An Introduction to Active Galactic Nuclei in the X-Rays

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Outline

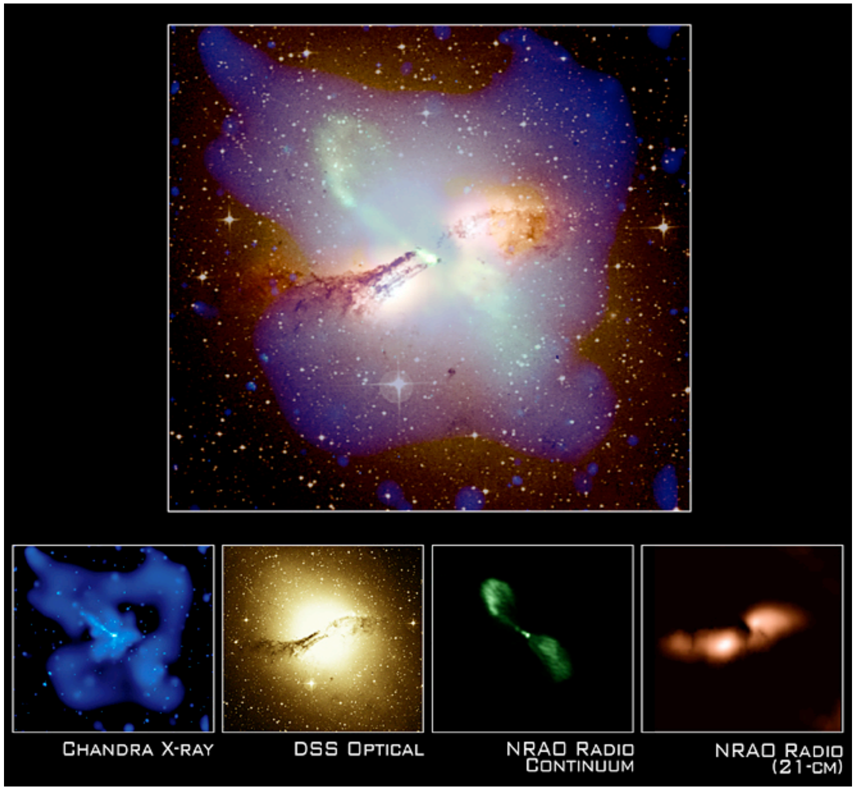
- Definition and basic properties
- Current AGN models
- The X-ray view of AGN
- What have we learned from Chandra and XMM
- What should I do with my AGN X-ray data?

Definition and Properties

At optical λ, emission from most galaxies is dominated by starlight.

Observations in other wavebands (radio, IR, UV, X-rays & Gamma-rays) often also reveal emission indicating a variety of non-stellar processes are present.

Active Galactic Nucleus (AGN) indicate existence of highly energetic phenomena in the nucleus or central region of a galaxy not directly attributable to stars (**QUASARS** are the more distant and highly luminous AGN)



A composite X-ray (blue), radio (pink and green), and optical (orange and yellow) image of the galaxy Centaurus A (image credit CXC)

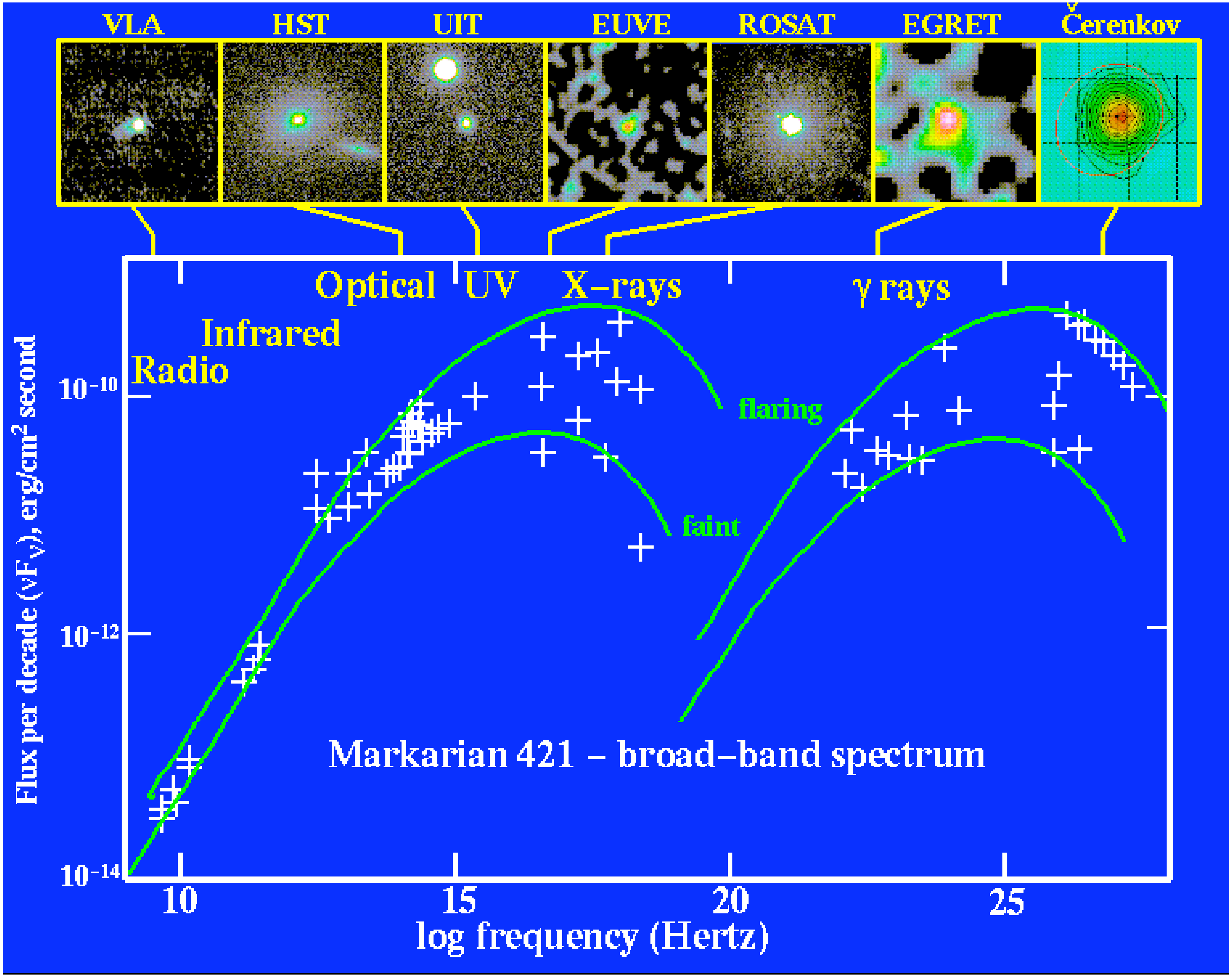
Quasars and AGN were identified as a class about 40 years ago and despite an ever-growing number of observations (and papers!) in all wavebands since then, we still only know them *well* "phenomenologically" rather than "physically".

I.e. we can list the observable phenomena that we use to find them, but we do not have direct signatures of their structure.

The single most common characteristic of AGN is probably that they are all luminous X-ray sources! (Elvis 1978)

AGN: Observational data

- **Highly luminous:** $L_{bol} \sim 10^{42}$–10^{48} ergs s^{-1} (10^9–10^{15} Lsun)
- **Compact**: size << 1pc
- **Broad-band** continuum emission: *dL/dlog n = const.* From IR to X-rays and γ-rays



VLA
HST
UIT
EUVE
ROSAT
EGRET
Čerenkov
Optical
UV
X-rays
γ rays
Infrared
Radio
flaring
faint
Markarian 421 – broad-band spectrum
Flux per decade (νFν), erg/cm² second
10⁻¹⁰
10⁻¹²
10⁻¹⁴
10
15
20
25
log frequency (Hertz)

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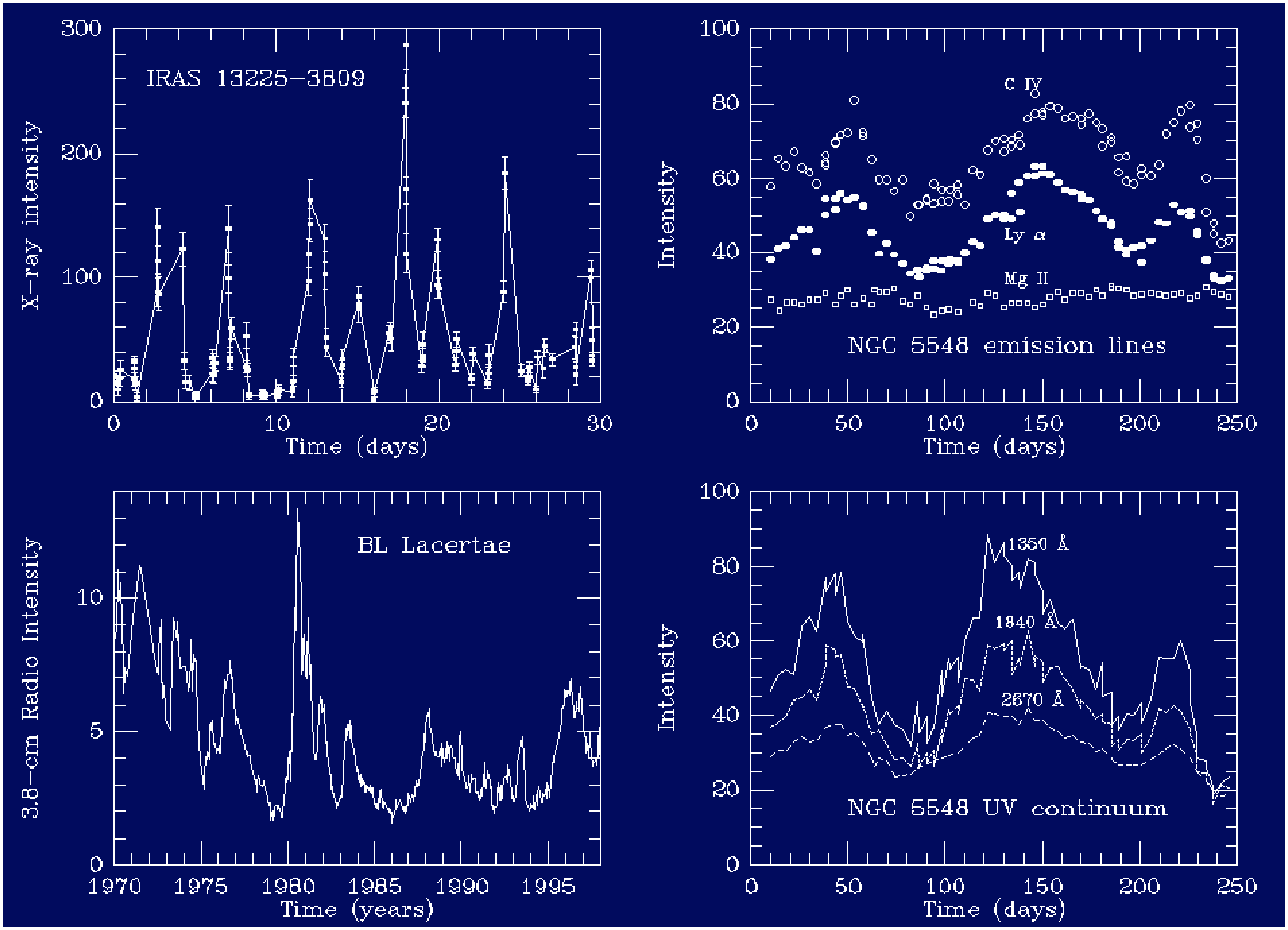
- **Variable:** on different times scales. Rapid variability in the X-ray indicate that emission comes from the innermost region


IRAS 13225−3809
X−ray intensity
Time (days)
Intensity
C IV
Ly α
Mg II
NGC 5548 emission lines
Time (days)
BL Lacertae
3.8−cm Radio Intensity
Time (years)
Intensity
1350 Å
1840 Å
2670 Å
NGC 5548 UV continuum
Time (days)

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- **Variable:** on different times scales. Rapid variability in the X-ray indicate that emission comes from the innermost region
- **Strong Radio emitters:** in some sources extended, jets are present
- **Polarized**

But what about models?

AGN Models

How is the energy that is detected as radiation generated?

The AGN paradigm (the "working model" most widely accepted): a "central engine" that consist of a hot accretion disk surrounding a massive black hole. Energy is generated by gravitational infall of material which is heated to high T in a viscous accretion disk.

