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Spectroscopy and polarimetry of X-ray coronae in AGN

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Many thanks to: ***A. Marinucci, F. Ursini, …***

Plan of the talk

- **The primary X-ray emission: the hot corona**

  Physical parameters: spectroscopy
  Geometry: polarimetry

- **The X-ray soft excess: warm coronae?**

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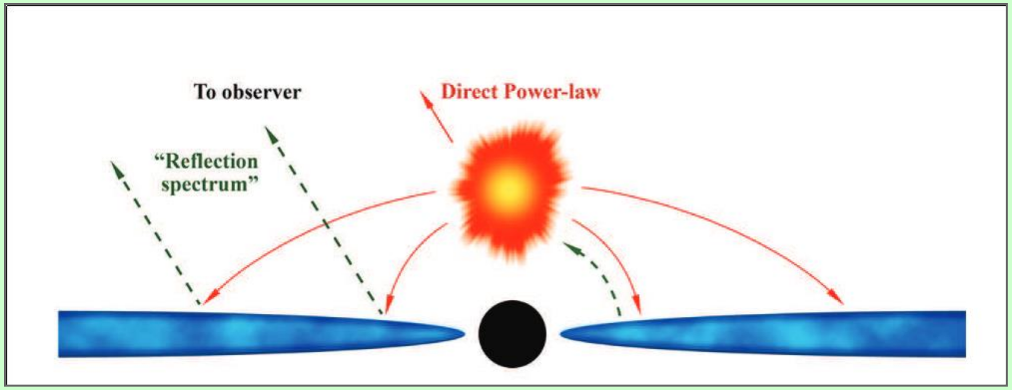
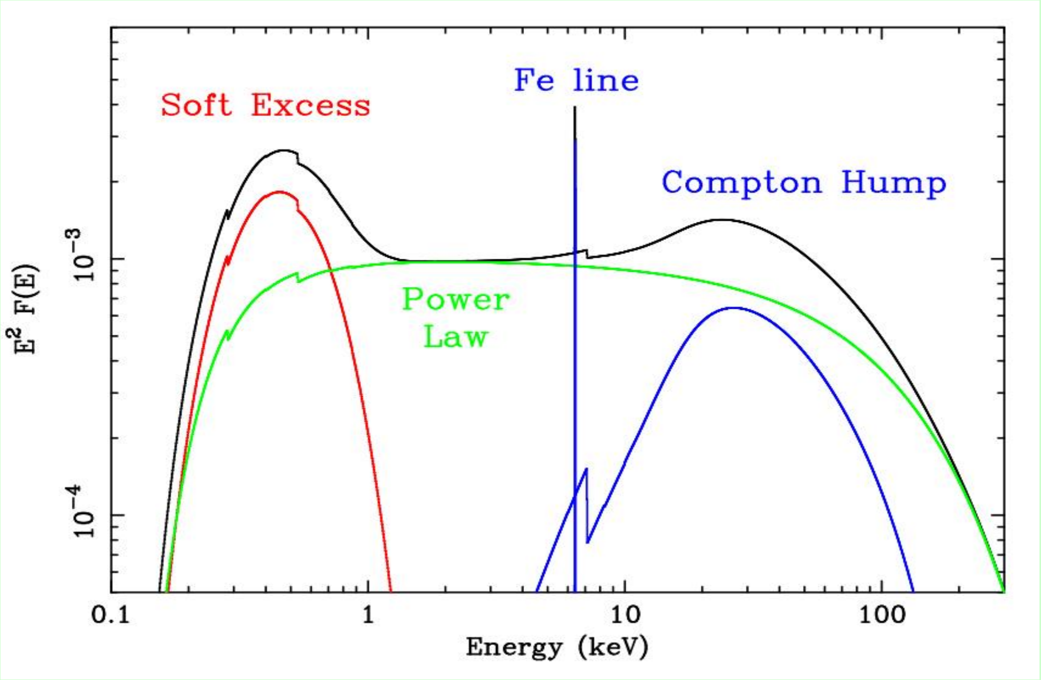
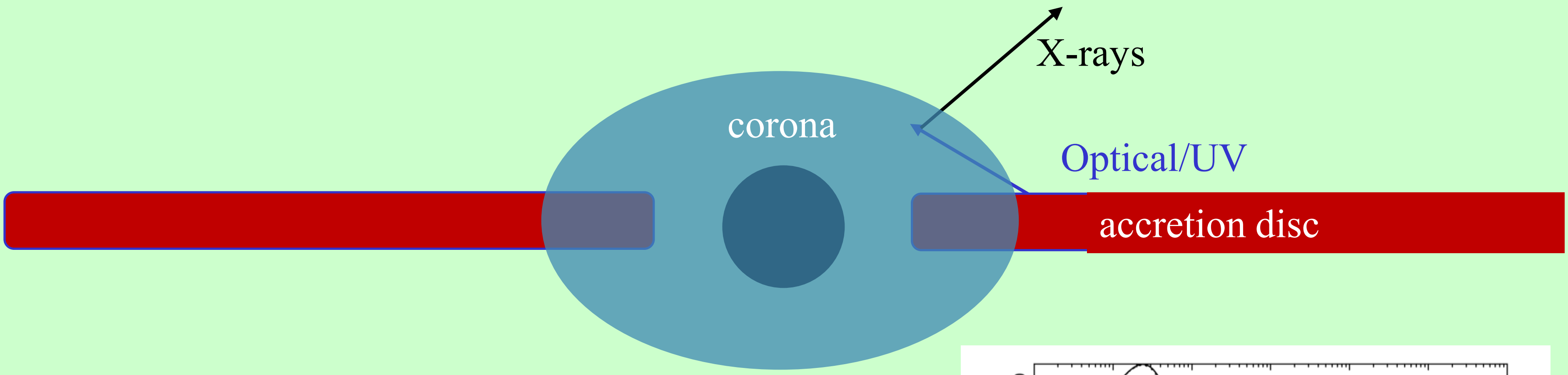
The X-ray spectrum of AGN

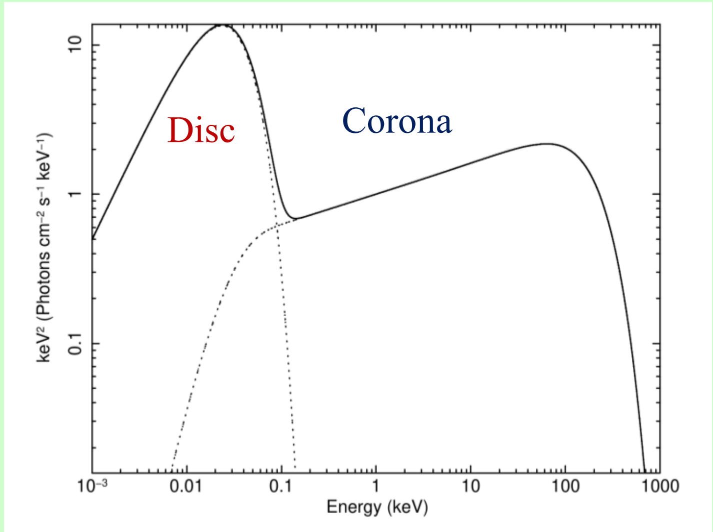




The hot corona

The primary X-ray emission is due to Comptonization by electrons in a hot corona of the UV/soft X-ray disc photons (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991, Poutanen and Svensson 1996, …)



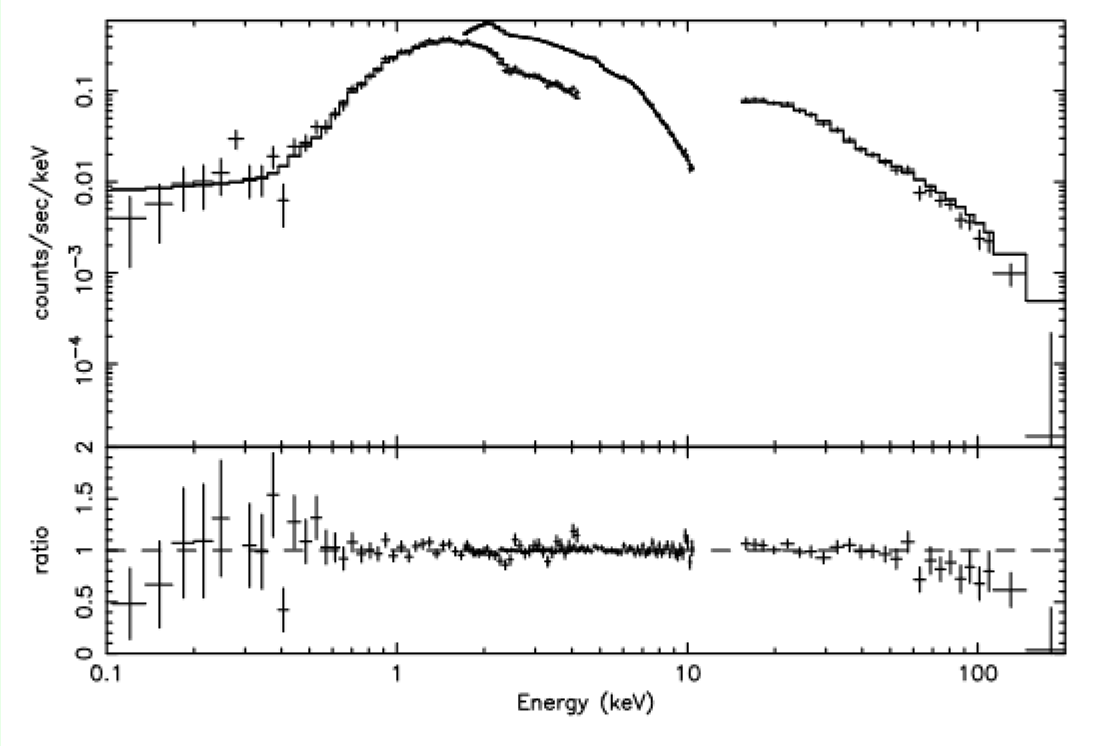


Cutoff power law $F_E \sim E^{-\Gamma} \exp(-E/Ec)$

$\Gamma = \Gamma(kT,\tau)$, while Ec depends on kT

After a first pioneering measurement on NGC4151 with OSSE/GRO (Johnson et a, 1993), E_c measurements on a sample of bright AGN were performed with 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}



IC 4329A - Perola et al. 1999

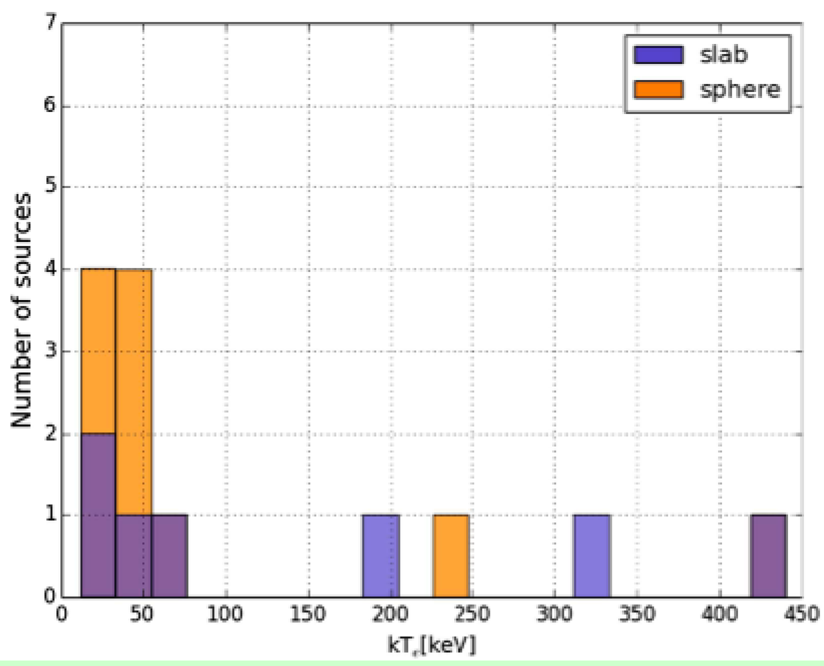
More results from XMM-INTEGRAL (e.g. Molina et al. 2013), Swift and Suzaku (e.g. Ricci et al. 2017)

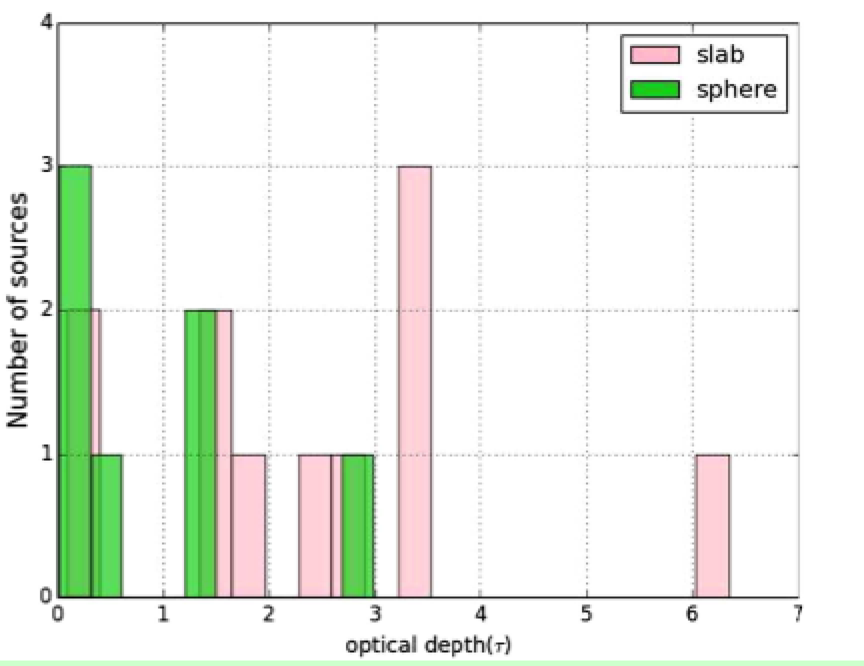
With NuSTAR (launched in 2012) - the first focusing telescope in hard X-rays – the quality and quantity of good measurements increased dramatically. Physical parameters (kt,τ) can be directly measured.

