Powering relativistic jets: lessons from Galactic microquasars

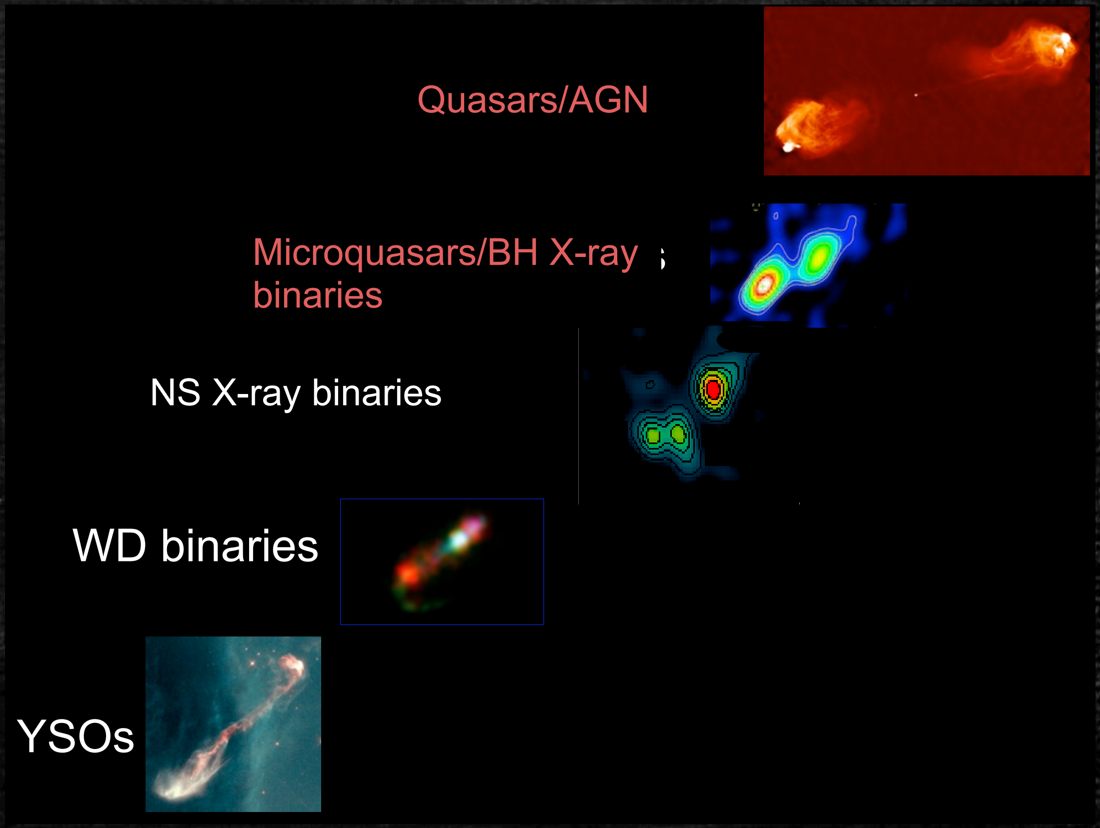
Elena Gallo
University of Michigan

Powering relativistic jets

Jets, a.k.a. highly collimated (<2 deg) **relativistic** outflows (Gamma>2)

Powering mechanism unknown

- Extraction of rotational energy from the black hole (Blandford-Znajek 1977)
- Large scale magnetic field + differentially rotating disk (Blandford-Payne 1982)

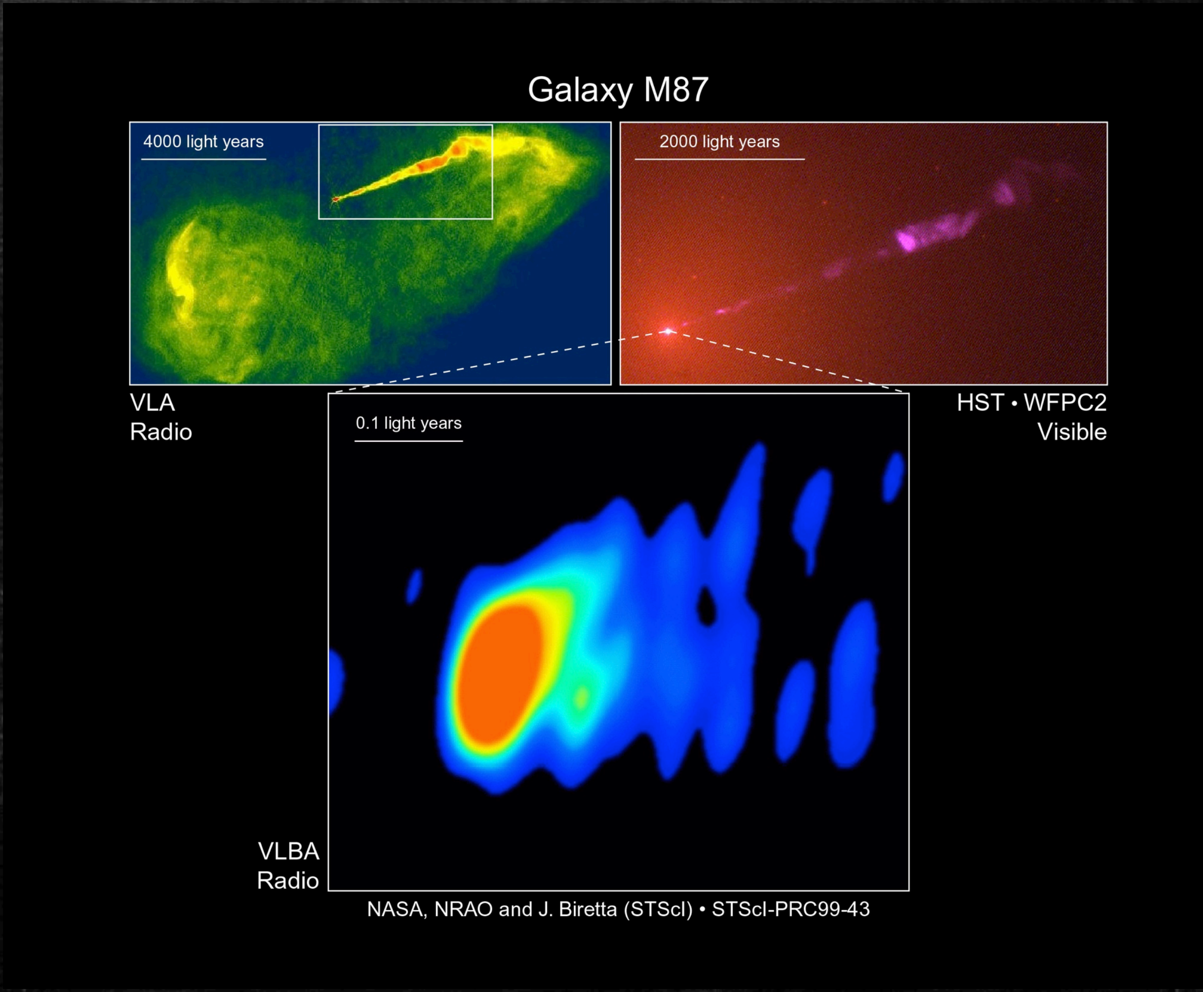


Relativistic jets from quasars

Engine: million-billion solar mass black hole

Jets: 1000s light years

Jet power output: comparable to accretion power



Relativistic jets from quasars

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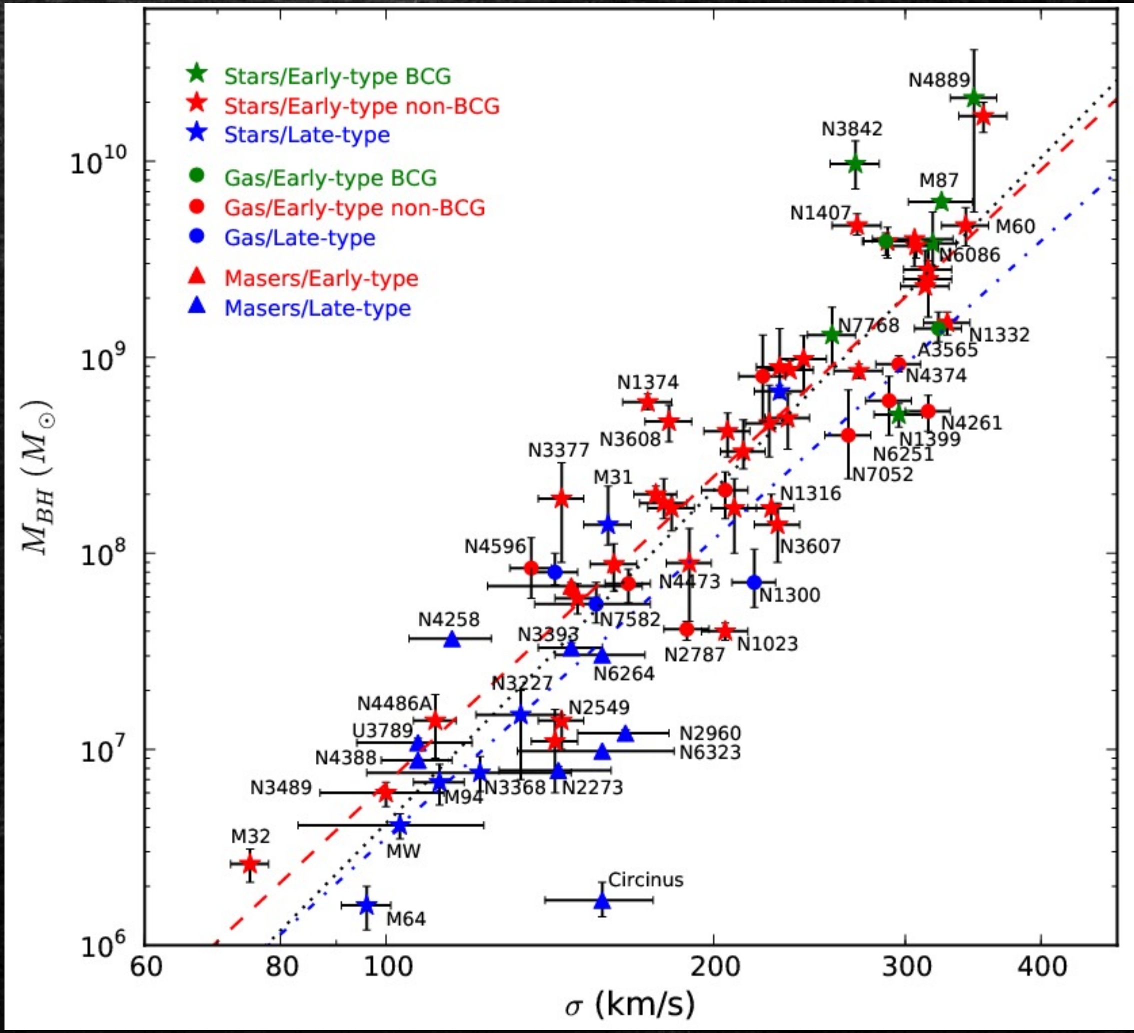
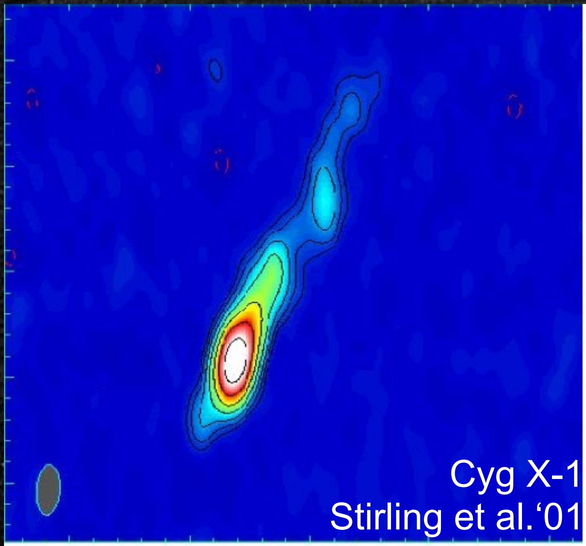
Jet likely plays a role in establishing local BH mass-galaxy "scaling relations"

