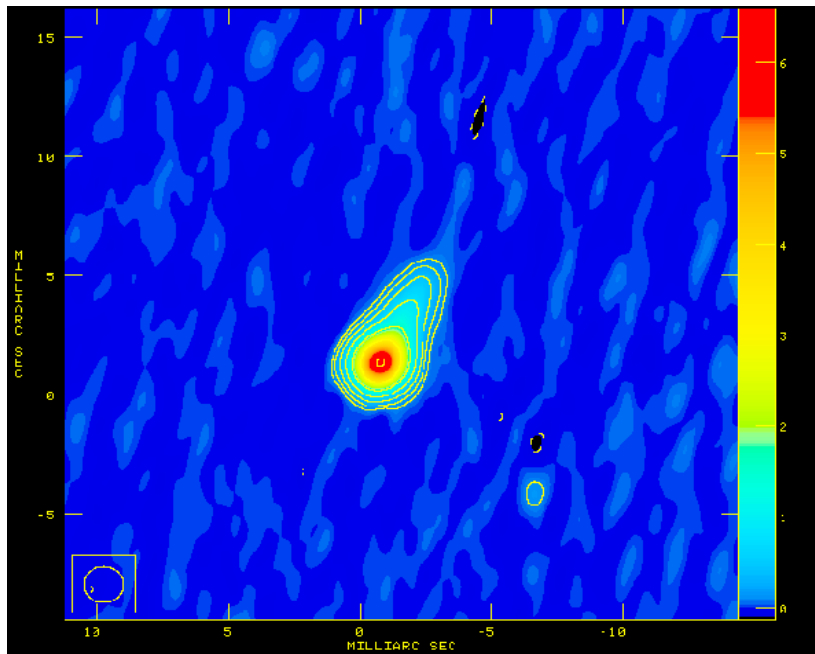


# Jets

- 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

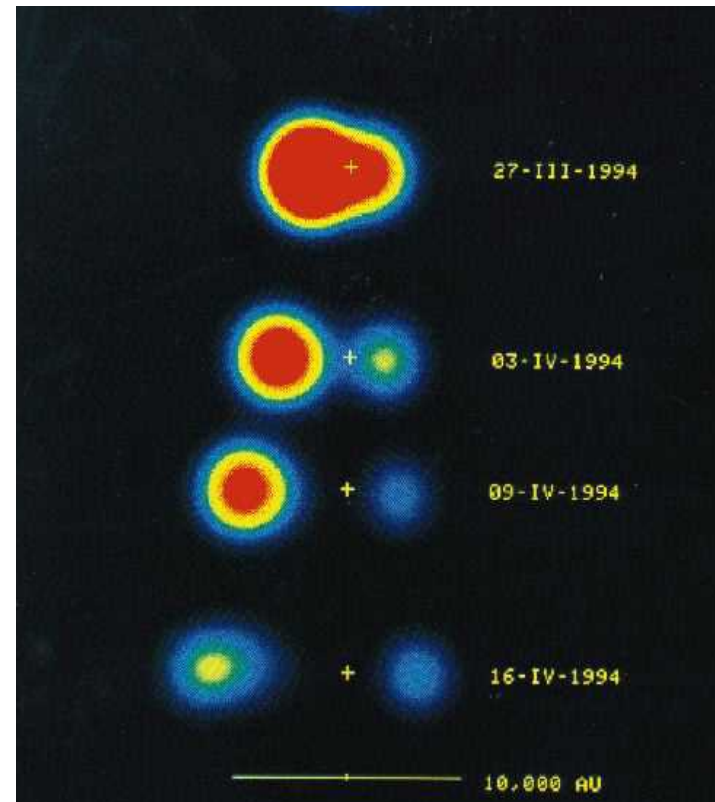
Compact – tens of AU, found  
in low/hard X-ray state



Stirling et al. 2001

High/soft state – no jet

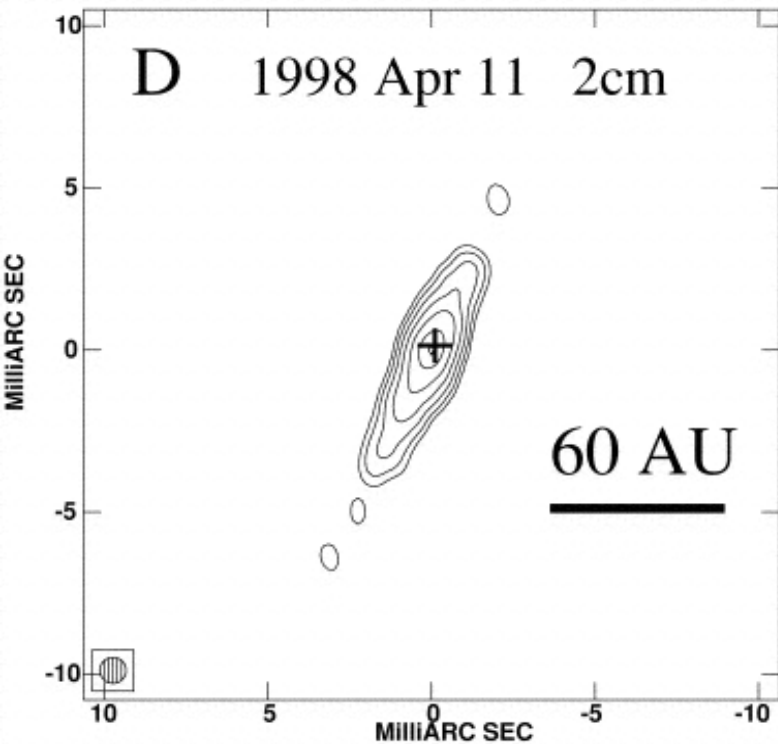
Large scale – up to parsecs,  
produced at state transitions



Mirabel et al. 1994

# Compact jets

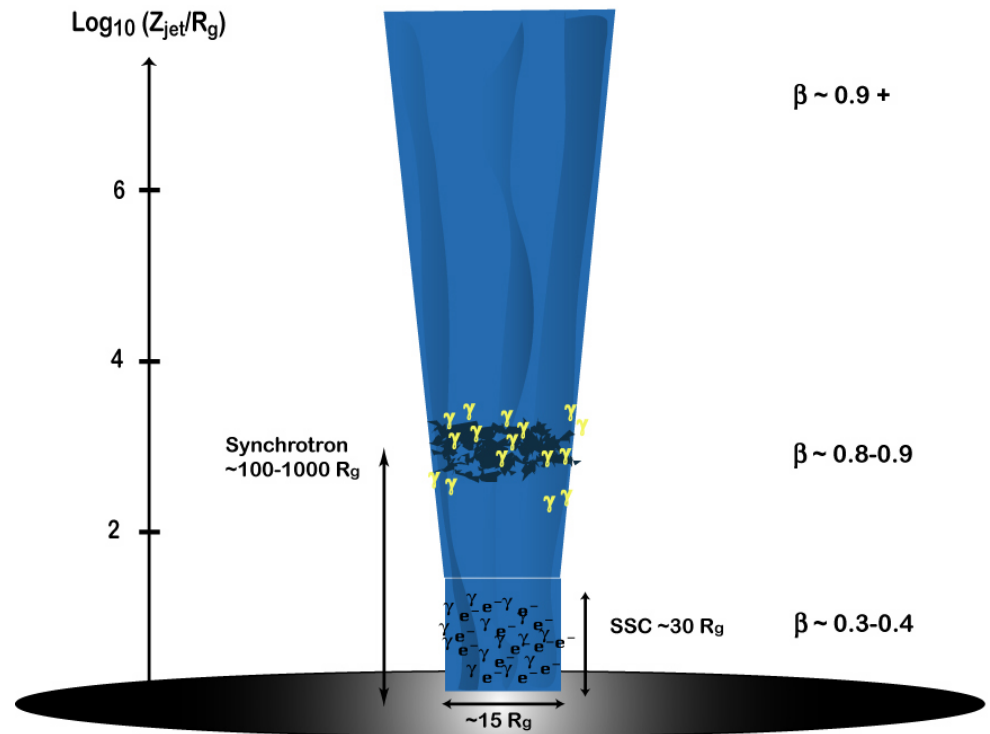
## GRS 1915+105



Dhawan et al. (2000)

Markoff & Nowak (2004)

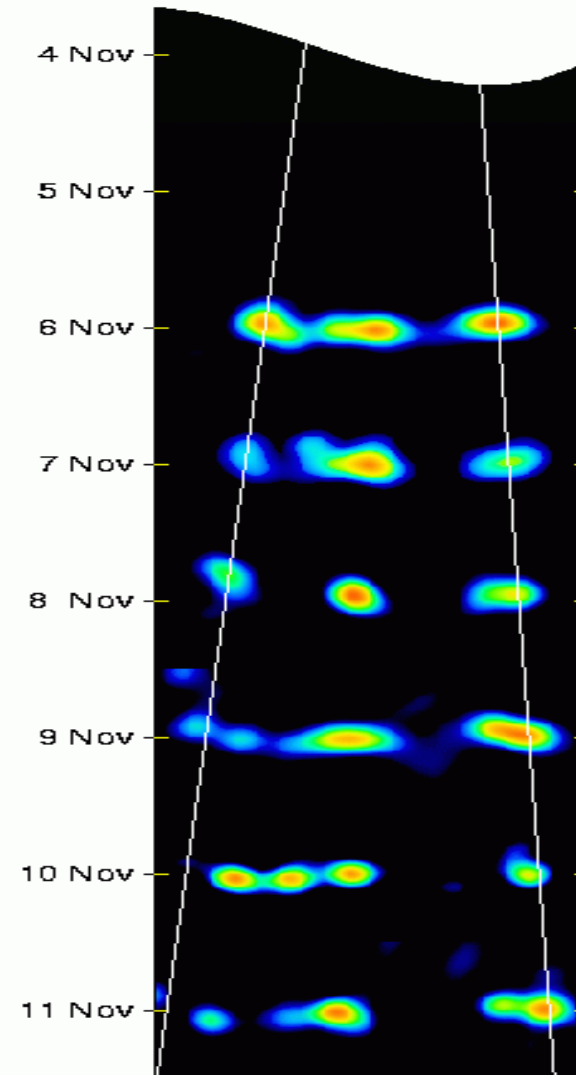
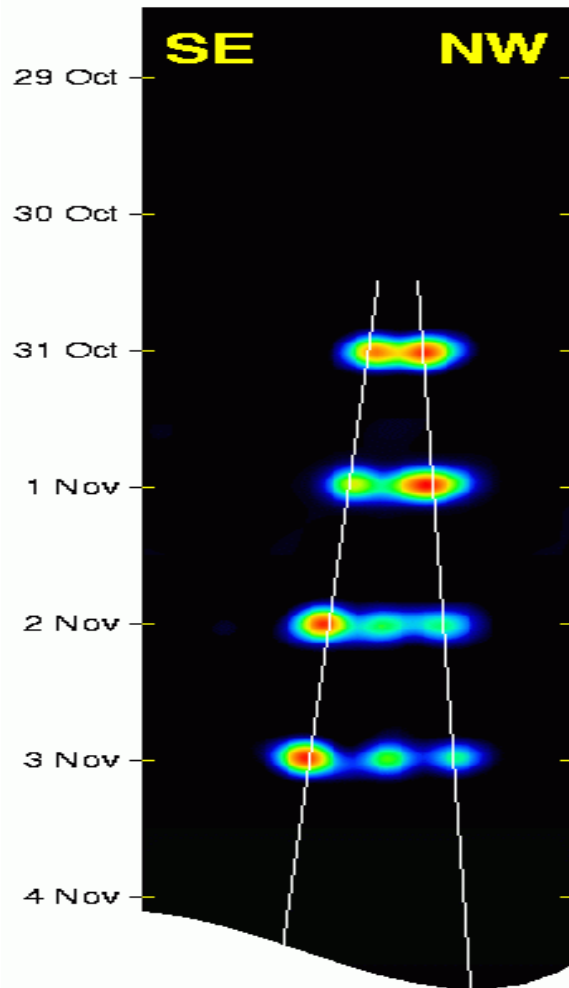
Small physical size, inverted or flat radio spectra  
 → optically thick synchrotron emission from a self-absorbed outflow



