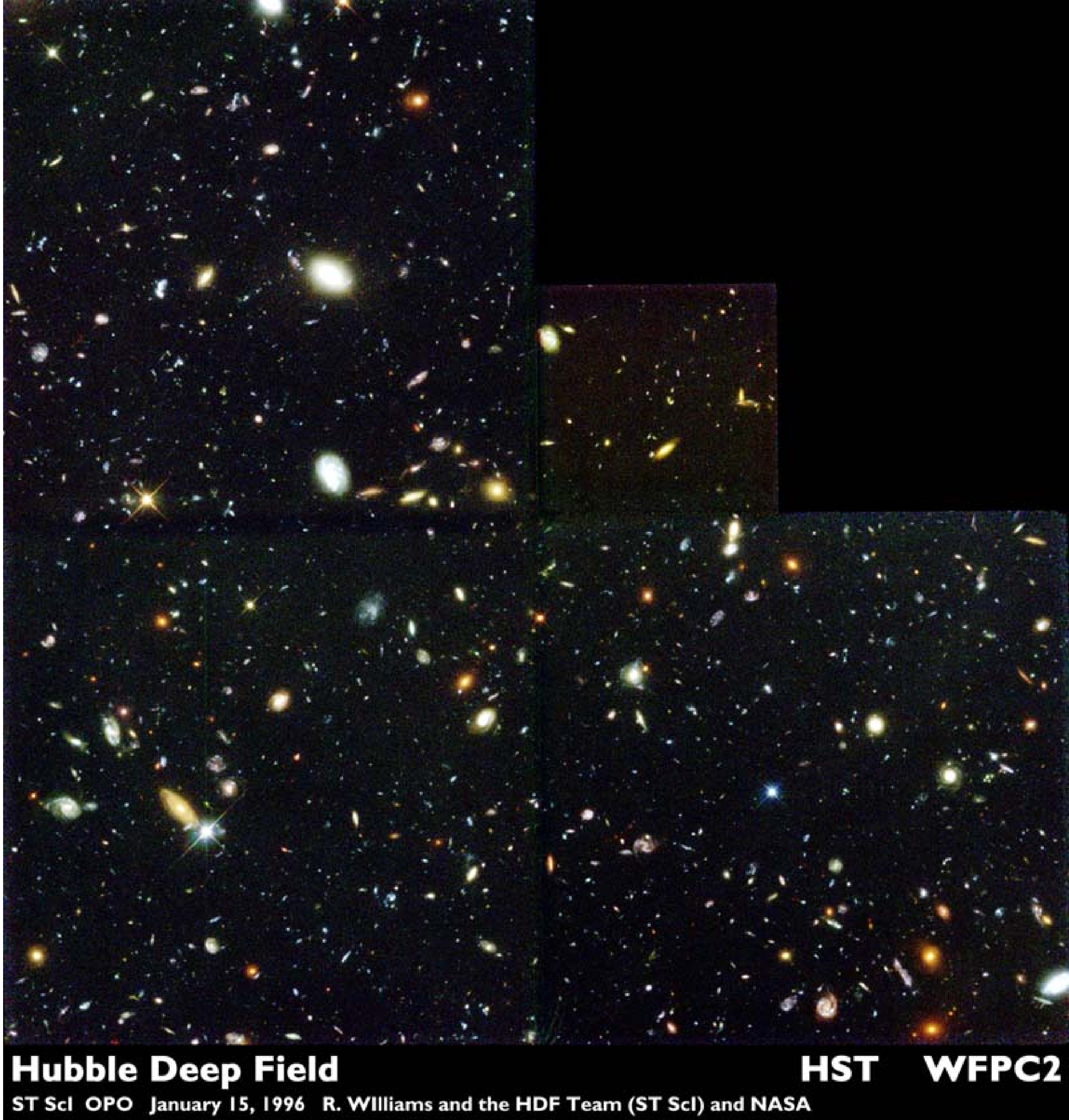
The Star Formation and Accretion Histories of the Universe

Amy Barger

Deep images probe the earliest galaxies

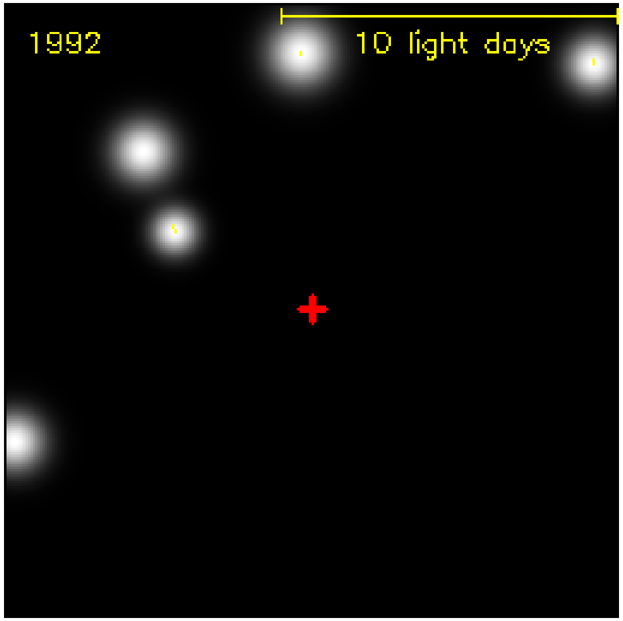
We want to trace how they evolved into present-day galaxies



Dormant supermassive black holes (SMBHs) lie at the centers of nearly all present-day galaxies

Thus, we need to understand how they evolved

The presence of these SMBHs has been detected through their gravitational influence on neighboring stars and gas, which orbit the black holes



R. Genzel

- We know from local observations that a tight relation exists between

  - The black hole mass & the spread of stellar velocities within the host galaxy

$$M_{bh} \propto \sigma^4$$

  - Or, less perfectly, the black hole mass & the host galaxy bulge mass

$$M_{bh} / M_{bulge} = 0.001\text{-}0.002$$

- This relation hints at a deep connection between the processes that formed

    - the stars in the host galaxy
    - the central black hole

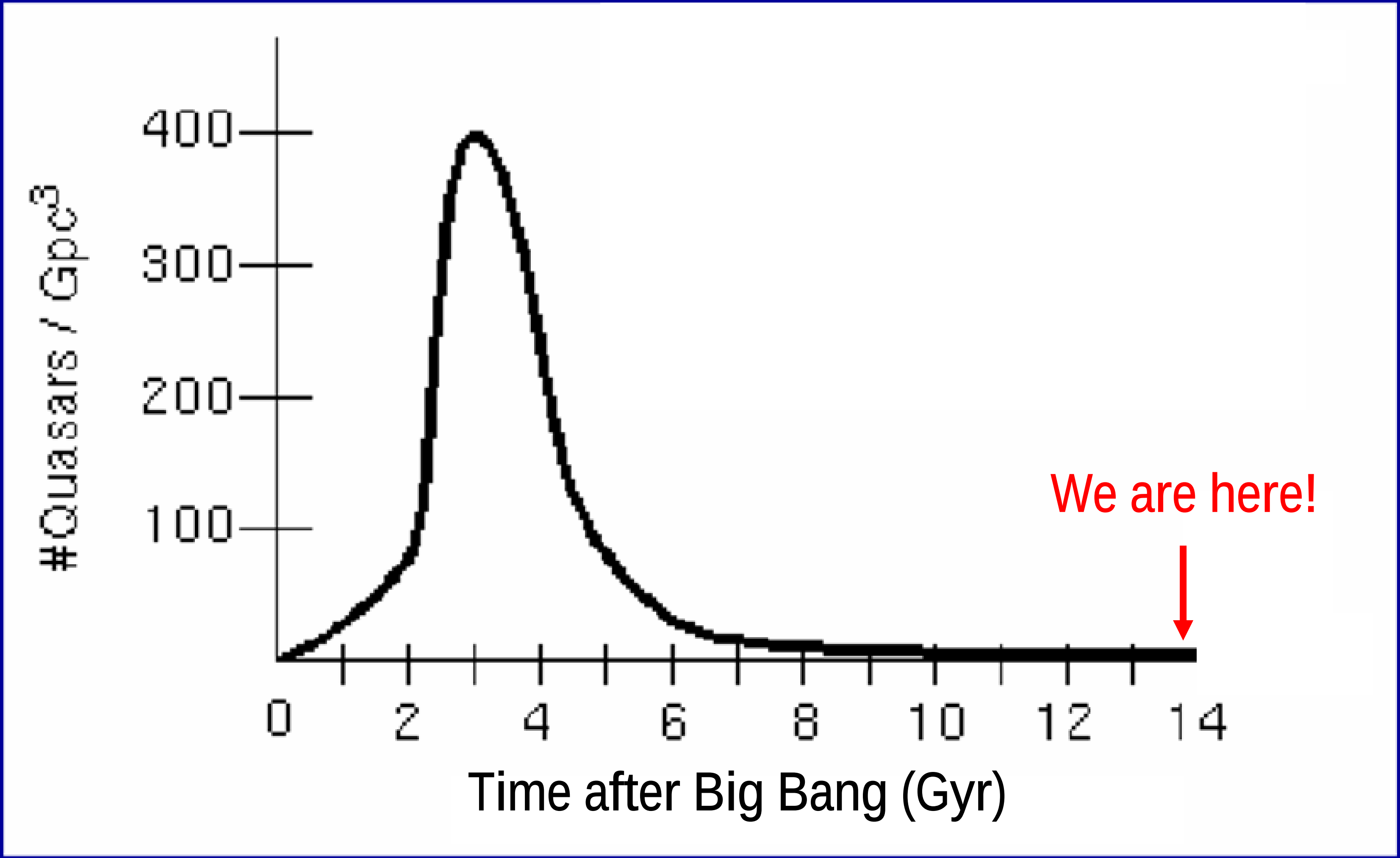
- We would like to explore this connection through observations of distant systems

When did the supermassive black holes form?

(When they are accreting, they should be easy to find, since they will be extremely luminous)

Historic Answer Based on Optical Data:

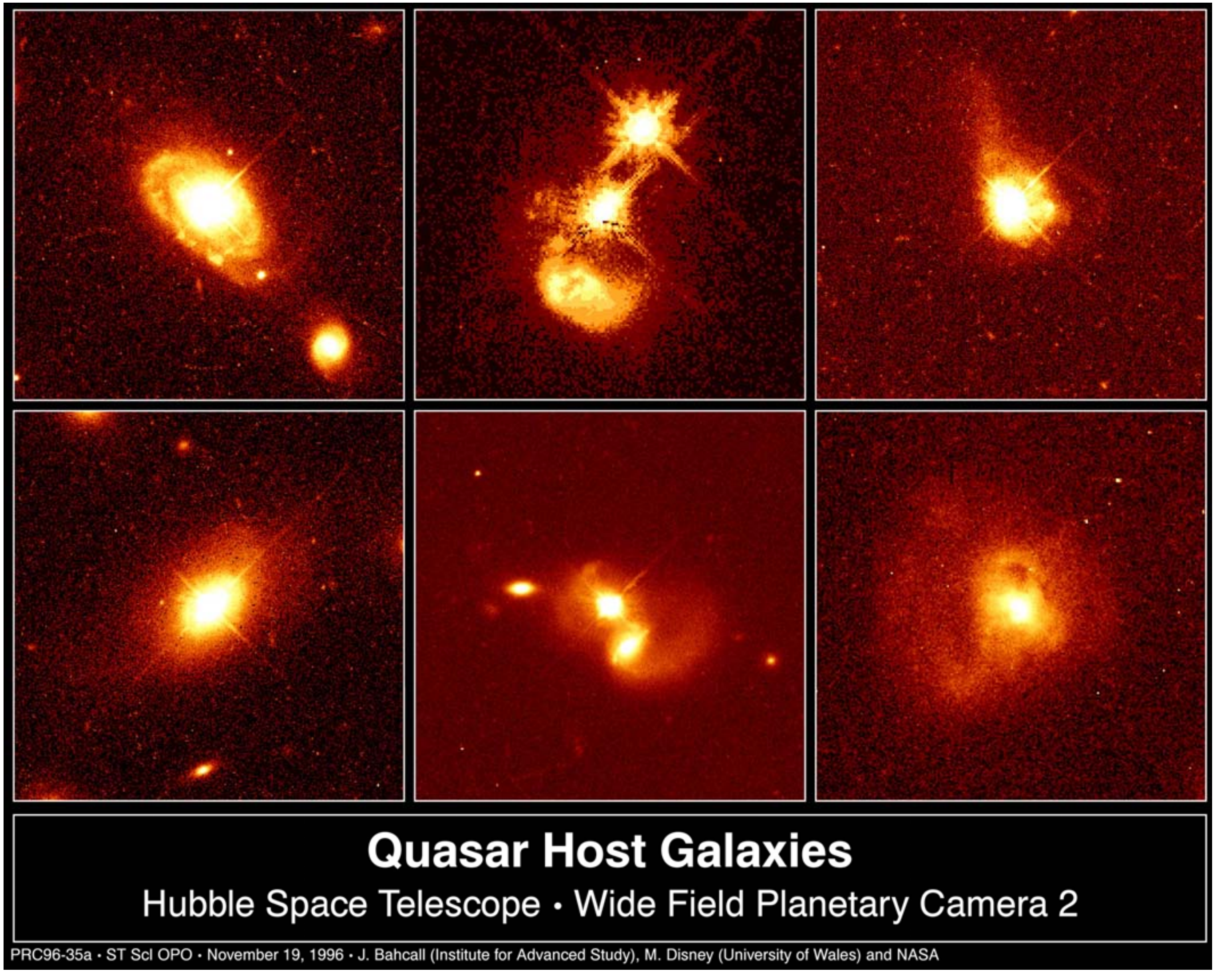
Number of optically selected quasars peaks at early times



Why? Where Did the Quasars Go?

- Galaxies in the past were closer together
  → collisions were more common, pushing gas into the black holes

- Galaxies in the past had more gas
  (not yet incorporated into stars)
  → feeding frenzy for the black holes!

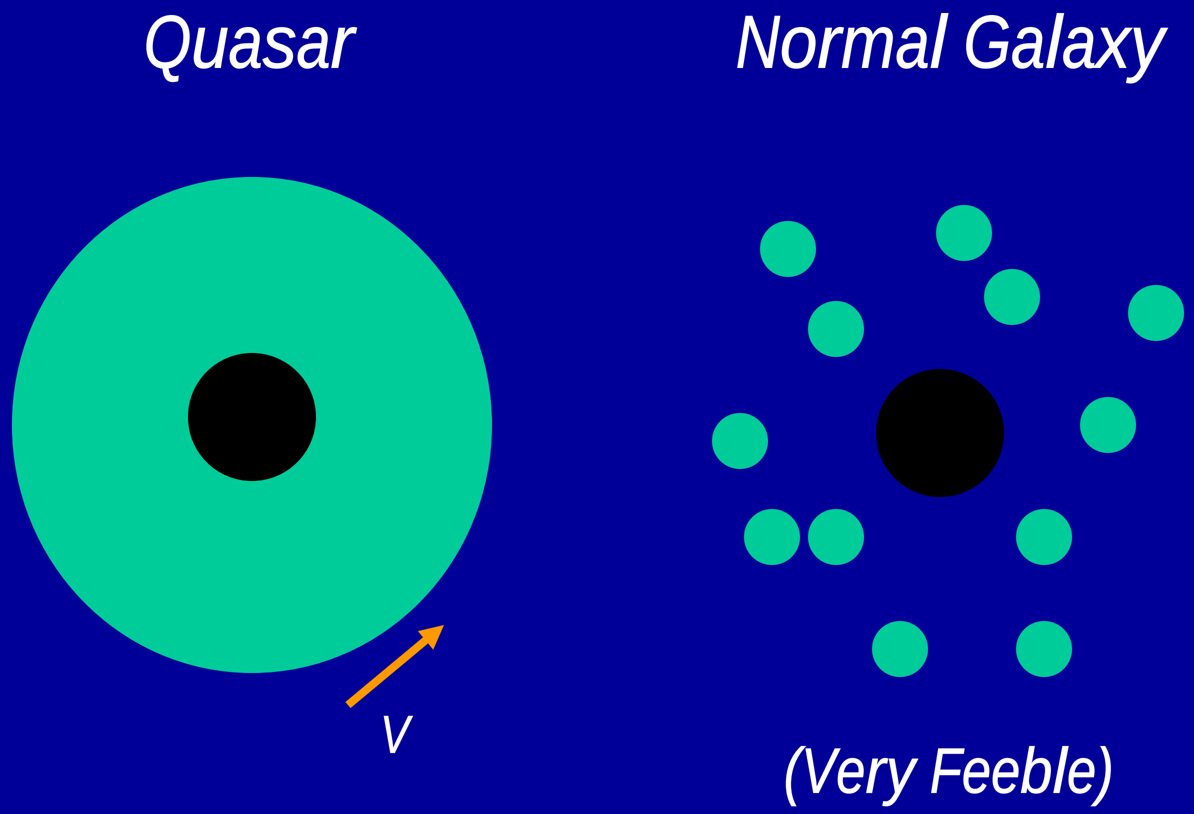


Indeed, often the galaxies hosting quasars are observed to be interacting or merging w/other galaxies

Quasars Only Shine While Accreting

- As a quasar's central black hole consumed most of its surrounding gas, the quasar probably faded w/time

- But the supermassive black hole itself cannot be destroyed



So, did all the action really take place at early times?

Problem Here!

Optical surveys may miss a lot of sources due to obscuration, which shifts the light into the far-infrared rather than the optical

Thus, the optical results may not be the whole story

A Windowed View

One gets a very different view of the universe depending on which wavelength "window" one uses

We can illustrate this by looking at a region of sky in two wavelengths, the submillimeter (200 μm-1mm) & the optical

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

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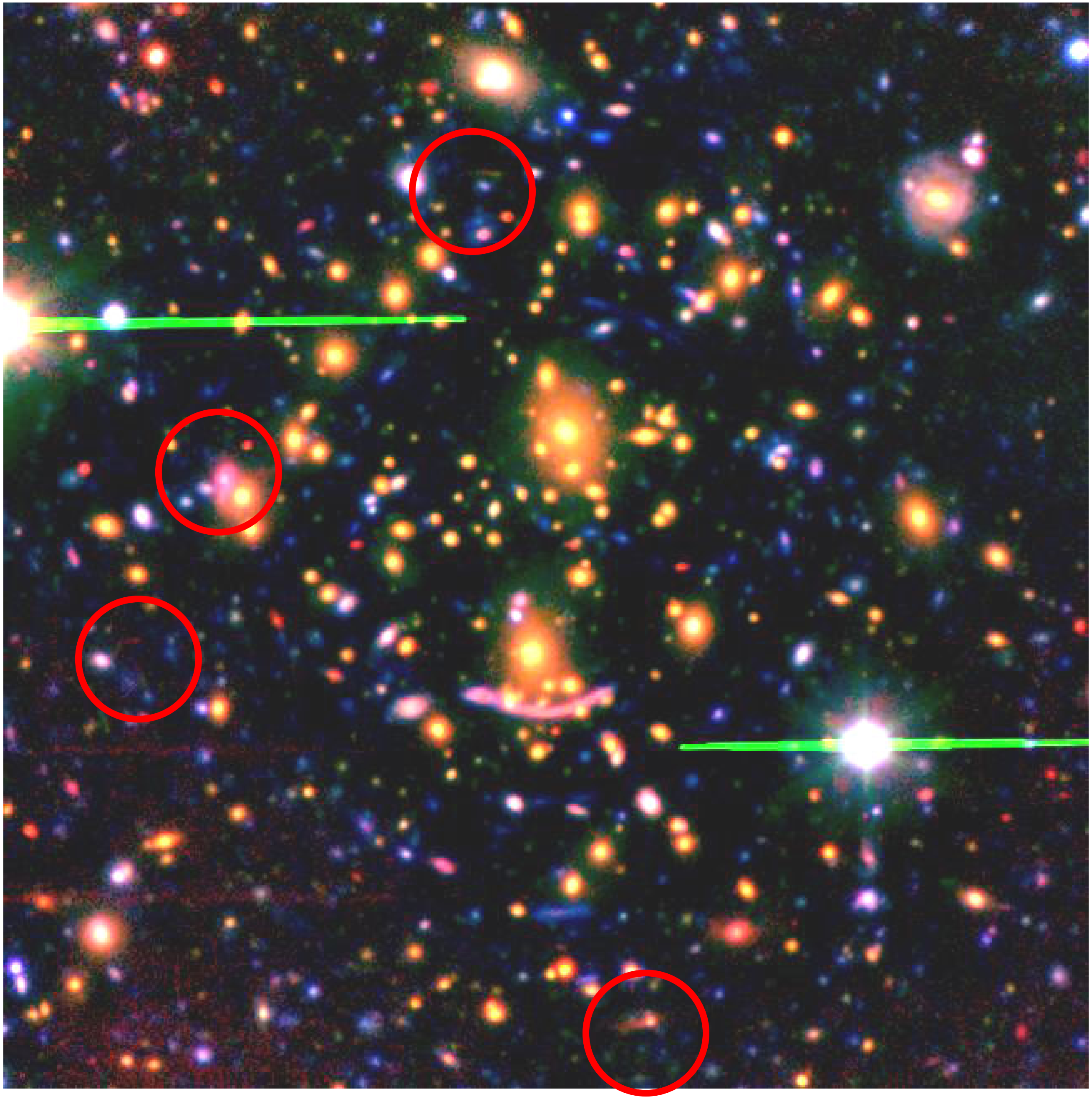
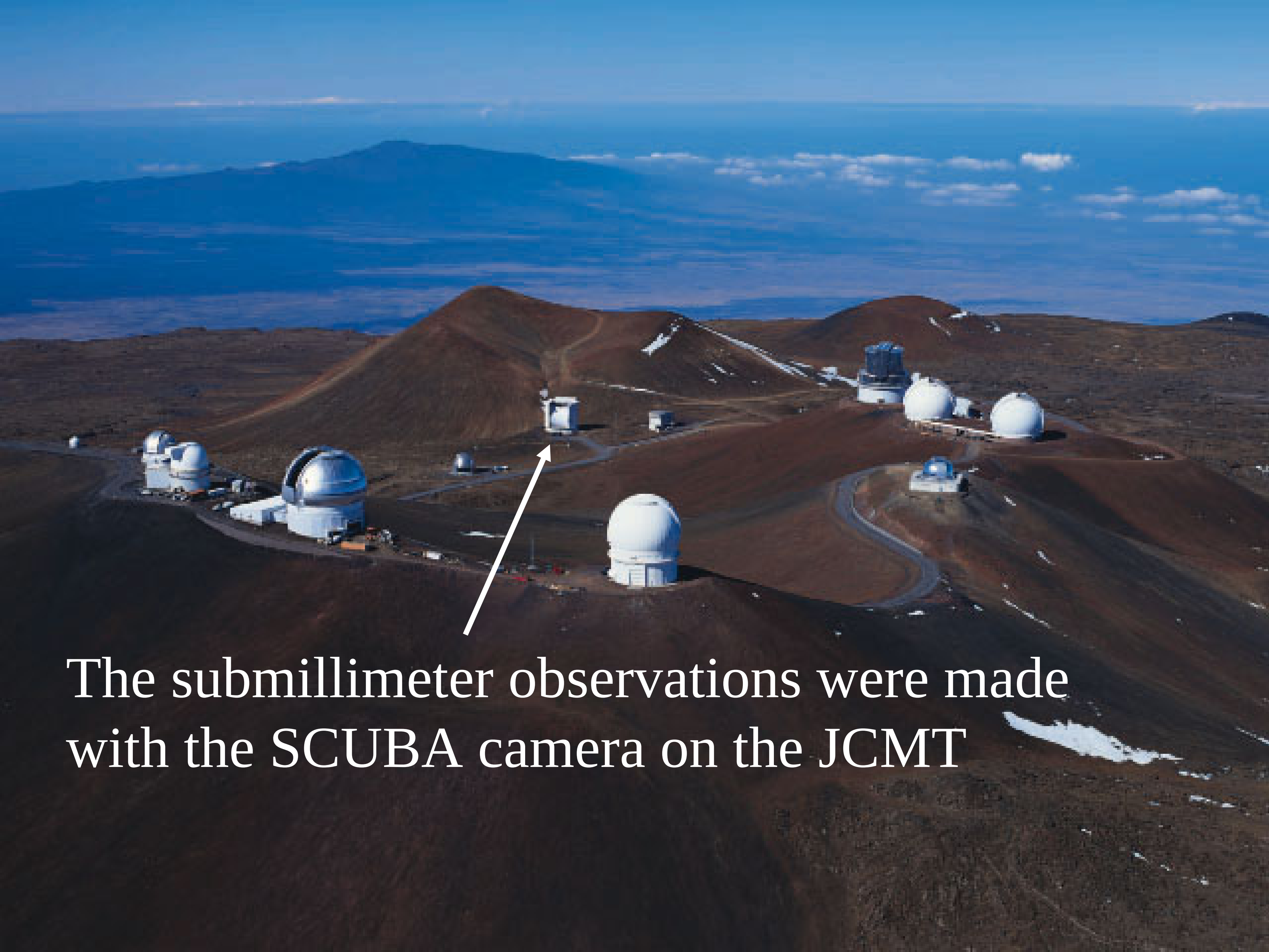
A370

