Evolution of BHs - Cosmological evolution of AGN Obscured AGN

2005 ARA&A..43,827 Brandt, W. N.; Hasinger, G. Deep Extragalactic X-Ray Surveys

2004ASSL..308, 53Mushotzky, R. How are AGN Found?

2005AJ....129..578 Barger, A. et al The Cosmic Evolution of Hard X-Ray-selected Active Galactic Nuclei

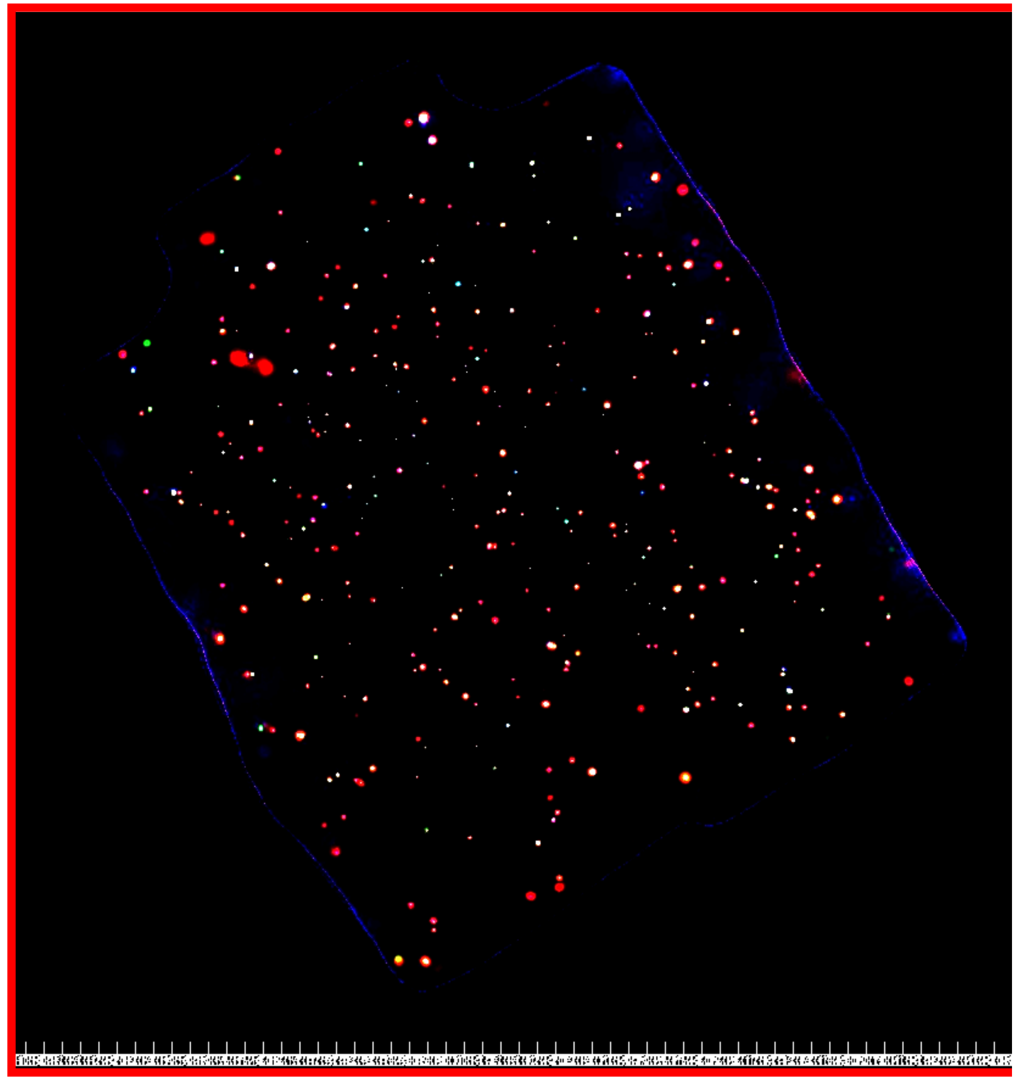
The History of Active Galaxies

- Active Galaxies (AKA quasars, Seyfert galaxies etc) are radiating massive black holes with $L \sim 10^{8}$-$10^{14} L_{sun}$

- The change in the luminosity and number of AGN with time are fundamental to understanding the origin and nature of massive black holes and the creation and evolution of galaxies

- ~10-20% of all energy radiated over the life of the universe comes from AGN- a strong influence on the formation of all structure.

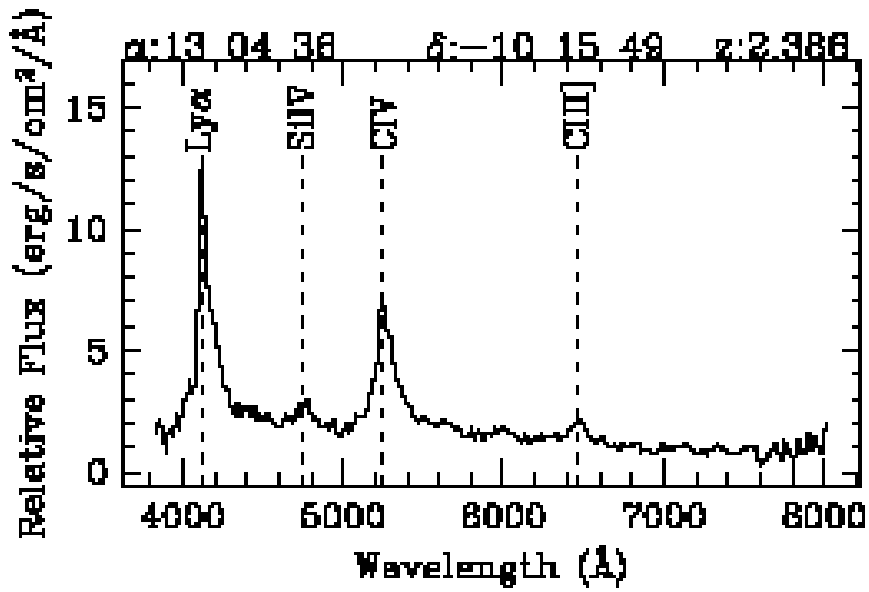
- **X-ray data have revolutionized our understanding of the number, luminosity and evolution of active galaxies from 0<z<4**

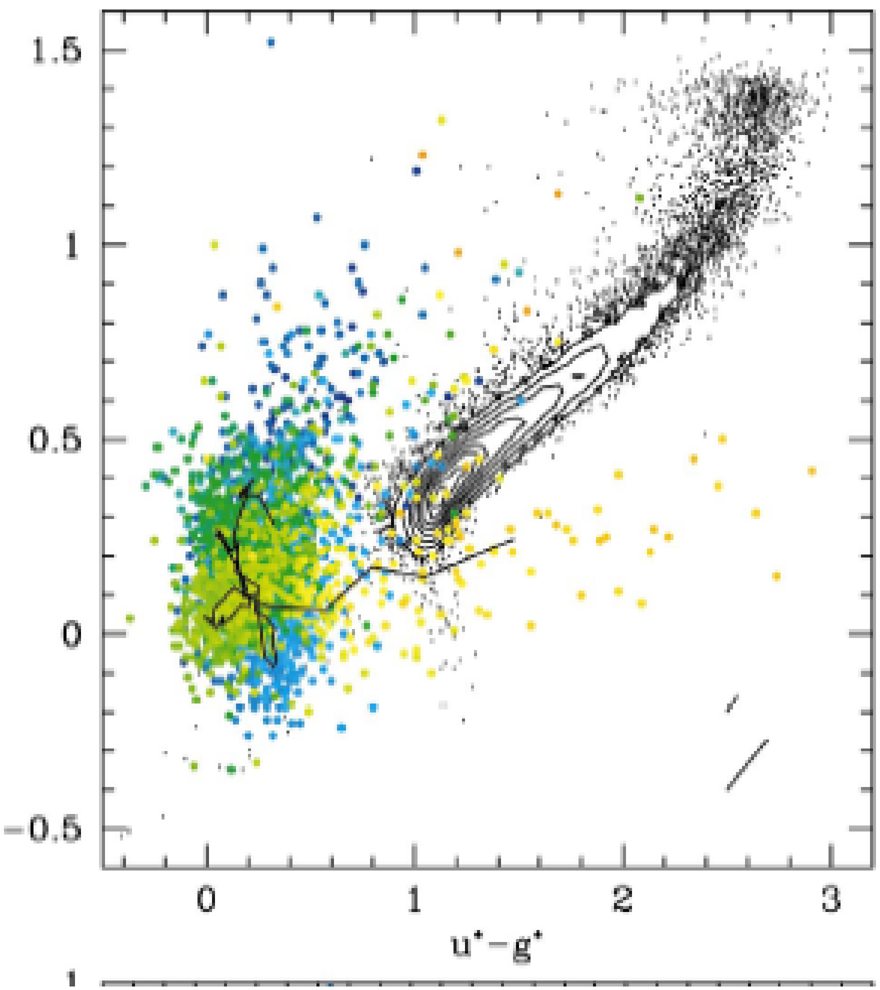


X-ray Color Image (1deg) of the Chandra Large Area X-ray Survey- CLASXS

Optical Properties of AGN

- Strong broad lines of hydrogen, carbon, silicon ….





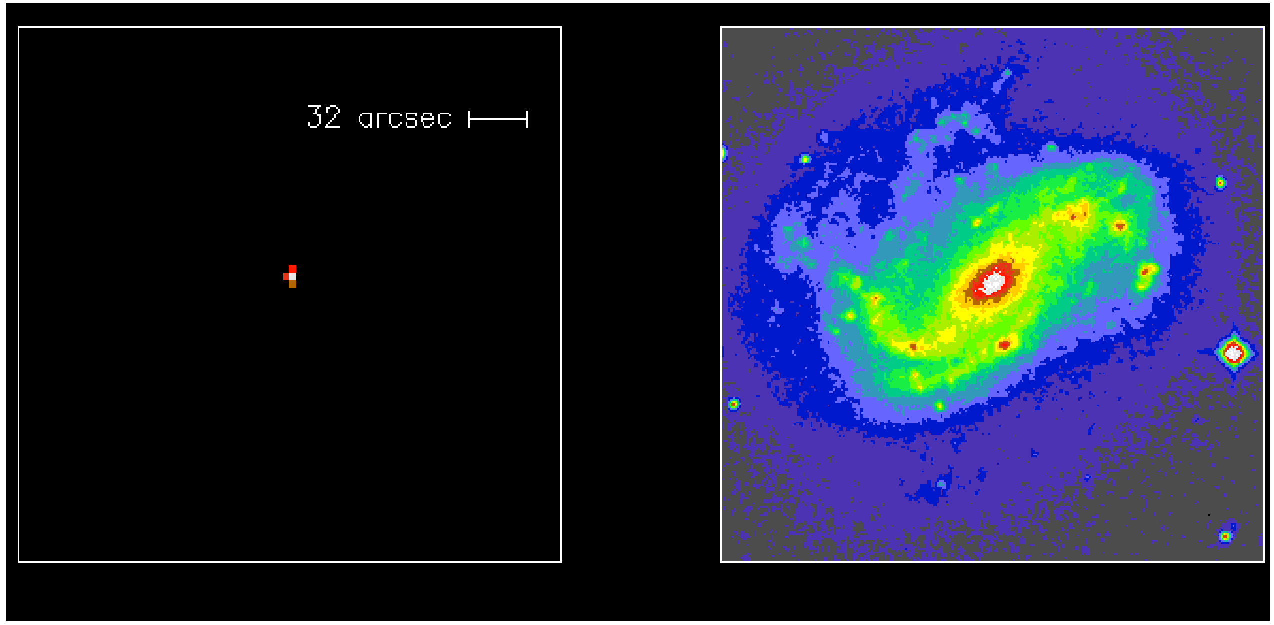
Unusual optical colors (Richards et al SDSS)- **quasars in color**, stars are black

Used since the 1960's to find and study AGN

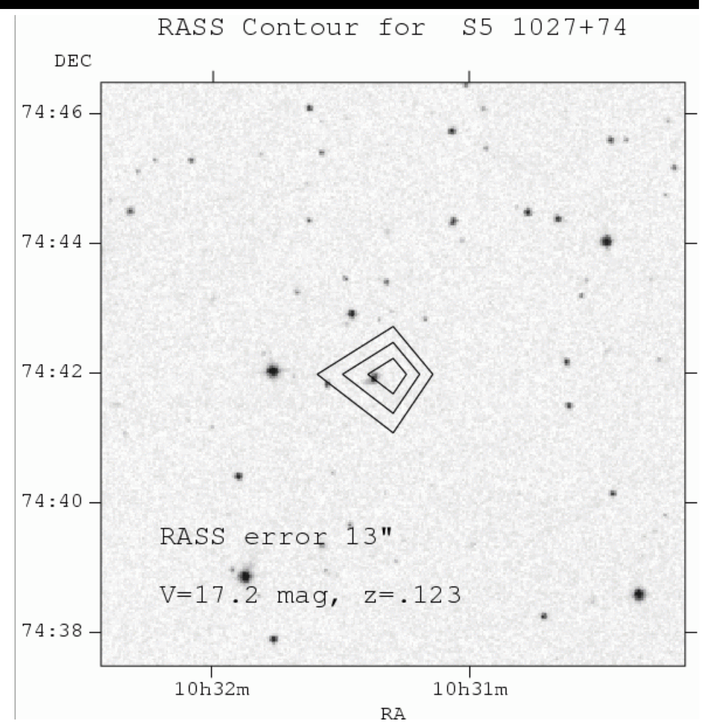
X-ray Selection of Active galaxies

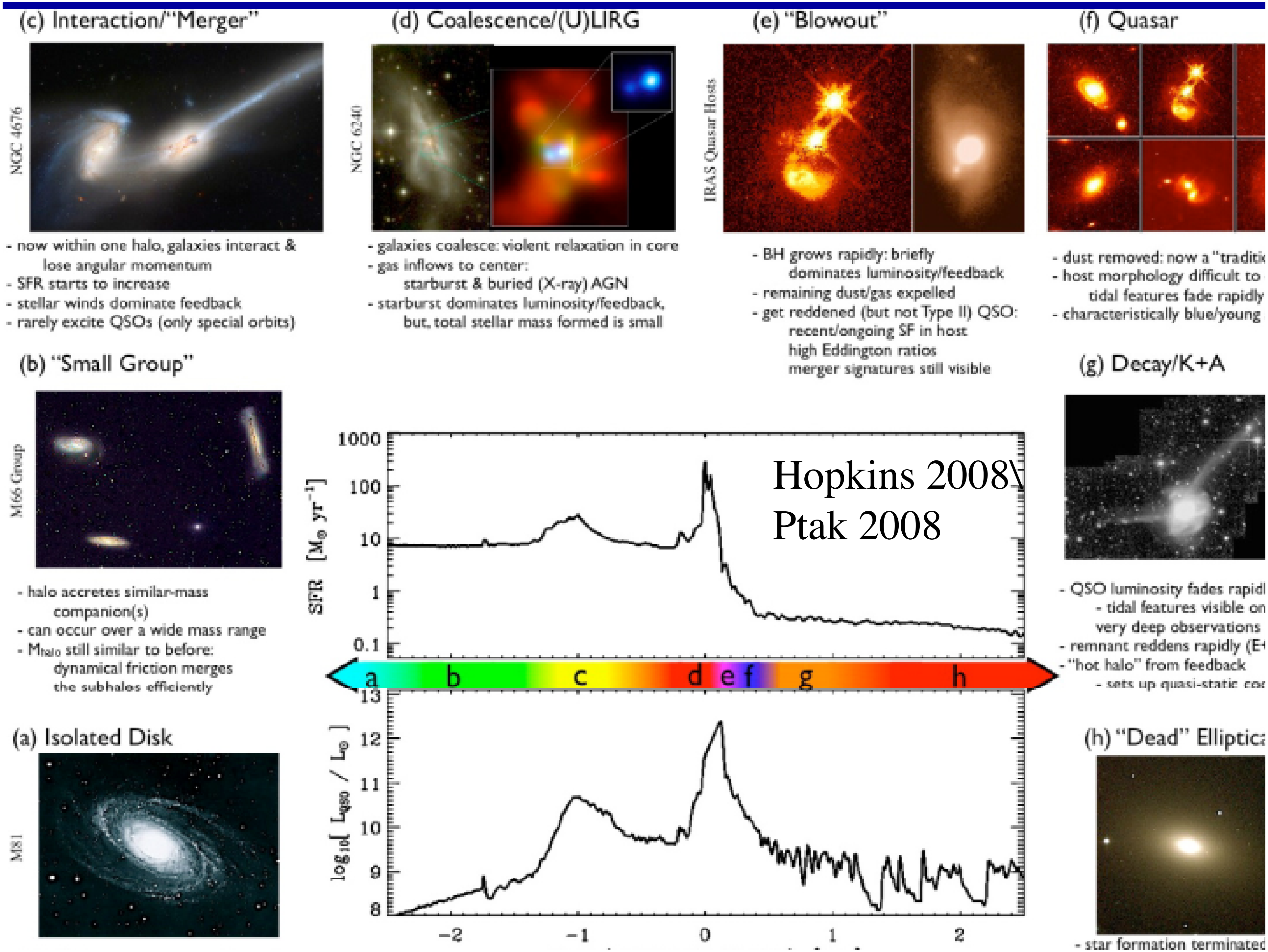
- X-ray and optical image of a nearby AGN NGC4051-
- Note the very high contrast in the x-ray image
- Find x-ray AGN via
  - luminous* pointlike x-ray source in nucleus of galaxy
  - hard x-ray spectrum
  - frequently variable

* Have to distinguish from x-ray binaries located near nucleus



Rosat x-ray all sky survey image overlaid on sky survey image





(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible
(f) Quasar
- dust removed: now a "traditi
- host morphology difficult to tidal features fade rapidly
- characteristically blue/young
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
- QSO luminosity fades rapidl
- tidal features visible on very deep observations
- remnant reddens rapidly (E+
- "hot halo" from feedback
- sets up quasi-static coo
(a) Isolated Disk
M81
(h) "Dead" Elliptica
- star formation terminated
Hopkins 2008\
Ptak 2008
SFR $[M_\odot\ yr^{-1}]$
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}[\ L_{QSO}\ /\ L_\odot\ ]$
13
12
11
10
9
8
−2
−1
0
1
2

History

- It was discovered in the1960-70s (Schmidt 1968-1978) that the number of AGN per unit volume per unit luminosity (f(L), the luminosity function) changed strongly with redshift
  – Schmidt used 'complete' samples (e.g. a flux limited sample in which all the objects were identified and had redshift)-original sample had 33 sources (!)
- AGN were more numerous and luminous in the past with the numbers rising as $(1+z)^N$, N~5
  – based on the log N-log S (number of sources per unit flux vs flux) which has a slope of 2.5 for a Eucledian non-evolving population- in GR the slope is slightly shallower
  – the distribution of V/Vmax (see Schmidt 1977 for definition) which has a value of 0.5 for a non-evolving population does not depend on the cosmological model

number counts - the surface density in the sky of a given class of sources as a function of the limiting flux of the observations. - this is the simplest observational tool that can be used to study the evolution of a sample of objects (and to test cosmological models).

