Extreme Black Hole Engines

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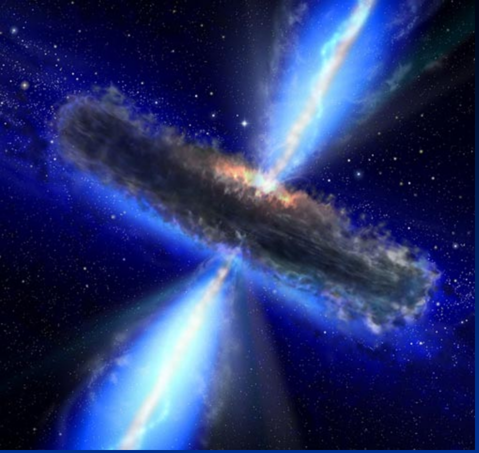
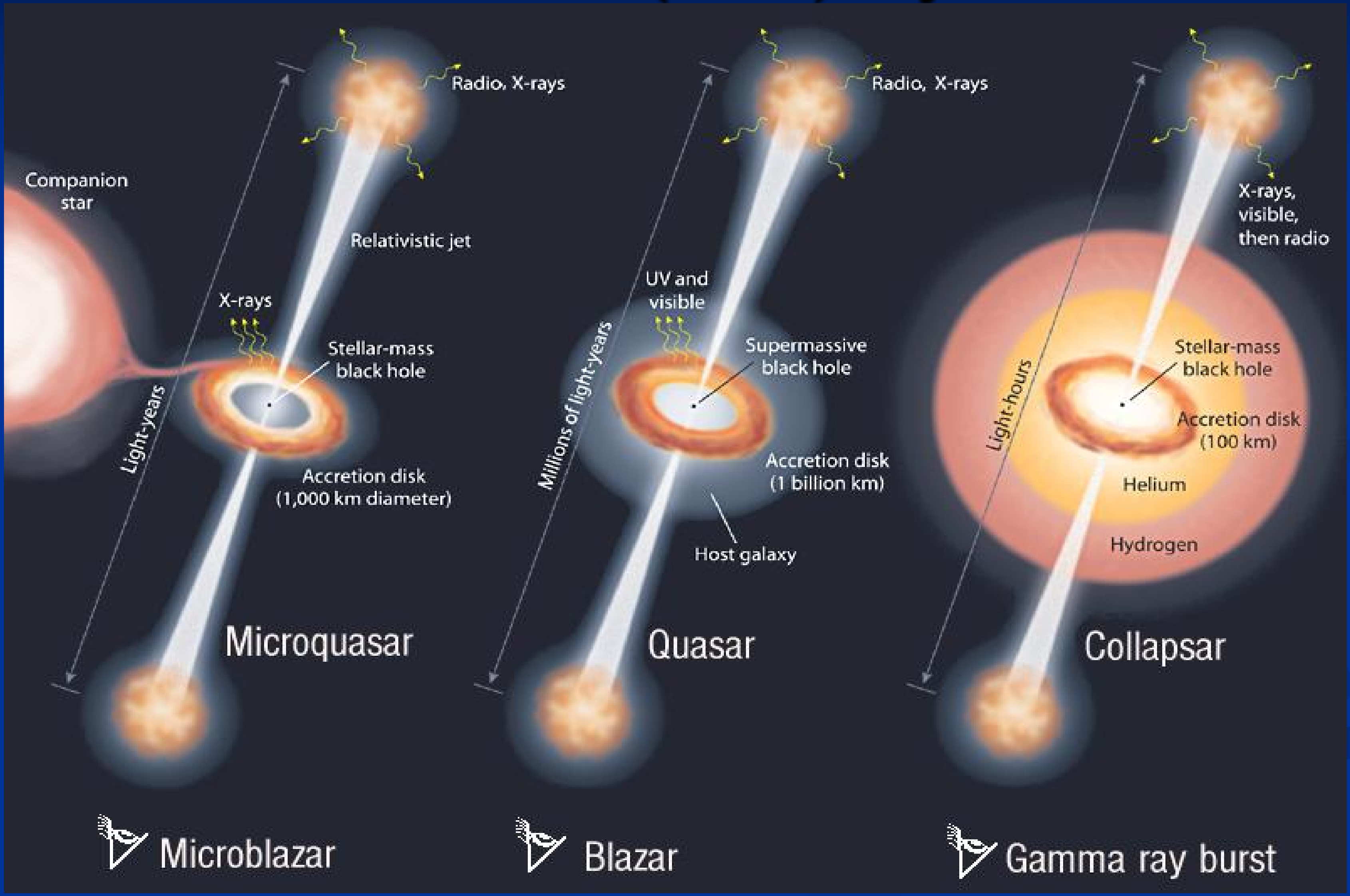


ESA/NASA (Beckmann)

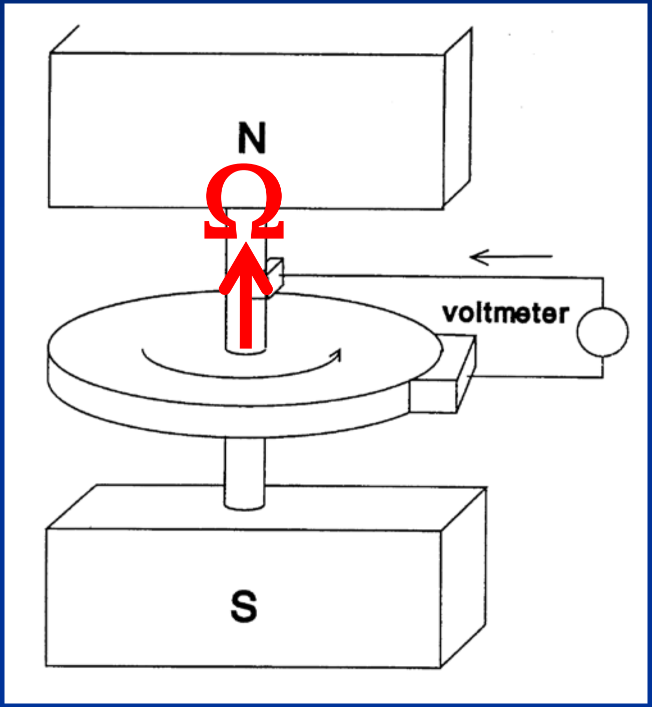
Road Map

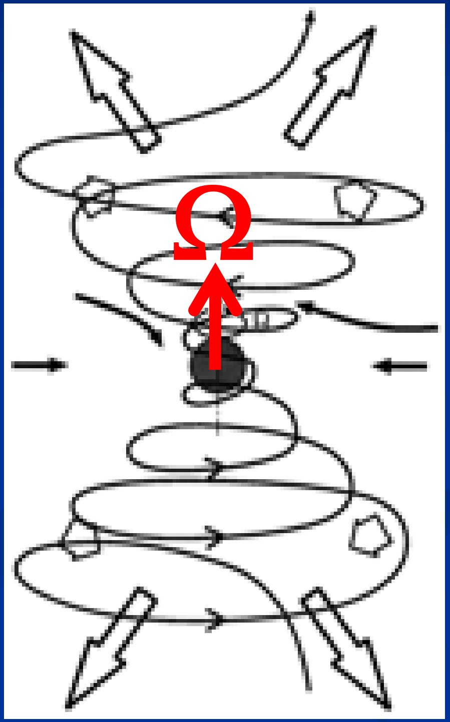
- Magnetic Field Accumulation and Destruction near Black Holes
- Unstable Magnetospheric Interfaces and QPOs
- Summary

Black Hole (BH) Systems



BH as Faraday Disk
(homopolar or unipolar generator)





Force = $q\, v \times B \propto V = IR$

Power = $P = IV = I^2 R$

$P \propto R\, B^2\, \Omega^2$

Membrane Paradigm: (Thorne et al.)