super massive black hole (M ~ 10^6 – 10^9 M_{sun}) Lynden-Bell 1969

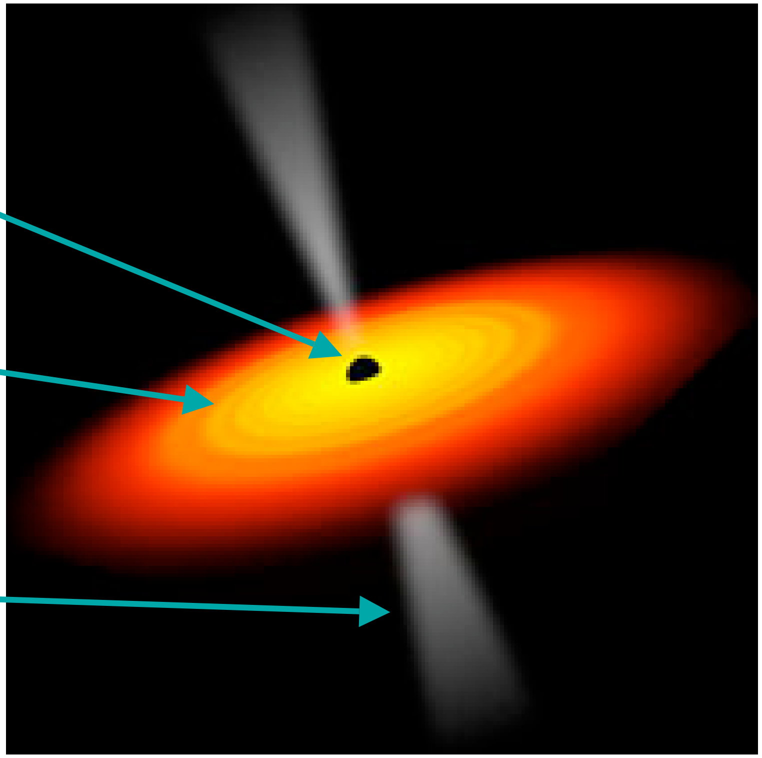
accretion disk

$L \sim \eta$[efficiency]$*\dot{M}c^2$**[accretion rate]**

Lynden-Bell 1969, Pringle & Rees 1972, Shakura & Sunyaev 1972

relativistic jet

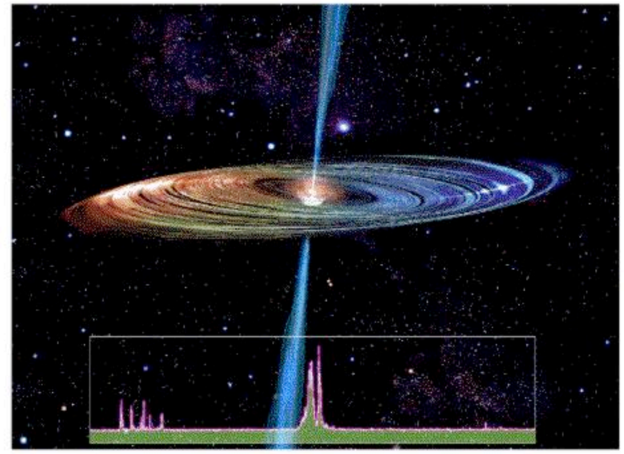
Rees 1967 [PhD], Blandford & Rees 1974



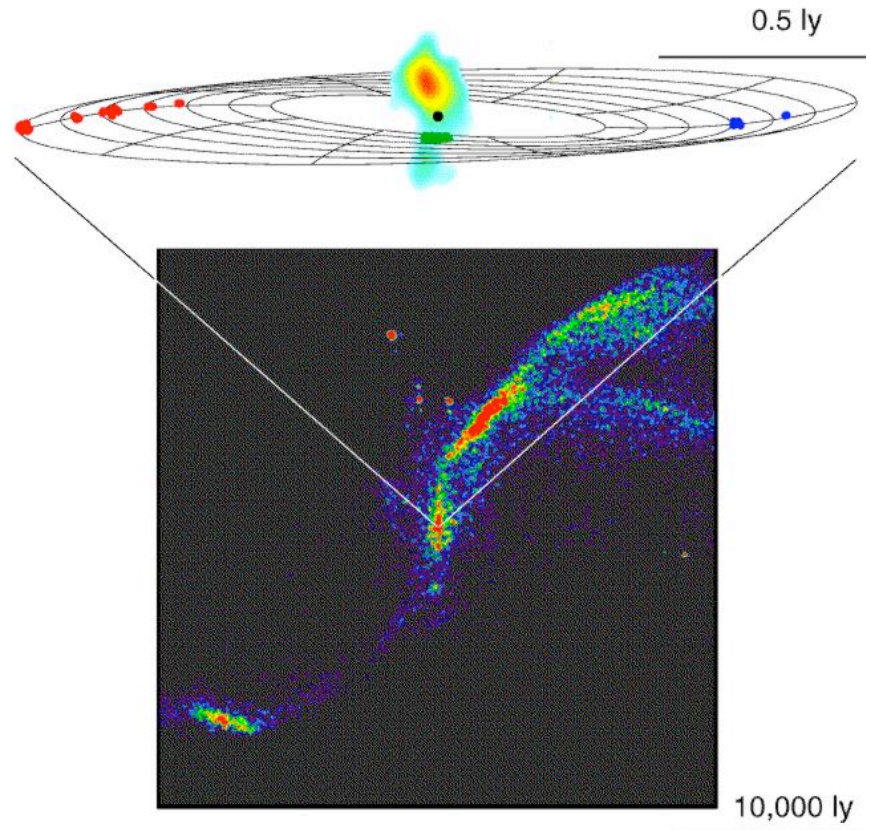
A TWO-SLIDES DIGRESSION…

- First direct evidence of accretion disk from the megamaser in NGC4258
- galaxy exhibits microwave (maser) emission from water vapor deep in the heart of the nucleus.
- Position and velocity of maser clouds precisely measured in radio (1 cm spectrum)
- Clouds map a keplerian disk to better than 1%

Miyoshi et al. (1995), Moran et al. (1995), Herrnstein et al. (1996, 1997),Greenhill et al. (1995)



NGC 4258



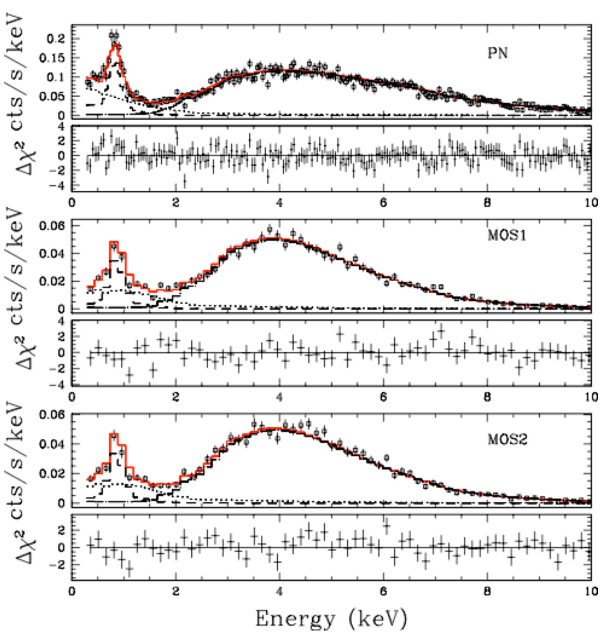
… and in the X-Rays for 9 years

Fruscione et. 2005

TABLE 2

SPECTRAL DATA FOR NGC 4258

Observatory	Date	kT (keV)	$f_{0.5-2}$ (10^{-12})[a]	$L_{0.5-2}$ (10^{38})[b]	N_H $(10^{22}\ cm^{-2})$[c]	Γ_{pl}	f_{5-10} (10^{-12})[a]	L_{5-10} (10^{40})[b]	f_{2-10} (10^{-12})[a]	L_{2-10} (10^{40})[b]	E_{lin} (keV)	EW_{lin} (eV)	f_{lin} (10^{-13})[a]	Reference
ASCA	1993 May 5	0.5 ± 0.2[d,e]	…	…	15 ± 2	1.78 ± 0.29	…	…	…	4.2	6.5 ± 0.2	250 ± 100	…	1
	1993 May 5	…	…	…	$13.6^{+2.1}_{-2.2}$	$1.78^{+0.22}_{-0.26}$	5.1	4	…	…	…	…	…	2
ASCA	1996 May 23	…	…	…	9.2 ± 0.9	$1.71^{+0.18}_{-0.17}$	8.3	6.1	…	…	…	…	…	2
ASCA	1996 Jun 5	…	…	…	$8.8\pm^{+0.7}_{-0.6}$	1.83 ± 0.13	8.8	6.4	…	…	…	…	…	2
ASCA	1996 Dec 18	…	…	…	9.7 ± 0.8	1.87 ± 0.15	9.5	6.9	…	…	…	…	…	2
BeppoSAX	1998 Dec 19	0.6 ± 0.1	1.6[d]	…	9.4 ± 1.2	2.11 ± 0.14	5.2	3.8	8	10	6.57 ± 0.20	85 ± 65	…	3
ASCA	1999 May 15	$0.47^{+0.03}_{-0.09}$	…	…	8.2 ± 0.9	$1.79^{+0.31}_{-0.11}$	…	…	…	5.8	…	…	…	2[f]
	1999 May 15	$0.36^{+0.03}_{-0.02}$	…	…	$9.5^{+2.1}_{-0.9}$	$1.86^{+0.40}_{-0.13}$	4.0	2.9	…	…	$6.45^{+0.10}_{-0.07}$	107^{+42}_{-37}	…	2[g]
Chandra	2000 Mar 8	…	…	…	7.2 ± 1.8	1.4 ± 0.5	…	…	14.4	13.2	…	…	…	4
	2000 Mar 8	N/A	N/A	N/A	$6.9^{+2.2}_{-1.8}$	1.3 ± 0.6	…	…	…	12	6.4	<887	…	5
	2000 Mar 8	N/A	N/A	N/A	$6.0^{+1.8}_{-1.4}$	$1.0^{+0.5}_{-0.4}$	15.9	11.0	21.2	17.4	6.4	<369	<12	6
Chandra	2000 Apr 17	$1.3^{+\infty}_{-0.9}$[e]	…	1.6	$7.2^{+0.7}_{-0.4}$	$1.5^{+0.1}_{-0.0}$	…	…	…	13	…	…	…	5
	2000 Apr 17[h]	0.5 ± 0.1	0.07	1.7	$6.7^{+1.0}_{-0.9}$	1.4 ± 0.3	8.3	5.8	11.8	10.6	6.4	<61	<1.2	6
XMM-Newton	2000 Dec 8	…	…	…	8.0 ± 0.4	1.64 ± 0.08	…	…	7.6	7.5	6.45	<40	…	4
	2000 Dec 8	0.6 ± 0.03	0.2	14.6	8.6 ± 0.4	1.7 ± 0.1	6.1	4.4	9.0	9.1	6.4	<69	<1.0	6
XMM-Newton	2001 May 6	$0.5^{+0.06}_{-0.05}$	0.2	15.3	9.8 ± 0.7	1.9 ± 0.1	4.8	3.5	7.1	7.8	6.4	<49	<0.6	6
Chandra	2001 May 28	$1.3^{+\infty}_{-0.8}$[e]	…	1.4	$6.5^{+0.6}_{-0.3}$	1.5 ± 0.1	…	…	…	7.9	6.4	<132	…	5
	2001 May 28[h]	$0.6^{+\infty}_{-0.18}$	0.06	1.3	6.0 ± 0.7	$1.4^{+0.3}_{-0.2}$	6.6	4.5	9.4	8.1	6.4	<191	<2.8	6
Chandra	2001 May 29	$1.0^{+0.6}_{-0.7}$[e]	…	1.5	$6.8^{+1.2}_{-1.0}$	1.4 ± 0.3	…	…	…	7.4	6.4	<94	…	5
	2001 May 29	0.8 ± 0.2	0.06	1.5	$5.9^{+0.8}_{-0.7}$	1.3 ± 0.2	6.2	4.3	8.8	7.6	6.4	<100	<1.4	6
XMM-Newton	2001 Jun 17	0.5 ± 0.05	0.2	14.1	$8.5^{+0.7}_{-0.6}$	1.8 ± 0.1	4.3	3.1	6.4	6.5	$6.3^{+0.07}_{-0.08}$[i]	66 ± 43[i]	0.7	6
XMM-Newton	2001 Dec 17	$0.5^{+0.06}_{-0.12}$	0.3	16.4	$8.4^{+1.0}_{-0.9}$	$1.5^{+0.2}_{-0.1}$	4.1	2.9	5.8	5.5	6.4	<67	<0.7	6
XMM-Newton	2002 May 22	0.5 ± 0.04	0.2	14.9	$13.2^{+1.4}_{-1.3}$	1.5 ± 0.2	3.7	2.8	4.9	5.4	6.4	<100	<0.9	6



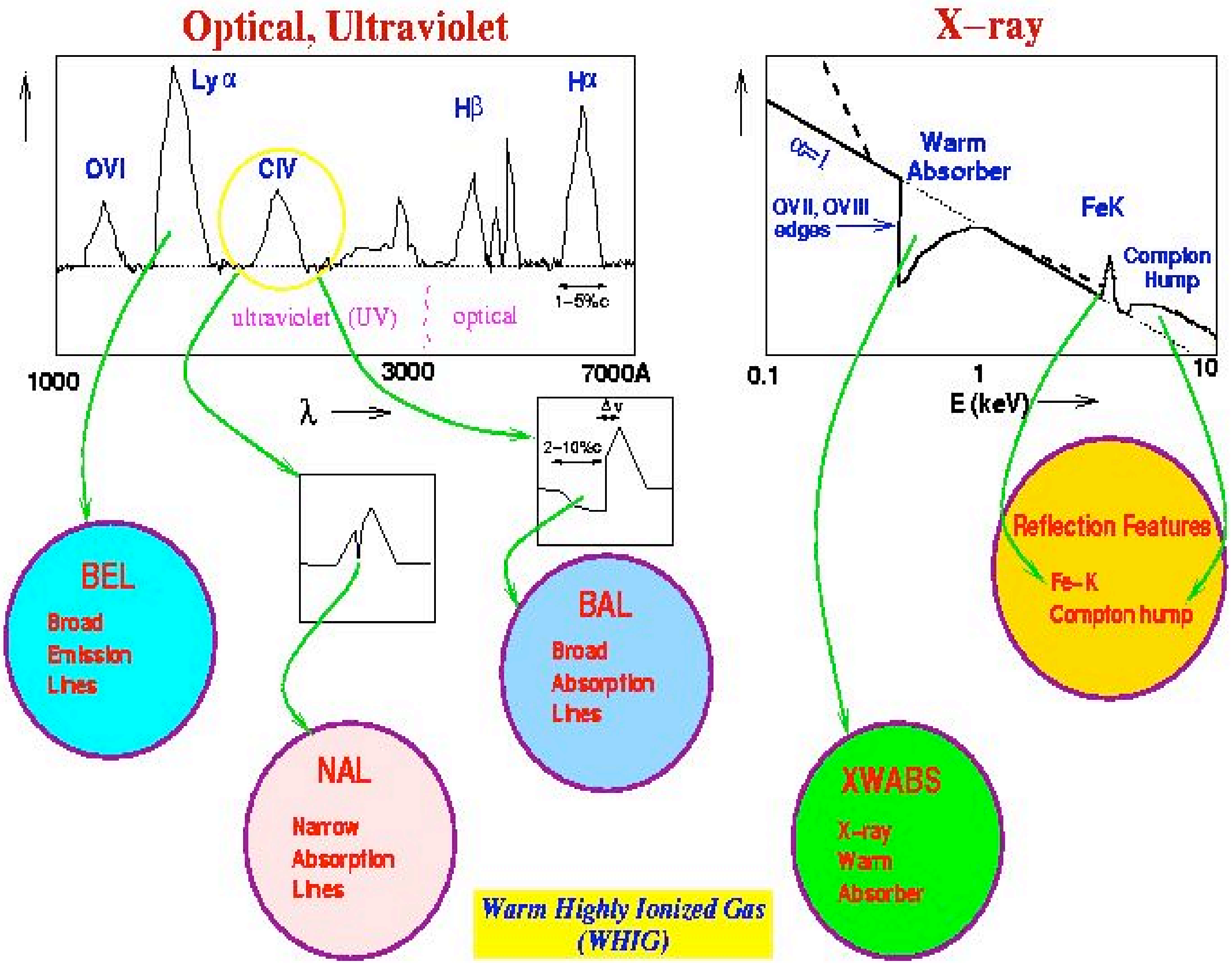
Spectra fitted by absorbed hard power law + soft components

Changes in NH and flux are not correlated indicating intrinsic variability of the central engine

Variations of NH due to inhomogeneities of the disk (0.29pc).Warped disk is the absorbing medium?

No Fe-K line detected (was in ASCA 1999). If lines comes from the disk why it has disappeared while masers have not changed?

A Quasar Primer



The "unified" model of AGN

- Several phenomenological elements are added *ad hoc* to the naked quasar model to explain the observational data.

