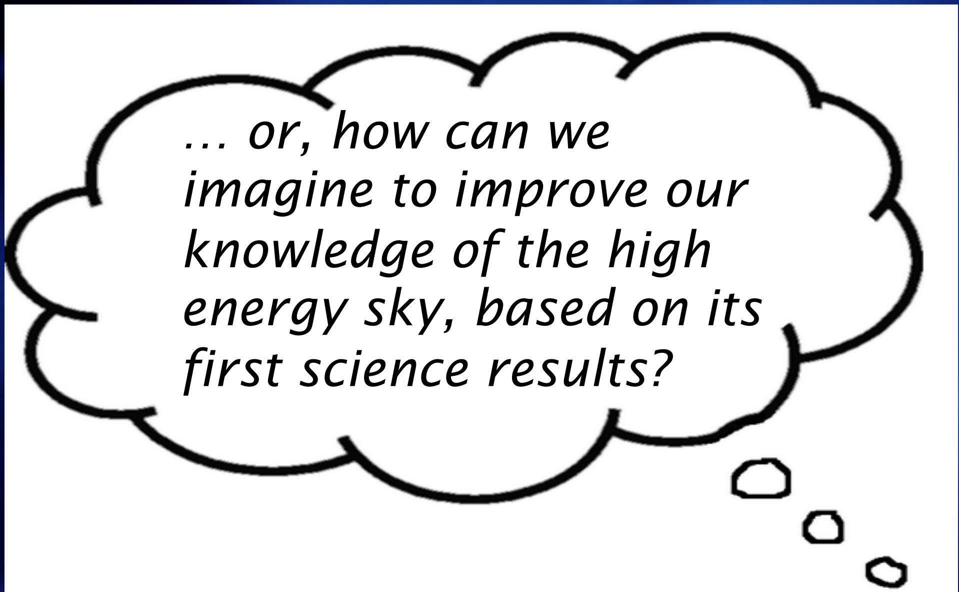
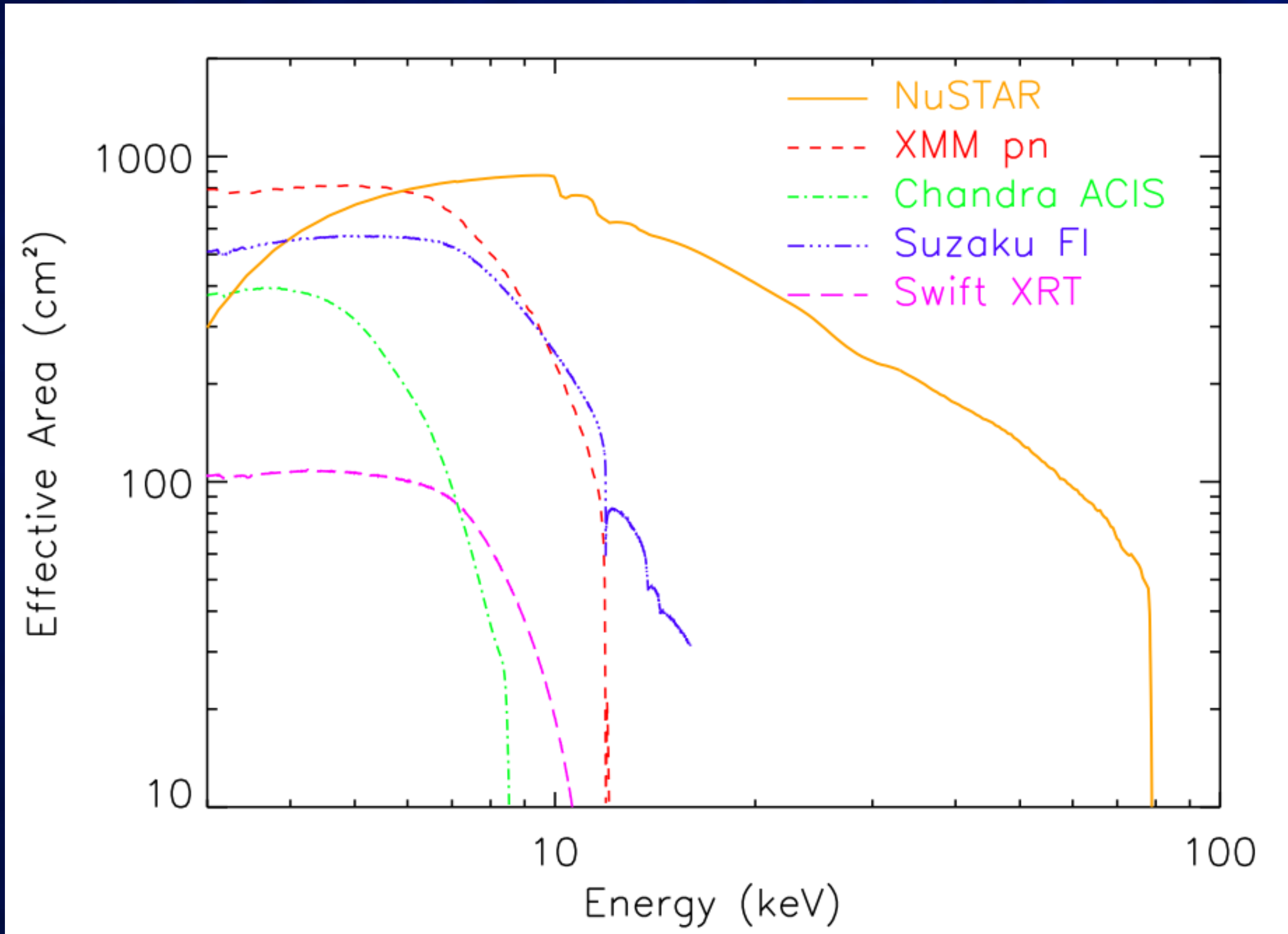
Beyond Nustar (*)

