Similarities and scaling laws for AGN and XRB

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P. Kaaret, J. Orosz, J. Tomsick, …

Outline

- Introduction: AGNs and XRBs
- Relativistic jets in XRBs and X-ray spectral states
- Compact cores
- Large scale jets
- Conclusions

Introduction: X-ray binaries

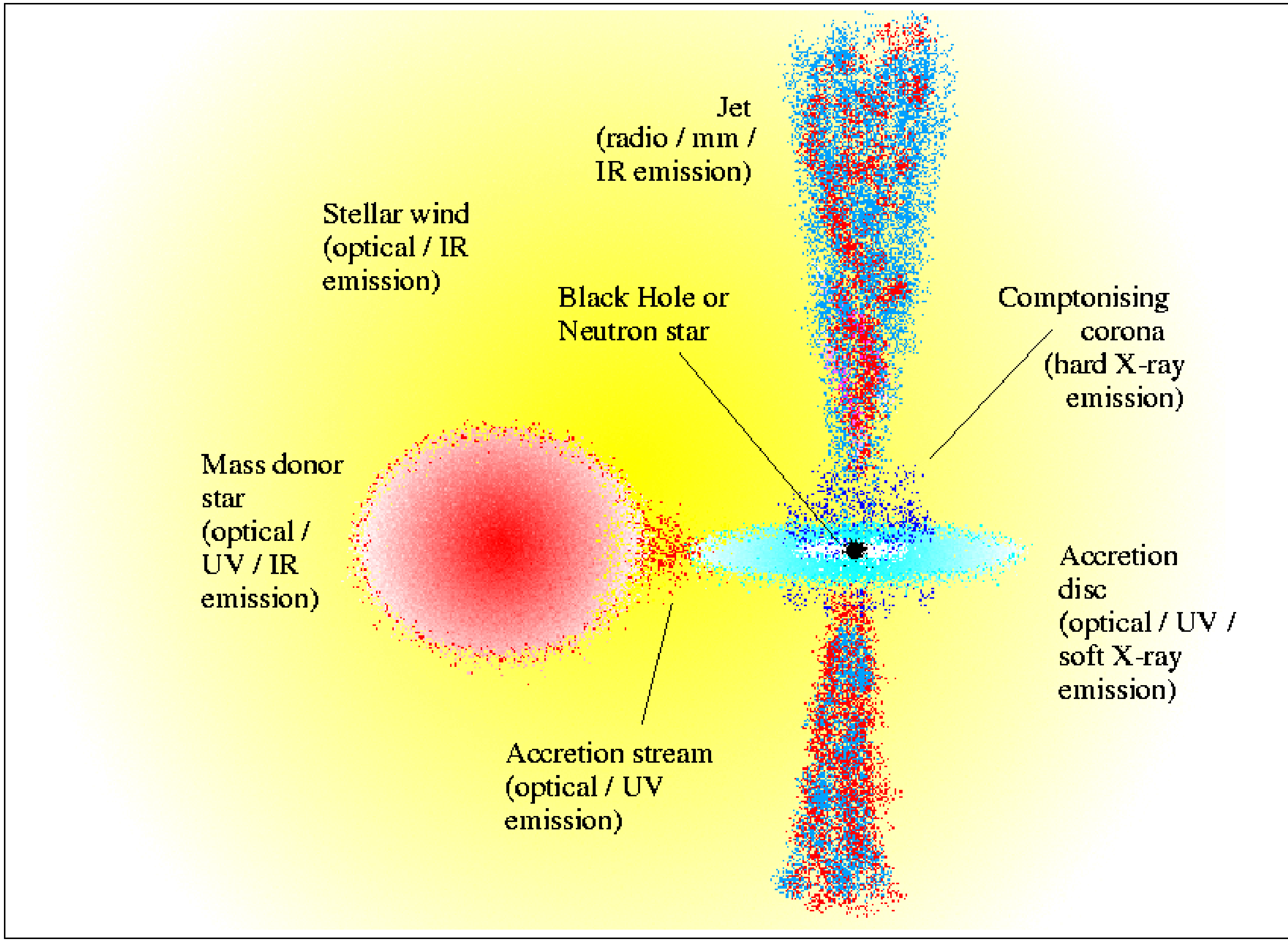


Image: R. Fender

Compact Objects

Masses from binary motion of companion stars or pulsars

Black Hole Binaries

M_x = 4-18 M_o

Neutron Stars (X-ray & radio pulsars)

M_x ~ 1.4 M_o

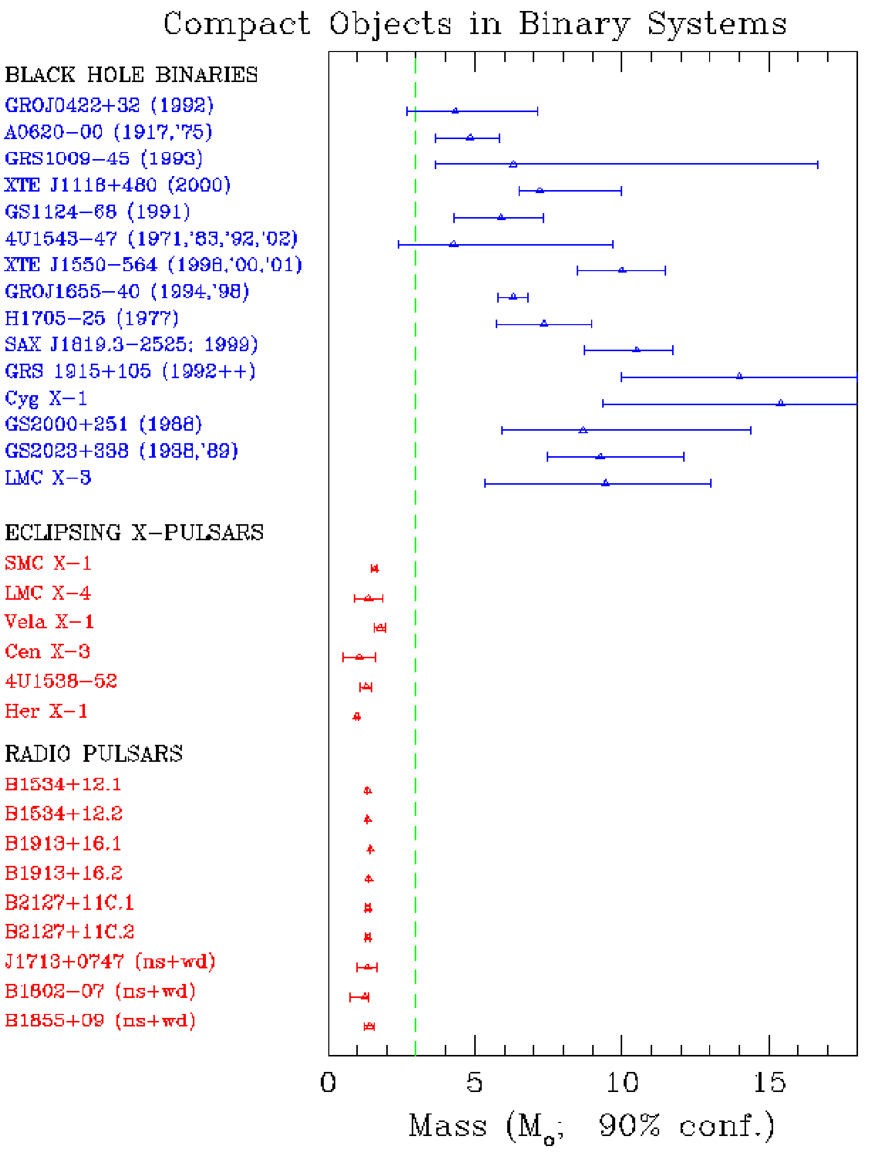


Image: J. Orosz

Black Holes in the Milky Way

16 Black-Hole Binaries in the Galaxy

(Jerry Orosz, SDSU)

Scaled, tilted, and colored for surface temp. of companion star.

Black Hole Properties:
mass (M_x) and
spin ($a_* = cJ / GM_x^2$)

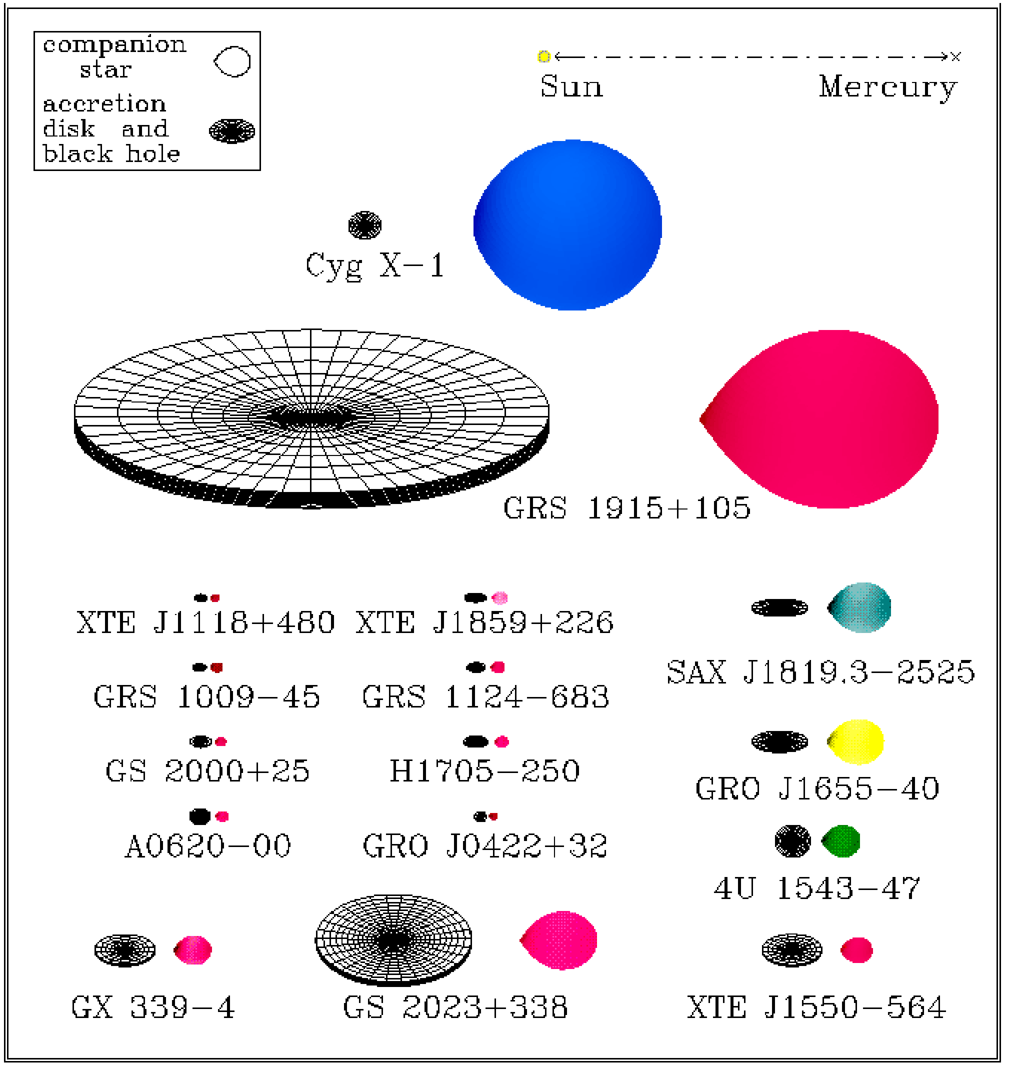
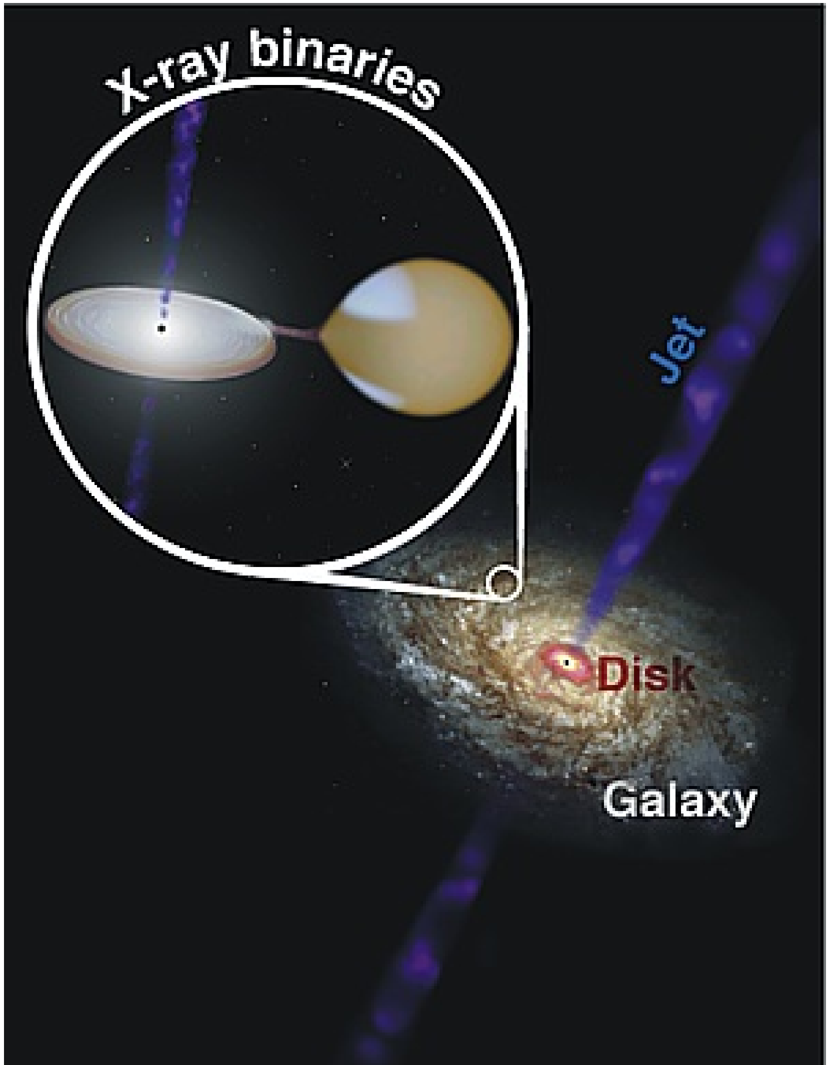


