The AGN central engine studied with X-ray spectroscopy and polarimetry

Giorgio Matt

(Università Roma Tre, Italy)

Plan of the talk

X-ray spectroscopy

Coronae
Soft excess
Strong gravity (reflection vs. absorption, BH spin)
Obscuration and outflows
The future: Athena

X-ray polarimetry

Coronae
Strong gravity (reflection vs. absorption, BH spin)
Circumnuclear matter
*Sgr A**
The future: XIPE (and IXPE and Praxys)

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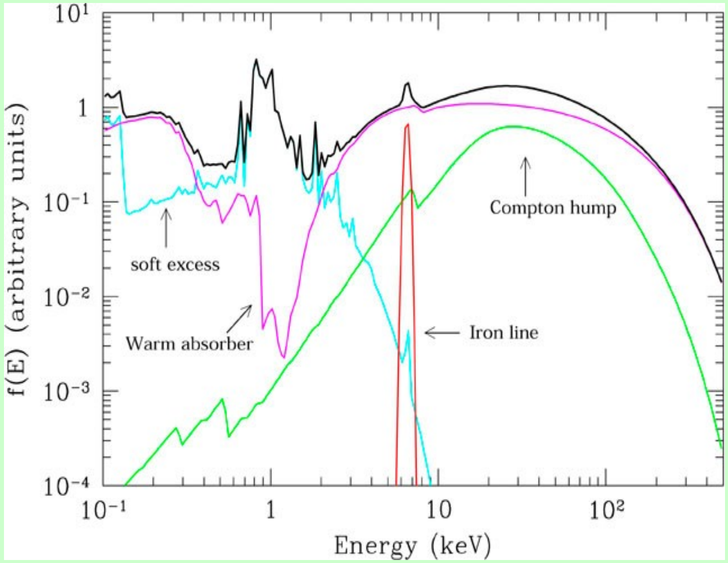
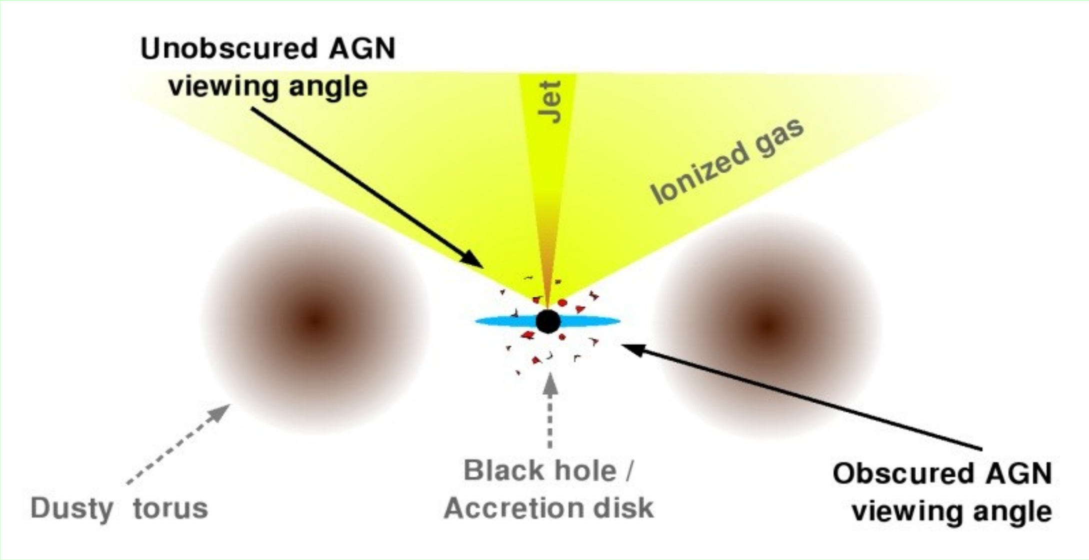
I. X-ray spectroscopy

The X-ray spectrum of AGN is quite complex, being the sum of different components. To avoid degeneracies in the spectral deconvolution, broad band coverage (as provided by NuSTAR plus XMM/Suzaku/Chandra) and high resolution spectroscopy (as will be provided by Athena) are very useful





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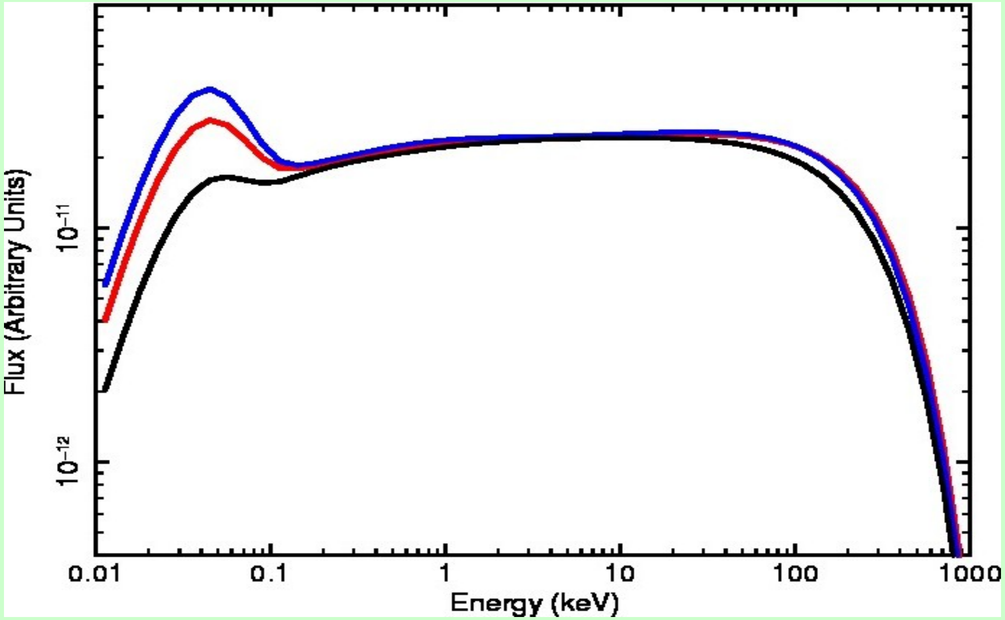
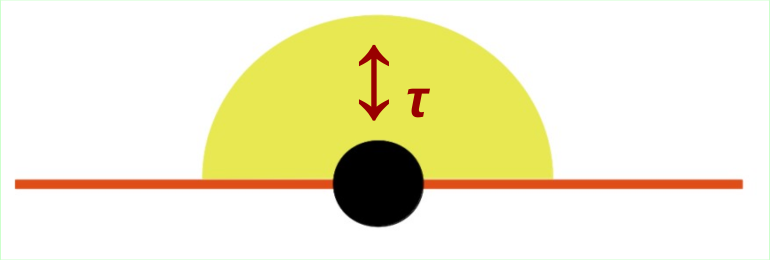
Coronal parameters

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 (much more in Andrea Marinucci's talk later on)





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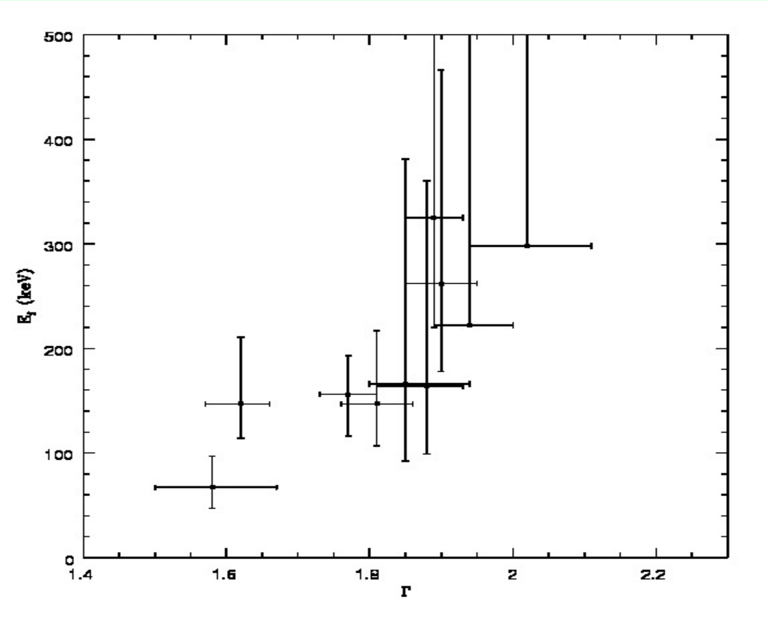
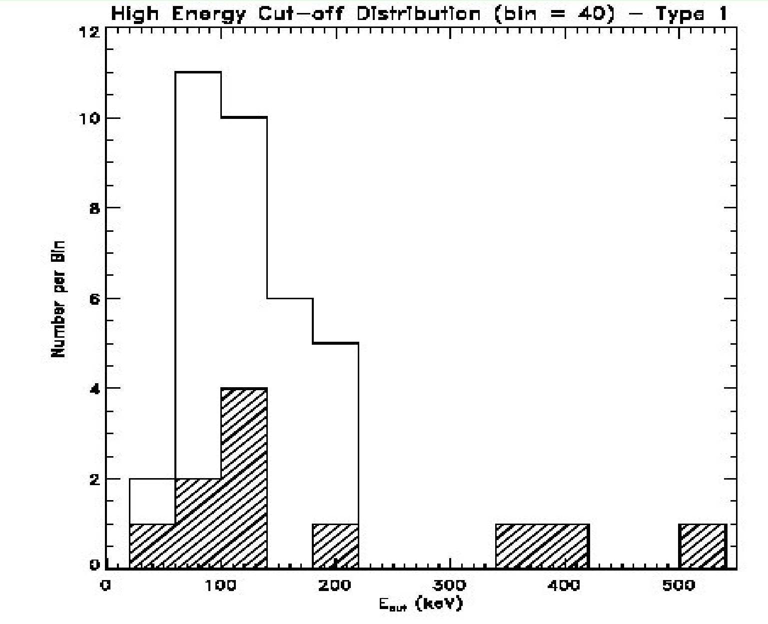


(Perola et al. 2014)



(Malizia et al. 2014)

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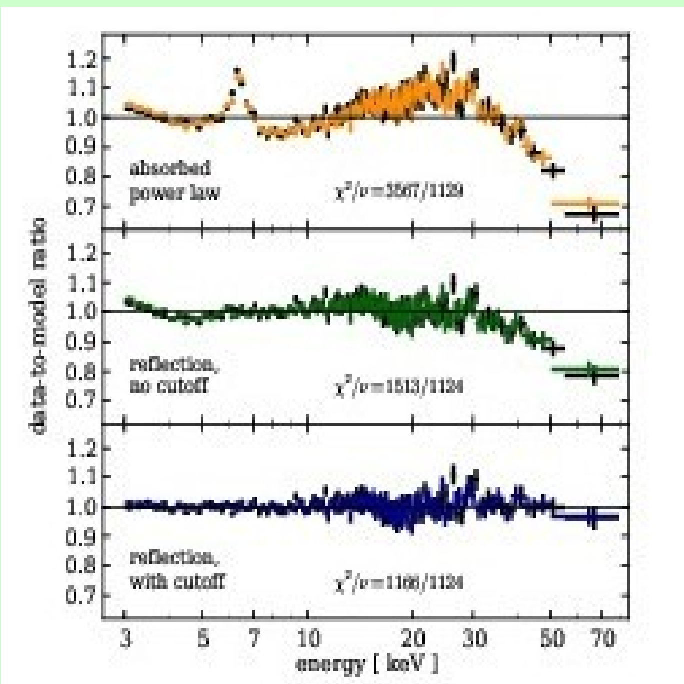
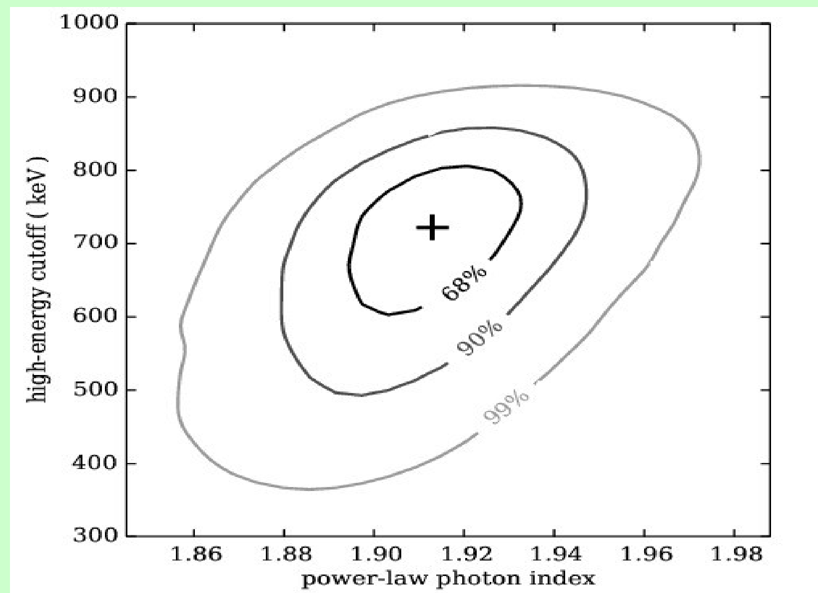


MCG-5-23-16
(Balokovic et al. 2015)

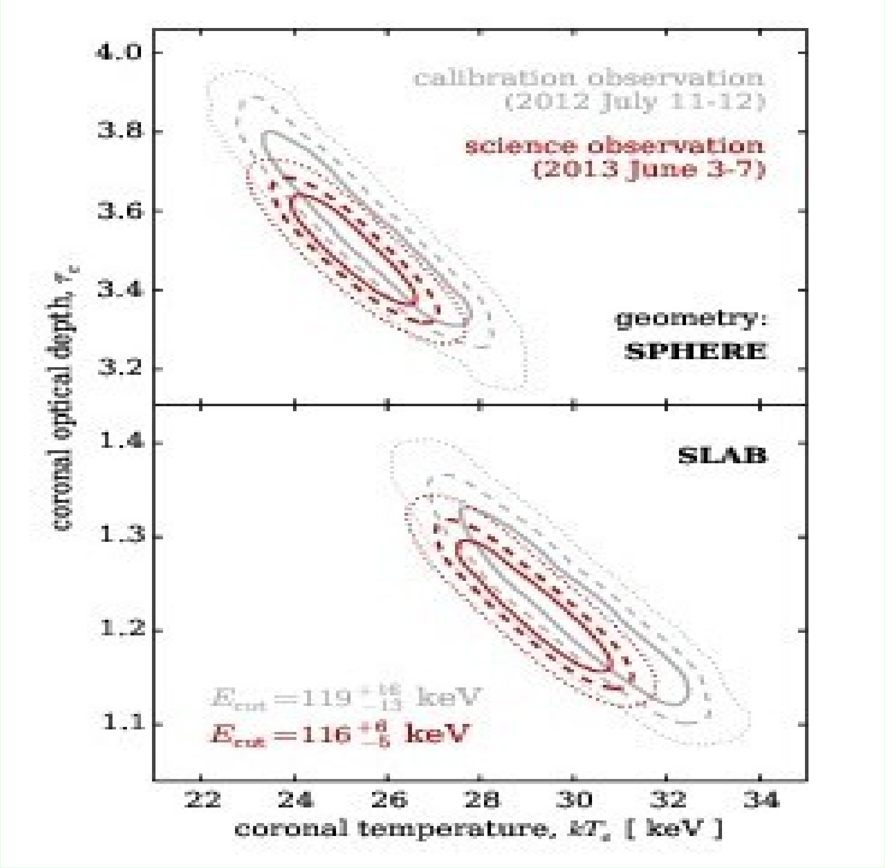


NGC 5506 (Matt et al. 2015)

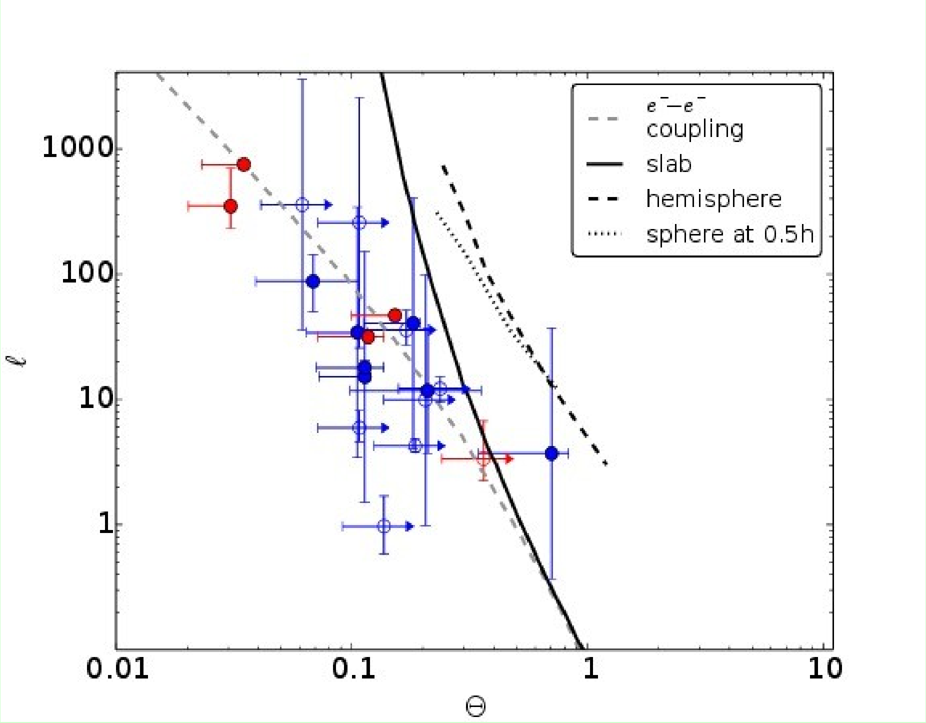
Coronal parameters

Large spread of coronal temperatures (from ~10 to >100 keV)

Coronae are often optically thick



MCG-5-23-16
(Balokovic et al. 2015)



Fabian et al. (2015)

Just below the runaway pair production line

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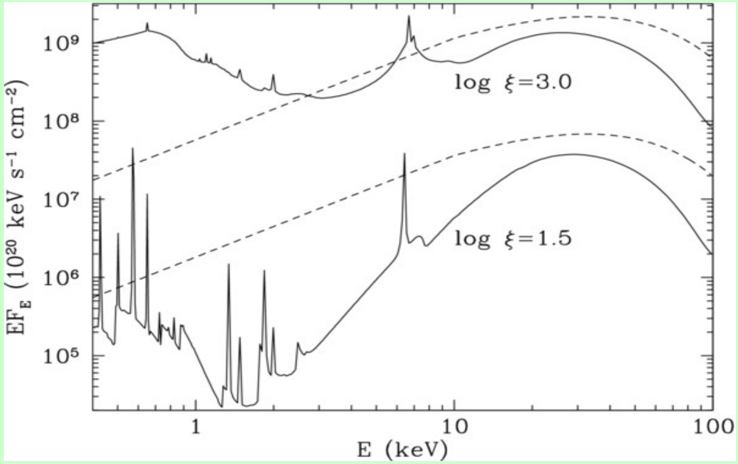
Soft excess

