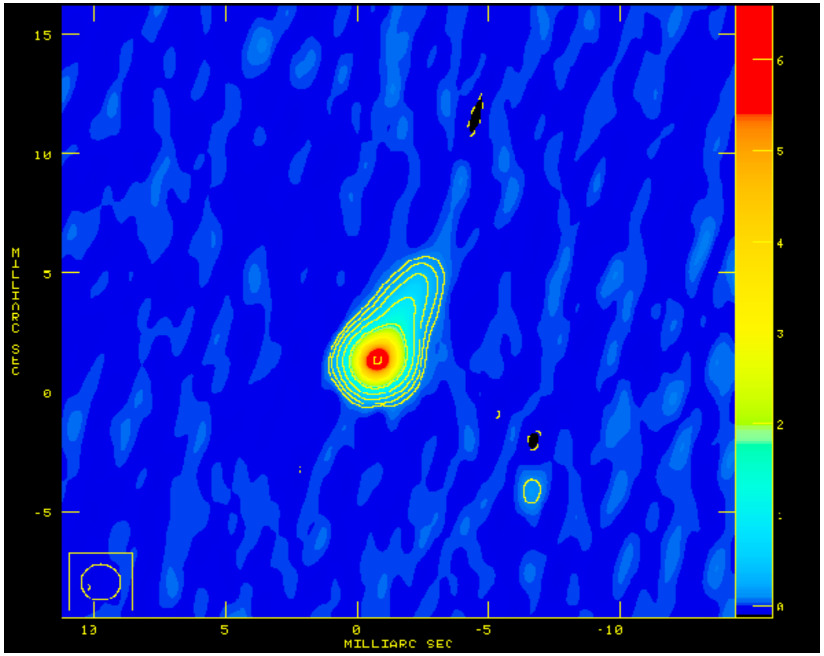
Jets

- Two classes of jets from X-ray binaries
- Jet power versus accretion power
- Jet composition
- Large-scale jets and interactions with ISM
- Jet production and collimation

Two Flavors of Radio Jets

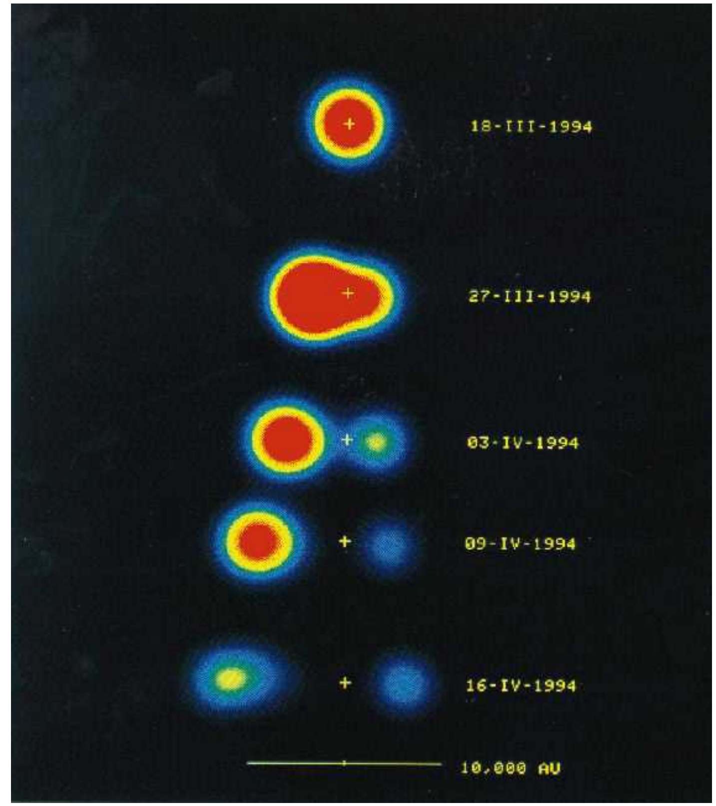
Compact – tens of AU, found in low/hard X-ray state



Stirling et al. 2001

High/soft state – no jet

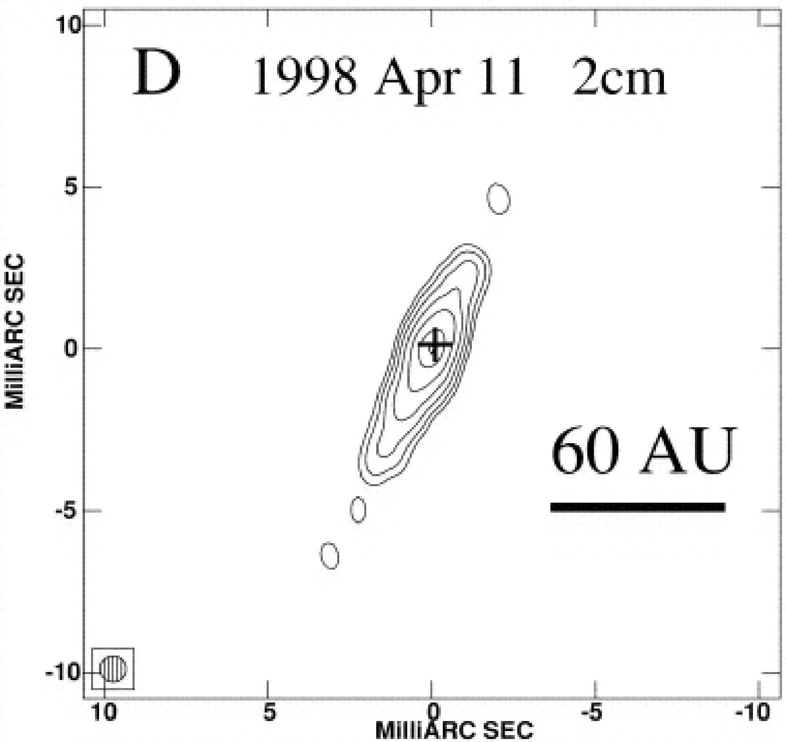
Large scale – up to parsecs, produced at state transitions



Mirabel et al. 1994

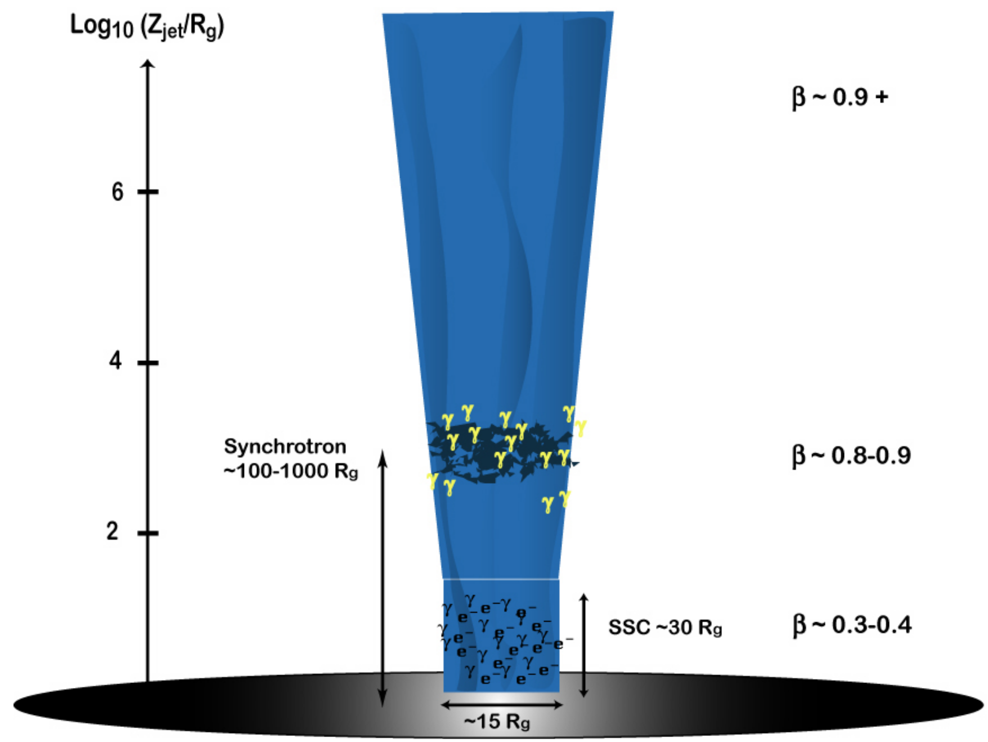
Compact jets

GRS 1915+105



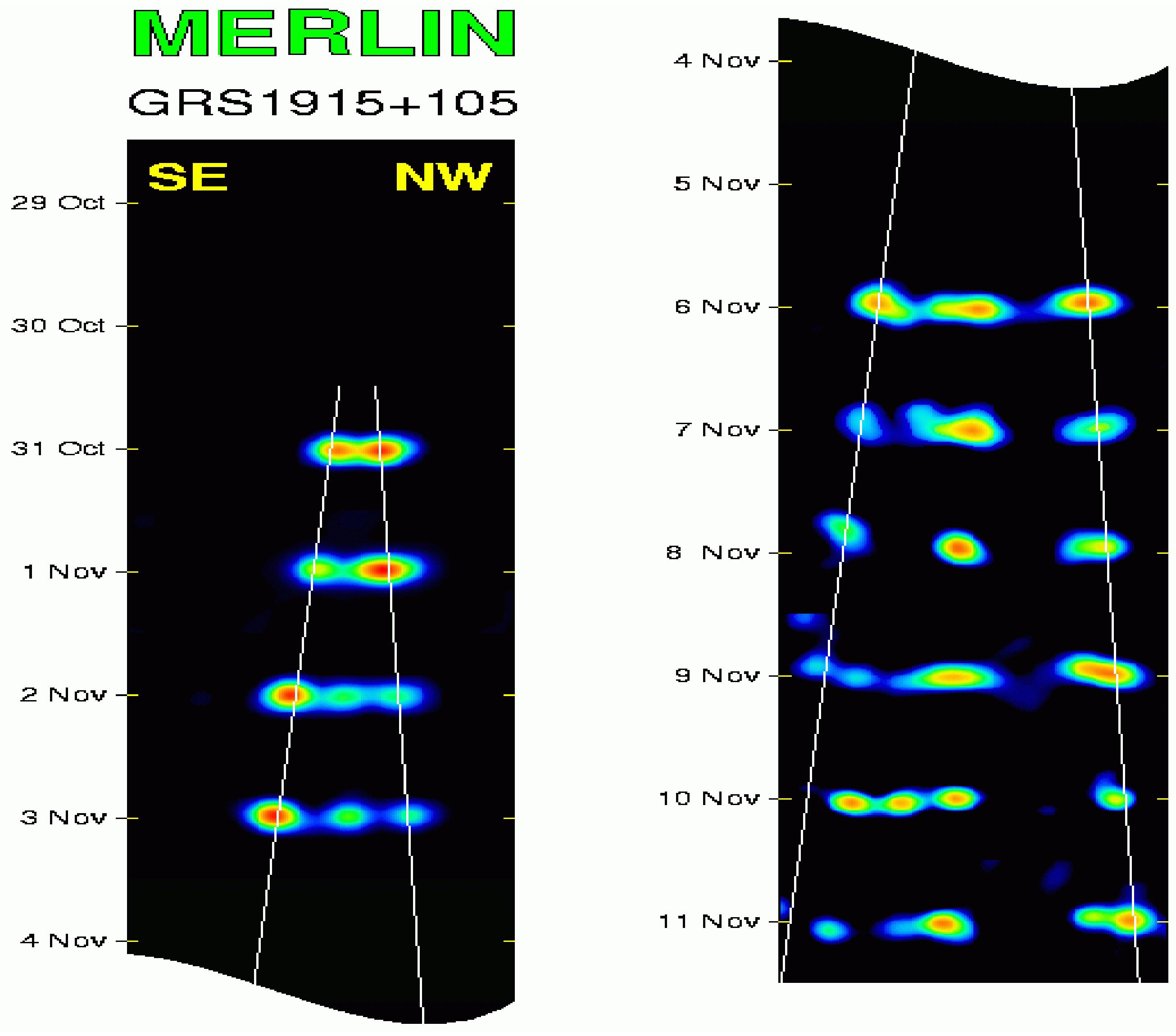
Dhawan et al. (2000)

