PROBING STRONG GRAVITY AROUND BLACK HOLES

(WITH E.M. RADIATION)

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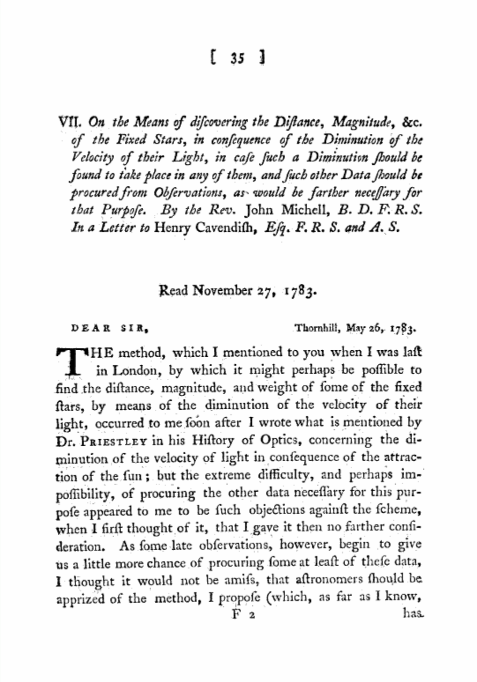
Plan of the talk

- Black holes : general properties

- Strong gravity effects on e.m. radiation

- Black hole spin measurements

Black Holes



[35]

VII. *On the Means of diſcovering the Diſtance, Magnitude,* &c. *of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

Read November 27, 1783.

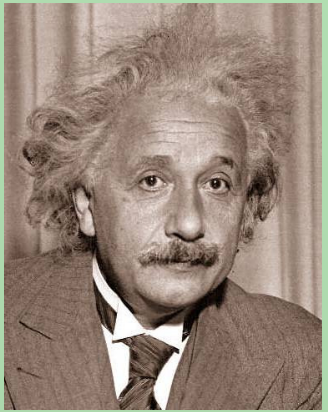
DEAR SIR, Thornhill, May 26, 1783.

THE method, which I mentioned to you when I was laſt in London, by which it might perhaps be poſſible to find the diſtance, magnitude, and weight of ſome of the fixed ſtars, by means of the diminution of the velocity of their light, occurred to me ſoon after I wrote what is mentioned by Dr. PRIESTLEY in his Hiſtory of Optics, concerning the diminution of the velocity of light in conſequence of the attraction of the ſun; but the extreme difficulty, and perhaps impoſſibility, of procuring the other data neceſſary for this purpoſe appeared to me to be ſuch objections againſt the ſcheme, when I firſt thought of it, that I gave it then no farther conſideration. As ſome late obſervations, however, begin to give us a little more chance of procuring ſome at leaſt of theſe data, I thought it would not be amiſs, that aſtronomers ſhould be apprized of the method, I propoſe (which, as far as I know,

F 2 has

The existence of "invisible stars" was postulated by J. Michell e P.S. Laplace at the end of the 18th century. They noted that a star with a radius smaller than $2GM/c^2$ would have an escape velocity larger than the speed of light *c*.

Invisible Stars were not *Black Holes* in the modern sense (indeed, the name was introduce only in 1967 by John A. Wheeler), i.e. objects from which nothing can escape. They became so only when Einstein postulated that nothing can travel at a speed larger than *c*.



Black Holes

A Black Hole is fully described by three quantities:

- The mass **M**
- The angular momentum **J**
- The electric charge **Q**

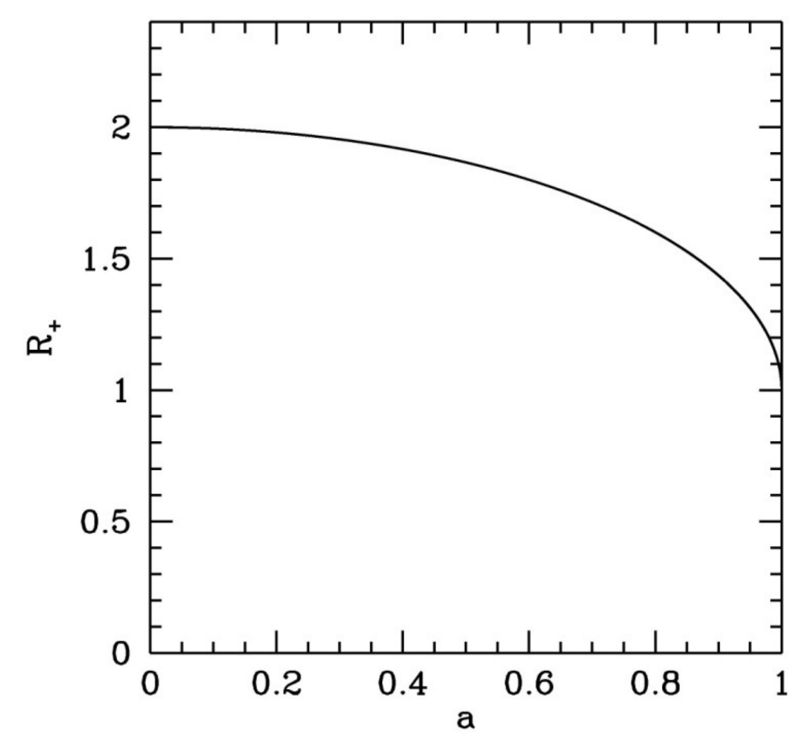
If **Q=0** (as usually assumed), the space-time is described by the **Kerr** metric

If also **J=0** (i.e. spherical symmetry), the (much simpler) **Schwarzschild** metric can be used

$r_g = GM/c^2$ is the gravitational radius. In the following, all distances will be given in units of r_g

$a = Jc/GM^2$ is the adimensional angular momentum per unit mass, usually called spin

The radius of the Event Horizon (i.e. the surface of "no return") is given by:



$$R_+ = 1 + (1 - a^2)^{1/2}$$

(note that this implies $0 \leq a \leq 1$).

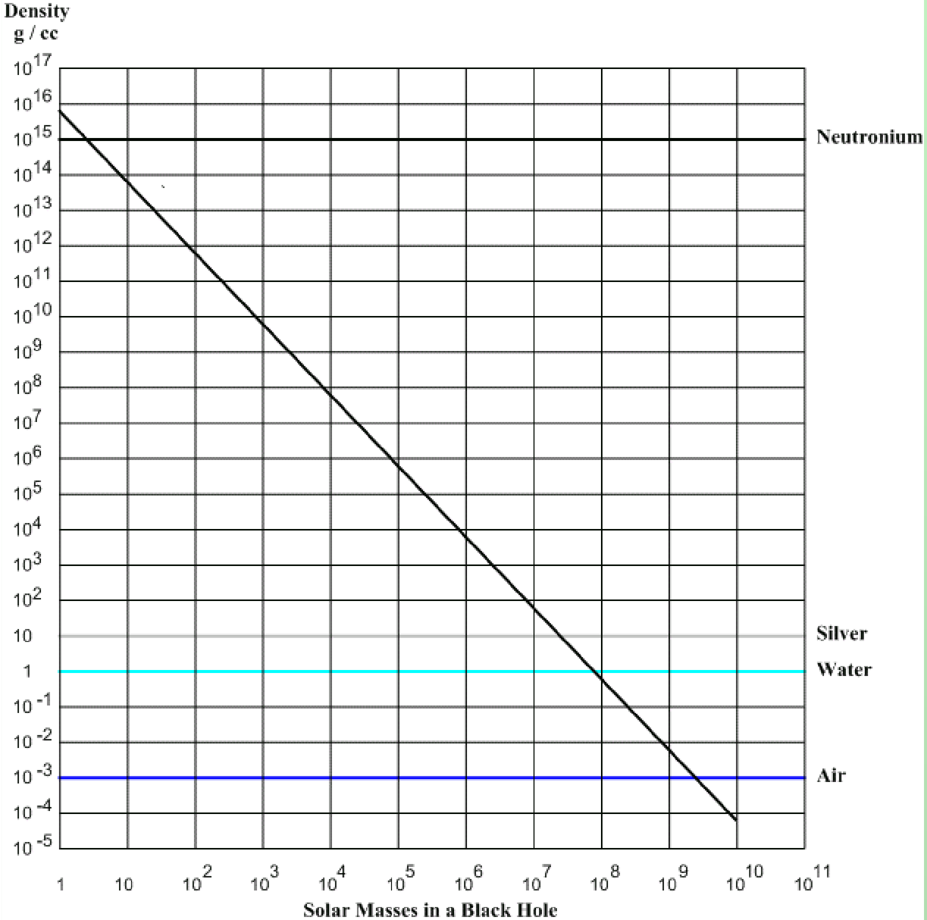
If $a=0$ (static BH) $\Rightarrow R_+ = 2$ (i.e. the Schwarzschild radius).

If $a=1$ (maximally rotating BH) $\Rightarrow R_+ = 1$

The “density” of a BH

Warning: Black Holes are the most compact objects, but not necessarily the densiest. In fact:

$$\rho = M/V = 3M/4\pi R_s^3 = 3c^6/32\pi G^3 M^2$$



The larger the Black Holes, the less dense !!!!

(10 millions of billions the density of water for a BH with the mass of the Sun, but can be of the same order or even less for the black holes we know are present in the center of galaxies)

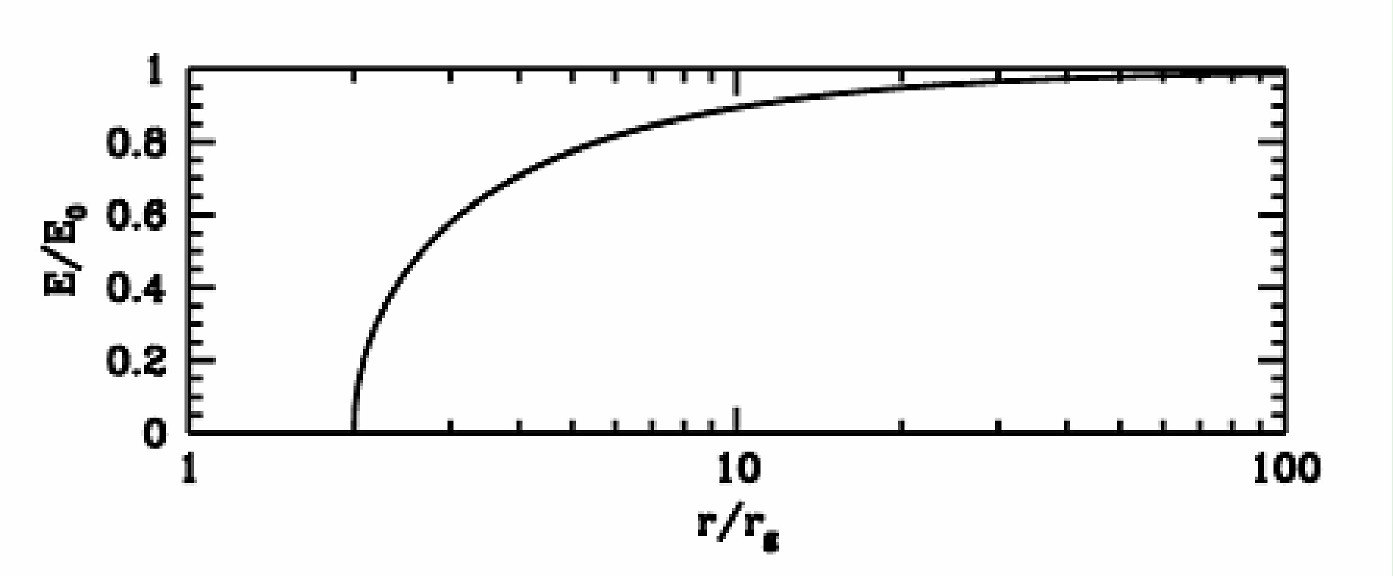
The “compactness” is determined by the M/R ratio, not by the density

Gravitational redshift

The Gravitational Redshift, formally defined as $(-g_{00})^{1/2}$, is given, in Schwarzschild metric, by:

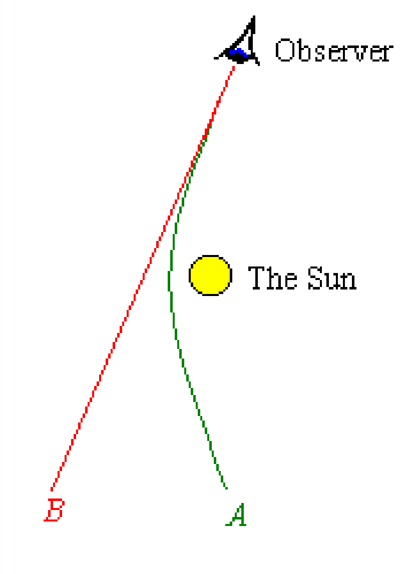
$$\boxed{\nu_\infty = \sqrt{1-\frac{2r_g}{r}}\nu_{em}}$$

(in Kerr metric the formula and the very meaning of it is more complicated)



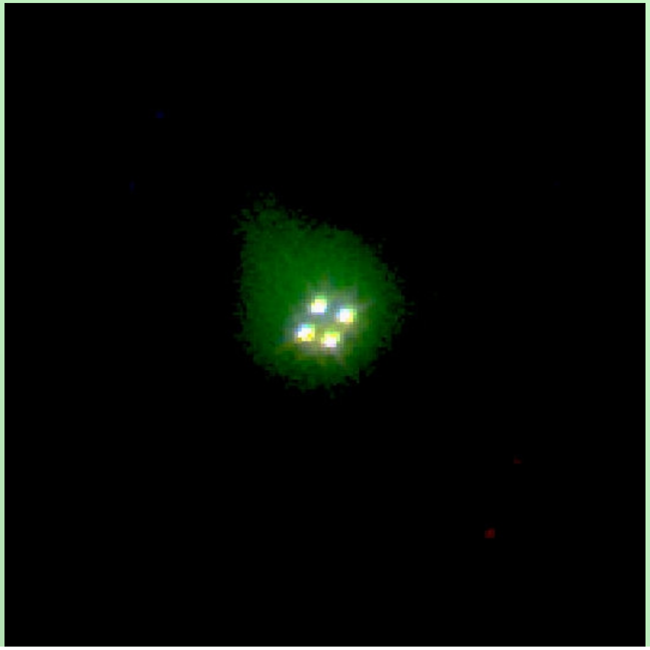
Light Bending

In GR light travels along geodesics which, in a gravitational field, are no longer straight lines



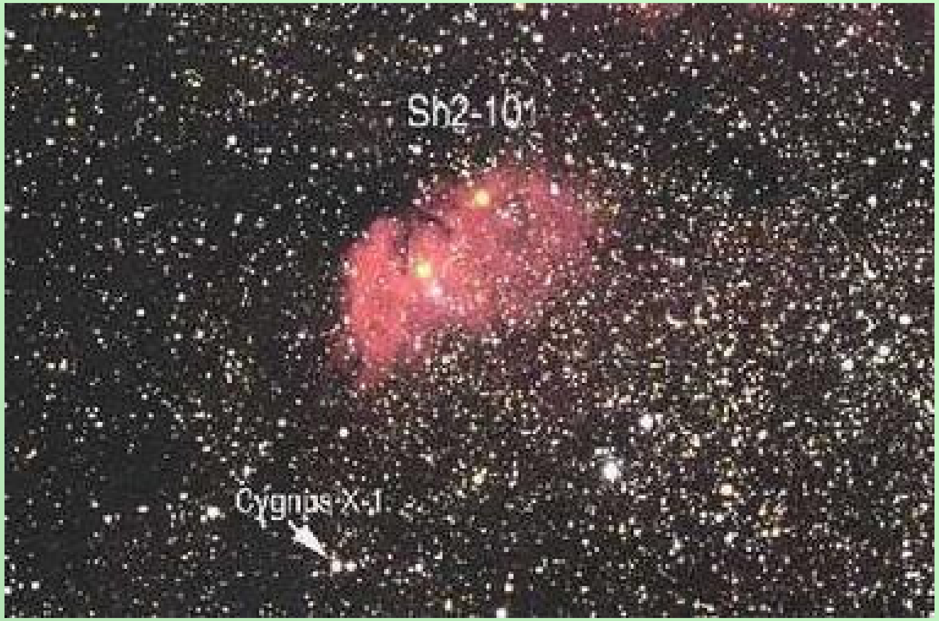
The measurement by Arthur Eddington in 1919 of the deflection of the light of a star eclipsed by the Sun was the first successful experimental test of the General Relativity

Gravitational lensing **on distant quasars from intervening matter forms multiple images of the Quasar**



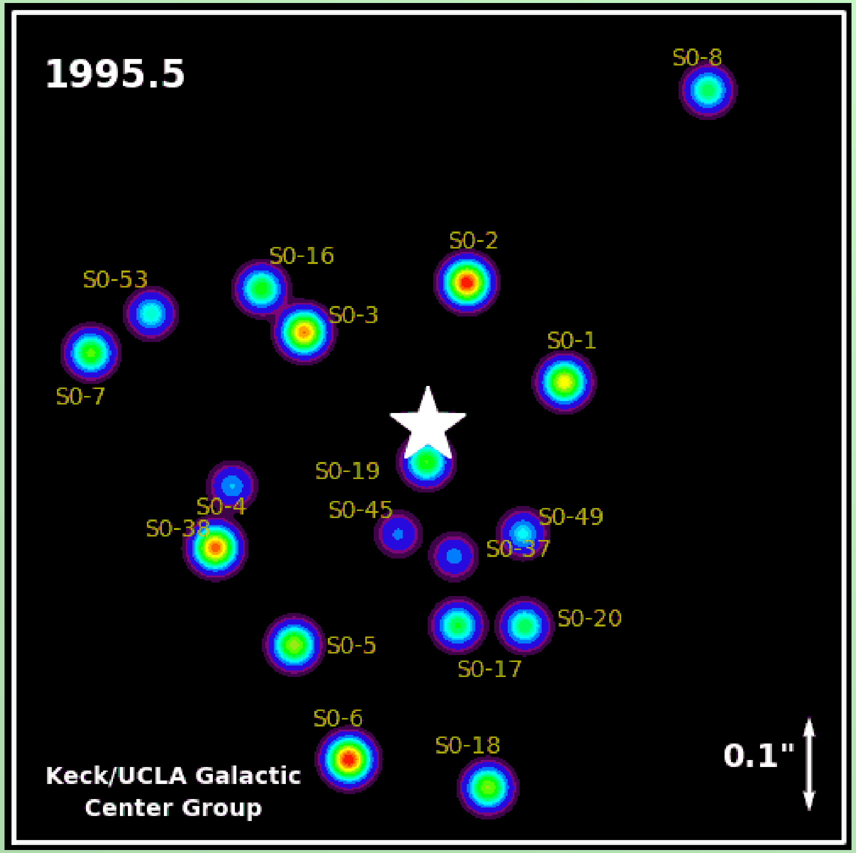
Black Holes in the Universe

**Black Holes are relatively common in the Universe.
They are one of the possible result of a Supernova explosion.
In this case, the mass is about 10 times the solar mass**



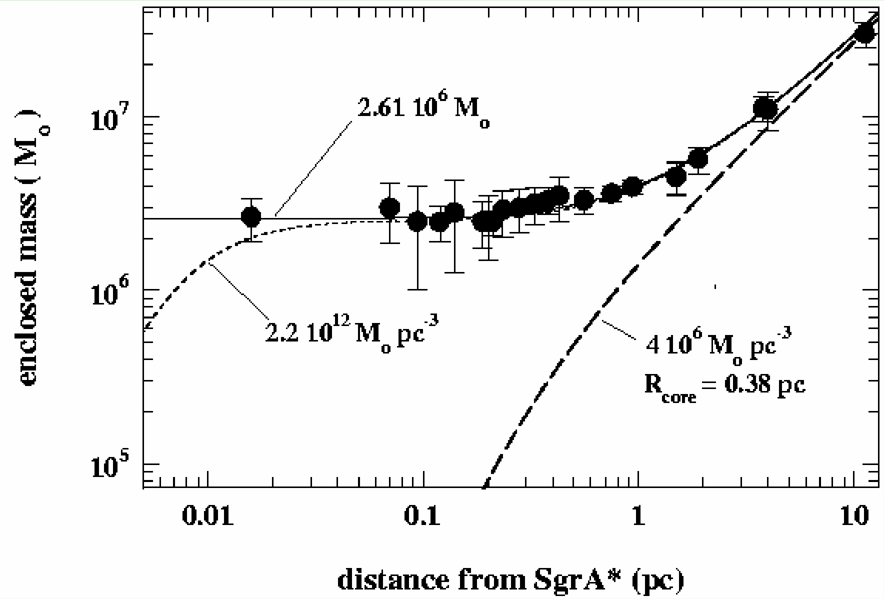
Black Holes with masses of millions to billions times the solar mass are now known to reside in the centre of galaxies.

The BH in the Milky Way



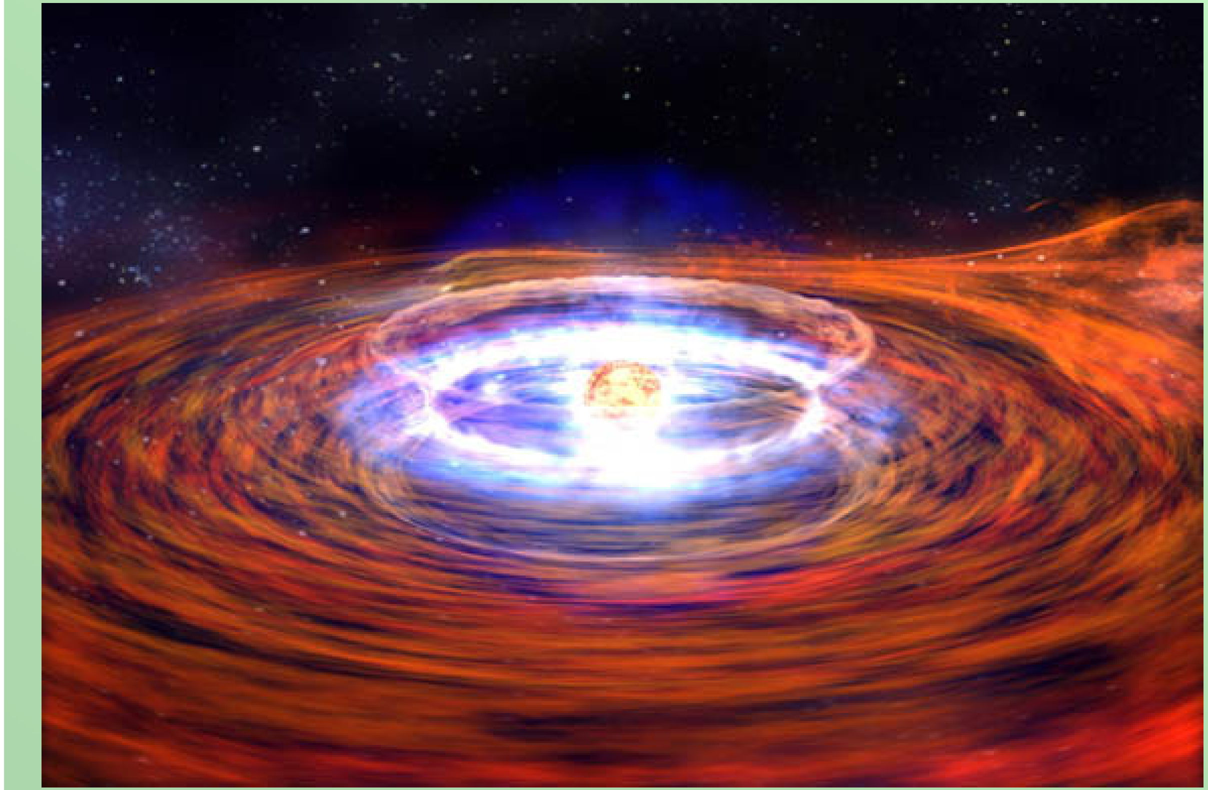
The presence of a Black Hole with a mass of about *4 millions solar masses* in the centre of our own Galaxy is deduced from the orbits of nearby stars.

