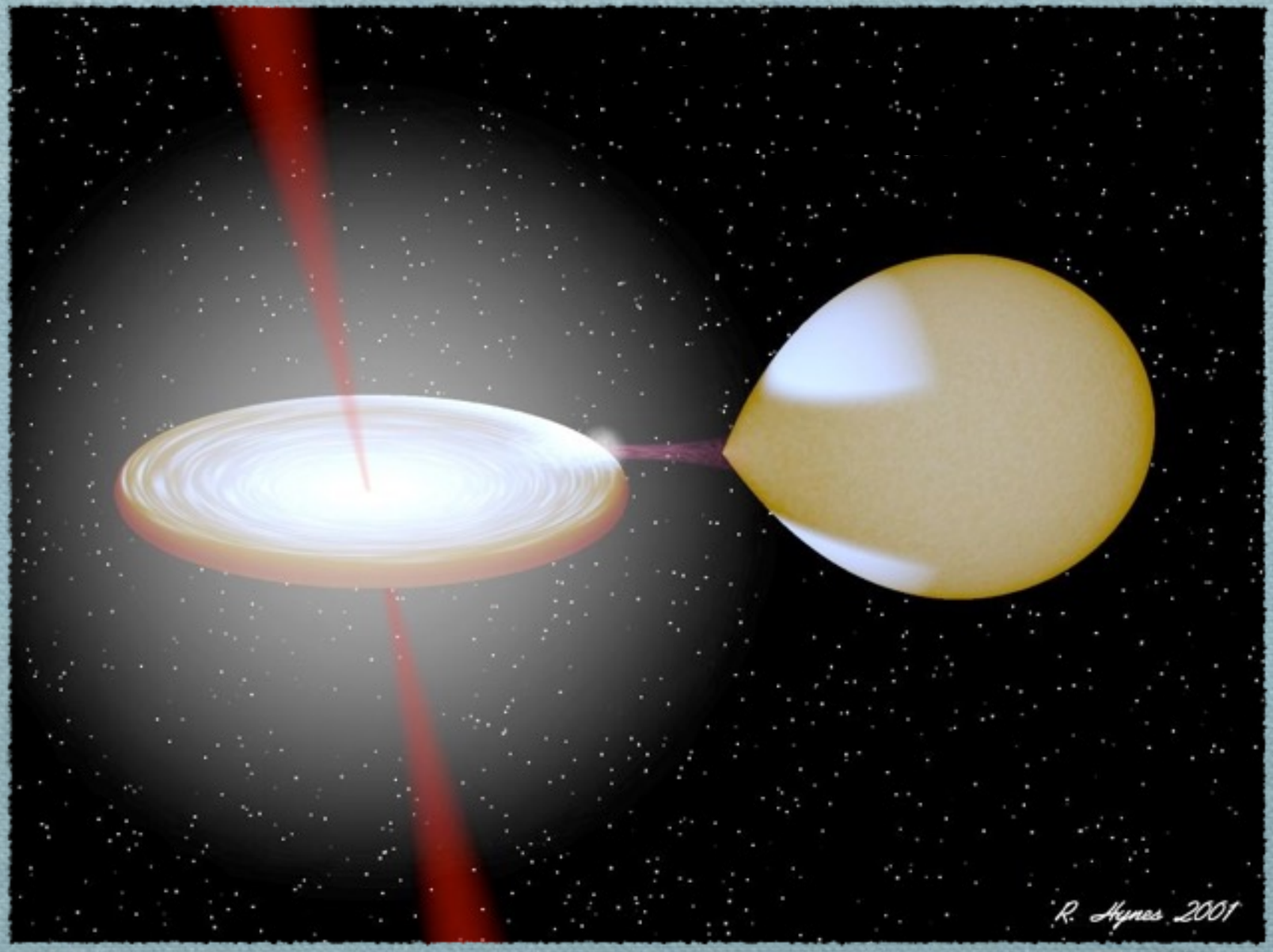

Black-hole binaries

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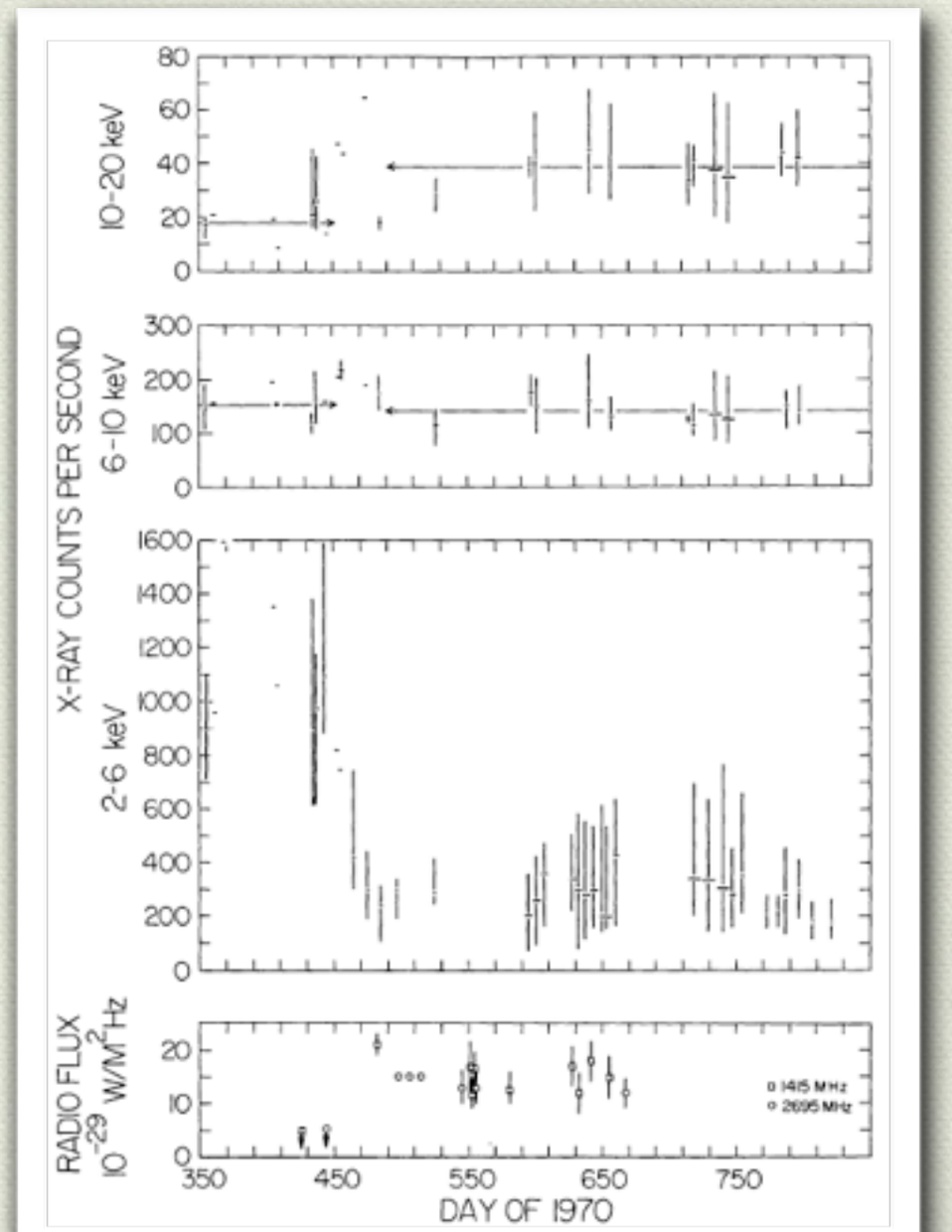
OUTLINE

- Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars
- Lecture II: High-energy emission and spectra
- Lecture III: Time variability on all scales
- **Lecture IV: Radio emission, jets, accretion/ejection**
- Lecture V: BH parameters & GR, AGN connection
- Lecture VI: Neutron-Star binaries + ULX + more

First radio measurements

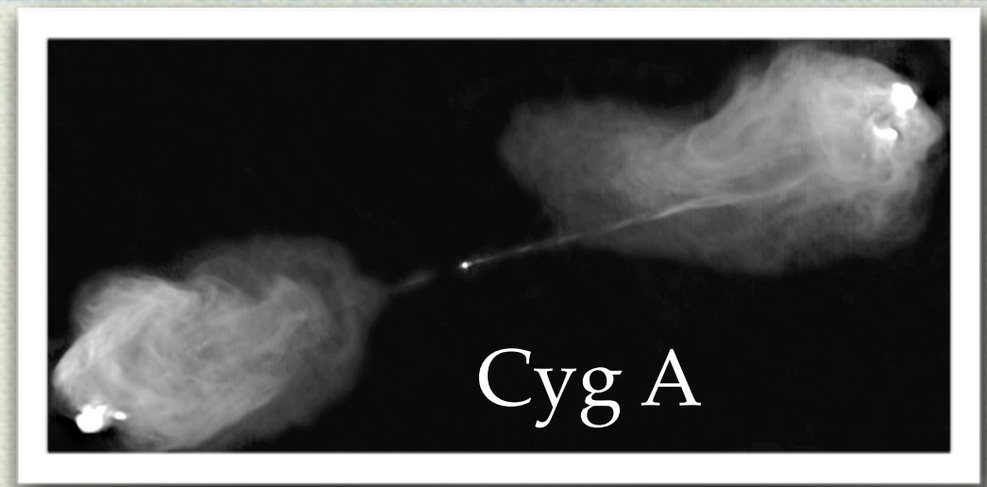
- As usual, Cyg X-1
- Radio emission is state related

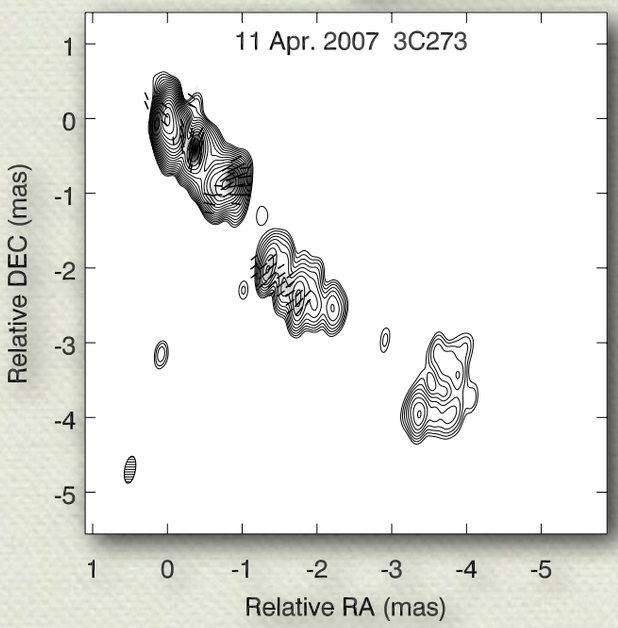


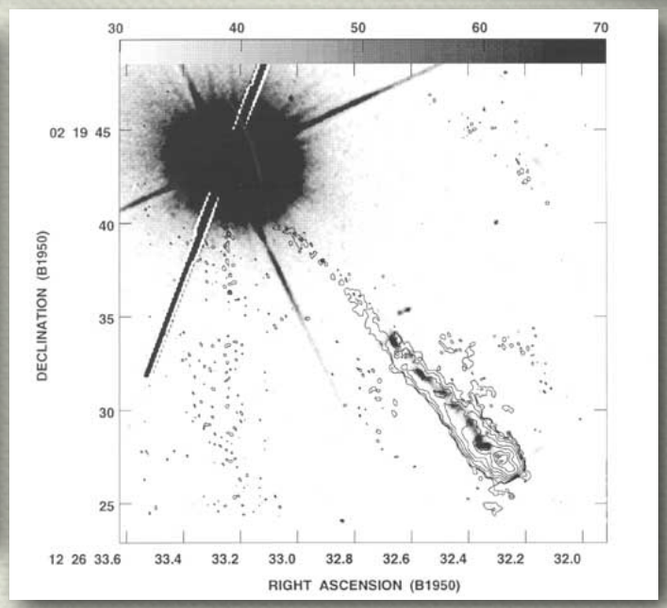
Tananbaum et al. (1972)

AGN Radio jets

- Observed since the the 80's
- From radio lobes..
- ... to relativistic jets



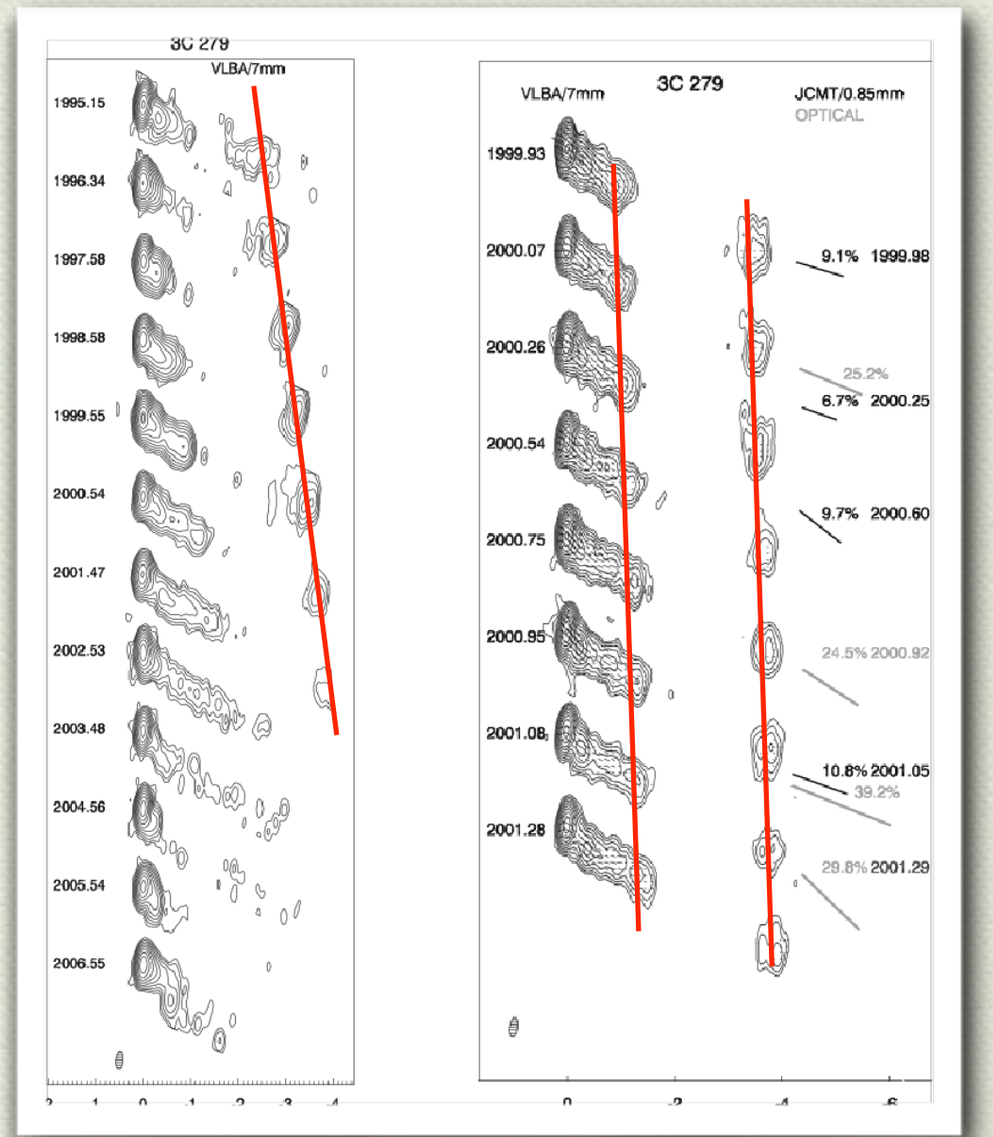




Superluminal motion

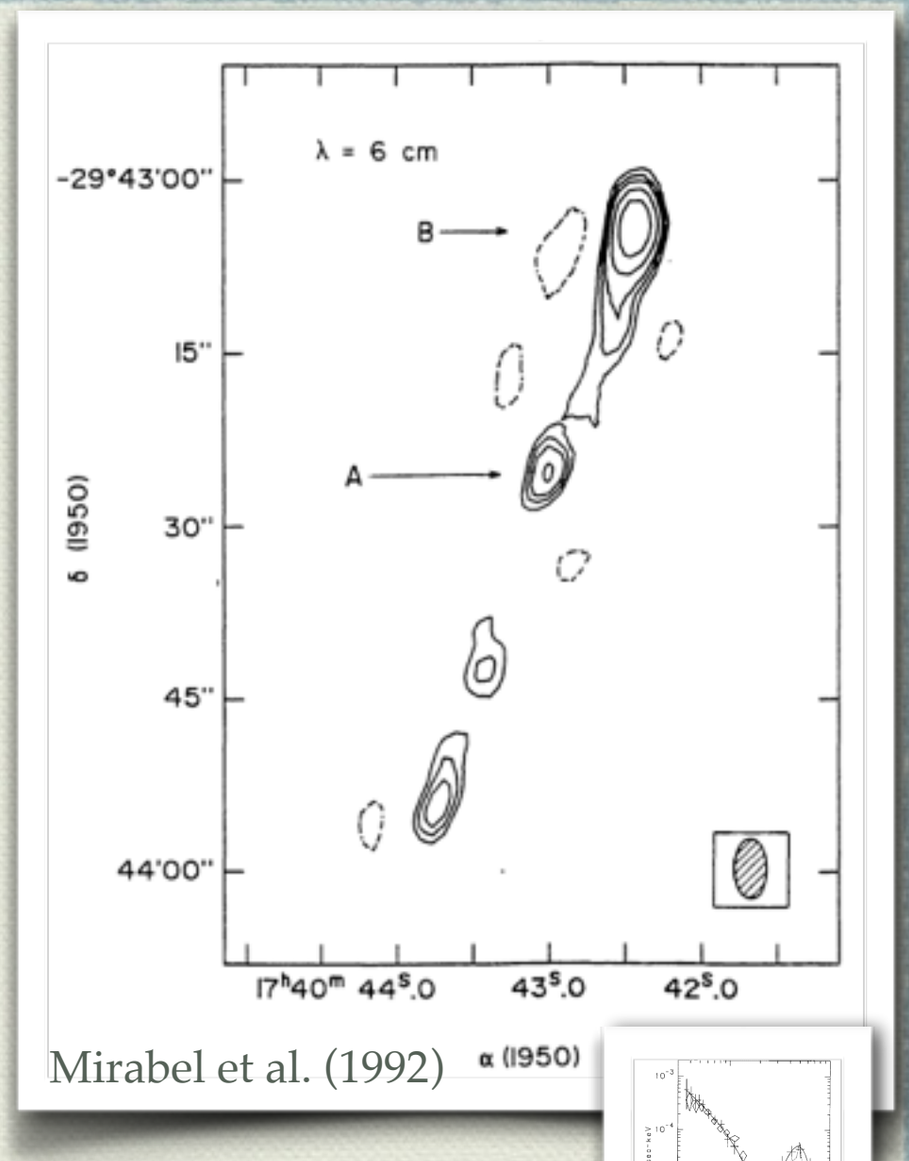
- Radio “blobs” faster than light
- Relativistic explanation
- Jet is beamed towards us

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

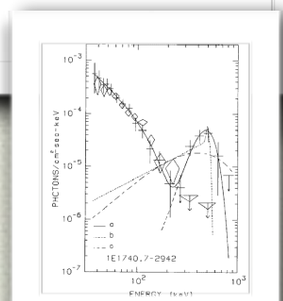


The great annihilator

- Same source with 511 keV line
- Double jets like AGN
- Dubbed a “microquasar”



Mirabel et al. (1992)

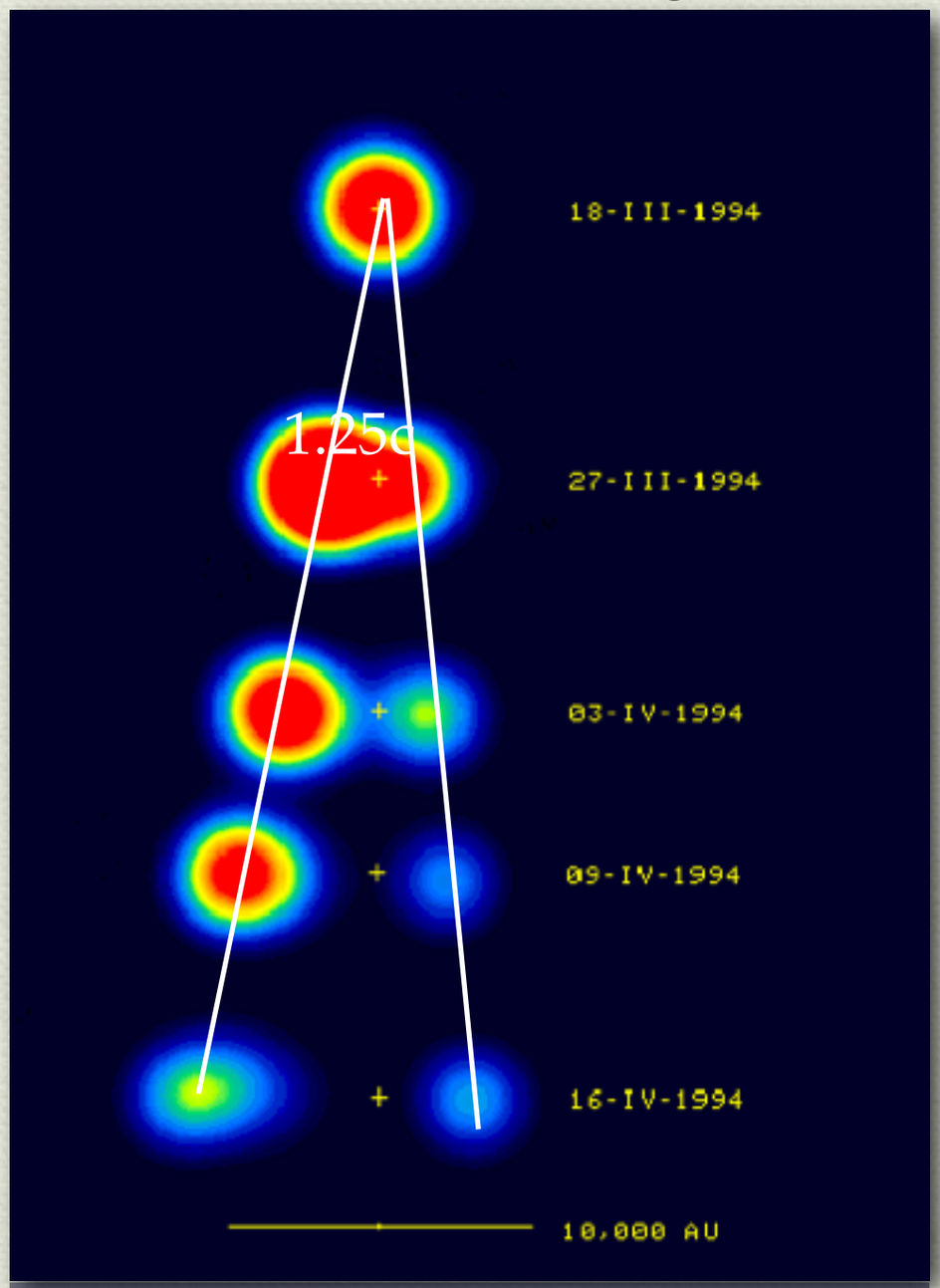


GRS 1915+105

- Very peculiar source
- Superluminal jets
- Double!

$$\beta \cos\theta = \frac{\mu_{app} - \mu_{rec}}{\mu_{app} + \mu_{rec}}$$

Mirabel & Rodríguez (1994)



