High energy gamma-rays and neutrinos from Cygnus X-3

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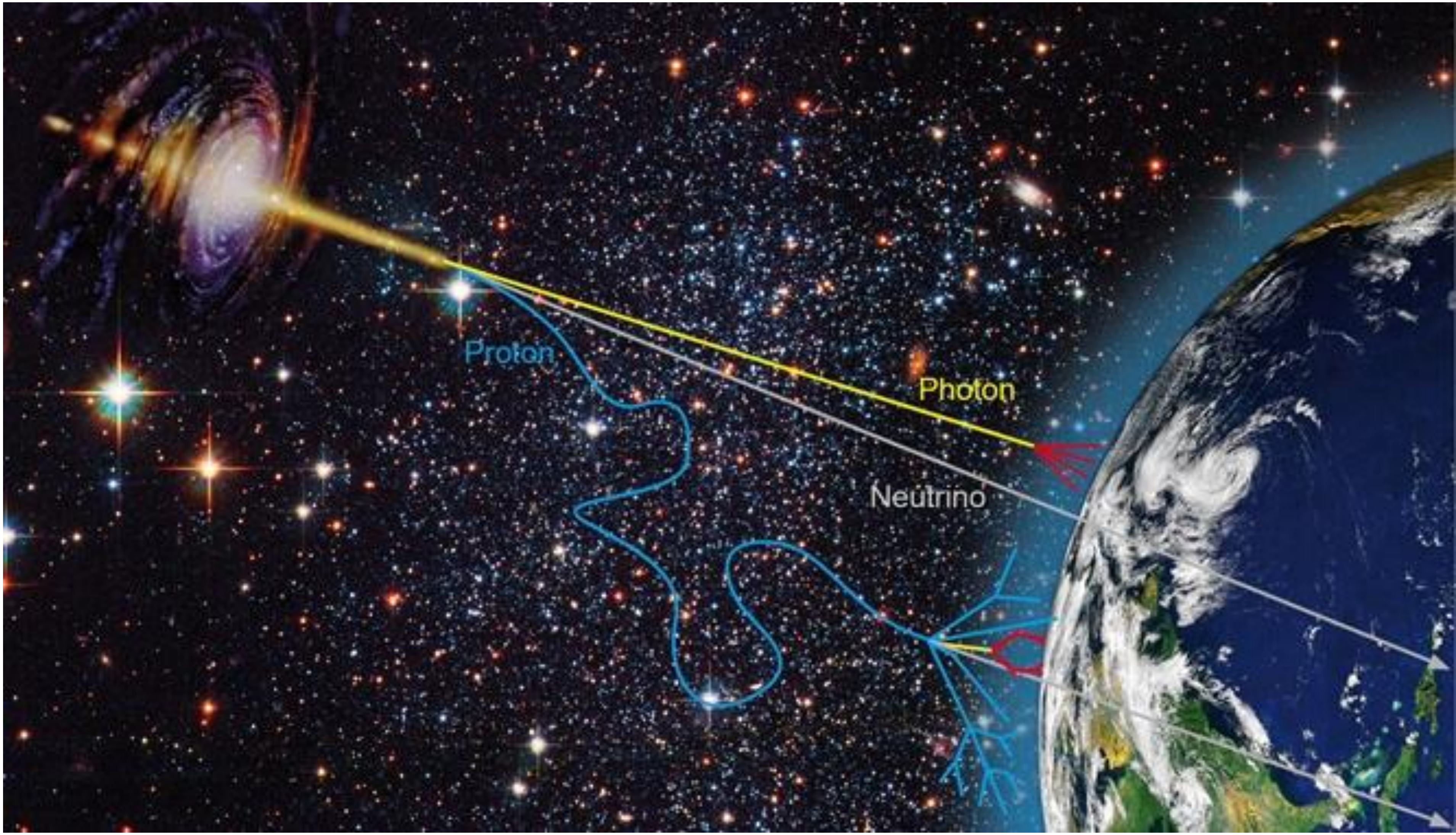
Outline

- Nonthermal messengers: why HE neutrinos ?
- Sources of high energy neutrinos
- HE neutrinos from SNRs: why binary systems ?
- Cygnus X-3: transient gamma-rays from Cyg X-3
- Hadronic gamma-rays and neutrinos from Cyg X-3
- Conclusion

Nonthermal messengers



HE neutrinos

Proton-proton interaction

Accelerated protons interact with low density plasma $\Rightarrow$ pions are generated. Neutral pion decays to two photons and charged pions decays producing neutrinos:

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

Proton-gamma interaction

Accelerated protons interact with photon field. In this case also neutral and charged pions are produced and from their decay photons and neutrinos are produced.

In both cases effective acceleration of protons is required.

Sources of HE neutrinos

For production of HE neutrinos (>1 TeV) the source should accelerate the protons to the energies above TeV. From the known sources not all can accelerate protons above TeV energies, therefore the number of sources producing HE neutrinos is limited.

The first sample of the powerful sources are SNRs:

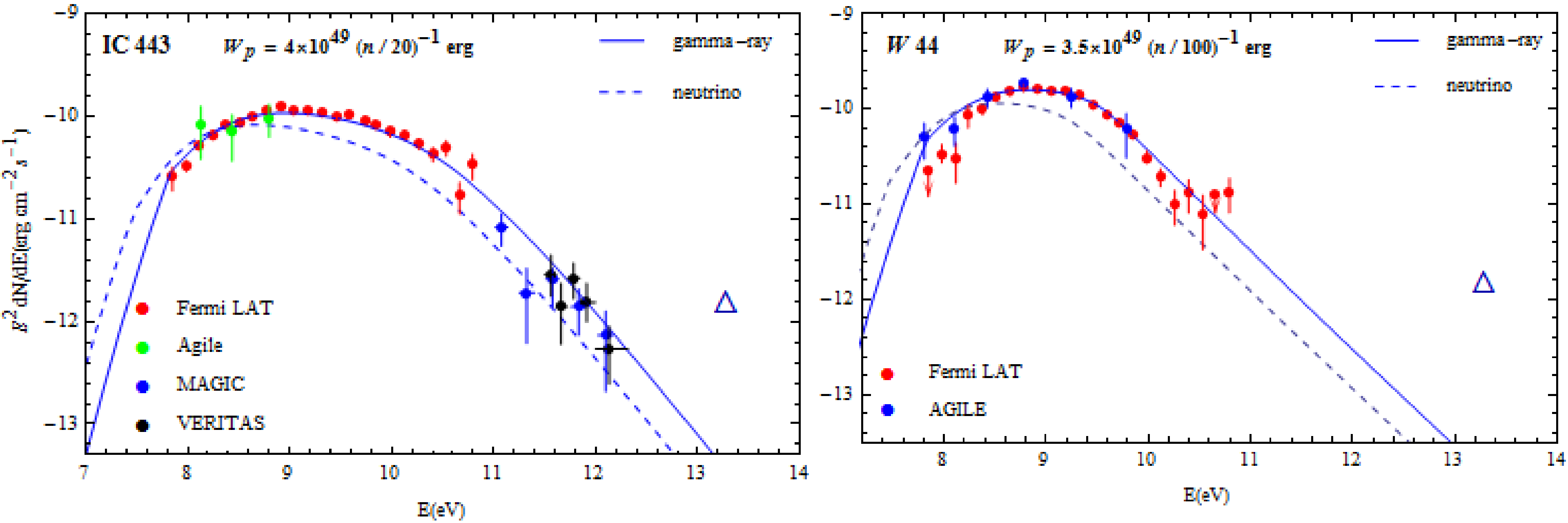
i) Effective acceleration of protons (up to 100 TeV)

ii) molecular clouds in the vicinity of SNR serve target for effective pp interaction

and relatively close distance makes SNRs potential sources of HE neutrinos.

