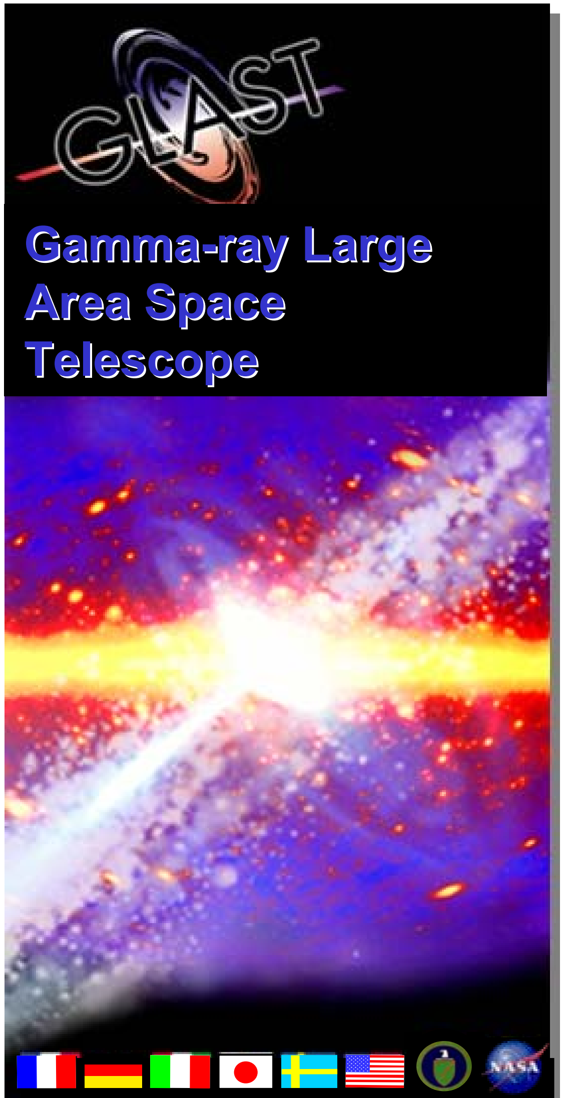


GLAST Science at Lunch

LS 5039

Neutron star or Black hole XRB?

Richard Dubois(*)

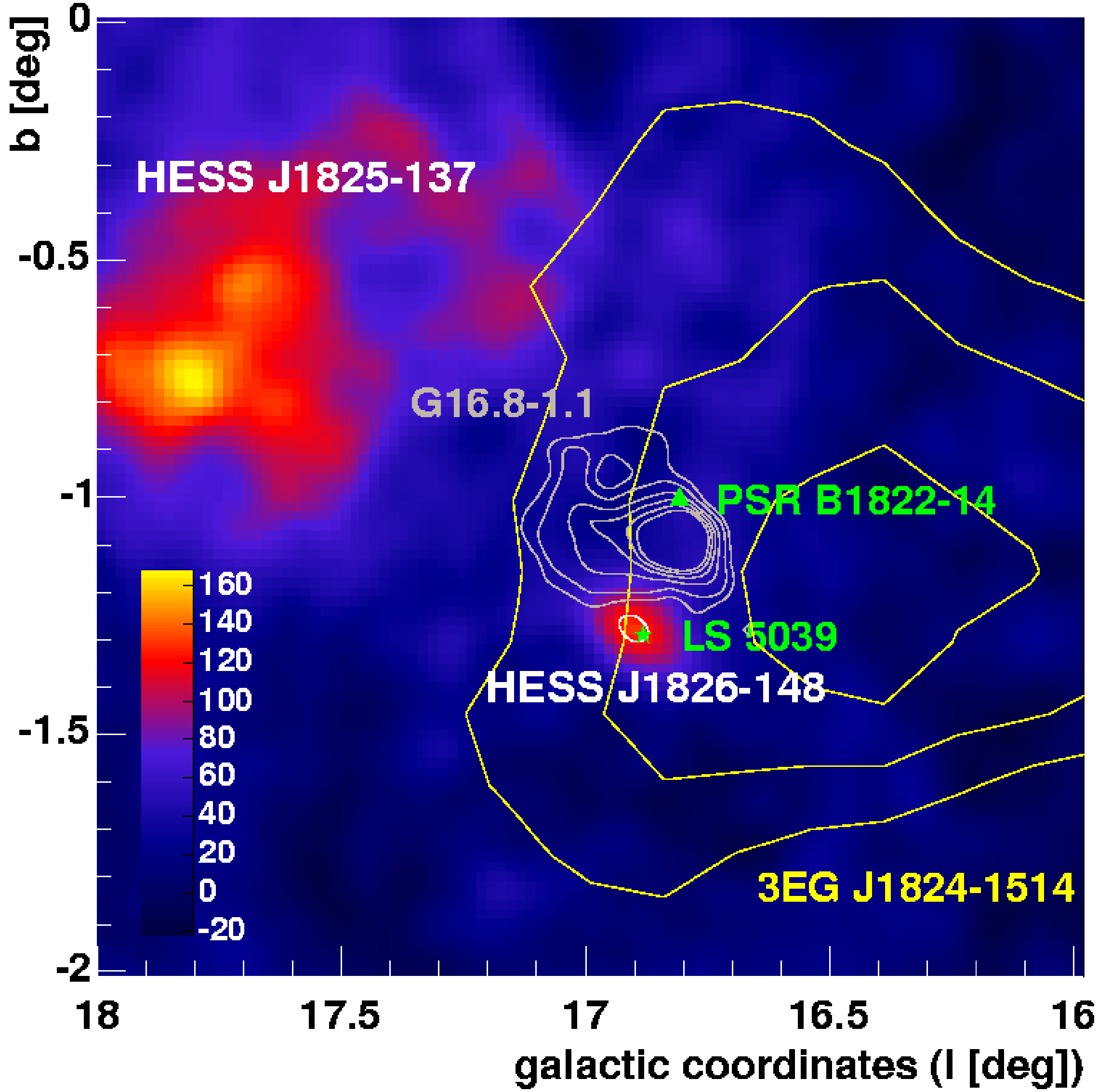
(*) Usual caveats and groveling

Outline

- HESS sees LS 5039 in TeV
- What is/was known about it
- Reminders about microquasars
- Evidence for black hole
- Evidence for pulsar

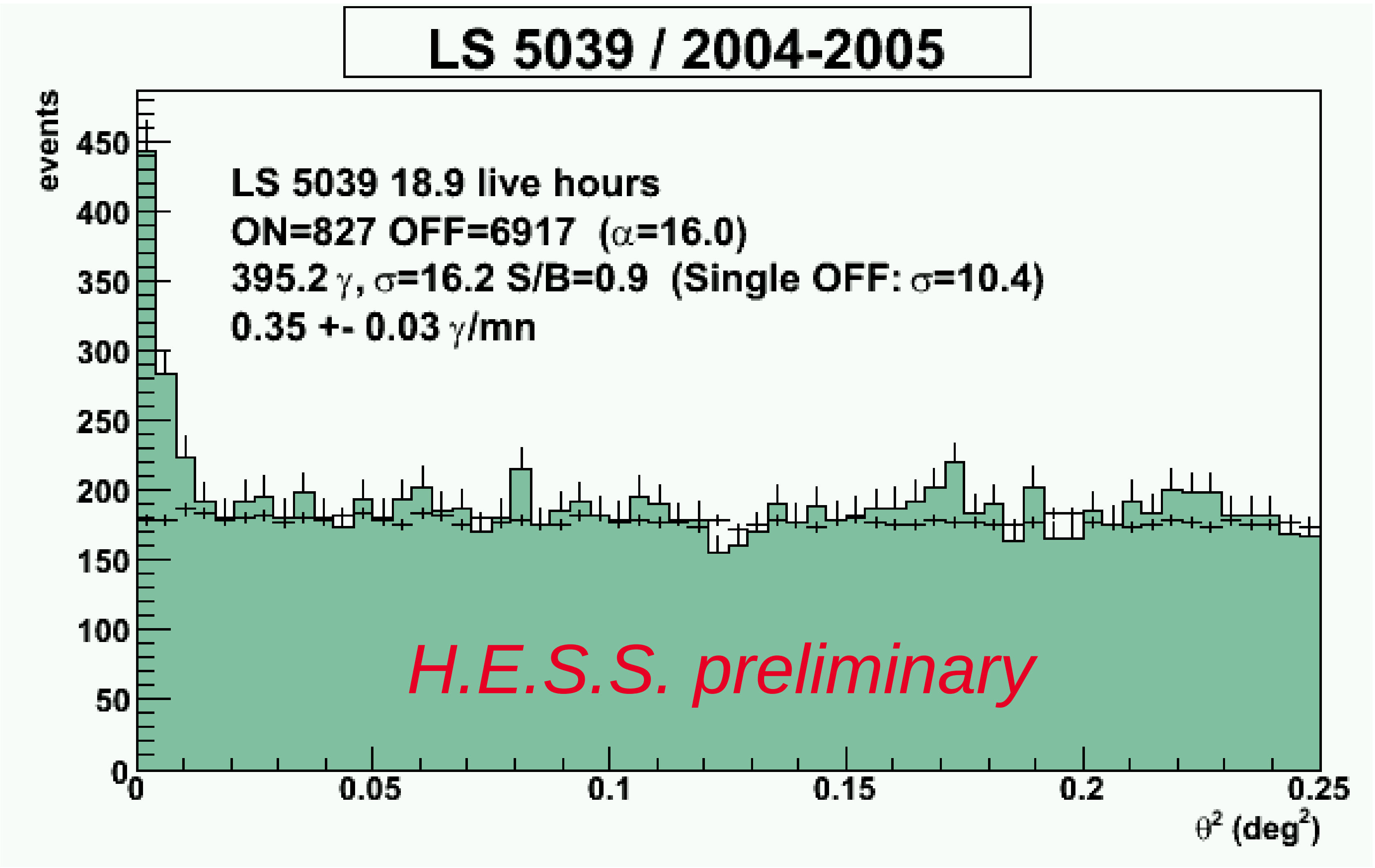
References:
- HESS – Science 29 (2005) 746
- Casares et al – astro-ph 0507549
- Dubus – Einstein 2005 Paris talk

Thanks to Olaf, Guillaume and Berrie for advice!