GRS 1915+105

- Limit on distance

$$D \leq \frac{c}{\sqrt{\mu_{app}\mu_{rec}}} \leq 13.7\text{kpc}$$

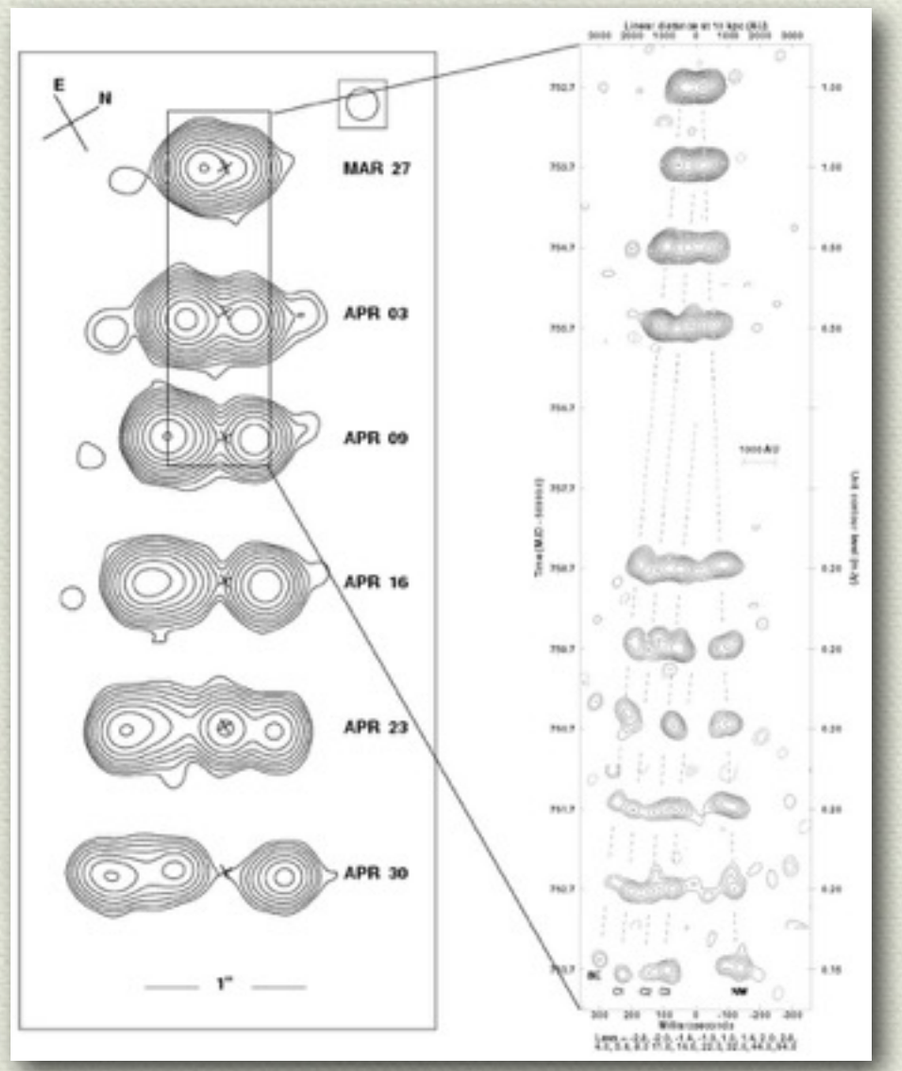
- From HI: 12.5 kpc

- *v=0.98c ; θ=66°*

- Flux ratio:

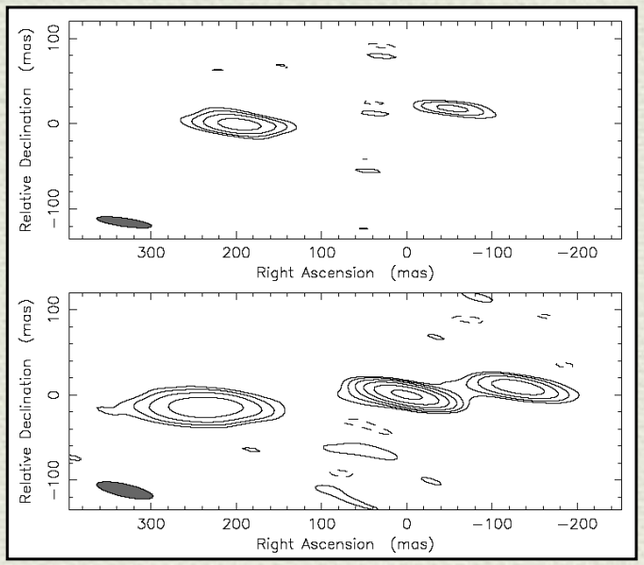
$$\frac{S_{app}}{S_{rec}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{k-\alpha}$$

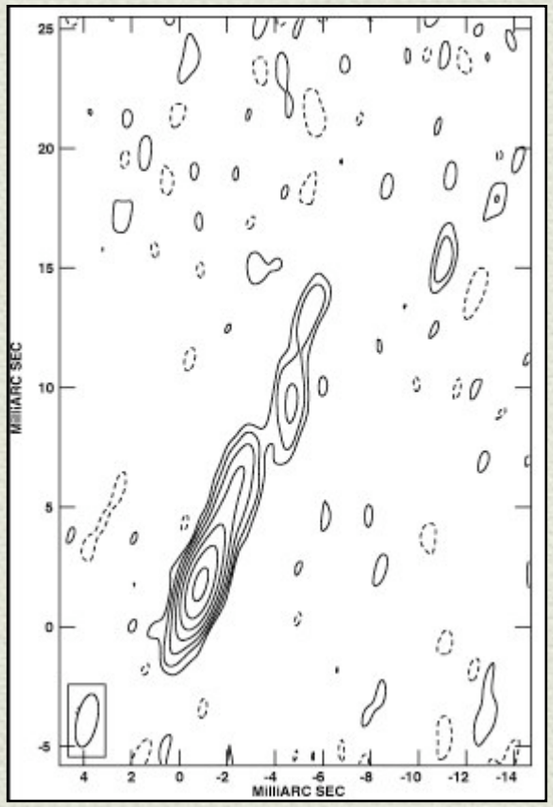
Fender et al. (1999)

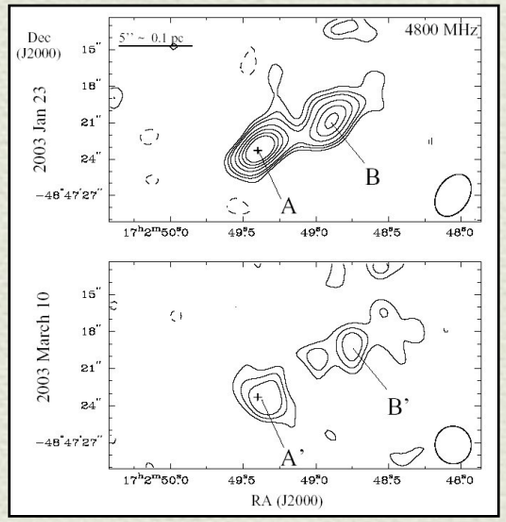


Other sources

- Many detections of moving jets
- Many detections of radio flares
- Many detections of persistent radio emission



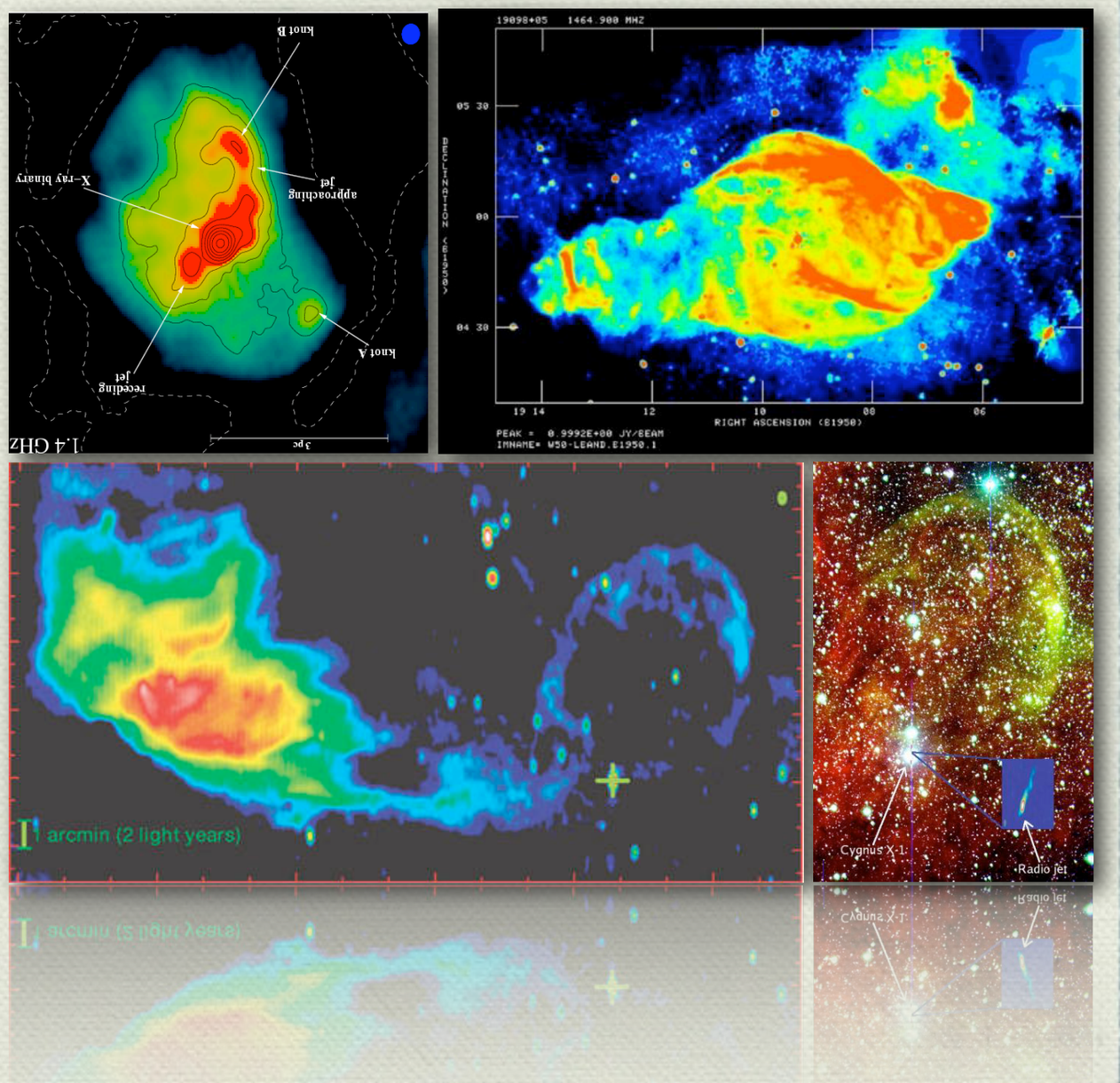




Jet-driven nebulae

- Important for estimate of power in the jet
- SS 433: $>10^{39}$ erg/s
- Cir X-1: $>10^{35}$ erg/s average
- Cyg X-1: one-sided
- Not many nebulae compared to AGN

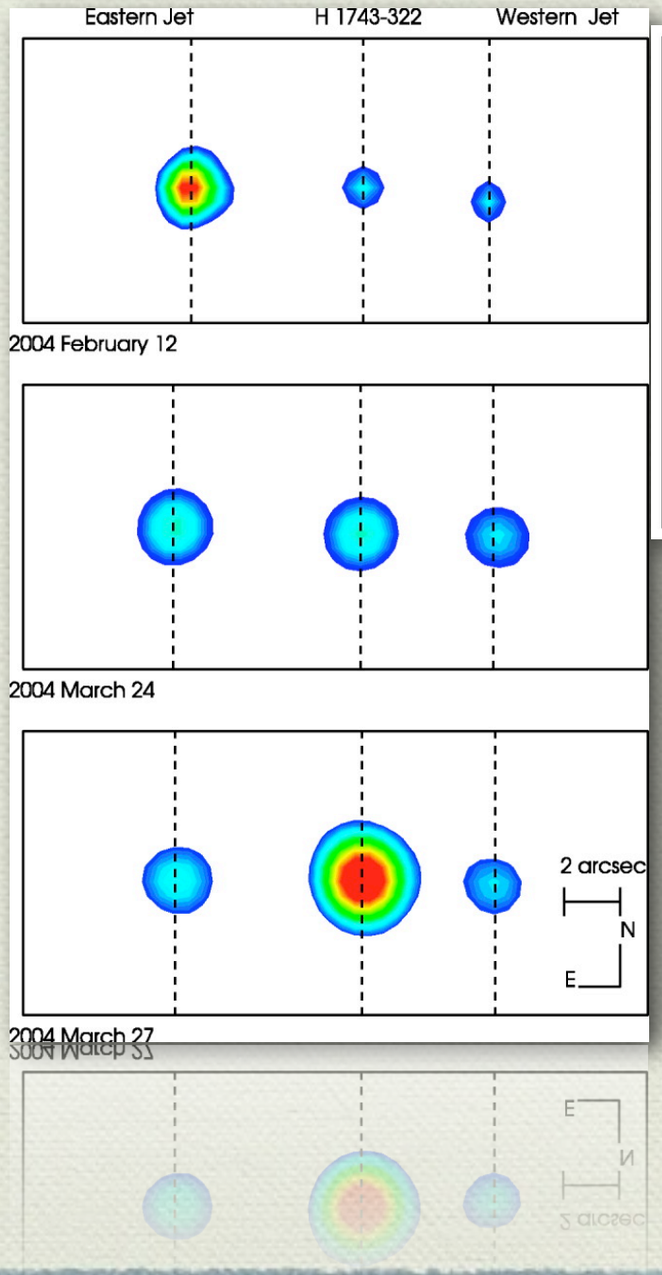
Gallo (2009)

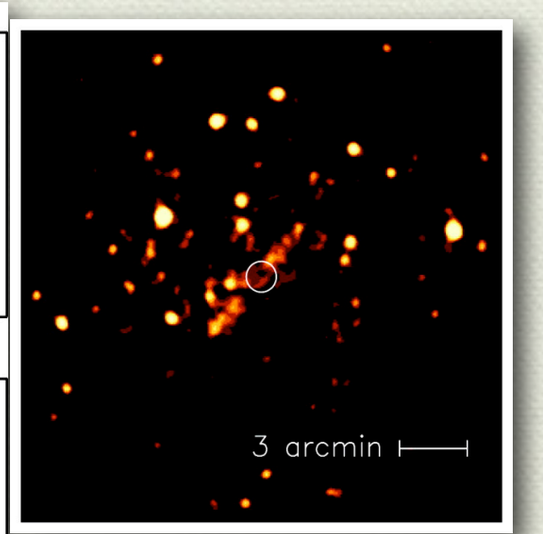


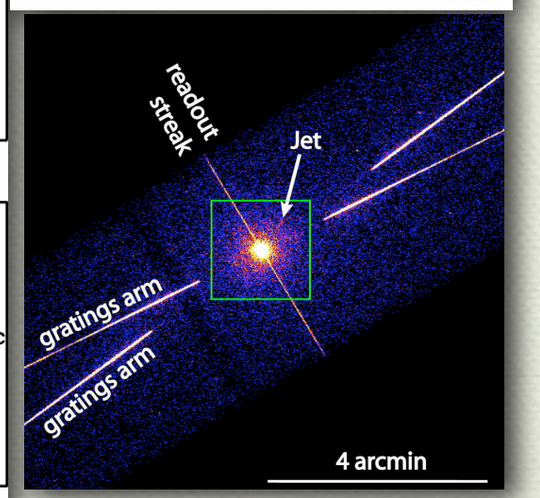
X-ray jets

- As in AGN
- Chandra detections
- Optically thin synchrotron
- In situ acceleration
- Production of TeV particles?
- Remnant jet

Gallo (2009)

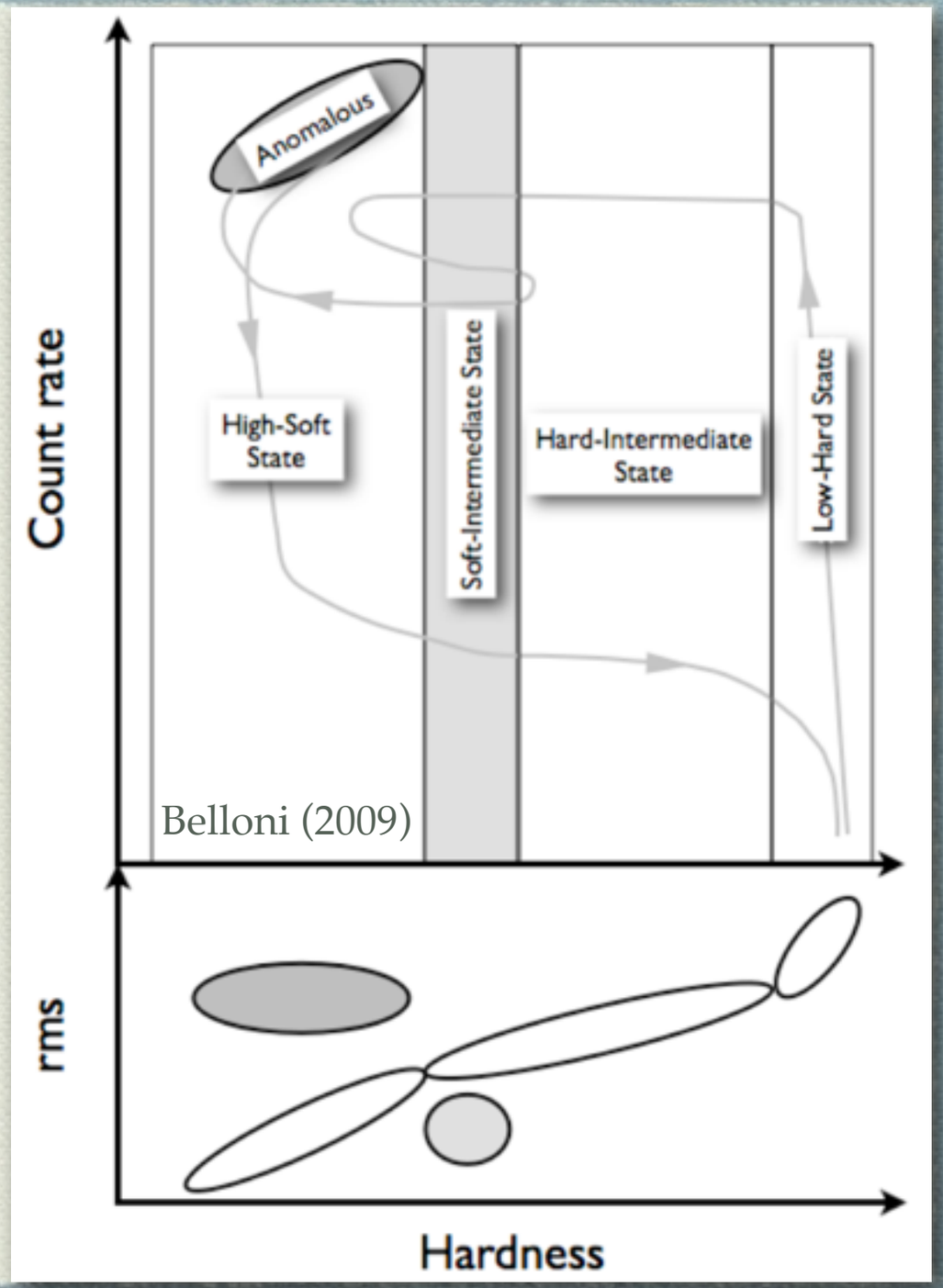






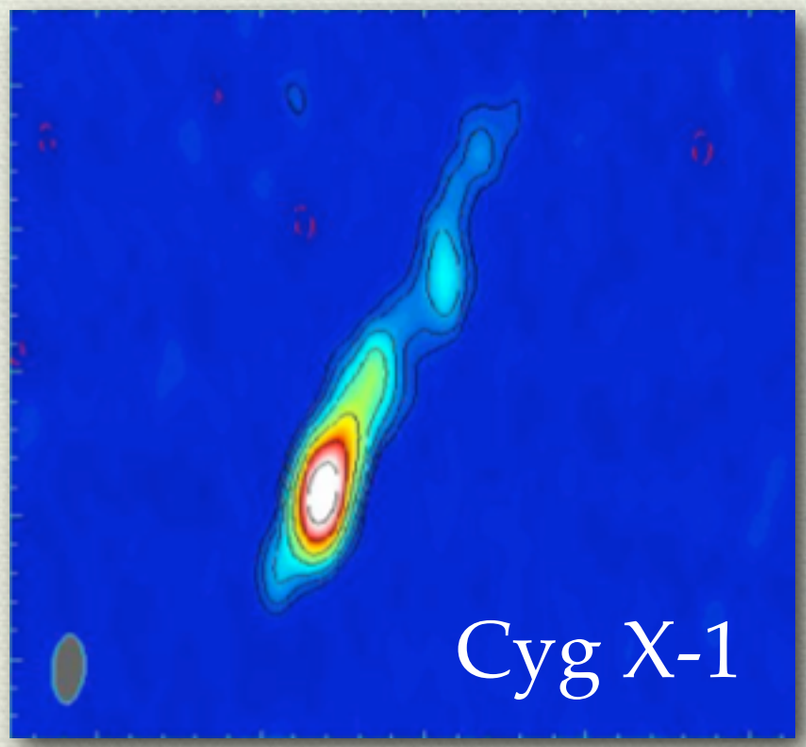
Relation to states

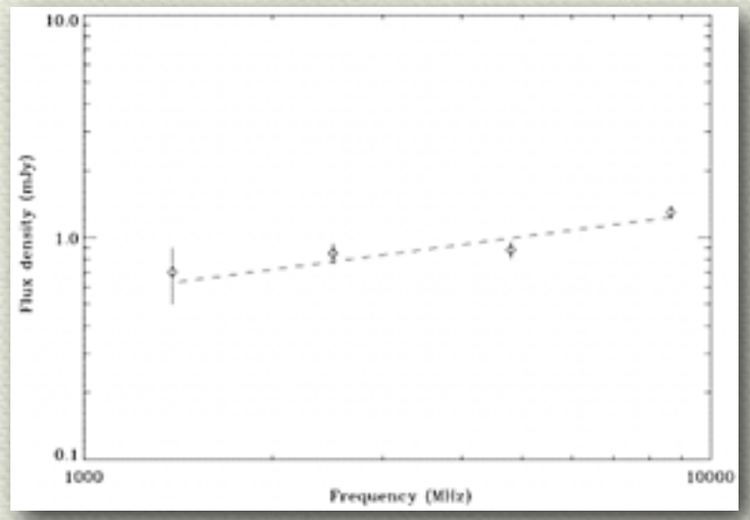
- Strong connection with jets
- Strong connection with radio
- A picture emerges

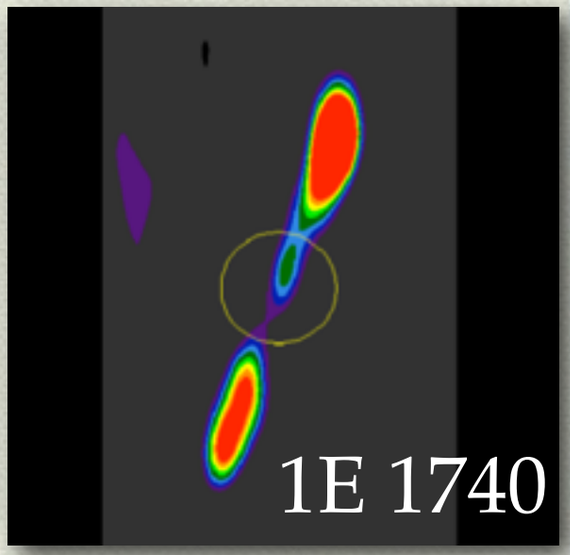


Compact jets

- Hard state
- Small-scale elongations
- Inverted spectrum $F_\nu \propto \nu^\alpha \quad \alpha \sim 0.0 - 0.3$
- Self-absorbed synchrotron
- Similar yo LLAGN
- Small Γ (later)