In fact, for the first time, the spectra – at least for relatively bright objects – are source- (and not bkg-) dominated.

Correlations between the spectral parameters and other properties of the sources (BH mass, luminosity, accretion rate, etc..) could finally be investigated.

Tortosa et al. 2018



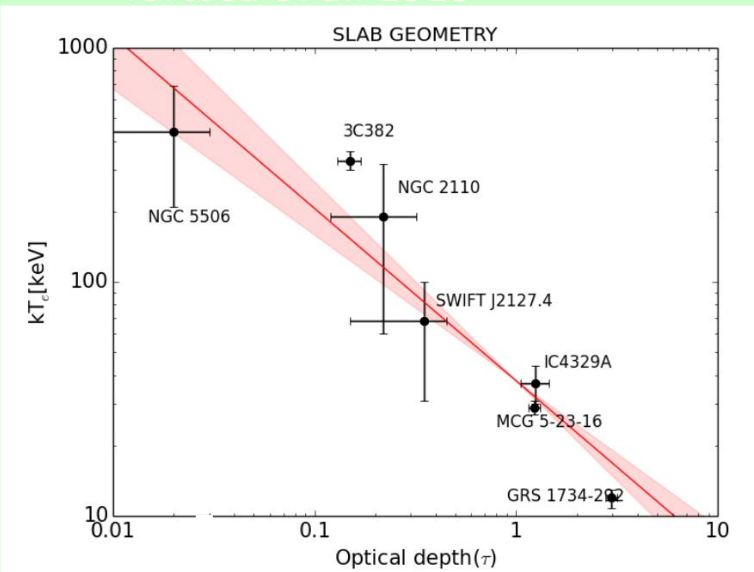


X	Y	ρ	h_0	geometry
Γ	E_c	0.18	0.47	-
$\log(M_{bh}/M_\odot)$	E_c	-0.11	0.61	-
L_{bol}/L_{Edd}	E_c	-0.14	0.56	-
τ	kT_e	-0.88	0.004	slab
τ	kT_e	-0.63	0.02	sphere
$\log(M_{bh}/M_\odot)$	τ	-0.22	0.63	slab
$\log(M_{bh}/M_\odot)$	τ	-0.26	0.46	sphere
L_{bol}/L_{Edd}	τ	0.49	0.27	slab
L_{bol}/L_{Edd}	τ	0.38	0.28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

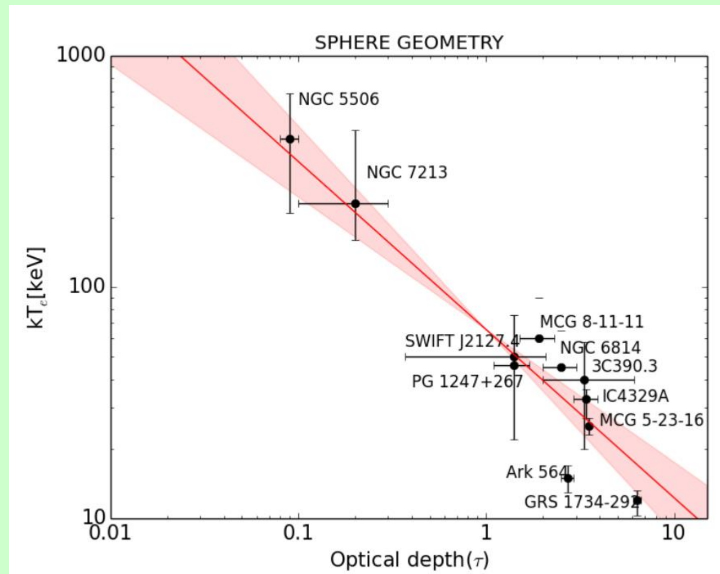
Tortosa et al. (2018) investigated the properties of the brightest 19 AGN observed by NuSTAR.

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

Tortosa et al. 2018

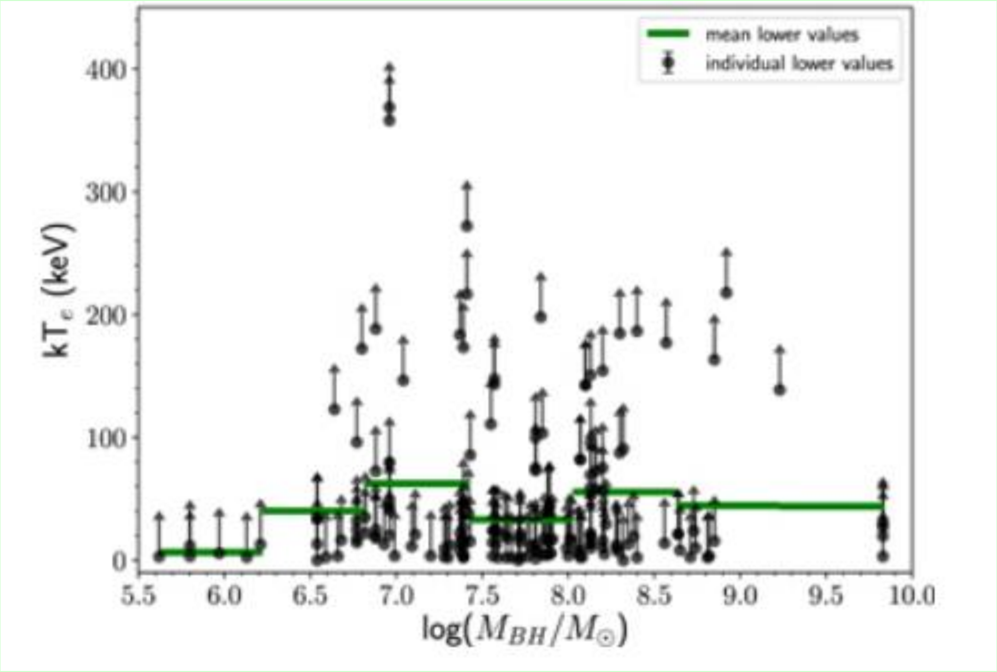


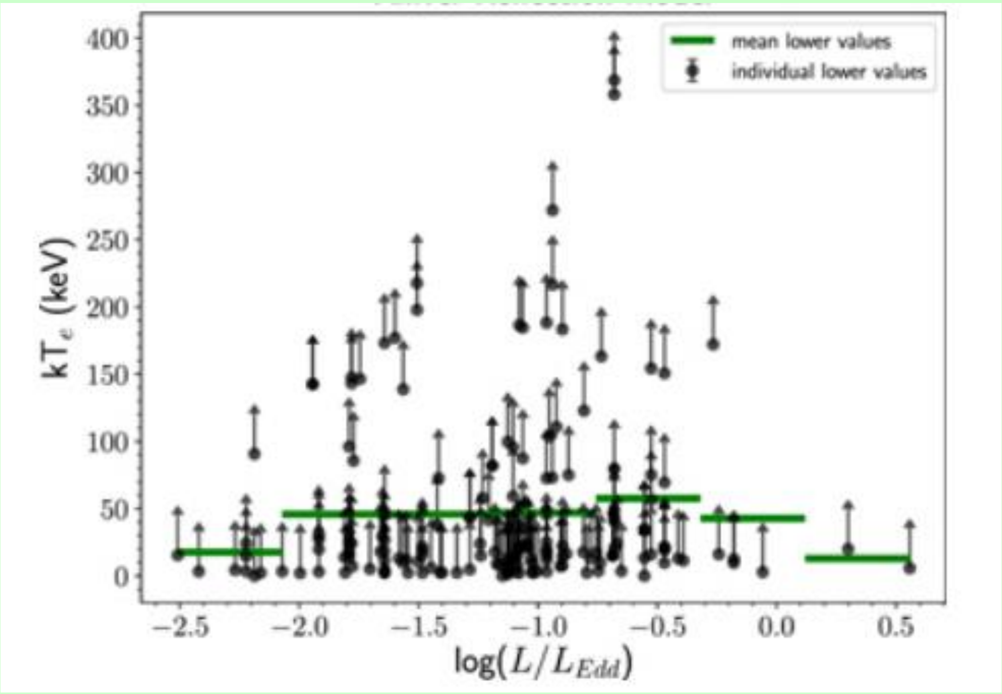
$$\log(kT_e) = (-0.7 \pm 0.1)\log(\tau) + (1.60 \pm 0.06)$$



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

These results were later confirmed in a much larger sample by Kamraj et al. (2022): no correlation found between Γ or Ec with BH mass and accretion rate.



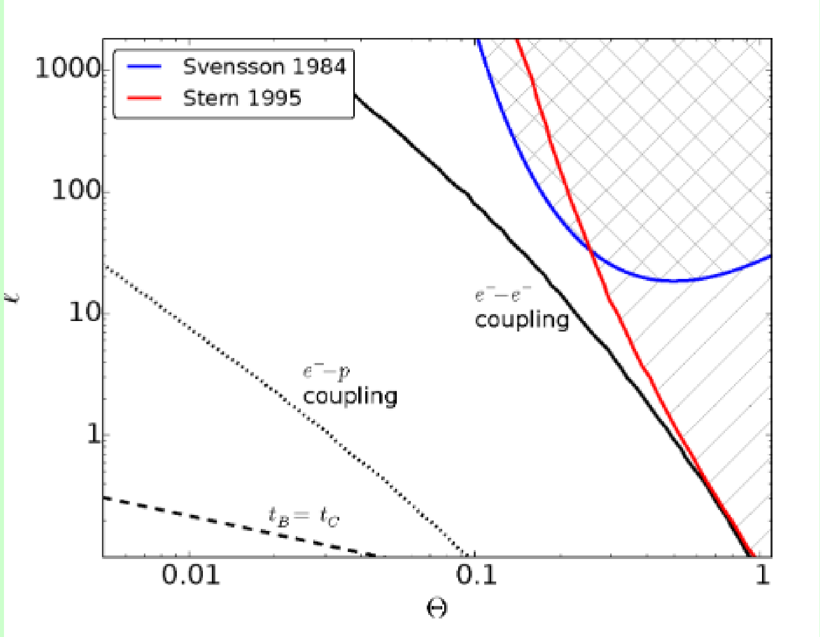


Kamraj et al. 2022

An important parameter in the hot corona is the ratio between luminosity and size, usually described by the dimensionless compactness parameter (Cavaliere & Morrison 1980; Guilbert, Fabian & Rees 1983)

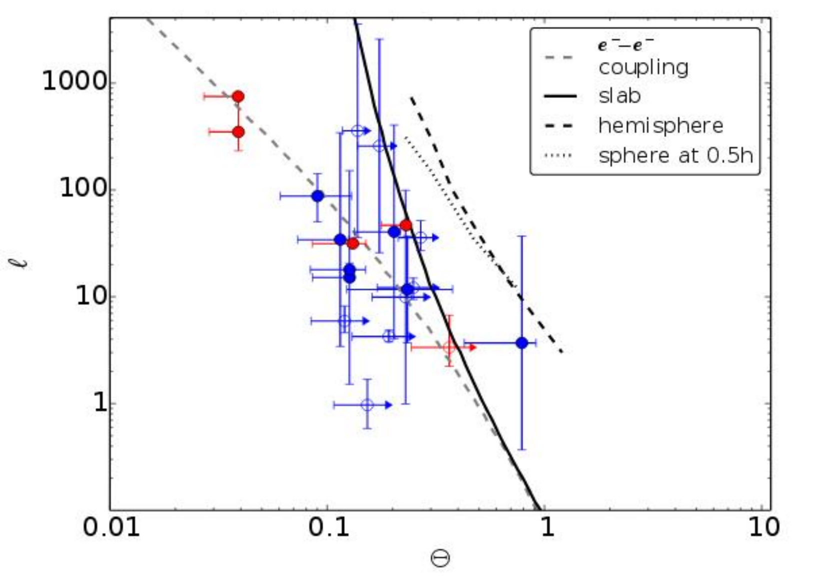
$$\ell = 4\pi \frac{m_{\rm p}}{m_{\rm e}} \frac{R_{\rm g}}{R} \frac{L}{L_{\rm E}}.$$

When the temperature increases, pair production starts to be important, affecting the emission from the corona (e.g. Svensson 1982, Zdziarski 1985). The pair density is proportional to L and kT and inversely proportional to the size. A runaway process occurs, limiting the maximum plasma temperature



In the l-Θ plane, this translates into the existence of a forbidden region (e.g. Svensson 1984, Stern et al. 1985)

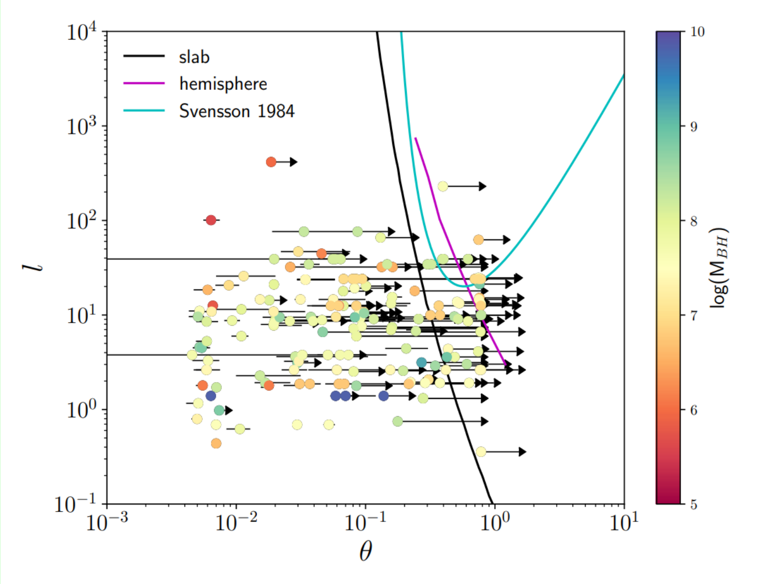
$$\Theta = kT_{\rm e}/m_{\rm e}c^2$$



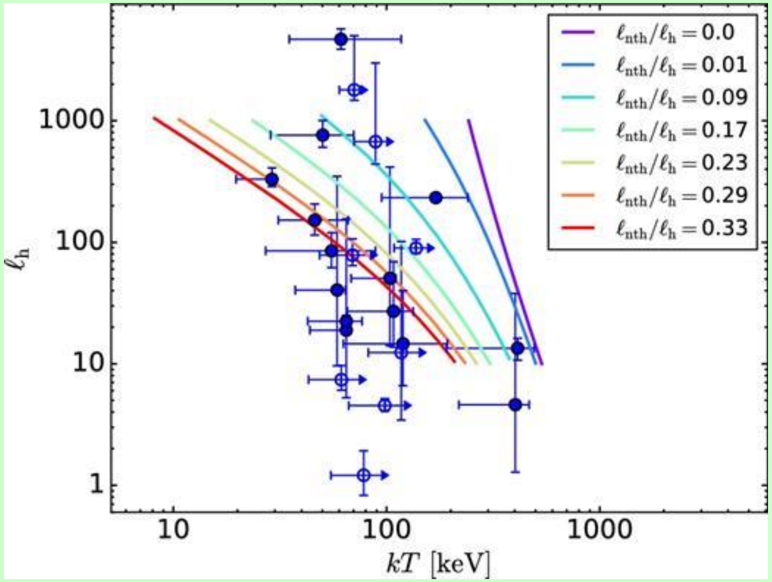
Fabian et al. 2015

Observations broadly agree with this scenario.

