The X-ray emission of radio-quiet AGN in the NuSTAR era

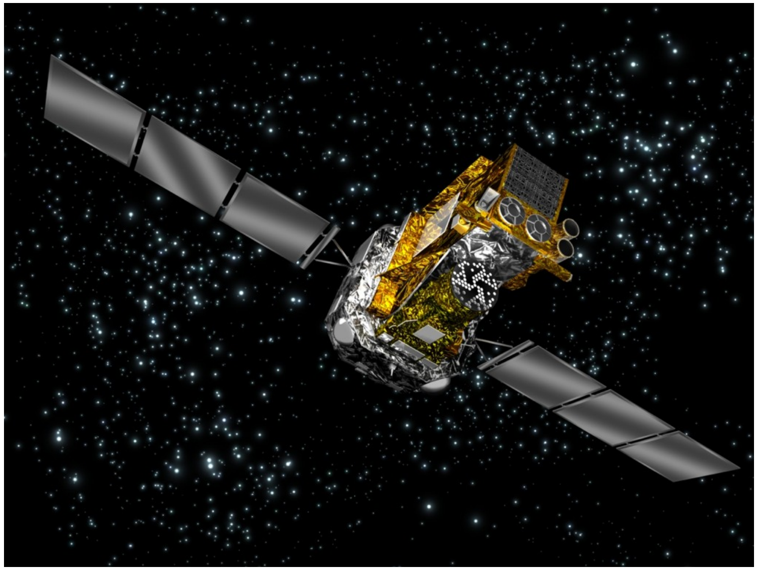
Giorgio Matt

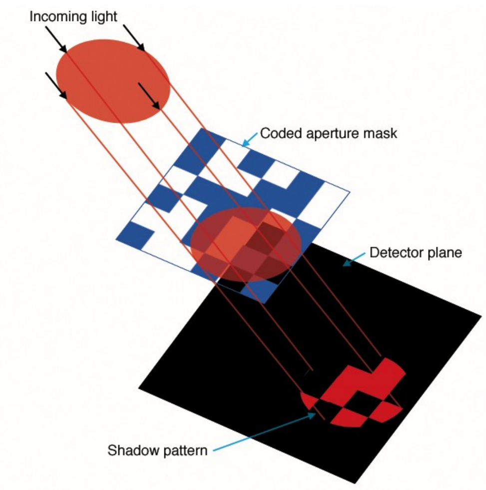
(*Universita' Roma Tre, Italy*)

On behalf of the NuSTAR AGN Physics WG

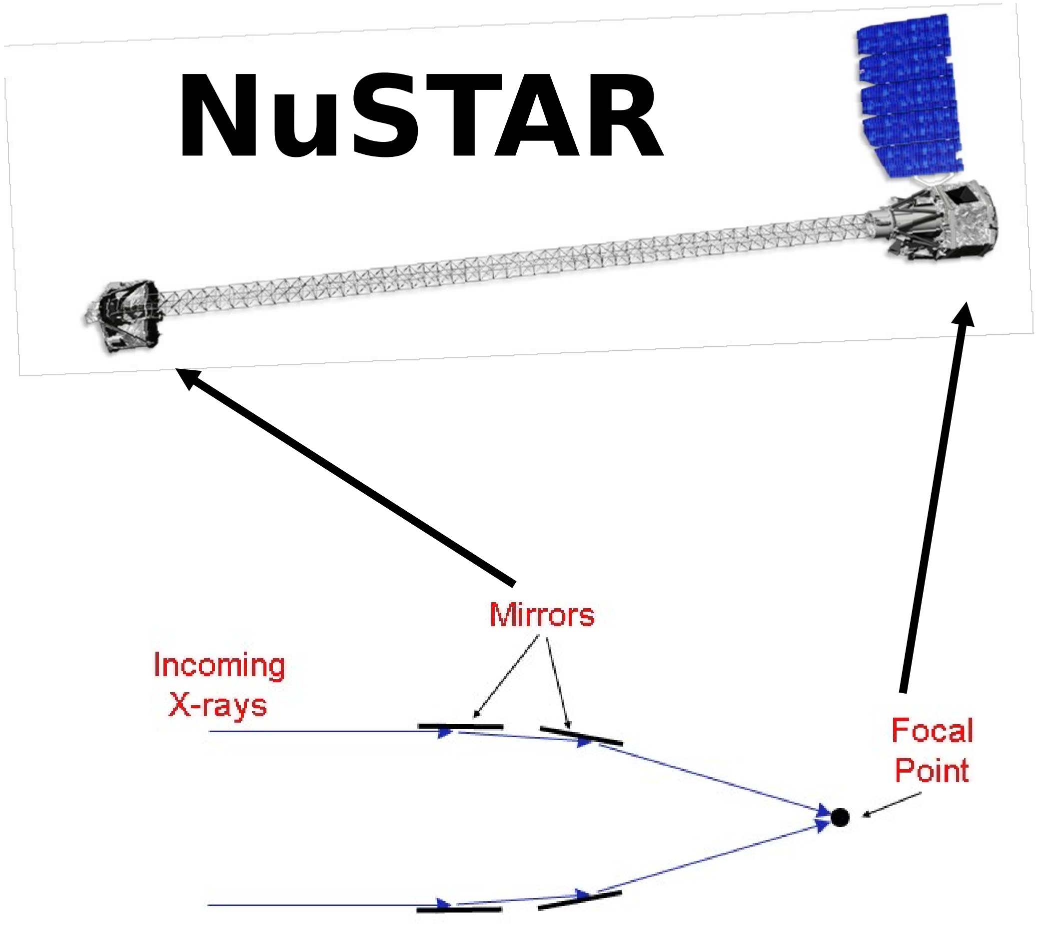
SEVENTH FRAMEWORK PROGRAMME
STRONGGRAVITY
EU FP7-SPACE research project 312789
2013 - 2017

NuSTAR is the **first** focusing hard X-ray satellite



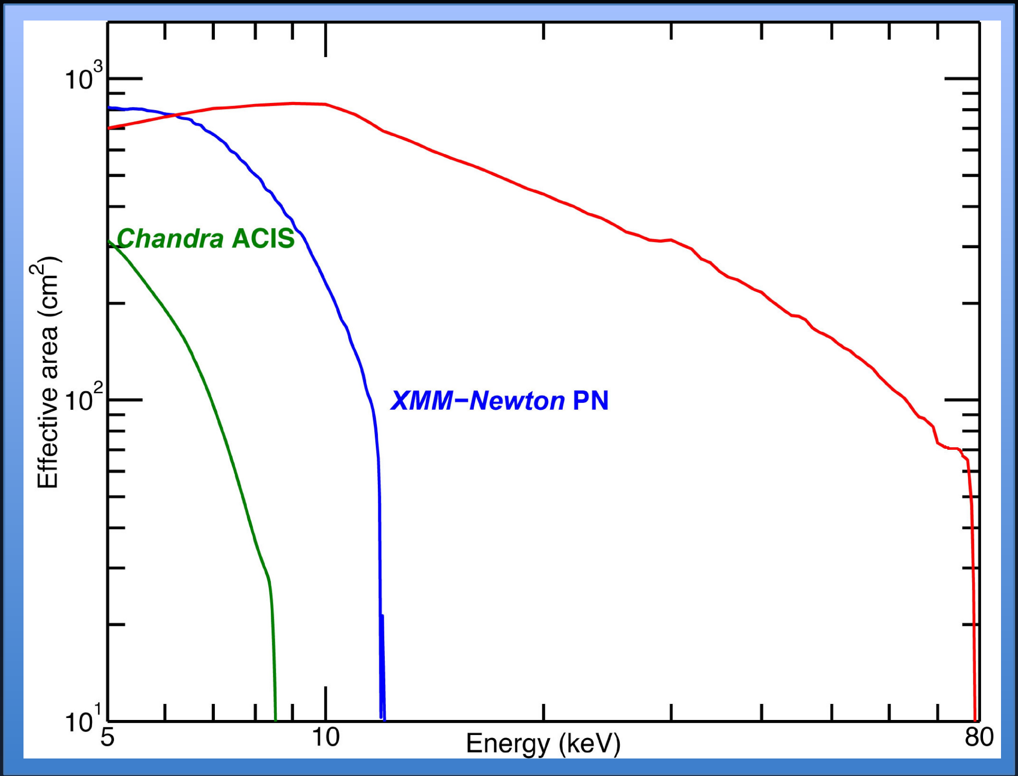


Coded Aperture Optics:
high background, large detector



Grazing Incidence Optics:
low background, compact detector

Collecting Area



NuSTAR two-telescope total collecting area

Sensitivity comparison

INTEGRAL (20-100 keV) ***~0.5 mCrab (ISGRI) with >Ms***

Swift (BAT) (15-150 keV) ***~0.8 mCrab with >Ms***

NuSTAR ***~0.8 µCrab (10-40 keV) In 1 Ms***

1 Ms Sensitivity

3.2×10^{-15} erg/cm2/s
(6 – 10 keV)
1.4×10^{-14} (10 – 30 keV)

Timing

relative 100 microsec
absolute 3 msec

Spectral response

energy range 3-79 keV

threshold	2.0 keV
ΔE @ 6 keV	0.4 keV FWHM
ΔE @ 60 keV	1.0 keV FWHM

Imaging

HPD	58”
FWHM	18”
Localization	2” (1-σ)