U', R, K'



4''
radius
error
circles


The submillimeter observations were made
with the SCUBA camera on the JCMT

An Absorbing Tale

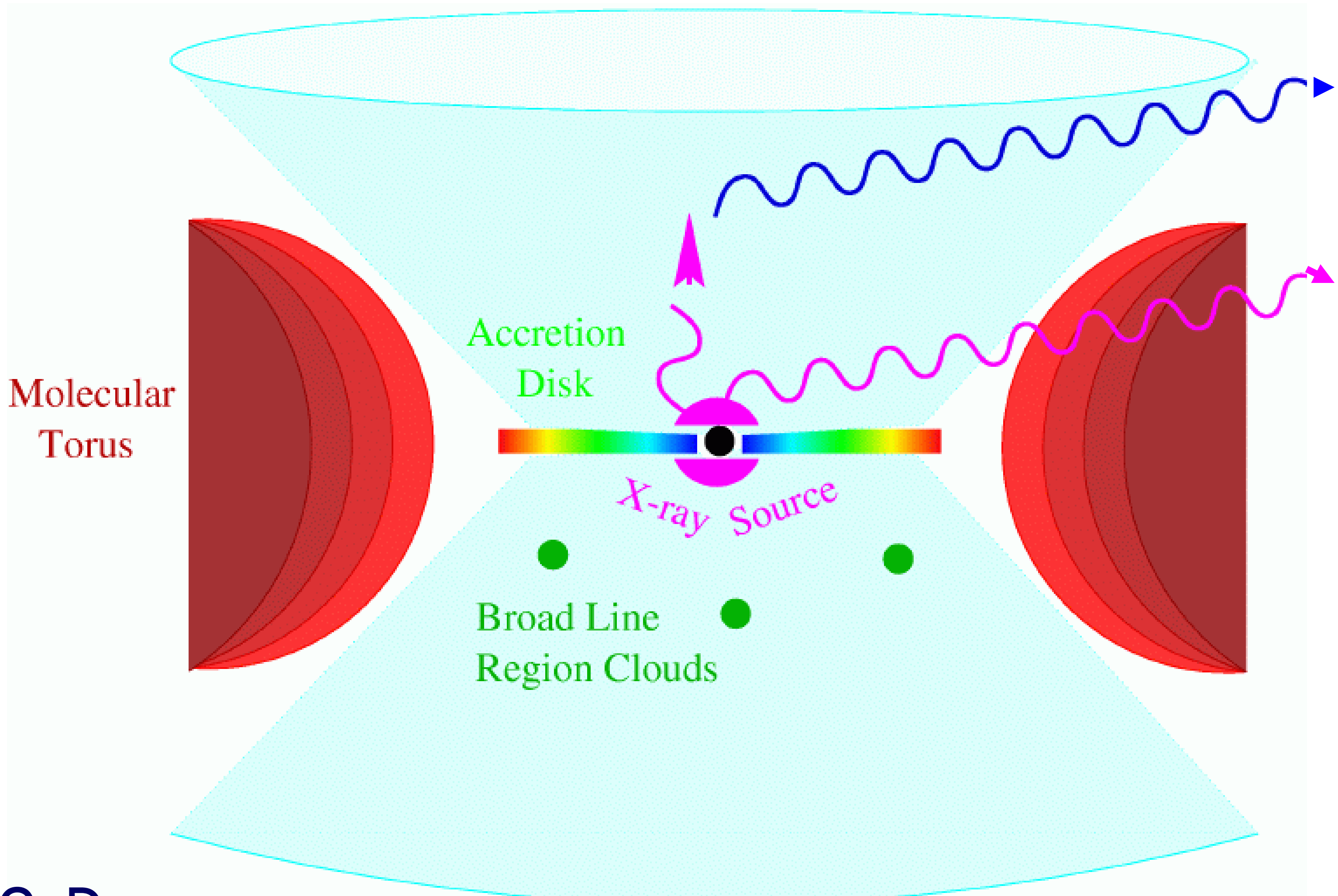
- The SCUBA sources are distant, exceptionally luminous dust-obscured sources

- Although they are rare, they are among the most luminous galaxies in the universe---yet before SCUBA, we did not even know they existed!

- Their star formation rates are hundreds of times greater than those of present-day galaxies

Might the universe be covering up other violent activity?

YES! Accretion onto SMBHs can also be obscured by dust & gas that absorbs optical light. How about trying X-ray observations?

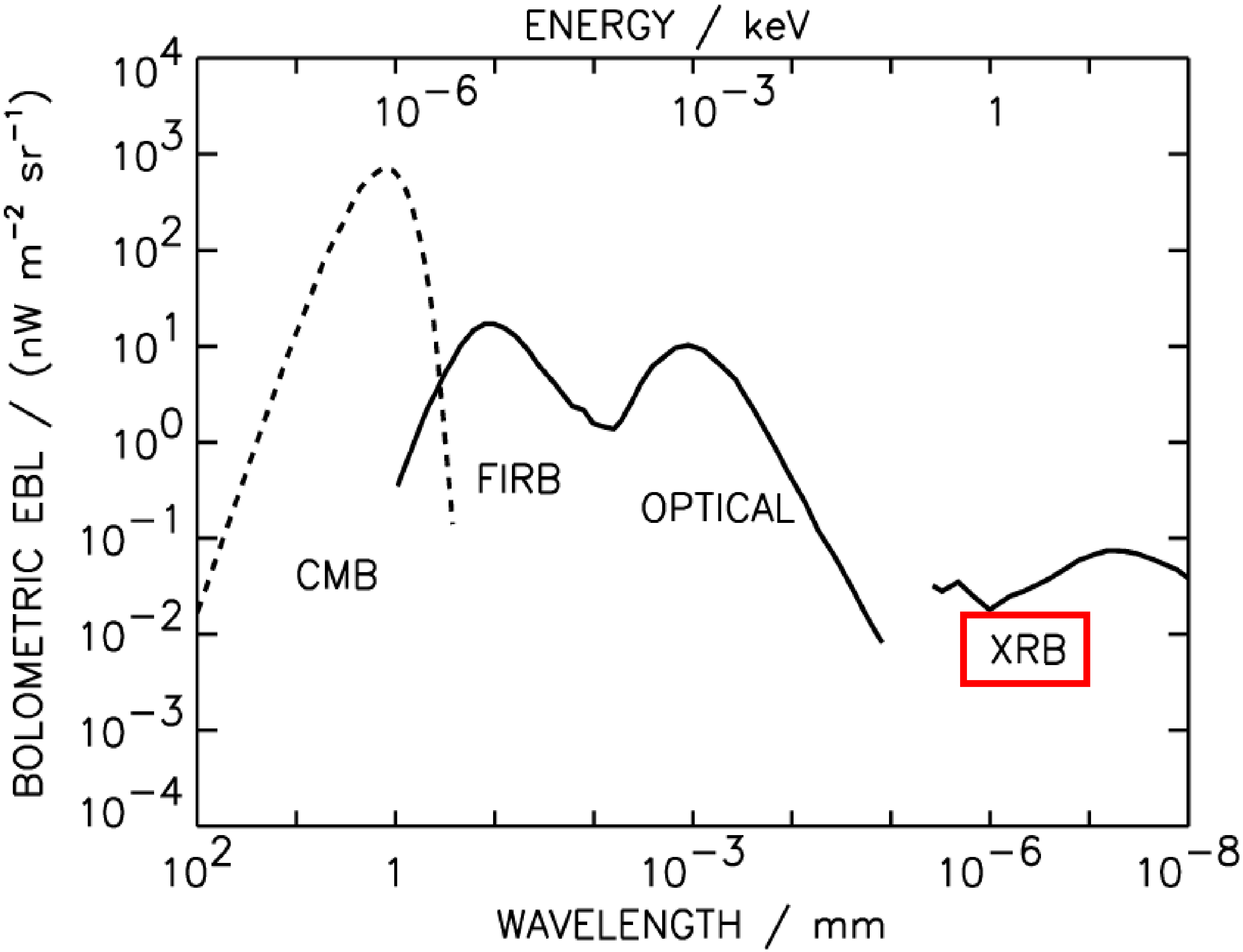


C. Done

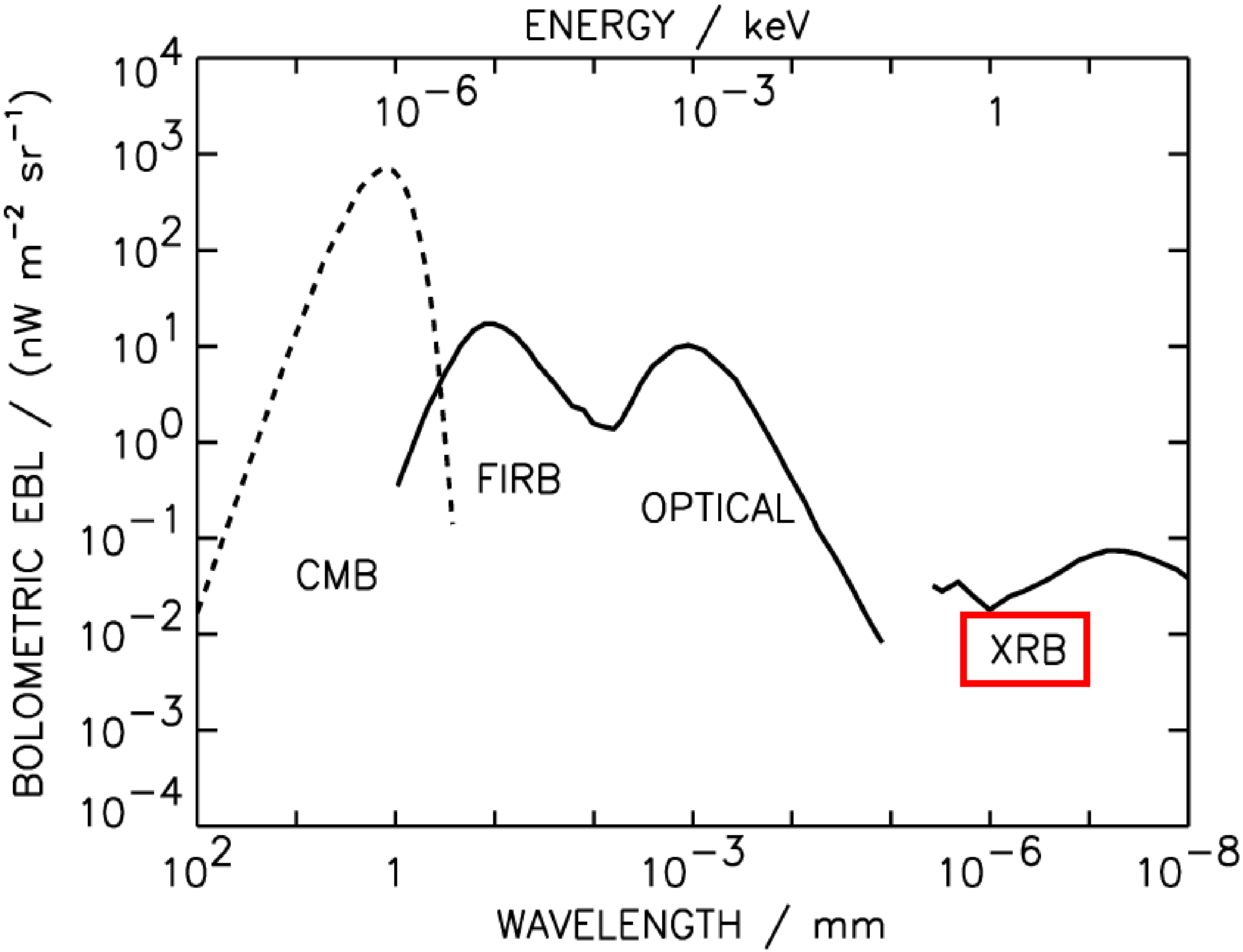
The Background Glow

- In 1962, Riccardo Giacconi (2002 Nobel Prize in Physics) had a rocket mission to study X-rays from the Moon
- He discovered a diffuse uniform X-ray “glow” from the sky
- X-ray telescopes can resolve the glow into individual sources

Only a small fraction of the total energy produced in the universe emerges in X-rays



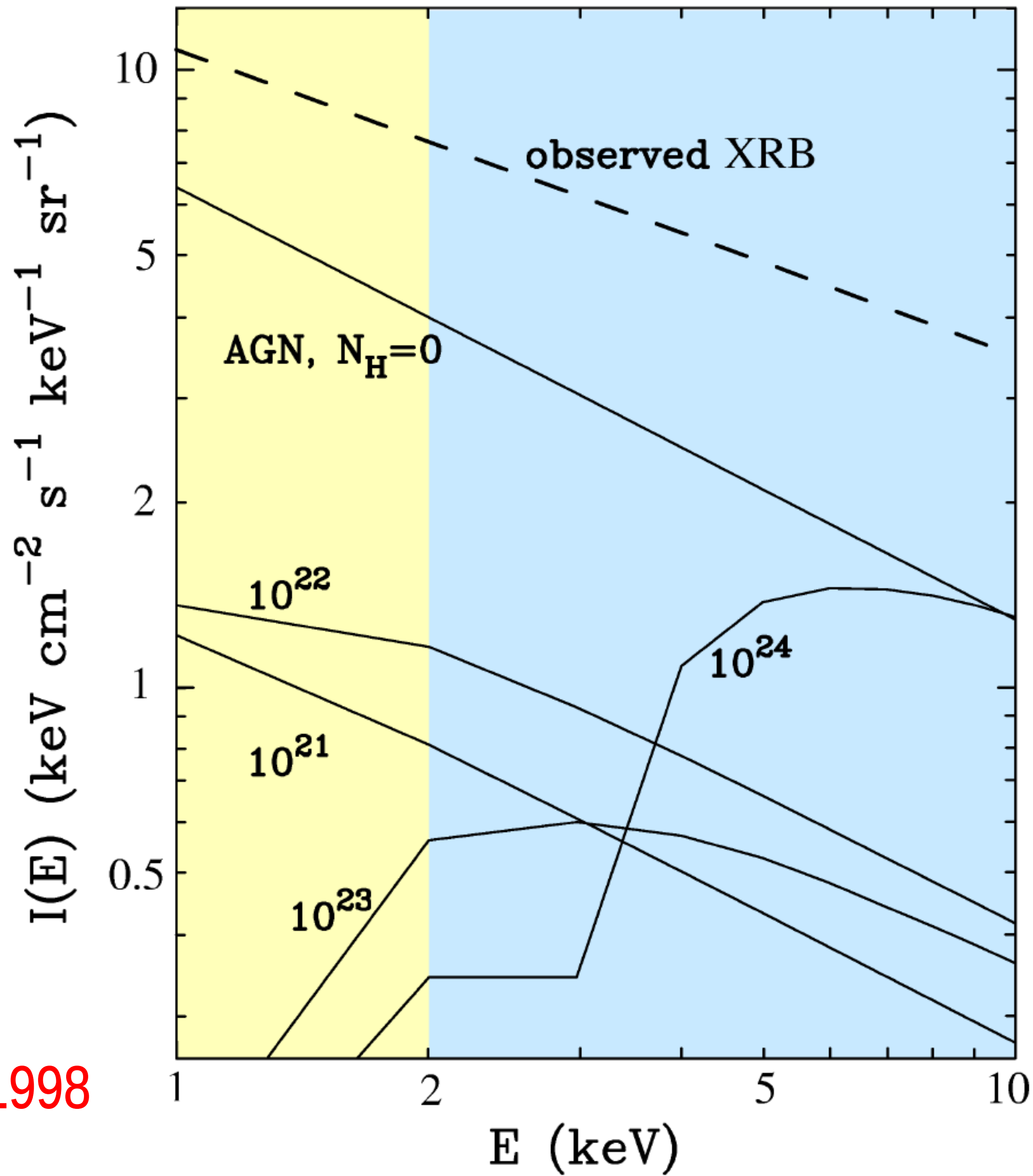
But X-ray surveys provide a window on black hole evolution



The Great Escape

- Early X-ray telescopes could only produce images in low-energy (soft; 0.5-2 keV) X-rays
- Unfortunately, these surveys could not find most of the sources that make up the X-ray background
- Only high-energy X-rays (>2 keV) can penetrate the gas & dust cocoon that may be obscuring a SMBH

Modelers had a heydey predicting what one should find (i.e., a population of obscured quasars at z=2-3)



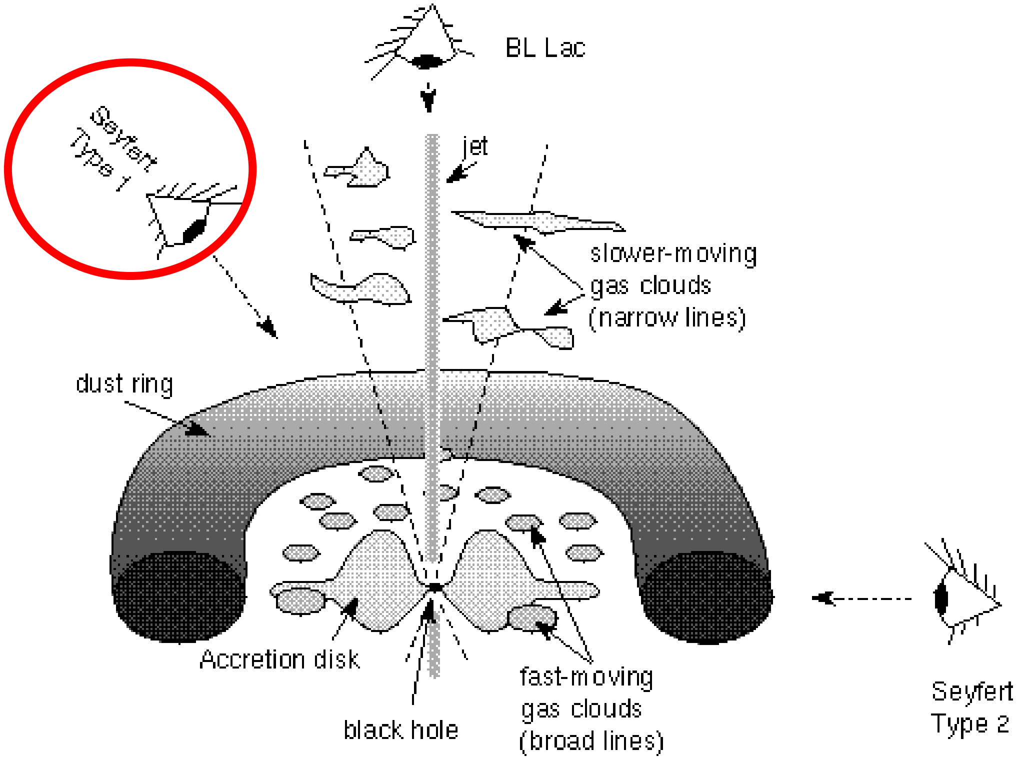
N_H is the column density of material to the source (particles per cm^2)

