Microquasars and jets: their role in Astroparticle physics

S. Chaty
(University Paris 7 / CEA Saclay)

Vulcano Workshop 2006

Vulcano Island, 25th May 2006

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their (potential) role in Astroparticle physics

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Plan

- 0. Prelude to microquasars
- I. Discovery of microquasars
- II. Microquasars: HE physics laboratories
  - Accretion/ejection
  - Compact jets
  - Interaction between jets and surroundings
- III. Microquasars and astroparticle physics
  - VHE photons, CRs, ν

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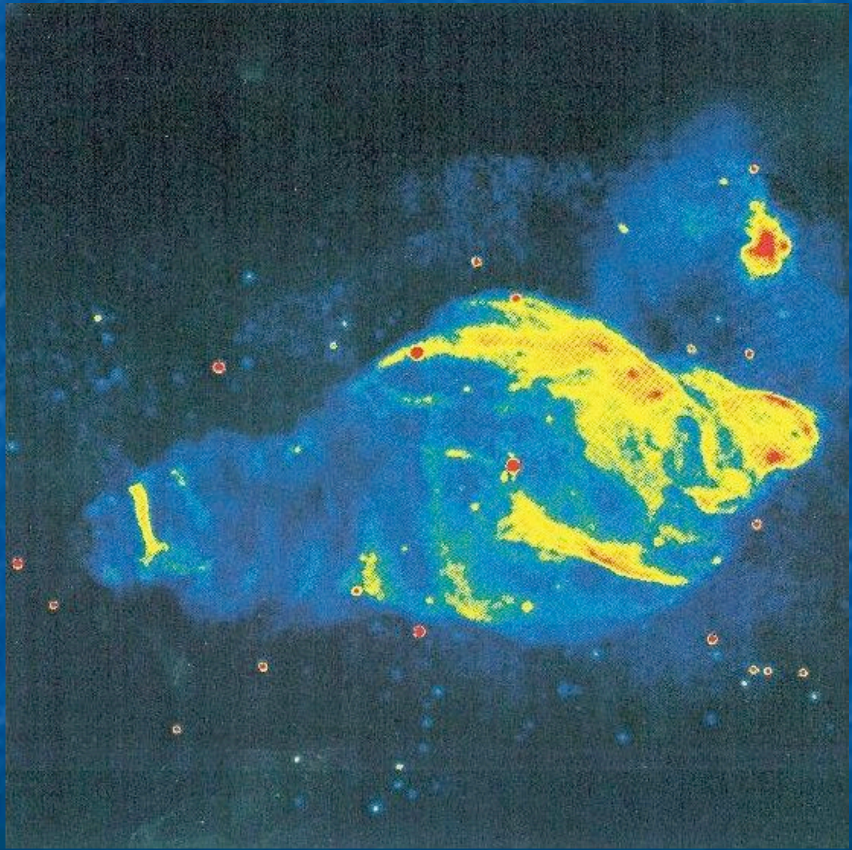
0. Prelude to microquasars: SS 433

- 1979: **Microquasar prototype**: SS 433, or how a galactic object ejects matter at 0.26c (Γ=1.04 Margon 1984)
- Observations of emission lines in optical: content of jets is baryonic
- Properties too special to be classified in a family



SS433 & W50: 2°x2° (Dubner et al., 1998)

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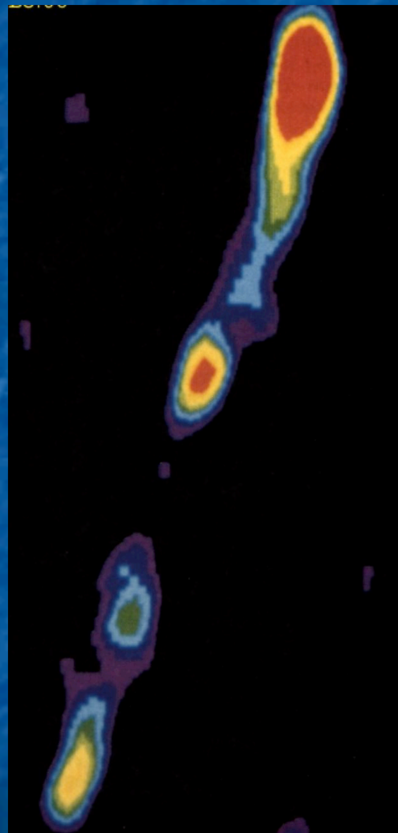
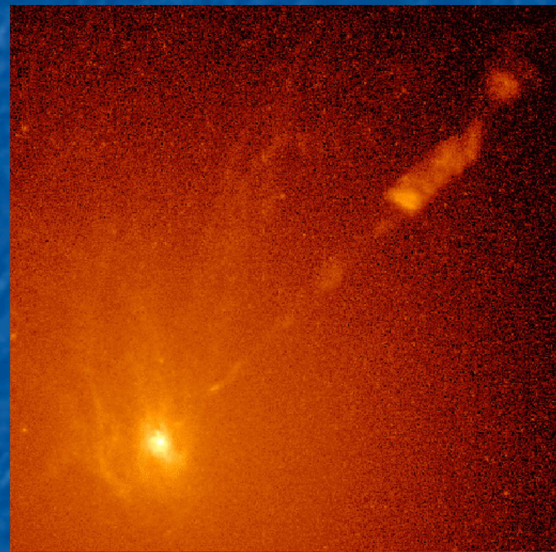
I. Discovery of microquasars: 1E 1740.7-2942

- 1990: SIGMA, orbiting on Granat, observes galactic black hole candidates
- 1992: **First microquasar**: 1E 1740.7-2942: bipolar radio jets spread over several light-years
- The great annihilator of the Galaxy
- Analogy with quasars



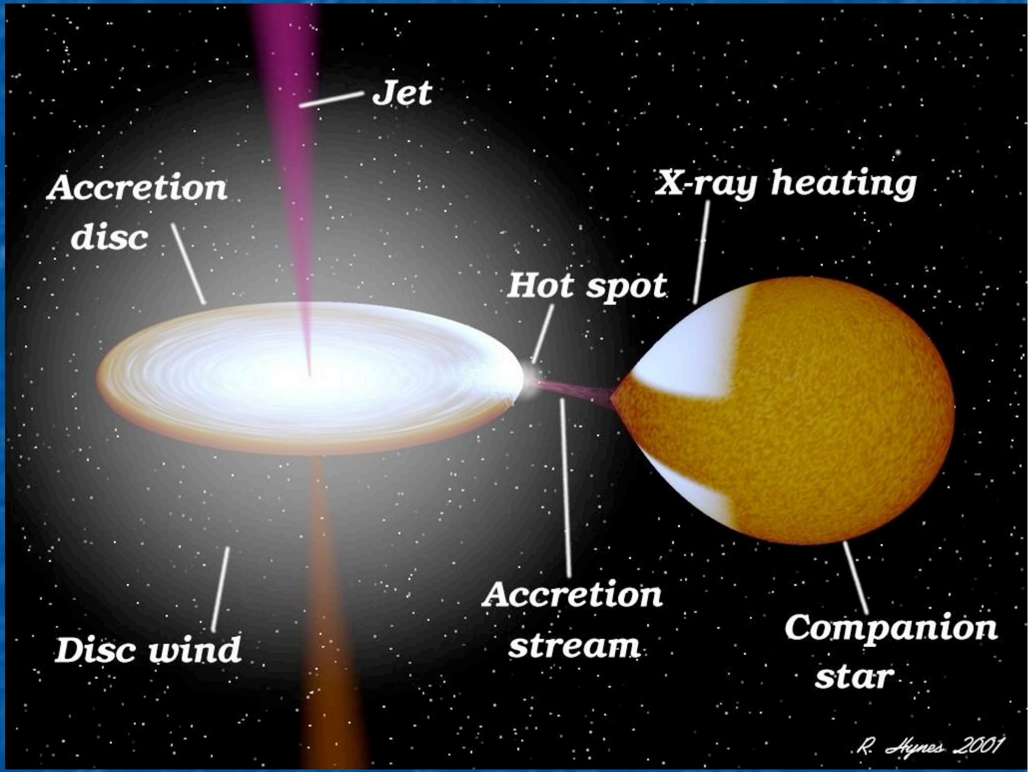
1E1740, 1′x1′: Mirabel et al. 1992



M87

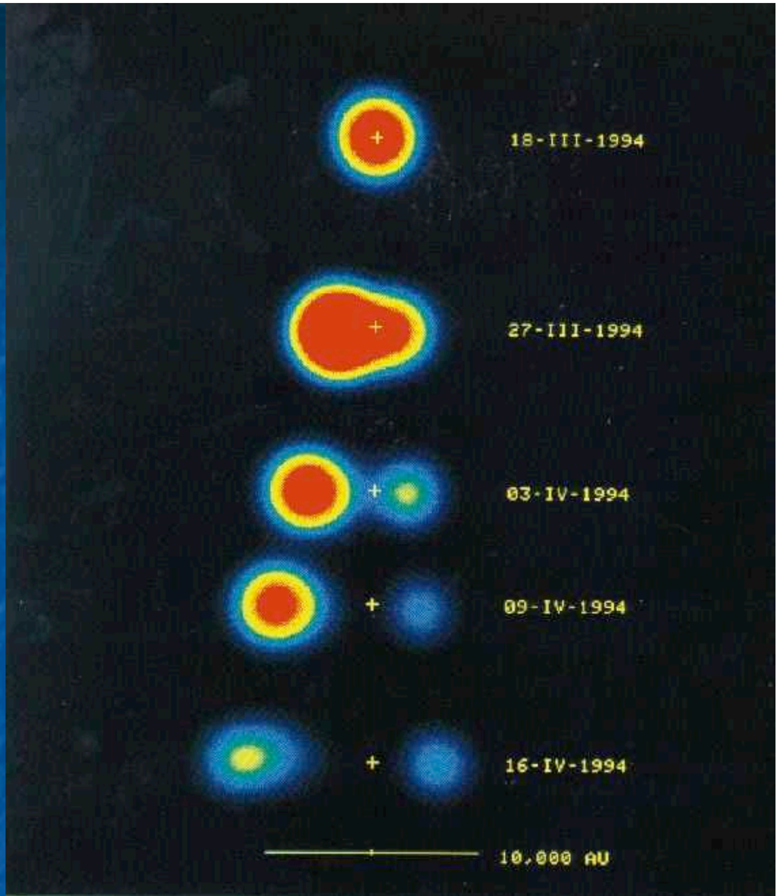
I. Discovery of microquasars: the scenario

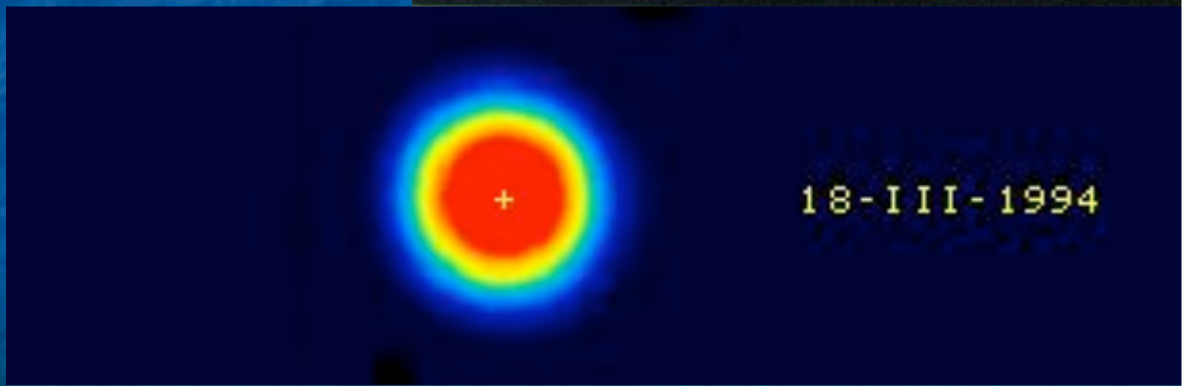
- Binary system of the Galaxy, black hole or neutron star, surrounded by an accretion disc, and a companion star
- Necessity of multi-wavelength observations to understand various components, at different scales of the system
- Now ~20 microquasars in our Galaxy



I. Discovery of microquasars: GRS 1915+105

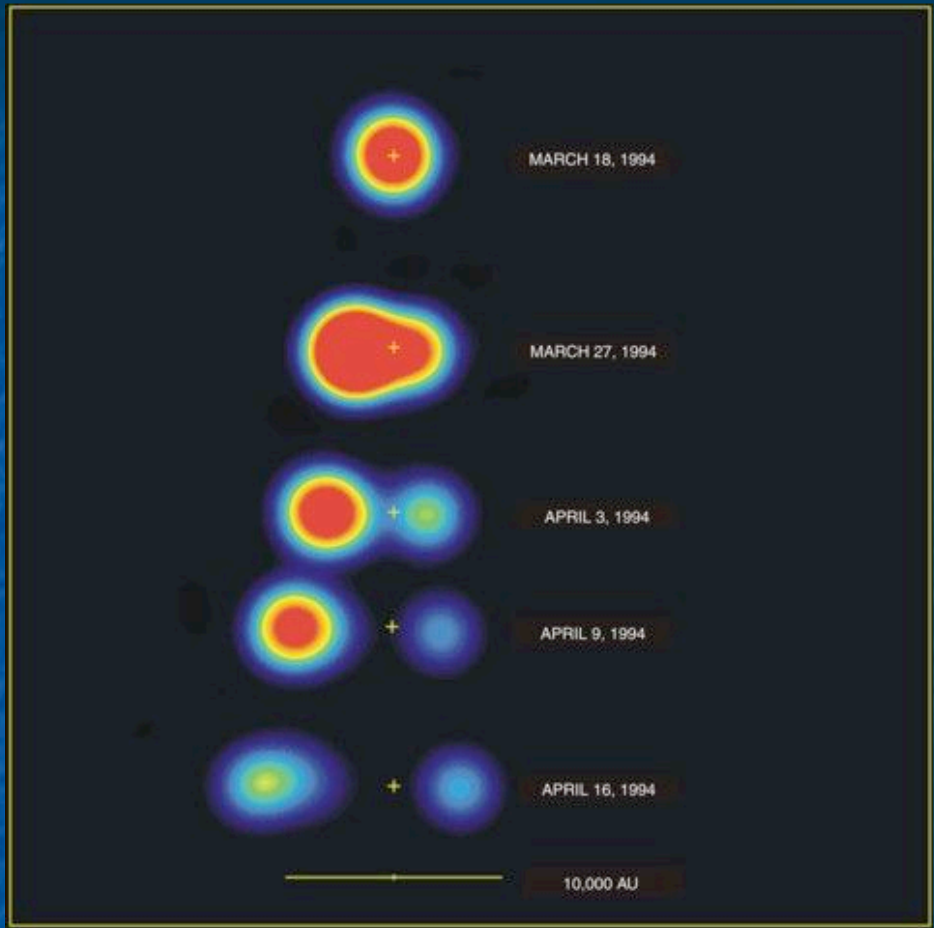
- 1992: Discovery of the black hole candidate GRS 1915+105, **archetype of microquasars**
- 1994: Observations of superluminal motion; frame velocity: v~0.92c
- Physical analogy: microquasars really become "micro"-quasars
- Only microblazars were still missing to the family…



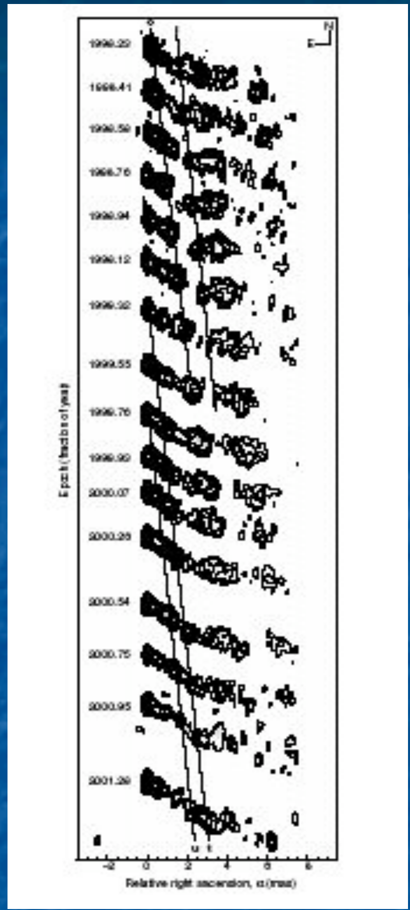


10 000 AU = 800 mas
Mirabel & Rodriguez 1994

I. Discovery of microquasars: analogy with quasars



GRS 1915+105 observed during 1 month
(Mirabel & Rodriguez 1994)