Small physical size, inverted or flat radio spectra
→optically thick synchrotron emission from a self-absorbed outflow

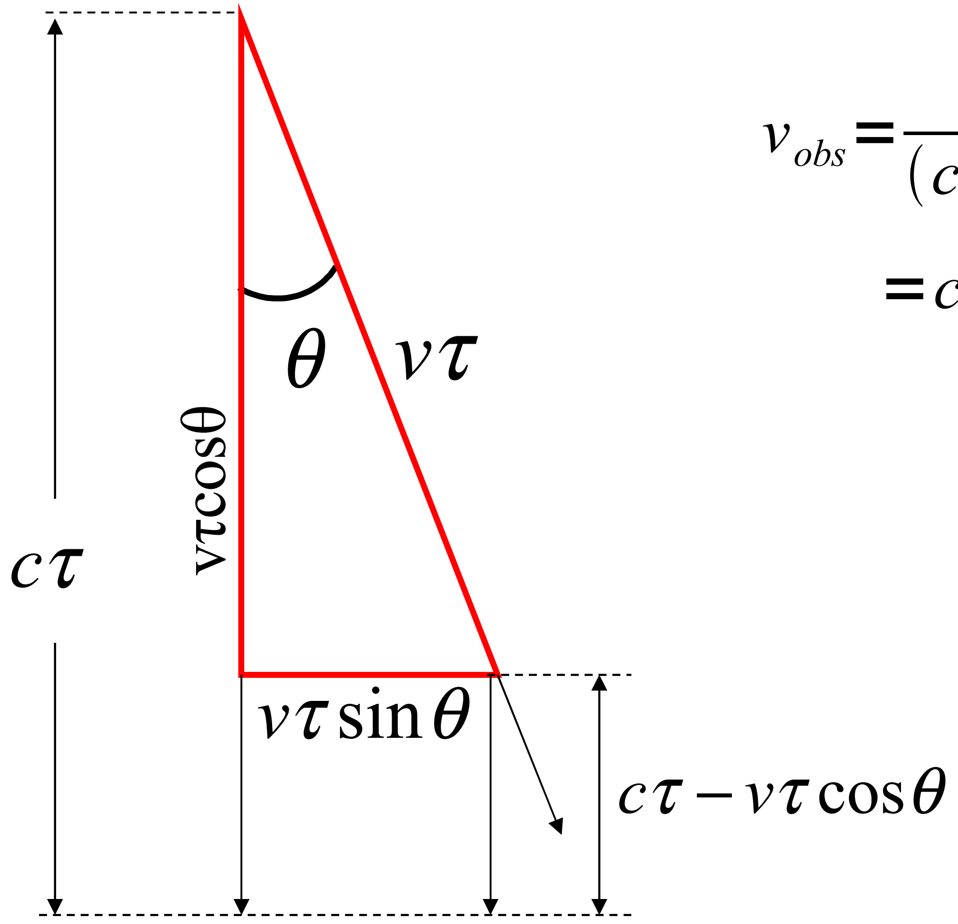


Markoff & Nowak (2004)

Superluminal Motion



Optical Illusion

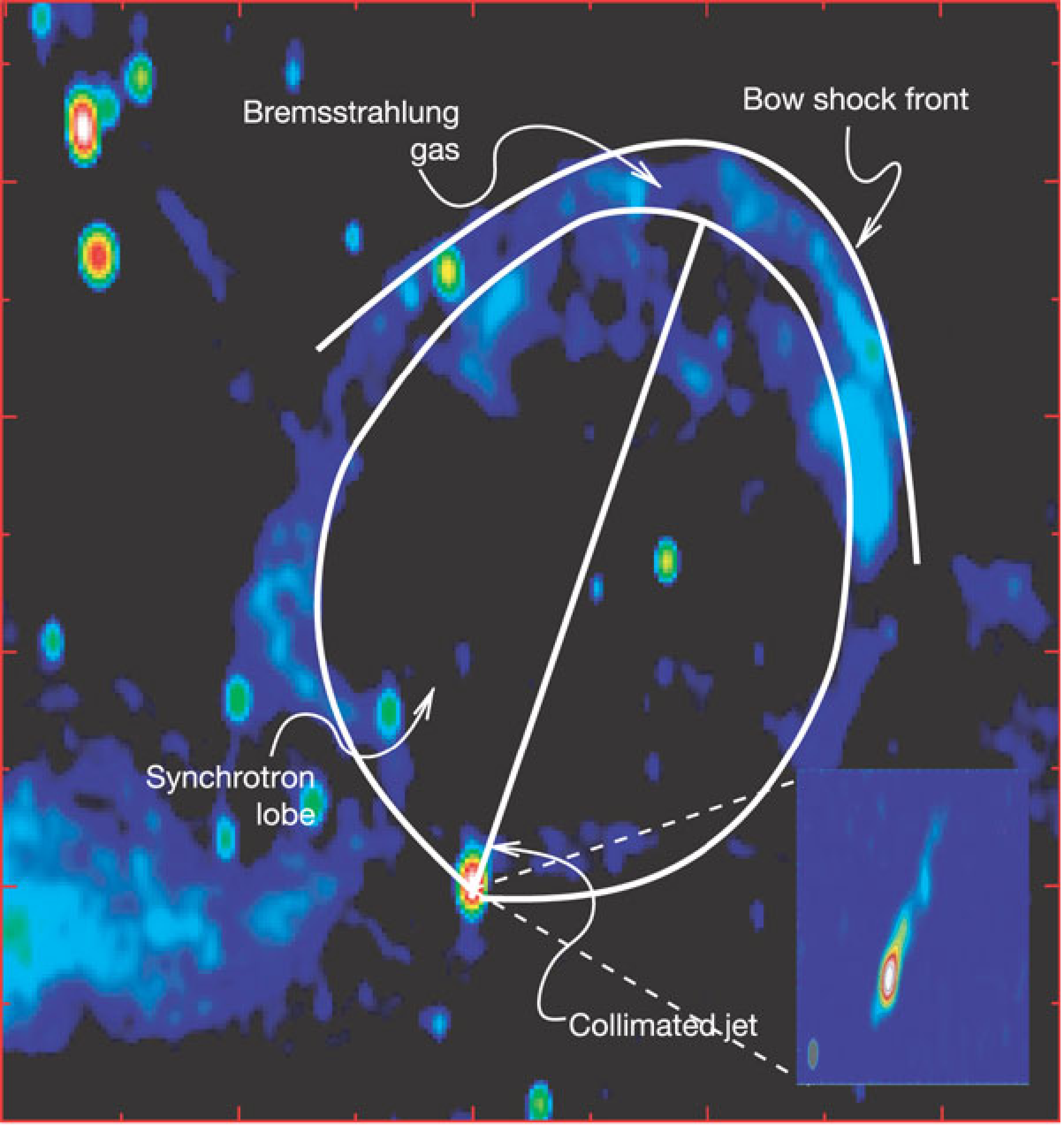


$$v_{obs} = \frac{v\tau\sin\theta}{(c\tau - v\tau\cos\theta)/c}$$

$$= c\frac{\beta\sin\theta}{1-\beta\cos\theta}$$

Seeing two jets gives us two equations to solve for velocity and inclination angle!

- What fraction of the total power output of compact objects is in jets versus radiated energy?



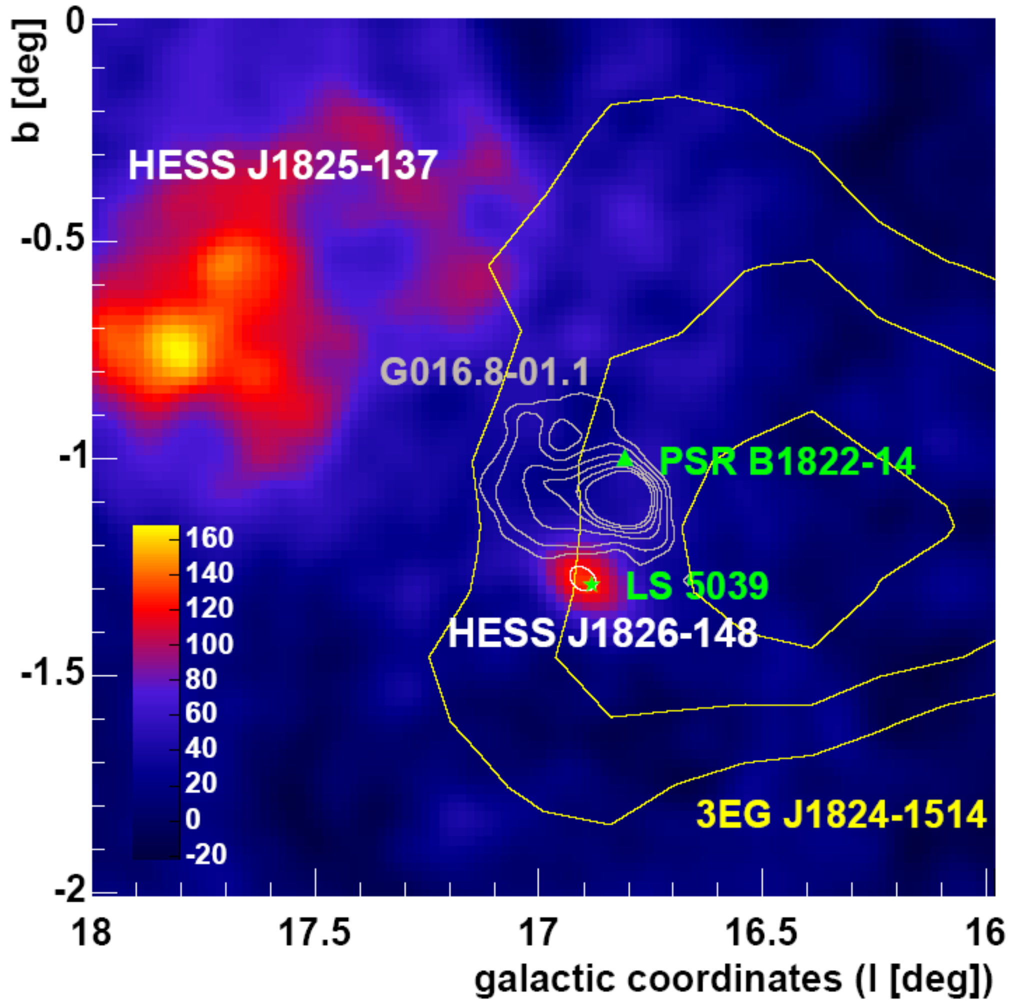
Gallo et al. 2004

Jet from Cygnus X-1

Radio/optical ring near Cyg X-1 serves as calorimeter for jet power.

Indicates ratio of jet power to X-ray luminosity is in the range 0.06 - 1.0.

