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Microquasars in the GeV-TeV era

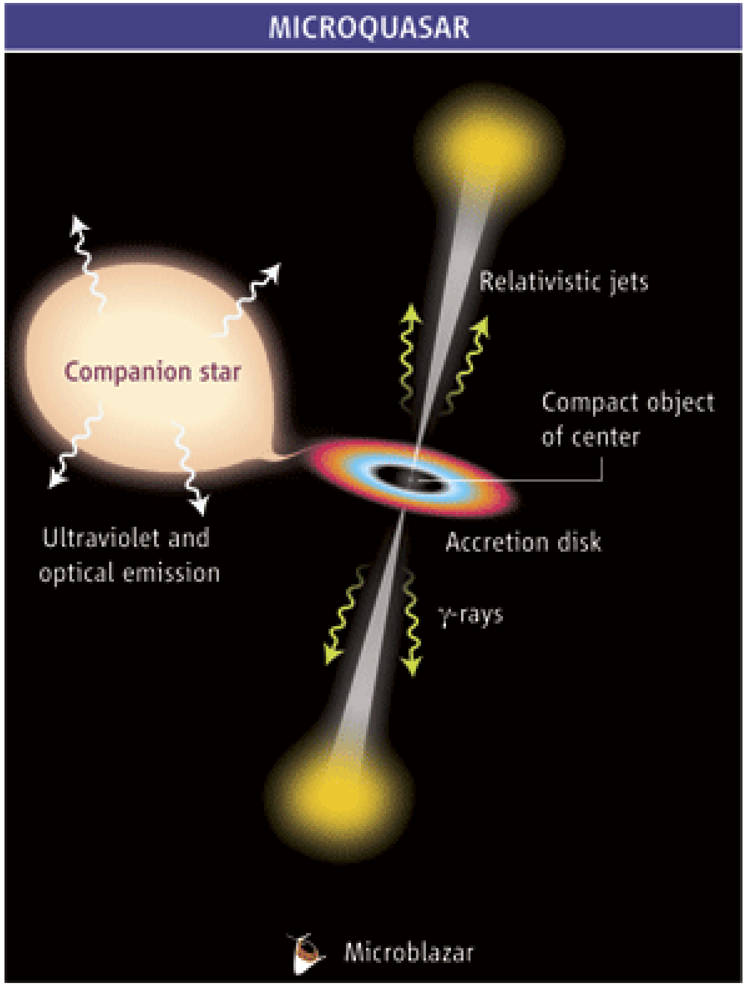
7th Agile Meeting & The Bright Gamma-Ray Sky

29 September - 1 October 2009, ASDC-ESRIN, Frascati (Italy)

OUTLINE

1. X-ray binaries and microquasars
2. Superluminal jets
3. Strong radio outbursts
4. Jet-medium interaction
5. Young pulsar wind interacting with the companion star
6. Periodic TeV sources
7. New BTV candidates
8. 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.

299 XB in the Galaxy (HMXB, Liu et al. 2006, A&A 455,1165 and LMXB 2007, A&A 469, 807).

HMXBs: (114) Optical companion with spectral type O or B. Mass transfer via decretion disc (Be stars) or via strong wind or Roche-lobe overflow.

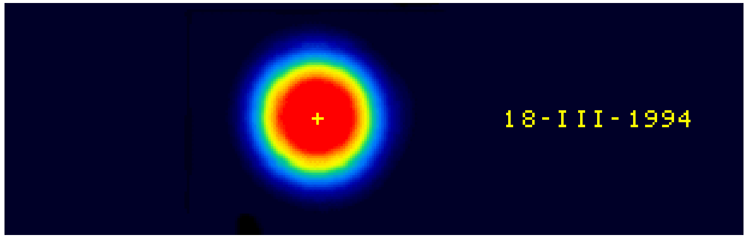
LMXBs: (185) Optical companion with spectral type later than B. Mass transfer via Roche-lobe overflow.

299 XB → 65 (22%) REXBs { 9 HMXBs, 56 LMXBs }

Maybe the majority of RXBs are microquasars (Fender 2001)

At least 15 microquasars

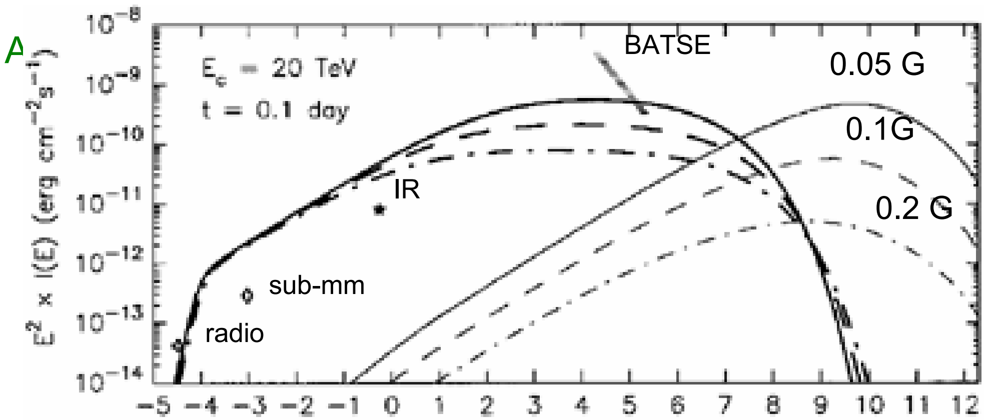
GRS 1915+105 *Superluminal jets*



- 1992: LMXB detected as very variable in X-rays

  Castro-Tirado et al. 1992

- 1994: first superluminal microquasar Mirabel & Rodríguez 1994



STEADY EMISSION FLUX INTEGRAL UPPER LIMITS ABOVE 250 GEV

Synchrotron self Compton model

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

Atoyan & Aharonian 1999, MNRAS 302, 253

	Eff. Time [h]	N_{ex}	σ	U.L. [cm^{-2}s^{-1}] / [C.U.]
Cyg X-1	36.2	-49.6 ± 51.7	-0.96	1.24e-12 / 0.75%
Cyg X-3	32.8	-56.4 ± 47.1	-1.19	1.01e-12 / 0.61%
GRS 1915	22.3	-94.0 ± 52.3	-1.87	1.17e-12 / 0.71%
SS 433	6.6	-9.7 ± 27.9	-0.35	4.30e-12 / 2.61%

Saito et al. (MAGIC Col.) 2009, Proc. 31st ICRC

$$I(> 410\ \mathrm{GeV}) < 0.61 \times 10^{-12} \quad \mathrm{cm^{-2}s^{-1}}$$

Szostek et al. (HESS Col.) 2009, Proc. 31st ICRC

Cygnus X-3

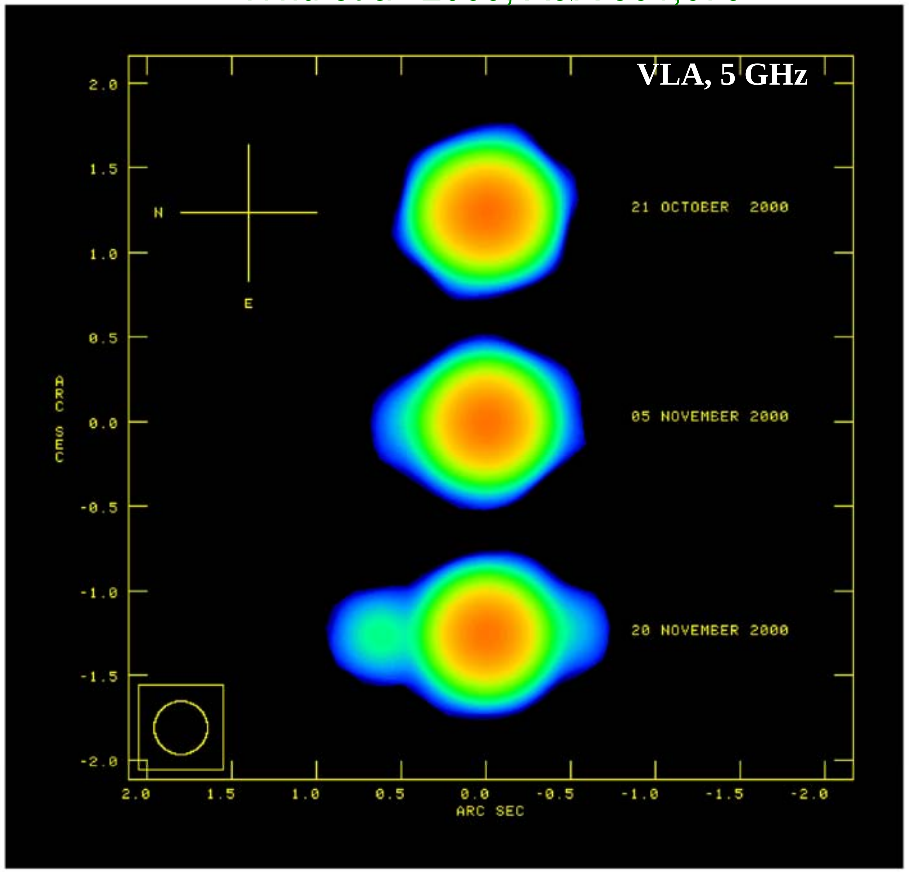
Strong radio outbursts

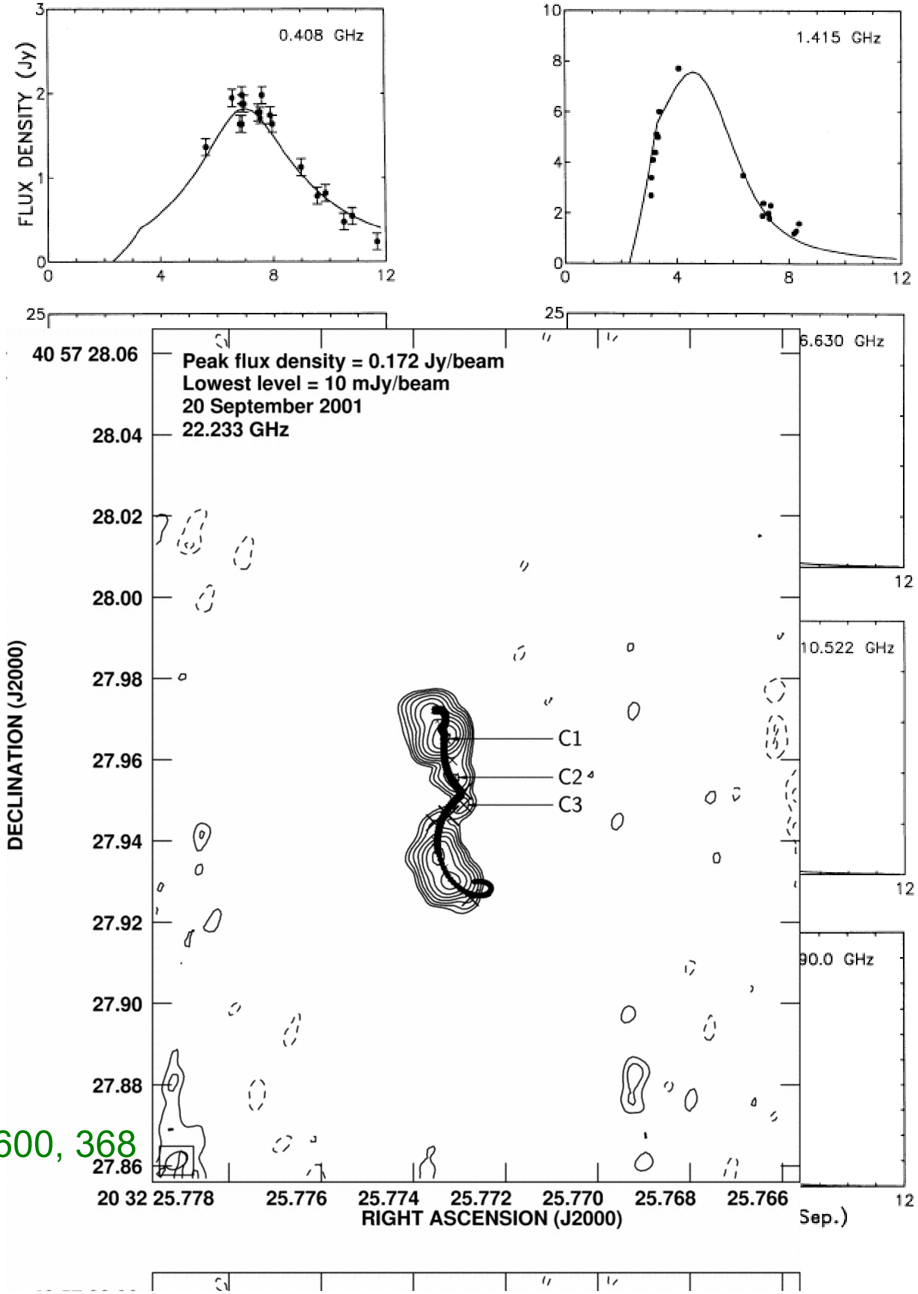
- HMXB, WR+NS?

