Accretion History of the Universe

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Talk Outline

Introduction to X-ray Astronomy

Outlook of X-ray Emission processes

Instrumentation and the X-ray missions

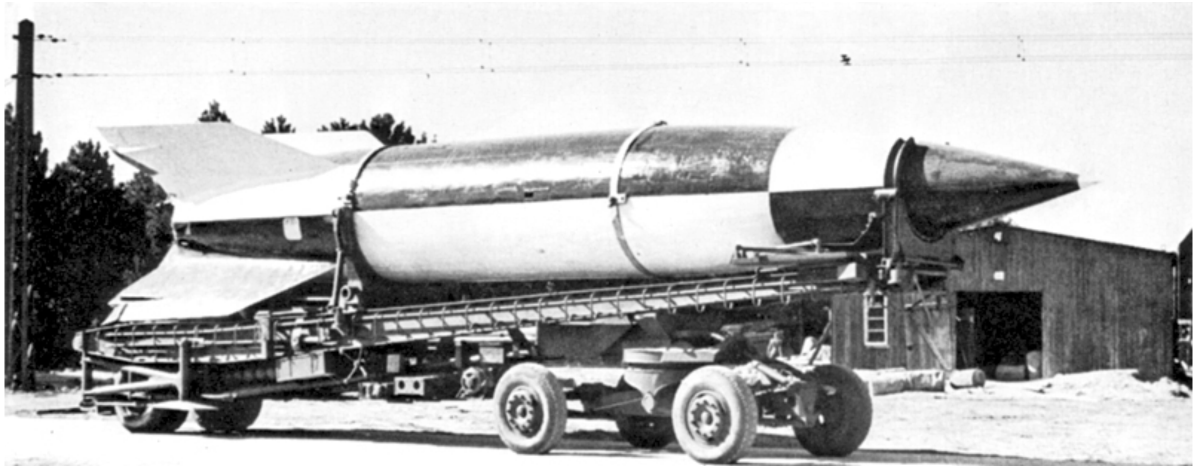
X-ray Surveys: Data & Tools

History of X-ray Astronomy

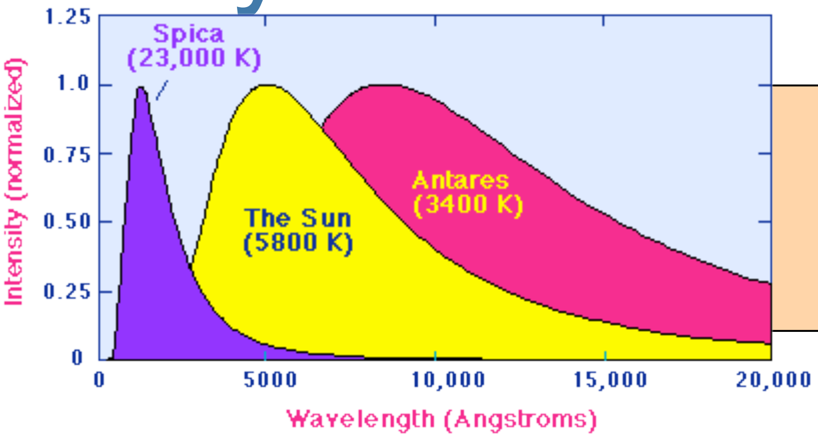
The Earth's atmosphere blocks all X-rays , photoelectric absorption

Thus, Space Astronomy was only born after the war with the V-2 rockets
The first X-ray experiments were observations of the solar corona.

The sun emits X-rays through
a) Solar corona b) flares



Why observe in X-rays ?



WIEN’s LAW

Wavelength inversely prop. Temperature

λmax= $3x10^7$ / T

- **Energetic phenomenae, temperatures of million degrees (very large gravitational potentials: BH, clusters of galaxies)**

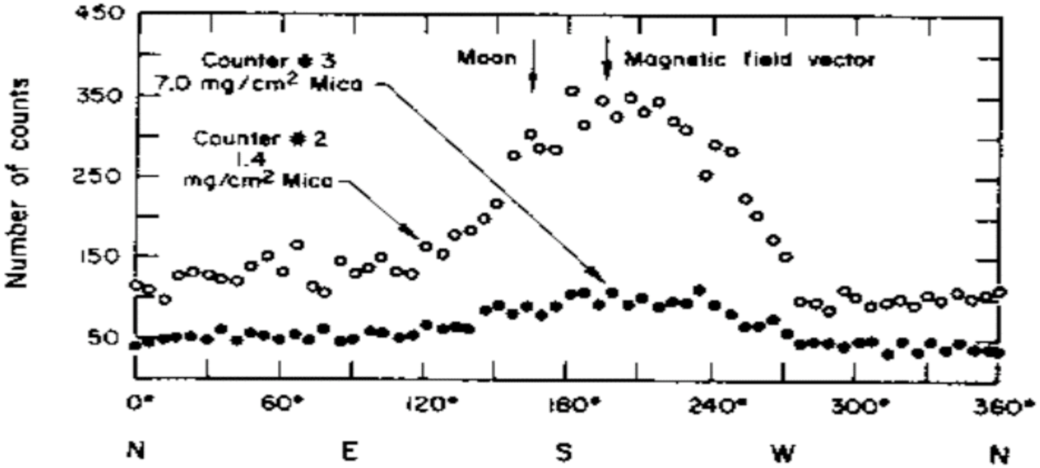
The birth of X-ray Astronomy

X-ray Astronomy starts in 1962 when a rocket detects:

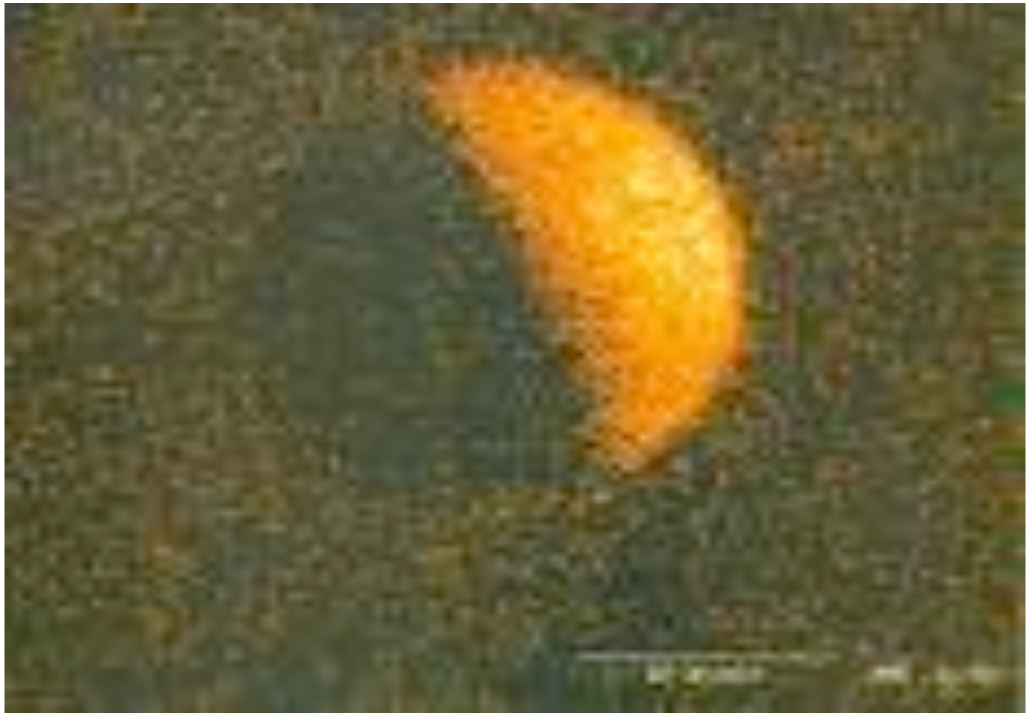
1) **the first X-ray source Sco-X1**
2) **an intense glow over the whole sky (the X-ray background)**

Giacconi et al. 1962 Nobel prize

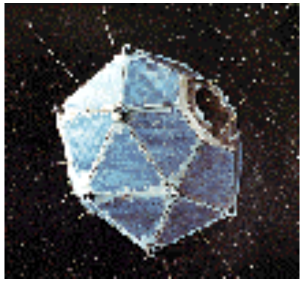
BUT does not observe the moon

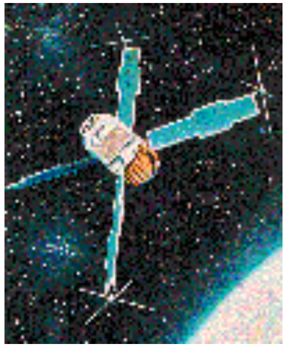


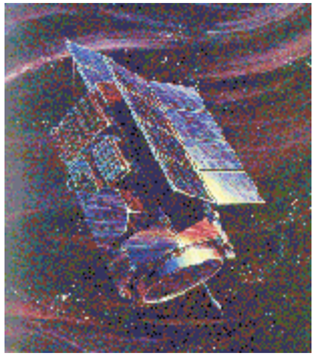
The Moon by ROSAT

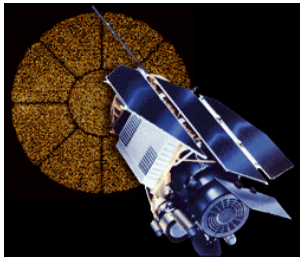


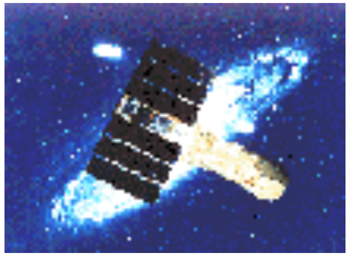
1960	1970	1979	1990	1993	1999
Aerobee	Vela	Einstein	ROSAT	ASCA	Chandra
	Uhuru				XMM
	HEAO-1				

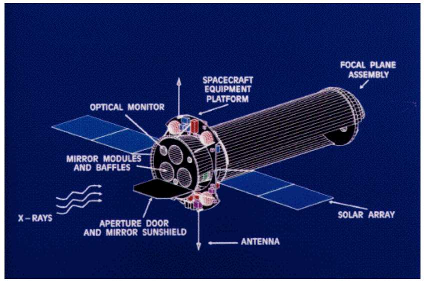








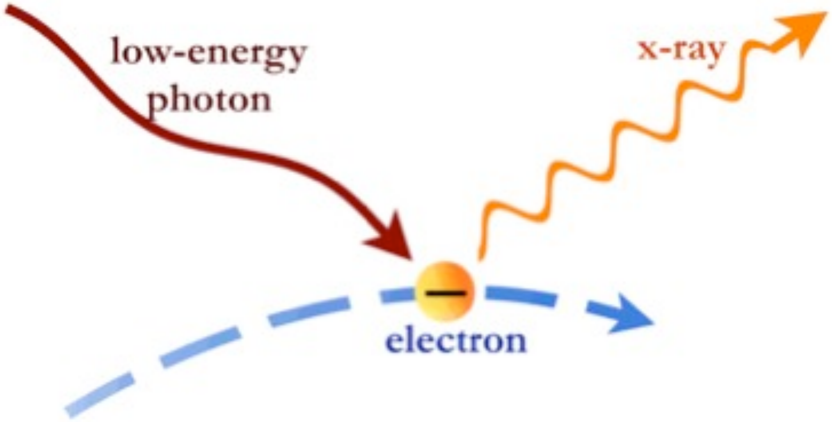




X-ray Emission mechanisms

- Free-Free emission (Stars, clusters of galaxies, hot gas in galaxies)
- Synchrotron Radiation (Supernova remnants, Jets in AGN)
- Black-body (accretion disks in X-ray binaries)
- Inverse-Compton scattering (AGN)

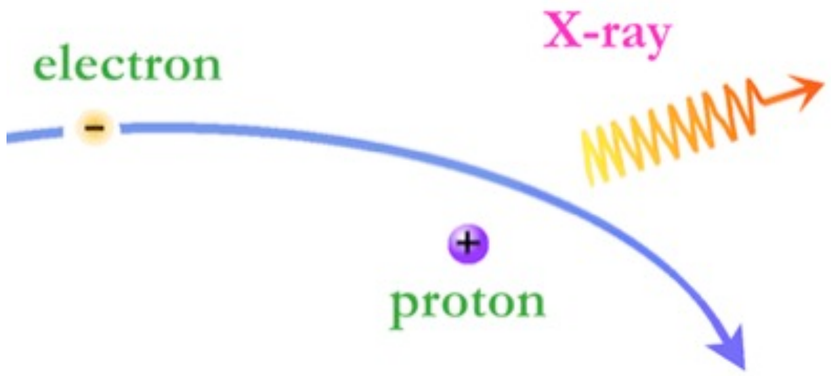
Compton-scattering

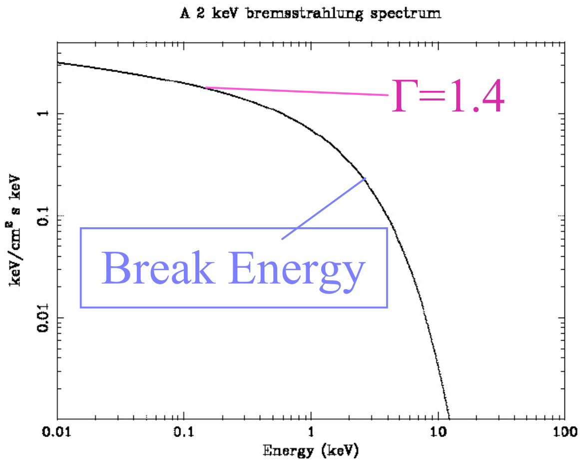


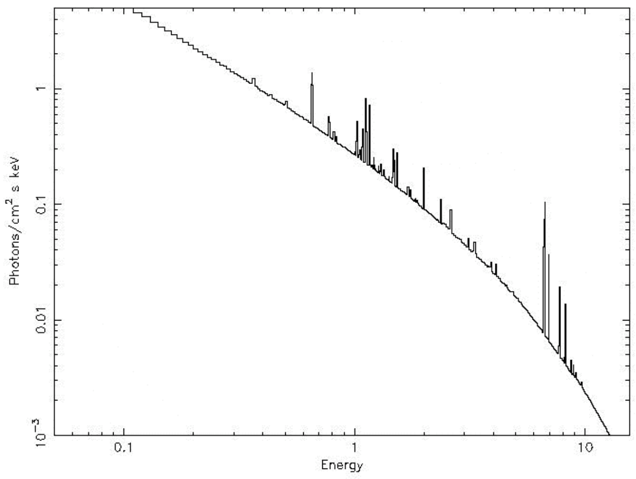
- upscatter UV photons to X-rays
- **kT >> hv**
- Energy gained
- **δE/E ~ 4κT / mc2**
- Temperature of the ‘corona’ about 40 keV. The physical conditions (temperature, Optical depth) in this corona must be VERY similar as the output X-ray spectrum has always a slope 1.9

