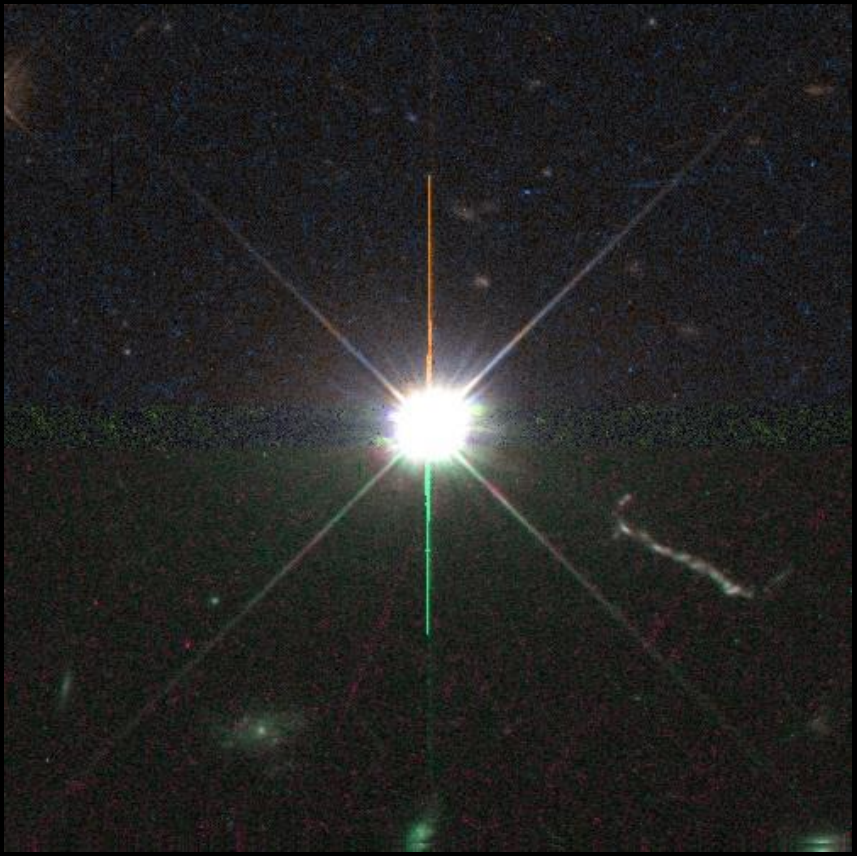
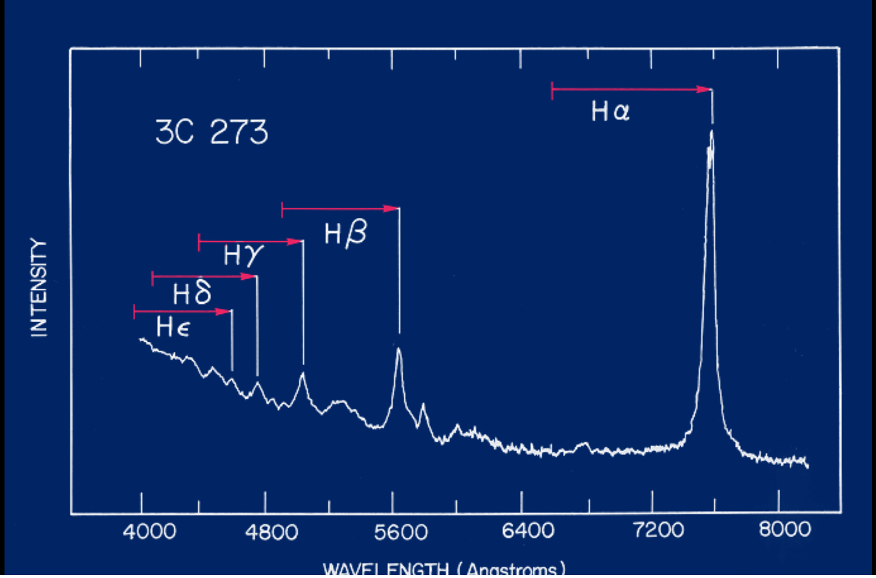
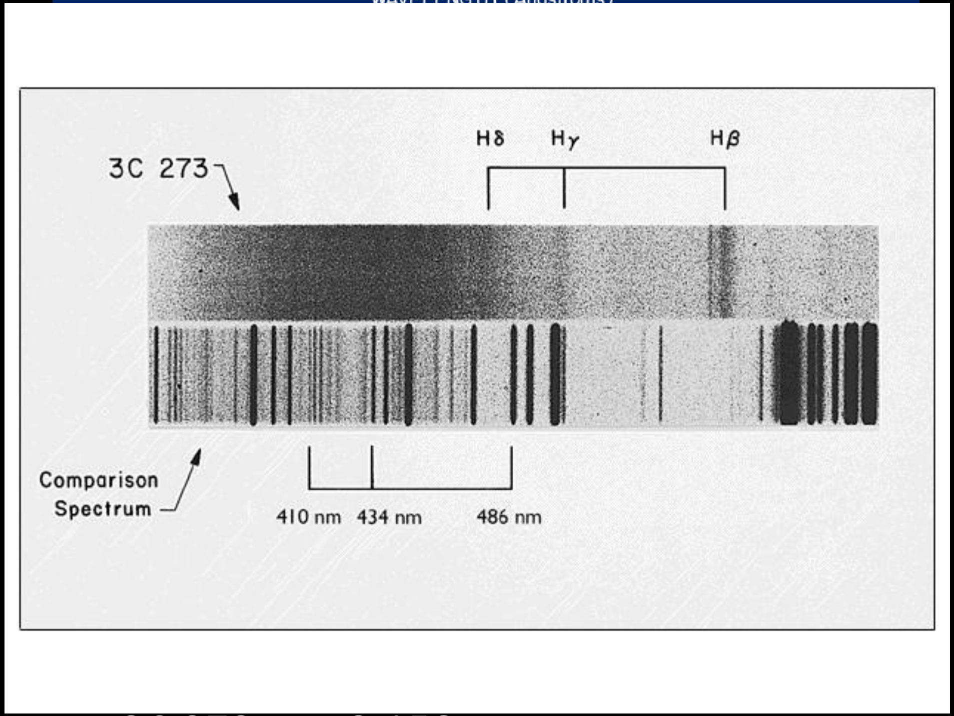
Active Galactic Nuclei

- quasars = quasi-stellar radio sources
- initially discovered by the optical follow-up of radio sources
- appeared point-like or star-like when viewed in the optical



The quasar 3C 273





3C 273: $z = 0.158$

- optical spectra show broad emission lines
- wavelengths of lines did not correspond to known features
- In 1963, Maarten Schmidt could make sense of the 3C 273 spectrum if the lines were shifted to longer wavelengths (*redshifted*) by 15.8%

- Seyferts & Quasars
  - Seyferts : $M_B > -21.5 + 5 \log h_0$, closer, mainly in spirals

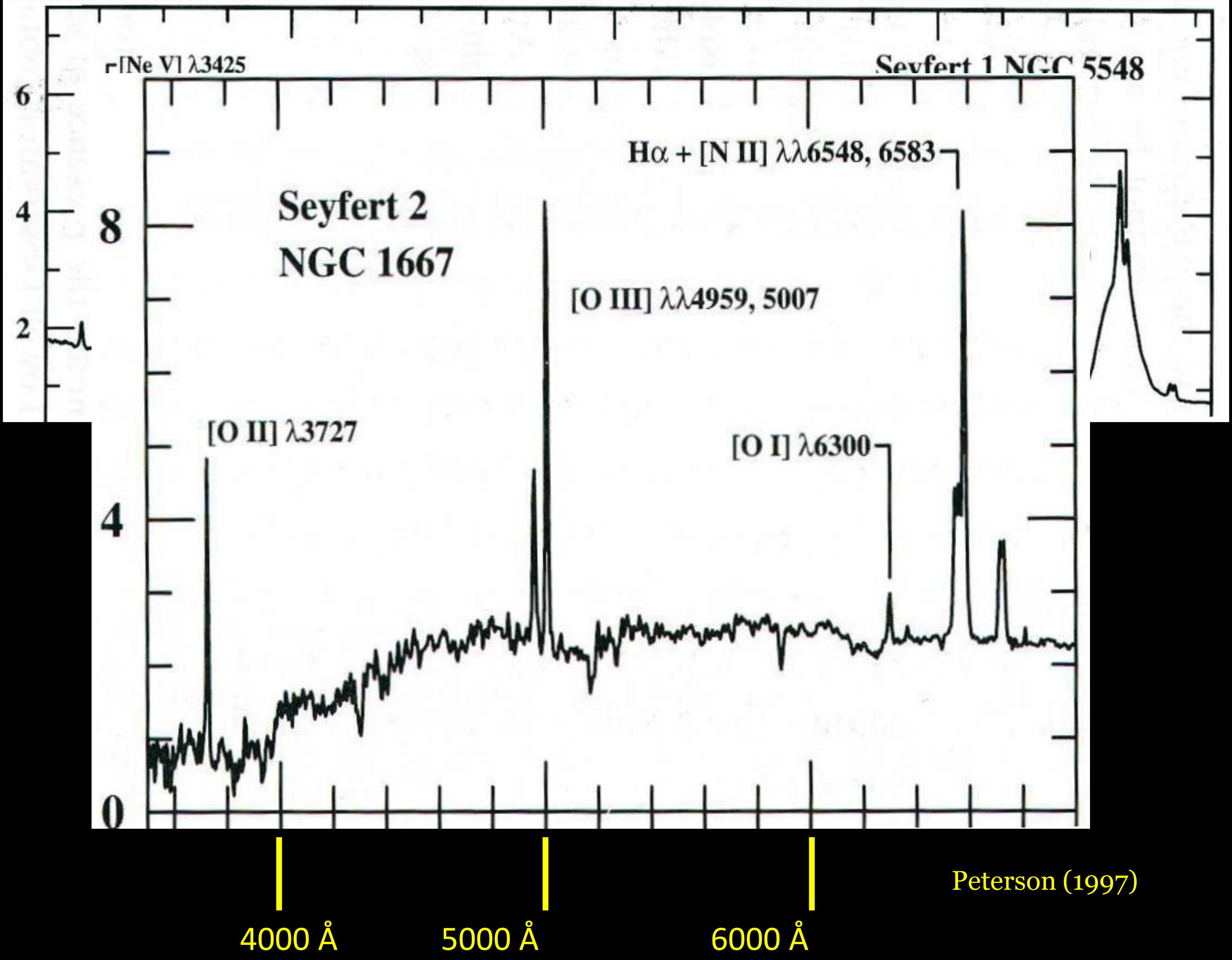
Galaxy NGC 7742

Hubble Heritage

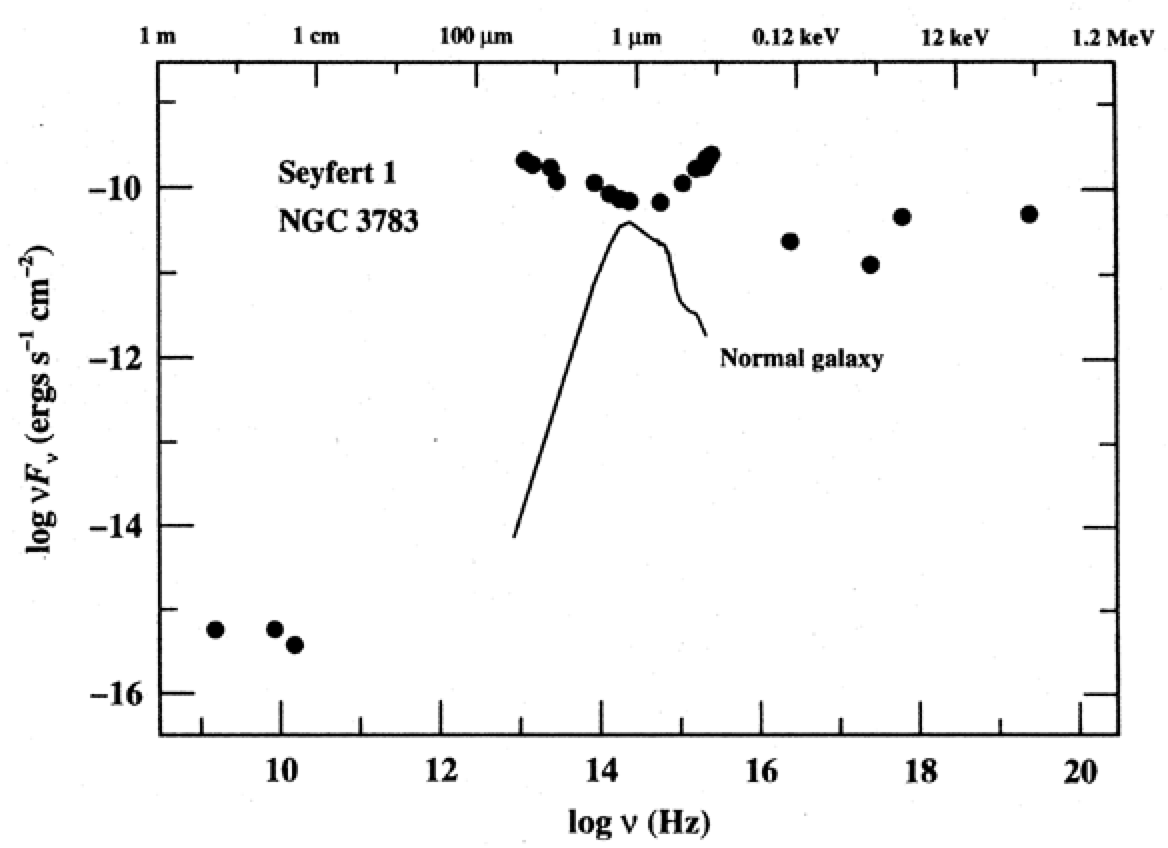
PRC98-28 • Space Telescope Science Institute • Hubble Heritage Team

- First noticed by Carl Seyfert in the 1940s
- Typically spiral galaxies which had a bright, point-like nucleus
- Since less luminous as quasars, harder to detect at such large redshifts

- AGNs are split into 2 classes
  - Type 1: Optical spectra show broad ($v \sim 10^4$ km s^{-1}) permitted lines and narrow (a few hundred km s^{-1}) forbidden lines
  - Type 2: no broad lines are visible

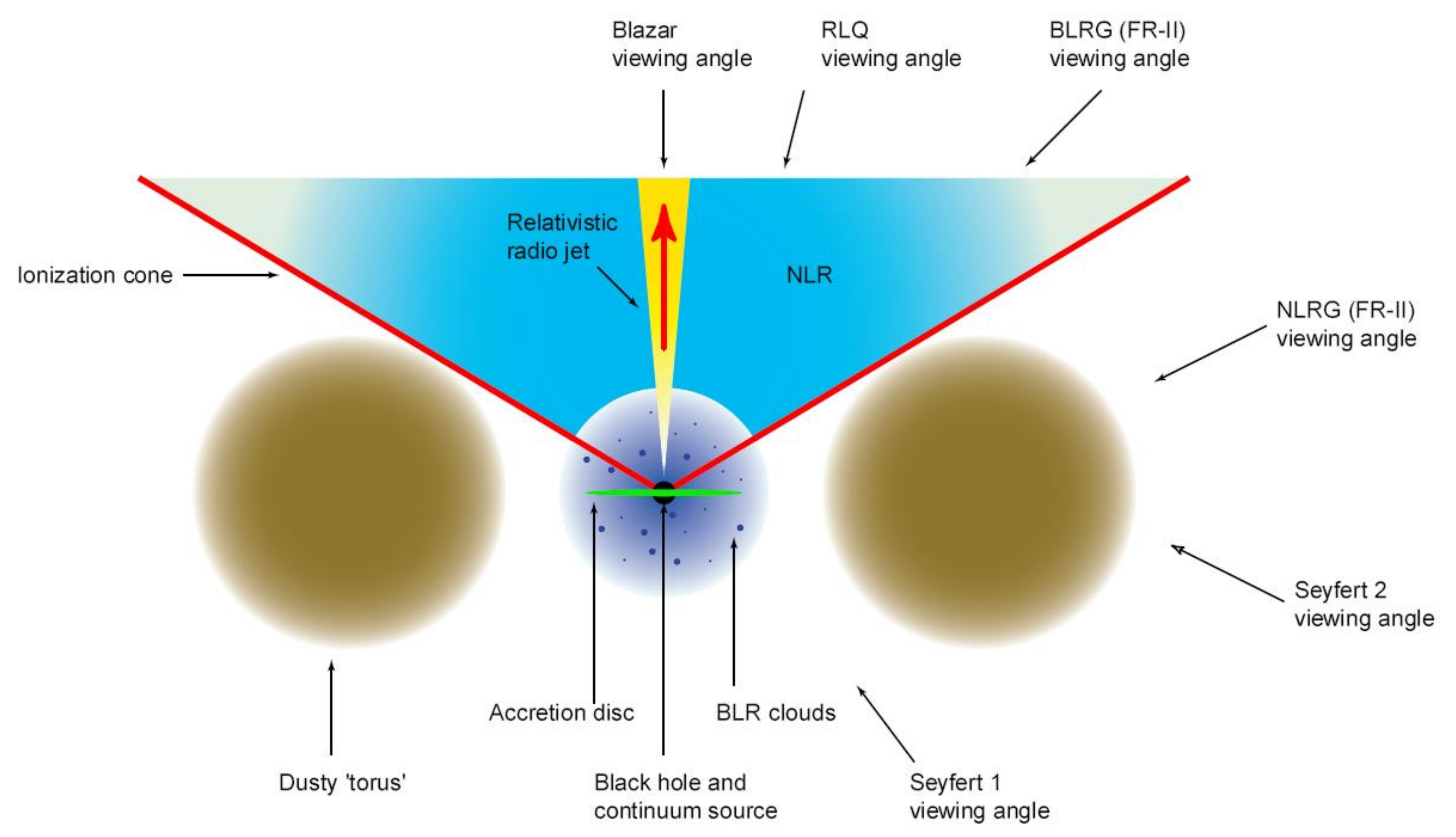


Peterson (1997)



AGNs produce strong emission across the entire electromagnetic spectrum.