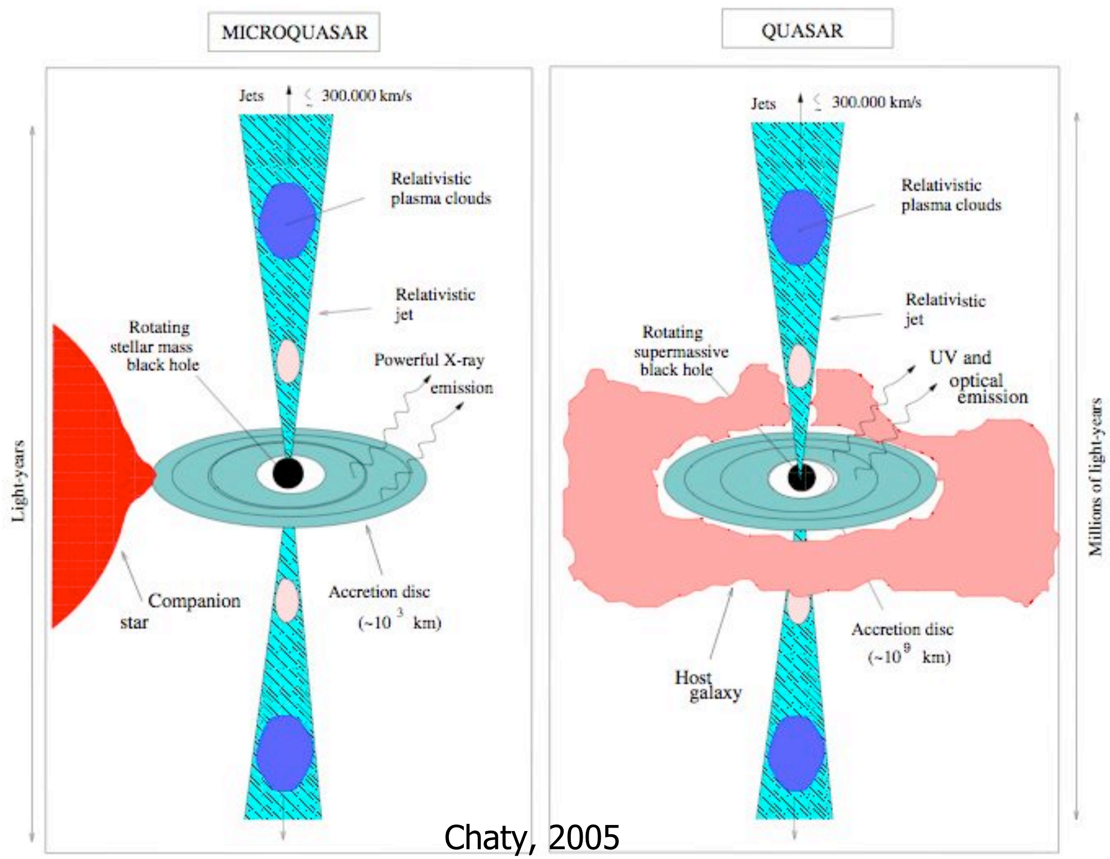


3C120 observed during 3 years
(Marscher et al. 2002)

- Move on the plane of the sky ~10^3 times faster
- same Lorentz factor as in Quasars : Γ ~ 5-10
- Advantage of AGN at <100 Mpc: collimation at 30-100 R_{Sch} (M87, *Junor et al. 1999)*

I. Discovery of microquasars: analogy with quasars

- In "microquasar" there is "micro" and "quasar"!
- Advantage microquasars:
  - Closer
  - Observation of both approaching and receding jets: allow to solve equations ⇒ max. distance
  - Accretion/Ejection timescale proportional to black hole mass: much shorter
- Advantage quasars:
  - active galaxies jet models applied to describe ejection in microquasars
- Fruitful analogy quasars/ microquasars



Chaty, 2005

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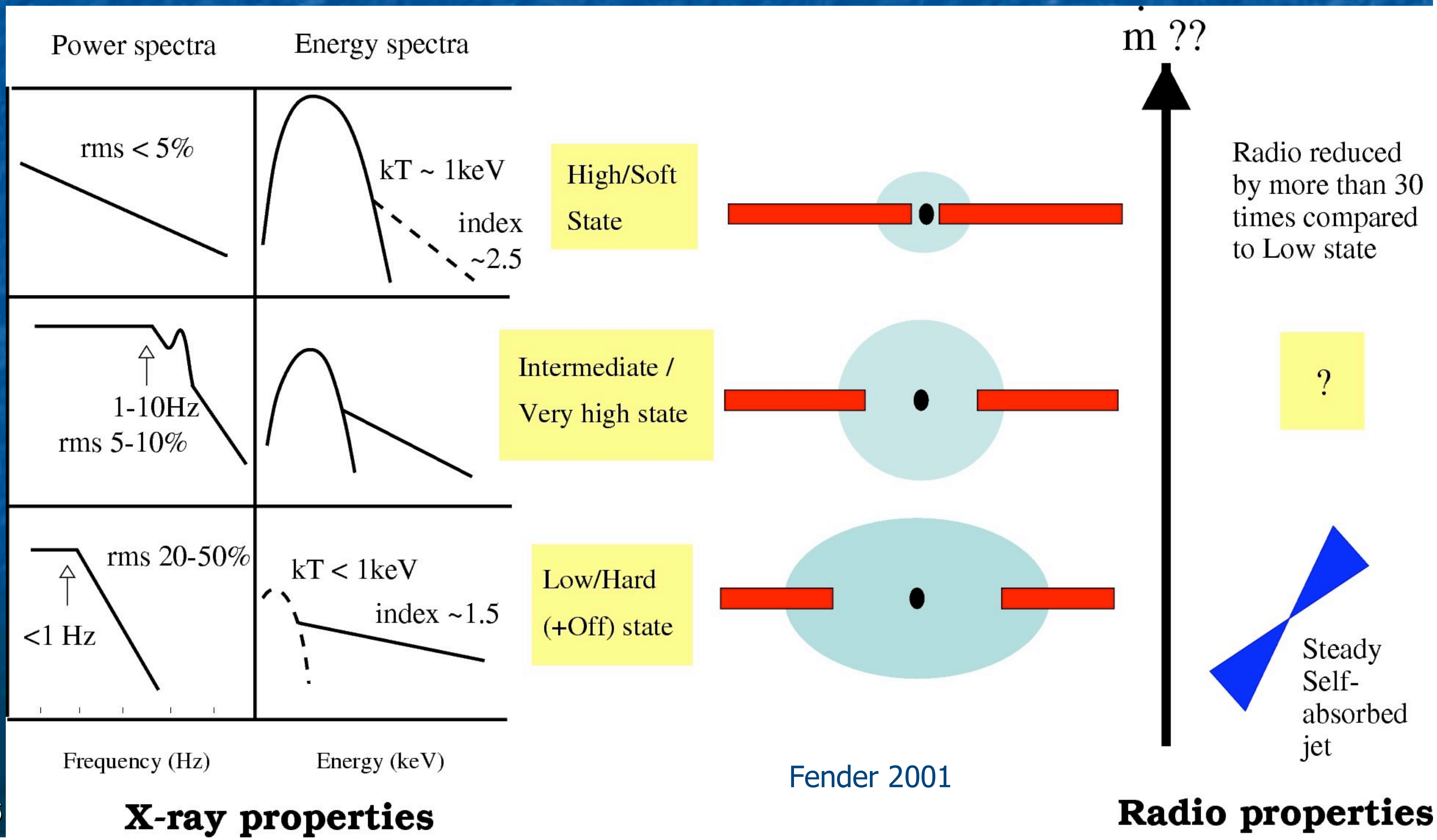
II. Microquasars: accretion/ejection

Black holes display different X-ray spectral states:

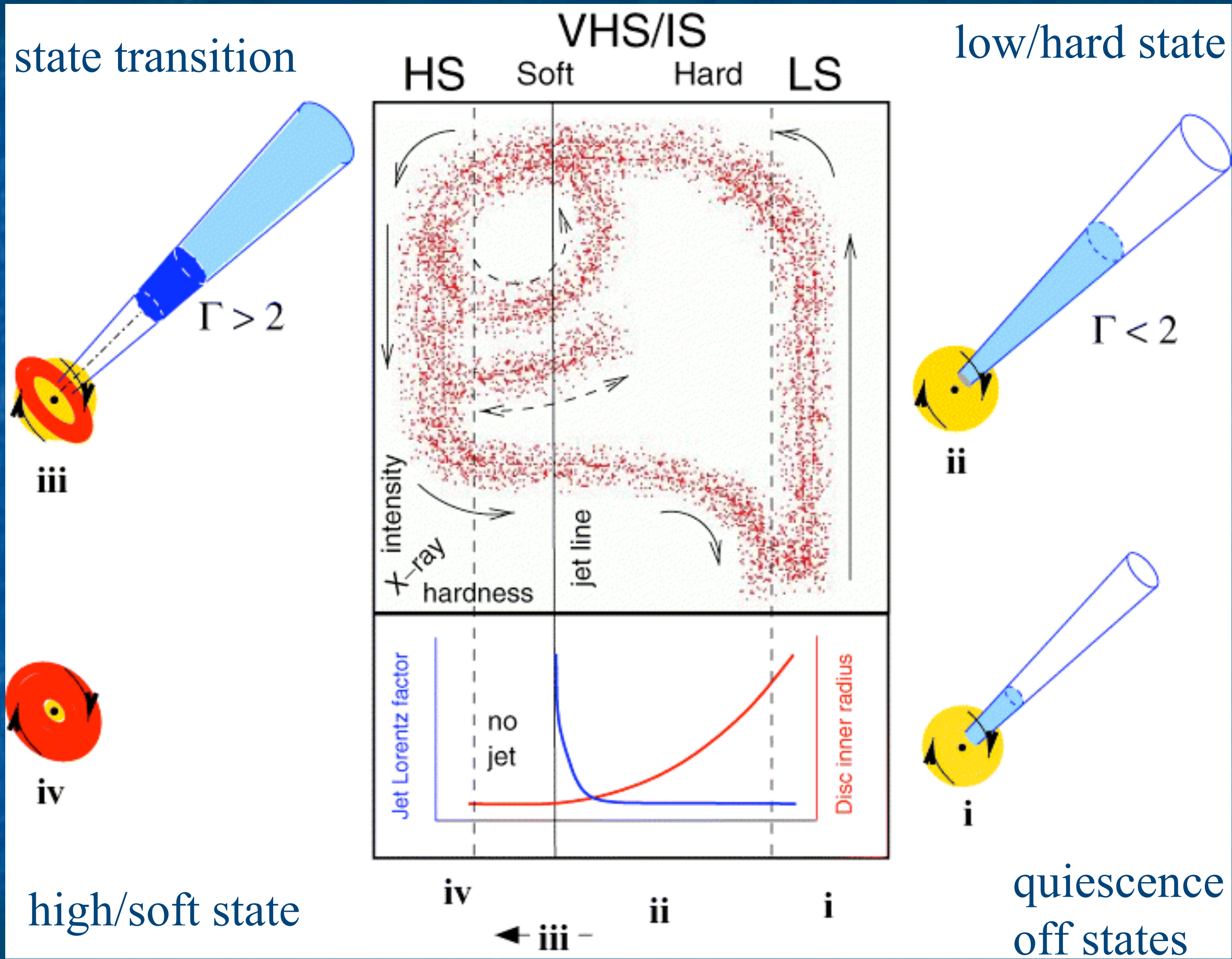
- **Low/hard** state (a.k.a. power-law state). **Compact radio jet**.
- **High/soft** state (a.k.a. thermal-dominant state). **No radio emission**.
- **Intermediate** and **very high** states → transitions. **Transient radio emission**.

- Standard model:
  - thermal emission of multicolour accretion disc + non-thermal emission of plasma corona
  - And jet synchrotron emission from radio to X?



Fender 2001

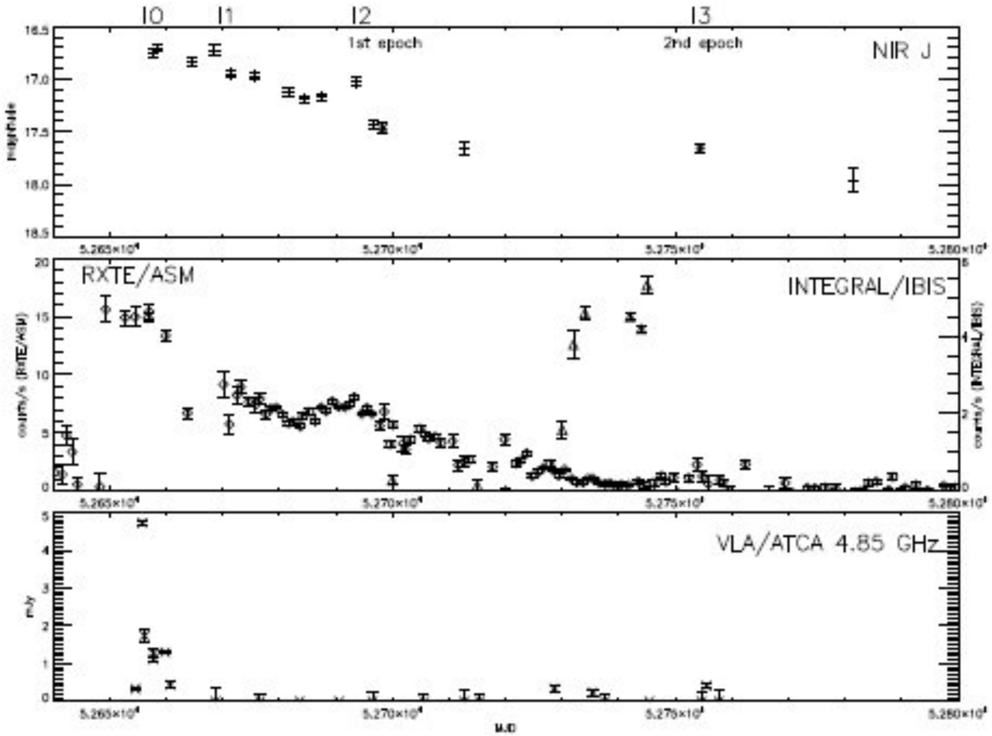
II. Microquasars: accretion/ejection

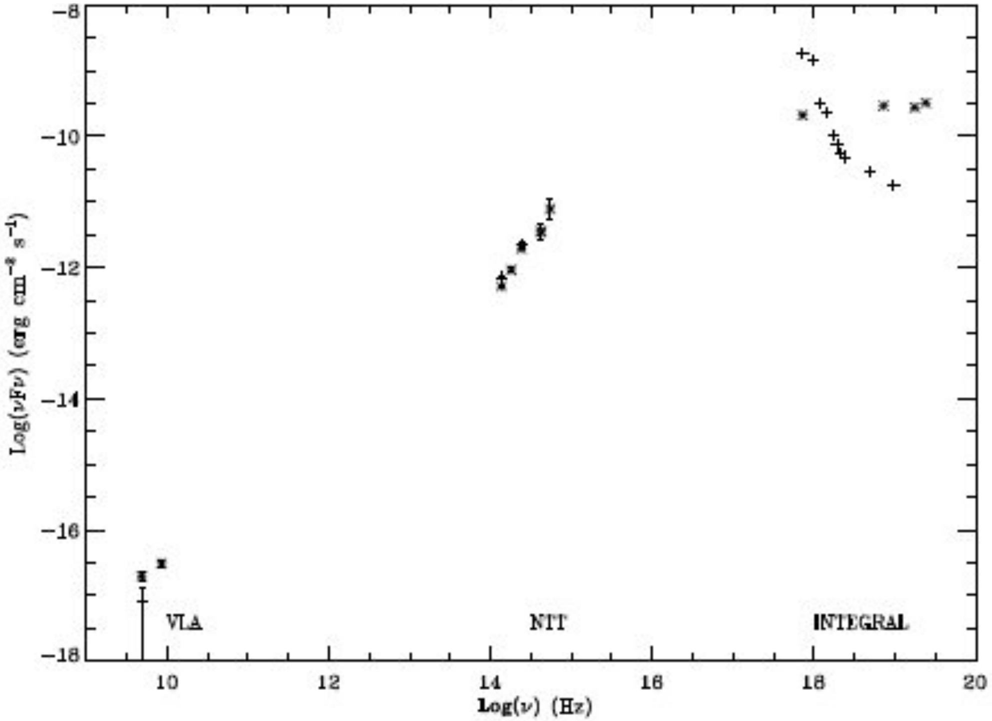


Fender, Belloni & Gallo (2004)

II. Microquasar XTE J1720-318: from high-soft to low-hard state

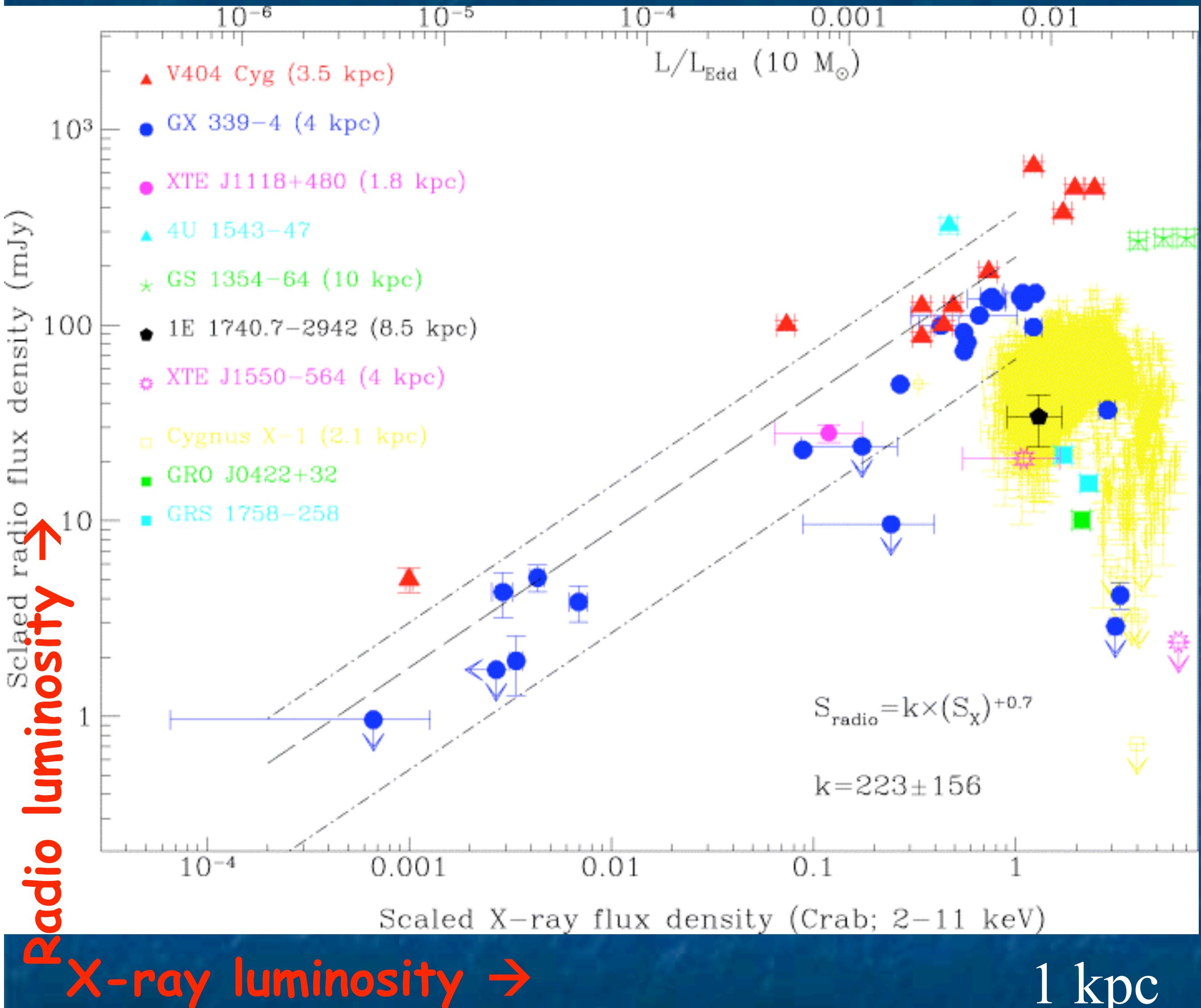
- ESO/NTT ToO Optical/NIR observations (February/April 2003)
  - Discovery of optical counterpart (R ~21.5), confirmation of NIR counterpart
  - XTE J1720-318: intermediate mass X-ray binary (Black Hole + late B -> early G main sequence star)
- Observations simultaneous with the 3rd secondary X-ray/NIR outburst.
- SED evolution: transition from a high-soft to a low-hard state.





