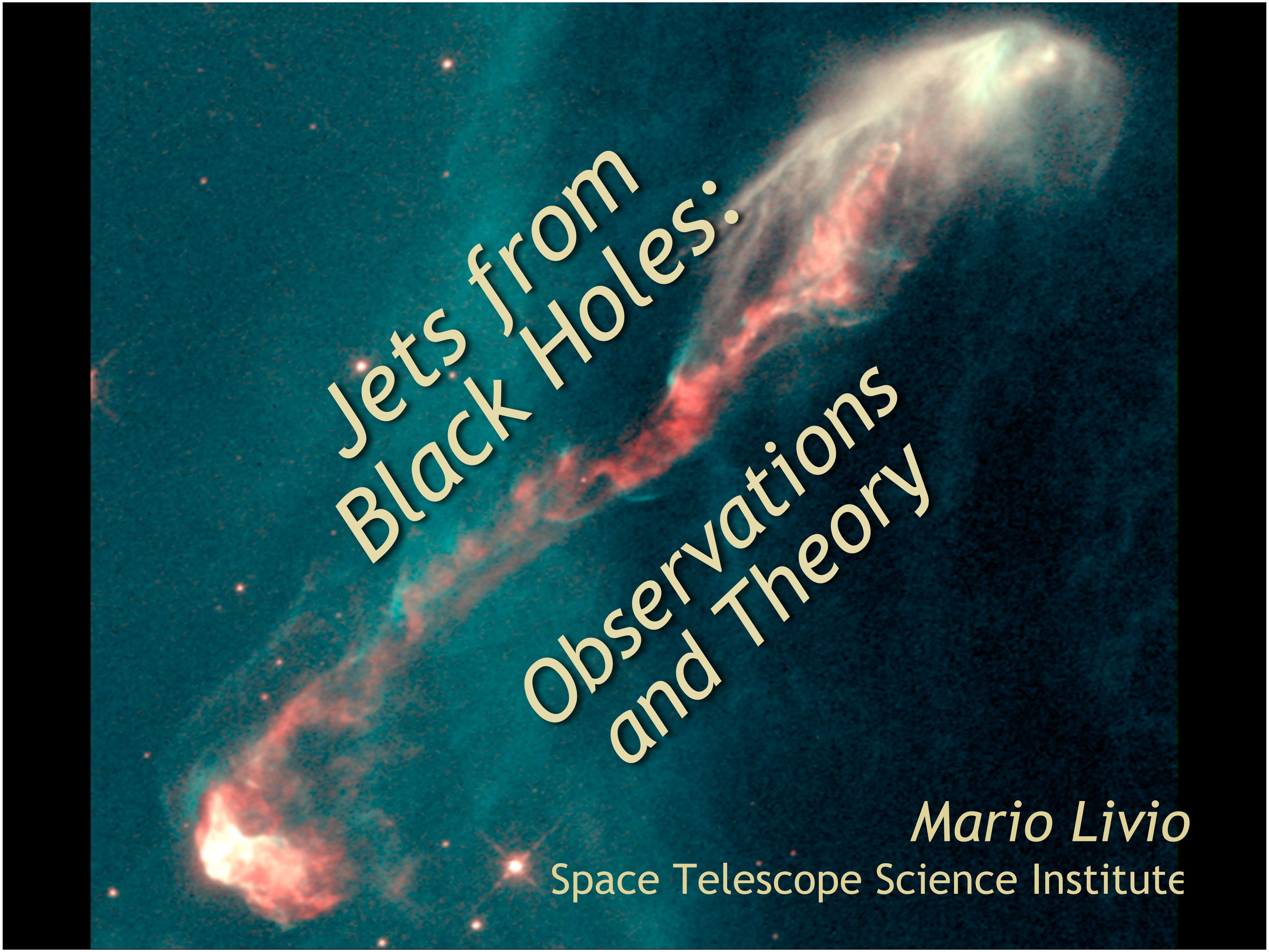
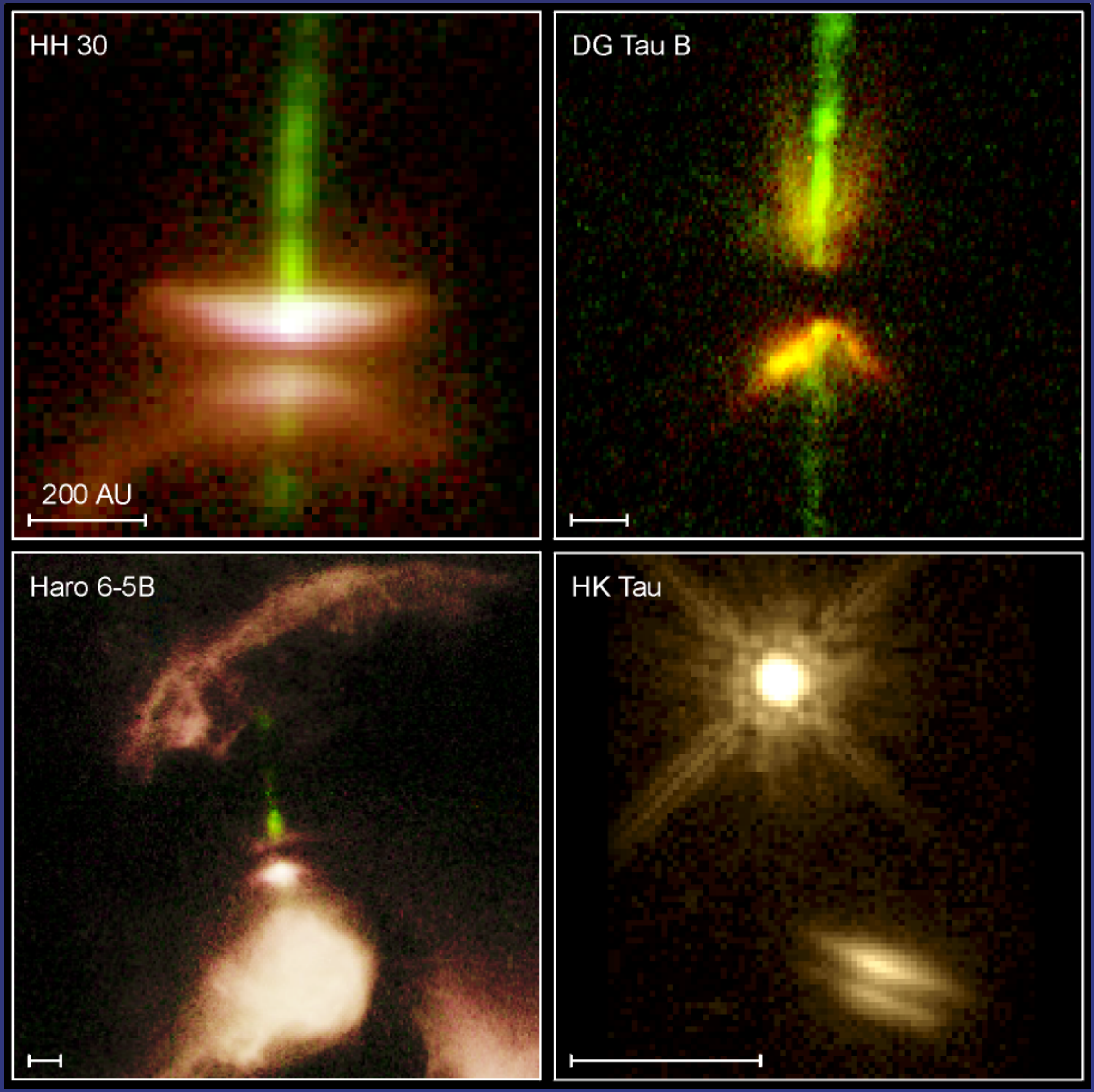

Jets from Black Holes:
Observations and Theory
Mario Livio
Space Telescope Science Institute

Which Systems Have Highly Collimated Jets?

Stellar *Object*	*Physical System*
Young Stellar Objects	Accreting Star
HMXBs	Accreting NS or BH
X-ray Transients	Accreting BH
LMXBs	Accreting NS
Supersoft X-ray Sources	Accreting WD
Symbiotic stars	Accreting WD
Pulsars	Rotating NS
Planetary Nebulae (?)	Accreting Nucleus or Interacting Winds

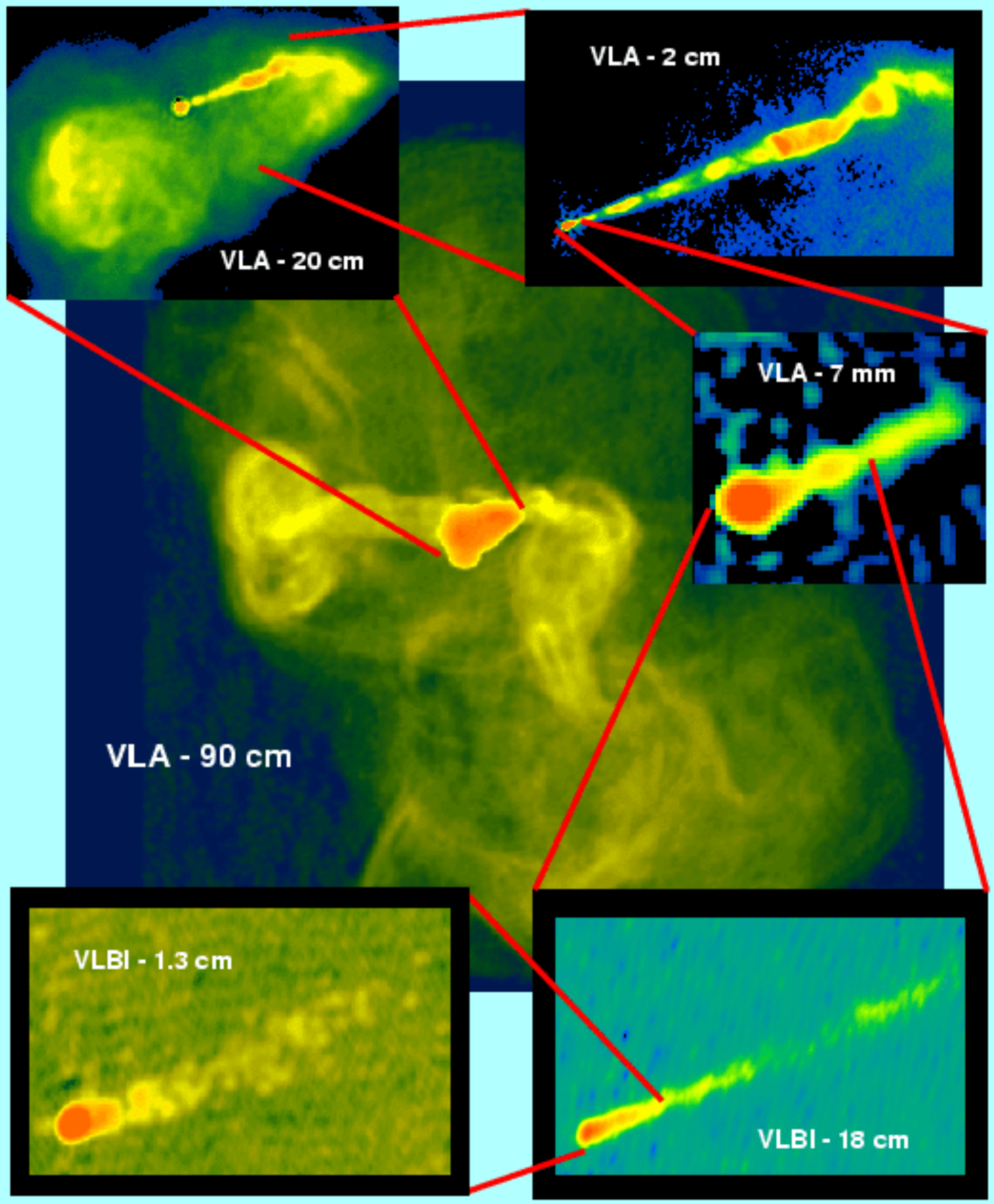
Extragalactic *Object*	*Physical System*
AGN	Accreting Supermassive BH
GRBs	Accreting BH