Free-Free

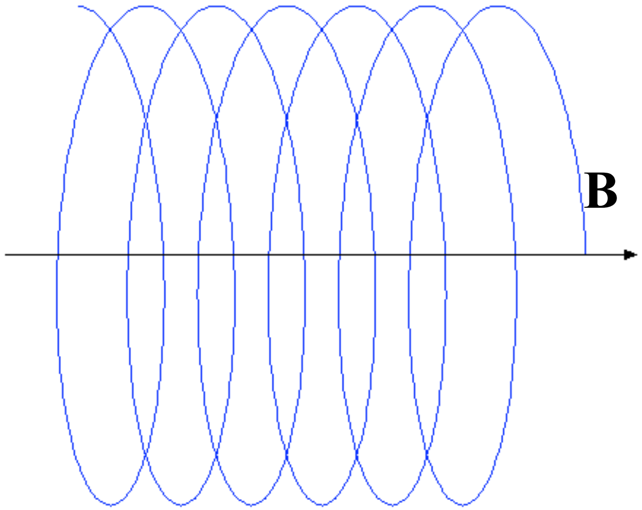
- Flux $\propto n^2 T^{1/2} \exp(-E/kT)$







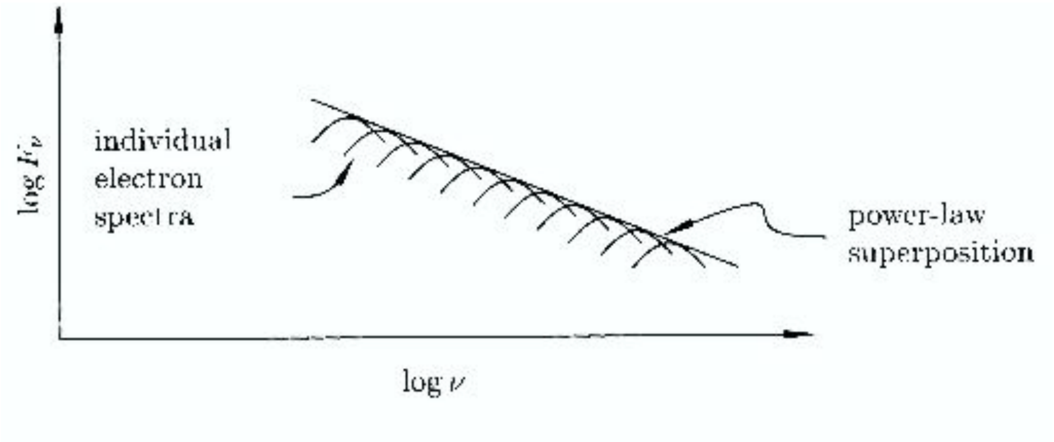
Synchrotron



$$-\left(\frac{dE}{dt}\right)=\frac{4}{3}\sigma_T c\left(\frac{E}{m_e c^2}\right)^2\frac{B^2}{2\mu_0}$$

$$N(E)\propto E^{-\alpha}$$

$$\beta=(\alpha-1)/2$$



Black-body Radiation

$$B_\nu = 2h\nu^3 c^{-2}\left(\exp\left(h\nu / kT\right) - 1\right)^{-1}$$

- Optically thick emission i.e. large optical depth

Question: what is the most likely emission process in AGN ?

- Photon index 1.9 or energy index 0.9

Compton scattering

Synchrotron

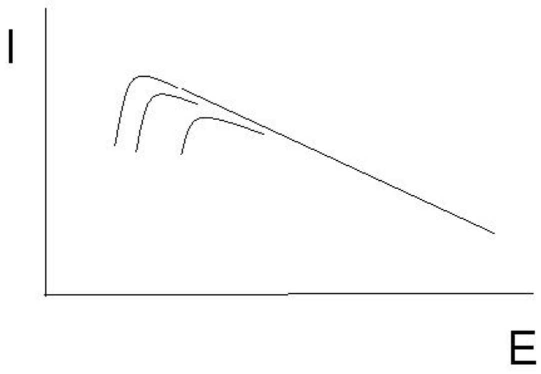
Free-Free

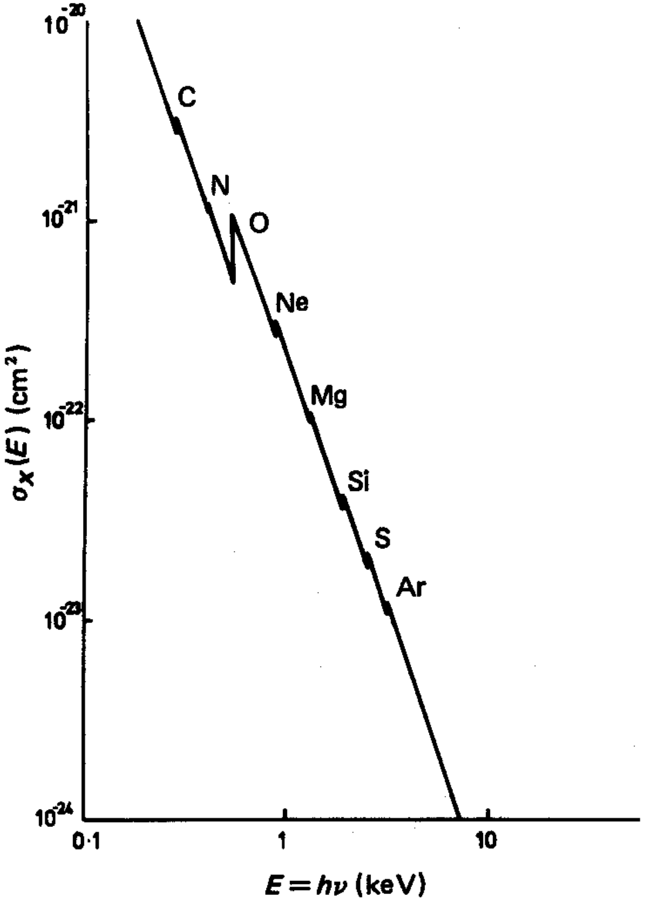
Black-body

Absorption processes: photoelectric absorption

$$I = I_o e^{-\sigma N_H}$$

$$\tau = \int_0^x \sigma_x(E) N_H dx$$



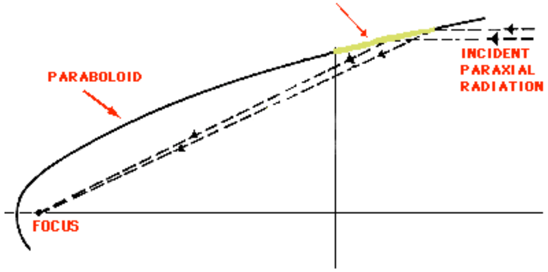


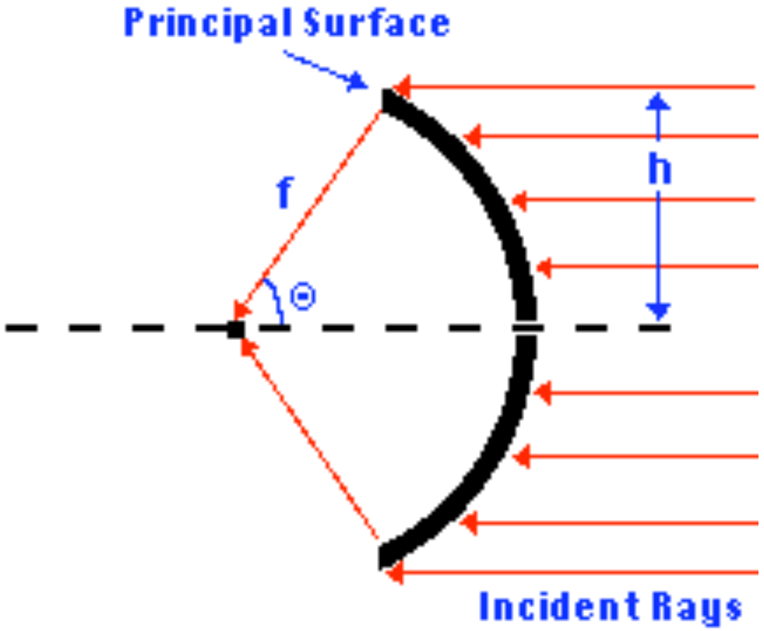
Is any of the absorption in X-ray due to hydrogen ?

X-ray telescopes

- Abbe sine condition

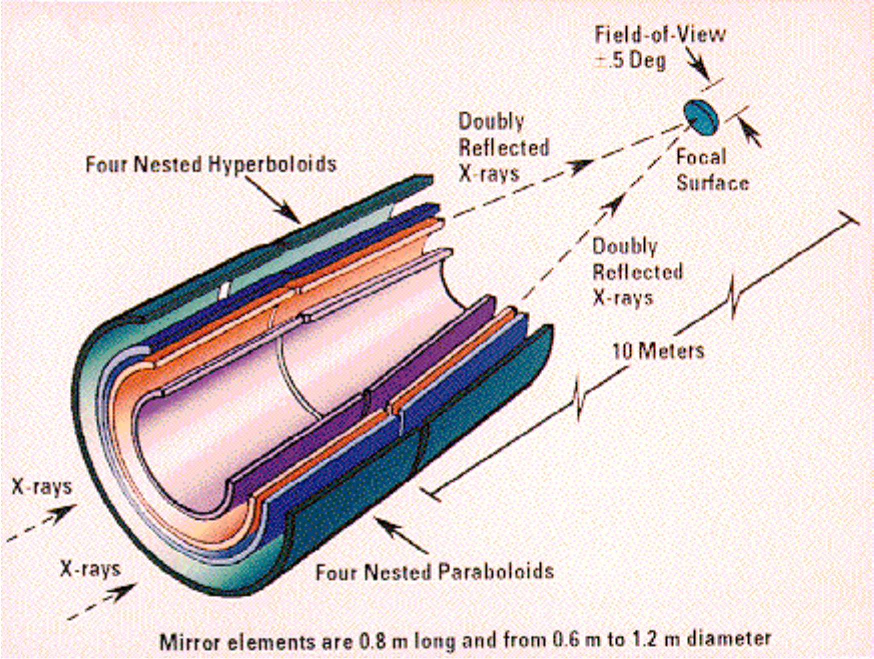
- $h/\sin(\Theta)=f$



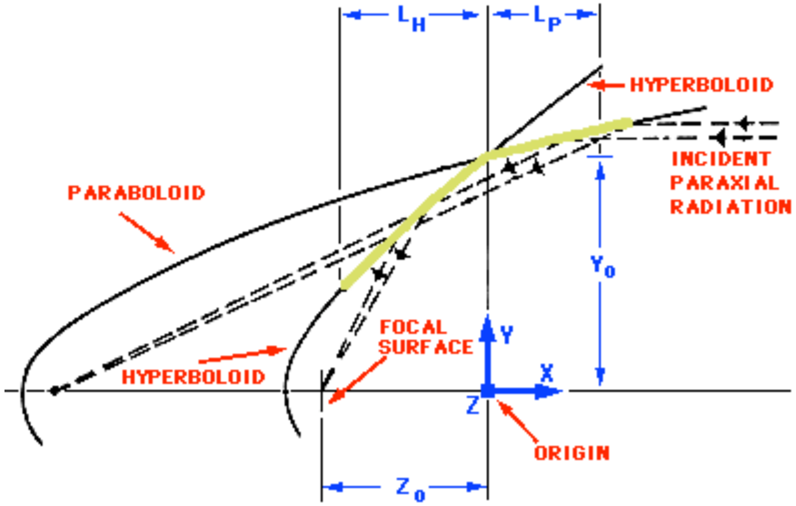


Wolter X-ray Telescopes

-- where the X-rays are scaterred on two tubes.



