Extragalactic X-ray Surveys: Source Populations and their Evolution

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X-ray School 2011

Preface

This review, like so many surveys, will be

- *incomplete*
- *biased*

Survey types include

SYNOPTIC

- repeated monitoring

KNOWN OBJECTS

- pointed sample surveys
- raster/mosaic/tiling of individual objects

SERENDIPITOUS

- deep pencil beam serendipitous
- raster/ mosaic/ tiling of 'blank sky' region
- all-sky serendipitous

I'll speak only about serendipitous, extragalactic X-ray surveys from focusing telescopes, and almost exclusively about

AGN and Galaxies

Dangers of Targeted Samples

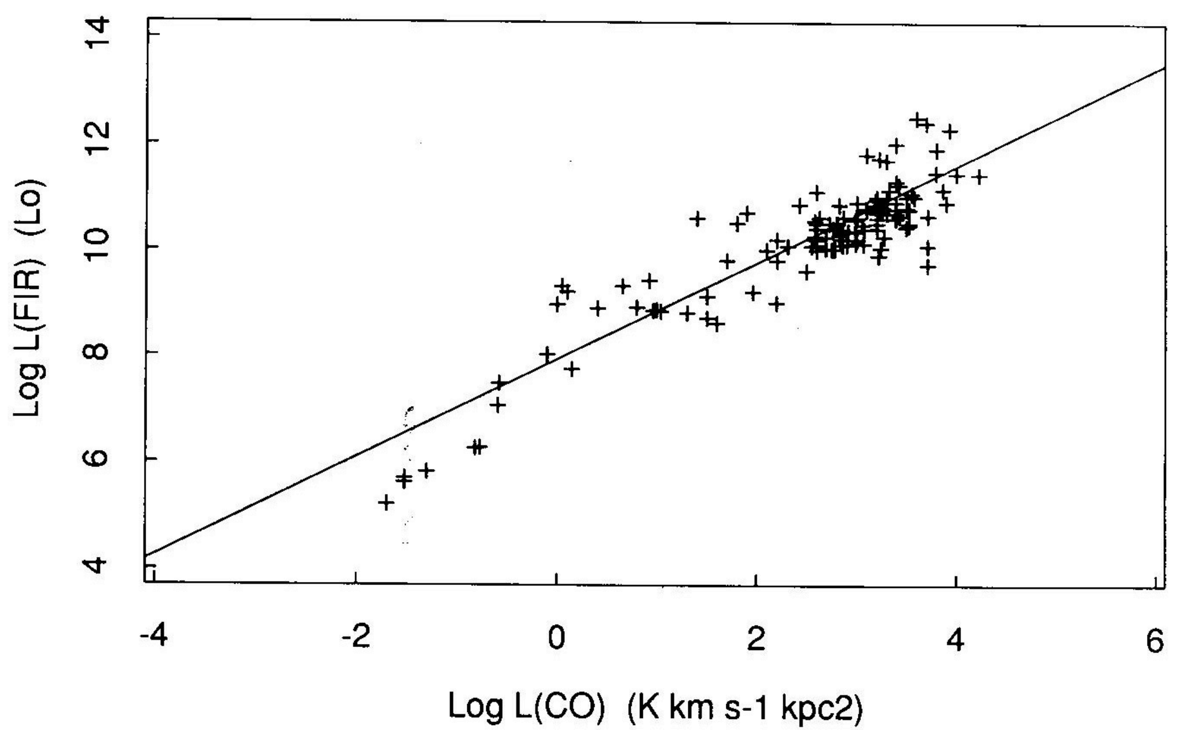


Fig. 5. (a) Correlation between total FIR luminosity and CO luminosity for galaxies, with a least-squares fit. Data from Tacconi and Young (1987) and Solomon and Sage (1988). Upper limits included.

Kennicut 1990

Dangers of Targeted Samples

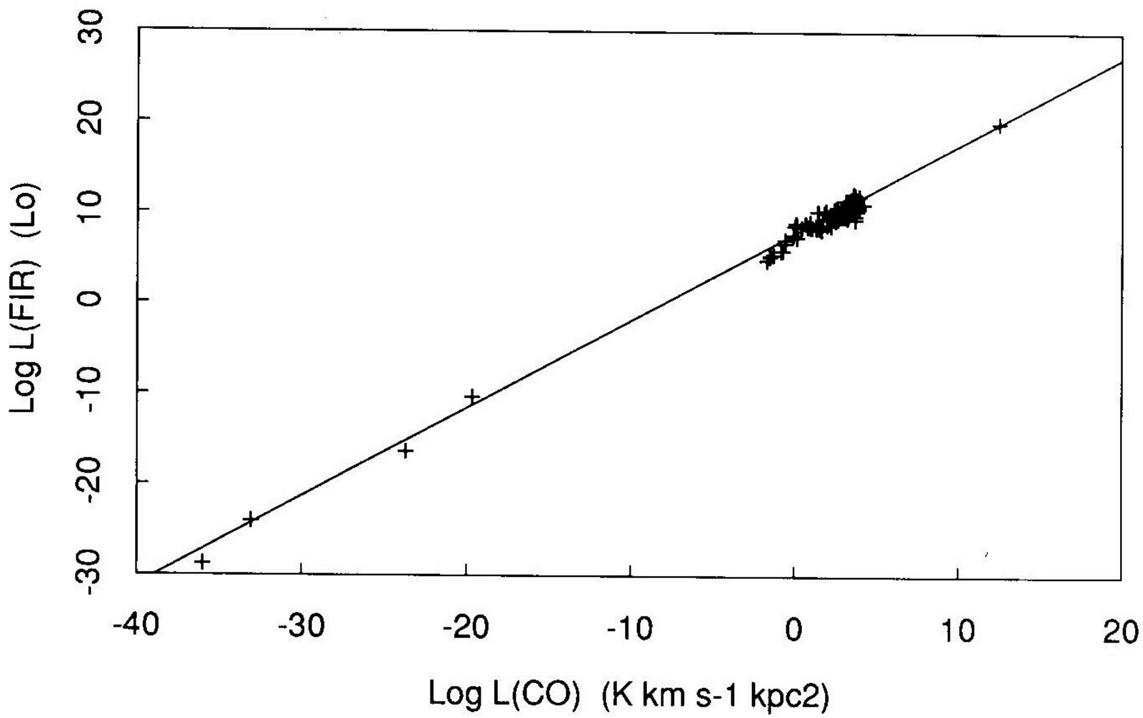


Fig. 5. (b) Same data as above, but also including calculated luminosities for (increasing order) a burning cigar, a Jeep Cherokee which has been sitting in a closed garage for an hour with the engine running, the 1988 Yellowstone Park forest fire, Venus, and the observable universe (assumed to be 10^{11} average galaxies). The line is a least-squares fit.

Kennicut 1990

Outline

- Why survey?
- Advantages and characteristics of X-ray selection
- Historical X-ray surveys
- The log*N*-log*S*
- Cosmic X-ray Background
- Current surveys, Deep and Wide
- Analyzing survey data
- Multiwavelength followup
- Source types
- Science Motivations
- Science Results

Why Survey?

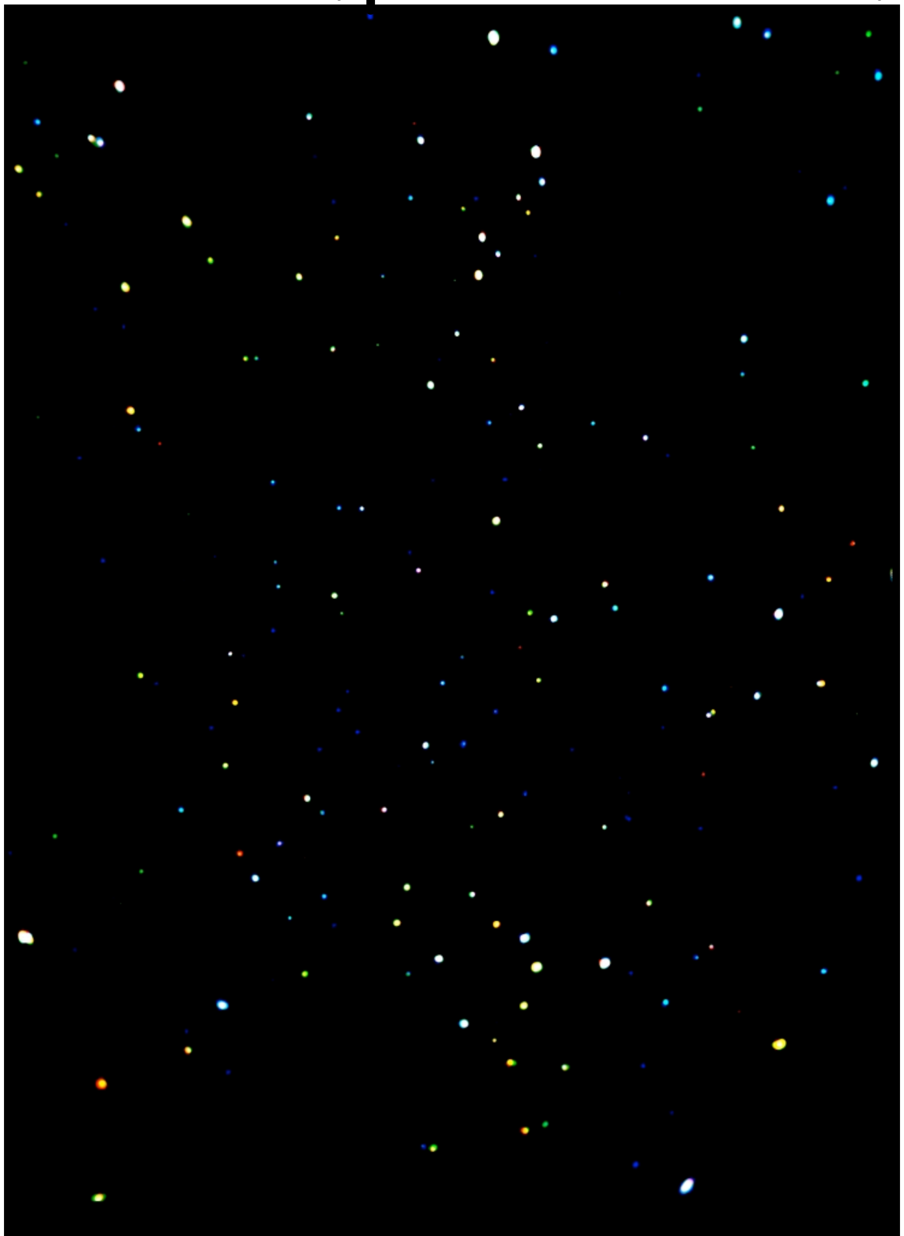
- "Census of the Universe"
- Outliers, novel sources and serendipity.
- Resolve the Cosmic X-ray background.
- Accumulate a statistical samples.
- Study populations, e.g.
  - Luminosity functions
  - Spectral energy distributions
  - Accretion, star formation
  - Clustering
  - Morphology
  - Evolution

X-ray Survey Advantages

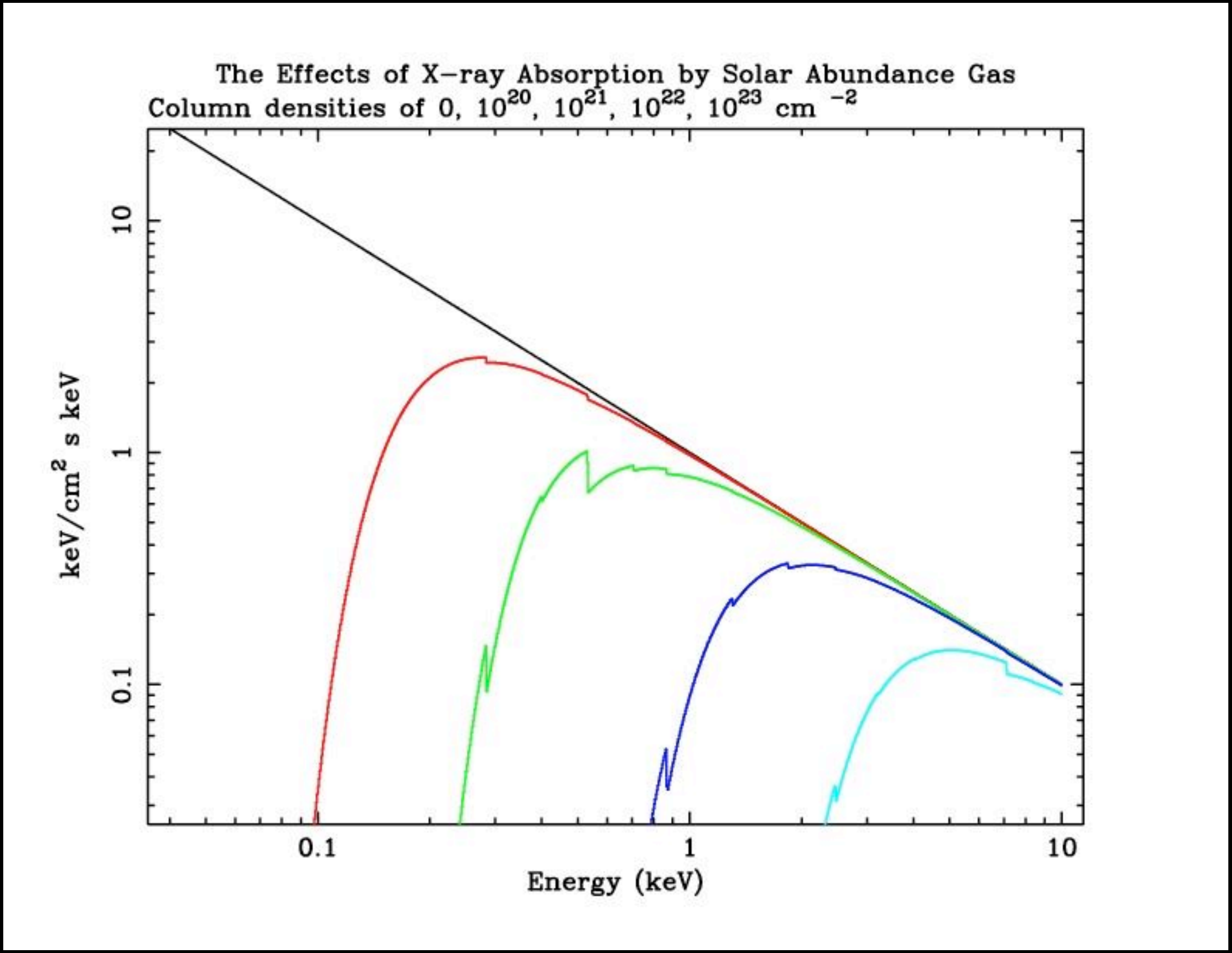
- *Most* X-ray sources are AGN (purity).
- *Most* AGN produce X-rays (completeness).
- Surface density of X-ray-selected AGN far exceeds optical AGN by 10-20 (Bauer et al 2004)
- X-rays sample the circumnuclear region ($R<100*R_{grav}$)
- Weaker z-dependence than optical.
- X-rays penetrate large columns of gas and dust.
- Negative *k*-correction *favors* high-z

$$N^{eff}_H \sim N^{intr}_H / (1+z)^{2.6}$$

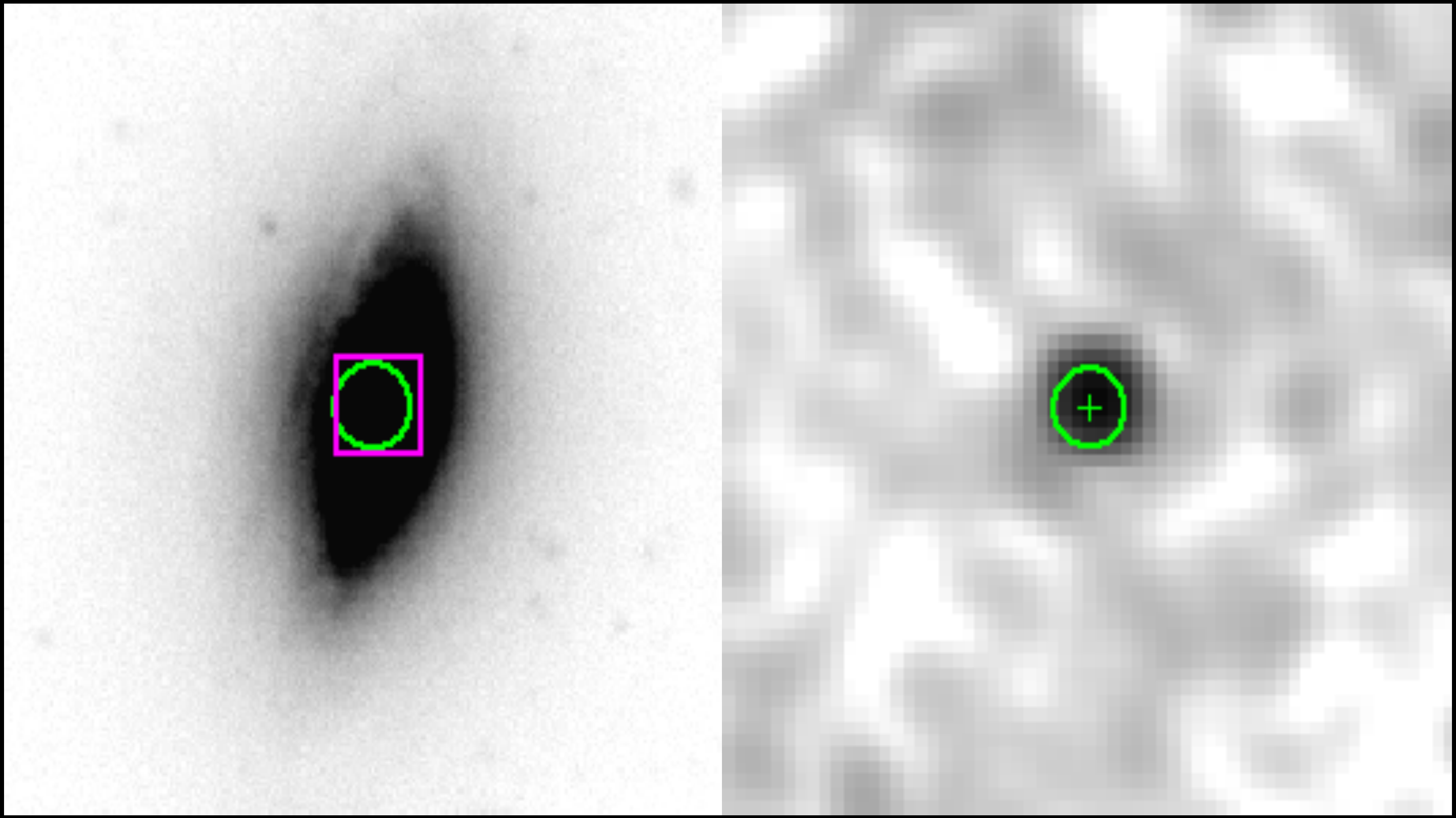
Striking how modest the number of X-ray sources is compared to the number of optical sources