But can we detect this neutrinos ?

SNRs

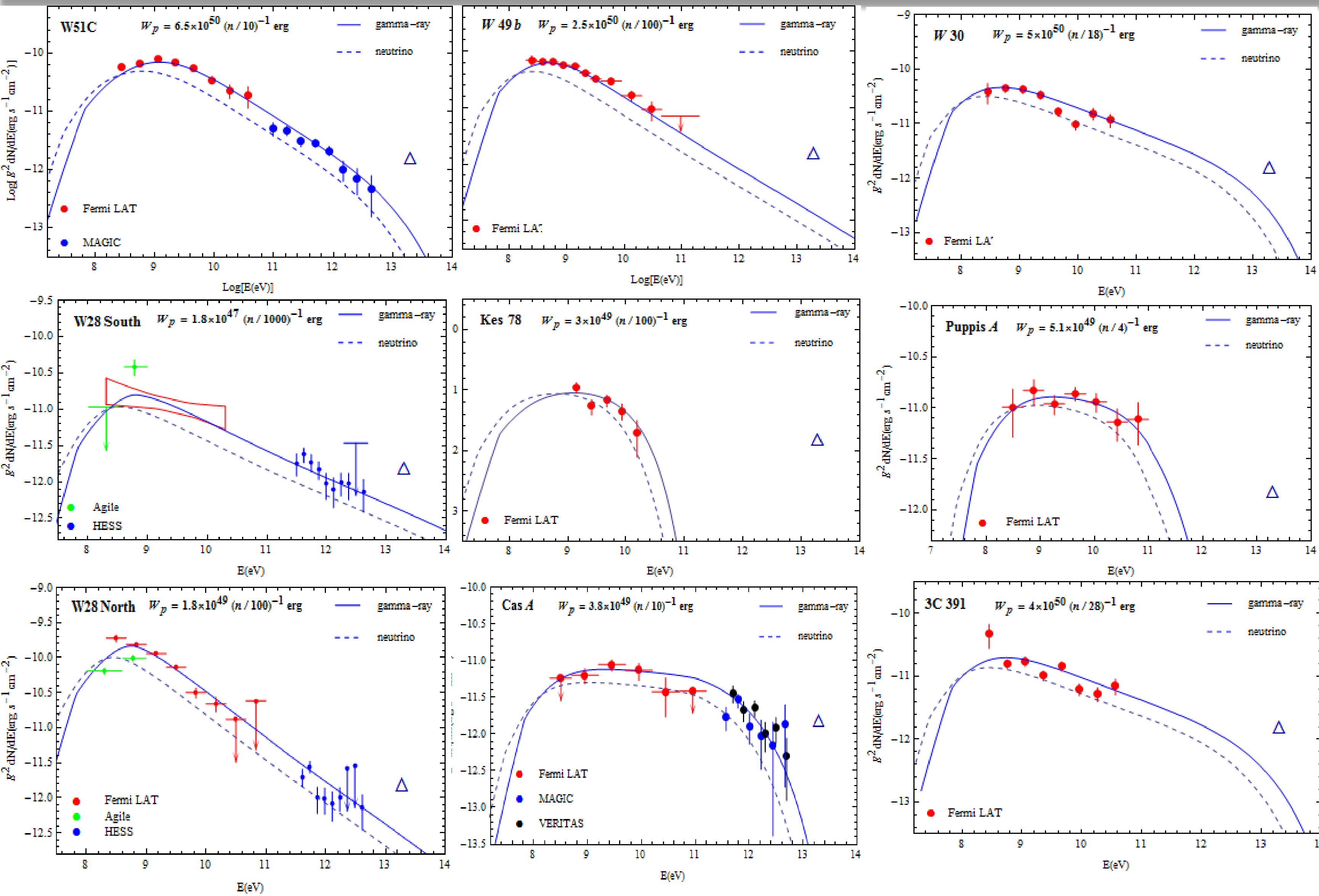


△ -characterizes the region of energies and of intensities where the *gamma*-ray observations are more relevant for the high energy neutrino detectors (when when accompanying flux of HE neutrinos can be detected with current instruments, Vissani, Aharonian and Sahakyan (2011) (1 neutrino in 1 year in 1kmxkm))

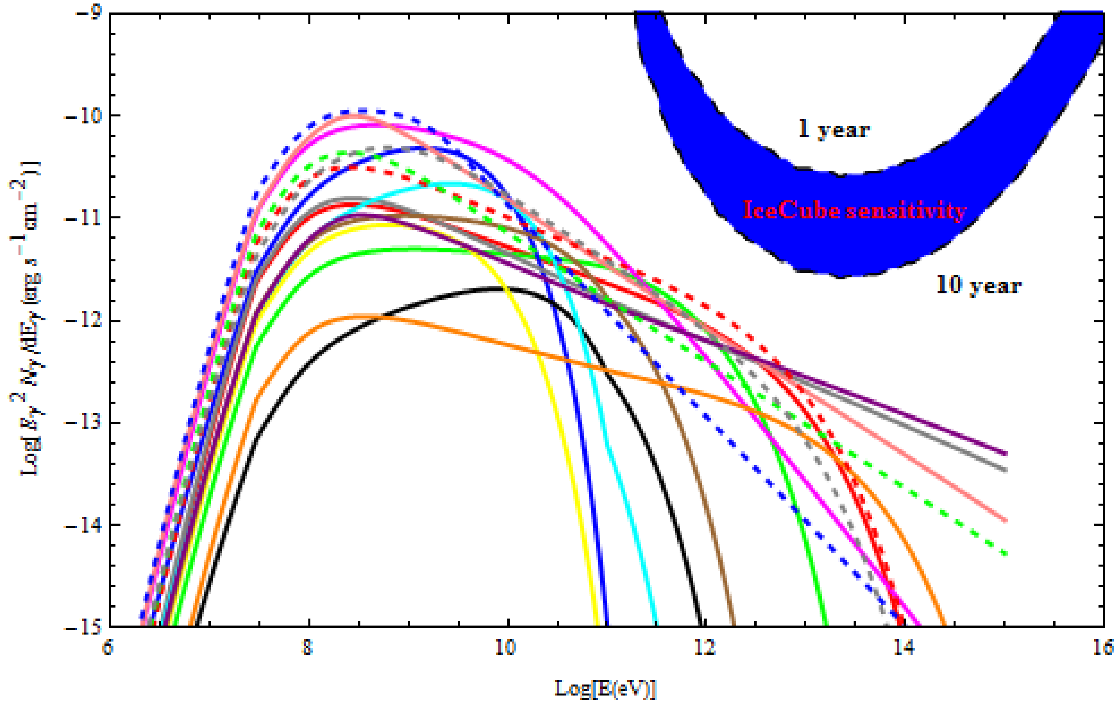
For both SNRs the gamma-ray flues are below than the limit derived in Vissani, Aharonian and Sahakyan (2011).