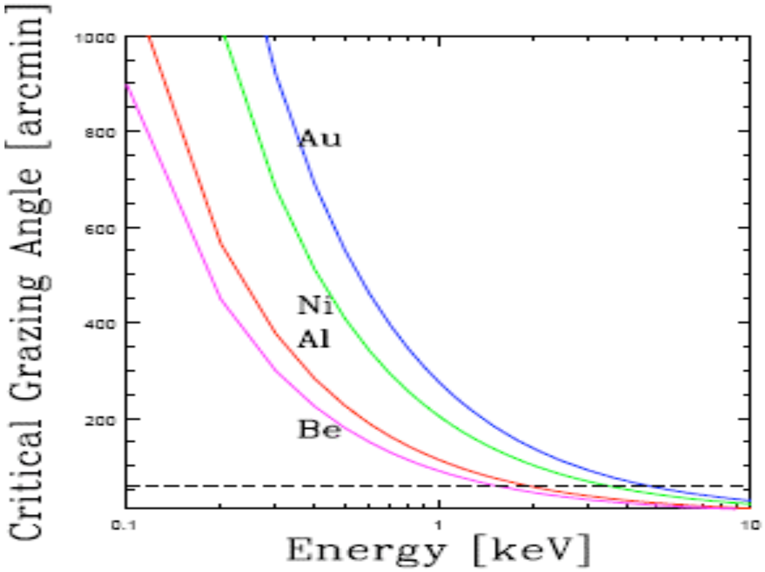
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter



Grazing angle

Max grazing angle:

$\theta_c \propto E^{-1} \sqrt{Z}$



Angular Resolution

- Rayleigh criterion:

$$R = \frac{\lambda}{D}$$

At 6000 Angstrom we get ~0.1 arcsec resolution with a 1-m telescope

At 6 Angstrom we would have ~0.0001 arcsec with XMM but we don’t

-- MICROROUGHNESS
-- Mirror Shape

X-ray detectors

1. Gas filled proportional counters [PAST]
(poor energy resolution, spatial resolution)

2. CCD [PRESENT]
(good $\Delta E/E \sim 6\ \%$ spectral resolution)
(better resolution with the use of gratings)

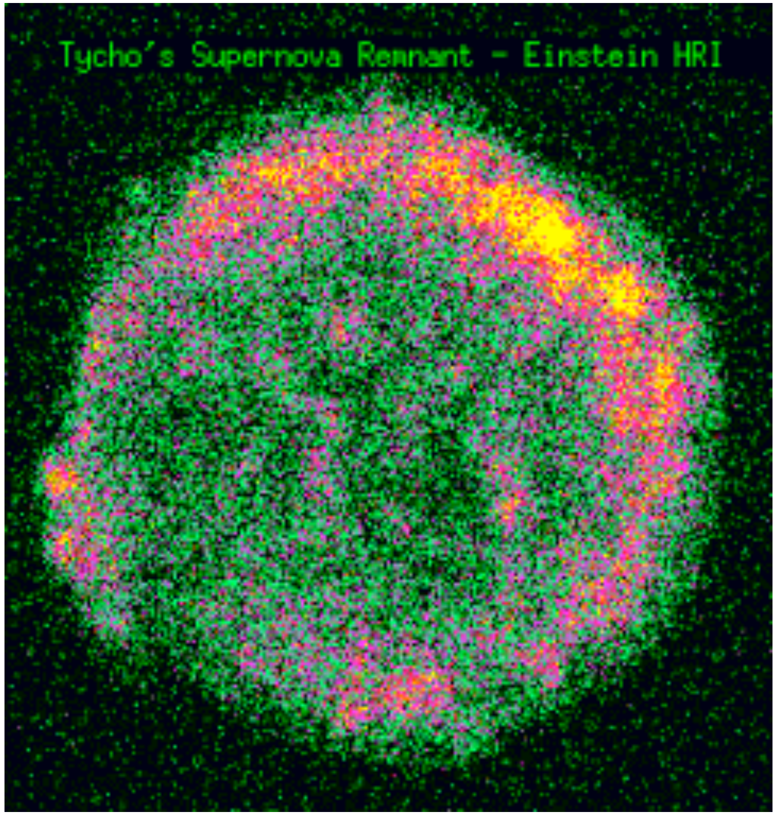
NOT ONLY IMAGING BUT SPECTROSCPY AS WELL

3. Microcalorimeters (Excellent spectral resolution $\Delta E/E \sim 0.5\ \%$)

SPECTROSCOPY ONLY

[FUTURE]

First X-ray image (Einstein)

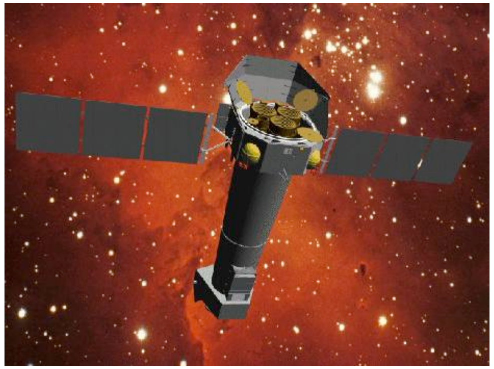


microchannel plates

Problems:

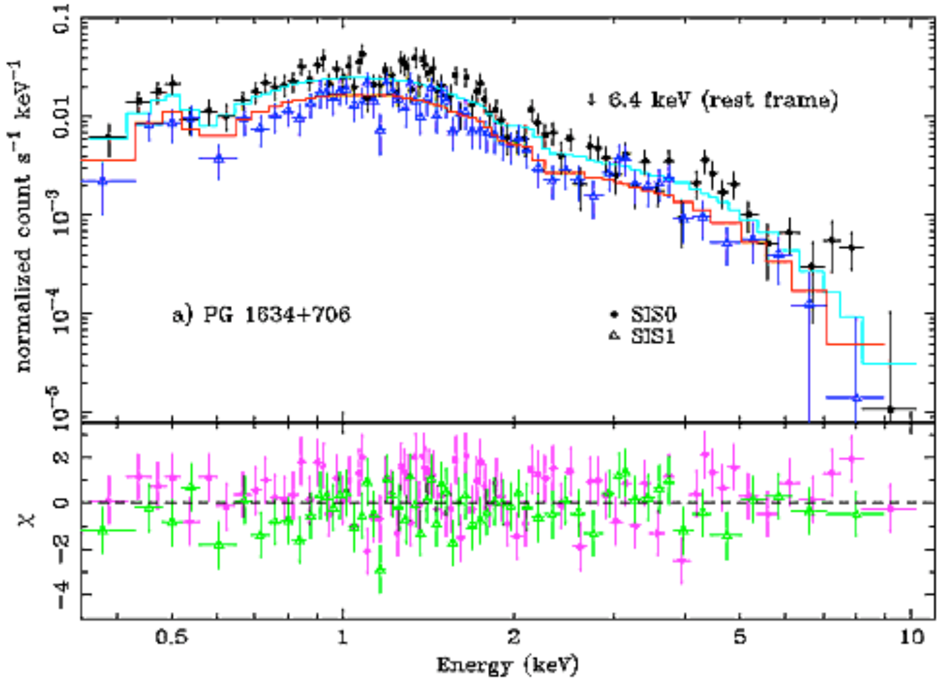
1. PSF degrades off-axis
2. Vignetting
3. Particle Background

Chandra vs. XMM

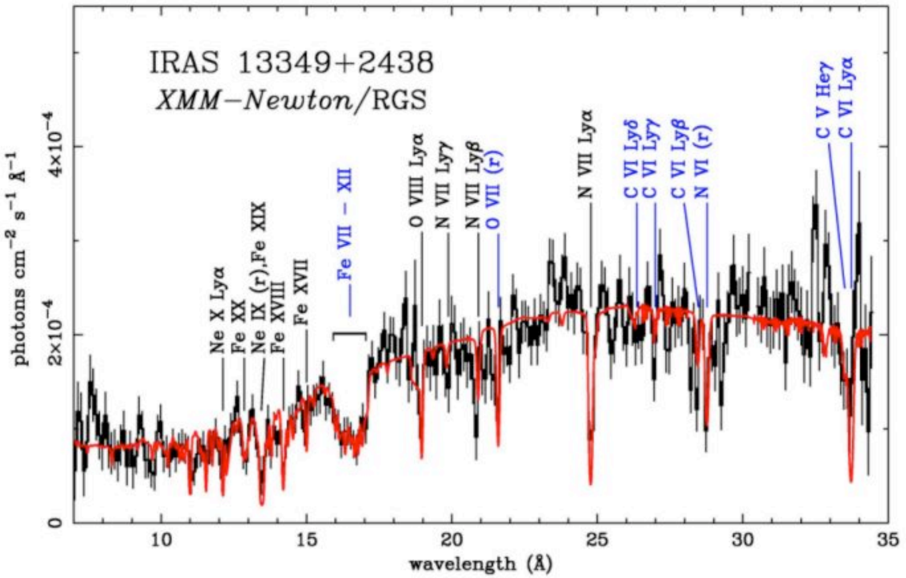


- XMM (ESA)
  - a. 5000 cm2 @ 1keV   largest telescope
  - b. moderate spatial resolution 6arcsec FWHM
  - c. CCDs
  - d. Grating (high resolution) spectra at low energies
- Chandra (NASA)
  - a. Highest spatial resolution ever achieved 1 arcsec (optical astr
  - b. 1000 cm2
  - c. CCDs
  - d. Grating (high resolution spectra) at both high and low energies

Grating vs CCD spectra



XMM-NEWTON SCIENCE RESULTS



6 December 2000

Fig. 4

The future: The x-ray cosmology mission XEUS

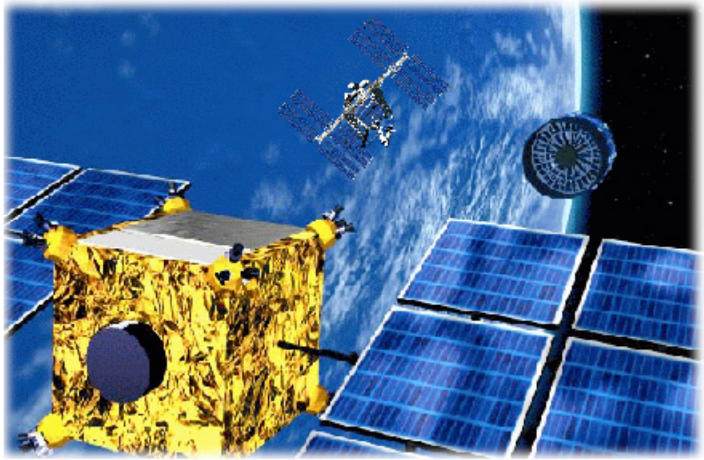
Largest collecting power in X-ray ever

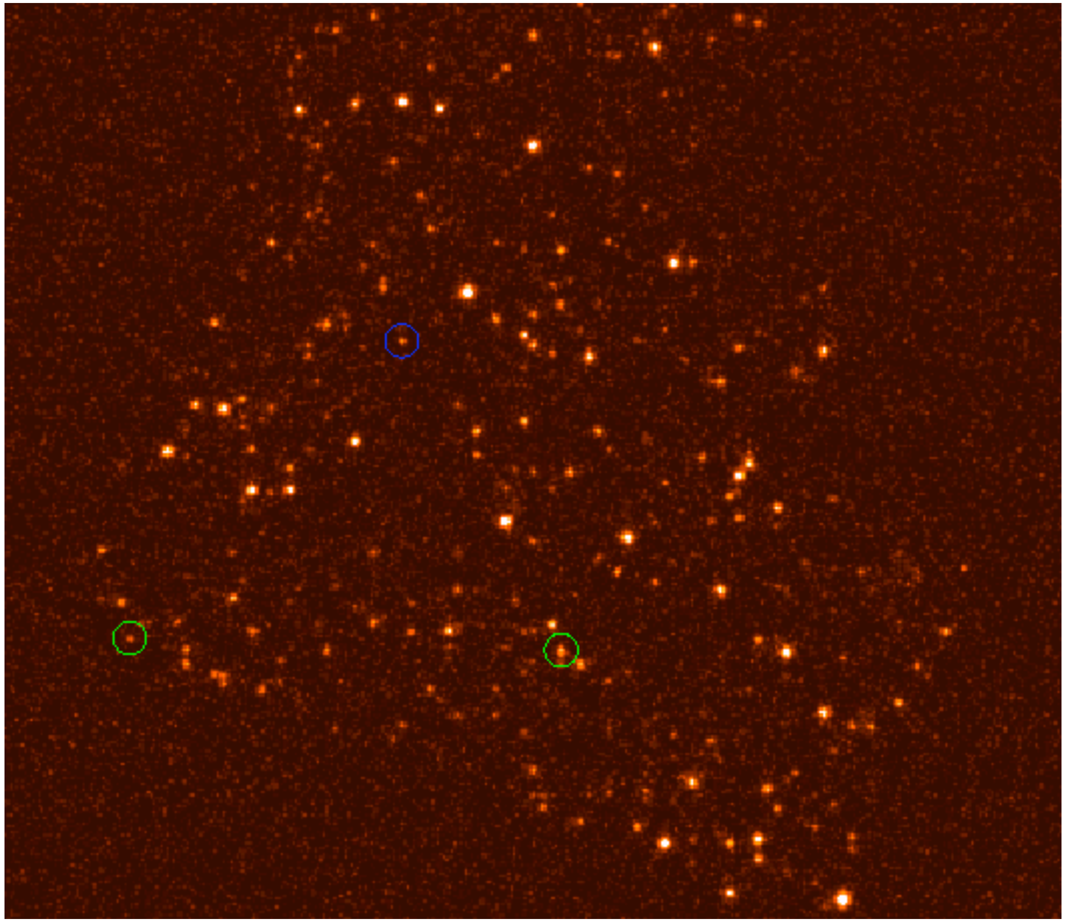
5 m^2 at 1 keV

(Chandra has 0.1 m2)

Microcalorimeter

Imaging at hard x-rays >10 keV



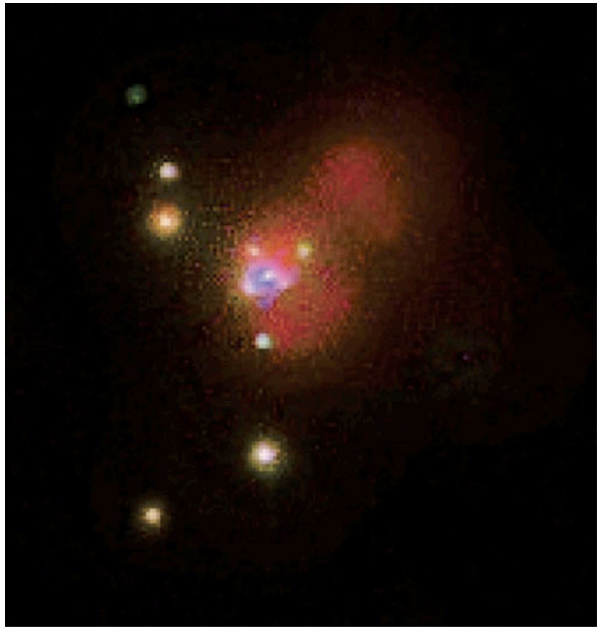


X-ray sources in the Galaxy(ies)