Similar (even if much less precise) results are obtained for external galaxies.



Active Galactic Nuclei

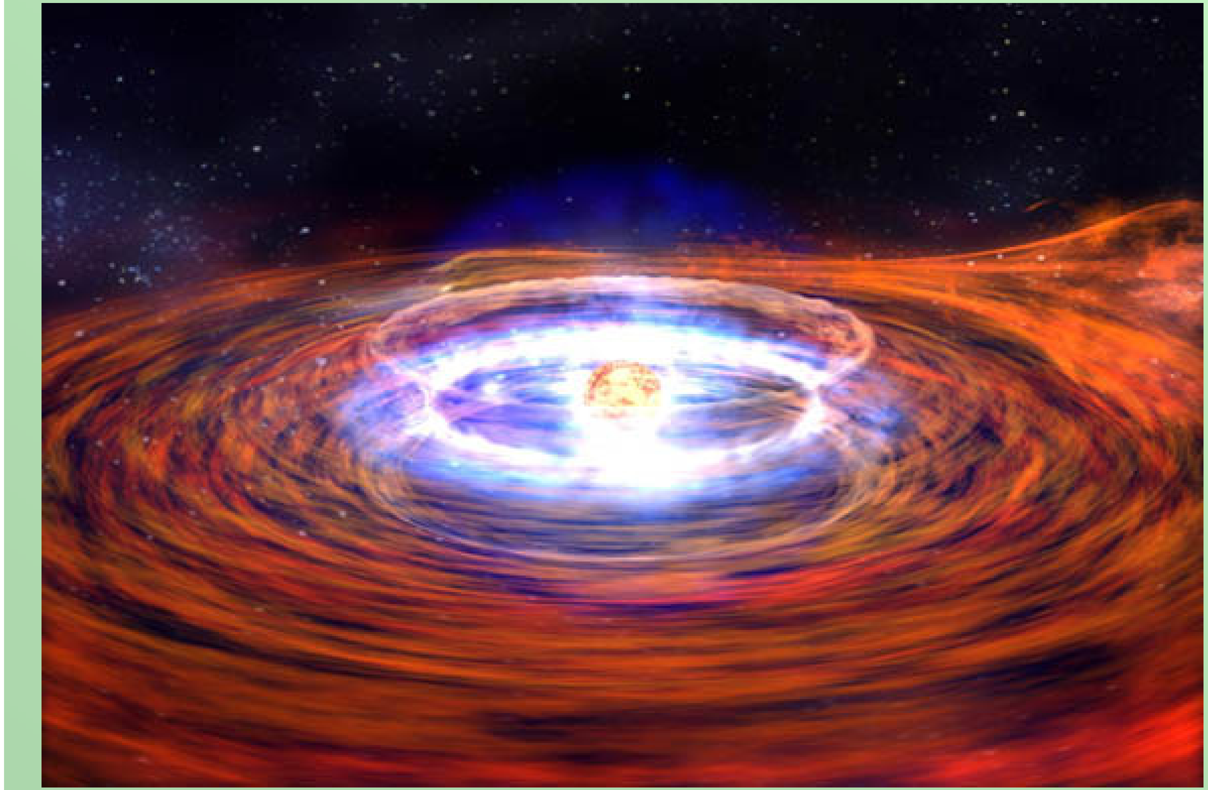
Active Galactic Nuclei (AGN) are point-like sources in the centre of a few percent of galaxies. They emit, in a region of the size of the solar system, an amount of radiation which may exceed that of the entire host galaxy.



The "engine" of AGN is the *accretion* of matter onto the central Black Hole, with conversion of gravitational energy into (eventually) radiation.

Active Galactic Nuclei

Accretion cannot occur spherically. As Black Holes do not have a solid surface, matter would be swallowed by the Hole with all its energy. However, if matter possesses angular momentum, an *accretion disc* may form, where energy is dissipated by viscous processes.



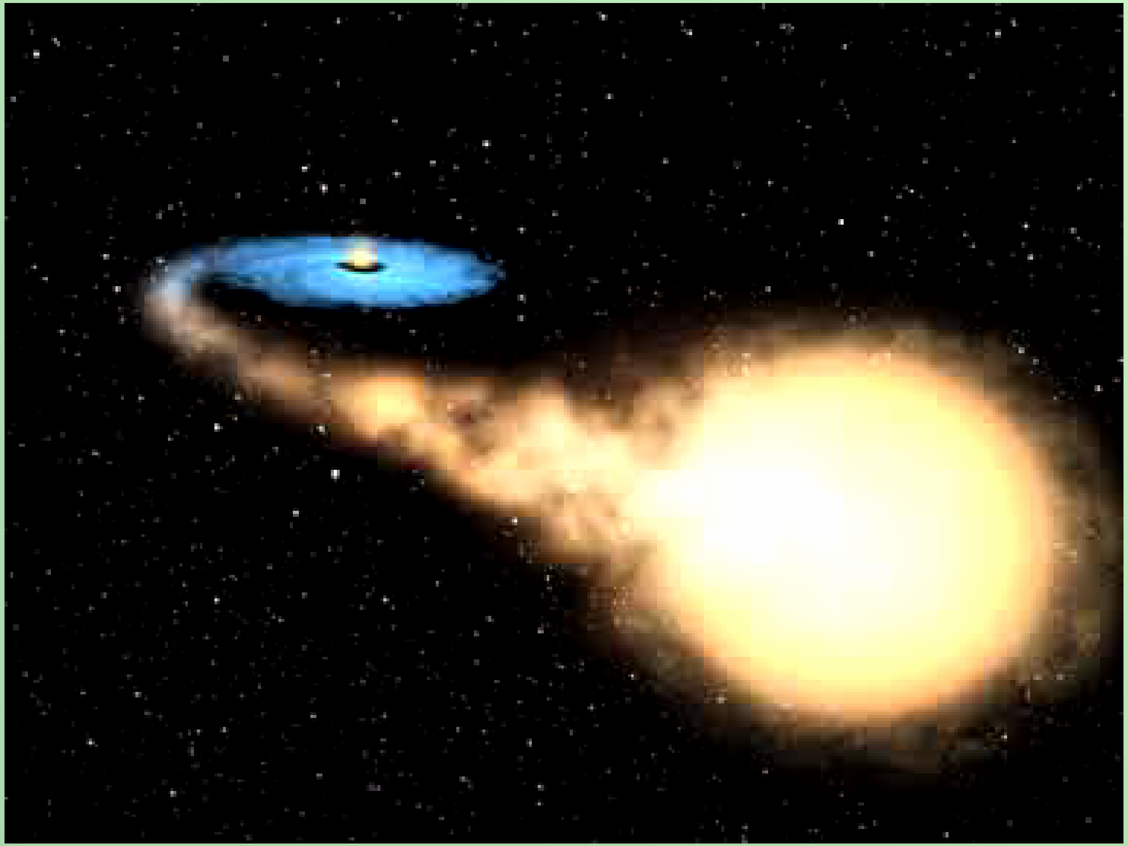
This process may be very efficient in converting gravitational energy into radiation.

$$L = \eta \, (dM/dt) \, c^2$$

$$\eta = 0.057 \ (a=0)$$
$$= 0.42 \ (a=1)$$

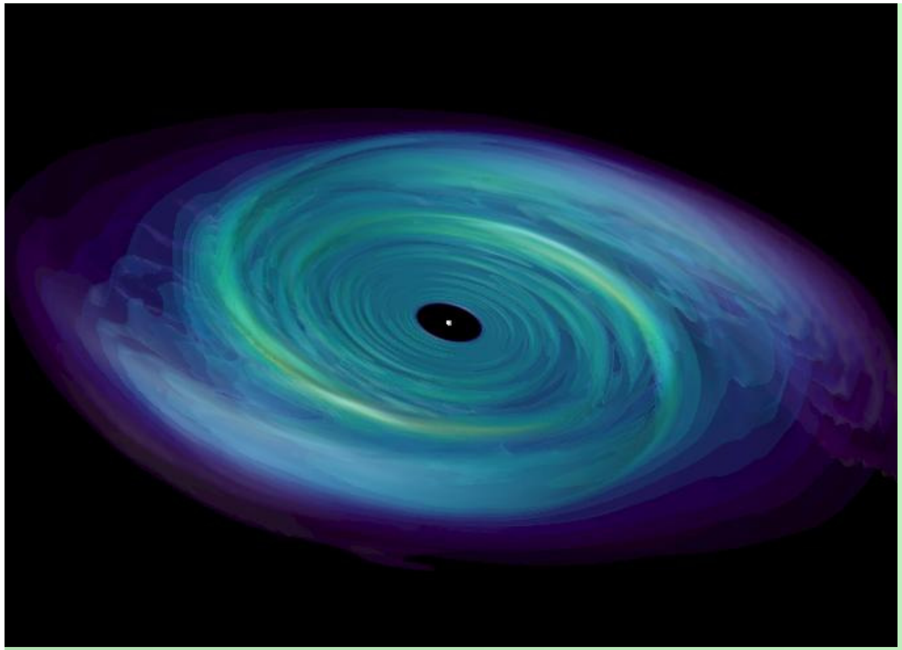
BH in binary systems

Black holes can form due to the gravitational collapse of a massive star. If the black hole is in a binary system, it may accrete matter from the companion.

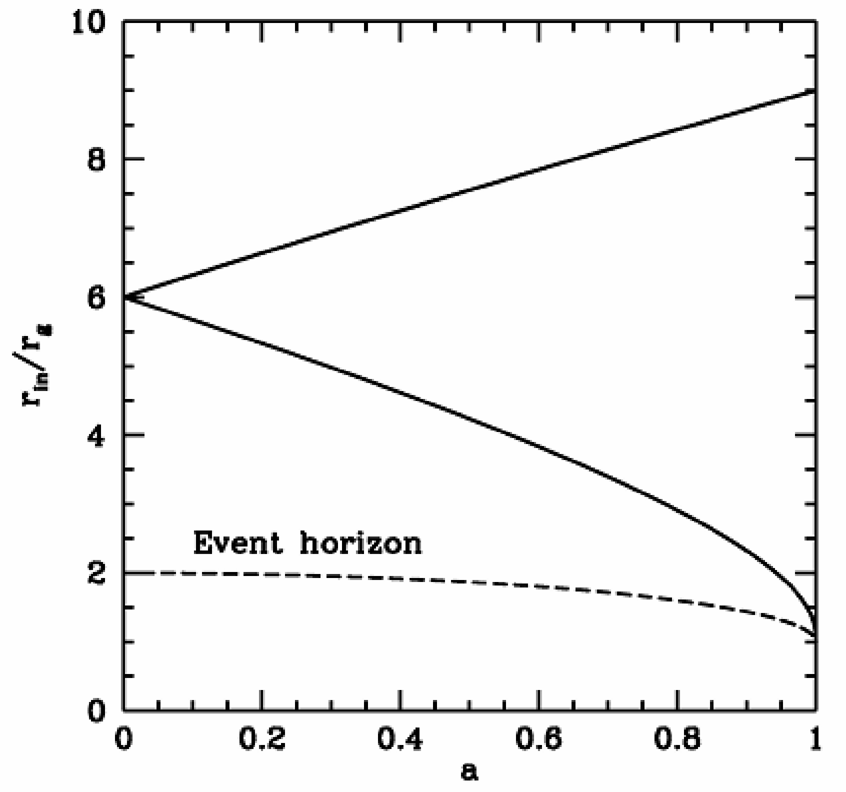


The basic properties of accretion are the same for AGN and BH binaries.

Accretion discs



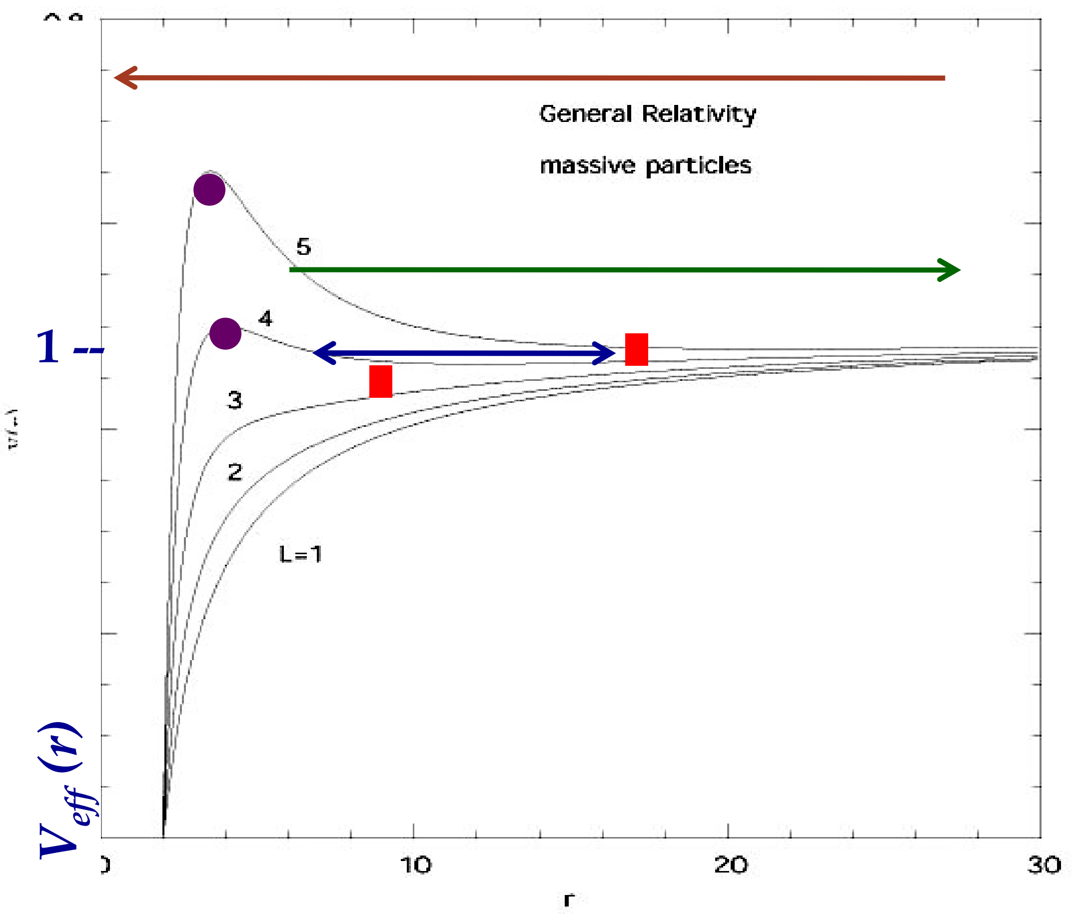
Let us assume a geometrically thin, optically thick accretion disc. Matter rotates in (quasi) circular orbits (i.e. **Vφ >> Vr**) with Keplerian velocities.



We can assume that the inner disc radius corresponds to the innermost stable circular orbit (**ISCO**)

The **ISCO** depends on the BH spin and on whether the disc is co- or counter-rotating with the BH

NB: all e.m. measurements of the BH spin are based on this relation



■ Circular stable orbits

● Circular unstable orbits

↔ Bound orbits (precessing ellipses)

→ Unbound orbits

→ Unbound infalling orbits.

$$r_c = \frac{L^2 \pm \sqrt{L^4 - 12 r_g{}^2 L^2}}{2r_g}$$

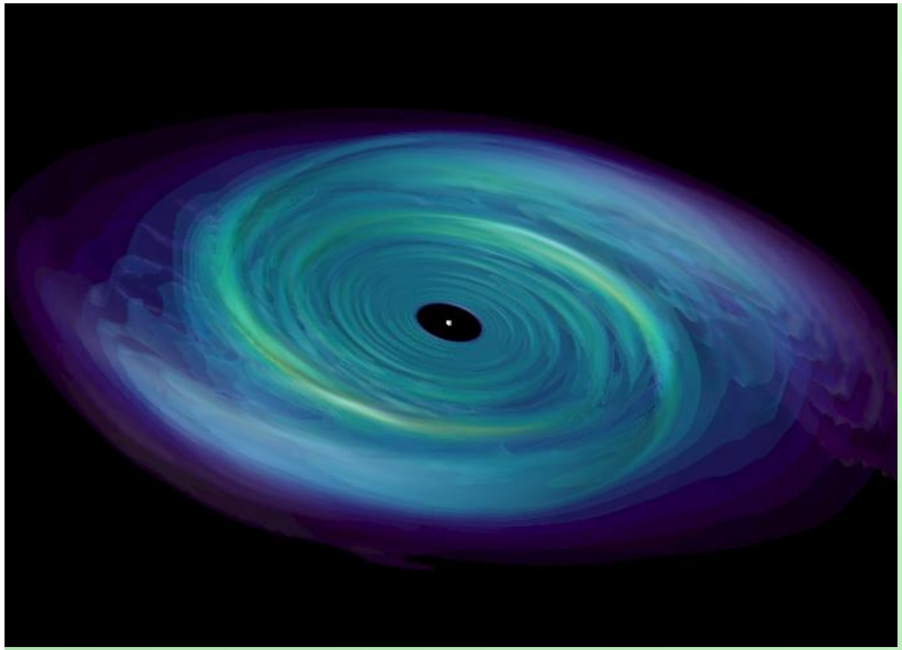
$$\begin{cases} L \gg \sqrt{12} r_g \rightarrow r_c = \left(\dfrac{L^2}{r}, 3r_g \right) \\ (1 \quad stable, \quad 1 \quad unstable) \\ L < \sqrt{12} r_g \rightarrow no\ solutions \\ L = \sqrt{12} r_g \rightarrow r_c = 6\mathrm{r_g} \\ \text{(unstable towards lower radii)} \end{cases}$$

⬇

Marginally Stable Orbit (MSO)

or

Innermost Stable Circular Orbit (ISCO)



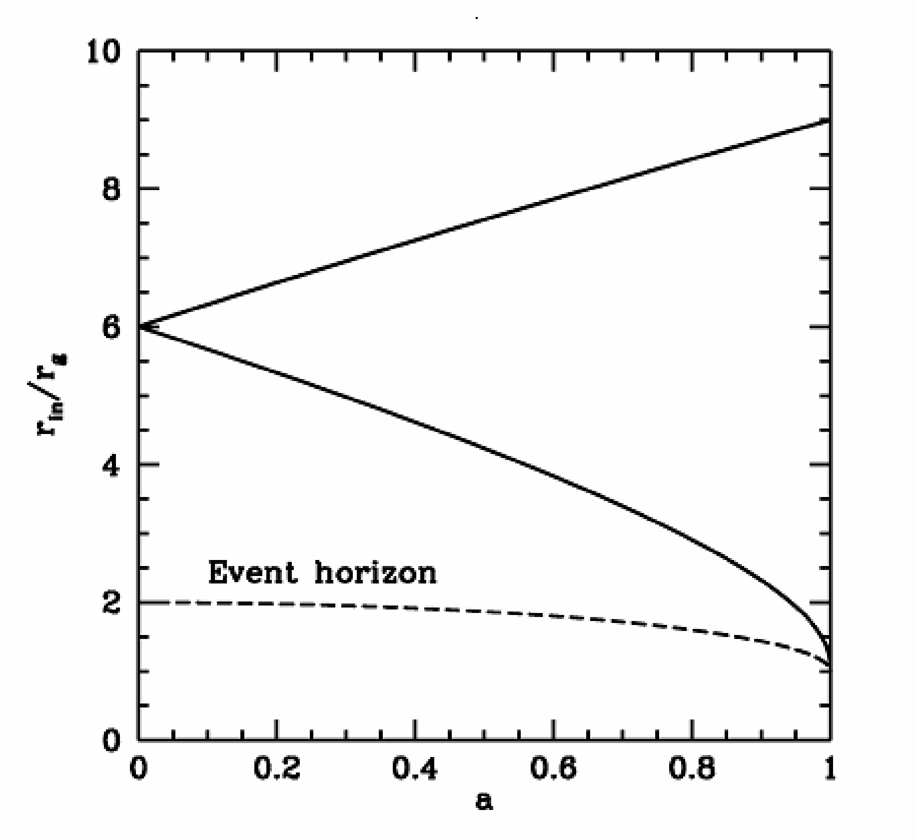
Accretion discs

Let us assume a geometrically thin, optically thick accretion disc. Matter rotates in (quasi) circular orbits (i.e. Vφ >> Vr) with Keplerian velocities.