Orbital modulation of X-ray emission lines

i>60 NS, i<60 BH

Vilhu et al. 2009, A&A 501,679





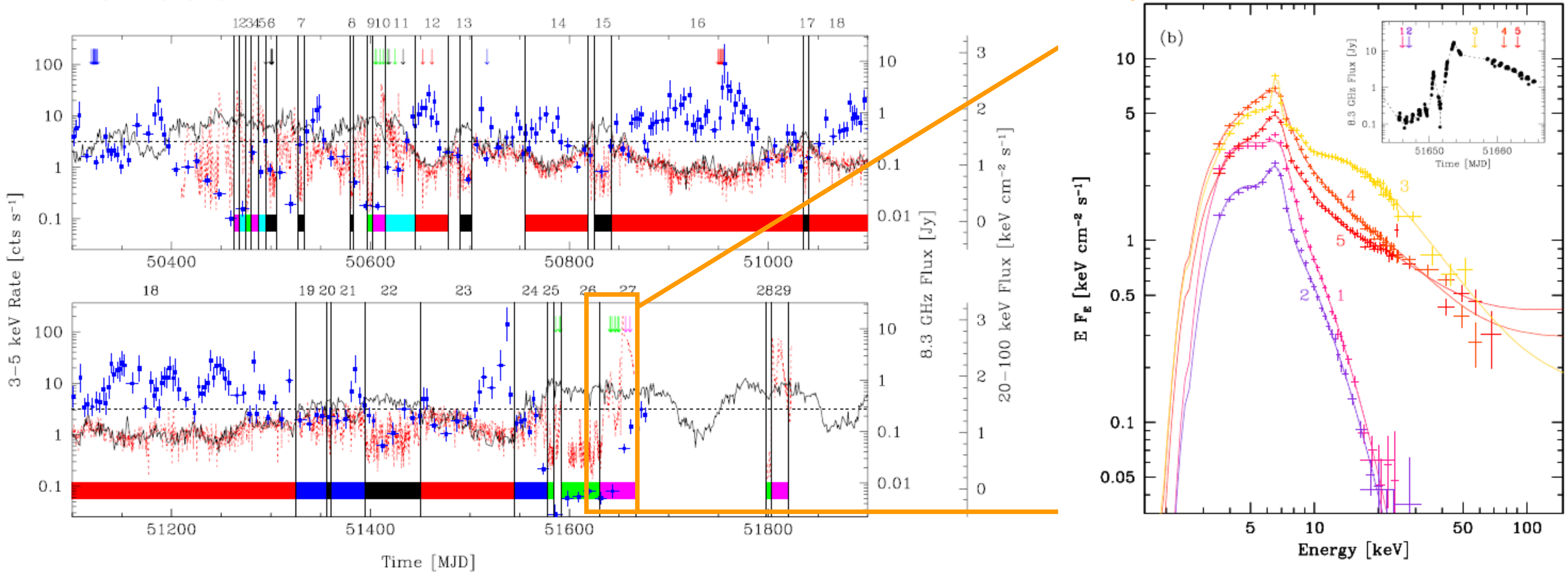
Development of arcsecond radio jets in CYGNUS X-3

Miller-Jones et al. 2004, ApJ 600, 368

Martí et al. 2001, A&A 375, 476

RXTE ASM 3–5 keV —
BATSE 20–100 keV +
GBI 8.3 GHz ....

Szostek et al. 2008, MNRAS 388, 1001



Strong radio flares occur only when the source is in the soft state

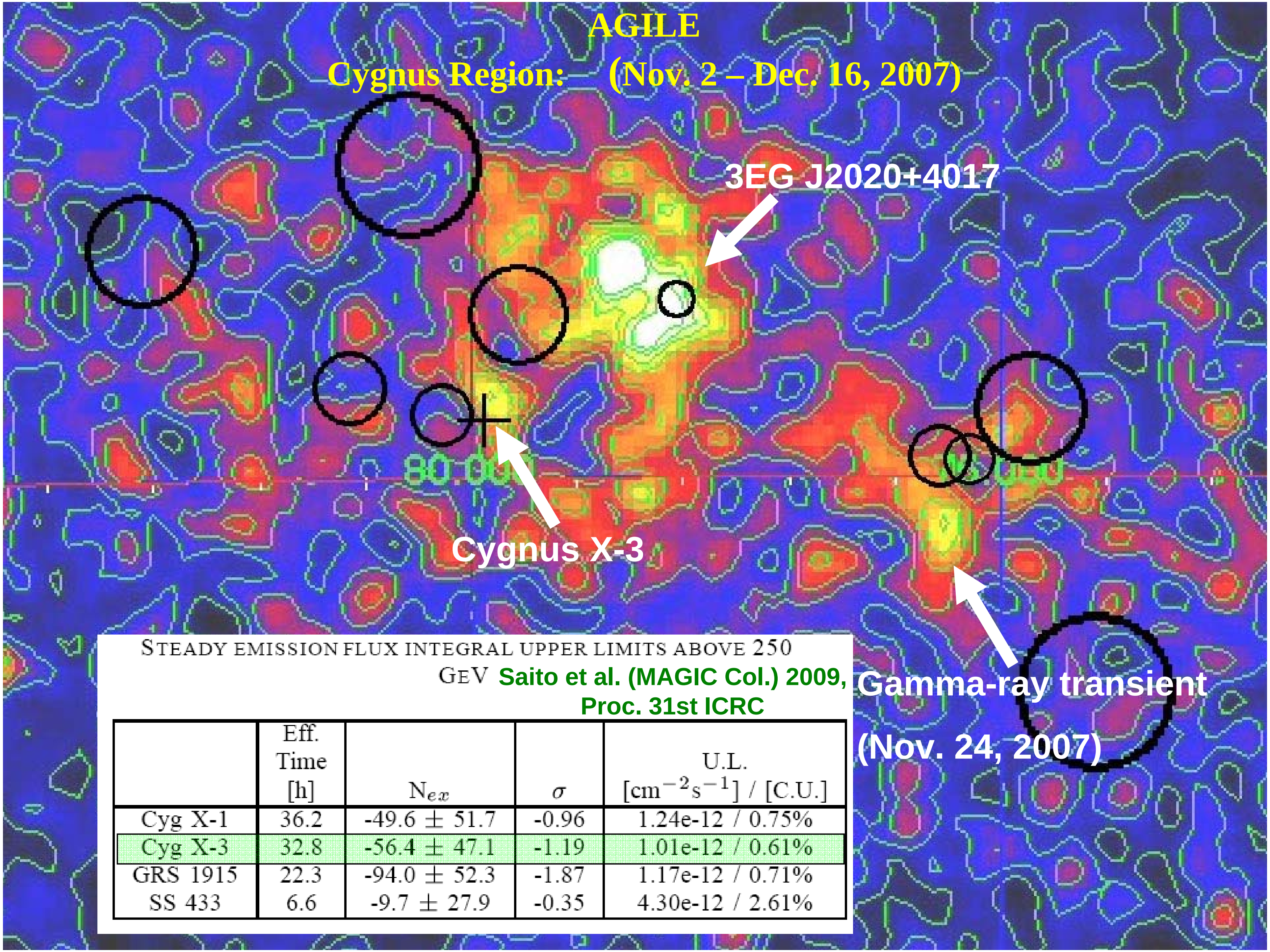
If the non-thermal electrons responsible for either

the hard X-ray tails or

the radio emission during major flares

were accelerated to high enough energies then detectable emission in the γ-ray range, e.g., the GeV or TeV band, would be possible.

Given that major radio flares indicates the presence of hard X-ray tails, **GeV and TeV emission should be searched for during those radio flares.**



STEADY EMISSION FLUX INTEGRAL UPPER LIMITS ABOVE 250 GEV

Saito et al. (MAGIC Col.) 2009, Proc. 31st ICRC

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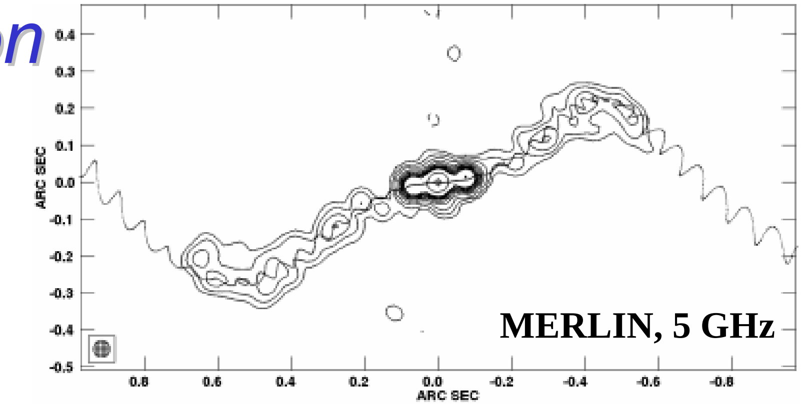
SS 433	6.6	-9.7 ± 27.9	-0.35	4.30e-12 / 2.61%

SS 433 *Jet-medium interaction*



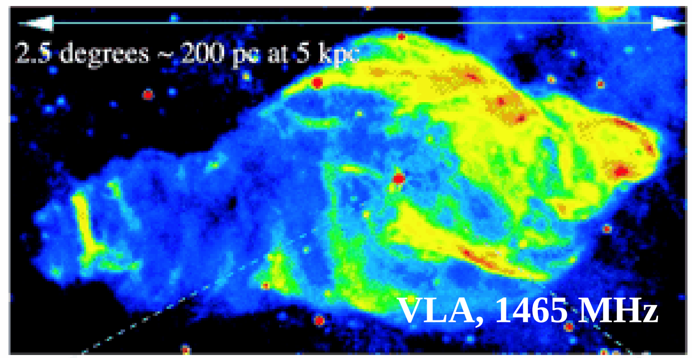
- HMXB, A+NS?

  Jets: Precession, hadronic

Moving lines in relativistic jets (0.26c) with precession movement. Jets precession observed in radio.

- Image of SS 433 and the predicted jet precession cycle (twin-corkscrew pattern)

  Stirling et al. 2002, MNRAS 337, 657



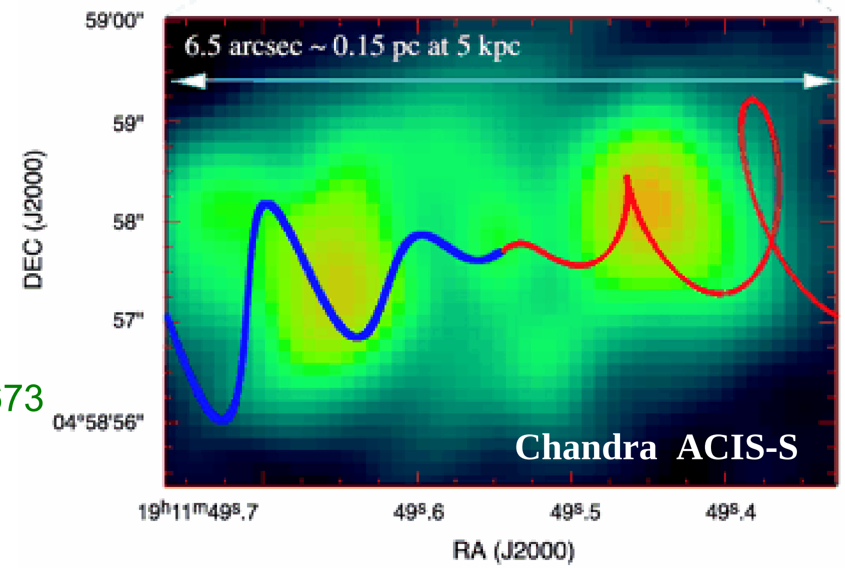
- The surrounding W50 radio nebula. Clear traces of the interaction of the jets of SS 433 with the surrounding gas are shown.

  Dubner et al. 1998, AJ 116, 1842

X-ray image

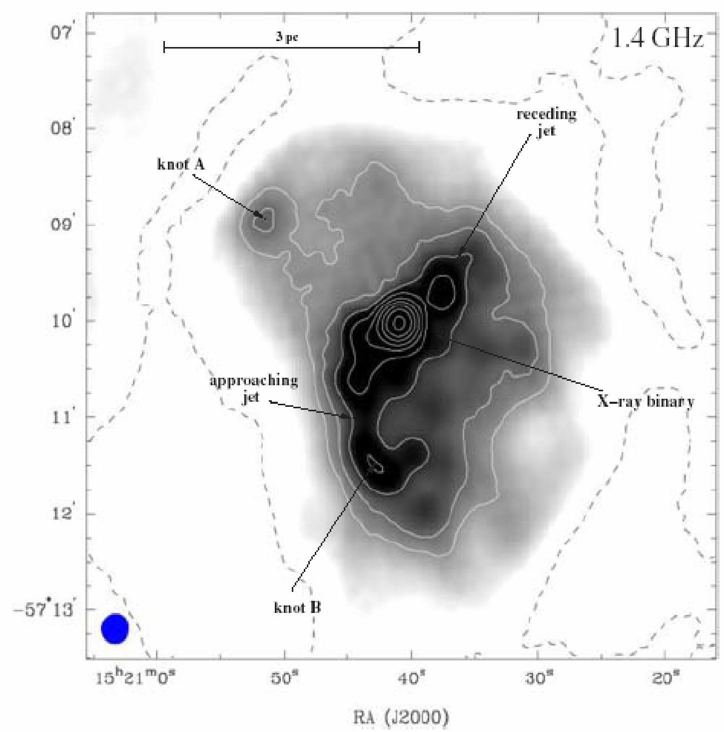
- Doppler-shifted iron emission lines from spatially resolved regions
- Particle re-acceleration in a relativistic jet can act also on atomic nuclei.