Chaty & Bessolaz, A&A in press

II. Microquasars: accretion-ejection

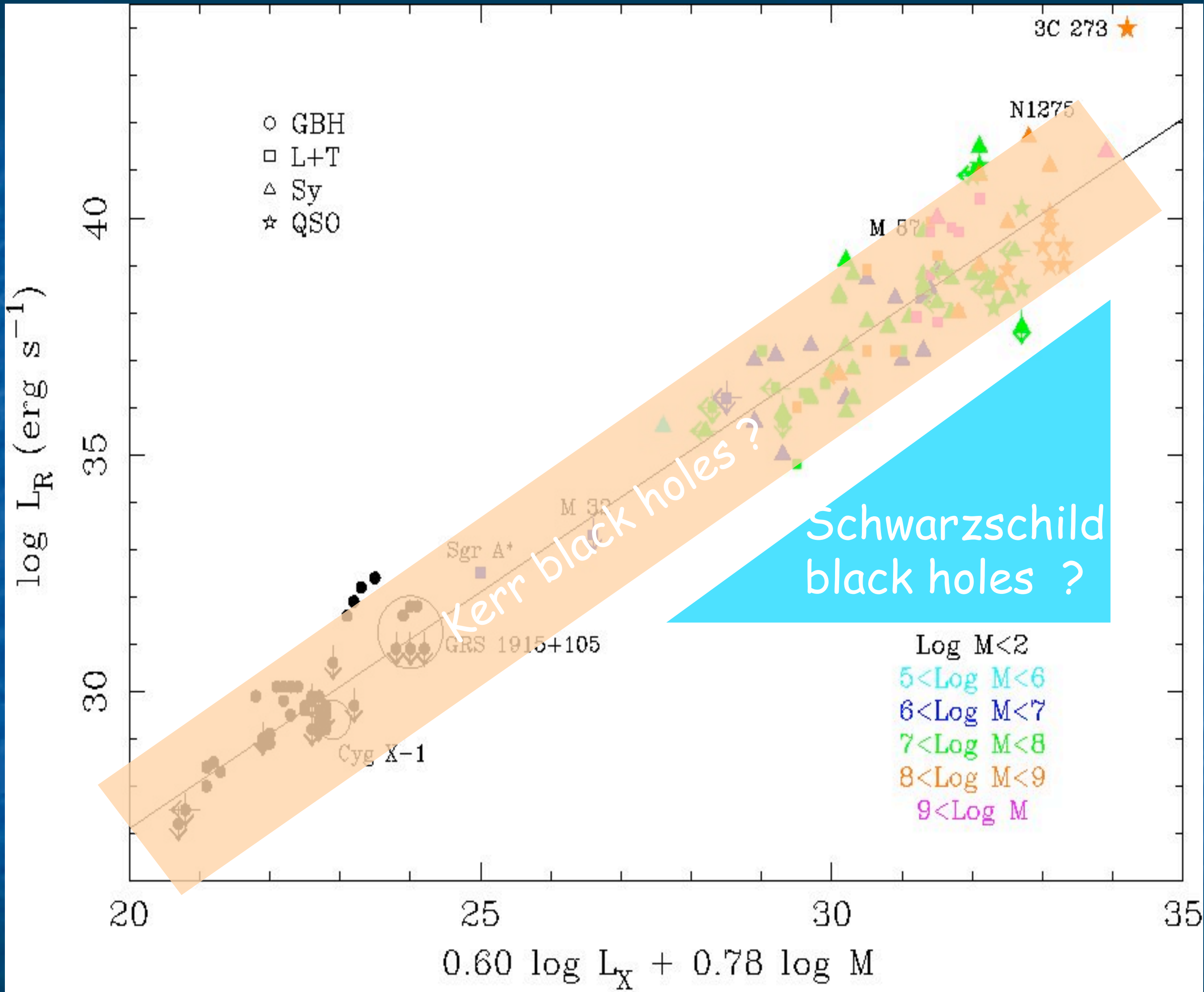


Gallo, Fender, Pooley (2003)

Coupling: $F_{rad} \propto F_X^{+0.7}$

- Universal law for black holes in low/hard state
- Understanding of accretion/ejection models.
- Small scattering of the correlation (no strong Doppler amplification)=>
  - If X-rays not beamed:
  - Lorentz factors of compact radio jets $\Gamma<2$
  - low velocity jet $\beta<0.8c$
- Coupling at higher energy???

Extending the L_R:L_X correlation to AGN - add a mass term?



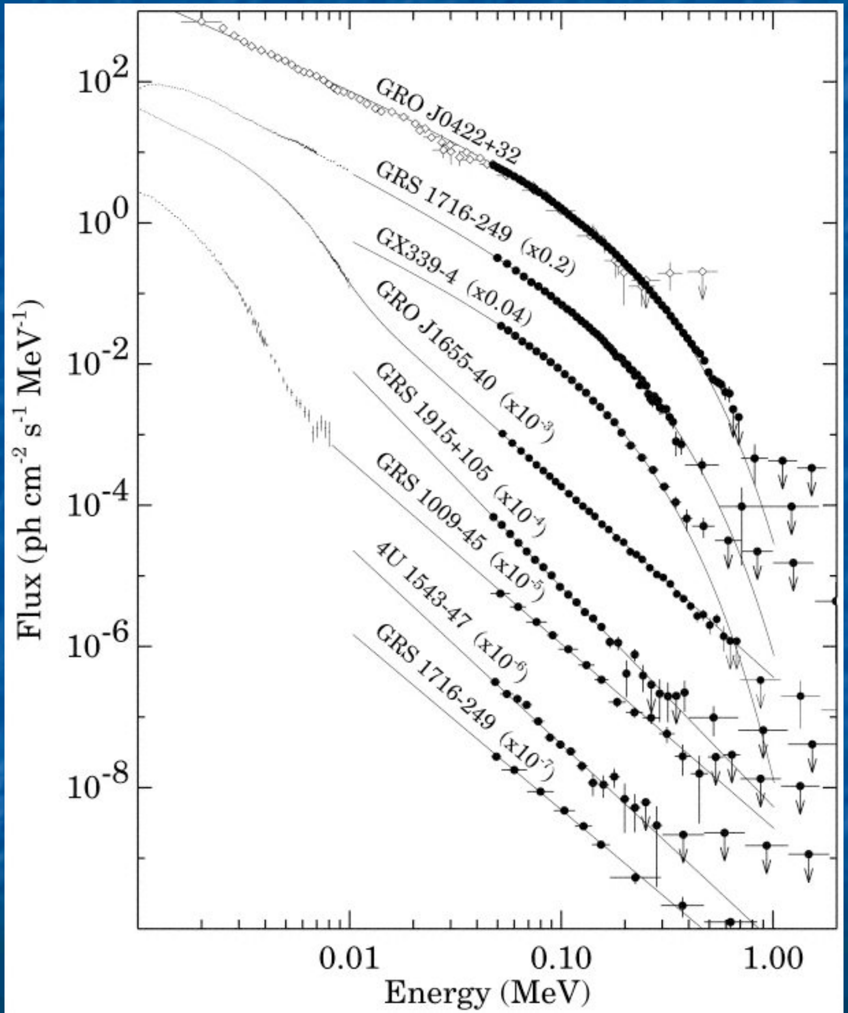
Merloni, Heinz & di Matteo (2003); Falcke, Körding & Markoff (2004)

II. Microquasars: accretion-ejection

- Some microquasars emit at high energy, emission dominated by power law (spectral index 2.5-3), no cut-off.
- What is the underlying physical process: comptonization or synchrotron?
  - => need polarization…

<u>High-energy observations:</u>

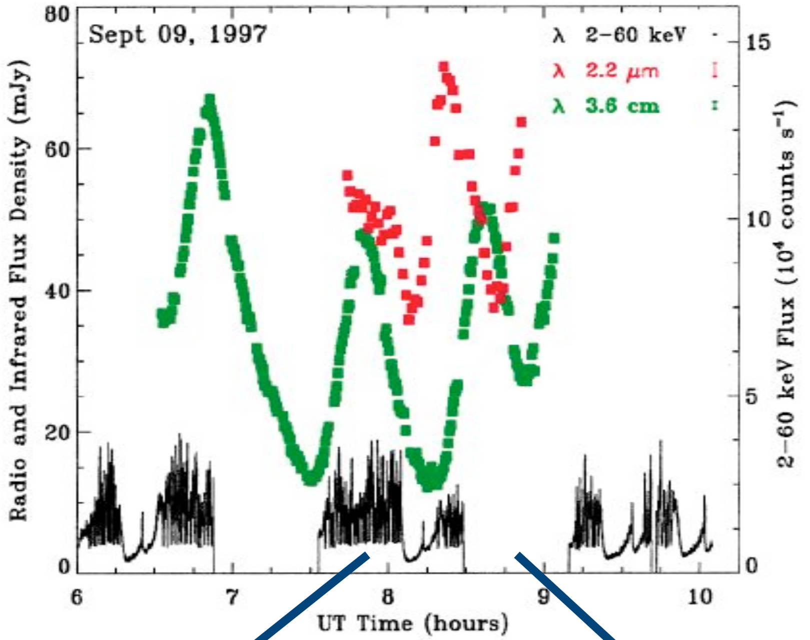
- Constraints on accretion-ejection models: Blandford-Payne, Blandford-Znajek, MRI…
- Jets made of e^-/e^+ or e^-/p?
- Answer with detection of (Doppler) shifted or annihilation emission lines?

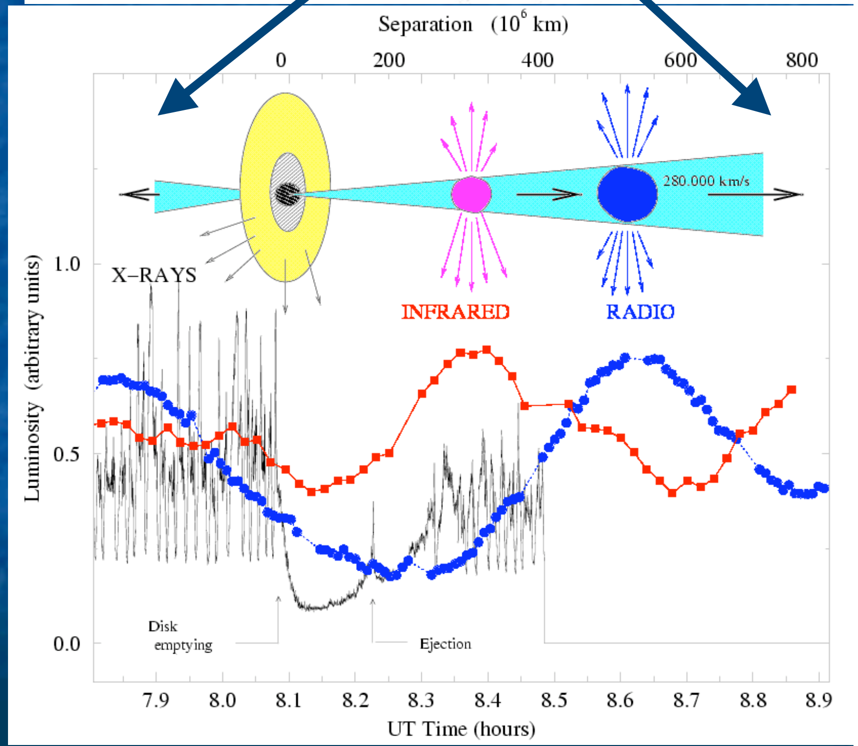


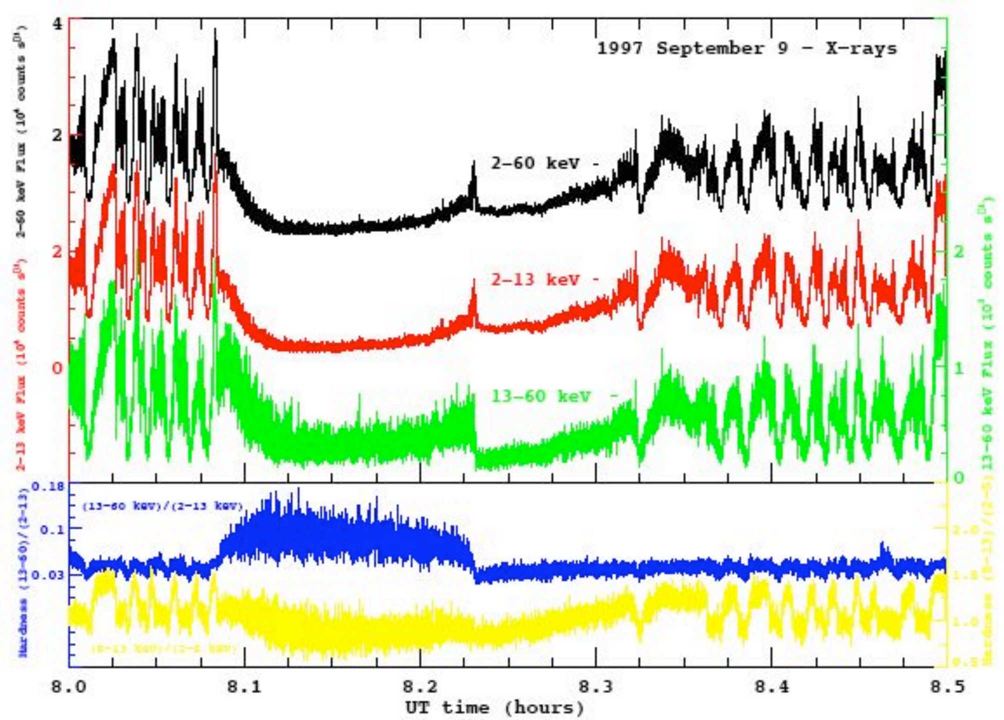
Grove et al. 1998

II. Microquasar GRS 1915+105

- 1997: First observations of link between accretion-ejection in GRS 1915+105
- Disappearance/refilling of internal part of accretion disc, followed by ejection of relativistic plasma clouds
- Transient ejections during state changes
- Recurrent ~30-45mn cycle