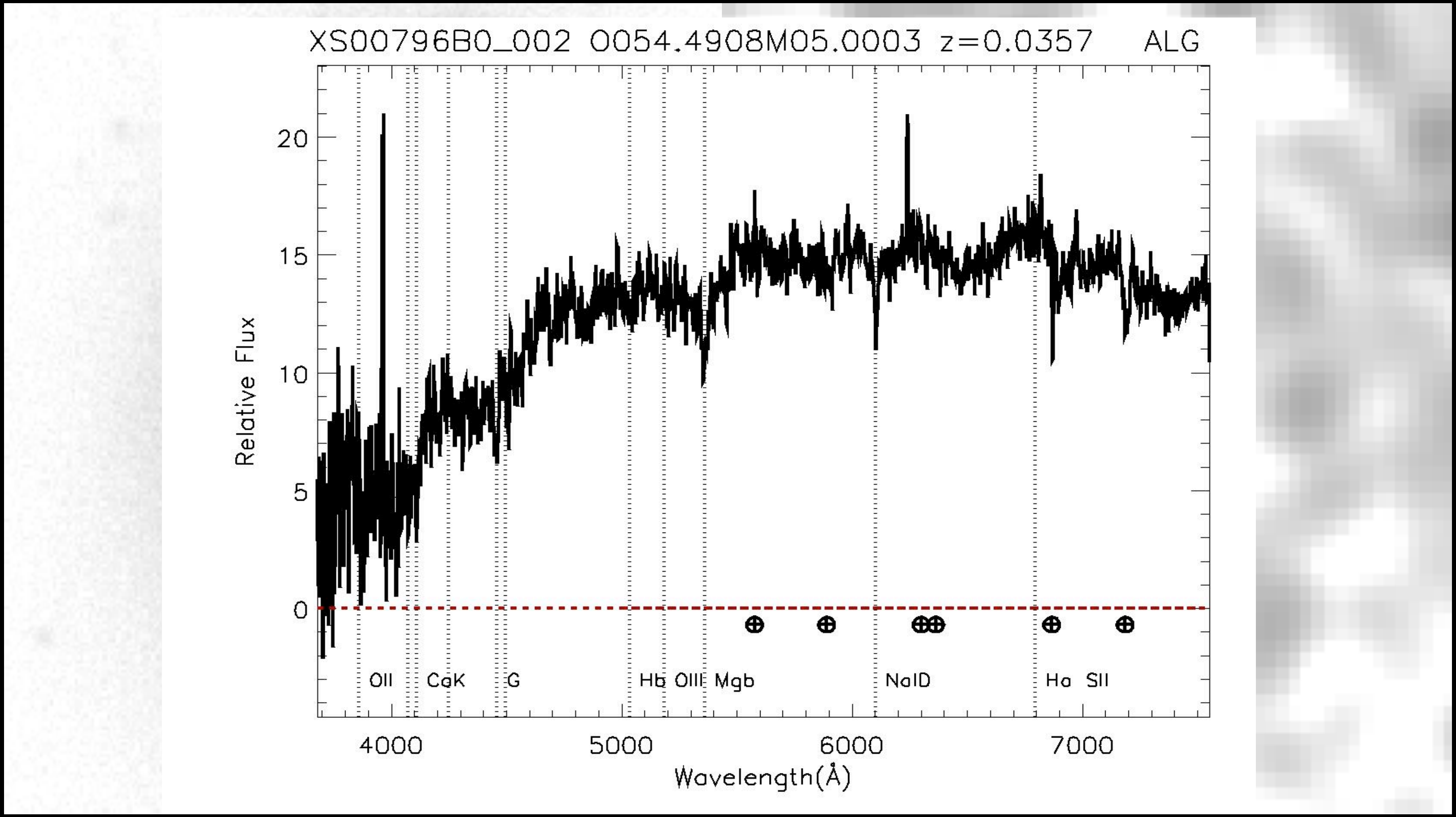
Advantage: Penetrating Power of X-rays



Advantage: High contrast between AGN and stellar light



Advantage: High contrast between AGN and stellar light

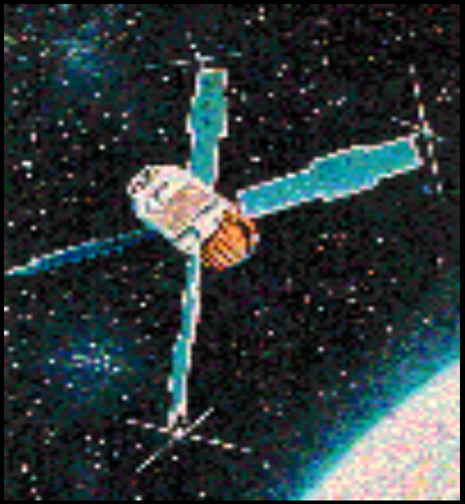
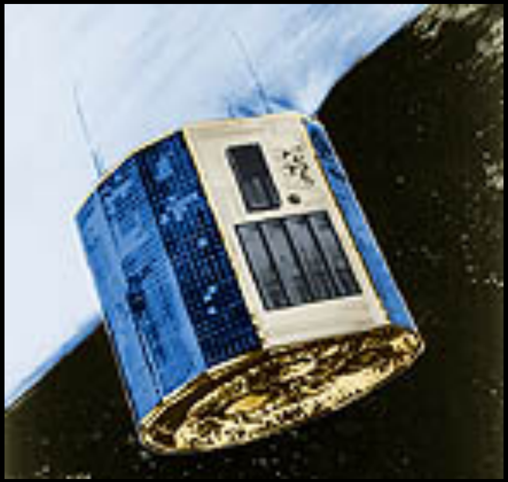
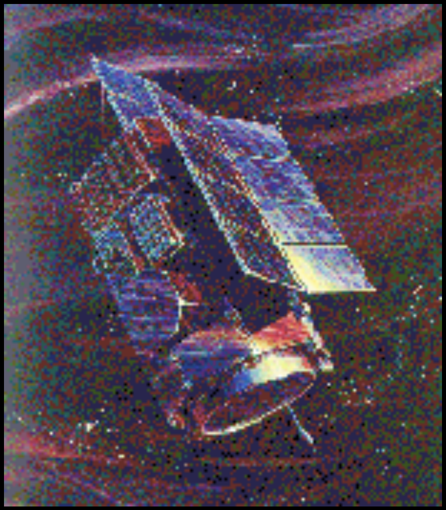


X-ray Survey Downers

- X-ray detectors are non-uniform
  - PSF size and flux sensitivity vary with off-axis angle
- Deep or wide X-ray surveys are expensive & time consuming
- "Cosmic Variance"
  - can use serendipitous detections from archived observations
- Require multi-wavelength followup and usually spectroscopy

Early X-ray Surveys

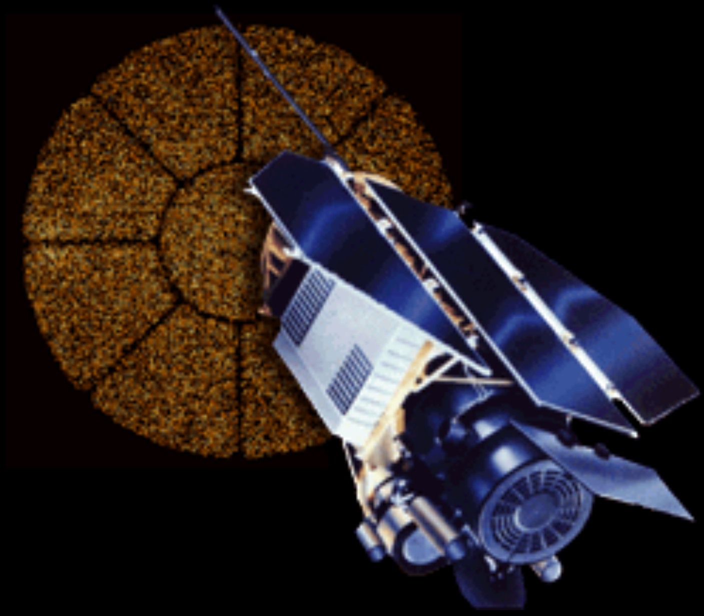
- Uhuru (1970-1973) [2-20 keV]
- Ariel-V (1973-1980) [0.3-40 keV]
- HEAO-1 (1977-1979) [0.2keV-10MeV]

Soft X-ray Surveys

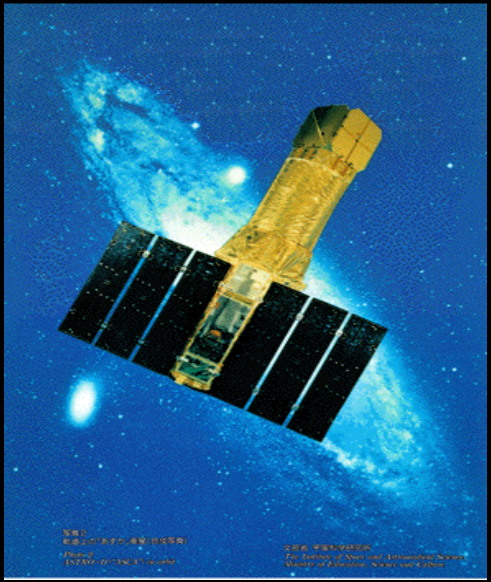
- Einstein (1978-1981) [0.2-20 keV]
  aka HEAO-2, first imaging telescope

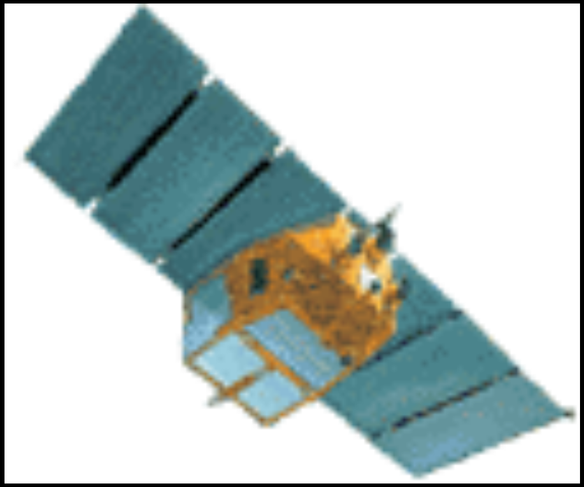
- ROSAT (1990-1999) [0.1-2.5 keV]



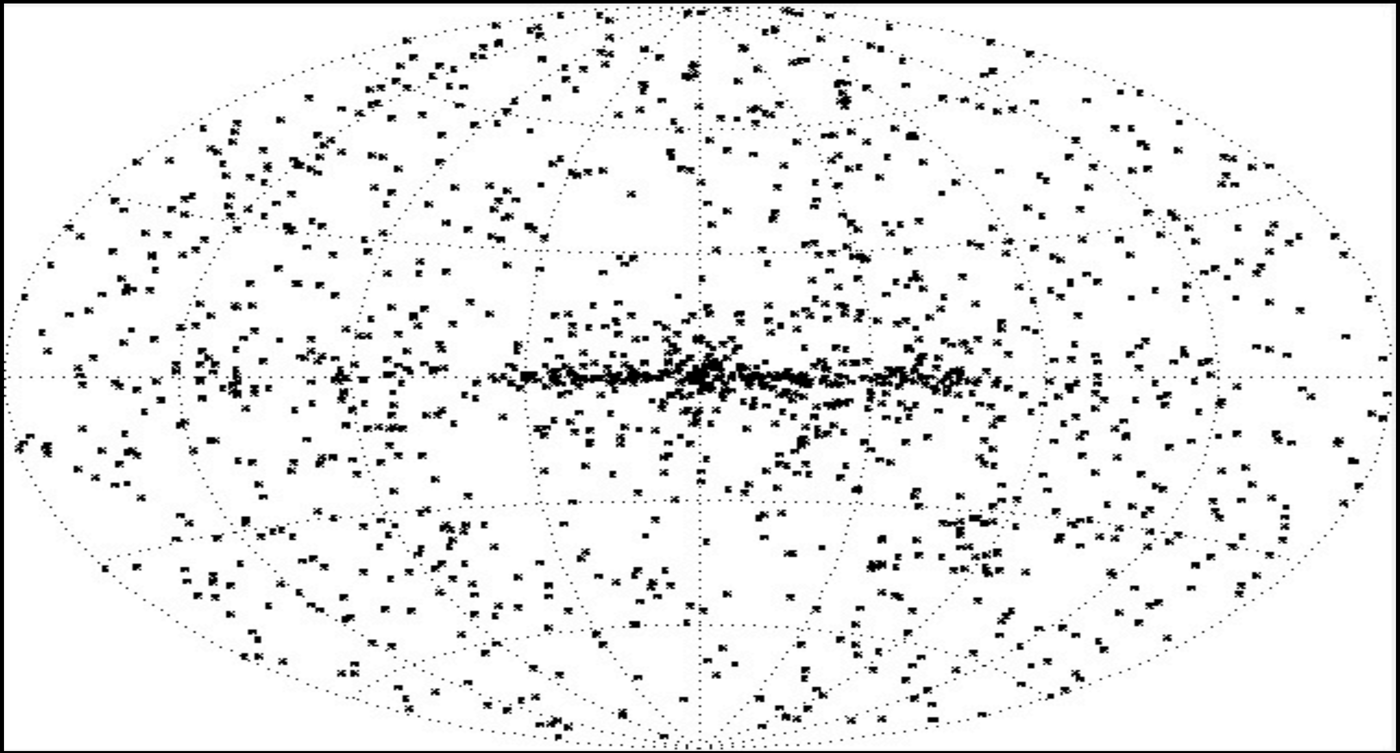
Hard X-ray Surveys

- ASCA (1993-2001) [0.4-10 keV]
- *Beppo*SAX (1996-2002) [0.1-300 keV]
- INTEGRAL/IBIS (2002 -) [15keV - 10 MeV]
- Swift/BAT (2004 -) [15 - 150 keV]





The Hard X-ray Sky: Mostly AGN

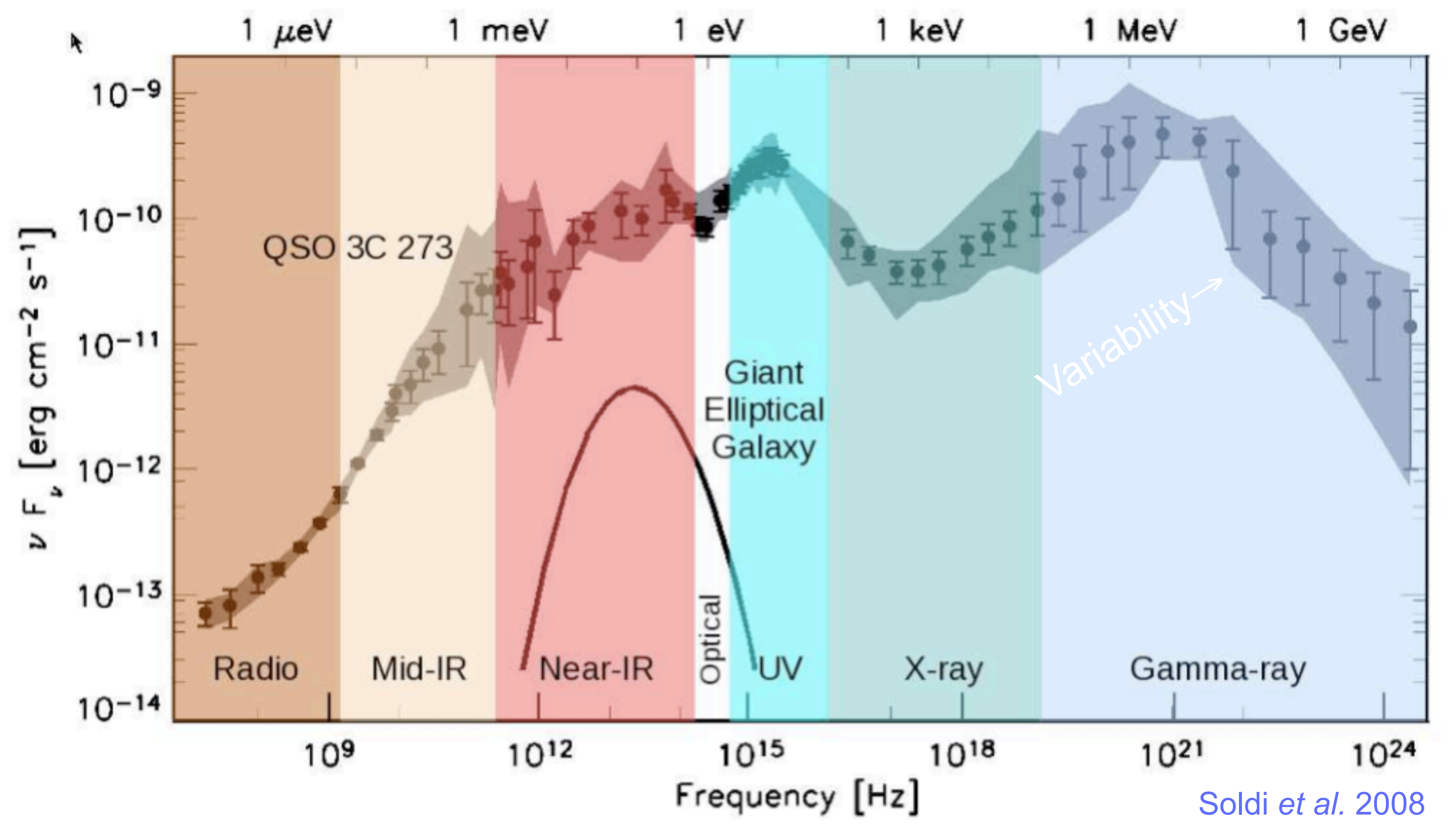


ADAPTED FROM SWIFT-BAT/ INTEGRAL-IBIS SURVEYS

(CUSUMANO ET AL. 2010, BIRD ET AL. 2010, TUELLER ET AL. 2009, KRIVONOS ET AL. 2007)

