X-ray (and multiwavelength) surveys

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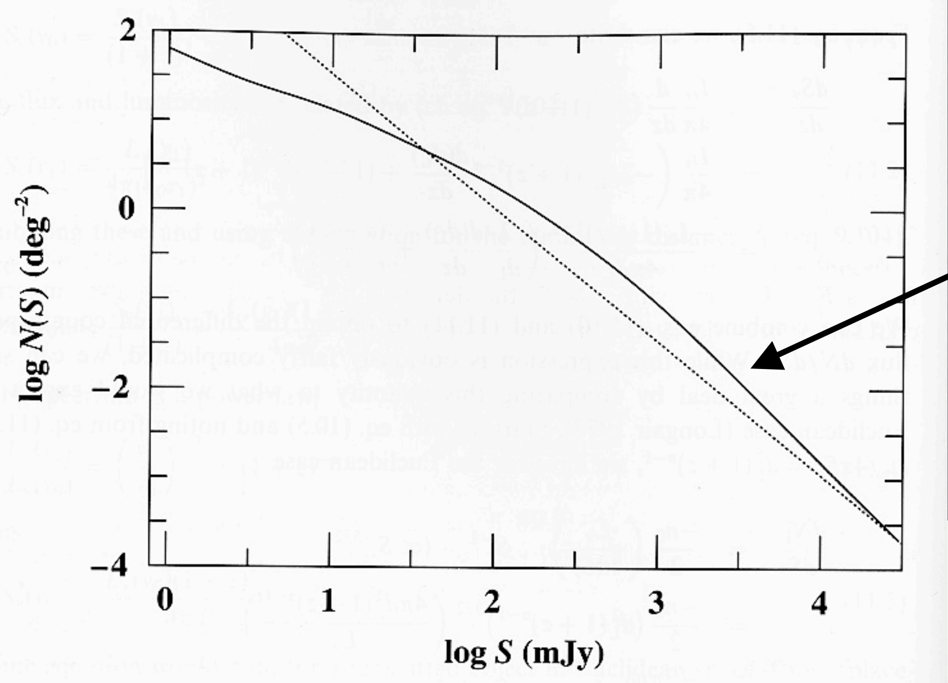
A historical perspective

- First survey of cosmological objects: radio galaxies and radio loud AGN
- The discovery of the Cosmic X-ray Background
- The first imaging of the sources making the CXB
- The resolution of the CXB
- What next?

Radio sources number counts



First results from Cambridge surveys during the 50': Ryle Number counts steeper than expected from Euclidean universe

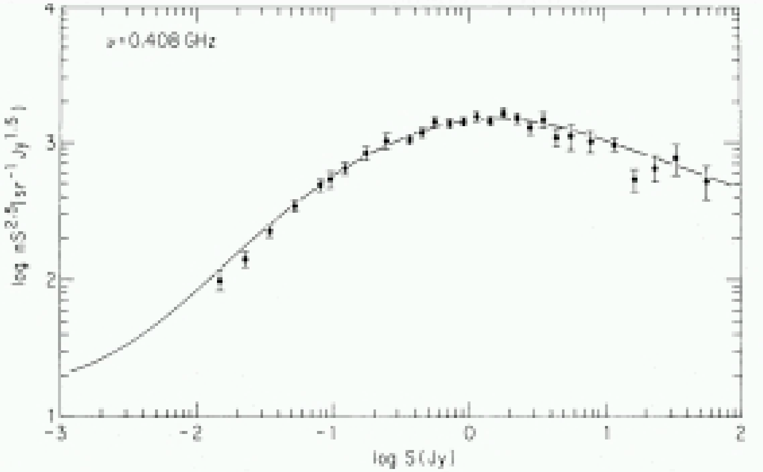


FIG. 1.—Normalized differential source counts at ν = 0.408 GHz. *Abscissa*, log flux density (Jy). *Ordinate*, log differential number of sources multiplied by $S^{2.5}$ (sr^{-1} Jy$^{1.5}$).

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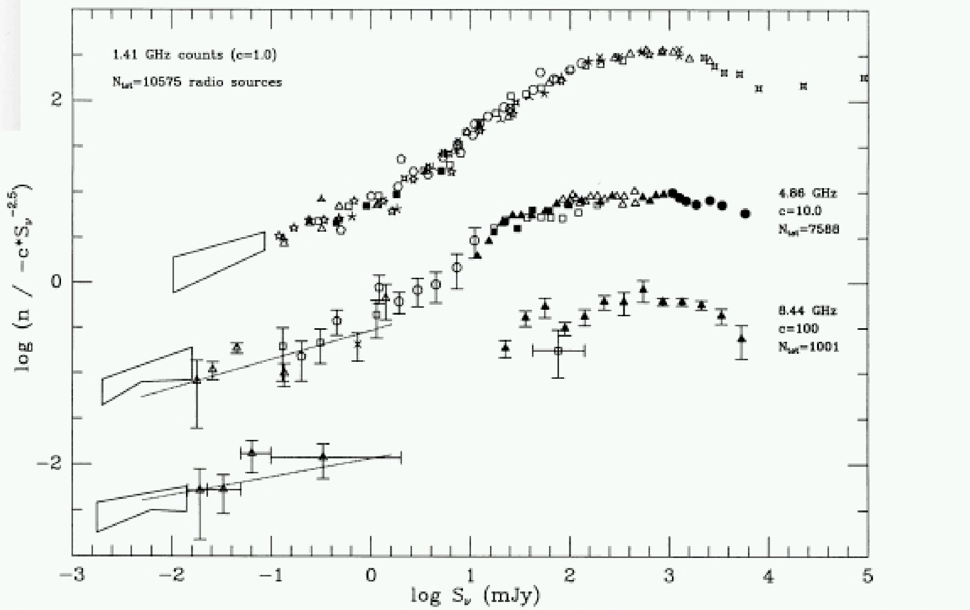


FIG. 3.—Differential source counts at 1.41, 4.86, and 8.44 GHz, *normalized* to a Euclidean count of $cS_\nu^{-2.5}$ (Jy^{-1} sr^{-1}). For clarity, the 4.86 GHz counts were scaled downward with $c = 10$, the 8.44 GHz counts with $c = 100$, while the 1.41 GHz were not shifted ($c = 1.0$). The various source samples are reviewed in the text. The counts at all three frequencies now cover a factor of 10^7 in S_ν. They all show the initial steep rise between $S_\nu \simeq 10$ and 1 Jy, the maximum excess plateau with respect to Euclidean between $S_\nu \simeq 1.0$ and $S_\nu \simeq 0.1$ Jy, and continuous convergence between $S_\nu \simeq 100$ and $S_\nu \simeq 3$ mJy. At all three frequencies, the counts show an upturn between $S_\nu \simeq 3$ and $S_\nu \simeq 3000$ μJy with a similar slope ($\gamma \simeq 2.2 \pm 0.2$).

Number counts

Flux limited sample: all sources in a given region of the sky with flux > than some detection limit Flim.

- Consider a population of objects with the same L
- Assume Euclidean space

$n(r)$ = space density; $dN(r) = n(r)dV = n(r)r^2 dr d\Omega$ total number of sources

$\dfrac{dN(r)}{d\Omega} = n(r)r^2 dr$ surface density; $F = \dfrac{L}{4\pi r^2}$ Flux; $F > F_{\lim}$ $r_{\max} = \left(\dfrac{L}{4\pi F_{\lim}}\right)^{1/2}$

$$N(F_{\lim}) = \int \frac{dN}{d\Omega}(F > F_{\lim}) = \int \frac{dN}{d\Omega}(r < r_{\max}) \int_0^{r_{\max}} n(r) r^2 dr$$

Total number of sources per unit solid angle (cumulative distribution)

Uniform density of objects $\Rightarrow n(r) = n_0$

$$N(F_{\lim}) = n_0 \frac{r_{\max}^3}{3} = \frac{n_0}{3}\left(\frac{L}{4\pi F_{\lim}}\right)^{3/2}$$

$$\log(N(F_{\lim})) = \log\left(\frac{n_0 L^{3/2}}{3(4\pi)^{3/2}}\right) - \frac{3}{2}\log(F_{\lim}) \quad \Rightarrow \quad \alpha = -1.5$$

Number counts

Test of evolution of a source population (e.g. radio sources). Distances of individual sources are not required, just fluxes or magnitudes:

the number of objects increases by a factor of $10^{0.6}=4$ with each magnitude. So, for a constant space density, 80% of the sample will be within 1 mag from the survey detection limit.

$$m \propto -2.5\log(F_{\lim}) \text{ so } \log(F_{\lim}) \propto -0.4m$$

$$-\frac{3}{2}\log(F_{\lim}) = 0.6m \quad \Rightarrow \quad \log N(m) \propto 0.6m$$