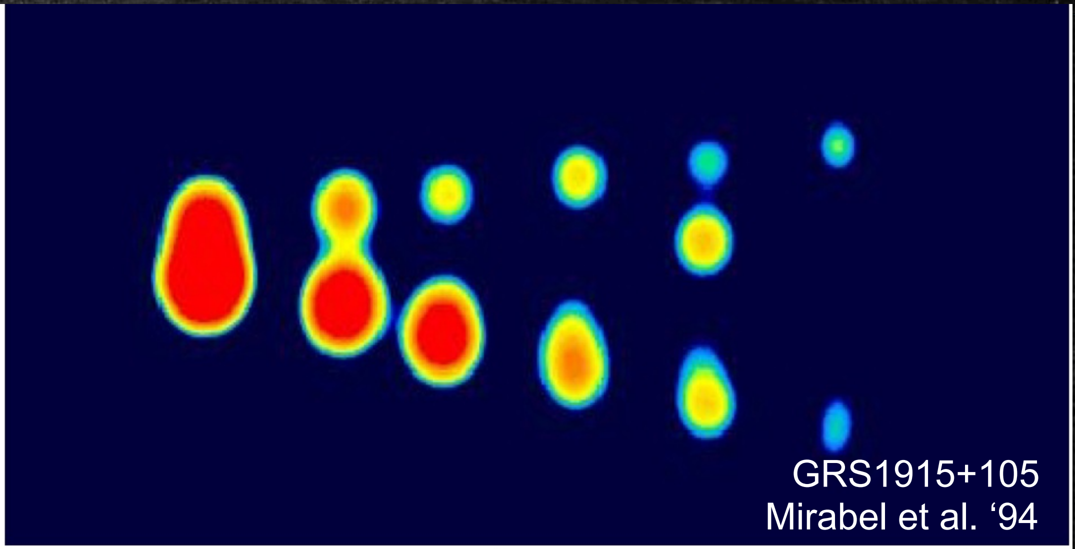
Galaxy evolution simulations *rely* on BH-rotation powered jets



McConnell & Ma 2012

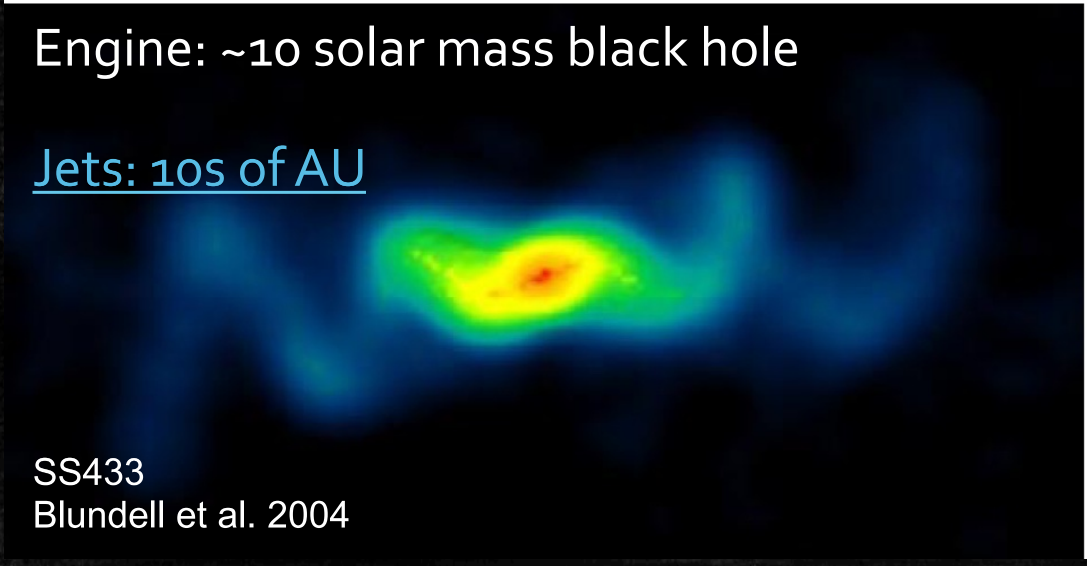
Relativistic jets from microquasars

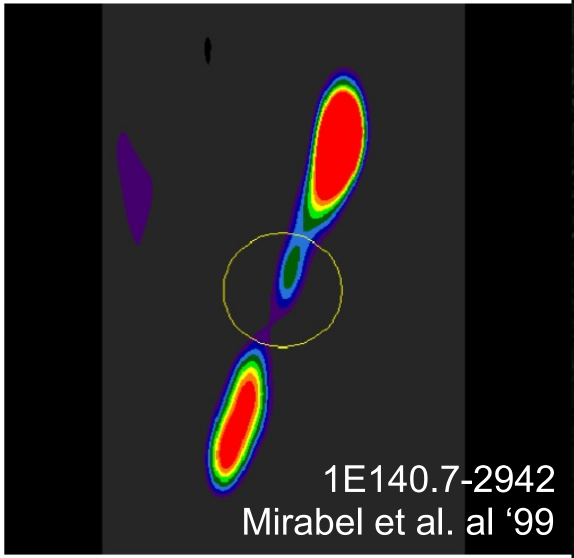




Engine: ~10 solar mass black hole

Jets: 10s of AU





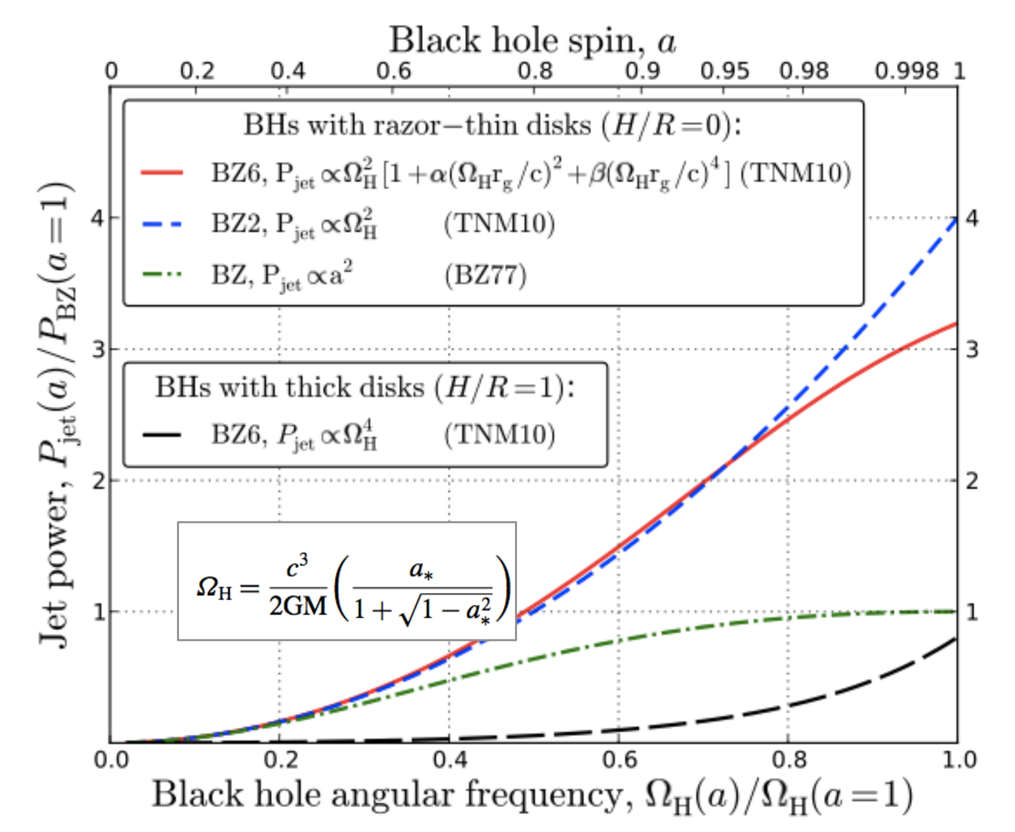
Are black hole jets spin-powered?