TeV emission from LS 5039

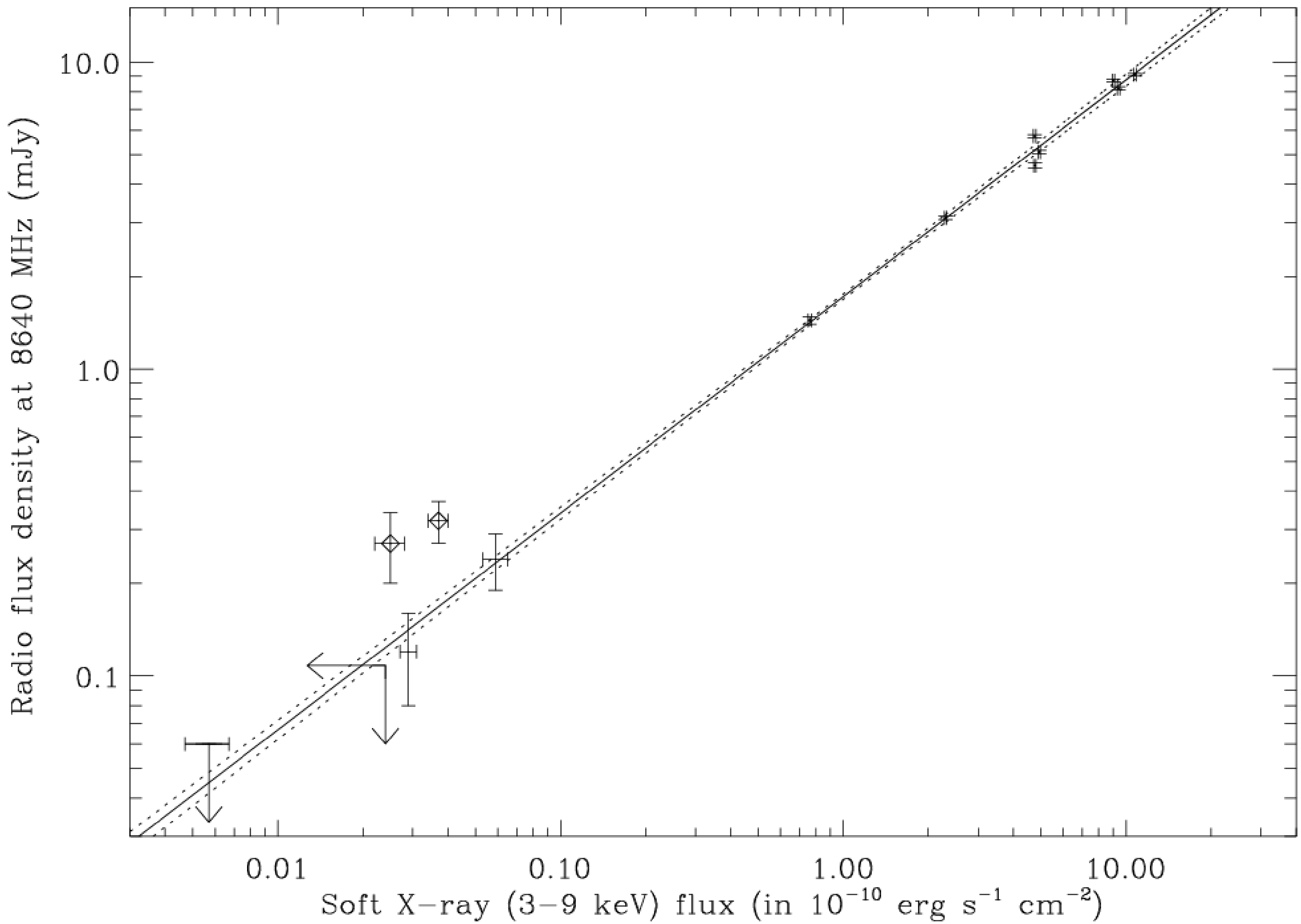


TeV from inverse-Compton of jet electrons on photons from O6.5V companion or jet protons interacting with stellar wind.

TeV luminosity indicates an extremely powerful outflow. For 10% acceleration efficiency, the jet kinetic power must be equal the X-ray luminosity.

Aharonian et al. 2005

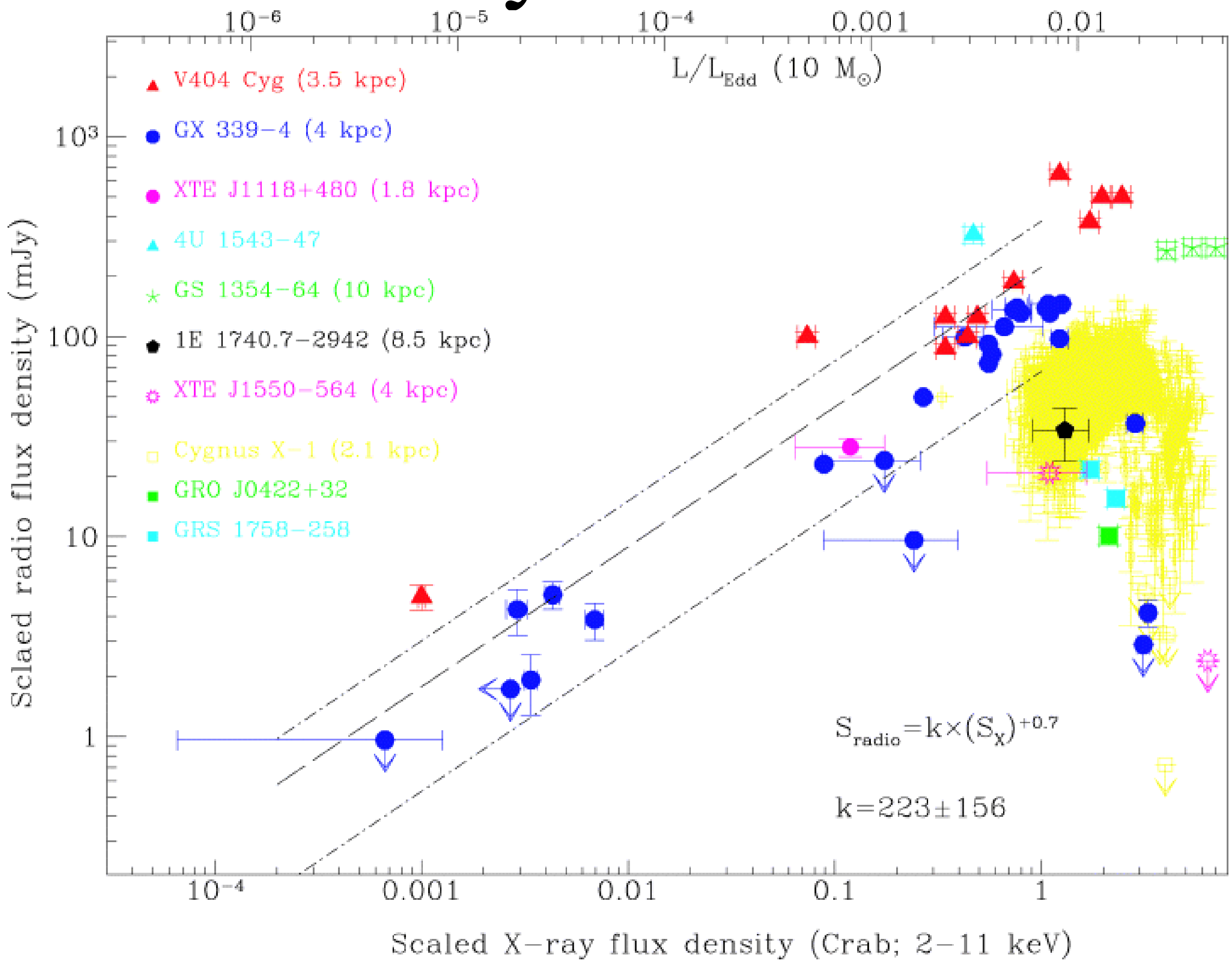
Radio/X-ray Flux Correlation



$F_{radio} \propto F_X^{+0.7}$

Corbel et al. (2000,2003)

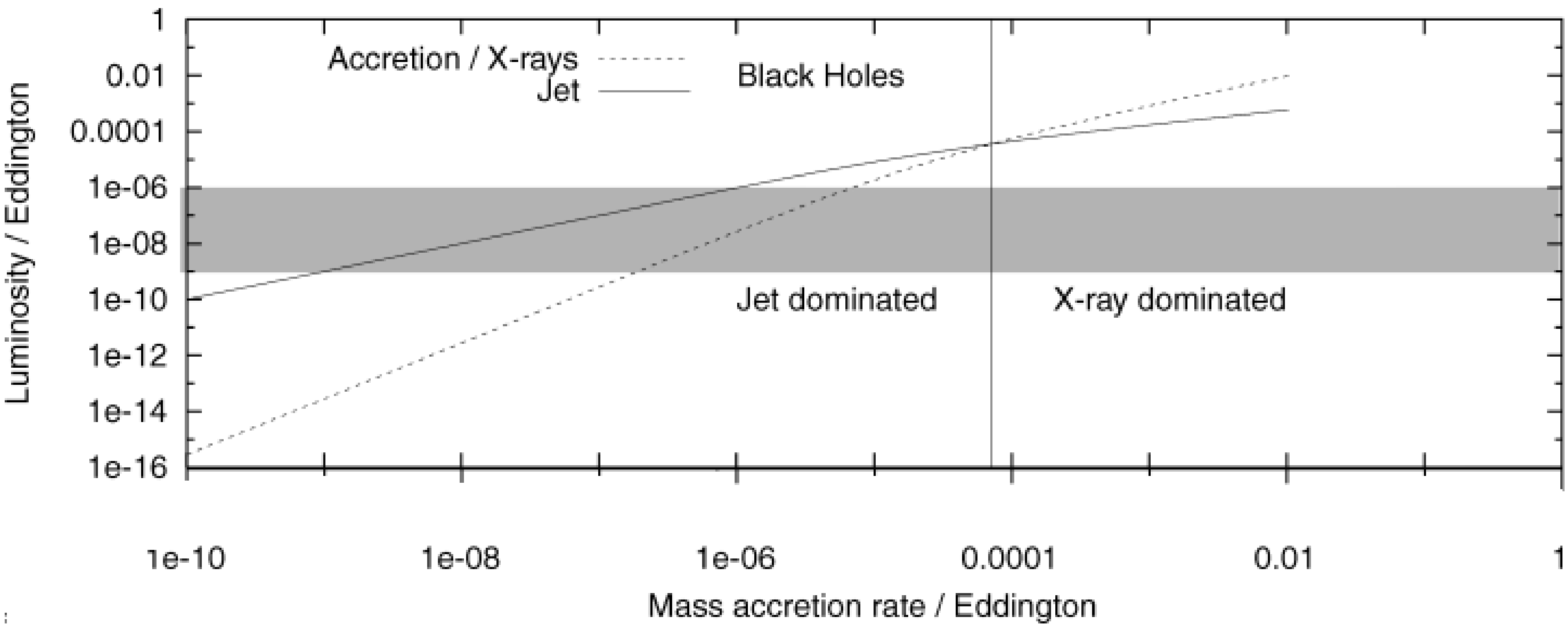
Radio/X-ray Flux Correlation



$F_{radio} \propto F_X^{+0.7}$

Corbel et al. (2000,2003)