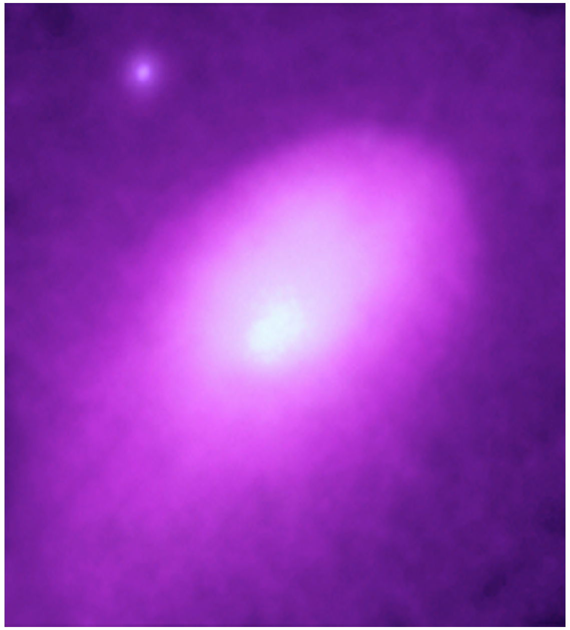
- X-ray binaries 10 ^{38}- 10^{41} erg s^{-1}
- Supernova remnants 10^{35} erg s^{-1}
- Cataclysmic variables 10^{32}
- Stars 10^{26}

The contents of the extragalactic X-ray sky

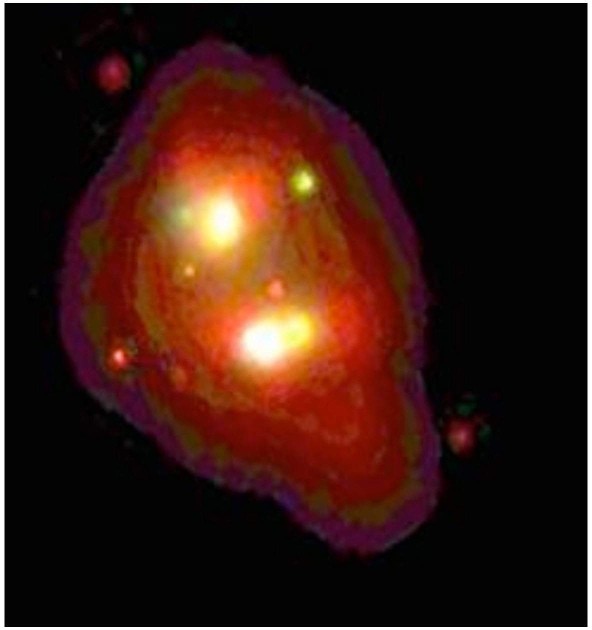
1. AGN	accretion disks around black holes
2. Clusters of galaxies	gas <10^8 K heated by the gravitational potential
3. Galaxies	X-ray binaries, SNR, hot gas



AGN (Circinus)



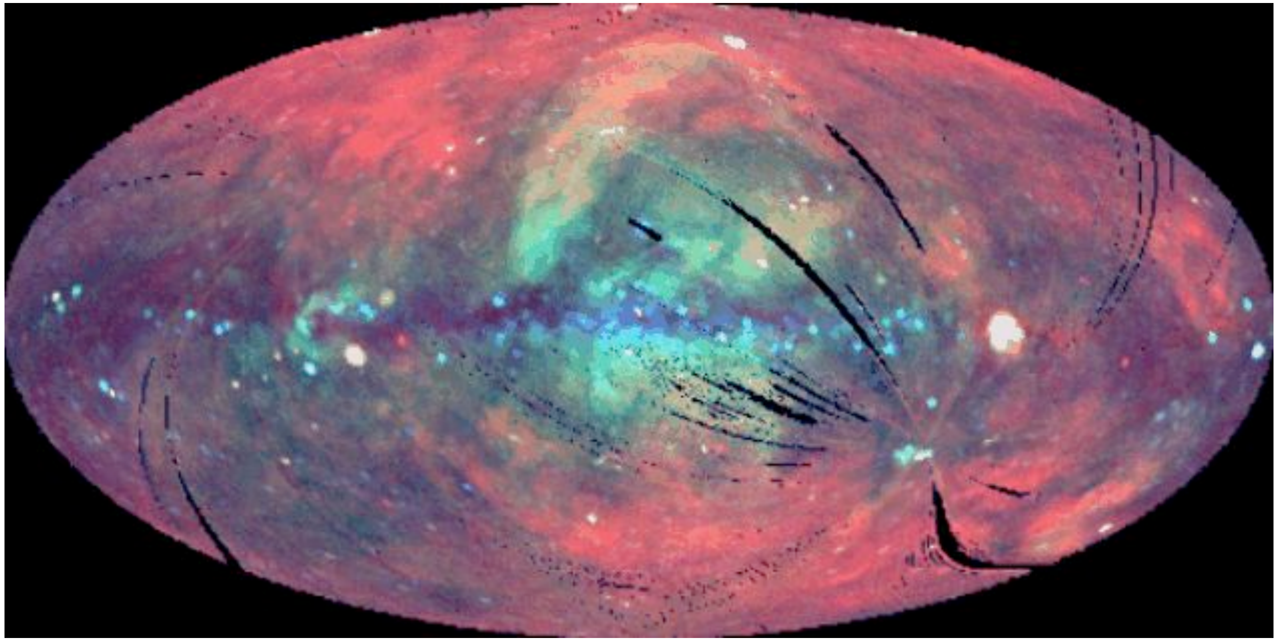
Cluster (A2142)



Galaxy (NGC3690)

X-ray Surveys

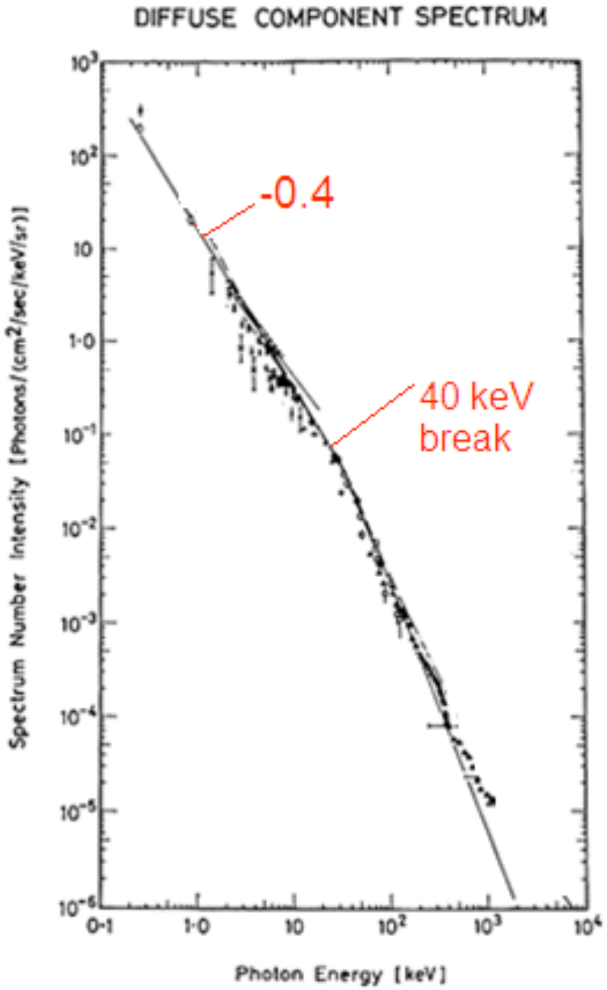
X-ray background



HEAO-1 performed an all-sky survey but had no resolution (3x3 degrees)

Observed a uniform glow but is this: a) DIFFUSE   or
b) co-addition of point sources ?

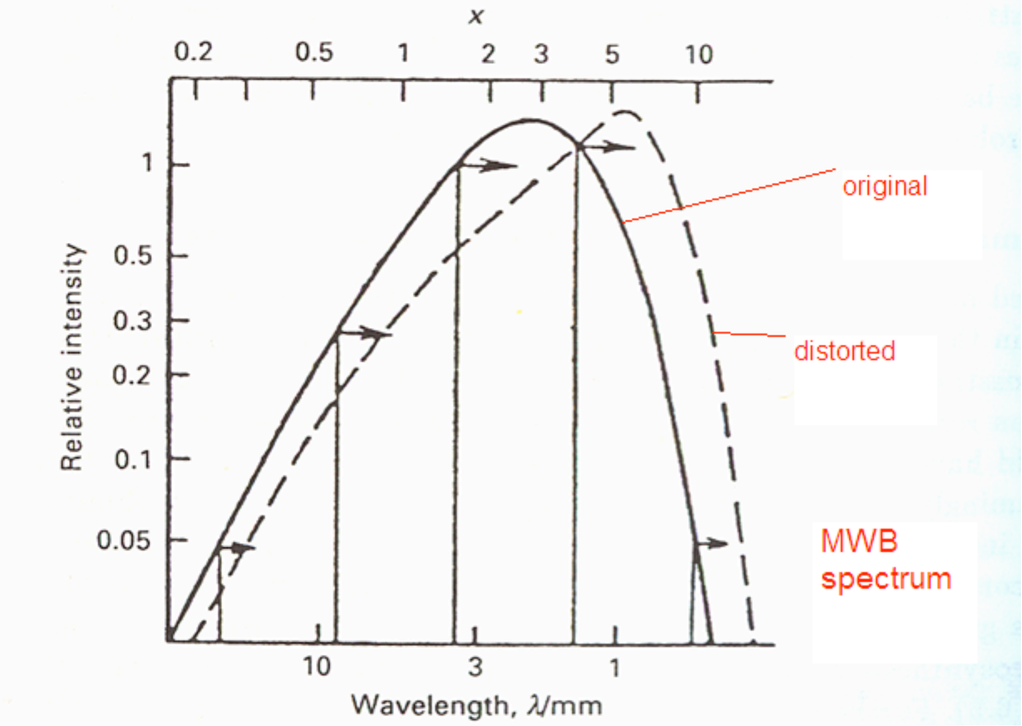
Spectrum XRB



The spectrum of the X-ray background
was that of free-free emission
with a temperature of 40 keV

$$I(E) \propto E^{-0.4}\, e^{-E/kT}$$

Microwave Background constraints



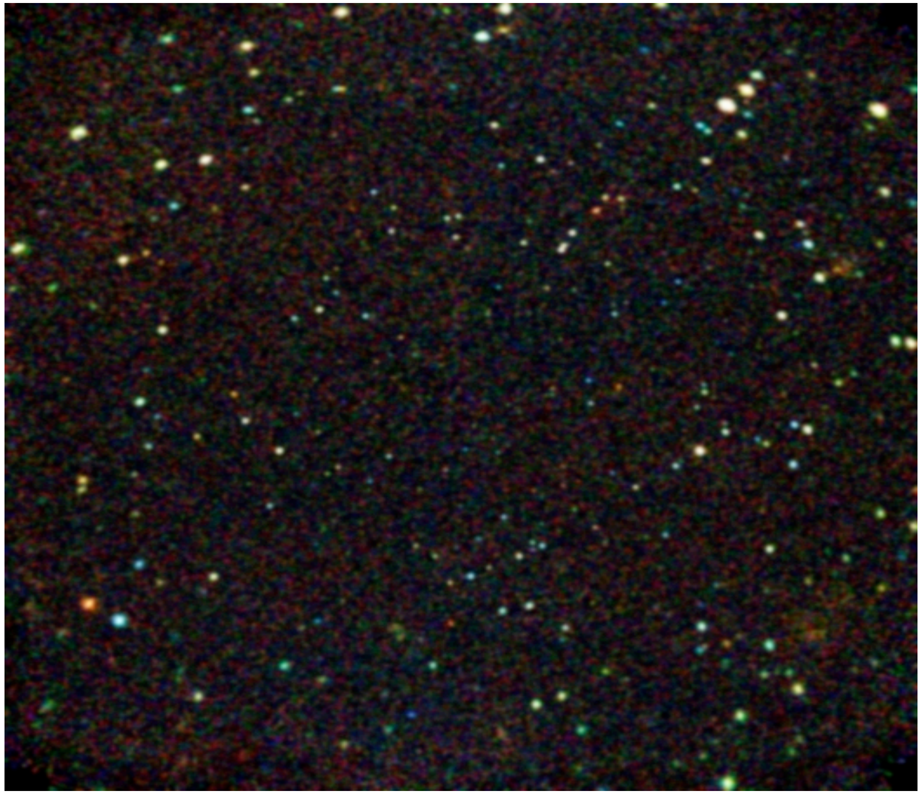
If there were a population of Hot electrons these would scatter the MWB photons

Comptonization parameter

$$y = 4kT_e\tau^2/m_ec^2$$

The Chandra Deep field

The deepest exposure (2 Msec ~ 24 days)



