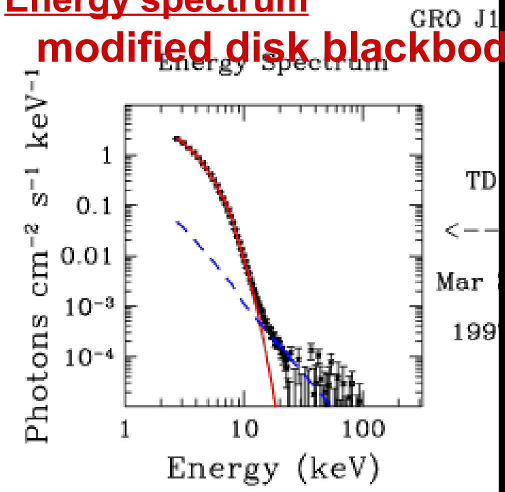
Thermal / Soft X-ray State

Energy spectrum

modified disk blackbody

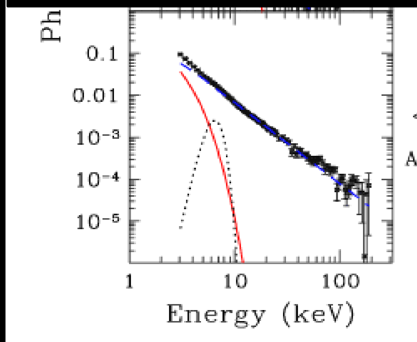


inner accretion disk

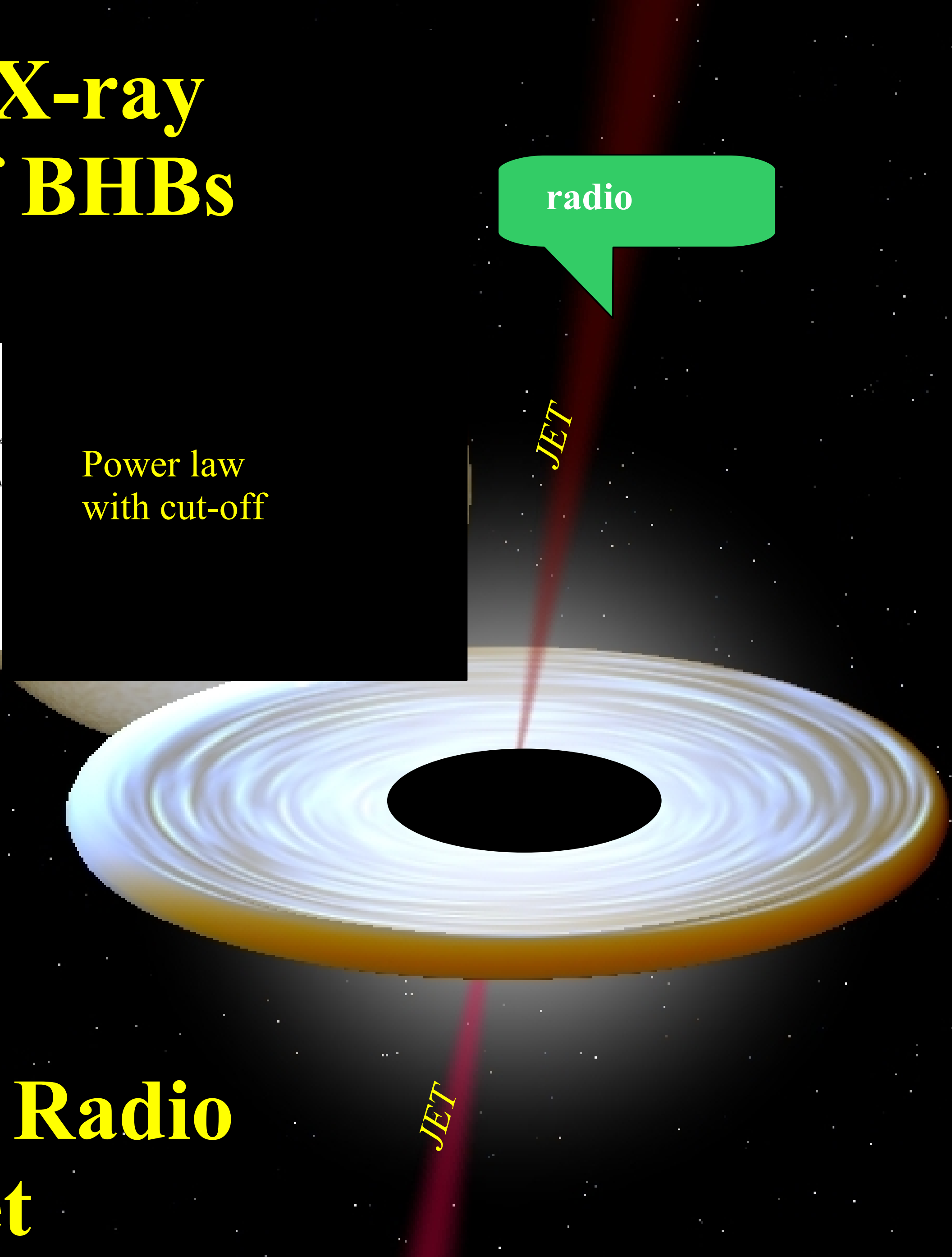
Soft state
no radio emission

Hard X-ray State of BHBs

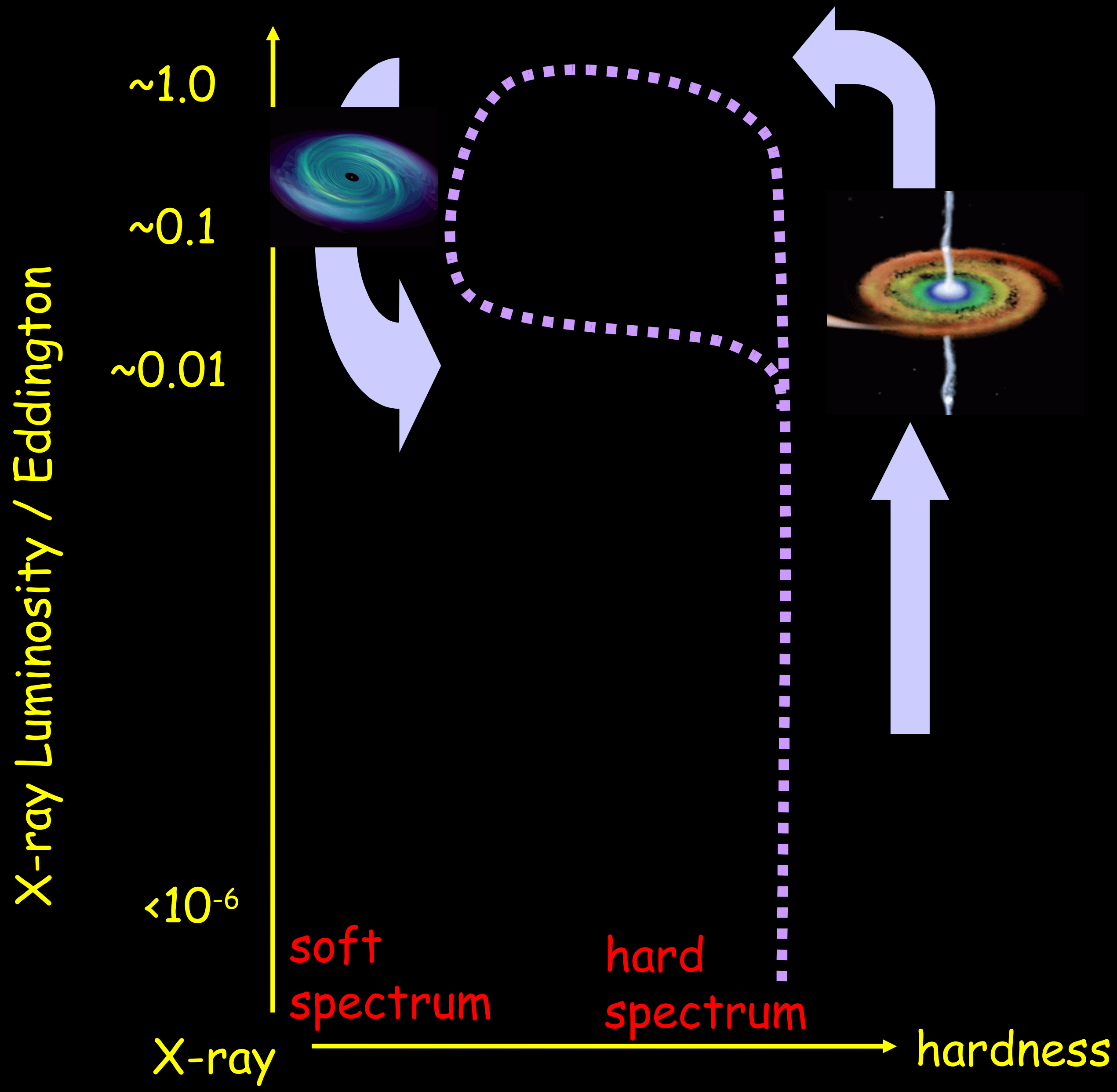
Energy spectrum



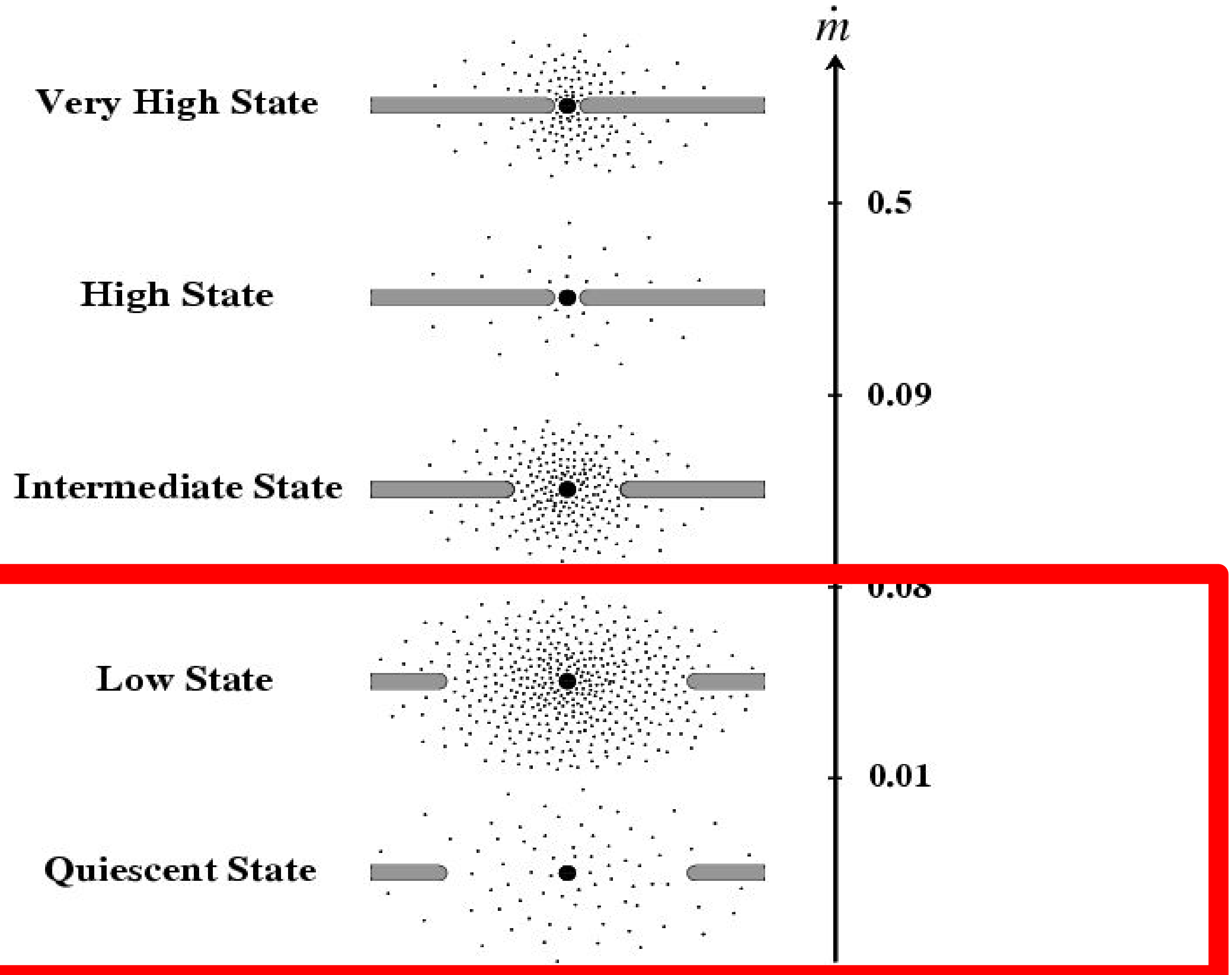
Power law
with cut-off



Steady Radio Jet



www.astro.lsa.umich.edu/Events/Meetings/mctpwww/.../Fender.ppt

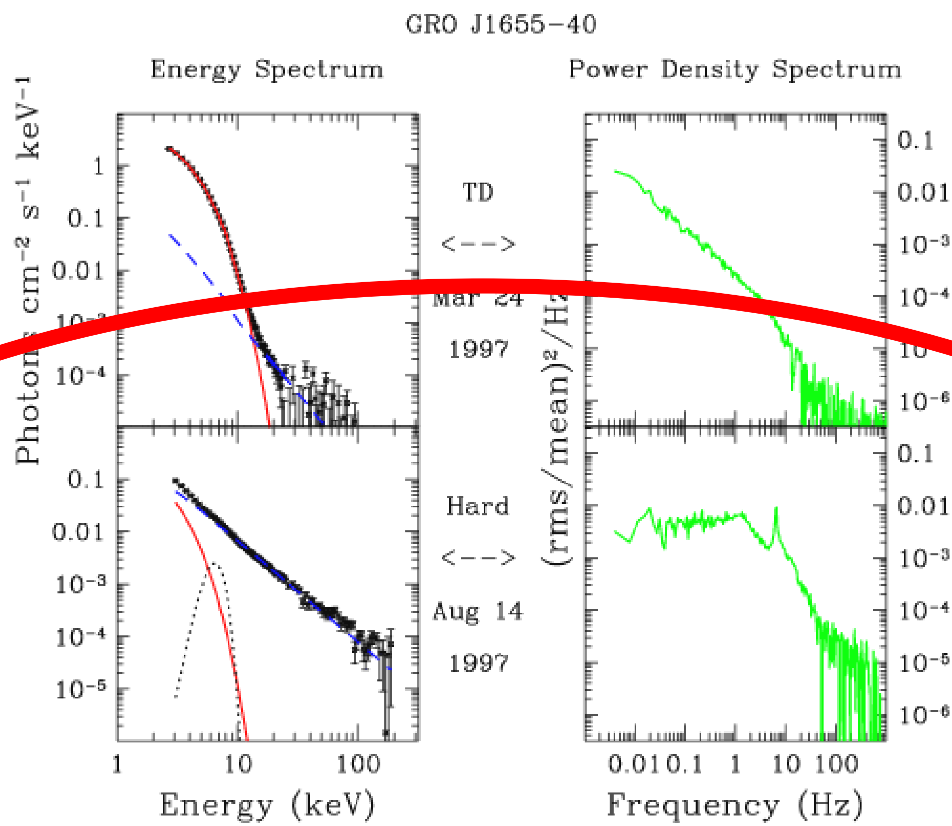


$\dot{m}$
Very High State
0.5
High State
0.09
Intermediate State
Low State
0.01
Quiescent State

Low / Hard State of BHBs

2. Hard State $f_{disk} < 20\%$; $\Gamma \sim 1.4 - 2.1$;

steady jet



For low accretion rates, the accreting plasma becomes so tenuous that the electrons and ions may lose thermal contact with each other (assuming that they are principally coupled via Coulomb collisions). The ions are very poor radiators; thus if most of the accretion energy is channeled to the ions rather than the electrons, it will not be radiated and instead remain as thermal energy advected along within the accretion flow.