Lorenzo Natalucci
INAF-IAPS, Rome

(*) largely based on results from the NuSTAR Science Team



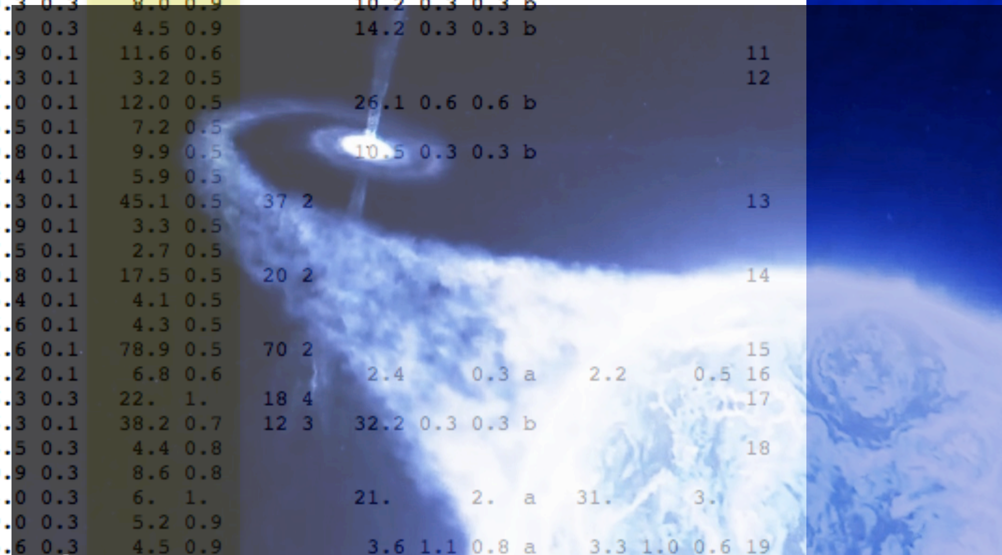
Effective Areas



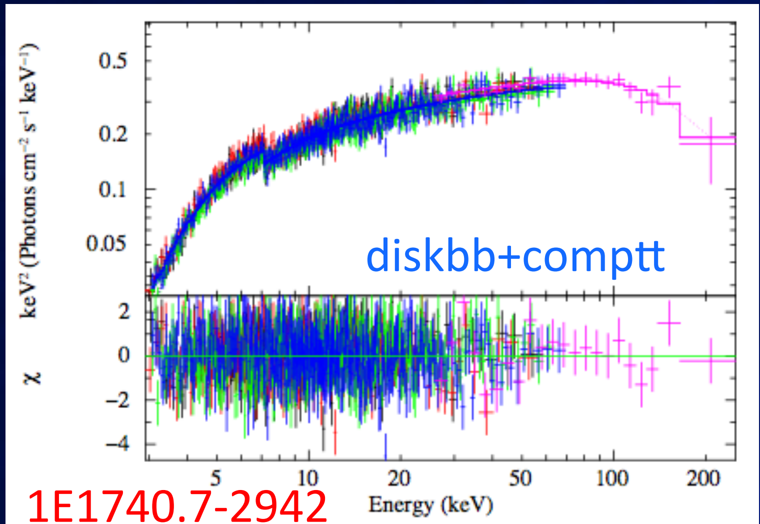
IBIS sources > 100 keV

Bazzano et al, ApJ 2007

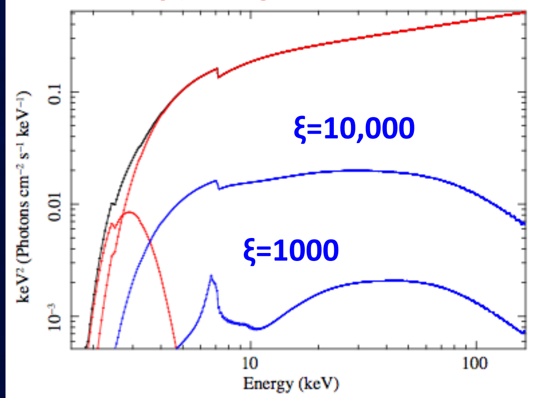
4U0142+61	AXP	1.5	0.3	3.4	0.5	8.	2.										1
Crab	PWN PSR	1000.0	0.4	1000.0	0.6	1000.	2.	1000	6	1000.		3.	c	1000.		3.	
MKN3	AGN	4.2	0.2	6.1	0.4	10.	2.										
VelaPulsar	PWN PSR	6.74	0.09	8.4	0.1	10.3	0.7										
GS0836-429	LMXB T B	30.58	0.09	27.2	0.1	14.6	0.7										
NGC4151	AGN Sey1.5	32.0	0.6	40.	1.	35.	4.			28.5	0.3	0.3	b	18.0	0.3	0.5	2
NGC4388	AGN Sy1	15.9	0.7	17.	1.	25.	5.										3
3C273	AGN QSO	7.7	0.3	9.2	0.6	12.	2.			23.7		0.7	a	27.		1.	4
NGC4507	AGN Sy1h	8.7	0.4	10.7	0.6	10.	3.										
NGC4945	AGN Sey2	13.2	0.3	20.3	0.4	22.	1.			23.1	0.6	0.6	b				
CenA	AGN Sey2	36.5	0.2	47.4	0.4	57.	2.	65	6	49.5	0.3	0.3	b	52.0	0.5	1.0	5
Cir galaxy	AGN Sy1h	13.6	0.2	11.4	0.3	7.	1.			3.4	1.1	0.5	c				
PSRB1509-58	PSR	8.5	0.2	11.0	0.3	14.	1.										6
XTEJ1550-564	LMXB T BH	70.8	0.2	114.4	0.3	146.	1.	155	4	115.	1.	1.	a	114.2	0.5	1.5	7
4U1608-522	LMXB T B A	14.3	0.2	7.7	0.3	5.	1.										
ScoX-1	LMXB Z	629.0	0.4	21.0	0.6	12.	2.										
4U1630-47	LMXB T BHC	44.2	0.2	34.4	0.3	30.	1.	30	4	48.5	0.3	0.3	a	43.0	0.5	0.5	8
4U1636-536	LMXB B A	22.6	0.2	13.0	0.3	8.	1.										
OAO1657-415	HMXB XP	78.6	0.2	42.5	0.3	7.3	0.9										
GX339-4	LMXB T BH	28.3	0.2	34.4	0.3	34.	1.	31	4	43.4	0.3	0.3	b	28.8	0.5	0.5	9
4U1700-377	HMXB	196.21	0.09	120.6	0.1	52.5	0.7	23	3								10
4U1702-429	LMXB B A	16.1	0.2	10.3	0.3	8.0	0.9			10.2	0.3	0.3	b				
4U1705-440	LMXB B A	23.7	0.2	13.0	0.3	4.5	0.9			14.2	0.3	0.3	b				
IGRJ17091-3624	BHC?	8.78	0.09	10.9	0.1	11.6	0.6										11
XTEJ1720-318	LMXB T BHC	2.59	0.09	3.3	0.1	3.2	0.5										12
GRS1724-30	LMXB B A G	19.21	0.09	17.0	0.1	12.0	0.5			26.1	0.6	0.6	b				
GX354-0	LMXB B A	39.17	0.09	15.5	0.1	7.2	0.5										
GX1+4	LMXB XP	38.98	0.09	30.8	0.1	9.9	0.5			10.5	0.3	0.3	b				
SLX1735-269	LMXB B	9.33	0.09	8.4	0.1	5.9	0.5										
1E1740.7-294	LMXB BHC	35.84	0.09	45.3	0.1	45.1	0.5	37	2								13
KS1741-291	LMXB T B	5.64	0.09	4.9	0.1	3.3	0.5										
A1742-294	LMXB T B	13.86	0.09	7.5	0.1	2.7	0.5										
IGRJ17464-3213	LMXB BHC	28.08	0.09	20.8	0.1	17.5	0.5	20	2								14
SLX1744-299	LMXB B	8.31	0.09	5.4	0.1	4.1	0.5										
IGRJ17597-2201	LMXB B D	7.02	0.09	6.6	0.1	4.3	0.5										
GRS1758-258	LMXB BHC	53.58	0.09	71.6	0.1	78.9	0.5	70	2								15
SGRJ1806-20	SGR	3.05	0.09	4.2	0.1	6.8	0.6			2.4		0.3	a	2.2		0.5	16
4U1812-12	LMXB B A	25.6	0.2	26.3	0.3	22.	1.	18	4								17
GS1826-24	LMXB B	79.26	0.09	66.3	0.1	38.2	0.7	12	3	32.2	0.3	0.3	b				
PKS1830-211	AGN QSO	2.8	0.2	3.5	0.3	4.4	0.8										18
1RX1832-33	LMXB B T G	10.81	0.09	10.9	0.3	8.6	0.8										
KES73	SNR AXP	2.0	0.2	4.0	0.3	6.	1.			21.		2.	a	31.		3.	
4U1909+07	HMXB T XP	14.3	0.2	9.0	0.3	5.2	0.9										
AqlX1	LMXB B A T	9.6	0.2	5.6	0.3	4.5	0.9			3.6	1.1	0.8	a	3.3	1.0	0.6	19
GRS1915+105	LMXB BH	260.8	0.2	105.4	0.3	59.	1.	47	4	82.6	0.2	0.2	b	55.5	0.2	0.1	20
CygX-1	HMXB BH	665.7	0.3	712.5	0.4	632.	2.	522	6	950.	3.	3.	b	870.	5.	5.	21
EXO2030+375	HMXB XPBe T	38.8	0.2	20.4	0.4	3.6	0.9										22
CygX-3	HMXB	204.1	0.2	85.1	0.3	31.	1.	20	5	18.0	0.3	0.3	b	12.1	0.5	0.5	23
IGRJ21247+5058	AGN Sy 1?	5.6	0.2	7.0	0.4	6.0	1.5										



