Observational constraints on the AGN corona

Andrea Marinucci

Finding Extreme Relativistic Objects
(9th edition)
Heraklion, Crete

Outline

- Introduction
- High-energy cutoff measurements
- One corona, two coronae …
- The NuSTAR era
- Conclusions

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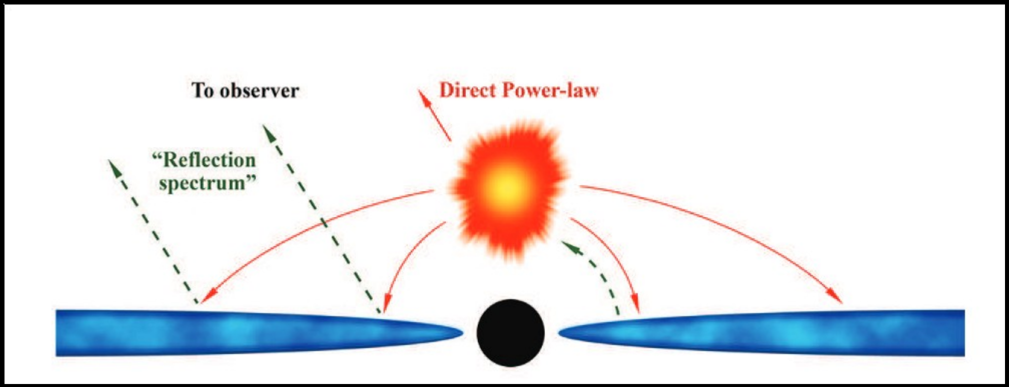
Introduction

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

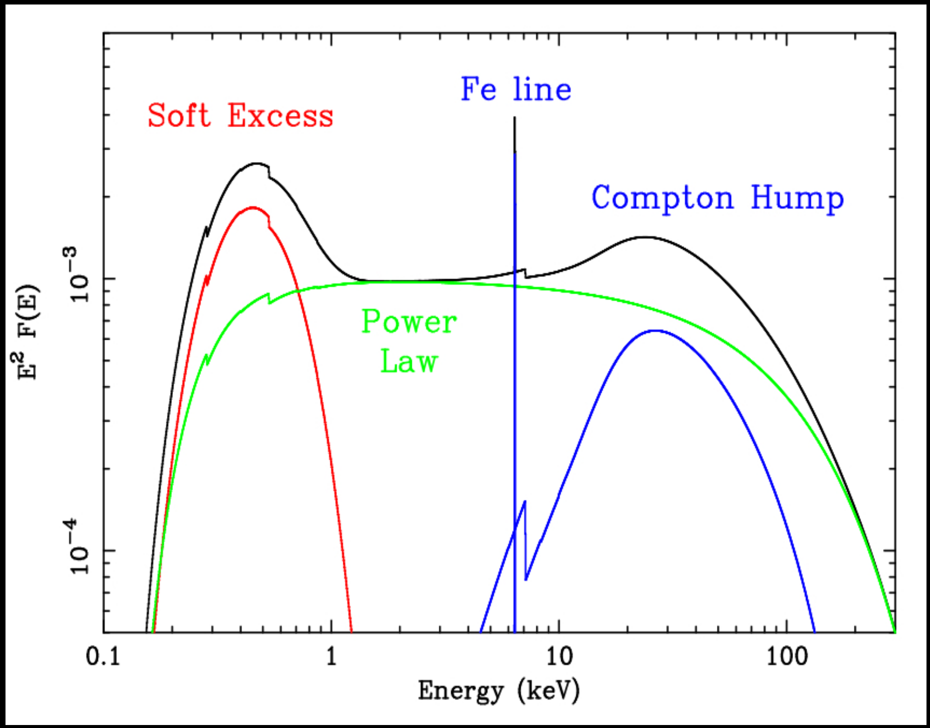
In the X-rays, it can be well approximated with a power law with photon index Γ=1.5-2.2 (Bianchi+09; Sobolewska & Papadakis+09)



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

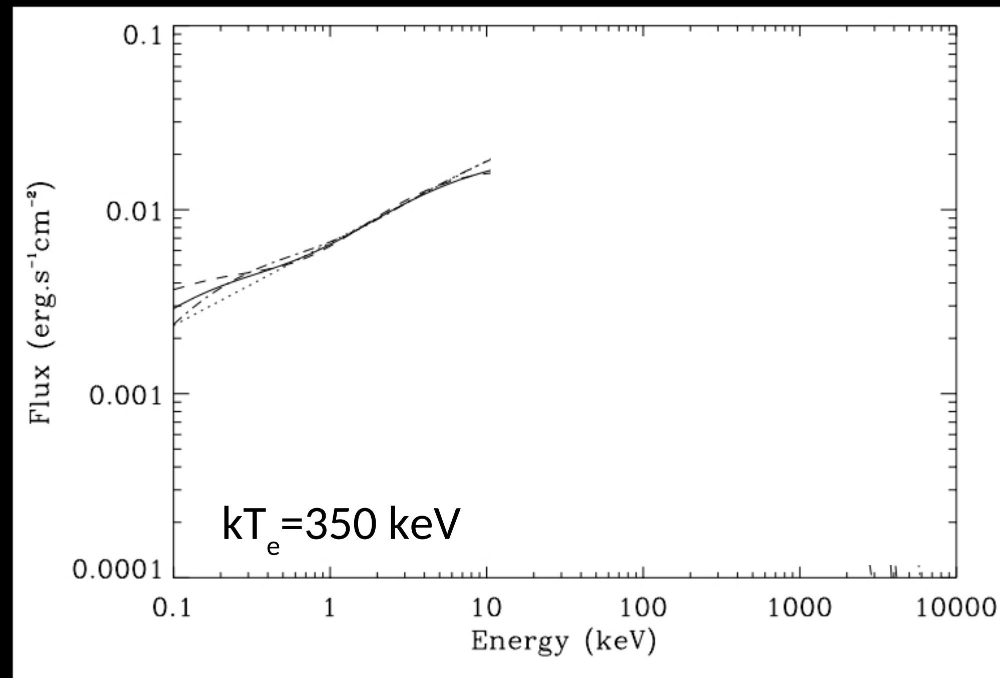
High energy turnover → $f(kT_e)$

Photon index → $f(kT_e, \tau)$

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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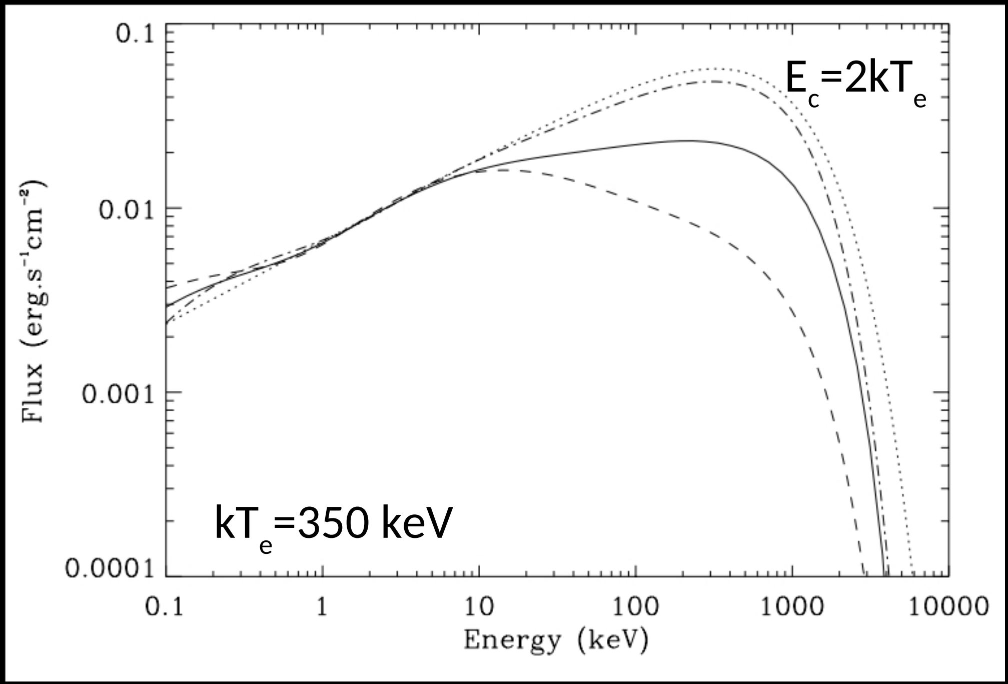

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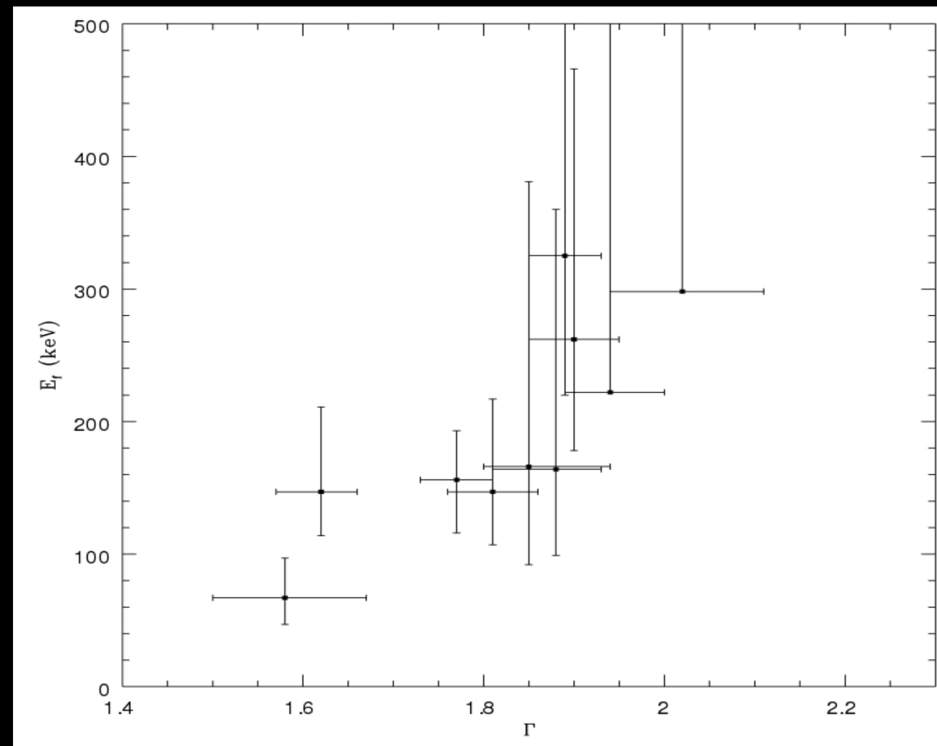
The search for high-energy cutoffs

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}



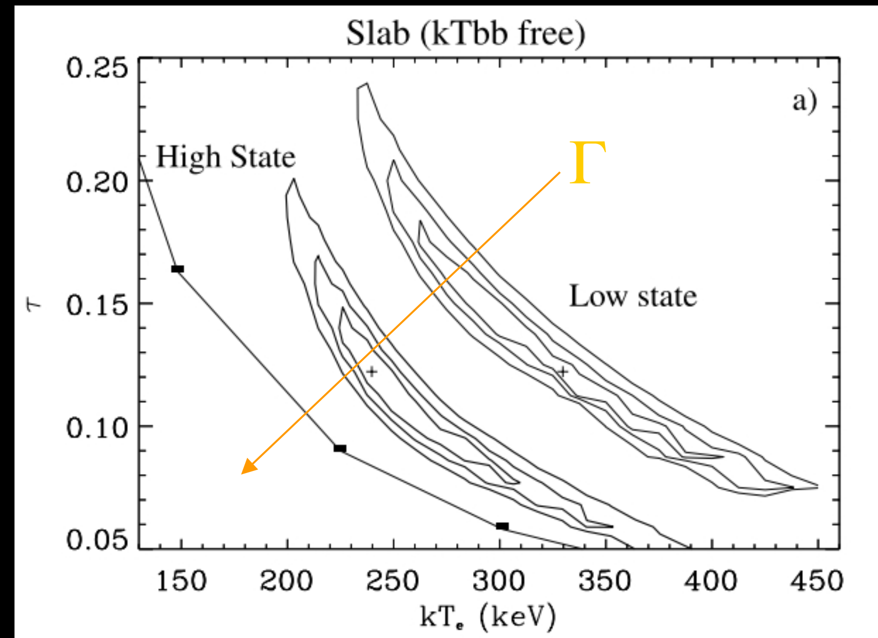
A E_c-Γ degeneracy (and R parameter) can be observed.

