Microquasars and Unidentified TeV Sources

Chuck Dermer (NRL)

TeV Unidentified Sources Workshop

Penn State University

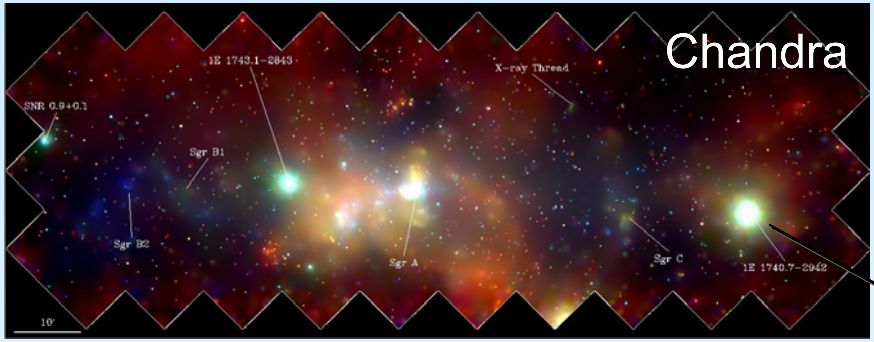
June, 2008

Microquasars: X-ray binaries with jets

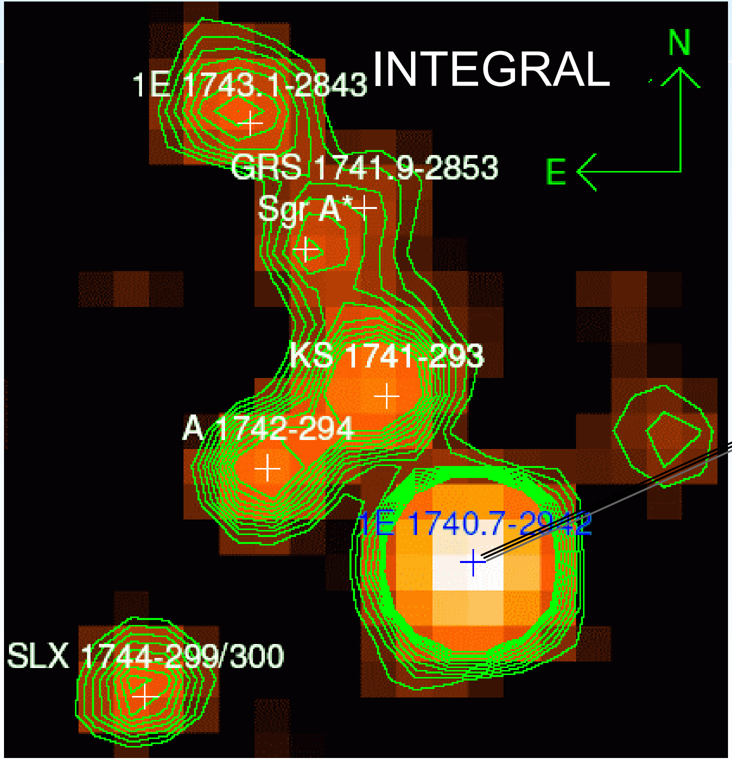
Refs. and acknowledgments:
Felix Mirabel talk;
Isabelle Grenier Merida ICRC talk;
work with Markus Böttcher, Swati Gupta

Discovery of Microquasars

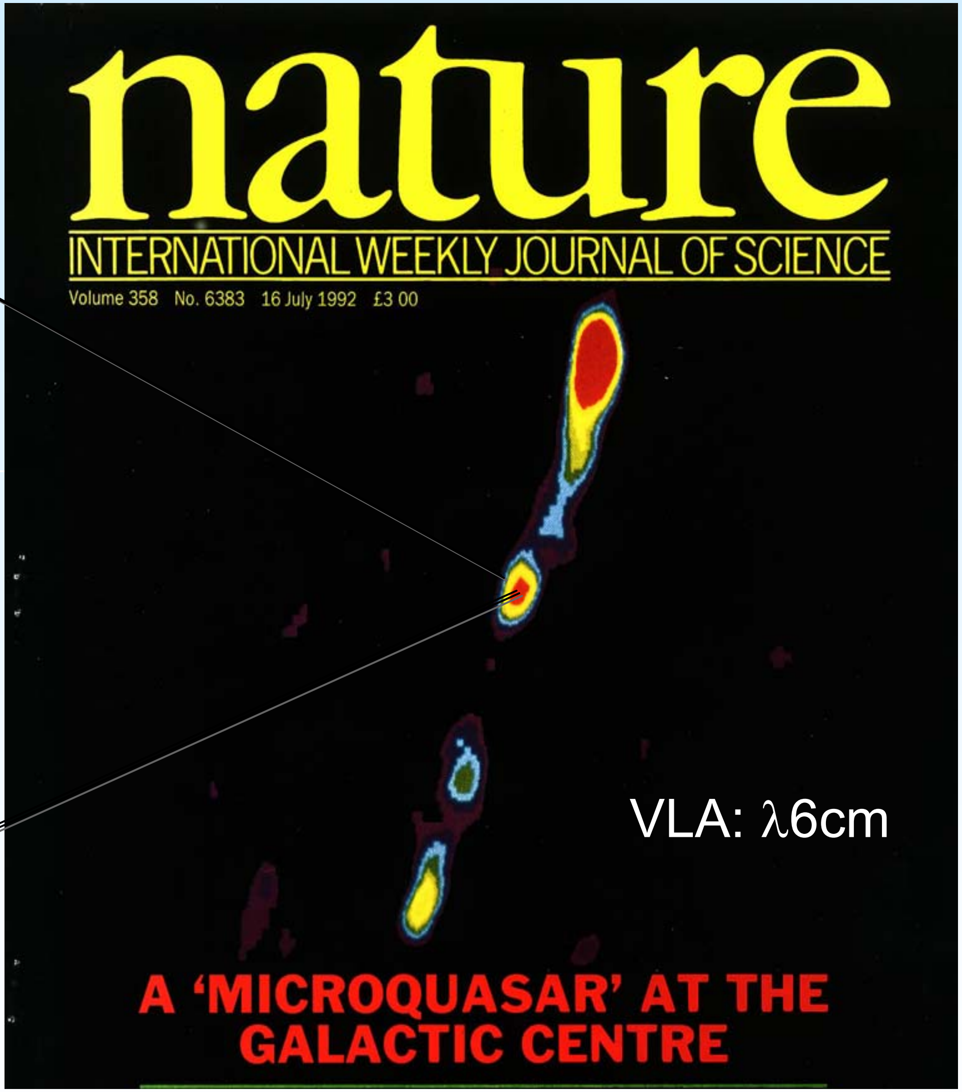
Wang et al. ApJ 2002



Belanger, Goldwurm, Goldoni, ApJ 2003



Mirabel, Rodriguez, et al, 1992



nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 358 No. 6383 16 July 1992 £3 00

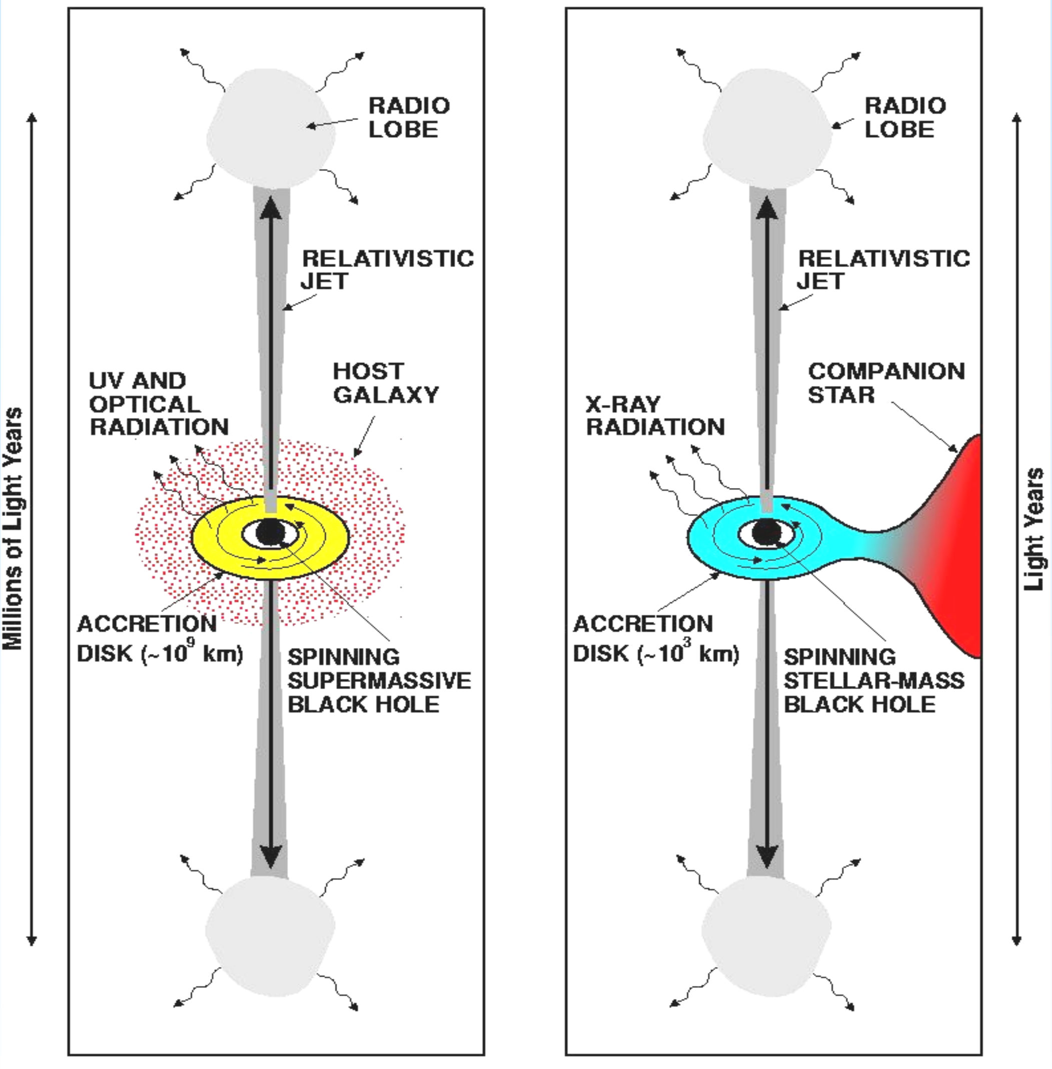
A 'MICROQUASAR' AT THE GALACTIC CENTRE

VLA: λ6cm

1E 1740.7: LMXB

Quasar-Microquasar Analogy

QUASAR **MICROQUASAR**



Mirabel & Rodriguez (Nature 1998)

The scales of length and time are proportional to M_{BH}

$$R_{sh} = 2GM_{BH}/c^2 \;;\; \Delta T \,\alpha\, M_{BH}$$

Unique system of equations:

The maximum color temperature of the accretion disk is:

$$T_{col} \,\alpha\, (M/\,10M_{\odot})^{-1/4}$$

(Shakura & Sunyaev, 1976)

For a given Eddington ratio l_{jet} :

$$L_{Bol} \,\alpha\, l_{jet} \;;\; l_{jet} \,\alpha\, M_{BH} \;;$$

$$B \,\alpha\, M_{BH}^{-1/2} ;\; t_{jet} \,\alpha\, M_{BH}$$

(LMXB μQSR model)

APPARENT SUPERLUMINAL MOTIONS IN μQSRs AS IN QSRs ?

Superluminal Motion in the Galaxy

Mirabel & Rodriguez, 1994

WITH SAME BULK LORENTZ FACTORS AS IN QSRs

nature

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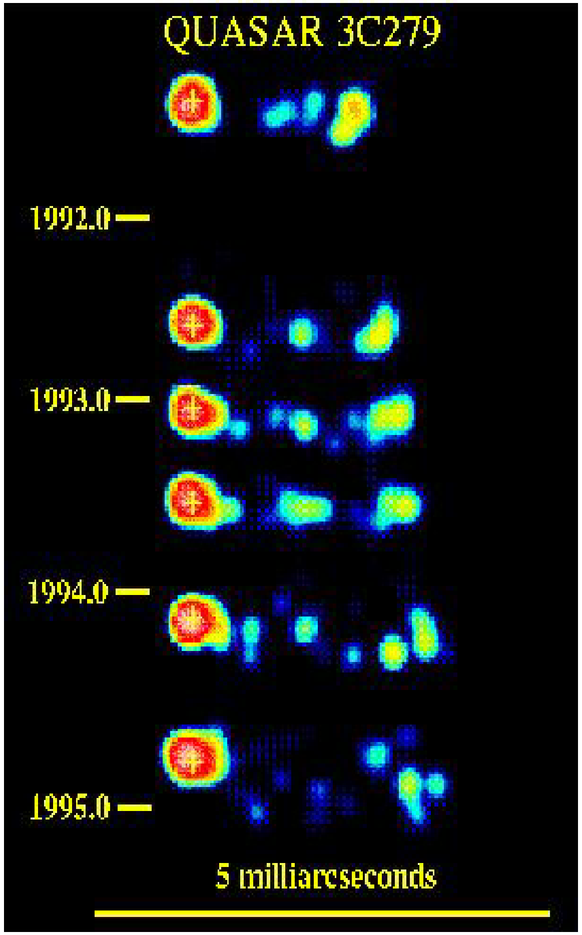
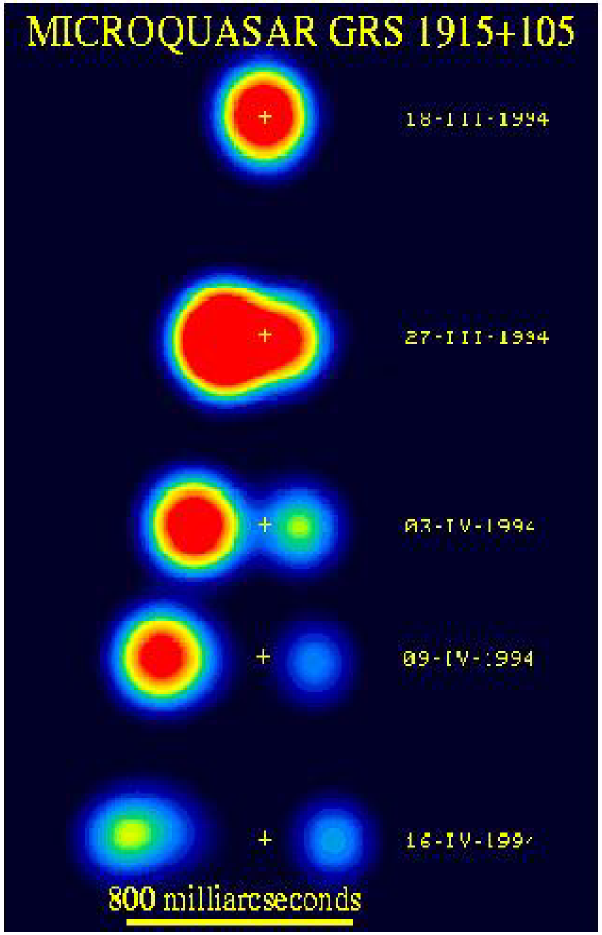
Superluminal motion in the Galaxy





-RELATIVISTIC ABERRATION FROM TWIN JETS SEEN TWO-SIDED

- μQSR JETS MOVE ON THE SKY ~10^3 TIMES FASTER THAN QSR JETS

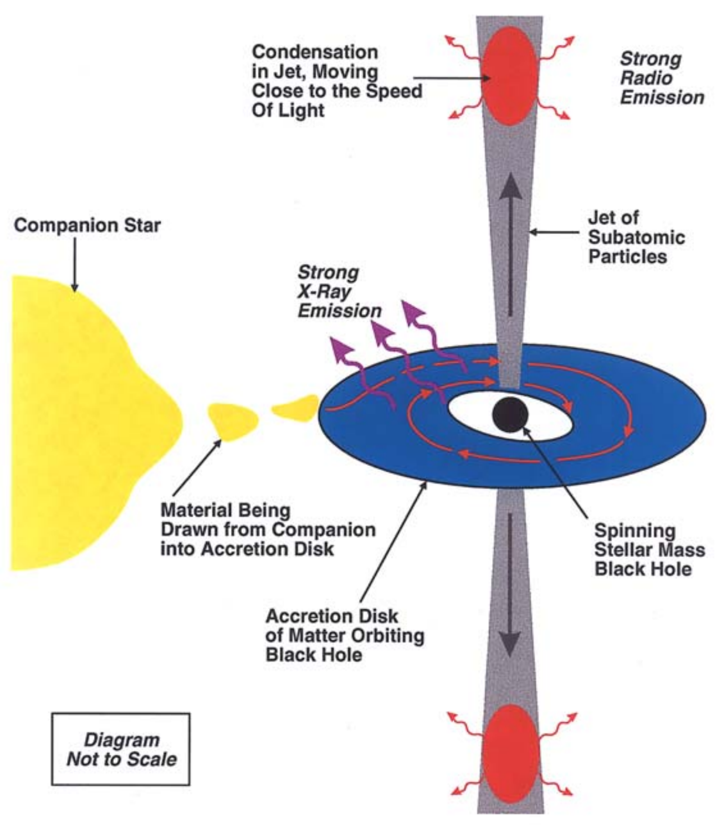
- IN AGN AT D<100 Mpc JETS ARE RESOLVED AT ~50 R_{sh} (e.g. M87,Biretta)