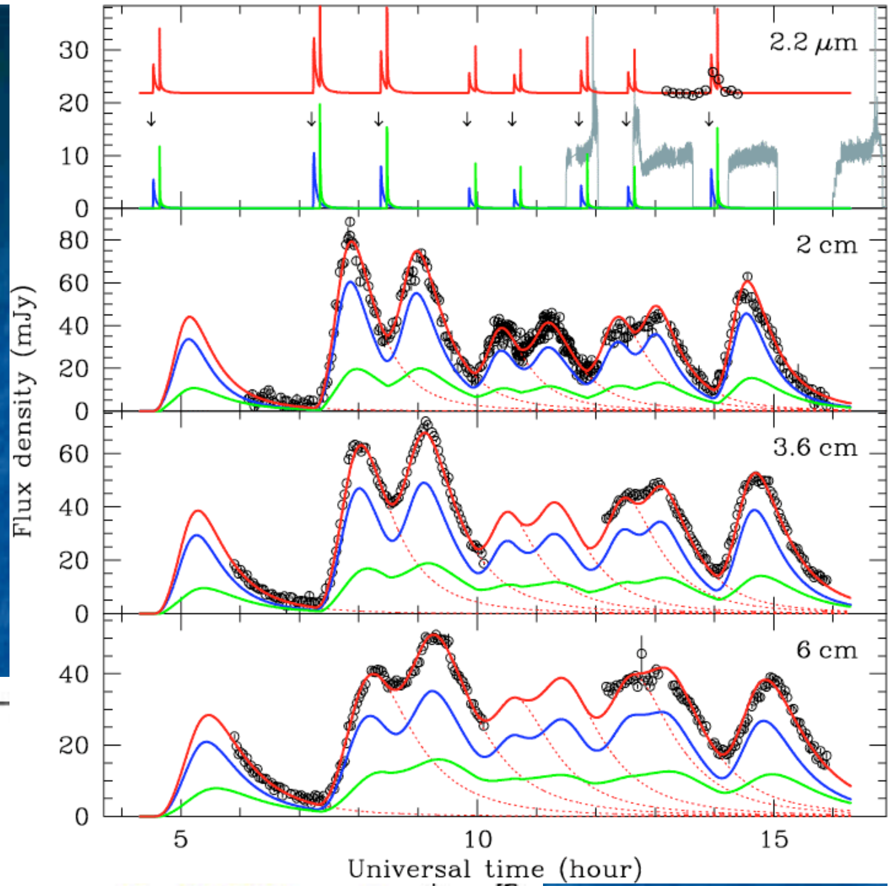




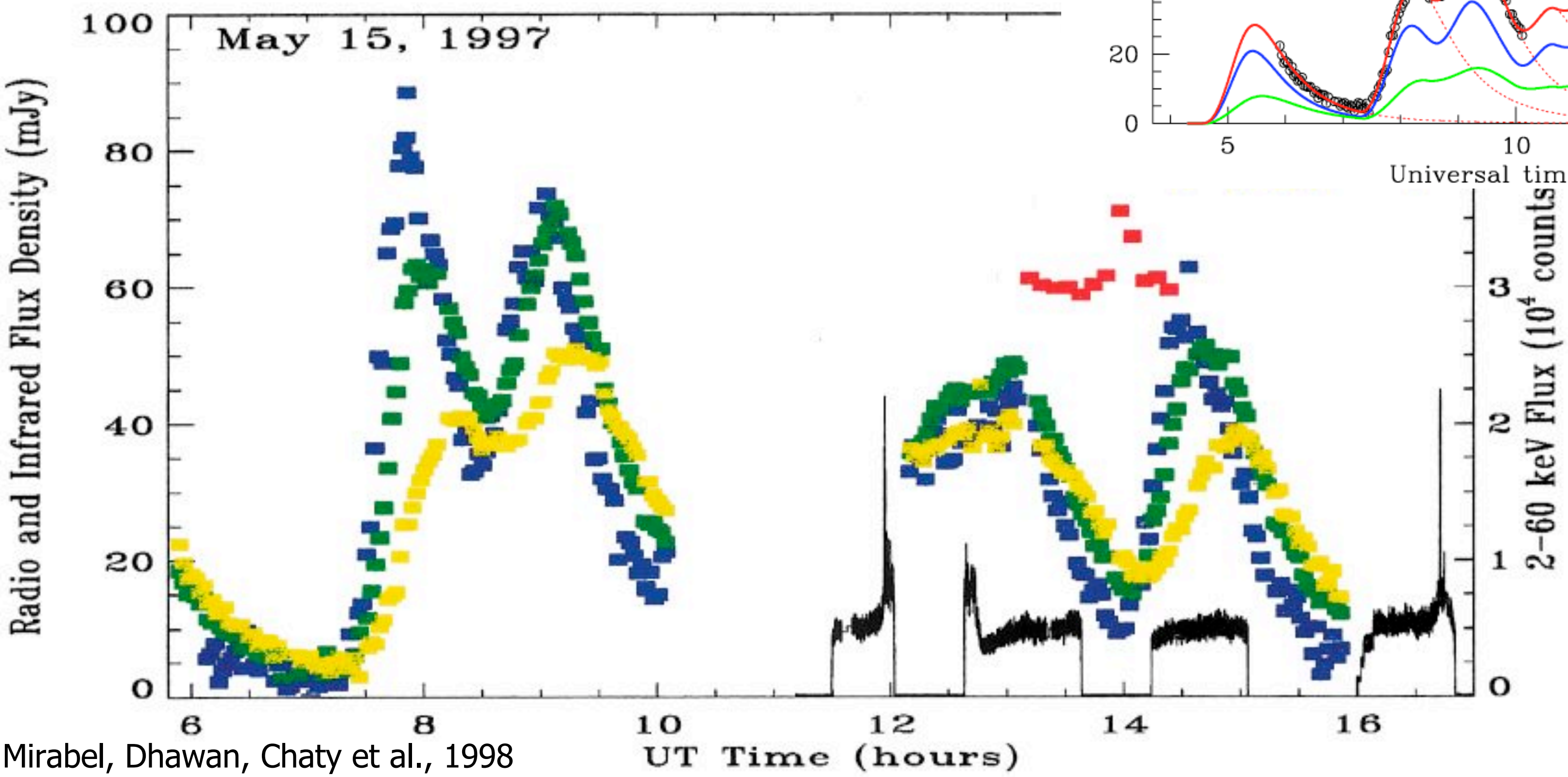
Chaty 2005; Chaty, PhD, 1998
Mirabel, Dhawan, Chaty et al. 1998

II. Microquasars & jets

- Microquasar community: jet = propagation of plasma clouds
- Extragalactic community: jet = propagation of shock wave
- Application of 3C273 model to GRS 1915+105: Propagation of shock wave forming at 1AU, with dissipative stream at v=0.6c



Türler, Courvoisier, Chaty, Fuchs, 2004



Mirabel, Dhawan, Chaty et al., 1998

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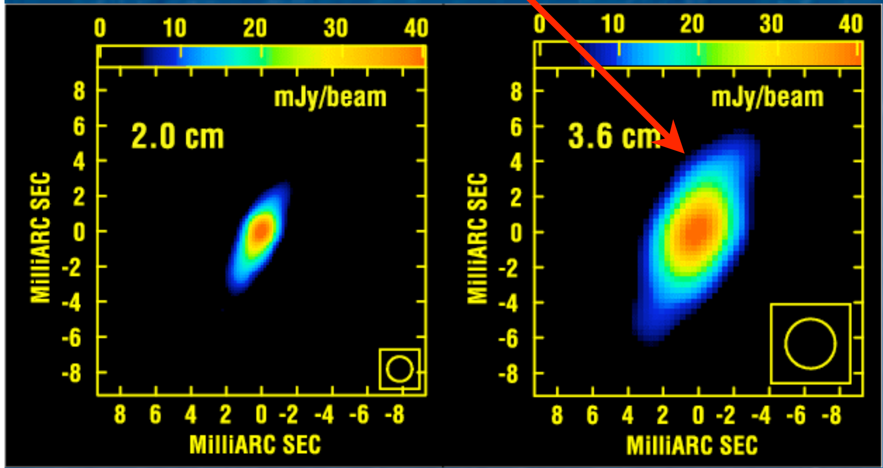
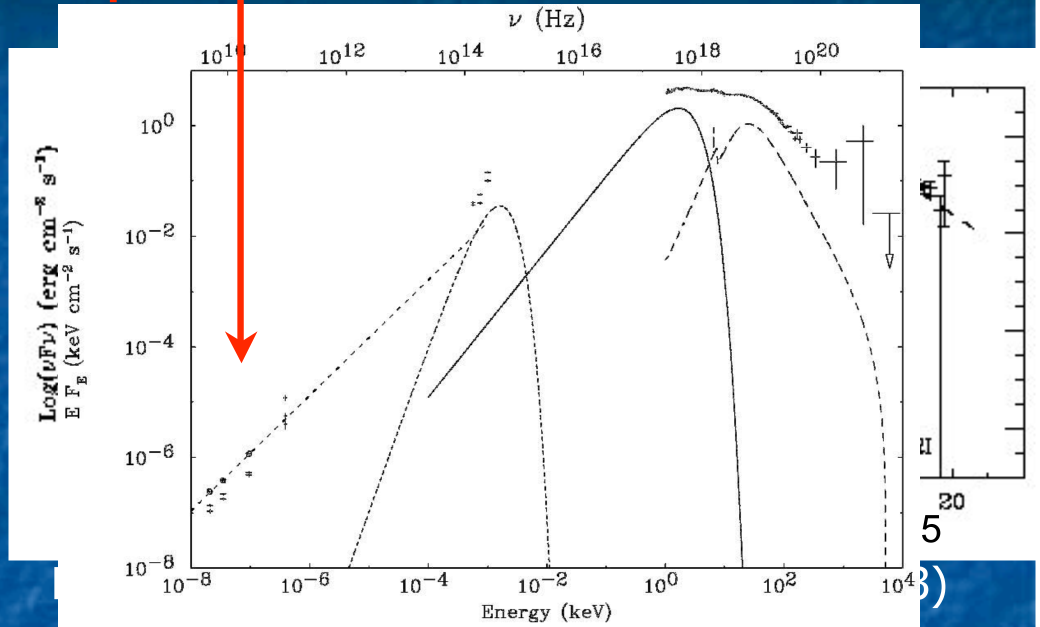
II. Microquasars & compact jets: from radio… to NIR

GRS 1915+105 SED

Observations : **image** in radio or **spectrum** in radio: flat

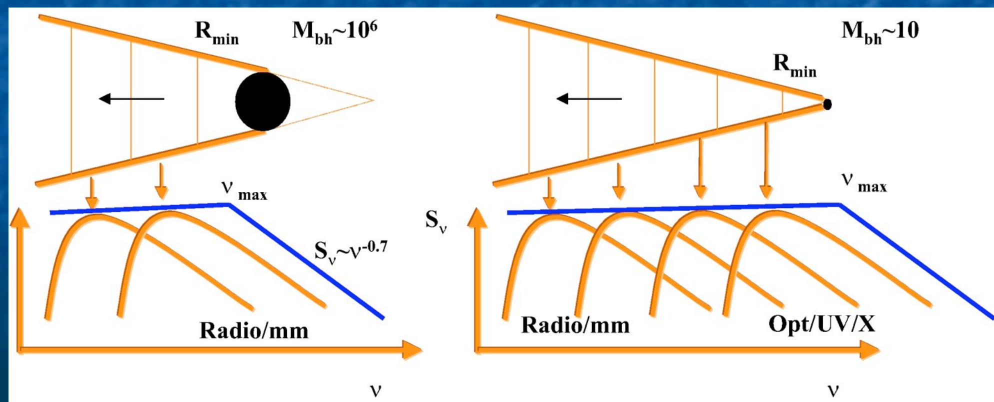


GRS 1915+105: 5 mas = 60 au



Ueda, Yamaoka, Sanchez, Dhawan, Chaty et al. (2002)

- Flat or inverted radio spectrum, Plateau (low-hard) state
- model: conical jet of shock accelerated e^- $\Rightarrow \nu_{max} \propto 1/R_{min}$
- Optically thick synchrotron emission (jet) from radio → NIR

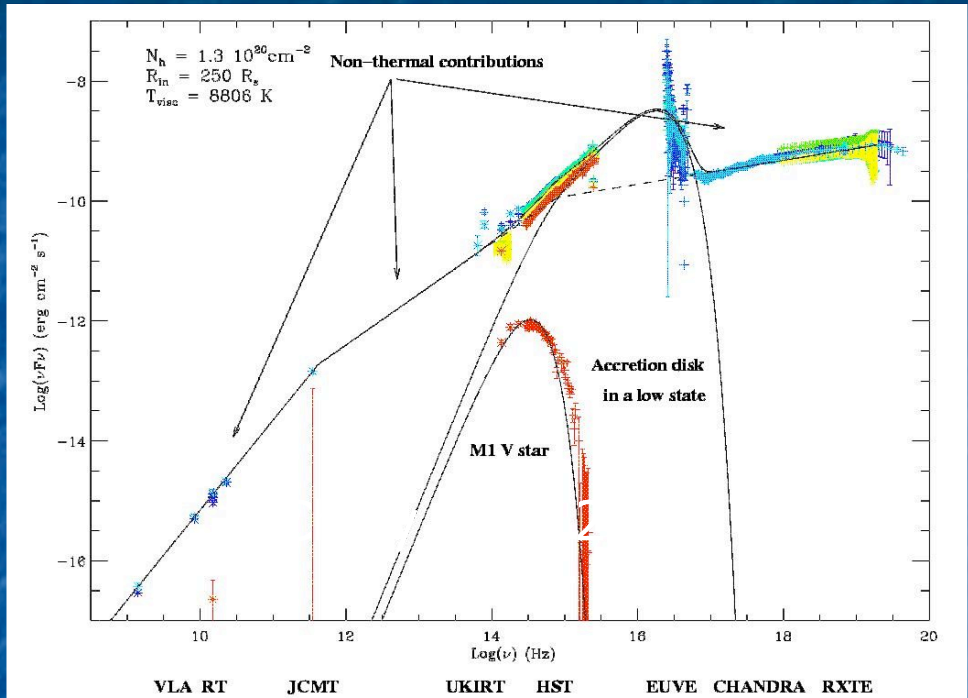


Falcke et al. (2002)

II. Microquasars & compact jets: from radio… to X-rays
XTE J1118+480 SED

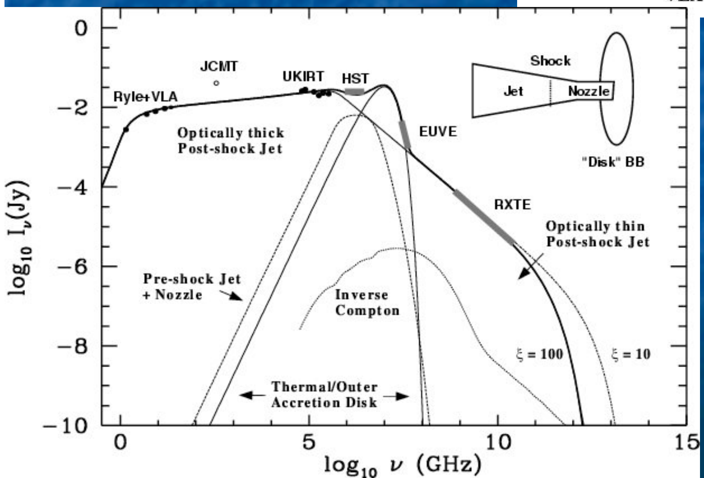
XTE J1118+480:
accretion disc
+ non-thermal
+ stellar emission
in low/hard state

- Optically thin Synchrotron emission: inverted spectrum
- radio ➞ IR ➞ X ?



•Inverse Compton of the soft photons by e^- from the jet basis

•Non-linear Monte-Carlo simulation with hot spherical plasma in the centre

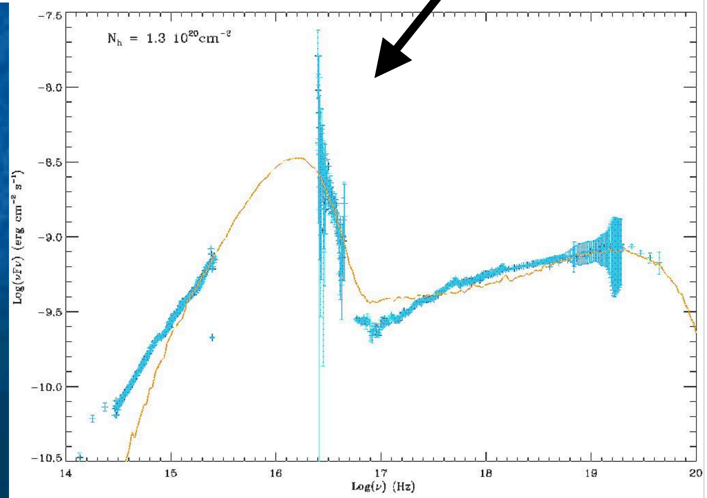


Markoff et al. 2001

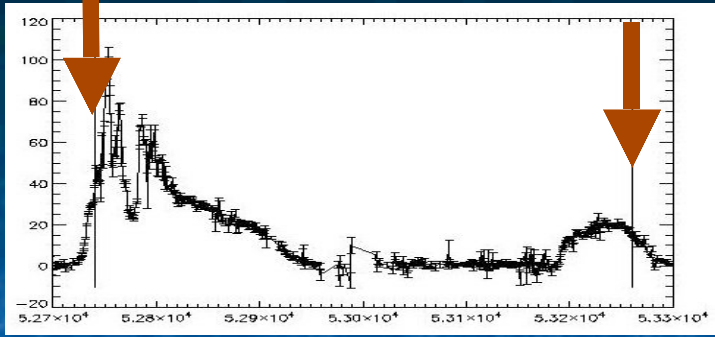
Chaty et al. 2003

•What is the jet contribution???