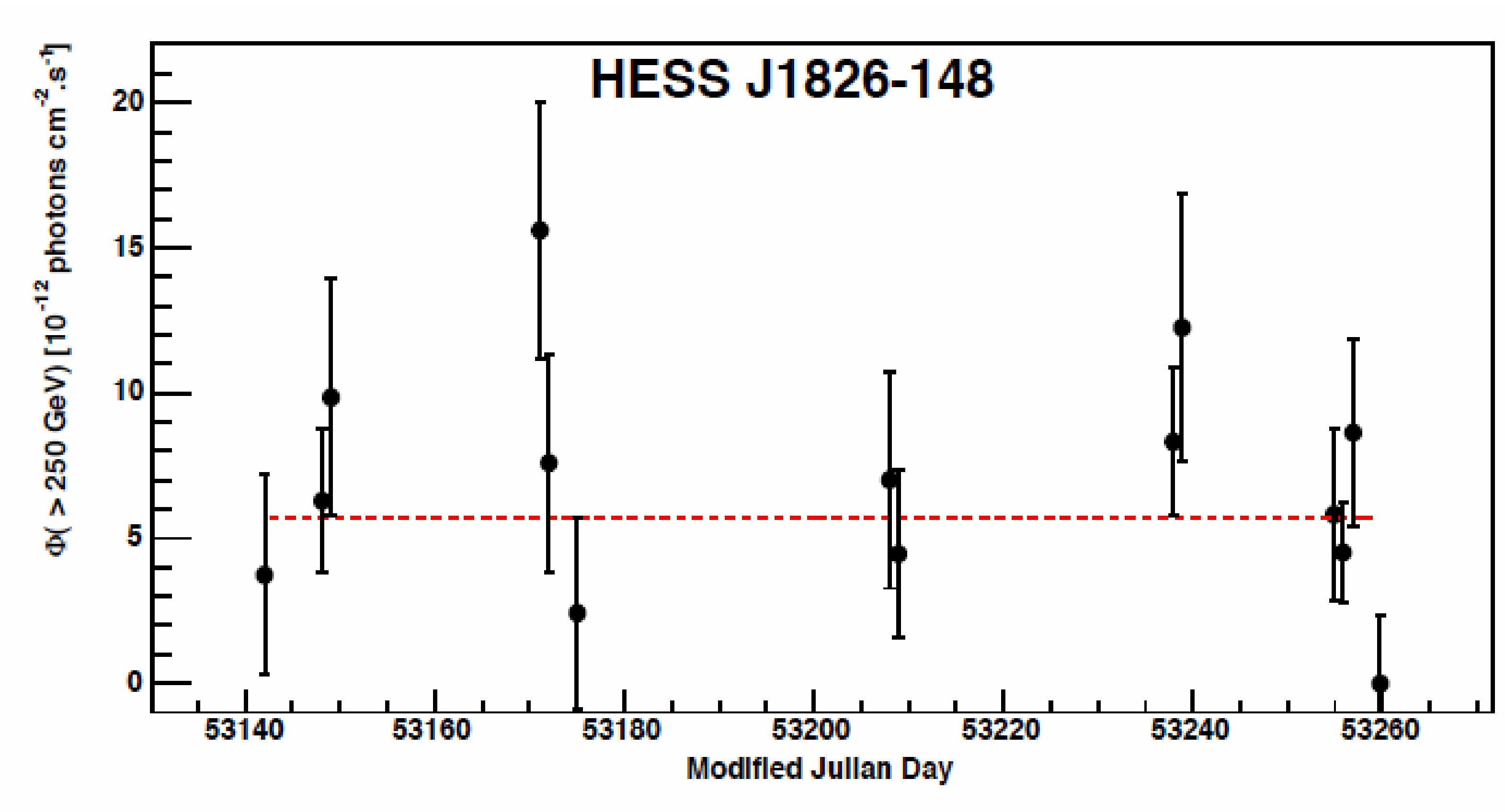


Aharonian et al., Science (in press)

HESS: Detected again this year



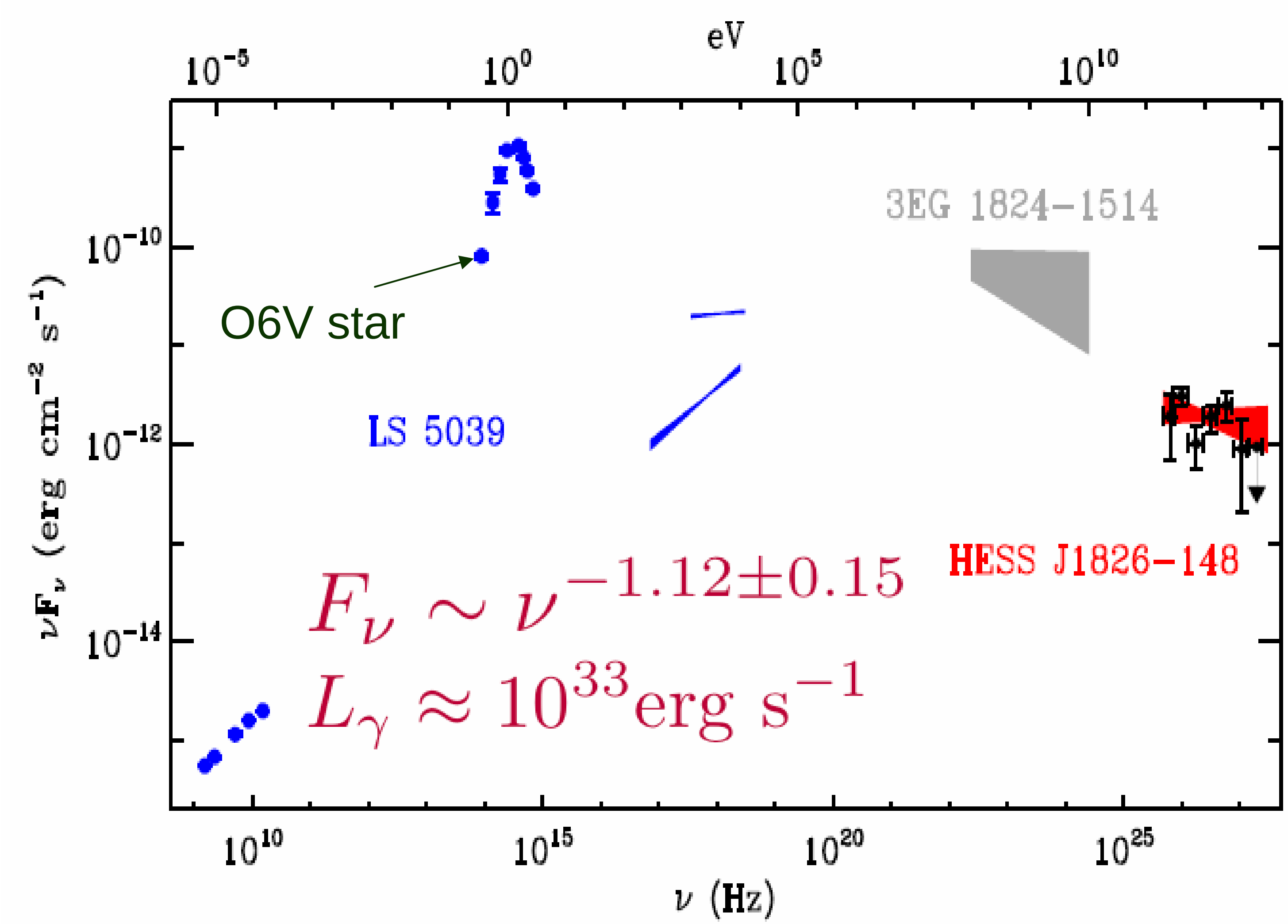
H.E.S.S. lightcurve (2004)



No significant variations

Aharonian et al., Science (in press)

H.E.S.S. spectrum: hard



Aharonian et al., Science (in press)

Orbital Parameters – McSwain et al

d ~ 3 kPc
M_{comp} ~ 1-1.5 M_{sun}
M_{opt} ~ 22 M_{sun}

Use rotational broadening of optical lines to get rotation velocity

Doppler shift of centroids show motion relative to CoM

TABLE 3
Orbital Elements

Element	Value
P	4.4267 ± 0.0005 days
T (HJD−2,450,000)	2756.49 ± 0.07
K	17.6 ± 1.3 km s^{-1}
V_0	4.1 ± 0.8 km s^{-1}
e	0.48 ± 0.06
ω	268° ± 10°
rms	5.5 km s^{-1}
$f(m)$	0.0017 ± 0.0005 $M_\odot$
$a_1 \sin i$	1.36 ± 0.12 $R_\odot$

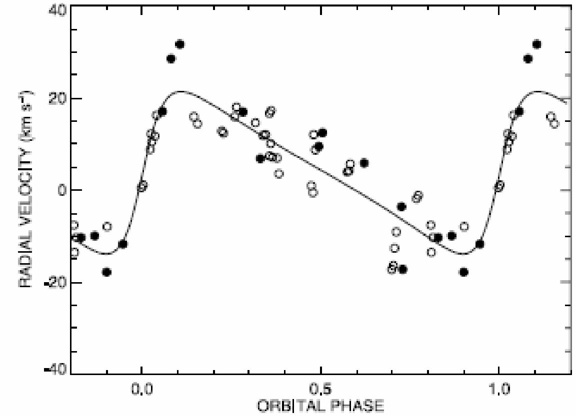


Fig. 1.—Revised radial velocity curve (*solid line*) for LS 5039, together with the original measurements from McSwain et al. (2001; *open circles*) and the new measurements (*filled circles*).