Jets in Young Stellar Objects

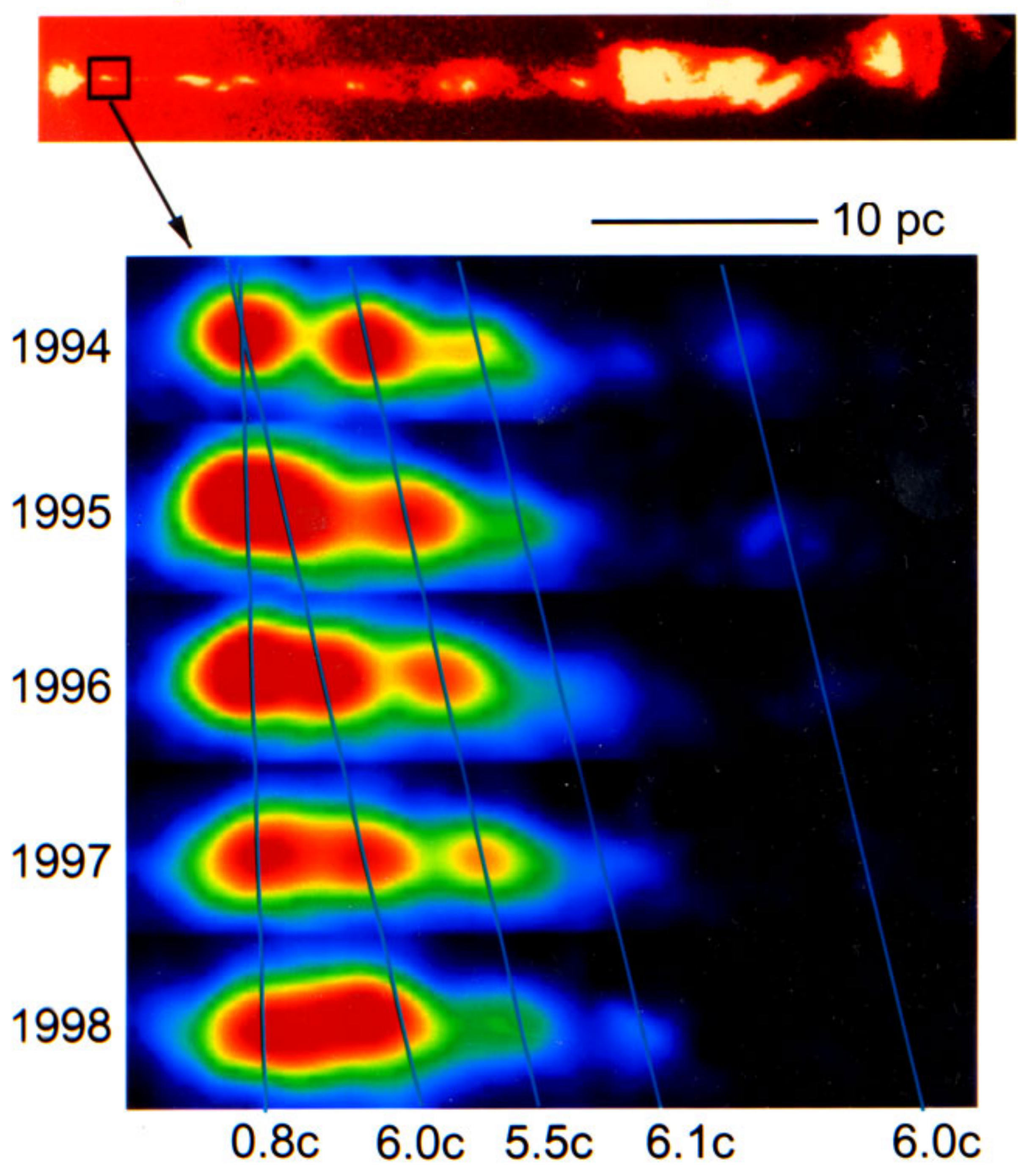


HH 901 Carina Nebula

Jet in M87: From 60 kpc to 0.06 pc



Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

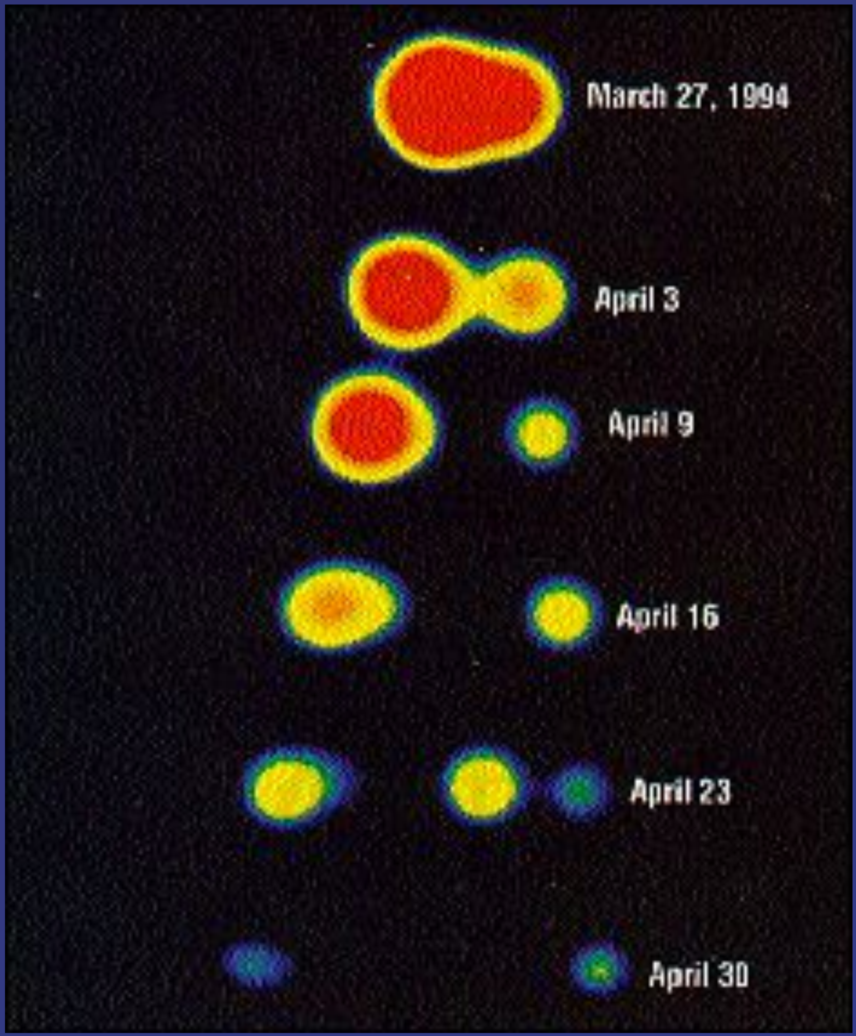


Superluminal Motion in M87 HST-1

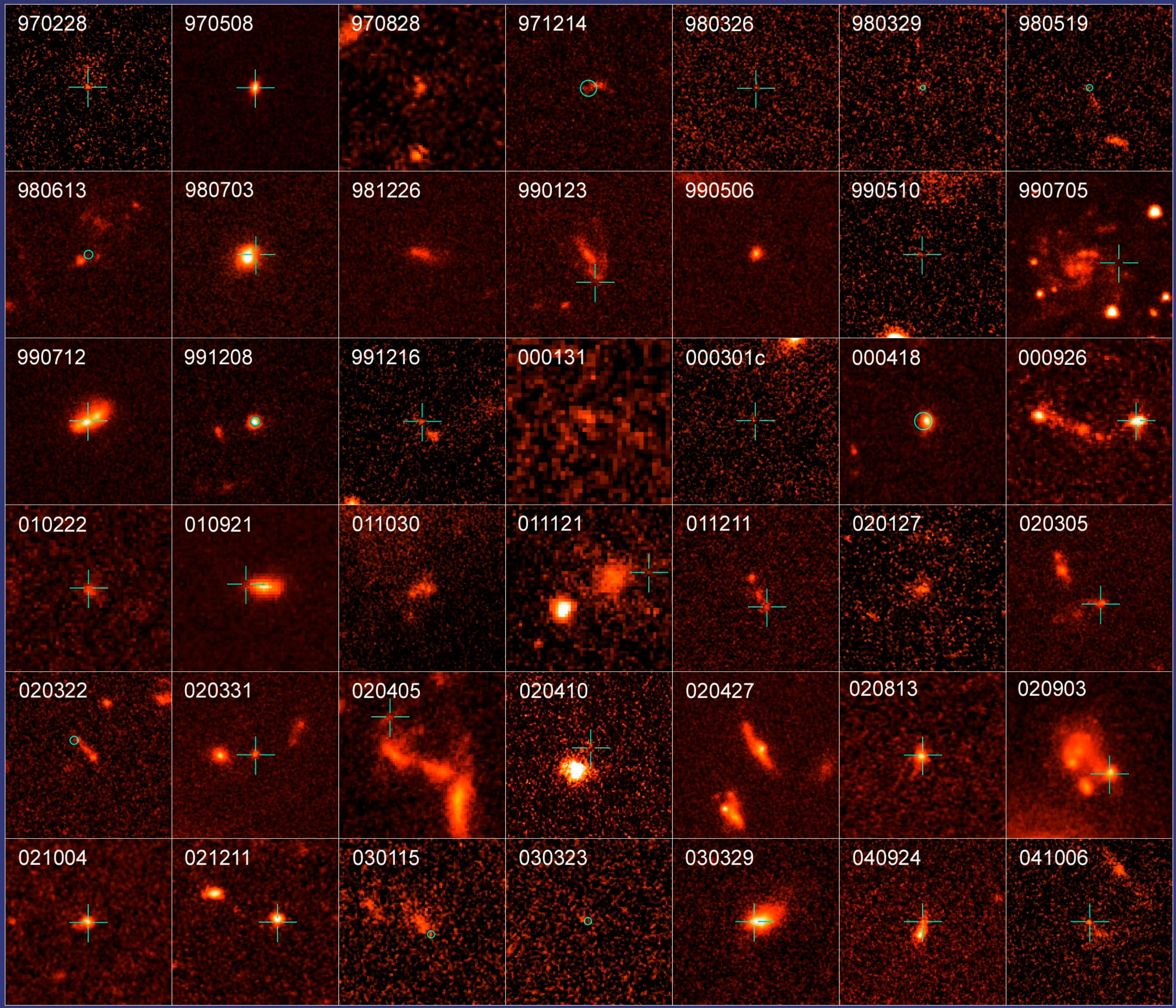
Do FR I radio galaxies have relativistic jets like BL Lacs?