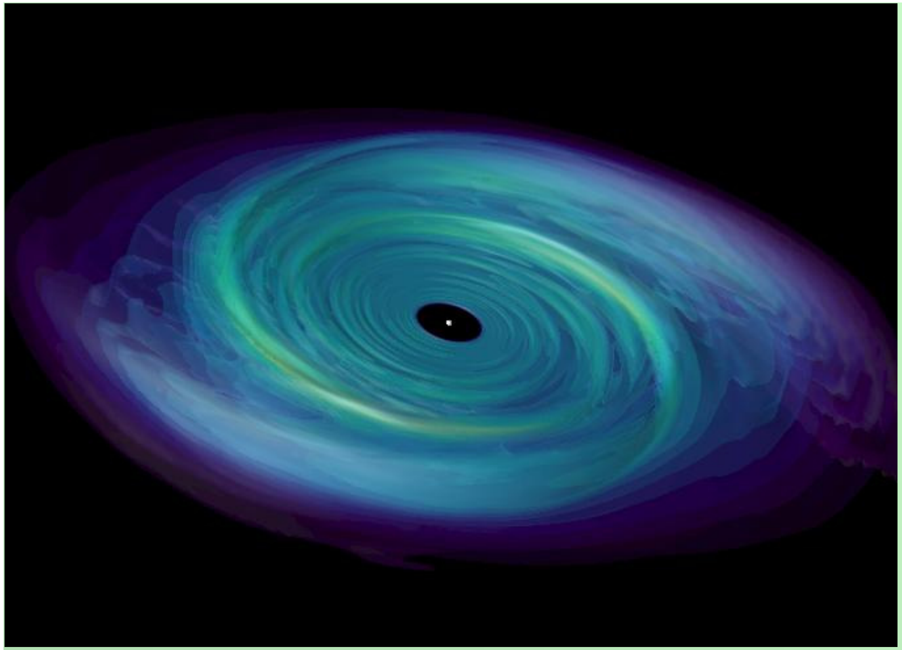
We can assume that the inner disc radius corresponds to the innermost stable circular orbit (ISCO)

The ISCO depends on the BH spin and on whether the disc is co- or counter-rotating with the BH

NB: all e.m. measurements of the BH spin are based on this relation



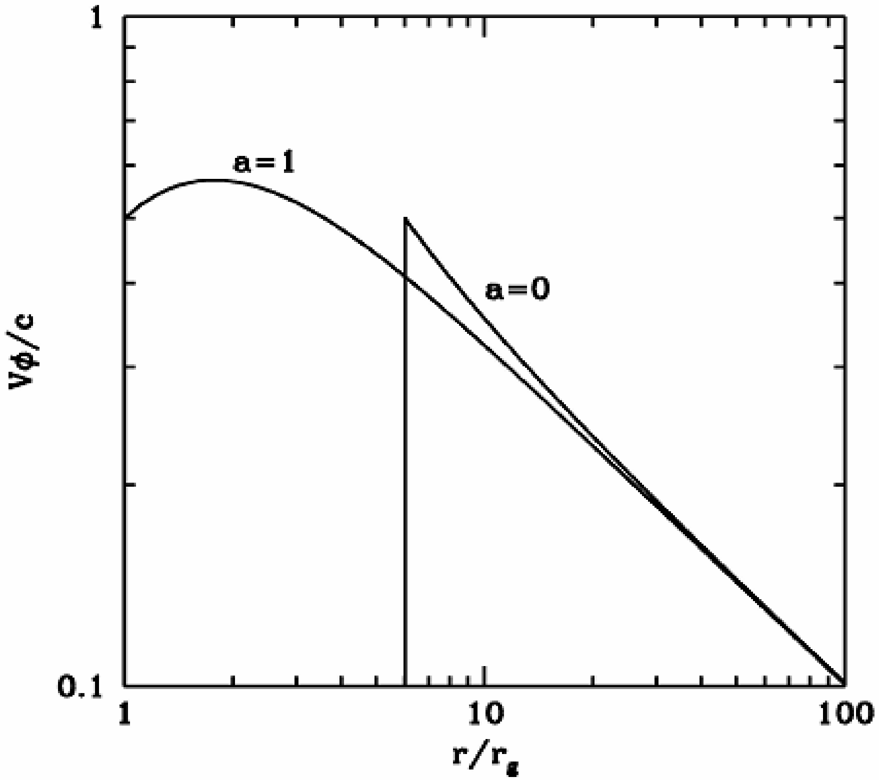
Accretion discs



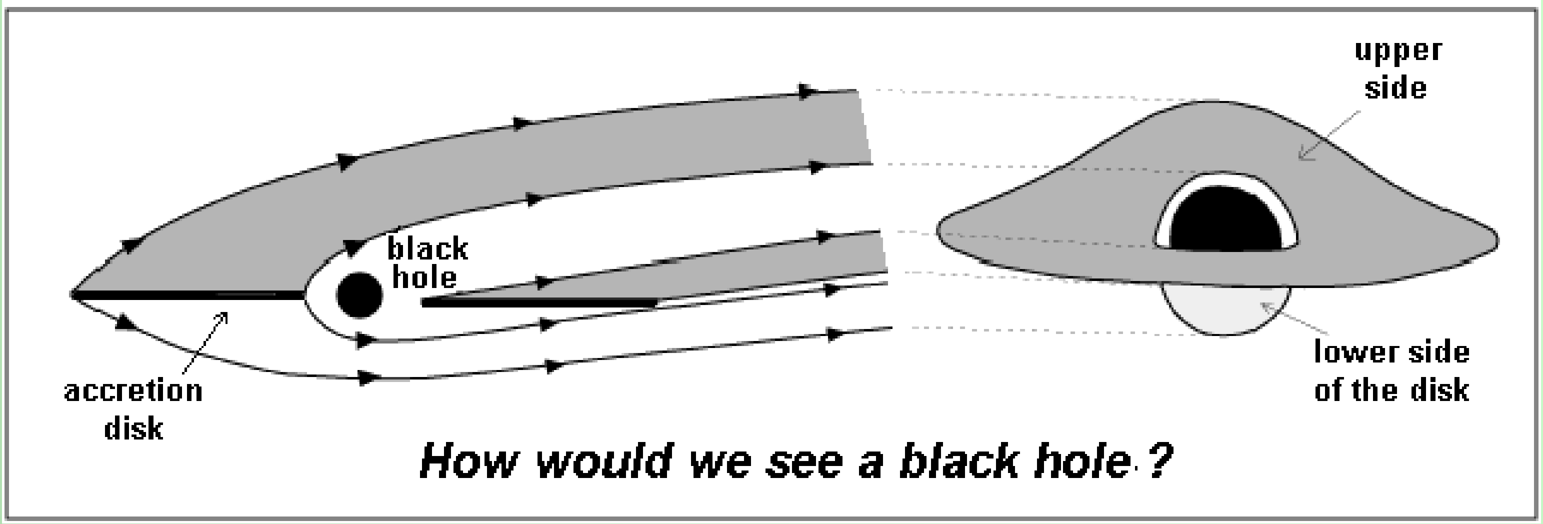
The Keplerian velocity (in the Locally Non-Rotating Frame) is given by:

$$V\varphi/c = (r^2 - 2ar^{1/2} + a^2\,) \\ /(r^2 + a^2 - 2r)^{1/2}\,(r^{3/2} + a)$$

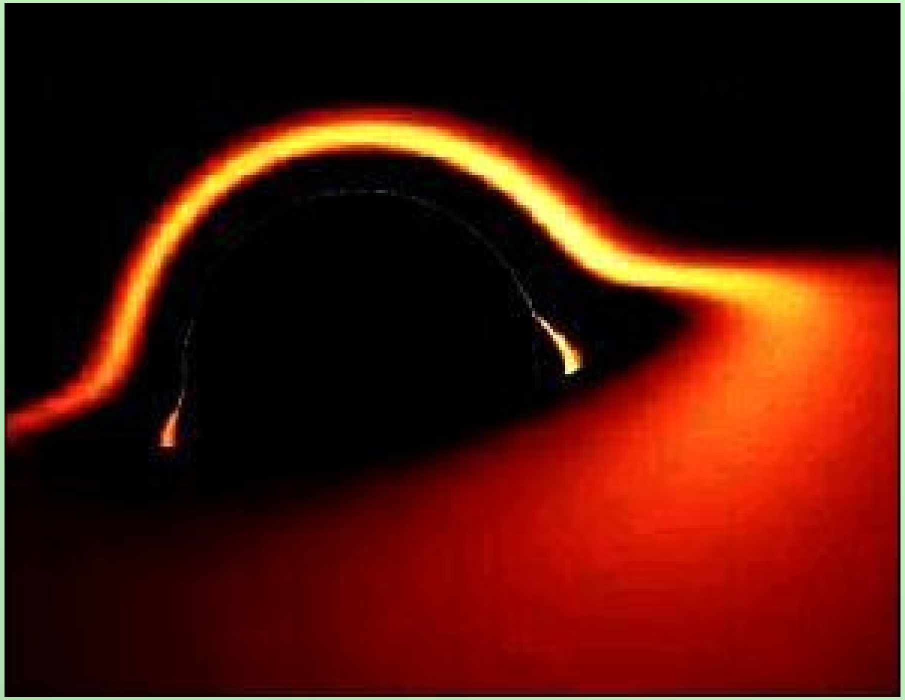
which, for small r, can be a significant fraction of *c*



Photon trajectories



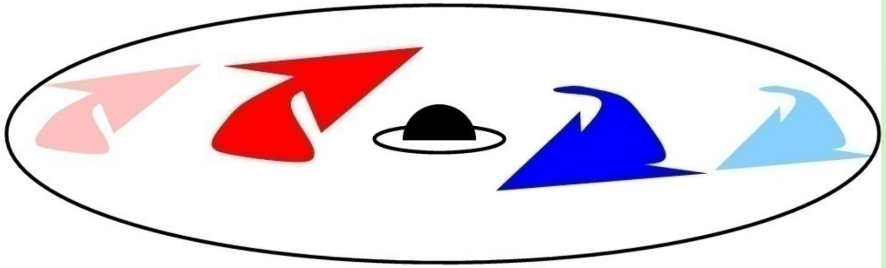
Luminet 1979



In GR, photon geodesics are no longer straight lines (light bending)

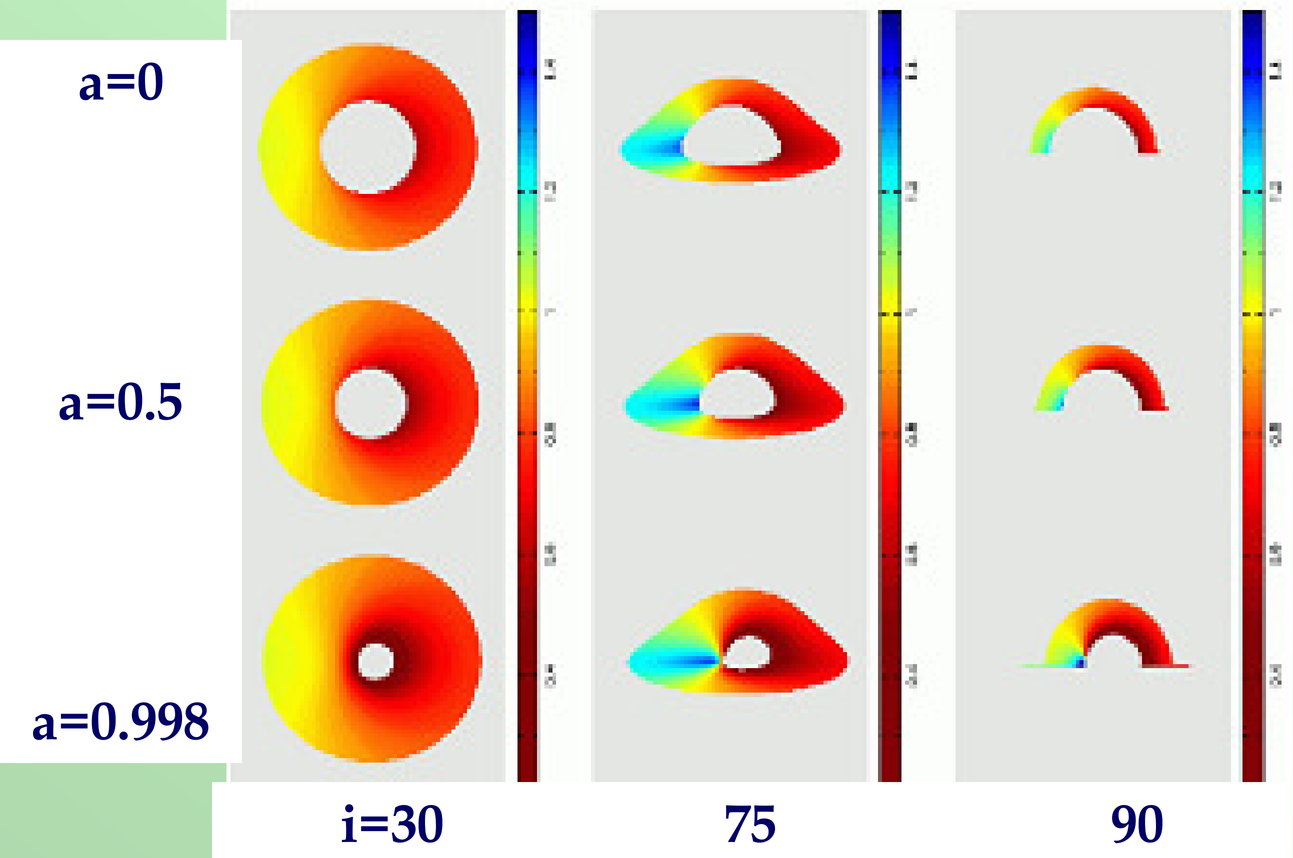
In Schwarzschild metric the trajectories are two-dimensional, in Kerr metric they are fully three-dimensional

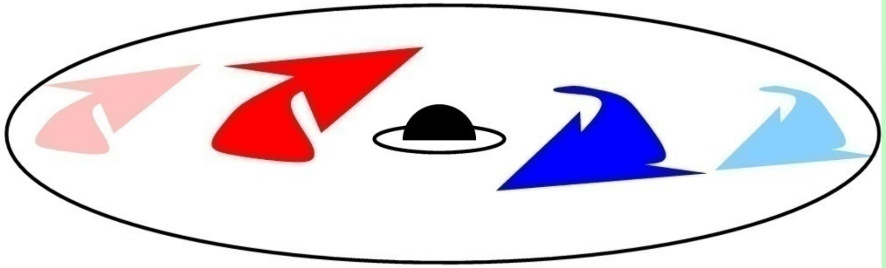
Photon shifts



Photons emitted in the accretion disc appear to the distant observer as redshifted because of the Gravitational redshift and the Doppler transverse effect, and blueshifted /redshifted by the Doppler effect when the matter is approaching/receding

(Dabrowski 1998)

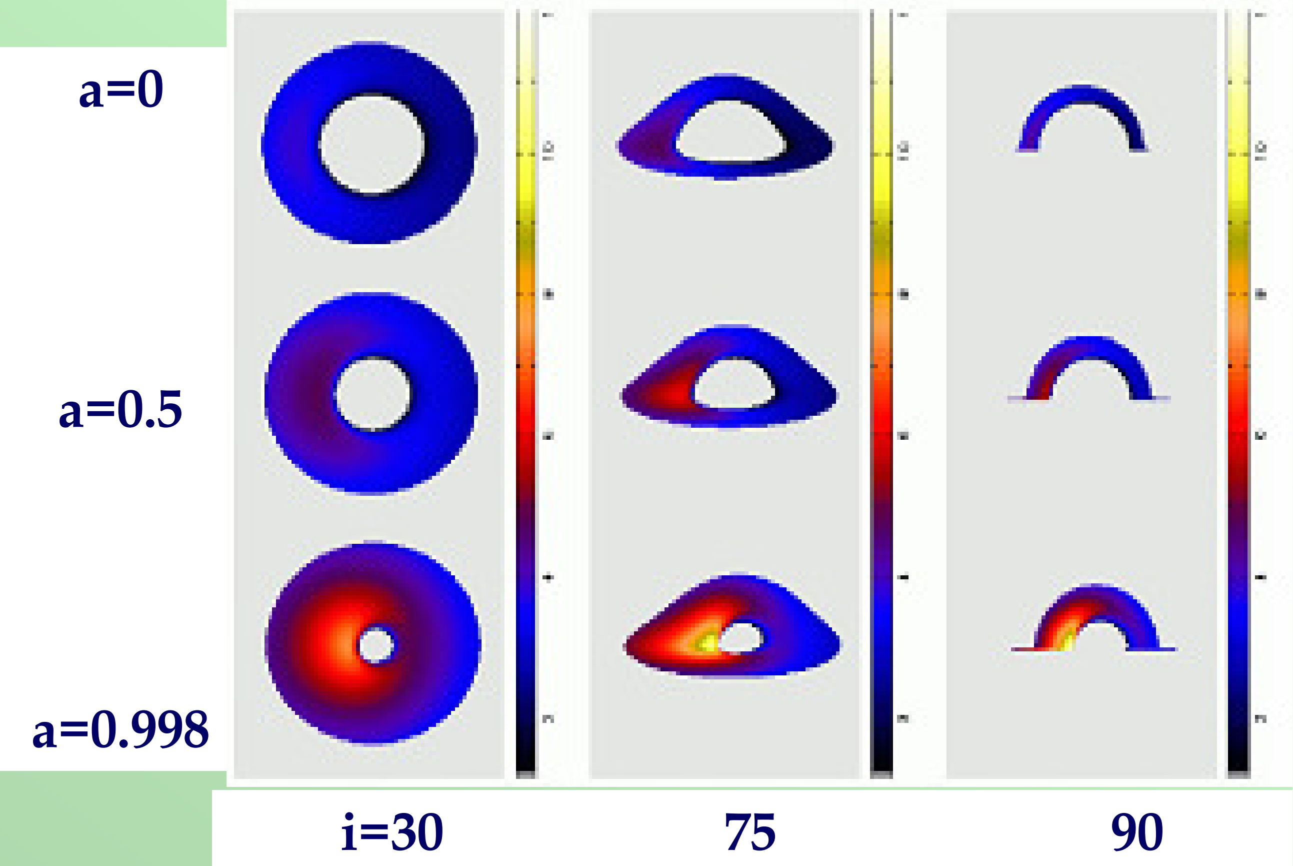




Doppler boosting

The quantity
I_ν/ν^3
is a Lorentz
invariant.

Therefore, the
blueshifted
radiation is brighter
(*Doppler boosting*),
the redshifted
is fainter.

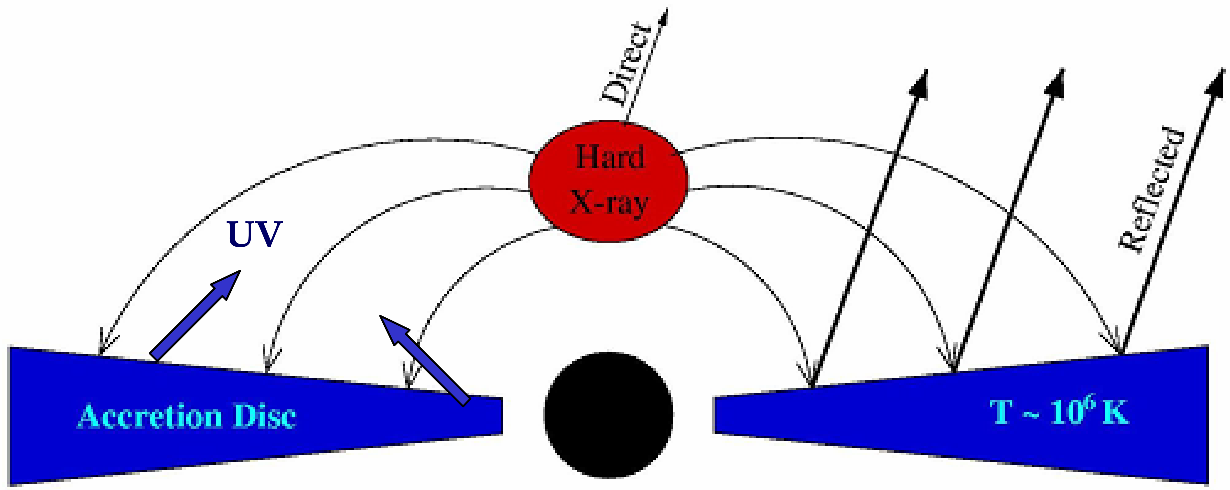


(Dabrowski 1998)

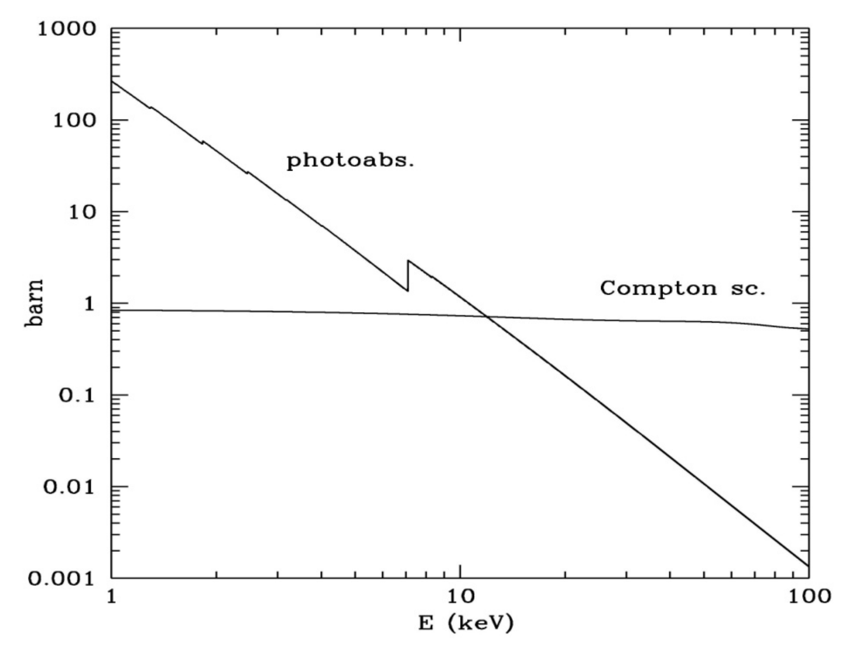
X-ray emission

The standard explanation for the hard X-ray emission in AGN and GBHS is Comptonization of disc photons by hot (T=100-200 keV) electrons in a corona (e.g. Haardt & Maraschi 1991). The resulting spectrum is, in the first approximation, a power low with a high energy cutoff, as observed (e.g. Perola et al. 2002, Petrucci et al. 2001)

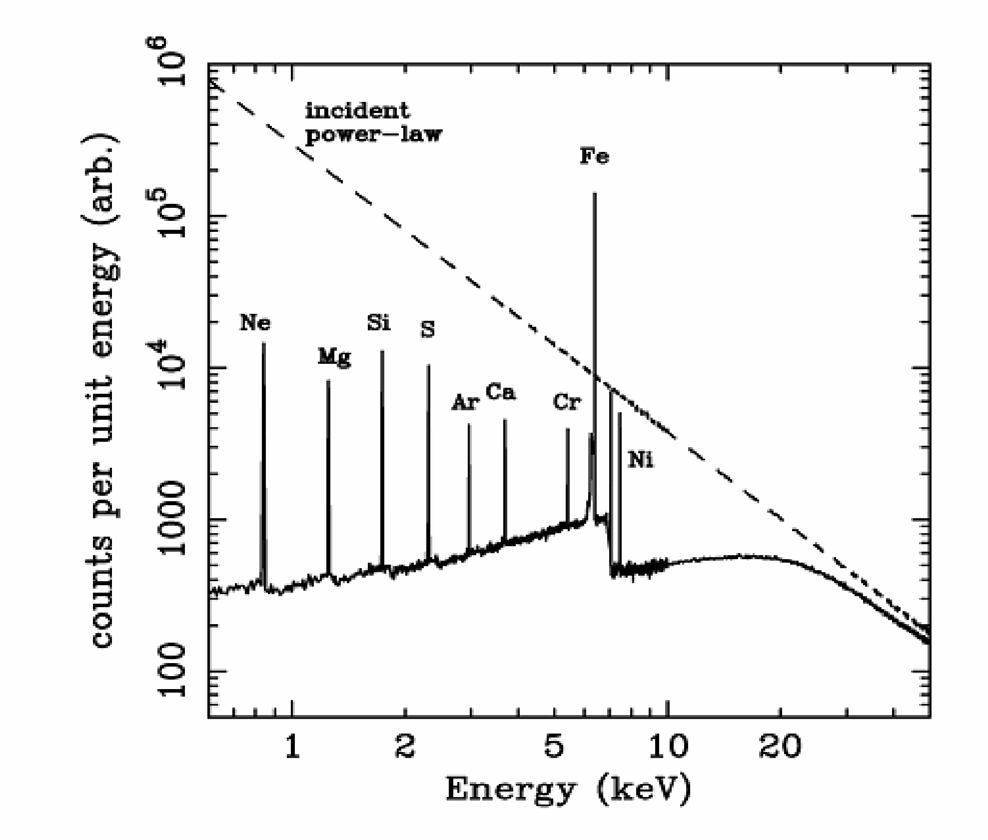
AGN (the same for GBHS, but the disc emission is harder)



X-ray reprocessing



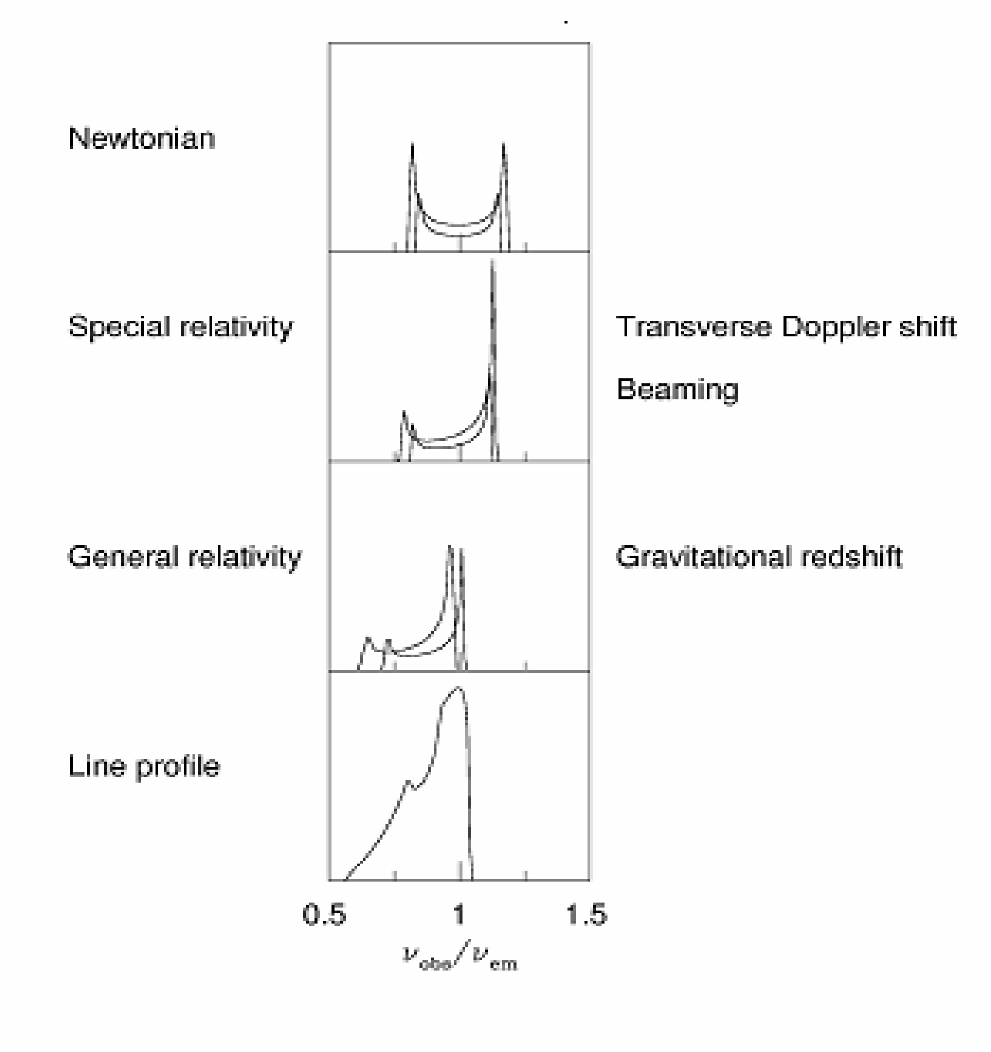
(Reynolds et al. 1995)



X-ray illumination of the accretion disc produces the so-called ‘Compton reflection’ continuum plus several fluorescent lines, by far the most important being the Fe Kα (e.g. Matt et al. 1991, George & Fabian 1991).