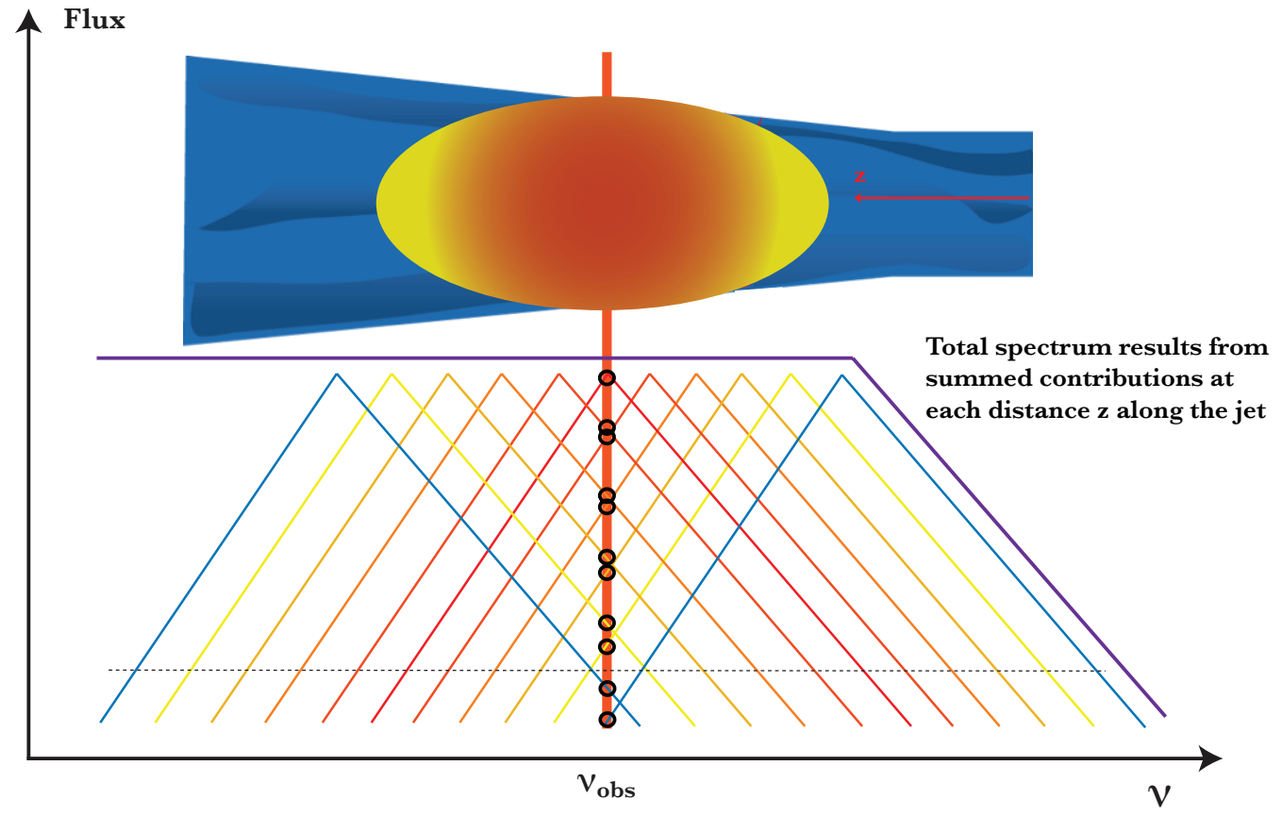






Self-absorbed synchrotron

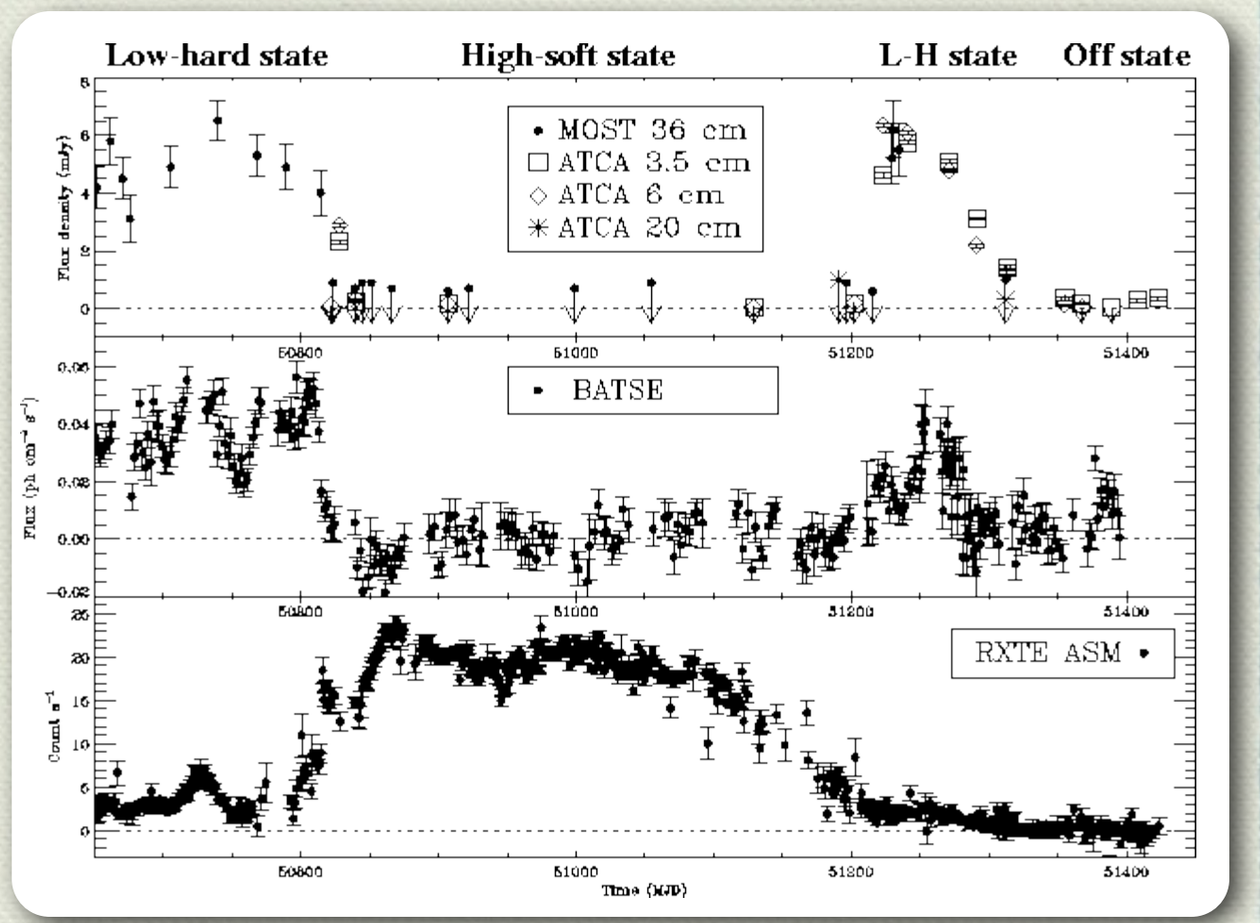
- Optically thick, stratified
- Steady jet, smoothly expanding
- Frequency peak changes with position
- Tricky to image at one frequency

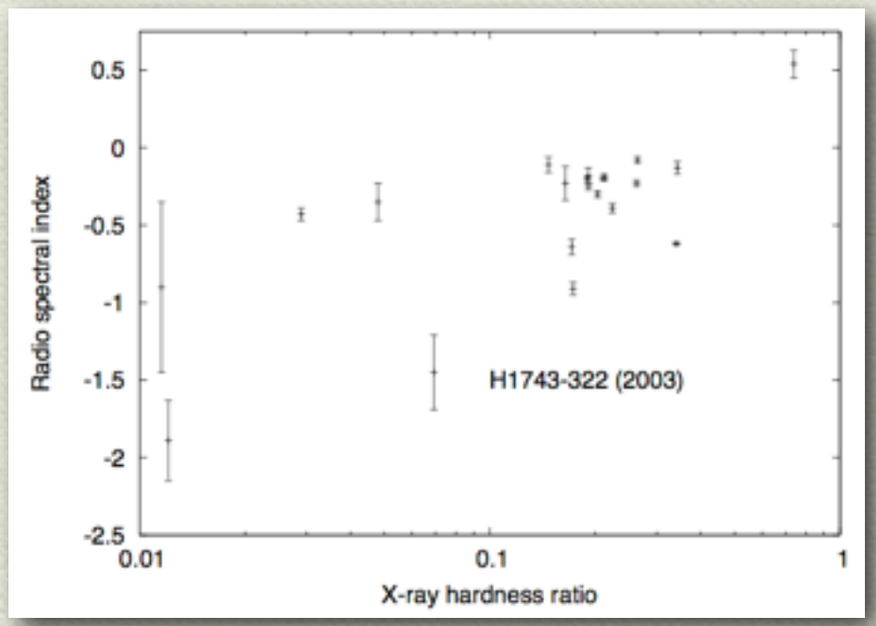


Markoff (2009)

Soft state: quenching

- Soft state
- No detection in many..
- Some detection in others..
- .. but steep spectrum



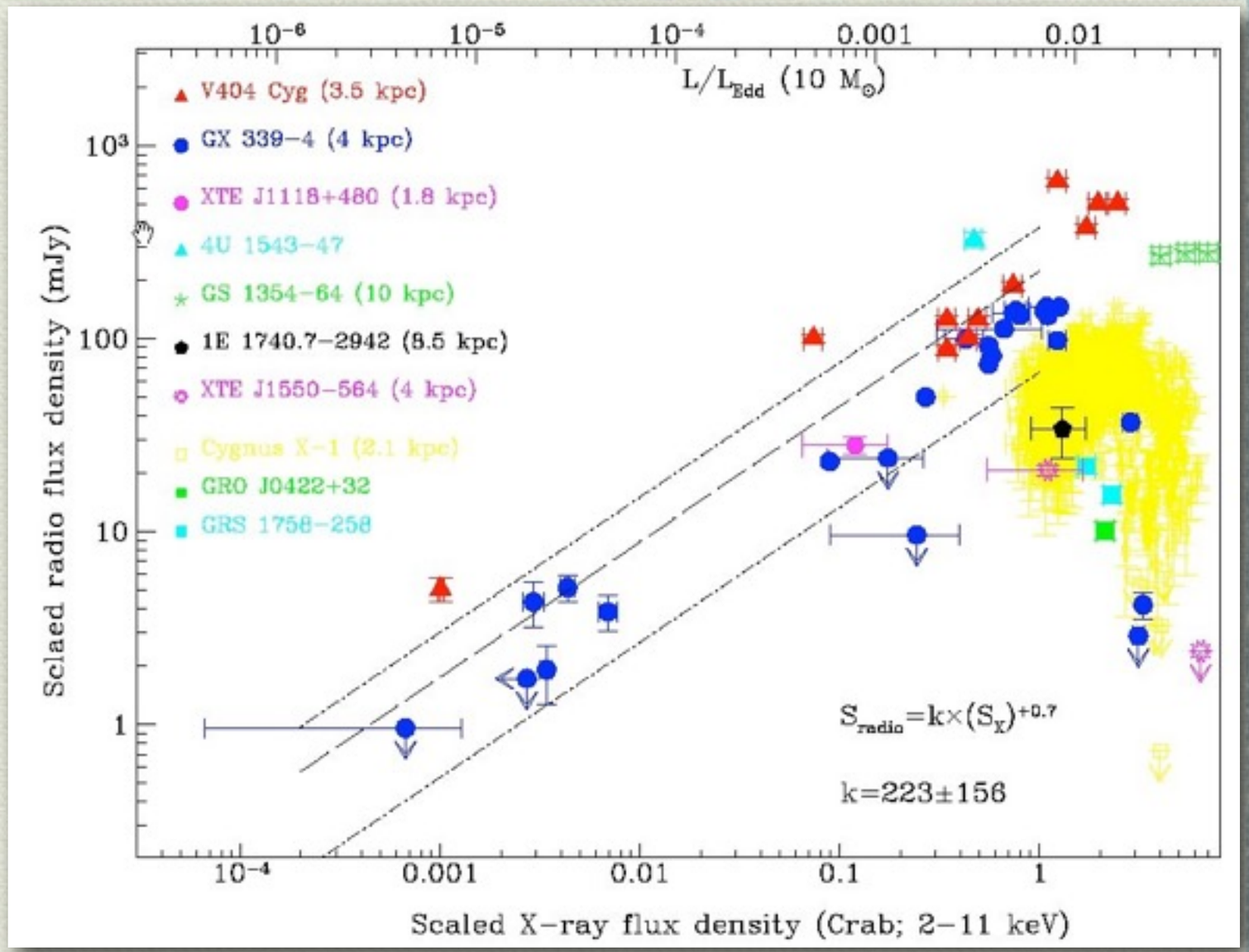


No core emission?

Fender, Homan & Belloni (2009)

Correlations

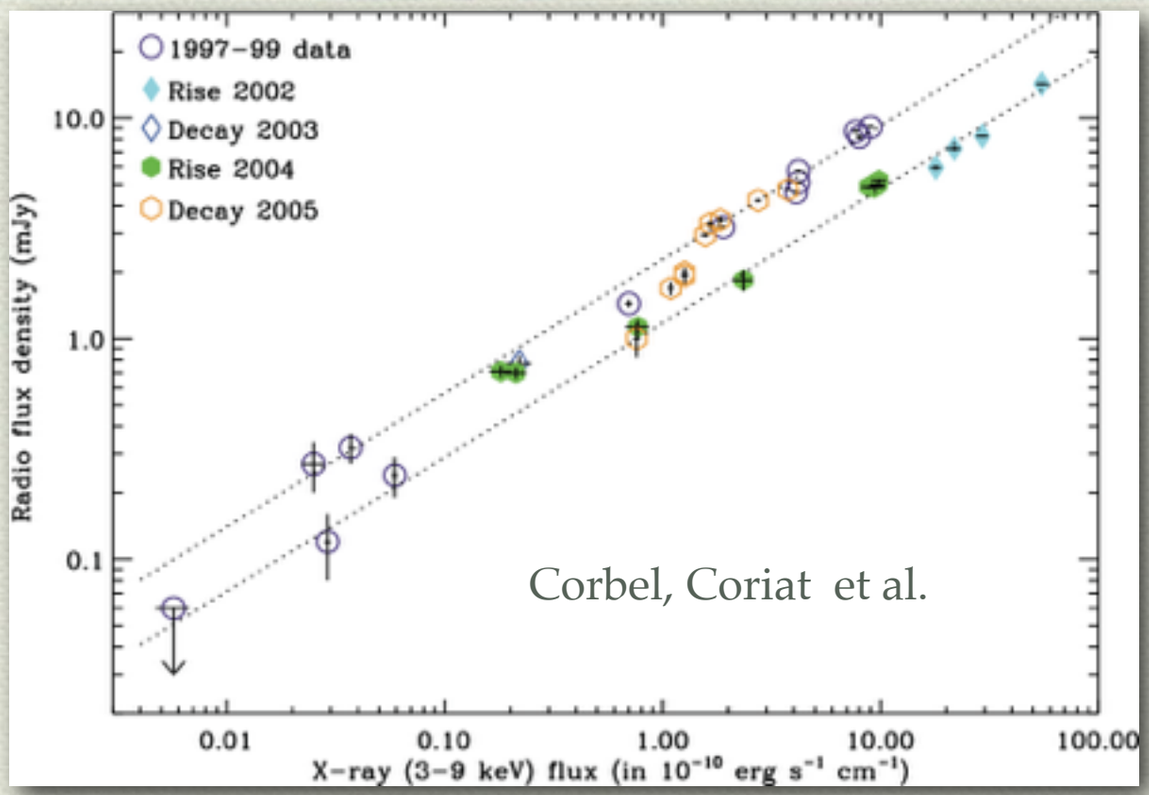
- Radio-X correlation
- Break @ HSS
- Three decades



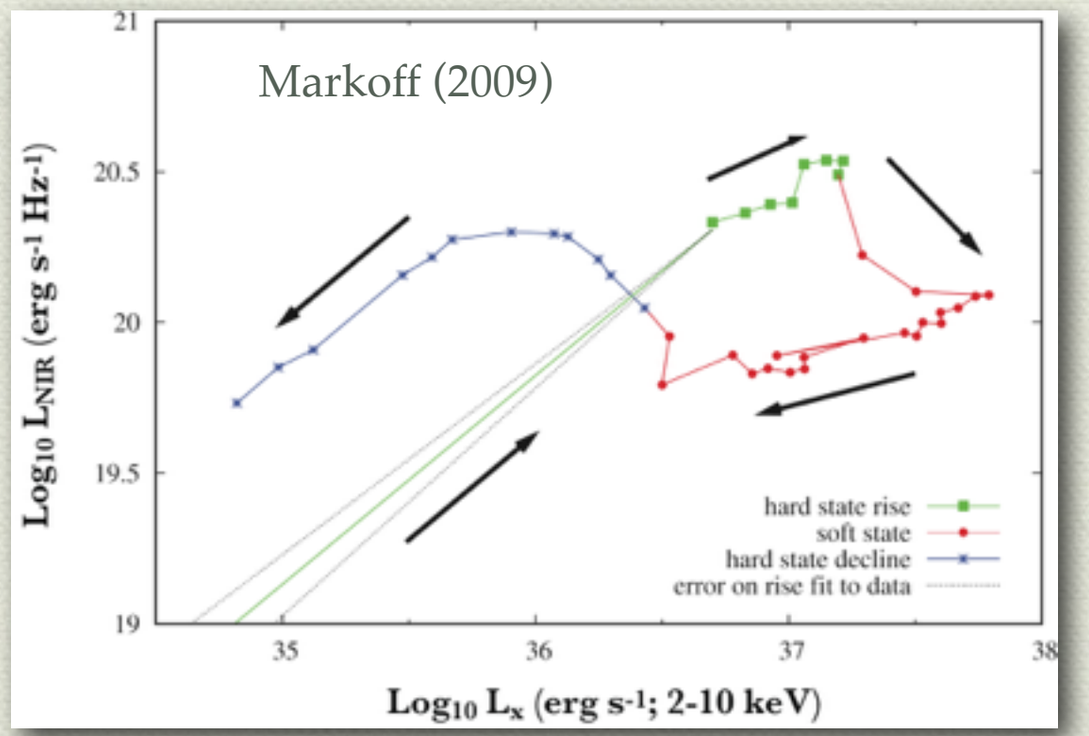
Gallo et al. (2003)

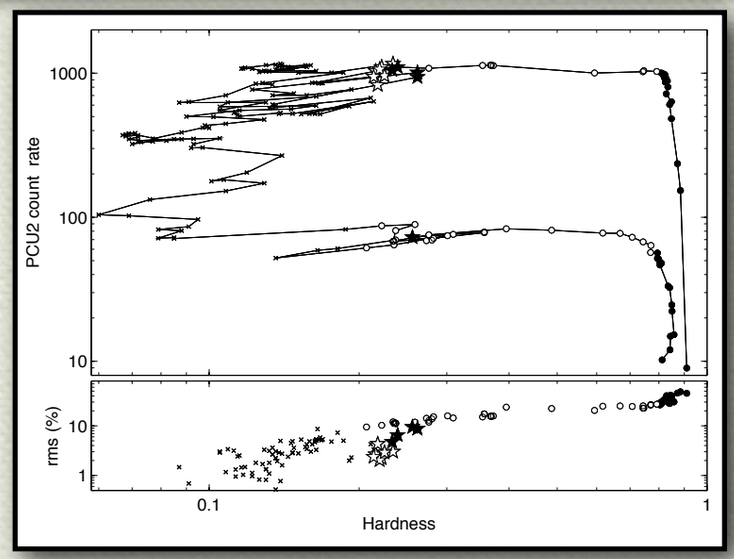
Correlation & hysteresis?

- Not exactly there
- Hysteresis effect
- Also in infrared



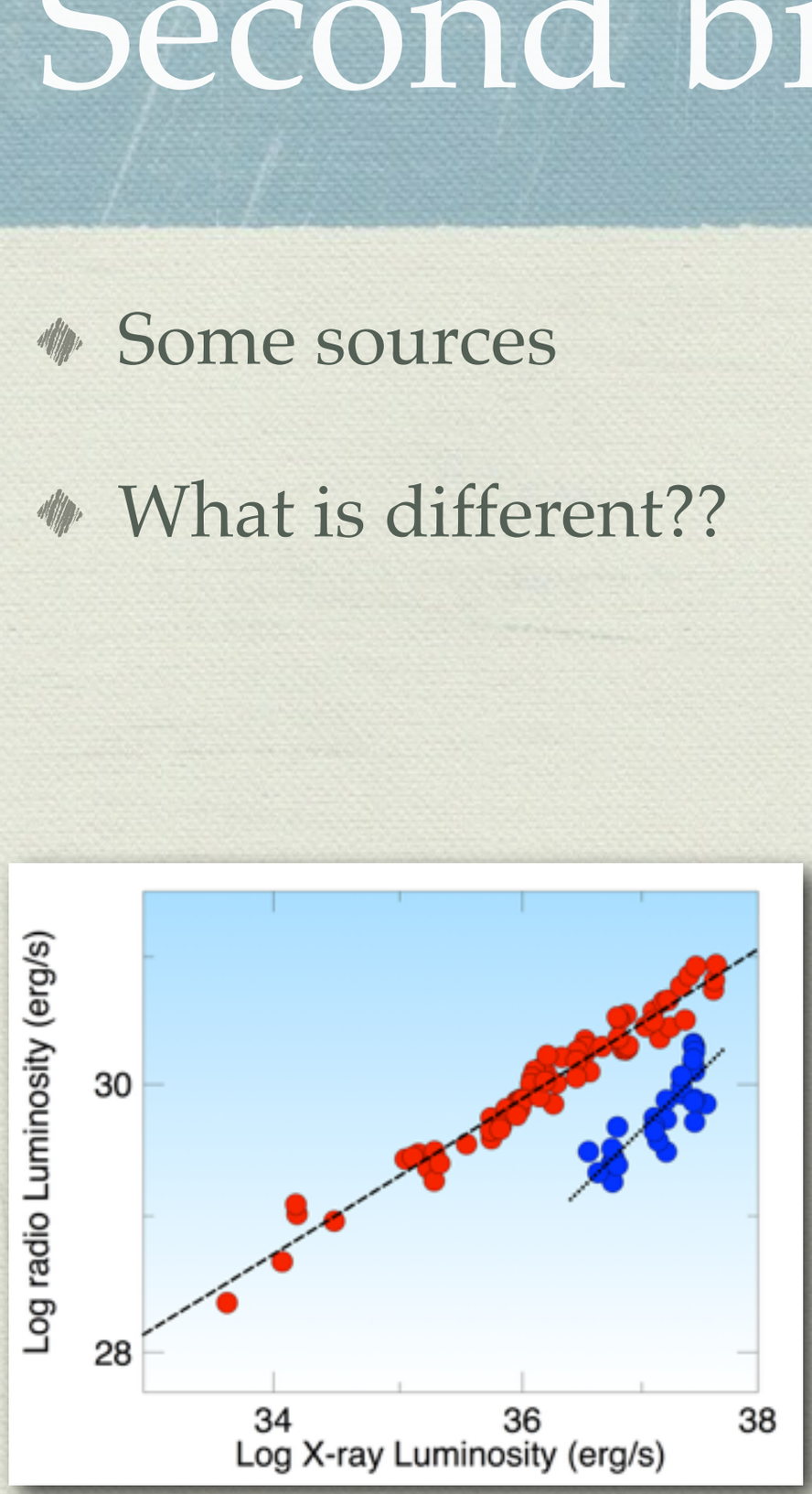
Corbel, Coriat et al.

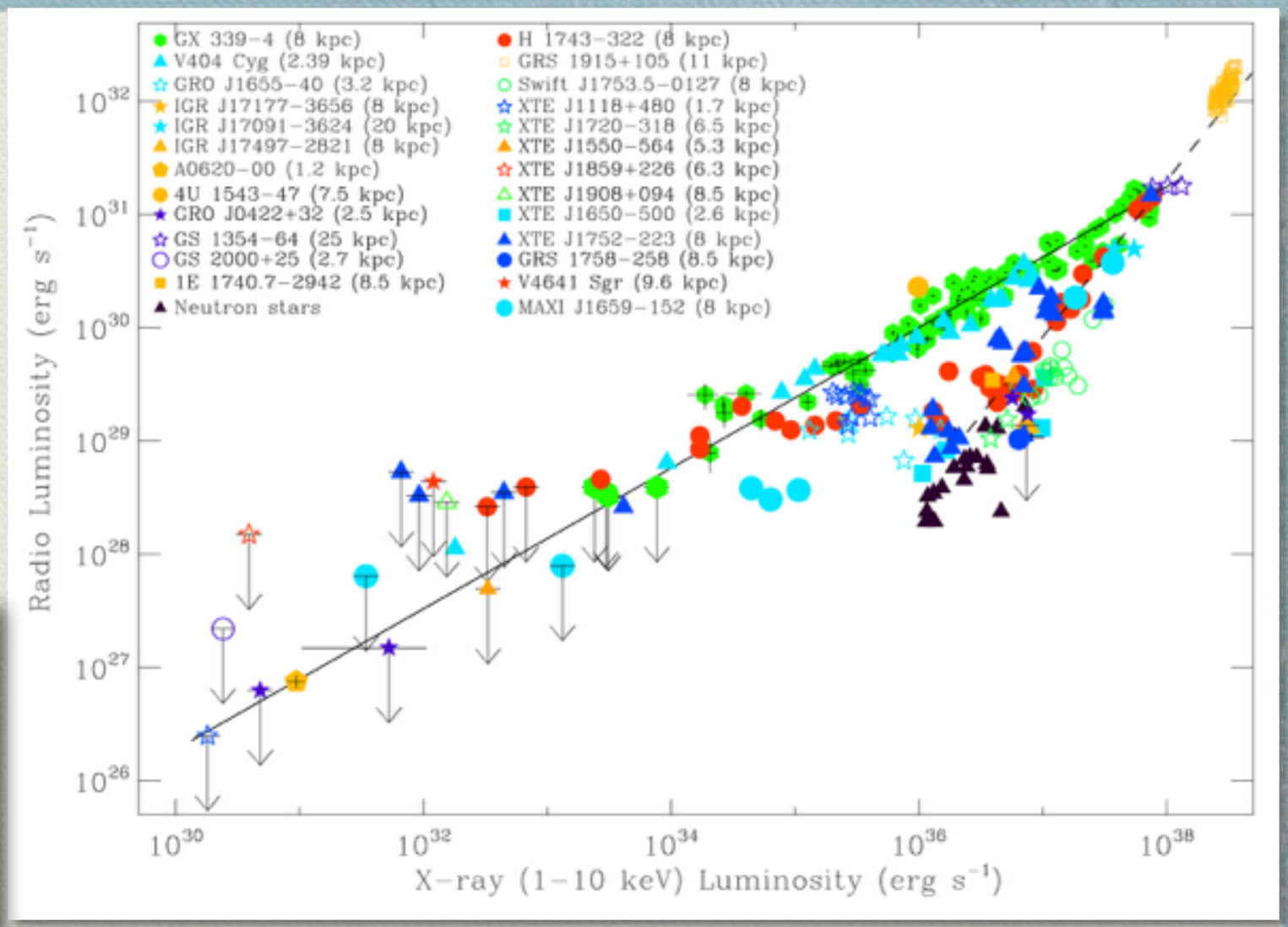




Second branch

- Some sources
- What is different??