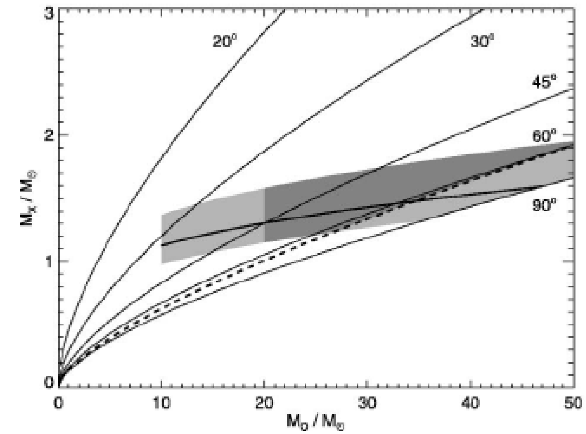


Fig. 8.—Mass plane diagram for LS 5039 with constraints from the wind accretion model. The thinner solid lines starting at the origin trace the mass solutions from the orbital elements for the labeled values of orbital inclination. The thicker solid line segment in the center of the diagram shows the mass relationship derived by matching the observed and predicted X-ray fluxes from the wind accretion model (with the lightly shaded region showing possible solutions found by adjusting parameters discussed in the text). The dashed line indicates the lower limit on M_X established by the lack of observed eclipses, and the darker shaded region shows the most probable mass solution space.

Orbital Layout

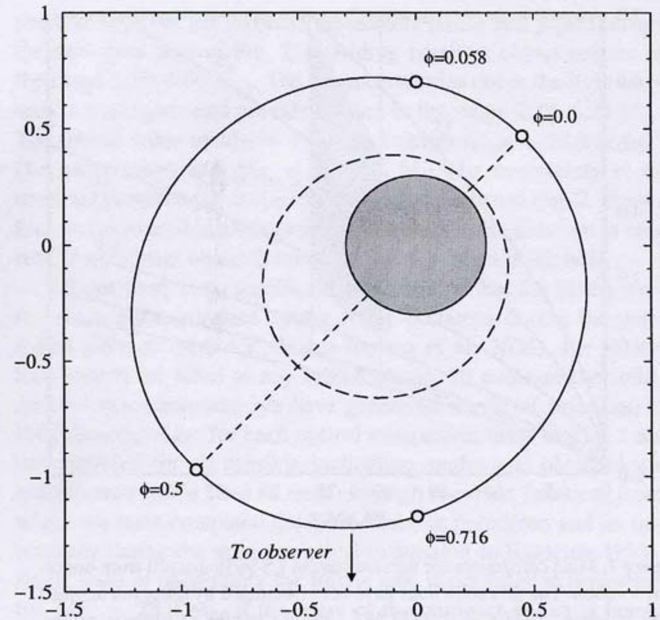


Figure 6. Relative orbit as seen from above of the compact object around the optical component, which lies in the ellipse focus, computed using our adopted solution from Table 2. The coordinates are in units of the orbital semi-major axis. Relevant phases such as the periastron, apastron, and conjunctions are indicated, with the dashed line joining periastron and apastron. The grey circle represents the optical companion to scale in the case of $R_O = 9.3\,R_\odot$, while the long-dashed ellipse represents the radius of the Roche lobe at each orbital phase for the adopted masses of $M_O = 22.9\,M_\odot$ and $M_X = 3.7\,M_\odot$ (see Sect. 4). The star is at 85 per cent of filling the Roche lobe during the periastron passage.

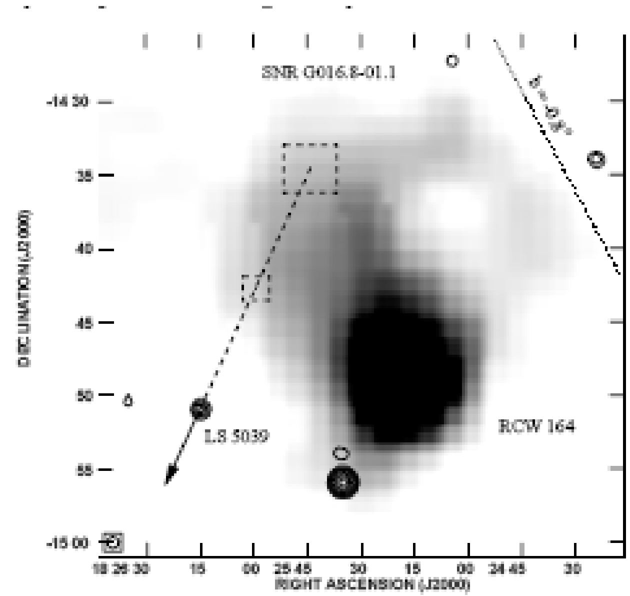


Fig. 2. Wide field radio map of LS 5039, its nearby shell-like SNR G016.8−01.1 and the H II-region RCW 164 (which is the stronger source in the field). The grey scale emission is taken from the Parkes-MIT-NRAO tropical survey at the 6 cm wavelength (Tasker et al. 1994). The overlaid contours correspond to the NVSS map of the region at the 20 cm wavelength (Condon et al. 1998). The arrow marks the proper motion sense (see text). The dashed line is the computed trajectory for the last 10^5 yr, with the corresponding error boxes in position at that epoch and 5×10^4 yr ago. The dotted line represents positions with a galactic latitude of -0.8° for reference purposes.

