UNIVERSITAT DE BARCELONA

Libertas Perfundet Omnia Luce

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BROAD-BAND EMISSION FROM MICROQUASAR JETS

Cracow, June 26-30, 2006

OUTLINE

1. How many microquasars we know

2. Non-thermal low energy radiation from MQ jets

3. MQ jets as HE and VHE γ-ray sources:
   Theoretical point of view
   Observational point of view

4. Summary

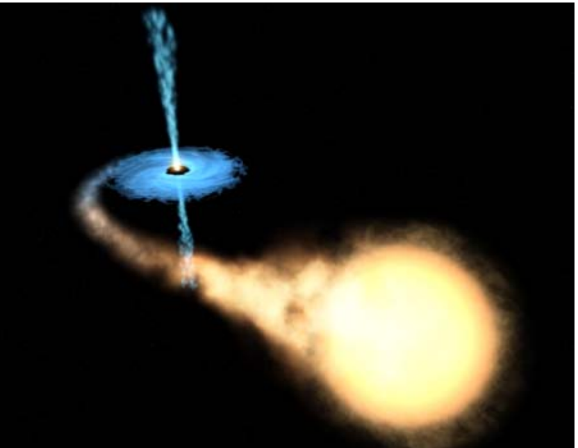
Microquasars: X-ray binaries with relativistic jets

XB: A binary system containing a compact object (NS or a stellar-mass BH) accreting matter from the companion star. The accreted matter forms an accretion disc, responsible for the X-ray emission. A total of 280 XB (Liu et al. 2000, 2001).

HMXBs: (131) Optical companion with spectral type O or B. Mass transfer via decretion disc (Be stars) or via strong wind or Roche-lobe overflow.

LMXBs: (149) Optical companion with spectral type later than B. Mass transfer via Roche-lobe overflow.

280 XB → 43 (15%) REXBs { 8 HMXBs, 35 LMXBs }



At least 15 microquasars

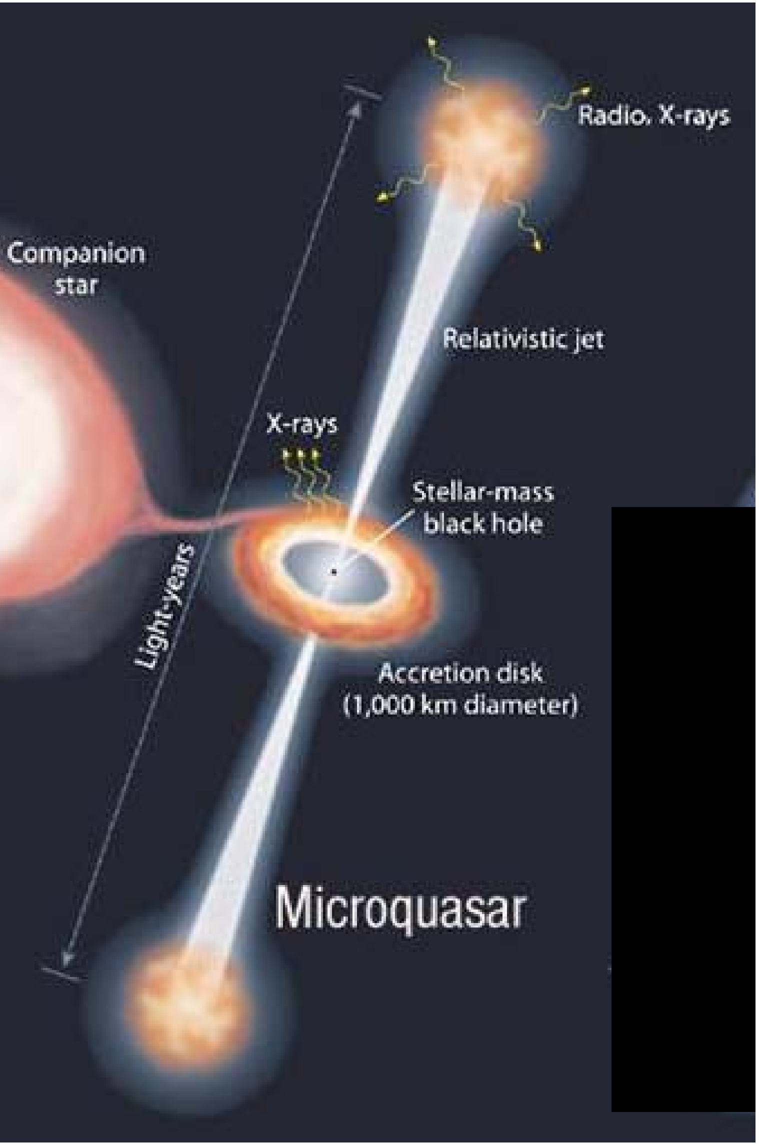
Maybe the majority of RXBs are microquasars (Fender 2001)

MICROQUASARS IN OUR GALAXY **High Energy Detections**

Name	M_{comp} ($M_\odot$)	Radio p/t	Jet β_{app}	Jet Size (AU)	Note	INTEGRAL 30-50 keV (significance)	INTEGRAL 40-100 keV (count/s)	BATSE 20-100 keV (significance)	BATSE 160-430 keV (mCrab)	COMPTEL 1-30 MeV	EGRET >100 MeV	VHE
High Mass X-ray Binaries												
LS I +61 303	–	p	≥ 0.4	10 – 700	Prec ?	–	det.	5.2	5.1 ± 2.1	yes?	3EGJ0241+6103	MAGIC
V4641 Sgr	**9.6**	t	$\geq$ **9.5**	–		–	–	–	–	–	–	
LS 5039	**5.4**	p	0.18	10 – 1000	Prec ?	–	det. ?	10.7	3.7 ± 1.8	yes?	3EGJ1824 – 1514	HESS
SS 433	11±5?	p	0.26	$\sim 10^4 - 10^6$	Prec.	13.5	<1.02	21.7	0.0 ± 2.8	–	–	
			Hadronic, X-ray jet									
Cygnus X-1	**10.1**	p	–	~40		676.6	66.4 ± 0.1	1186.8	924.5 ± 2.5	yes	–	
Cygnus X-3	–	p	0.69	$\sim 10^4$	Radio outb.	122.7	5.7 ± 0.1	197.8	15.5 ± 2.1	–	–	
Low Mass X-ray Binaries												
Circinus X-1	–	t	> **15**	$>10^4$		–	–	3.8	0.3 ± 2.6	–	–	
XTE J1550-564	**9.4**	t	$\geq$ **2**	$\sim 10^3$	X-ray jet	8.6	0.6 ± 0.07	17.1	-2.3 ± 2.5	–	–	
Scorpius X-1	1.4	p	0.68	~40		111.6	2.3 ± 0.1	460.6	9.9 ± 2.2	–	–	
GRO J1655-40	**7.02**	t	**1.1**	8000	Prec?	–	–	40.6	23.4 ± 3.9	–	–	
GX 339-4	**5.8** $\pm$ 0.5	t	–	< 4000		21.9	0.55 ± 0.03	89.0	58.0 ± 3.5	–	–	
1E 1740.7-2942	–	p	–	$\sim 10^6$		147.3	4.32 ± 0.03	92.4	61.2 ± 3.7	–	–	
XTE J1748-288	> 4.5?	t	**1.3**	$> 10^4$		–	–	-12.4	–	–	–	
GRS 1758-258	–	p	–	$\sim 10^6$		135.9	3.92 ± 0.03	74.3	38.0 ± 3.0	–	–	
GRS 1915+105	**14** $\pm$ 4	t	**1.2** – 1.7	$\sim 10 - 10^4$	Prec?	144.9	8.63 ± 0.13	208.8	33.5 ± 2.7	–	–	

he first IBIS/ISGRI soft gamma-ray galactic plane survey catalog (Bird et al. 2004, ApJ 607, L33)

ATSE Earth Occultation Catalog, Deep Sample Results (Harmon et al. 2004, ApJS, 154, 585)



Leptonic models:

SSC Atoyan & Aharonian 1999, MNRAS 302, 253
Latham et al. 2005, AIP CP745, 323

EC Kaufman Bernadó et al. 2002, A&A 385, L10
Georganopoulos et al. 2002, A&A 388, L25

SSC+EC Bosch-Ramon et al. 2004 A&A 417, 1075

Synchrotron jet emission Markoff et al. 2003, A&A 397, 64

Hadronic models:

Pion decay Romero et al. 2003, A&A 410, L1
Bosch-Ramon et al. 2005, A&A 432, 609

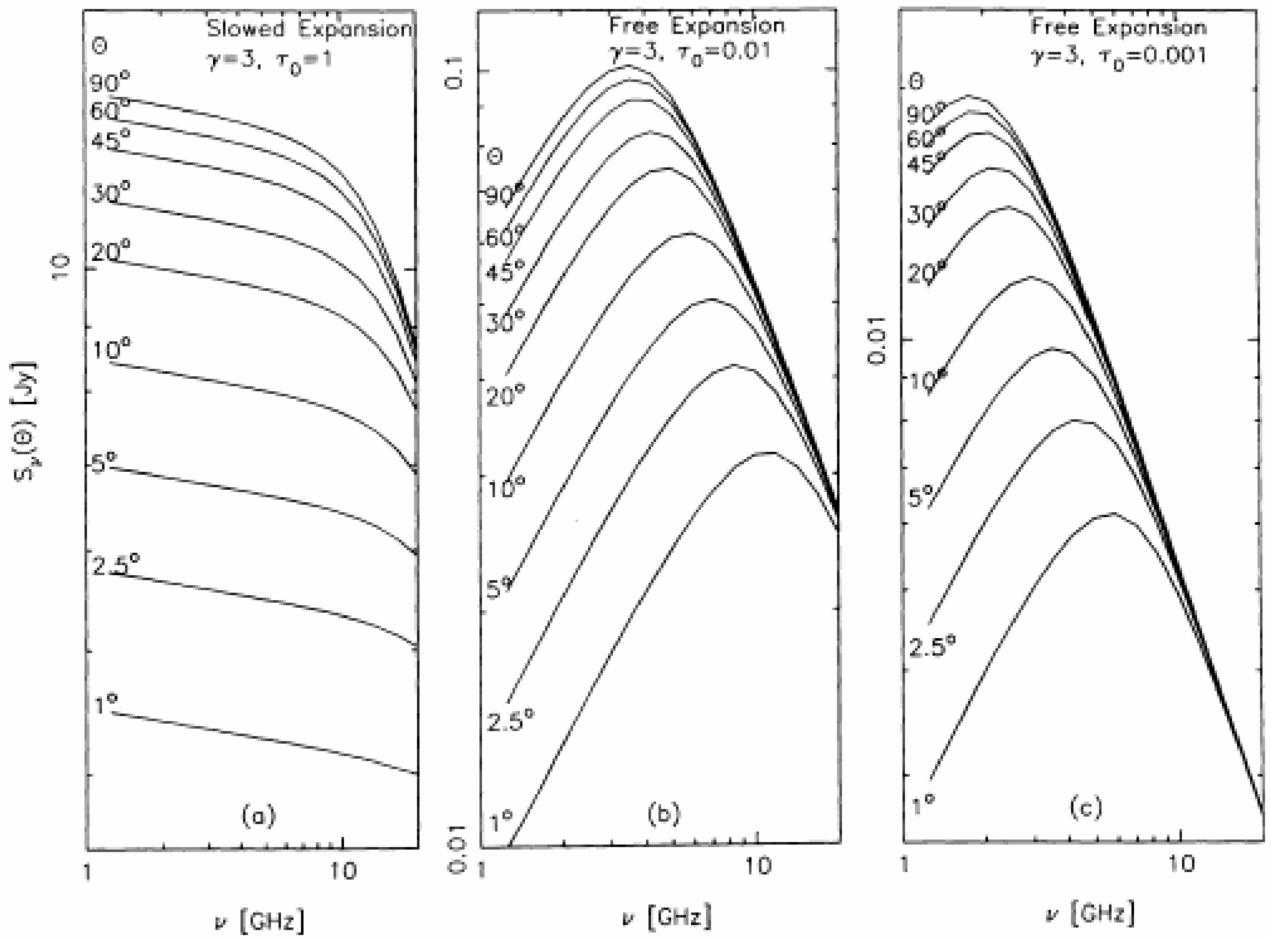
Non-thermal low energy radiation from MQ jets

The first models were leptonic

- Van der Laan model (Van der Laan 1966, Nature 211, 1131)
  - ➢ Expanding cloud of relativistic electrons emitting synchrotron radiation.
  - ➢ Cooling dominated by adiabatical losses.