Most AGN show soft X-ray emission in excess of the extrapolation of the hard primary emission

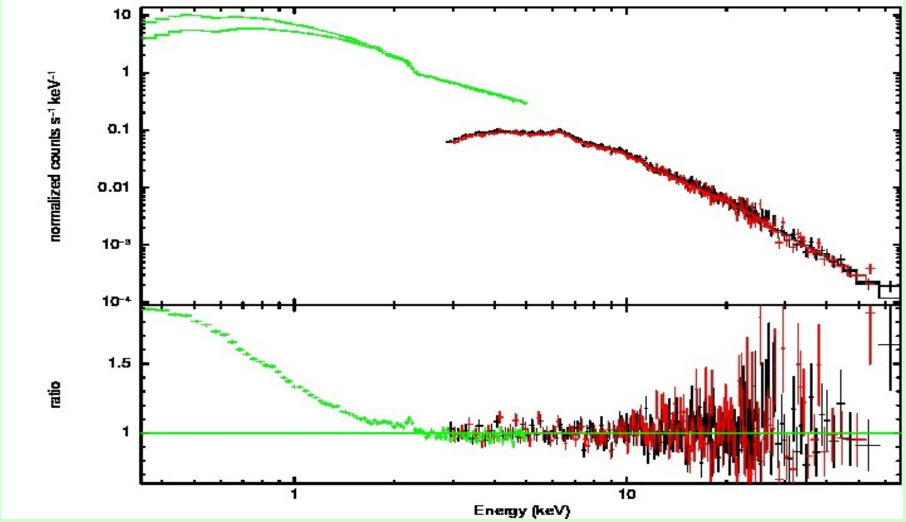
In many sources the soft excess is well explained by ionized reflection (e.g Walton et al. 2013)

However, there are sources in which another component is required (Petrucci et al. 2013, Patrick et al. 2012, Lohfink et al. 2012)

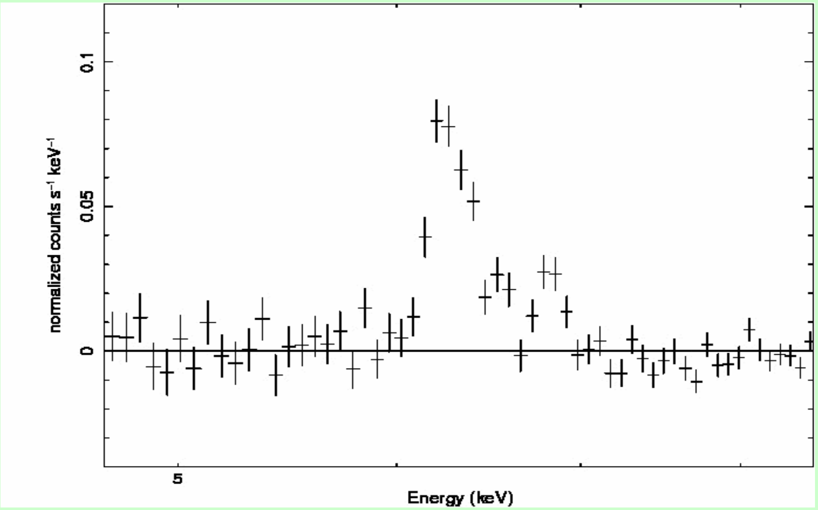
Ark 120 is one of them (Matt et al. 2014)



(Ross & Fabian 2005)



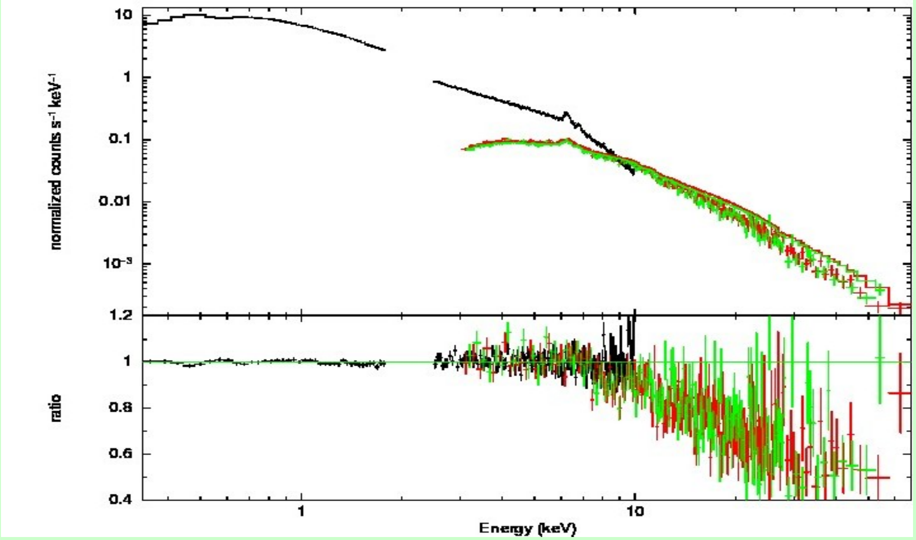
Ark 120 XMM+NuSTAR (Matt et al. 2014)

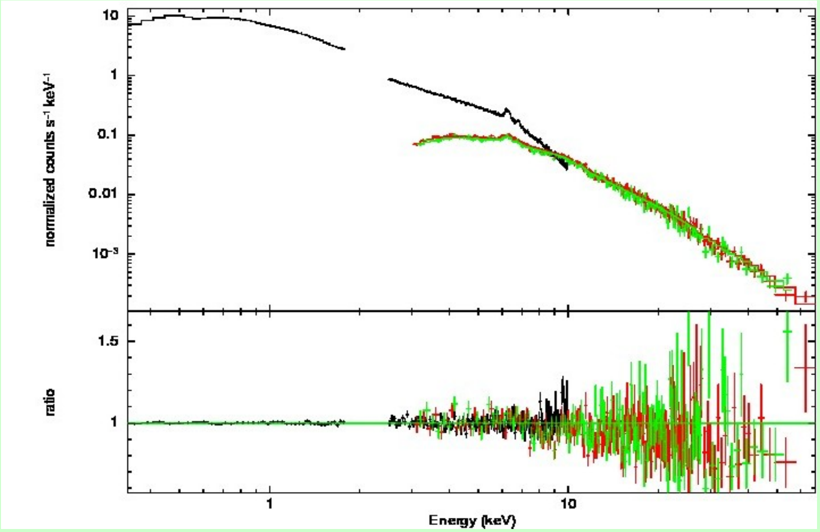


No obvious evidence for a relativistic iron line (differently from a previous Suzaku obs, Nardini et al. 2011)

Soft excess

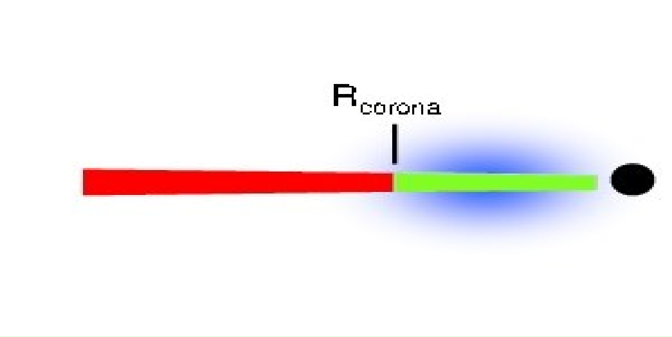
Soft excess with a simple power law or with a Comptonization model give comparable fits to the XMM-Newton spectrum, but very different extrapolations to NuSTAR (cold and ionized reflection included in the fit)

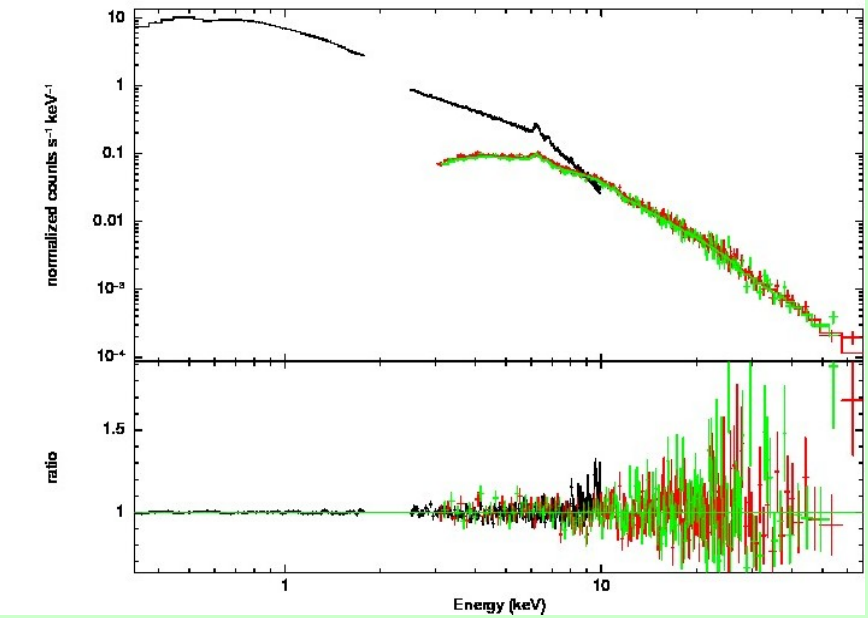




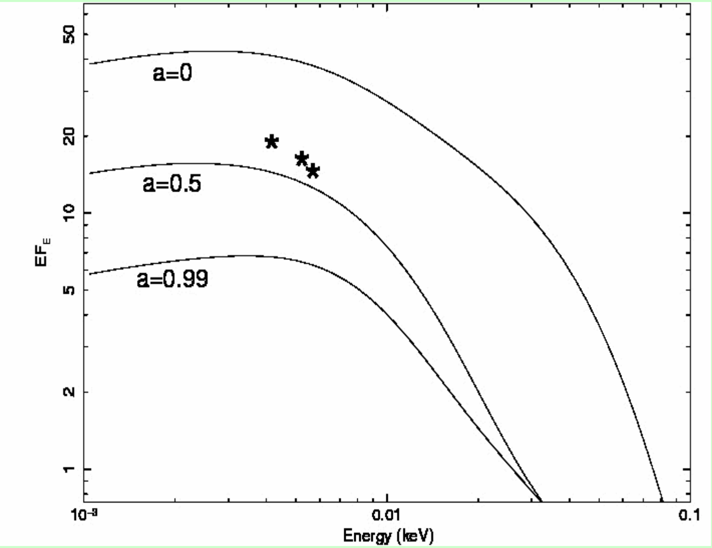
Soft excess

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.





Ark 120 XMM+NuSTAR (Matt et al. 2014)



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

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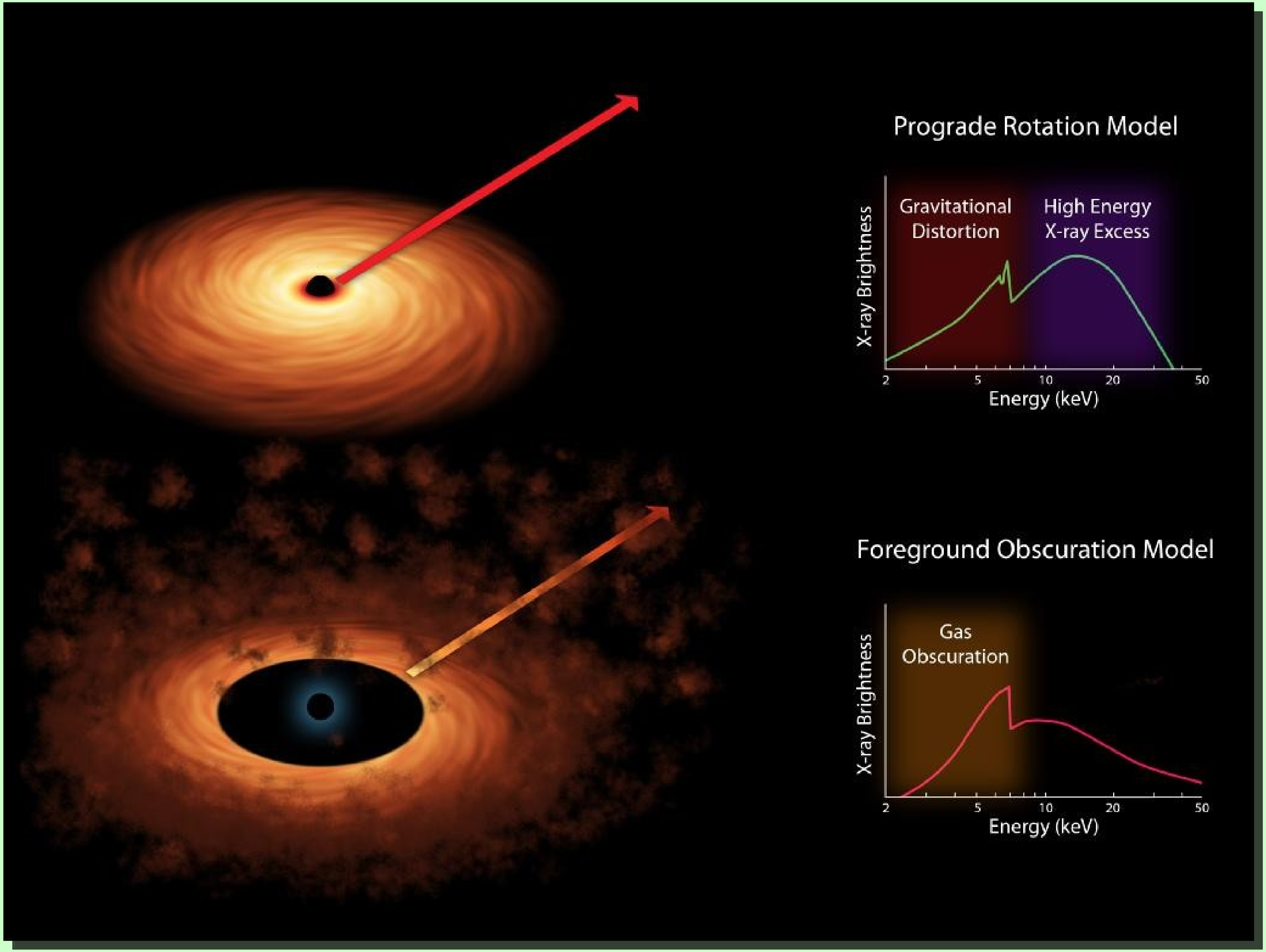
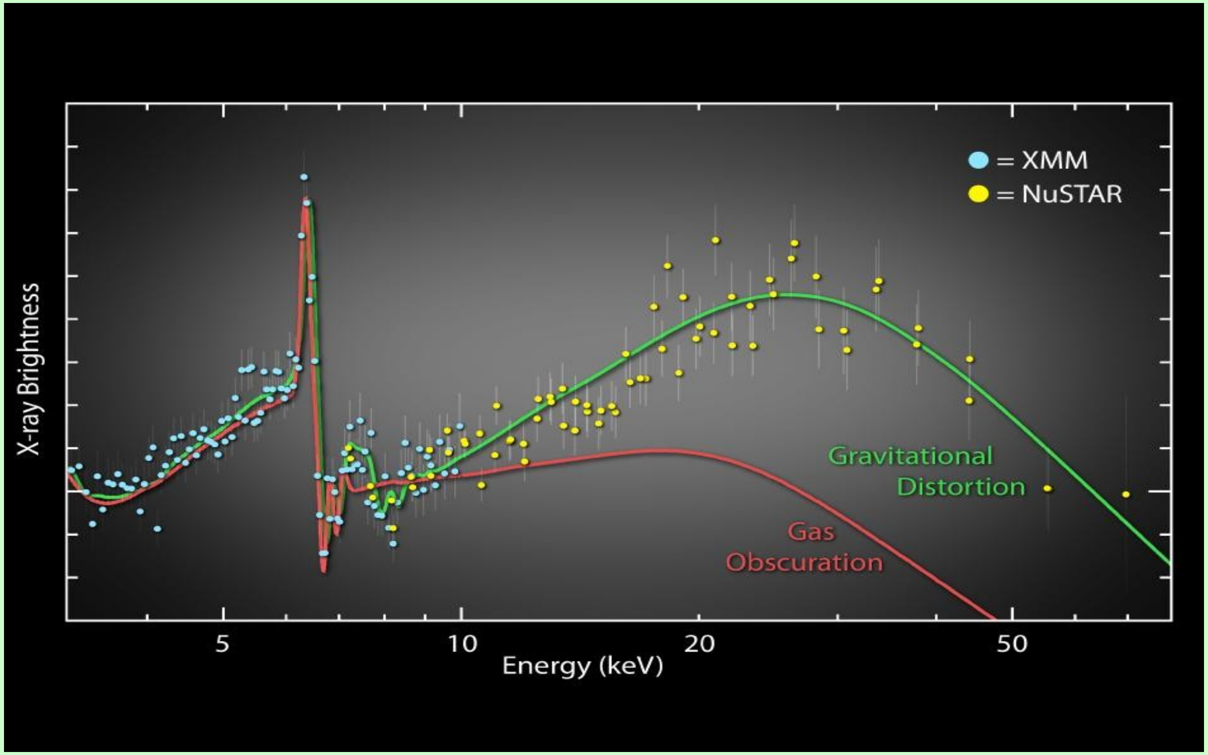
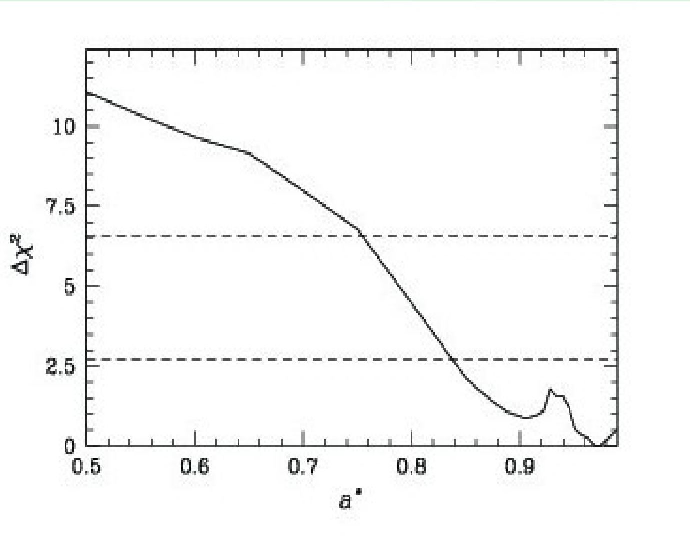
Relativistic reflection - NGC1365