Possible presence of a (small) non-thermal fraction of electrons (hybrid plasma) may explain the large range in temperatures (e.g. Fabian et al. 2017)



Kamraj et al. 2022



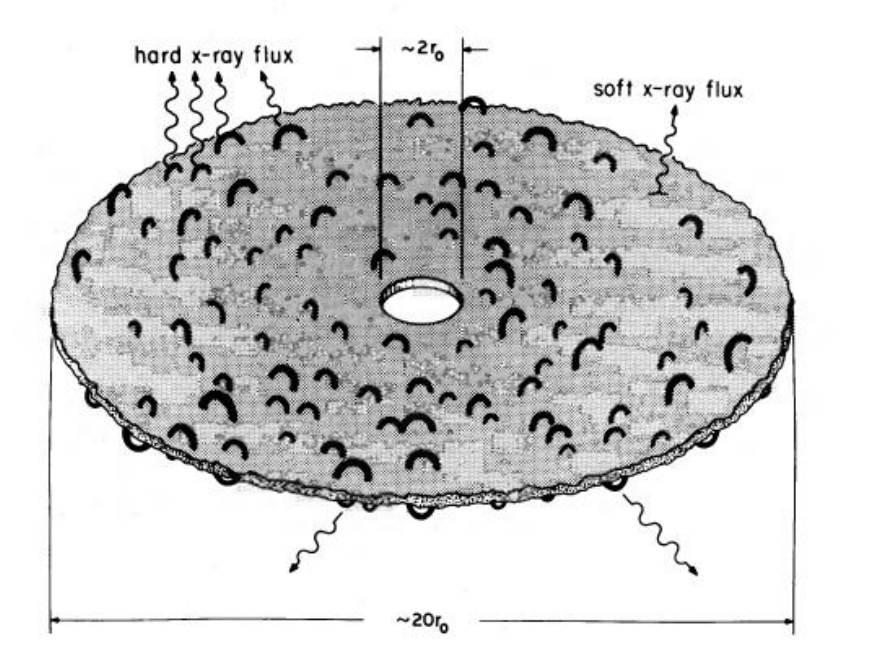
Fabian et al. 2017

Compton cooling time in the hot corona is very short – even shorter than the light crossing time if l > a few. Need for a continuous energy supply to the corona.

Energy supplied to electrons probably by magnetic field (e.g. Galeev, Rosner & Vaiana 1979; Merloni & Fabian 2001). As a consequence, synchrotron processes likely to play an important role in the coronal emission:

Thermalization
("Synchrotron Boiler", e.g. Ghisellini, Guilbert & Svensson 1988)

SSC radiation
(e.g. Veledina, Vurm & Poutanen 2011)



Galeev, Rosner & Vaiana 1979

The geometry of the hot corona

X-ray spectroscopy can constrain the physical parameters of the corona.

However, it is almost insensitive – at least in the fitting procedure - to its shape and location.

This is sad, because the coronal geometry is likely related to its physical origin.

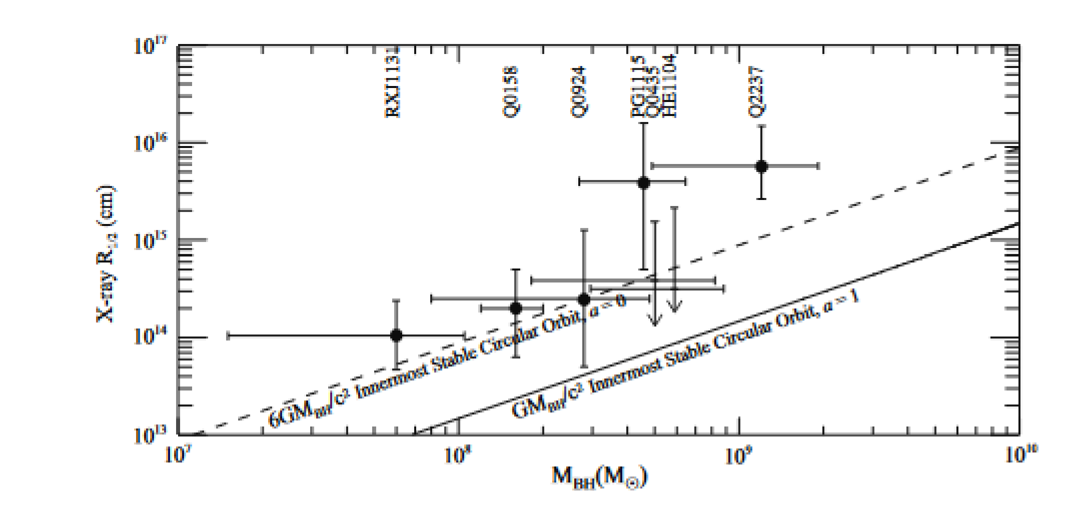
MCG -5-23-16

(Balokovic et al 2015)

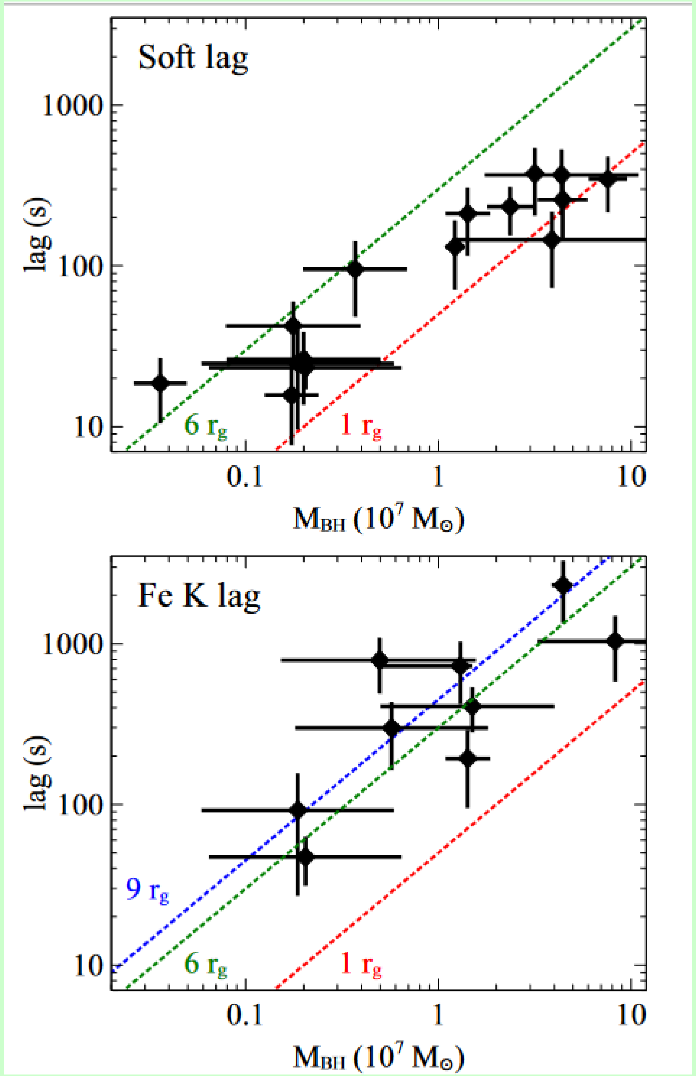
Comptonized continuum model: compPS		
Assumed corona geometry: slab		
χ^2	1159	690
R	0.65 ± 0.05	0.83 ± 0.09
kT_e (keV)	26 ± 2	26 ± 3
τ_e	2.2 ± 0.1	2.2 ± 0.2
Assumed corona geometry: sphere		
χ^2	1161	691
R	0.69 ± 0.04	0.89 ± 0.08
kT_e (keV)	25 ± 2	25 ± 3
τ_e	3.2 ± 0.2	3.3 ± 0.3

The size of the hot corona

For sure, the hot corona is small (a few tens of gravitational radii at most) as deduced from time variability, X-ray reverberation, microlensing.

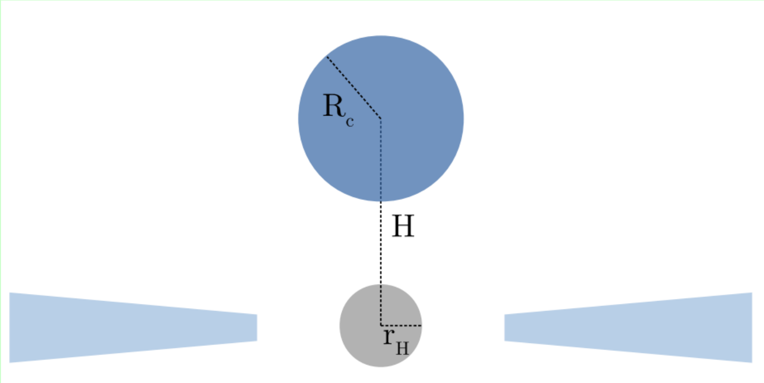


Chartas et al. 2016

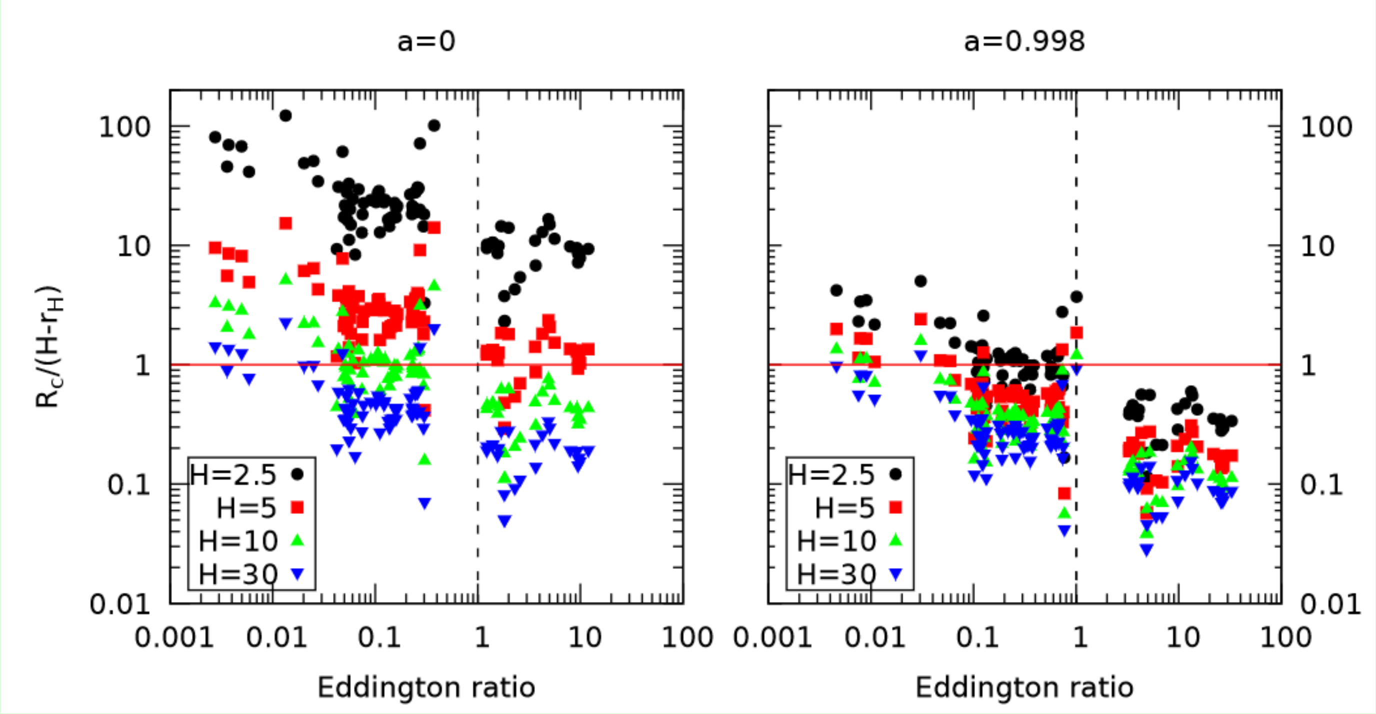


De Marco et al. 2013,
Uttley et al. 2014

Geometry: «the lamppost»