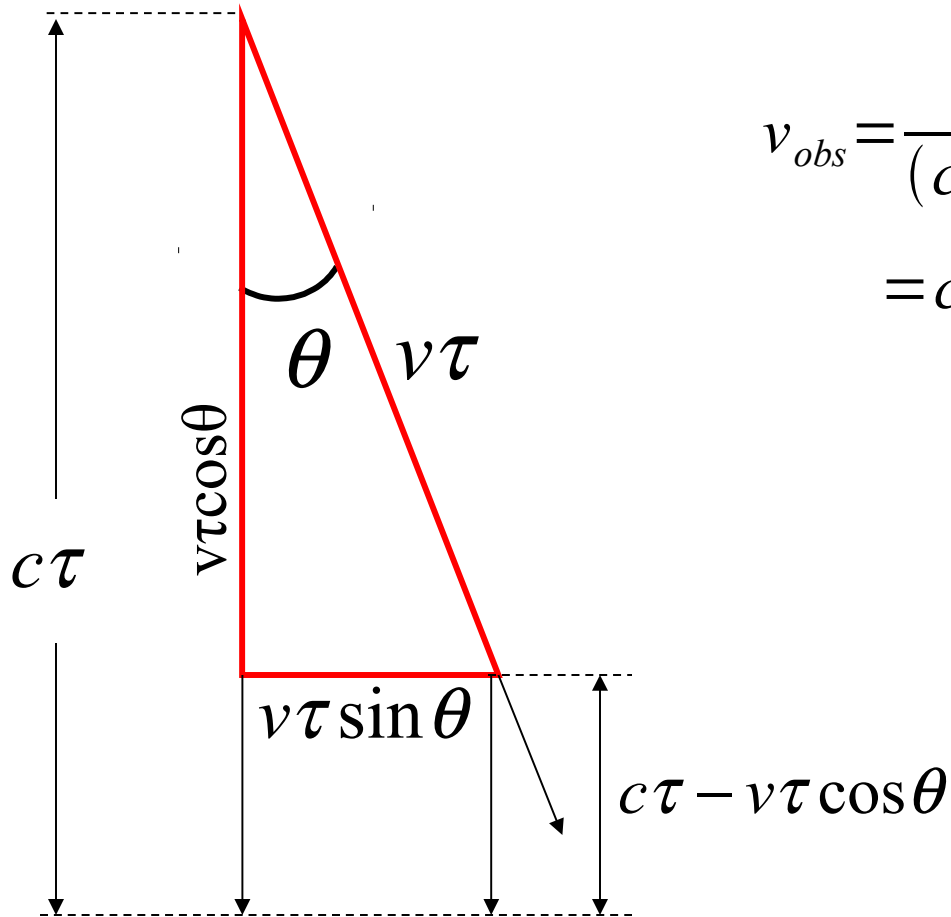
# Superluminal Motion

**MERLIN**

GRS1915+105



# Optical Illusion

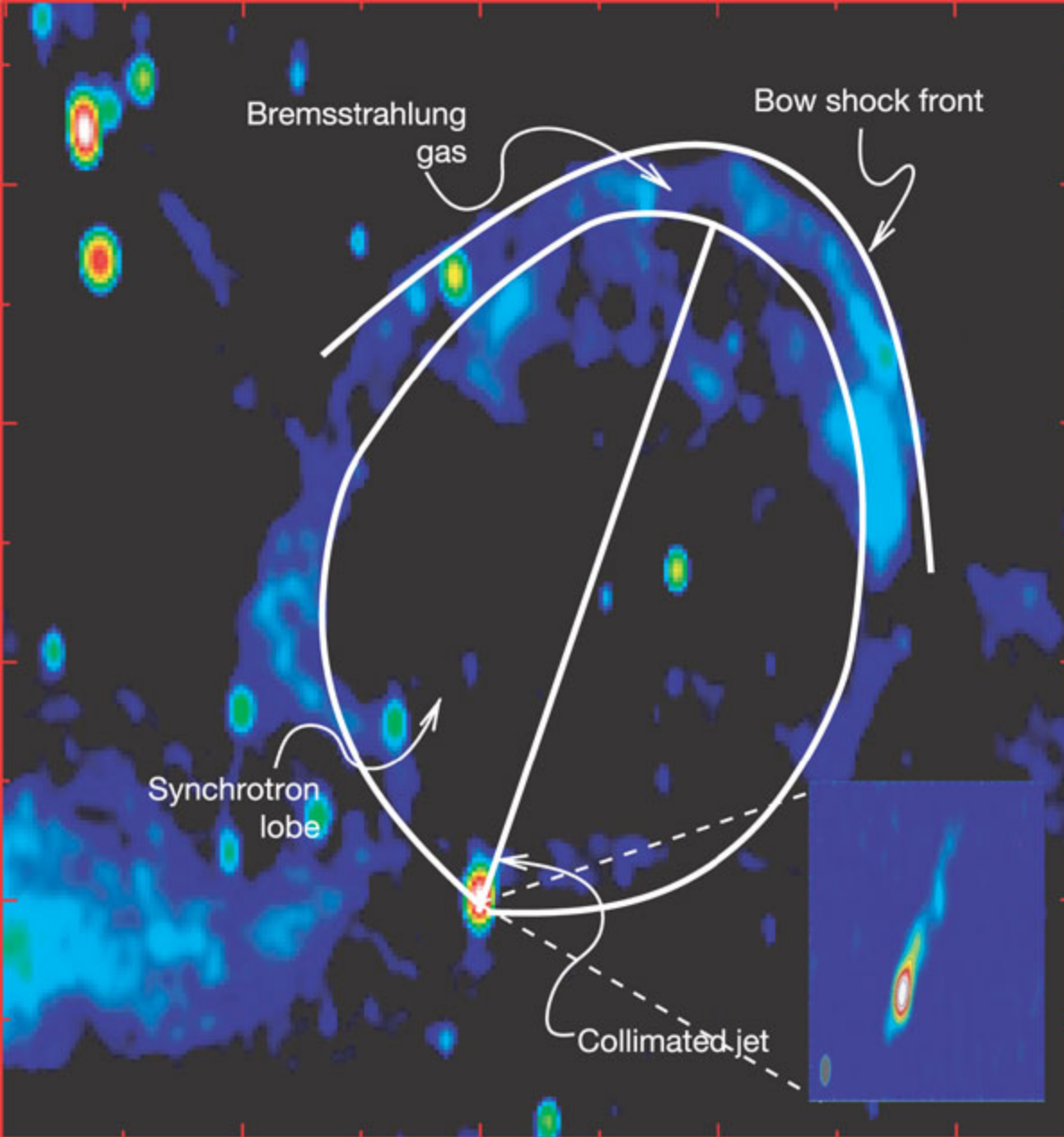


$$\begin{aligned} v_{obs} &= \frac{v\tau \sin \theta}{(c\tau - v\tau \cos \theta)/c} \\ &= c \frac{\beta \sin \theta}{1 - \beta \cos \theta} \end{aligned}$$

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?