If the sources have some distribution in L:

$$n(r,L)drdL = n(r)\Phi(L)drdL$$

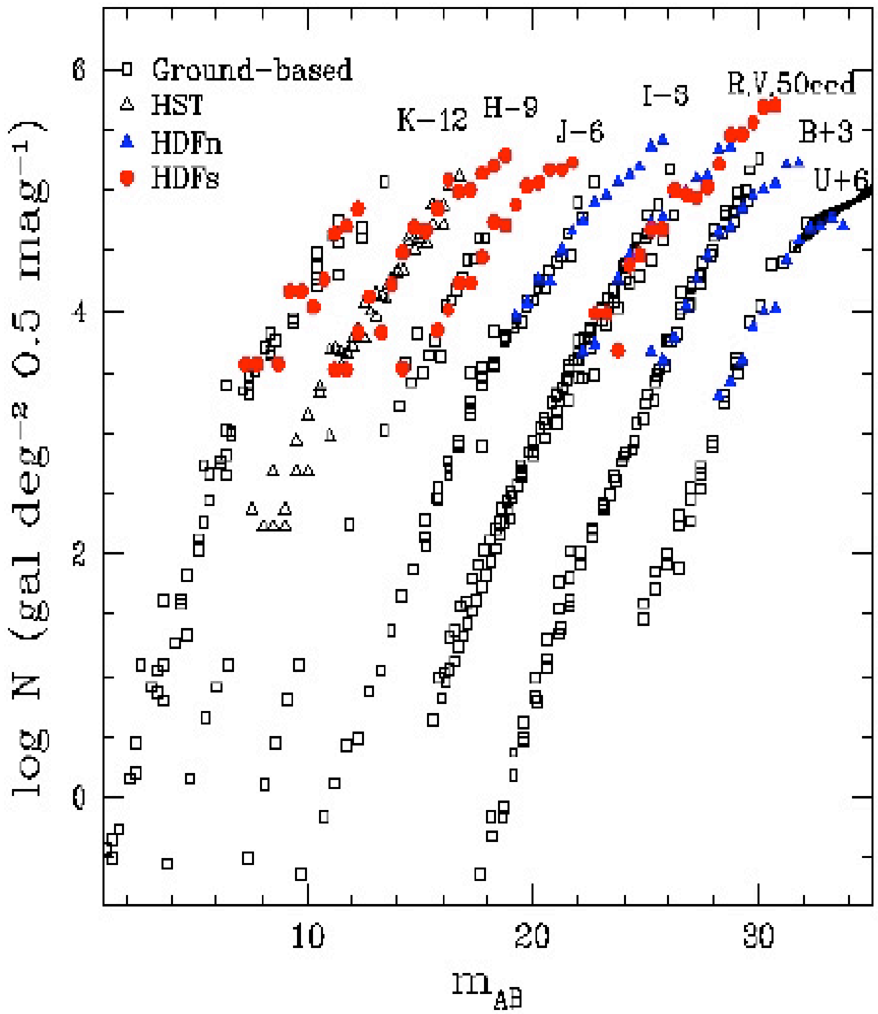
$$\Phi(L)dL \equiv \text{ Luminosity Function}$$

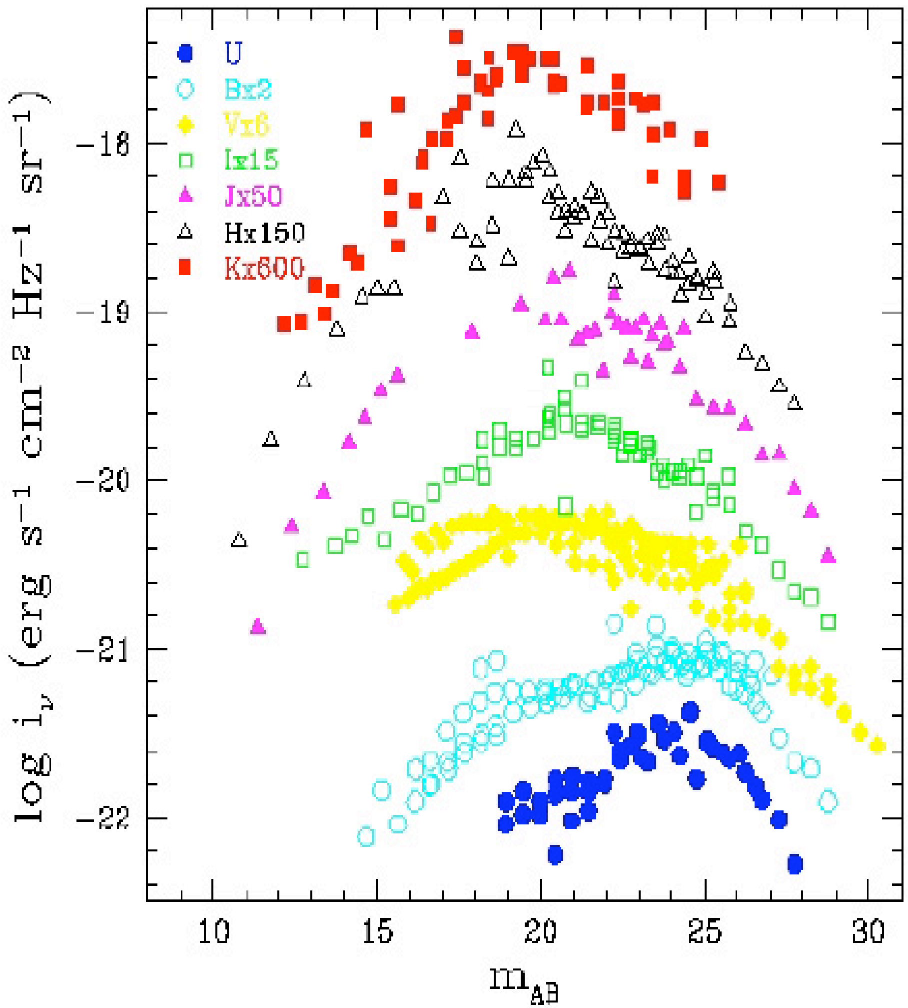
$$N(r) = \int \int_0^{r_{\max}(L)} n(r,L)r^2 drdL = \frac{n_0}{3}(4\pi F_{\lim})^{-3/2} \int L^{3/2}\Phi(L)dL$$

Problems with the derivation of the number counts

- Completeness of the samples.
- Eddington bias: random error on mag measurements can alter the number counts. Since the logN-logFlim are steep, there are more sources at faint fluxes, so random errors tend to increase the differential number counts. If the tipical error is of 0.3 mag near the flux limit, than the correction is ~15%.
- Variability.
- Internal absorption affects "color" selection.
- SED, *'K-correction'*, redshift dependence of the flux (magnitude).