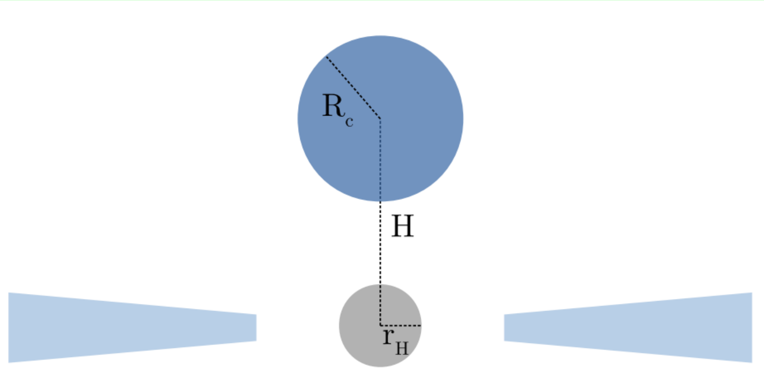


Size of the corona self-consistently calculated based on the UV and X-ray fluxes (Dovčiak & Done 2016, Ursini et al. 2020)

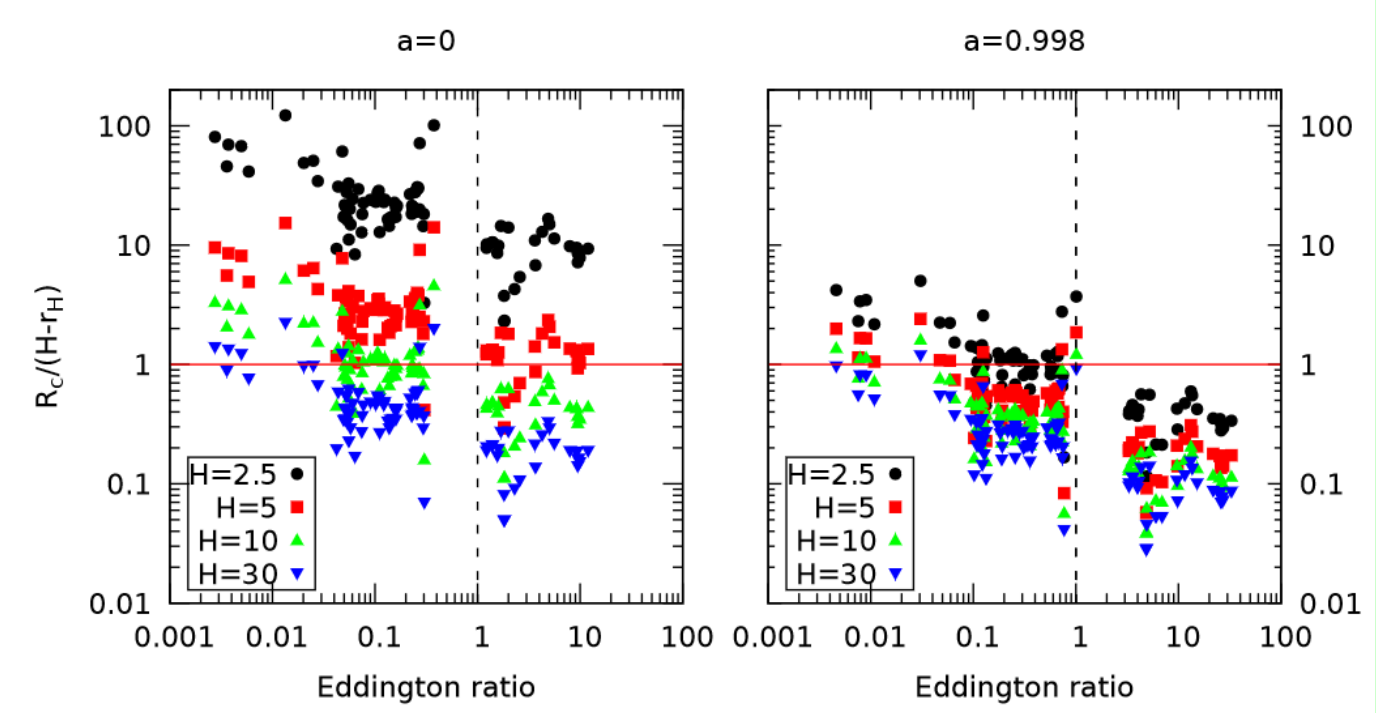


Ursini et al. 2020

Geometry: «the lamppost»

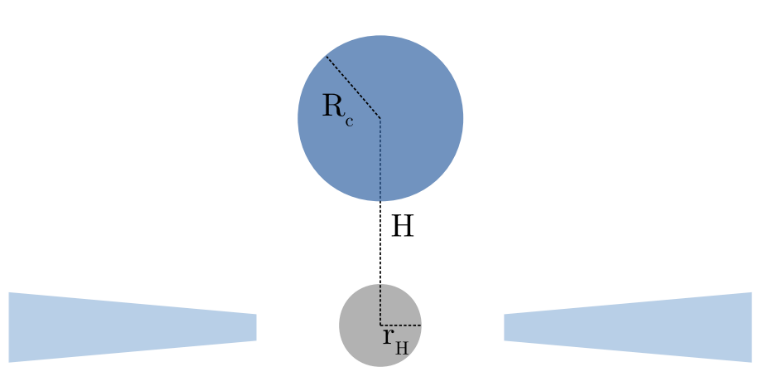


Viable solutions found only for relatively large heights, expecially for non-spinning BHs



Ursini et al. 2020

Geometry: «the lamppost»



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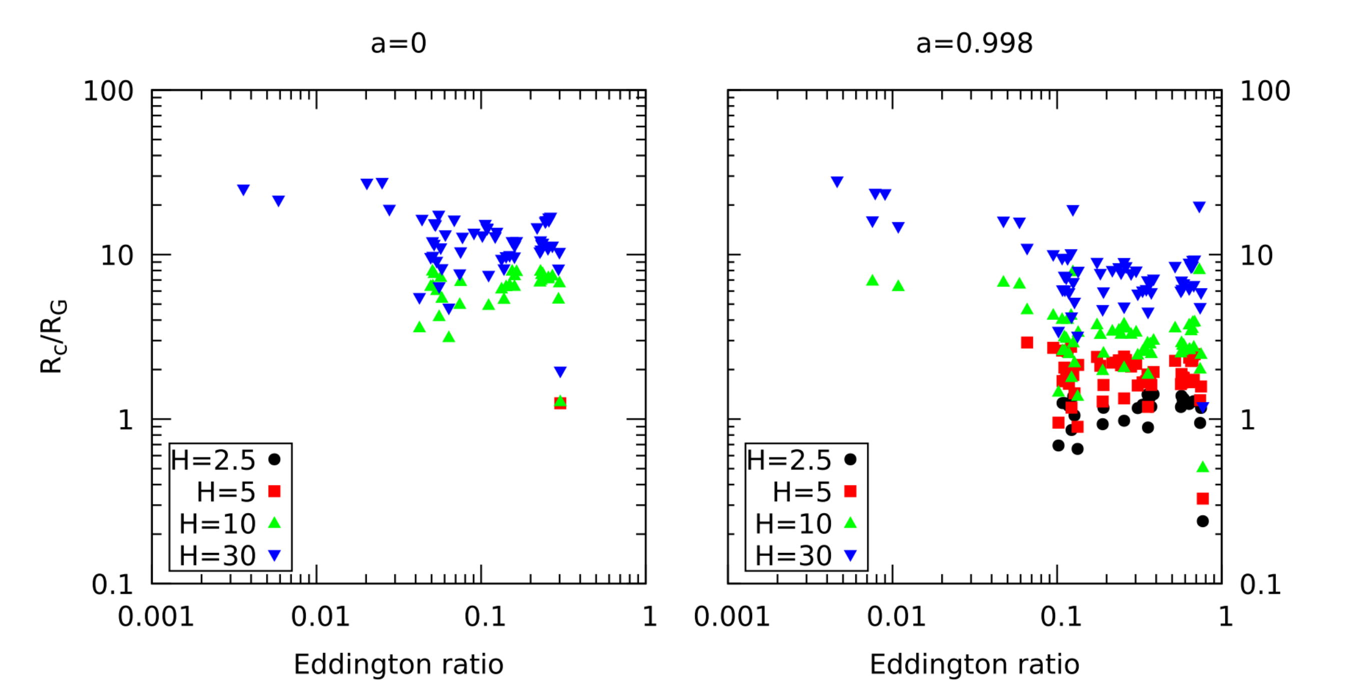
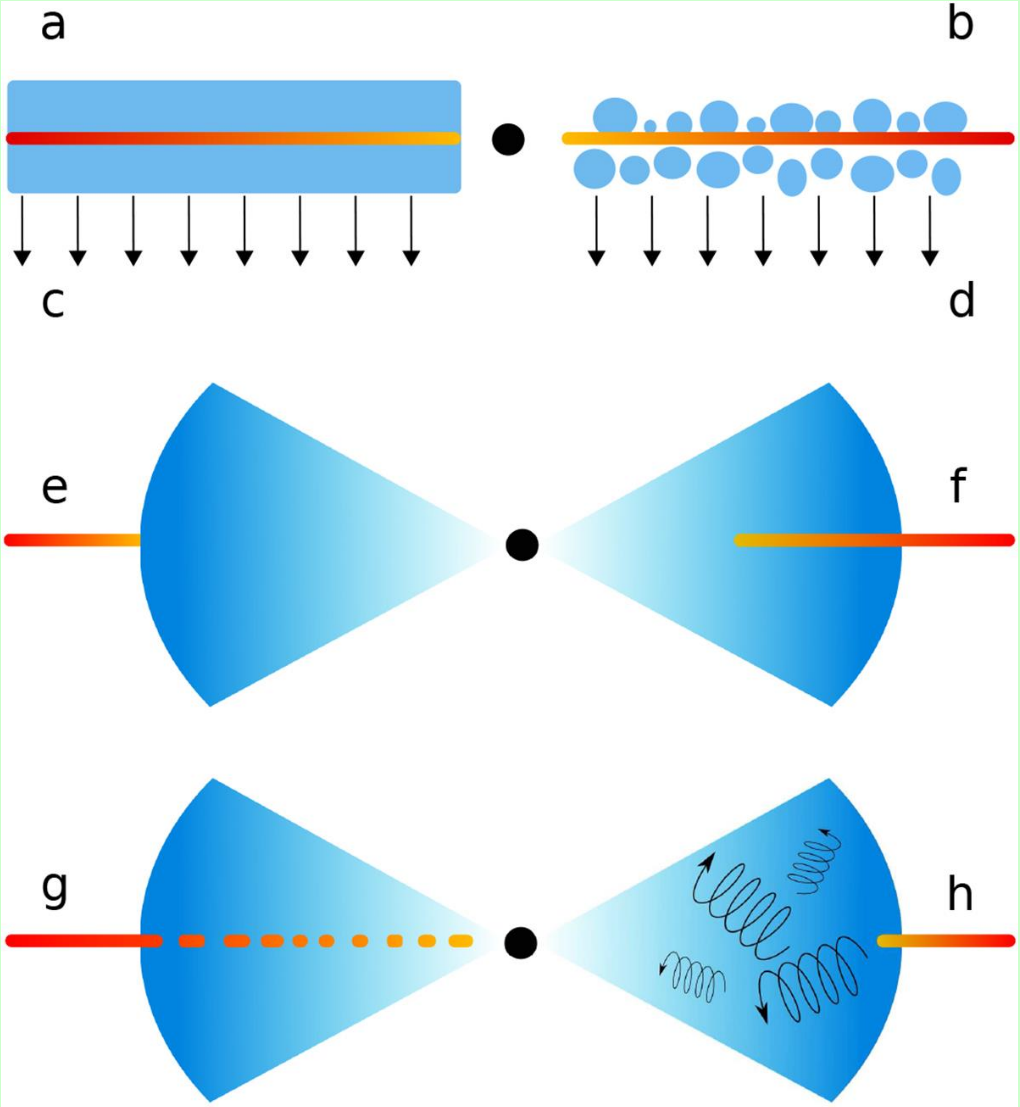
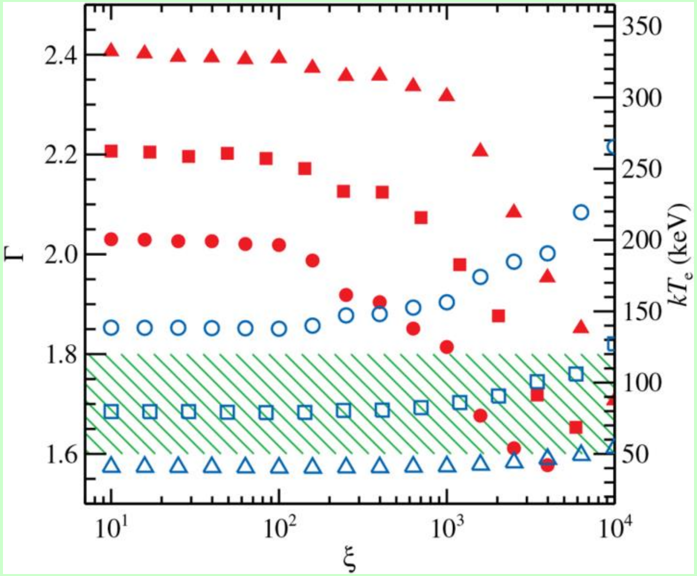


Ursini et al. 2020

Other geometries



Sandwich corona



Red: Photon index Γ

Blue: coronal temperature

τ = 0.2 (circles)

= 0.4 (squares)

= 0.8 (triangles)

Poutanen, Veledina & Zdziarski et al. 2018

The geometry of the hot corona

Differently from spectroscopy, polarimetry is very sensitive to the geometry of the corona, and can measure deviations from a spherical symmetry

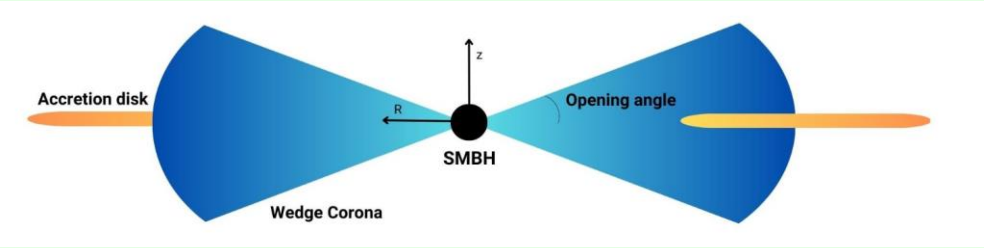
IXPE is providing the first results on the polarizaton of X-ray coronal emission in AGN. Unfortunately, only a handful of sources could be profitably observed due to the limited sensitivity (polarimetry is a photon-hungry technique!)