The same results for the other known SNRs detected in gamma-rays (almost for all)

SNRs examples



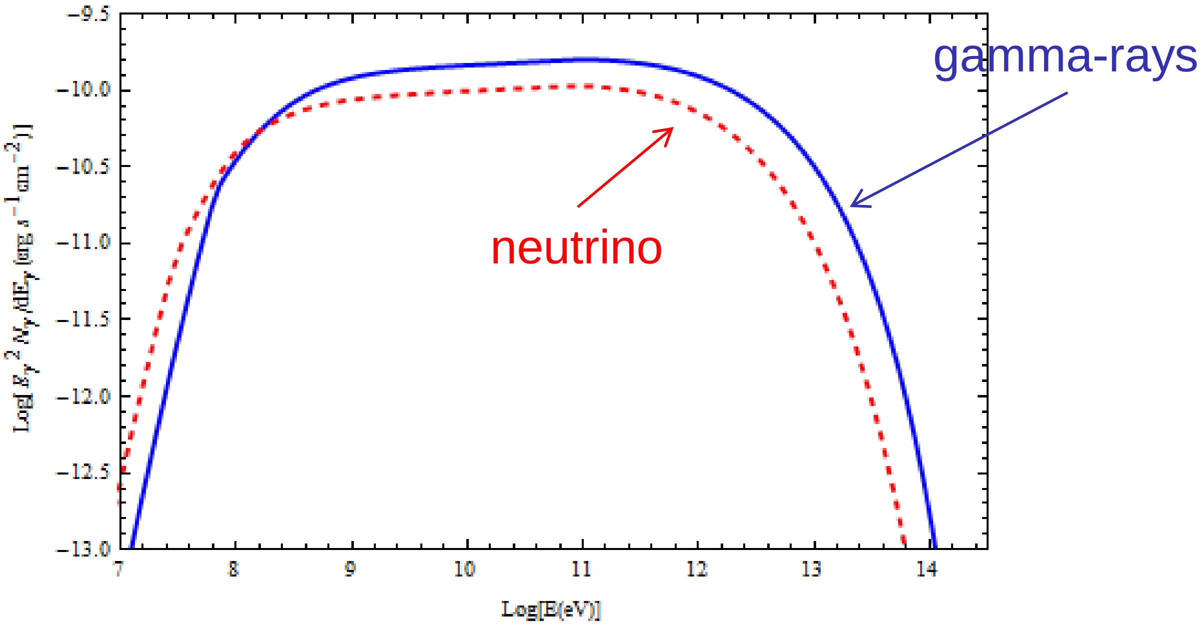
HE neutrino flux vs IceCube sensitivity



All the fluxes of HE neutrinos (estimated using gamma-ray) data are below than IceCube sensitivity. Even for 10 year exposure time is not enough for the detection of HE neutrinos.

➢ Search HE neutrinos from other sources, e.g. binary systems (microquasars), systems with luminous optical star and a compact object. Recent observations demonstrate that these objects are sites of effective acceleration of particles to GeV/TeV energies.

No absorption



In the absence of absorption photon neutrino ratio is approximately 1 thus gamma-rays flux can be used for the estimation of HE neutrino flux.

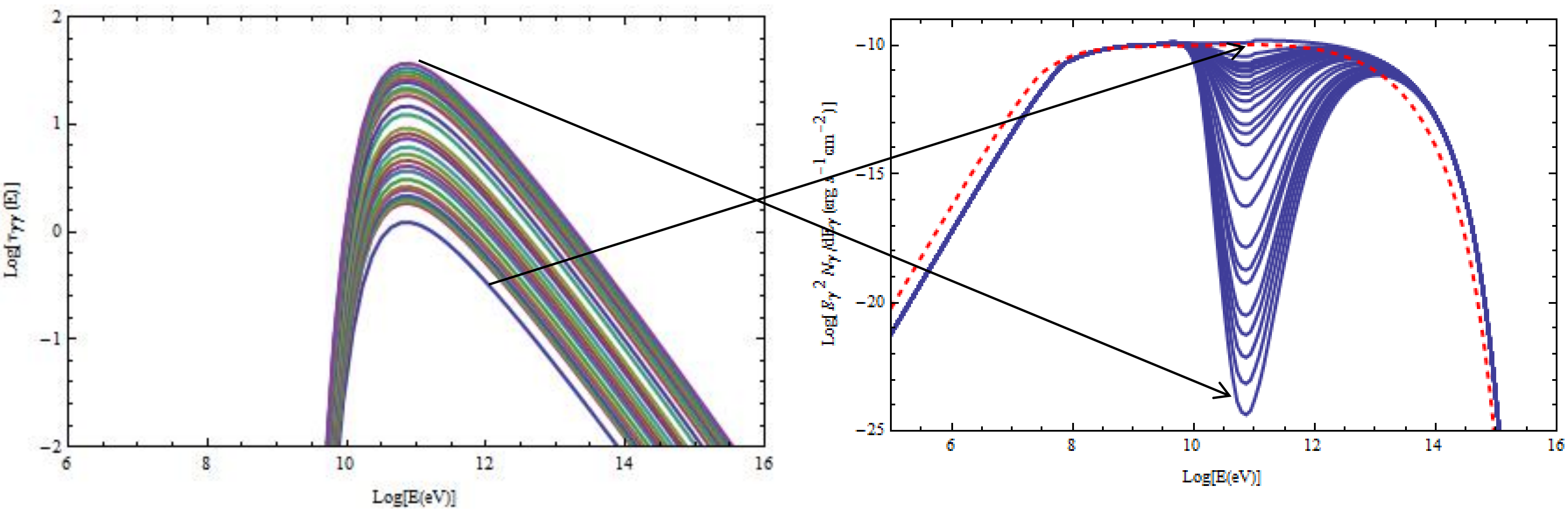
Instead with the absorption, no connection between gamma-ray and neutrino fluxes.

The opacity of photon-photon pair production averaging over the injection angles:

$$\tau_\gamma(E_\gamma, r) = \int_r^\infty \int_{\epsilon_{min}}^\infty n(\epsilon_0, r')\sigma_{\gamma\gamma}(\epsilon_0, E_\gamma)d\epsilon_0\, dr'$$ for the BD distribution $$n(E_{\epsilon_0}, r) = \frac{2\pi\epsilon_0^2}{(h\,c)^3}\frac{1}{e^{\epsilon_0/k\,T_{\rm eff}} - 1}\frac{R_\star^2}{r^2}$$

For the parameters similar to the Cygnus X-3 : $T_{eff} = 10^5\,K \quad and \;\; R_* = 6\times10^{10}\,cm \Rightarrow$

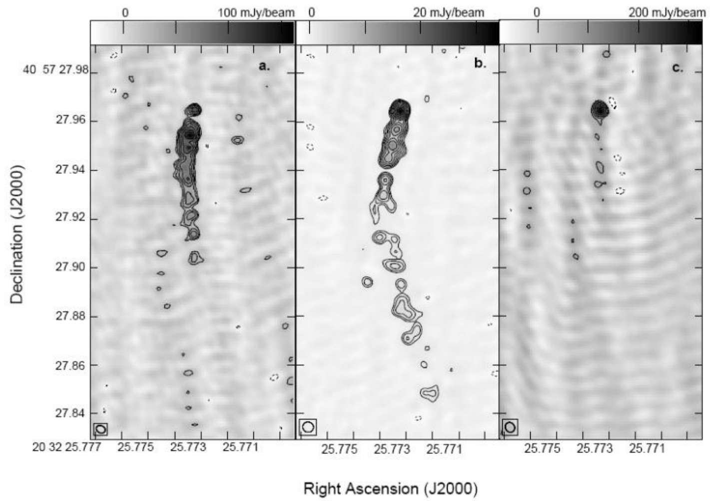
Absorption



The flux of gamma-rays is suppressed due to absorption, instead the neutrino flux remains constant. Maybe surprising high flux of HE neutrinos.

