The innermost region of accreting supermassive black holes: corona/jet/ISCO

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Finding Extreme Relativistic Objects
(10th edition)
IRAP, Toulouse

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Outline

- Introduction

- The hot corona

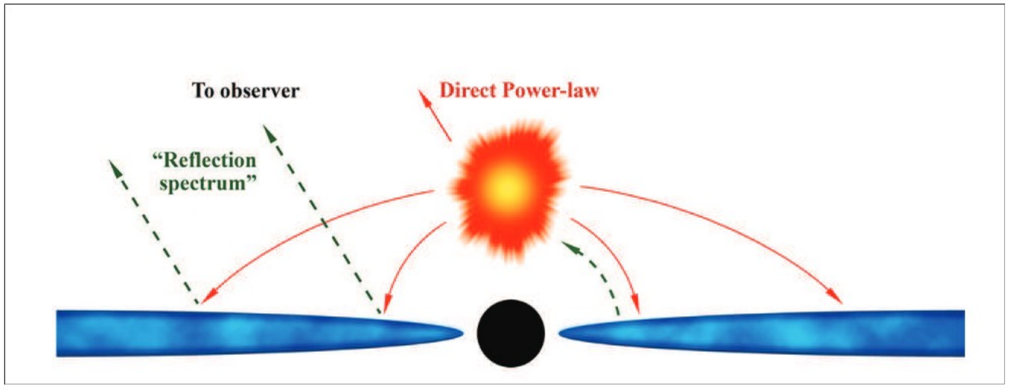
- Down to the ISCO

- Future perspectives

Introduction

One of the main open problem for AGN is the nature of the primary X-ray emission.

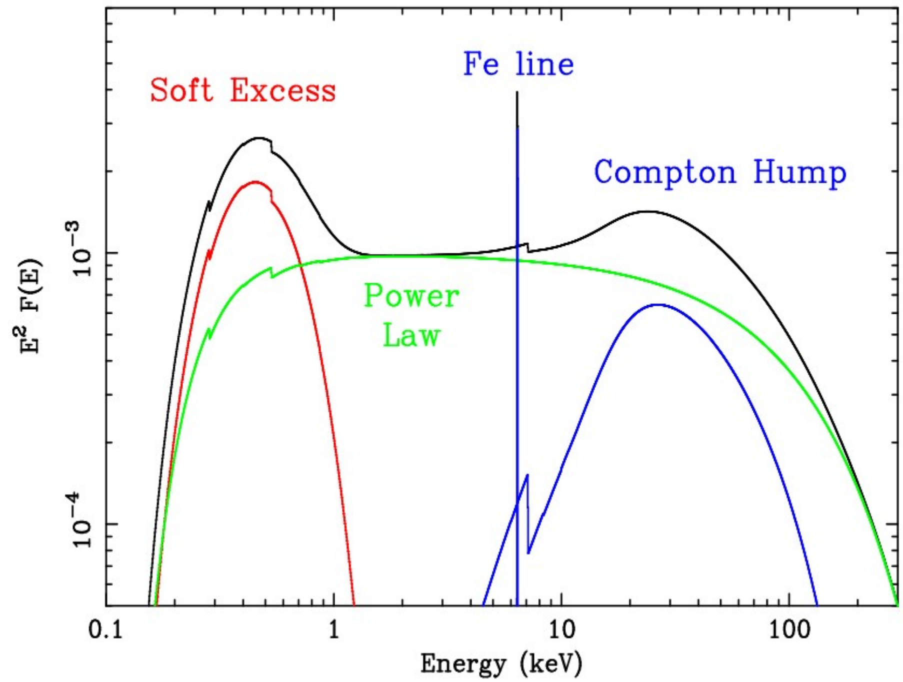
In the X-rays, it can be well approximated with a power law with photon index Γ=1.5-2.2 (Bianchi+09; Sobolewska & Papadakis+09)



It is thought to arise from the innermost regions surrounding the central SMBH, in a hot corona above the accretion disc.

Introduction

It is due to Comptonization of soft photons (Rybicki & Lightman 1979), but the geometry, optical depth and temperature of the emitting corona are largely unknown.



Fabian & Miniutti+05

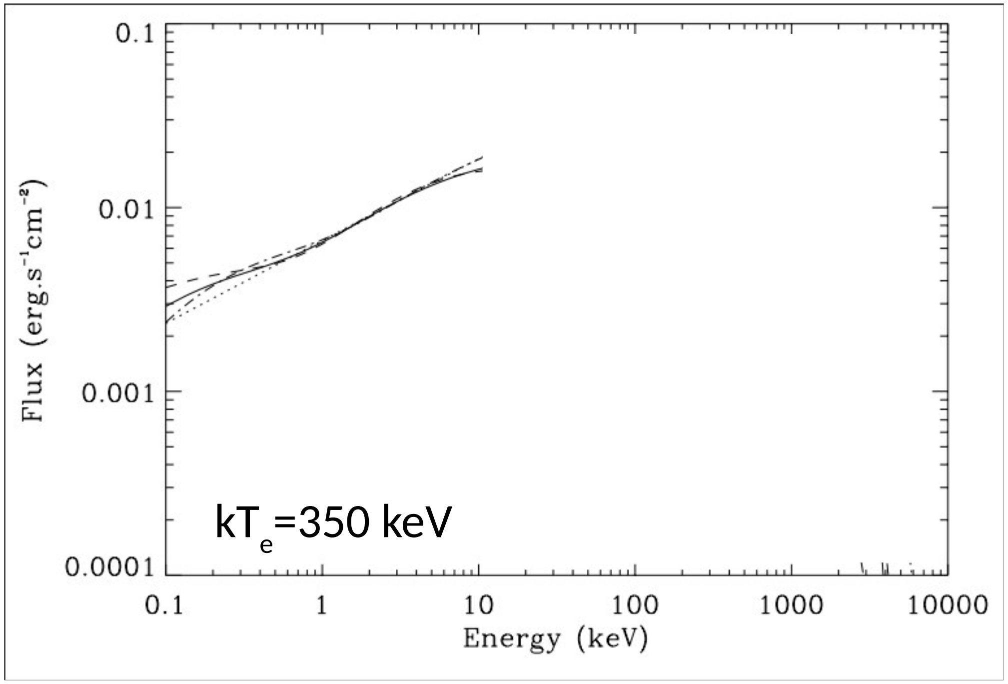
High energy turnover → f(kT_e)

Photon index → f(kT_e, τ)

Introduction

$$\Gamma - 1 = \left[\frac{9}{4} + \frac{m_e c^2}{kT_e \tau(1 + \tau/3)}\right]^{1/2} - \frac{3}{2}$$

Shapiro,Lightman, & Eardley+76
Sunyaev & Titarchuk+80
Lightman & Zdziarski +87



Petrucci+00

The same spectral index can be obtained with the combination of different parameters, adopting various geometries for the Comptonizing material (slab, hemisphere, sphere).

Introduction

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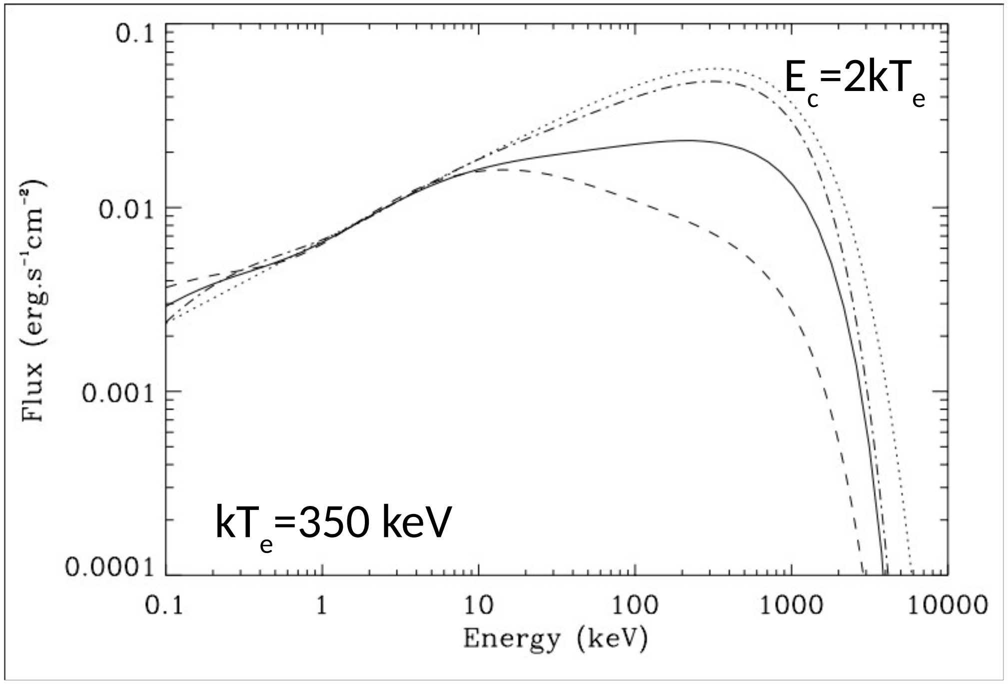

Petrucci+00

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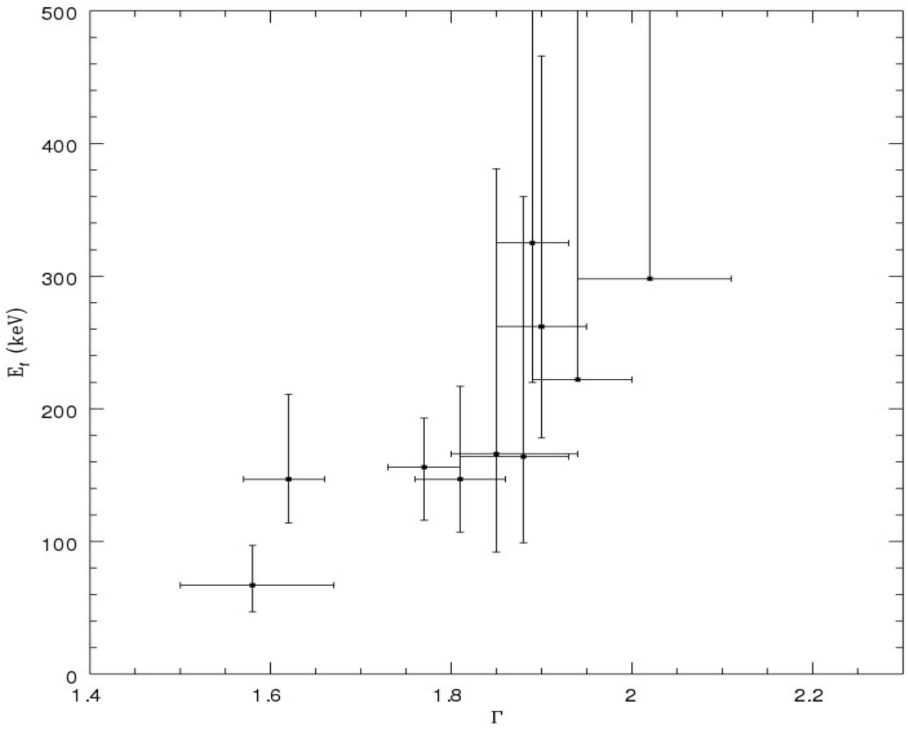
The search for high energy cutoffs

The first collection of E_c measurements in bright AGN was obtained using BeppoSAX (Perola+02, Dadina+07).

Source name	Γ	E_f (keV)
MCG 8-11-11	$1.85^{+0.09}_{-0.05}$	166^{+215}_{-74}
MCG–5-23-16	1.81 ± 0.05	147^{+70}_{-40}
NGC 3783	1.77 ± 0.04	156^{+37}_{-40}
NGC 4593	$1.94^{+0.06}_{-0.05}$	>222
IC 4329A (1)	1.89 ± 0.04	325^{+277}_{-105}
IC 4329A (2)	1.90 ± 0.05	262^{+204}_{-84}
NGC 5506	$2.02^{+0.09}_{-0.08}$	>298
NGC 5548	$1.62^{+0.04}_{-0.05}$	147^{+64}_{-33}
Mrk 509	$1.58^{+0.09}_{-0.08}$	67^{+30}_{-20}
NGC 7469	$1.88^{+0.05}_{-0.07}$	164^{+196}_{-65}



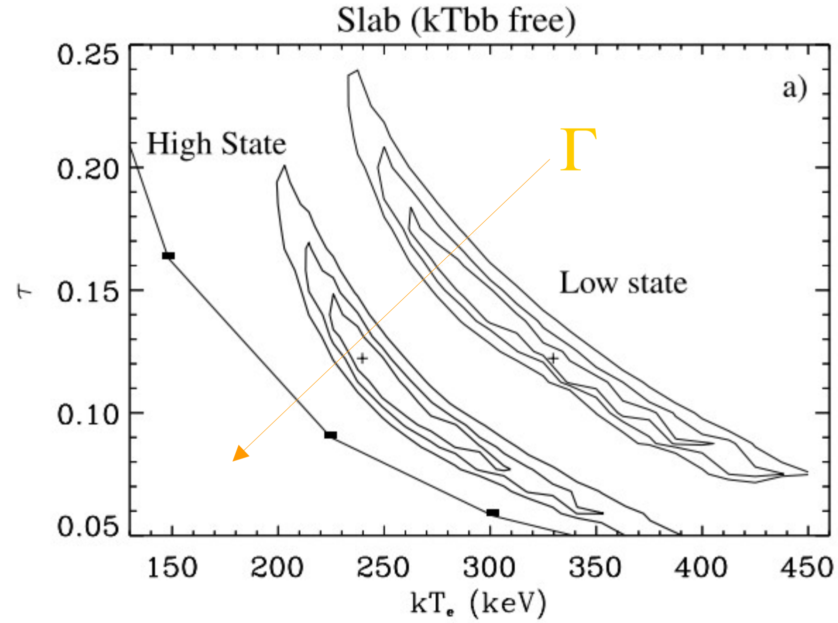
A E_c-Γ degeneracy (and R parameter) can be observed.

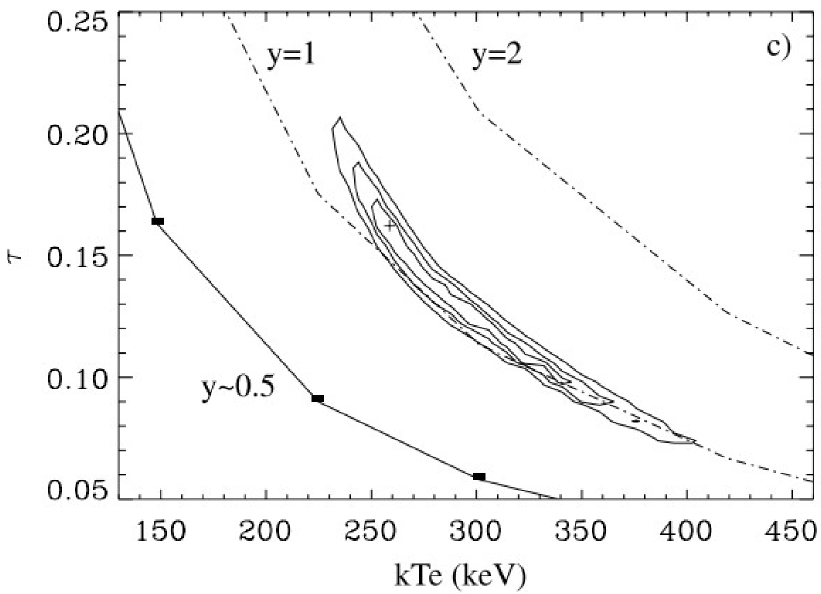
The search for high energy cutoffs

Different Comptonization models were then tested on a long (~320 ks) BeppoSAX observation of NGC 5548 (Nicastro+00, Petrucci+00)

Best-Fit Values of Low and High States for Comptonization Model

Geometry	kT_{bb} (eV)	kT_e (keV)	τ	Γ	R	χ^2/dof
Low State						
Slab	8^{+10}_{-4}	330^{+70}_{-80}	$0.12^{+0.08}_{-0.04}$	...	0.9 ± 0.2	82/113
Hemisphere......	5^{+12}_{-3}	360^{+80}_{-120}	$0.21^{+0.28}_{-0.06}$	...	1.8 ± 0.3	80/113
pexrav...........	...	55^{+25}_{-10}	$2.6^{+0.2}_{-0.6}$	$1.55^{+0.02}_{-0.02}$	$0.5^{+0.2}_{-0.2}$	93/114
High State						
Slab	15^{+2}_{-10}	245^{+55}_{-30}	$0.12^{+0.04}_{-0.05}$	...	1.0 ± 0.4	135/144
Hemisphere......	13^{+2}_{-8}	235^{+65}_{-20}	$0.27^{+0.08}_{-0.11}$	...	2.2 ± 0.5	142/144
pexrav...........	...	80^{+200}_{-35}	$1.6^{+0.8}_{-1.0}$	$1.71^{+0.03}_{-0.04}$	$0.6^{+0.4}_{-0.4}$	142/145