Schmidt 1998

They Assumed the Unified Model

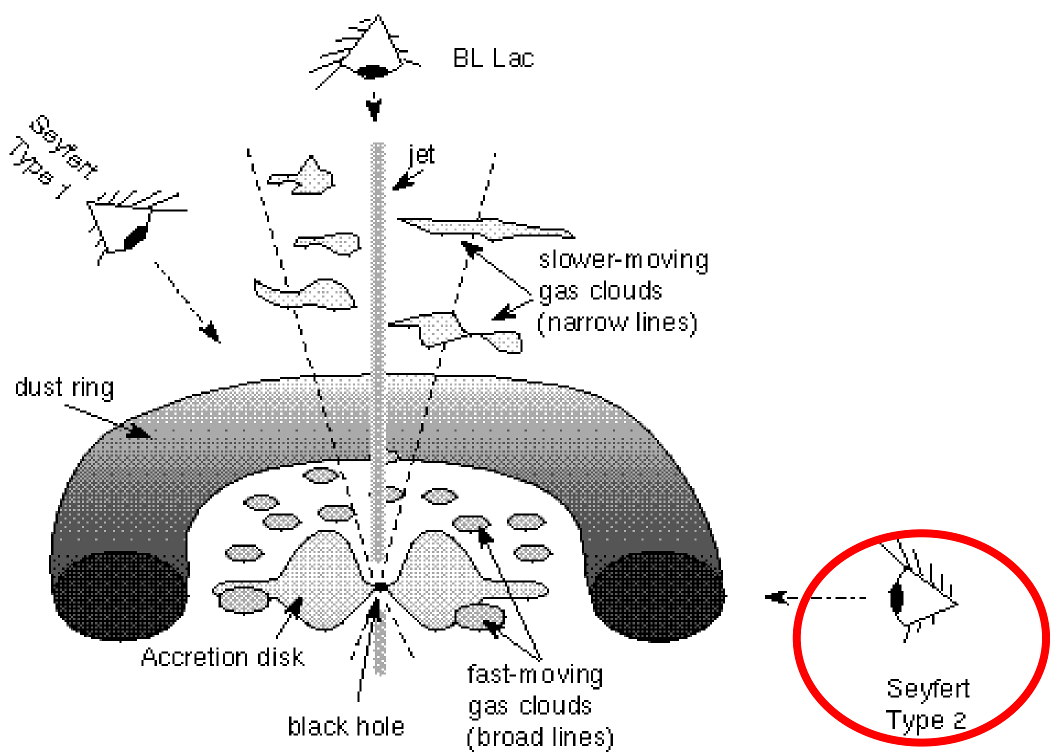
Type of AGN seen in the optical depends on line of sight:

- Around the accretion disk are relatively dense, fast-moving clouds of hot gas responsible for the broad emission lines seen in unobscured AGN

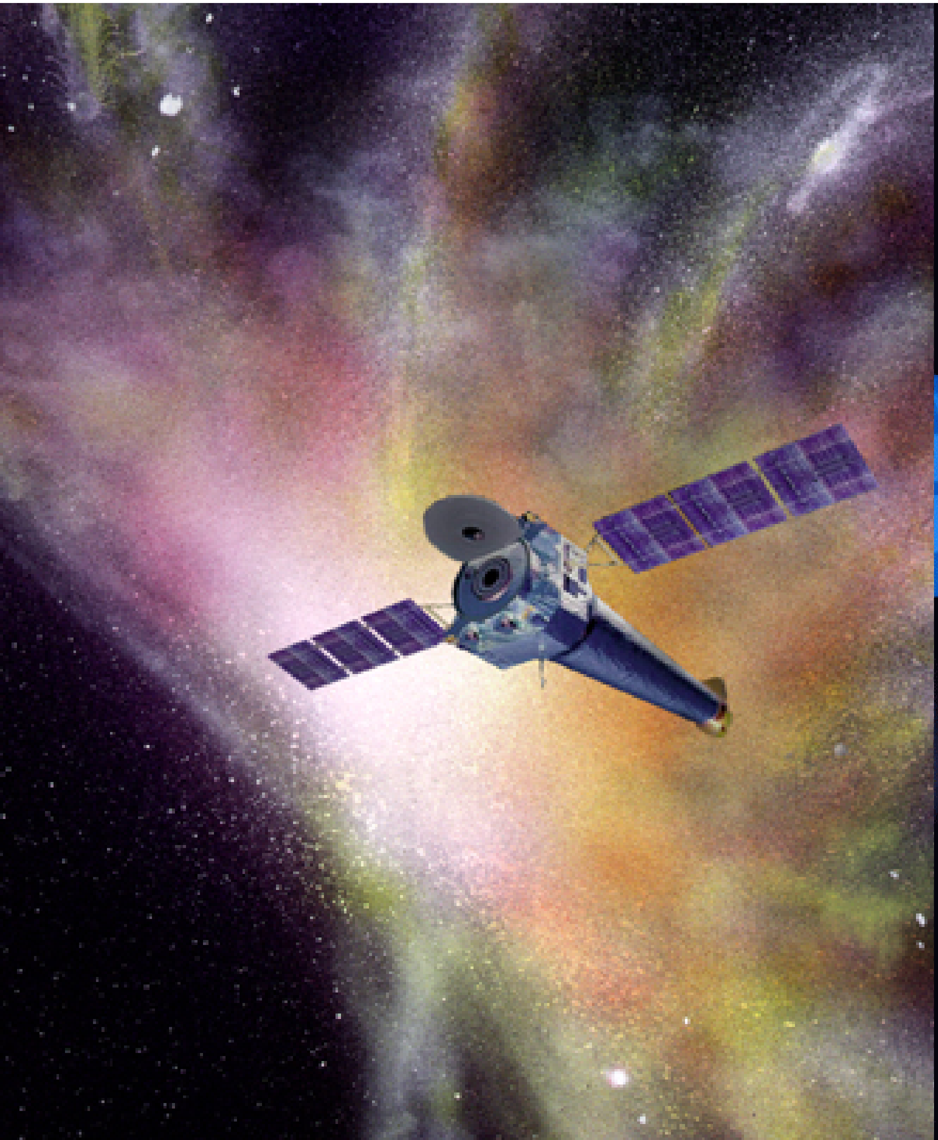


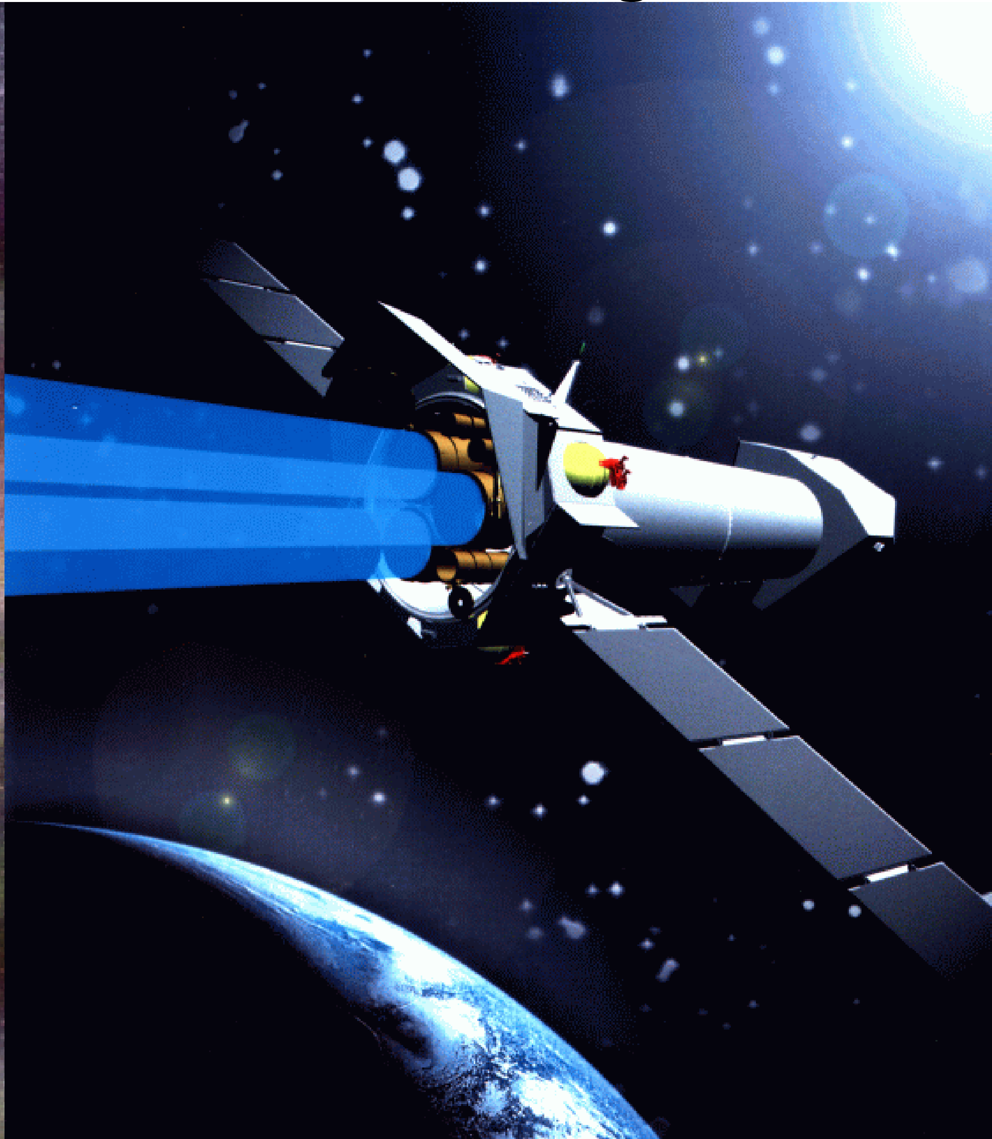
• But, if you are viewing the AGN through a gas & dust torus that hides the accretion disk, then only slower-moving hot clouds farther from the black hole are visible

There should be no luminosity or redshift dependence of the obscuration because it is all geometry



The fundamental goal of the Chandra and XMM-Newton X-ray Observatories was to resolve the sources of the 2-8 keV `hard' background





Chandra and XMM have revolutionized distant AGN studies

Now possible

- to map the history of the AGN population using hard X-ray surveys, and
- *for the first time*, to compare high-redshift & low-redshift samples chosen in the *same* rest-frame hard energy (2-8 keV) band

Deepest X-ray Images of the Sky

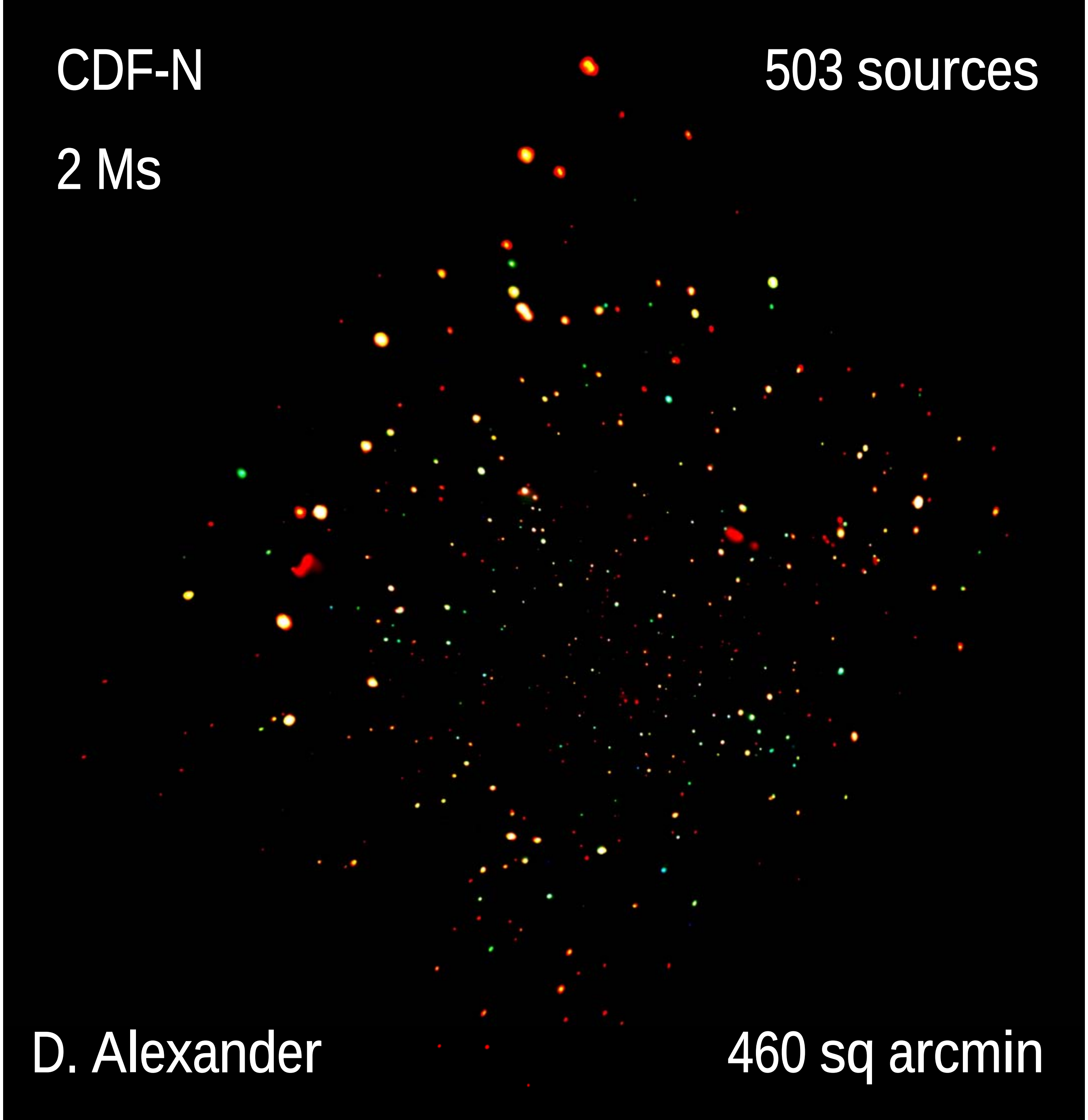
- 2 Ms Chandra Deep Field-North (CDF-N)
  [Brandt et al. 2001; Alexander et al. 2003]

- 2 Ms Chandra Deep Field-South (CDF-S)
  [Giacconi et al. 2002; Luo et al. 2008]