Relativistic reflection - NGC1365



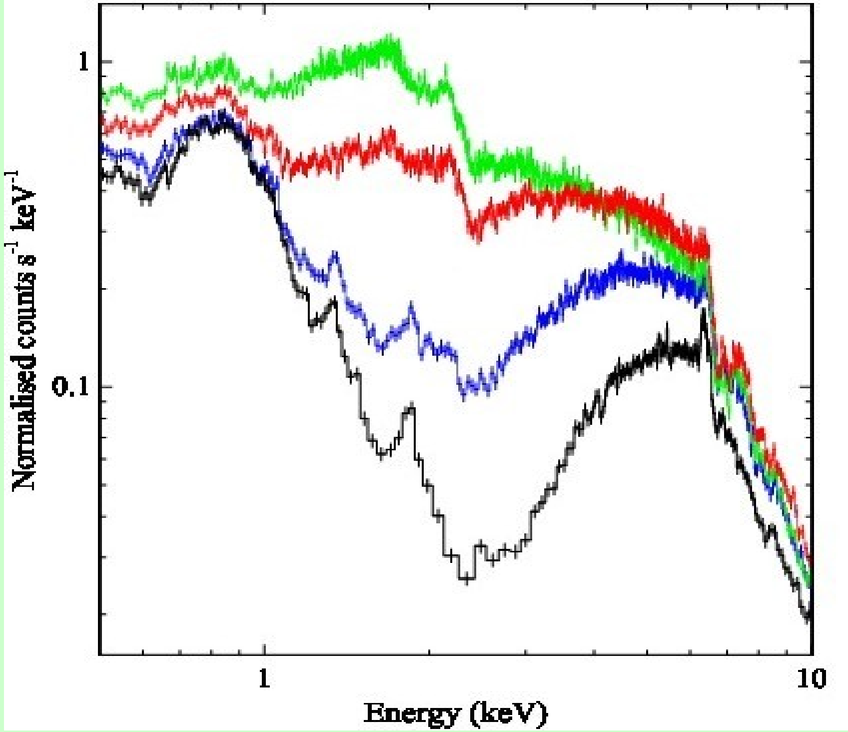
NGC 1365: a source with BOTH absorption and relativistic reflection. Observed simultaneously by XMM and NuSTAR. Both absorption and reflection models fit well the XMM data, but only reflection fits the NuSTAR data (Risaliti et al. 2013)

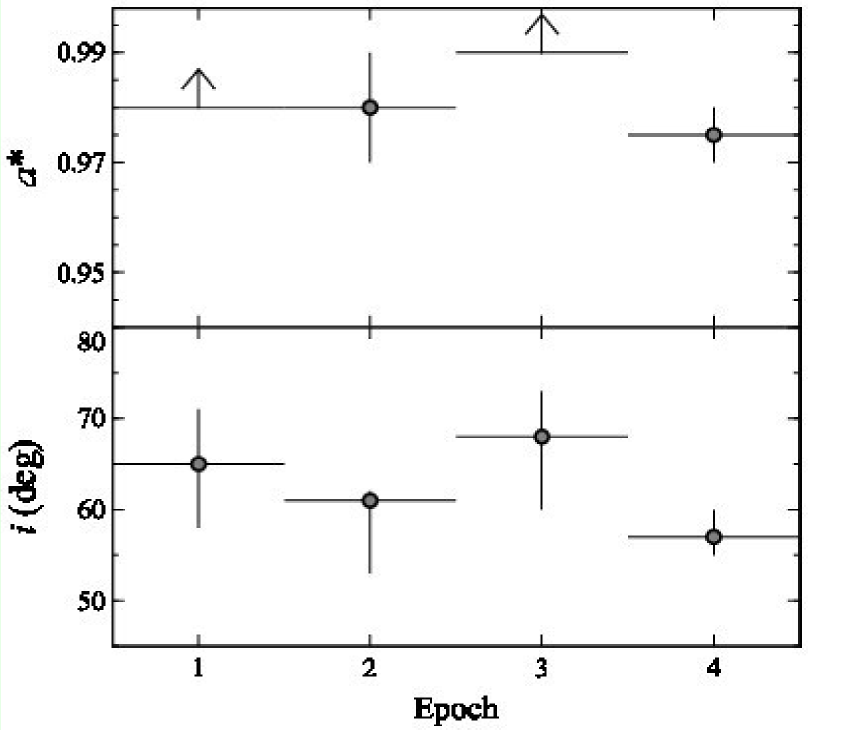


Consistent with a maximally rotating BH

Relativistic reflection – NGC1365

NGC 1365 was observed by XMM-Newton and NuSTAR four times. Despite large variations in the absorbers, no variations in the spin and inclination are found, showing the robustness of the result.

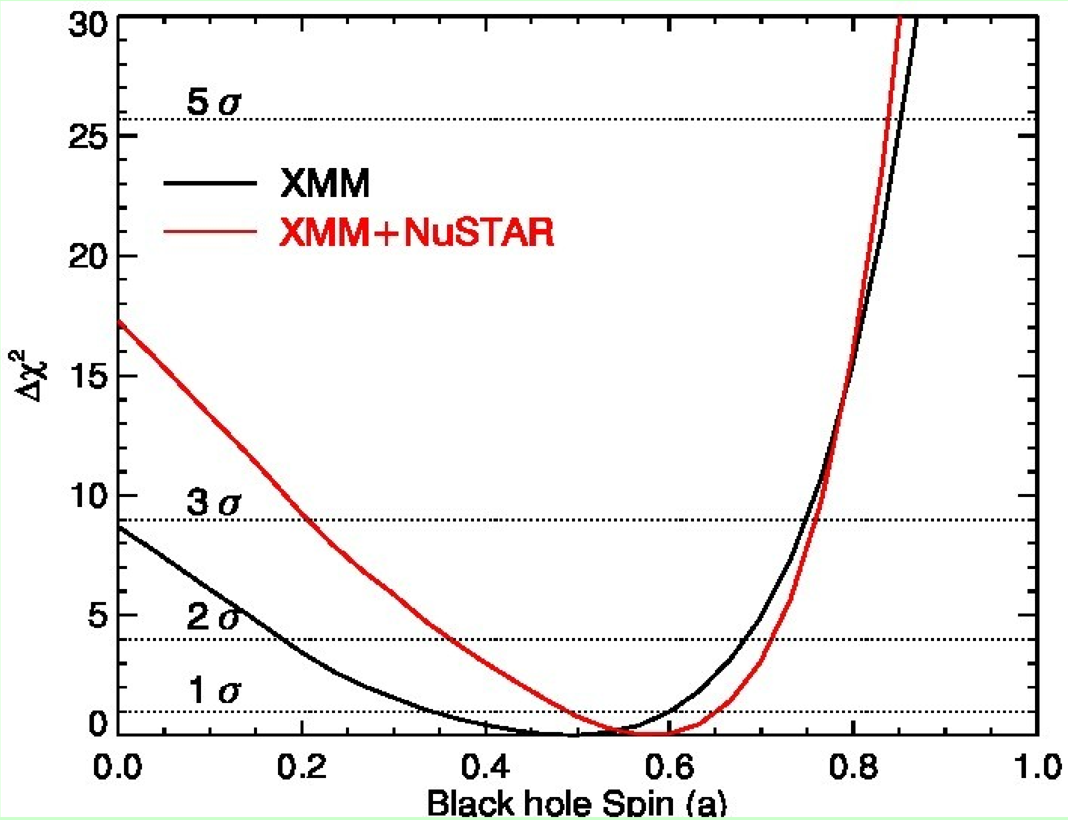




(Walton et al. 2014)

Relativistic reflection – BH spin

Other high quality XMM-NuSTAR observations provide robust measurements of the spin which is e.g. confirmed to be consistent with extreme Kerr in MCG-6-30-15 (Marinucci et al. 2014a). More in Andrea Marinucci's talk

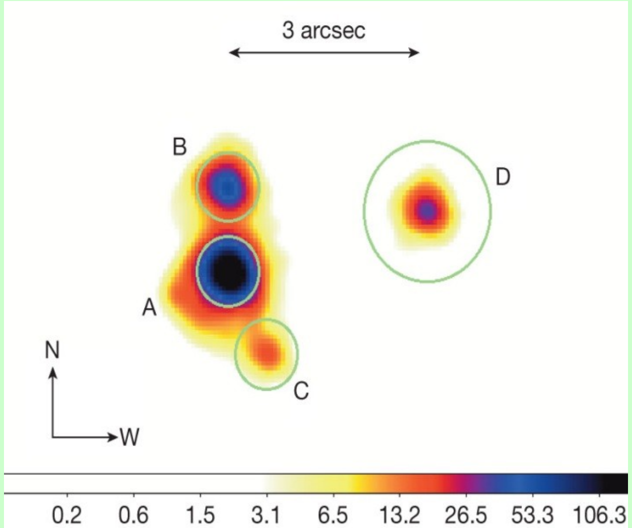


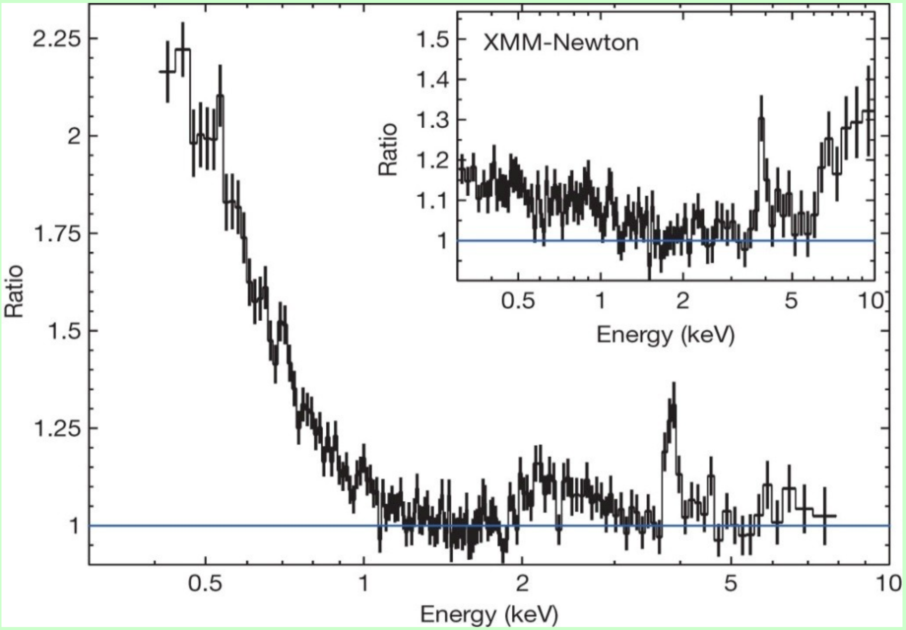
Intermediate spin confirmed in the NLSy1 Swift J2127.4+5654 (Miniutti et al. 2009, Marinucci et al. 2014b)

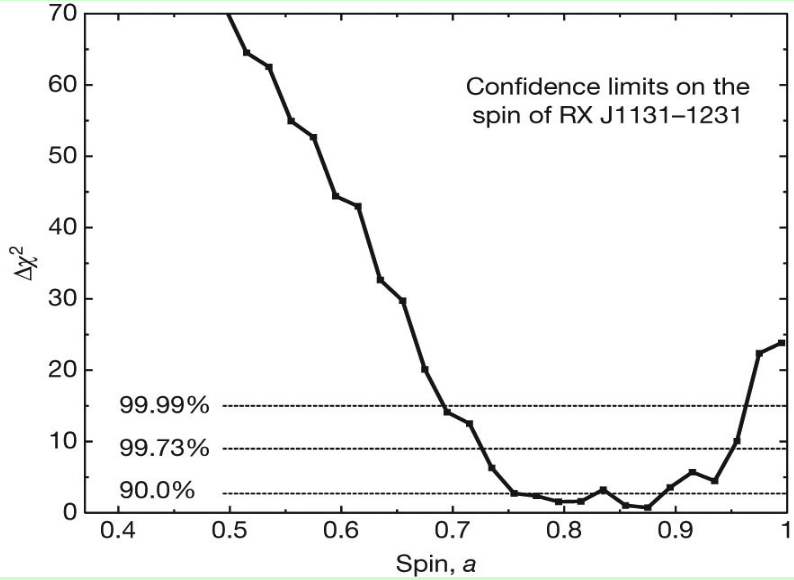
Swift J2127.4-5654 XMM+NuSTAR (Marinucci et al. 2014b)

Relativistic reflection – BH spin

Use of lensed quasar allows to study relativistic reflection beyond the local Universe, as in the z=0.658 quasar RXJ1131-1231 (Reis et al. 2014)







RX J1131-1231 XMM+Chandra
(Reis et al. 2014)

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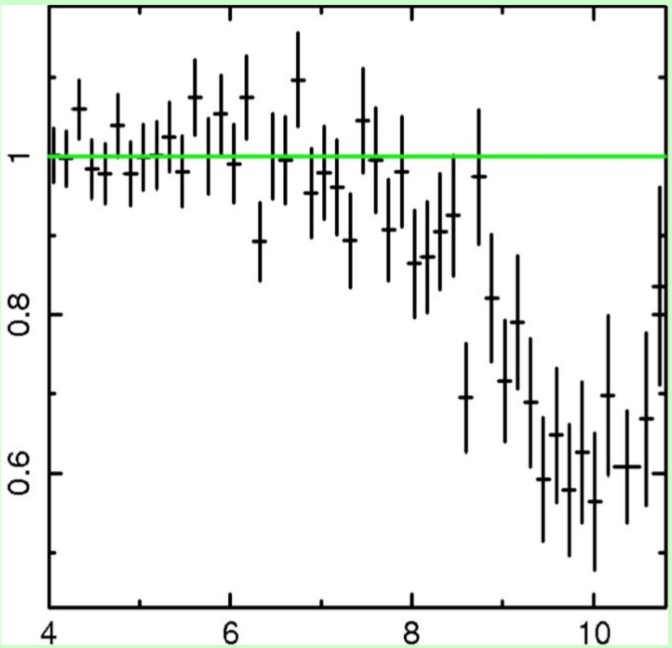
Black hole feedback in PDS456

Most luminous RQ AGN in the local Universe



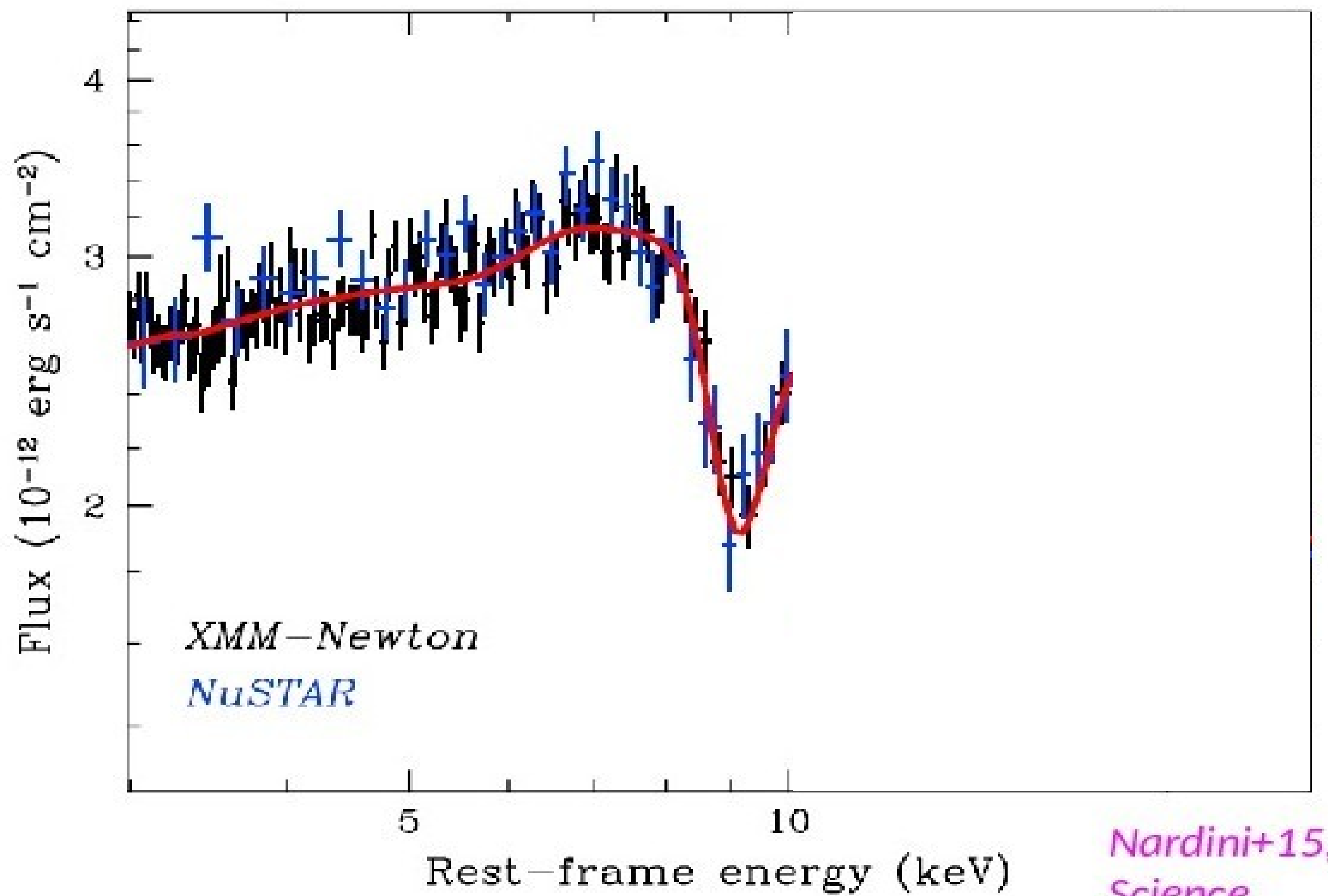
Systematic detection of a deep trough above 7 keV rest-frame: evidence for a large column of highly ionised matter outflowing at about one third of the speed of light