Jet Domination at Low Accretion Rates

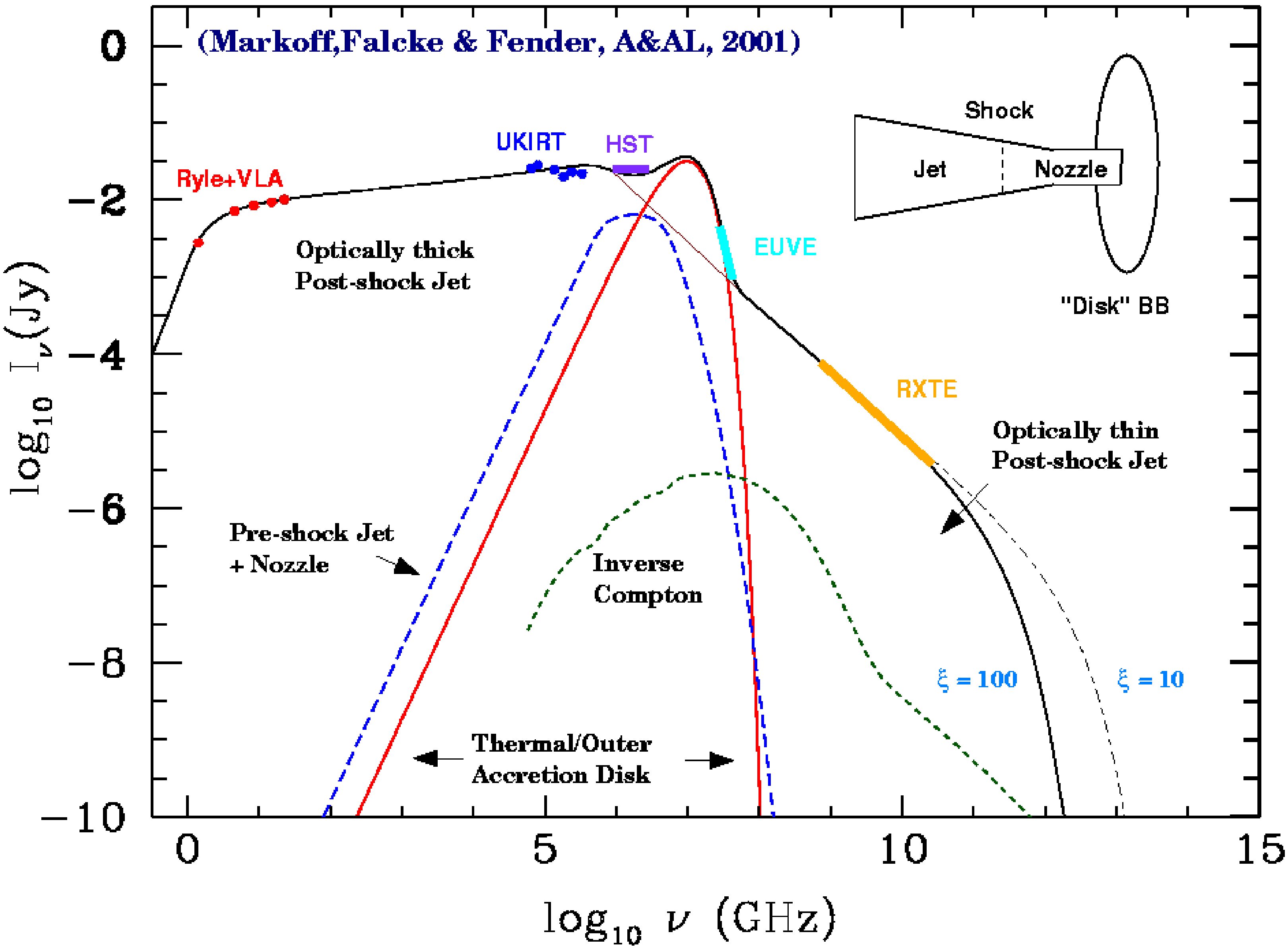


Fender et al. 2003

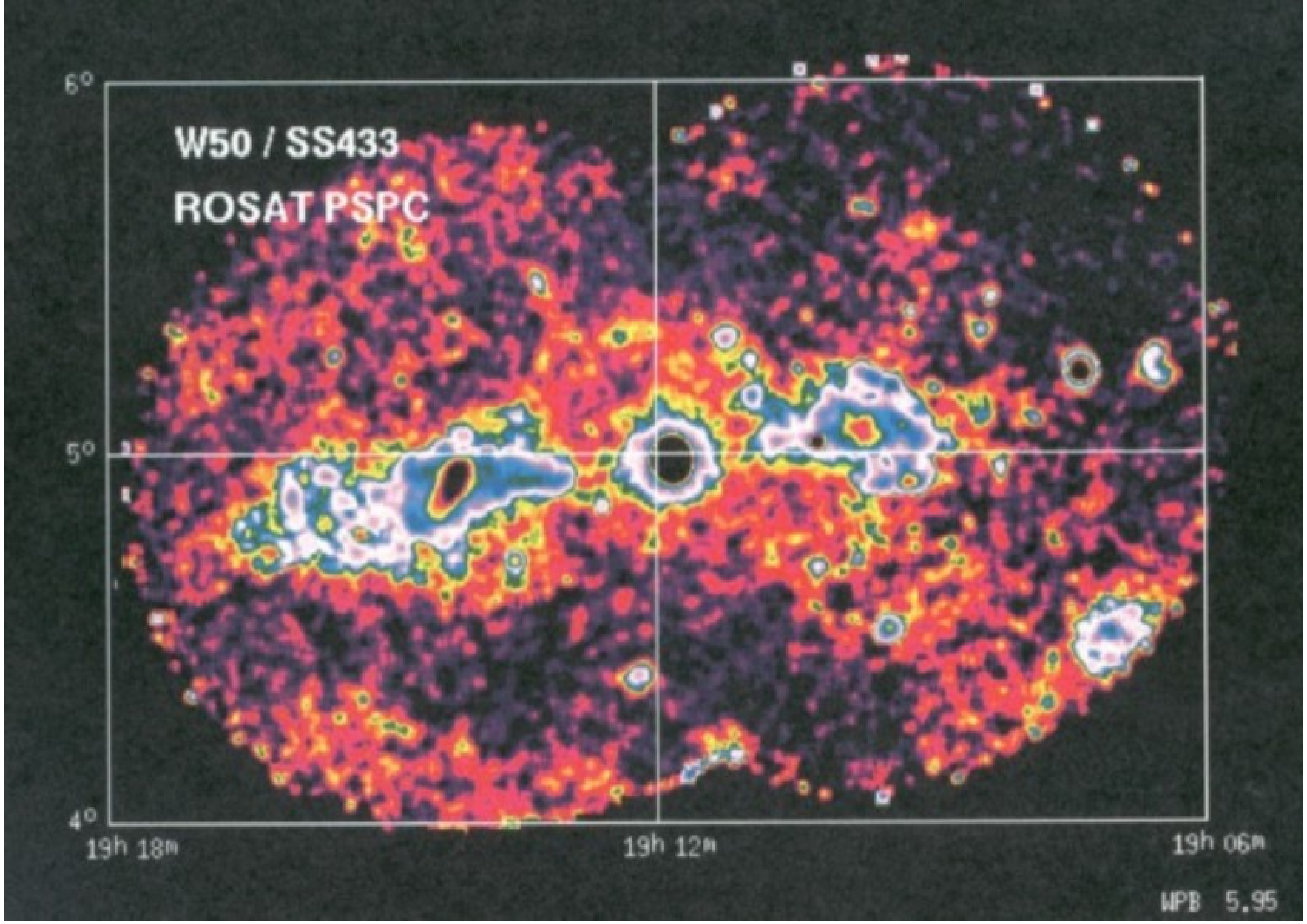
For optically thick jets, the jet power scales as $L_{radio} \propto L_{jet}^{0.5}$

At low accretion rates, this would suggest that the jet power dominates over the X-ray luminosity.

Do the Jets Produce X-Rays?

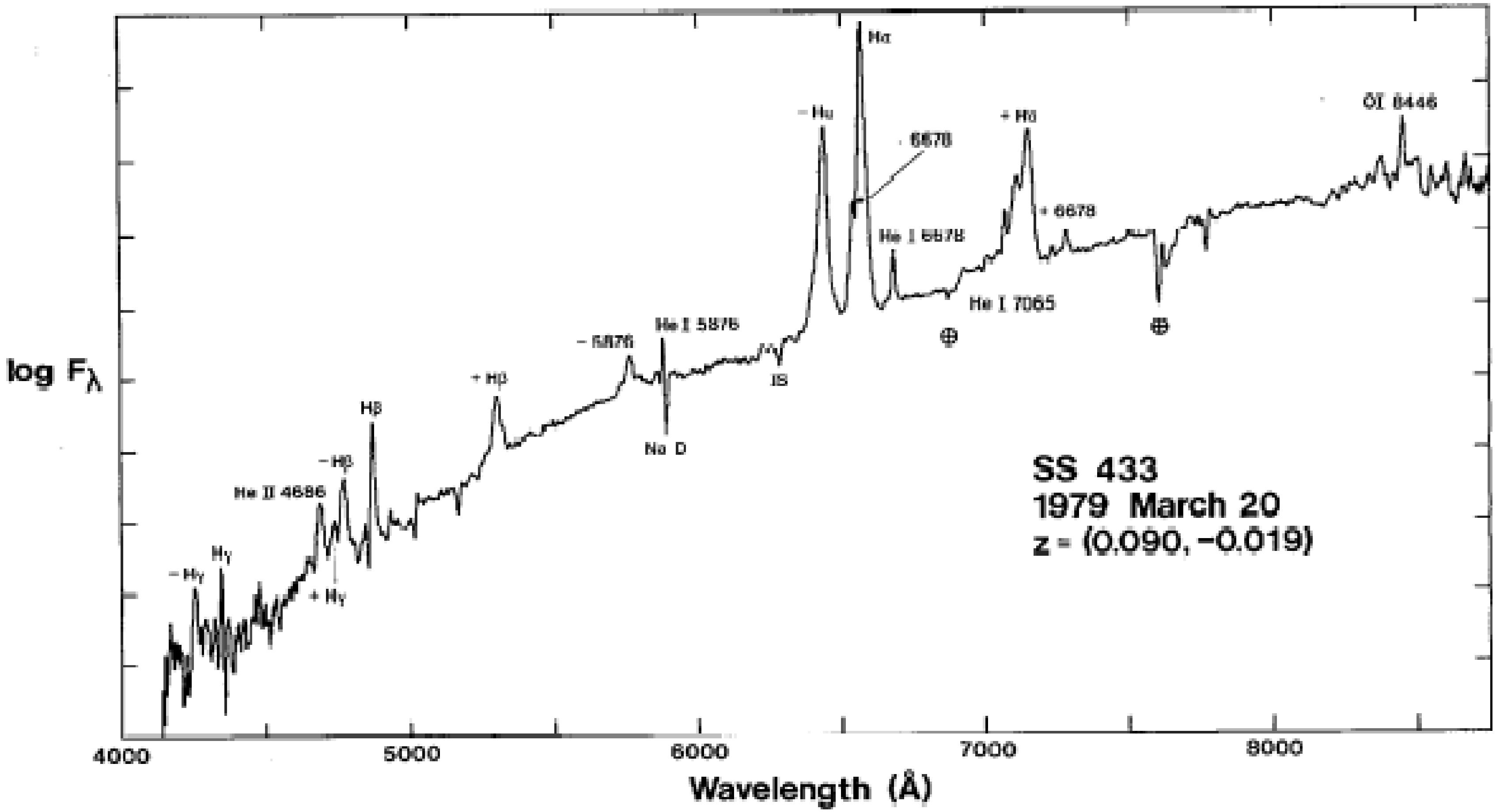


- Are jets electron/proton or electron/positron?