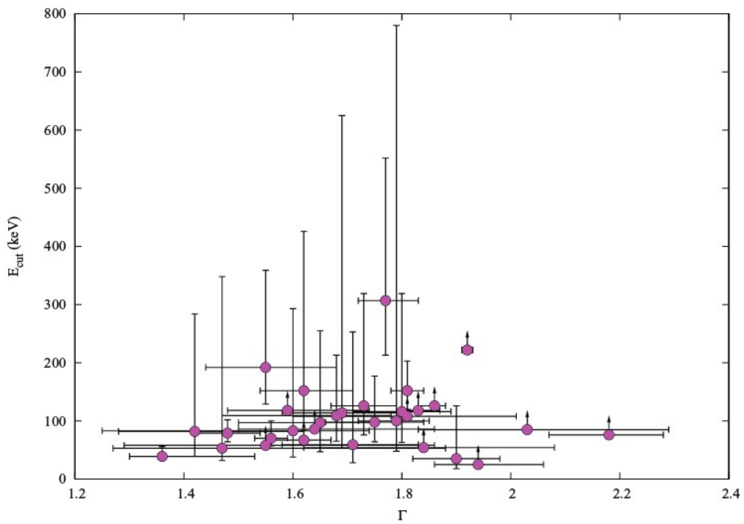


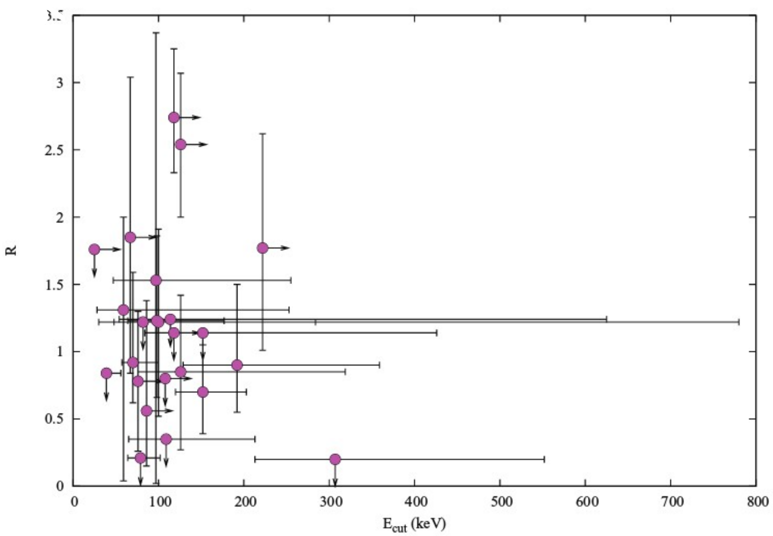
Compton parameter y (i.e. amplification of the Comptonization process)

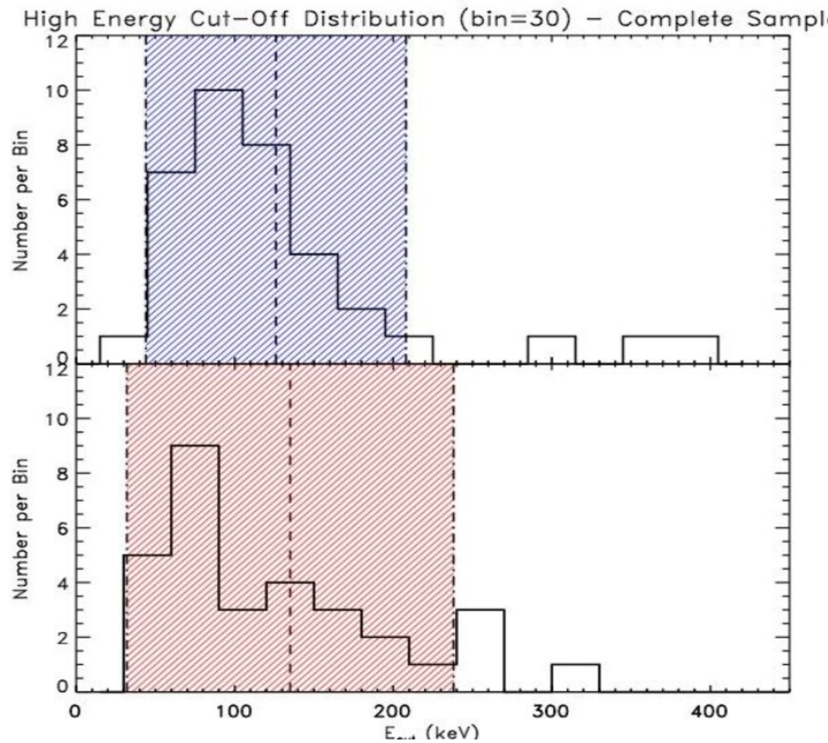
$$y \simeq 4(kT_e/m_e c^2)[1 + 4(kT_e/m_e c^2)]\tau(1 + \tau)$$

The search for high energy cutoffs

Many more measurements in type 1 and 2 AGN using INTEGRAL and XMM (Molina+09, Panessa+11, De Rosa+12, Molina+13)







De Rosa+12, Molina+13

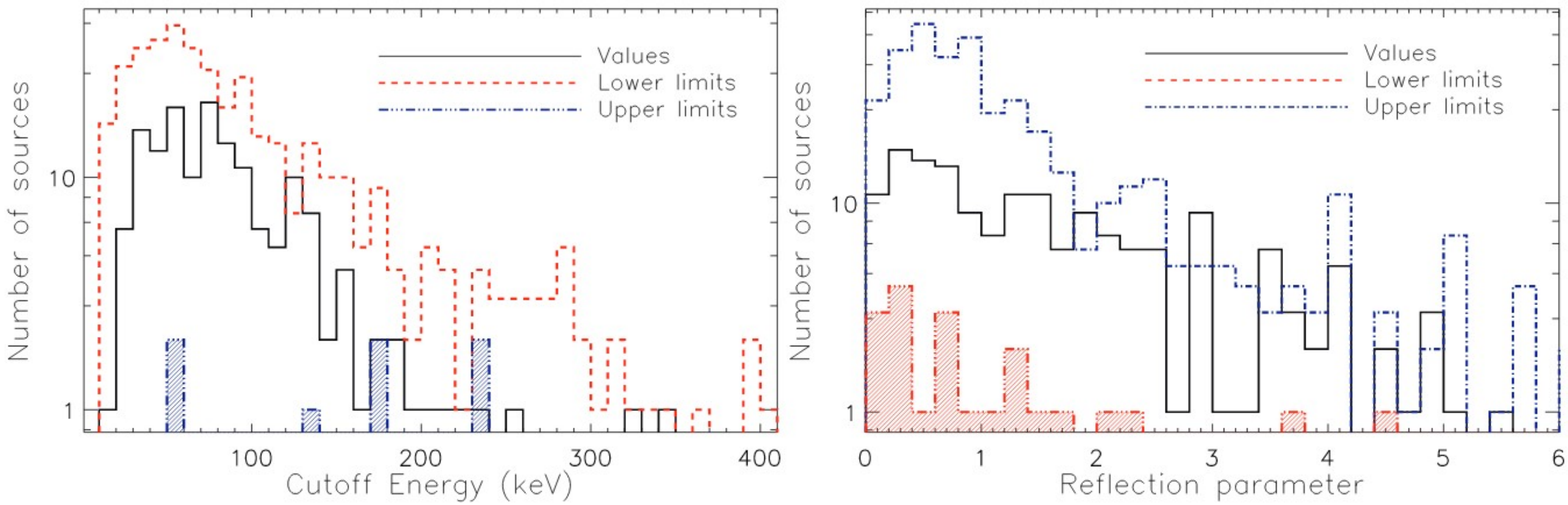
$\Gamma = 1.76^{+0.22}_{-0.24}$

$E_c = 106^{+186}_{-61}$ keV

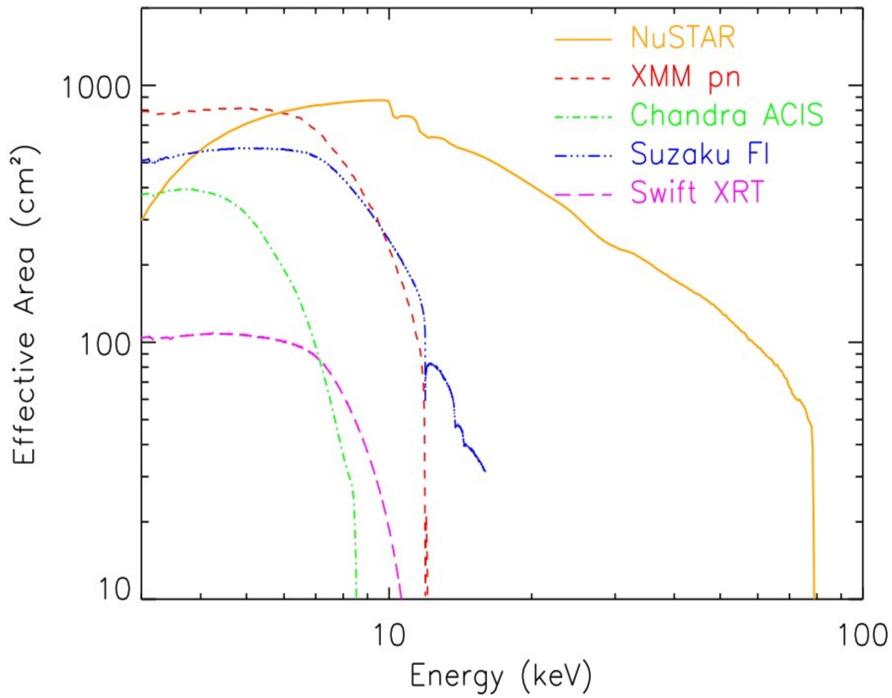
$R = 1.5^{+1.5}_{-1.0}$

The search for high energy cutoffs

Swift-BAT + XRT/Suzaku/Chandra/XMM (Ricci+17)

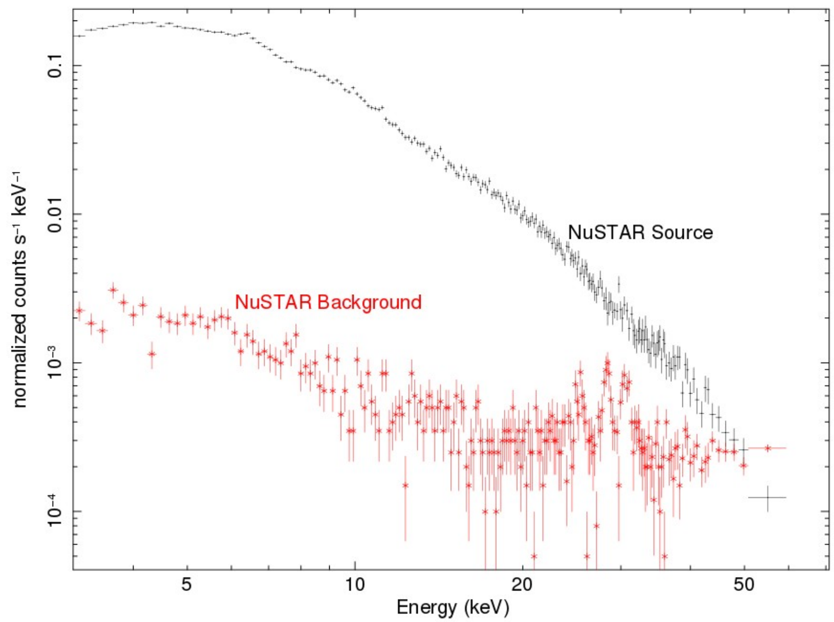


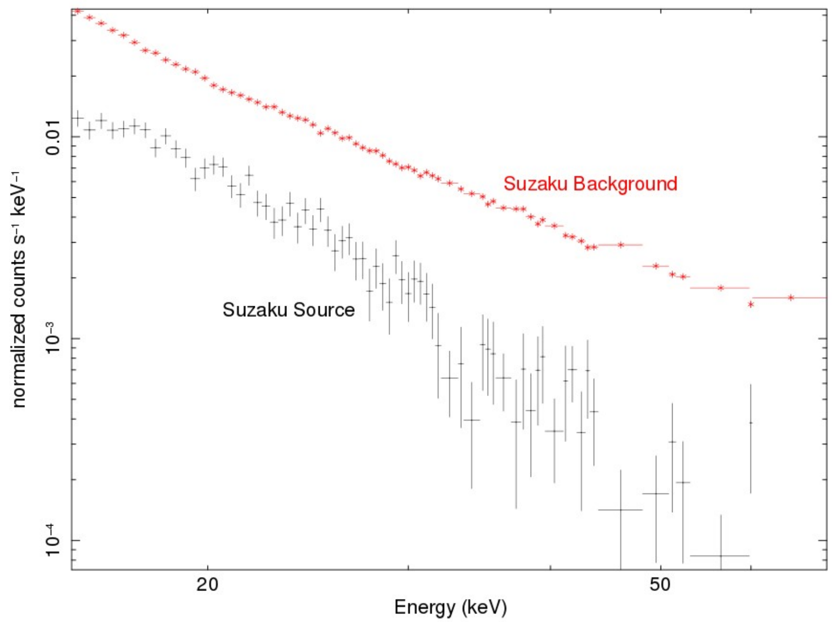
The NuSTAR era: from Γ-Ec to τ-kT planes



The combination of NuSTAR high effective area and low background yelds ~100x better S/N versus Suzaku HXD-PIN

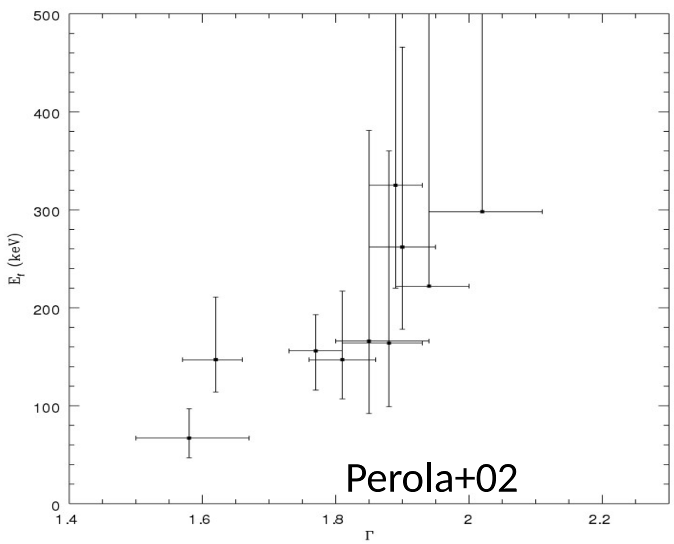
AM+14

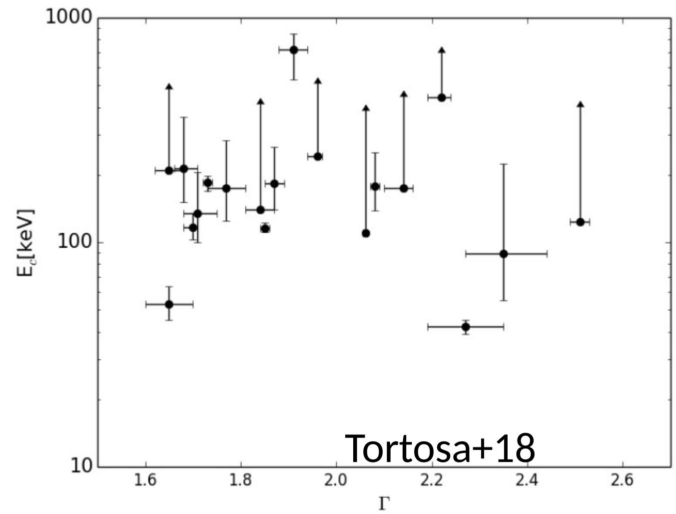




The NuSTAR era: from Γ-Ec to τ-kT planes

With NuSTAR, the degeneracy between the photon index, the reflection fraction and the cutoff energy is broken.

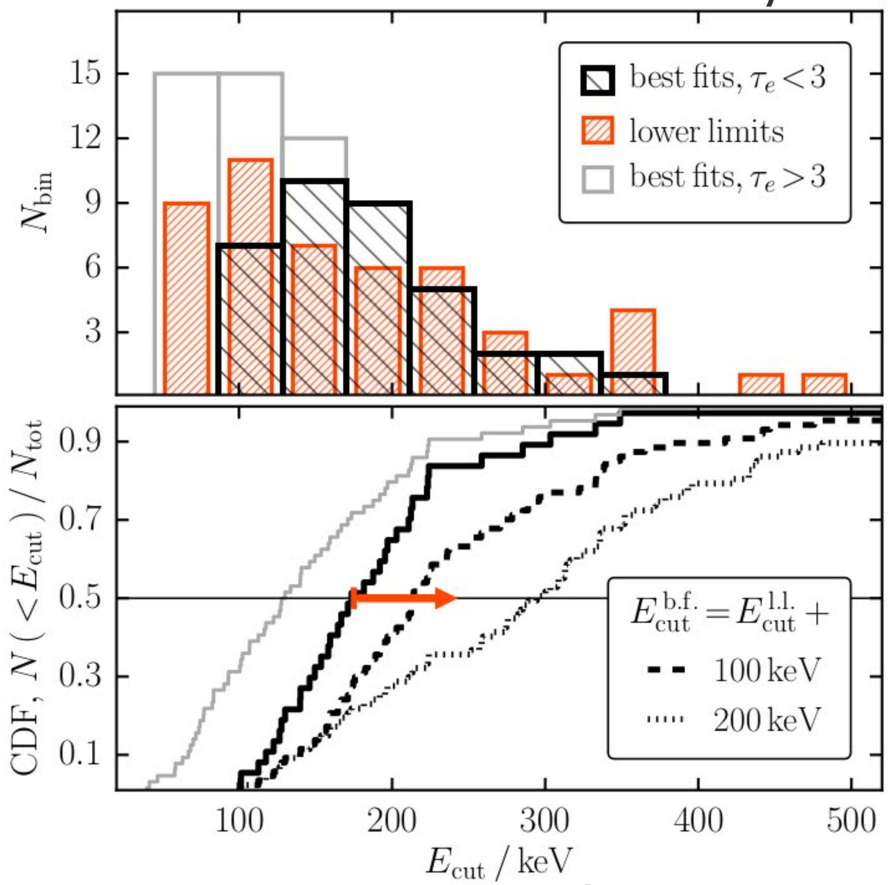




The dependence between the cutoff energy and other physical observables (BH mass, luminosity, accretion rate, etc..) could finally be investigated.