Looks plausible that LS 5039 was ejected from SNR G016.8-01.1

Relativistic Radio Jet

Paredes: Science 288 (2000) 2340

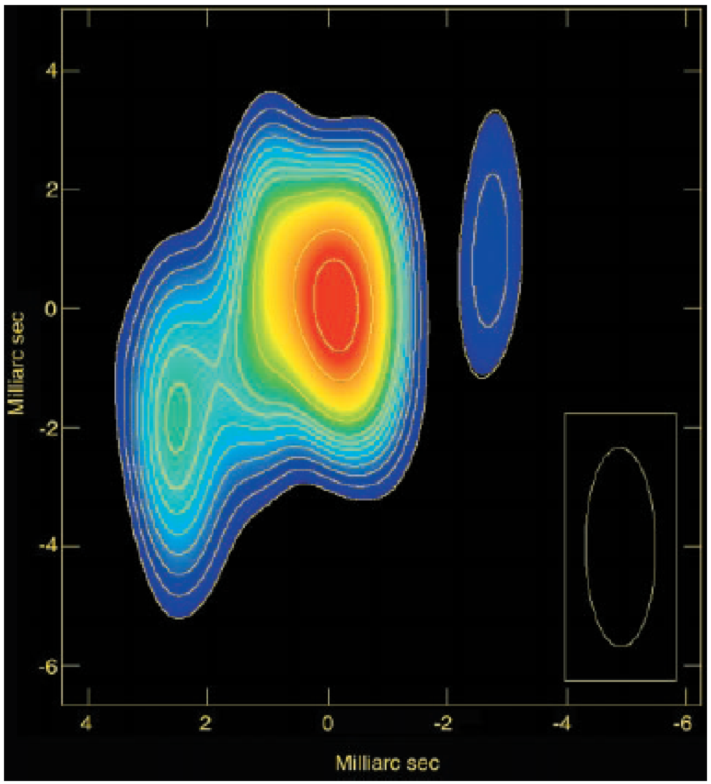


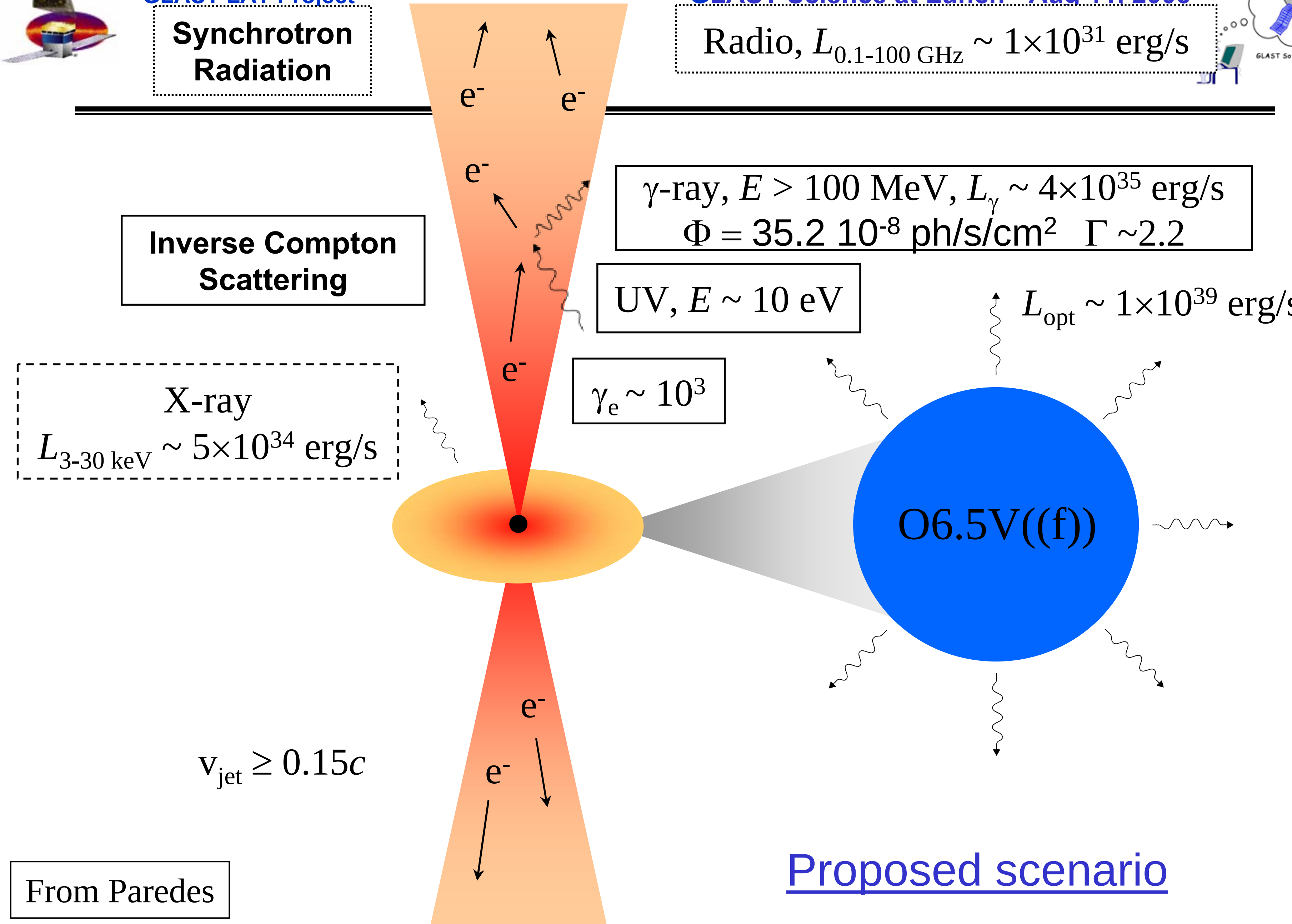
Fig. 1. High-resolution radio map of the nearby star LS 5039 obtained with the VLBA and the VLA in phased array mode at 6-cm wavelength. The presence of radio jets in this high-mass x-ray binary is the main evidence supporting its microquasar nature. The contours shown correspond to 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 40, and 50 times 0.085 mJy per beam, the rms noise. The ellipse at the bottom right corner represents the half-power beam width of the synthesized beam, 3.4 × 1.2 (milliarc sec^2) with a PA of 0°. The map is centered at the LS 5039 position $\alpha_{J2000} = 18^h26^m15.056^s$ and $\delta_{J2000} = -14°50'54.24''$. North is at the top and east is at the left. One milliarc sec is equivalent to 4.5×10^{13} cm (3 AU) for a distance of 3 kpc.

They assume these are 2 jets with Doppler boosting affecting apparent luminosity.

2:1 density difference → v > 0.15 c

Hence = microQuasar!

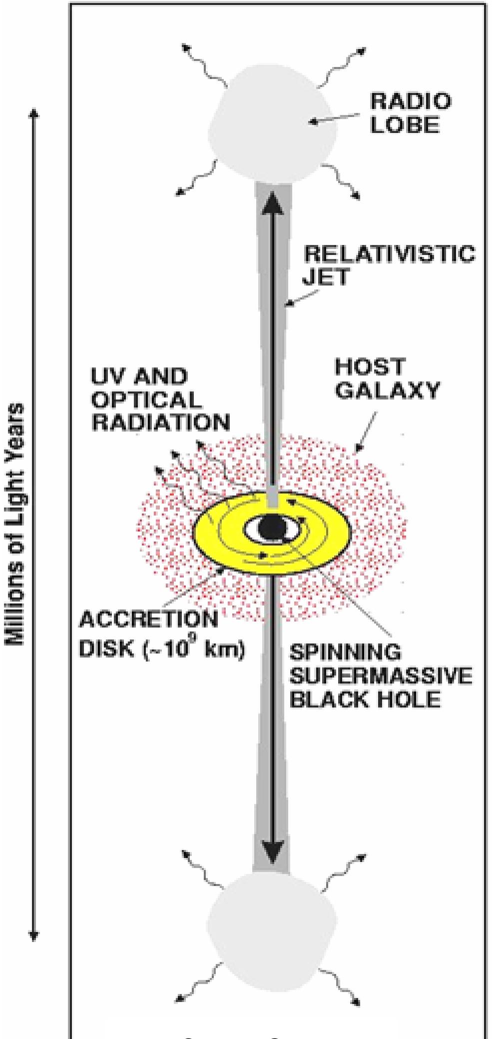
VLBA/VLA radio map



Proposed scenario

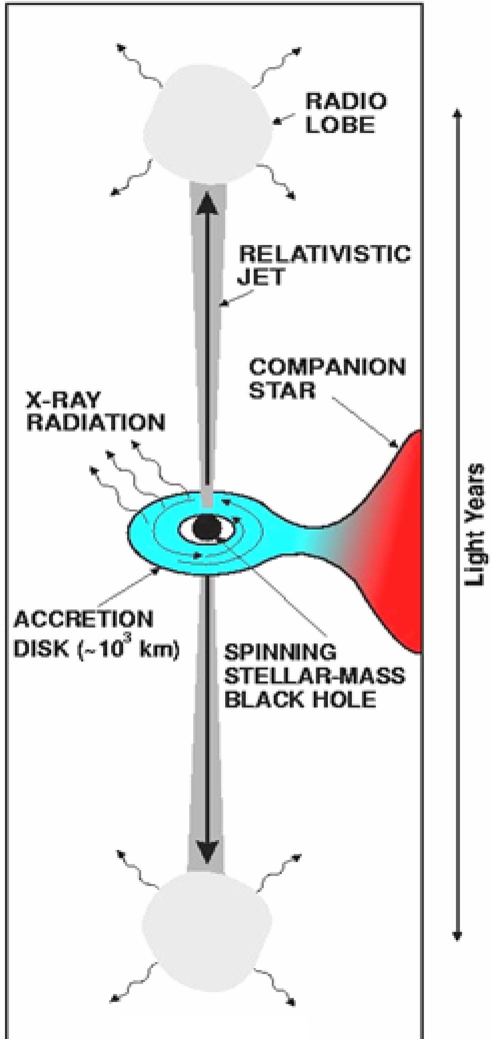
QUASAR-MICROQUASAR ANALOGY

QUASAR



10^6-10^9 $M_\odot$

MICROQUASAR



$10\ M_\odot$

M. & L.F. Rodriguez; Nature 1992, 94, 98

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

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

The maximum color temperature of the accretion disk is:

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

(Shakura & Sunyaev, 1976)

For a given accretion rate:

$L_{Bol} \propto M_{BH}$; $l_{jet} \propto M_{BH}$;

$\varphi \propto M_{BH}^{-1}$; $B \propto M_{BH}^{-1/2}$

(Sams, Eckart, Sunyaev, 96; Rees 04)

Length scale better for spatial measurements with quasars

From Mirabel: Hong Kong 2003

Parameter	All	Balmer	He I	He II (adopted)
P_{orb} (days)	3.90603 ± 0.00017	3.90603 (fixed)	3.90603 (fixed)	3.90603 (fixed)
T_0 (HJD−2 451 000)	943.09 ± 0.10	943.09 (fixed)	943.09 (fixed)	943.09 (fixed)
e	0.31 ± 0.04	0.34 ± 0.04	0.24 ± 0.06	0.35 ± 0.04
w (°)	226 ± 8	226.7 ± 3.3	228.0 ± 4.2	225.8 ± 3.3
γ (km s^{-1})	8.1 ± 0.5	9.2 ± 0.8	12.9 ± 0.8	17.2 ± 0.7
K_1 (km s^{-1})	19.4 ± 0.9	30.4 ± 1.6	21.1 ± 1.3	25.2 ± 1.4
$a_1 \sin i$ ($R_\odot$)	1.42 ± 0.07	2.20 ± 0.12	1.58 ± 0.10	1.82 ± 0.10
$f(M)$ ($M_\odot$)	0.0025 ± 0.0004	0.0094 ± 0.0015	0.0035 ± 0.0007	0.0053 ± 0.0009
rms of fit (km s^{-1})	6.8	11.2	11.5	9.1

Compact Object as Black Hole: Casares et al

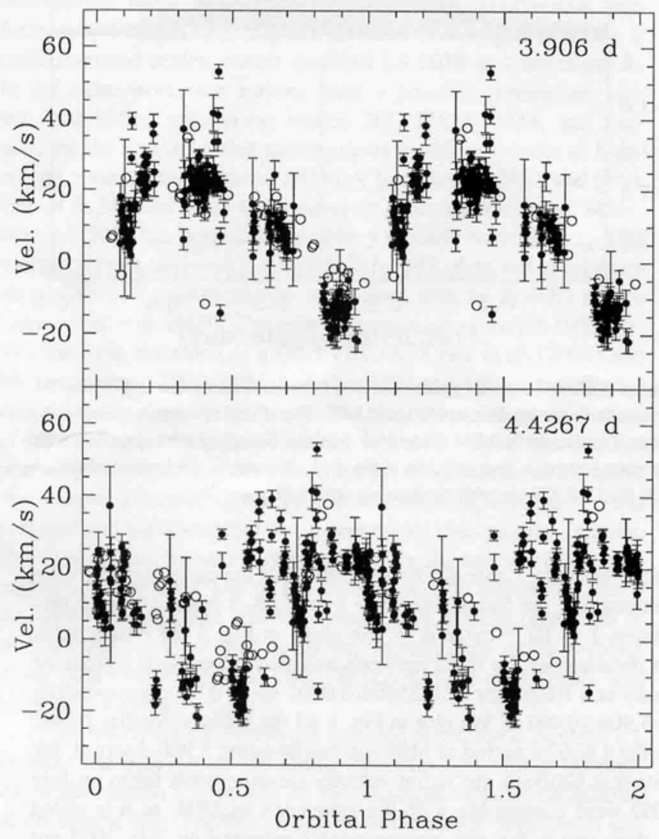


Figure 4. INT (filled circles) and McSwain's (open circles) velocities folded on the 3.906 d and 4.4267 d periods using T_0=HJD 2 451 943.09. Two orbital cycles are shown for better display. As can be seen, the new data rule out the M04 period.