Galaxy number counts





Optically selected AGN number counts

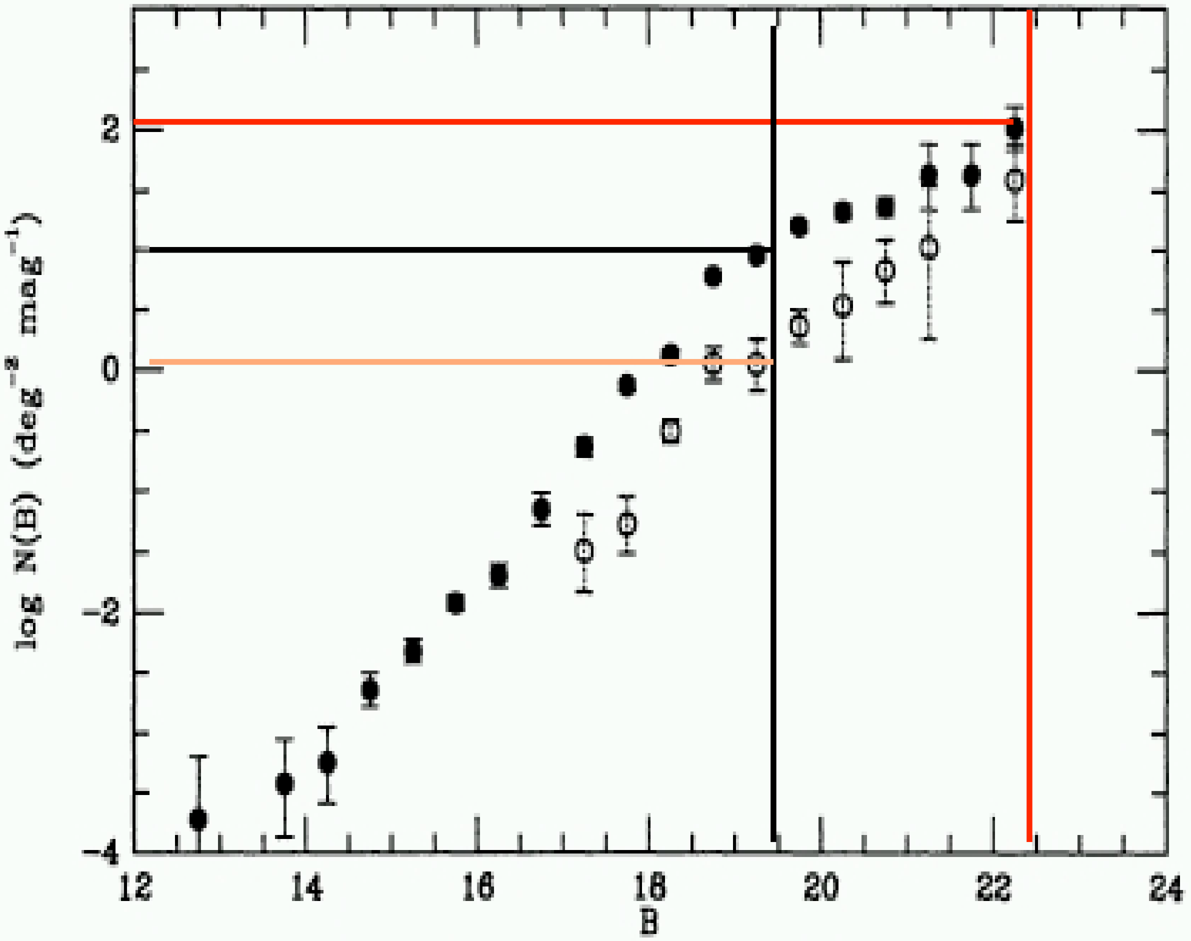


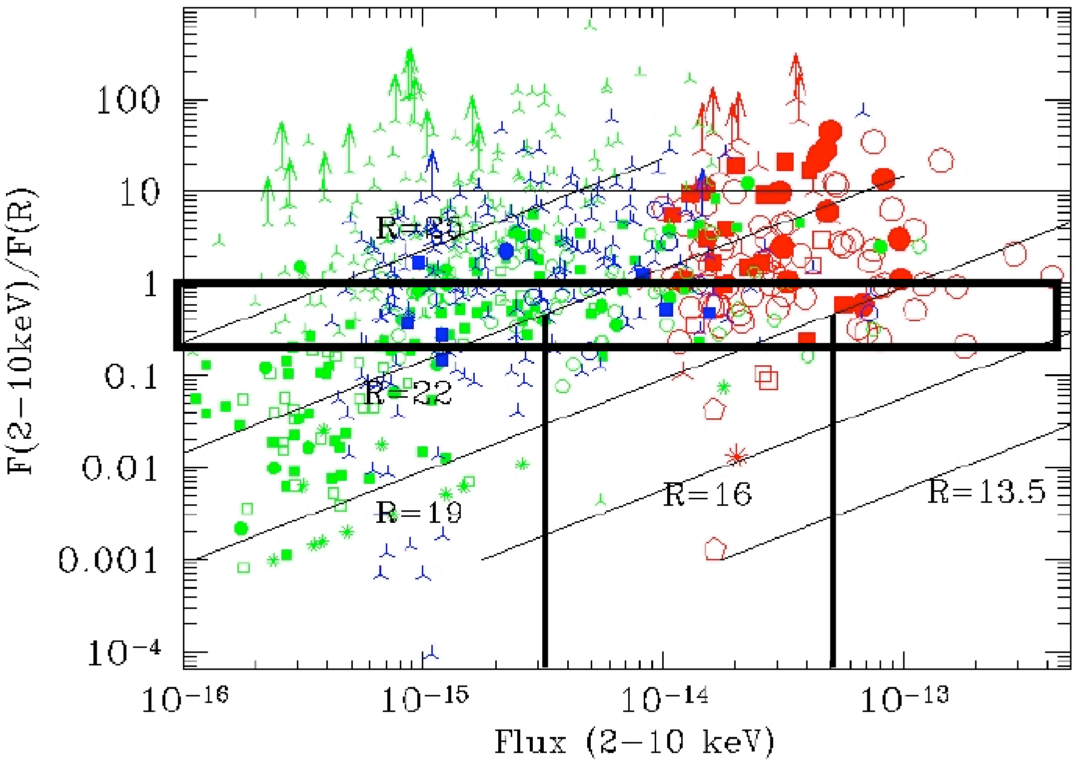
Figure 1 The surface density of quasars from the combined sample (*solid symbols*: $0 < z < 2.2$; *open symbols*: $2.2 < z < 3.3$).

z<2.2
B=22.5
~100 deg^{-2}
B=19.5
~10 deg^{-2}

z>2.2
B=22.5
~50 deg^{-2}
B=19.5
~1 deg^{-2}

B-R=0.5

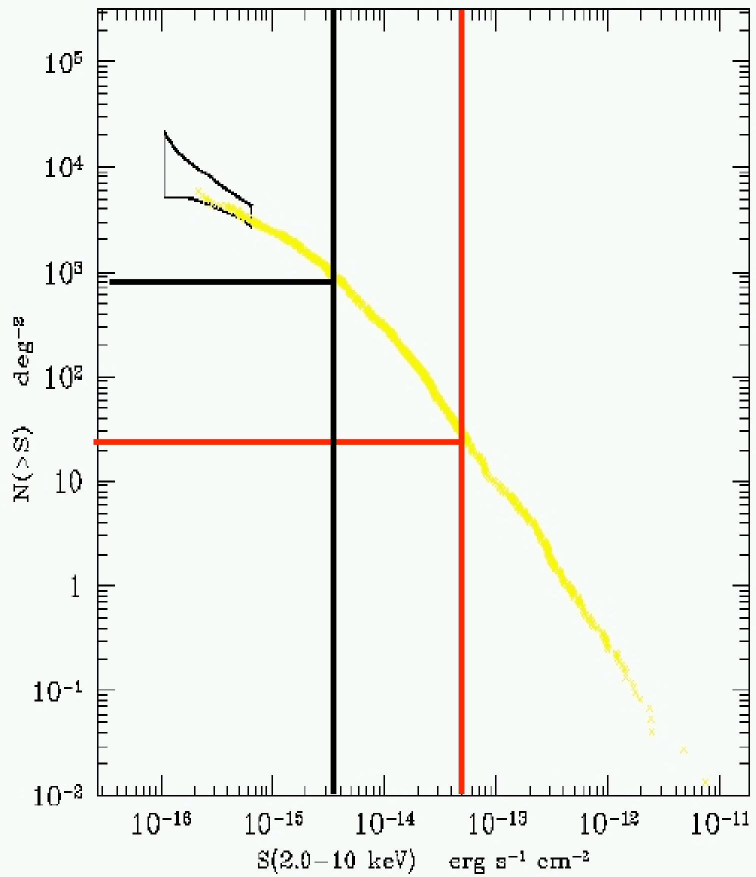
X-ray AGN number counts



<X/O> OUV sel. AGN=0.3

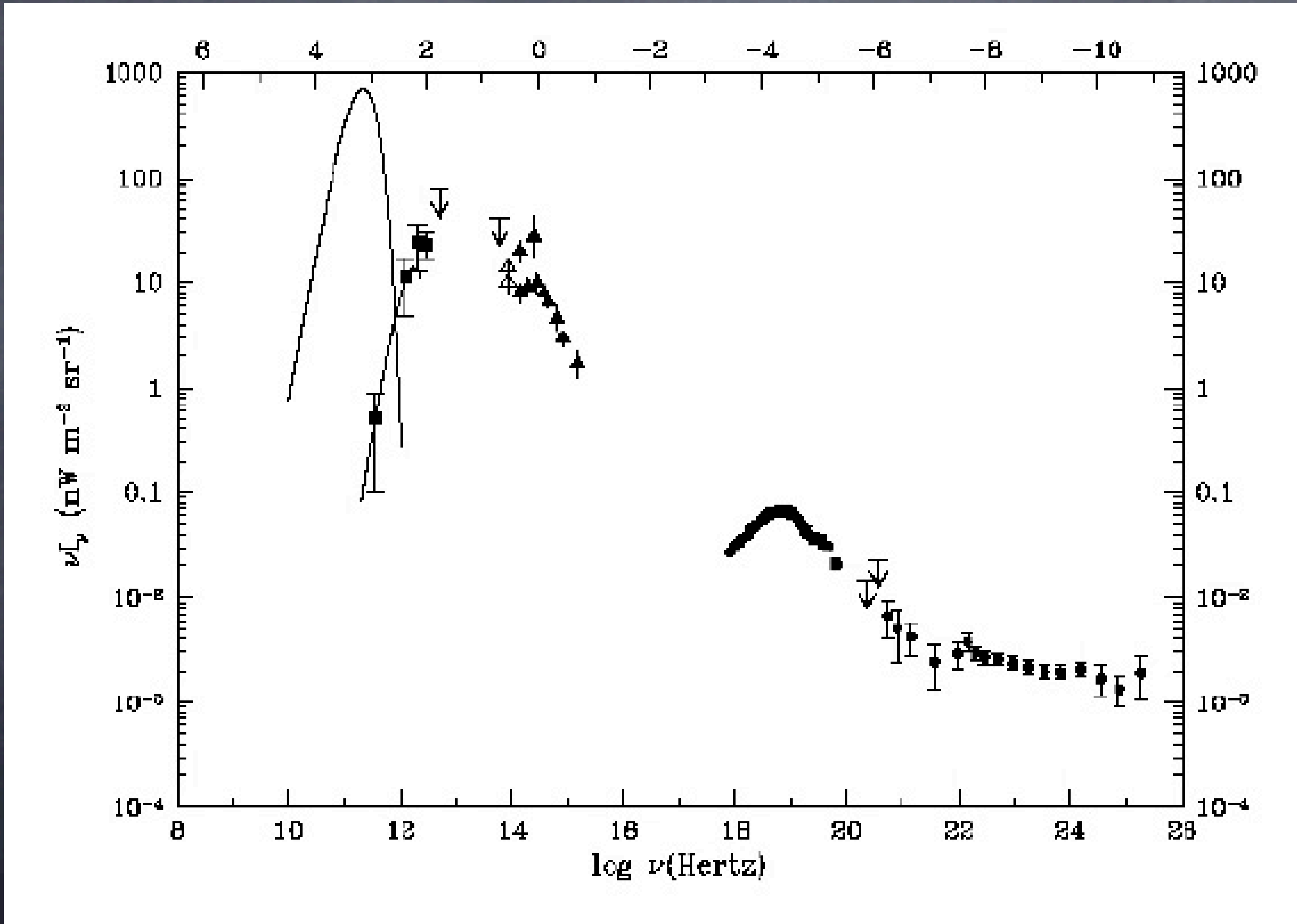
R=22 ==> 3×10^{-15} ~$1000 deg^{-2}$

R=19 ==> 5×10^{-14} ~$25 deg^{-2}$

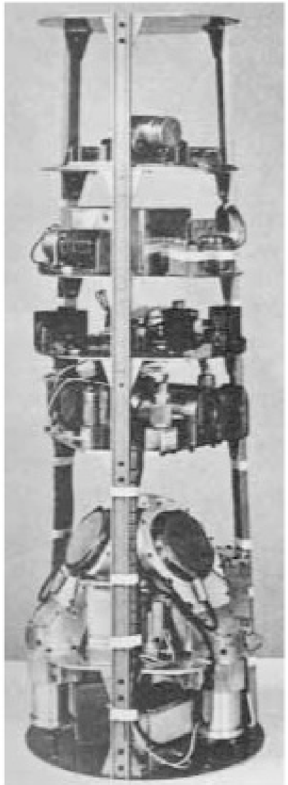


The surface density of X-ray selected AGN is 2-10 times higher than OUV selected AGN

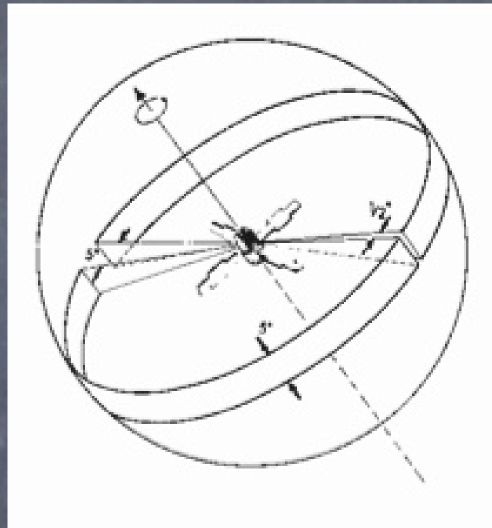
The cosmic backgrounds energy densities



The Cosmic X-ray Background



Giacconi (and collaborators) program:
1962 sounding rocket
1970 Uhuru
1978 HEAO1
1978 Einstein
1999 Chandra!