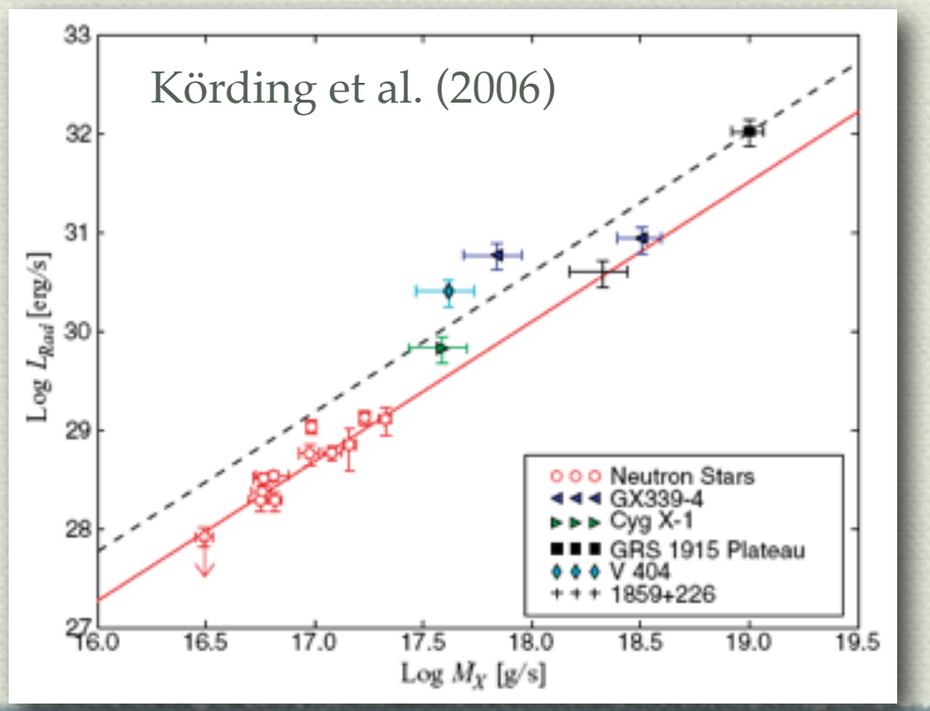


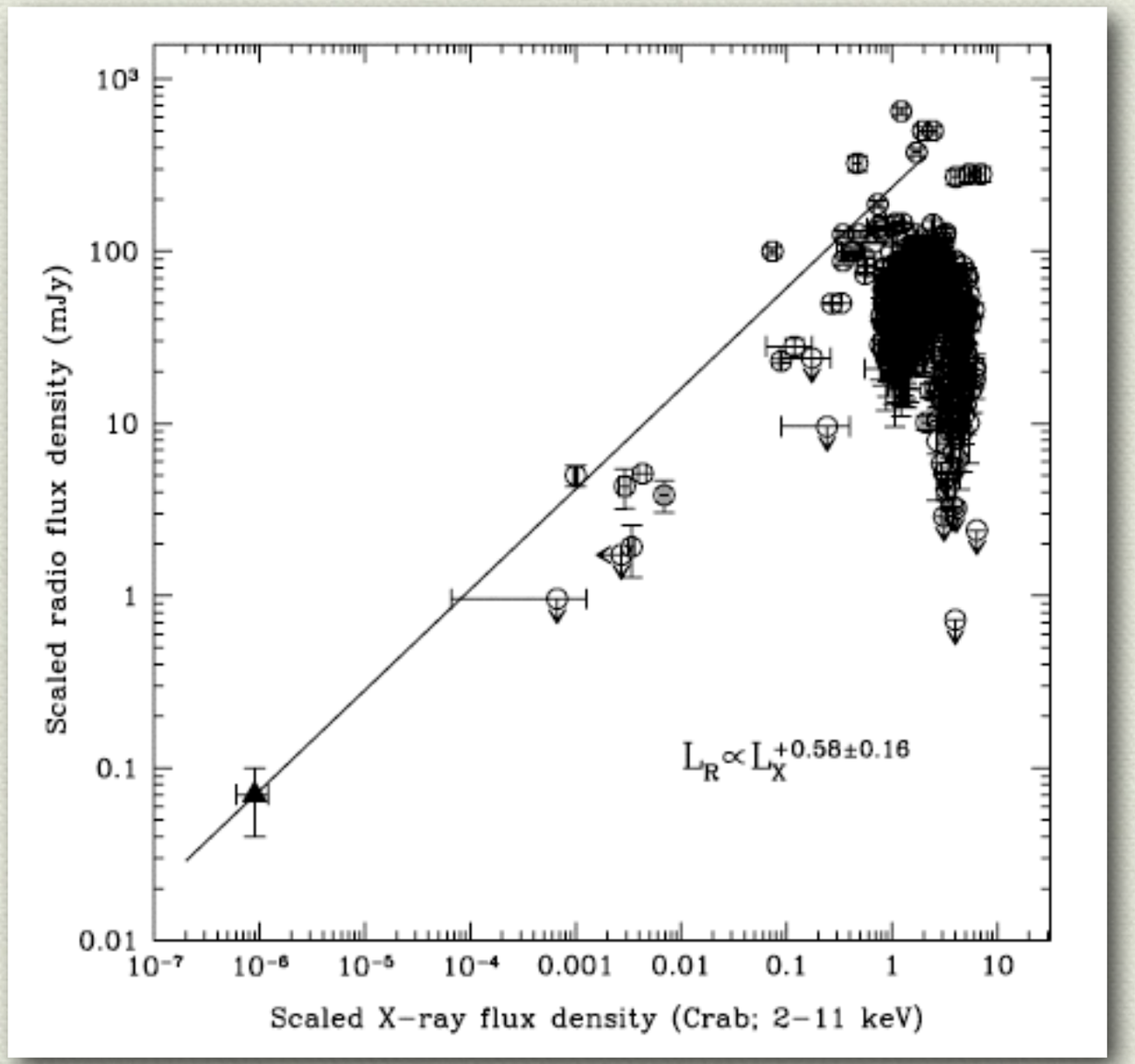


Corbel et al. (2013)

Also quiescence!

- A0620-00 in quiescence
- Right on correlation
- Radio as a proxy for accretion rate?

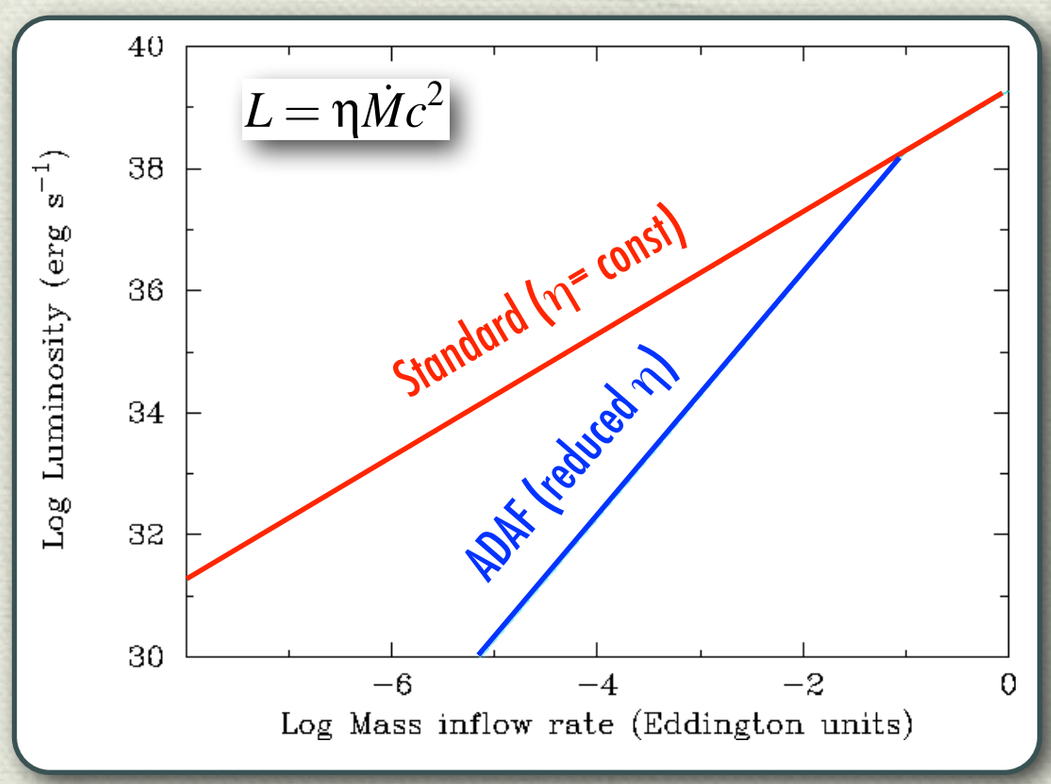


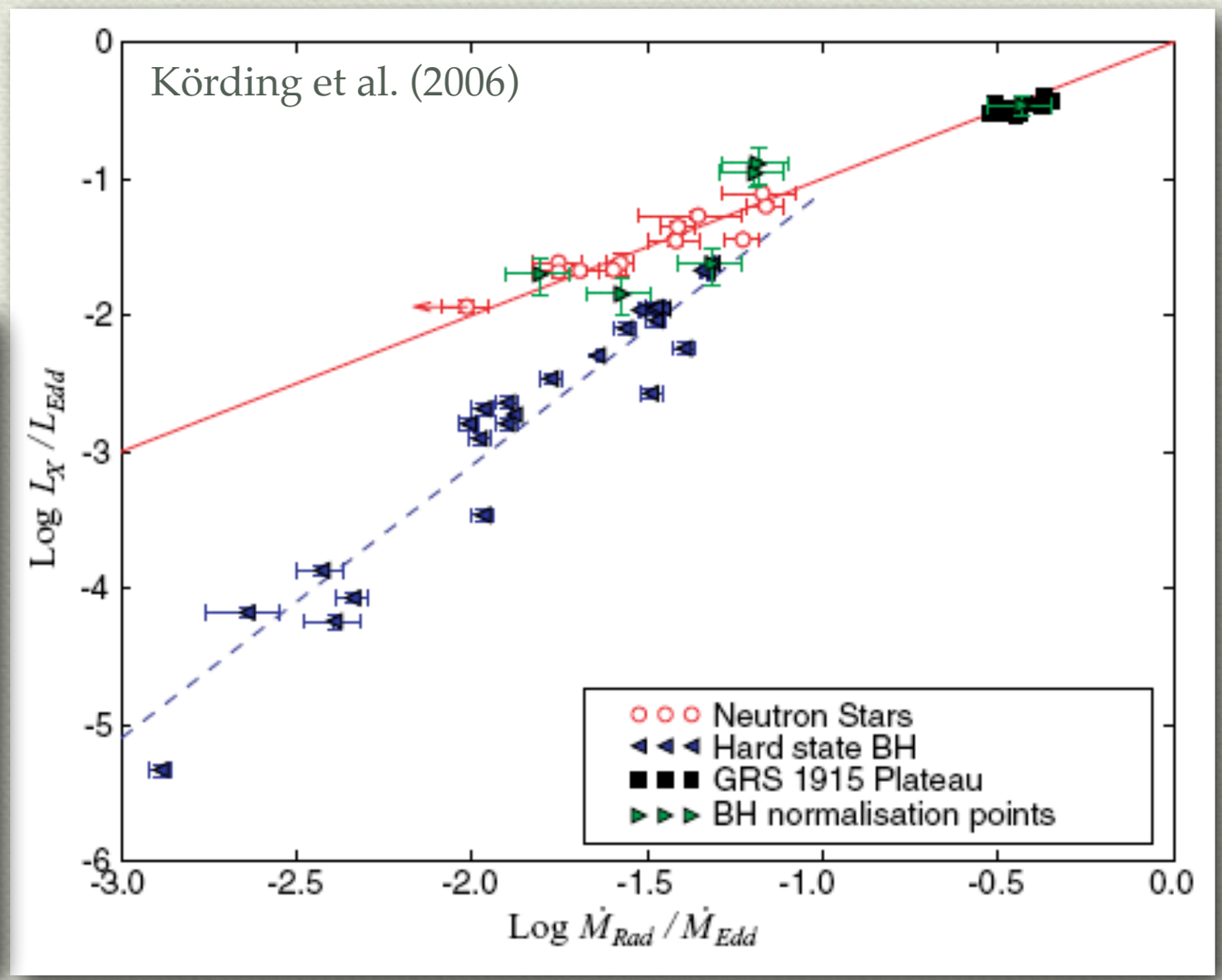


Gallo et al. (2006)

Advective flows

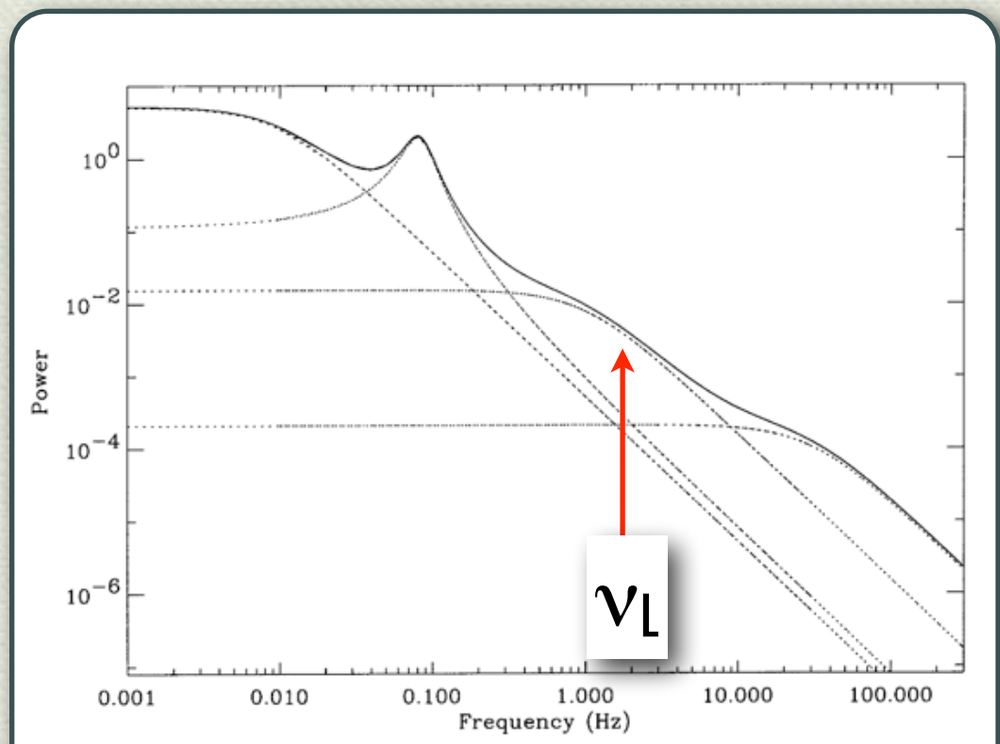
- L_X vs. $\dot{M}$
- Remember Lecture 2

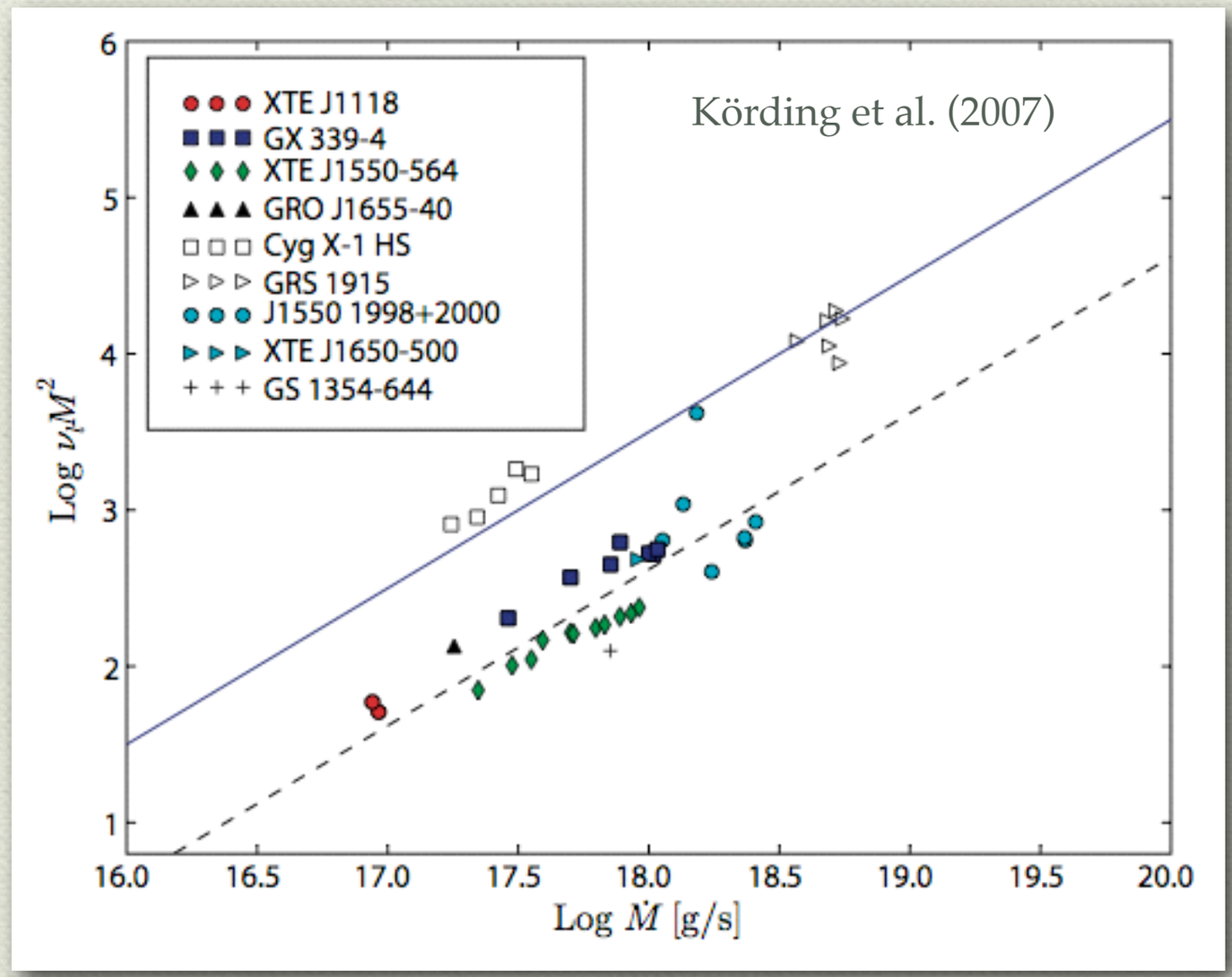




Timing correlation

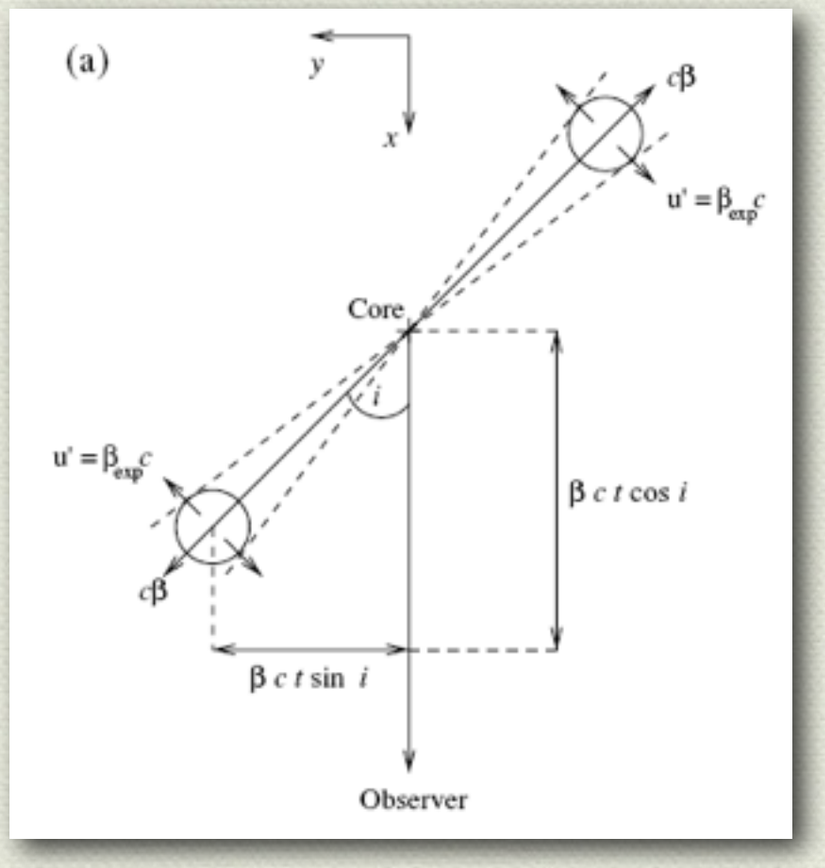
- Timing feature vs. $\dot{M}$

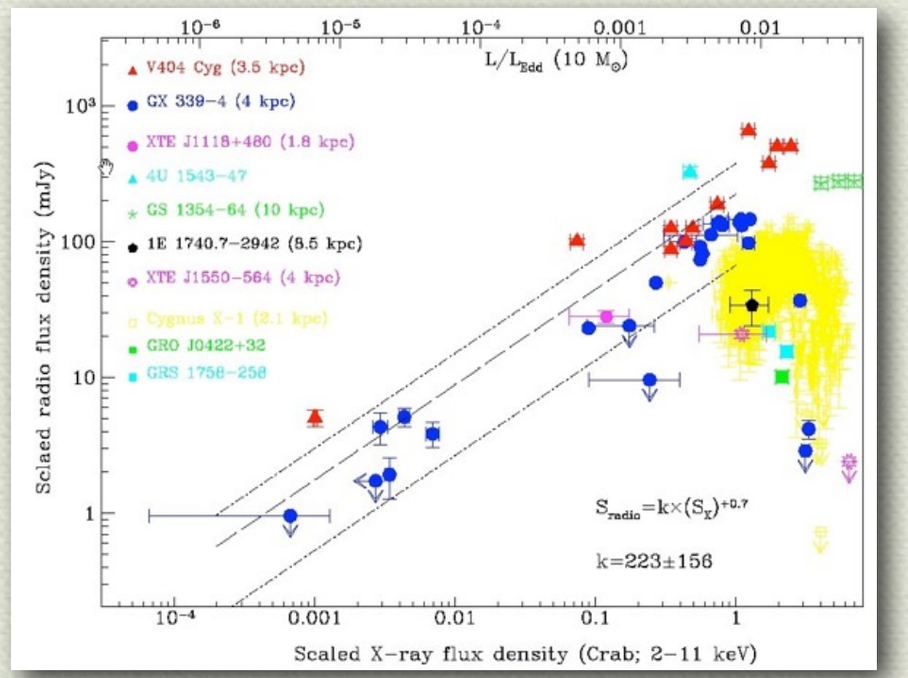




How fast is the jet?