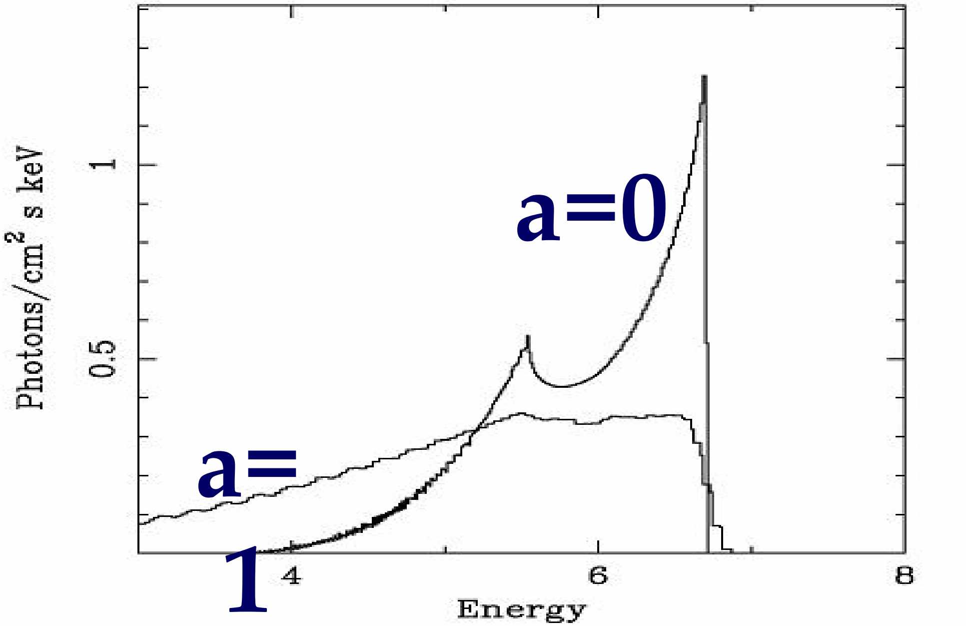
Line profiles

SR and GR effects modify the line profile in a characteristic and well-recognizable way

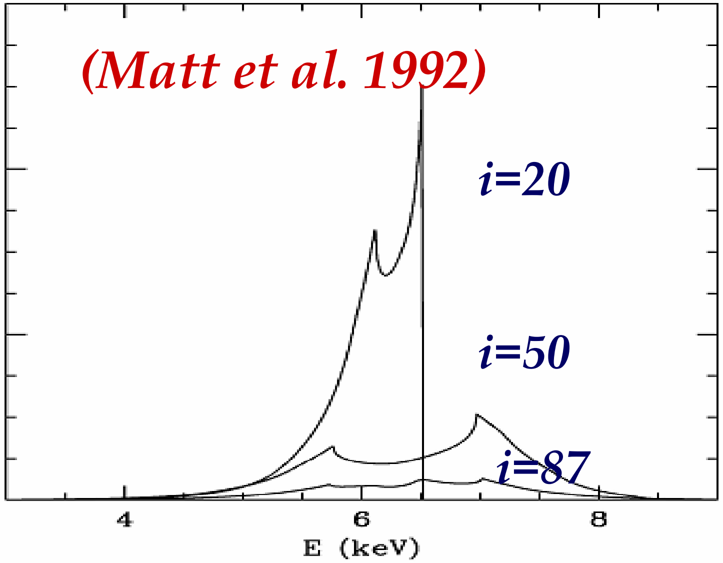


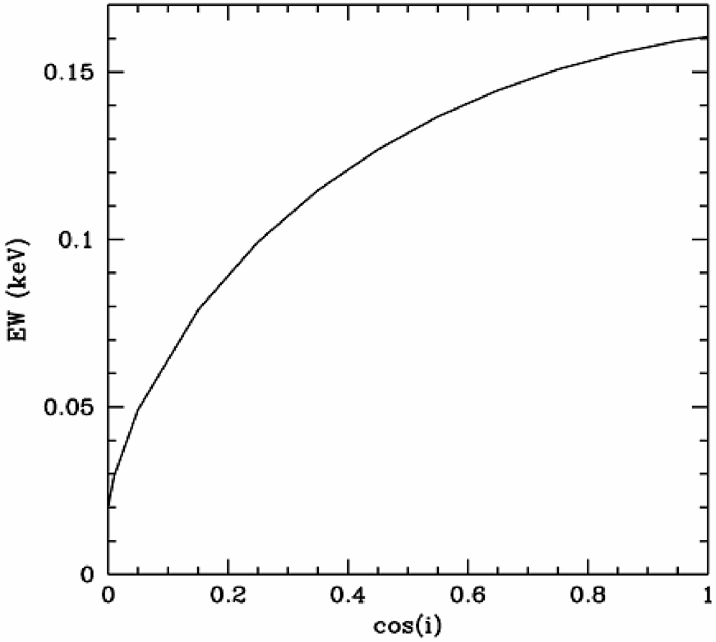
(Fabian et al. 2000)

Line profiles



Fabian et al. (2000)



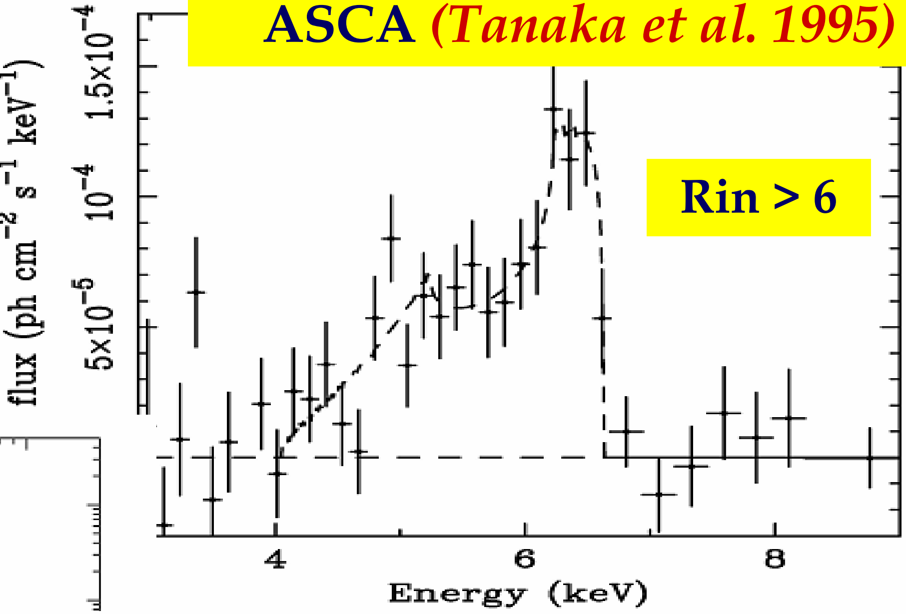


Isotropic illumination
(e.g. George & Fabian 1991, Matt et al. 1991, 1992)

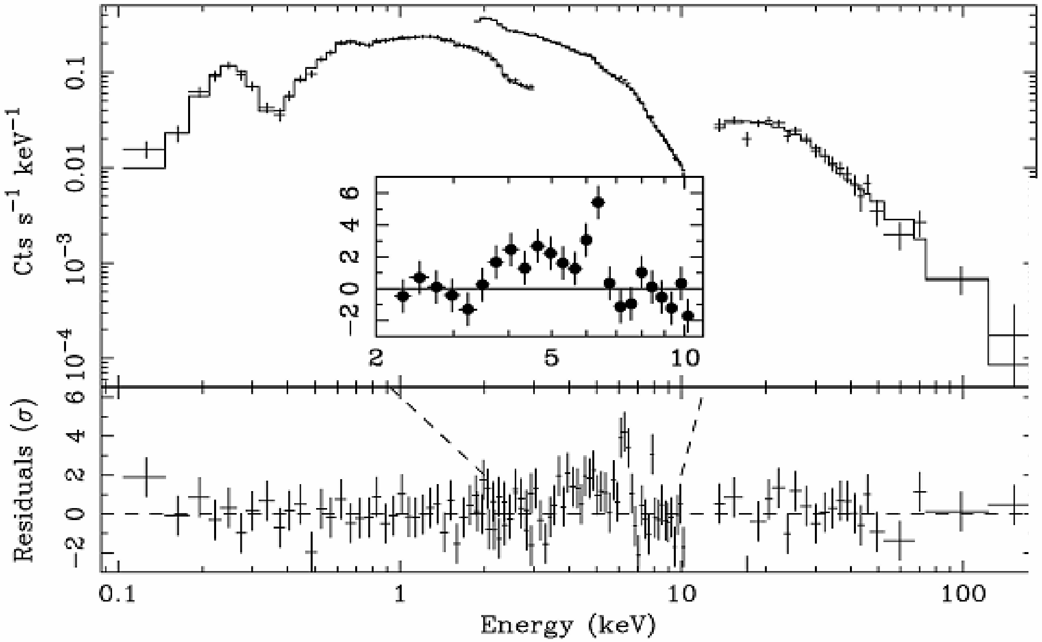
Observations

MCG-6-30-15

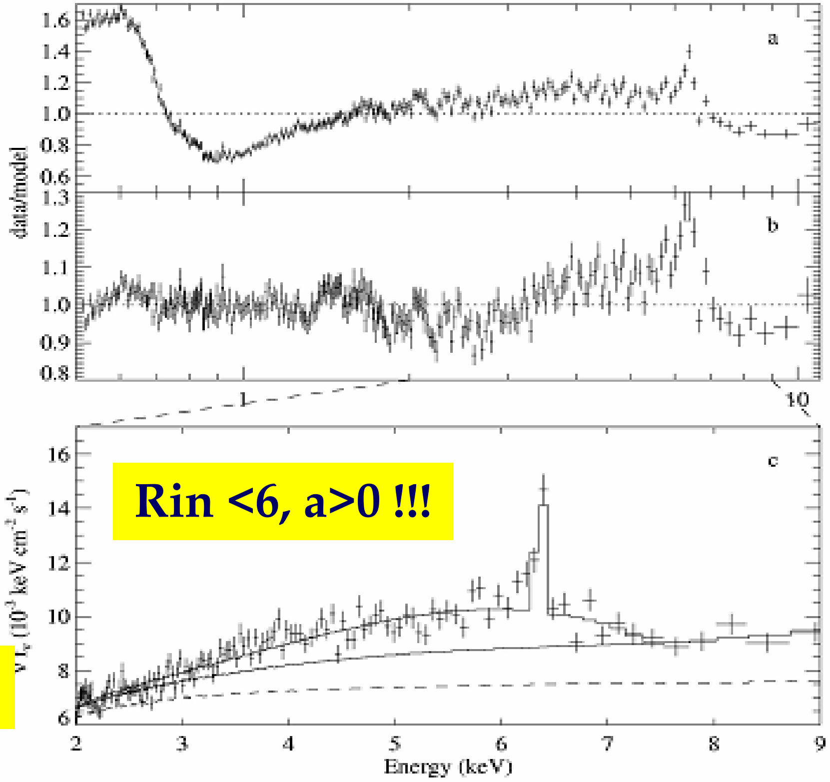
ASCA *(Tanaka et al. 1995)*



Rin > 6



BeppoSAX *(Guainazzi et al. 1999)*



Rin <6, a>0 !!!

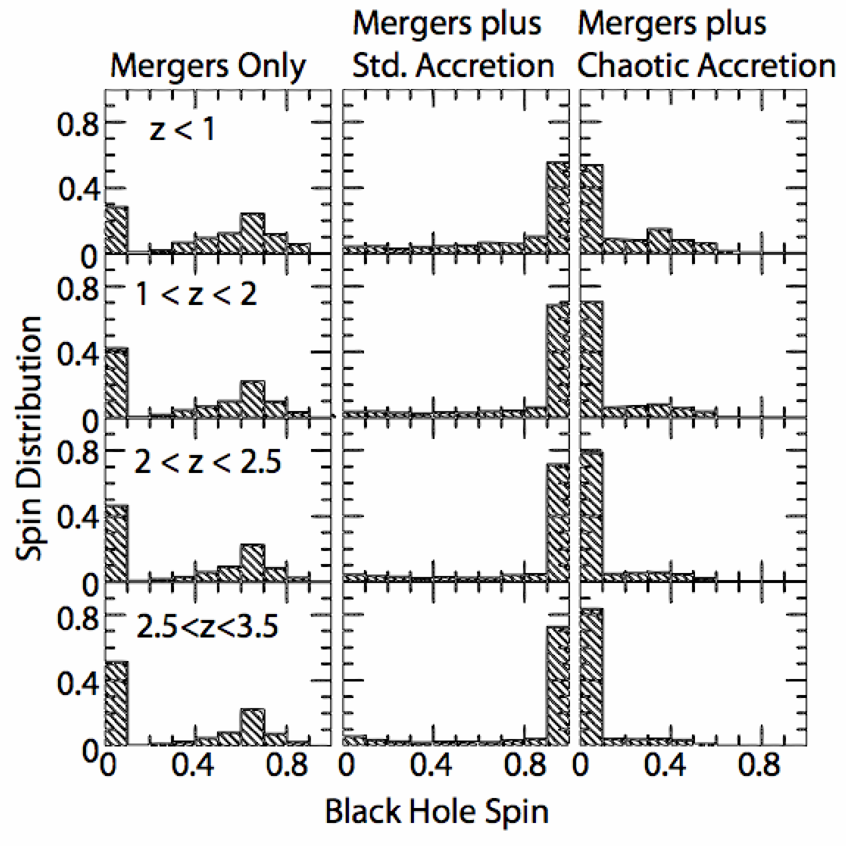
XMM-Newton *(Wilms et al. 2001)*

The importance of spin measurements

Why is important to know the BH spin distributions?

In AGN, it can discriminate between different growth histories (spin is mainly acquired during the SMBH evolution)

In GBHS, it tells us about the origin of the BH (spin is mainly pristine)



Berti & Volonteri 2008

Pros of the method

Conceptually, a very simple and straighforward method.

Observationally, only requires to measure the extension of the red tail of the line profile (once the inclination is known). No detailed physical modeling is required.

Cons of the method. I

- It provides only a lower limit to the angular momentum (the iron line emitting region does not necessarily extend down to the ISCO)

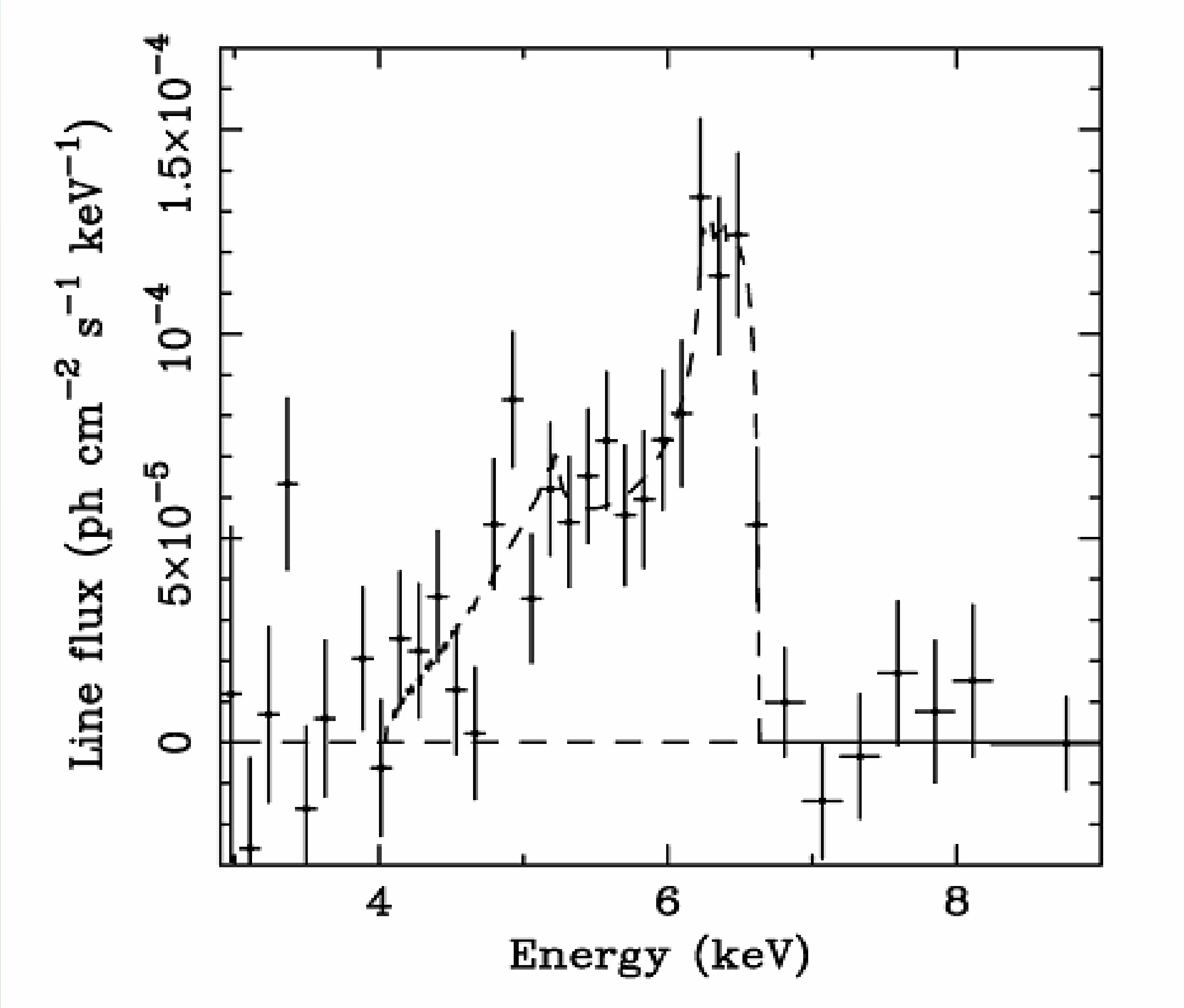
- The energy at zero intensity may be difficult to measure

MCG-6-30-15

(ASCA)

(Tanaka et al. 1995)

$R_{in} > 6$

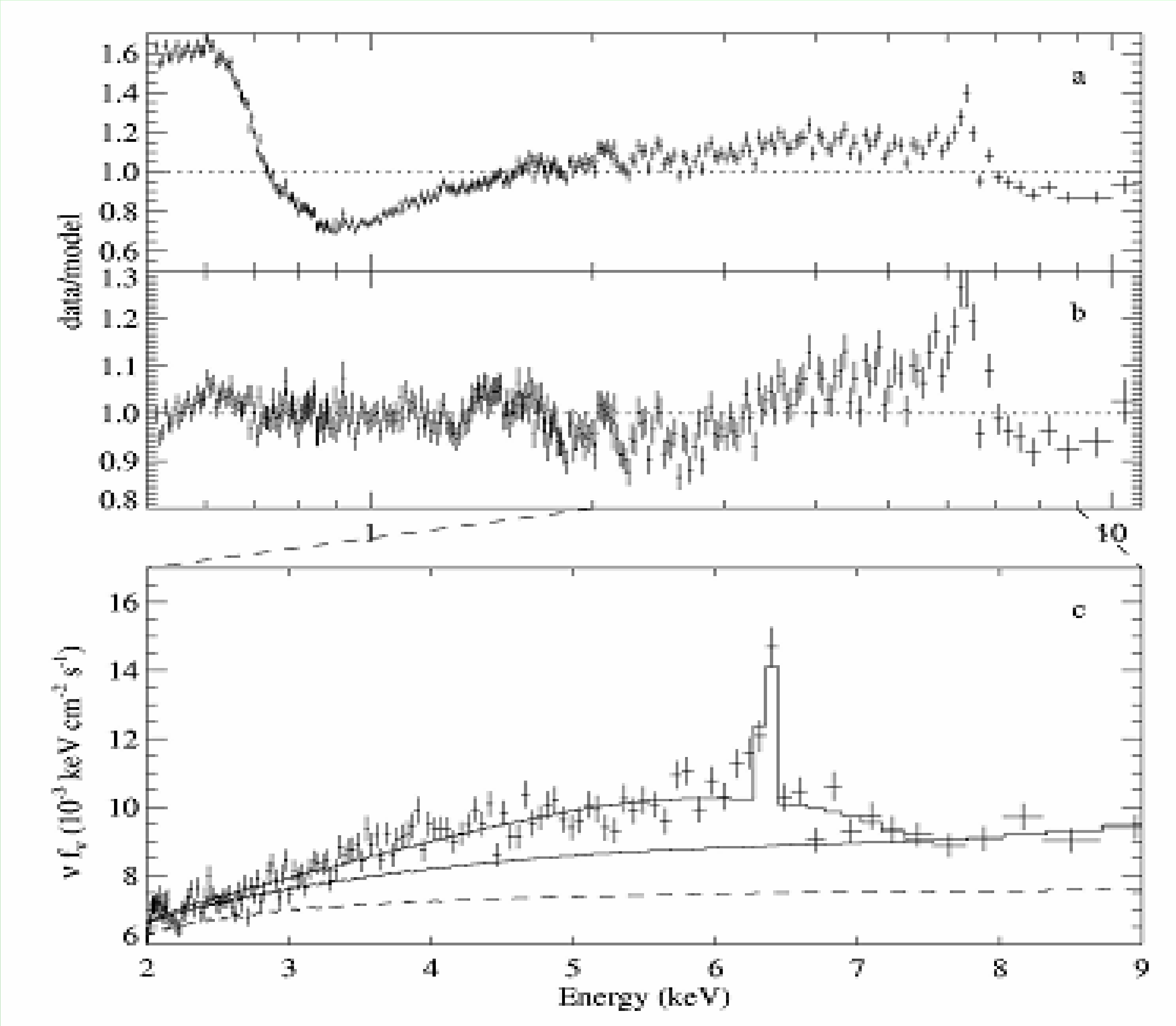


MCG-6-30-15

XMM-Newton

(Wilms et al. 2001, Fabian et al. 2002)