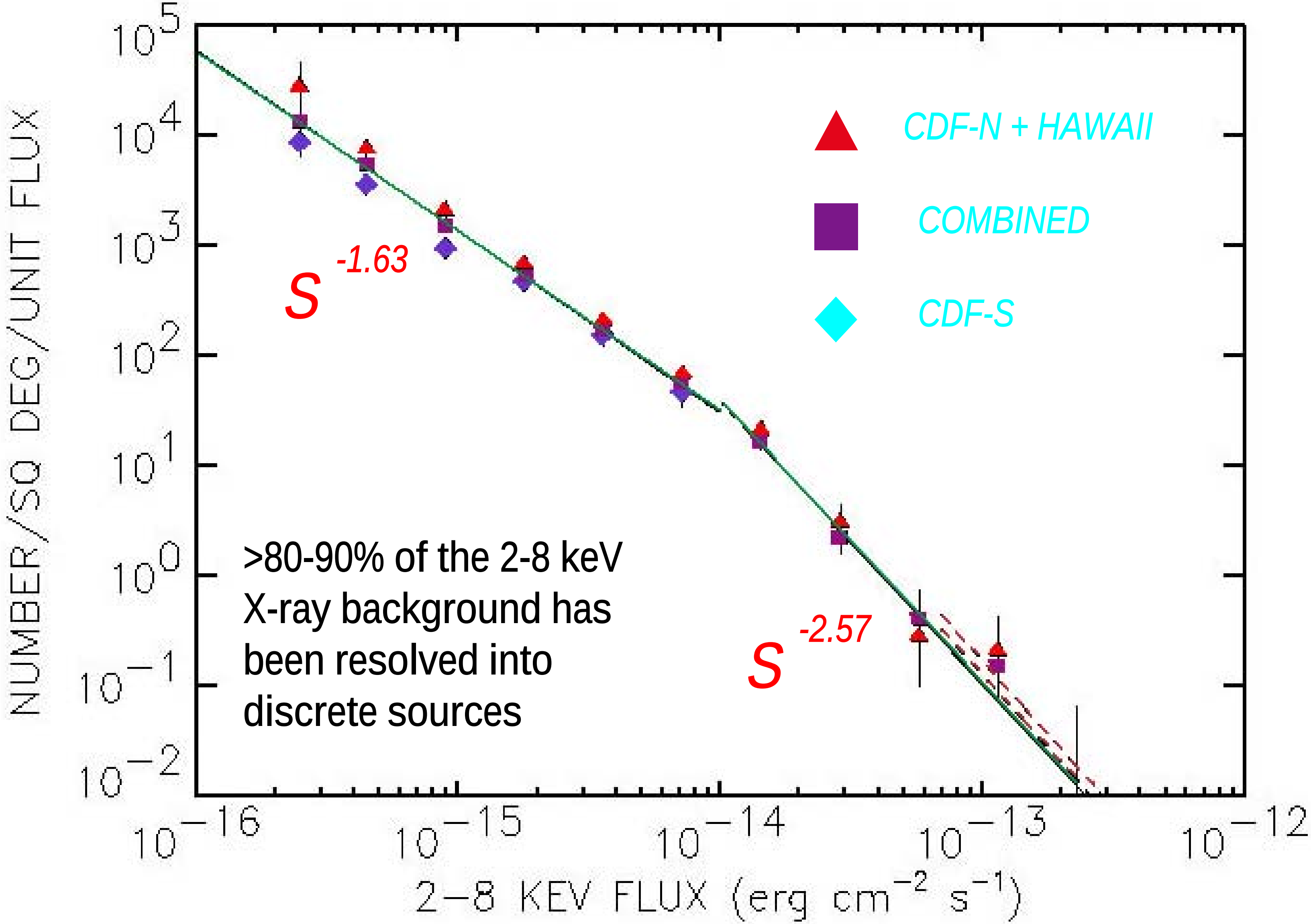
RED:
0.5-2 keV

GREEN:
2-4 keV

BLUE:
4-8 keV

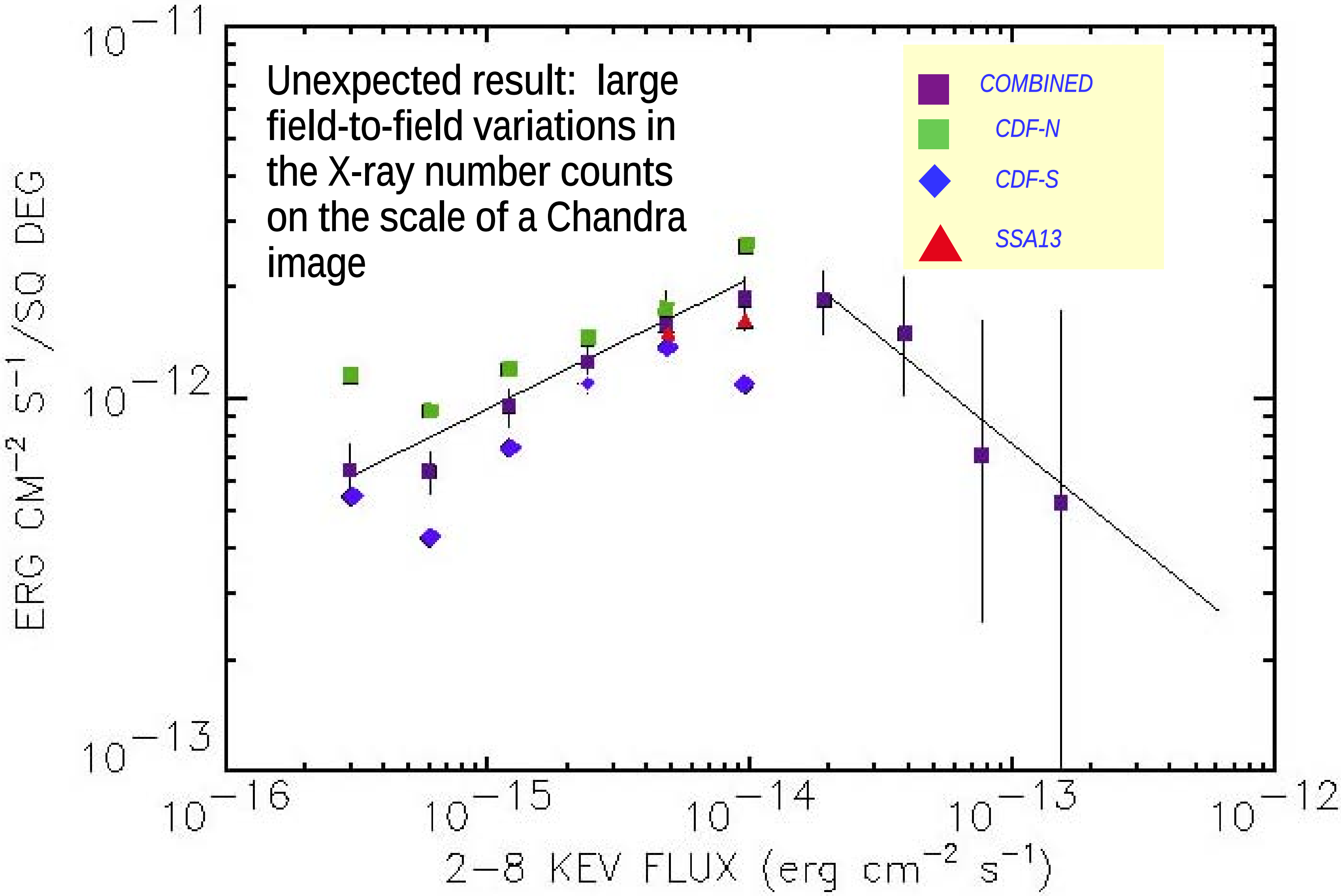


Differential X-ray Number Counts



Cowie et al. 2002

Contributions to the 2-8 keV XRB



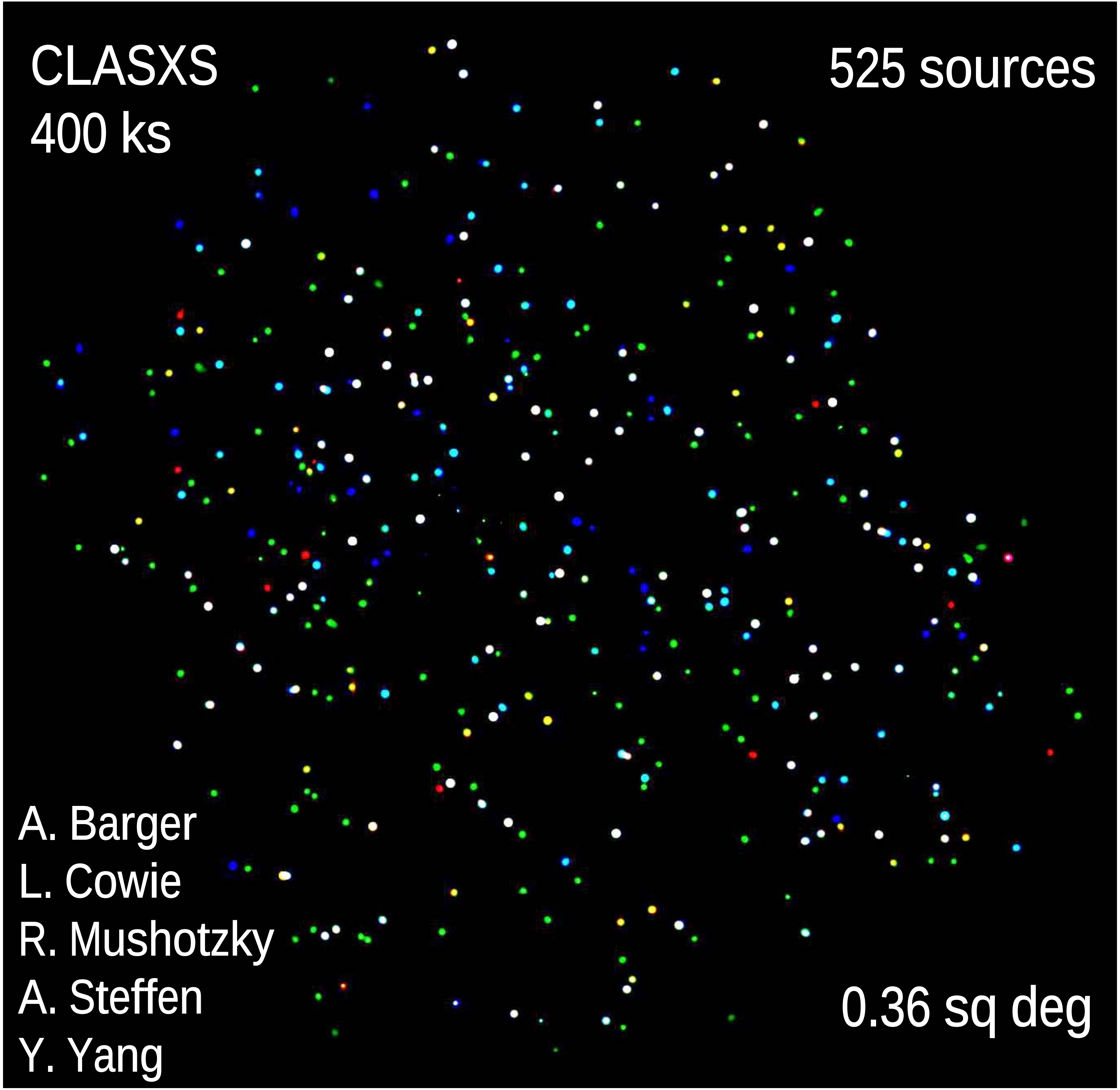
Need many Chandra fields to get average true number counts

Deep is Good but so is Wide!

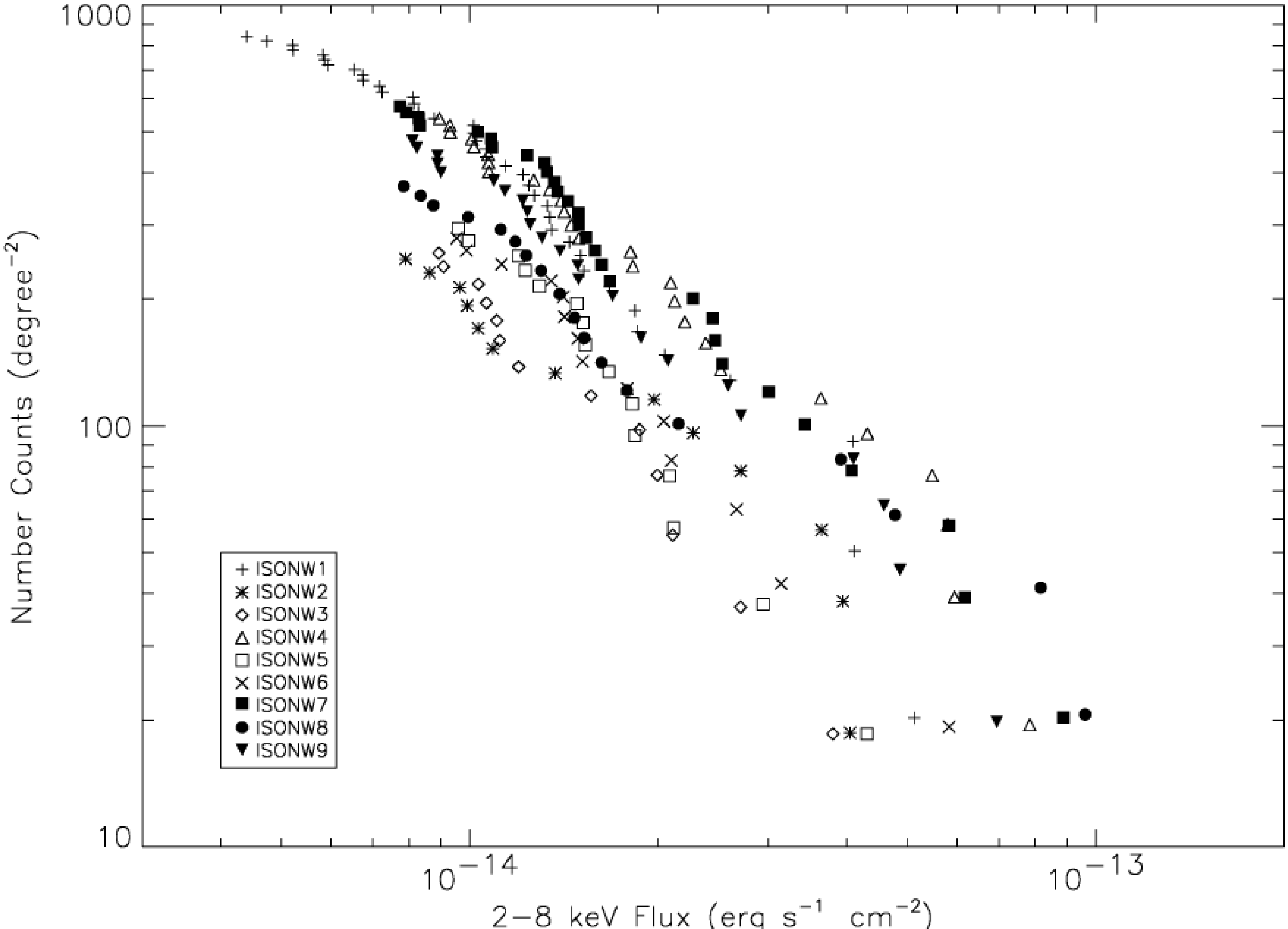
Large areas also allow us

- to obtain the volume needed to map the nearby universe

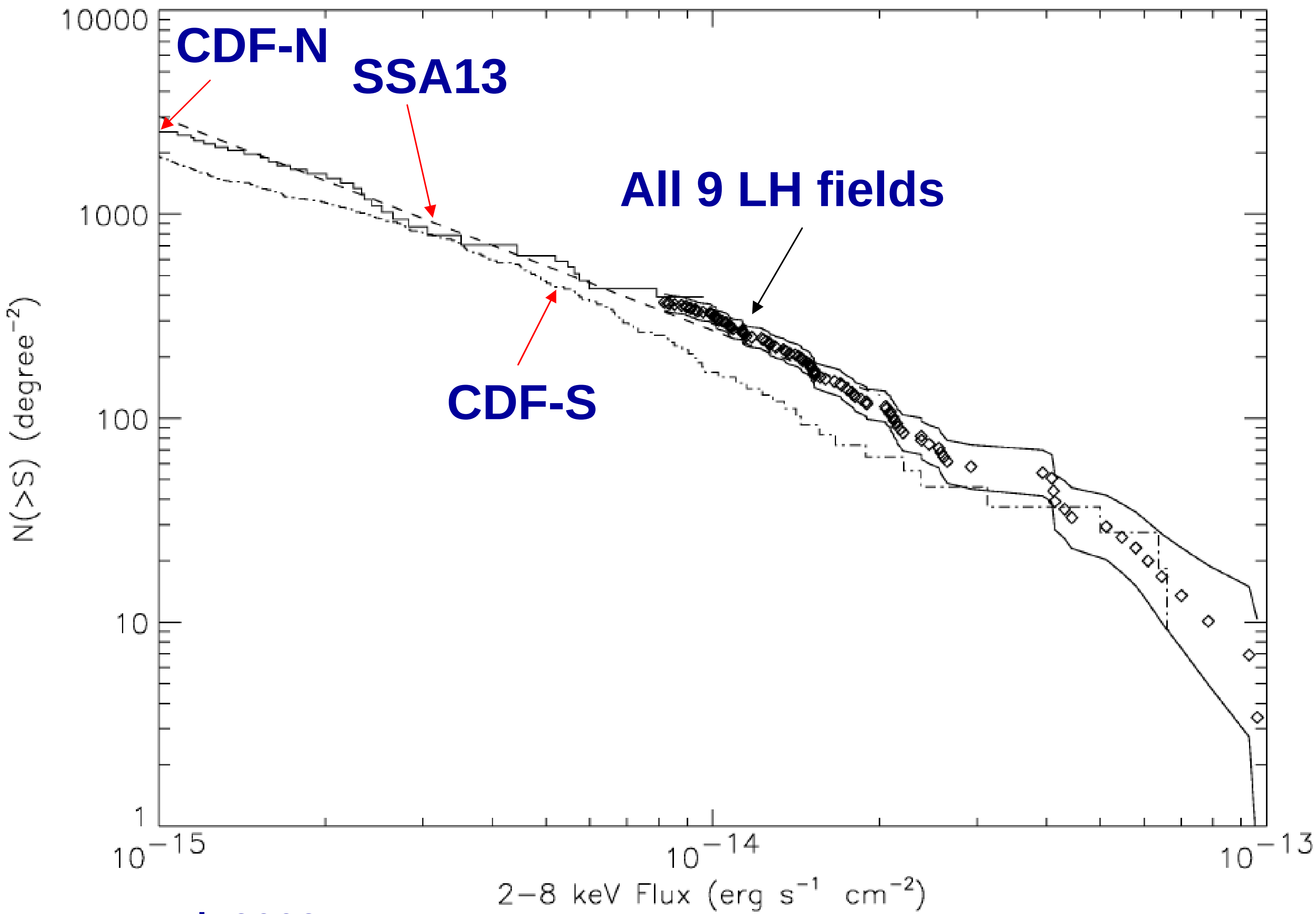
- to find the rare, bright, very distant sources


CLASXS
400 ks
525 sources
A. Barger
L. Cowie
R. Mushotzky
A. Steffen
Y. Yang
0.36 sq deg

Field-to-field variance of ~50% on solid angles of ~240 arcmin²



Yang et al. 2003



Yang et al. 2003

A Multiwavelength Approach

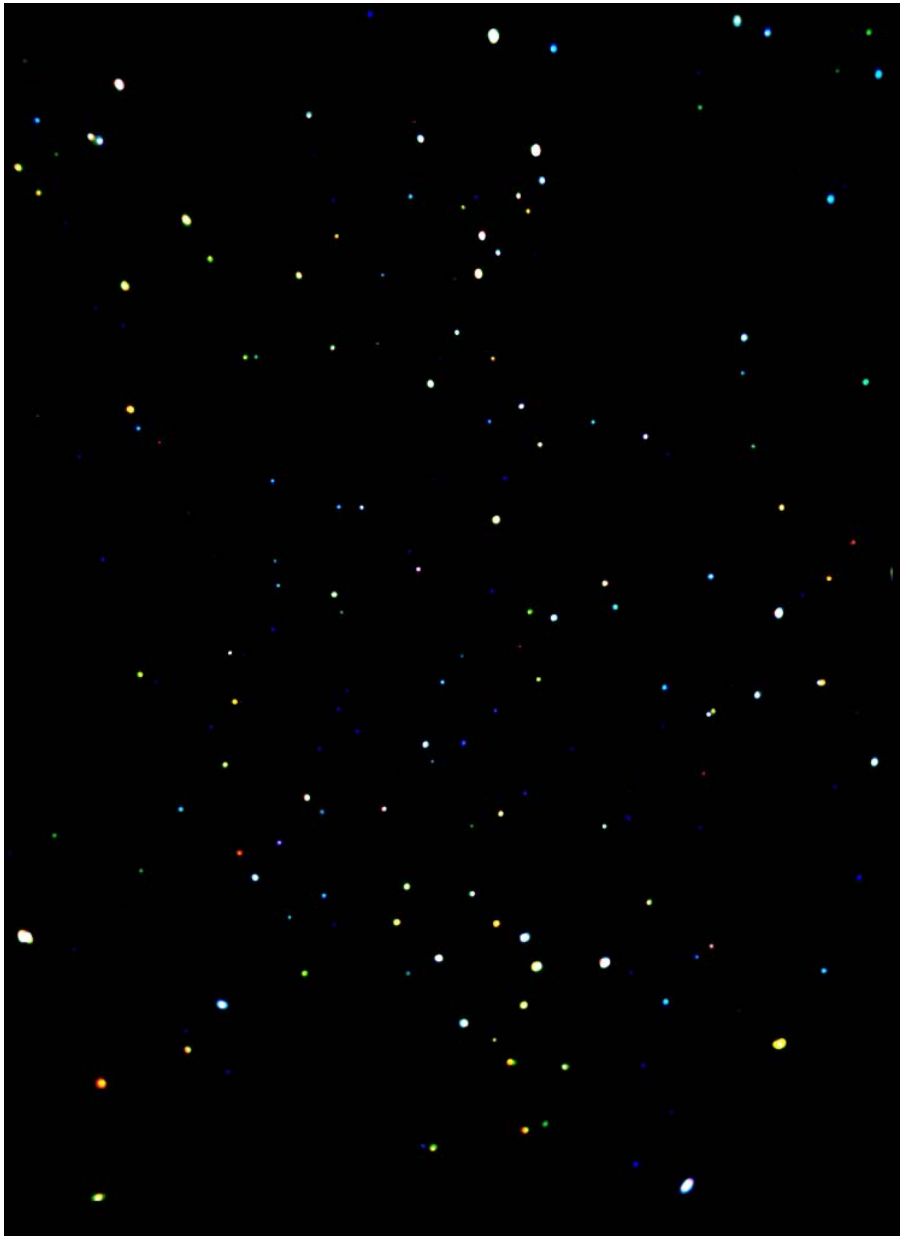
- X-ray observations are essential for finding hidden black holes, but they are not sufficient for

    - fully understanding the nature of the sources
    - determining their distances

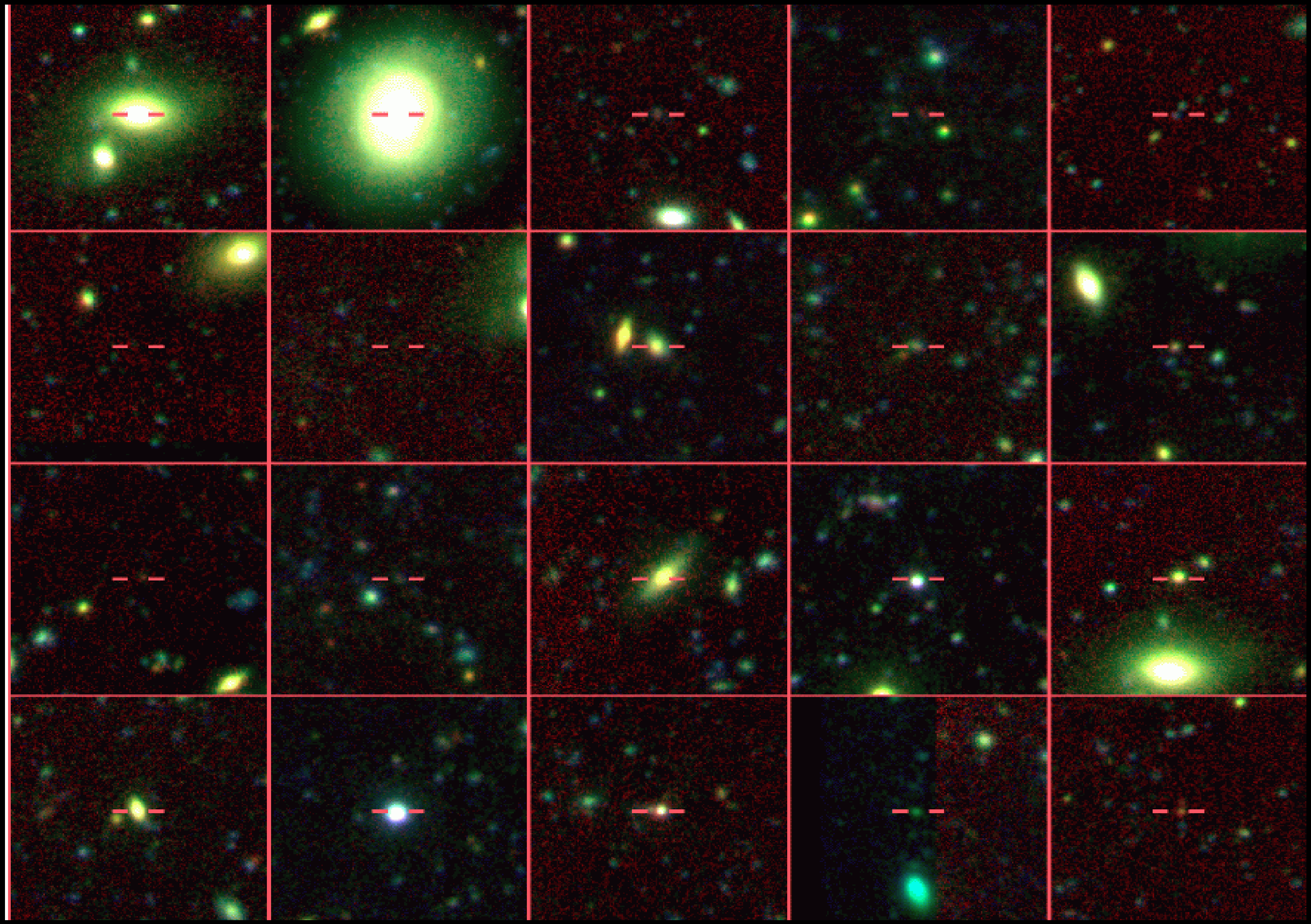
- We need observations at many different wavelengths for this