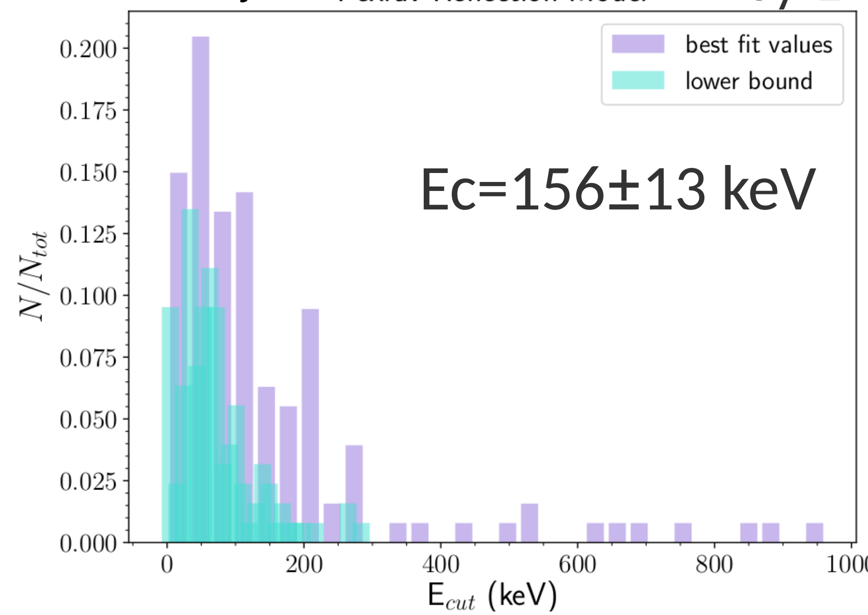
The NuSTAR era: from Γ-Ec to τ-kT planes

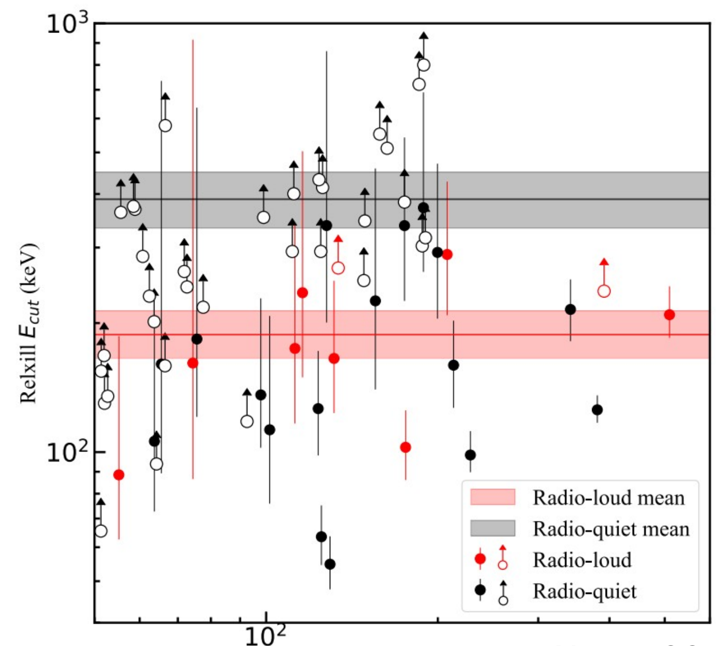
Balokovic+21 Sy 2



Ec=290±20 keV

Kamraj+22 Sy 1



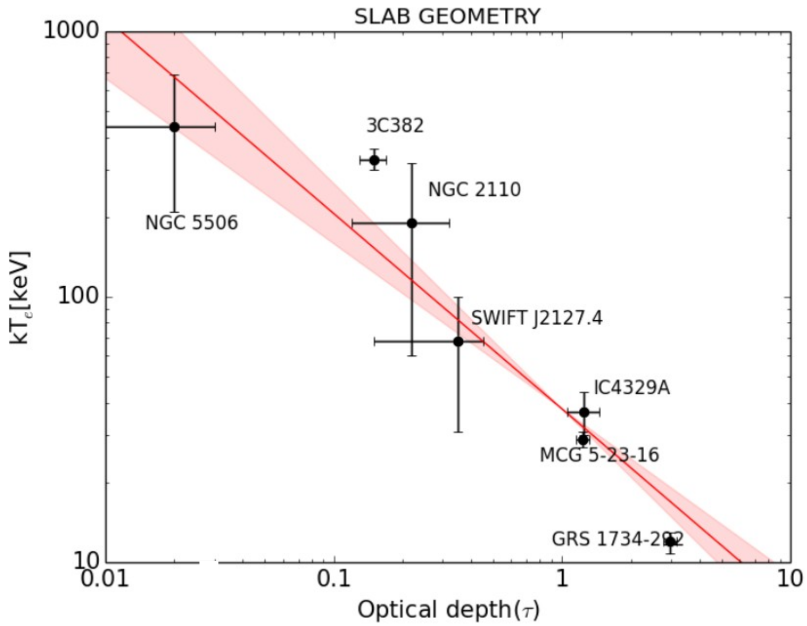


Kang+22

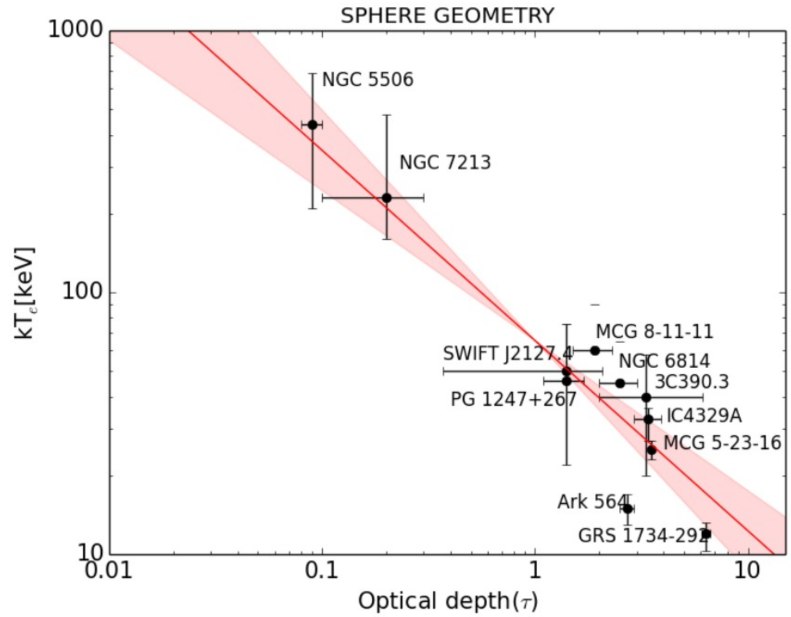
The NuSTAR era: from Γ-Ec to τ-kT planes

X	Y	ρ	h_0	geometry
Γ	E_c	0.18	0.47	-
$\log(M_{bh}/M_\odot)$	E_c	-0.11	0.61	-
L_{bol}/L_{Edd}	E_c	-0.14	0.56	-
τ	kT_e	-0.88	0.004	slab
τ	kT_e	-0.63	0.02	sphere
$\log(M_{bh}/M_\odot)$	τ	-0.22	0.63	slab
$\log(M_{bh}/M_\odot)$	τ	-0.26	0.46	sphere
L_{bol}/L_{Edd}	τ	0.49	0.27	slab
L_{bol}/L_{Edd}	τ	0.38	0.28	sphere
$\log(M_{bh}/M_\odot)$	kT_e	0.20	0.64	slab
$\log(M_{bh}/M_\odot)$	kT_e	0.18	0.47	sphere
L_{bol}/L_{Edd}	kT_e	-0.37	0.41	slab
L_{bol}/L_{Edd}	kT_e	-0.36	0.32	sphere

The only inferred correlations are between the temperature of the corona and the optical depth.



$$\log(kT_e) = (-0.7 \pm 0.1)\log(\tau) + (1.60 \pm 0.06)$$

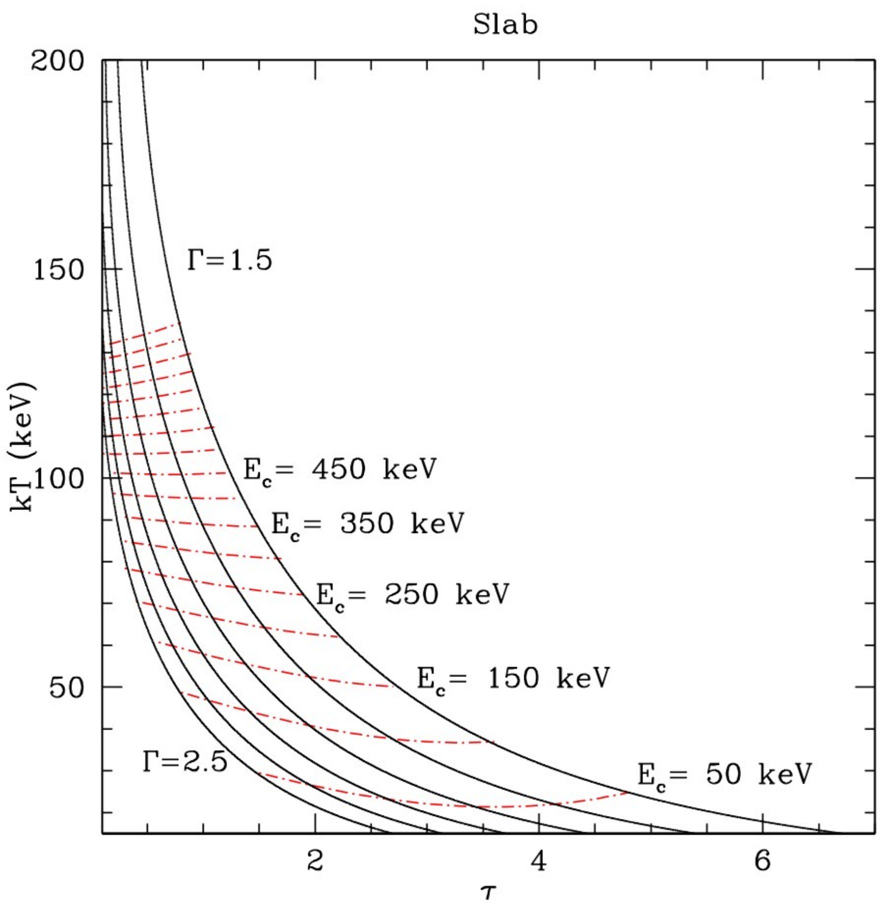


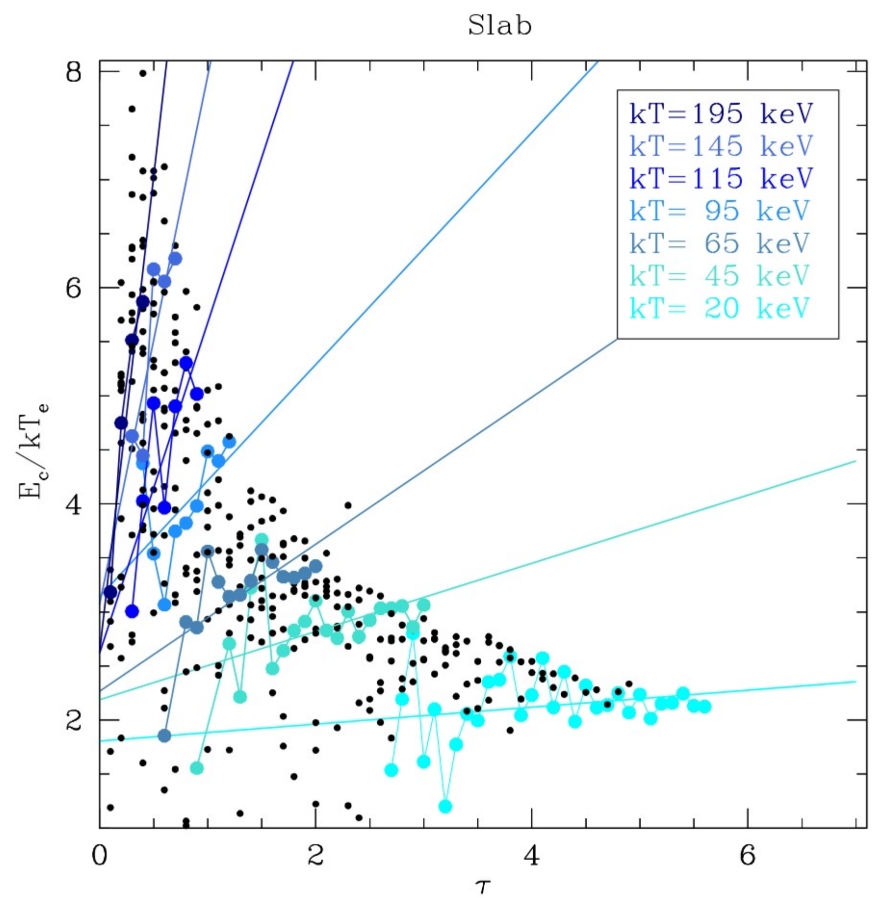
$$\log(kT_e) = (-0.7 \pm 0.2)\log(\tau) + (1.8 \pm 0.1).$$

Tortosa+18

The NuSTAR era: from Γ-Ec to τ-kT planes

Comptonization models (Beheshtipour+17, Tamborra+18, Zhang+19) allow a traslation of Γ-Ec observed pairs into τ-kT coronal parameters.

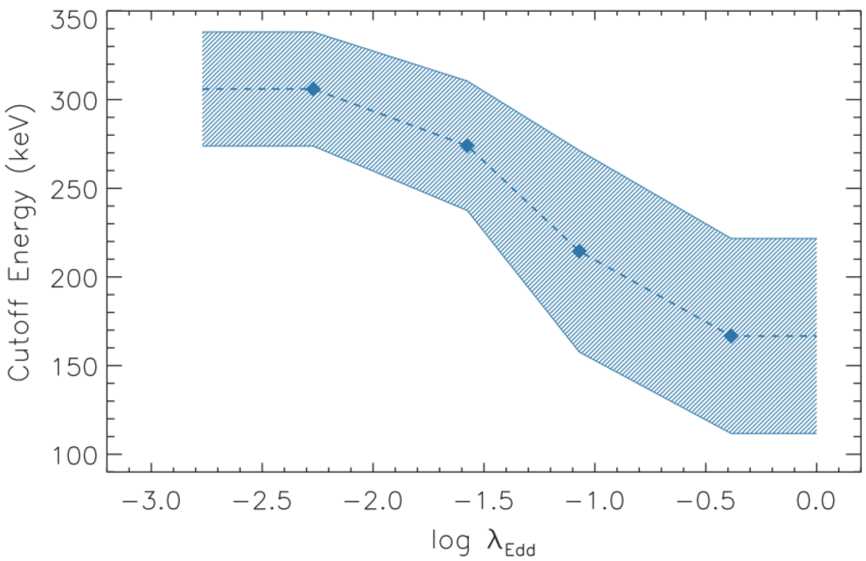


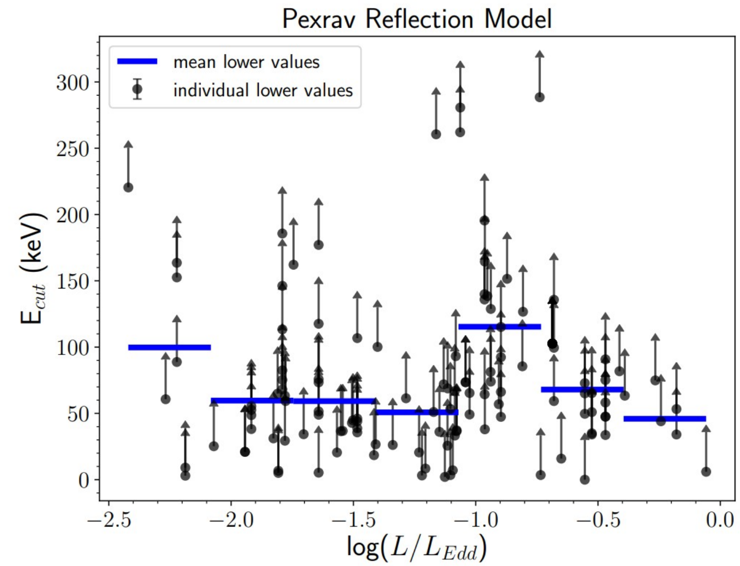


Middei+19

The NuSTAR era: from Γ-Ec to τ-kT planes

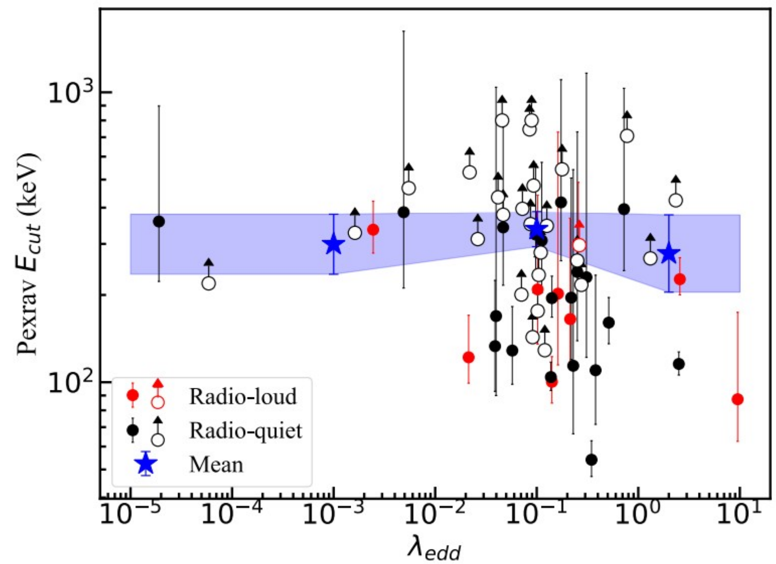
Swift-BAT: Ricci+18





NuSTAR: Kamraj+22, Kang+22

While a trend between the high energy cutoff and the accretion rate was proposed in the past, this is not observed in recent works on a bright, high S/N NuSTAR sample