R_{in} = 1-2



Cons of the method. I

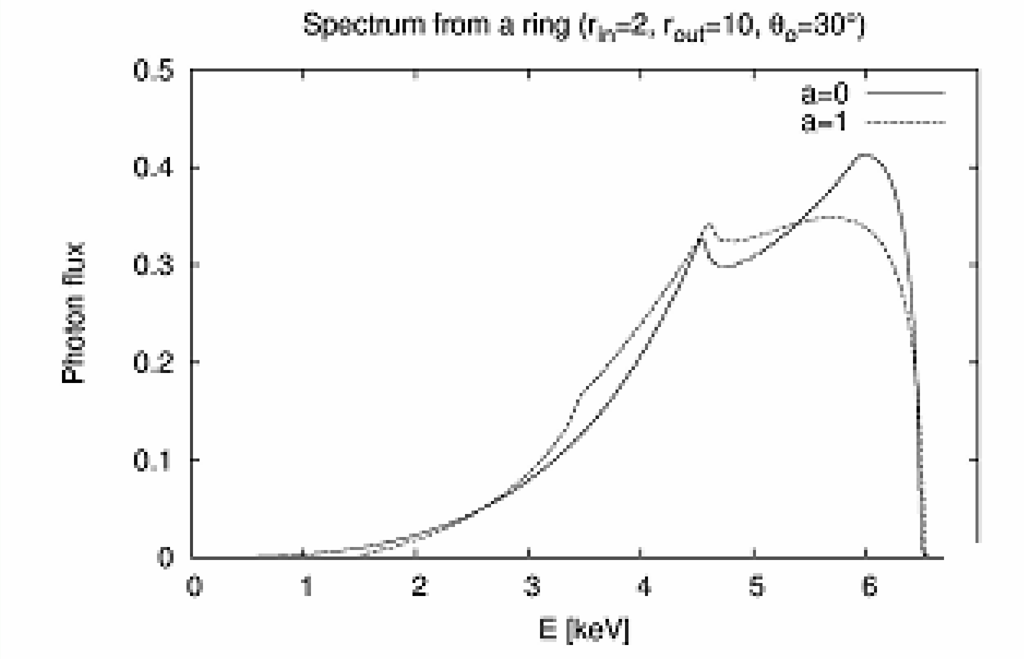
- It provides only a lower limit to the angular momentum (the iron line emitting region does not necessarily extend down to the ISCO)

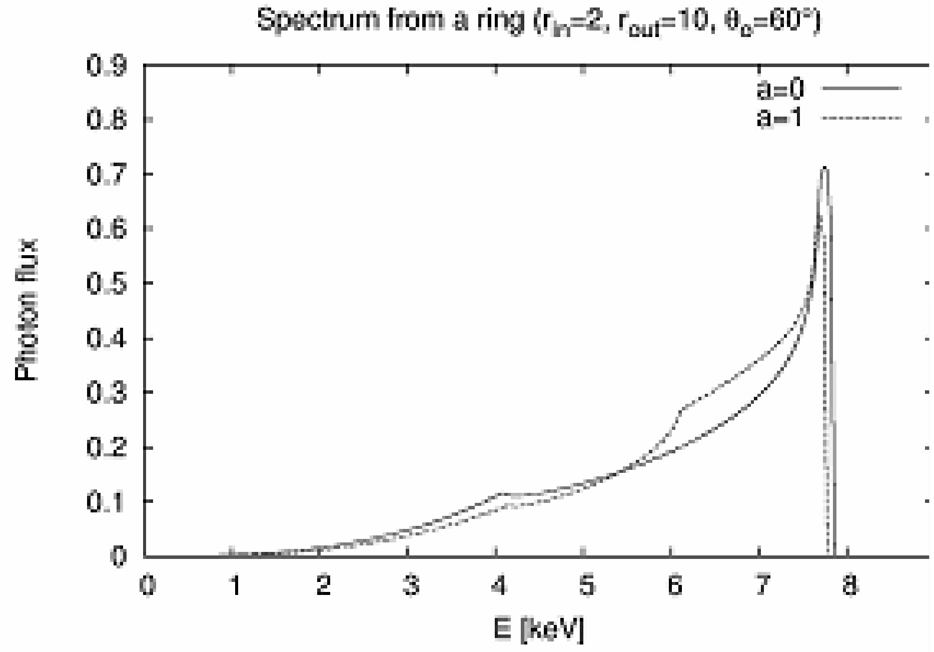
- **The energy at zero intensity may be difficult to measure (importance of good understanding of the underlying continuum)**

Cons of the method. II

Emission may arise also within the ISCO from matter spiralling in (Reynolds & Begelman 1997). If the inner radius results to be smaller than 2, there is of course no ambiguity. Otherwise, one can (in principle..) use the subtle differencies in the line profiles.

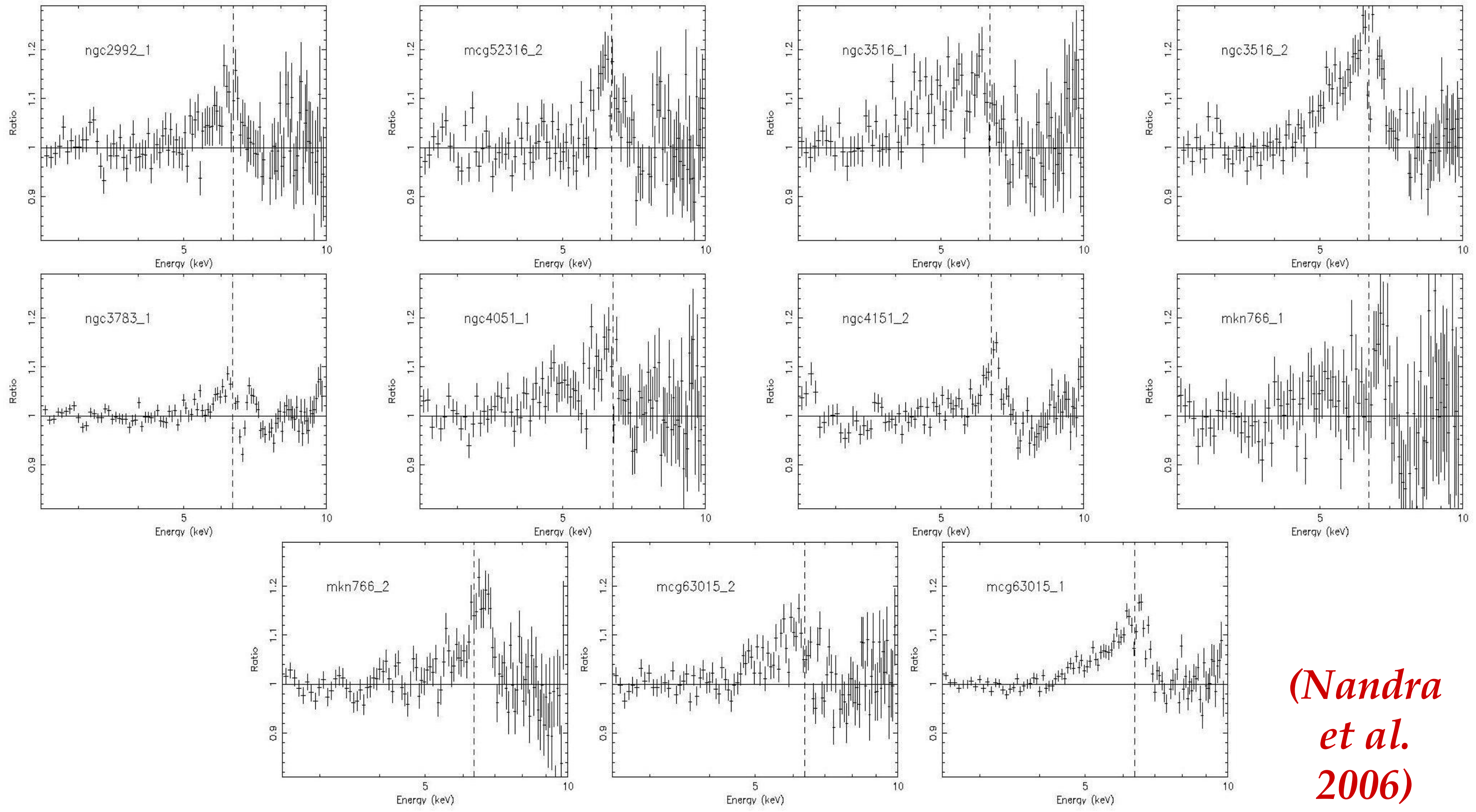
Cons of the method. II





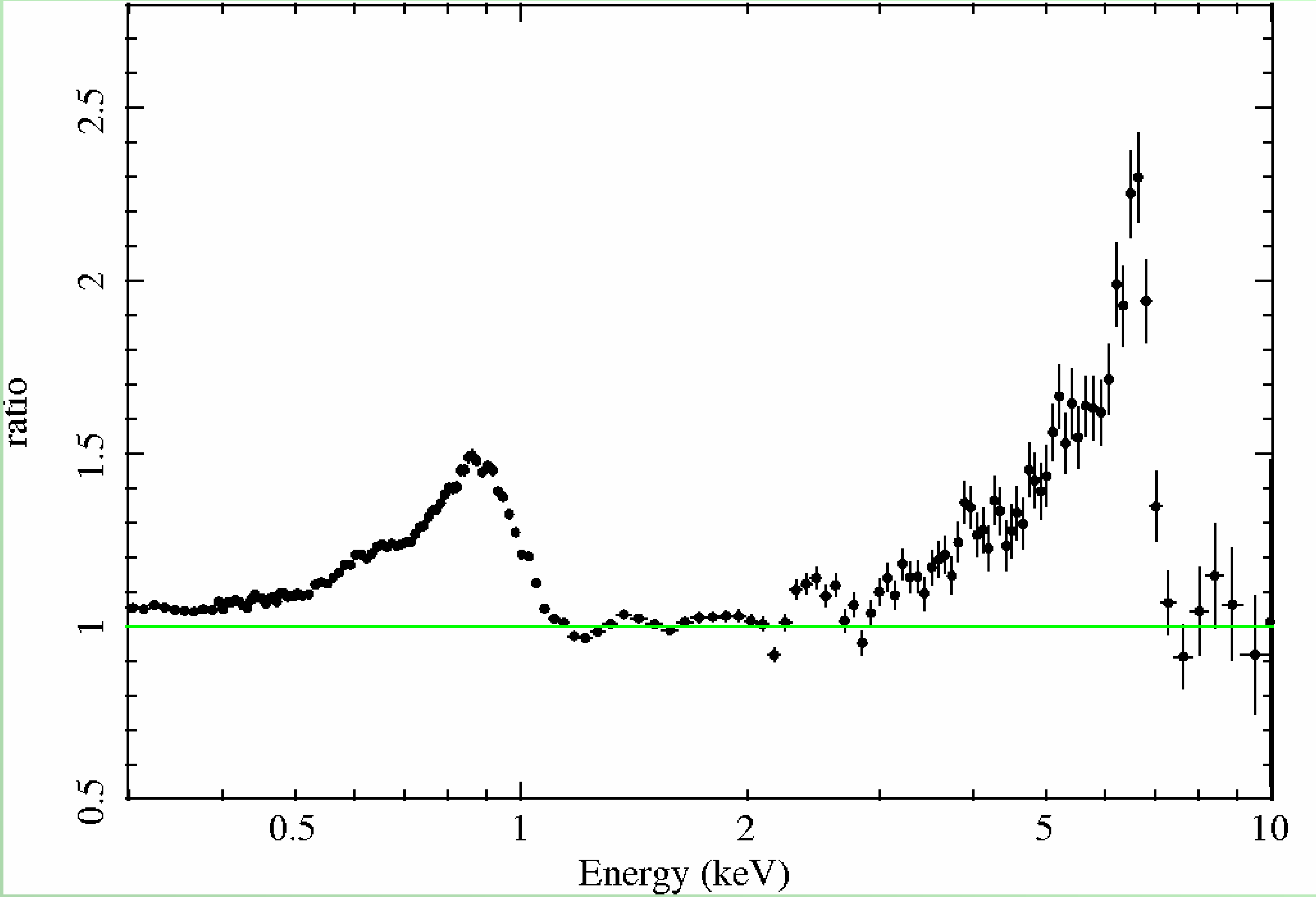
Courtesy
of
M. Dovciak
& V. Karas

Is MCG-6-30-15 unique ?



(Nandra et al. 2006)

Is MCG-6-30-15 unique ?

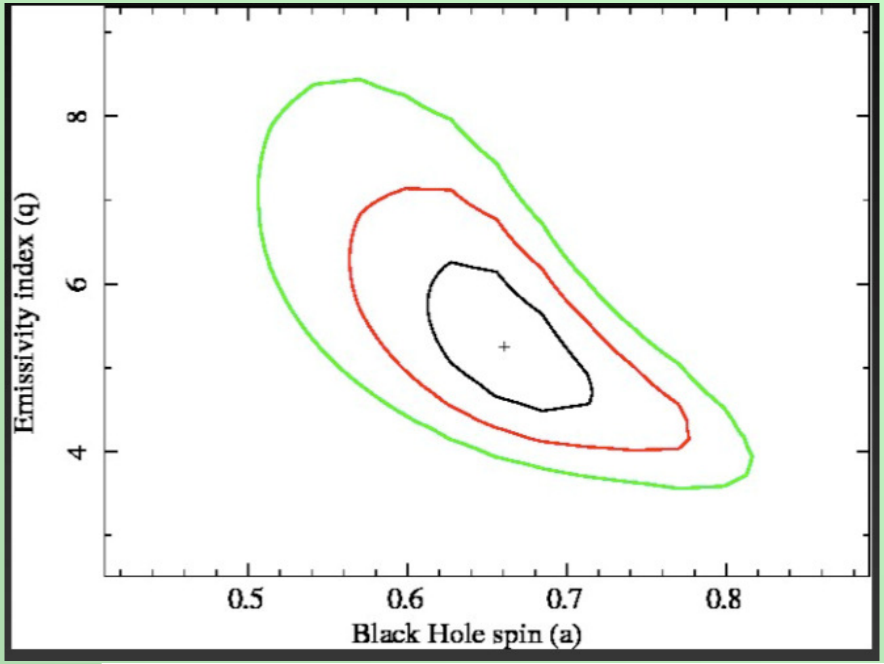


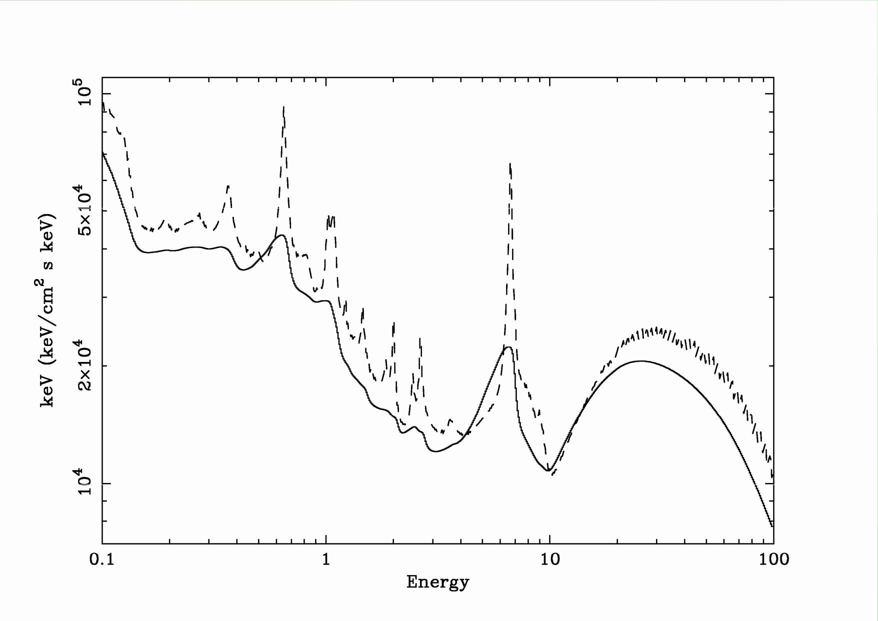
(Fabian et al. 2009)

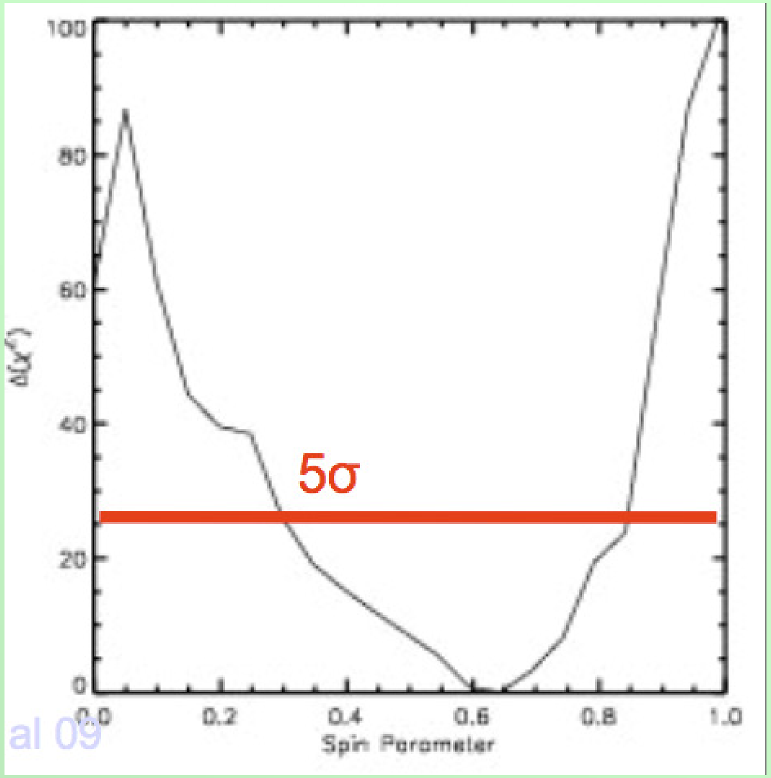
1H 0707-495

SWIFT J1247 (Miniutti et al. 2010)

Fairall 9 (Schmoll et al. 2010)

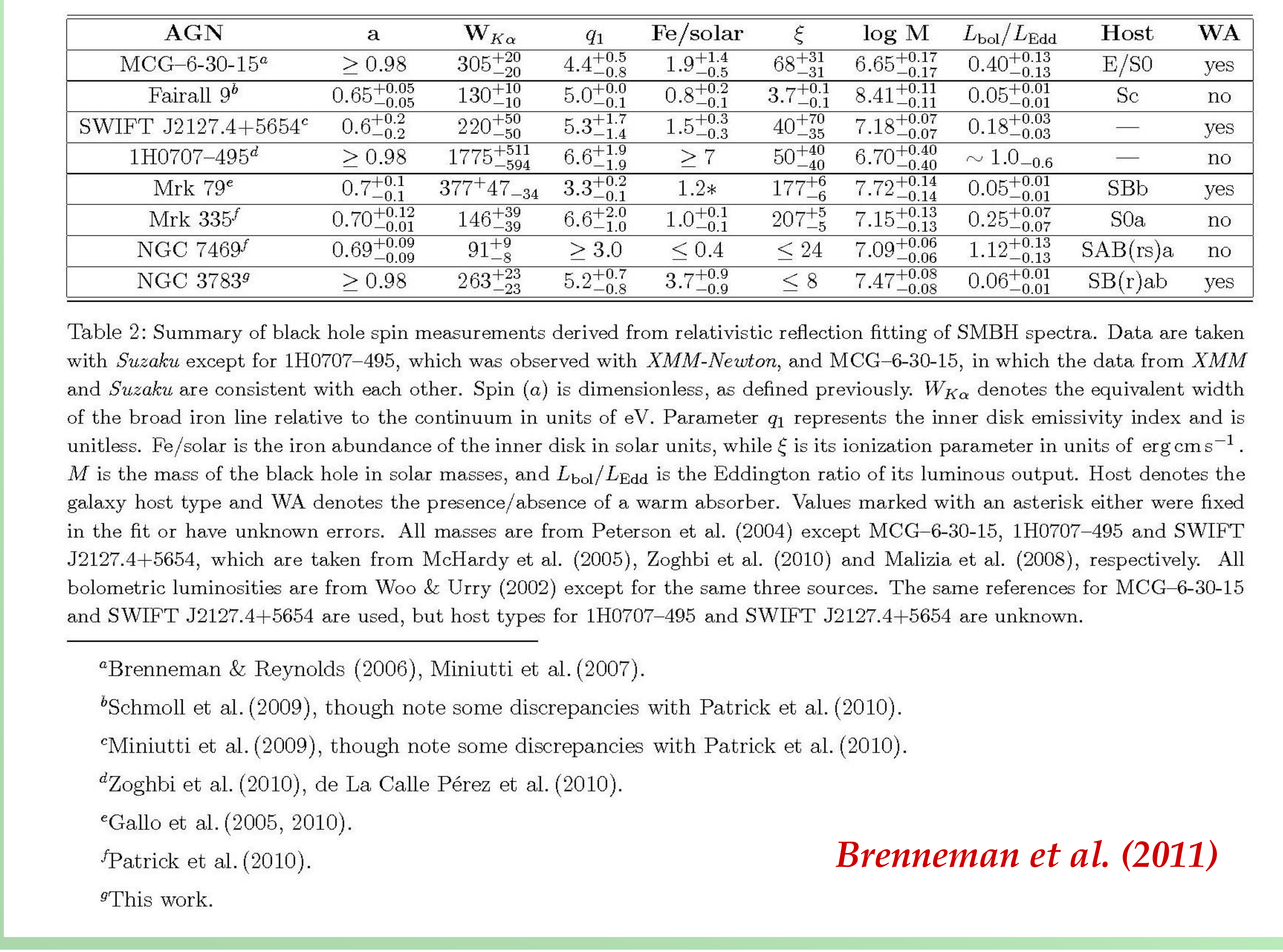






NB: results obtained by fitting simulateneously the line and the reflection continuum

Is MCG-6-30-15 unique ?