- Sophisticated blob models
  - ➢ Expanding cloud with continuous injection of electrons.
  - ➢ Production of X-rays by inverse Compton scattering of external photons and synchrotron-self-Compton scattering
  - ➢ Radiative and adiabatical cooling
  - ➢ Applied to SS433 (Band & Grindlay 1986, ApJ 311, 595)

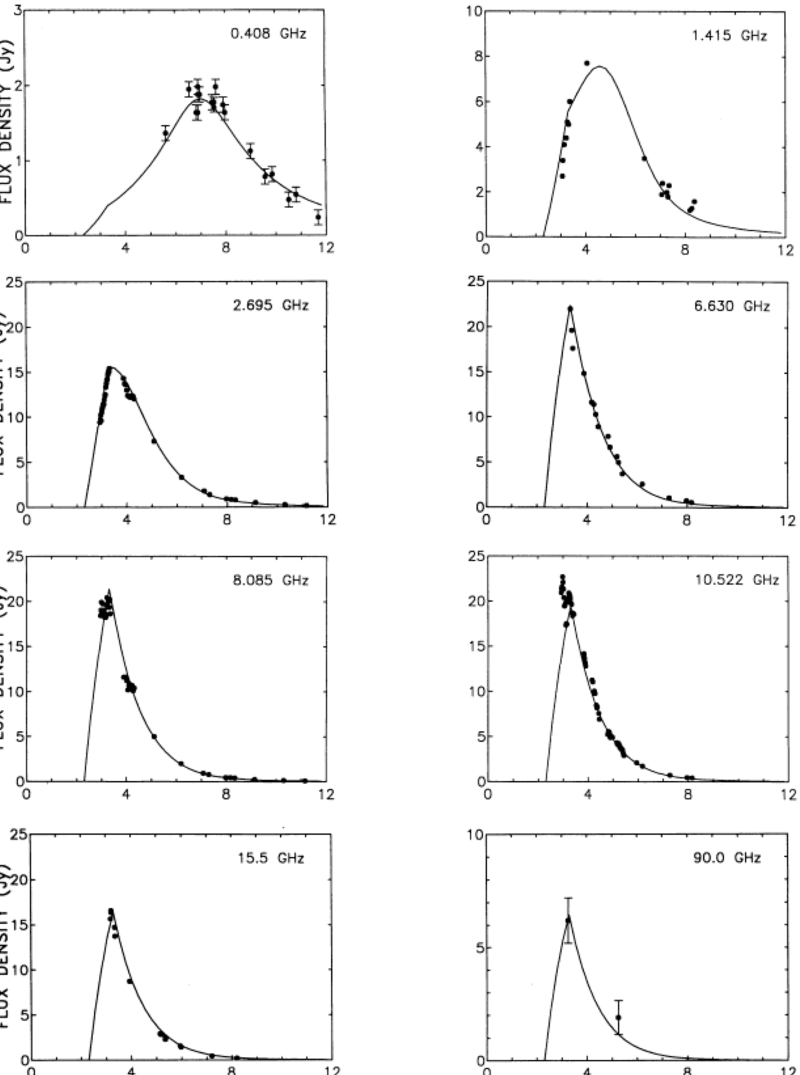
Models of adiabatically expanding synchrotron radiation-emitting conical jets may explain some of the characteristics of radio emission from X-ray binaries. Hjellming & Johnston 1988, ApJ 328, 60



Cyg X-1 Cyg X-3 quiesc. LSI+61303

Particle injection into twin jets

- Cyg X-3 exhibits flaring to levels of 20 Jy or more
- In 1972 was first "caught" flaring above 20 Jy. These events are amongst the best-known examples of observed expanding synchrotron-emitting sources (21 papers in Nature Phys. Sci. 239, No. 95 (1972))



- Modelling Cyg X-3 radio outbursts: particle injection into twin jets

Martí et al. 1992, A&A 258,309

$$\beta = 0.48 \, , \, \theta = 73°$$

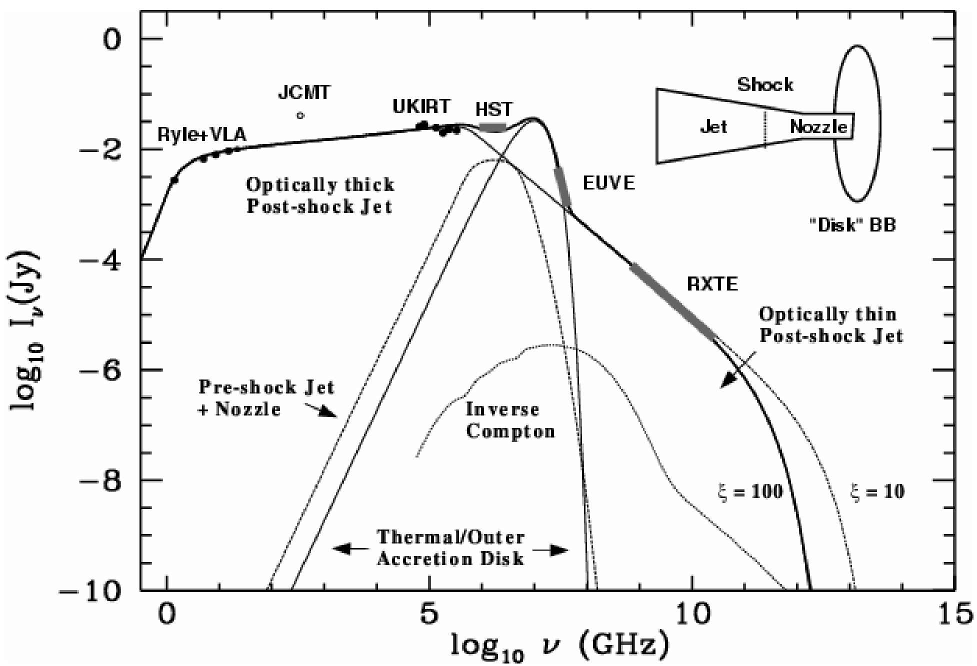
Synchrotron jet emission

- X-ray synchrotron emitting jets:

➢ Conical jet populated by relativistic particles emitting by synchrotron processes.

➢ Particle acceleration balanced by adiabatic and radiative losses in the jet "base". Truncated accretion disk ➔Weak disk emission ➔ Low external photon density

➢ Applied, e.g., to XTE J1118+480 (Markoff, Falcke & Fender 2001, A&A).



XTE J1118+480

External Compton Scattering

ECS with a dominant contribution from the companion star field

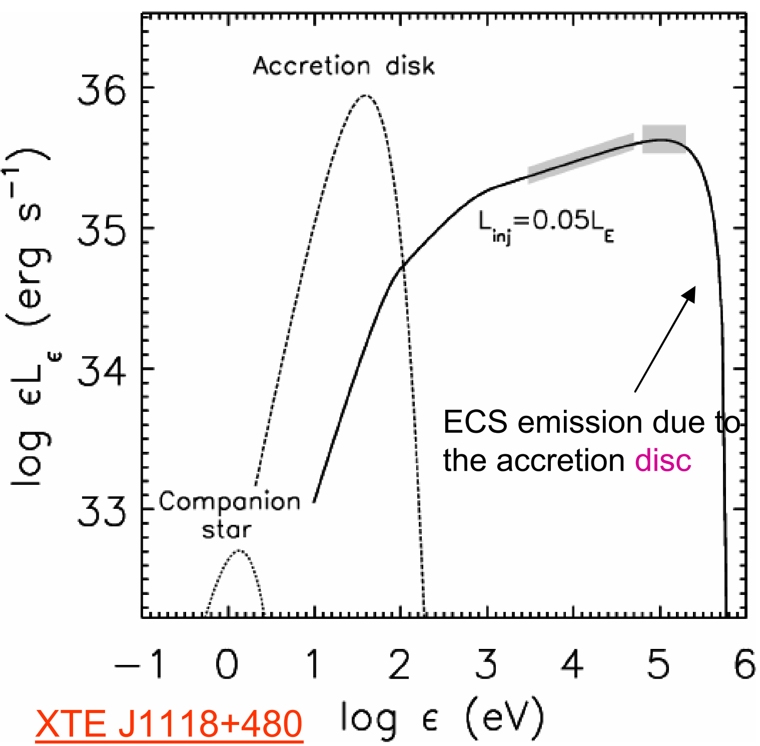
- X-ray IC emitting jets:

➢ Cylindrical jet populated by relativistic particles emitting by IC processes.

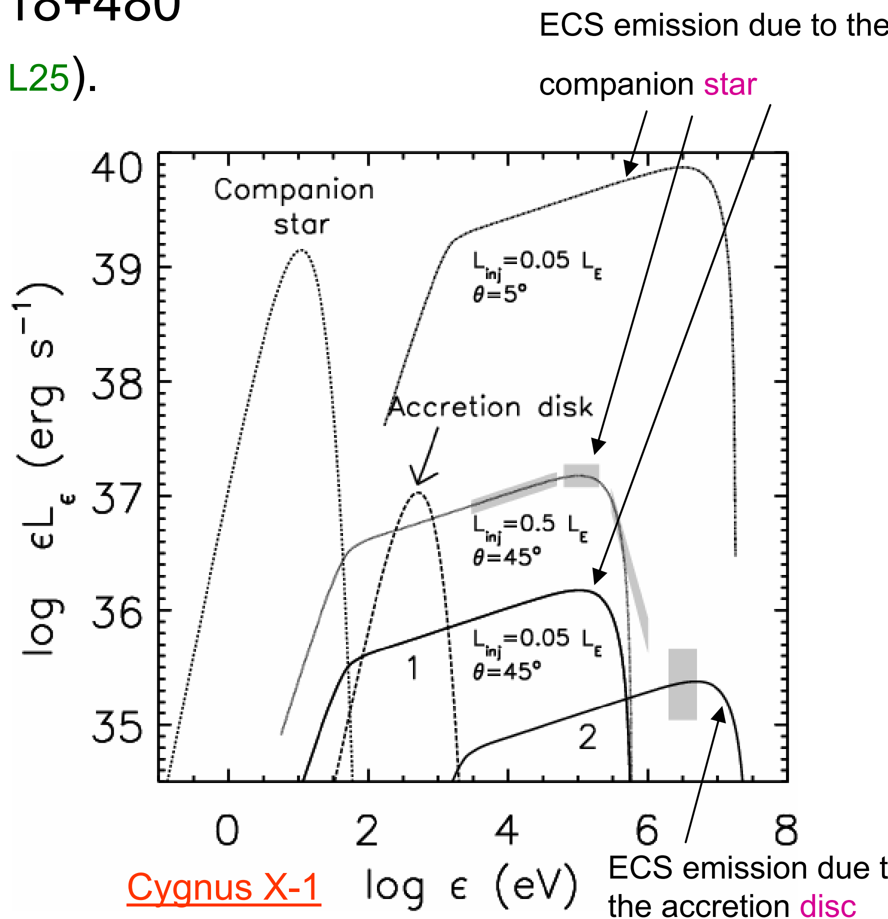
➢ Injected 100 MeV e^- interact via Thomson with stellar and disk photons.

➢ Applied to Cygnus X-1 and XTE J1118+480

(Georganopoulos, Aharonian & Kirk 2002, A&A 388, L25).