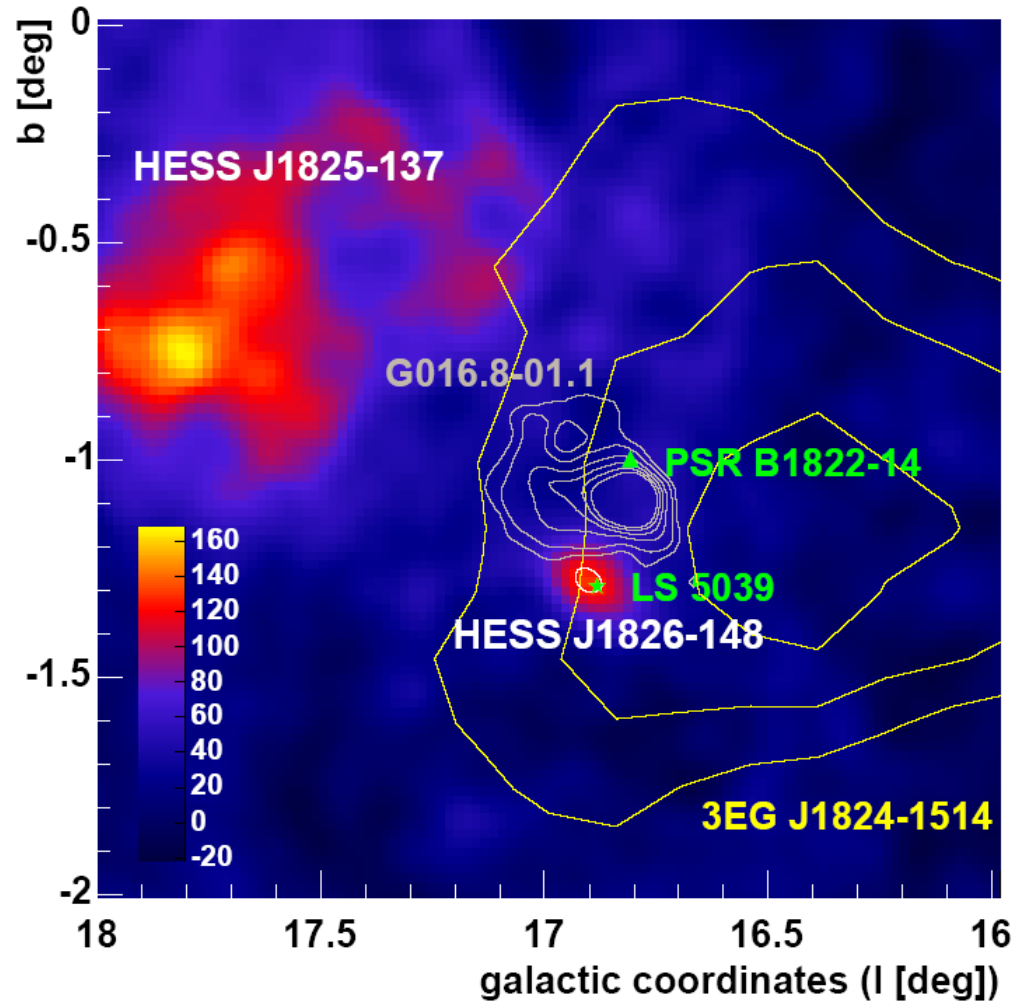
# Jet from Cygnus X-1



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

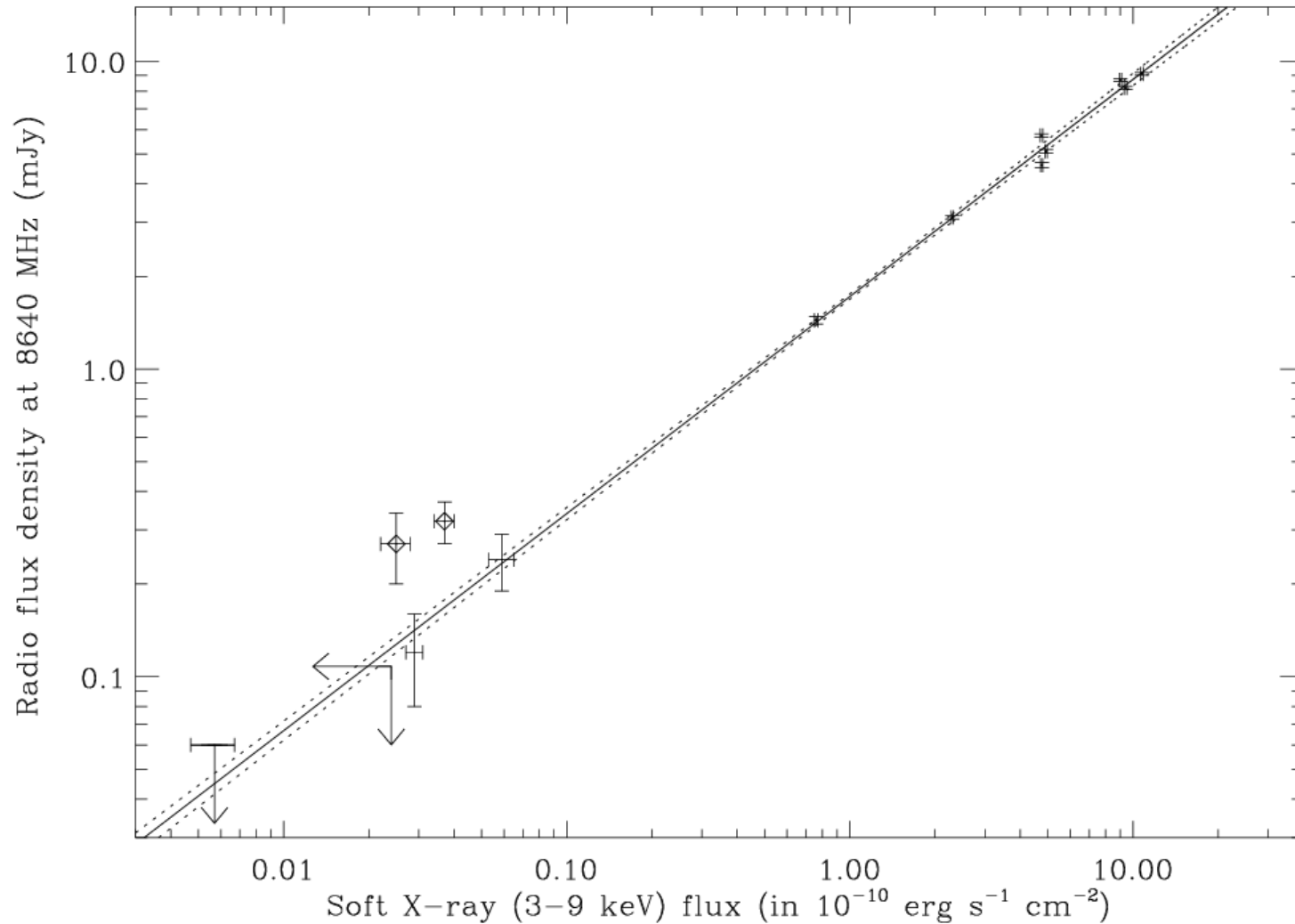


TeV from inverse-Compton of jet electrons on photons from O6.5V companion or jet protons interacting with stellar wind.

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



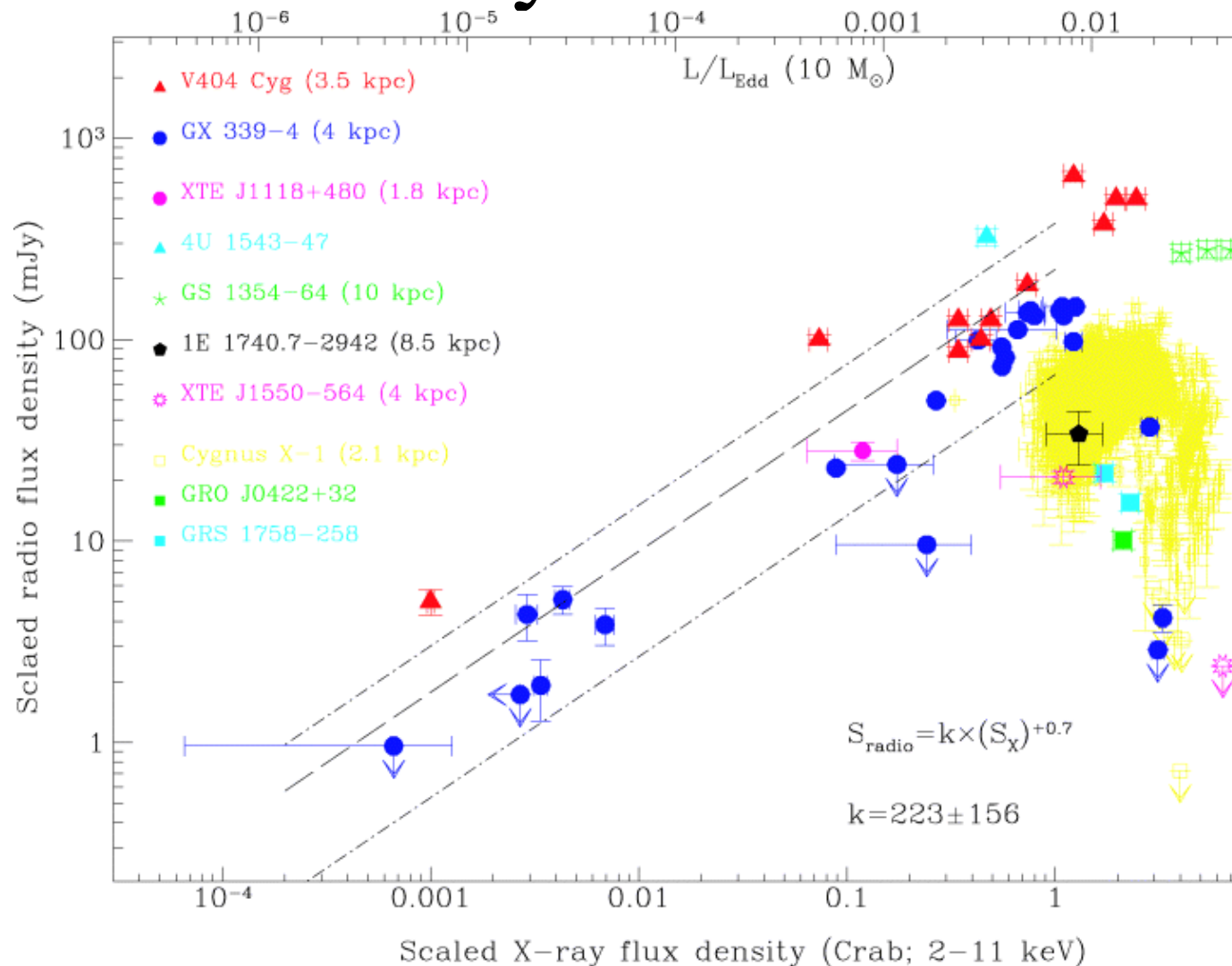
# Radio/X-ray Flux Correlation



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

Corbel et al. (2000,2003)

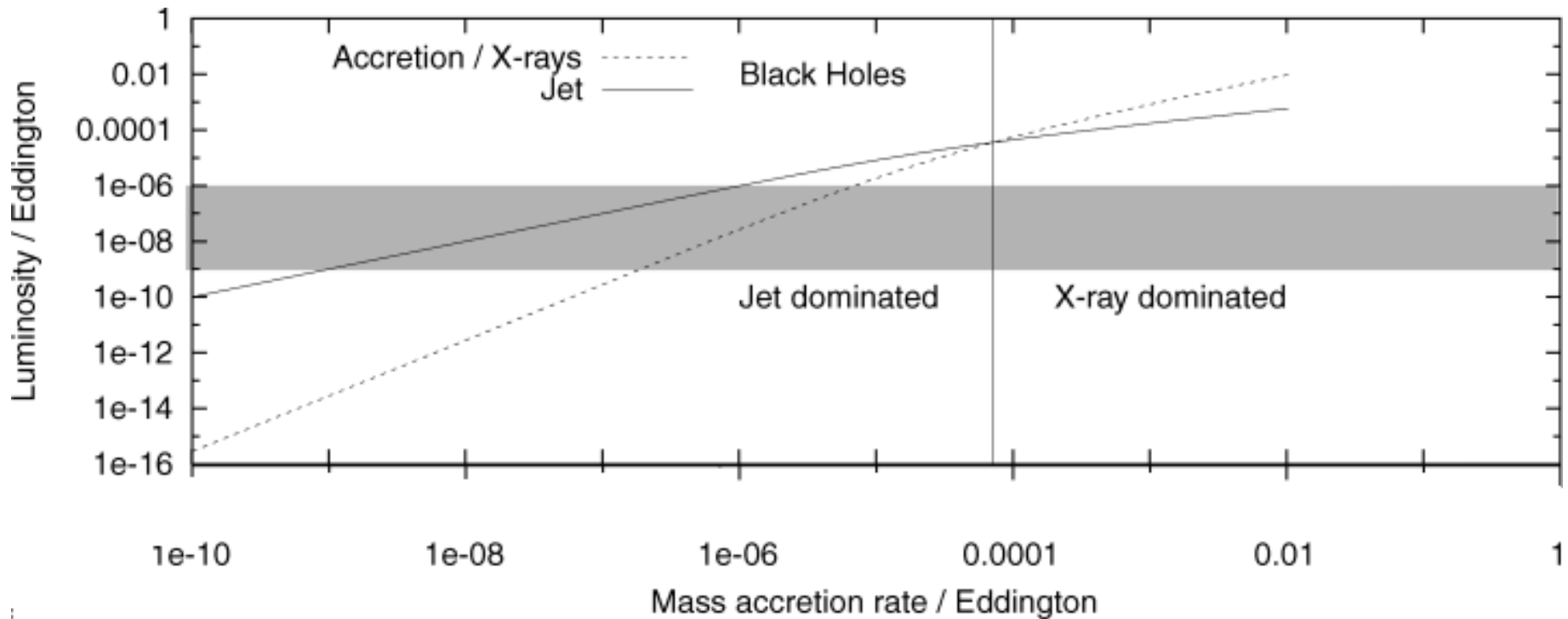
# Radio/X-ray Flux Correlation



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

Corbel et al. (2000,2003)