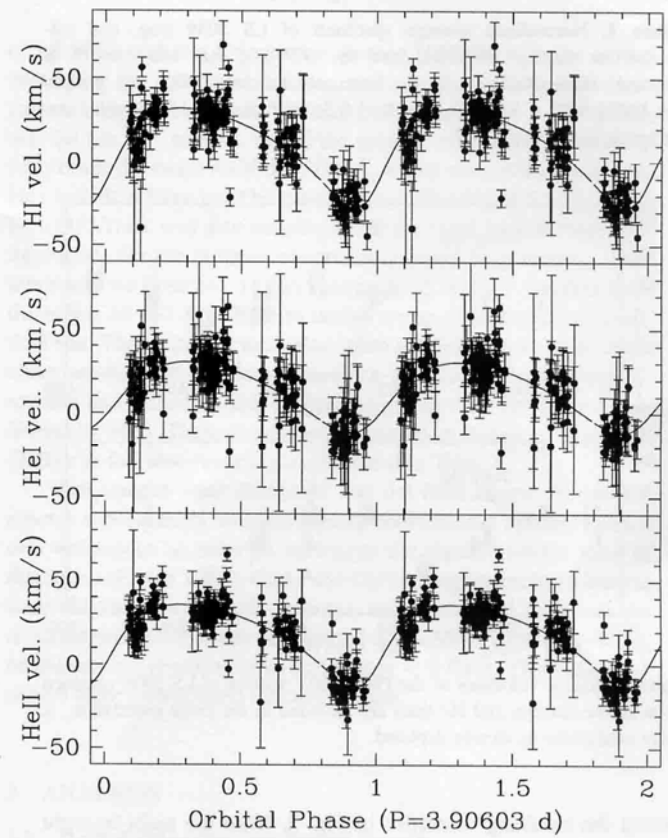


Figure 5. INT velocities folded on the 3.90603 d period with T_0=HJD 2 451 943.09. The radial velocities have been obtained through cross-correlating all Balmer (top), He I (middle) and He II lines (bottom). We superimpose the best eccentric orbital fits, the parameters of which are quoted in Table 2.

Use rotational broadening of optical lines to get rotation velocity

Doppler shift of centroids show motion relative to CoM

Eccentricity shown in non-sinusoidal phase

Compact Object Mass Estimate

Assumes Moon-like synchronicity of orbits

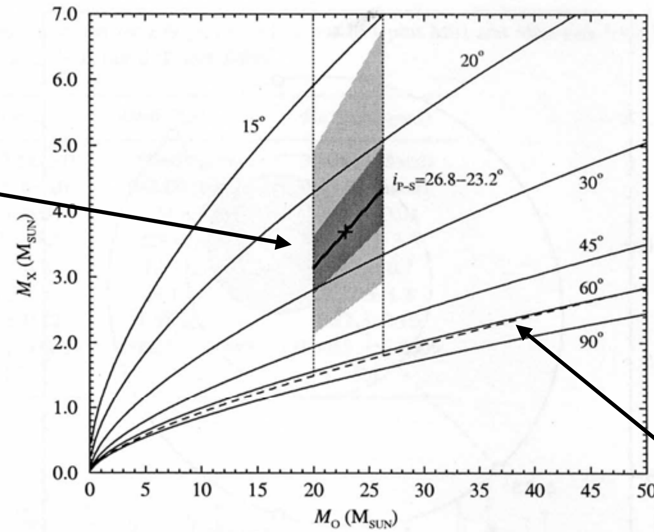


Figure 7. Mass constraints for the two stars in LS 5039 derived from our orbital solution. The thin solid lines have been calculated by using our adopted mass function, $f(M) = 0.0053\ M_\odot$, and the quoted inclination angles. The dashed line indicates the lower limit of M_X from the absence of X-ray eclipses. The dotted lines enclose the area of valid solutions for the interval of likely values of M_O. The thicker line represents the valid solutions by assuming pseudo-synchronization, while the dark-grey region represents all their possible 1σ errors, and the light-grey region their 3σ errors. The cross indicates the case of $M_O = 22.9\ M_\odot$, which implies $i_{P-S} = 24.9°$ and $M_X = 3.7\ M_\odot$.

Limit from mass function and inclination only

[1] The original Wilson & Devinney code has suffered major upgrades since its first release, including significant improvements in the underlying physical models. The most recent version of the code together with the relevant documentation can be found in ftp://astro.ufl.edu/pub/wilson/lcdc2003.

$$f(M) = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2}$$

HESS Variability?

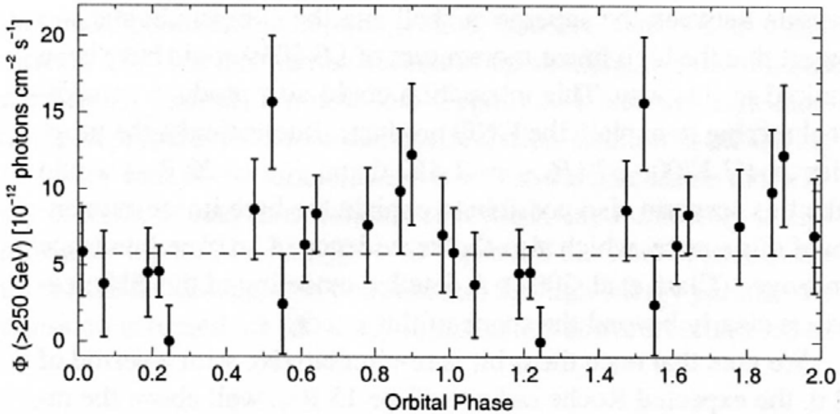


Figure 8. Very high energy gamma-ray fluxes of HESS J1826−148, the proposed TeV counterpart of LS 5039, folded with our orbital ephemeris ($P_{\rm orb}$ = 3.90603 d period with T_0=HJD 2 451 943.09). The dashed line represents the weighted mean of all data points. Despite the large error bars, there seems to be peak around phase 0.9 and a minimum around phase 0.3., a behaviour similar to the one found in X-rays.

Re-plot HESS times against new orbit period:
hint of regularity??

Blazar-like jet emission ?

G.Dubus

- **jet is natural interpretation for resolved radio.**
- **black hole ⇔ low inclination ⇔ microblazar**
- ***But*:**
  - **No resolved motion, low bulk Lorentz factor**
  - **Radio and X-ray properties ≠ known microquasars**
  - **Low variability in radio-X-γ ?**
  - **Low luminosity ?**

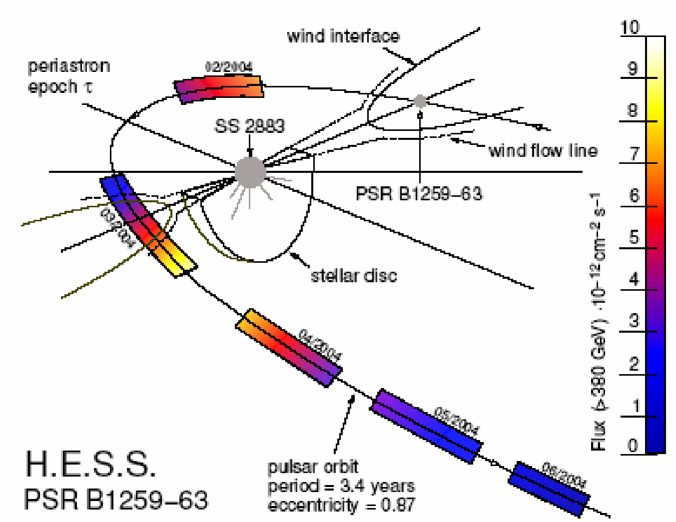
Does a ms pulsar provide a (better) alternative ?