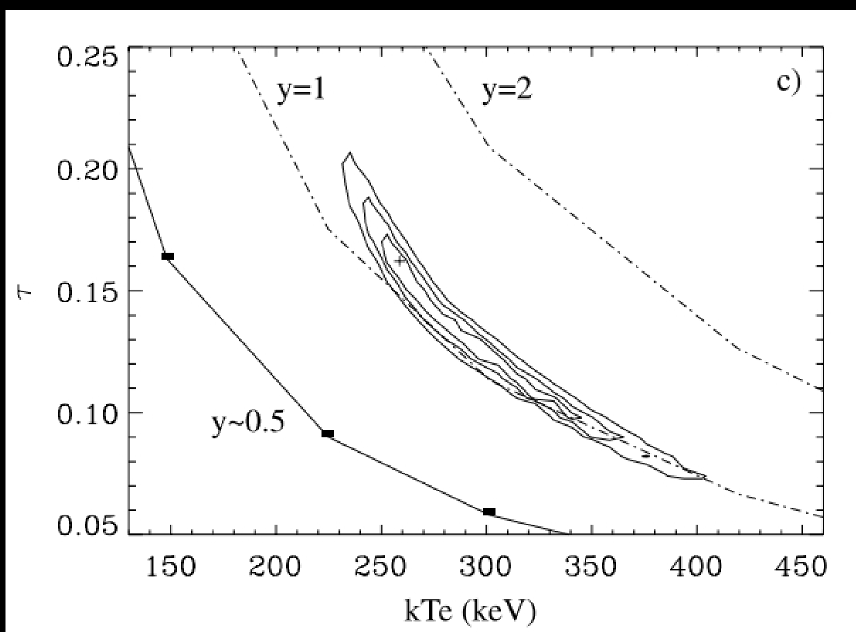
The search for high-energy cutoffs

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





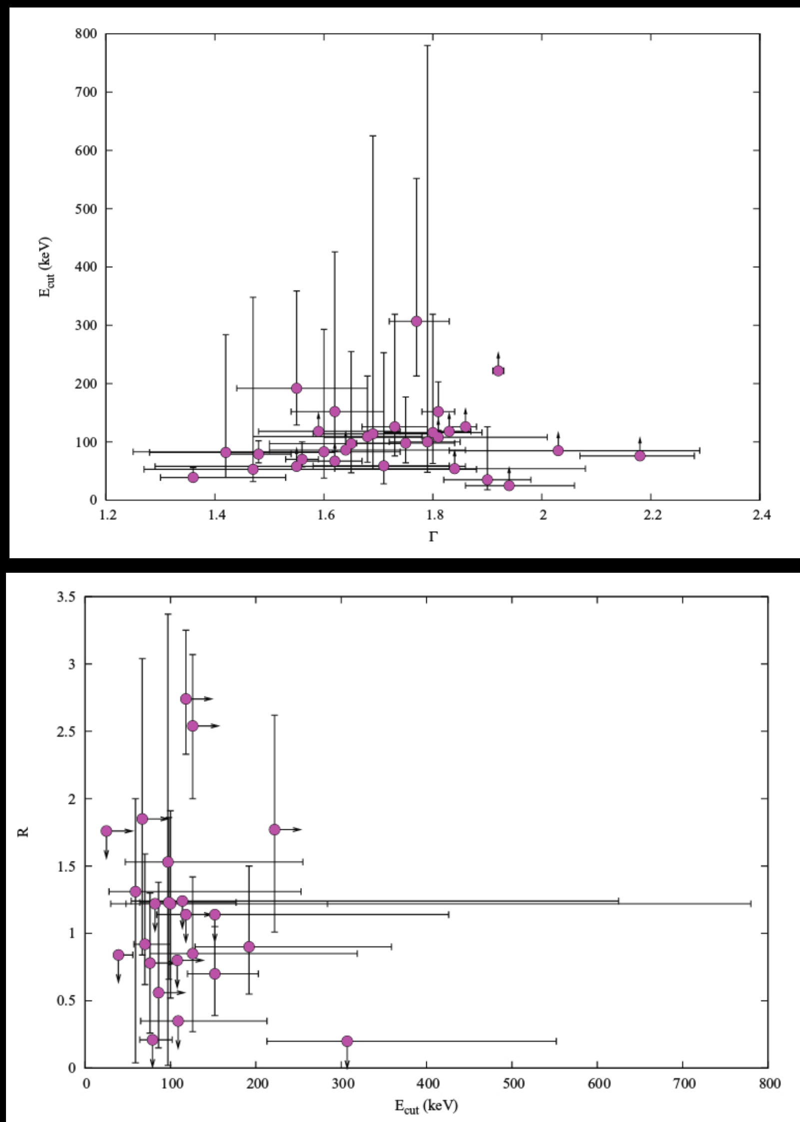
Compton parameter y
(i.e. amplification of the Comptonization process)

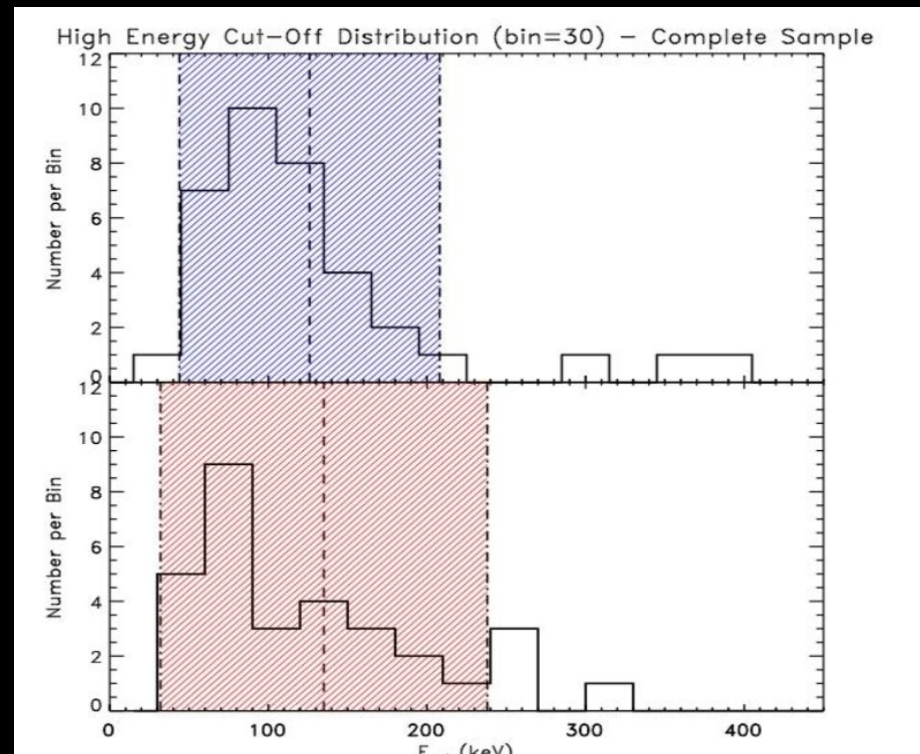
$$y \simeq 4(kT_e/m_e c^2)[1 + 4(kT_e/m_e c^2)]\tau(1+\tau)$$

The search for high-energy cutoffs

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

Molina+09





De Rosa+12, Molina+13

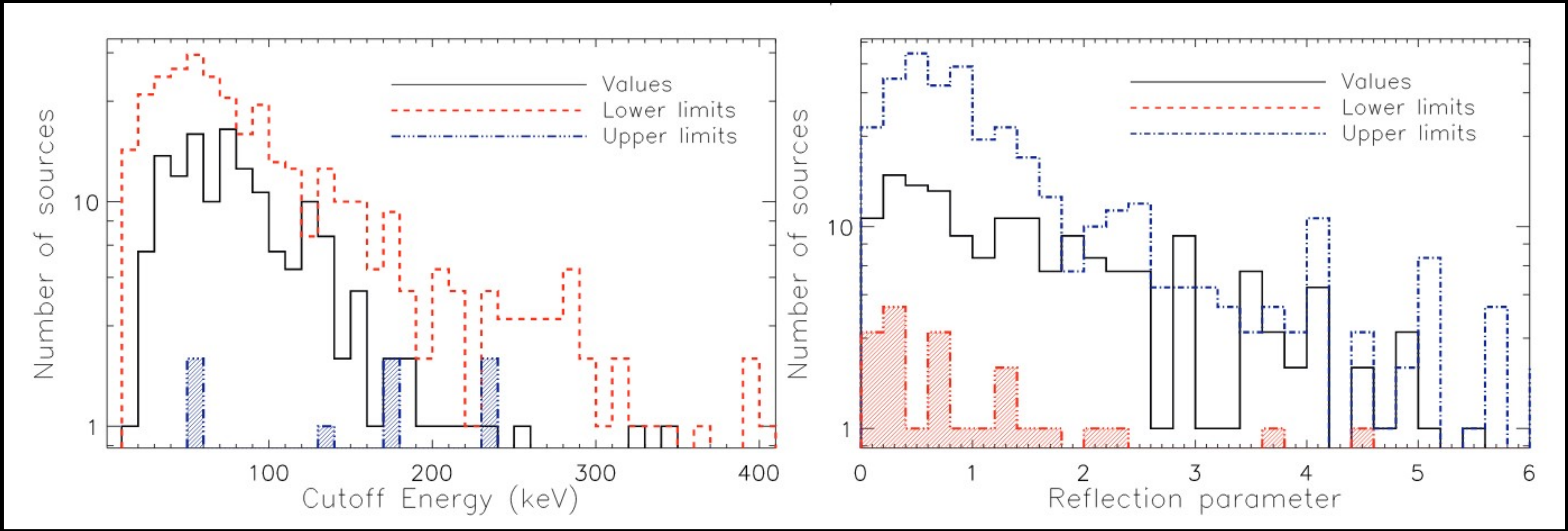
$\Gamma = 1.76^{+0.22}_{-0.24}$

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

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

The search for high-energy cutoffs

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



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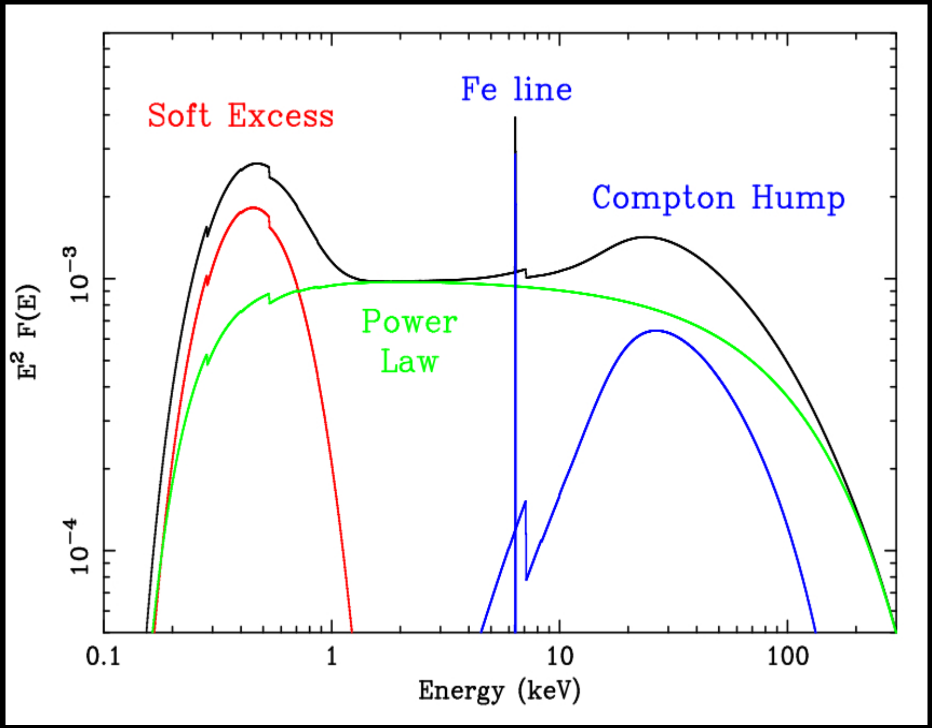
The soft excess in AGN, Comptonization?