# Jet Domination at Low Accretion Rates

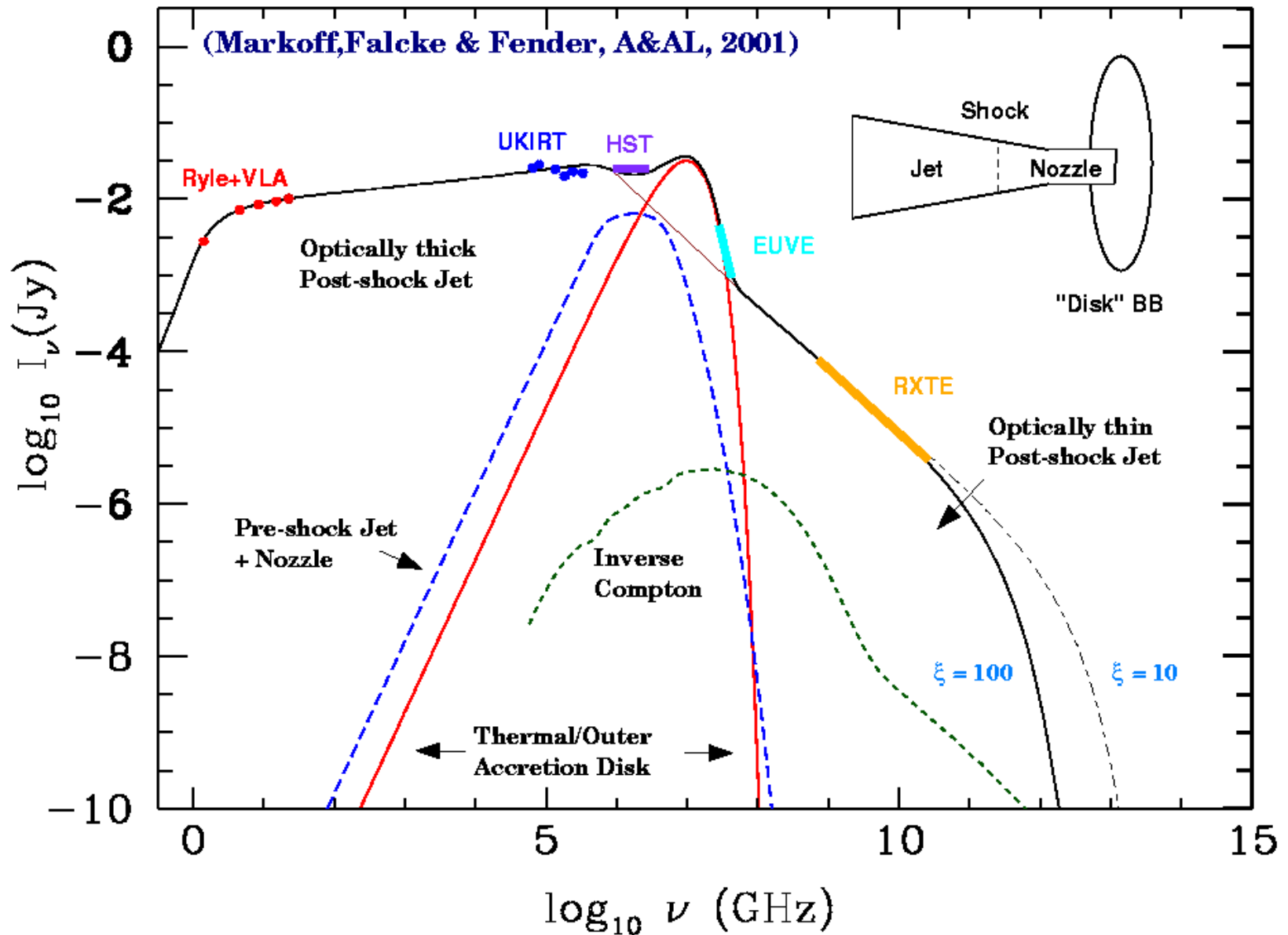


Fender et al. 2003

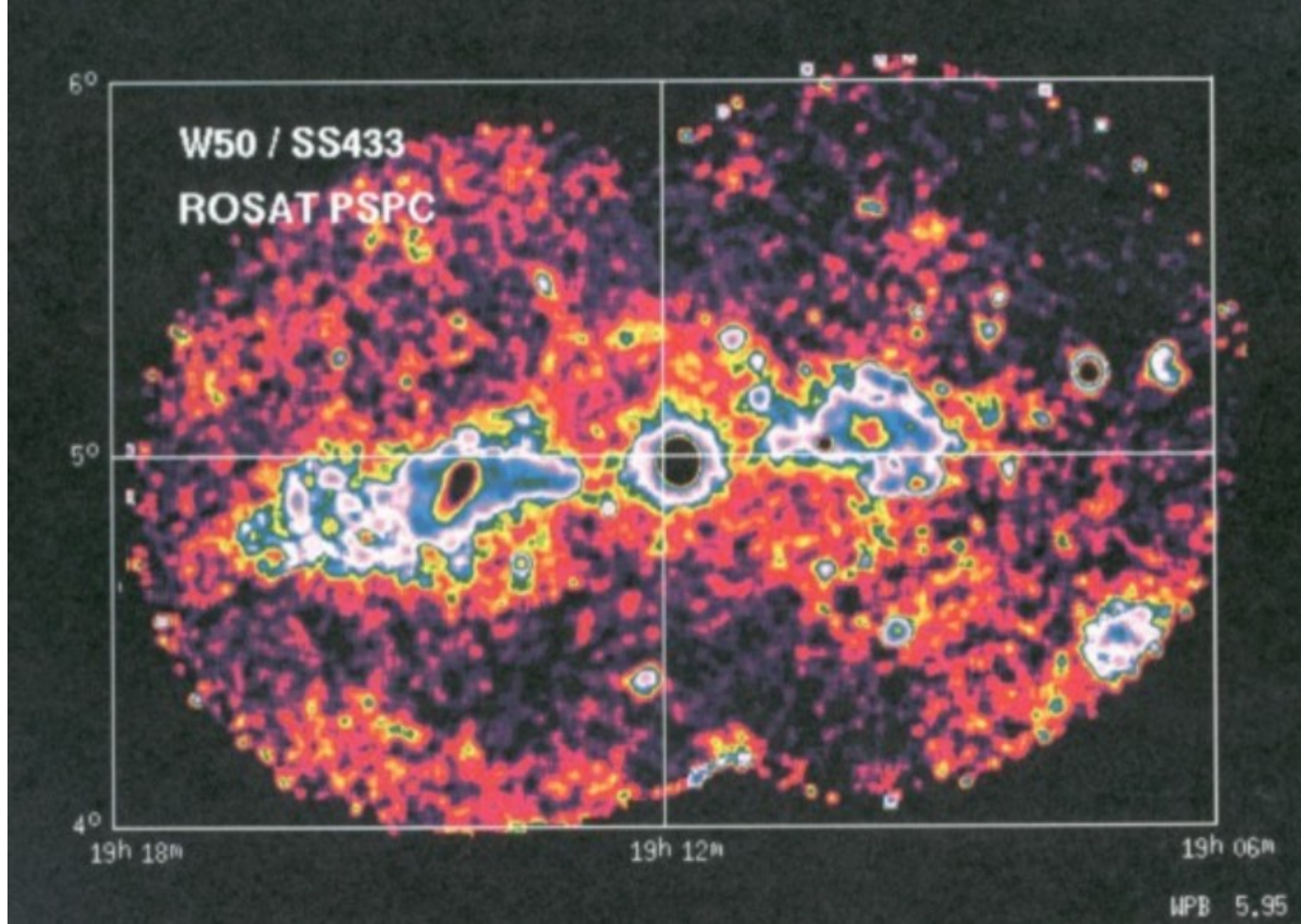
For optically thick jets, the jet power scales as  $L_{\text{radio}} \propto L_{\text{jet}}^{0.5}$

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

# Do the Jets Produce X-Rays?

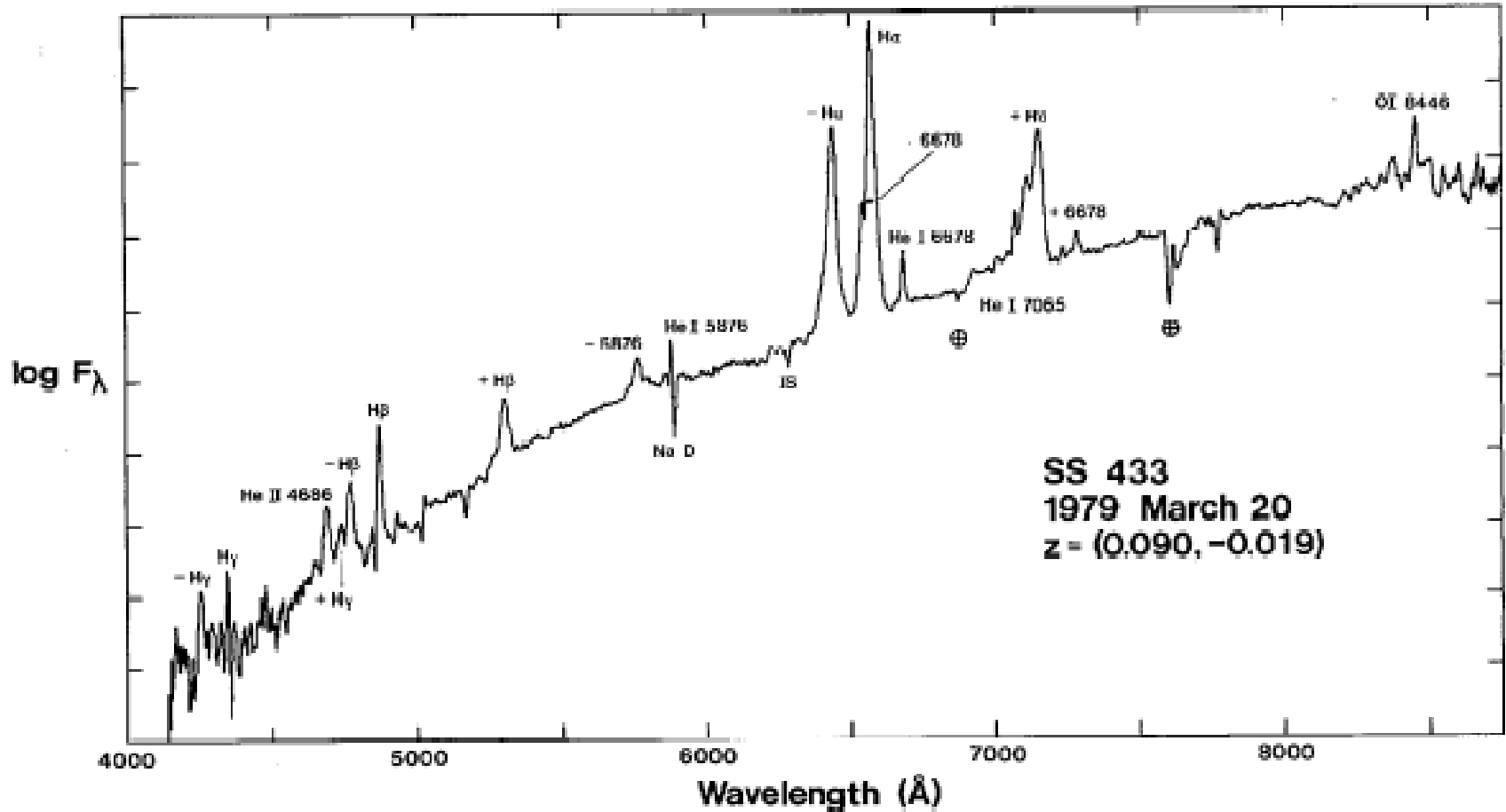


- Are jets electron/proton or electron/positron?



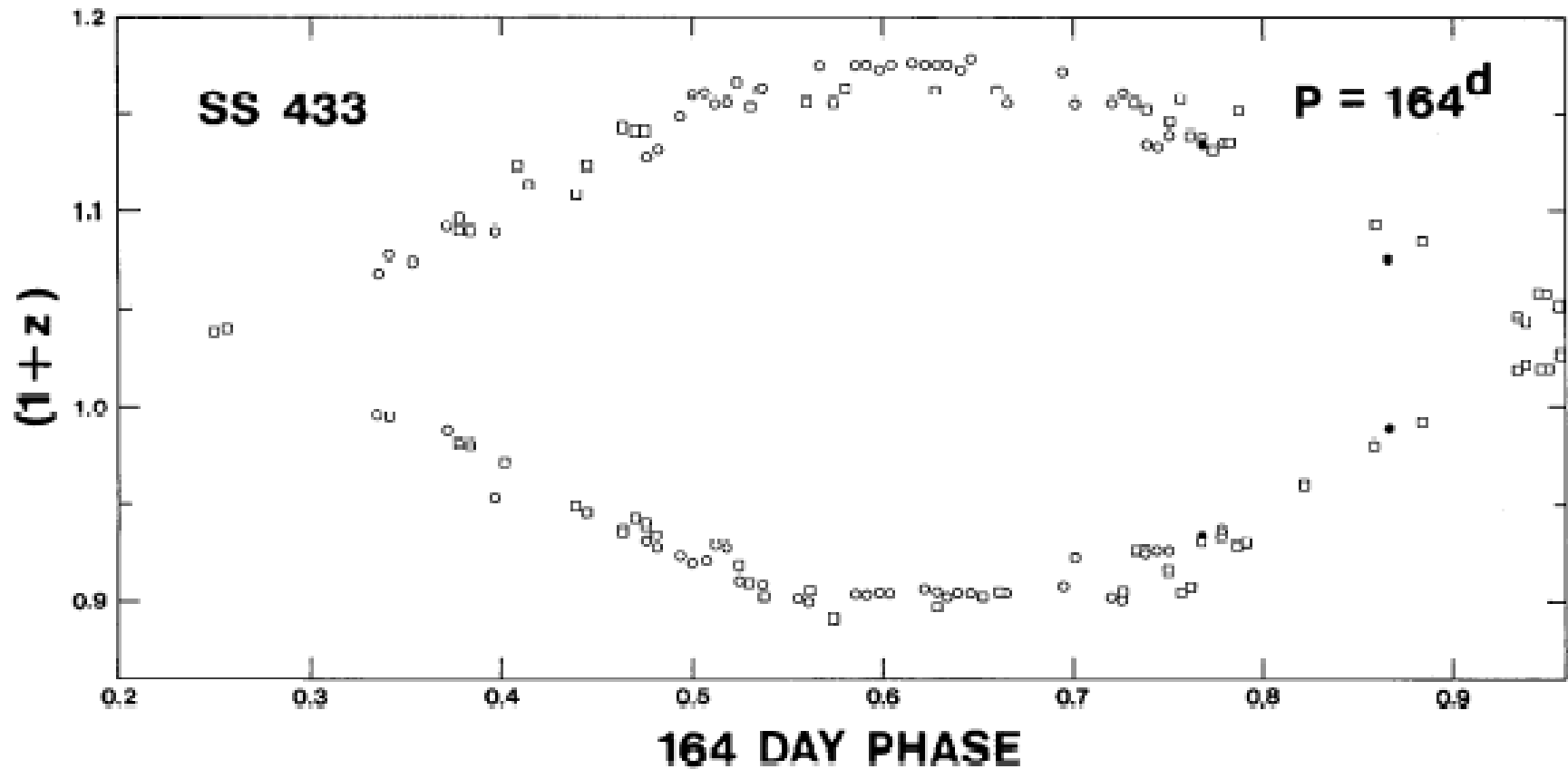
- Jet discovered via blue/red shifted Balmer emission lines (Margon et al. 1979)
- Jet extends to scales of 45' (60 pc) (Seward et al. 1980)
- Large scale jet is non-thermal (Kotani et al. 1994)