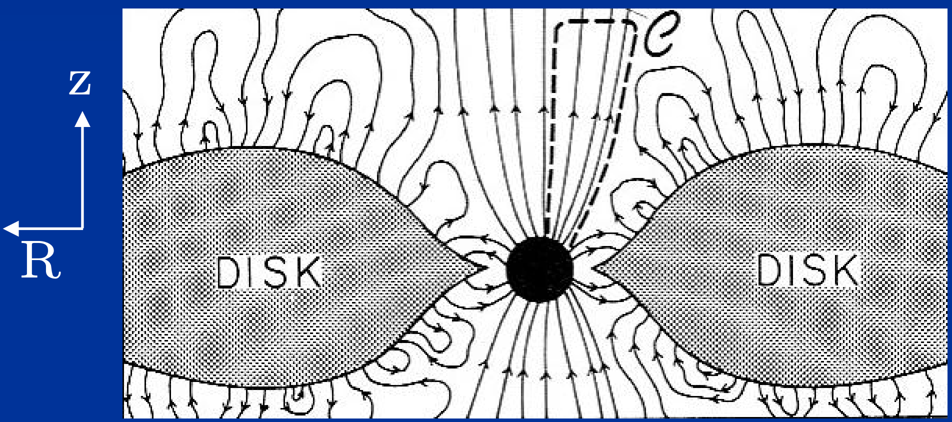
$R = 4\pi/c \sim 377$ Ohms

Blandford & Znajek (1977)

$P \propto B_r^{\,2}\, \Omega^2_{H}$

Role of Magnetic Field / Flux

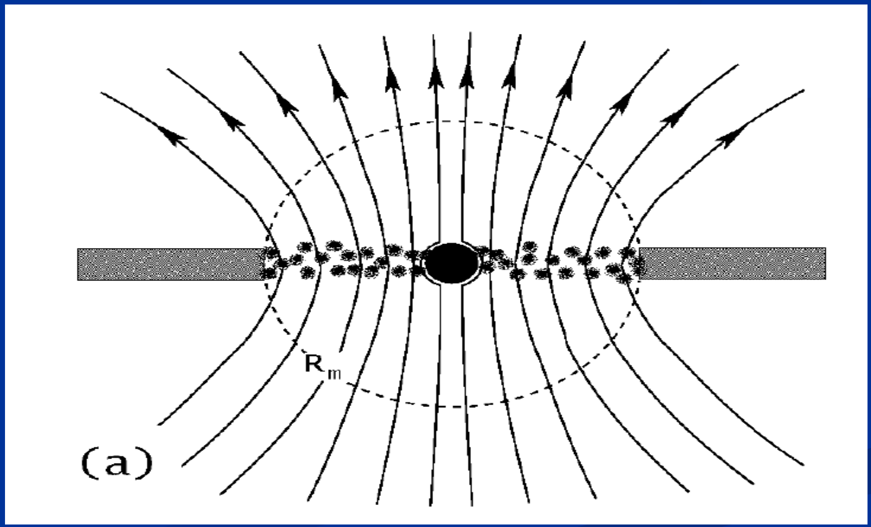
Weak Field MRI Disk
+ BZ Jet
= Fine-Tuned Flux



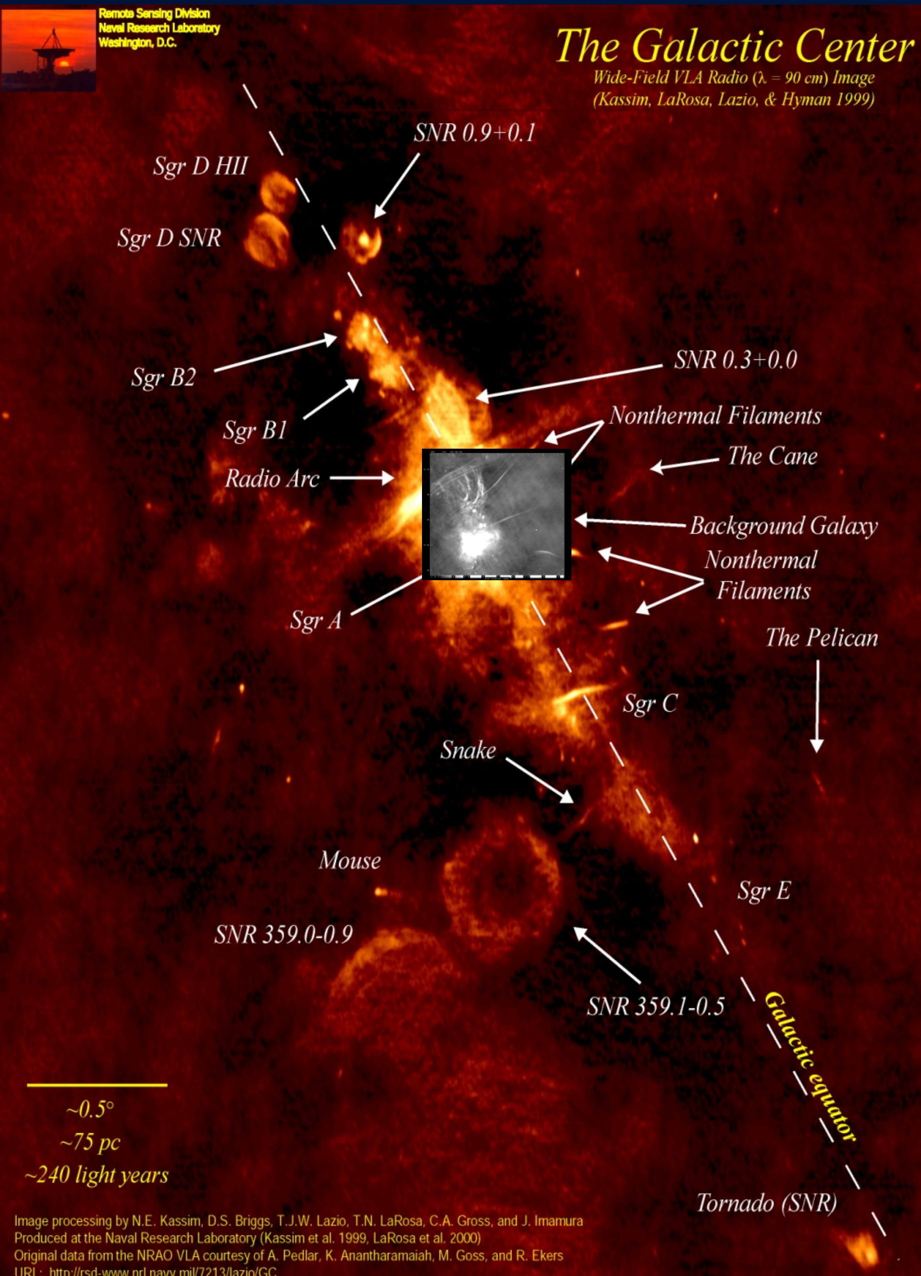
Blandford & Znajek (77)
MacDonald & Thorne (82)

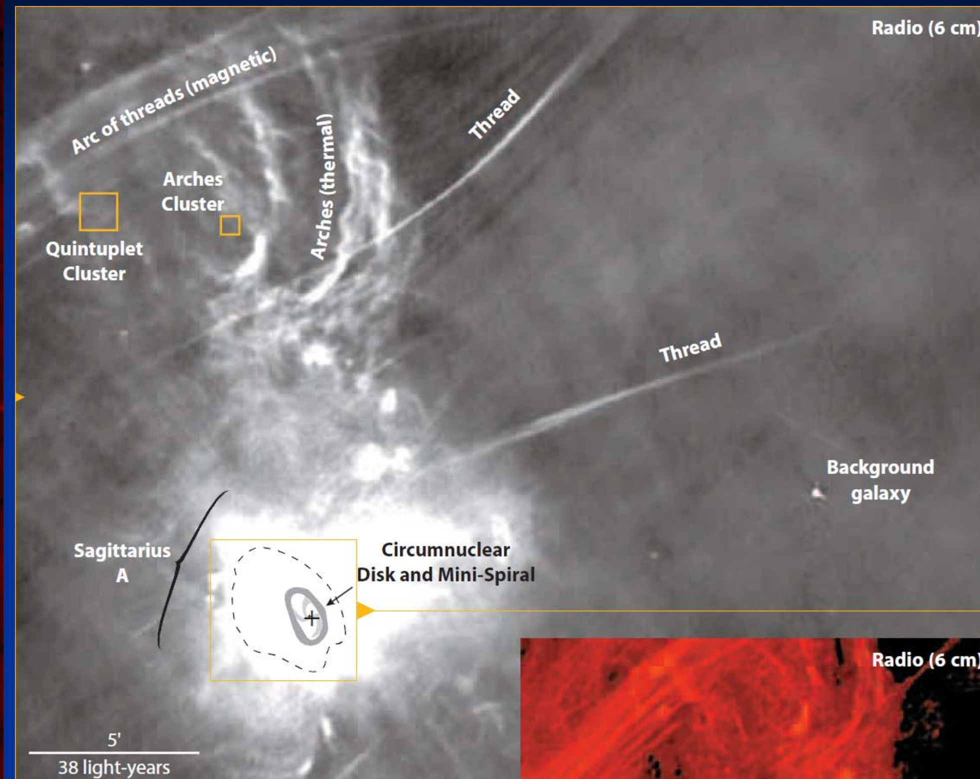
Balbus & Hawley (1991,1998)