- All AGN are intrisically "equal" (a part from a small number of physical paramenters eg L) but they appear different because of orientation effects (eg observer-dependent)

Typical Scales

BH=10^{-5} pc

Disk (x-ray) ~ few* 10^{-5} pc

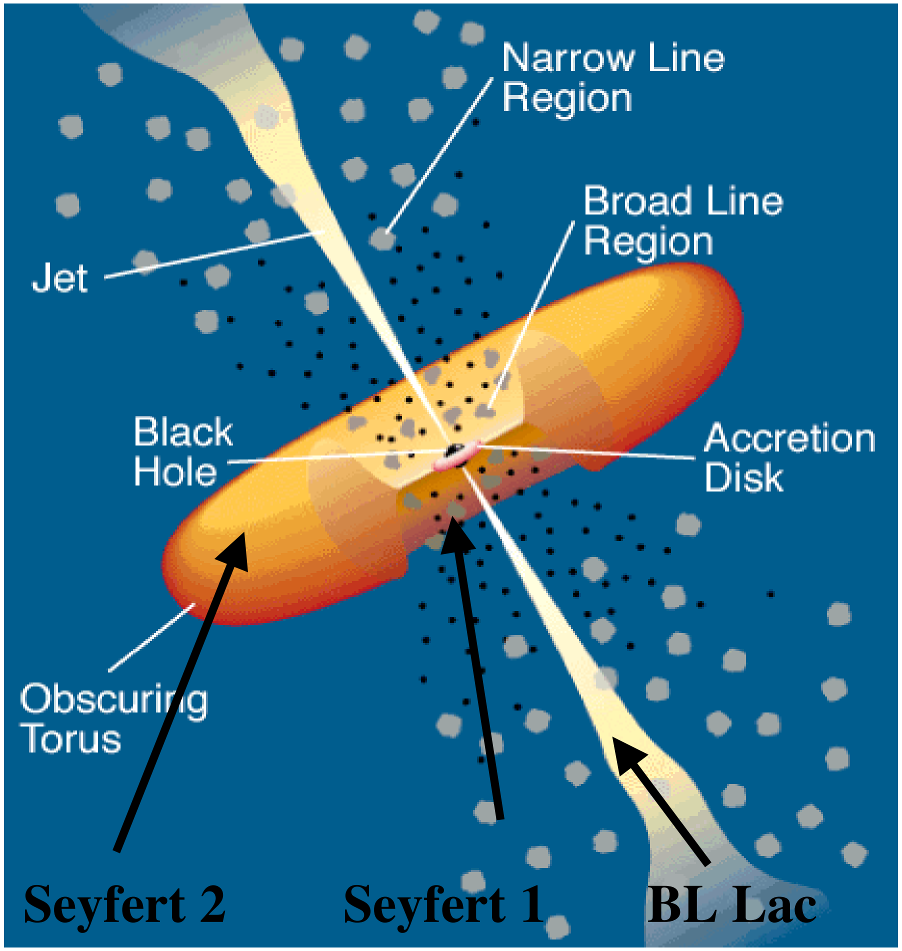
Disk (UV) ~ 0.001pc

BLR ~ 0.01pc

NLR ~ 10^4-10^5pc

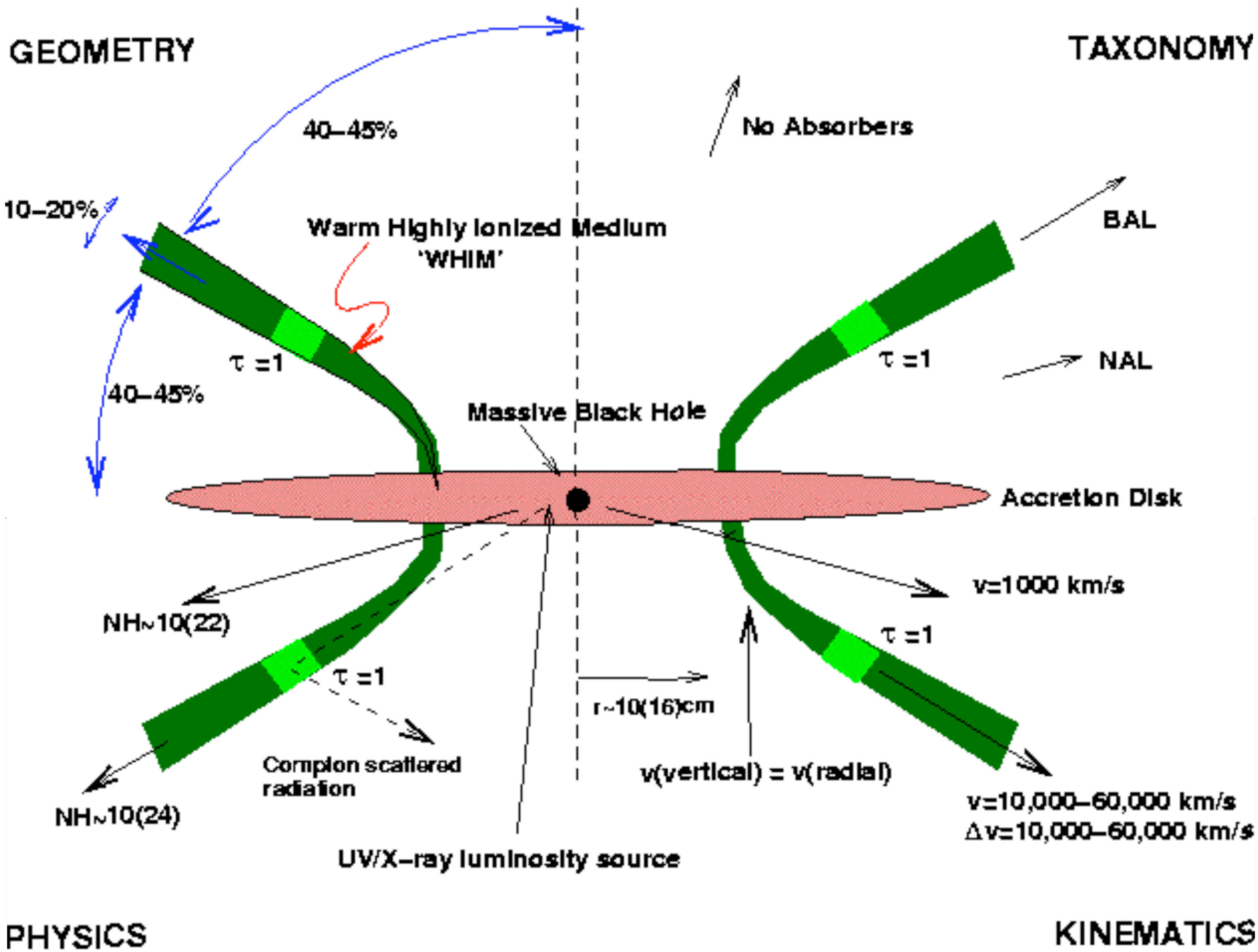
Jet > 10^5pc

Galaxy ~ 10^4pc

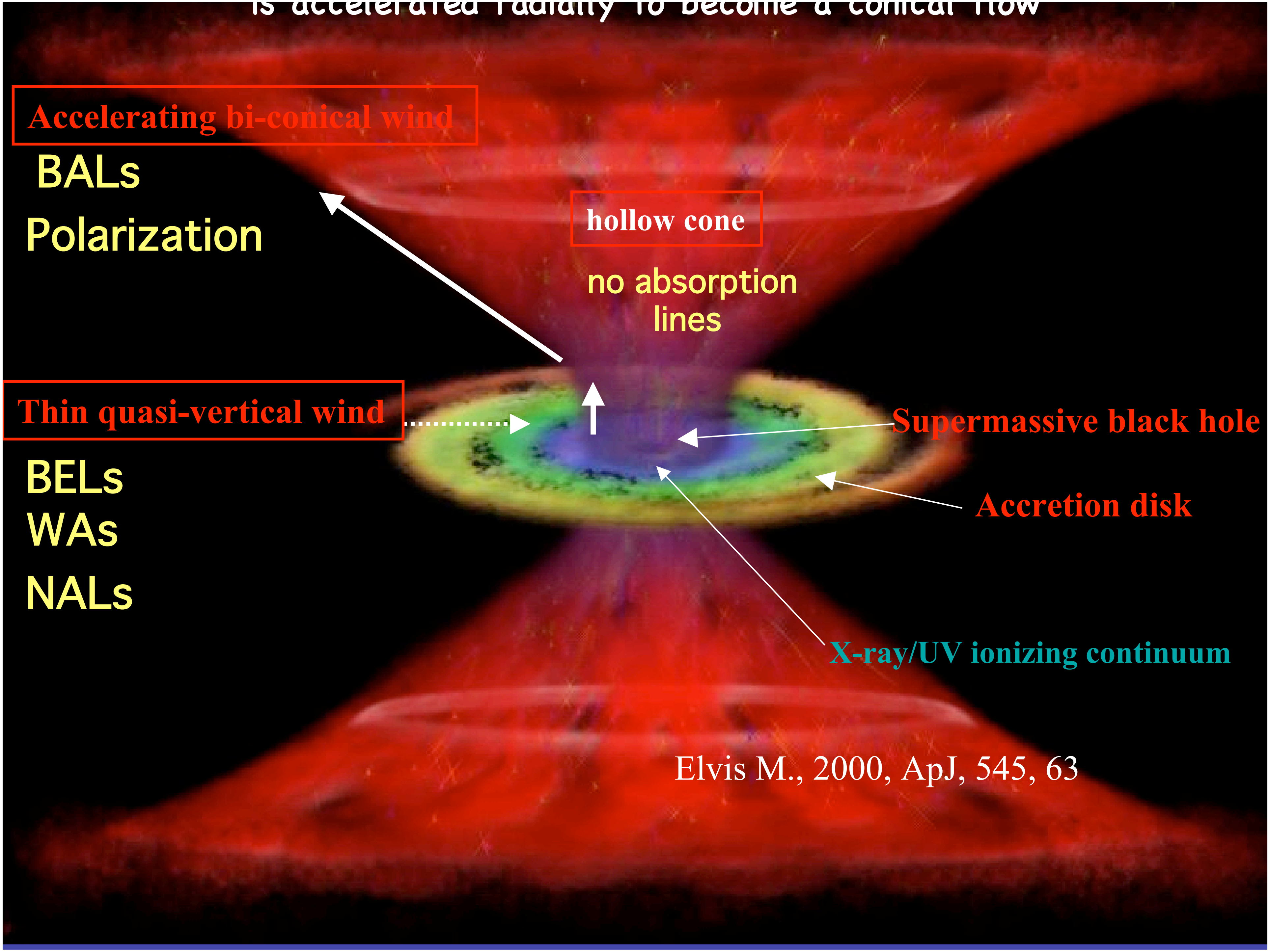


Urry & Padovani 1998

A Structure for Quasars



Elvis M. 2000 Ap.J. 545,63. (astro-ph/0008064)


is accelerated radially to become a conical flow
Accelerating bi-conical wind
BALs
Polarization
hollow cone
no absorption lines
Thin quasi-vertical wind
BELs
WAs
NALs
Supermassive black hole
Accretion disk
X-ray/UV ionizing continuum
Elvis M., 2000, ApJ, 545, 63

How can X-rays help our understanding of AGN?

Two fundamental clues:

- *Thermal emission from very hot gas: 10^5–10^7 K*

  => hot gas is there!

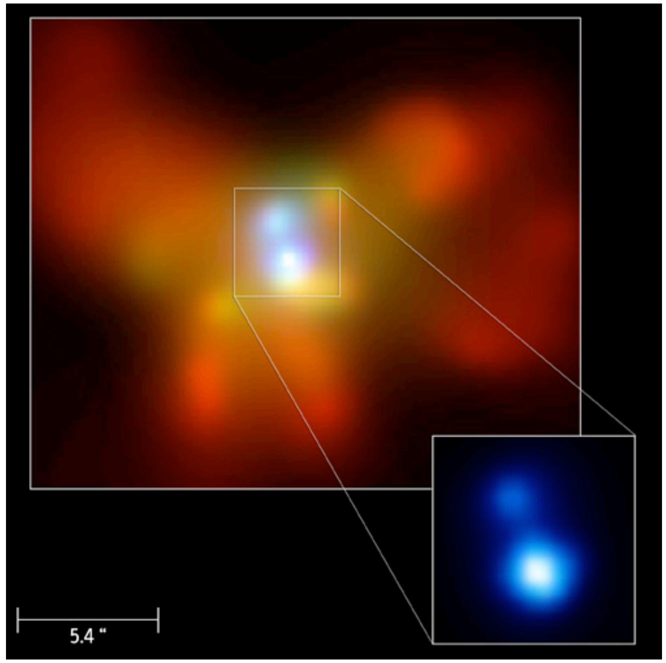
- *Non-thermal emission: synchrotron, Comptonization*

  => relativistic plasma!

…and from X-ray data we can learn about

- X-ray emission regions:
  - Nucleus – unresolved component
  - Extended emission on different scales: parsec to hundreds kpc
  - Jets and radio lobes
- Absorption properties:
  - Amount of absorbing material
  - Outflow/Inflow velocity
  - Cold/Warm absorbers
  - Ionization State
  - Abundance
- Variability:
  - Scale/Size of the emitting and reprocessing regions

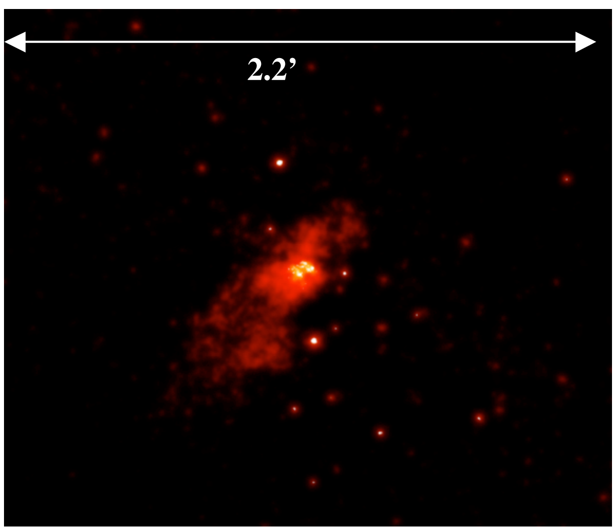
NUCLEUS: Chandra can resolve structures at 1 arcsec scale!