(Credit F. Panessa 2011)

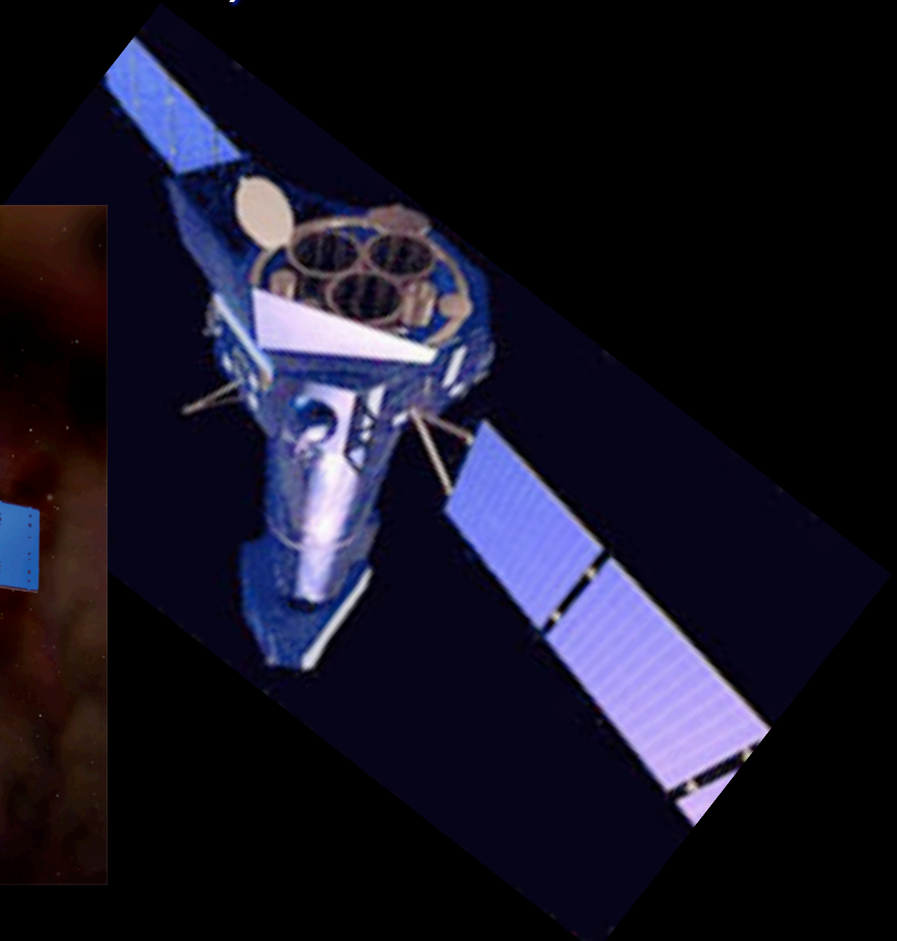
Most X-ray Sources are AGN



Soldi *et al.* 2008

Chandra and *XMM-Newton* Surveys

- Chandra (1999-present)
- XMM-Newton (1999-present)



“Just” Count the Sources: the log*N*-log*S*

- Derive the source density on the sky as a function of flux.

- Requires detailed understanding of survey sensitivity and area.

- Given an assumed cosmology, the log*N*-log*S* places limits on source populations, luminosity functions, and evolution.

- Population models must eventually reproduce the log*N*-log*S*, including how it changes with observed bandpass.

The Extragalactic log-N-logS

$$N = \rho V = \rho \left(\frac{\Omega}{4\pi}\right)\frac{4}{3}\pi D_{lim}^3$$

but

$$L = 4\pi D_{lim}^2 S$$

so

$$D_{lim} = \sqrt{\frac{L}{4\pi S}}$$

therefore

$$N \propto \rho\Omega L^{\frac{3}{2}} S^{-\frac{3}{2}}$$

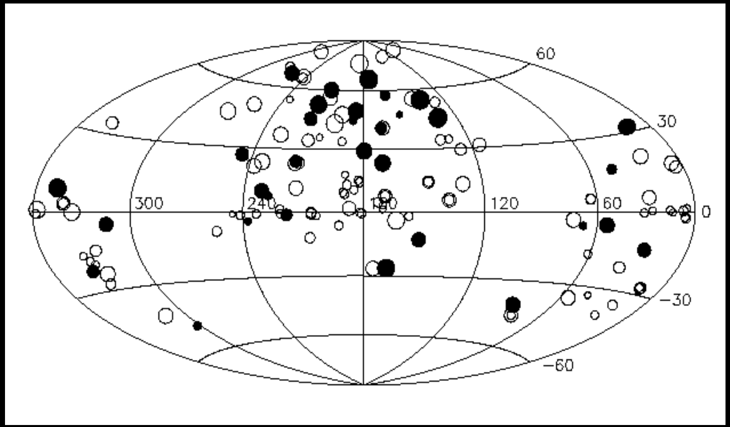
So the slope of the log$N$-log$S$ curve should be $\frac{-3}{2}$ for a non-evolving population in an infinite, Euclidean universe!

Flux Limits

- Flux limit is a function of
  - Telescope effective area and Exposure
  - Background level (particle, diffuse bkg, and unresolved/undetected sources)
  - PSF (function of detector position)
  - Source spectrum

- Definitions of f_X^{lim} differ:
  - Counts
  - flux
  - S/N
  - *Prob*
  - *% Completeness*

ChaMP X-ray Simulations

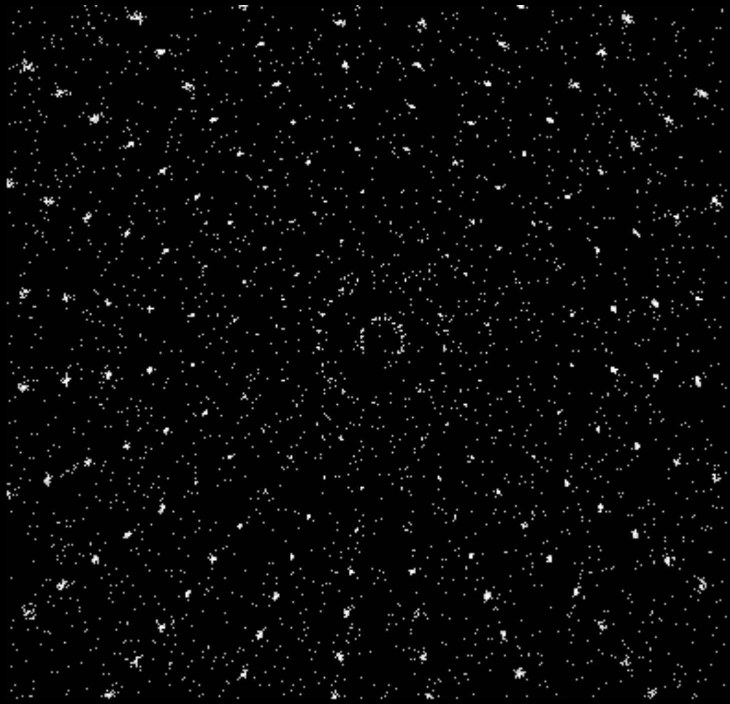


SAOSAC raytrace simulations

Grid of off-axis angles

10 – 1000 count sources

Std XPIPE detection & Photometry

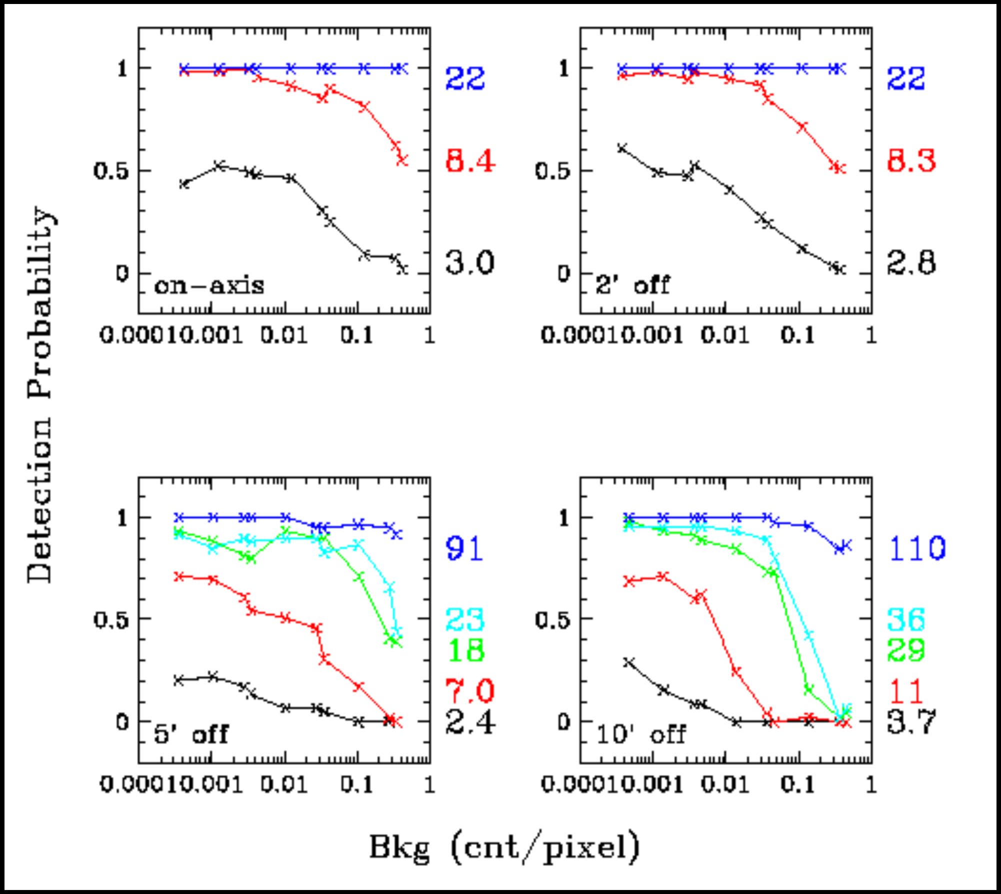


Compare input/output

- detection rates
- positions

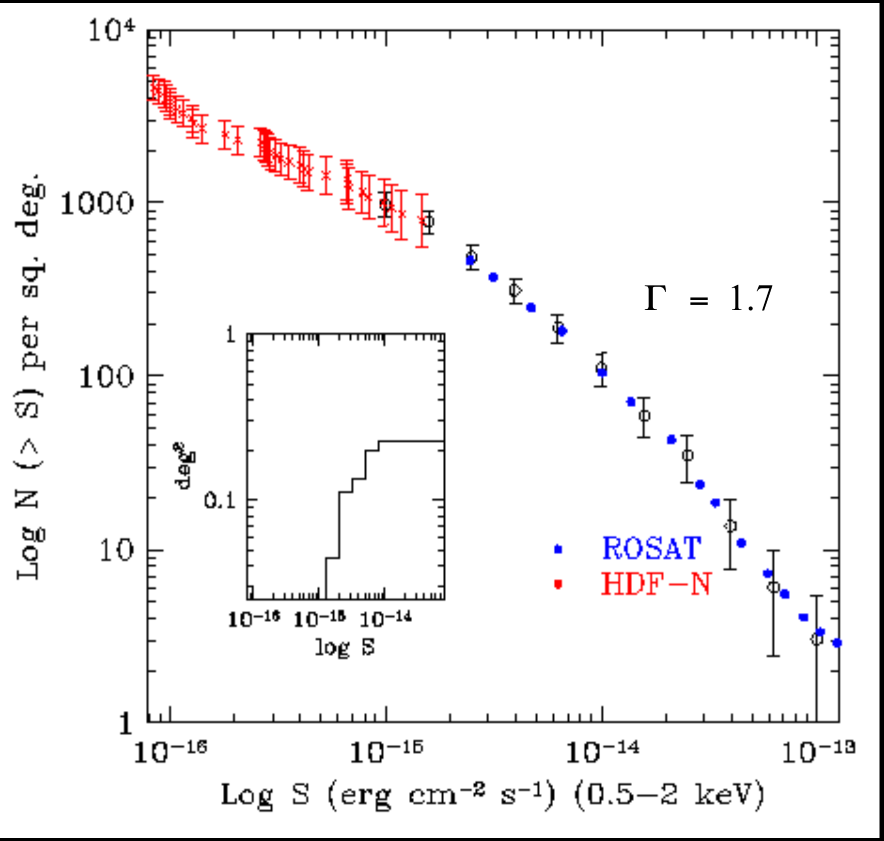
X-ray Sensitivity & Incompleteness

- Detailed corrections required for an accurate logN-logS or XLF using full field area:
  - Total survey area vs. flux
  - Limiting flux at each pixel
  - Incompleteness