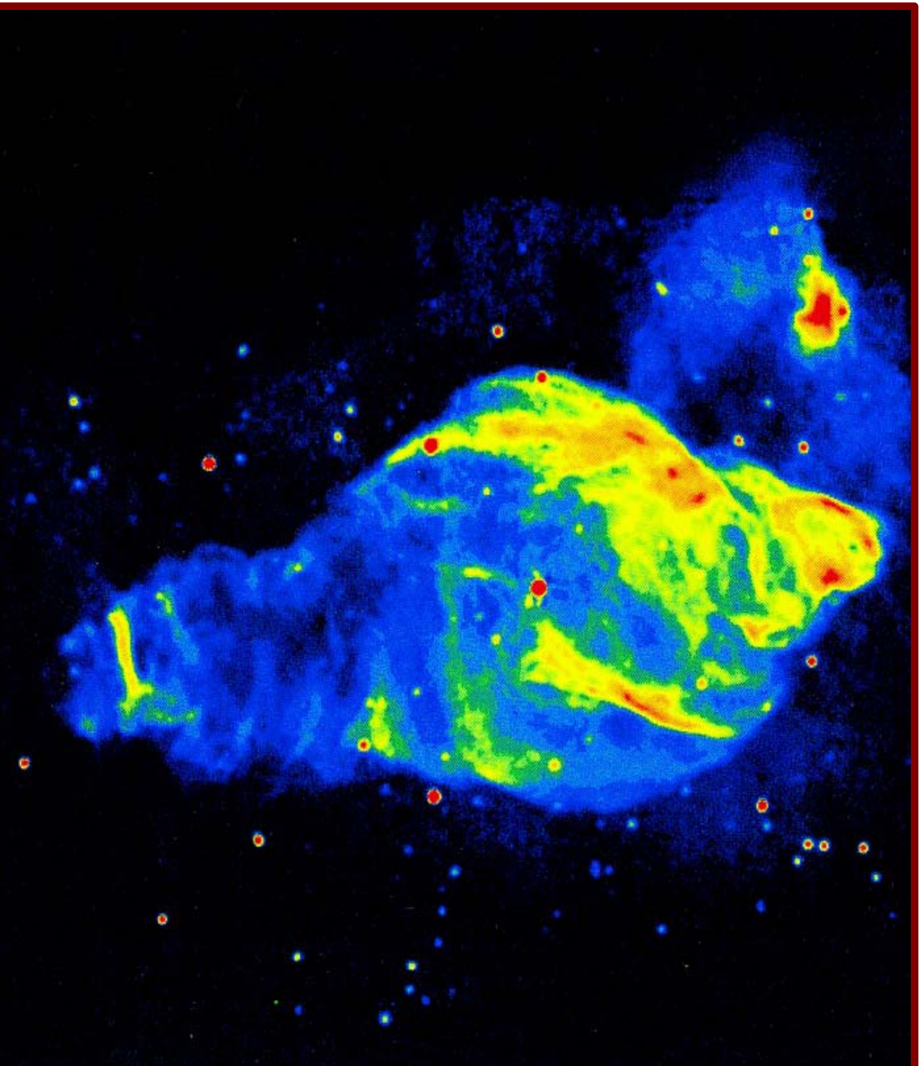
XTE J1118+480



Cygnus X-1

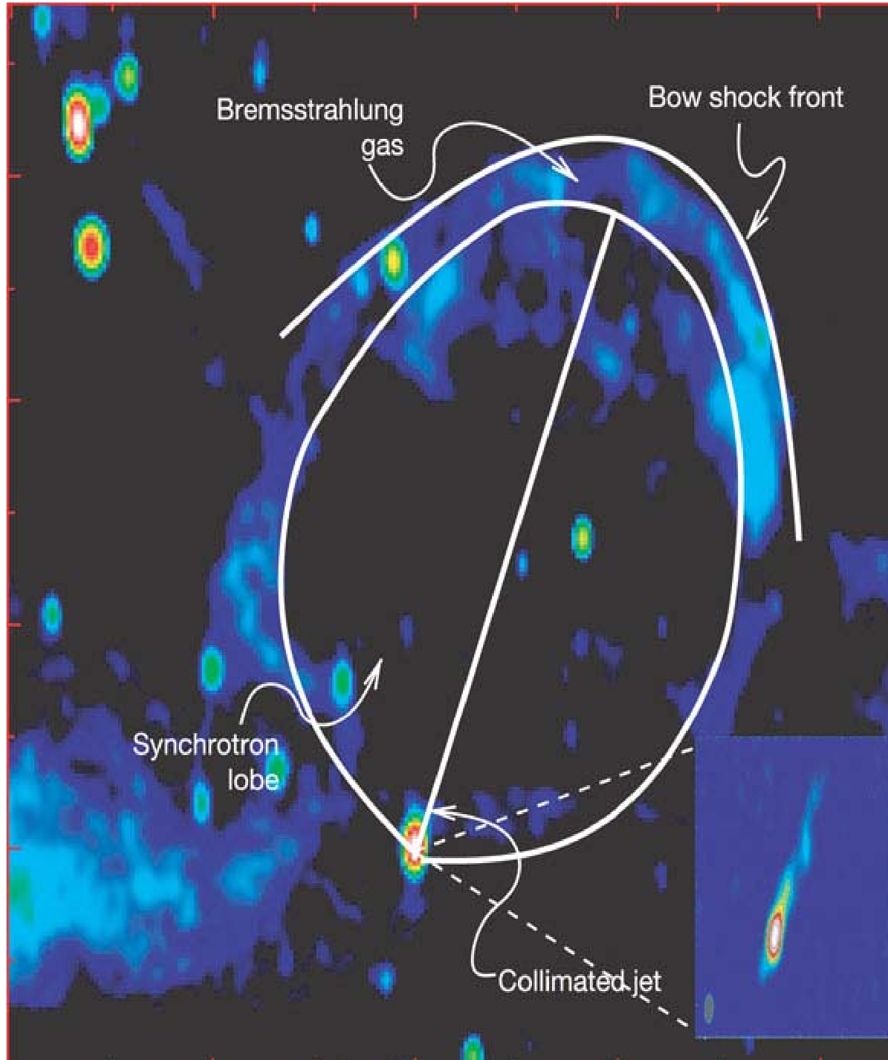
Jet/ISM interaction

SS 433



Dubner et al. 1998, ApJ

Cygnus X-1

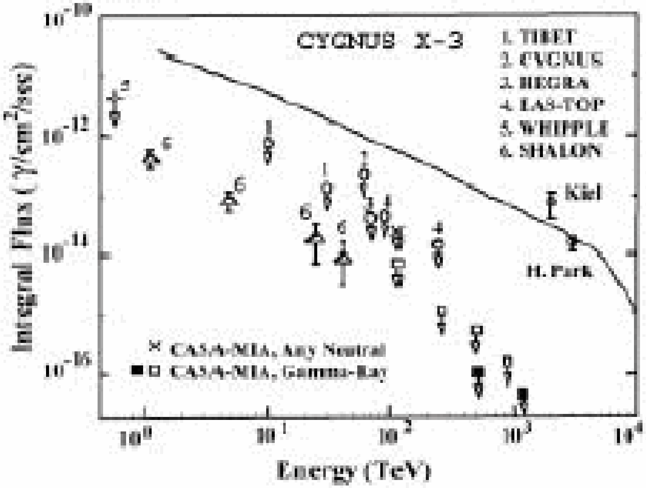


Gallo et al. 2005, Nature

MQ jets as HE and VHE γ-ray sources

Observational and theoretical point of view

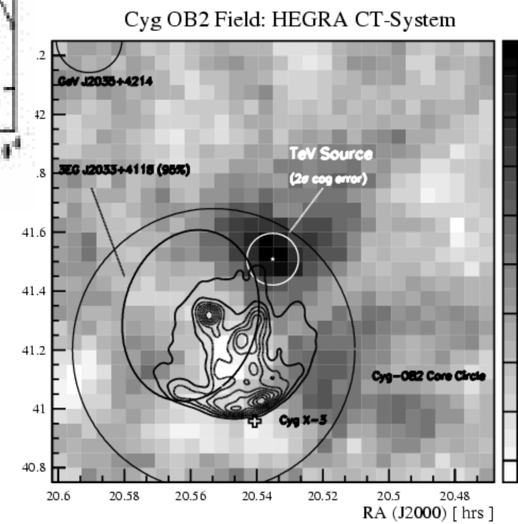
Cygnus X-3



Suggested to emit TeV γ-rays
Chadwick et al. 1985, Nature 318, 642

Other groups have failed to detect it
O'Flaherty et al.1992, ApJ 396, 674

SHALON (4.20±0.70) x10^{-13} photons/cm^2/s above 0.8 TeV
Sinitsyna et al. 2001, Nuc. Phys. B (Proc. Suppl.) 97, 219



Aharonian et al. 2002, A&A 293, L

GRS 1915+105

TeV observations:

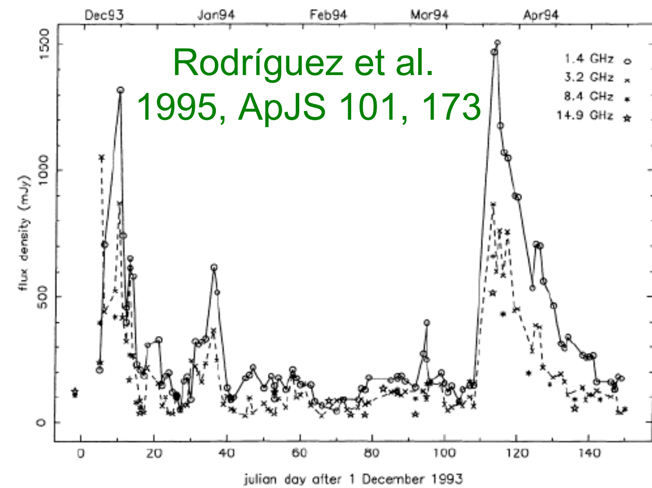
- 0.25 Crab (May-June 1996), marginal Aharonian & Heinzelmann (1998)
- 3.1sigma, marginal, Whipple (April 1998) Rovero et al. 2002, BAAA 45, 66
- (April 2003) less than 35% the flux of the Crab

(or < 3.5x10^{-11} photons/cm^2/s) above 400 GeV Horan & Weekes (2003)

Leptonic high energy models

Synchrotron self Compton model

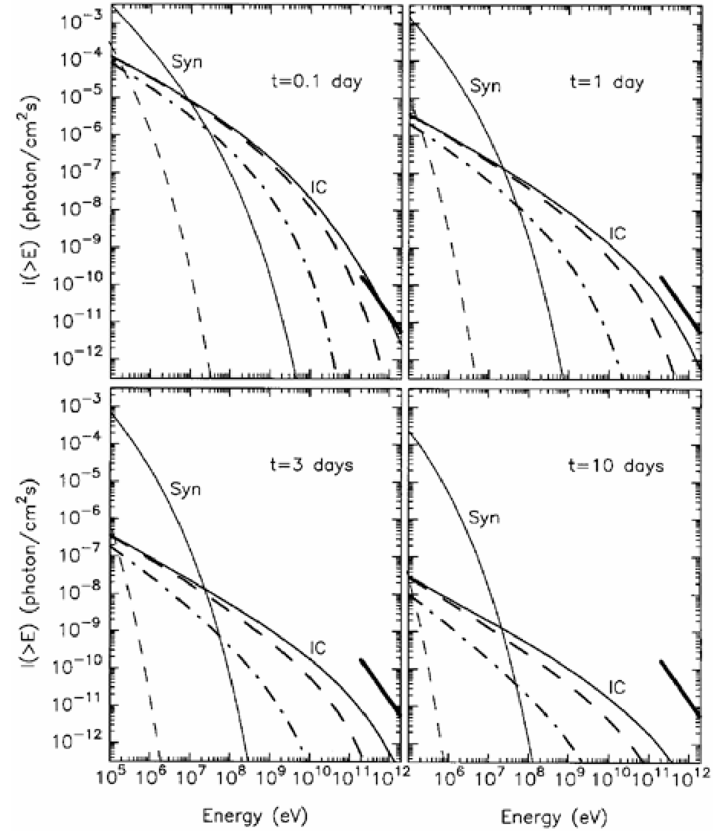
- Non-thermal flares GRS1915+105
  (Atoyan & Aharonian 1999, MNRAS 302, 253)

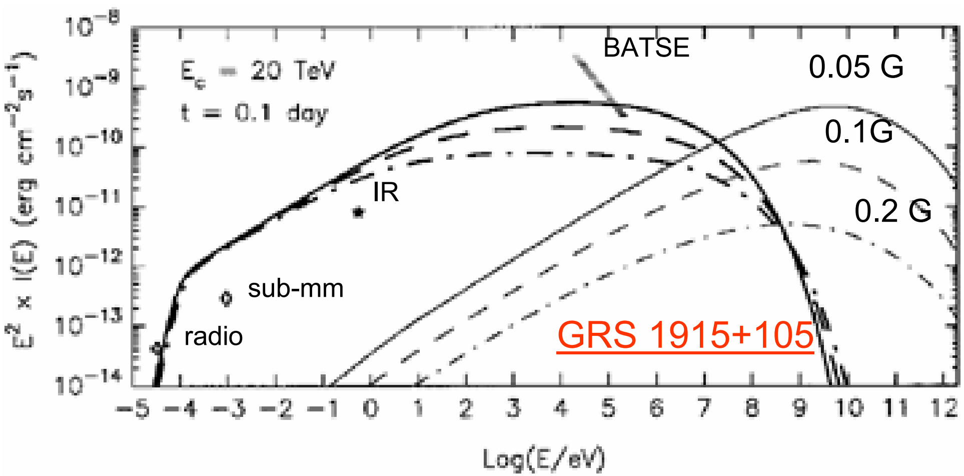


➢ Flares are caused by synchrotron radiation of relativistic e⁻ suffering radiative, adiabatic and energy-dependent escape losses in fast-expanding plasmoids (radio clouds)

➢ Continuous supply or in-situ acceleration of radio e⁻

➢After limiting, from the radio data, the basic parameter characterizing the expanding plasmoids, the e^- may be accelerated up to TeV energies, and the fluxes of synchrotron radiation could then extend beyond the X-ray region and the fluxes of the IC γ-rays to HE and VHE.





Exponential cutoff energies:

20 TeV ______

1 TeV _ _ _ _

30 GeV _ . _ . _

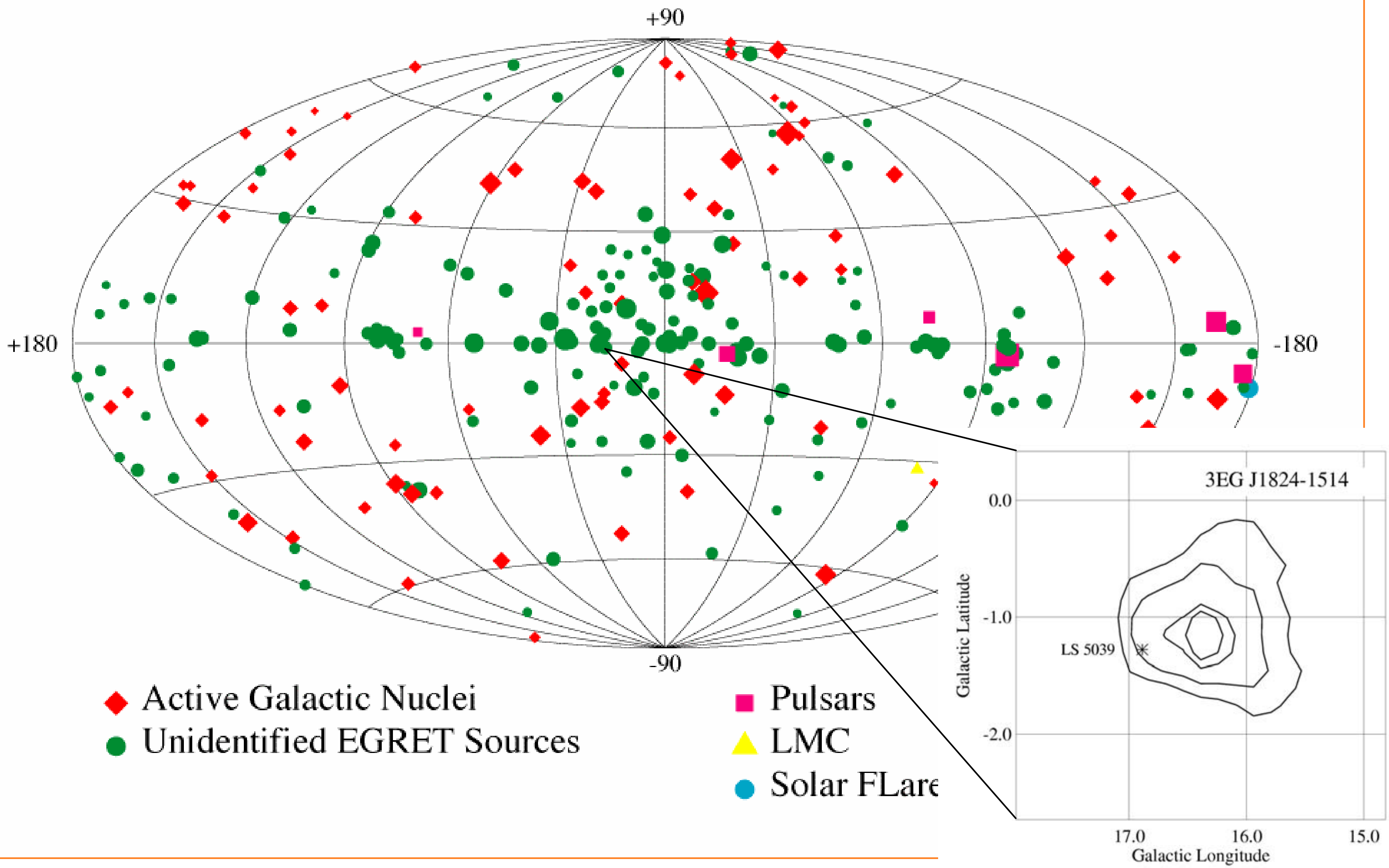
IC scattering or maybe even direct synchrotron emission from the jets could dominate the high-energy emission above an MeV or so