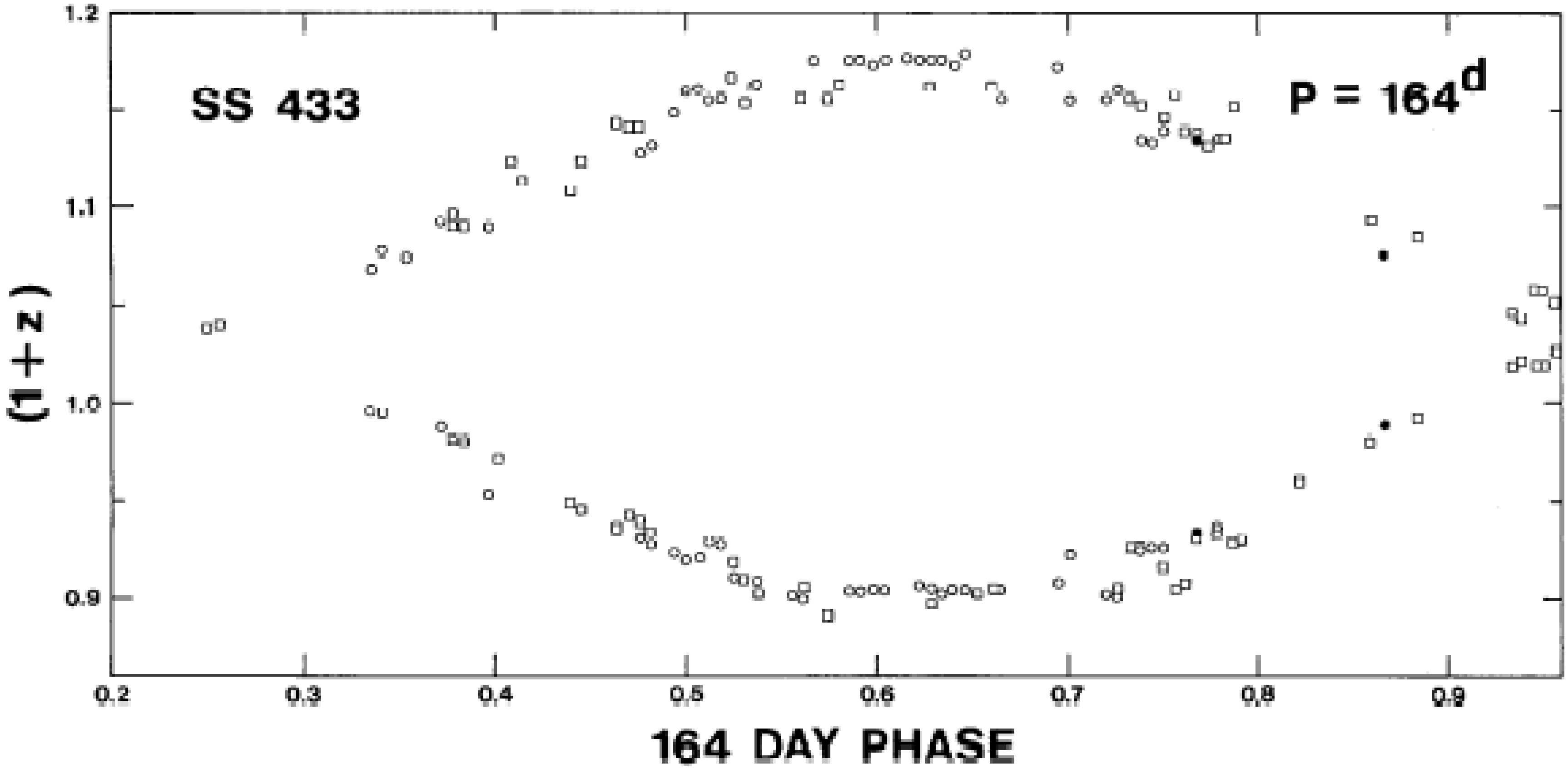
- Jet discovered via blue/red shifted Balmer emission lines (Margon et al. 1979)
- Jet extends to scales of 45' (60 pc) (Seward et al. 1980)
- Large scale jet is non-thermal (Kotani et al. 1994)