Field of View

FWZI	12.5’ x 12.5’
FWHI	10’ @ 10 keV
	8’ @ 40 keV
	6’ @ 68 keV

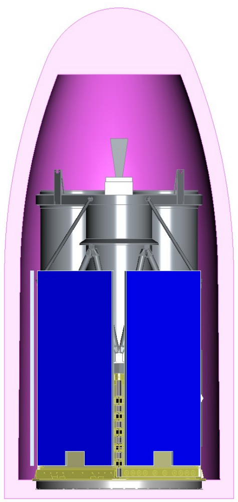
Target of Opportunity

response <24 hr
typical 6-8 hours
80% sky accessibility

Launch June 13, 2012

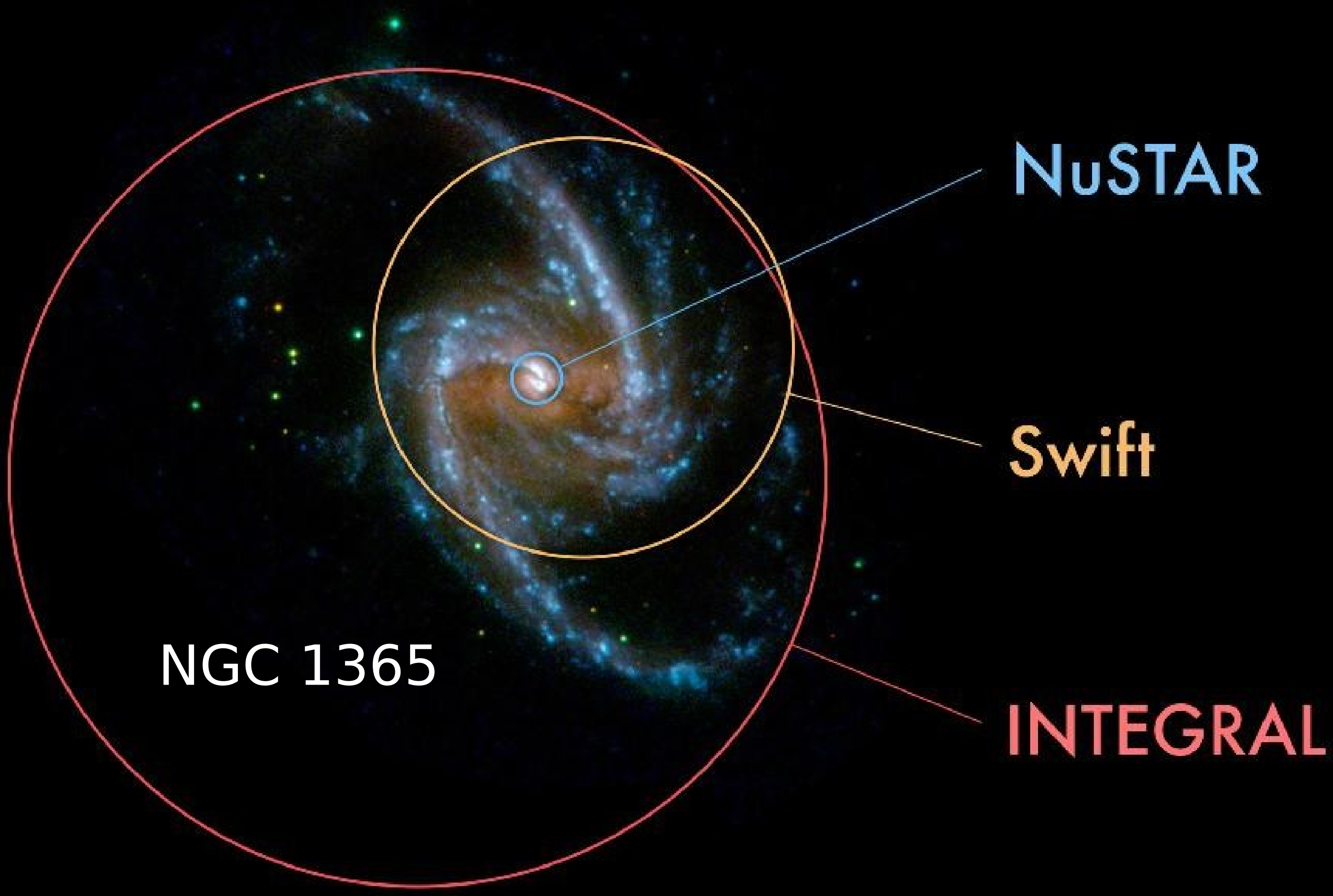
Reagan Test Site, Kwajalein Atoll

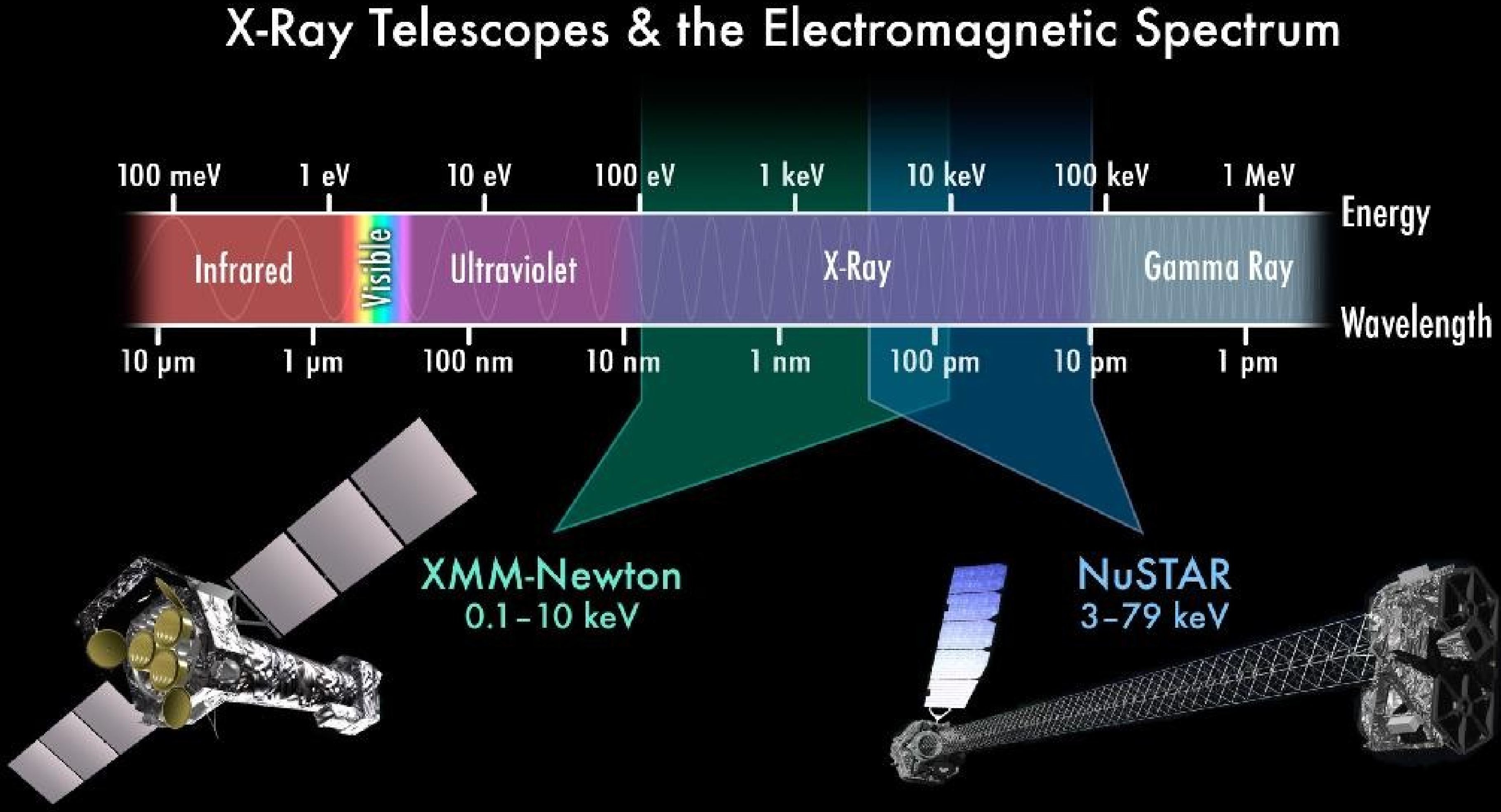
NuSTAR Launch & Orbit



Pegasus launch
from Kwajelein:
low earth orbit,
550x600 km
low inclination, 6°

High-Energy Missions in Orbit:
comparison of pixel scales





low-energy X-rays
“soft” X-rays

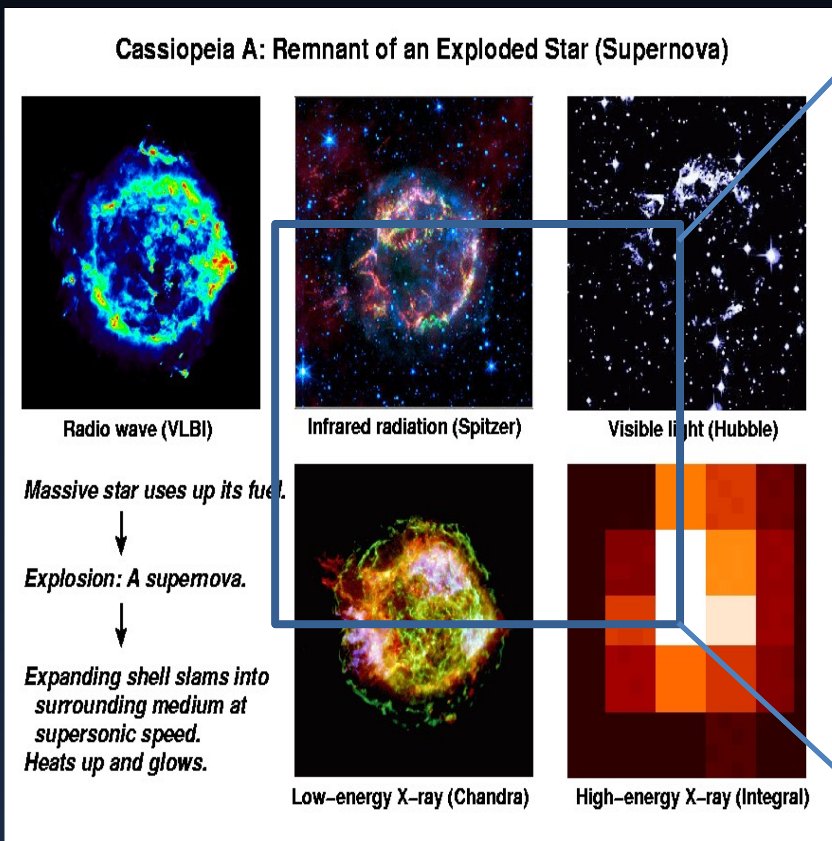
high-energy X-rays
“hard” X-rays

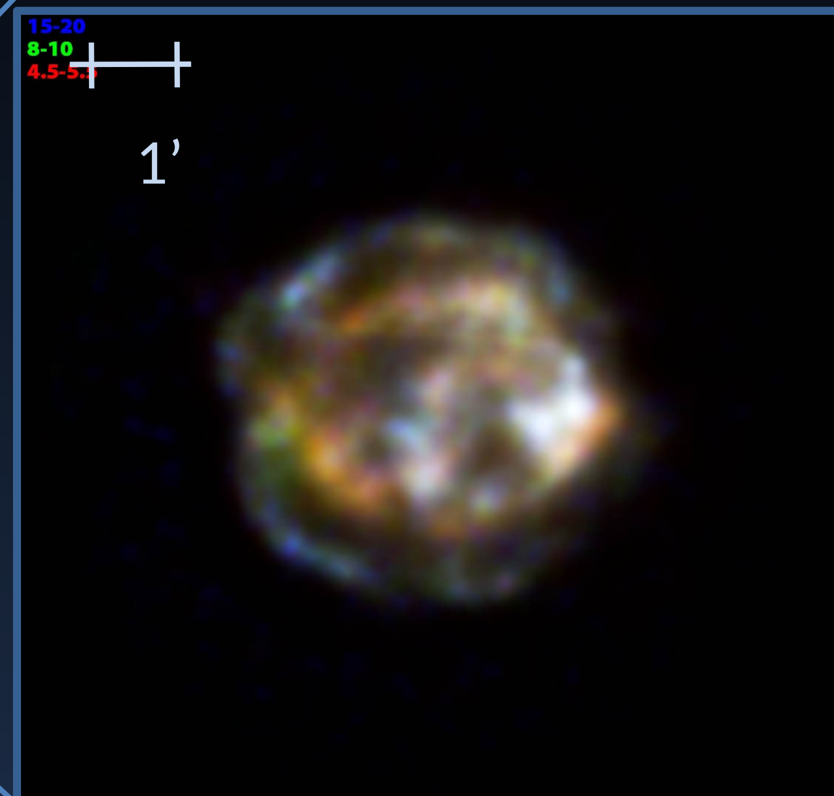
Imaging

Cas A supernova remnant

INTEGRAL ISGRI
E>15 keV

NuSTAR Image
Red : 4.5 – 5.5 keV
Green: 8 – 10 keV
Blue: 10 – 25 keV



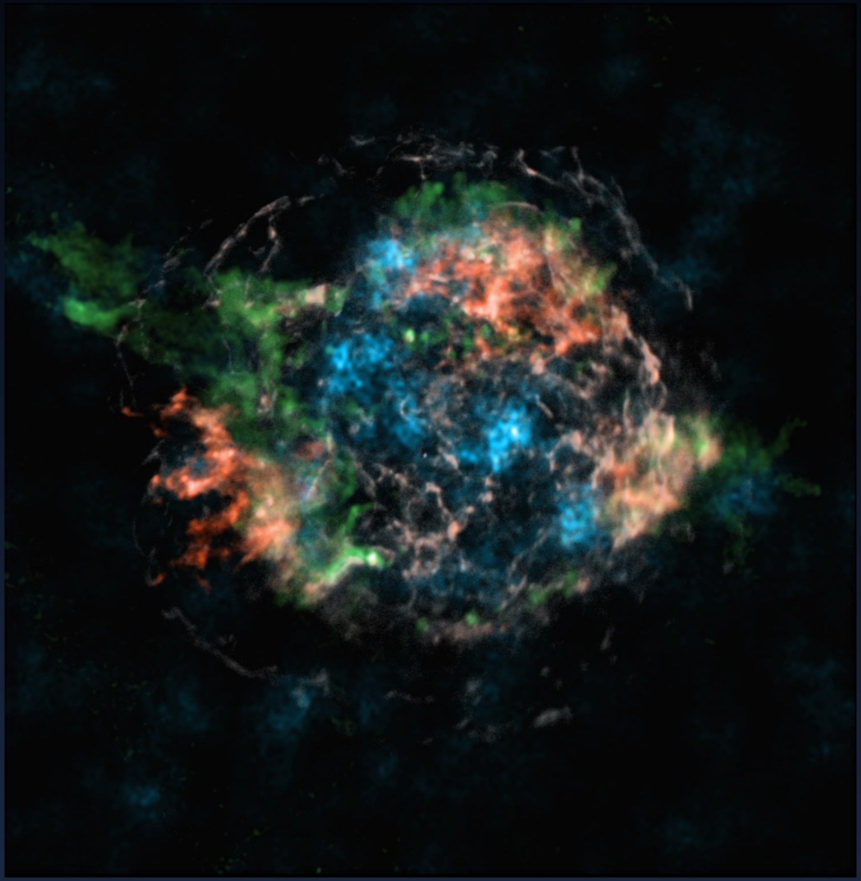


Grefenstette et al. (2014)

Imaging

Cas A supernova remnant

NuSTAR Image
Red : Fe K (Chandra)
Blue: ^{44}Ti

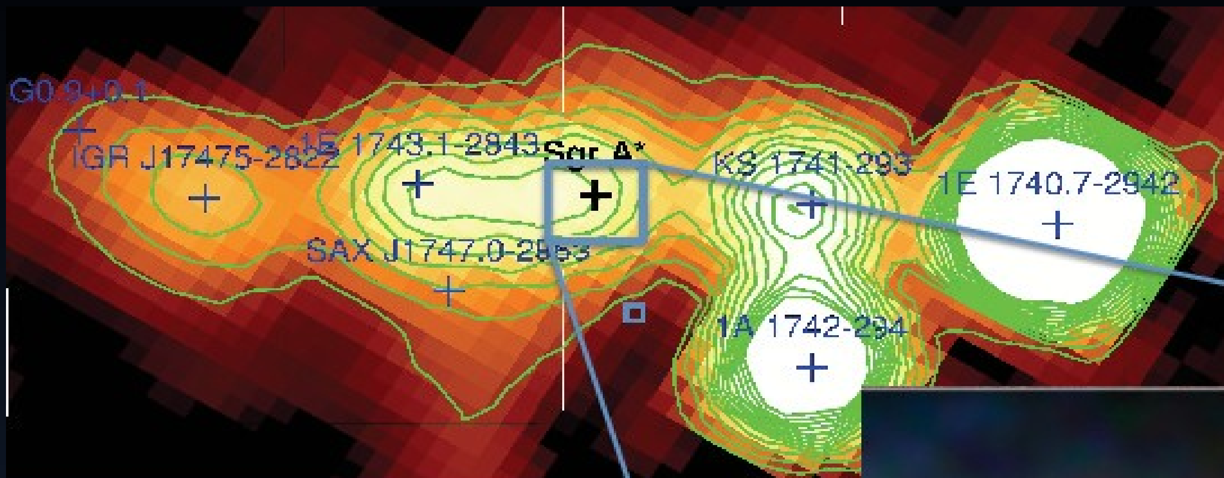


Explosion is highly asymmetric as shown by
the ^{44}Ti map.

Fe K maps the shocked region (iron in unshocked regions difficult to observe)

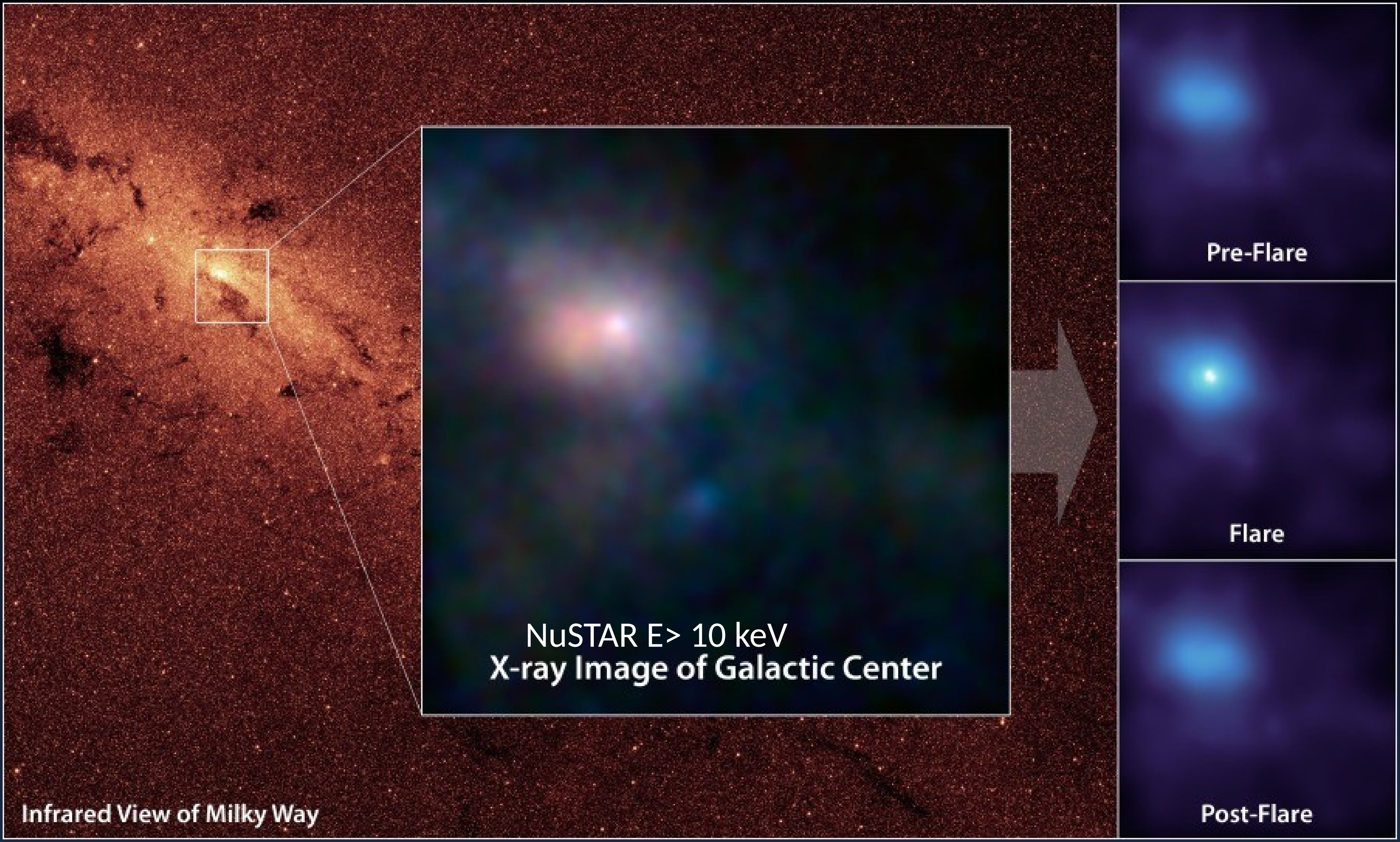
Grefenstette et al. (2014)

Imaging

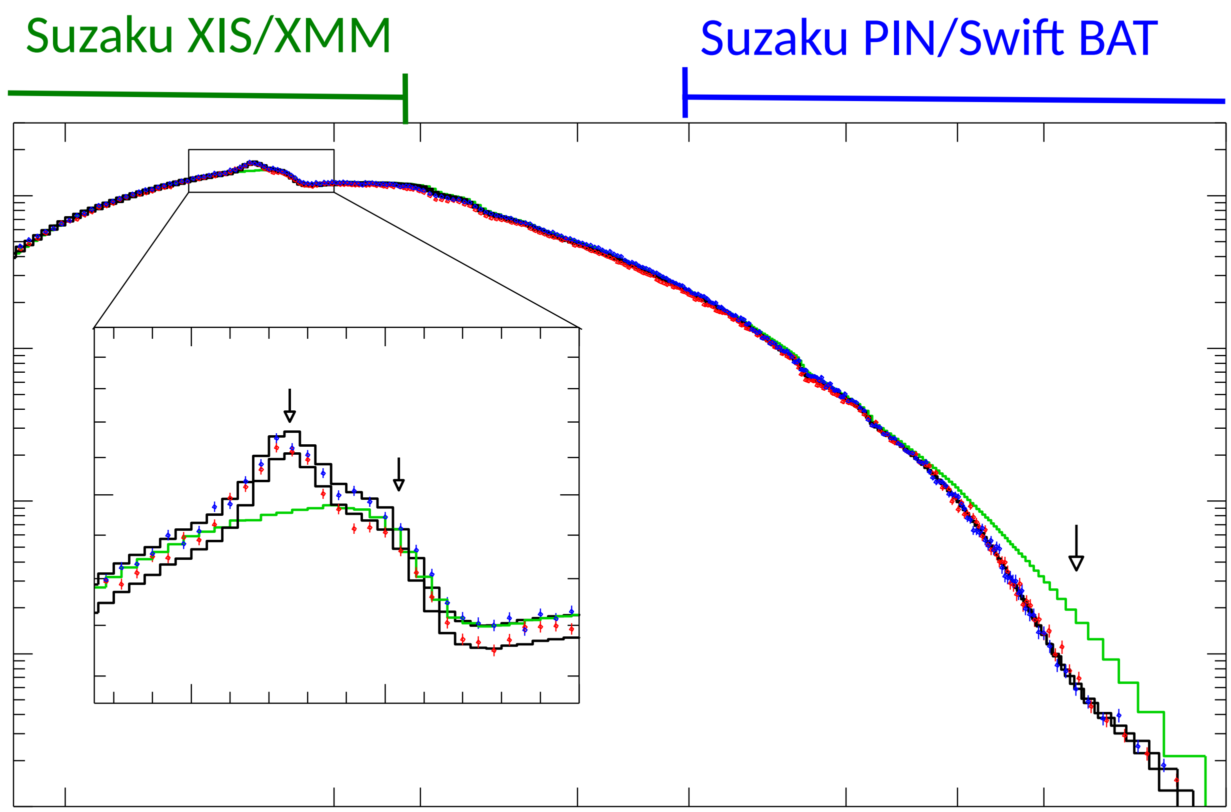


Previous high-energy X-ray view of the heart of the Milky Way

Imaging

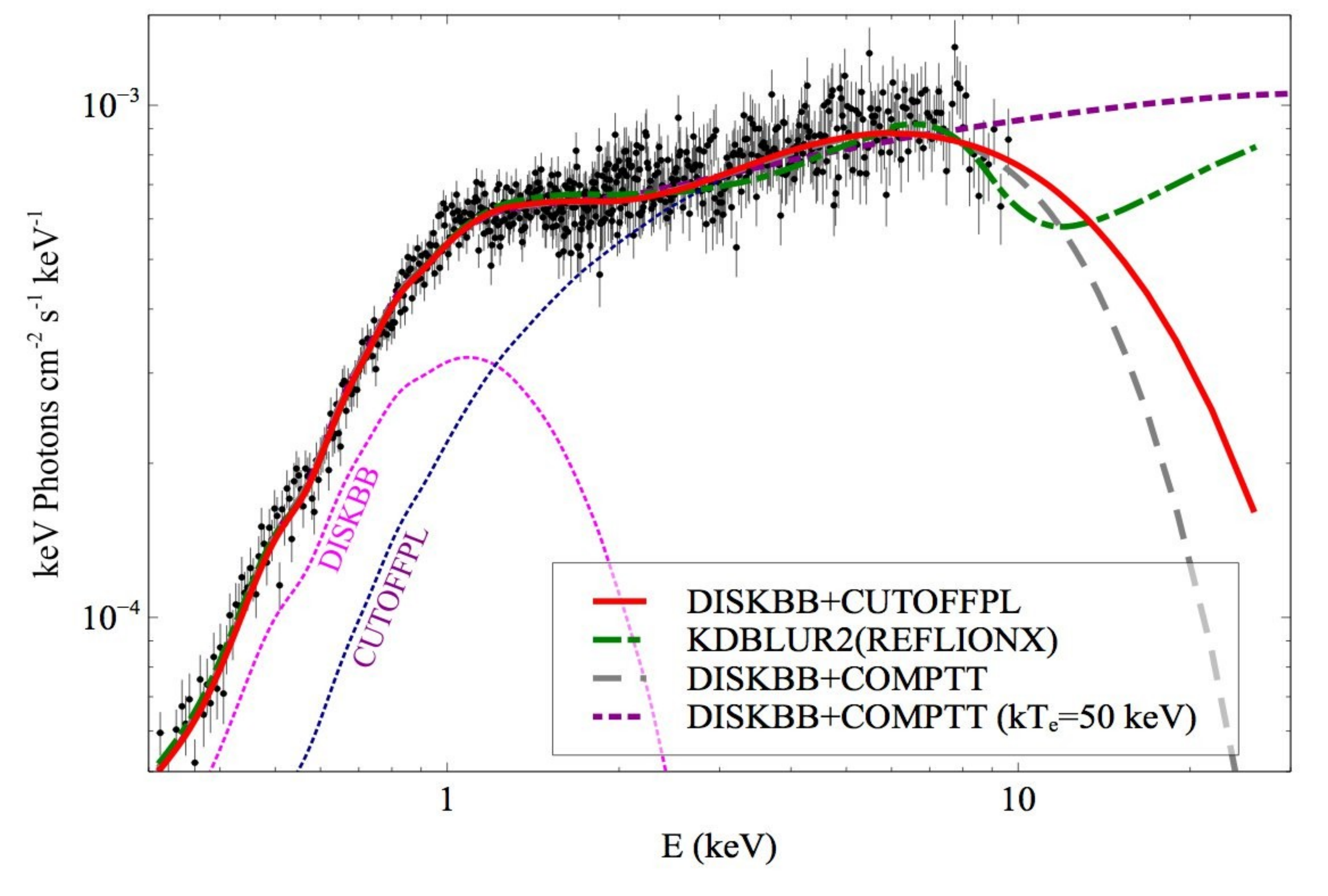

Infrared View of Milky Way
NuSTAR E> 10 keV
X-ray Image of Galactic Center
Pre-Flare
Flare
Post-Flare