V/V_{max}
Compute for each source in the sample the maxim redshift at which it could be detected given the flux limit of the sample
- the corresponding volume is V_{max}

The actual volume at which the object is detected is V

Distribution of V/V_{max}=1/2 for a uniform sample of objects

Quasars (Schmidt 1978) have V/V_{max}=0.65

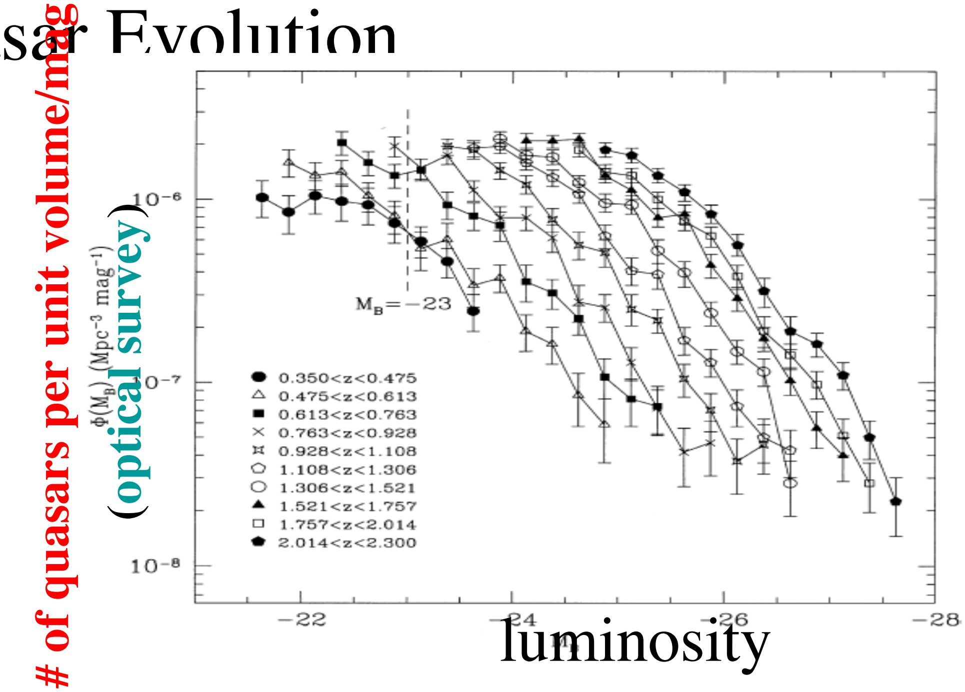
Optical Quasar Evolution

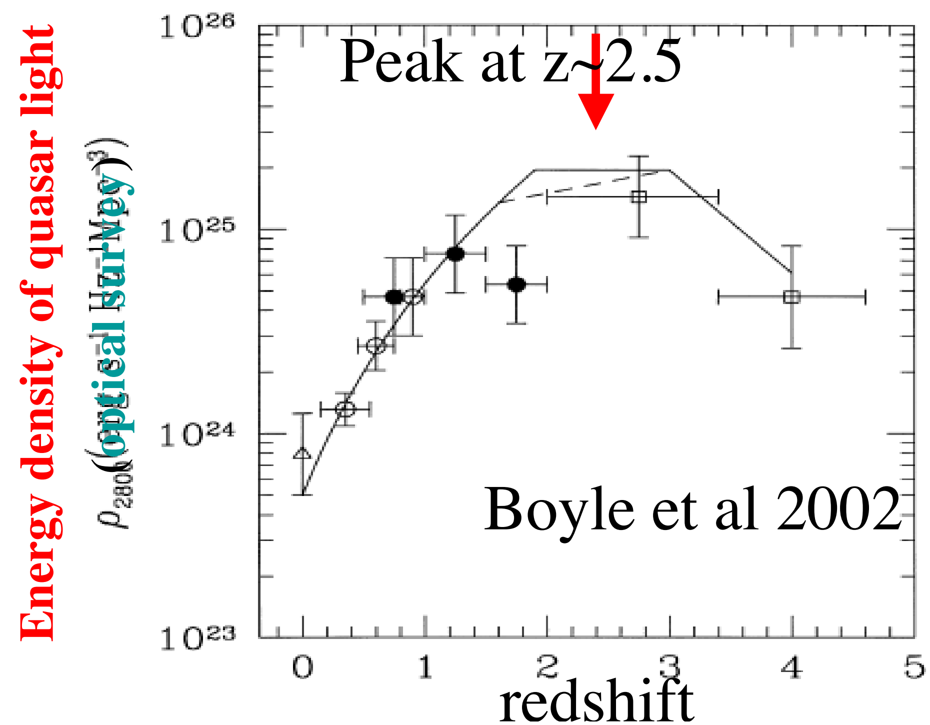
- Historically AGN were found in the optical band by a variety of techniques
  - Presence of strong very broad (1-10,000km/sec) optical and UV emission lines (Broad line objects)
  - The presence of a bright, semi-stellar nucleus (Quasar)
  - Variability of the nucleus
  - “Unusual” colors of the nucleus
  - Optical counterparts to radio source
- Large numbers were found out to z~6
- Since the late 1960’s (Schmidt)

  “well known” that quasars were much more numerous and luminous in the past.

Thus AGN activity was thought to peak in the early universe.

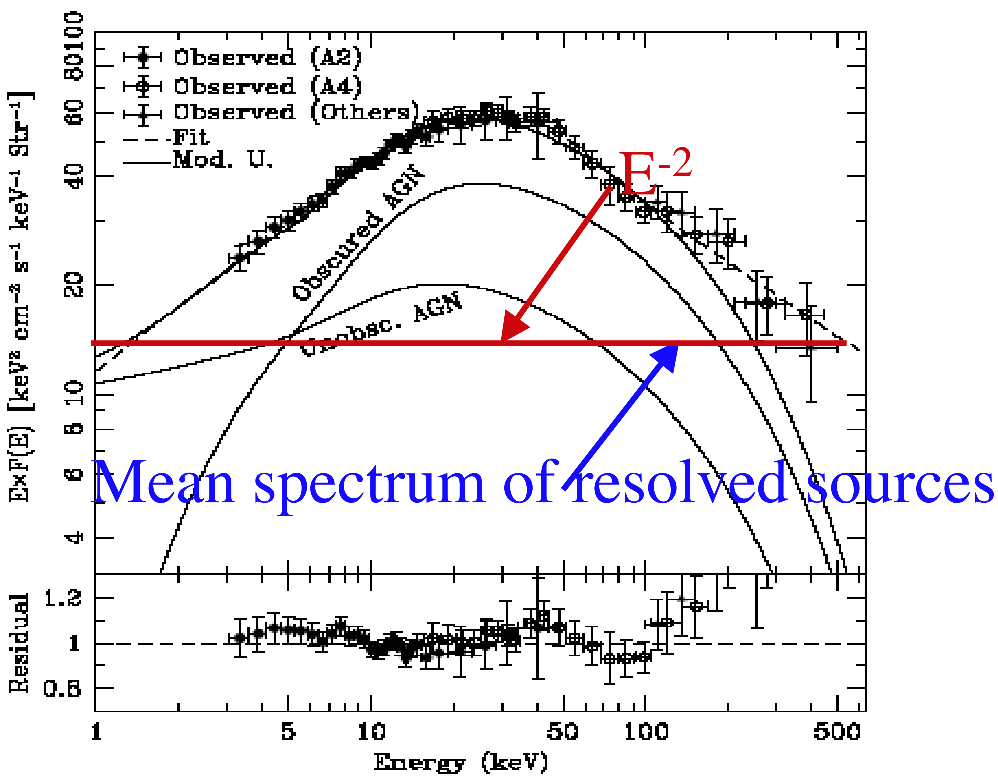
Many theories were developed to explain this.





Origin of X-ray Background

- the background is made up of the superposition of a huge number of (mostly) AGN- **and represents the sum of their output over cosmic time**
- by 1980 it was clear that **the number of objects required to make up the XRB exceeded (in surface density) that of known AGN by >10**
- However the x-ray spectra of the objects detected (clusters of galaxies, active galaxies, blazars etc) showed that none (individually) had the spectrum of the x-ray background-



- this is the so-called "spectral paradox"
- Paradox is resolved by the sum of the (redshifted) spectra of 2 classes of objects in the right mixture
  - broad optical line AGN (Seyfert Is and quasars)
  - absorbed (narrow line) AGN- type II Seyferts

Accretion History of the Universe

Obscuration is a dominant effect - models of the x-ray background and direct observation of ‘hard’ x-ray selected objects (Antonucci and Miller 1994, Fabian 2003)

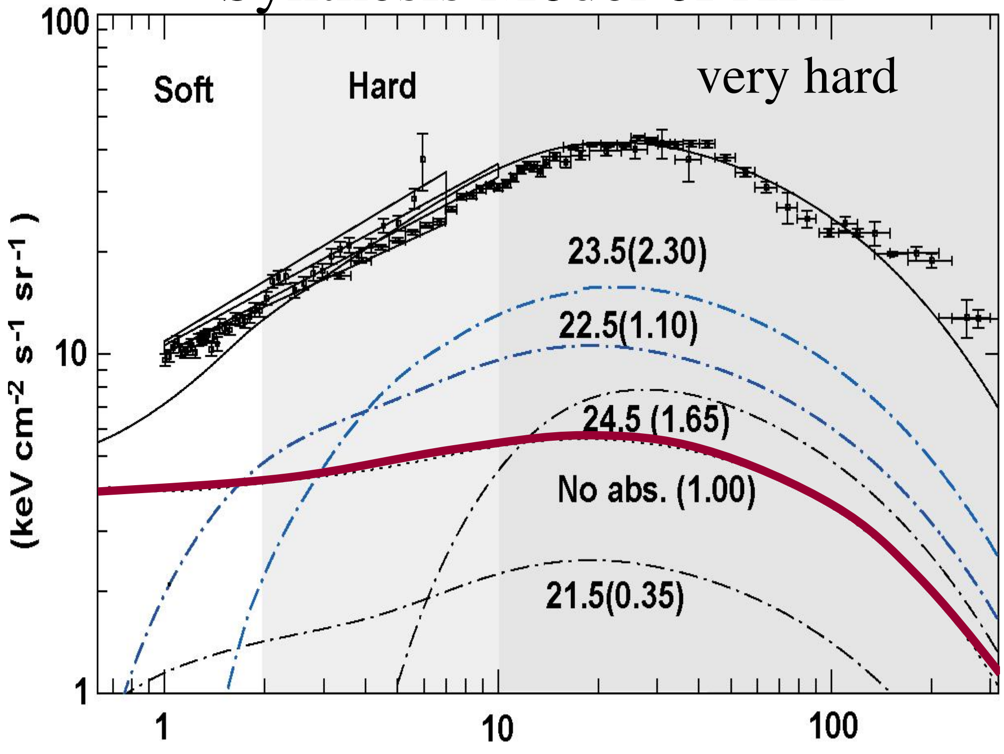
- Major problem with detecting/modeling these sources
  - not “detectable”/recognizable in the optical, soft x-ray; -IR band- correlation with intrinsic properties poorly understood
  - 2-8 keV x-ray spectra do not predict the E>10keV data
  - breakdown of “unified” models
  - ->25% (?) of all energy radiated by AGN is only detectable by E> 10 keV “surveys”

Most of energy in XRB is at <E>~40 keV for which the E<10 keV models have no predictive power

Require hard x-ray observations to properly characterize these objects

•The “best” way to study these objects - a sensitive <u>broad band x-ray mission</u>” Astro-H

Synthesis Model of XRB



Status in 2000

- Large optical surveys (Boyle et al 2000) found that $\phi(L)$ can be described by 'luminosity' evolution)
- e.g. $L(z)=L(0)\exp(k\tau)$
  - where τ is lookback time and k is a constant

$\phi(L)$ has the form

$\phi(L,z)=\phi(L)/\{(L/L^*)^a+(L/L^*)^b\}$

where a and b are constants and L^* is a fiducial luminosity

e.g. a broken power law such that the slope is flat at low L and steep at high L with a 'break' at L^*

The luminosity function is the number of AGN per unit comoving volume, per unit luminosity:

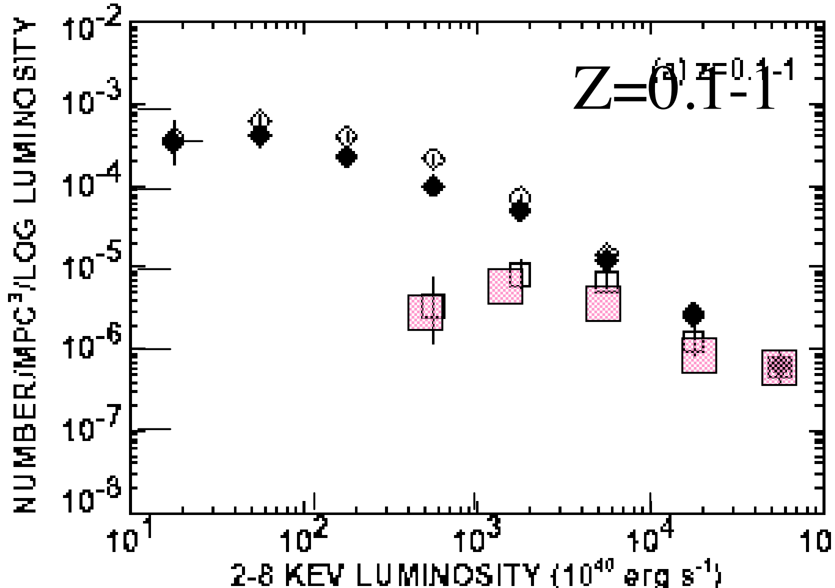
$$\frac{d\Phi(L_X,z)}{dLogL_X}=\frac{dN(L_X,z)}{dV_c\,dLogL_X}$$

However a large fraction of AGN are missed in optical surveys

Whats Missing in Optical Surveys?