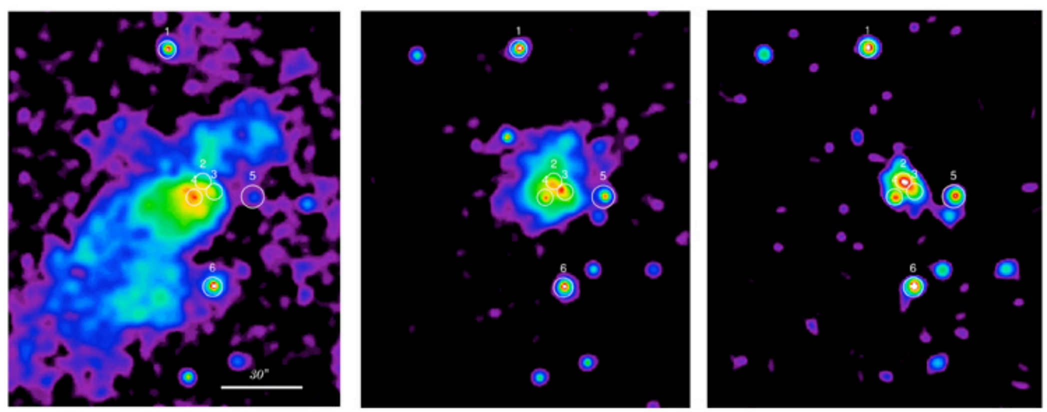
Credit:NASA/CXC/MPE/S.Komossa et al.

“The Chandra image of ***NGC 6240****, a butterfly-shaped galaxy that is the product of the collision of two smaller galaxies, revealed that the central region of the galaxy (inset) contains not one, but two active giant black holes.”(Chandra press release)*

NGC 253 *has at least six ultraluminous point sources, and Chandra shows that four of them are located within about 3,000 light years from the galaxy's core.*

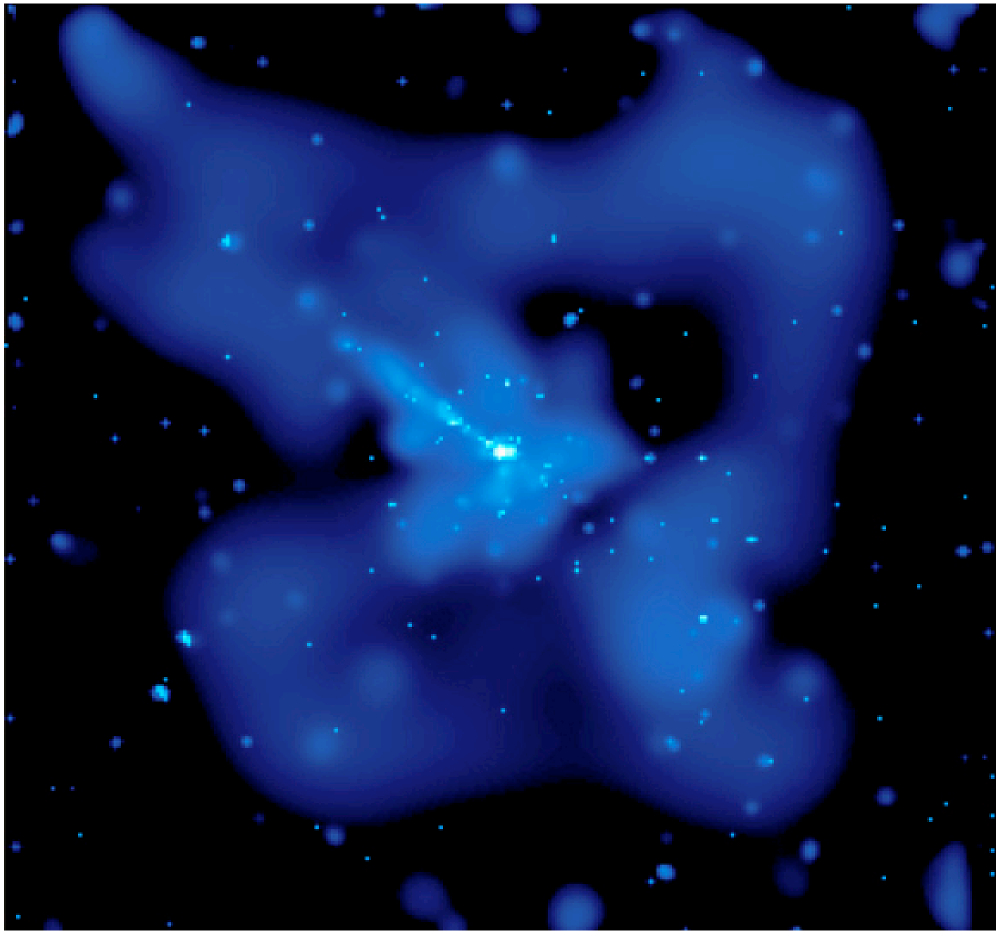


(Credit: NASA/SAO/CXC)



(Credit: NASA/GSFC/K.Weaver et al.)

X-RAY EXTENDED EMISSION

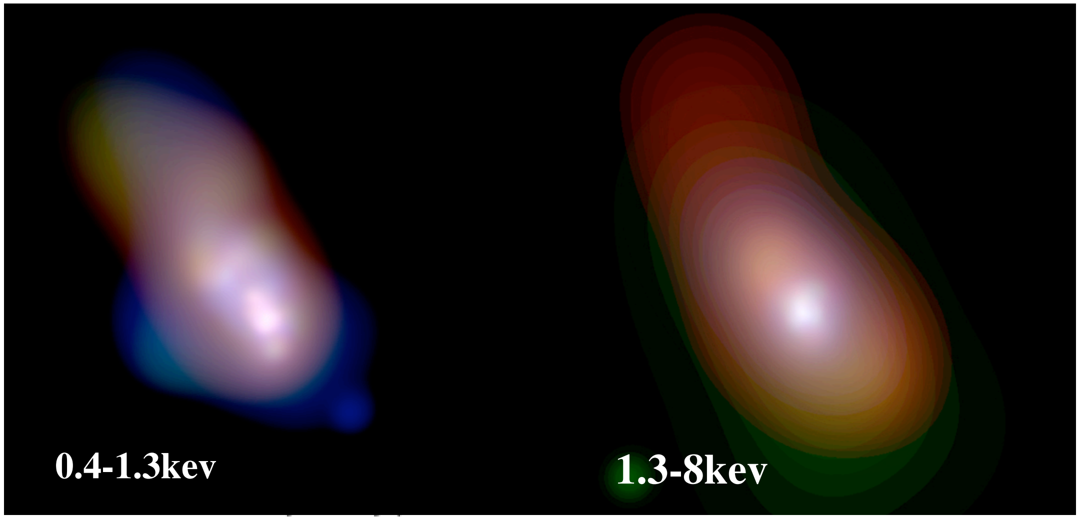


Karovska et al 2002

Centaurus A

- arclike soft X-ray structures, extending to ~8 kpc in the direction perpendicular to the jet.
- diffuse X-ray and the optical emission in the arcs could originate in a region of interaction (possibly a shock) between the infalling material from the outer regions of the galaxy and the cool dust and H I-emitting material in the center or from an equatorial outflow resulting from an outburst of nuclear activity ~10^7 yr ago.

Extended Emission: NGC 1068



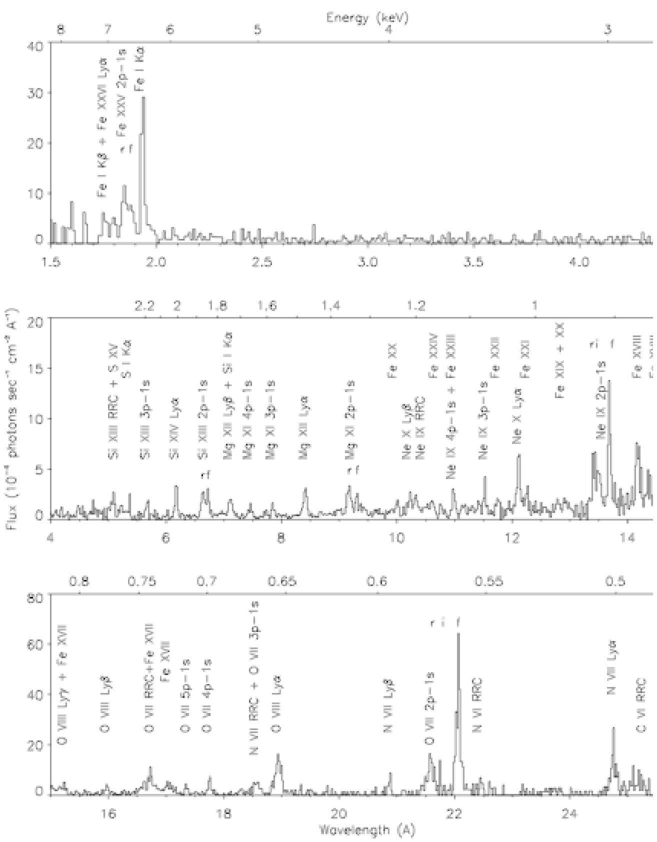


Fig. 1. *Chandra* HETGS spectra of the central 1."5 radius nuclear region. The top panel is from the HEG (0.005 Å bins); from MEG (0.01 Å bins). The strong forbidden emission lines (f) and narrow recombination continuum features (RRC) indicat following photoionization by the hidden nucleus. Fe I, Si I, and S I Kα emission lines indicate fluorescence from a low-ionizatio may be identified with the obscuring molecular torus.

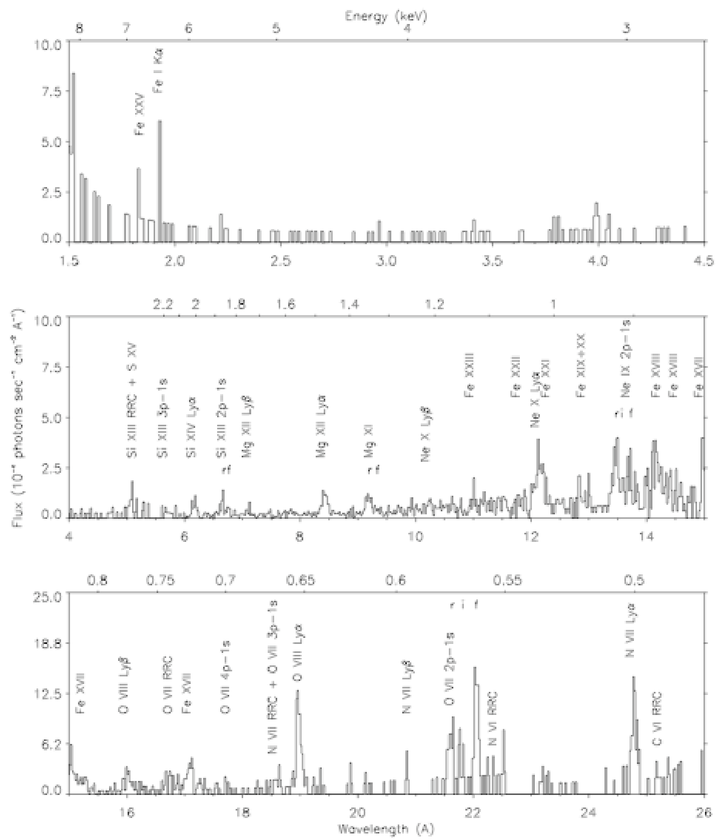


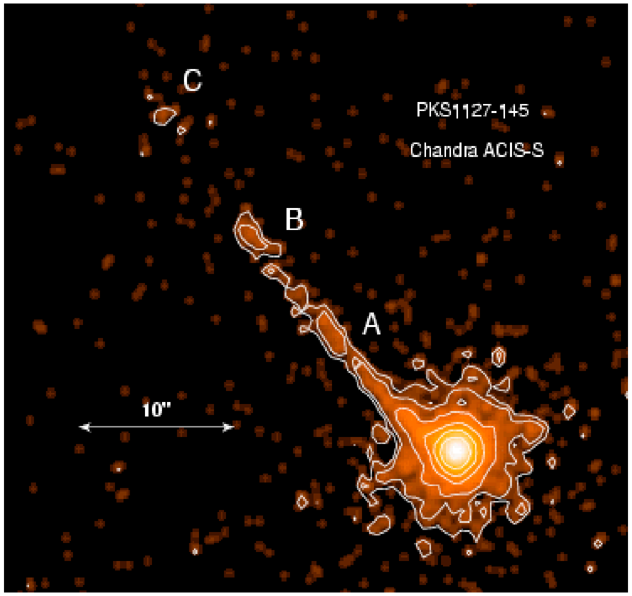
Fig. 2. *Chandra* HETGS spectra of the NE cloud, centered 3."1 NE of the nucleus. Binning is the same as in Fig. 1. The forbidden lines (f) and RRCs are weaker than in the nuclear region (Fig. 1), due to lower column density. The H-like and He-like resonance lines are relatively stronger from photoexcitation. The Fe L emission lines are stronger, indicating a greater Fe abundance. Fe Kα emission is weaker because there is relatively little neutral matter in this region.

X-RAY JETS

- Many Chandra observations revealed X-ray jets associated with quasars: => jets are common phenomena.
- Some jets were discovered in quasars where there was no previously known radio jet emission. Examples: PKS 1127-145, B20738+393
- Relativistic motion at hundreds kpc distance from the quasar!
- Comparison of X-ray, optical and radio data rules out thermal emission, SSC and simple direct synchrotron emission as primary source of the X-ray emission.