Broad Band Spectroscopy



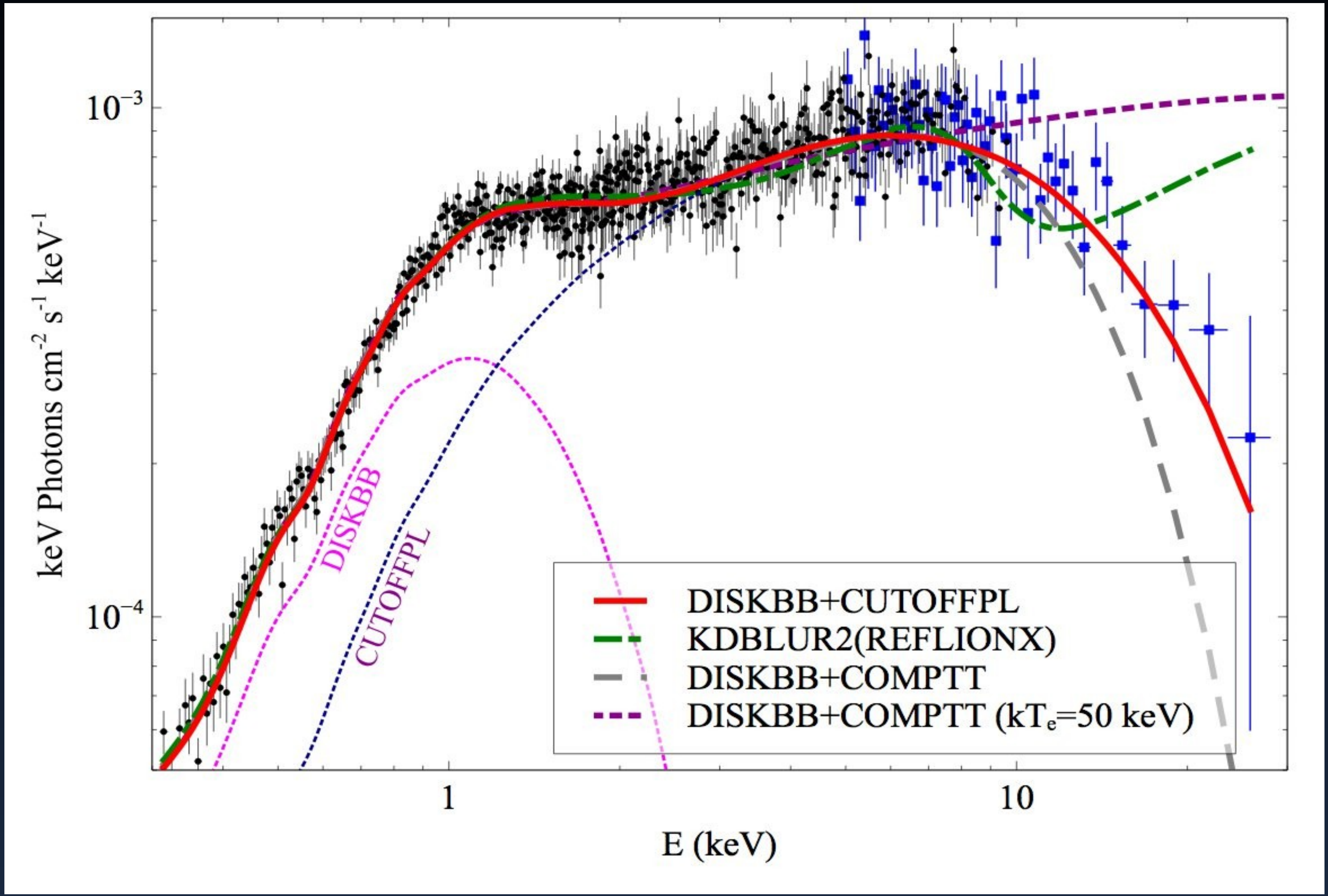
Vela X-1 accreting pulser -15 ksec with NuSTAR

Broad Band Spectroscopy



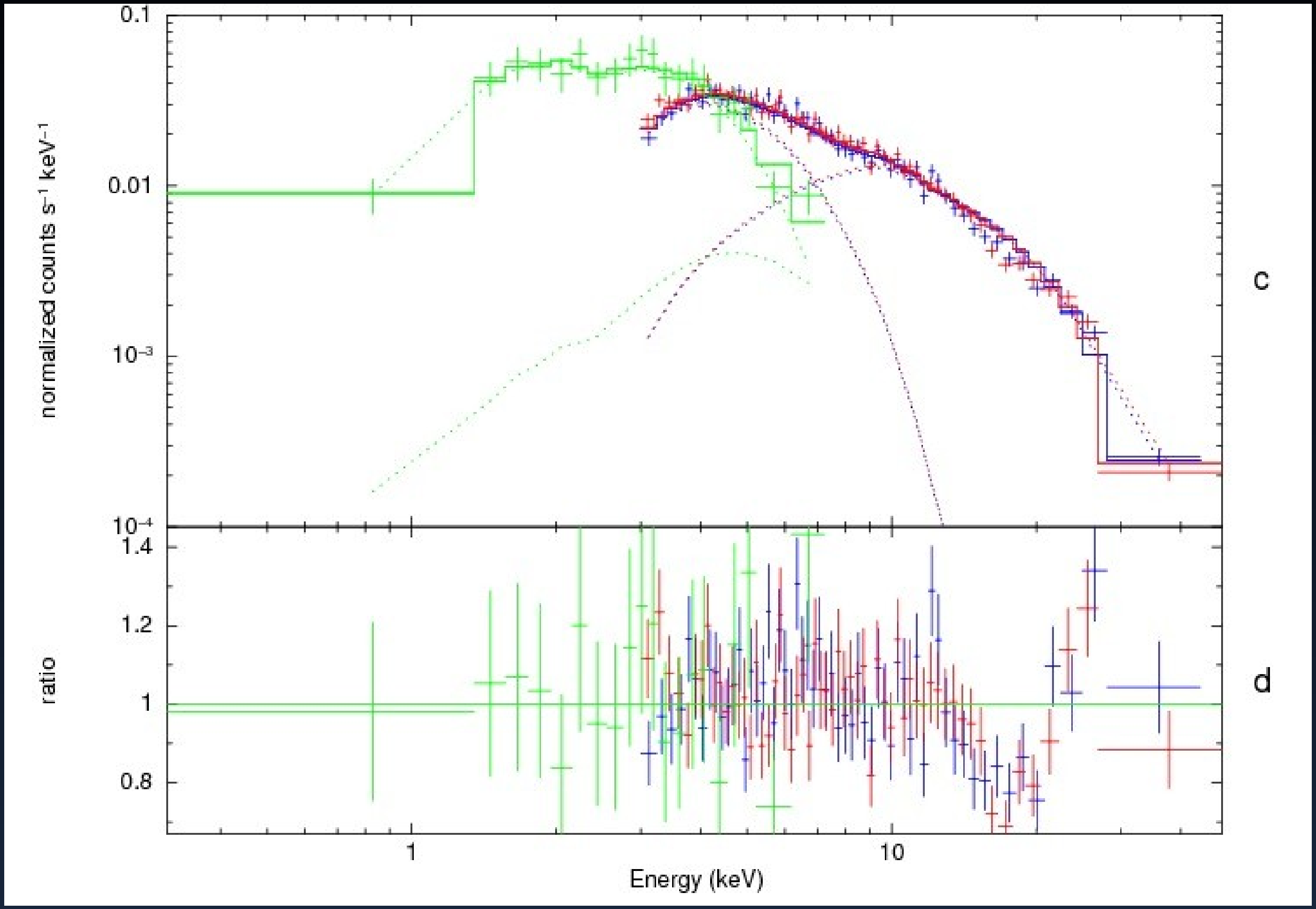
ULX: what is the right model?

Broad Band Spectroscopy



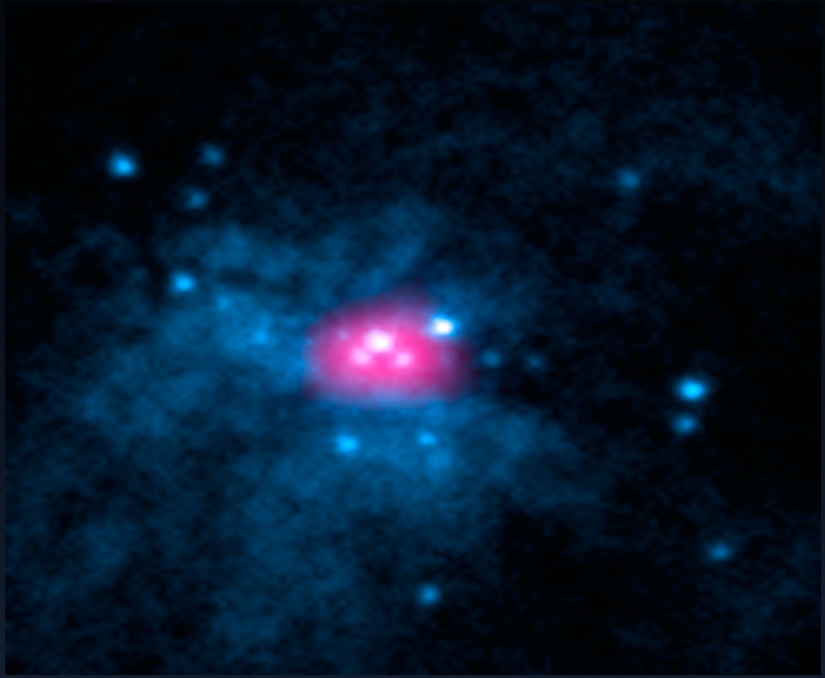
NGC 1313 X1 (Bachetti et al. 2013)

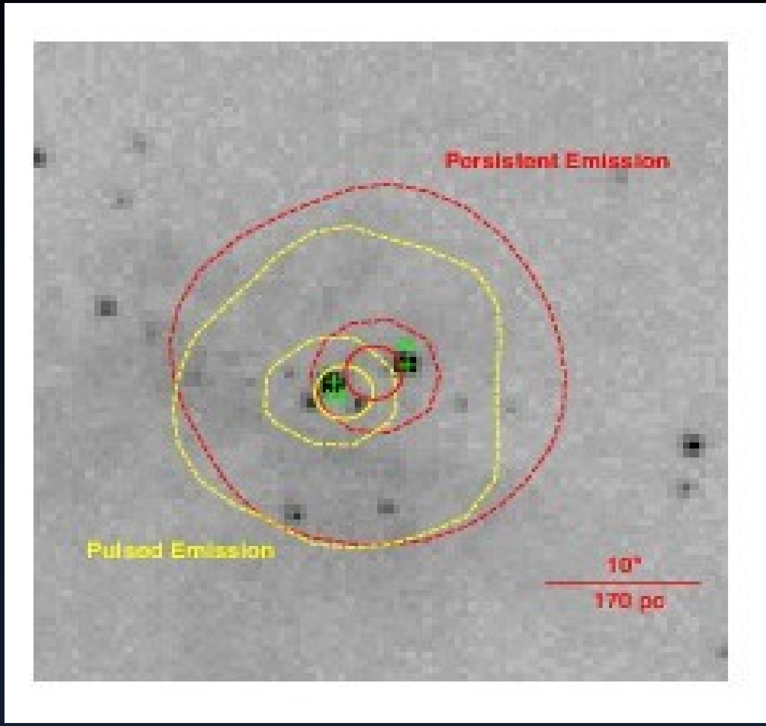
Broad Band Spectroscopy



First cyclotron line in a SFXT
IGR J17544-2619   (Valerao et al. 2015)

Timing





Pink: NuSTAR
Blue : Chandra

Discovery of a pulsing ULX M82 X-2 (Bachetti et al. 2014).
More discovered afterwards

Baseline Science Mission

- As typical for an Explorer mission, all baseline observations led by the science team during the nominal lifetime (~2 yrs)

- ~150-person international science team broken into 13 science working groups

- After the current initial calibration period has been completed, observations became public through HEASARC two months after a data set is completed

- 1.5 Ms of NuSTAR made available for coordinated observations with XMM from AO13 (with a factor ~6 oversubscription). Similar agreement with Chandra and INTEGRAL

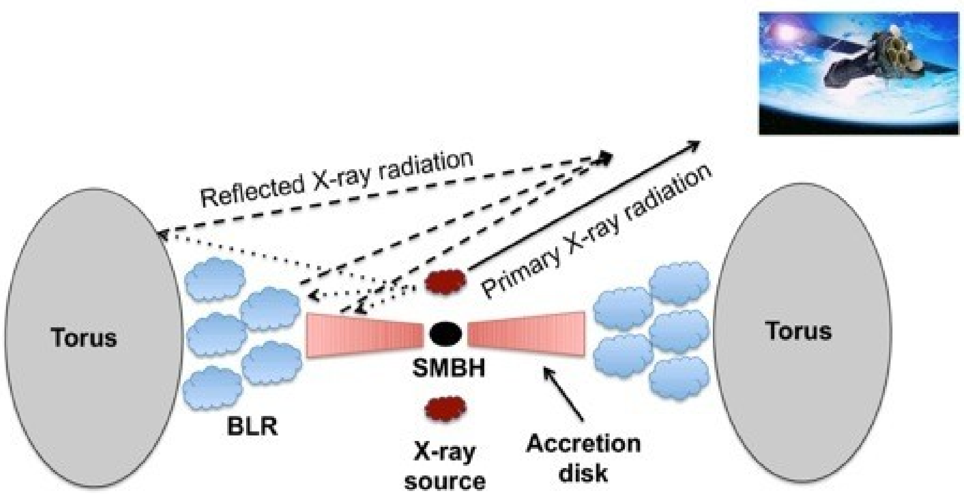
- Mission extended to 2015-18. Observations now open to the worldwide community.

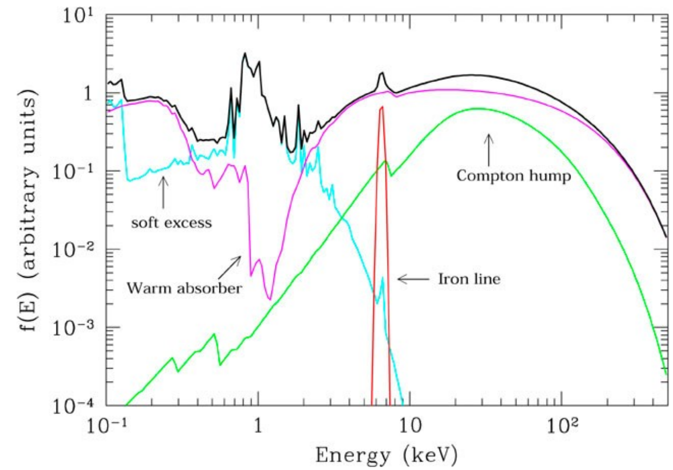
Science Working Groups

Science Group	Working Group Chair
Galactic Survey	Chuck Hailey
Supernovae and ToOs	Steve Boggs
Supernova Remnants and PWN	Fiona Harrison
Magnetars and RPP	Vicky Kaspi
Galactic Binaries	John Tomsick
Ultraluminous X-ray Sources	Fiona Harrison
Extragalactic Surveys	Daniel Stern
Blazars	Greg Madejski/Paolo Giommi
Obscured AGN	Daniel Stern
AGN Physics	Giorgio Matt
Galaxy Clusters	Allan Hornstrup/Silvano Molendi
Starburst Galaxies	Ann Hornschemeier
Solar Physics	David Smith

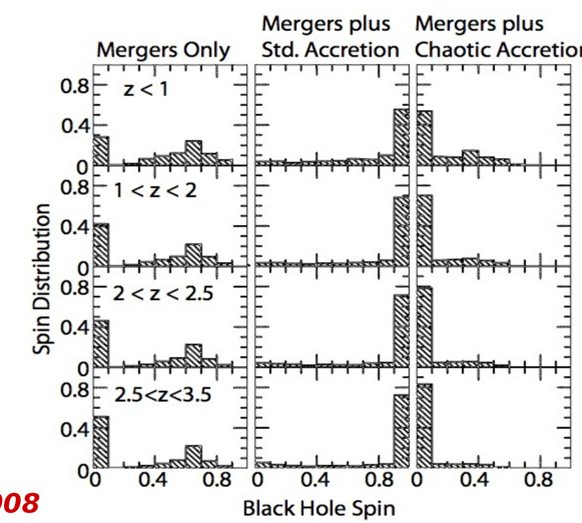
AGN Physics: Scientific rationale

- ❖ **Determine the physical parameters of the hot corona (temperature, optical depth)**



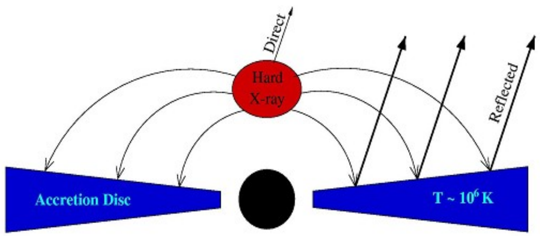


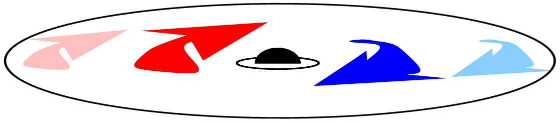
- ❖ **Measure the spin of the Black Hole**