In the so-called **Advection Dominated Accretion Flows (ADAFs),** this energy is advected right through the event horizon

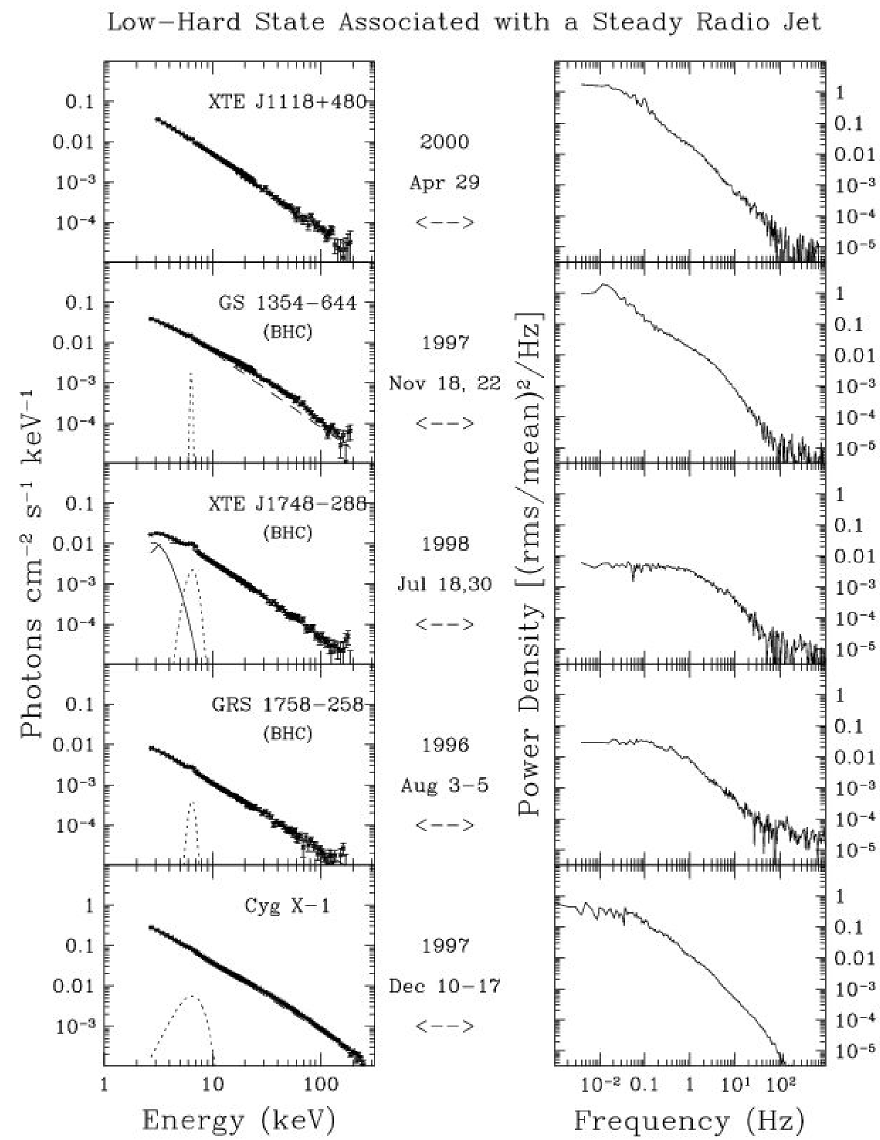
Such models were in fact first proposed to explain the hard state spectrum of Cyg X-1 , but were later applied to AGN , and they have been used to model the Galactic Center.

It was later realized that the situation described by these low luminosity ADAF models was dynamically unlikely leading to a powerful wind or strong convection. These suggestions **remain controversial and are the subject of active research** , but in any case, such a flow is likely to be extremely hot (electron temperatures of 10^9 K) and optically-thin.

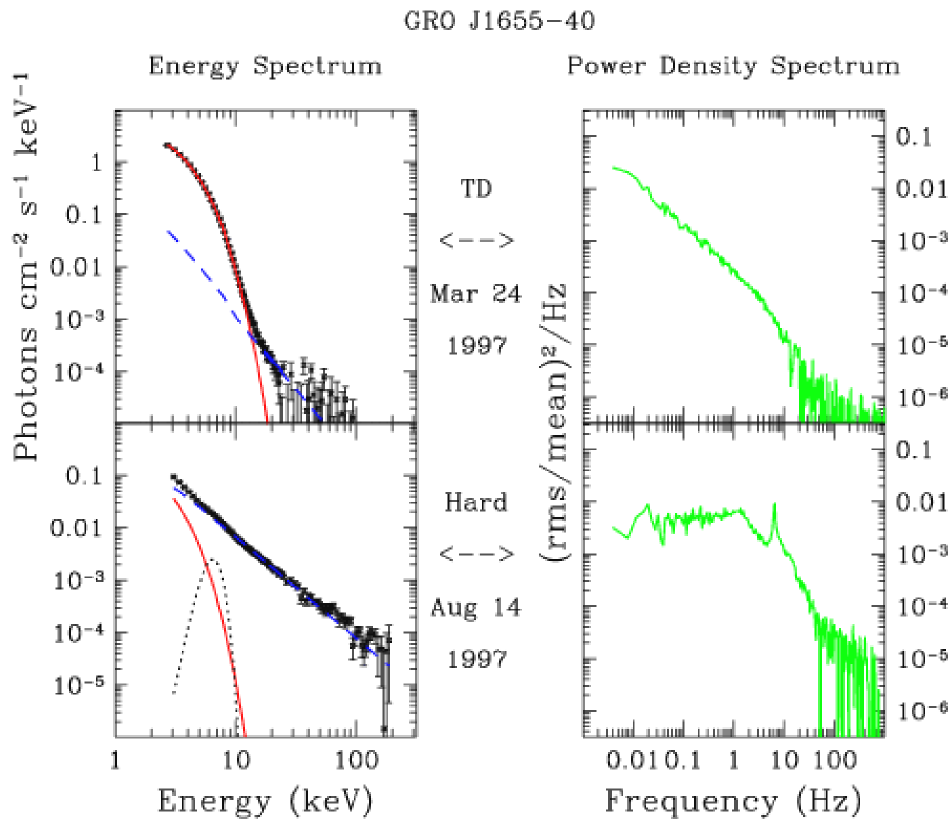
X-Ray States: McC & R

*Low/*Hard X-Ray State

- (*but* some sources show high luminosity)
- PL with $\Gamma \sim 1.7$
- broad enhancement at 20-100keV
- steep cut-off near 100keV
- compact quasi-steady radio jets present (disappear upon return to TD state)
- physical conditions that give rise to this state are still debated



Hard State of BHBs: Steady Radio Jet



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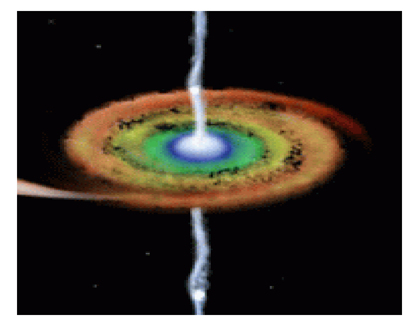


2. Hard State $f_{disk} < 20\%$; $\Gamma \sim 1.4 - 2.1$; $rms > 0.10$

radio : X-ray correlations: Corbel et al. 2000; Gallo et al. 2003

X-Ray States: McC & R

blackbody radiation truncated at large radius ~100R_g

what's going on inside this radius?

- truncated disk, inner region filled by ADAF?
- relativistic flow entrained in a jet?
- disk intact but depleted of energy in some sort of Compton corona?

answer could be found by

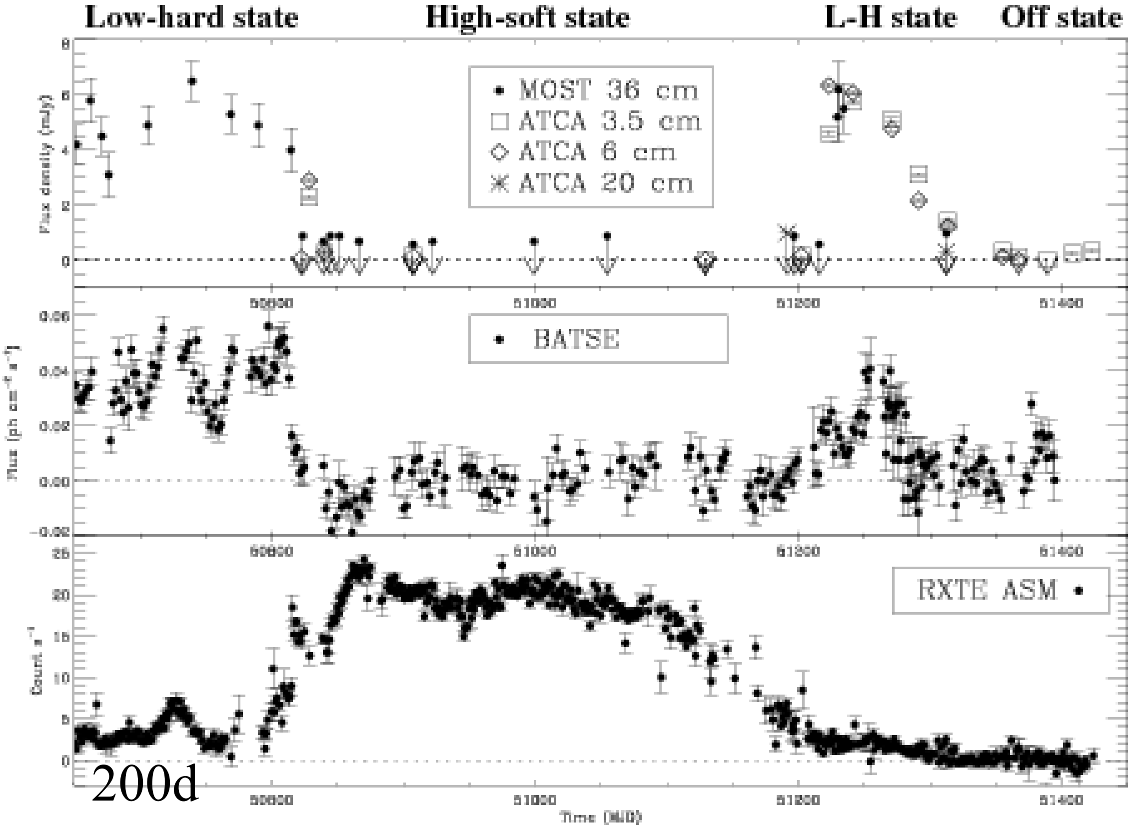
- optical/x-ray variability studies
- spectral analysis focused on broad Fe emission features

origin of x-ray PL also debated – many possible mechanisms

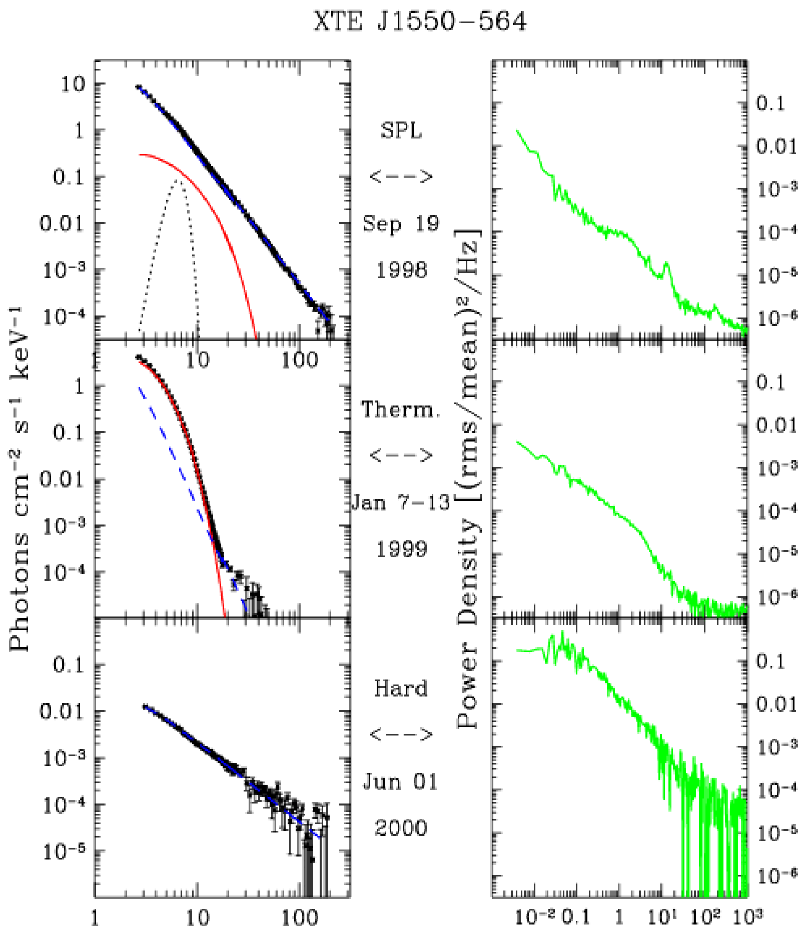
"Association of hard state with radio jet is an important step forward. […]

three conditions: spectrum dominated (>80% at 2-20keV) by power law, spectral index in the range 1.5 < Γ < 2.1

Hard State of BHBs: Steady Radio Jet



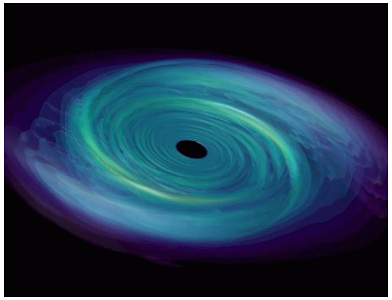
Physical Models for BHB States



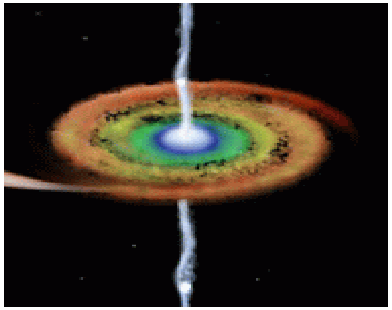
steep power law

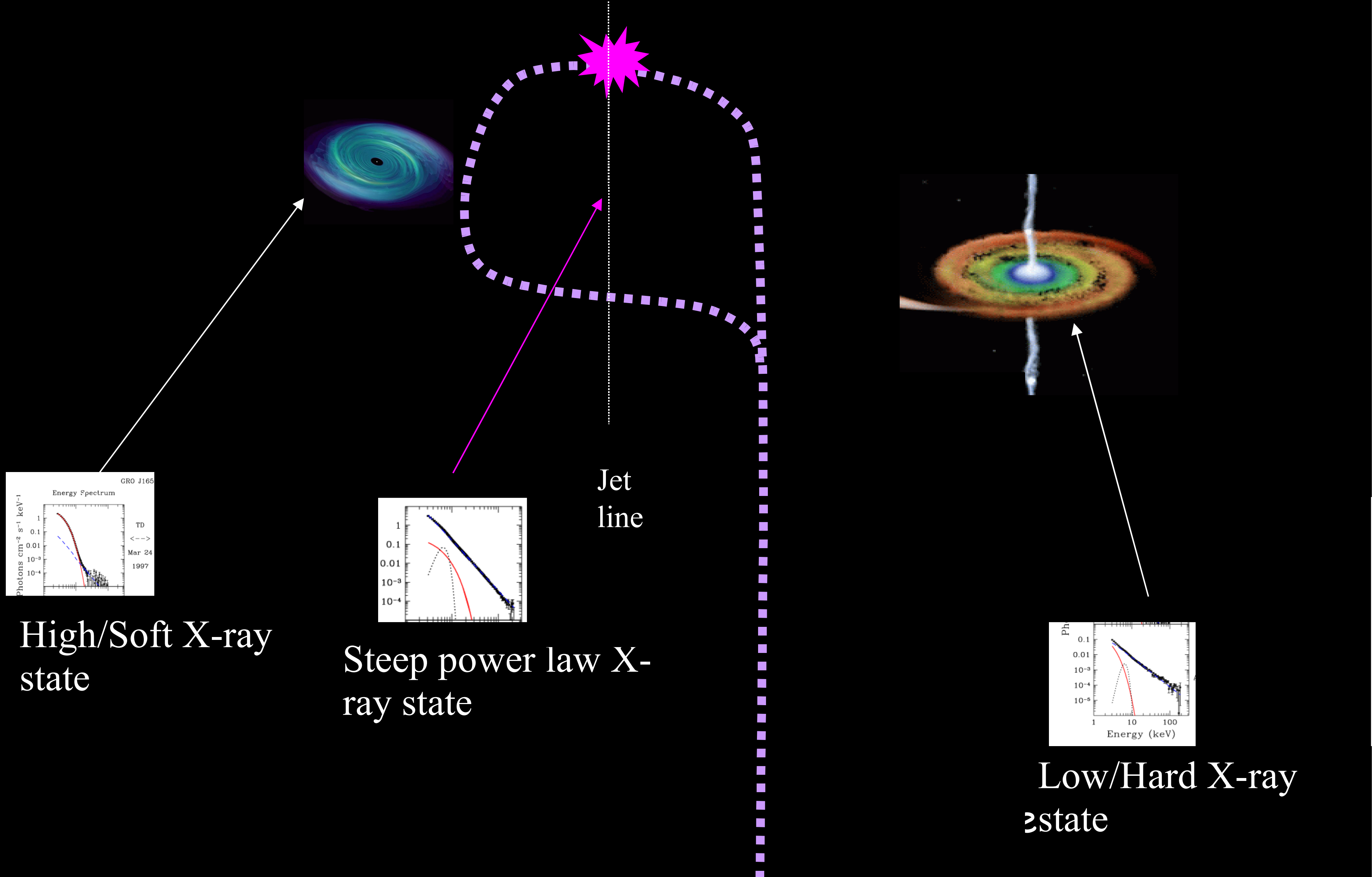
Disk + ??