Spectra of BHs in low/hard state



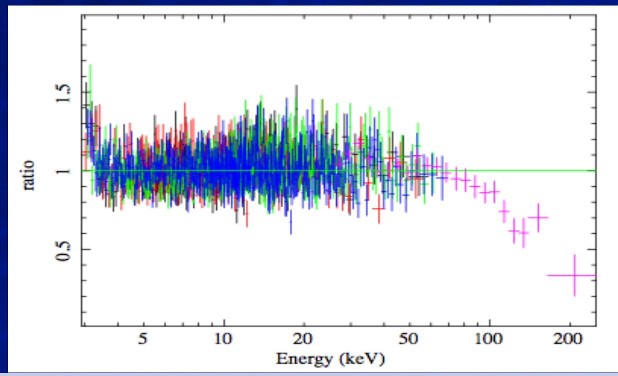
1E1740.7-2942



Unfolded model with upper limit reflection components

Natalucci et al, ApJ 2014

- 1E1740.7-2942, July-Sept 2012 *(Nustar 10ks,* IBIS 130ks*)*
- *Nustar* alone cannot detect the high energy cutoff.



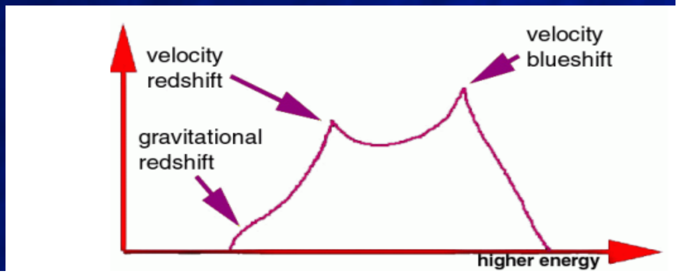
Ratio to absorbed PL model

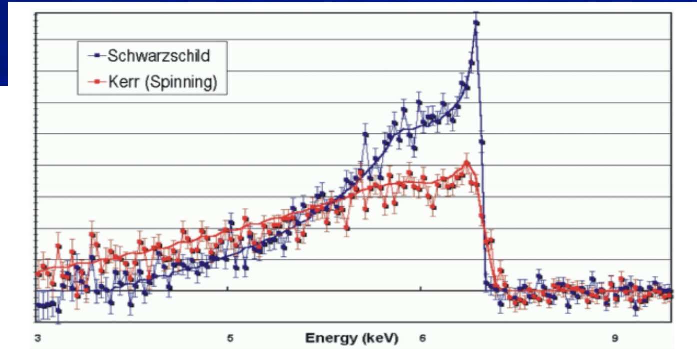
Results of fitting NuSTAR and IBIS/ISGRI spectra (epoch 2 and epoch3, respectively) with an absorbed (Tbabs) cutoff power law model.

Instrument/ Range	N_H (10^{22} cm^{-2})	Γ	E_{fold} (keV)	χ^2	Fl_{20-50}(*) (10^{-12} erg cm^{-2} s^{-1})
NuSTAR, 3-70 keV	18.3 ± 0.9	1.58 ± 0.04	215(-74,+232)	761/740	442 ± 8
IBIS/ISGRI *26-250 keV*	20 (fixed)	1.43 ± 0.19	123(-34,+69)	24.6/19	490 ± 13