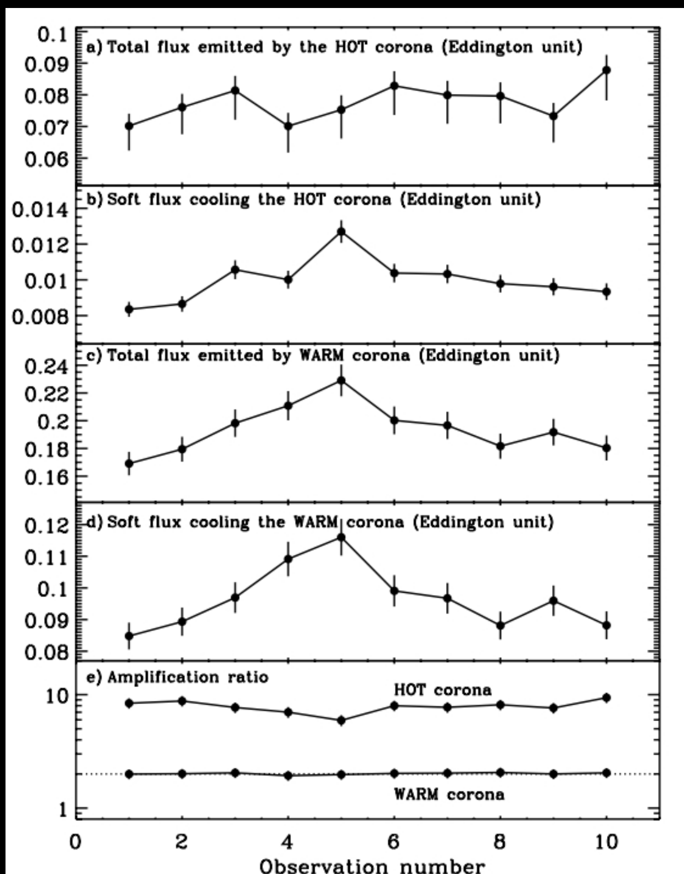
Different models, assuming thermal comptonisation in an optically thick ($\tau > 1$) and warm ($kT \sim 1$ keV) plasma, have been proposed to reproduce this component (Crummy+06, Magdziarz+98, Done+12, Jin+12).



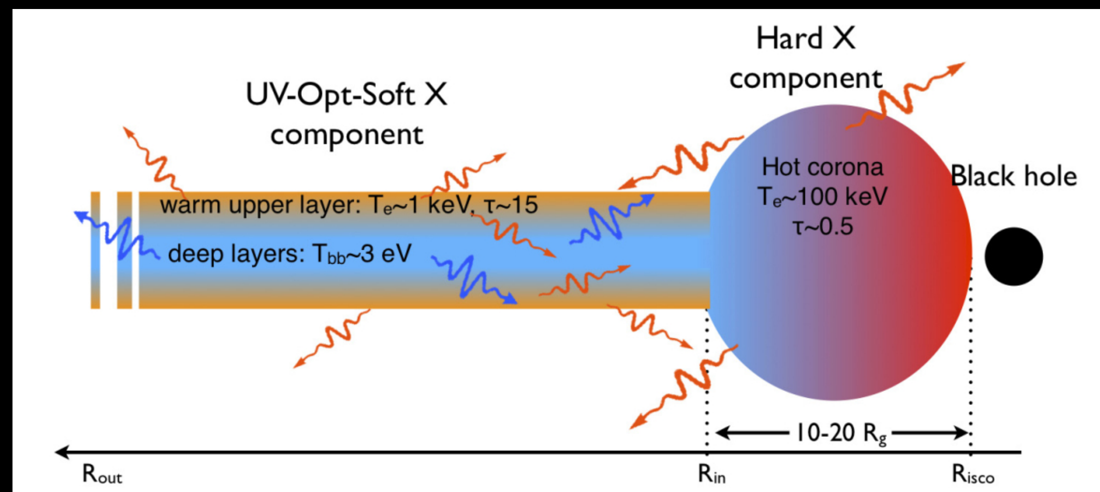
Fabian & Miniutti+05

A warm + hot corona scenario

The thermal comptonisation modeling of the soft X-ray excess has been applied to the monitoring campaign on Mrk 509 (Kaastra+11, Petrucci+13), based on the two-phase scenario (Haardt+93, Haardt+94)

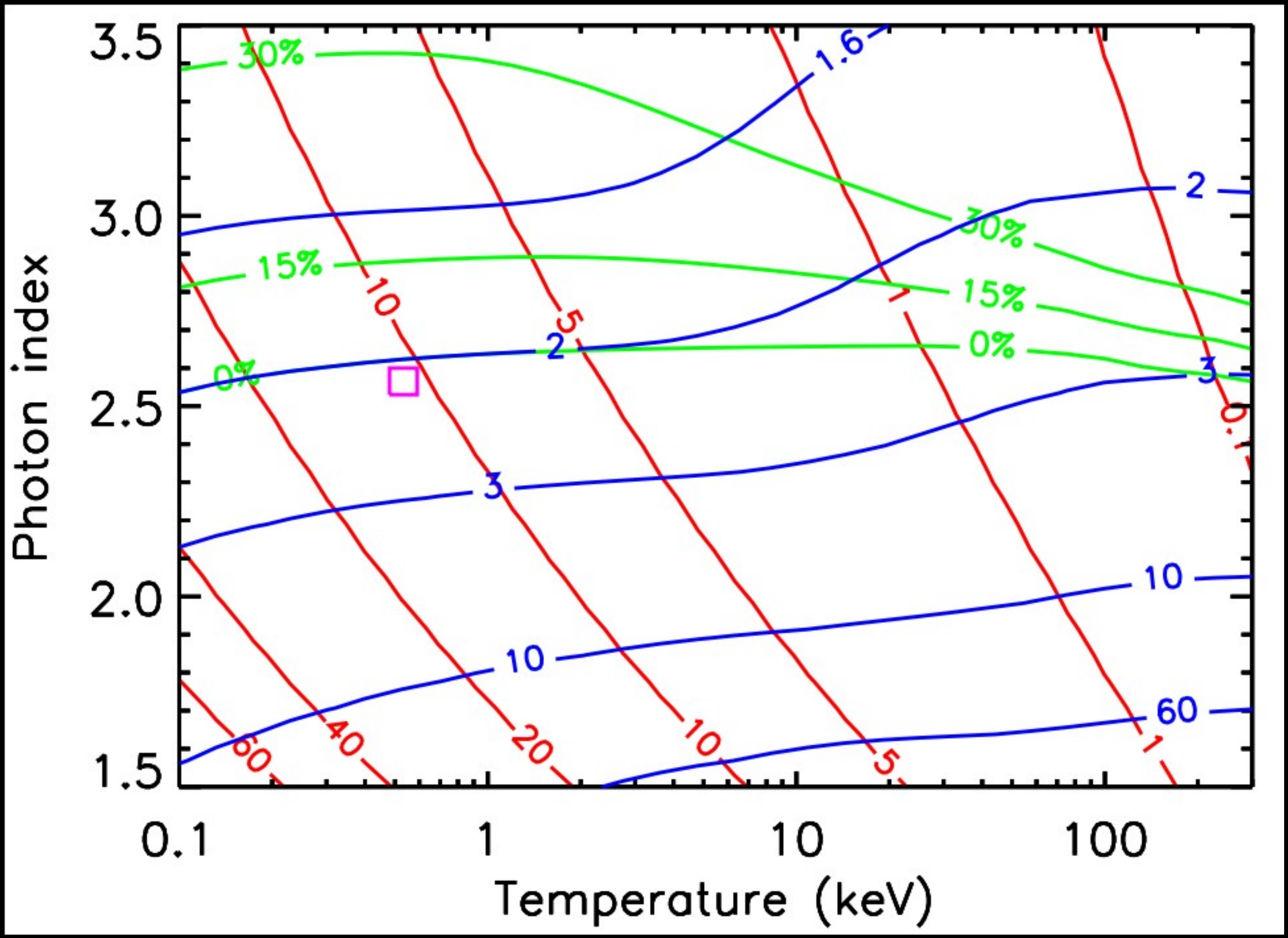


Petrucci+13



A warm + hot corona scenario

The same scenario has been tested on an XMM (EPIC+OM) sample of variable AGN (Petrucci+18), using the nthcomp model (Zdziarski+96, Zycki+99)



- Optical depth
- Disc intrinsic emission (low-→ patchy slab)
- Amplification factor warm (~1-3) hot (~10)

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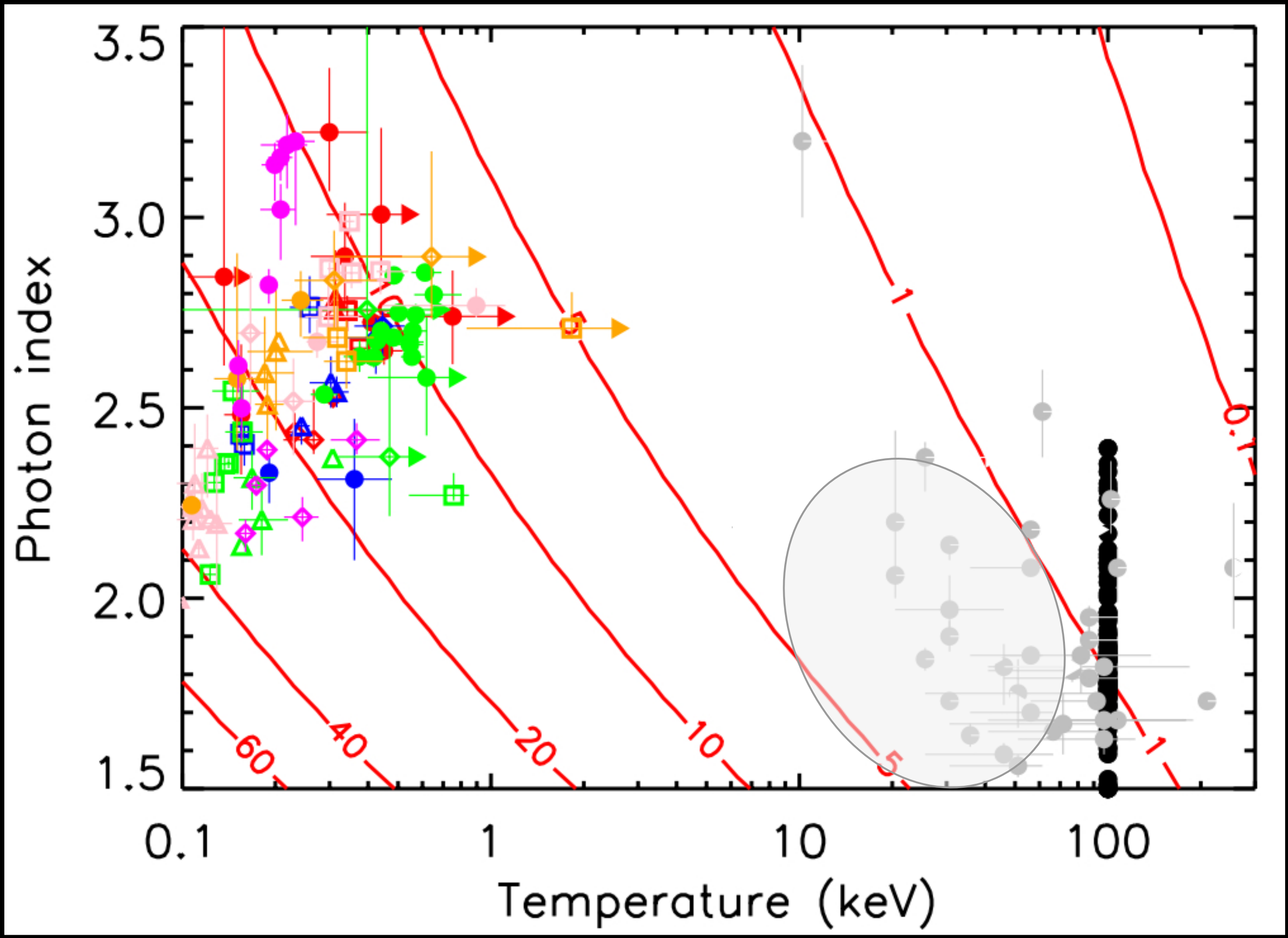
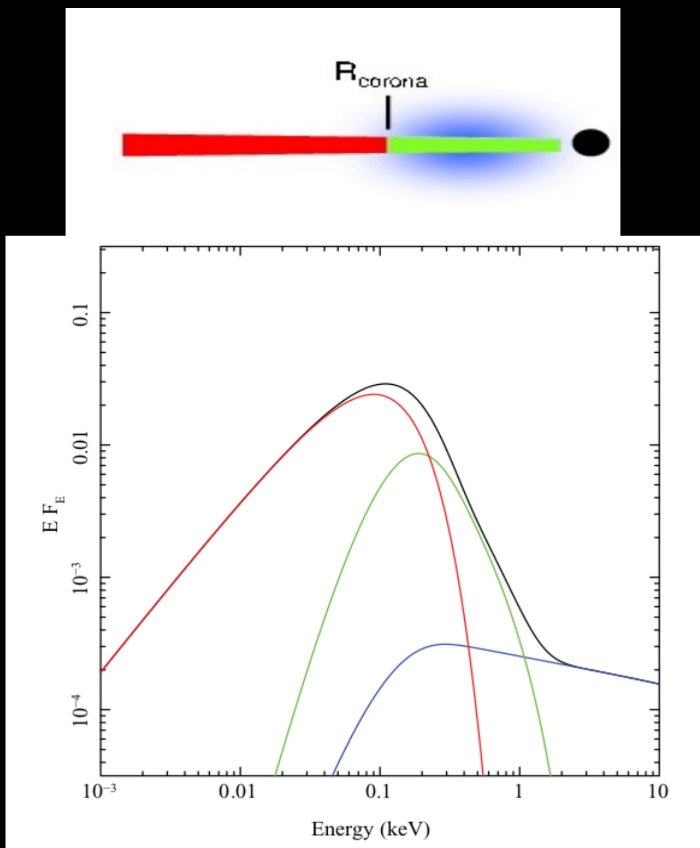


