Not so close to the event horizon: latest results on circumnuclear matter in SMBHs

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From the Dolomites to the event horizon: sledging down the Black Hole potential well (4th edition)

ROMA TRE UNIVERSITÀ DEGLI STUDI

SEVENTH FRAMEWORK PROGRAMME

STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017

Outline

- Introduction
(far away from the event horizon)

- Sub-pc absorption

- Absorption/reflection on the pc-scale

- Hard X-ray view of Seyfert 2 galaxies

- Conclusions

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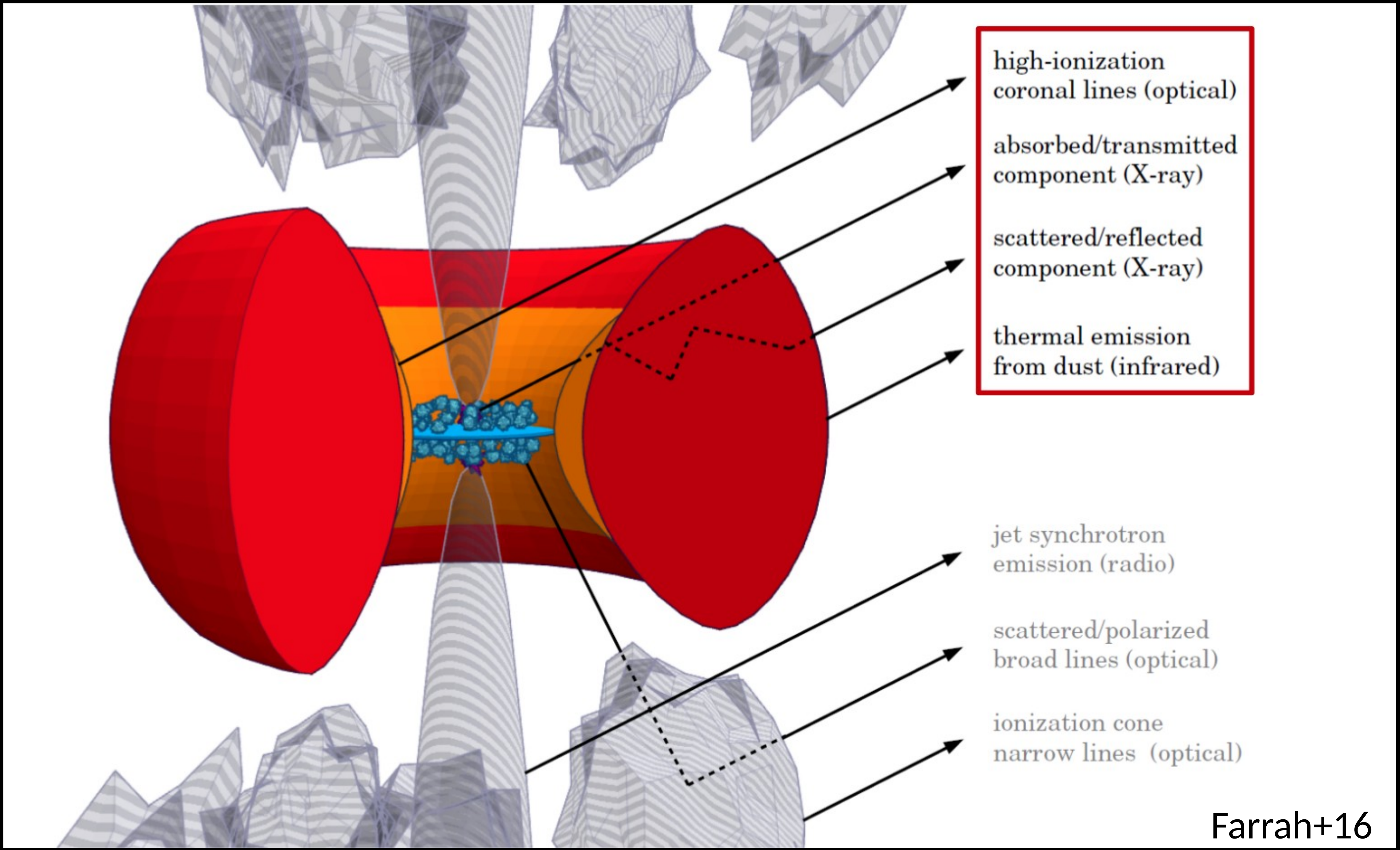
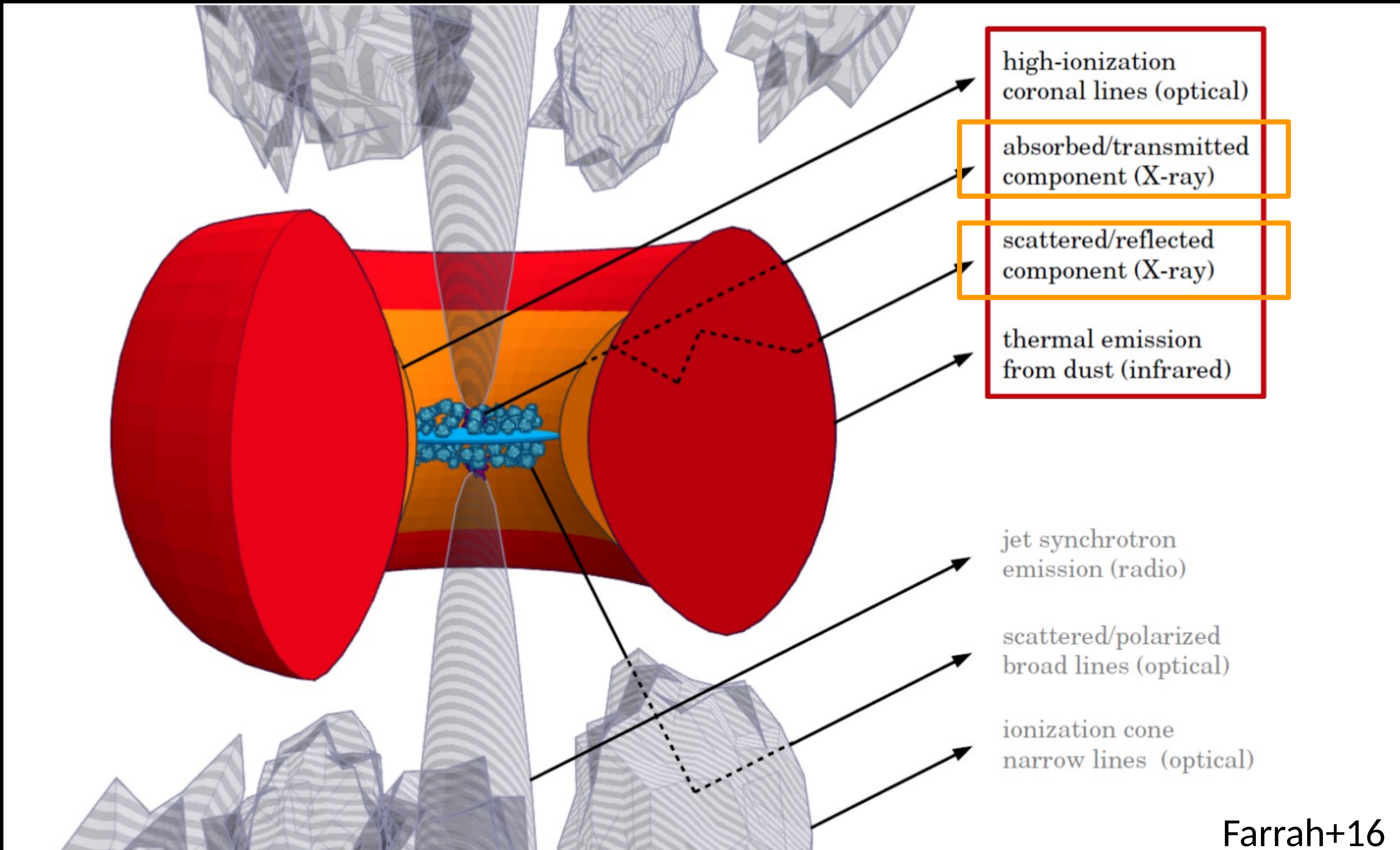
Introduction



Introduction



Introduction

Geometry (c_F, inclination) and composition (number of clouds, distance) of the cold circumnuclear reprocessor?

high-ionization coronal lines (optical)

absorbed/transmitted component (X-ray)

scattered/reflected component (X-ray)

thermal emission from dust (infrared)

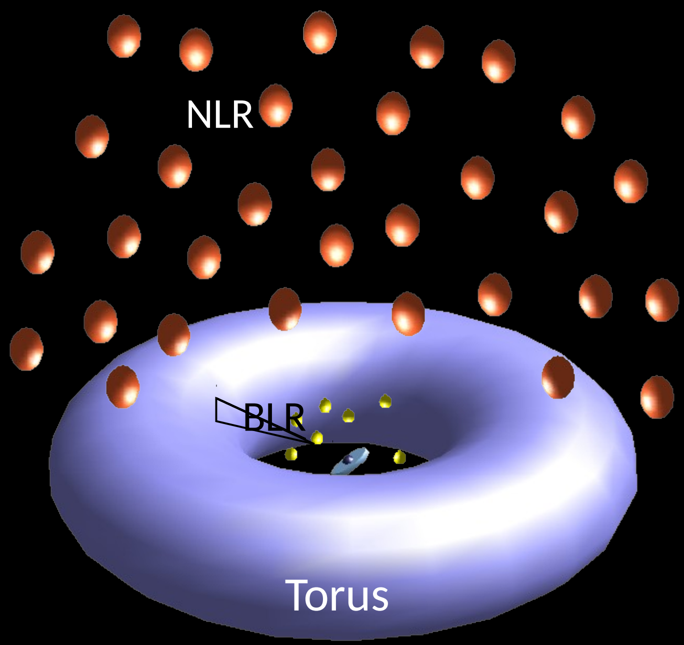
jet synchrotron emission (radio)

scattered/polarized broad lines (optical)

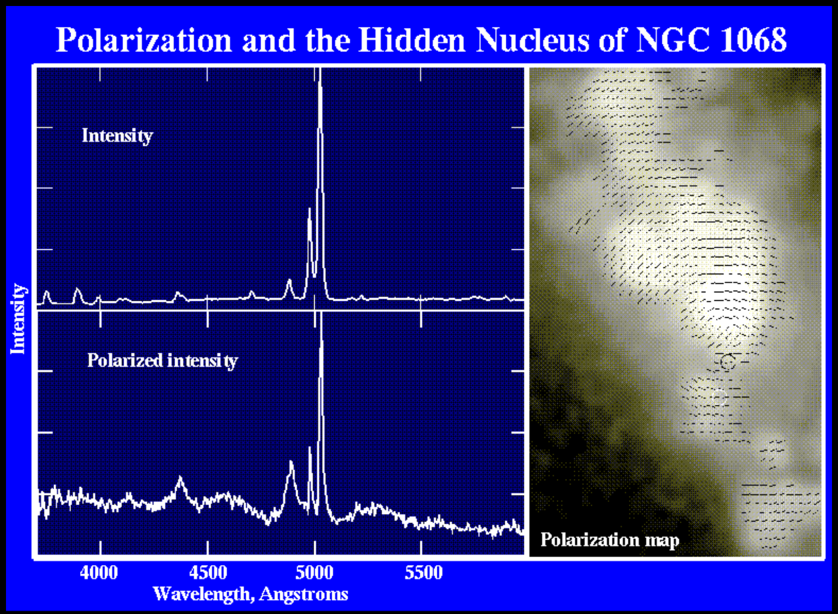
ionization cone narrow lines (optical)

Farrah+16

The geometry of absorption



The absorber must break the simmetry of the polarization angles:
a “torus” is the most natural configuration.



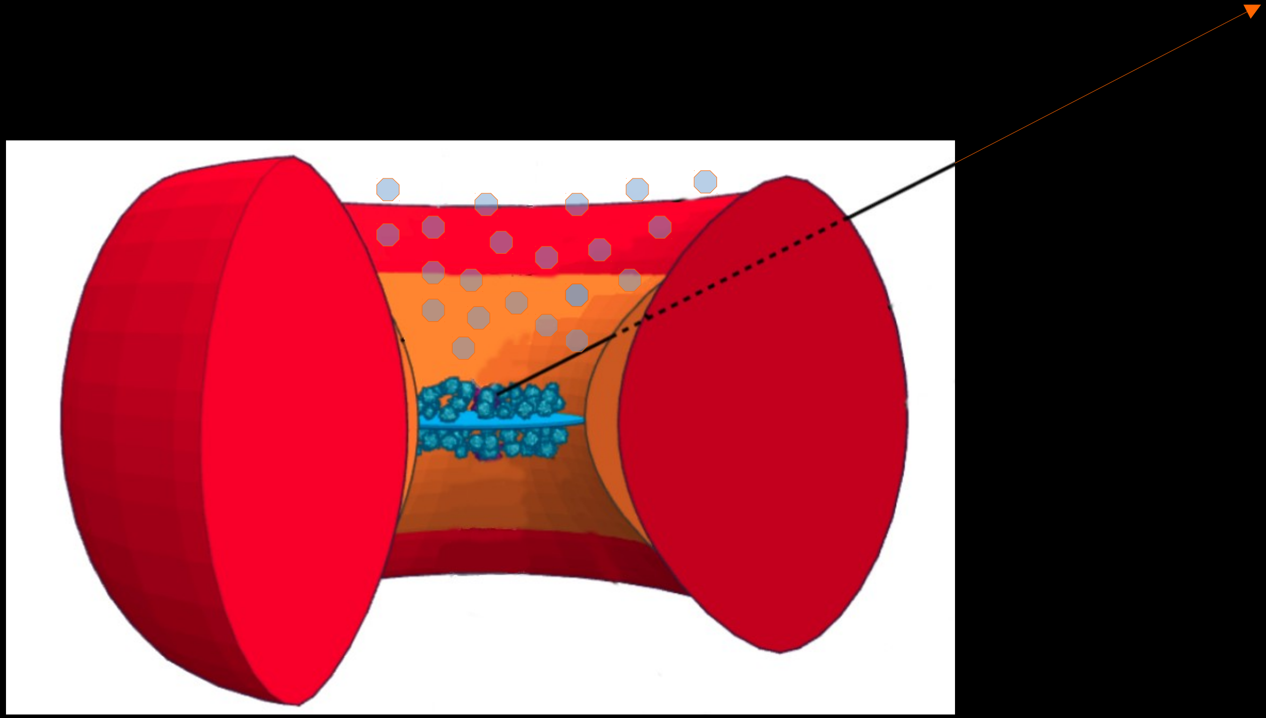
Antonucci & Miller, 1985

The size of the torus was postulated to be on the parsec scale (Krolik & Begelman, 1986, 1988):

- Large enough to obscure the BLR
- Small enough not to obscure the NLR

The geometry of absorption

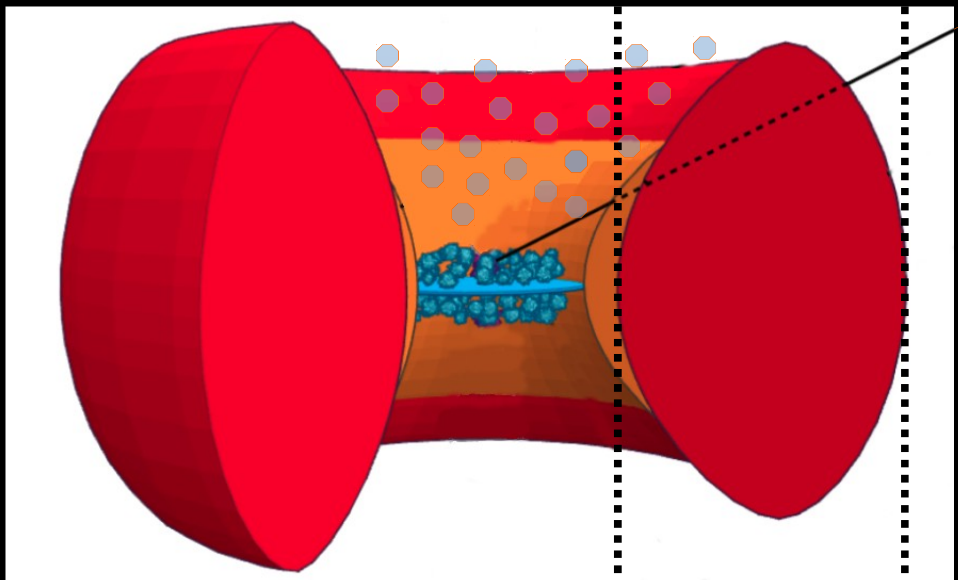
While the AGN unified picture remains valid in its more general sense (the presence of non-spherically symmetric absorbers at the origin of the type 1/type 2 dichotomy), several new observations and models, mostly in the X-ray and infrared domain, suggest that multiple absorbers are present around the central source, on quite different physical scales (e.g. Bianchi, Maiolino & Risaliti 2012)



The geometry of absorption

On the sub-pc scale, dust-free gas along the line of sight has been observed through X-ray absorption variability: part of the observed X-ray absorption is due to BLR clouds

On the parsec scale, and down to the dust sublimation radius, the "standard" torus has been directly imaged in a few sources with interferometric techniques, and its presence is suggested by X-ray reflection properties, and dust reverberation mapping in the near-IR



On scales of hundreds of parsecs, or even larger (galactic dust lanes), circumnuclear matter has been imaged, and is clearly responsible of the "type 2" (in optical/UV) or "absorbed" (in X-rays) classification of a significant fraction of AGN