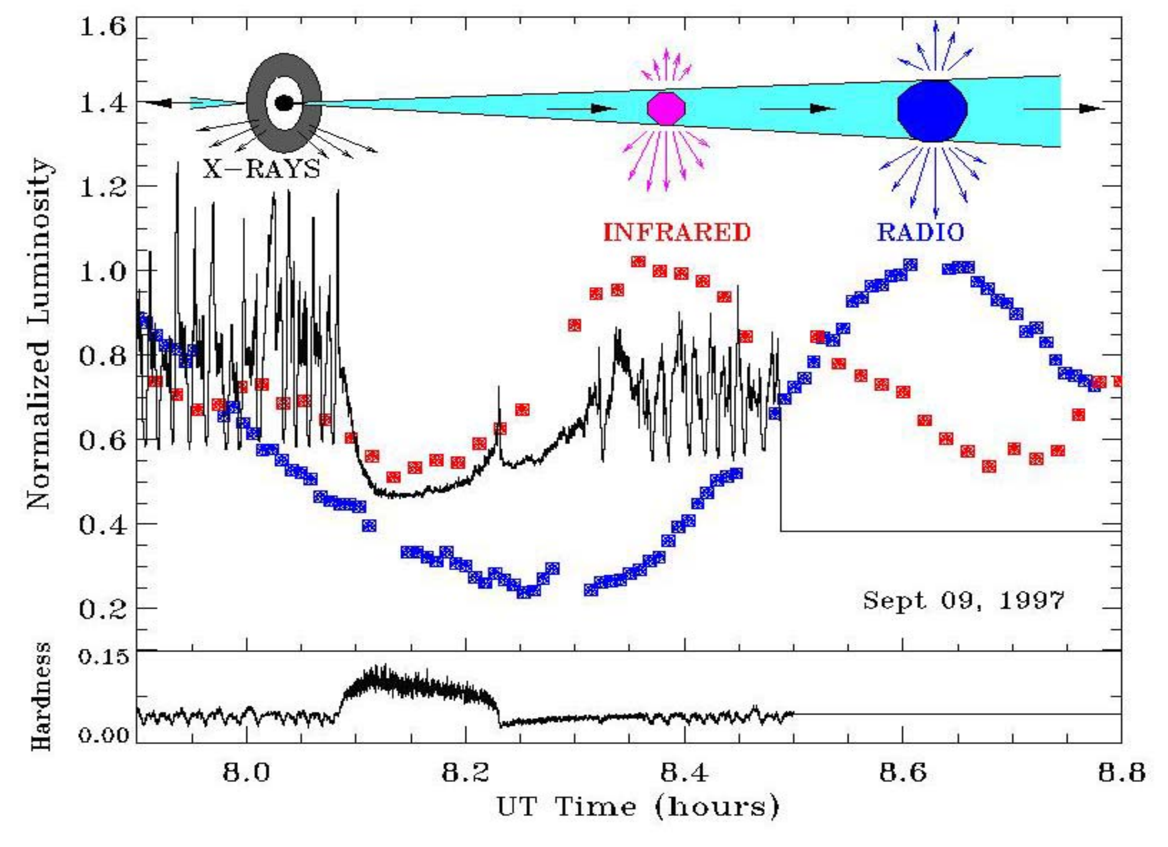
PHYSICS: NEED TO STUDY BHs ACROSS ALL MASS SCALES

Accretion-Jet Connection

$\Delta T \; \alpha \; M_{BH}$

1 hr in GRS 1915+105 = 30 yr in SgrA* Mirabel et al. 1998





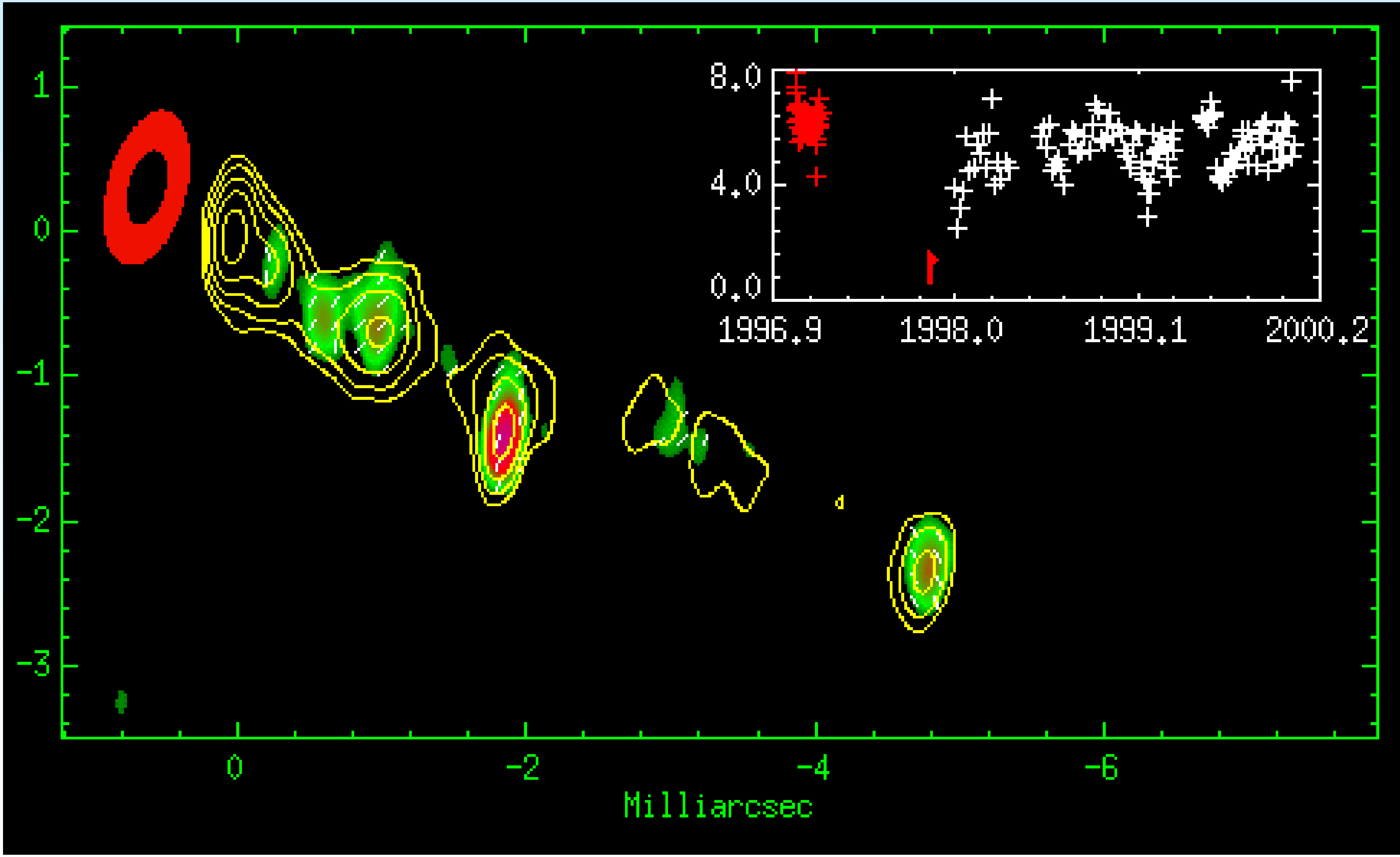
- **Triggers of jets are instabilities in the accretion disk (transition between low hard and high soft). The X-ray "spike" marks the onset of a shock through the compact steady jet**

- **Analogous accretion-disk/jet connection in 3C 120** Marscher (2002)

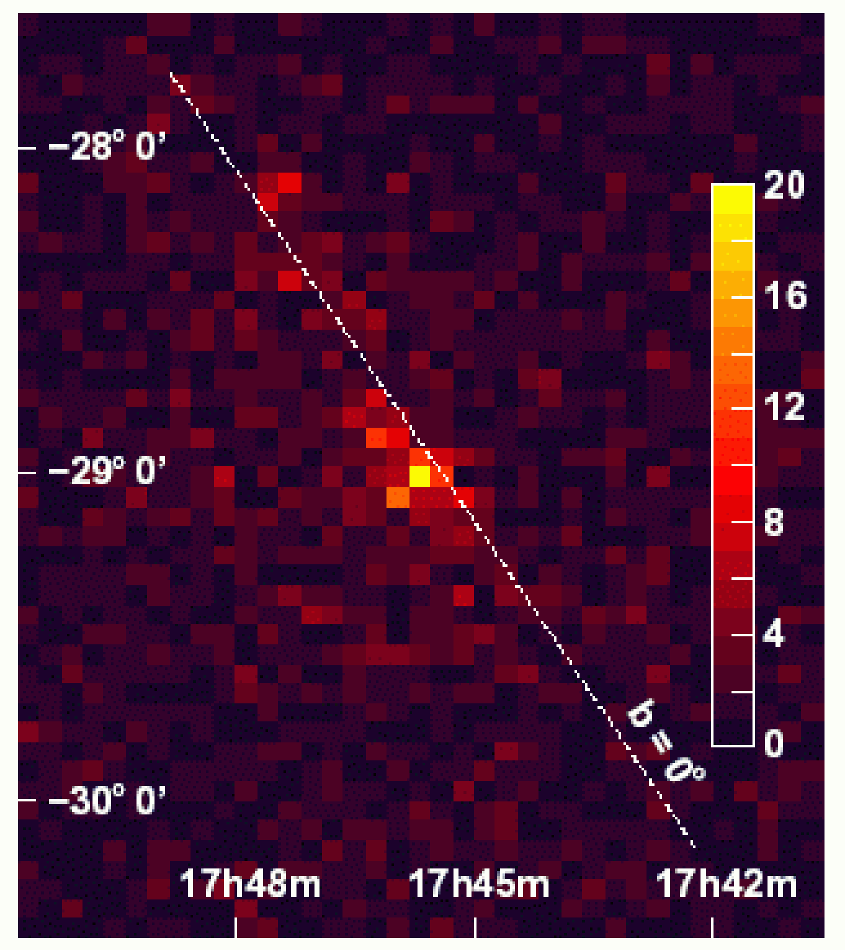
ANALOGOUS ACCRETION-JET CONNECTION IN 3C 120 ?

BUT ON TIME SCALES OF YEARS

Marscher, Marti et al. Nature 2002

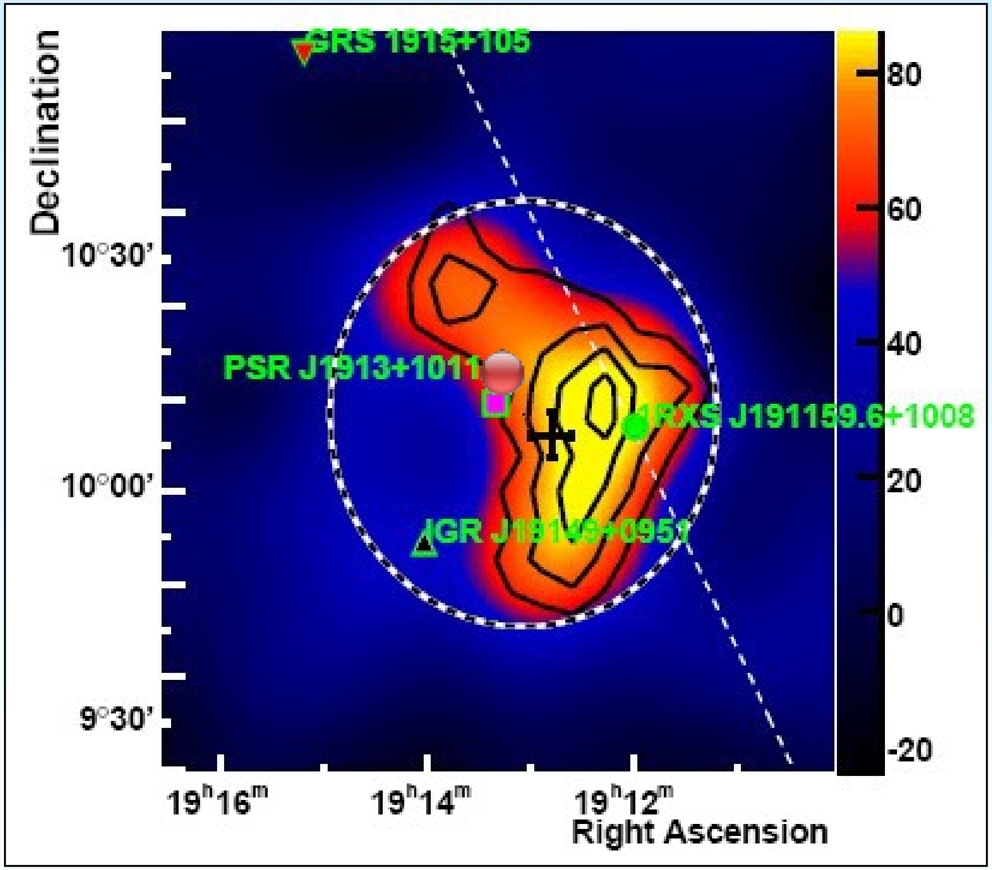


TeV Emission from Galactic Center



None from
1E 1740.7-2942

GRS 1915+105 ↔ HESS J1912+101 (?) ↔ PSR J1913+1011



None from GRS 1915+105

Binary vs. Isolated Pulsars

Pulsars in Binaries:

ref. George Pavlov

~6 high mass
incl. 1 (SMC)
+ 1 (GC) +

76 + 49 (125 recycled, incl. GC and field, resp.)

3 or 4 pulsars with high mass Be companions, e.g.,

B1259-63: $M_2 \sim 10$, $e = 0.87$, $\log \tau = 5.5$
J0045-73193: $M_2 \sim 8.8$, $e = 0.81$, $\log \tau = 6.5$
J 1740-3052: $M_2 \sim 10$, $e = 0.58$, $\log \tau = 5.5$

Binary fraction low due to disruption during formation
Low likelihood to have both high mass + young pulsar

High-mass microquasars

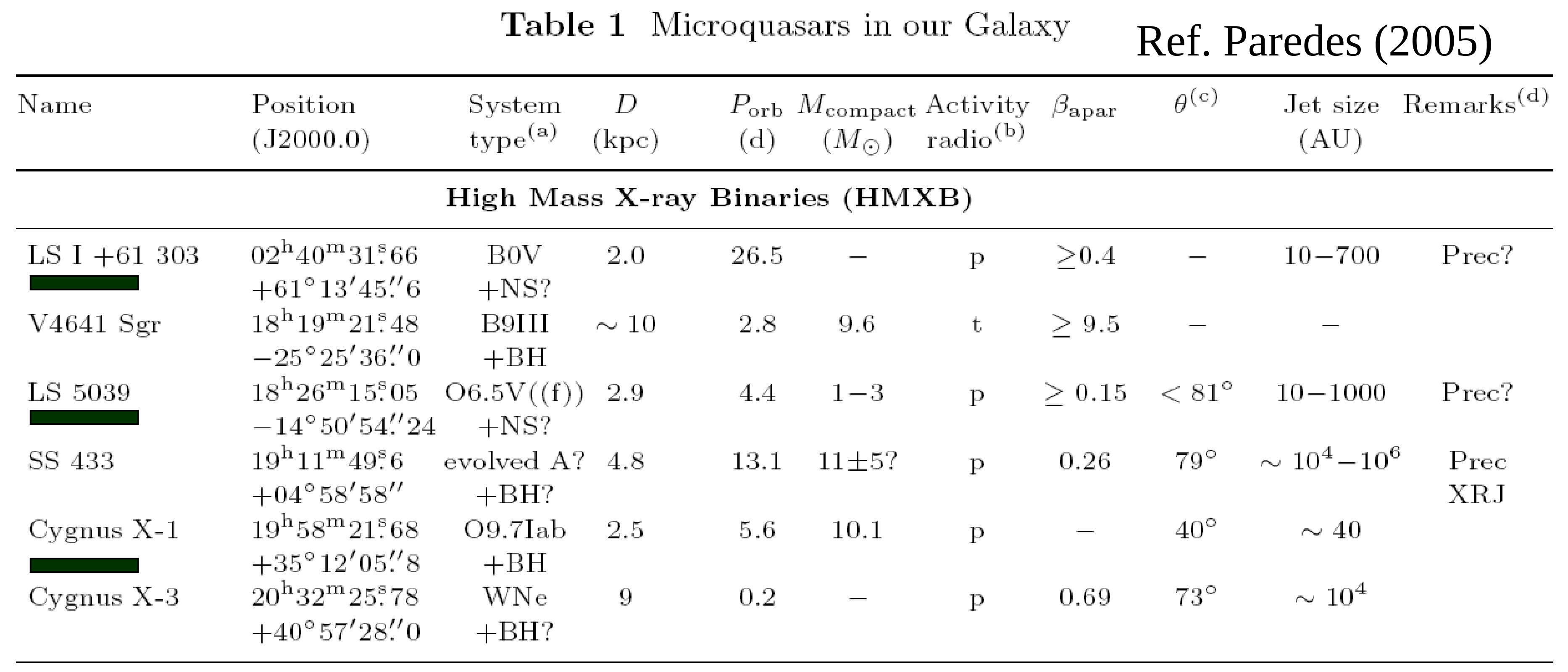


Table 1 Microquasars in our Galaxy

Ref. Paredes (2005)