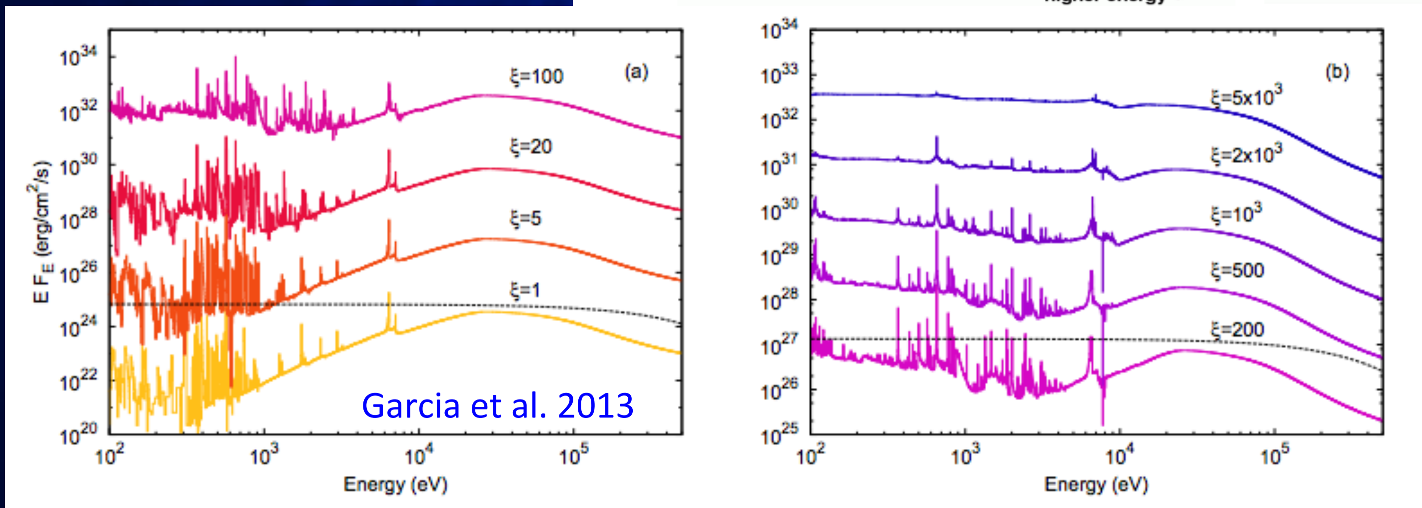
Reflection spectra

- Simultaneous coverage of soft and hard X-ray band is needed for complete study of reflection spectra
- In bright BH and NS sources, due to its high sensitivity *NuSTAR* can resolve the curvature of the continuum from the one induced by reflection.
- The driver is then the effective area, but for higher ionizations energy extension >100 keV is desirable



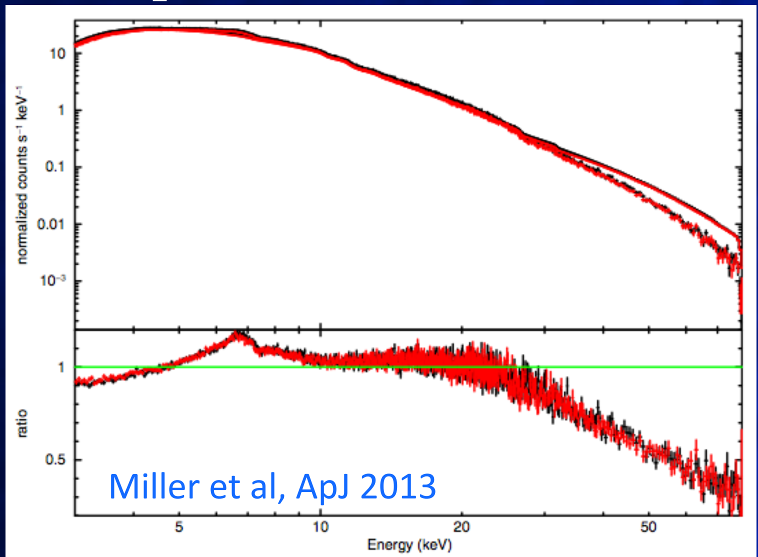


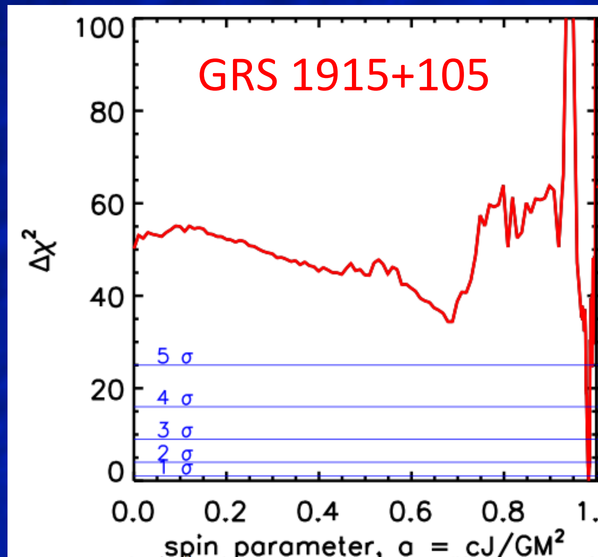
Credit: J.Miller



Black holes: reflection and spin measurements

- Most important limitations concern systematic errors in models (and sometimes, instrument calibration)
- In addition, spin measurements assume that the inner radius of the BH is spatially coincident with the ISCO. The spin is determined by the fact that the location of the ISCO is a function of spin
- *NuSTAR* as other X-ray instruments shows preference for high values of spin