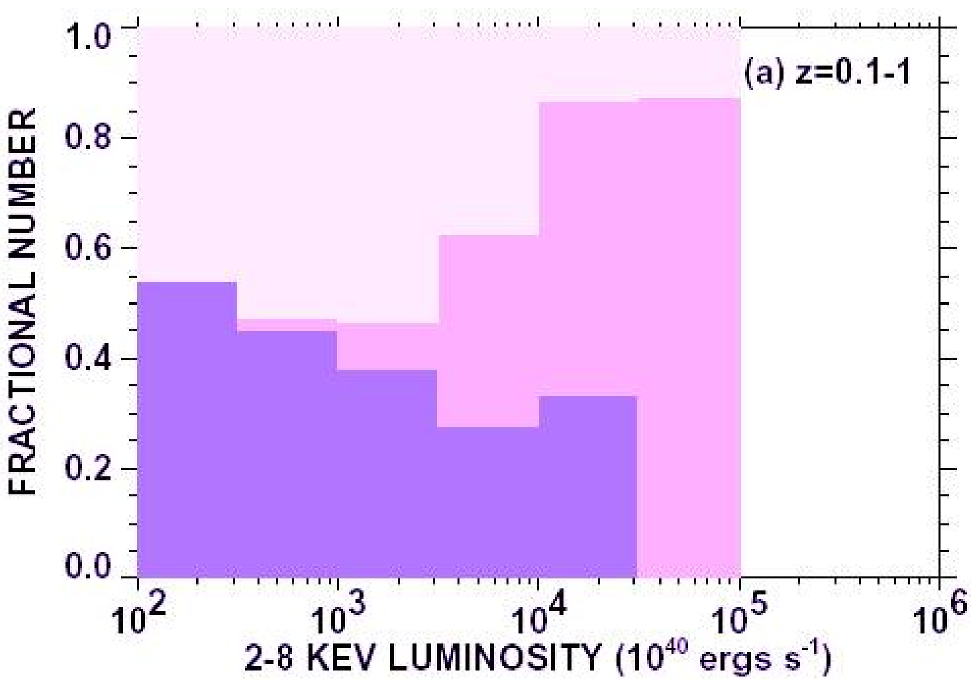
- Chandra/XMM observations show that number of x-ray selected AGN **exceeds optically selected ones by ~7:1**
- X-ray selected objects have very different properties than "optically" selected AGN
- most luminous AGN have broad optical lines, most lower luminosity AGN do not have obvious optical AGN signatures- violation of unified model

Most AGN are "invisible" to optical searches



Z=0.1-1

L(x)x10^{40} ergs/sec



Objects with broad optical lines ("optical AGN")

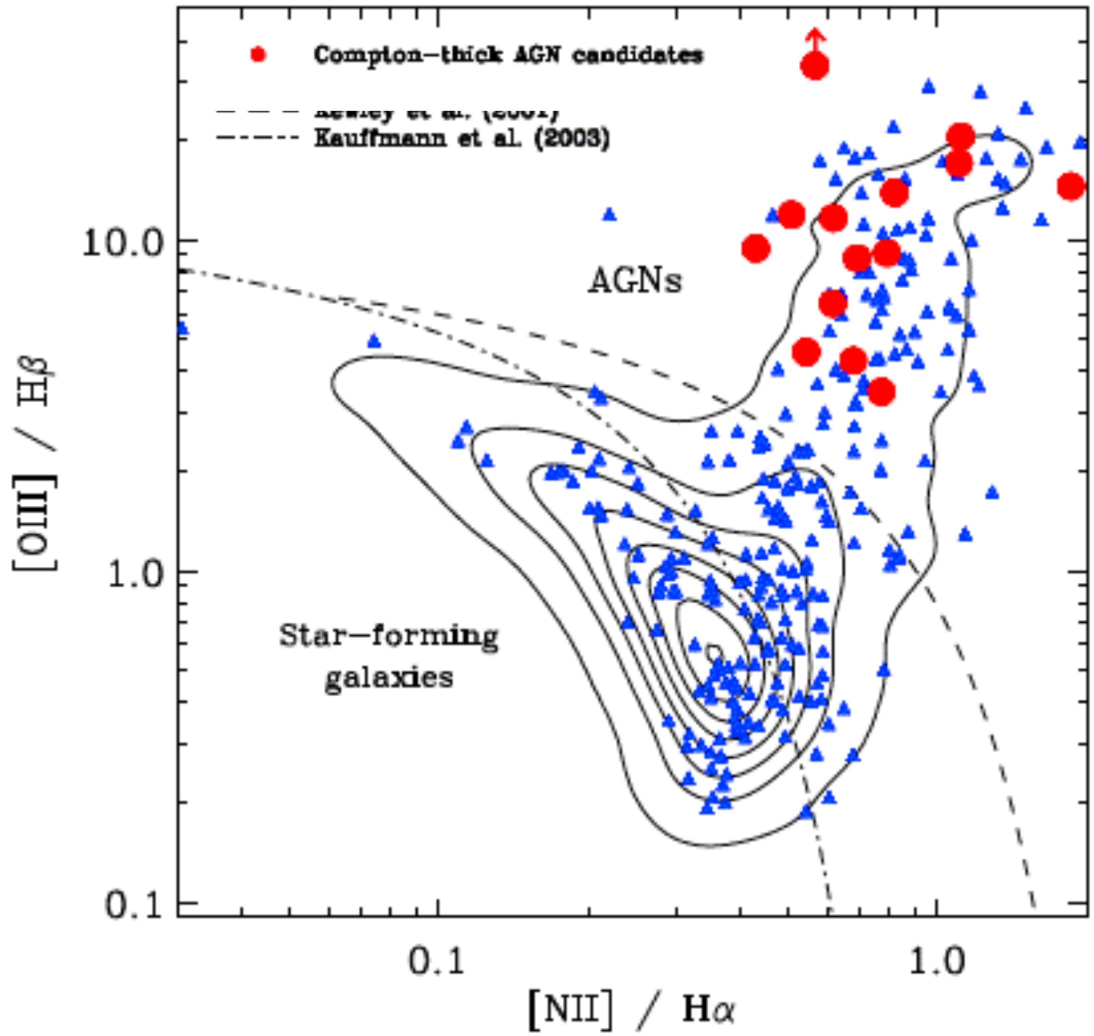
X-ray selected objects

AGN without strong lines

Steffen et al 2003

Comparison of Optical and X-ray AGN Selection

- Best" way to find AGN: classical optical line ratio indicators miss (even at low z) many AGN (>1/2)-same with IR
- The broad properties of x-ray selected AGN are representative of the total population (Hickox et al 2009)- IR selected AGN tend to have high Eddington ratios and small masses, radio selected high black hole masses , low Eddington ratios



x-ray detected AGN

Goulding et al 2010

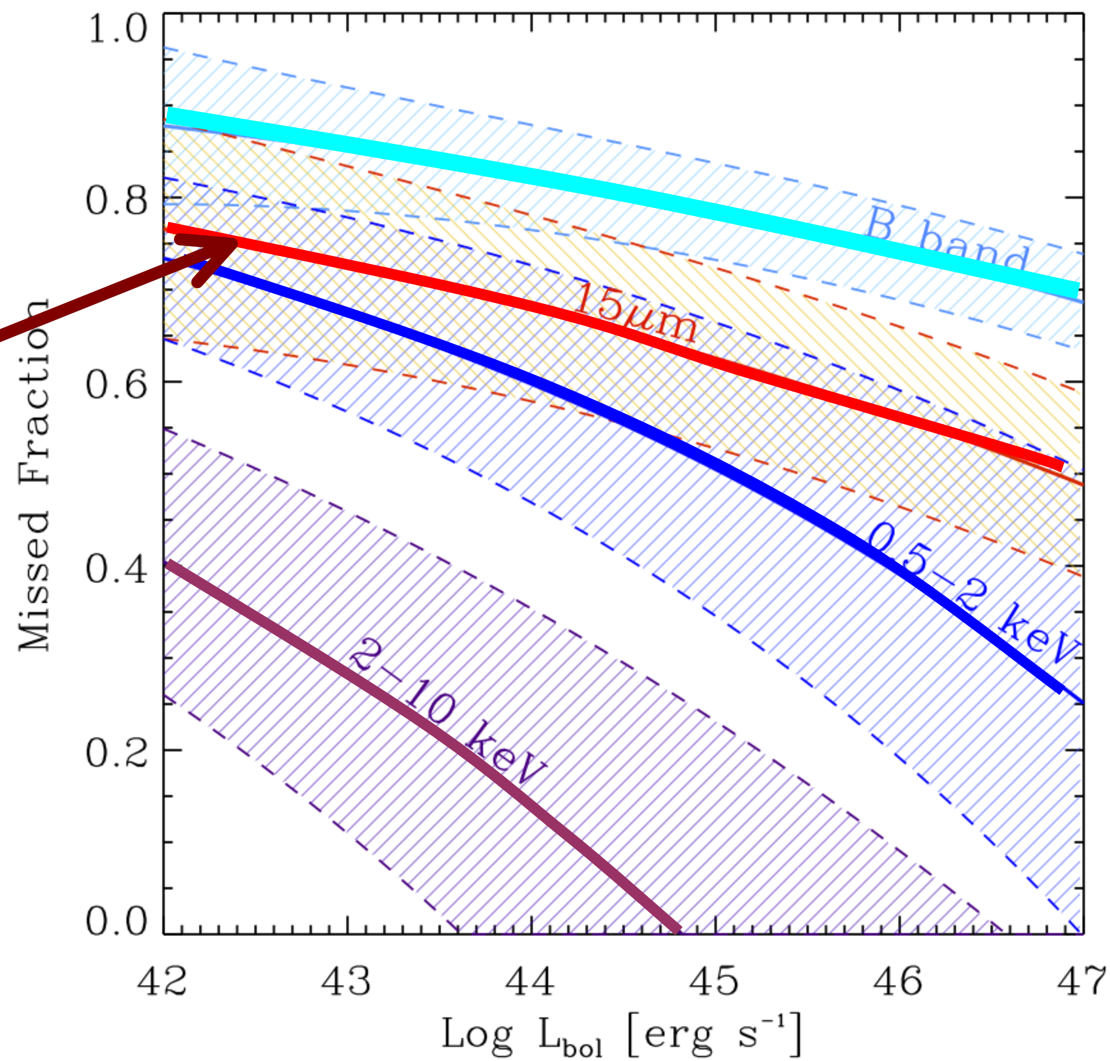
Trouille and Barger 2010

How are AGN Selected

Hard X-rays provide the most complete census of AGN activity (Merloni 2011)

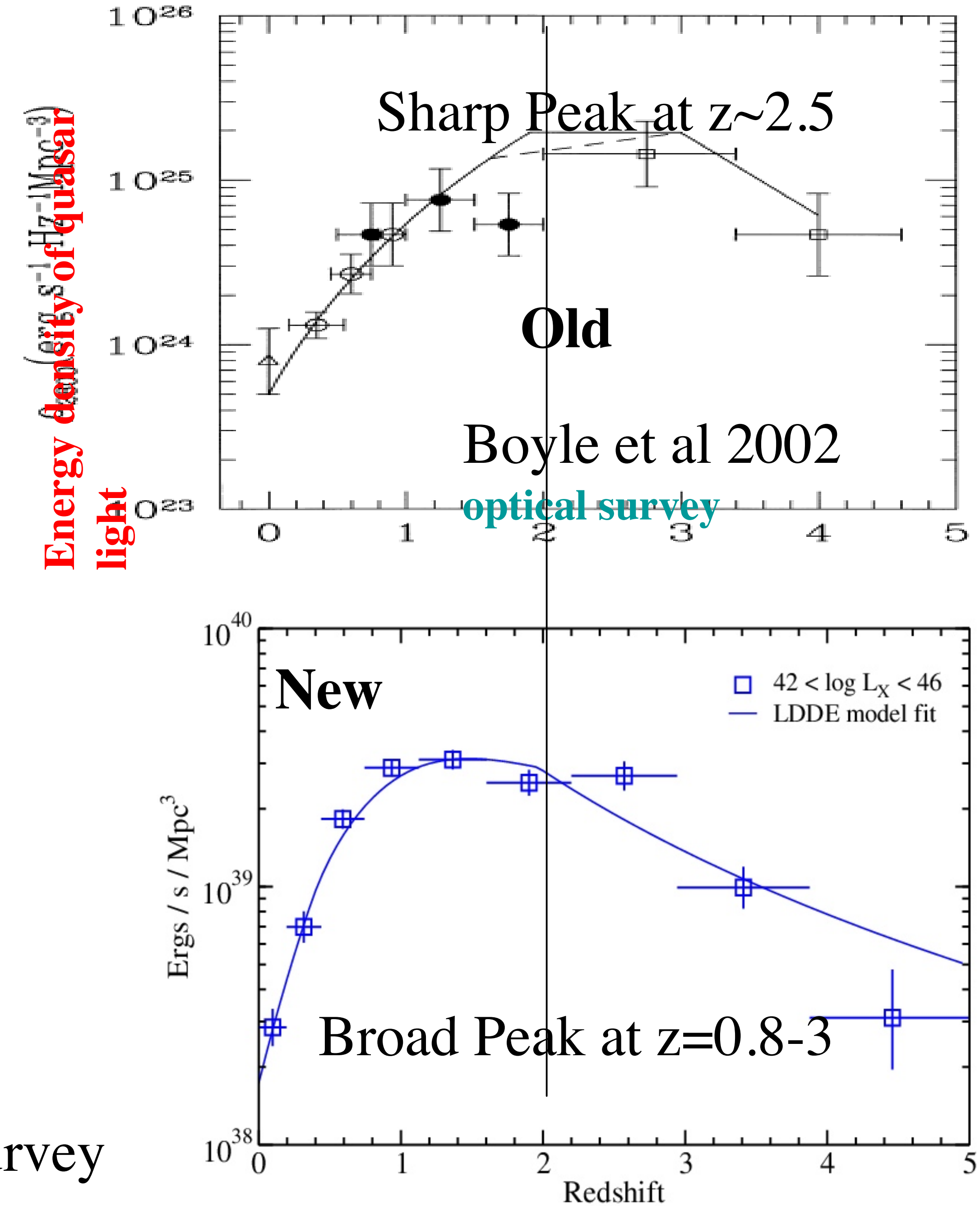
the fraction of AGN that are missed in a survey in a given band as a function of the energy range observed

The fraction missed in the 10-30 keV band is even lower



Change in Our Understanding due to X-ra Surveys

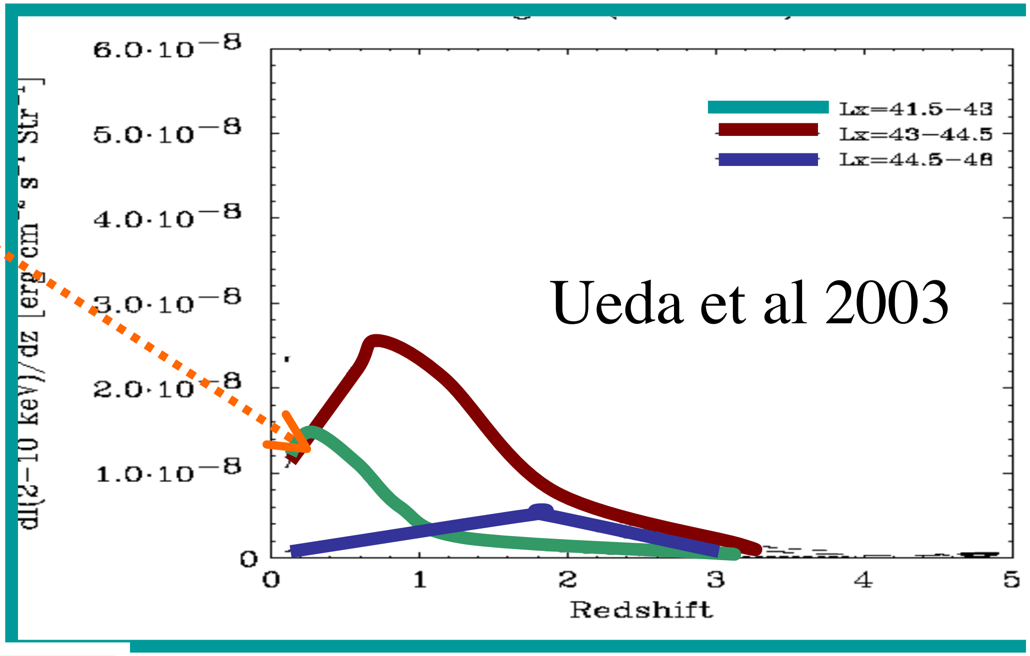
- AGN Evolution
- Discovery that most of the AGN in the universe are obscured
- Strong indications that AGN have had a major influence on the formation and evolution of structure

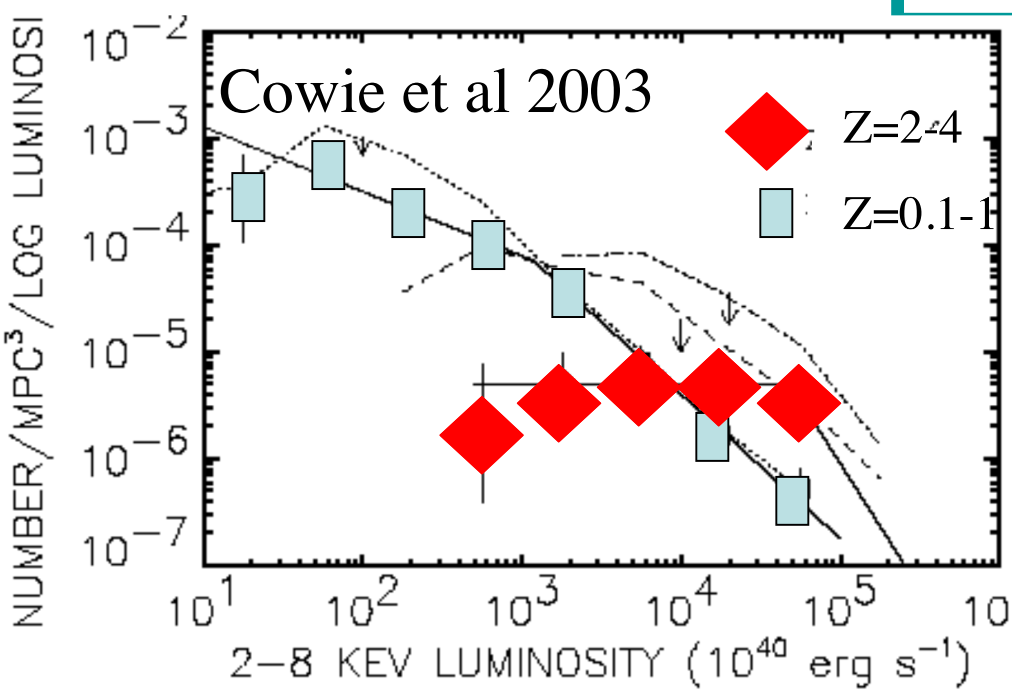


Yencho et al 2009- xray survey

Discovery of "Backwards" Evolution of X-ray AGN

- In x-ray samples the low luminosity objects decrease in number at higher redshift
- The medium luminosity objects increase from z~0 to z~1 and then decrease at higher redshift
- The high luminosity objects behave like optically selected AGN and increase out to z~2