▪XTE J1118+480 & GRS 1915+105 have an accretion/outflow energy ratio falling into the regime of radio-quiet quasars

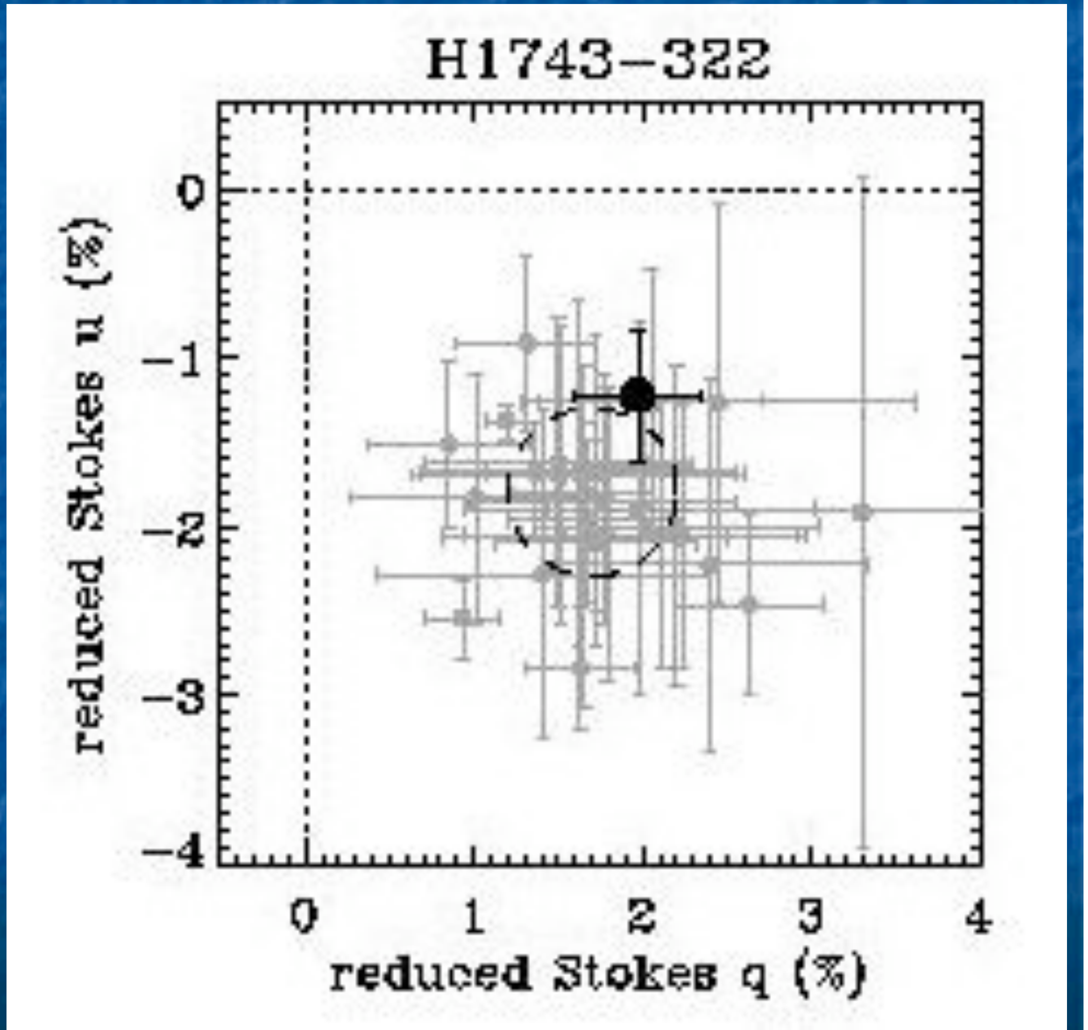


Chaty et al. 2003

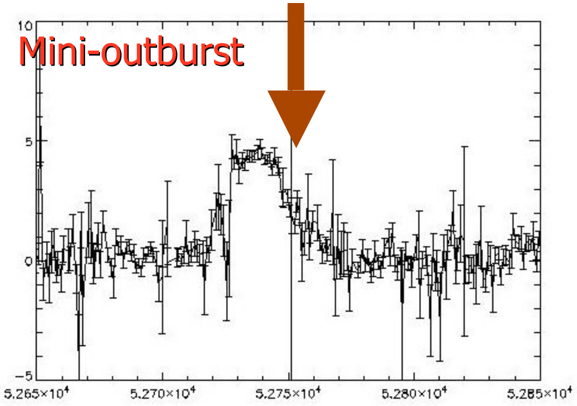


II. Microquasars: Ks Polarimetry of H1743-322

- During outbursts: propitious to detect polarisation from IR jet
- H1743-322 observed in outburst in 2003 and 2004
- Linear polarisation of H1743-322: p=2.25 +/- 0.75%
  - Polarisation is interstellar (average p=1.4-3.5%.), consistent with a large extinction (A_V~ 11; towards the Galactic centre)
- No sign of intrinsic polarisation



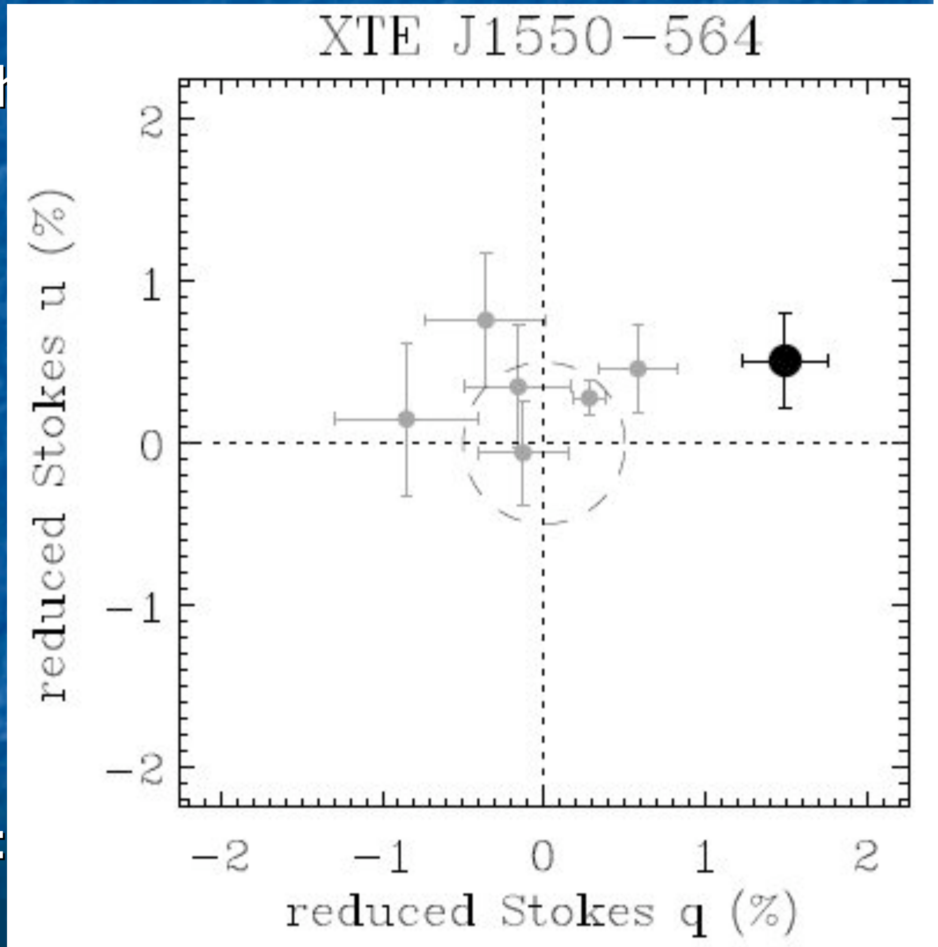
Dubus & Chaty, A&A subm.



II. Microquasars: Ks Polarimetry of XTE J1550-564

- RXTE ASM: small amplitude outburst: 4.5 counts/s peak lasting about a month (Sturner & Shrader 2005).
- ESO/NTT 2003 observations:
  - on the decline at ~2.5 counts/s
  - Ks 3.2 mag brighter than 2MASS (K_S~ 15.6 in quiescence)
- Ks polarimetry:
  - Stars cluster around the origin, dispersion of 0.5%.
  - Position of XTE J1550-564 inconsistent with other stars at the 2.5σ level

  => intrinsic infrared polarization p=0.9-2.0% (expected interstellar polarisation: p_K~0.7%)
- Association with outburst?



Dubus & Chaty, A&A subm.

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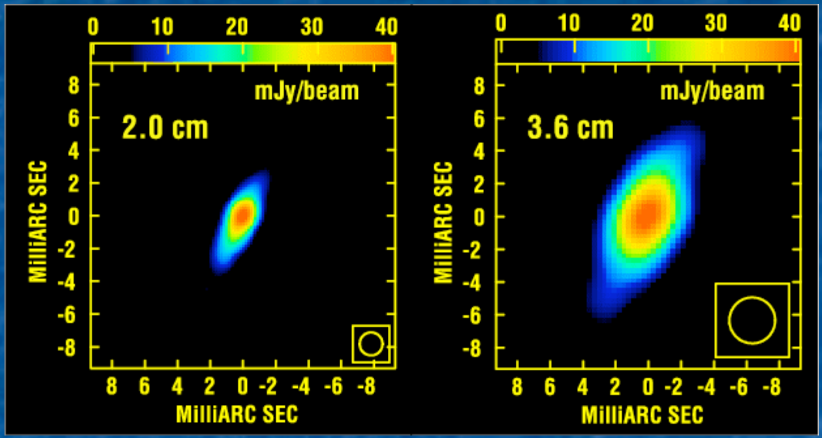
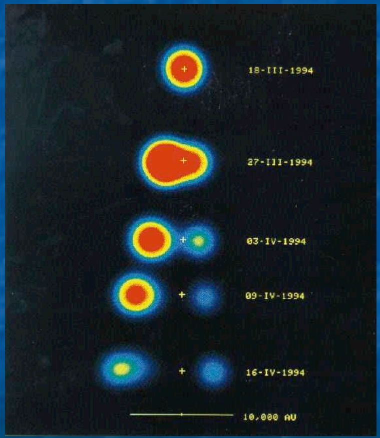
II. Microquasars: multi-scale observations of jets

- Observation of a steady compact jet in GRS 1915+105, 1mas=10AU



Fuchs, Rodriguez, Mirabel, Chaty et al. 2003

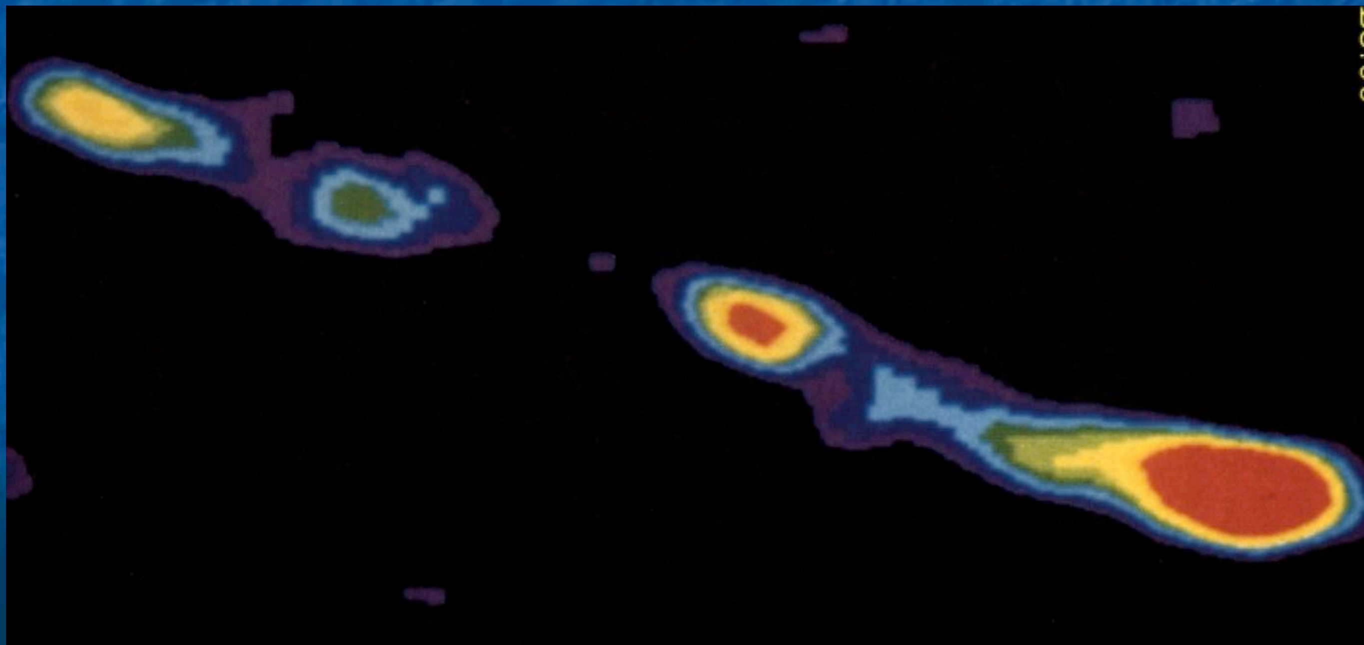
- Observation of sporadic ejections at large scale



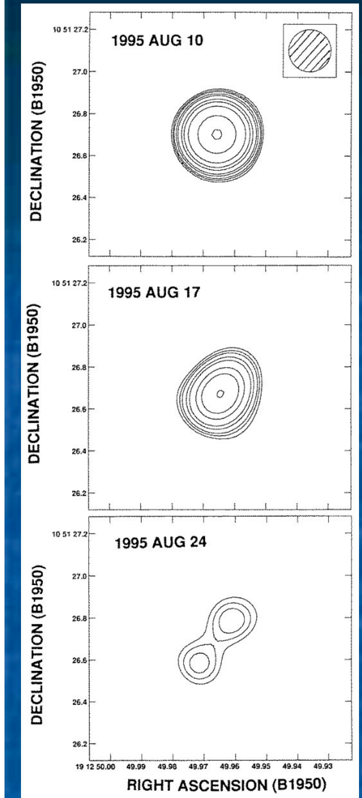
0.2"/week

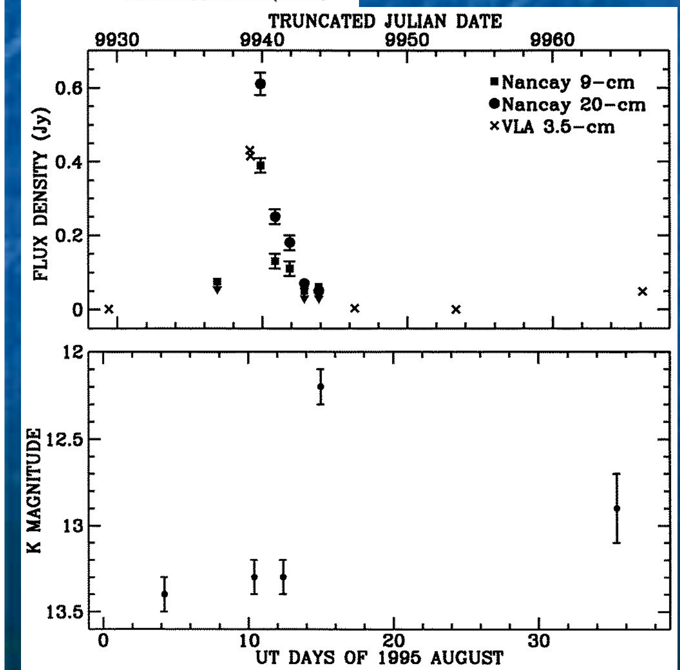
II. Microquasars: jet-interstellar medium interaction

- 1E 1740.7-2942: steady jet: braking of jet in interstellar medium?
  - signature: narrow annihilation lines at 511 keV? need better sensitivity



II. Microquasars: Jet-interstellar medium interaction: GRS 1915+105's outburst



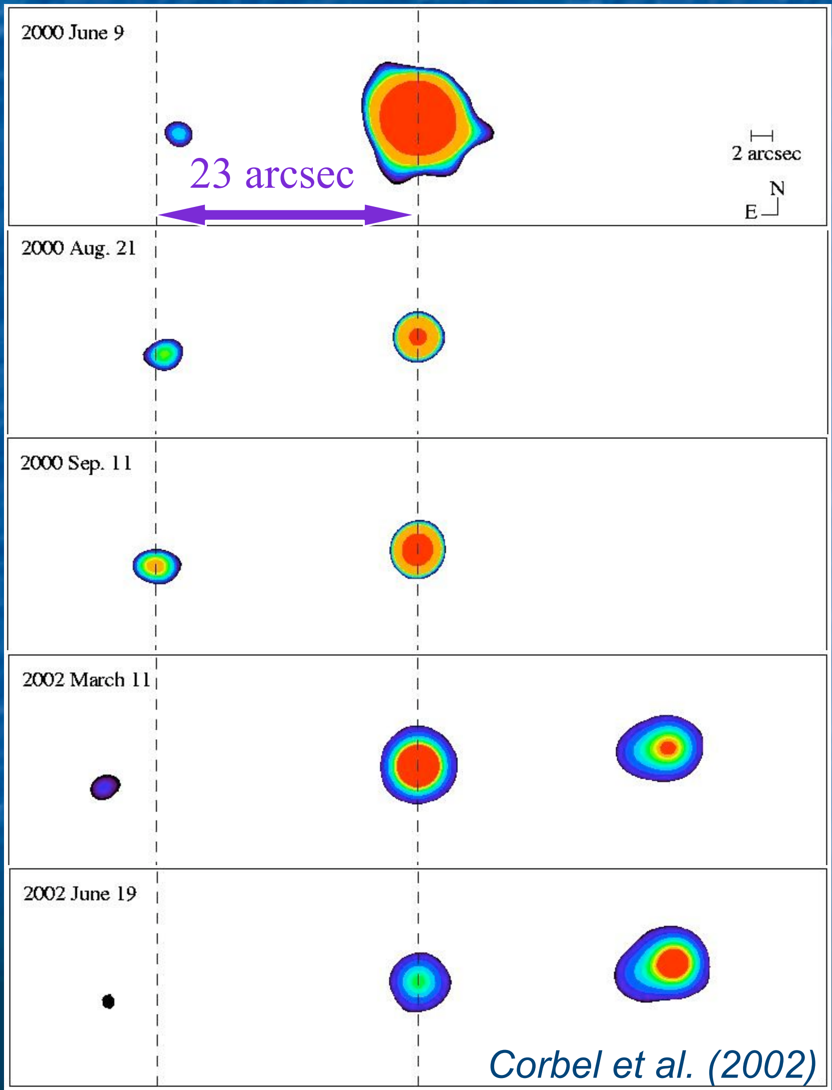


- Strong & long X-ray outburst of GRS 1915+105 in 08/1995
- Radio source resolved in 2 jets
- Increase of NIR emission between 2 and 5 days after the radio burst
- Presence of extended cocoon of dust, heated by ejections
- Cocoon created by previous ejections, jets, ISM dust???
- Dust later confirmed by CHANDRA and ISO observations

Mirabel, Rodriguez, Chaty et al. 1996, ApJ, 472, L111

II. Microquasars: jet-interstellar medium interaction
XTE J1550-564 & Large scale X-ray jets

Chandra images 0.3 - 8 keV



Jets at large distance: 45″

- Discovery of X-ray sources associated with the radio lobes
  - Moving eastern source
  - Alignment + proper motion

⇓

Related to the brief flare of Sept. 1998

Observation of moving relativistic X-ray jets

- evidence for gradual deceleration
- radio-X-ray spectrum: compatible with synchrotron emission from the same e^- distribution
- **external shocks with denser medium?**