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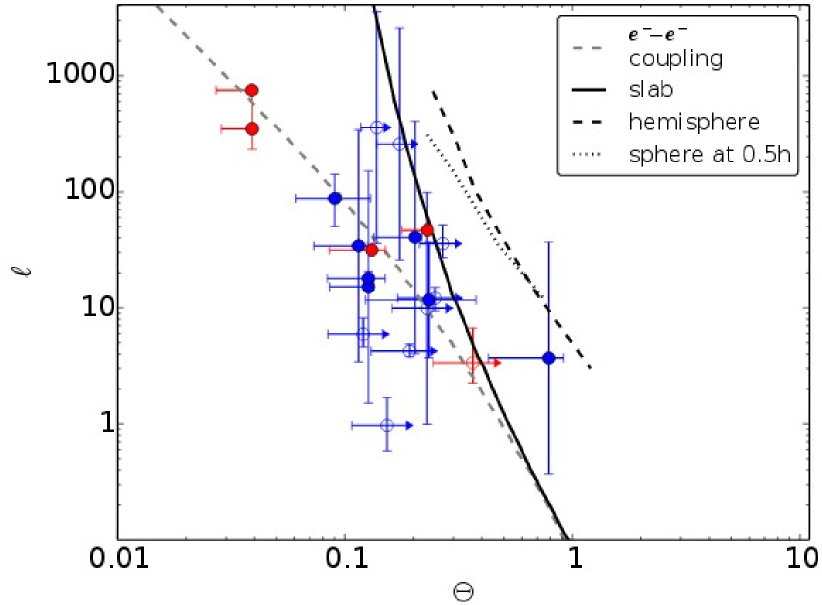
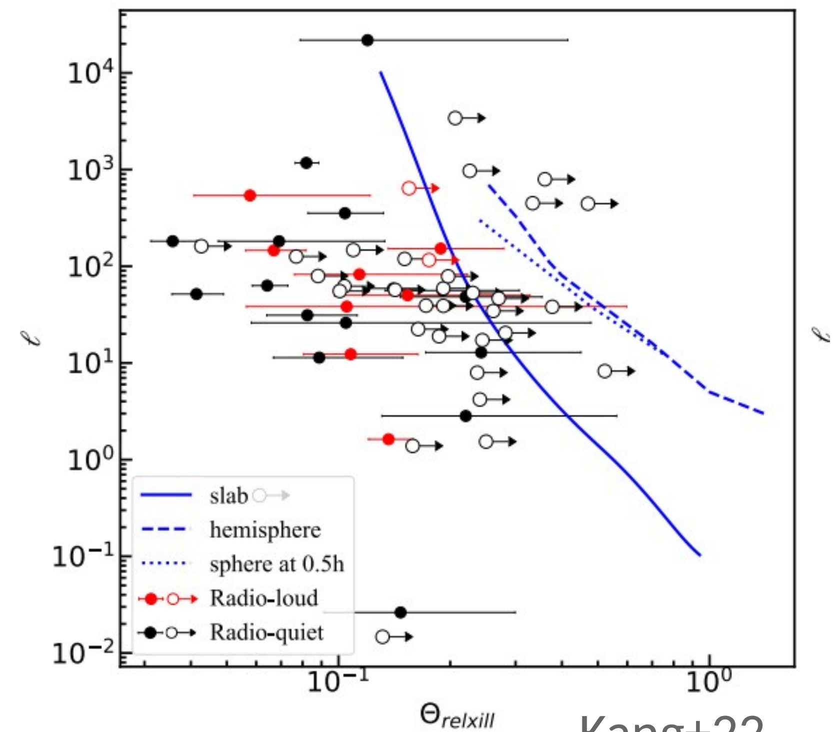
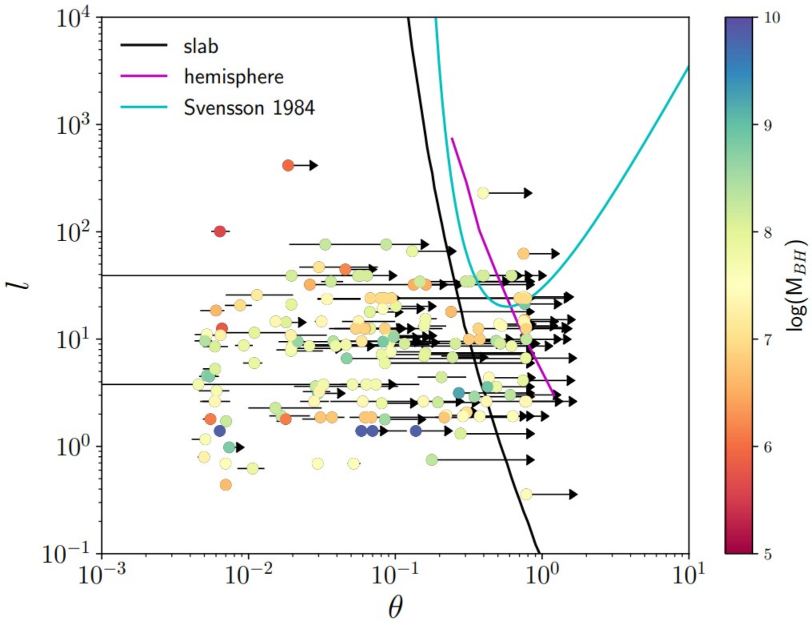


Fabian+15,+17



Kang+22



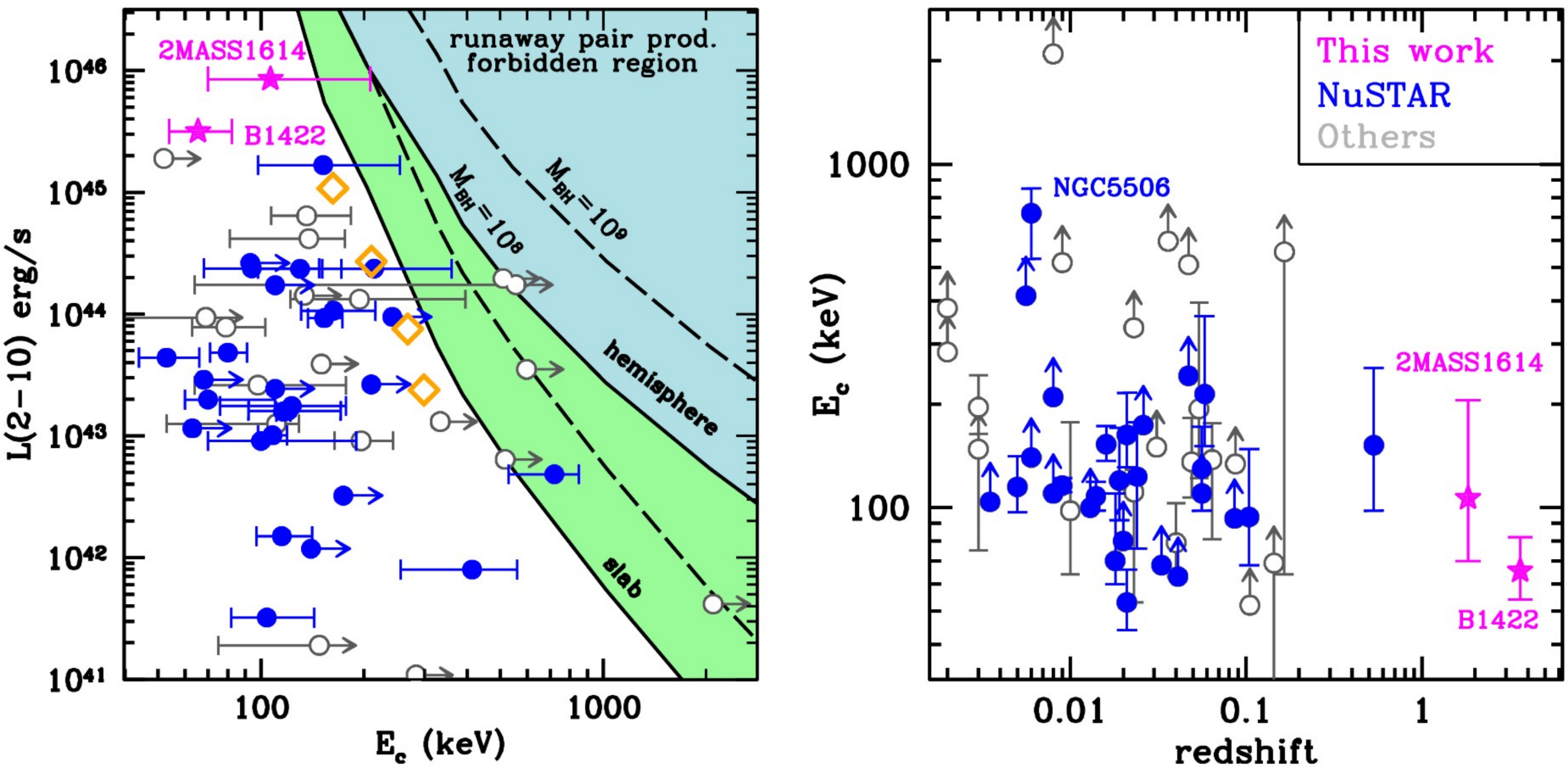
Kamraj+22

$$\ell = 4\pi \frac{m_p}{m_e} \frac{R_g}{R} \frac{L}{L_E}.$$

$$\Theta = kT_e/m_e c^2$$

Coronal parameters in less-local AGN

Lanzuisi+19, Kammoun+17

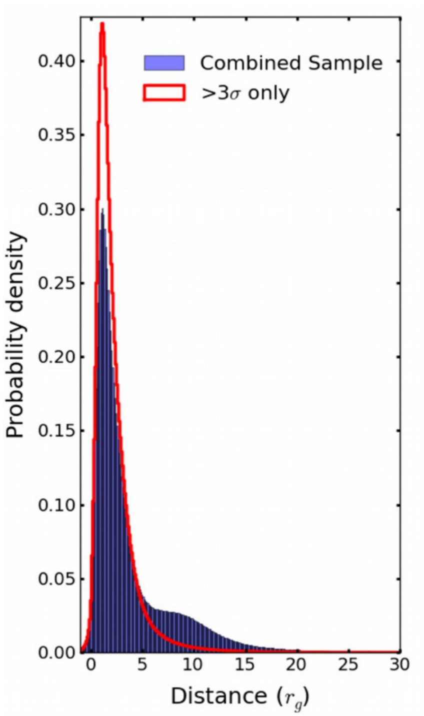


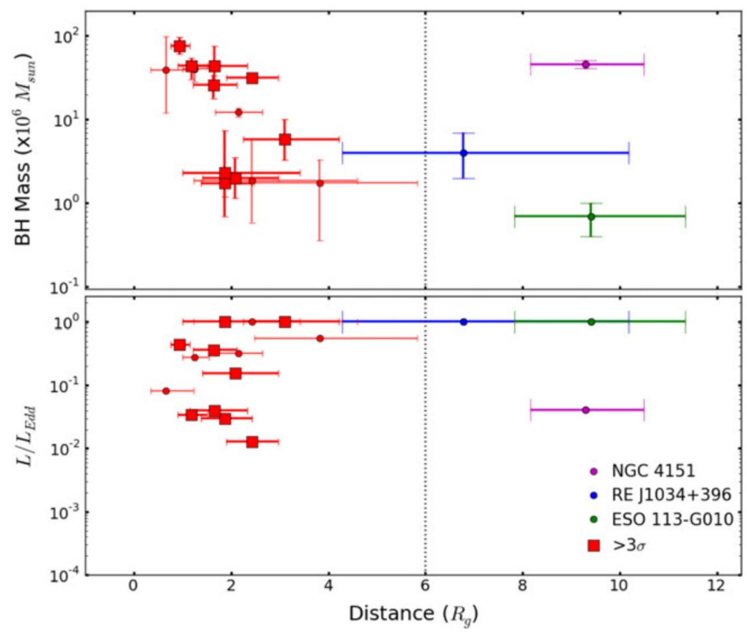
Size and location

What about its size and location?

- microlensing variability (Chartas+02,+06,+16)

- X-ray reverberation lags (Fabian+09, Cackett+14, Kara+16, De Marco & Ponti+19)





Reis&Miller+13

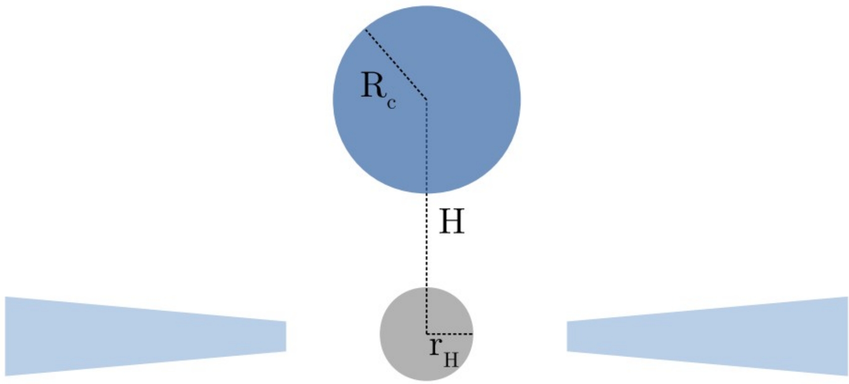
R_{ISCO}=3.15 r_g

↓

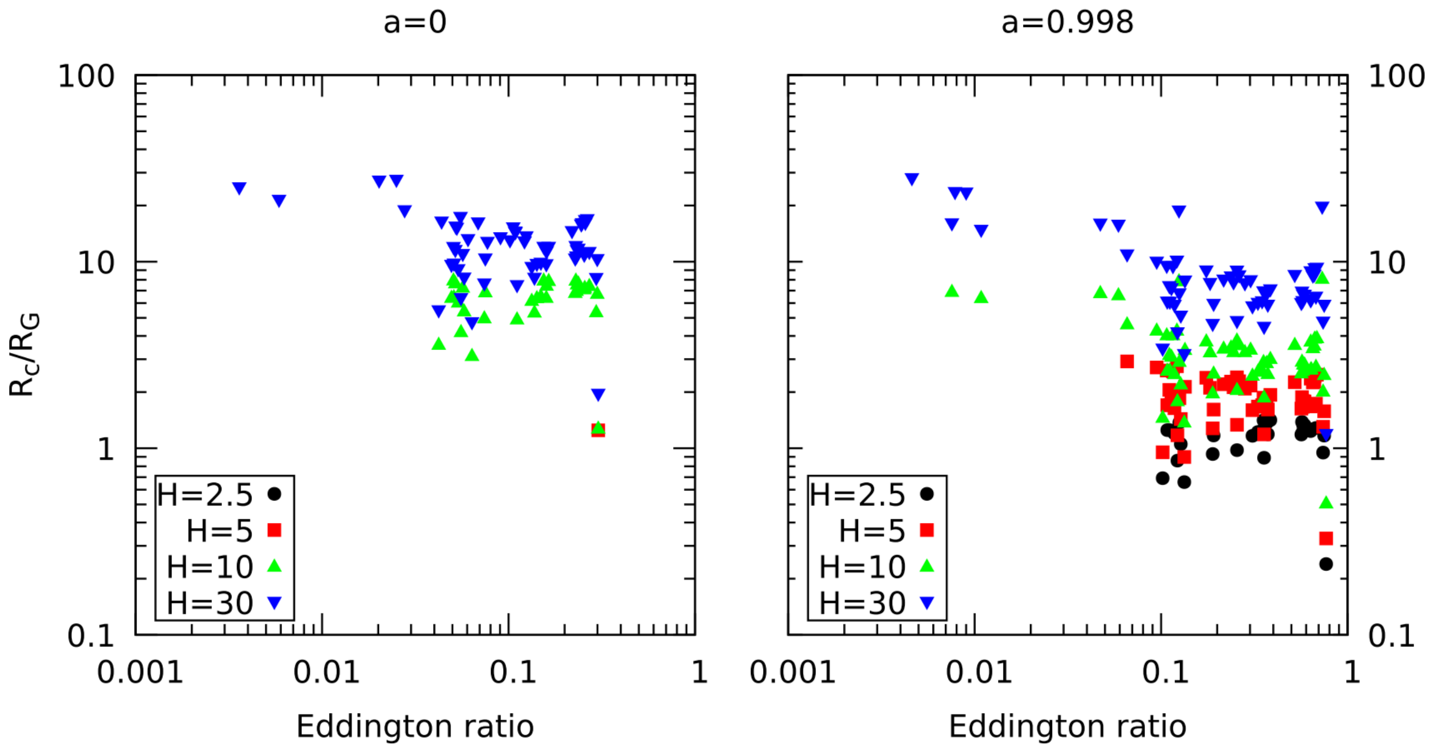
a=0.75Jc/GM^2

- direct fitting with dedicated models (Dovčiak&Done+16)

Size and location



Ursini+20



The FERO sample

“With the beginning of XMM-Newton AO6 observations, the count-down has started for the completion of a flux-limited sample of unobscured nearby AGN in the framework of the accepted proposal: "Statistics of broad relativistic lines in AGN: a counts and flux-limited sample", also christened as "FERO" (Finding Extreme Relativistic Objects), where the acronym is how Romans (mis)spell the Italian word for iron.”