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

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

Black hole feedback in PDS456

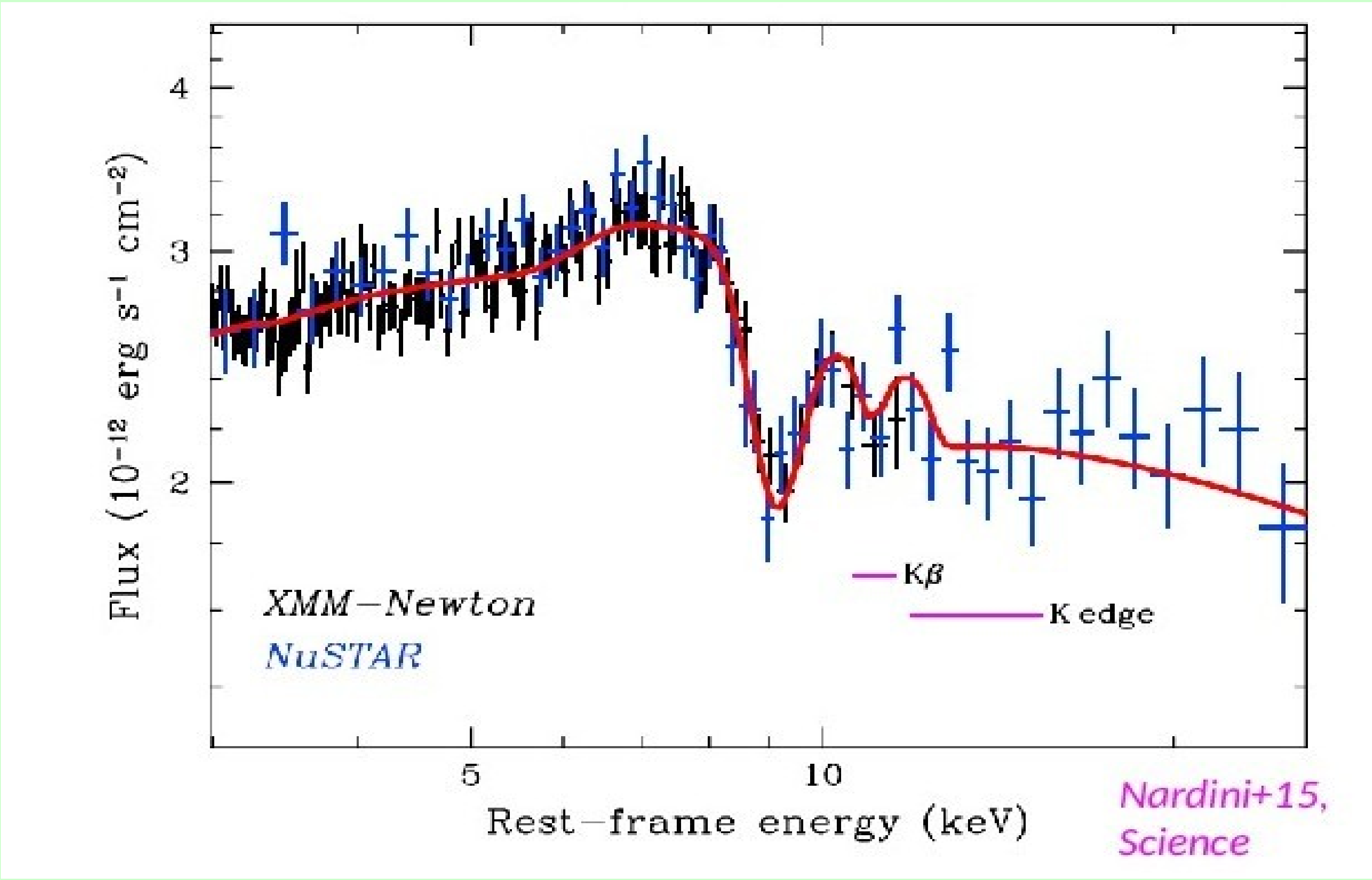
XMM ONLY



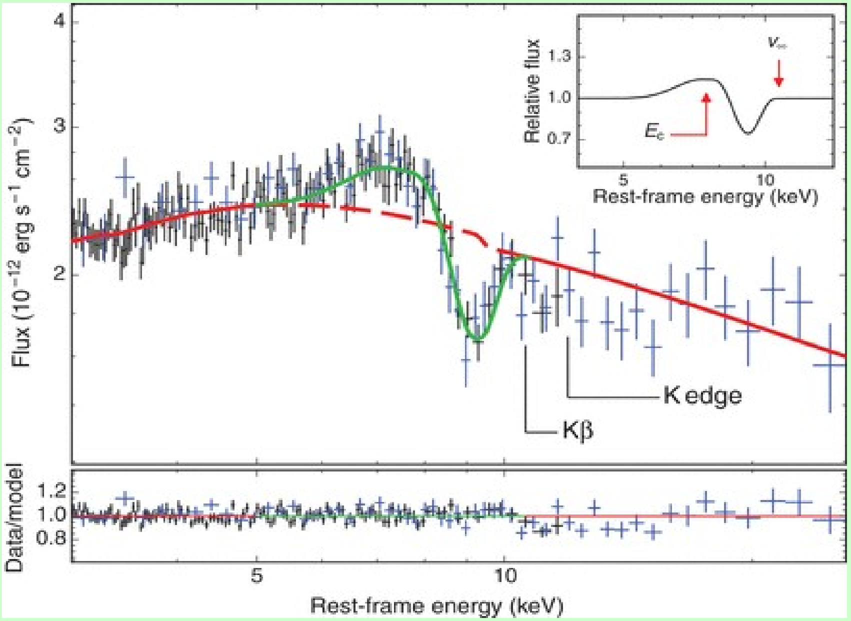
Nardini+15, Science

Black hole feedback in PDS456

XMM + NuSTAR



Black hole feedback in PDS456



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

The emitted/absorbed luminosity ratio provides the solid angle Ω

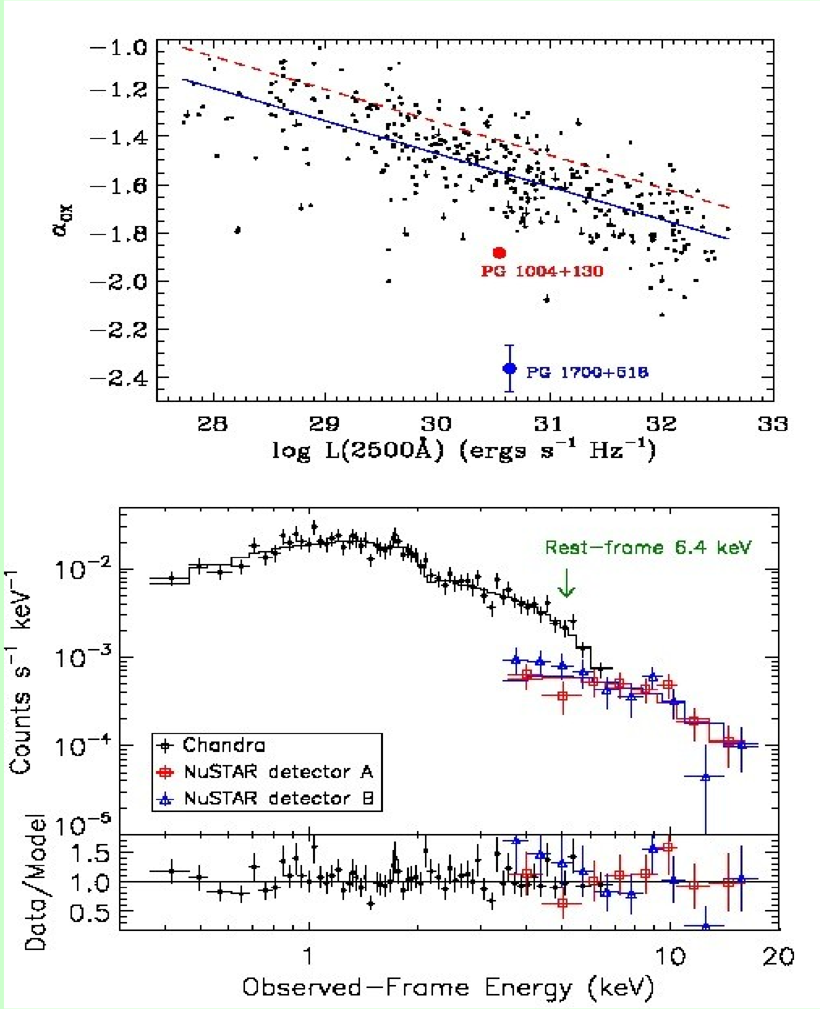
$$\dot{M}_{\rm out} \sim 10\, M_\odot\,{\rm yr}^{-1} \Rightarrow P_{\rm kin} \sim 2\times 10^{46}\,{\rm erg\,s}^{-1} \sim 0.2\, L_{\rm bol}$$

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

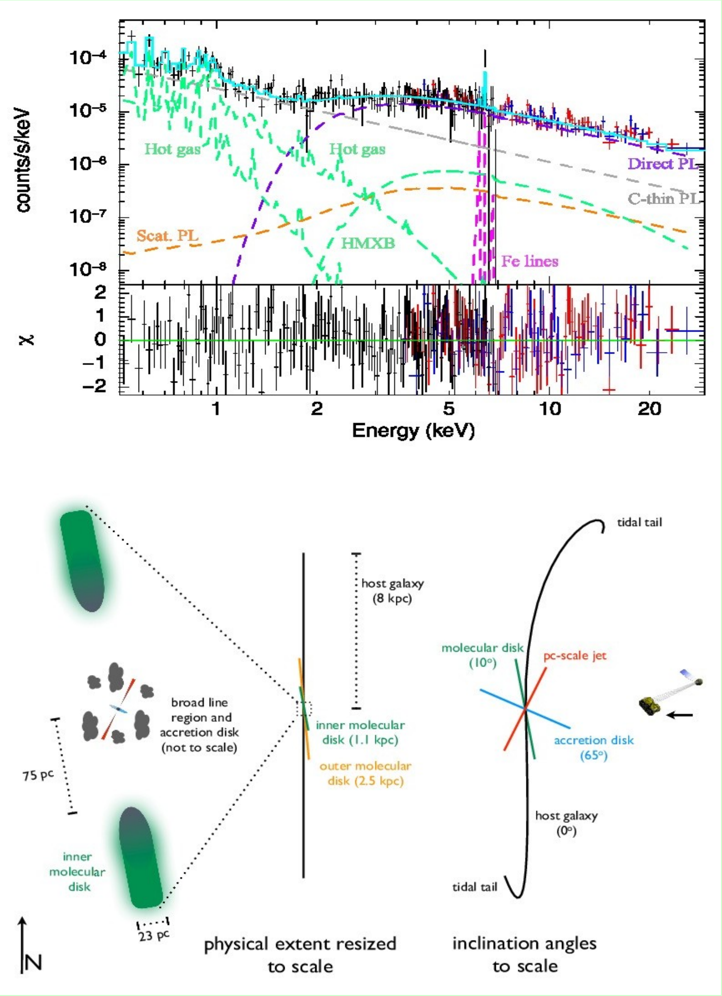
$$E_{\rm wind} \sim 10^{61}\,{\rm erg} \sim 3\times M_{\rm bulge}\,\sigma^2$$

BAL: Absorption or X-ray weakness?

Broad Absorption line quasars have a low X-ray-to-optical flux ratio
Absorption or intrinsic X-ray weakness?

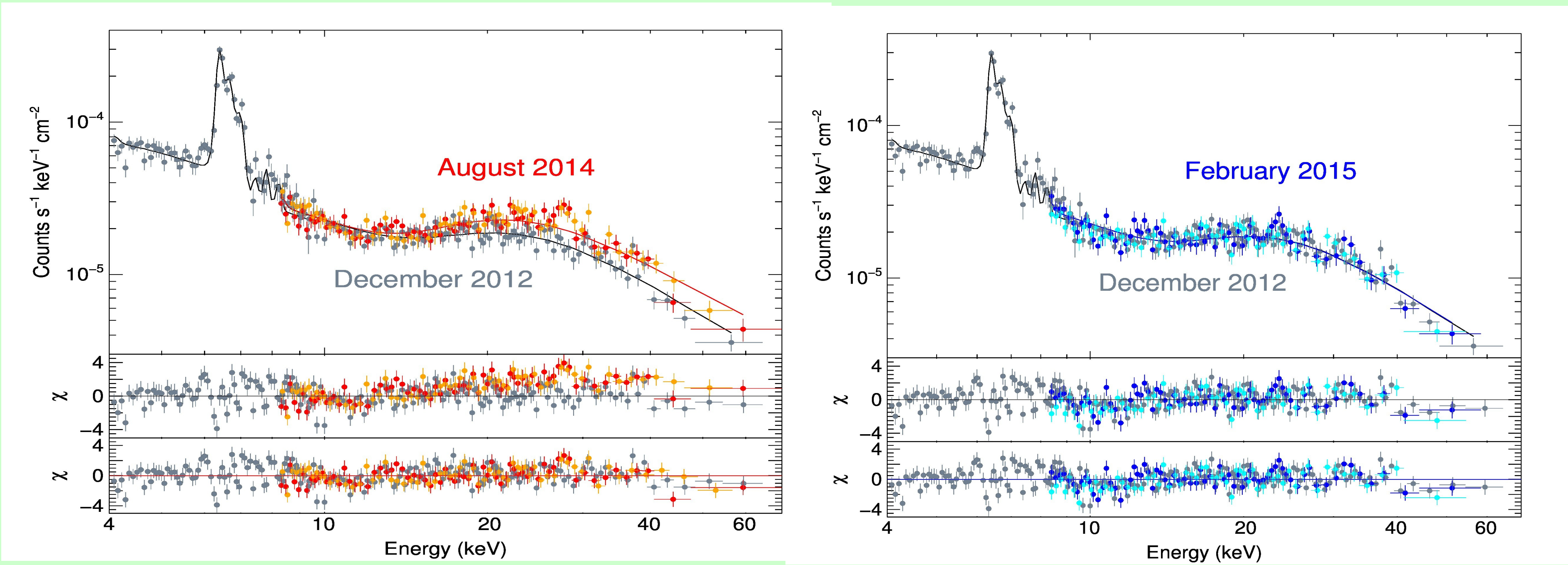


PG 1004+130 Chandra+NuSTAR
(Luo et al. 2013)



Mrk271 Chandra+NuSTAR
(Teng et al. 2014)

The clumpy torus of NGC1068



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 7x10^{24} cm^{-2}).

One less single cloud on the line of sight?

→ **Clumpy Torus**

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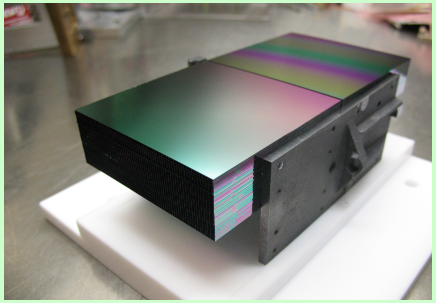
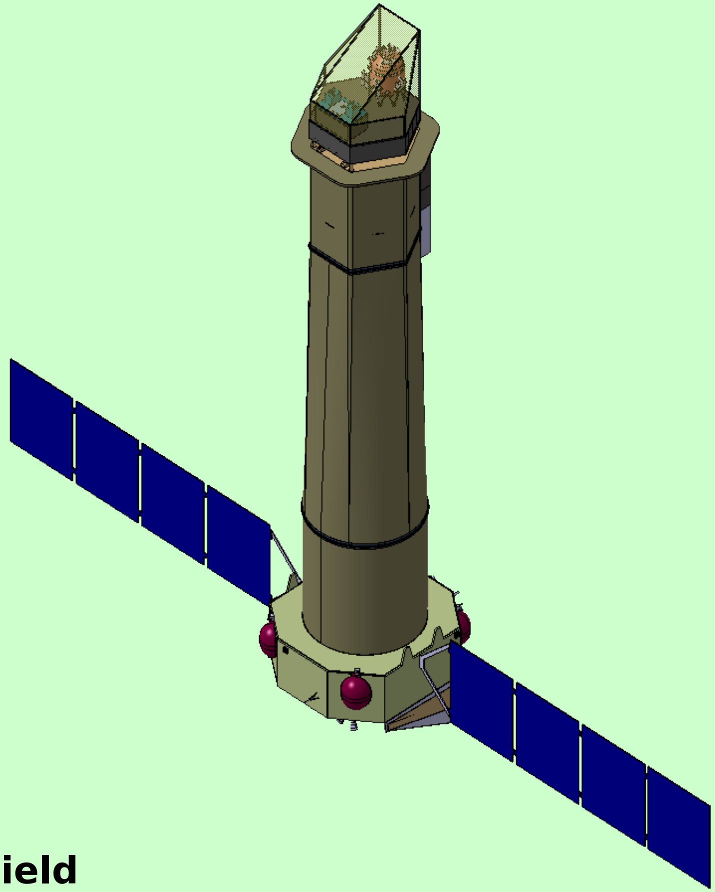
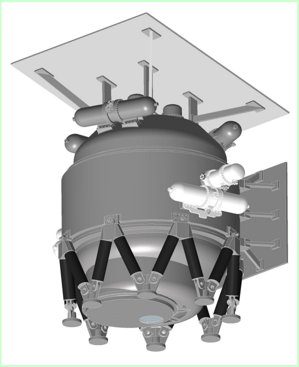
ATHENA

L2 orbit Ariane VI
Mass < 5100 kg
Power 2500 W
5 year mission
12 m focal length

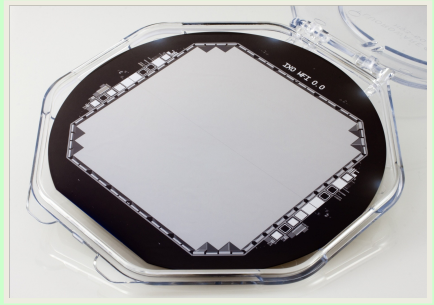


Silicon Pore Optics:
2 m^2 at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: 3 10^{-17} erg cm^{-2} s^{-1}



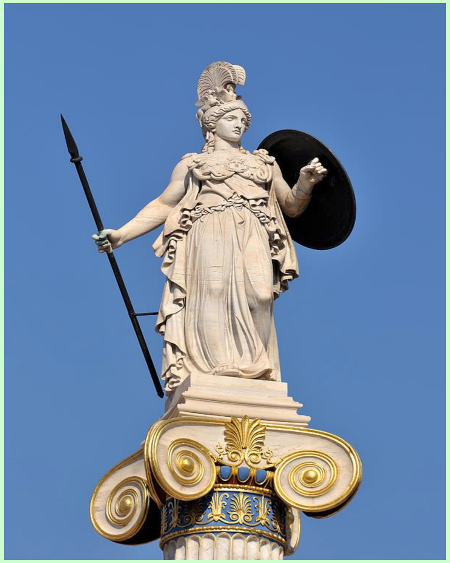


X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk



Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability

ATHENA



Selected by ESA in June 2014 as L2 mission

Currently in Phase A study by two industrial consortia under ESA contract

Phase A will run until late 2017, Phase B1 will then follow until mid 2019

Mission adoption by ESA's Science Program Commmittee expected in 2020

Launch in 2028

ATHENA

Athena Science Requirements

Parameter	value	enables (driving science goals)
Effective area at 1 keV	2 m^2	Early groups, cluster entropy and metal evolution, WHIM, high redshift AGN, census AGN, first generation of stars
Effective area at 6 keV	0.25 m^2	Cluster energetics (gas bulk motions and turbulence), AGN winds & outflows, SMBH & GBH spins
PSF HEW (< 8 keV)	5" on axis, 10" off axis	High z AGN, census of AGN, early groups, AGN feedback on cluster scales
X-IFU spectral resolution	2.5 eV	WHIM, cluster hot gas energetics and AGN feedback on cluster scales, energetics of AGN outflows at z~1-4
X-IFU FoV	5' diameter	Metal production & dispersal, cluster energetics, WHIM
X-IFU background	< 5 10^{-3} counts/s/cm^2/keV (75%)	Cluster energetics & AGN feedback on cluster scales, metal production & dispersal
WFI spectral resolution	150 eV	GBH spin, reverberation mapping
WFI FoV	40' x 40'	High-z AGN, census AGN, early groups, cluster entropy evolution, jet-induced cluster ripples
WFI count rate	80% at 1 Crab	GBH spin, reverberation mapping, accretion physics
WFI background	< 5 10^{-3} counts/s/cm^2/keV (75%)	Cluster entropy, cluster feedback, census AGN at z~1-4
Recons. astrometric error	1" (3s)	High z AGNs
GRB trigger efficiency	40%	WHIM
ToO reaction time	< 4 hours	WHIM, first generation of stars