B = 0.05 G

Atoyan & Aharonian 1999, MNRAS 302, 253, and 2001

Third EGRET Catalog

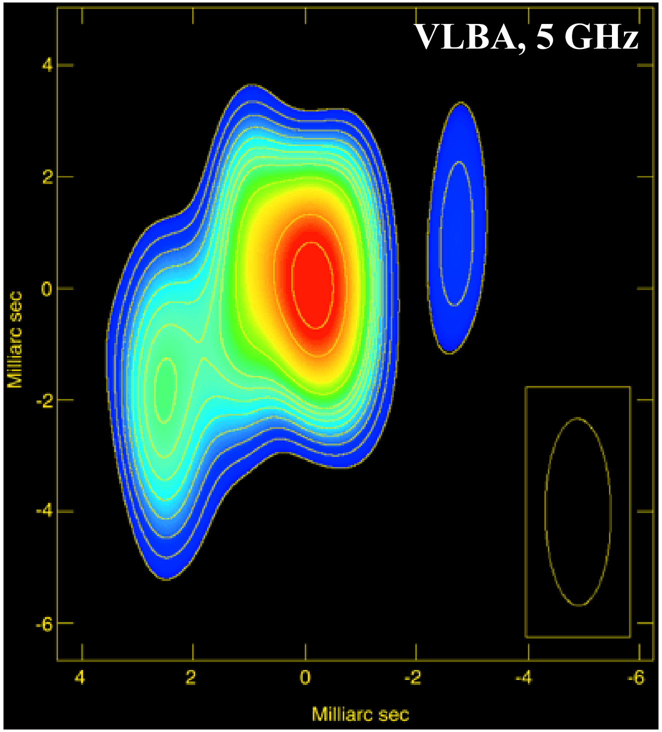
E > 100 MeV



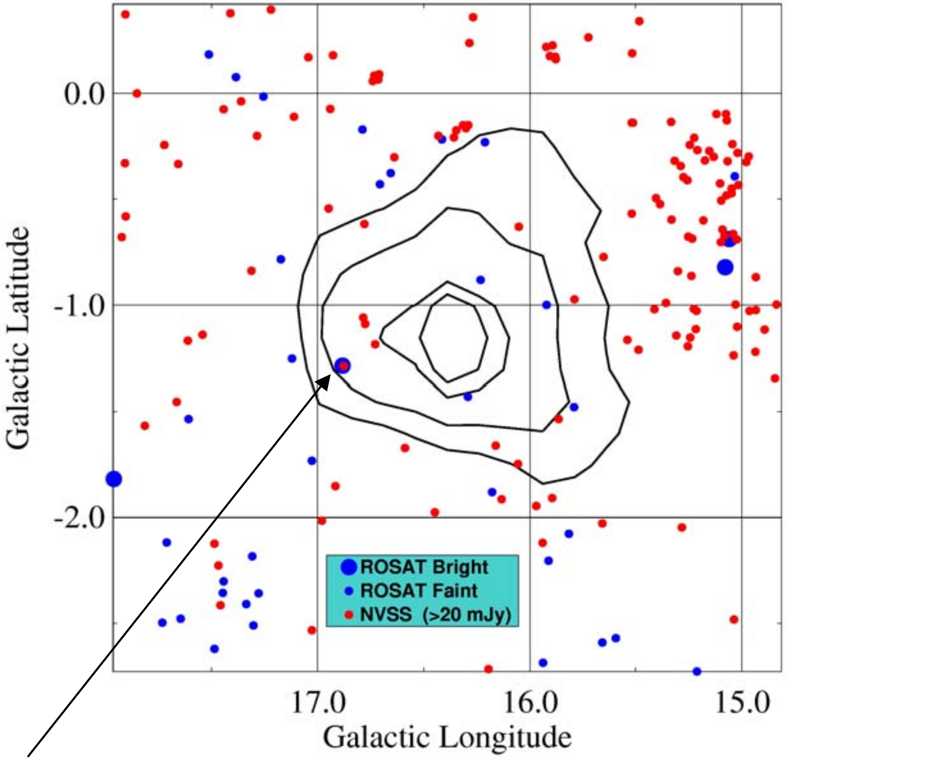
Hartman et al. 1999, ApJS 123, 79

EGRET candidate: LS 5039

Orbital phase 0.2



LS 5039 could be related to the high energy gamma-ray source 3EG J1824-1514



Jet parameters:

$\beta > 0.15$, $\theta < 81°$

$T_B = 9.4 \times 10^7$ K

Equipartition:

$E_e = 5 \times 10^{39}$ erg

B = 0.2 G

The photon spectral index is steeper than the $\alpha < 2$ values usually found for pulsars

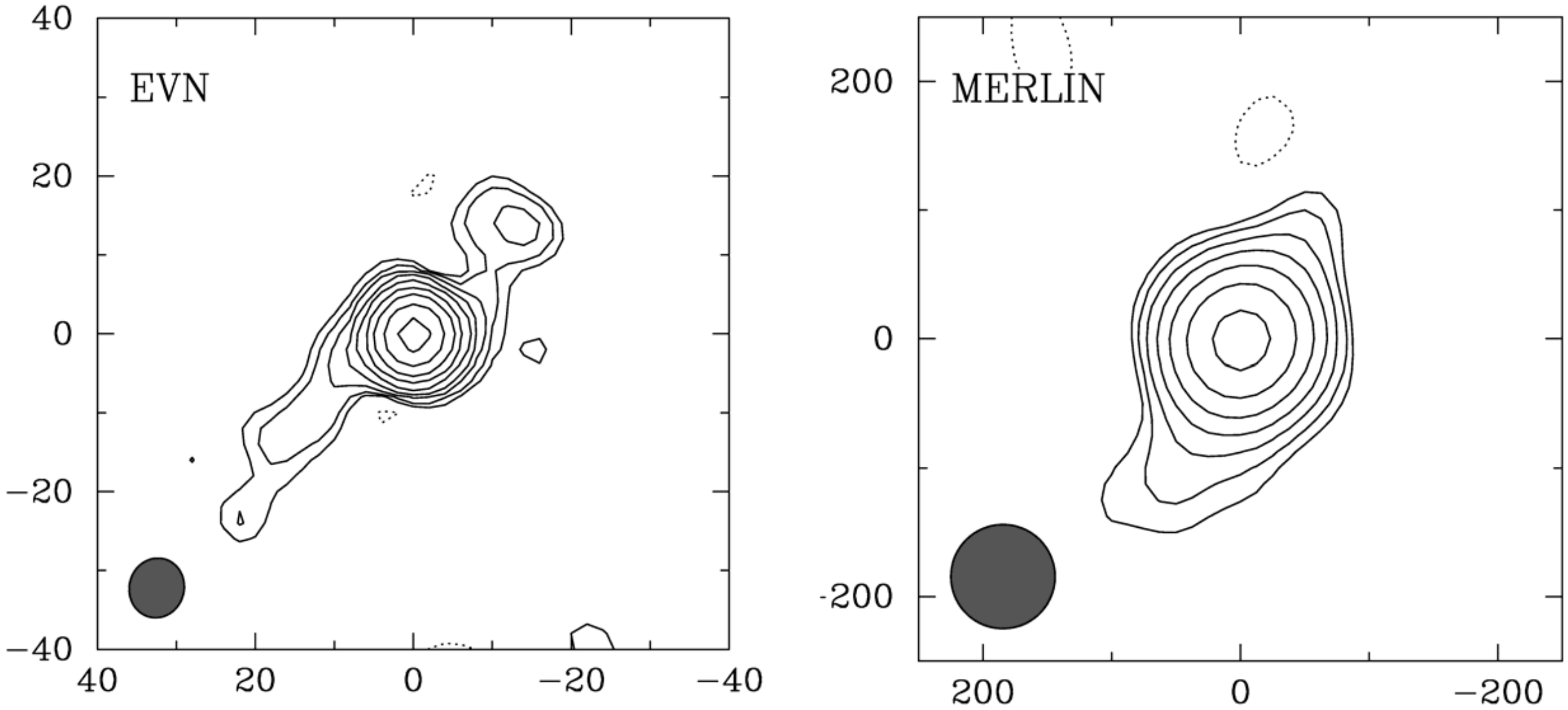
Merk et al.1996, A&ASS 120, 465

It is the only simultaneous X-ray/radio source within the 3EG J1824-1514 statistical contours.

Paredes et al. 2000, Science 288, 2340

Confirmed the **persistent nature of the jets** thanks to **EVN** and **MERLIN** observations on 2000 March 1 (Paredes et al. 2002, A&A 393, L99)

Orbital phase 0.5 $\beta > 0.17\ ,\ \theta < 80^\circ$



A black hole in LS 5039 ?

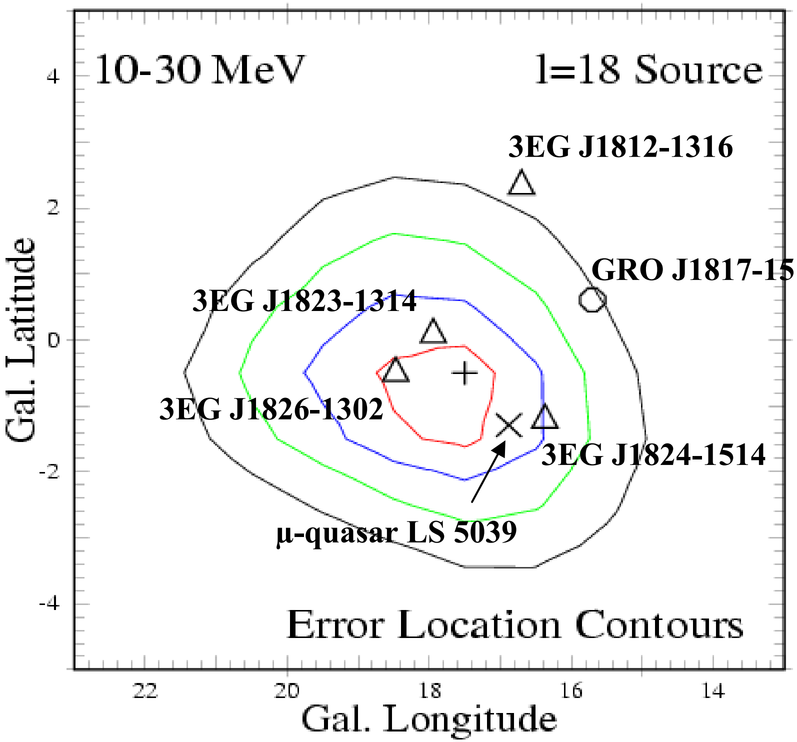
P = 3.9060 ± 0.0002 d
e = 0.35 ± 0.04
Periastron at phase 0.0

assuming pseudo-synchronisation at periastron

i = 20.3˚ ± 4.0
Mcompact = 5.4 (+1.9-1.4) M⊙

Casares et al., 2005, MNRAS, 364, 899

GRO J1823-12 (l/b: 17.5/-0.5)



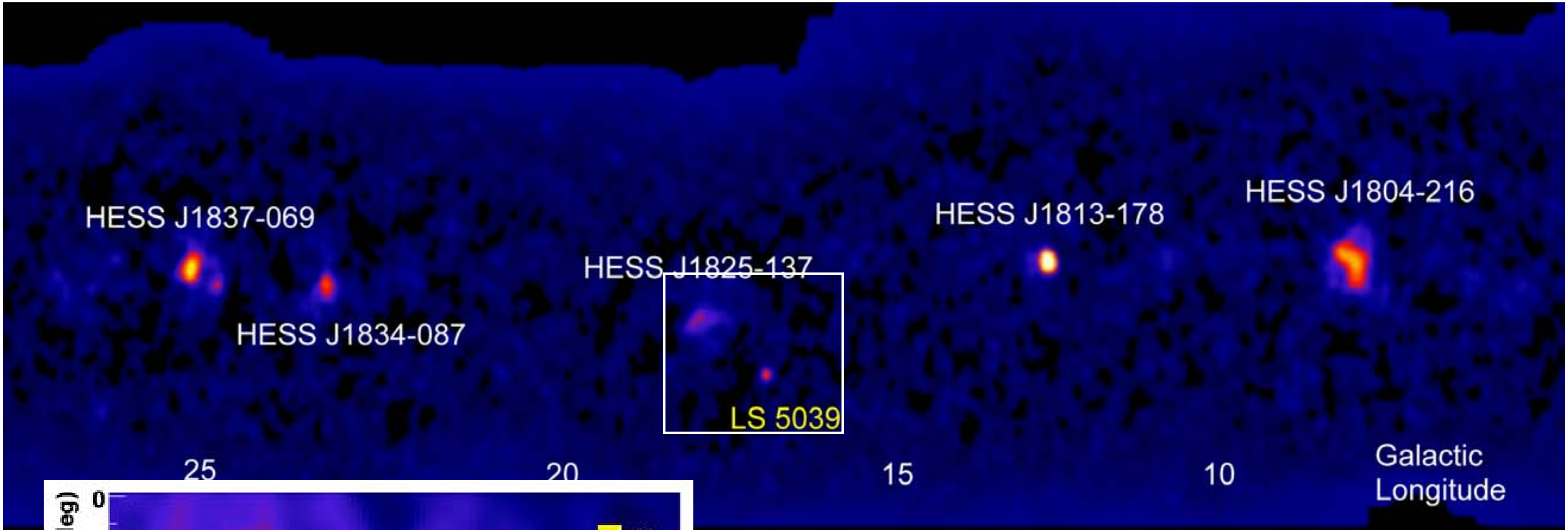
Summary

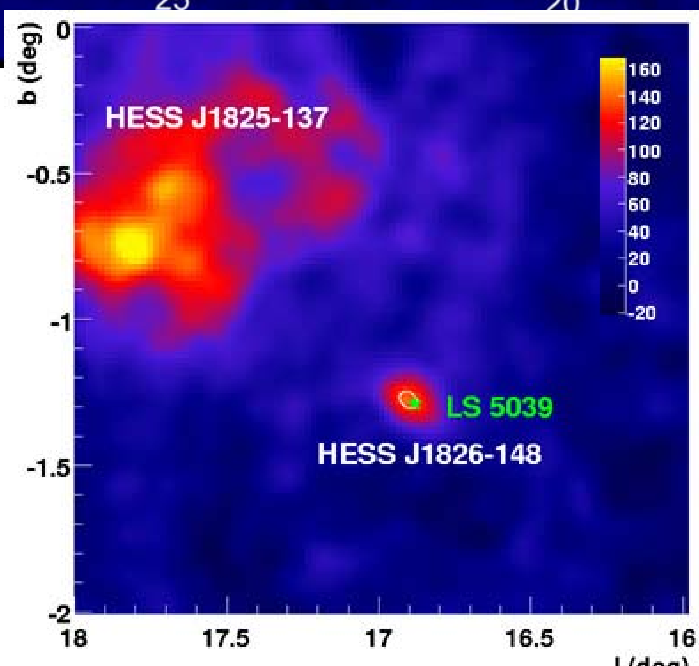
- **complicated source region**
- **possible counterparts:**
  - **3 known γ-sources (unid. EGRET) (MeV emission: superposition ?)**
  - **micro quasar RX J1826.2-1450/LS 5039 (sug. counterpart of 3EG J1824-1514; Paredes et al. 2000)**
- **work in progress**