Name	Position (J2000.0)	System type[a]	D (kpc)	$P_{\rm orb}$ (d)	$M_{\rm compact}$ ($M_\odot$)	Activity radio[b]	$\beta_{\rm apar}$	θ[c]	Jet size (AU)	Remarks[d]
				High Mass X-ray Binaries (HMXB)						
LS I +61 303	$02^{\rm h}40^{\rm m}31^{\rm s}.66$ $+61^\circ13'45''.6$	B0V +NS?	2.0	26.5	–	p	≥ 0.4	–	10–700	Prec?
V4641 Sgr	$18^{\rm h}19^{\rm m}21^{\rm s}.48$ $-25^\circ25'36''.0$	B9III +BH	~ 10	2.8	9.6	t	≥ 9.5	–	–	
LS 5039	$18^{\rm h}26^{\rm m}15^{\rm s}.05$ $-14^\circ50'54''.24$	O6.5V((f)) +NS?	2.9	4.4	1–3	p	≥ 0.15	$< 81^\circ$	10–1000	Prec?
SS 433	$19^{\rm h}11^{\rm m}49^{\rm s}.6$ $+04^\circ58'58''$	evolved A? +BH?	4.8	13.1	11 ± 5?	p	0.26	79°	$\sim 10^4-10^6$	Prec XRJ
Cygnus X-1	$19^{\rm h}58^{\rm m}21^{\rm s}.68$ $+35^\circ12'05''.8$	O9.7Iab +BH	2.5	5.6	10.1	p	–	40°	~ 40	
Cygnus X-3	$20^{\rm h}32^{\rm m}25^{\rm s}.78$ $+40^\circ57'28''.0$	WNe +BH?	9	0.2	–	p	0.69	73°	$\sim 10^4$	

PSR 1259-63 Be X-ray binary P_{orb} = 3.5 yr (not a microquasar)

Low-mass microquasars

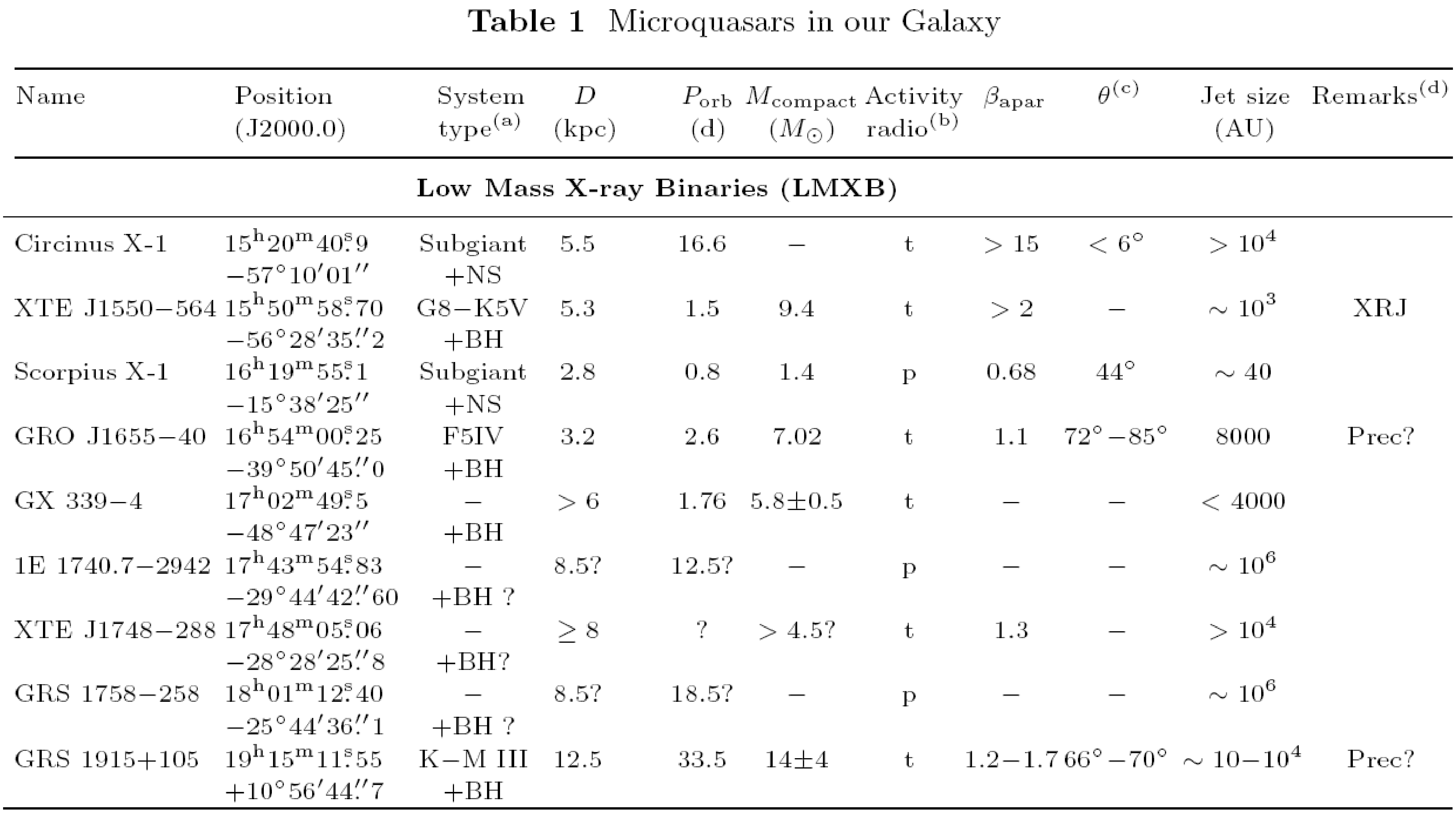


Table 1 Microquasars in our Galaxy

Name	Position (J2000.0)	System type[(a)]	D (kpc)	$P_{\rm orb}$ (d)	$M_{\rm compact}$ ($M_\odot$)	Activity radio[(b)]	$\beta_{\rm apar}$	θ[(c)]	Jet size (AU)	Remarks[(d)]
				Low Mass X-ray Binaries (LMXB)						
Circinus X-1	$15^{h}20^{m}40^{s}.9$ $-57^{\circ}10'01''$	Subgiant +NS	5.5	16.6	–	t	> 15	$< 6^{\circ}$	$> 10^{4}$	
XTE J1550−564	$15^{h}50^{m}58^{s}.70$ $-56^{\circ}28'35''.2$	G8−K5V +BH	5.3	1.5	9.4	t	> 2	–	$\sim 10^{3}$	XRJ
Scorpius X-1	$16^{h}19^{m}55^{s}.1$ $-15^{\circ}38'25''$	Subgiant +NS	2.8	0.8	1.4	p	0.68	44°	~ 40	
GRO J1655−40	$16^{h}54^{m}00^{s}.25$ $-39^{\circ}50'45''.0$	F5IV +BH	3.2	2.6	7.02	t	1.1	$72^{\circ}-85^{\circ}$	8000	Prec?
GX 339−4	$17^{h}02^{m}49^{s}.5$ $-48^{\circ}47'23''$	– +BH	> 6	1.76	5.8 ± 0.5	t	–	–	< 4000	
1E 1740.7−2942	$17^{h}43^{m}54^{s}.83$ $-29^{\circ}44'42''.60$	– +BH ?	8.5?	12.5?	–	p	–	–	$\sim 10^{6}$	
XTE J1748−288	$17^{h}48^{m}05^{s}.06$ $-28^{\circ}28'25''.8$	– +BH?	≥ 8	?	> 4.5?	t	1.3	–	$> 10^{4}$	
GRS 1758−258	$18^{h}01^{m}12^{s}.40$ $-25^{\circ}44'36''.1$	– +BH ?	8.5?	18.5?	–	p	–	–	$\sim 10^{6}$	
GRS 1915+105	$19^{h}15^{m}11^{s}.55$ $+10^{\circ}56'44''.7$	K−M III +BH	12.5	33.5	14 ± 4	t	1.2−1.7	$66^{\circ}-70^{\circ}$	$\sim 10-10^{4}$	Prec?

Ref. Paredes (2005)

VHE (>100 GeV) FROM γ–RAY BINARIES

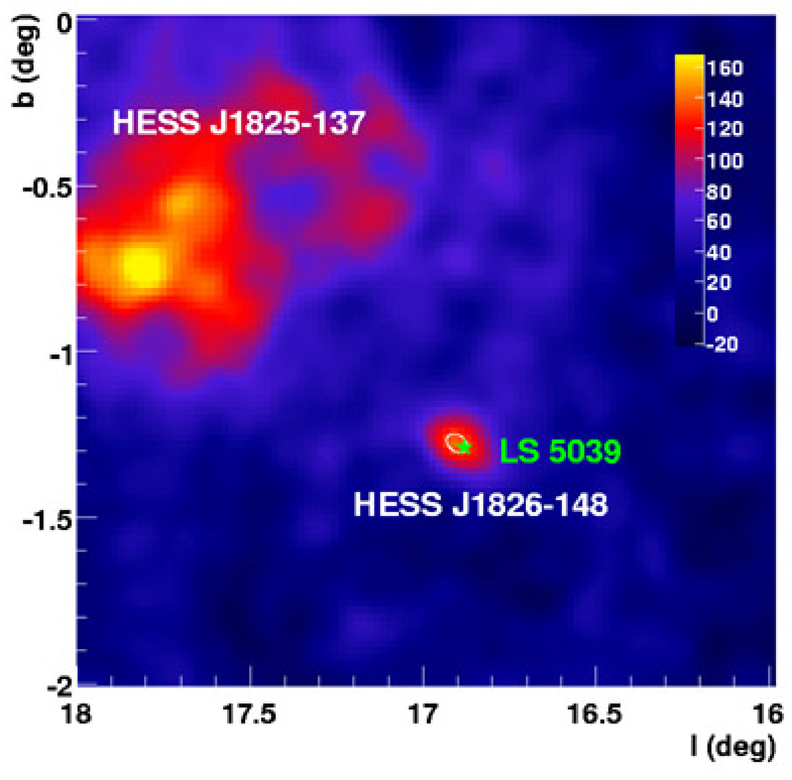
LS 5039 with HESS

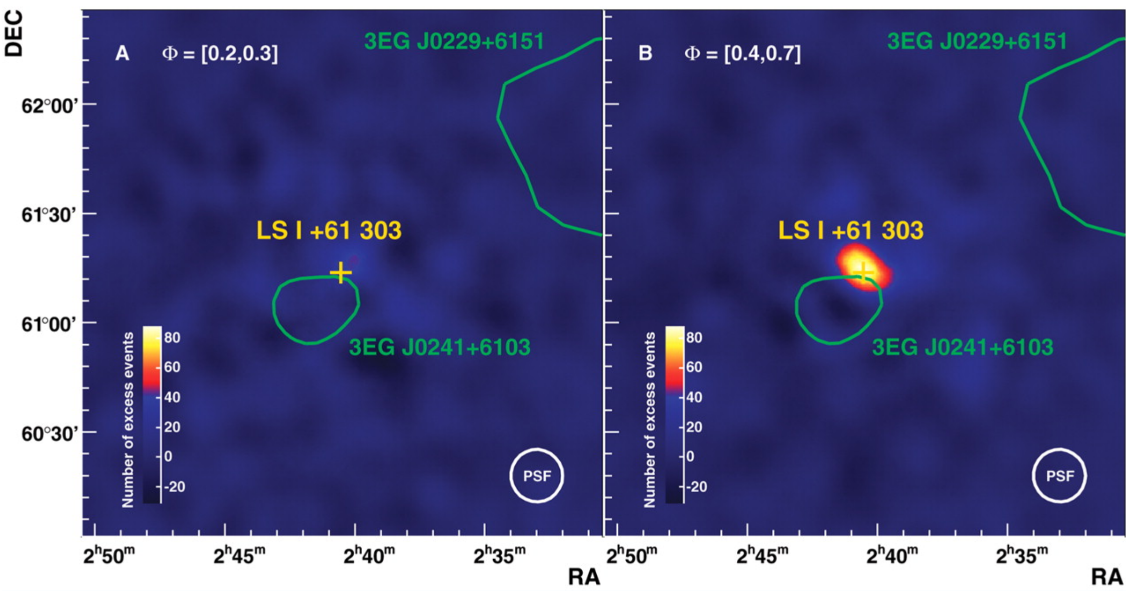
(Aharonian et al. Science 2005)

LSI +61 303 with MAGIC

(Albert et al. Science 2006)

VHE emission is variable





Consistent with point source (< 50″) in TeV maps; much smaller compared with TeV PWNe

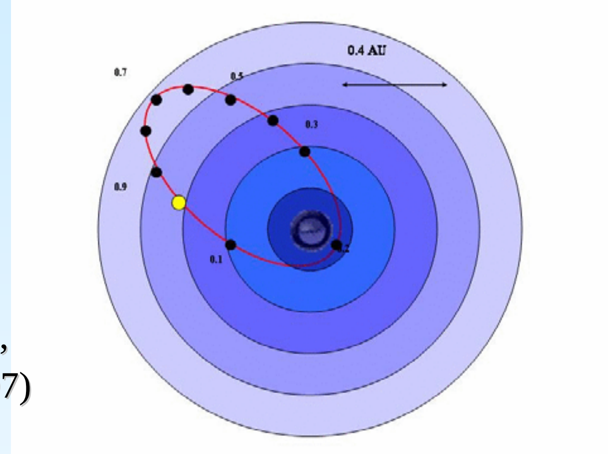
- **Both have compact objects with masses $M < 4 M_\odot$**
- **Both are runaway HMXBs formed < 2 x 10^6 yrs ago**

3 eccentric binaries

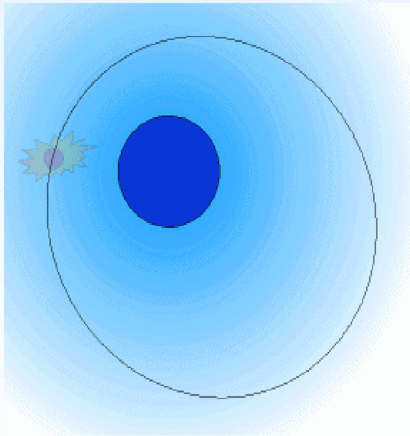
- $M_{BH} < 4\ M_{\odot}$ or NS
- age < 2-3 Myr

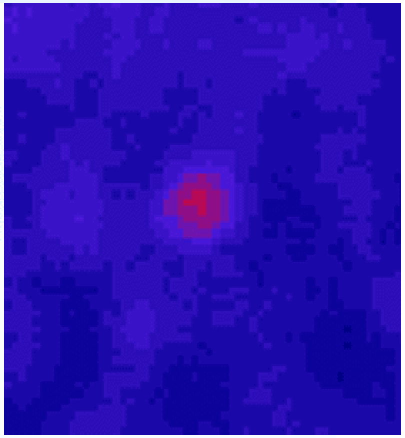
LSI +61°303; e ~ 0.72

LS 5039, e ~ 0.35



Orbital parameters
of LS 5039:
Casares et al. (2004),
Grunstrom et al. (2007)