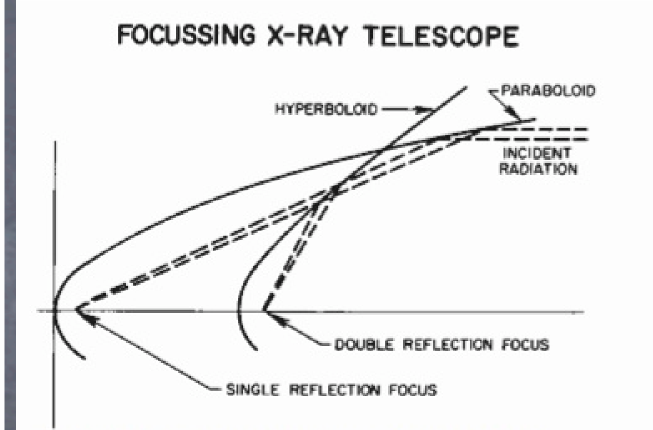


Figure 13. Principle of x-ray grazing incidence telescope. Illustration of R. Giacconi.

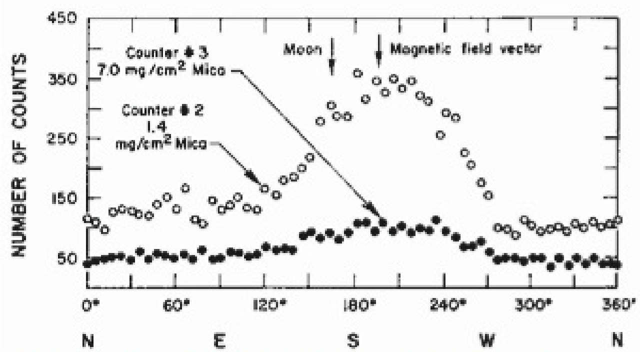
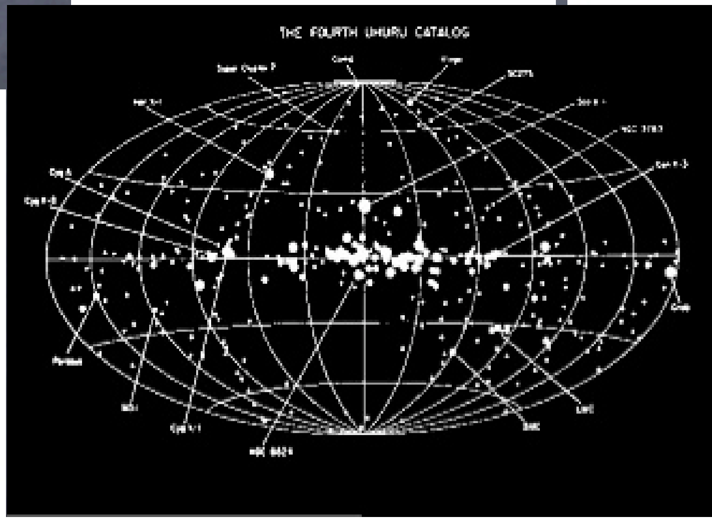
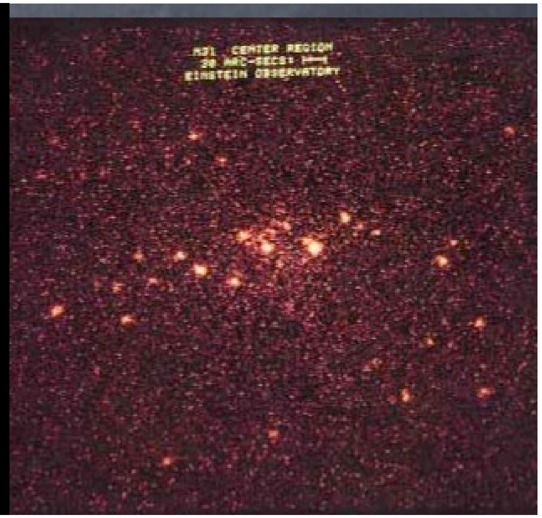


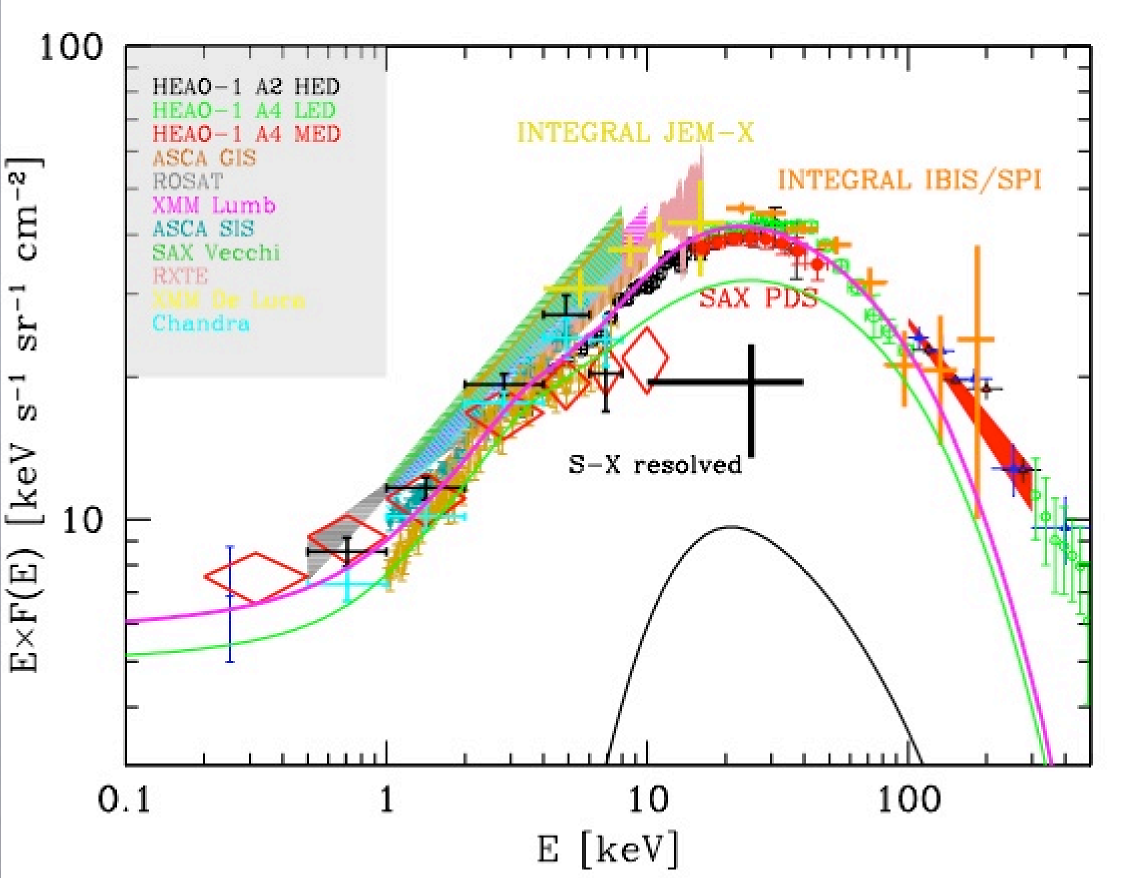
Figure 2. The first observation of Sco X-1 and of the x-ray background in the June, 12, 1962 flight. From Giacconi, *et al.*, 1962.





The Cosmic X-ray Background

- The CXB energy density:
- Collimated instruments:
  - 1978 HEAO1
  - 2006 BeppoSAX PDS
  - 2006 Integral
  - 2008 Swift BAT
- Focusing instruments:
  - 1980 Einstein 0.3-3.5 keV
  - 1990 Rosat 0.5-2 keV
  - 1996 ASCA 2-10 keV
  - 1998 BeppoSAX 2-10 keV
  - 2000 RXTE 3-20 keV
  - 2002 XMM 0.5-10 keV
  - 2002 Chandra 0.5-10 keV
  - 2012 NuSTAR 6-100 keV
  - 2014 Simbol-X 1-100 keV
  - 2014 NeXT 1-100 keV
  - 2012 eROSITA 0.5-10 keV
  - 2020 IXO 0.5-40 keV



The V/V_{max} test

Marteen Schmidt (1968) developed a test for evolution not sensitive to the completeness of the sample.

Suppose we detect a source of luminosity L and flux $F > F_{lim}$ at a distance r in Euclidean space:

$$r = \left(\frac{L}{4\pi F} \right)^{1/2}$$

the same source could have been detected at a distance $r_{max} = \left(\frac{L}{4\pi F_{lim}} \right)^{1/2}$

So we can define 2 spherical volumes: $V = \frac{4\pi r^3}{3}$; $V_{max} = \frac{4\pi r_{max}^3}{3}$

If we consider a sample of sources distributed uniformly, we expect that half will be found in the inner half of the volume V_{max} and half in the outer half. So, on average, we expect $V/V_{max}=0.5$

The V/V_{max} test

$$\langle V \rangle = \frac{\int_{\Omega}\int_0^{r_{max}} (4\pi r^3/3) n(r) r^2 dr d\Omega}{\int_{\Omega}\int_0^{r_{max}} n(r) r^2 dr d\Omega} = \frac{\frac{4\pi n_0}{3}\int_0^{r_{max}} r^5 dr}{n_0 \int_0^{r_{max}} r^2 dr}$$

$$= \frac{4\pi}{3}\frac{r_{max}^6/6}{r_{max}^3/3} = \frac{4\pi}{3}\frac{r_{max}^3}{2} \quad \text{so :} \quad \left\langle \frac{V}{V_{max}} \right\rangle = 0.5$$

In an expanding Universe the luminosity distance must be used in place of r and r_{max} and the constant density assumption becomes one of constant density per unit *comuving volume* .

$$\left\langle \frac{V}{V_{max}} \right\rangle = \sum_{i=1}^{N} \frac{V_i(z)}{V_i(z_{max})}$$

Luminosity function

In most samples of AGN $\langle V/V_{max} \rangle > 0.5$. This means that the luminosity function cannot be computed from a sample of AGN regardless of their z. Rather we need to consider restricted z bins.