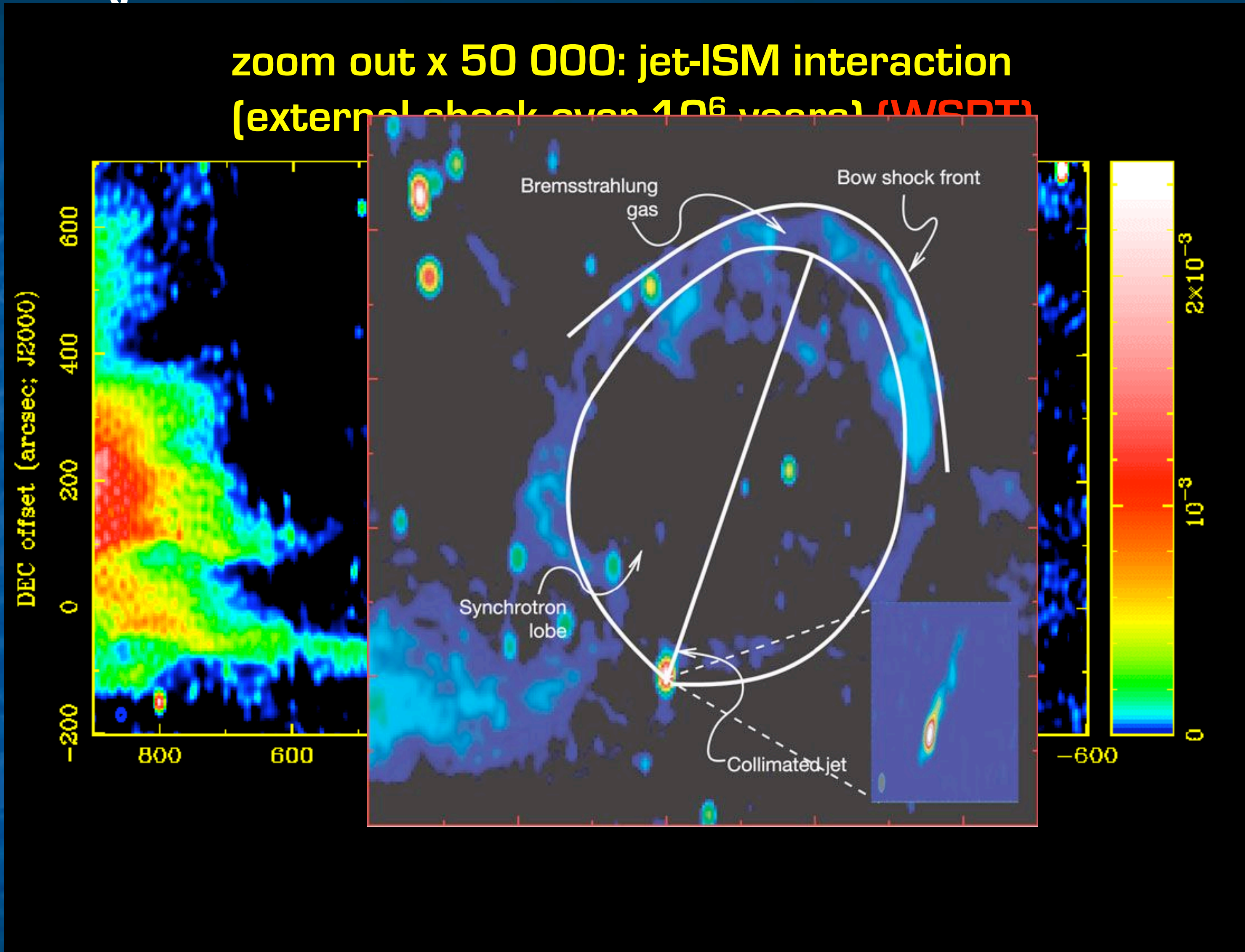
↳Particle acceleration up to TeV ?
Analogy with quasars

=> What is the e- maximal energy???

Also the source **H 1743-322**

II. Microquasars: surroundings of Cygnus X-1???

3 phases of jet from black hole to ISM



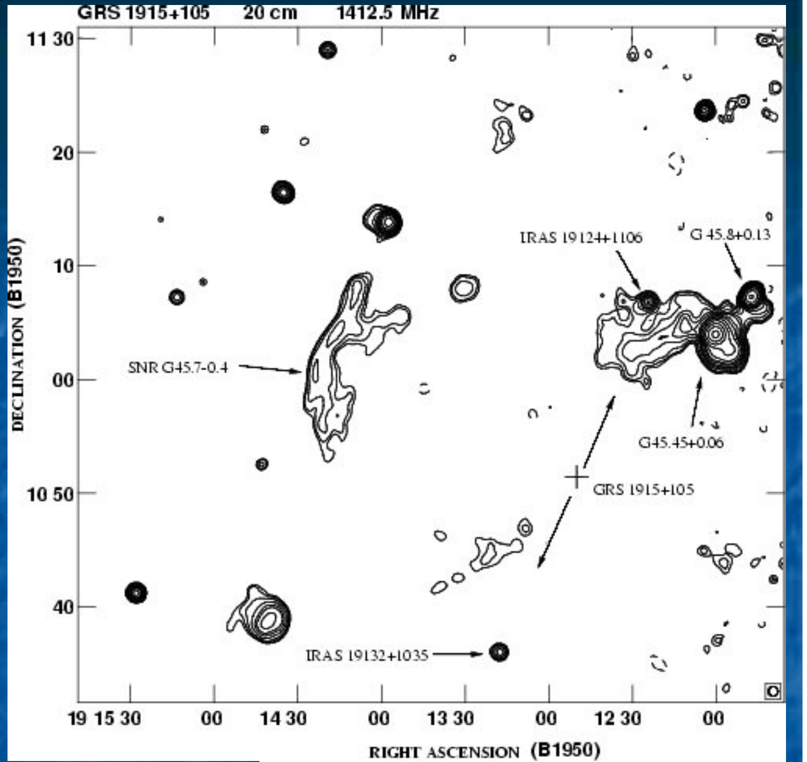
Jet-blown HII nebula Sh2-101: **strong jet/ISM shock**

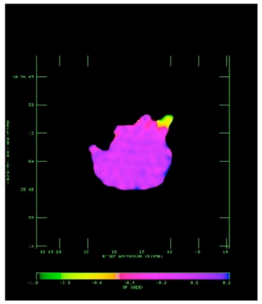
But most of the **energy stored in non-radiating particles**, presumably **baryons**…

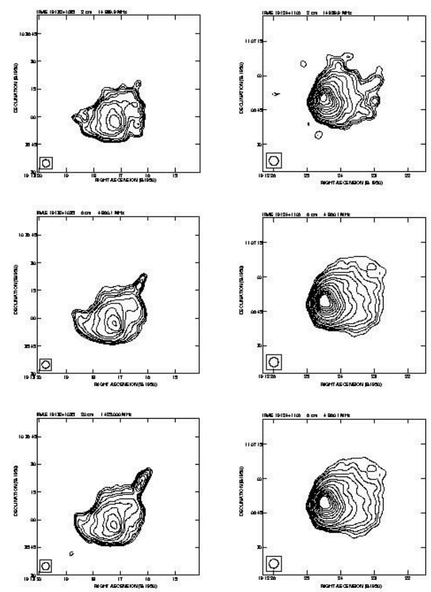
(Stirling et al. 2001; Stirling, Fender 2006; Gallo et al. 2005)

II. Microquasars: What about the surroundings of GRS 1915+105???

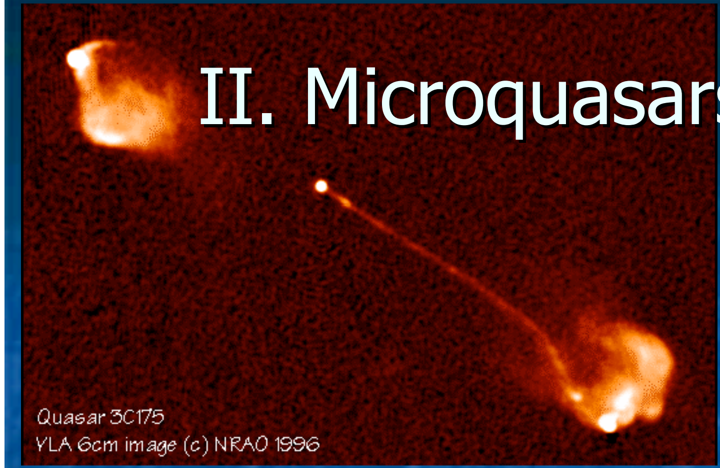
- Low-resolution cm map: 2 sources aligned with central source
- Strange non-thermal features in the south-east lobe
- Synchrotron signature=> interactions between jets and ISM?







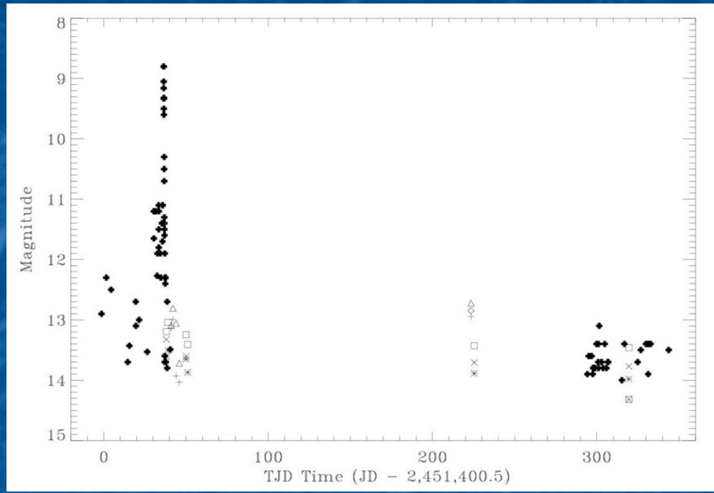
Chaty et al. 2001, A&A, 366, 1035

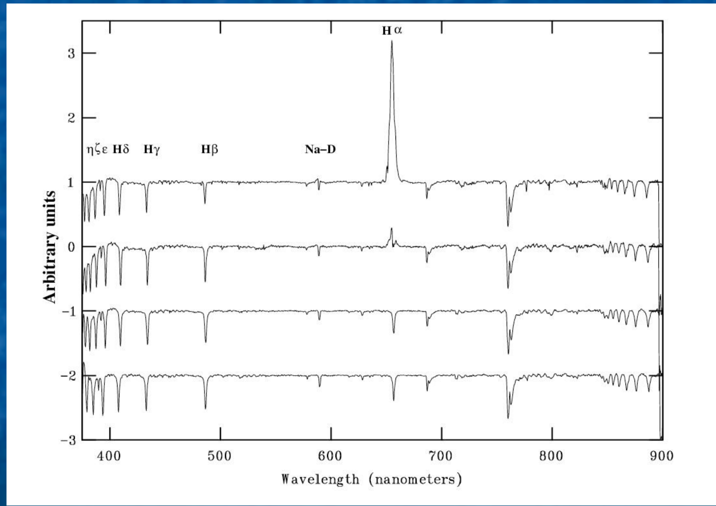


II. Microquasars: observation of microblazars…

- Microblazar = Microquasar whose jet points towards the observer
- V=0.98c: time/10, flux*1000, increase of photon energy
- BUT sources difficult to observe since flares, although strong, are short
- Jet Precession: intermittent microblazar

- V4641 Sgr: at distance of 6 kpc, jets exhibit apparent velocity of v~10c: microblazar?





V4641 SGR: 1 day flare, 1.6->12.2 Crab, 14→8.8mag, wind velocity 5000km/s

Chaty et al. 2003

II. Microquasars: observation of ULXs…

- ULXs: ultra-luminous X-ray sources
  - observed near active galactic nuclei at high stellar formation rate
- Beamed jets from microquasars?
- Or black holes of intermediate mass (~1000 M_{sol})?
- Are there ULXs in our Galaxy?
- Some associations between galactic microquasars and gamma-ray sources: e.g. LS 5039…
- …and hundreds of unidentified gamma-ray sources exist…
- Need better angular resolution for ULXs

Plan

- 0. Prelude to microquasars
- I. Discovery of microquasars
- II. Microquasars: HE physics laboratories
  - Accretion/ejection
  - Compact jets
  - Interaction between jets and surroundings
- III. Microquasars and astroparticle physics
  - VHE photons, CRs, ν

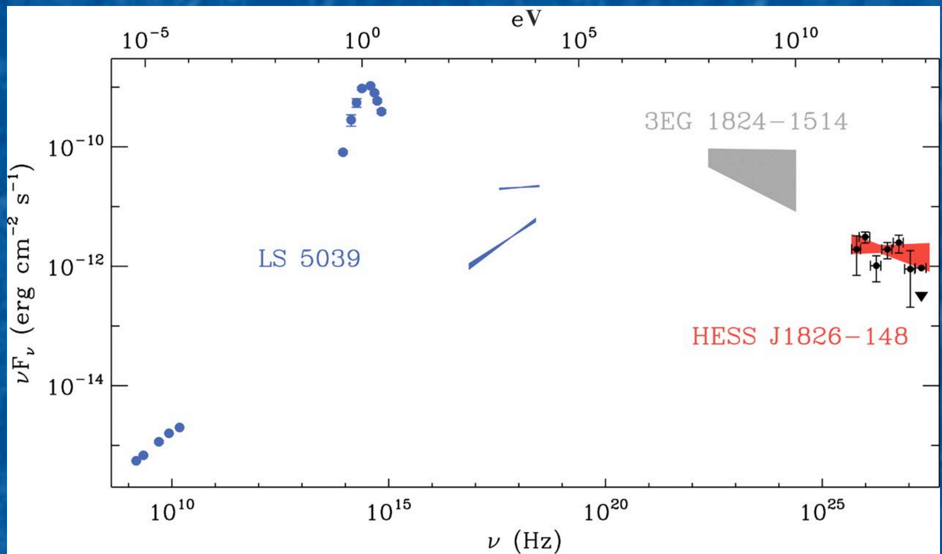
III. The role of microquasars in astroparticle physics

- Microquasars are the site of:
  - Accretion
  - Ejection
  - Interaction of jets with interstellar medium

- Therefore all ingredients are present in microquasars to emit astroparticles:
  - VHE photons
  - Cosmic rays
  - Neutrinos

III. Microquasars and VHE photons

LS 5039: from radio and GeV emission from **EGRET** (Paredes et al. 2000) to VHE γ-rays, TeV, with **HESS** (Aharonian et al. 2005).



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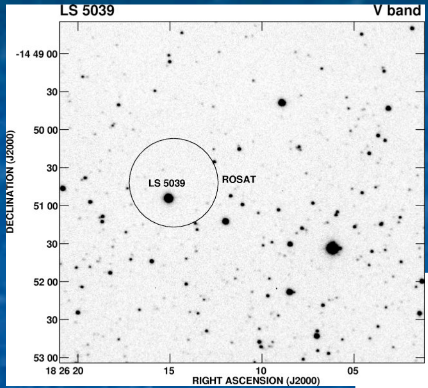

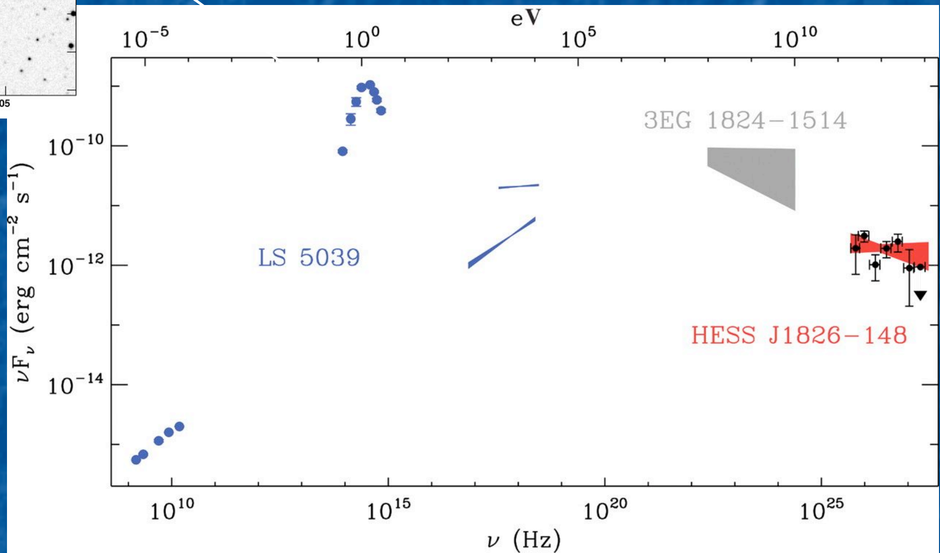

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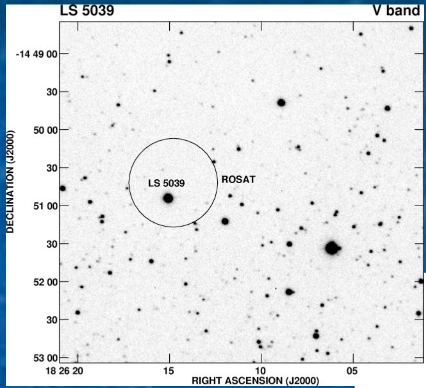

