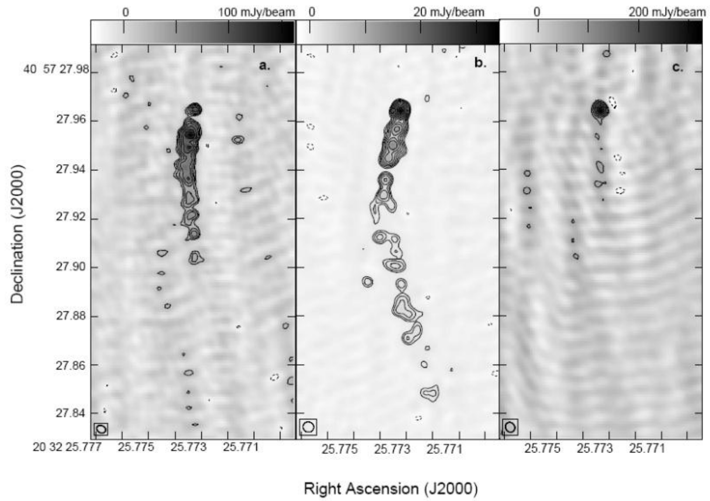
LETTERS

Extreme particle acceleration in the microquasar Cygnus X-3

Tavani et al. 2009

Cygnus X-3

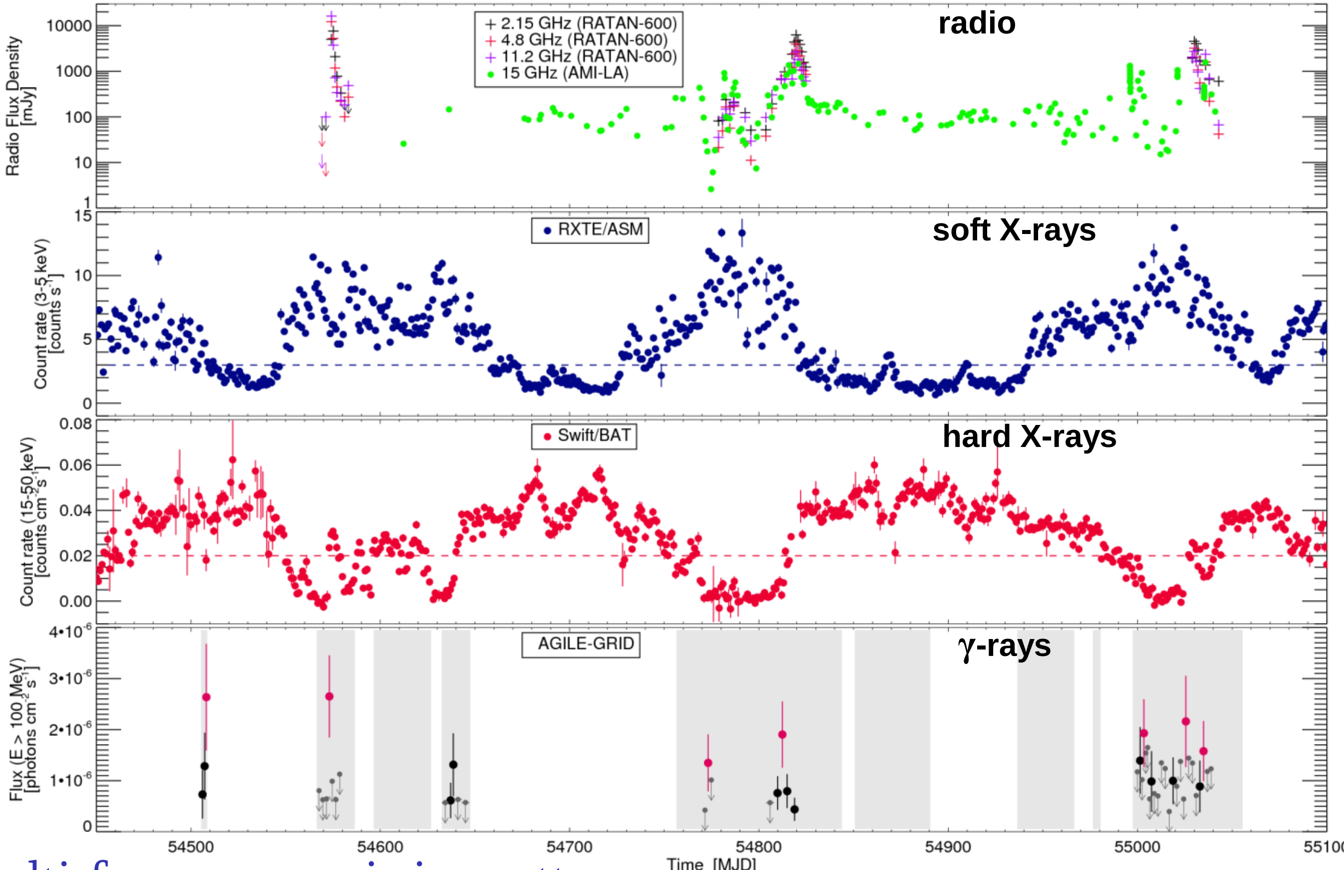
- high-mass X-ray binary discovered, as an X-ray source, in 1966 (Giacconi et al. 1967)
- distance -> 7-10 kpc
- compact object - UNKNOWN. or Neutron Star of 1.4 solar mass or a Black Hole with up to10 solar mass
- donor Star -> Wolf-Rayet star with strong stellar wind
- orbital period (X-ray, Infrared, gamma-ray): 4.8 hr
- strong radio outbursts (up to 20 Jy) with jet morphology at milliarcsec scale (expansion speed of 0.3-0.7c.)
- transient gamma-ray emission above 100 MeV (detected by AGILE and Fermi)