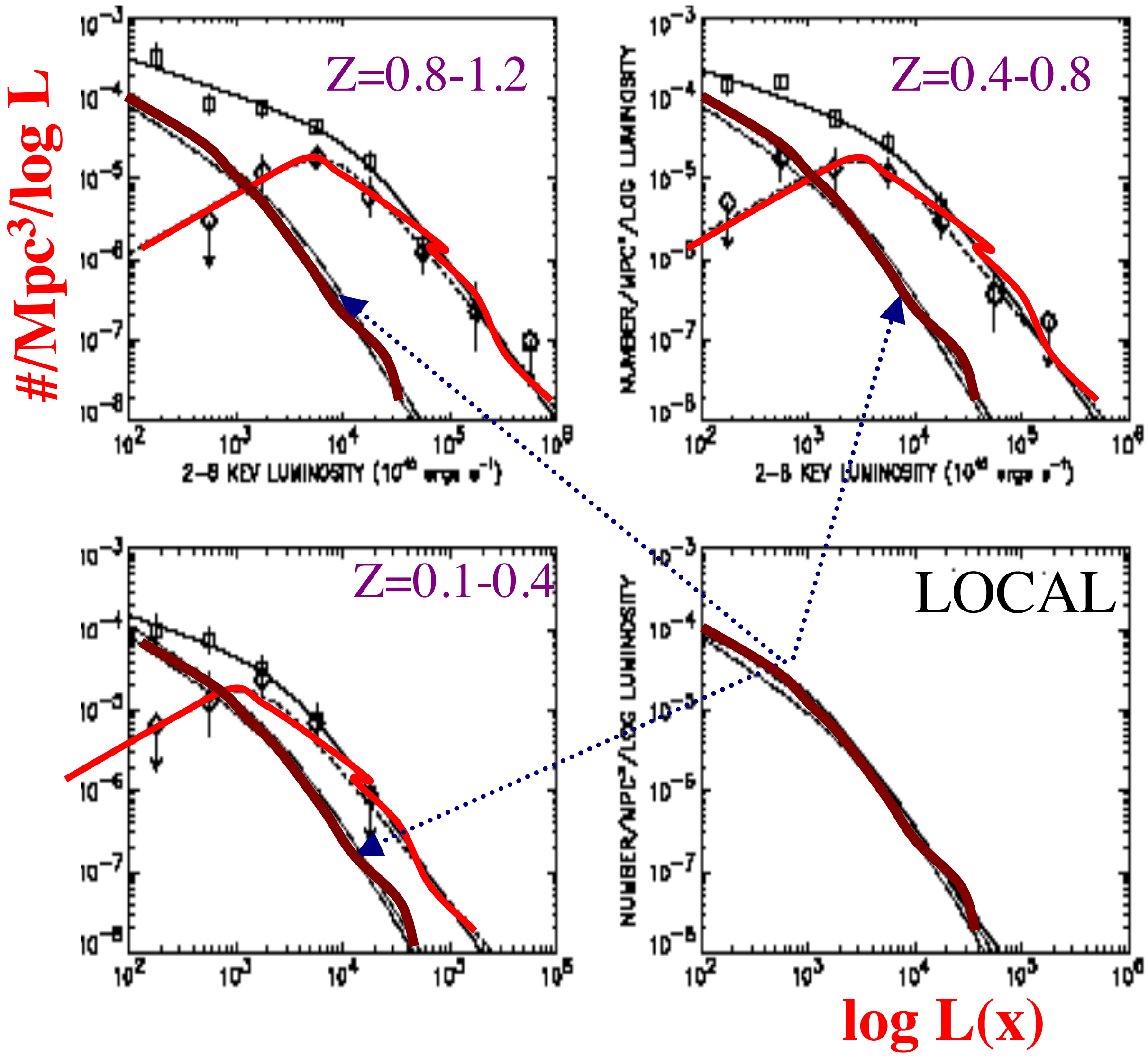


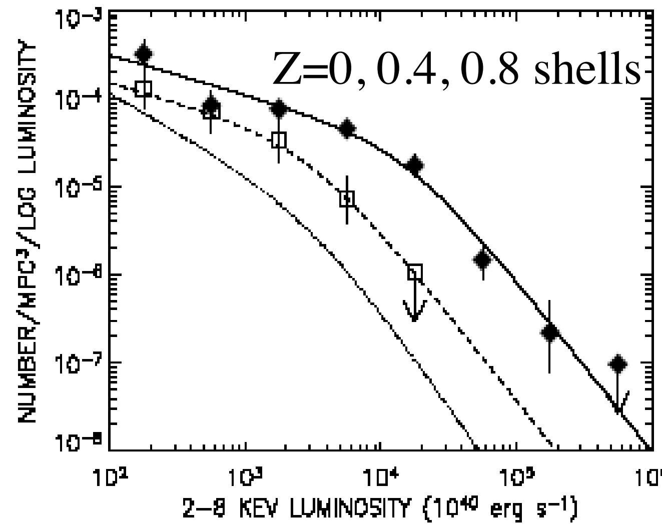
The x-ray sources represent **almost all of the AGN in the universe**

- all optically selected broad line AGN in 2 deep well studied fields are also are x-ray detected

The Evolution of the 2-8 keV Luminosity Function for z<1

Barger et al 2005





ame 2 − 8 keV luminosity function per unit logarithmic luminosity a
Revnitsev's 2004 *RXTE* analysis), $z = 0.2 - 0.4$ *(open squares)*, and z
curve is a double power law fit to the $z = 0.8 - 1.2$ HXLF. Dashed cu
n model where only the characteristic luminosity evolves, in this case
nodel also fits the local *RXTE* determination.

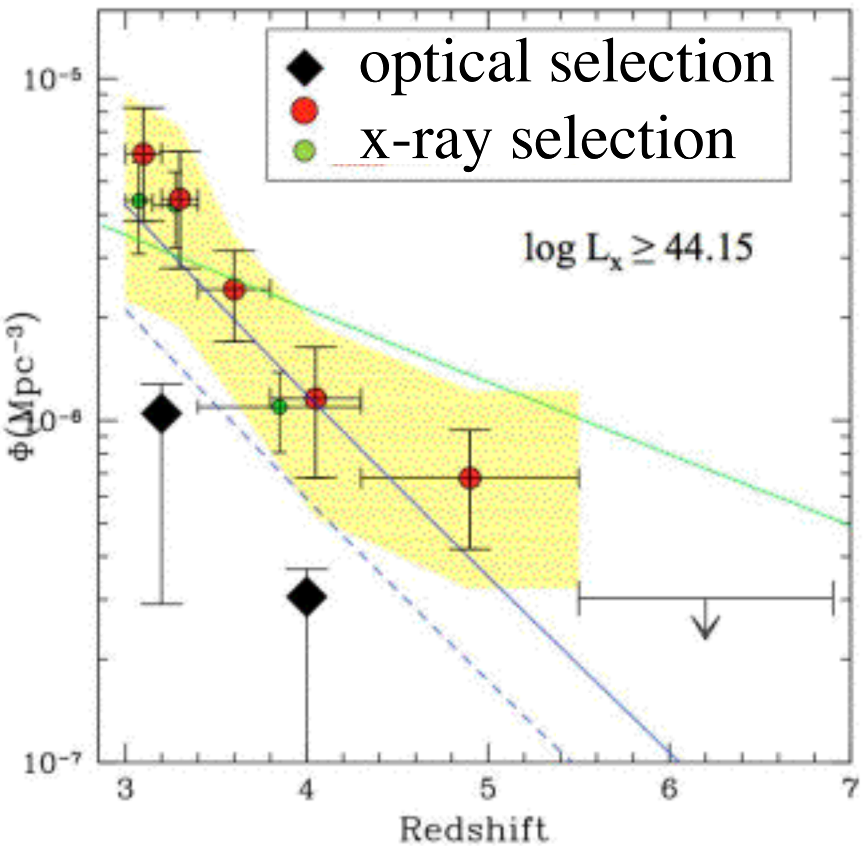
At z<1 the evolution of the total AGN population is consistent with pure luminosity evolution $L(x) \sim (1+z)^{3.5}$

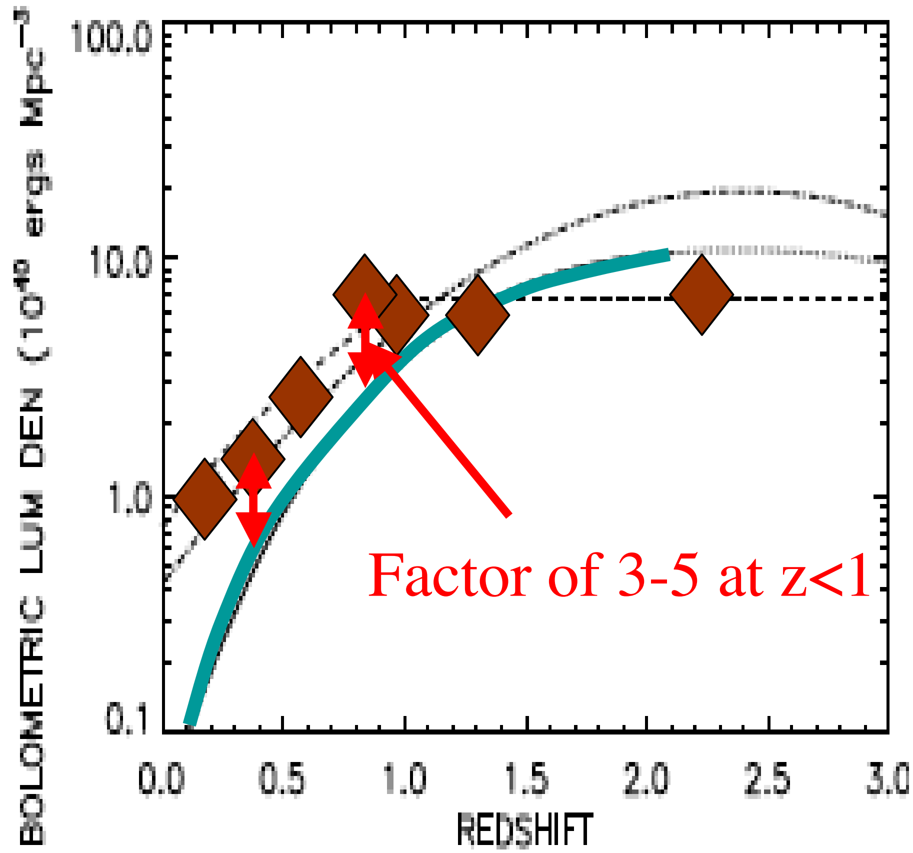
At z>1 the evolution radically changes

Red= broad line objects only
Black= all objects

Comparison of Energy Densities and Evolution

- **Optical surveys 'miss' ~75% of the energy emitted by AGN at z< 2;**
- **1/3 of energy density in broad line AGN and 1/2 in objects of luminosity <8x10[43] ergs/sec which are mostly narrow or no-line objects.**





Barger et al 2004

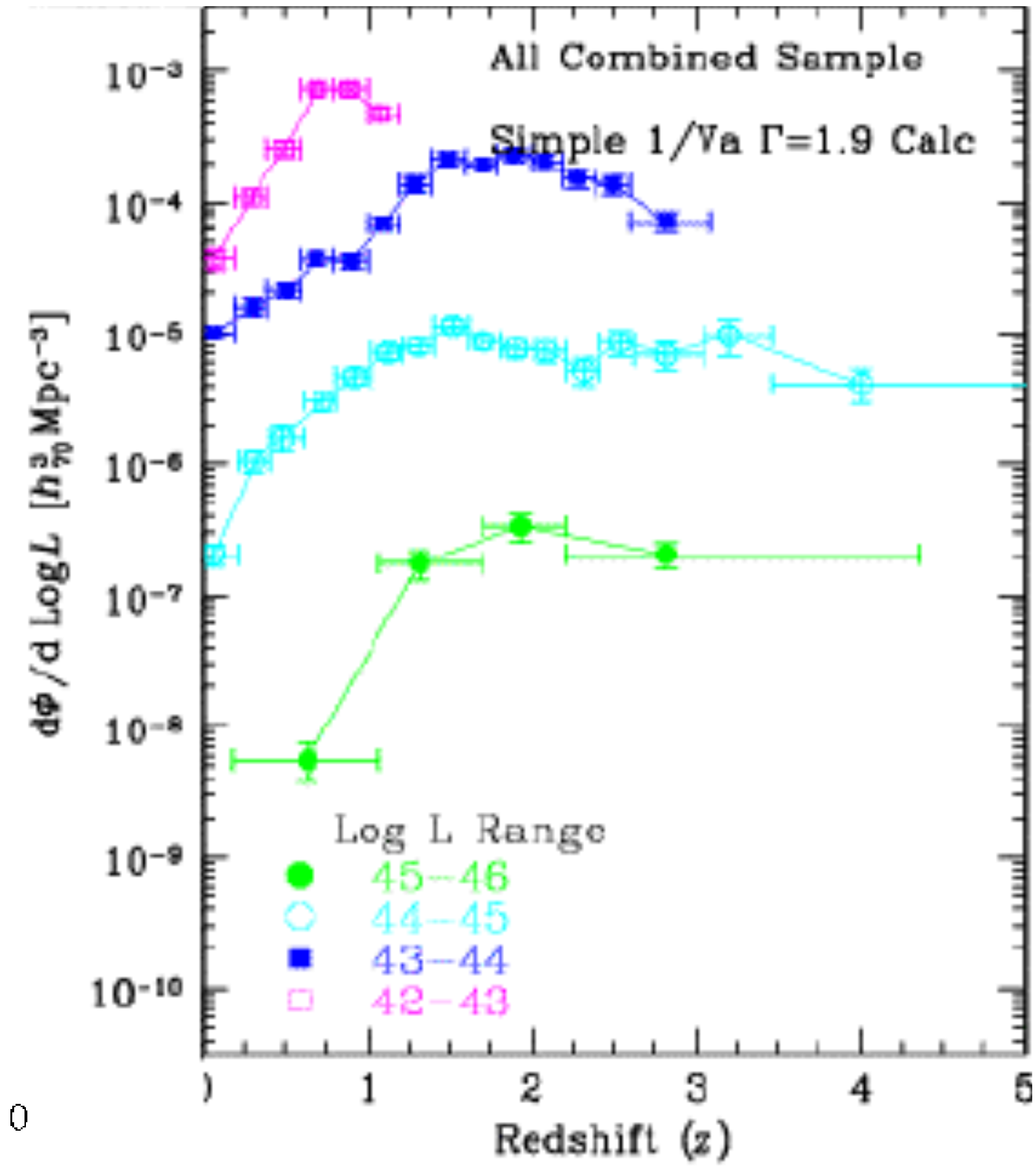
Energy densities from AGN from Optical (—) x-ray (◆) surveys

Downsizing

- The luminosity functions do not have the same shape or evolution as the 2000 optical data sets.
- High Luminosity objects evolve first, low L later

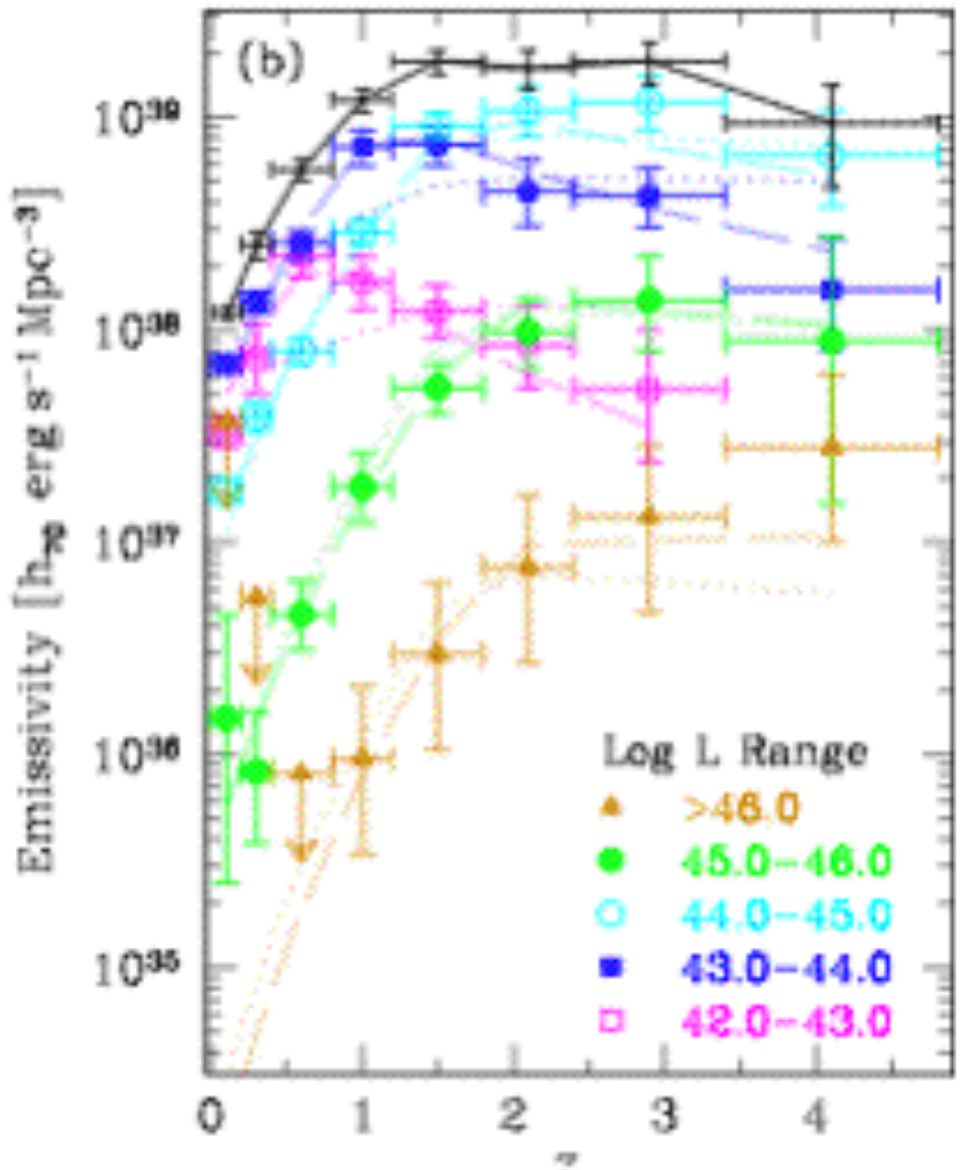
X-rays (2-10 keV)

Miyaji et al. in prep.