AGN Unified Model



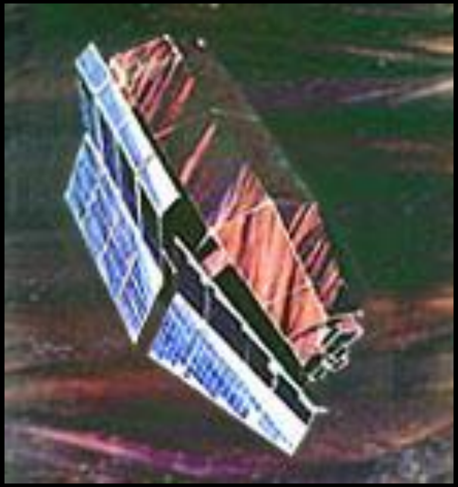
X-rays from AGN: The Past

Ariel-V (1974-1980) 0.3-40 keV
Established that all Seyfert 1 galaxies are bright X-ray sources.

HEAO-1 (1977-1979) 0.2 keV-10 MeV
First large spectral sample of AGN. Well modelled over 2-20 keV by power law:

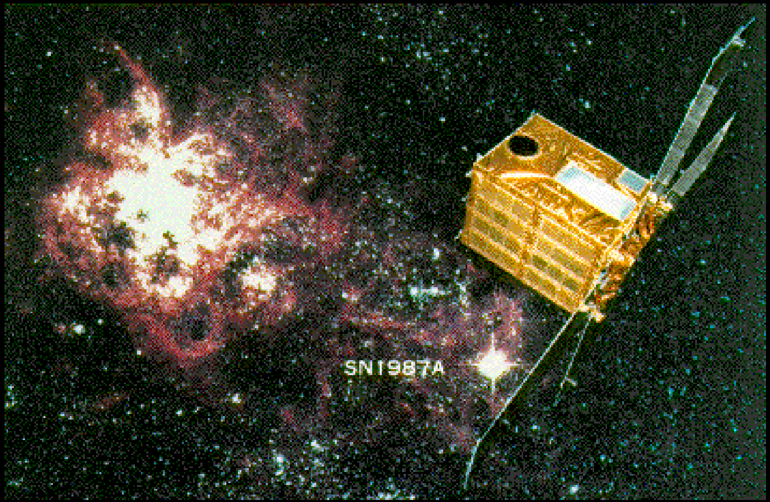
Photon Flux $\propto E^{-\Gamma}$ ph cm^{-2} s^{-1}keV^{-1}

Found narrow dist'n around $\Gamma = 1.7$



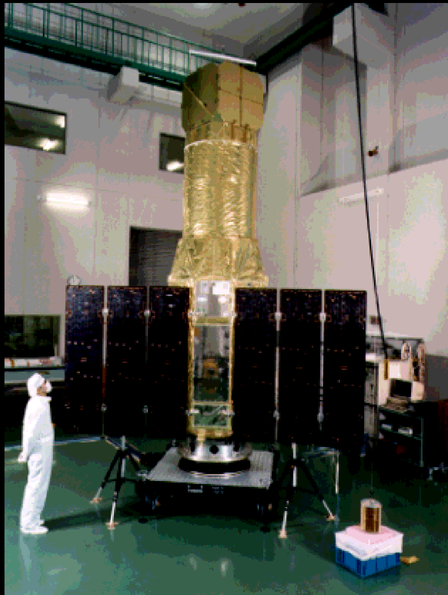
Einstein Obs. (1978-1981) 0.2-20 keV
First focusing X-ray telescope with 2” resolution.
Showed that all AGN are strong X-ray emitters. Confirmed the $\Gamma=1.7$ slope in the 0.7-4 keV band for Sy 1s.

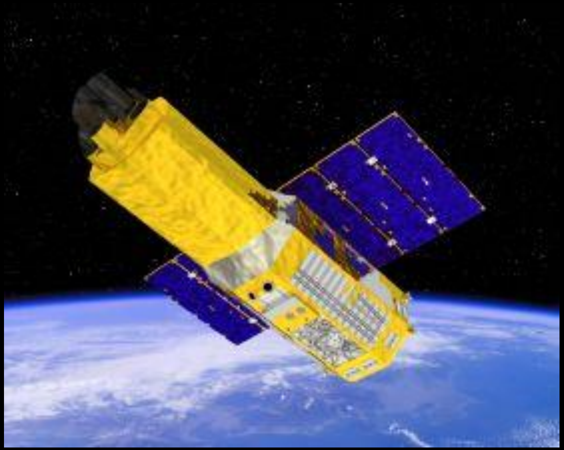
EXOSAT (1983-1986) 0.05-50 keV
Discovered a ‘soft excess’ in $\sim$50% of Seyferts. 3 day orbit allowed long timing studies. First derivation of AGN power density spectra.



Ginga (1987-1991) 1.5-37 keV
Increase in sensitivity allowed discovery of strong Fe Kα line emission in many Seyferts. Also discovered the spectral hardening > 8 keV. Ushered in the reflection paradigm.

ASCA (1993-2001) 0.4-10 keV
First X-ray telescope to use CCDs. First detection of relativistically broadened Fe Kα lines. Allowed characterization of the warm absorber. Extended studies to quasars.



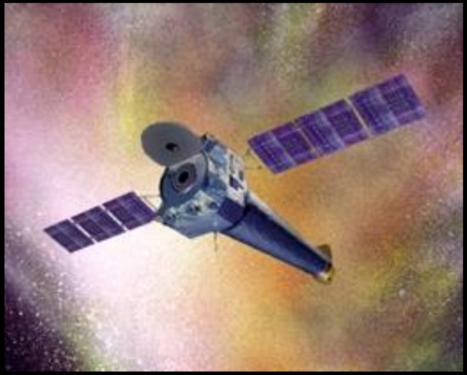


Suzaku (2005-2015) 0.2-600 keV

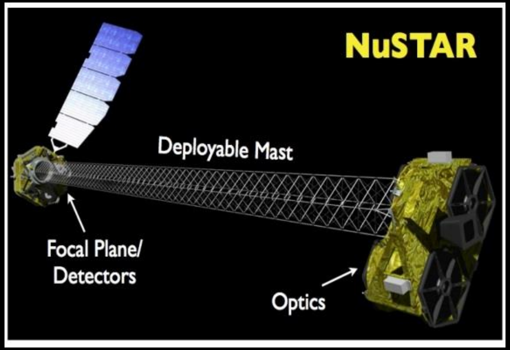
Carried hard X-ray instruments (non-imaging) plus 3 CCD soft X-ray detectors allowing broadband spectroscopy. Area was smaller than *XMM-Newton* but had higher resolution around the Fe K line.

X-rays from AGN: The Present (1999-?)

XMM-Newton



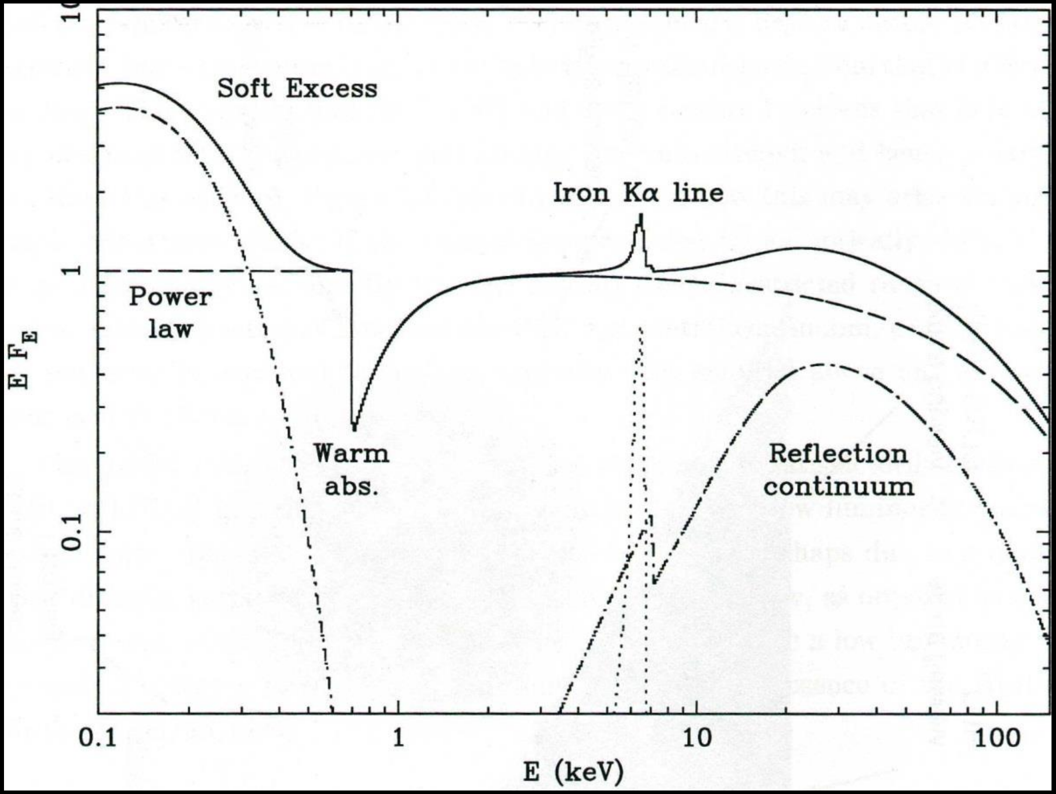
Chandra



NuSTAR

Chandra & *XMM* have combined range of 0.2-12 keV. Both carry gratings to provide dispersed spectra. *Chandra* has sub-arcsecond imaging. *XMM-Newton* has more than 10× the sensitivity of *ASCA*. *NuSTAR* has an energy range of 3-80 keV. First ever hard X-ray imaging telescope.

Current Spectral Model: Overview



Taking into account reflection increases the intrinsic power law to $\Gamma \sim 2$.

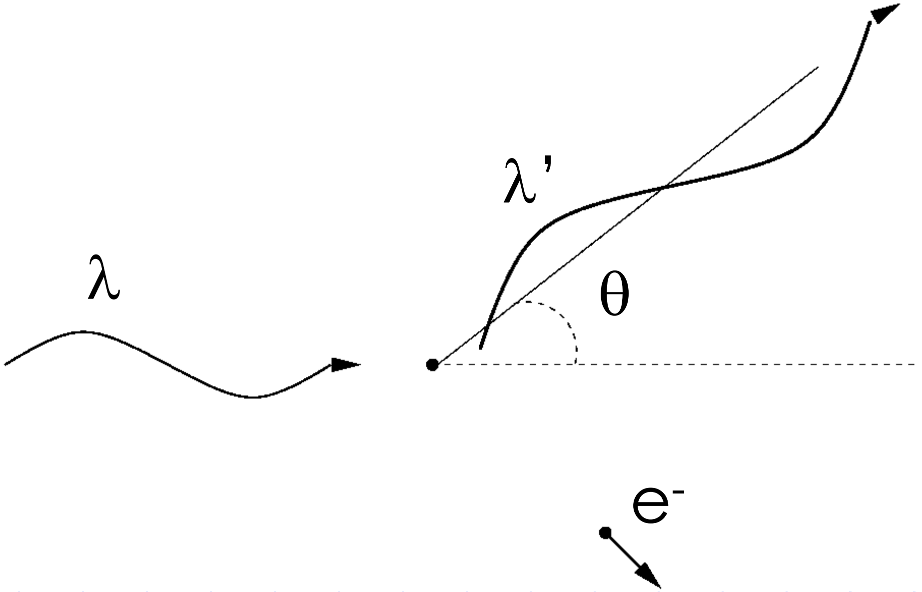
Spectral Model: The power law

- In a sense, it is not clear why AGN emit X-rays at all. But $L_{2\text{-}10\ \mathrm{keV}} \sim 0.15\ L_{\mathrm{Bol}}$.
- Optically-thick accretion disc:

$$T_{\max} = 12\left(\frac{\dot{M}}{0.1\dot{M}_{\mathrm{Edd}}}\right)^{1/4}\left(\frac{\eta}{0.1}\right)^{-1/4}\left(\frac{M}{10^{7}M_{\odot}}\right)^{-1/4}\ \mathrm{eV}$$