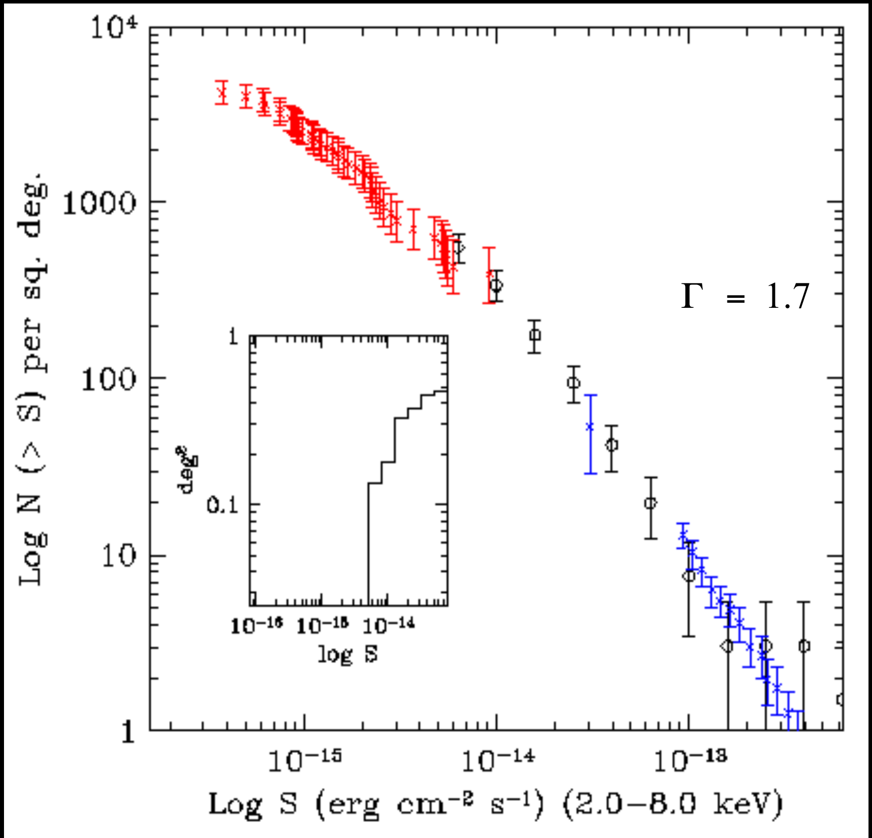


ChaMP logN-logS

Kim et al. 2004



Soft Band



Hard Band

Bridges flux gaps between ROSAT, ASCA & Chandra Deep Fields

Results consistent with CDFs and XMM

ChaMP logN-logS: Results

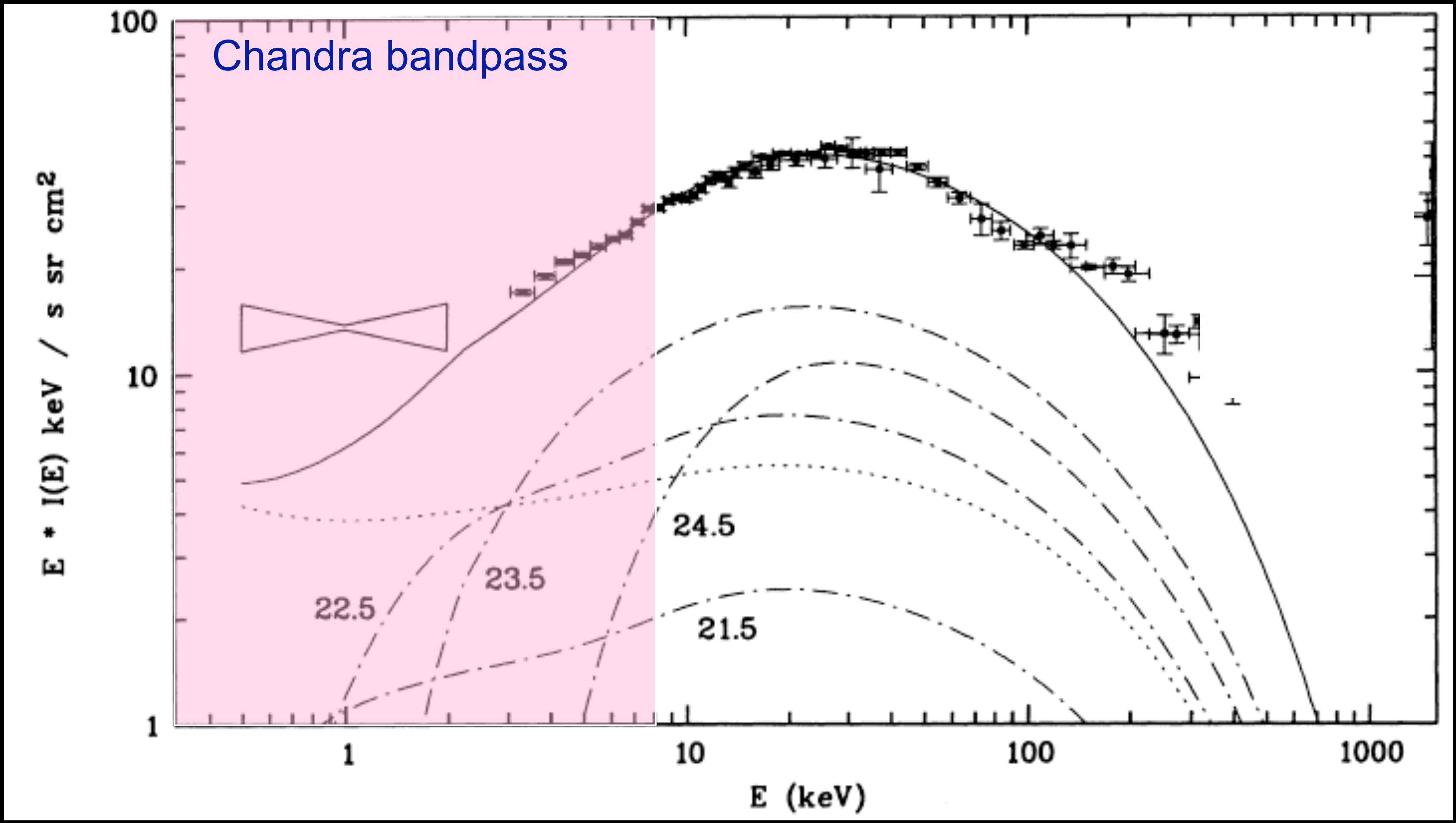
Kim et al. 2004

- Soft band differential log*N*-log*S* requires a broken powerlaw
  - β_{bright}=2.3±0.2, β_{faint}=1.7±0.1, $S_{break}=6\times10^{-15}$
- Hard band: β=1.3±0.1 single PL acceptable
- Results consistent with

XMM (Baldi et al. 2001)

CDF-N (Brandt et al. 2001)

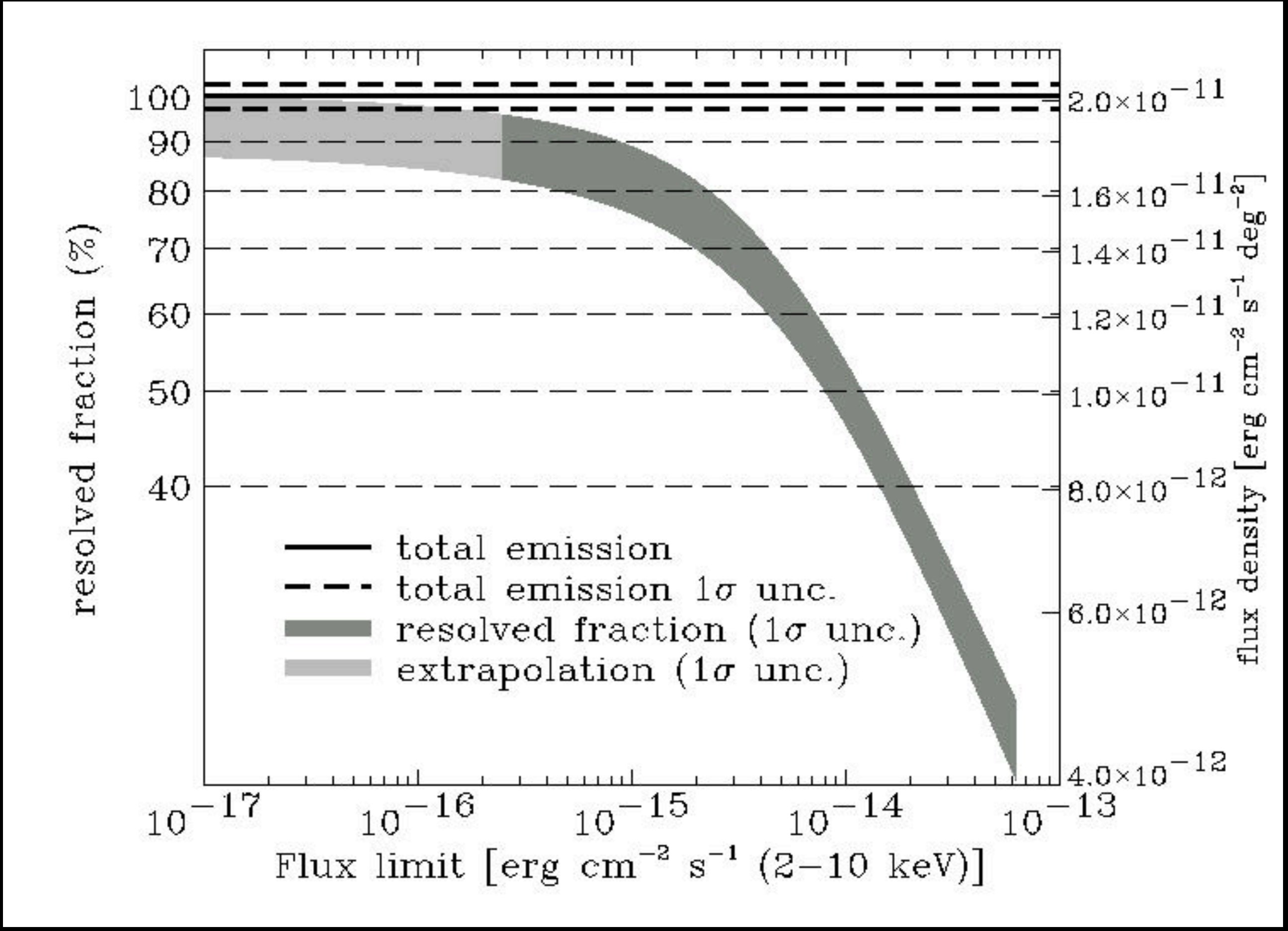
The Cosmic X-ray Background and AGN Population Synthesis



Comastri et al. 1995

- Discovered 1962 (Giacconi et al., flying Geiger counters)
- Peaks at ~30keV
- *Not* hot gas, since expected CMB distortion's not seen (Wright et al. 1994)

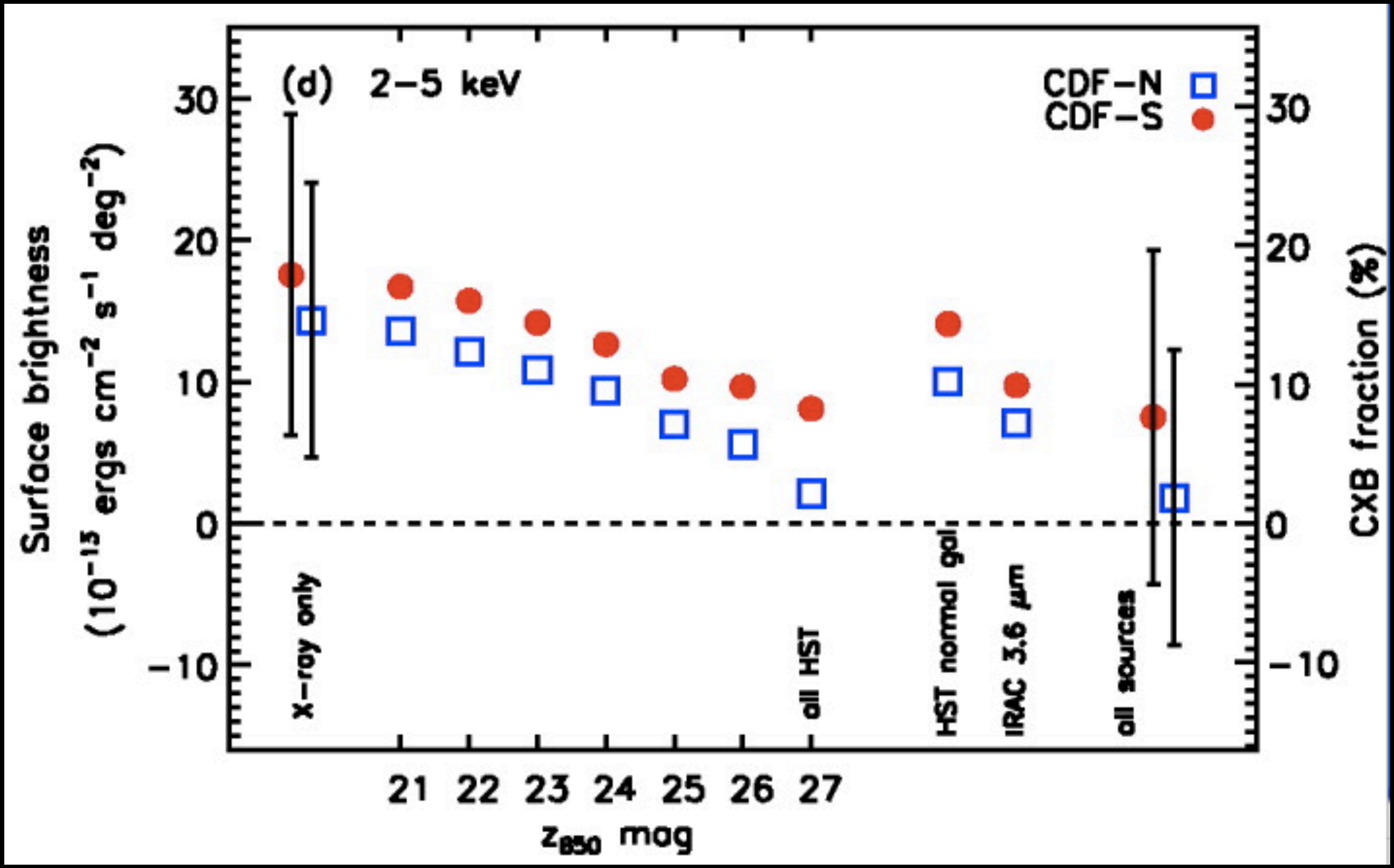
The "Formerly Diffuse" Cosmic X-ray Background



(Moretti et al. 2003)

- About 80% of the 2-8 keV CXRB resolved:
  CDF-N (Brandt et al. 02) , CDF-S (Giacconi et al 01), Lockman Hole (Hasinger et al. 01)

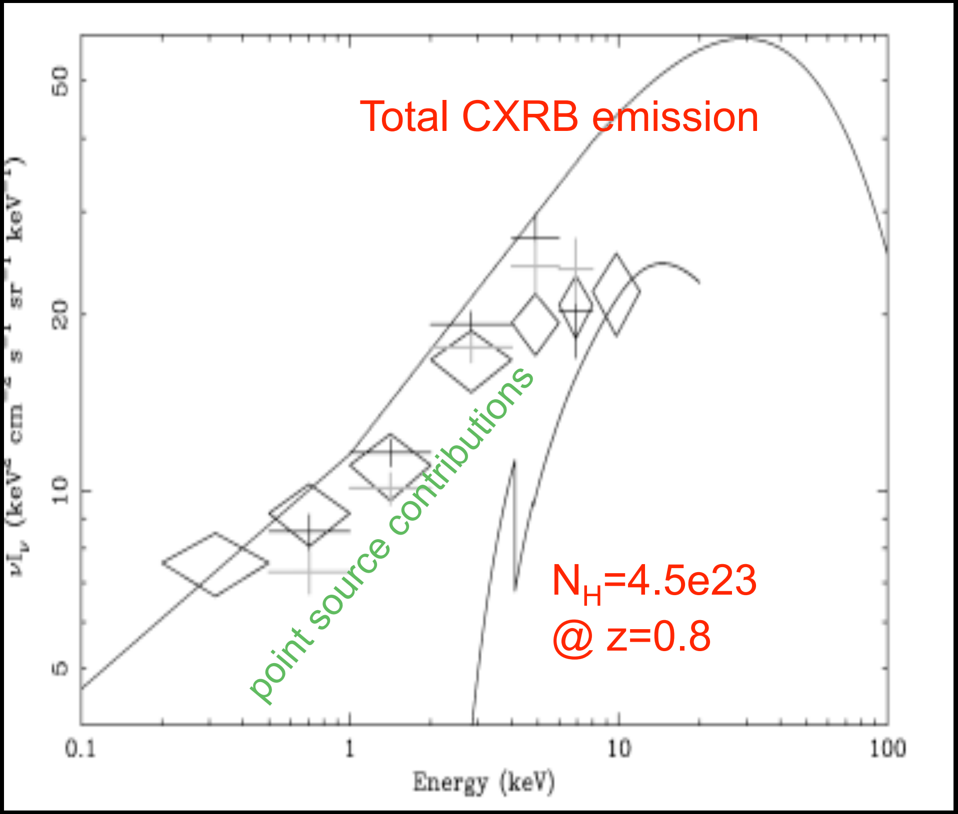
Most of the Rest Associated with Faint Galaxies

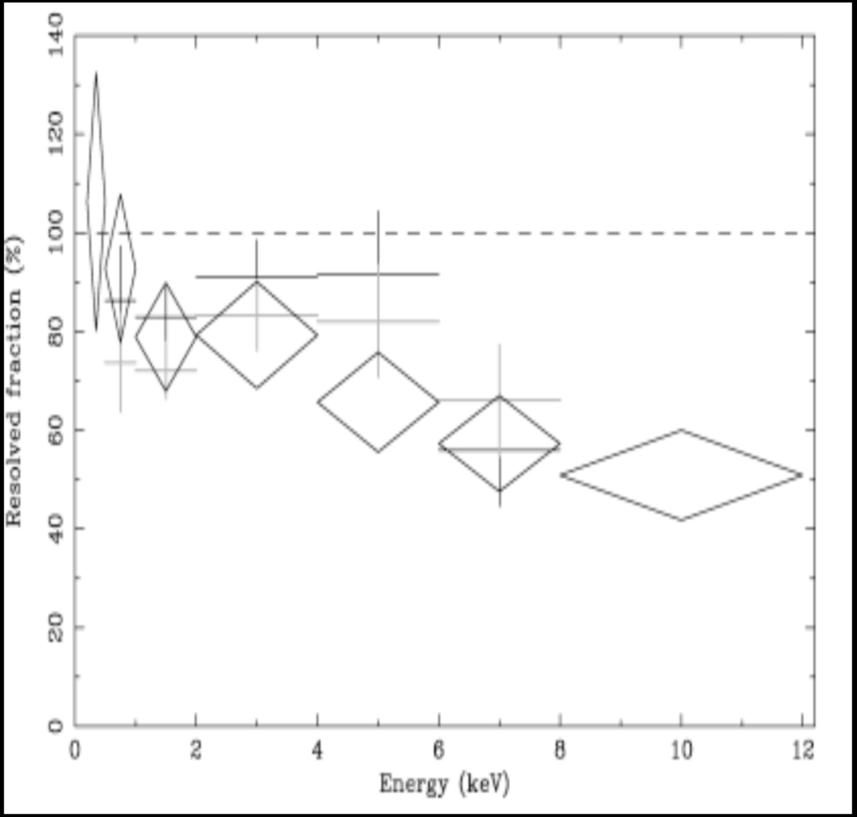


Hickox & Markevitch 2007

- after excluding Chandra, HST and Spitzer IRAC sources, only only a marginal % of Chandra CXB still remains