Image: J. Orosz

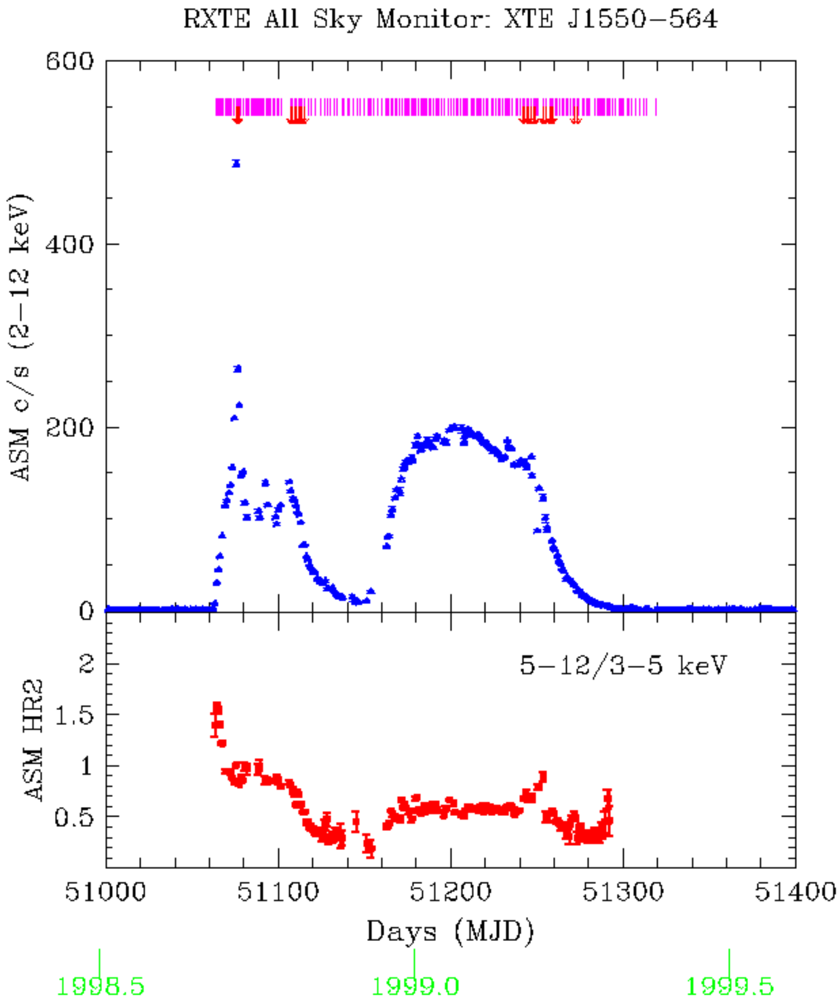
Similarities in AGNs and XRBs

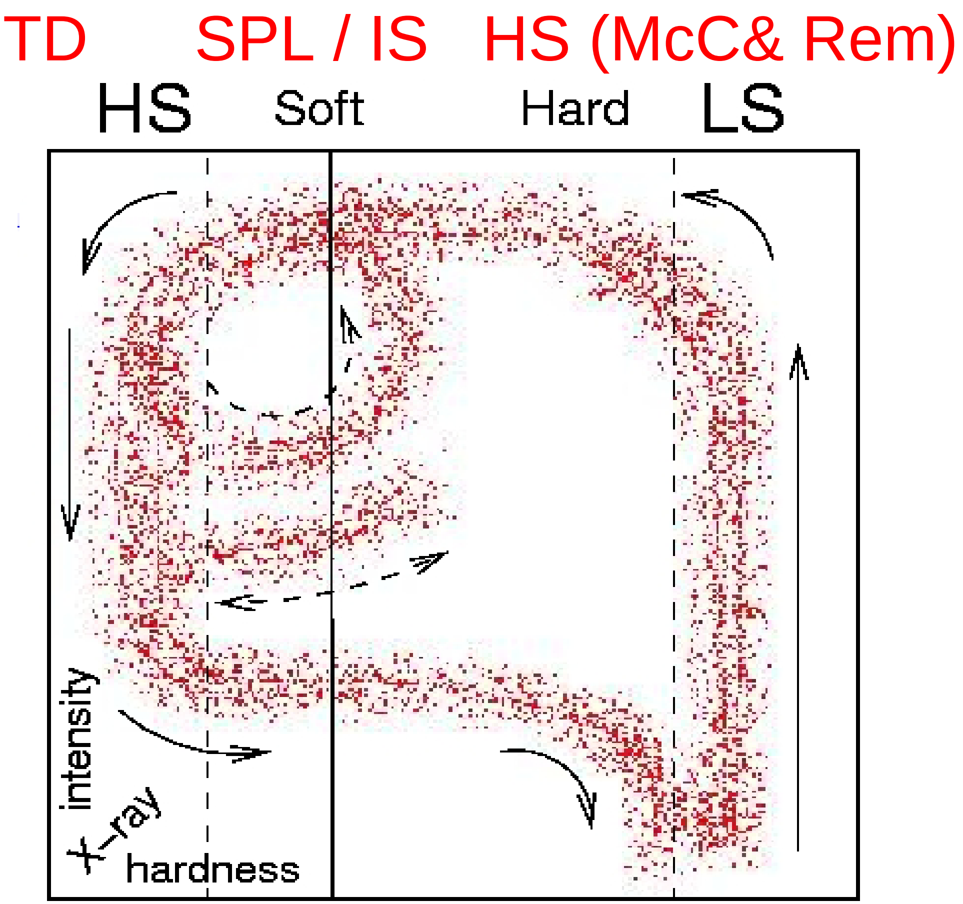


- Same ingredients: Black hole + accretion disk + jets
- Same physics on these different mass scale and geometry ??

Image: S. Heinz et al.

X-ray States of Black Hole Binaries

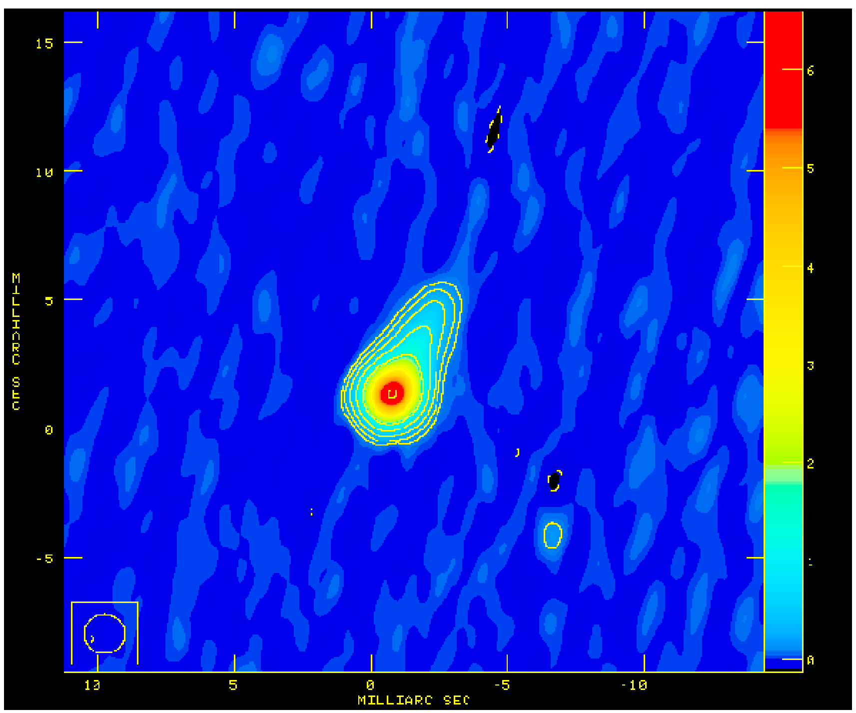


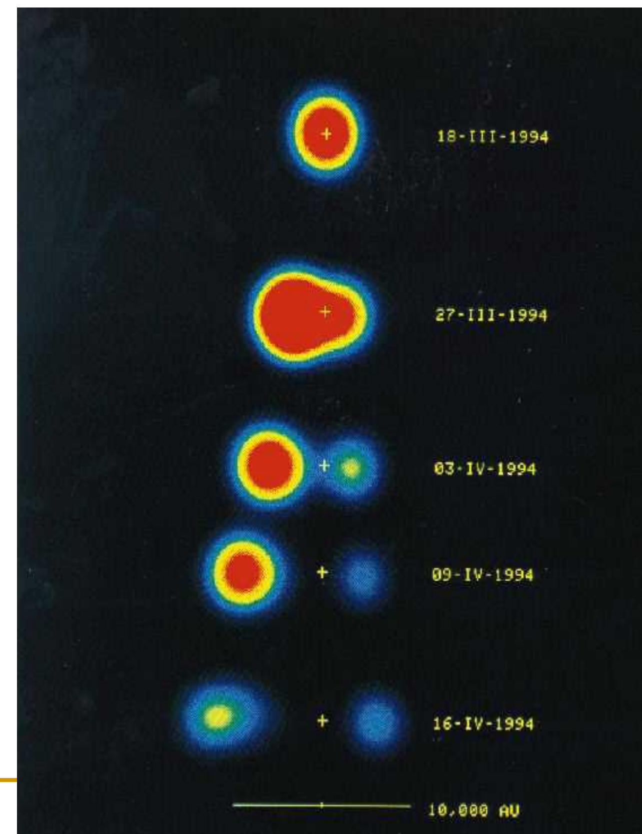


Hardness Intensity Diagram (HID)

Two flavors of relativistic jets from microquasars

- Compact, self-absorbed jets (on mas scale).
- Discrete ejections (superluminal, ballistic).



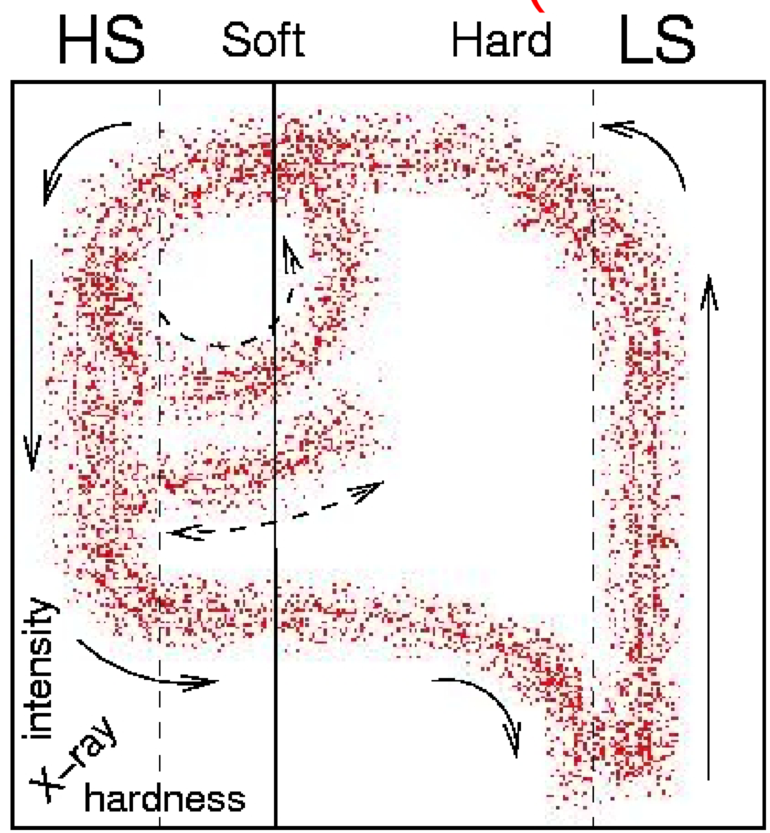


Stirling et al. 2001

Mirabel et al. 94

On the relation of relativistic jets with the X-ray spectral states

TD SPL / IS HS (McC& Rem)



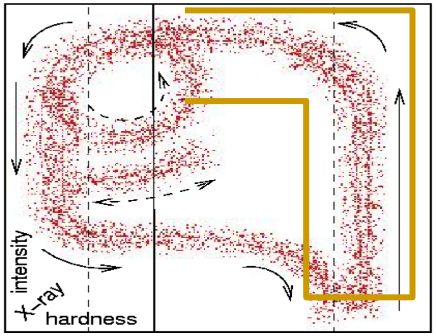
- Compact jet in the LH and IS (hard) X-ray state.
- Discrete ejections during the transition from IS (hard) to SPL state.
- No jet in the TD (or HS) state.