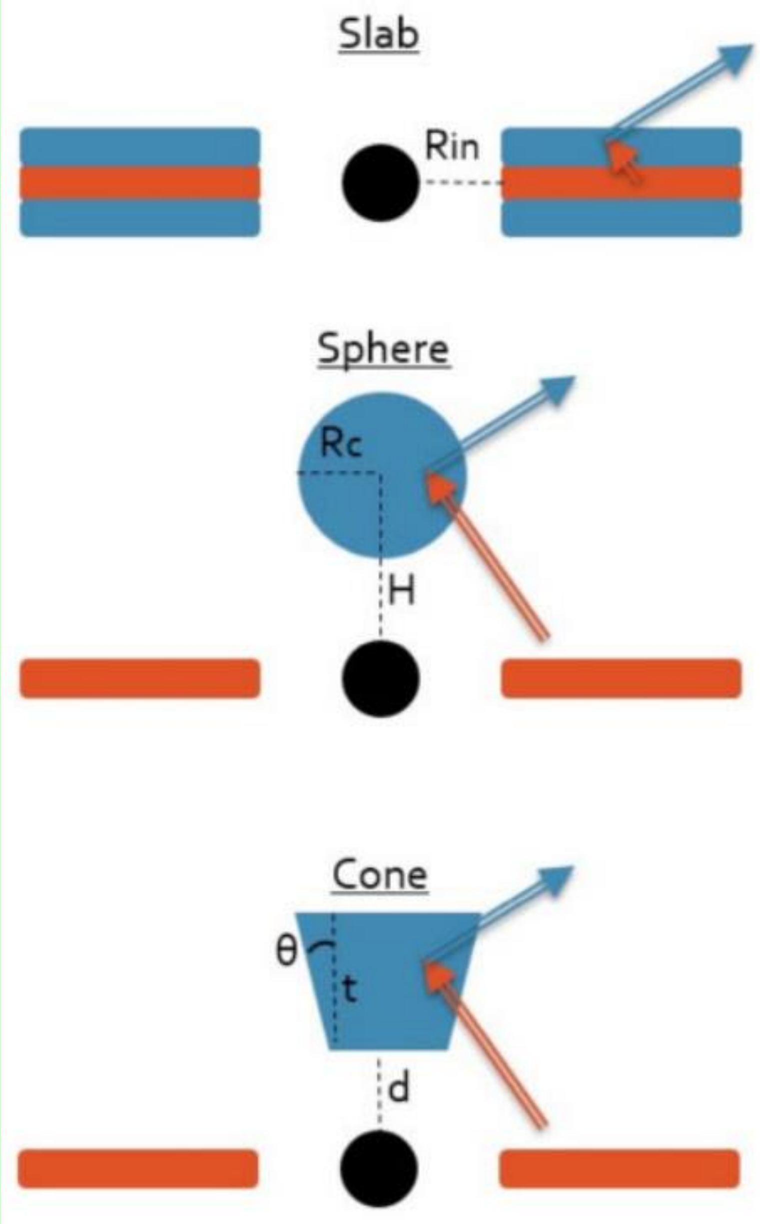
- *Energy range: 2-8 keV*
- *Spatial resolution: 30'' (FWHM)*
- *FOV=13'*
- *Energy resolution: 0.57 keV @ 2 keV (FWHM)*

MonteCarlo simulations normally used to predict the polarization properties. Many codes available.

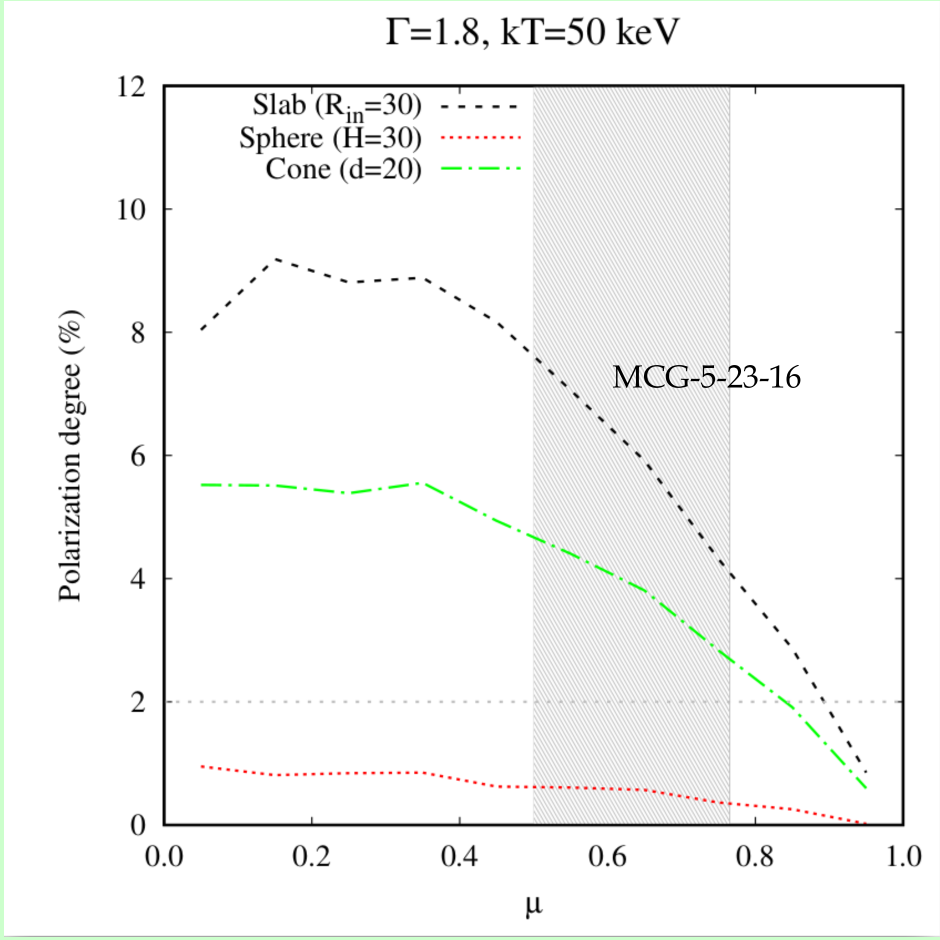
We performed numerical simulations of the expected coronal polarization with the Monte-Carlo radiative transfer code MONK (Zhang et al. 2019), which includes also special and general relativistic effects. Pure thermal plasma assumed (Maxwell-Jüttner distribution)

We explored different configurations and physical parameters of the disc/corona/BH system: e.g. a slab, a wedge, a spherical lamppost, an outflowing (v=0.3 c) cone (Ursini et al. 2022, Tagliacozzo et al. 2023)





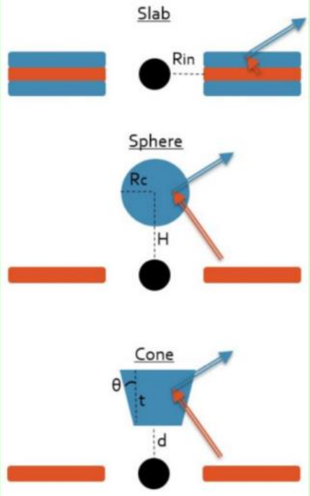
Preliminary results



Polarization from slab and wedge geometries much higher than for spherical lamppost geometries.

Intermediate values for the conical geometry

The exact values depends on the temperature and optical depth → need for good spectroscopic simultaneous observations



IXPE observations of unobscured AGN

To study the geometry of the hot corona in AGN three bright Compton-thin Seyfert galaxies have been observed by IXPE

MCG-05-23-16 May/November 2022 (Marinucci et al. 2022, Tagliacozzo et al. 2023)

$M_{BH}=2x10^7$ M_{sun} (Ponti et al. 2012)
IXPE: 486 ks+642 ks
XMM-Newton: 58 ks/none
NuSTAR: 83 ks/85ks

P<3.2%

NGC 4151 December 2022 (Gianolli et al. 2023)

$M_{BH}=4.6x10^7$ M_{sun} (Bentz et al. 2006)
IXPE: 632 ks
XMM-Newton: 33 ks
NuSTAR: 97 ks

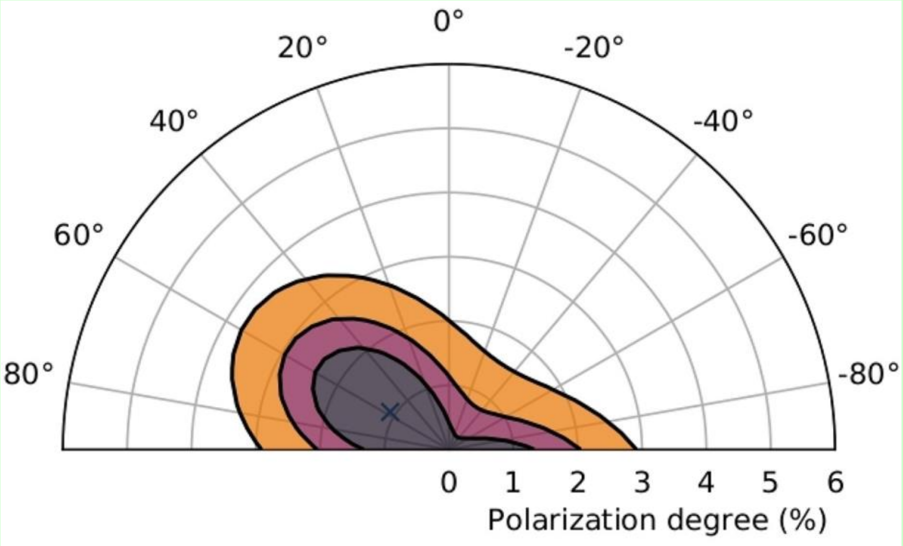
P=(4.9±1.1)%
Ψ=(86±7)°

IC 4329A January 2023 (Ingram et al. 2020)

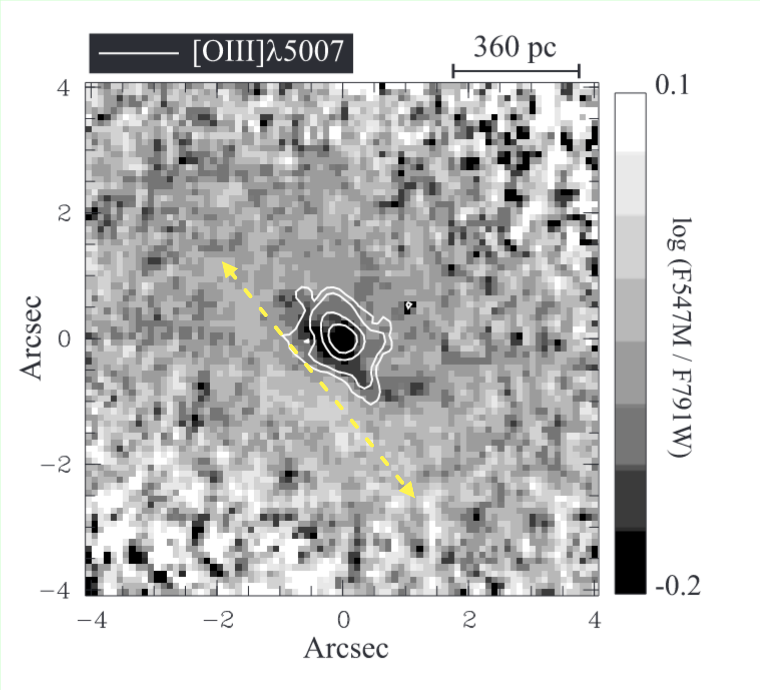
$M_{BH}=7x10^7$ M_{sun} (Bentz et al. 2023)
IXPE: 458 ks
XMM-Newton: 62 ks
NuSTAR: 82 ks