e.g. PSR B1259-63

G.Dubus

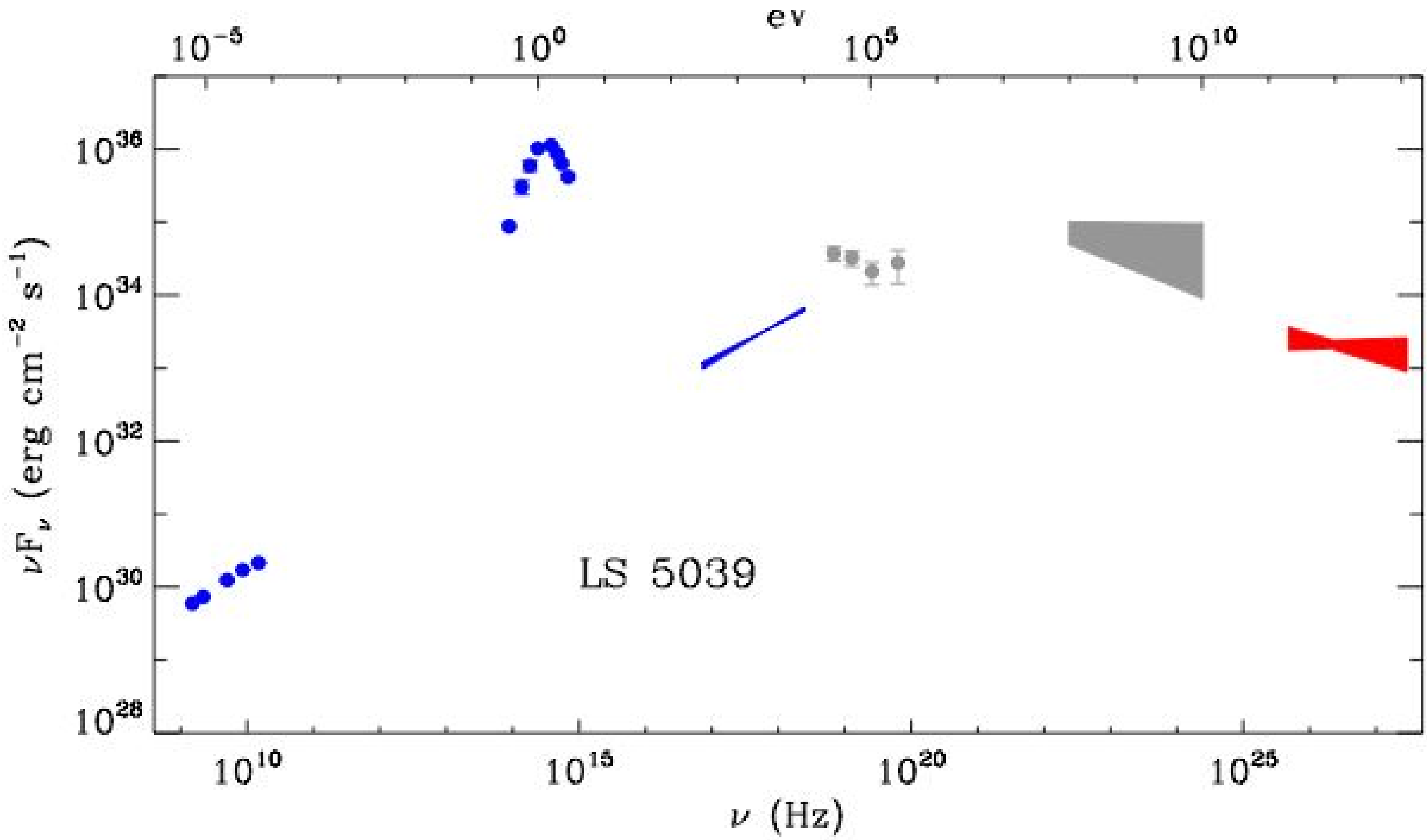
- ms pulsar in 3.5 yr orbit around Be star
- Pulsar spindown power 5 10^{36} erg/s
- Containment of pulsar wind by stellar wind: shock acceleration, VHE emission.

H.E.S.S. detection at periastron in 2004



LS 5039 spectrum similar to that of millisecond PSR B1259-63

G.Dubus



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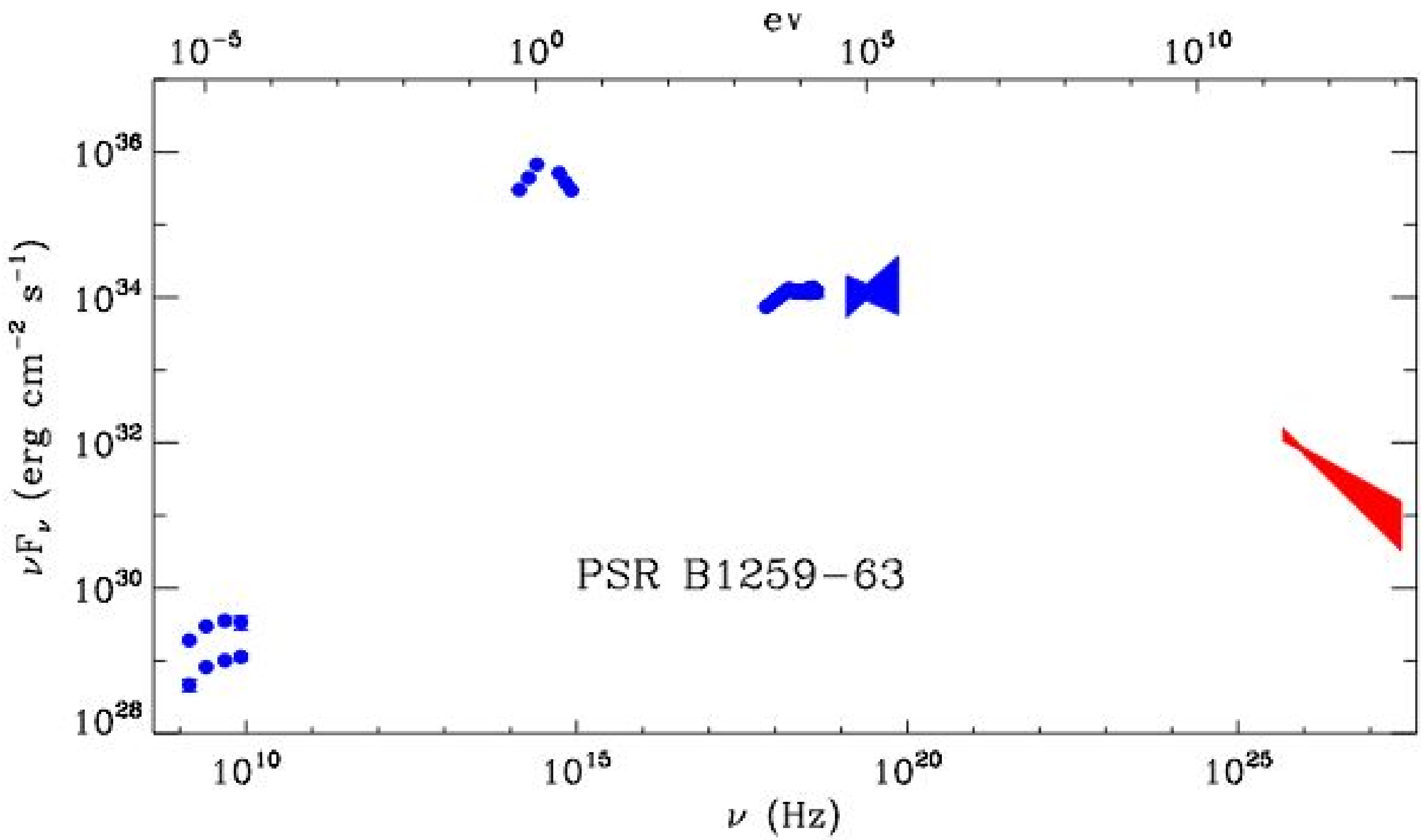
G.Dubus



Pulsar bow shock emission ?

G.Dubus

- Neutron star easily fits radial velocity
- Steady, low luminosity
- Similarity to PSR B1259-63 spectrum
- Radio pulse dispersed/absorbed in strong wind
- Radio jet = electrons advected in comet tail !

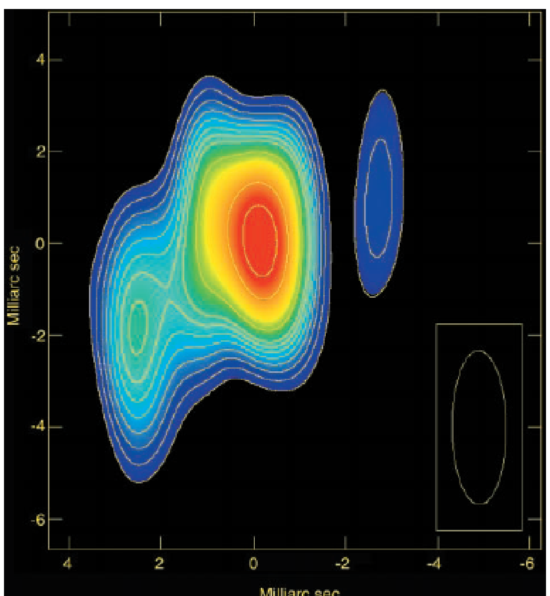
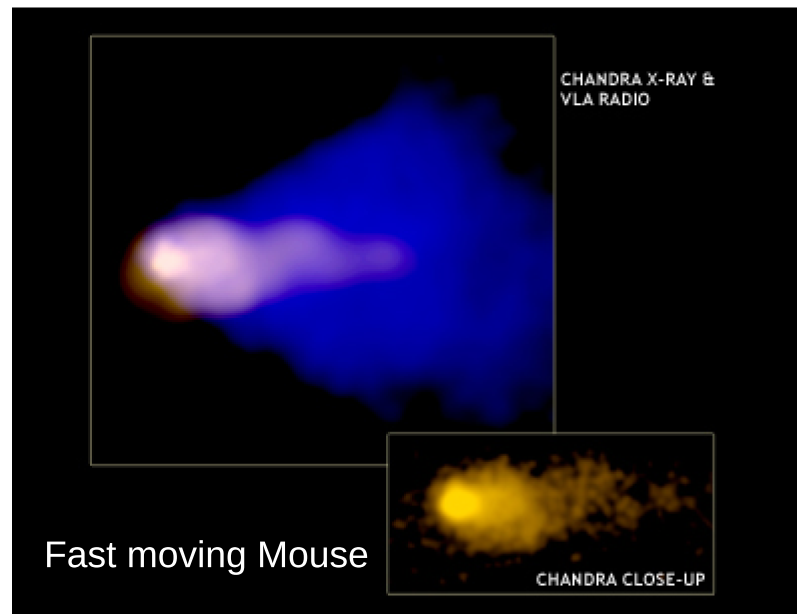


Fig. 1. High-resolution radio map of the nearby star LS 5039 obtained with the VLBA and the VLA in phased array mode at 6-cm wavelength. The presence of radio jets in this high-mass x-ray binary is the main evidence supporting its microquasar nature. The contours shown correspond to 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 40, and 50 times 0.085 mJy per beam, the rms noise. The ellipse at the bottom right corner represents the half-power beam width of the synthesized beam, 3.4 × 1.2 (milliarc sec^2) with a PA of 0°. The map is centered at the LS 5039 position α_{J2000} = 18^{h}26^{m}15.056^s and δ_{J2000} = −14°50′54.24″. North is at the top and east is at the left. One milliarc sec is equivalent to 4.5 × 10^{13} cm (3 AU) for a distance of 3 kpc.