Corbel et al. (2004)

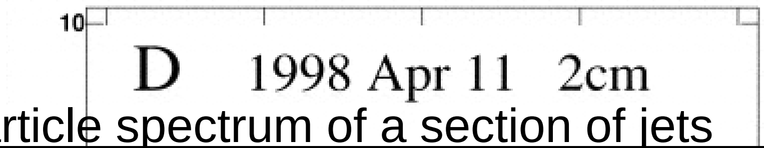
Fender, Belloni & Gallo (2004)

Part 2: The compact jets

Compact self-absorbed jets

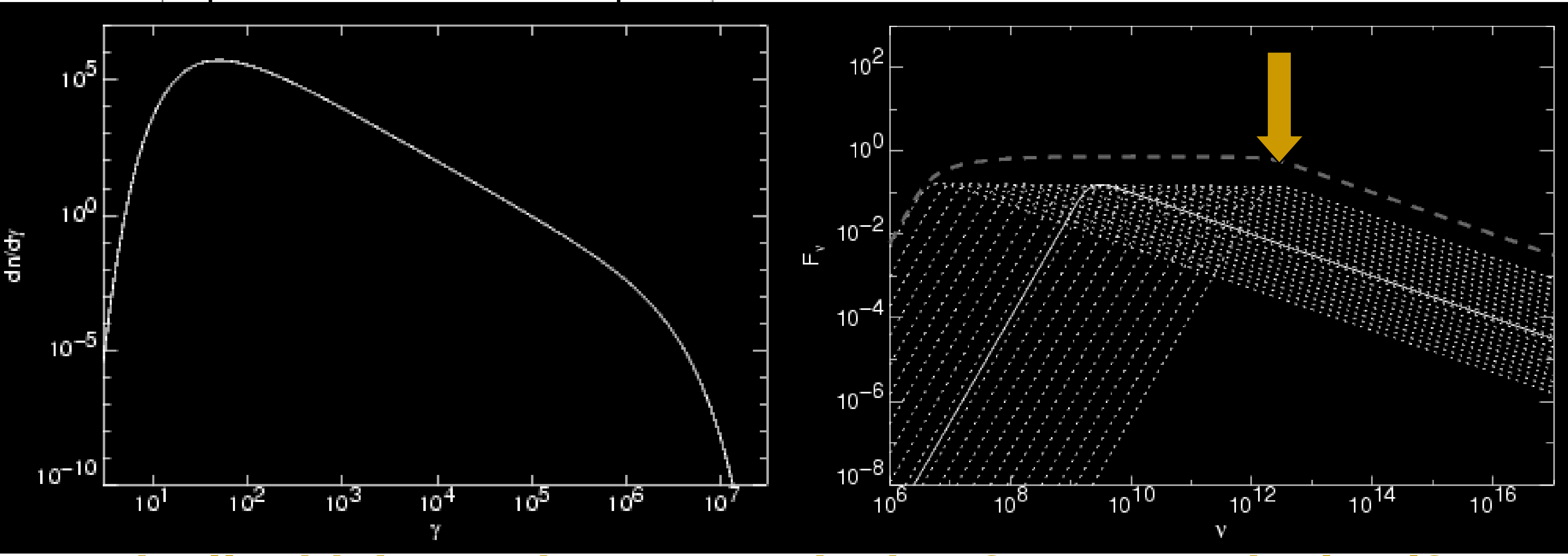


GRS 1915+105 (plateau state)



Particle spectrum of a section of jets

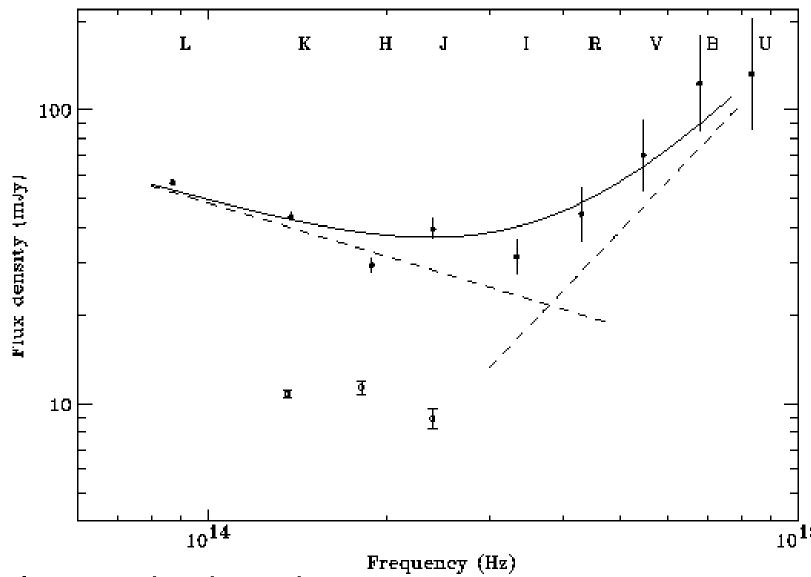
Total synchrotron spectrum



Optically thick synchrotron emission from a conical self-absorbed outflow: Blandford & Konigl (1979) , Hjellming & Johnson (1988)

Image: S. Heinz

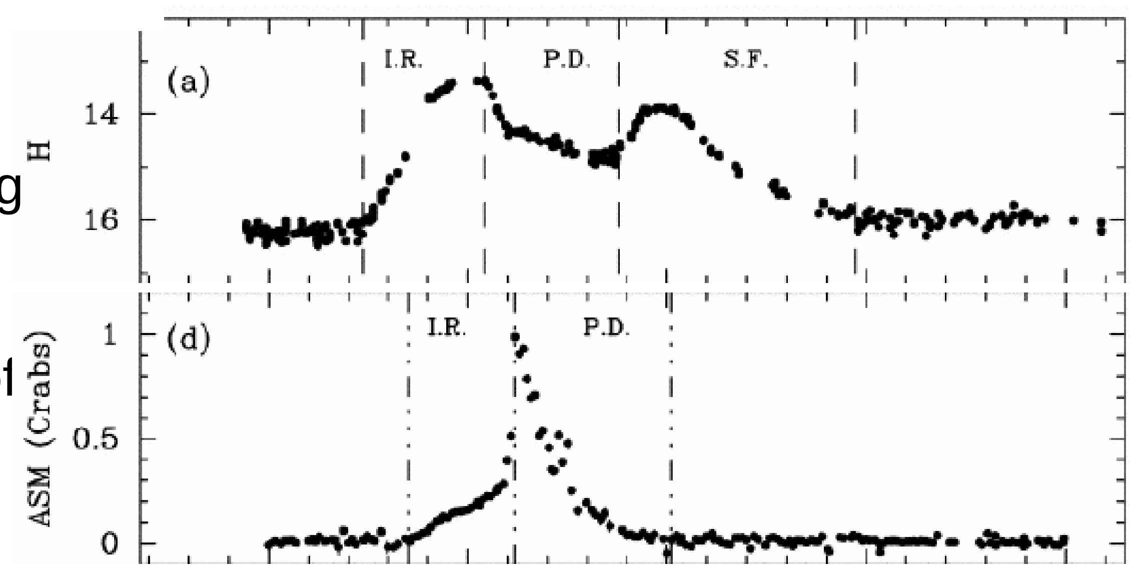
Cut-off frequency in near-infrared



Corbel & Fender (2002)

IR synchrotron emission in GX 339-4, but also XTE J1550-564,…

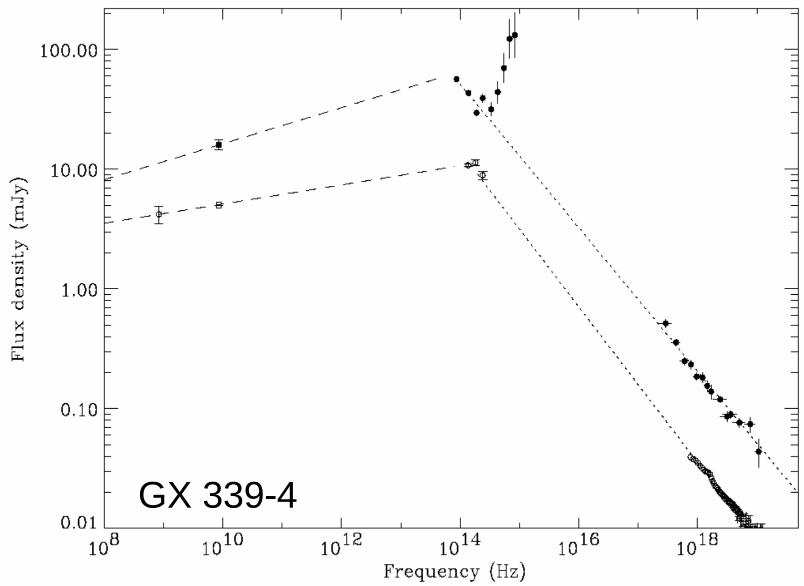
Secondary peak (corresponding to a HS transition) due to nonthermal infrared emission associated with the formation of the compact jet (Jain et al. 01)



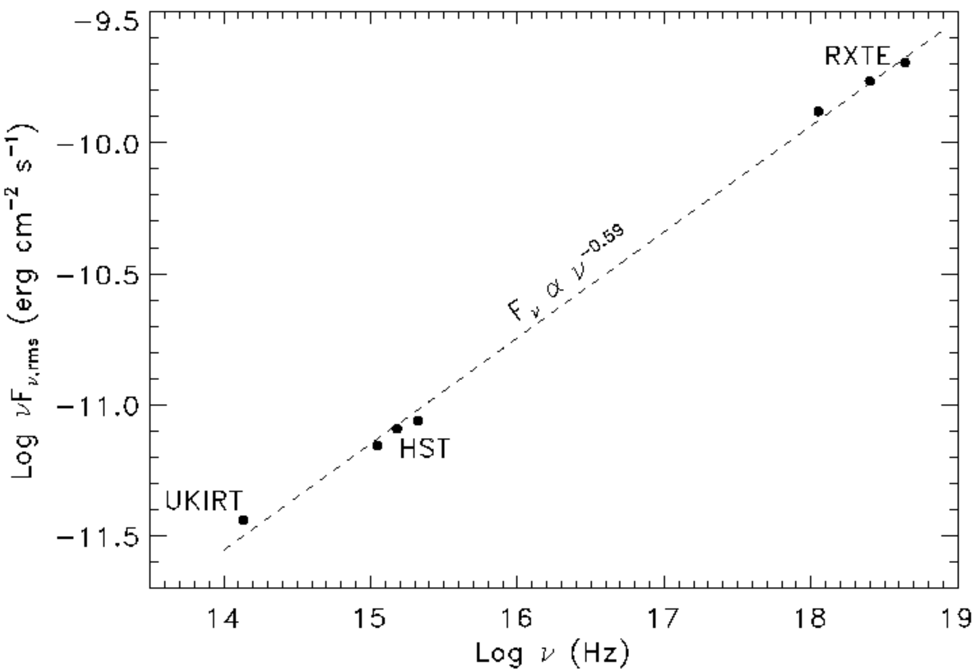
2000 outburst of XTE J1550-564 (Jain et al. 01)

See now also 4U 1543-47, GX 339-4 (Buxton)

Above this frequency: the X-ray spectra are consistent with an extension of a powerlaw from the IR: optically thin synchrotron emission in X-rays?



Corbel & Fender (2002)

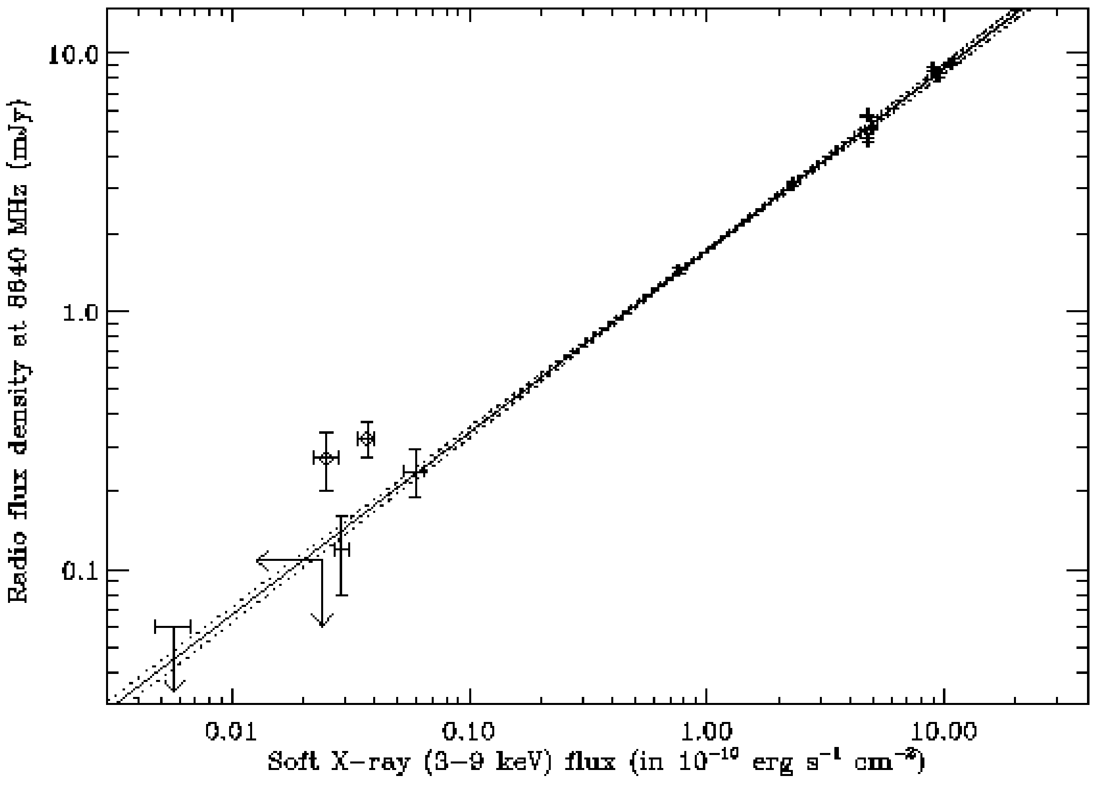


Hynes et al. 2003

Broadband SED of the rms variability of XTEJ1118+480: consistent with expectation of optically thin synchrotron emission (Hynes et al. 03)