Subaru 8.2 m telescope for wide-field imaging with Suprime-Cam

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



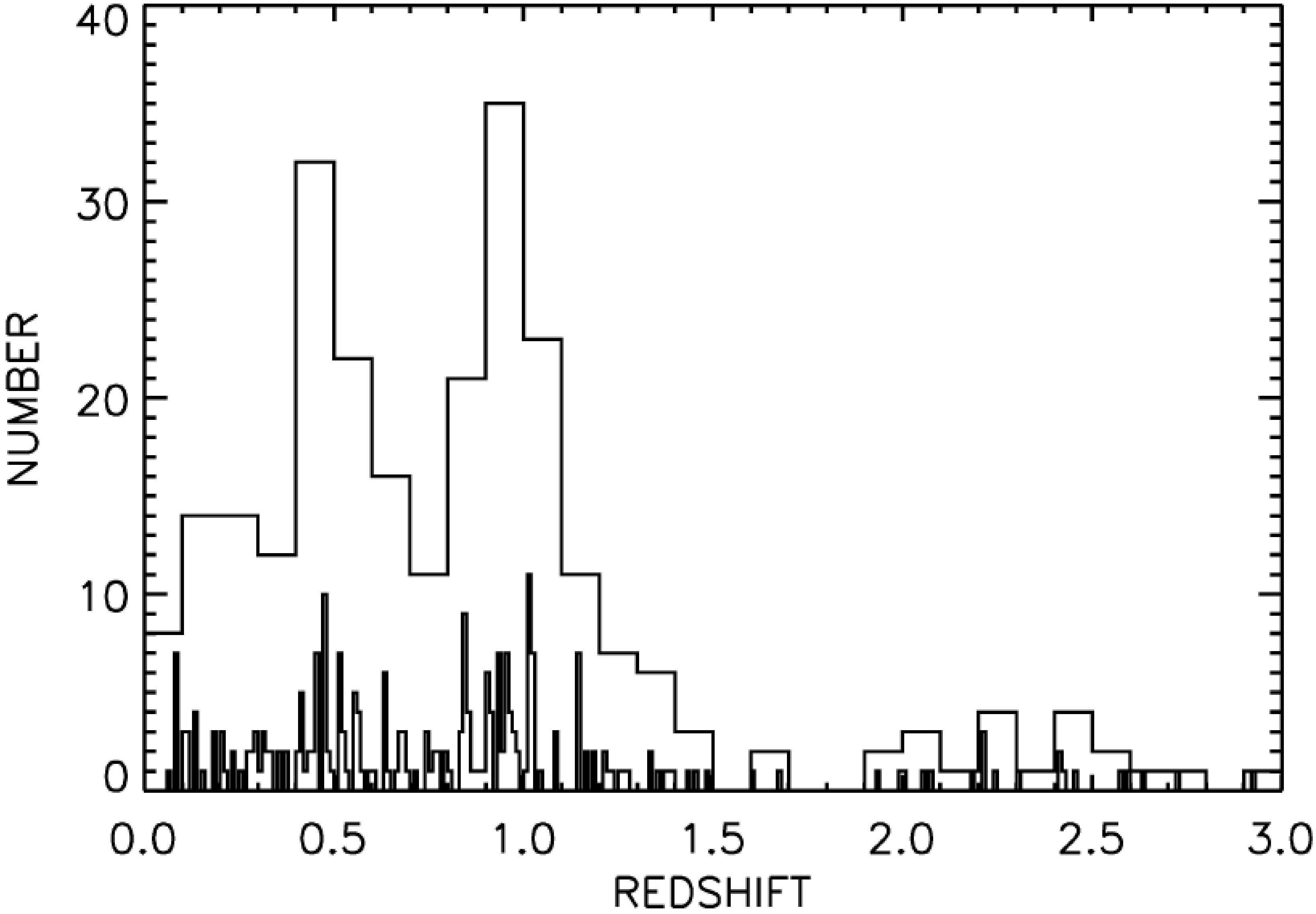
Diverse assortment of counterparts to hard X-ray sources



Redshift Distribution & Optical Spectral Classification of the X-ray Sources

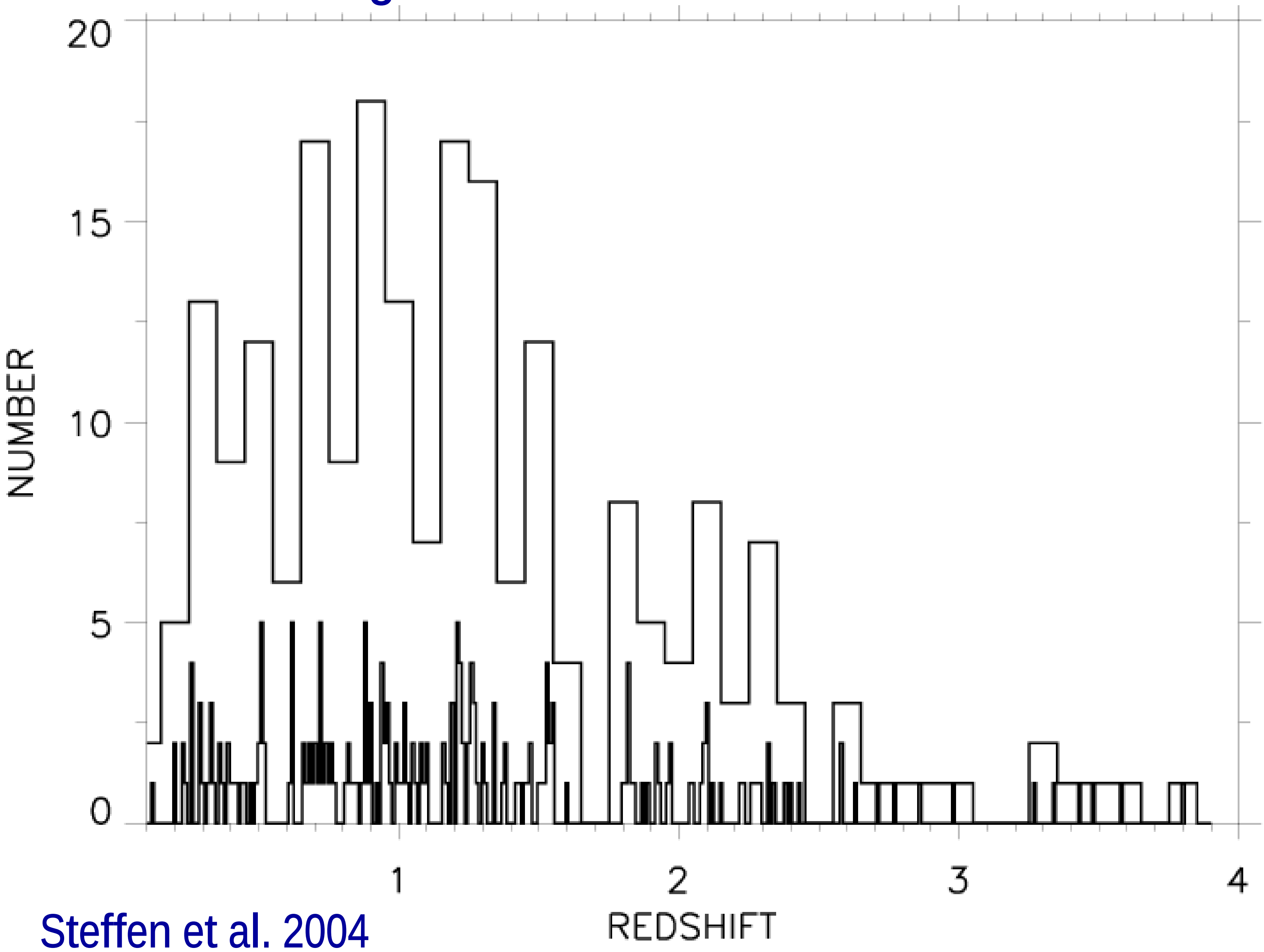

Keck 10 m telescopes for optical spectroscopy

Large Scale Structure in Deep Field



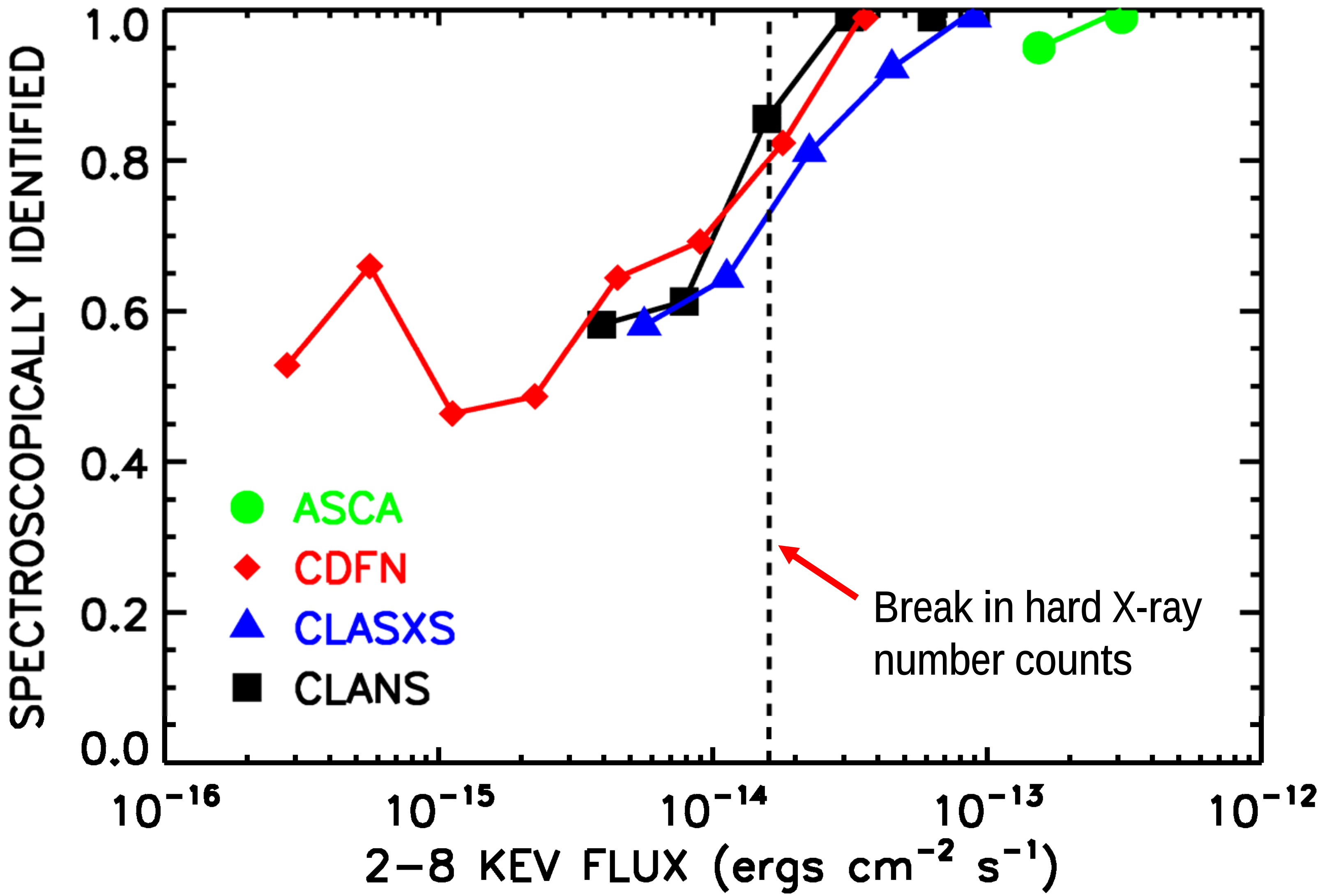
Barger et al. 2002

Averages Out When Include Wide Field



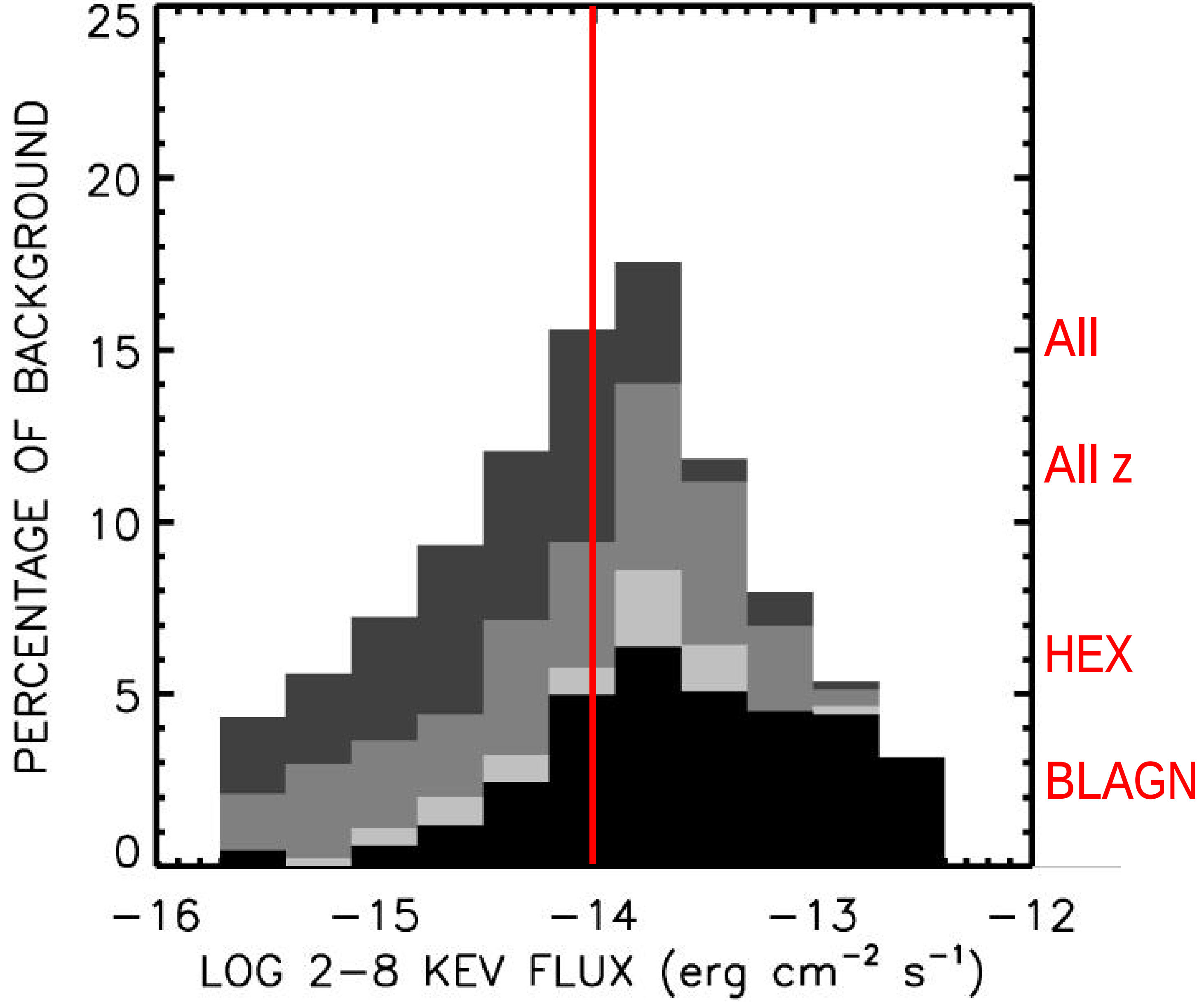
Steffen et al. 2004

Above f(2-8 keV)~10^{-14} ergs cm^{-2} s^{-1}, 80-90% of hard X-ray sources have redshifts, while below this flux, ~60%

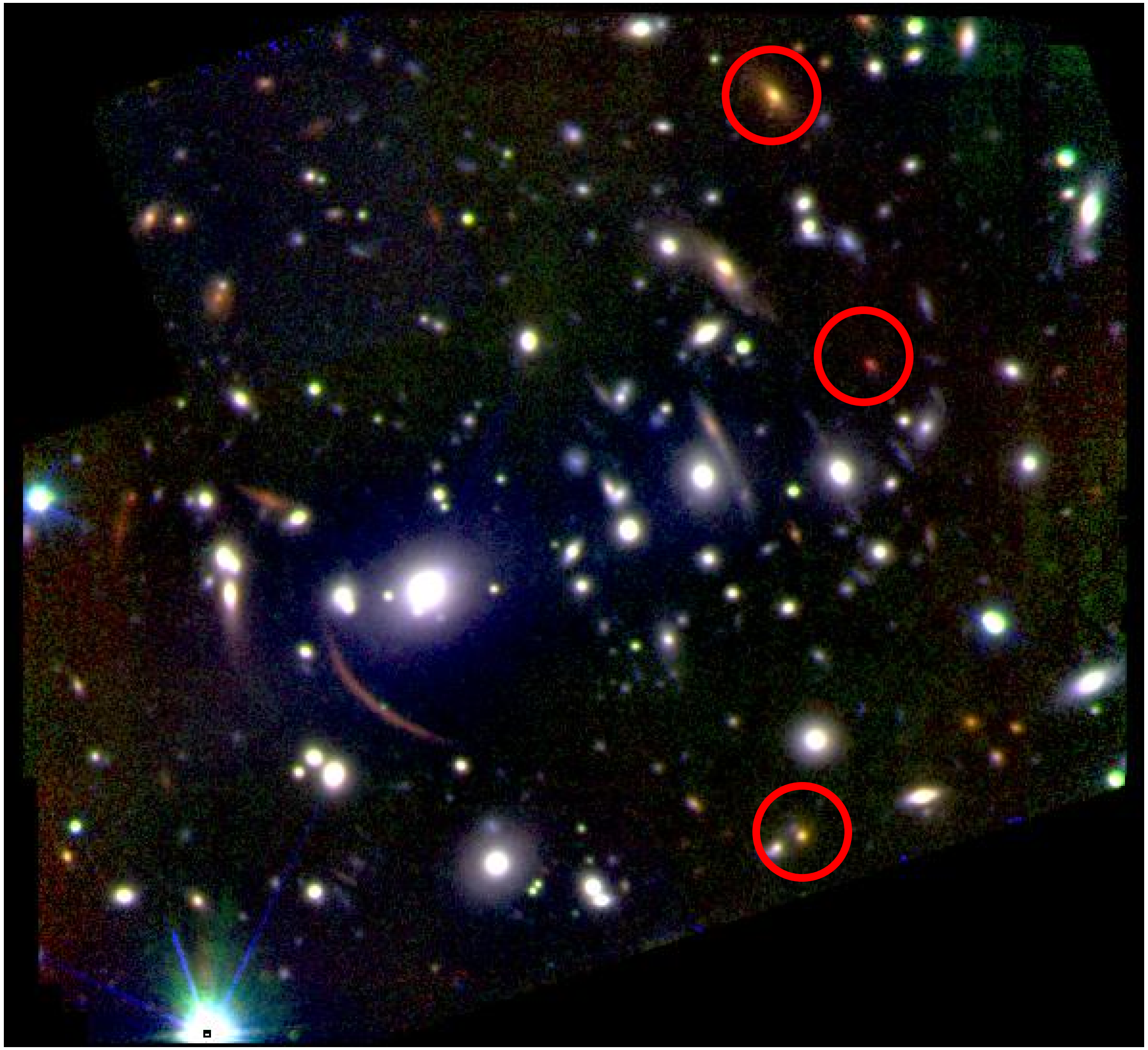


Trouille et al. 2008

Relative Contributions to the 2-8 keV Light by Spectral Class



Lower X-ray flux sources are often optically faint and red and hence difficult to identify spectroscopically