# SS 433 Optical Spectrum



Margon et al. 1979

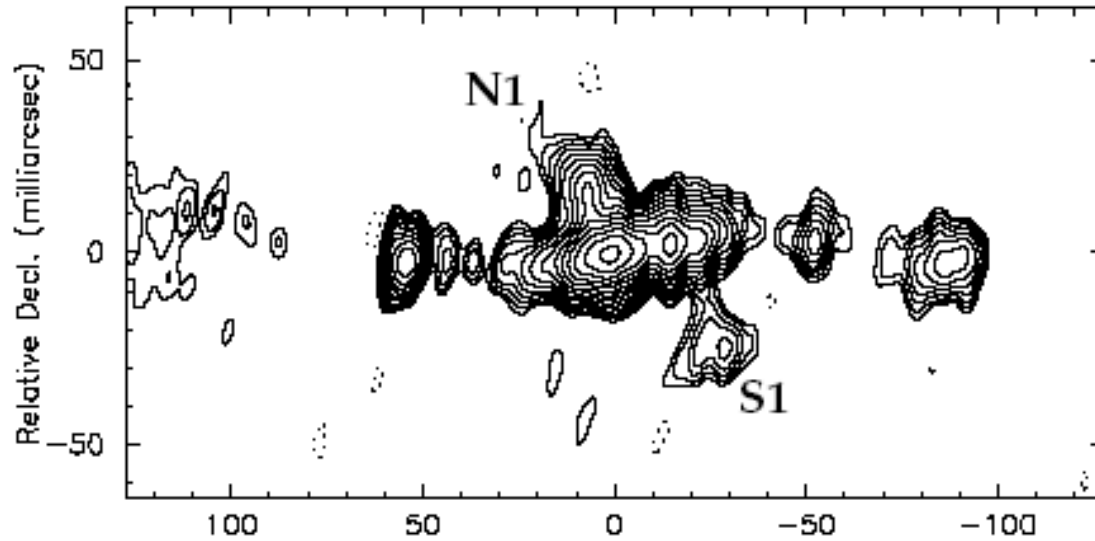
# SS 433 H $\beta$ variations



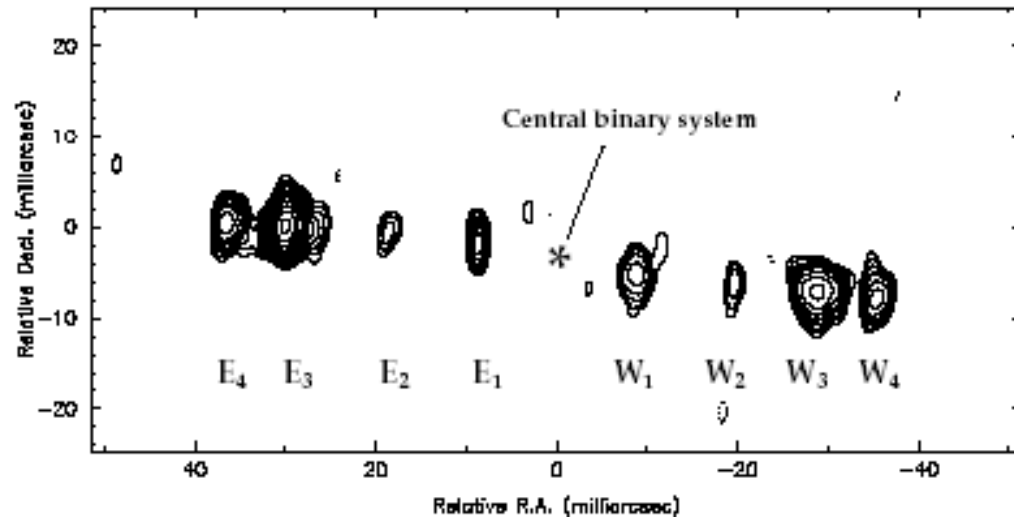


# High-resolution image of SS433

SS433 EVN+VLBA 1.655 GHz 1998-06-06

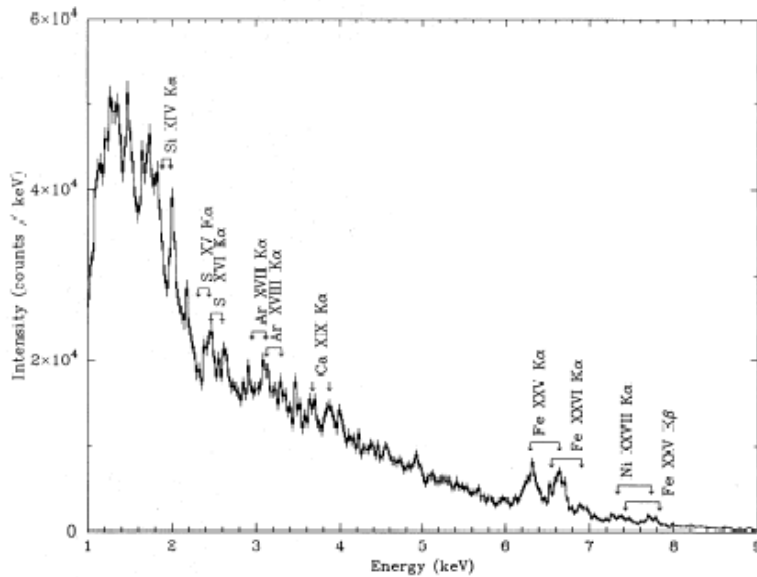


SS433 VLBA 4.993 GHz 18/04/98

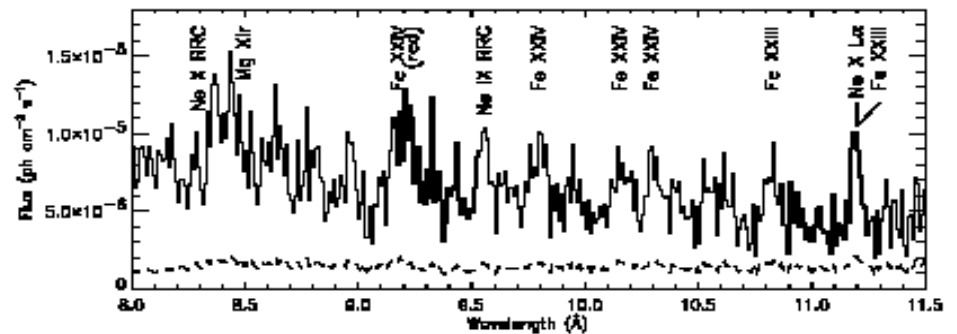
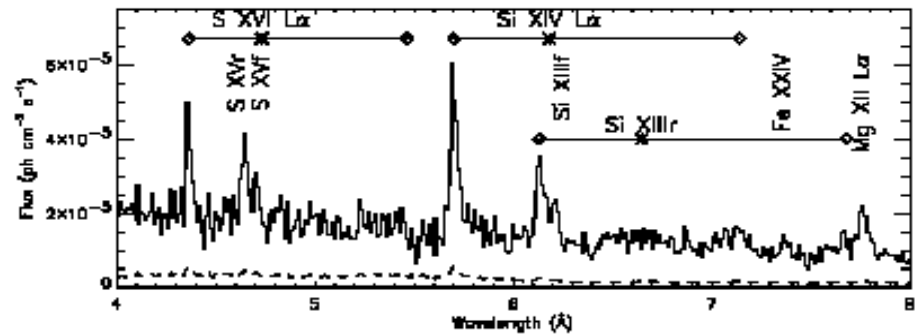
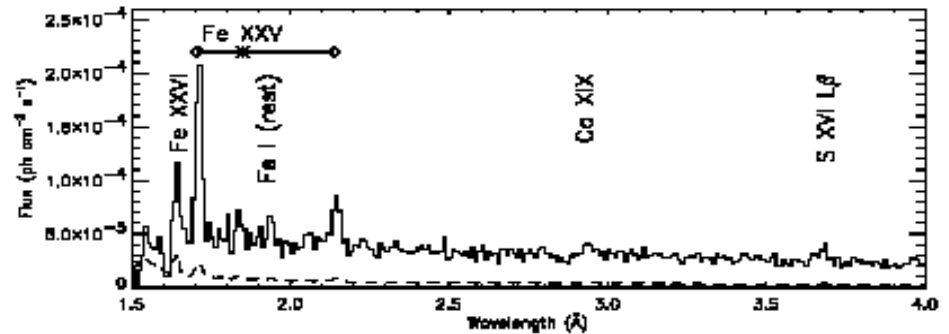