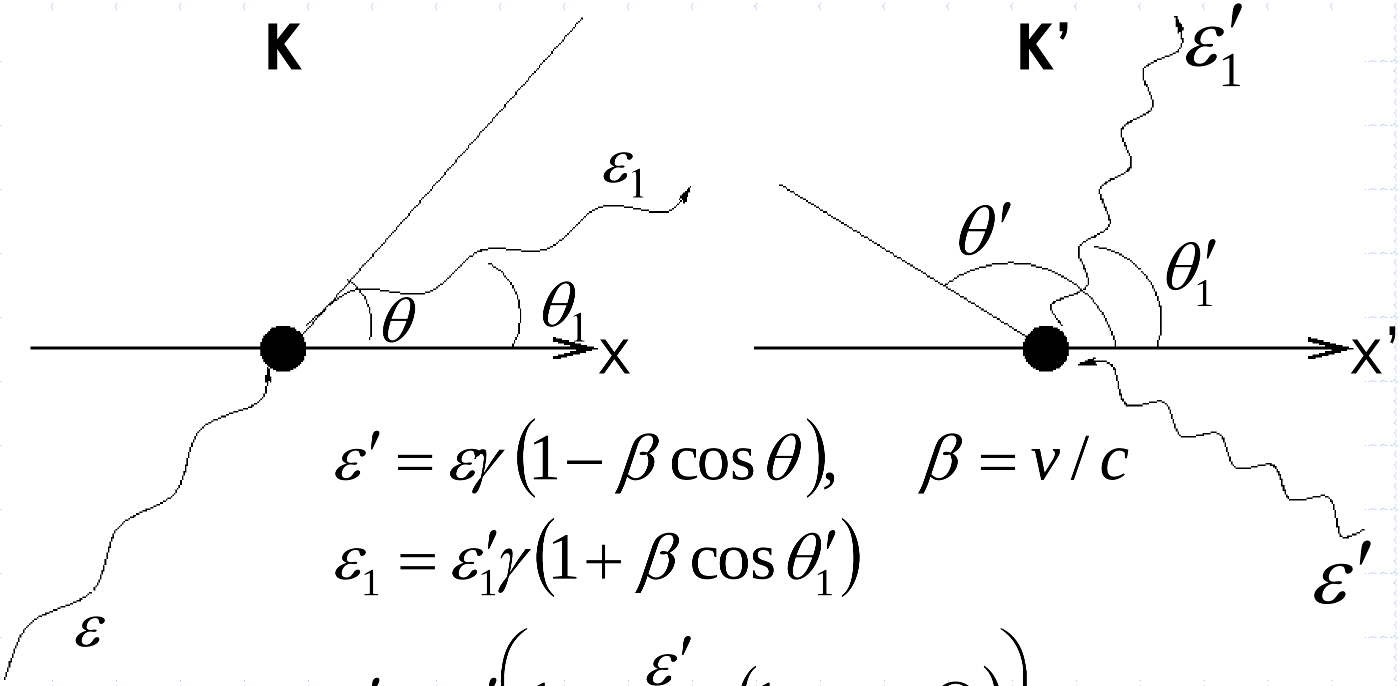
- Synchrotron does not work (predicts sig. γ-ray emission)
- Bremsstrahlung requires a large volume of very hot gas ($\sim 10^9$ K), but variability causes problems

- If there are some hot electrons around, then UV photons can be 'up-scattered' to X-rays
- Recall Compton scattering:



$$\Delta\lambda = \frac{h}{m_e c}\left(1 - \cos\theta\right)$$

- But when e^- is moving, then photon can gain energy ⇒ inverse Compton scattering



$$\varepsilon' = \varepsilon\gamma\left(1-\beta\cos\theta\right), \quad \beta = v/c$$

$$\varepsilon_1 = \varepsilon_1'\gamma\left(1+\beta\cos\theta_1'\right)$$

$$\varepsilon_1' = \varepsilon'\left(1-\frac{\varepsilon'}{mc^2}\left(1+\cos\Theta\right)\right)$$

- If e^- with Lorentz factor γ then photon energy can be boosted by $\sim\gamma^2$.

- More interesting case: repeated scatterings off of thermal electrons by low energy photons ($h\nu \ll m_e c^2$)
- Restrict attention to non-relativistic e^- ($kT \ll m_e c^2$)

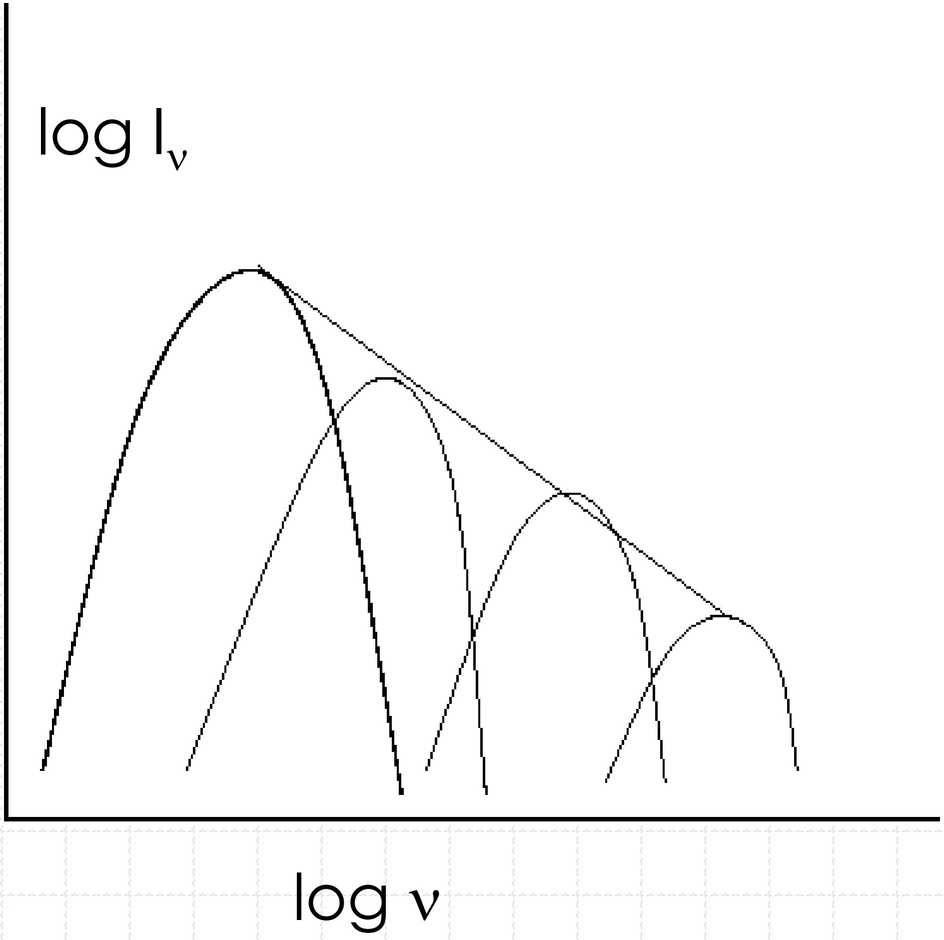
In this case the average fractional change in energy per scattering:

$$\left\langle \frac{\Delta\varepsilon}{\varepsilon} \right\rangle = \frac{4kT}{m_e c^2} - \frac{\langle \varepsilon \rangle}{m_e c^2}$$

If $\varepsilon > 4kT$ energy transferred to electrons.

If $\varepsilon < 4kT$ energy transferred to photons.

- The importance of Compton scattering is given by:



$$(\tau,\tau^2)$$

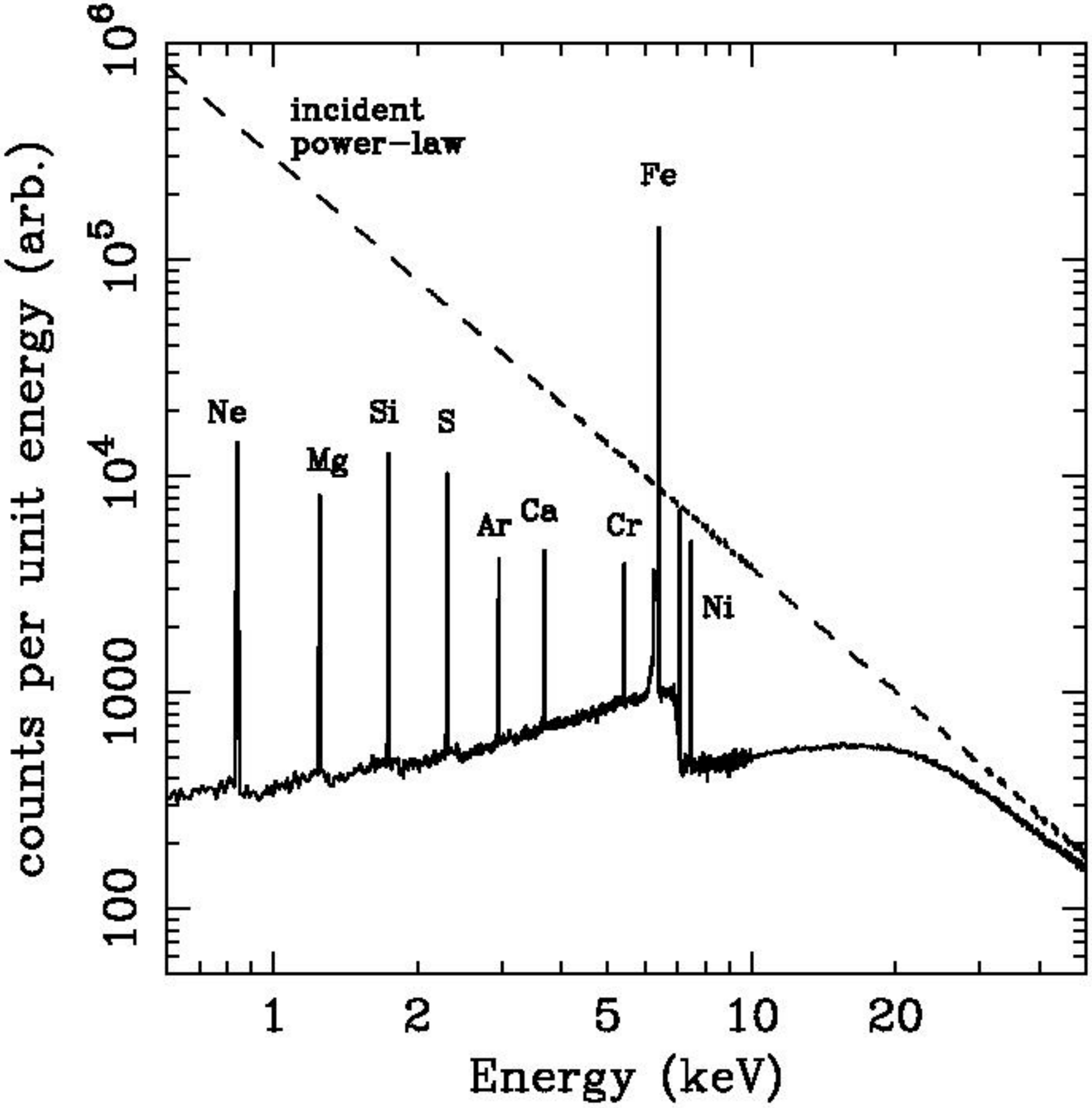
hot gas.

rum: $I_\nu \propto \nu^3 e^{-h\nu/kT}$

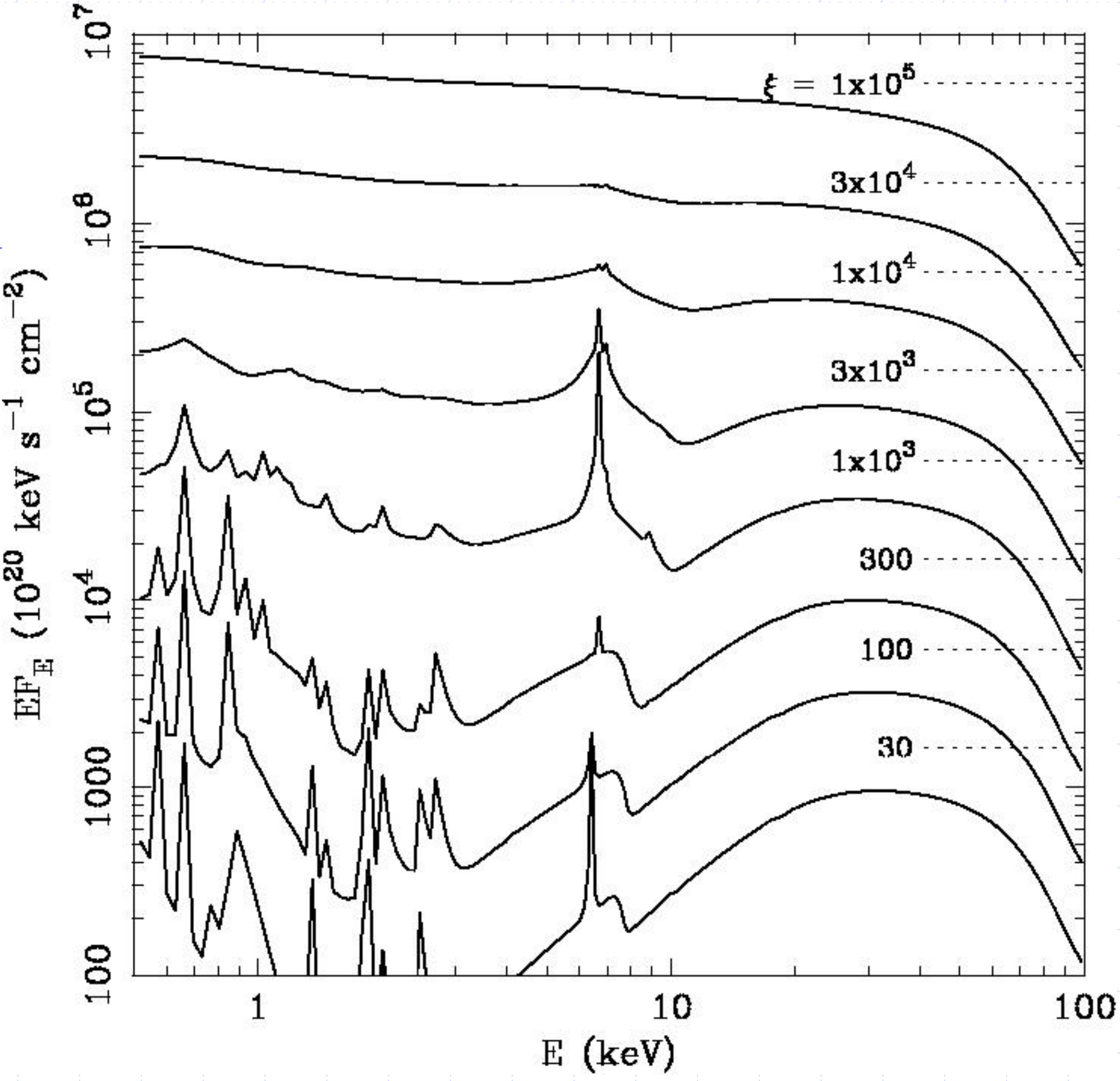
$$I_\nu \propto \nu^{3/2-\sqrt{9/4+4/y}} e^{-h\nu/kT}$$

Spectral Model: Reflection

- *Ginga* found strong Fe Kα emission at 6.4 keV (cold iron). This is a fluorescence line.
- No correlation of line strength with line-of-sight absorption.
- *Ginga* also found spectral hardening above 8 keV
- Both features explained by X-ray reprocessing in optically-thick material.
- Out of the line-of-sight but would subtend a significant solid-angle as seen from the X-ray source



George & Fabian (1991); Matt, Perola & Piro (1991)

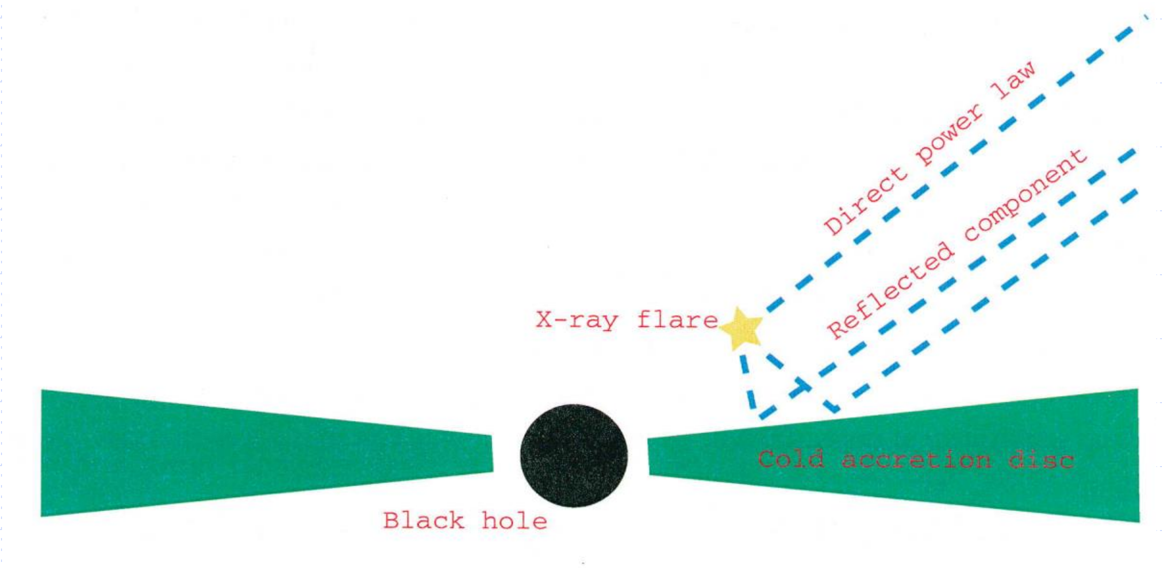


$$\xi = \frac{4\pi F_X}{n_H}$$

Ross, Fabian & Young (1999)

- So, where is the reflector?