Spectral fit

G.Dubus

- Take PSR B1259, put it in LS 5039.
- Wind parameters & orbit are constrained.
- Solve for stagnation point, MHD shock conditions and acceleration with $N_\gamma \sim \gamma^{-2}$.
- Calculate synchrotron and inverse Compton emission close to system.

High Energy Absorption:

$$\sigma(q) = \frac{3}{8}\sigma_T f(q)$$

- bounce them off star light – peaks around 1 eV
- $f(q)$ max at q_{max} = 0.05 → 1 eV absorbs 500 GeV gammas

$$q = \frac{m_e^2}{E_\varepsilon}\frac{2}{1-\cos\theta}$$

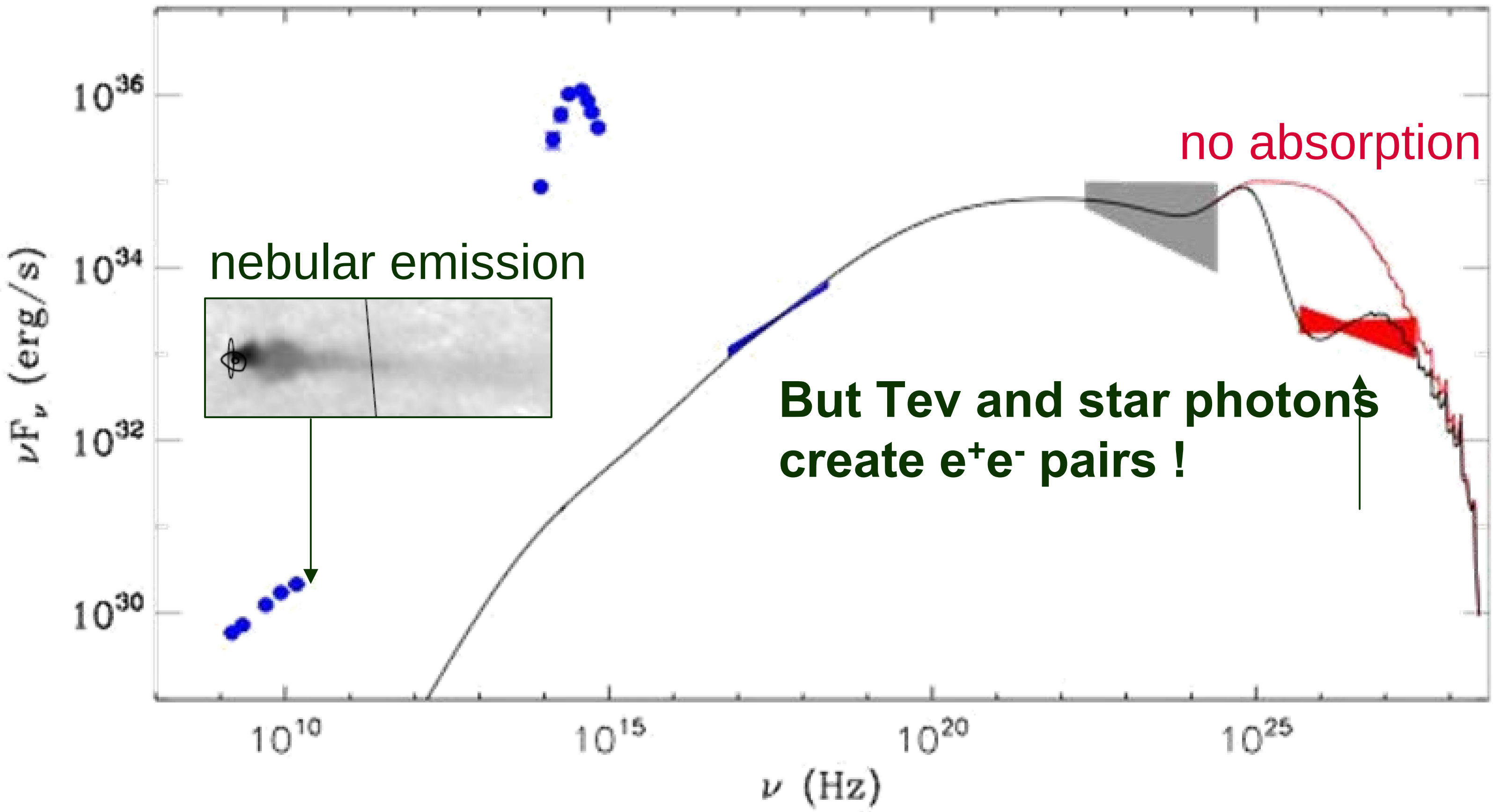
$$\tau_{\gamma\gamma} \approx \frac{\sigma_T}{4} n_* d \approx 25\,(d/0.1\,\mathrm{AU})$$