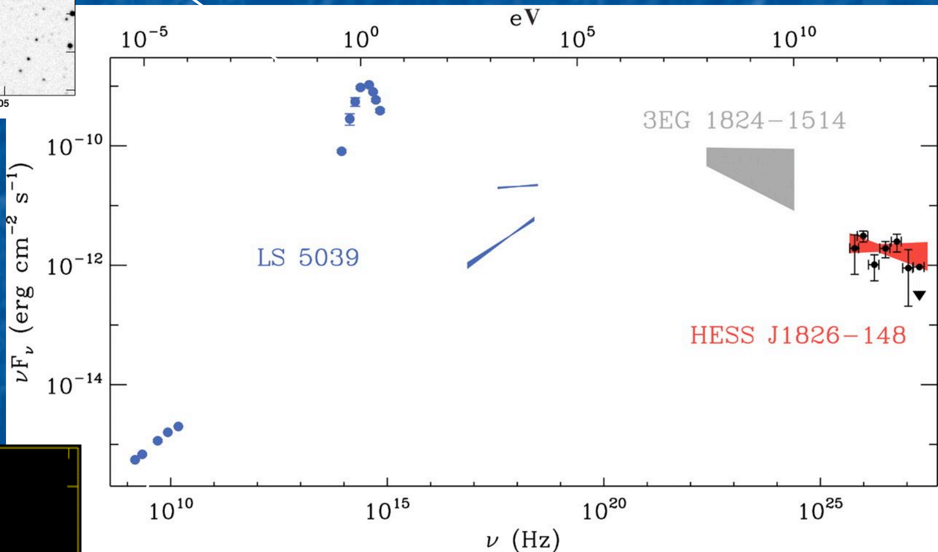

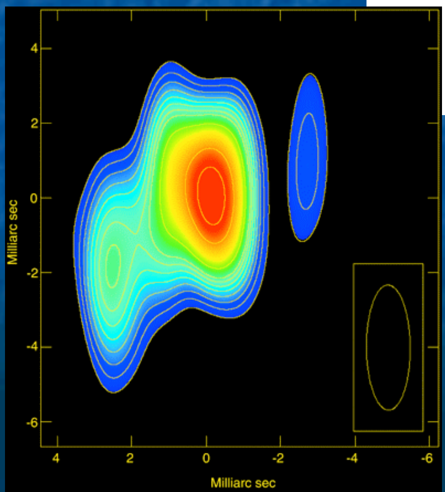

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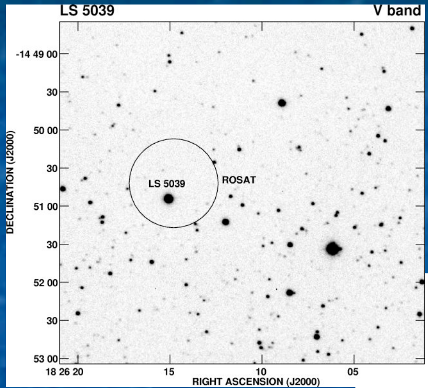

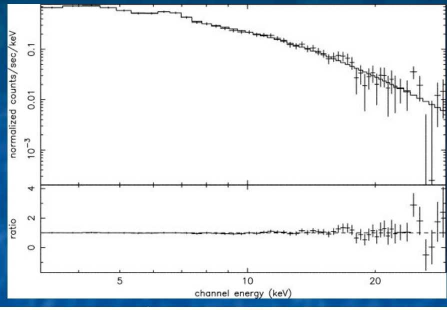

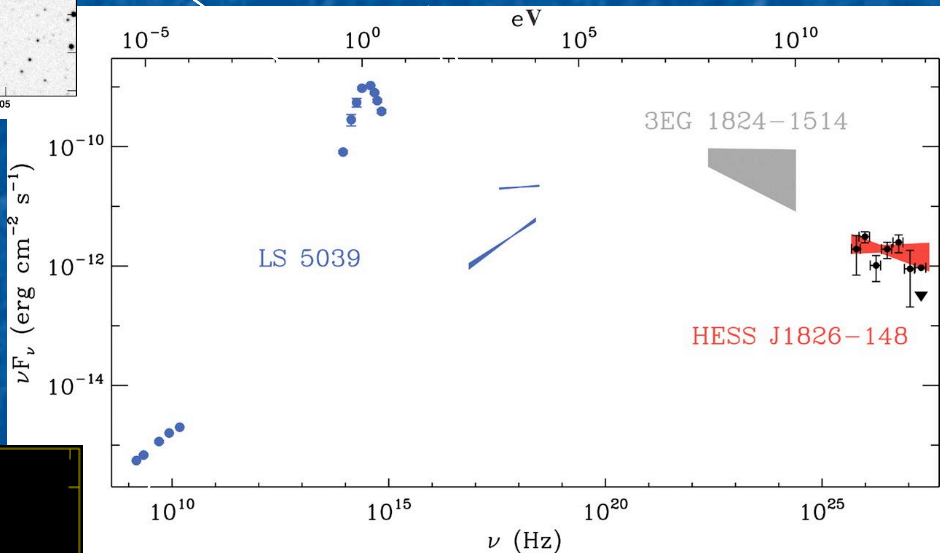

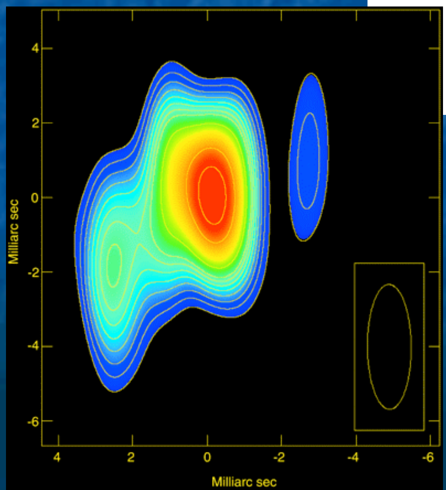

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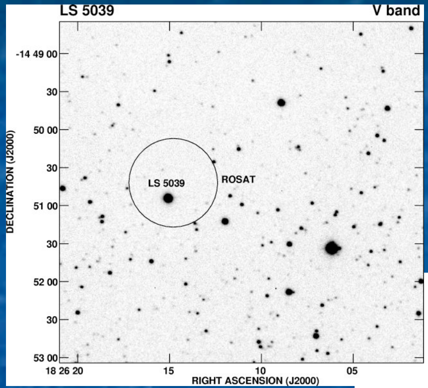

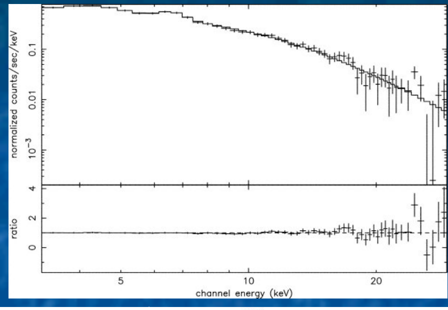

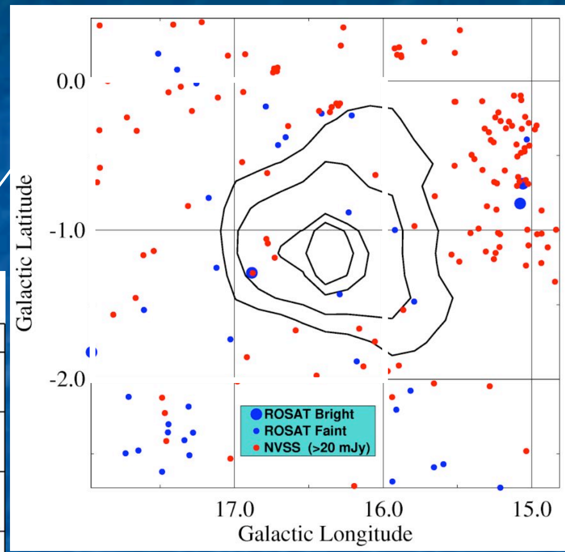

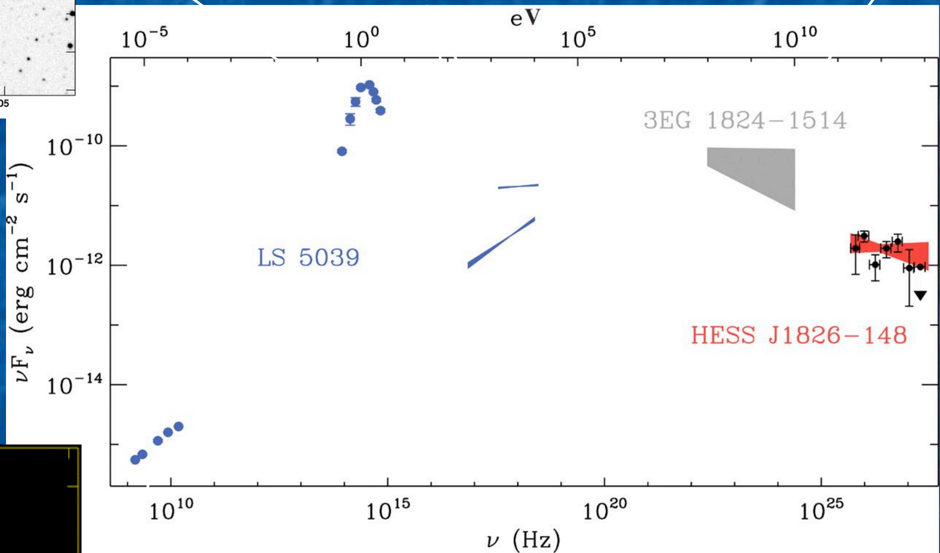

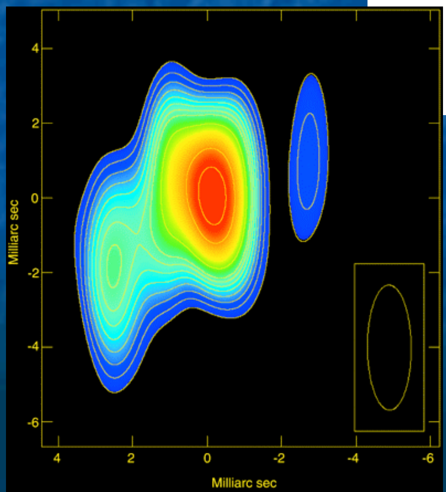

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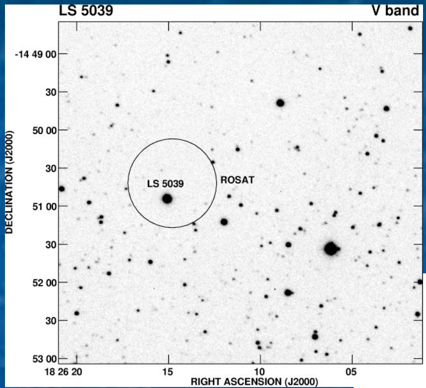

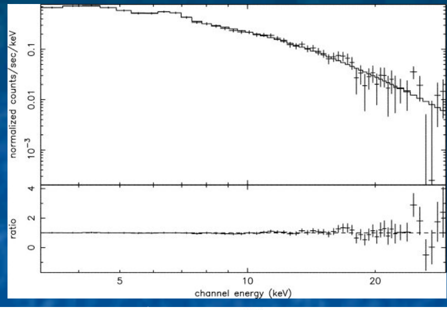

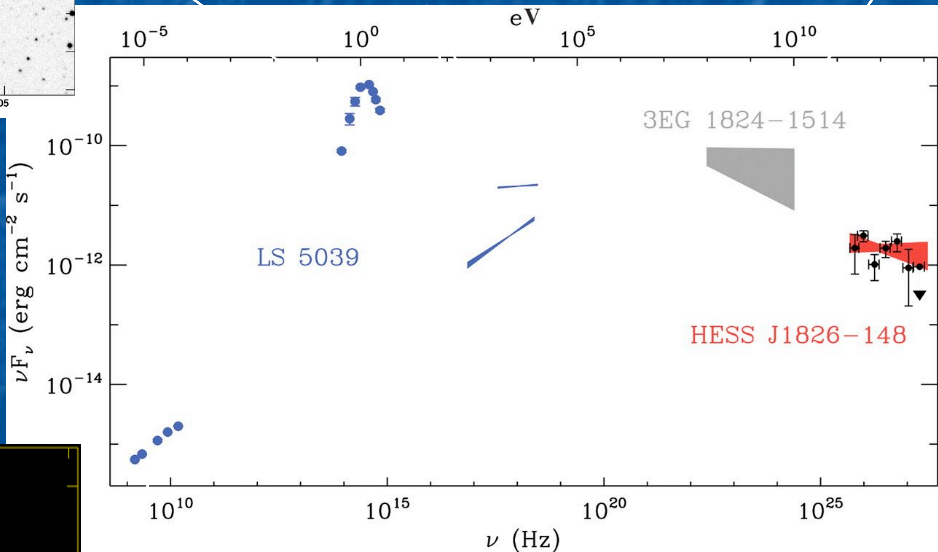

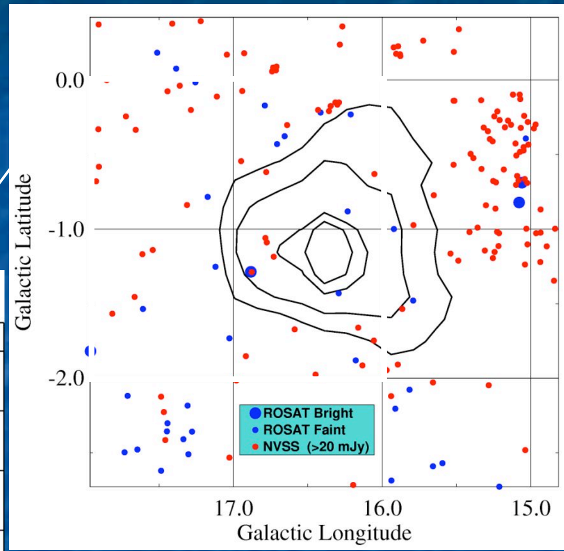

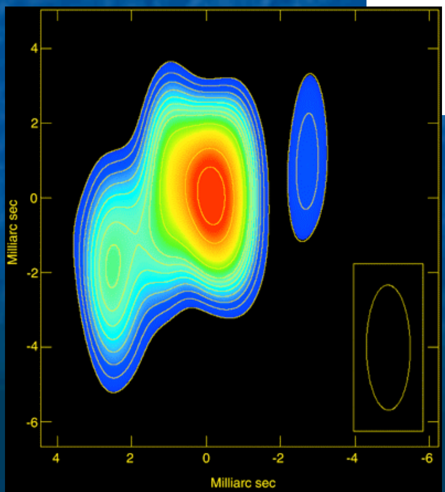

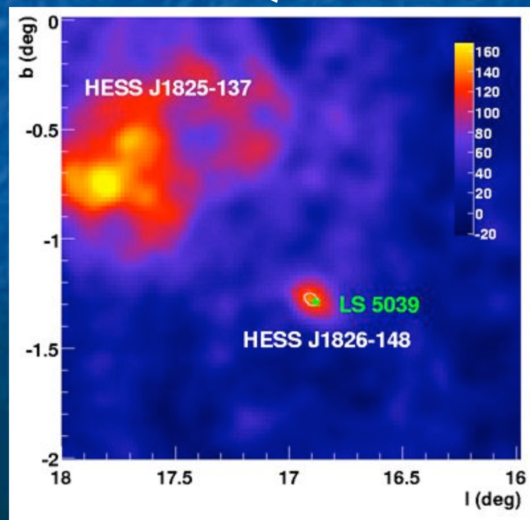

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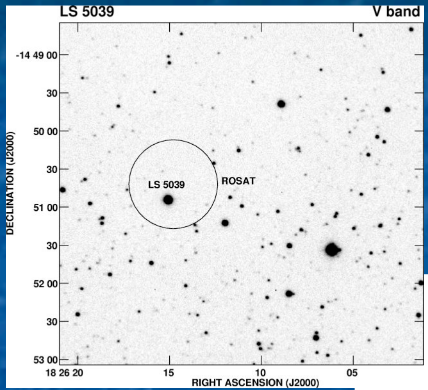
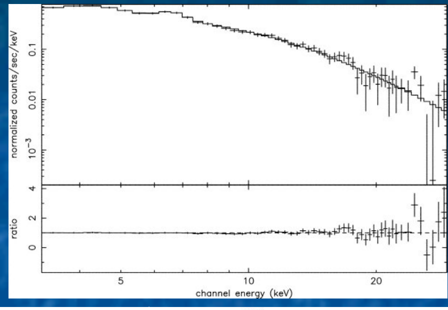
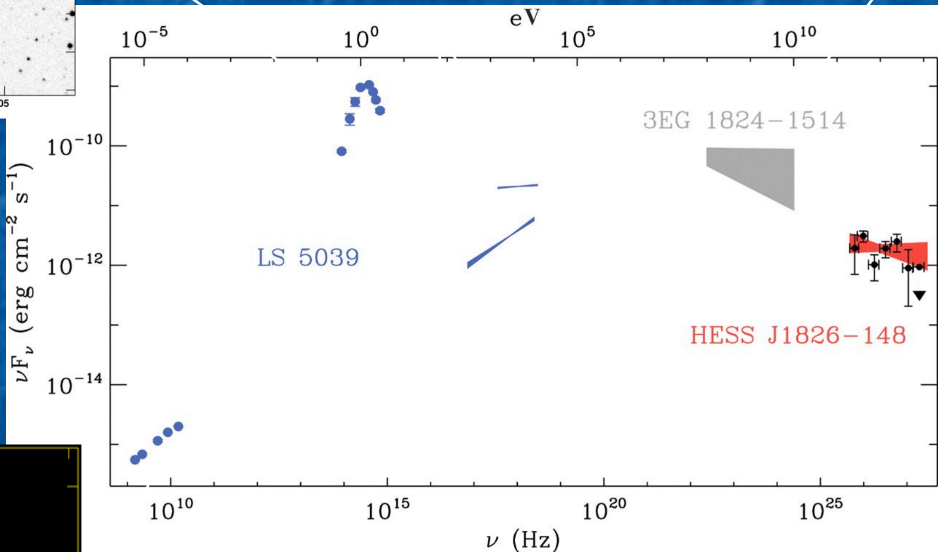
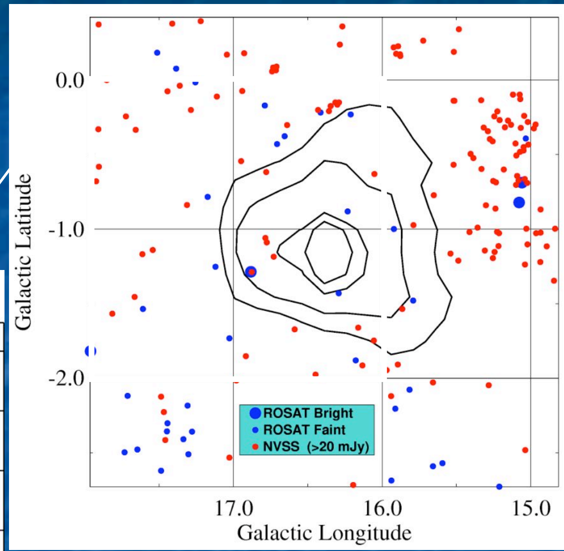
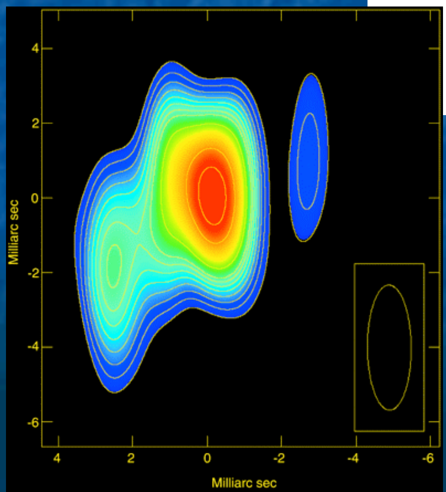


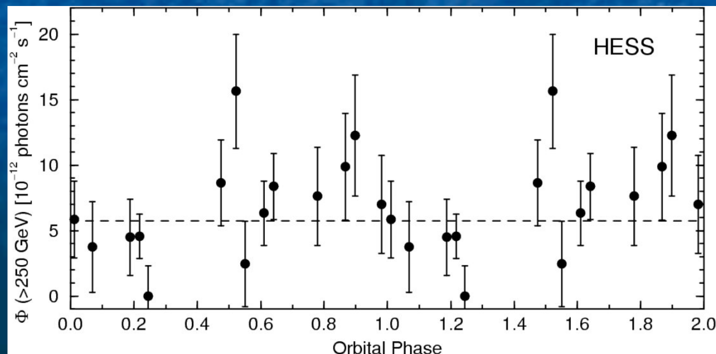


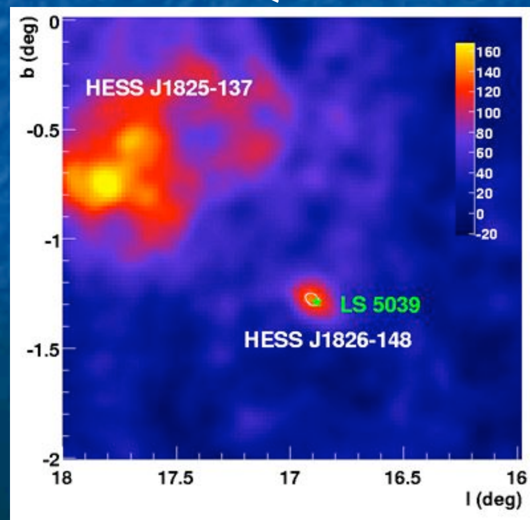




A pulsar in disguise? see Dubus 2006...