thermal



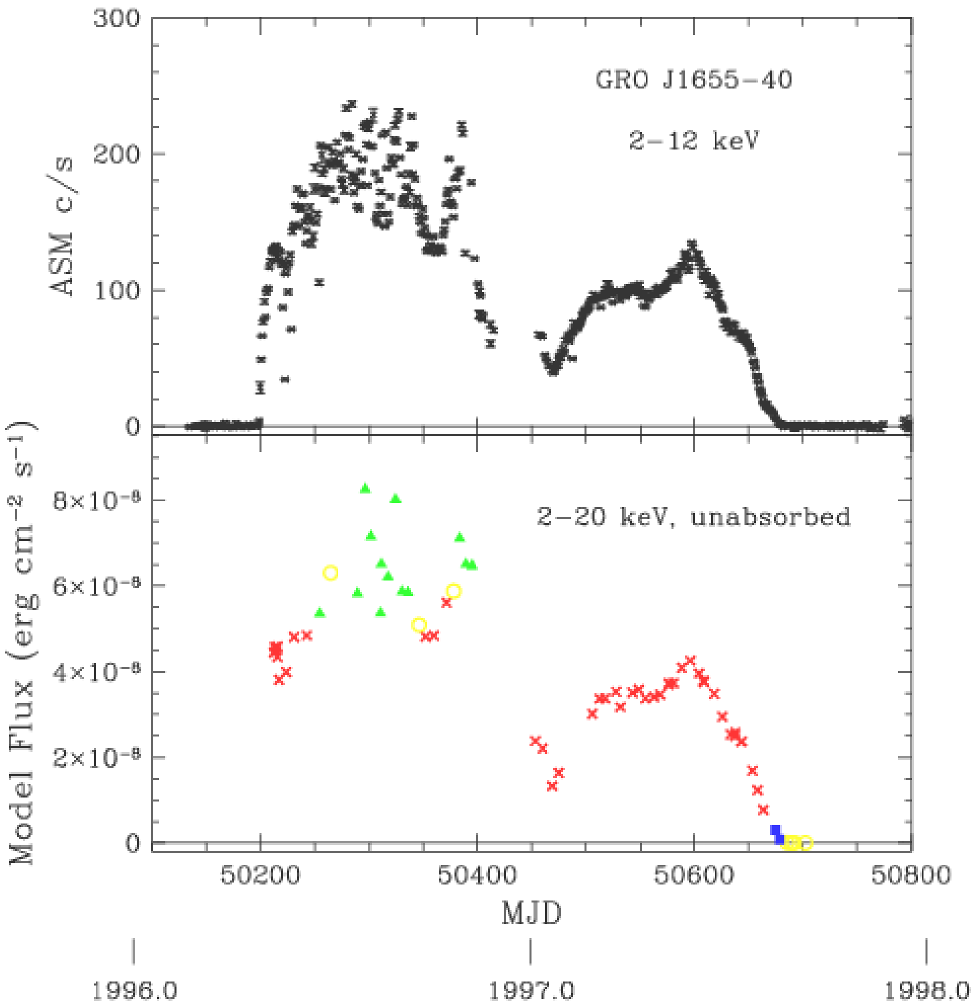
hard state





Fender, Belloni, & Gallo 2004

BH Outbursts & States



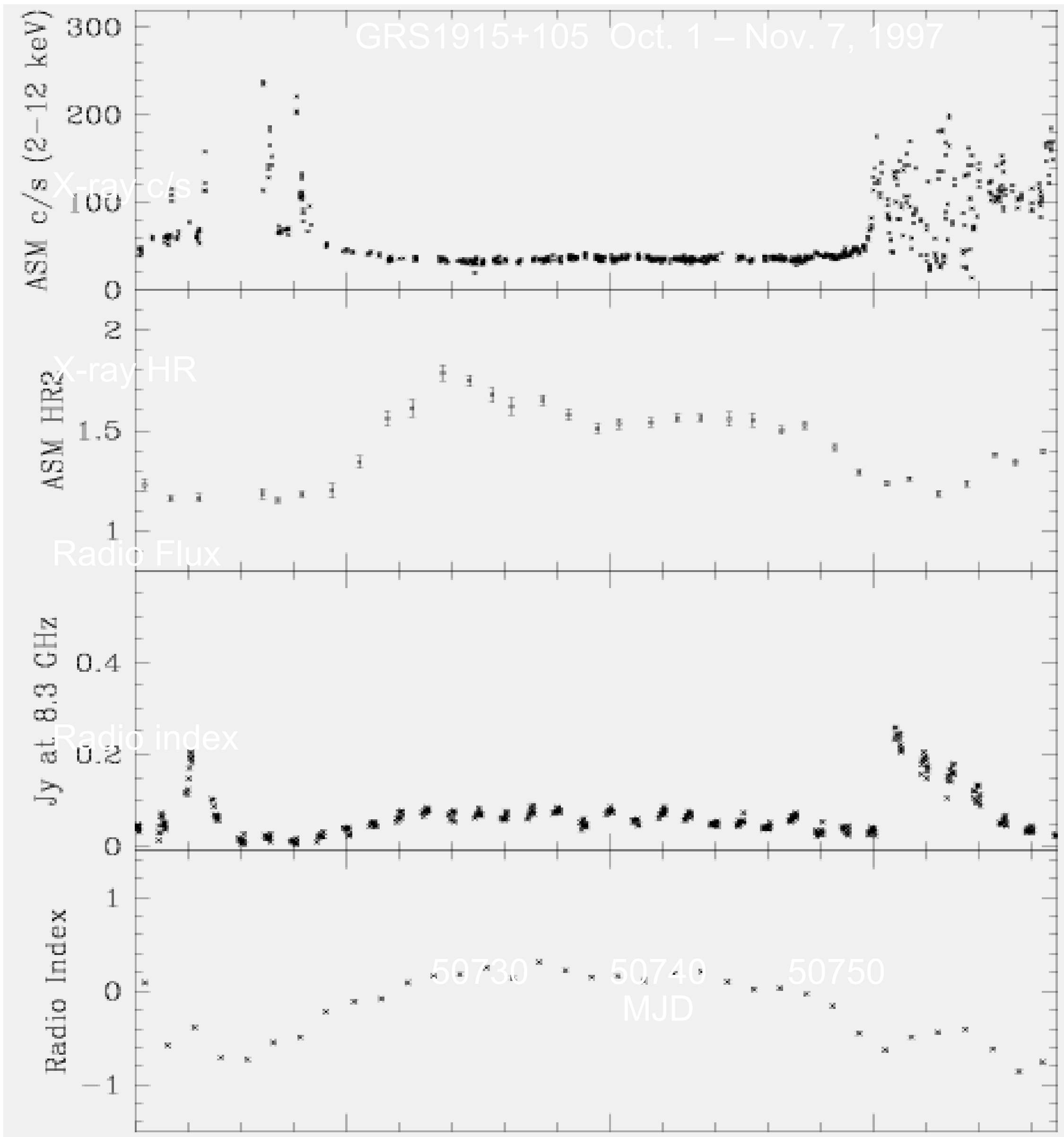
<u>**GRO J1655-40**</u>

Thermal x

Hard (jet) ■

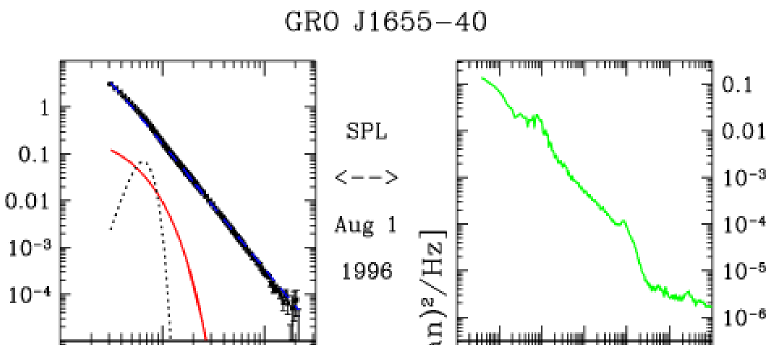
Steep Power Law Δ

Intermediate O


GRS1915+105 Oct. 1 – Nov. 7, 1997
X-ray c/s
ASM c/s (2–12 keV)
300
200
100
0
X-ray HR
ASM HR2
2
1.5
1
Radio Flux
Jy at 8.3 GHz
0.4
0.2
0
Radio index
Radio Index
1
0
−1
50730
50740
50750
MJD

States of Black Hole Binaries

3. steep power law



compact corona ?

$\Gamma > 2.4$;

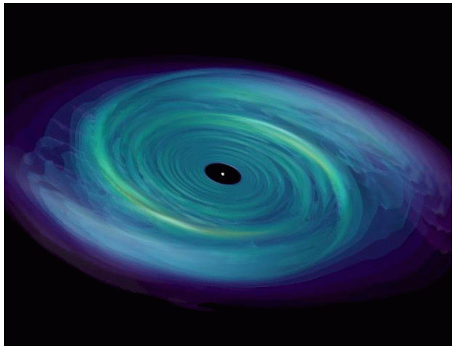
$f_{disk} < 80\%$ + QPOs (or $f_{disk} < 50\%$)

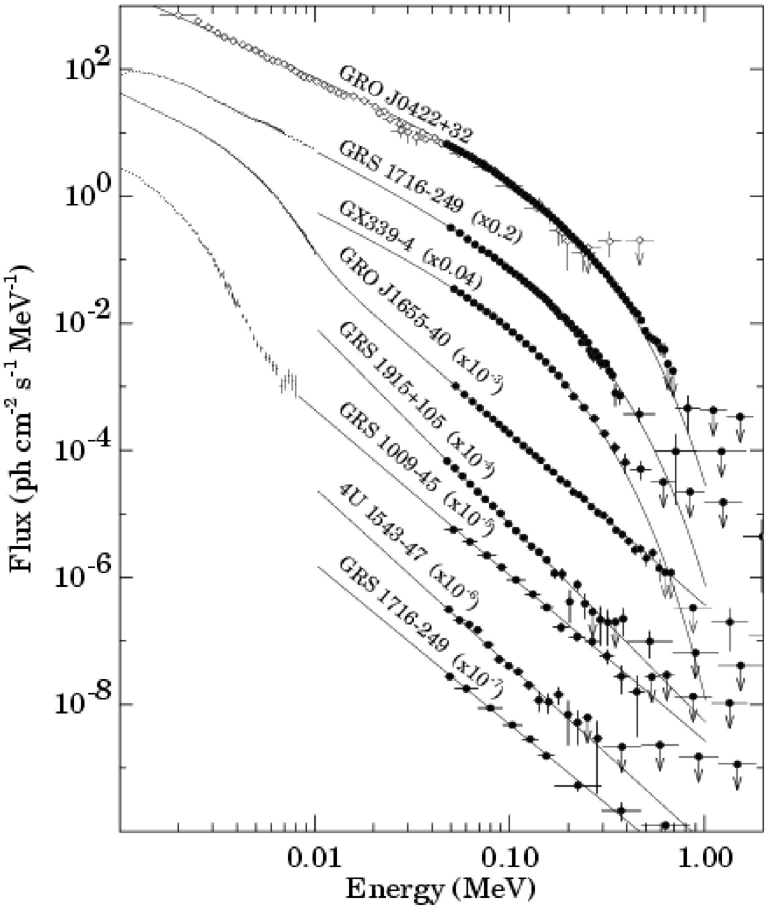
mechanism? : inverse Compton

origin? : magnetized disk ?

Neutron stars (atoll type) have thermal and hard States, but they never show SPL-dominated spectra

Steep Power Law





OSSE has observed seven transient black hole candidates: GRO J0422+32, GX339–4, GRS 1716–249, GRS 1009–45, 4U 1543–47, GRO J1655–40, and GRS 1915+105. Two gamma-ray spectral states are evident and, based on a limited number of contemporaneous X-ray and gamma-ray observations, these states appear to be correlated with X-ray states. The former three objects show hard spectra below 100 keV (photon number indices $\Gamma < 2$) that are exponentially cut off with folding energy $\sim$ 100 keV, a spectral form that is consistent with thermal Comptonization. This "breaking gamma-ray state" is the high-energy extension of the X-ray low, hard state. In this state, the majority of the luminosity is above the X-ray band, carried by photons of energy $\sim$100 keV. The latter four objects exhibit a "power-law gamma-ray state" with a relatively soft spectral index ($\Gamma \sim 2.5 - 3$) and no evidence for a spectral break. For GRO J1655–40, the lower limit on the break energy is 690 keV. GRS 1716–249 exhibits both spectral states, with the power-law state having significantly lower gamma-ray luminosity. The power-law gamma-ray state is associated with the presence of a strong ultrasoft X-ray excess (kT $\sim$ 1 keV), the signature of the X-ray high, soft (or perhaps very high) state. The physical process responsible for the unbroken power law is not well understood, although the spectra are consistent with bulk-motion Comptonization in the convergent accretion flow.

Grove, J.E., Johnson, W.N., Kroeger, R.A., McNaron-Brown, K., Skibo, J.G., \& Phlips, B.F.
1998, ApJ, 500, 899

We fit the average spectra using one of two general analytic spectral models, either a simple power law, or a power law that is exponentially truncated above a break energy:

$$f(E) = \begin{cases} A\,E^{-\Gamma} & E < E_b \\ A\,E^{-\Gamma}\,\exp(-(E-E_b)/E_f) & E > E_b \end{cases} \tag{1}$$

where A is the photon number flux, Γ is the photon number index, E_b is the break energy, and E_f is the exponential folding energy. Below the break energy, the exponential factor is replaced by unity, and the model simplifies to a power law. Best-fit model parameters are given in Table 2, along with the corresponding luminosities in the gamma-ray band (i.e. above 50 keV). Uncertainties in the model parameters are statistical only and reported as 68%-confidence intervals or 95%-confidence lower limits. If the simple power law is a statistically adequate fit, we report in Table 2 the photon number index from that model along with lower limits to E_b and E_f. Because of the strong correlation between these two parameters when neither is required by the data, to establish the lower limits we fixed $E_f = 2E_b$, since that relation roughly holds for GRO J0422+32.

Object	$<\Gamma>$	$\Delta\Gamma$	$<E_{break}>$ (keV)	$<E_{fold}>$ (keV)	ΔE_{fold} (keV)	$<L_\gamma>$ ($\times 10^{36}$ erg/s)	ΔL_γ ($\times 10^{36}$ erg/s)
Breaking gamma-ray state							
GRO J0422+32	1.49±0.01[a]		60±3[a]	132±2[a]	120–155	19.	14.–26.
GX339–4	1.38±0.08		<50	87±6	80–90	5.4	8.7–9.3
GRS 1716–249	1.53±0.06		<50	115±8	80–140	6.0	2.3–11.2
Power-law gamma-ray state							
GRS 1009-45	2.40±0.06	≃2.4	>160	>320		3.9	≃3.9
4U 1543–47	2.78±0.05	≃2.8	>200	>400		0.8	0.5–1.7
GRO J1655–40	2.76±0.01	2.6–3.0	>690	>1380		6.1	5.1–9.5
GRS 1716–249	2.42±0.08	≃2.4	>250	>500		1.1	0.6–1.7
GRS 1915+105	3.08±0.06	2.9–3.3	>390	>780		31.	27.–45.