Siemiginowska et al 2002

PKS 1127-145 z=1.187



CHANDRA ACIS-S

PKS 1127-145

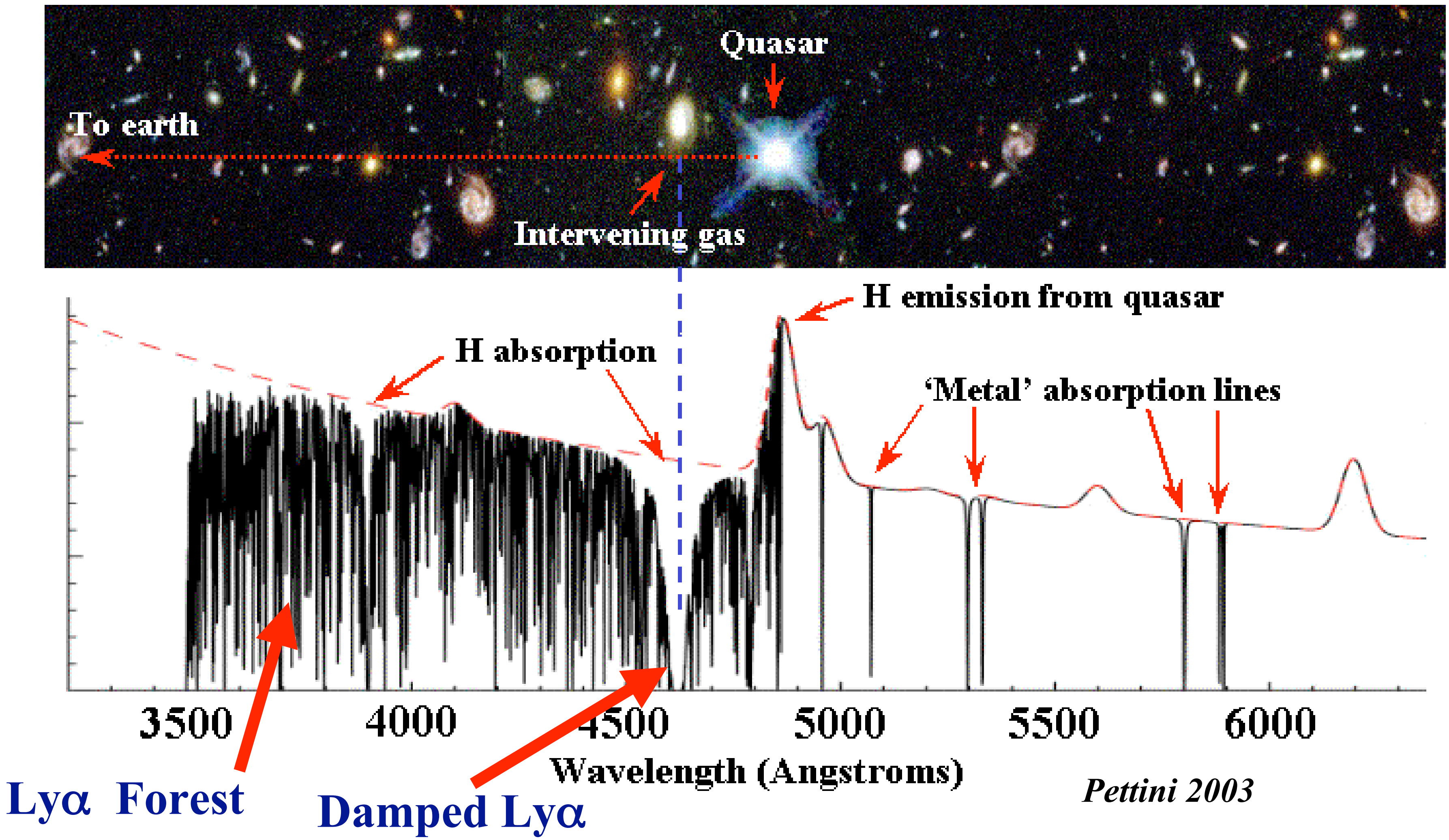
- X-ray jet is ~ 30 arcsec long => $330h_{50}^{-1}$ kpc at the quasar redshift.
- The jet curves;
- The ratio of individual knots to the core is ~ 1 : 260 − 460.

$f_{2-10keV}(core)$=2.41 × 10^{-12} ergs cm^{-2} sec^{-1}

$f_{2-10keV}(A)$=9.3×10^{-15} ergs cm^{-2} sec^{-1}

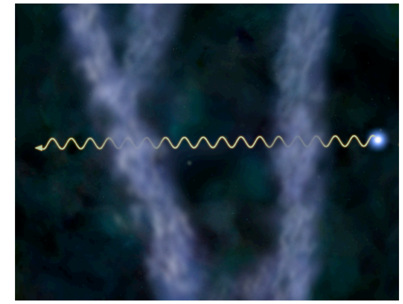
Absorbers and Outflows

Optical/UV Absorption due to IGM
=> Studies of Matter in the Universe



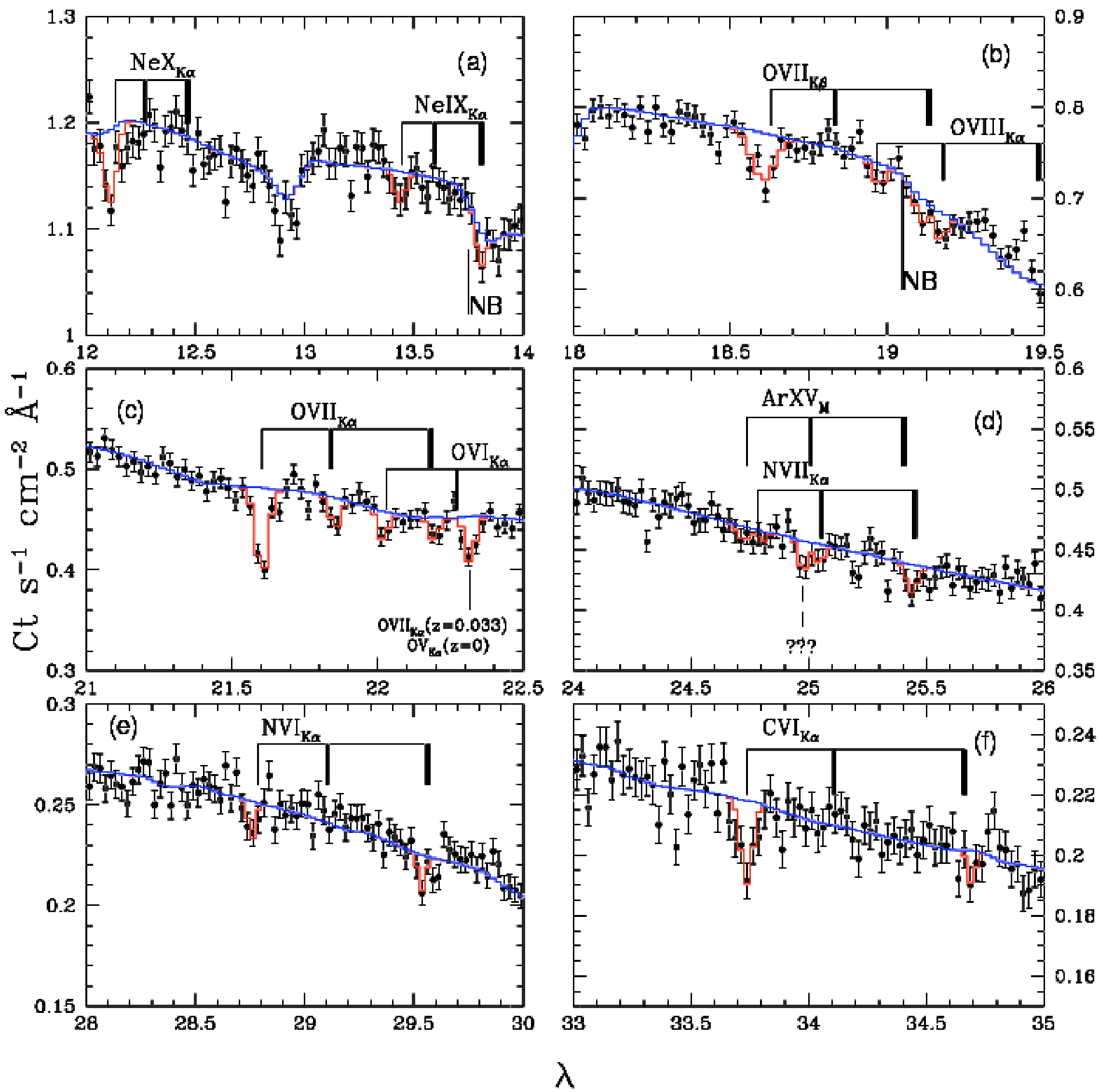
Pettini 2003

X-RAY ABSORPTION: the intergalactic medium



Credit:CXC

Nicastro et al. 2005



Mrk 421 (z=0.03) observed by Chandra ACIS/HRC-LETG as a powerful "background" light source.

X-ray emission absorbed by intervening filaments of gas - the warm-hot intergalactic medium (WHIM)

Detection two intergalactic ionized absorbers at redshifts z=0.011 (NVII,OVII,OVIII) and z=0.027 (CIV,NVI,NVII,OVII and NeIX)

X-ray Absorption: Ionized Gas close to the nucleus

X-ray reprocessing and **absorption** are the processes generally invoked to interpret deviations from the power-law form of the AGN spectra in X-ray.

Many AGN show absorption edges of ionized oxygen (OVII and OVIII) characteristic of optically thin, photoionized material along the line of sight - the so-called "warm-absorber".

BUT there are other interpretations…

At the center of the controversy one of the most studied AGN: MCG-6-30-15

Branduardi et al. 2001

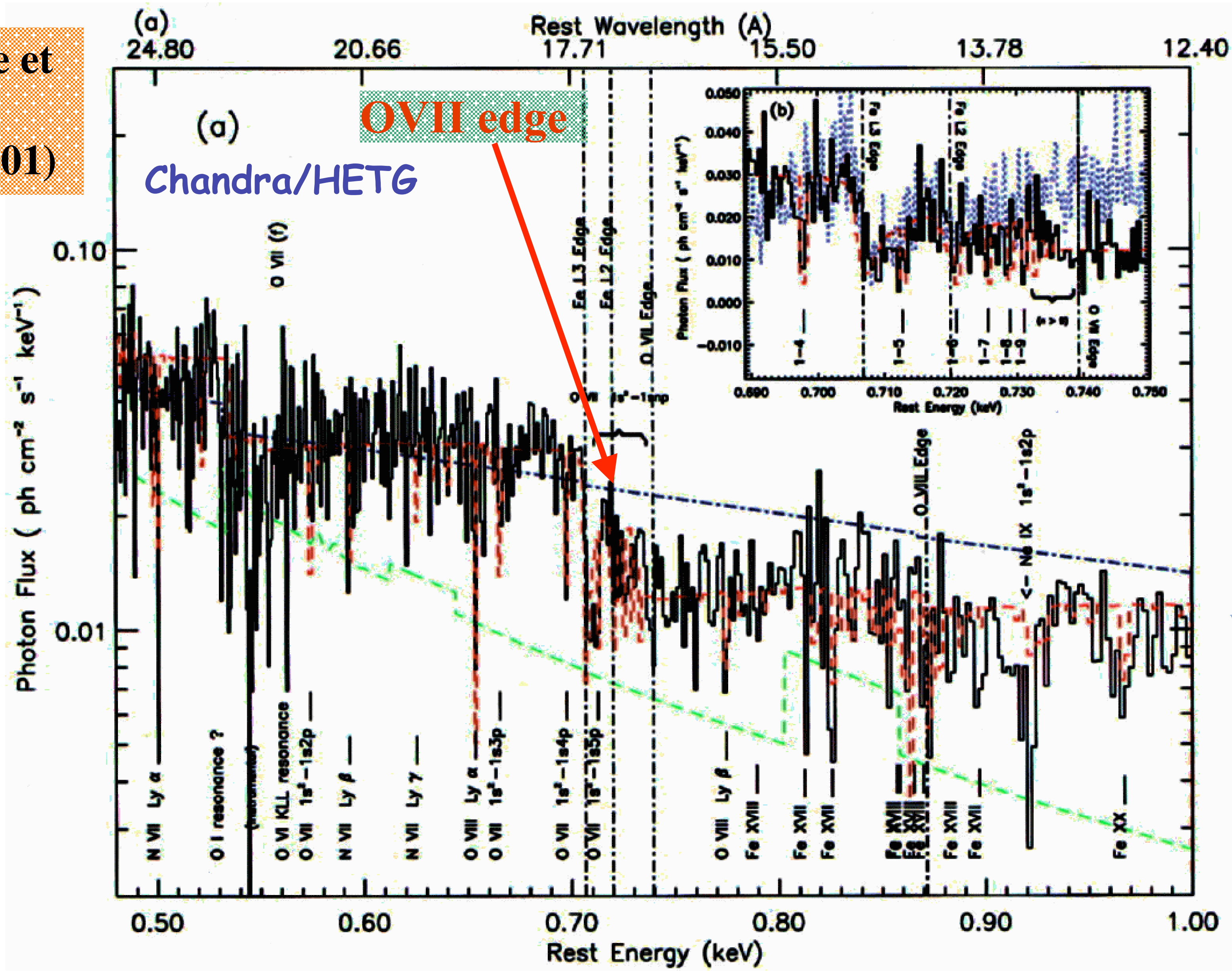
Lee et al. 2001

Our *Chandra* HETG spectrum of MCG–6-30-15 shows that a dusty warm-absorber model is not only adequate to describe all the spectral features $\gtrsim 0.48$ keV ($\lesssim 26$ Å), the data *require* it.

from a relativistic disk surrounding a maximally rotating Kerr black hole seems to explain the data remarkably well. The physical self-consistency of this scenario remains

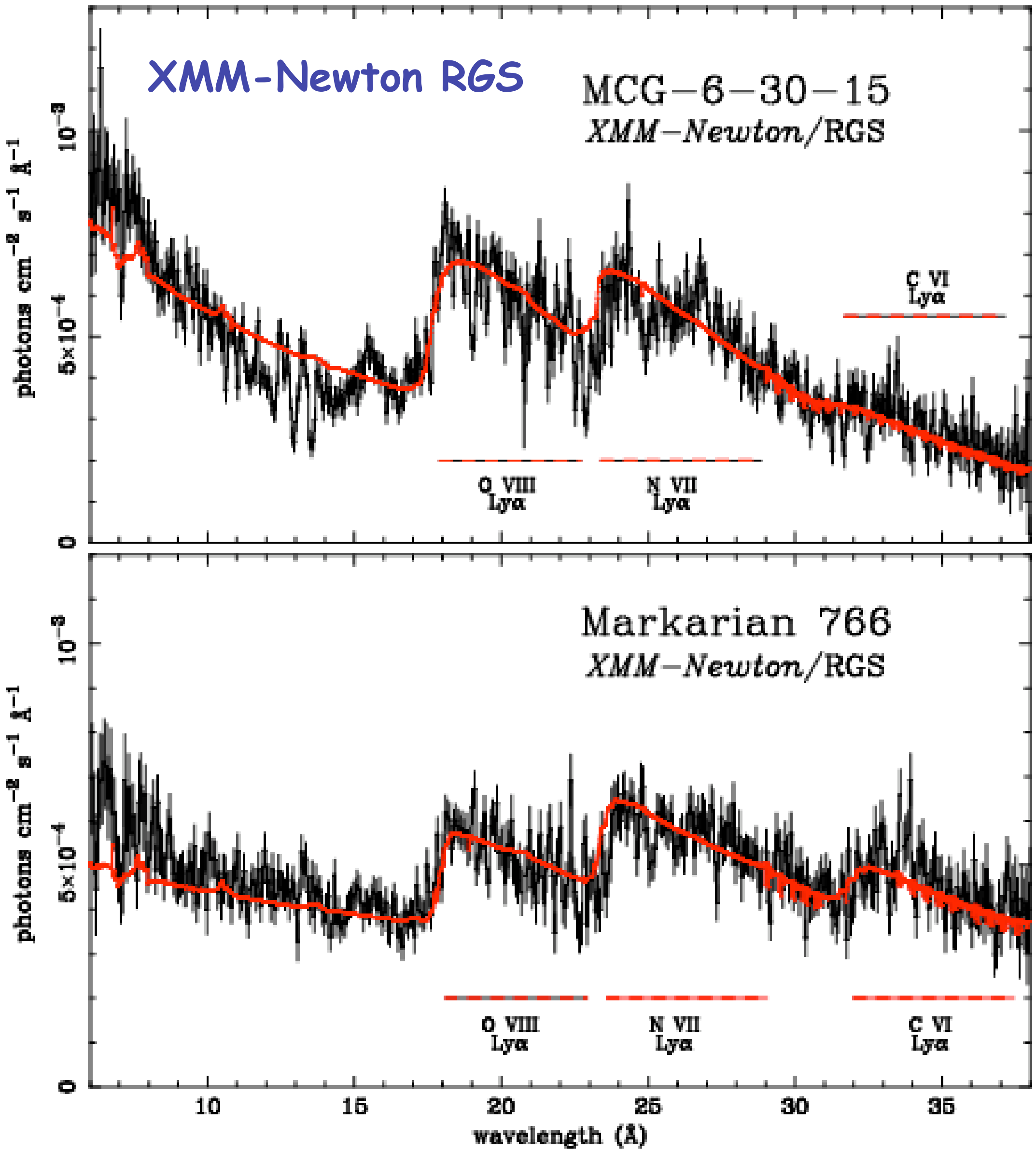
Dusty Warm Absorber in MCG 6-30-15?