SS 433 Optical Spectrum

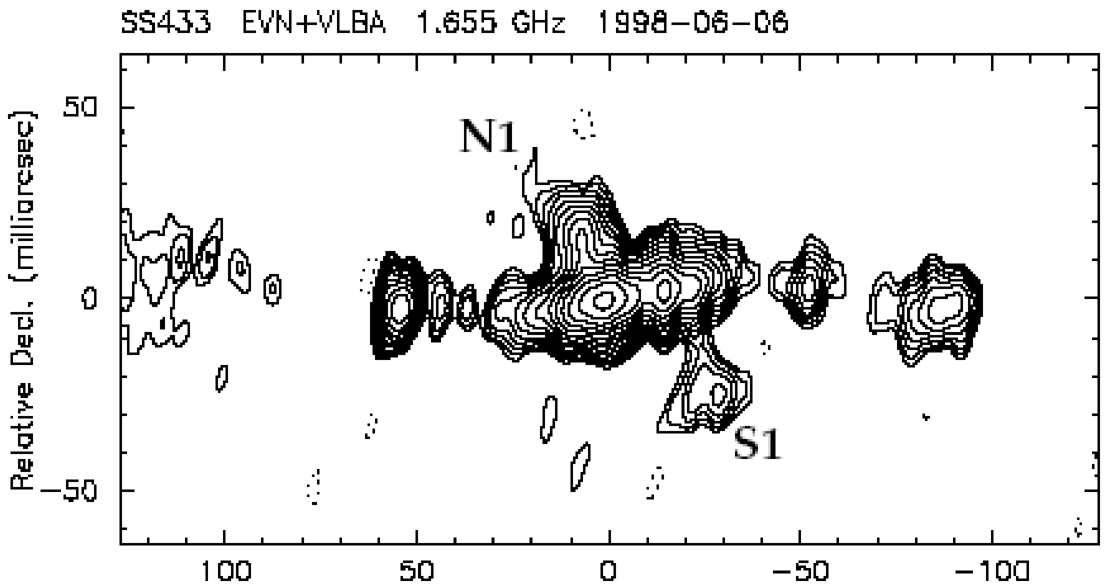


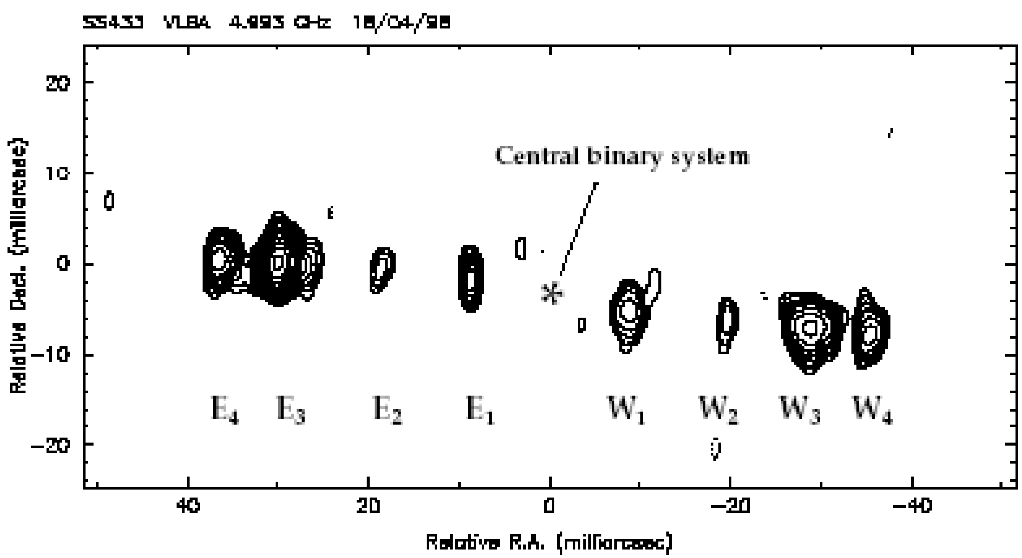
Margon et al. 1979

SS 433 Hβ variations



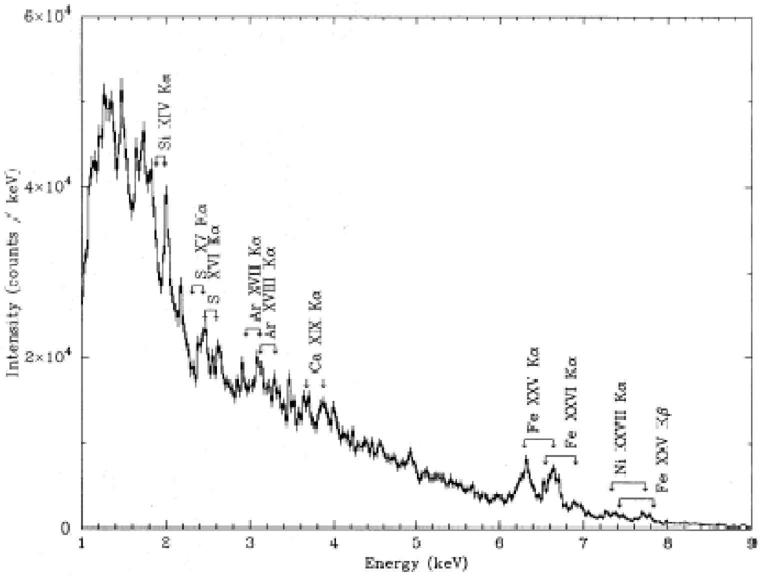
High-resolution image of SS433



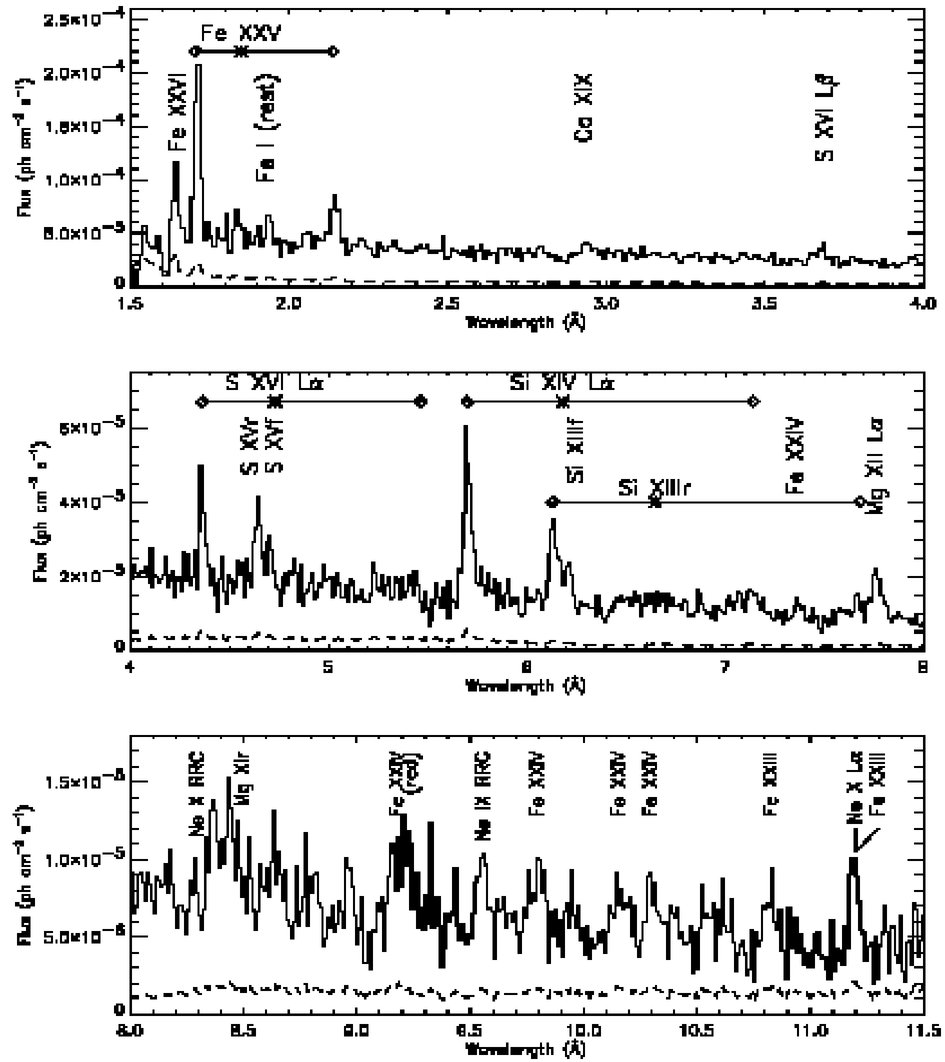


X-rays from the jets

ASCA

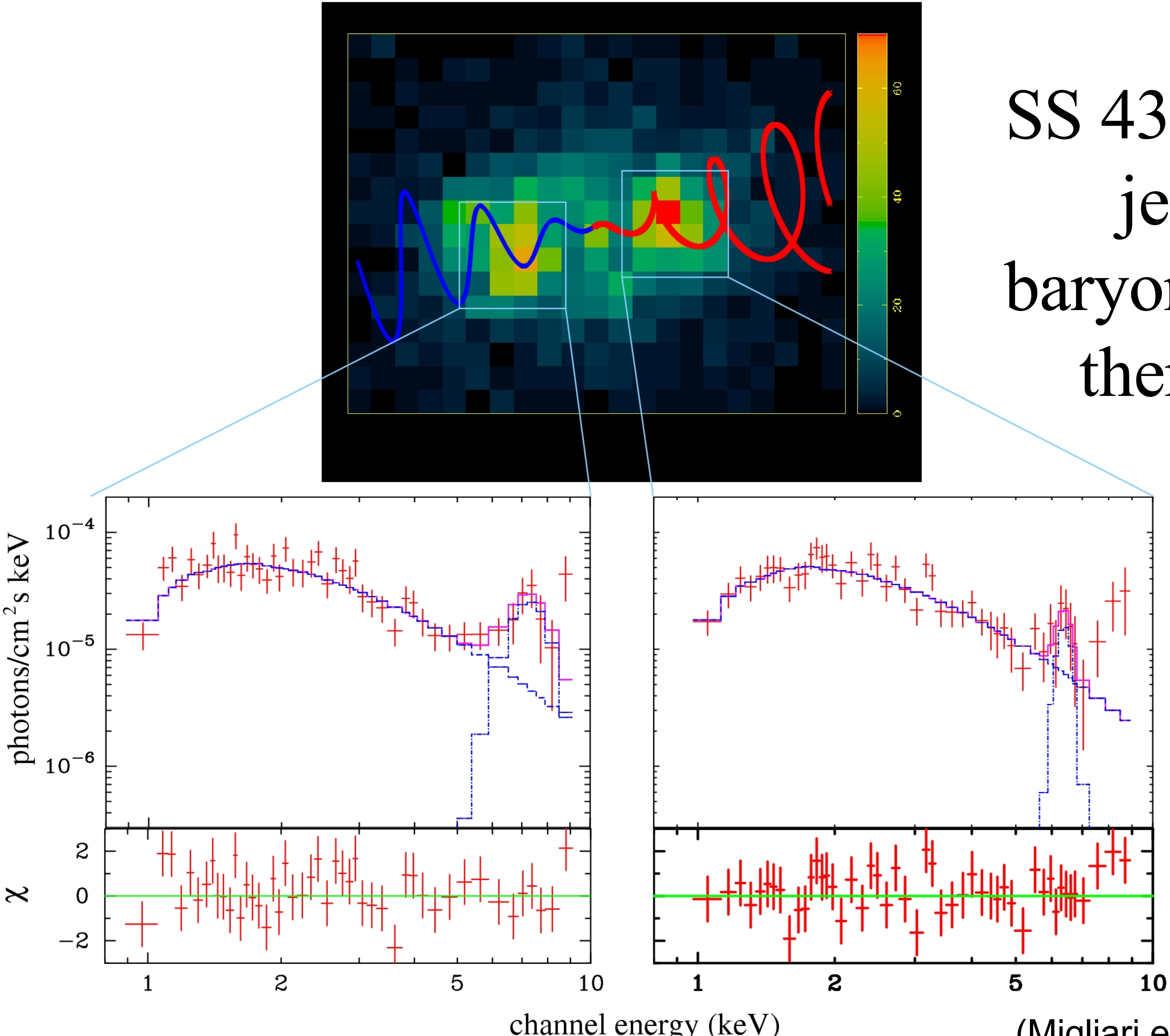


Chandra



- **Baryonic**
- **Highly ionized**
- **Collisional excitation**
- **Large temperature and density gradients**

SS 433 inner jet is baryonic and thermal

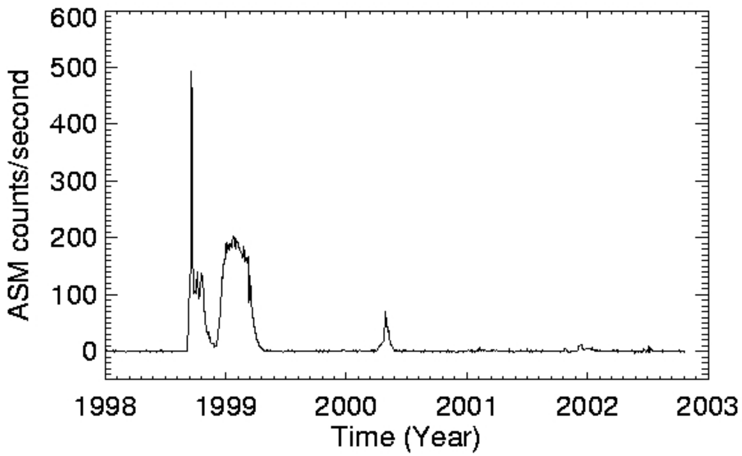


(Migliari et al. 2002)

Questions

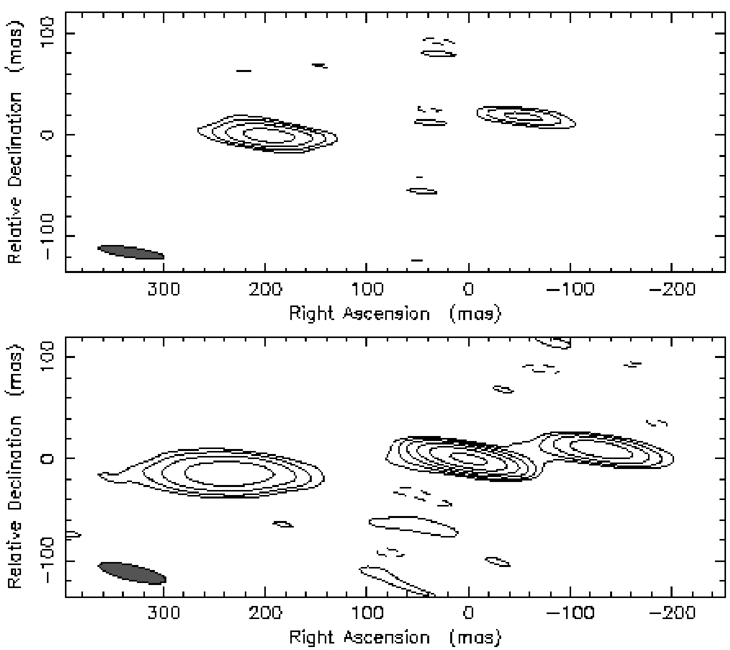
- Are jets re-energized at large distances from origin?

Outbursts of XTE J1550-564



Discovery outburst in 9/1998

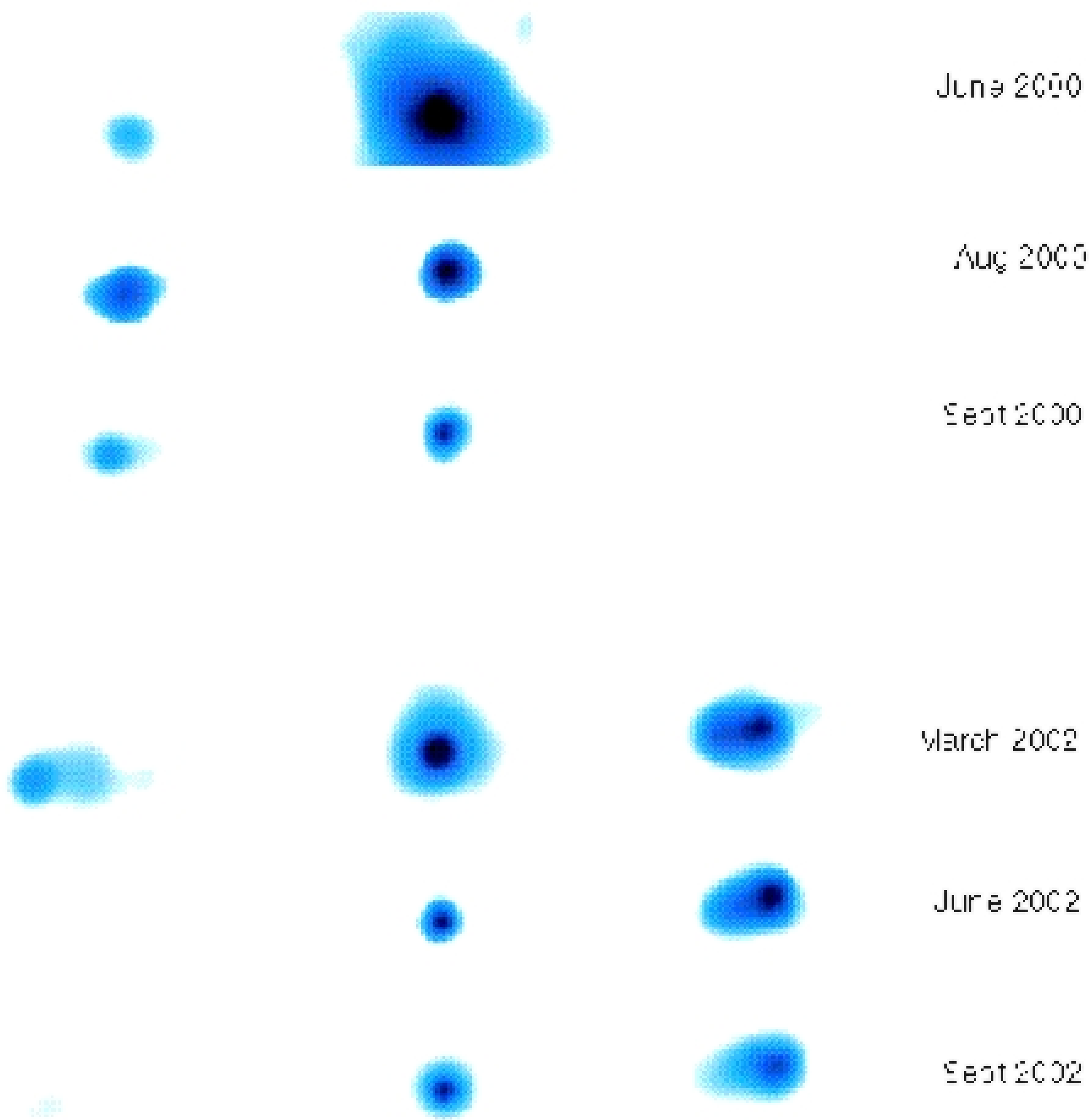
Activity in 2000, 2001/2002, 2003.



Radio jets in 9/1998 (Hannikainen et al. 2001)

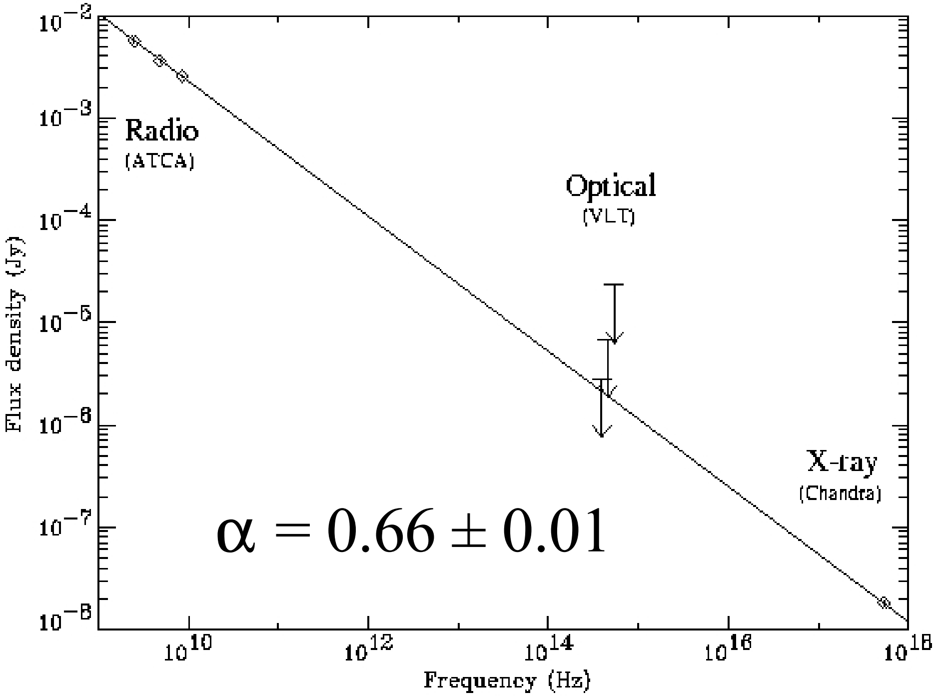
Separation speed > 2c.