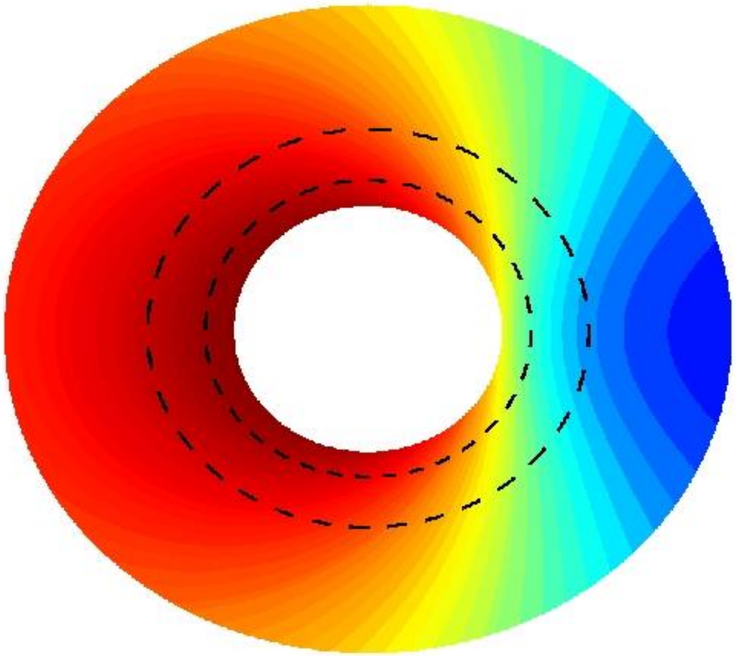
How about the accretion disc:

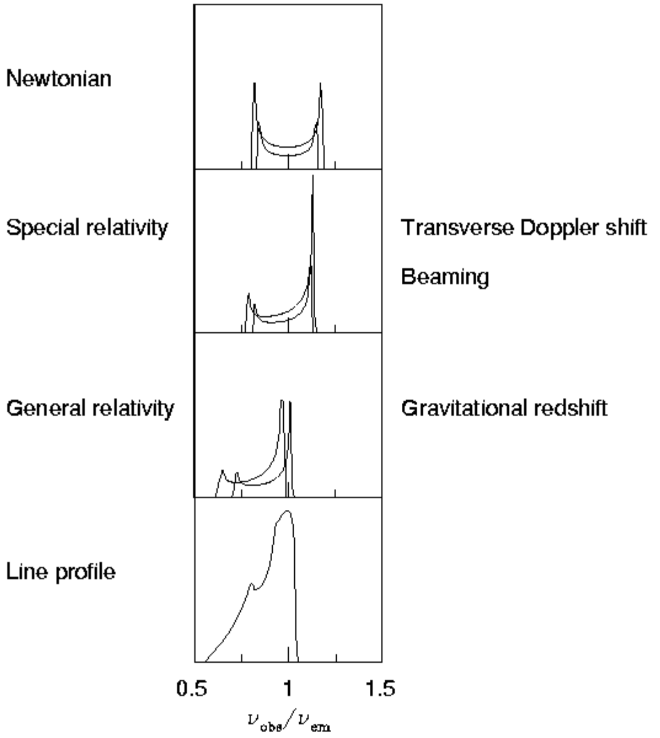


This makes an interesting prediction…

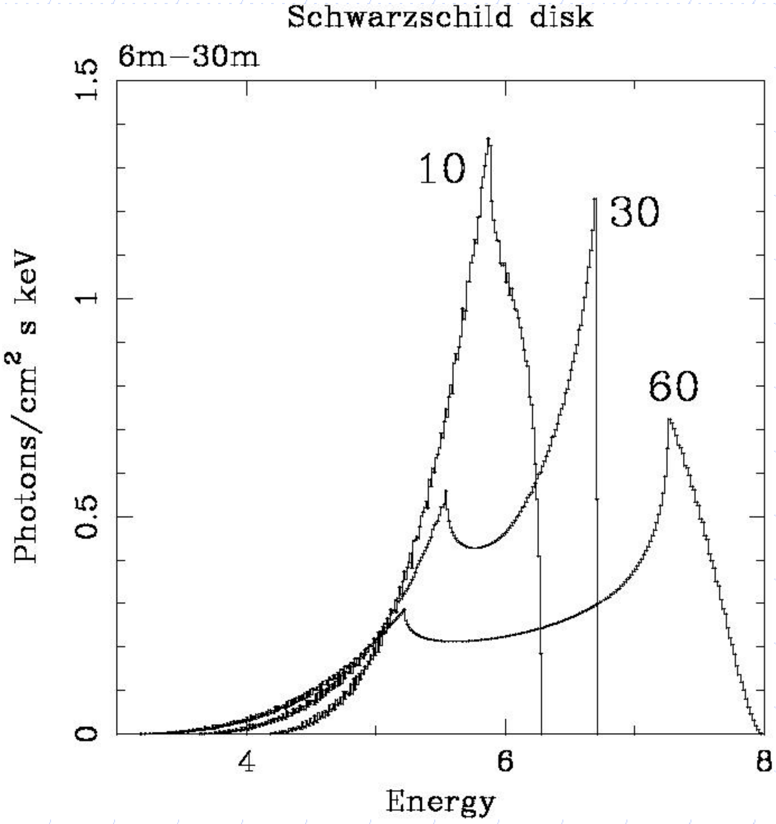
Spectral Model: The Fe Kα line

- What happens to an emission line which originates from a spinning disc close to a black hole?





- Shape depends on inner and outer radius of emission region, inclination of disc and emissivity profile.

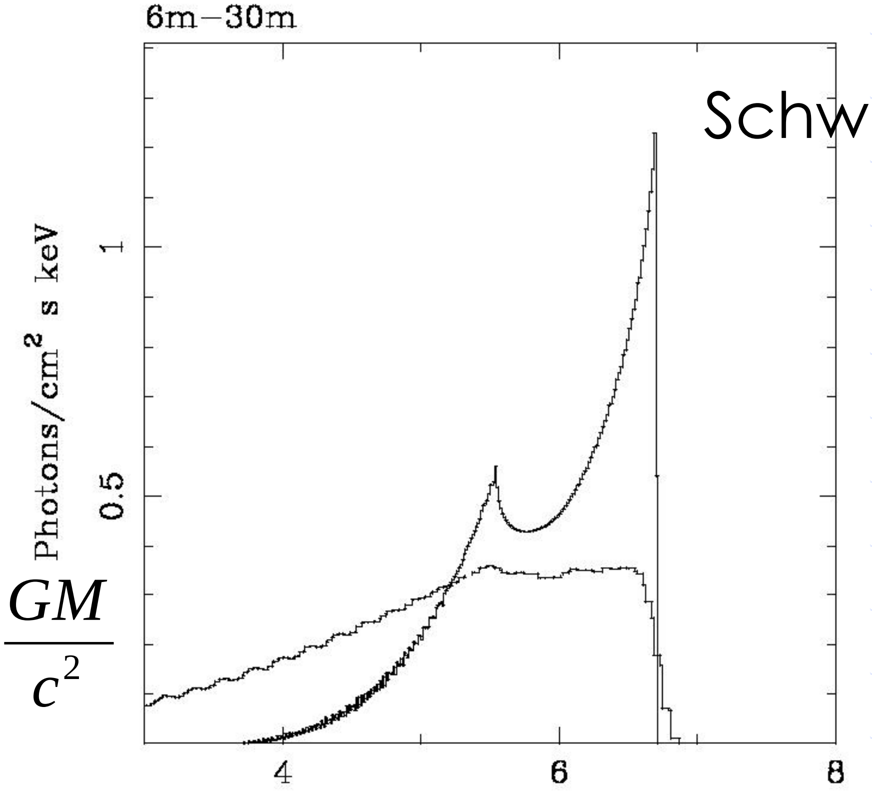


Inclination angle.

Fabian et al. (2000)

- The red-wing primarily determined by inner radius

$\therefore$ Possible to determine space-time around black hole.



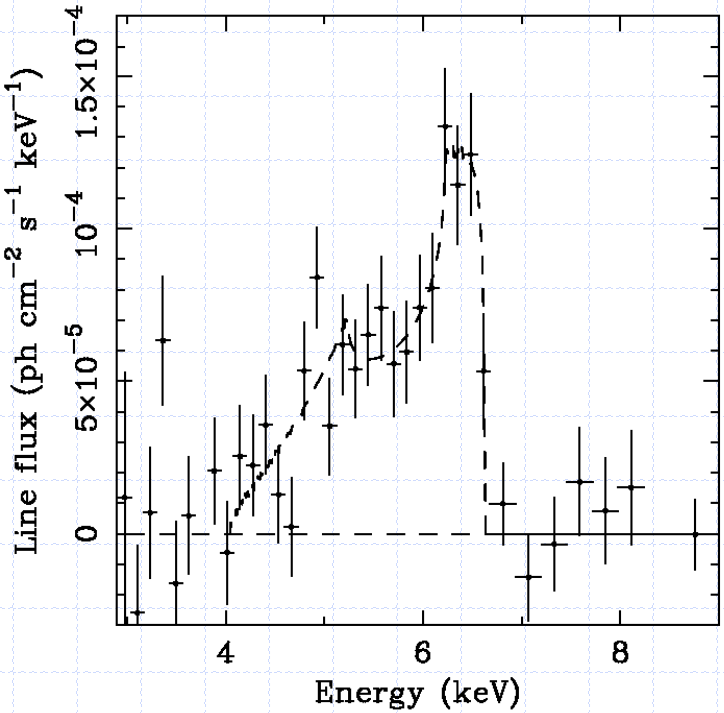
Schwarzschild

$$r_{in} = 6\frac{GM}{c^2}$$

Kerr

$$r_{in} = 1.25\frac{GM}{c^2}$$

Fabian et al. (2000)

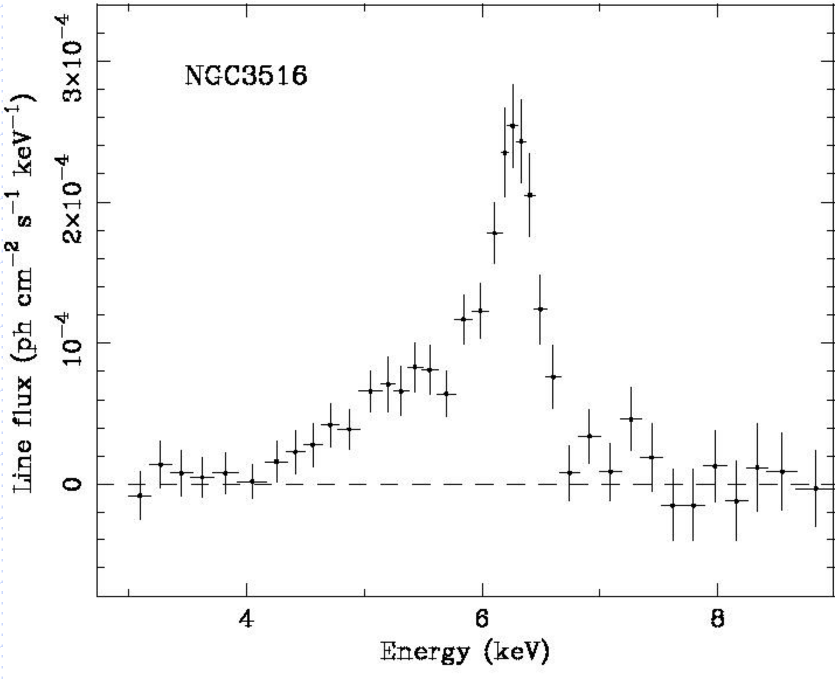


MCG—6-30-15

Tanaka et al. (1995)

NGC 3516

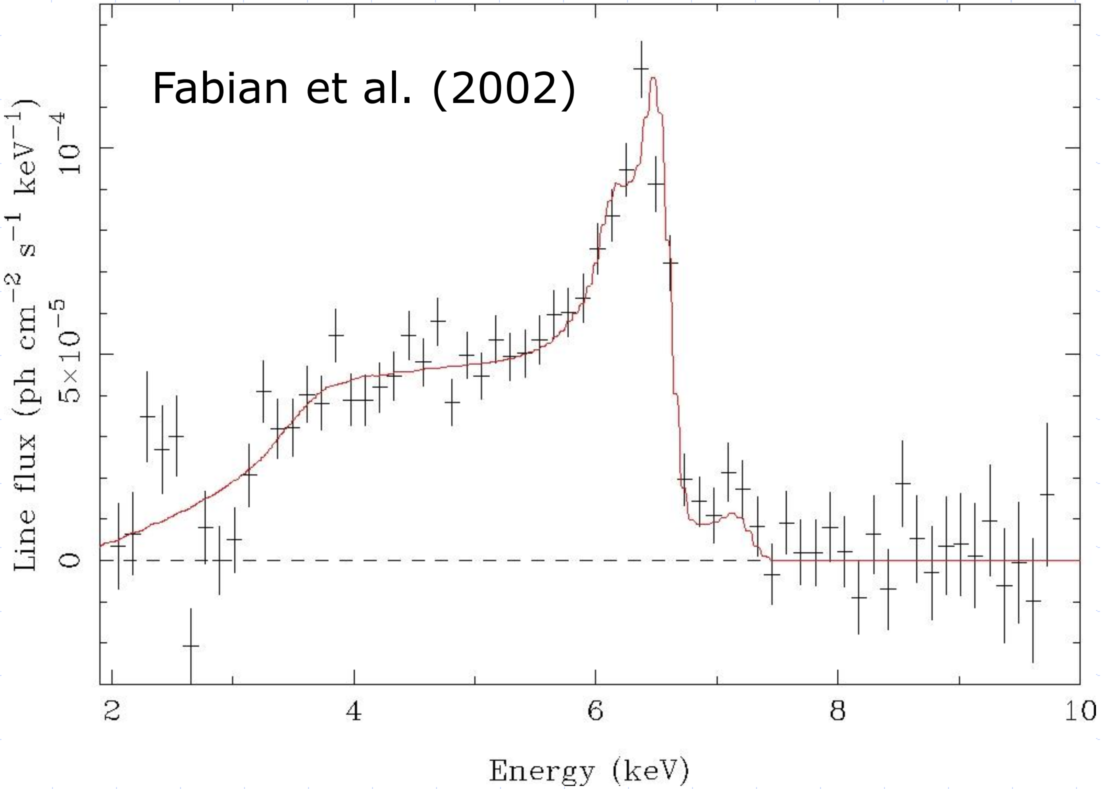
Nandra et al. (1999)



The Case of MCG-6-30-15

- 330 ks = 3.8 days *XMM-Newton* observation of MCG-6-30-15.