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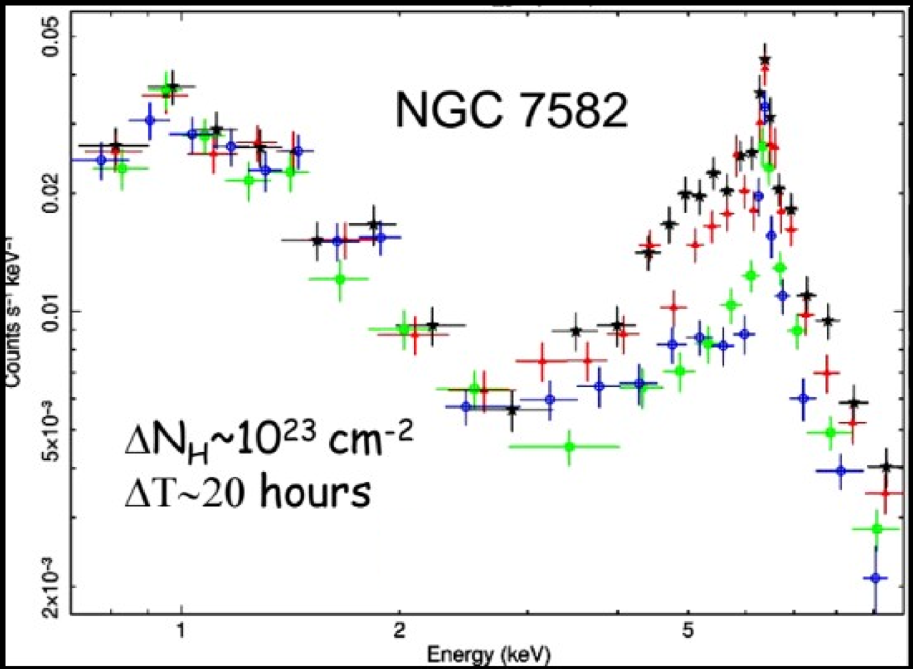
Sub-pc absorption

X-ray absorption variability is common in AGN: the circumnuclear X-ray absorber (or, at least one of its components) must be clumpy and located at subparsec distance

N_H variations (10^{22}-10^{23} cm^{-2}) on scales from months to hours are found in a growing number of sources
(Risaliti et al. 2002, Torricelli-Ciamponi et al. 2014)

NGC 1365 (Risaliti et al. 2005, Rivers et al. 2015), NGC 7582 (Bianchi et al. 2009), Swift J2127.4 (Sanfrutos et al. 2013), MCG-6-30-15 (Marinucci et al., 2014)

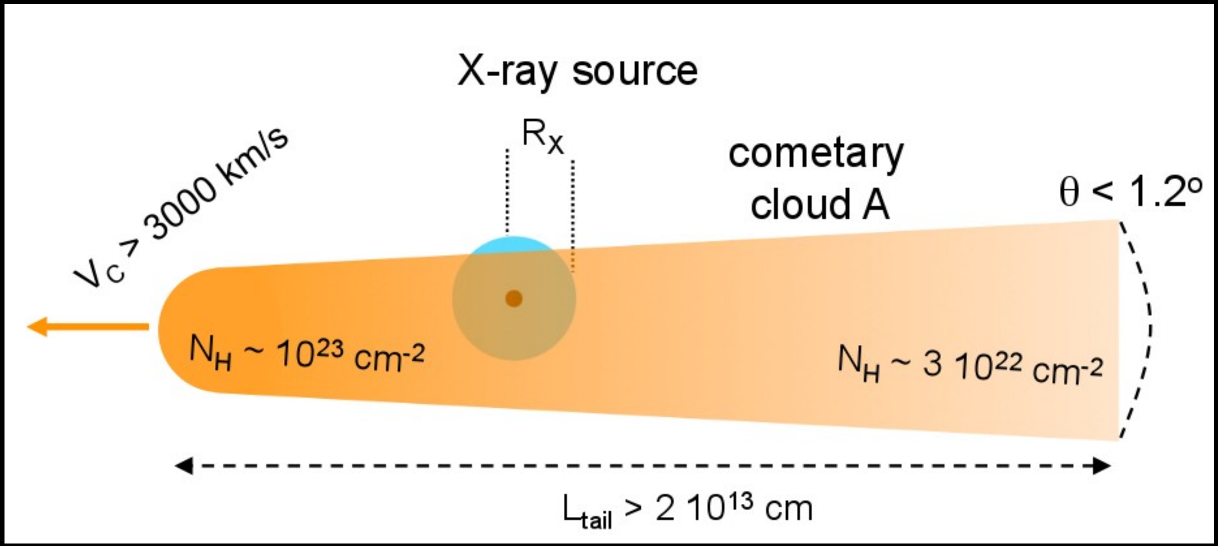


Bianchi et al. 2009

Sub-pc absorption

NGC 1365 shows absorption variability down to ∼10 hours: absorption is due to clouds with velocity >10^3 km s^{-1}, at distances of ~10^4 R_g. Their physical size and density are ~10^{13} cm and ~10^{10}-10^{11} cm^{-3}

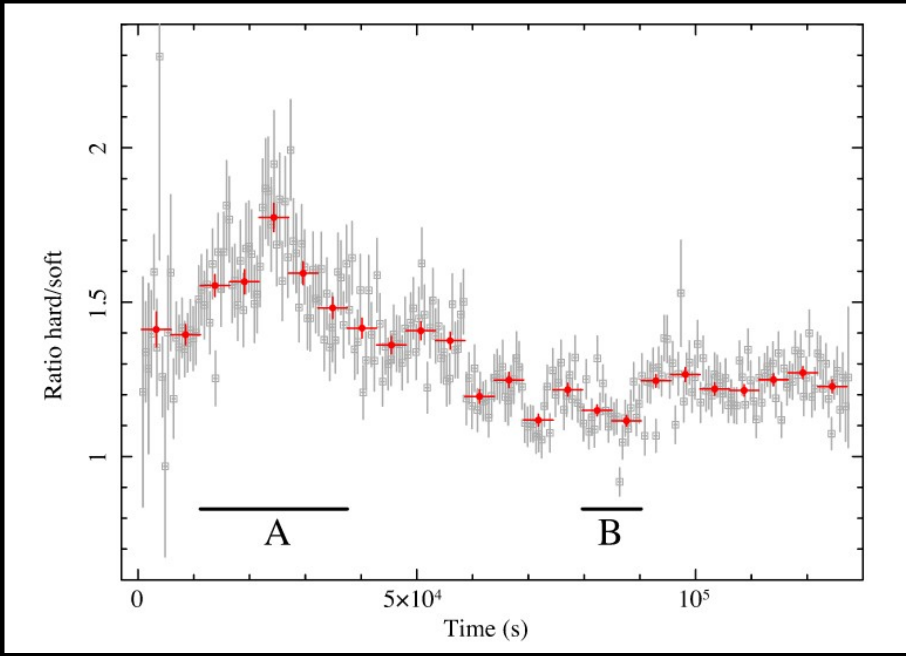
All these physical parameters are typical of BLR clouds: the X-ray absorber and the clouds responsible for broad emission lines in the optical/UV are one and the same.



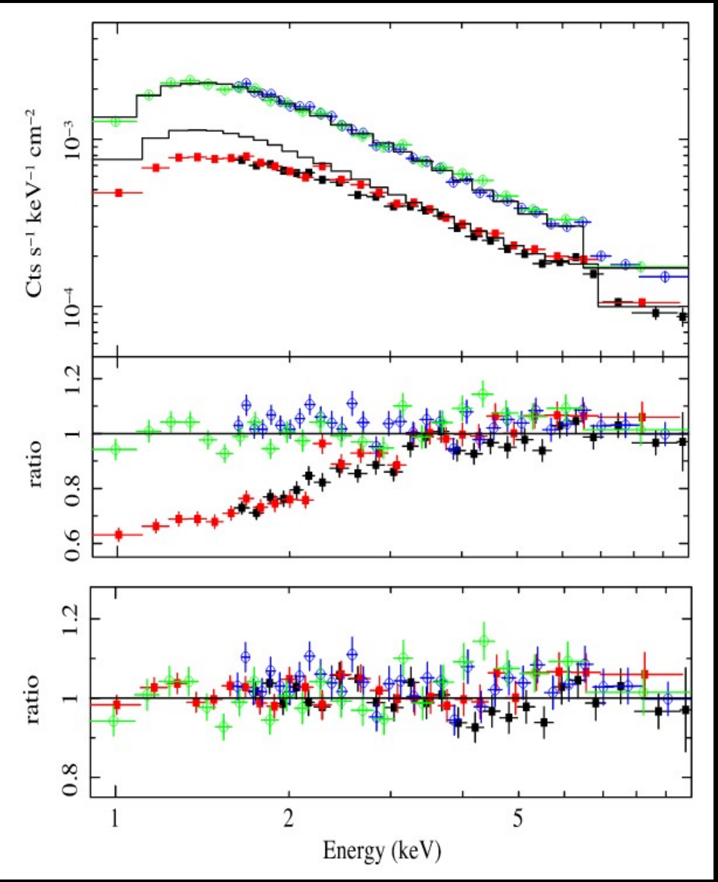
Maiolino et al. 2010

The obscuring clouds appear to have a "cometary" shape: a high-density head, and an elongated, lower-density tail

Sub-pc absorption (Swift J2127.4) – a~0.6



Sanfrutos et al. 2013



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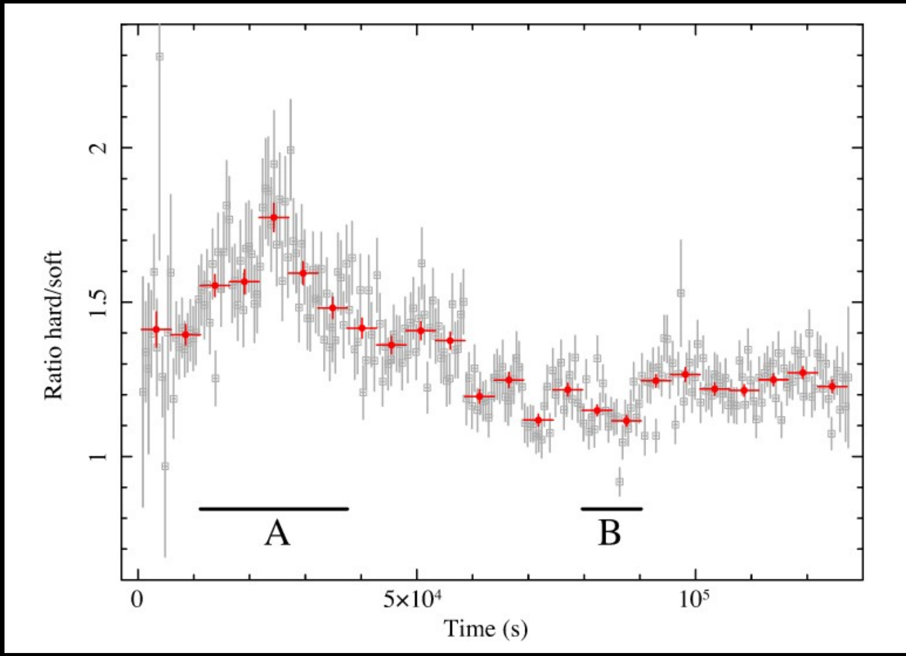

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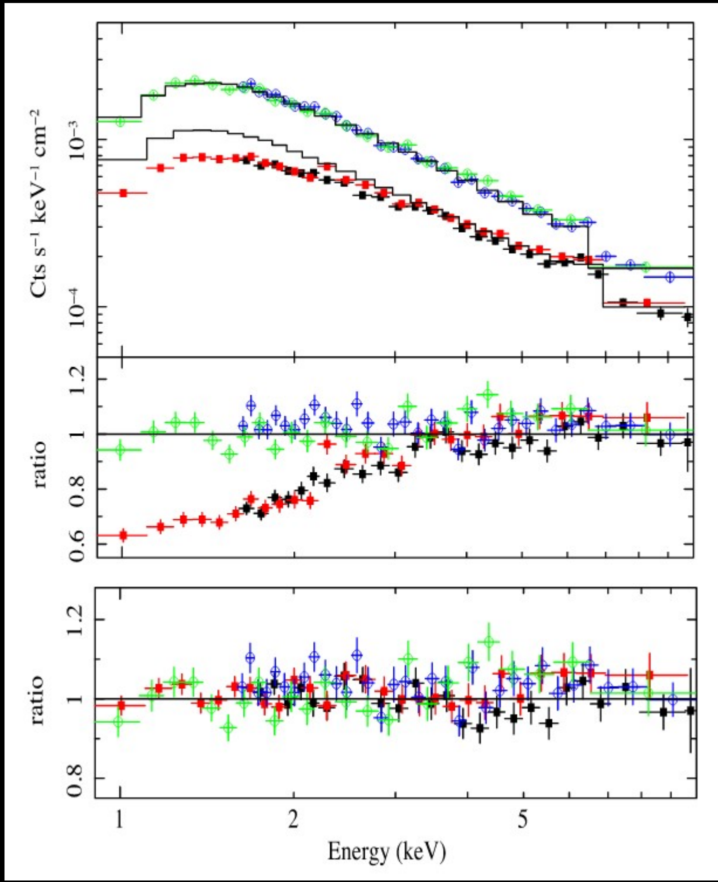