If the sources are drawn from a volume limited sample:

$$\Phi(L)\Delta l = \sum \frac{1}{V_{\max}} = \frac{N_L}{V_{\max}}$$

More often sources are drawn from flux-limited samples, and the volume surveyed is a function of the Luminosity L. Therefore, we need to account for the fact that more luminous objects can be detected at larger distances and are thus over-represented in flux limited samples. This is done by weighting each source by the reciprocal of the volume over which it could have been found:

$$\Phi(L,z)dL = \sum_i \frac{1}{V_i(z_{\max})}$$

Luminosity function

$1/V_{max}$ method or

maximun likelihood method:

$$? = \prod_{i=1}^{N} \frac{\Omega(L_i)dzdL}{\sum_j ?_j \int_{z1}^{z2} \frac{dV}{dz} dz \int_{\infty}^{L_{\lim}^{j}(z)} \Phi(L)dL}$$

Black Hole Mass Density

Soltan (1982) argument: the BH mass density due to growth by accretion

$$\varepsilon_{\rm rad}(1+\langle z\rangle) = \eta\rho_\bullet c^2 \qquad (1)$$

$\varepsilon_{\rm rad}$ can be obtained by integrating the sources luminosity function (2) or from the background radiation they produce (3)

$$\rho_\bullet = \frac{k_{bol}}{\eta c^2}\int\frac{dt}{dz}dz\int L\phi(L)dL \qquad (2)$$

η accretion efficiency, k_{bol} Bolometric correction

Using bright quasars optical counts, $\eta = 0.1$ and $k^B_{bol} \simeq 15$

$2.2\times10^5\ M_\odot\ Mpc^{-3}$ (Yu & Tremaine 2002)

$2\times10^5\ M_\odot\ Mpc^{-3}$ (Salucci et al. 1998)

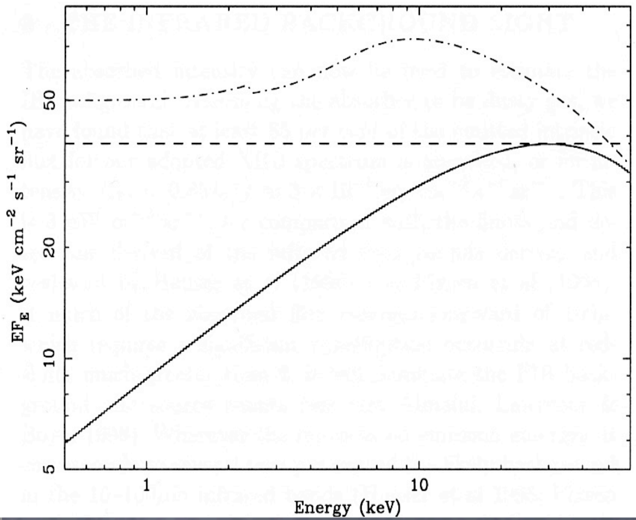
$$\rho_\bullet = \frac{k_{bol}}{\eta c^2}(1+\langle z\rangle)\frac{4\pi I_0}{c} \qquad (3)$$

I_0 Background Intensity

Using the XRB spectrum, $\eta = 0.1$ and $k^X_{bol} \simeq 30$

$6-9\times10^5\ M_\odot\ Mpc^{-3}$ (Fabian & Iwasawa 1999)

$7.5-17\times10^5\ M_\odot\ Mpc^{-3}$ (Elvis, Risaliti, Zamorani 2002)



Assume that the intrinsic spectrum of the sources making the CXB has α_E=1

$I_0=9.8\times10^{-8}$ erg/cm^2/s/sr

$\varepsilon'=4\pi I_0/c$

The local BH mass density

$\rho^{direct} \rightarrow$ Using the $M_\bullet - M_{bulge}$

$\sim 10 \times 10^5 \ M_\odot \ Mpc^{-3}$ (Magorrian et al. 1998)

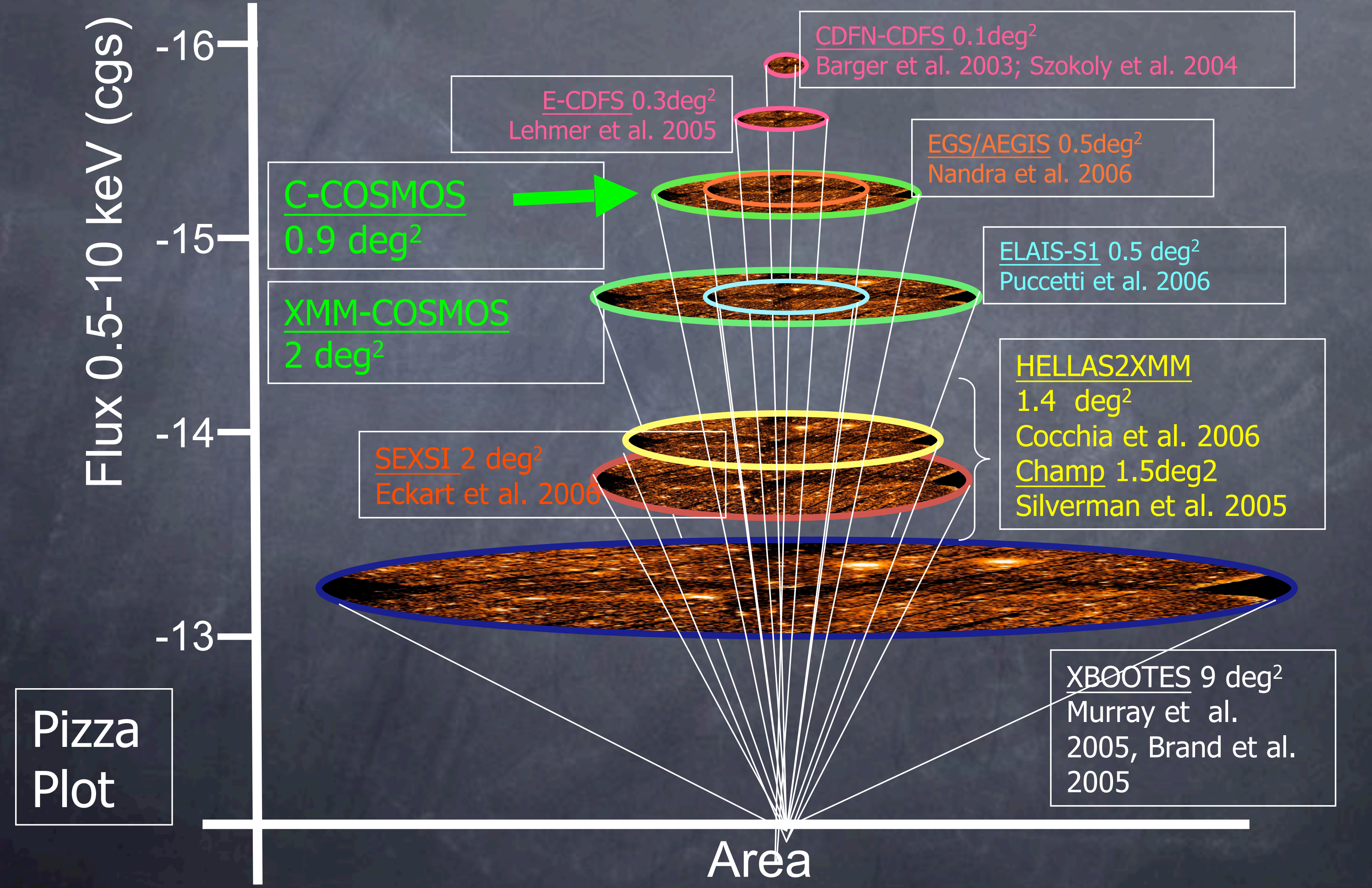
$\rho^{direct} \rightarrow$ Using the $M_\bullet - \sigma$

$2.5 - 3.5 \times 10^5 \ M_\odot \ Mpc^{-3}$ (Yu & Tremaine 2002)

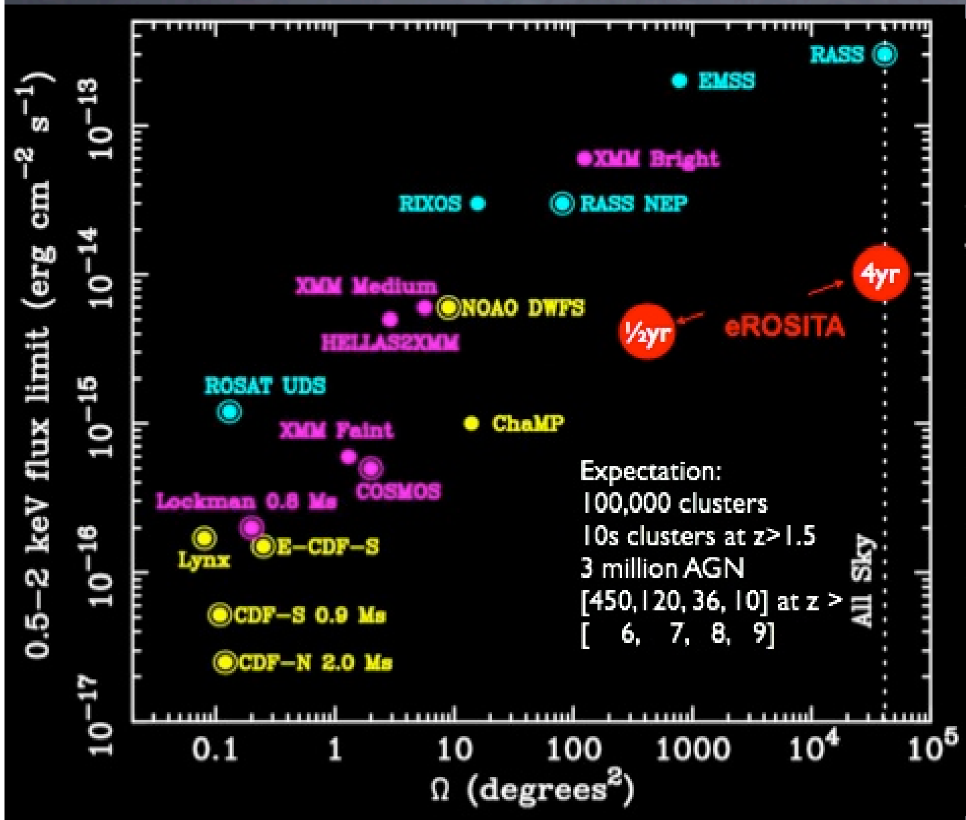
$4 - 5 \times 10^5 \ M_\odot \ Mpc^{-3}$ (Ferrarese 2002)