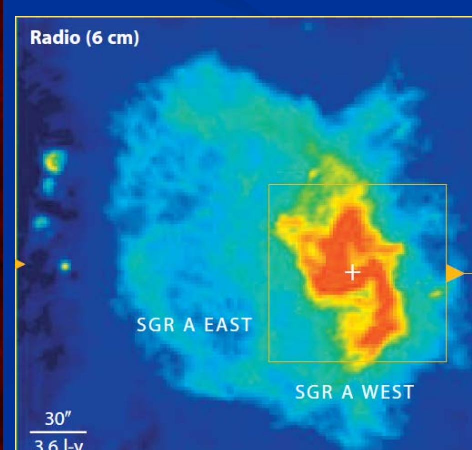
Magnetically Arrested Disk
= Flux in Force Balance

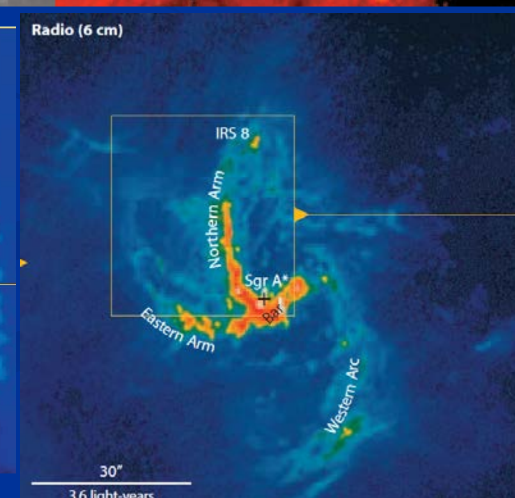


Znajek (76), Bisnovatyi-Kogan & Ruzmaikin (74,76), Narayan et al. (03), Reynolds et al. (06), Igumenshchev et al. (03)


Remote Sensing Division
Naval Research Laboratory
Washington, D.C.
The Galactic Center
Wide-Field VLA Radio (λ = 90 cm) Image
(Kassim, LaRosa, Lazio, & Hyman 1999)
SNR 0.9+0.1
Sgr D HII
Sgr D SNR
Sgr B2
Sgr B1
Radio Arc
SNR 0.3+0.0
Nonthermal Filaments
The Cane
Background Galaxy
Nonthermal
Filaments
Sgr A
The Pelican
Sgr C
Snake
Mouse
SNR 359.0-0.9
SNR 359.1-0.5
Sgr E
Galactic equator
Tornado (SNR)
~0.5°
~75 pc
~240 light years
Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, C.A. Gross, and J. Imamura
Produced at the Naval Research Laboratory (Kassim et al. 1999, LaRosa et al. 2000)
Original data from the NRAO VLA courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, and R. Ekers
URL: http://rsd-www.nrl.navy.mil/7213/lazio/GC


Radio (6 cm)
Arc of threads (magnetic)
Thread
Arches Cluster
Arches (thermal)
Quintuplet Cluster
Thread
Background galaxy
Sagittarius A
Circumnuclear Disk and Mini-Spiral
Radio (6 cm)
5'
38 light-years


Radio (6 cm)
SGR A EAST
SGR A WEST
30″
3.6 l-y


Radio (6 cm)
IRS 8
Northern Arm
Sgr A*
Bar
Eastern Arm
Western Arc
30″
3.6 light-years

How much Magnetic Flux?

- Coherent Flux near Galactic Nucleus:
  - $\Phi \sim 0.1\ \mathrm{pc}^2\mathrm{G}$ or greater Lang, C. C., Morris, M., & Echevarria, L. 1999, ApJ, 526, 727
- Magnetospheric Radius (McKinney, Tchekhovskoy, Blandford 2012):

1) Mass Flux: $\Sigma = \dot{M}/(2\pi r \epsilon v_{\rm ff})$ $\dot{M} = \dot{M}_{\rm H}\ (r/r_g)^n$

2) Gravity Balancing Field: $GM\Sigma/R^2 \sim 2B_R B_z/4\pi \sim B_z^2/2\pi$

3) Solve for Bz: $B_z \sim 10^5 \epsilon_{-1}^{-1/2} m_8^{-1/2} \dot{m}^{1/2} (r/r_g)^{-5/4+n/2}\ \mathrm{G}$

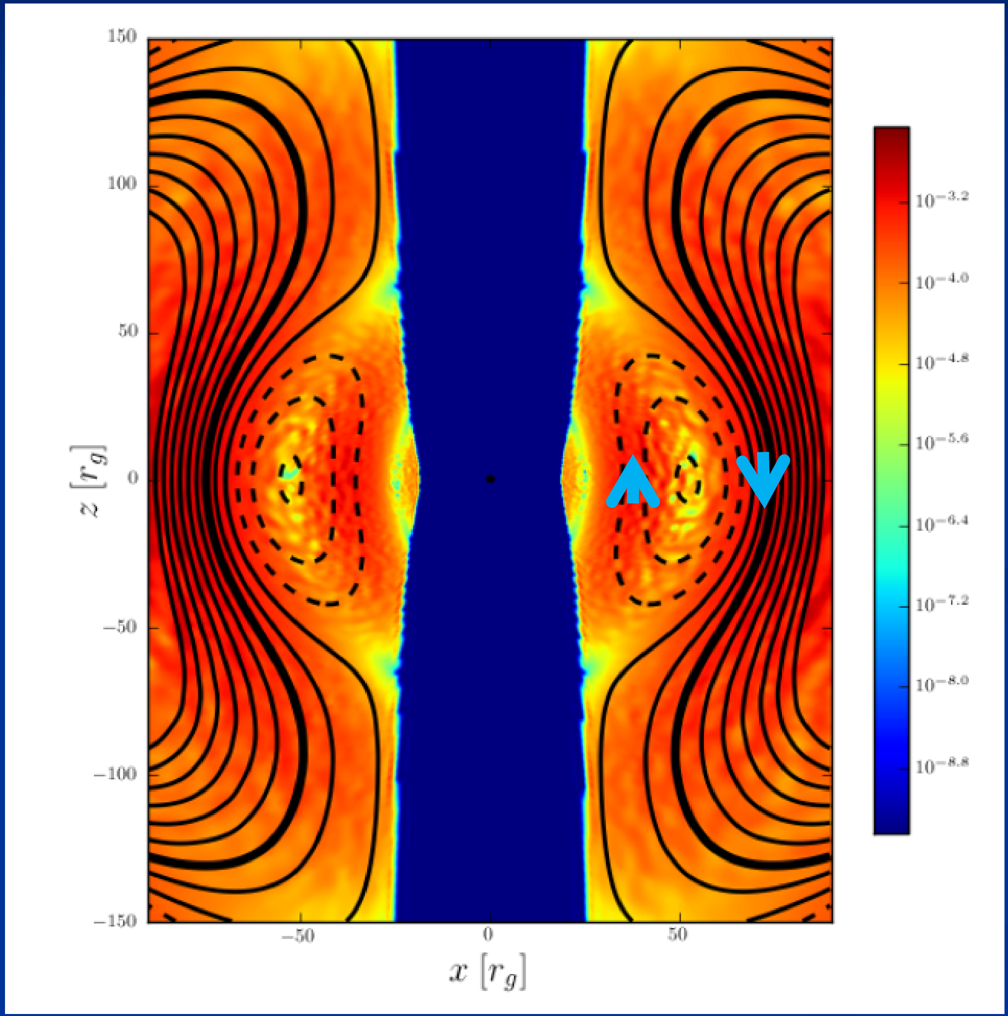
4) Integrate Bz within r_m to get magnetic flux (Φ) within r_m .