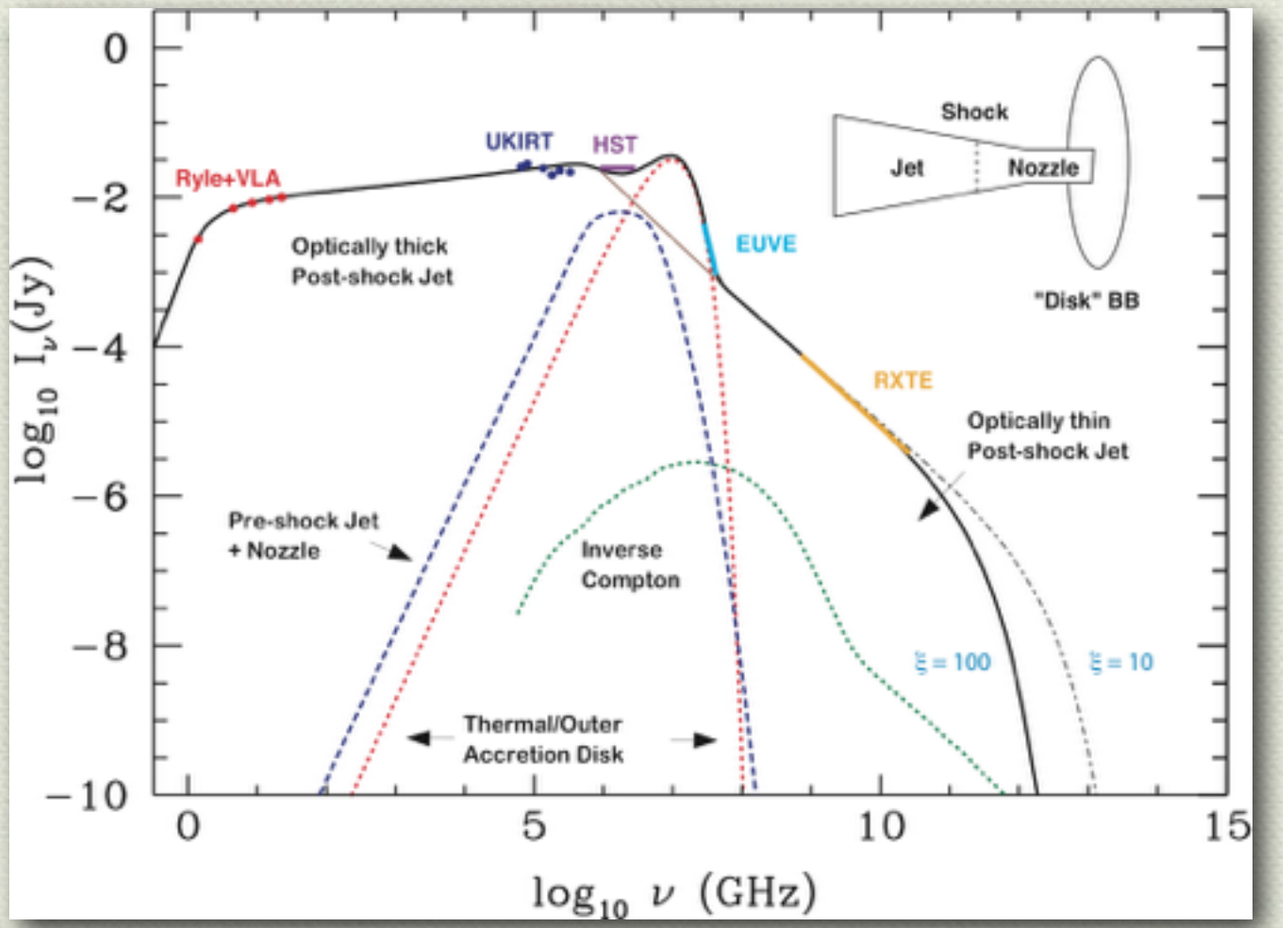
- From the correlation
- Spread means little beaming
- Therefore $\Gamma \sim 1\text{-}2$





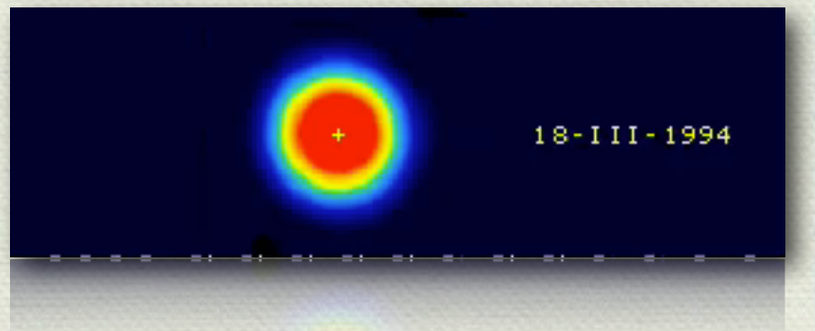
Origin of the emission

- We have the hard "corona" component in X rays
- Where is the corona? It could be the base of the jet itself

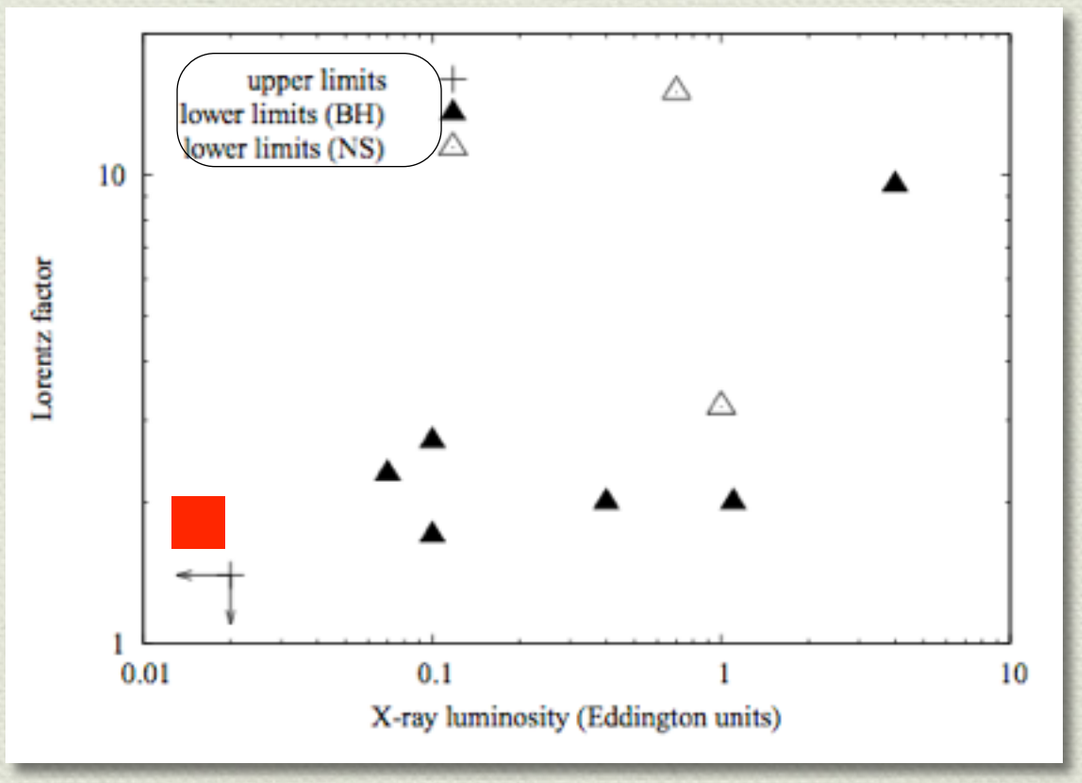


Markoff (2009)

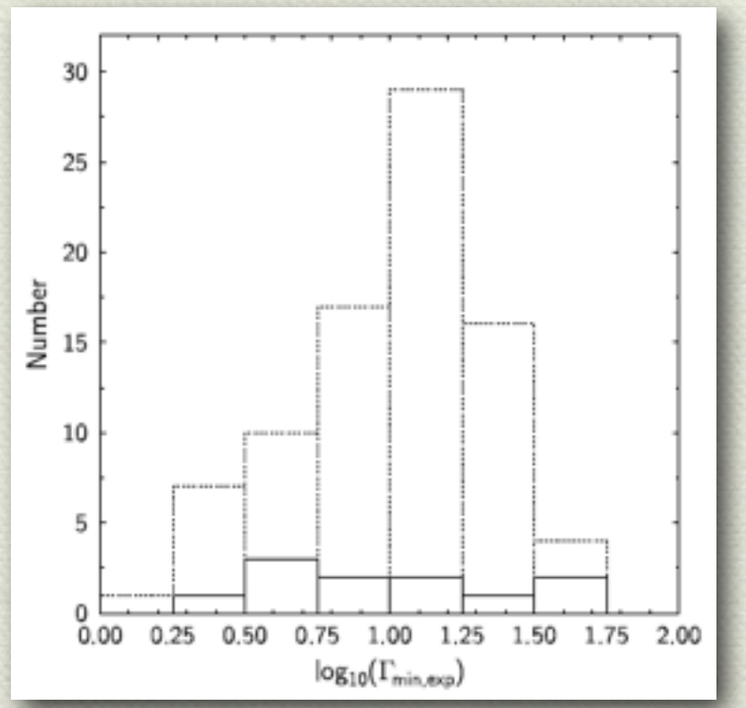
Relativistic ejections



- A different type of jet?
- Can we measure their Γ?
- We measure β $\Gamma = \frac{1}{\sqrt{1-\beta^2}}$ lower limits



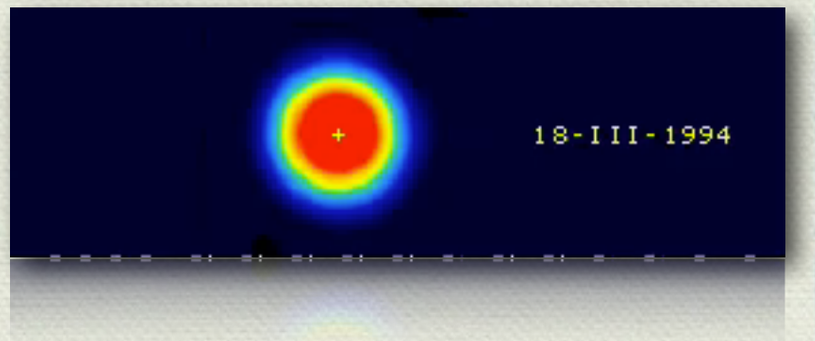
Fender, Belloni & Gallo (2004)

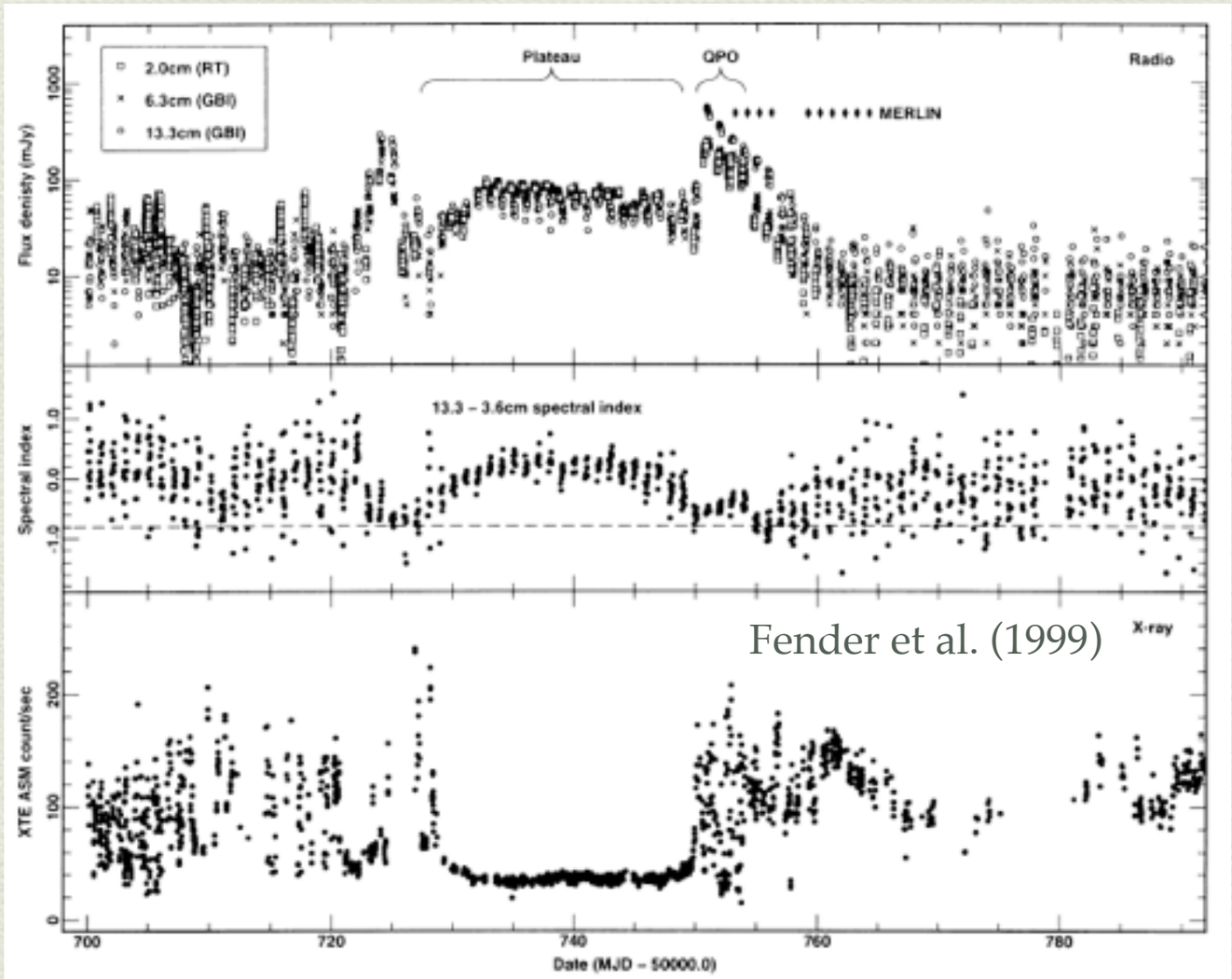


Miller-Jones et al. (2006)

Back to GRS 1915+105

- Major ejection: X-ray related

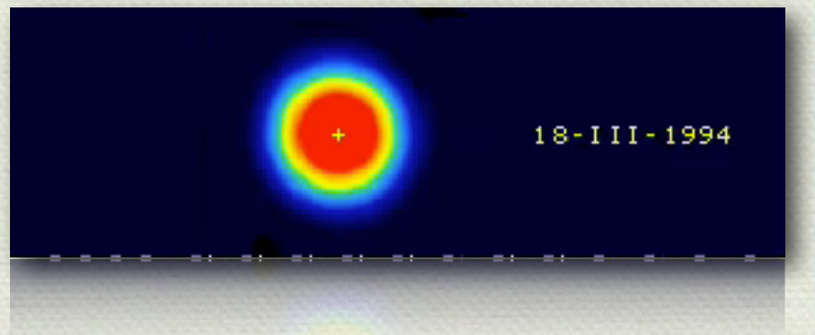




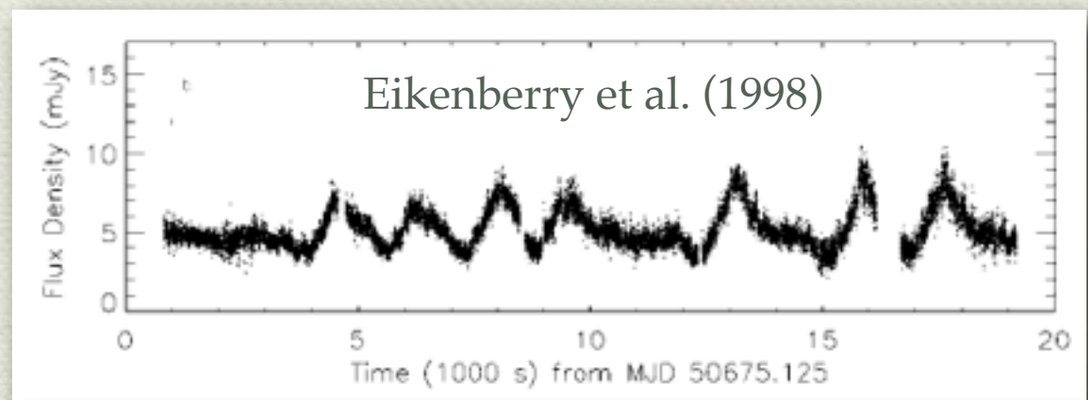
Fender et al. (1999)

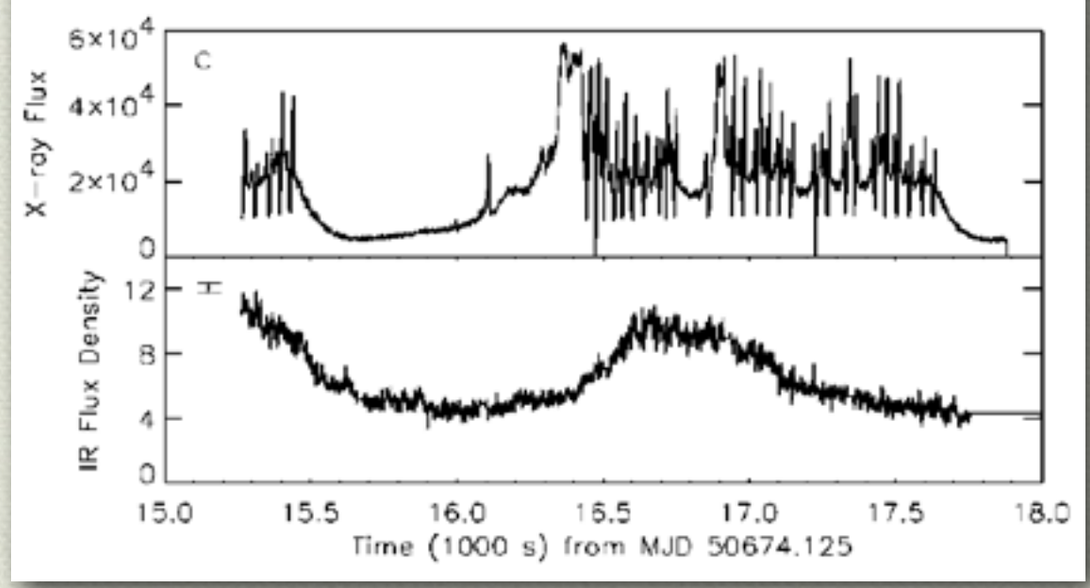
Oscillations

- X-ray oscillations: instability
- Radio/IR correlates: 1 to 1 to X

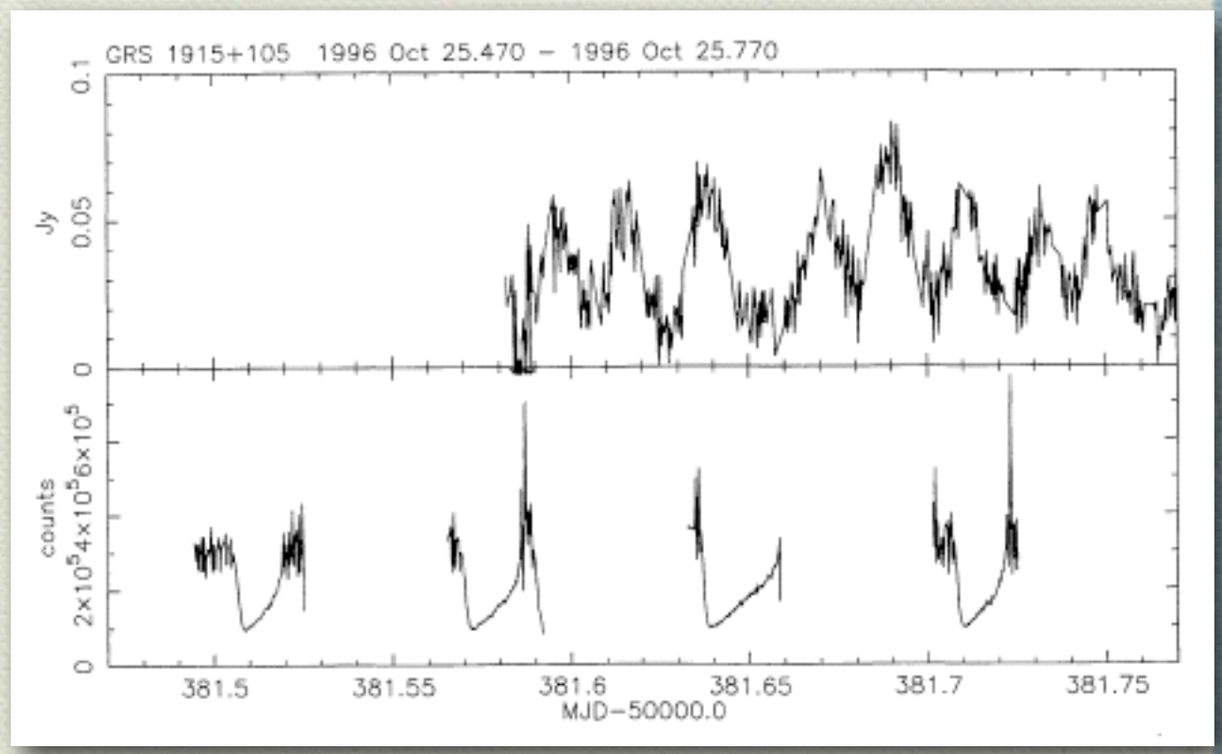


Eikenberry et al. (1998)



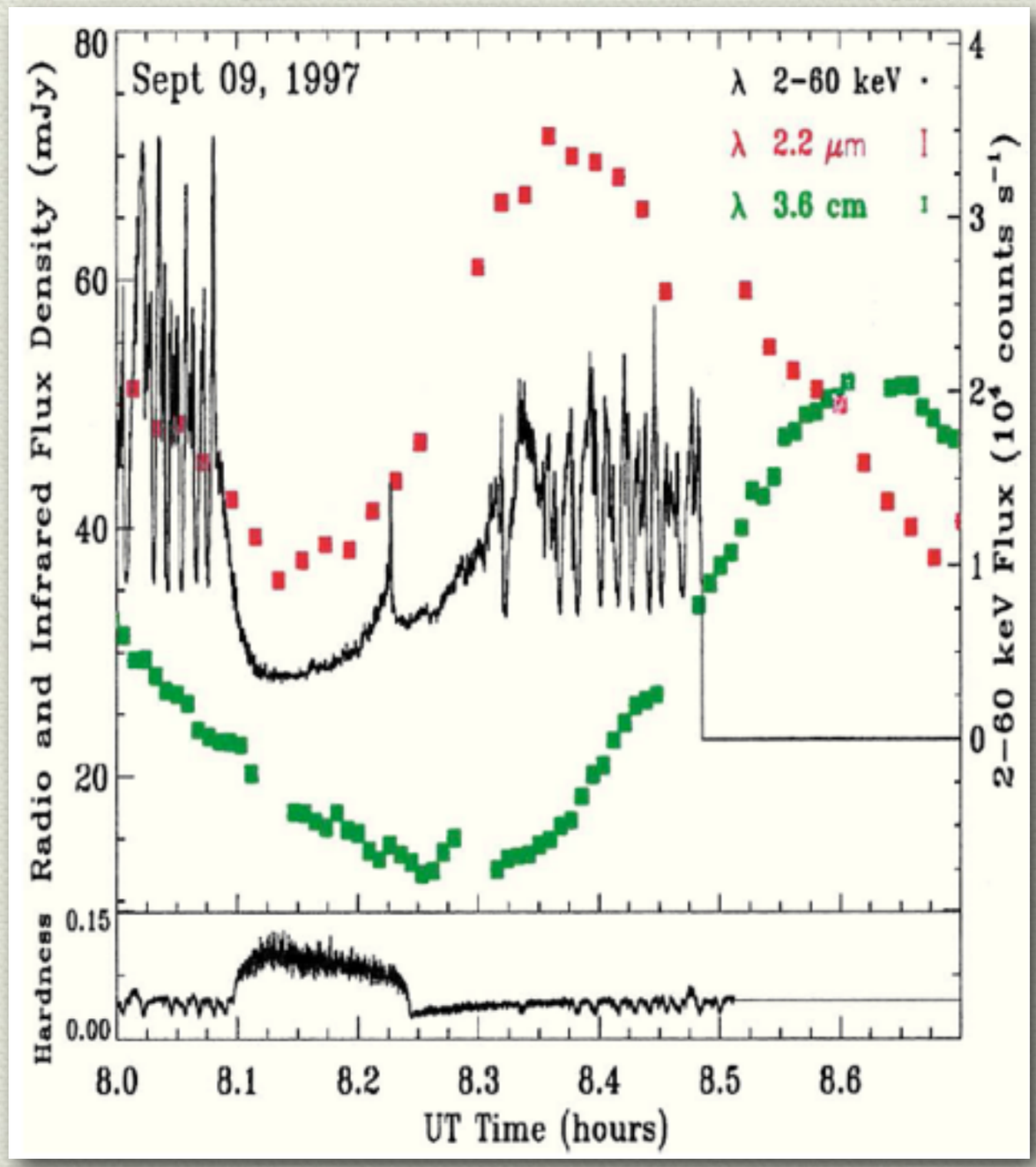


Pooley & Fender (1997)



Multi-λ picture

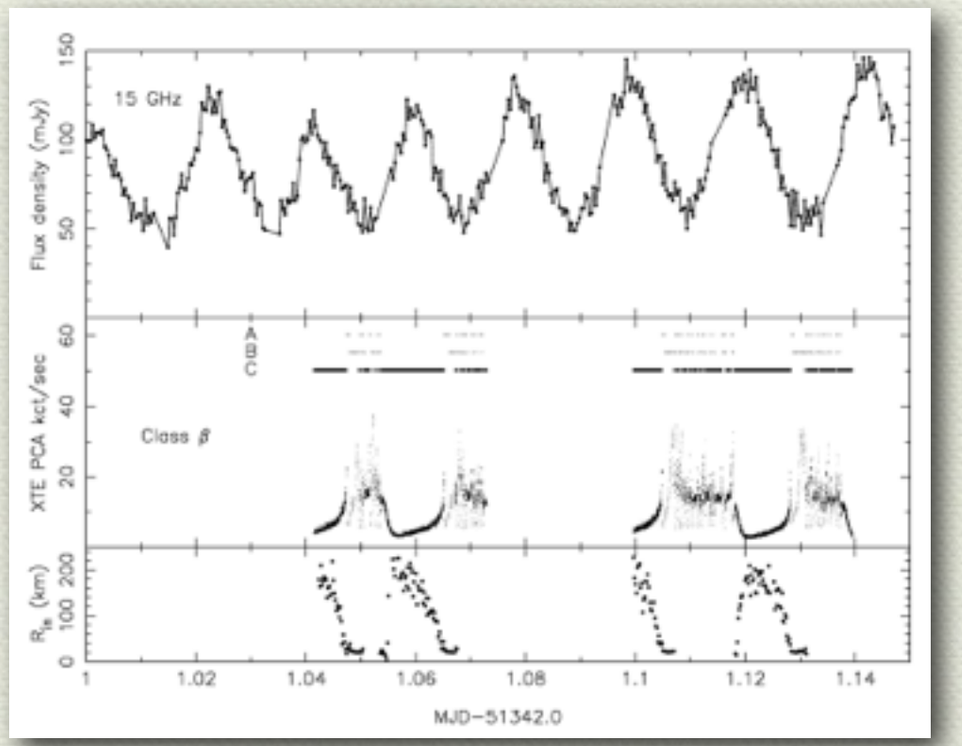
- X-ray oscillations
- Relativistic expanding jet
- Specific timing connection?