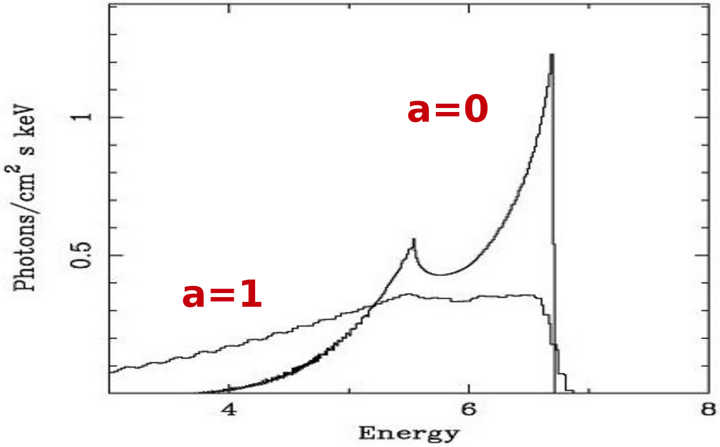


Berti & Volonteri 2008

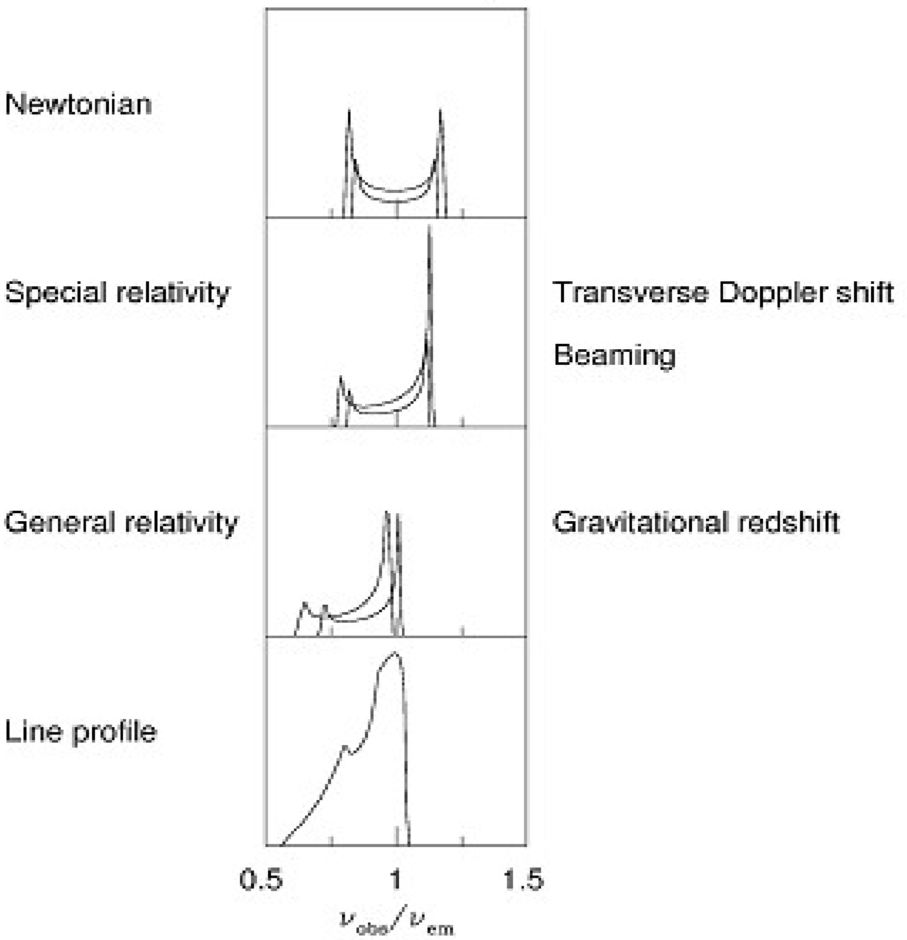
Measuring the Black Hole spin





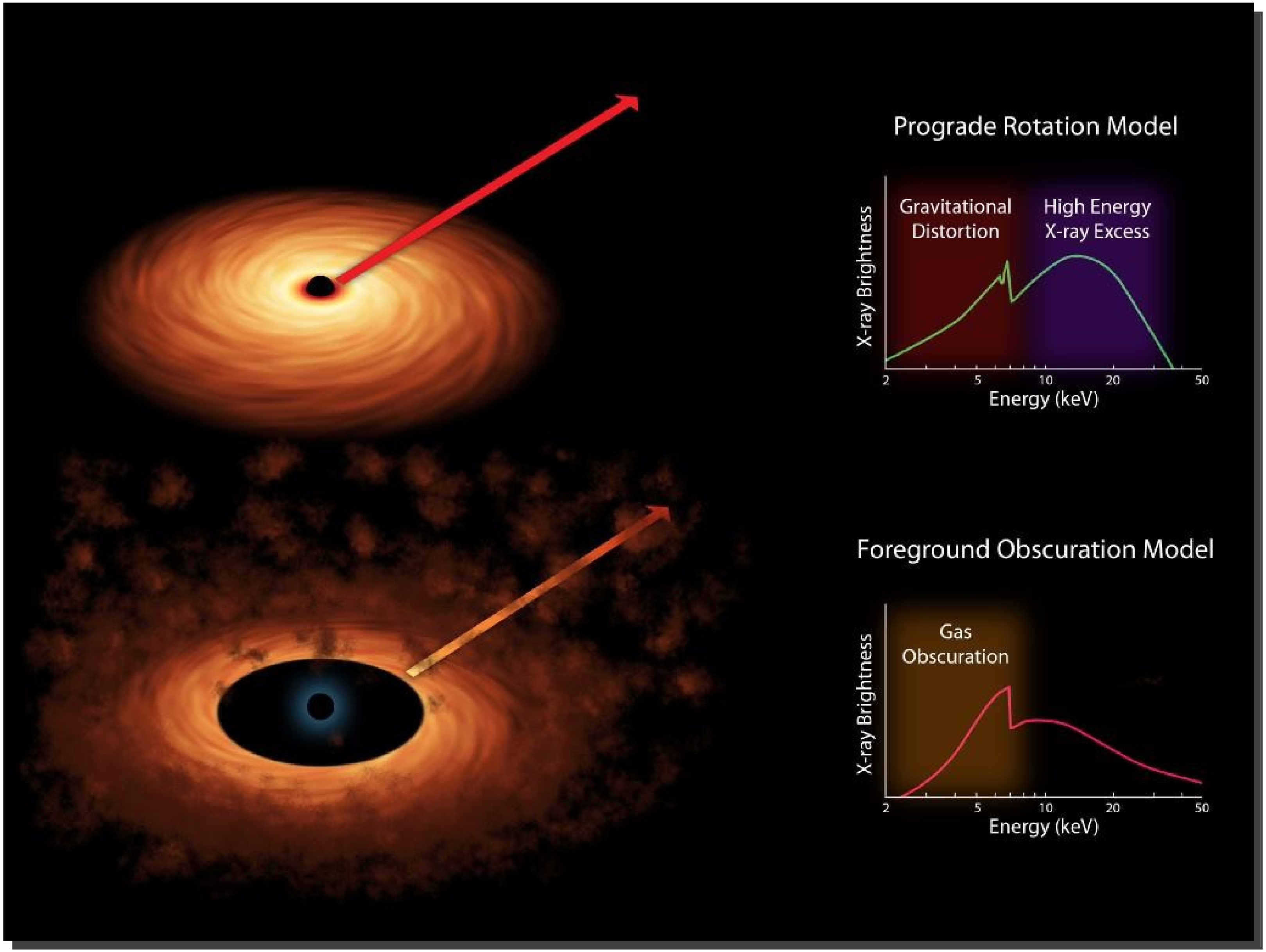


(Fabian et al. 2000)



a = adimensional angular momentum per unit mass (spin) **a ∈ (0,1)**

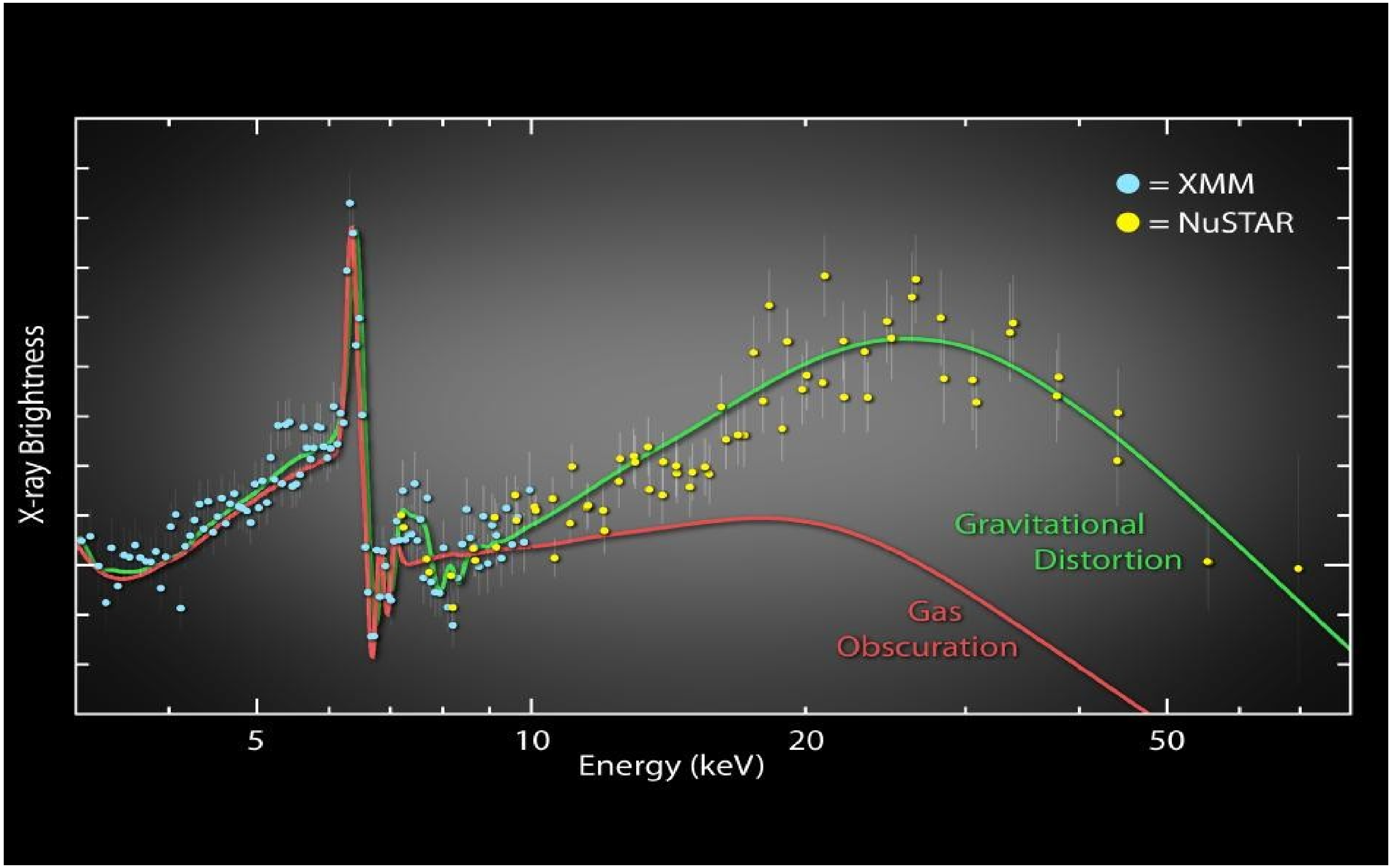
The relativistic reflection in NGC1365



The relativistic reflection in NGC1365

Observed simultaneously by XMM and NuSTAR.

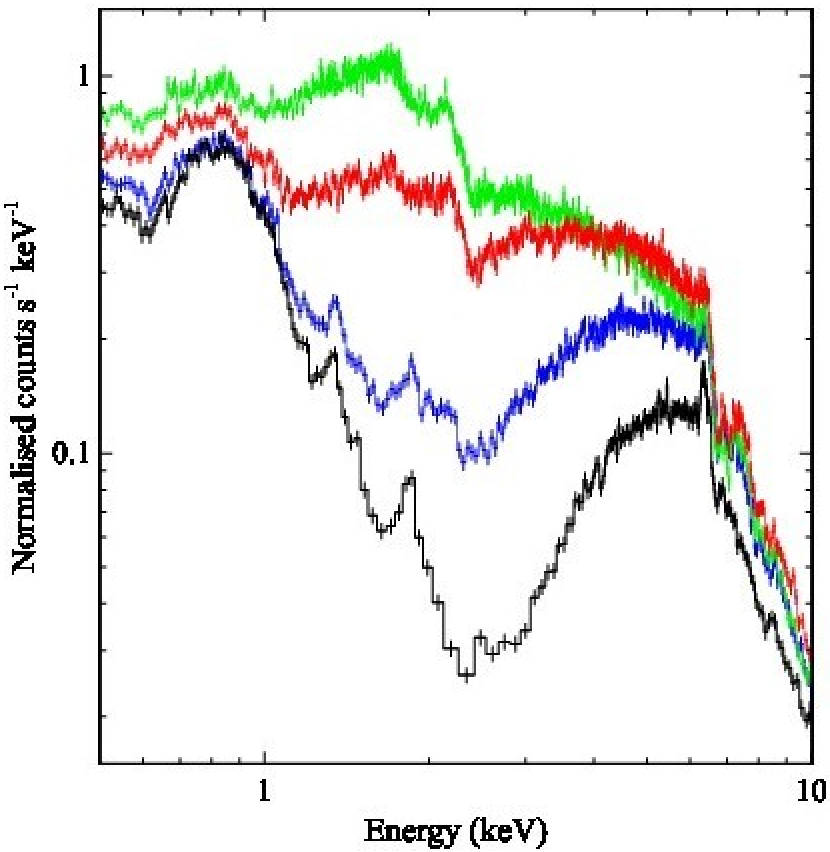
Both absorption and reflection models fit well the XMM data, but only reflection also the NuSTAR data (Risaliti et al. 2013)

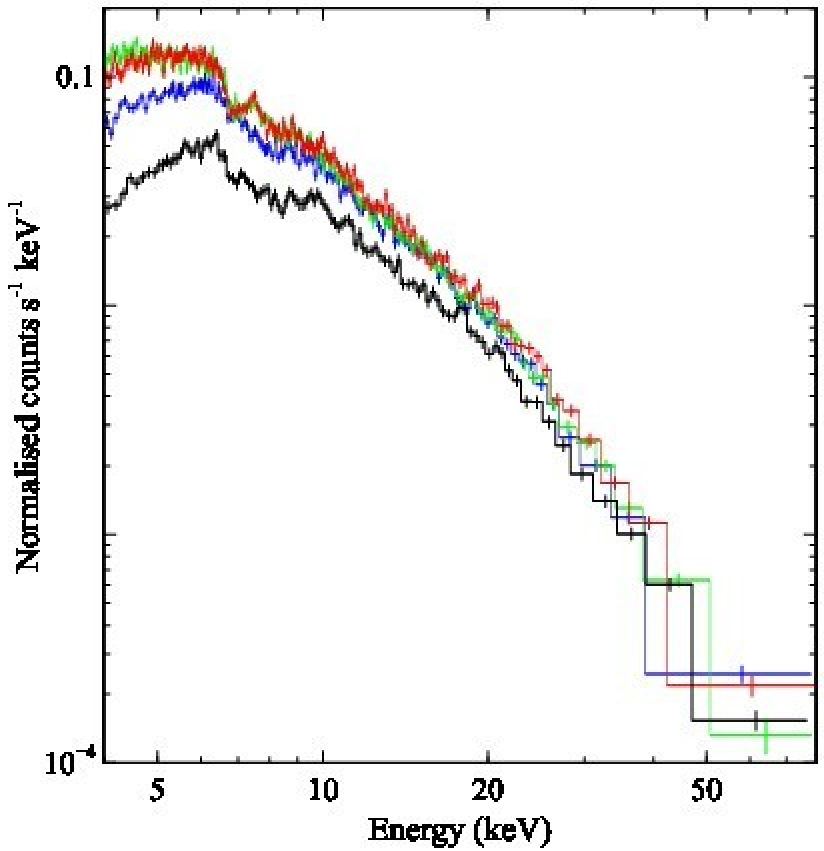


The relativistic reflection in NGC1365

Observed simultaneously by XMM and NuSTAR.

Consistent results are found in all observations, despite huge differences in the absorption parameters (Walton et al. 2014)

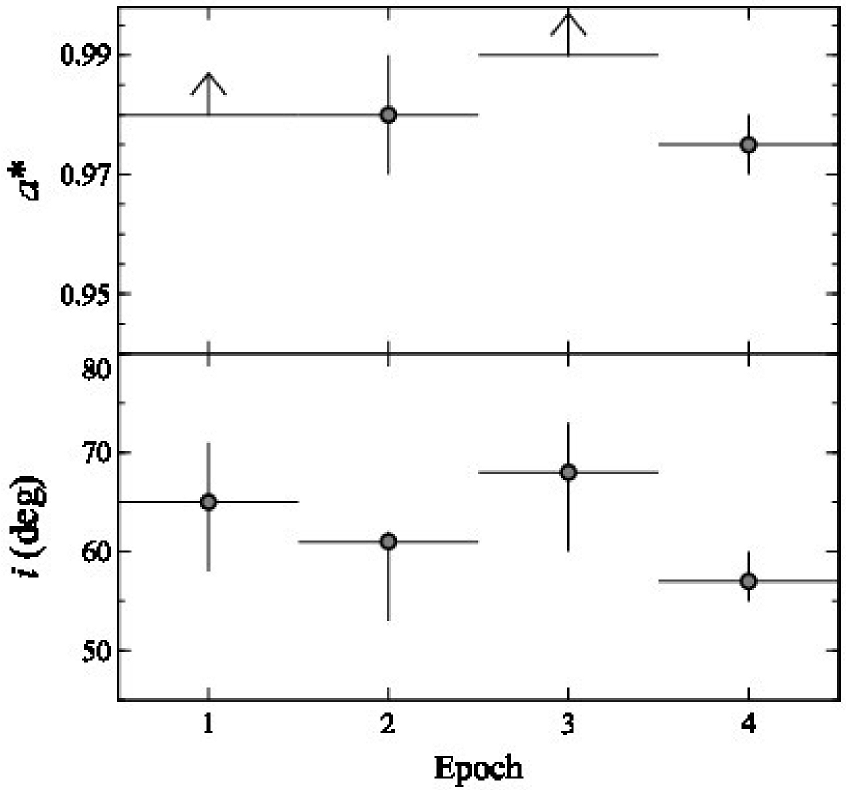


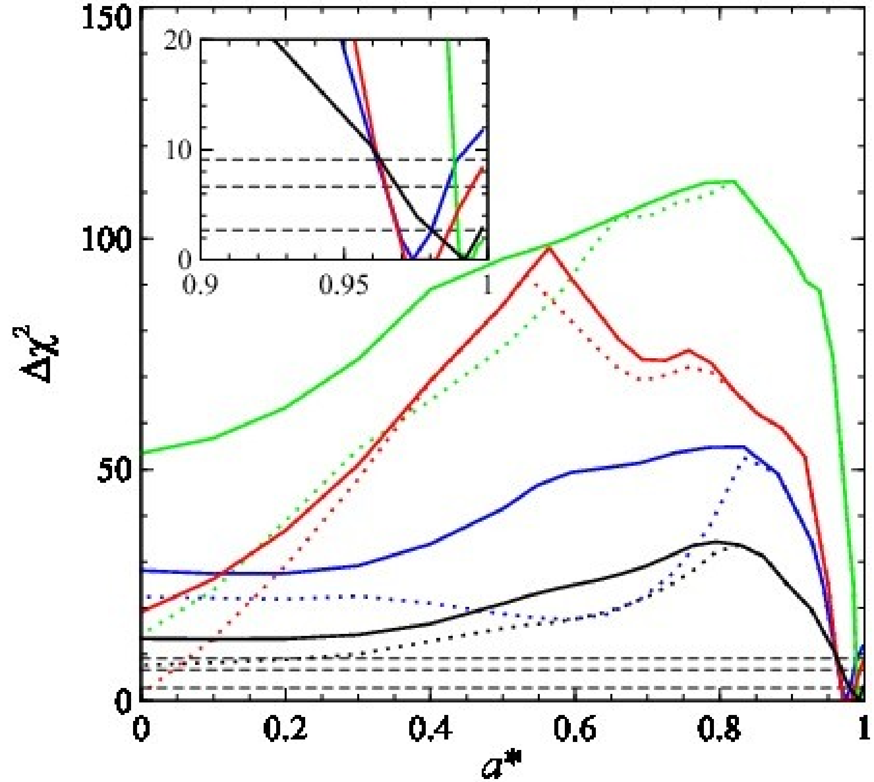


The relativistic reflection in NGC1365

Observed simultaneously by XMM and NuSTAR.