A pioneering group of scientist gathered together in 2008 at ESAC and looked (intensively) for the cleanest sample of AGN to study the properties of the accretion disk

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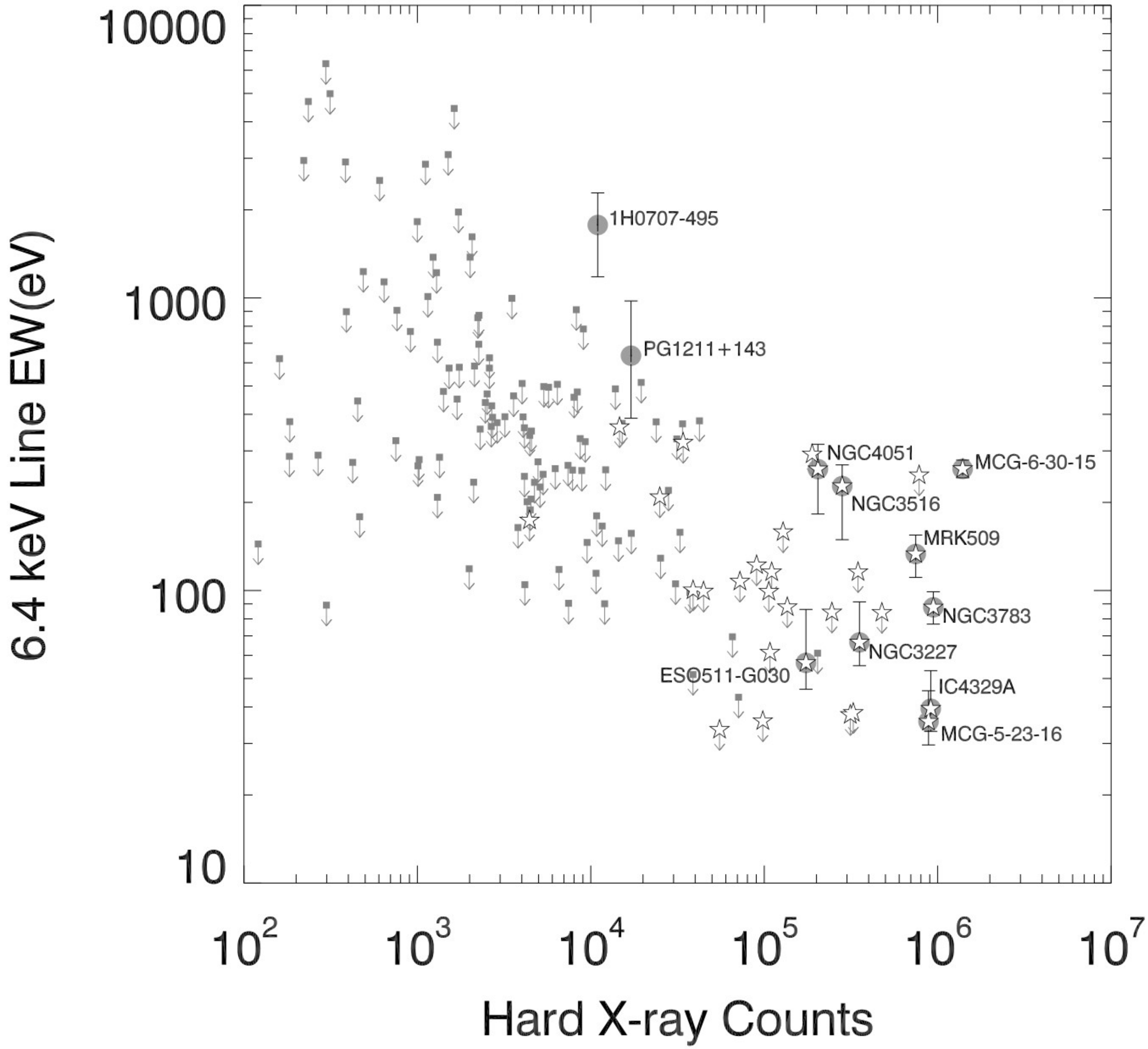
The FERO sample

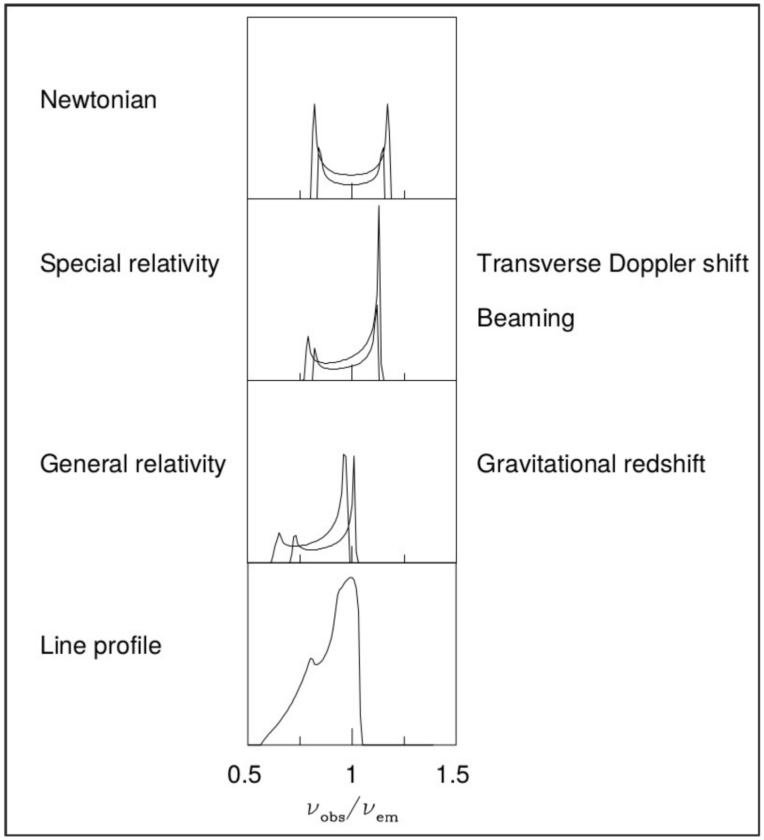
De La Calle Pérez+10



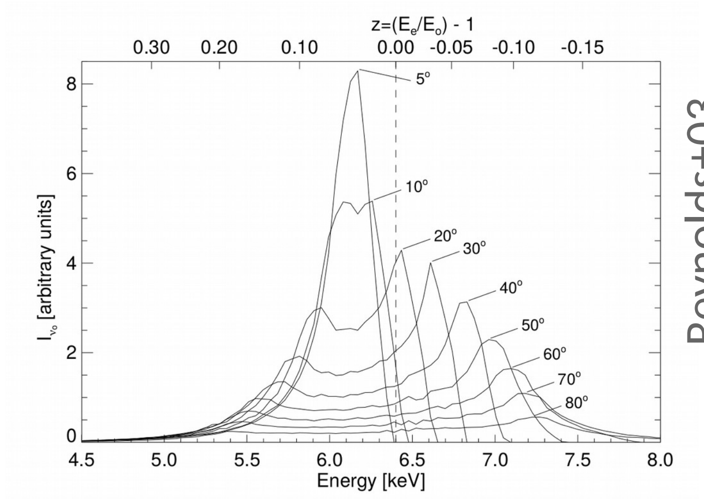
From **The** FERO sample down to the ISCO

Special and general relativistic effects have a clear impact on the shape of an emission line produced in the accretion disk.

If an intense emission line, typically Fe II-XXVI Kα (6.4-6.966 keV), is produced in a certain angular sector of the disc, we can infer the location of the emitting material by observing its temporal evolution.



Fabian+00



Reynolds+03

From **The** FERO sample down to the ISCO

A plethora of up-to-date models is present in the literature:
- relxill family (Dauser+10,+13, Garcia+14)
- kyn family (Dovčiak+04)
- reflkerr (Niedźwiecki)
- reltrans (Ingram+09)

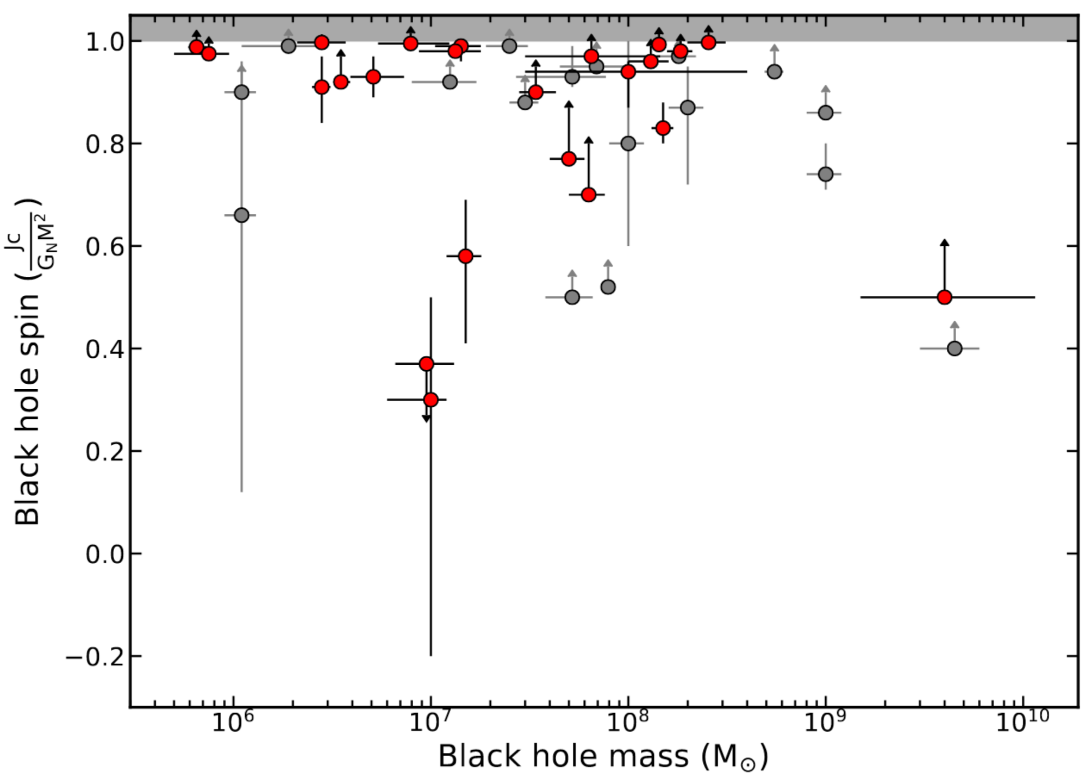
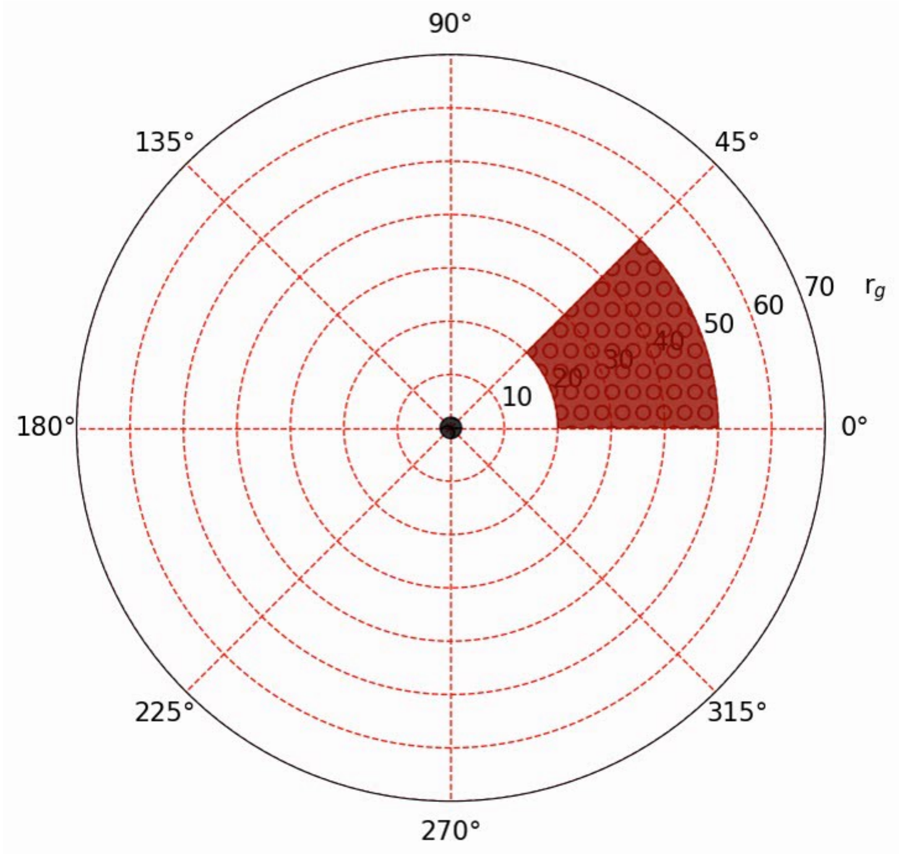


Fig. 20 The BH spin a_* is plotted against the BH mass, for our sample of 40 AGN. red (gray) dots are for BH spin measurements that include (do not include) *NuSTAR* data.

and the full list of black hole spin measurements has ~40 AGN, obtained via the broad Iron Kα component fitting method (Reynolds+14, Brenneman+13, Reynolds 19,20, Bambi+21)

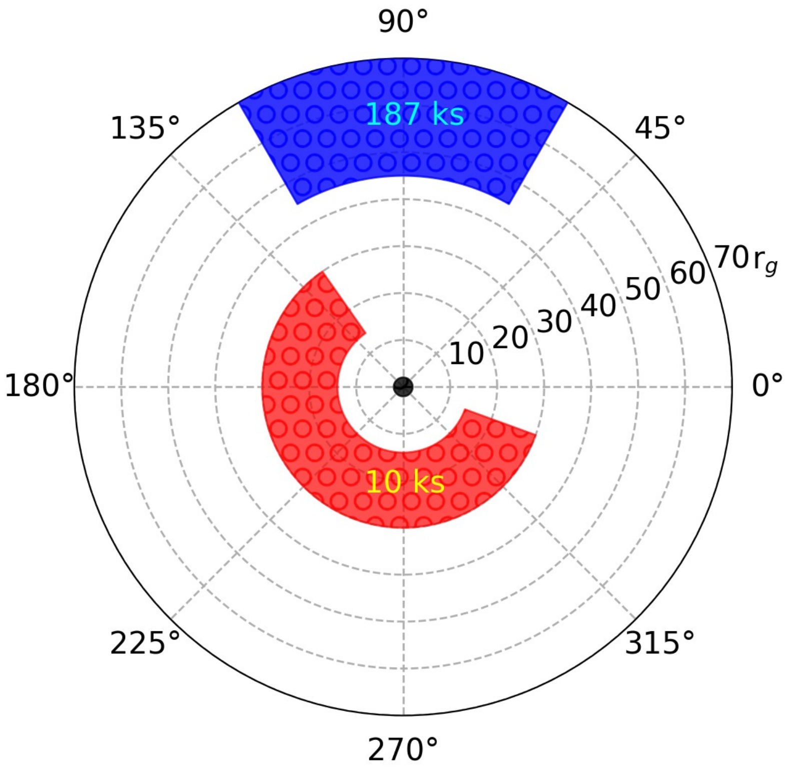
Iron Kα emission transients

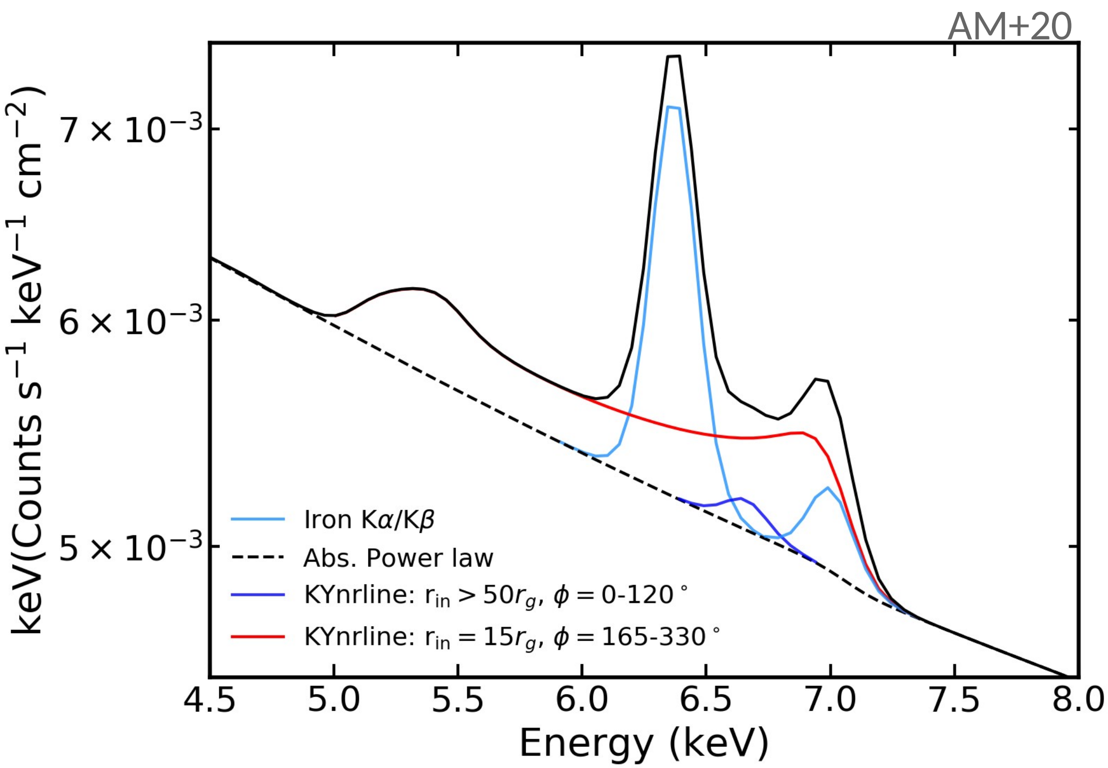
The main parameters we can retrieve are the inclination of the accretion disk, the inner/outer radius of the emitting sector, its azimuthal extension and the energy at rest of the emission line (KYN: Dovčiak+04*).