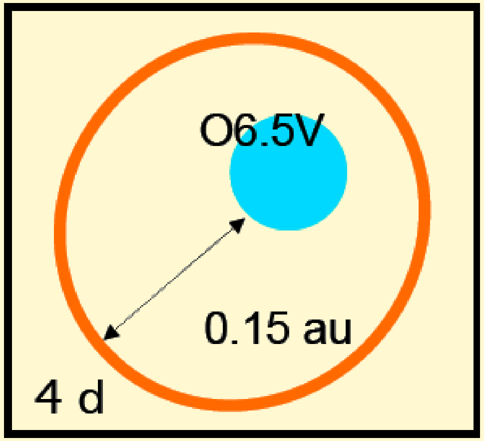




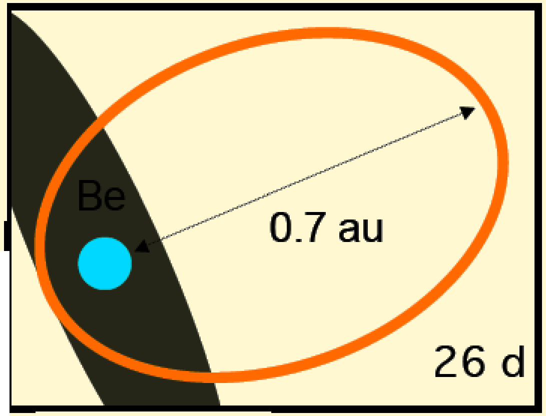
Aharonian et al. 2005

Albert et al. 2005

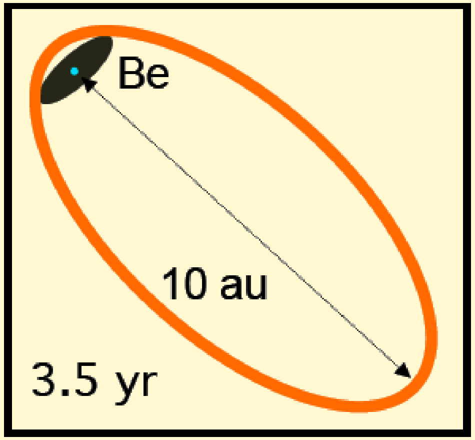
LS 5039



LS I +61 303

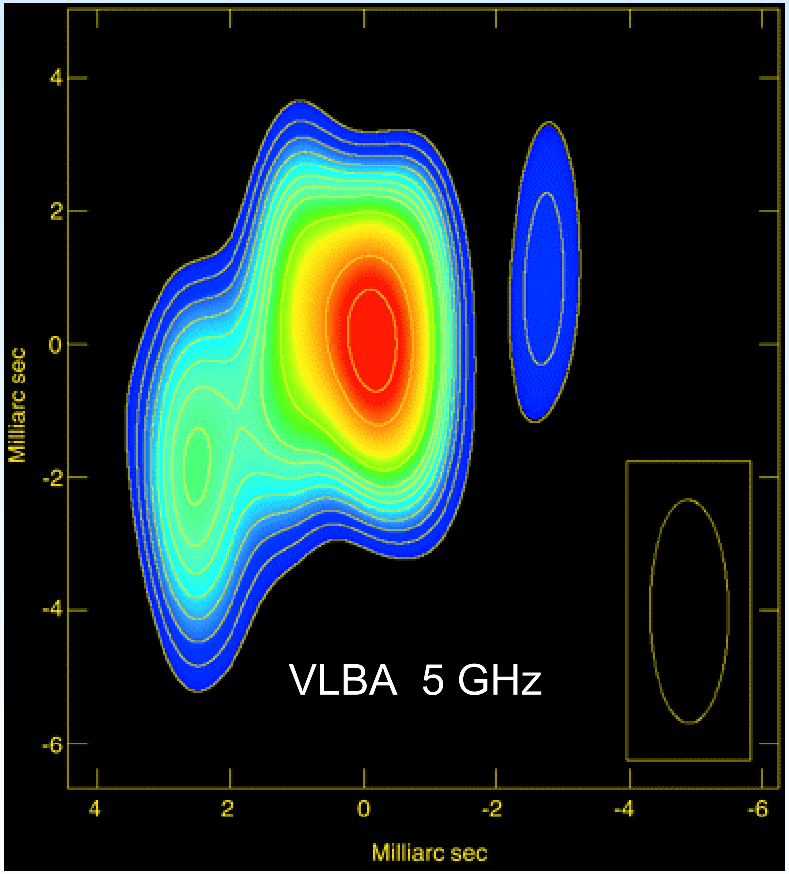


PSR B1259-63

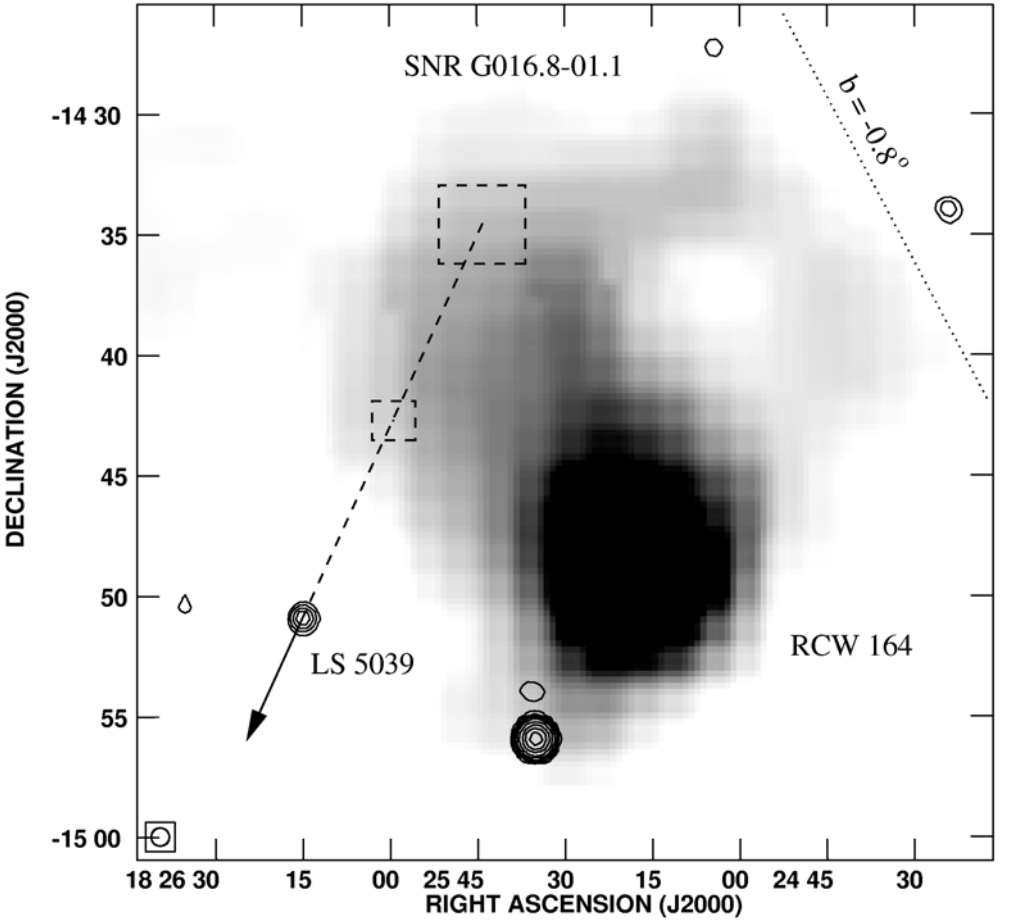


LS 5039 EJECTED FROM THE GALACTIC PLANE?

Paredes, Ribo et al. 2002



Ribo, Paredes et al. 2002



V = 100-140 km/s; e~0.5; Mj = 2000-5000 Km/s $M_\odot$; $M_{ejected}$ in SN = 5-15 $M_\odot$

Radio emission from LS 5039

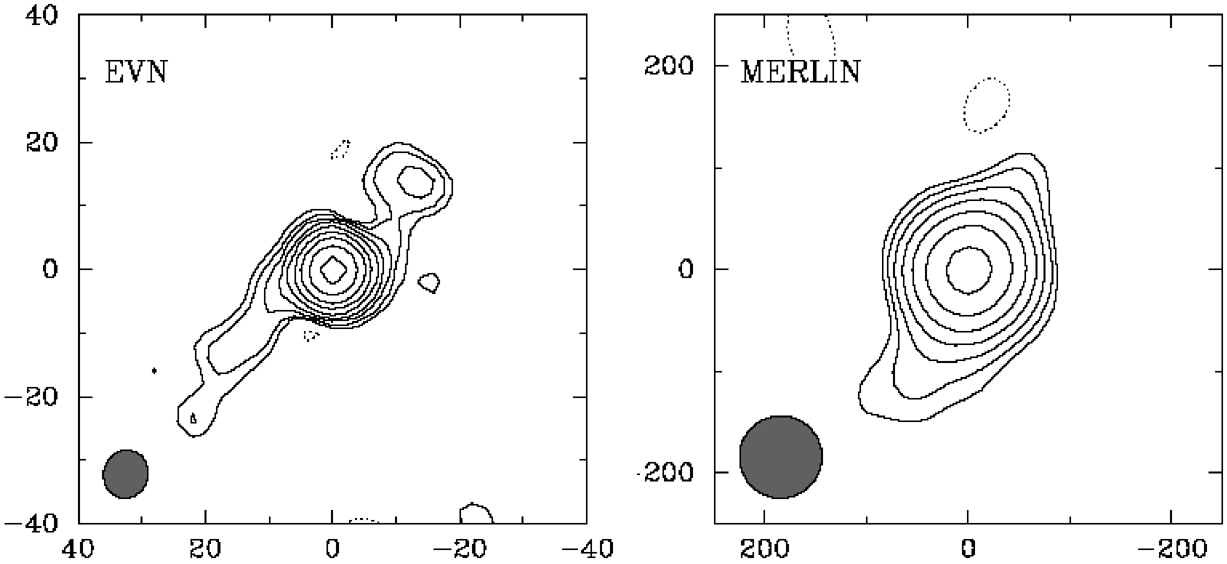


Fig. 3 Self-calibrated images of LS 5039 at 5 GHz obtained on March 1 2000 with the EVN (left) and MERLIN (right). Axis units are in milliarc-seconds (Paredes et al. 2002).

Radio emission from LSI

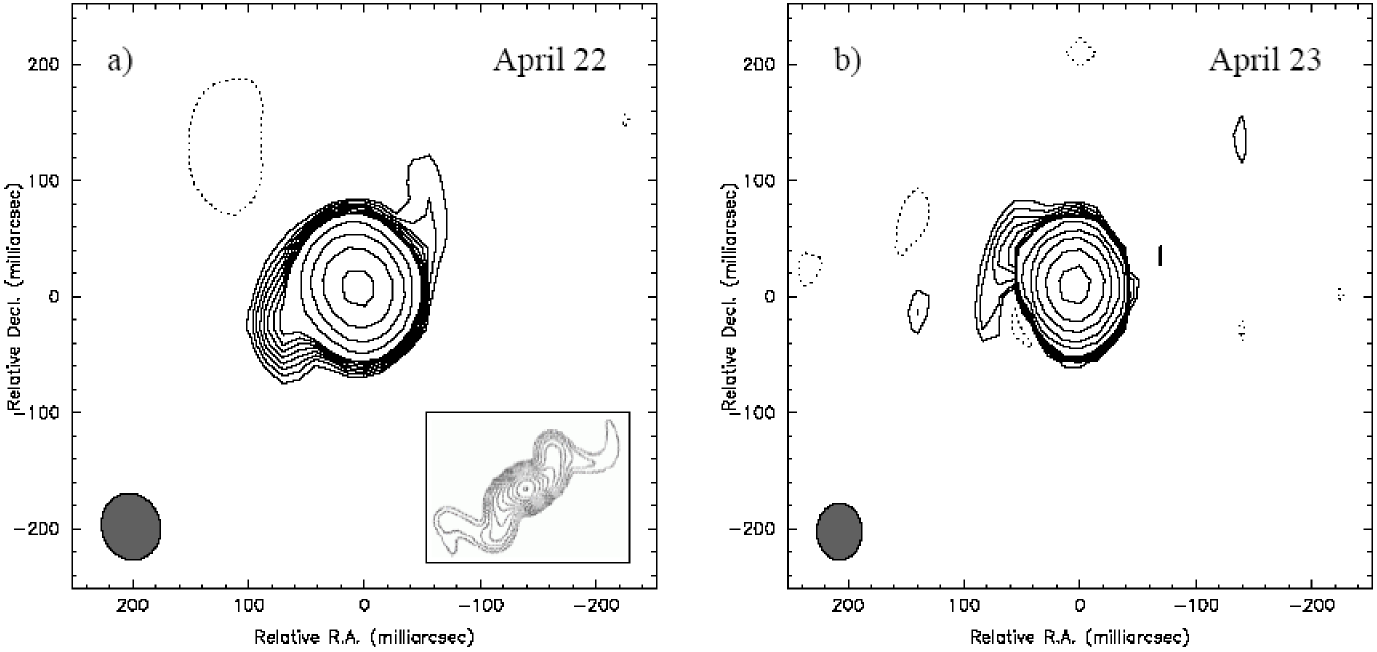
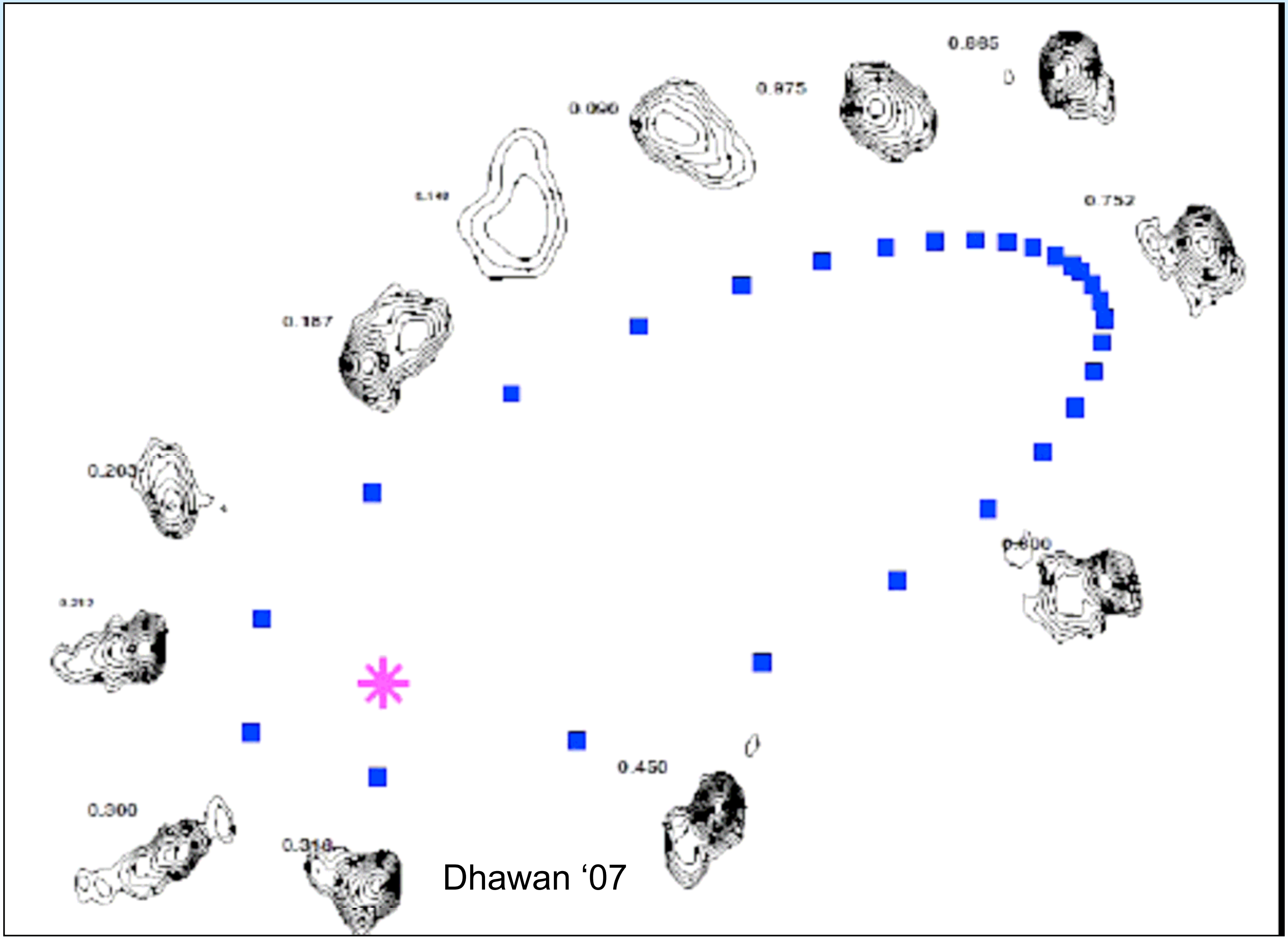


Fig. 7 MERLIN self-calibrated images of LS I +61 303 at 5 GHz obtained on April 22 (left) and April 23 (right). The S-shaped morphology recalls the precessing jet of SS 433, whose simulated radio emission is given in the small box (Massi et al. 2004).

Radio emission from LSI



Dhawan '07

VHE from Compact Binaries

MICROQUASAR JET MODELS: Power by accretion (Bosch-Ramon)

- Particle energy in QSRs and μQSRs are comparable (blazar-microblazar analogy)
- The kinetic power in μQSRs is equal or larger than the radiated power
- Electrons in the jets are accelerated up to TeV energies
- LS 5039: jets are steady, two-sided, seem to have bulk motions of 0.2-0.3c as compact μQSR jets, and no radio outbursts have been observed (Paredes et al.)
- Definitive proof: VHE emission from confirmed BHs (e.g Cyg X-1, V 4641,GRS 1915)

MAGIC Obs. of Cyg X-1

PULSAR WIND MODEL: Power by rotational energy (Dubus, 2006)

- PSR B1259-63, LS 5039 & LSI +61 303 have compact objects with $M < 4 M_{SUN}$
- Time variability & x-ray spectrum of LSI +61 303 resemble those of young pulsars
- LSI +61 303 is a Be star like PSR B1259-63 & all known Be/X-ray binary are NSs
- But does not satisfactorily fit the GeV & radio wavelength fluxes in LSI & LS 5039
- Definitive proof: Detection of pulsations in LS 5039 & LSI +61 303

NEEDED: Period analysis on GLAST data of LS sources; higher sensitivity and angular resolugion radio images

massive γ-ray binaries

- jet
  - $e_{\text{jet}} + UV_{*} \rightarrow \gamma$
  - $p_{\text{jet}} + p_{\text{wind}\,*} \rightarrow \pi^0 \rightarrow 2\gamma$
- when closer to star on eccentric orbit
  - accretion rate ↑

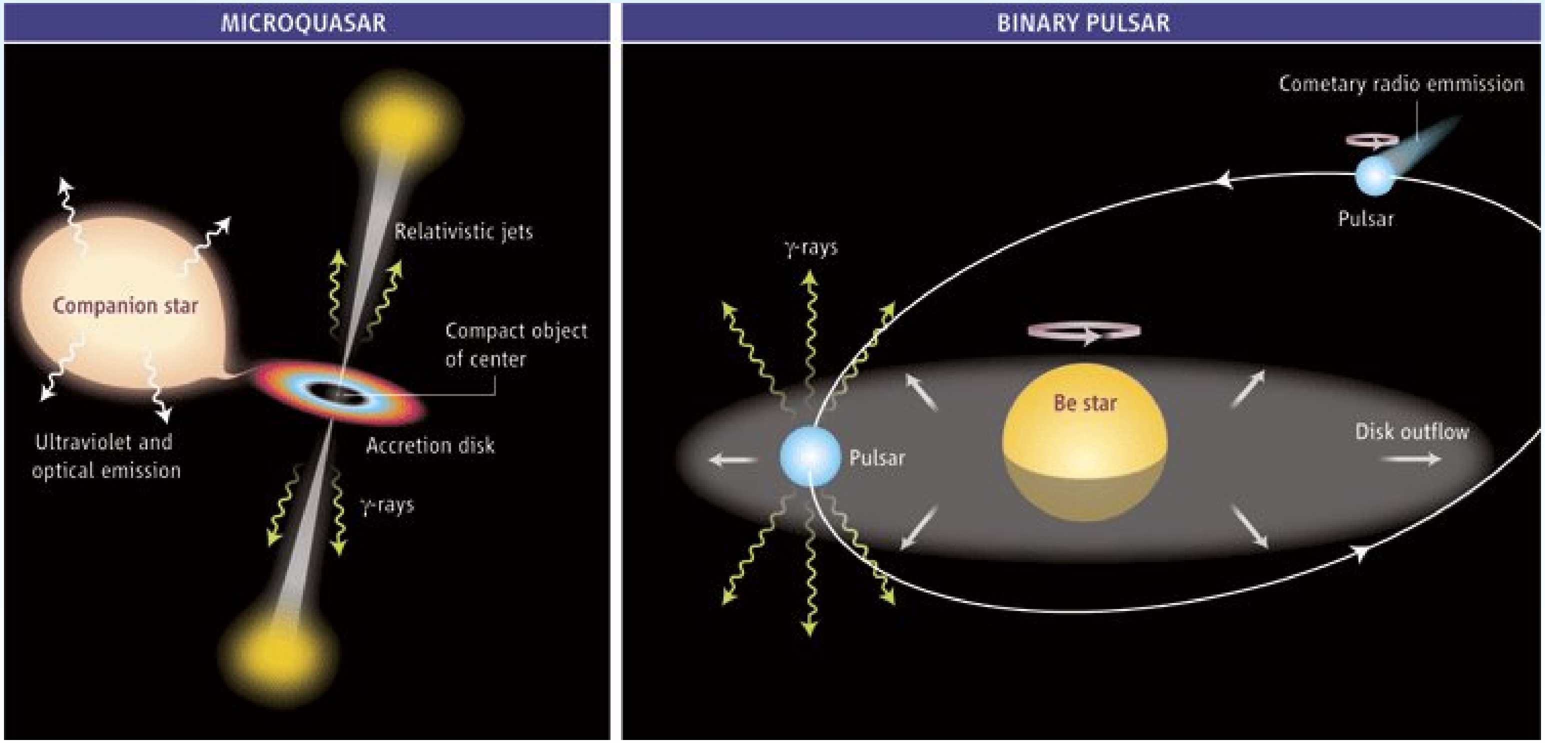
(cf. PSR B1259-63)