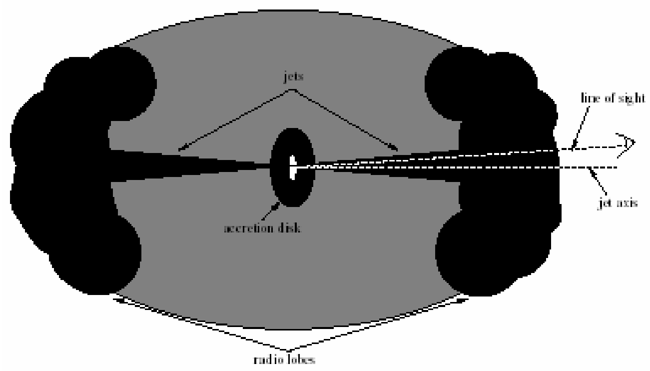
  Migliari et al. 2002, Science 297, 1673



Circinus X-1

ATCA & CHANDRA





Tudose et al. 2006, MNRAS 372, 417

- LMXB, Subgiant+NS, 16.6 d, superluminal

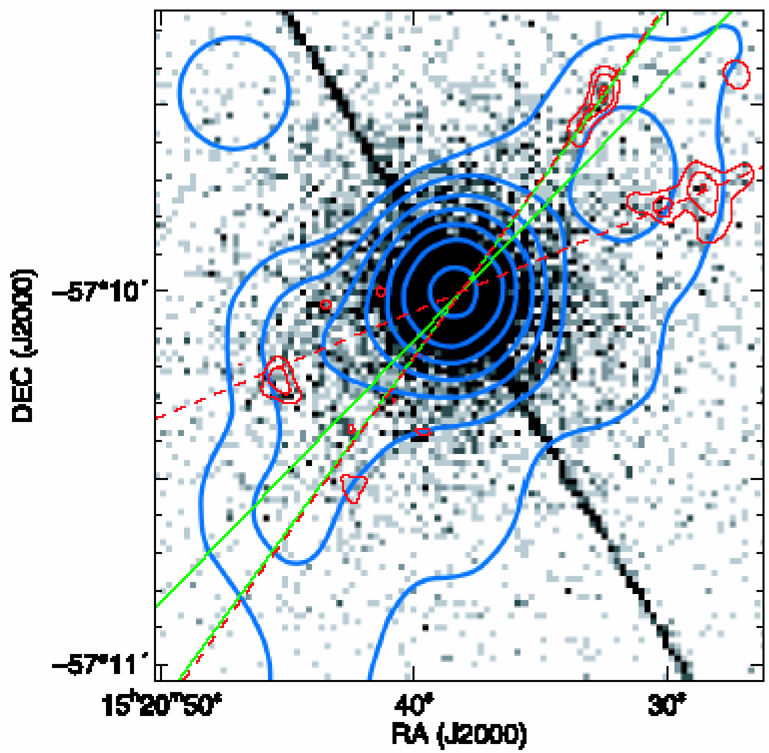


FIG. 3.—Radio–X-ray overlay. *Blue contours*: 1.4 GHz surface brightness (adapted from Tudose et al. 2006; levels increase by $\sqrt{2}$ between contours; *outermost contour*: 22 mJy beam^{-1}; beam size shown on top left). *Gray scales*: X-ray image (top right panel of Fig. 1). *Red contours*: Adaptively smoothed, normalized, PSF-subtracted image (bottom left panel of Fig. 1). *Green lines*: Estimated allowed range of PAs from high-resolution radio observations of approaching jet (Fender et al. 2004). *Red lines*: Allowed range in PA for X-ray jet from top panel of Fig. 2.

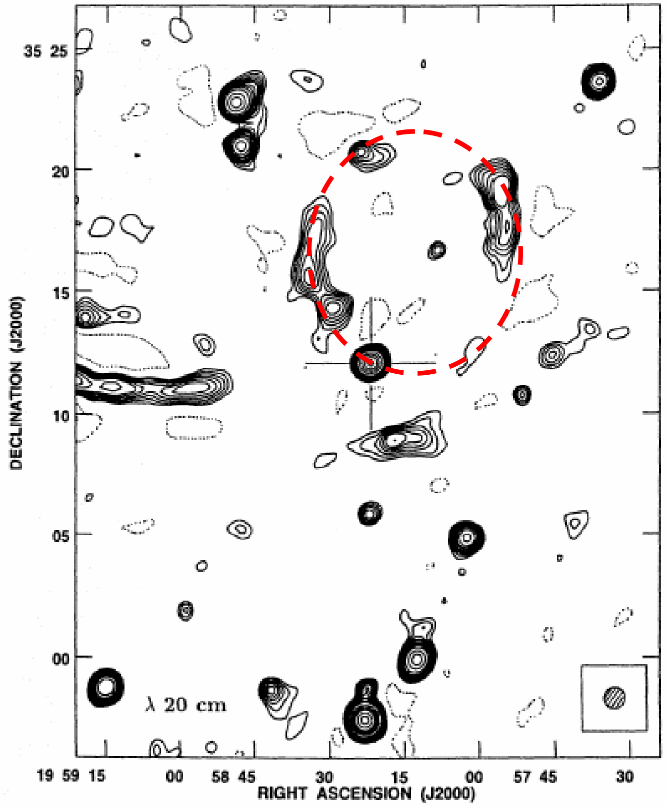
Heinz et al. 2007, ApJ 663, L93

Cygnus X-1 Stellar Mass Black Hole

- HMXB, O9.71+BH

5 pc (8’) diameter ring-structure of bremsstrahlung emitting ionized gas at the shock between (dark) jet and ISM.

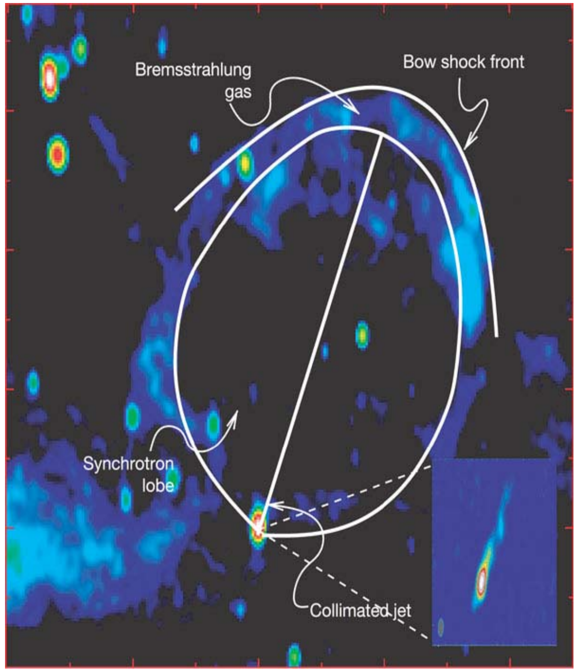
VLA



Cyg X-1. On the other hand, it is intringuing that Cyg X-1 does appear surrounded by several clumps of extended emission. All these clumps also appear in maps made from the individual visibility data sets. At a marginal level, their disposition reminds an elliptical ring-like shell with Cyg X-1 offset from the center by a few arcminutes.

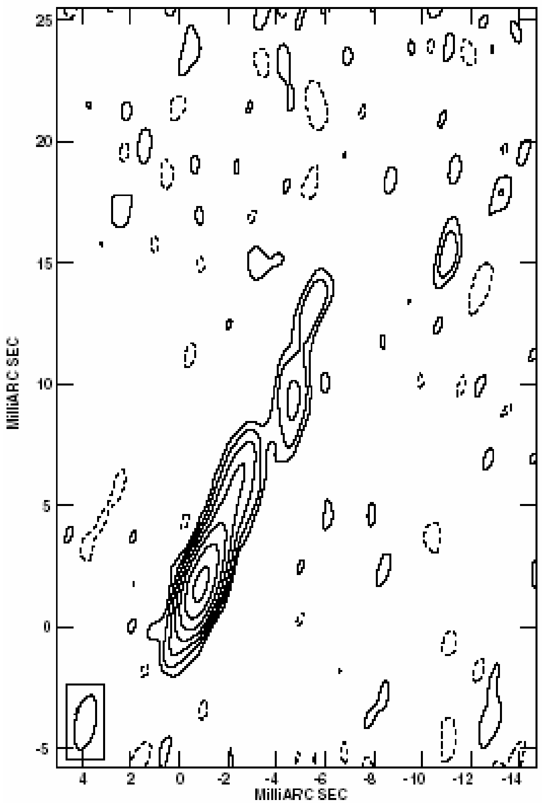
Martí et al. 1996, A&A 306, 449

WSRT



Gallo et al. 2005, Nature

VLBA+VLA

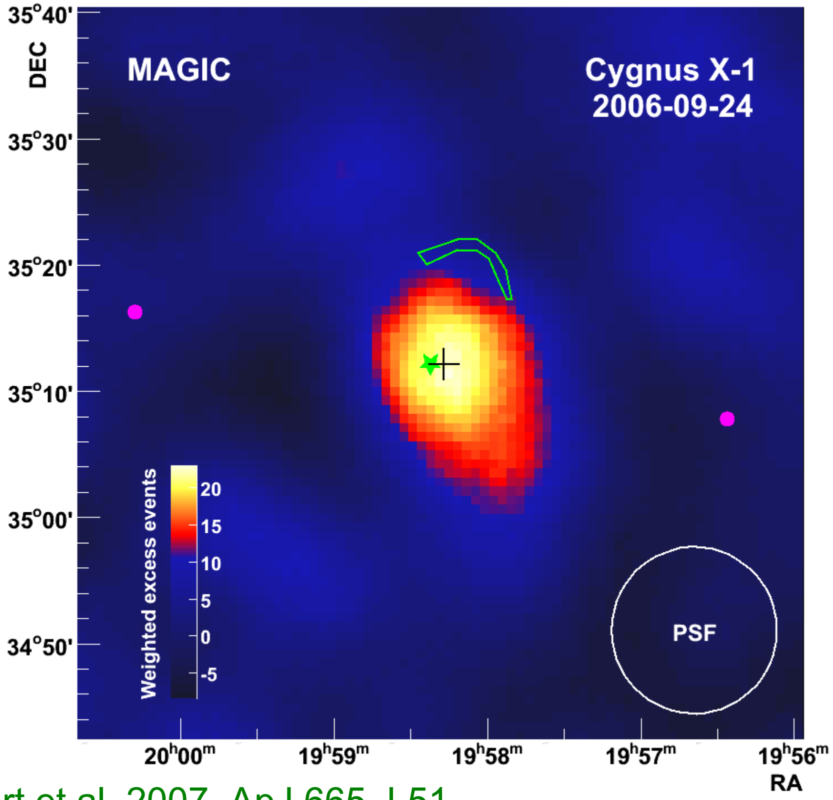


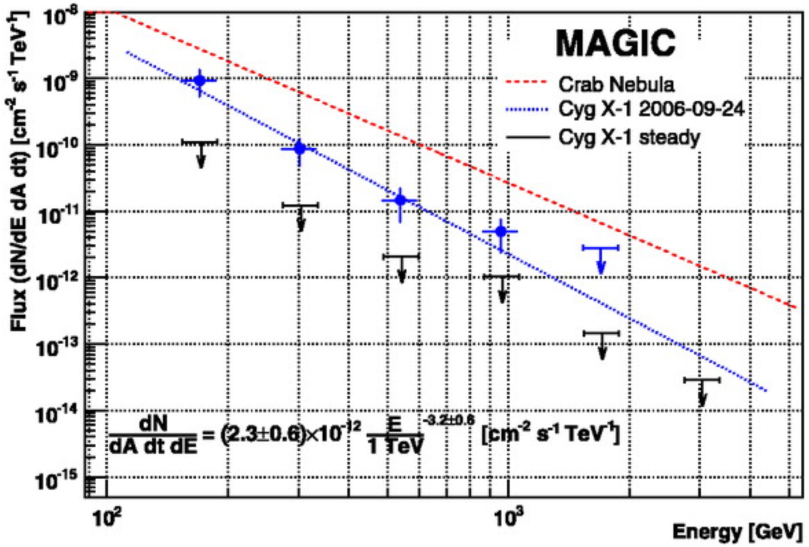
15 mas 30 AU

Stirling et al. 2001, MNRAS 327, 1273

MAGIC

TeV source: Cygnus X-1





Albert et al. 2007, ApJ 665, L51

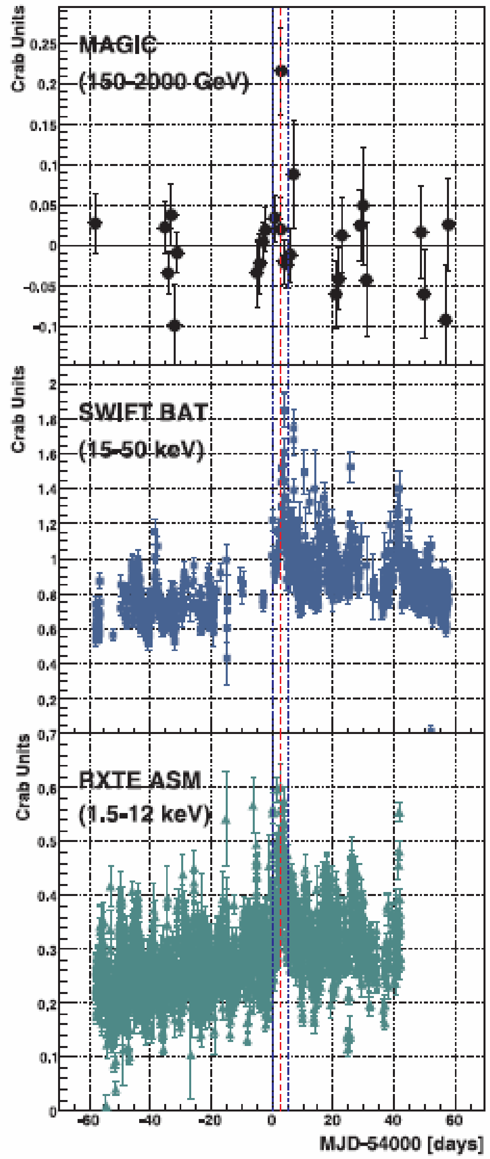
- Strong evidence (4.1σ post trial significance) of intense short-lived flaring episode for the second halve of the night (at phase 0.9 -1.0, when the BH is behind the star)
- Orbital phase 0.9-1.0, when the black hole is behind the star and photon-photon absorption should be huge: flare in the jet?