Theory: Likely so (at least the most powerful ones) E.g.: McKinney+ 07,09,12; Tchekhovskoy+ 10,11,12

Observations: Possibly

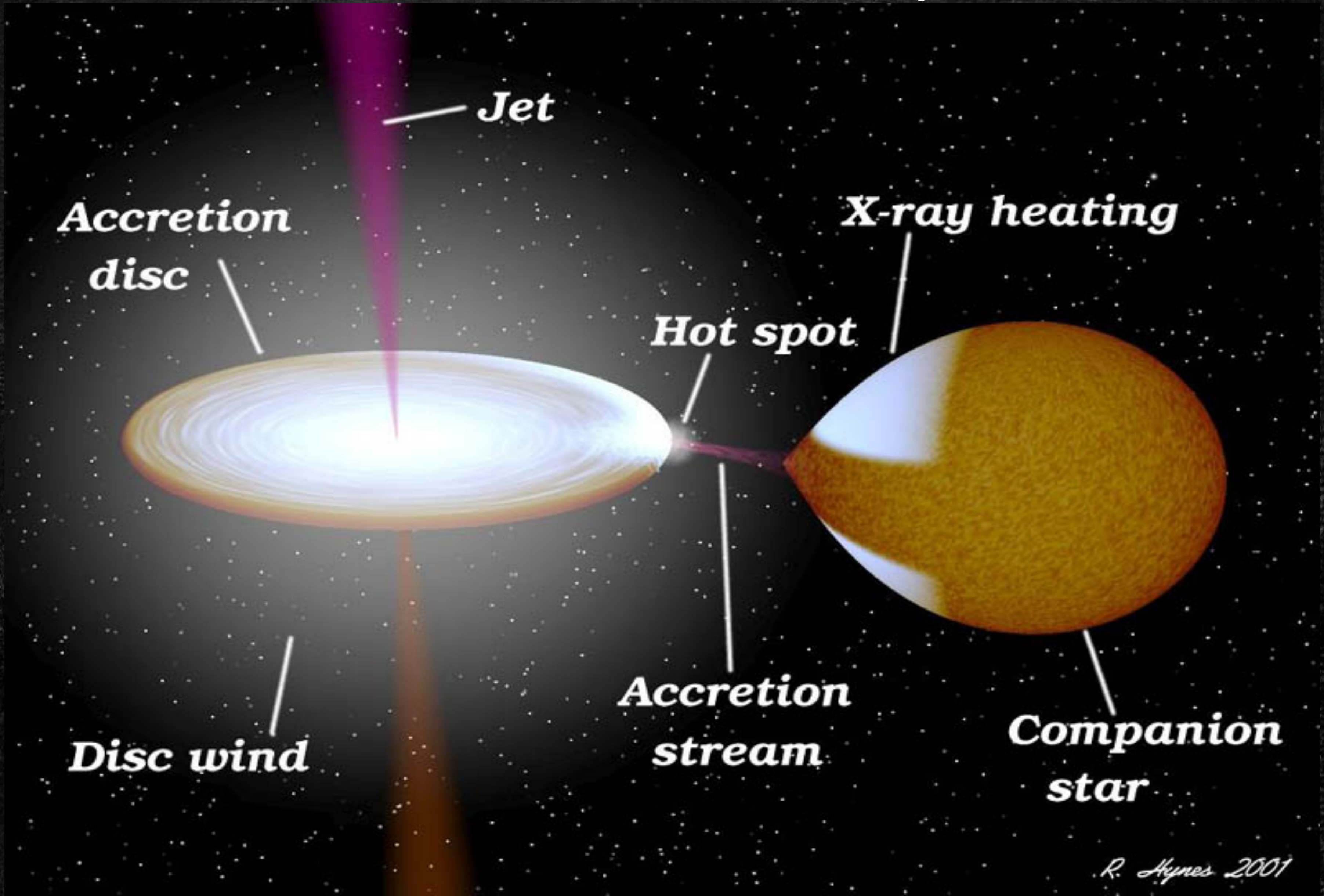
This talk:

- Spin and jet power measurements
- Microquasars
  - Continuum vs. reflection fitting
  - Steady vs. transient jets
  - Neutron stars vs. black hole microquasars



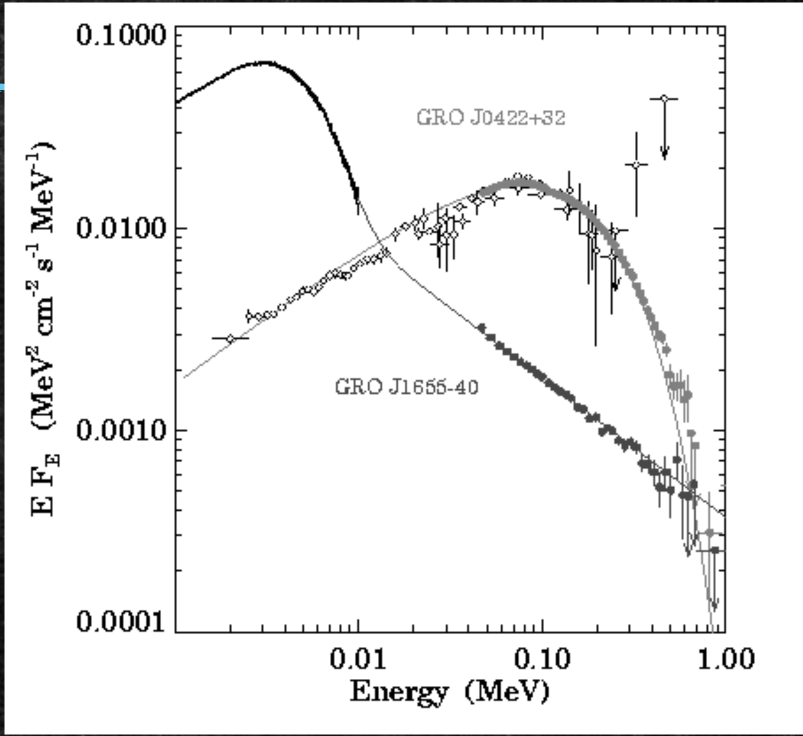
Tchekhovskoy+ 10

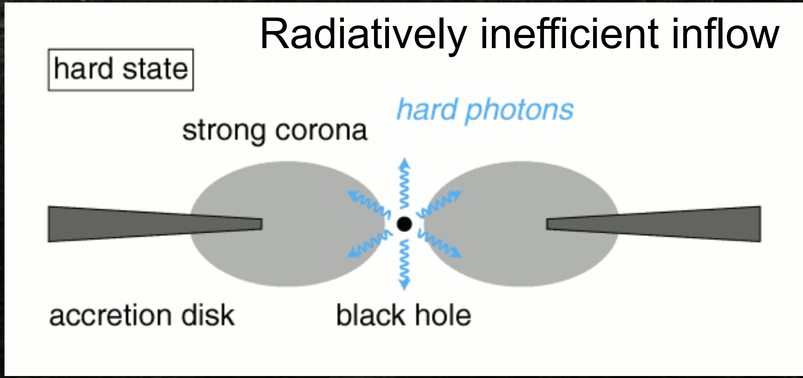
DISK-JET COUPLING. Black hole X-ray states



DISK-JET COUPLING. Black hole X-ray states

- X-ray states (McClintock & Remillard 05)
  - Hard (& quiescent): power-law dominated, reflection weak, high rms variability. L/L_{edd} <1e-2. Models: ADAF, ADIOS, CDAF, JDAF
  - Soft: thermal-dominant, reflection dominated, low rms variability. 1e-2< L/L_{edd} <1. Model: SS disk
- "Corona" < few 10s R_g (Reis & Miller 13, Jiménez-Vicente+14)
- Possible inner disk re-condensation in luminous hard states (Reis+10, Meyer-Hofmeister & Meyer 12,14)





Meyer, Liu & Meyer-Hofmeister 2006

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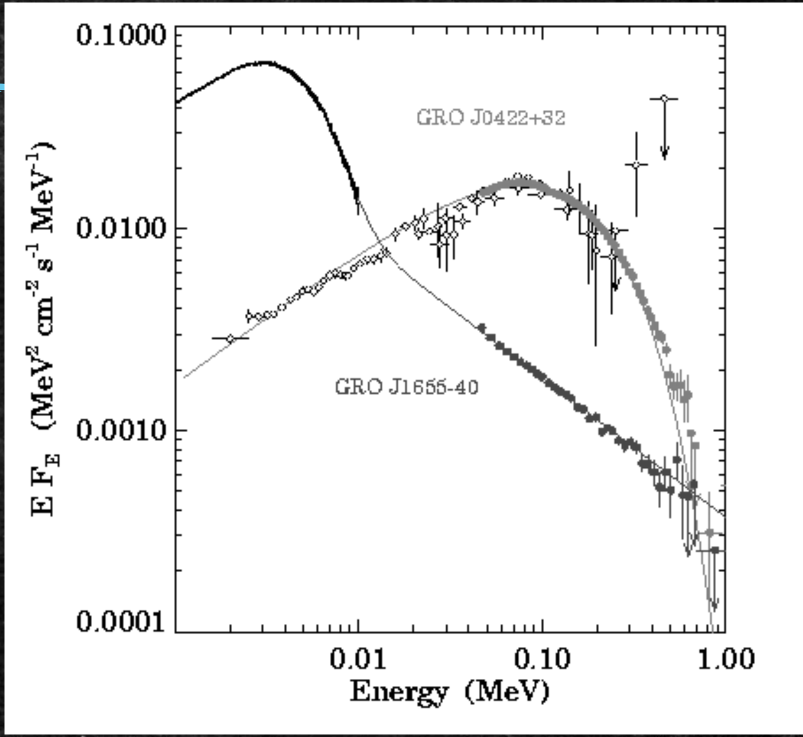
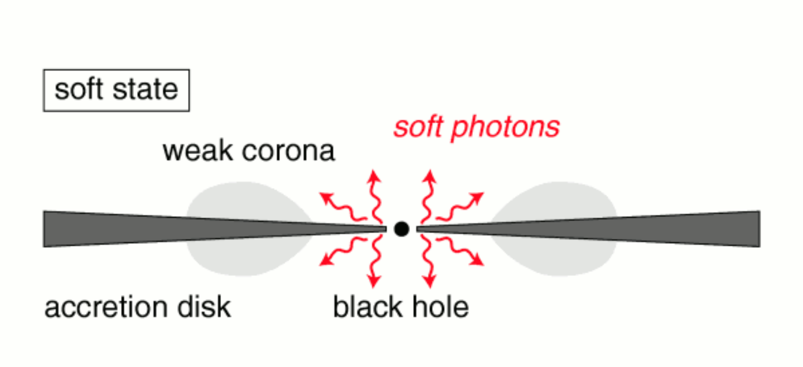
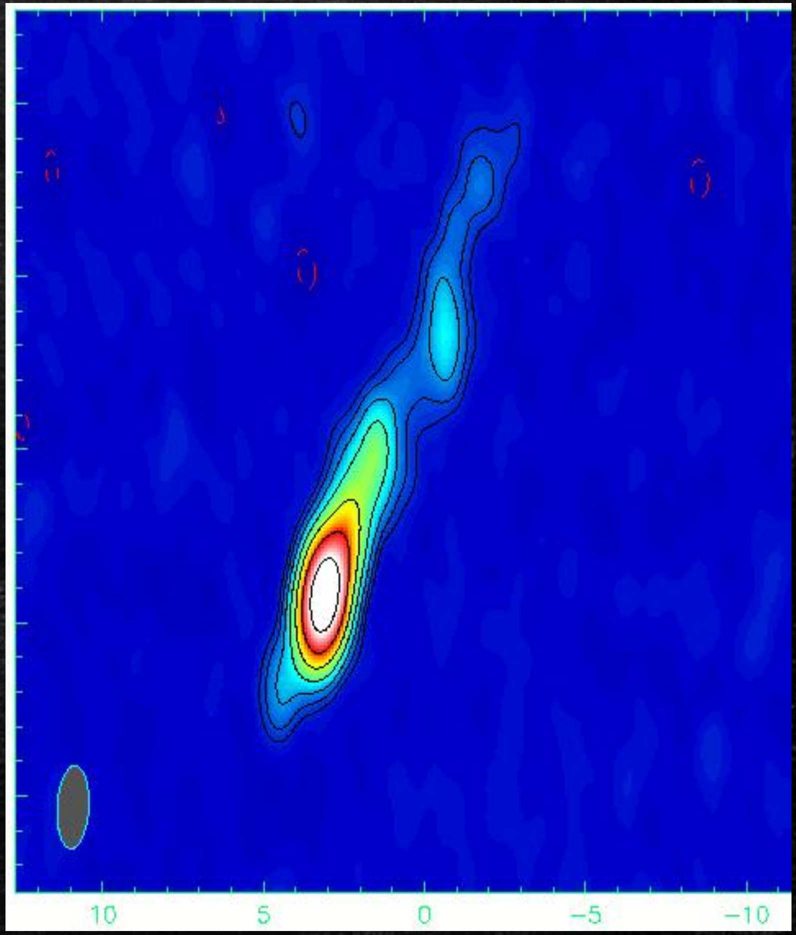