Table 2: Best-fit model parameters

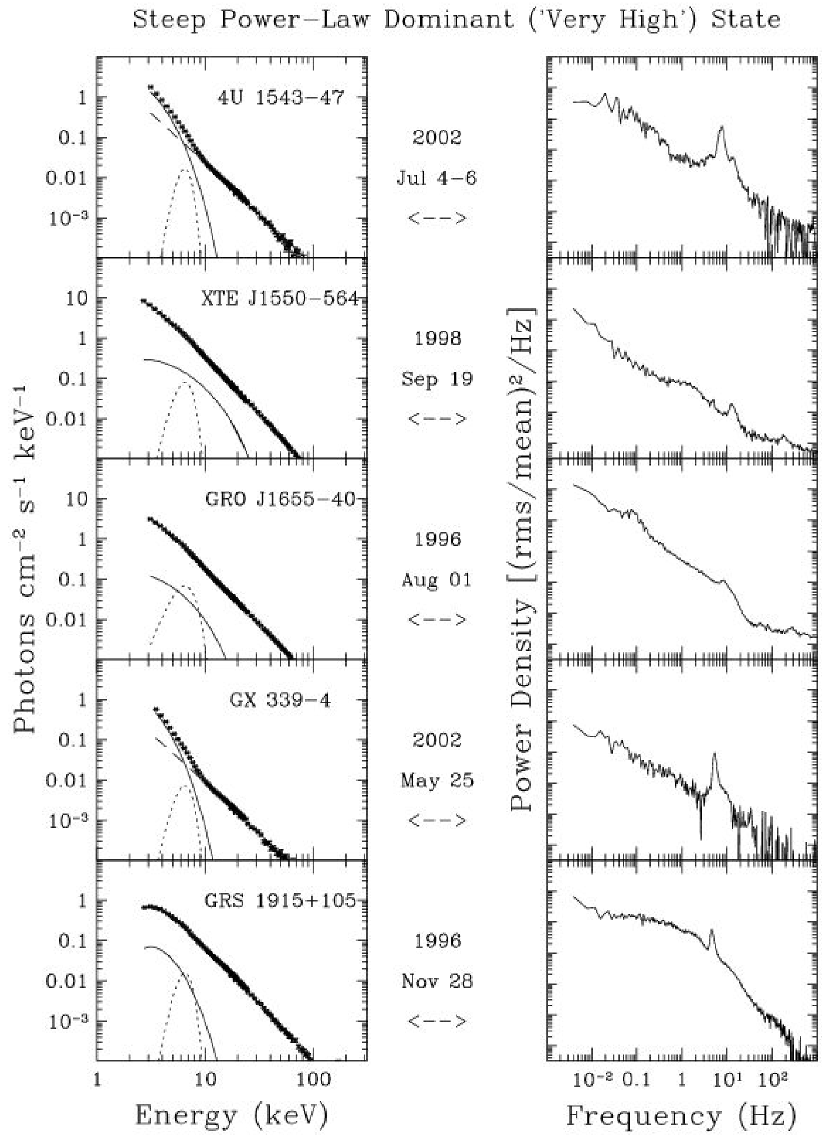
We have demonstrated the existence of two distinct spectral states of gamma-ray emission from galactic BHCs. The first state exhibits a relatively hard power-law component with photon index roughly 1.5 that breaks at ≃50 keV and is exponentially truncated with an e-folding energy of ≃100 keV. This "breaking gamma-ray" is firmly identified with the X-ray low, hard state, i.e. with the absence or weakness of an ultrasoft X-ray component. Sources exhibiting this spectral signature include GRO J0422+32 and GRS 1716–249, as well as GX 339–4 and Cyg X-1 in their X-ray low, hard states. The second state exhibits

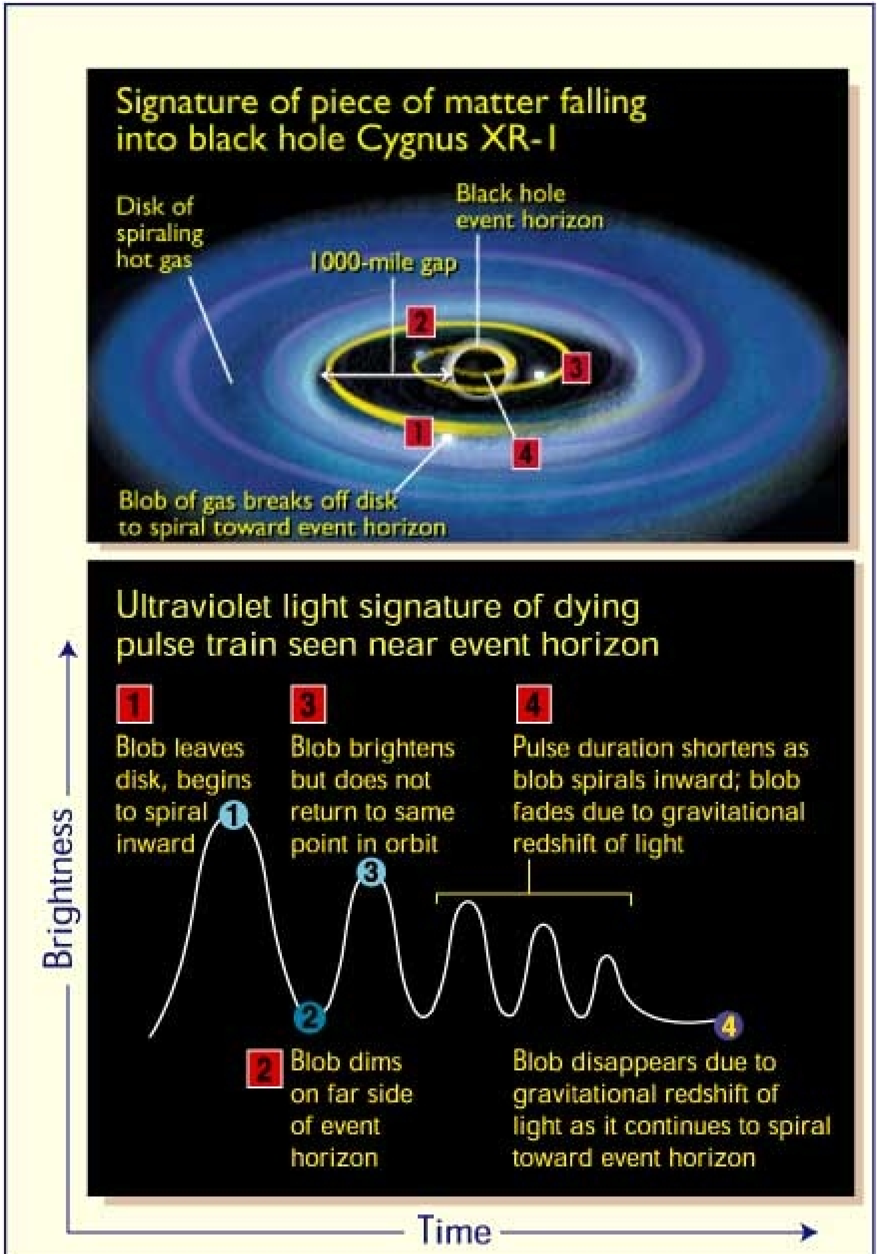
X-Ray States: McC & R

Steep Power-Law (SPL)

- new name for VHS
- often exceedingly bright ($L_x > 0.2 L_{Edd}$), but not always
- very steep unbroken (x-ray to gamma-ray) PL ($\Gamma \geq 2.4$)
- QPOs in *0.1–30* Hz range
- <u>no evidence for high-energy cutoff</u>
- transitions between TD and H states usually pass through SPL state
- essentially radio-quiet; <u>though sometimes shows impulsive</u> jets

McClintock, J. E. And Remillard, R. A. 2003, 2006





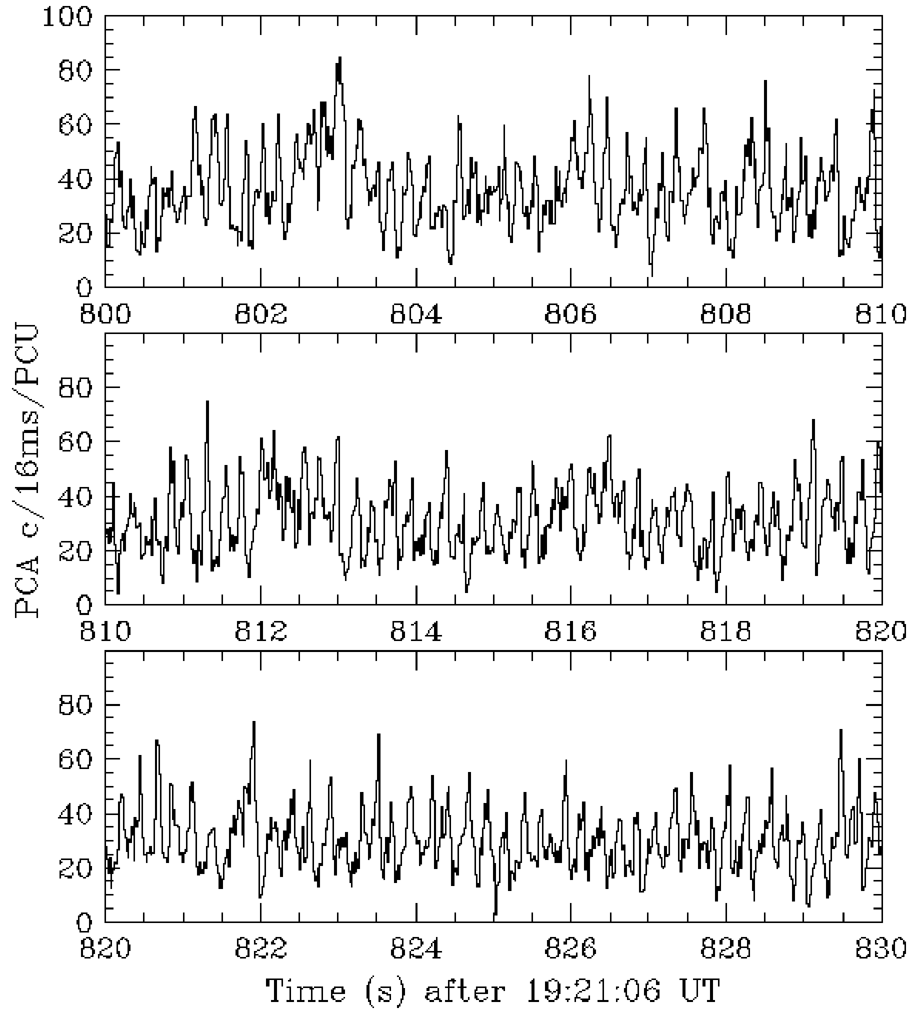
http://science.nasa.gov/headlines/images/blackhole/cygxr1w.jpg

Observation: X-ray pulses from accretion disks around black holes. Pulses have very short periods – as short as 0.00075 s. Because of the changing pulse period, these are called QPO's (quasi-periodic oscillations).

Explanation: Blobs of material near the surface of a neutron star or black hole emit x-rays while orbiting in the accretion disk.

Dolan, J.F. 2001, PASP, 113, 974

Low Frequency QPOs (0.05-30 Hz)



- **Accretion-Ejection Instability in disk** (magnetic spiral waves) (Tagger & Pellat 1999)

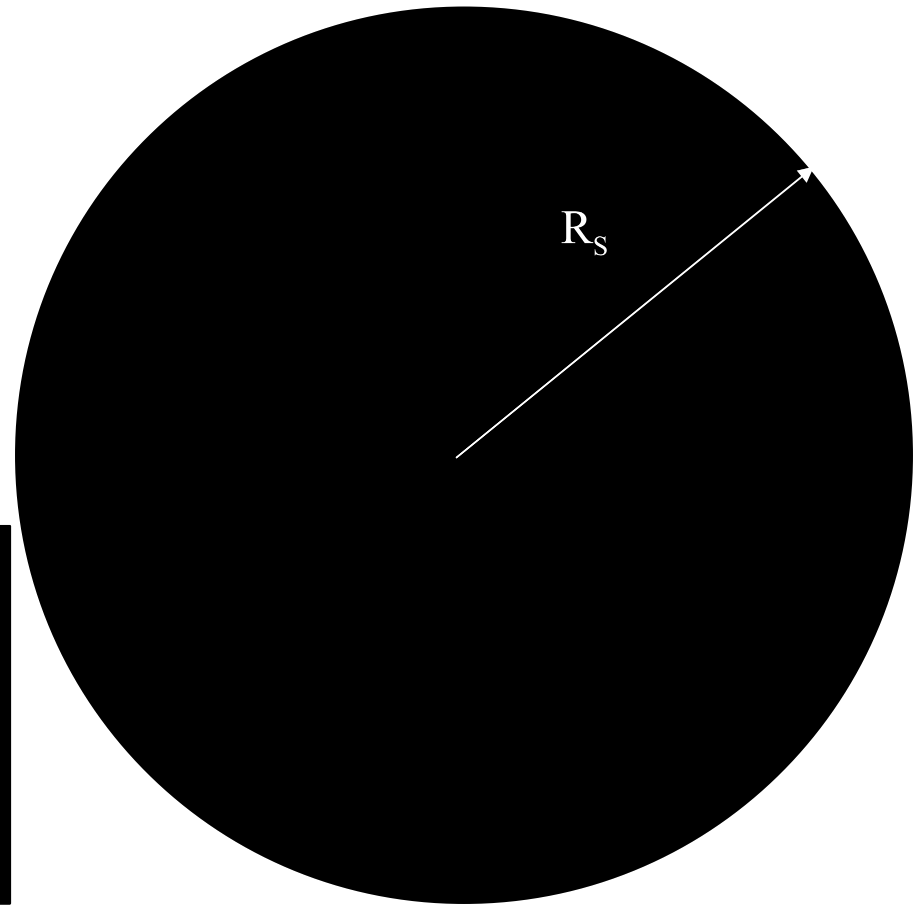
LFQPO Mechanisms

- Periastron precession of emitting blobs in **GR** (Stella et al. 1999)
- Frame Dragging in GR (Stella & Vietri 1998; Fragile et al. 2001)
- Global disk oscillations (Titarchuk & Osherovich 2000)
- Alfven waves (C.M. Zhang et al. 2005)
- Accretion-Ejection Instability in disk (magnetic spiral waves) (Tagger & Pellat 1999)

The Event Horizon of a Non-rotating (Schwarzschild) Black Hole

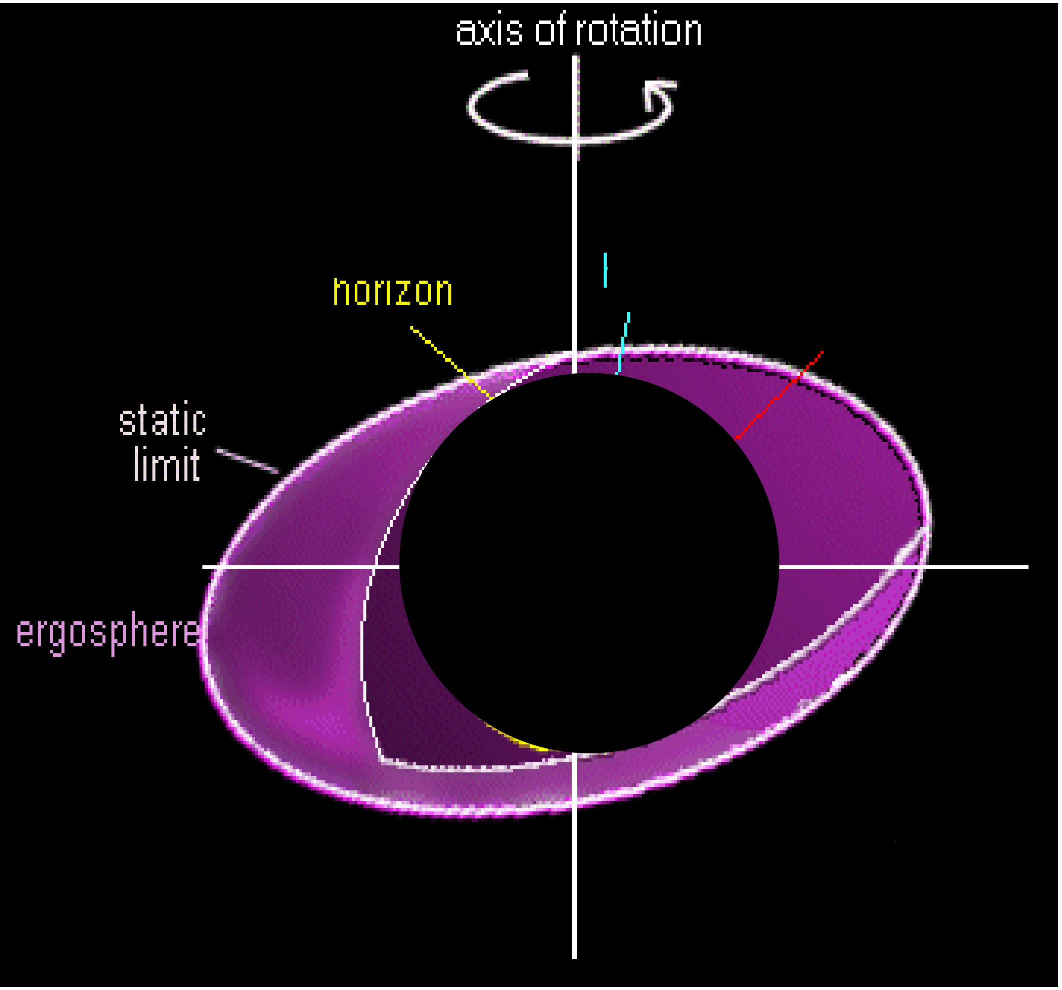
If the core of a dead star has a mass greater than about $3M_e$, nothing can stop it from collapsing to zero volume; it becomes a "singularity".