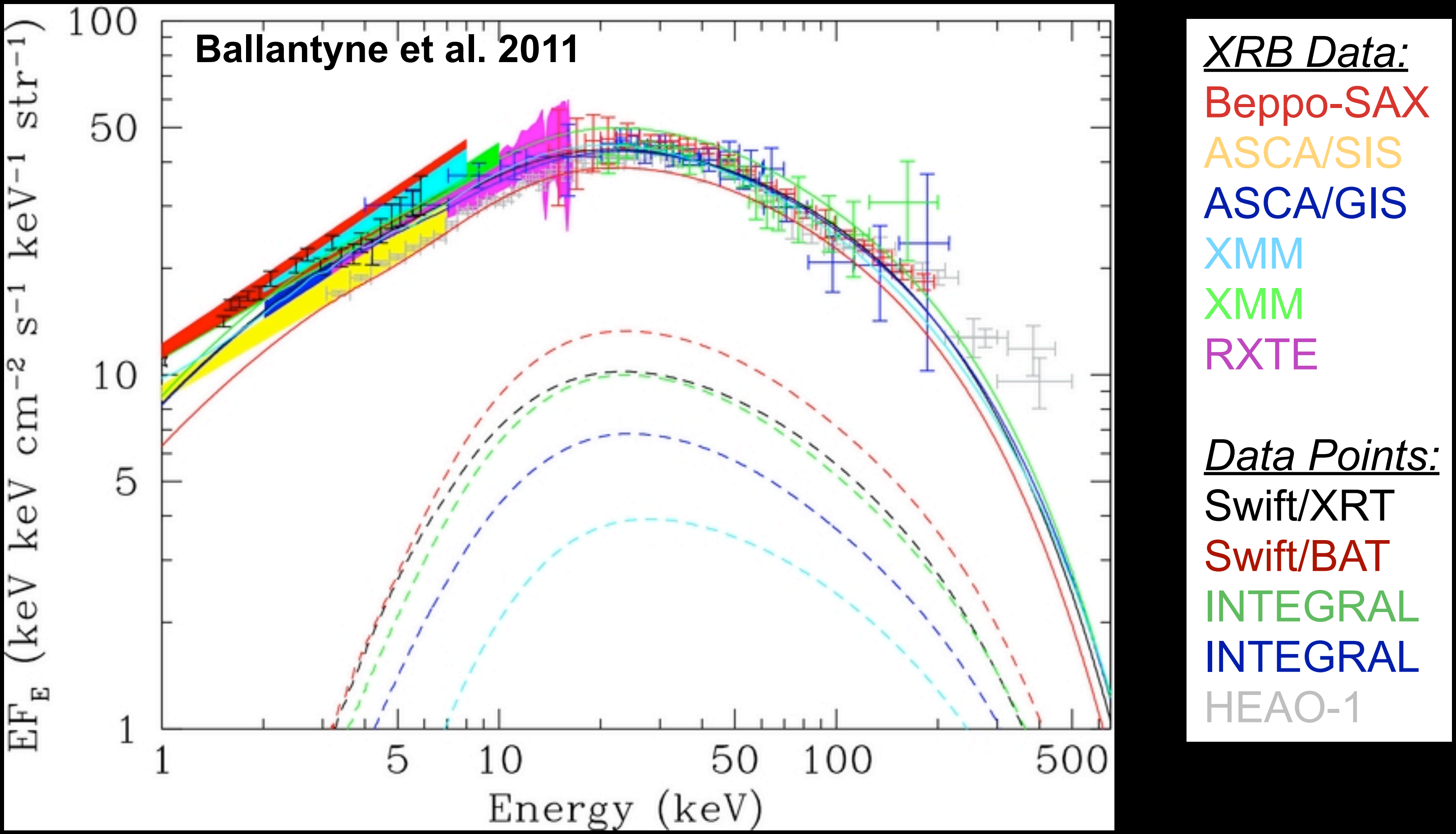
The *Un*resolved Hard X-ray Background (*XMM* and *Chandra* Deep Fields)





(Worsley et al. 2005)

The CXRB and AGN Population Synthesis



5 recent AGN evolution models (solid lines) and their Compton thick components (dashed).

Model parameters include HXLF, Γ dispersion, reflection efficiency, CT ratio, *and* evolution.

Deep Extragalactic X-ray Surveys (>75ksec)

Table 1: Deep Extragalactic X-ray Surveys with *Chandra* and *XMM-Newton*

Survey Name	Max. Eff. Exp. (ks)	Solid Angle (arcmin^2)	Representative Reference or Note
	Chandra		
Chandra Deep Field-North	1950	448	Alexander et al. (2003b)
Chandra Deep Field-South	940	391	Giacconi et al. (2002)
HRC Lockman Hole	300	900	PI: S.S. Murray
Extended CDF-S	250	900	PI: W.N. Brandt
Extended Groth Strip	200	1800	Nandra et al. (2005)
Lynx	185	286	Stern et al. (2002a)
LALA Cetus	174	428	Wang et al. (2004b)
LALA Boötes	172	346	Wang et al. (2004a)
SSA13	101	357	Barger et al. (2001a)
Abell 370	94	357	Barger et al. (2001b)
3C 295	92	274	D'Elia et al. (2004)
SSA22 "protocluster"	78	428	Cowie et al. (2002)
ELAIS N1+N2	75	586	Manners et al. (2003)
	XMM-Newton		
Lockman Hole	770	1556	Hasinger (2004)
Chandra Deep Field-South	370	802	Streblyanska et al. (2004)
Chandra Deep Field-North	180	752	Miyaji et al. (2003)
13 hr Field	130	665	Page et al. (2003)
Subaru *XMM-Newton* Deep	100	4104	PI: M.G. Watson
ELAIS S1	100	1620	PI: F. Fiore
Groth-Westphal	81	727	Miyaji et al. (2004)
Marano Field	79	2140	Lamer et al. (2003)
COSMOS	75	7200	PI: G. Hasinger

Brandt 2005 ARAA

ADD: C-COSMOS 1.8Ms; CDFS 3.8Ms

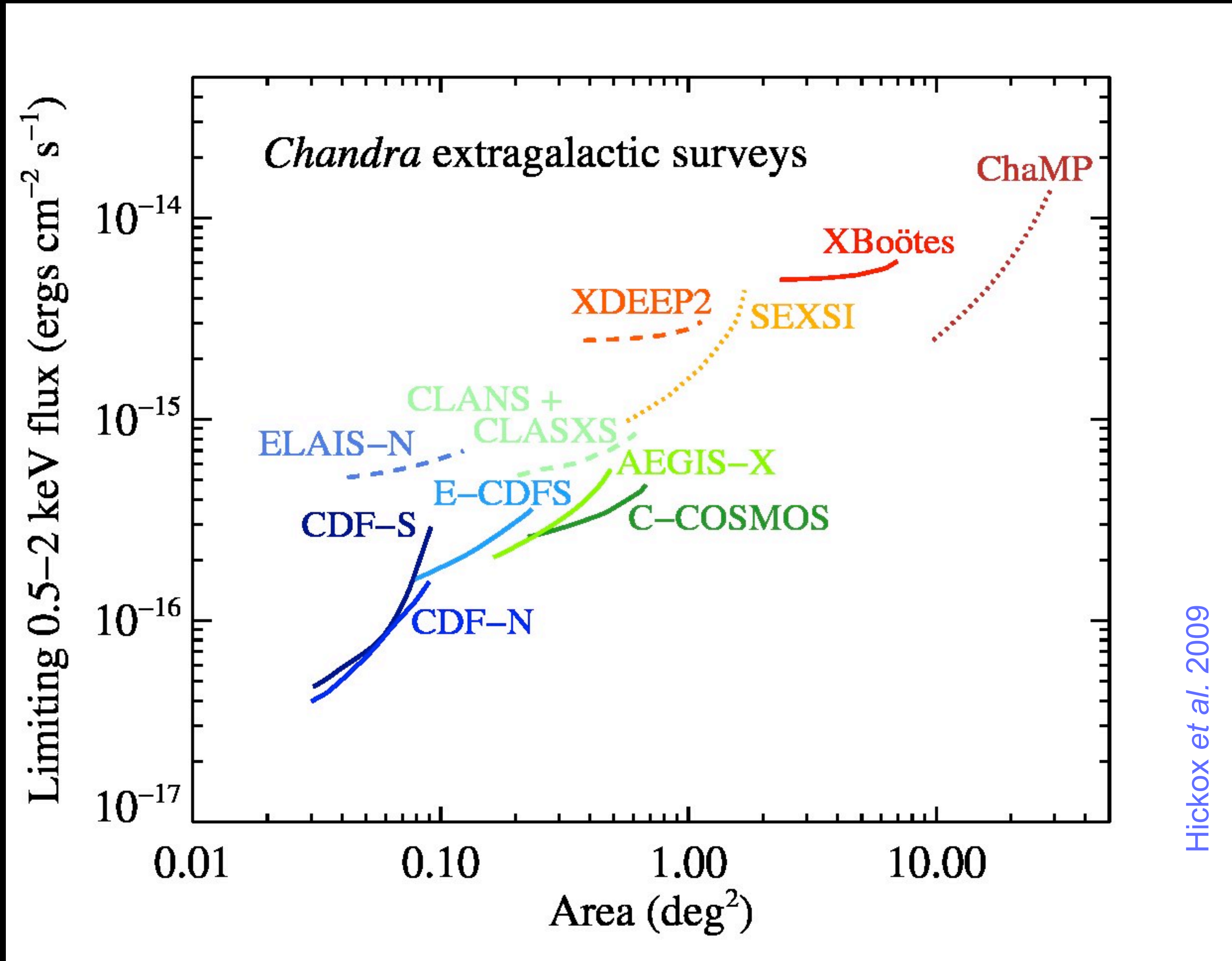
Chandra Advances

~1” positions, small PSF & low background

- 10-100× fainter flux limits
- unambiguous source IDs
- Source extent and morphology

XMM-Newton is Complementary

4× Effective Area + larger Field-of-View
Harder energy band: 0.5-20 keV



Deeper

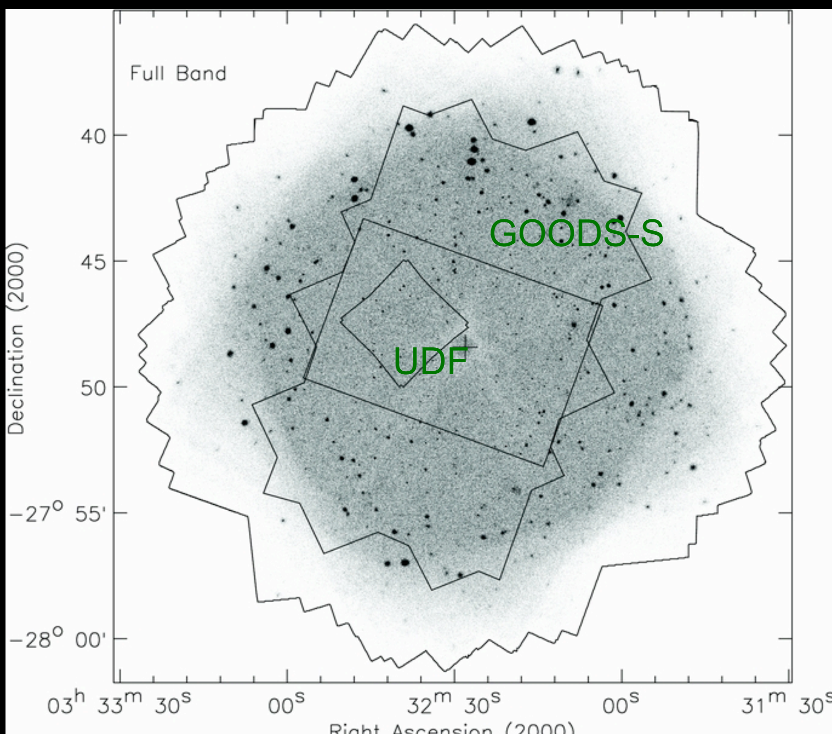
Wider

Chandra Deep Field South

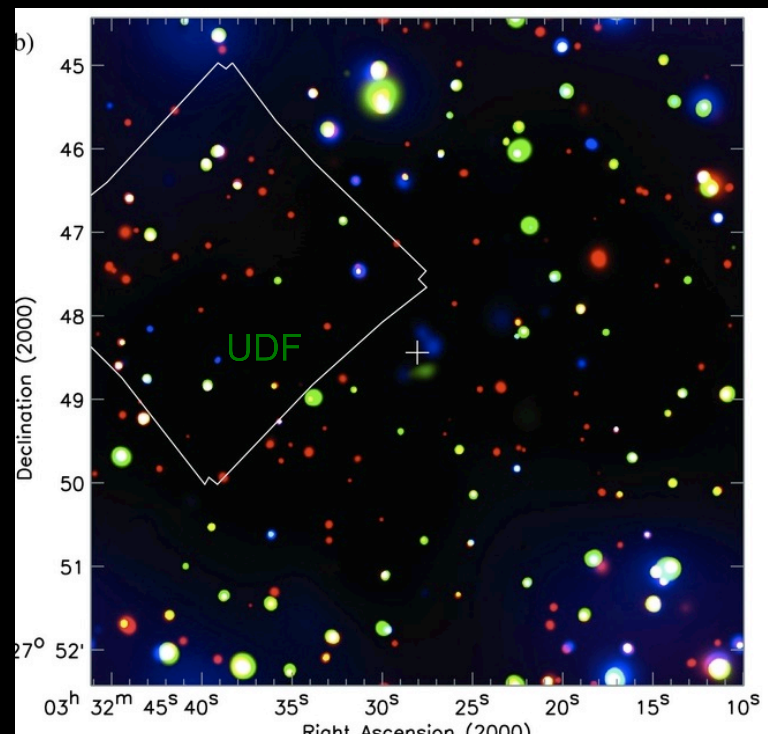
CDF-S: 4Msec in 52 obsids, May 2000 - July 2010.

Merged dataset at

http://cxc.harvard.edu/cda/Contrib/CDFS.html

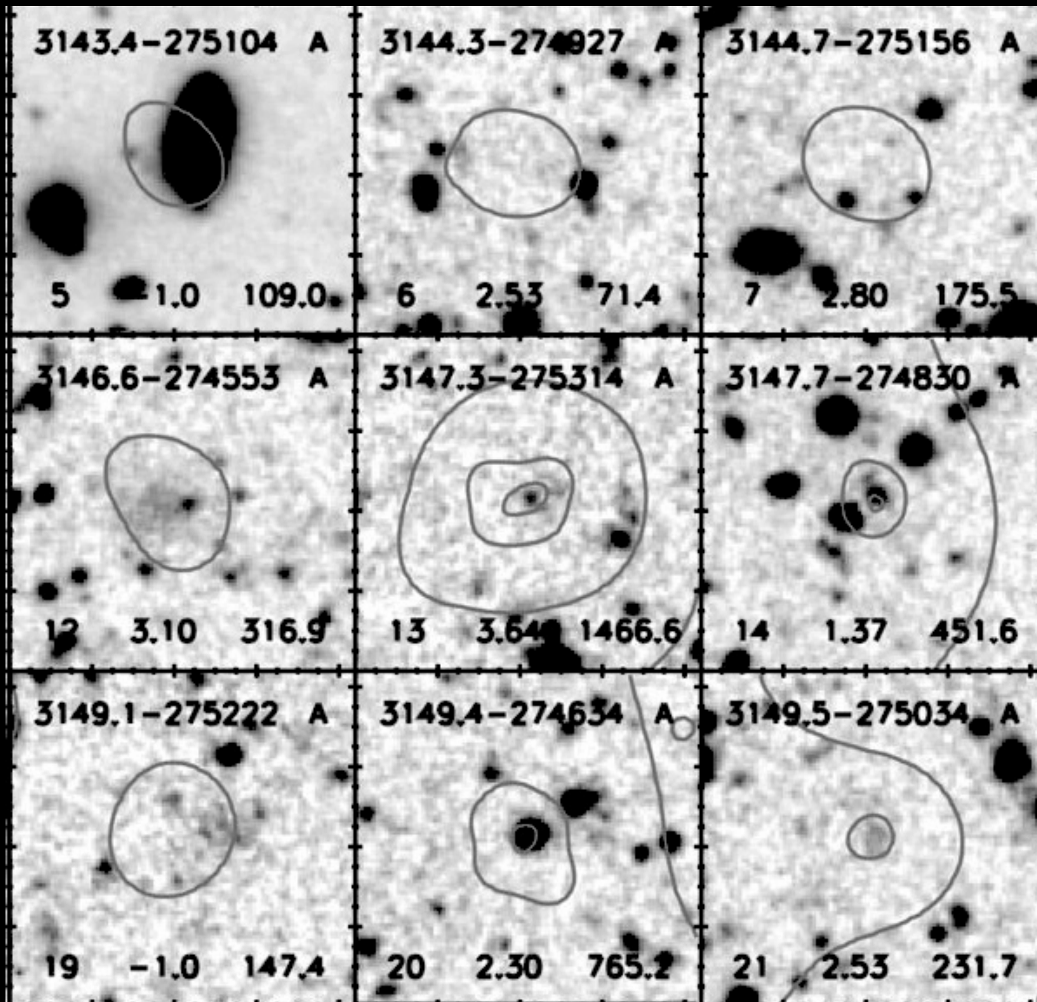


Greyscale image: 26’ x 26’



False color image: Central 8’ x 8’