T_{occ}~70±30 ks

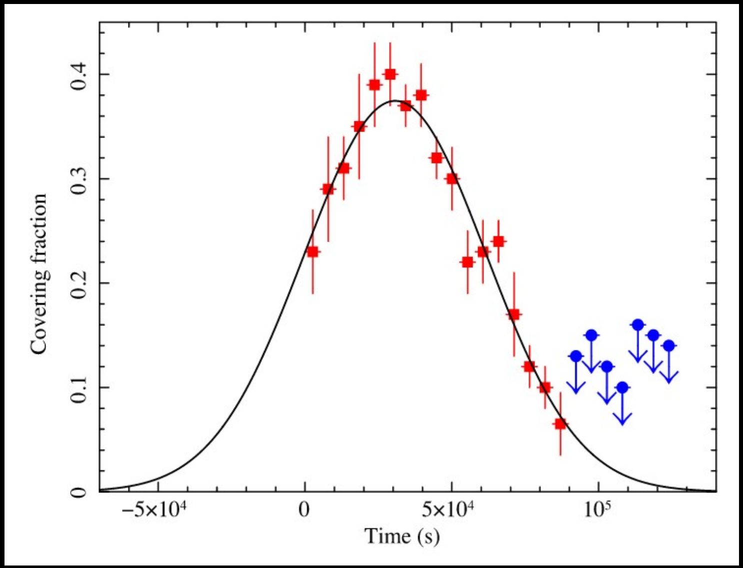
Cf=0-0.4

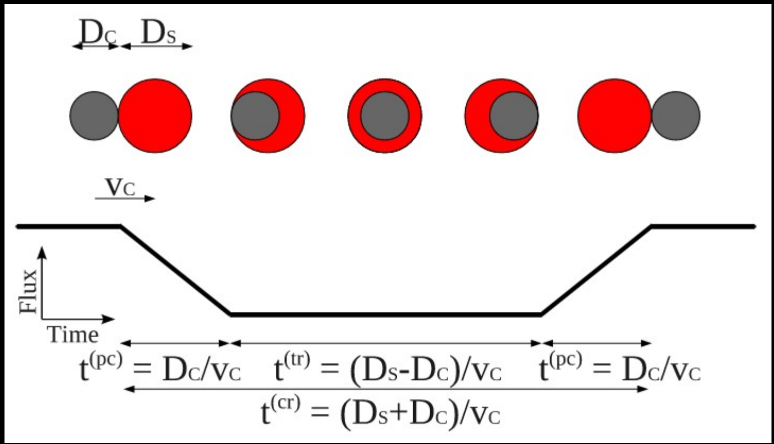
N_H=2x10^{22} cm^{-2}

v_K~2000 km/s

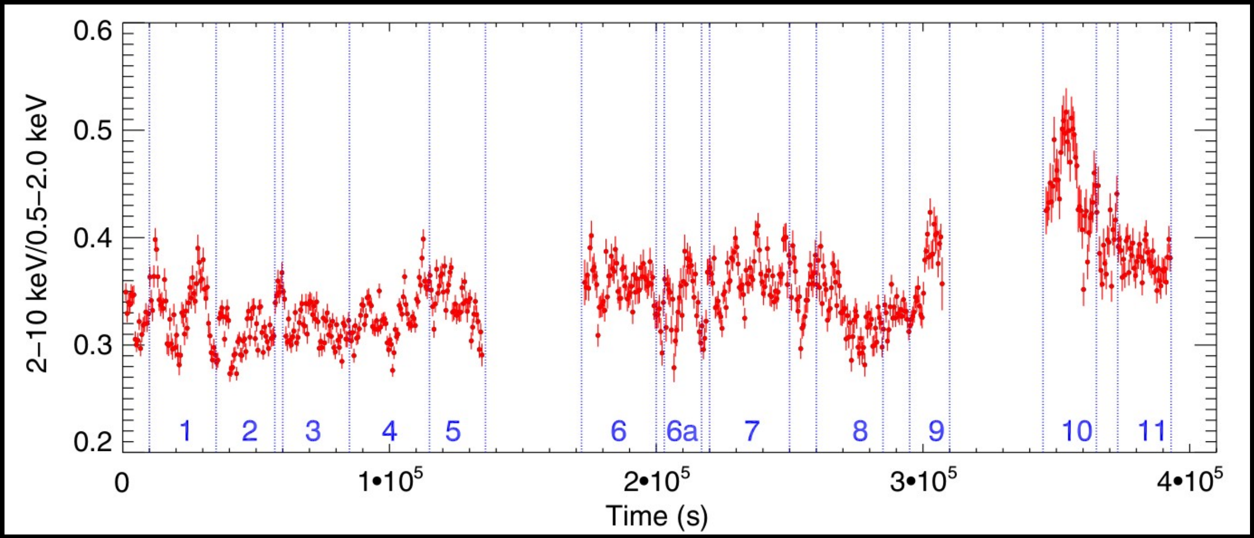
R>4x10^{16} cm

n~2x10^{9} cm^{-3}

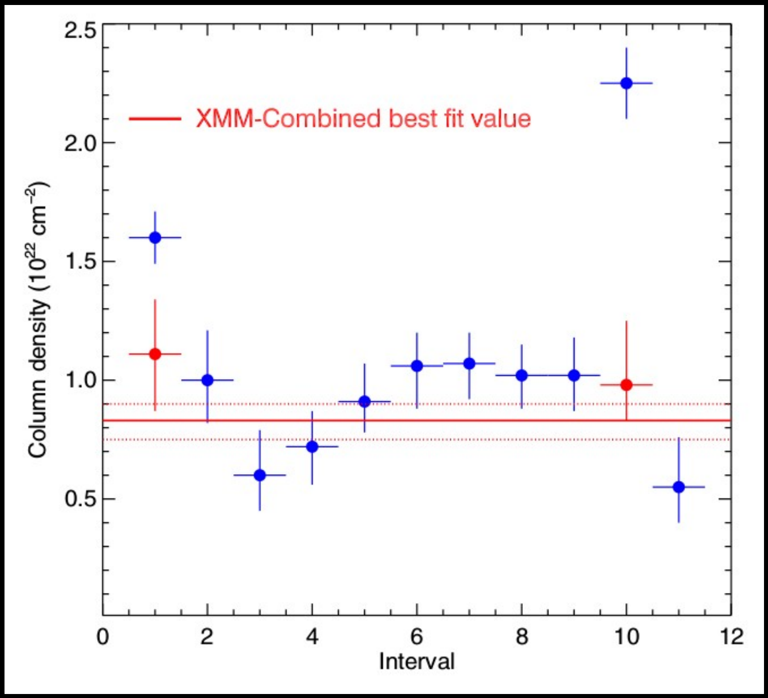




Sub-pc absorption (MCG-6-30-15) – a~0.9



Marinucci et al. 2014



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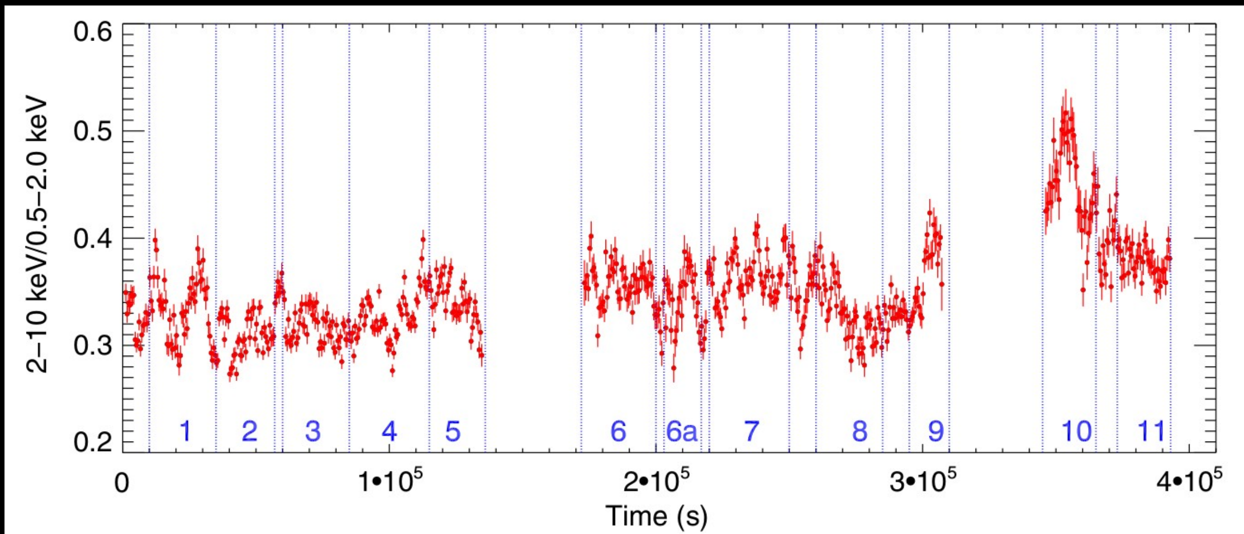
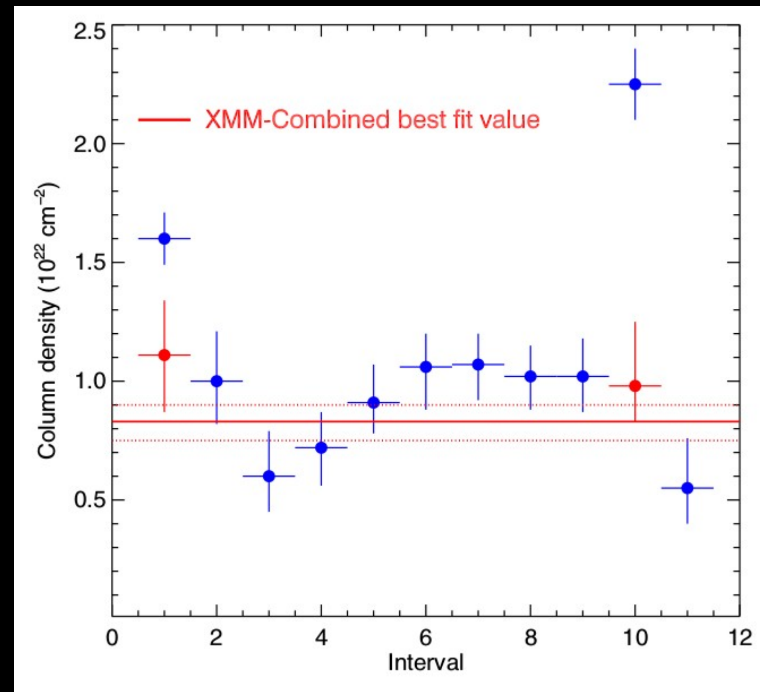
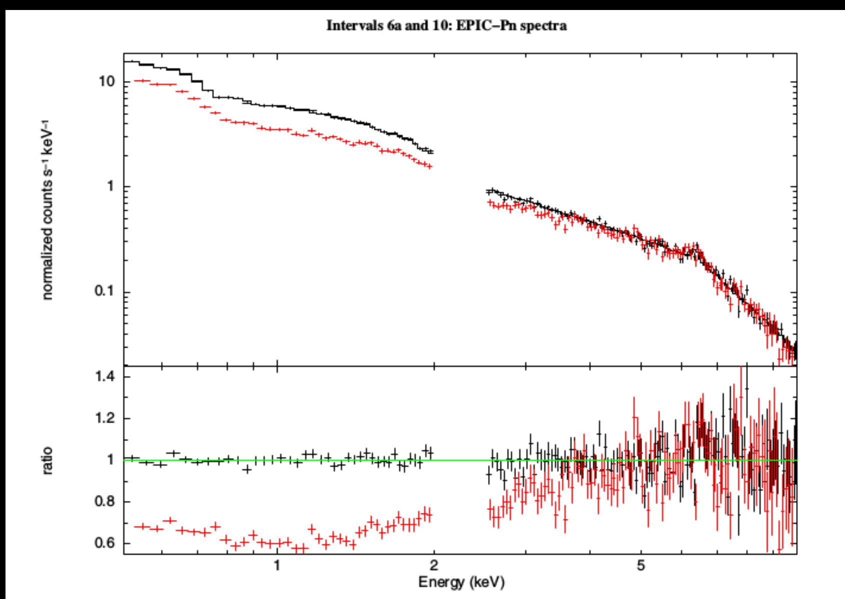




Marinucci et al. 2014



T_{occ}~20 ks

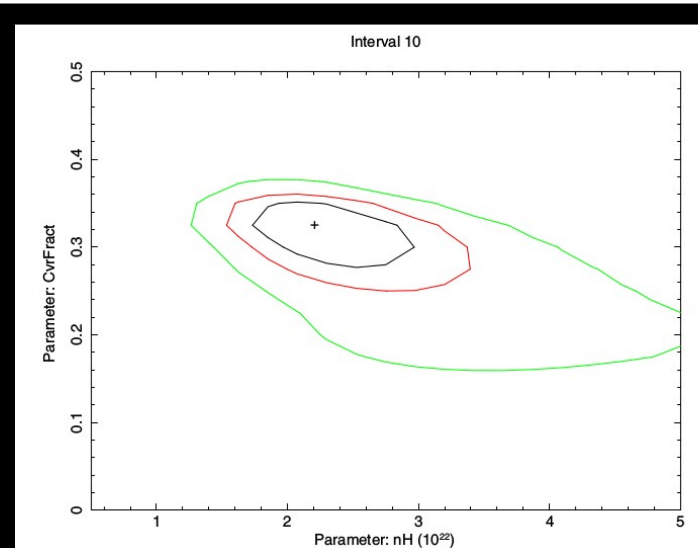
ΔCf=0.32

v_K~3000 km/s

$R=GM_{BH}v^{-2}=$

$=7\times10^{15}$ cm$=10^4$ R_g

$n\sim N_H/D_s\sim7\times10^9$ cm^{-3}



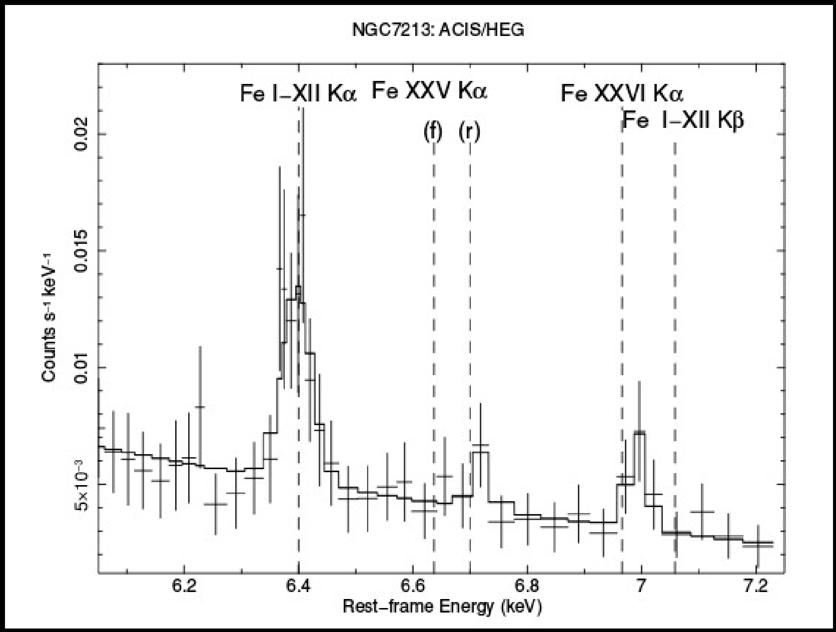
Sub-pc absorption/reflection

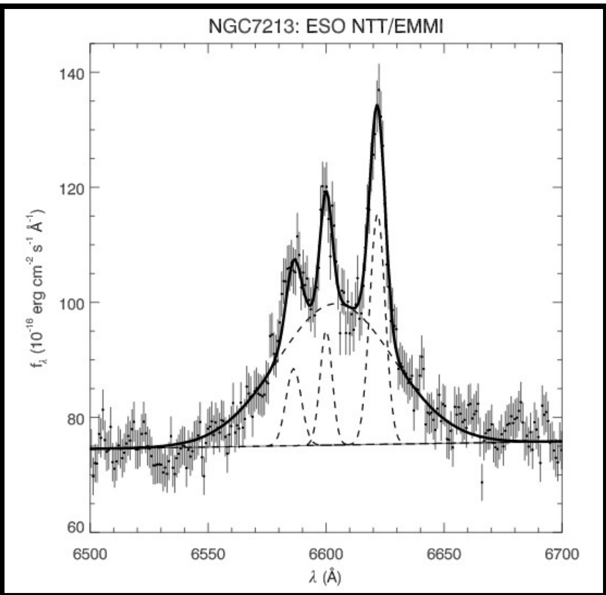
If the covering factor and the optical depth of the BLR are large enough, a significant fraction of the iron Kα emission line should be produced there.

NGC 7213 has no Compton reflection (Bianchi et al. 2003, 2004, Lobban et al. 2010, Ursini et al. 2015): the observed iron line cannot be associated to a Compton-thick material, like the torus or the disc.

Simultaneous optical/X-ray (Chandra HEG) observations show that the FWHM of the iron line Kα and that of the Hα are both ~2500 km/s

The iron Kα in NGC7213 is produced in the BLR!
(see also NGC2110: Marinucci et al 2015
and Ark 120: ~5000 km/s, Nardini et al. 2016)





Bianchi et al. 2008

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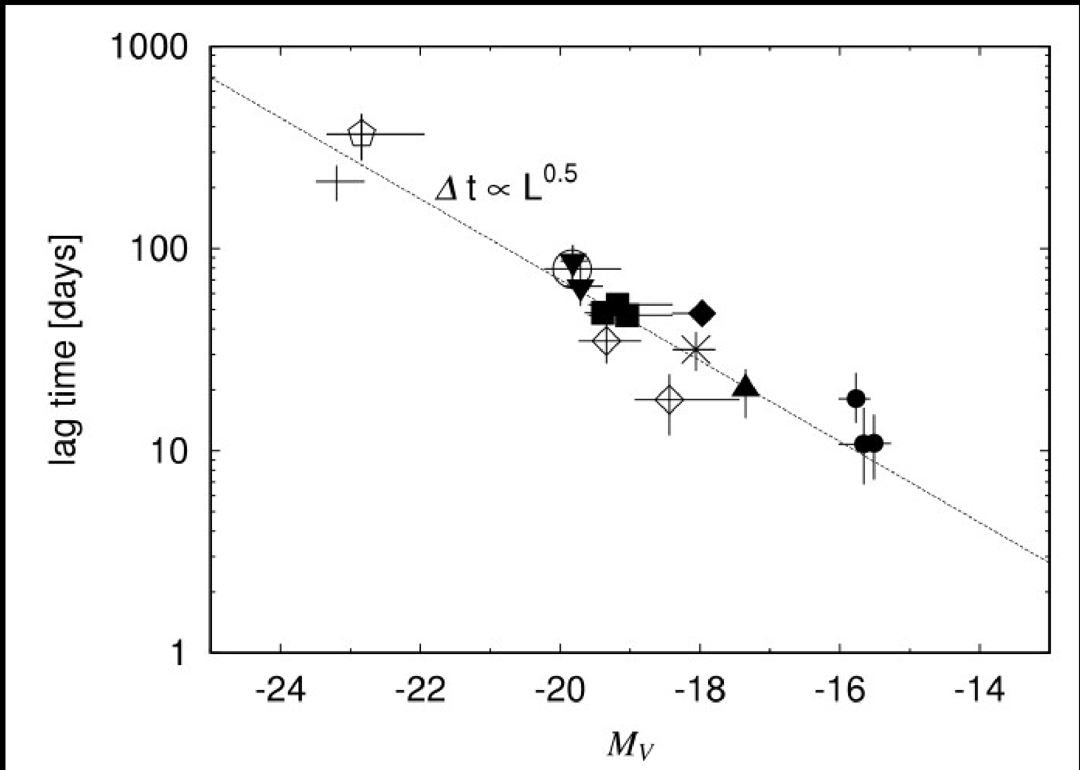
Pc-scale absorption

Early evidence for a circumnuclear dusty medium on (sub)parsec scales was obtained from near-IR studies, which revealed the presence of very hot dust, close to the sublimation temperature (Storchi-Bergmann et al. 1992, Alonso-Herrero et al. 2001, Oliva et al. 1999)

Extensive reverberation observational campaigns also confirmed the expected $L^{1/2}$ dependence of the sublimation radius (Suganuma et al. 2006)