P<6.2%

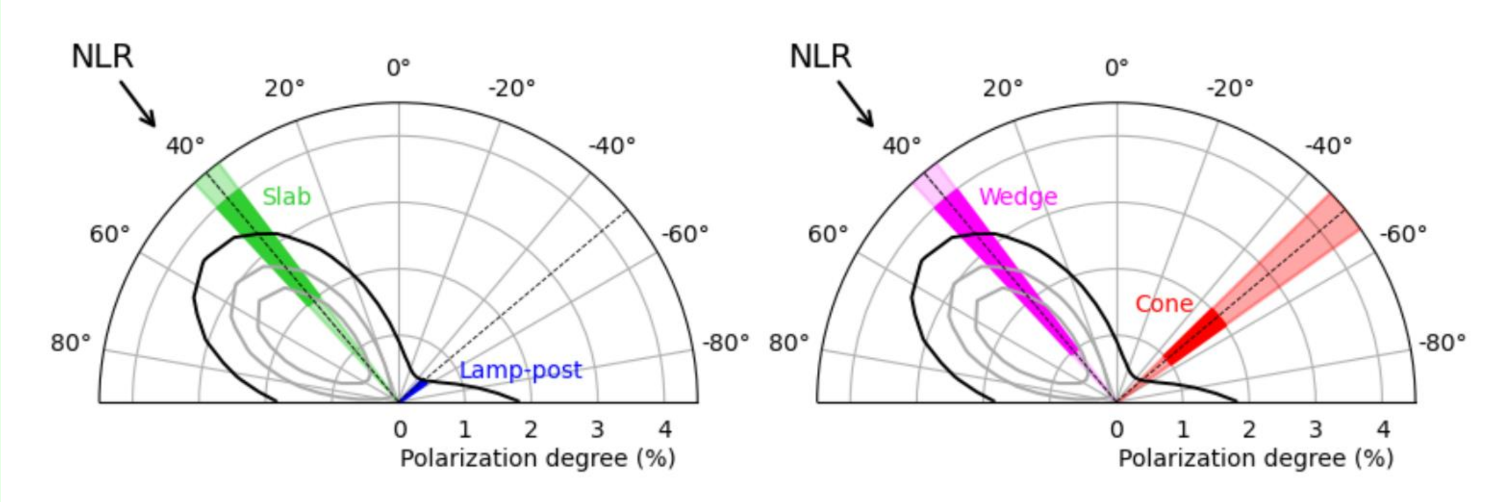
MCG-05-23-16



Tagliacozzo et al. 2023



Ferruitt et al. 2000

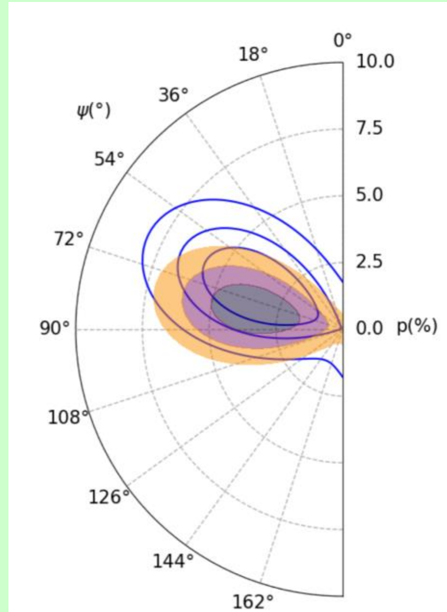


IC 4329A

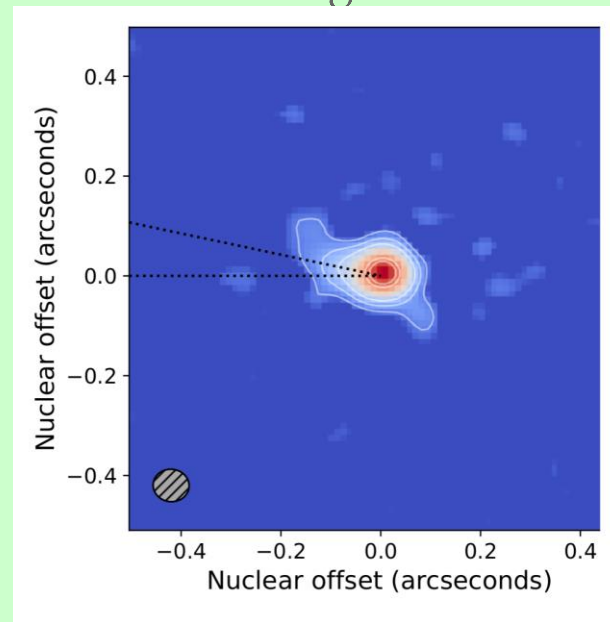
Strictly speaking, an upper limit.

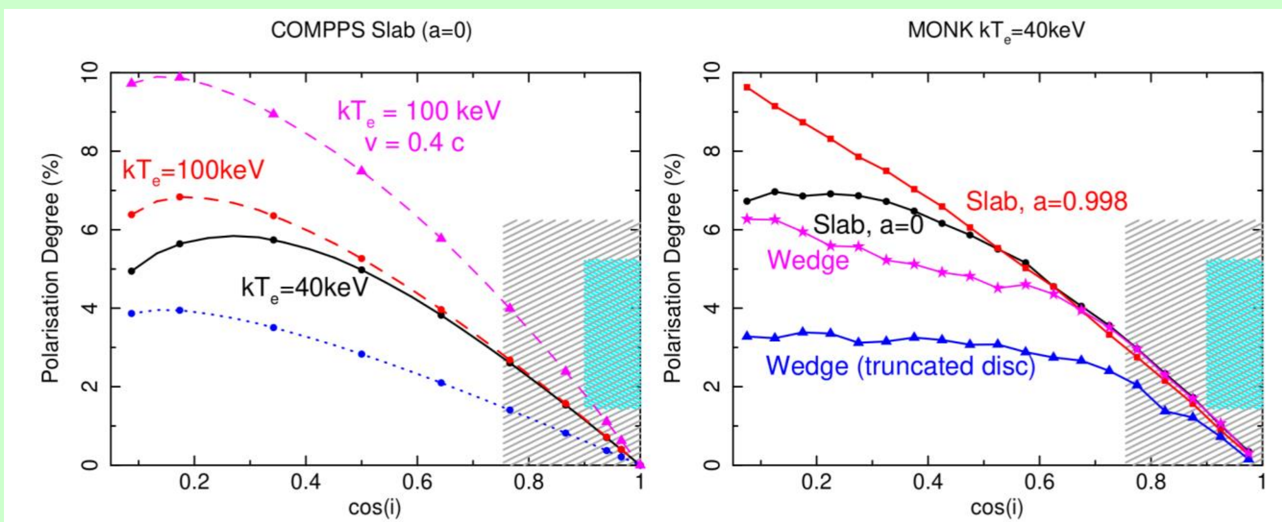
However, a 2.97σ result with P=3.3%

Ingram et al. 2023

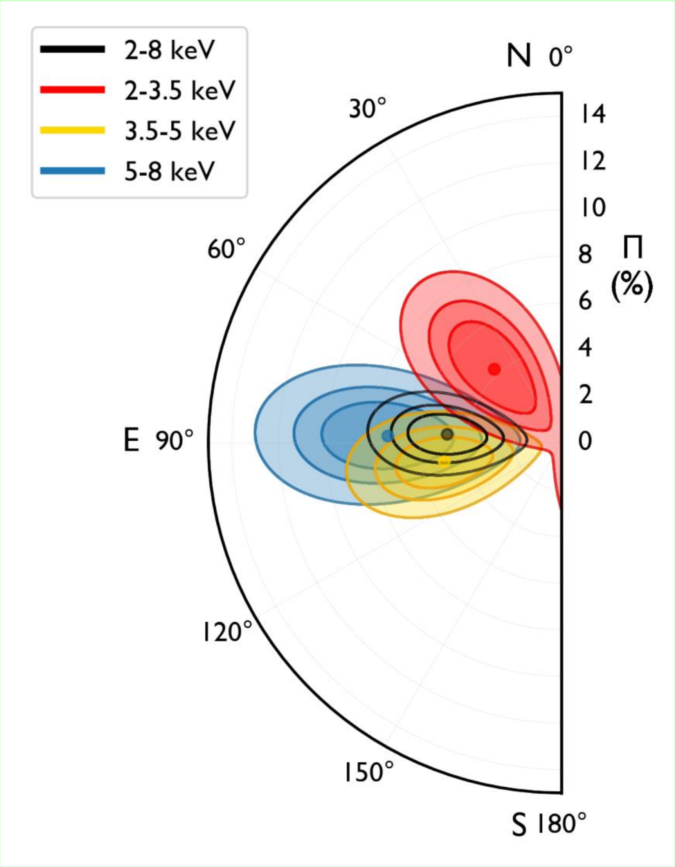


ALMA image at 100 GHz



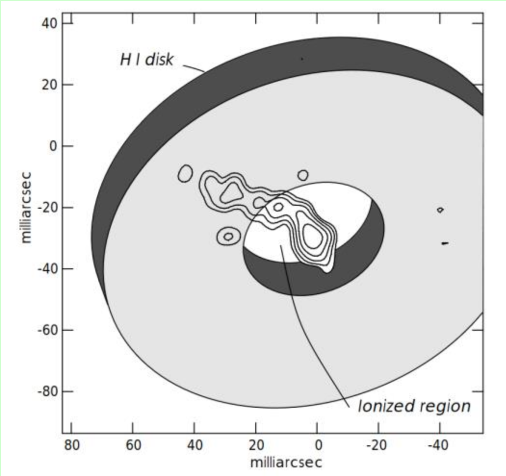


NGC 4151



Gianolli et al. 2023

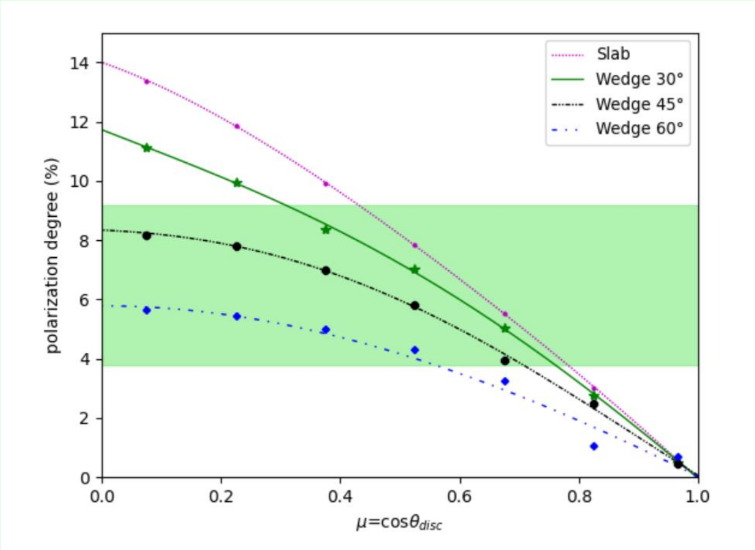
P=4.9±1.1% in the 2-8 keV range



Ulvestad et al. 1998

The measured Ψ is in the direction of the radio emission (P.A.~83°: Wilson & Ulvestad 1982, Harrison et al. 1986, Pedlar et al. 1993)

The polarization degree and angle disfavours the lamppost geometry for the hot corona.



Plan of the talk

- **The primary X-ray emission: the hot corona**

    Physical parameters: spectroscopy
    Geometry: polarimetry

- **The X-ray soft excess: warm coronae? (*)**

(*) Work supported by ISSI through ISSI International Team project #514 (Warm Coronae in AGN: Observational Evidence and Physical Understanding)

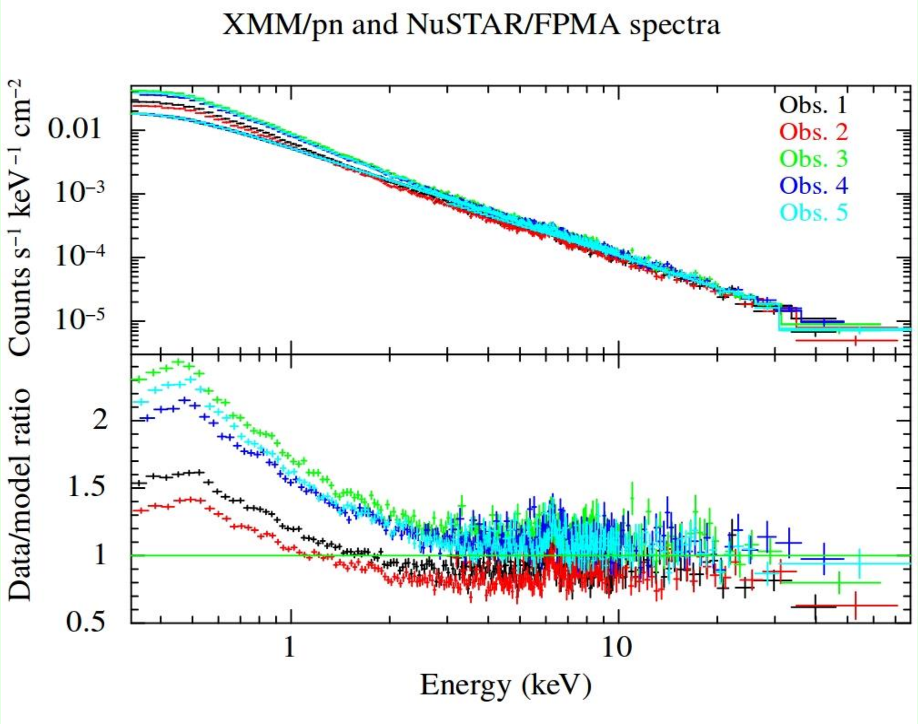
The soft excess

An excess emission below ~1 keV with respect to the extrapolation of the hard X-rays. Discovered by EXOSAT (Arnaud et al. 1985), then found to be very common in Seyfert 1s (e.g. Walter & Fink 1993)

Usually less variable than hard X-rays

Initially believed to be related to thermal emission from the disc, but almost constant temperature across a large range of masses (e.g. Gierlinski & Done 2004)