# X-rays from the jets

ASCA

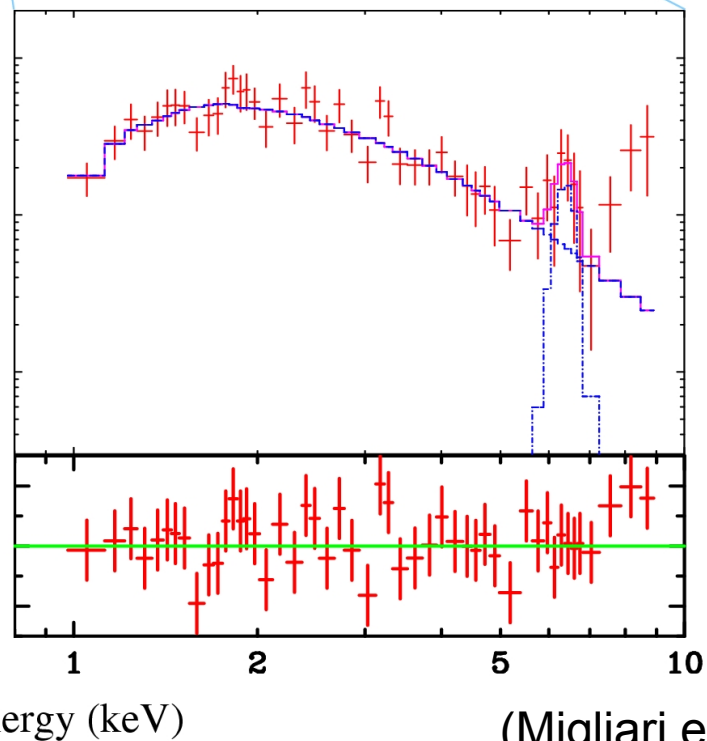
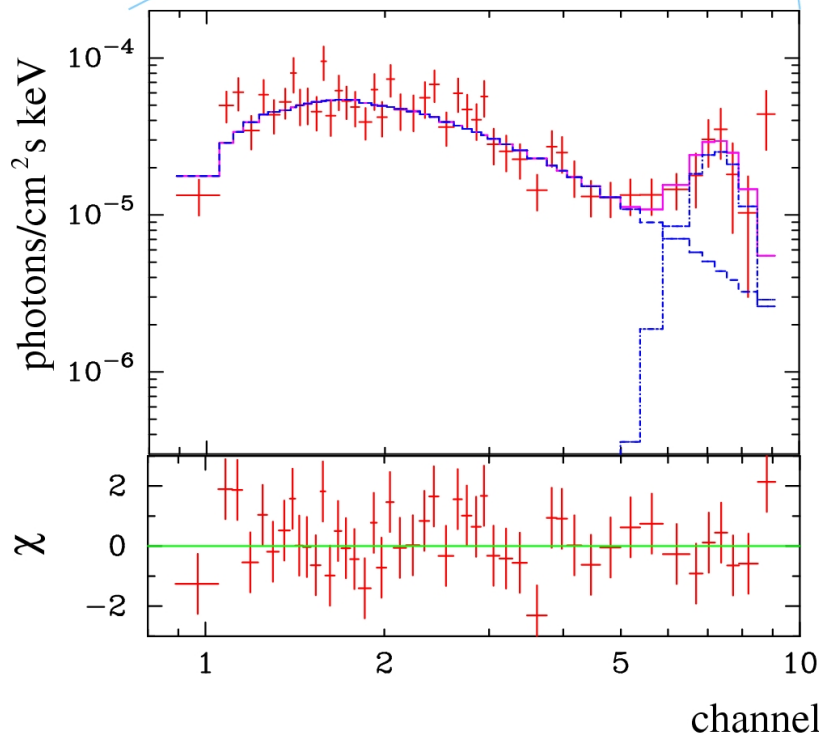
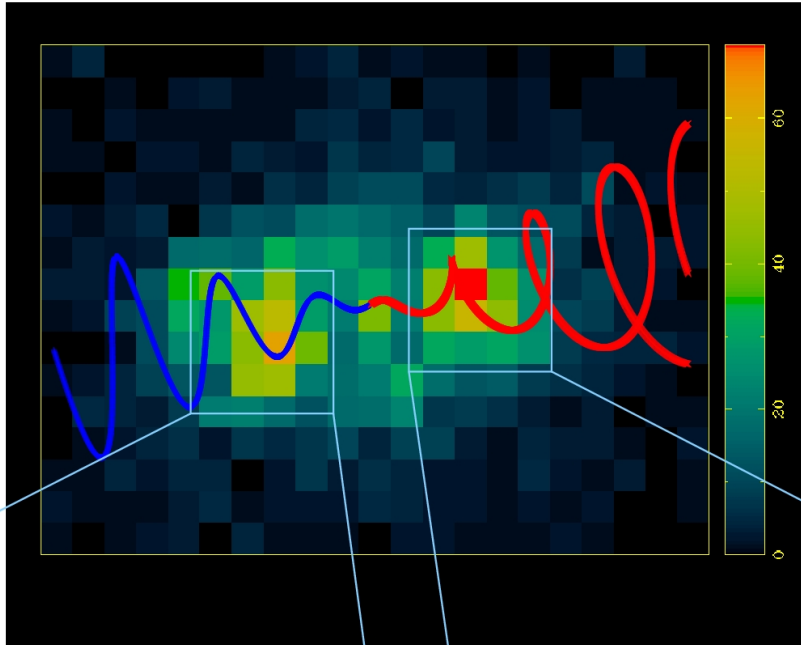


Chandra



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

SS 433 inner  
jet is  
baryonic and  
thermal

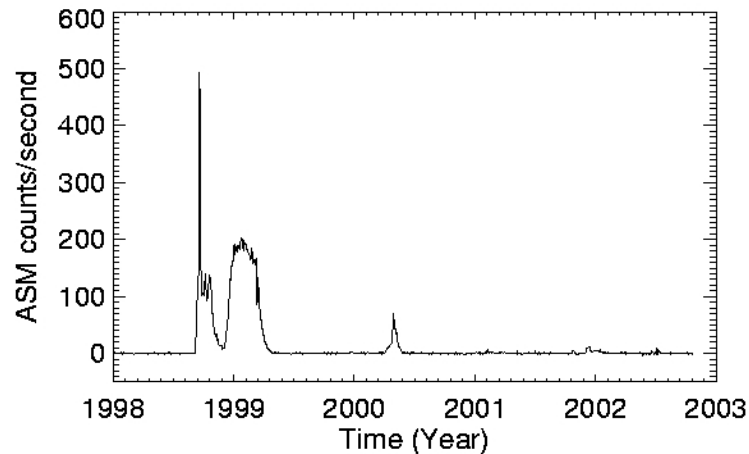


(Migliari et al. 2002)

# Questions

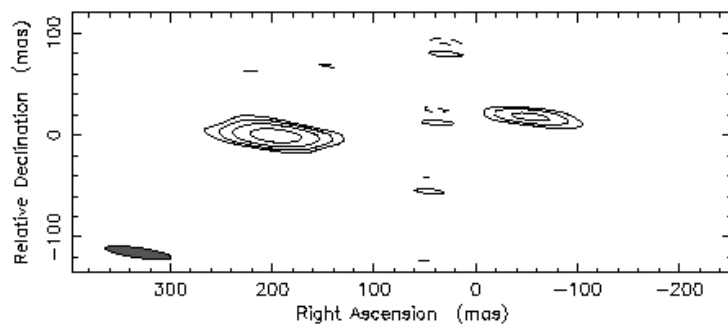
- Are jets re-energized at large distances from origin?

# Outbursts of XTE J1550-564

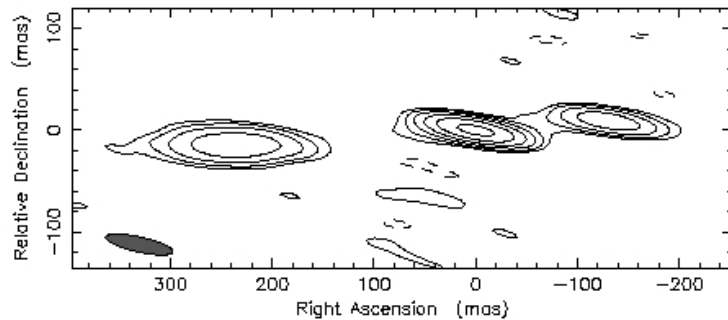


Discovery outburst in 9/1998

Activity in 2000, 2001/2002, 2003.

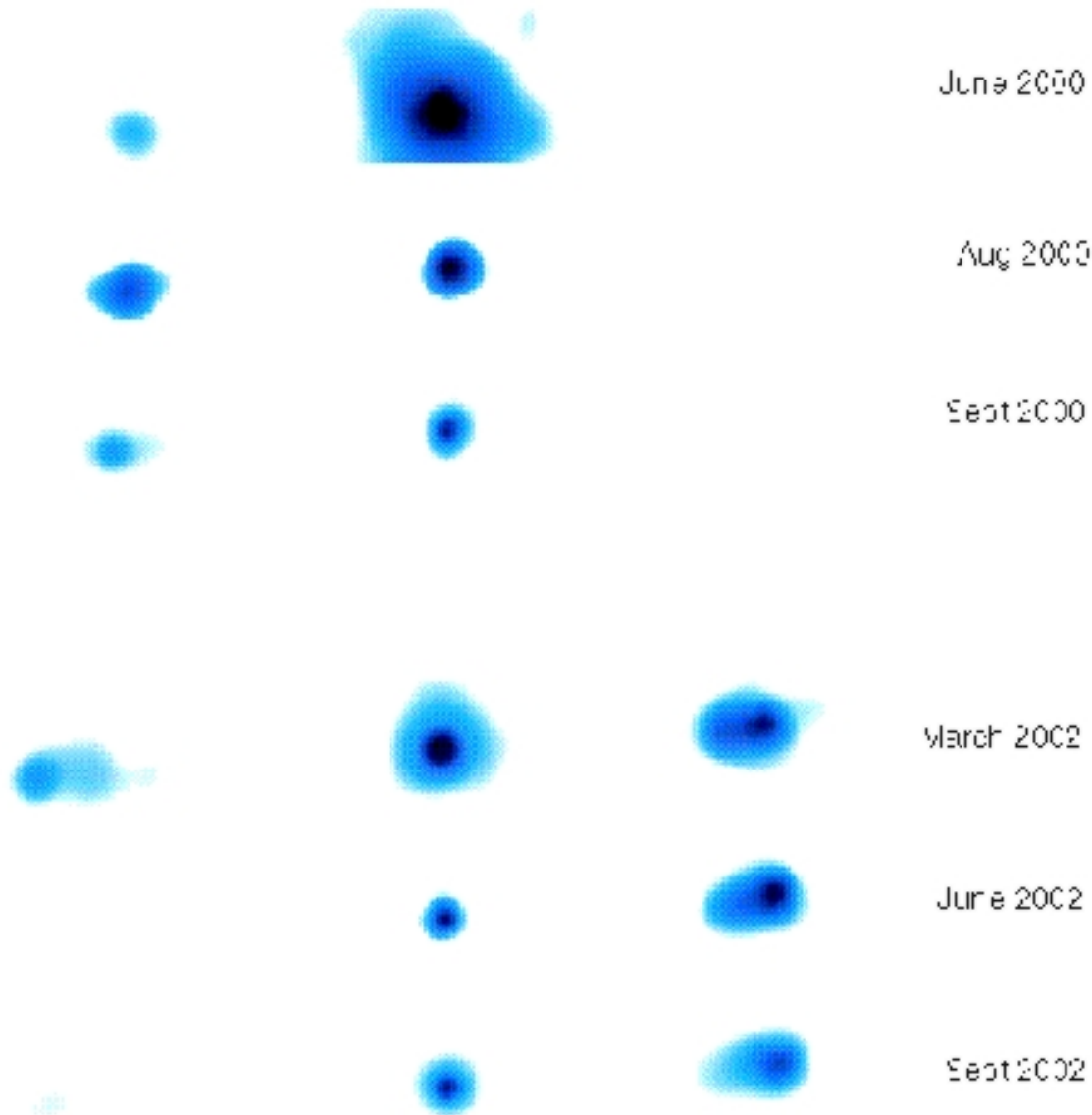


Radio jets in 9/1998  
(Hannikainen et al. 2001)



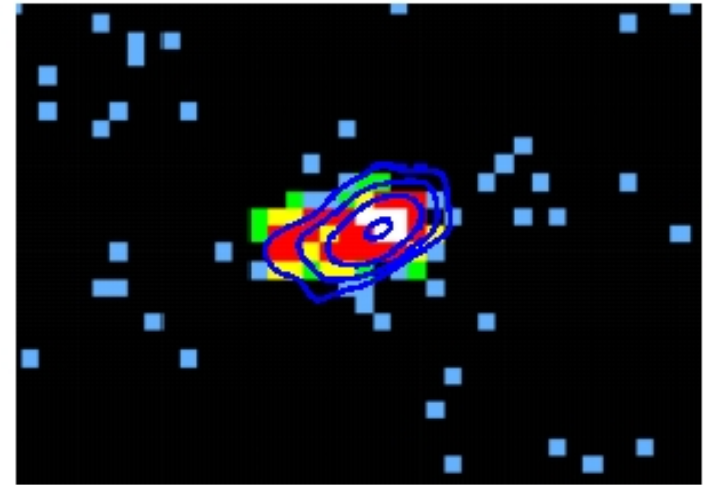
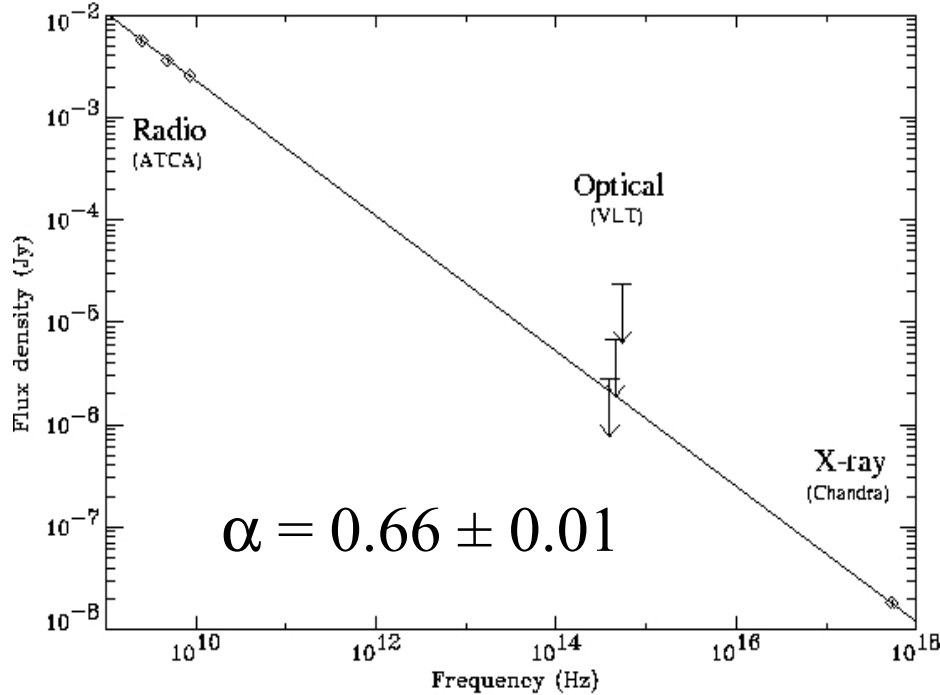
Separation speed  $> 2c$ .