“Superluminal” sources

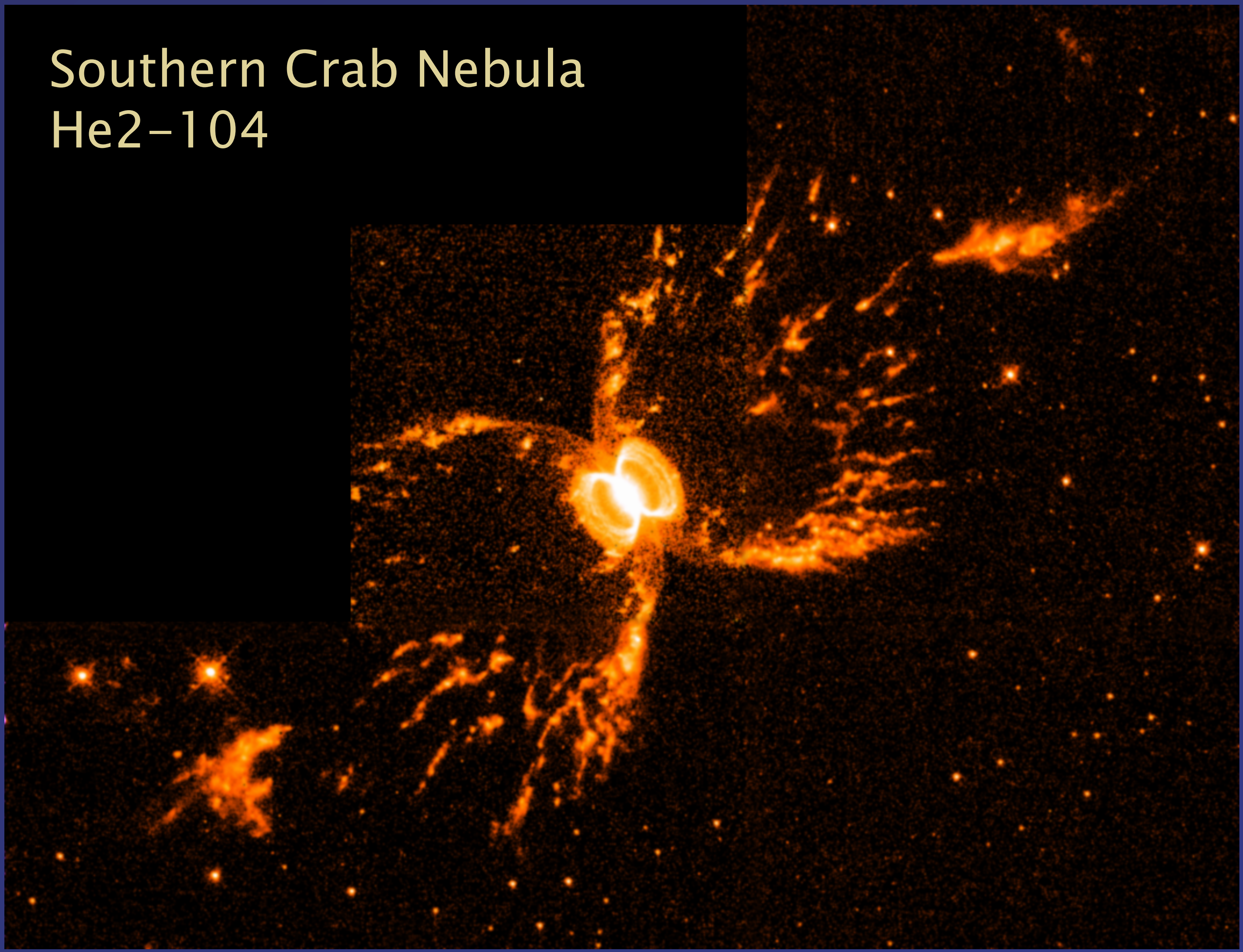
- GRS 1915+105
  V ~ 0.9c
- Some extragalactic jets show
  V > 0.995c



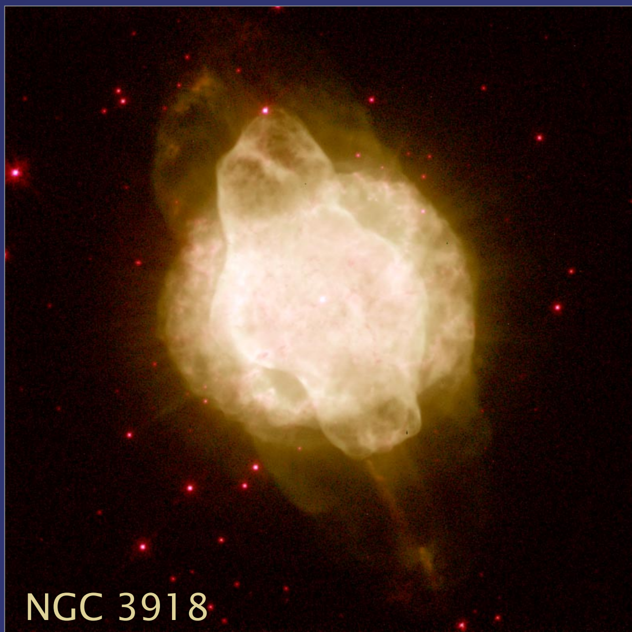
Gamma Ray Burst Hosts



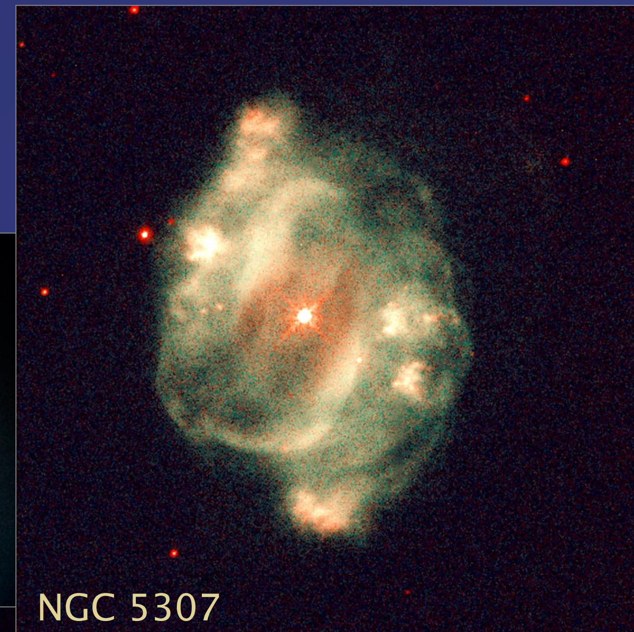
Symbiotic Systems

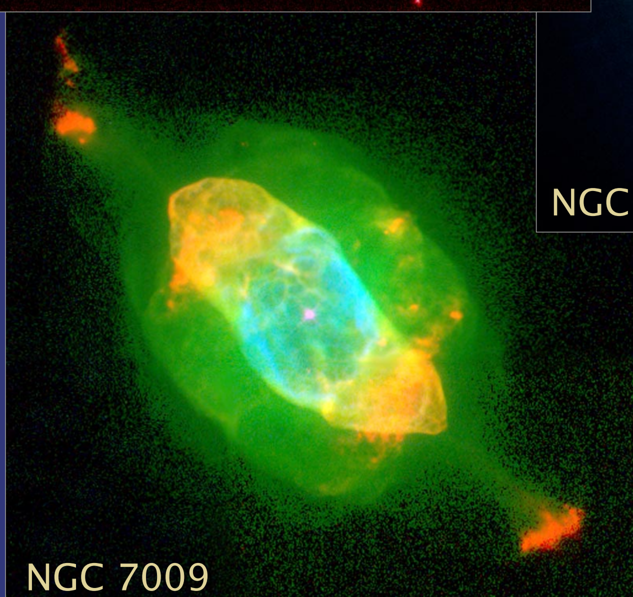


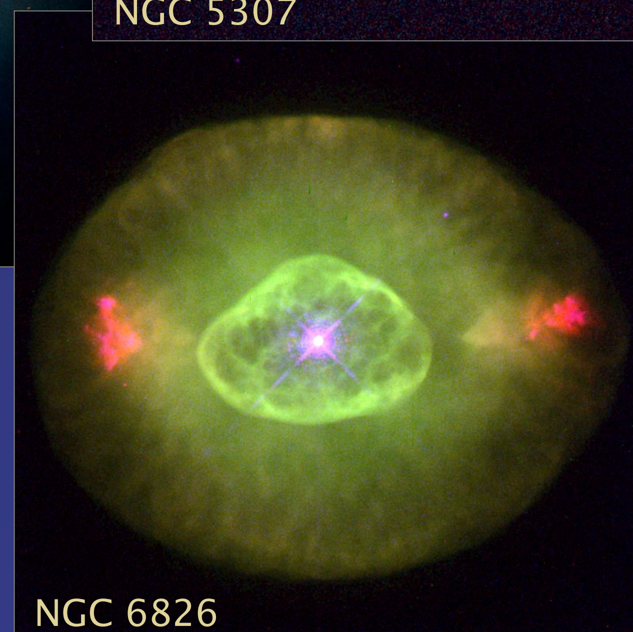
Jets in Planetary Nebulae?