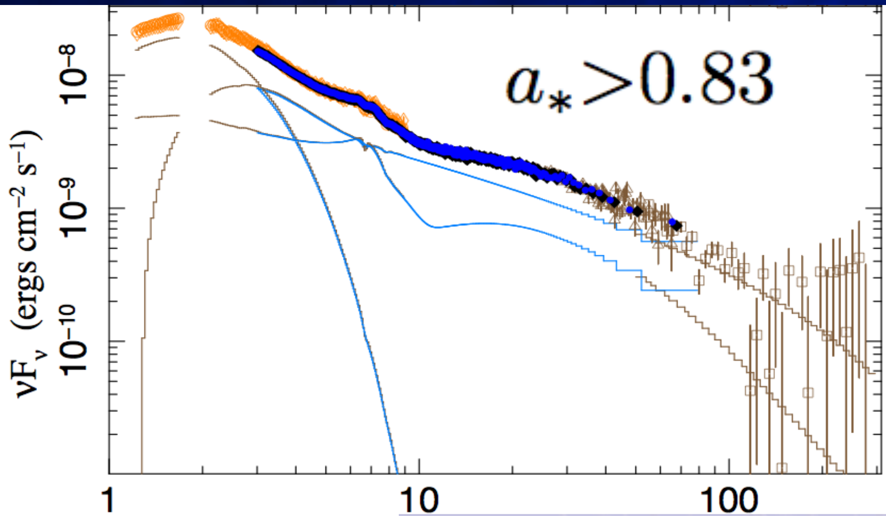


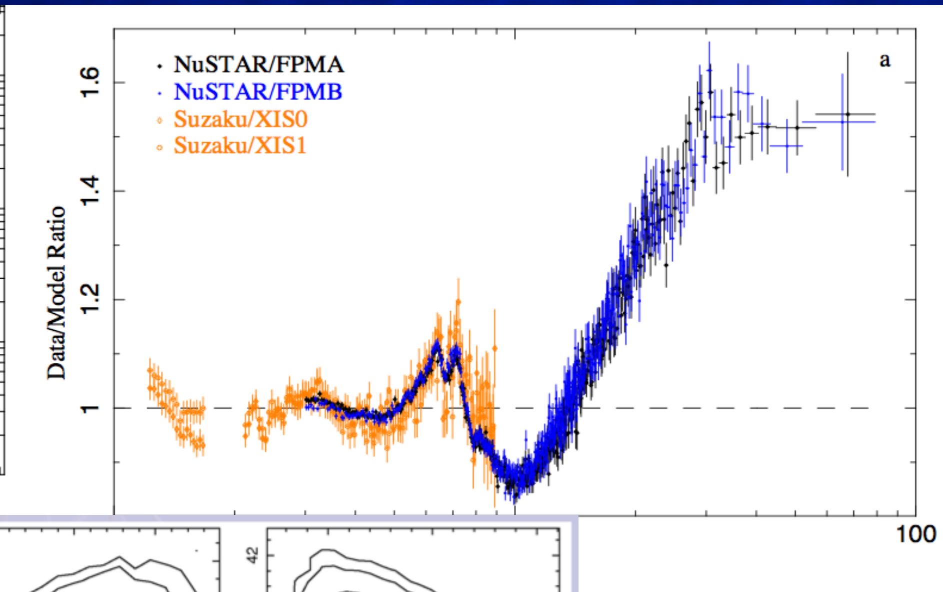


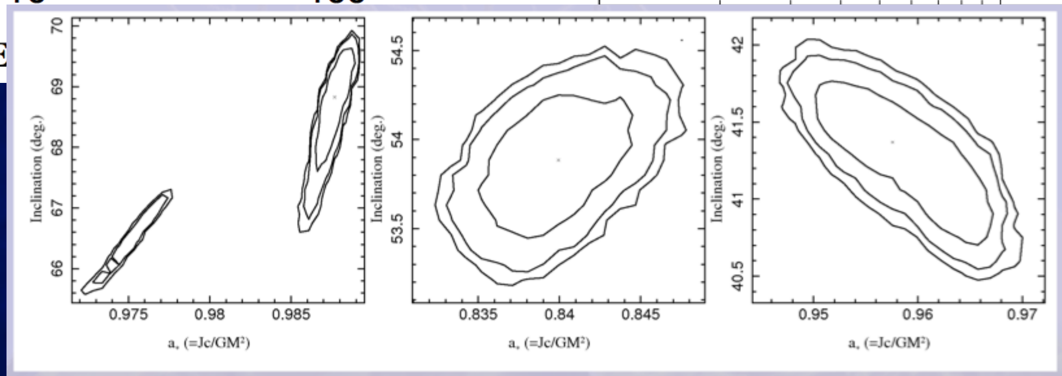
Soft states spectra: Cyg X-1

◆ *NuSTAR*,16ks exposure. Suzaku/XIS,~2ks.

◆ Fit by reflection models with relativistic, blurred iron line. The data could constrain the spin of the BH and inner disk inclination

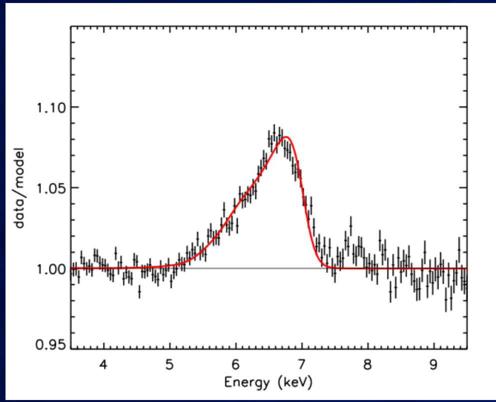






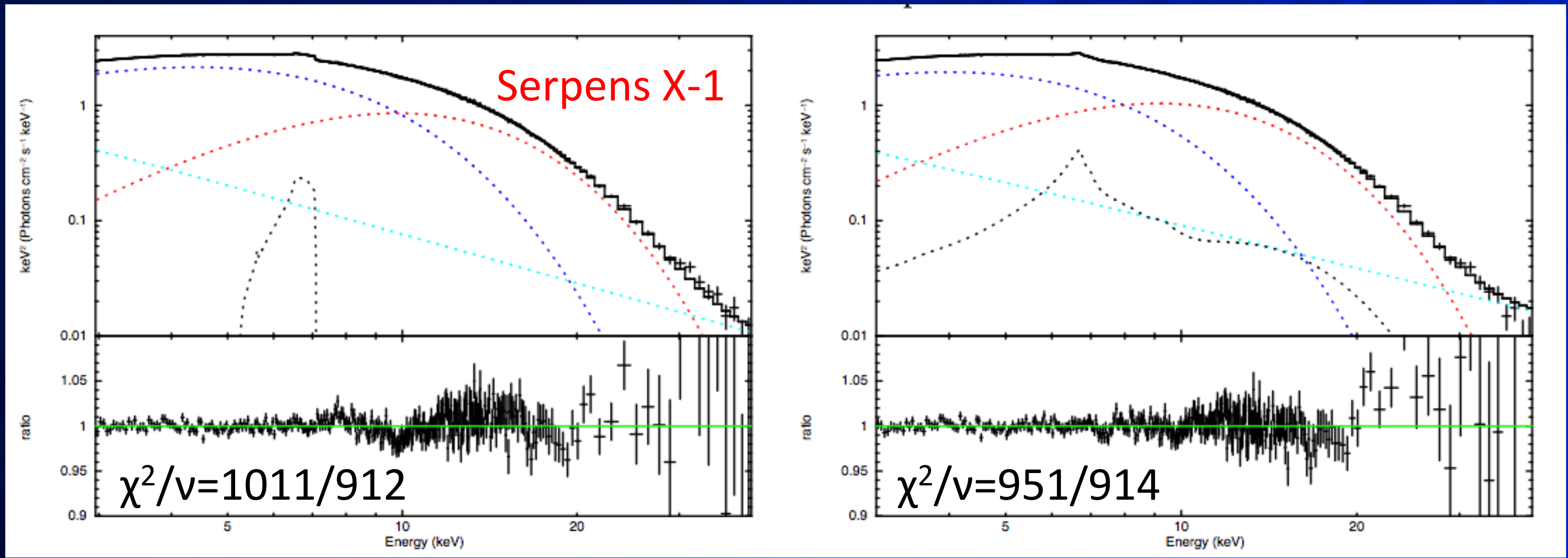
Tomsick et al, ApJ 2014

Reflection from NS sources: Serpens X-1



- Self-consistent reflection model convolved with relativistic line
- Constraint on NS radius: R<12.5 km assuming $M=1.4M_{sun}$