# Large Scale jets of XTE J1550-564



Corbel et al. 2002,  
Kaaret et al. 2003

# Emission mechanism



Contours = radio,  
pixels = X-ray

→ Synchrotron emission from single population.

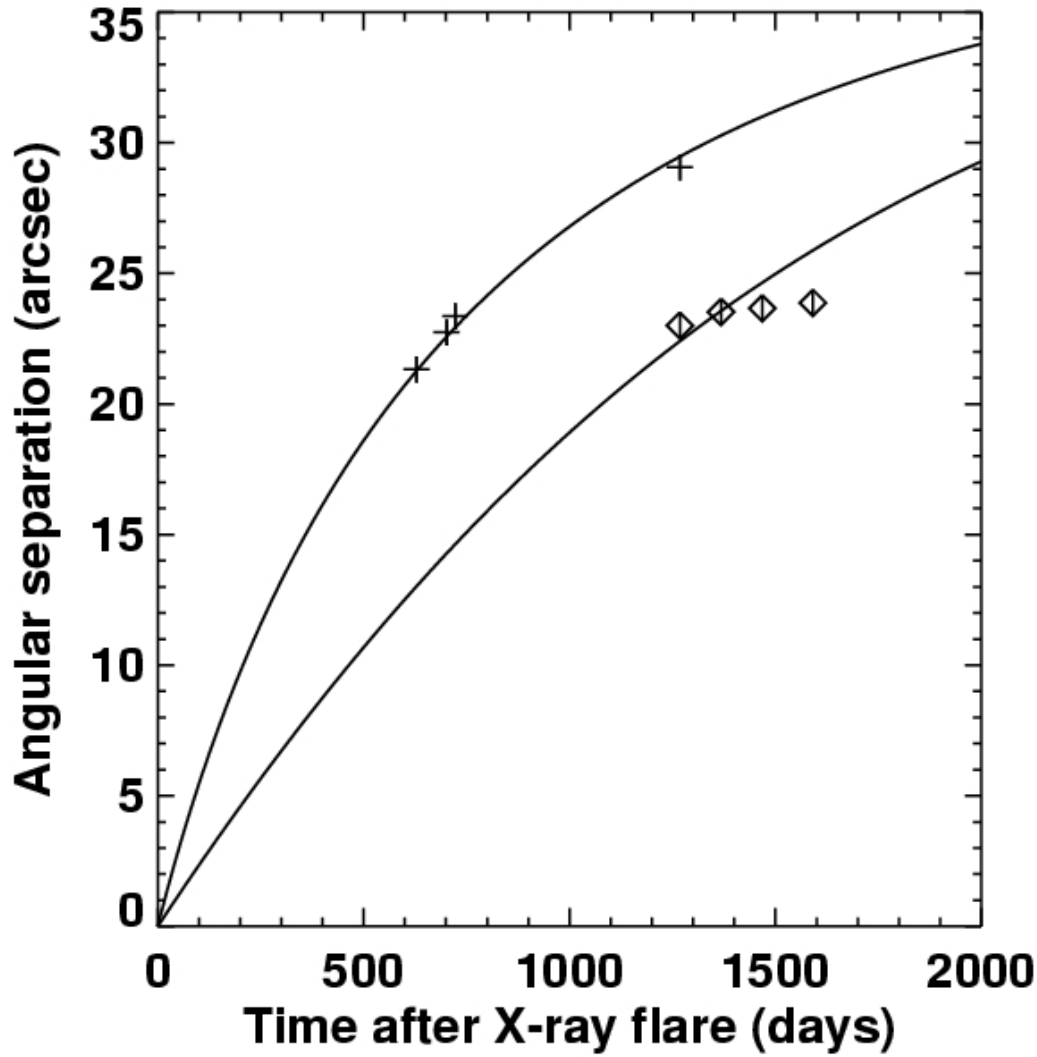
Equipartition →  $B \sim 300 \mu\text{G}$

X-ray emitting electrons:  $\gamma_e > 2 \times 10^7$ , energy  $\sim \text{TeV}$

Number electrons  $\sim 10^{45}$ ; if one p/e, mass  $\sim 10^{21} \text{ g}$

Synchrotron lifetime  $\sim 10 \text{ years}$

# 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  $\sim 1\%$  efficiency for conversion of bulk deceleration to particle acceleration.

First direct observation of gradual deceleration of BH jet.



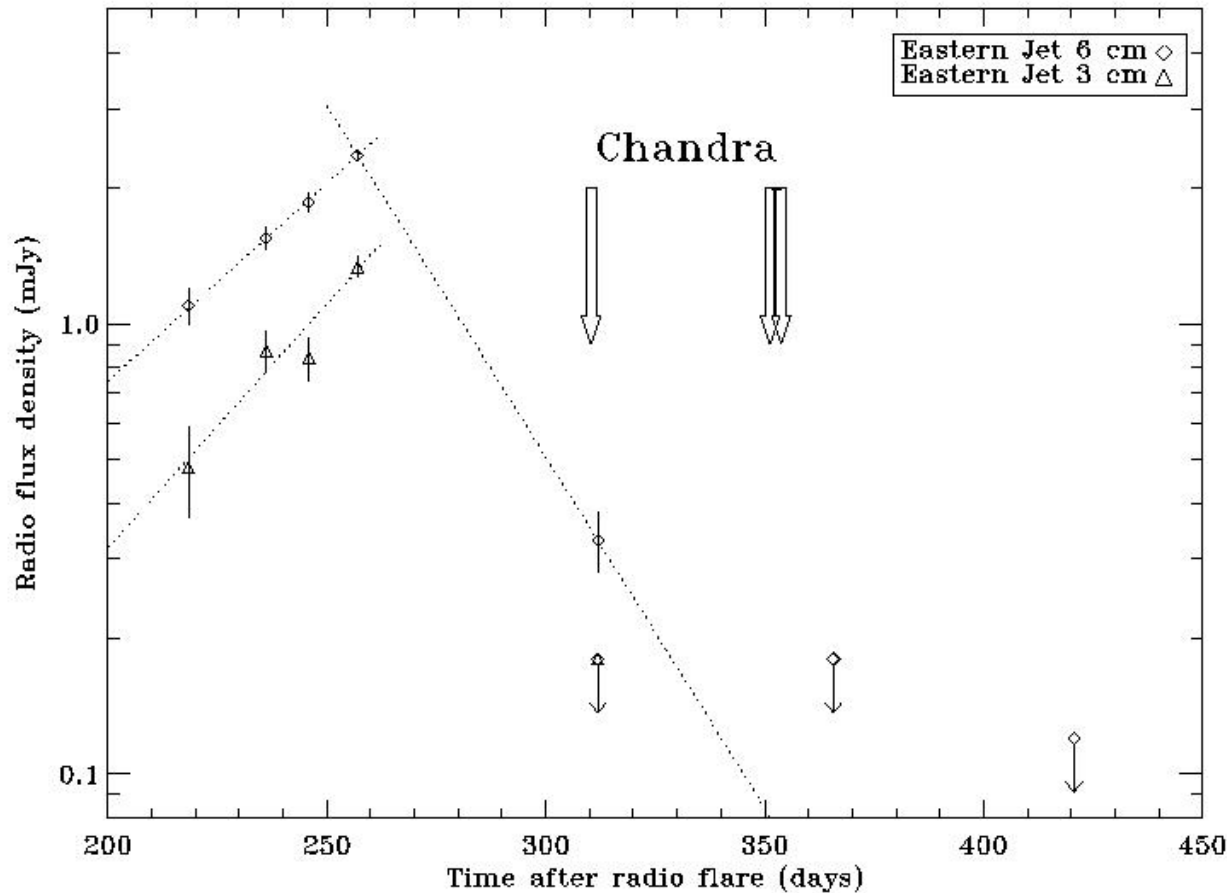
# Jet/ISM Interactions

- Appear to have in-situ particle acceleration
  - Deceleration from profile fitted to eastern jet implies kinetic energy loss rate  $\sim 10^{34}$  erg/s in June 2000.  
Compare to luminosity  $\sim 10^{32}$  erg/s
- need efficiency of  $\sim 1\%$  for conversion of bulk deceleration to particle acceleration

## Mechanism?

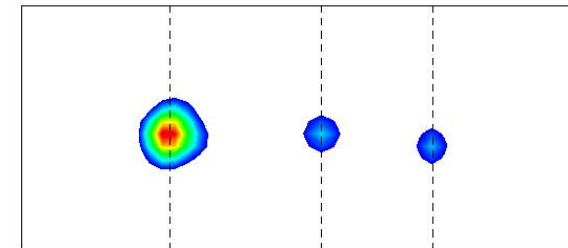
- Internal shocks: internal instabilities, varying flow speed
- External shocks: interactions with denser ISM

# Large scale jet in H1743-322

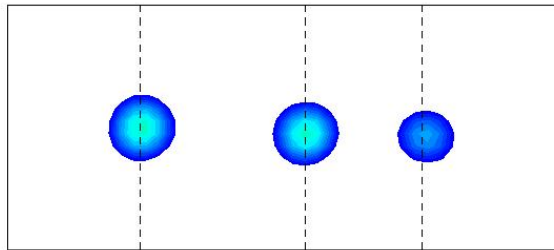


- Outburst starting in March 2003
- Radio flare on April 8
- Radio rise in  $\sim 45$  days, decay in  $\sim 30$  days