NGC 3918

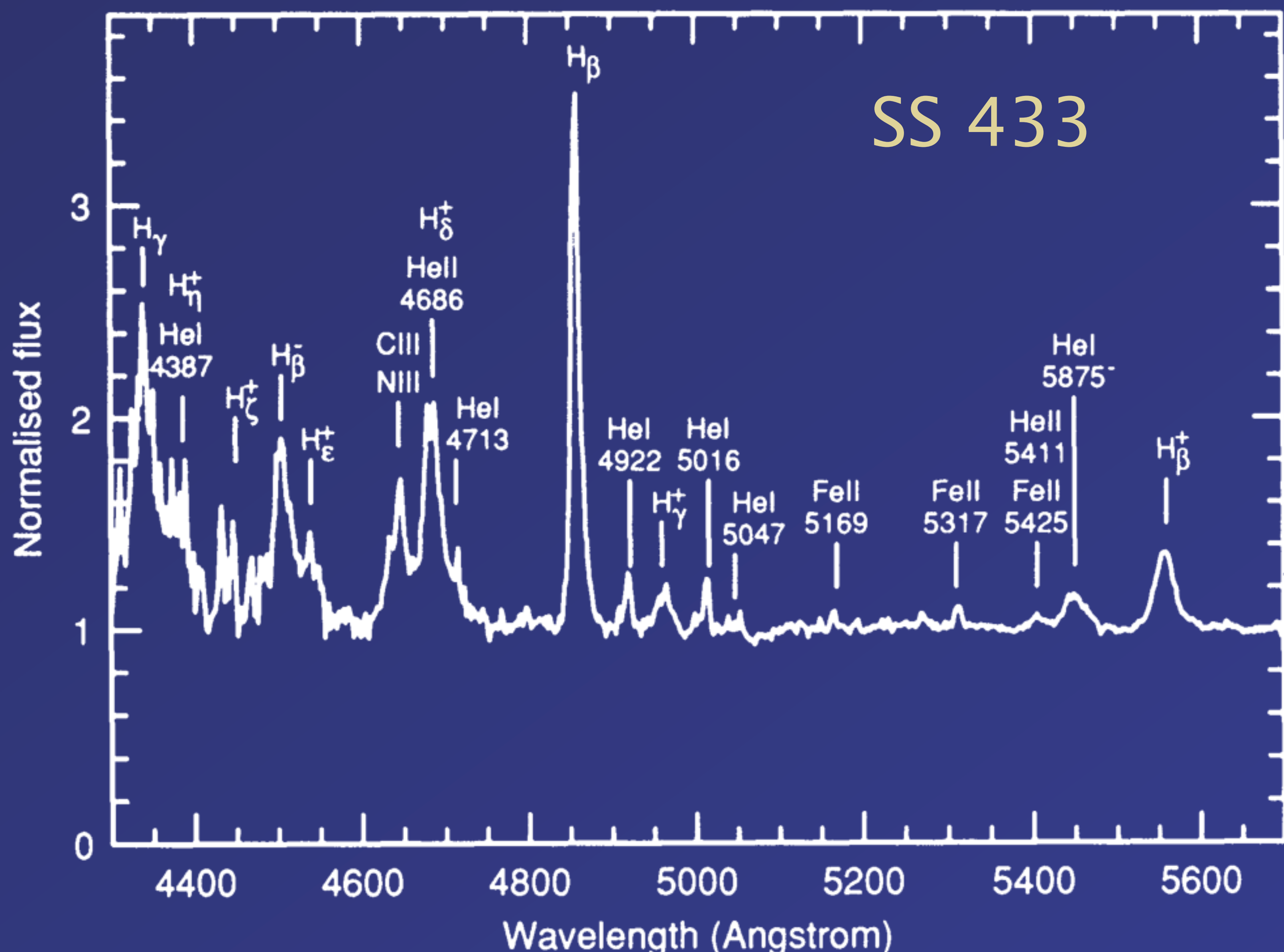

NGC 6543


NGC 5307

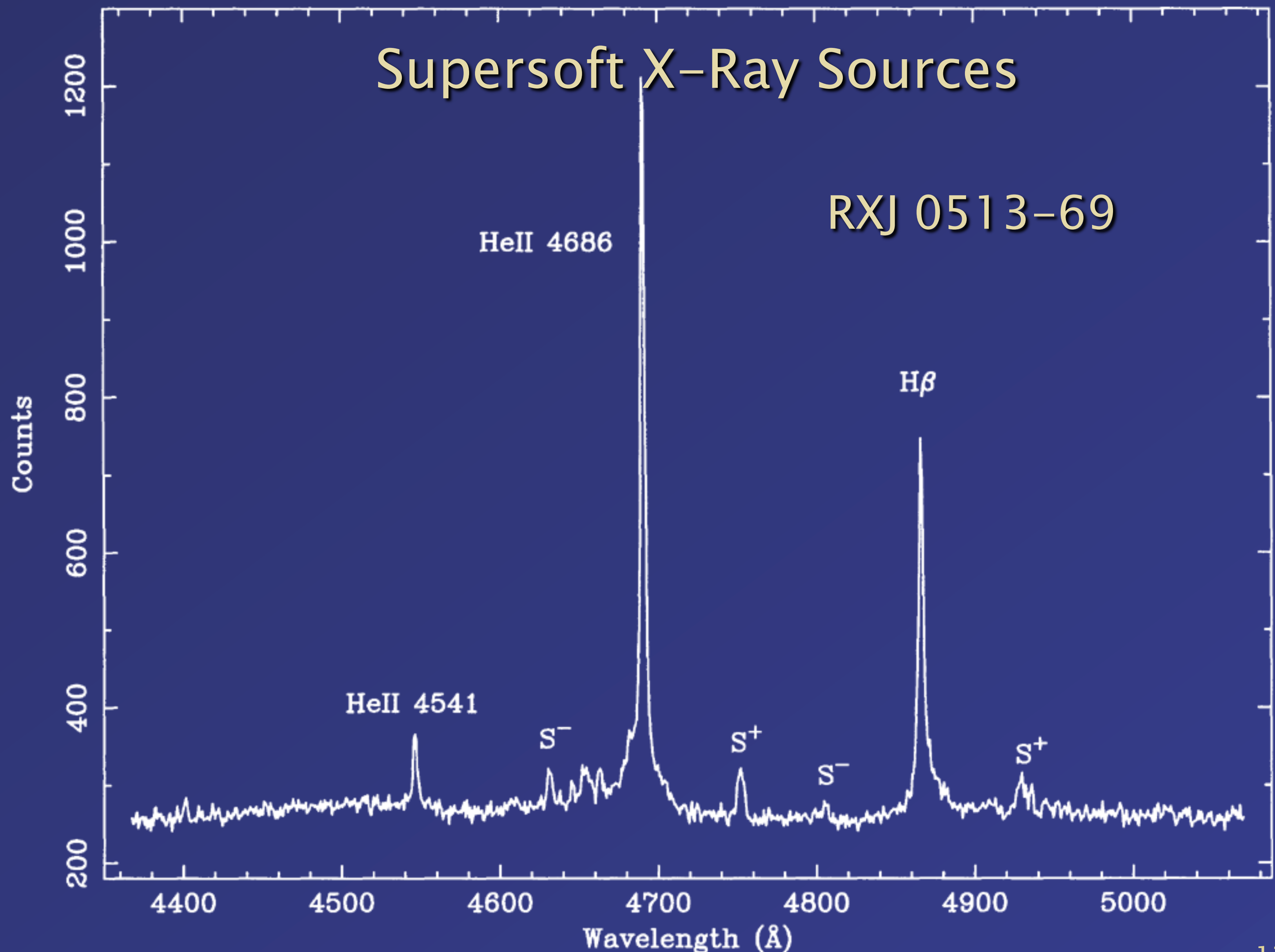

NGC 7009


NGC 6826

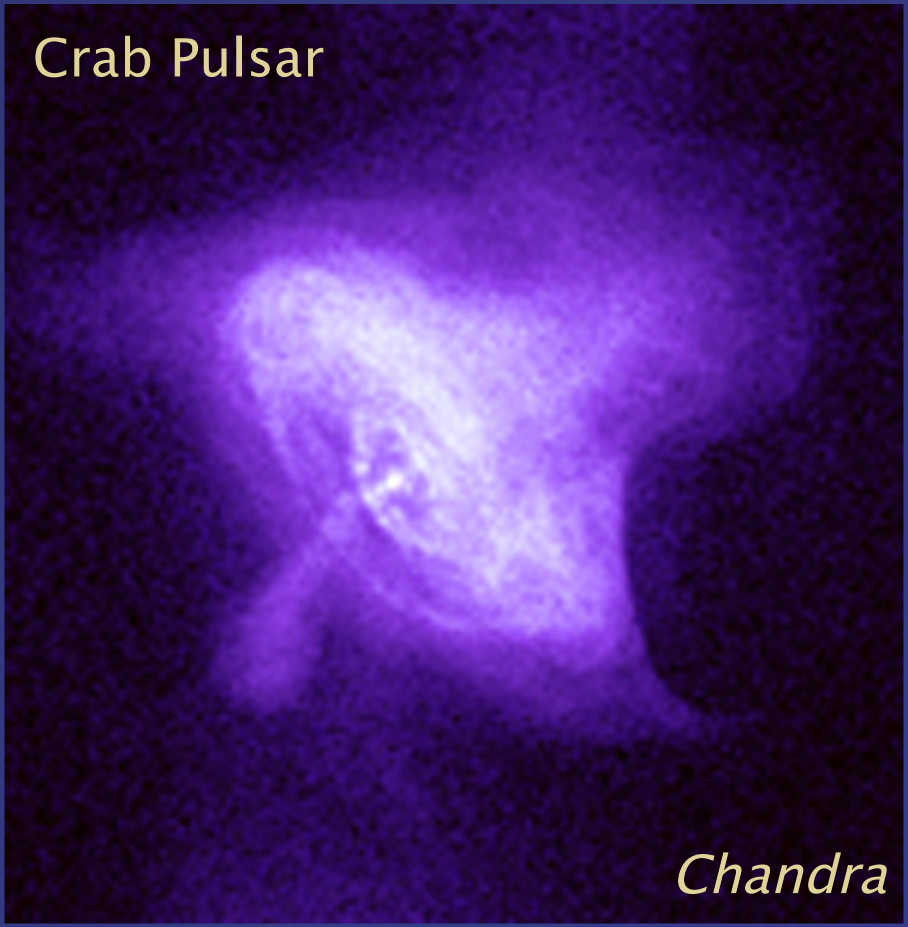
High mass x-ray binaries



Supersoft X-Ray Sources



Pulsar Jets

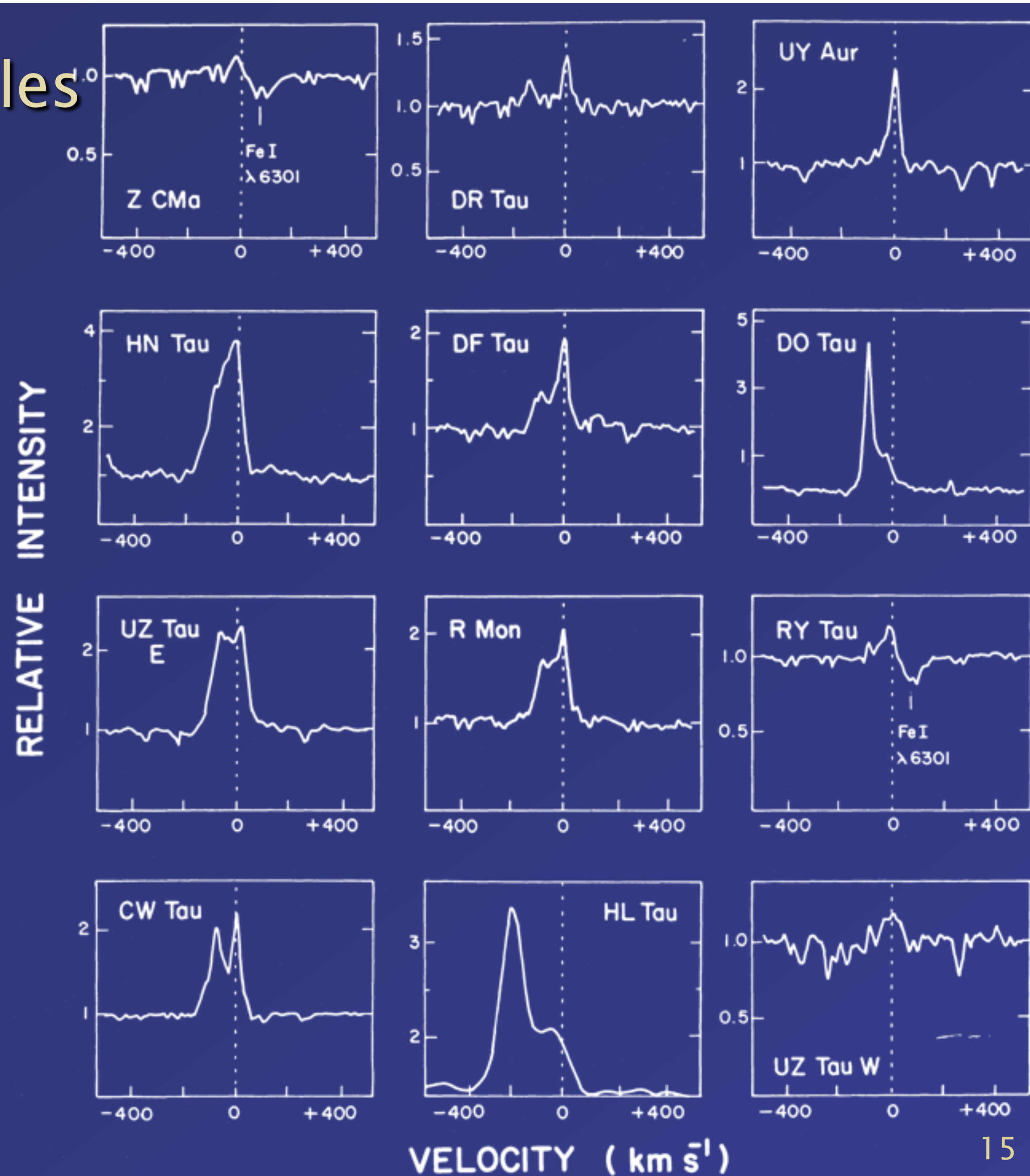


Do jet-producing systems have accretion disks?