Meyer, Liu & Meyer-Hofmeister 2006

DISK-JET COUPLING. Black hole OUTFLOWS

- X-ray states and outflows (Fender & Gallo 14)
- Ubiquitous **steady jets** in hard state
  - persistent flux density
  - flat radio-IR spectrum, paertially self-absorbed
  - 10s of AU
  - long lived: months-yrs



Cygnus X-1, Stirling+ 01

DISK-JET COUPLING. Black hole outflows

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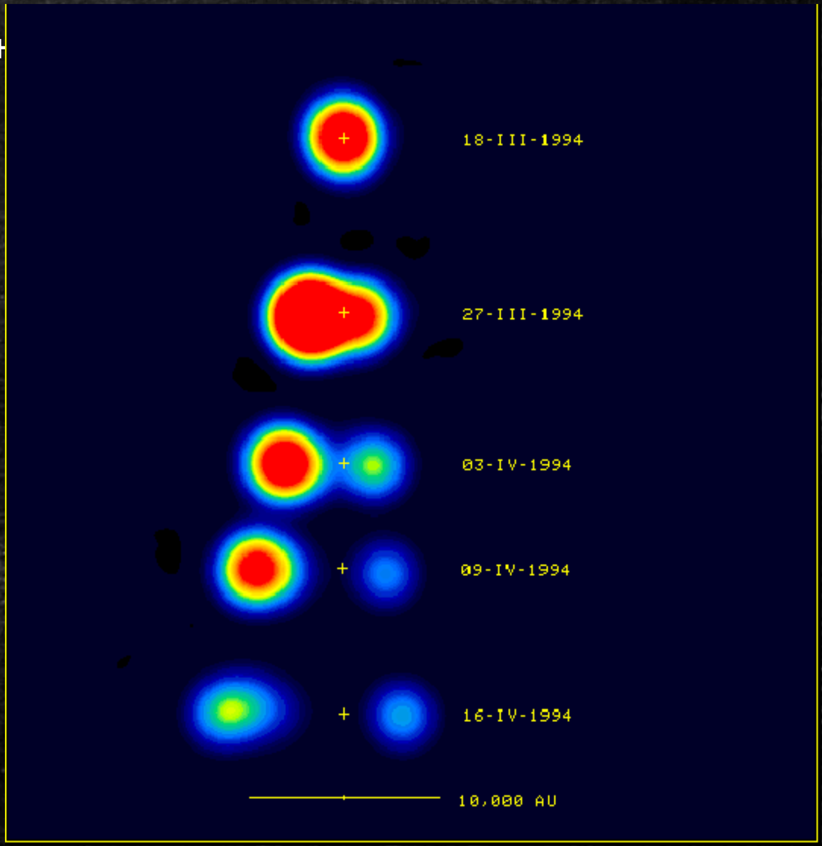
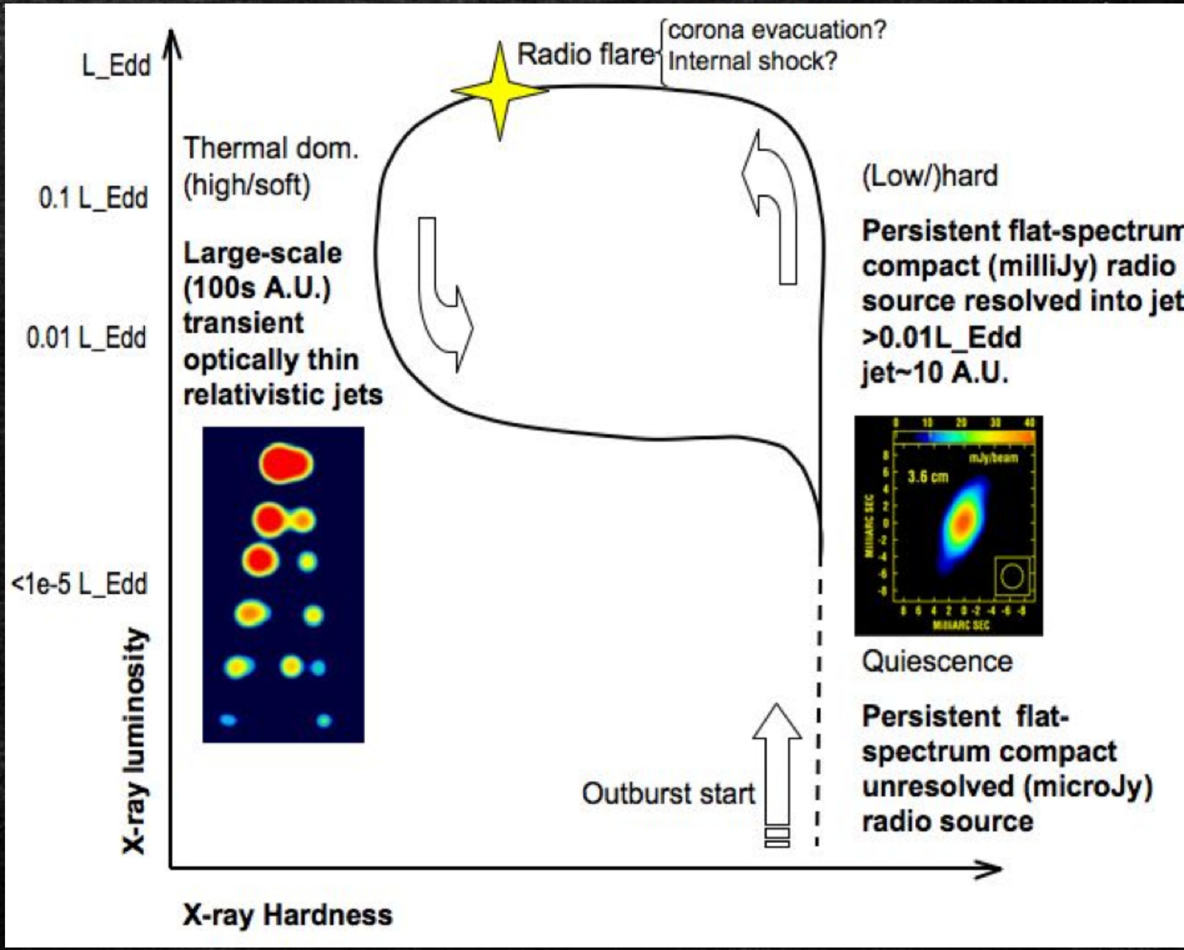
- Ubiquitous **steady jets** in hard state
  - persistent flux density
  - flat radio-IR spectrum, paertially self-absorbed
  - 10s of AU
  - long lived: months-yrs
- Transient, flaring jets during hard-to-soft transitions
  - adiabatically expanding
  - optically thin
  - 100s AU
  - short lived: days-weeks