According to general relativity, the singularity is enclosed by a spherical surface called the event horizon. The radius of the event horizon, R_s, is called the Schwarzschild radius.



$$R_s = \frac{2GM}{c^2}$$

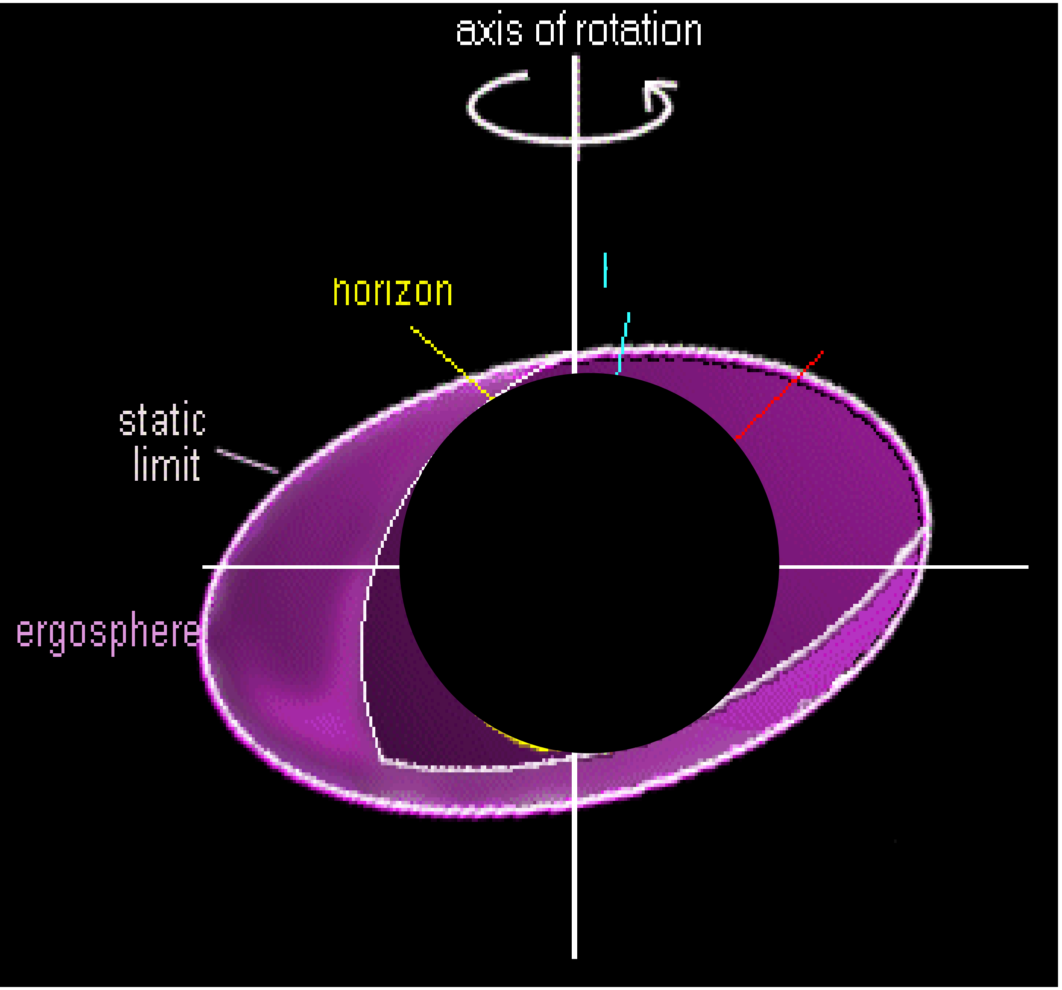
$$R_s = (3.0\text{km})\,M$$



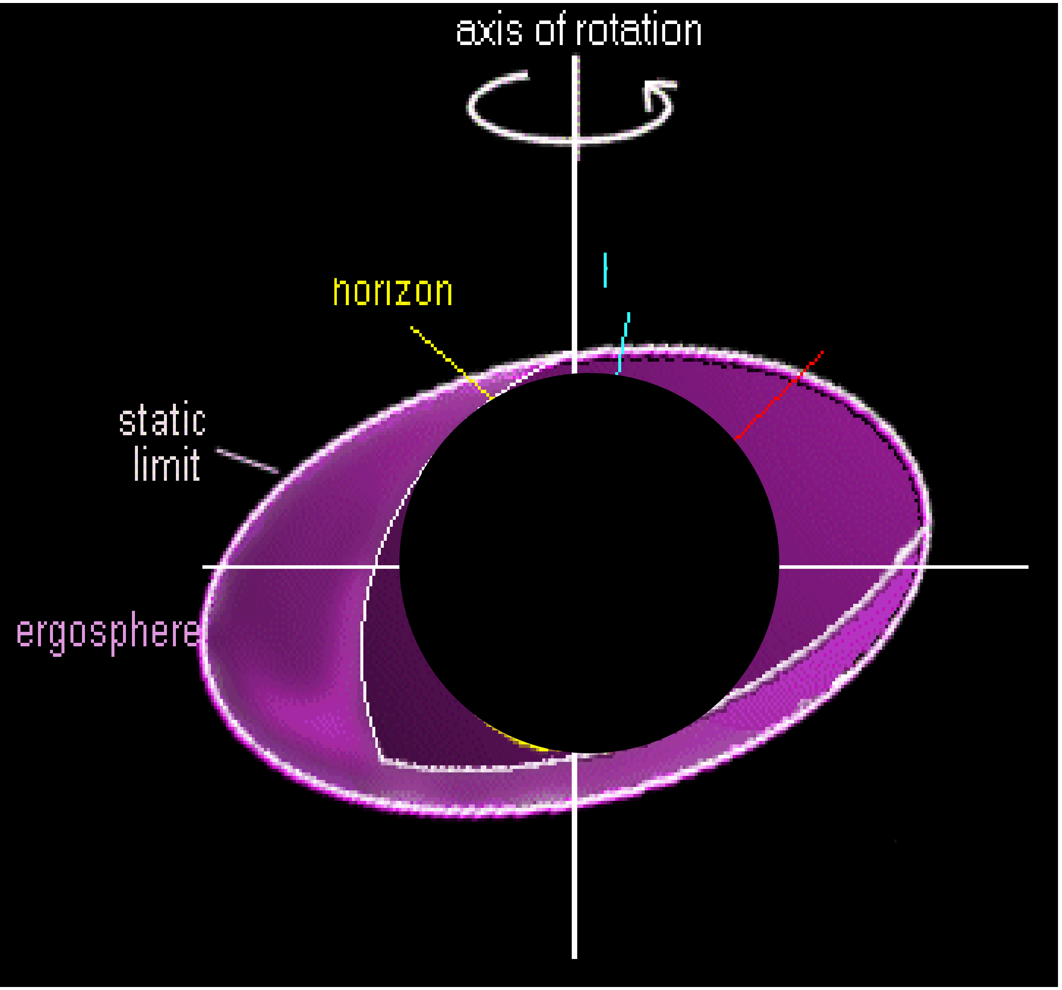
Like the Schwarzschild black hole, the Kerr black hole has an event horizon.

The radius of the event horizon is dependent both on the mass and the angular momentum of the black hole.
For a given mass, the circumference of the event horizon is at its maximum for zero angular momentum.
The circumference falls as the magnitude of the angular momentum rises.

At the maximum angular momentum, a minimum circumferences of half the maximum circumference is found.

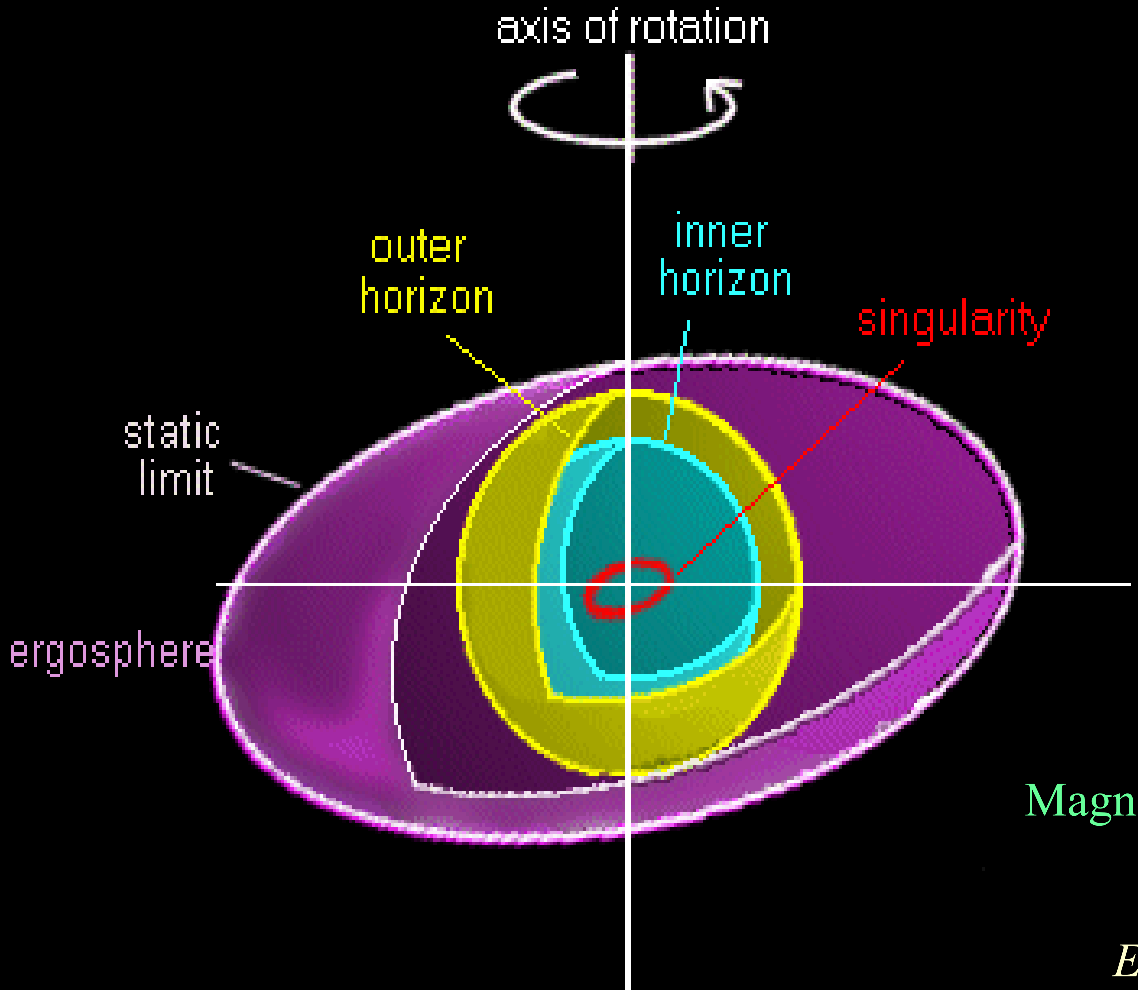


The striking feature of a spinning black hole is that the gravitational field pulls objects around the black hole's axis of rotation. This effect, called frame dragging in the jargon of general relativity, prevents an accelerating observer close to the black hole's event horizon from holding a fixed position relative to the stars. Regardless how much he accelerates, the observer is incapable of stopping his motion around the black hole, although he can keep a fixed distance above the event horizon.



The boundary surrounding the black hole that separates the space where an accelerating observer can remain static with the distant stars from the space where no amount of acceleration can keep an observer at a static location is called the static limit. This boundary touches the event horizon at the poles, but it extends much farther out than the event horizon away from the poles, reaching its maximum radius at the black hole's equatorial plane. The volume enclosed between the event horizon and the static limit is called the ergosphere.