YSOs	Yes
SSS	Yes
H/LMXBs	Yes
BHXTs	Yes
GRBs	We don’t know
AGN	Yes
PNe	Not clear

What are the *absolutely necessary* ingredients for the mechanism of jet acceleration and collimation?

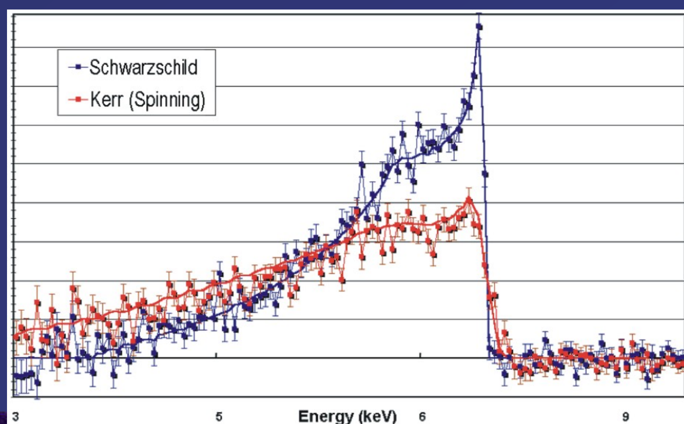
[O I] λ6300 Profiles for T Tauri Stars

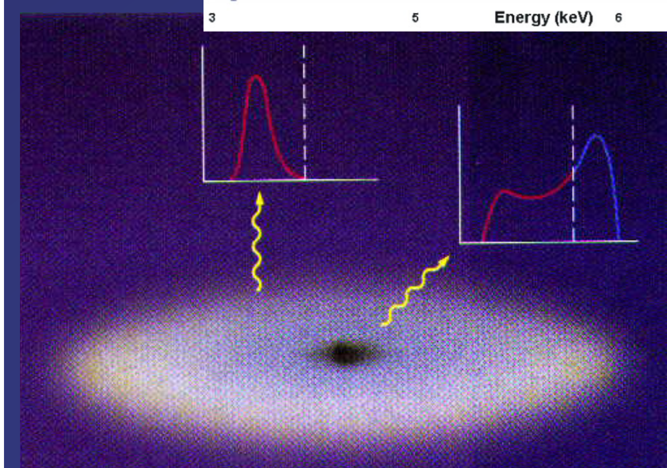


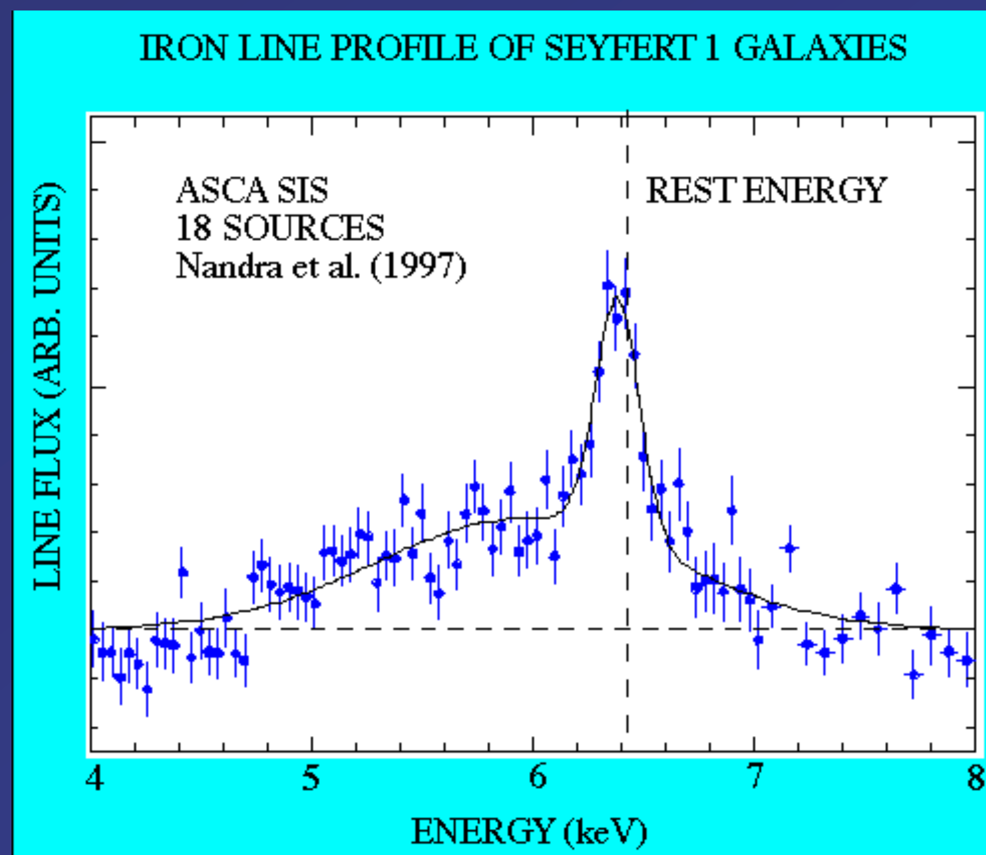
Redshifted component not seen because of disk.

X-Ray Spectroscopy of Accretion Disks in AGNs

- MCG-6-30-15
- Gravitational redshift plus Doppler shift







Do Jets Require an Accretion Disk?

Qualified Yes

"Interacting winds", "ion torus", Pulsars, GRBs, need more work

Do Accretion Disks *Require* Jets or Outflows?

- Are outflows/jets the *main* mechanism for transport/removal of angular momentum?
- Angular momentum carried by wind

$$J_w \simeq \dot{M}_W \Omega r_A^2$$

Do Accretion Disks *Require* Jets or Outflows?

Angular momentum that needs to be removed from disk

$$\dot{J}_{acc} = \tfrac{1}{2}\Omega r^2 \dot{M}_{acc}$$

$$\Downarrow$$

$$\frac{\dot{M}_W}{\dot{M}_{acc}} = \frac{1}{2}\left(\frac{r}{r_A}\right)^2$$

$$\Downarrow$$

For $r_A \sim 10r$, only 1% of the accreted mass needs to be lost in wind.

Behavior of Disk Radius During Dwarf Nova Outburst

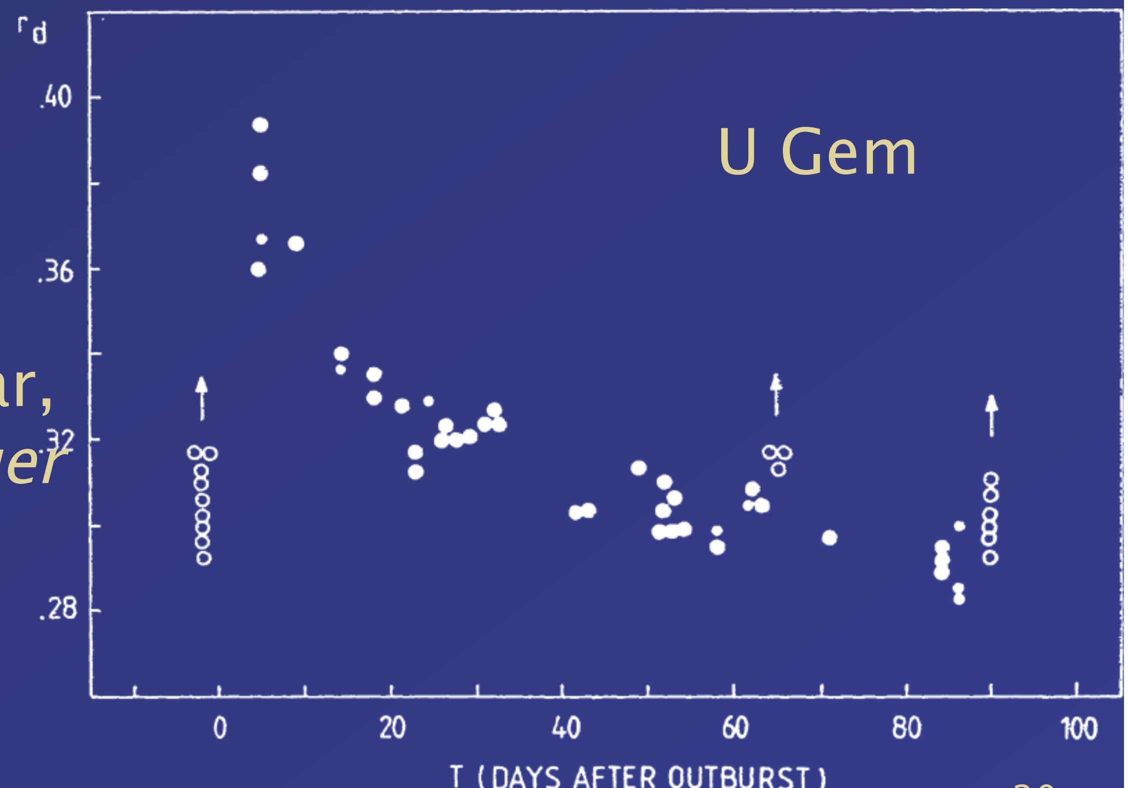
- At outburst, matter diffuses inward. Angular momentum of that matter is transferred to outer parts of the disk.

⇓

Radius expands

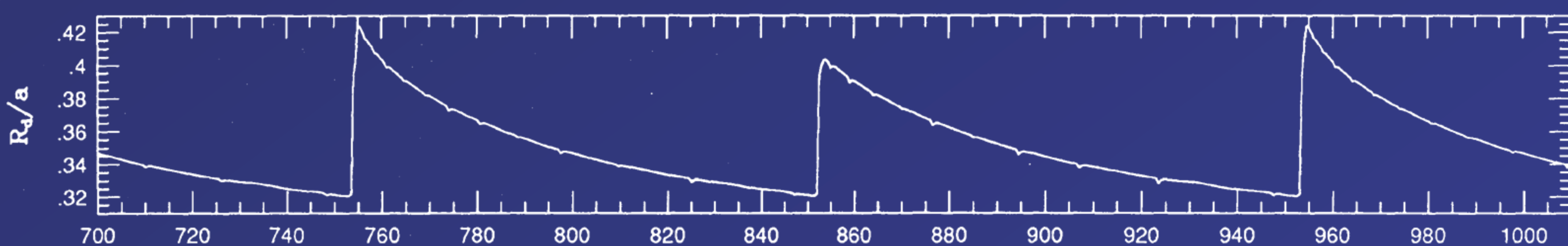
Observationally:

- Disks in U Gem, OY Car, HT Cas and Z Cha *larger* in outburst.



Behavior of Disk Radius During Dwarf Nova Outburst

Theory: disk instability



Do accretion disks *require* jets or outflows for angular momentum removal?

Probably not.

- More observations of rotation in jets and bipolar outflows are needed (velocity gradients).