Source Matching Ambiguity



Xue et al. 2011

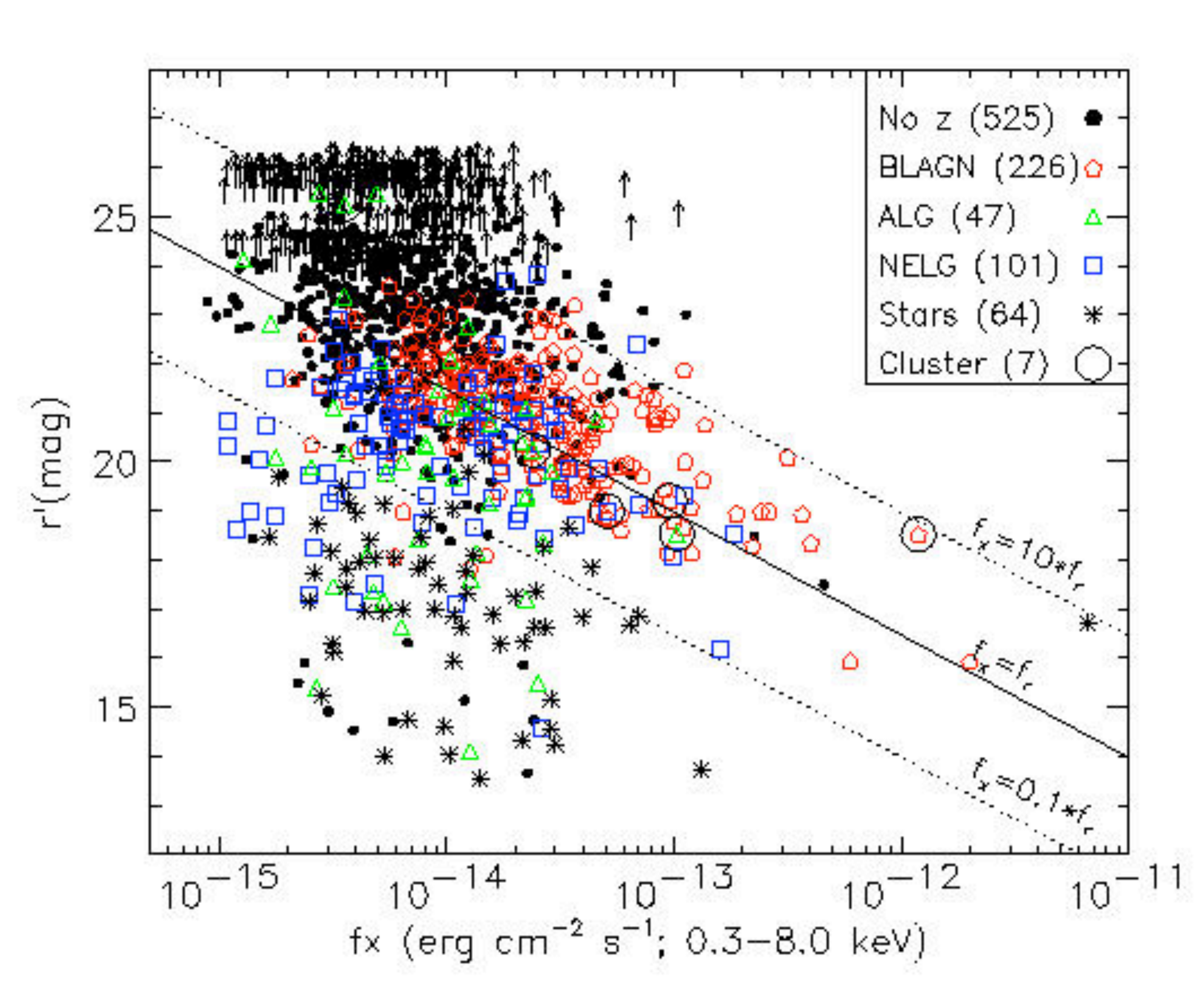
- Image: R <~ 27mag
- X-ray contours: logarithmic ≈0.003% to 30% of max
- **Fraction of matched / multiple/ spurious all depend on PSF size, and relative flux limits**
- Demands visual inspection

Deep Extragalactic X-ray Surveys

- Source classification difficulties
  - Many of the X-ray sources have modest optical luminosities, often due to obscuration
  - Many are too faint to be identified by optical spectra
  - AGN unification is “broken” between optical (type1 and type2) and X-ray (unobscured and obscured)

ChaMP Optical Spectroscopic Program

J. Silverman, P. Green, P. Smith,
E. Romero-Colmenero (SAAO), A. Constantin, M. Trichas



- 24 Fields
- 445 IDs
- 52% BLAGN

Broad emission Line AGN
(FWHM > 1000 km/s)

- 25% NELG

Narrow Emission Line Galaxy
(FWHM<1000 km/s; W^e_λ>5 Å)

- 11% ALG

(absorption line galaxy)

- 13% Stars
- 1% Clusters

Basic **AGN** Types from X-ray Surveys

- Unobscured AGN
- Obscured AGN with clear optical/UV AGN signatures.
- Optically faint X-ray sources
- XBONGs

Basic **AGN** Types from X-ray Surveys

- Unobscured AGN
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- Optically faint X-ray sources
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(X-ray Bright Optically Normal Galaxies)

Wide Extragalactic X-ray Surveys

- Amass rare bright sources
- Smooth out “cosmic variance”.
- Bridge flux gap between deep and all-sky surveys
- Still sufficiently deep that complete source classification is quite challenging

Wide Extragalactic X-ray Surveys

Chandra

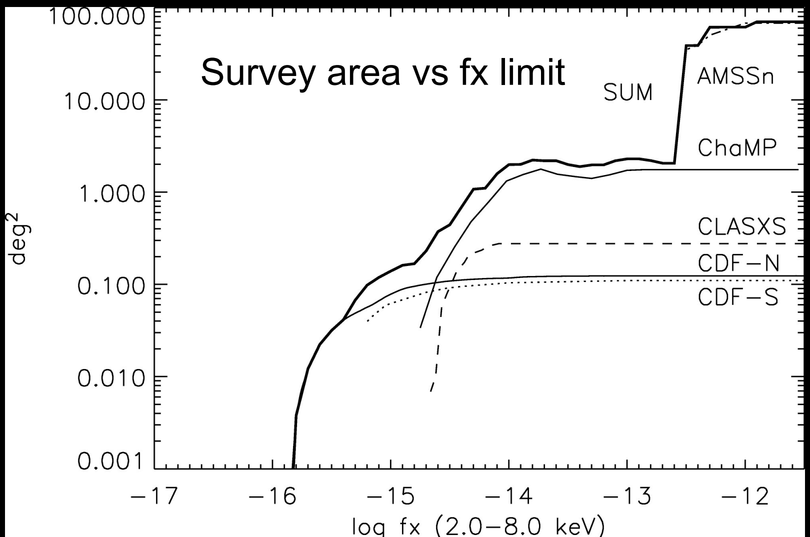
- ChaMP (Green et al. 2004; Kim et al 2004)
- CYDER (Treister 2005)
- CLASXS (Lockman Hole; Steffen, Barger, Yang)
- XBootes/NDWFS (Murray, Jones, Kenter, Brand)
- SEXSI (Harrison, Helfand)

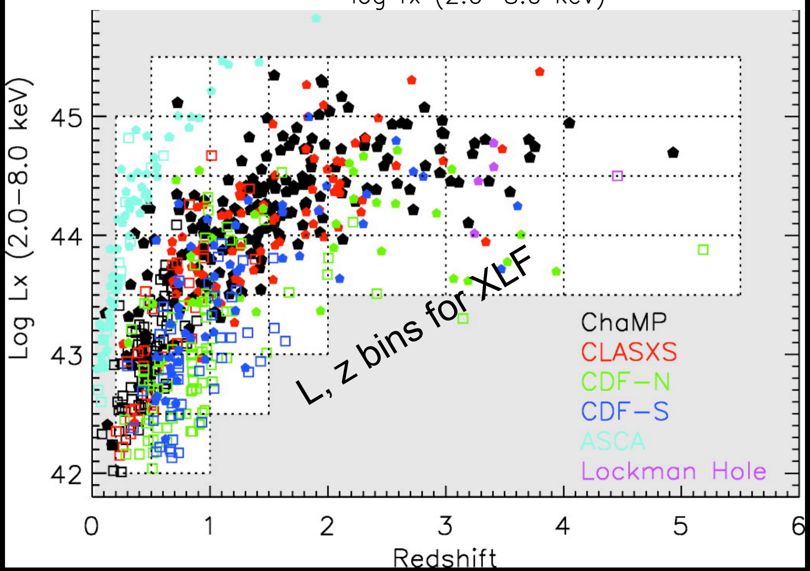
XMM-Newton

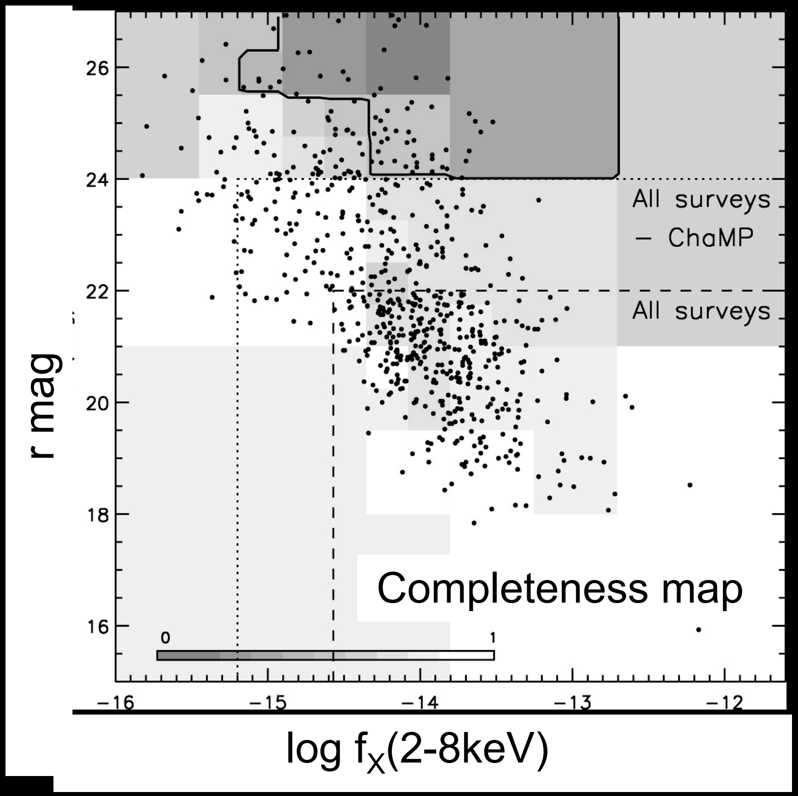
- HELLAS2XMM (Baldi, Fiore, Brusa)
- XMM/2dF (Georgakakis, Georgantopolous)
- XMM-SSC (Watson)
- XMM-LSS (Pierre)

Combining Deep & Wide for XLFs

Silverman et al. 2008







X-ray Luminosity Function (2-8 keV)

$$\phi(L,z) = \frac{\mathrm{d}^2 N}{\mathrm{d}V\mathrm{d}L}(L,z)$$

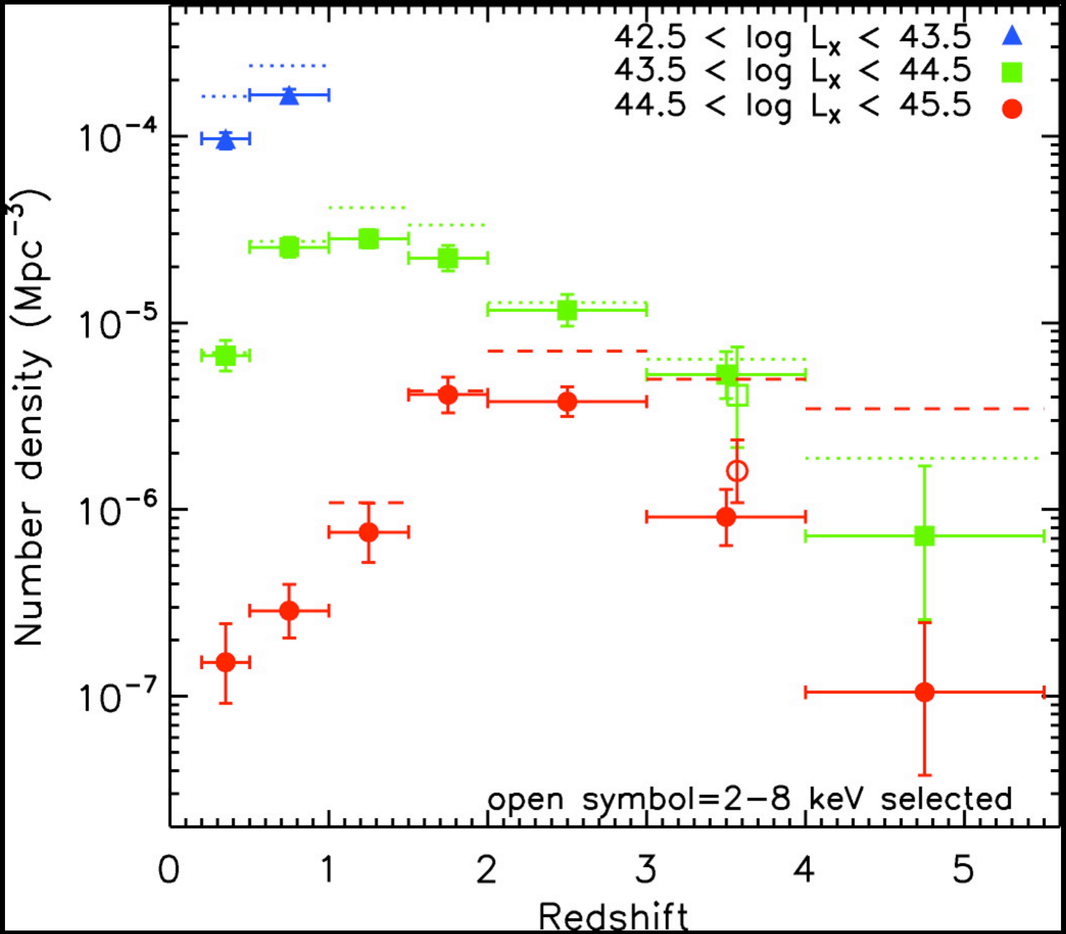
1/V_a method

$$\phi_{1/V_a}(L,z) = \frac{1}{\Delta \log L} \sum_{i=1}^{N} \frac{1}{C(i)V_a(i)}$$

$$V_a = \int_{z_1}^{z_2} \frac{\mathrm{d}V_c}{\mathrm{d}z}\,\mathrm{d}z\mathrm{d}\Omega$$

<ins>Identified fraction</ins>

$0.3 < C(i) < 1.0$



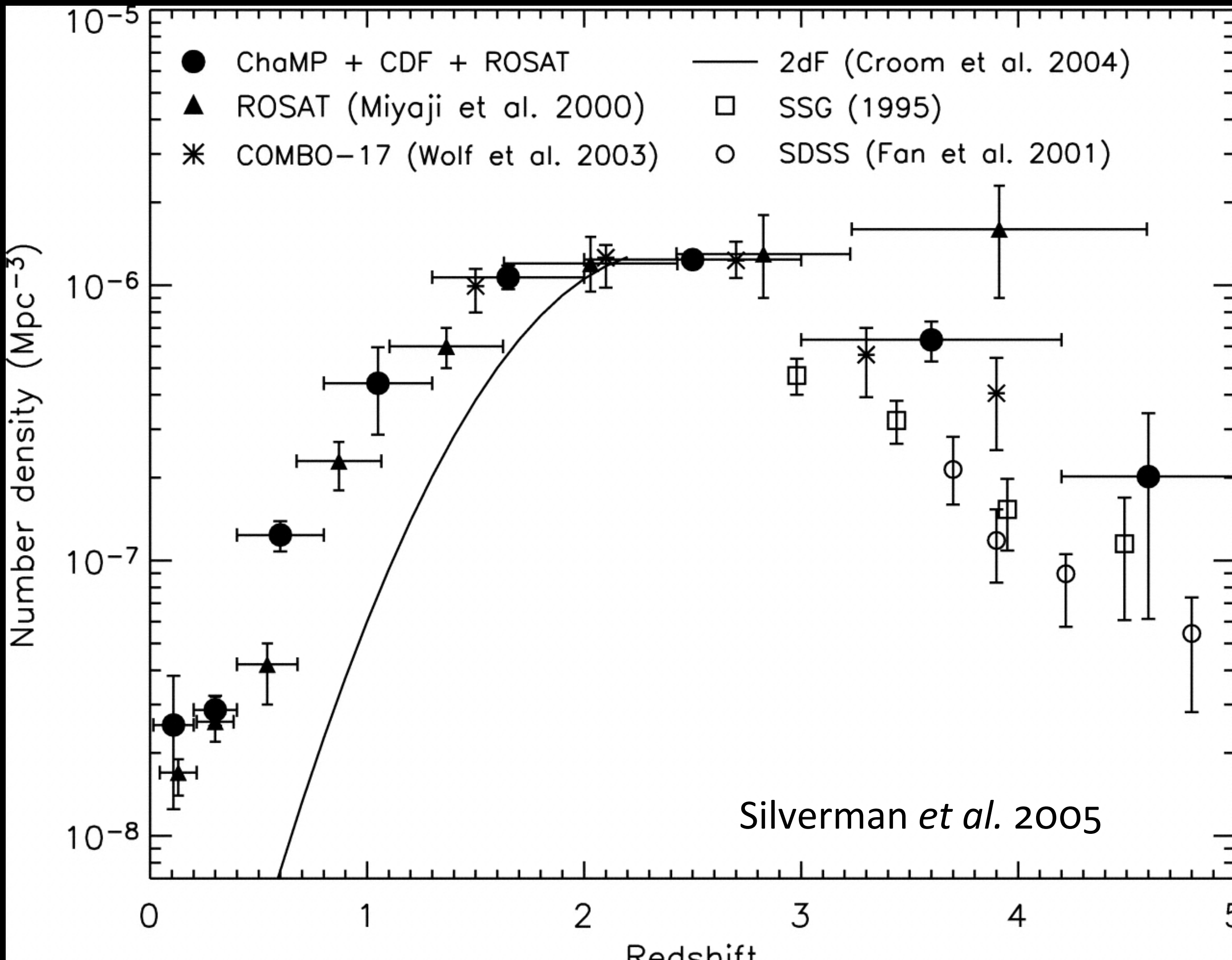
Ω_M=0.3, Ω_Λ=0.7, H_o=70 km s^{-1} Mpc^{-1}