Optical (and soft X-ray) surveys gives values 2-3 times lower than those obtained from the CXB
(and of the F.&M. and G. et al. estimates)

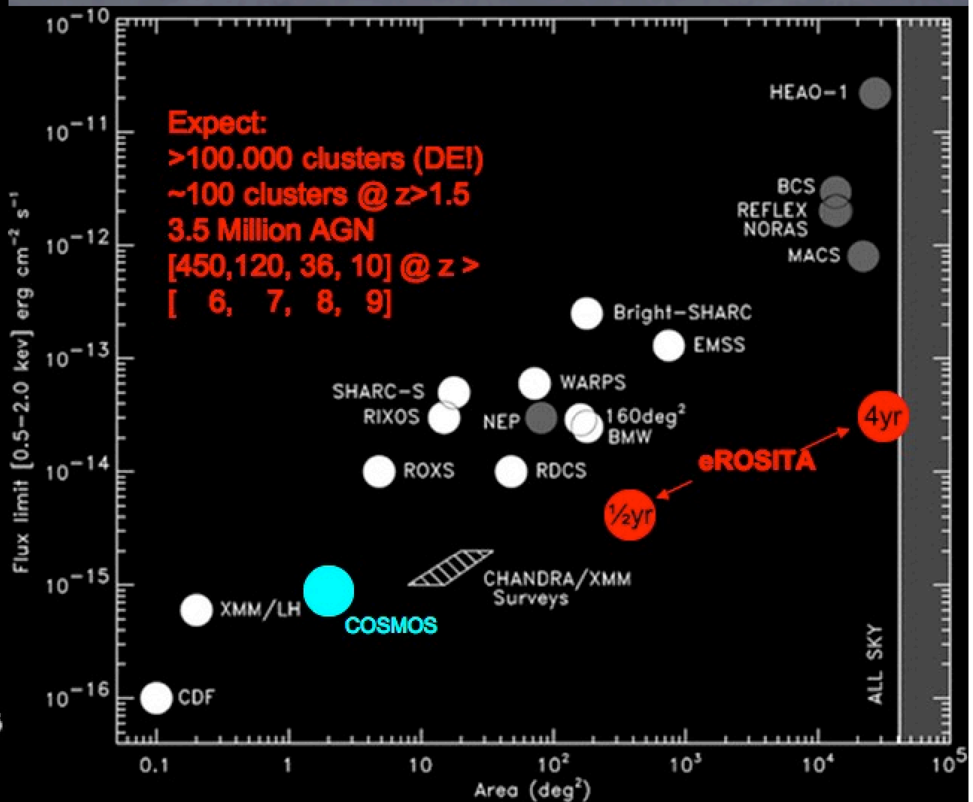
A survey of X-ray surveys



A survey of X-ray surveys



Point sources



Clusters of galaxies

A survey of surveys

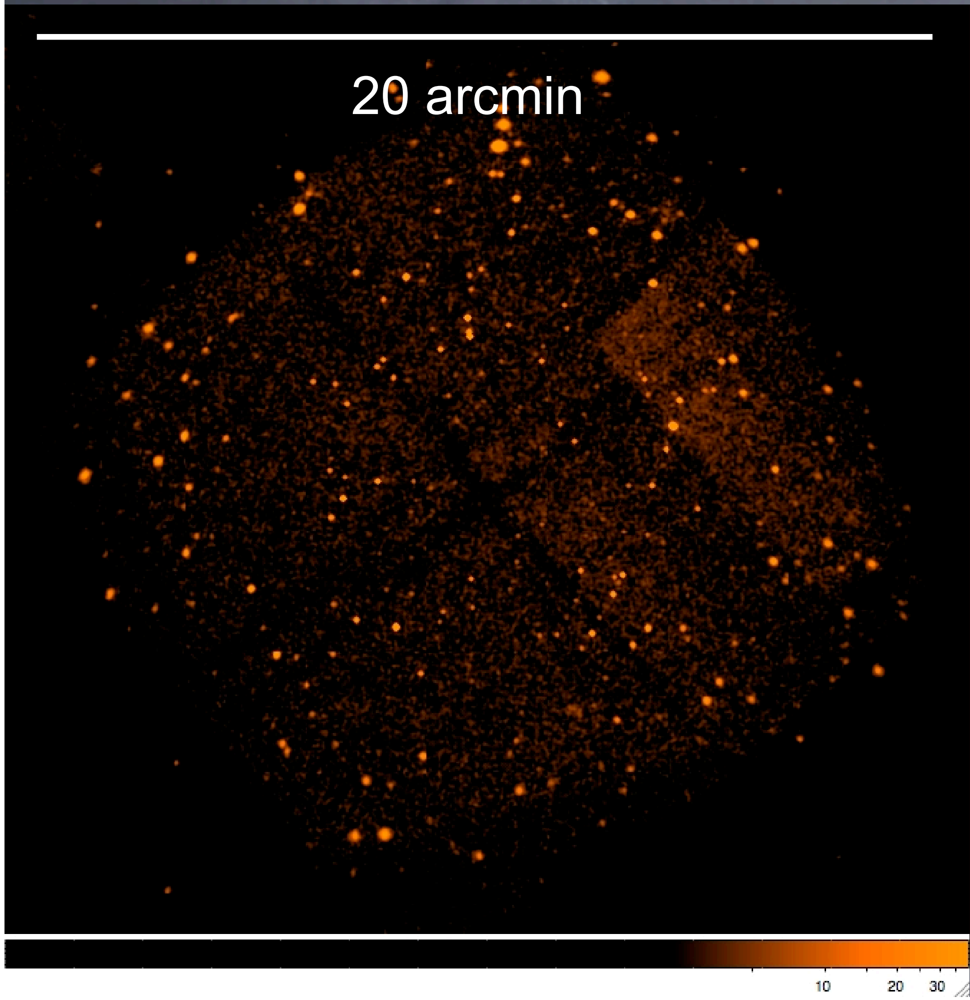
Main areas with large multiwavelength coverage:

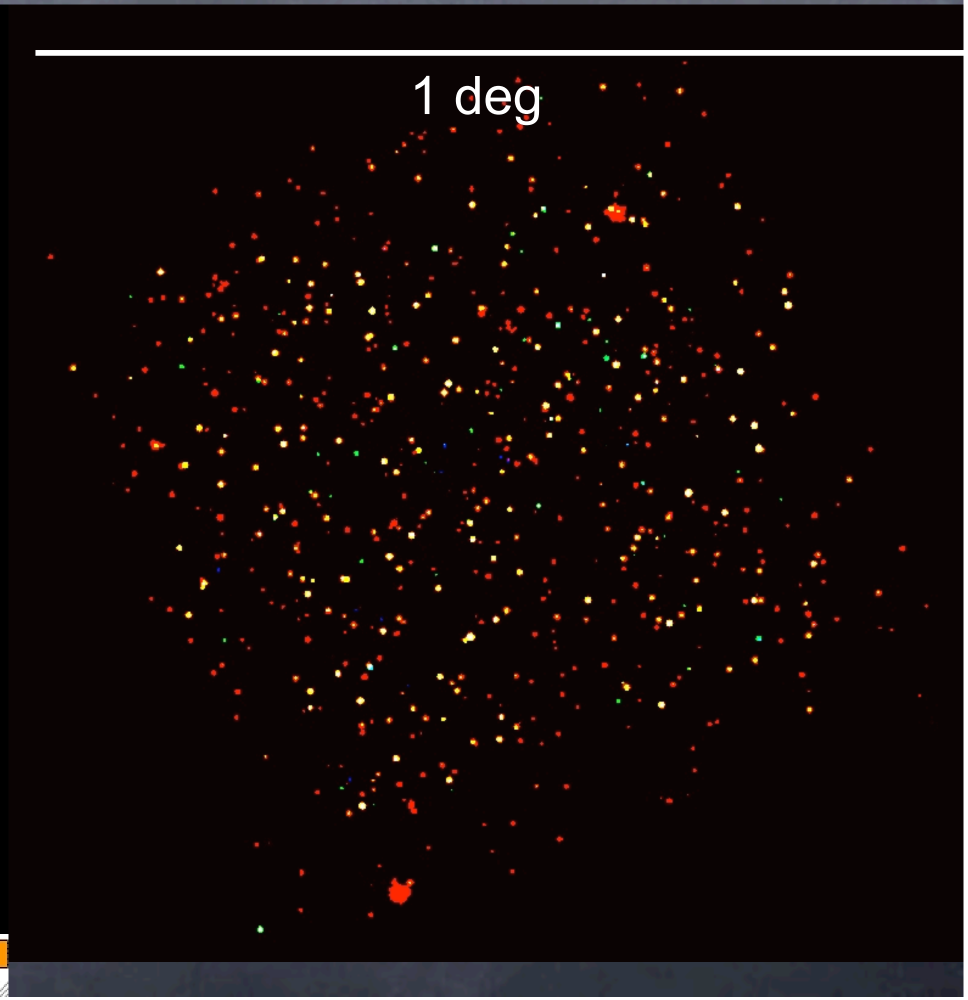
- CDFS-GOODS 0.05 deg^2: HST, Chandra, XMM, Spitzer, ESO, Herschel, ALMA
- CDFN-GOODS 0.05 deg^2: HST, Chandra, VLA, Spitzer, Hawaii, Herschel
- AEGIS(GS) 0.5 deg^2: HST, Chandra, Spitzer, VLA, Hawaii, Herschel
- COSMOS 2 deg^2: HST, Chandra, XMM, Spitzer, VLA, ESO, Hawaii, LBT, Herschel, ALMA
- NOAO DWFS 9 deg^2 : Chandra, Spitzer, MMT, Hawaii, LBT
- SWIRE 50 deg^2 (Lockman hole, ELAIS, XMMLSS,ECDFS): Spitzer, some Chandra/XMM, some HST, Herschel
- eROSITA! 20.000 deg^2 10^{-14} cgs 200 deg^2 3×10^{-15} cgs