Cyg X-3 radio jets
(Mioduszewski, Rupen, Hjellming, Pooley, Waltman, 2001)

Agile observation Cygnus X-3

(Piano et al., 2012)



Repetitive multi-frequency emission pattern:

- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission:
- γ -ray sharp/local minima in the hard X-ray light curve (*Swift*/BAT count rate ≤ 0.02 counts cm^{-2} s^{-1})
- γ-ray flares coincident with soft spectral states (*RXTE*/ASM count rate ≥ 3 counts s^{-1})
- γ-ray flares around hard-to-soft or soft-to-hard spectral transitions
- γ-ray flares a few days before major radio flares

Hadronic gamma-rays

The protons are accelerated in the jet with the maximum energy defined from $r_L \leq R_{jet}$

At some distance from the compact objet proton can escape from the jetand interact

with cold protons from the wind of WR star producing gamma-rays and neutrinos.

Required jet power: L_{jet} – the luminosity of relativistic protons-> $L_p = \kappa L_{jet}$

The gamma-ray luminosity- $L_\gamma = c_{p\to\gamma} L_p \Rightarrow L_\gamma = \kappa c_{p\to\gamma} L_{jet} = \eta L_{jet}$

Assuming 10% efficiency of proton acceleration, $c_{p\to\gamma} = 0.1$ and $L_\gamma \approx 10^{36} erg\, s^{-1}$

Jet power- $L_{jet} \approx 10^{38} erg\, s^{-1}$ -lower than the Eddington accretion limit.

The modulated gamma-rays are produced only if the protons are confined in the binary

system in time scales less than *otherwise the protons will escape* from the binary

system. Considering 4.8 hr modulation of gamma-ray, the condition is satisfied only for the

densities *n greater than* $\geq 6\times 10^{12}\, cm^{-3}$

Accordingly, this condition is satisfied only in the superior conjunction

Absorption

The gamma-ray produced from *pp* interaction are effectively absorbed by stellar photon field and this absorption depends strongly on the geometry. It will vary depending upon the relative location of the source of gamma-rays, the companion star and observer.
In this case we used averaged over the injection angles opacity which depends on the distance (r) from the star where it is created.