GRS1915+105
Mirabel et al 1994

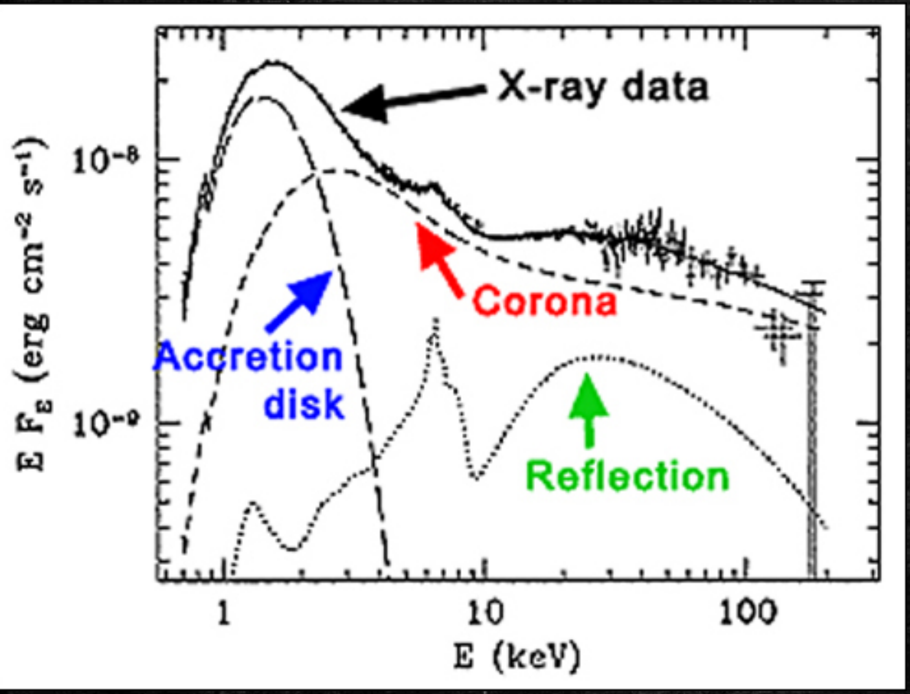
Microquasar outburst phenomenology

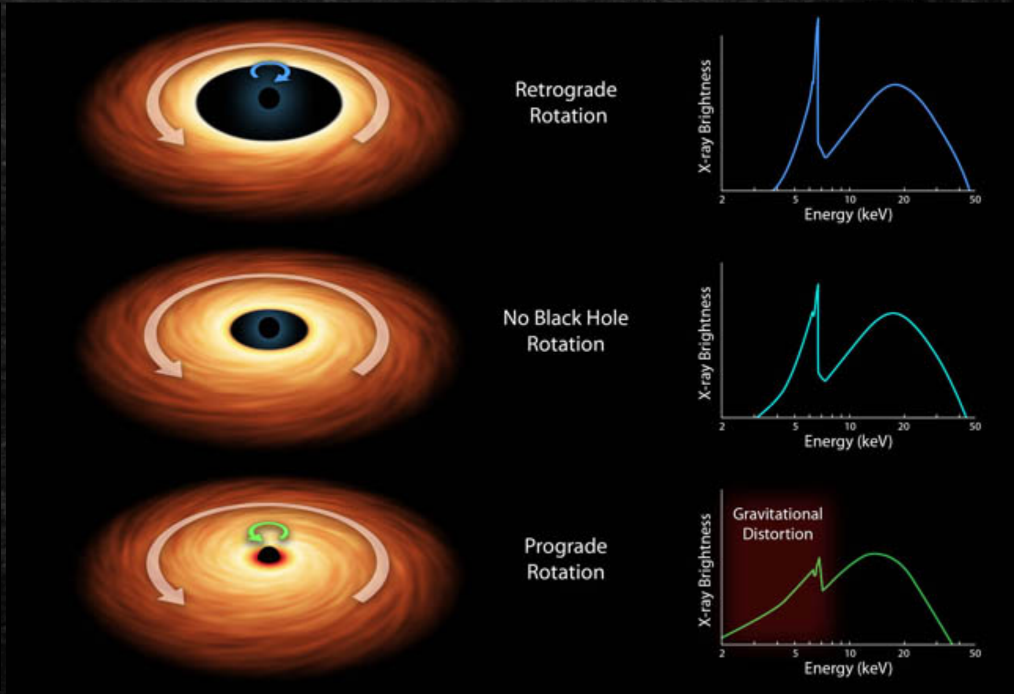
- Hard state: compact self-absorbed steady radio jet
- Soft state: broad equatorial wind (detected from X-ray abs. lines)/ compact radio jet suppressed
- State transitions: ballistic radio ejections



Fender & Gallo 2014

Measuring spin via X-ray spectroscopy





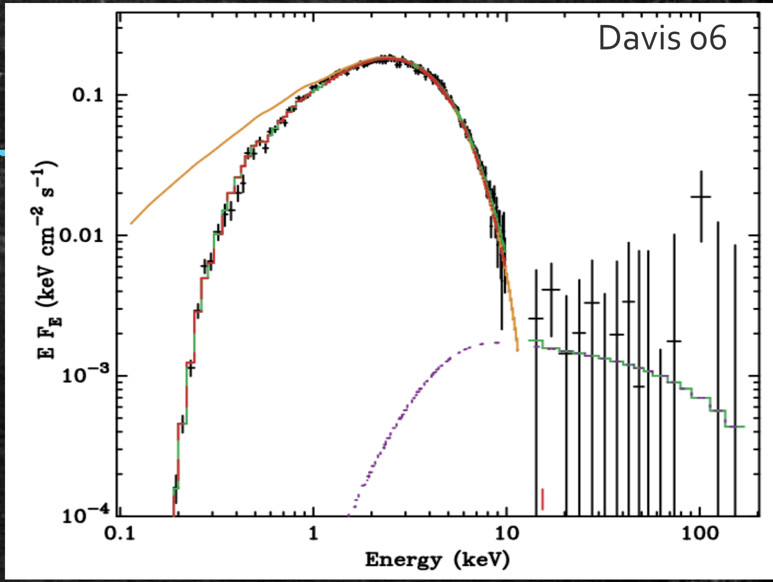
Measuring spin I.

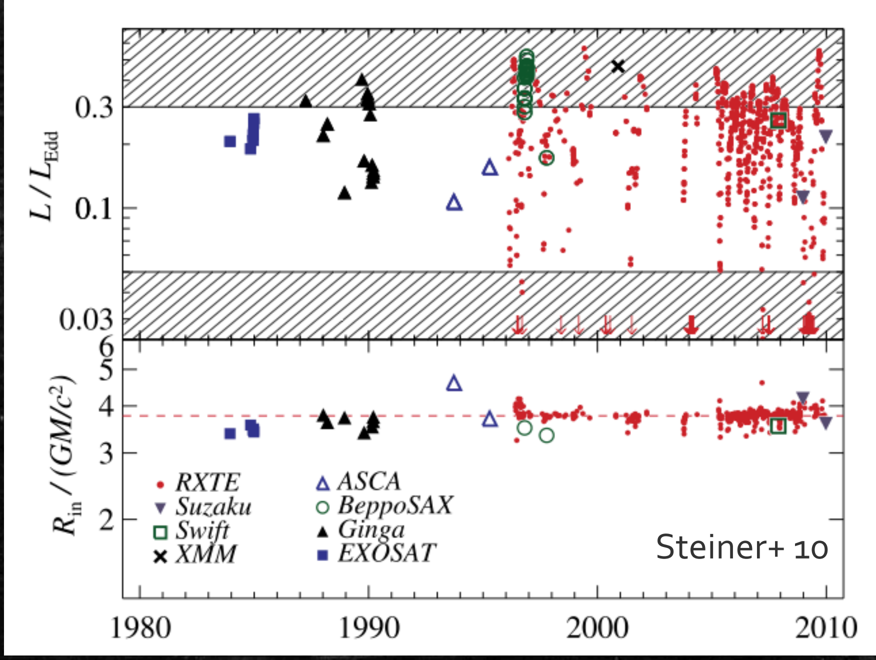
X-ray continuum fitting

Uses the S-B law to measure the emitting area of the disk and hence the ISCO size *for stellar BHs*

- Requires 'pure' thermal-dominant state (<30% Eddington), knowledge of X-ray calibration and hardening correction (Davis+)
- Relies on independent estimates of
  - BH mass
  - Distance
  - Inclination
- 10 stellar BHs with estimated spins, remarkable stability of multiple obs.

McClintock+11; McClintock Narayan & Steiner 14





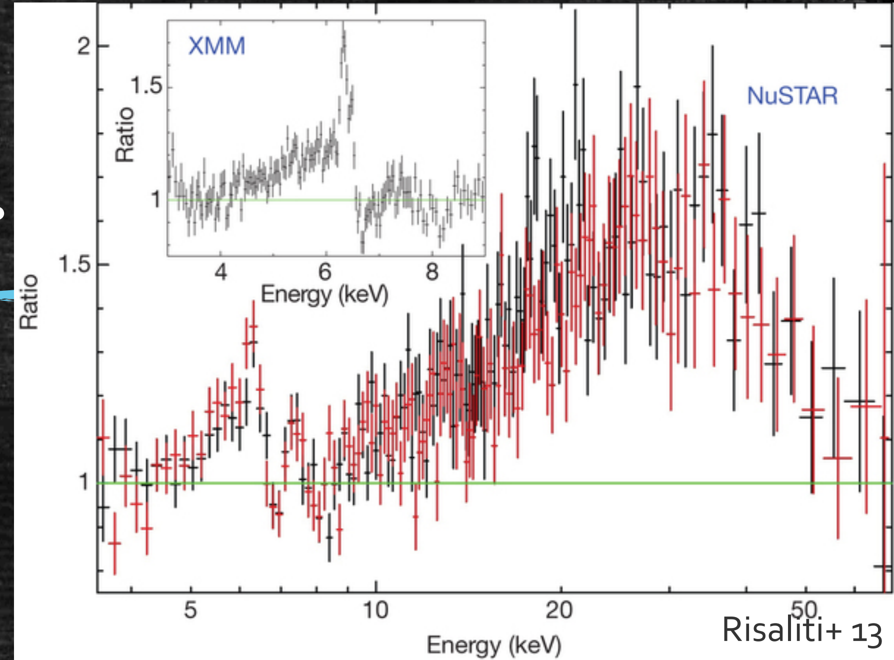
Measuring spin II.

Relativistic reflection

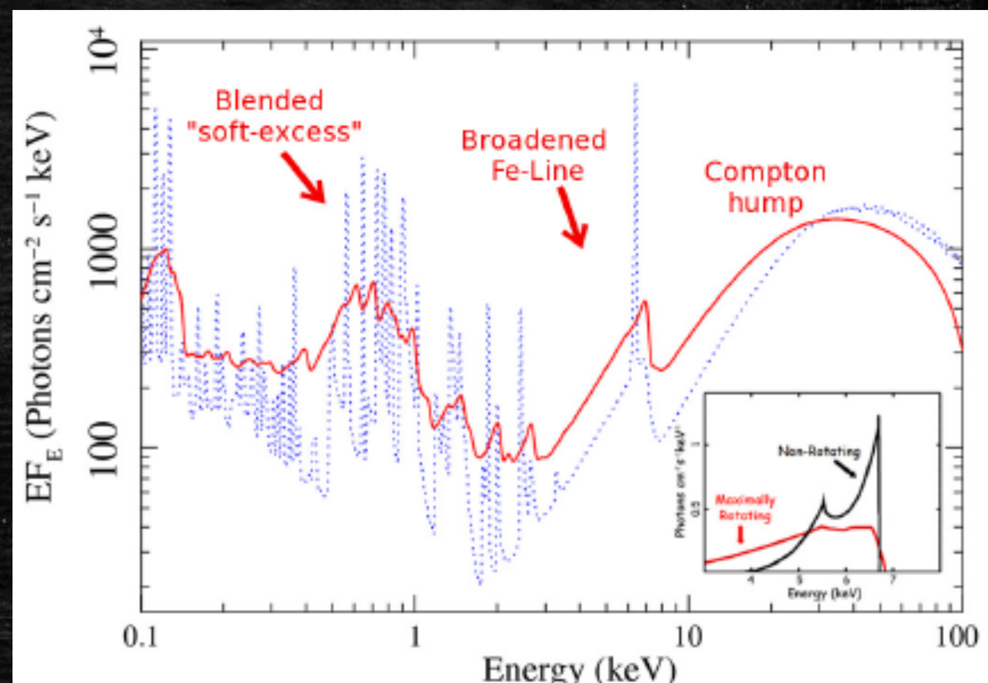
Relies primarily on atomic physics and *relative* measurements (such as widths); uses GM/c^2 units

- Inner disk inclination free to vary
- Sensitive to shape of the disk refl. emissivity, and its cutoff
- Spin-Fe abundance degeneracy
- 16 stellar and 22 super-massive BHs with refl. constraints.
- NuSTAR highlights:
  - Cyg X-1 (Tomsick+ 14)
  - NGC1365 (Risaliti+ 13)