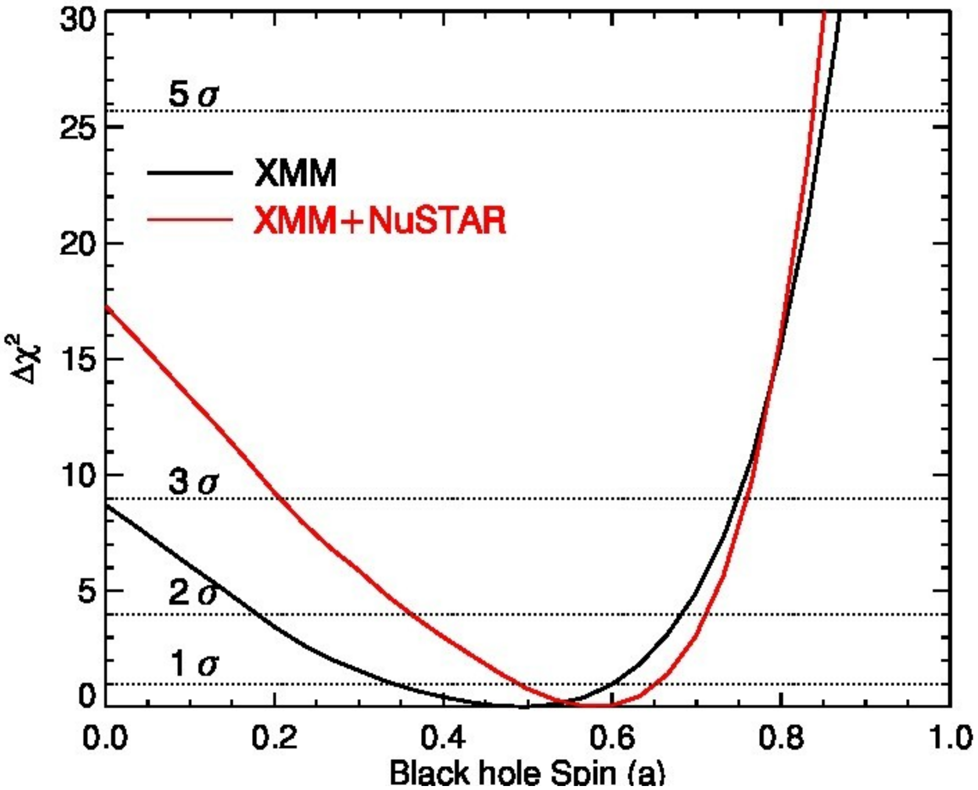
Consistent results are found in all observations, despite huge differences in the absorption parameters (Walton et al. 2014)





BH spin measurements

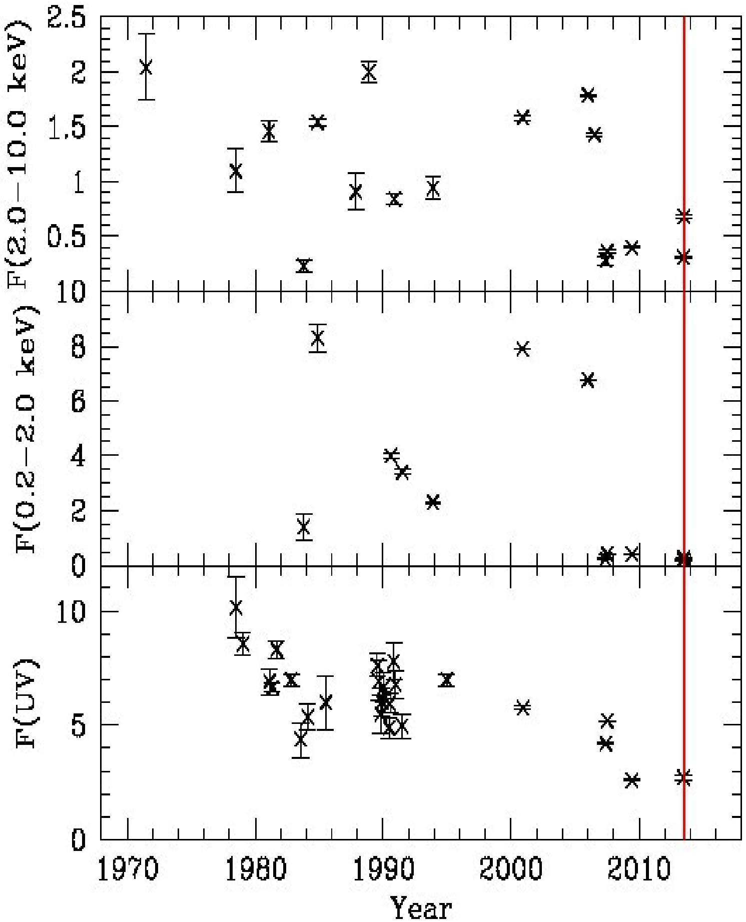
The broad band provided by NuSTAR + XMM (or Suzaku) allows a good estimate of the continuum spectrum, and so a robust measurement of the BH spin via relativistic effects on the iron line and the reflection component

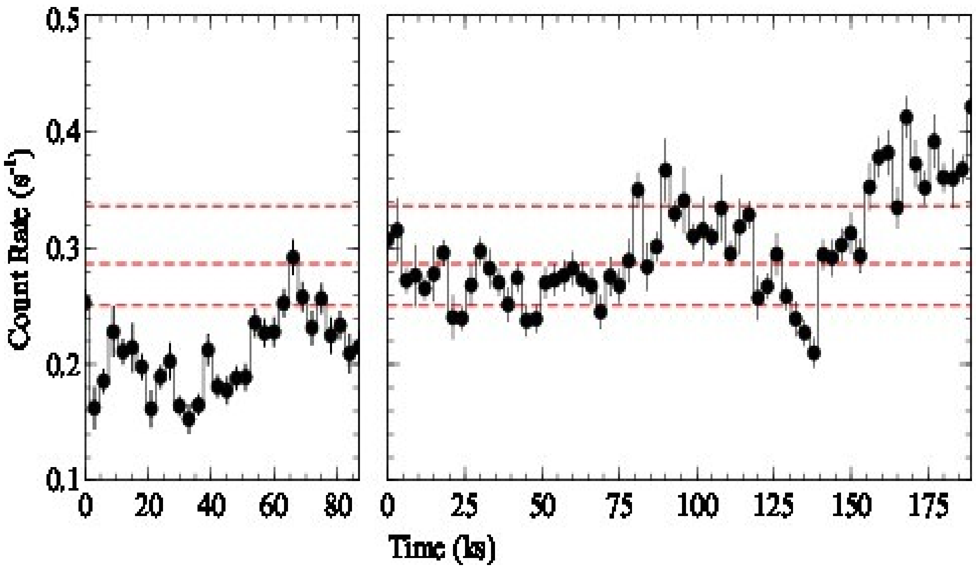


Spin ~1 confirmed in MCG-6-30-15 (Marinucci et al. 2014b)

Swift J2127.4+5654 (Marinucci et al. 2014a)

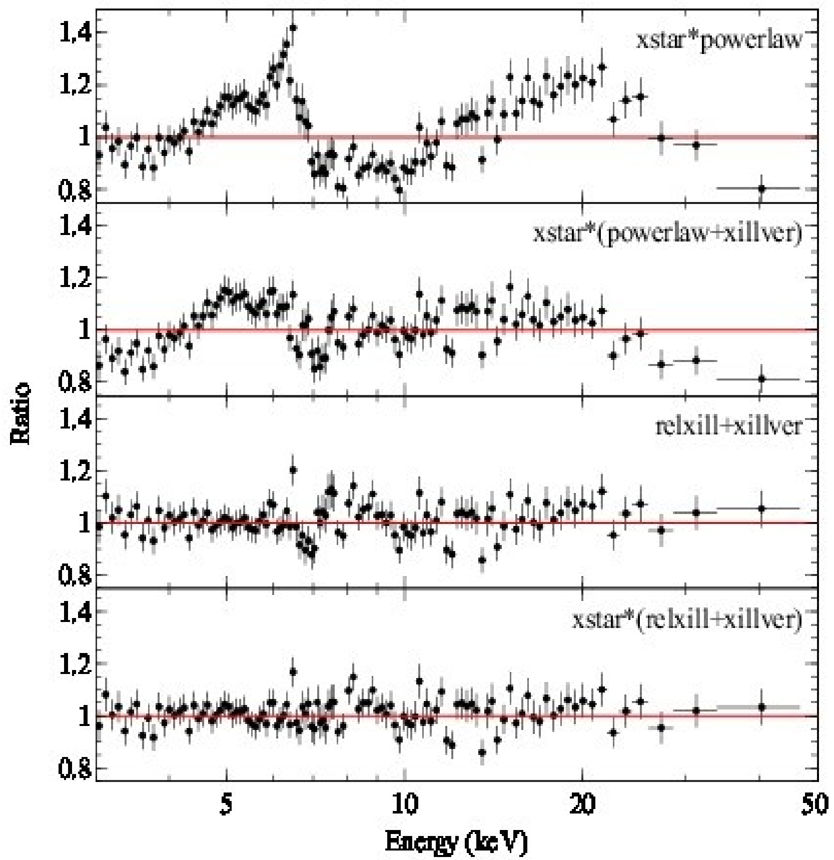
Mrk 335: Relativistic effects within 2 Rg from the event horizon?

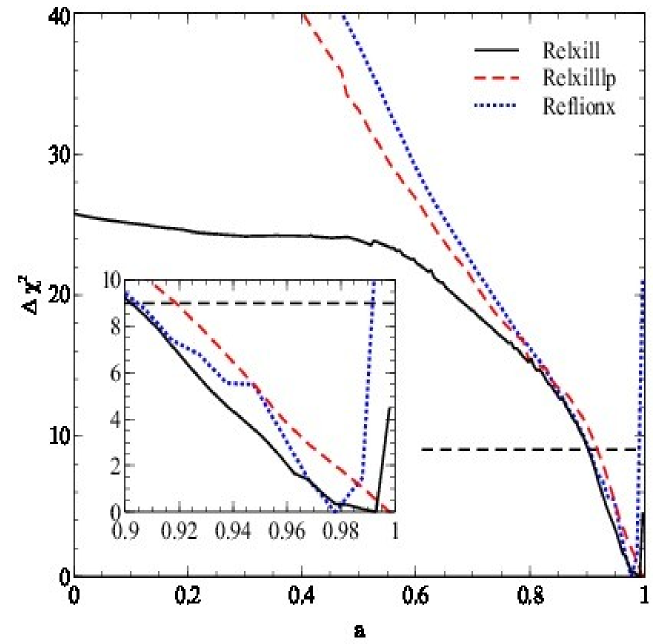




The source was found in a very low flux state (Parker et al. 2014).

Mrk 335: Relativistic effects within 2 Rg from the event horizon?





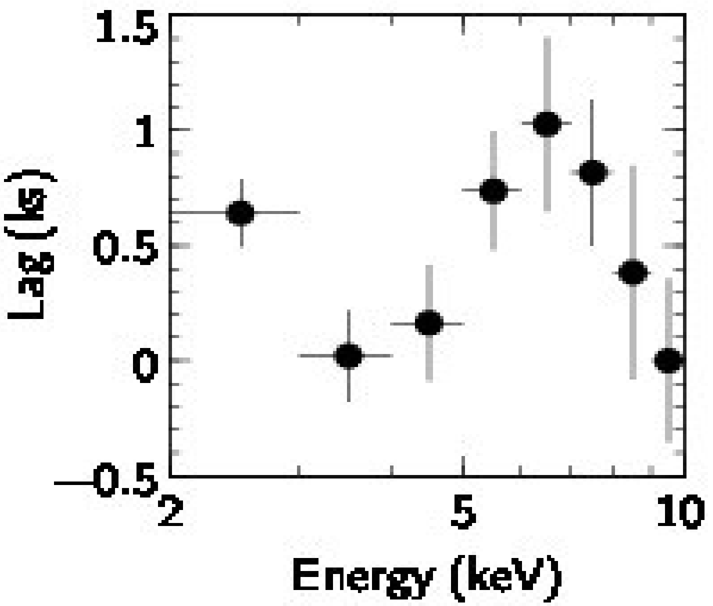
The spectrum is well fitted by an almost pure relativistic reflection component. Applying a lamp-post geometry, a very small height is found, as well as a high BH spin (Parker et al. 2014)

The hard X-ray time lag in MCG-5-23-16

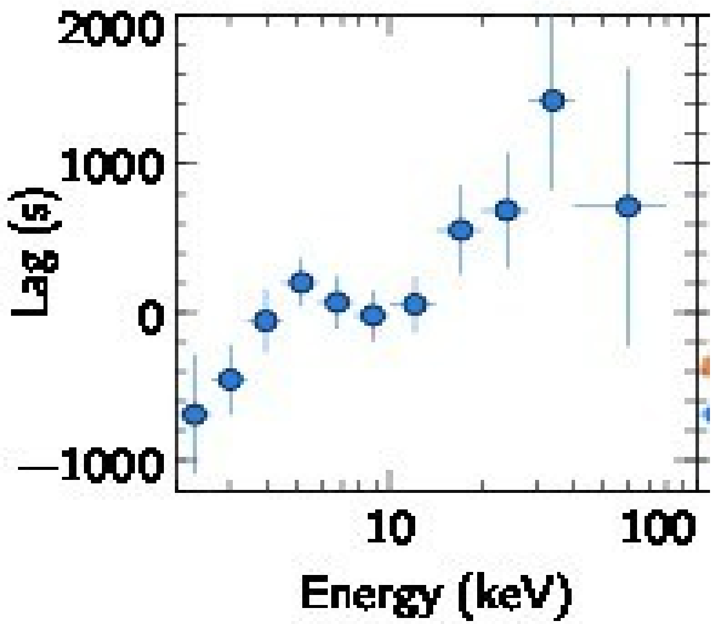
Soft time lags observed in many AGN (e.g. Fabian et al. 2009, De Marco et al. 2013, Uttley et al. 2014) --- Reflection from inner disc

More recently, reverberation of iron lines have also been observed (e.g. Zoghbi et al. 2012, Kara et al. 2014)

Compton hump reverberation expected !!



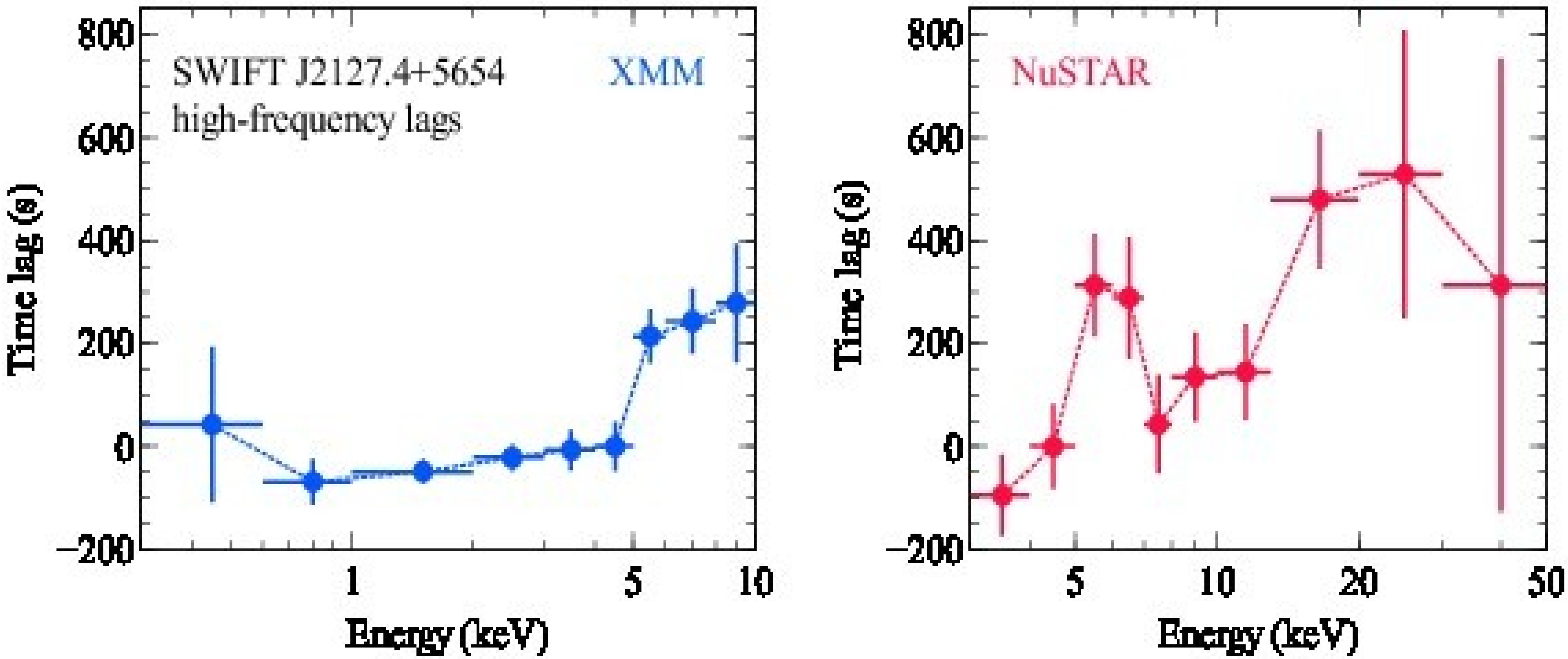
XMM (*Zoghbi et al. 2013*)



NuSTAR (*Zoghbi et al. 2014*)