Lee et al (2001)

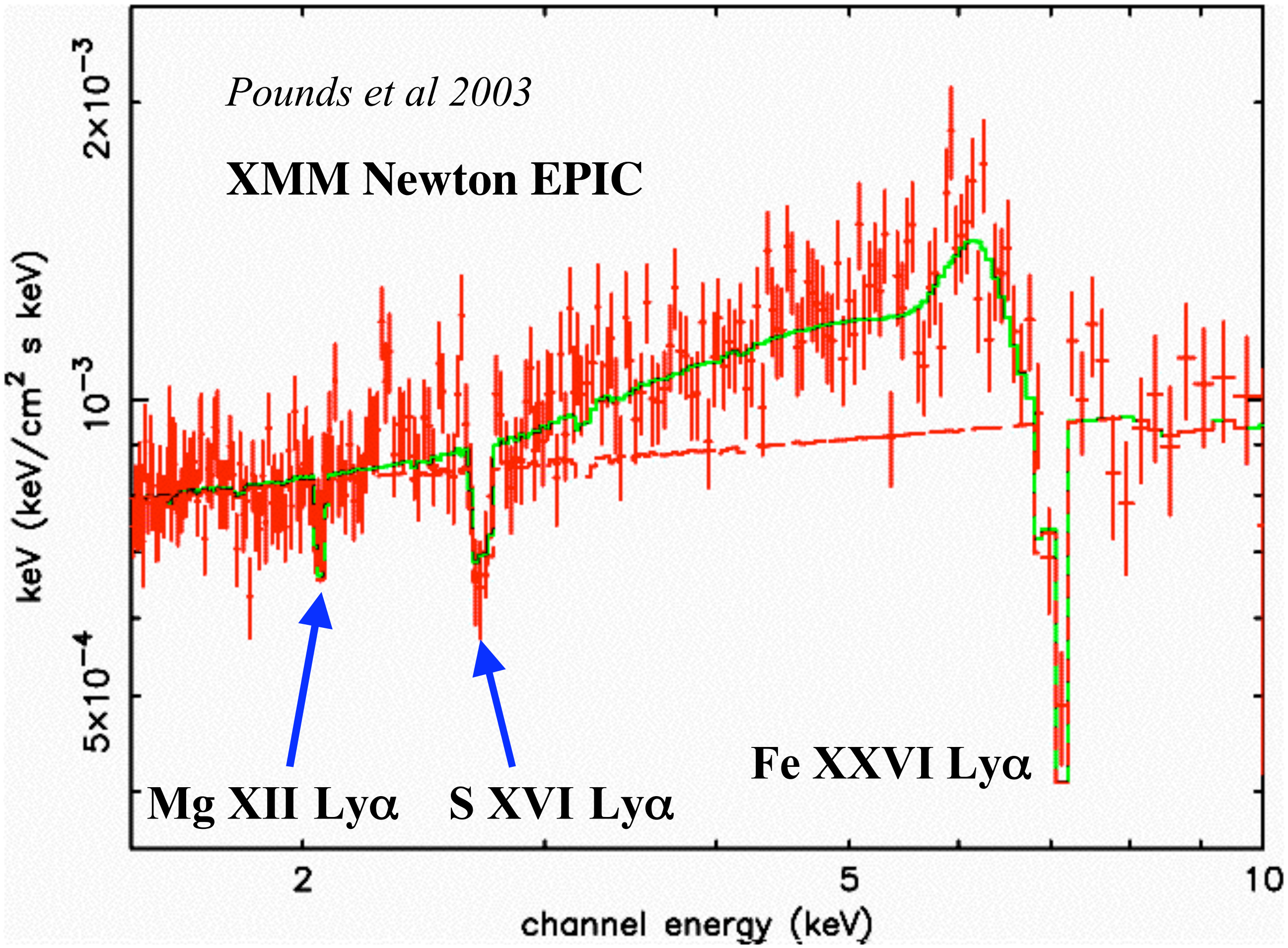


Broad O VII,VIII Emission Lines in MCG 6-30-15?

Branduardi-Raymont et al (2001)



X-Ray absorption: High velocity outflow in PG 1211+143

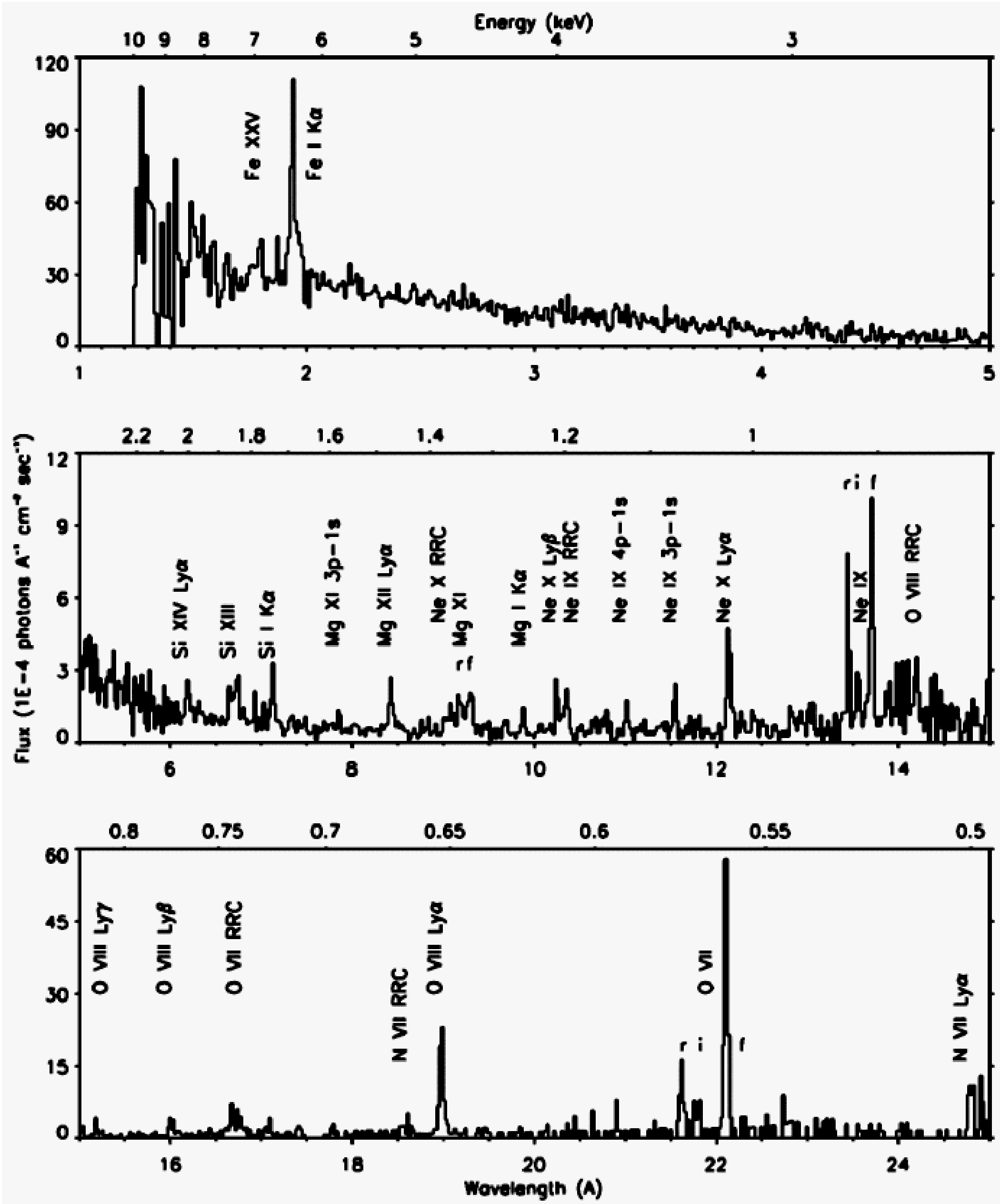


Velocity of outflowing ionized gas based on observed line broadening ~ 0.09-0.1c

Emission Lines

- ***Originate in the nucleus:***
  - ***Accreting matter***
  - ***Relativistic broadening – Fe-line***
  - ***BLR clouds***
- ***Originate in the hot gas away from the nucleus – NLR in Seyfert 2***

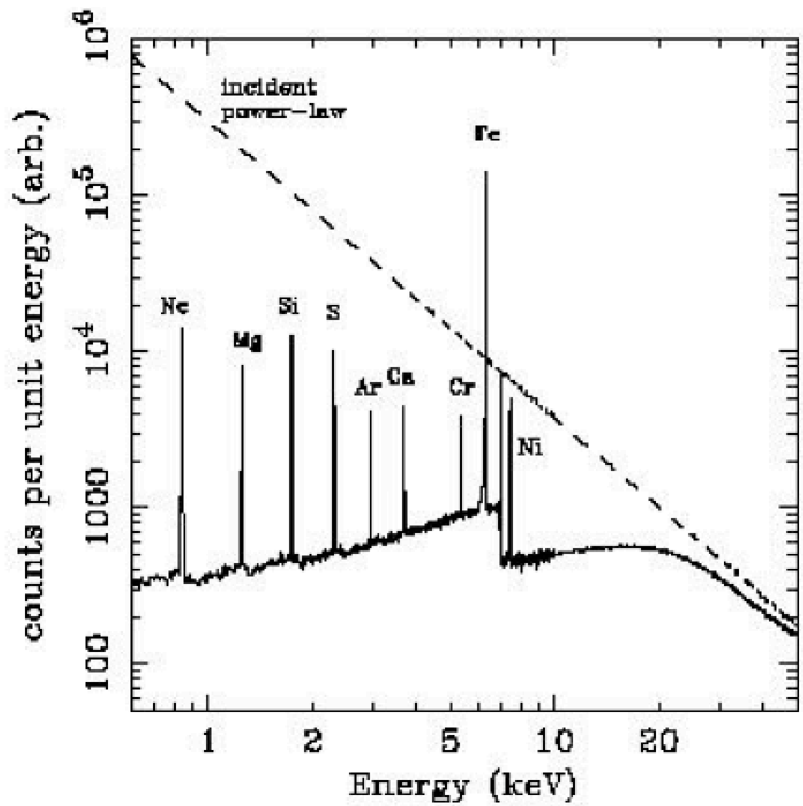
The Narrow Line Region: NGC 4151



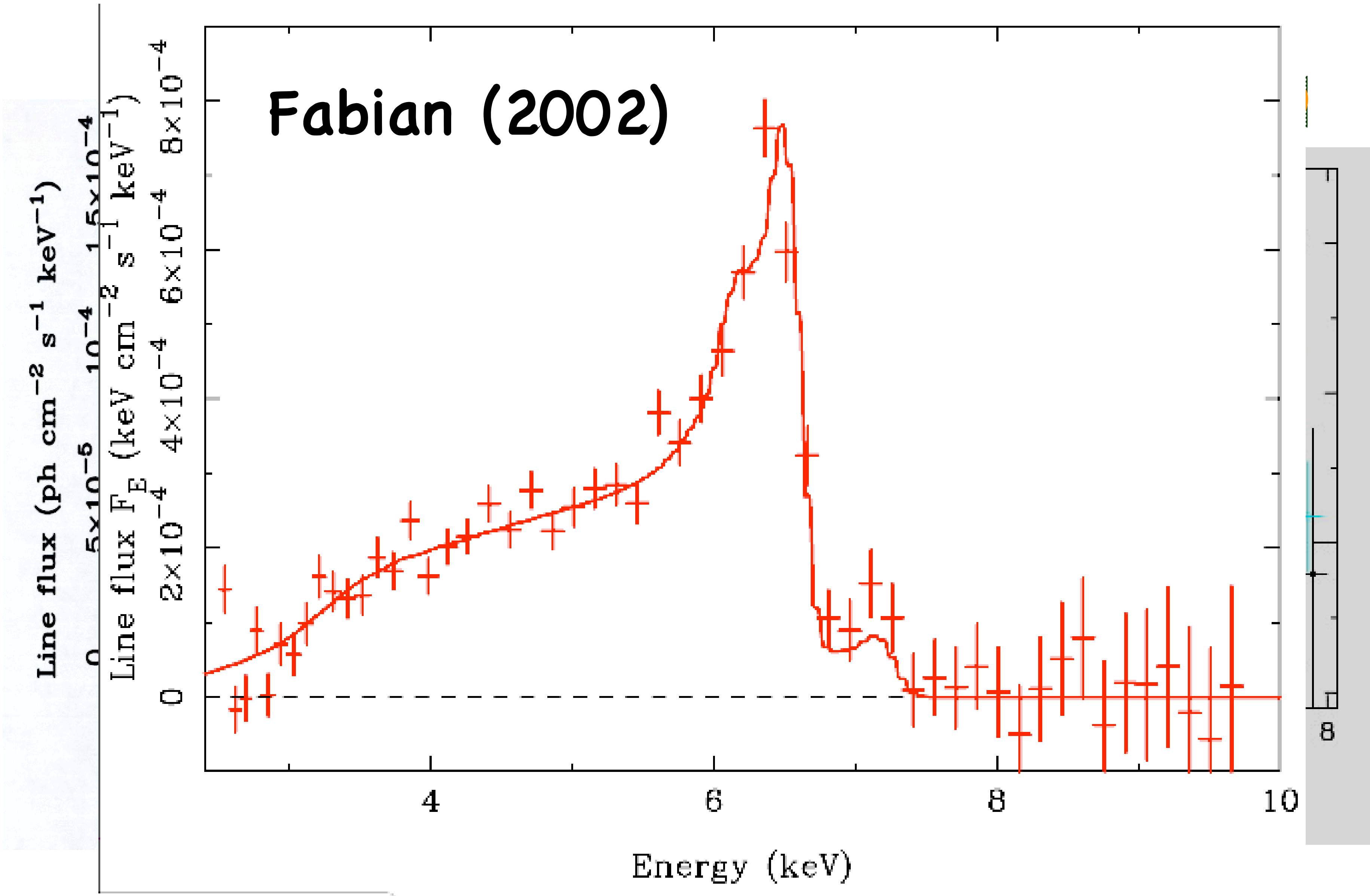
- Direct emission from nucleus highly absorbed - good view of NLR
- Weak hard continuum (absorbed?)
- Emission lines from 1.5kpc ionized nebula
- X-ray NRL is composite - both photoionized and collisionally ionized components
- First direct evidence of the hot ($\sim 10^7$K) plasma that may provide pressure confinement for cooler (3×10^4K) photoionized clouds