Other Clues on Jets

Jet Origin

Object	*Example*	V_{jet}/V_{escape}
YSOs	HH30, 34 $V_j \sim 100\text{–}350$ km/s $V_{esc} \sim 500$ km/s	~1
AGN	M87; radio sources $\gamma >\sim 3$; $\gamma <\sim 10$	~1
GRBs	$\gamma \sim 100$	~1
XRBs	SS 433; Cyg X-3 $V_j \sim 0.6c$	~1
XRTs	GRO 1655-40 GRS 1915+105 $V_j >\sim 0.9c$	~1
Pne	Fliers, Ansae $V \sim 200$ km/s	~1
SSS	0513-69 $V_j \sim 3800$ km/s	~1

Other Clues on Jets

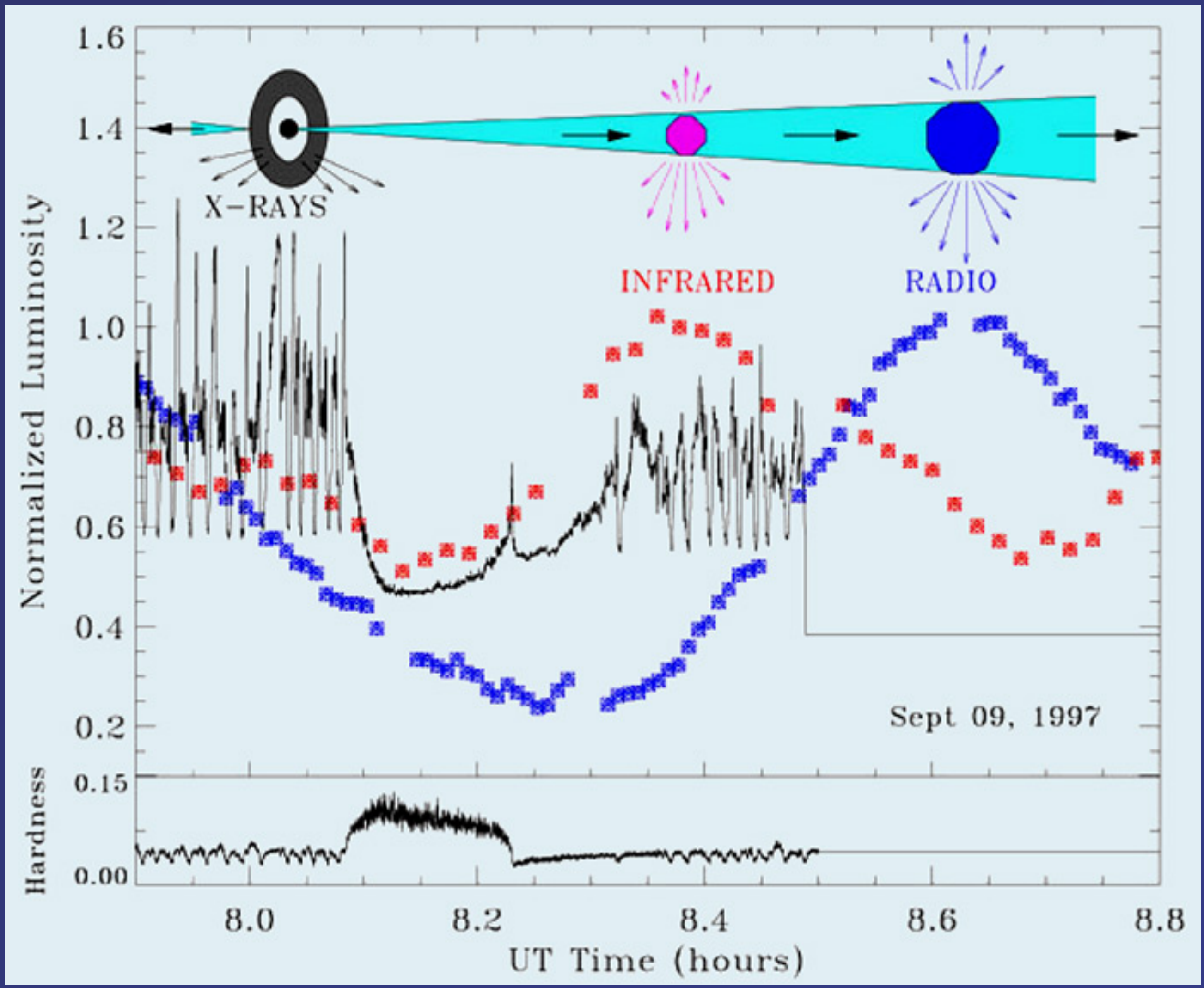
$$\Downarrow$$

- Jets originate from the *center* of the accretion disk!

$$\Downarrow$$

- Models which work at *all* radii are probably not the “correct” ones, (e.g. self similar).

Black Hole Jets – x-ray transients



Two states:

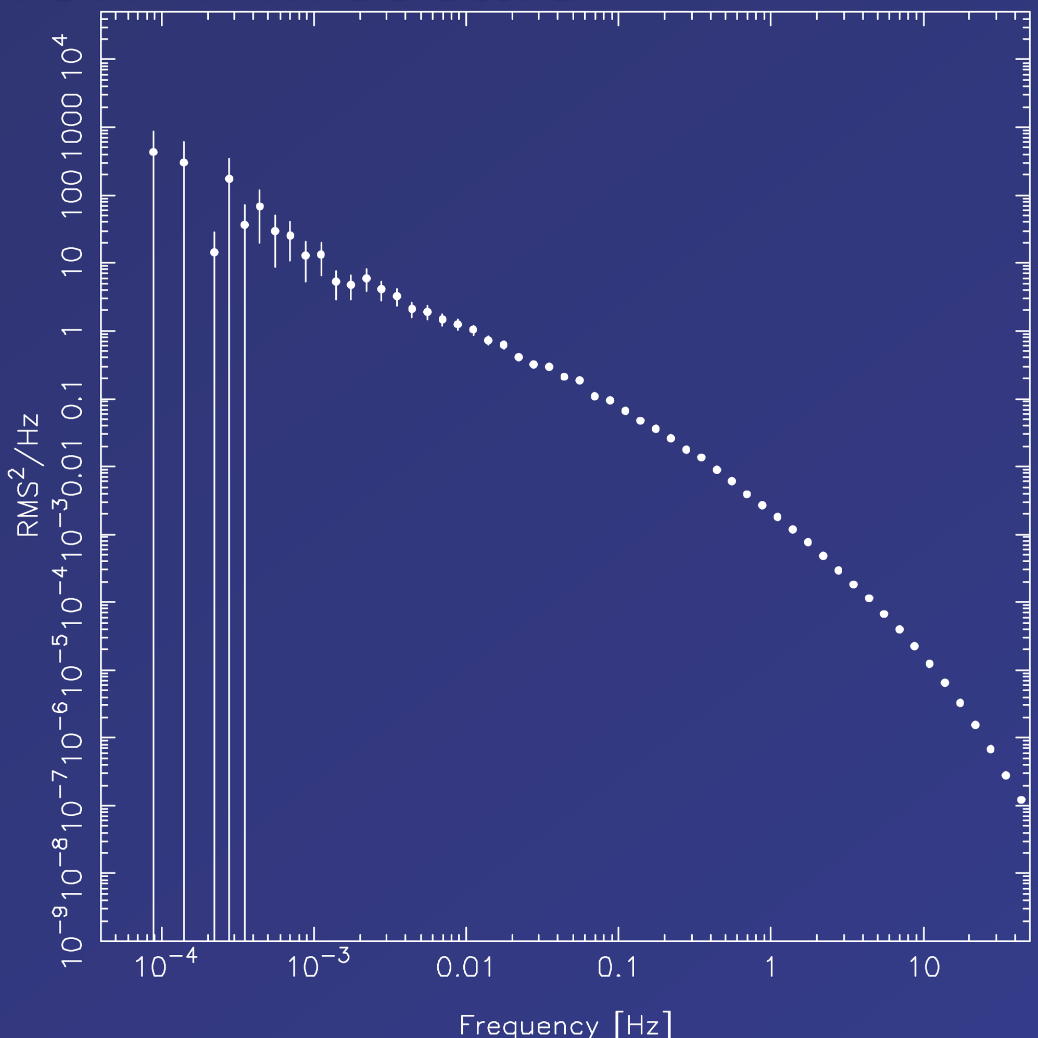
(i) dissipation and disk luminosity,

(ii) bulk flow and jet.

New Timescale

Timescale
for jet

$t_j \sim t_d 2^{R/H}$



1/f power spectrum below a break frequency.

Main Question:

Which ingredients play a *major* role in the acceleration and collimation?

Ingredients which may *not* be absolutely necessary

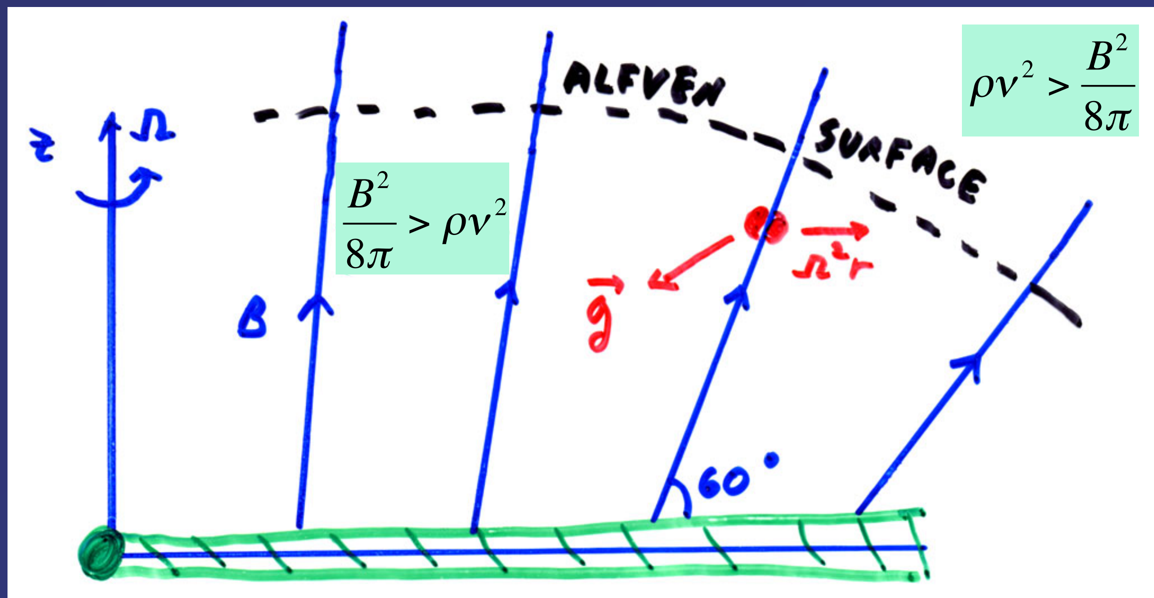
	YSOs	*AGN*	*XRBs*	*SSS*	*GRBs*	*CVs*
Central object near break-up rotation	No	?	No, ?	?	?	?
Relativistic central object	No	Yes	Yes	No	Yes	No
“Funnel”	No (?)	No (?)	No (?)	No	Yes (?)	No
$L >\sim L_{Edd}$ (Radiation pressure) (wind can be driven)	No	No	No	Yes	?	No
Extensive hot atmosphere (gas pressure)	Yes (?)	Yes	No	No	Yes (?)	No
Boundary layer	Yes (?)	No	?	Yes (?)	No	Yes (?)

What Does Work?

$\Downarrow$

A reasonably ordered large-scale magnetic field threading the disk!