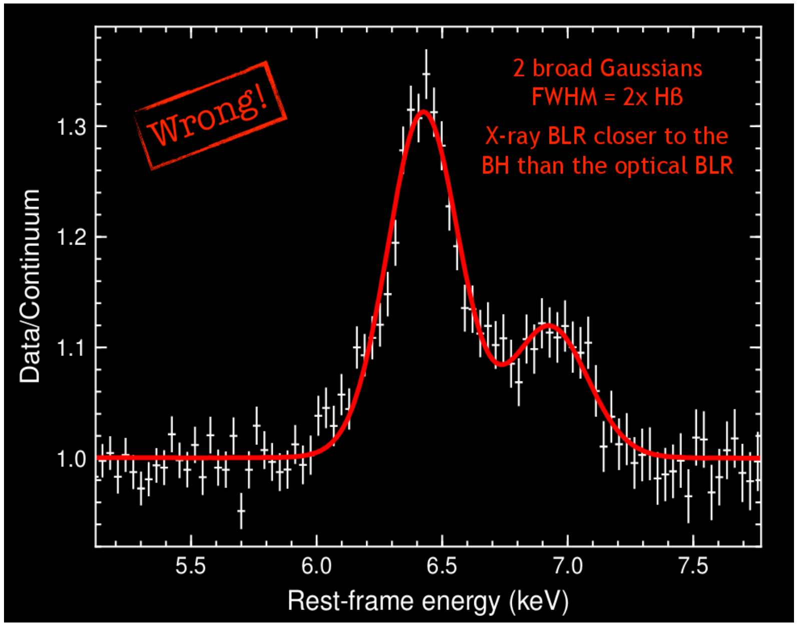
*https://projects.asu.cas.cz/stronggravity/kyn/

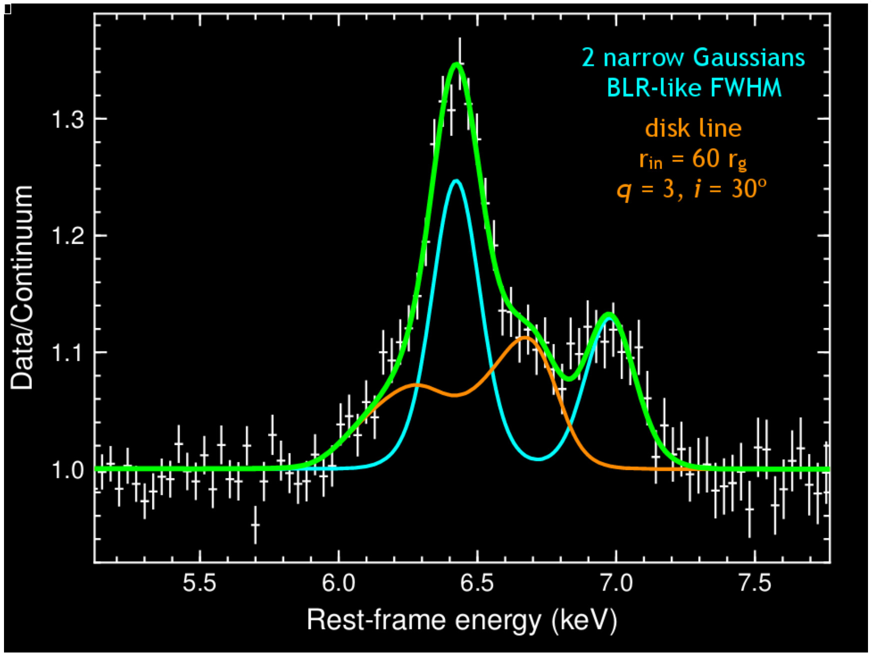
Iron Kα emission transients





From **The** FERO sample down to the ISCO





Courtesy of E. Nardini

Iron Kα emission transients

What timescales do we need for AGN?

$$T = 310\left[a + \left(\frac{r}{r_g}\right)^{\frac{3}{2}}\right] M_7 \text{ (s)},$$

Bardeen+72

Period

BH spin

Radial distance of the flare from the BH

Black hole mass in 10^7 M_{sun} units

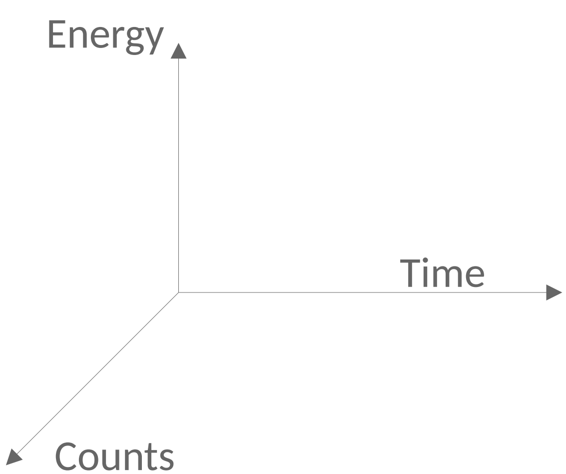
M_7=3, r=10r_g, a=0.998 → T=30 ks

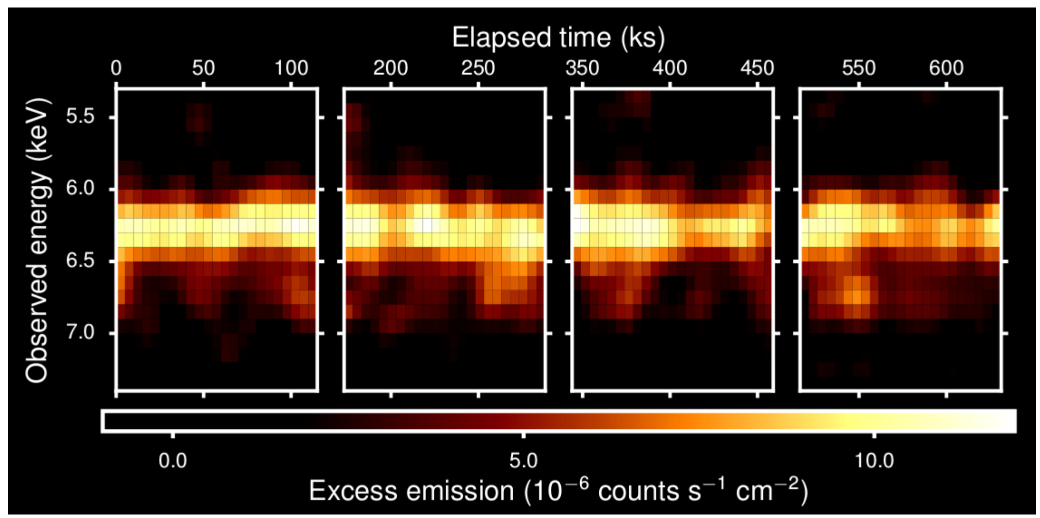
M_7=3, r=15r_g, a=0.998 → T=55 ks

Iron Kα emission transients: XMM results

The excess map technique (Iwasawa+04, Turner+06, Tombesi+07, Petrucci+07, De Marco+09, Costanzo+21) revealed transient emission lines in the 5-7 keV energy band in a handful of AGN.

The analysis is based on the process of constructing an image of the excess of counts with respect to the nuclear continuum, vs time and energy. A smoothing kernel is then used to suppress the noise between adjacent pixels.

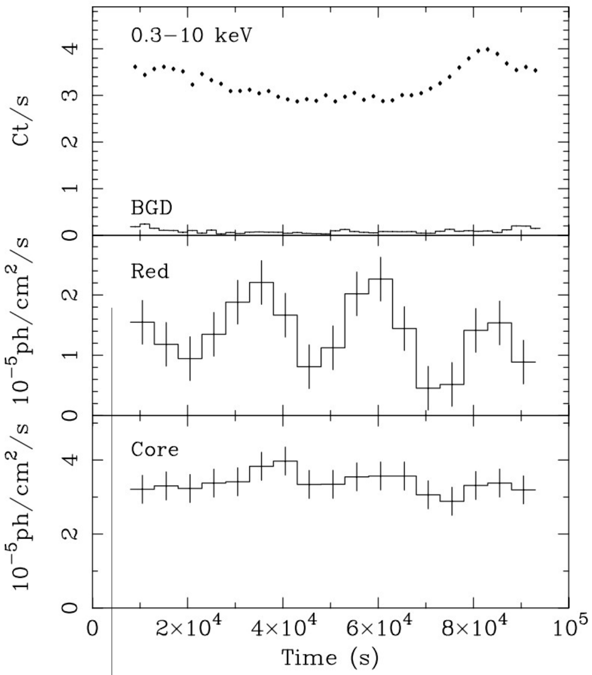


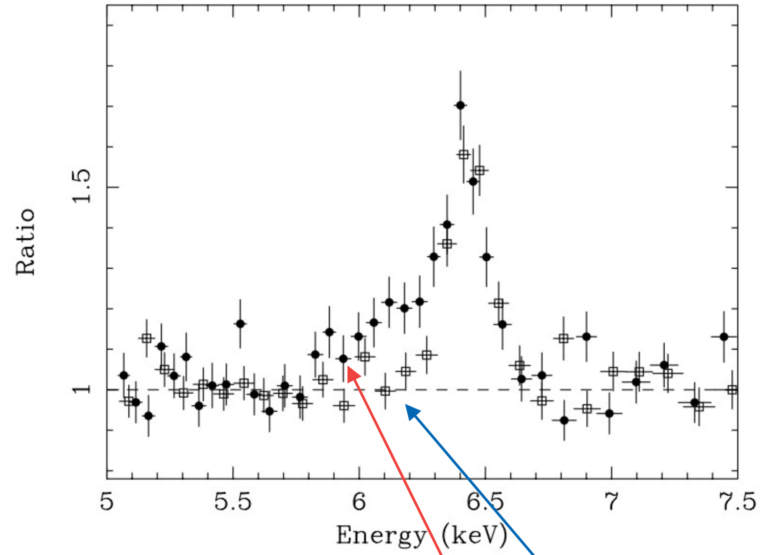


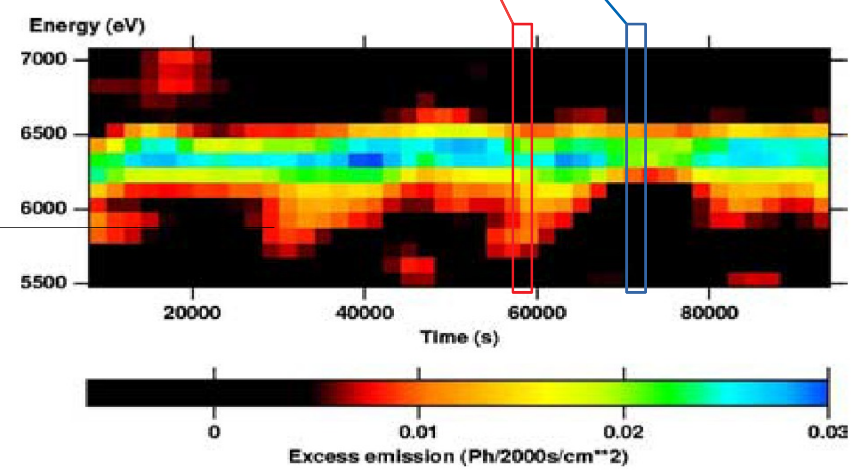
Ark 120: Nardini+16

Iron Kα emission transients: XMM results

NGC 3516: Iwasawa+04







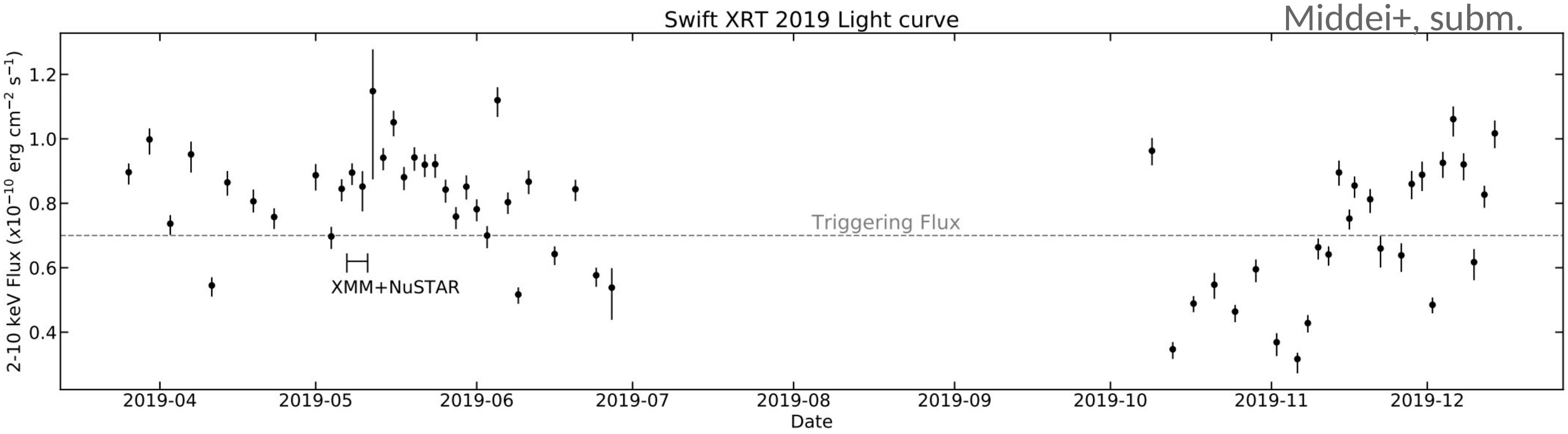
$$T = 310\left[a + \left(\frac{r}{r_g}\right)^{\frac{3}{2}}\right] M_7 \text{ (s)},$$

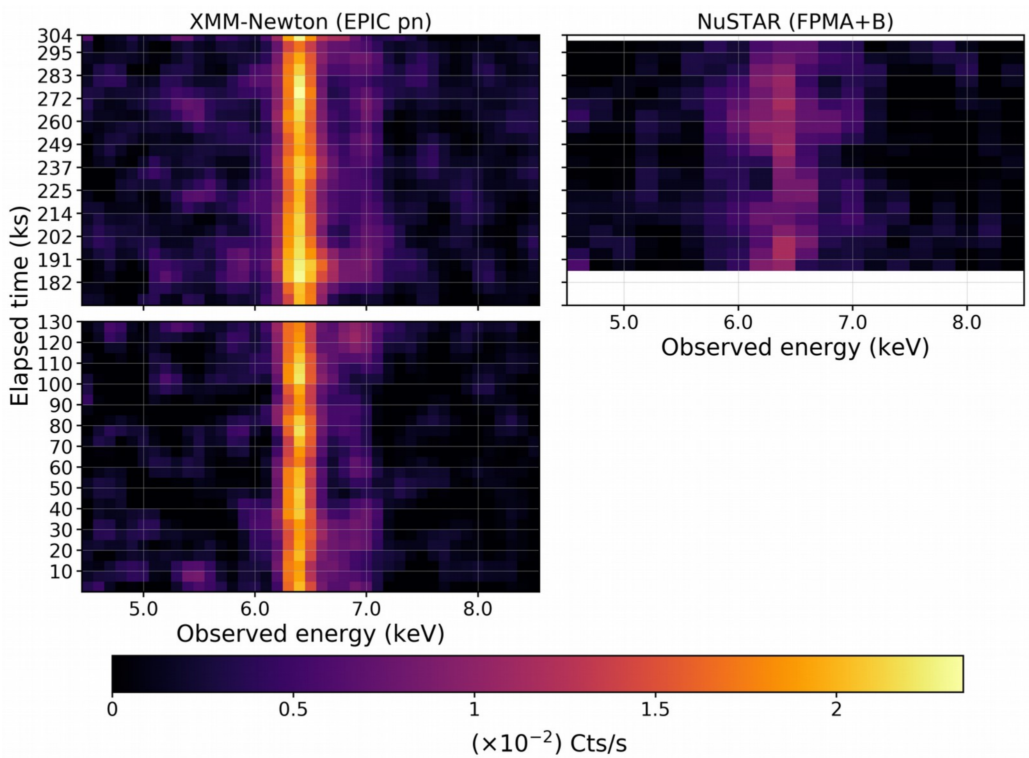
$$1.0 \times 10^7\ \mathrm{M}_\odot \lesssim M_{\mathrm{BH}} \lesssim 5.0 \times 10^7\ \mathrm{M}_\odot.$$

An indirect measurement of the BH mass can be found

Iron Kα emission transients: XMM(+NuSTAR) results

Middei+, subm.