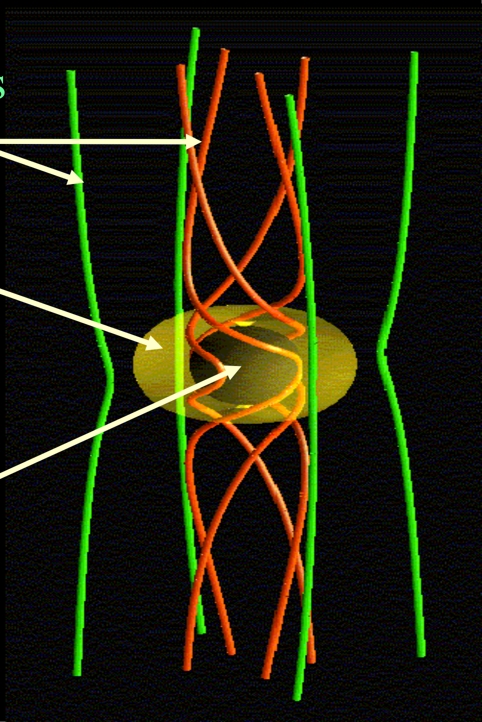
Kerr Black Hole



Magnetic Field Lines

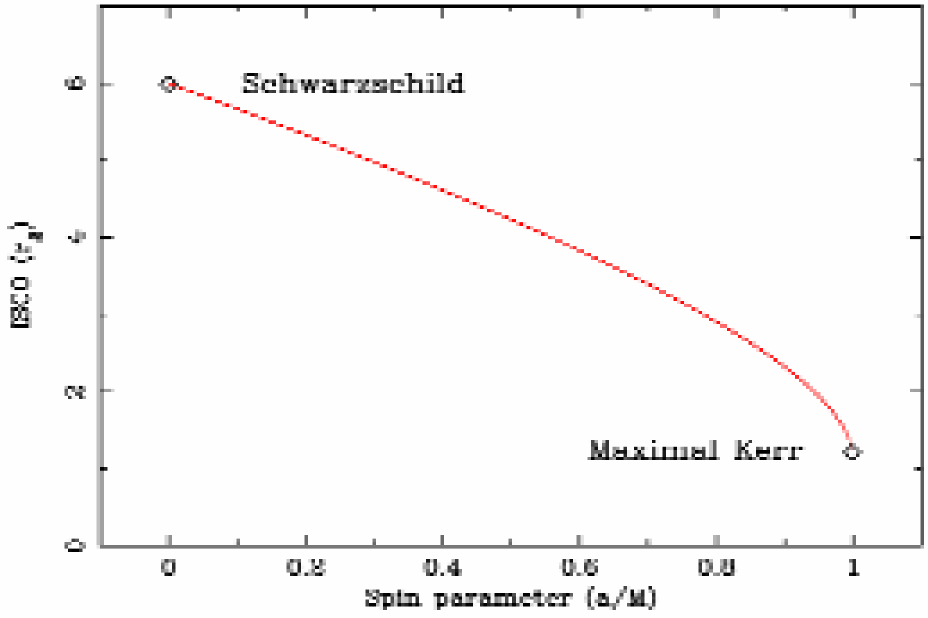
Ergosphere

Black Hole

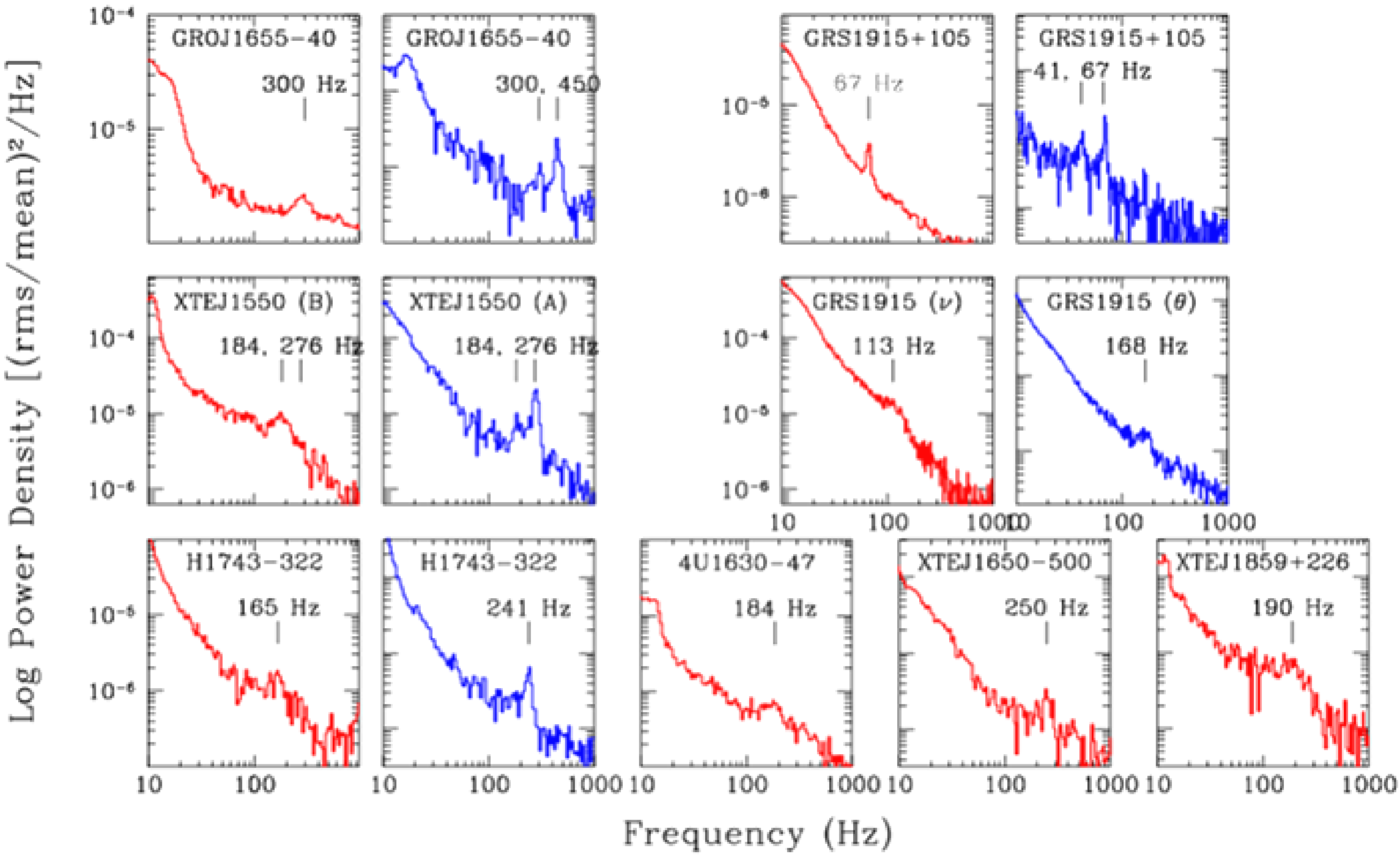


Black hole spin

Innermost stable circular orbit (ISCO) moves in from $6GM/c^2$=6m for non-spinning BH towards 1m for spinning (Kerr) BH



High Frequency QPOs (40-450 Hz)



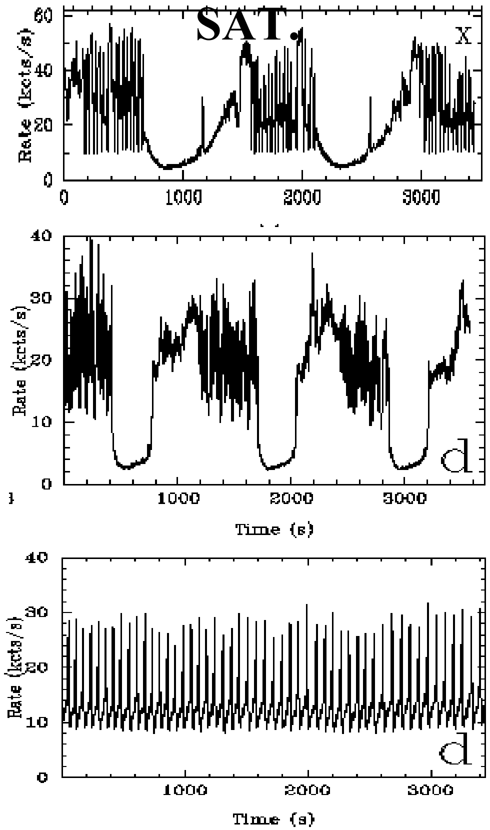
High Frequency QPOs

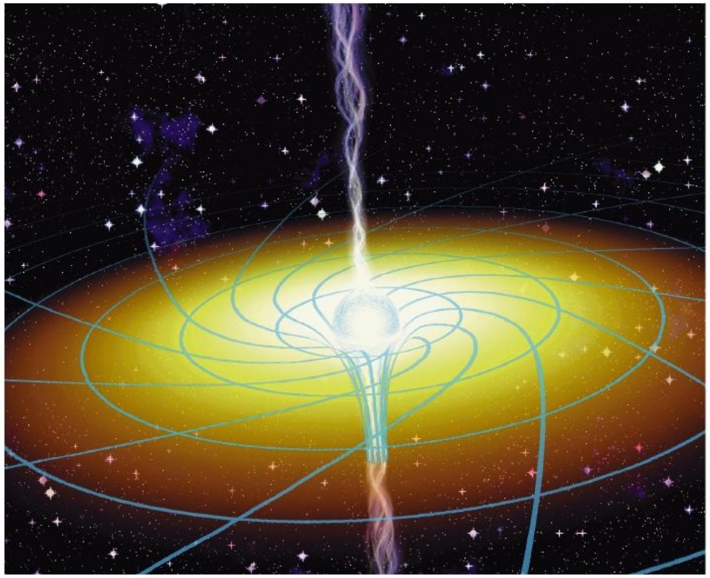
source	HFQPO ν (Hz)
GRO J1655-40	300, 450
XTE J1550-564	184, 276
GRS 1915+105	41, 67, 113, 168
XTE J1859+226	190
4U1630-472	184 + broad features (Klein-Wolt et al. 2003)
XTE J1650-500	250
H1743-322	166, 242

ISCO for 10 M_o BH: ν_ϕ = 220 Hz (a_* = 0.0) → 728 Hz (a_* = 0.9)

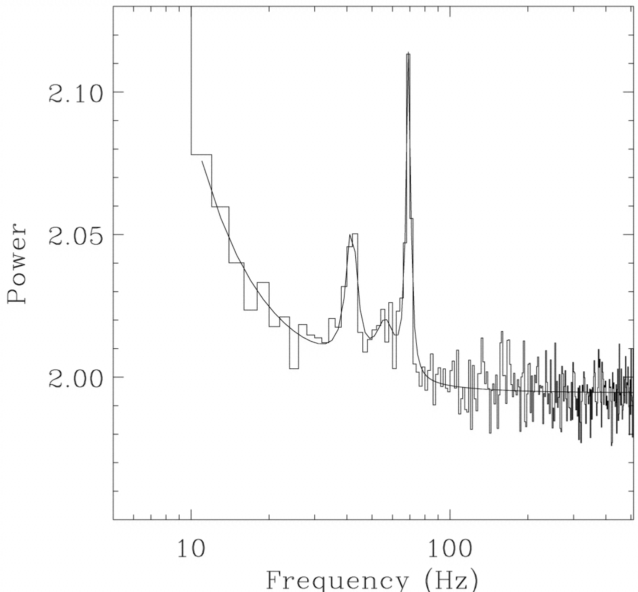
(Schnittman & Bertschinger 2004)

XTE & INDIAN SAT.





GRS 1915+105 (Strohmayer)



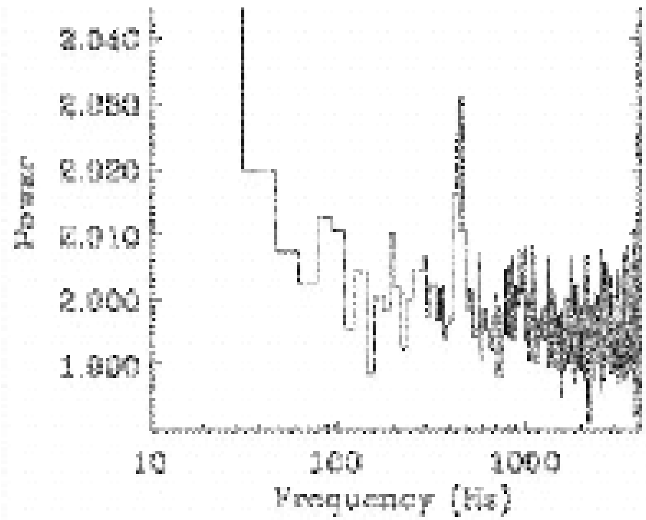
•High frequency QPOs (e.g. 40 & 67 Hz repeat in GRS)

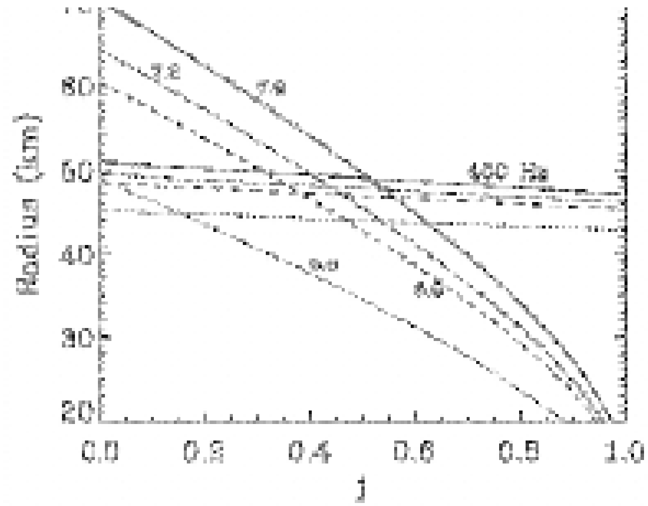
Jerome Rodriguez et al.

$\nu_{max} = f(M_{BH}, \text{Spin}) \Rightarrow$ DETERMINE THE SPIN OF BLACK HOLES

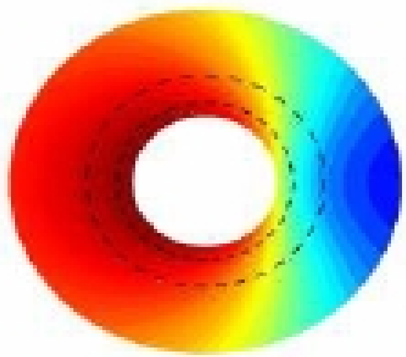
QPO in GRS J1655-40
Strohmayer ApJ 2001

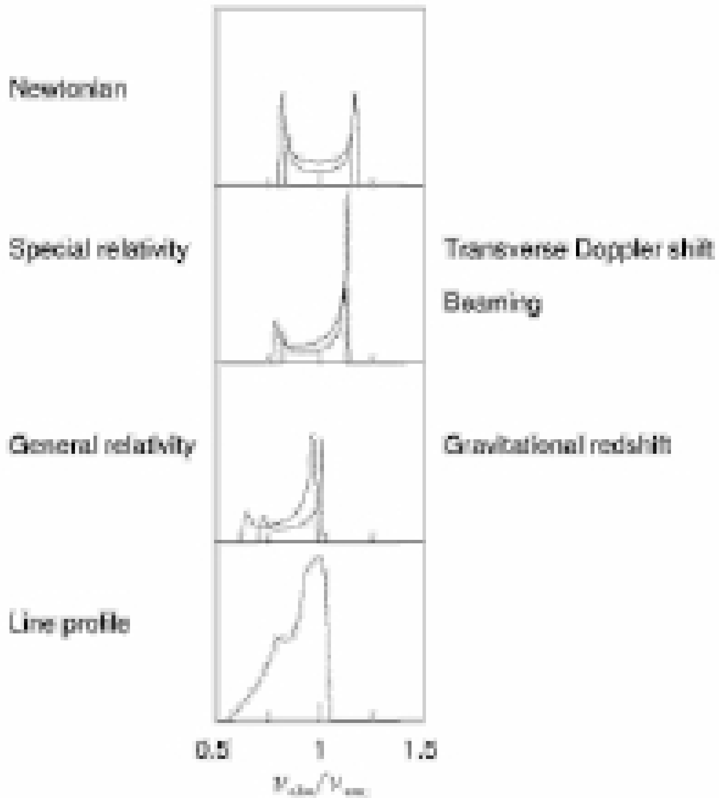
We report the discovery with the Proportional Counter Array on board the Rossi X-Ray Timing Explorer of a **450 Hz quasi-periodic oscillation (QPO)** in the hard X-ray flux from the Galactic microquasar GRO J1655-40.

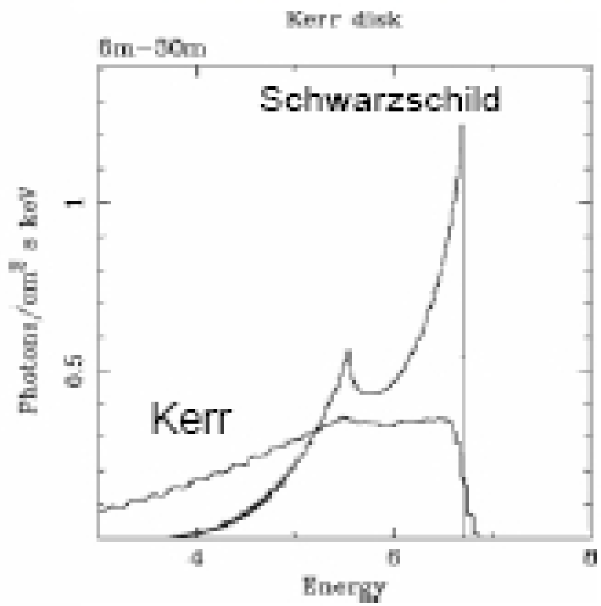




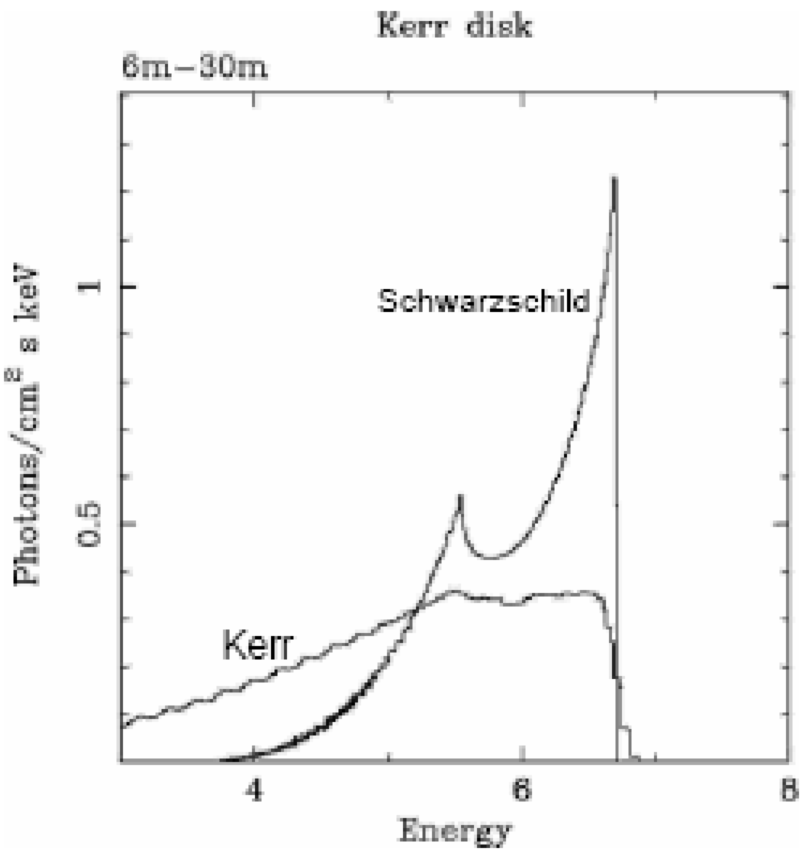
For a nonrotating black hole with mass between 5.5 and 7.9 Msolar, the innermost stable circular orbit (ISCO) ranges from 45 to 70 km. For any mass in this range the radius at which the orbital frequency reaches 450 Hz is less than the ISCO radius, indicating that, **if the modulation is caused by Kepler motion,** the black hole must have appreciable spin. If the QPO frequency is set by the orbital frequency of matter at the ISCO, then for this mass range the dimensionless angular momentum lies in the range 0.15<j<0.5. Moreover, if the modulation is caused by oscillation modes in the disk or Lense-Thirring precession, then this would also require a rapidly rotating hole.