1Msec Exposure
Chandra deep south
Blue=hard
Red=soft
White=intermediate

90% X-ray background resolved

Sky density 10000 deg-2

Practically all AGN

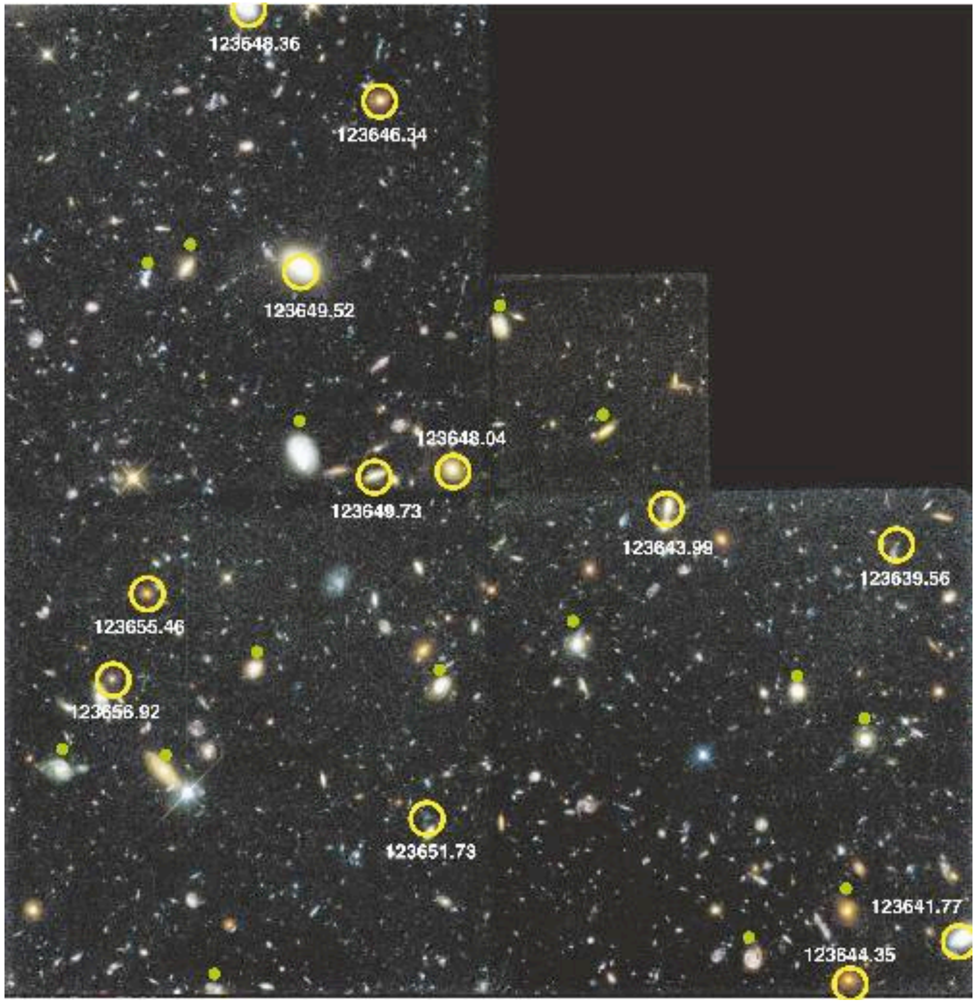
Accretion History of Universe

X-rays very efficient in finding AGN !!

- X-ray Surface density 10.000 deg-2

In contrast the optical QSO surveys reach surface densities of few hundred per square degree (eg COMBO-17 survey Wolf et al.)

Difference between X-ray and optical surveys

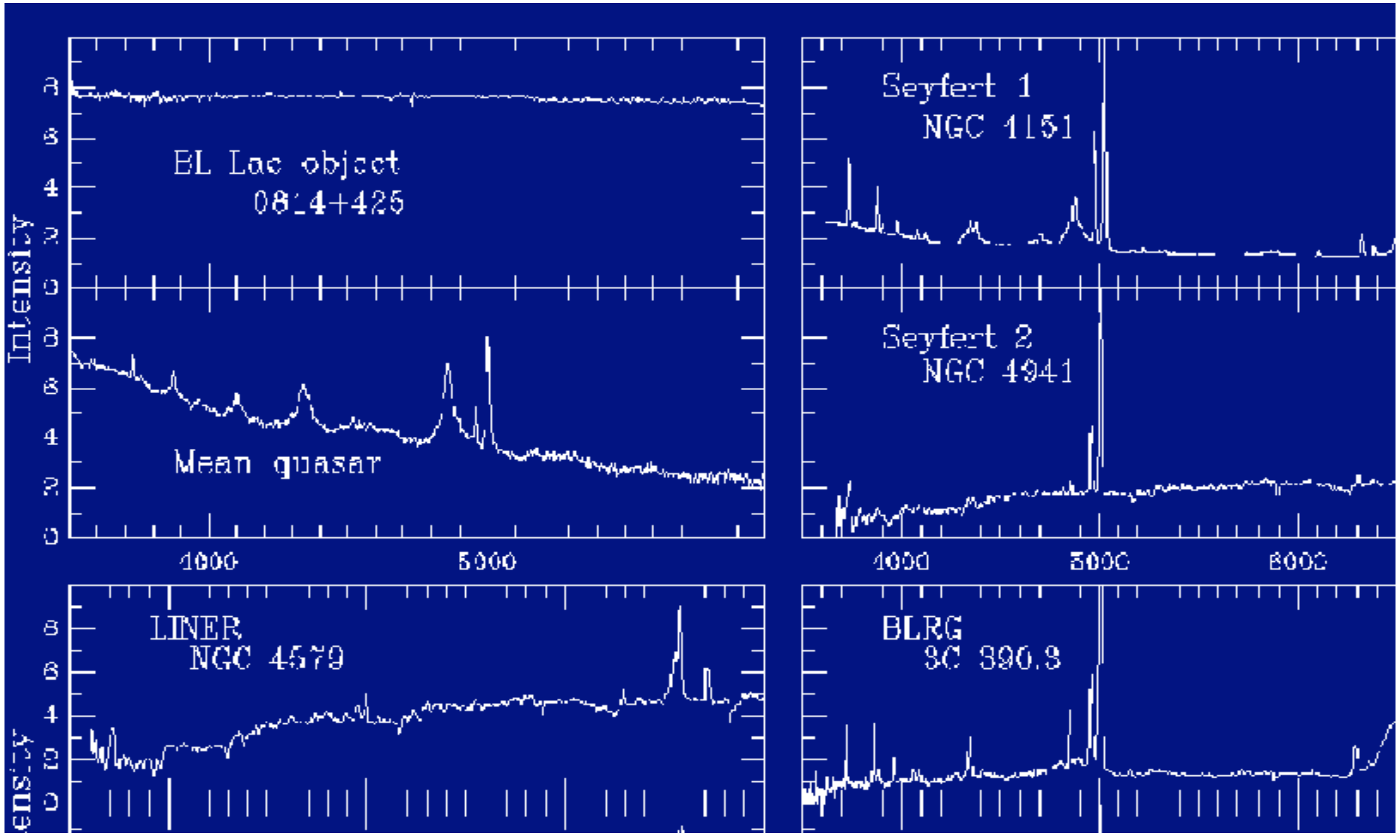


The HDF (optical)
~3000 galaxies

overimposed (yellow circles)
are the 12 X-ray sources
detected by Chandra
(mostly AGN)

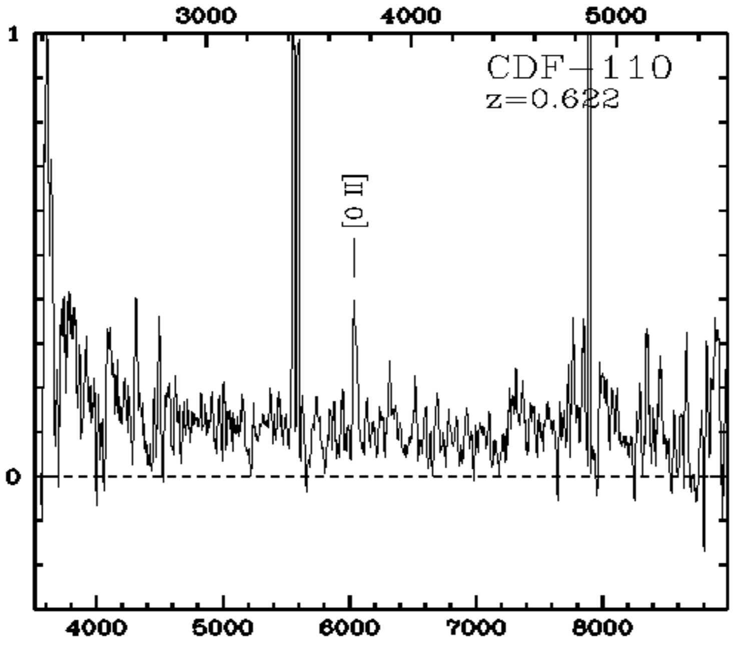
X-rays mainly probe accretion processes instead of starlight in contrast to the optical

Optical spectra: classification and distance

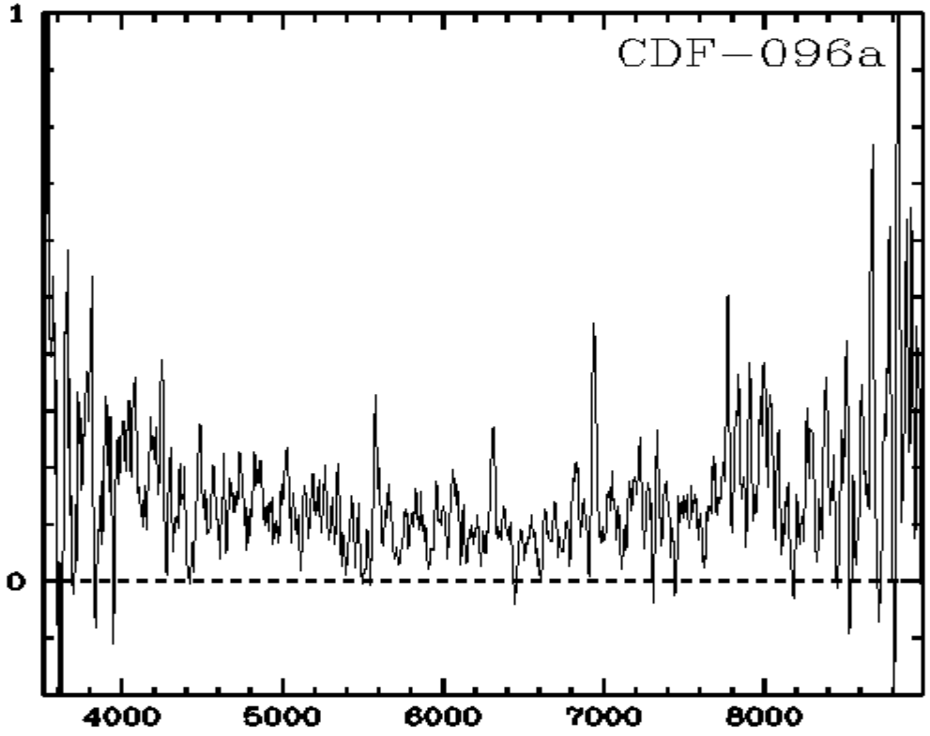


Type-1 AGN(eg Seyfert-1): Broad and narrow lines OPTICAL
Type-2 (eg Seyfert-2): Only narrow lines OPTICAL

Real spectra of faint sources

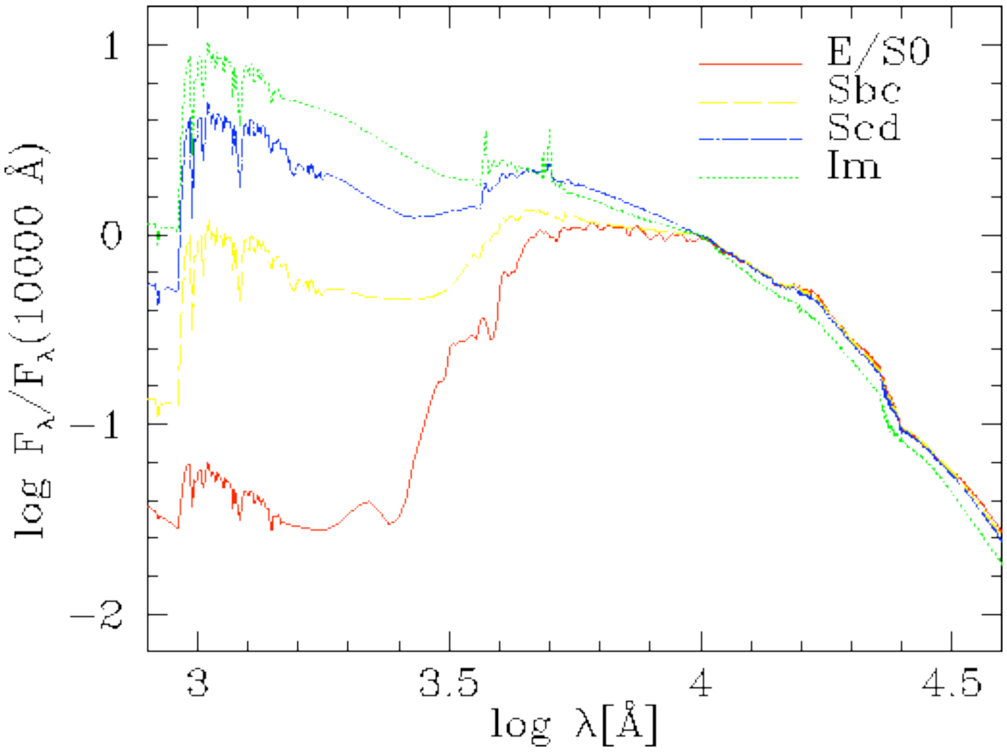


R=23.2



R=24.5

Photometric redshifts



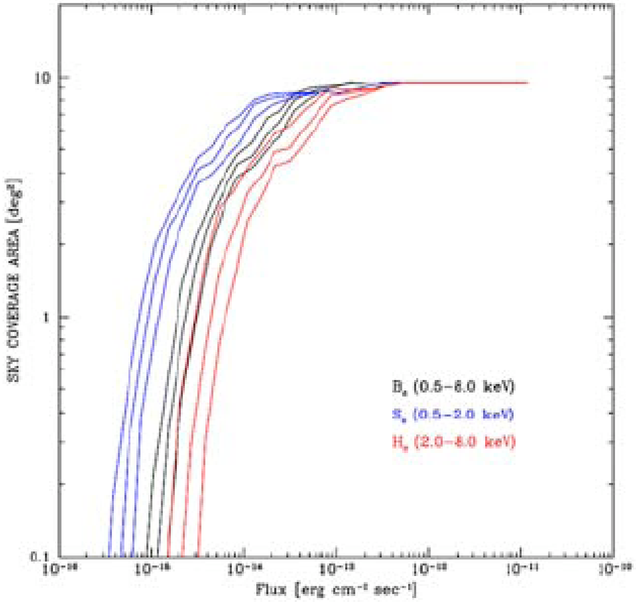
$$\chi^2(z) = \sum_{i=1}^{N_{\rm filters}} \left[\frac{F_{{\rm obs},i} - b \times F_{{\rm temp},i}(z)}{\sigma_i} \right]^2 ,$$

LogN-logS derivation

$$N(>f) = \Sigma_{\iota=1} 1/\delta\Omega_\iota$$

The sensitivity is not uniform in the field-of-view because of the degradation of the PSF and the vignetting.