Radio/X-ray flux correlation

GX 339-4



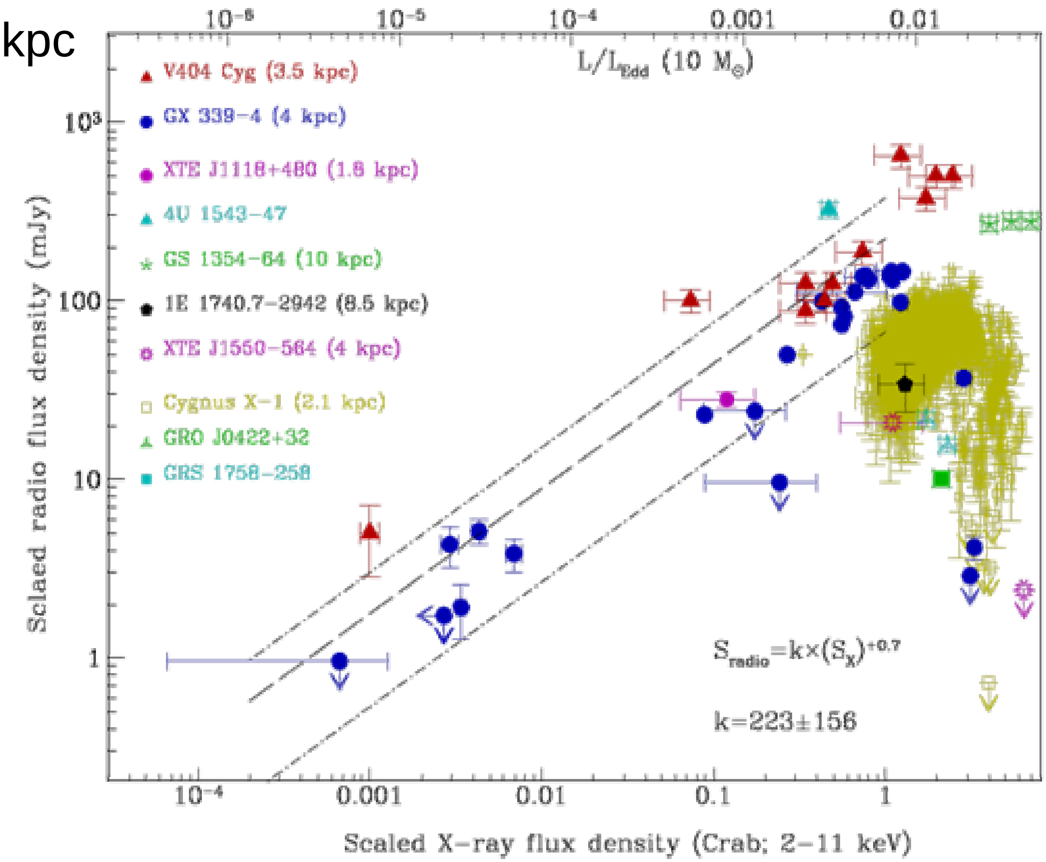
Corbel et al. (2000), Corbel et al. (2003)

Very strong correlation between radio and X-ray emission over more than 3 decades in flux (down to quiescence !!!)

$$\boxed{F_{rad} \propto F_X^{+0.7}}$$

A universal radio/X-ray correlation

1 kpc



Gallo, Fender, Pooley (2003)

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

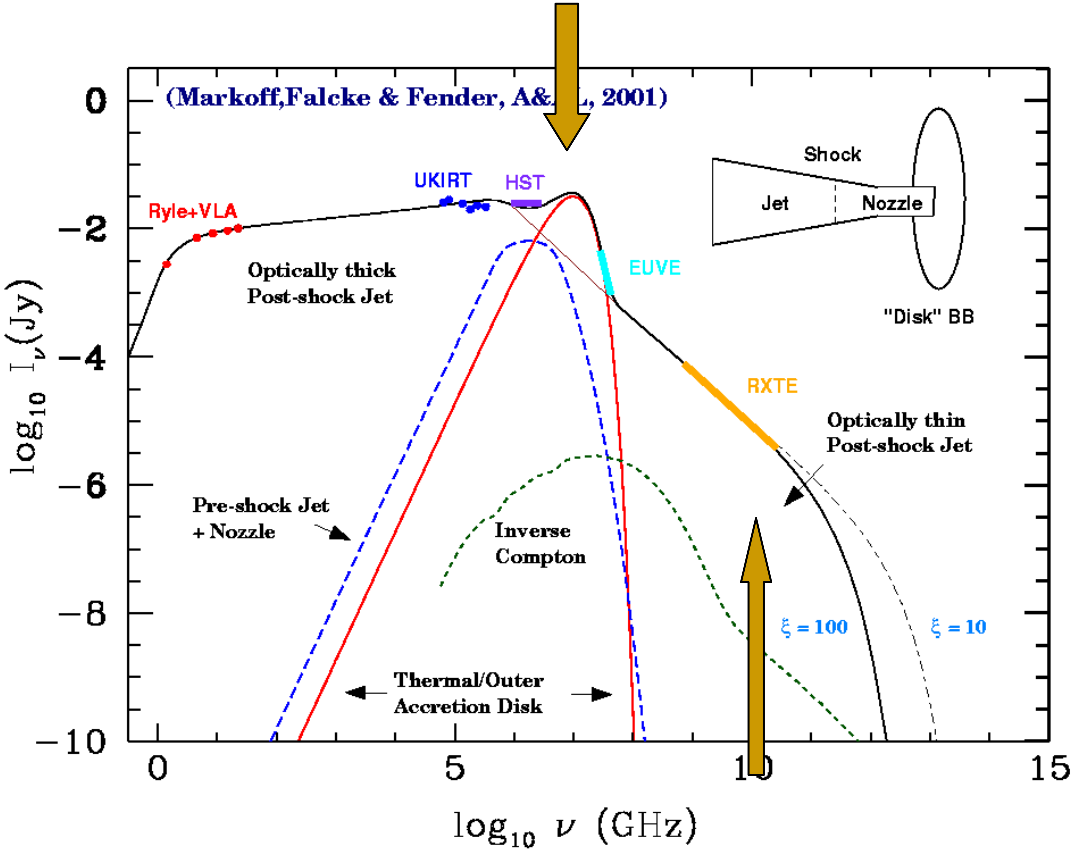
Same coupling !!!

No strong Doppler boosting: low velocity jet (β < 0.8 c)

Important for understanding of accretion/outflow coupling: role of jets at higher energies ?

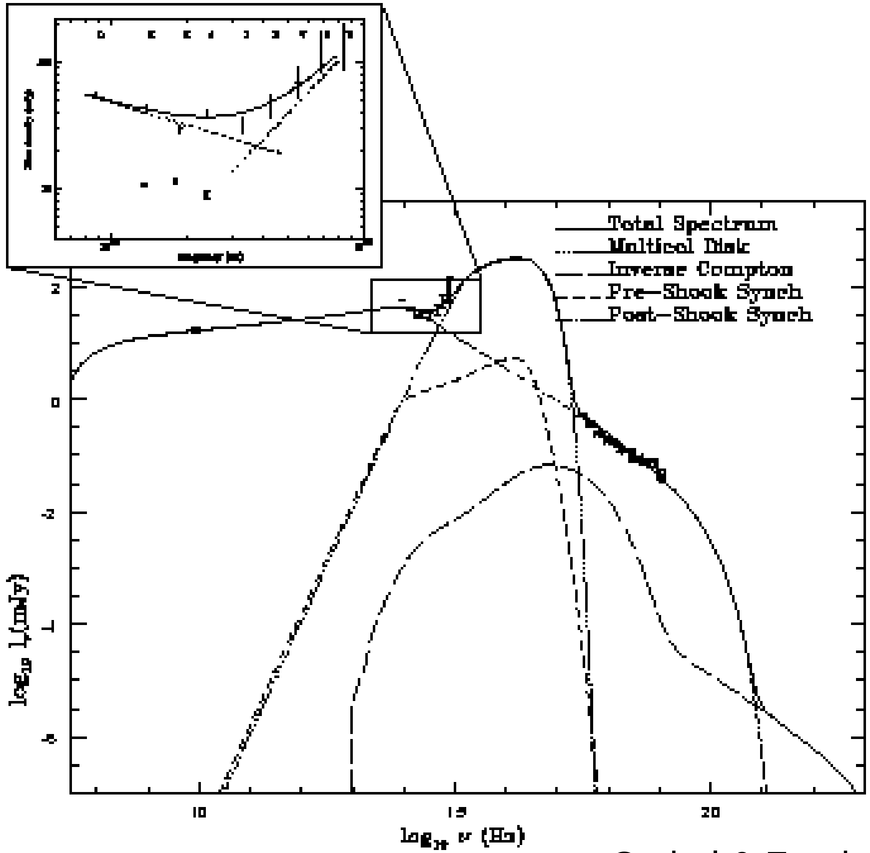
Broadband spectra: role of jets

If jet emission extends up to optical band, jet has > 10% of all power



If jet emission dominates X-ray band, jet has > 90% of all power !!!!

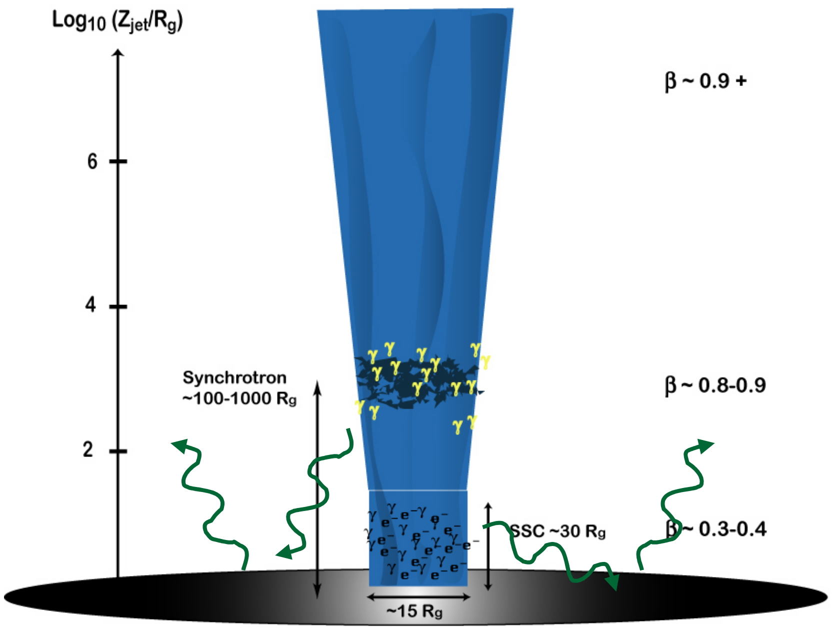
Another example of SED: 1981 bright low-hard state of GX 339-4

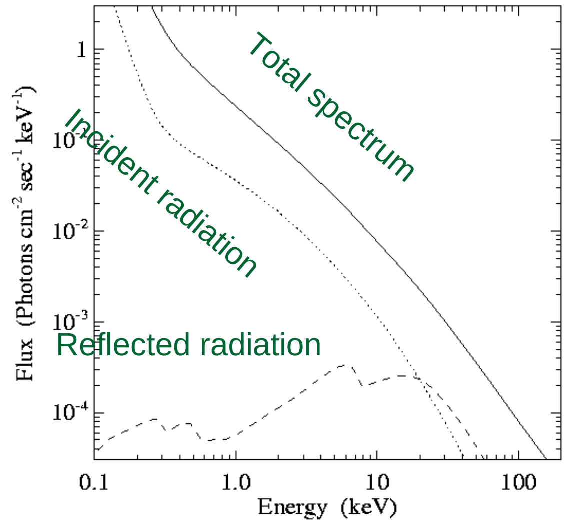


Corbel & Fender (2002), Markoff et al. (2003)

Jet model can account for all broadband spectra of GX 339-4, by changing only two parameters: the input power and the location of the first acceleration zone, Markoff et al. (2003)

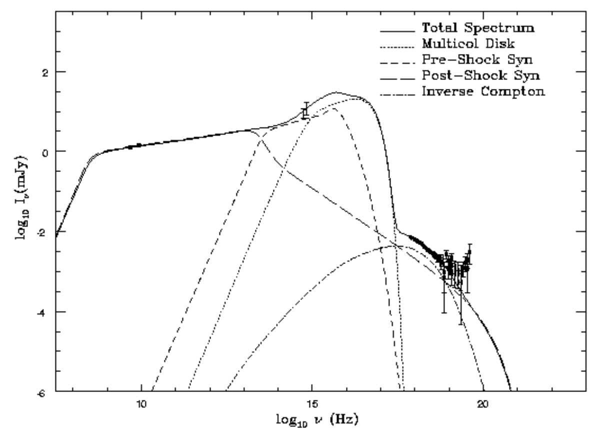
Jet model with SSC and reflection





~20% reflection fraction for SSC

(even without disk warping)



Markoff & Nowak (2004)

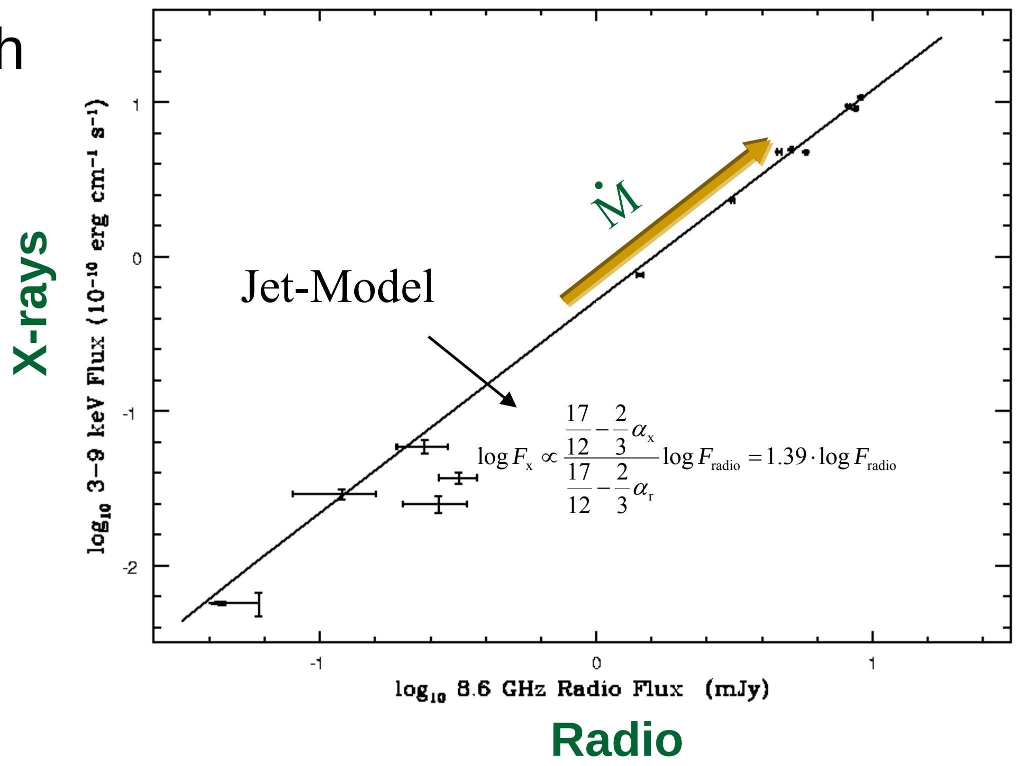
See also: Georganopoulos et al. (2002): jet model with external IC

Jet model and the GX 339-4 correlation

- The X-ray emission in GX339-4 seems to tightly follow the radio emission.
- The slope is non-linear with α=1.40.
- Mass = cte
- Analytic theory predicts α=1.39.