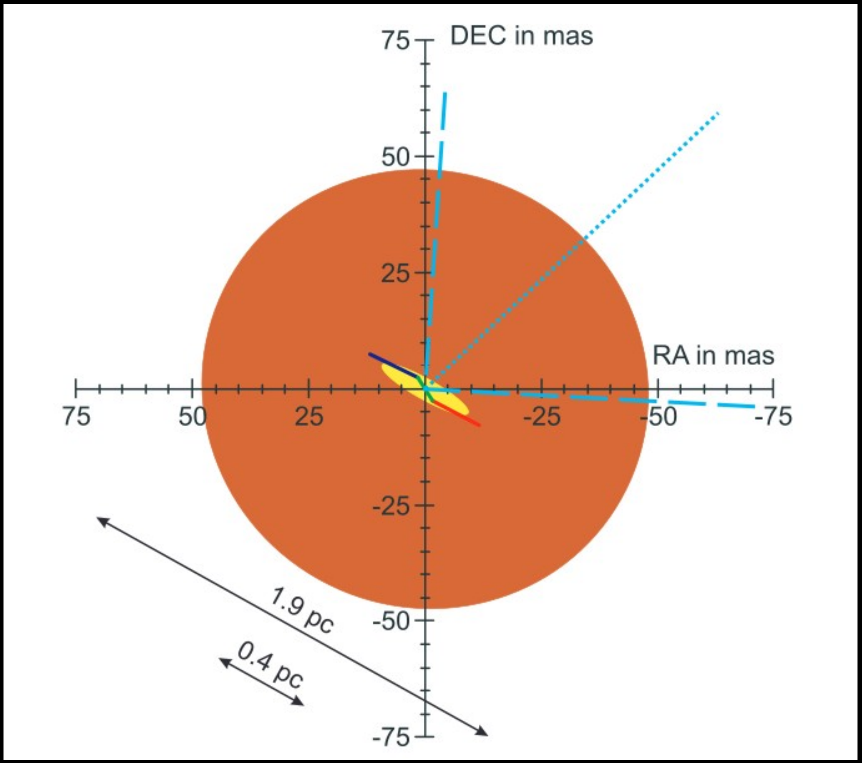
Suganuma et al. 2006

Pc-scale absorption

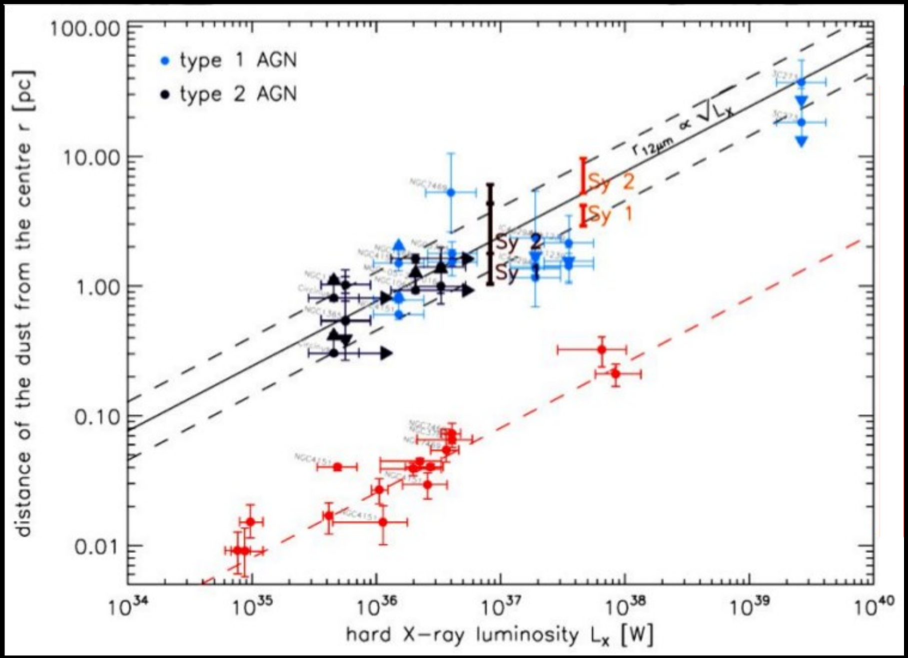
Mid-IR interferometry of NGC 1068 is consistent with a two-component dust distribution: an inner(0.5 pc) elongated hot (T>800 K) component, and a more extended (3-4 pc), less elongated colder (T~300 K) component (Jaffe et al. 2004)

Most of the absorption is located outside 1 pc.

A similar result was found for Circinus: again two components, an inner and more compact (0.4 pc), and an outer (2 pc) component.



Circinus: Tristram et al. 2007



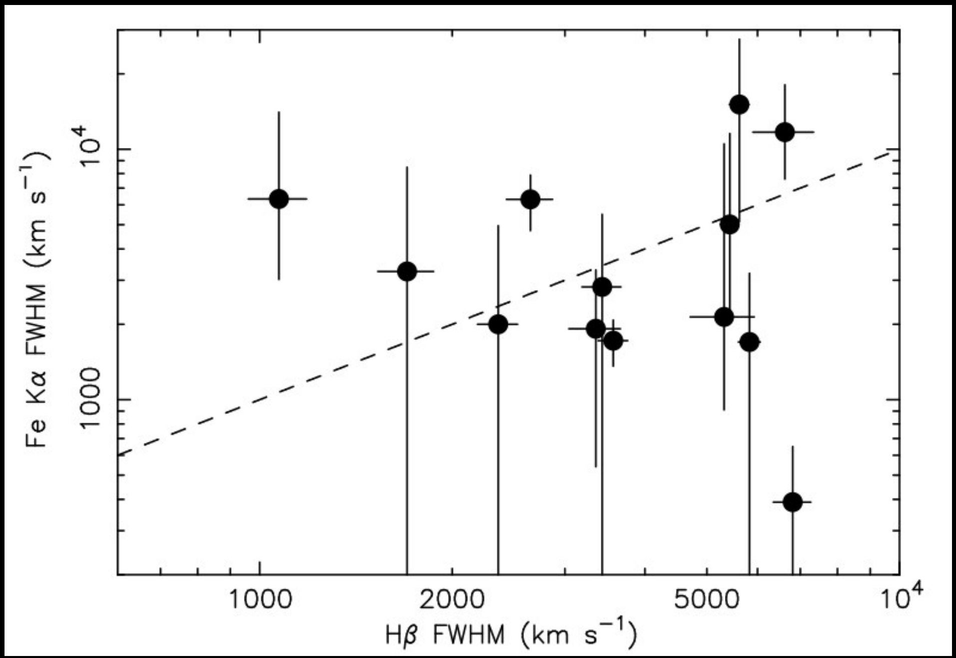
Tristram et al. 2011

No significant differences are found between type 1 and 2 sources and the size of the dusty emitter scales with the square root of the luminosity (Tristram et al. 2009, 11; Kishimoto et al. 2011)

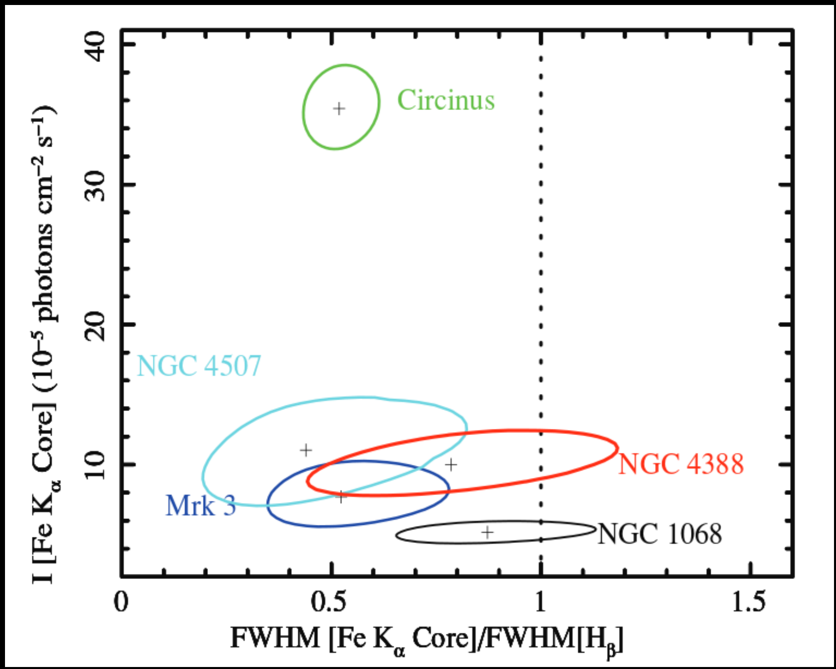
Pc-scale absorption/reflection

Compton-thick material with large covering factor is needed by the ubiquitous presence of the iron line and the Compton reflection component (Perola et al. 2002; Bianchi et al. 2004, 2009)

The line, typically unresolved (FWHM < thousands km/s), must be produced far (BLR/torus/NLR). Current X-ray satellites resolve its FWHM only in a few objects and with limited information, generally leading to inconclusive estimates on its location (Nandra et al. 2006, Shu et al. 2011)



Nandra, 2006



Shu et al. 2011

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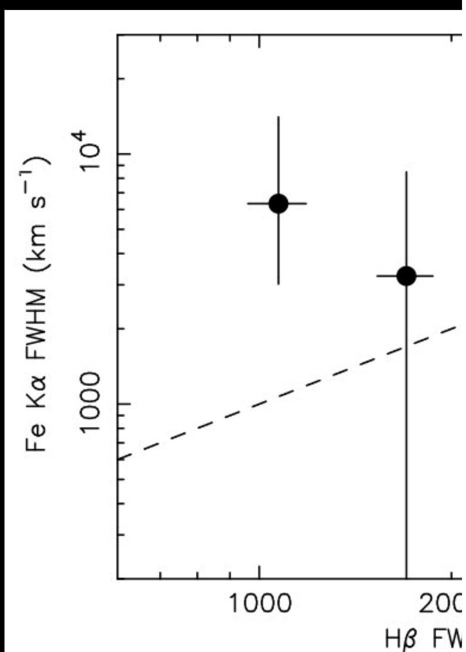
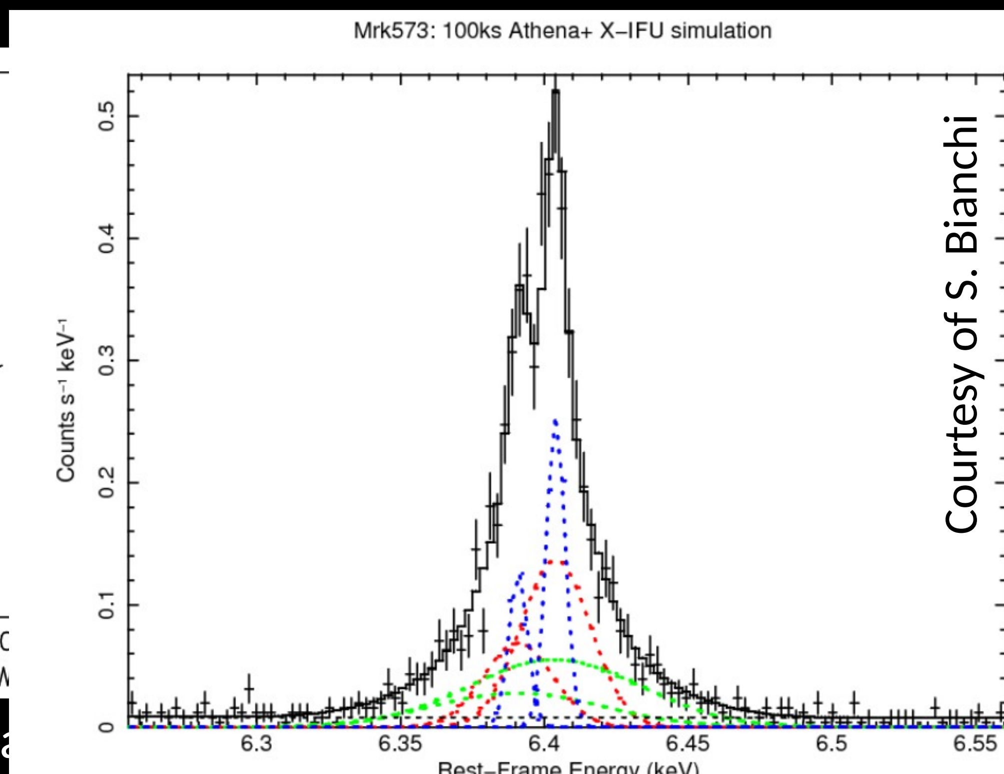
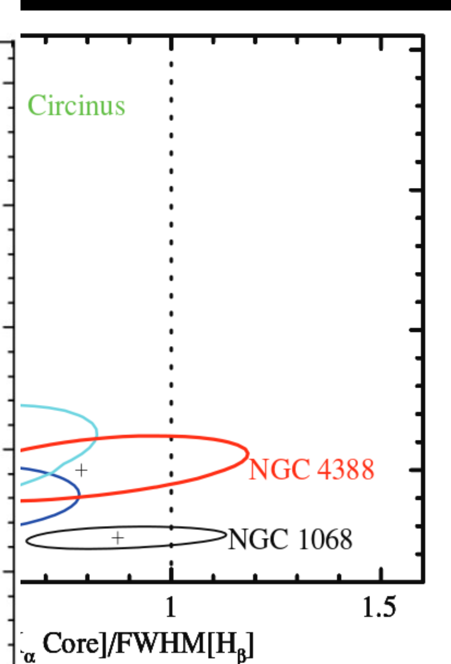




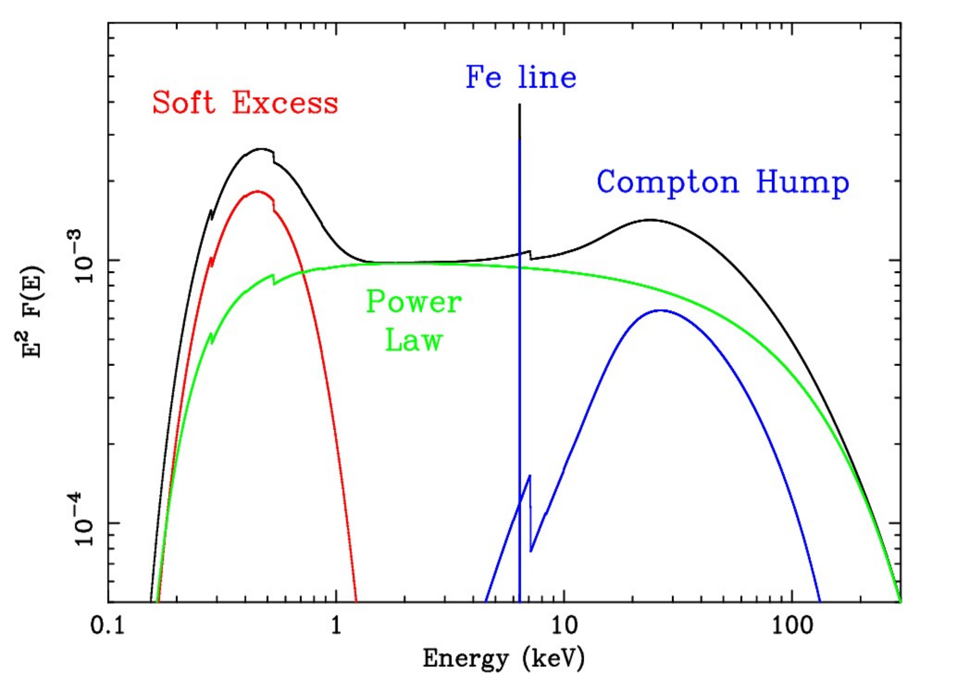


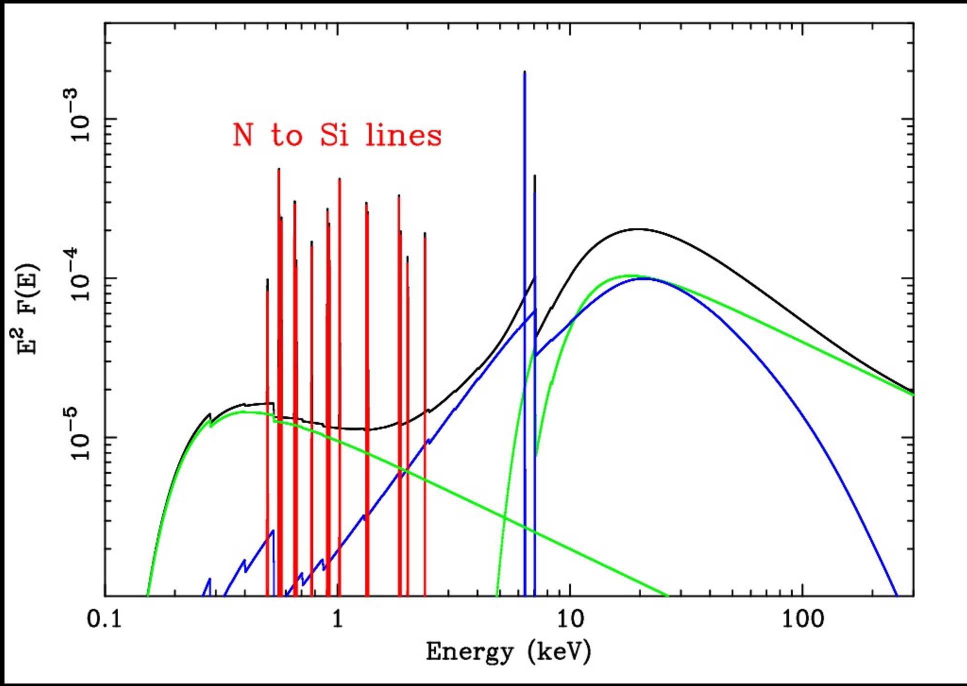
Nandra

et al. 2011

Pc-scale absorption/reflection

Nevertheless, strongly absorbed Seyfert 2 galaxies are the perfect laboratory for studying the circumnuclear cold material.