Reynolds 14



Risaliti+ 13



after Ross & Fabian 05; see Reynolds 13, 14

Measuring spin

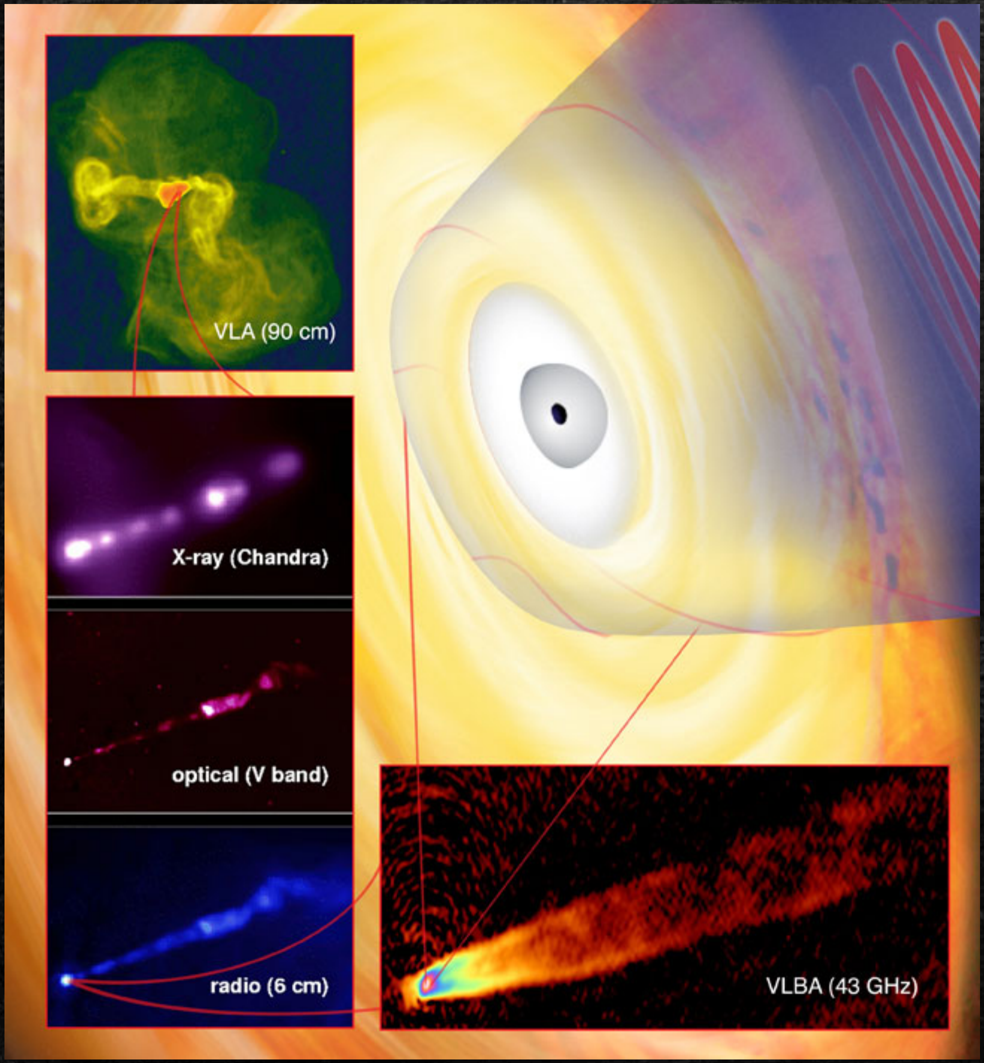
Object	Spin from Reflection	Spin from CF	References
4U 1543–475	0.3 ± 0.1	0.8 ± 0.1	Mi09/Sh06
Cygnus X-1	$> 0.95^*$	> 0.95	Fa12/Go11
GX339–4	0.94 ± 0.02	—	Mi09/–
GRS1915+105	$> 0.97^\dagger$	> 0.95	Bl09/Mc06
GRO J1655–40	$> 0.9^*$	0.7 ± 0.1	Rei09/Sh06
LMC X 1	> 0.55	> 0.87	St12/Go09
MAXI J1836–194	0.88 ± 0.03	—	Rei12/–
SAX J1711.6–3808	$0.6^{+0.2}_{-0.4}$	—	Mi09/–
Swift J1753.5–0127	$0.76^{+0.11}_{-0.15}$	—	Rei09/–
XTE J1550–564	$0.33 - 0.77^\ddagger$	$0.34^{+0.37}_{-0.45}$	Mi09/St11
XTE J1650–500	0.79 ± 0.01	—	Mi09/–
XTE J1652–453	0.45 ± 0.02	—	Hi11/–
XTE J1752–223	0.52 ± 0.11	—	Rei11/–
XTE J1908+094	0.75 ± 0.09	—	Mi09/–

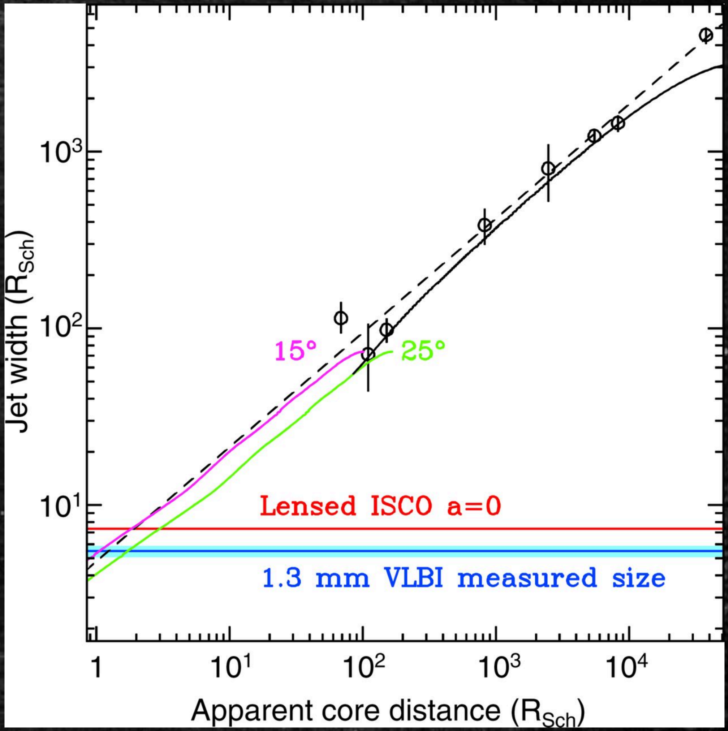
C. Miller & J. Miller 15

Agreement within 2 sigma for stellar BHs with spin measurements from both methods (cf. Fabian)

Others mothods: QPOs ratios and rel. precession model (Motta+); X-ray reverberation (Zoghbi+, Cackett+)

Measuring jet power





Doeleman+ 12

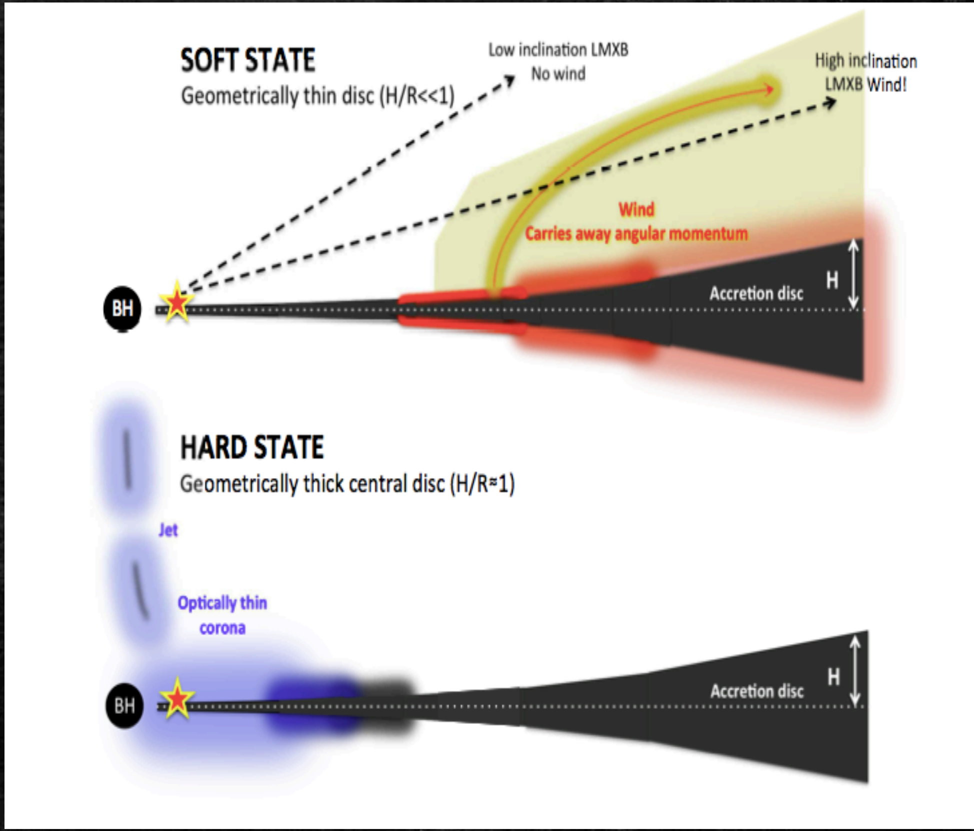
Radio luminosity, radio loudness, work?
Which jet?