5) Solve for r_m : $r_m \sim r_g \left(12000\left(\frac{3}{4}+\frac{n}{2}\right)\right)^{\frac{4}{3+2n}} \epsilon_{-1}^{\frac{2}{3+2n}} m_8^{-\frac{6}{3+2n}} \dot{m}_{\rm H}^{-\frac{2}{3+2n}} \left(\frac{\Phi}{0.1\mathrm{pc}^2\mathrm{G}}\right)^{\frac{4}{3+2n}}$

SgrA* : $r_m \sim 10^7\ r_g$ (n=1)

M87 : $r_m \sim 10^2\ r_g$ (n=1)

GR-MHD Simulations of Disks with Lots of (poloidal) Magnetic Flux

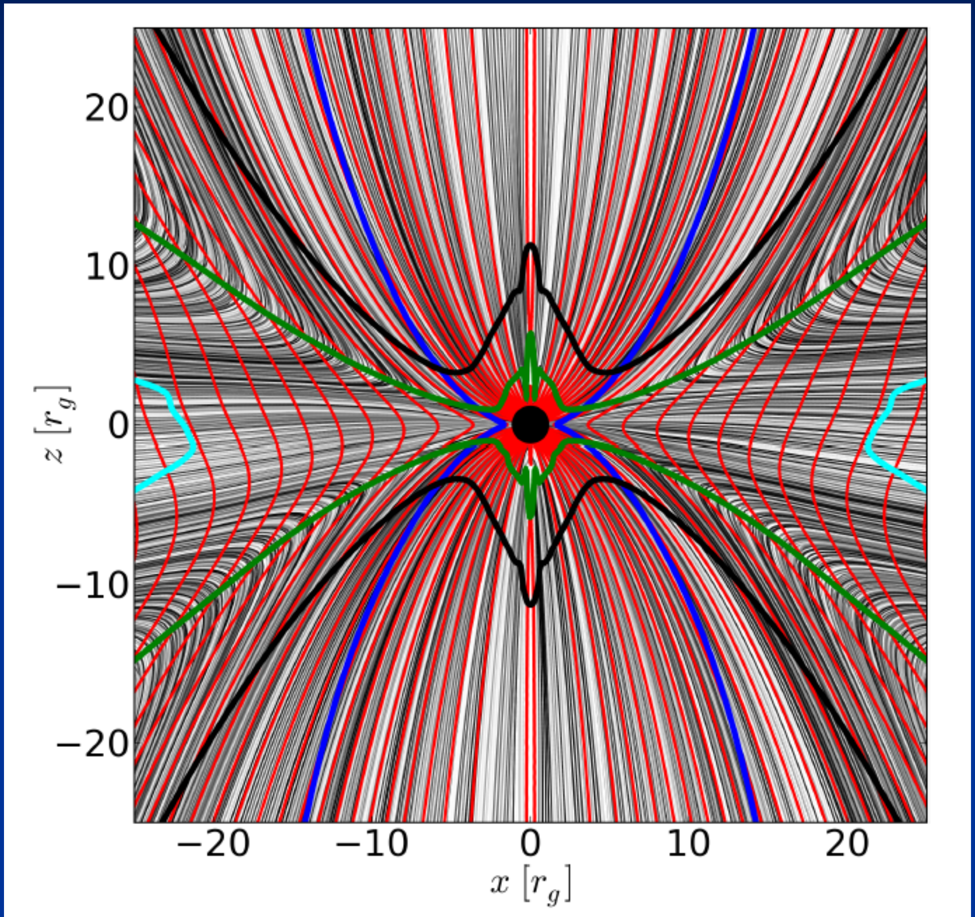


Physical Setup:
Spin: a=0.94
Radiatively Inefficient
Thick Disk

Numerical Setup:
Fully 3D (no syms)
KS Coords
~1E5M outer radius

EM Energy Density & Field Lines

Magnetically Choked Accretion Flow



Time-Azimuthal Average:

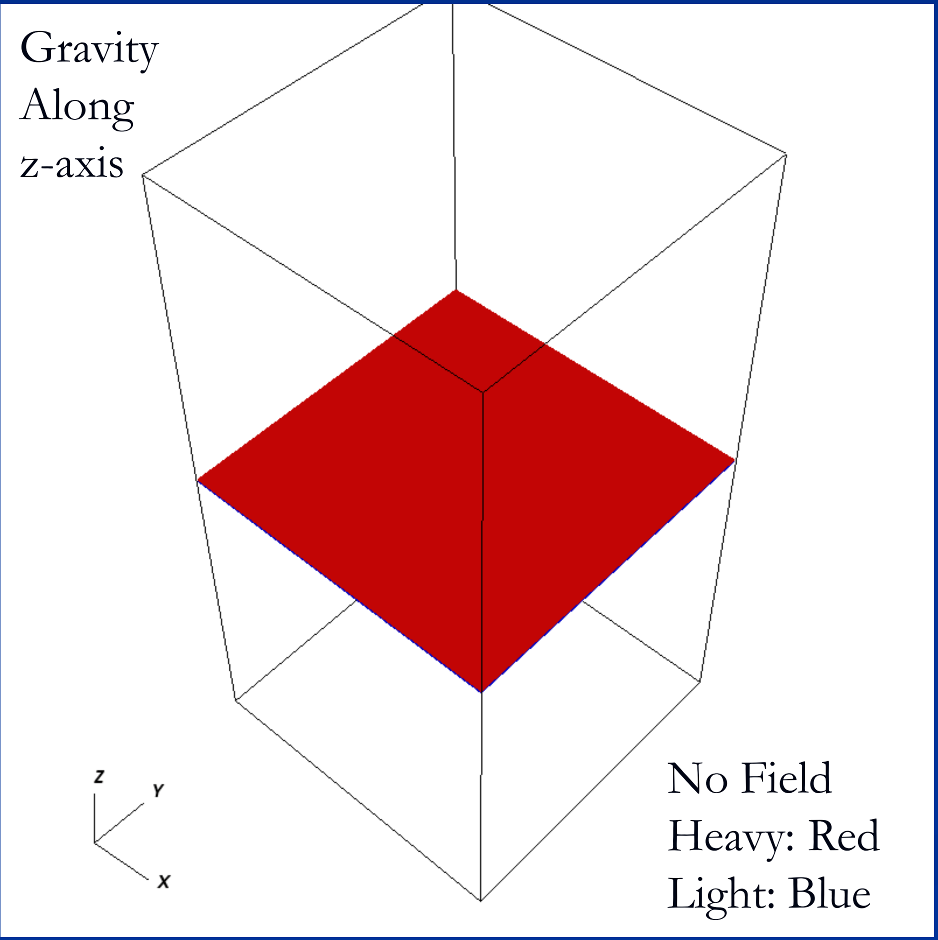
Red: Magnetic Field Lines
Gray: Velocity Stream Lines

- **Magnetic Flux Saturates to Natural Limit**
- **Force Balance between Ram/Gravity and Magnetic Flux**
- **MRI (magneto-rotational/Balbus-Hawley instability) suppressed!**

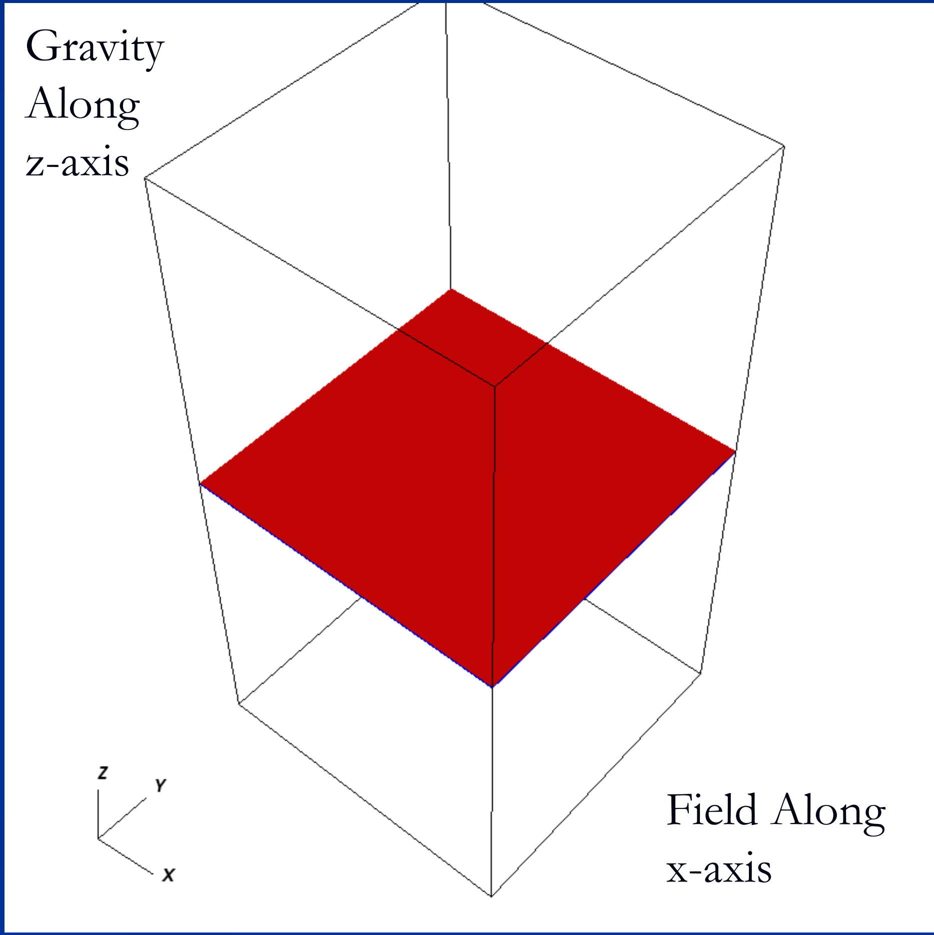
Igumenshchev et al. (08,09), Tchekhovskoy et al. (11,12), McKinney et al. (12)