- Optical depth
- Disc intrinsic emission (low-→ patchy slab)
- Amplification factor warm (~1-3) hot (~10)

How crude is the $E_c=2kT$ approximation for hot coronae?

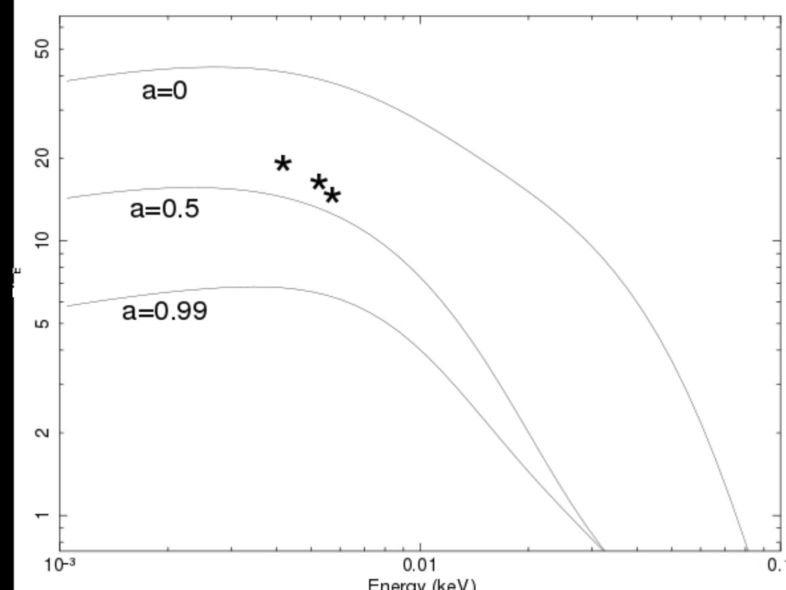
A warm + hot corona scenario

Optxagnf (Done+12) is a disc/corona emission model which assumes a thermal disk emission outside the coronal radius, and soft and hard Comptonization inside.



a	0	0.50	0.99
L/L_{Edd}	$0.16^{+0.16}_{-0.08}$	$0.05^{+0.01}_{-0.01}$	$0.04^{+0.03}_{-0.01}$
R_c (R_G)	$11.5^{+0.1}_{-3.4}$	$31.3^{+39.2}_{-16.6}$	$24.9^{+16.0}_{-15.2}$
kT (keV)	$0.33^{+0.02}_{-0.02}$	$0.32^{+0.01}_{-0.01}$	$0.32^{+0.02}_{-0.01}$
τ	$12.9^{+1.1}_{-0.9}$	$13.6^{+0.6}_{-0.2}$	$13.6^{+0.4}_{-0.7}$
Γ	$1.73^{+0.02}_{-0.02}$	$1.73^{+0.02}_{-0.02}$	$1.73^{+0.02}_{-0.02}$
E_c (keV)	>190	>190	>190

Ark 120 XMM+NuSTAR



Matt+14

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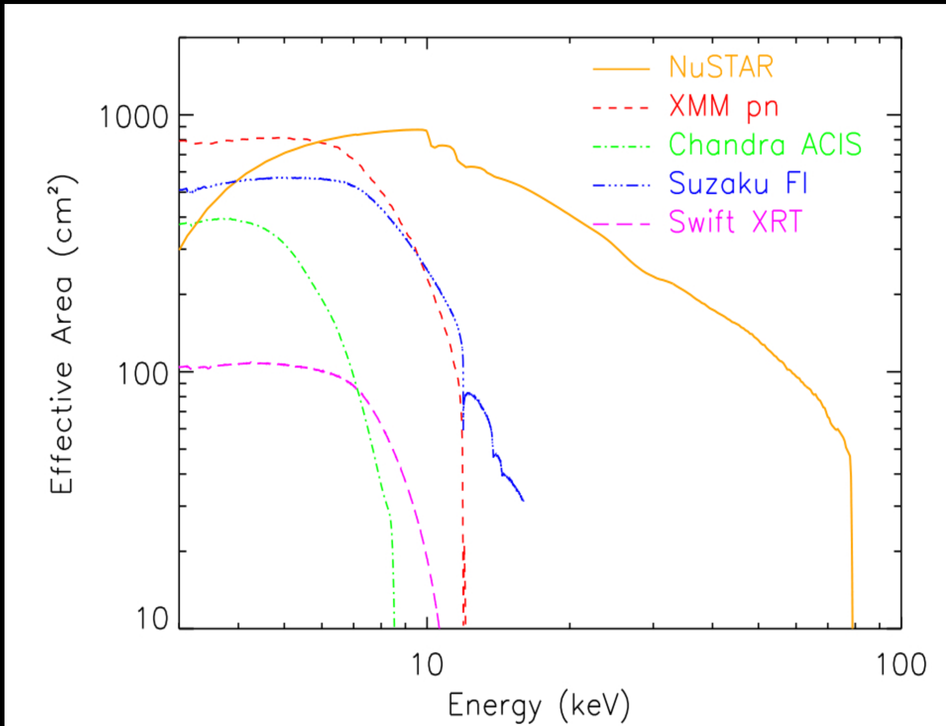
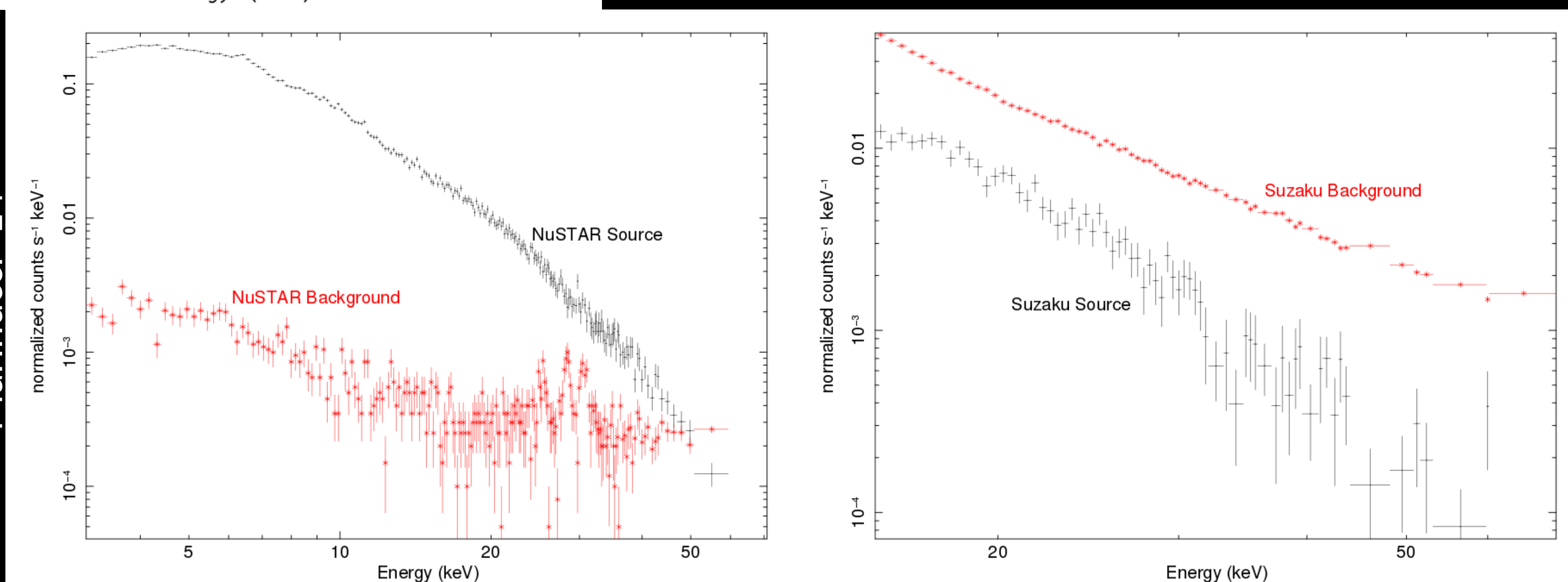
The NuSTAR era



Harrison+13

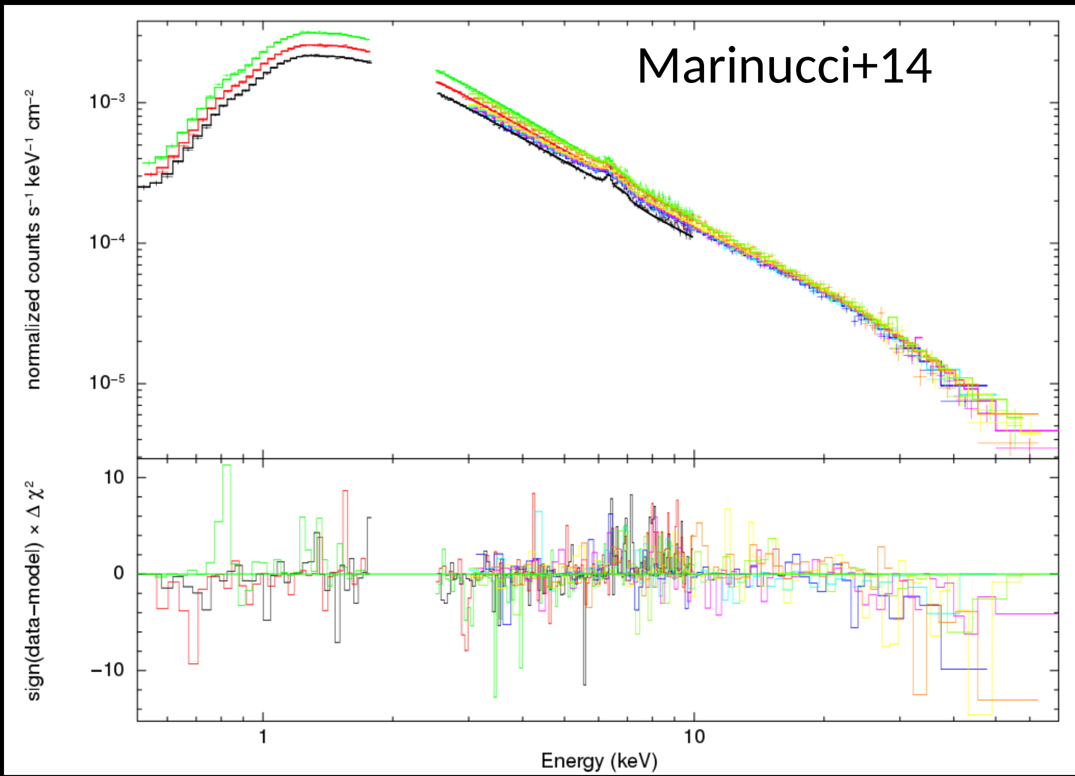
The combination of NuSTAR high effective area and low background yelds ~100x better S/N versus Suzaku HXD-PIN