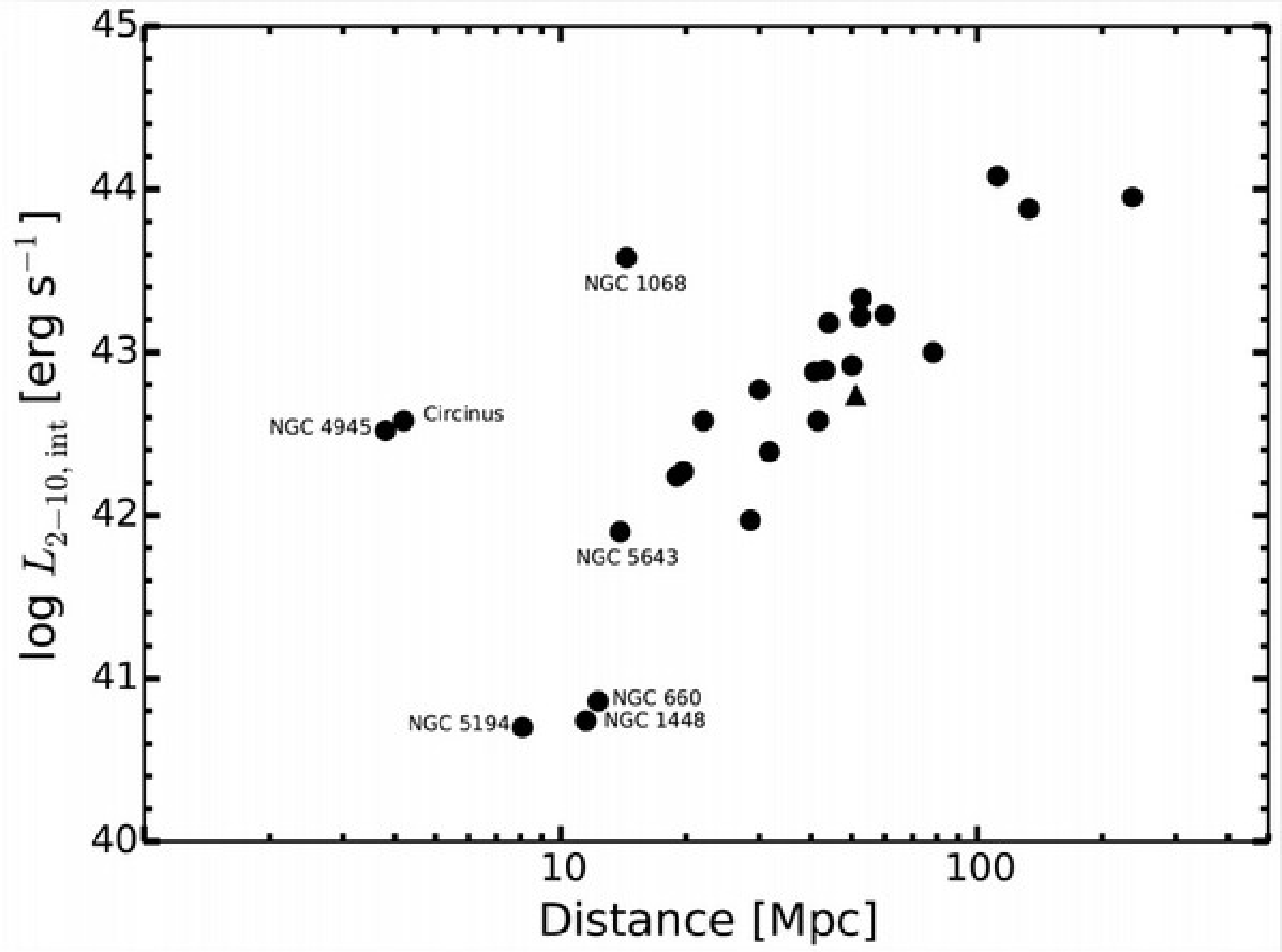




Fabian & Miniutti 2005

X-ray spectra of Compton-thick sources are completely dominated by reflection features, and they typically do not show any variability even on long time scales: the narrow iron line and the Compton reflection component are mostly produced on parsec-scale distance

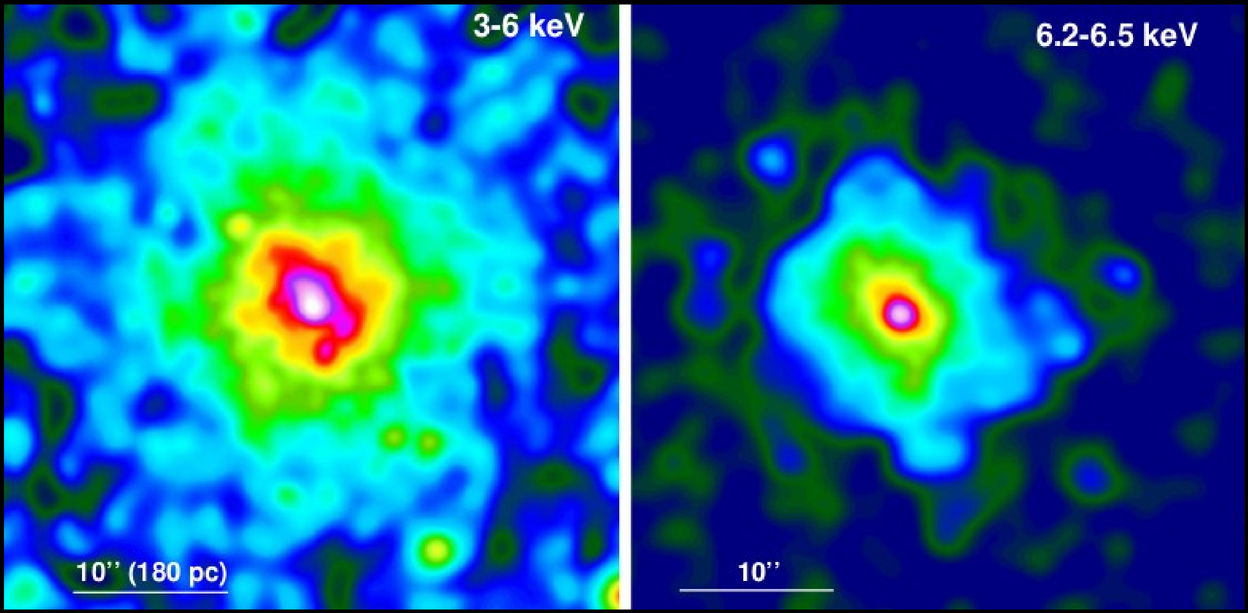
Pc-scale absorption/reflection



Gandhi et al. 2014; Annuar et al. 2017

With Chandra we have the angular resolution to spatially resolve some of this systems.

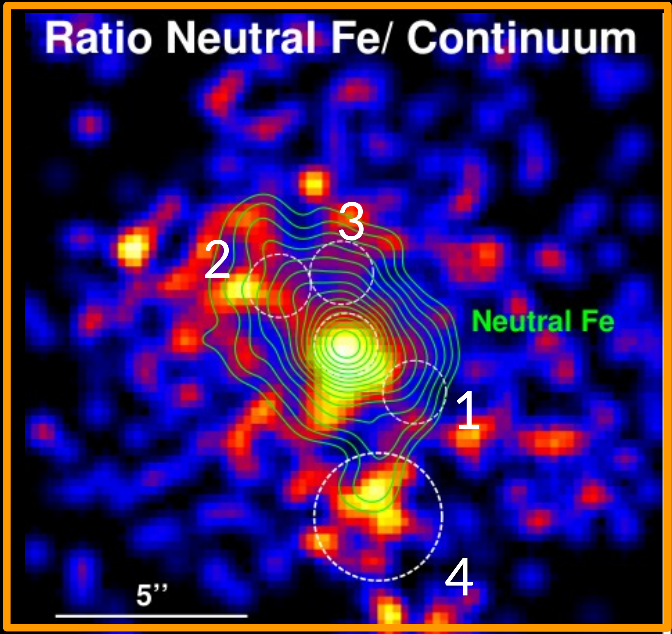
Pc-scale absorption/reflection (NGC 4945)



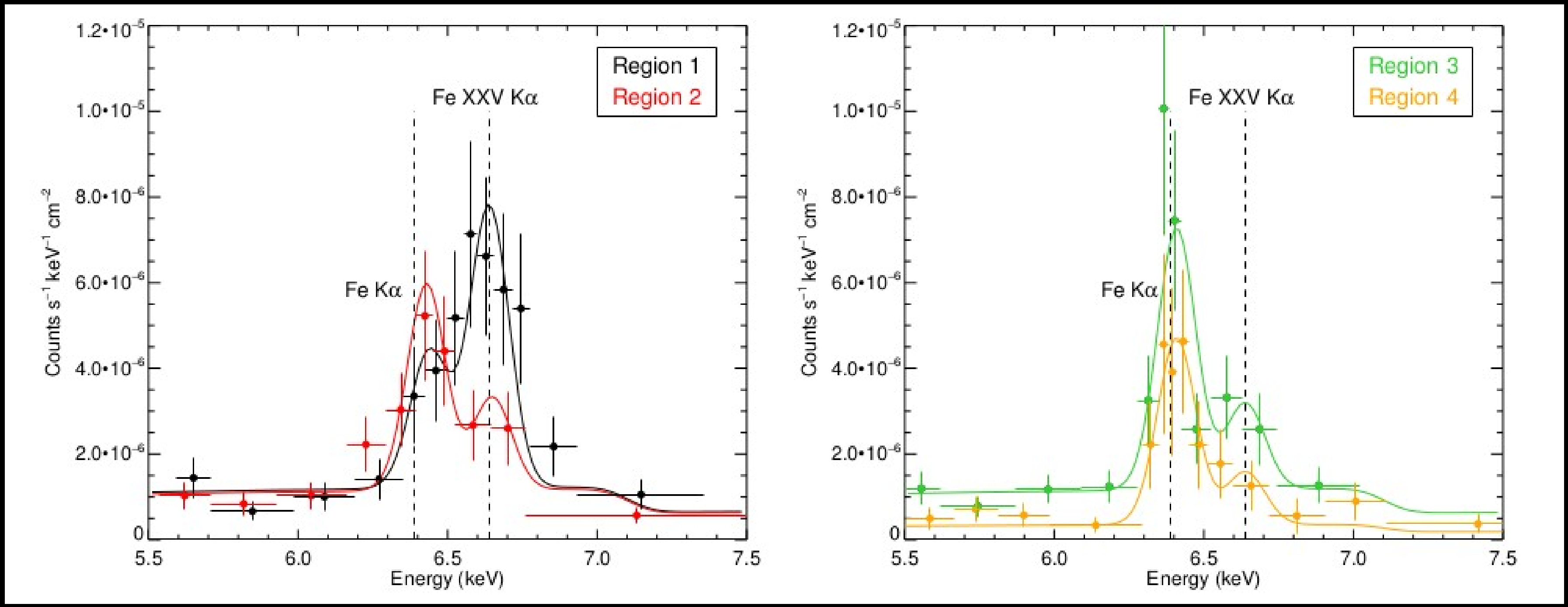
Marinucci et al. 2017

Imaging analysis with Chandra (~ 420 ks) revealed that the Iron Kα and the associated Compton reflection continuum are spatially extended on scales of hundreds of parsecs.

The unresolved, nuclear emission confirms to remain constant throughout the 13 years of monitoring.
The Equivalent Width of the neutral Fe Kα emission line is 2.7±0.5 keV.



Pc-scale absorption/reflection (NGC 4945)



Parameter	Reg. 1	Reg. 2	Reg. 3	Reg. 4
N_{pexrav}	0.40 ± 0.03	0.39 ± 0.03	0.37 ± 0.08	0.12 ± 0.02
Fe Kα				
Energy	6.44 ± 0.05	6.43 ± 0.03	6.40 ± 0.03	$6.40^{+0.02}_{-0.03}$
Flux	0.05 ± 0.02	0.08 ± 0.02	0.09 ± 0.03	0.07 ± 0.02
EW	$0.45^{+0.30}_{-0.20}$	$0.65^{+0.30}_{-0.25}$	$0.75^{+0.40}_{-0.25}$	$2.15^{+1.30}_{-0.85}$
Fe XXV Kα				
Energy	$6.65^{+0.03}_{-0.04}$	6.66 ± 0.07	6.65 ± 0.06	6.60 ± 0.10
Flux	0.11 ± 0.03	0.04 ± 0.02	0.03 ± 0.02	0.02 ± 0.01
EW	0.90 ± 0.30	0.30 ± 0.25	0.35 ± 0.30	$0.60^{+0.70}_{-0.45}$
$F_{3-10\ keV}$	0.80 ± 0.07	0.75 ± 0.08	0.85 ± 0.08	0.28 ± 0.05
C/d.o.f.	37/51	65/40	28/38	26/31

Pc-scale absorption/reflection (NGC 4945)

The Fe Kα EW, depends on the Fe abundance (Matt et al, 1997), on the angle θ between the polar direction and the line of sight (Matt et al., 1991; George & Fabian, 1991) and on the column density of the illuminated material (Yaqoob et al. 2010, Matt 2002).

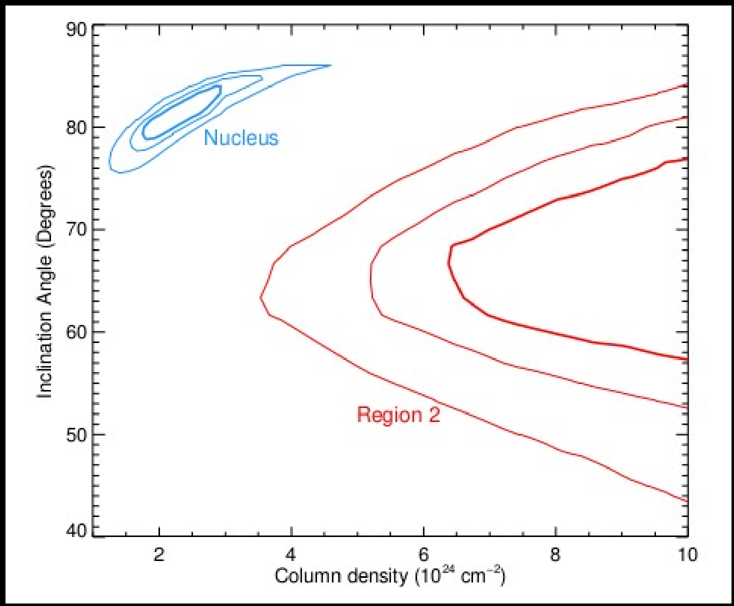
We therefore used different models to retrieve the observed EWs of the Fe Kα in the nuclear region (2.7±0.5 keV) and in region 2 (0.65±0.30 keV).