Accretion Occurs through Magnetic Rayleigh-Taylor Modes

Hydrodynamics

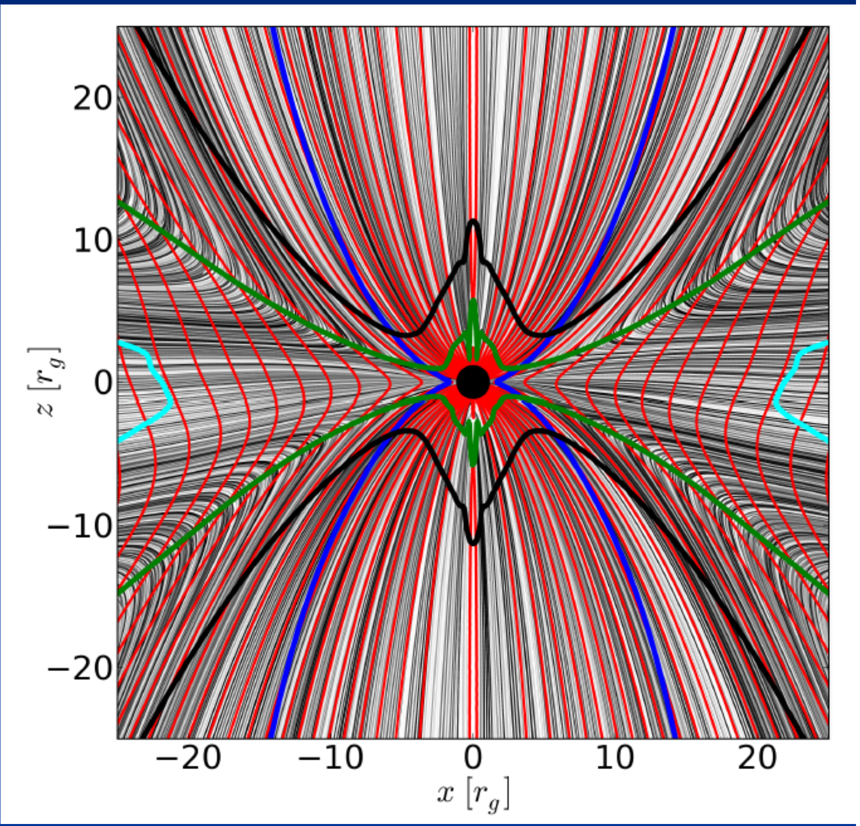


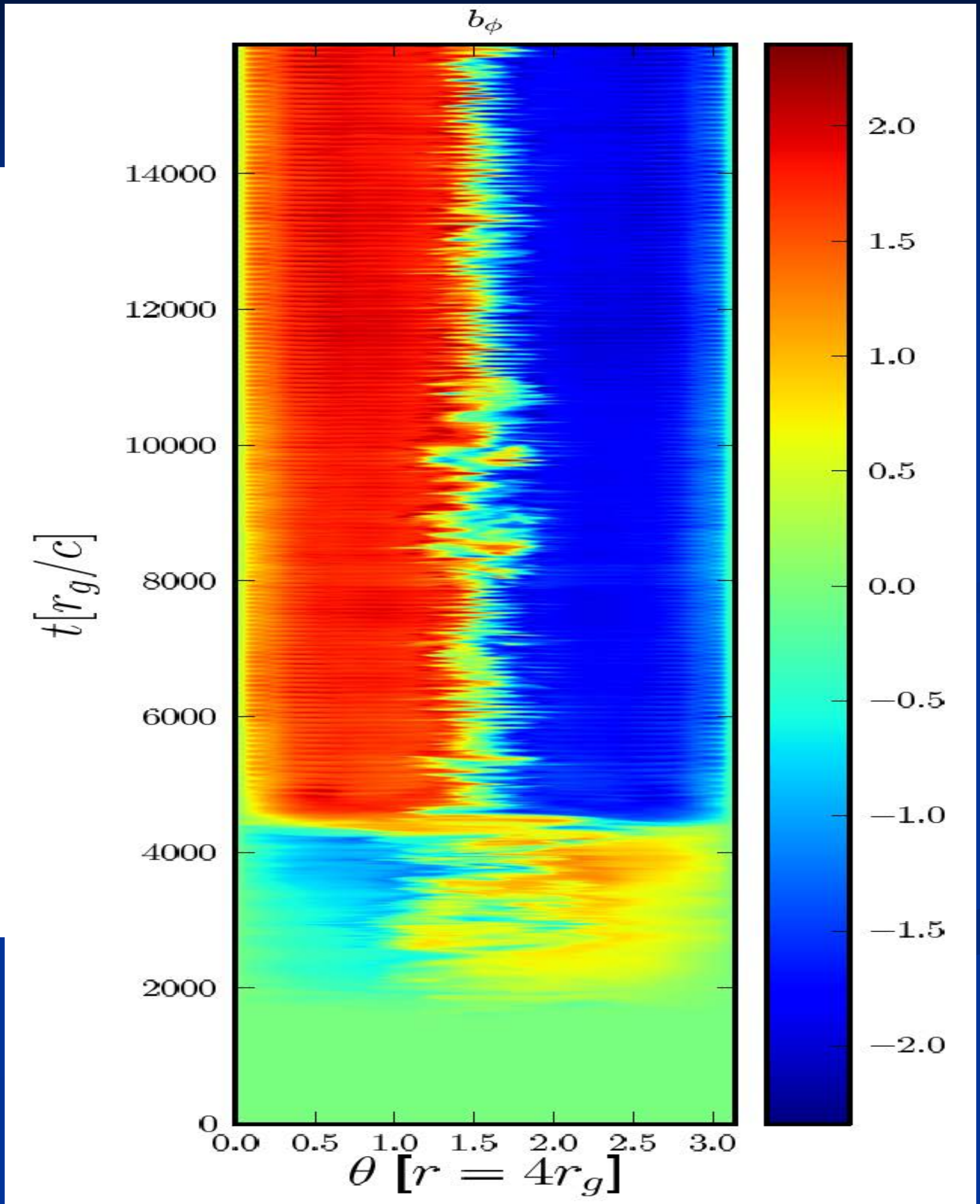
MagnetoHydrodynamics



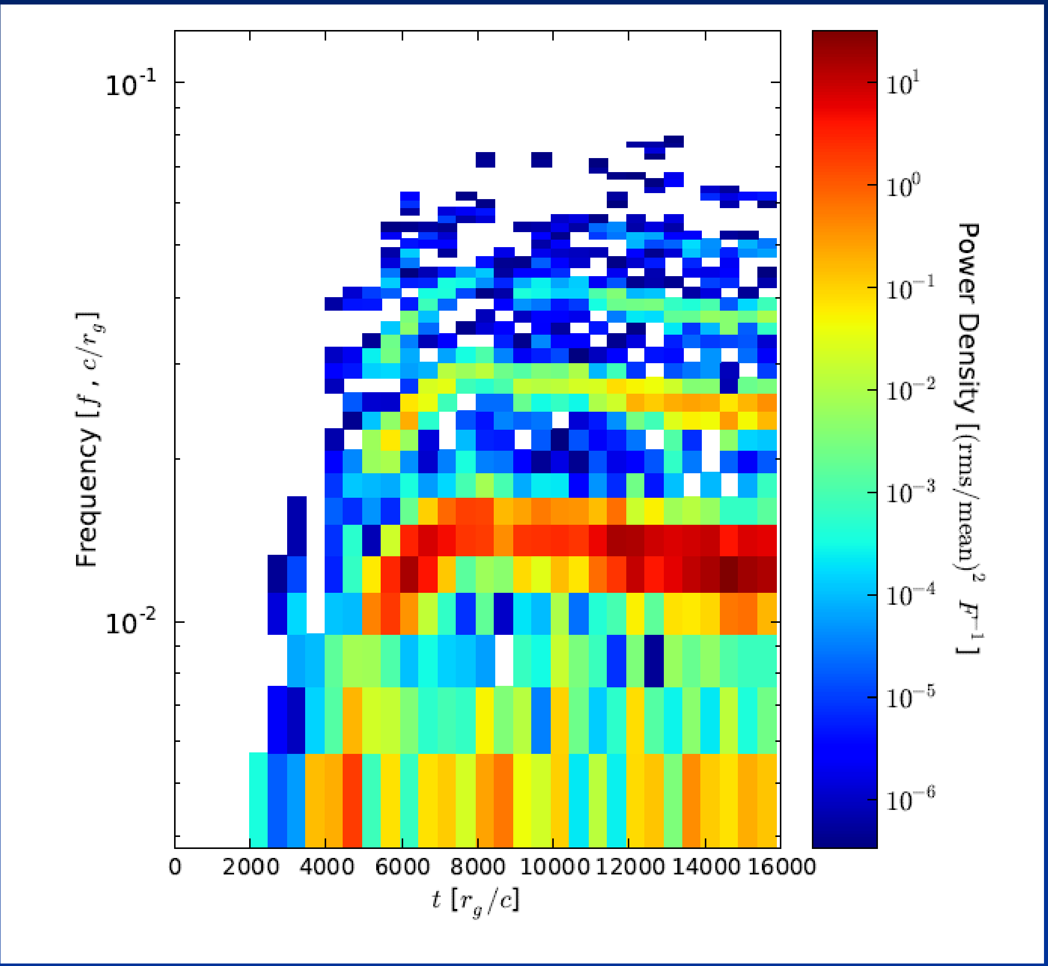
Athena, Stone et al.