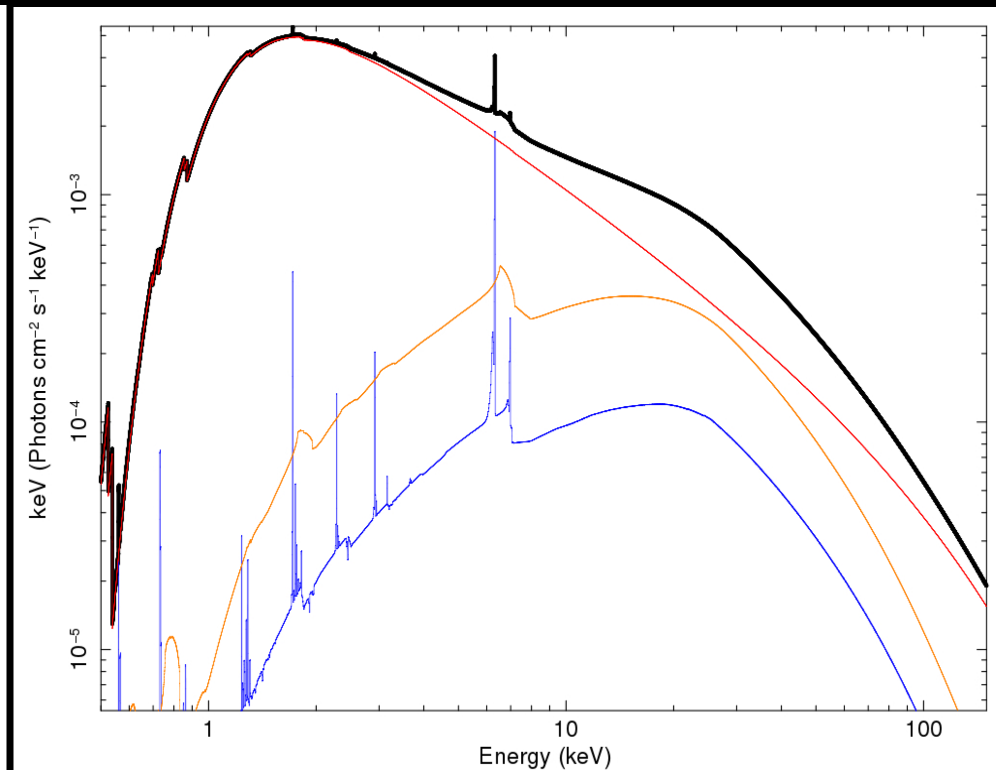


Marinucci+14

The NLS1 Swift J2127.4+5654

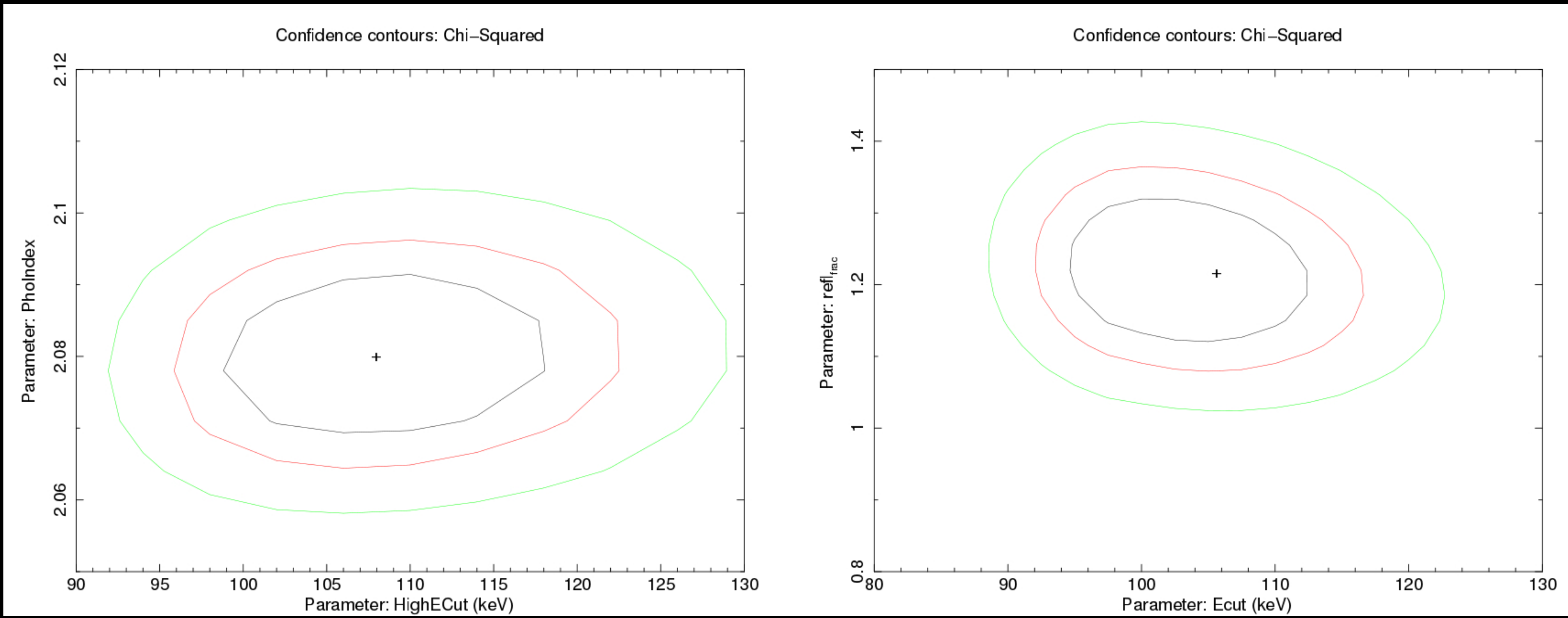
NLS1 with a relativistically broadened Fe Kα emission line (a=0.6±0.2), a steep continuum Γ=2-2.4), E_c=30-90 keV, L_{bol}/L_{Edd}~0.18 (Miniutti+09, Malizia+08, Panessa+11, Sanfrutos+13)





Each spectral component can be clearly distinguished (relativistic reflection, neutral reflection, primary continuum) and studied

The NLS1 Swift J2127.4+5654



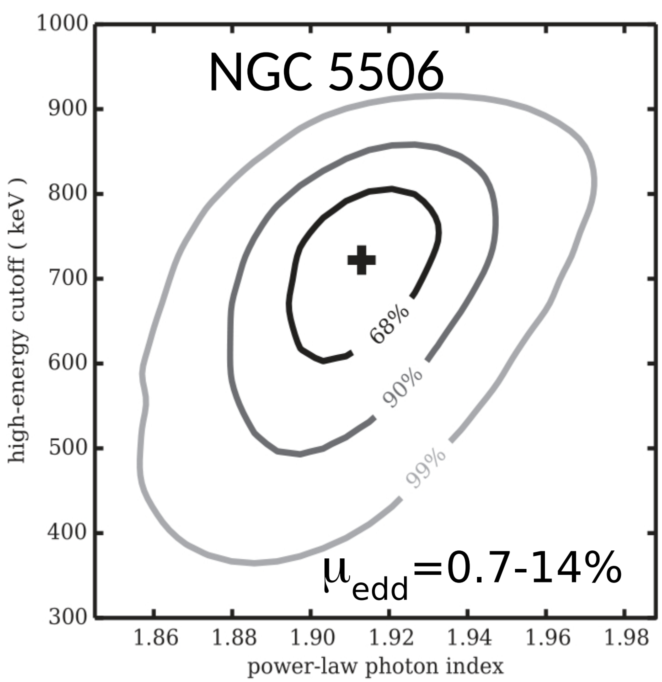
Using compTT (Titarchuk+94) with two different geometries:

SLAB	SPHERE
$kT_e=68^{+37}_{-32}$ keV	$kT_e=53^{+28}_{-26}$ keV
$\tau=0.35^{+0.35}_{-0.19}$	$\tau=1.35^{+1.03}_{-0.67}$

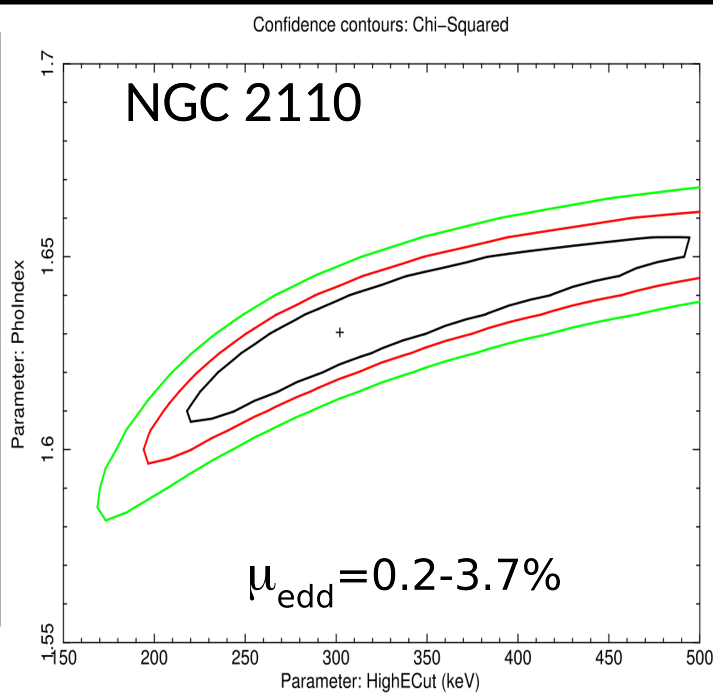
They are statistically equivalent: we are not able to distinguish between the two geometry using spectroscopy (see Matt's talk).

Do we always find a high-energy turnover?

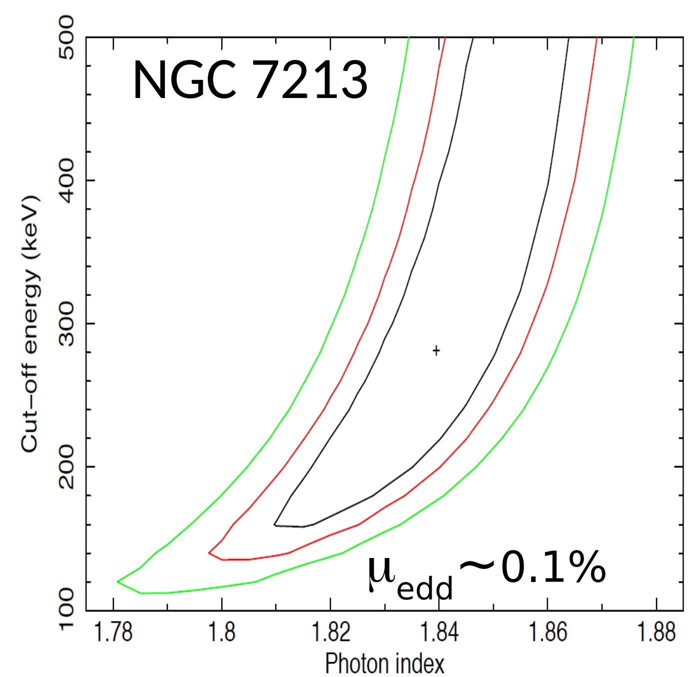
In other bright sources, high values or lower limits to the cutoff energy have been found, suggesting the presence of a very hot corona surrounding the accretion disc.