AGN	a	$W_{K\alpha}$	q_1	Fe/solar	ξ	log M	$L_{\rm bol}/L_{\rm Edd}$	Host	WA
MCG–6-30-15[a]	≥ 0.98	305^{+20}_{-20}	$4.4^{+0.5}_{-0.8}$	$1.9^{+1.4}_{-0.5}$	68^{+31}_{-31}	$6.65^{+0.17}_{-0.17}$	$0.40^{+0.13}_{-0.13}$	E/S0	yes
Fairall 9[b]	$0.65^{+0.05}_{-0.05}$	130^{+10}_{-10}	$5.0^{+0.0}_{-0.1}$	$0.8^{+0.2}_{-0.1}$	$3.7^{+0.1}_{-0.1}$	$8.41^{+0.11}_{-0.11}$	$0.05^{+0.01}_{-0.01}$	Sc	no
SWIFT J2127.4+5654[c]	$0.6^{+0.2}_{-0.2}$	220^{+50}_{-50}	$5.3^{+1.7}_{-1.4}$	$1.5^{+0.3}_{-0.3}$	40^{+70}_{-35}	$7.18^{+0.07}_{-0.07}$	$0.18^{+0.03}_{-0.03}$	—	yes
1H0707–495[d]	≥ 0.98	1775^{+511}_{-594}	$6.6^{+1.9}_{-1.9}$	≥ 7	50^{+40}_{-40}	$6.70^{+0.40}_{-0.40}$	$\sim 1.0_{-0.6}$	—	no
Mrk 79[e]	$0.7^{+0.1}_{-0.1}$	$377^{+}47_{-34}$	$3.3^{+0.2}_{-0.1}$	$1.2*$	177^{+6}_{-6}	$7.72^{+0.14}_{-0.14}$	$0.05^{+0.01}_{-0.01}$	SBb	yes
Mrk 335[f]	$0.70^{+0.12}_{-0.01}$	146^{+39}_{-39}	$6.6^{+2.0}_{-1.0}$	$1.0^{+0.1}_{-0.1}$	207^{+5}_{-5}	$7.15^{+0.13}_{-0.13}$	$0.25^{+0.07}_{-0.07}$	S0a	no
NGC 7469[f]	$0.69^{+0.09}_{-0.09}$	91^{+9}_{-8}	≥ 3.0	≤ 0.4	≤ 24	$7.09^{+0.06}_{-0.06}$	$1.12^{+0.13}_{-0.13}$	SAB(rs)a	no
NGC 3783[g]	≥ 0.98	263^{+23}_{-23}	$5.2^{+0.7}_{-0.8}$	$3.7^{+0.9}_{-0.9}$	≤ 8	$7.47^{+0.08}_{-0.08}$	$0.06^{+0.01}_{-0.01}$	SB(r)ab	yes

Table 2: Summary of black hole spin measurements derived from relativistic reflection fitting of SMBH spectra. Data are taken with *Suzaku* except for 1H0707–495, which was observed with *XMM-Newton*, and MCG–6-30-15, in which the data from *XMM* and *Suzaku* are consistent with each other. Spin (a) is dimensionless, as defined previously. $W_{K\alpha}$ denotes the equivalent width of the broad iron line relative to the continuum in units of eV. Parameter q_1 represents the inner disk emissivity index and is unitless. Fe/solar is the iron abundance of the inner disk in solar units, while ξ is its ionization parameter in units of $\rm erg\,cm\,s^{-1}$. M is the mass of the black hole in solar masses, and $L_{\rm bol}/L_{\rm Edd}$ is the Eddington ratio of its luminous output. Host denotes the galaxy host type and WA denotes the presence/absence of a warm absorber. Values marked with an asterisk either were fixed in the fit or have unknown errors. All masses are from Peterson et al. (2004) except MCG–6-30-15, 1H0707–495 and SWIFT J2127.4+5654, which are taken from McHardy et al. (2005), Zoghbi et al. (2010) and Malizia et al. (2008), respectively. All bolometric luminosities are from Woo & Urry (2002) except for the same three sources. The same references for MCG–6-30-15 and SWIFT J2127.4+5654 are used, but host types for 1H0707–495 and SWIFT J2127.4+5654 are unknown.

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[a] Brenneman & Reynolds (2006), Miniutti et al. (2007).

[b] Schmoll et al. (2009), though note some discrepancies with Patrick et al. (2010).

[c] Miniutti et al. (2009), though note some discrepancies with Patrick et al. (2010).

[d] Zoghbi et al. (2010), de La Calle Pérez et al. (2010).

[e] Gallo et al. (2005, 2010).

[f] Patrick et al. (2010).

[g] This work.

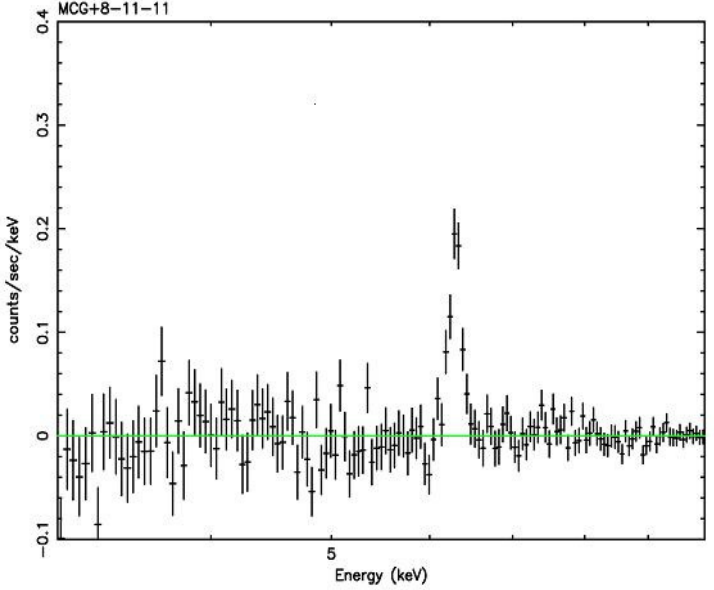
Brenneman et al. (2011)

Is the relativistic line always there ?

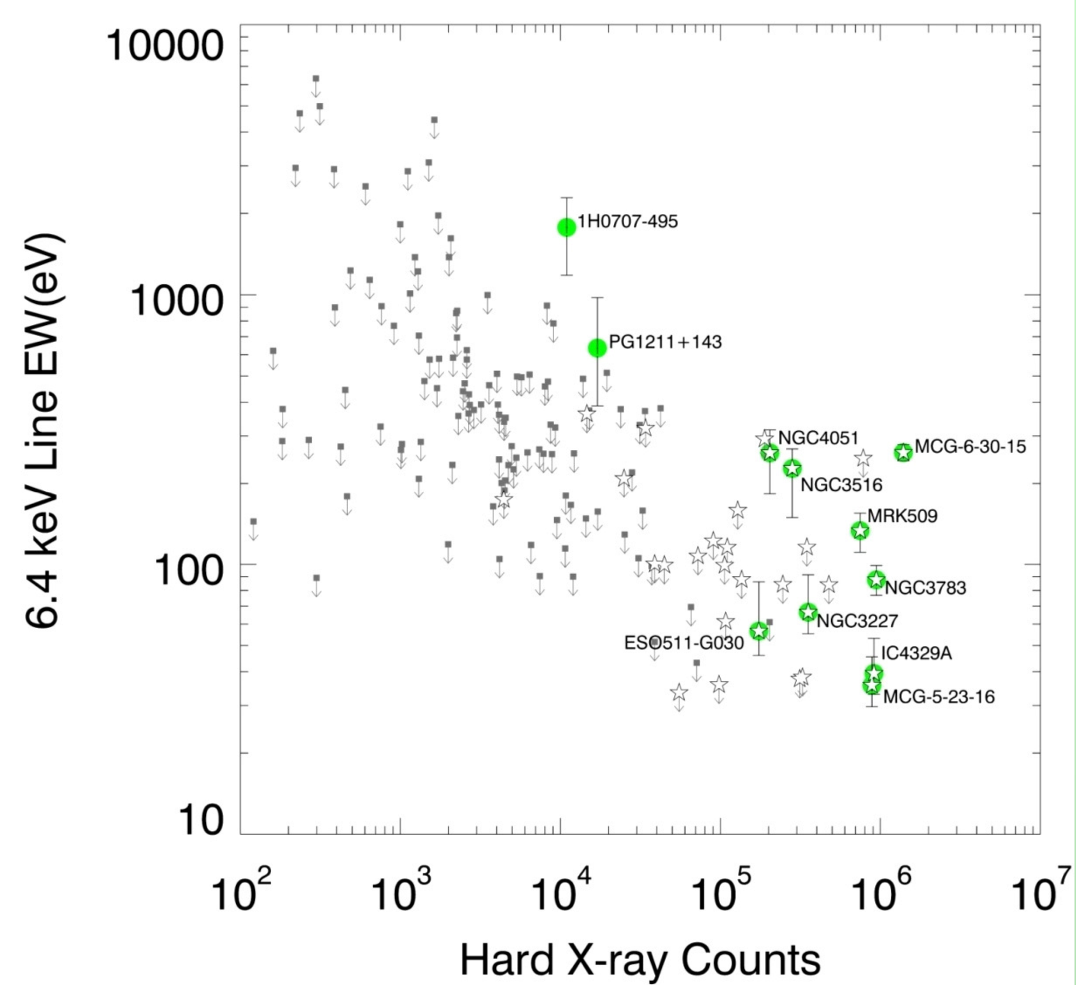
Recent XMM-Newton observations of many other bright AGN, however, found only a narrow line (which is almost ubiquitous) (e.g. Pounds & Reeves 2002, Bianchi et al. 2004)

**The relativistic line is certainly not ubiquitous,
at least in nearby AGN.**

MCG-8-11-11 *(Matt et al. 2005)*



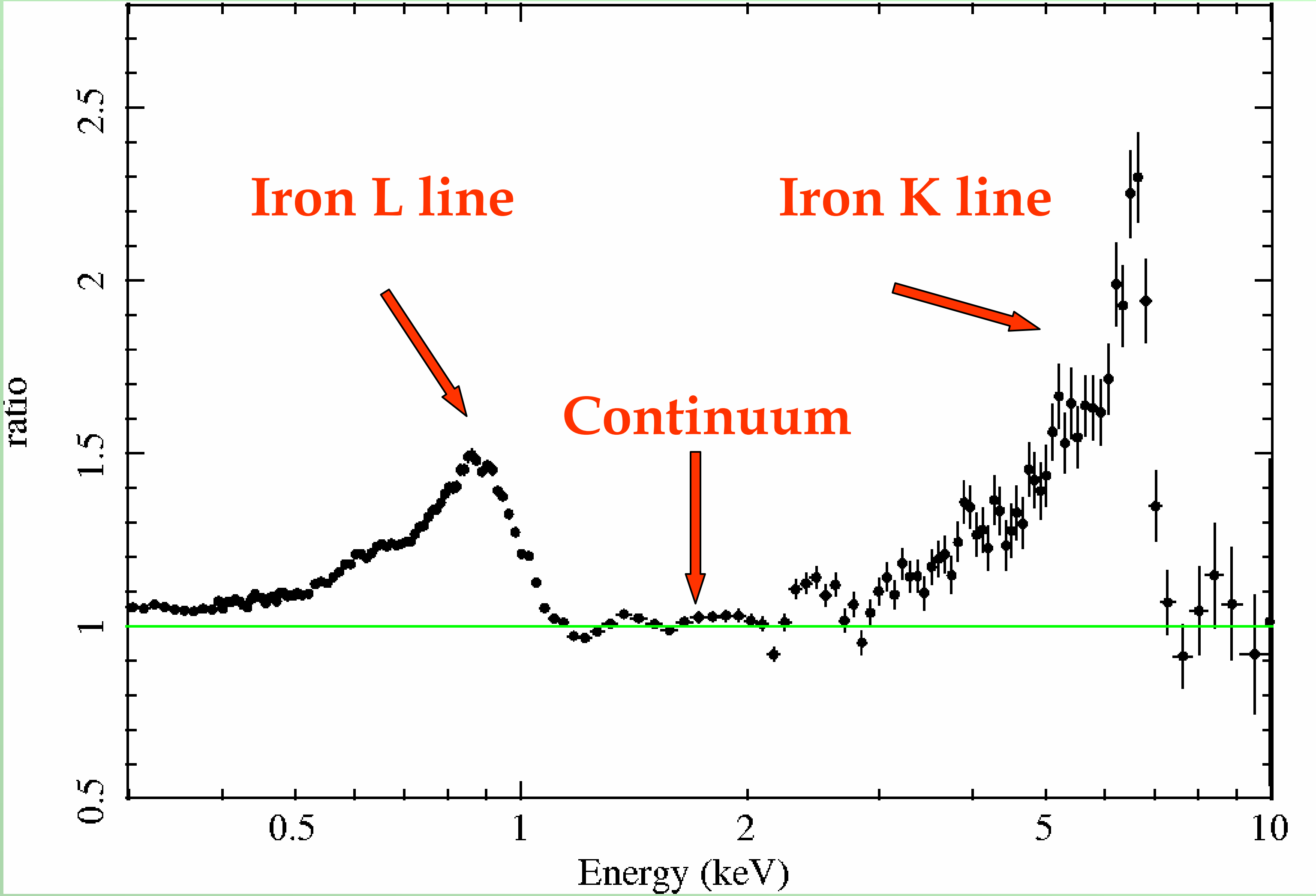
How common are relativistic lines in AGN ?



To search for a relativistic line, a good spectrum is required!!

About 30-40 % of `well exposed' objects show clear evidence for relativistic lines (Guainazzi et al. 2006, Nandra et al. 2007, de la Calle 2010).
In many other sources we simply cannot tell.

Time lags

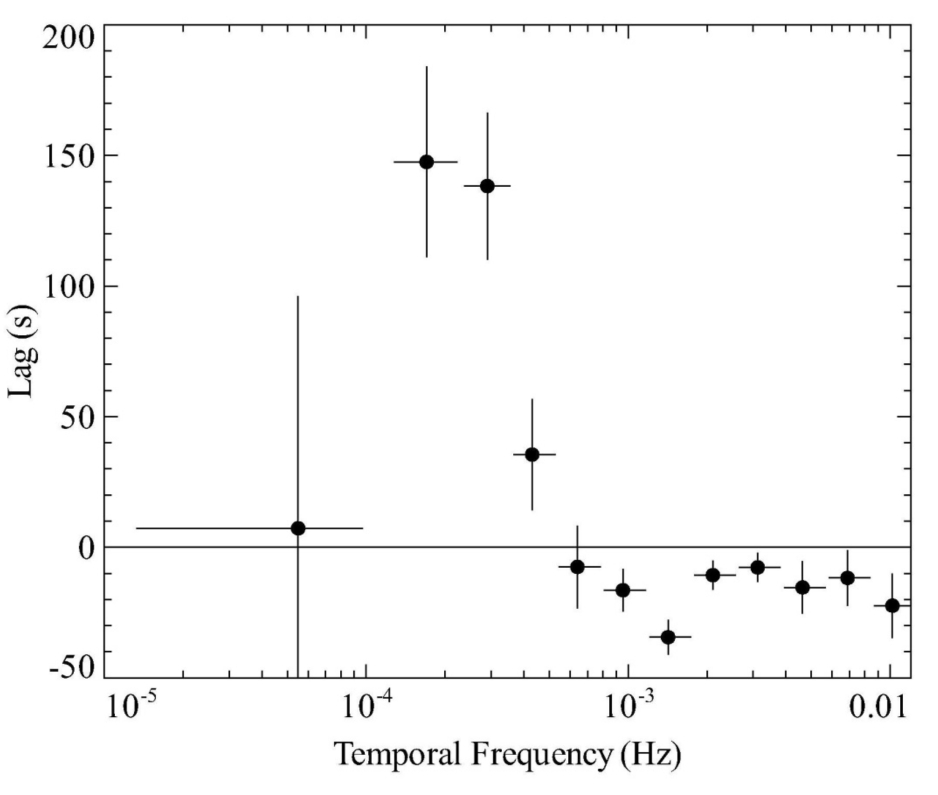


1H 0707-495

Fabian et al. (2009)

Time lags

The reprocessed emission lags behind the primary emission (Fabian et al. 2009, Zoghbi et al. 2010, E Emmanuelopoulos et al. 2011, De Marco et al. 2011).

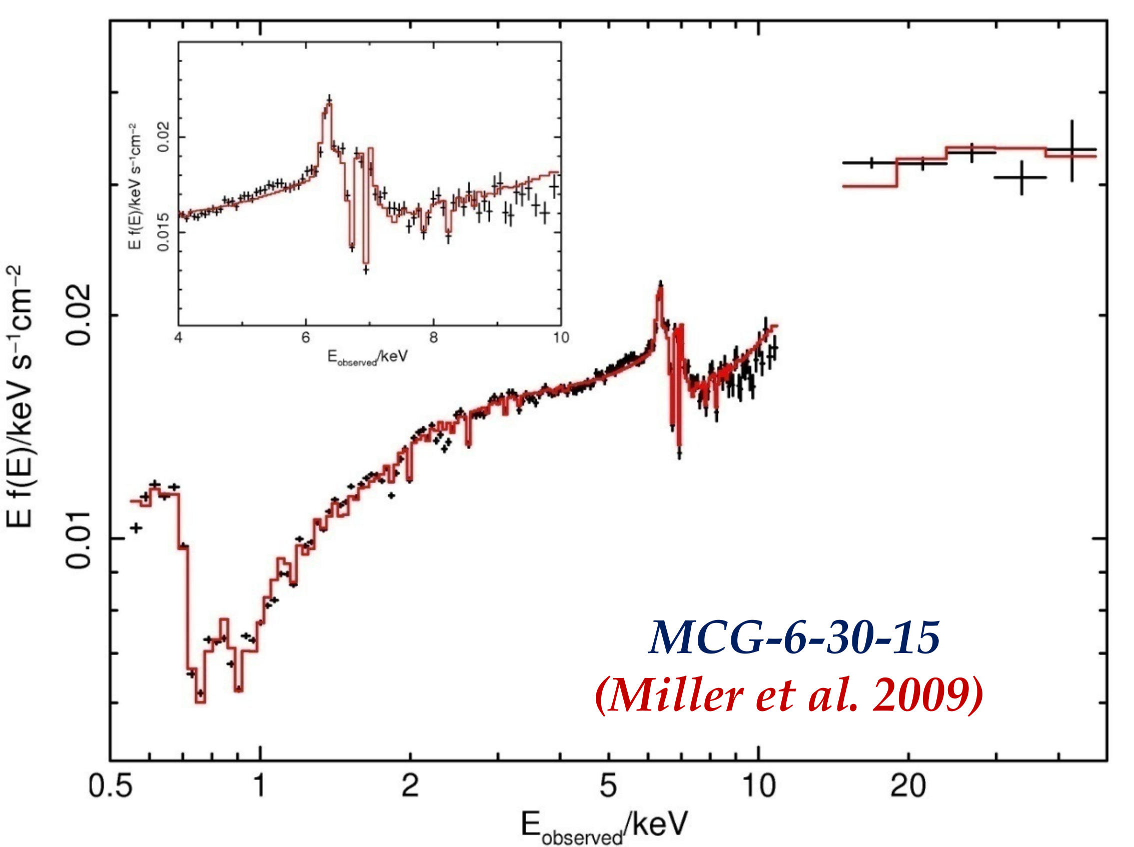


If interpreted as light-crossing time, it implies that the reprocessing occurs close to the black hole (inner accretion disc)

Zoghbi et al. (2010)

Is relativistic reflection the right model ?

Caveat: the broad feature - usually interpreted as a relativistic iron line - can be fitted equally well with a sufficient number of ionized absorbers, partially covering the X-ray source (e.g. Turner & Miller 2009).

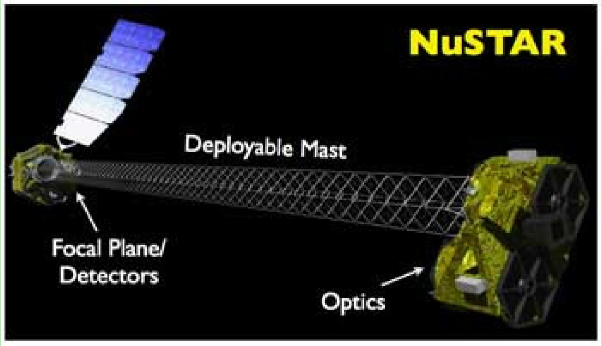


MCG-6-30-15

(Miller et al. 2009)

NuSTAR

will solve the issue !!!

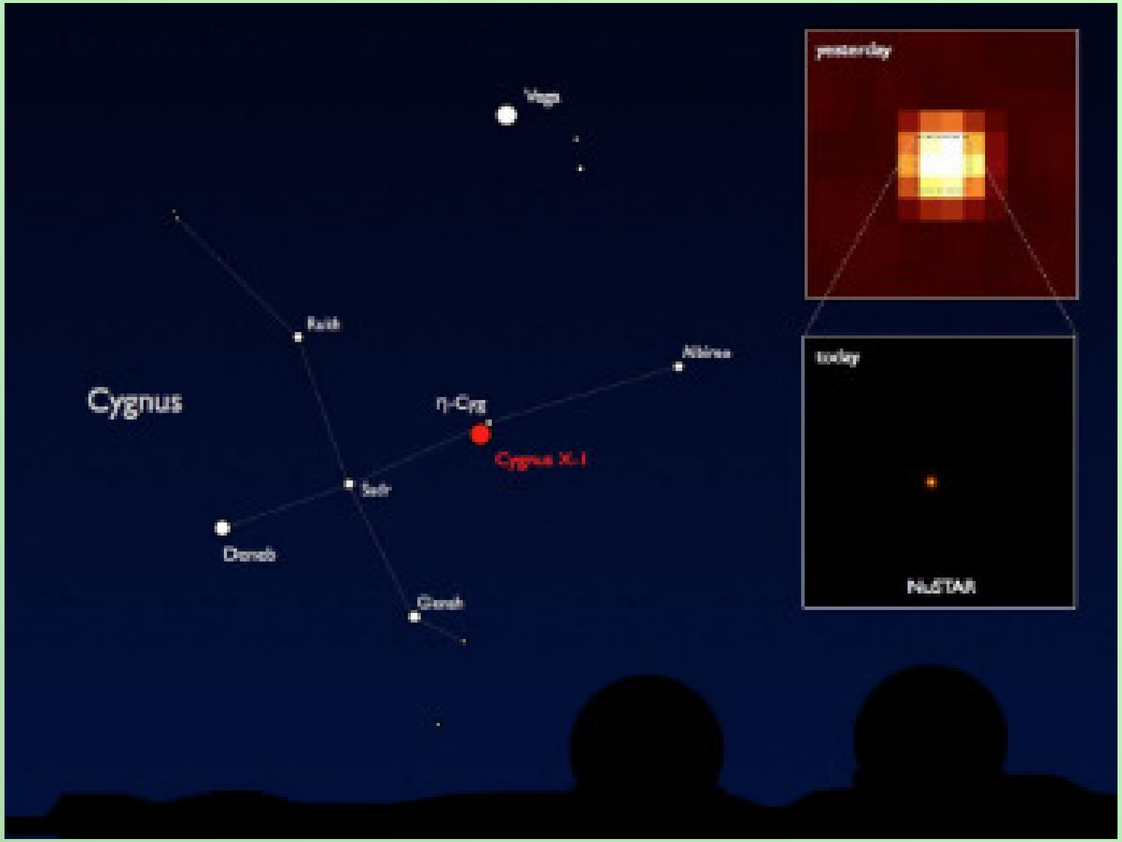


NuSTAR

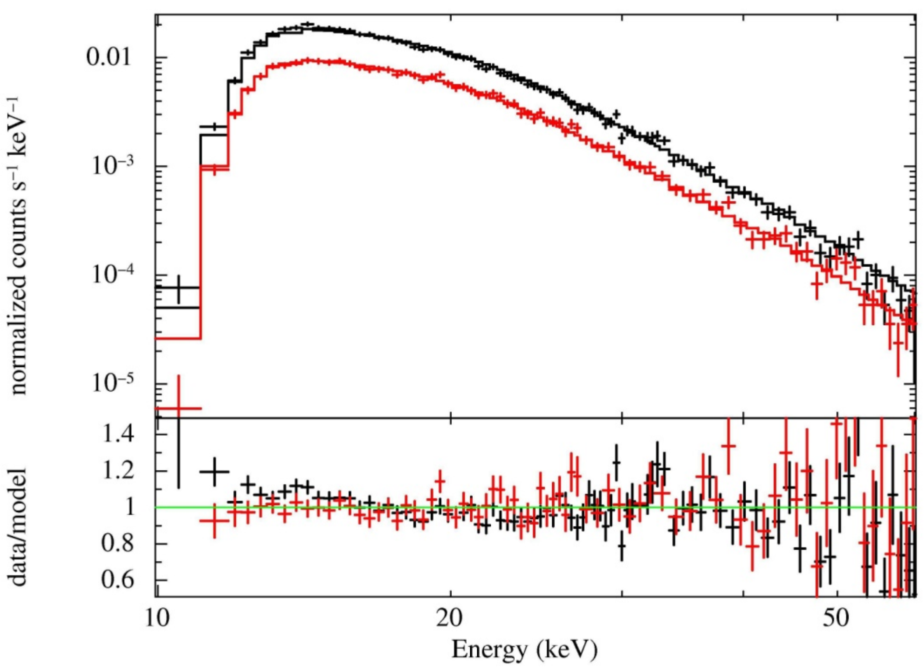
NuSTAR deploys the first focusing telescopes to image the sky in hard X-rays (6-79 keV), with an improve in sensitivity of 2 orders of magnitude.