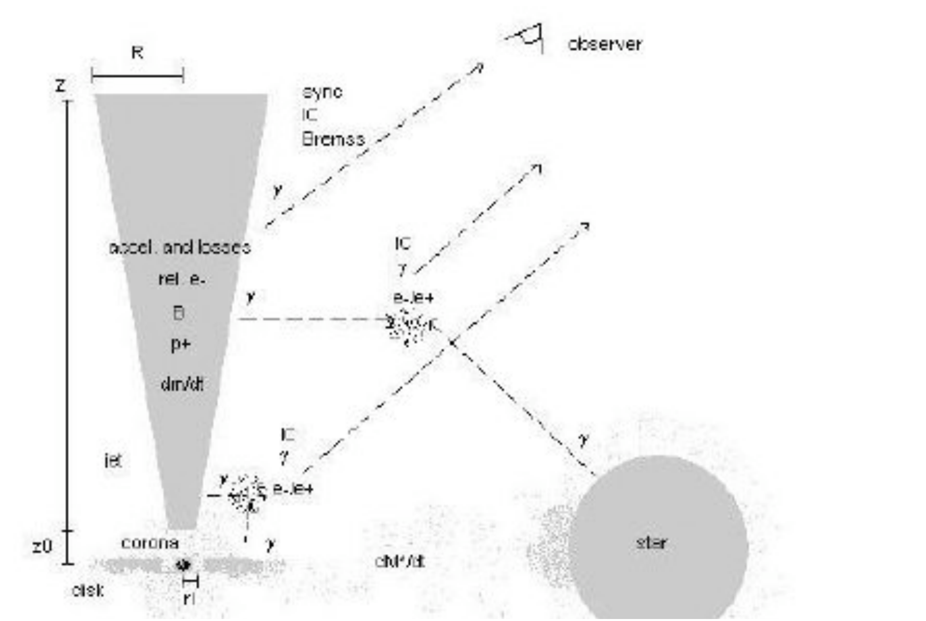


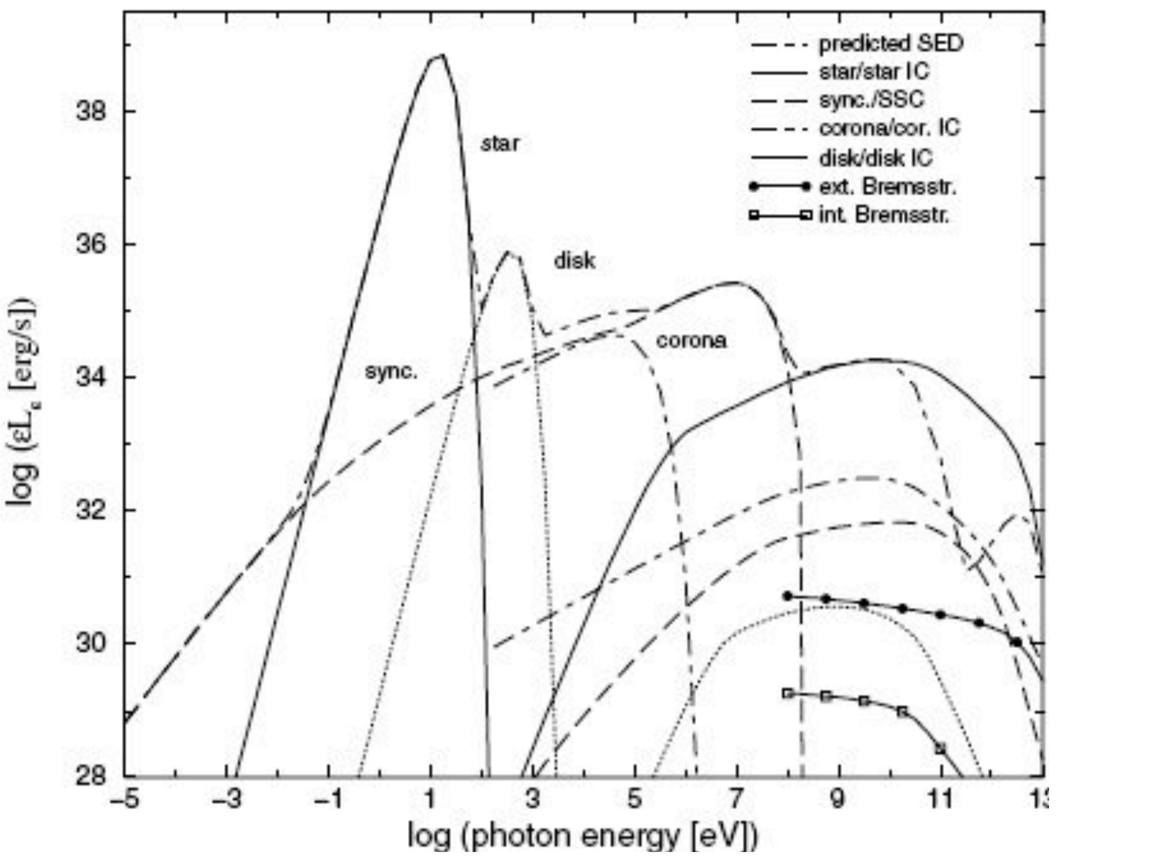




III. Microquasars and VHE

- Broad-band leptonic model for gamma-ray emitting microquasars (Bosch-Ramon et al. 2006)
- Jet dominated:
  - dynamically by cold protons,
  - radiatively by relativistic leptons
- Magnetic field at equipartition
- Emission from radio to VHE:
  - Synchrotron
  - Relativistic Bremsstrahlung
  - Inverse Compton
- This model:
  - provides predictions about shape of SEDs
  - Points to MQs as VHE sources (as LS 5039)





III. Microquasars, VHE photons and ν

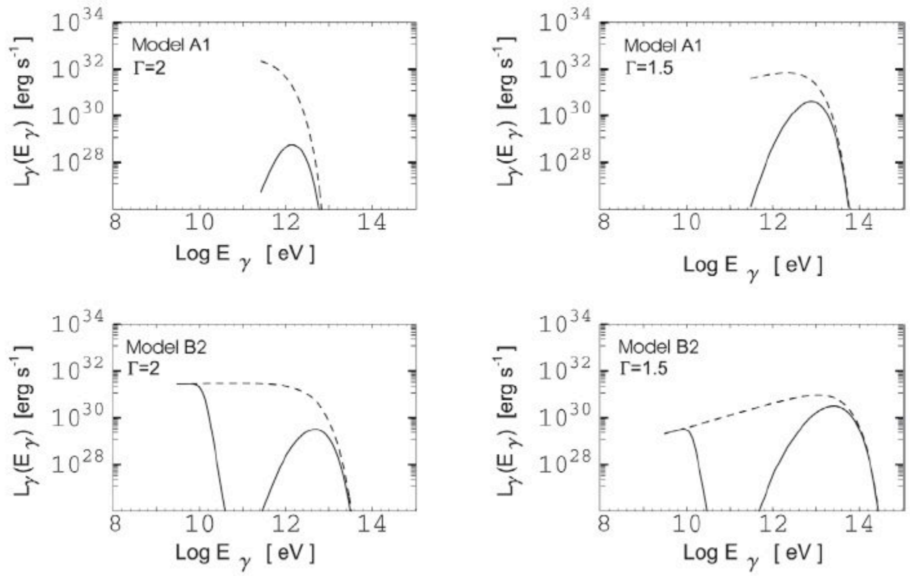


Fig. 1. Spectral high-energy distribution at TeV energies from the jet-wind interaction in a misaligned MQ. The left panel corresponds to Γ = 2, and the right to Γ = 1.5 (see text). The dashed lines correspond to the production spectra whereas the solid lines represent the absorbed spectra.

- γ-ray and ν emission from misaligned microquasars (Romero and Orellana, 2005):
  - If jet is misaligned with the perpendicular to the orbital plane
    - (35° from orbital plane for V4641 Sgr; precession in SS 433, LSI +61 303, Cygnus X-3)
  - and donor star is an early-type star:
  - => jet collides with stellar wind: standing shock between compact object and stellar surface
  - If jet has hadronic content: TeV protons diffuse into inner, dense wind leading to γ-rays and ν

- Predictions
  - ν: Signal at 3 σ (ICECUBE, AMANDA, ANTARES) for T_{obs} 15 years of a source at 2 kpc, close alignment of jet with line of sight, duty cycle 20%
  - γ-ray: enhancement of TeV signal (HESS, MAGIC, Veritas), periodic variability

III. Microquasars & ν

- Microquasars: emitters of TeV ν, possible detection by km² ν telescopes.
  - If jets are protonic
  - If fraction of a few percent of jet energy is dissipated on sufficiently small scales
- Model: photopion production in the jet (Distefano et al. 2002)
- Also sources with large bulk Lorentz factors ,directed along our line of sight: identified by ν and γ-ray emission?
  - AGILE, GLAST

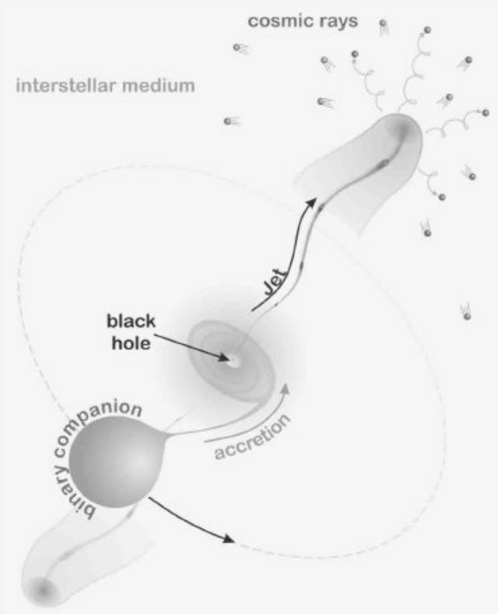
PREDICTED NUMBER OF MUON EVENTS, N_μ, IN A 1 km^2 DETECTOR

Source Name	Δt (days)	N_μ	$N_{\mu,\mathrm{bkg}}$ (deg/0°.3)^2
CI Cam	0.6	0.05	0.002
XTE J1748−288	20	2.5	0.054
Cyg X-3	3	4.8	0.008
LS 5039	Persistent	0.2	0.986
GRO J1655−40	6	1.8	0.016
GRS 1915+105	6	0.5	0.016
Cir X-1	4	0.2	0.011
LS I 61°303	7	0.1	0.019
LS I 61°303	20	0.1	0.054
XTE J1550−564	5	0.04	0.014
V4641 Sgr	0.3	0.03	0.001
V4641 Sgr	0.3	3.9	0.001
Sco X-1	Persistent	0.9	0.986
SS 433	Persistent	252	0.986
GS 1354−64	2.8	0.02	0.008
GX 339−4	Persistent	183.4	0.986
Cyg X-1	Persistent	2.8	0.986
GRO J0422+32	1−20	0.1−2	0.003−0.1
XTE J1118+480	30−150	6−30	0.081−0.405

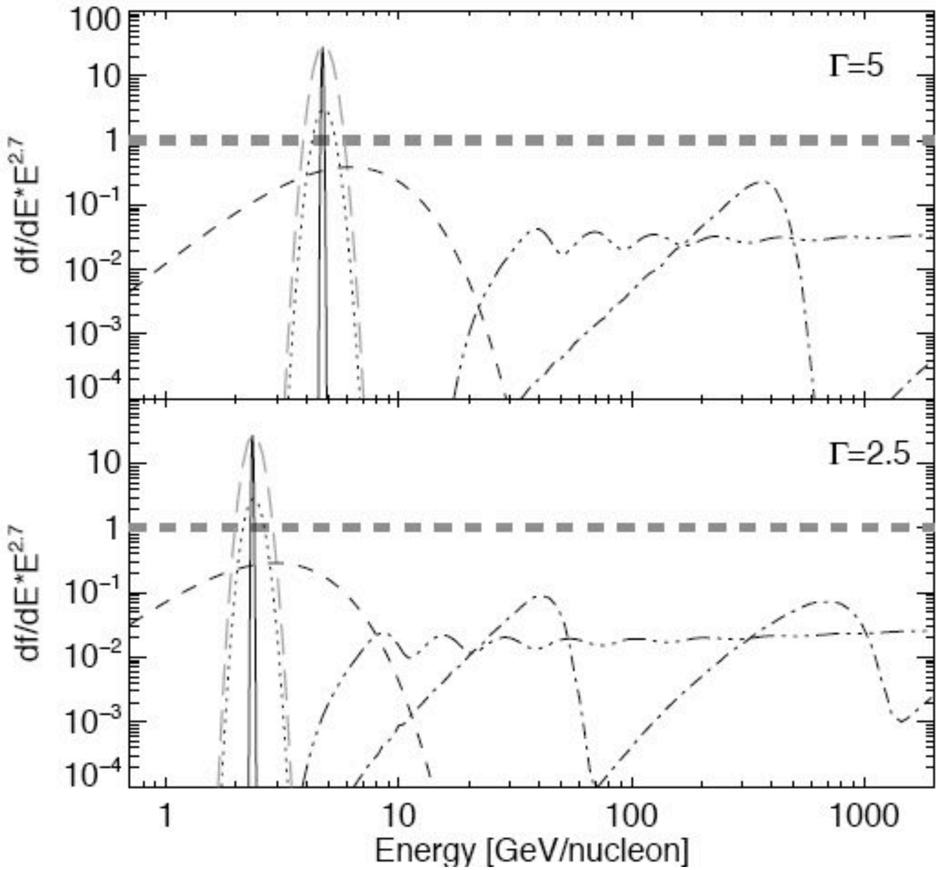
NOTE.—Values are based on the neutrino fluxes given in Tables 2 and 3. For bursting sources, the number of events expected in a burst of duration Δt is quoted. For persistent sources, 1 yr integration time is assumed. The two values quoted for the periodic source LS I +61°303 refer to a bursting state of duration 7 days and to a quiescent state of duration ~20 days. $N_{\mu,\mathrm{bkg}}$ is the expected number of background atmospheric neutrino events, assuming an angular resolution of 0°.3.

III. Microquasars and cosmic rays

- Cosmic-rays from microquasars could represent a narrow component to the CR spectrum (Heinz & Sunyaev 2002)



- If jets contain cold protons and heavy ions (as SS 433): narrow component at 3-10 GeV.
  - Single MQ (GRS 1915+105) active for 10^7 years, 10^{38}ergs/s, 1 kpc
  - Normalized to differential Galactic CR background spectrum



- Prediction: if not detected => e-/e+ jets

IV. Conclusions

- Microquasars: excellent laboratories for astroparticle physics

- Many questions:
  - Accretion-ejection mechanisms, Coupling high-energy and radio (jet) emission
  - Infrared & high-energy emission: synchrotron contribution???
  - Annihilation line emitted by microquasars, from jet (or e+) colliding the ISM?
  - What is the nature of the jet: baryonic/leptonic?
  - Propagation of jet
  - Existence of microblazars
  - Nature of ULXs

- To answer to these questions:
  - Multi-wavelength observations
    - Radio: VLA/VLBA…; ALMA
    - IR/optical: VLT
    - HE: XMM, Chandra, Swift, Suzaku, INTEGRAL, RXTE, HESS(-2)…; GLAST
    - RCs: AUGER
    - ν: AMANDA, ANTARES…

- Need:
  - close link theory/model/observations
  - And… more Vulcano-like workshops!!!