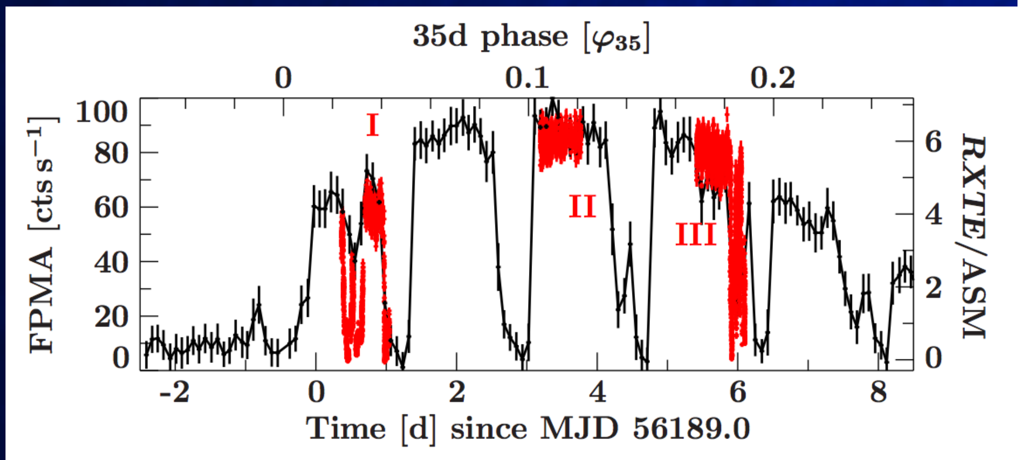
Miller et al, ApJ 2013



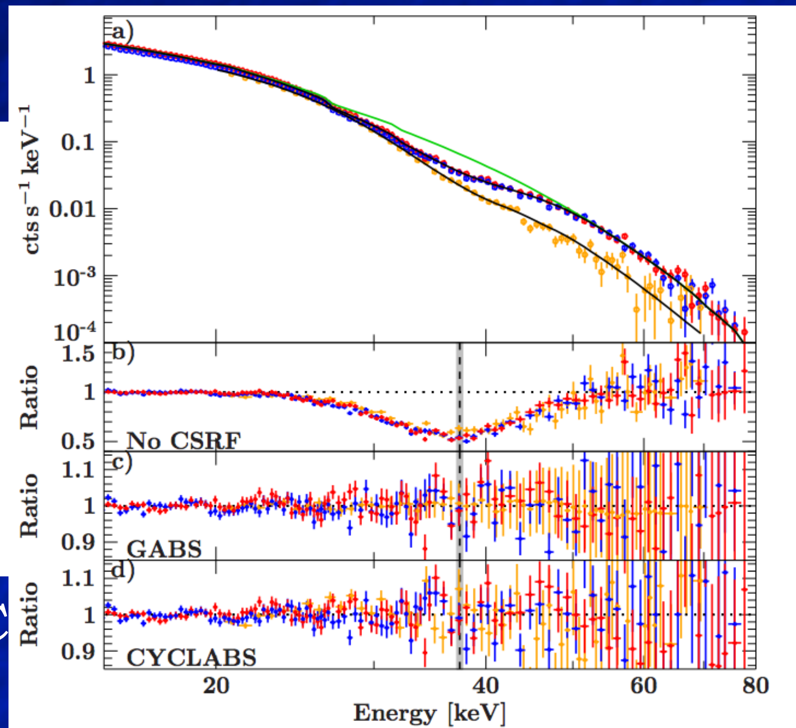
Hercules X-1

Cyclotron line shaping

- *NuSTAR* and *Suzaku* simultaneous observations, spaced in time during 35 days cycle phase (exposures 11,22,17ks)
- CSRF well modeled with either gaussian (*gabs*) or Lorentzian (*cyclabs*) optical depth profile (*cyclabs*)
- Line is smooth (no evidence for wings). Indication for a fan beam pattern



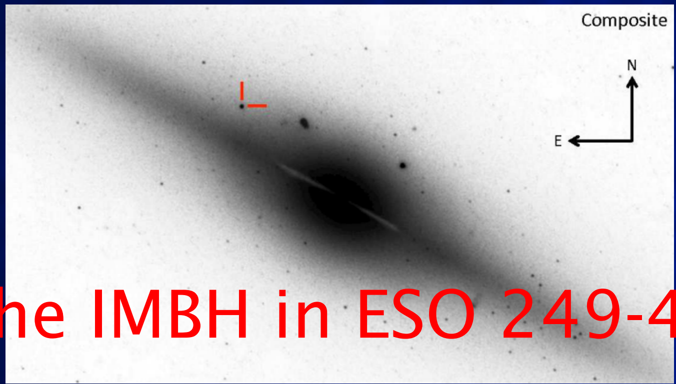
RXTE/ASM 35 days folding phase LC (Klochkov et al. 2006)



Fuerst et al. 2013, ApJ

On the way to SMBHs: Ultraluminous sources

- Are ULX super-Eddington sources? Are they intermediate mass BHs?
- HLX-1 in ESO 249-49 (~95 Mpc) is the most luminous ULX, with a peak luminosity (0.2-10 keV) as high as $\sim 1.3 \times 10^{42}$ erg/s
- Bright outbursts & correlated spectral variability similar to the states of bright LMXBs



HLX-1: the IMBH in ESO 249-49

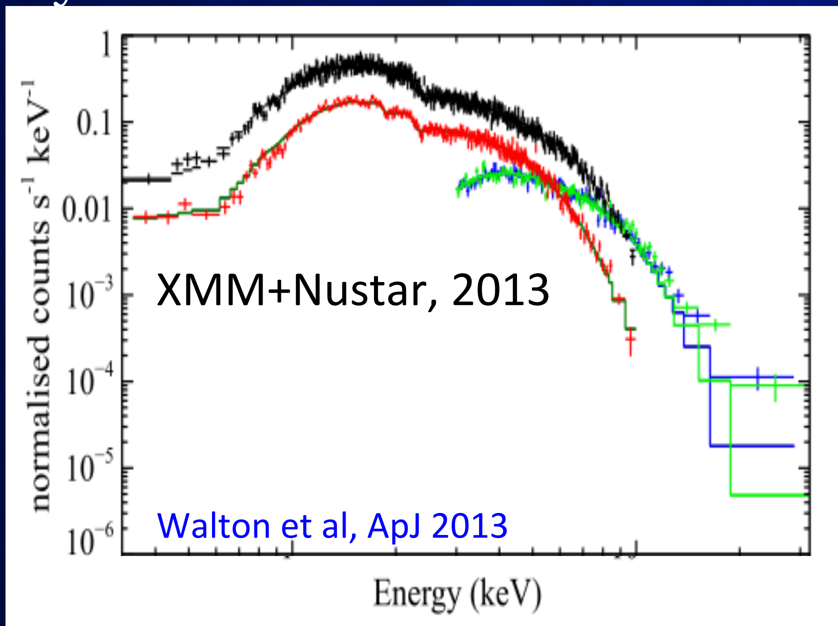
HLX-1 as observed by HST.
A population of massive young stars is seen around it *(Farrell et al 2012)*

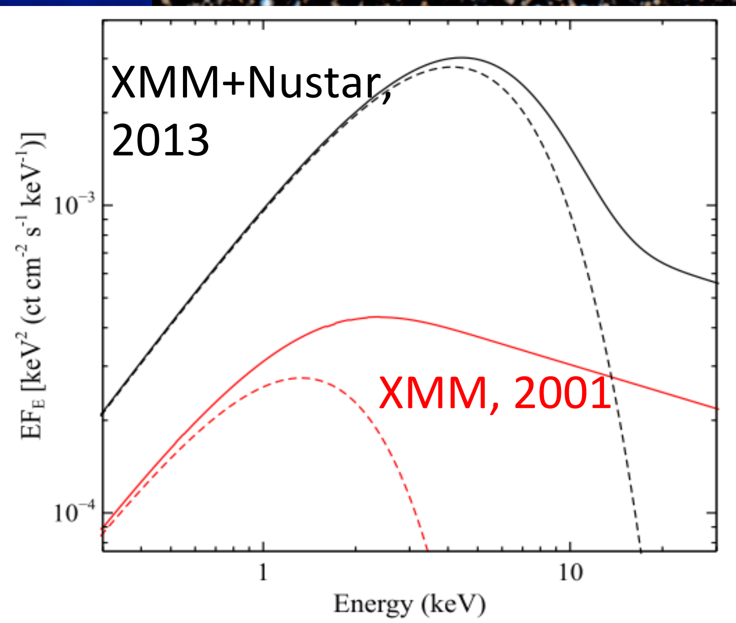
Composite HST image of ESO 249-49 from near-IR, optical & UV data. ULX-1 is indicated by red tic marks
Figure 1 from Farrell et al. 2012, ApJL in press (arXiv: 1110.6510)