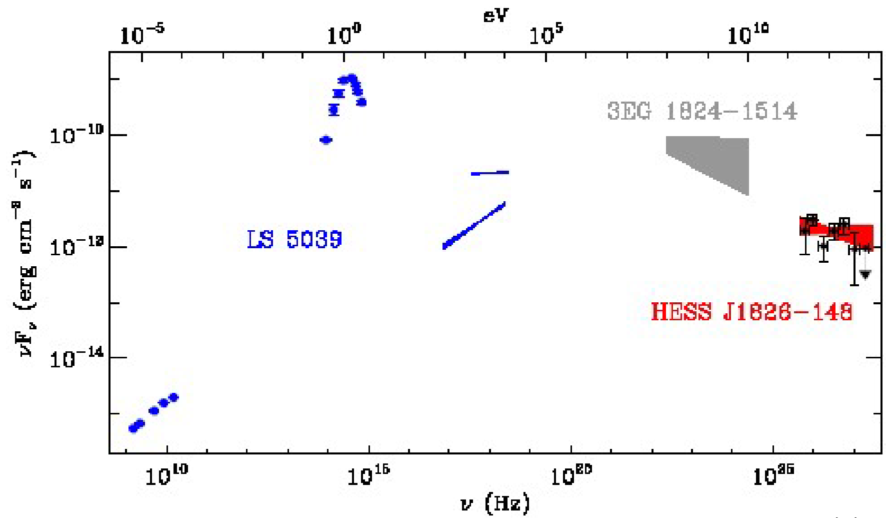
Collmar 2003, Proc. 4th Agile Science Workshop

HESS detects LS 5039

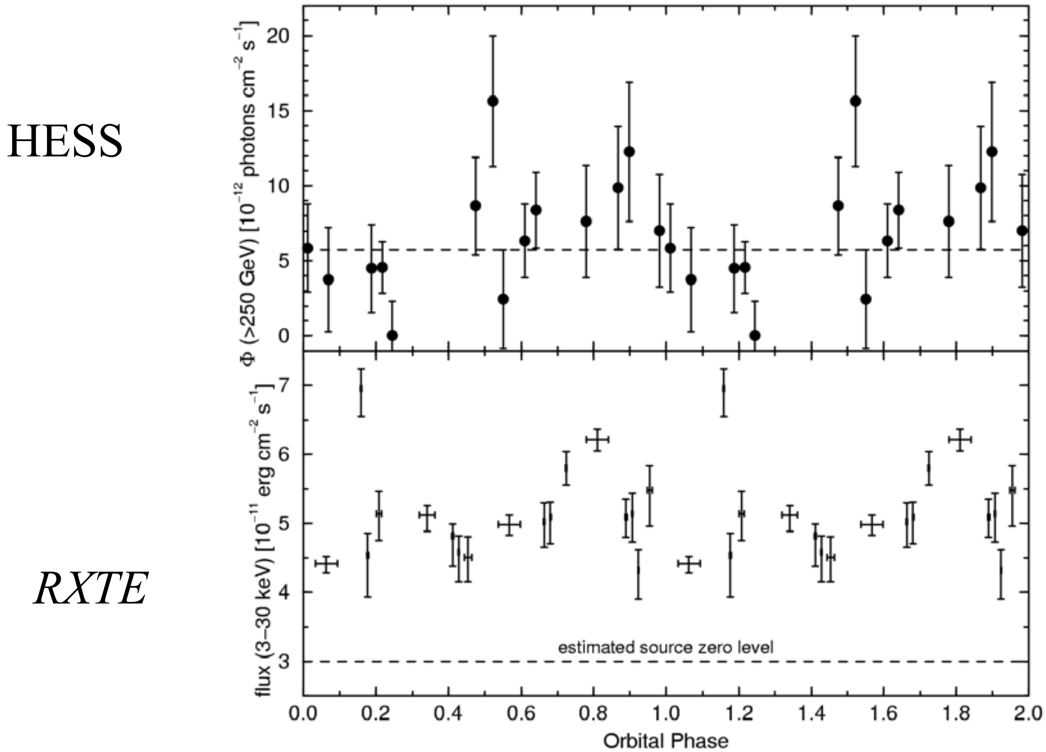
Discovery of the TeV counterpart by HESS (Aharonian et al. 2005, Science). Good position agreement with LS 5039.







With the new orbital ephemerides (Casares et al. 2005), there are hints of **TeV variability correlated with the X-ray orbital one**.

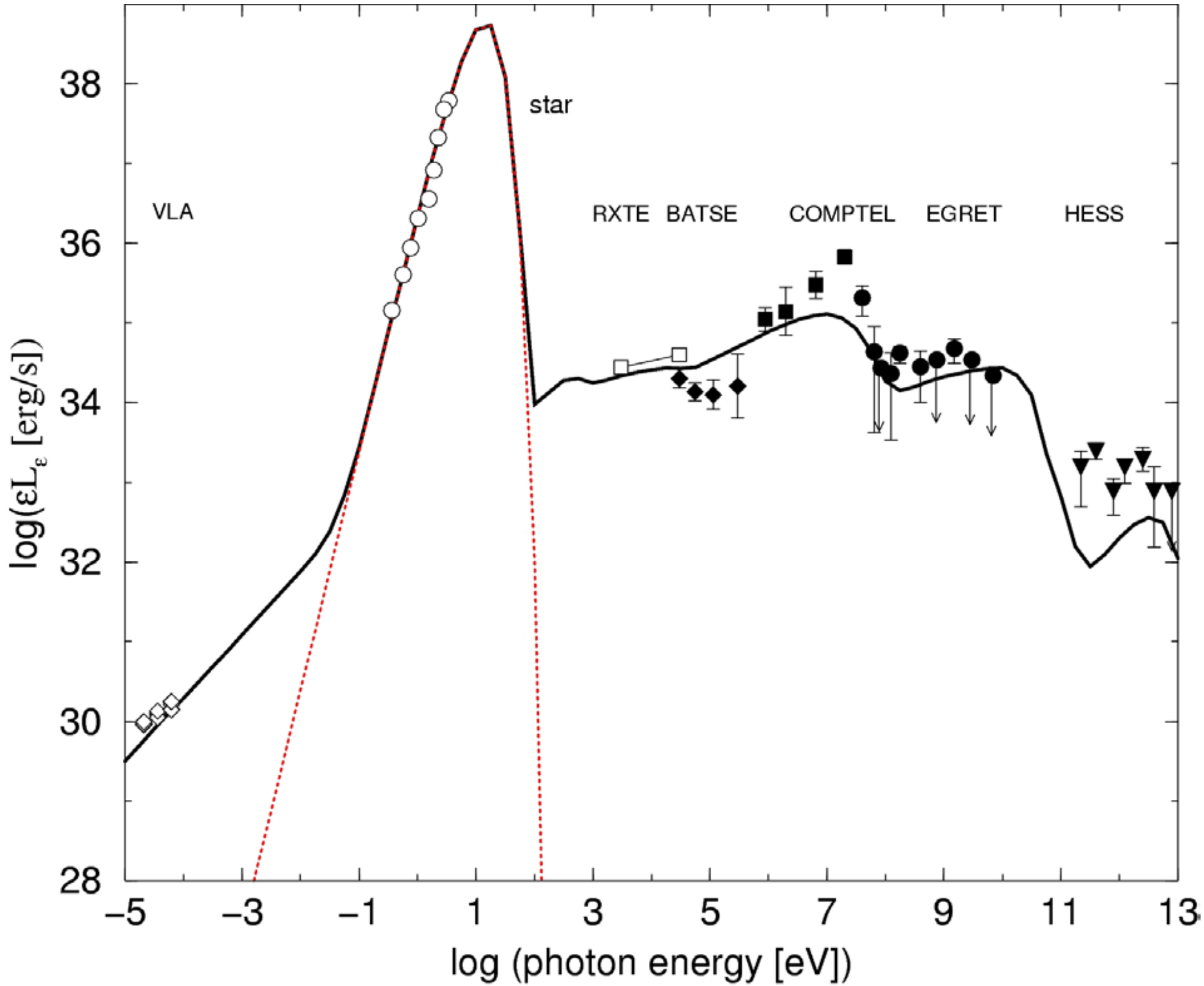


But HESS new data….