- Highest quality hard X-ray spectrum of a Sy1 ever made



Best fit with a broken power law emissivity:

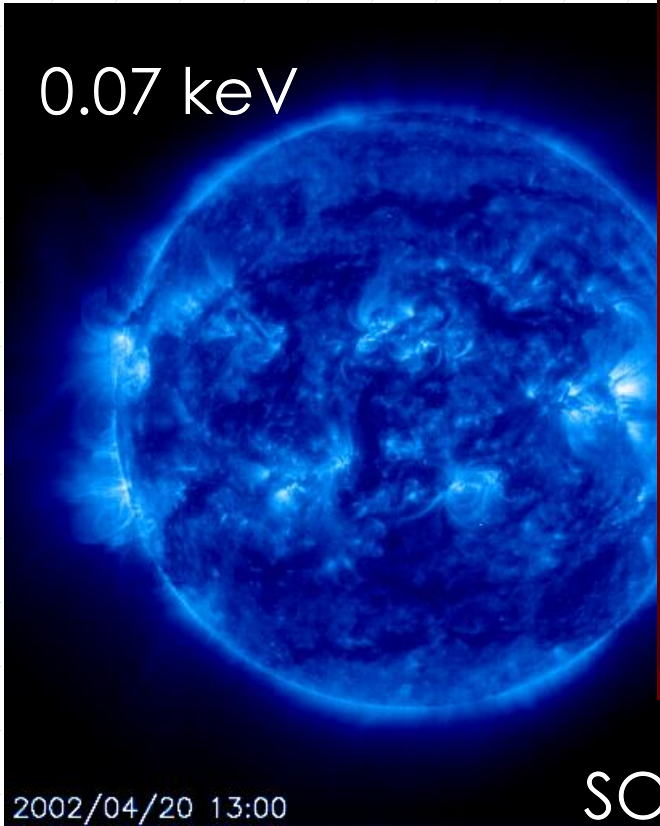
$$F(r) \propto r^{-q}$$

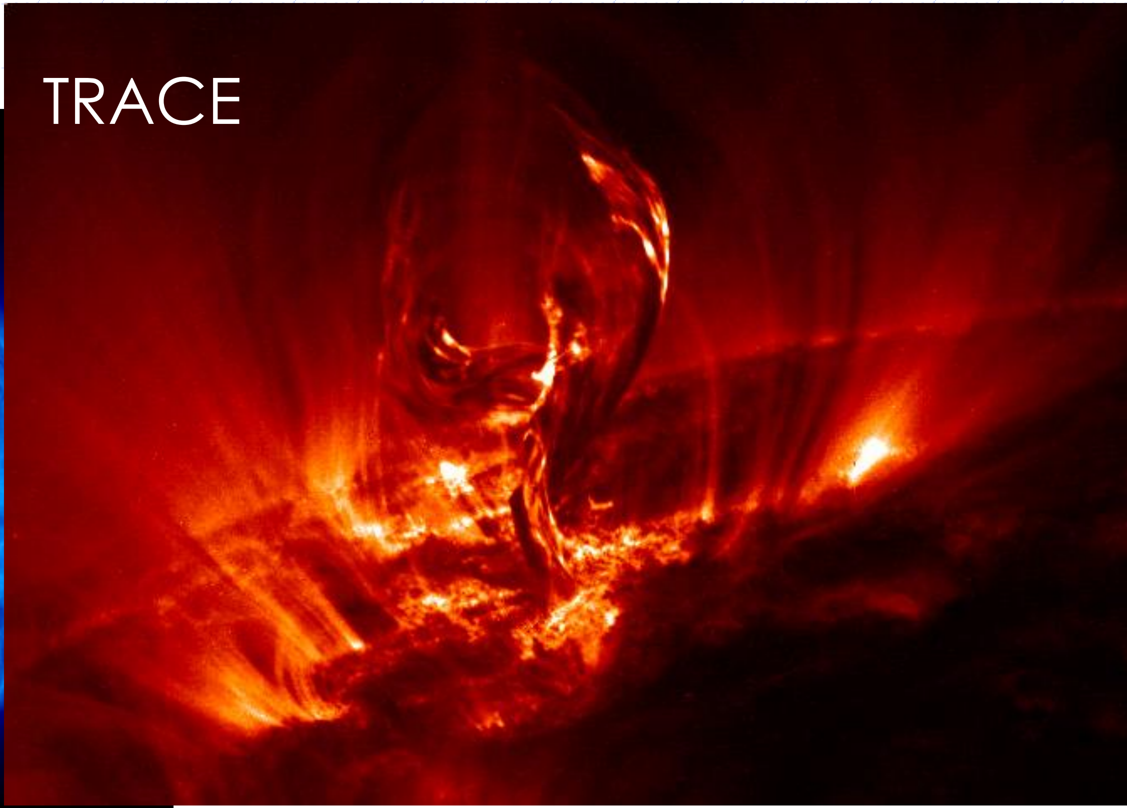
$$q = 4.8, r < 6\frac{GM}{c^2}$$

$$q = 2.6, r > 6\frac{GM}{c^2}$$

Accretion Discs

- The energy that produces the X-rays must come from the accretion power. How to convert into X-rays?
- Look to the Sun…

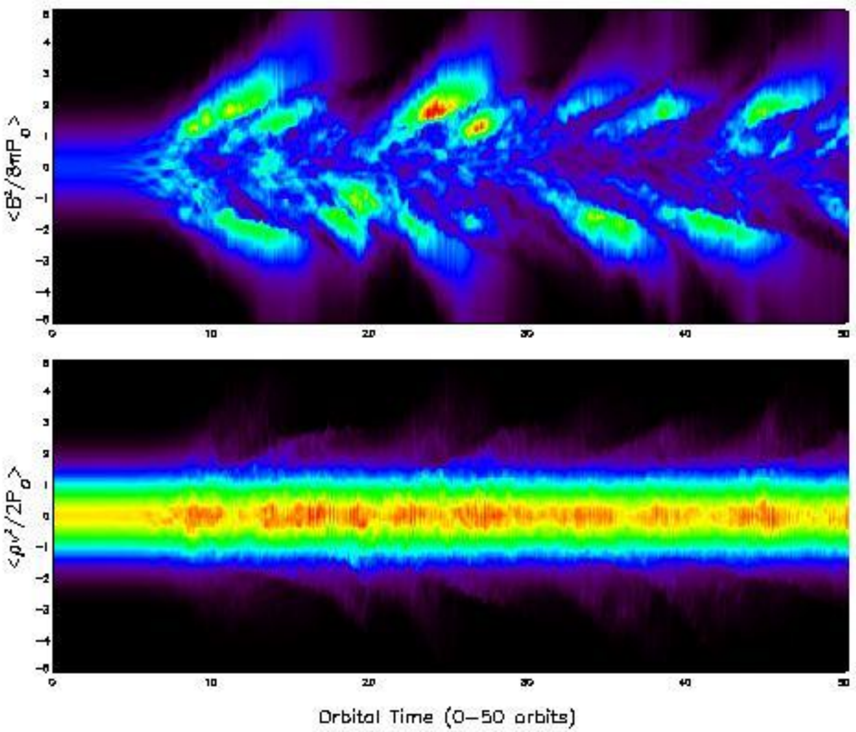




- Buoyancy and Parker instabilities will cause the generated magnetic field to be expelled ⇒ magnetically dominated corona

$$\left\langle \frac{B^2}{8\pi P_0} \right\rangle$$

$$\left\langle \frac{\rho v^2}{2P_0} \right\rangle$$

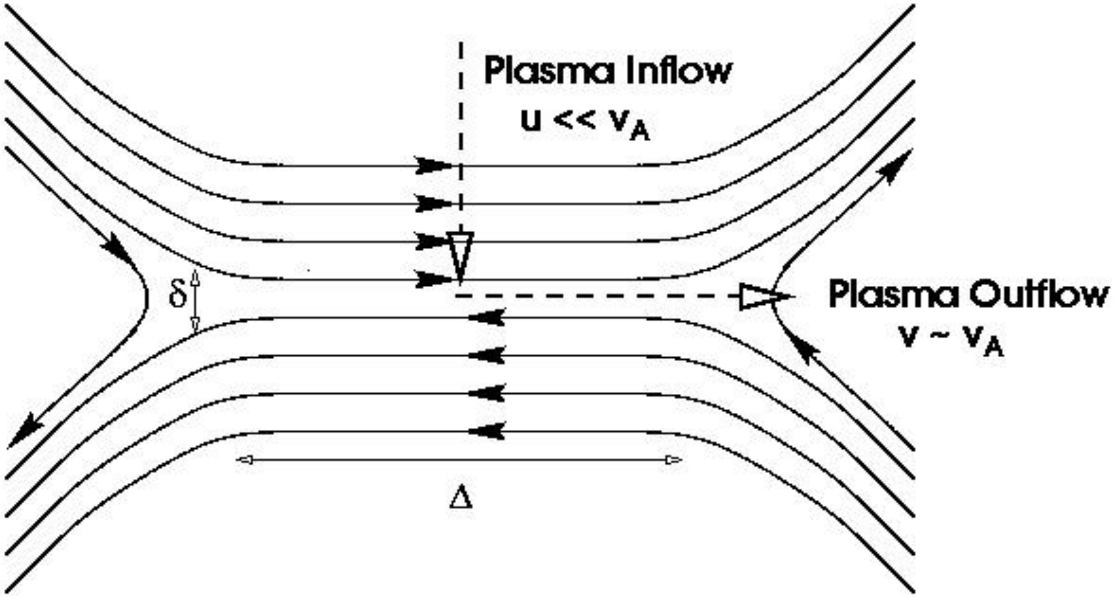


Miller & Stone (2000)

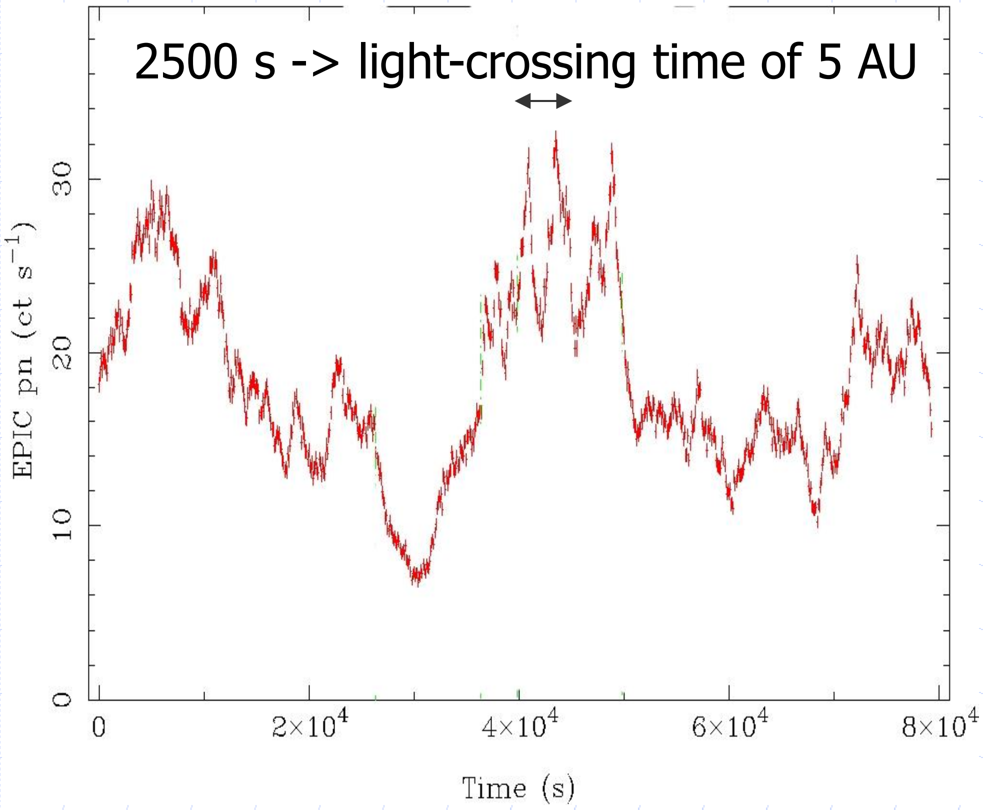
+/- 5 disc scale heights

Orbital Time

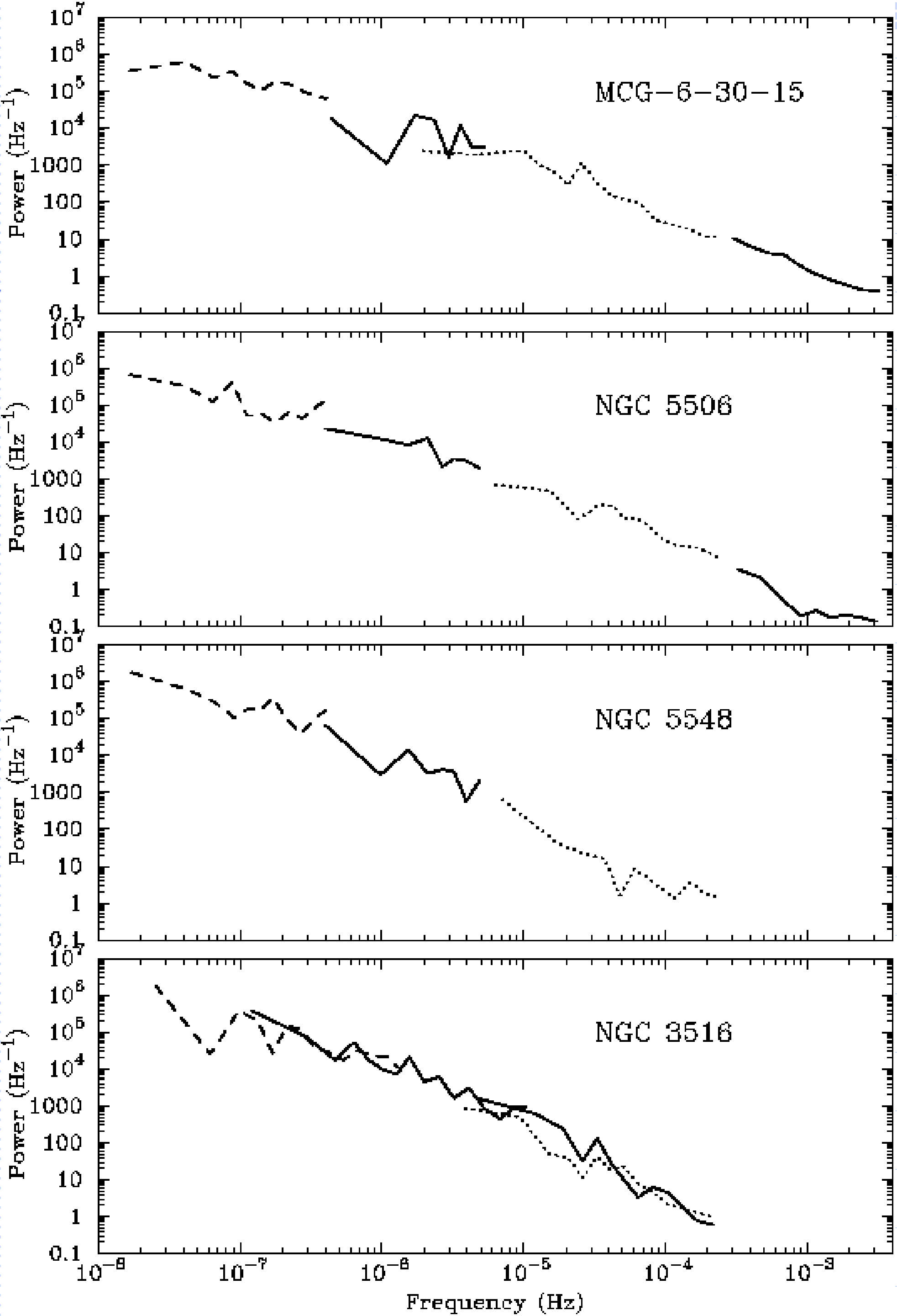
- Magnetic reconnection would then presumably occur above the disc.
- This would release the accretion energy carried by the magnetic field and generate a hot plasma



X-ray Variability



MCG-6-30-15; Fabian et al. (2002)



Roughly power law power density spectra.