Launched on June 13

First light on June 28



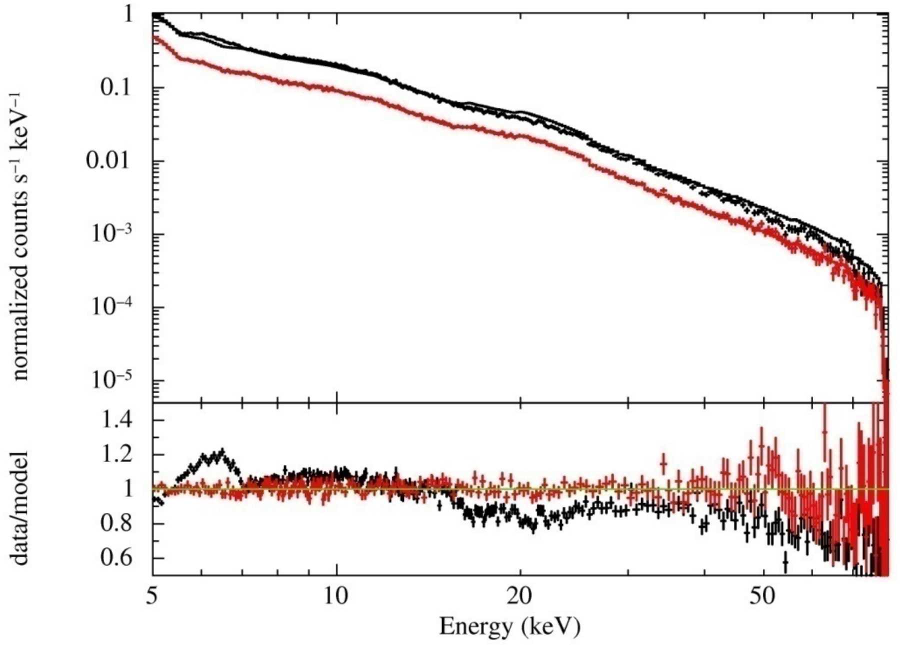
NuSTAR-XMM simultaneous observations (early 2013) of bright AGN to measure the spin with unprecedented precision



Suzaku

XMM-NuSTAR

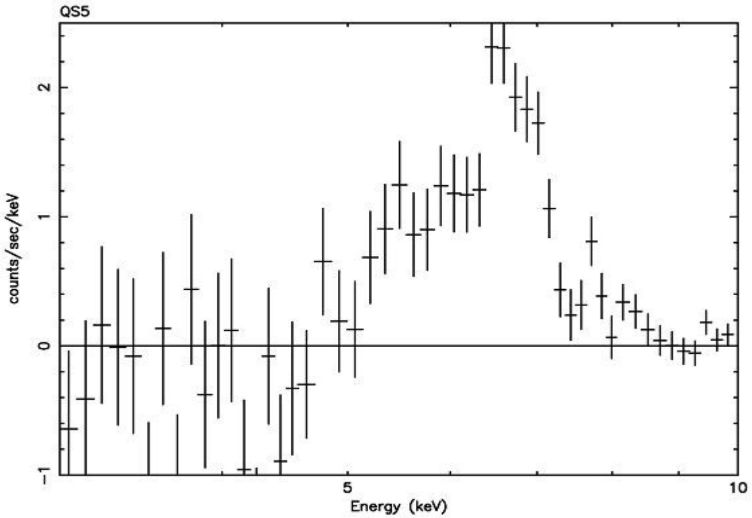
Courtesy: Laura Brenneman



Observations:
GBHC

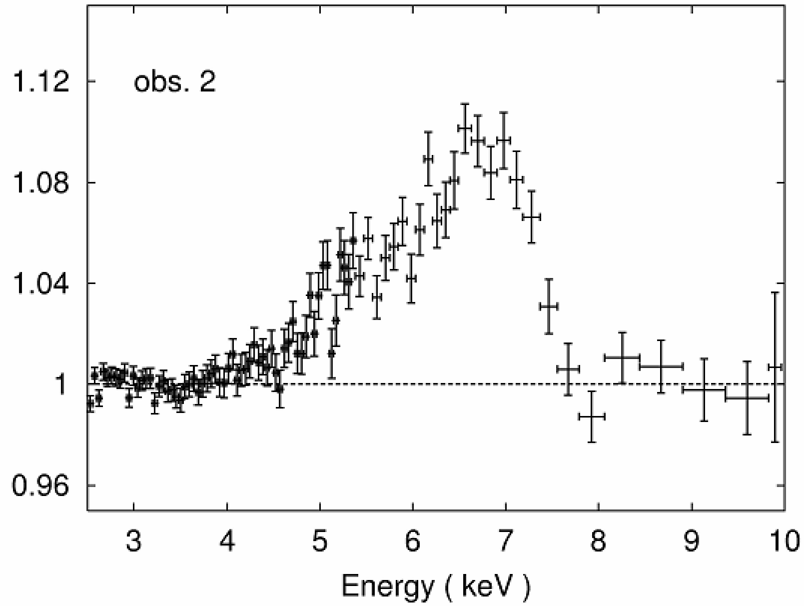
GRS 1915-105

(Martocchia et al. 2002)



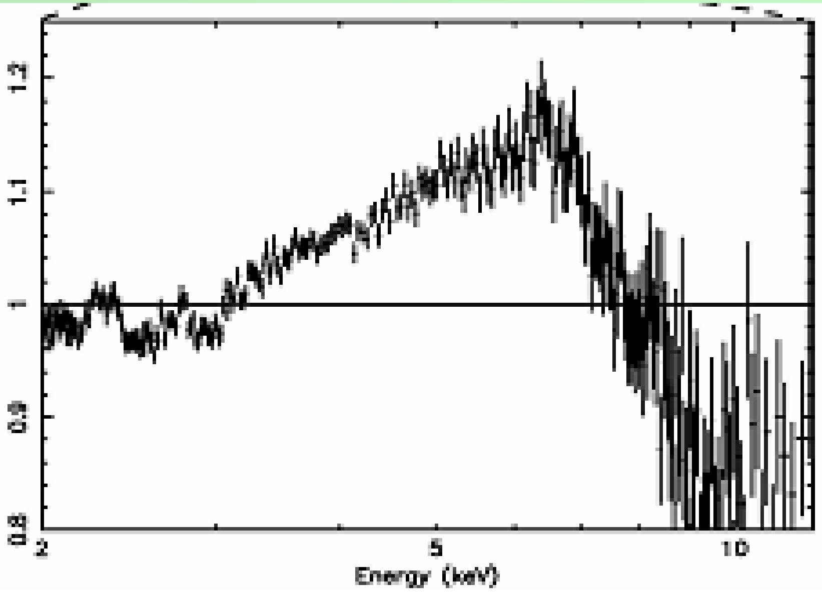
XTE 1650-500

(Miniutti et al. 2003)



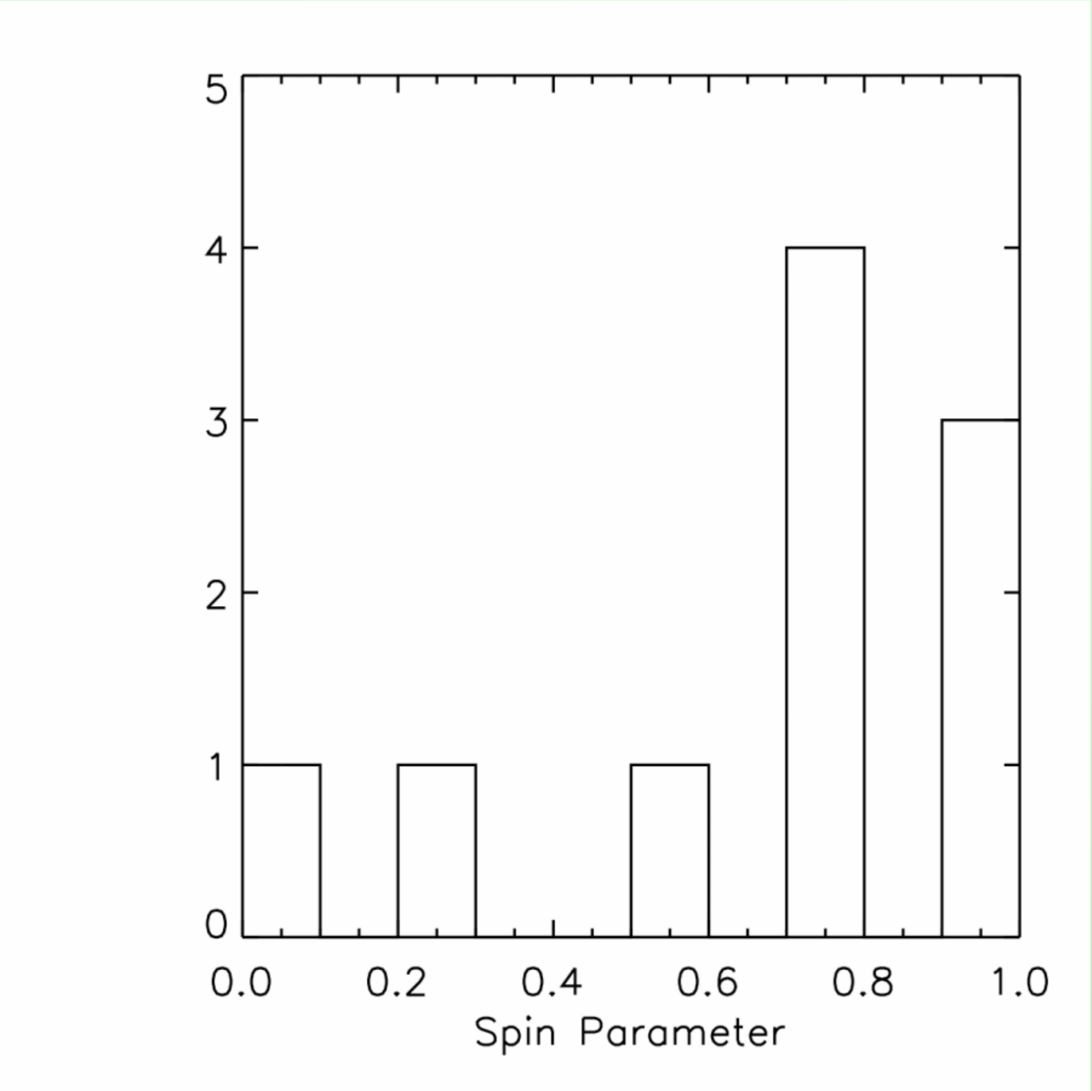
GX 339-4

(Miller et al. 2004)



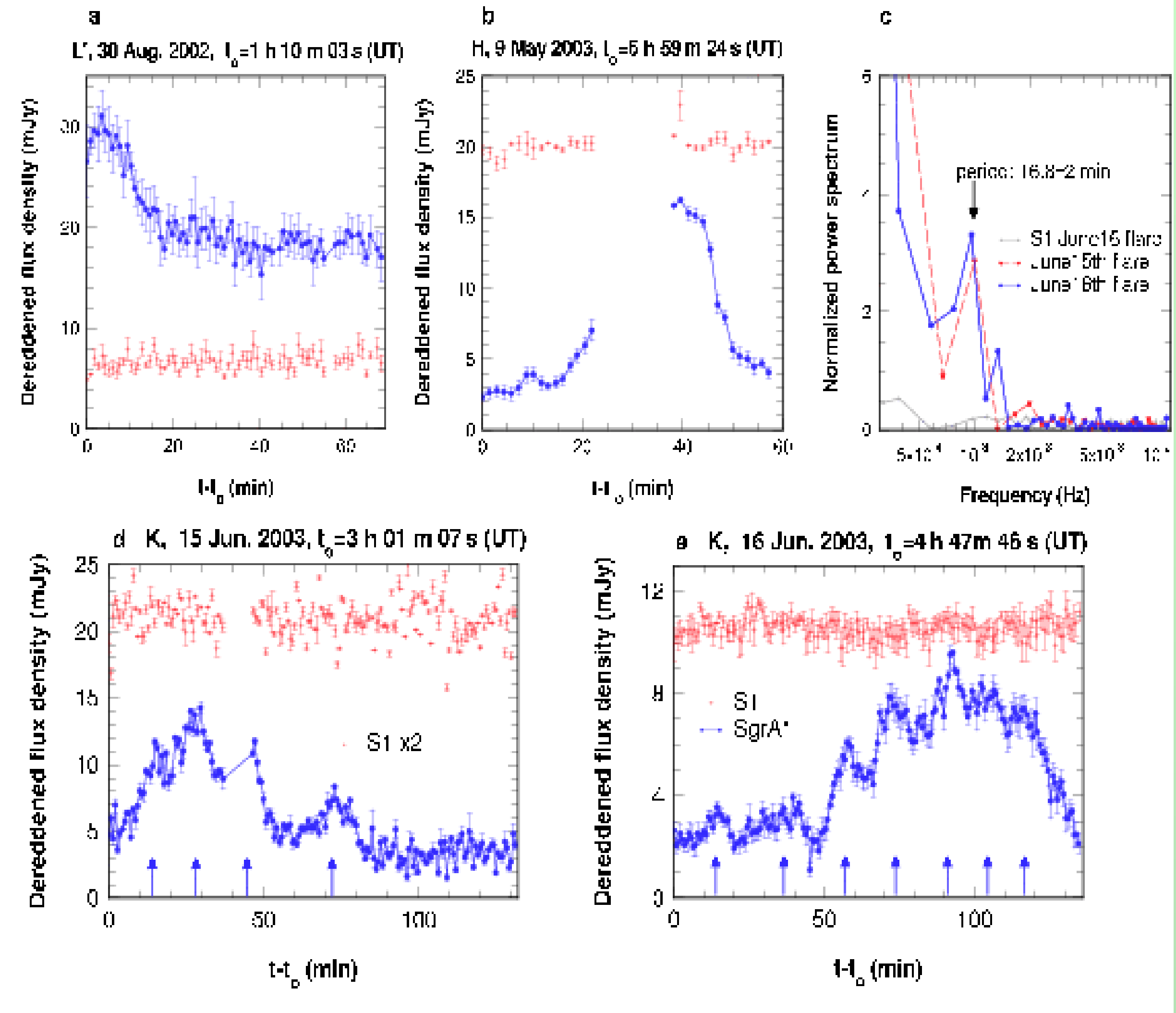
Observations: GBHC

Miller et al. 2009



GC: a spinning BH?

A possible periodicity of the IR emission in SgrA* (MPE IR group). Orbiting spot?



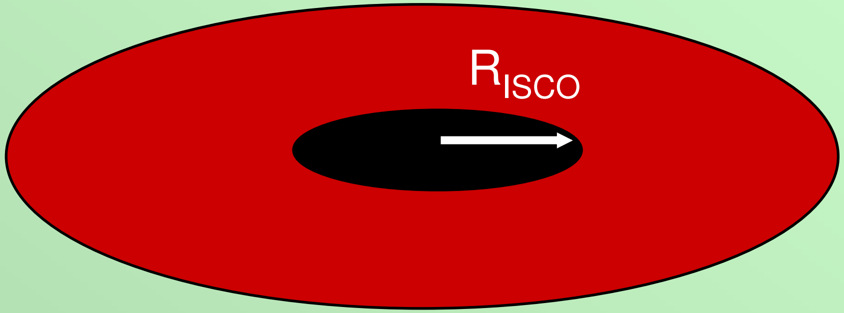
If radius identified with ISCO, then the BH is spinning

Continuum spectroscopy

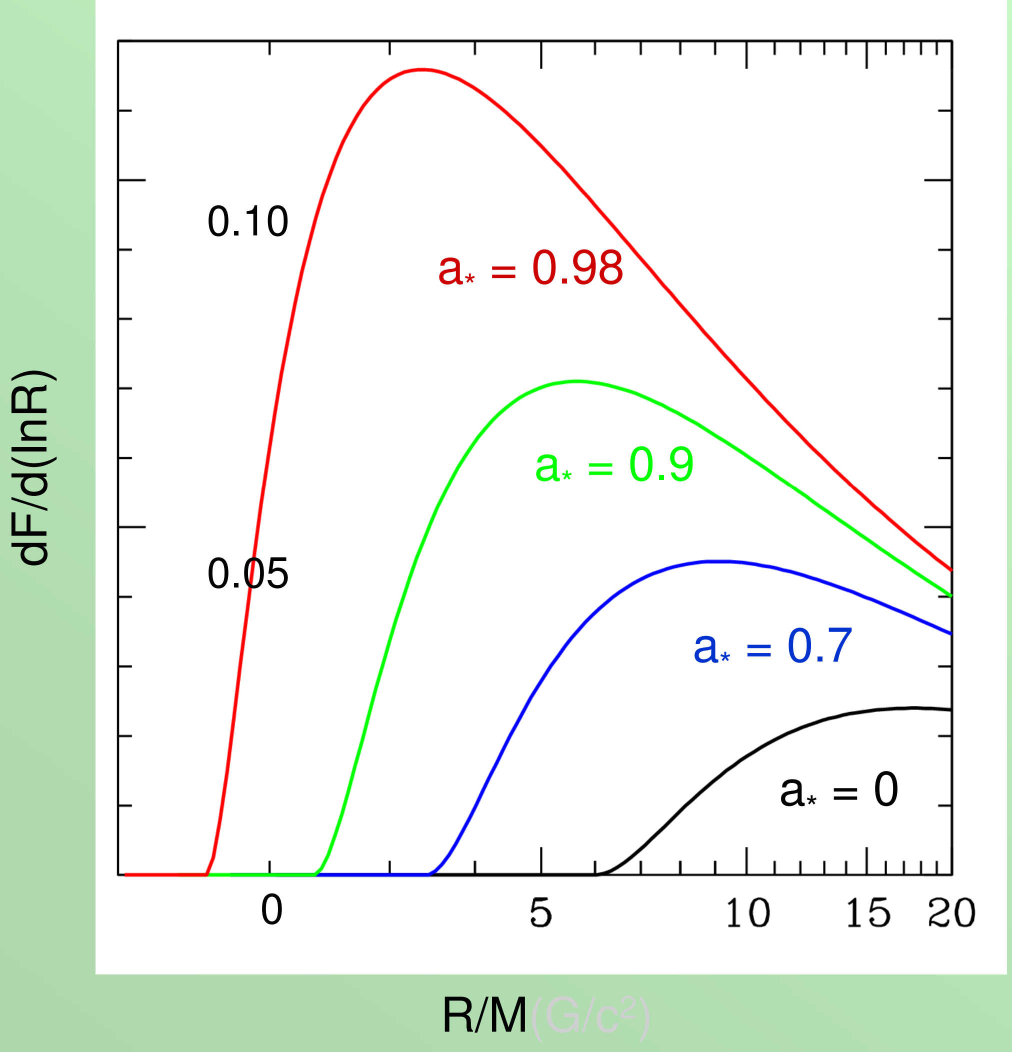
Fitting the disc thermal emission provides a measurement of ISCO.

Requires:

a) Spectrum dominated by thermal emission (soft state)
b) A very good modelling of the emission
c) Accurate values of M, i, D



Much work by McClintock, Narayan et al.



Strong dependence on R_{ISCO} and thence on the spin

Spin Results to Date

Source	a_*	Reference
GRS 1915+105	0.99 ± 0.01	McClintock et al. 2006
LMC X-1	0.92 ± 0.06	Gou et al. 2009
4U 1543-47	0.80 ± 0.05	Shafee et al. 2006
M33 X-7	0.77 ± 0.05	Liu et al. 2008
GRO J1655-40	0.70 ± 0.05	Shafee et al. 2006
A0620-00	0.12 ± 0.18	Gou et al. 2009

McClintock et al. (2010)

QPOs

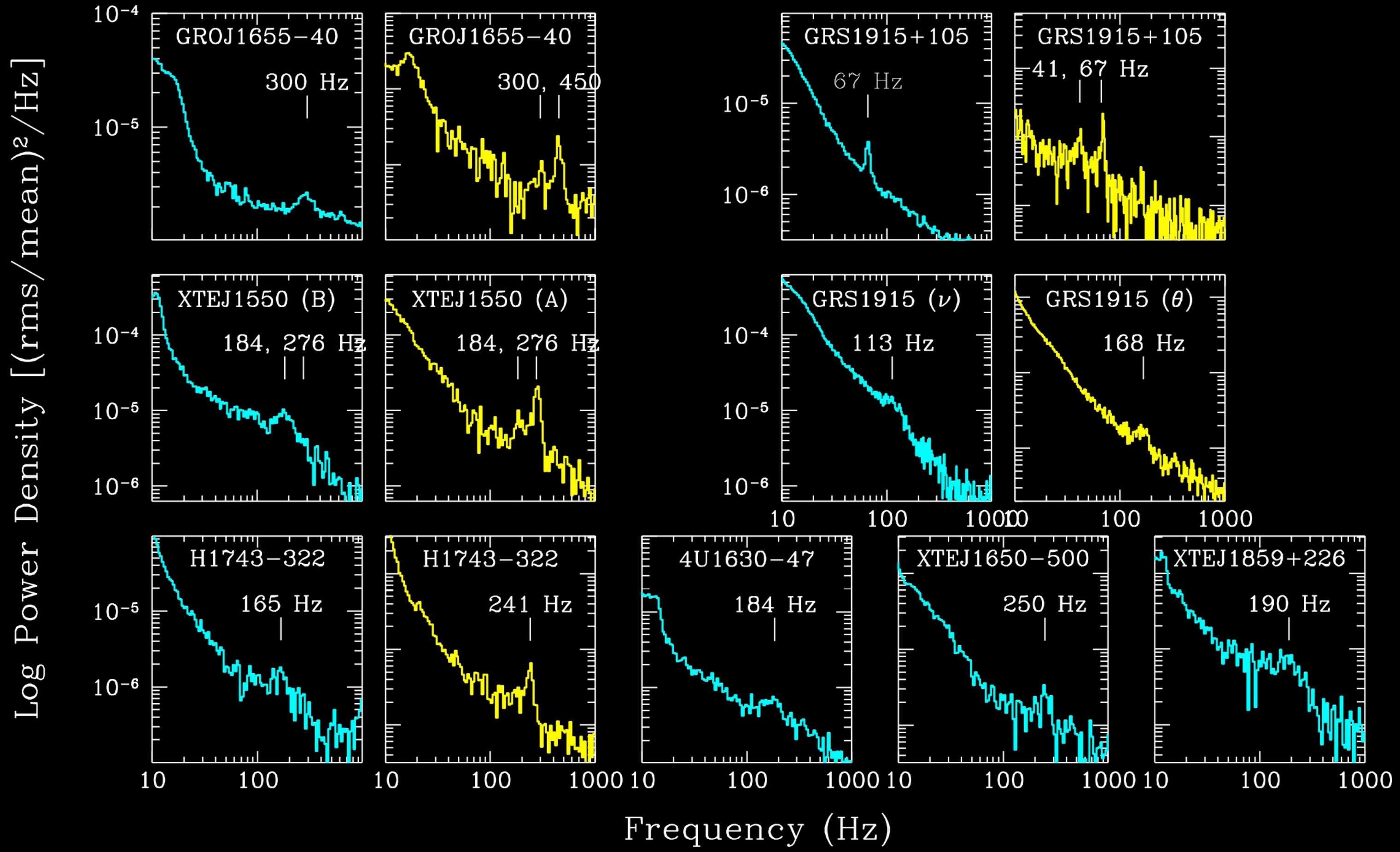


Figure 1: HFQPOs detected in the X-ray PDS of BH and BHC systems. This figure shows the entire sample of HFQPOs detected at high significance. Blue traces are used for PDS for 13–40 keV. Red traces show PDS for a broader energy range, either 2–30 or 6–30 keV [29].