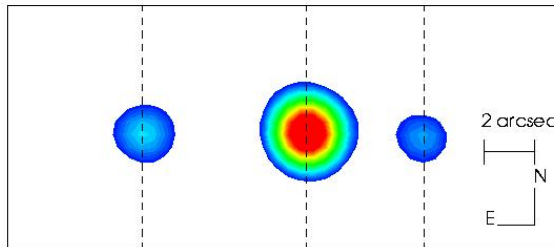
# X-ray jets in H1743-322



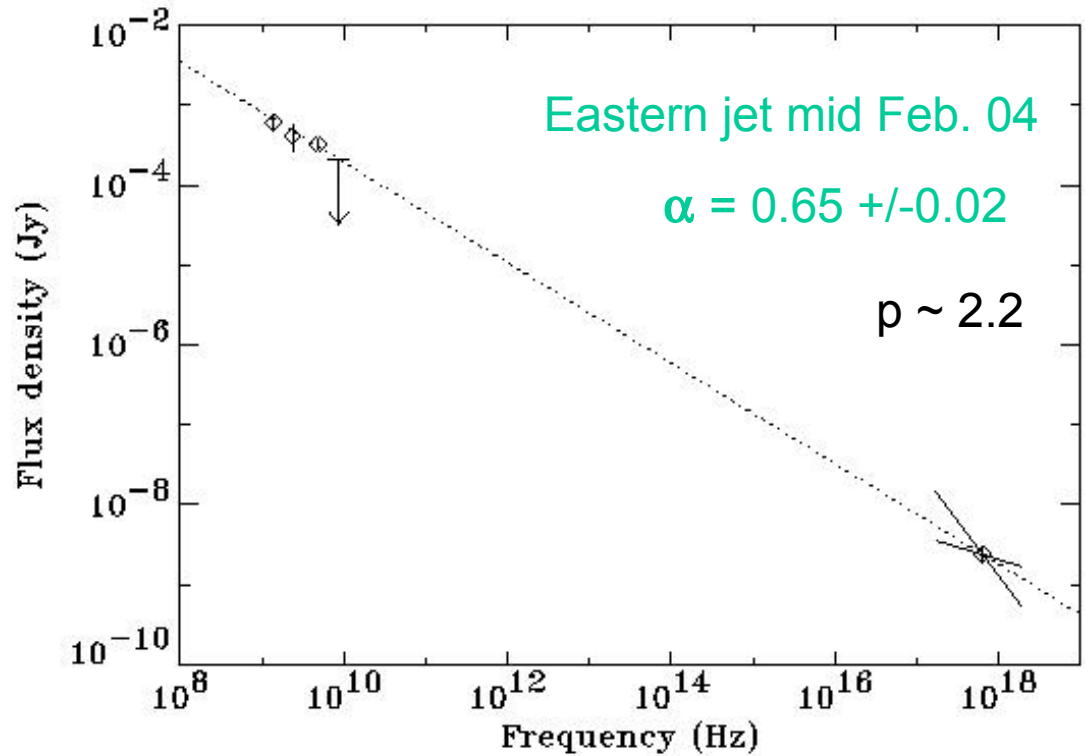
2004 February 12



2004 March 24



2004 March 27

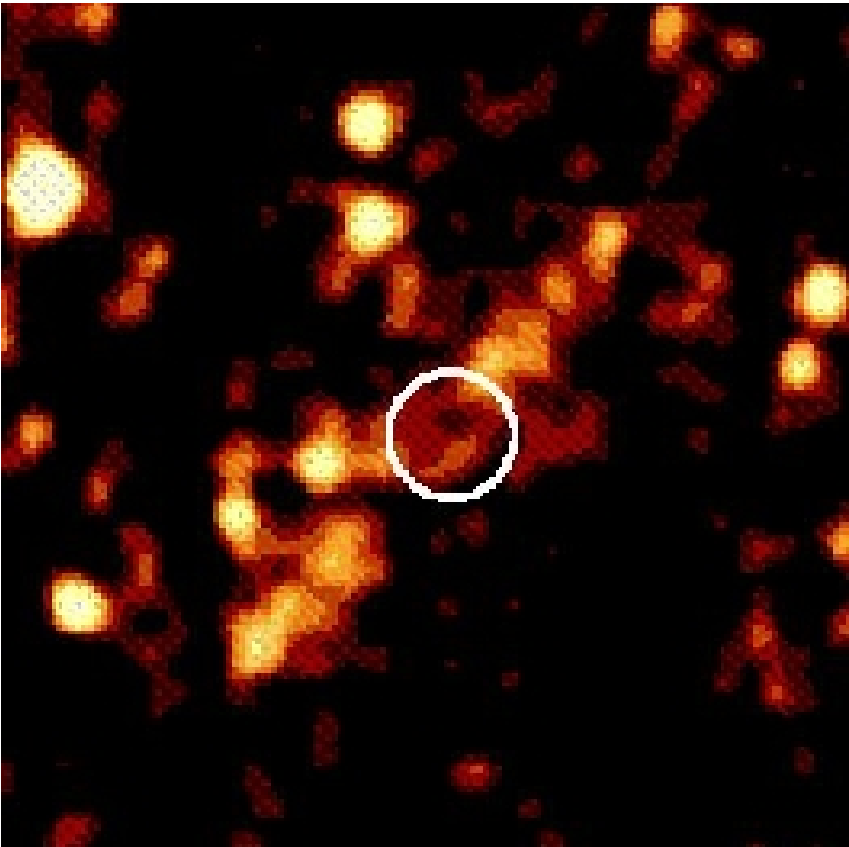


E. jet

W. Jet

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

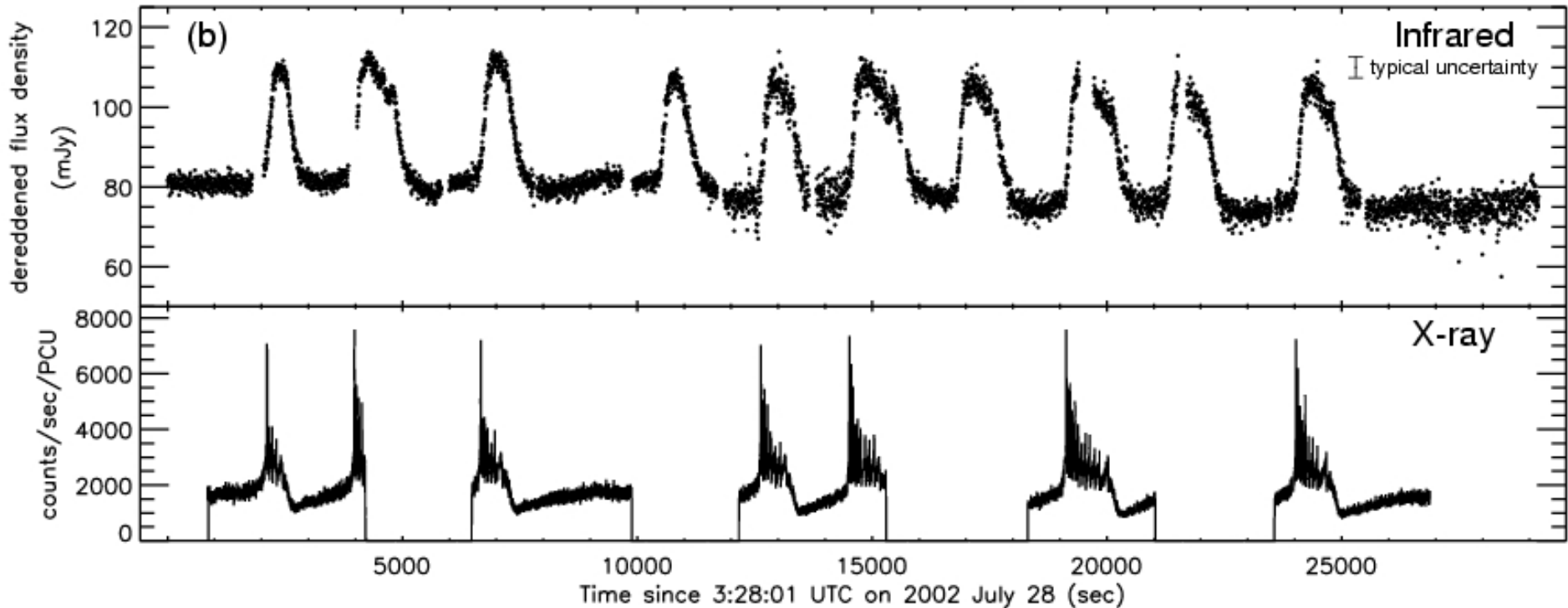
# Fossil Jet from 4U 1755-33



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

- Source was active for at least 20 years
- X-ray jet extends  $\sim 4$  pc
- Thermal X-ray emission is ruled out
- Synchrotron is OK
  - TeV electrons
  - $B \sim 100 \mu\text{G}$
- Long lifetime of jet means particles injected into ISM continuously for decades

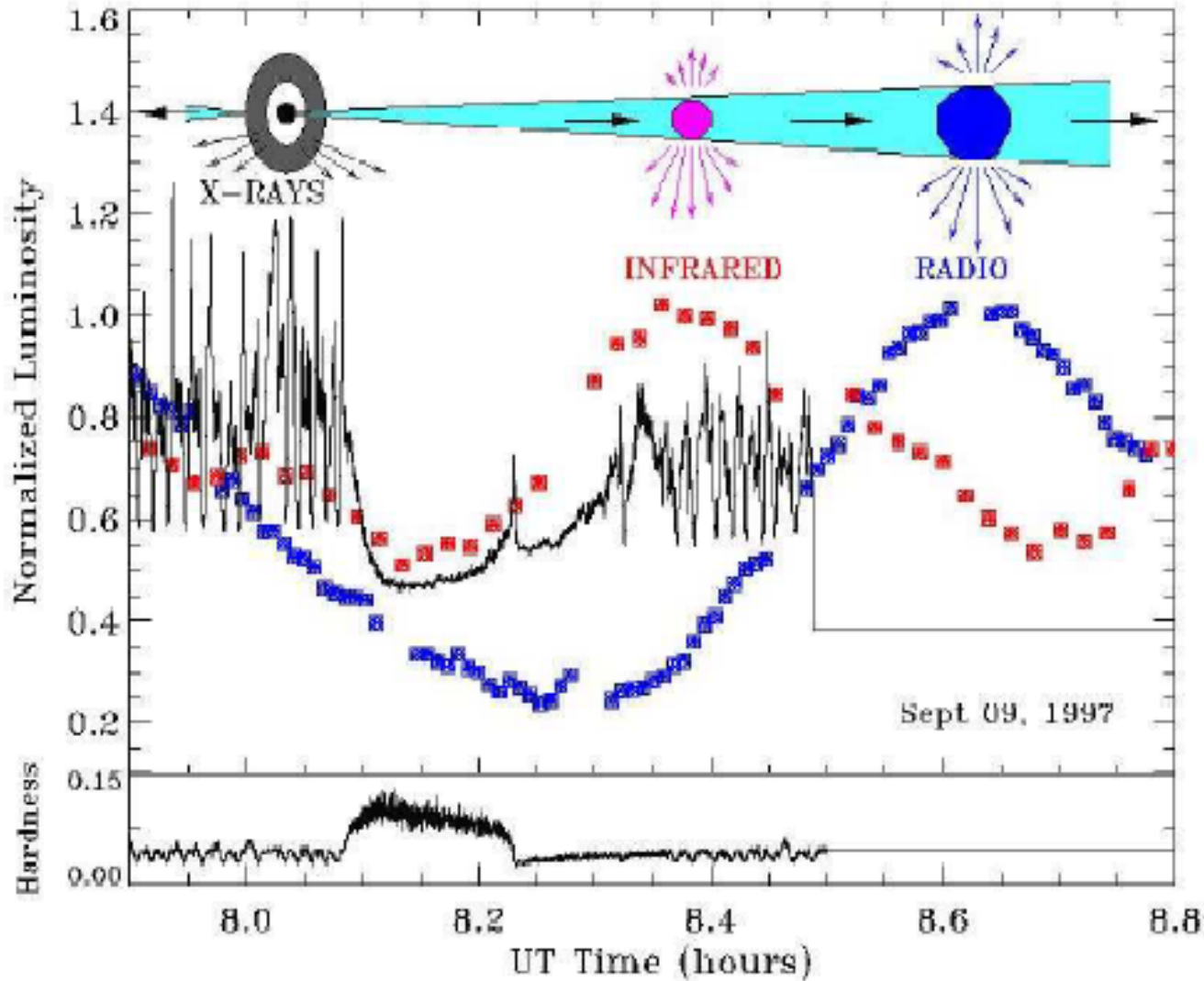
# Jet Production



Eikenberry et al. 1998

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

# Jet Production



Cooling of particles in the jets due to adiabatic expansion