⇒ Jet scaling laws reproduce radio-x-ray slope perfectly.

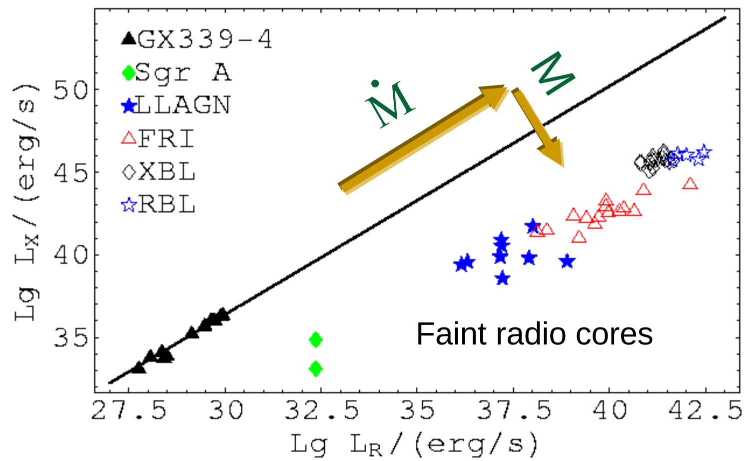
X-ray vs. Radio correlation (GX339-4)

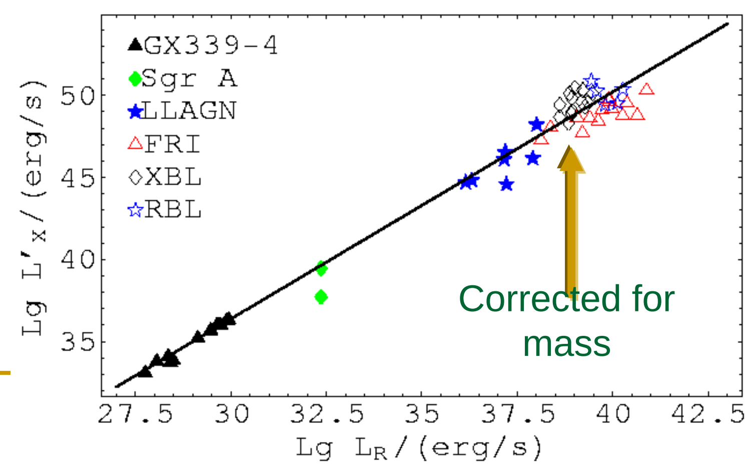


X-ray/Radio Correlation and LLAGNs: scaling with accretion rate

- Radio and X-ray/optical emission for VLA and VLBA **radio cores** from **sub-Eddington black holes** (Liners, FRIs, BL Lacs, Sgr A*).
- 'Correct' X-ray/optical flux for black hole mass:
  - ⇒ Sub-Eddington AGN magically fall on XRB extension + pure jet model
  - ⇒ Jet domination works very well!
  - ⇒ Mass and accretion rate form a „fundamental plane".

(see also Merloni et al. 2003)

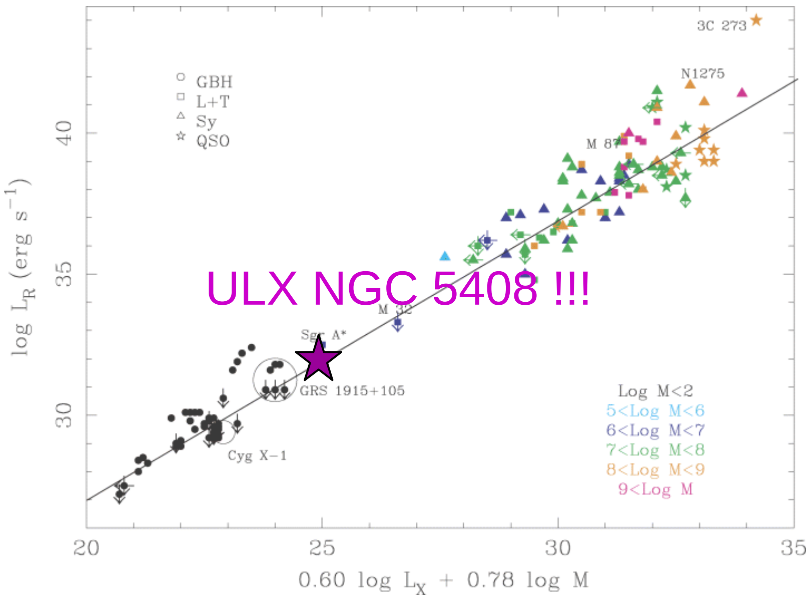




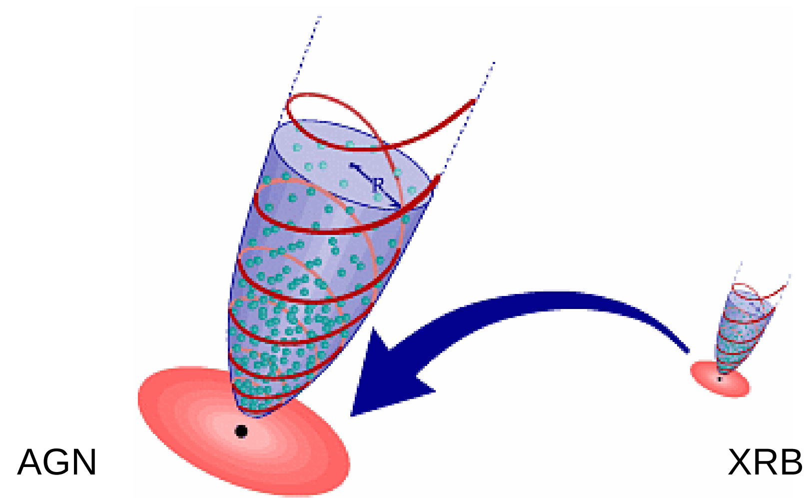
Courtesy: Heino Falcke

Falcke, Körding, Markoff (2003, A&A)

The fundamental plane: no X-ray jet emission ?



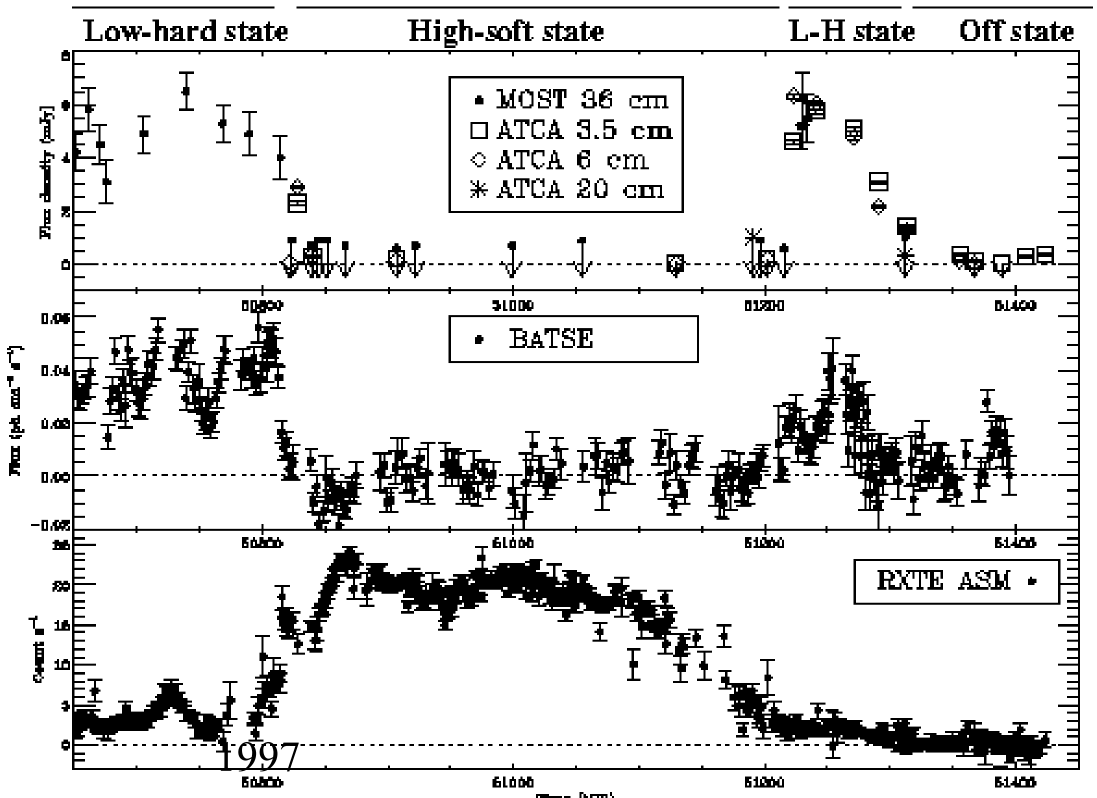
Merloni, Heinz & Di Matteo 03; Heinz 04
Heinz & Sunyaev 03

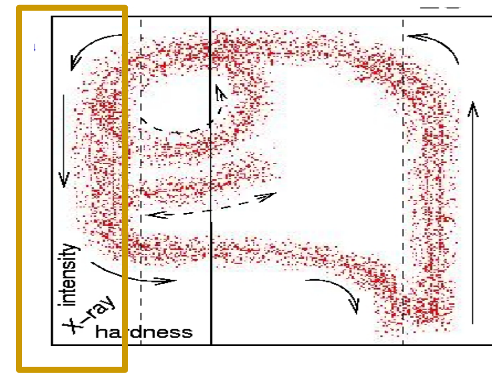


Scale invariance hypothesis:
only one scale (r_g) for jets !!!

Radio/X-ray correlation : consistent with inefficient accretion, inconsistent with efficient accretion and also inconsistent with synchrotron X-rays if synch. cooling included.

Quenched radio emission in the high/soft state





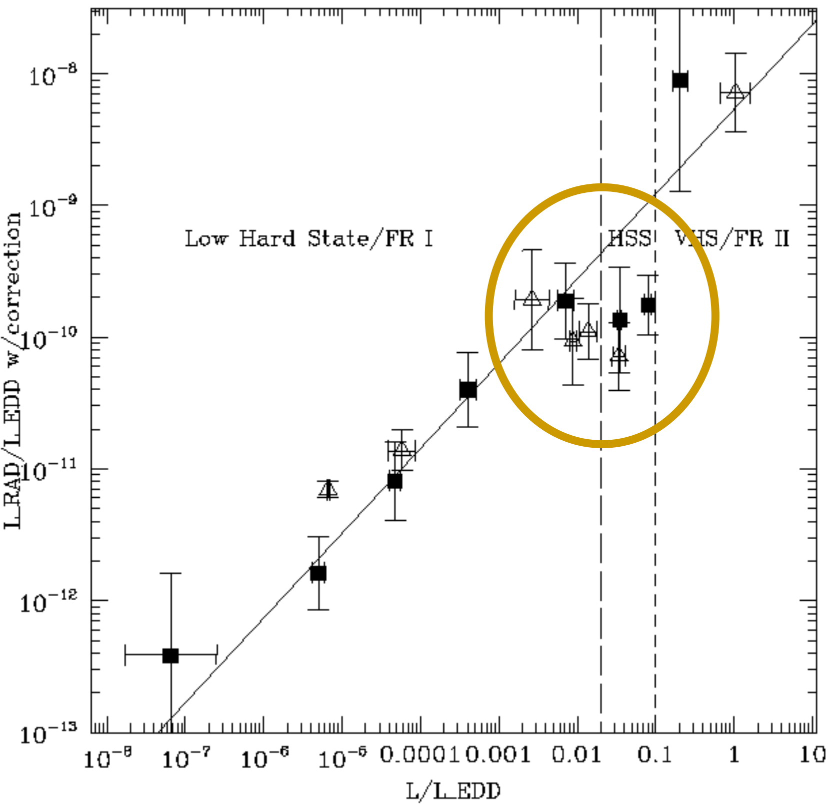
1999

Fender et al. (1999), Corbel et al. (2000)

Quenched radio emission also in Cyg X-1 (Tannanbaum et al. 72)

Similar to GRS 1915+105: « Soft X-ray states are never associated with bright radio emission » (Klein-Wolt et al. 02)

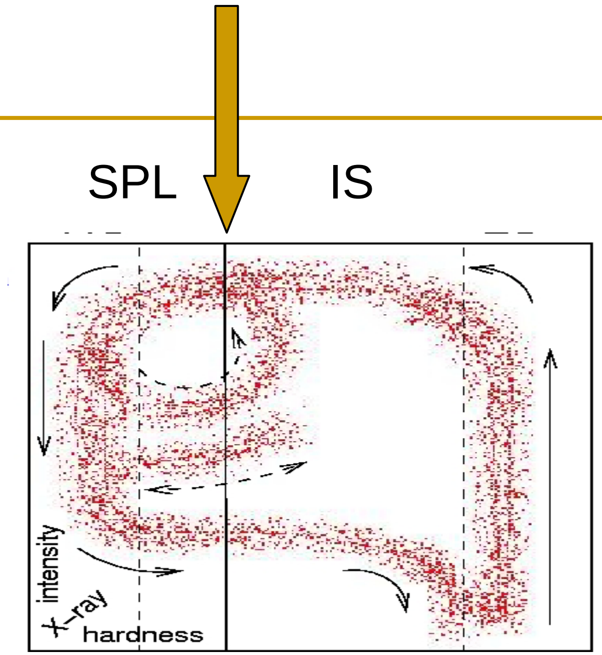
QUENCHING IN AGNs



Maccarone, Gallo, Fender 03

AGN show the same spectral state phenomenology and related disk-jet coupling as the stellar mass accreting black holes