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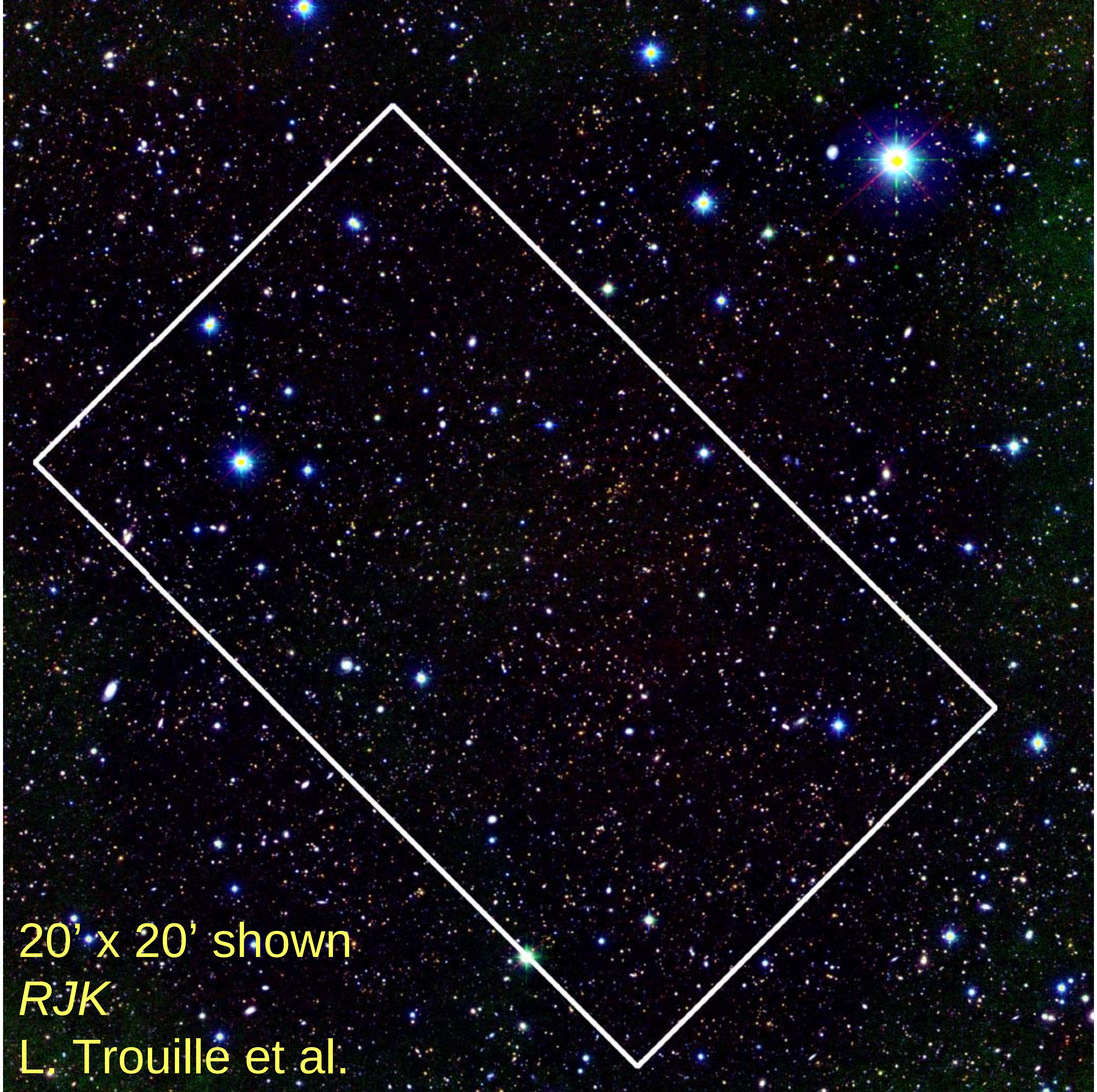
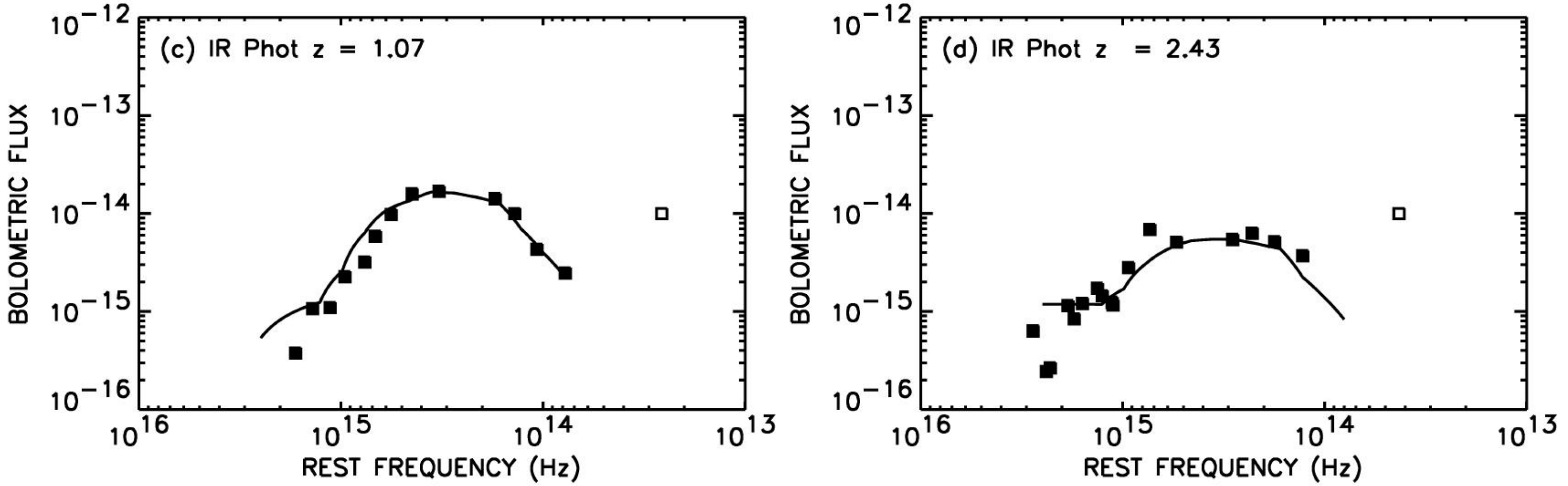
CISCO + *HST*

I, J, H


20’ x 20’ shown
RJK
L. Trouille et al.

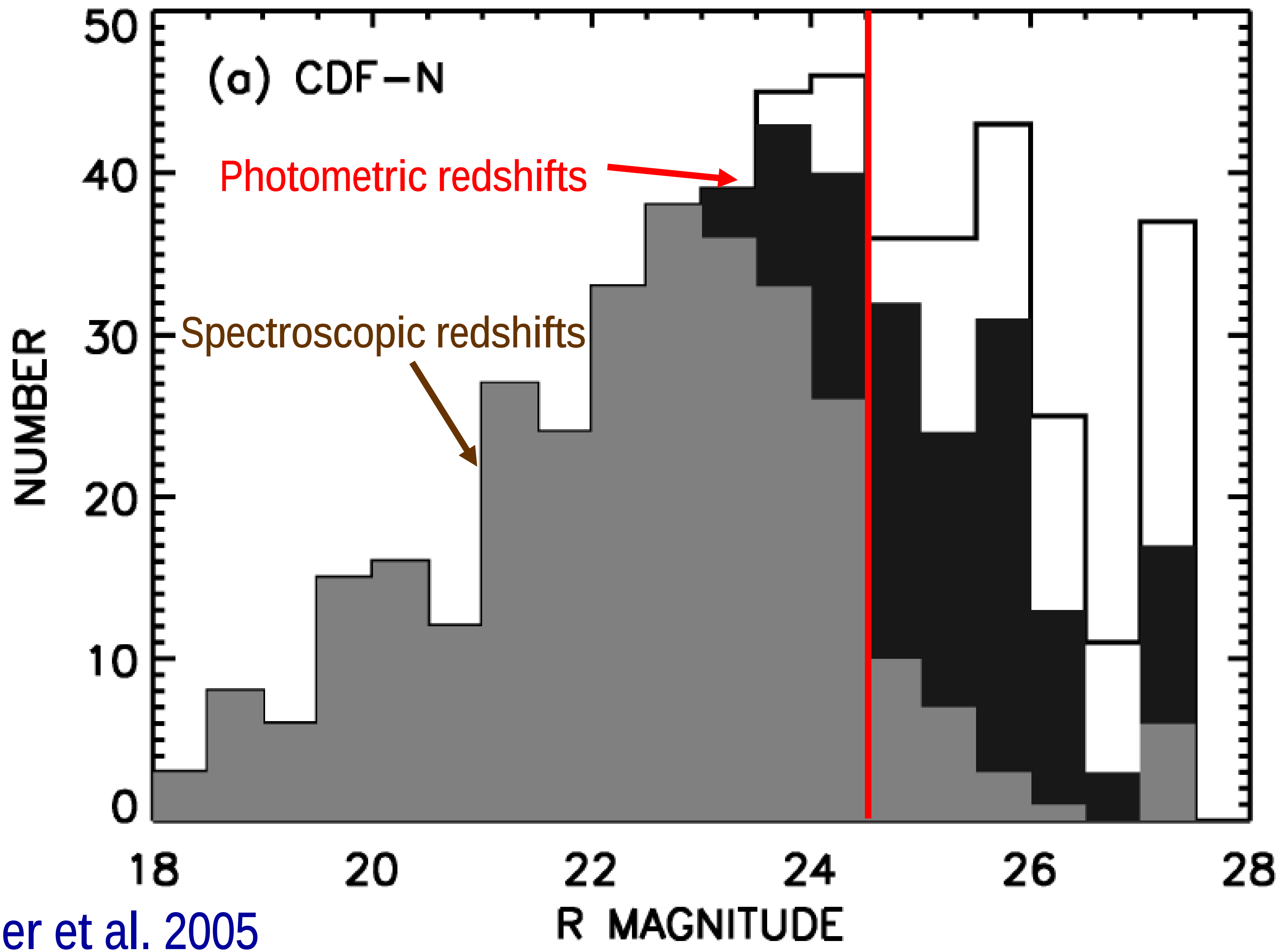
Distance Estimates

However, with the addition of NIR data from the ground and MIR data from the Spitzer Space Telescope, we can construct the spectral energy distributions of these sources and measure their redshifts photometrically

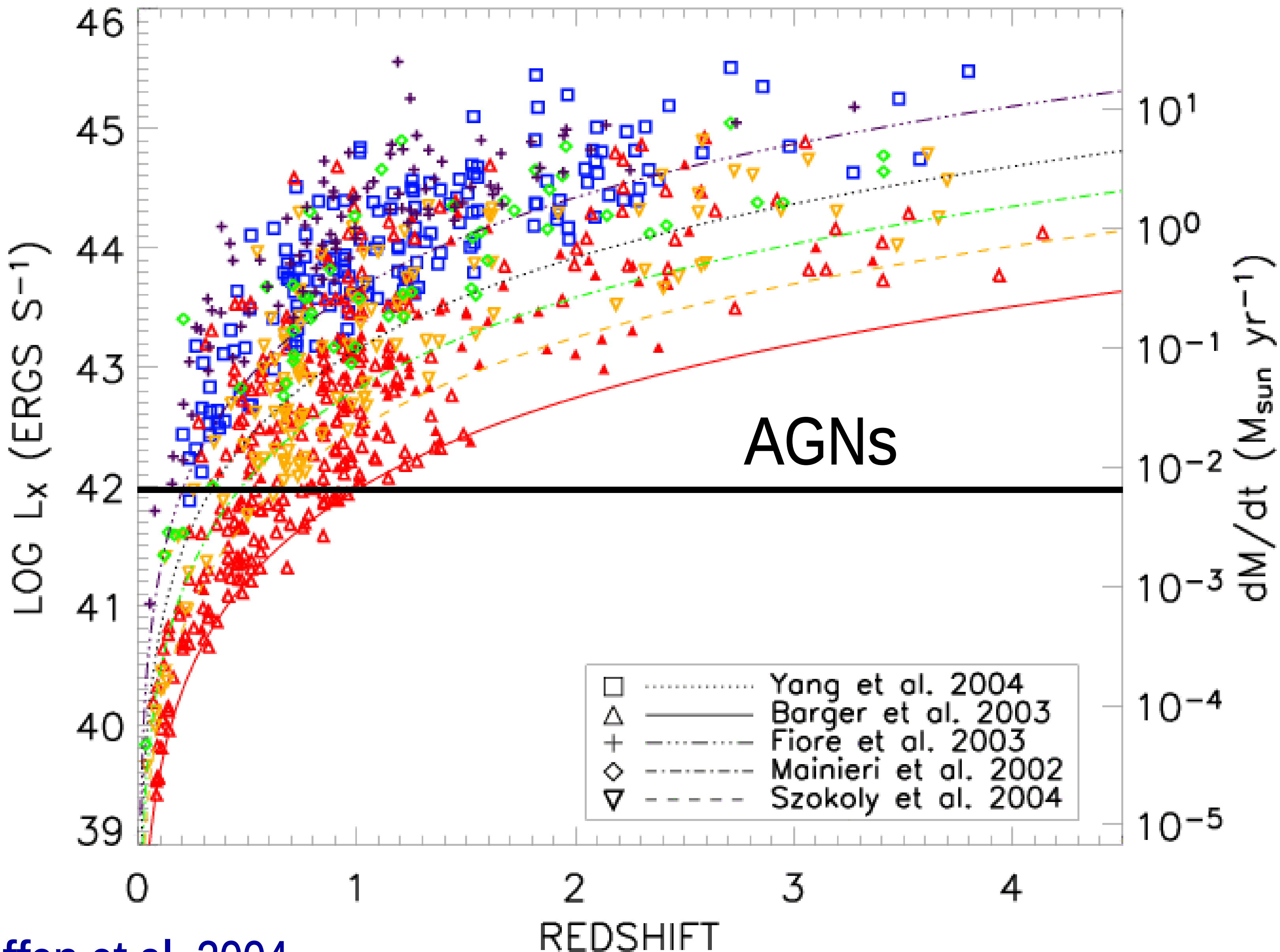


Spectroscopic samples are highly complete to R=24.5

Photometric redshifts increase overall identified fraction to about 85%



Barger et al. 2005



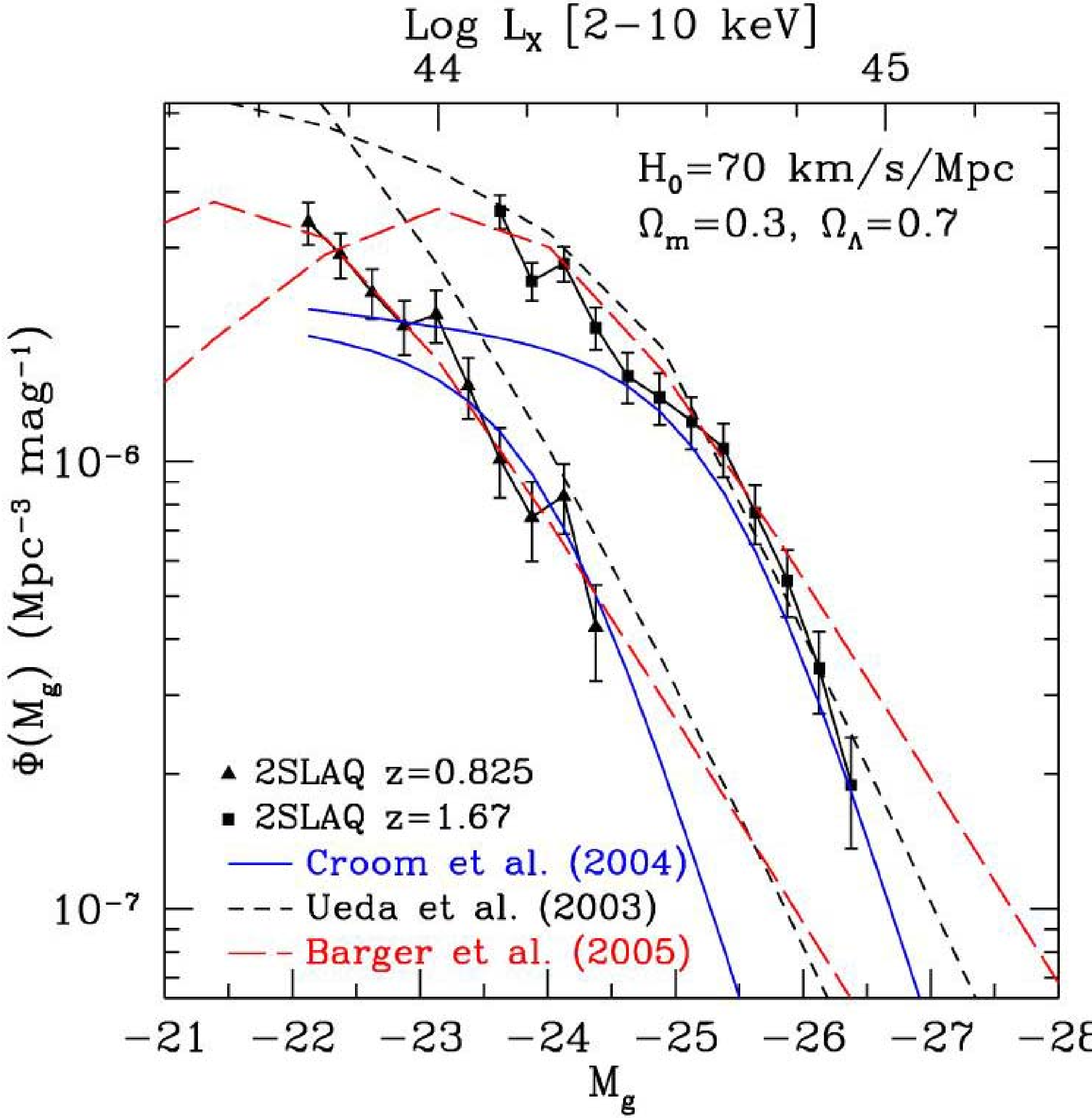
Steffen et al. 2004

Now that we have a census of AGNs from our X-ray observations, we can return to our question of when did SMBHs form?

That is, was the optically-determined picture of an exciting, quasar-filled early universe followed by a boring, nearly quasar-less middle-aged universe correct?

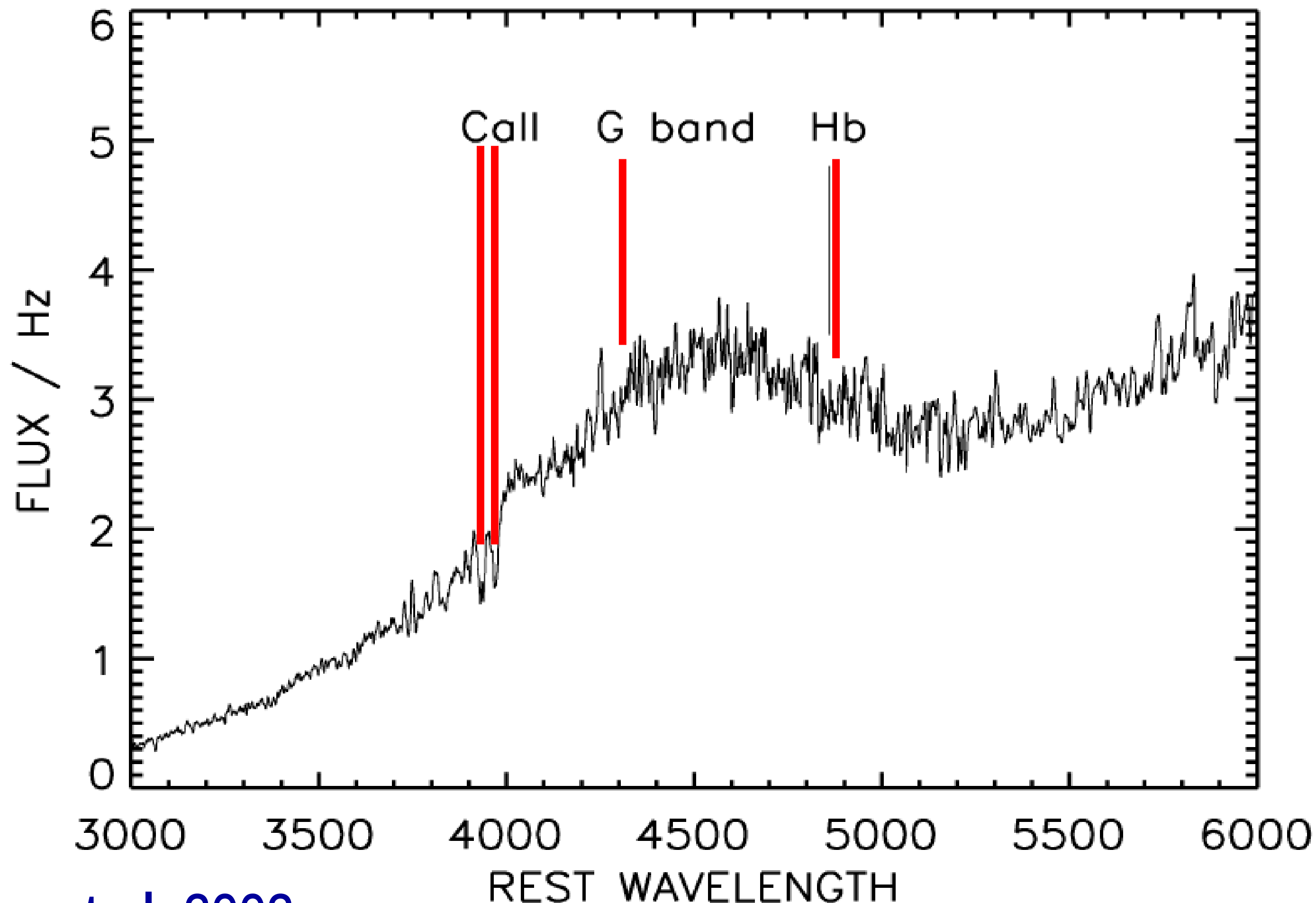
Sanity Check

First of all, with our X-ray data we were able to re-find all of the optically identified quasars (luminous unobscured sources with broad lines)



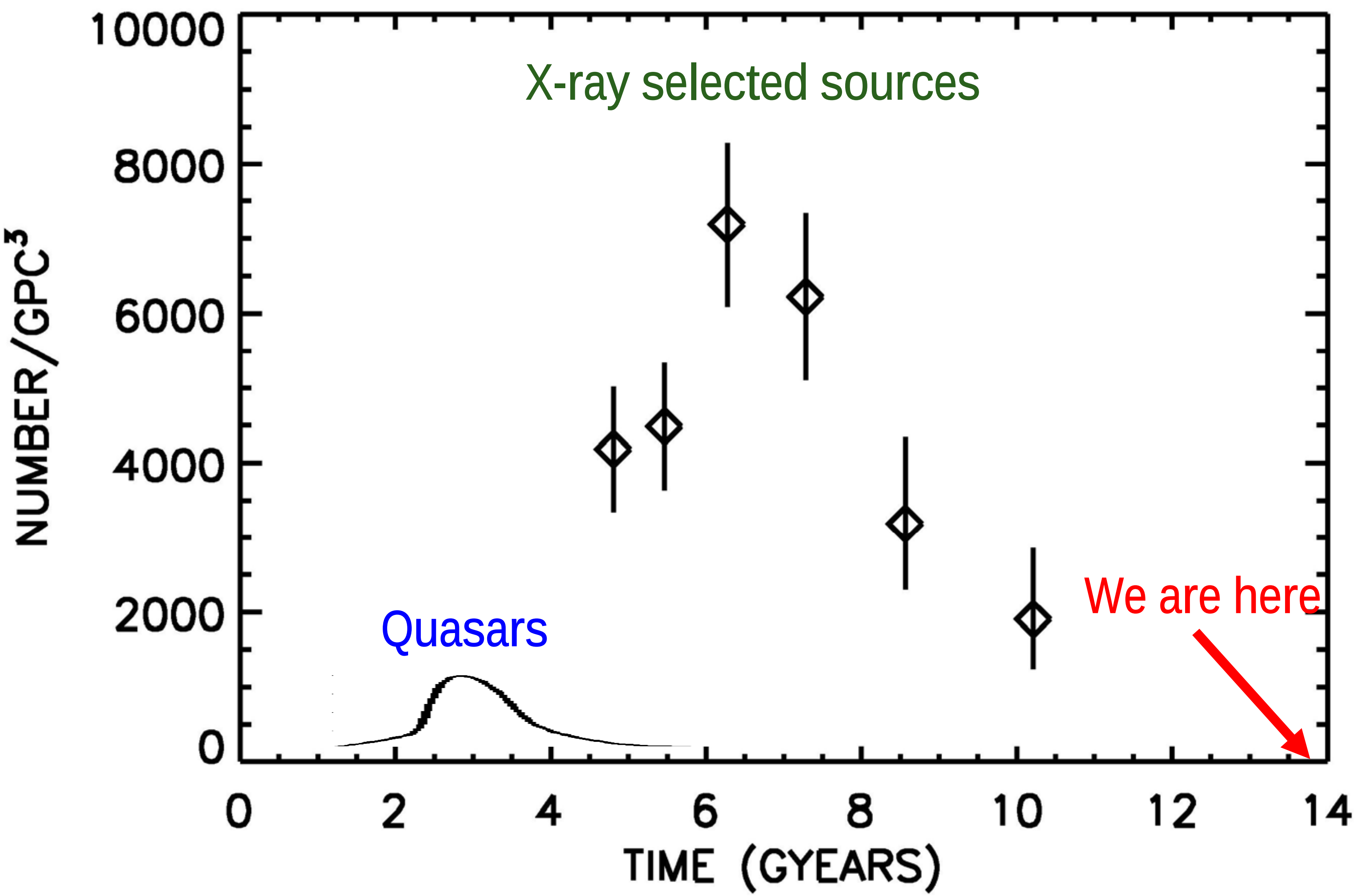
Richards et al. 2005

BUT, the optical spectra of many of our other X-ray sources show no evidence of black hole activity at all---these AGNs are hidden from optical view