Pexmon

A_{fe}(Nucleus)=3.2±0.4

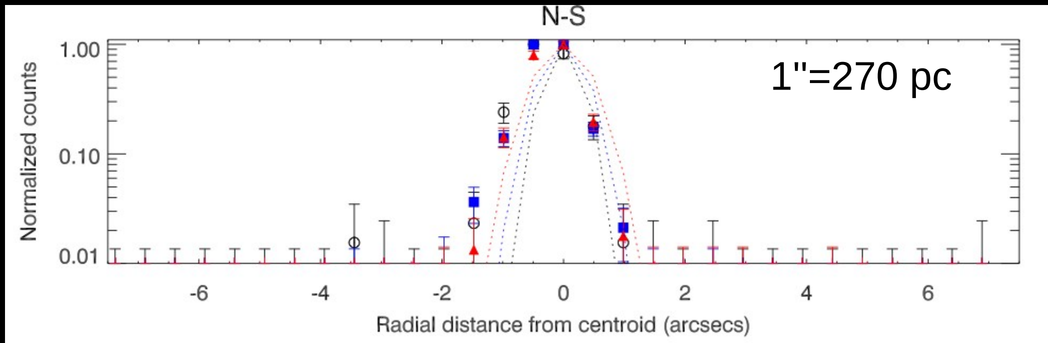
A_{fe}(Region 2)=0.8±0.5

MYtorus



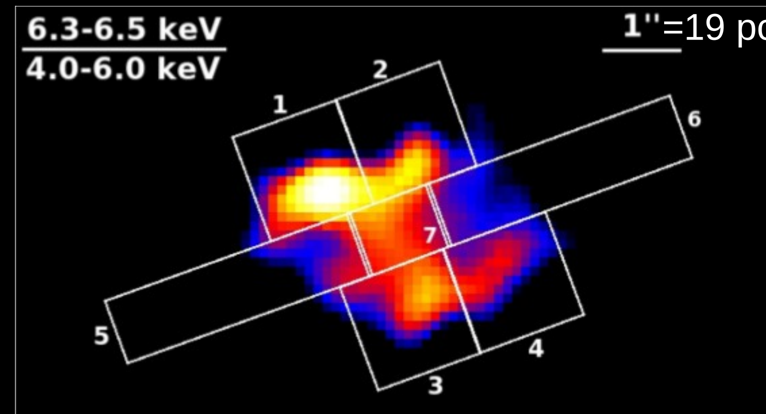
(Not so-)Pc-scale absorption/reflection

Mrk 3



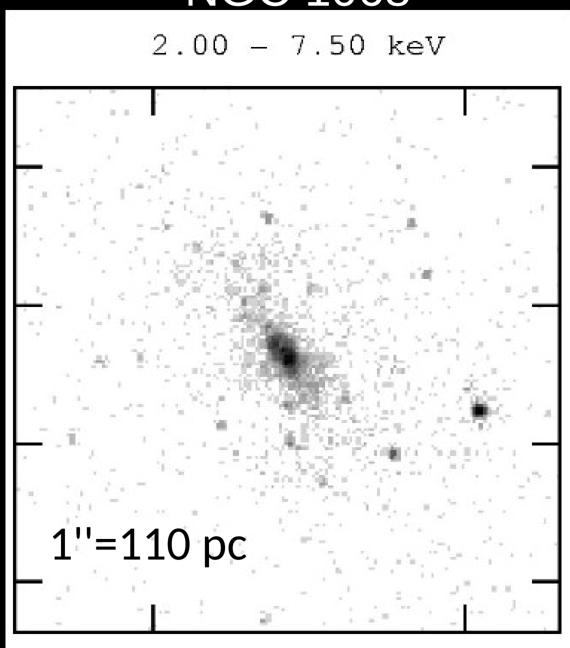
Guainazz et al 2011

Circinus



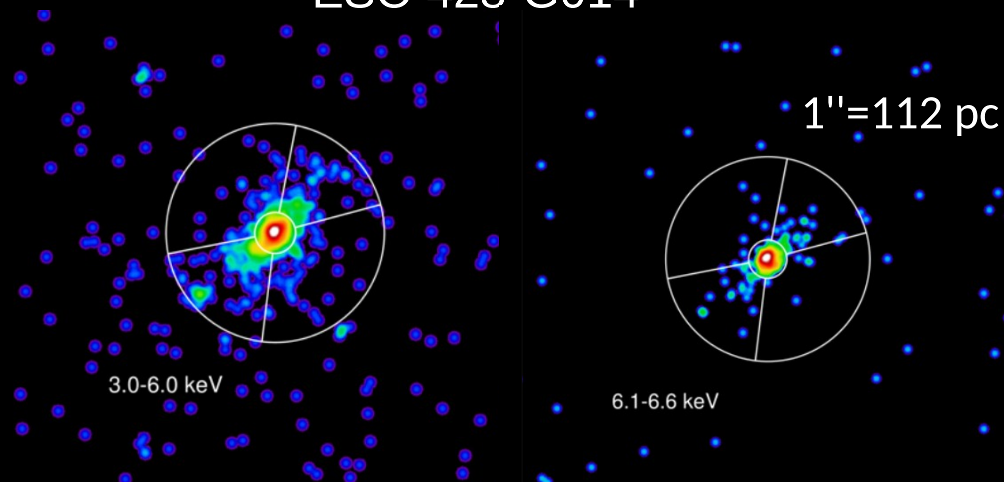
Marinucci et al. 2013

NGC 1068



Young et al 2001

ESO 428-G014



Fabbiano et al. 2017

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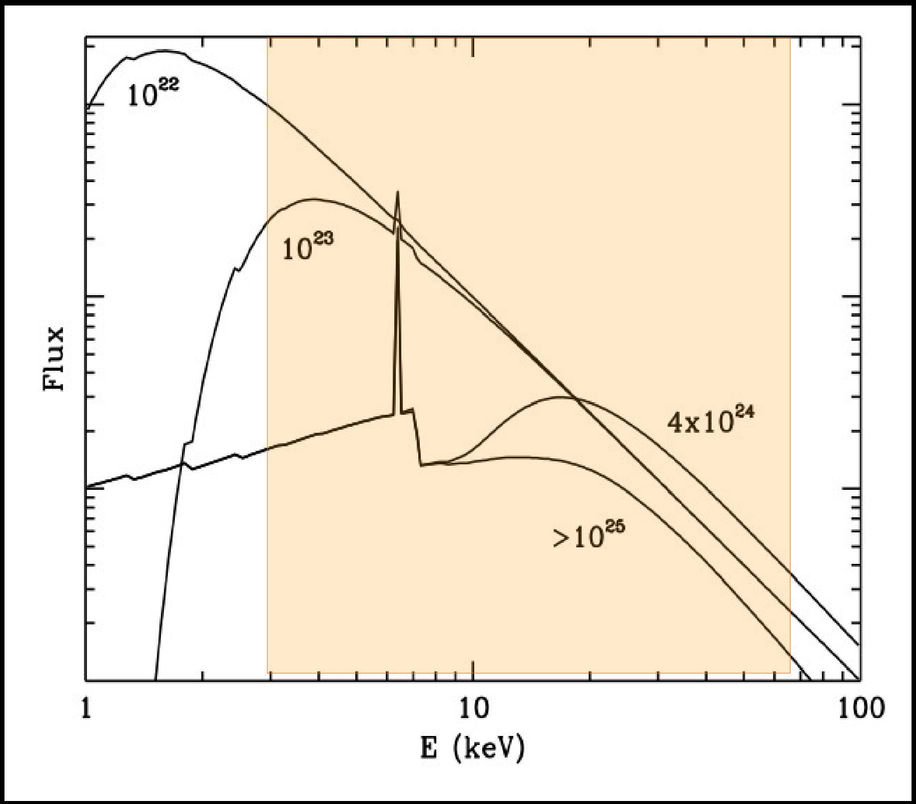
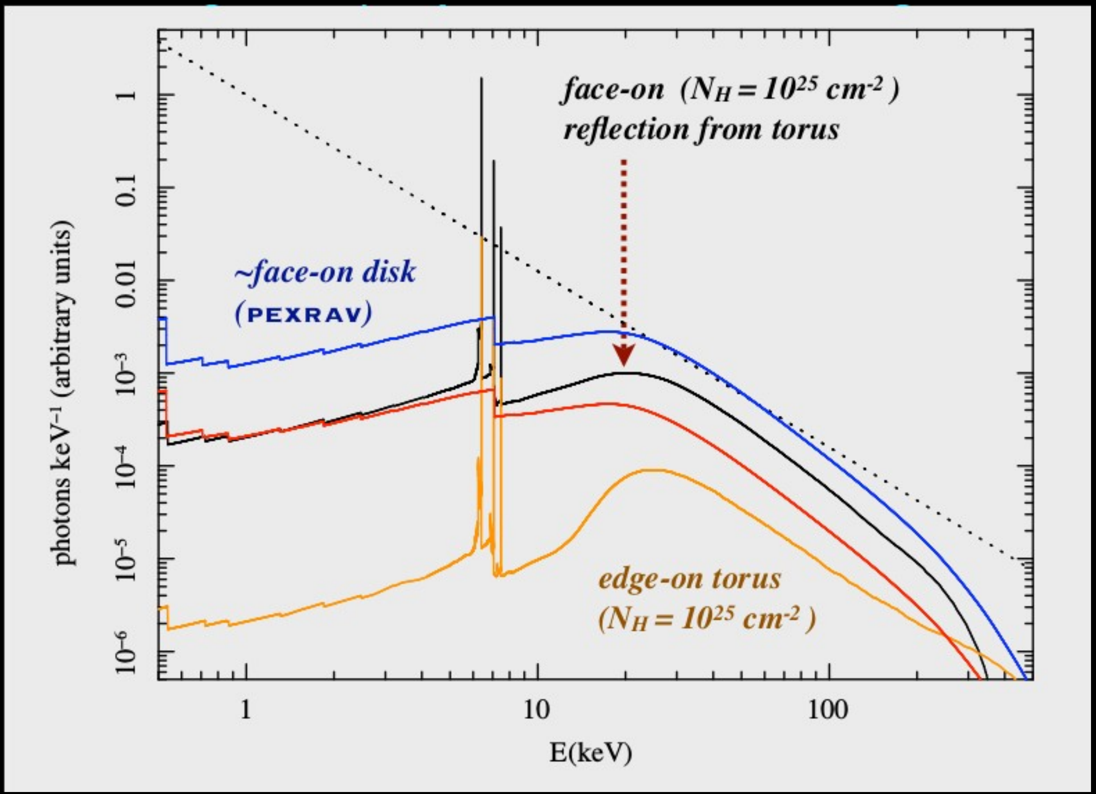
Hard X-ray view of Seyfert 2 galaxies

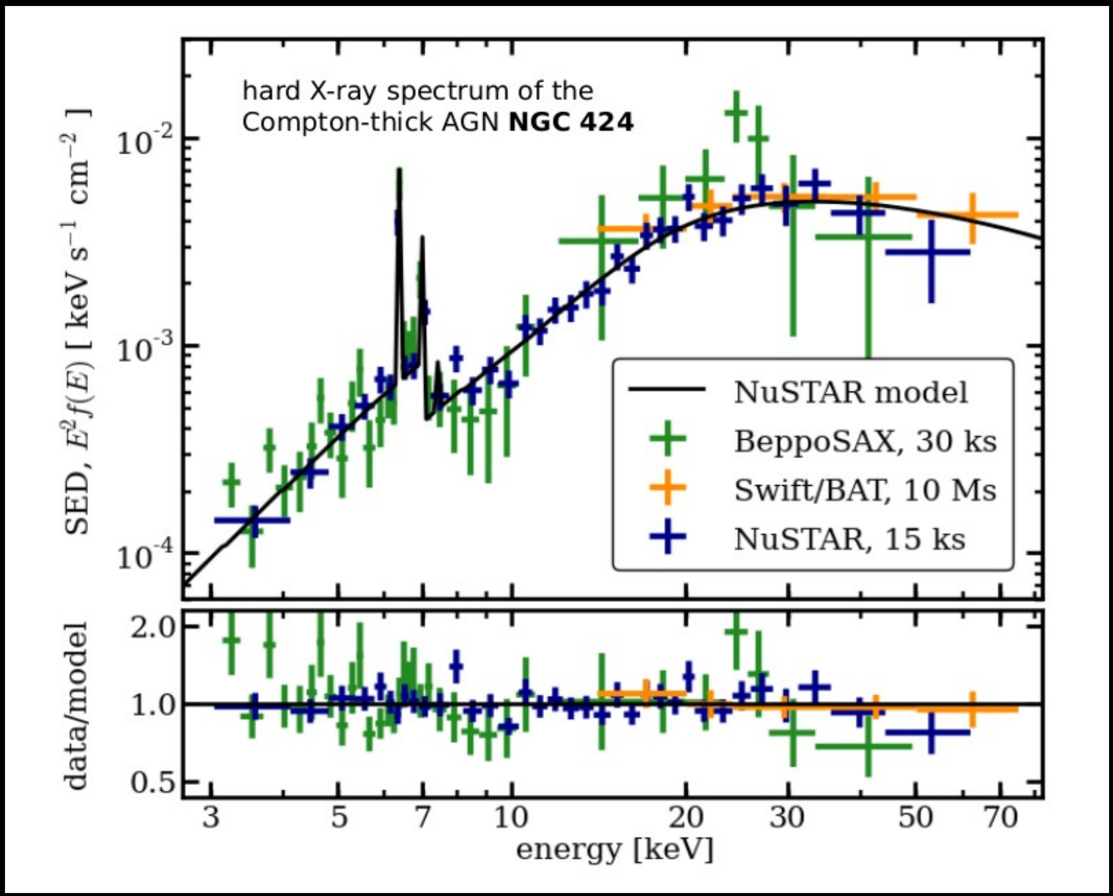


Matt et al., 2003

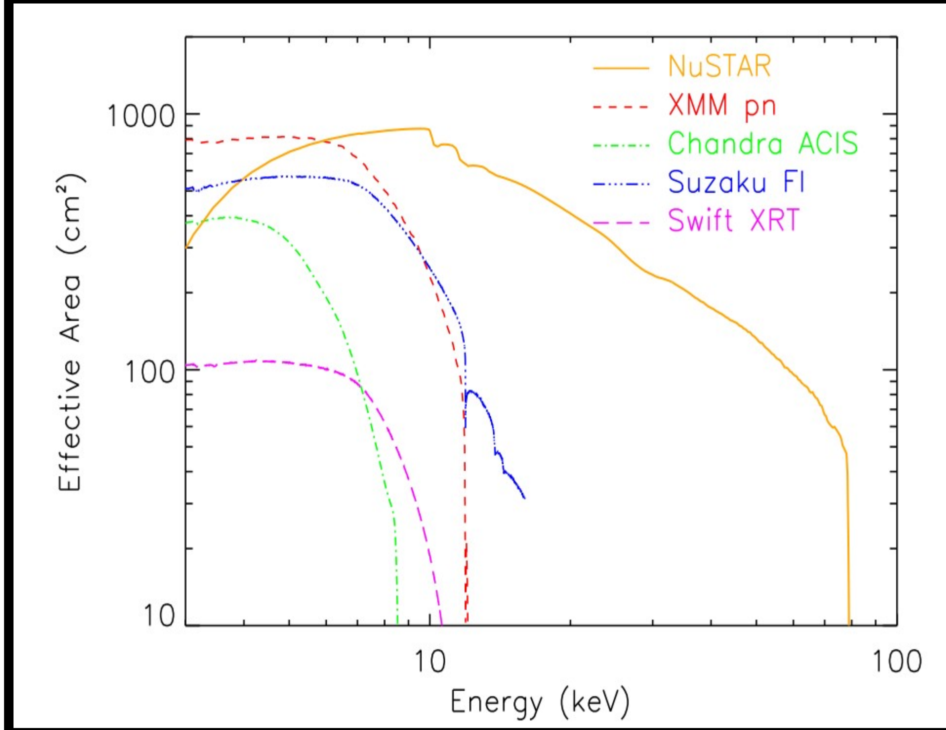


Yaqoob & Murphy, 2010

Hard X-ray view of Seyfert 2 galaxies



Balokovic et al. 2013



Harrison et al. 2013

NuSTAR Survey of Swift/BAT AGN

Swift/BAT 70-month catalog AGN

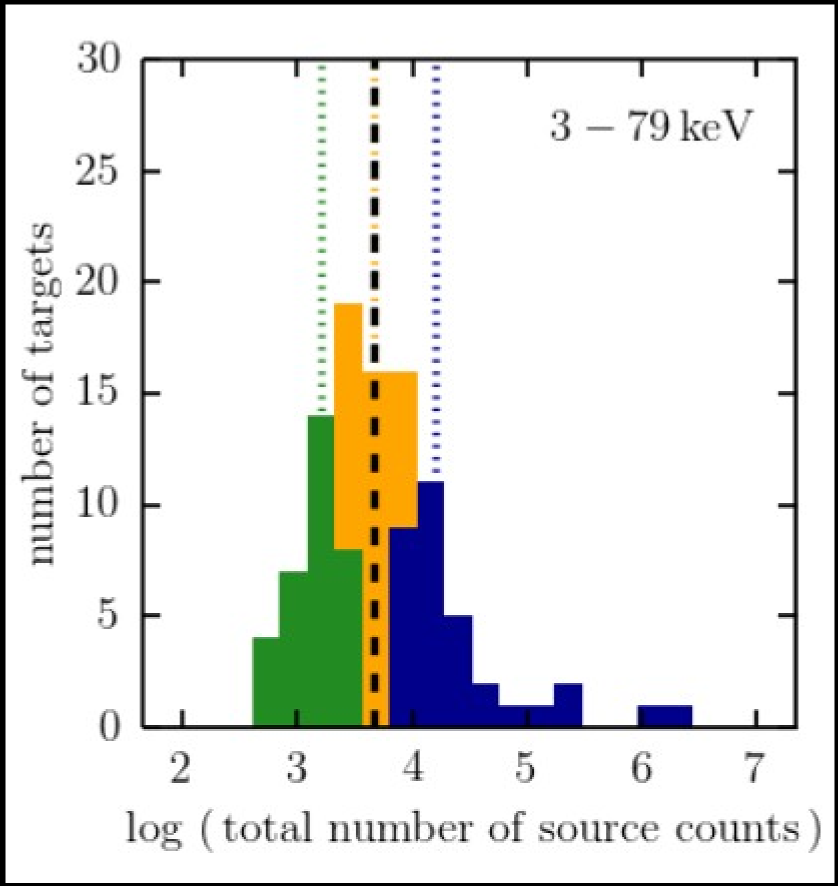
- some targeted programs

→ ~100 ks of NuSTAR exposure
→ simultaneous soft X-ray coverage

- mostly “snapshot” observations
→ short 15-25 ks exposures
→ simultaneous Swift/XRT (7 ks)

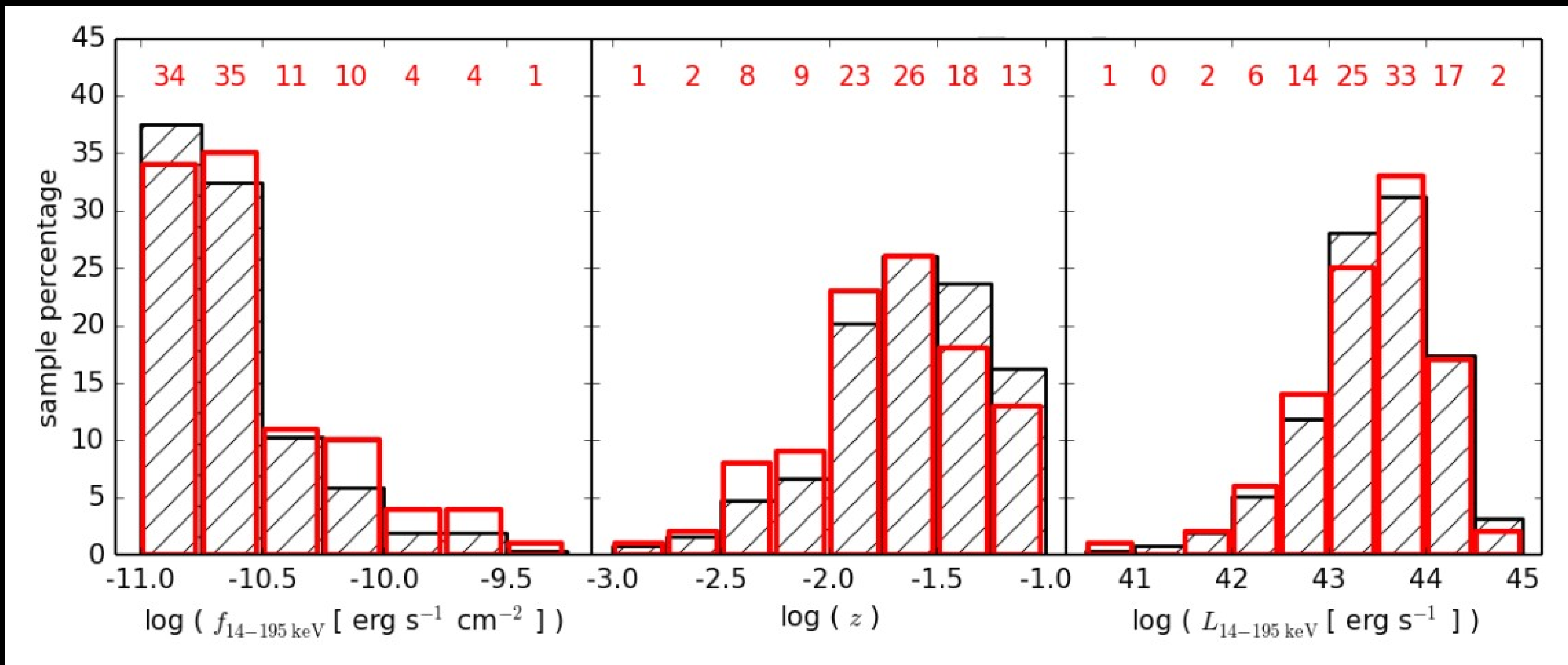
- typically ~5000 cts in total (500–10 6)