Opacity of gamma-gamma interaction

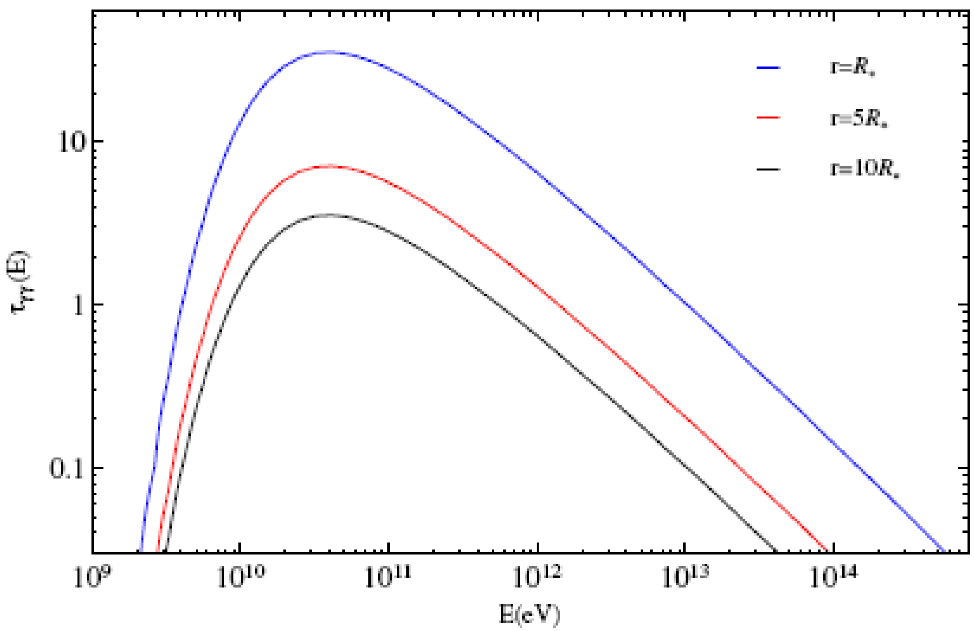
$$\tau_\gamma(E_\gamma, r) = \int_r^\infty \int_{\epsilon_{min}}^\infty n(\epsilon_0, r')\sigma_{\gamma\gamma}(\epsilon_0, E_\gamma) d\epsilon_0\, dr'$$

Distribution of stellar photon field

$$n(E_{\epsilon_0}, r) = \frac{2\pi\epsilon_0^2}{(h\,c)^3}\frac{1}{e^{\epsilon_0/k\,T_{\rm eff}} - 1}\frac{R_\star^2}{r^2}$$

For the parameters:

$$T_{eff} = 10^5\,K \quad and \;\; R_* = 6\times 10^{10}\,cm \Rightarrow$$



(NS,Piano and Tavani ApJ 2014)

Proton spectrum

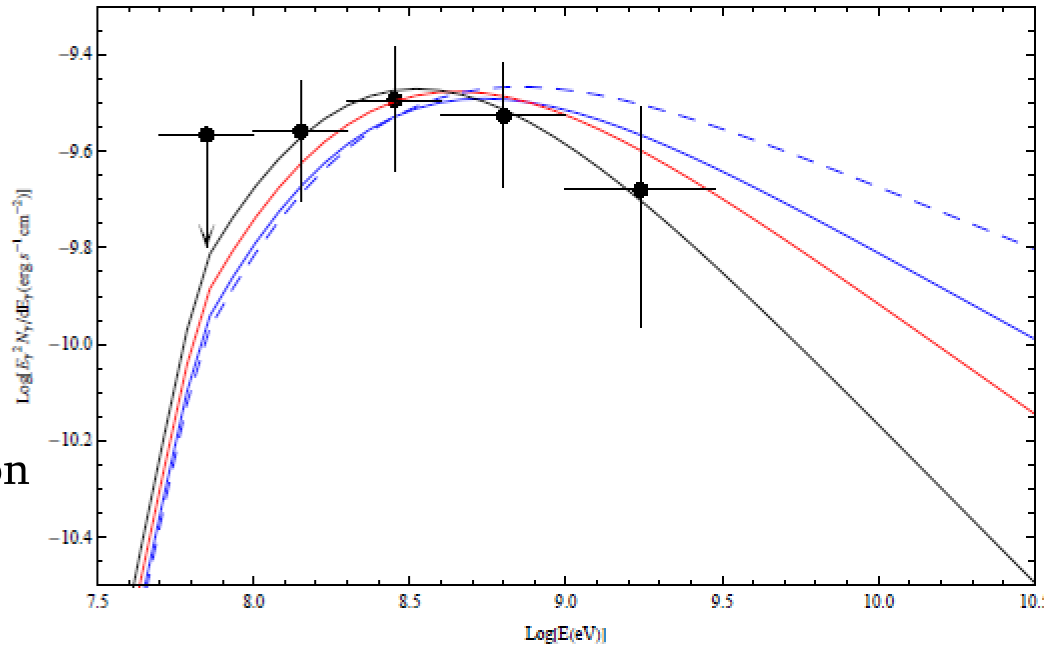
It is assumed a power-law with exponential cut off for proton distribution: $N_p(E_p) \sim E_p^{-\alpha} exp(-\frac{E_p}{100TeV})$