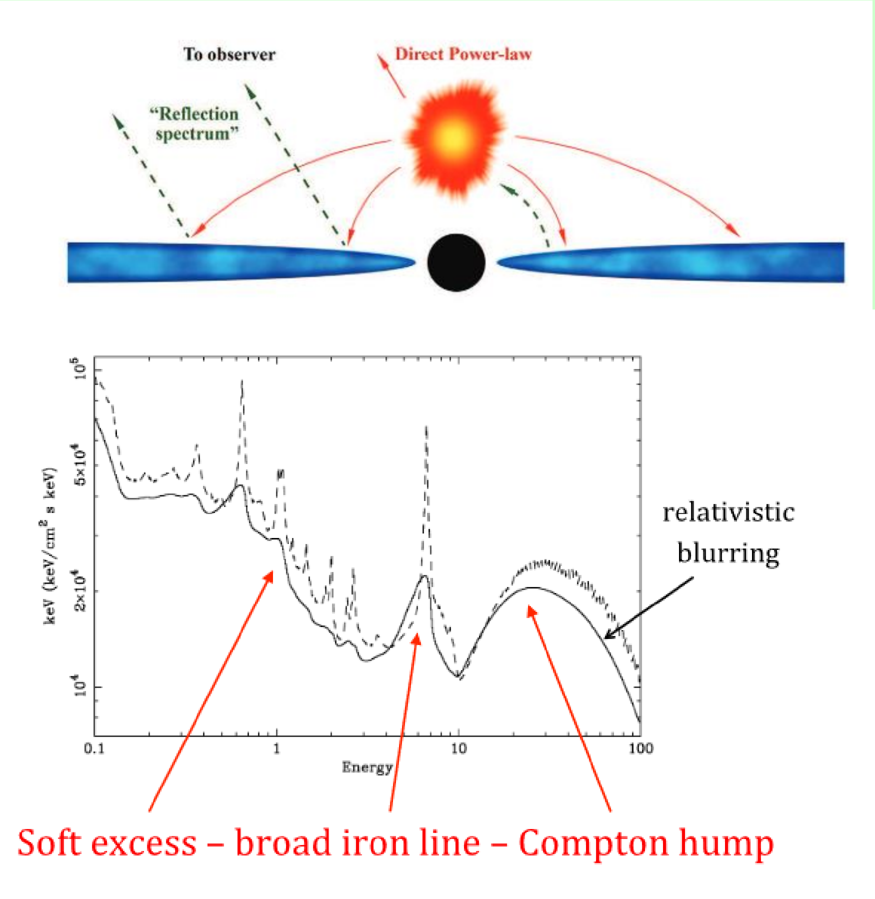
Reflection from relativistic, ionized disc? (e.g. Crummy et al. 2006)



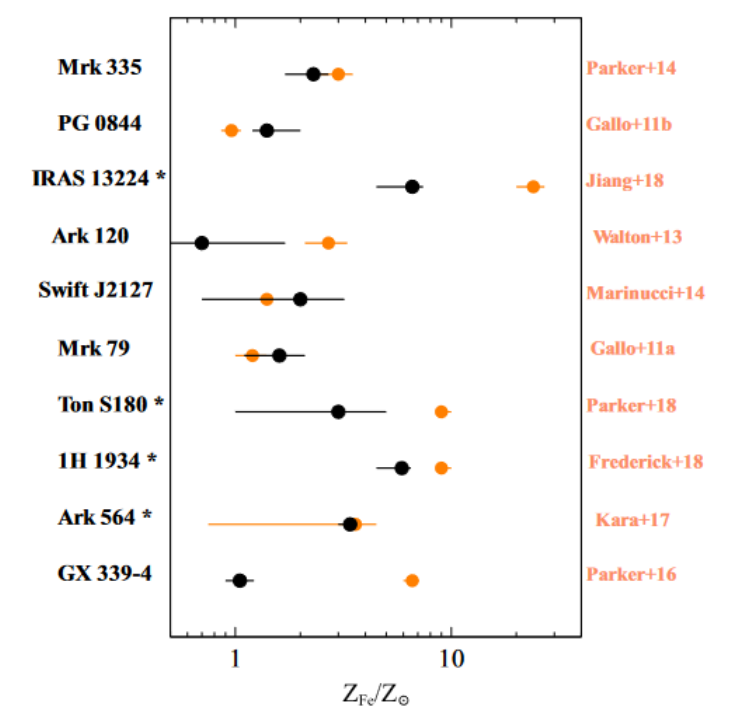
Ursini et al. (2020)

Relativistic reflection

Generaly fits the data well (e.g Walton et al. 2013), but parameters are often extreme: very high BH spin, very low height of the corona, very high iron abundance - the latter mitigated by high density disc models (e.g. Jiang et al. 2019)



Uttley et al. (2014)

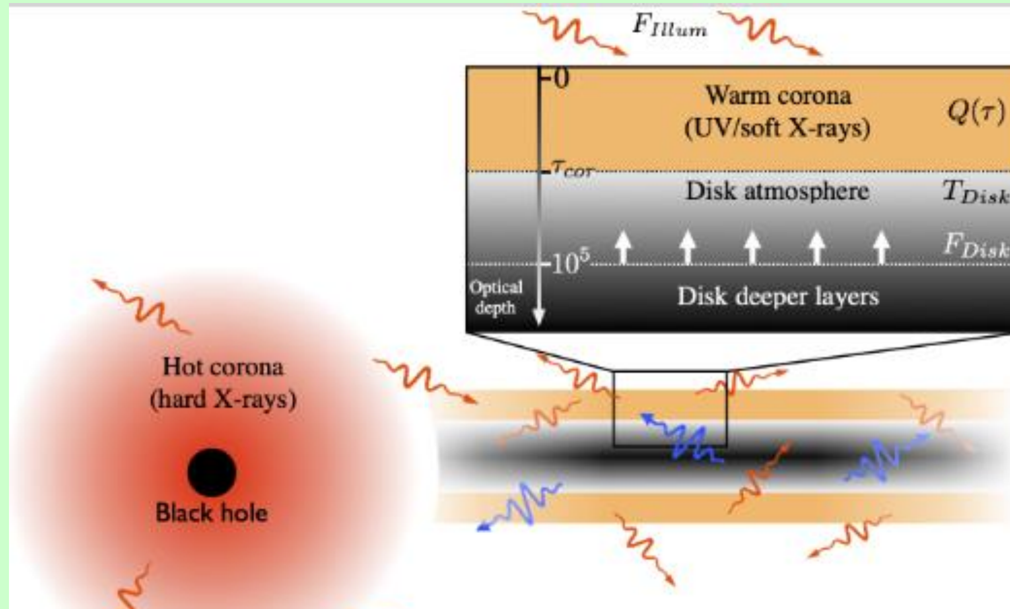


Jiang et al. (2019). Black: high density model

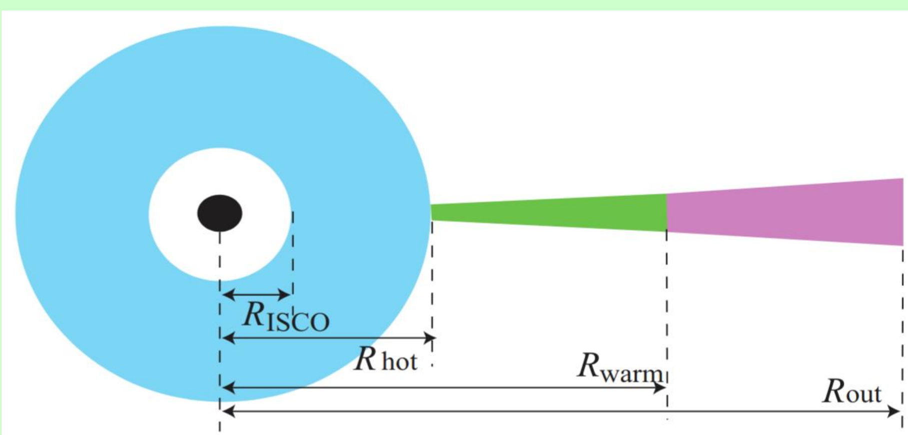
Orange: low density model

A "two-coronae" scenario

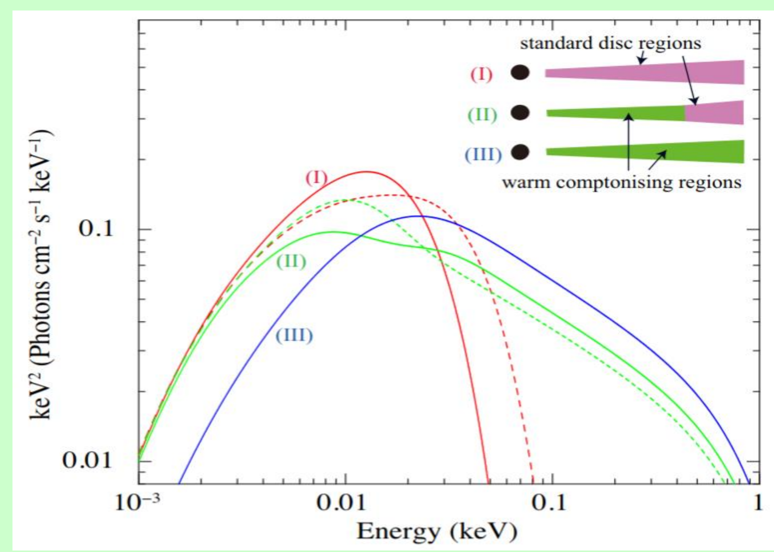
An alternative solution: a warm corona above the disc, which comptonizes the termal radiation coming from deeper layers (e.g. Magdziarz et al. 1998, Petrucci et al. 2013, 2018, 2020, Różańska et al. 2015)



Petrucci et al. (2020)



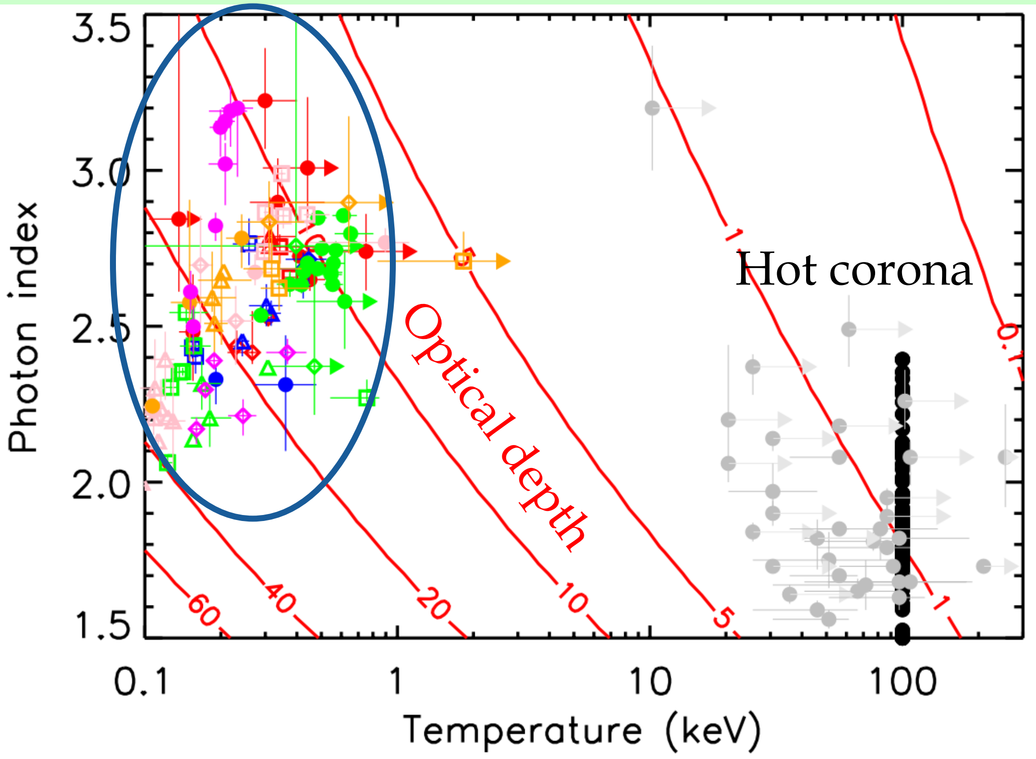
Kubota & Done (2018): AGNSED see also Done et al. (2012)

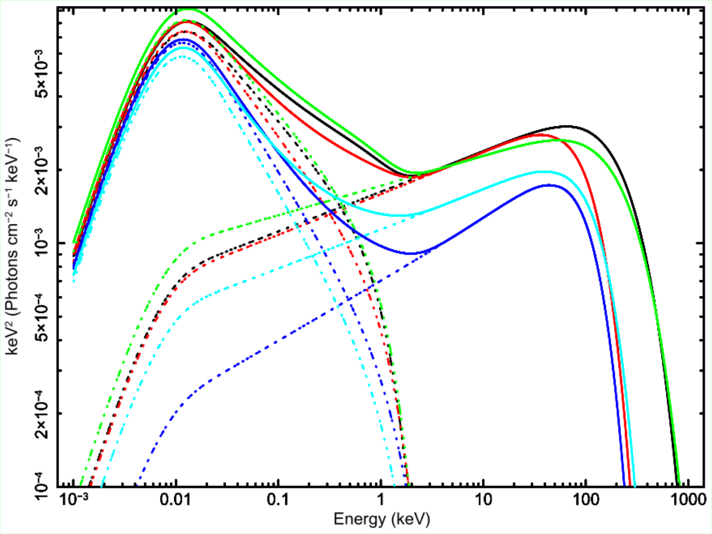


Two coronae:

A hot corona (kT~100 keV, τ~1) for the hard X-ray emission

A warm corona (kT~0.5 keV, τ~10) for the UV to soft X-ray emission



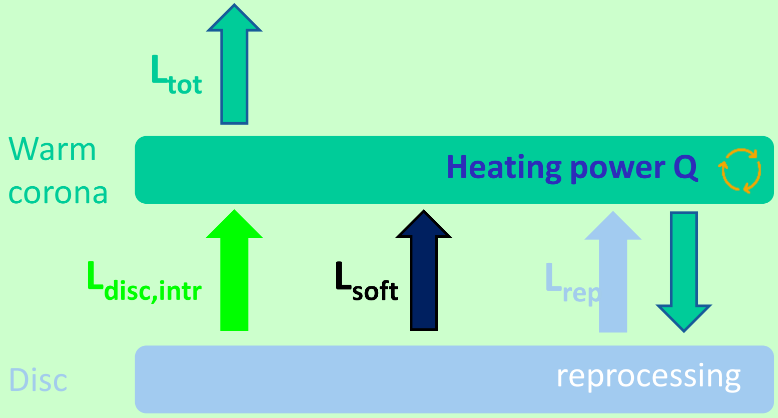


Petrucci et al. (2018)

Results of simulations (including illumination from the hot corona) and comparison with data show that (e.g. Różańska et al. 2015, Petrucci et al. 2020, Gronkiewicz et al. 2023):

Most of the energy dissipation occurs in the warm corona – the disc is basically non-dissipative, radiating mostly the reprocessed emission from the corona. A significant internal heating – of magnetic origin? – is required.