Flaring Activity

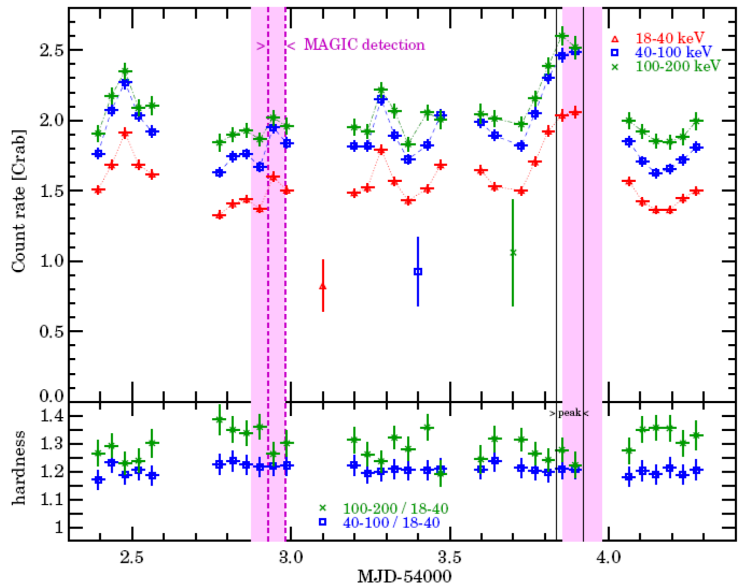
- MAGIC sees an excess right before the first Swift peak rise

- An intense state of hard X-ray emission is observed with INTEGRAL

- Hard x-rays could be produced at the base of the jet (non-thermal e in the hot comptonising medium, McConnell et al. 2002) and γ-rays further away by interaction with stellar wind (shocks located in the region where the outflow originating close to the BH interacts with the wind of the star, Perucho & Bosch-Ramon 2008, A&A 482, 917)



Albert et al. 2007, ApJ 665, L51



INTEGRAL

Malzac et al. 2008, A&A 492, 527

Young pulsar wind interacting with the companion star

PSR B1259-63 The first variable galactic source of VHE

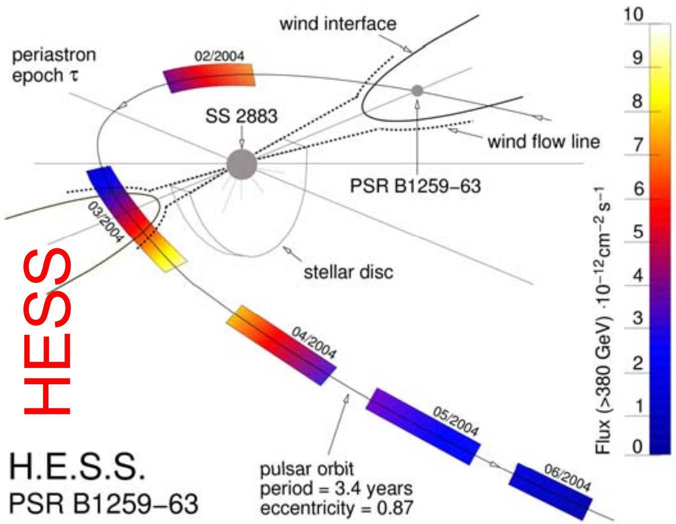
PSR B1259-63 / SS 2883: B2Ve + 47.7 ms radio pulsar, *P*= 3.4 yr, *e*=0.87. No radio pulses are observed when the NS is behind the circumstellar disk (free-free absorption).

Tavani & Arons 1997, ApJ 477, 439 studied the radiation mechanisms and interaction geometry in a pulsar/Be star system

The observed **X-ray/soft gamma-ray** emission was

- not compatible with accretion or propeller-powered emission
- consistent with the shock-powered high-energy emission produced by the pulsar/outflow interaction

HESS



VHE gamma-rays are detected when the NS is close to periastron or crosses the disk (Aharonian et al. 2005, A&A 442, 1).

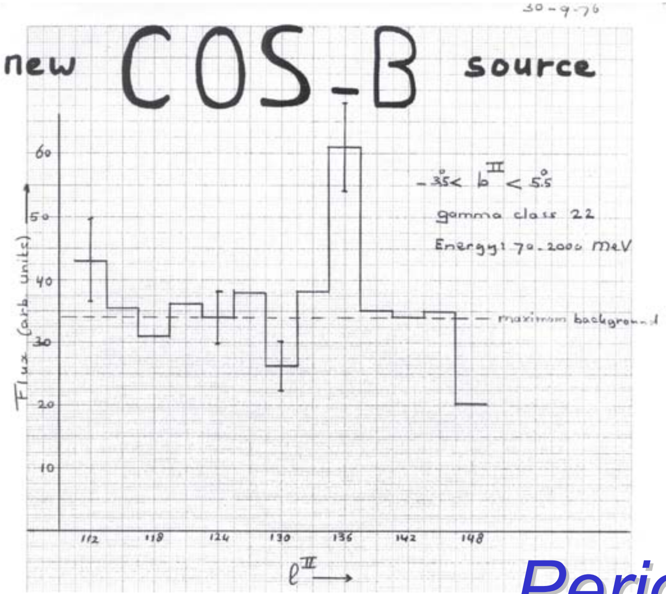
- significant variability

- power-law spectrum (Γ=2.7) explained by IC scattering processes

- the TeV, and radio/X-ray light curves, can be explained if the interaction with the circumstellar disk is considered. (Chernyakova et al. 2006, MNRAS 367, 1201)

LS I +61 303

Historical association with a γ-ray source



First high-energy (> 100 MeV) COS-B gamma-ray source: CG/2CG 135+01

Hermsen et al. 1977, Nature 269, 494

The radio emitting X-ray binary LS I+61 303, since its discovery as a variable radio source, has been proposed to be associated with the γ-ray source 2CG 135+01 (= 3EG J0241+6103) (Gregory & Taylor 1978, Nature 272, 704)

Periodic emission

26.5 days periodicity

Radio (P=26.496 d) Taylor & Gregory 1982, ApJ 255, 210; Gregory 2002, ApJ 575, 427

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

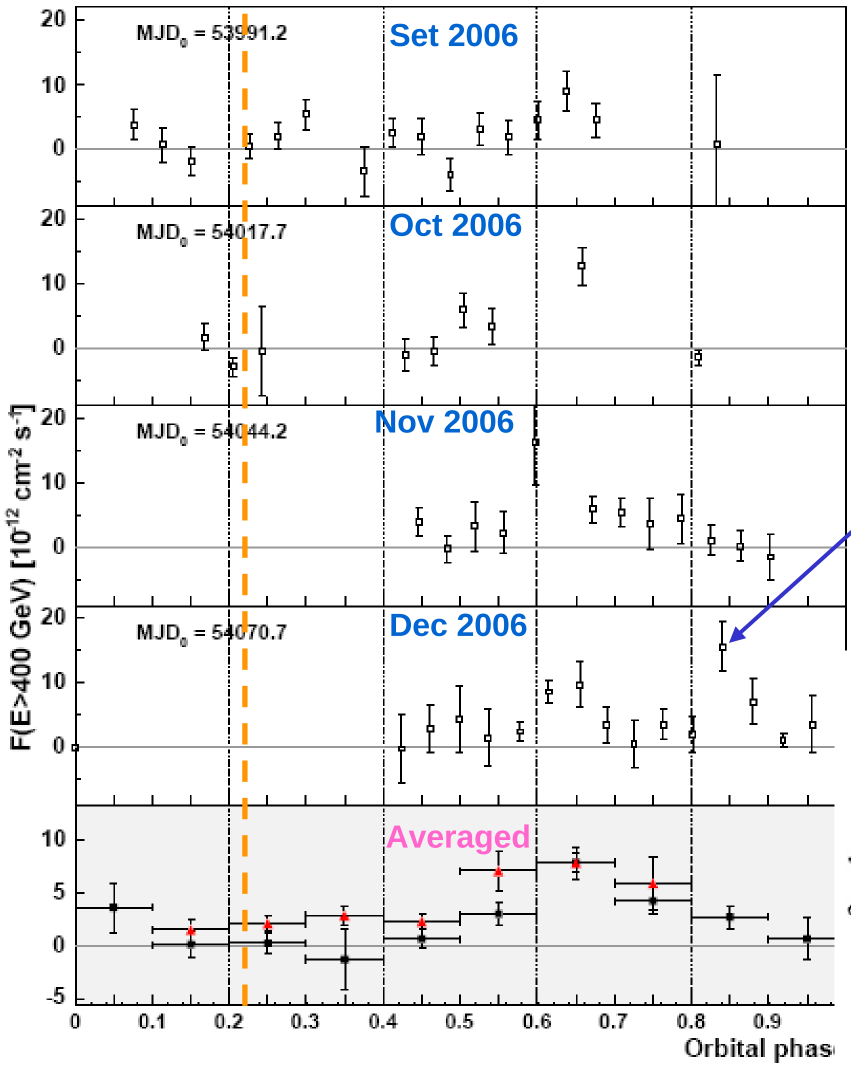
HE gamma-rays Abdo et al. 2009, ApJ (0907.4307)

VHE gamma-rays Albert et al. 2009, ApJ 693, 303

MAGIC

Albert et al. 2009, ApJ 693, 303

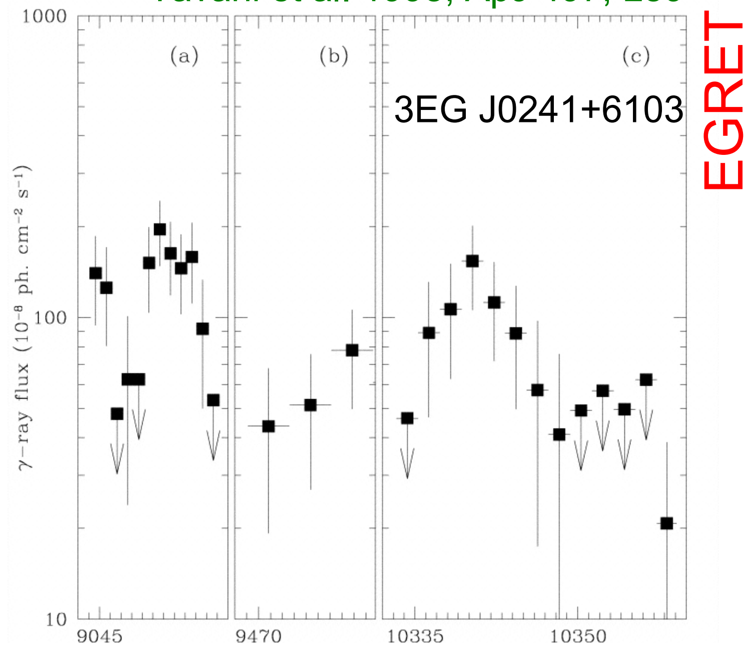
New MAGIC data (cycle II)

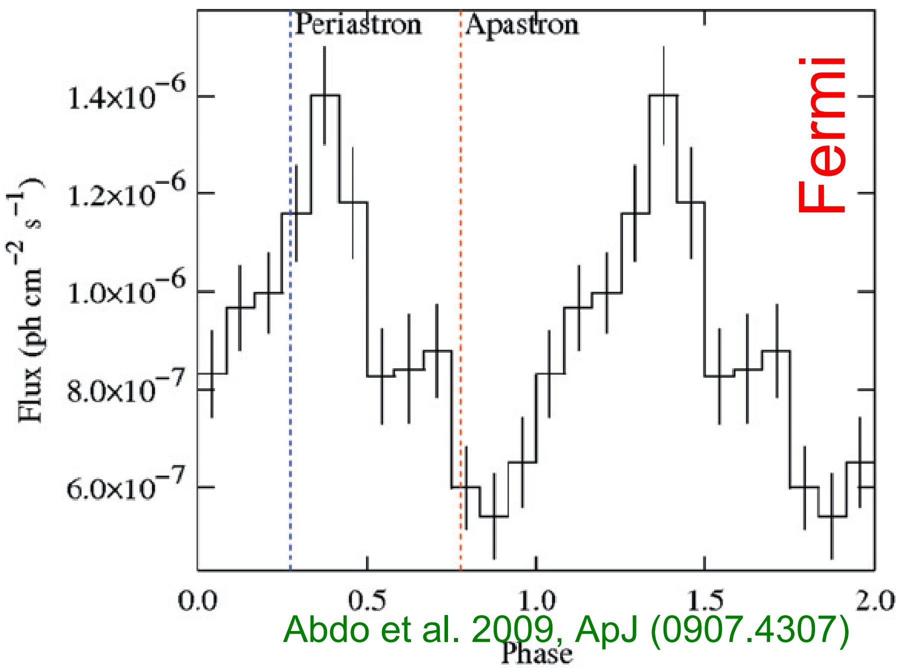


- **More complete** orbital coverage
- **Similar behaviour** as last year
- **Maximum flux** detected at phase 0.(
- Exception one point at Φ~0.85