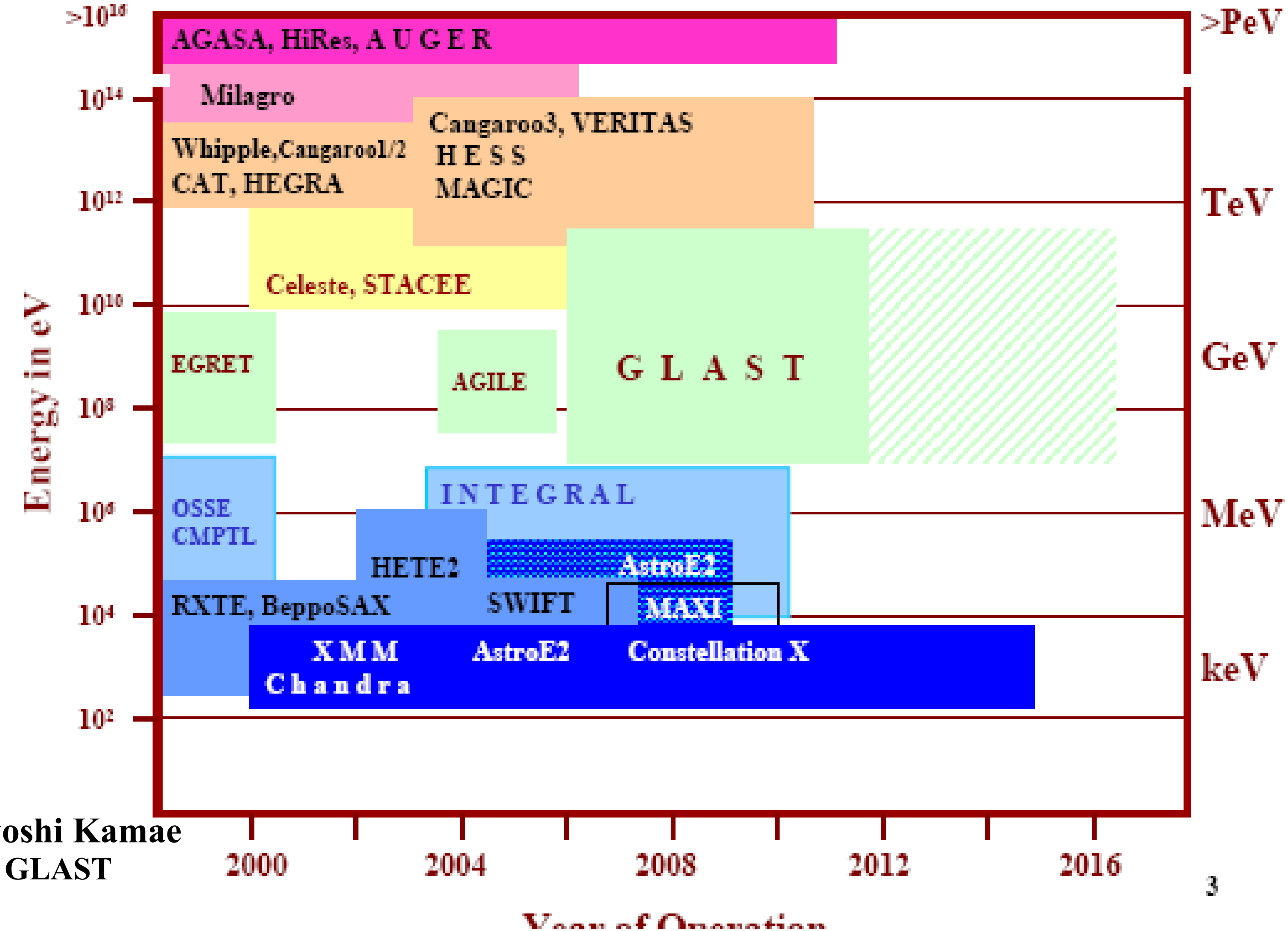


Fabian+89, Laor 90...
Dovciak+04; Beckwith+Done05



Iron line extending below 4 keV generally implies a spinning Kerr BH (spin parameter from r_{ms})
(mag field caveat on ISCO: Gammie, Krolik...)

Gamma-ray Observatories in Next Decade



Tuneyoshi Kamae
SLAC, GLAST Group

Cherenkov Technique

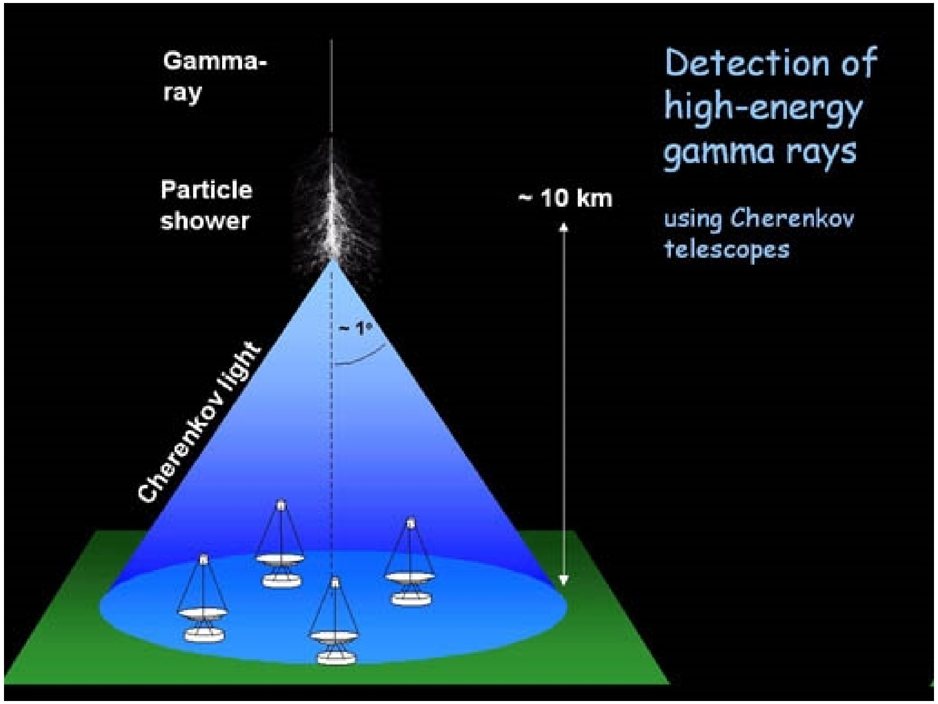
Imaging Atmospheric Cherenkov Telescopes (IACTs):

Telescopes like HESS, MAGIC and VERITAS observe the Cherenkov signal from γ-ray induced showers

When a very high-energy gamma ray strikes the atmosphere a cascade of relativistic charged particles is produced .

This shower of charged particles is initiated at an altitude of 10–20 km.

The cascade of charged particles produces a flash of Cherenkov radiation lasting between 5 and 20 ns. The total area on the ground illuminated by this flash corresponds to many hundreds of square meters, which is why the effective area of IACT telescopes is so large.

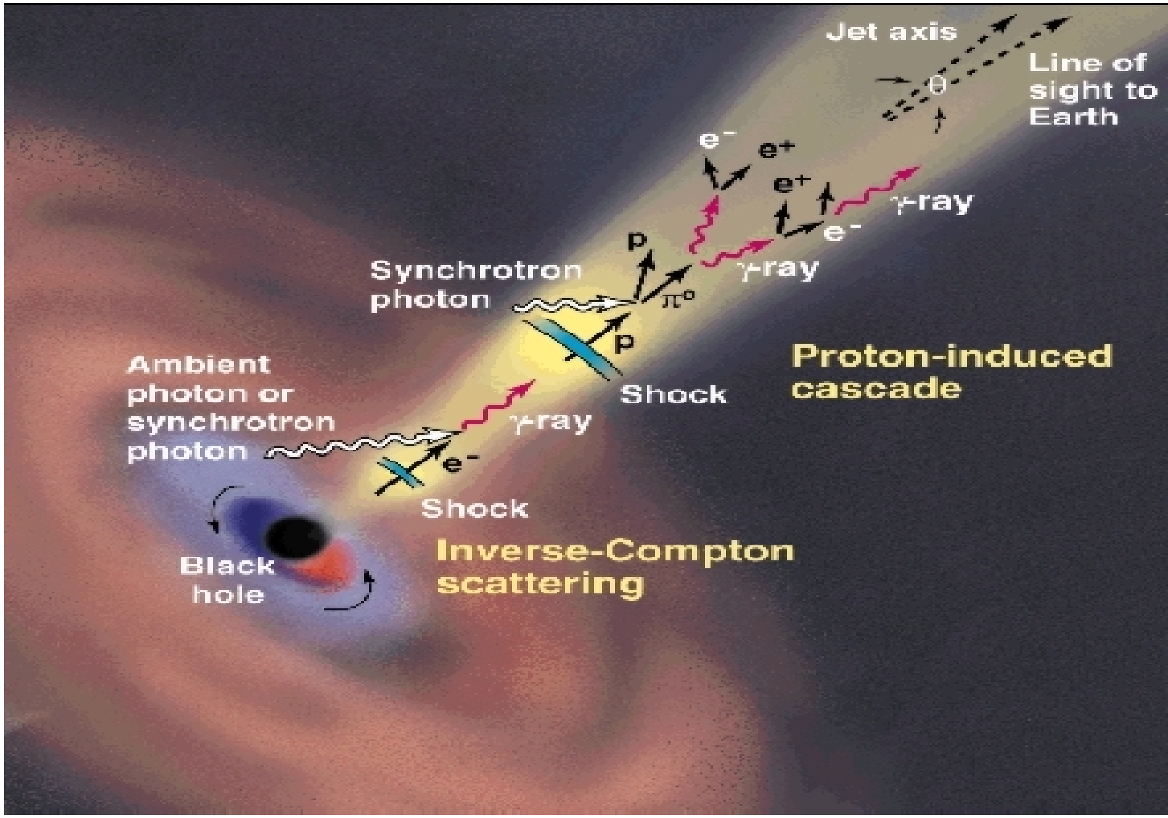

Gamma-
ray
Particle
shower
~ 10 km
Cherenkov light
~ 1°
Detection of
high-energy
gamma rays
using Cherenkov
telescopes


H.E.S.S.
High Energy Stereoscopic System

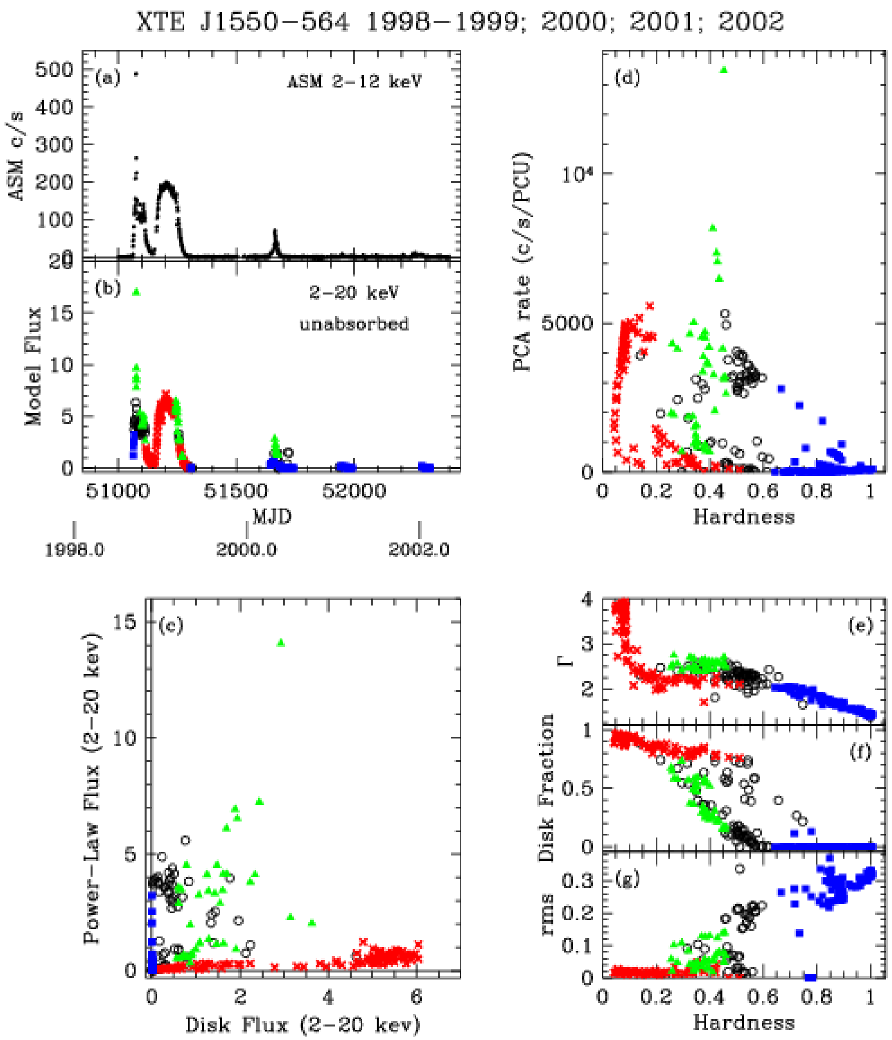
Gamma-ray emission:

Pure leptonic model : electrons interact (IC) with synchrotron radiation. Gamma-ray emission due to synchrotron self-Compton (SSC) emission

Hadronic model : assume a population of highly relativistic protons with $\gamma \sim 10^6$ to 10^8 Produce **pions** by various mechanisms (pp, pγ)