Chandra deep and wide fields

CDFS 2Msec 0.05deg^2
~400 sources

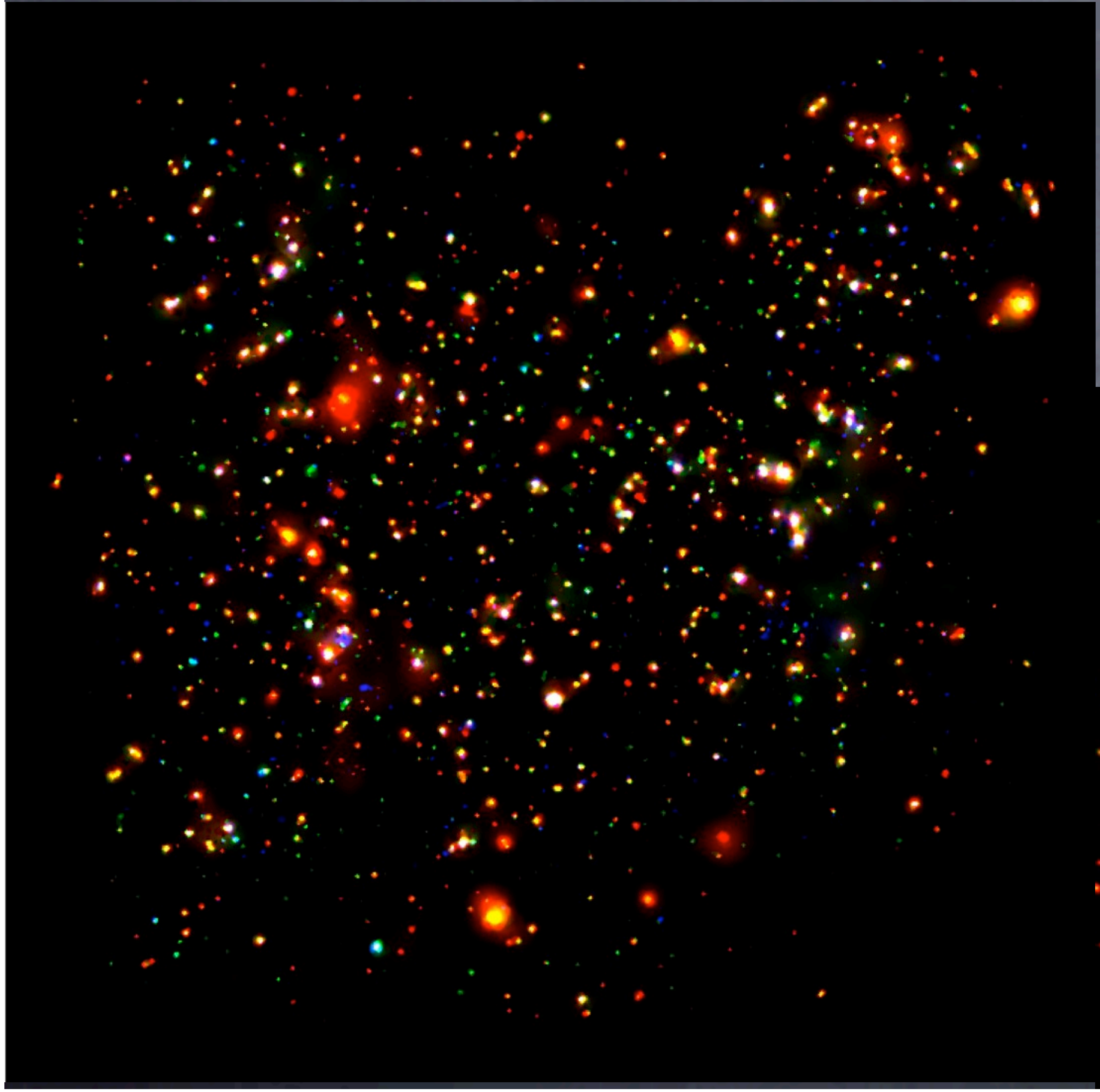
CCOSMOS 200ksec 0.5deg^2 100ksec 0.4deg^2
1.8 Msec ~1800 sources
Elvis et al. 2008