ATHENA and FERO science

Topical Panel 2.4 – The close environment of SMBH
(chairs: M. Dovciak, G. Matt, G. Miniutti,
with much help from B. De Marco)

241 – Athena shall determine the geometry of the hot corona / accretion disc system
Reverberation mapping of 8 bright local AGN

242 – Athena shall determine the SMBH spin distribution in the Local Universe as a probe of the predominant SMBH growth mode
Measuring BH spins in 30 nearby AGN

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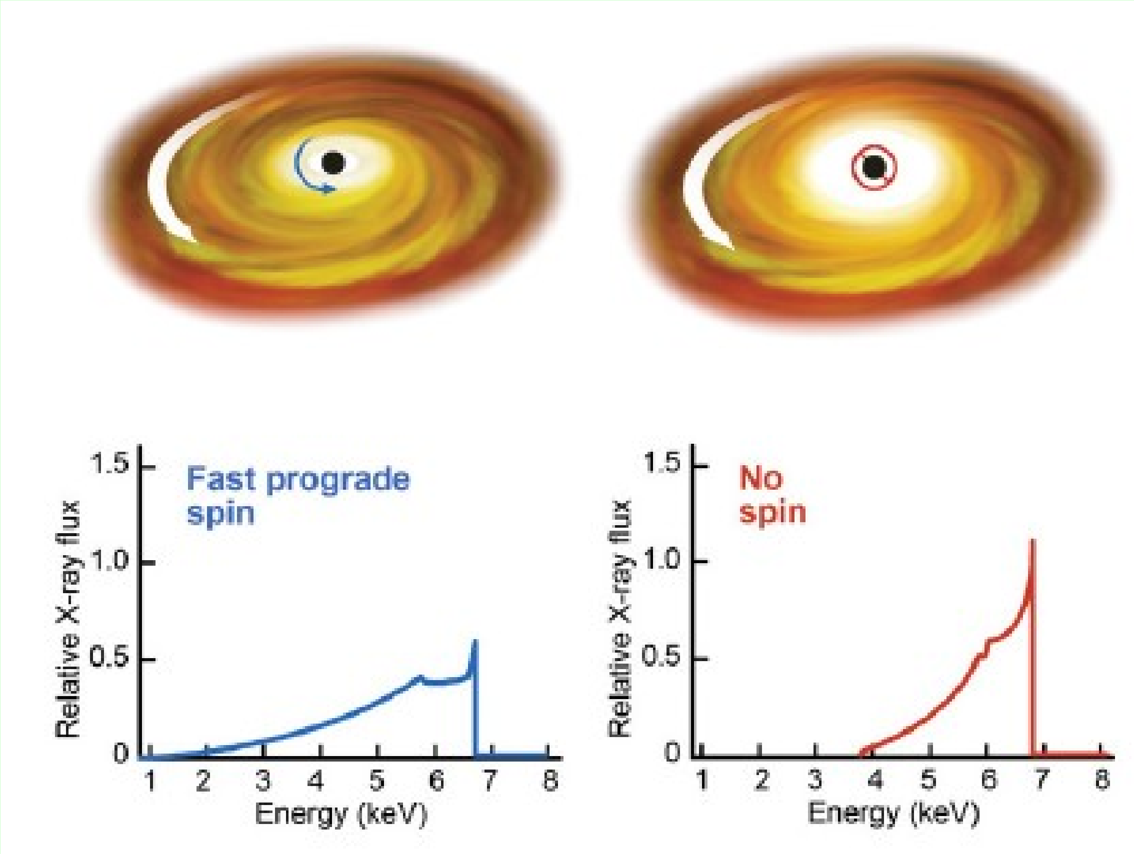
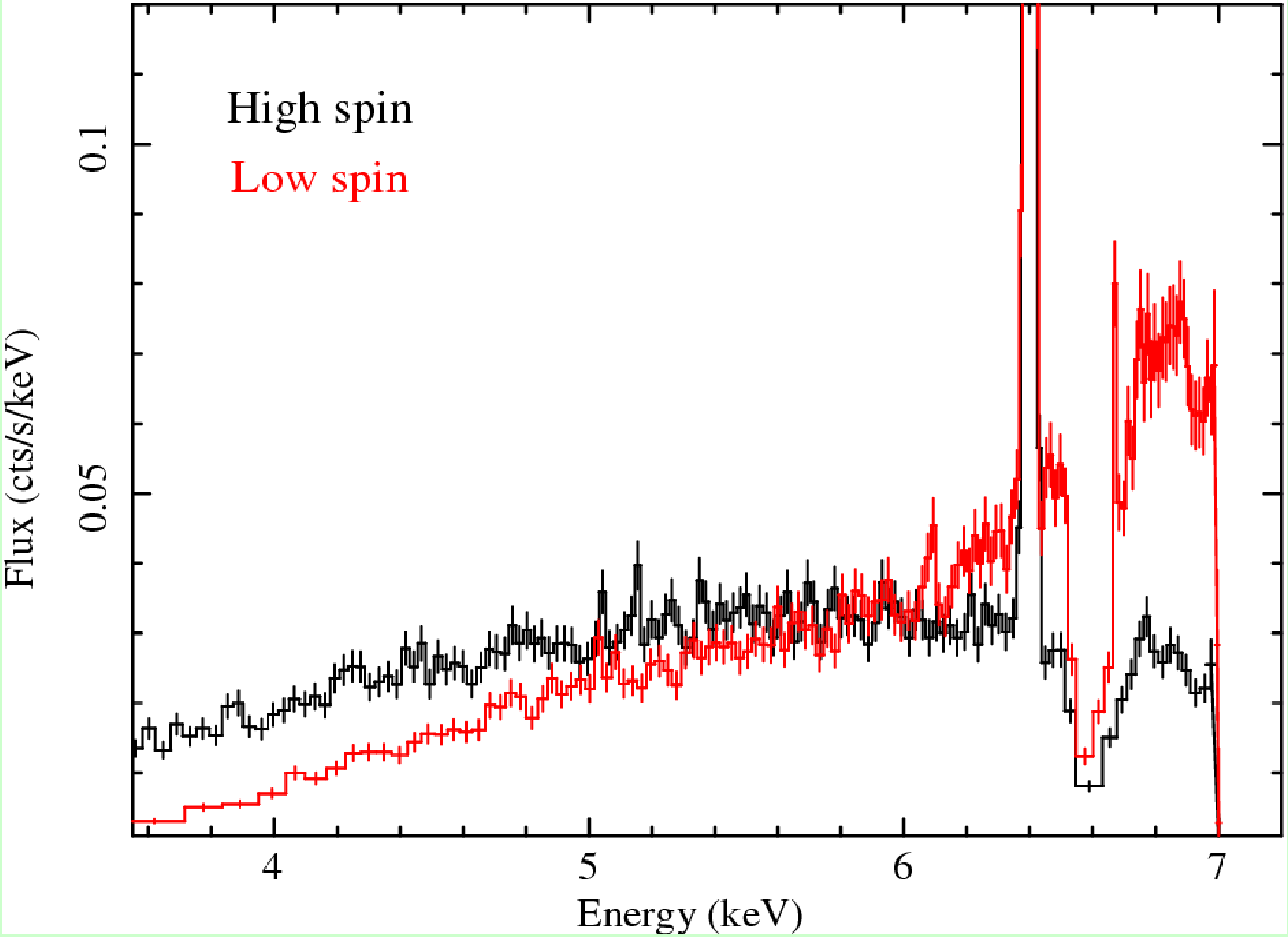
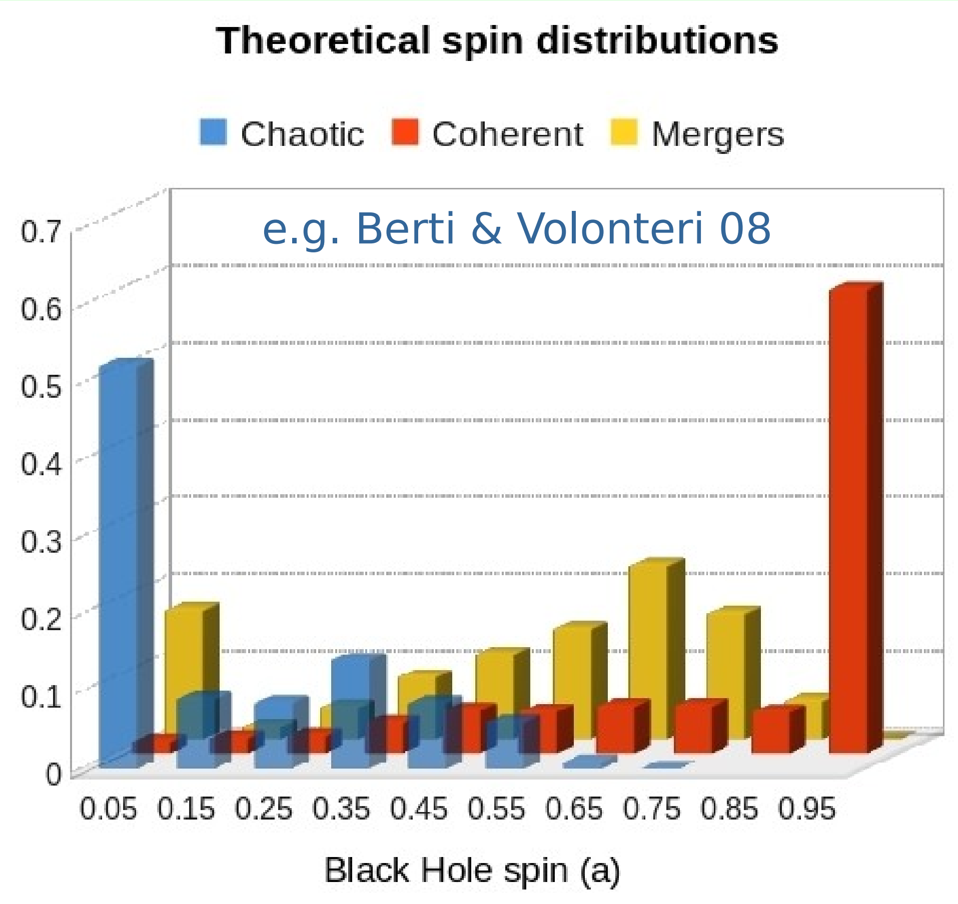
Measuring BH spins in 30 nearby AGN



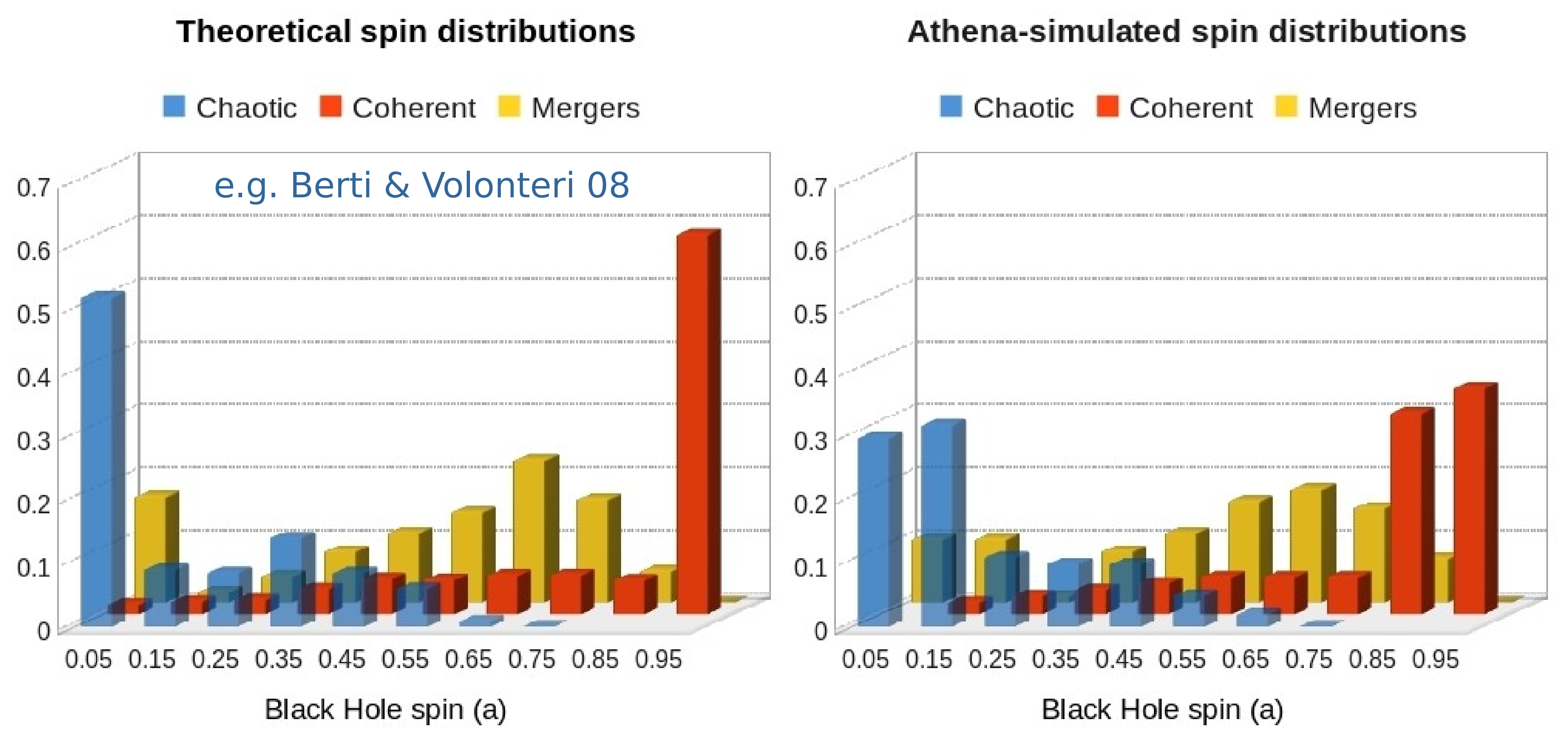
The shape of the Fe line strongly depends on BH spin (as well as on disc emissivity, inclination, ionization state …) and is one of the most powerful probes of the innermost accretion flow

The Athena XIFU will allow to properly model all emission and absorption components, excising any narrow feature possibly present





BH spin is a tracer of the BH growth history

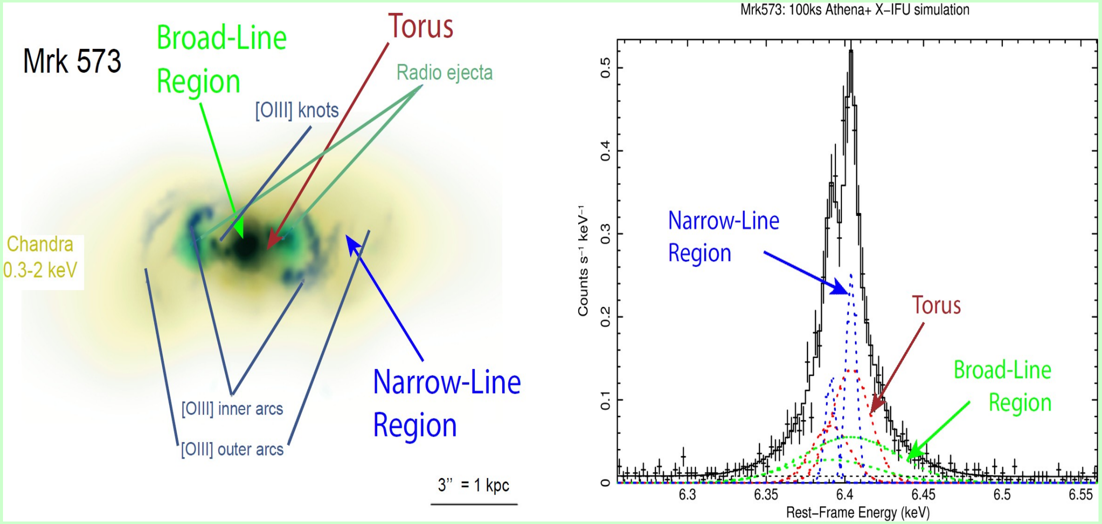


BH spin is a tracer of the BH growth history

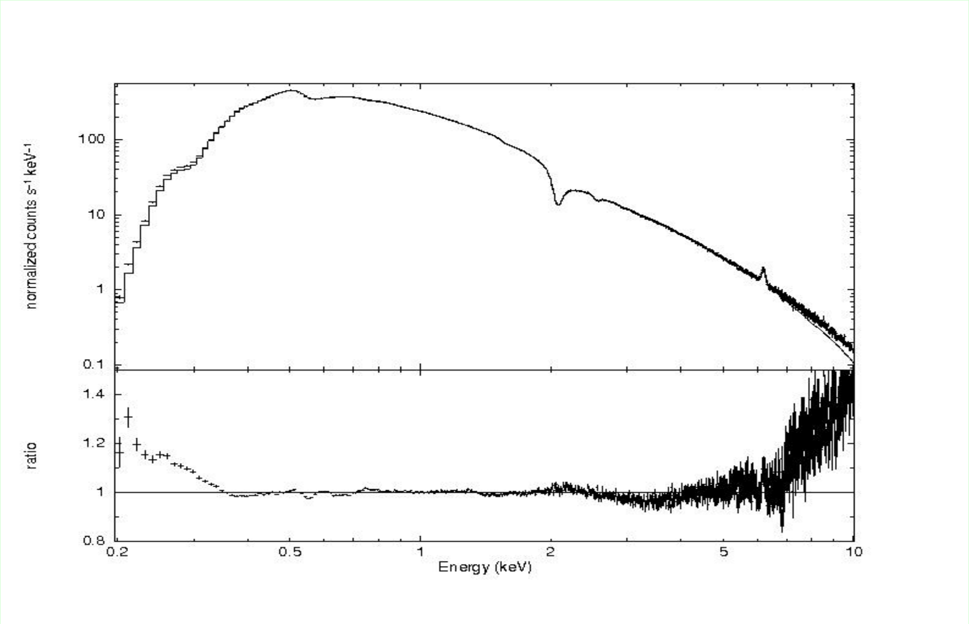
Athena allows us to reconstruct the BH spin distribution in the local Universe providing information about the prevailing channel of BH growth and evolution (mergers only, chaotic accretion events, prolonged stable accretion)