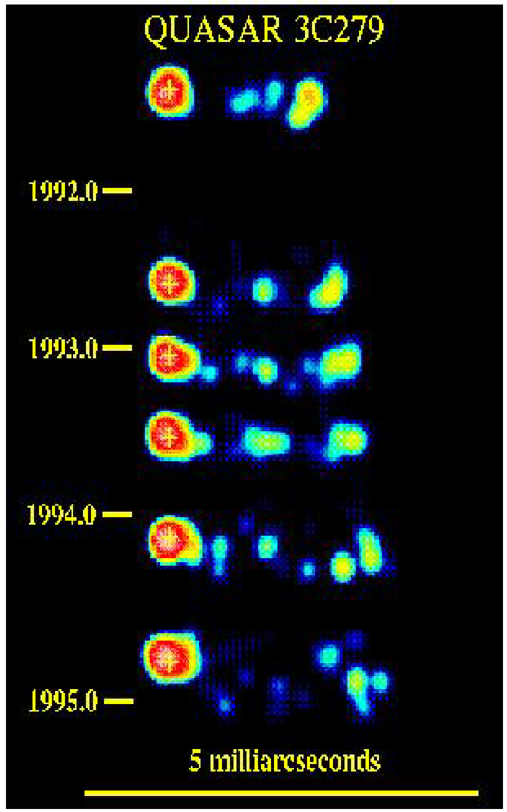
Part 3: transient ejection events (and large scale jets)

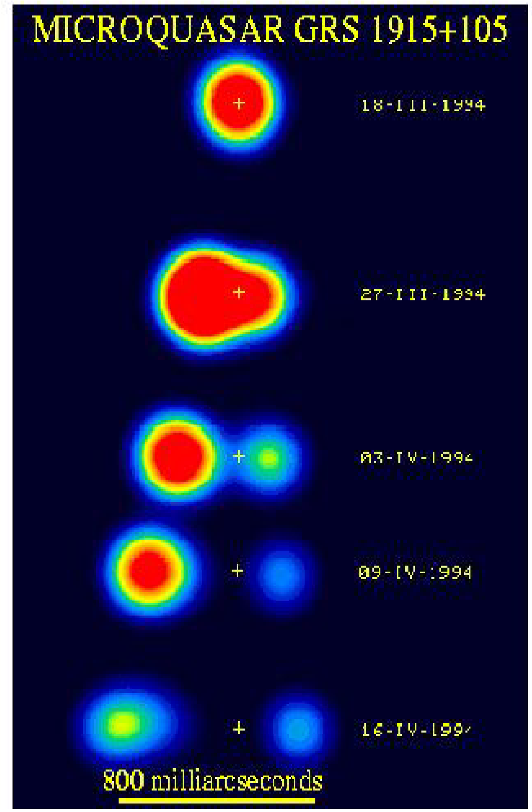


«Superluminal » ejections

VLBI at 22 GHz ~ 1.3 cm

~ milliarcsec. scale





VLA at 3,5 cm

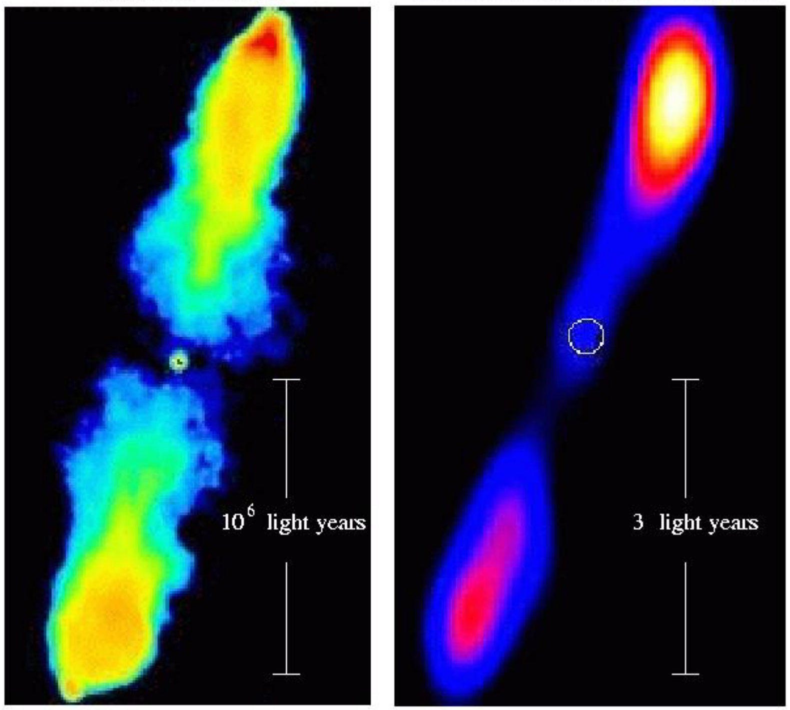
~ arcsec. scale

Mirabel & Rodriguez (1994)

- Move on the plane of the sky ~10^3 times faster
- Jets are two-sided (allow to solve equations $\Rightarrow$ max. distance)

Quasar – microquasar

Quasar 3C 223 1E1740.7-2942



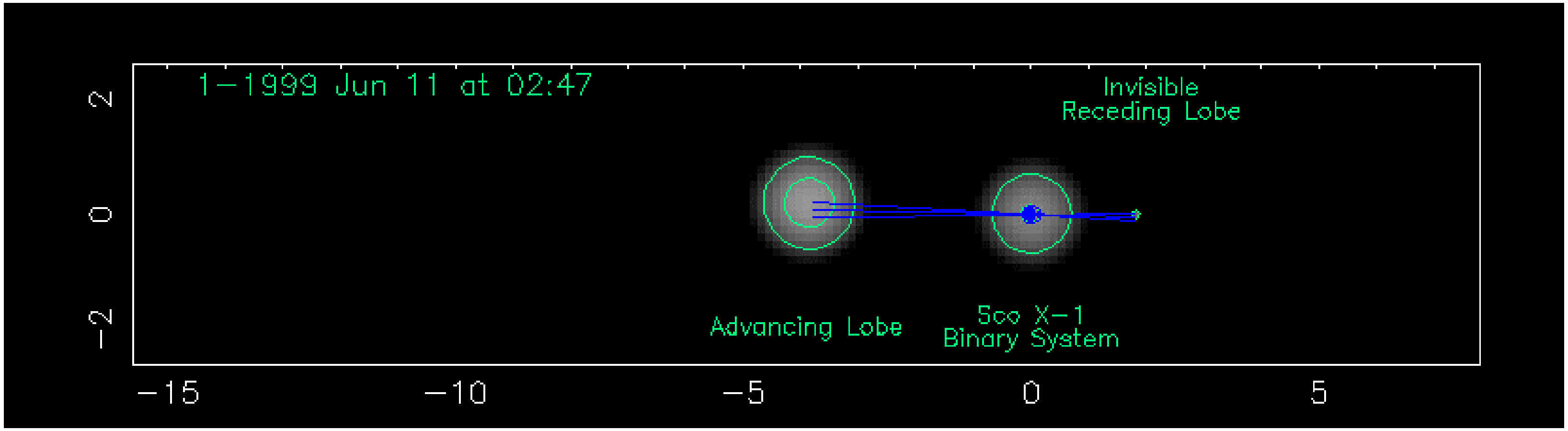
Steady jets in radio at arcminute scale

$\Rightarrow$ long-term action of steady jets on the interstellar medium

In both BH and NS systems, transient X-ray outbursts are accompanied by radio outbursts.

When resolved, these reveal highly relativistic ejection events

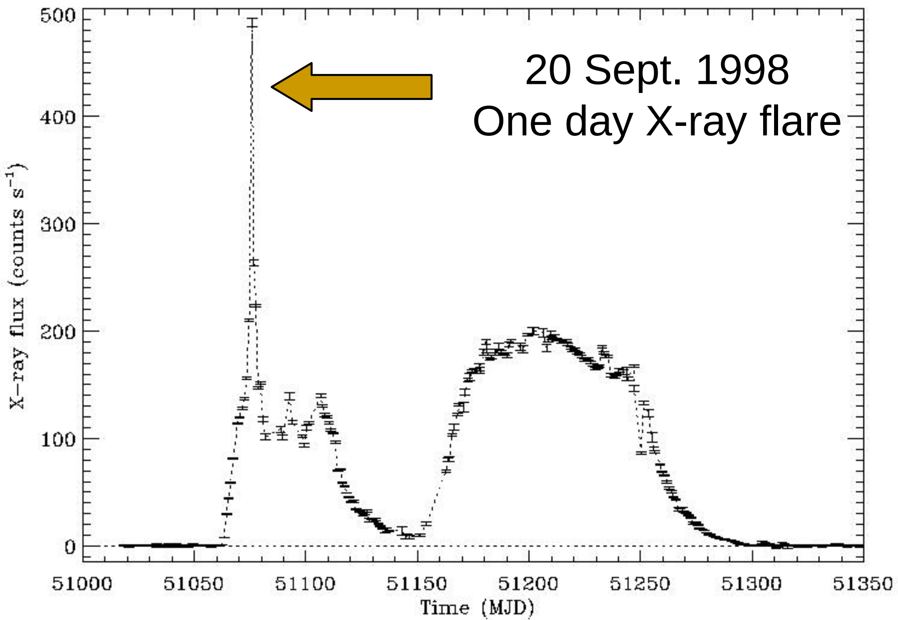
Energy transfer from the core to the lobes



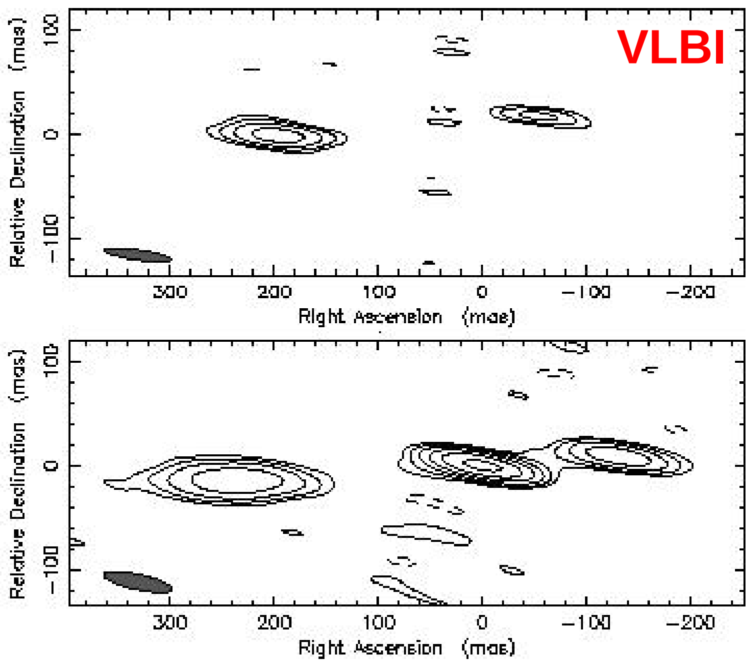
Highly relativistic jets in Sco X-1 acting on sub-relativistic sites of particle re-acceleration… (bulk Lorentz factor > 3; for Cir X-1 > 15)

The observed radio knots are only tracers of an underlying (unseen) ultrarelativistic flow

Large-scale, decelerating relativistic jets from XTE J1550-564

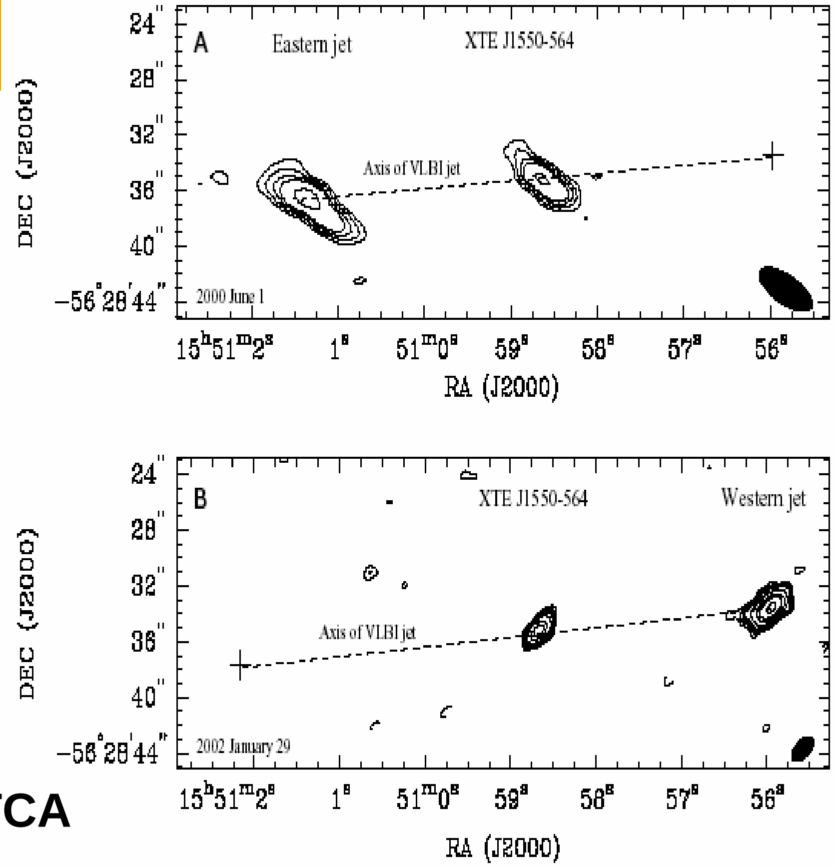


RXTE/ASM lightcurve (1998-99)