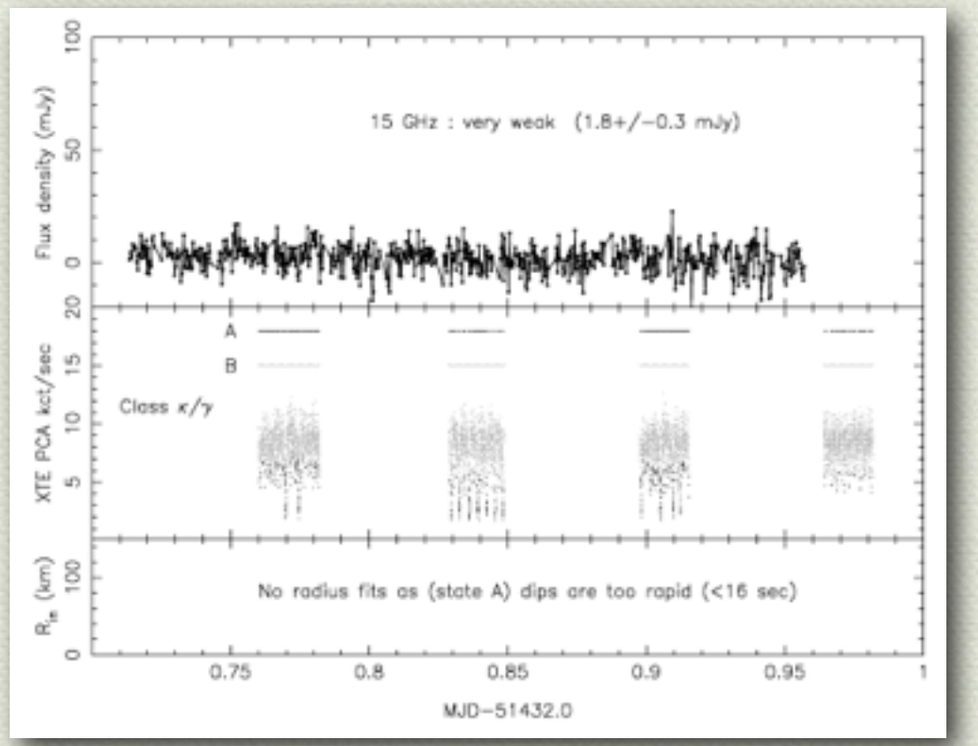


Mirabel et al. (1998)

Hard-soft?

- GRS 1915+105 has three states: two soft and one hard
- Radio oscillations only when hard is involved

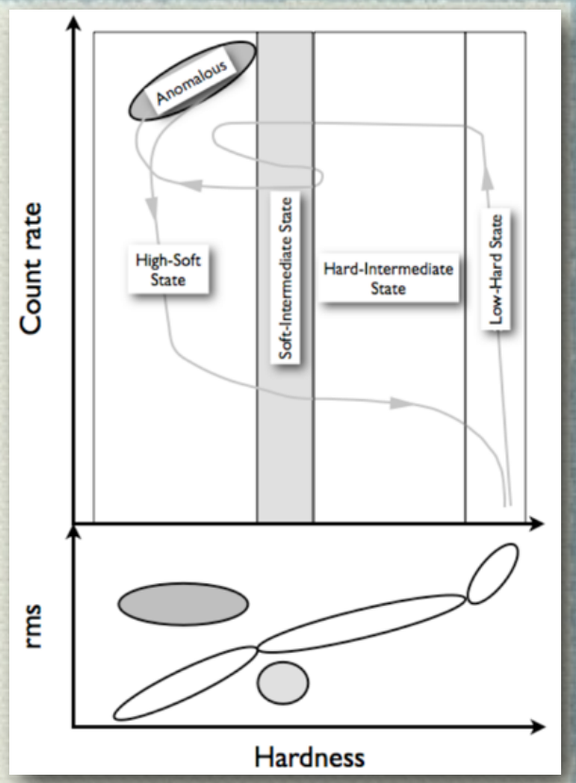




Klein-Wolt et al. (1999)

Recap on ejections

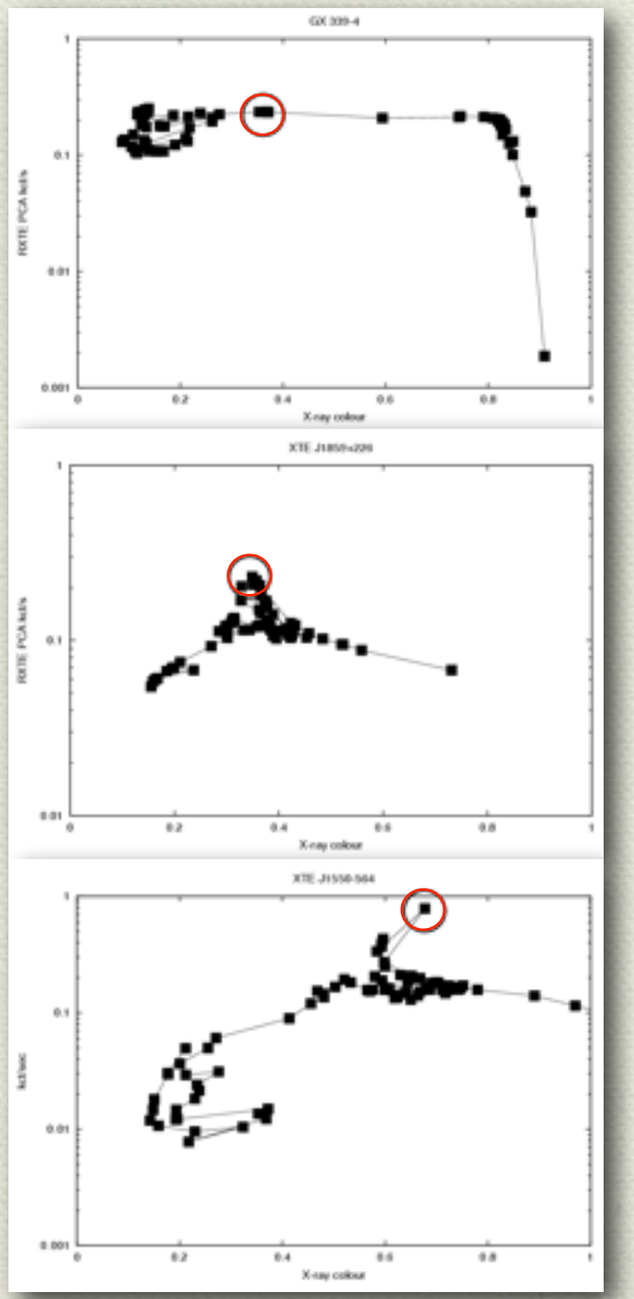
- High Lorentz factor
- In GRS 1915+105, associated to X-ray events
- X-ray events are hard-to-soft



- When do they take place in a normal transient?
- Hard, soft or intermediate?

Transient ejections

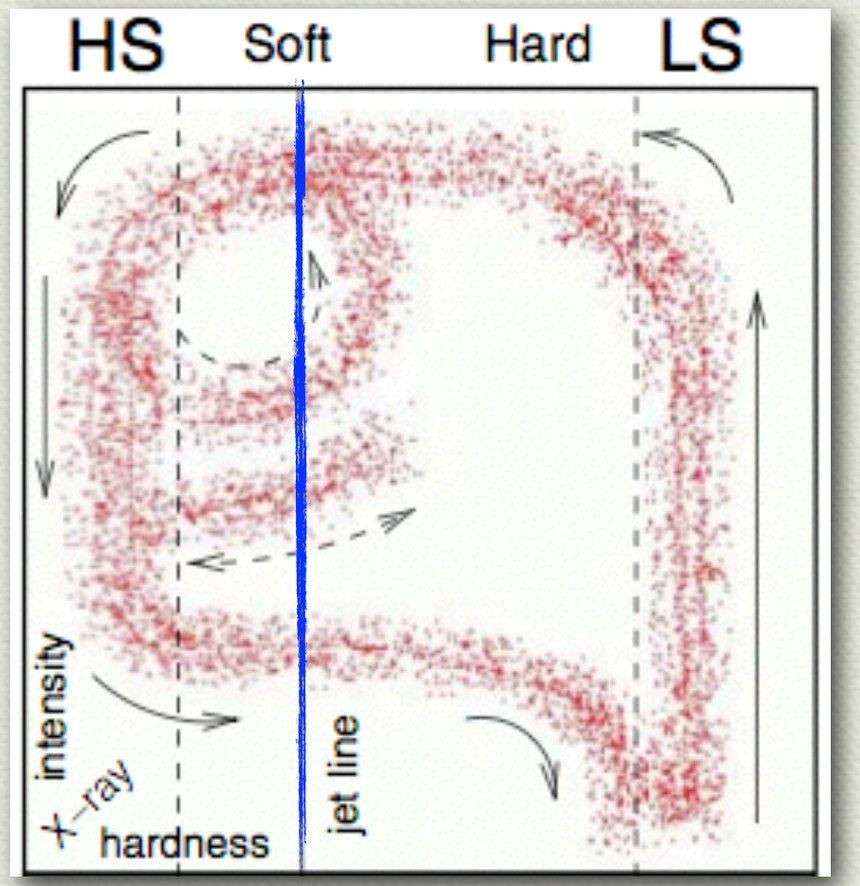
- Major flares or ejections
- Always intermediate
- Only in hard to soft
- Precisely at HIMS-SIMS transition?
- Noise disappears - jet appears
- Not causal



Fender, Belloni & Gallo (2004)

The jet line

- Major ejection (flare) crossing the line
- Only right to left
- Not on reverse transition
- Some: multiple crossings
- GRS 1915+105: many crossings

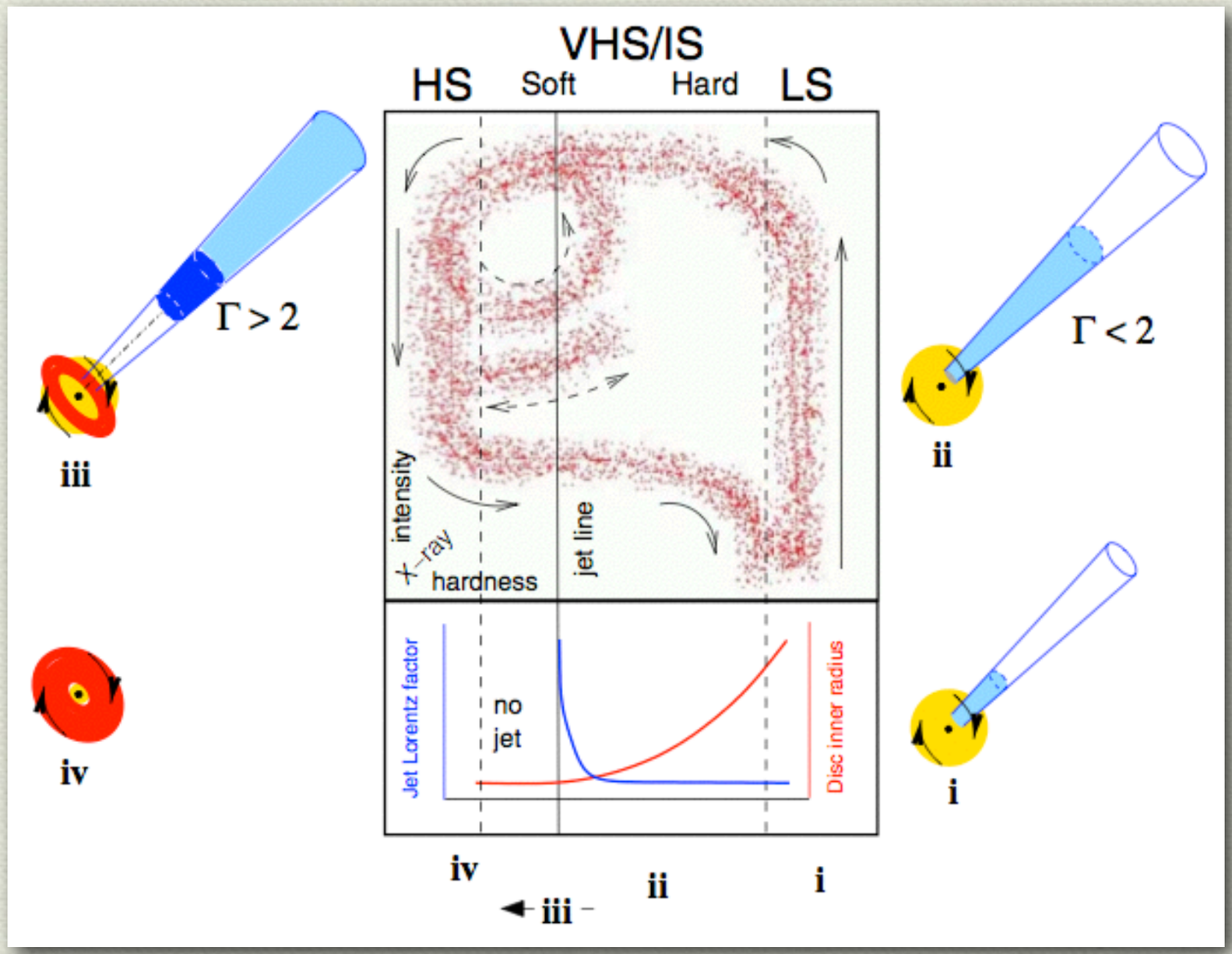


Fender, Belloni & Gallo (2004)

- This leads to a toy model

One jet to rule them all

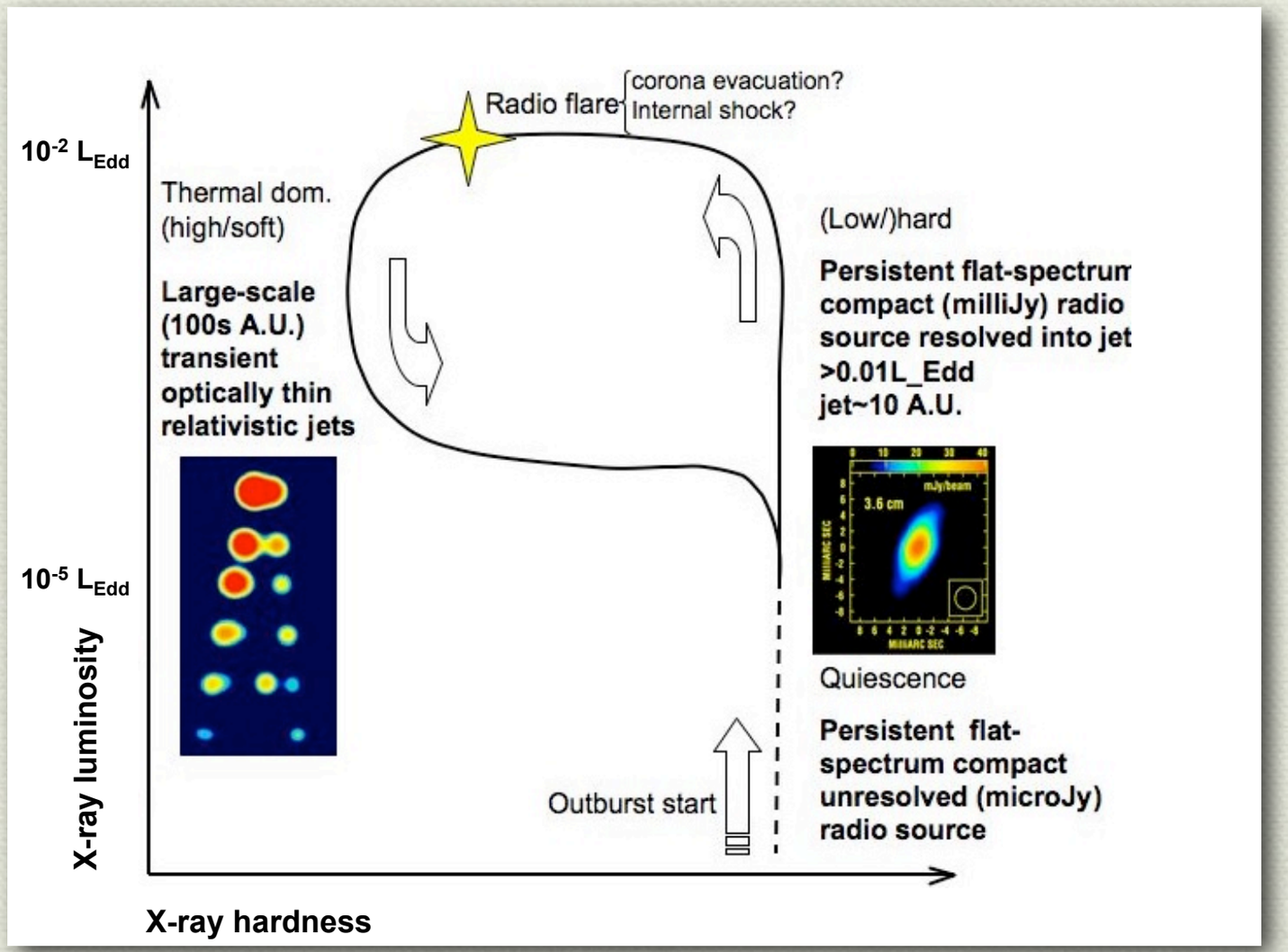
- Jet accelerates
- Then quenched
- Internal shocks (GRB model)
- Not on reverse



Fender, Belloni & Gallo (2004)

One jet to rule them all

- It fits everything
- It does not need complications
- Only one jet
- Can shocks power it?

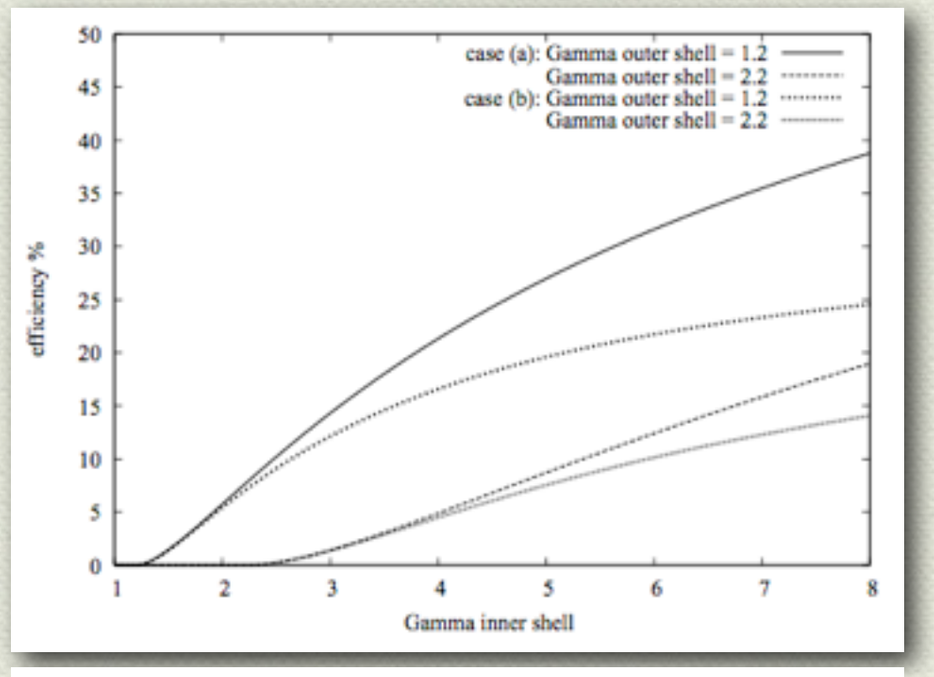


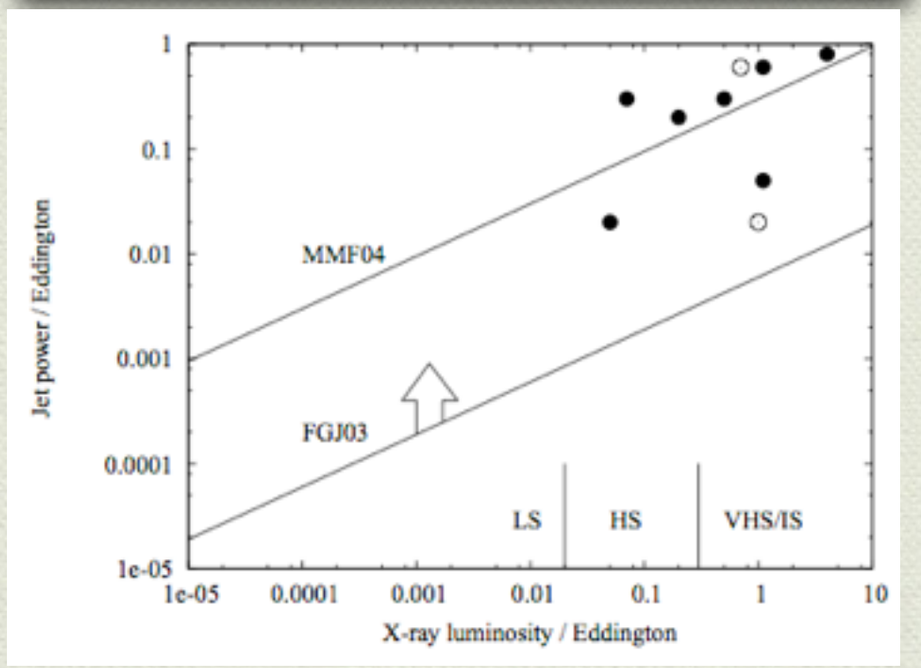
Gallo (2009)

Internal shocks

- Yes, they can
- Power scaling works
- Moreover...
- Jet *could* be dominating power..
- .. outside soft states

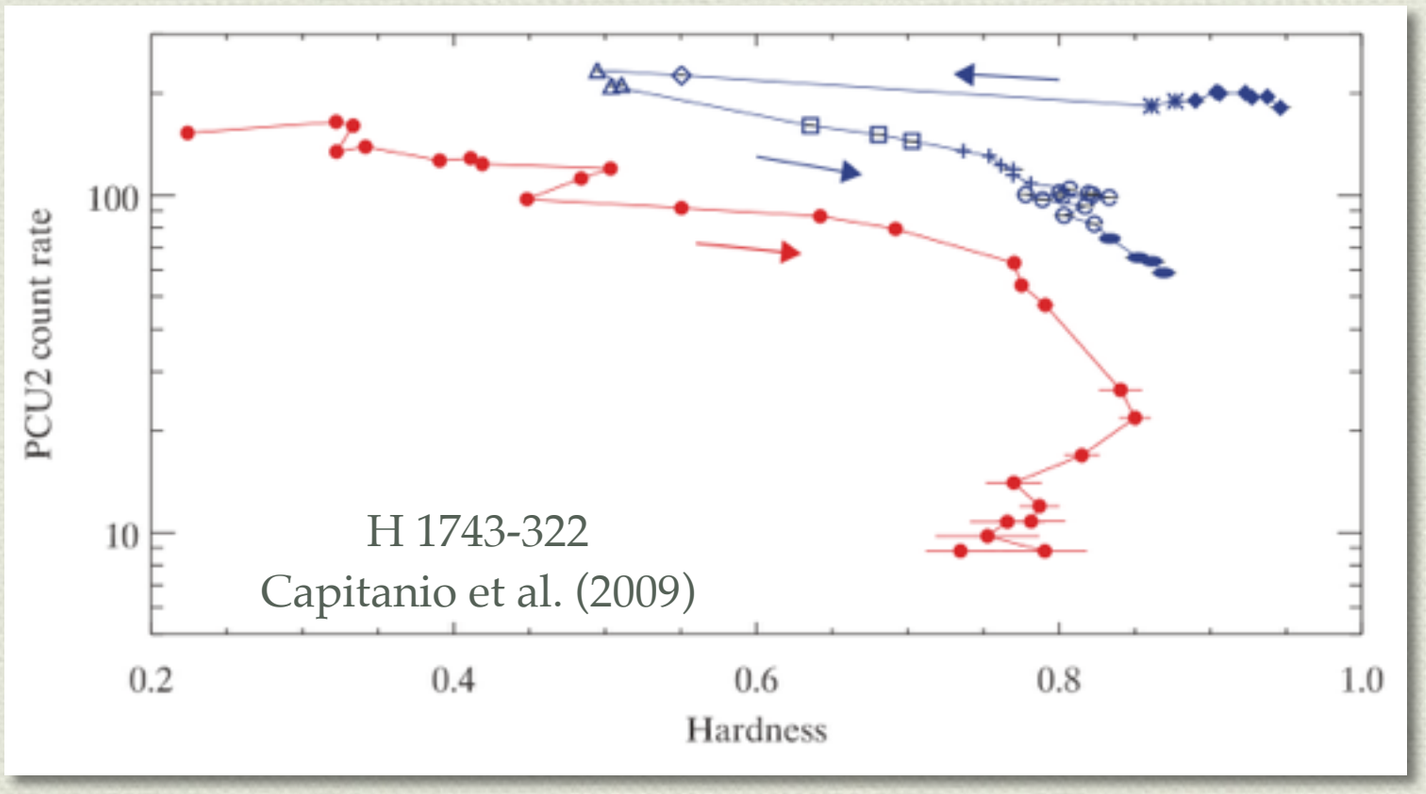
Fender, Belloni & Gallo (2004)