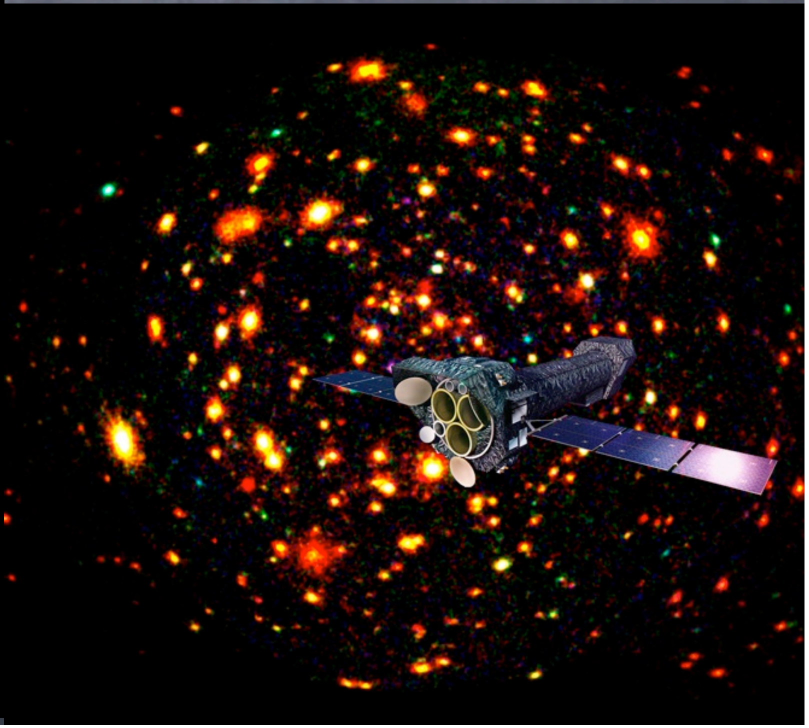


XMM surveys

COSMOS 1.4Msec 2deg^2



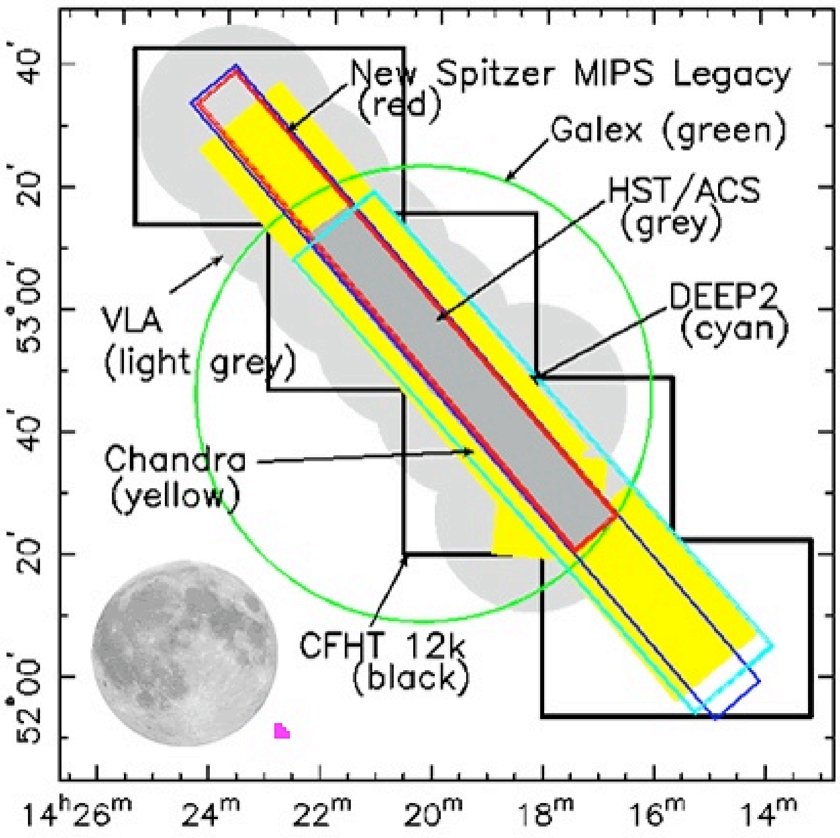
Lockman Hole 0.7Msec 0.3deg^2

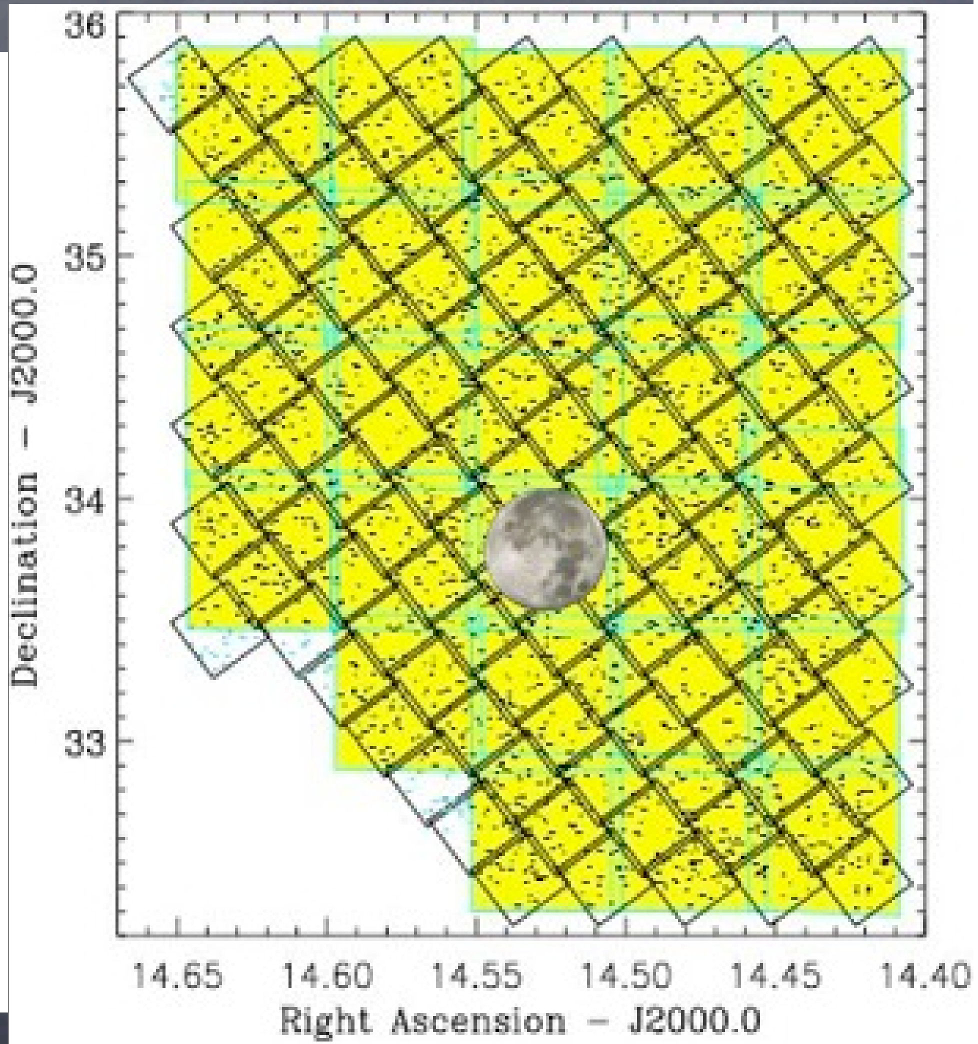


Chandra surveys

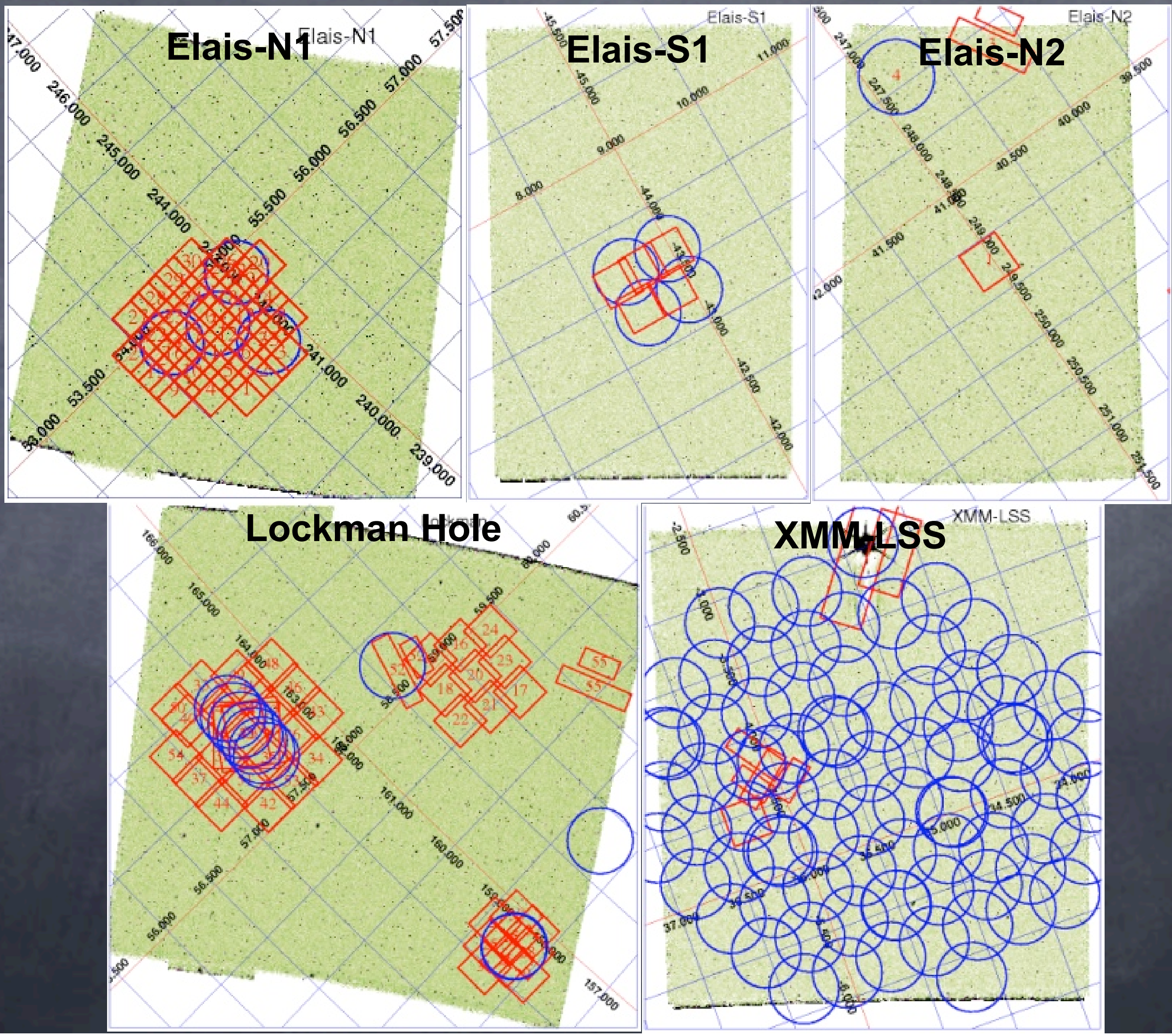
AEGIS: Extended Groth Strip

Bootes field

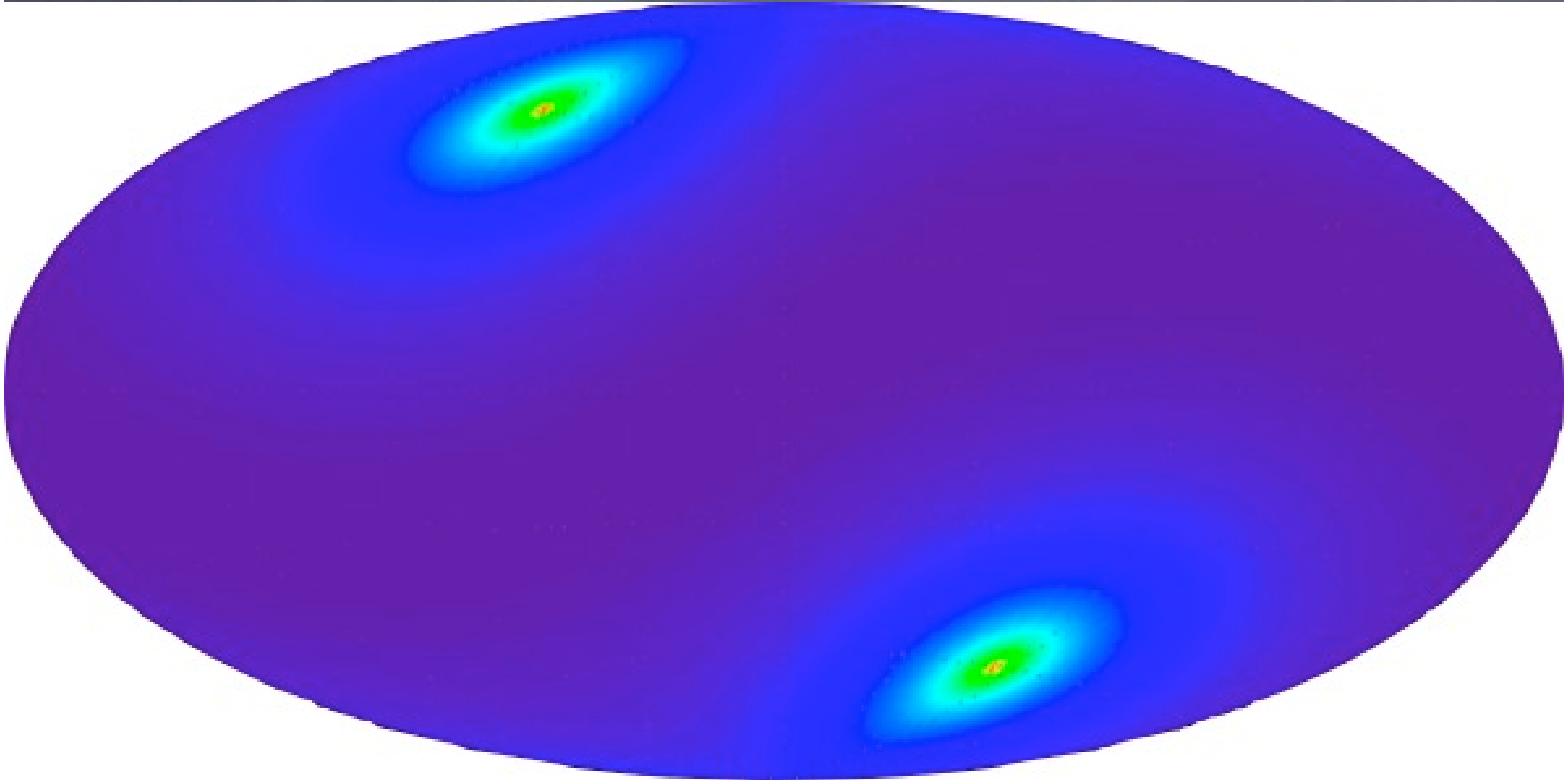




Spitzer large area surveys: SWIRE



eROSITA



~30ks on poles, ~1.7ksec equatorial

What next?
The X-ray survey discovery space