Cygnus X-3

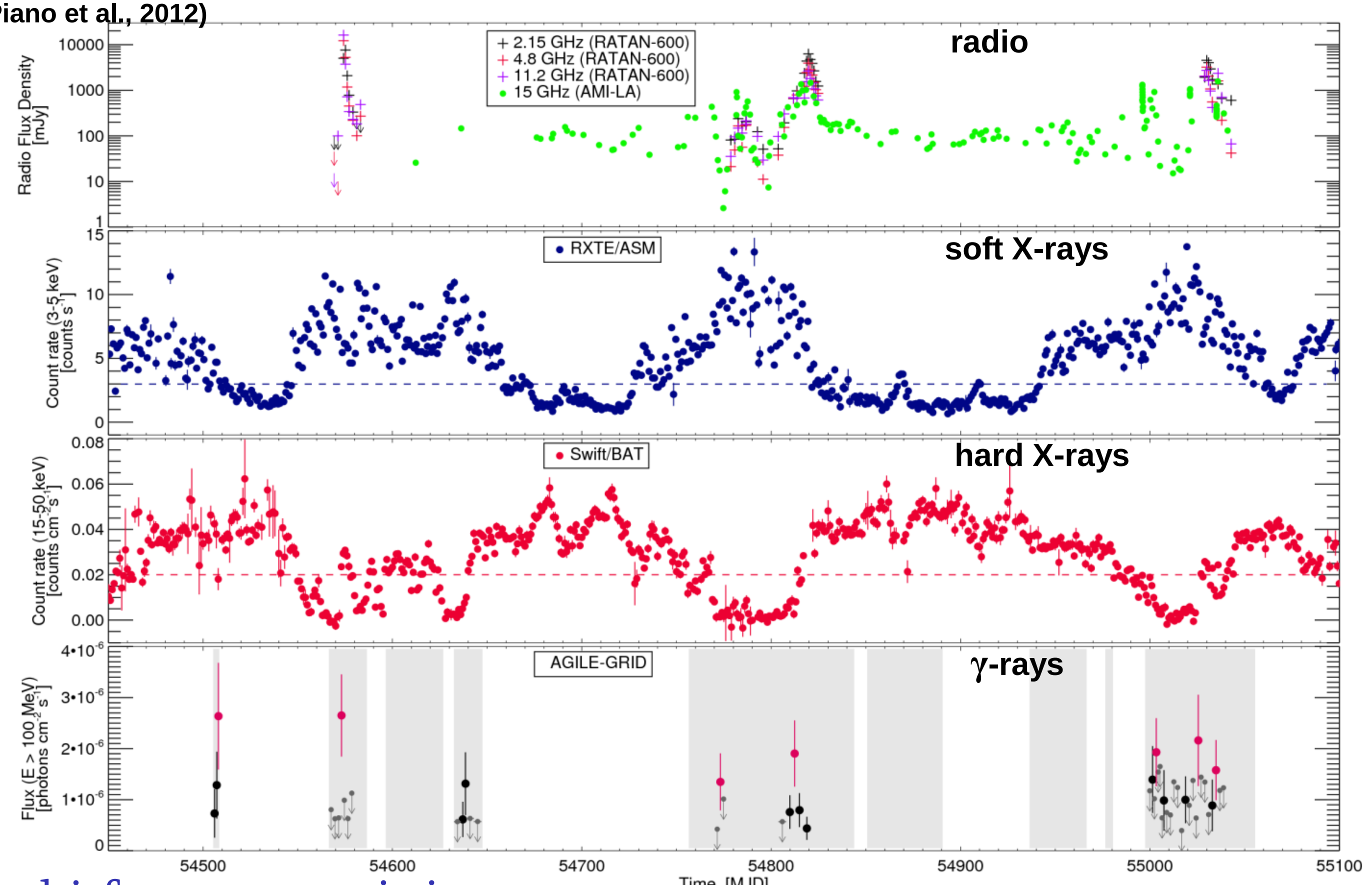
- high-mass X-ray binary discovered, as an X-ray source, in 1966 (Giacconi et al. 1967)
- distance -> 7-10 kpc
- compact object - UNKNOWN. or Neutron Star of 1.4 solar mass or a Black Hole with up to10 solar mass
- donor Star -> Wolf-Rayet star with strong stellar wind
- orbital period (X-ray, Infrared, 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

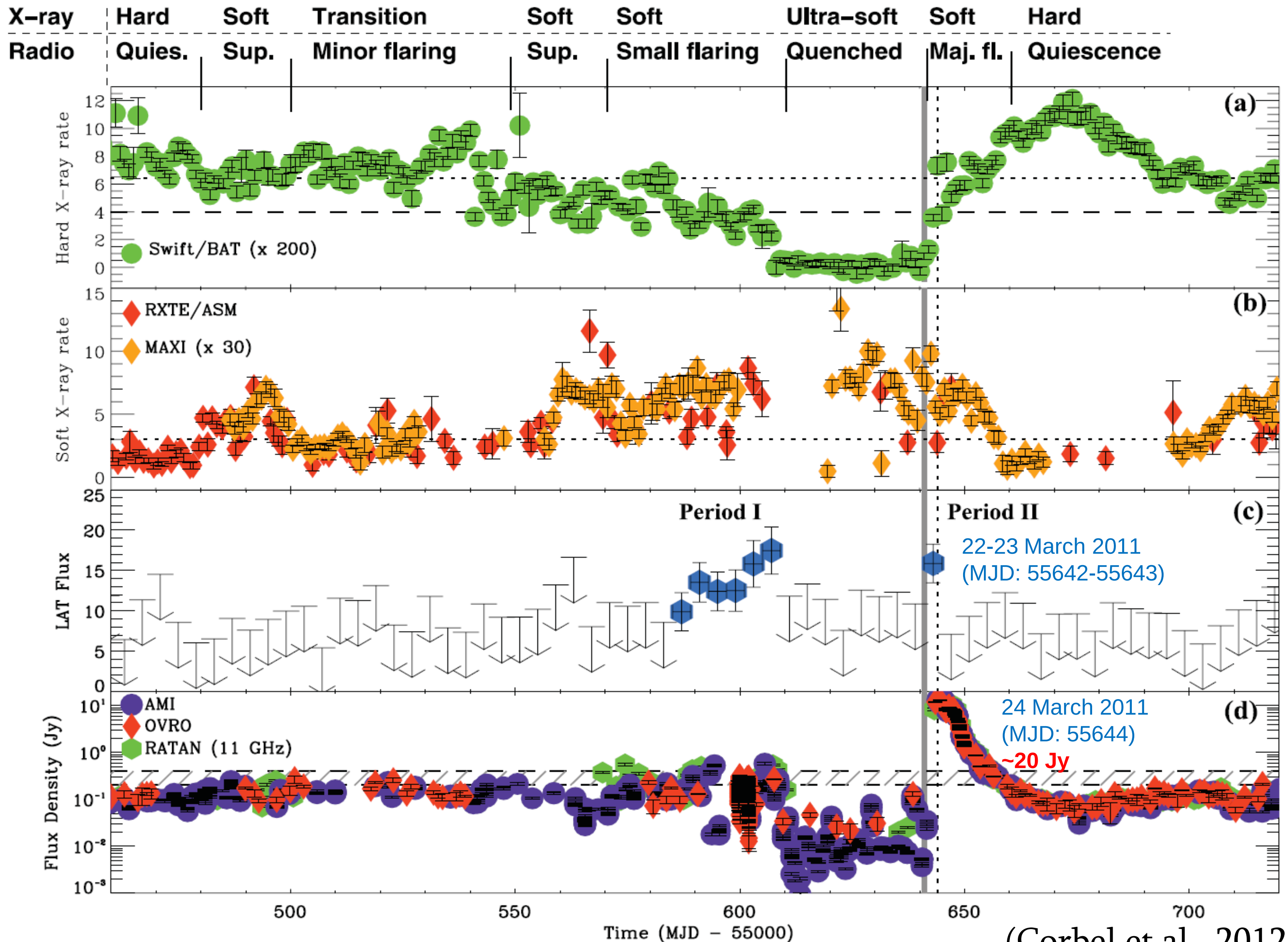
(Piano et al., 2012)



Repetitive multi-frequency emission pattern:

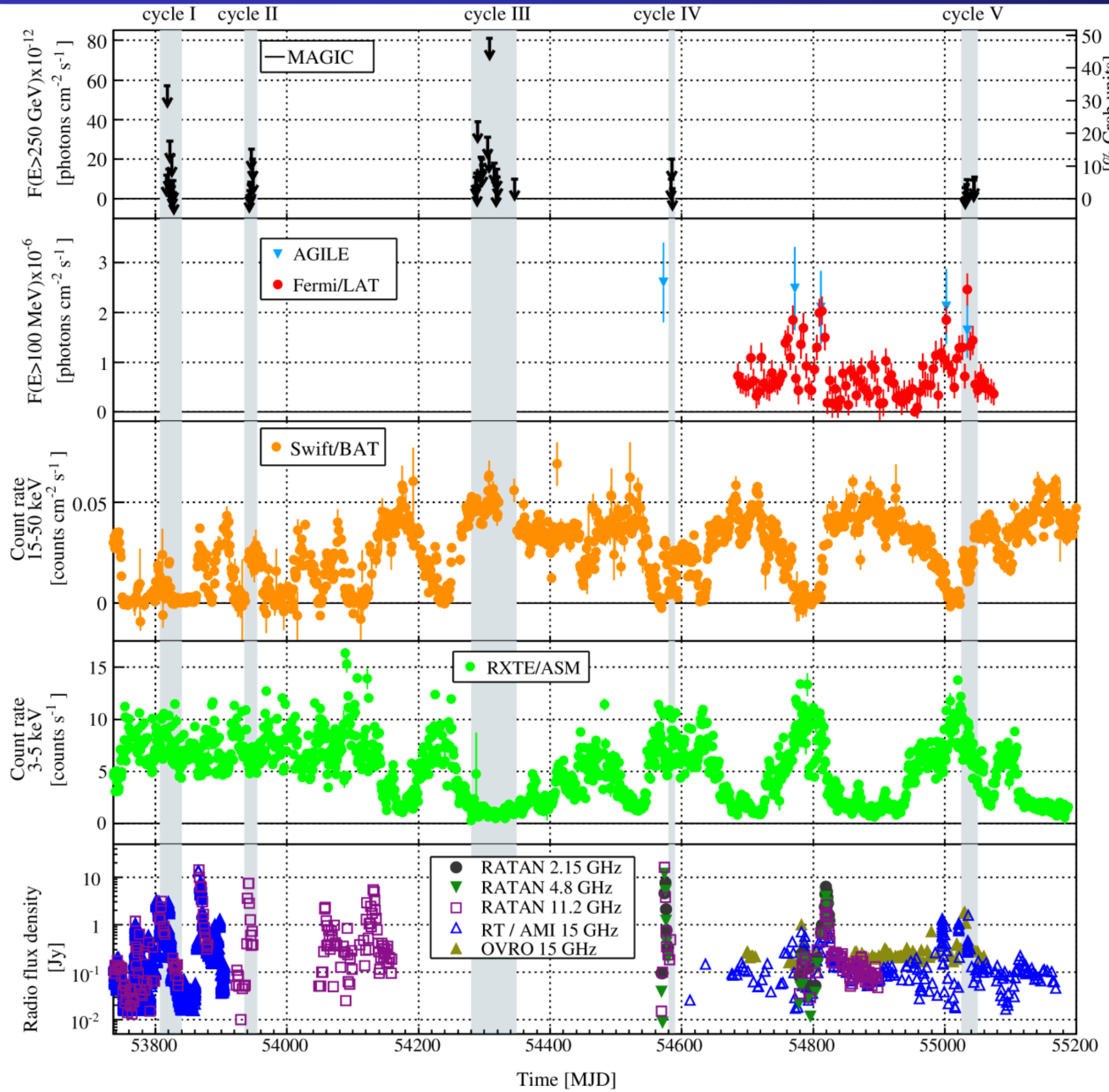
- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission:
- γ -ray sharp/local minima in the hard X-ray light curve (*Swift*/BAT count rate ≤ 0.02 counts cm^{-2} s^{-1})
- γ-ray flares coincident with soft spectral states (*RXTE*/ASM count rate ≥ 3 counts s^{-1})
- γ-ray flares around hard-to-soft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

Fermi LAT observation of Cygnus X-3



(Corbel et al., 2012)

MAGIC observation of Cygnus X-3



Magic observed Cygnus X-3 for about 70 hr between 2006 March and 2009 August in different X-ray/radio spectral states and also during a period of enhanced gamma-ray emission.

An upper limit to the integral flux for energies higher than 250 GeV has been set to

$$2.2\times10^{-12}\ photons\ cm^{-2}s^{-1}$$

(Aleksic et al., 2010)

IceCube observation of Cygnus X-3

Recently, IceCube collaboration reported on searches for neutrino sources at energies above 200 GeV in the Northern sky of the Galactic plane, using the data collected by the South Pole neutrino telescope, IceCube, and AMANDA.

The searches in the Cygnus region were performed during, or close to, the observed flaring activity in Cygnus X-3.

With a maximum likelihood test using a time-dependent version of the unbinned likelihood ratio method no evidence of a signal is found and upper limits are reported.

The upper limits on E^{-2} *and* E^{-3} spectrum are:

$$\frac{d\Phi_{\nu_\mu}}{dE} \leq 0.7\times10^{-11}\left(\frac{E}{1TeV}\right)^{-2} TeV^{-1}cm^{-2}s^{-1} \quad \text{and} \quad \frac{d\Phi_{\nu_\mu}}{dE} \leq 5\times10^{-11}\left(\frac{E}{1TeV}\right)^{-3} TeV^{-1}cm^{-2}s^{-1}$$

(Abbasi et al. 2013)

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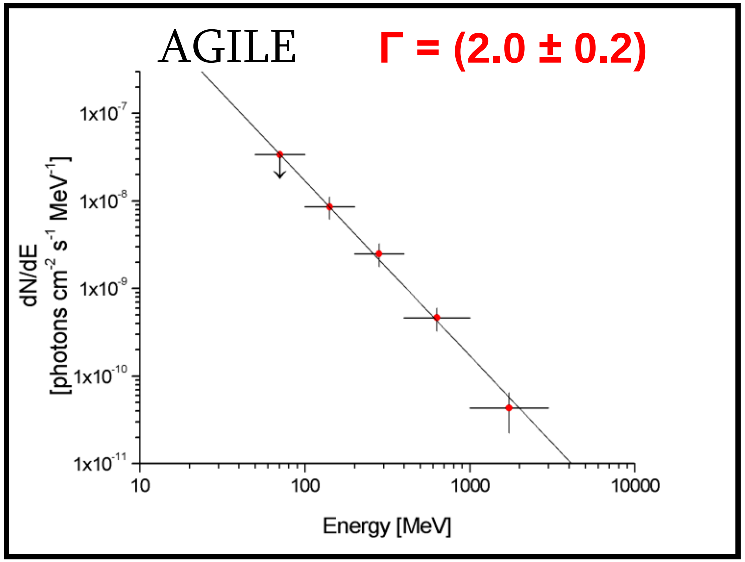
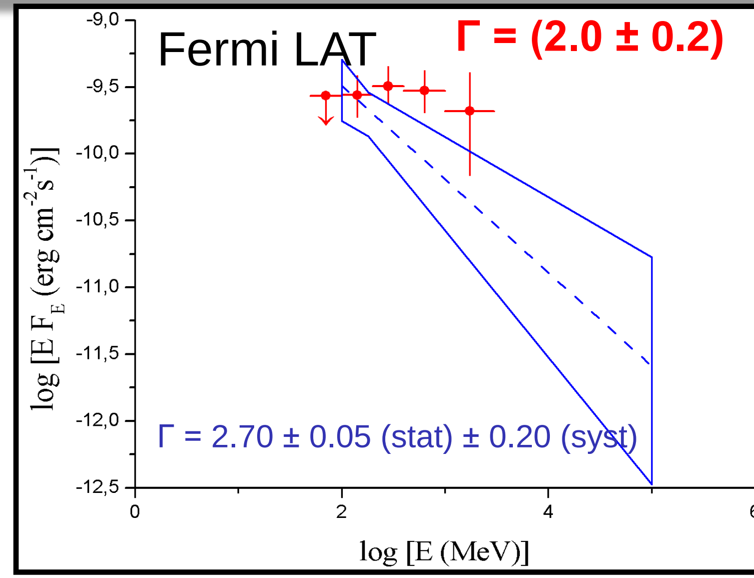
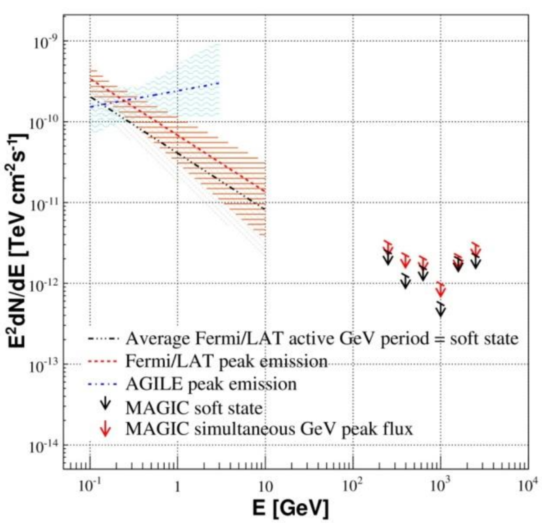