When Does the Energy Get Emitted

- Most of the x-ray energy emitted by AGN is emitted between z~1-3 (Hasinger et al 2005)
- The relative contributions of different luminosity AGN changes greatly with redshift with more luminous AGN being more important at higher redshift



Why Backward??

- Cold Dark Matter (CDM) theory of structure formation says that
  - small things form first
  - merge together over time to form big things
- Expect massive (luminous)BHs to appear later in the universe than smaller mass BHs

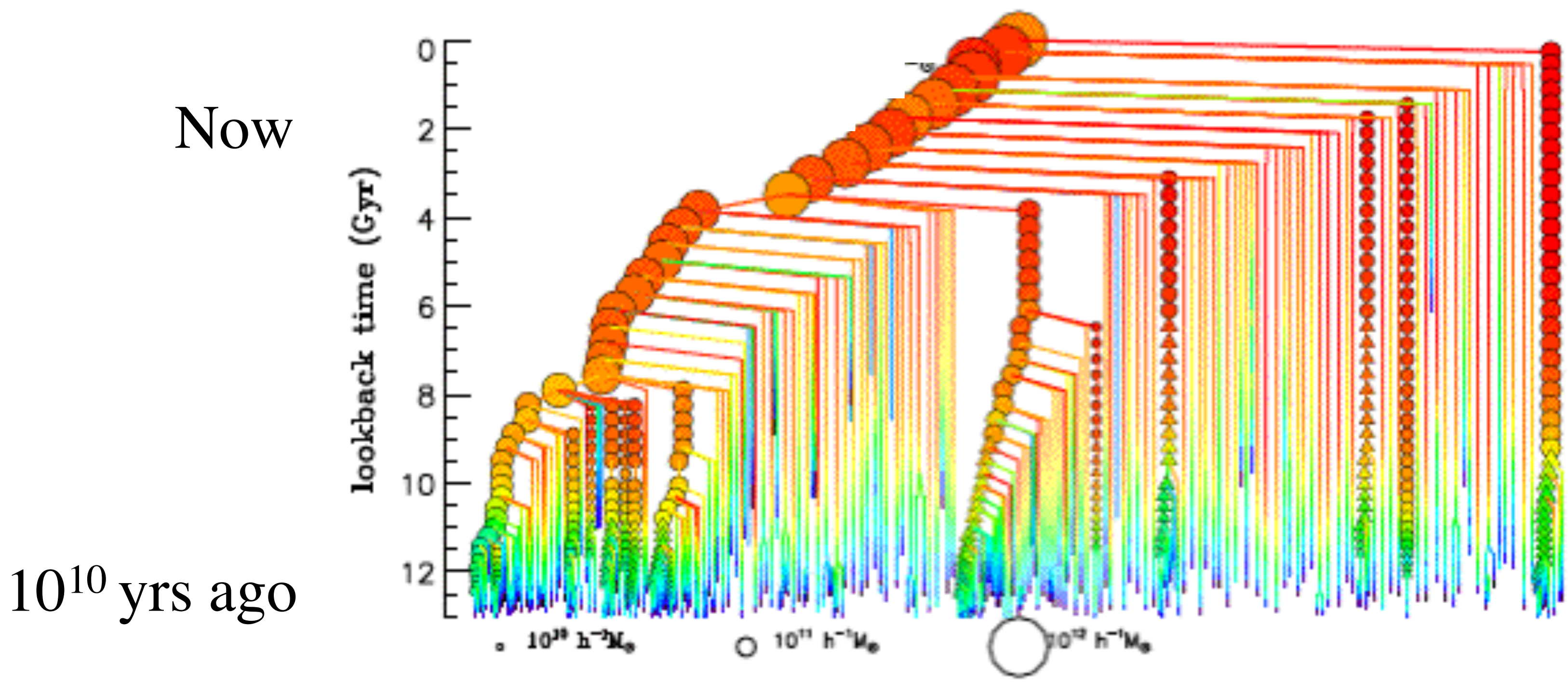
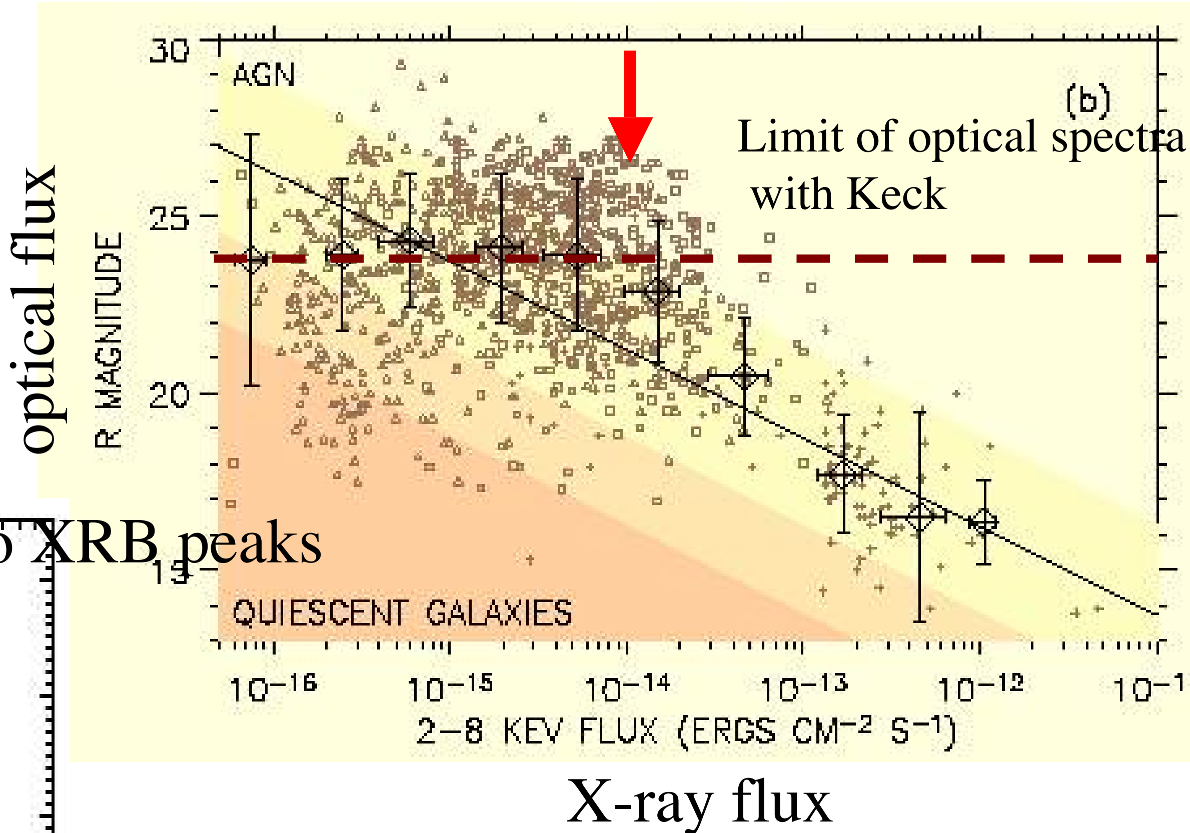
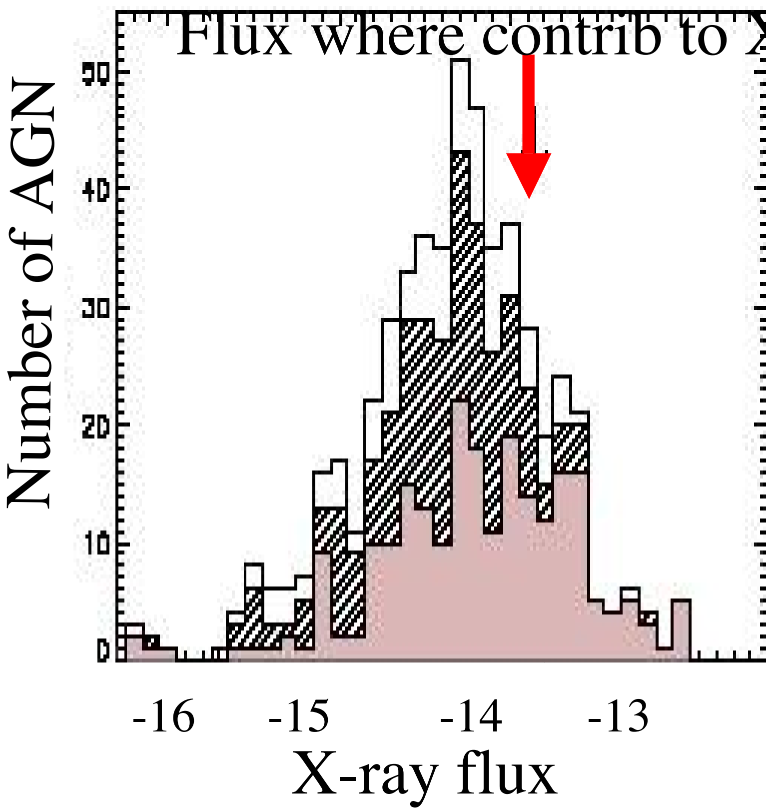


Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_\odot$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

Chandra/XMM AGN samples

- large samples of AGN have been obtained by Chandra and XMM over a wide range of flux, solid angle and redshift (Hasinger and Brandt 2005)





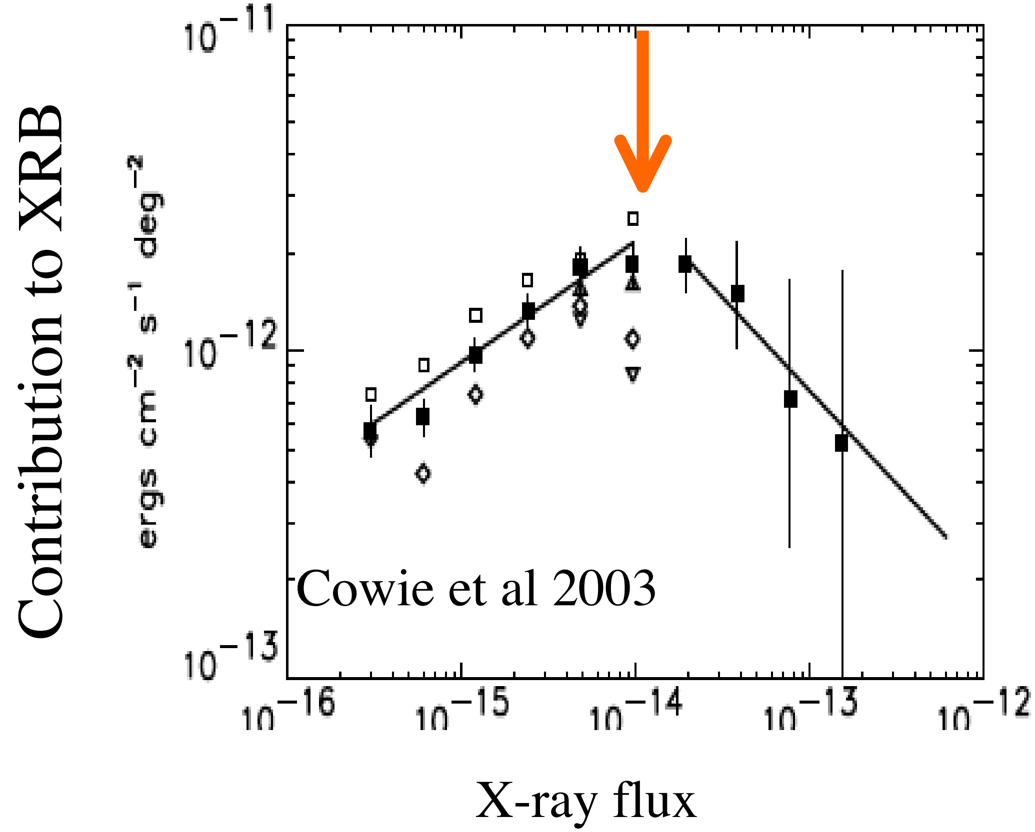
- Faintness of Chandra/XMM sources makes optical redshifts difficult- photometric redshifts

Objects with redshifts

Spectra -no redshift

Where Does the X-ray Background Come From

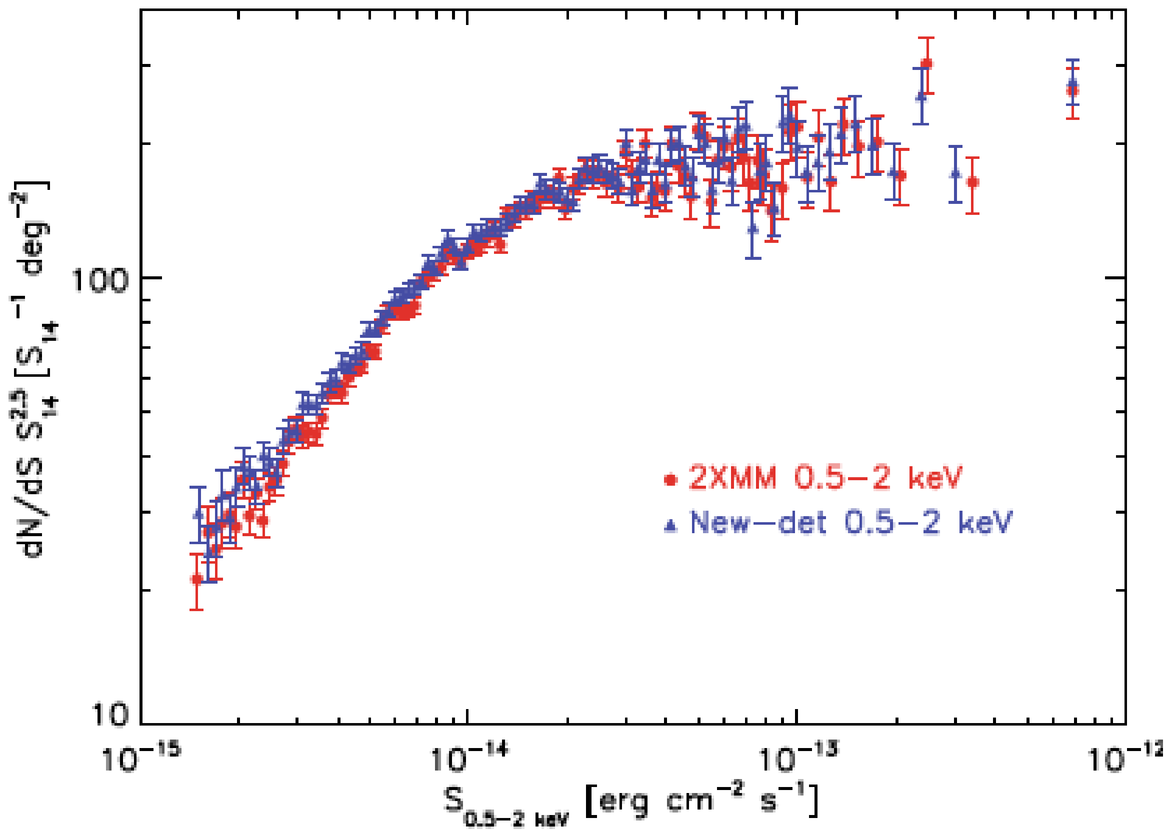
- The contribution of point sources to the XRB peaks at f(x)~10^{-14} ergs/cm^2/sec ~80% of the 2-8 Kev XRB originating at f(x)>3x10^{-15}



The apparently diffuse x-ray background is due to the superposition of weak sources- primarily AGN Culmination of a 40 year research effort

Chandra Source Counts

- Integrating the Faint X-ray Sources counts **should** produce the x-ray background over all energies
- Most of the sources are AGN- at very low fluxes normal galaxies become important



Synthesis models of the x-ray background try to reproduce the observed x-ray background spectrum from a sum of obscured and unobscured AGN +small contributions from clusters and normal galaxies

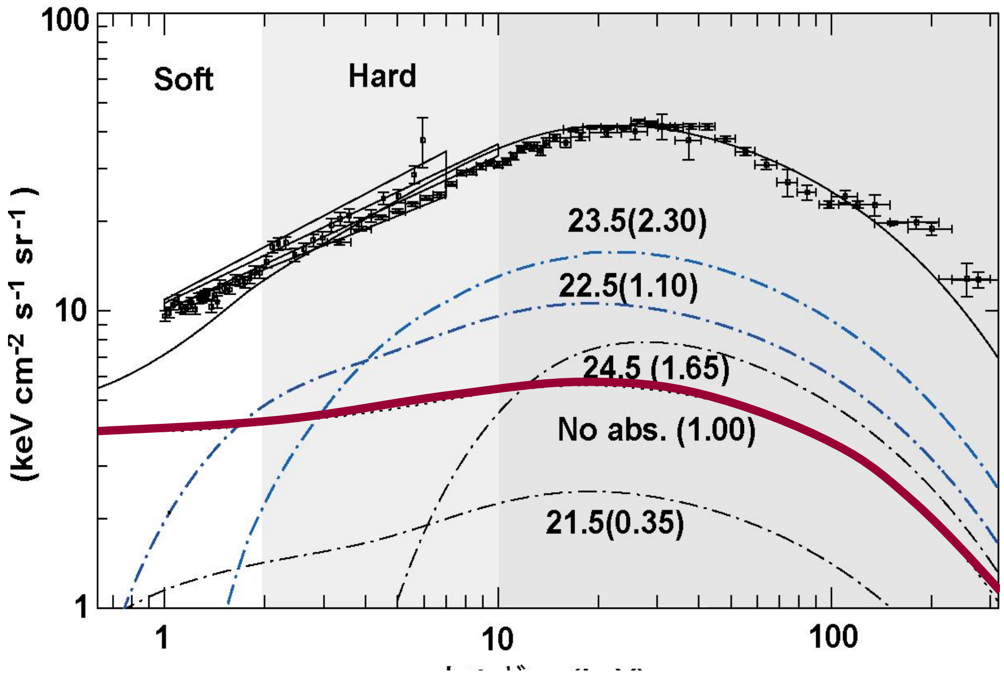
A possible answer

- The main assumption - most of the flux is produced by supermassive black holes in the center of galaxies containing large amounts of dust and gas and thus having x-ray spectra dominated, at low energies, by photoelectric absorption.