Area Curve (Area – Flux)



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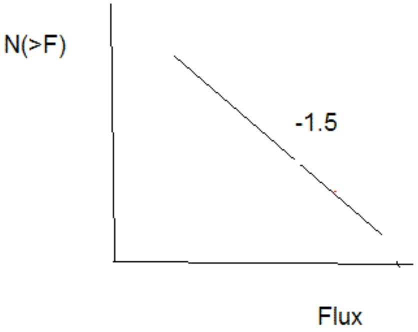


LogN-logS theory

The number of sources N in a solid angle $\delta\Omega$ is

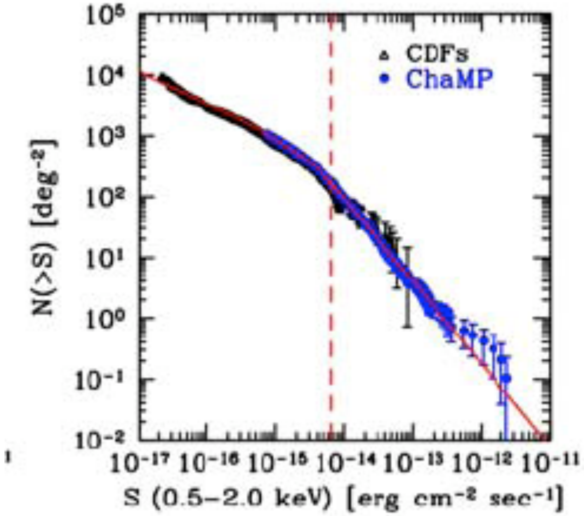
$$N = \rho\ \delta V = \rho\ r^3/3\ \delta\Omega$$

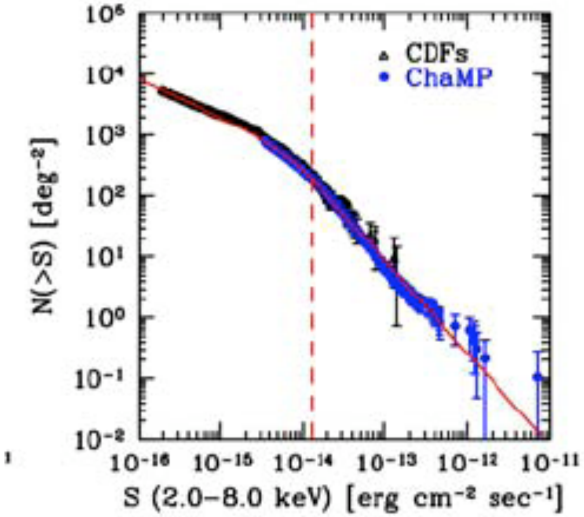
where the distance can be found from the inverse square law :

$$f = L / 4\pi r^2$$

$$N = \rho\ \delta\Omega/3\ (L/4\pi f)^{3/2} \propto f^{-3/2}$$

LogN-logS observations





At Bright fluxes slope -1.5

At Faint fluxes -1.0

The flat slope implies that we run out of sources
i.e. Limited volume, flattening of the LF

The normalization of the
2-8 keV logN-logS is a
Factor of two higher

This constrains the source’s spectrum

Relation between Luminosity function and Number counts

$$N(>f) = \int \int \Phi(L)\, dL\, dv/dz\ \ dz$$

$\Phi(L)$ is the luminosity function i.e. the number density of Sources at luminosity L

The lower limit on luminosity at a redshift z depends on the Flux limit of the survey f_{lim}

The AGN unification model

Supermassive black hole (10^6-$10^{10} M_\odot$)
$M = 10^8 M_\odot \Rightarrow R_G \sim 3\times10^{13}$ cm.

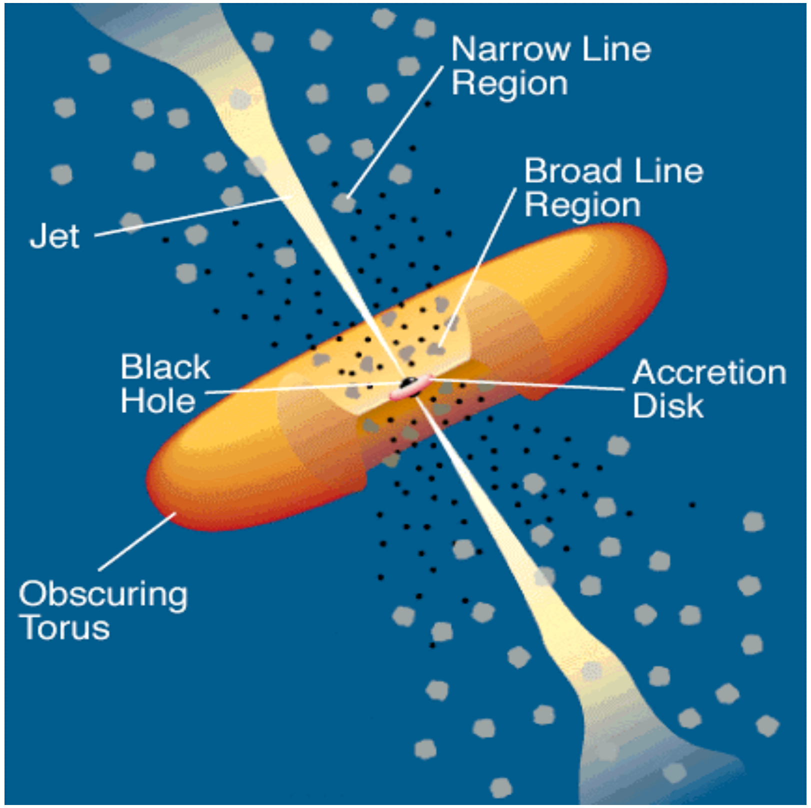
Accretion disk; thermal UV/X & lines
from highly ionized atoms
(3-100 R_G).

High velocity (>10^3 km/s) **broad-line**
clouds ($R \sim 10^{3-4}\ R_G$).

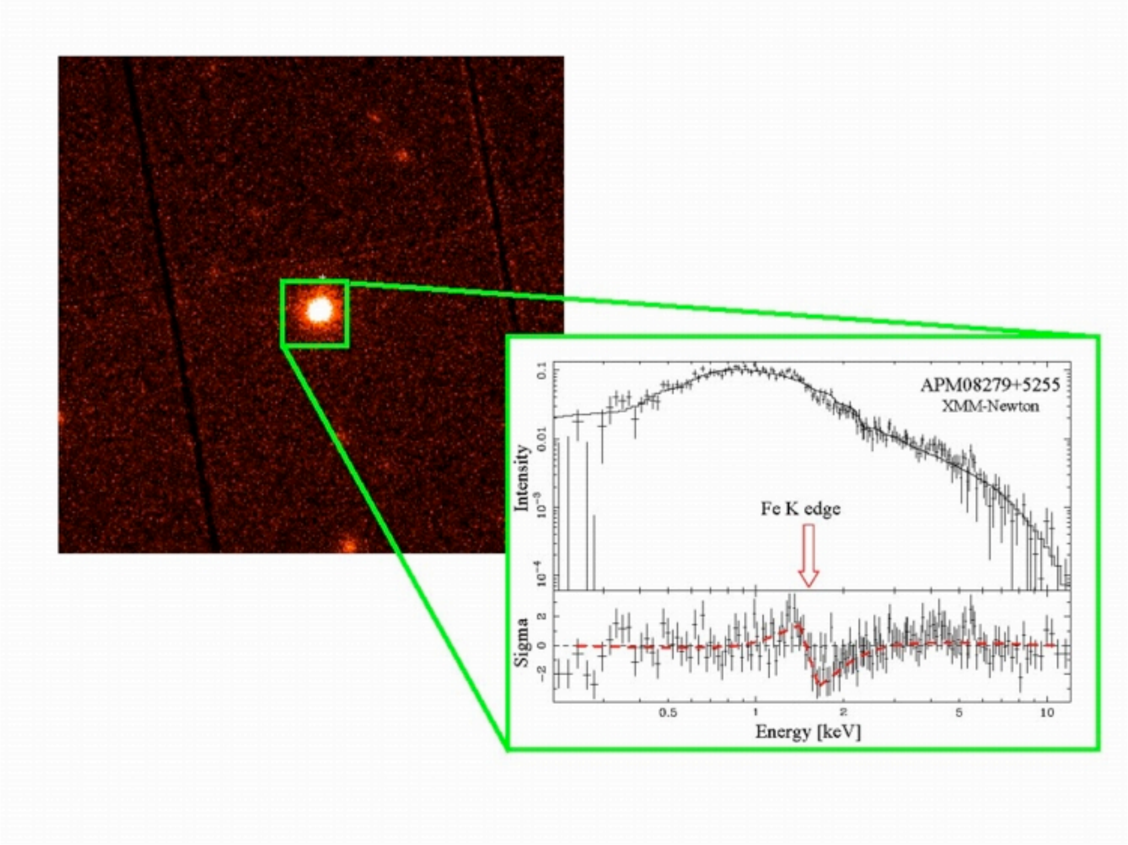
Dusty torus, which orbits in/near
plane of accretion disk
($R \sim 10^{4-5}\ R_G$).

Lower velocity (few hundred km/s)
narrow-line clouds ($R \sim 10^{5-7}\ R_G$).

Relativistic jet ($\Gamma \sim$ 5-30), which may be
collimated on ~50 R_G scales.

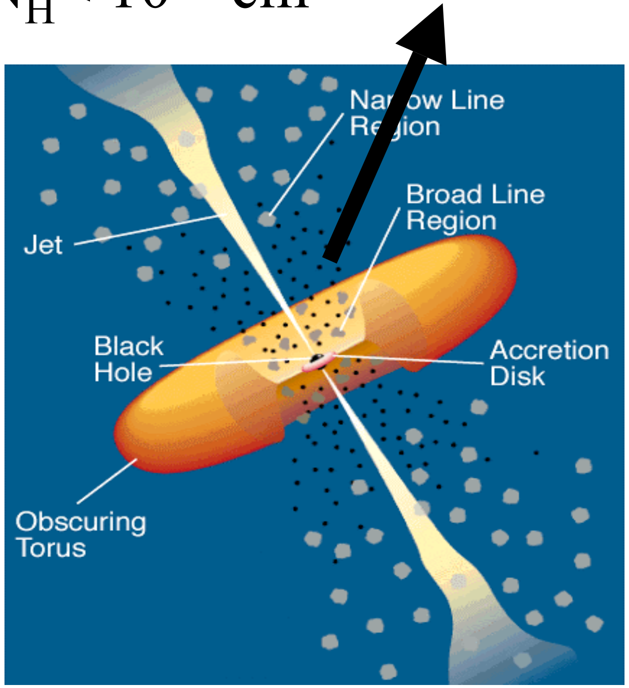


AGN spectra (unabsorbed)

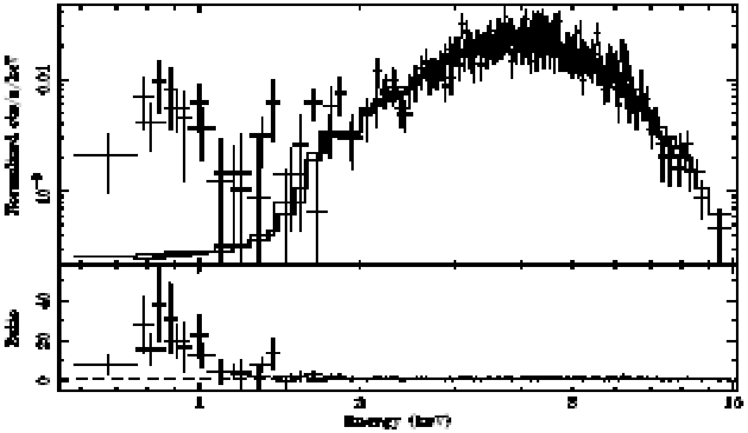


Broad Lines in the optical

$N_H < 10^{22}$ cm^{-2}



X-ray spectra (type-2)