Reflection components

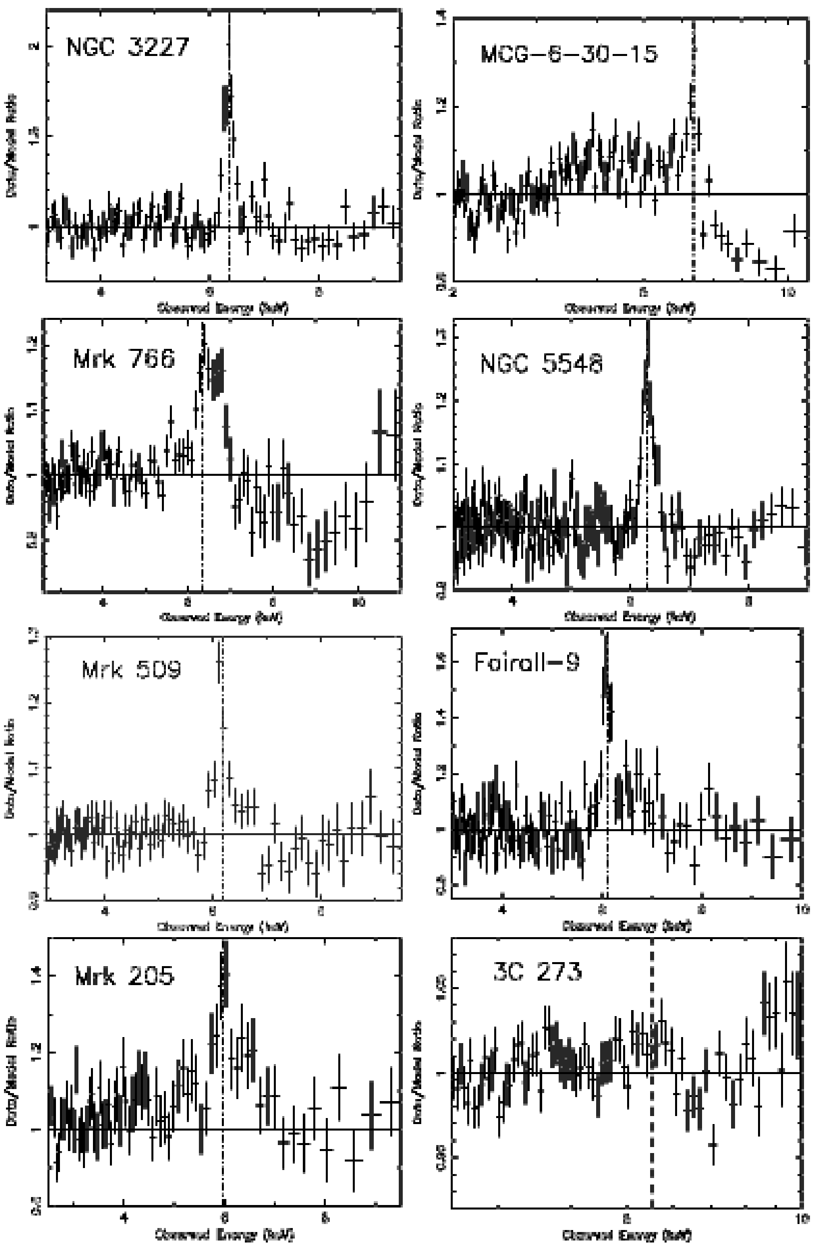
- Substantial power in AGN emitted as X-rays from disk corona in active or flaring regions
- Flares irradiate the accretion disk, which is relatively cold, resulting in the formation of a “reflection” component within the X-ray spectrum
- Incident photons are absorbed, scattered or reprocessed into fluorescent line photon
- Spectrum has a broad humplike shape + emission line, mostly fluorescent K lines. The iron K line at 6.4 is the strongest of these lines
- Narrow Fe K emission lines are common in Seyfert 1 galaxies. Interpreted as fluorescence from cold material, but location is still debated
- Broad Fe K line seen in some objects (MCG-6-30-15 is the prototype!) and the broadening is explained as a relativistic effect with the line originating very close to the central BH



A case for a broad line in MCG 6-30-15?



XMM- Newton Observations of Fe-line in Type 1 AGN



MCG 6-30-15

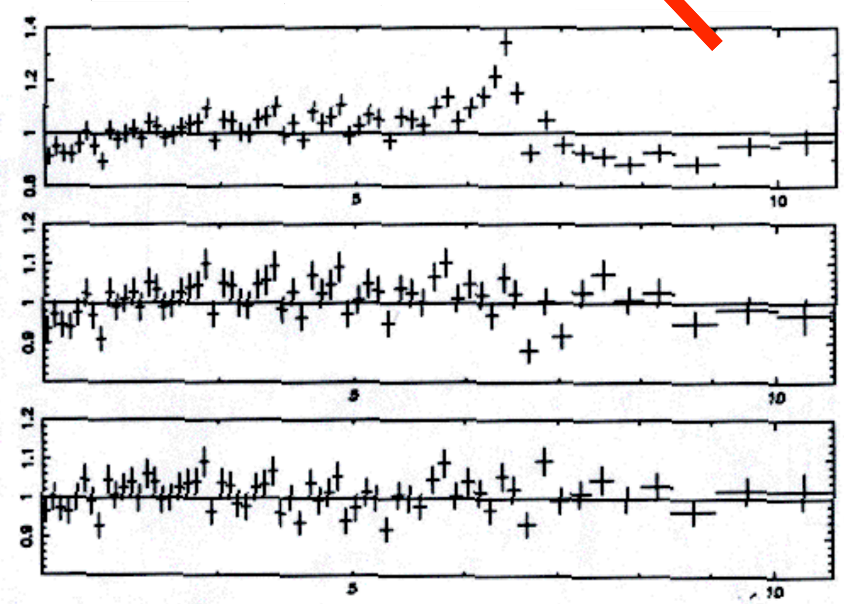


Figure 5. Data/model ratio plots for fits to (a) a power law, (b) a power plus narrow Fe K line and absorption edge, (c) a power law, absorption edge plus narrow and broad Fe K lines fit to the MCG-6-30-15 EPIC data

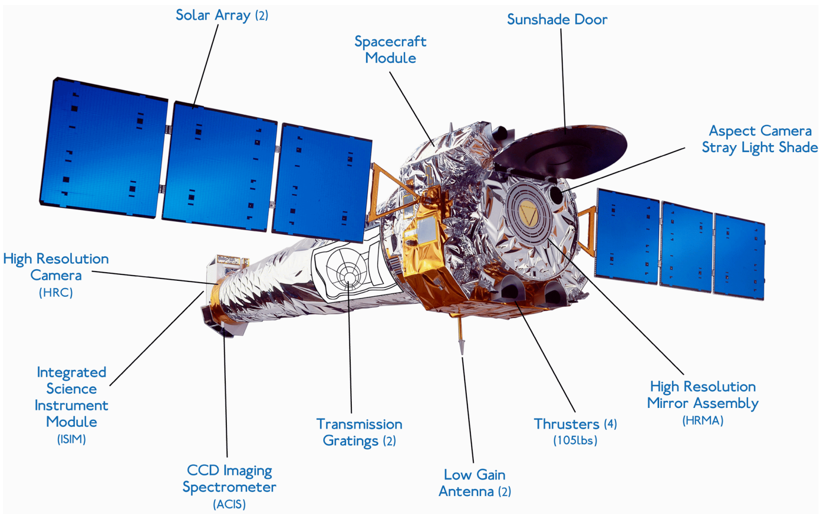
XMM-Newton
EPIC-PN

Reeves 2002 (astro-ph/0211381)

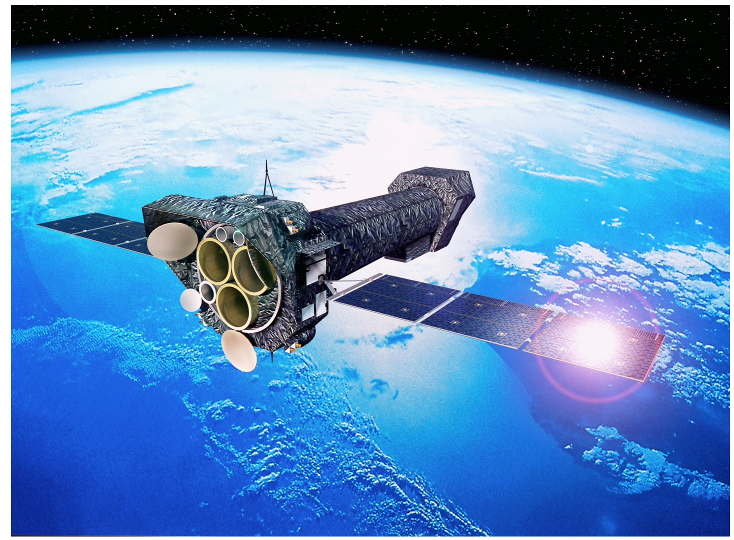
Now what do I do with my AGN data?

Most likely you will analyze data from

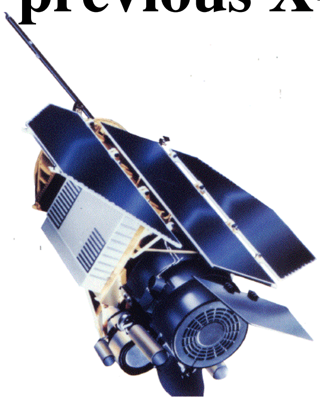
C
H
A
N
D
R
A

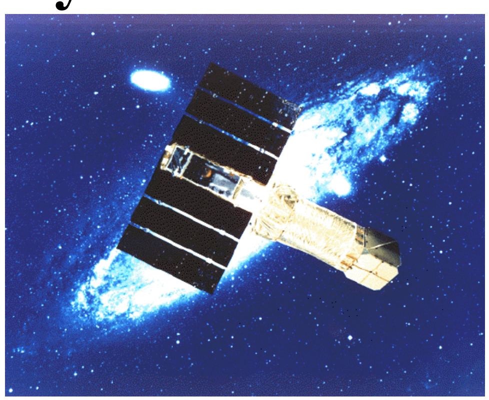


X
M
M



But many times you will have to compare your finding to those of previous X-Ray missions…

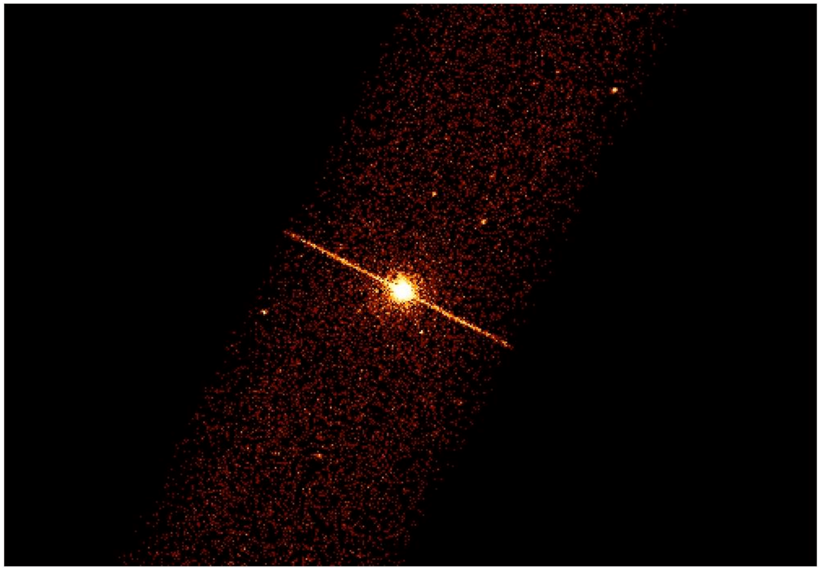


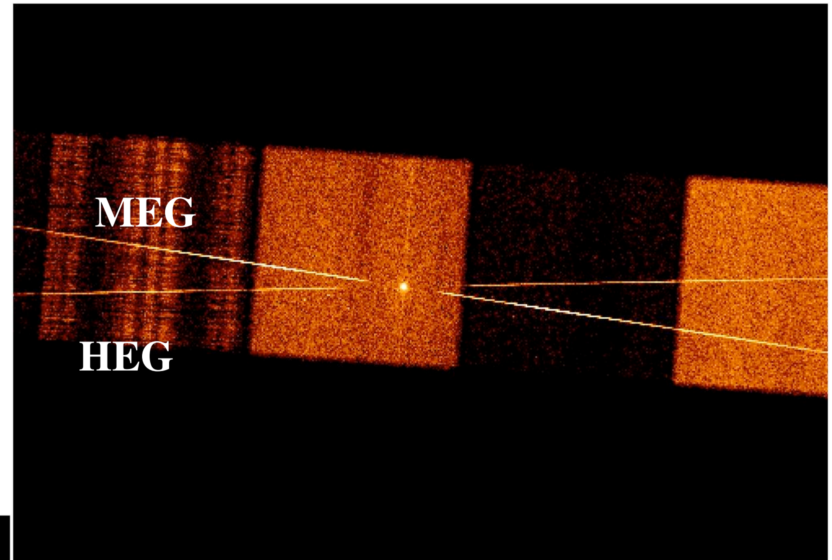


What will your data look like? The NGC 4051 example:

CHANDRA

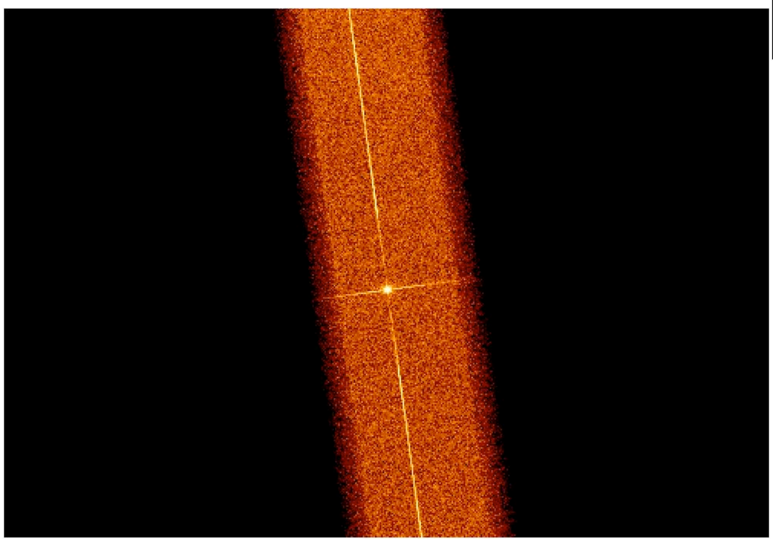
ACIS-S no grating: readout streak, small window for pileup, other sources