Upper limits from IceCube

Gamma-rays from Cygnus X-3-1

Star:

L ~ 10^{39} erg/s

Disk:

T_{bb} ~ 1.3 keV

Spherical plasmoid:

r ~ $3{\cdot}10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e\,\gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

Geometry of the interaction:

(d ≡ orbital distance)

(R ≡ star-blob distance)

(H ≡ disk-blob distance)

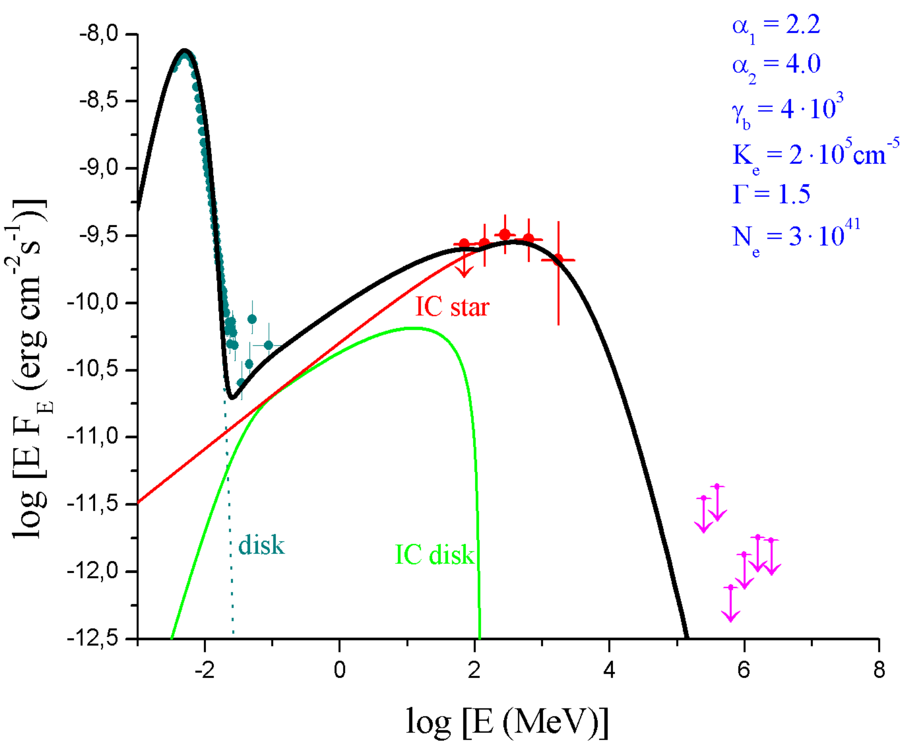
H ~ $3{\cdot}10^{10}$ cm ~ 10^{-1} d

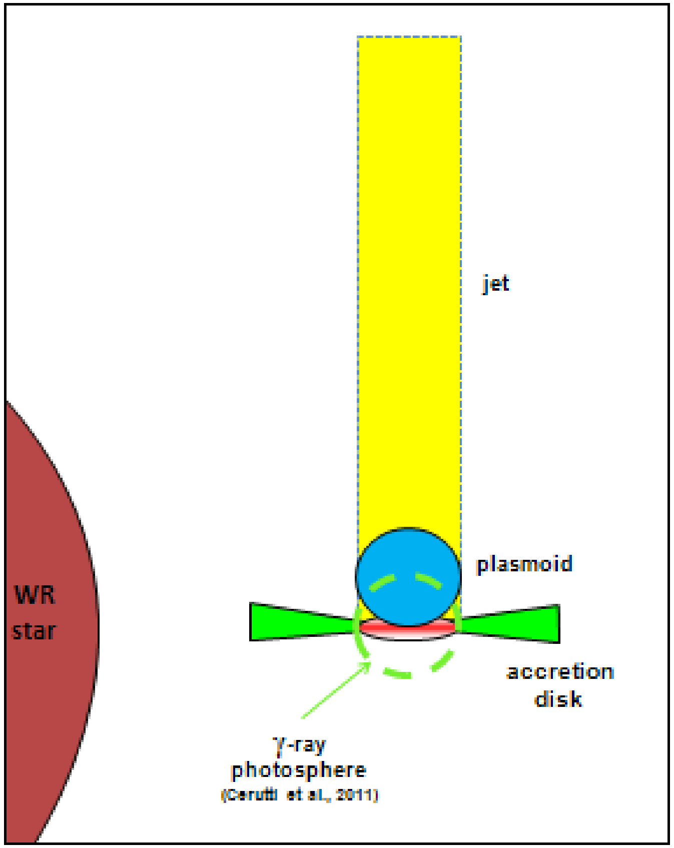
R ~ d ~ $3{\cdot}10^{11}$ cm

(plasmoid close to the disk)

i = 14°

electron density ~ $3{\cdot}10^{9}$ cm^{-3}





$L^{A}_{kin,\,e} \approx 2 \times 10^{35}$ erg s^{-1} (Piano et al., 2012)

Gamma-rays from Cygnus X-3-2

Star:

L ~ 10^{39} erg/s

Disk:

T_{bb} ~ 1.3 keV

Spherical plasmoid:

r ~ $3 \cdot 10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

Geometry of the interaction:

(d ≡ orbital distance)

(R ≡ star-blob distance)

(H ≡ disk-blob distance)