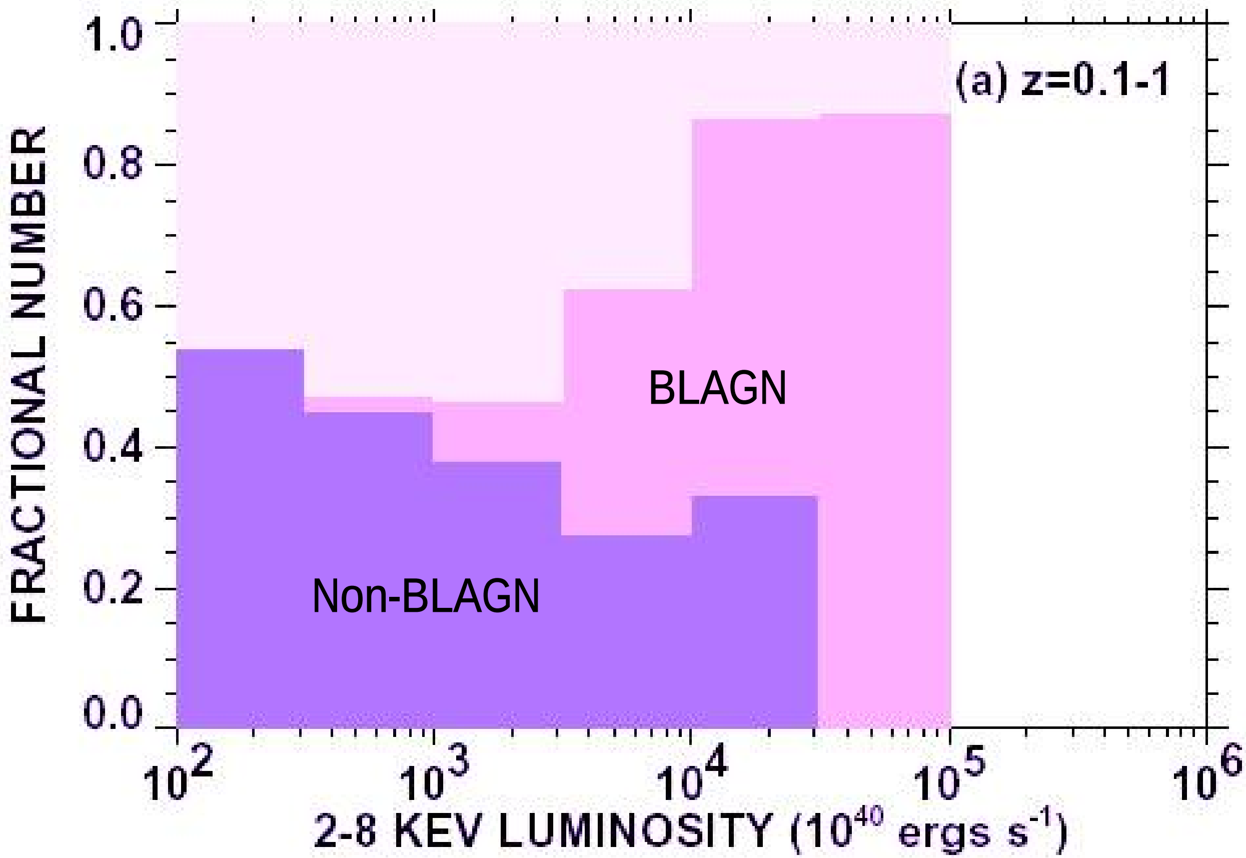
Barger et al. 2002

Thus, we discovered many new active black holes using X-ray data. Unlike the quasars, they are located relatively nearby, and there are many more of them!



What Else Did We Discover?

Broad-line AGN dominate the number densities at the higher X-ray luminosities, while non-broad-line AGN dominate at the lower X-ray luminosities



This Means We Need a Luminosity-Dependent Unified Model

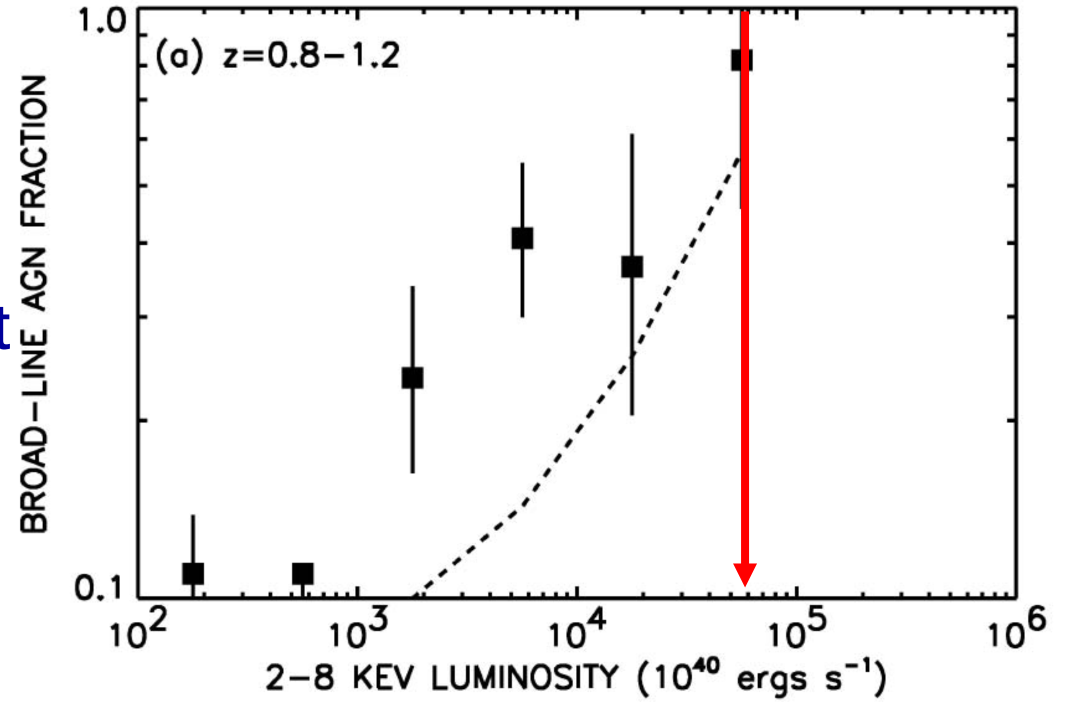
Such that the covering fraction of obscuration is

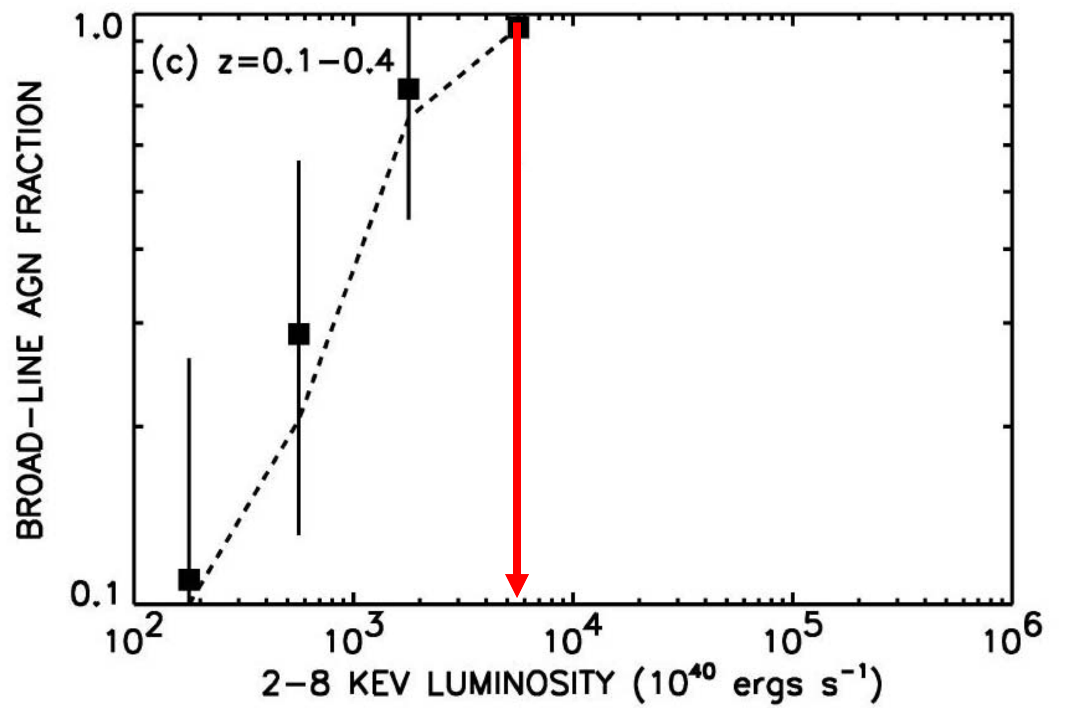
- extremely small at *high* X-ray luminosities (so all we see at these high luminosities are broad-line AGN)

- extremely large (near unity) at *low* X-ray luminosities (so we do not see broad-line AGN at these low luminosities)

However, the X-ray luminosities where all we see are BLAGN are much higher at high redshifts than they are at low redshifts

Thus, we also need a redshift-dependent unified model





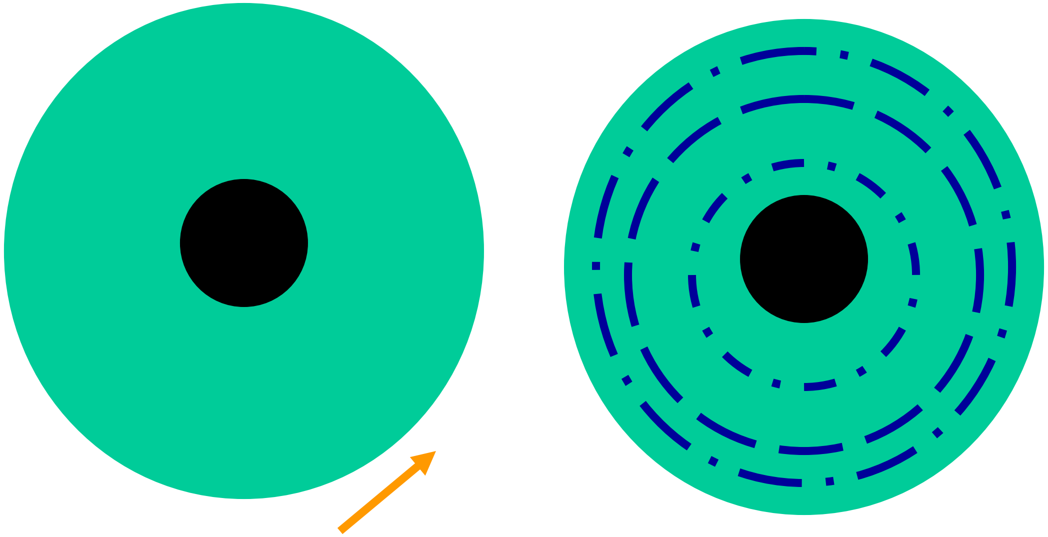
A New Paradigm

• With these new observations, we have learned that not all supermassive black holes were formed in the quasar era after all

• In fact, the newly discovered AGN show that supermassive black holes are being assembled from the earliest times to the present

• However, they do not exhibit the same behavioral patterns as the distant quasars

Quasars are voracious consumers, accreting the material around them at an enormous rate



In contrast, most of the nearby active galaxies discovered by Chandra are more moderate consumers and thus radiate less intensely (perhaps less gas is available to consume?)

A Chandra Revelation

- Although the moderate X-ray sources do not consume as much as the distant quasars do, there are many more of them at recent times

- Thus, taken together, they produce a lot of light

- Active supermassive black holes in the universe have downsized, but as a population, they still provide quite a punch

How does the evolution of accretion onto supermassive black holes compare with the evolution of star formation in galaxies?

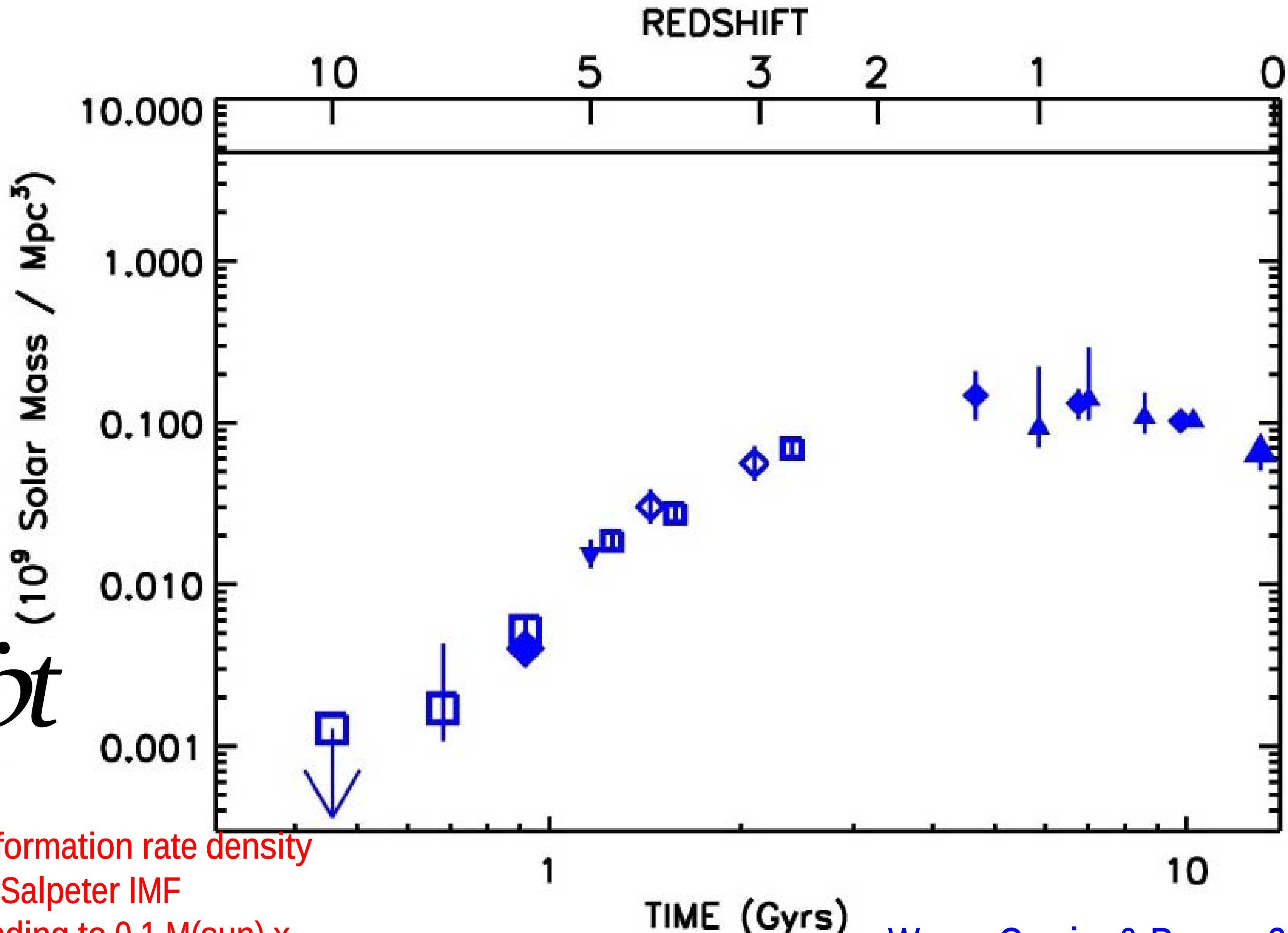
Star Formation History

- We are beginning to understand the broad outline of the star formation history to z=6-7 rather well

- We can map the UV light density to z=7 and even put constraints on it to z~10 using HST

- We know the amount of star formation at these early times is quite small compared to the later star formation

Star formation directly seen in the rest-frame UV



$\dot{\rho} t$

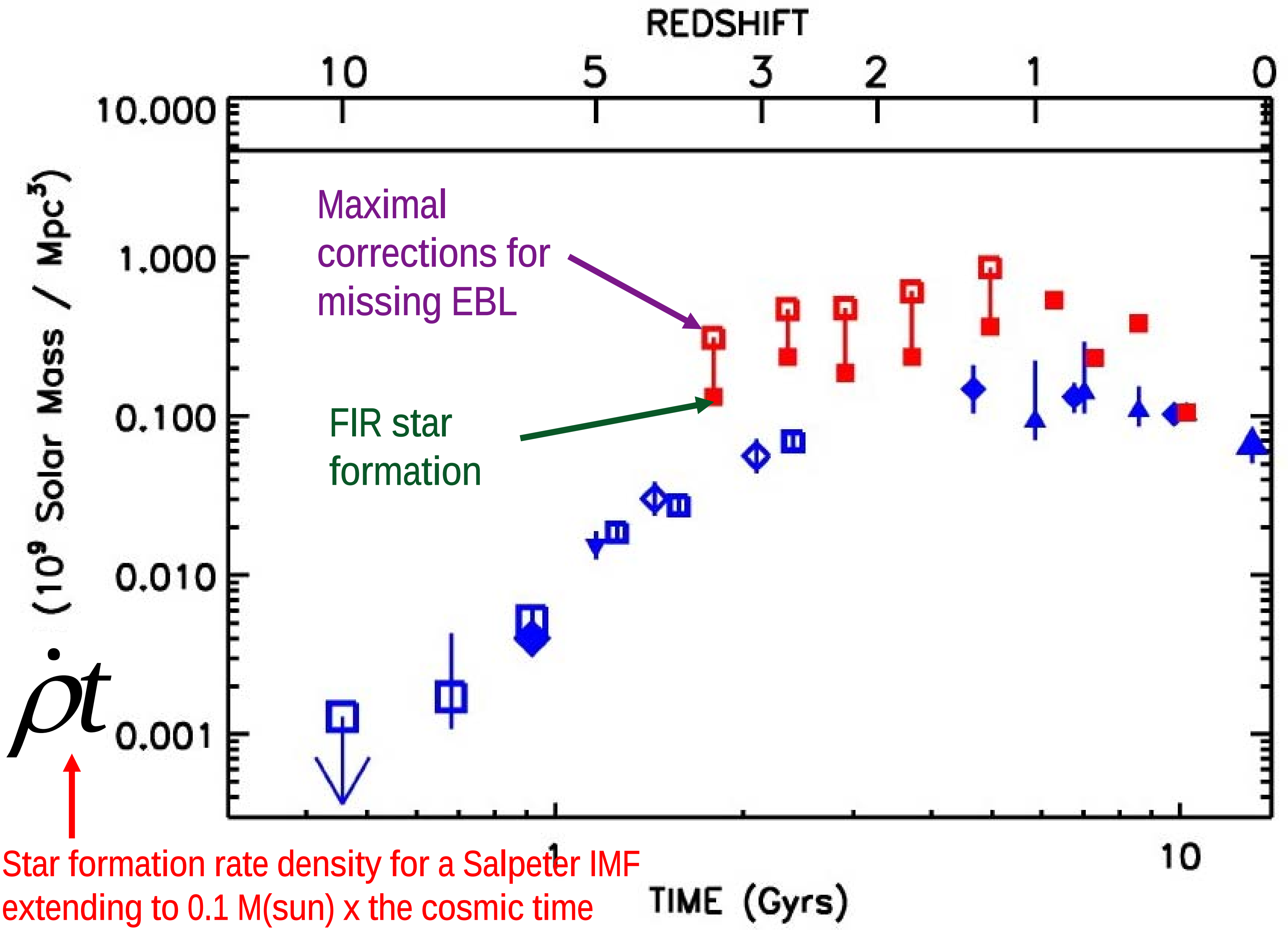
Star formation rate density for a Salpeter IMF extending to 0.1 M(sun) x the cosmic time