Matt+15

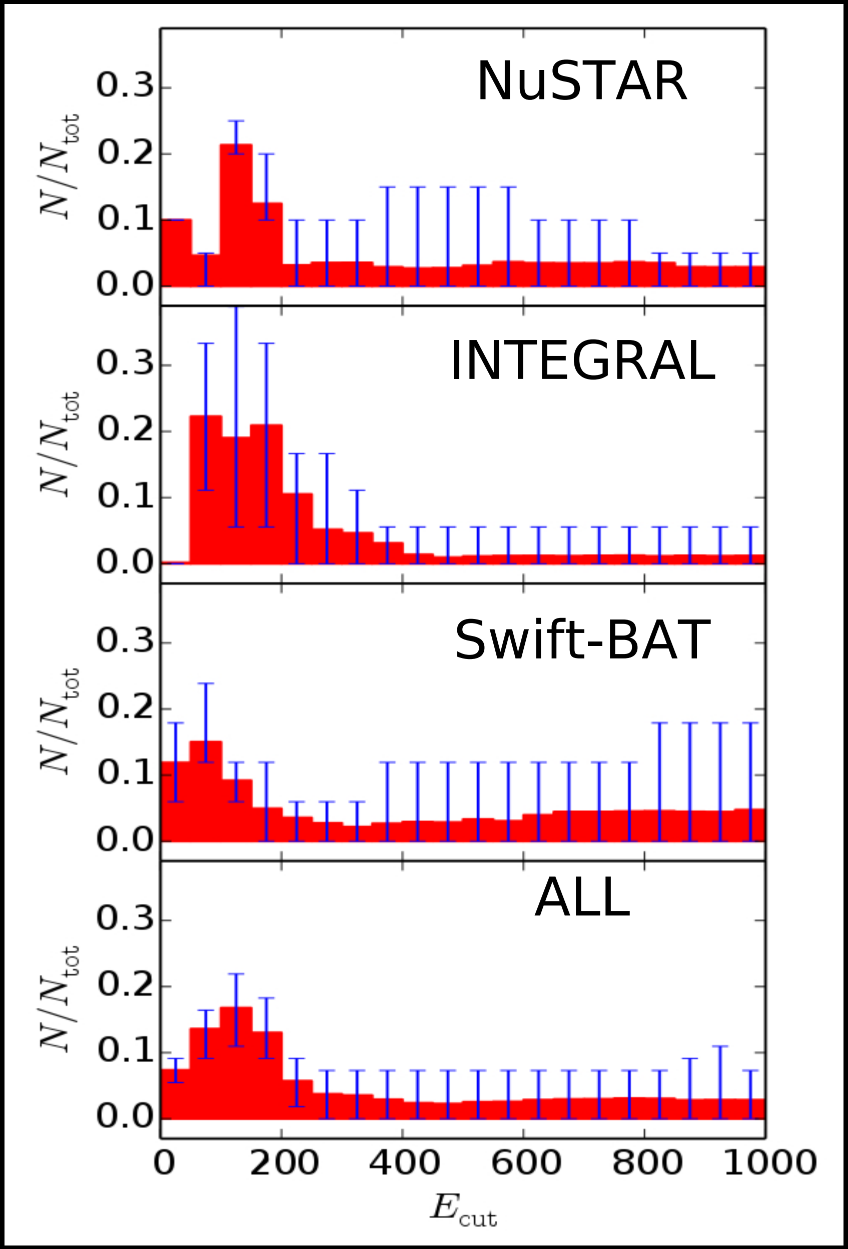


Marinucci+15

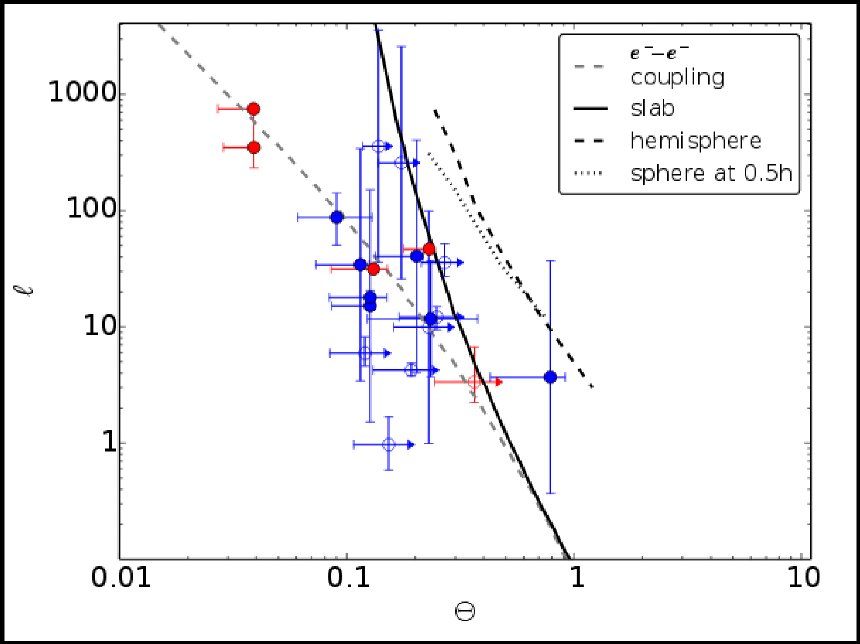


Ursini+15

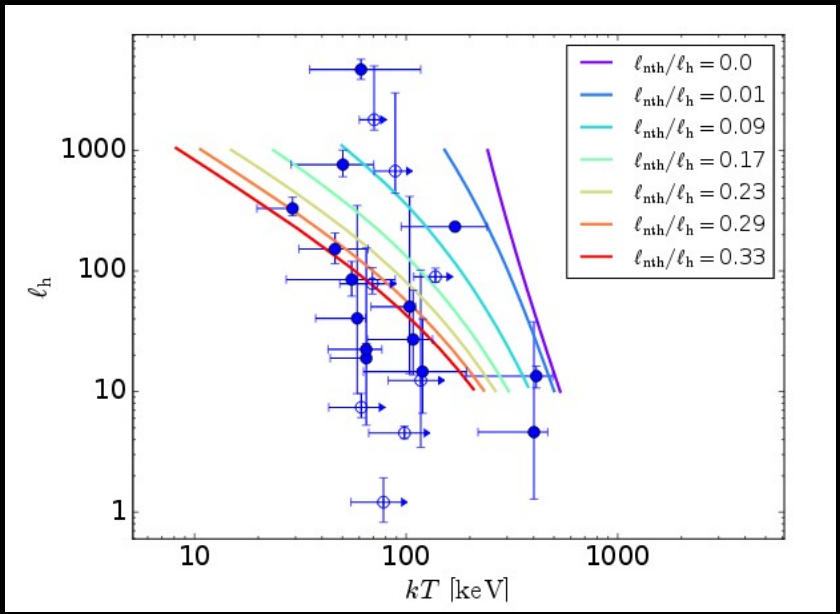
Coronal parameters in local AGN



Fabian+15



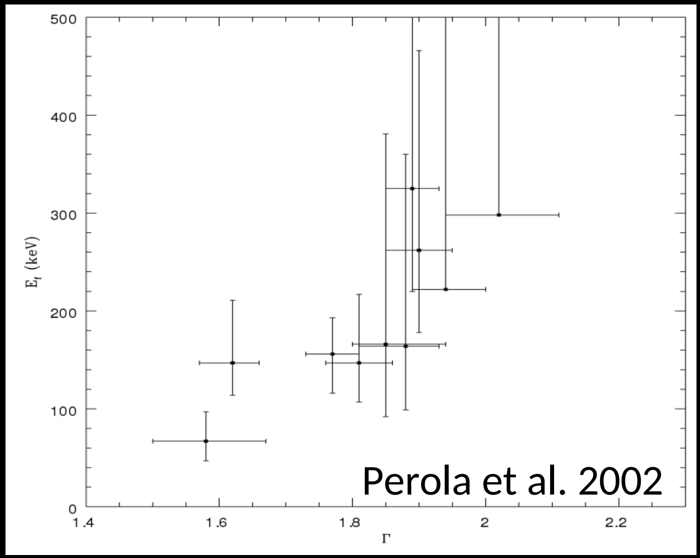
Fabian+15

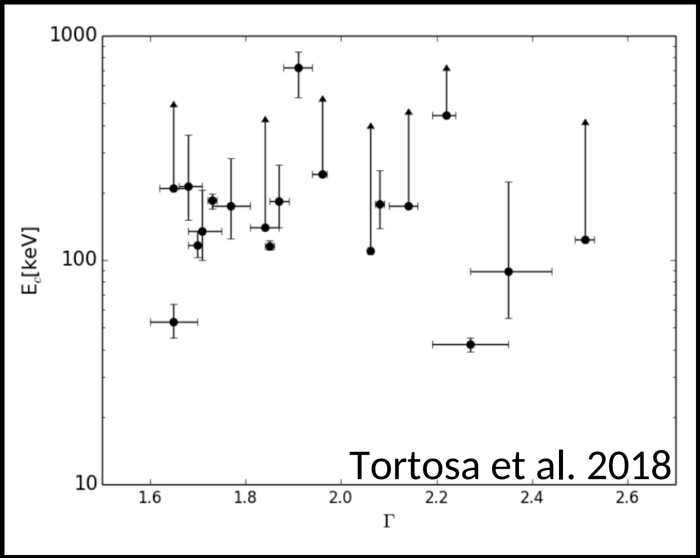


Fabian+17

Coronal parameters in local AGN

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





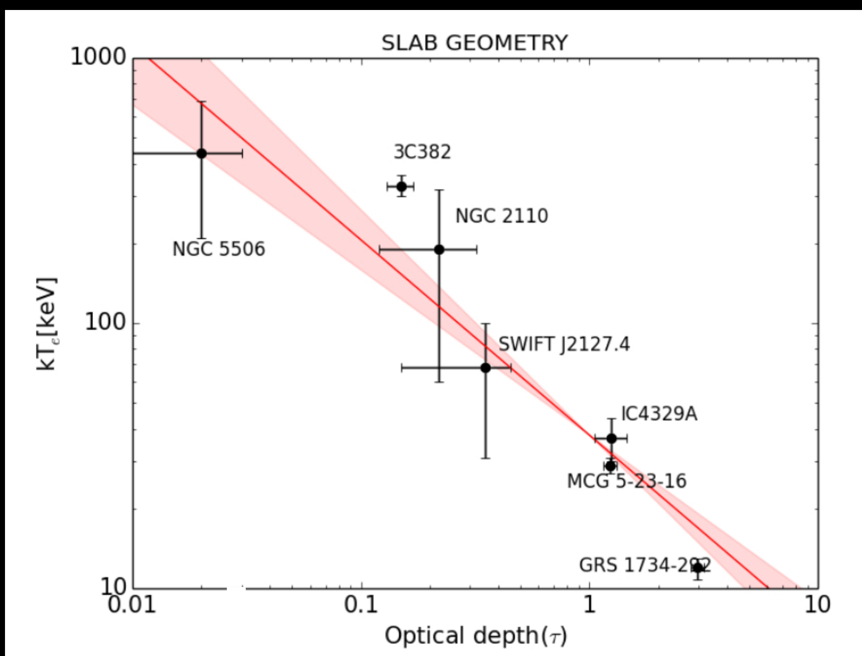
The dependance between the cutoff energy and other physical observables (BH mass, luminosity, accretion rate, etc..) has been studied.