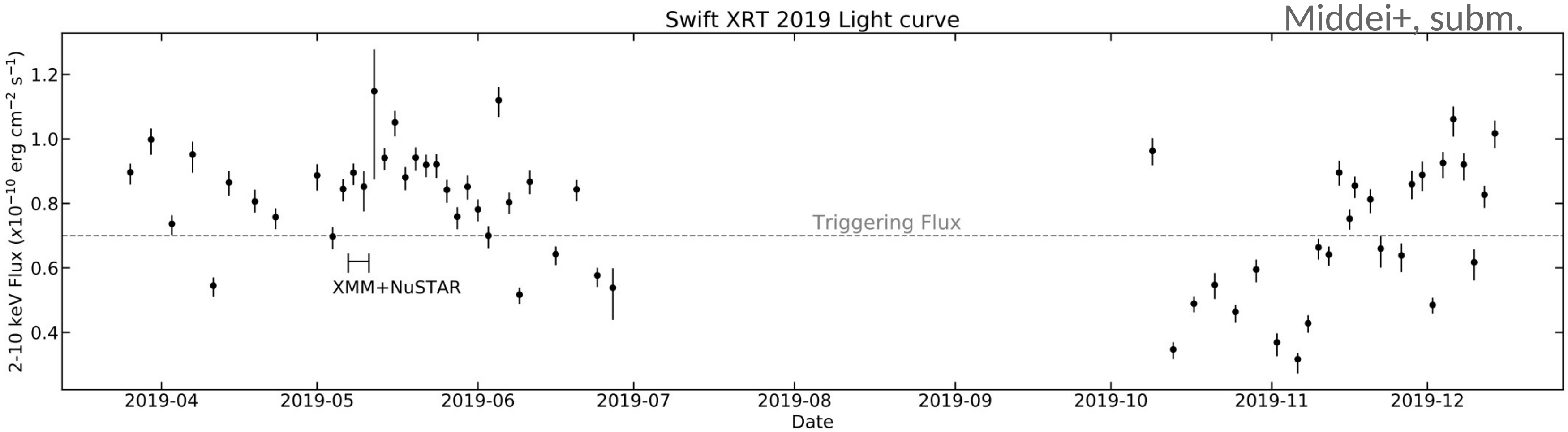


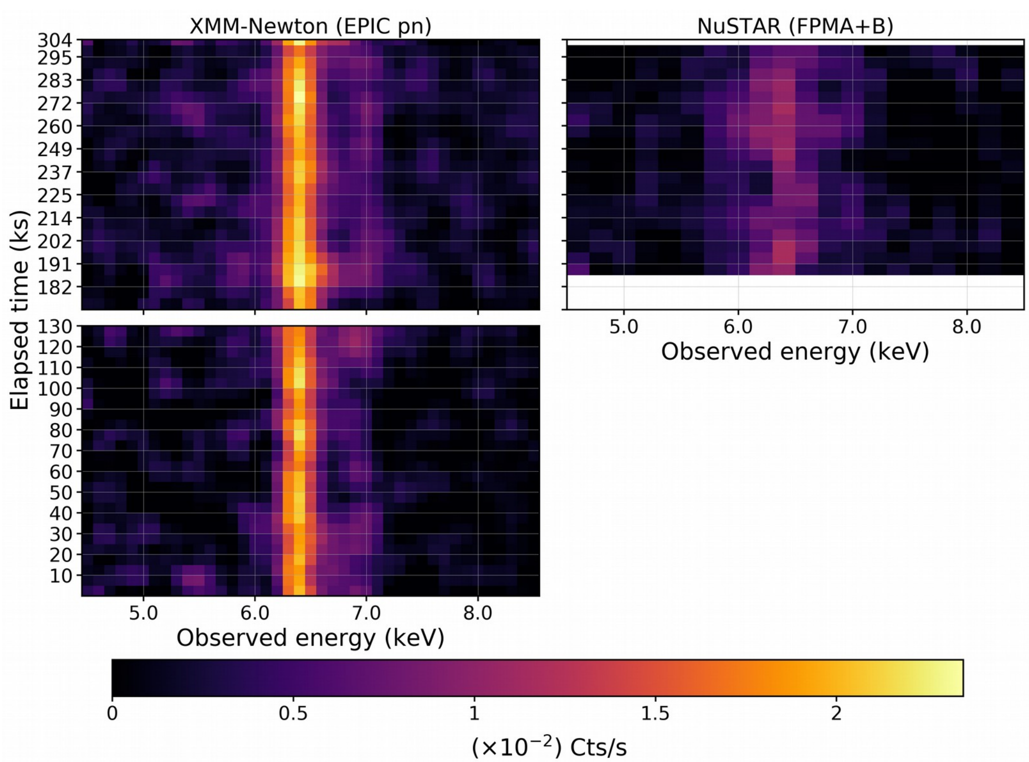


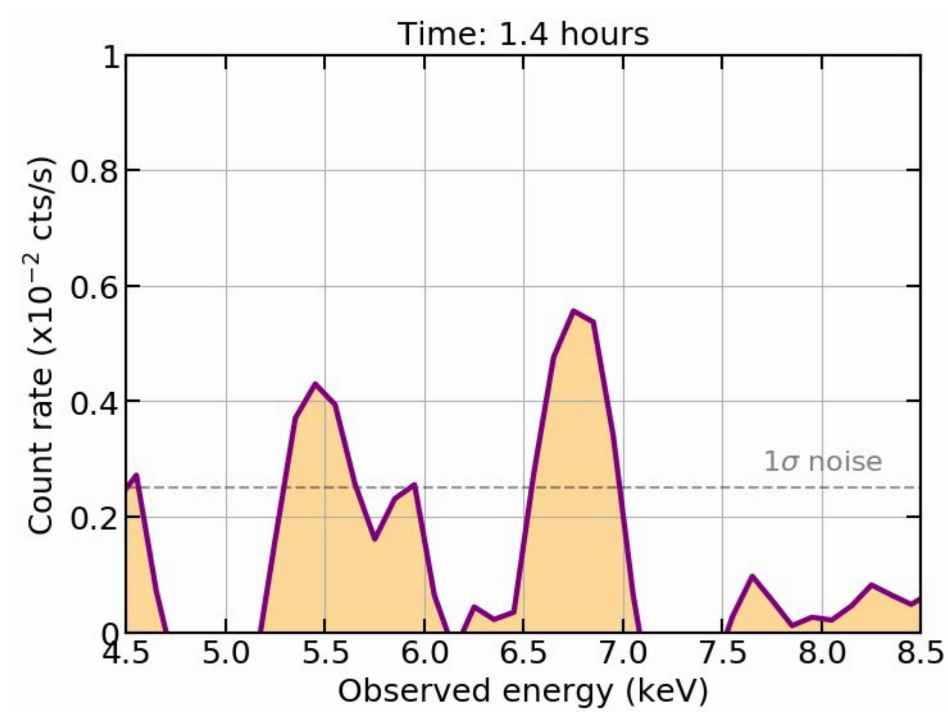
NGC 2992: AM+20

Iron Kα emission transients: XMM(+NuSTAR) results

Middei+, subm.





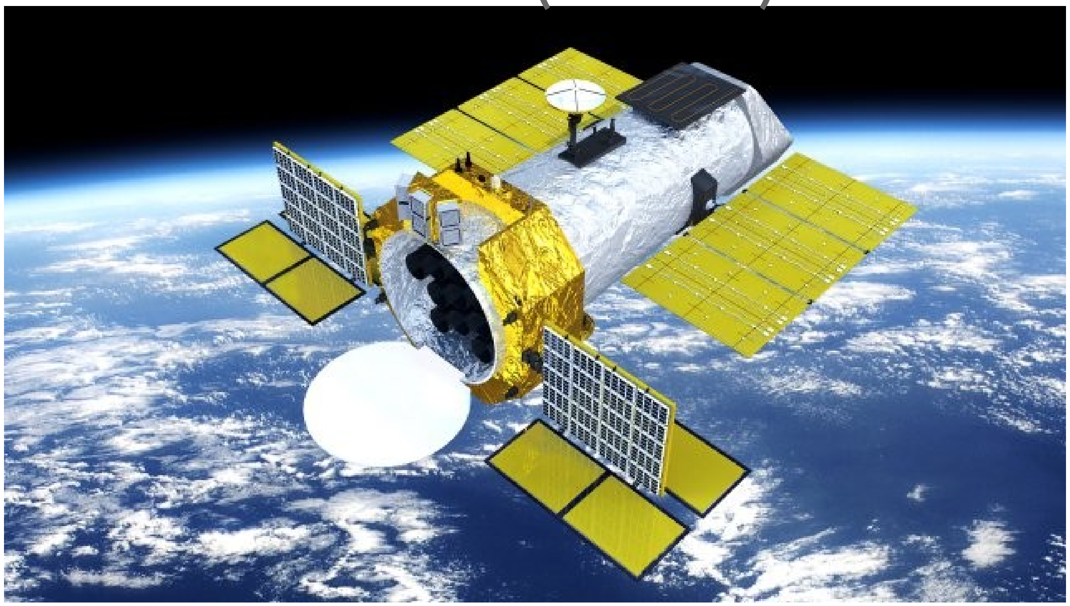


NGC 2992: AM+20

Future perspectives

Athena (~2034)

eXTP (~2027)



Future perspectives

Athena (2030)

E. NARDINI ET AL.

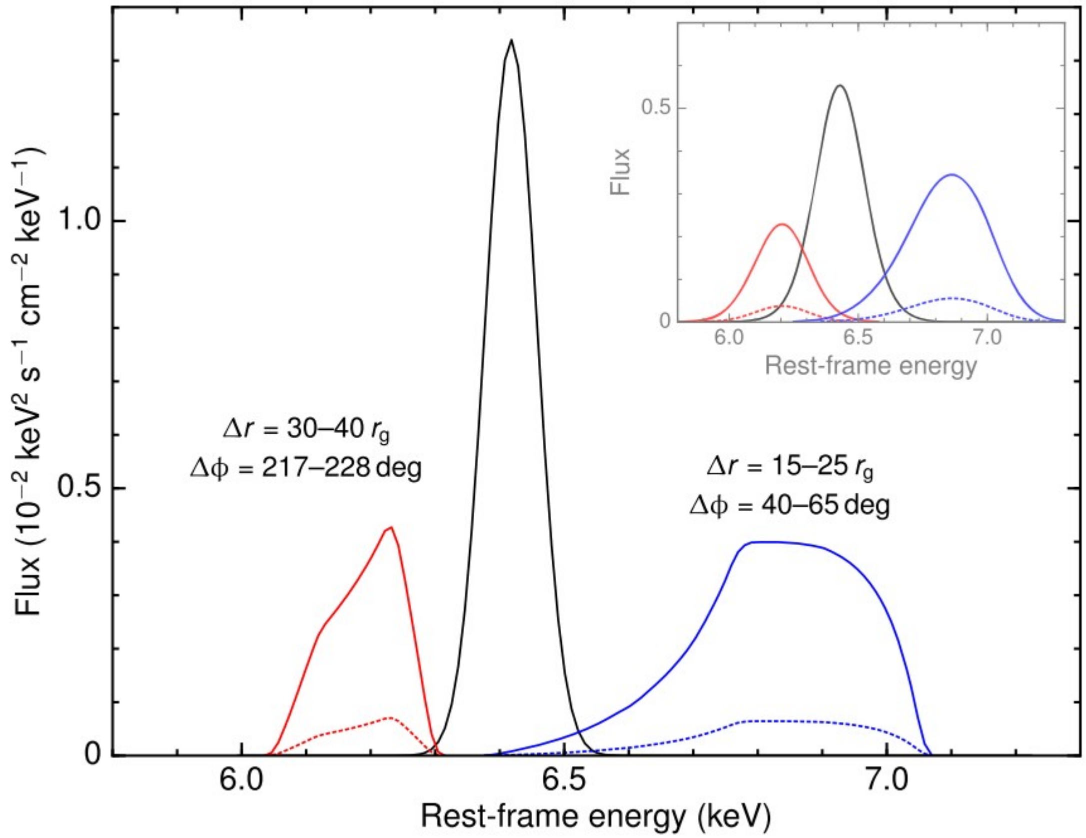
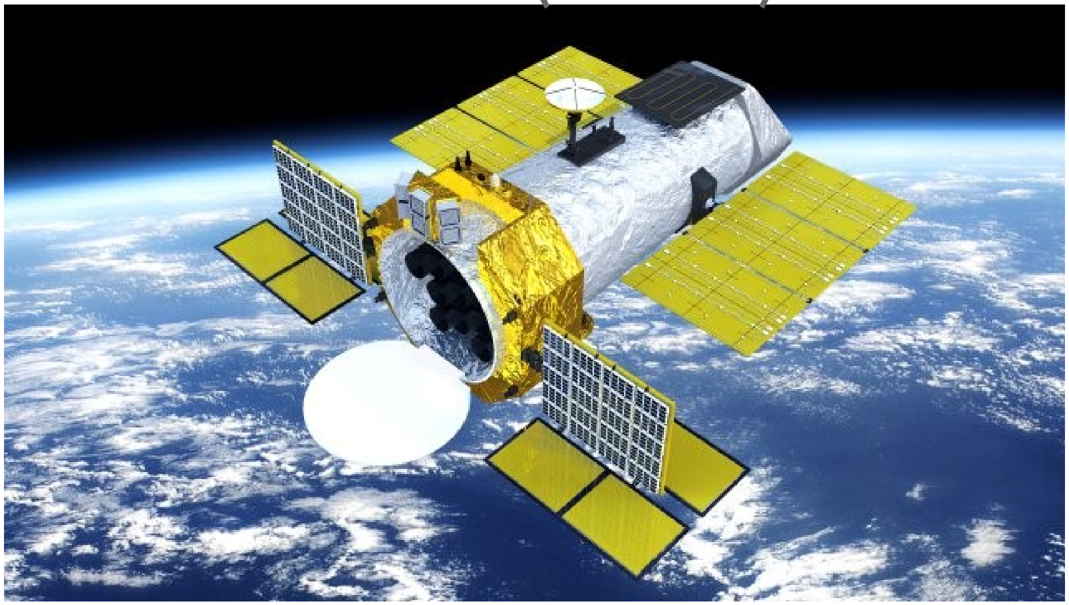


Figure 10. Fe K emission components in the quiescent, red flare, and blue flare spectral states for the hotspot model. The narrow, BLR-like Kα from neutral iron at 6.4 keV (in black) is constant, while the highest (solid) and lowest (dashed) intensities are shown for the red and the blue transient features. The radial and azimuthal coordinates of the relative active regions are also printed, for $a^* = 0$, $i = 30°$, and a rest energy of the line of 6.97 keV ($\phi = 0°$ corresponds to the maximal approaching speed). The profiles are computed assuming an ideal response with linear resolution of 10 eV, while the inset shows their smearing after convolution with the EPIC/pn response (note that the vertical scale is compressed by a factor of two). The intrinsic asymmetry is almost completely lost at CCD resolution.