Red dots from Albert et al. 2006

Tavani et al. 1998, ApJ 497, L89

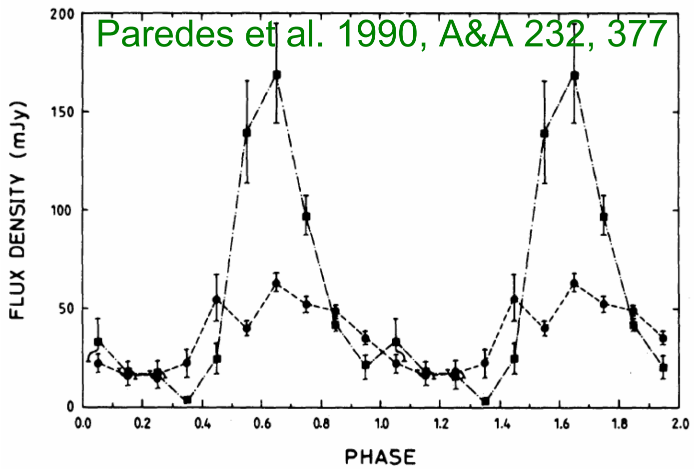


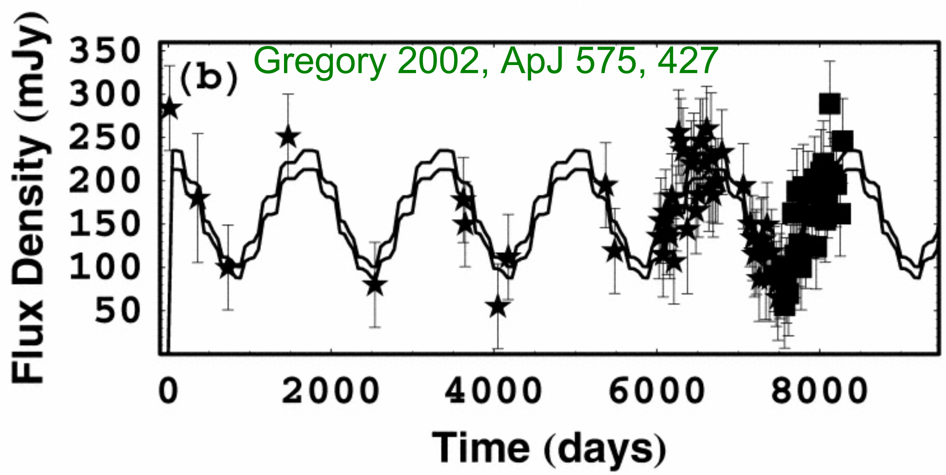


Abdo et al. 2009, ApJ (0907.4307)

4.4 yr periodicity

Radio (P= 1667 d) Paredes 1987, PhD Thesis; Gregory 2002, ApJ 575, 427





A 4.4 yr modulation at HE and VHE gamma-rays?

The amplitude of the Fermi orbits observed varies, suggesting some orbit-to-orbit variability Abdo et al. 2009, ApJ (arXiv:0907.4307)

LS I +61 303

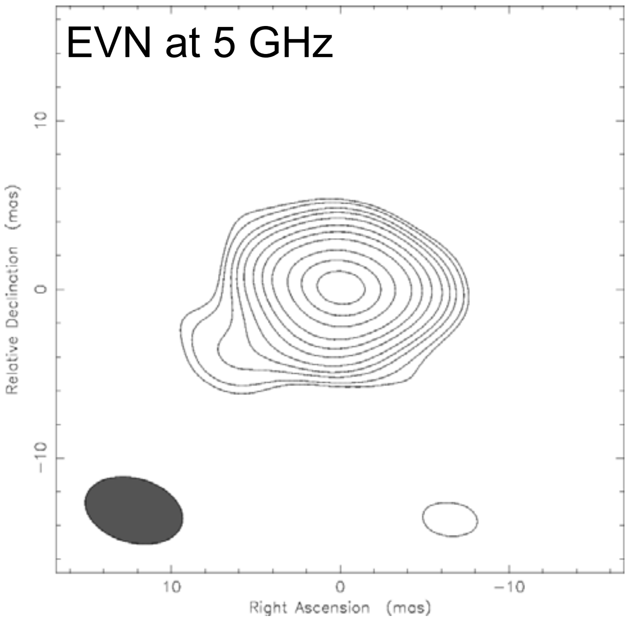
Accretion onto a compact object (NS or BH) embedded in mass outflow of the B-star

Taylor & Gregory 1982, ApJ 255, 210; Taylor et al. 1992, ApJ 395, 268

Non-accreting young pulsar in orbit around a mass-losing B star

Powered by the spindown of a young pulsar (Maraschi & Treves 1981, MNRAS 194,1)

Revived after the discovery of PSR B1259-63 (Tavani et al. 1994, ApJ 433, L37)



Resolved radio emission pointed towards the microquasar scenario (Massi et al. 2001 A&A 376, 217)

Microquasar scenarios with acceleration in jet: LS 5039 and LS I +61 303

leptonic

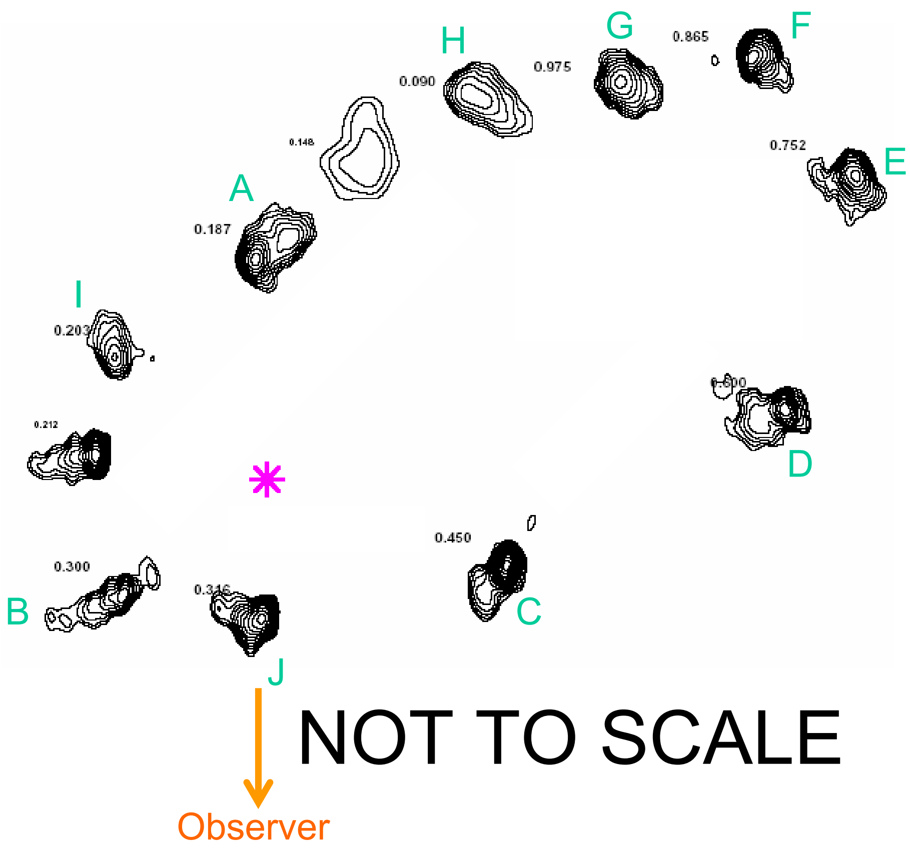
- Bosch-Ramon & Paredes 2004, A&A 425, 1069
- Bosch-Ramon et al. 2006, A&A 459, L25
- Gupta & Böttcher 2006, ApJ 650, L123
- Bednarek 2006, MNRAS 371, 1737

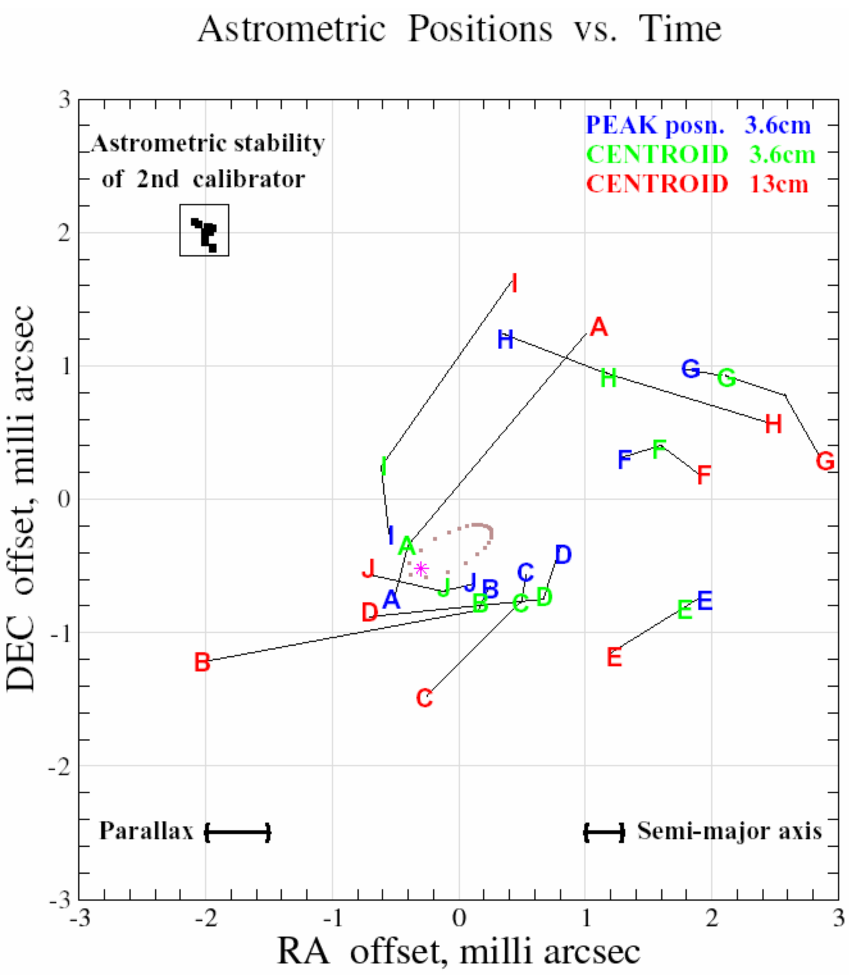
hadronic

- Romero et al. 2005, ApJ 632, 1093
- Orellana & Romero 2007, ApSS 309, 333

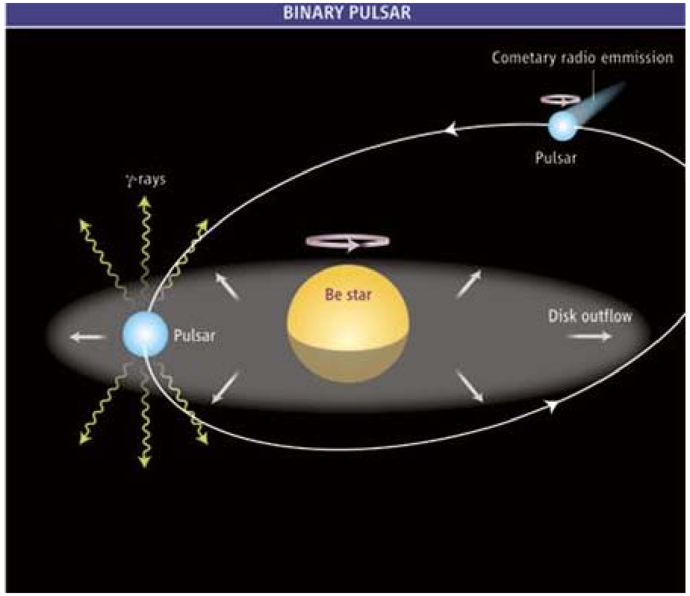
VLBA

Jet-like features have been reported several times, but show a puzzling behavior (Massi et al. 2001, 2004). VLBI observations show a rotating jet-like structure (Dhawan et al. 2006, VI Microquasars Workshop, Como, Setember 2006)