Coronal parameters in local AGN

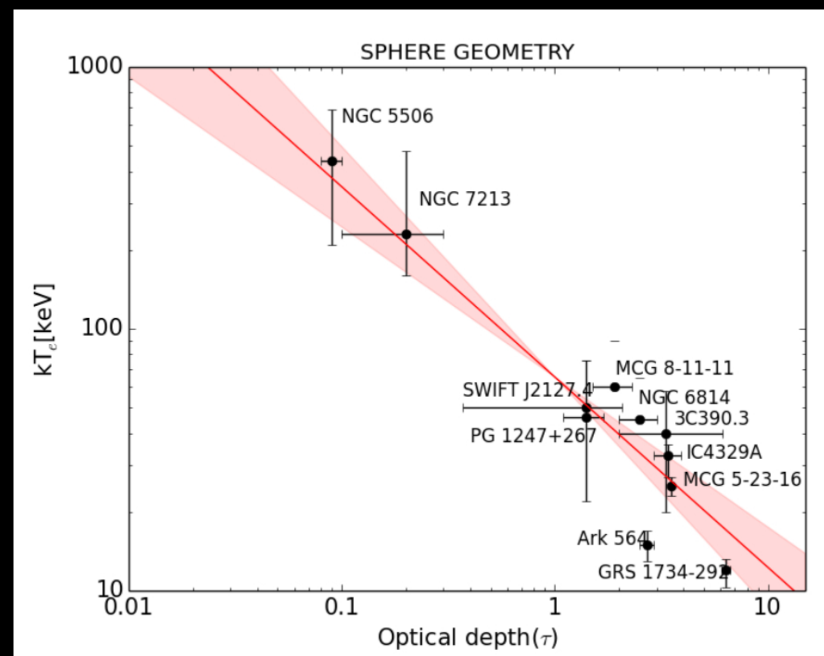
X	Y	ρ	h_0	geometry
Γ	E_c	0.18	0.47	-
$\log(M_{bh}/M_\odot)$	E_c	-0.11	0.61	-
L_{bol}/L_{Edd}	E_c	-0.14	0.56	-
τ	kT_e	-0.88	0.004	slab
τ	kT_e	-0.63	0.02	sphere
$\log(M_{bh}/M_\odot)$	τ	-0.22	0.63	slab
$\log(M_{bh}/M_\odot)$	τ	-0.26	0.46	sphere
L_{bol}/L_{Edd}	τ	0.49	0.27	slab
L_{bol}/L_{Edd}	τ	0.38	0.28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

Tortosa et al. 2018

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



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



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

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From FERO 8 to FERO 9

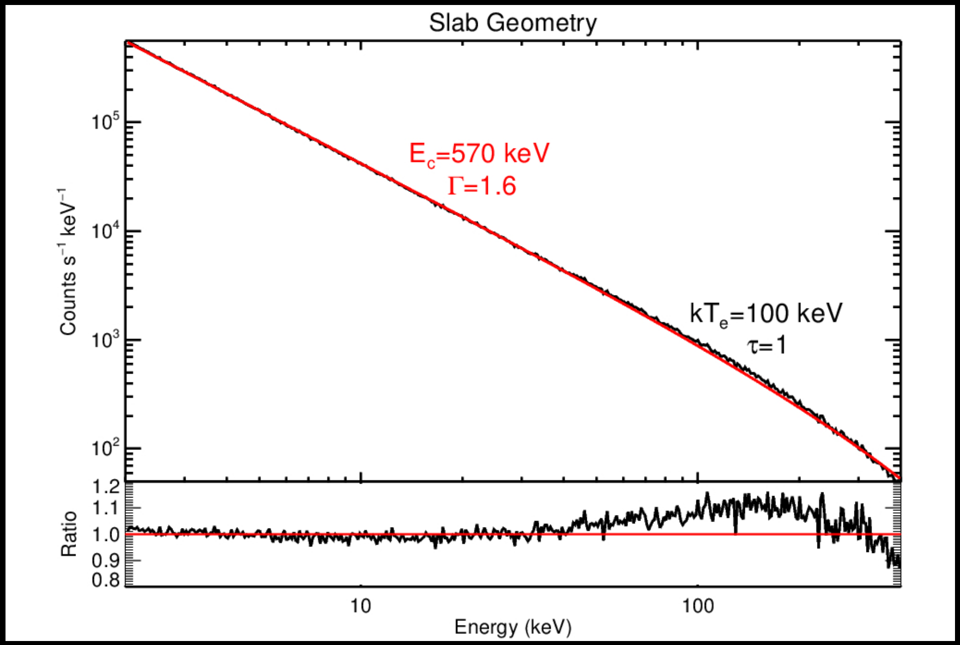
Two questions from Vinice Hnanice:

"How do we translate the observed cutoff energies and photon indices into physical quantities?"

"Any variability and relation to the broad Iron component?"
(i.e. does the accretion disc notice if something happens to the corona?)

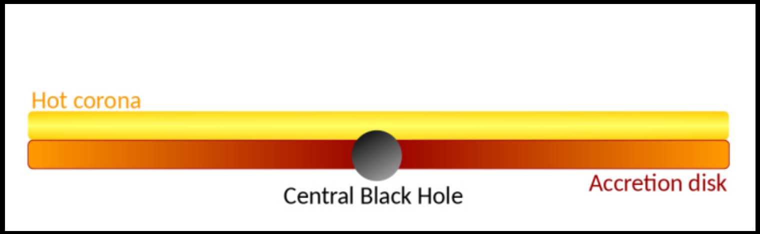
A MC code for accretion in Astrophysics

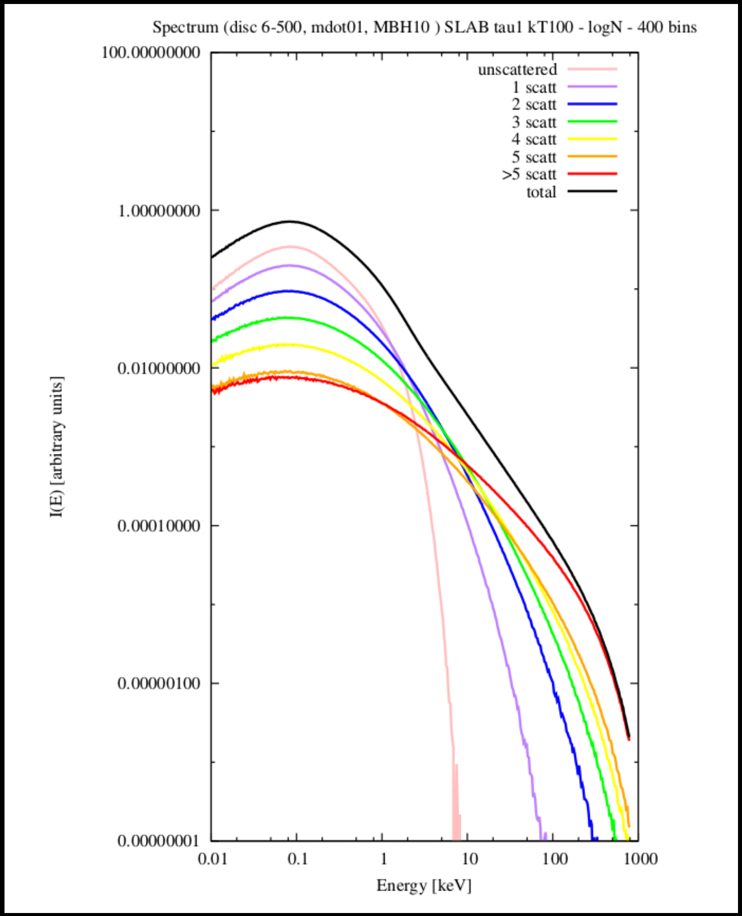
MoCA has been used to produce synthetic spectra for different ranges of temperatures and optical depth to retrieve the observed parameters (see Tamborra's and Middei's talks).



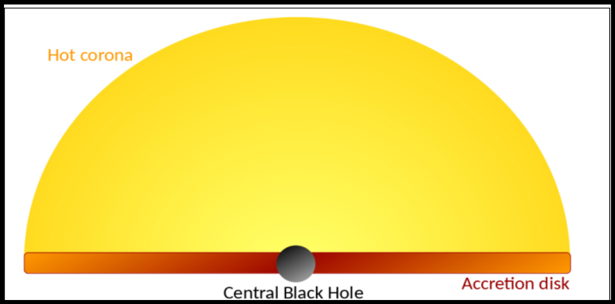
Middei et al., in prep.

$M_{bh}=10^8 M_{sun}$; $\dot{m}=0.1$, $kT_e=100$ keV; $\tau=1$





Tamborra+, submitted



The bare AGN Ark 120

Matt+2013
- Soft X-ray excess due to Comptonization
- No relativistic Iron Kα detected

Reeves+2016 (Paper I)
- XMM RGS data analyzed and N_H inferred
- Several emission lines ass

Nardini+2016 (Paper II)
- Chandra HETGS analyzed and more complex Iron Kα structure revealed
- Accretion disk hotspots originating at 6

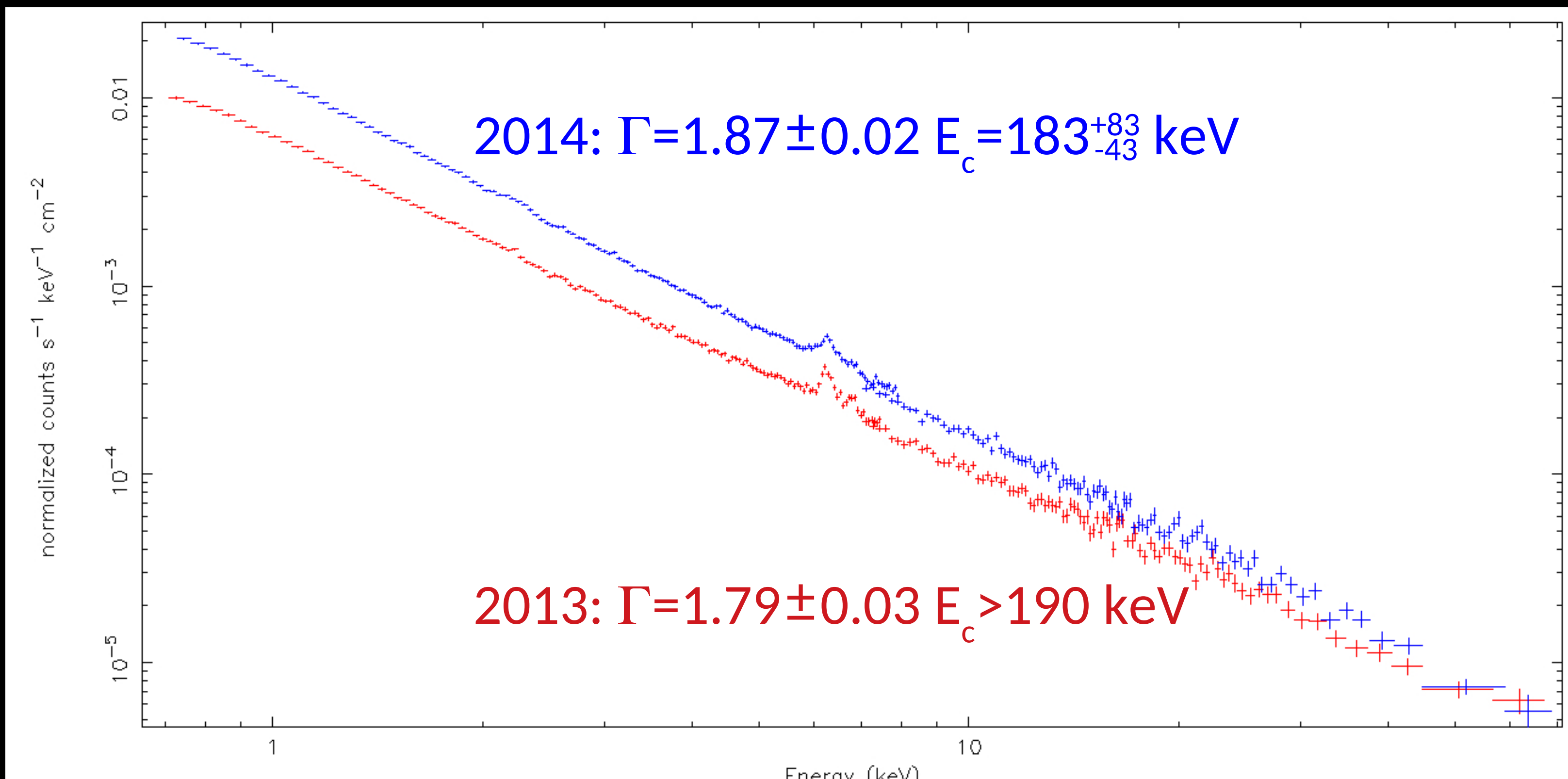
Lobban+2017 (Paper III)
- Timing analysis of the XMM EPIC-pn data
- Previous findings are confirmed

Porquet+2017 (Paper IV)
- Comprehensive study of the XMM/NuSTAR 2014 campaign
- Warm+Hot Comptonization, relativistic ref

Porquet, in prep (Paper V)
- see Porquet's talk

The bare AGN Ark 120

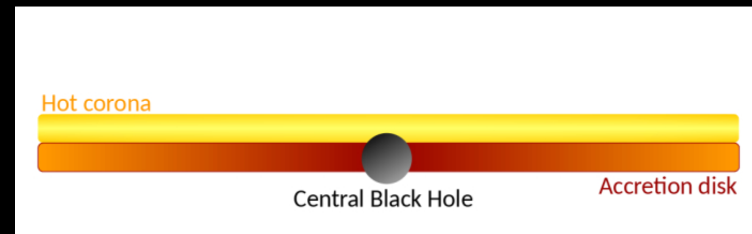
A significant steepening has been observed in the 2014 XMM/NuSTAR spectra: our aim is to investigate the hot coronal component.
The warm Comptonization is found to be variable only in terms of relative normalizations, while kT and τ are compatible (kT=0.5 keV, τ=10).