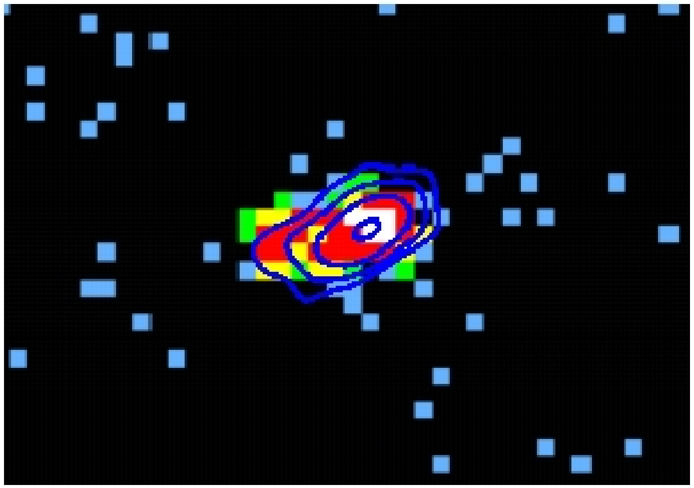
Large Scale jets of XTE J1550-564



Corbel et al. 2002,
Kaaret et al. 2003

Emission mechanism





Contours = radio, pixels = X-ray

$\rightarrow$Synchrotron emission from single population.

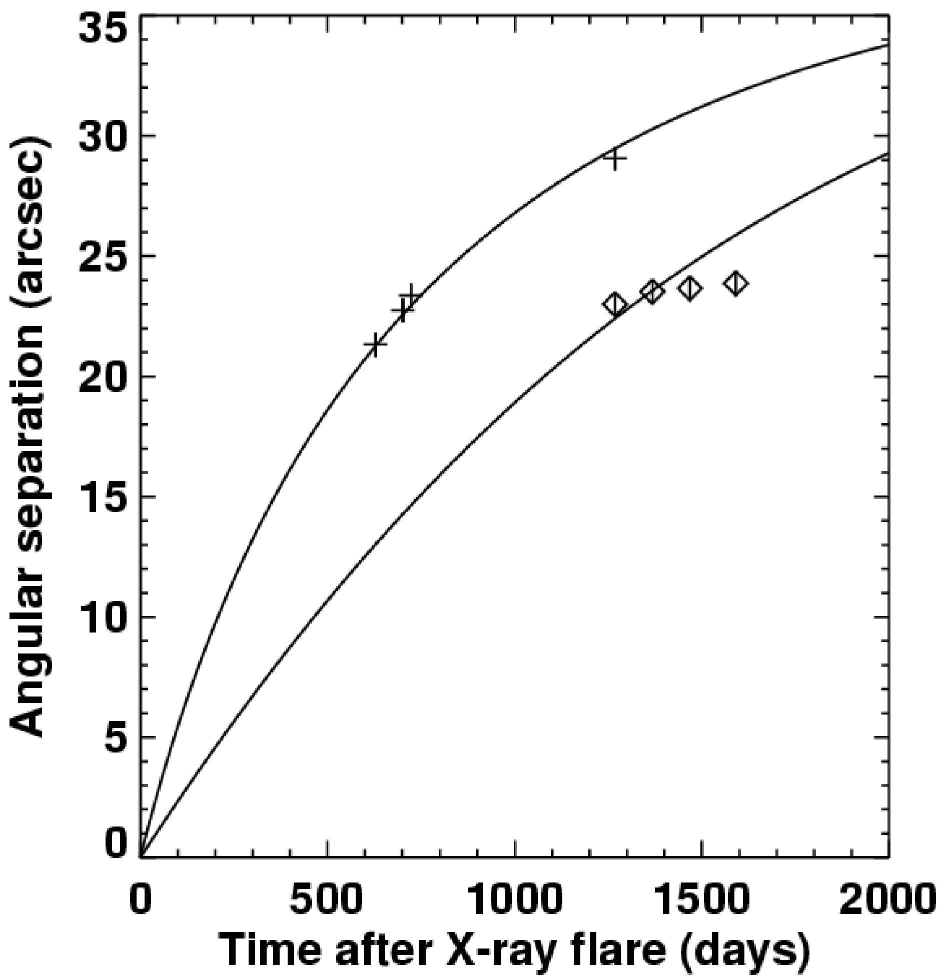
Equipartition $\rightarrow$B ~ 300 μG

X-ray emitting electrons: $\gamma_e > 2 \times 10^7$, energy ~ TeV

Number electrons ~ 10^{45} ; if one p/e, mass ~ 10^{21} g

Syncrotron lifetime ~ 10 years

Jet deceleration



- Approaching jet decelerates gradually.
- Receding jet brightens only after sharp deceleration.
- Approaching jet kinetic energy loss rate of 10^{34} erg/s in June 2000. Luminosity is 10^{32} erg/s.
- Need ~ 1% efficiency for conversion of bulk deceleration to particle acceleration.

First direct observation of gradual deceleration of BH jet.

Jet/ISM Interactions

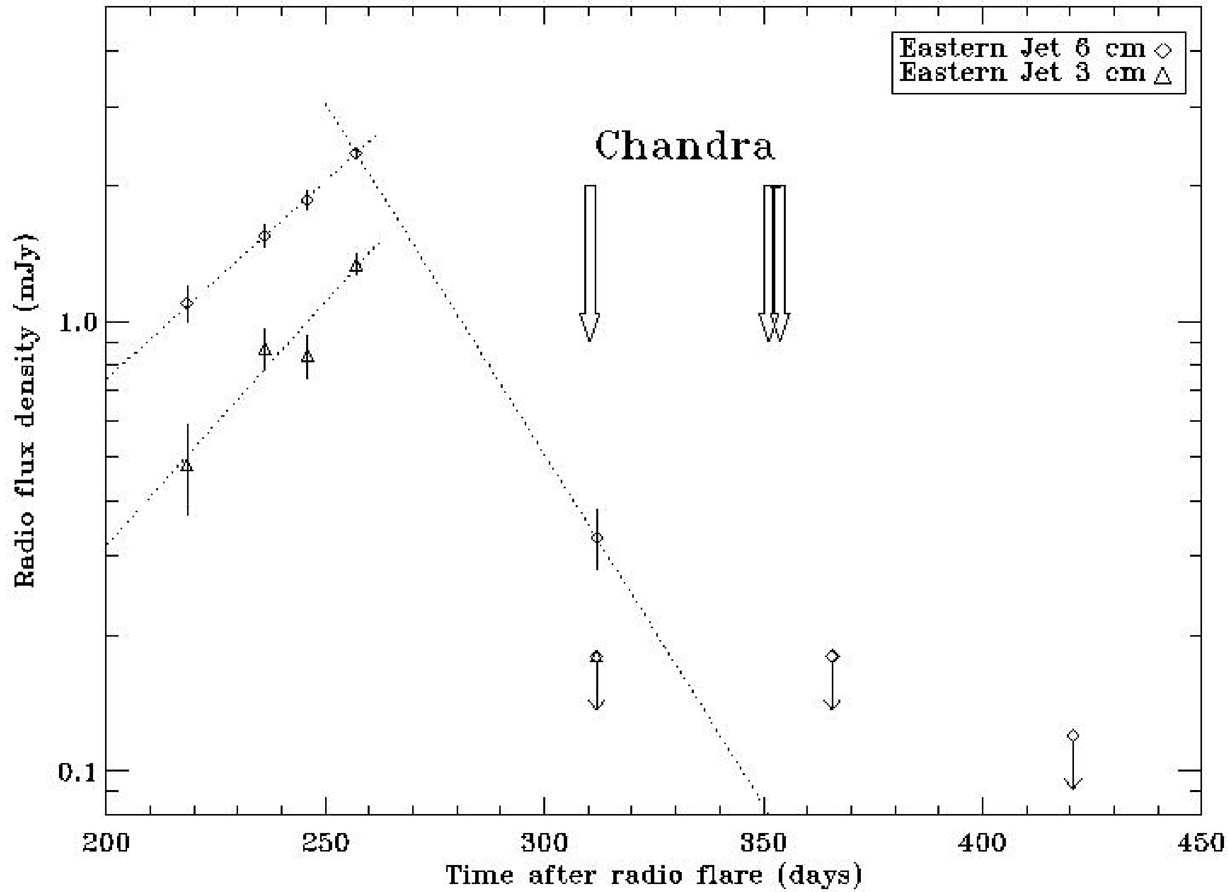
- Appear to have in-situ particle acceleration
- Deceleration from profile fitted to eastern jet implies kinetic energy loss rate ~ 10^{34} erg/s in June 2000. Compare to luminosity ~ 10^{32} erg/s

→need efficiency of ~ 1% for conversion of bulk deceleration to particle acceleration

Mechanism?

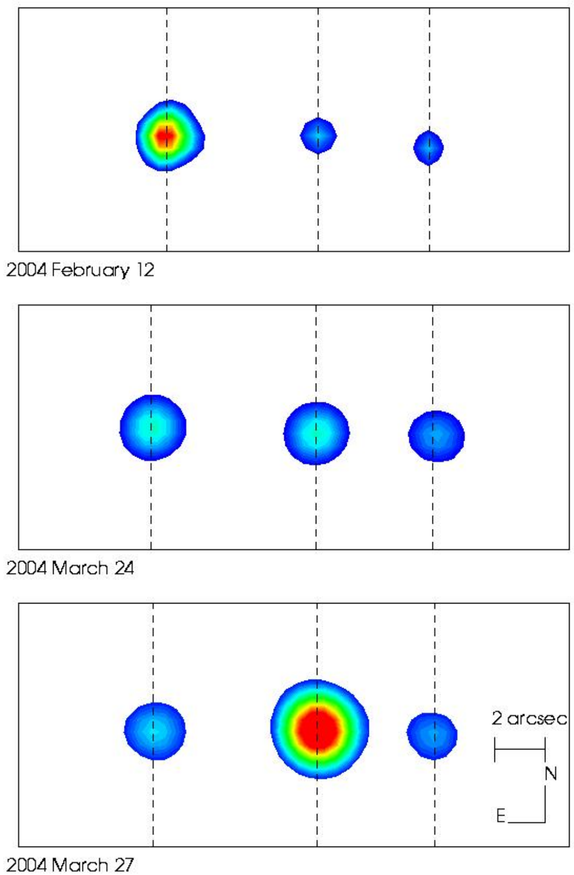
- Internal shocks: internal instabilities, varying flow speed
- External shocks: interactions with denser ISM