$e_{\text{wind pulsar}} + UV_{*} \rightarrow \gamma$

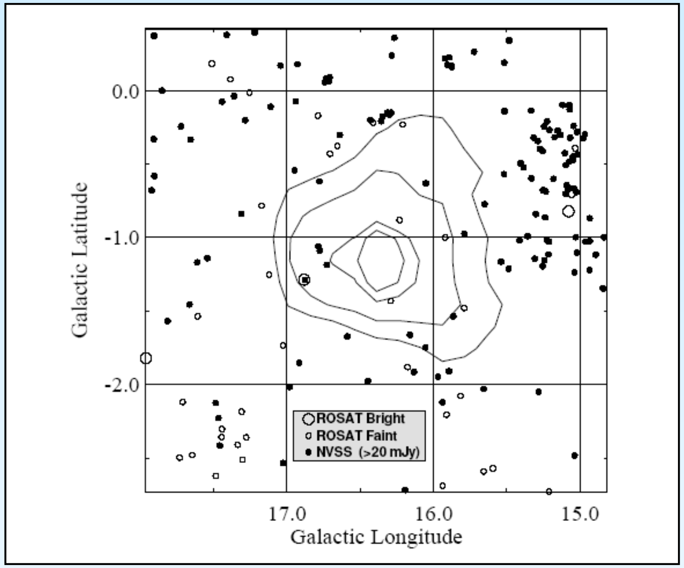
$p_{\text{wind}} + p_{\text{wind}\,*} \rightarrow \pi^0 \rightarrow 2\gamma$

acceleration zone between star and pulsar

$\gamma + \gamma_{*} \rightarrow e^{\pm}$



Jet Model for High-Energy Radiation from Microquasars

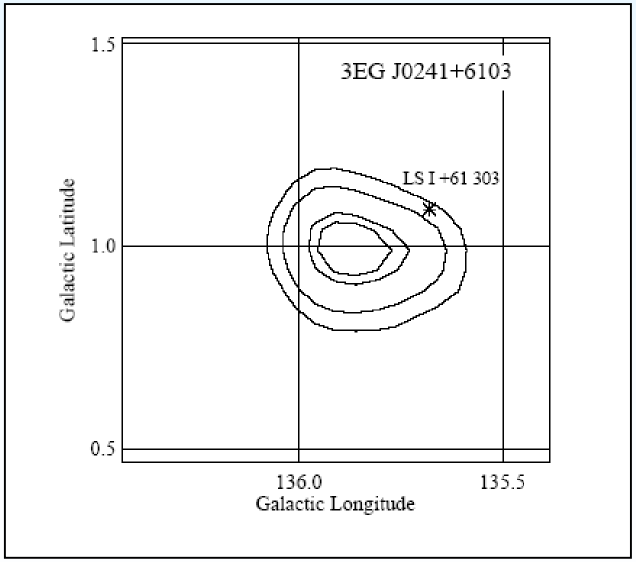


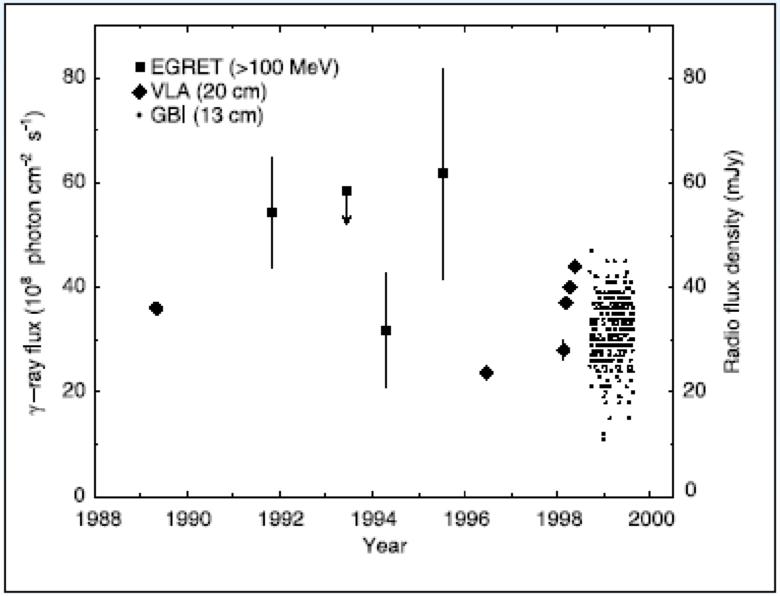
LS 5039:

$M_{BH} \approx 3.7\ M_o$, D ≈ 2.5 kpc, P = 3.906 d,

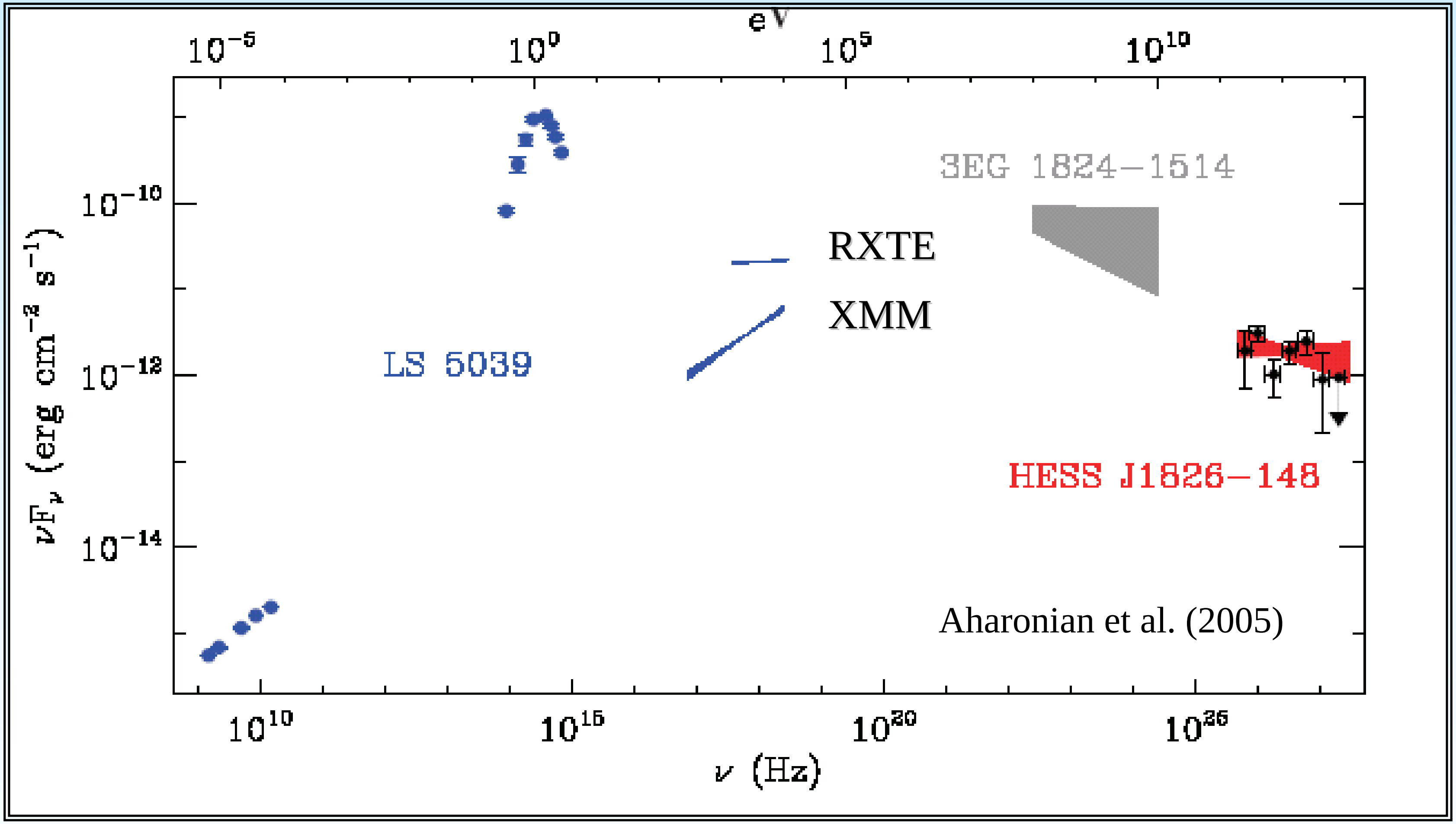
(Casares et al. 2005)

- Associated with 3EG J1824-1514 (Paredes et al. 2000) – new class of γ-ray sources?





Multiwavelength Spectrum of LS 5039

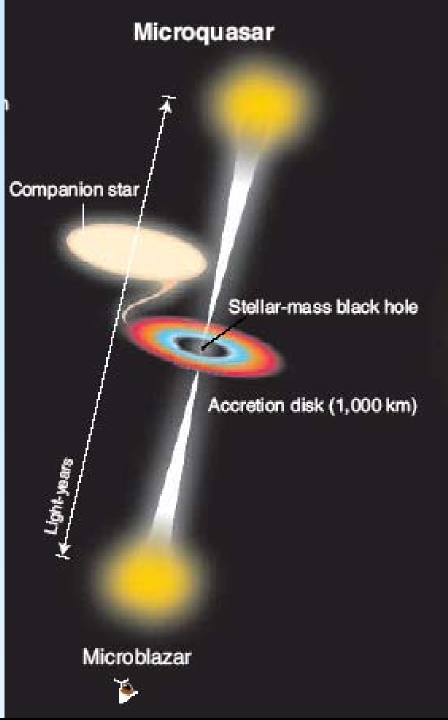


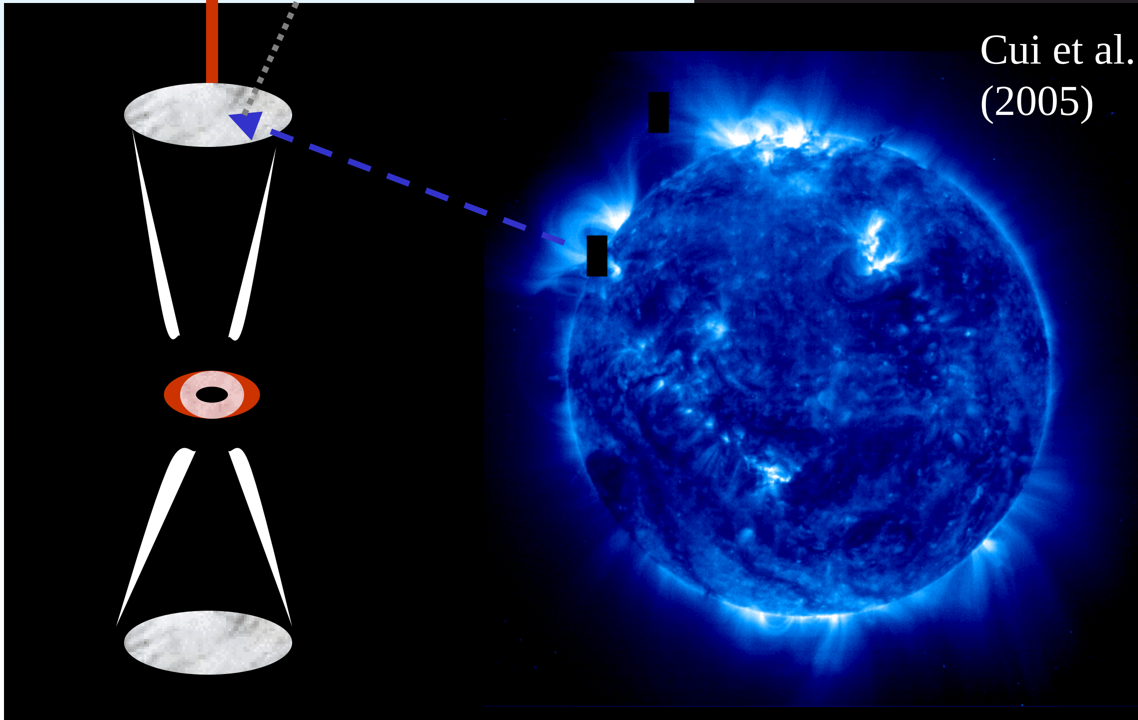
- Companion O7 Star (L ≈ 7×10^{38} ergs s^{-1})
- Optical/UV stellar radiation is highly absorbed (T~40000 K)
- Radio emission from jets reaches 10 AU

Jet Model for LS 5039

- Leptonic Jet Model (as in blazars)   Dermer & Böttcher (2006)
- Predicts stochastic variability of jet γ-ray emission
- Synchrotron radio/optical/X-ray emission
- (in addition to thermal/nonthermal accretion disk and thermal stellar radiation)
- Compton-scattered origin of γ rays
  - Target Photons:
    - Accretion Disk
    - Stellar radiation field

cf. model of Paredes, Bosch-Ramon, and Romero (2006)





Cui et al. (2005)

Assumptions of the Model

1. Jets are steady and oriented normal to orbital plane
2. Star and accretion disk treated as point sources of radiation
3. Nonthermal electrons isotropic in comoving jet frame have a fixed (broken power-law) distribution
4. Cascade processes negligible

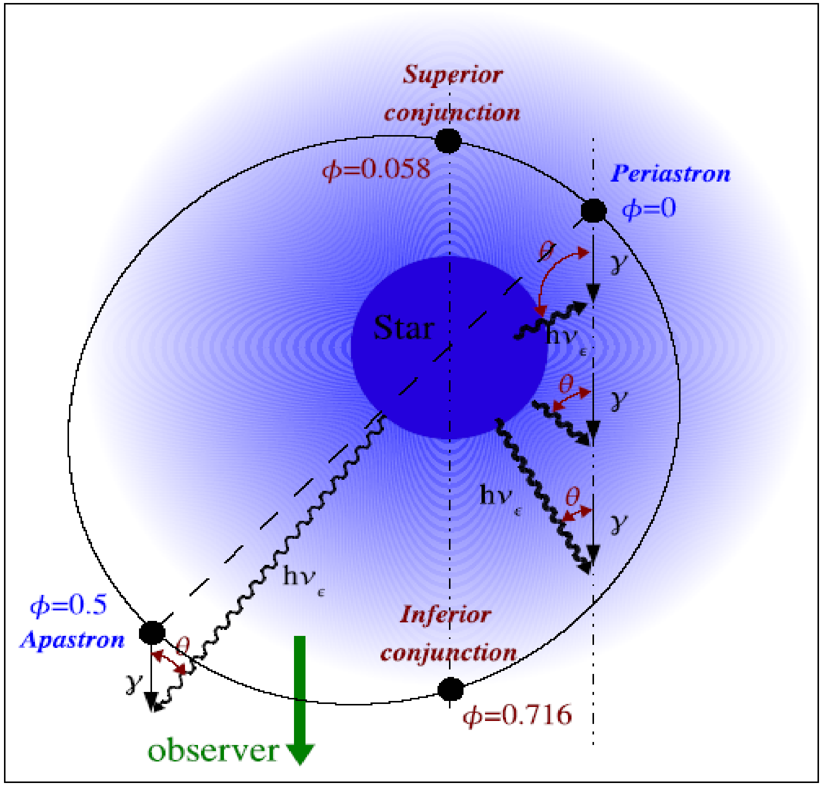
LS 5039 (to scale)