- Suitable algebraic superposition- just the *right* number of objects, evolving the *right* way with redshift, with the *right* distribution of column densities **can** produce the volume emissivity, log N-log S and the x-ray spectrum.

- **Such models are remarkably flexible. (Ueda)**

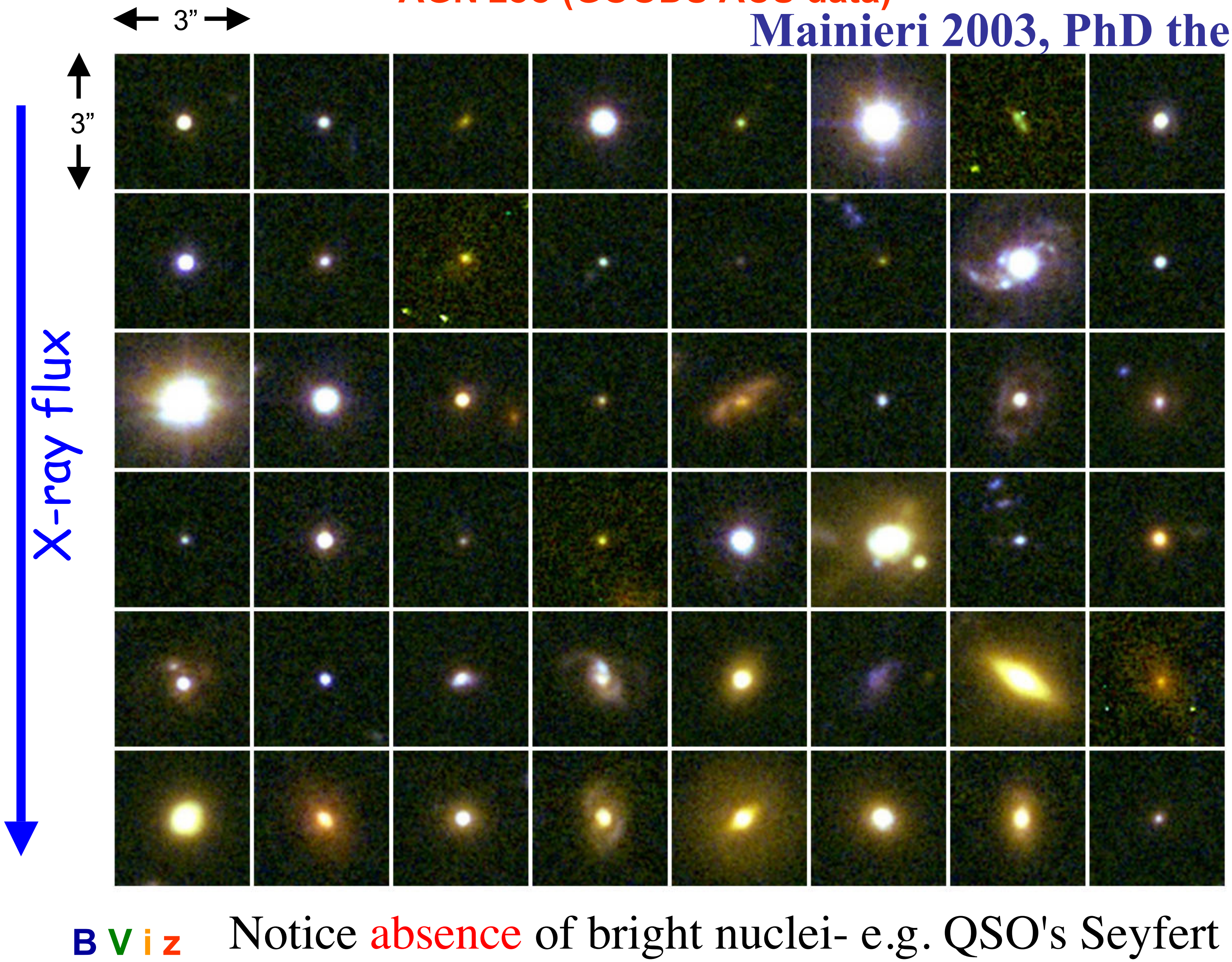
Spectrum of individual objects sums to XRB spectrum



Energy (keV)

AGN zoo (GOODS ACS data)

Mainieri 2003, PhD thesis



Notice absence of bright nuclei- e.g. QSO's Seyfert Is

What are the optical properties of the AGN

HST allows first estimate of nuclear optical fluxes (from the ground the objects are too blurry)

- For the **broad line objects** x-ray and UV flux are strongly correlated
- For the “narrow” line objects optical and x-ray fluxes are uncorrelated and many of the optical nuclei are invisible with deep HST observations.

Relative nucleus vs galaxy

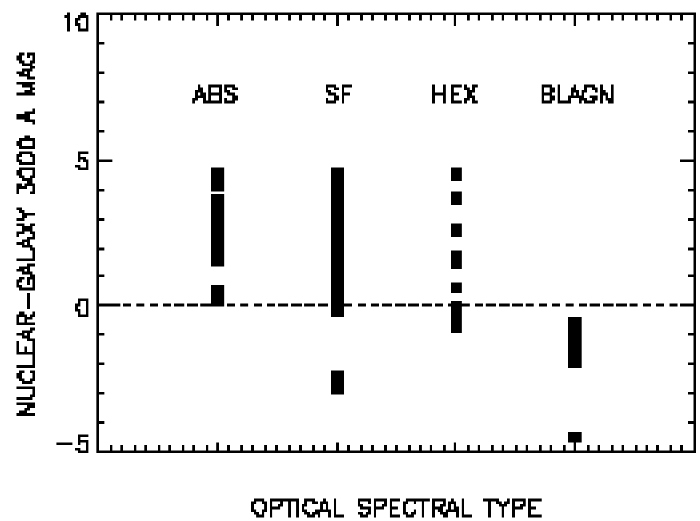
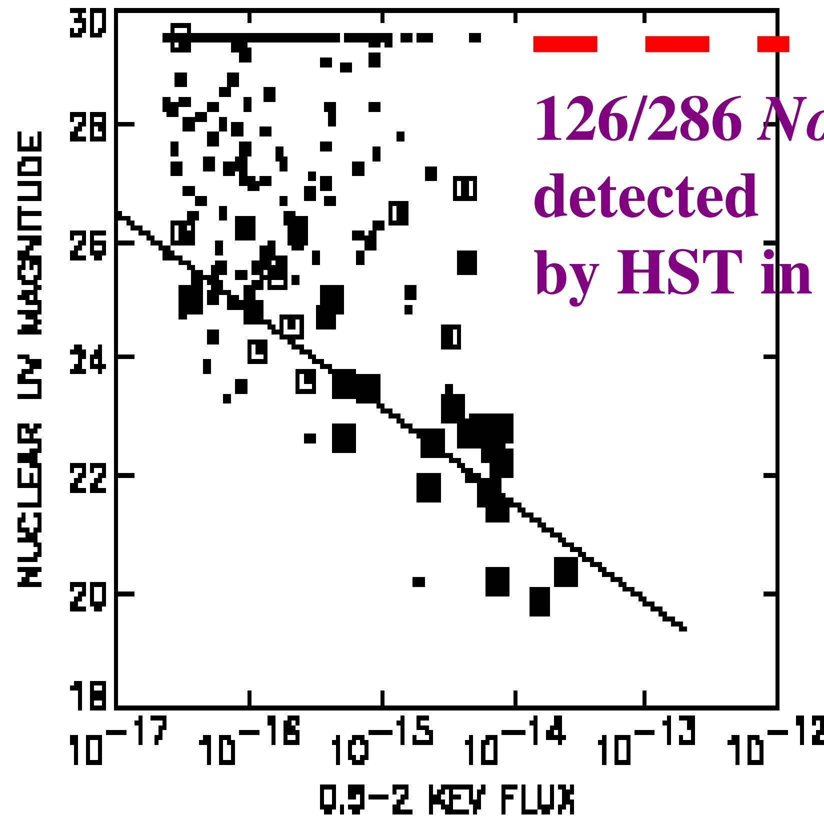


FIG. 16.— Rest-frame (nuclear – galaxy) 3000 Å magnitude computed by interpolating between the GOODS bandpasses vs. optical

Negative values mean nuclear dominated

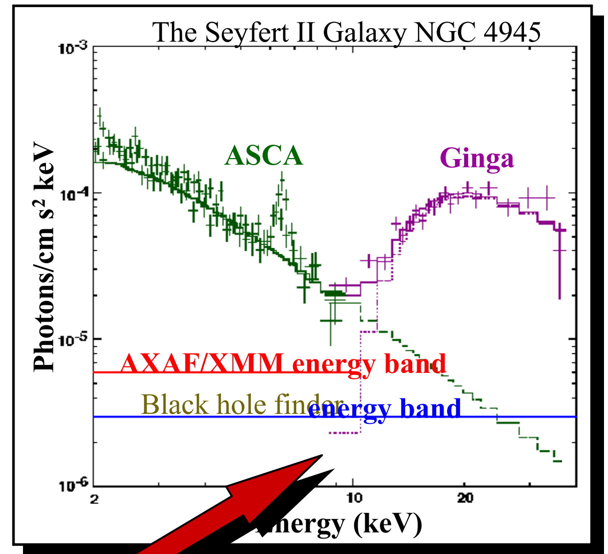


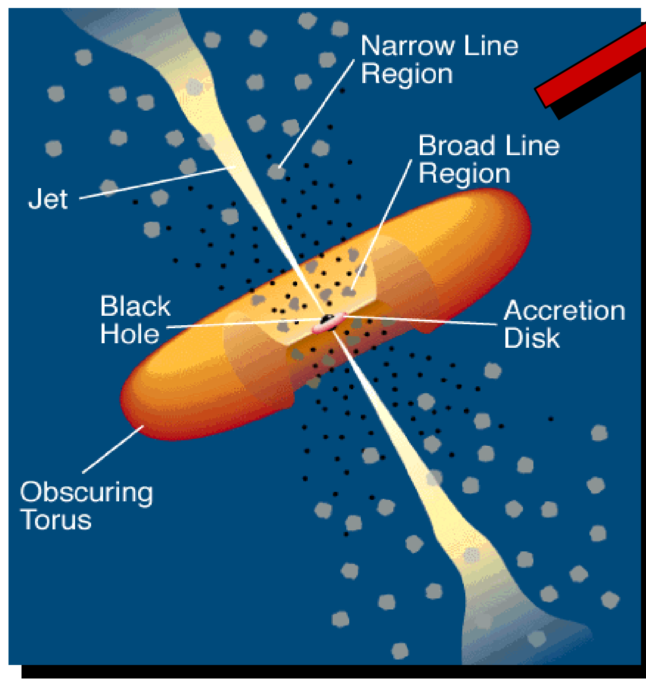
126/286 *Not* detected by HST in z’

Nucleus is often 5 mags fainter than expected; at 3000A this corresponds to N(H)~10^{22} atm/cm^2 for MW dust to gas ratio-e.g. obscured AGN (type IIs)

Why Hard X-rays Important

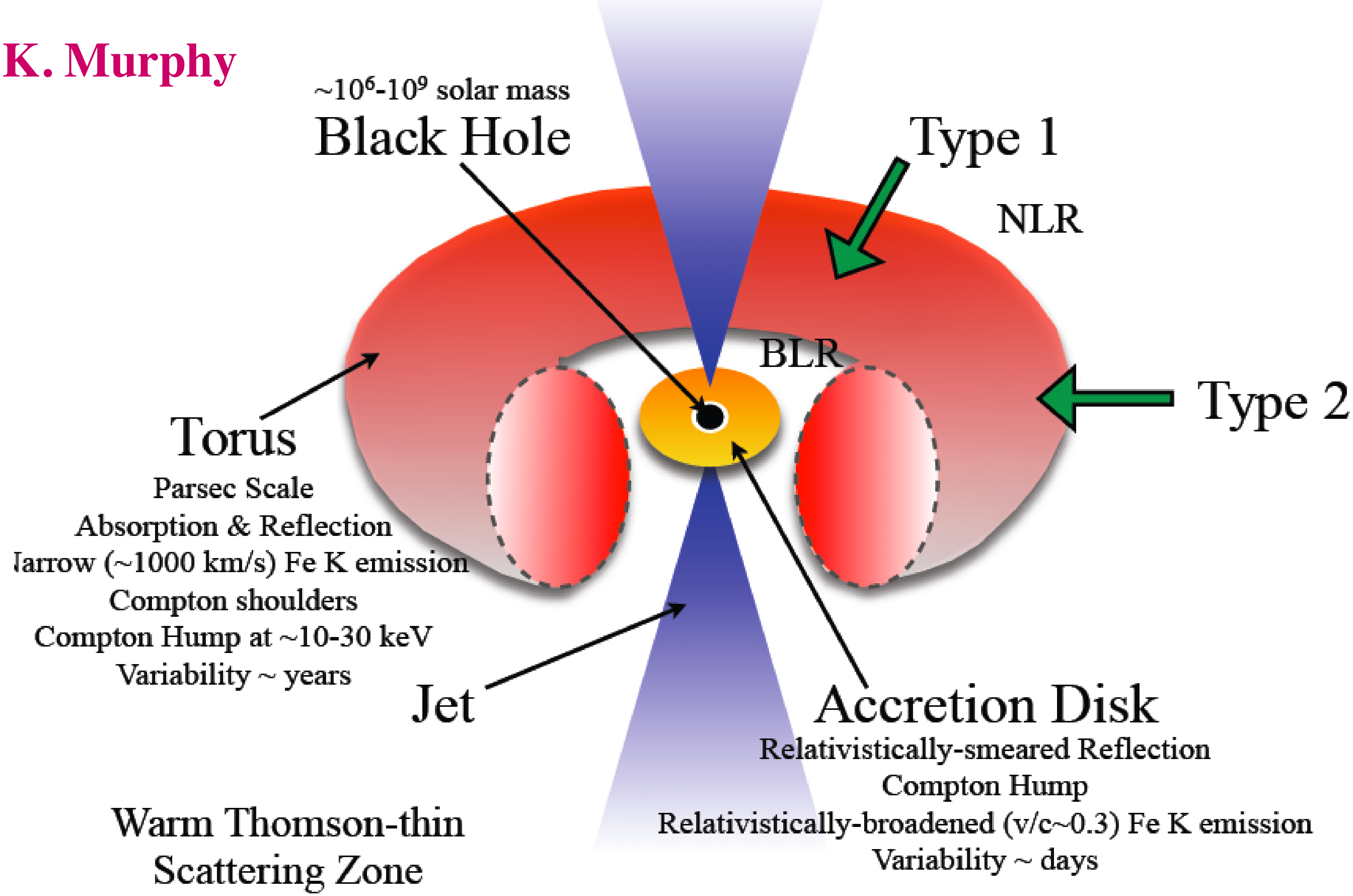
- From past x-ray experiments (Chandra,XMM, BeppoSax, ASCA) we know that many (most?) radiating massive black holes in the center of galaxies (active galaxies)
  - emit a large fraction of their energy in the x-ray band)
  - are obscured from our view by large amounts of dust and gas.
- This material absorbs optical, ultraviolet and low energy x-rays and prevents the detection of the central AGN
- However this material is relatively transparent to high energy x-rays (E> 15 keV)