ATHENA and FERO science

Mapping the circumnuclear regions



Understanding the origin of the soft excess



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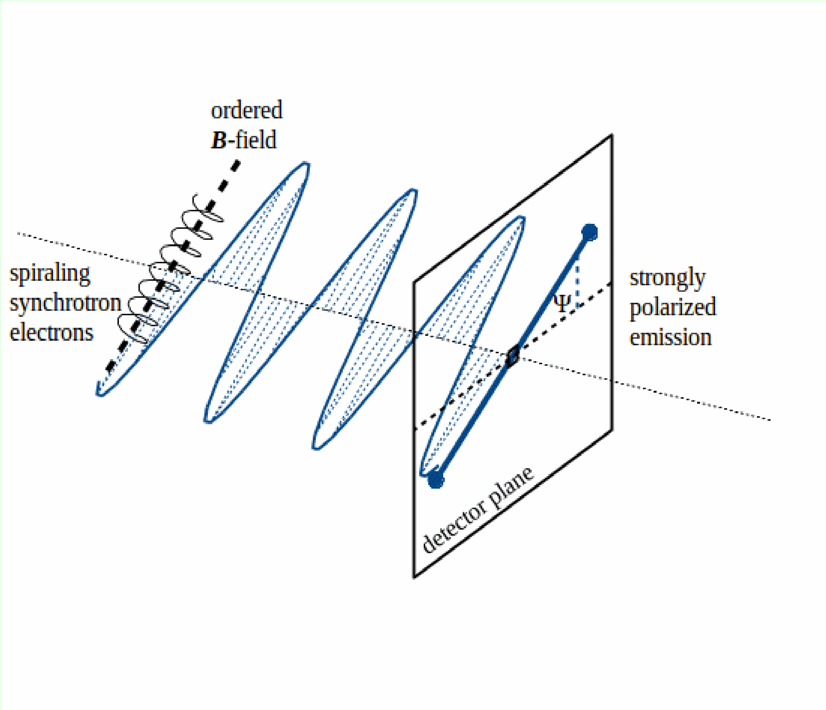
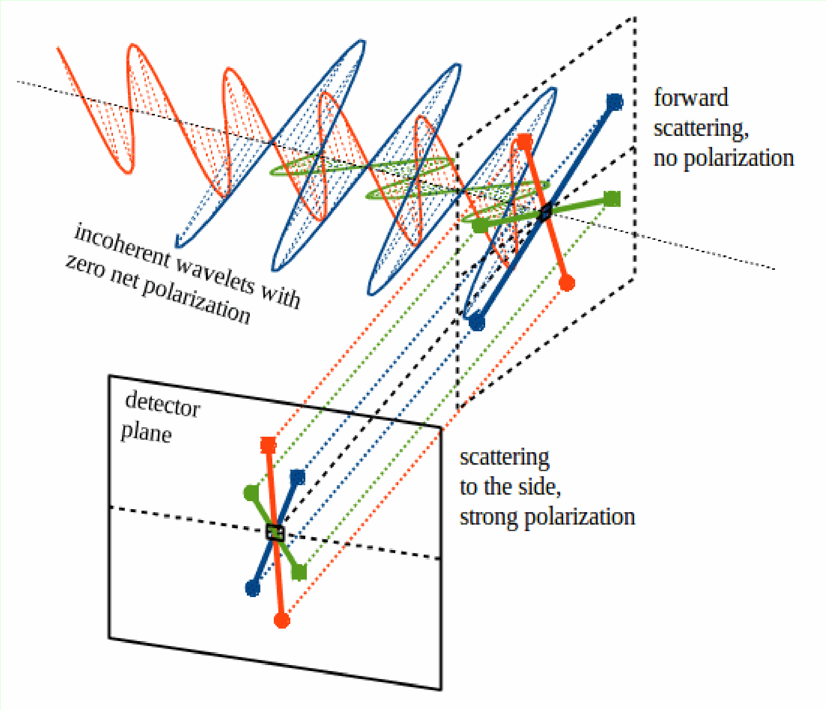
Strong gravity (reflection vs. absorption, BH spin)
Circumnuclear matter
*Sgr A**
The future: XIPE (and IXPE and Praxys)

II. X-ray polarimetry

X-ray polarimetry may provide an independent view on the physical and expecially geometrical properties of AGN. No results are available yet, but the future looks promising.





Synchrotron emission

Compton Scattering

(courtesy of Rene' Goosmann)

X-ray polarimetry so far

Polarimetry has proved very important in radio, IR and optical bands (eg. jet emission in blazars, Unification Model of AGN, ...).

In X-rays, where non-thermal processes and aspherical geometries are likely to be more common than at lower energies, polarimetry is expected to be vital to fully understand emitting sources.

However, only one measurement (P=19% for the Crab Nebula) has been obtained so far, together with a tight upper limit to Sco X-1. These measurements date back to the 70s, for the two brightest sources in the X-ray sky.

The lack, for many decades, of significant technical improvements implied that no polarimeters were put on board of X-ray satellites. The situation has changed with the advent of polarimeters based on the photoelectric effect. Such detectors, coupled a X-ray telescope, may provide astrophysically interesting measurements for hundreds of sources (remember that polarimetry is a photon hungry technique...).

The brightest specimens of all major classes of X-ray sources are now accessible!

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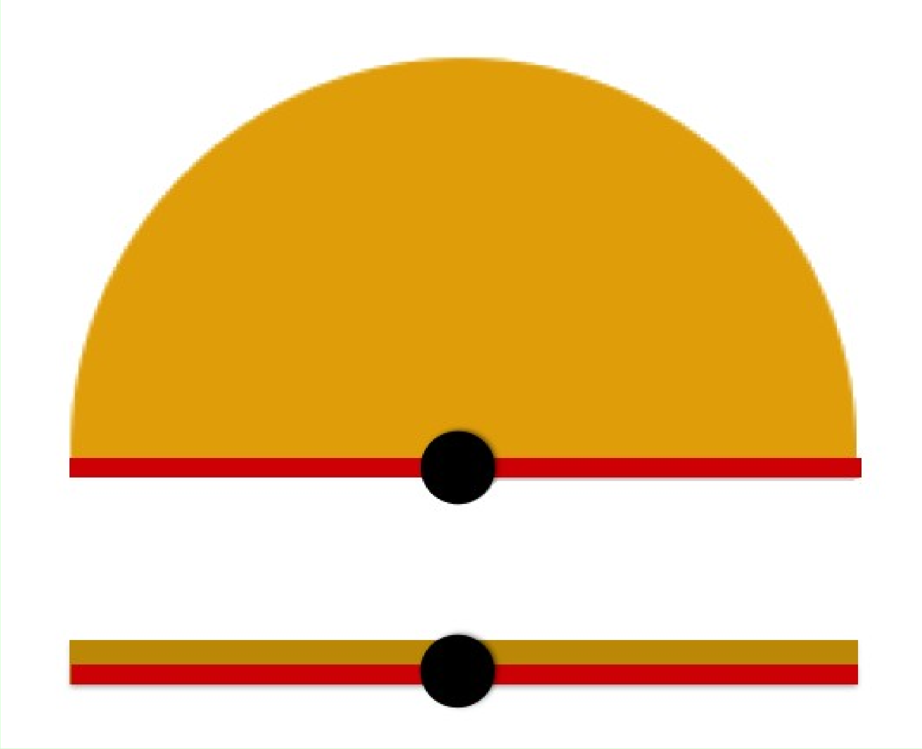
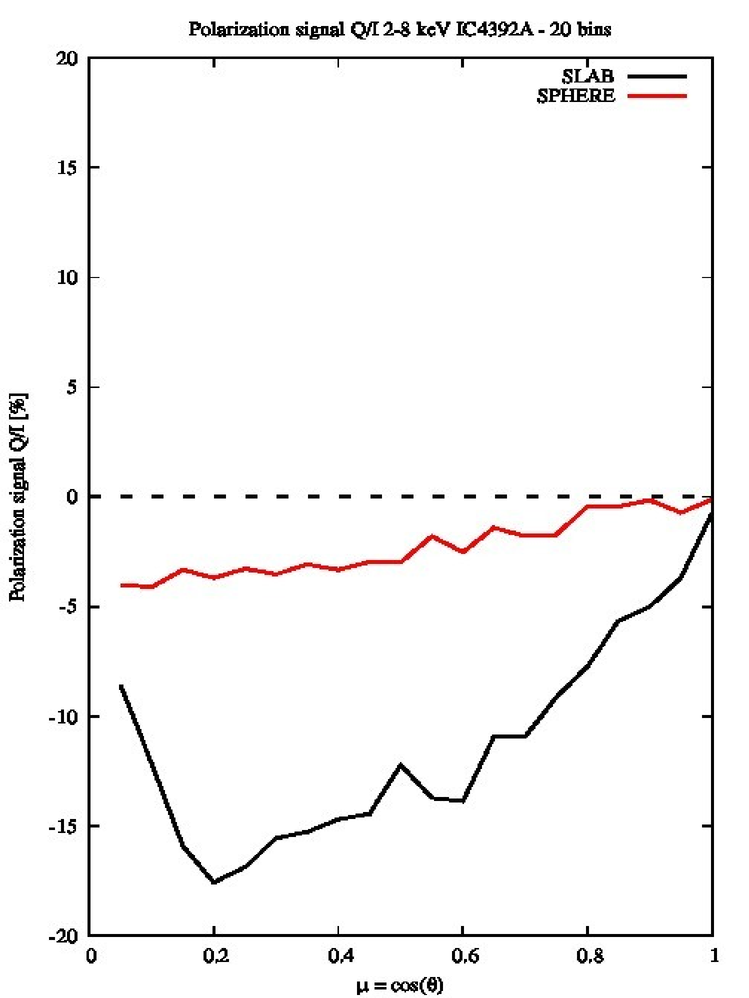
The geometry of the hot corona

The geometry of the hot corona is unknown. Emission is expected to be polarized if the corona OR the radiation field are not spherical





Slab and sphere geometries, temperature and τ as per IC4329A (Brenneman et al. 2014)

Tamborra et al., in prep.

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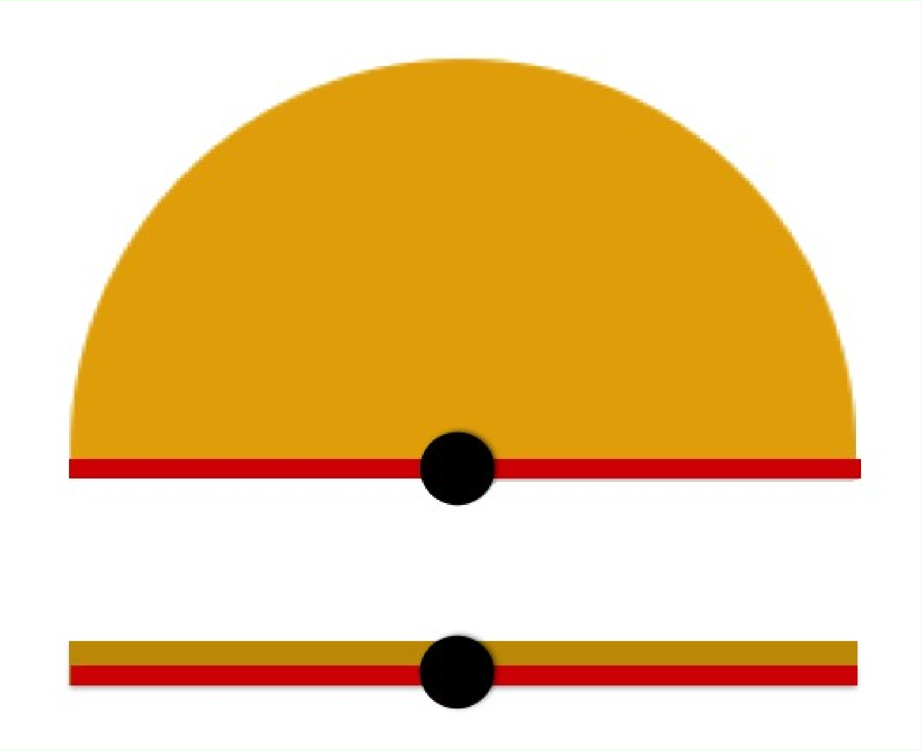

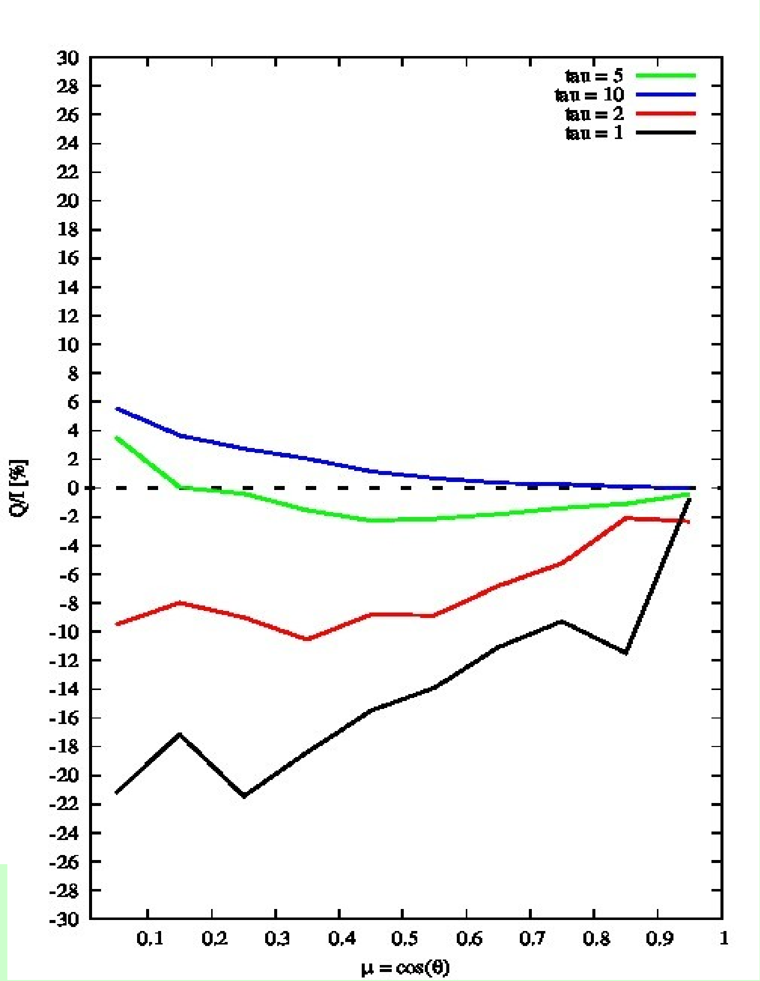

Slab geometry, temperature as per IC4329A, different values of τ

Tamborra et al., in prep.

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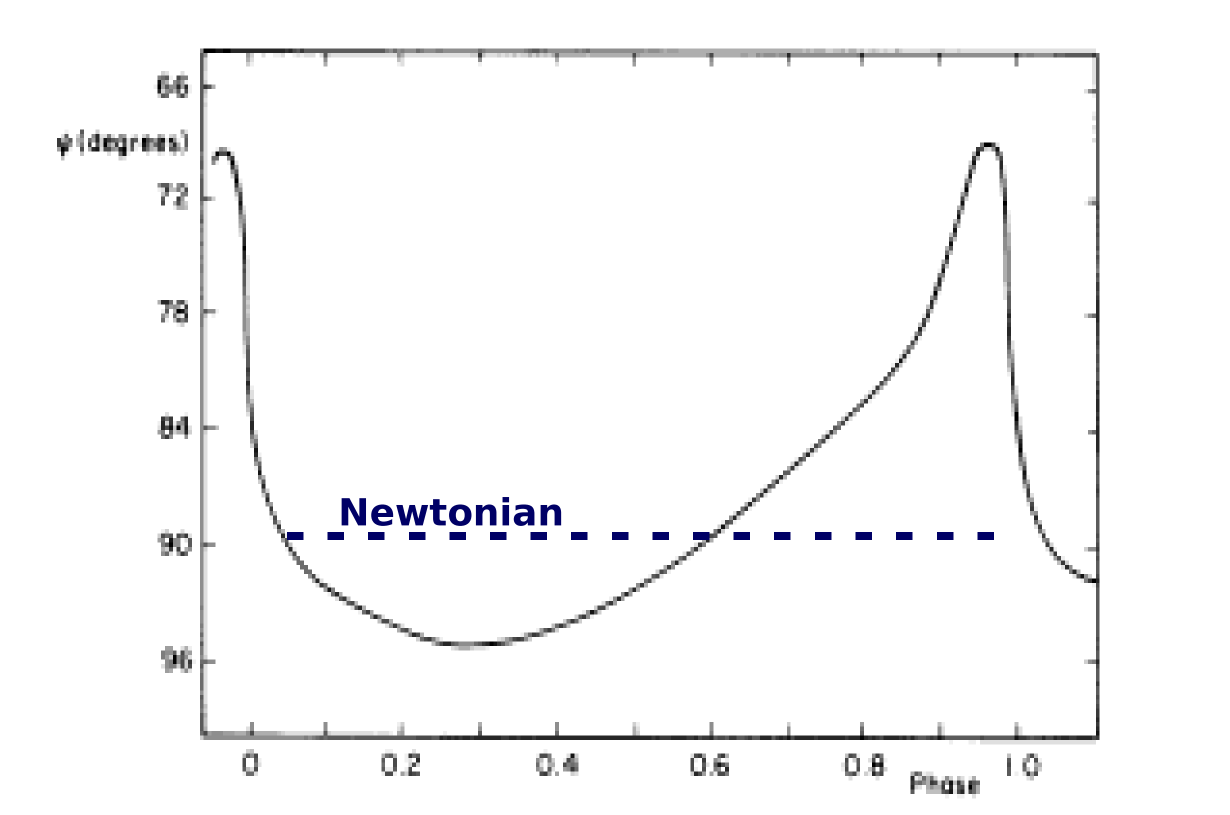
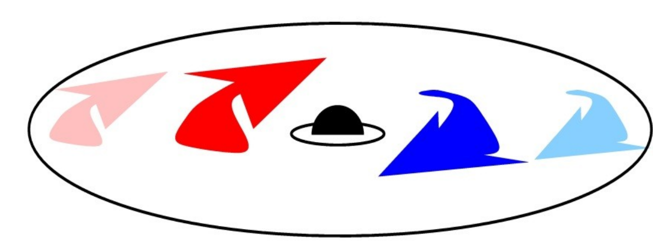
Probing strong gravity effects

General and Special Relativity effects around a compact object ("strong gravity effects") significantly modifies the polarization properties of the radiation. In particular, the Polarization Angle (PA) as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects (e.g. Connors & Stark 1977; Pineault 1977).