Roche Lobe radius

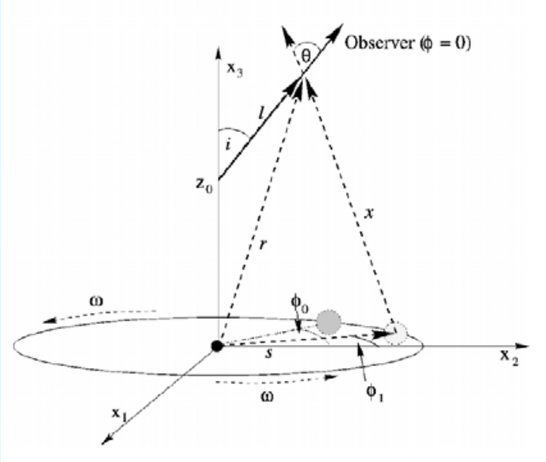
Stellar orbit

eccentricity = 0.35

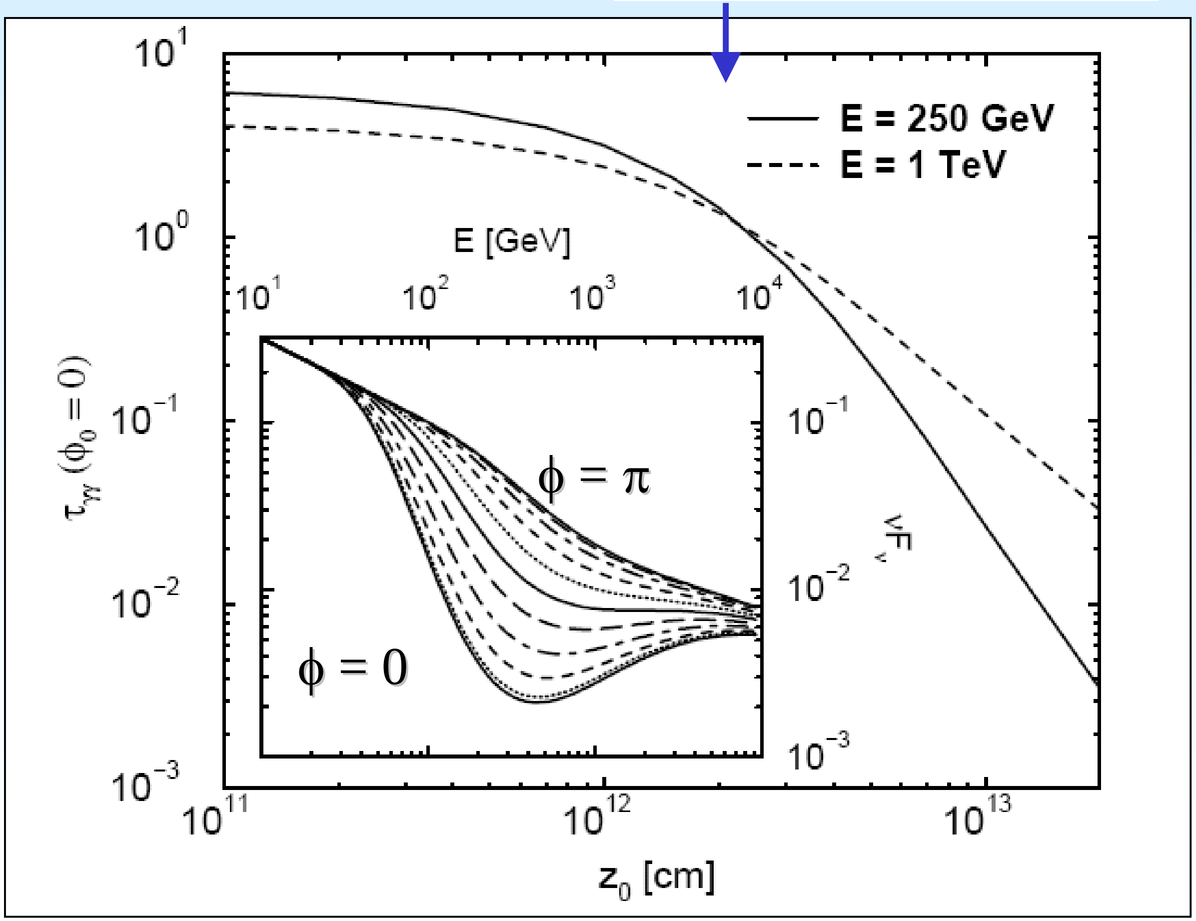
Casares et al. (2005)



γ Rays from Microquasars: Production and Attenuation



- Compton Scattering in KN regime for TeV γ rays
  - Companion Star Temperature = 39000 K = 3.4 eV
- Orbital Modulation of Compton Scattered radiation
  - Anisotropic stellar radiation field
- γγ Attenuation



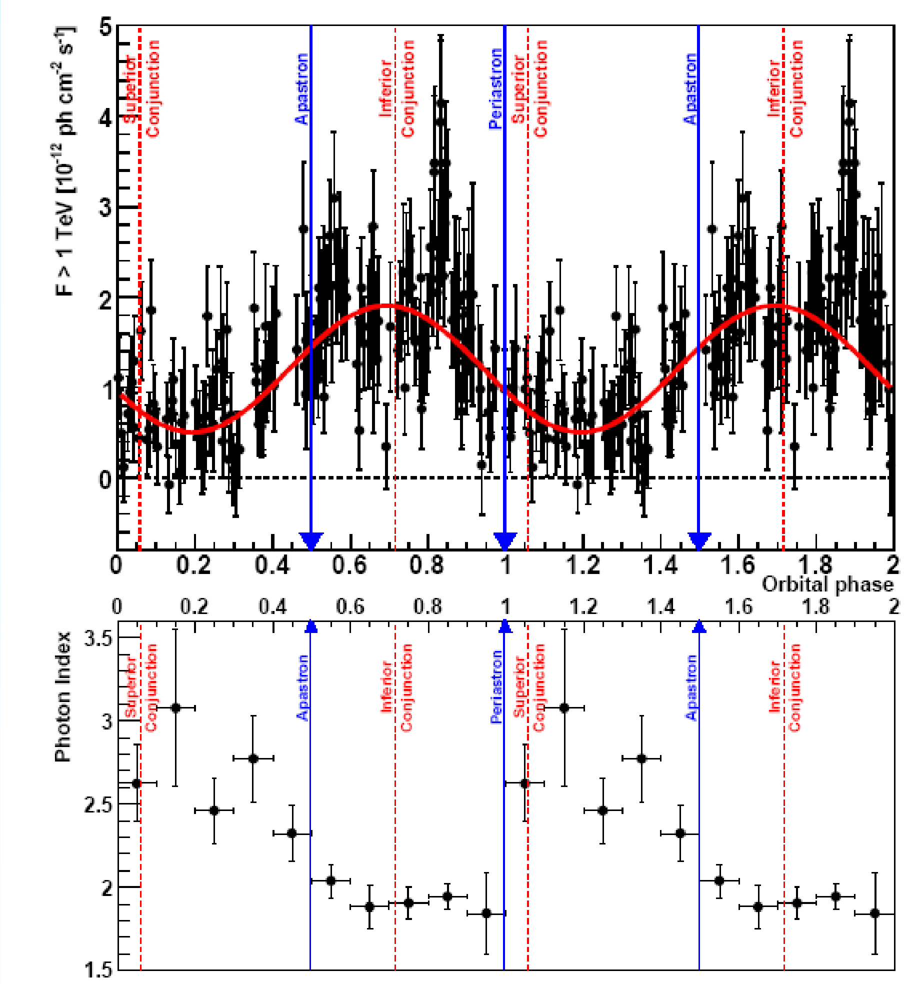
Phase ϕ = 0

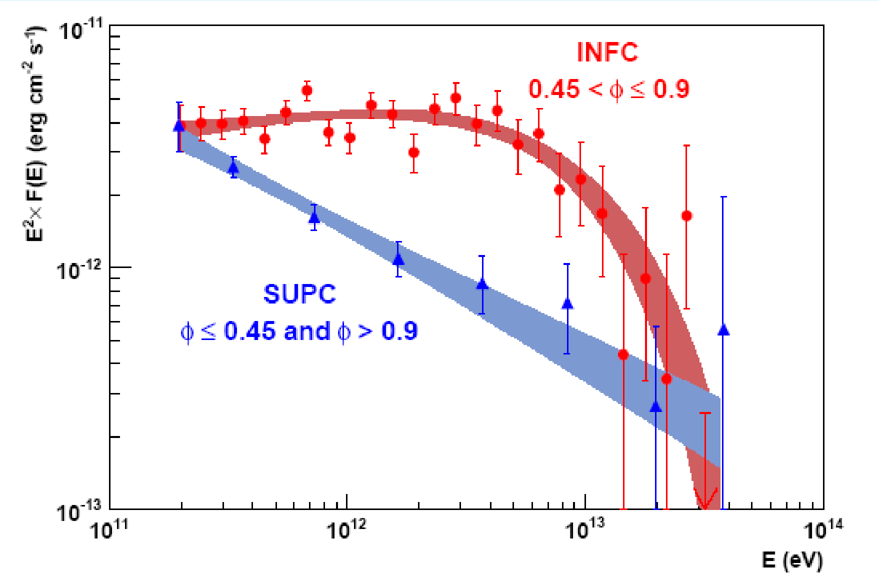
High mass companion star closest to observer

(Superior conjunction)

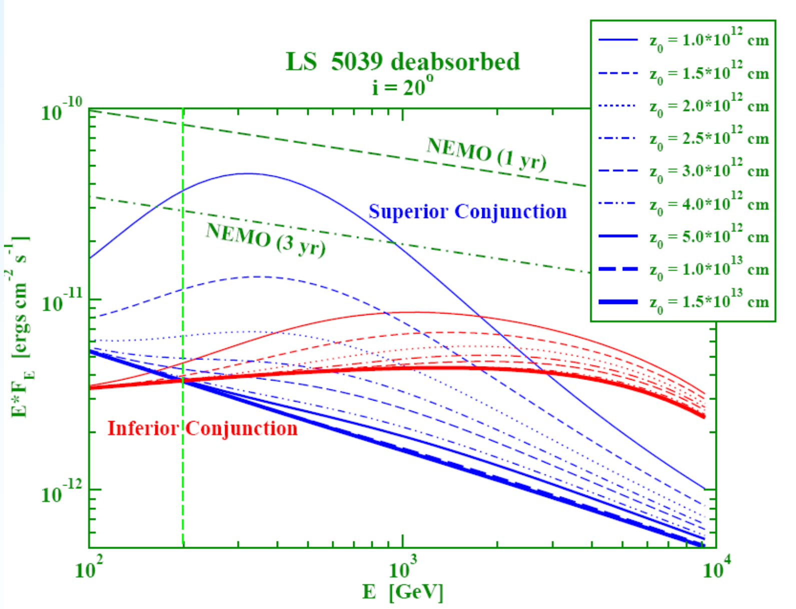
Böttcher and Dermer, ApJ Letters (2005)

γ-γ Pair Production Attenuation





Aharonian et al. 2006



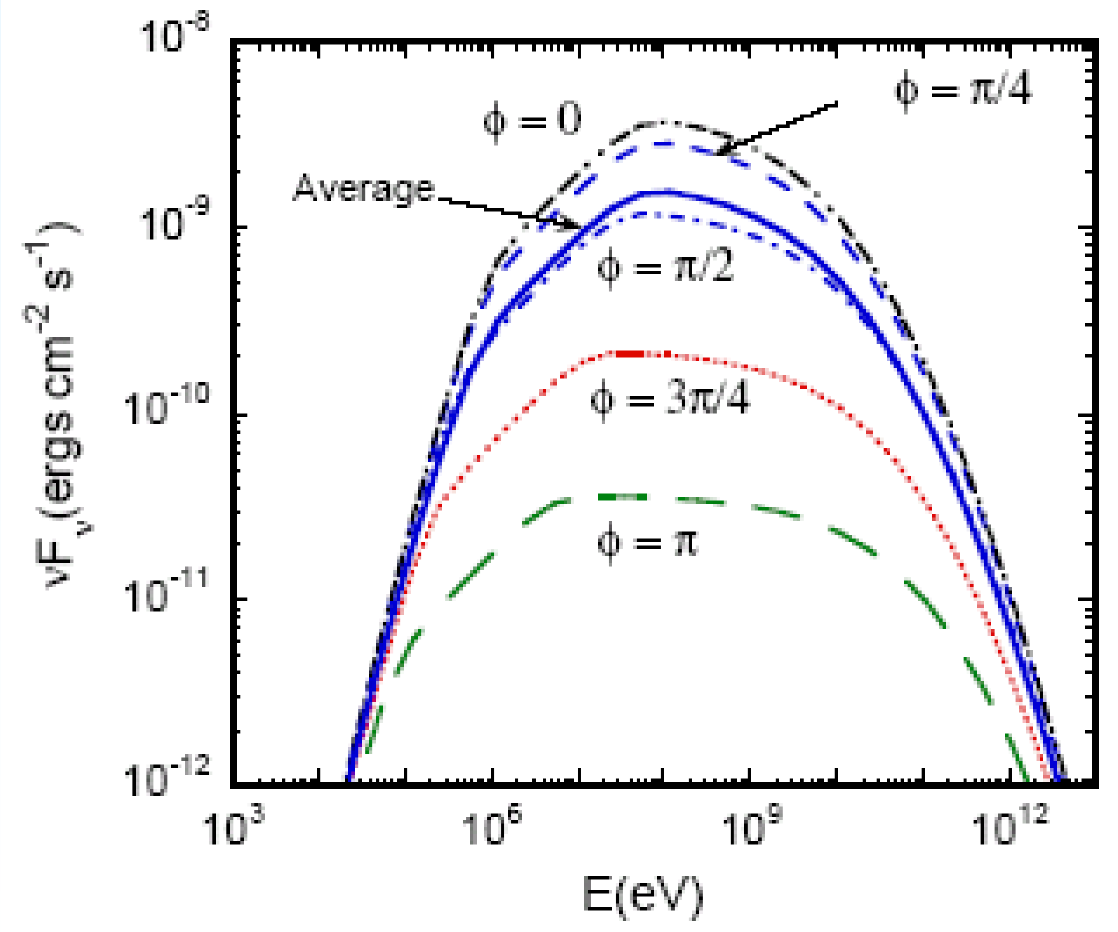
Böttcher (2007)

Phase Dependence of Compton scattered stellar radiation

- Rapid decline when scattering in KN regime

$$E_{\rm KN} \cong (\frac{m_e c^2}{4 \times 2.7\Theta} \cong \frac{20\ \mathrm{GeV}}{(1 - \cos\bar{\psi}')}$$

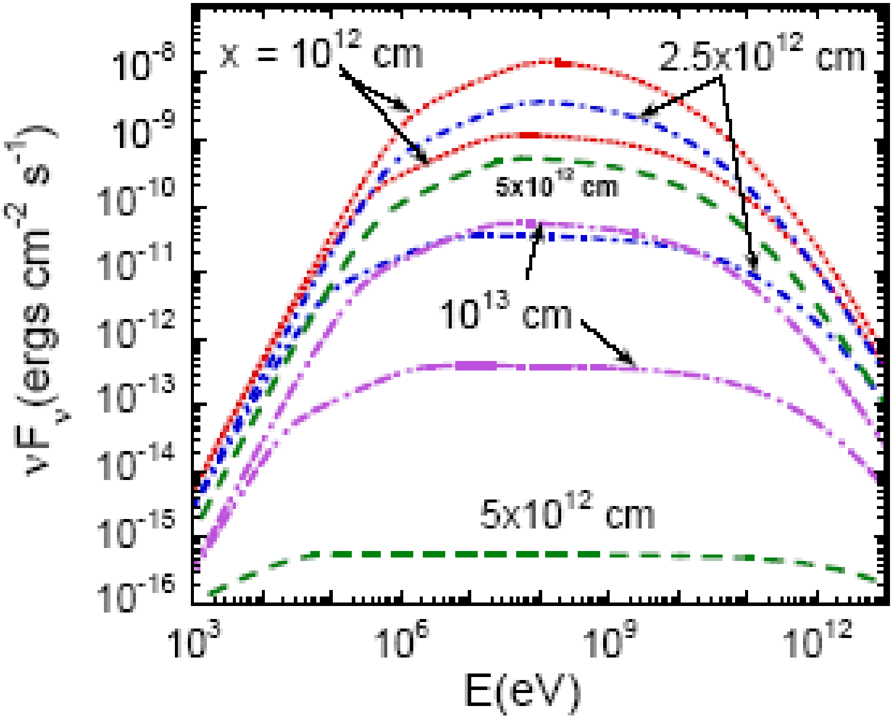
- Strong phase-dependent modulation of intensity and spectrum

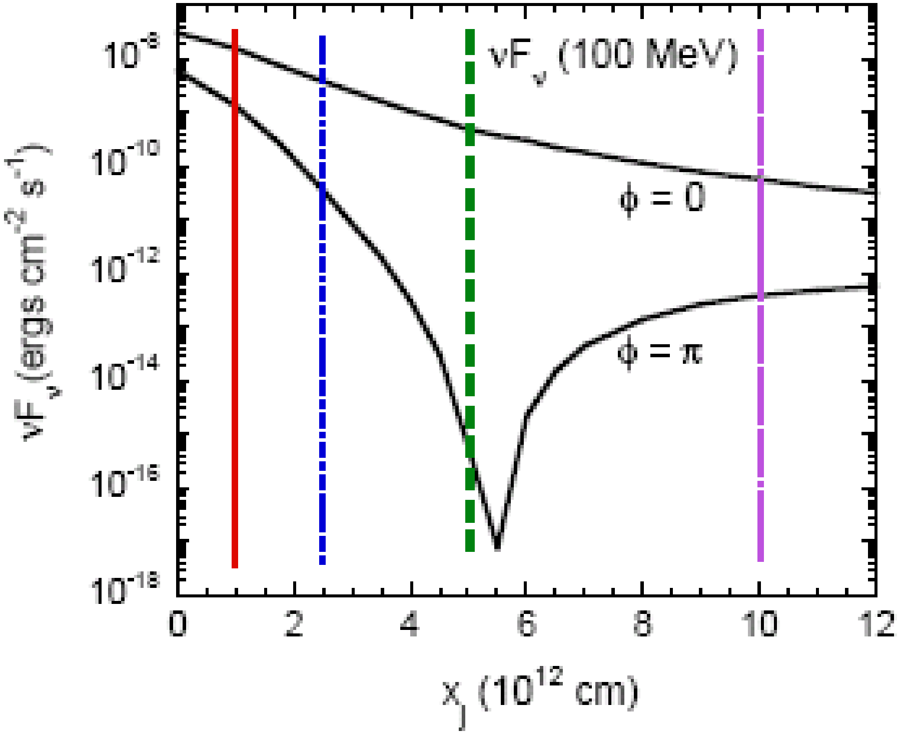


Jet height $x_j = d$
$= 2.5\times 10^{12}$ cm

Jet-Height Dependence of CSSR

- Gamma-ray nulling when target photons are almost exactly "tail-on"
- Phase-dependent modulation (by 10%) at $x_j = 5\times10^{14}$ cm (compared to x = 10^{13} cm for γ–γ attenuation)