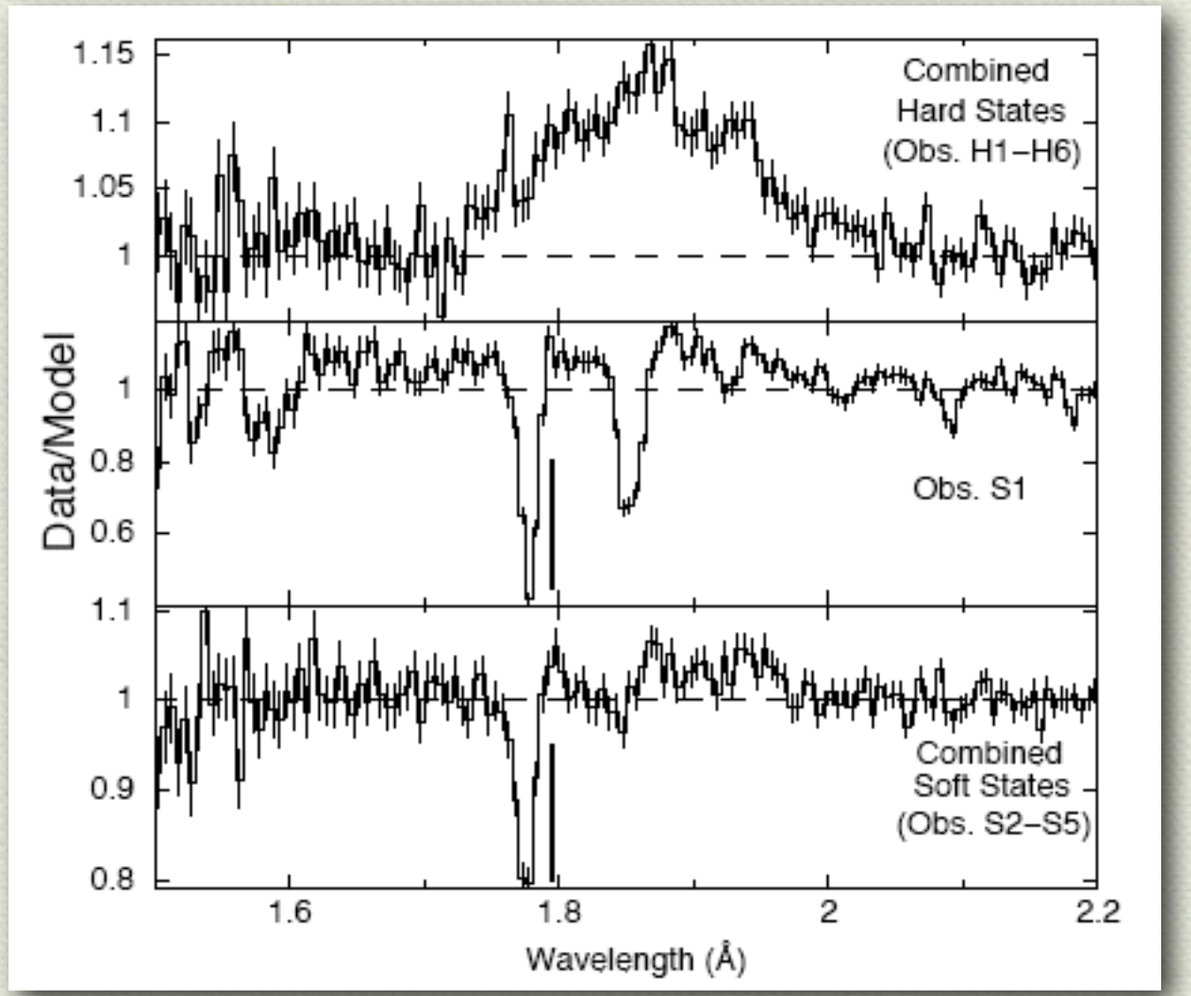
Failed outbursts

- LHS only, no transitions
- HIMS but no jet
- Jet (and state transition) can be called off



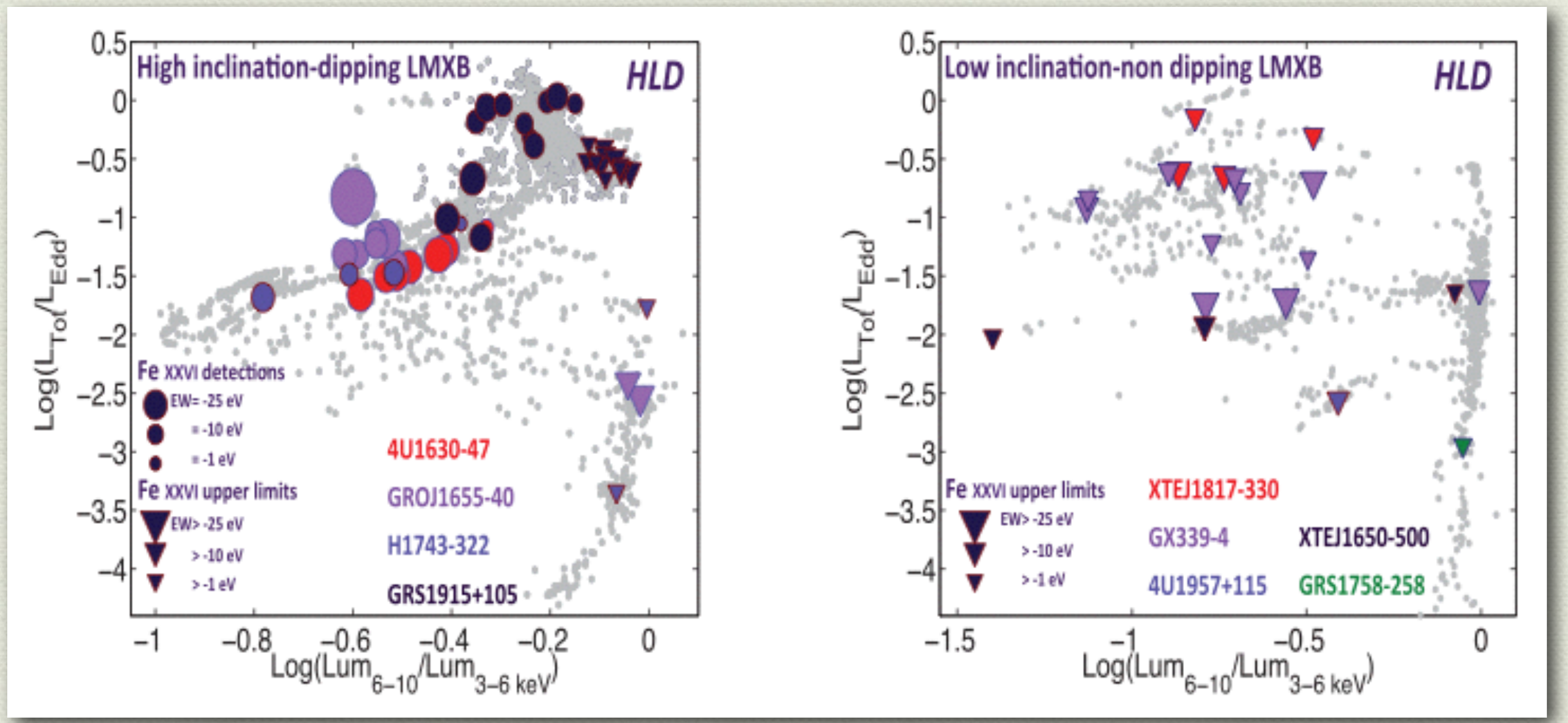
Jets and winds

- GRS 1915+105
- All Chandra observations
- Hard: emission line
- Soft: wind absorption lines
- Take away more power
- ~1000 km/s
- Either jet or wind



Neilsen & Lee (2009)

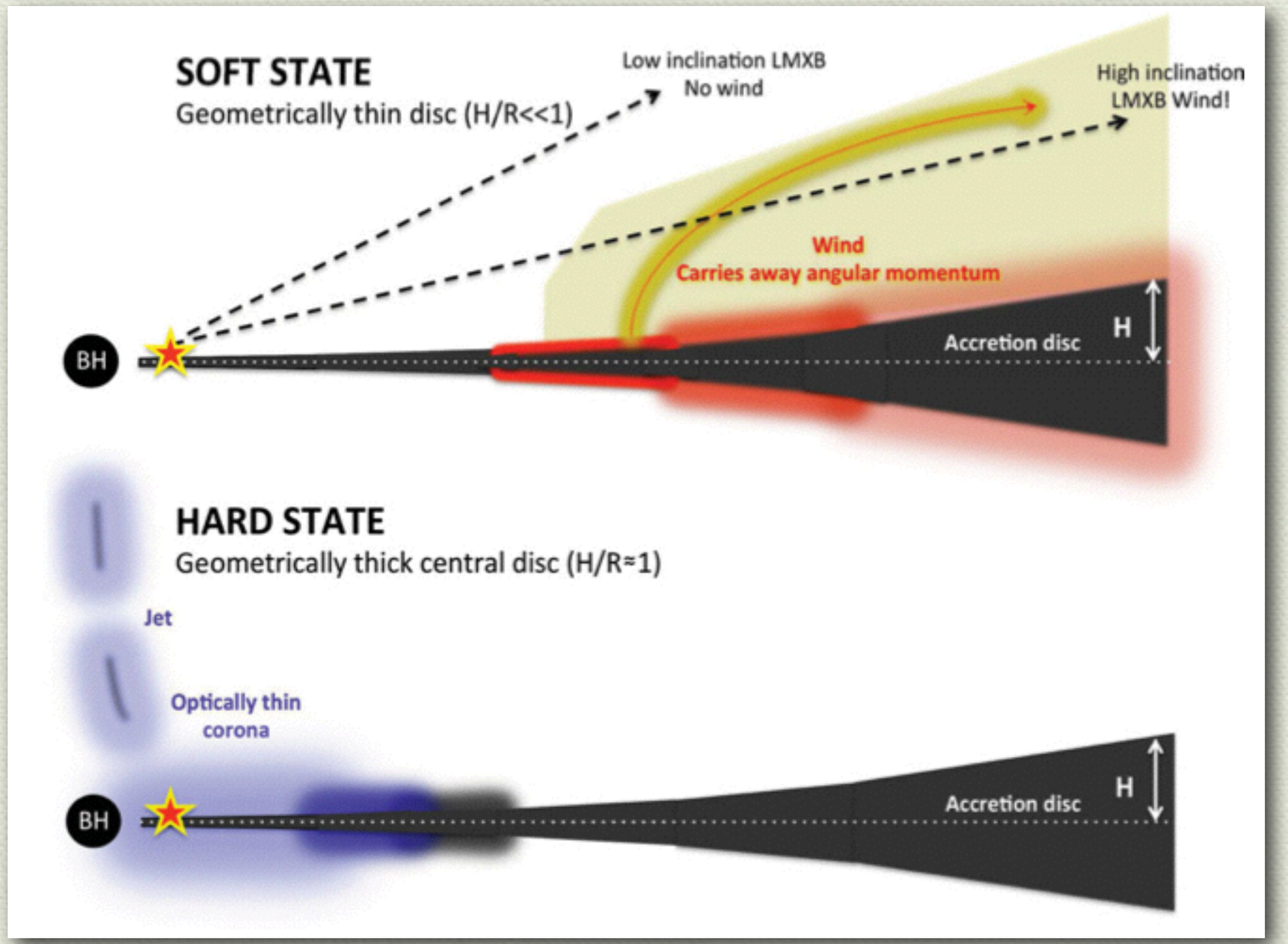
Jets and winds



Ponti et al. (2012)

- Inclination effects

Jets and winds

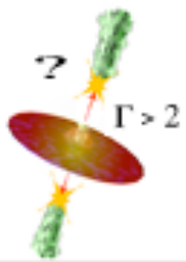


Ponti et al. (2012)

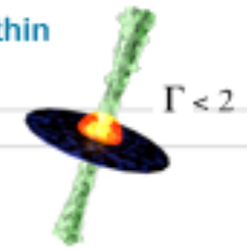
The full picture

Belloni et al. (2010)

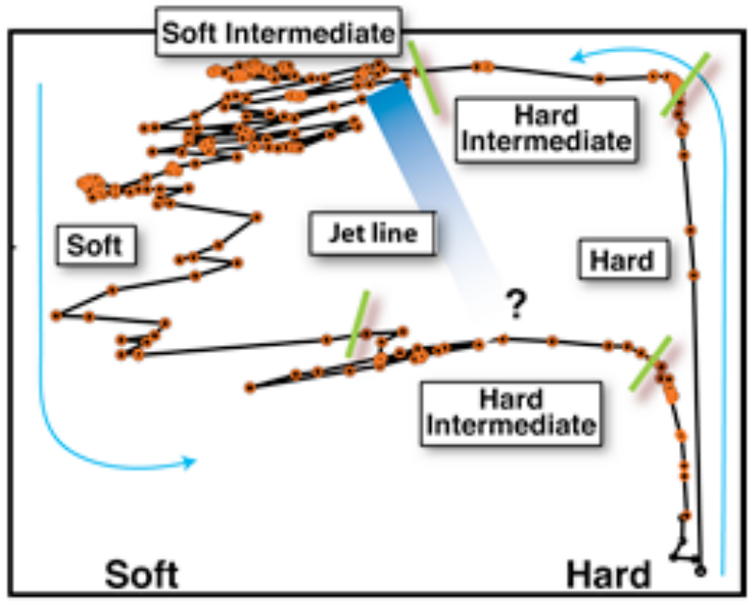
JET LINE AREA:
- 2 - 50% L_{Edd}.
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~0.2 Hz lowest freqency Lorentzian, close to ejecta time.



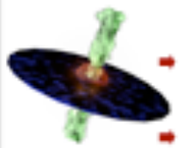
HIMS:
- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd}.
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).



SOFT STATE:
- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to ~MeV.
- Thin disk ~0.1-1.0 L_{Edd} at ISCO.



HARD STATE:
- Disk moves in to ~ few R_g by 10% L_{Edd}.
- Lorentzian/broad noise components.
- High RMS variability.
- Flat spectrum jet up to IR/opt.
- Compact jet sometimes resolved.
- Radio/IR/X-ray correlations.
- Reflection "bump".



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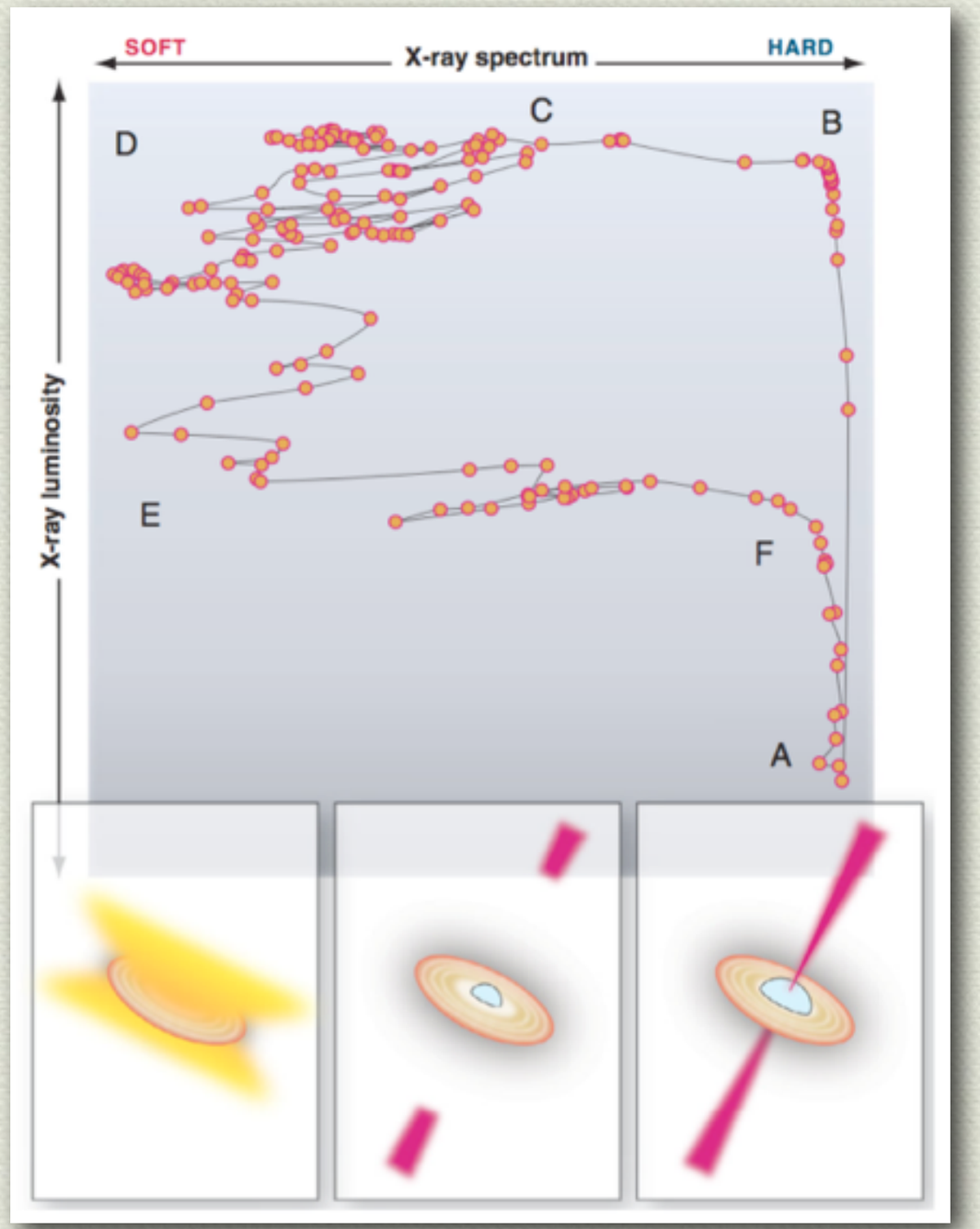
S. Markoff
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

HIMS:
Same as upper branch but:
- No optically thin radio flare.
- Radio recovers close to hard state.
- Lower flux level (hysteresis).

QUIESCENCE:
- Thin disk recessed to > 10^2 R_g.
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By ~10^{-4} L_{Edd}.
- No iron lines?

Probing the Accretion/Outflow Connection in X-Ray Binaries and Active Galactic Nuclei

The full picture

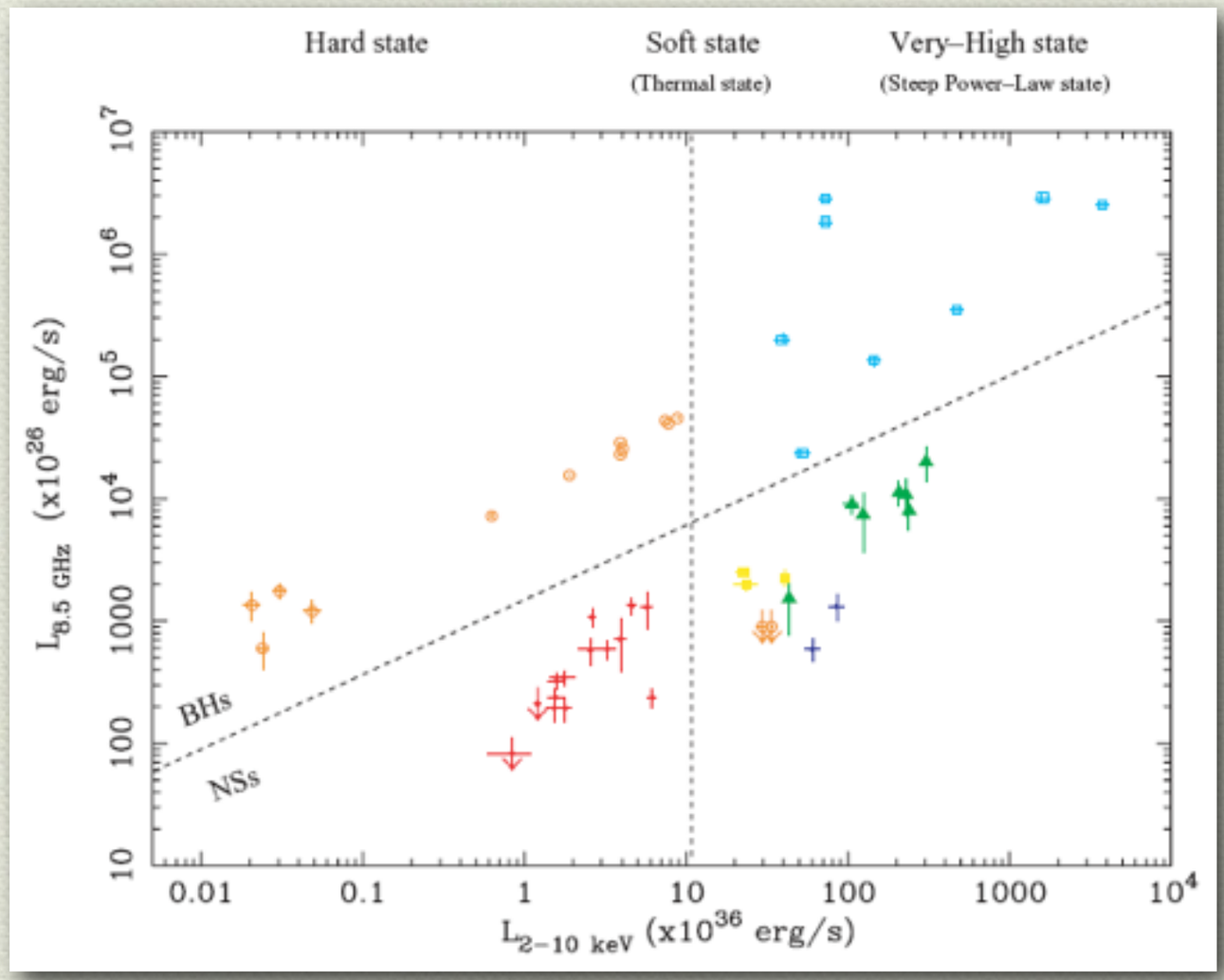


Fender & Belloni (2012)

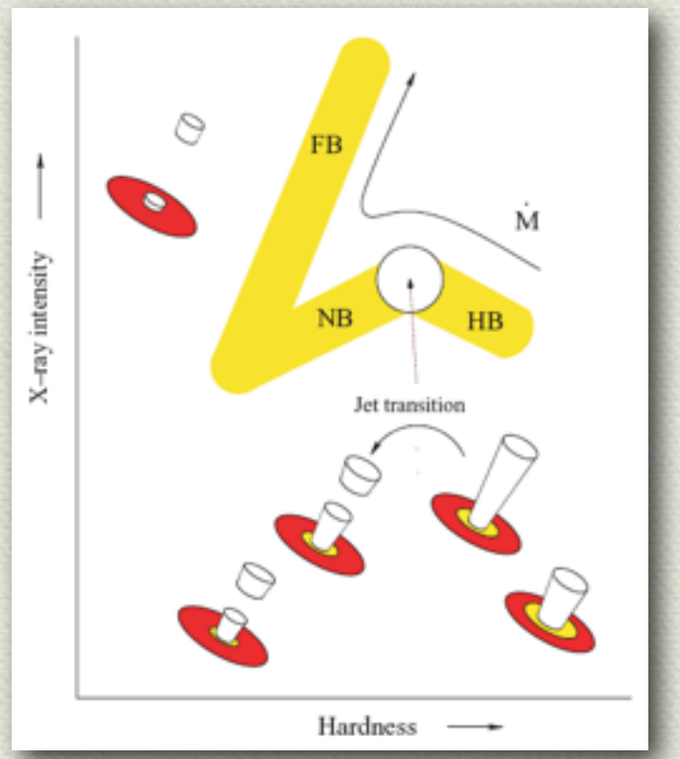
Neutron star binaries

- Hard-state correlation: similar to black holes, but radio-quiet (factor 30)

Migliari & Fender (2006)