- not representative in general, but the Sy2 subsample can be made representative



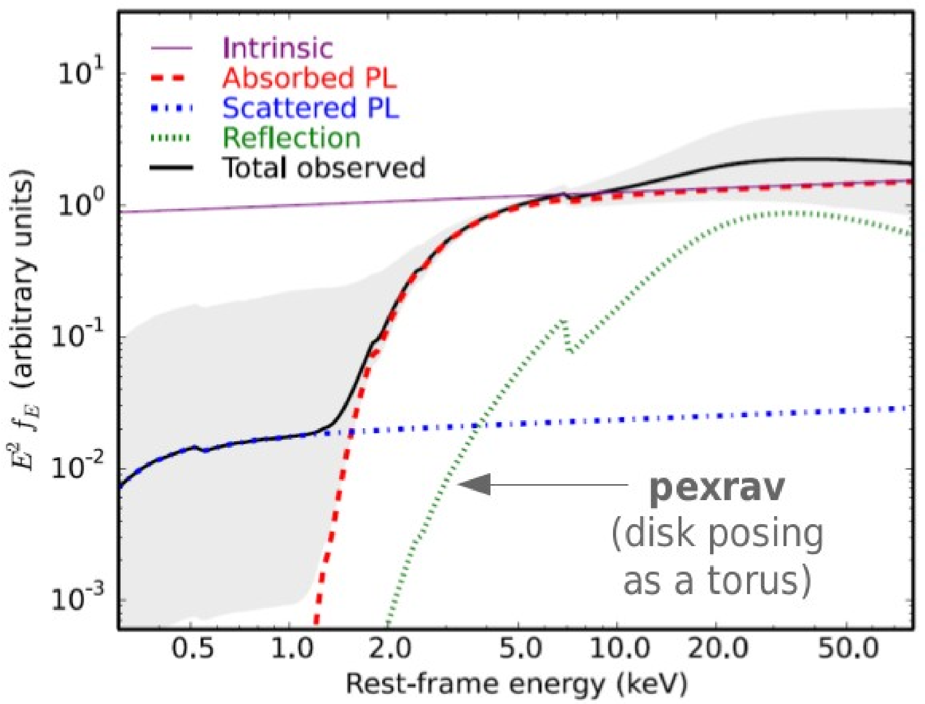
Baloković et al., in prep.

Subsample of 120 Seyfert 2 galaxies



Baloković et al., in prep.

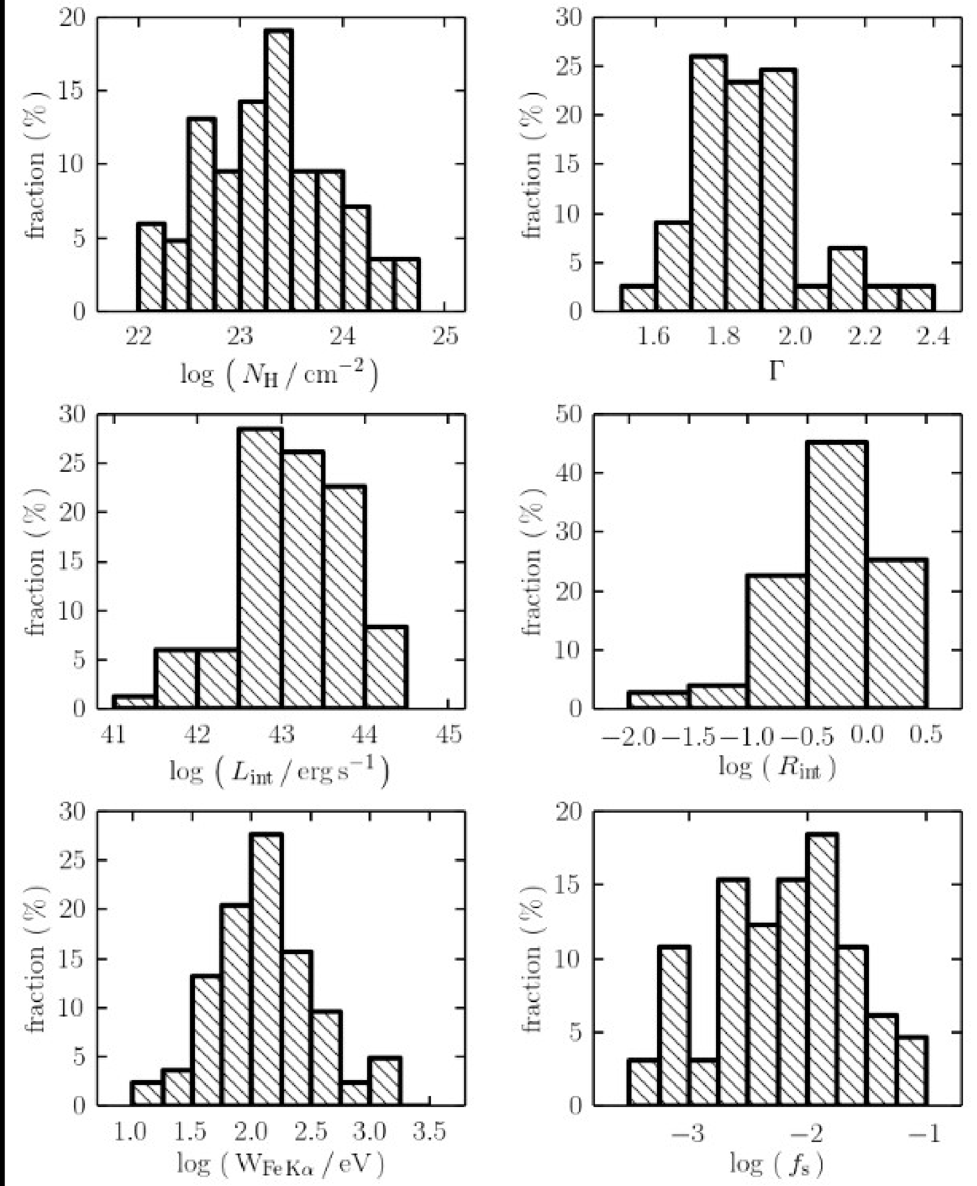
NuSTAR view of Seyfert 2s



→ with minor variations, used ubiquitously in the literature to describe Sy2 spectra

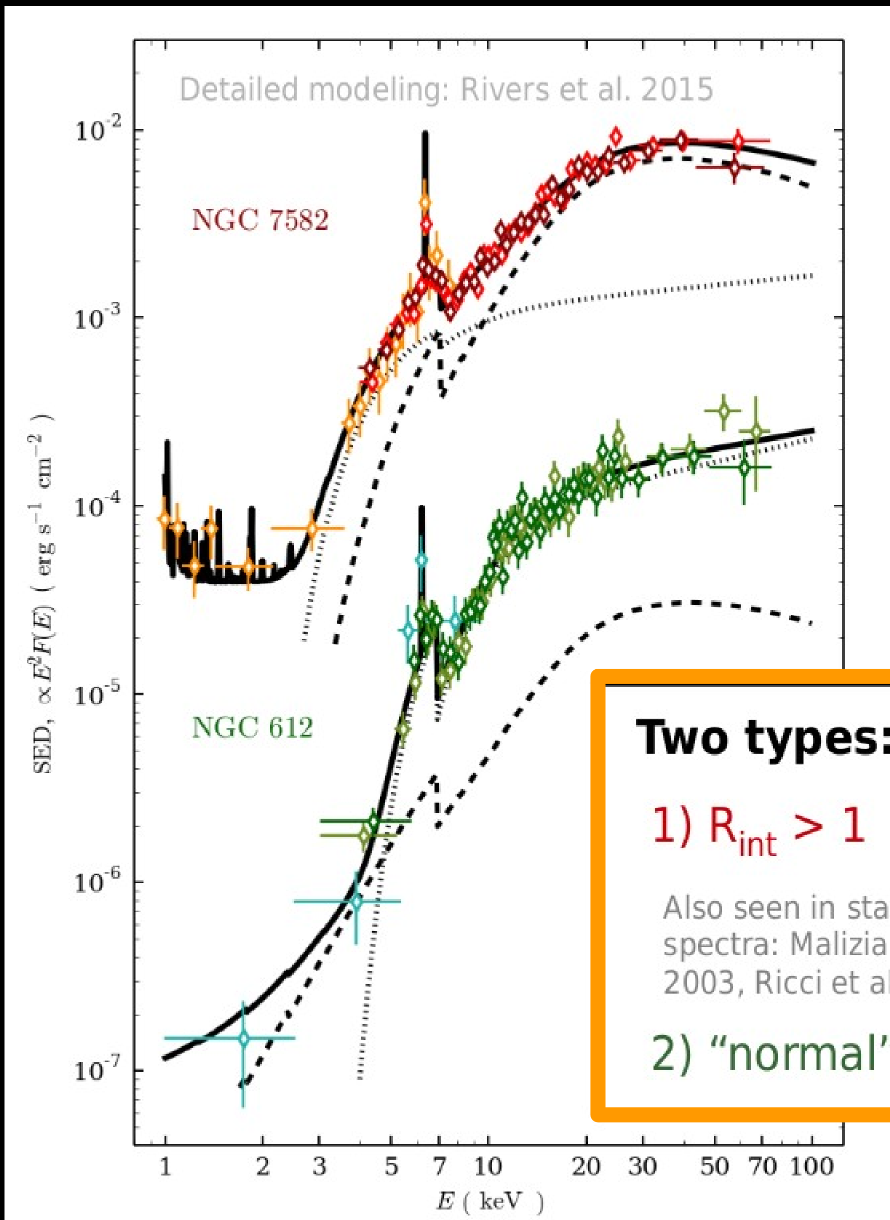
R_{int} as a replacement for R_{pexrav}

$R_{int} = L_{reflection} / L_{intrinsic}$ (10-50 keV)



Balokovic et al., in prep.

NuSTAR view of Seyfert 2s

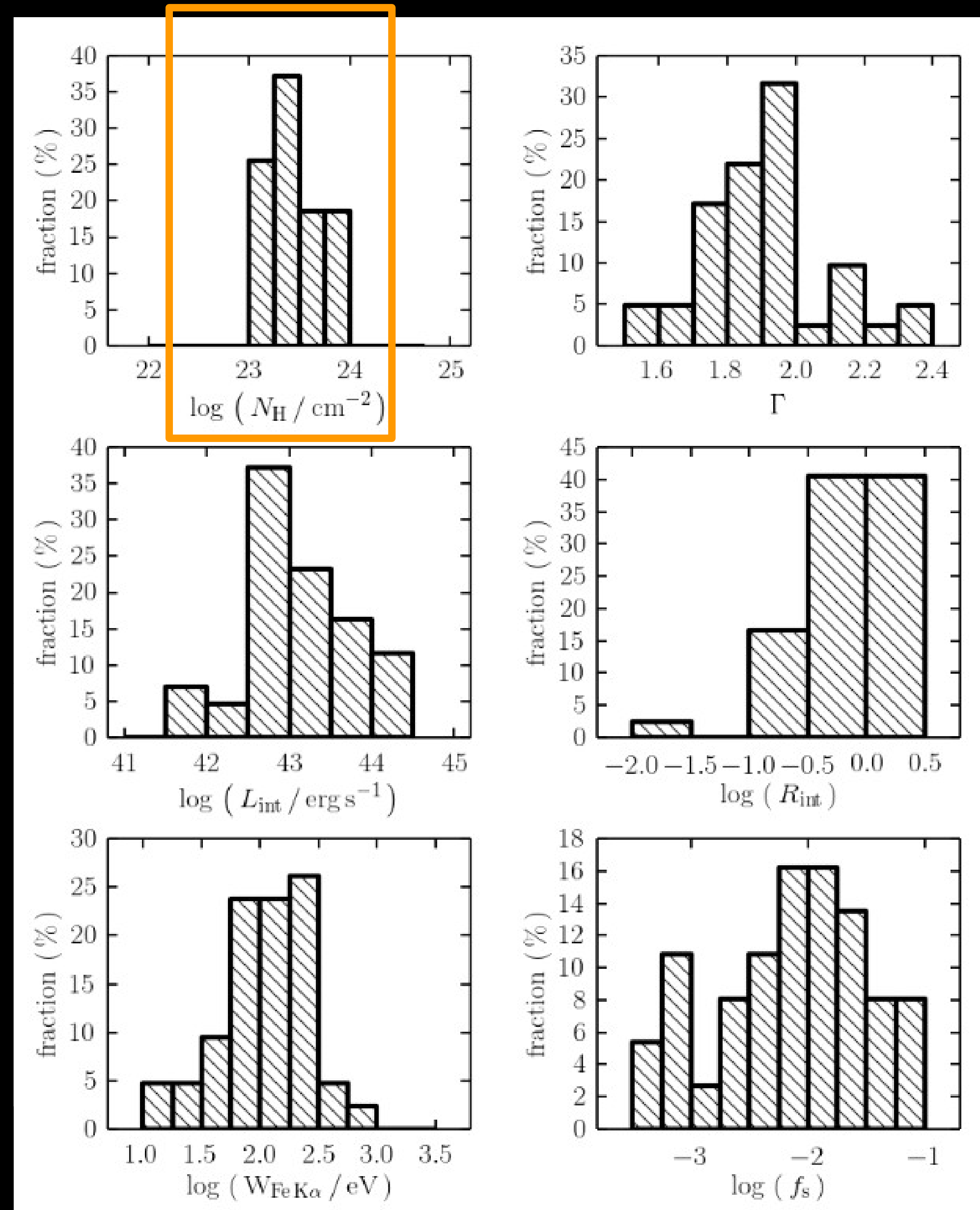


Two types:

1) $R_{int} > 1$

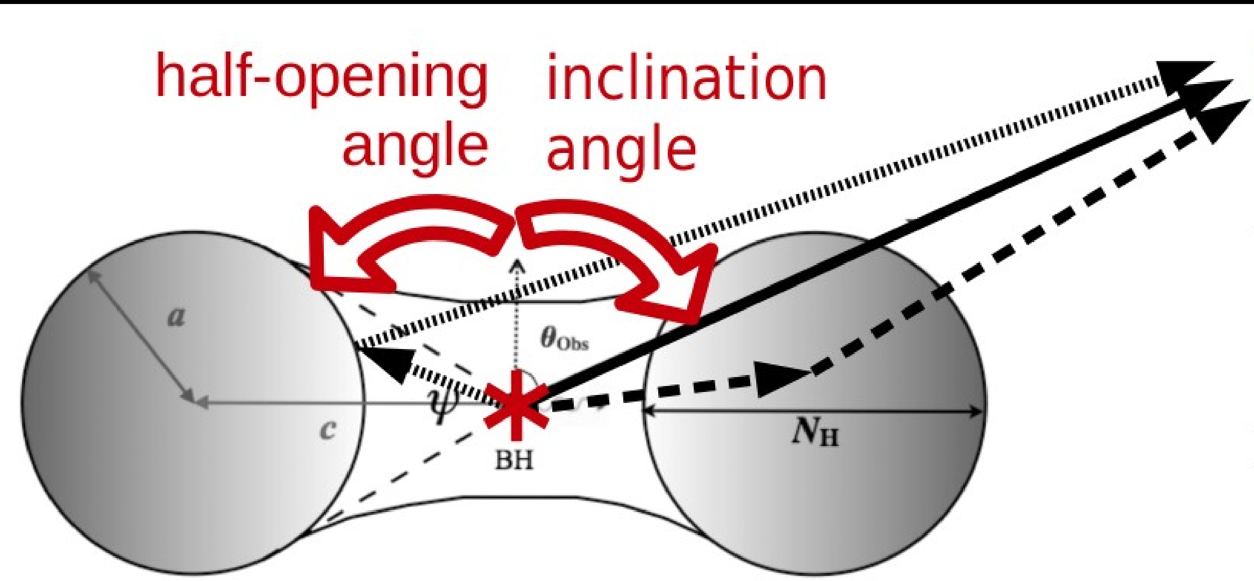
Also seen in stacked spectra: Malizia et al. 2003, Ricci et al. 2011

2) “normal”



Baloković et al., in prep.