Model Fit to the Multiwavelength Spectrum of LS 5039

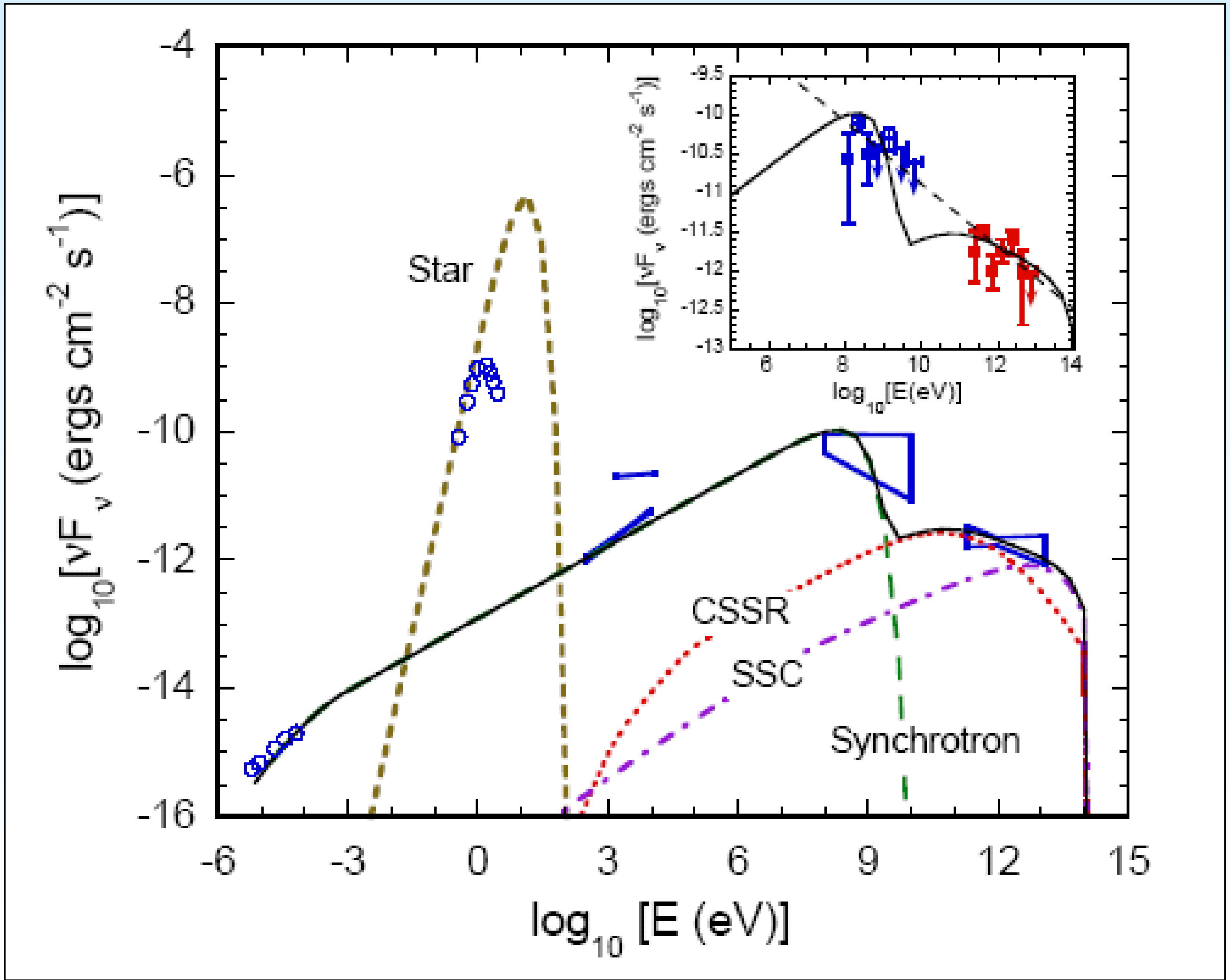
Fit assuming that EGRET and HESS data *are representative* of simultaneously measured SED

EGRET emission: high-energy extension of synchrotron spectrum

Combination of CSSR and SSC for TeV

Do not favor this model:

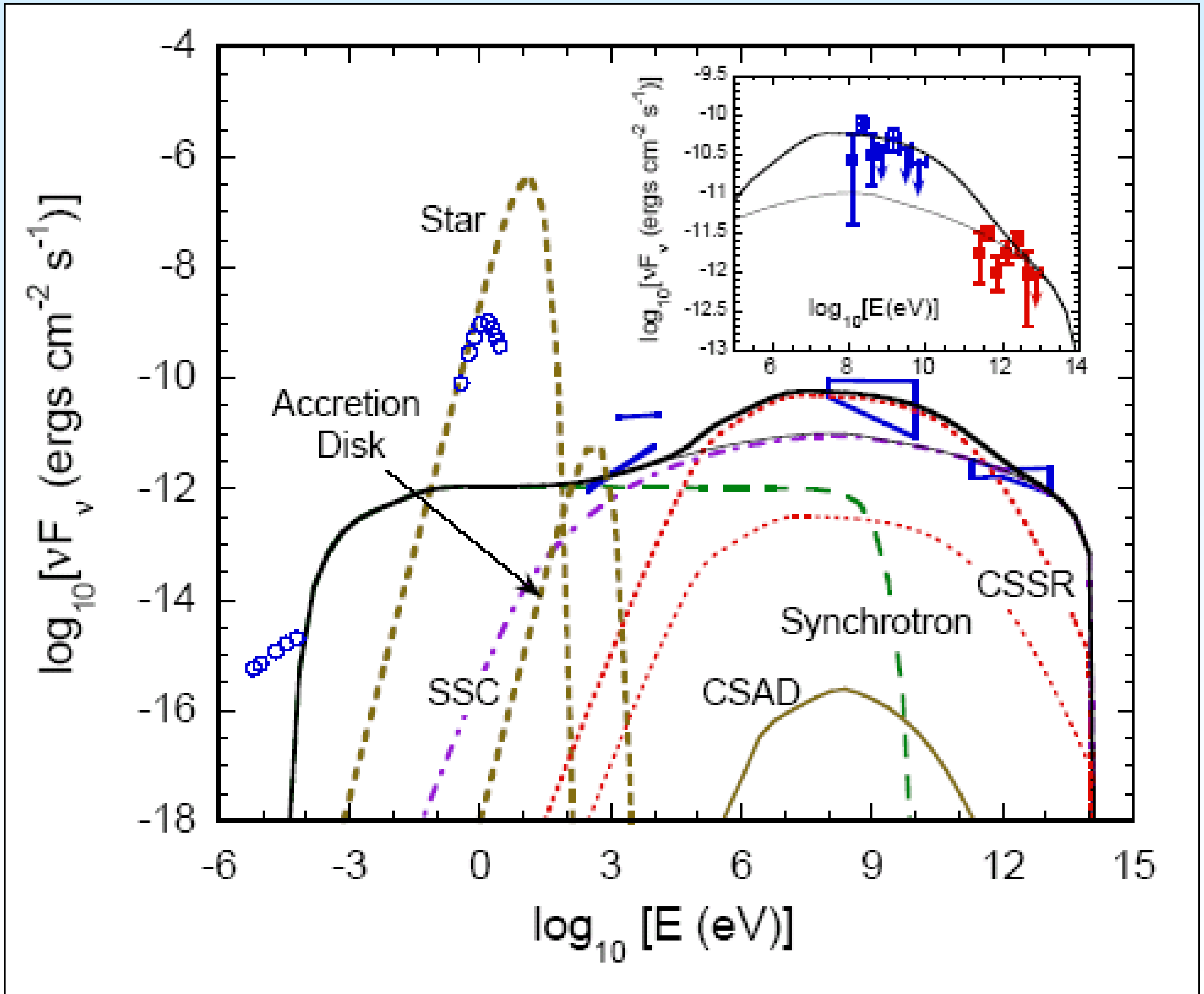
requires acceleration of electrons with maximal frequency and no break in synchrotron spectrum



Model Fit to the Multiwavelength Spectrum of LS 5039

Fit assuming that EGRET and HESS data *are different* between two epochs of measurement

- In accord with variability expected from leptonic model
- Predict orbital modulation of TeV γ-rays for inner jet model;
- Orbital modulation of GeV γ-rays for inner or extended jet model
- GLAST will quickly test this prediction



radiation components

- LS 5039
  - Dermer & Böttcher ’06
  - Paredes et al. ’06

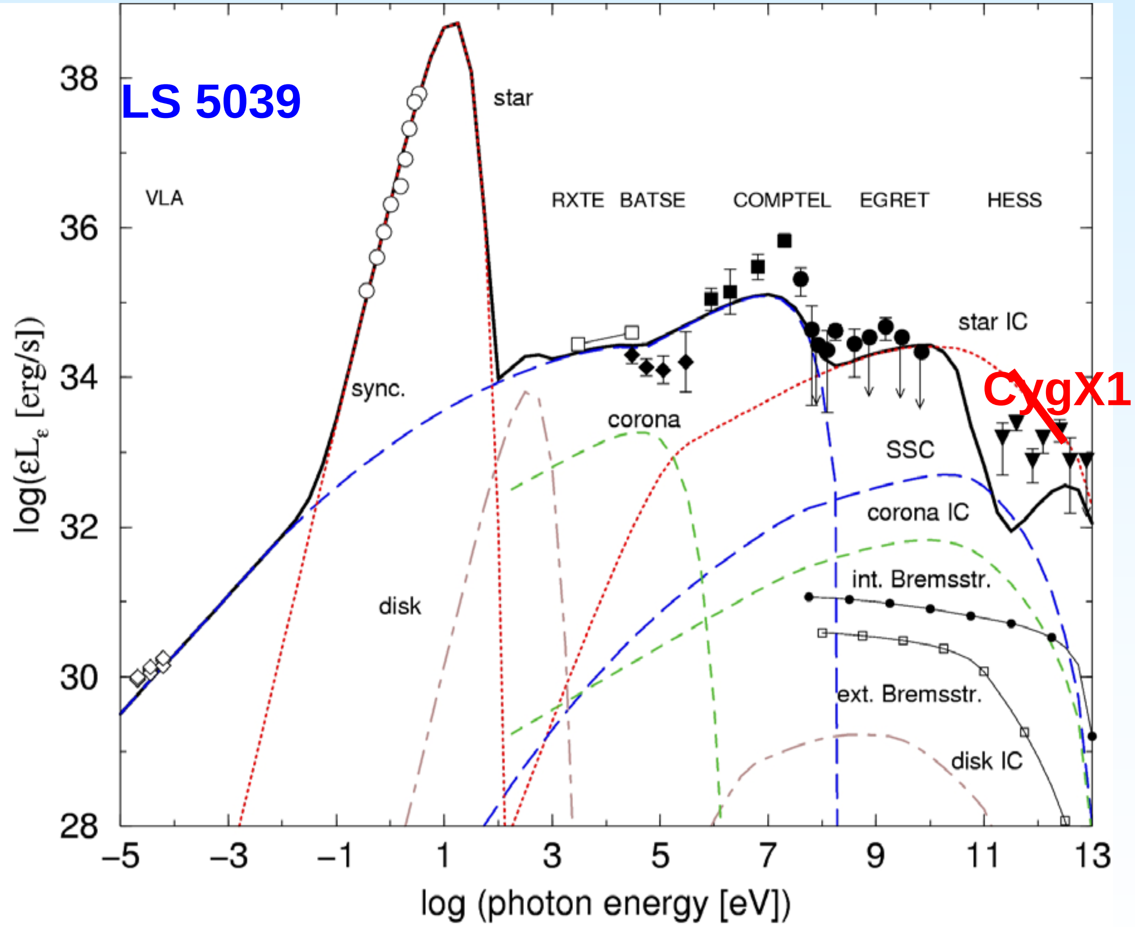
Cygnus X-1

Romero et al. ’02 (too bright)

- competition between absorbed star IC and SSC contributions
  - stellar radiation best known

- much fainter low-mass binary systems
  - << visibility

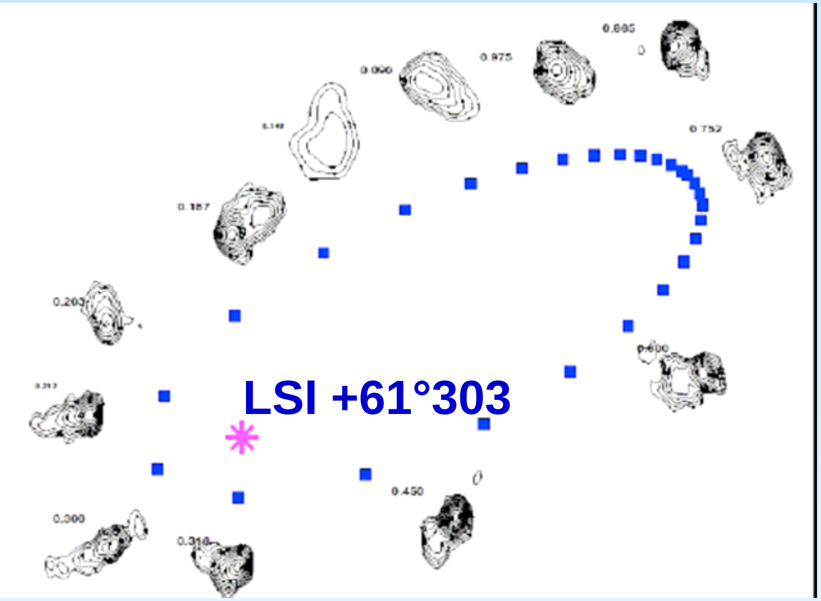
    Grenier et al. ‘05



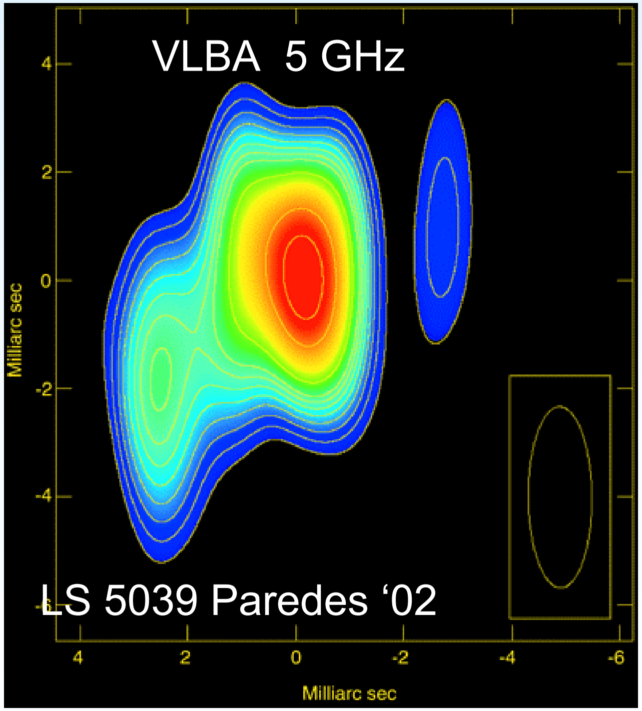
Paredes ’06

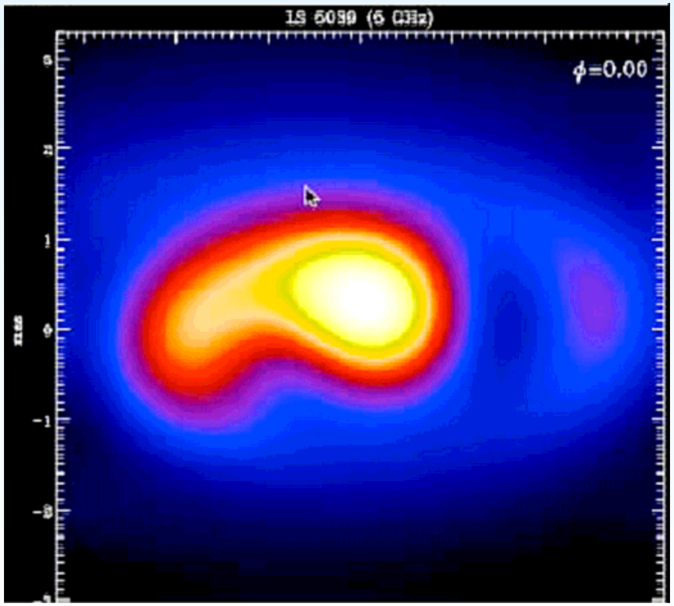
jet or wind?