The hard X-ray time lag in Swift J2127.4+5654

Similar results found in Swift J2127.4+5654



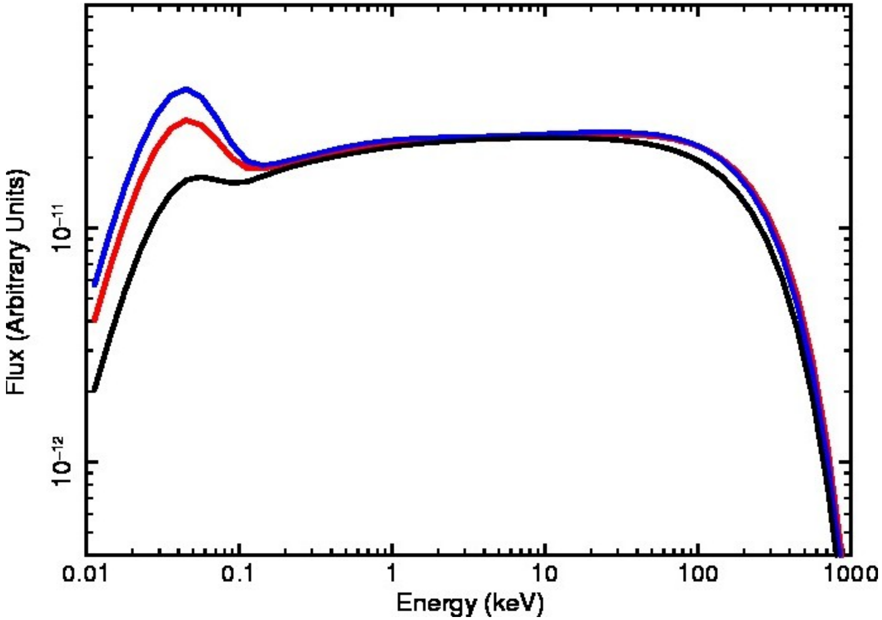
Kara et al. 2015

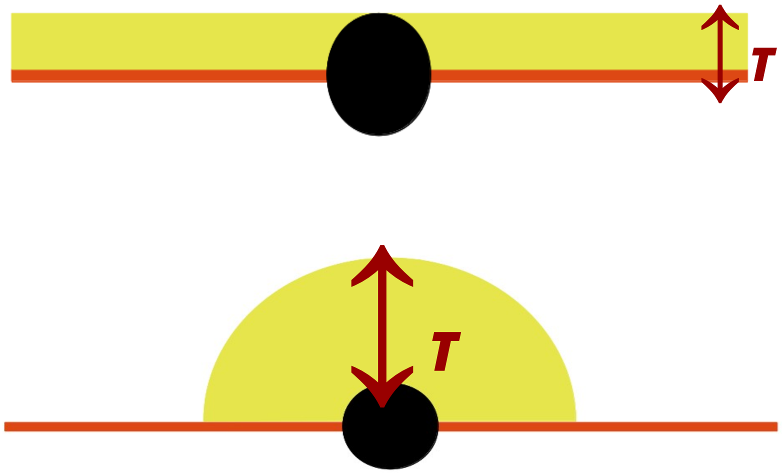
Coronal parameters

Primary hard X-ray emission likely due to Comptonization in a hot corona → quasi-exponential high energy cutoffs expected

Evidence for high energy cutoffs in BeppoSAX and XMM - INTEGRAL samples

NuSTAR is providing for the first time source-dominated obs above 10 keV → coronal parameters



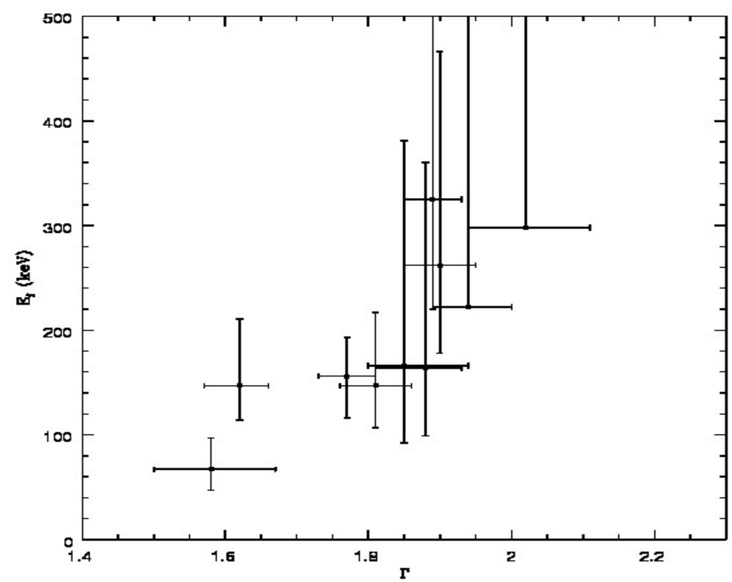


Coronal parameters

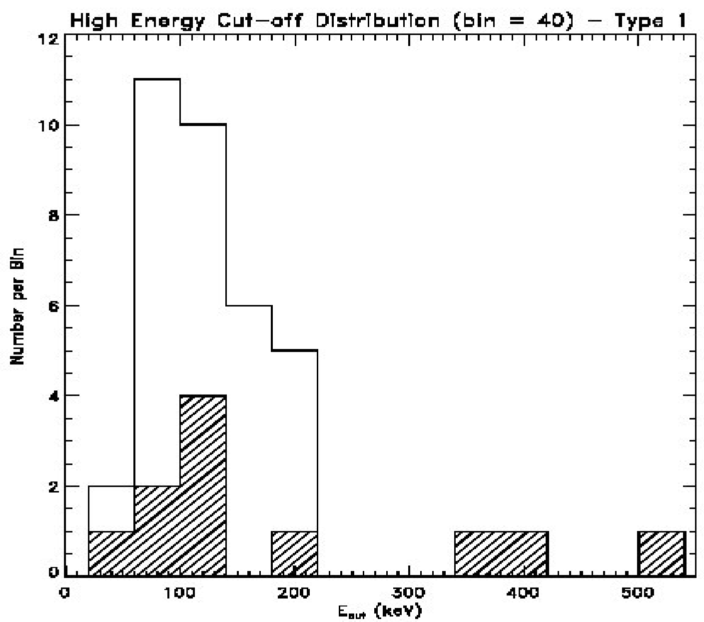
Primary hard X-ray emission due to Comptonization in a hot corona → high energy cutoffs expected

Evidence for high energy cutoffs in BeppoSAX and XMM - INTEGRAL samples

NuSTAR is providing for the first time source-dominated obs above 10 keV → coronal parameters



(Perola et al. 2002)



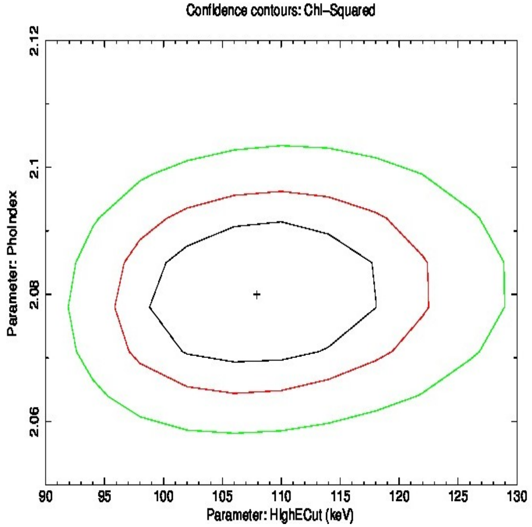
(Malizia et al. 2014)

Coronal parameters

Primary hard X-ray emission due to Comptonization in a hot corona → high energy cutoffs expected

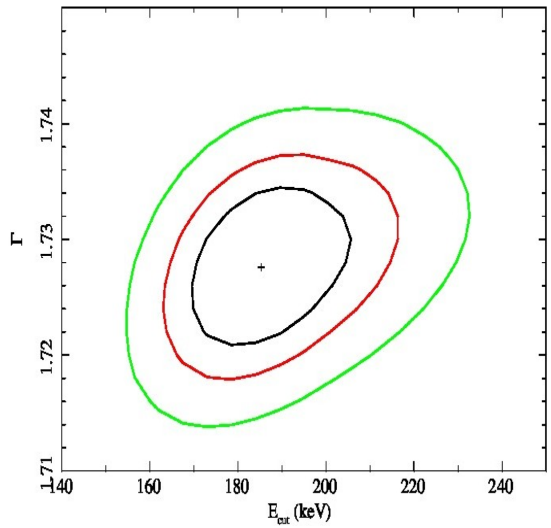
Evidence for high energy cutoffs in BeppoSAX and XMM - INTEGRAL samples

NuSTAR is providing for the first time source-dominated obs above 10 keV → coronal parameters



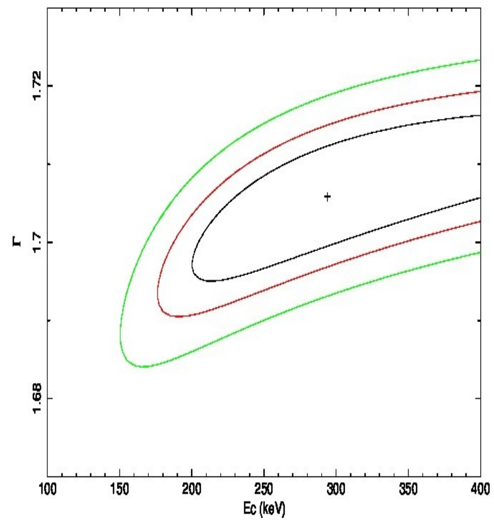
Swift J2127.4+5654 (Marinucci et al. 2014)

kT~68/53 keV τ~0.35/1.35 (slab/sphere)



IC4329A (Brenneman et al. 2014)

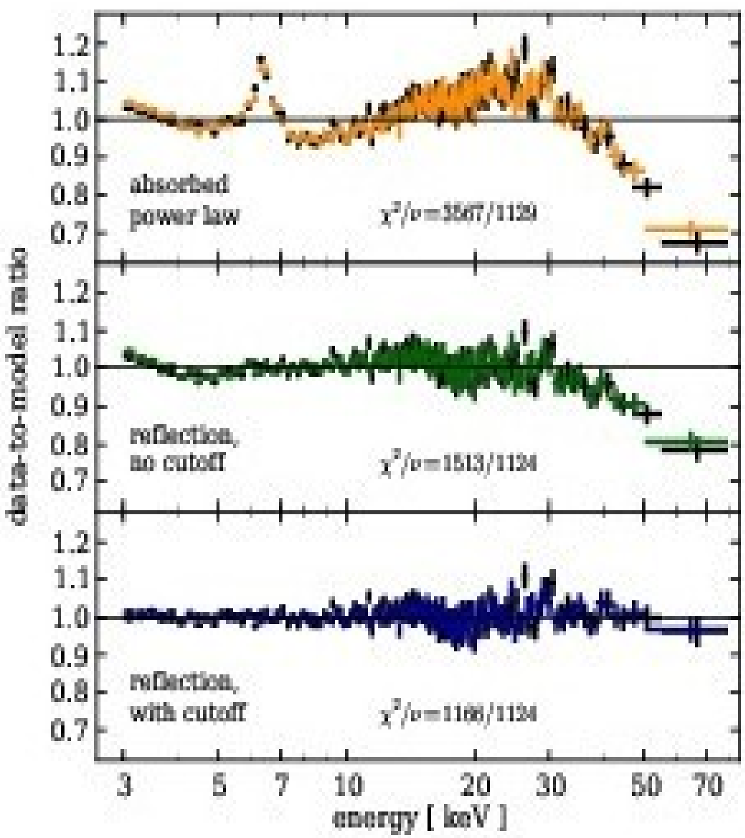
kT~61/50 keV τ~0.7/2.35 (slab/sphere)

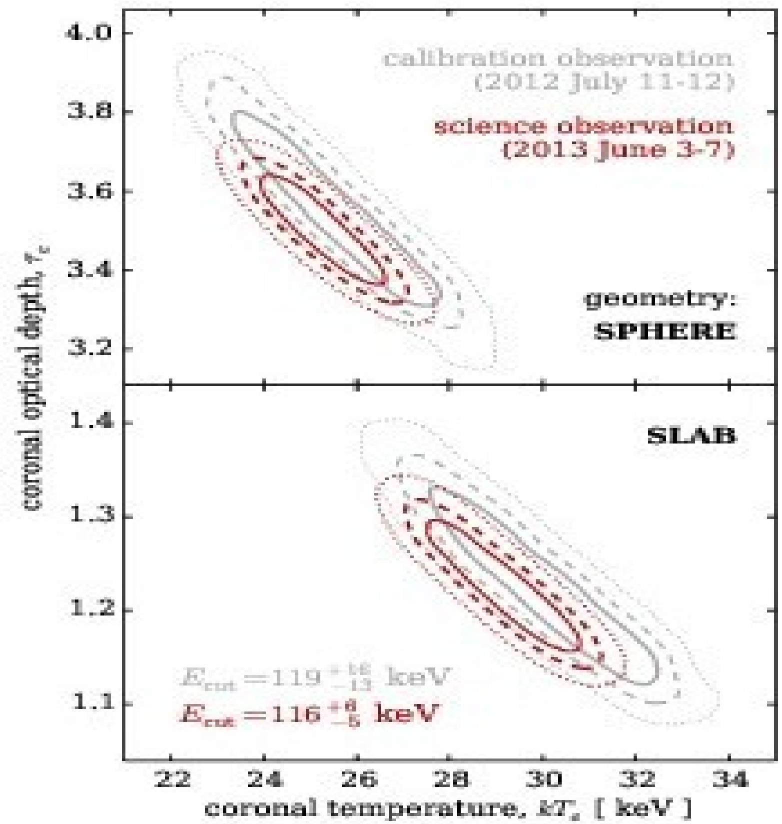


Ark 120 (Matt et al. 2014)

Coronal parameters

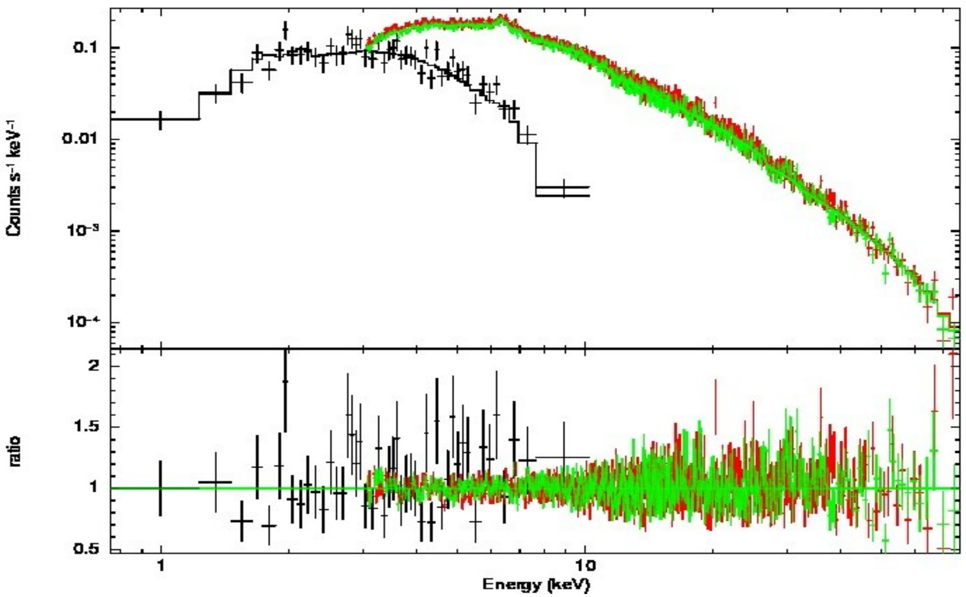
The best case so far: MCG-5-23-16 (Balokovic et al., 2015)

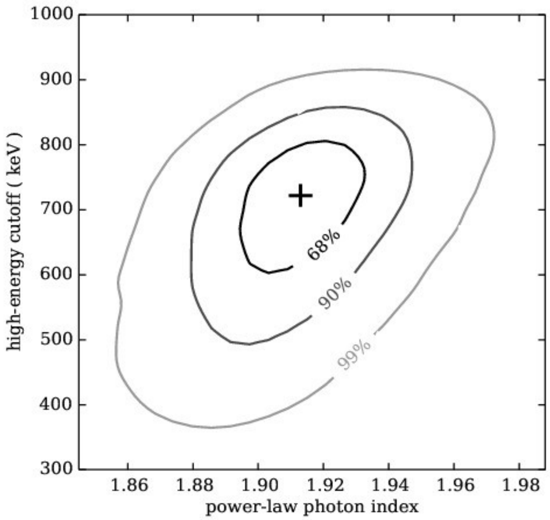


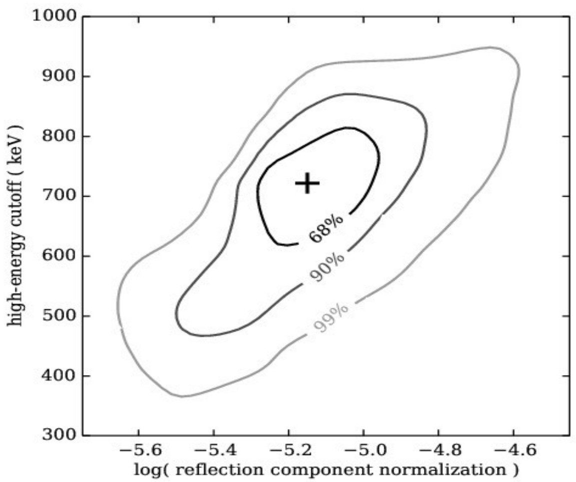


Coronal parameters

What Ec values can be measured with NuSTAR? NGC 5506 (Matt et al., 2015)







Coronal parameters

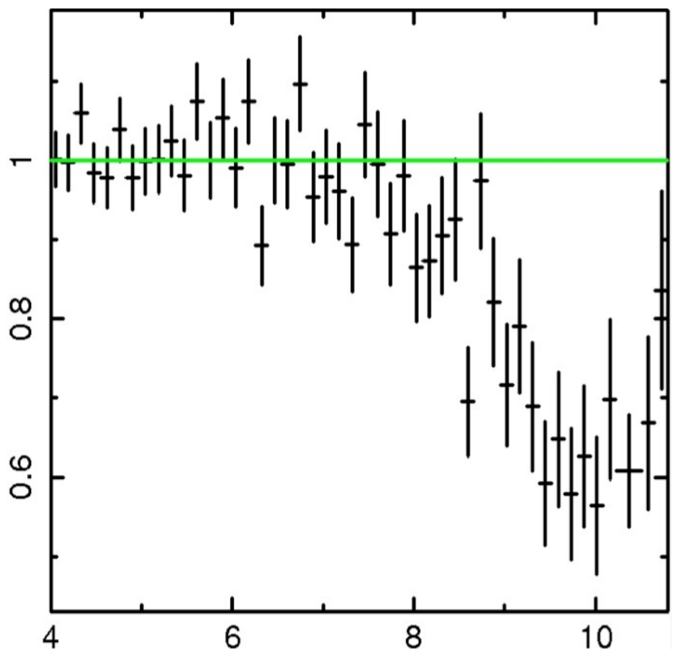
Name	Γ	E_c (keV)	log(M) ($M_\odot$)	Reference
3C 382	$1.68^{+0.03}_{-0.02}$	214^{+147}_{-63}	9.2 ± 0.5	1-2
3C 390.3	1.70 ± 0.01	116^{+24}_{-8}	8.4 ± 0.1	2-12
Ark 120	1.73 ± 0.02	> 190	8.2 ± 0.1	3-12
IC 4329A	1.73 ± 0.01	186 ± 14	6.8 ± 0.2	4-13
Fairall 9	$1.96^{+0.01}_{-0.02}$	> 242	8.4 ± 0.1	2-12
MCG 5-23-16	1.85 ± 0.01	116^{+6}_{-5}	7.8 ± 0.2	5-13
MCG 6-30-15	2.061 ± 0.005	> 110	6.2 ± 0.1	6-13
Mrk 335	$2.14^{+0.02}_{-0.04}$	> 174	7.1 ± 0.1	7-12
NGC2110	1.65 ± 0.03	> 210	8.3 ± 0.2	8-14
NGC5506	1.91 ± 0.03	720^{+130}_{-190}	8.0 ± 0.2	9-2
NGC7213	1.84 ± 0.03	> 140	8.0 ± 0.2	10-2
SWIFT J2127.4+5654	2.08 ± 0.01	108^{+11}_{-10}	7.2 ± 0.2	11-2

A brief digression ....