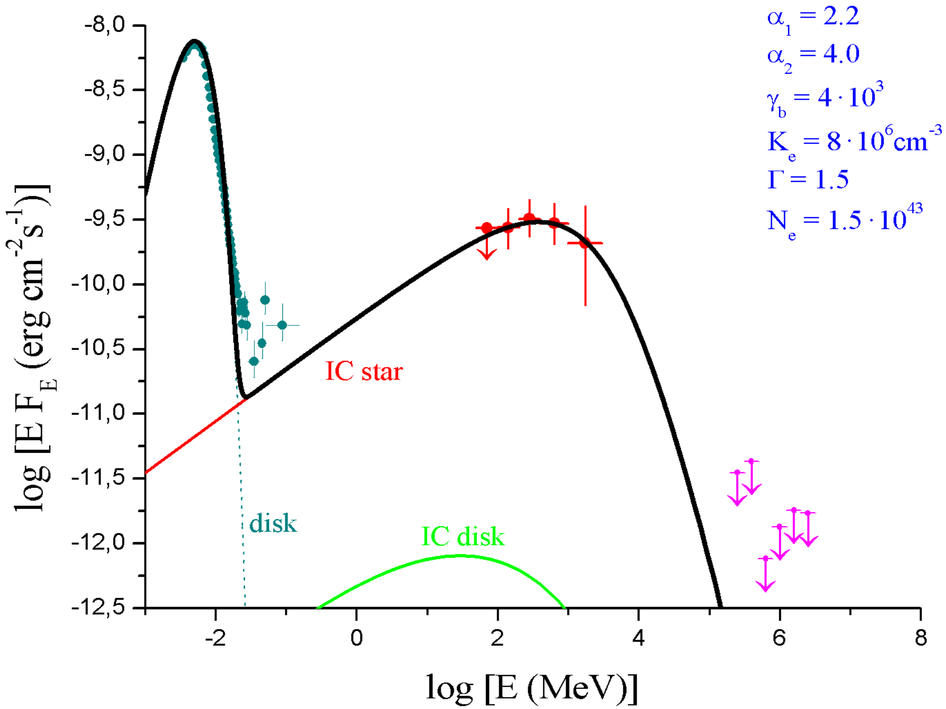
H ~ $3 \cdot 10^{12}$ cm ~ 10 d

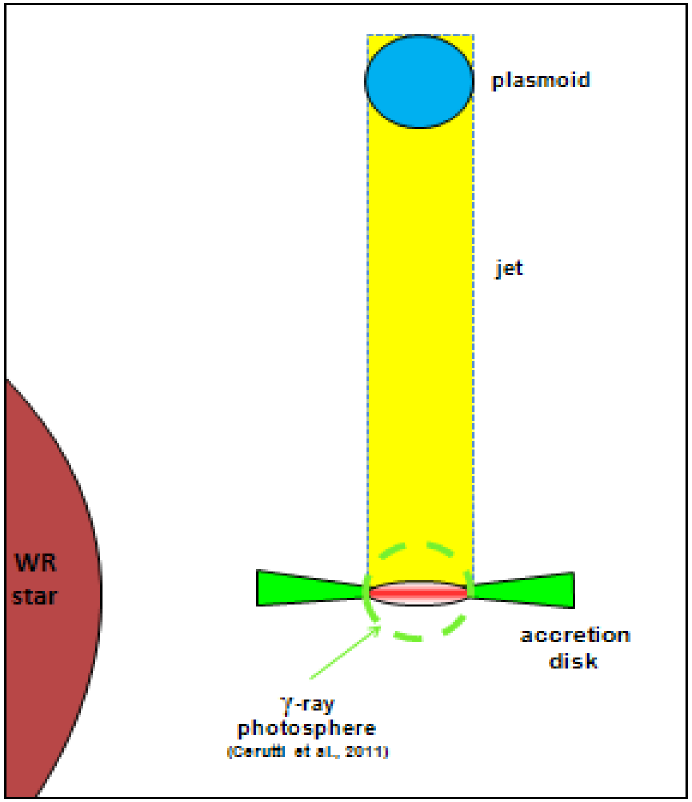
R ~ H ~ $3 \cdot 10^{12}$ cm

(plasmoid far away from the disk)

i = 14°

electron density ~ $1.5 \cdot 10^{11}$ cm^{-3}





$$L^B_{kin,\, e} \approx 10^{37} \text{ erg s}^{-1}$$

(Piano et al., 2012)

Hadronic gamma-rays

Transient gamma-rays detected by AGILE and Fermi LAT can have also hadronic origin as discussed in (Piano et al., 2012) if so Cygnus X-3 can be source of HE neutrinos.

Model: in the hadronic scenario modulation of gamma-rays can be explained due to the variation of the density of the wind -> inhomogeneous wind. The necessary condition is that the cooling time of pp interaction should be less than 4.8 hr which is valid for a wind proton density:

$$t_{pp} \leq 4.8\,h \Rightarrow n \geq 1.15 \times 10^{11}\,cm^{-3}$$

Accordingly, this condition must be satisfied in the superior conjunction, while in the other positions along the orbit, the density of the wind should be significantly lower.

(Sahakyan,Piano and Tavani 2013, in preparation)

Hadronic model

We assume that the jet has significant population of protons.

These protons can be cold in the reference frame of the jet $\Rightarrow \Gamma m_p c^2$ in the frame of BS

The accelerated protons escape from the region due to the drop of B, *then interact* within BS neutral and charged pions are produced:

$$N_p(\gamma) = N_0 \, \gamma^{-\alpha} \exp(-\gamma / \gamma_c)$$

where γ_c is the protons maximum energy.

Using data from AGILE and Fermi LAT observations $\Rightarrow$ spectrum of gamma-rays $\Rightarrow$ are constrain by MAGIC upper limits $\Rightarrow$ the spectrum of protons $\Rightarrow$ flux of HE neutrinos.

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 gamm-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

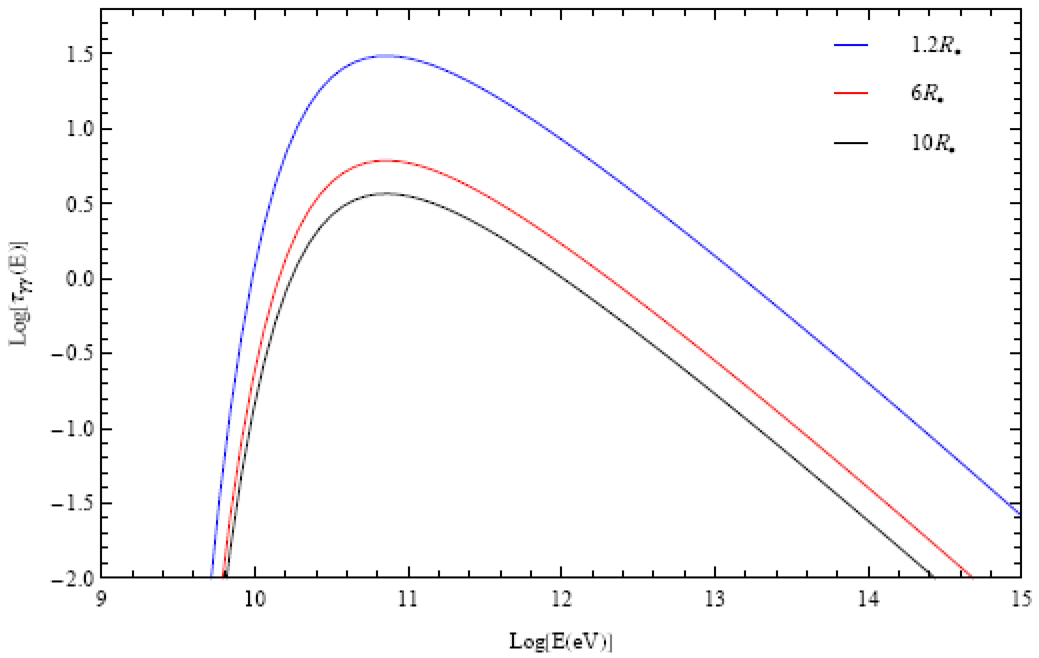
$$\tau_\gamma(E_\gamma, r) = \int_r^\infty \int_{\epsilon_{min}}^\infty n(\epsilon_0, r')\sigma_{\gamma\gamma}(\epsilon_0, E_\gamma) d\epsilon_0\, dr'$$

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:

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



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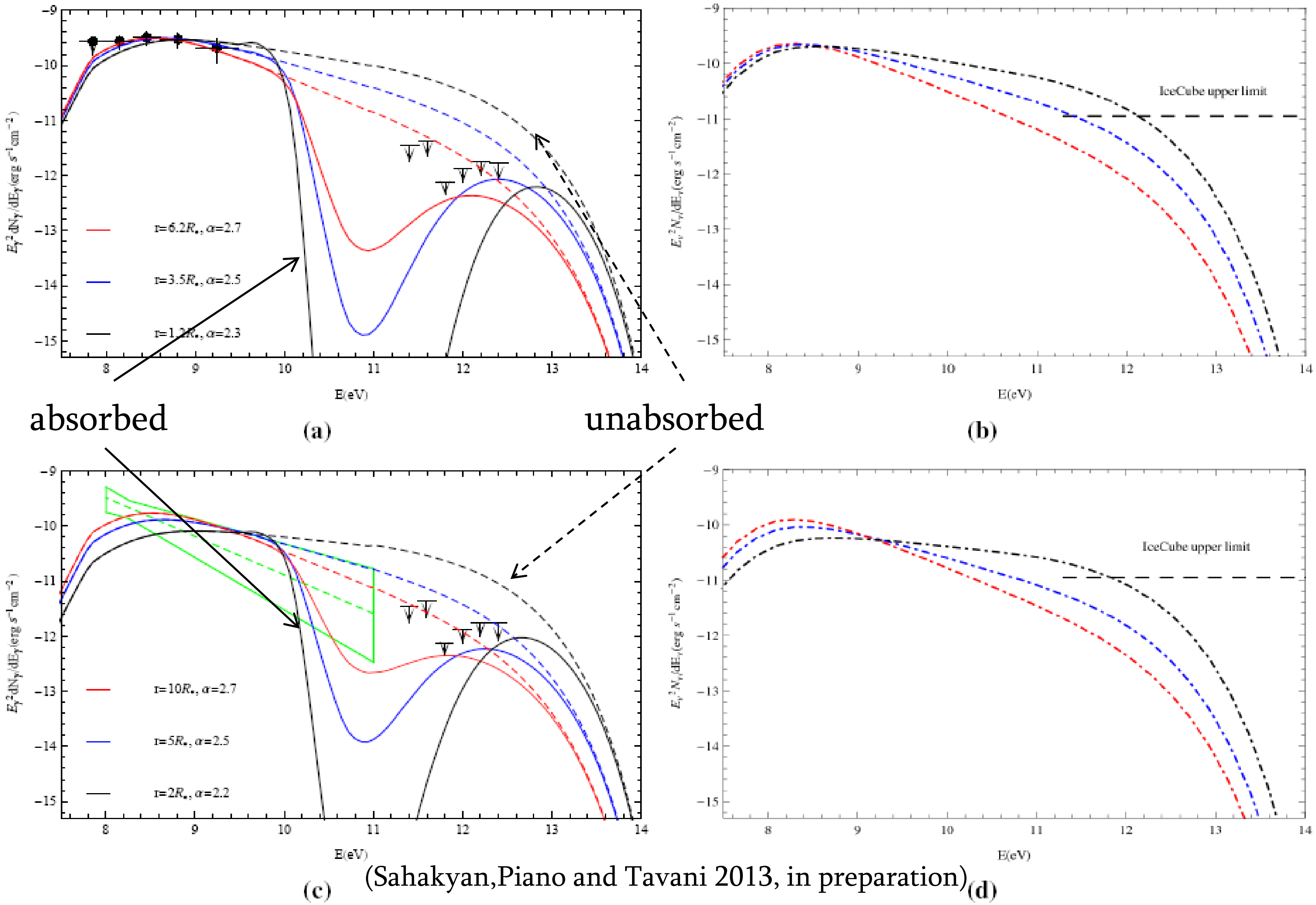


(Sahakyan,Piano and Tavani 2013, in preparation)

Discussion

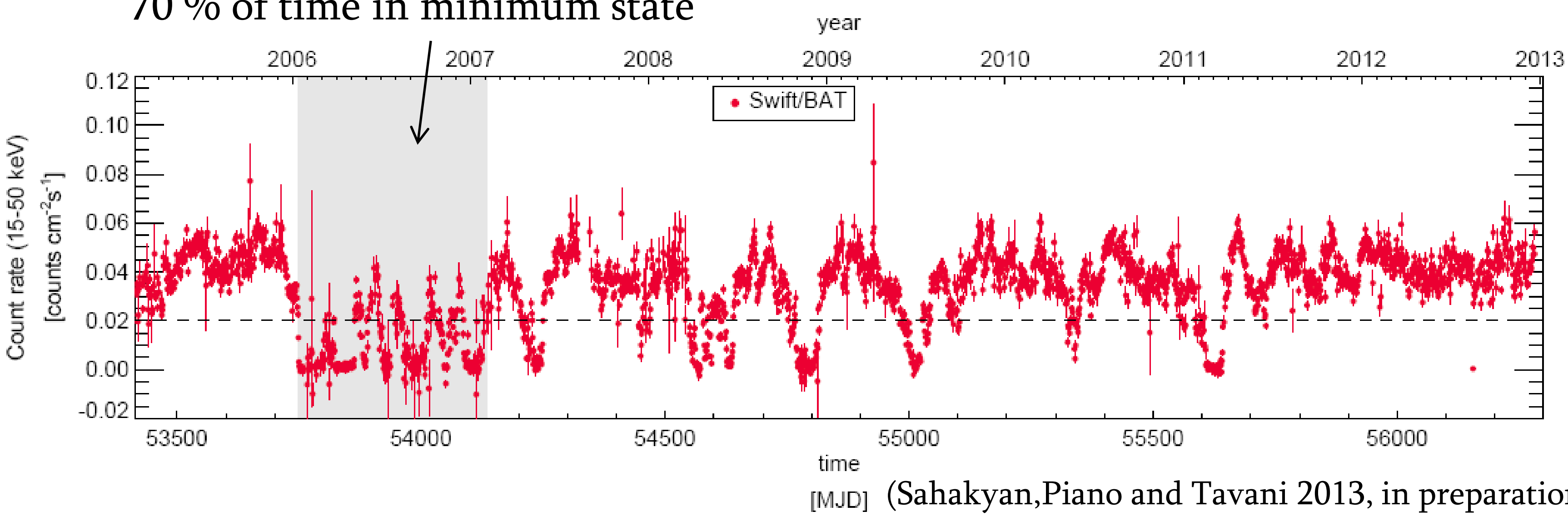
From the above we show that the spectrum of accelerated protons in Cygnus X-3 in the flaring period are softer that ~2.3. Thus using this spectrum of protons the number of neutrino events accumulated in a certain exposure time can be calculated by:

$$N_{\nu_\mu+\bar{\nu}_\mu} \approx T_{exp} \int A^{eff}_{\nu_\mu+\bar{\nu}_\mu} \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE} dE.$$

The number of events corresponding to two-month exposure time (61 day) is 0.028 events $\Rightarrow$ no events of neutrinos. Similar results in the case of pγ found by Baerwald & Guetta 2012.

Possible longer gamma-ray emission ?

70 % of time in minimum state



(Sahakyan,Piano and Tavani 2013, in preparation)

Conclusion

- Detection of HE neutrinos from currently known gamma-ray SNRs seems hardly possible. Situation can be changed with arrival of CTA
- Binary systems can be sources of HE gamma-rays and neutrinos ?
- Transient gamma-rays from Cygnus X-3 can be naturally explained within hadronic scenario
- The current data (AGILE+Fermi LAT) can be explained within hadronic scenario for the proton spectrum softer than 2.3 (considering the absorption of produced gamma-rays).
- In the future possible such flaring event with longer period and full string operation of IceCube makes Cygnus X-3 exciting not only for observations from radio to gamma-ray bands but also for observation for HE neutrinos.