BH States: Overview



XTEJ1550-564

$M_x = 9.6 \pm 1.2\ M_o$

Outbursts: 1998 ; smaller, 2000;
+ 3 faint hard-state outbursts
2001, 2002, 2003

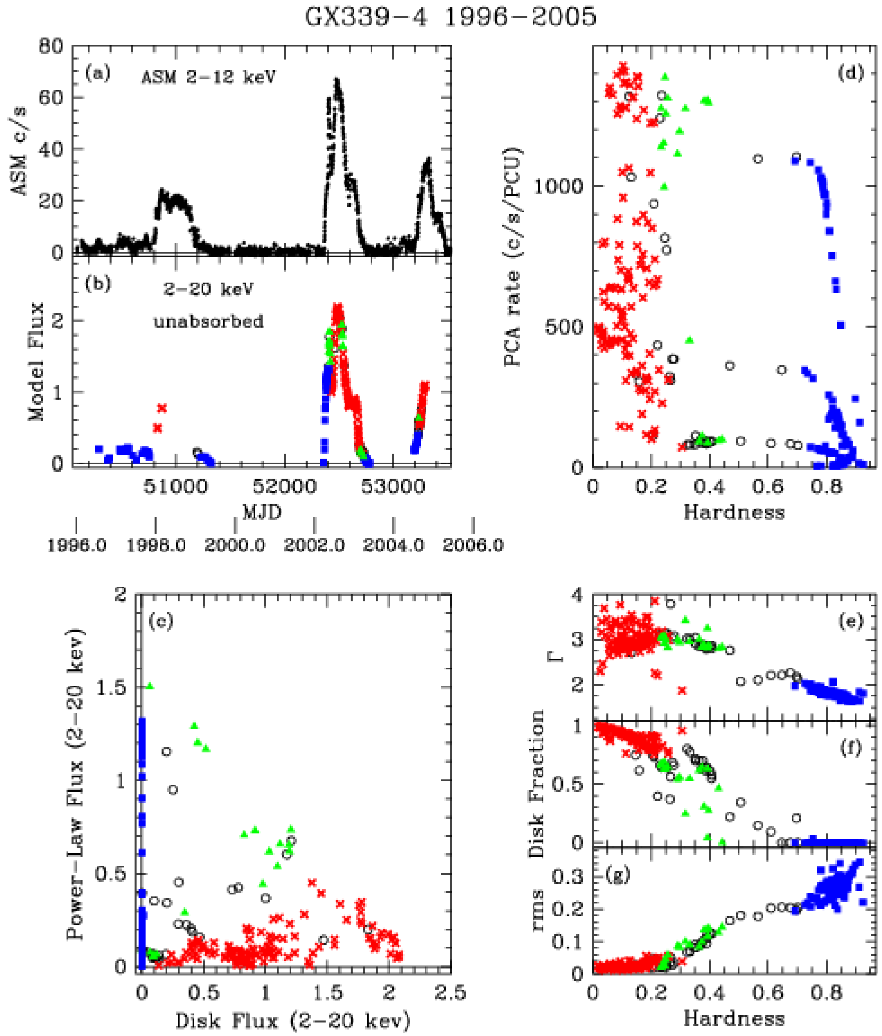
Thermal x

Hard (jet) ■

Steep Power Law Δ

Intermediate O

BH States: Overview



GX339-4

M_x = 5 – 15 M_o

Frequent outbursts: 1970 - 2005
+ extended, faint, hard states

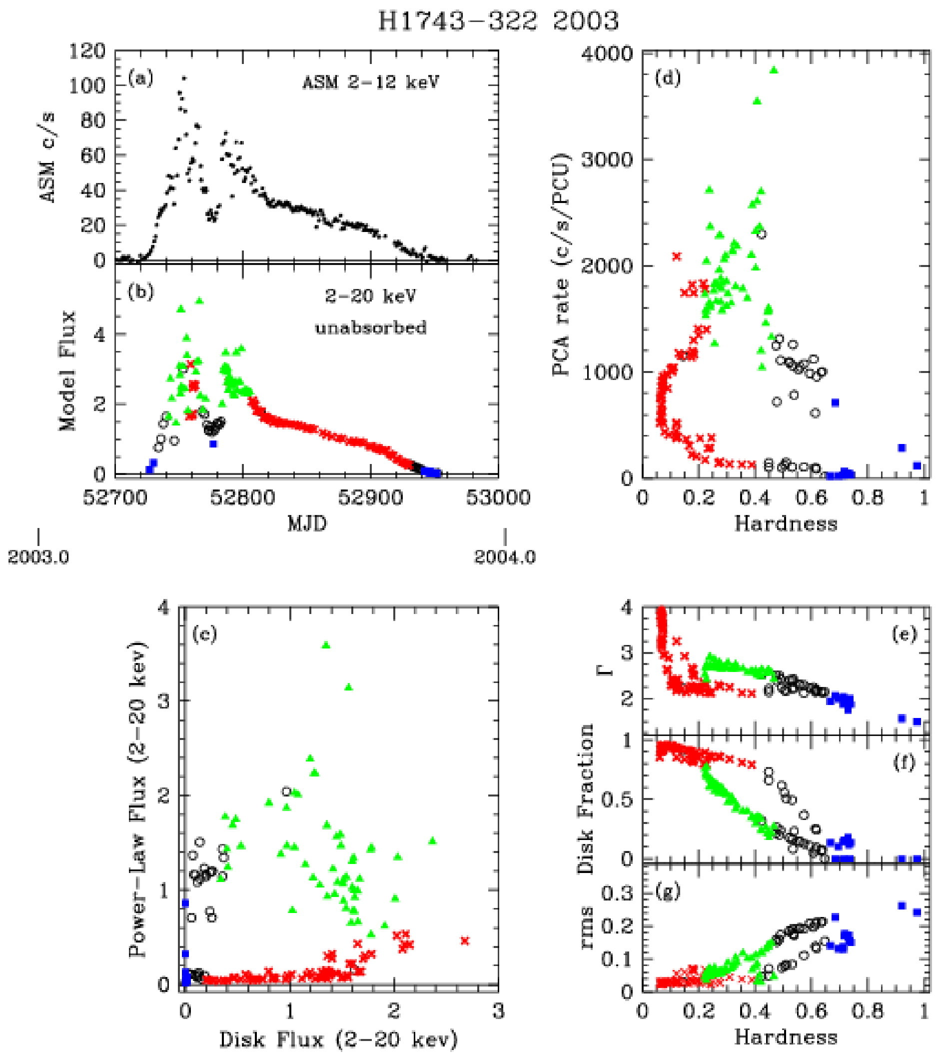
Thermal x

Hard (jet) ■

Steep Power Law Δ

Intermediate O

BH States: Overview



H1743-322

M_x unknown (ISM dust)

HEAO-1 outburst: 1977
RXTE: 2003; minor outburst 2005

Thermal x

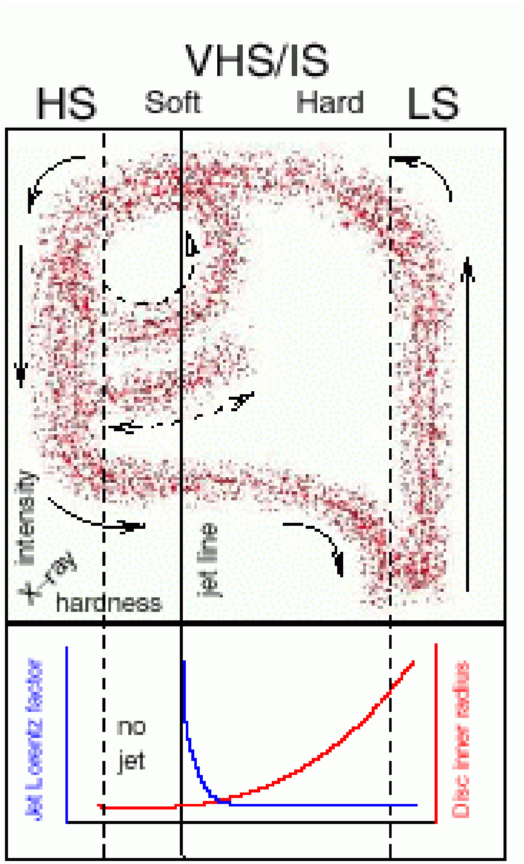
Hard (jet) ■

Steep Power Law Δ

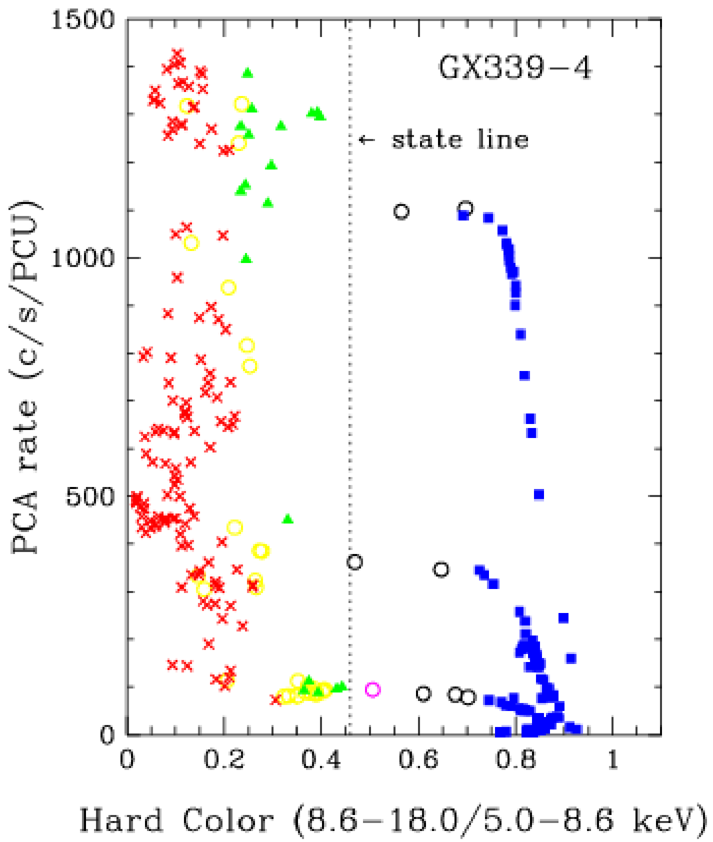
Intermediate O

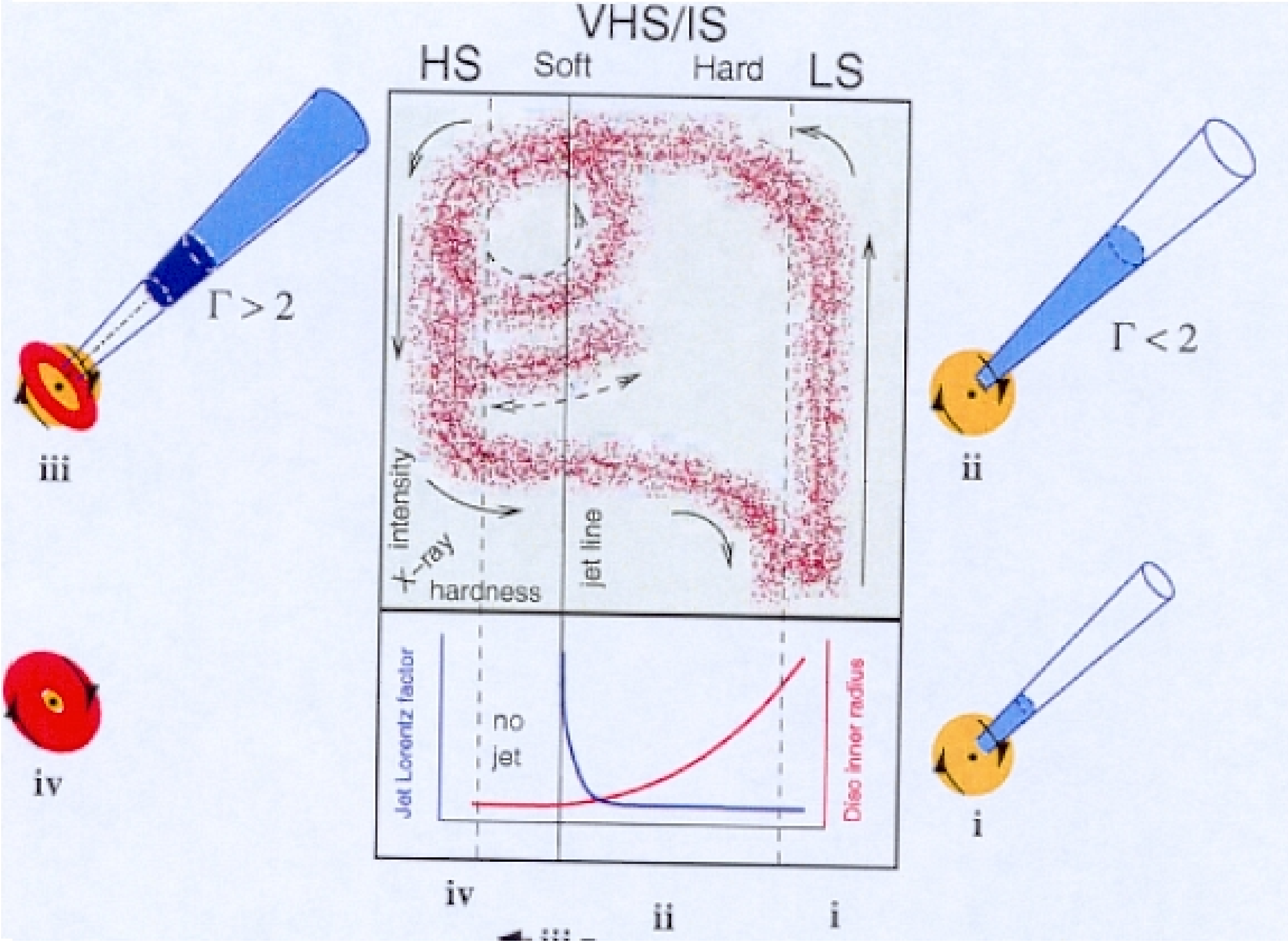
“Unified Model for Jets in BH Binaries”

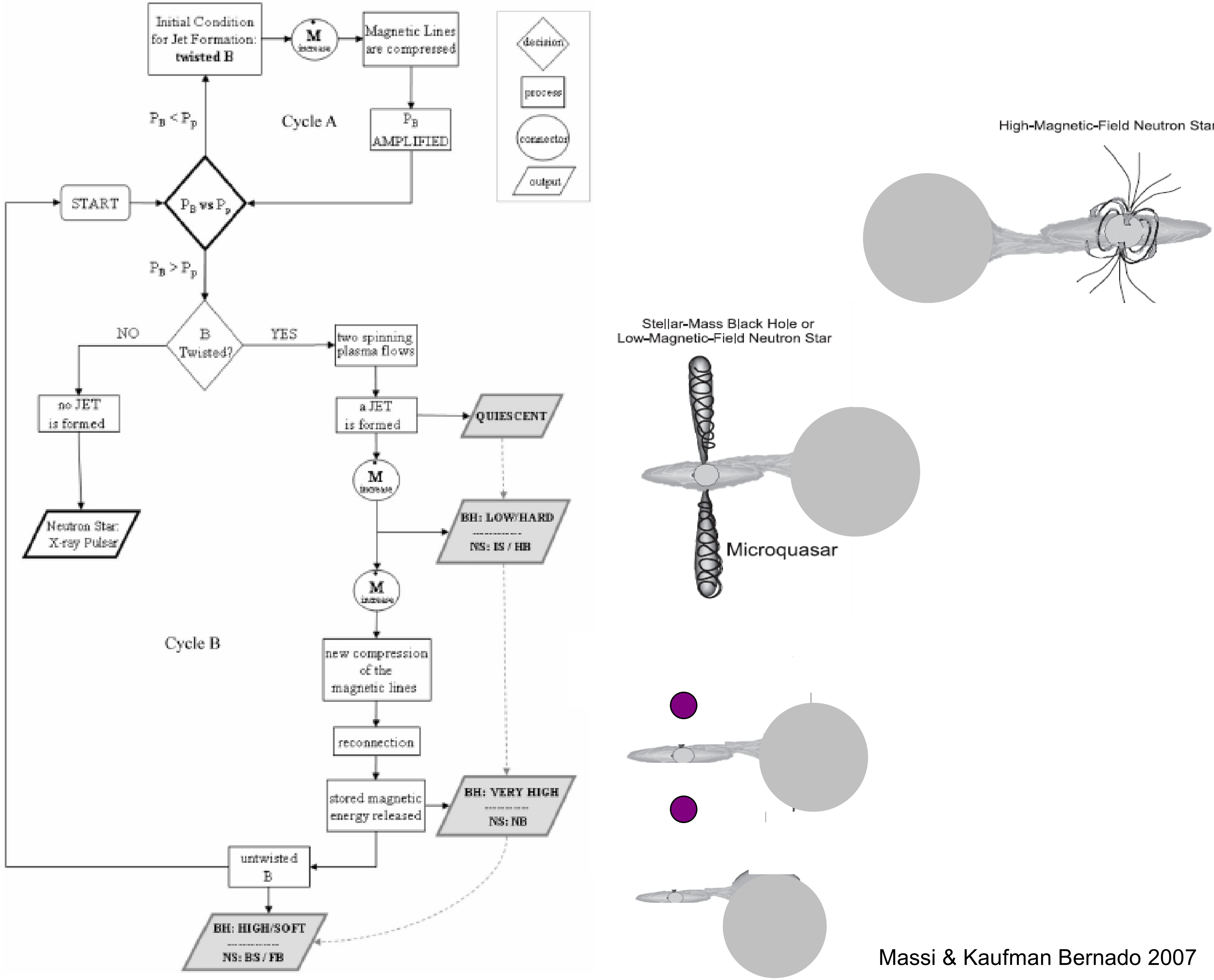
Fender, Belloni, & Gallo 2004



Remillard 2005




VHS/IS
HS
Soft
Hard
LS
Γ > 2
Γ < 2
iii
ii
iv
i
X-ray
intensity
hardness
jet line
no
jet
Jet Lorentz factor
Disc inner radius
iv
ii
i
iii



Massi & Kaufman Bernado 2007