- We have started to measure the physical parameters of the corona, but its geometry is largely unknown
- The geometry of the corona is related to its nature and origin (disk perturbation, base of a jet, ...)
- The geometry may be probed by **X-ray Polarimetry**
- No polarimeters on board of X-ray satellites since the 70s, when the only measurement so fare was obtained (the Crab Nebula)
- The **Imaging X-ray Polarimetry Explorer (IXPE)** has been recently selected by NASA for a launch in 2020. A X-ray Polarimetry mission (XIPE) is still competing in the ESA M4 program
- **IXPE** will be able to obtain meaningful measurements for the brightest specimens of almost all classes of X-ray sources, including AGN

Black hole feedback in PDS 456

Most luminous RQ AGN in the local Universe



Rest-frame energy (keV)

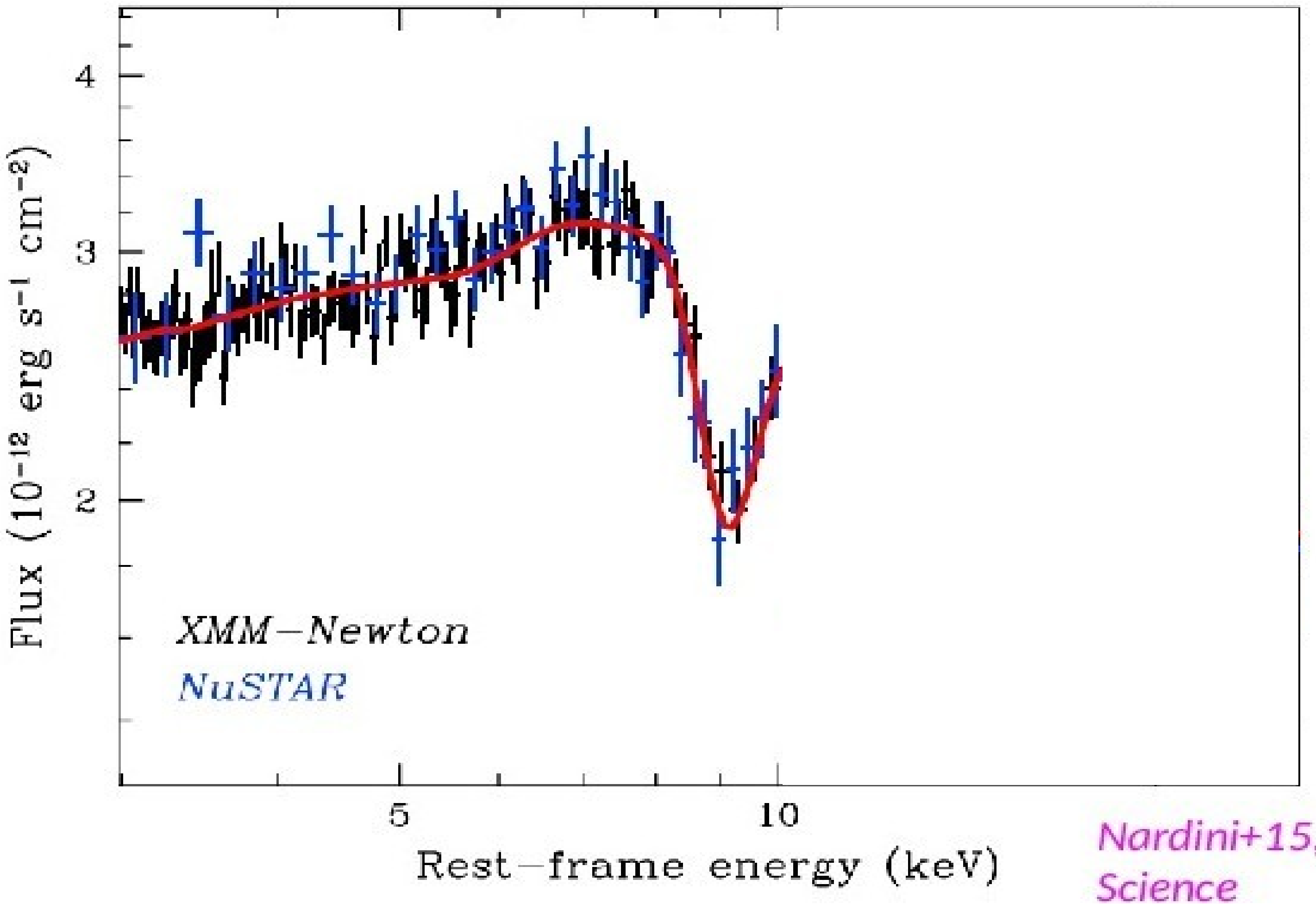
Systematic detection of a deep trough above 7 keV rest-frame: evidence for a large column of highly ionised matter outflowing at about one third of the speed of light

Ideal target for studying BH winds in the Eddington-limited regime

2013/14 campaign: 5 simultaneous *XMM* + *NuSTAR* observations

Black hole feedback in PDS 456

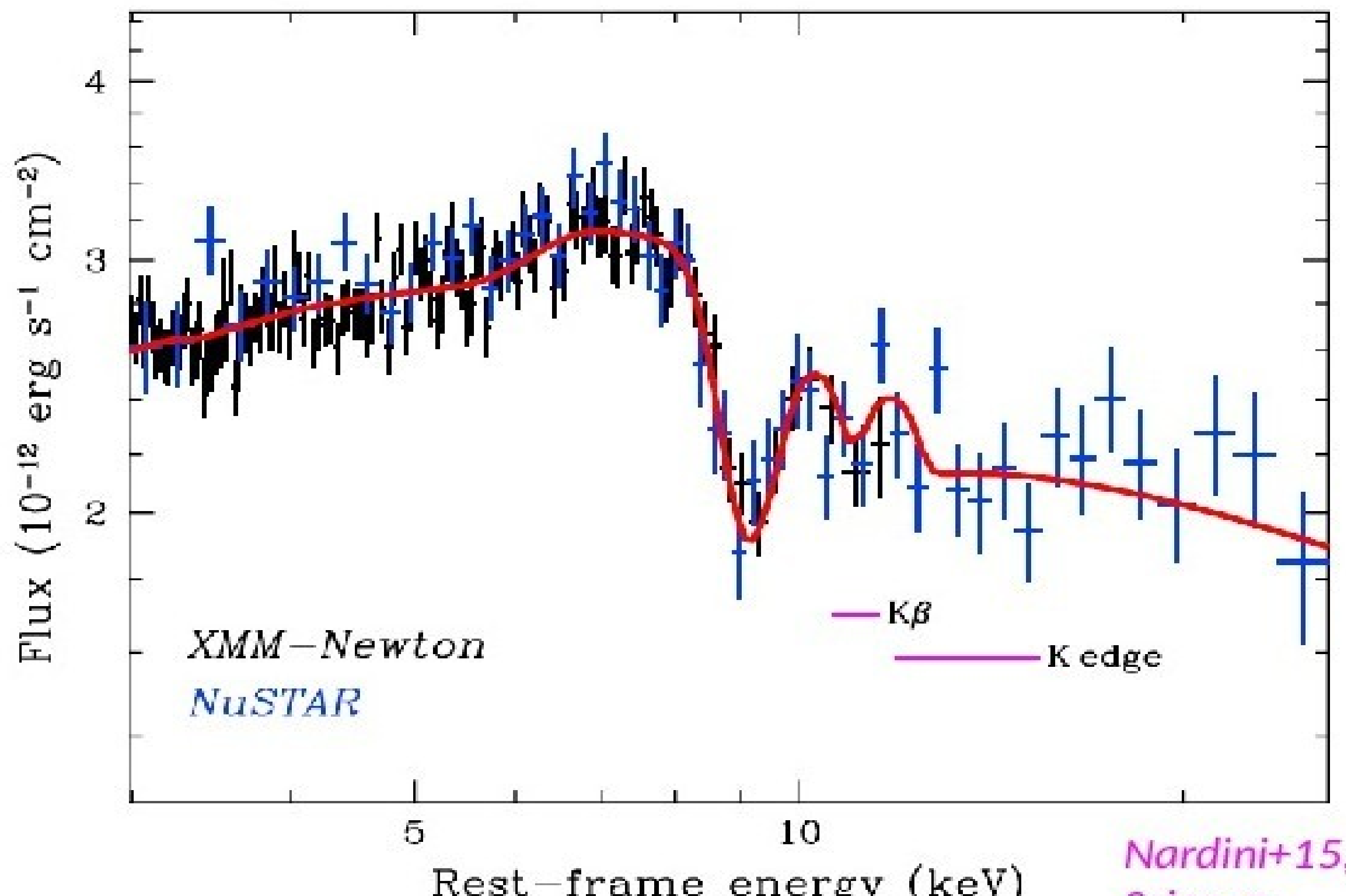
XMM only



Nardini+15, Science

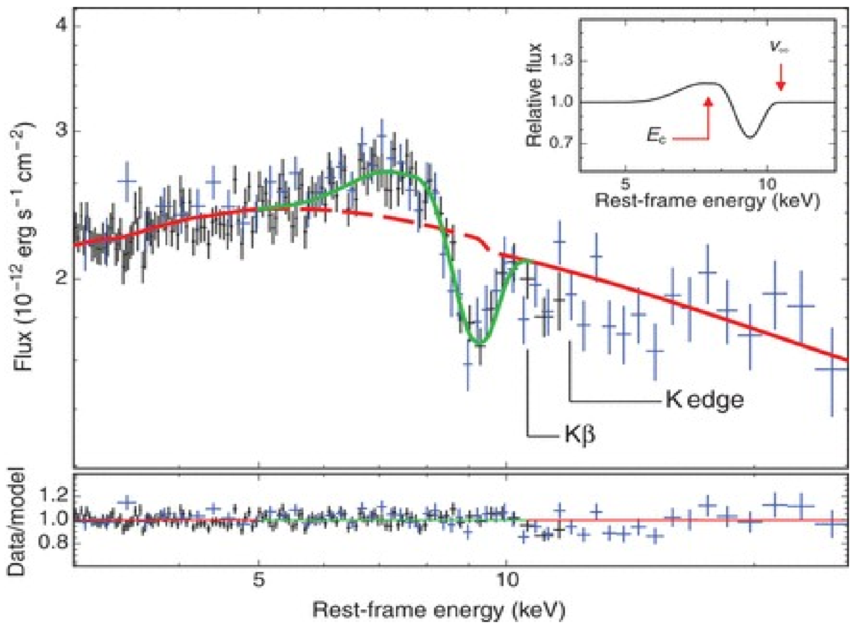
Black hole feedback in PDS 456

XMM + NuSTAR



Nardini+15, Science

Black hole feedback in PDS 456



$$\dot{M}_{\rm out} \sim \frac{\Omega}{4\pi} \times \frac{N_{\rm H}}{10^{23}\,{\rm cm}^{-2}} \times \frac{v_{\rm out}}{c} \times \frac{R_{\rm in}}{10^{15}\,{\rm cm}}\, M_\odot\,{\rm yr}^{-1}$$

The solid angle is obtained from the emitted/absorbed luminosity ratio, and the launch radius from the variability timescale

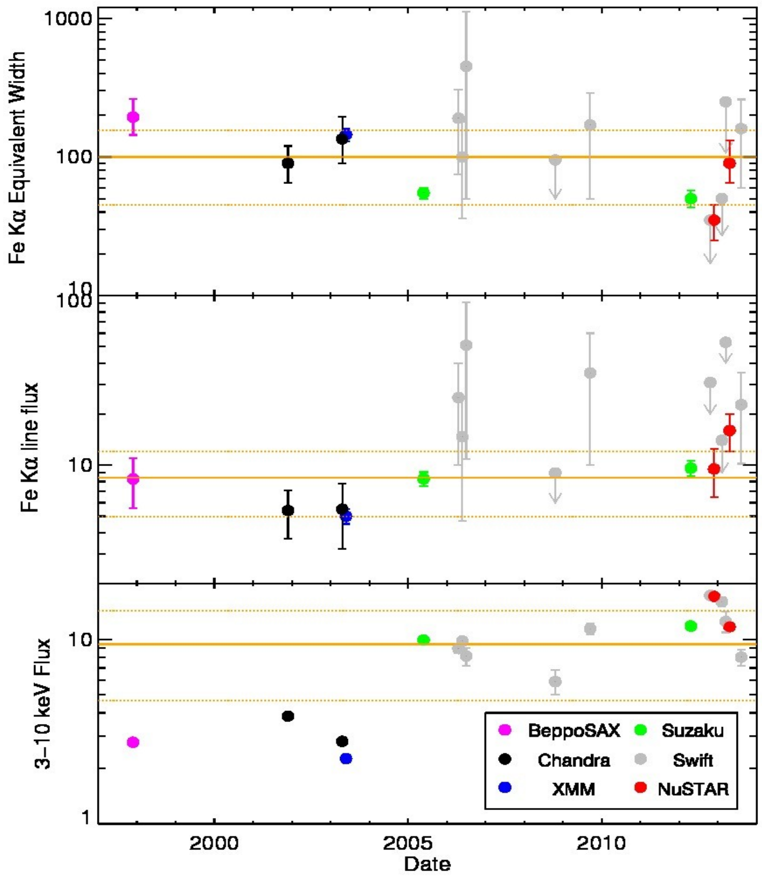
$$\dot{M}_{\rm out} \sim 10\, M_\odot\,{\rm yr}^{-1} \Rightarrow P_{\rm kin} \sim 2 \times 10^{46}\,{\rm erg\,s}^{-1} \sim 0.2\, L_{\rm bol}$$

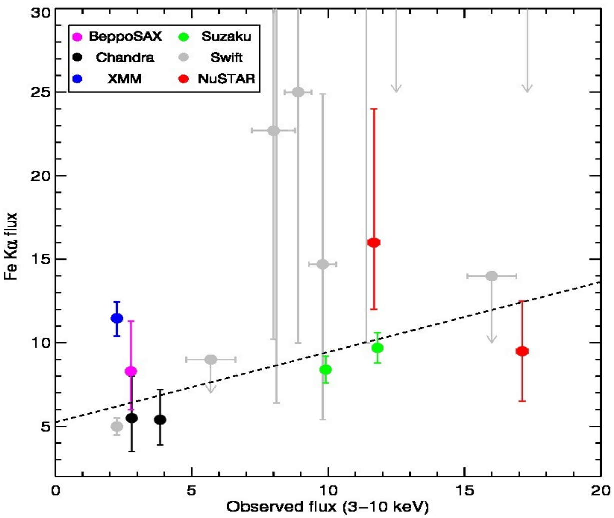
The deposition of a few % of the total radiated energy is enough to prompt significant feedback on the host galaxy *(Hopkins & Elvis 10)*. Over a lifetime of 10^7 yr the energy released through the accretion disk wind likely exceeds the binding energy of the bulge

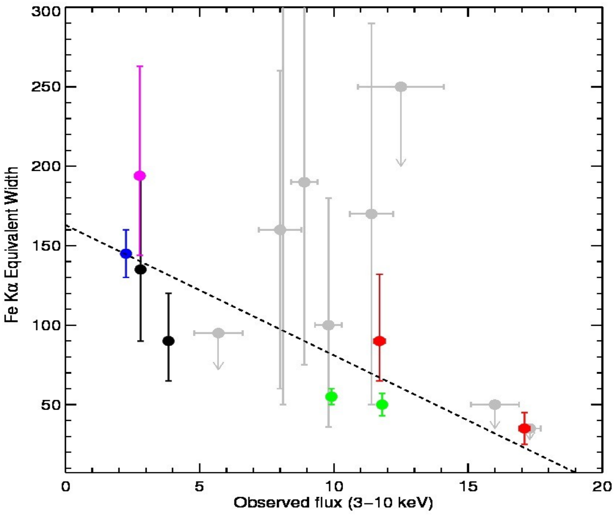
$$E_{\rm wind} \sim 10^{61}\,{\rm erg} \sim 3 \times M_{\rm bulge}\,\sigma^2$$

The origin of the narrow iron line

NGC 2110 (Marinucci et al., 2015)
Two components?