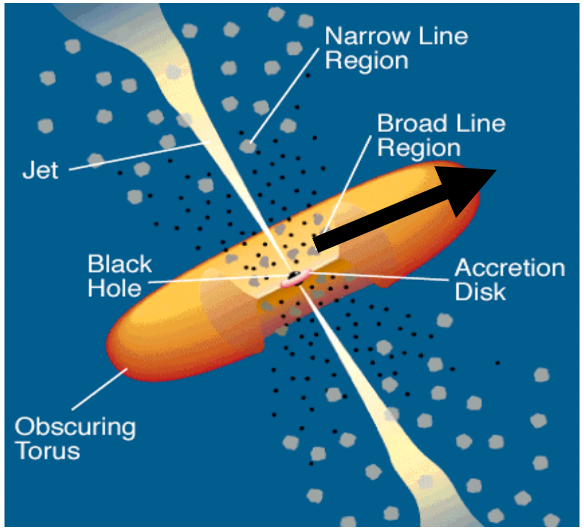
1. Power-law

+ photoelectric absorption

$I(E) = e^{-\sigma N} E^{-\Gamma}$

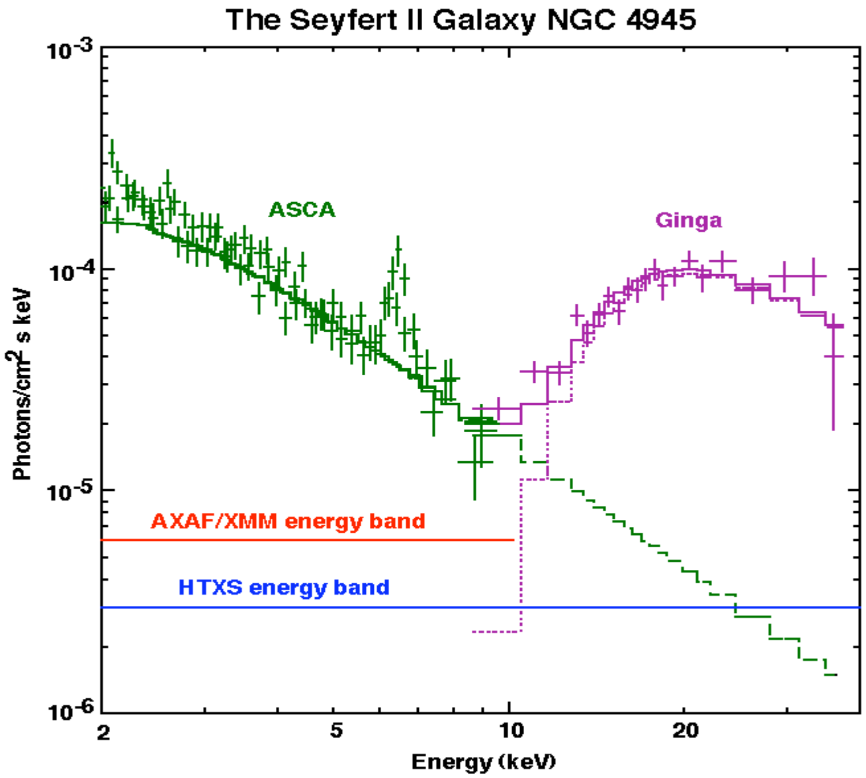
NGC7172, $N_H > 10^{23}$ cm^{-2}

2. FeKα Line at 6.4 keV



Narrow Lines in the optical

AGN spectra : Compton thick (extreme case of absorption)

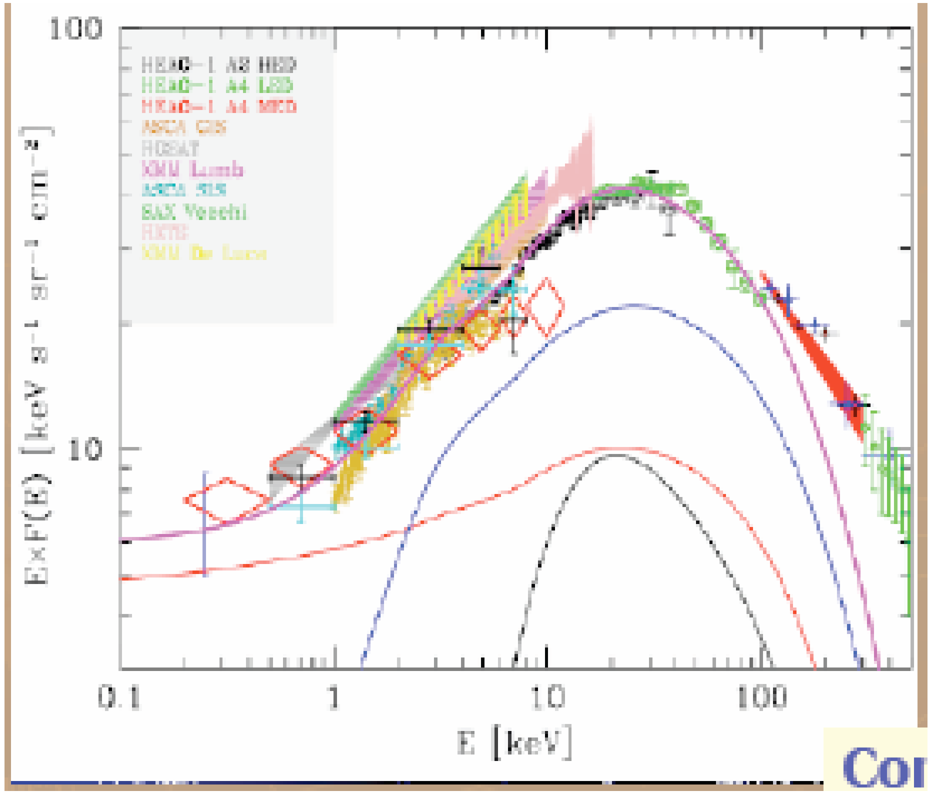


1. NH > 10^24 cm-2
Compton scattering dominates

2. FeKα Line at 6.4 keV
very strong, Equivalent Width> 1 keV

Two out of the three nearest AGN are Compton-thick : NGC1068, Circinus

Are we missing AGN in X-ray ?



Clue 1: The spectrum of the X-ray background.

Are we missing AGN in X-ray ?

Clue 2: the mass of the Black holes in the Universe

X-ray energy density
at redshift z

$$\int L_X \Phi(L_X, z) \mathrm{dLog} L_X . \quad \text{erg s}^{-1}\ \text{Mpc}^{-3}$$

$Lx = \varepsilon mc^2$ where $\varepsilon=0.1$, m=accreted mass

Mass deposited in
Black hole

$$M_\bullet = L_{bol}(1-\epsilon)/\epsilon c^2$$

$$\dot{\rho}_\bullet(z) = \frac{1-\epsilon}{\epsilon c^2} \int K L_X \Phi(L_X, z) \mathrm{dLog} L_X$$

Integrating over redshift we obtain $3.2x10^{5}$ M. Mpc^{-3}

- We can compare with the BH density in the local Universe (Marconi et al. 2004)

- HOW do we estimate BH density ?

  - $M_{BH} = k\ \sigma^5$ (Magorrian relation)

  - We find that the BH from X-rays are lower by about a factor of two

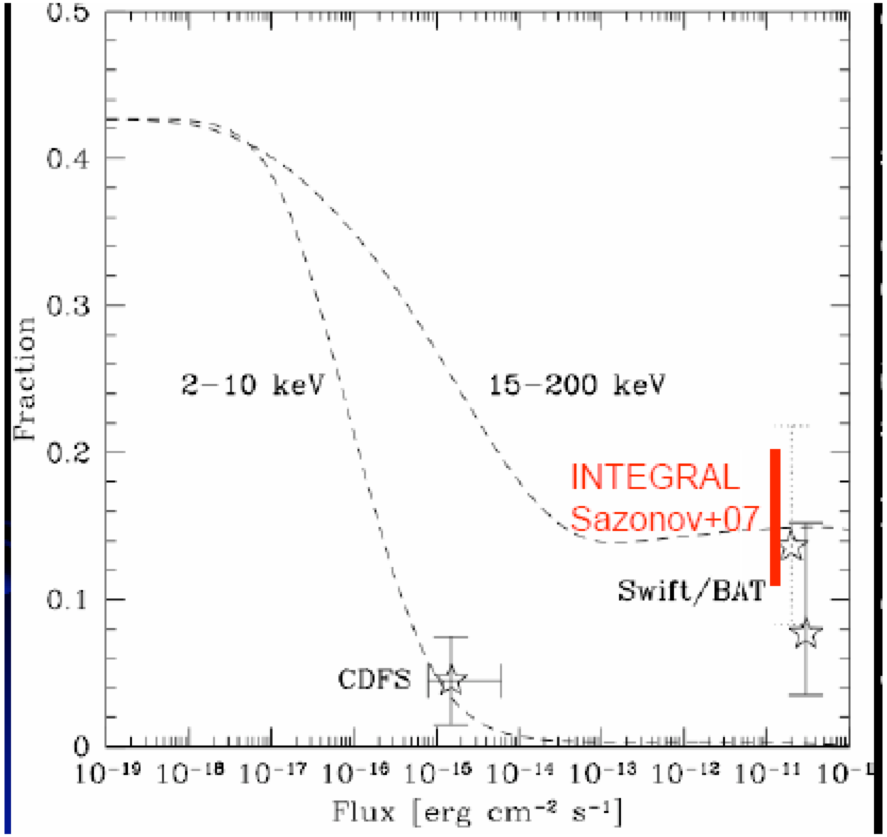
How will we find these ?

- Imaging at very hard energies >10 keV

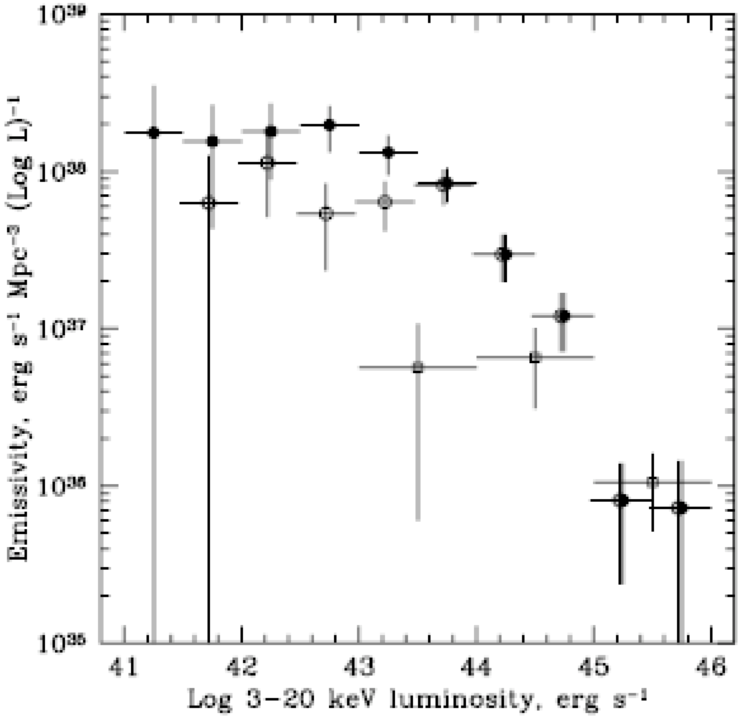
Simbol-X

Nustar

Next



The luminosity function Φ(L)

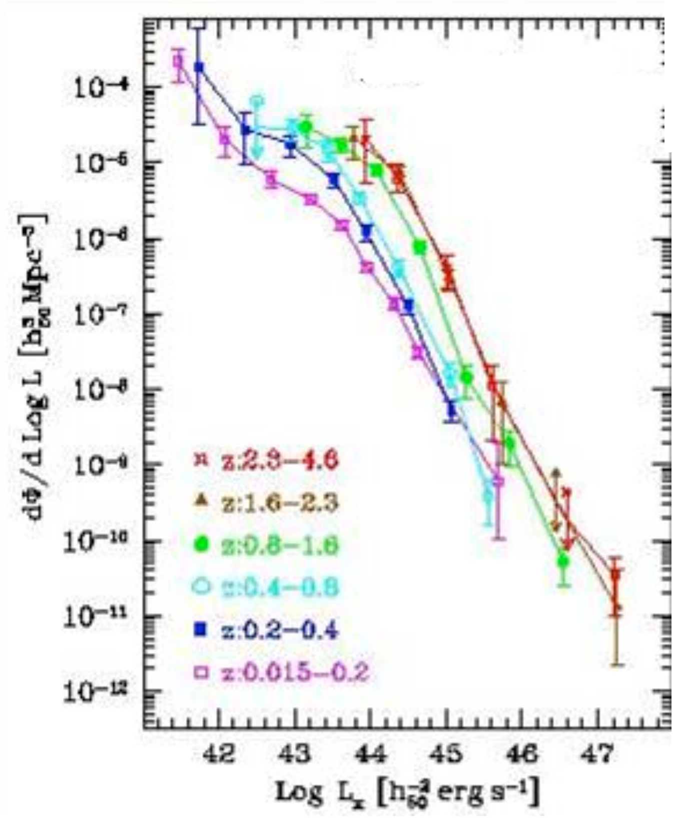


The luminosity function of local AGN

RXTE 3-20 keV

Sazonov & Revnivtsev 2006

AGN Evolution



$$\frac{d\Phi(L_X, z=0)}{d\mathrm{Log}L_X} = A[(L_X/L_*)^{\gamma 1} + (L_X/L_*)^{\gamma 2}]^{-1}.$$

$$Lx(z) \propto Lx(z=0)\,(1+z)^3$$

Pure Luminosity evolution

QSOs were brighter in the past

Φ evolves along the x-axis

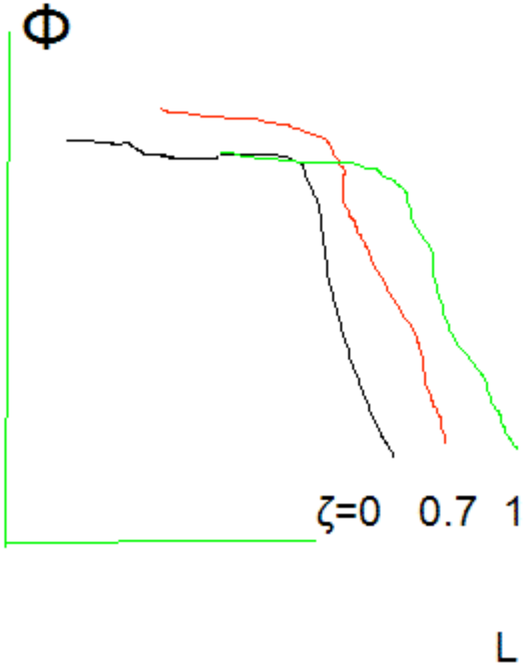
This is similar to the evolution of optical QSOs.