NuSTAR view of Seyfert 2s

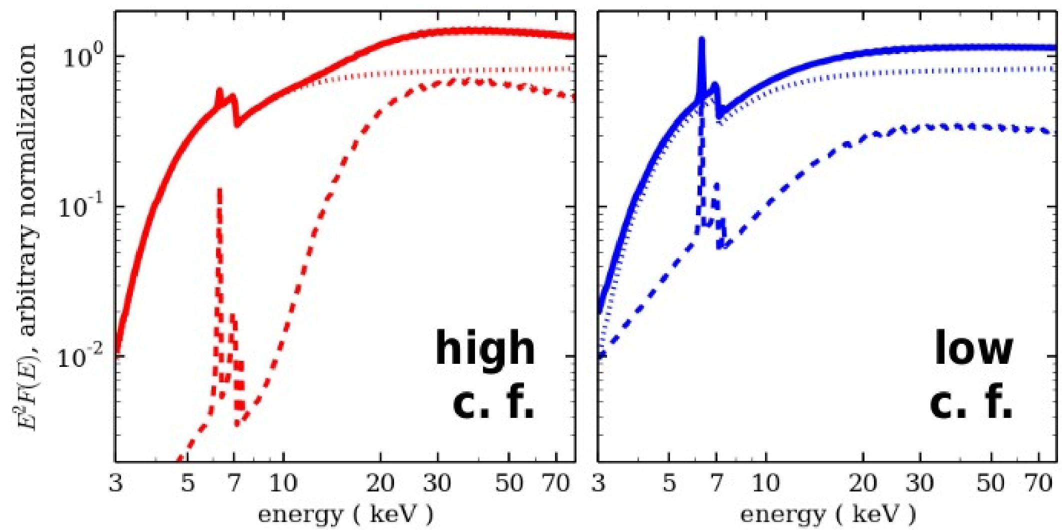


Murphy & Yaqoob (2009)

→ fixed covering factor (1/2)

Brightman & Nandra (2011)

→ $N_{H,l.o.s.} = N_{H,torus}$ (or zero)



"Majority of local Swift/BAT-selected Seyfert 2 nuclei have an inhomogeneous borderline Compton-thick torus-like obscurer with a high covering factor."

Baloković et al., in prep.

The variable absorber in NGC 1068

We observed NGC 1068 with a joint XMM-*Newton* and NuSTAR monitoring campaign, from July 2014 until February 2015

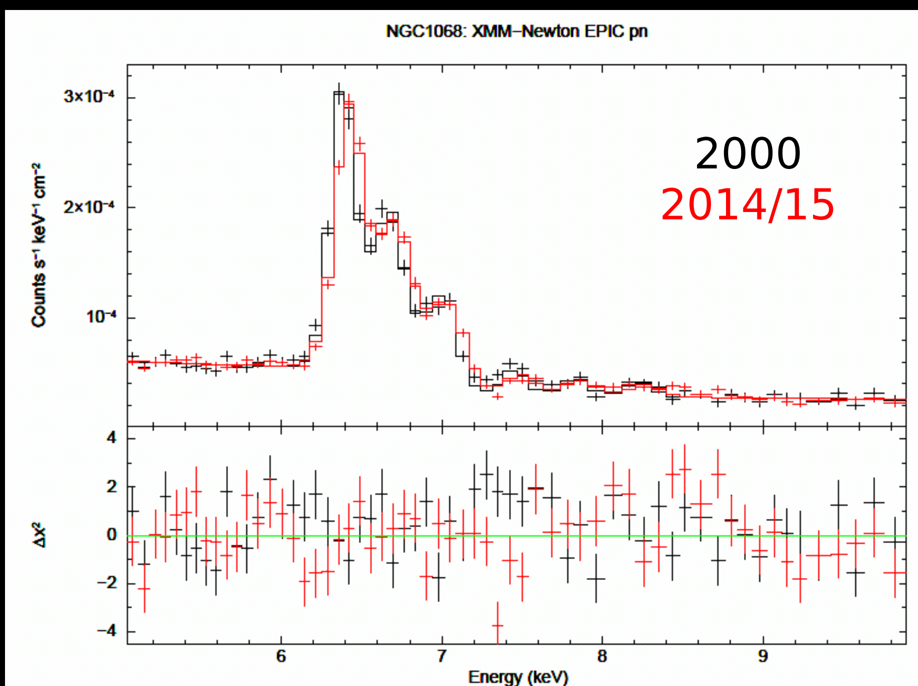
Longer time-scales can be probed thanks to the two previous XMM-*Newton* observations performed in 2000 (Matt et al. 2003), and the NuSTAR observation performed in 2012 (Bauer et al. 2014)

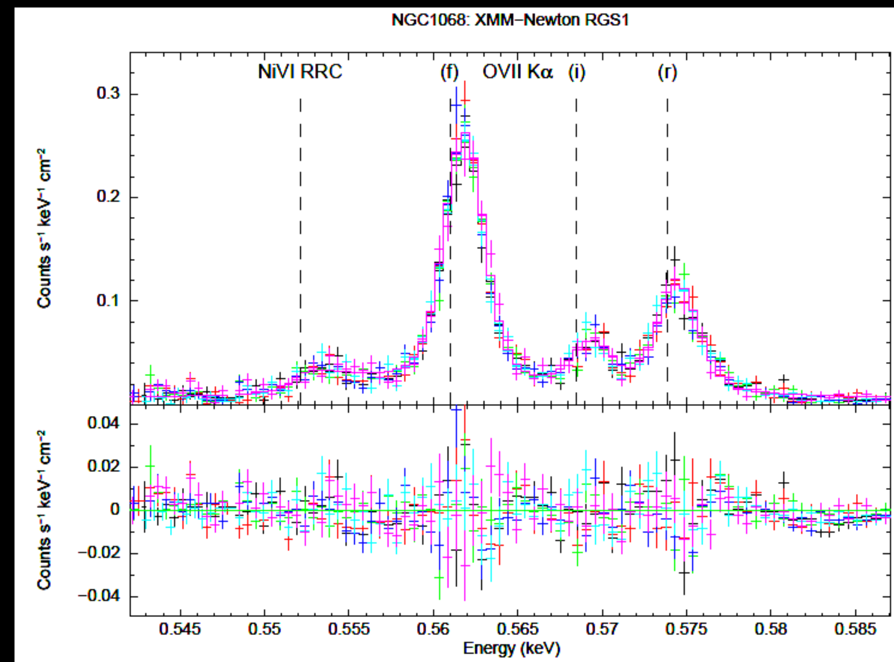
The variable absorber in NGC 1068

No variability is found between the four XMM spectra, and with respect to the spectrum taken in July 2000

<u>The neutral Iron Kα line is constant within 5%</u>

Although the intrinsic variability is unknown, this suggest that most of the line/reflection is produced far away





Bianchi et al., in prep.

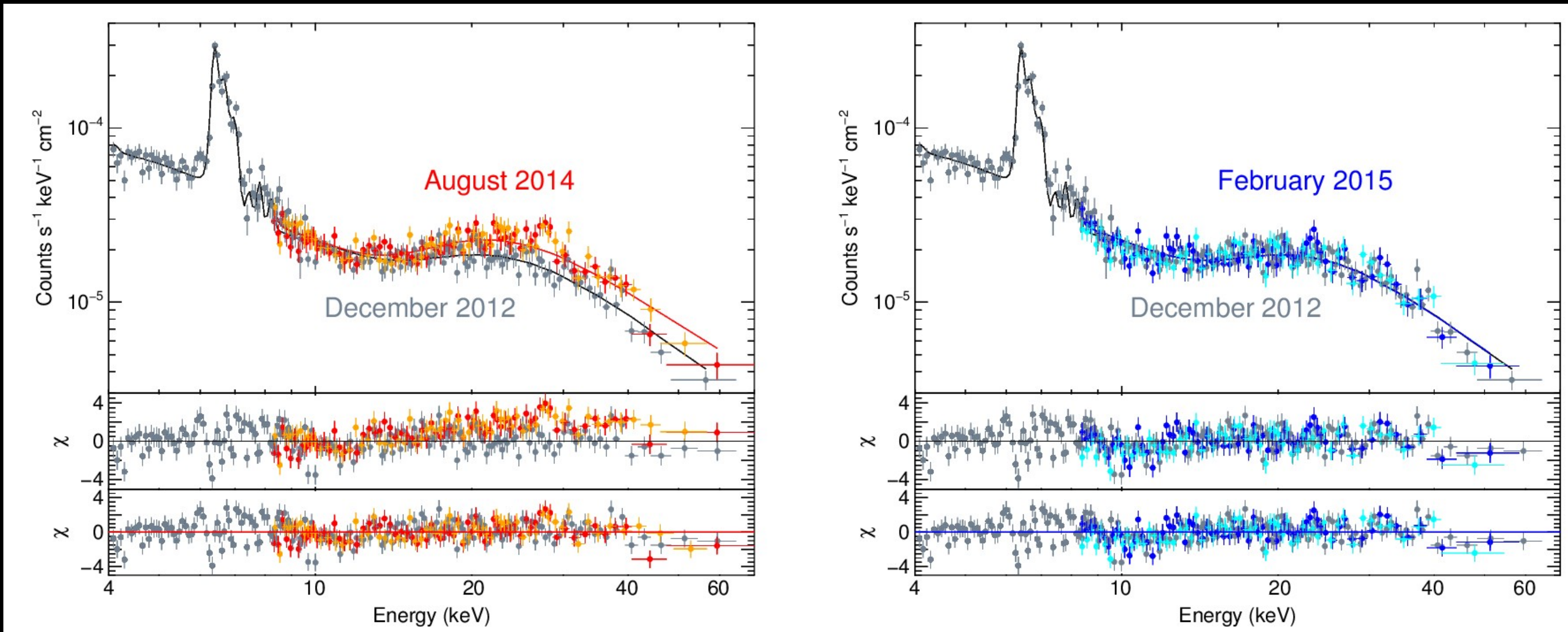
<u>The forbidden component of the OVII Kα line triplet is constant within 1%</u>

We know that it is produced in an extended emission coincident with the NLR, but e.g. NGC5548 (Detmers et al. 2009)

The variable absorber in NGC 1068

Above ~15 keV, a clear excess (~30%) is present in the August 2014 NuSTAR spectra!

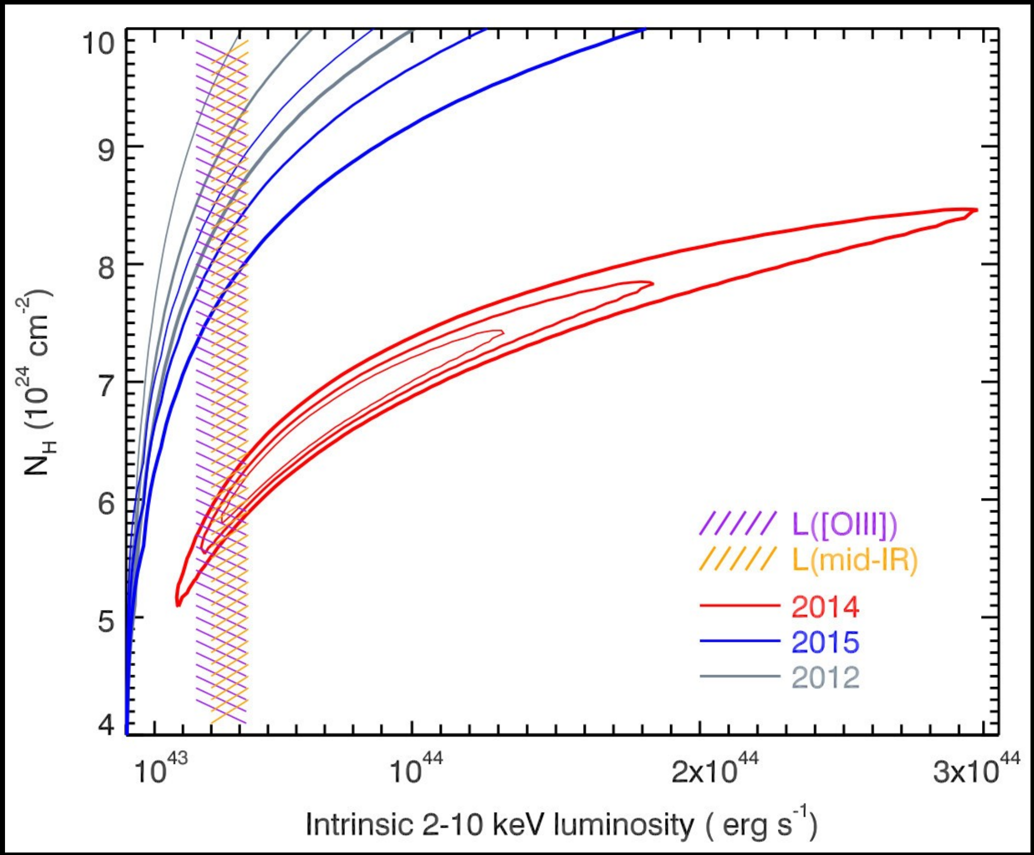
Marinucci et al. 2016



This variation strongly suggests an unveiling event in NG1068 due to a change of the absorbing column density along the line of sight and/or a brightening of the intrinsic continuum.

We test this scenario adopting the Bauer+14 model to fit the multi-epoch data and leaving only the primary component (N_H and flux) free to vary

The variable absorber in NGC 1068



Marinucci et al., 2016

The intrinsic X-ray luminosity for the three NuSTAR observations is consistent with the ones inferred using other proxies ([OIII], mid-IR) if all the spectral difference can be attributed to a change in the absorbing column density, from N_H~10^{25} cm^{-2} in 2012/2015 to N_H~6×10^{24} cm^{-2} in 2014

The variable absorber in NGC 1068

So, what now?

We propose to observe NGC 1068 with *NuSTAR* four times, for 50 ks each, to sample variability time-scales from 1 month to 6 months. The four observations, separated by one month, three months, and six months (relative to the first), will probe spatial scales from 0.05 pc up to 2 pc (see next section).

ACCEPTED

$$\text{1st observation} \rightarrow |\text{1 month}| \rightarrow \text{2nd observation} \rightarrow |\text{2 months}| \rightarrow \text{3rd observation} \rightarrow |\text{3 months}| \rightarrow \text{4th observation}$$

We will start monitoring the source again on next August, trying to catch a new variation in the hard X-rays.

Conclusions

- Obscured AGN remain the perfect laboratory to study the circumnuclear environment (origin of the iron Kα line, location of the Compton absorbing/scattering material, Compton-thick eclipses)

- We have significant statistics with Chandra to resolve and study nearby Compton-thick sources, leading to important information on the reprocessing material on scales of hundreds of pc (geometry, extension)

- Hard X-ray surveys are of great importance to disentangle and characterize the reprocessed and primary continuum (and test self-consistent models for the torus)

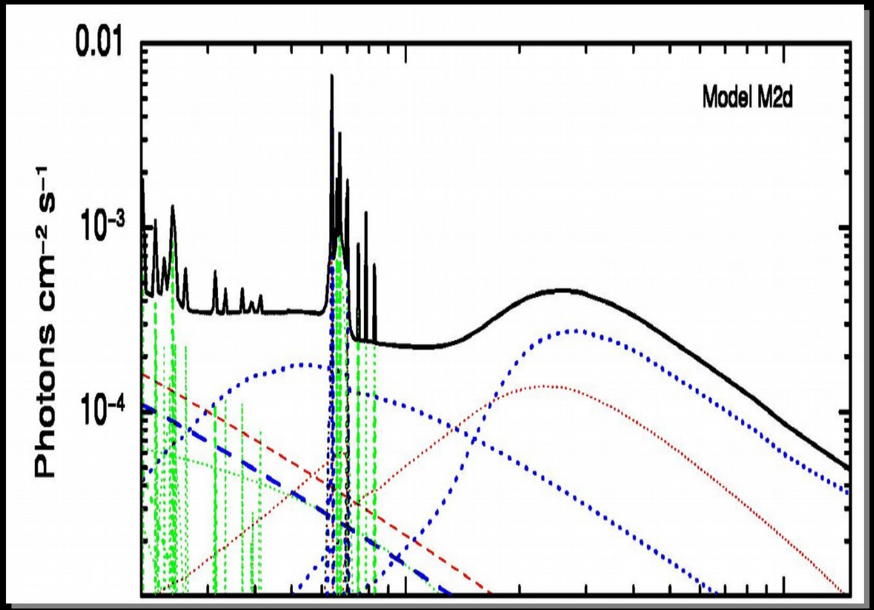
- Still some surprises from the usual suspects (NGC 1068, MCG-6-30-15, Mrk 3, NGC 1365)

Backup slides

Recently, Bauer et al. (2014) analysed NGC 1068 using data from different observatories, including the 3-79 keV data from the NuSTAR 2012 observation

They interpreted the broadband cold reflected emission of NGC 1068 as originating from multiple reflectors with three distinct column densities.

The higher N_H component ($N_{H,1} \simeq 10^{25}$ cm^{-2}) contributes most to the Compton hump (and is also responsible for the total suppression of the intrinsic continuum), while the lower N_H component ($N_{H,2} \sim 1.5 \times 10^{23}$ cm^{-2}) produces much of the neutral iron line emission



Bauer et al., 2014

Almost 30% of the neutral Fe Kα line flux arises from regions outside the central 140 pc and is clearly extended (see also Young et al, 2001; Ogle et al., 2003)