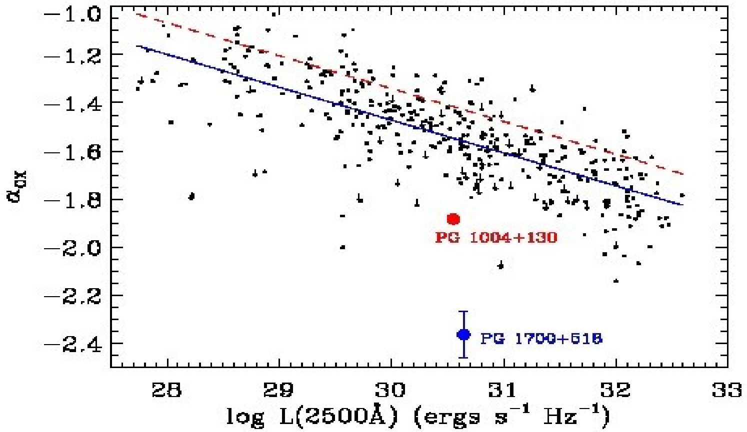


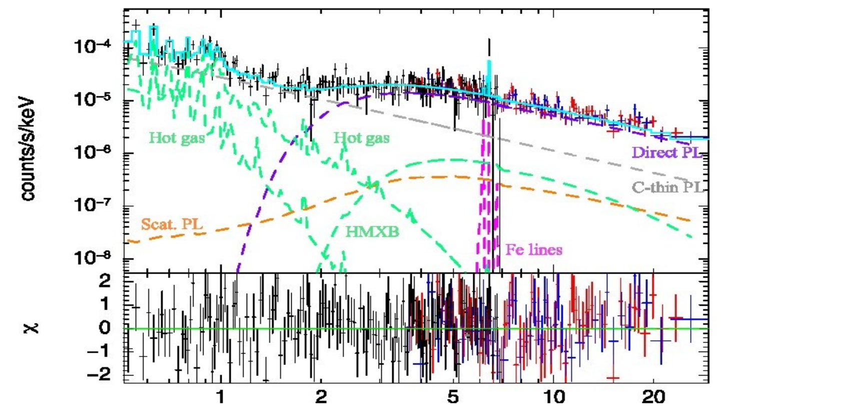


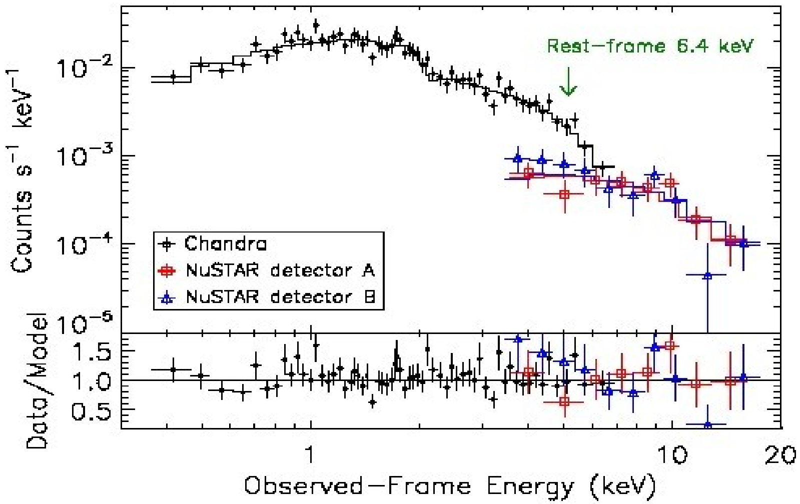
BAL: Absorption or X-ray weakness?

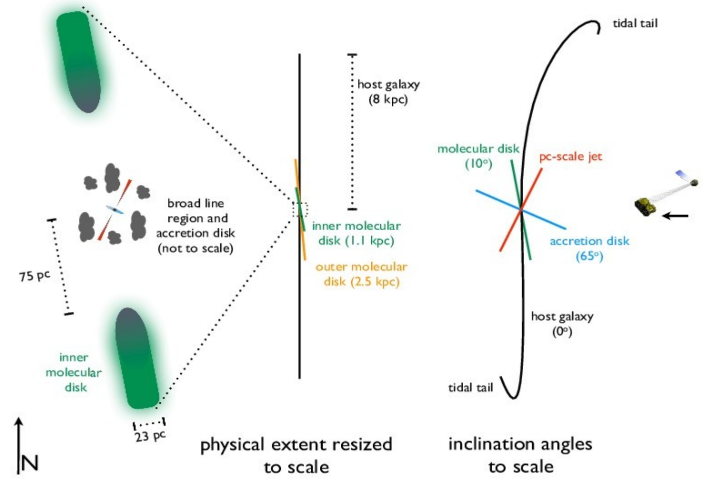
Broad Absorption Line QSOs have a low X-ray-to-optical flux ratio.

Absorption or intrinsic X-ray weakness?





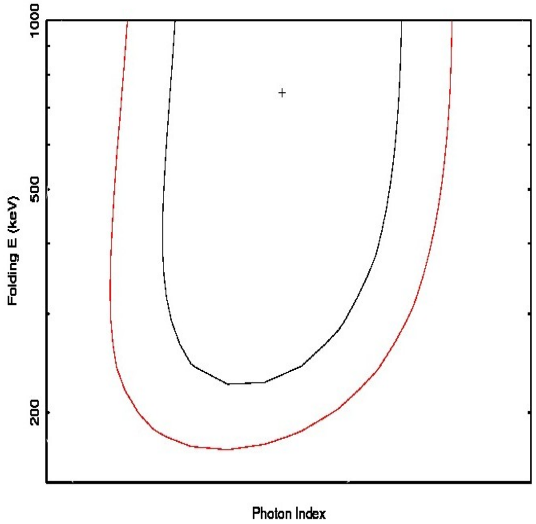




PG 1004+130 Chandra+NuSTAR (Luo et al. 2013)

Mrk 231 Chandra+NuSTAR (Teng et al. 2014)

The soft excess of Ark 120

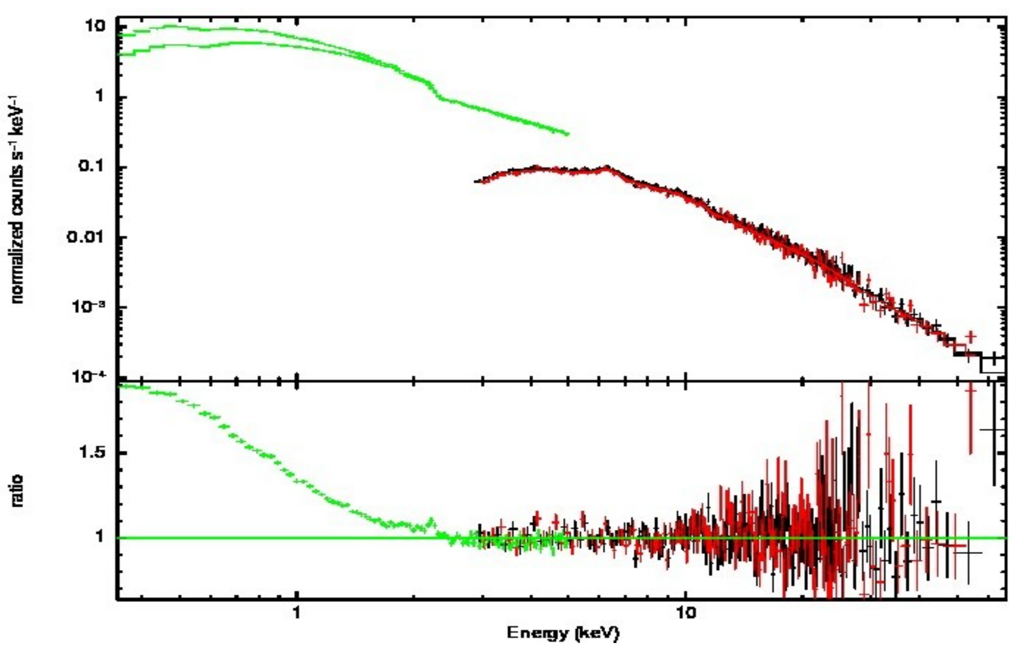


Bright, "bare" Seyfert 1 galaxy

Fit with NuSTAR data only (power law + reflection + iron line)

No High Energy Cutoff detected

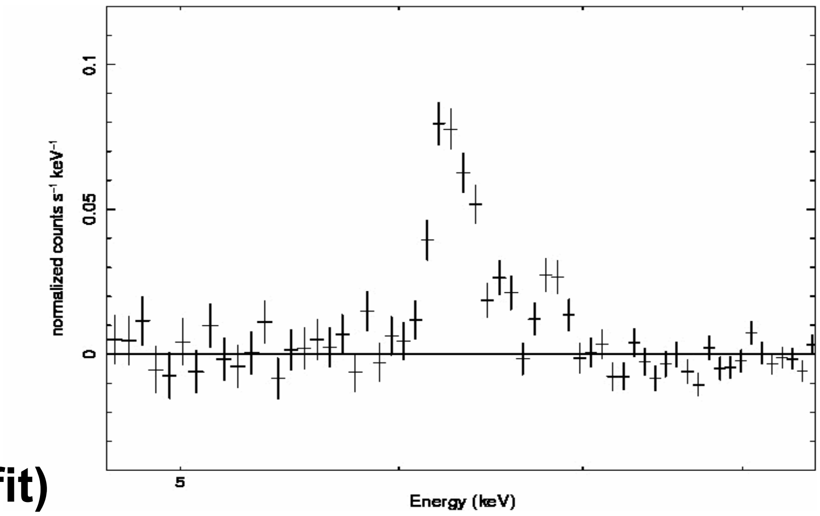
Extrapolation to XMM shows strong excess



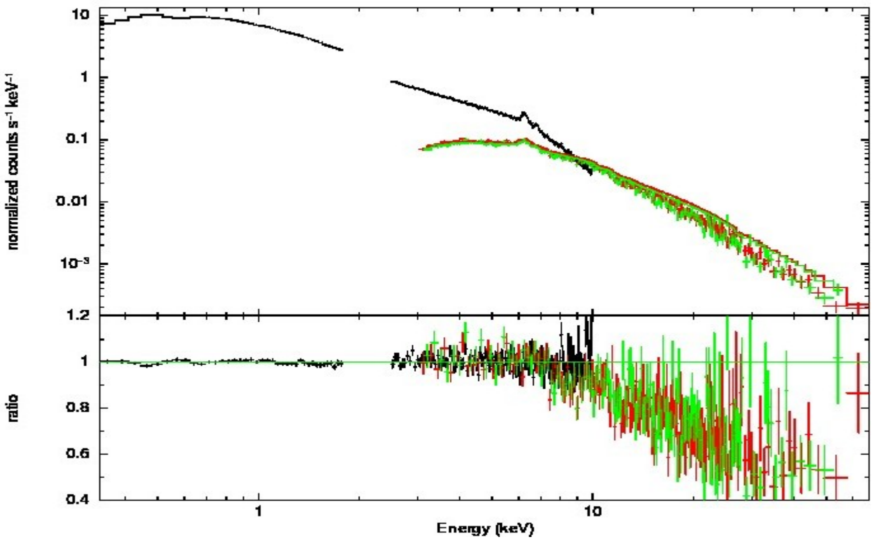
(Matt et al. 2014)

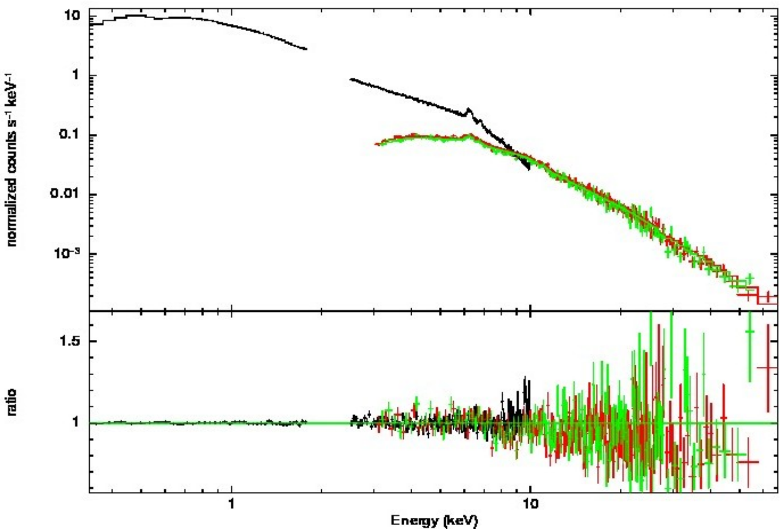
The soft excess of Ark 120

XMM: no obvious evidence for rel. Line (differently from a previous Suzaku obs, Nardini et al. 2011)

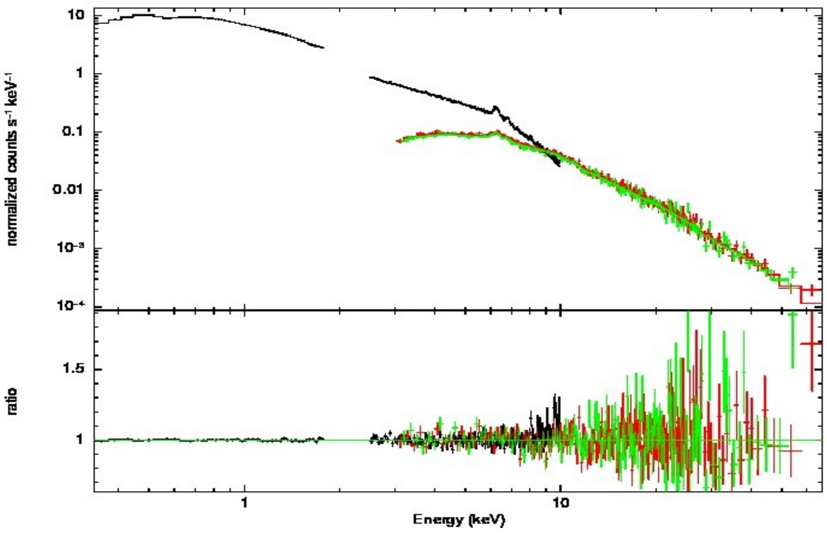


Soft excess with a simple power law or with a Comptonization model give comparable fits to the XMM spectrum, but very different extrapolation to NuSTAR (cold and ionized reflection included in the fit)

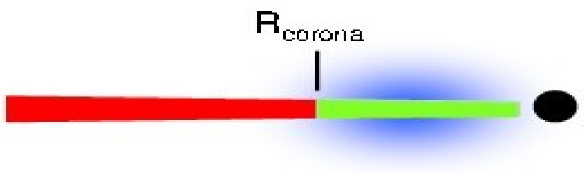


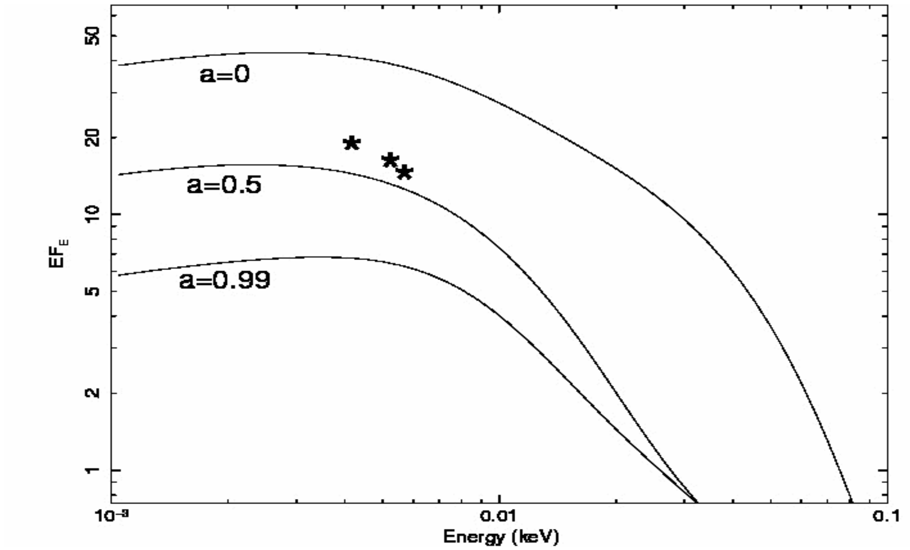


The soft excess of Ark 120



Indeed, the broad-band best fit is with a Comptonization model for the soft excess. A *cutoff p.l.*, *compTT, nthcomp* or *optxagnf* provide fits of comparable quality.



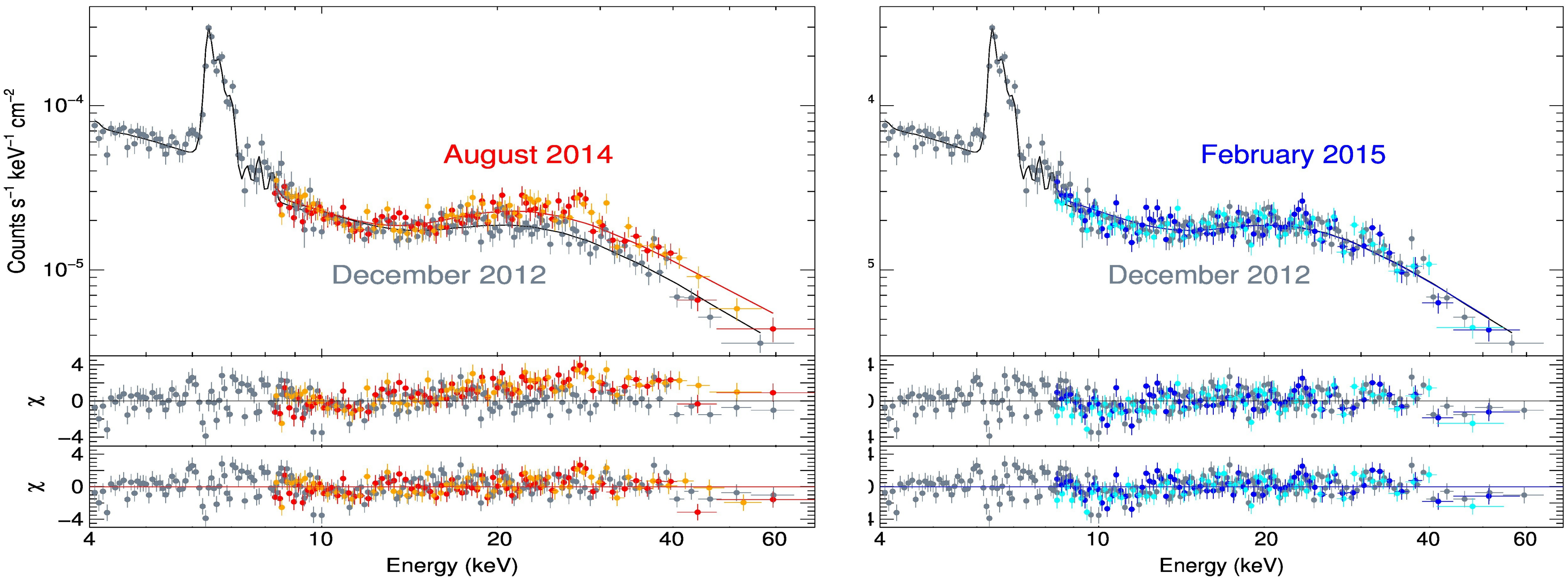


Optxagnf **(*Done et al. 2012*) is a disk/corona emission model which assumes a thermal disk emission outside the coronal radius, and soft and hard Comptonization inside.**

Extrapolating the best fit X-ray model to the OM UV data, an estimate of the black hole spin is possible

The clumpy torus of NGC 1068

(Marinucci et al. 2014)



An excess is seen in the NuSTAR data of Aug 14 with respect to both Dec 12 and Feb 15.

Best explanation: a decrease of NH (from >10^{25} to about 7×10^{24} cm^{-2}).

One less single cloud on the line of sight?

$\longrightarrow$ Clumpy Torus

Summary

- NuSTAR is providing AGN spectra of unprecedented quality above 10 keV
- The very broad band spectra from observations coordinated with XMM or Suzaku allow to disentangle the various spectral components (including relativistically distorted reflection) and shed light to poorly known components like eg the soft excess