Disk/jet phenomenology in stellar BHs

X-ray states (cf McClintock & Remillard 05; see Fender & Gallo 14, Gilfanov & Merloni 14 for recent reviews)

- Hard state: RIAF, steady radio jet on, reflection weak
- Soft state: thin disk, steady radio jet off, reflection-dominated

- "Corona" < few 10s R_g (Reis & Miller 13, Jiménez-Vicente+14)
- Possible inner disk re-condensation in luminous hard states (Reis+10, Meyer-Hofmeister & Meyer 12,14)

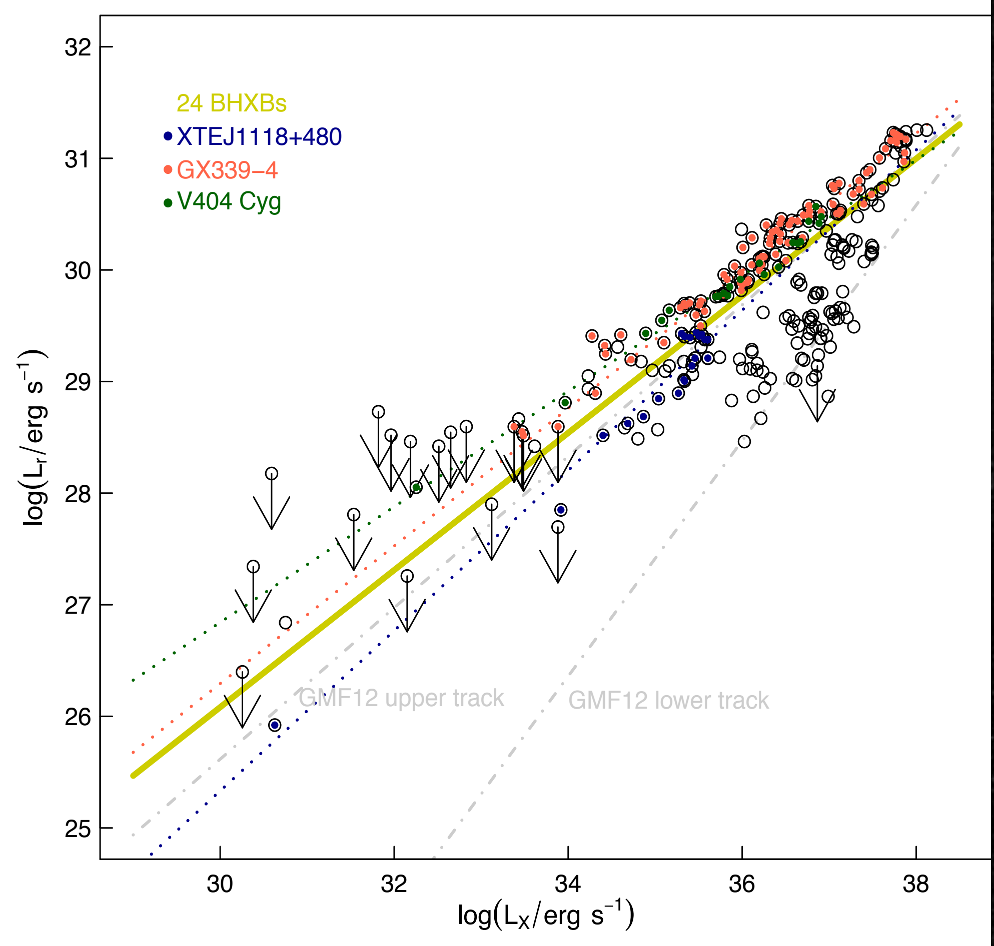


Ponti+ 12

see also: Miller+ 12,14; King+ 12,13a,b,14; Neilsen 13, Neilsen+ 12a,b

Jet power: caveats

- Steady jet luminosity
  - Synchrotron luminosity is at most few % of the total jet power – radio lum. varies over >7 decades for same BH
  - Transient jet luminosity
  - Peak radio flare luminosity as a proxy for P_{jet} (relies on implicit assumption that the flare duration is constant among different outbursts/ sources)
- Radio luminosity-based power: factor 10 uncertainty *at best*



Gallo+ 14
see also Jonker+10, Miller-Jones+11, Coriat+ 11, Ratti+ 12, Gallo+12, Corbel+13

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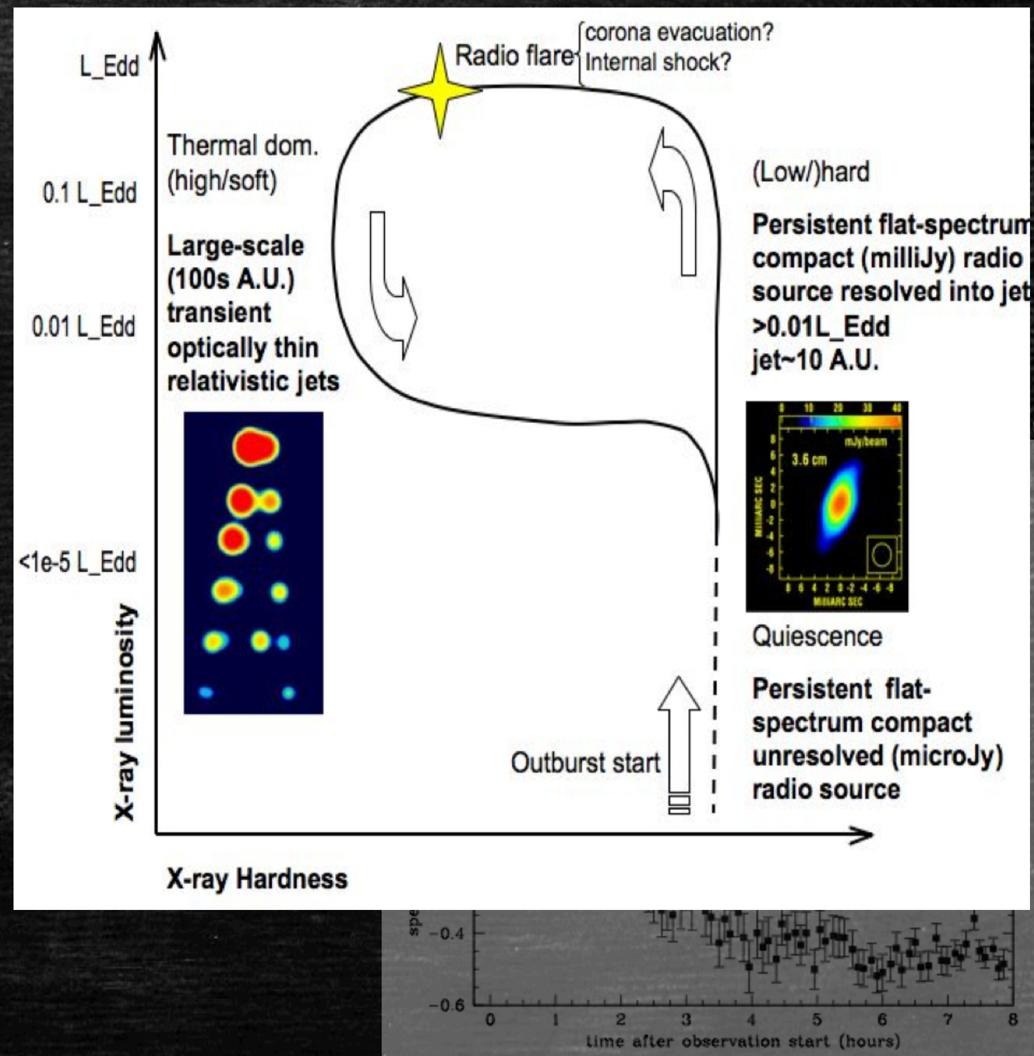

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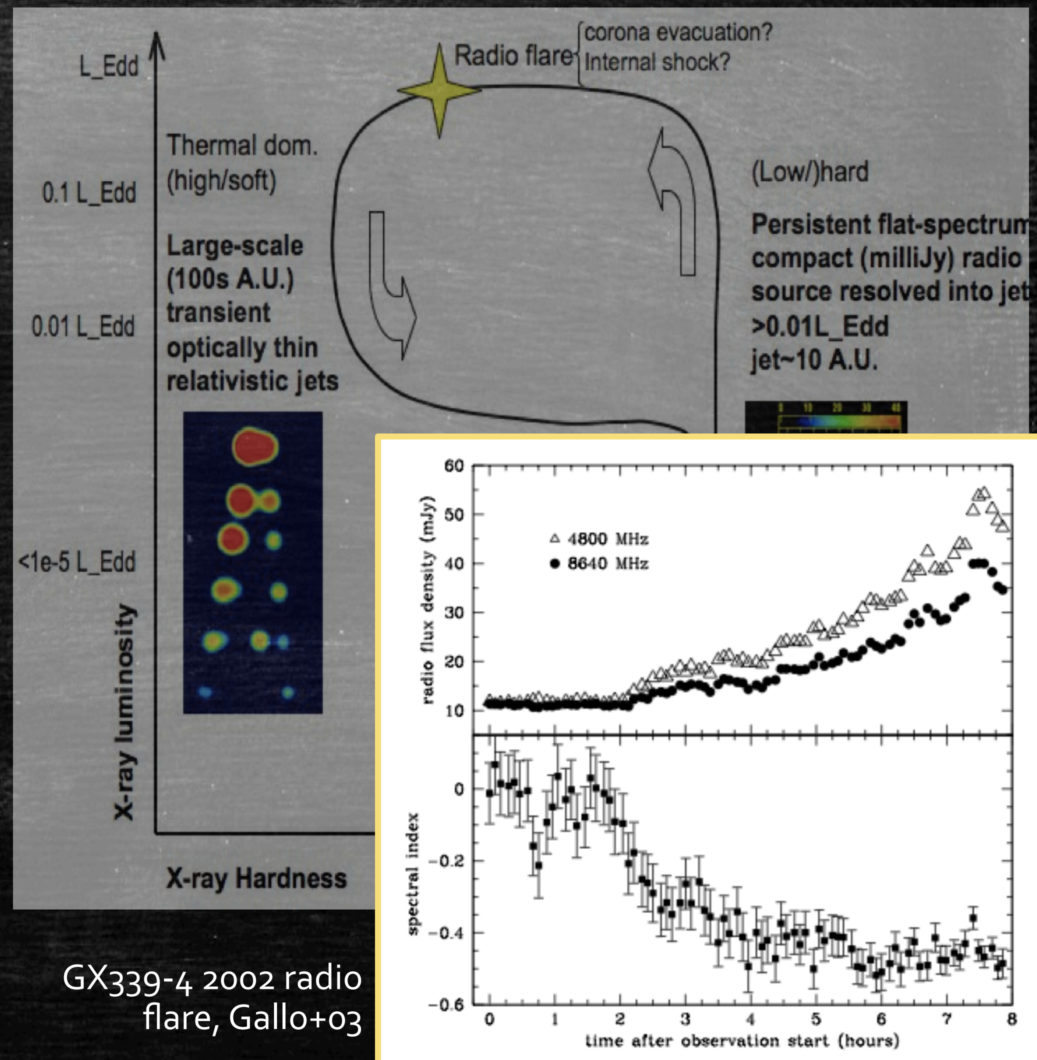