The evolution is strikingly similar to the evolution of star-forming galaxies

Luminosity function

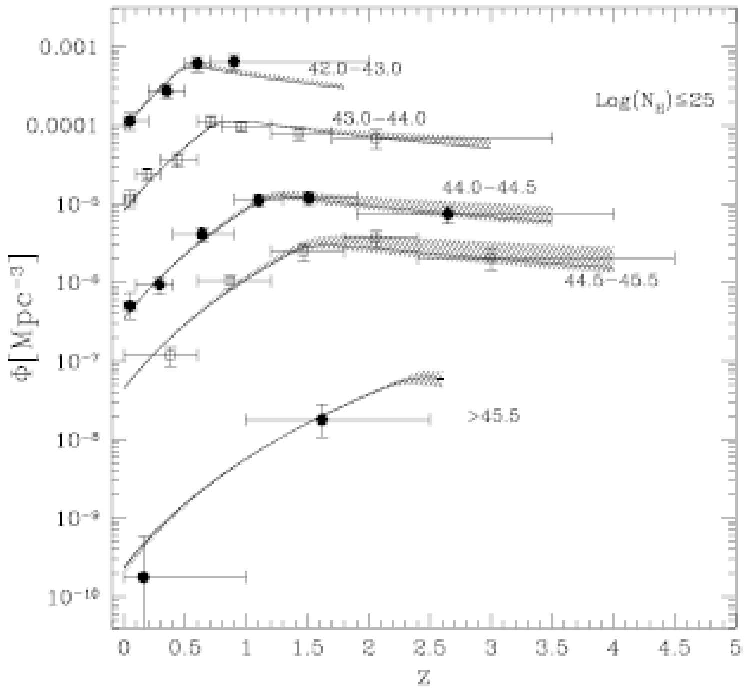
Therefore the picture is rather more complicated when we go at faint luminosities:
Luminosity Dependent Density Evolution
(Miyaji et al. 2001 , La Franca et al. 2005)

i.e. evolution along the y-axis (density) depending on luminosity



Density evolution for low
Luminosity objects up to z=0.7

Cosmic down-sizing

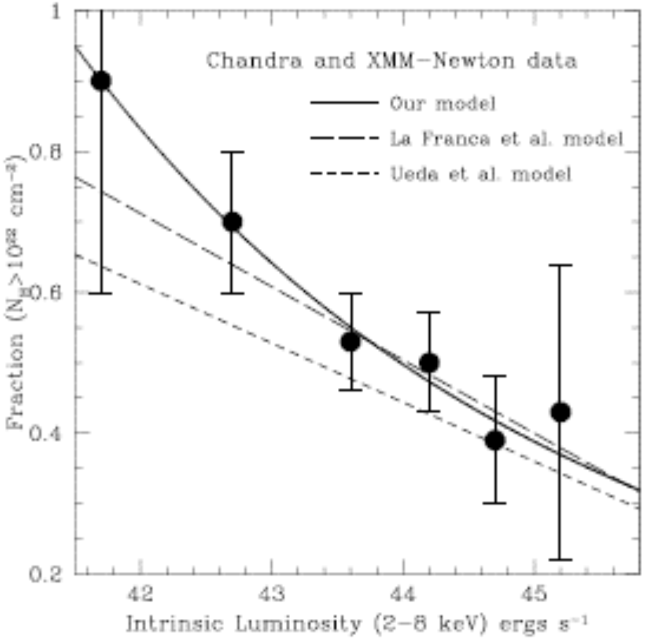


Anti-hierarchical model:

Less-luminous (less massive)
AGN form later (peak $z=0.7$)

high luminosity
(more massive sources)
peak at $z=1.5\text{-}2$

Absorption depends on Lx



Luminosity Function Derivation: $1/V_{max}$

- $\Phi(L_i) = n\ \Sigma\ 1/V_{max}$

Where V is the maximum volume where we can detect our source at the flux limit of the survey.

Essentially we give weight to the less luminous sources which cannot be detected at large redshifts.

For nearby sources where inverse square law applies:

$f_{limit} = L_i / 4\pi r^2$ we find r_{max} and thus V_{max}

The Cosmological “inverse square law”

The inverse square law is valid but instead the distance is:

$$d_L = \frac{c}{H_0 q_0^2}\left(q_0 z + (q_0 - 1)\left(\sqrt{1 + 2q_0 z} - 1\right)\right) \qquad \Lambda=0$$

Ω = matter density= 2q_o , z=redshift, Ho=Hubble constant

For $\Lambda>0$ things are even more complicated:

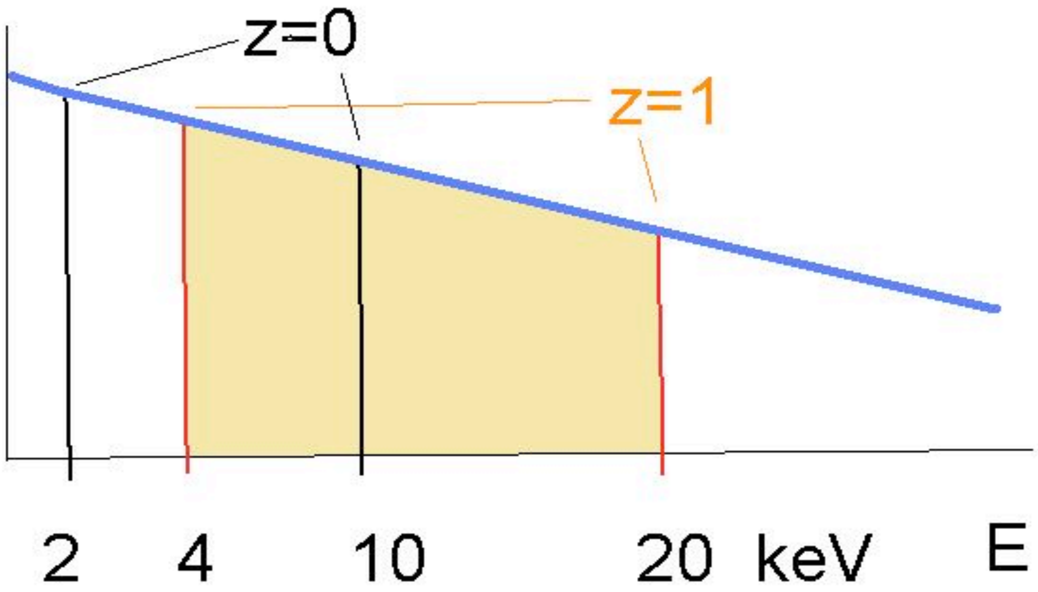
d_L = (1+z) (c/Ho) $\int$ dz / E(z)   where

$$E(z) \equiv \sqrt{\Omega_{\mathrm{M}}\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_\Lambda}$$

The k-correction

- The k-correction is introduced because at different redshifts we observe a different part of the spectrum.
- However, we need to refer to a ‘standard’ Common luminosity for all sources eg the luminosity in the 2-10 keV band.

Assuming that the spectrum is a single power law $I(E) \propto E^{-\alpha}$



$$K(z)=(1-\alpha)\log(1+z)$$

The cosmological distance modulus

$$\log Lx = 50.05 + \log F + 2 \log dL + (1-\alpha) \log(1+z)$$

Lx in erg s^{-1}, Flux in erg cm^{-2} s^{-1}, d_L in Mpc

As an example in the deepest X-ray image in the CDFN at z=5 we can detect a luminosity of Lx= 43.6 erg s-1

Survey Basics: flux limit

- The flux limit depends on the exposure time, the background and the angular resolution of the detector.

- In a given detection cell the signal-to-noise ratio:

$SNR = S / \sqrt{B}$ where S and B are the source and background photons.

We can increase the SNR i.e. the flux limit by <u>increasing the exposure time</u>

But both the background and source photons increase: then flux goes with $\sqrt{t}$

One way is to <u>reduce the background</u> that comes mainly from the particles. Another way is to make better the spatial resolution (essentially we make less the background).

Background Isotropy

One measure of anisotropy is the number of counts in cells

This IS NOT $\sqrt{N}$ as one may knaively expect

The intensity observed:

$$I = \int dN(f)\, f\, df\, d\Omega \qquad (1)$$

While the variance is:

$$\delta I^2 = \int dN(f)\, f^2\, df\, d\Omega \qquad (2)$$

Combining (1) and (2) : $\delta I/I \propto 1/\sqrt{\delta\Omega}$

i.e. the smaller the angle the larger the anisotropy

Anisotropy II

The full distribution carries more information:

Anisotropy III

Sources are not distributed randomly

They are clustered following the function $\xi(r) = (r/ro)^{-1.8}$

which translates in two dimensions:

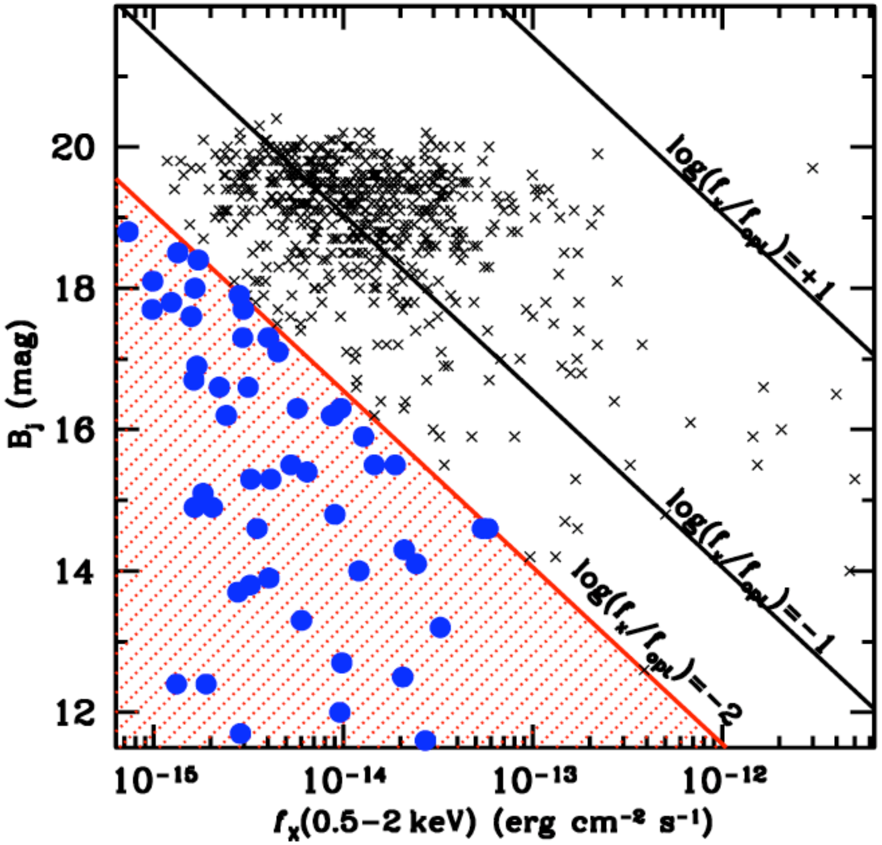
$$w(\theta) = (\theta/\theta o)^{-0.8}$$

The variance then becomes:

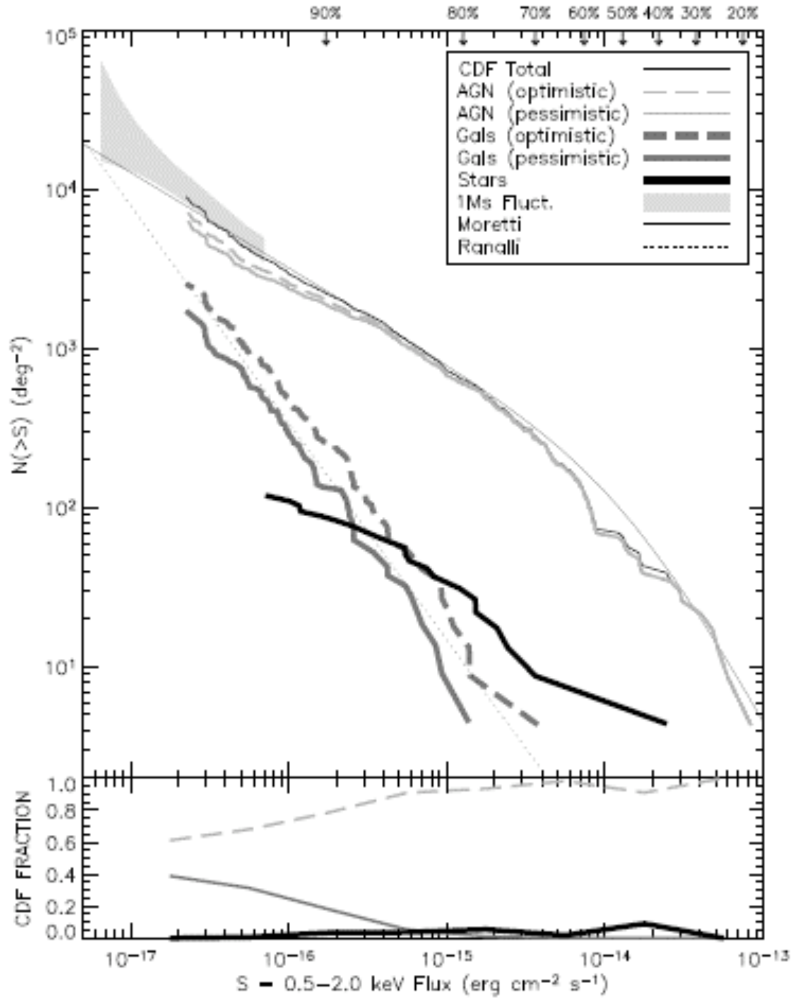
$I^2 \ \Omega + \int \ w(\theta)\ \delta\Omega_1\ \delta\Omega_2$ (Peebles 1980, Peebles 1993)

where $I = dN(f)\ f\ df\ d\Omega$

Contamination: galaxies



Normal galaxies logN-logS



THE END