PERIODIC TeV EMISSION

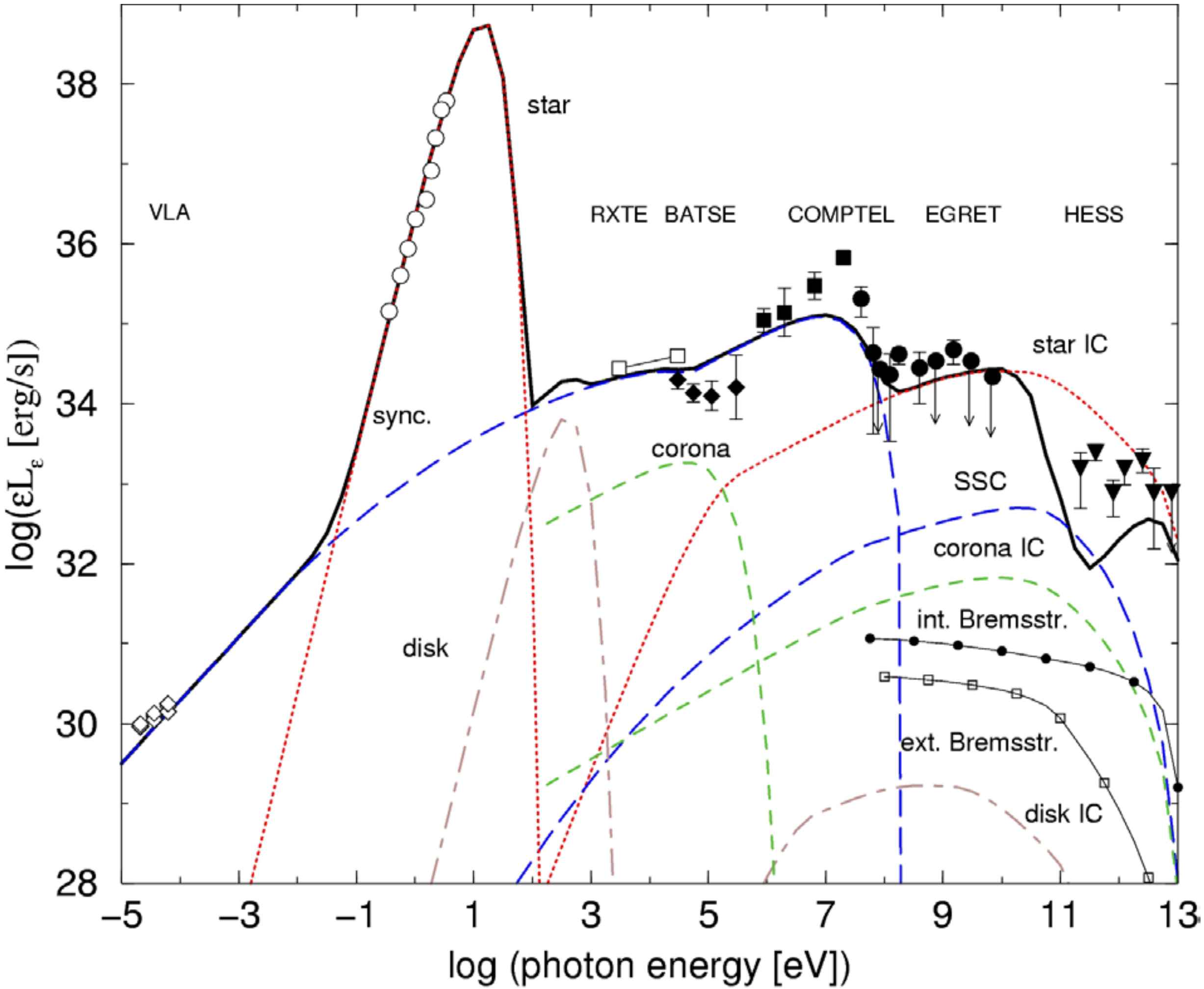
P=3.907 d   Wagner's talk

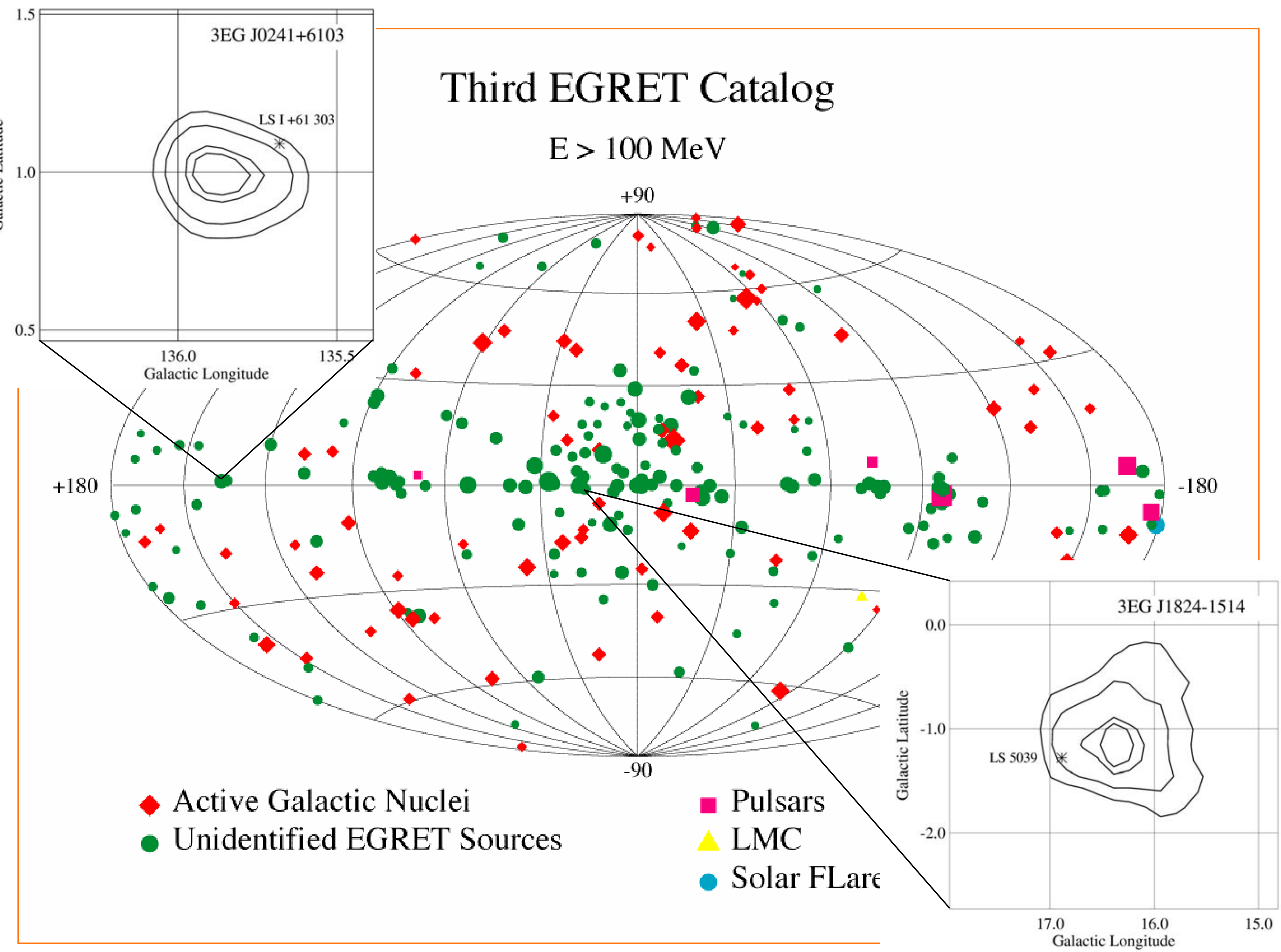
We have enough information to build up a **Spectral Energy Distribution**…



We have enough information to build up a **Spectral Energy Distribution**…

… that can be modeled to **extract physical information** (Paredes et al. 2006, A&A 451, 259).

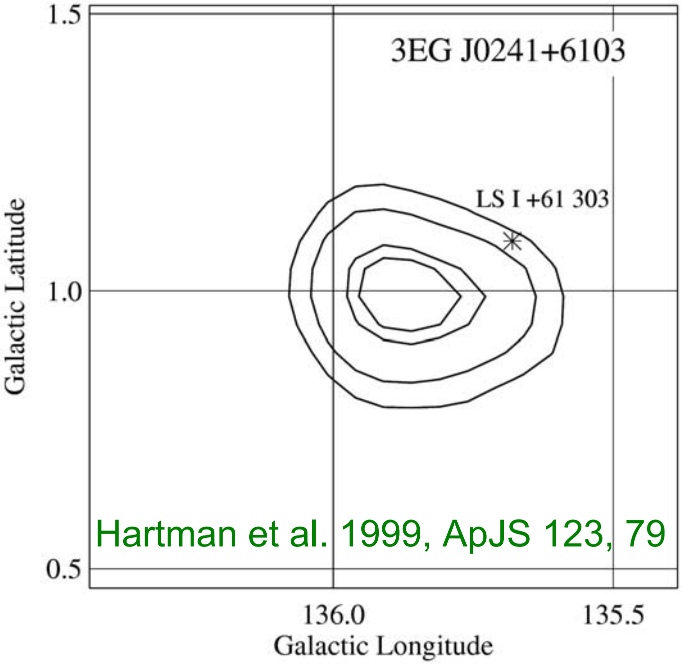




Hartman et al. 1999, ApJS 123, 79

EGRET candidate: LSI+61303

The radio emitting X-ray binary LSI+61 303, since its discovery, has been proposed to be associated with the γ-ray source 2CG 135+01 (= 3EG J0241+6103)

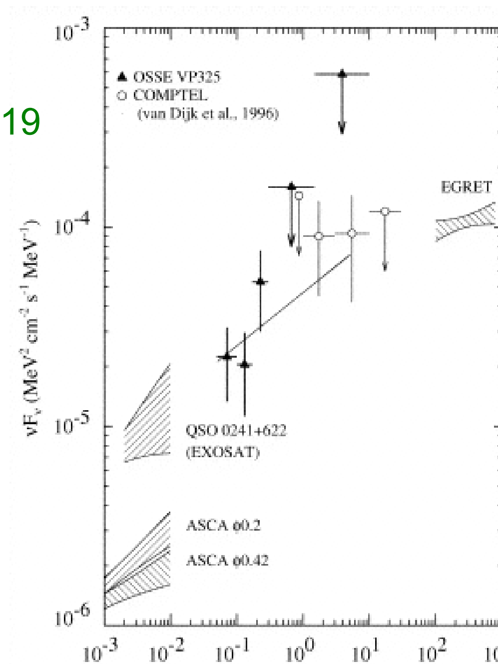


The broadband 1 keV-100 MeV spectrum remains uncertain (OSSE and COMPTEL observations were likely dominated by the QSO 0241+622 emission)

Harrison et al. 2000, ApJ 528, 454

The EGRET angular resolution is sufficient to exclude the quasar QSO 0241+622 as the source of γ-ray emission.

Strickman et al. 1998, ApJ 497, 419



Periodic emission

Radio (P=26.496 d) ⟷ accretion at periastron passage

Taylor&Gregory 1982, ApJ 255, 210

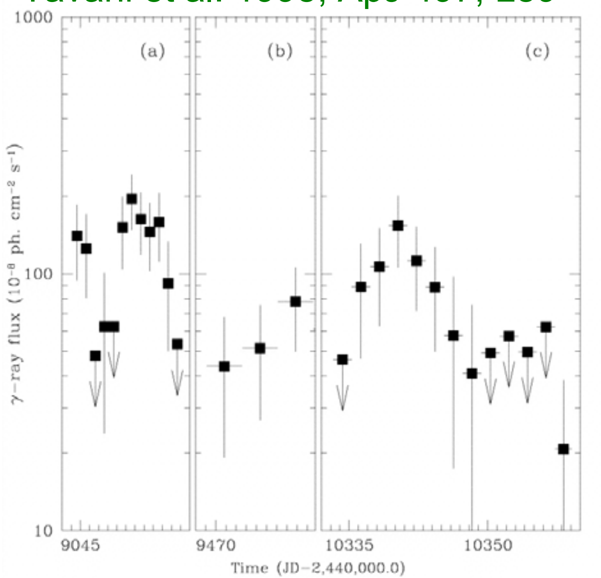
Optical and IR Mendelson&Mazeh 1989, MNRAS 239, 733; Paredes et al. 1994 A&A 288, 519

X-rays Paredes et al. 1997 A&A 320, L25

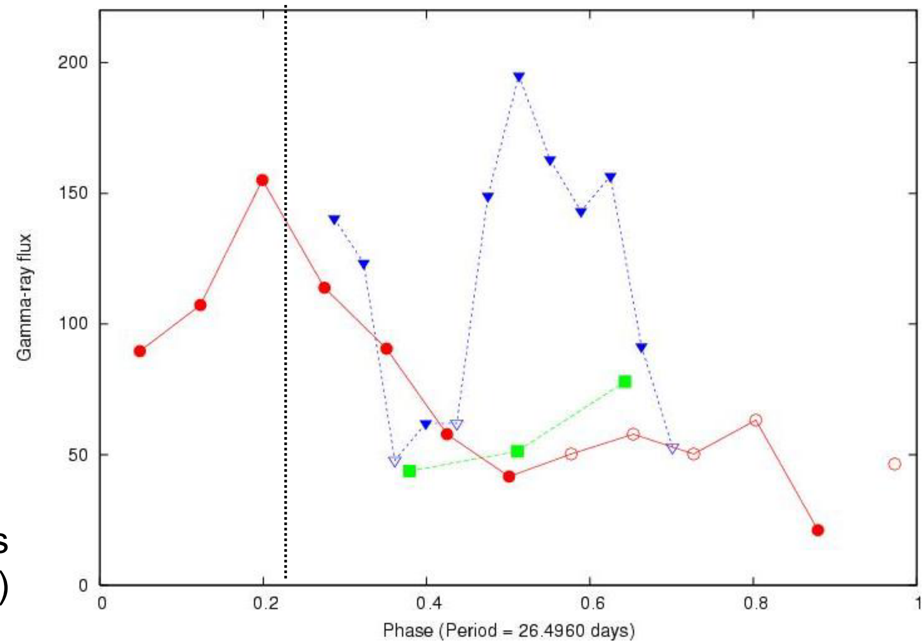
γ-rays ???

3EG J0241+6103 variability

Tavani et al. 1998, ApJ 497, L89



EGRET observations of 3EG J0241+6103 shows variability on short (days) and long (months) timescales

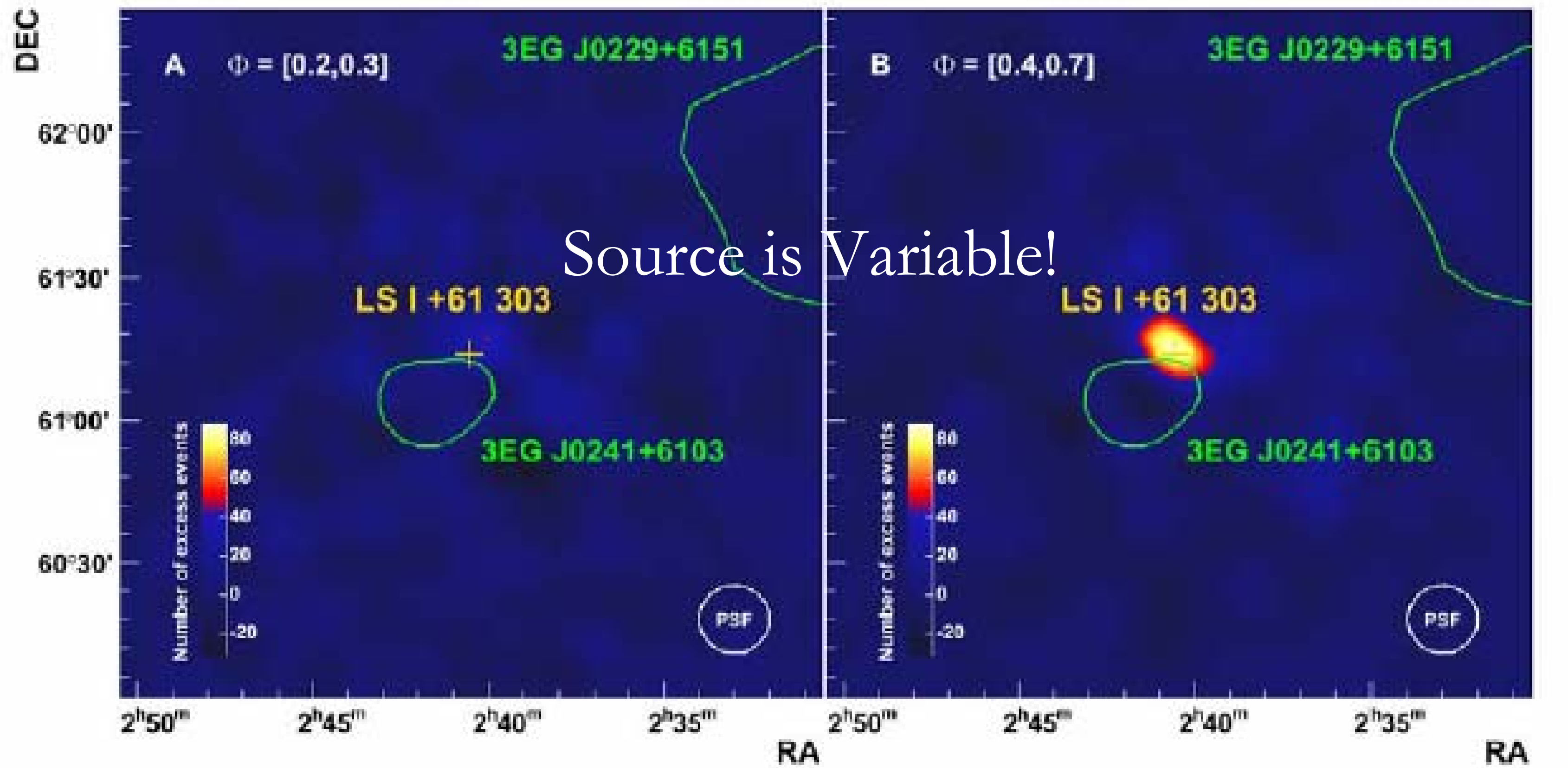


The data is consistent with an outburst at periastron passage

Massi et al. 2005 (astro-ph/0410504)

MAGIC detects LSI +61 303

MAGIC



Source is Variable!