QPOs

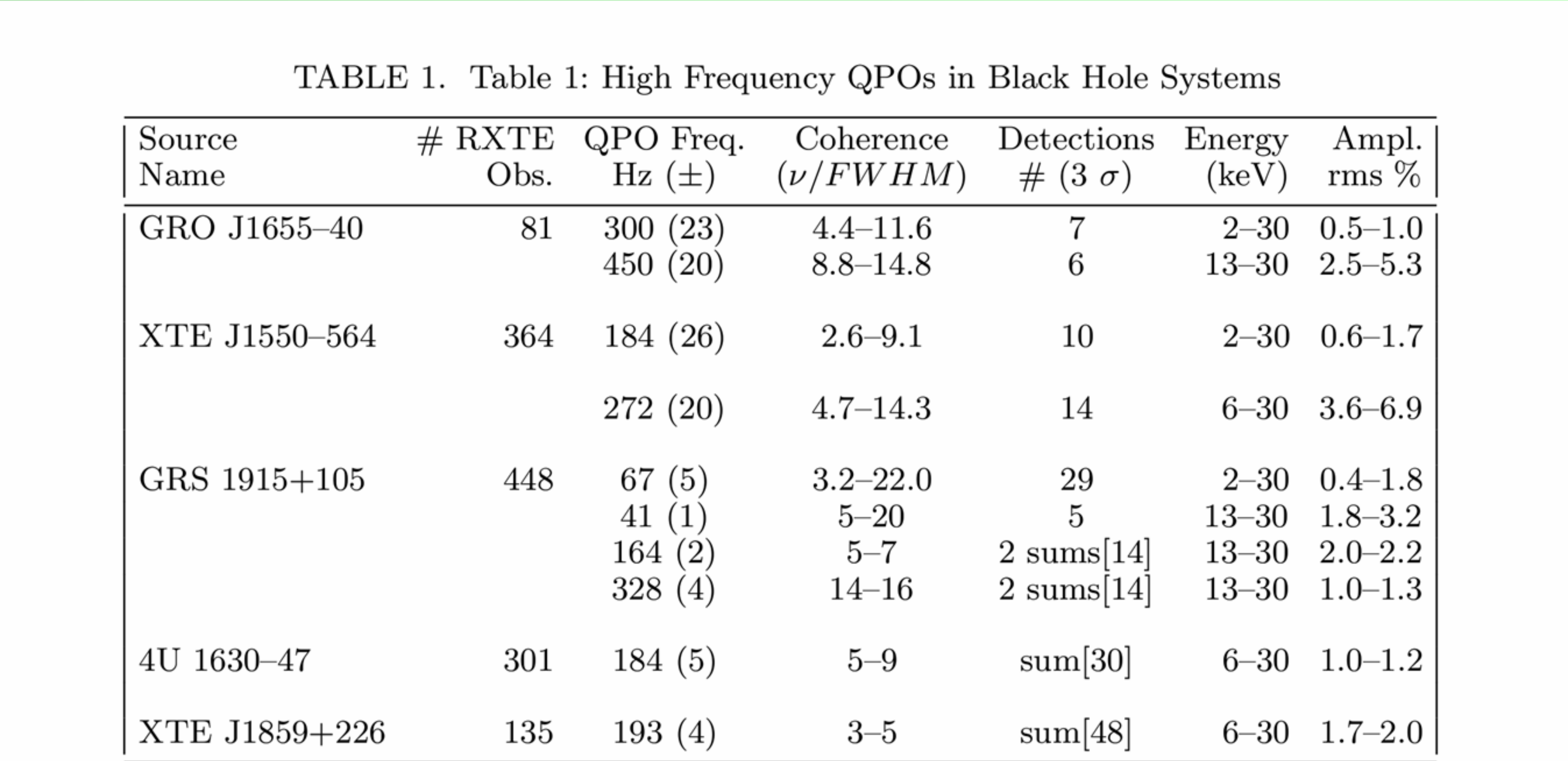
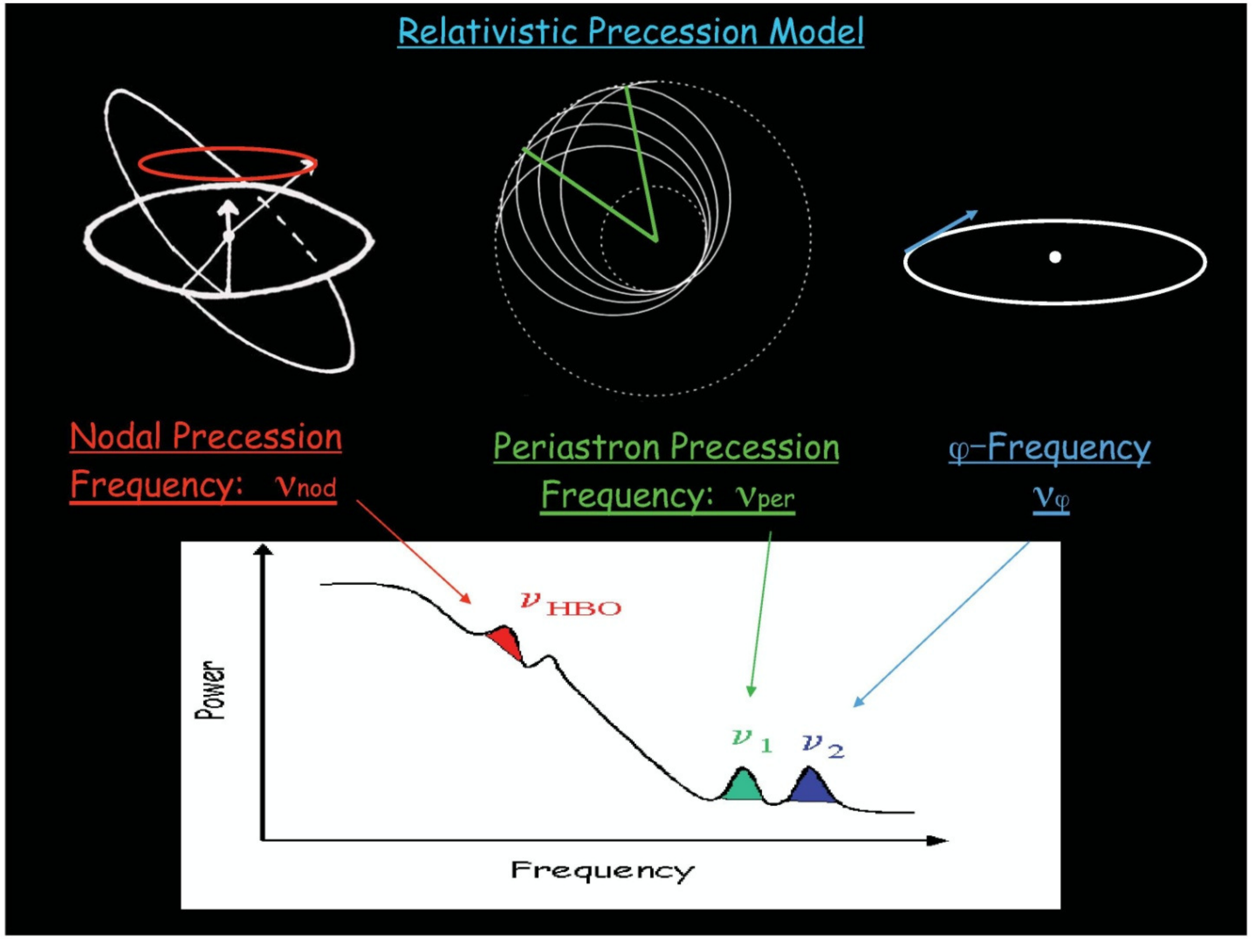


TABLE 1. Table 1: High Frequency QPOs in Black Hole Systems

Source Name	# RXTE Obs.	QPO Freq. Hz (±)	Coherence ($\nu/FWHM$)	Detections # (3 σ)	Energy (keV)	Ampl. rms %
GRO J1655–40	81	300 (23)	4.4–11.6	7	2–30	0.5–1.0
		450 (20)	8.8–14.8	6	13–30	2.5–5.3
XTE J1550–564	364	184 (26)	2.6–9.1	10	2–30	0.6–1.7
		272 (20)	4.7–14.3	14	6–30	3.6–6.9
GRS 1915+105	448	67 (5)	3.2–22.0	29	2–30	0.4–1.8
		41 (1)	5–20	5	13–30	1.8–3.2
		164 (2)	5–7	2 sums[14]	13–30	2.0–2.2
		328 (4)	14–16	2 sums[14]	13–30	1.0–1.3
4U 1630–47	301	184 (5)	5–9	sum[30]	6–30	1.0–1.2
XTE J1859+226	135	193 (4)	3–5	sum[48]	6–30	1.7–2.0

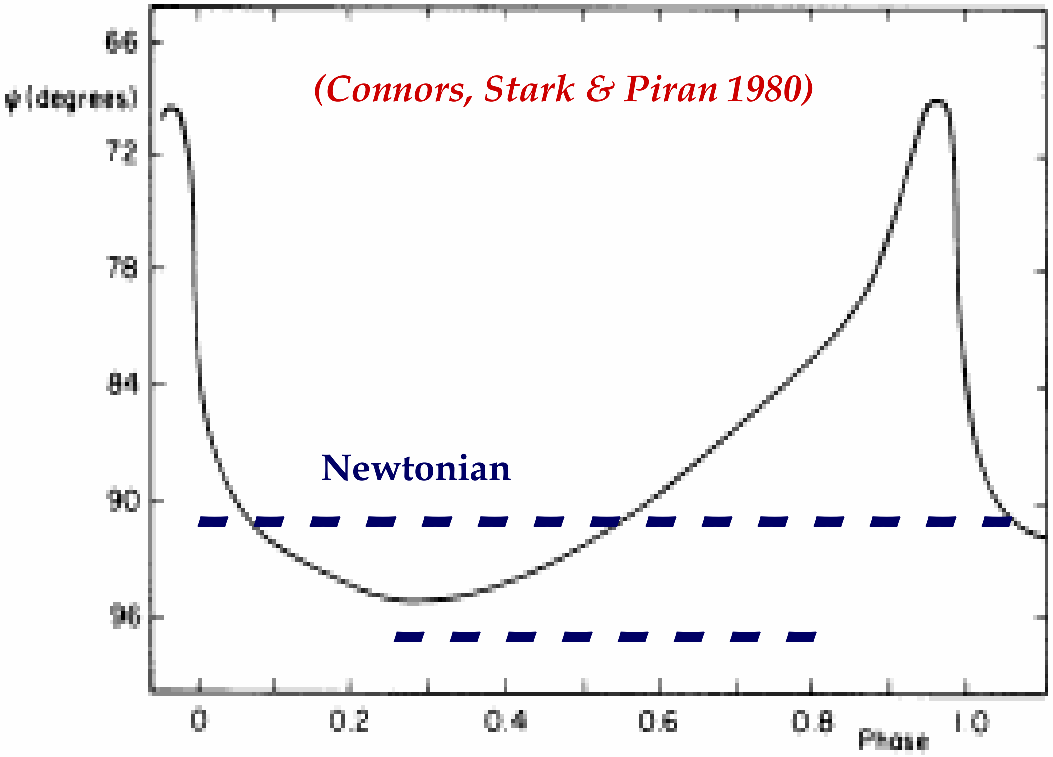
QPOs


Relativistic Precession Model
Nodal Precession
Frequency: νnod
Periastron Precession
Frequency: νper
φ-Frequency
νφ
νHBO
ν1
ν2
Power
Frequency

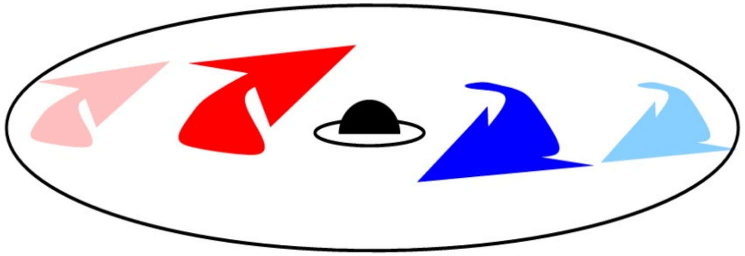
Strong gravity effects on polarization

General and Special Relativity significantly modifies the polarization properties of the radiation.

In particular, the Polarization Angle (PA) as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects (e.g. Connors & Stark 1977; Pineault 1977). The rotation is larger for smaller radii and higher inclination angles



(Connors, Stark & Piran 1980)



Orbiting spot with:
a=0.998; R=11.1 Rg
i=75.5 deg

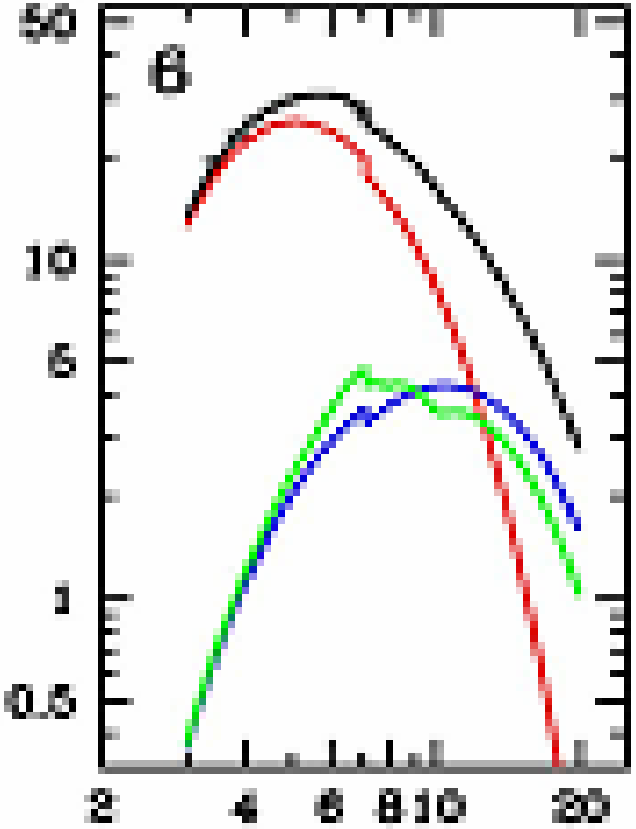
(Phase=0 when the spot is behind the BH).

The PA of the net
(i.e. phase-averaged)
radiation is also rotated!

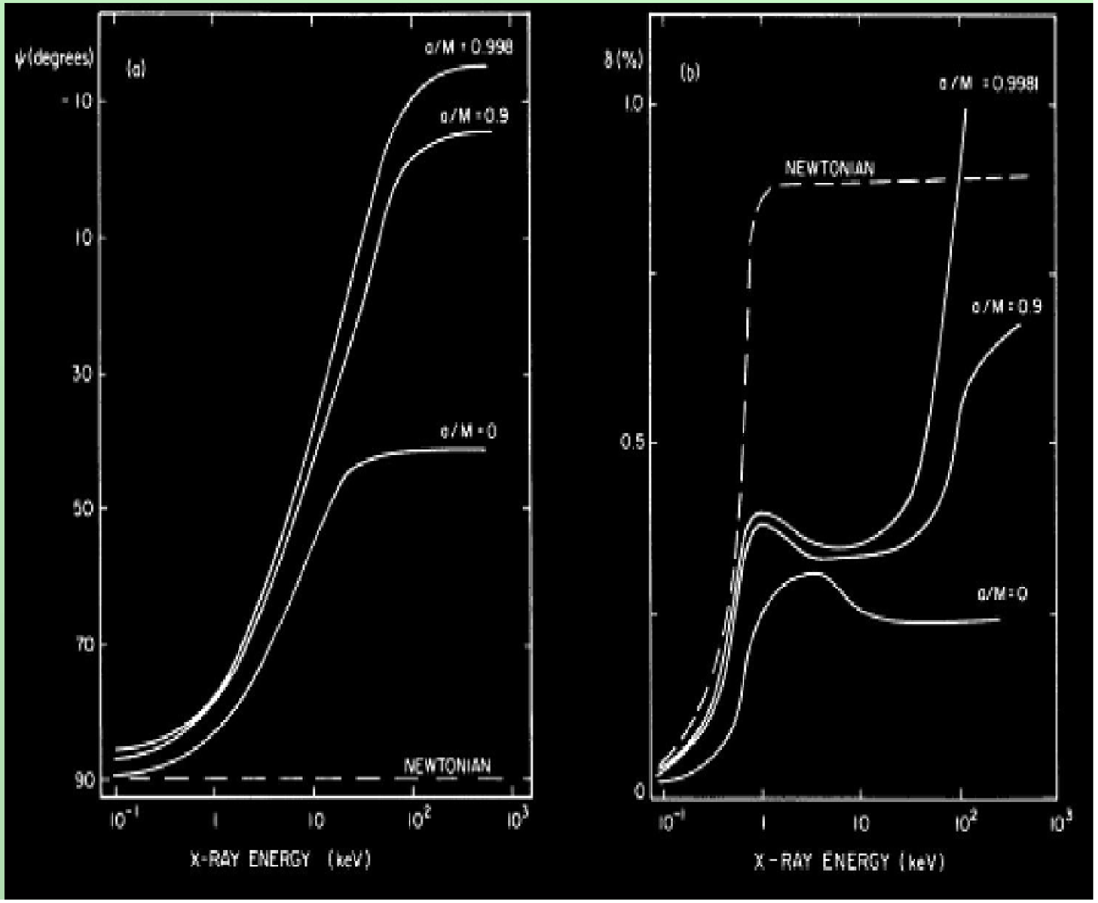
Galactic BH binaries in high state

X-ray emission in Galactic BH binaries in soft states is dominated by disc thermal emission, with *T decreasing with radius.*

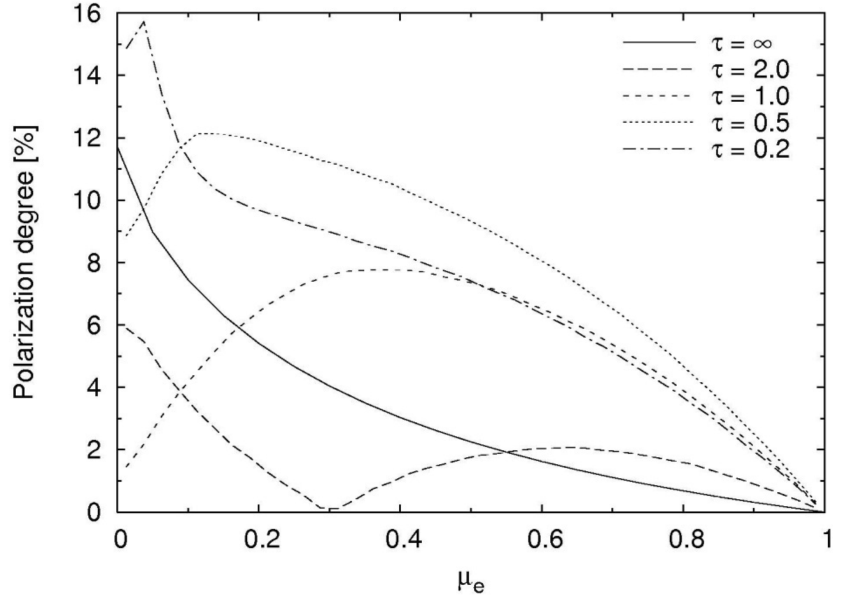
A rotation of the polarization angle with energy is therefore expected.



GRS 1915+105
(Done & Gierlinski 2004)

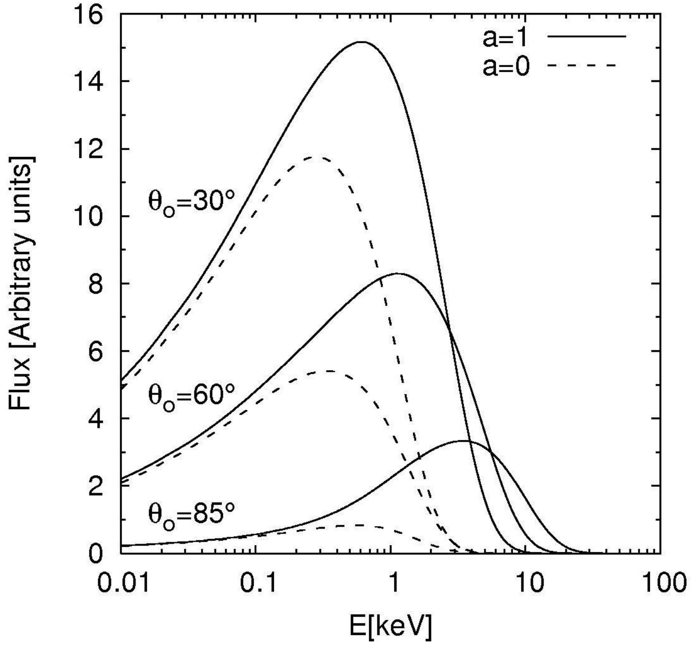


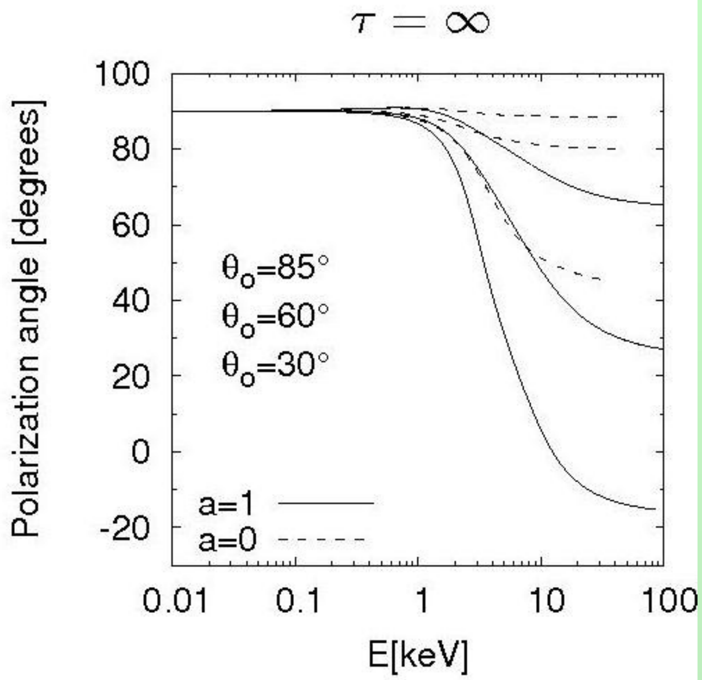
Connors & Stark (1977)



Revisited and refined by Dovciak et al. 2008 (see also Li et al. 2008, Schnittman & Krolik 2009).

Strongly dependent on the spin of the BH !!





Summary

- Strong gravity effects modify the imaging, spectral, timing and polarization properties of radiation emitted close to BH (and NS)

- Good BH spin measurements in a number of AGN and GBH systems. More to come very soon (NuSTAR) and, hopefully, in a few years (LOFT, see Feroci's talk)