Large scale jet in H1743-322

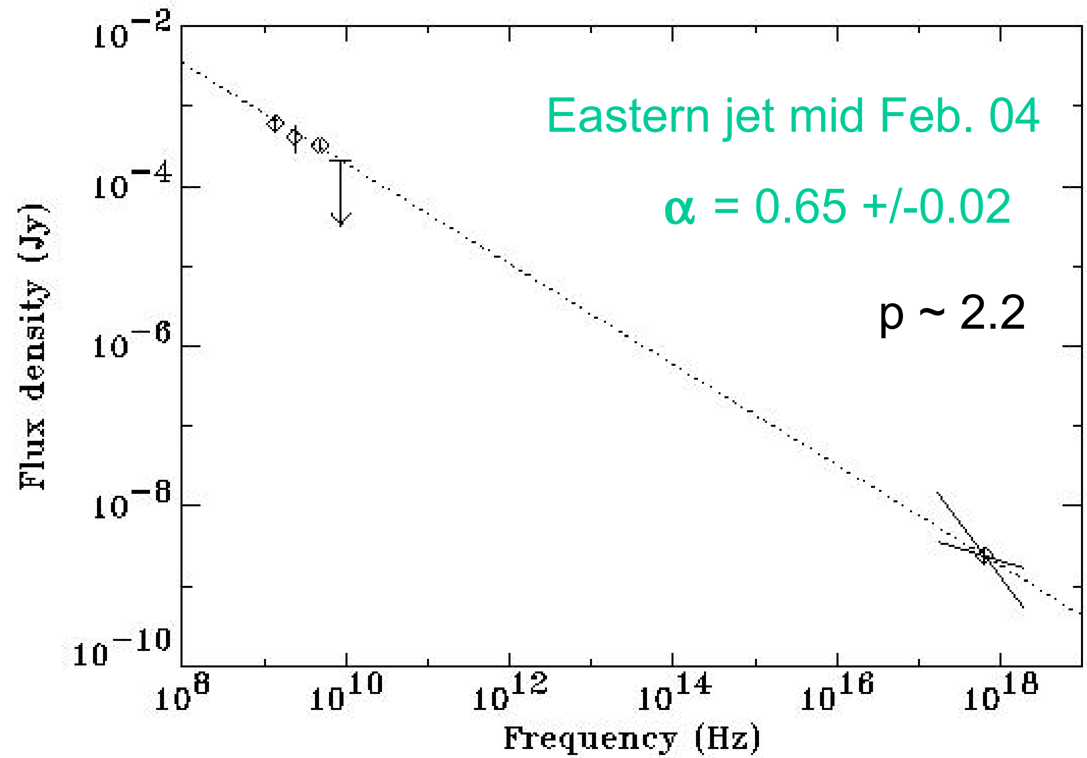


- Outburst starting in March 2003
- Radio flare on April 8
- Radio rise in ~ 45 days, decay in ~ 30 days

X-ray jets in H1743-322

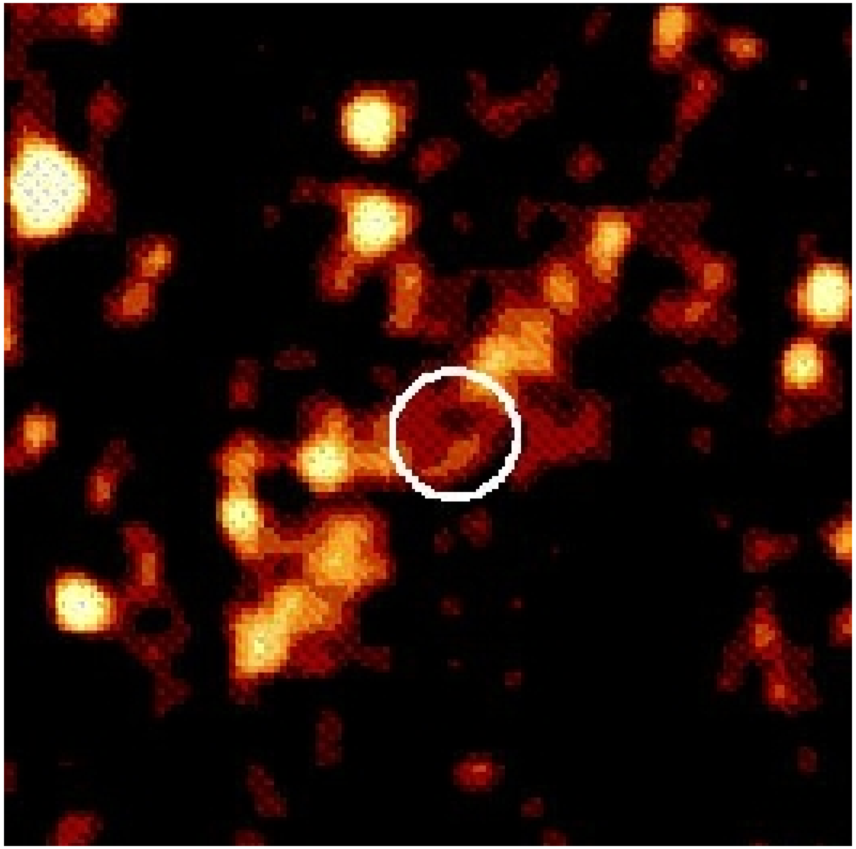


E. jet W. Jet



Similar properties to the X-ray jets of XTE J1550-564, but decay is much faster (Corbel et al. 2005).

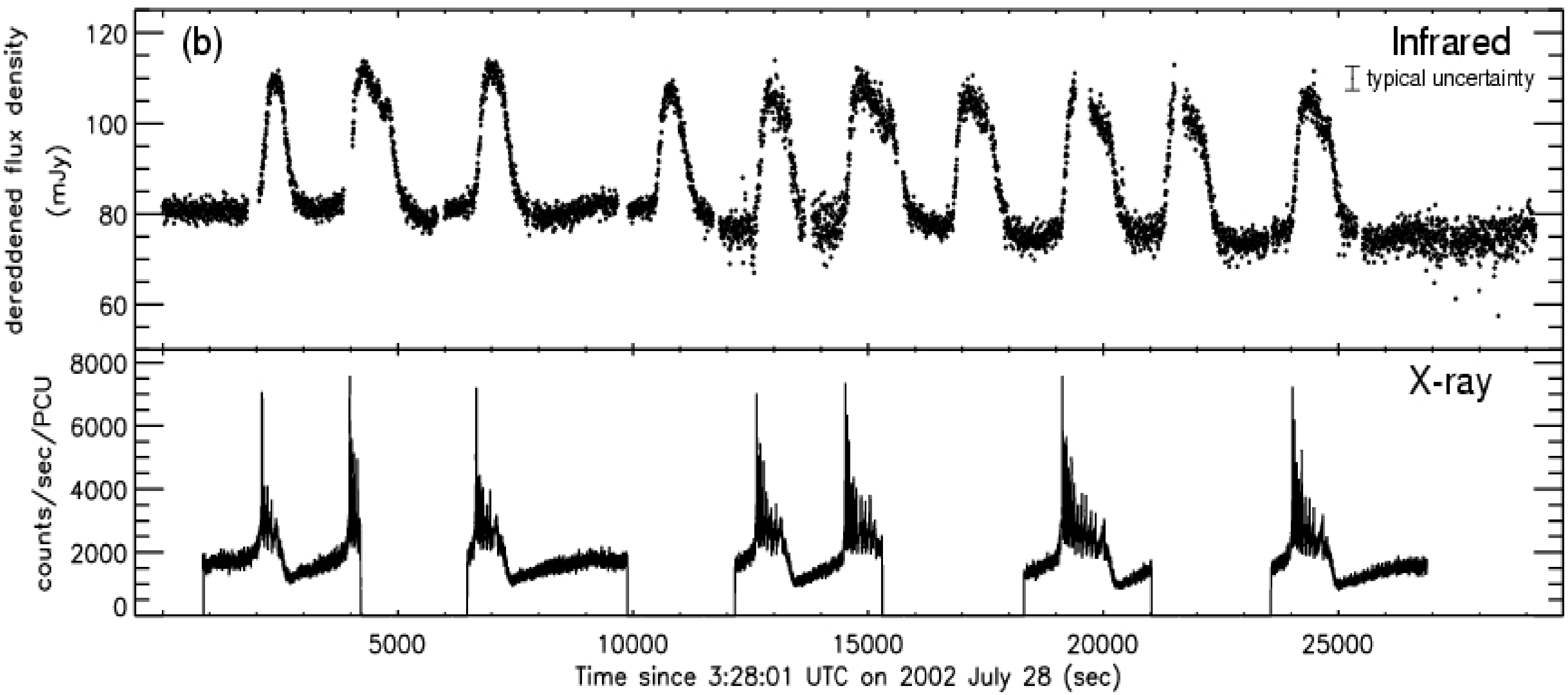
Fossil Jet from 4U 1755-33



(Angelini & White 2003; Kaaret et al. 2005)

- Source was active for at least 20 years
- X-ray jet extends ~ 4 pc
- Thermal X-ray emission is ruled out
- Synchrotron is OK
  - TeV electrons
  - B ~ 100 μG
- Long lifetime of jet means particles injected into ISM continuously for decades

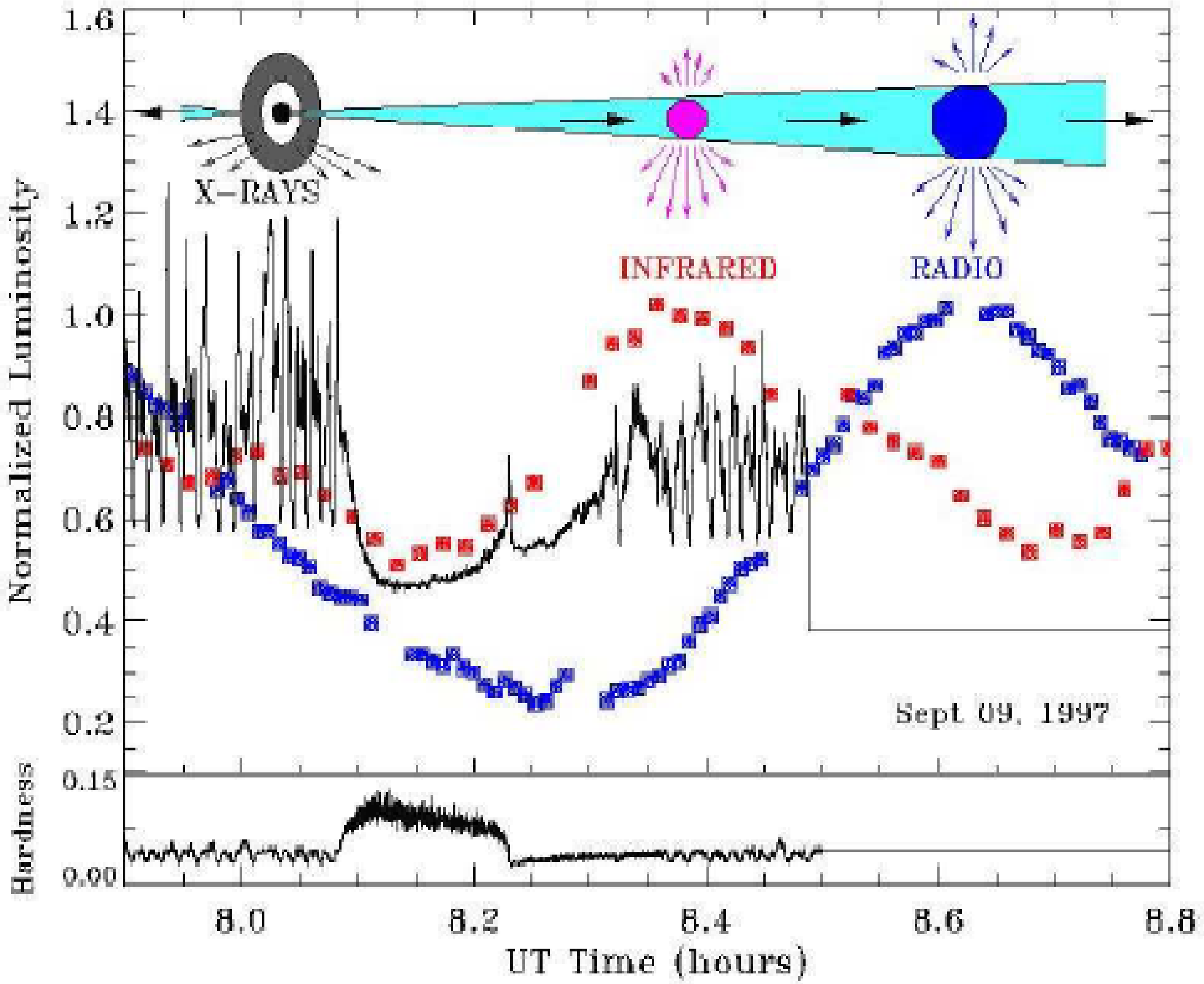
Jet Production



Eikenberry et al. 1998

Simultaneous IR (jet) and X-ray observations of GRS 1915+105 show jet ejection is tightly correlated with rapid disapperance of accretion disk.

Jet Production



Cooling of particles in the jets due to adiabatic expansion