Future perspectives

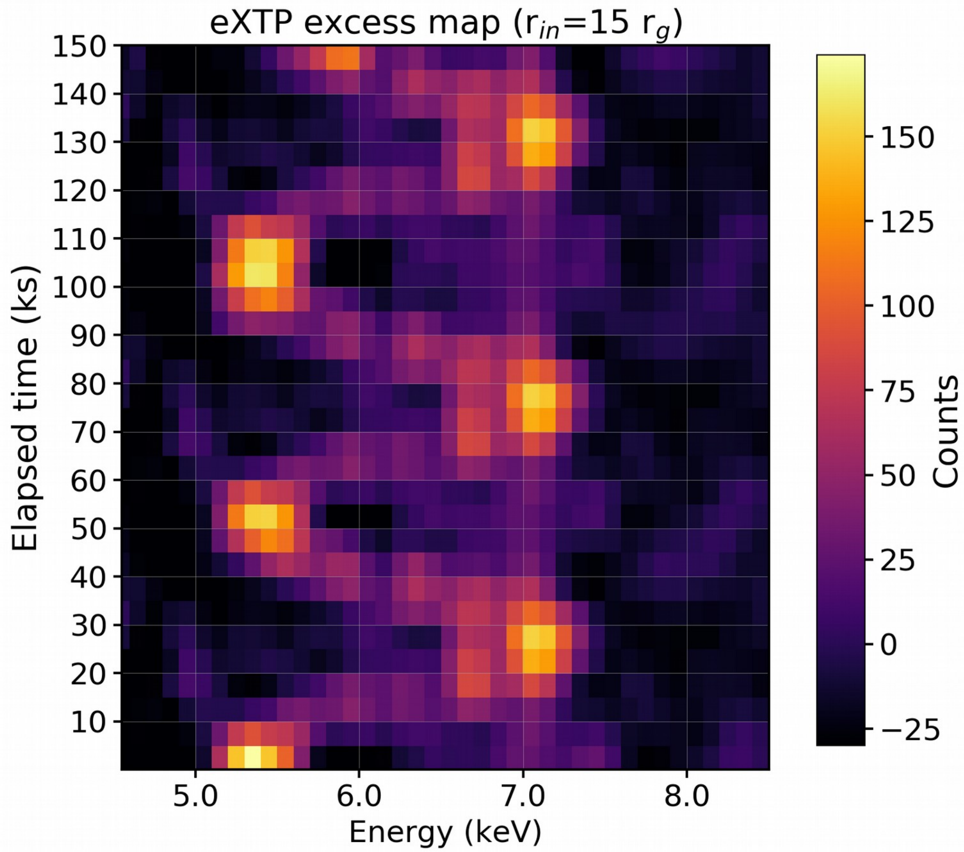
eXTP (~2027)



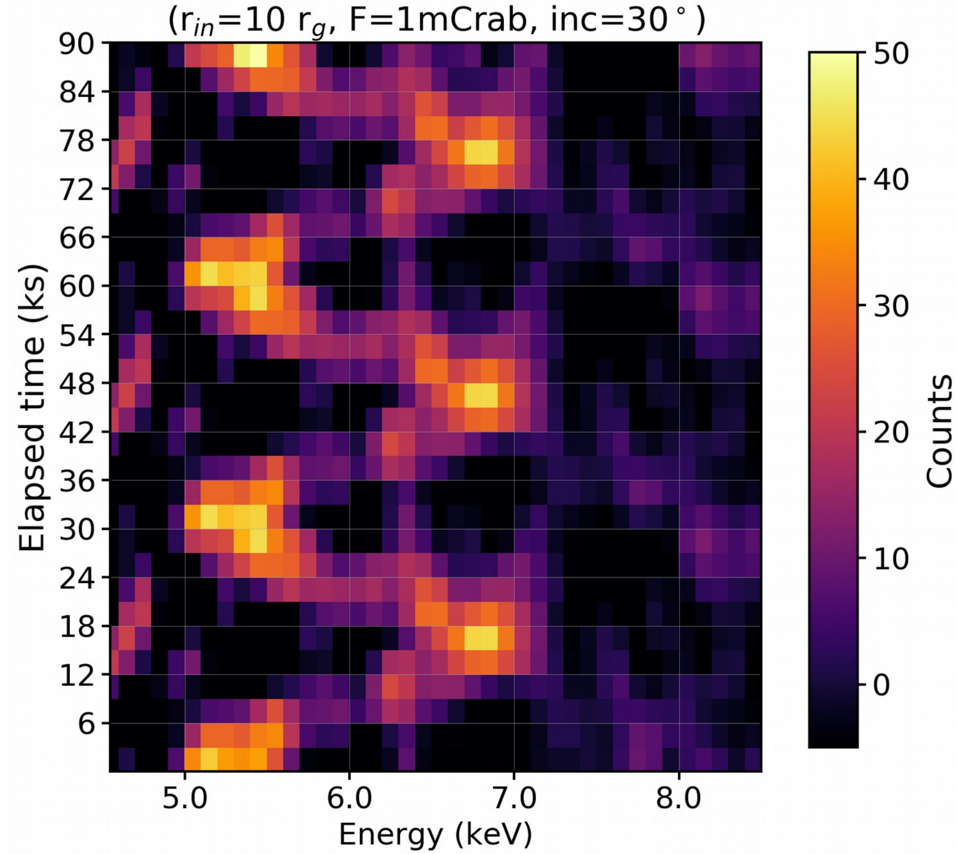
- **LAD**: 6x RXTE/PCA, 35x XMM-Newton (*but collimated*!) + hard-X response
- **SFA**: 8x XMM-Newton and 0.3-2x Athena/WFI (*but multiple optics and large PSF*!). Limiting sensitivity ~10^{-14} erg cm^{-2} s^{-1}
- **PFA**: 5x IXPE, 2x XIPE. Sensitivity: 1% MDP in 50ks for a 100 mCrab source
- **WFM**: largest FoV ever, first time with 300 eV resolution. 3 mCrab in 50ks

eXTP simulations

SFA – model 1



SFA – model 2



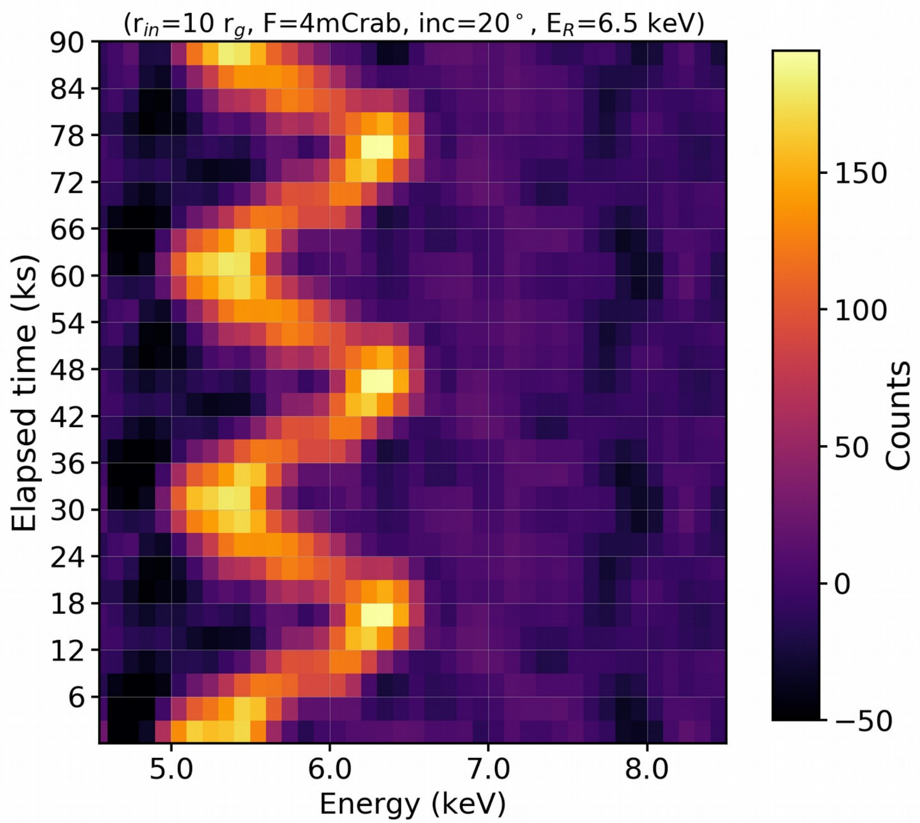
1 - Rin=15 r_g; inc=40°; Ec=6.7 keV, T=50 ks, T_{sam}=T/10; $F_{2-10}=5\times10^{-11}$ cgs (2mCrab)

2 - Rin=10 r_g; inc=30°; Ec=6.7 keV, T=30 ks, T_{sam}=T/10; $F_{2-10}=2.5\times10^{-11}$ cgs (1mCrab)

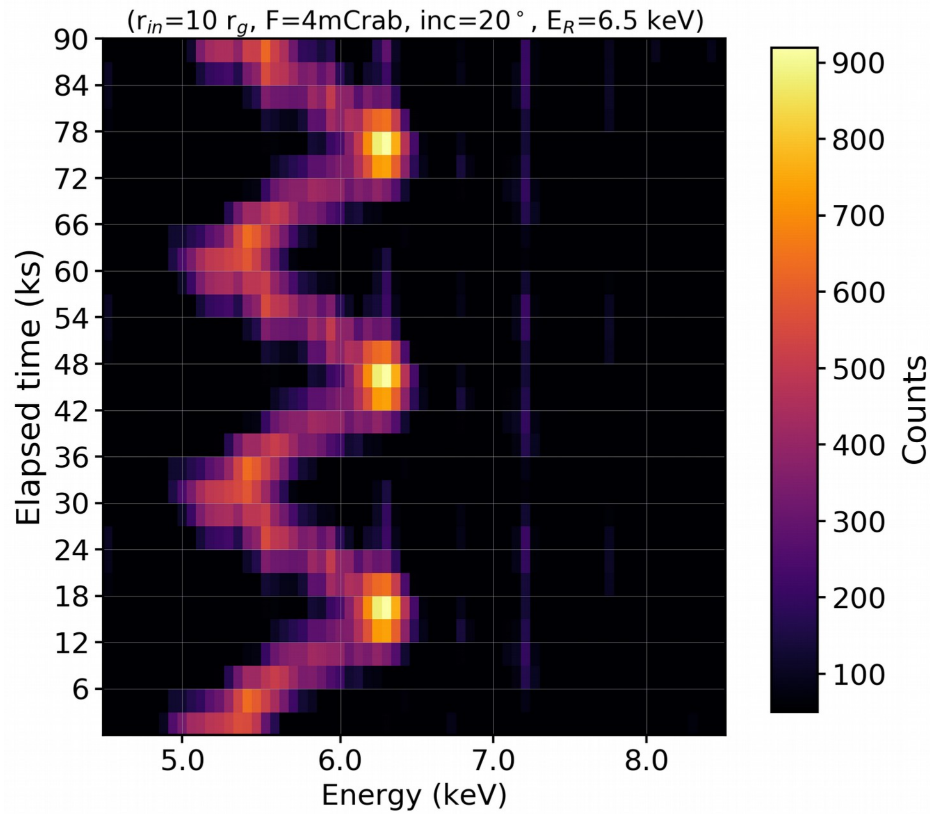
eXTP simulations

We also included LAD simulations for the high flux state (model 3)

SFA



LAD



Conclusions

- Hot coronae around SMBH seem to have the same properties across a wide range of Mbh, λ_{Edd} and z;

- their location and extension is a consistent with r~3-20 r_g;

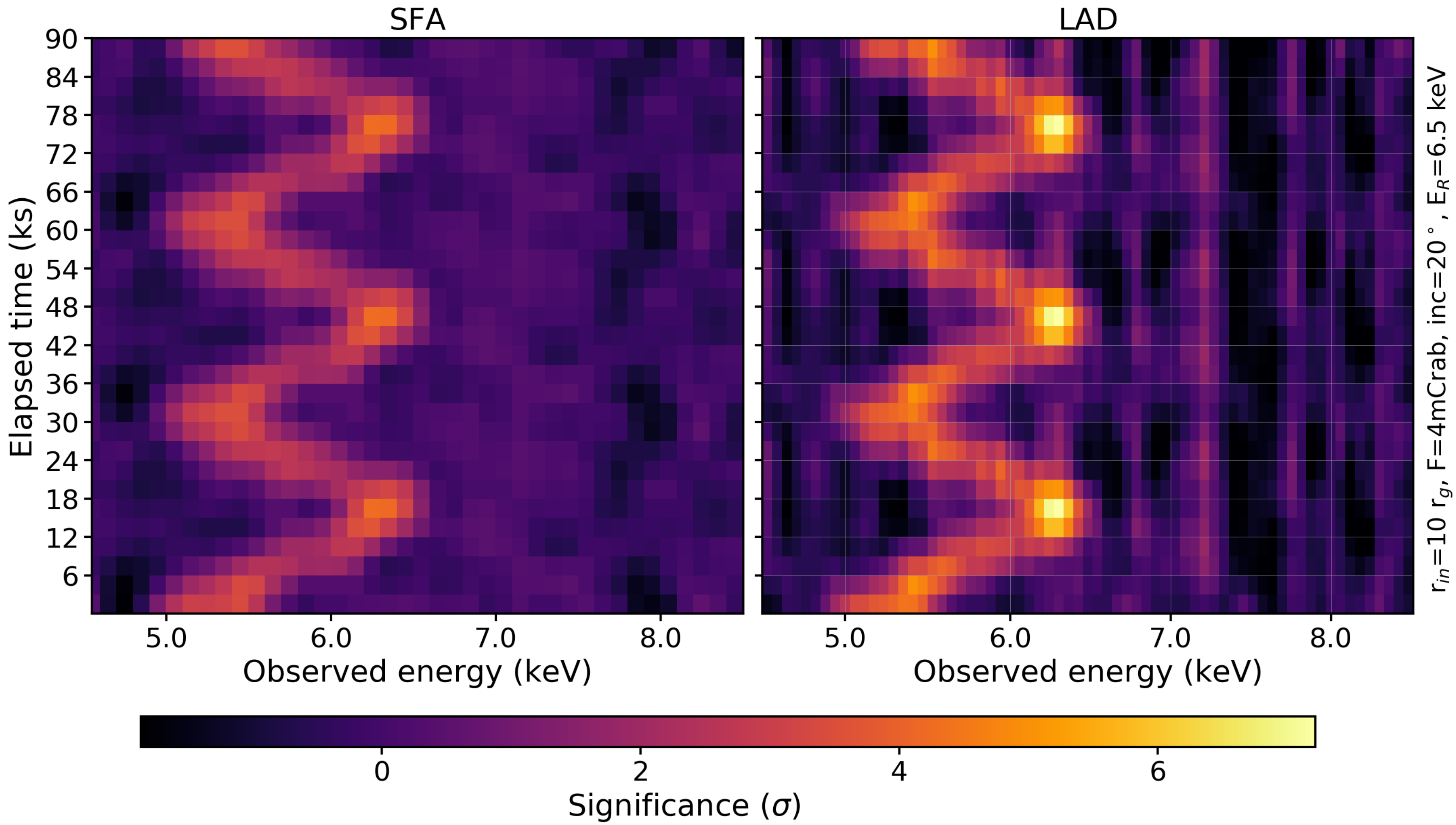
- the FERO paradigm still stands after 10 years;

- Iron Kα emission transients can be crucial for finding flares in the disk, down to the ISCO;

- the new generation of X-ray observatories will be therefore crucial for studying SMBH accretion disk

Thanks for the attention!

eXTP simulations



eXTP will be the perfect observatory to study iron K transients in AGN, in bright sources (>1mCrab).

eXTP simulations – next steps

List of possible eXTP targets for Doppler tomography:

Ark 120 – F=0.3x10^{-10} cgs, M=1.5x10^{8} M_{sun} ,$T_{10\,rg}$= 150 ks

IC 4329A – F=10^{-10} cgs, M=1.2x10^{8} M_{sun} , $T_{10\,rg}$= 120 ks

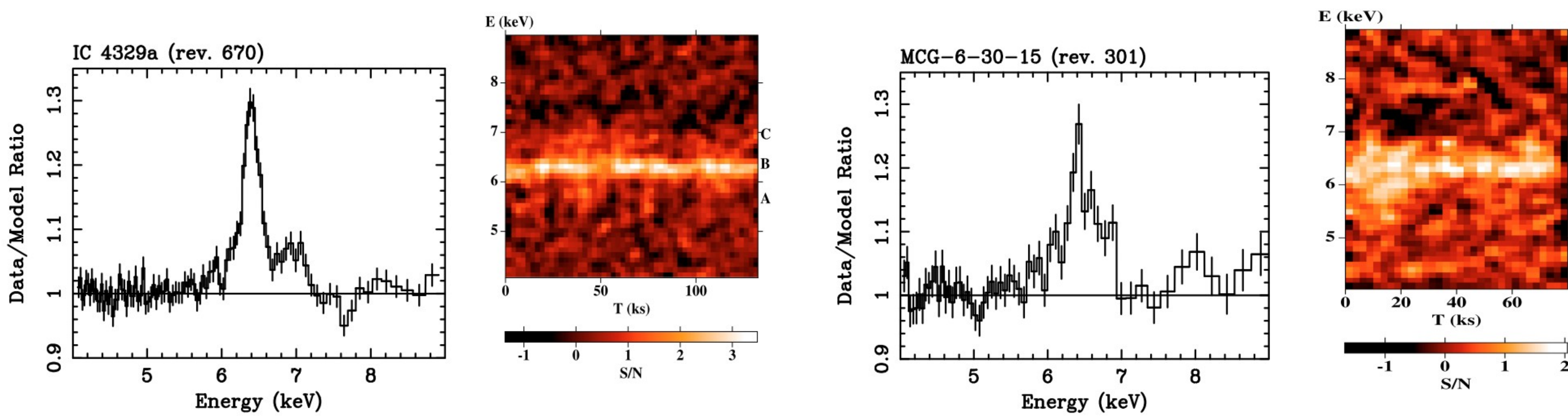
MCG-05-23-16 – F=(0.8-1.0)x10^{-10} cgs, M=2x10^{7} M_{sun} , $T_{10\,rg}$= 20 ks

MCG-06-30-15 – F=(0.2-0.4)x10^{-10} cgs, M=5x10^{6} M_{sun} ,$T_{10\,rg}$= 5 ks

NGC 2992 - F=(0.05-1.1)x10^{-10} cgs, M=3x10^{7} M_{sun} ,$T_{10\,rg}$= 30 ks

NGC 3516 – F=0.2x10^{-10} cgs, M=3x10^{7} M_{sun} ,$T_{10\,rg}$= 30 ks

NGC 4151 – F=1.5x10^{-10} cgs, M=4x10^{7} M_{sun} , $T_{10\,rg}$= 40 ks



De Marco+09