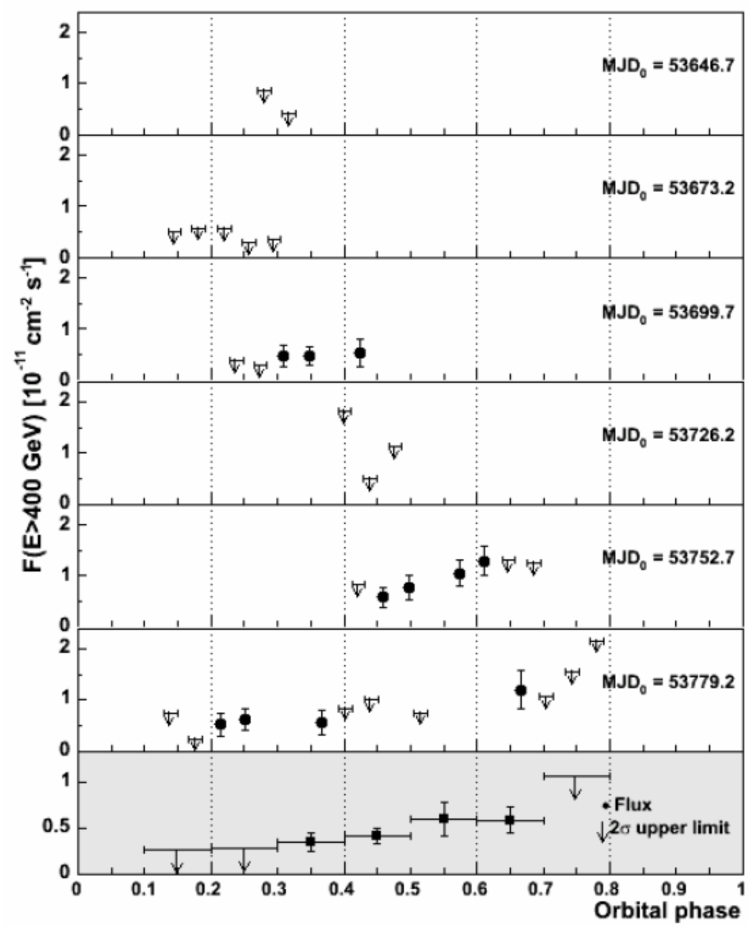
Smoothed maps of excess events above 400 GeV.

The position of the optical source LSI +61 303 (yellow cross)
The 95% confidence level (CL) contours for 3EG J0229+6151 and 3EG J0241+6103 (green contours)

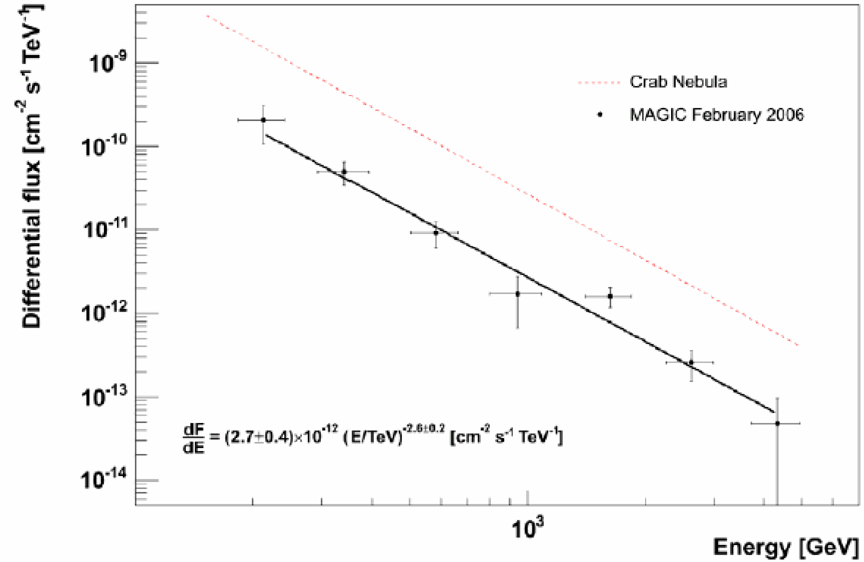
No significant excess in the number of events is detected around periastron passage, while it shows up clearly (9.4σ statistical significance) at later orbital phases, in the location of LS I +61 303.

Albert et al. 2006, Science 312, 1771

LS I +61 303



Spectrum for phases 0.4 and 0.7



The spectrum is consistent with that of EGRET for a spectral break between 10 and 100 GeV.

The intrinsic luminosity of LS I +61 303 at its maximum is:

a factor ~6 higher than that of LS 5039,

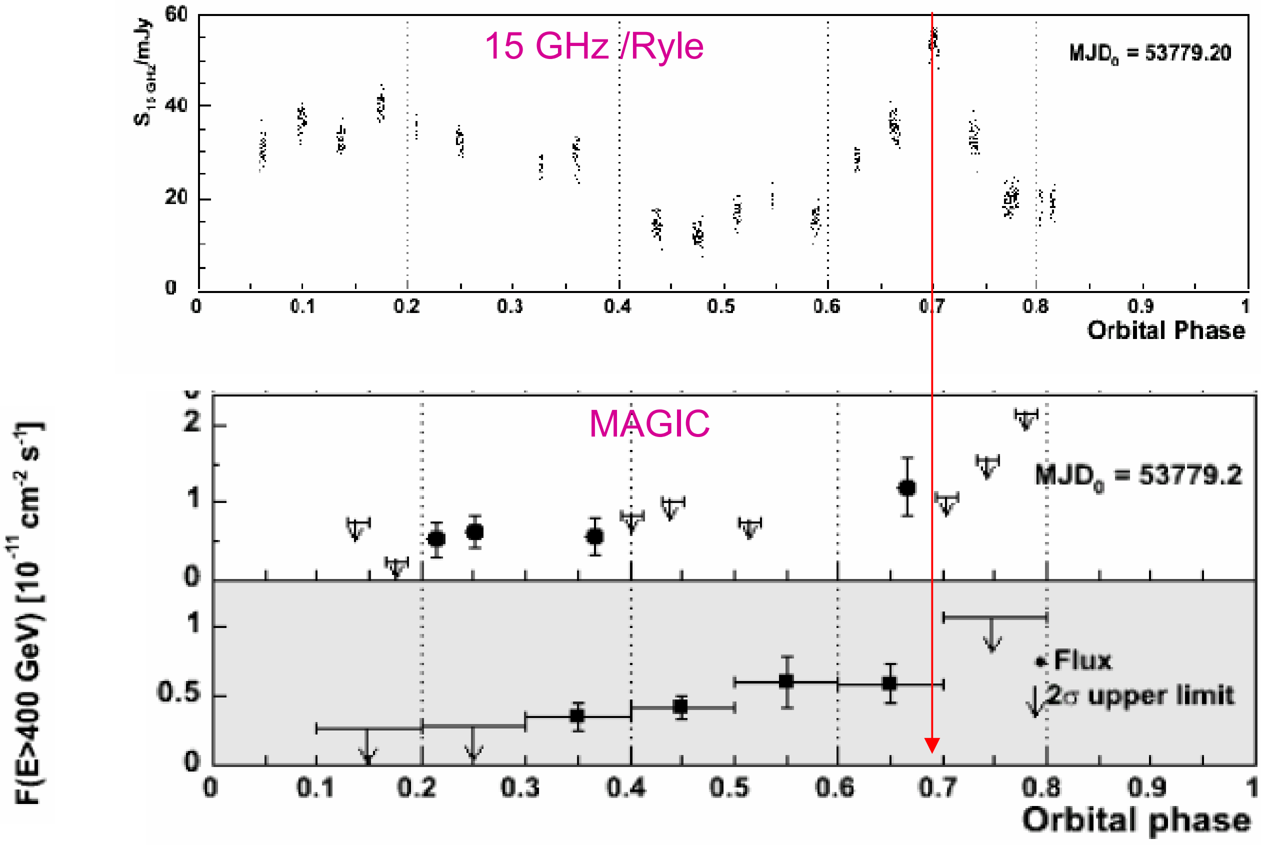
and

a factor ~2 lower than the combined upper limit obtained by Whipple (Fegan et al. 2005, ApJ 624, 638).

This behavior suggests that the VHE γ-ray emission from LSI +61 303 has a periodic nature

The variable nature of the TeV emission on timescales of ~1 day constrains the emitting region to be smaller than a few 10^{15} cm (or ~0.1” at 2 kpc). This is compatible with the emission being produced within the binary system, where there are large densities of seed photons for IC interaction. Under these strong photon fields opacity effects certainly play a role in the modulation of the emitted radiation (Dubus 2006, A&A 451, 9).

Simultaneous radio/TeV observations



TeV flux maximum:

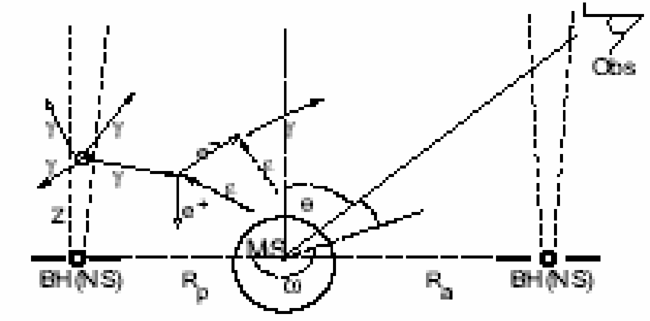
detected at phases 0.5 - 0.6 ⟶ the X-ray outburst and the onset of the radio outburst.

not detected at periastron, when the accretion rate is expected to be the largest ⟶ opacity effects

A power of several 10^{35} erg s^{-1} could explain the non thermal luminosity from radio to VHE gamma-rays. This power can be extracted from accretion in a slow inhomogeneous wind along the orbit.

Propagation of very high energy γ-rays inside massive binaries LS 5039 and LSI +61 303

Bednarek 2006, MNRAS 268, 579



- The matter accreting onto a compact object from the massive star creates an accretion disk.

- Particles (e^- or p) are accelerated inside the jet launched from the inner part of an accretion disk.

- Primary electrons and/or gamma-rays, injected at the distance z from the base of the jet, initiate an anisotropic IC e± pair cascade in the radiation field of the massive star. A part of the primary γ-rays and secondary cascade γ-rays escape from the binary system toward the observer.

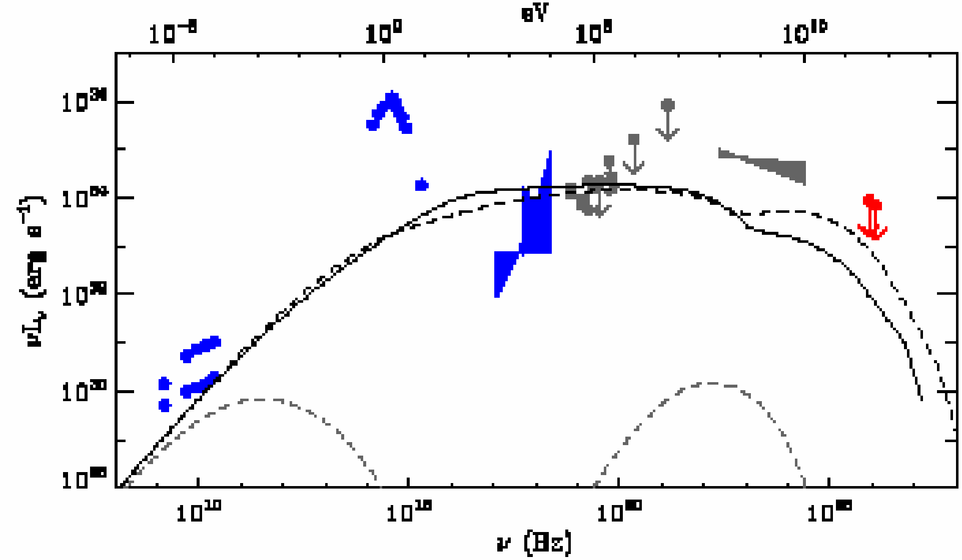
- The cascade processes occurring inside these binary systems significantly reduce the γ-ray opacity obtained in other works by simple calculations of the escape of γ-rays from the radiation fields of the massive stars

- The maximum in TeV γ-ray light curve predicted by the propagation effects in LSI +61 303 should occur after periastron passage (as has been observed).