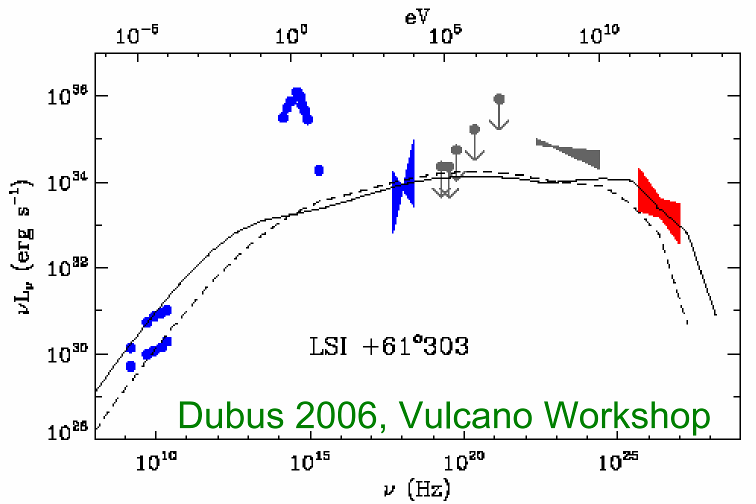




3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU.
Semi-major axis: 0.5 AU

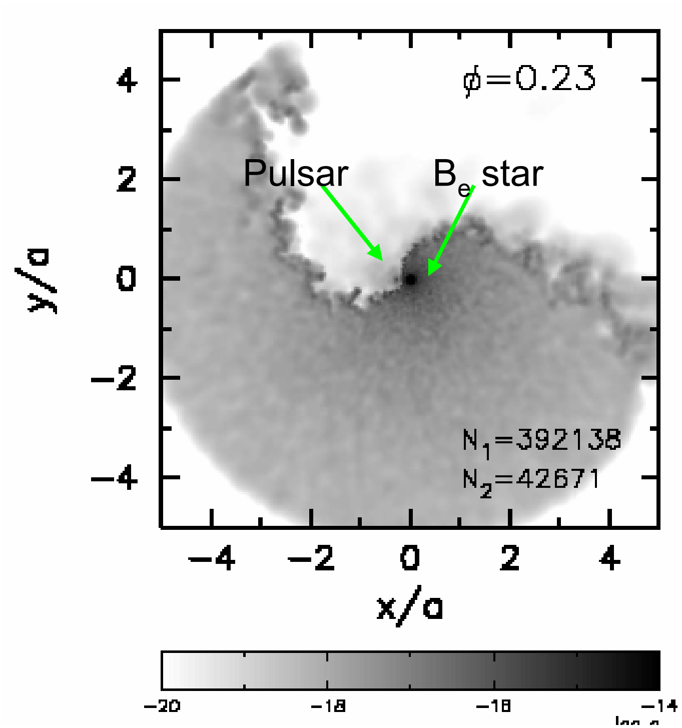


Pulsar scenario: Interaction of the relativistic wind from a young pulsar with the wind from its stellar companion. A comet-shape tail of radio emitting particles is formed rotating with the orbital period. We see this nebula projected (Dubus 2006, A&A 456, 801). UV photons from the companion star suffer IC scattering by the same population of non-thermal particles, leading to emission in the GeV-TeV energy range



Romero, Okazaki et al. apply a "Smoothed Particle Hydrodynamics" (SPH) code in 3D dynamical simulations for both the pulsar-wind interaction and accretion-jet models.

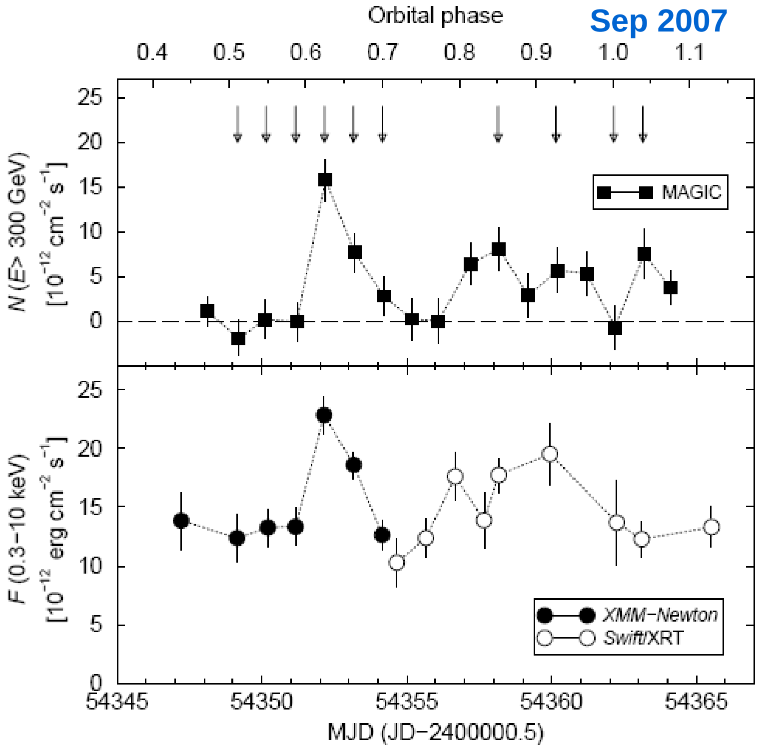
When orbital effects are included, even the most favourable assumptions toward a large Be/pulsar wind momentum ratio do not produce the simple elongated shape inferred in the VLBI radio image, which was previously cited as strong evidence in favour of a pulsar wind interaction scenario

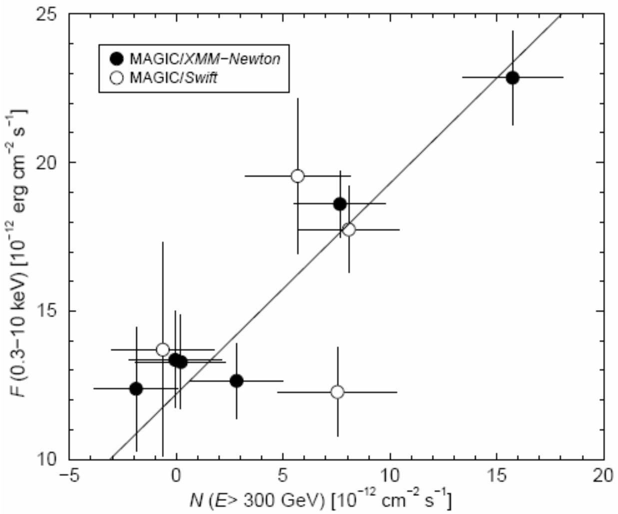


Romero et al. 2007, A&A 474, 15

MAGIC

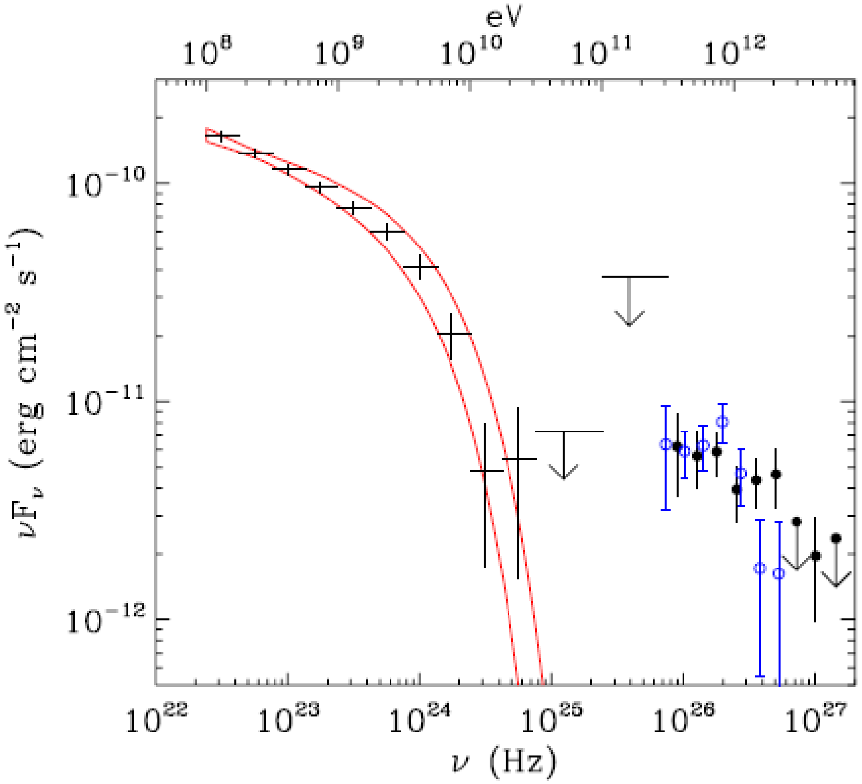
X-ray/VHE gamma-ray correlation





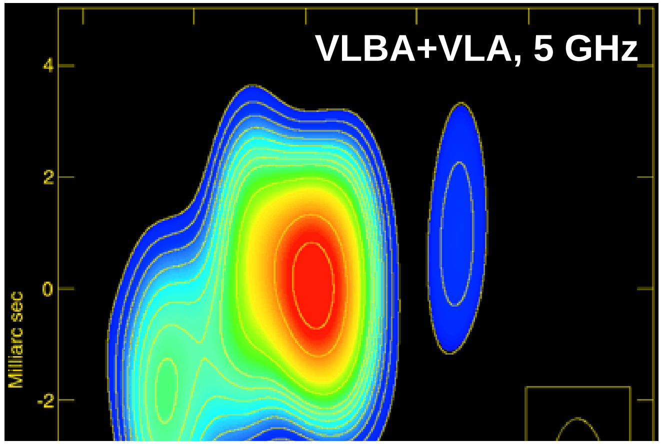
Jogler et al. (MAGIC Col.), 2009, 31th ICRC

Fermi
MAGIC blue, 0.5-0.7
VERITAS black, 0.5-0.8



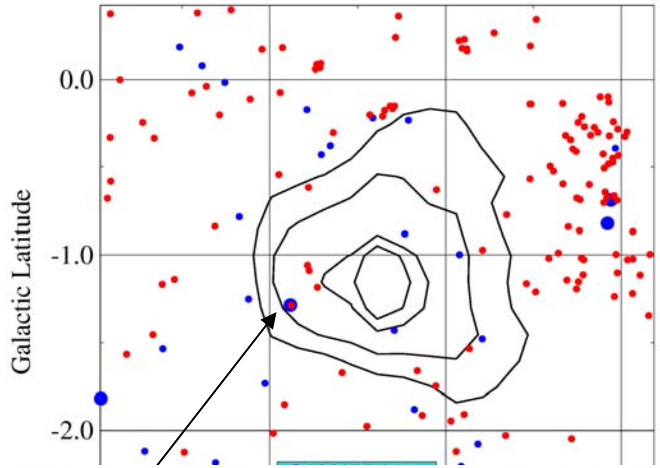
Abdo et al. 2009, ApJ (0907.4307)

LS 5039



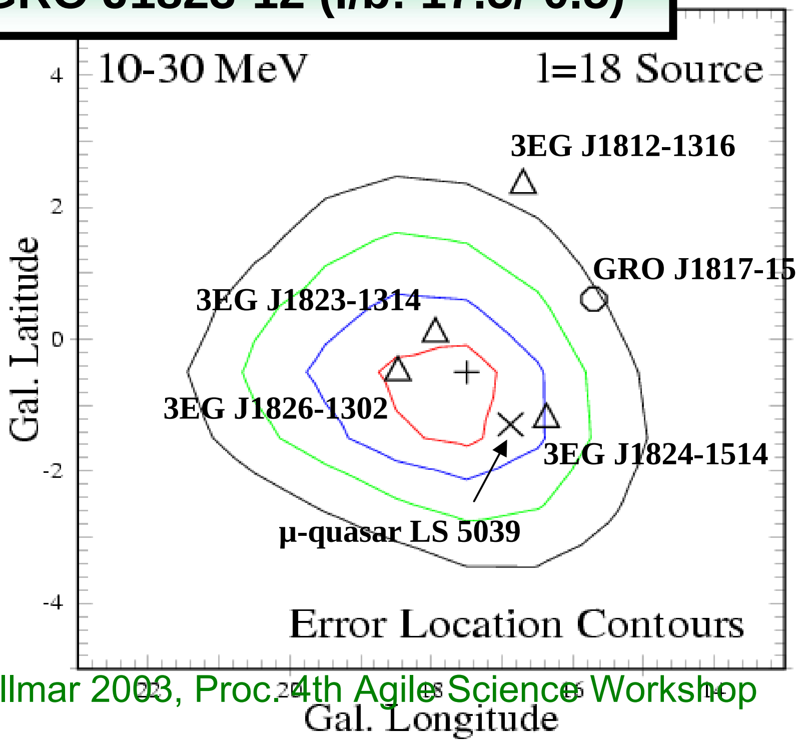
LS 5039 could be related to the HE γ-ray source 3EG J1824-1514

EGRET



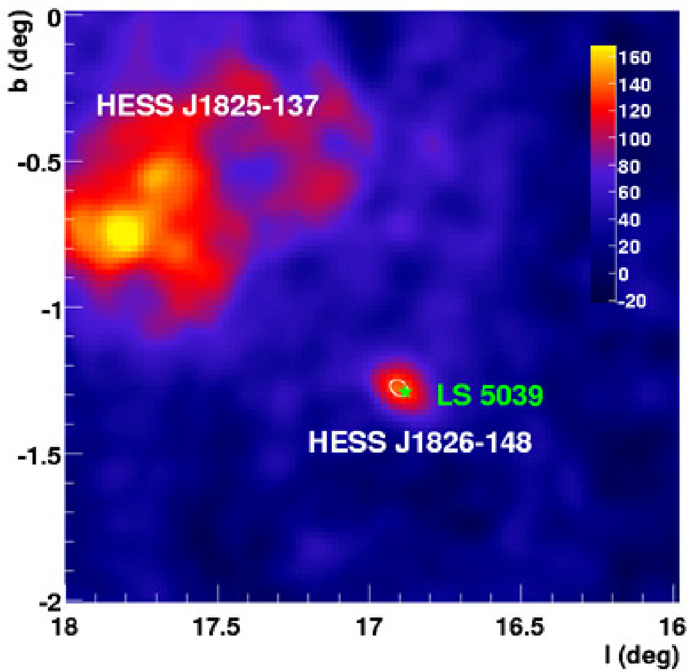
GRO J1823-12 (l/b: 17.5/-0.5)