- LSI +61°303 = PWN
  - unresolved by Chandra
  - PWN-like in VLBA
- LS 5039
  - jet-like in radio
  - µqsr spectral behaviour



Dhawan ‘07

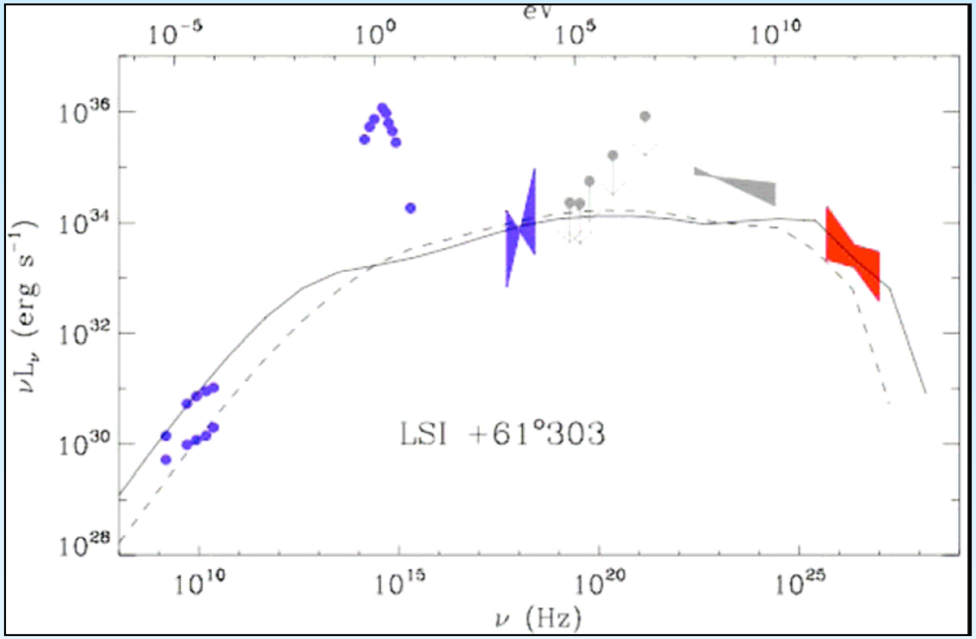


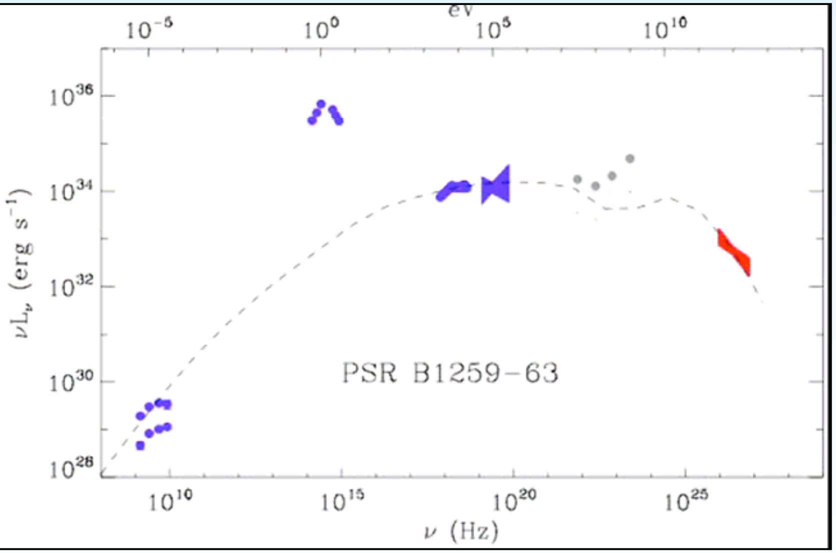


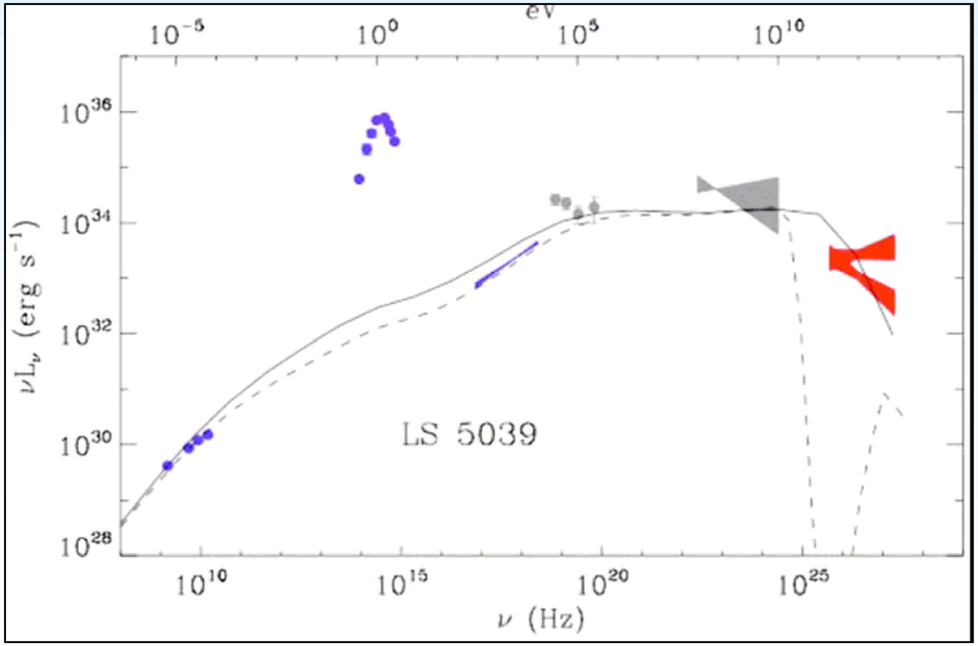
Dubus ‘06

Microquasar SEDs

- similar to PSR B1259-63



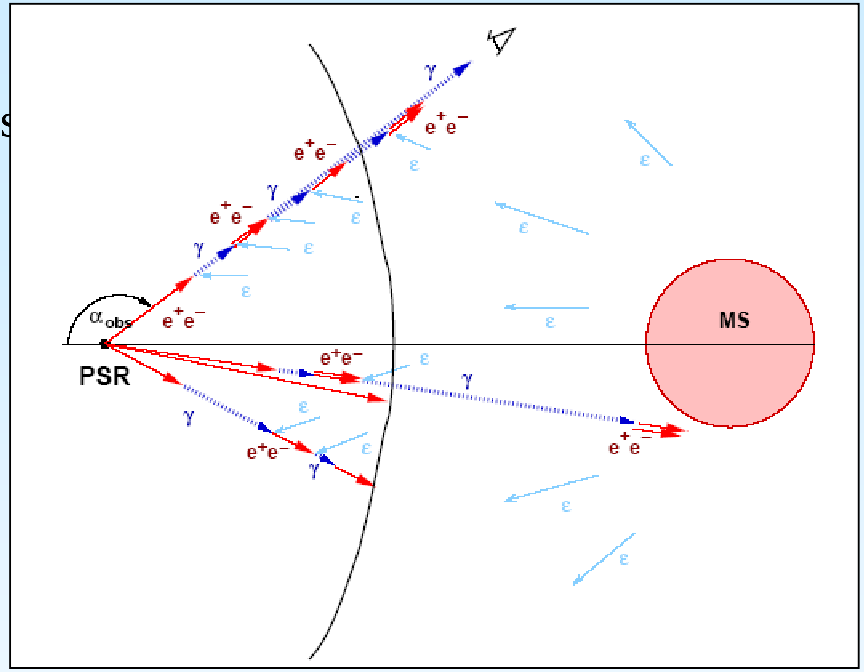




Dubus ‘06

Colliding Wind Model

- Colliding wind scenario
  - Cold MHD wind (also in young pulsars
  - Shocked wind

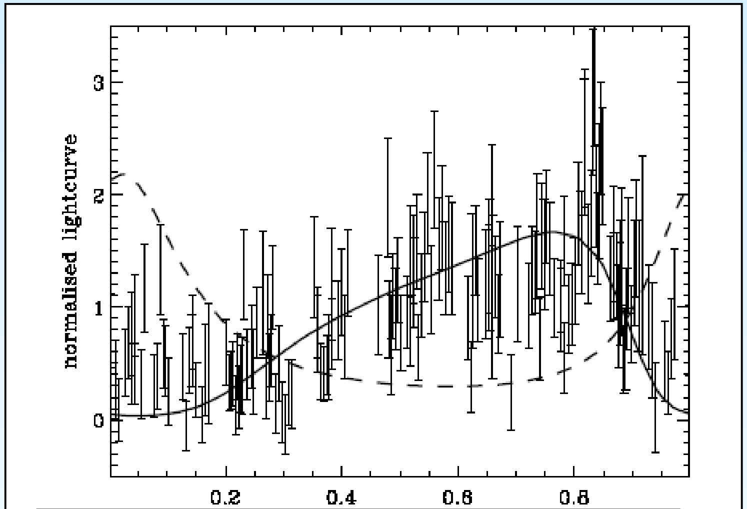


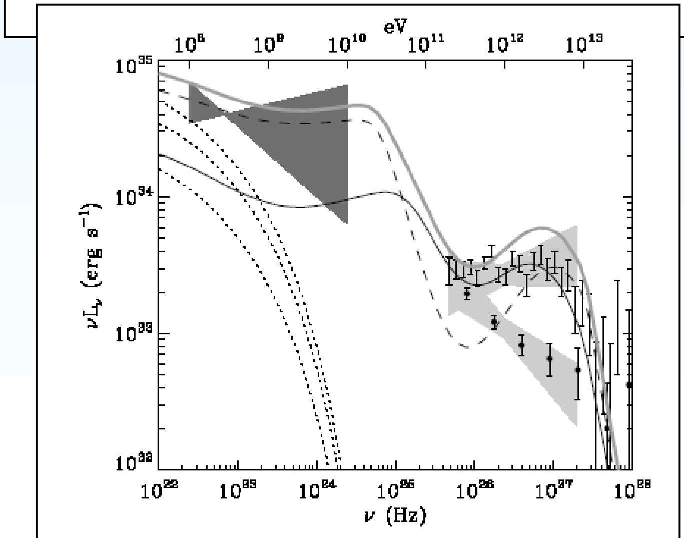
Sierpowska-Bartosik & Torres 2008

Cascades: Bednarek /Sierpowska

$$\eta = \frac{L_{sd}}{c(\dot{M}_s V_s)}$$

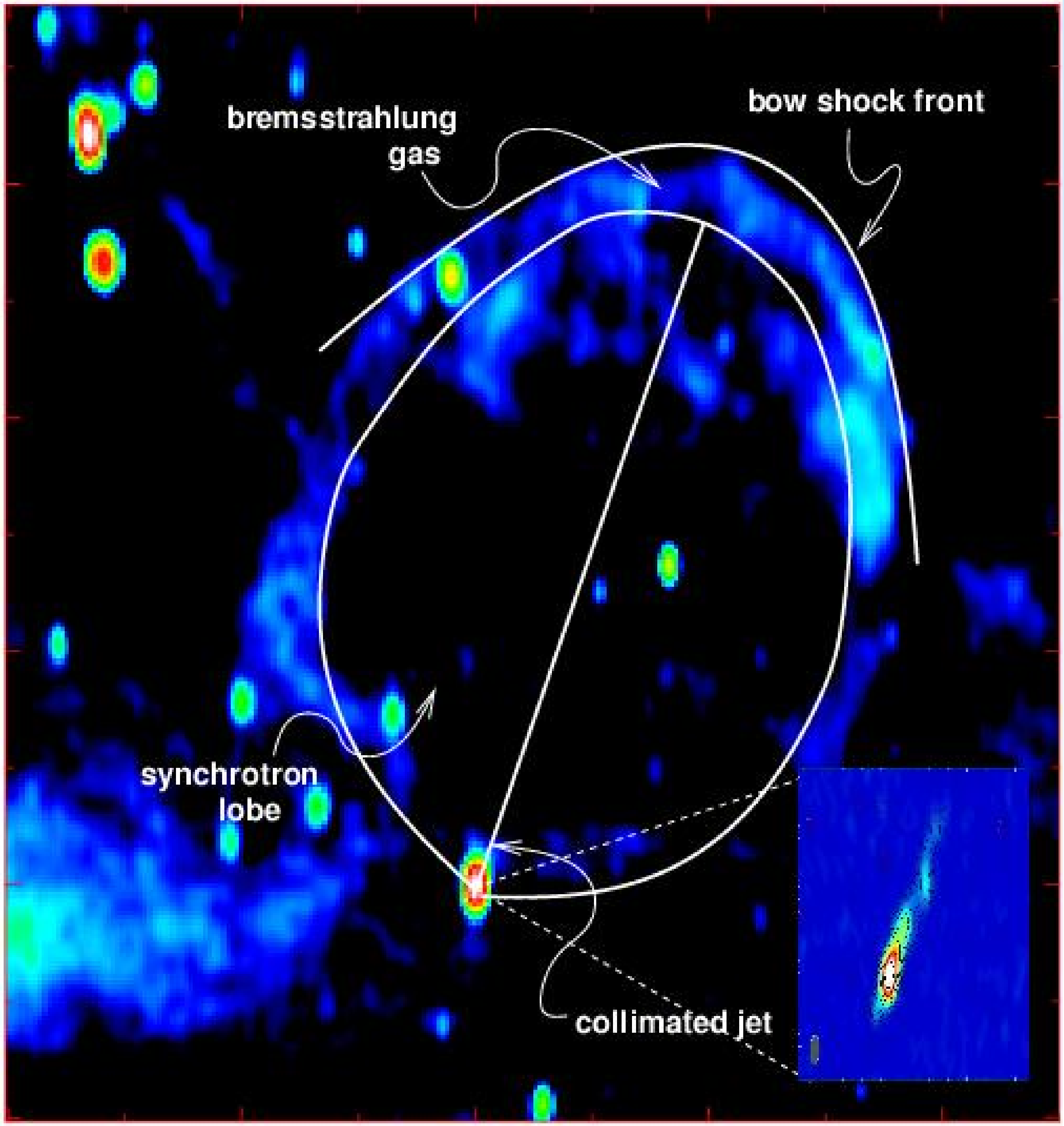
Why no PWN?





Dubus 2007

LARGE-SCALE JETS IN CYGNUS X-1



Gallo, Fender et al. Nature 2005

Ring diameter = 5 pc

> 50% OF THE RELEASED ENERGY IS NOT RADIATED

LARGE-SCALE JETS IN GRS 1915+105 ?

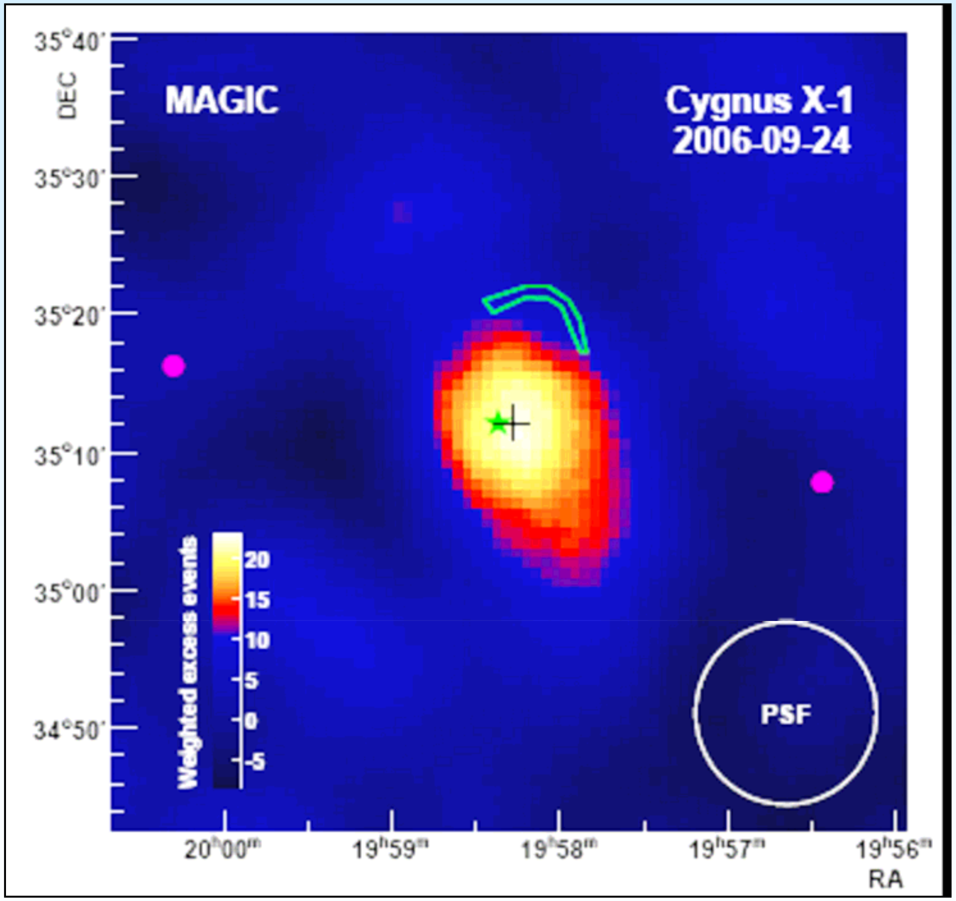
Rodriguez & Mirabel (2006)

Hot spots at ~ 50 pc

Cygnus X-1: a γ-ray black hole

Cygnus X-1 seen only one time with MAGIC in multiple pointings

Evidence for black-hole microquasars



Albert et al. '07

Microquasars vs. TeV X-ray Binaries

Pulsar vs. black hole in LS 5039, LSI

(strong periodic TeV variability surprising for black hole microquasars)

Leptonic vs. hadronic models: which is easier to fit SED?

which is easier to fit orbital variability?

New orbital parameters for LS 5039 may affect modeling of gamma-gamma in LS 5039

TeV luminosity of microquasars ~ 1e36 ergs/s

Factor of 100 greater energy in spin-down power

Power requirements for cosmic rays

Two components of pulsar wind/OB star wind-wind interactions: shocked and unshocked wind

Look for Unidentified TeV sources in LMXBs, not HMXBs

Unidentifed TeV Candidate Sources in the Galaxy

Variable

LMXRBs as counterparts to variable intermediate latitude sources (Grenier, Kaufman, Bernado & Romero 2005)

Isolated accreting black holes in the Galaxy (Dermer 1997)

Rapidly rotating, charged black holes (Punsly 1998)

Evaporating black holes (isotropically distributed)

(HMXB/microquasar easily identified)

Steady

PWNe; Pulsars
SNRs; GGRB Remant

Colliding Wind systems (slowly variable)