The maximum of gamma-gamma interaction cross section at $\varepsilon E/(mc^2)^2 \approx 4$ *the absorption of GeV gamma*-rays will be effectively in X-ray photon field. Since the gamma-rays are produced farther from the compact object -> density of X-ray photon field is low-> GeV photons escape the region.

Using the AGILE data limit on the power-law index:

$$\alpha \geq 2.4$$

For the smaller PL index, over prediction of gamma-ray data.

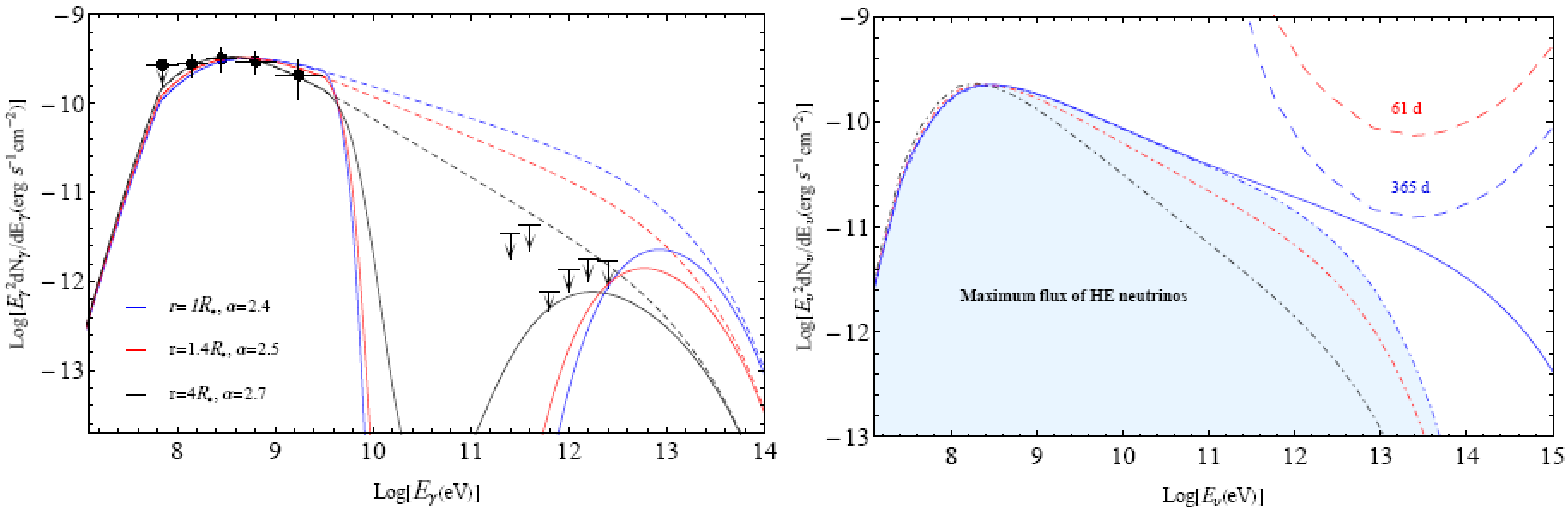


(NS,Piano and Tavani ApJ 2014)

Hadronic gamma-rays and neutrinos

The spectrum of accelerated protons in Cygnus X-3 in the flaring period are softer that ~2.4 and this corresponds to maximum flux of HE neutrinos.