COMPTEL



Collmar 2003, Proc. 4th Agile Science Workshop

HESS



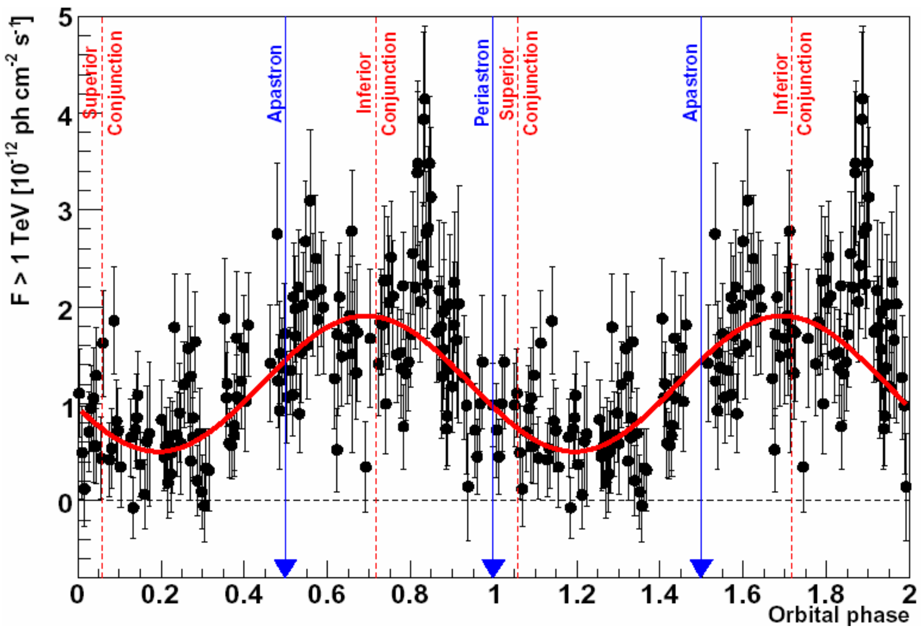
Aharonian et al. 2005 , Science 309, 746

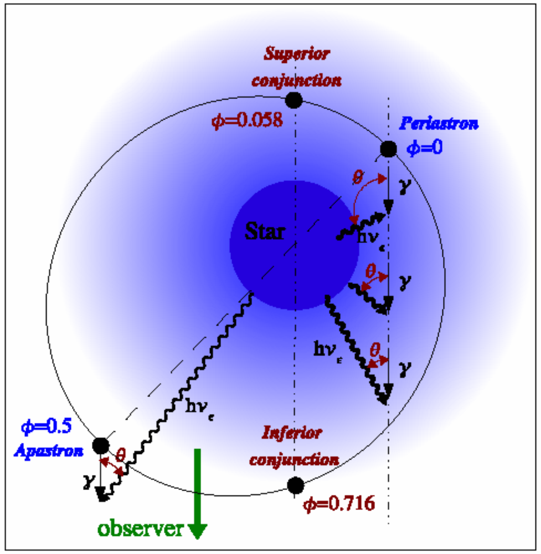
HESS

3.9 day orbital modulation in the TeV gamma-ray flux

Variable TeV emission with the orbital period of the binary system. Flux maximum at inferior conjunction of the compact object.

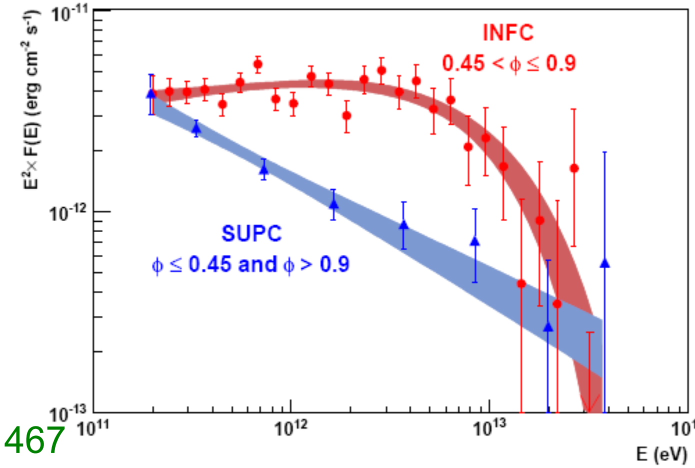
Aharonian et al. 2006, A&A 460, 743





This suggests that photon-photon absorption (e^+-e^- pair production on stellar UV photons), which has an angle dependent cross-section plays a major role but……

- the flux should be 0 at periastron and superior conjunction, and is not!
- the spectrum shows strong variability, but not at 200 GeV as predicted by absorption models! (Dubus 2006, Böttcher 2007)

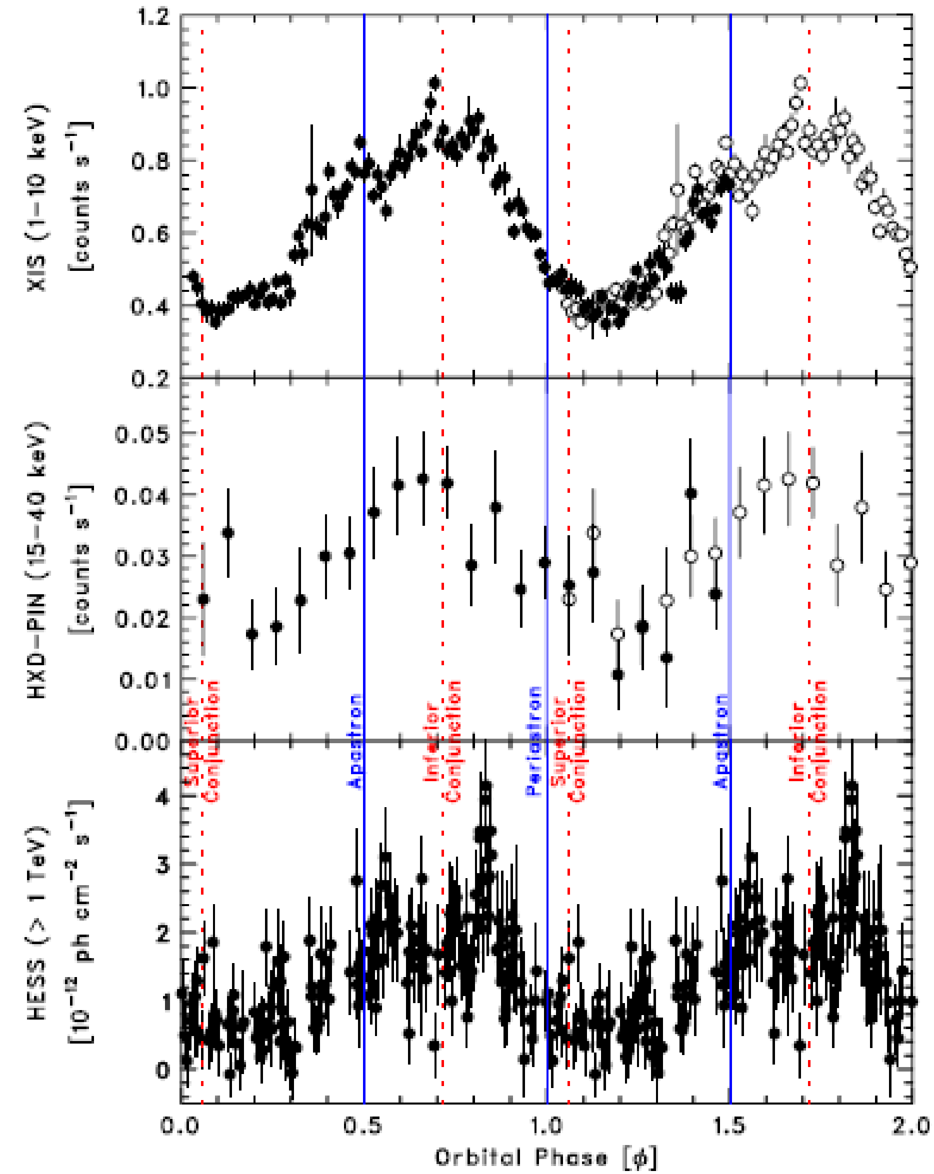


See also Khangulyan, Aharonian & Bosch-Ramon, 2008 MNRAS 383, 467

Close correlation of the X-ray and TeV light curves

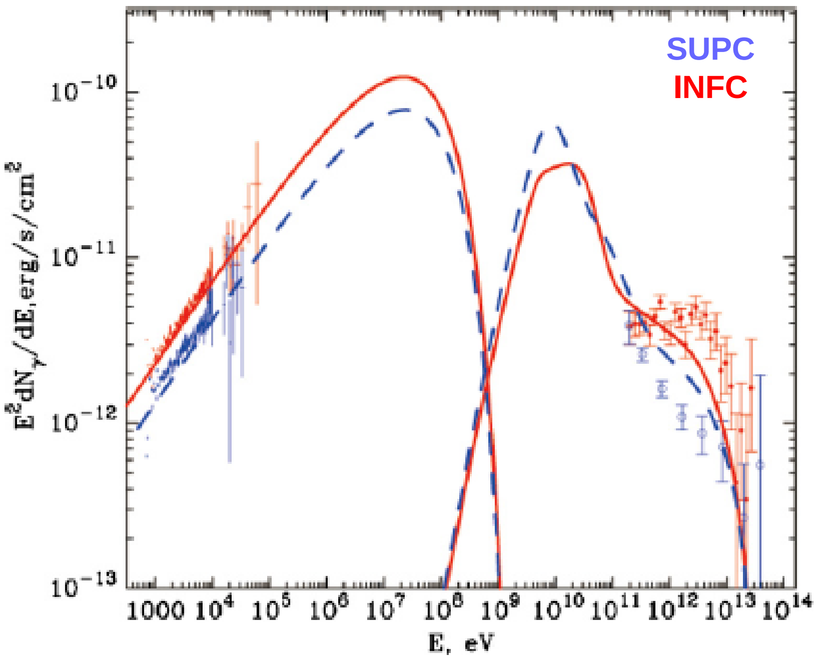
SUZAKU

HESS



Takahashi et al. 2009, arxiv:0812.3358

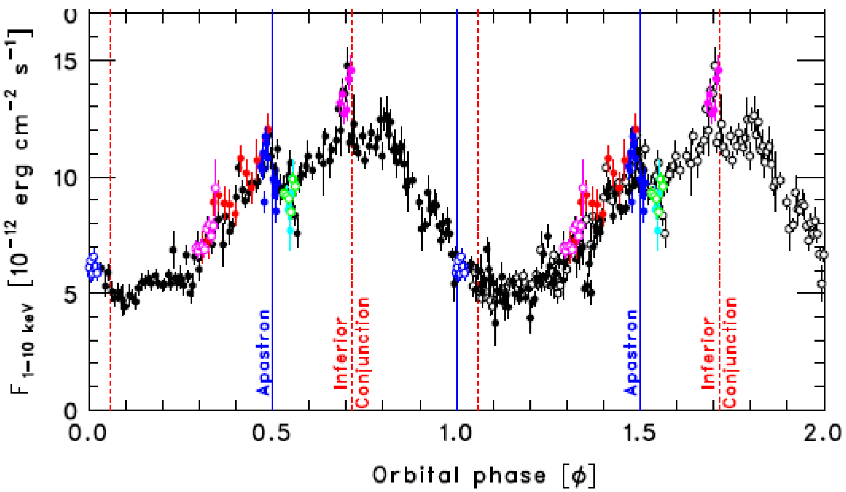
Same e population



The gamma-ray data require a location of the production region at the periphery of the binary system at ~10^{12} cm

See also Bosch-Ramon et al. 2008, A&A 489, L21 and Khangulyan et al. 2008

Modulation curves in 1999-2007 are surprisingly stable



XMM-Newton: blue, cyan, green
ASCA: red
Chandra: magenta
Suzaku: black

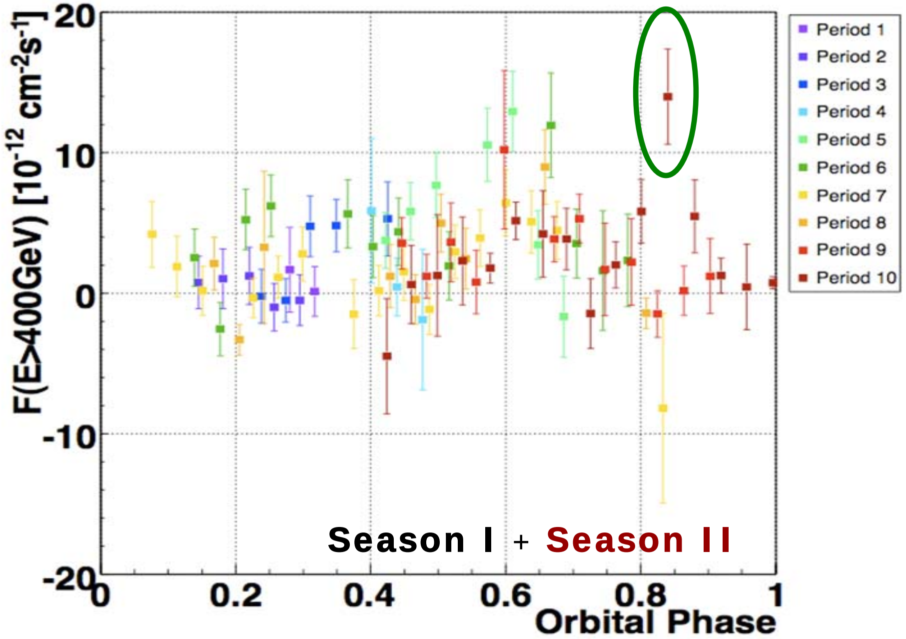
Kishishita et al. 2009, ApJ 697, L1

MHD collisions between the relativistic outflow from a CO and the stellar wind from the O star explain the clock-like non-thermal X-ray emission over 8 yr through remarkably stable production of high-energy particles near the binary system.