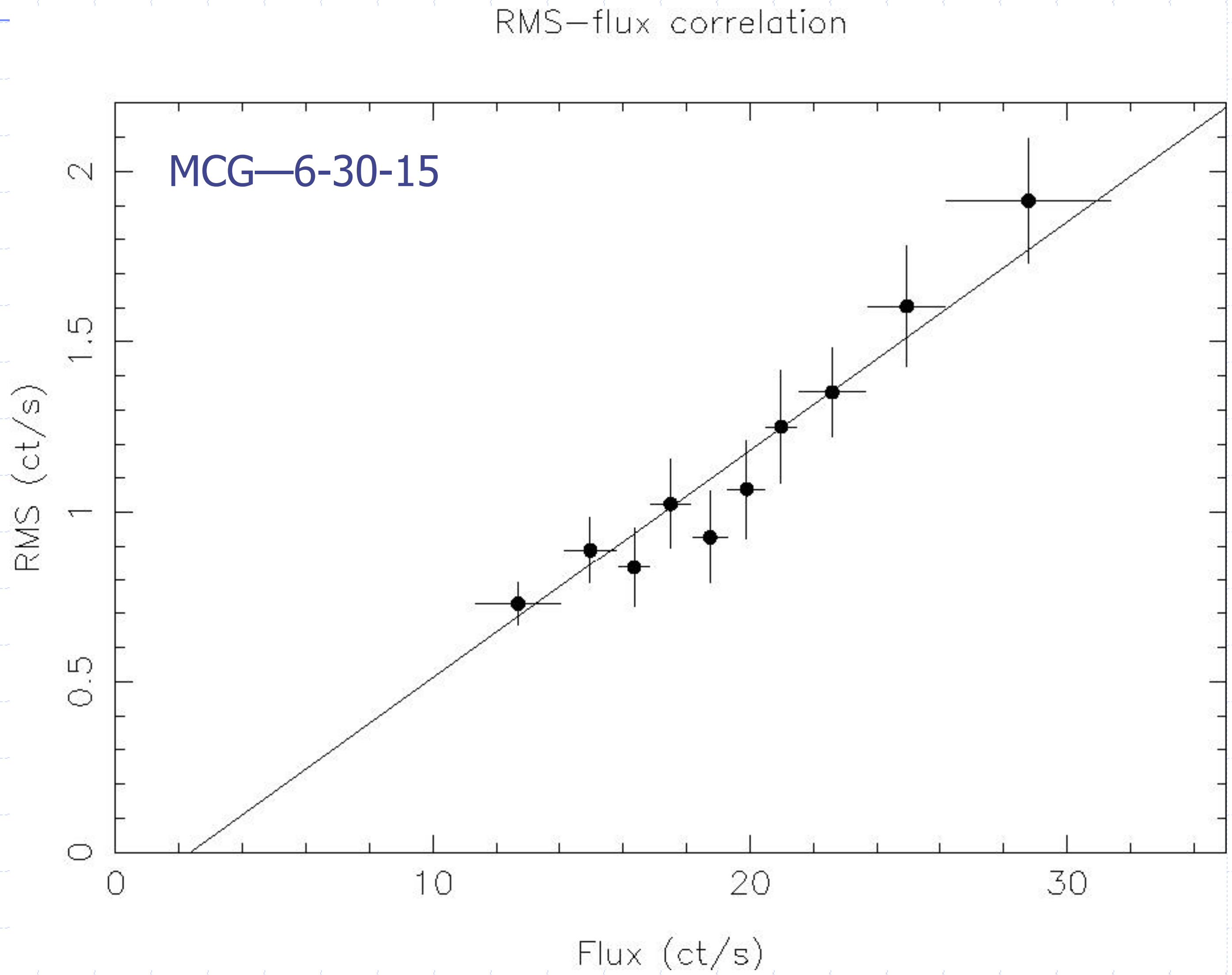
$$\mathrm{Power} \propto \nu^{-\alpha}$$

$$\alpha \approx -2$$

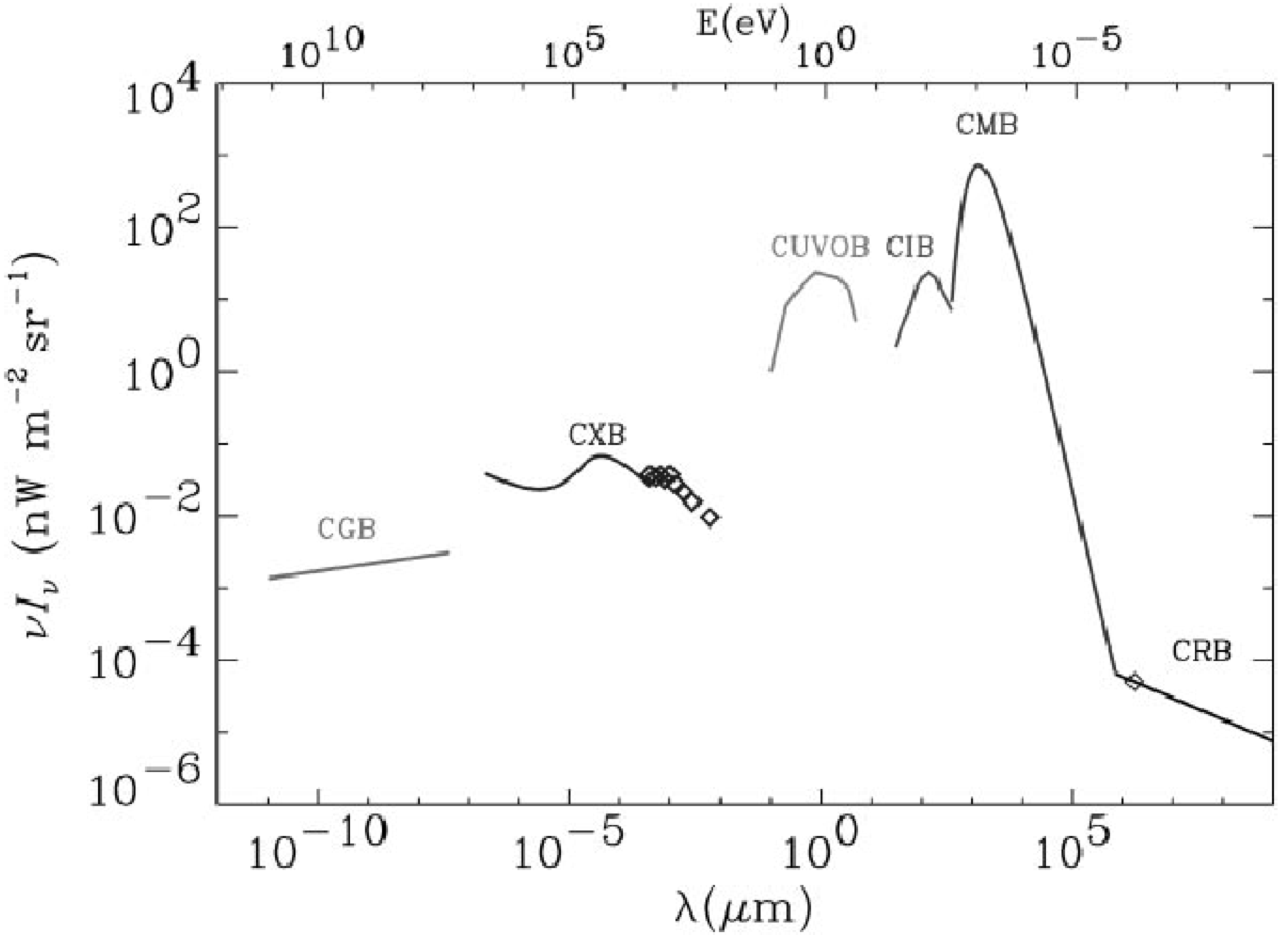
'Red-noise'

Uttley et al. (2002)

X-ray Variability

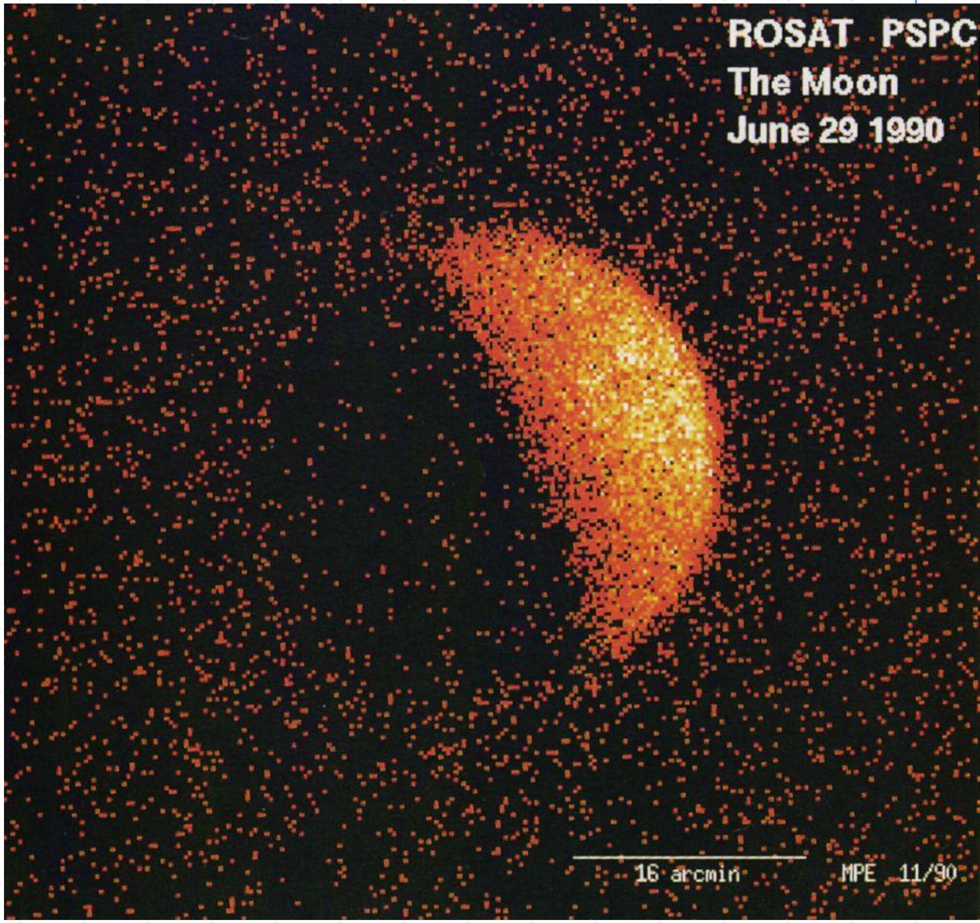


The Cosmic X-ray Background

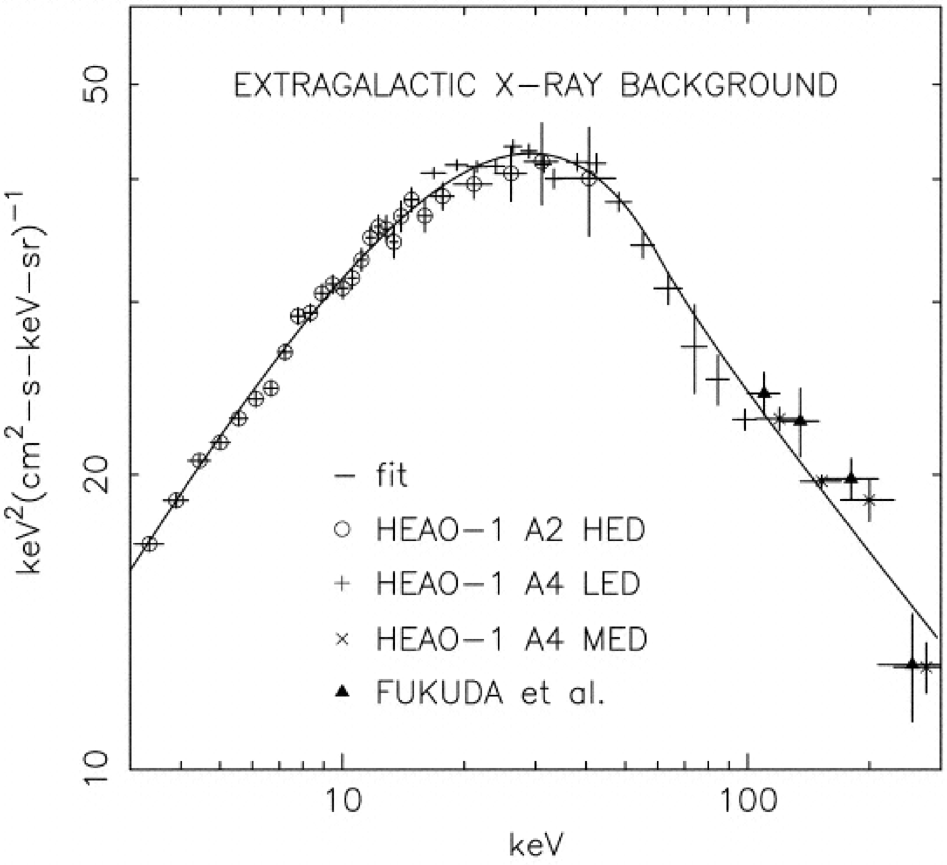


Hauser & Dwek (2001)

- XRB was the first cosmic background detected
- Discovered (along with Sco X-1) during a rocket flight that intended to detect the moon (Giacconi et al. 1962)
- Above 1-3 keV the XRB is isotropic to within a few per cent on large scales
- Strongly suggests an extragalactic origin



- spectrum peaks at 30-40 keV
- between ~1 and 20 keV the spectrum is well fit with a power-law with photon index, Γ = 1.4 (photon-flux ∝ $E^{-\Gamma}$)
- no obvious spectral features -> no z info

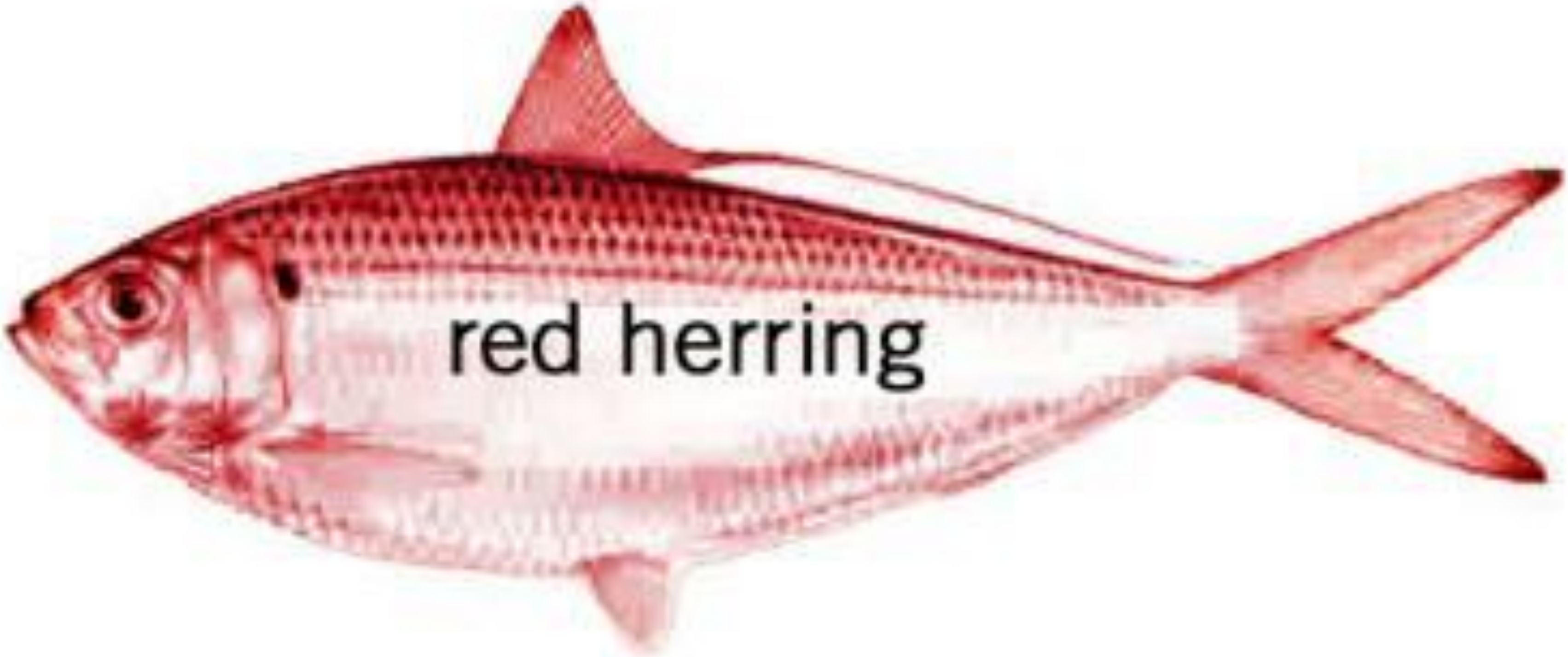


Gruber et al. (1999)