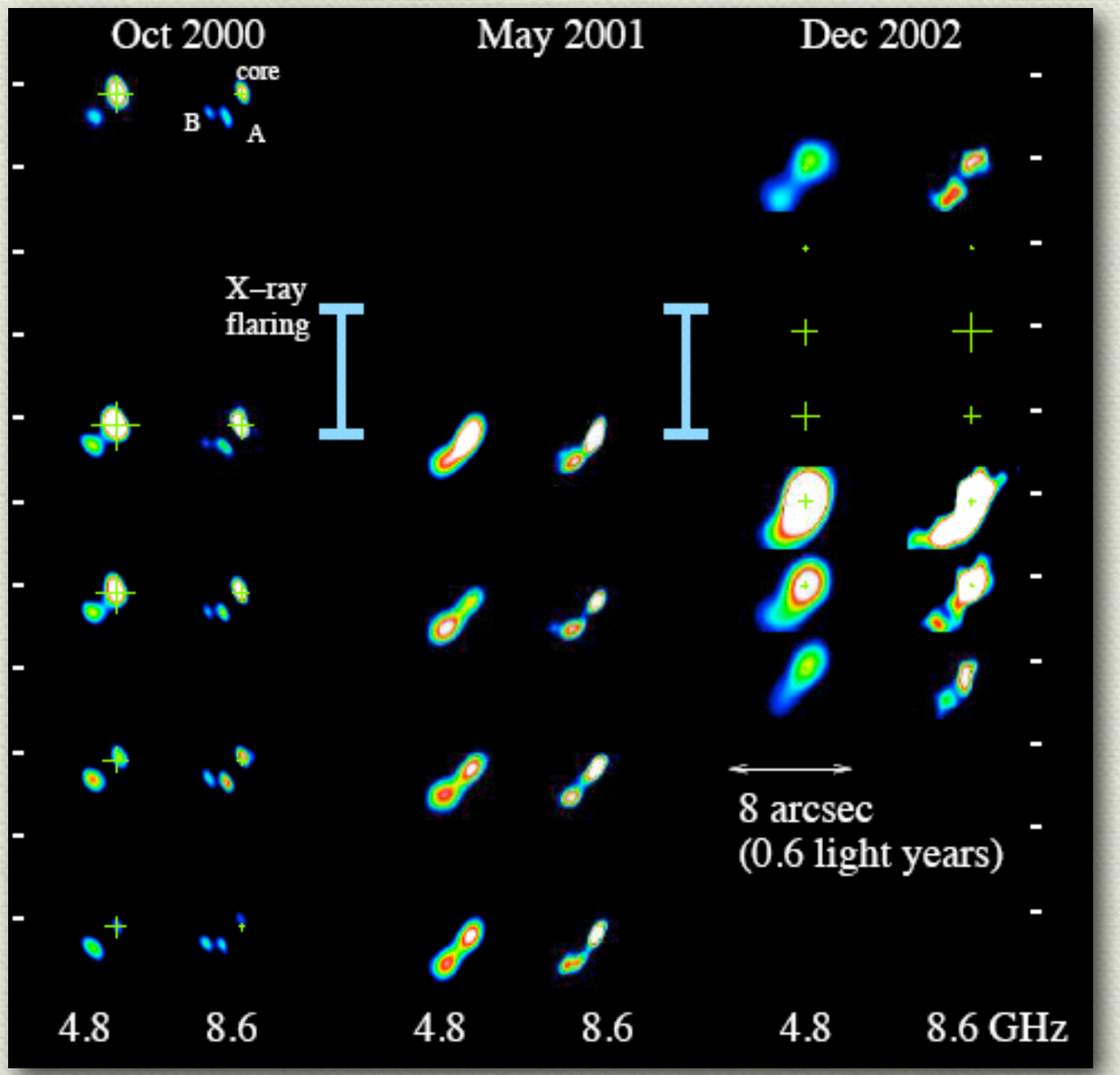
- Plus ejections



Neutron star blasts

- Circinus X-1
- Neutron-star binary
- X-ray flare...
- ... radio brightening
- $\Gamma > 15$!!
- No relation to v_{esc}

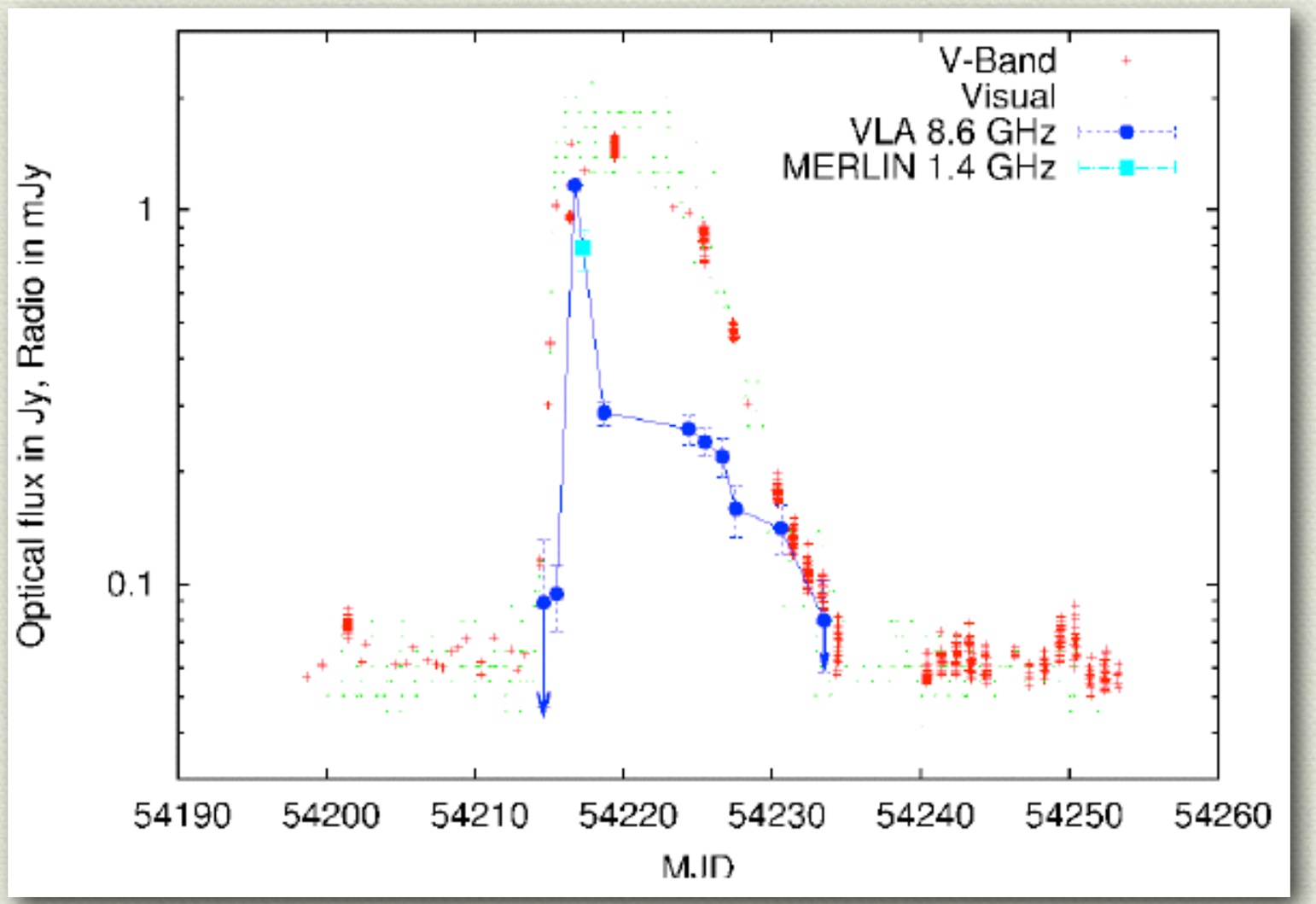
Fender et al. (2004)



White dwarfs!

- SS Cygni
- Dwarf nova
- Radio flare
- At transition!

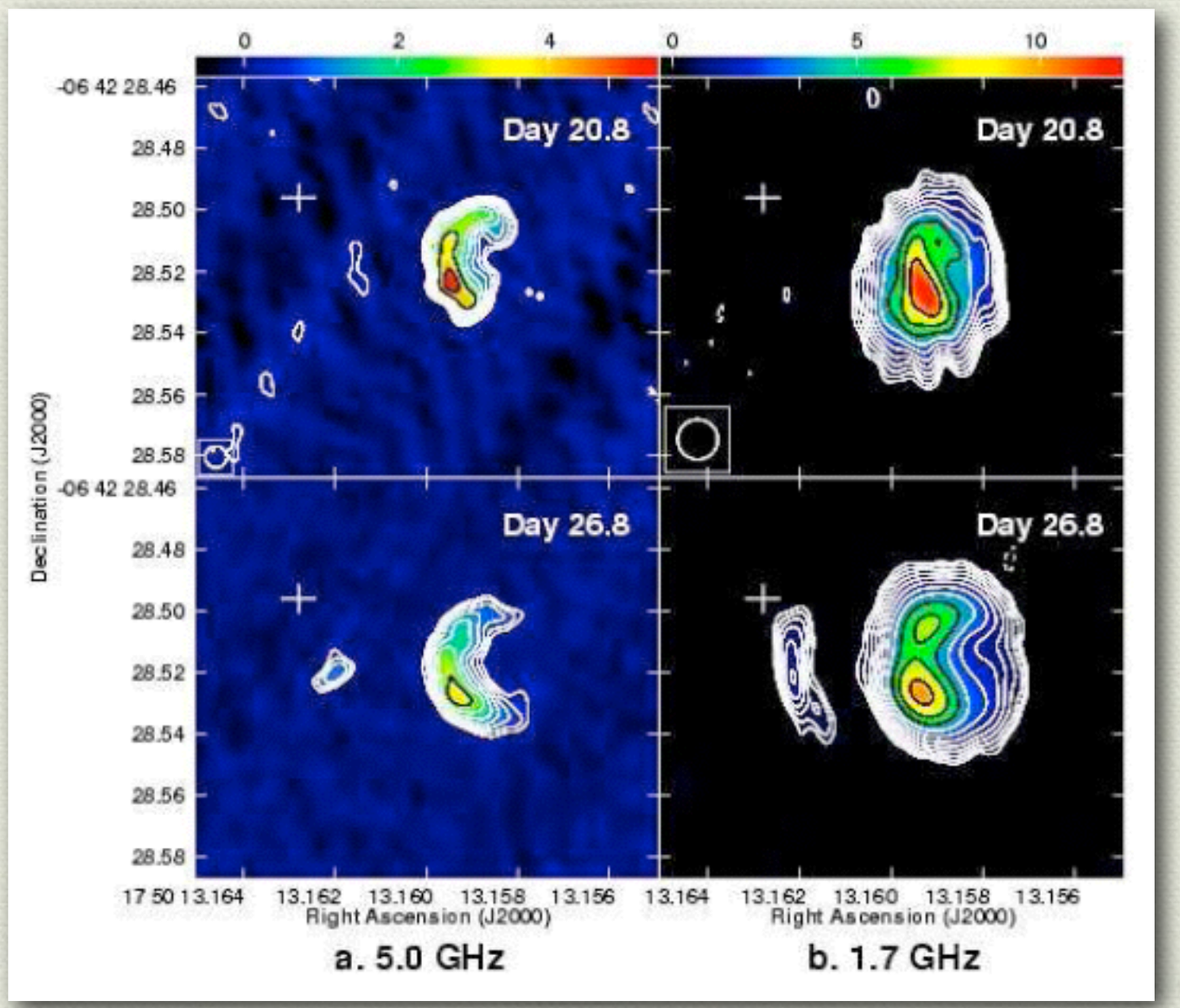
Kording et al. (2008)



More white dwarfs!

- RS Oph
- Recurrent nova
- Ejection
- Around 1 month after
- v comparable to v_{esc}

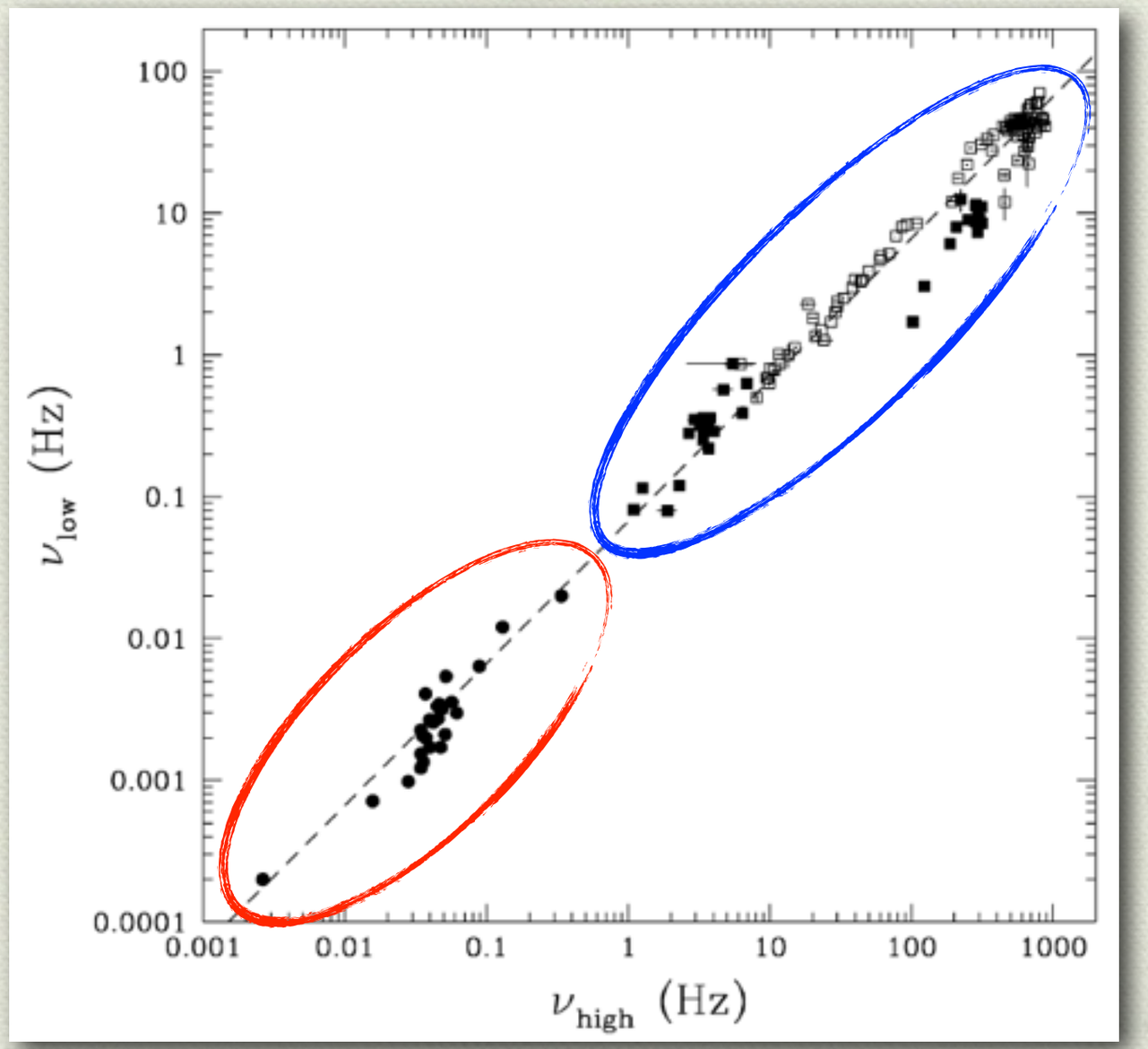
Rupen et al. (2007)



Timing white dwarfs

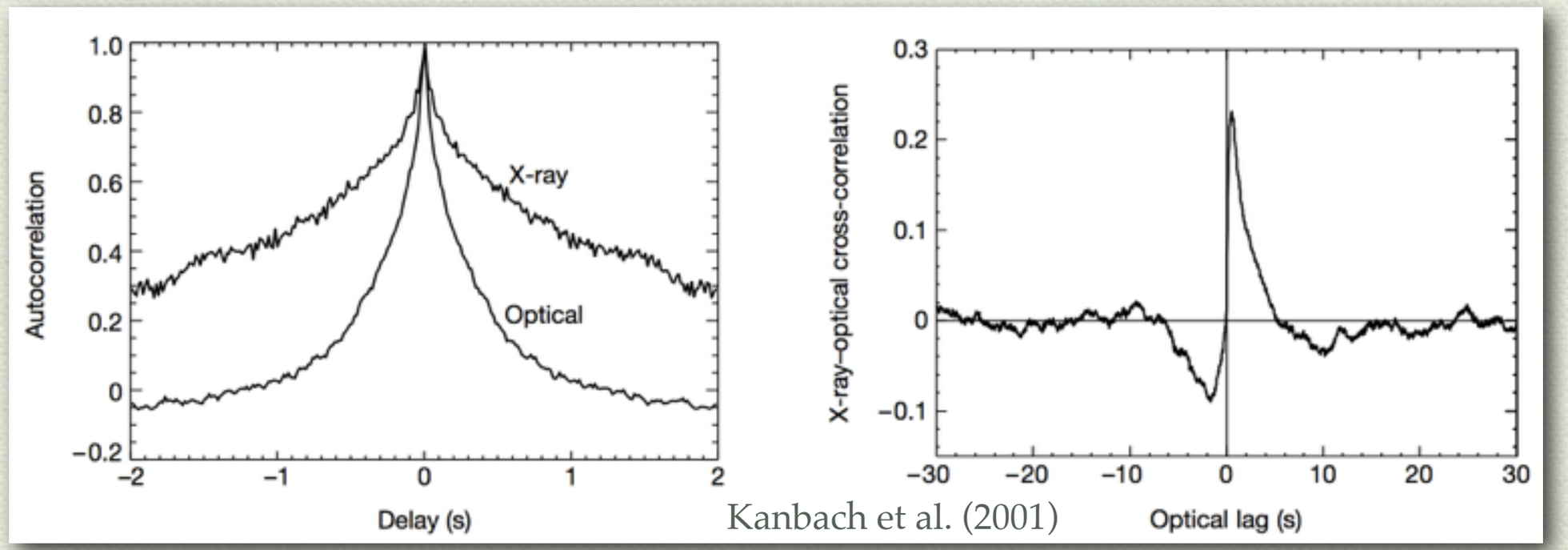
- Dwarf-nova oscillations & QPO
- They fit the correlation
- What this means..
- .. tomorrow

Warner, Woudt & Pretorius (2003)



Fast timing

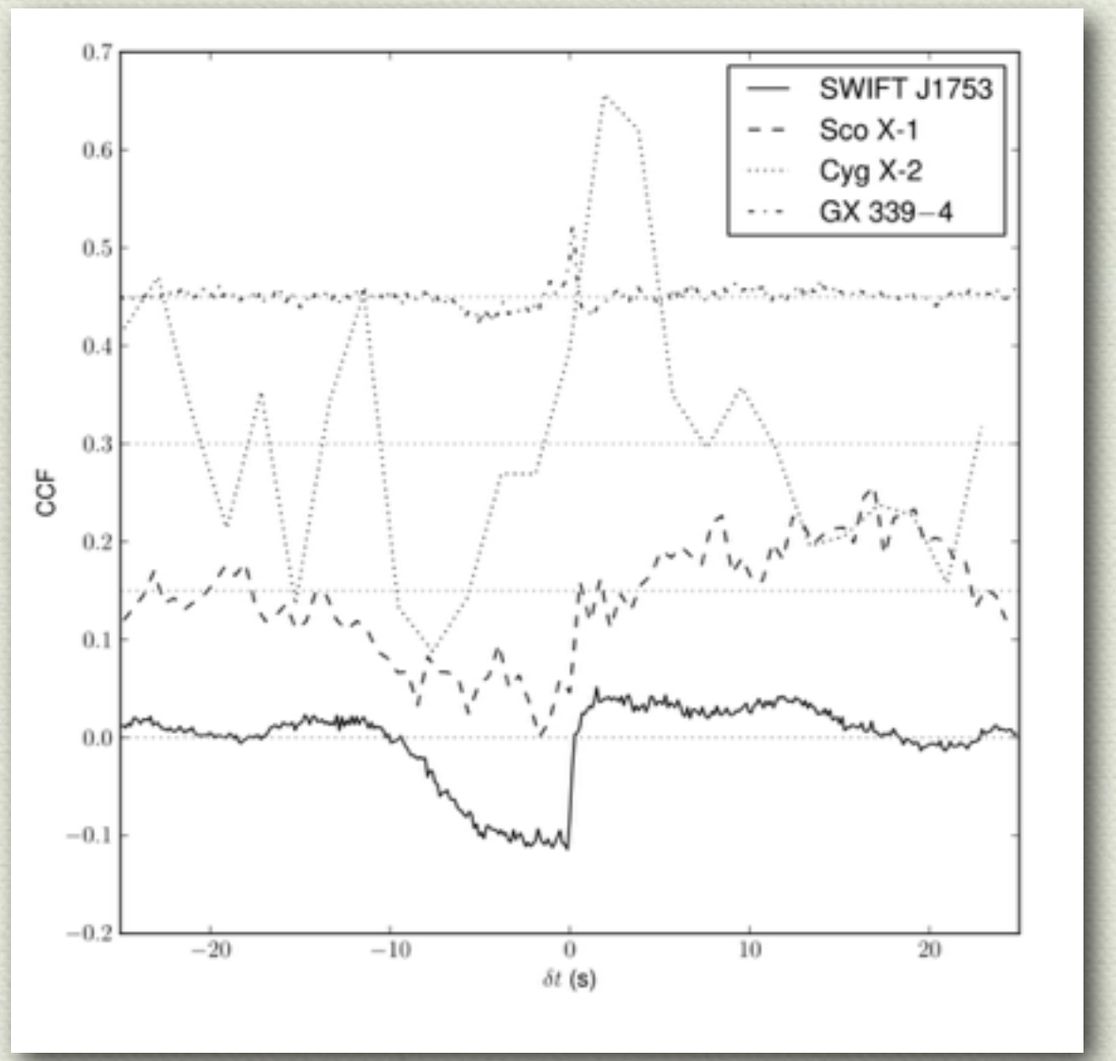
- Optical measurements



Kanbach et al. (2001)

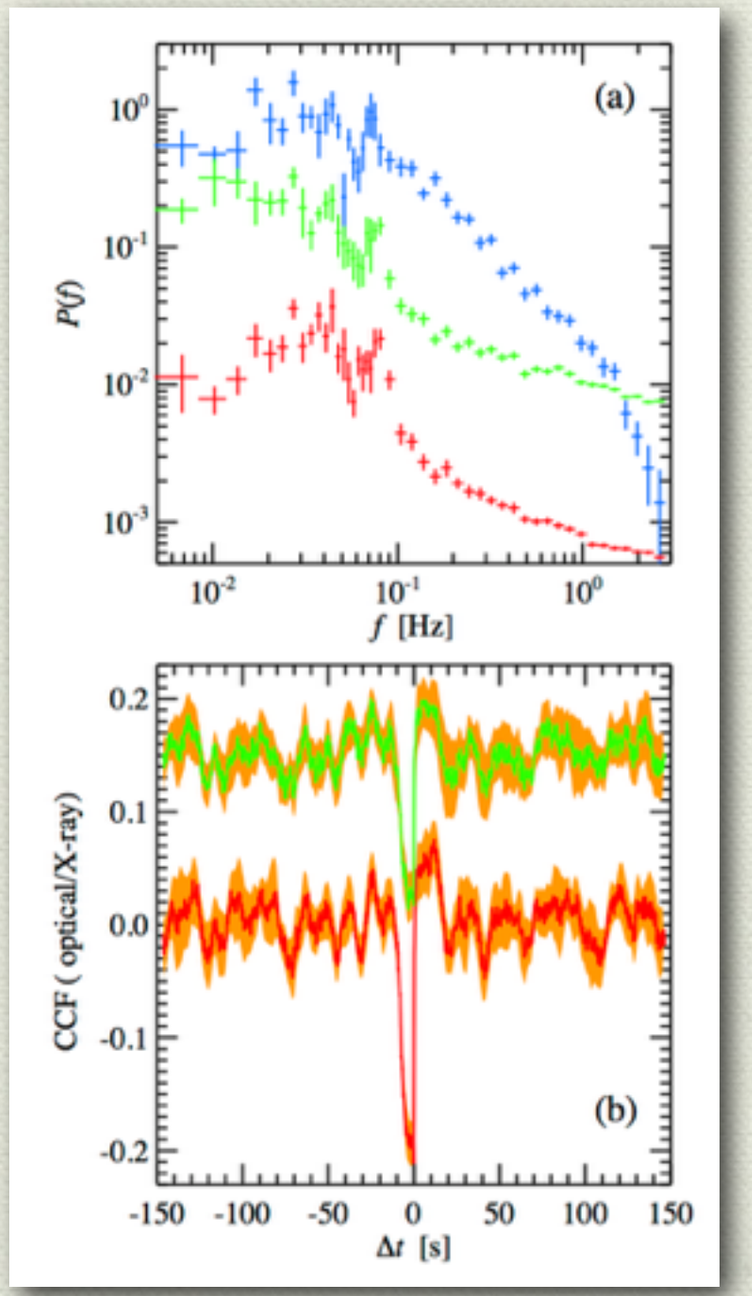
Fast timing

- Now more and more



Durant et al. (2011)

Veledina et al. (2015)



First IR QPO

- GX 339-4

Kalamkar et al. (2015)