What We Think We Know
Relevant to SMBHs and their Evolution

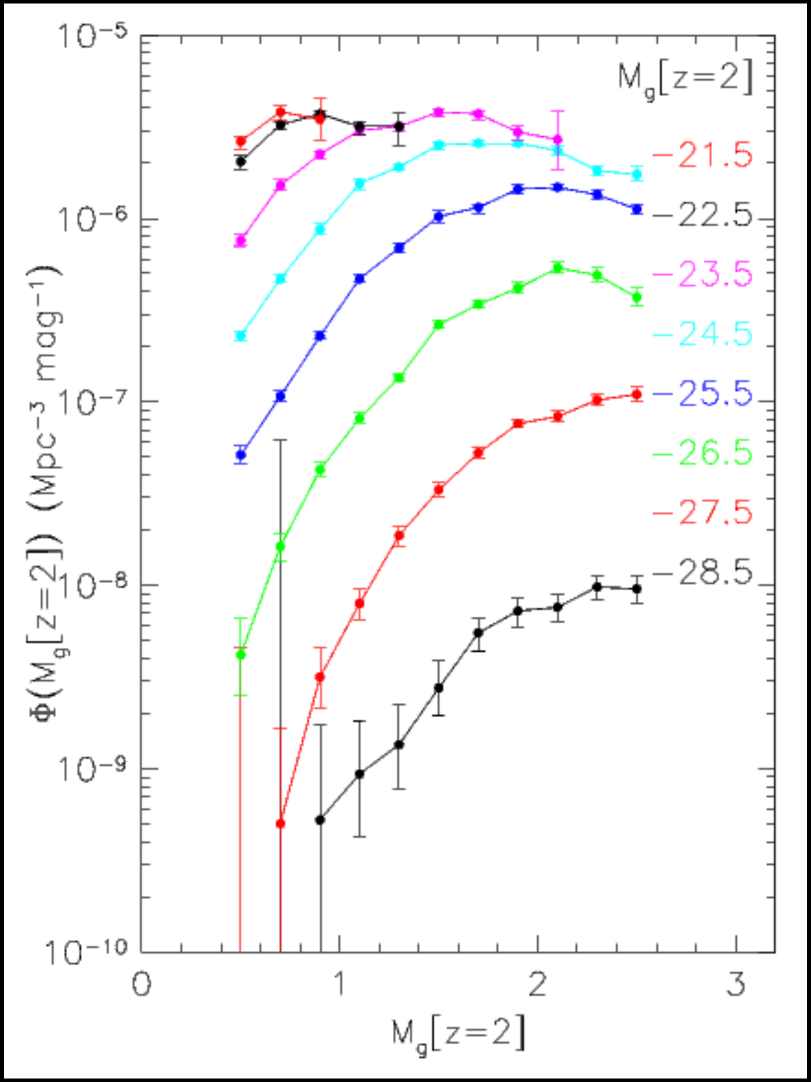
- ΛCDM Cosmology & Hierarchical Structure Formation
- Luminous quasars peaked at z=2
- SMBHs are common in local galaxies
- The CXRB is resolved at low energies

and *may* be explained by absorbed AGN

The Quasar Epoch



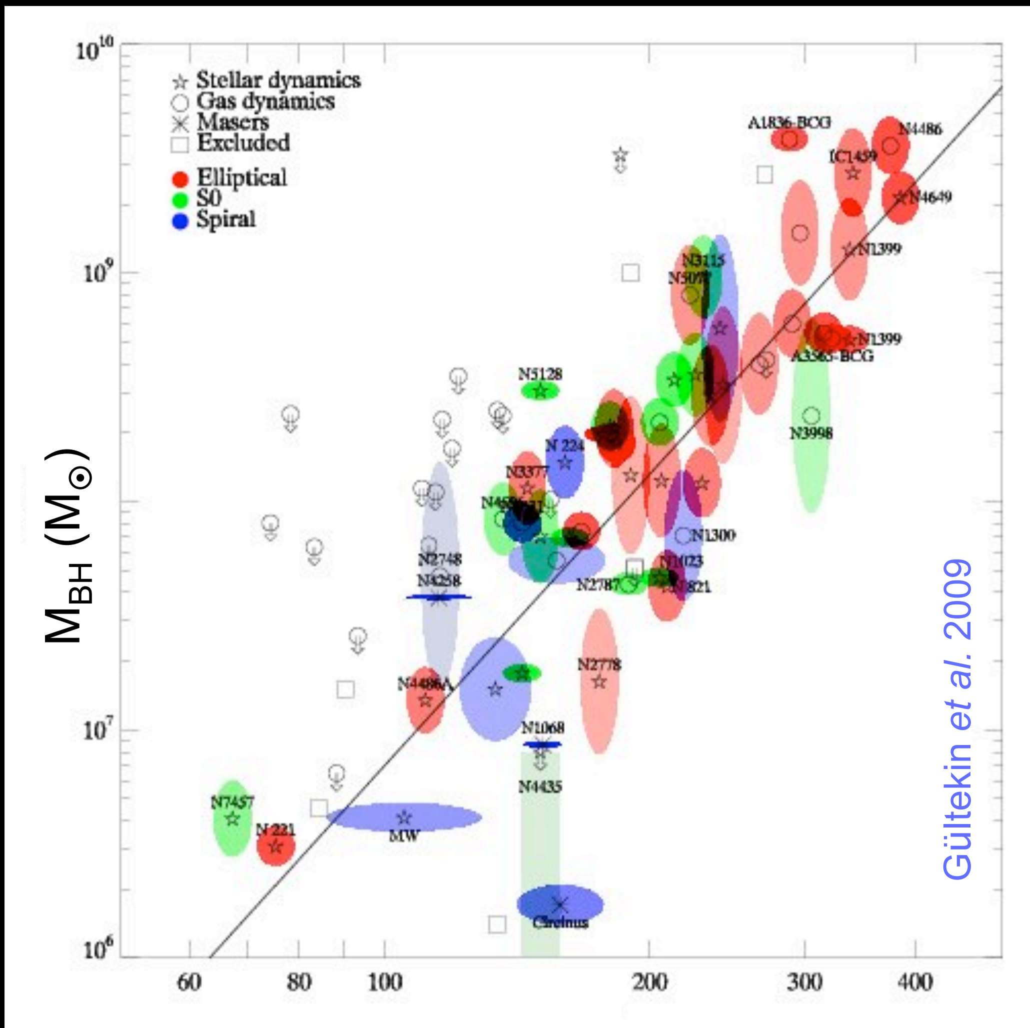
Downsizing



- Brightest QSOs peak at z~2.5 (or higher).
- Faintest QSOs peak at z~1 (or lower).

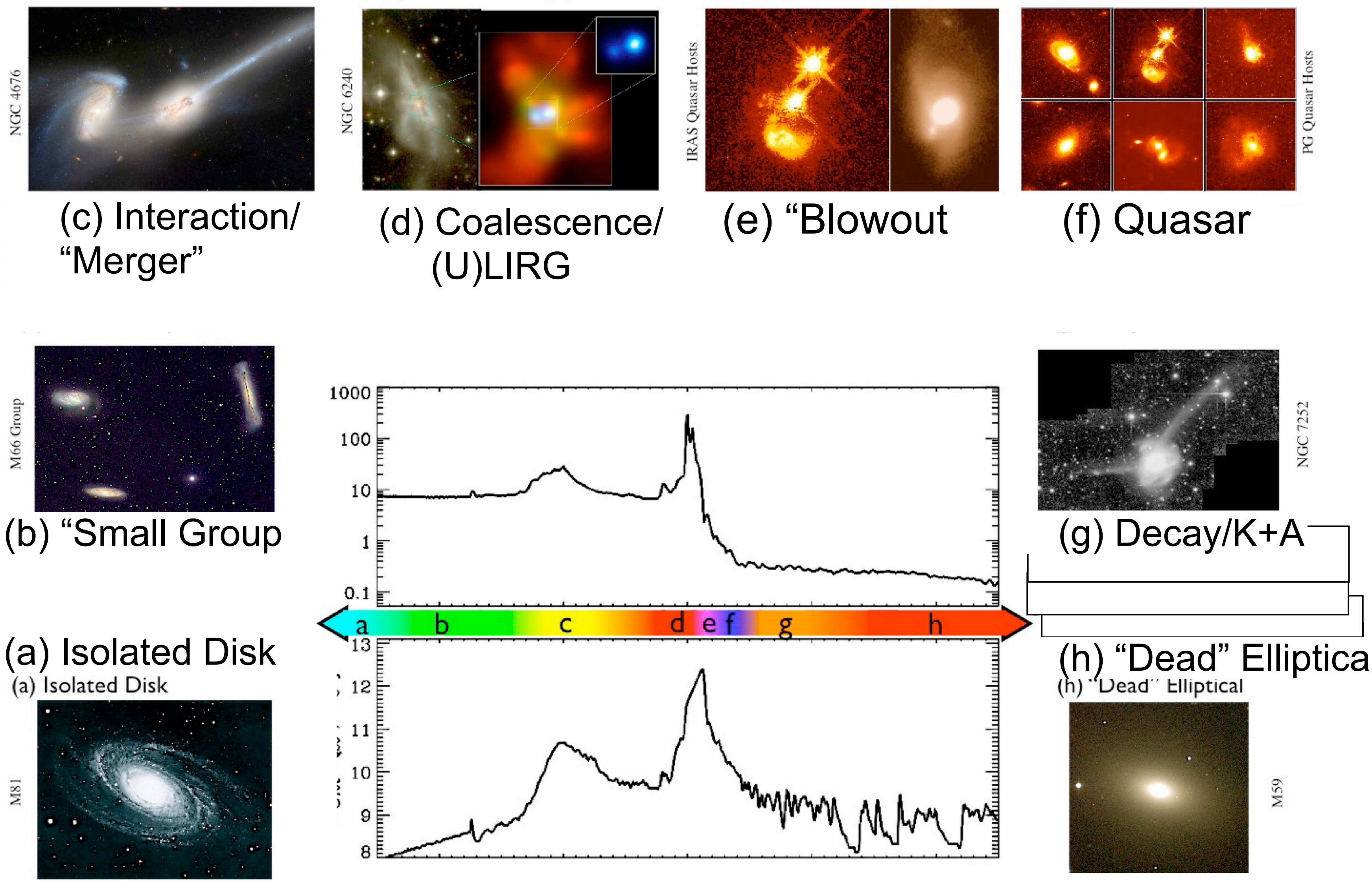
Croom *et al.* 2008

M_{BH}-σ Relation



- Correlation between SMBH mass and mass of the galaxy spheroid (via velocity dispersion σ_V)
- AGN and star formation activity may be concurrent
- AGN play key role in galaxy formation and evolution

AGN Fueling in a Gas-Rich Major Merger

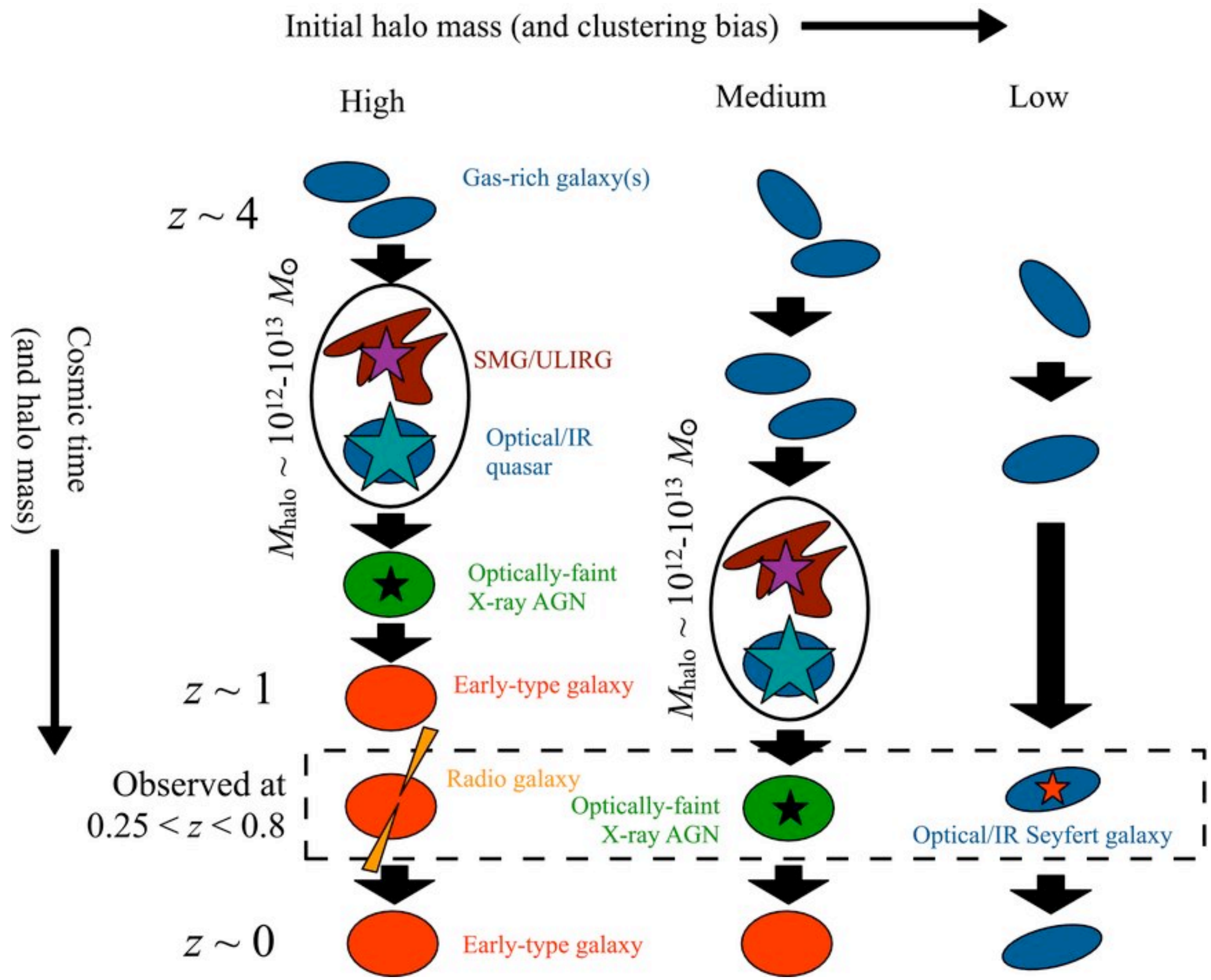


Hopkins *et al.* 2008

AGN/Host Co-Evolution Cartoon

Here luminous accretion occurs preferentially where $M_{halo} \sim$ ~10^{12} - $10^{13} M_{sun}$

Hickox (2009)



What We Know We Don’t Know

- What objects constitute the CXRB?

- What fraction of AGN are obscured?
  As a function of *L*. *Of z.*

- Do obscured and unobscured populations evolve in the same manner?

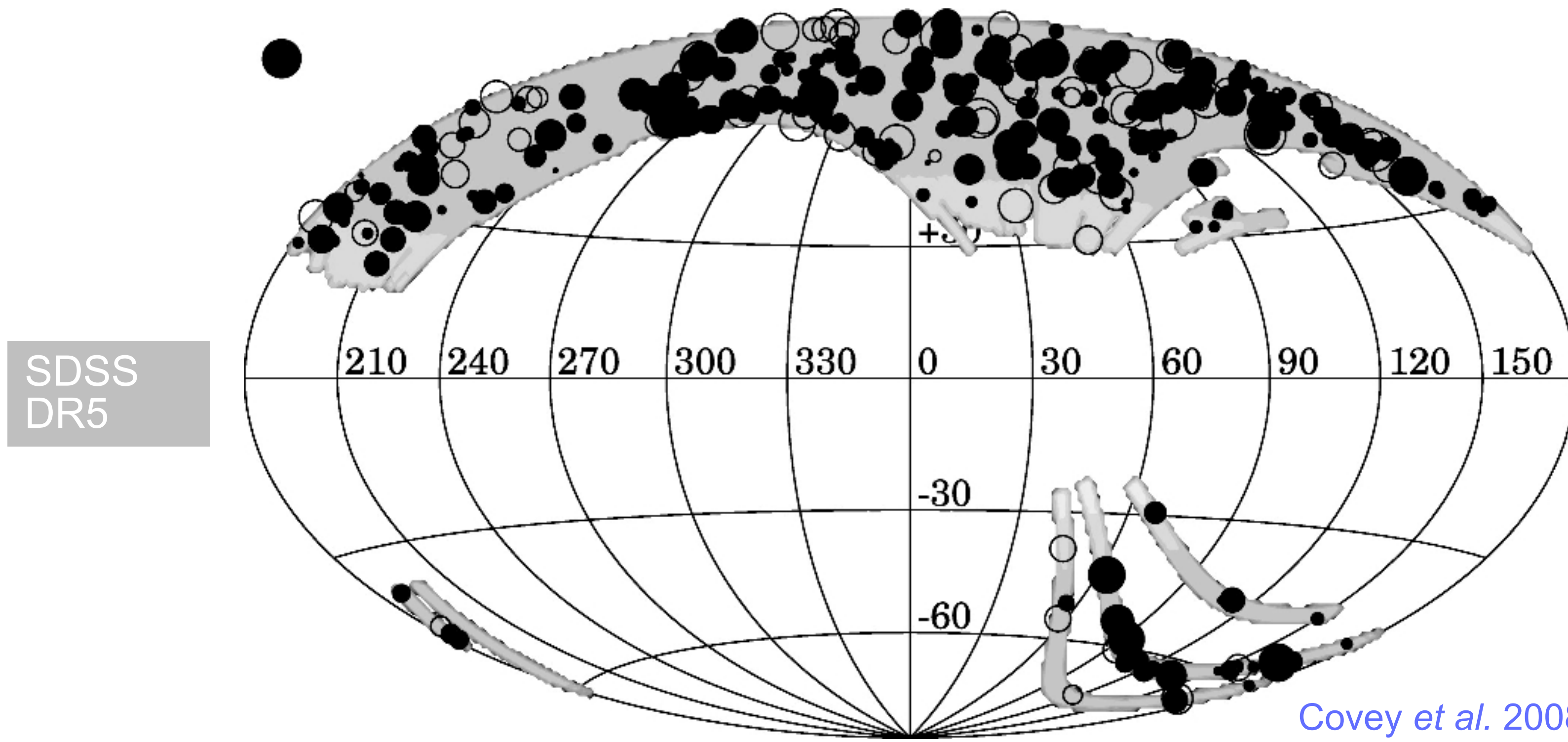
- How much SMBH accretion is hidden from optical/X-ray/IR surveys?