Diffuse Models of the XRB

- Felton & Morrison (1966): inverse Compton scattering of CMB photons by intergalactic electrons
  - hard to produce the 30-40 keV break (Coswik & Kobetich)
- Hoyle (1963) bremsstrahlung emission from hot IGM electrons produced by decaying neutrons in a Steady-State Universe
  - overproduced the XRB (Gould & Burbidge 1963; Friedman 1990)

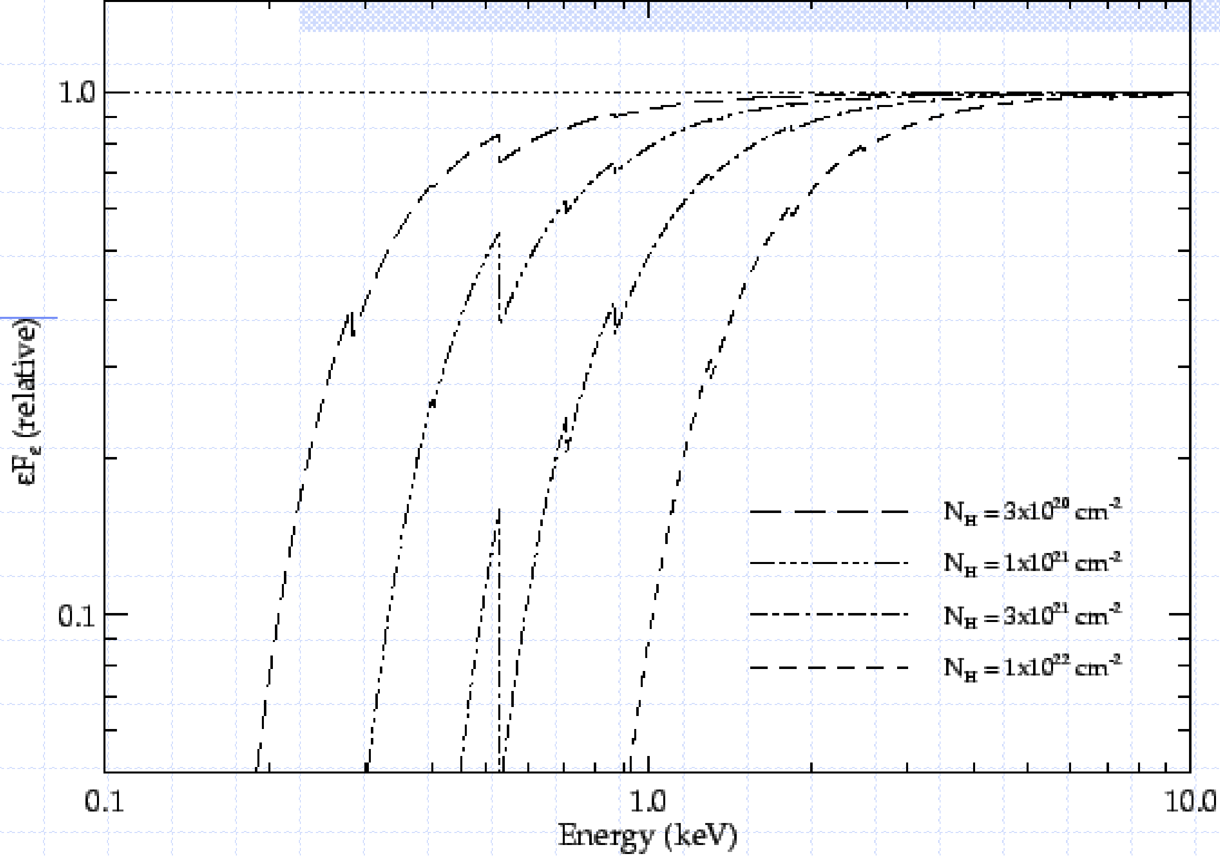
- The XRB spectrum can actually be well fit by a ~40 keV bremsstrahlung plasma
  - the emitting gas would be from a hot IGM (Cowsik & Kobetich 1972; Field & Perrenod 1977)
  - but the energy density in such a gas would be comparable to the CMB
  - moreover, $\Omega_{baryon}>0.23$ in order to match the observed intensity (Guilbert & Fabian 1986; Barcons 1987)
  - finally, such a large amount of hot gas would distort the shape of the CMB which is of course not observed



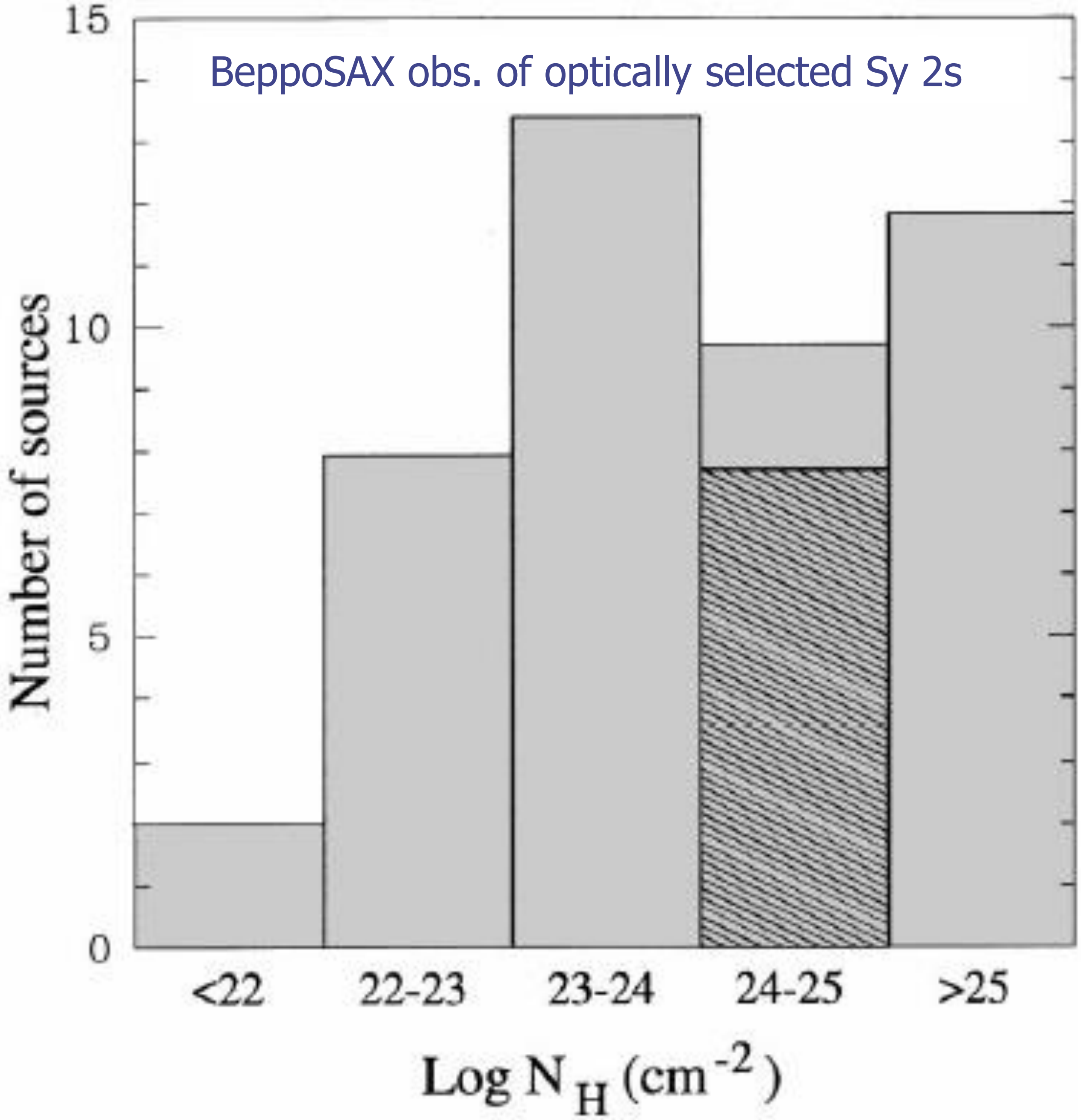
red herring

Discrete Models of the XRB

- the most common hard extragalactic X-ray sources are AGN
- they have power-law spectra above 2 keV
- but the average observed photon-index of AGN is $\Gamma \sim 1.7$

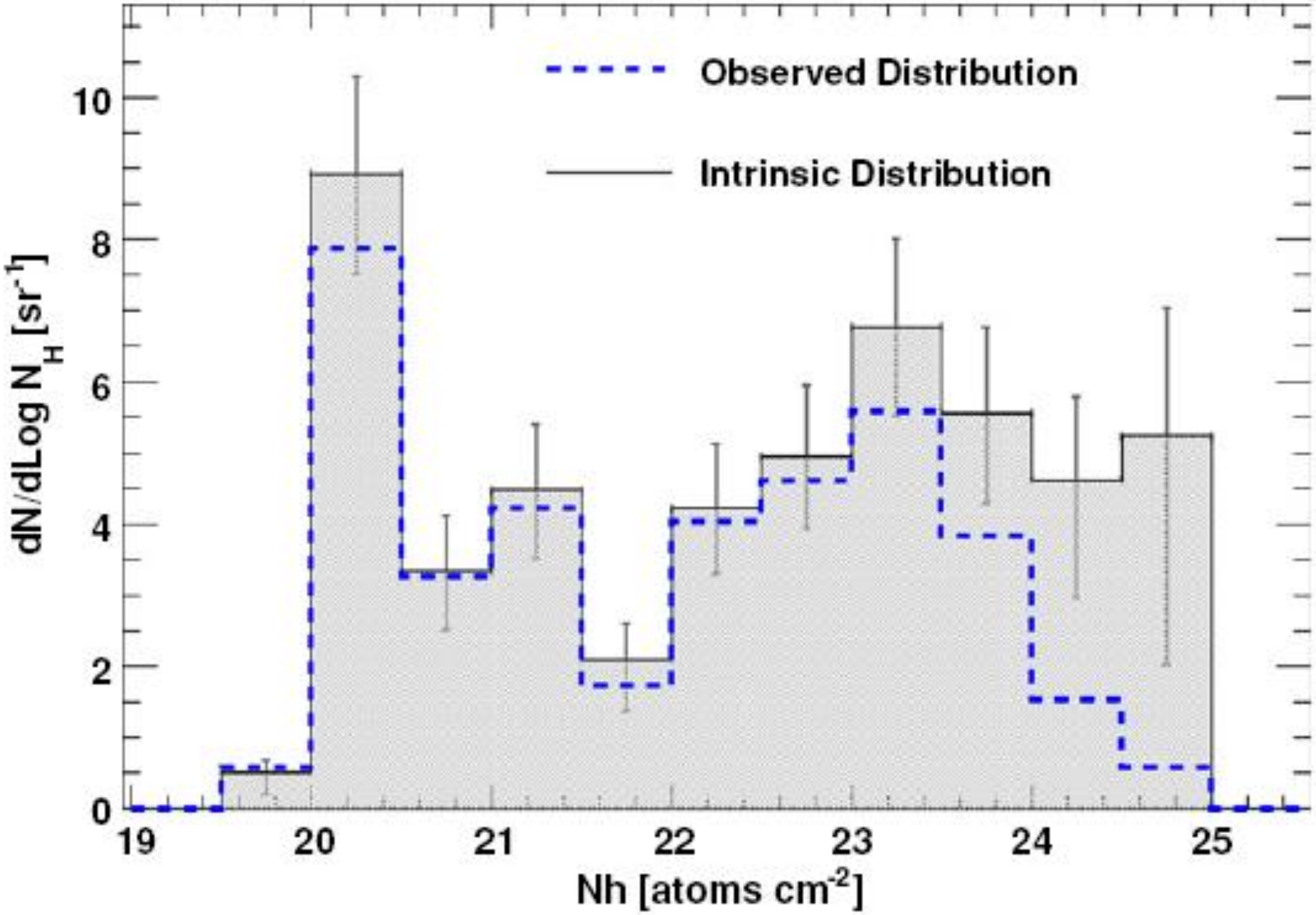


- Setti & Woltjer (1989) pointed out that *absorbed* AGN would have much steeper X-ray spectra
- proposed that the XRB was comprised of the sum total of emission from mostly obscured AGN over a range of luminosity, redshift and obscuring column
- they were inspired by the AGN unification model



BeppoSAX obs. of optically selected Sy 2s

Risaliti, Maiolino & Salvati (1999)