Considering the long-term stability, it is difficult to attribute the X-ray emission of LS 5039 to the emission from hot plasma around and accretion disk

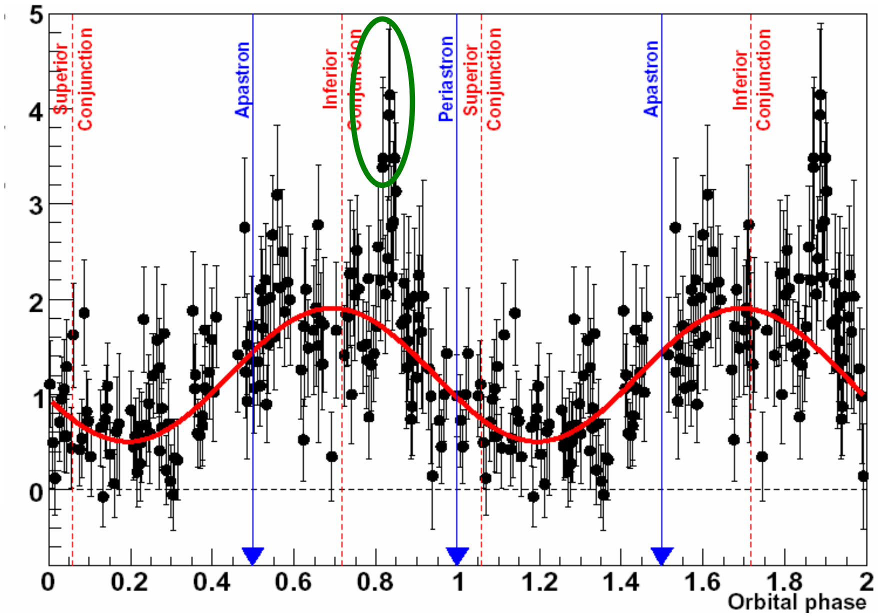
MAGIC

LSI+61303

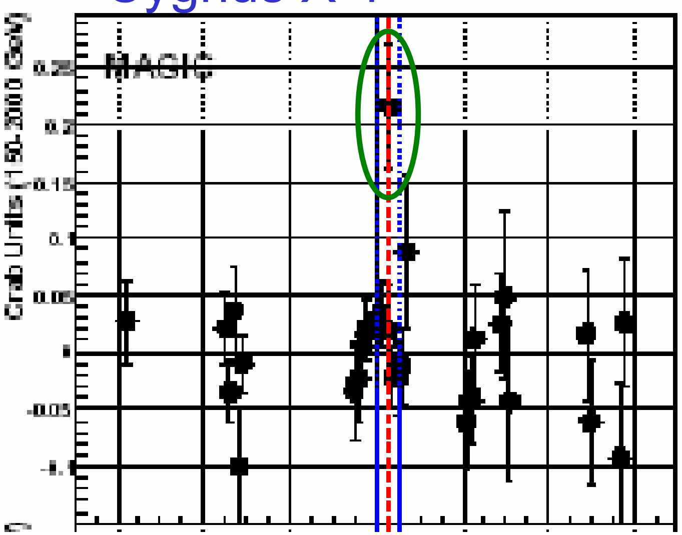


HESS

LS 5039



Cygnus X-1



Flare TeV emission?

If the wind has a clumpy structure, then jet-clump interactions can produce rapid flares of gamma-rays

Araudo et al. 2009, A&A 503, 673

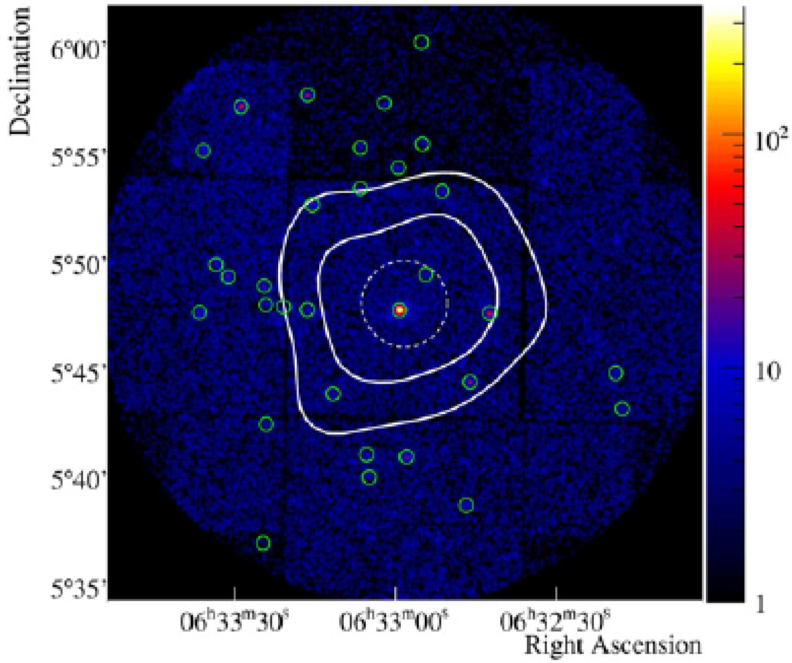
New BTV candidates

HESS J0632+057 A new gamma-ray binary?

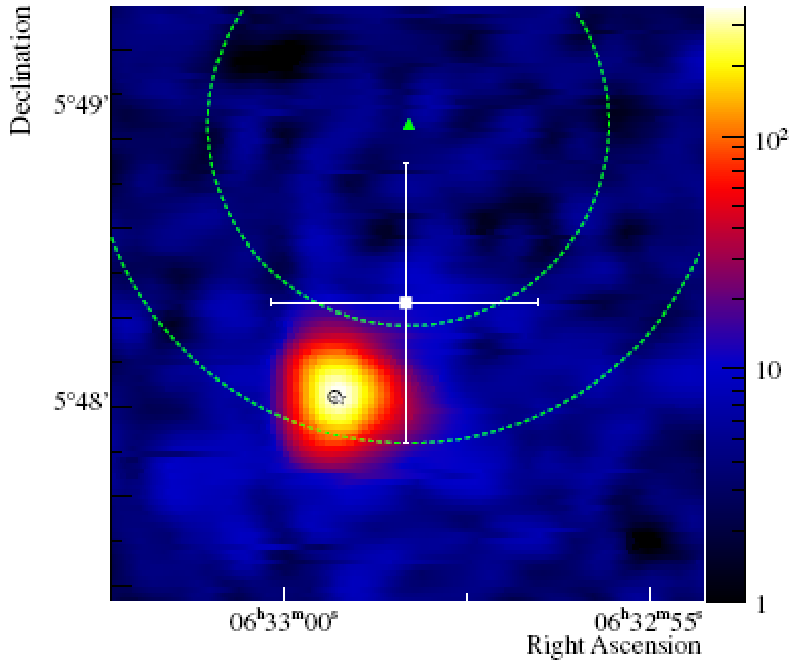
- Point-like Unid.
- Detected by HESS in 2004

Hinton et al. 2009, ApJ 690, L101

XMM-Newton



4 and 6 significance contours of HESS source: solid lines

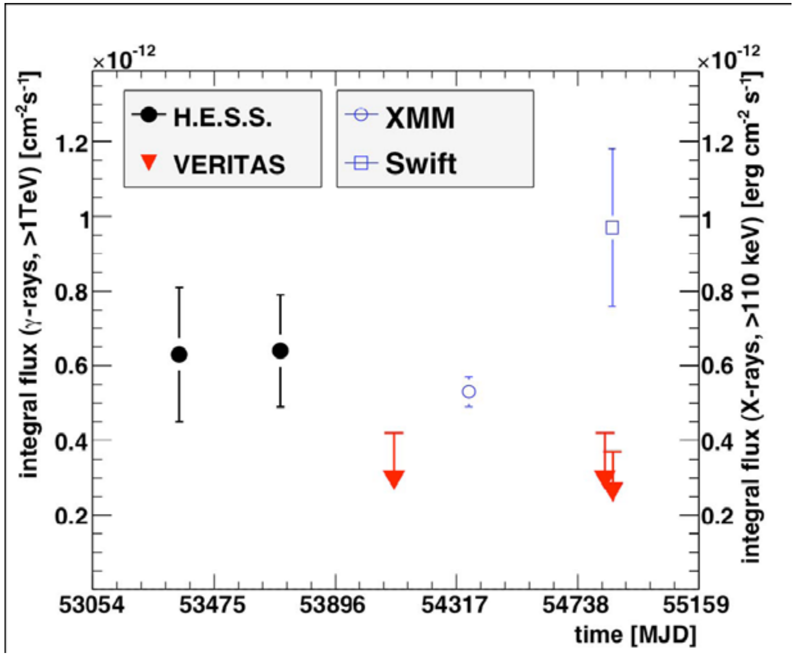


MWC 148: star
XMMU J063259.3+0548: open circle
Pos. uncertainty of CoG
of HESS J0632+057: square marker with error bar

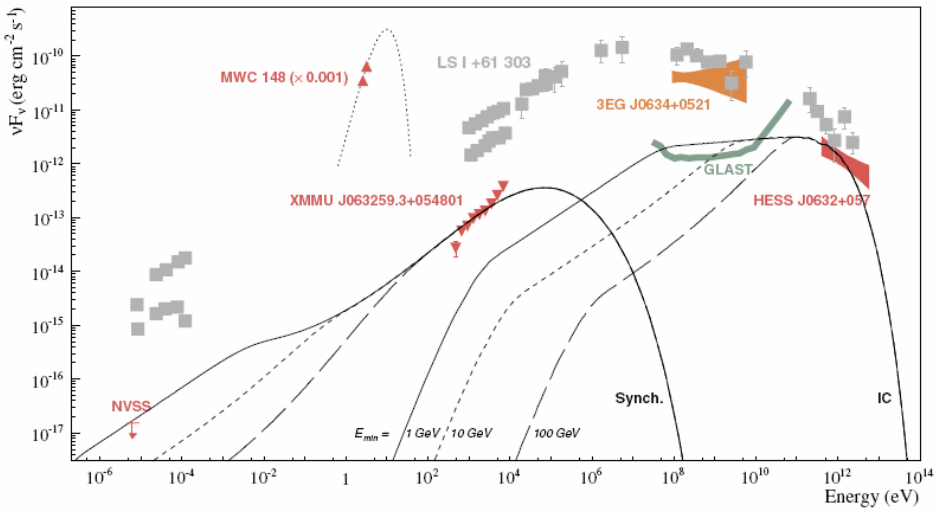
HESS J0632+057

- VERITAS Obs. Dec 2006, 2008, Jan 2009: upper limit ~ 1% Crab

- Rejection of constant flux hypothesis at prob. 0.007% (4 σ)



Acciari (for the VERITAS Col.), arxiv:0905.3139



Hinton et al. 2009, ApJ 690, L101

Binary system?

-Coincident with Be star MWC 148

- No companion yet detected; no information on period

- Variable X-ray emission

XRBs with gamma-ray emission

Instrument	PSR B1259-63	LS I +61 303	LS 5039	Cygnus X-1	Cygnus X-3
INTEGRAL 40-100 keV		yes	yes	yes	yes
BATSE 160-430 keV (mCrab)	—	5.1 ± 2.1	3.7 ± 1.8	924.5 ± 2.5	15.5 ± 2.1
COMPTEL 1-30 MeV	—	yes	GRO J1823-12	yes	—
EGRET >100 MeV	—	3EG J0241+6103	3EG J1824-1514	—	—
AGILE 30 MeV-50 GeV	—	yes	—	—	yes
FERMI 30 MeV-300 GeV	—	yes	yes	—	—
HESS >100 GeV	yes	not visible	periodic	—	—
MAGIC >60 GeV	not visible	periodic	—	yes	—
VERITAS >100 GeV	not visible	yes	—	—	—

Summary

- 4 HMXBs have been detected at TeV energies whereas any LMXB has
  - All of them are radio emitters
  - All of them have a bright companion (O or B star) → source of seed photons for the IC emission and target nuclei for hadronic interactions
- NS and BH are among these detected XRBs
- Periodic TeV emission is present in two systems
- Flare TeV emission might be common in all these sources
- Multi-wavelength (multi-particle) campaigns are of primary importance
- New gamma-ray binary?