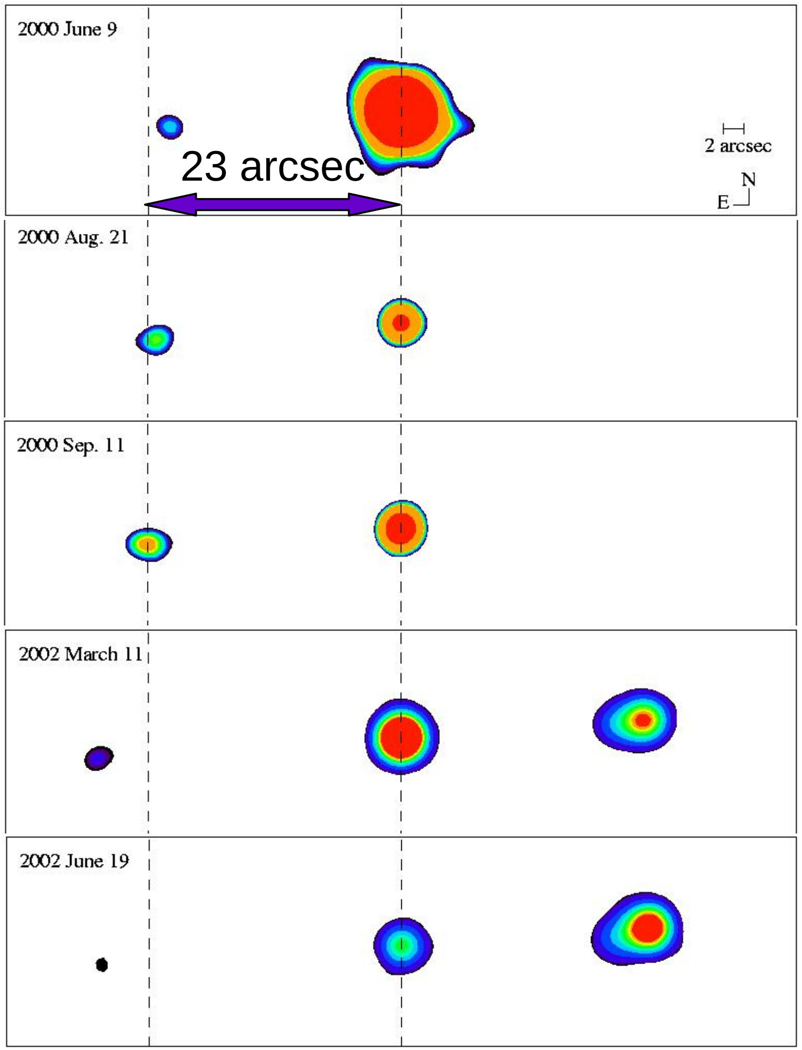
- M_{bh}= 10.5 +/- 1.0 $M_{\odot}$; d ~ 5 kpc (Orosz et al. 2002)
- 20 Sept. 1998: Strong and brief X-ray flare

Relativistic ejection imaged with VLBI (Hannikainen et al. 2001)



ATCA

Chandra (0. 3 - 8 keV)



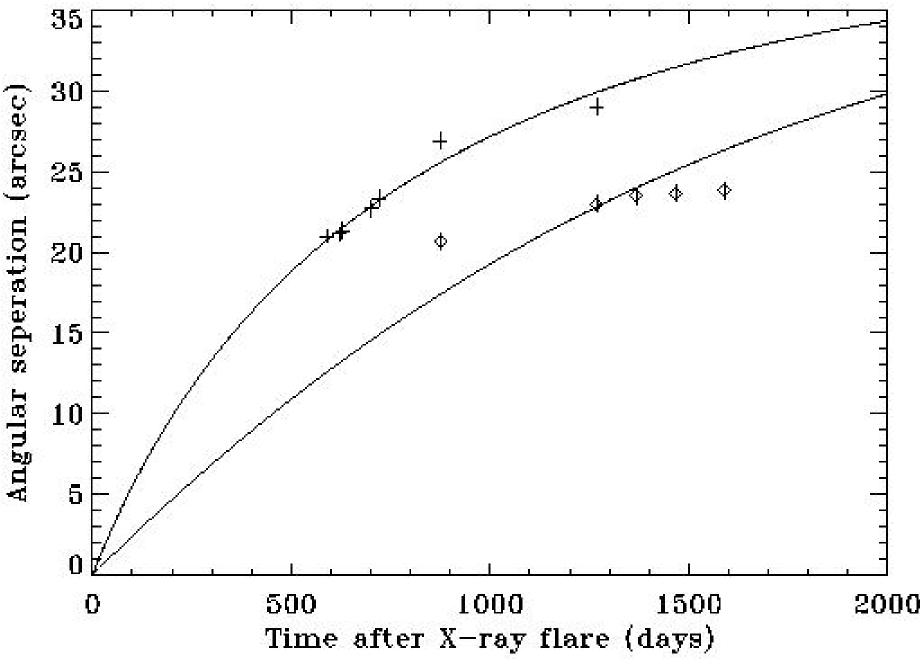
New radio source to the West of the BH in 2002 + another to the East in 2000: aligned with the axis of the VLBI jets

Moving X-ray sources associated with the radio lobes

Corbel et al., Science (2002),298, 196

Kaaret et al. , Tomsick et al. 2003

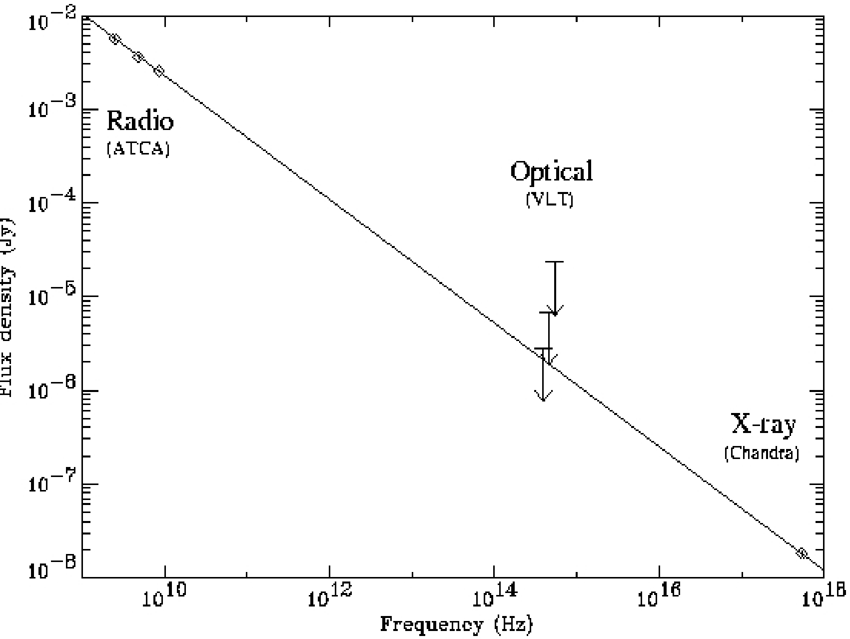
Jet deceleration



- Smooth deceleration over four years: from β(app) > 1.7 to β(app) ~ 0.3
- implies >50% of kinetic energy (>10^{34} erg/sec) been lost… but only about 1% of this has been observed: >99% has been dumped into the ISM

Direct evidence for gradual deceleration in a relativistic jet

Emission mechanism



- SED consistent with a PL of spectral index $\alpha = 0.66 \pm 0.01$
- Same morph. radio/X

Synchrotron emission from the same electron dist.

If synchrotron + Equipartition: $B_{eq} = 0.3$ mG

X-ray emitting electrons: Lorentz factor $\gamma_e > 2 \times 10^7$ (TeV electron

$N_e = 10^{45}$ electrons; if one p/e, mass $= 10^{21}$ g

if mass accretion rate $= 10^{18}$ g/s, then injection time ~ 1000 s

A jet/ISM collision ?

September 1998: ejection of few relativistic plasmoids
adiabiatic expansion --> decay of radio emission

Undetectable up to April 2000 (eastern jet) or January 2002 (western jet): brightenning

→ Evidence than radio through X-rays is synchrotron emission

- Internal shocks?: internal instabilities, varying flow speed
- External (reverse) shocks?: interactions with denser ISM

↓

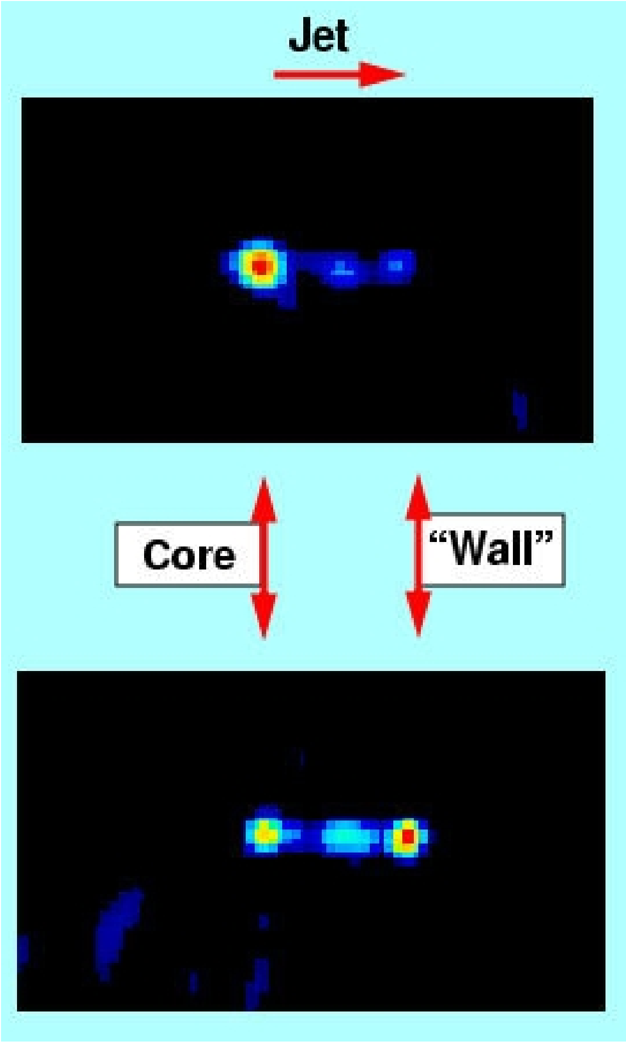
Particle *in-situ* acceleration powered by bulk deceleration

Beamed X-ray emission !!!

A large scale relativistic jets in H1743-322 !!

- Not available.

XTE J1748-248



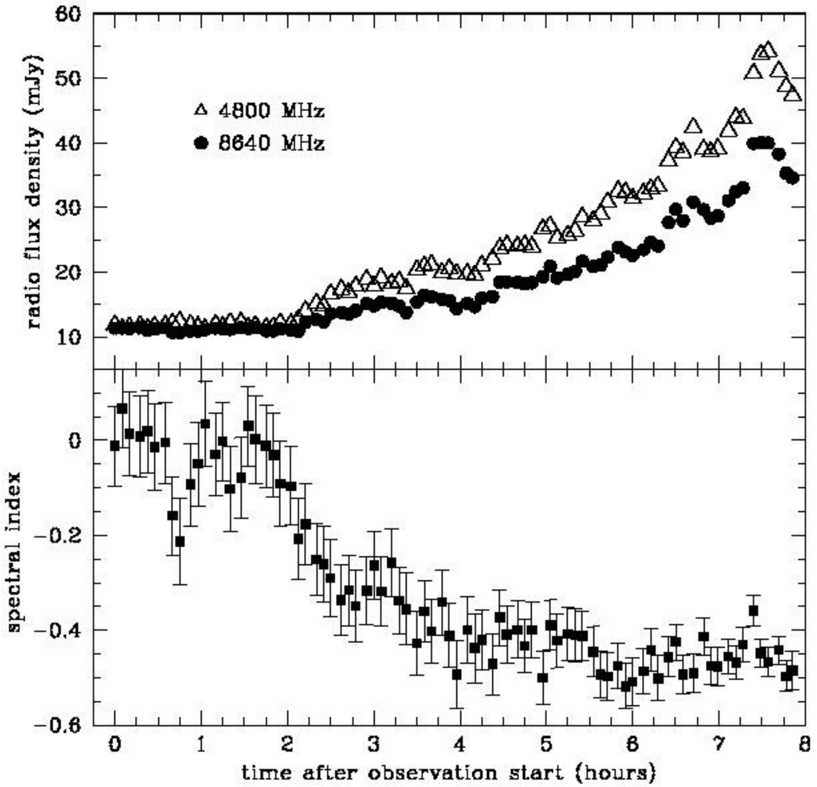
XTE J1748-248: a cosmic jet hits the wall in 1998 ? (Hjellming, unpublished)

Jet/ISM interaction ? The jets stoped when it possibly hits a dense cloud

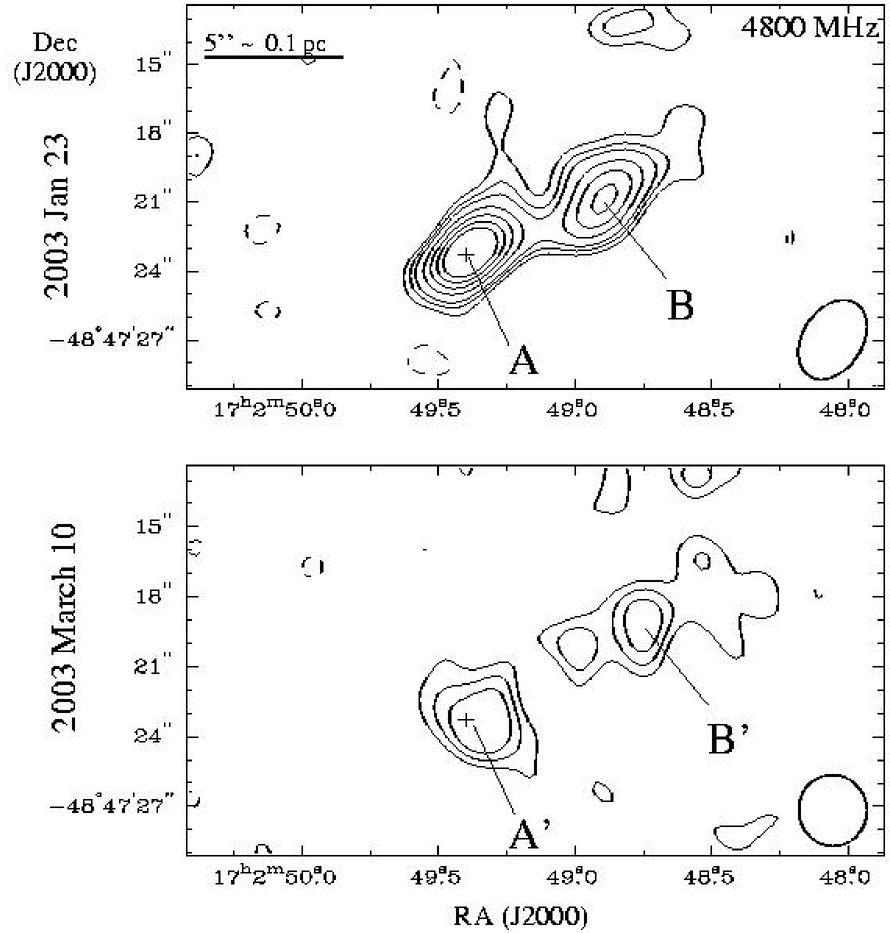
+ XTE J1650-500 (Corbel et al. 04)
+ Cyg X-3 (Heindl et al.03)
+ GRS 1915+105 (Kaiser et al. 04)