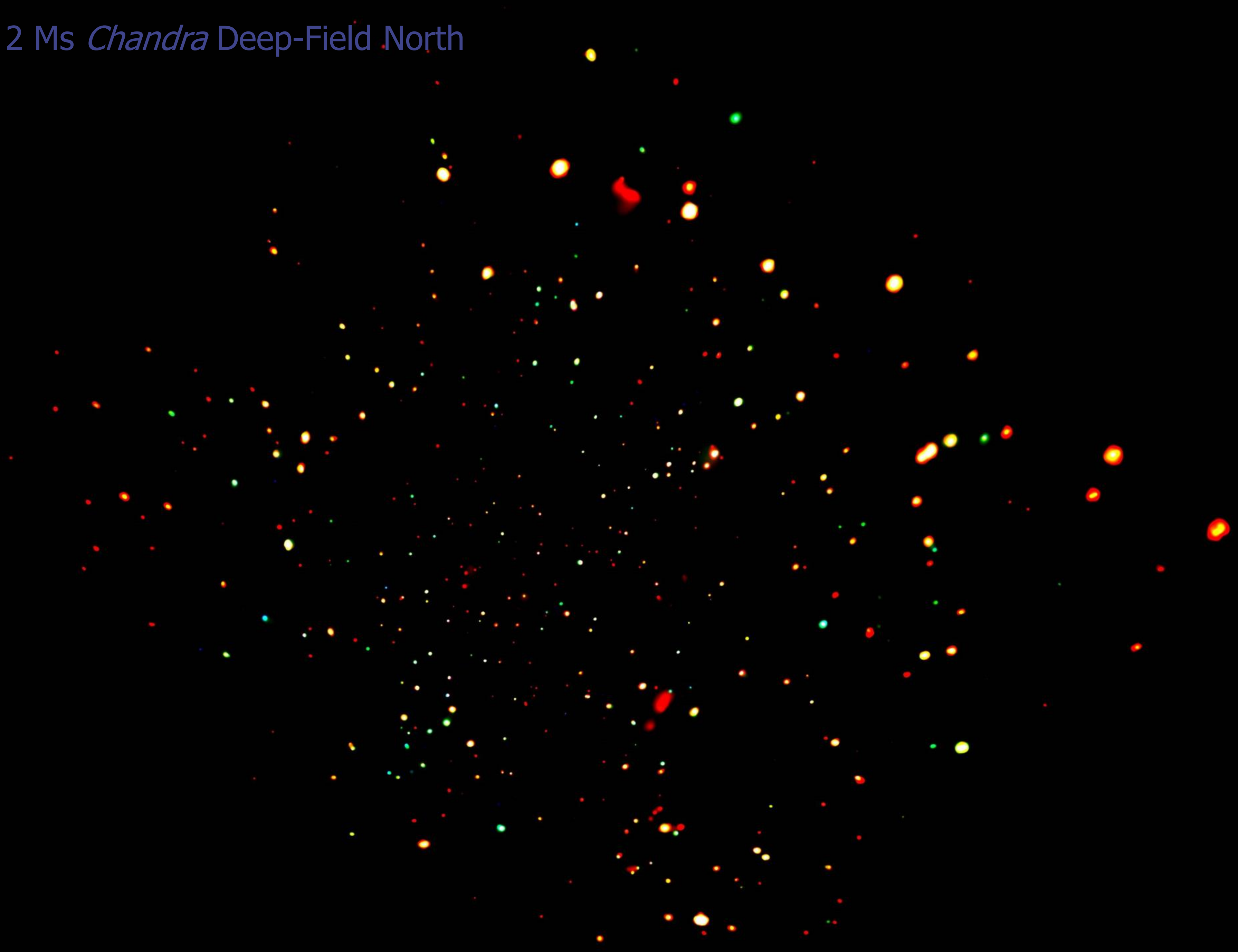


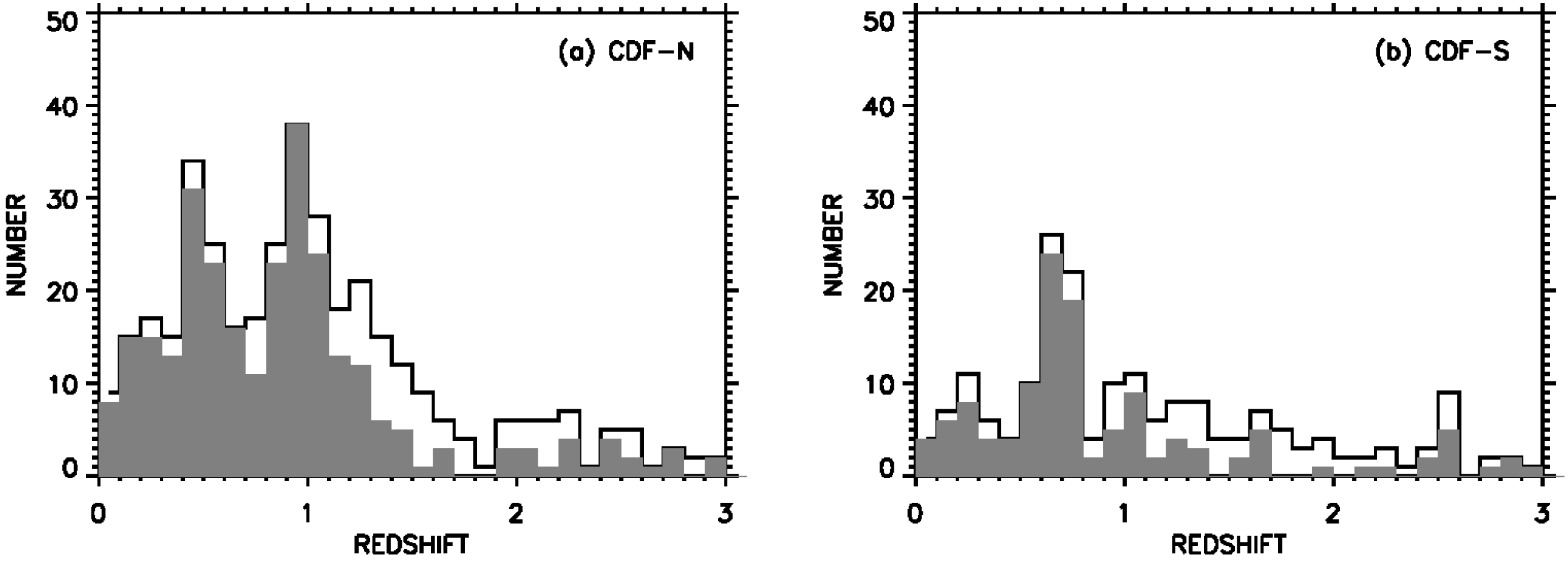
Burlon et al. (2011)

The XRB in the *Chandra* and *XMM-Newton* Era

- In the 1990s the theoretical machinery behind Setti & Woltjer's idea was developed (XRB synthesis models) and confirmed that the idea could work
- Required a hard X-ray luminosity function (LF) and its evolution
- X-ray satellites of this era lacked the spatial resolution to determine this to any significant redshift
- Optical LFs or a soft X-ray LF from *ROSAT* were used instead
- This all changed with the launch of *Chandra* and *XMM-Newton*

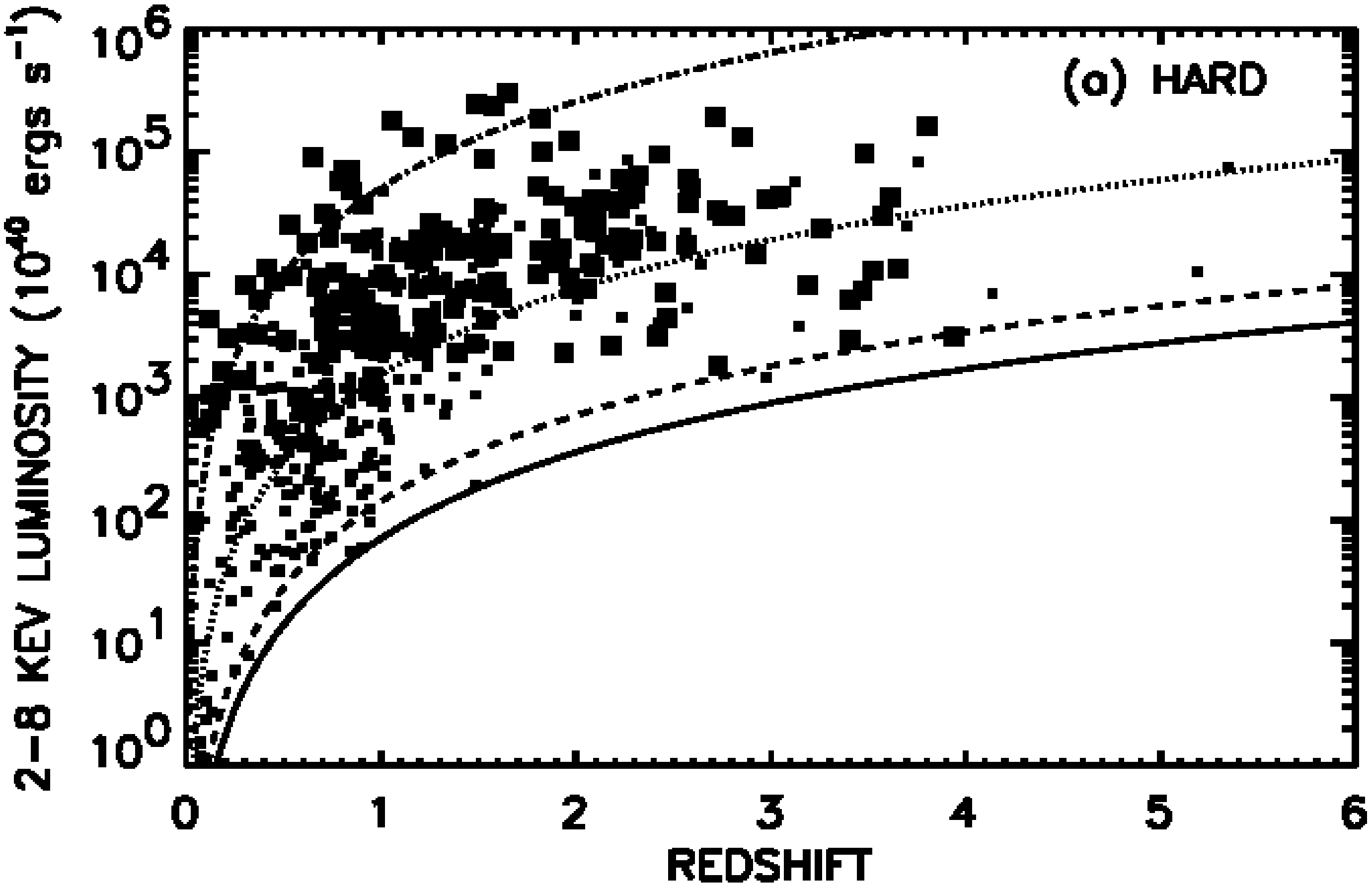
2 Ms *Chandra* Deep-Field North





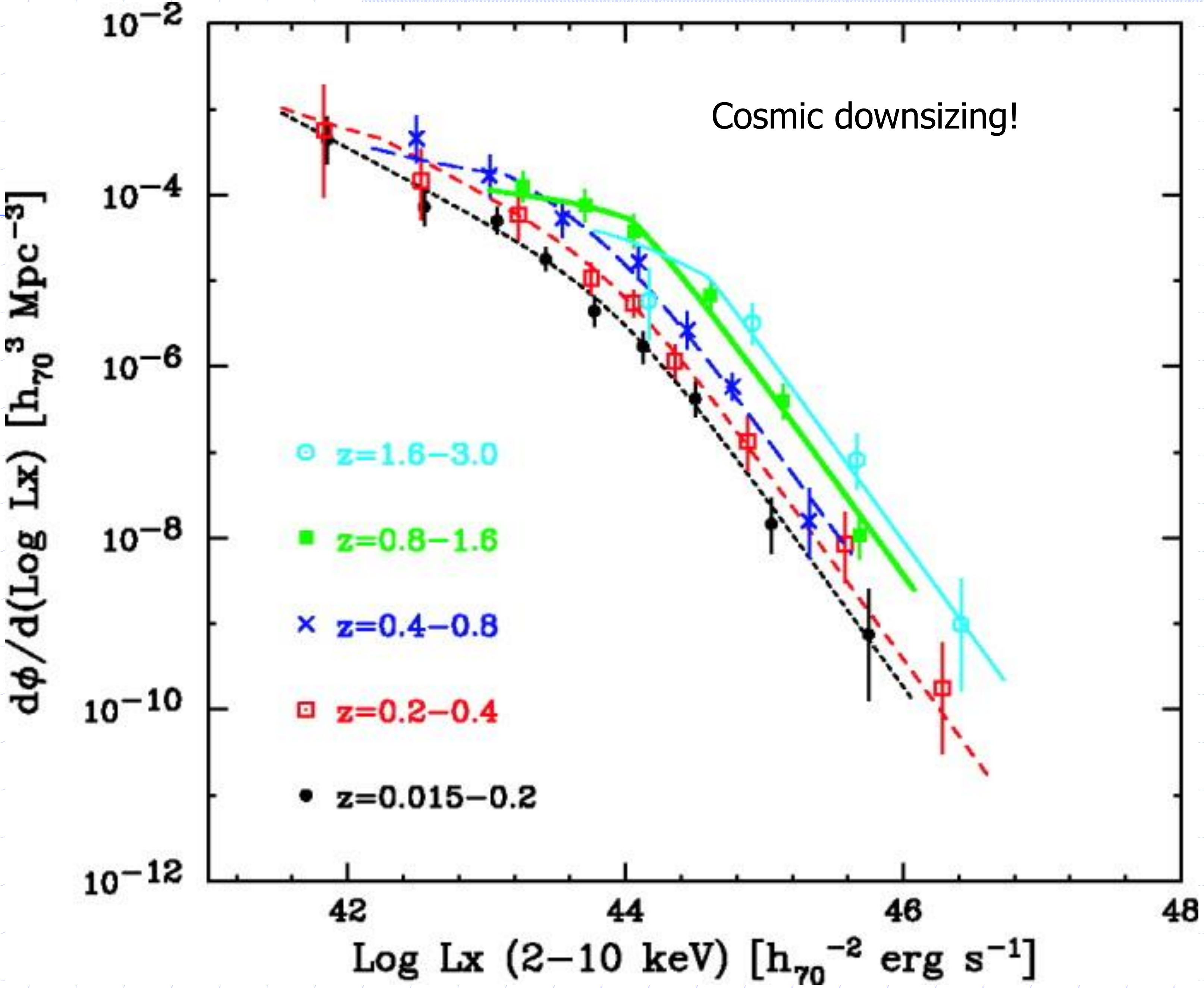
Barger et al. (2005)

- The redshift distribution of the sources peak at z <~ 1
- Quasars, the most powerful AGN, are mostly found at z ~ 2-3

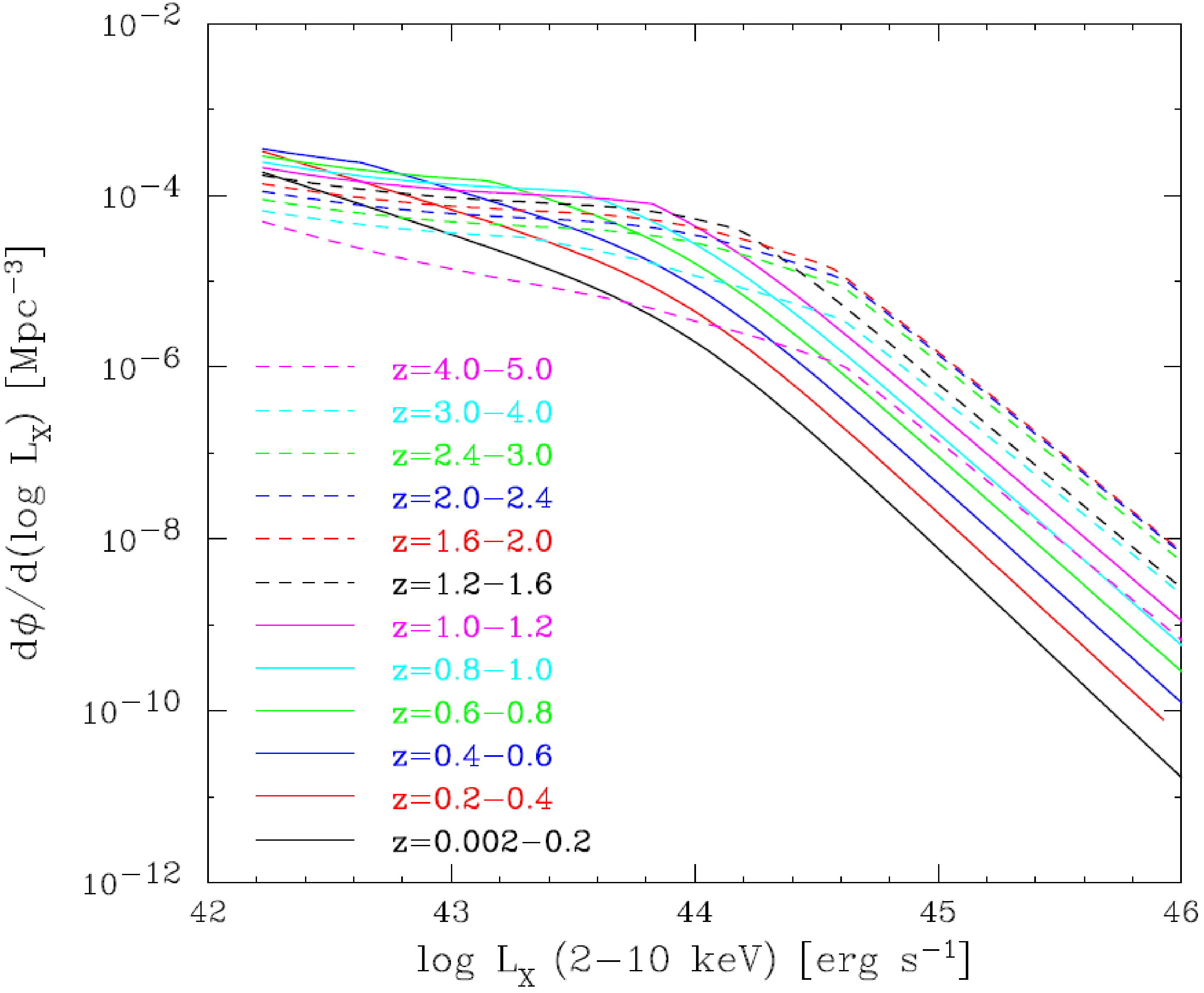


Barger et al. (2005)

- The sources typically have X-ray luminosities < 10^{44} erg/s
- Again much less than quasars (> 10^{45} erg/s)



Ueda et al. (2003)



LDDE model + high-z decline; Ueda et al. (2014)