This model predicts: $@1\,TeV - F_{\nu} = 8\times10^{-12} TeV^{-1} cm^{-2} s^{-1}$ less than IceCube sensitivity after 1 year operation. Short time period of gamma activity + strong background events-> no neutrinos are detected.



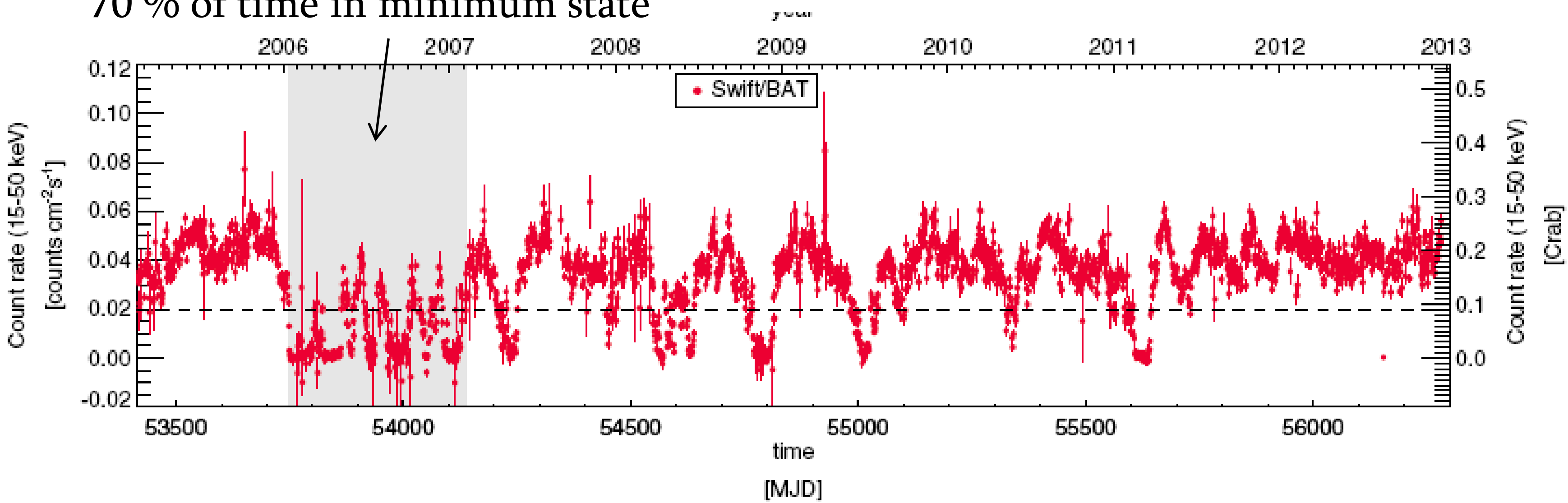
(NS,Piano and Tavani ApJ 2014)

Longer gamma-ray emission ?

Assuming spectrum reaching PeV energies- $\frac{f_{10TeV}}{f_{sens}} \approx 0.3$

Therefore only a hard proton injection rate $\alpha < 2.4$ can produce a detectable flux

70 % of time in minimum state



These considerations show how Cyg X-3 is a crucially interesting source, not only for radio-to-γ -ray observations, but also for new-generation neutrino detectors.

(NS, Piano and Tavani ApJ 2014)

Conclusions

- Knowing the flux of HE gamma-rays (@ 20 TeV or 1 TeV) –conclusion on the detectability of these sources by neutrino detectors can be drown. However, from currently known powerful accelerators SNRs and PWNe – detection of HE neutrinos seems unlikely : RX J1713.7-3946- to be tested with KM3NeT
- Galactic Binary Systems: seem to be right place to search for HE neutrinos. Due to the strong absorption-> maybe surprisingly high flux of HE neutrinos. Example: Cygnus X-3- extreme particle accelerator- hadronic origin-neutrino detection for long time flaring periods.

Thank you !