- The high luminosity of HLX-1 is evidence for an Intermediate Mass BH ($\sim 500 M_{\odot}$?) possibly accreting from a dense environment of stars and gas.
- High energy spectra of ULXs are lacking sensitive data beyond 10 keV: neither the nature of the PL component, nor any reflection or other feature from a disk can be firmly established. *Nustar* is foreseen to study this for a sample of ~10 selected objects

ULX5 in Circinus Galaxy

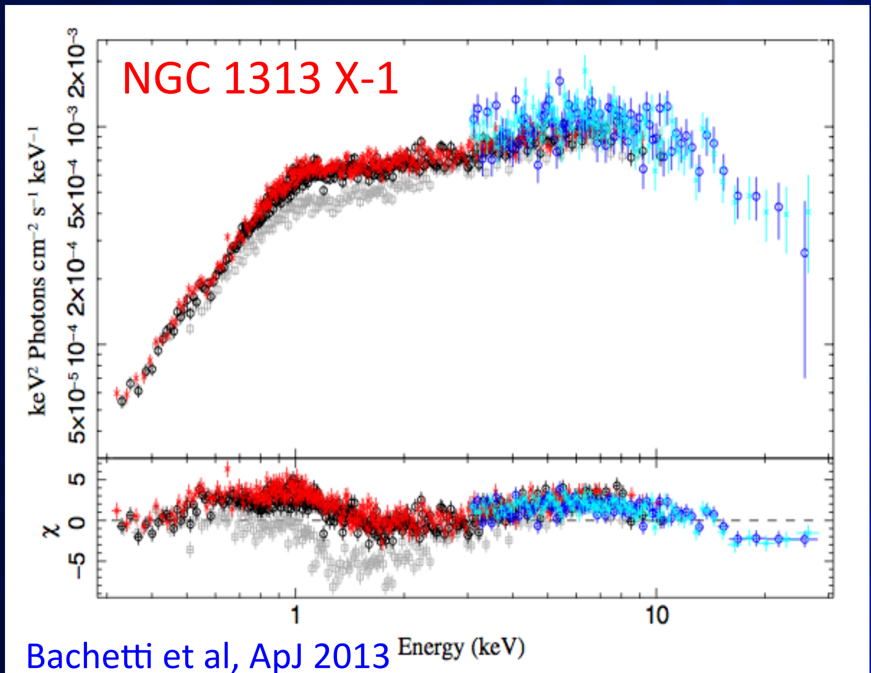
- *Nustar* observation of ULX5 in the outskirts of the Circinus Galaxy
- *Nustar+XMM* spectrum: in this case, a thermal dominated state, but there is also evidence for state transitions similar to sub-Eddington stellar BHs. *Nustar* exposure is 95ks
- Long term variability is also observed in many other ULXs