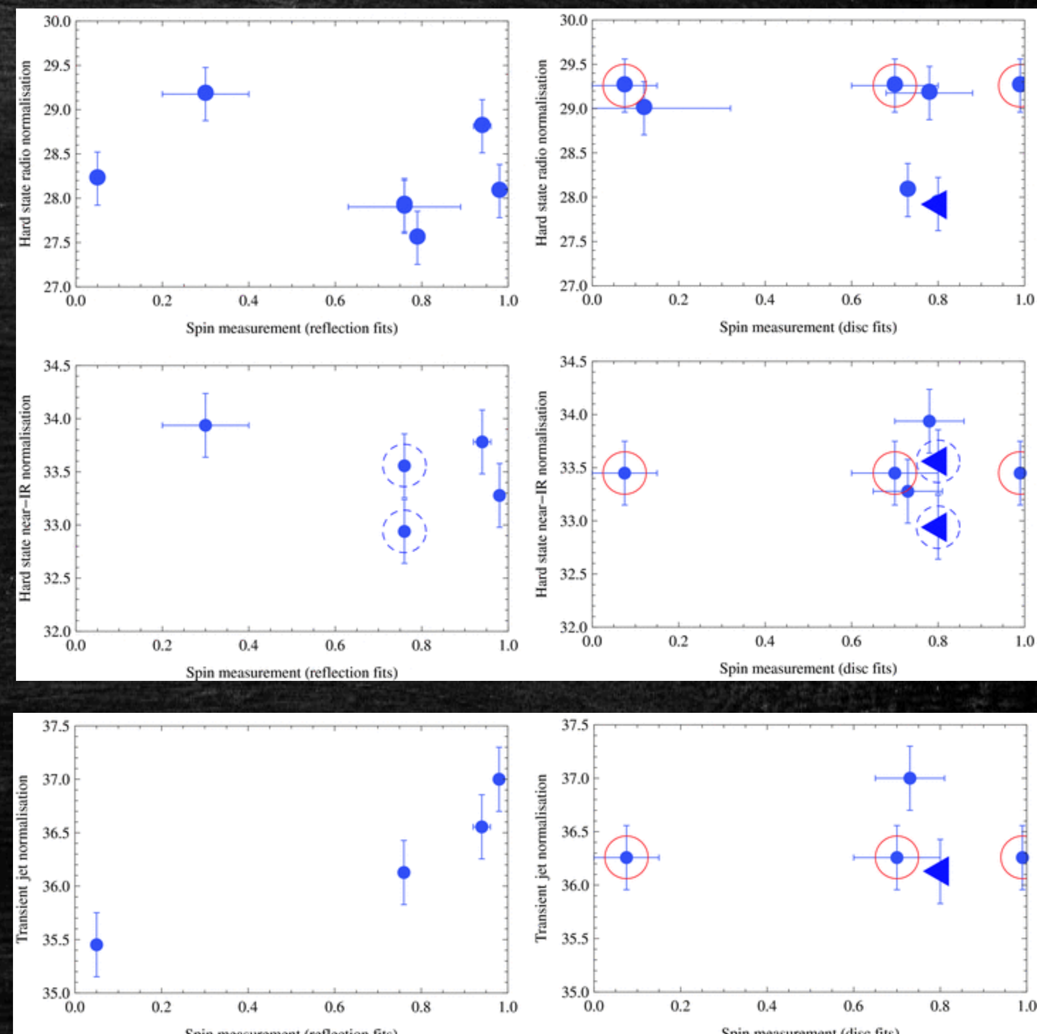
GX339-4 2002 radio flare, Gallo+03

Spin vs. jet power in stellar BHs

First comprehensive investigation fora handful BH X-ray binaries in hard state yields no P_{jet} vs *a* correlation, nor P_{jet} vs jet velocity

- P_{jet} for steady jet from the normalization of the radio(/IR):X-ray correlation in X-hard state
- P_{jet} for transient jets from min. energy / rise time
- Spin from either CF or Reflection

If measurements are to be trusted, then no evidence for BZ-powering of steady jets (notice: these are powered by *thick* disks!)



Fender Gallo Russell 2010

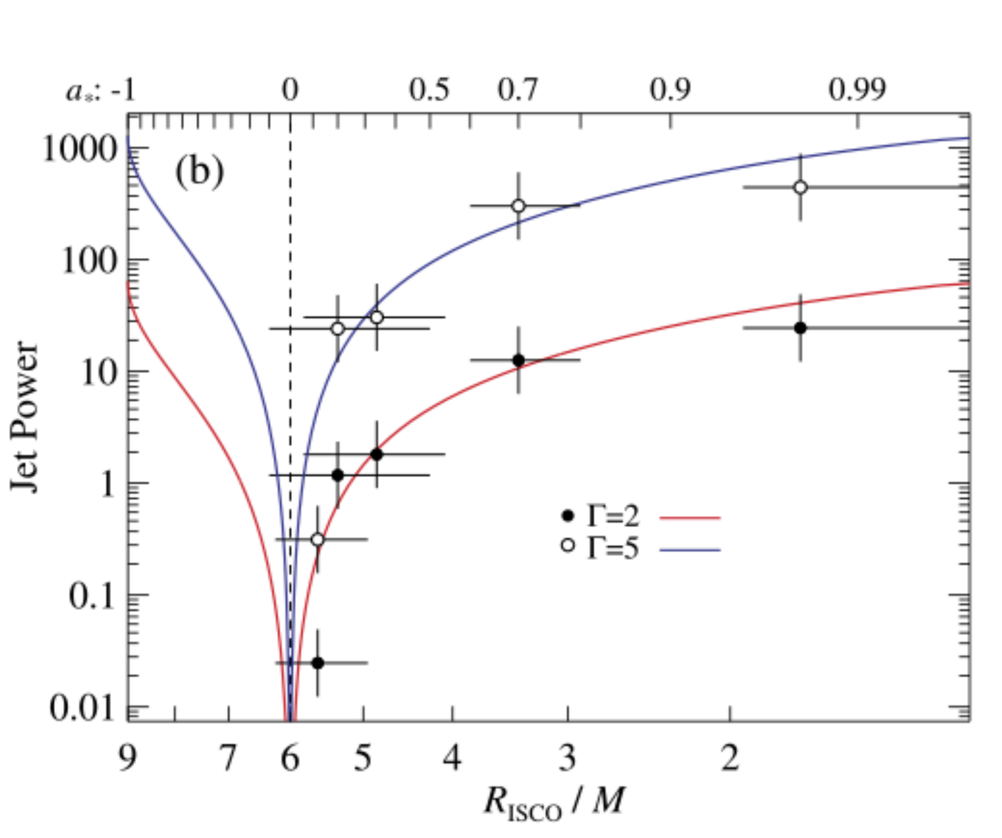
Spin vs. jet power in stellar BHs

Positive correlation (consistent with BZ-scaling) claimed for transient (a.k.a. ballistic) jets

- P_{jet} from peak radio luminosity of bright radio flare associated with hard to soft state transition

$$P_{\rm jet} = \left(\frac{\nu}{5\ {\rm GHz}}\right)\left(\frac{S^{\rm tot}_{\nu,0}}{\rm Jy}\right)\left(\frac{D}{\rm kpc}\right)^2\left(\frac{M}{M_\odot}\right)^{-1}$$

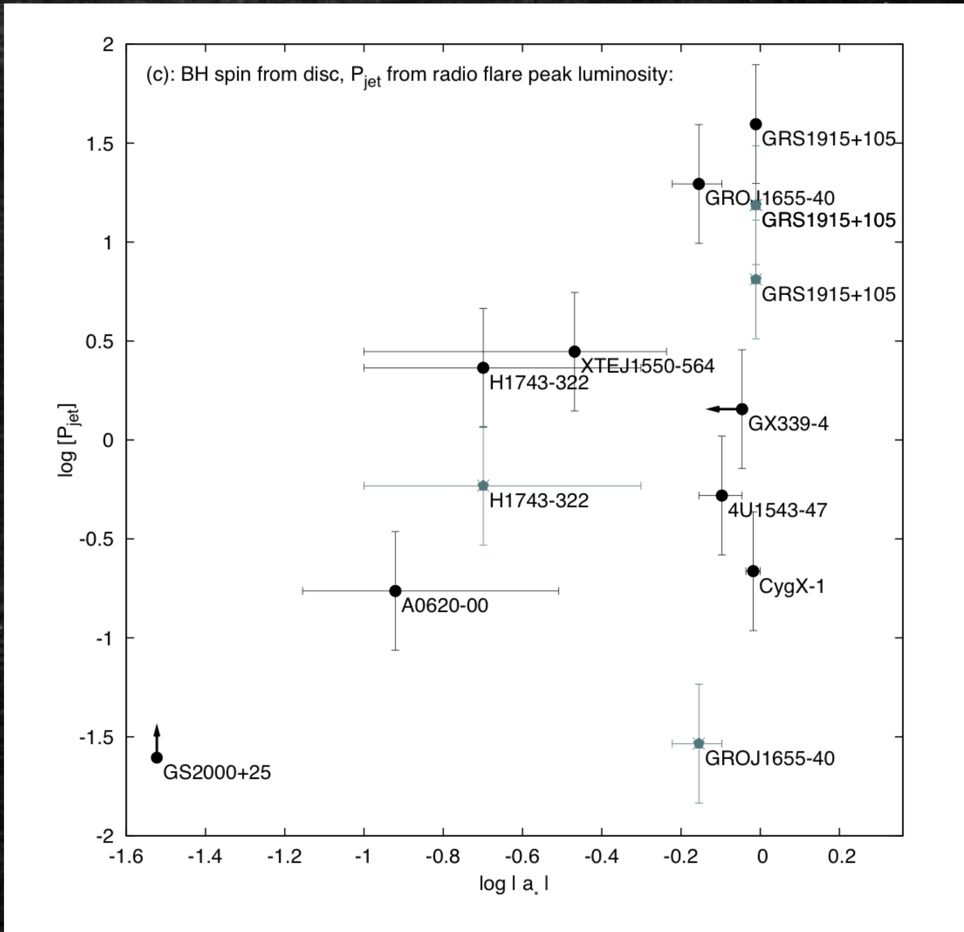
- Spin from thermal cont. fitting
- Low-mass X-ray binaries only



Narayan & McClintock 12
Steiner, Narayan & McClintock 13

Spin vs. jet power in stellar BHs

- Result sensitive to exclusion of the high mass X-ray binary Cyg X-1; Treatment of GROJ1665-40 and 4U1543-47
- Large scatter observed in peak radio lum. over different outbursts (though *maximum possible* lum. is adopted as proxy)
- Increased frequency of radio monitoring (e.g. with MeerKAT) needed



See McClintock, Narayan & Steiner 14 for a recent review of the controversy

Are BH jets spin powered?

- Strong *theoretical* support for P-B-Z process at work, at least in the most powerful jets.
- Is there strong observational evidence? NOT quite.
- If the jet-powering mechanism is scale-invariant, then *stellar-mass black holes remain the best lab* for probing a correlation between jet power and spin parameter.
  - Several (know) uncertainties in measuring spin
  - WILD uncertainties in "measuring" P_{jet}
- Radio luminosity of STEADY jet associated with THICK disks is at best a poor indicator of jet power. Claimed correlation for transient jets is at best an upper envelope. Results from cavities inconclusive.