Radio (VLA)

A large scale jet in GX 339-4

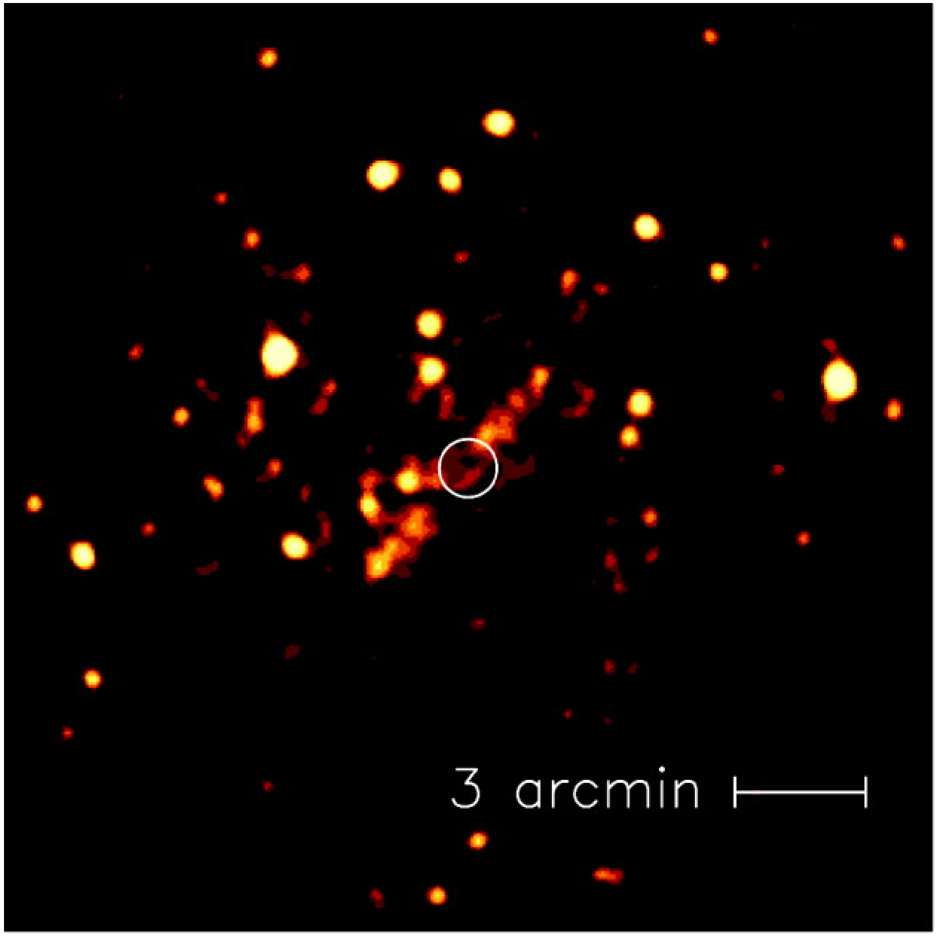


Radio flare in May 2002



Gallo et al. 04

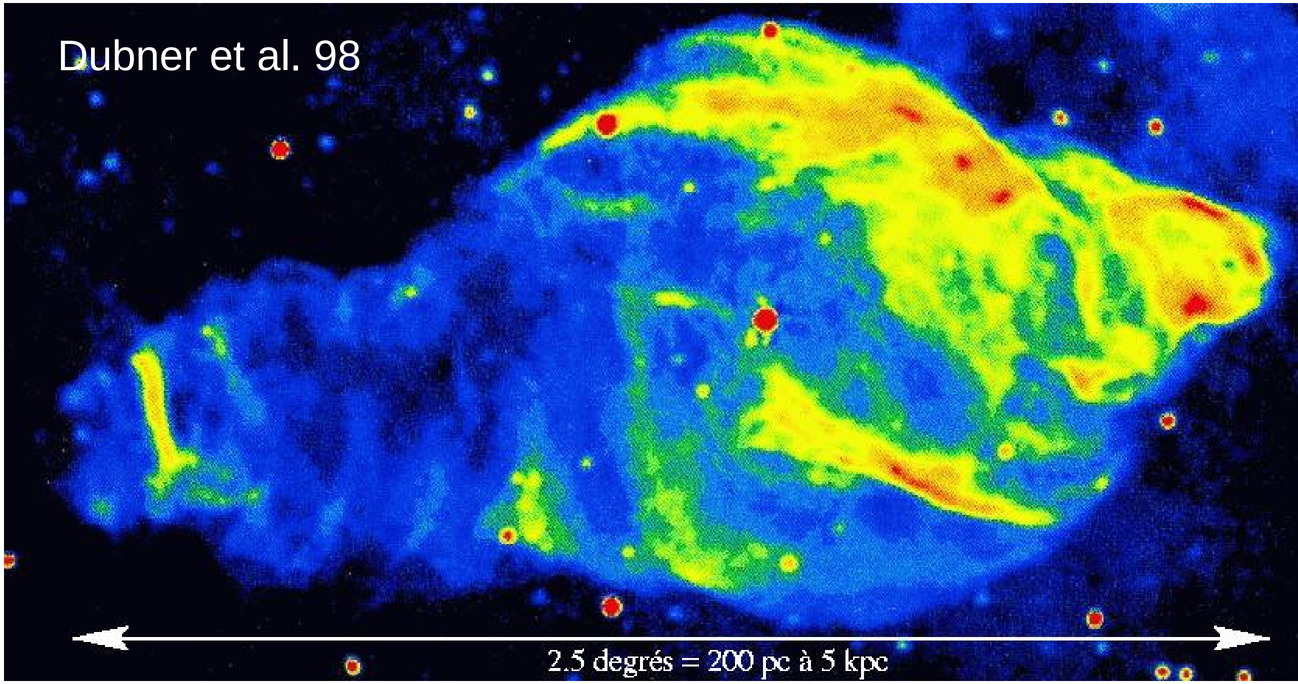
A fossil X-ray jets in 4U 1755-33



Angellini & White(2003)

- XMM newton observations of 4U1755 in 2000 (in quiescence since 1995)
- Large (7') scale two-sided X-ray jets
- BHC active for > 25 years
- If v~c, it would have taken 13 yrs to extend to its current length

SS 433



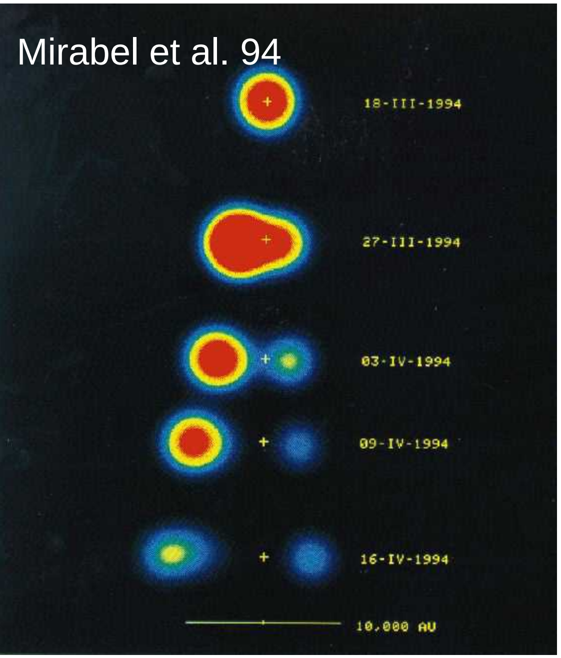
Radio map

- Large scale X-ray jets (but no motion observed)

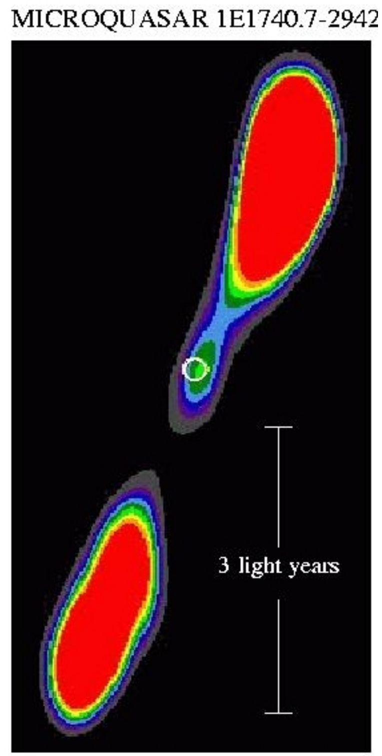
  Non thermal emission poss related to jet/ISM interaction
- Relativistic (0.26c) ejection on arcsec scale

  Associated thermal X-rays (Marshall et 01,Migliari et al. 02)

Jet morphological evolution in microquasars?



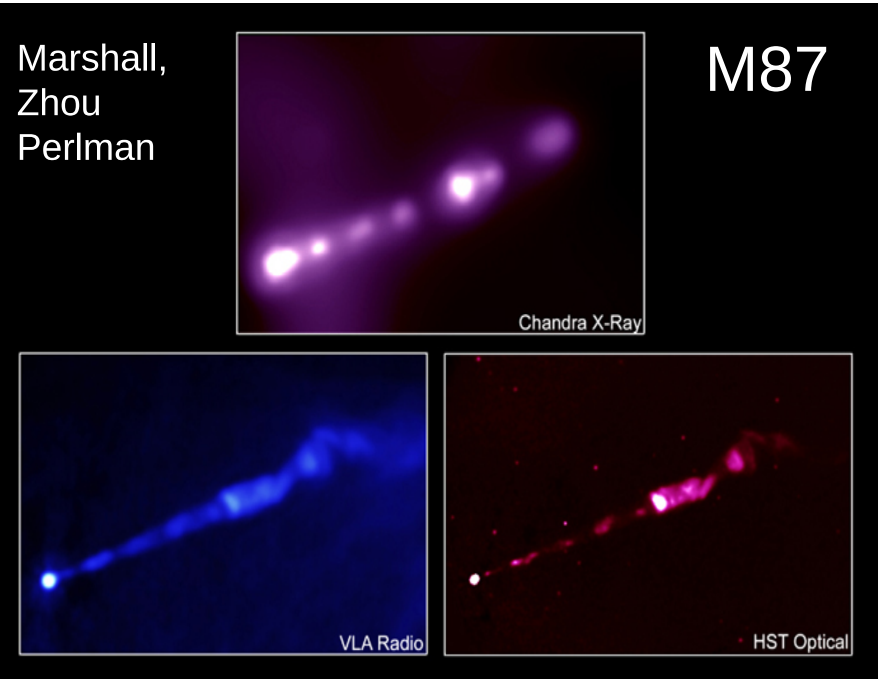
Arcsec scale (<0.1 pc) superluminal jets in GRS 1915+105 or other SXTs

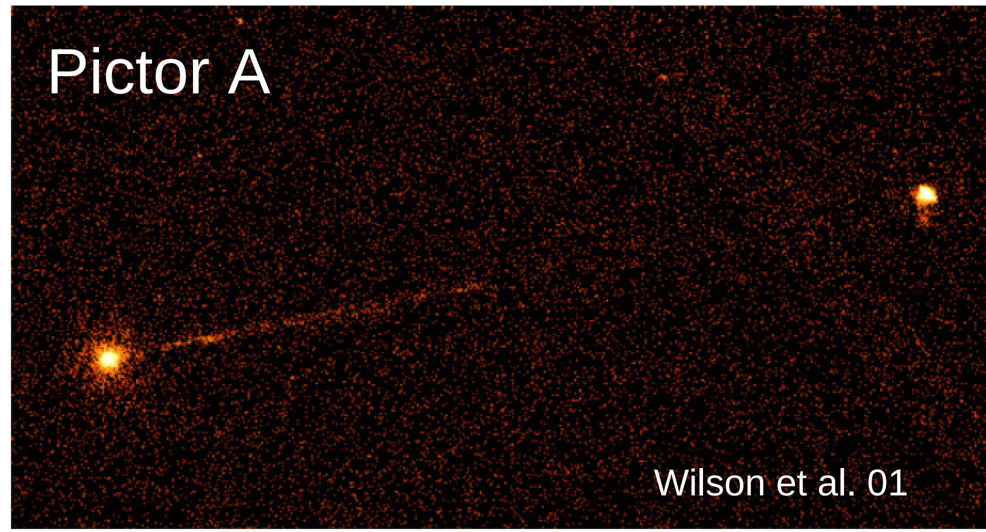


« Stationary » large scale (1 - 3 pc) radio jets in 1E 1740.7-2942 or GRS 1758-258 or X-ray jets in 4U 1755-33

- Jets of XTE J1550-564 (0.5 - 0.8 pc), H1743-322: intermediate size. Morphological evolution ?
- Large scale lobes = long term action of impulsive relativistic events.

Analogies with AGNs





Strong similarities with AGN jets

Study of dynamical evolution of relativistic jets
on timescale inaccessible for AGN

Conclusions: similarities XRBs/AGNs

- Compact cores: same coupling ? Evidence for high energy synchrotron emission ????
- Discovery of moving relativistic large scale X-ray jets in XTE J1550-564 and now H 1743-322 + others
  - Broadband spectra: synchrotron emission
  - In-situ acceleration of particles in shocks up to TeV: possibly jet/ISM interactions.
- Analogies with AGNs and therefore cool for our lifetime ! ☺
- Probably more common than previously thought (XTEJ1748, SS 433, 4U1755-33, XTE J1650, GRS1915, GX339, …