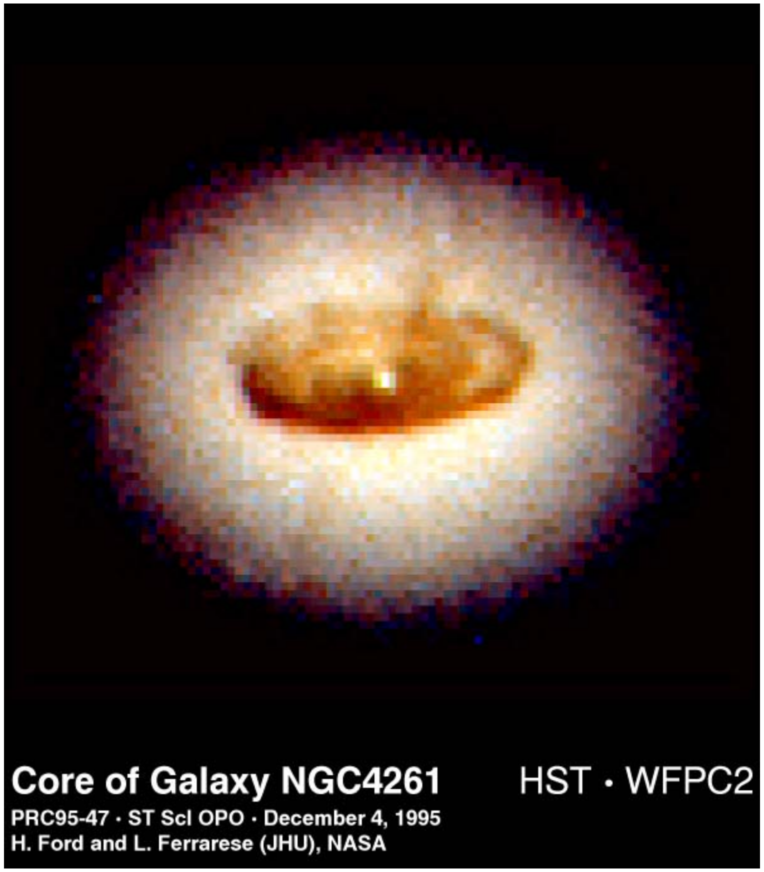
Active Galactic Nucleus

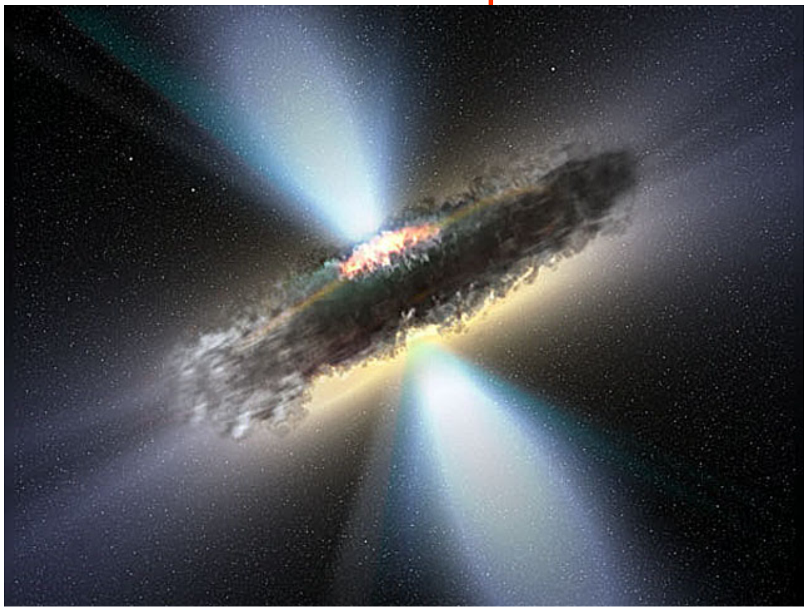
K. Murphy



The Dark Side of AGN

- ***Many AGN are obscured***- obscuring material is of several types
  - Located in the ISM of the host galaxy
  - A wind associated with the AGN
  - Perhaps a 'obscuring torus'
  - Etc
  - Lack of uniform sample not sensitive to absorption or emission

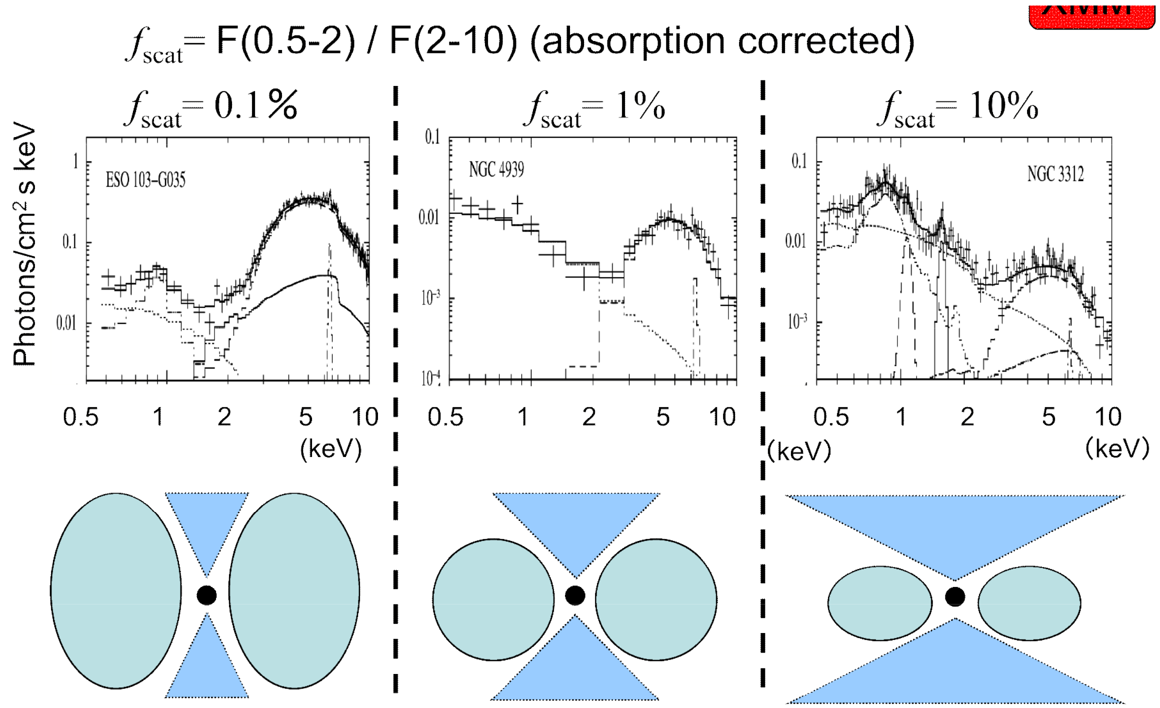




physical conditions in obscuring regions are not the same from object to object - can be complex with large and unpredictable effects on the spectrum

What's the Big Deal About Absorption

- Objects with high column densities of 'cold' material in the line of sight are
  - dim at soft x-rays
  - dim in the UV and optical
- These 3 bands are traditional wavelengths in which most AGN have been found and thus absorption strongly controls the results of surveys
- If the absorber has a high covering fraction it is 'hidden' and only detectable in hard x-rays or IR

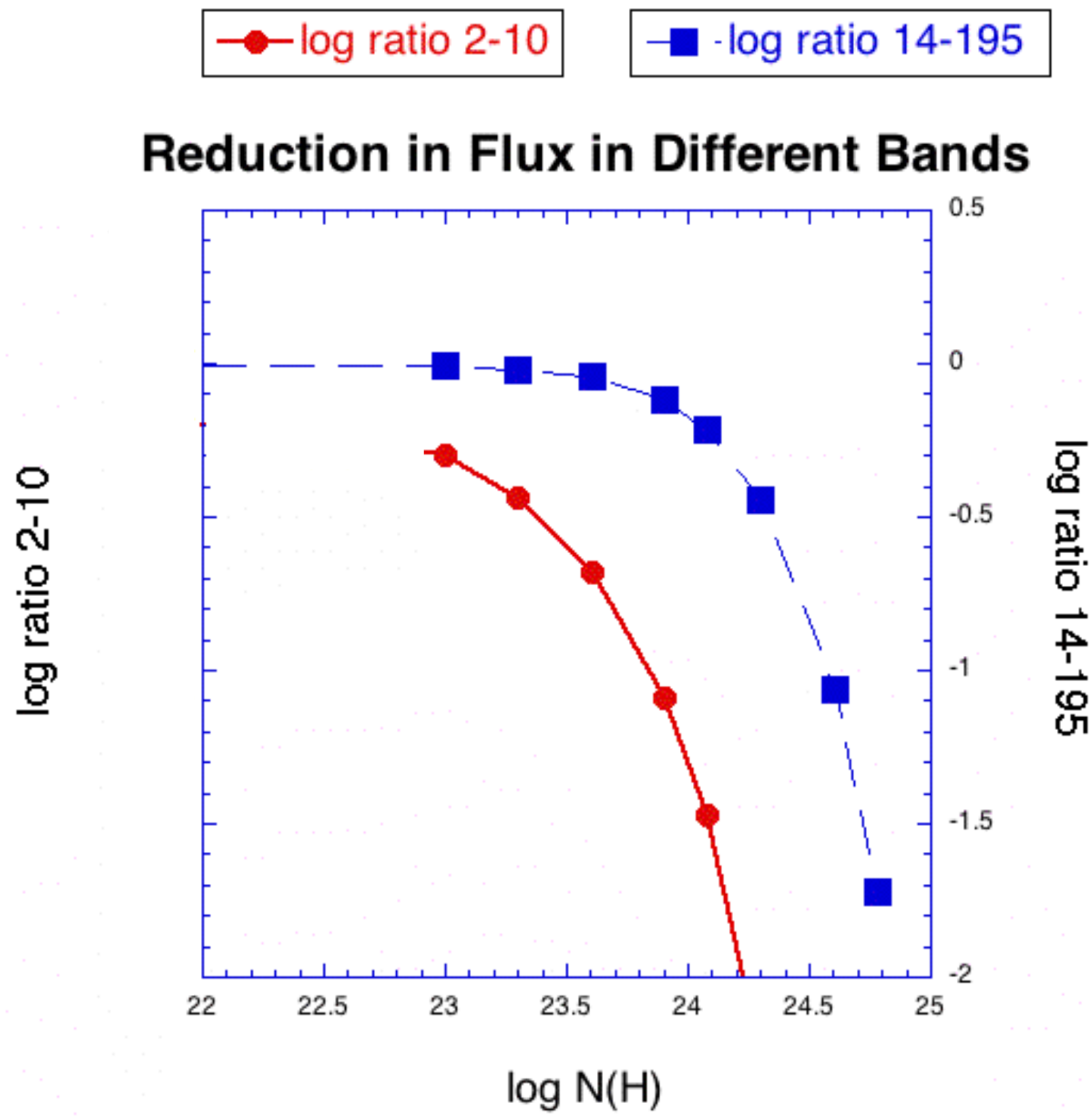


Y. Terashima

Covering fraction and column density control the nature of 0.3-5 kev spectrum- <u>higher energy x-rays relatively unaffected</u>

Effect of Obscuration on Sensitivity of Survey

- surveys in 2-10 keV band have reduction in flux by 10 at log N(H)>23.8
- surveys in 14-195 keV band have reduction in flux by 10 at log N(H)>24.6 ($\tau_{Thompson}$>2.6)
- Even hard x-ray surveys cannot find Compton thick objects (e.g. $\tau_{Compton}$>>1)



Questions for Class

- What is the physical mechanism(s) responsible for x-ray absorption
  - does it depend on anything other than the hydrogen column density?

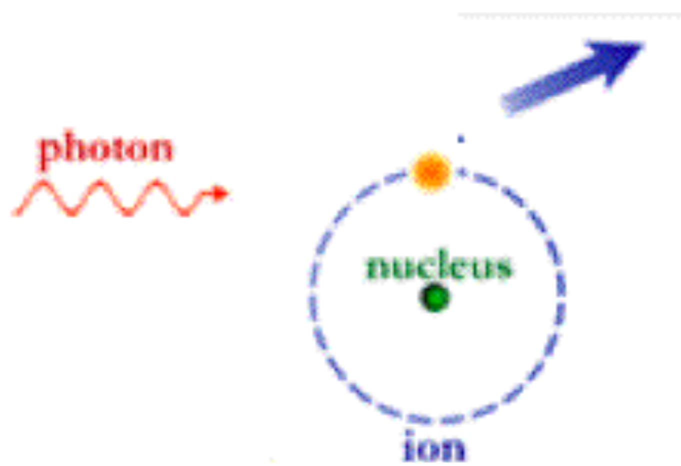
- What does backward evolution mean?

- Why are hard x-rays especially good for finding AGN?

PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O) are light: absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

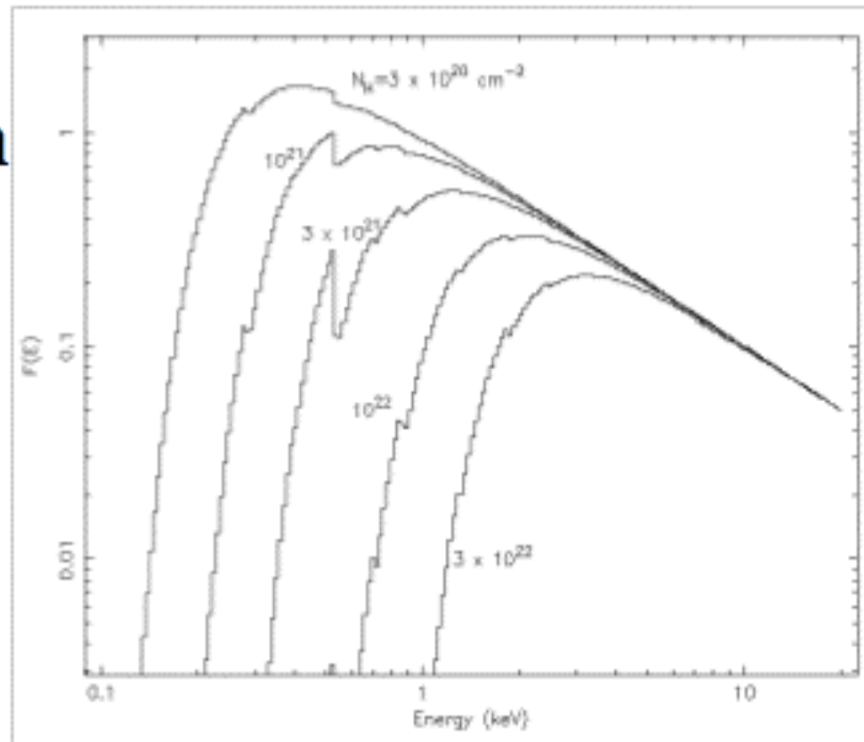
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

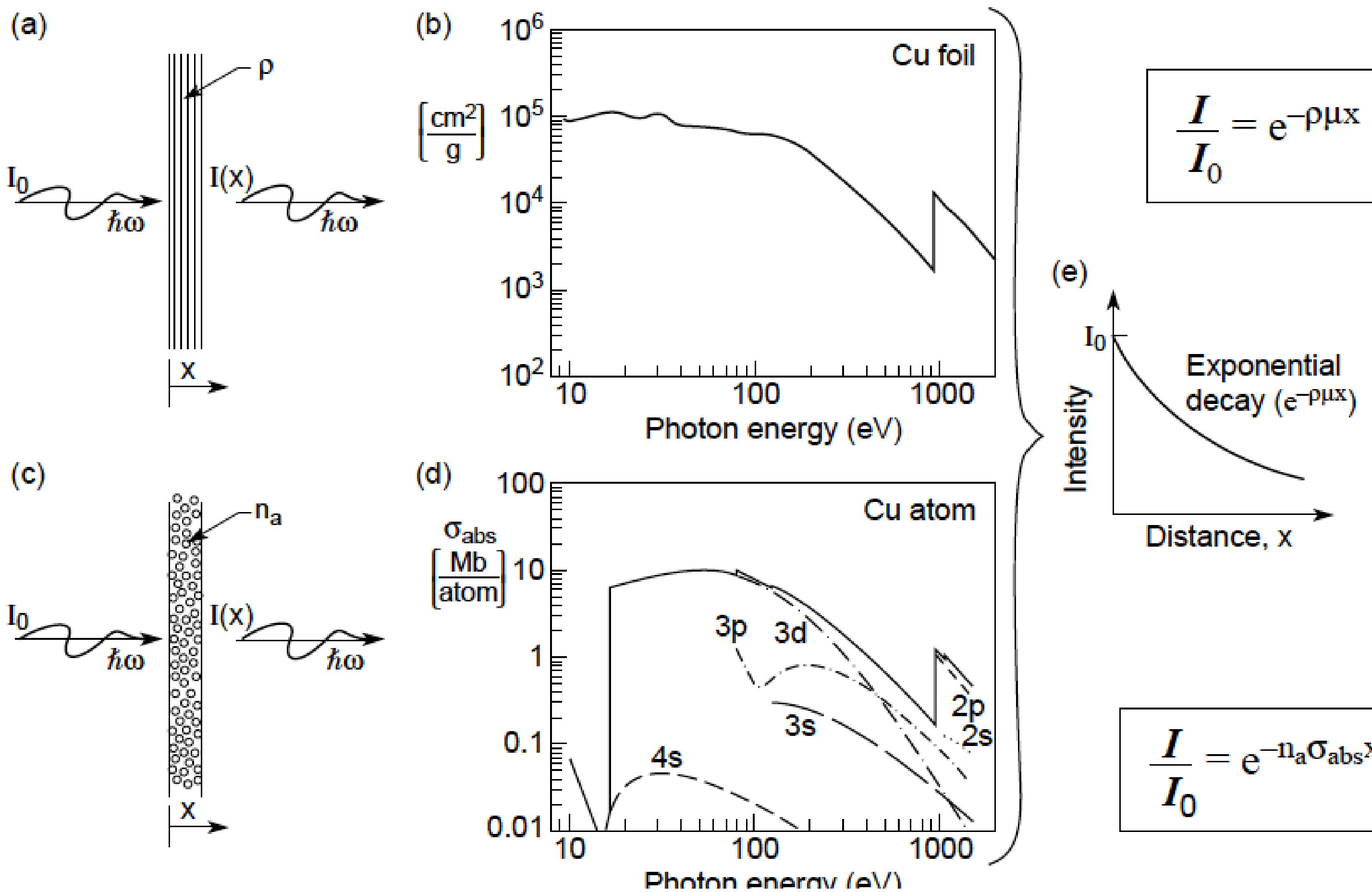
$F(E) = AE^{-\Gamma} e^{-\sigma(E) N_H}$