The rotation is larger for smaller radii and higher inclination angles



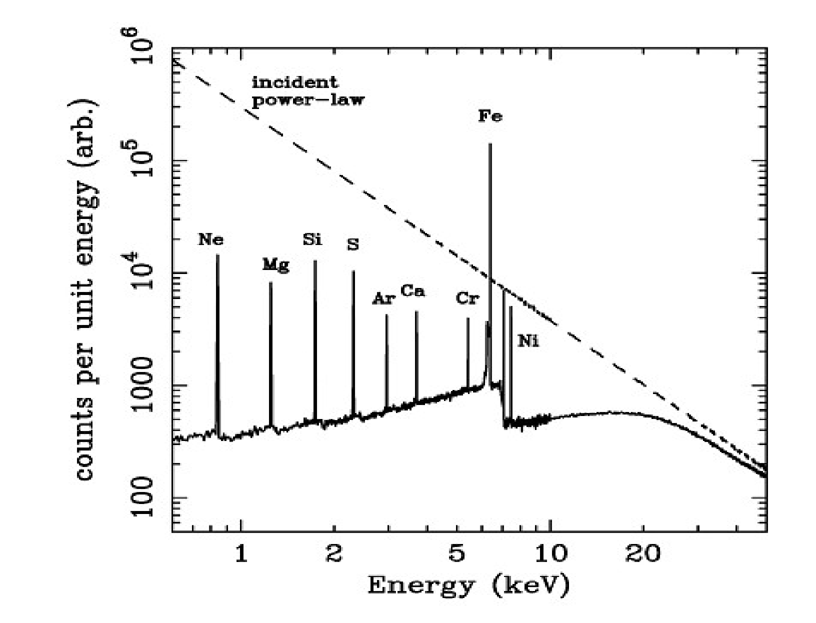


Orbiting spot with:
a=0.998; R=11.1 Rg
i=75.5 deg

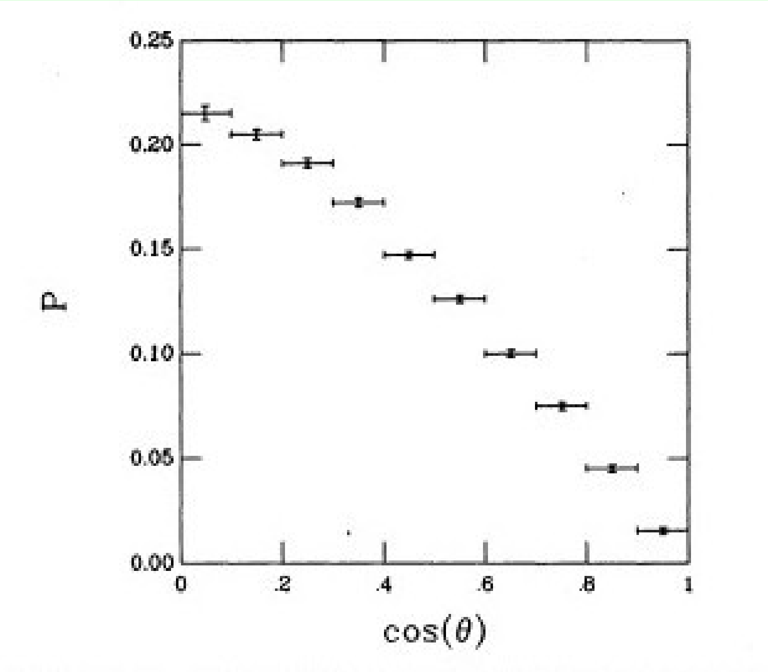
(Phase=0 when the spot is behind the BH).

The PA of the net (i.e. phase-averaged) radiation is also rotated!

Polarization of reflected flux

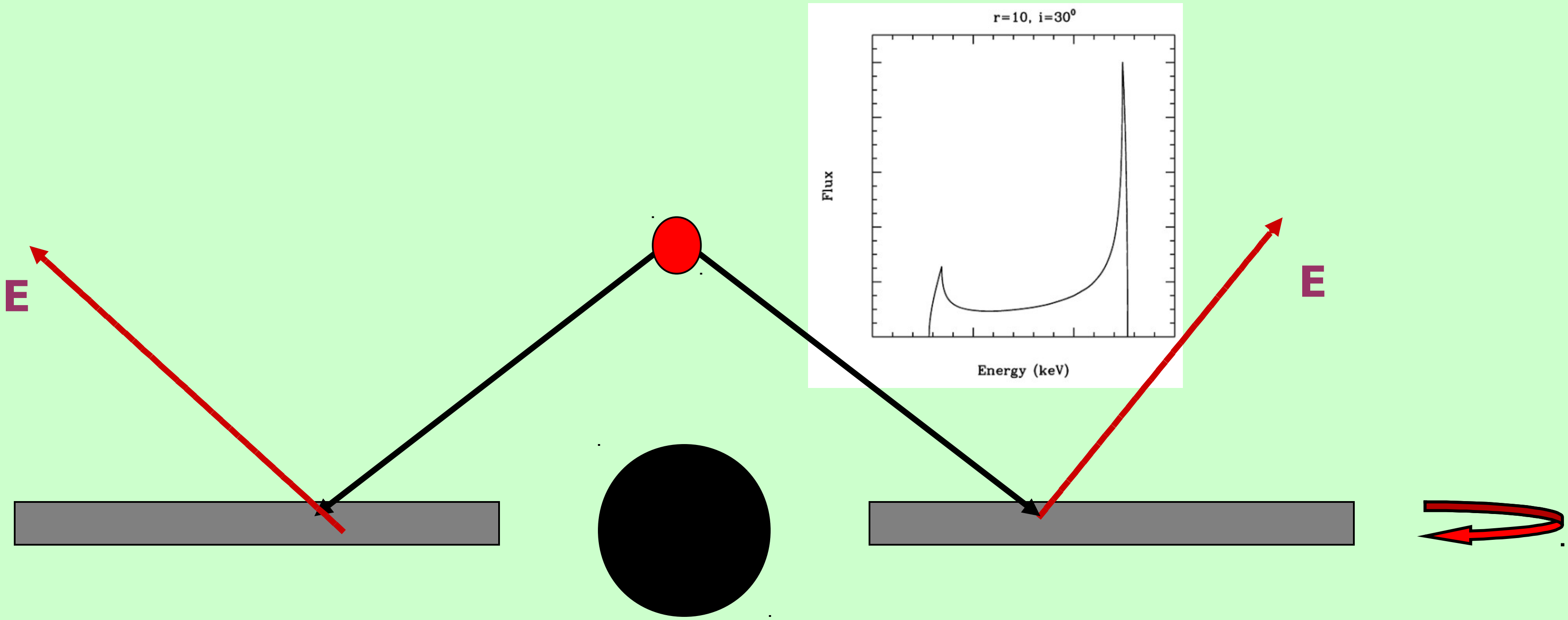


Polarization of reflected (continuum) radiation is large, up to 20% (Matt et al. 1989) assuming isotropic illumination, a plane-parallel reflecting slab and unpolarized illuminating radiation.



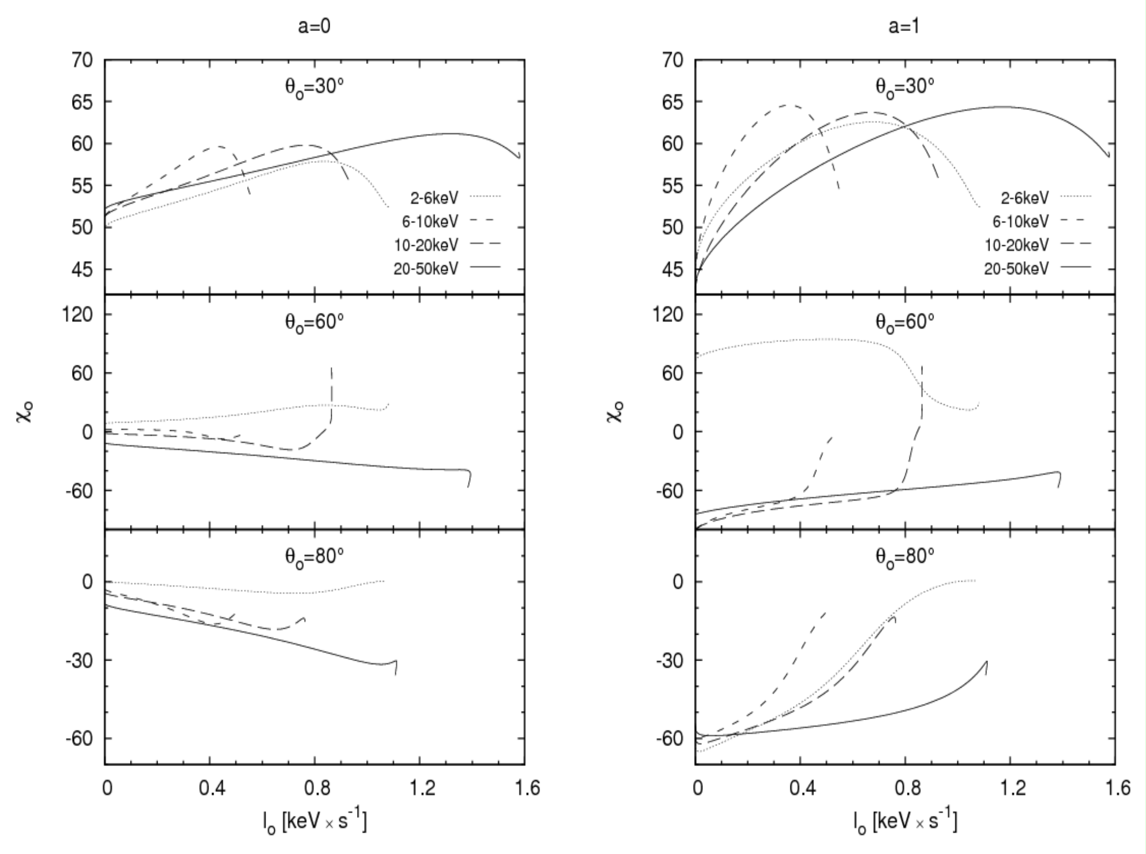
The exact values depend on the actual geometry of the system and on the polarization degree of the primary radiation.

Reflection in Relativistic discs



Breaking of the symmetry due to SR (Doppler boosting) also causes a rotation of the PA with respect to the Newtonian case. Changes in the illumination properties (e.g. in the height of the lamp-post) will cause changes in the total PA, which is therefore likely to be time- (and flux-) dependent. Variations of the height have been claimed in several AGN (e.g. Miniutti et al. 2003, Parker et al. 2014).

Reflection in Relativistic discs



Dovciak et al. (2011)

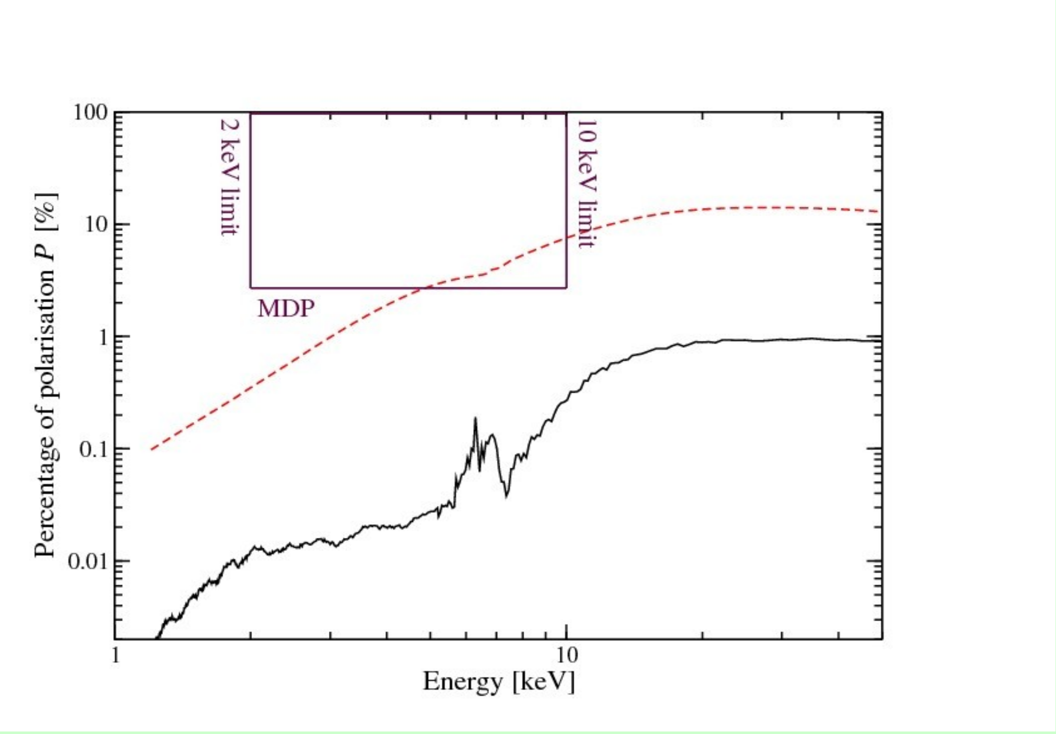
Variation of h with time implies a time and flux variation of the degree and angle of polarization.

The effect depends also on the BH spin.

Reflection or absorption?

The relativistic reflection interpretation of the broad feature often seen in Seyfert galaxies has been challenged: complex absorption?

Polarimety can distinguish between the two models!



Marin et al. (2012)

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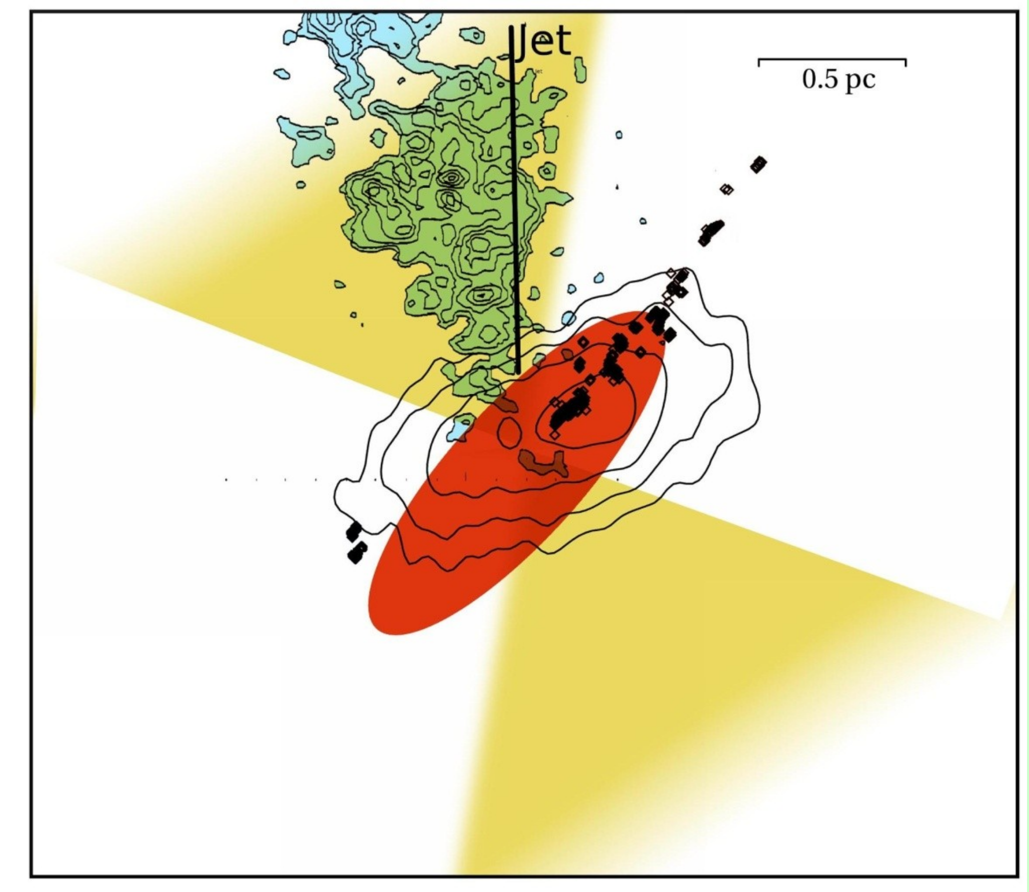
The orientation of the torus

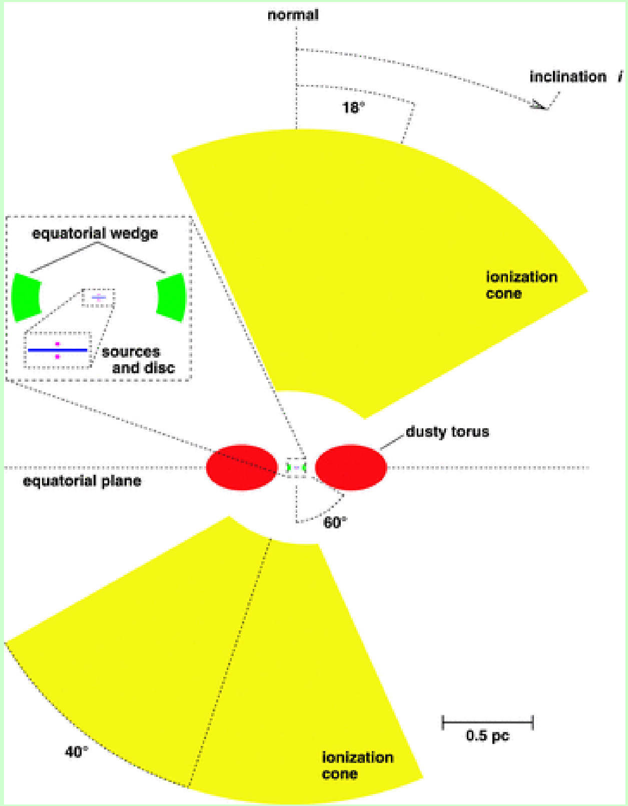
Geometry of the torus:

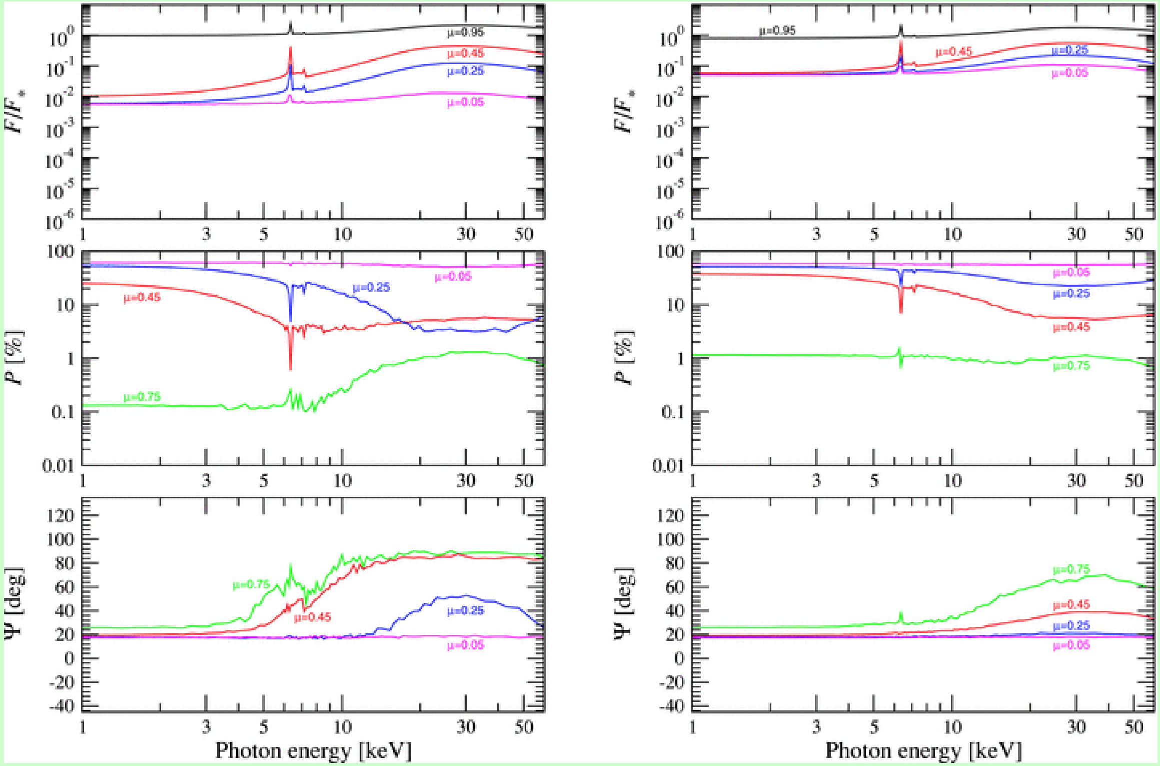
the polarization angle will give us the orientation of the torus, to be compared with IR results, and with the ionization cones (Goosmann & Matt 2011)