Unstable Magnetospheric Interface & QPOs





Spectrogram of Field showing QPOs



Magnetospheric Barriers to Accretion:

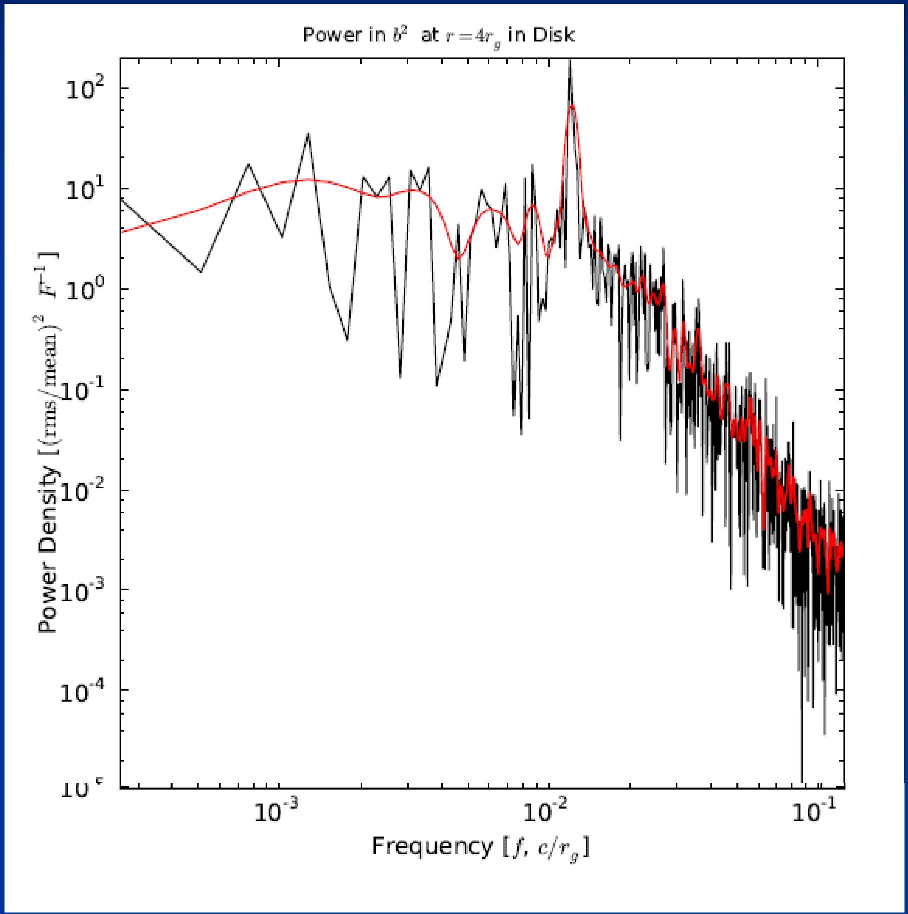
QPOs predicted by Li & Narayan (2004), Wu & Lai 2012).

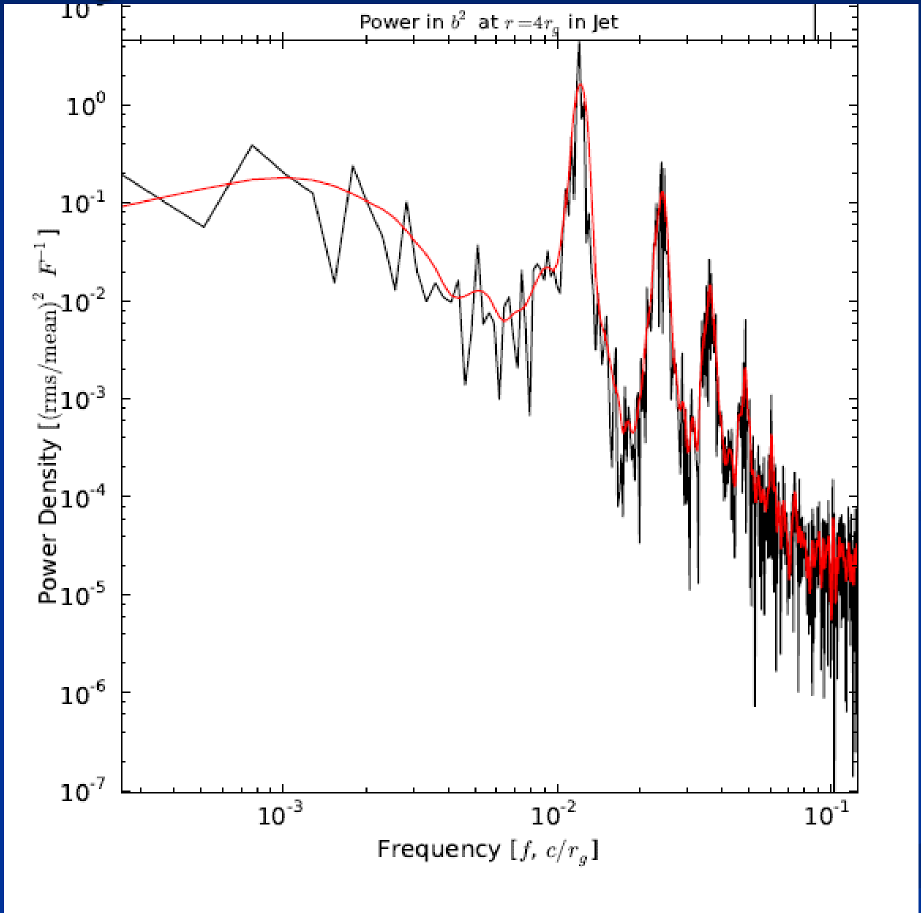
Polar field as strong as disk inflow -> Interface is KH unstable