HRC-S+LEG:

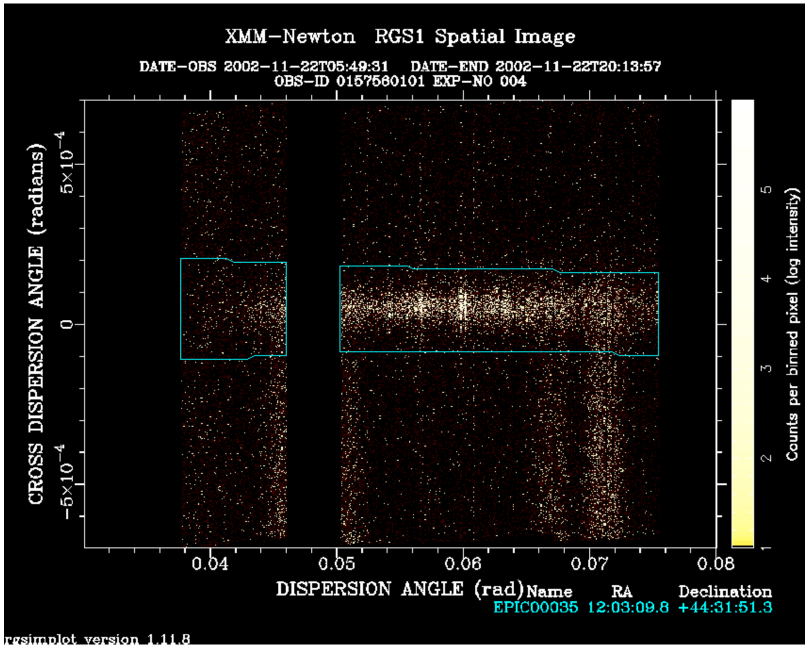
note support structure

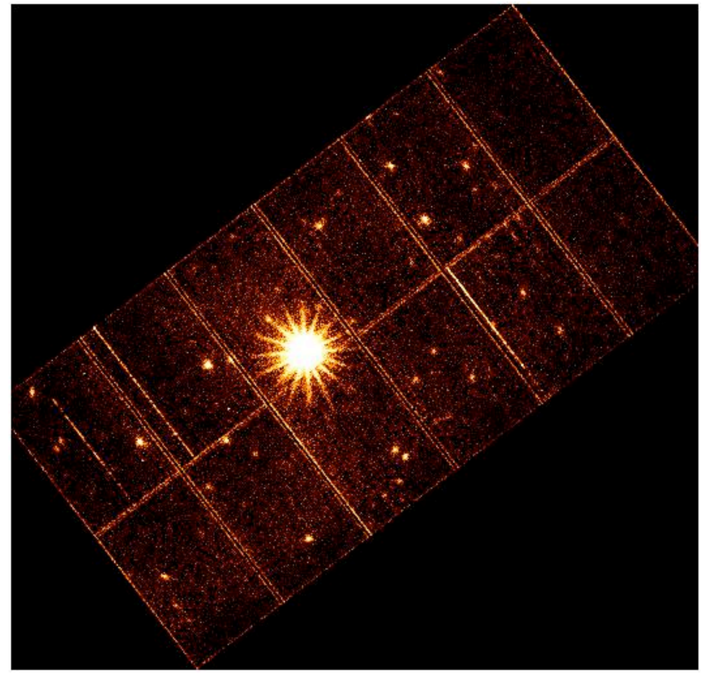


ACIS-S+HEG/MEG gratings: note grating arms, MEG has larger effective area, zero order image on S3, different background on different chips, “streaking” effect on S4

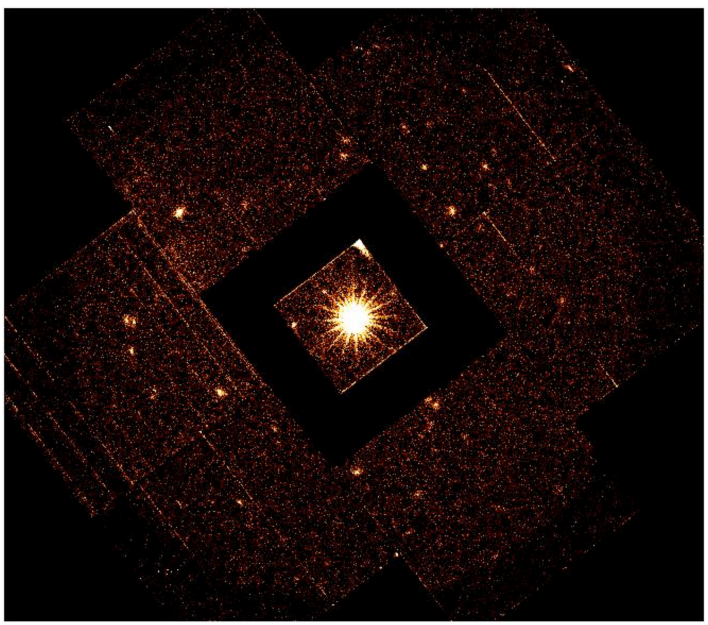
XMM

RGS1:note the background, extraction region, failing chip





EPIC: 12 chips, many additional sources



MOS1: observation in "Prime Partial" mode to mitigate pileup effects

PHA FILES

- For spectral analysis in all cases the end product we are looking for is either multiple type I or a type II "PHA" file(s): basically a *histogram of counts as a function of wavelength/energy*.

- PHA files come from:
  - the archive
  - a "reprocessing" (retrace the steps performed by the pipeline) from "raw" data.

- Depends on:
  - Observing date
  - calibration changes
  - are you interested in the default source
  - do you want non standard extraction regions etc.
  - Multiple sources

INSTRUMENTAL RESPONSES

- Instrumental responses (ARF and RMF) need to be derived (or obtained from calibration databases) for the source. They might depends on:
  - the position of the source on the detector
  - the aspect solution
  - the operating mode of the telescope
  - the epoch of the observation

- For grating data the RMF is a representation of the Line Response Function (LSF) or line profile.

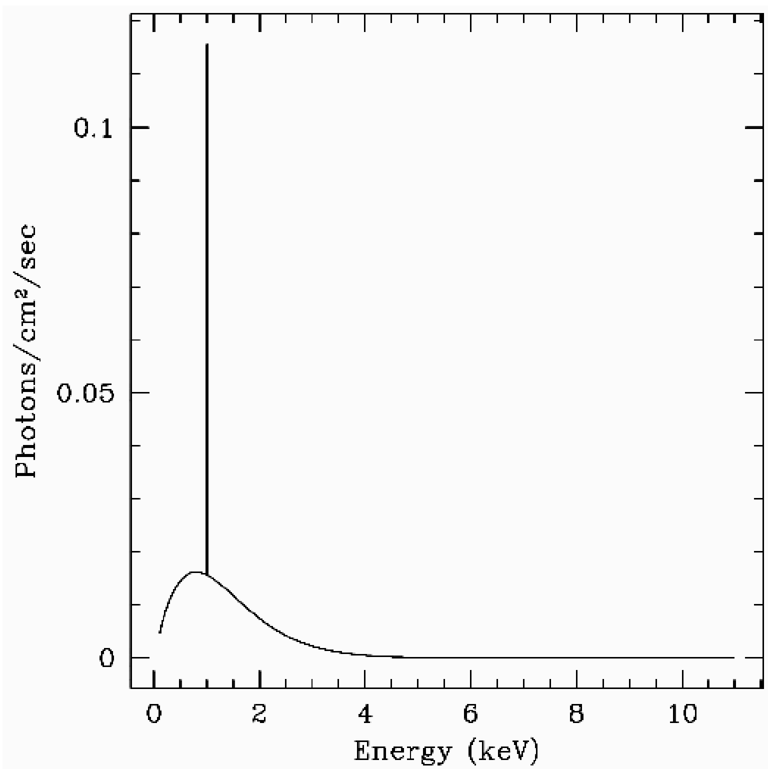
- With high-resolution data, it is not always necessary to use the RMF. If only the integrated flux is of interest, and there are no instrumental features within a spectral feature, then it suffices to divide the counts by the ARF (like for an optical spectrum)

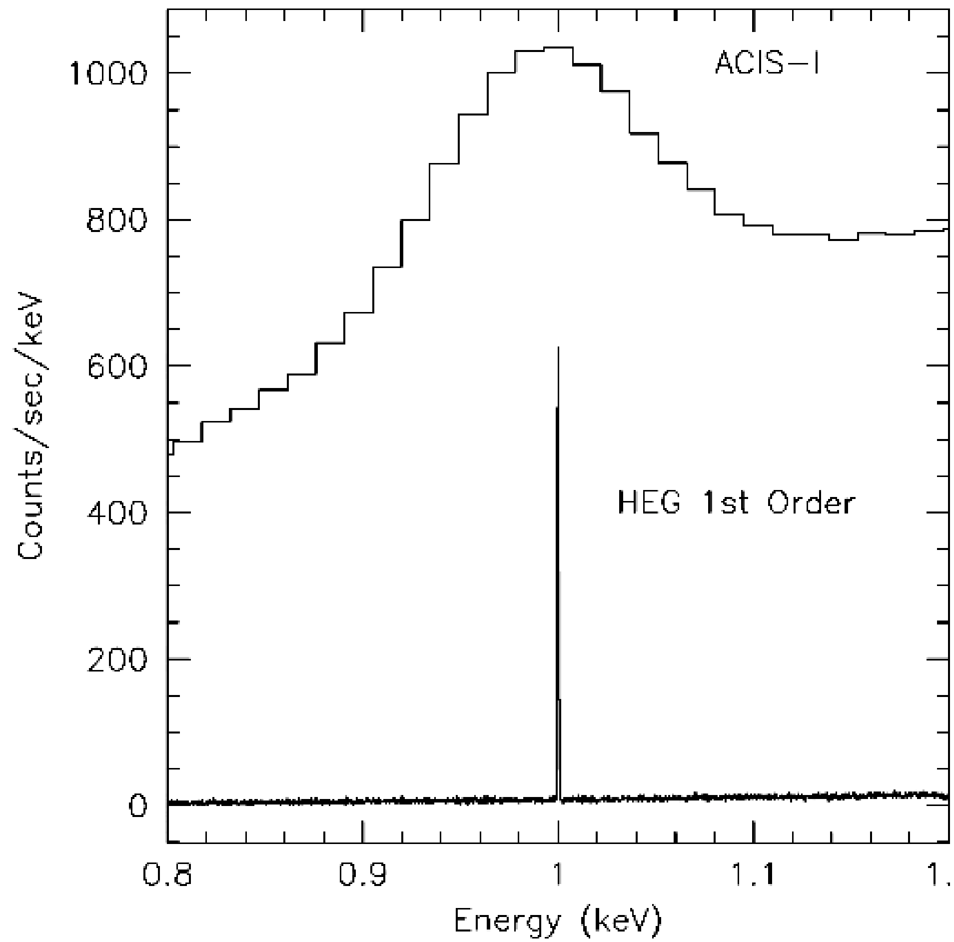
However…

- For the XMM RGS the wings of the LSF are very broad. You would make a mistake without the RMF

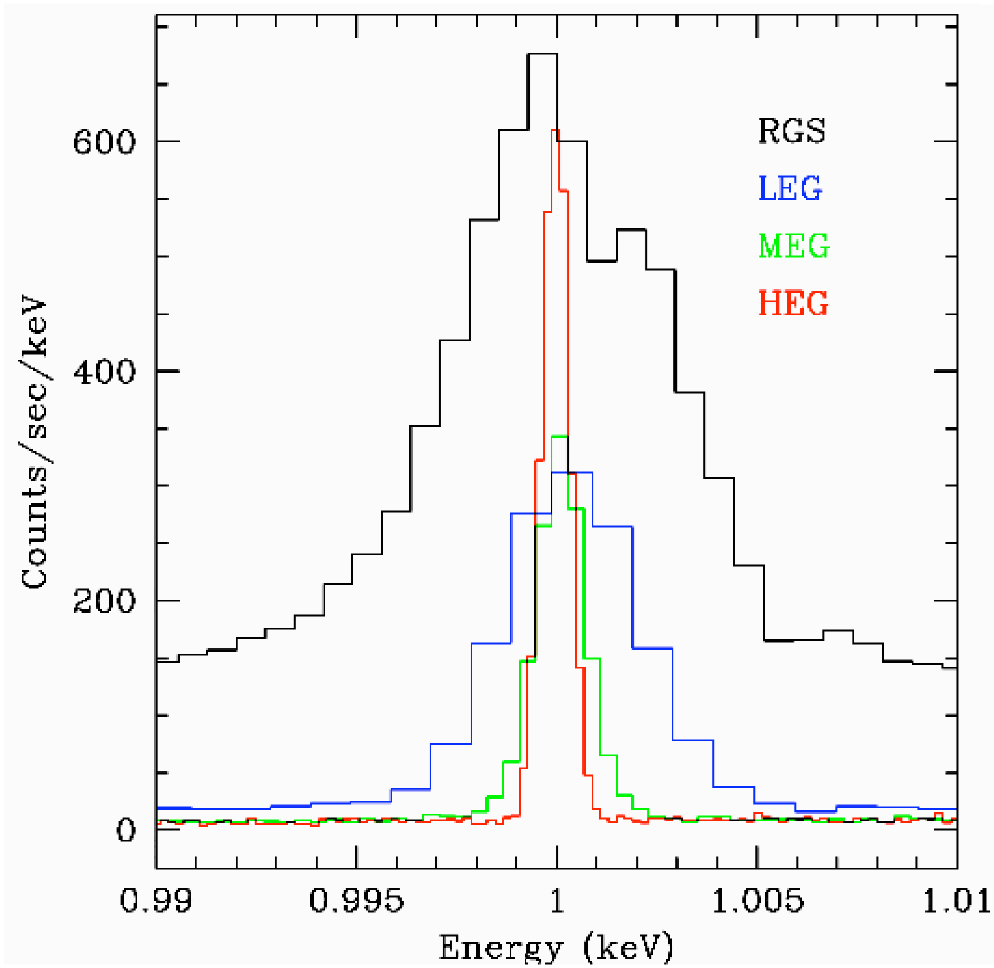
So, what can we do with grating data that we can't with CCDs?

Consider a line at 1.0 keV (12.398Å), on top of a 0.5 keV blackbody





Now consider the same spectrum observed by each of the four gratings:



If this data were fit assuming a pure Gaussian response, the scattering wings of the RGS would mean we'd measure only 1/2 the true power!

AND FINALLY…

- Load the data/responses into
  - Sherpa
  - XSPEC
  - SPEX
  - Other
- Define a source model (physics goes here)
- Fit your data
- Publish yet another paper on AGN!