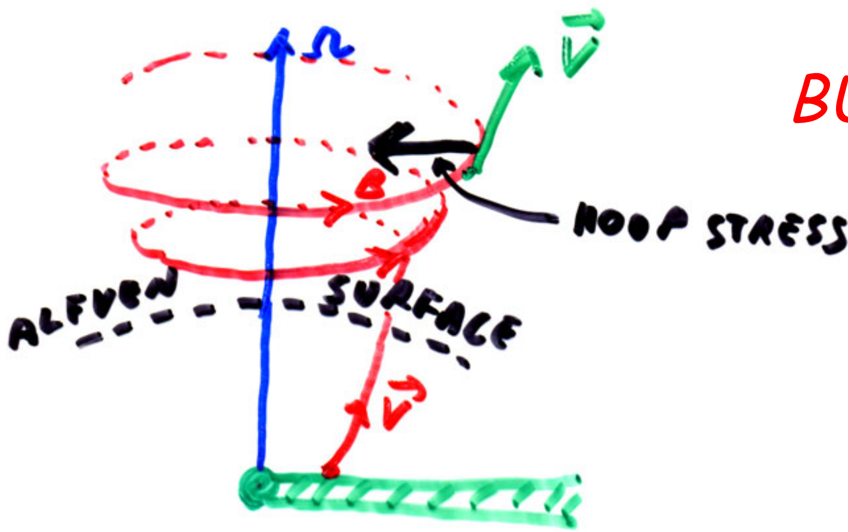
Magneto-Centrifugal Jet Acceleration and Collimation



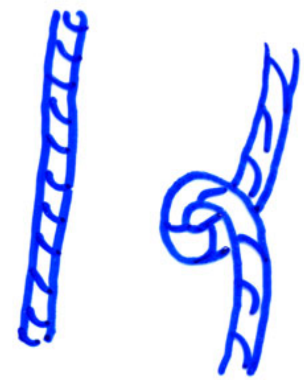
1. *Acceleration* like a bead on a wire
   up to the Alfven surface.
2. Acceleration optimal around inclination of 60°.

Collimation Outside Alfven Surface

Collimation by hoop stress?



BUT



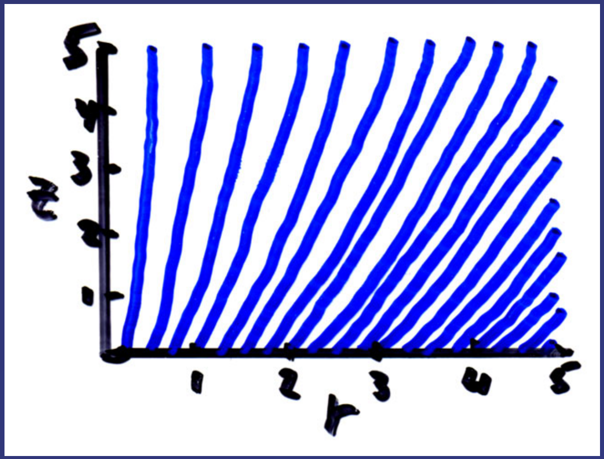
Kink Instability

$$(B_\phi^2 - B_z^2)/8\pi$$

Poloidal Collimation

Necessary Conditions

1. R_{disk}/R_{object} = Significant number of decades
2. B_z largest at inner disk but $\phi \sim \int r B_z dr$ largest at *outer disk* e.g. $B_z \sim (r/R_{in})^{-1}$