Raban et al. (2009)

The orientation of the torus





Goosmann & Matt (2011)

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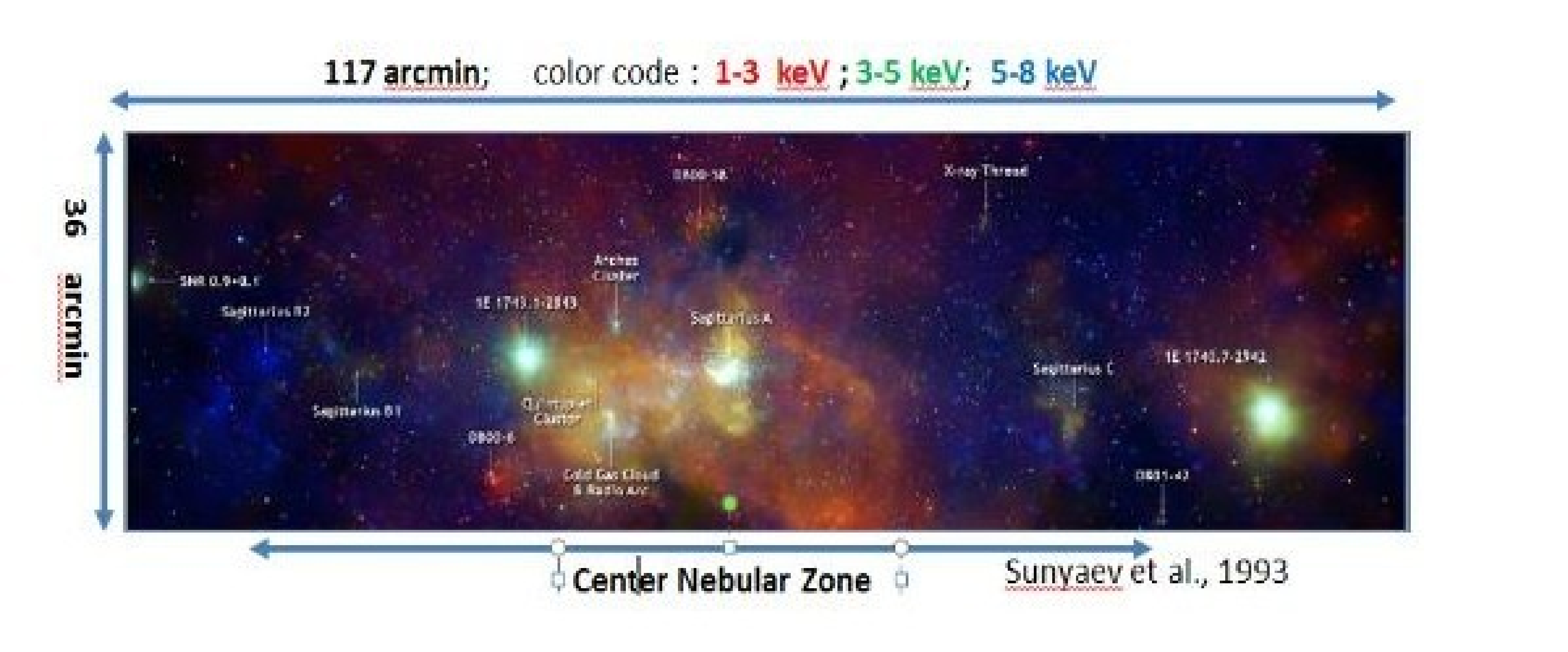
The GC as a low luminosity AGN

Cold molecular clouds around Sgr A* (i.e. the supermassive black hole at the centre of our own Galaxy) show a neutral iron line and a Compton bump → Reflection from an external source!?!

No bright enough sources are in the surroundings. Are they reflecting X-rays from Sgr A*? so, was it one million times brighter a few hundreds years ago? Polarimetry can tell! (Churazov et al. 2002)



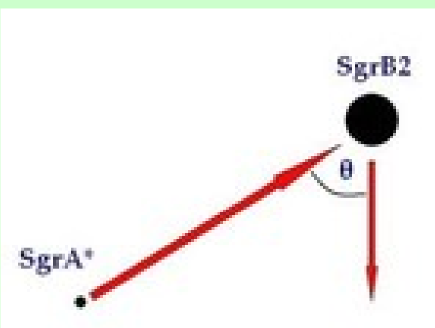
The GC as a low luminosity AGN

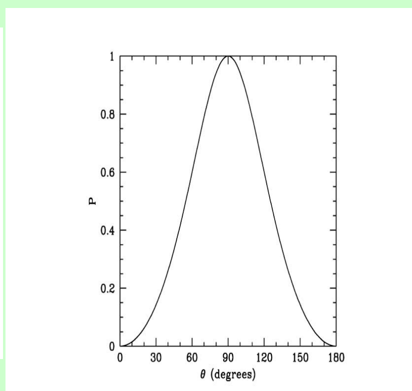
Polarization by scattering from Sgr B complex, Sgr C complex

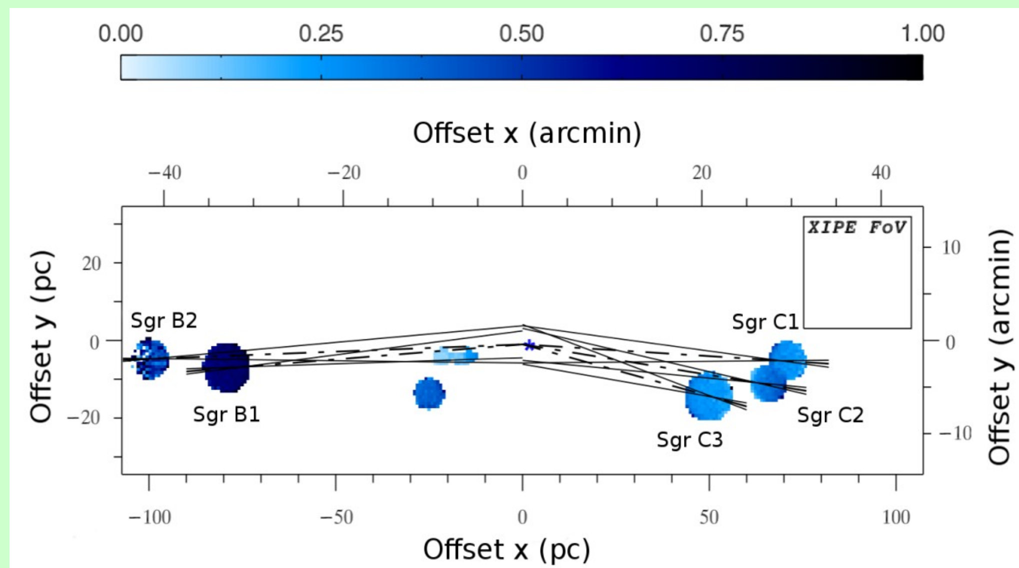
The angle of polarization pinpoints the source of X-rays

The degree of polarization measures the scattering angle and determines the true distance of the clouds from Sgr A*.

Marin et al. 2014







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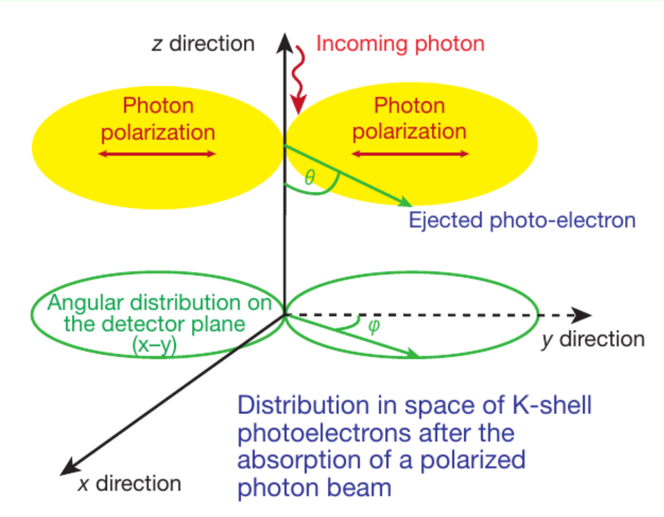
Observational perspectives

XIPE (X-ray Imaging Polarimetry Explorer)
Selected by ESA (M4) for phase A study
Final selection: May 2017
Launch: 2026

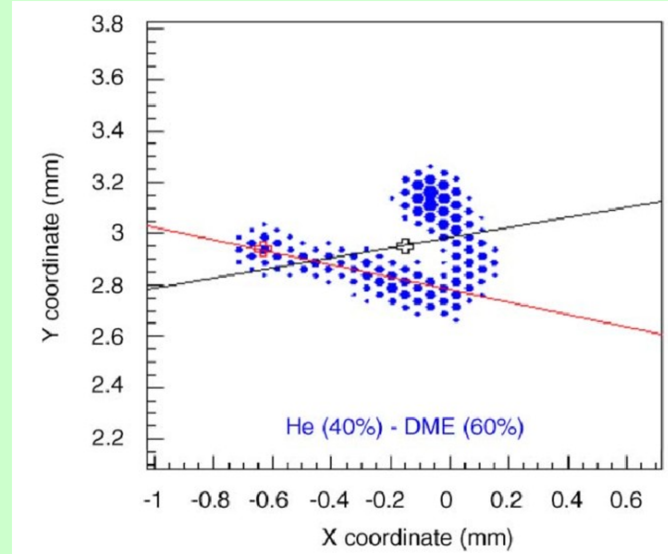
IXPE (Imaging X-ray Polarimetry Explorer)
Selected by NASA (SMEX) for phase A study
Final selection: Early 2017
Launch: 2020

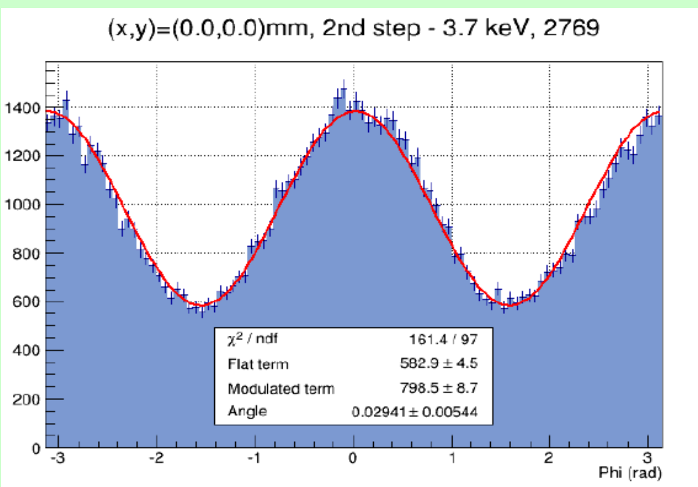
PRAXyS (Polarimeter for Relativistic Astrophysical X-ray Sources)
Selected by NASA (SMEX) for phase A study
Final selection: Early 2017
Launch: 2020

XIPE

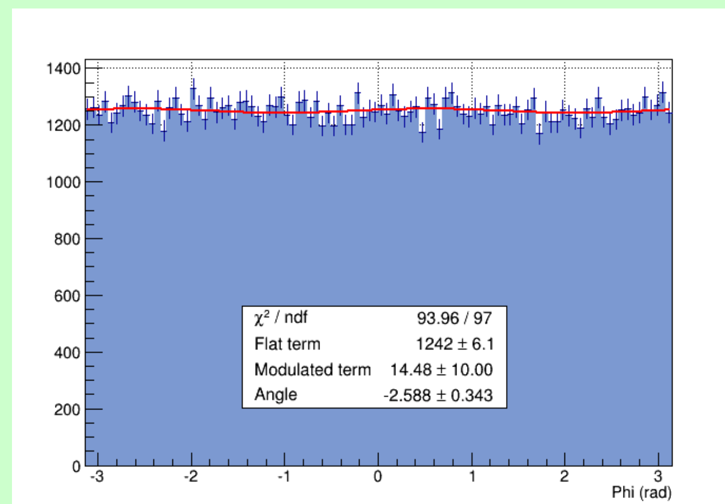


$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$





Real modulation curve derived from the measurement of the emission direction of the photoelectron.



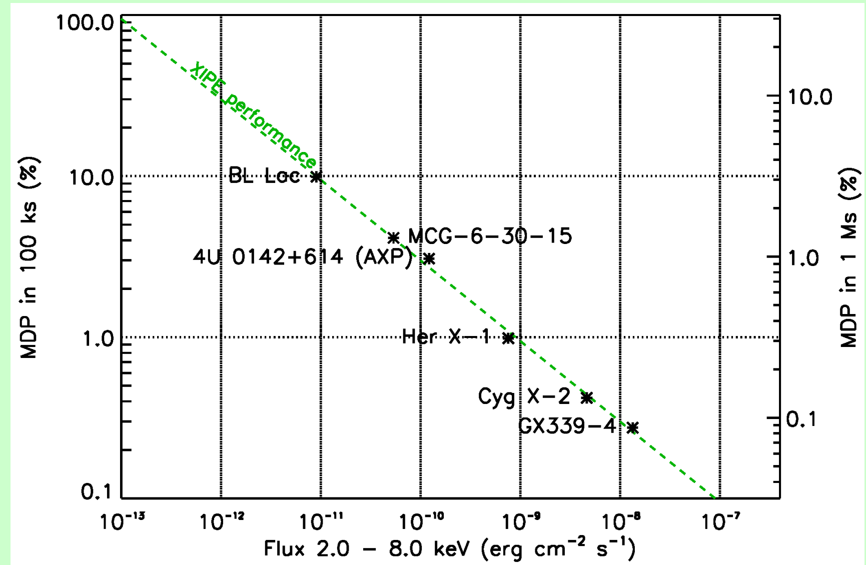
Residual modulation for unpolarized photons

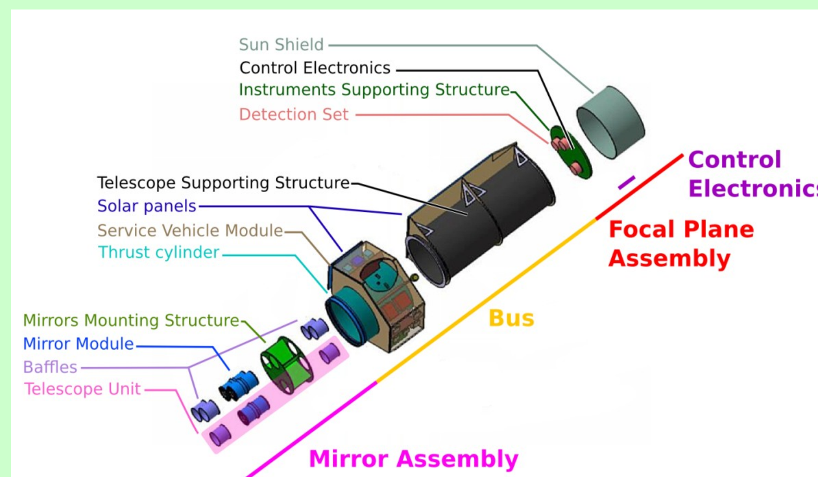
XIPE

Energy range	2-8 keV
Angular resolution	<26” (goal <20”)
F.o.V.	15x15 arcmin^2
Spectral resolution	16% @5.9 keV
Timing resolution	< 8 microseconds
Spurious polarization	<0.5% (goal <0.1%)

$$MDP = \frac{4.29}{\mu\sqrt{S}}\frac{1}{\sqrt{T}}$$

The MDP is the minimum detectable polarisation at the 99% confidence level





XIPE Science Working Groups

WG 1. Acceleration mechanisms (leaders: G. Tagliaferri, J. Vink)

- WG1.1 Pulsar Wind Nebulae (chair: E. de Ona Wilhelmi)
- WG1.2 Supernova Remnants (chair: A. Bykov)
- WG1.3 Blazars (chair: I. Agudo)
- WG1.4 Microquasars (chair: E. Gallo)
- WG1.5 Gamma-ray Bursts (chair: C. Mundell)
- WG1.6 Tidal Disruption Events (chair: I. Donnarumma)
- WG1.7 Active Stars (chair: N. Grosso)
- WG1.8 Clusters of Galaxies (chair: S. Sazonov)

WG 2. Magnetic Fields in Compact Objects (leaders: A. Santangelo, S. Zane)

- WG2.1 Cataclysmic Variables and Novae (chair: D. De Martino)
- WG2.2 Accreting millisecond pulsars (chair: J. Poutanen)
- WG2.3 Accreting X-ray Pulsars (chair: V. Doroshenko)
- WG2.4 Magnetars and RPP (chair: R. Turolla/E. Massaro)

WG 3. Scattering in Aspherical Geometries and Accretion Physics (leaders: E. Churazov, R.Goosmann)

- WG3.1 X-ray binaries and QPOs (chair: J. Malzac)
- WG3.2 Active Galactic Nuclei (chair: P.O. Petrucci)
- WG3.3 Molecular Clouds and SgrA* (chair: F. Marin)
- WG3.4 Ultraluminous X-ray sources (chair: H. Feng)

WG 4. Fundamental Physics (leaders: E. Costa, G. Matt)

- WG4.1 QED and X-ray polarimetry (chair: R. Perna)
- WG4.2 Strong Gravity (chair: J. Svoboda)
- WG4.3 Quantum Gravity (chair: P. Kaaret/L. Foschini)
- WG4.4 Axion-like particles (chair: M. Roncadelli)

XIPE

Activity	Date
Phase 0 kick-off	Jun-2015
Phase 0 completed (ARIEL, THOR, XIPE)	Oct-Nov 2015
ITT for Phase A industrial studies	Nov-2015
Phase A kick-off	Mar-2016
Preliminary Requirement Review completed	Apr-2017
Down-selection recommendation for M4 mission	May-2017
SPC selection of M4 mission	Jun-2017
Phase B1 kick-off for the selected M4 mission	Jul-2017
Phase B1 completed	Sep-2018
SPC adoption of M4 mission	Nov-2018
Phase B2/C/D kick-off	2019
Launch	2026

Table 1: Tentative timeline for M4 activities

Summary

X-ray spectroscopy

Coronae – First determination of T and τ
Soft excess – Warm Comptonization?
Strong gravity – Reflection favoured, BH spins
Obscuration and outflows - Feedback in PDS 456
The future: Athena

X-ray polarimetry

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