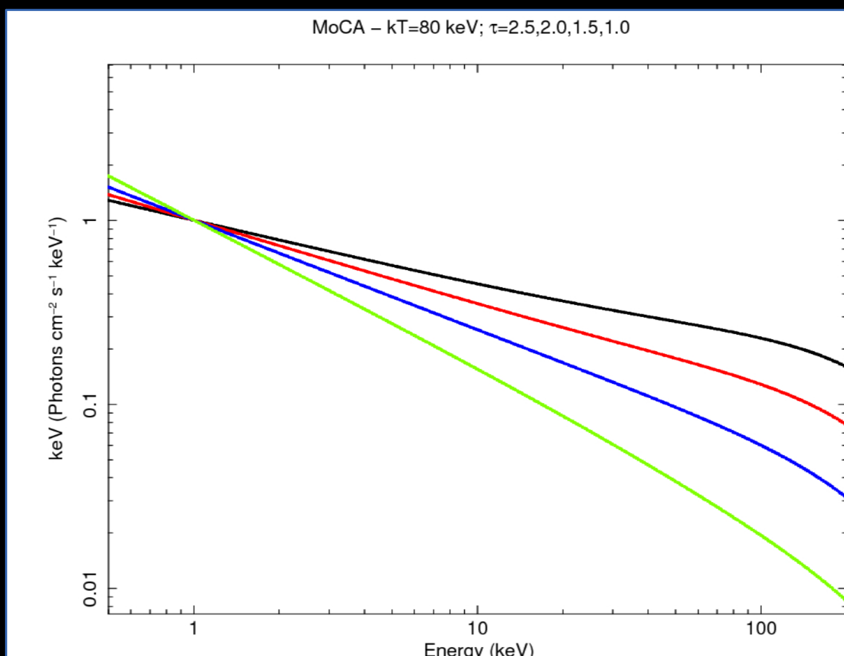


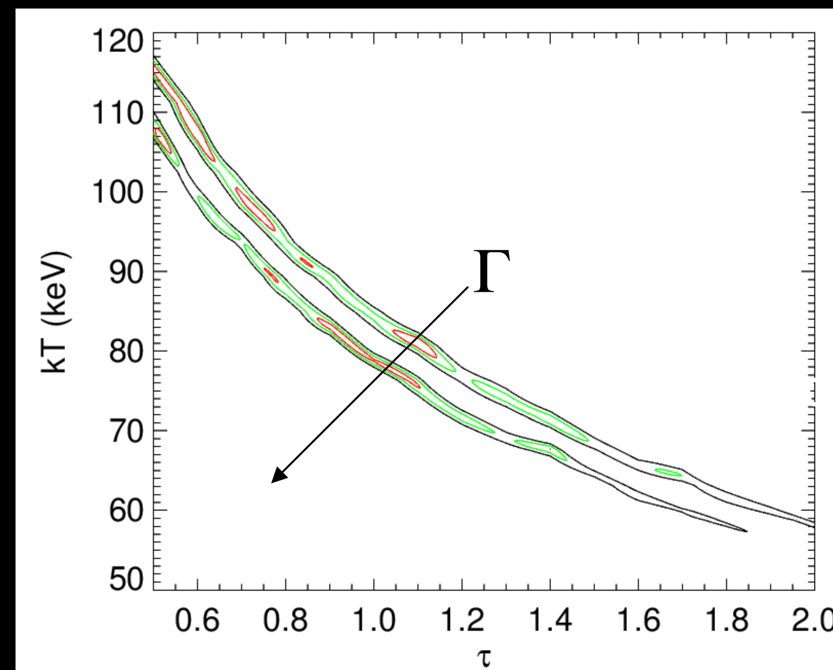
Paper VI, in prep.

The bare AGN Ark 120

MoCA-generated tables are converted into an XSPEC model and applied to the XMM+NuSTAR data

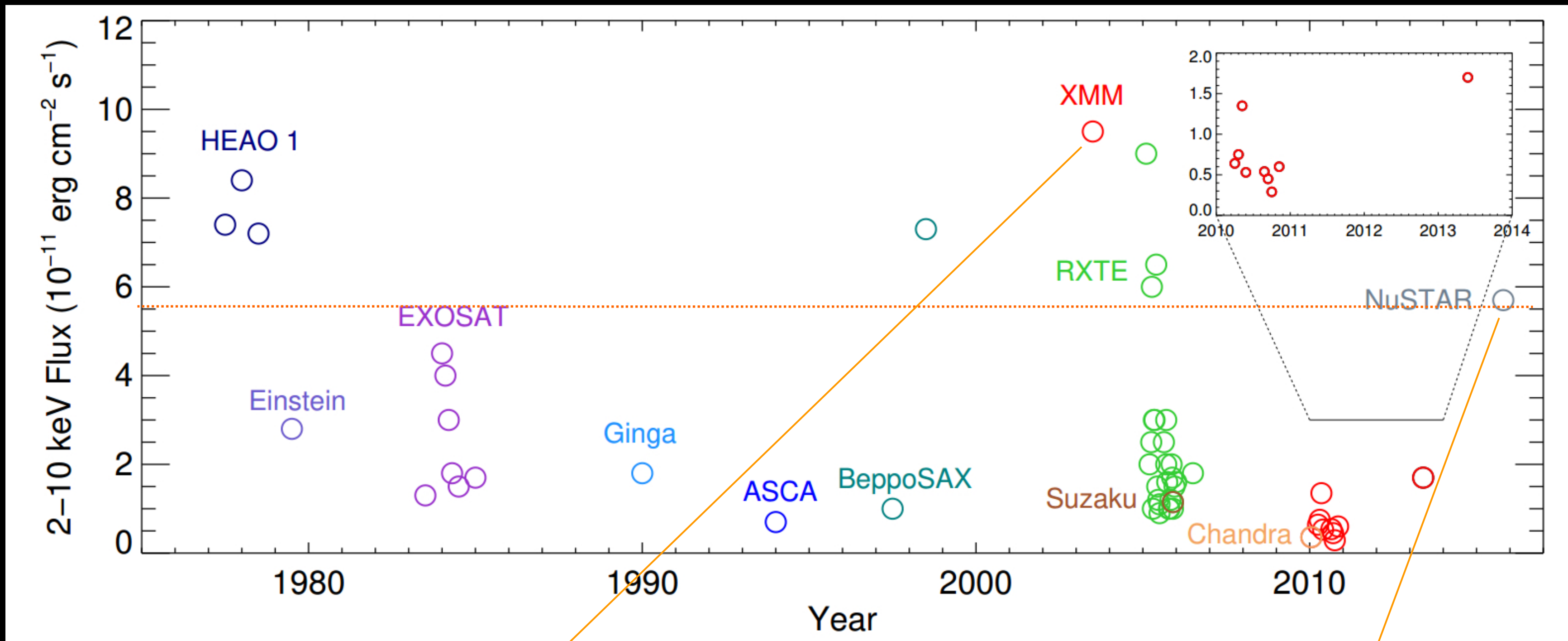




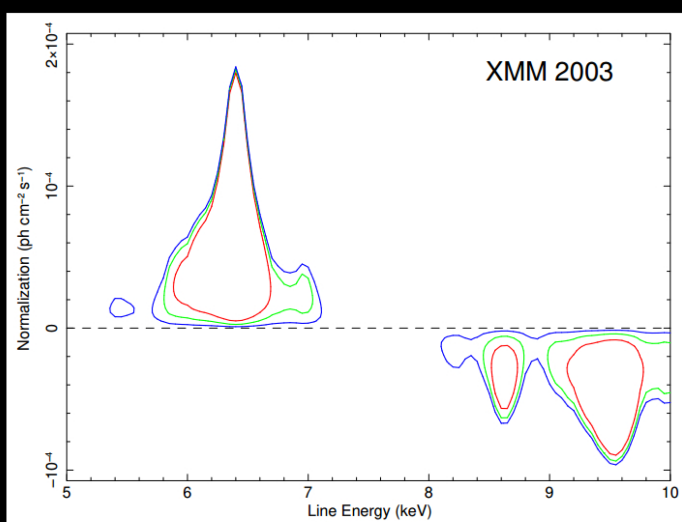


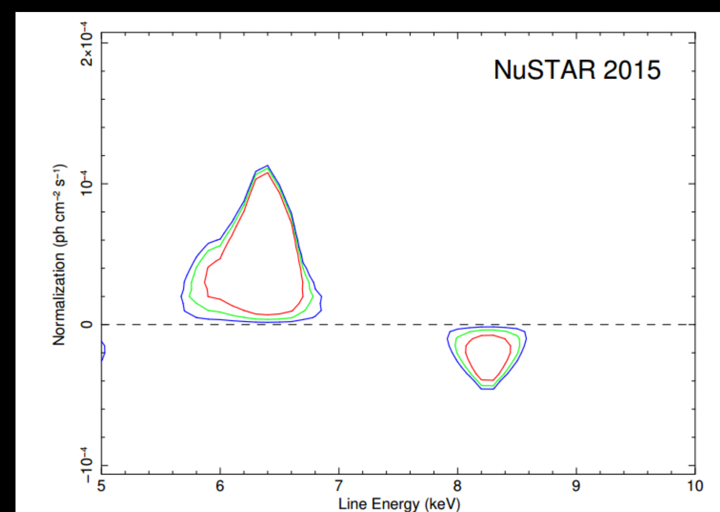
The next step is to try different geometries and play with the radius of the corona (see Porquet's talk).

NGC 2992 – a lively accretion disc



Marinucci+subm.





Outline

- Introduction

- High-energy cutoff measurements

- One corona, two coronae ...

- The NuSTAR era and beyond

- Conclusions

Conclusions

- The soft X-ray excess in AGN requires, in addition or alternatively to blurred reflection, a warm coronal component (Done+12, Jin+12, Petrucci+00,13,18, Matt+14)

- We have accurate measurements of high-energy cutoff in ~25 nearby AGN (Fabian+15,+17; Tortosa+18)

- Theoretical efforts have been spent on relating such physical observables (mainly Γ and Ec) to the intrinsic properties of the corona (Tamborra, Middei,)

- There seems to be an observational connection between the variation of the coronal parameters and the accretion disc winds and broad line (Ark 120, NGC 2992, ...)

	Energy (keV)	Flux (10^{-5} ph cm^{-2} s^{-1})	EW (eV)	Significance σ	v_{out}/c	$\Delta\chi^2$/dof
2015	$8.26^{+0.09}_{-0.12}$	-1.8 ± 0.8	-45 ± 20	2.6	0.21 ± 0.01	-9/2
2003	8.61 ± 0.05	-2.2 ± 1.2	-40 ± 25	2.7	0.209 ± 0.006	-9/2
	9.27 ± 0.10	-2.0 ± 1.3	-45 ± 30	1.9	0.31 ± 0.01	-8/2
	9.57 ± 0.06	-3.3 ± 1.3	-70 ± 25	3.6	0.307 ± 0.006	-26/2

	$\log N_H$ (cm^{-2})	$\log U$	v_{out}/c	$\dot{M}_{out}$ (g·s^{-1})	$\dot{E}_k$ (erg·s^{-1})	$\dot{p}_{out}$ (g·cm·s^{-2})
2015	22.25 ± 0.25	2.45 ± 0.25	0.21 ± 0.01	3.5×10^{23}	6.9×10^{42}	2.2×10^{33}
2003	$23.35^{+1.10}_{-0.55}$	> 3.1	0.215 ± 0.005	3.8×10^{24}	7.9×10^{43}	2.5×10^{34}
	$23.35^{+0.15}_{-0.40}$	$3.40^{+0.40}_{-0.15}$	0.305 ± 0.005	2.7×10^{24}	1.1×10^{44}	2.4×10^{34}