Good collimation obtained for

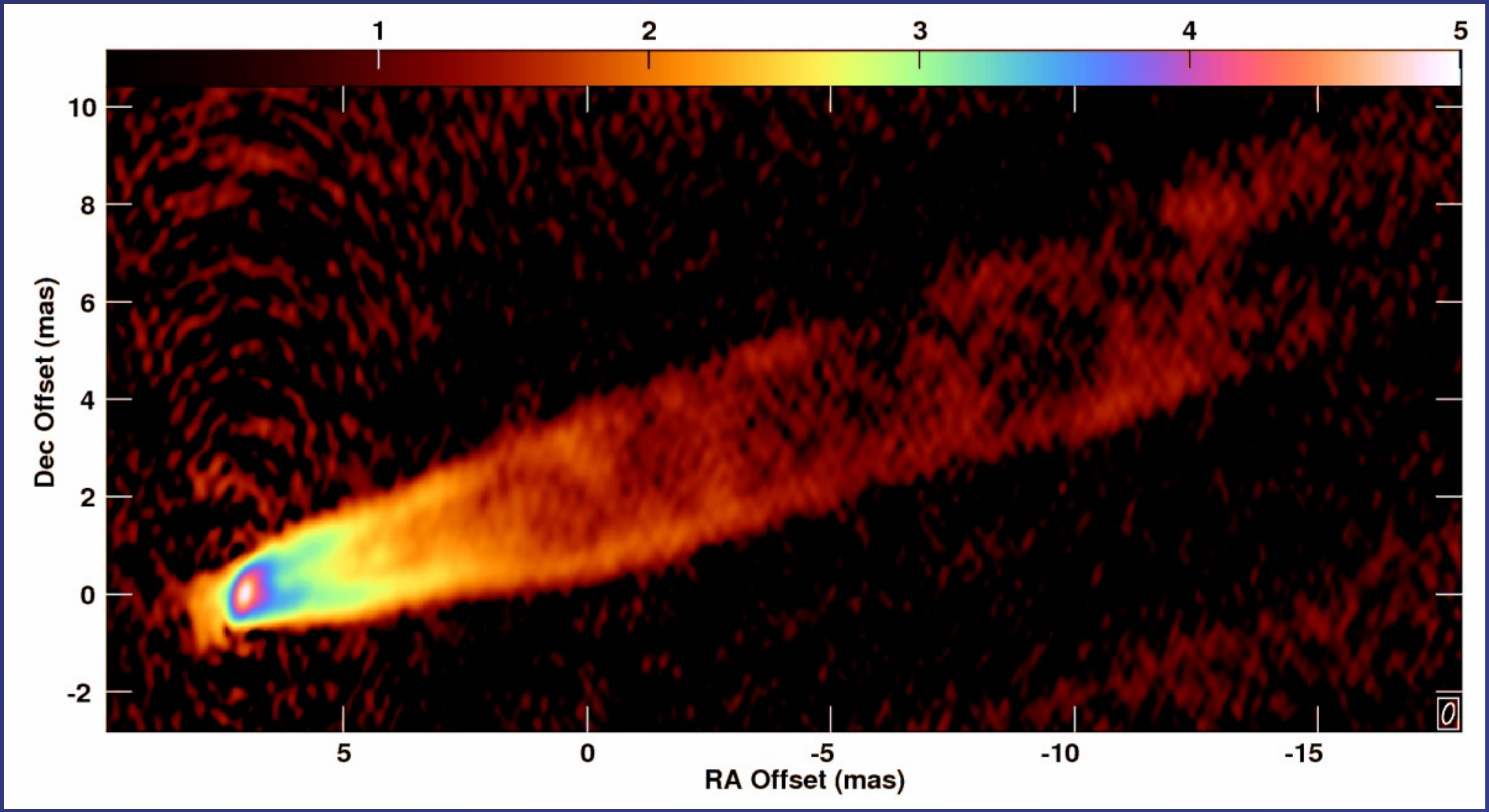
$R_{Alfven} \sim R_{disk}$

Consequences

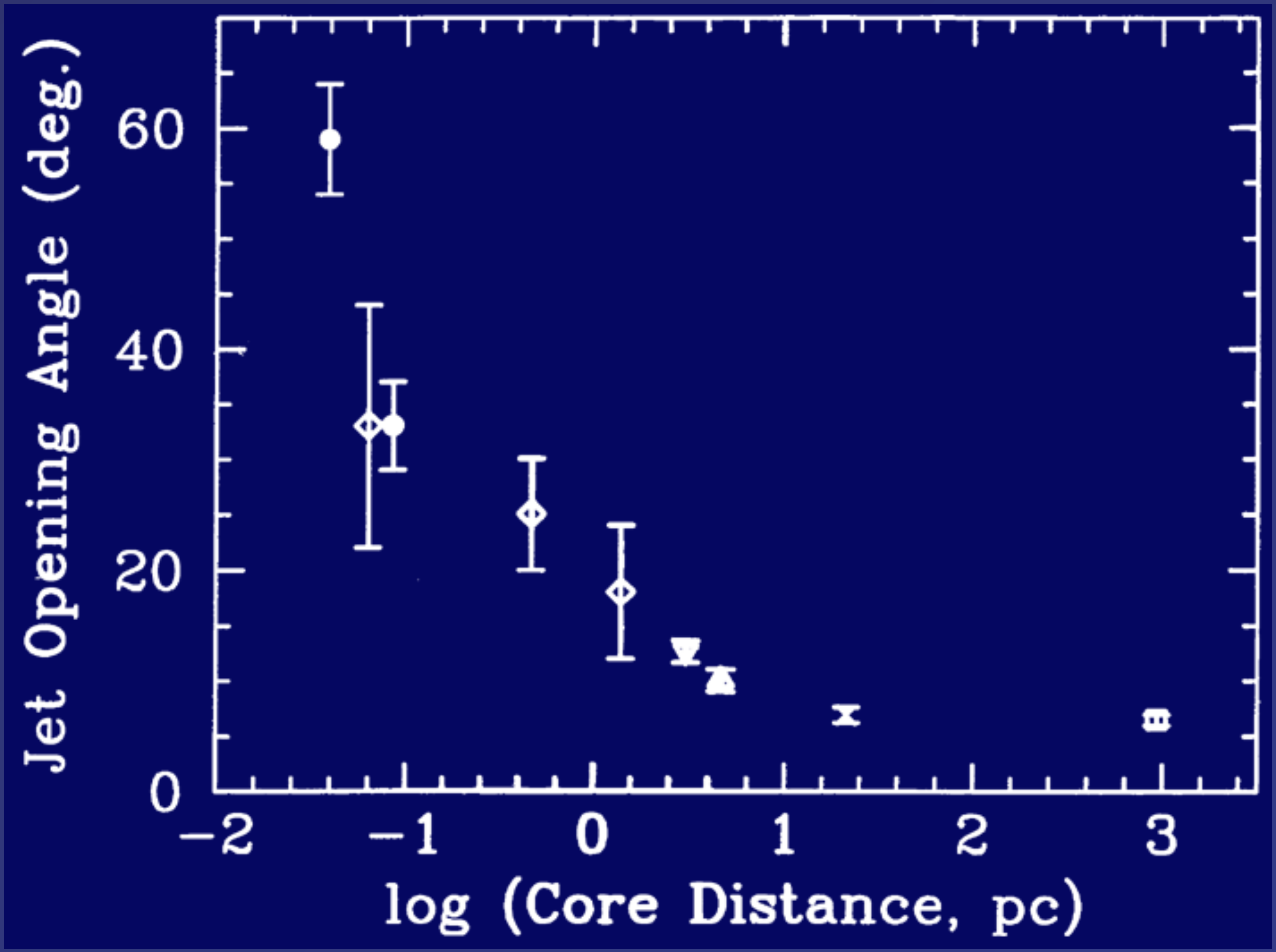
Minimum opening angle of jet

$\Theta_{min} \sim (R_{in}/R_{out})^{1/2}$

M87 VLBA at 43 GHz



M87



Long GRB: Collapse of Massive Star

Short GRB: Collision of Two Neutron Stars

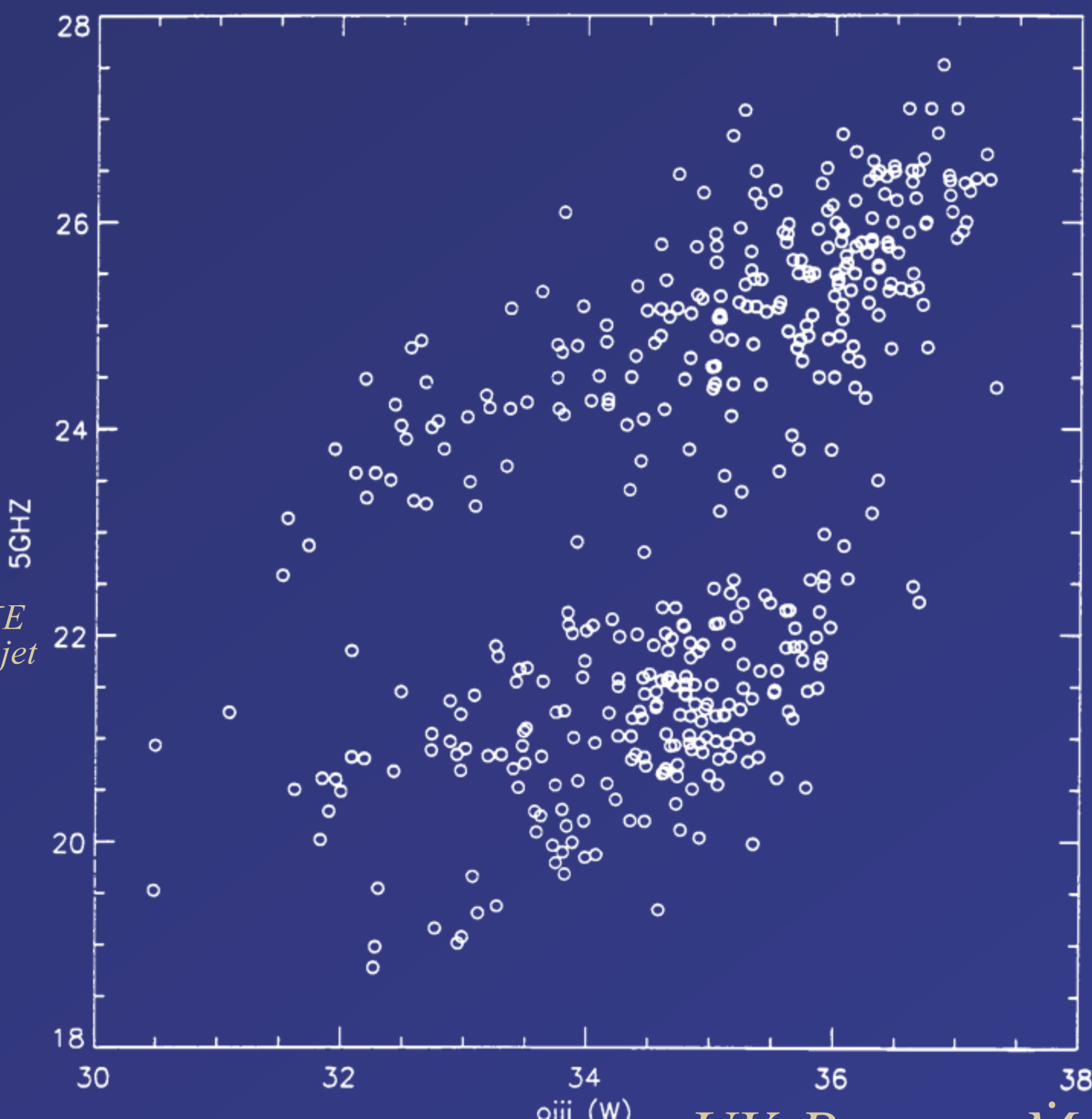
Are There Additional Ingredients?

1. Why are there radio-loud and radio-quiet AGN?
2. Why do CVs appear not to produce jets while SSS do?
3. How can pulsars produce jets?

Conjecture

- The production of powerful jets requires an additional heat/wind source.
- Solutions to transsonic flow in disk corona: for strong B a potential difference exists even for $i > 30$ $(\Delta\phi \sim B^4)$.

Radio Loud vs. Radio Quiet AGN



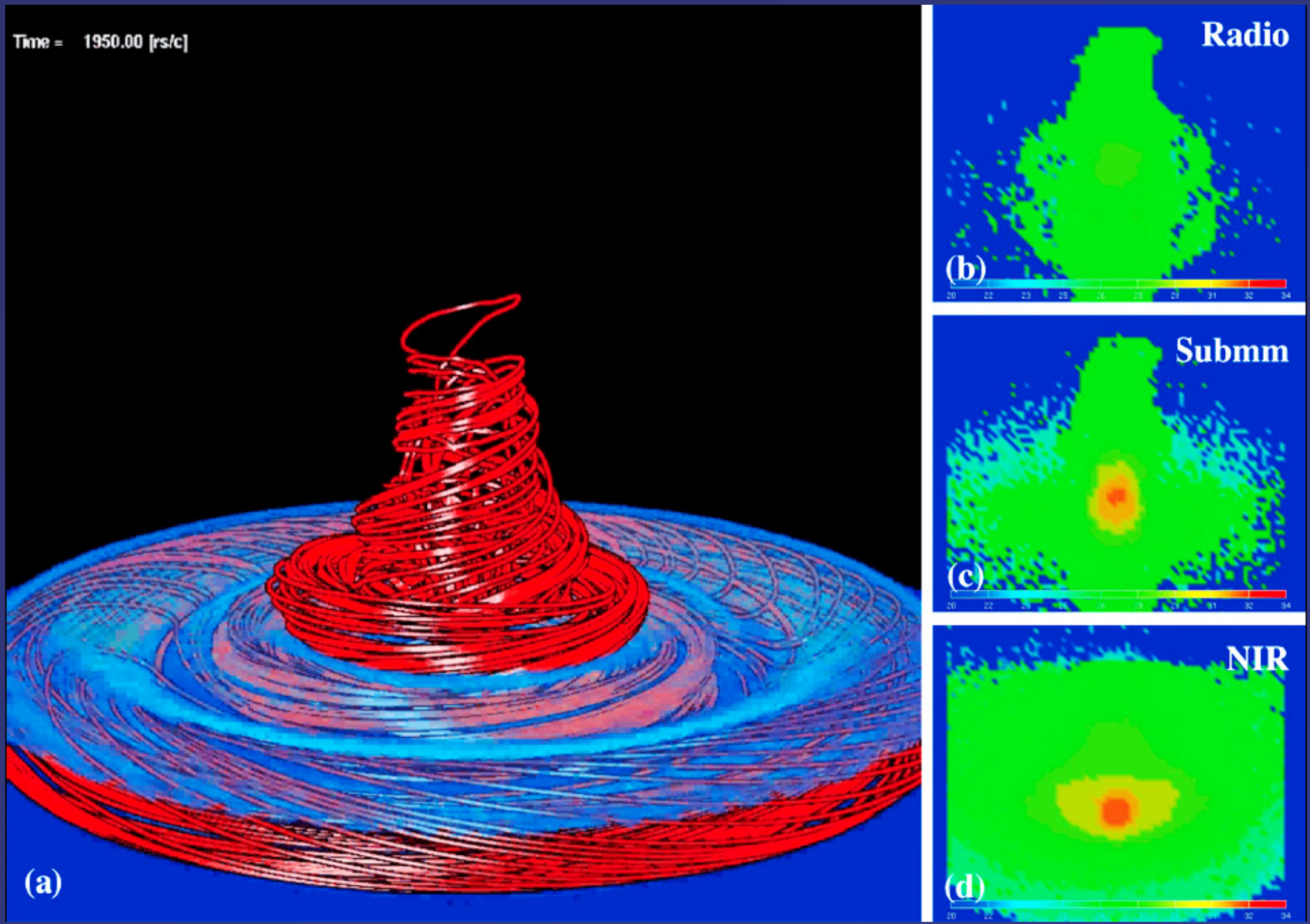
$Radio \sim \dot{M}^{E}_{jet}$

$\propto UV\ Power \sim \dot{M}_{Acc}$

Central engine parameters:

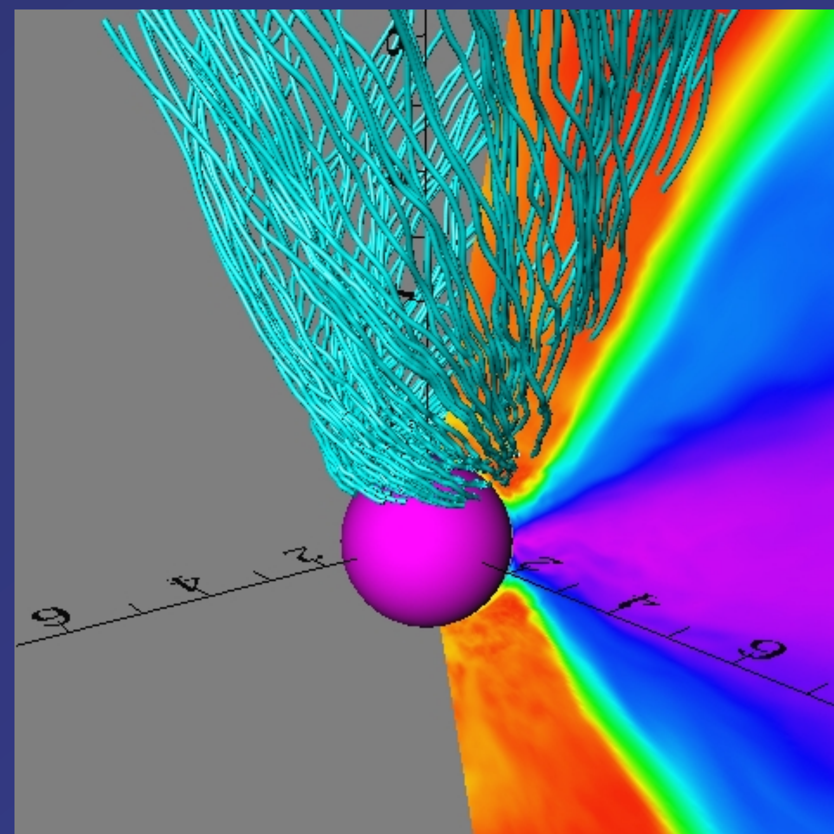
$M_{BH}, \dot{M}_{acc}, \theta, \lambda$

Recent simulations: Magnetic "Tower"



Simulation results for spinning black hole

- Outgoing velocity ~0.4 - 0.6 c in funnel wall jet
- Poynting flux dominates within funnel
- Both pressure and Lorentz forces important for acceleration
- Existence of funnel jet depends on establishing radial funnel field
- Jet luminosity increases with hole spin – Poynting flux jet is powered by the black hole



Simulations: dependence on black hole spin

a/M	η_{EM}
−0.9	0.023
0.0	0.0003
0.5	0.0063
0.9	0.046
0.93	0.038
0.95	0.072
0.99	0.21

Spins of Black Holes?

Source	*M* ($M_\odot$)	a_*
1655-40	6.3+-0.27	~0.7
1543-47	9.4+-1.0	~0.8
LMC X-3	~7	<0.26
M33 X-7	15.65+-1.45	~0.77
1915+105	14+-4.4	>0.98

- R_{ISCO}, a_*, determined on the basis of x-ray continuum data (even beyond thermal-dominant state).
- Study of plunging orbits important. Spin estimates based on stress-free inner boundary condition give upper limit on a_*?

Critical Observations

1. Determinations of the collimation scale in all classes of objects.
2. Detection and measurement of *rotation* and of toroidal magnetic fields in jets and bipolar outflows.
3. Searches for jets in other SSS, in PNe, in other XRTs (during flares, e.g. A0620-00, GS2023+338, GS 1124-683, Cen X-4, AQL X-1), and other symbiotic systems, in CVs!
4. Determination of black hole masses in AGN.
5. Determination of black hole spins.
6. Observations of collimated jets in pulsars.
7. Afterglow light curves and breaks in GRBs.
8. Differences between short and long burst in GRBs.