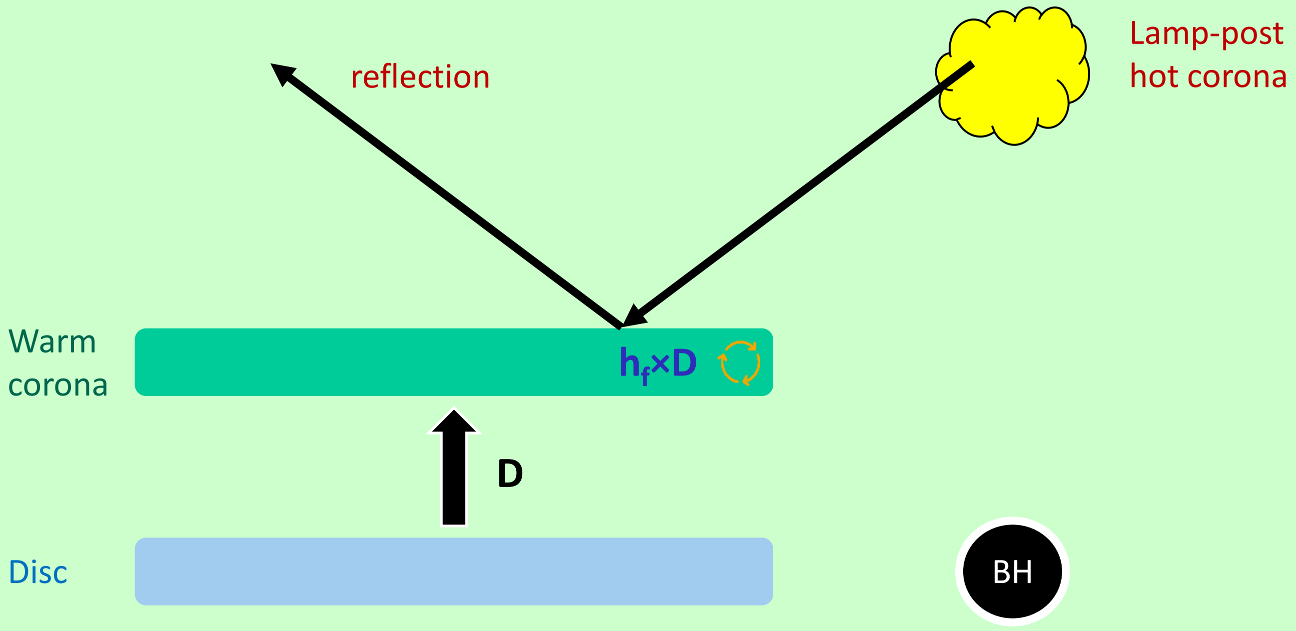
Compton is the dominant cooling process – no strong absorption/emission lines are expected.



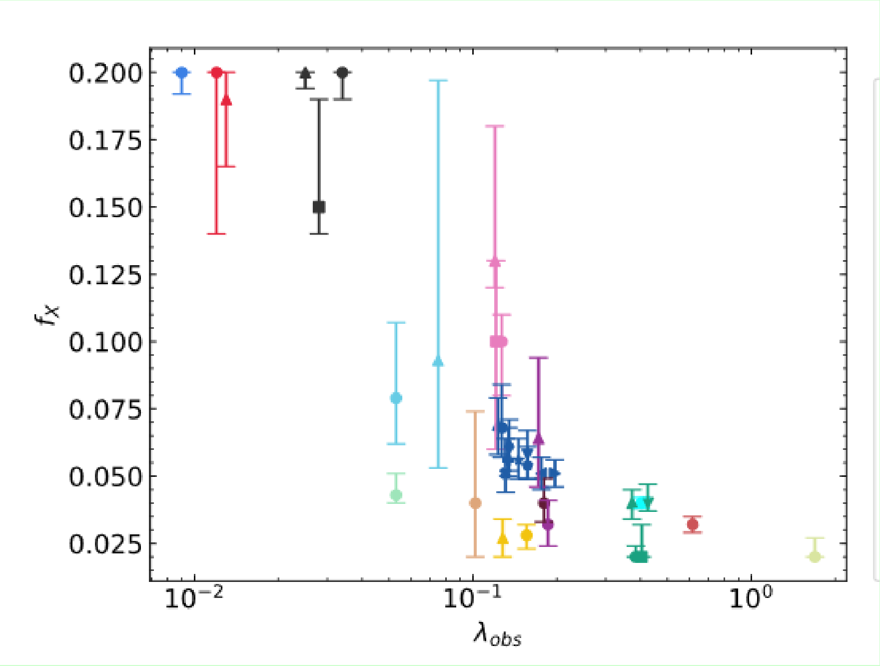
soft disc luminosity = intrinsic + reprocessed

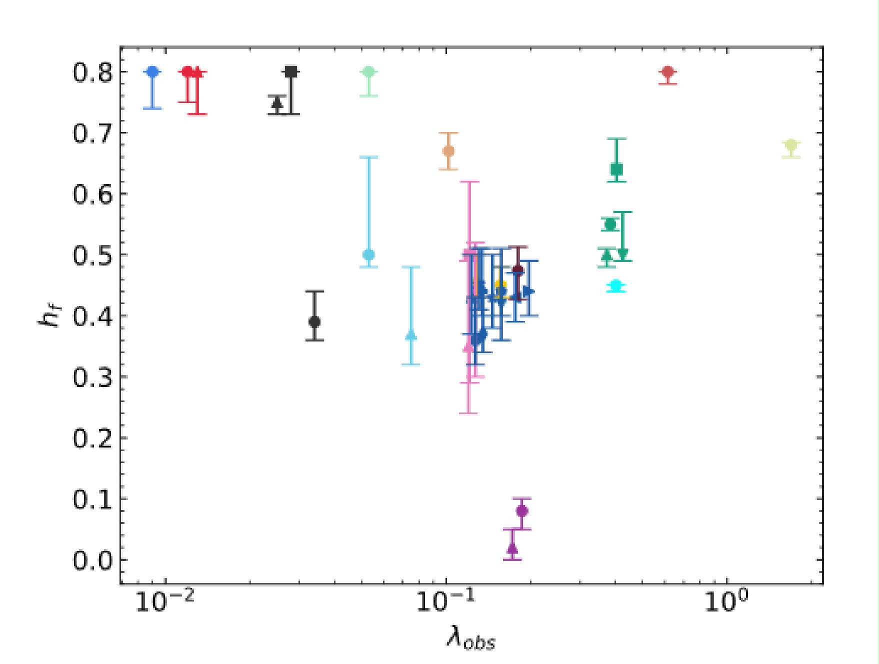
total corona luminosity = Compton amplification A(τ) × soft disc luminosity

… and reflection?



Ballantyne (2020) and Ballantyne & Xiang (2020) also stressed the importance of external illumination to achieve the required physical parameters in the warm corona. Reflection will naturally occurs!





The reXcor model (Xiang et al. 2022) combines ionized reflection and emission from a warm corona.

Ballantyne et al. (2024) analized a sample of AGN observed by XMM-Newton and found a mean warm corona heating fraction of 0.5 (the rest distributed between the disc and the hot corona)

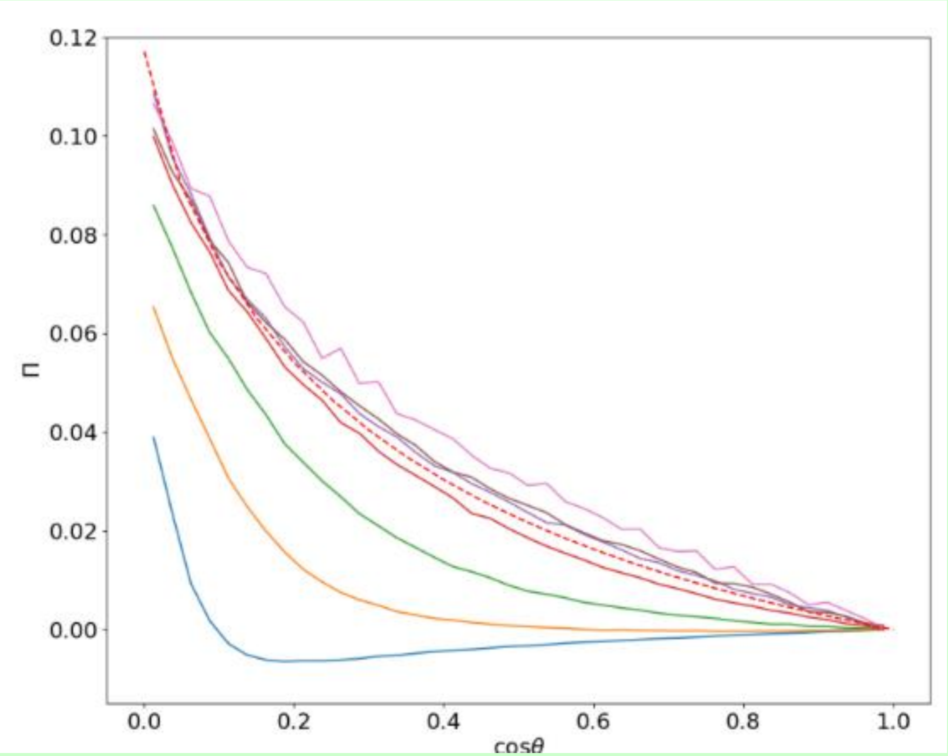
This result suggests that the warm corona emission is a crucial ingredient, but not the only one.

Ballantyne et al. (2024)

Polarimetry?

At present a pure speculative topic – no soft X-ray polarimeters with good enough sensitivity expected in the predictable future, unfortunately

Warm corona: if absorption/emission is negligible, Chandrasekhar/Sobolev results for a pure scattering, semi-infinite slab should apply, with pol. angle parallel to the disc (but GR may introduce rotation and depolarization)

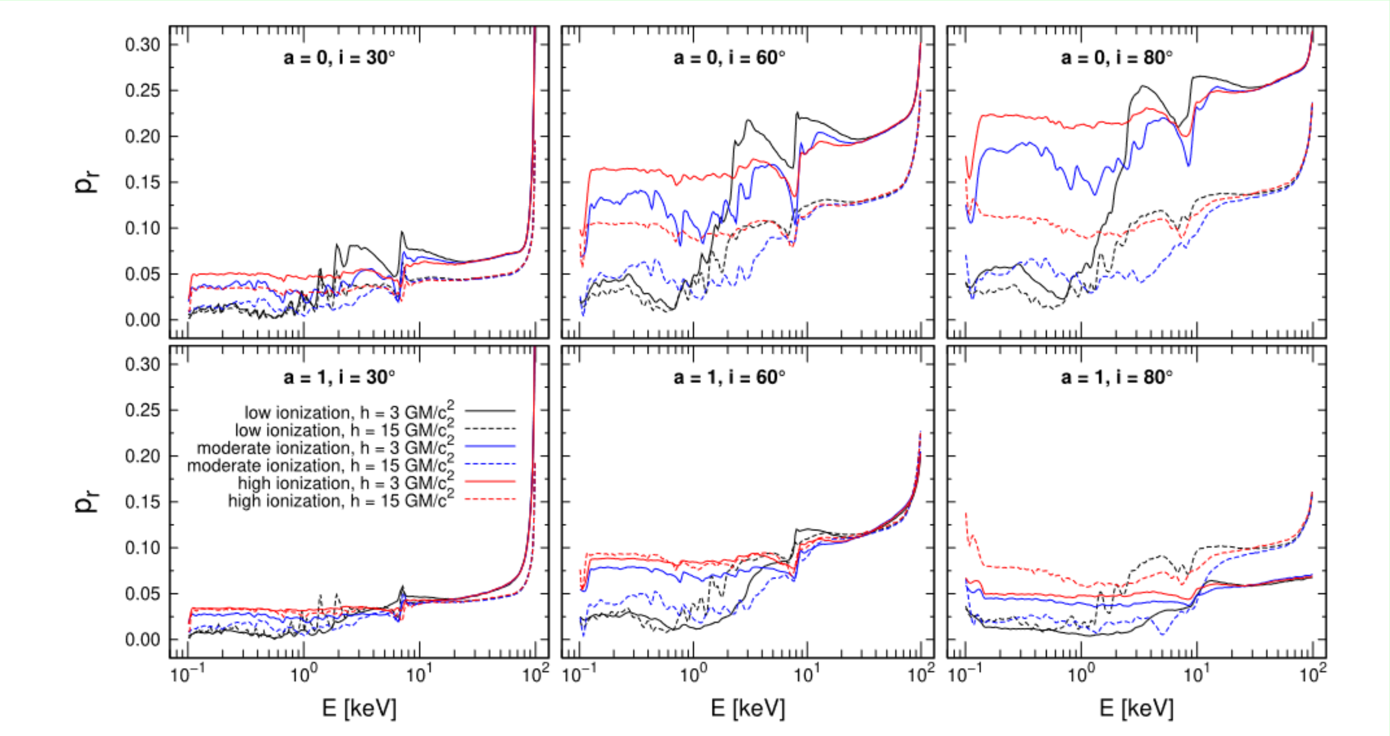


Taverna et al. (2021)

Polarimetry?

Disc reflection is also expected to be polarized. The polarization degree depends on the geometry of the corona/disc system and the ionization of the disc.

Polarization angle is preferentially perpendicular to the disc



Lamppost corona - Podgorný et al. (2023)

Summary and conclusions

Hot corona: temperature and optical depth measured with good precision thanks to NuSTAR

Some information on the geometry available, also thanks to polarimetry. ‘Lamppost’ geometry disfavoured

How is energy supplied to the corona?

Warm corona: a viable solution for the soft X-ray excess, if energy is mostly dissipated there. Reflection also likely to be important