Like Flag Flapping in Wind

Temporal Power Density at r=4M

Disk Power in b^2 Jet Power in b^2

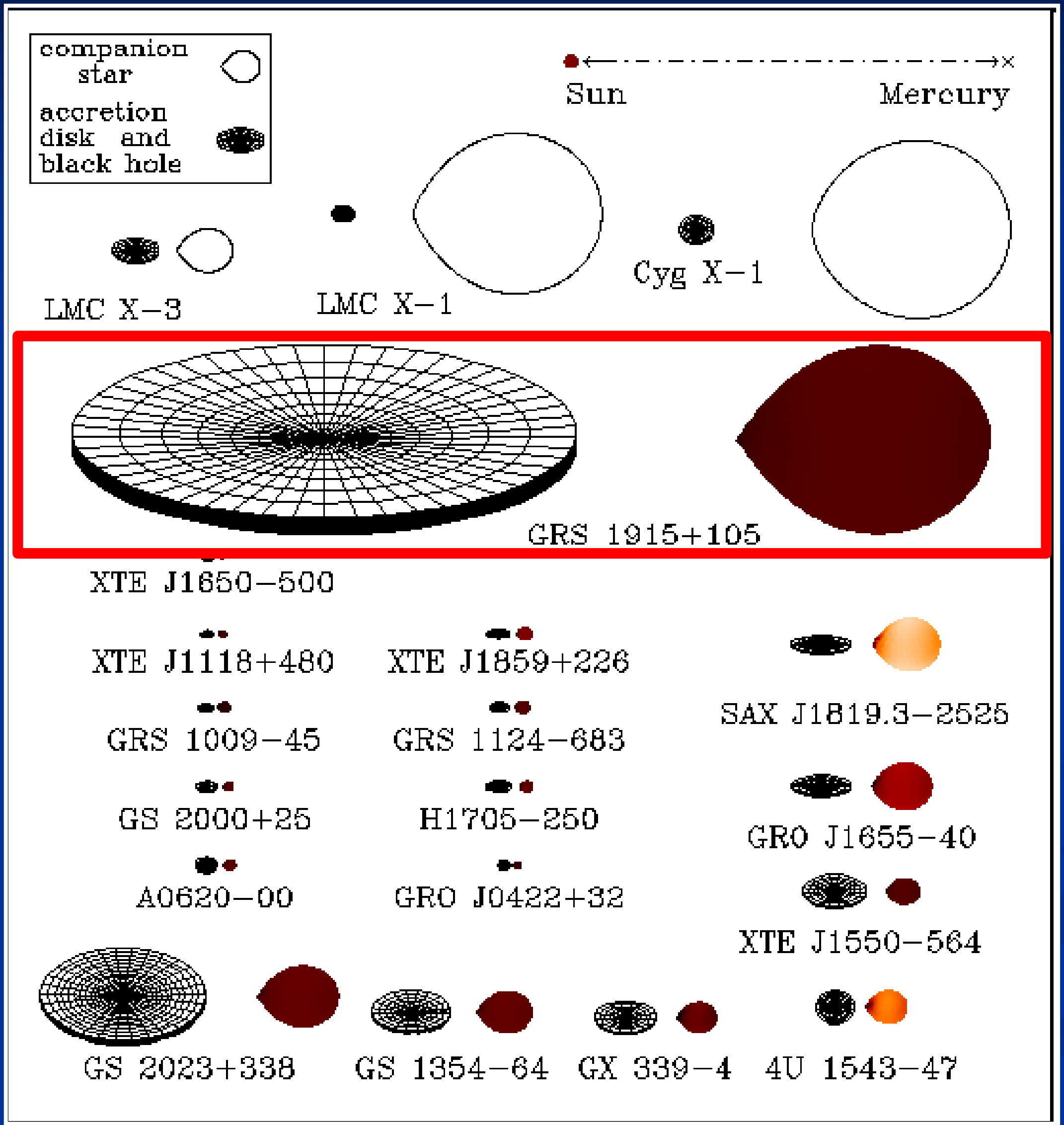




Jet-Disk Interface m-modes: $\tau\sim$ 70-140 M

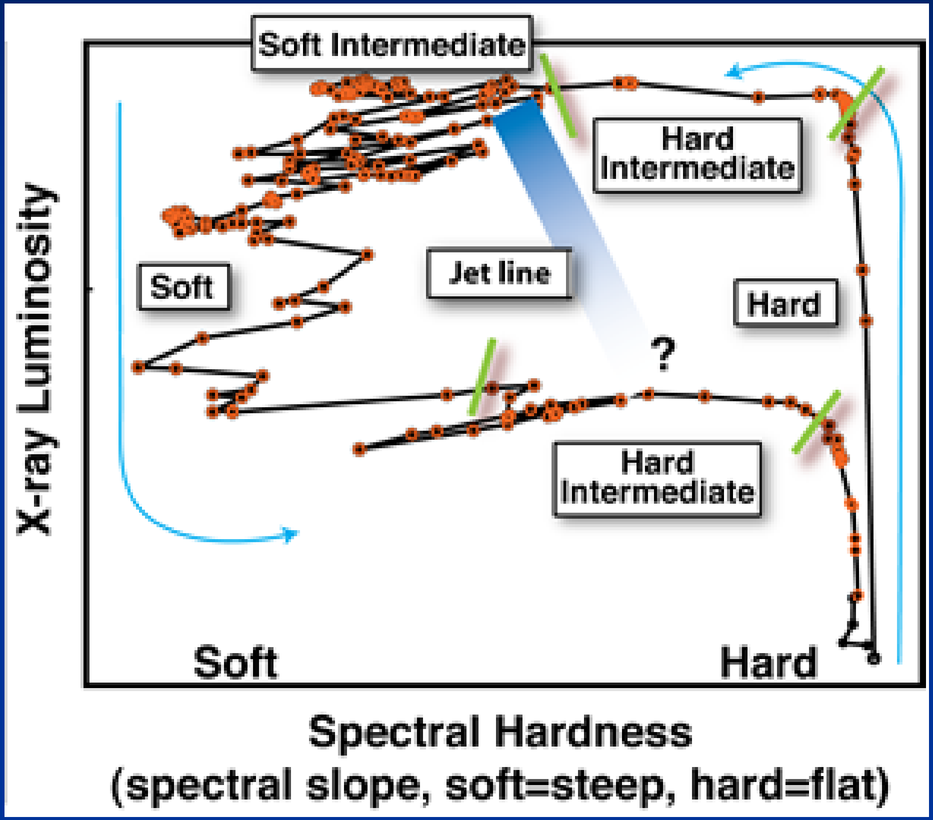
Same range as observed HFQPOs

BH X-Ray Binaries

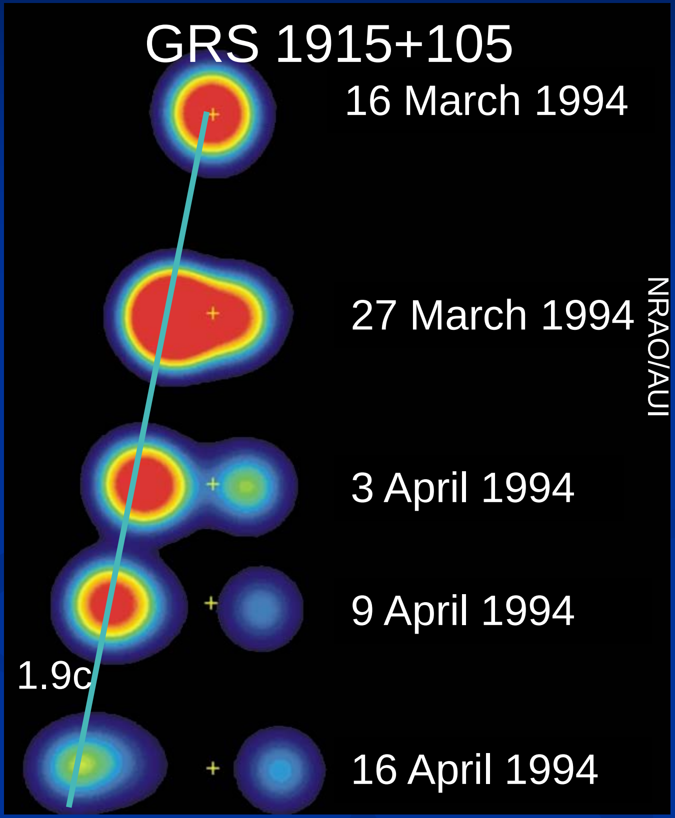


Orosz

BH X-Ray Binaries



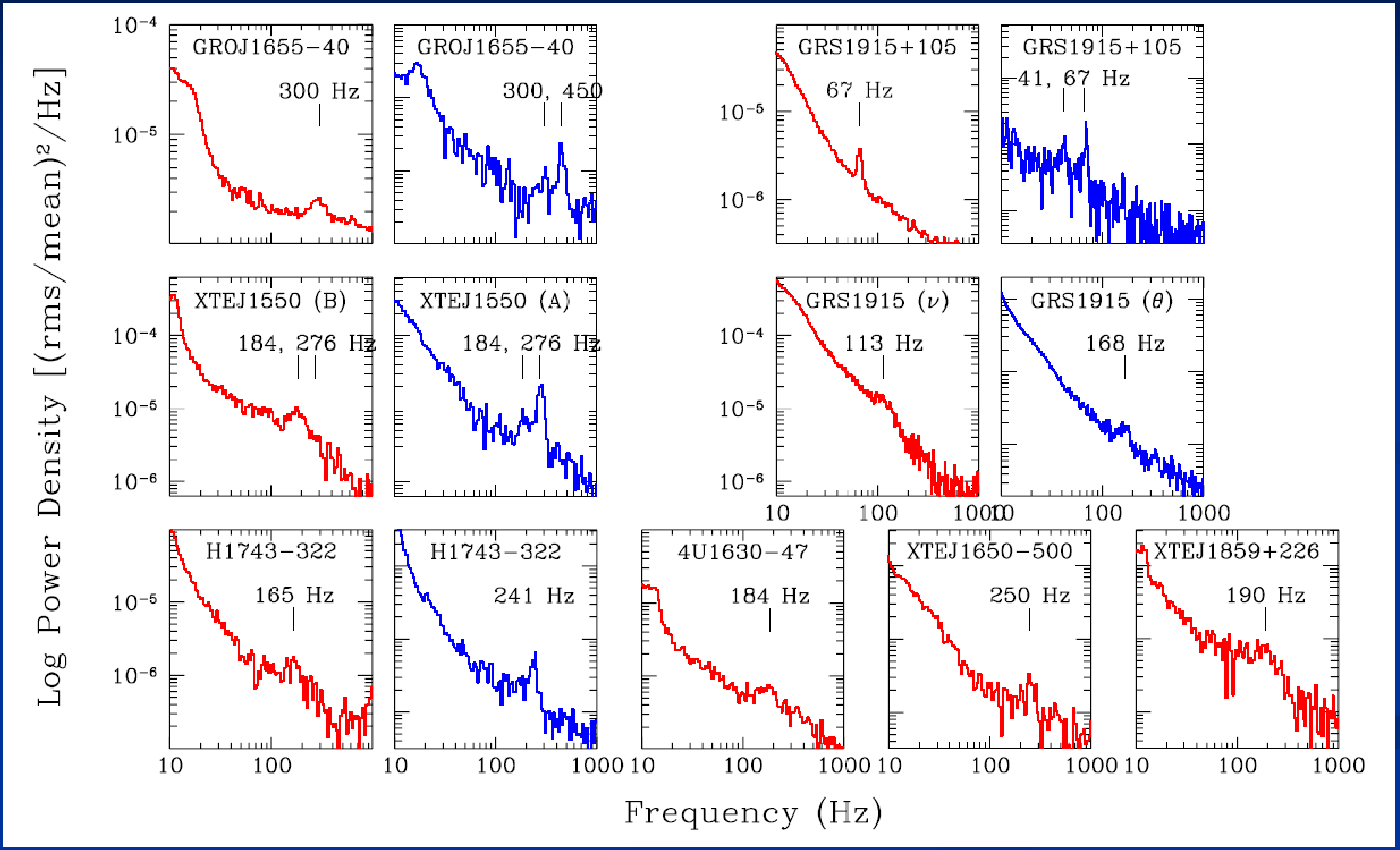
Belloni et al.



Mirabel & Rodriguez (1994,1999)

- Mass Accretion Rate sets luminosity?
- But then how to explain case of 2 states at same luminosity?
- Why only QPOs and Jets in Intermediate State and not Soft?

Black Hole X-ray Binary QPOs



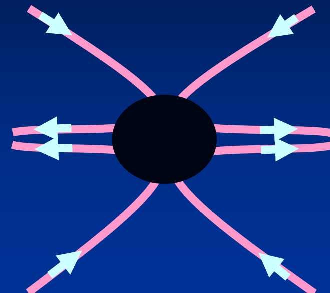
Black Hole X-ray Binary QPOs

Source	$M/M_{\odot}$	BH spin (method)	QPO f(Hz)	$Mf/10M_{\odot}$	BH spin (g-mode)
GRS1915+105	14.0±4.4(H)	$0.98<a<1.00$ (cont.,D)	41	57±18	$0.00<a<0.27$
		$0.97<a<0.99$ (line,F)	67	94±29	$0.00<a<0.72$
		$0.54<a<0.58$ (line,F)	**113**	158±50	$0.51<a<0.98$
			168	235±74	$0.82<a<1.00$
XTEJ1550-564	9.1±0.6(I)	$0.75<a<0.77$ (line,A)	92(?)	84±6	$0.13<a<0.46$
		$0.33<a<0.70$ (line,C)	**184**	167±11	$0.80<a<0.93$
		$0.00<a<0.71$ (cont.,C)	**276**	251±17	$0.98<a<1.00$
GROJ1655-40	6.3±0.5(J)	$0.65<a<0.75$ (cont.,E)	**300**	189±15	$0.86<a<0.98$