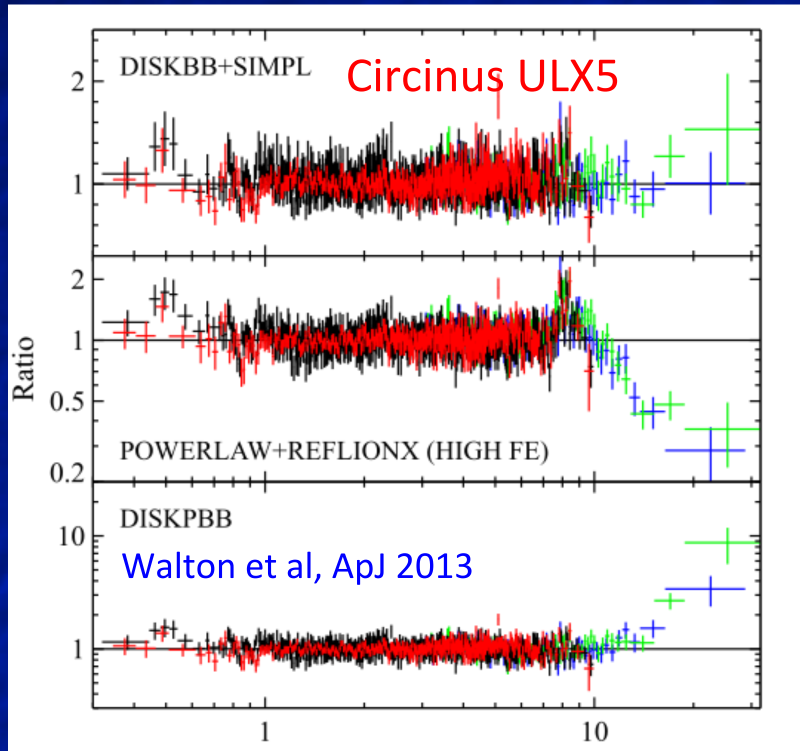




ULXs: source types and spectra

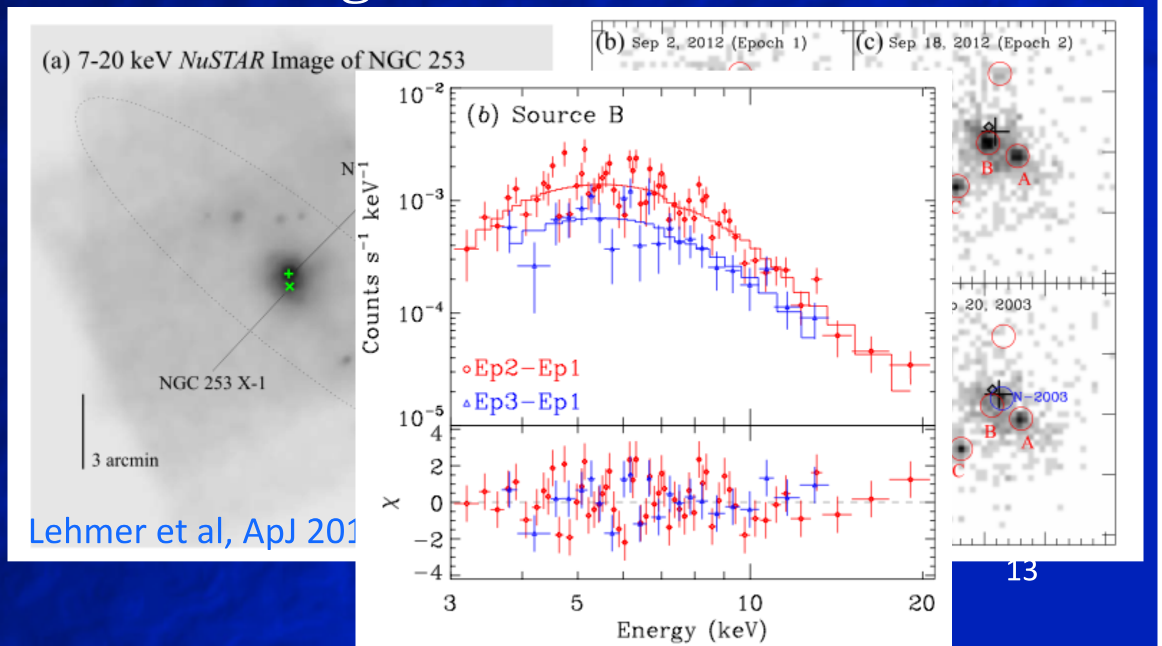
- Could there be a hidden population of fainter (or highly absorbed) ULXs?
- As other ULXs, the spectrum shows a curvature below 10 keV, the nature of which is unclear: Comptonization, residual of reflection or Fe line feature?



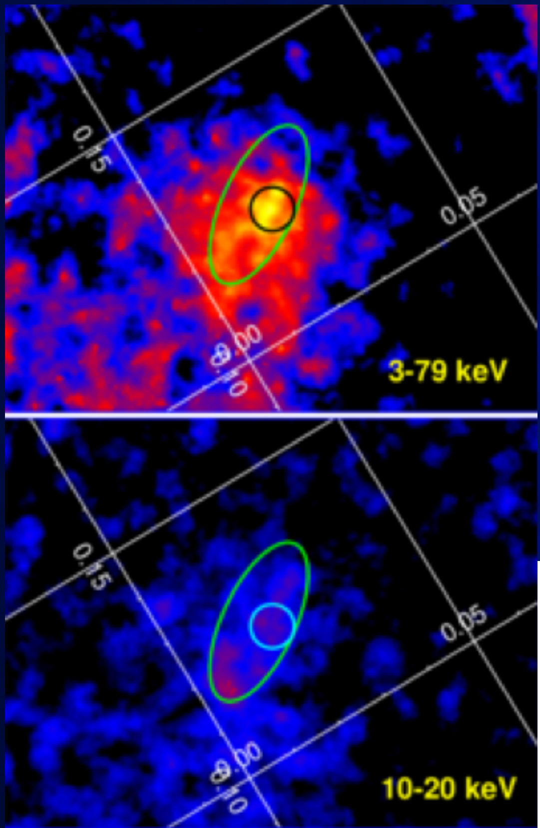


Nuclear activity and ULXs in Star Forming Galaxies

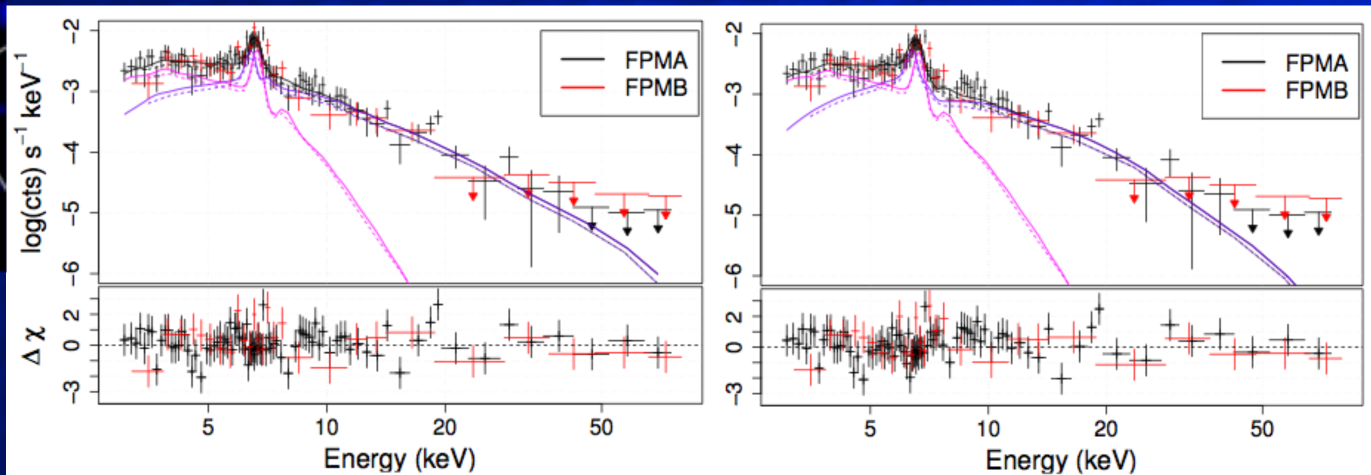
- Chandra-NuSTAR study of the nuclear region in NGC253. Nustar 165ks exposure, 20 ks Chandra
- A variable source (B) is detected, not coincident with the nucleus of the Galaxy.
- In this case it has been possible to measure a NuSTAR spectrum of the variable source by studying the time behaviour of sources monitored at high resolution in the soft X-rays
- A (now dormant) AGN is detected in the 2003 Chandra data
- AGNs in starburst Galaxies can be a class of highly absorbed sources: e.g. Arp299-B (Ptak et al., AAS 2014)



Arches cluster in the GC



- Fist time detection of hard X-ray (>10 keV) emission by the Arches cluster.
- High energy emission. What is it? LECR or reflection by MC.
- Spectral upper limits above 20-30 keV, relatively close to the models



Summary [1/2]

Most topics I considered show the advantages of improving the effective area in the range ~20-100 keV:

a. Studies of parameters of BHs at all mass scales.

b. NS and cyclotron line studies.

c. Study of highly absorbed sources (HMXB in our Galaxy, CT AGNs, and X-ray faint quasars)

d. Deeper surveys at all spatial scales

e. Characterize emission models for complex structures (e.g. non-thermal emission of the GC sources; and diffuse emission)

Summary [2/2]

Enhanced angular resolution is important at least for :

a. complex fields and Galactic surveys like GC, Norma and other high star formation regions, etc;
b. resolving nuclear activity in nearby Galaxies and detecting/ characterizing more ULXs;
c. mapping of diffuse regions, SNR, & PWN emission

Extension of the energy band beyond ~100 keV would allow:

a. studying in detail low/hard states and cutoffs in Galactic BHs and AGNs.
b. Constrain AGN contribution to X-ray background at higher energies
c. Help reflection studies for bright accreting sources
d. Extend the range of cyclotron line studies up to B fields of ~2×10^{13} Gauss