- What modes of accretion are there?
  What are their hosts? Their environments?

- How much and when do accretion and star formation overlap?

- Are local quiescent SMBHs relics of the bright quasars?

ChaMP + SDSS



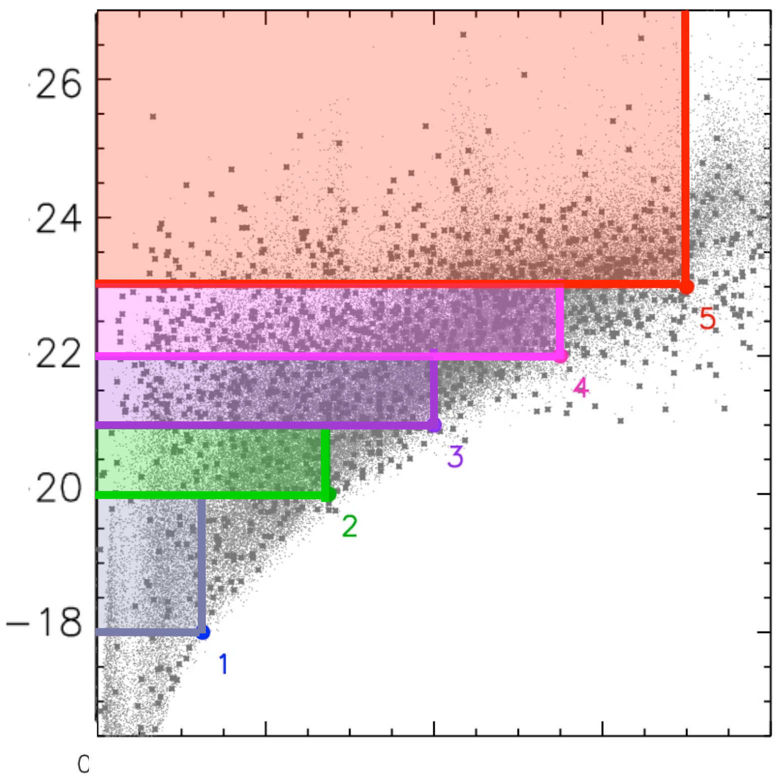
Covey *et al.* 2008

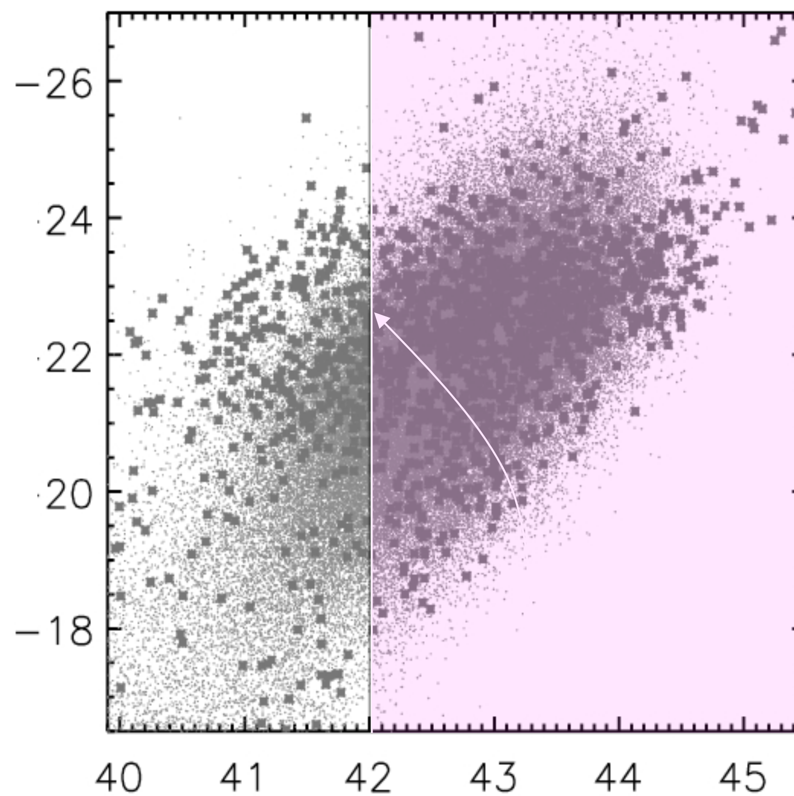
- 392 *Chandra* Cycle 1-6 ACIS Fields: ~33 deg^2
- Exposures: 1-120 *ks* (median = 21 *ks*, total = 8.4 *Ms*)
- X-ray detections or **limits** for all SDSS sources in ChaMP area

Active Fraction Sub-Samples

- Divide sample into 5 volume-limited optical samples
- Calculate fraction for any L_X threshold

Haggard *et al.* 2010

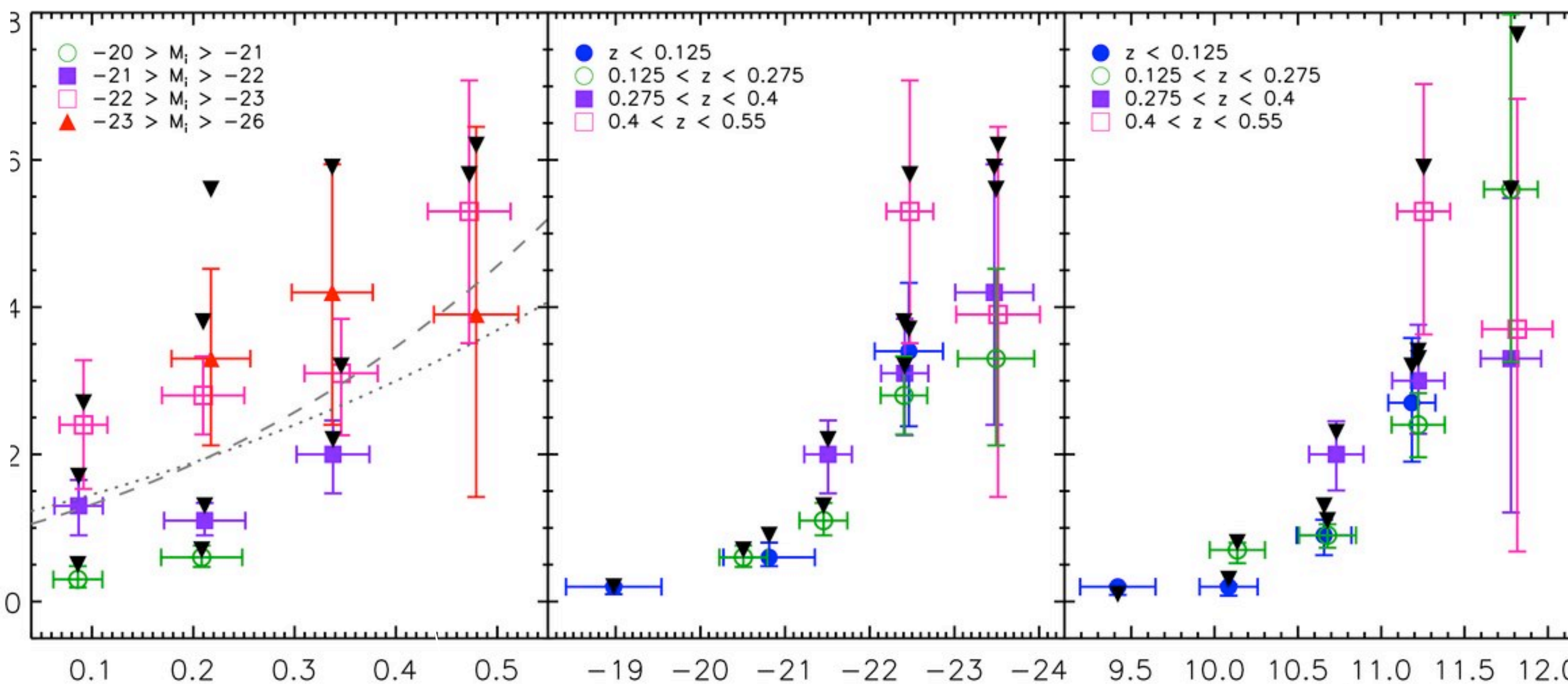




AGN Fraction by Redshift, M_i and Host Galaxy Stellar Mass

- Trend with bestz tracks AGN/QSO X-ray LF
- Stronger trends with M_i and Mass

Haggard *et al.* 2010



Comparing Field & Cluster Fractions

- Excellent agreement w/ Martini et al. (2007) cluster fractions: clusters $0.05 < z < 0.31$, 35 X-ray-detected ($M_R < -20$) galaxies
- At low-z, apparent X-ray point source overdensities toward clusters simply track cluster galaxy overdensity

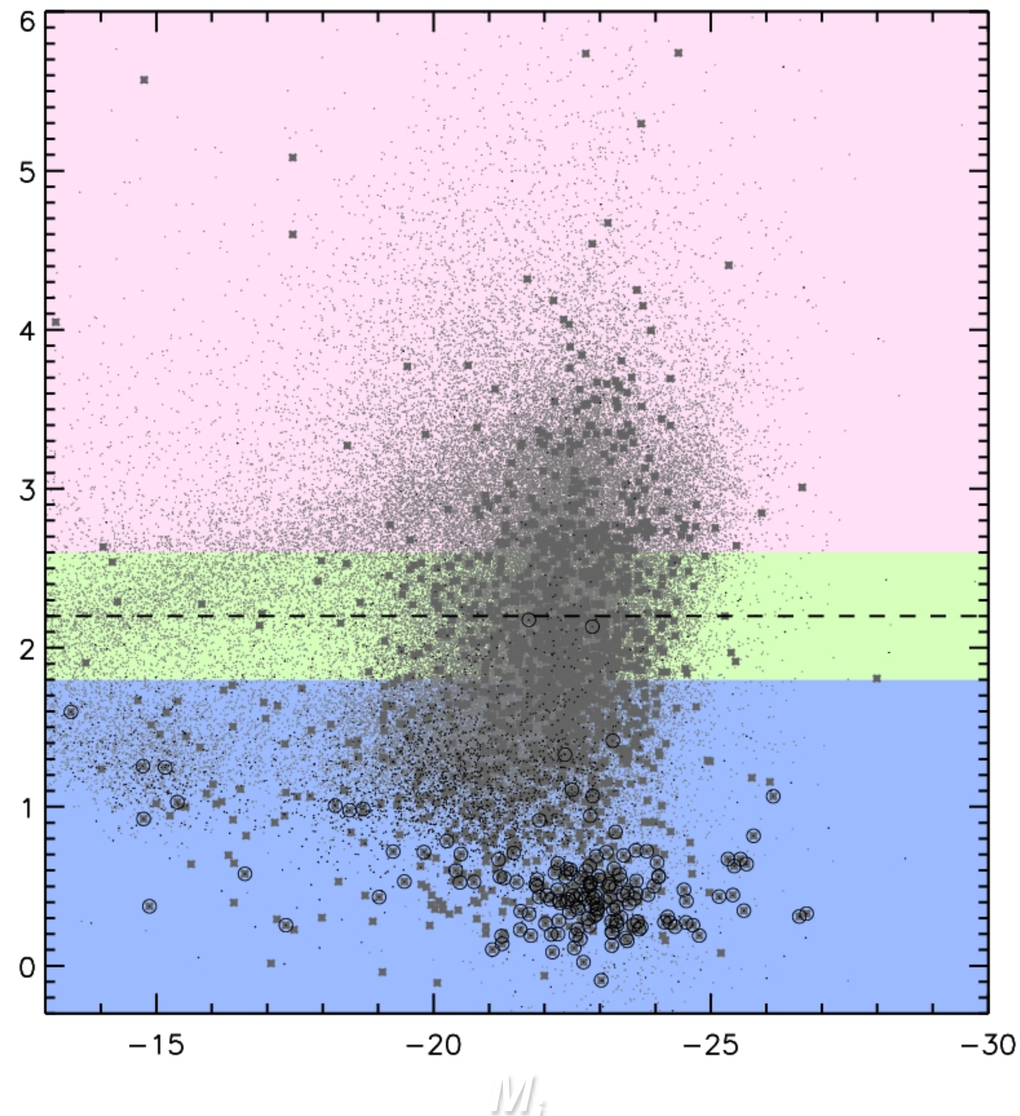
M_R<	$\log L_x$ min	$\log L_x$ max	N_x	N_{opt}	Frac %	Err	Cluster %
-20	40.9	43.6	28	476	6.0	1.1	6.0
-20	41.0	…	30	663	4.5	0.8	4.9
-20	42.0	…	110	9415	1.2	0.1	1.0
-21.3	41.0	…	27	232	12.4	2.3	9.8

Field vs. Cluster Fraction

- Mergers may not be fueling AGN in the local Universe?
- Other fueling mechanisms at work?
- ***OR*** a conspiracy where…
  - Other fueling mechanisms more efficient in clusters
  - Major mergers still prevail in the field
- Morphological evidence in the field shows no merger excess among $0.3<z<1$ AGN (COSMOS; Cisternas et al. 2010)

AGN Fraction by Host Color

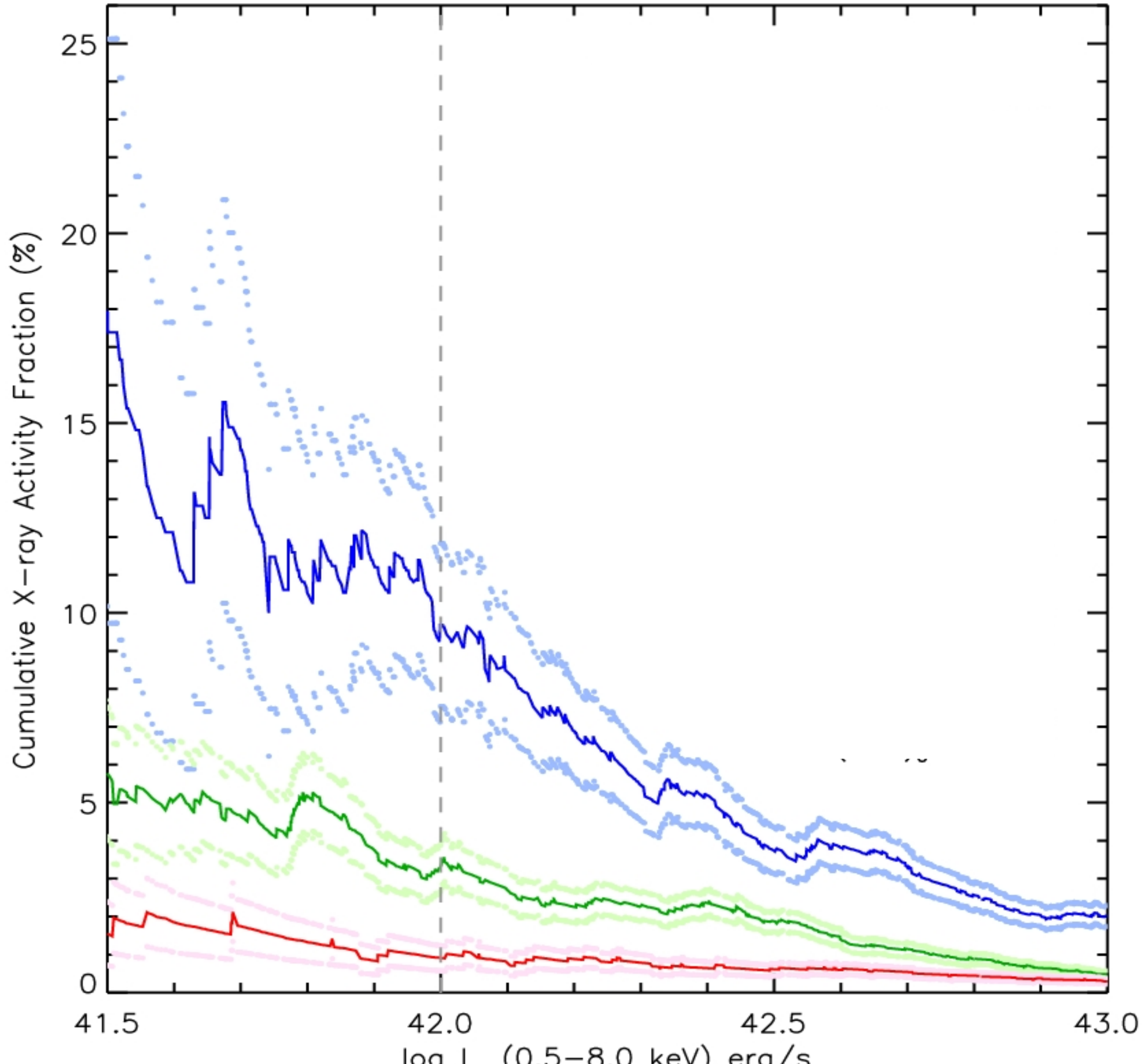
- Color is a proxy for morphology
- Does F_{AGN} peak in the green valley, blue cloud or the red sequence?
- May shed light on dominant fueling mechanism



Red
Green
Blue

Active Fraction by Restframe $(u\text{-}r)_0$ Color

Larger fractions in the Blue Cloud for all L_x



Conclusions

- X-ray survey sensitivity and completeness should be well-characterized.
- Multiwavelength observations are crucial.
- Matching to counterparts should be careful.
- Spectroscopic completeness also crucial.
- **OK, so it ain't easy!**

AGN/galaxy/structure co-evolution is a new and exciting frontier in astrophysics.

- Successful models should match
  - CXRB
  - log*N*-log*S*
  - XLFs
  - current local SMBH mass function
  - host galaxy properties
  - environments and clustering
  - evolution

The End

XBootes 126*5ksec Raster