Wang, Cowie, & Barger 2006

- However, much of the light from star formation is extinguished by dust

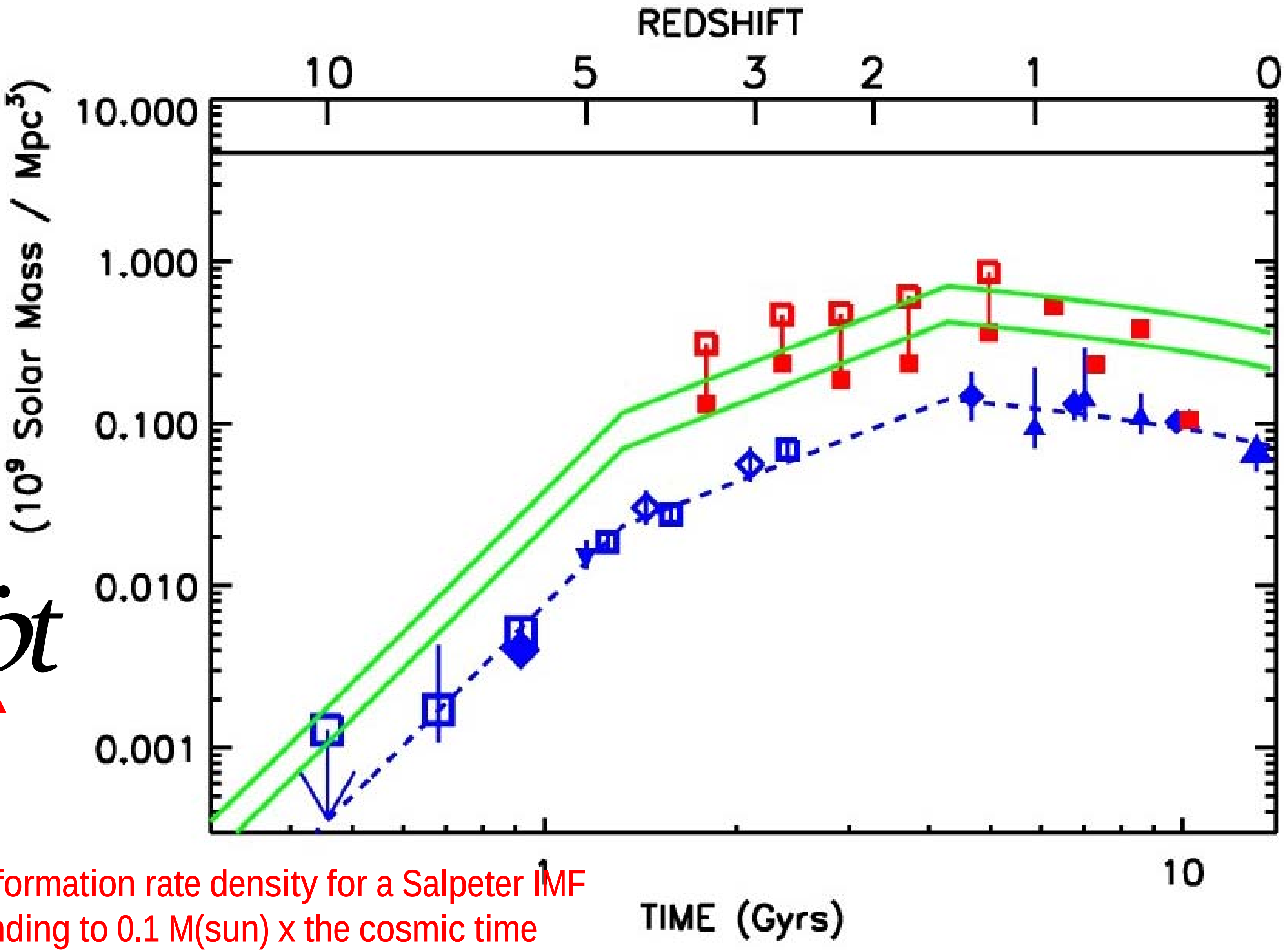
- As we saw earlier, the submm universe looks vastly different than the optical universe, and it is extremely hard to infer from an optical image which sources are going to be submm star formers

Comparison of the FIR-determined star formation with the UV-determined star formation



Star formation rate density for a Salpeter IMF extending to 0.1 M(sun) x the cosmic time

At low redshifts, the correction from the UV is not so large, but at higher redshifts, it is factors of 3-5 (green curves)



$\dot{\rho} t$

Star formation rate density for a Salpeter IMF extending to 0.1 M(sun) x the cosmic time

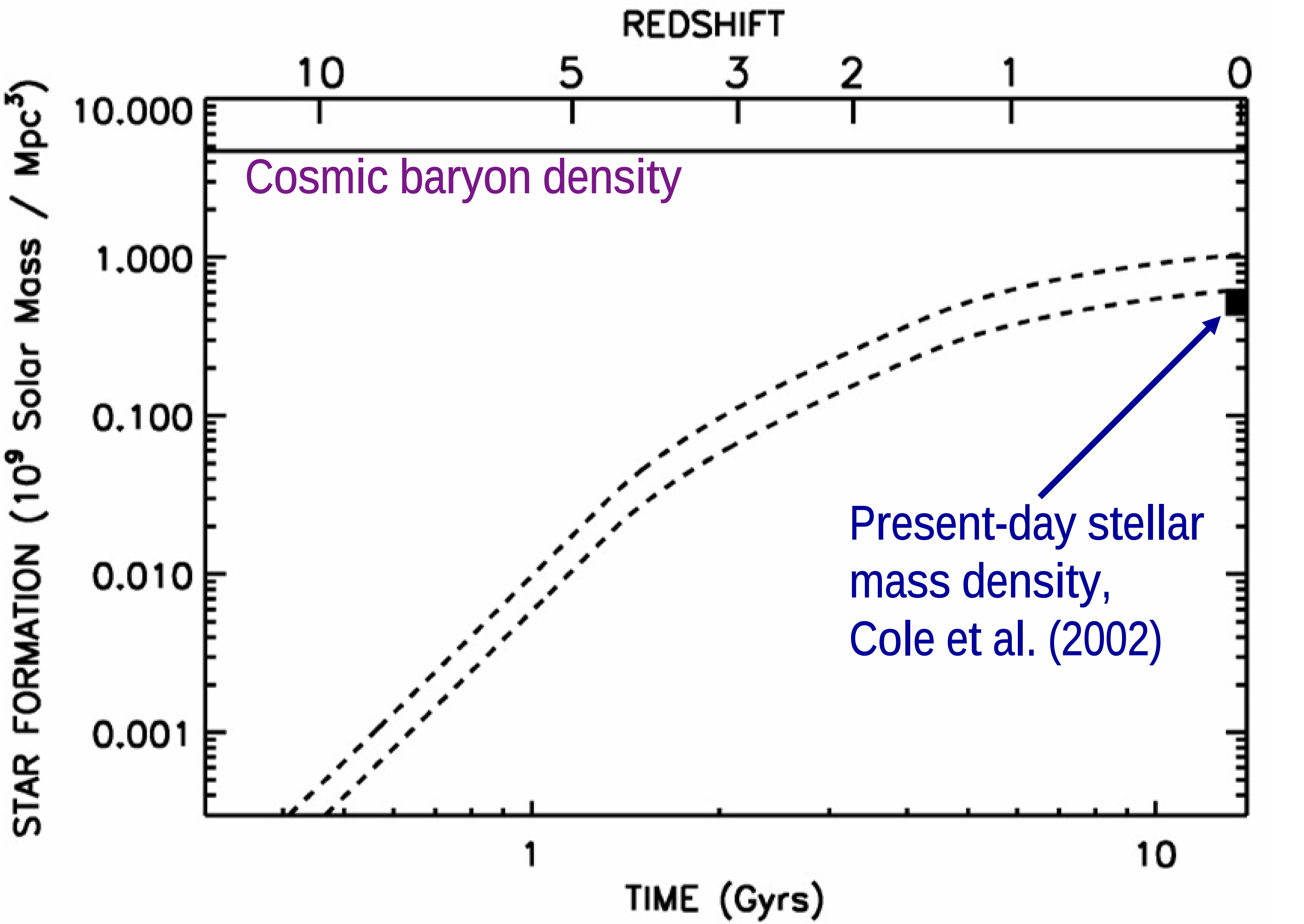
A Parallel History

We see the same behavior as in the accretion history: star formation also transitions from

- Big galaxies, whose light mostly comes out in the far-infrared (e.g., the galaxies detected by SCUBA)

- To a larger number of smaller galaxies at late times, whose star formation light comes out in the ultraviolet and optical

Cumulative star formation history (SFH) shows actual growth of galaxies with time



Now Returning to the Accretion History

Infer present-day supermassive black hole mass density accreted by AGN and compare with locally measured value (Soltan 1982)

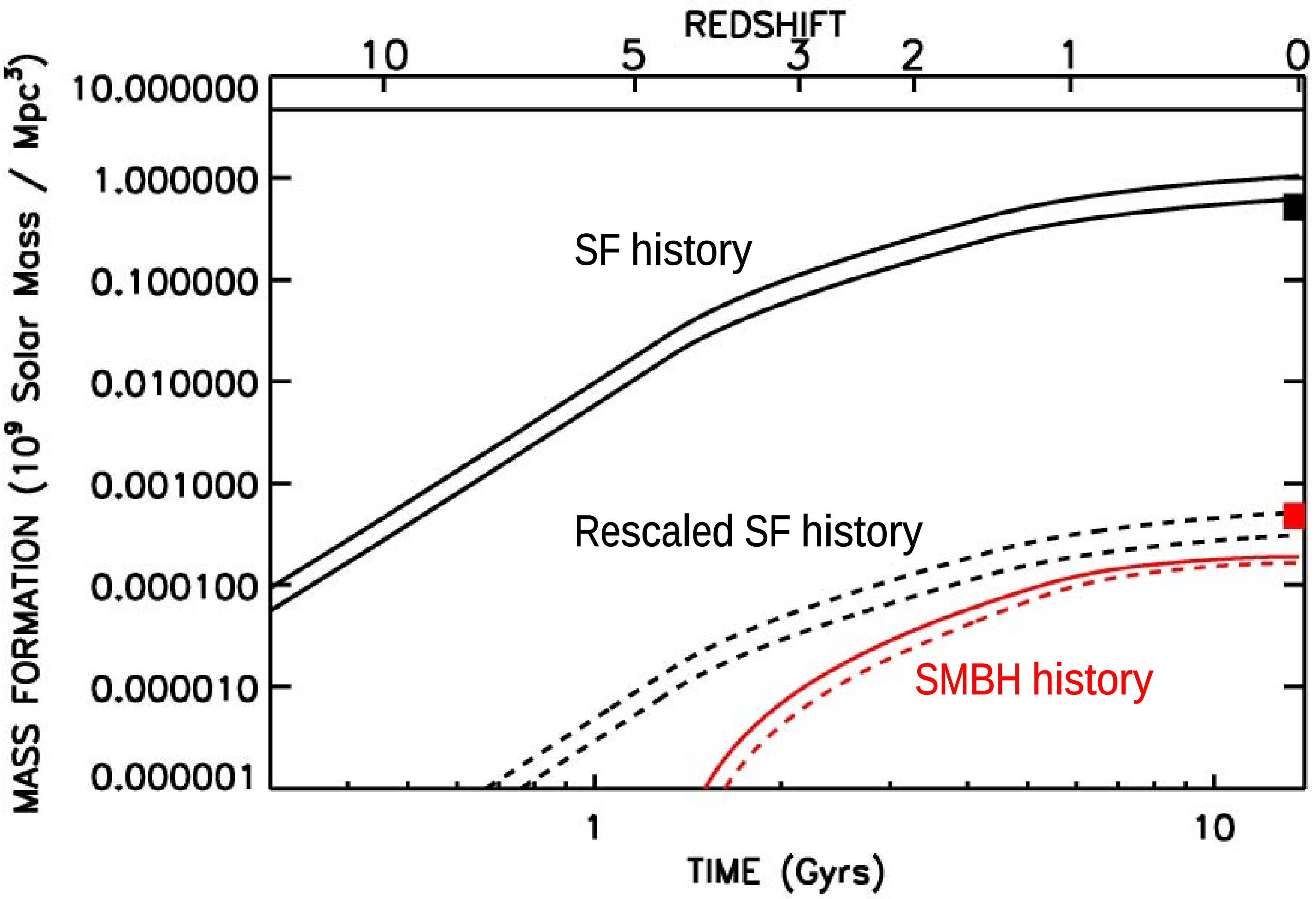
Mass inflow rate ($\dot{M}_{BH}$) related to AGN's L_{BOL} by

$$\epsilon \dot{M}_{BH} = L_{BOL}/c^2$$

[ϵ =radiative efficiency, 0.1 assumed]

(We estimated the bolometric correction from our multiwavelength data and multiplied it by the energy density production rate determined from hard X-rays)

Cumulative growth of supermassive black holes from Chandra (red curve) compared with the cumulative SFH



Both form most of their mass at late times. If AGN feedback has a significant effect, the relative histories can help diagnose that

Summary

The star formation and accretion histories are remarkably similar in many ways:

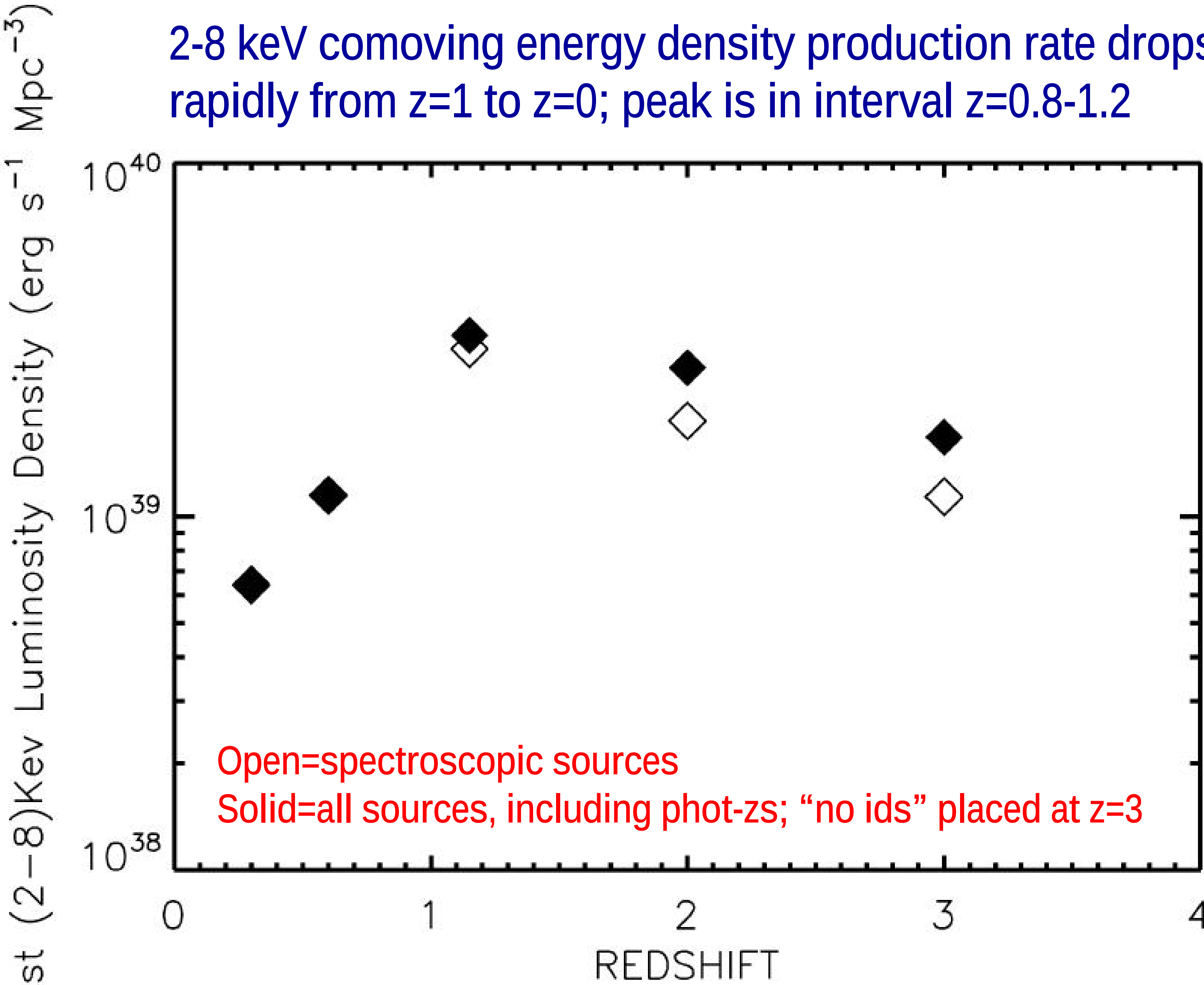
- Both show similar growth w/time, peaking around z=1

- Both show downsizing (Cowie et al. 1996) effects, with the high mass sources forming first, and the lower mass sources persisting to much later times

- Perhaps whatever is quenching the star formation in large galaxies is also switching off the AGN activity (it could be the AGN themselves)

The End

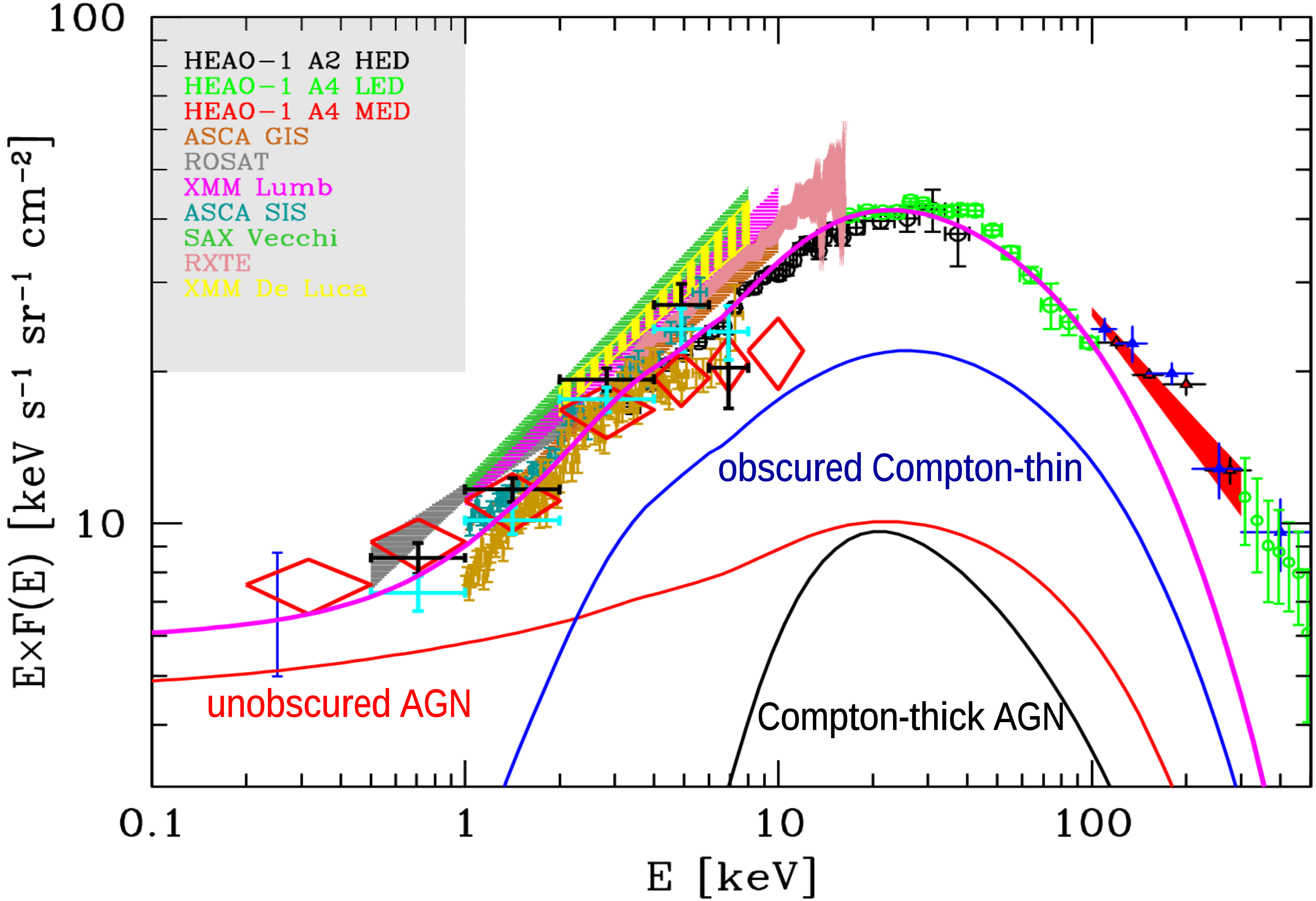
2-8 keV comoving energy density production rate drops rapidly from z=1 to z=0; peak is in interval z=0.8-1.2



At z<1.2, only 1/3 is due to broad-line AGNs

- If we first compare the local supermassive black hole mass density with that accreted from our unobscured AGN alone, we find there is still room for obscured accretion (only ½ to ¼ of the supermassive black hole mass density was fabricated in broad-line AGN)

- In fact, for $\varepsilon \sim 0.1$-0.2, we find reasonable agreement between the local supermassive black hole mass density and that accreted from all of our AGN



Gilli, Comastri, Hasinger 2007