LSI +61 303

Interaction of the relativistic wind from a young pulsar with the wind from its stellar companion

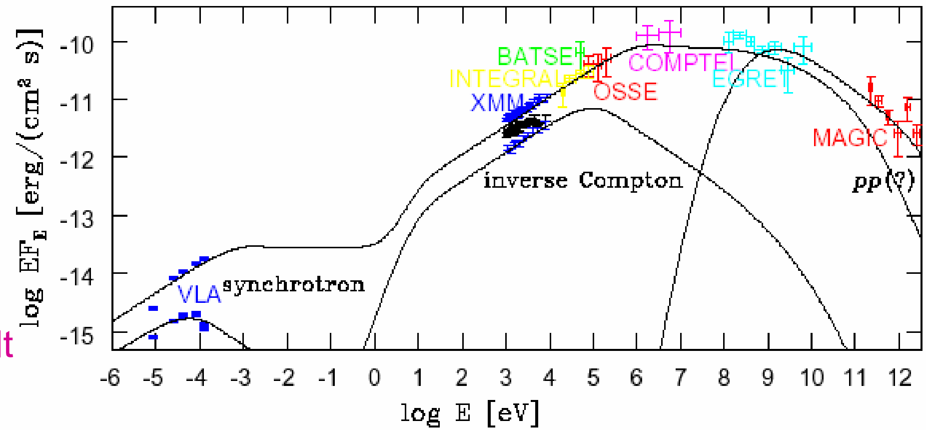
Dubus 2006, A&A in press (astro-ph/060528



Stellar wind is equatorial
Periastron: full black lines
Apastron: dashed black lines

Rotation powering pulsar

Chernyakova et al. 2006, astro-ph/0606070

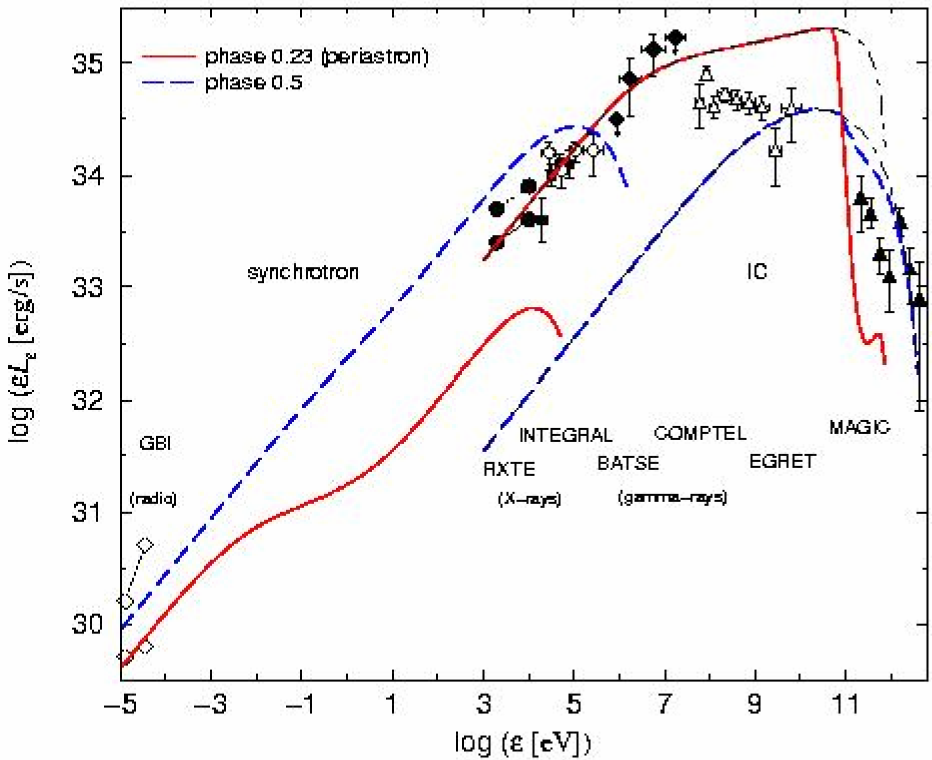


Morphological and variability properties difficult to explain in the pulsar scenario

A model based on accretion of matter from the slow inhomogeneous equatorial wind of the primary star

Bosch-Ramon et al. 2006, A&A submitted

LSI +61 303

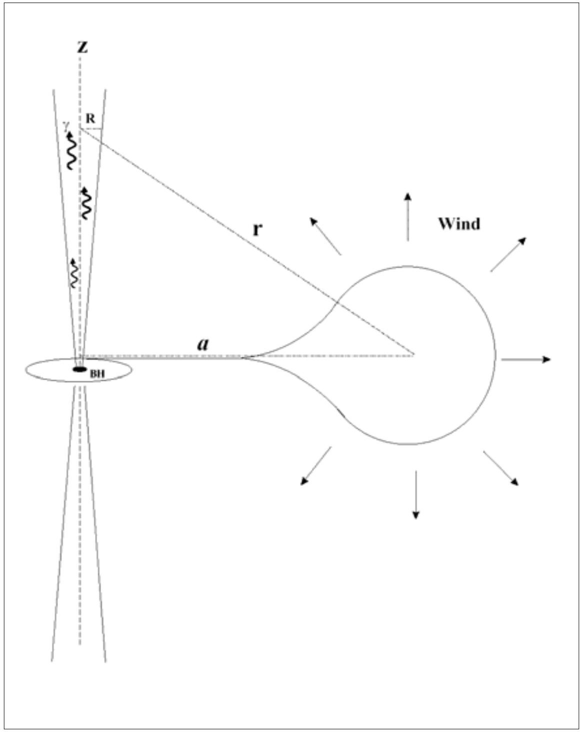


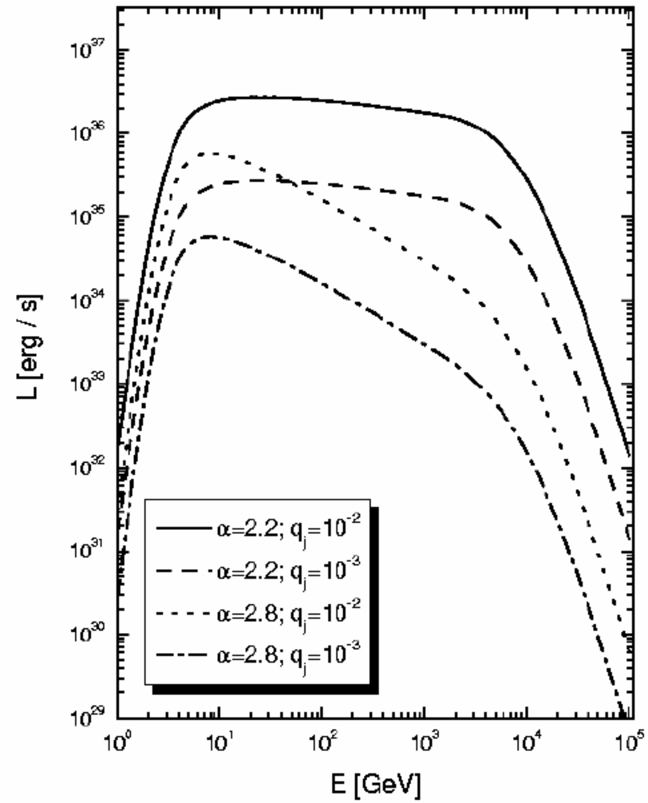
- Particle injection proportional to the accretion rate
- Relativistic e⁻ energy distribution is computed taking into account convective/adiabatical and radiative losses
- SED computed taking into account synchrotron and (Thomson/Klein Nishina) IC, and the photon-photon absorption in the ambient photon fields
- The geometry of the photon-photon and the electron-photon interaction, which changes along the orbit, is considered in the calculations of the γ-ray opacity and IC emission.

Hadronic jet models for microquasars

- Hadronic models (only) for gamma γ-ray emission:

➢ Conical jet 10^{14} eV protons interacting with strong stellar wind protons, assuming efficient wind proton diffusion inside the jet.
➢ Protons are injected in the base of the jet and evolve adiabaticaly.
➢ Applied to explain gamma-ray emission from high mass microquasars (Romero et al. 2003, A&A 410, L1).
➢ The γ-ray emission arises from the decay of neutral pions created in the inelastic collisions between relativistic protons ejected by the compact object and the ions in the stellar wind.





The only requisites for the model are a windy high-mass stellar companion and the presence of multi-TeV protons in the jet.

Spherically symmetric wind and circular orbit

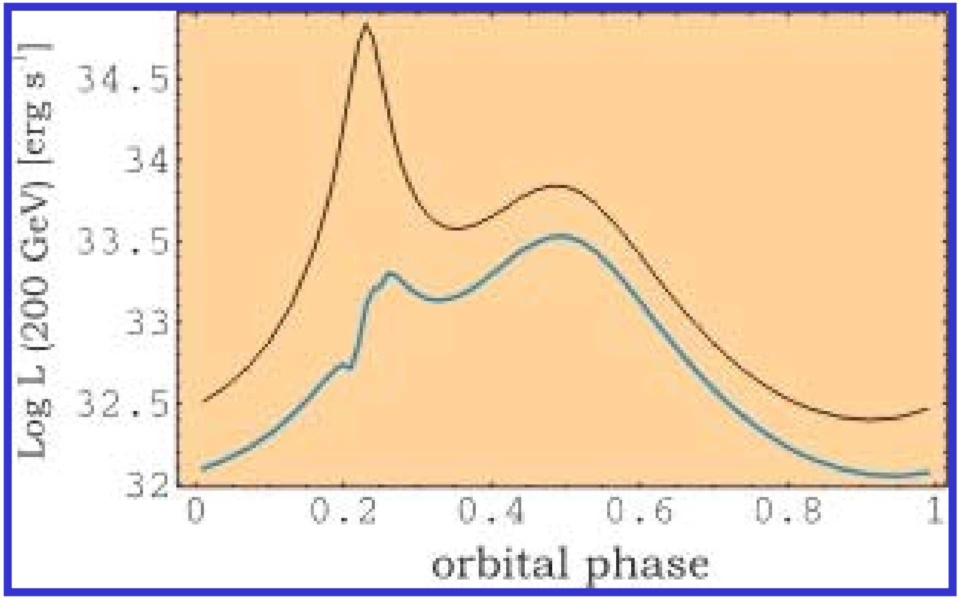
Romero,Torres, Kaufman, Mirabel 2003, A&A 410, L1

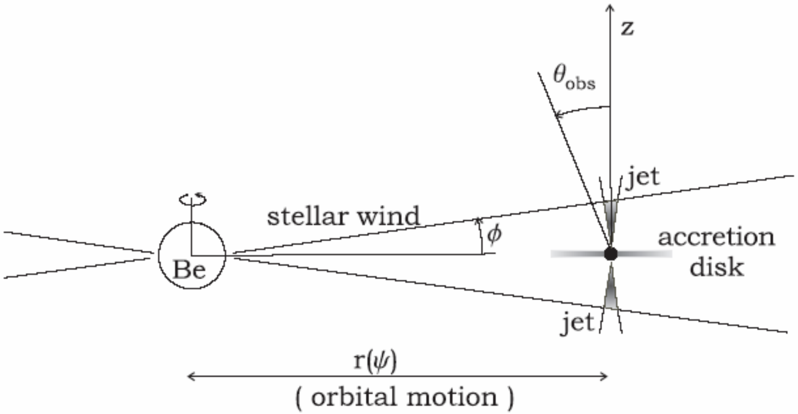
Interactions of hadronic beams with moving clouds in the context of accreting pulsars have been previously discussed in the literature by Aharonian & Atoyan (1996, Space Sci. Rev. 75, 357).

An application to LSI+61303

Romero, Christiansen & Orellana
2005, ApJ 632, 1093
POSTER 41 (model update)

- γ-ray emission originated in pp interactions between relativistic protons in the jet and cold protons from the wind.
- Opacity effects on the γ-rays introduced by the different photons fields





Blue: luminosity corrected by absorption in the stellar and disk photon fields

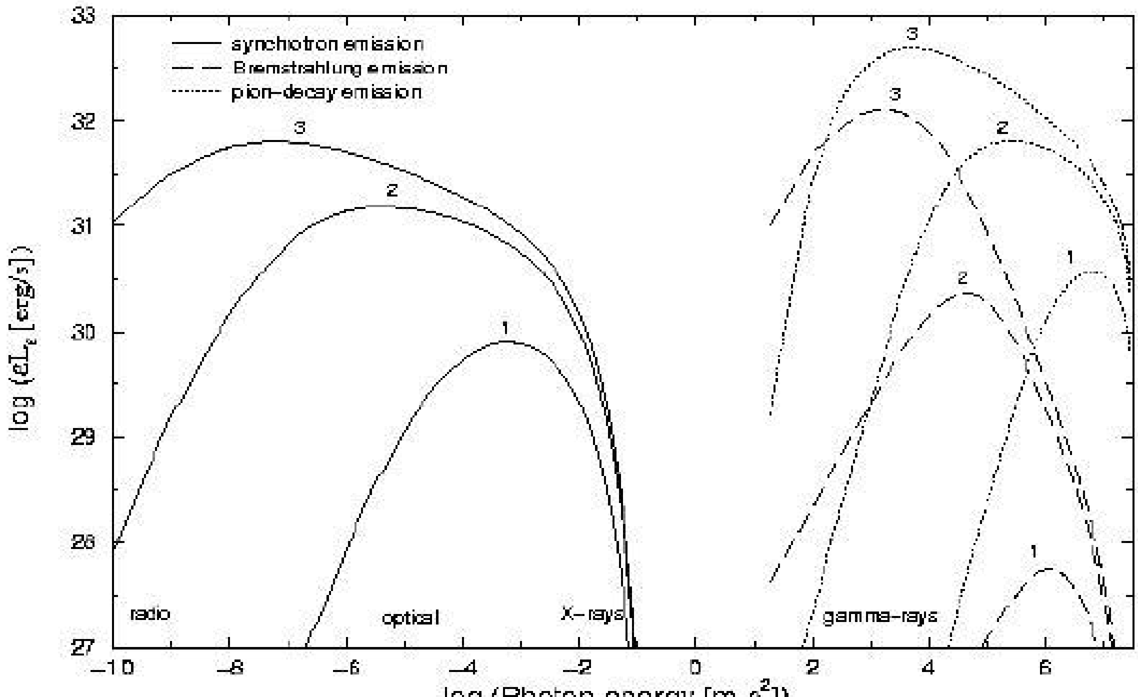
- Models from radio to VHE:

➢Released 10^{14} eV protons from the jet that diffuse through and interact with the ISM.

➢Computed the broadband spectrum of the emission coming out from the pp primary interactions (γ-rays produced by neutral pion decay) as well as the emission (synchrotron, bremsstrahlung and IC scattering) produced by the secondary particles produced by charged pion-decay.

➢All the respective energy losses have been taken unto account.

➢Applied to impulsive and permanent microquasar ejections.



1) 100 yr
2) 1000 yr,
3) 10000 yr
$d_{MQ/cloud}$=10pc
M_{cloud}=10^5Msun
L_{jet}=10^{37} erg/s

Bosch-Ramon et al. 2005, A&A 432, 609

Summary

- Microquasars are among the most interesting sources in the galaxy from the viewpoint of high-energy astrophysics.

- VHE gammas have been observed ➔ Microquasar jets are likely sites of particle acceleration and jets emit at TeV. How?

- Leptonic and hadronic processes could be behind TeV emission.

- Leptonic sources, unlike hadronic ones, will likely present bright counterparts at energies below 100 GeV.

- Multiwavelength (multi-particle) campaigns are of primary importance.