→ Angle dependence of absorption

Spectral fit

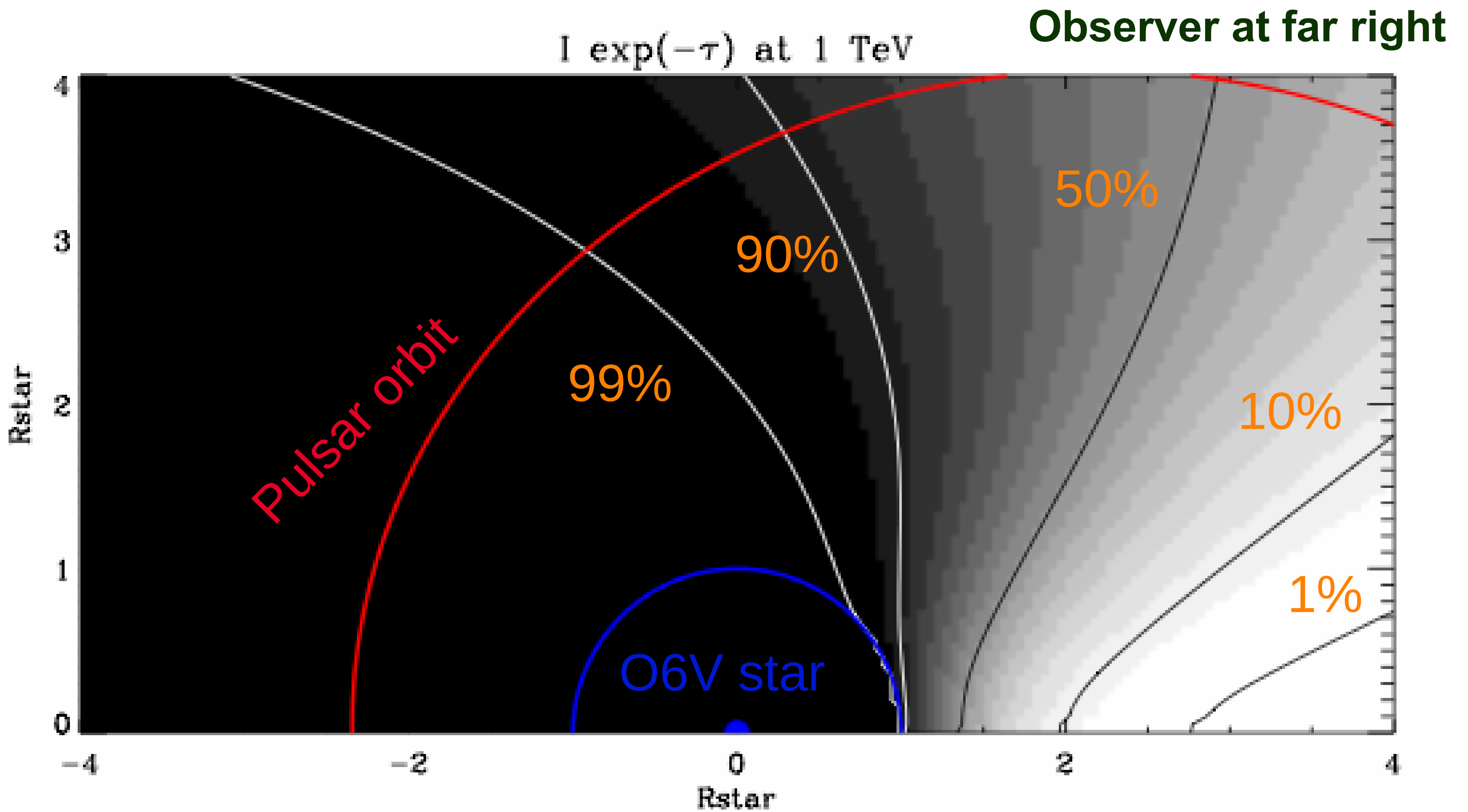
G.Dubus

Pulsar wind parameters:
10^{36} erg/s, $\gamma_w=10^6$ and $\sigma=0.001$



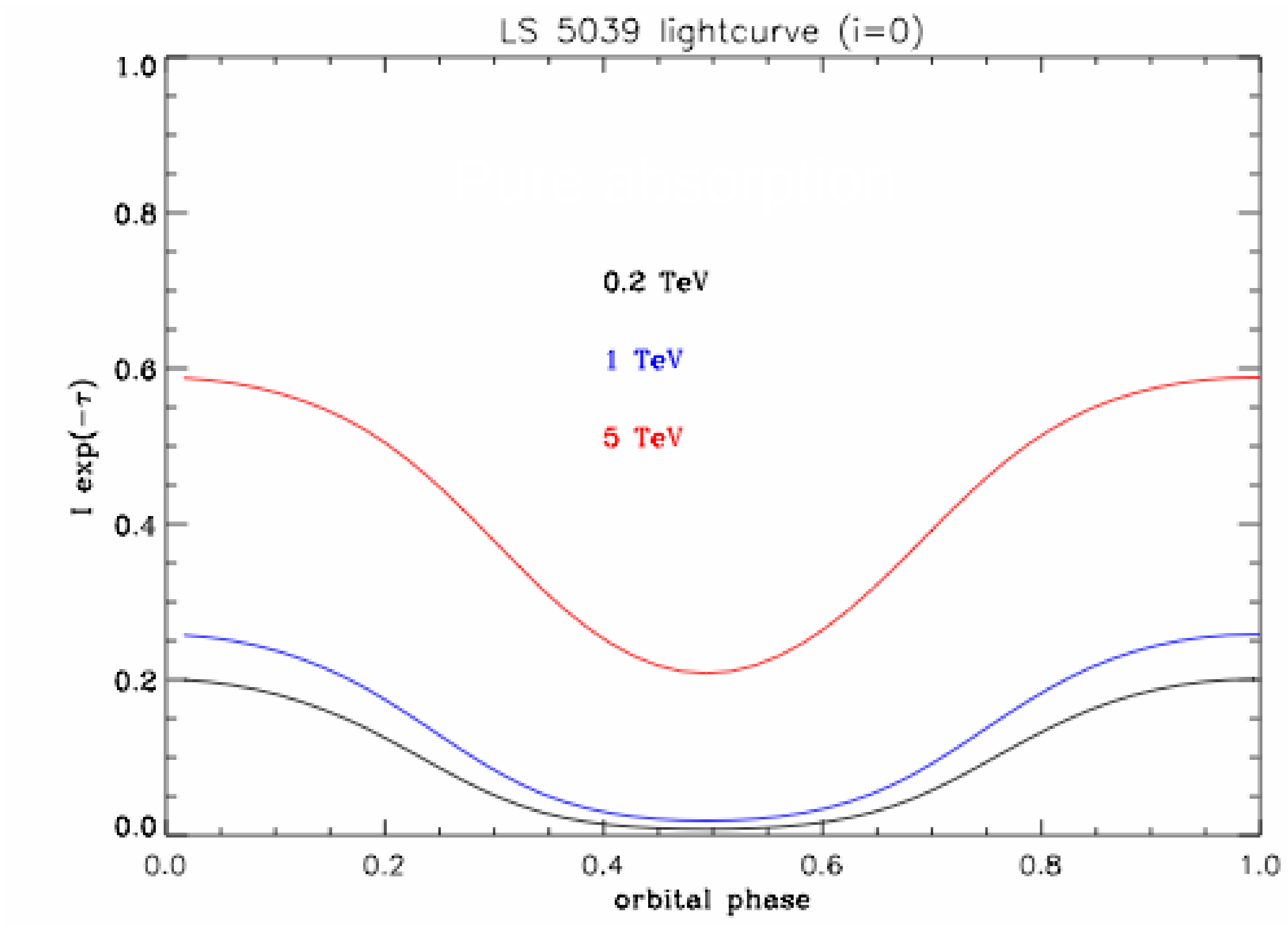
Fraction of absorbed 1 TeV flux

G.Dubus



Expect orbital variation

G.Dubus

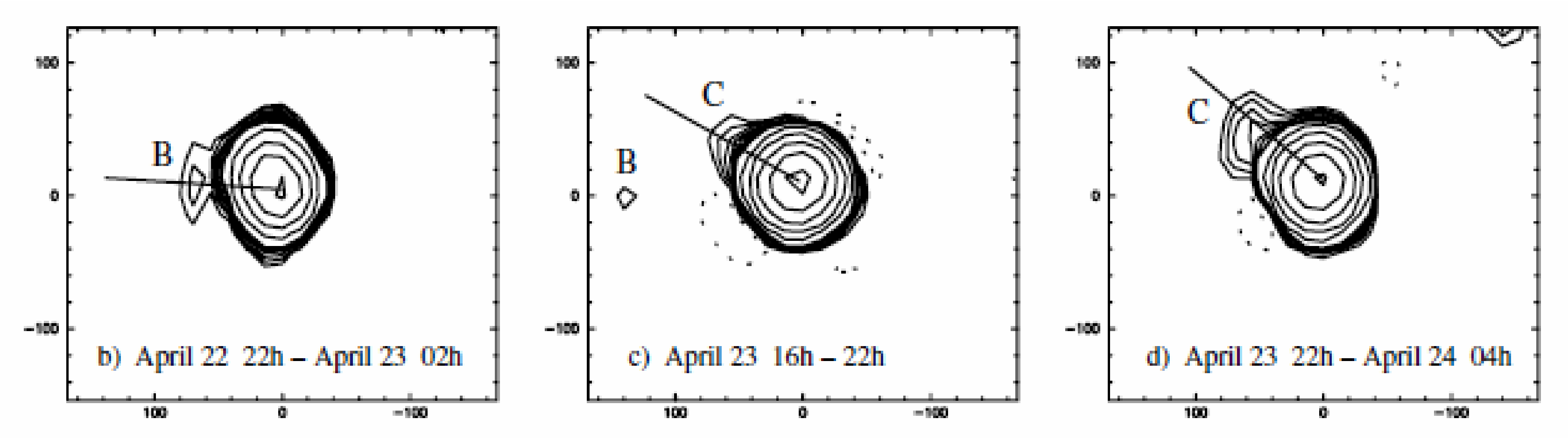


Dubus, in prep.

Some predictions

G.Dubus

- Orbital variability in gamma-rays.
- Pulsed gamma-rays ? (but cascade).
- One-sided radio outflow changes position angle with orbital phase.



LSI +61 303 (Massi et al. 2004)

Guillaume Rebuts BH

- He believes the radial velocities might be messed up by contamination of the lines
- If a pulsar, the system is much younger than the 1 MYr needed to synchronize (pulsar would have spun down)
  - Plus co-rotation is an assumption
- Perhaps backed up by CNO overabundance – still unmixed from SN?
- Otherwise consistent with NS masses
- He wonders if LS5039 is a "Crab with optical companion"

In a HESS Nutshell

- The binary system LS 5039, at a distance of about 3 kpc, was discovered by Motch et al. 1997, cross-correlating X-ray sources from the ROSAT catalog with OB star catalogues in order to locate systems made of a compact X-ray source orbiting a massive star. Using the VLA radio interferometer, Marti et al. 1998 identified LS 5039 as a nonthermal radio source, supporting the identification. New X-ray observations (Ribo et al. 1999) showed a hard spectrum, but neither pulsed nor periodic emission. Paredes et al. 2000 discovered that the system exhibits radio jets at the milliarcsecond scale; this was confirmed in Paredes et al. 2002. Clark et al. 2001 showed that the mass donor was a O6.5V(f) star. Using radial velocity measurements, McSwain et al. 2001, 2004 succeeded in determining the orbit period to 4.4 days, with an eccentricity of about 0.4. McSwain et al. 2002 suggest, on the basis of the modest X-ray flux, that the compact object accretes matter from the stellar wind of its companion, rather than by direct Roche-lobe overflow. McSwain et al. 004 favors a mass range for the compact object of 1-2 solar masses, a massive companion of 20 to 35 solar masses, and small inclination of the orbit relative to the line of sight. In a recent paper by Casares et al., the orbit period is revised to 3.9 days and based on atmosphere model fitting to the spectrum of the optical companion, a mass of the compact object of about 4 solar masses is estimated, which would point to a black hole rather than a neutron star. LS 5039 is moving with more than 100 km/s perpendicular to the Galactic plane, probably as a result of a recoil generated in the supernova explosion that generated the compact object (Ribo et al. 2002).

- The detection of LS 5039 in very high energy gamma rays by H.E.S.S. (Fig. 1, Fig. 2) provides clear evidence that microquasars are indeed capable of accelerating particles to multi-TeV energies. LS 5039 was initially discovered in the H.E.S.S. survey of the central region of the Galactic plane; follow-up observations were conducted to confirm the result. The photon spectrum is rather hard, with a spectral index of ~2.1 (Fig. 3). The detailed mechanisms how the gamma rays are generated are still under discussion. Possible scenarios include inverse-Compton scattering of photons from the companion star, from the accretion disk, or of synchrotron photons (e.g. Bosch-Ramon et al. 2005, Romero et al. 2003 and earlier references given there). However, the flux of photons from the companion star is so large, that gamma rays produced in the vicinity of the compact object are likely to be absorbed, resulting in production of electron-positron pairs (e.g. Bednarek 1997). If nucleons are accelerated, they ought to be able to carry their energy far enough away before interacting and generating gamma rays. A clue could come from an orbital modulation of the gamma-ray flux according to the 4 day orbital period; more data is being collected to probe the time dependence.

From "HESS Source of the Month"
http://www.mpi-hd.mpg.de/hfm/HESS/public/som/current.htm

Prospects for GLAST?

Perhaps we can see an orbital dependency? Guillaume shows some dependency still at 200 GeV