		$0.97<a<0.99$ (line,A)	**450**	284±23	No solution
		$0.90<a<1.00$ (line,B)			
Cyg X-1	14.8±1.0(K)	$0.97<a<1.00$ (cont.,G)	135	200±14	$0.90<a<0.99$
		$0.04<a<0.06$ (line,A)			
XTEJ1650-500	5±2(L,A?)	$0.78<a<0.80$ (line,A)	250	125±50(?)	$0.07<a<0.92$
XTEJ1859+226	9.7±2.5(?)		190	184±48(?)	$0.71<a<1.00$
	>5.4(M)			>103	$0.46<a$
H1743-322			**165**		
			241		
4U1630-472			184		

Note. Fundamental g-mode: $Mf/10M_{\odot} = F(a)[1-\varepsilon]$; $F = 71.4\text{-}246$, $\varepsilon \approx 0.1L/L_{Edd}$ $(0<L/L_{Edd}<0.5)$.

$\tau\sim$ 70-140 M – just like JD-QPO (a=0.6-0.98)

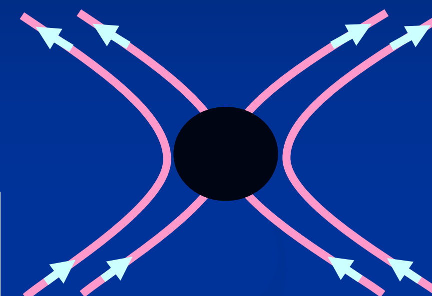
Origin of States, QPOs, and Transient Jet?



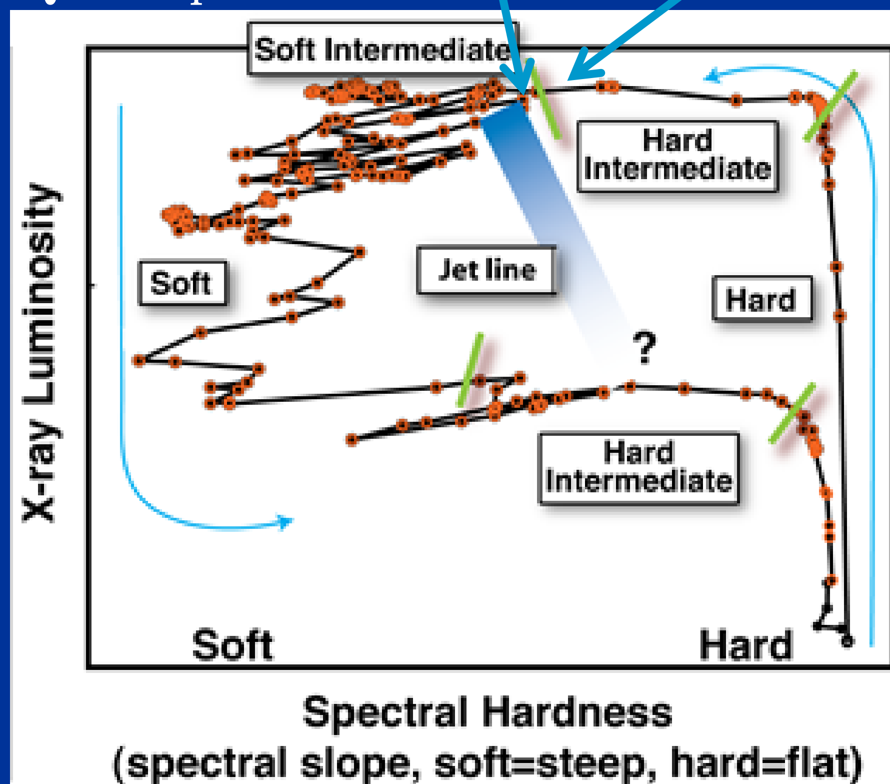
Mostly Quadrupolar

Transient Jet

HFQPOs



Mostly Dipolar



No Ordered Field

(mostly Toroidal)

Igumenshchev (2009) McKinney & Blandford (2009), McKinney, Tchekhovskoy, Blandford (2012)

Summary

- Magnetic Flux reaches Natural Saturation Point
- MRI is suppressed – not standard disk picture!
- Can explain most powerful Jets
- Might explain why QPOs in certain (SPL) disk state

- 2 parameters strongly control disk state:
  - Mdot & Magnetic Flux
  - State Transitions, Transient Jet, and QPOs?