$\sigma(E) \approx E^{-3}$



Profile dominated by bound-free edges of abundant elements

Photoabsorption by Thin Foils and Isolated Atoms



$$\frac{I}{I_0} = e^{-\rho\mu x}$$

$$\frac{I}{I_0} = e^{-n_a\sigma_{abs}x}$$

David Atwood UCB Course Ast 210

Review Articles On AGN Evolution in Different Wave Bands

- for a discussion of observations at radio wavelengthsvde Zotti et al. 2010A&ARv..18....1 Radio and millimeter continuum surveys and their astrophysical implications
- Croom et al. (2009) for optical QSOs 2009MNRAS.399.1755 Croom, et al The 2dF-SDSS LRG and QSO survey: the QSO luminosity function at $0.4 < z < 2.6$
- Brandt & Hasinger (2005) for X-ray studies.
- Broad Band Summary: 2007ApJ...654..731 Hopkins, P et al An Observational Determination of the Bolometric Quasar Luminosity Function

- Theory of Everything:

2006ApJS..163....1 Hopkins, Philip et al

A Unified, Merger-driven Model of the Origin of Starbursts, Quasars, the Cosmic X-Ray Background, Supermassive Black Holes, and Galaxy Spheroids

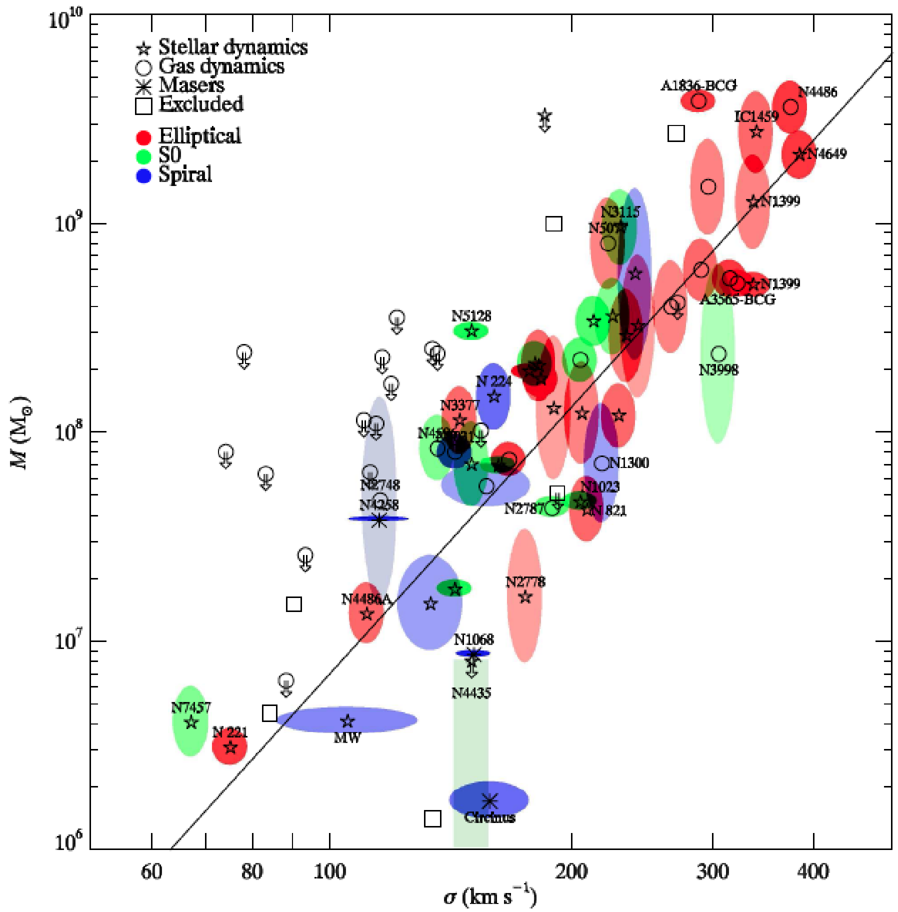
Comparison of AGN Mass and Galaxy Bulge Mass

- Strong Indication of co-evolution of galaxies and AGN- is this related to 'feedback'?

- Black holes at z=0 'know about' the mass of the bulge of the galaxy they are in
- most massive galaxies harbor massive black holes

mass of the black hole scales with the velocity dispersion of the stars in the bulge of the galaxy

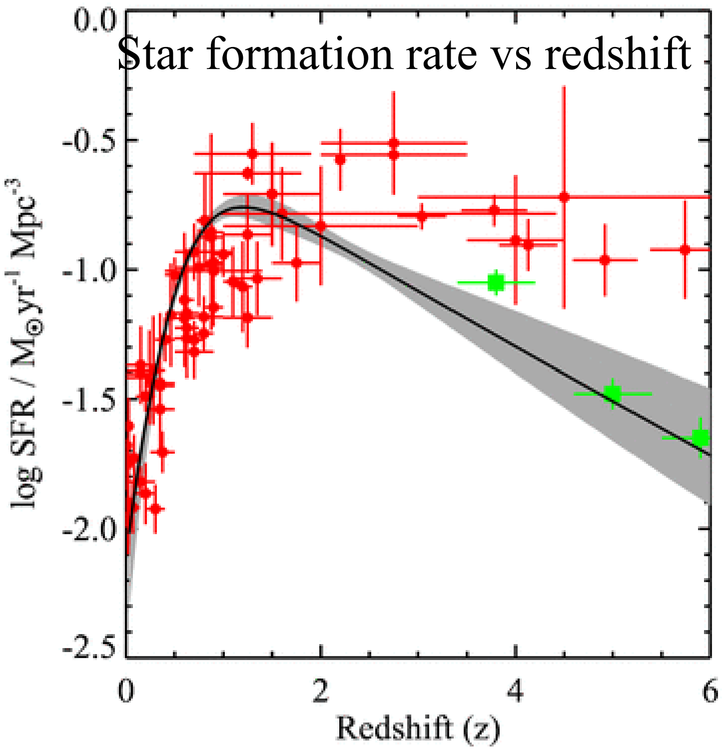
- M_{BH}~10^{-3} Mbulge
- **Galaxies know about their BH and vice versa**

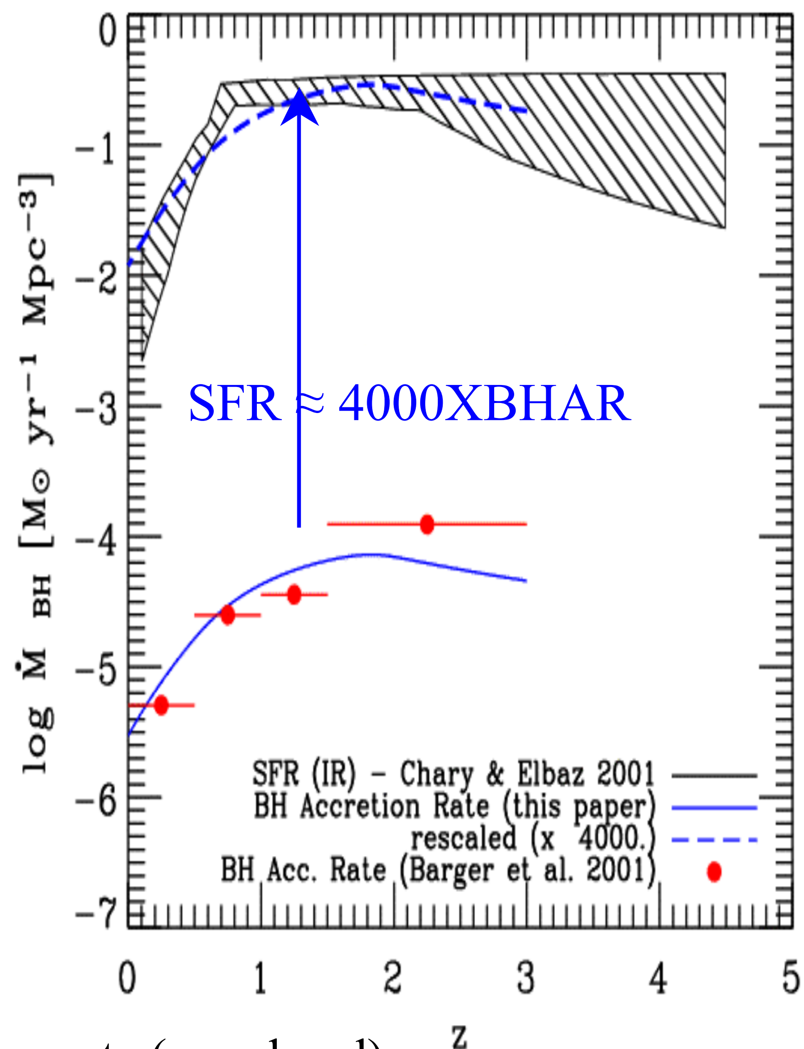


Gultekin et al 2010

Comparison of Growth of BH and Star Formation Rate

- half of the accreted supermassive black hole mass density has formed by z~ 1
- ~1/2 of the total mass of z=0 BHs is formed in low luminosity objects





Star formation rate (grey band)

AGN evolution rate ((red circles) scaled up by 5000 Aird et al 2010

BHAR = black hole accretion rate

Eddington implies limit on *growth rate of mass*: since

$$\dot{M} = \frac{L_{acc}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}$$

we must have

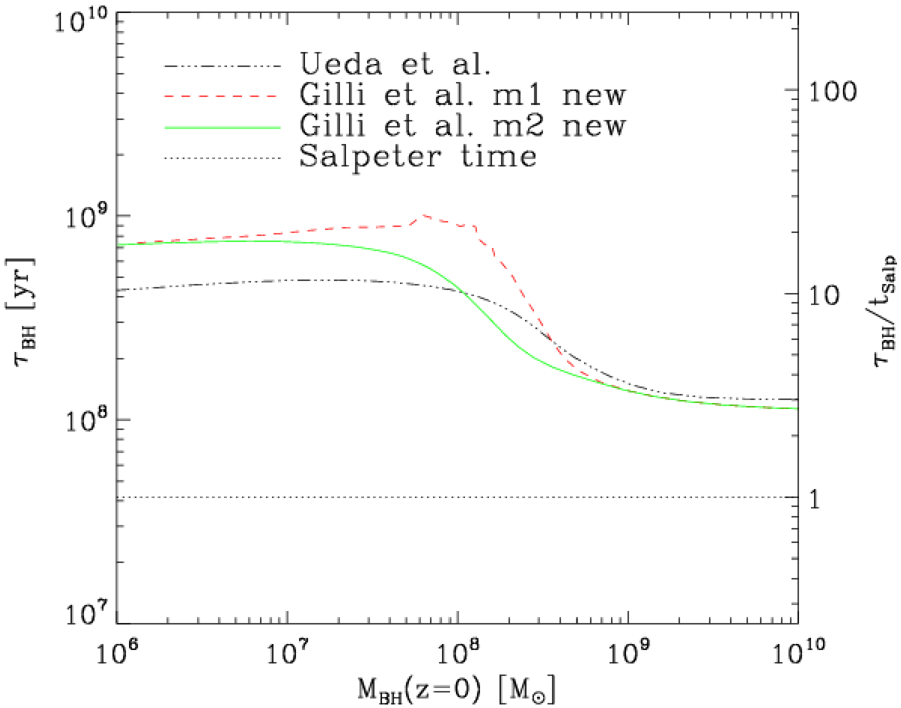
$$M \leq M_0 e^{t/\tau}$$

where

$$\boxed{\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5\times10^7\, yr}$$

Total Lifetime of active BHs

ε= efficiency
λ= Eddington ratio



- M_{BH} e-fold time (Salpeter's):

$$t_{Salp} = \frac{\varepsilon\, t_E}{(1-\varepsilon)\lambda} = 4.2\times 10^7\, yr \left[\frac{(1-\varepsilon)}{9\varepsilon}\right]^{-1} \lambda^{-1}$$

- To grow a BH SEVERAL t_{Salp} needed: 7 t_{Salp} $10^3 \Rightarrow 10^6\ M_\odot$
  14 t_{Salp} $10^3 \Rightarrow 10^9\ M_\odot$
- t_{Salp} independent of M_{BH}
- Estimated AGN lifetimes range from 10^6 to 10^8 yr

'Soltan' Argument

- If supermassive black holes grow primarily by accretion then the integral of the accretion rate across cosmic time should be equal to their present mass. (1982 MNRAS.200..115
- Integrating the bolometric luminosity function and assuming a conversion factor, ε, from mass to energy one can compare this to the present day mass of black holes integrated over all objects.
- $L_{bol}=\varepsilon(dm_{acc}/dt)c^2= \varepsilon(dm_{\bullet}/dt)c^2/(1-\varepsilon)$

dm_{acc}/dt=accretion rate

$dm_{\bullet}/dt$= BH growth rate

$$\rho_{\mathrm{BH,acc}}(z) = \int_z^\infty \frac{dt}{dz'}dz' \int_0^\infty \frac{(1-\epsilon)L_i\kappa_i}{\epsilon c^2}\phi(L_i,z)dL_i$$

The higher the conversion factor for converting energy to mass the smaller the predicted BH mass at a given redshift is for a fixed observed luminosity

ε derived this way is independent of the cosmological model

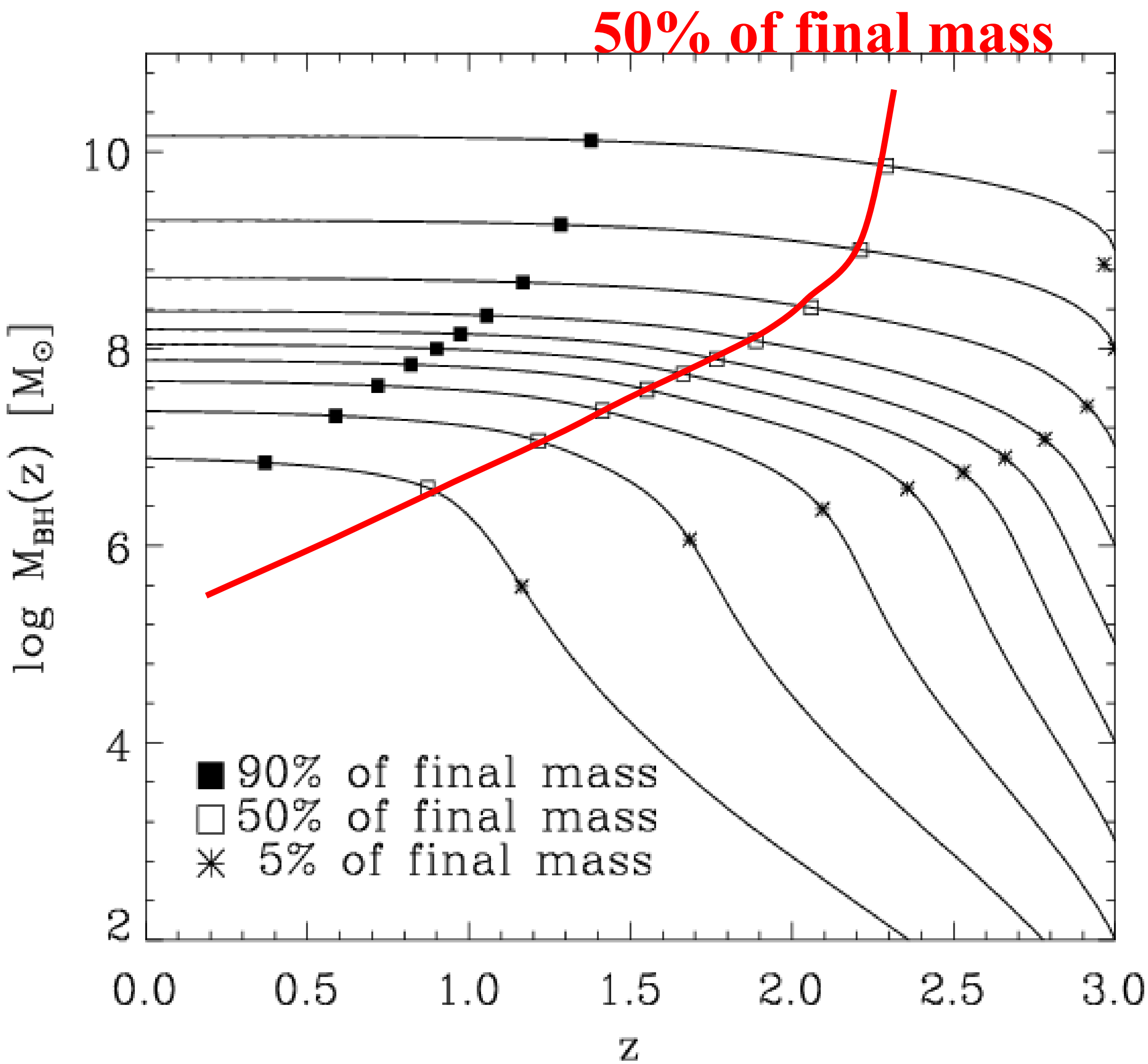
At z=0 the observed BH mass density is ~4×10^{-5} $M_{\odot}/Mpc^3$

Utilizing the best estimate of luminosity vs redshift this gives ε=0.06, marginally consistent with a non-spinning BH

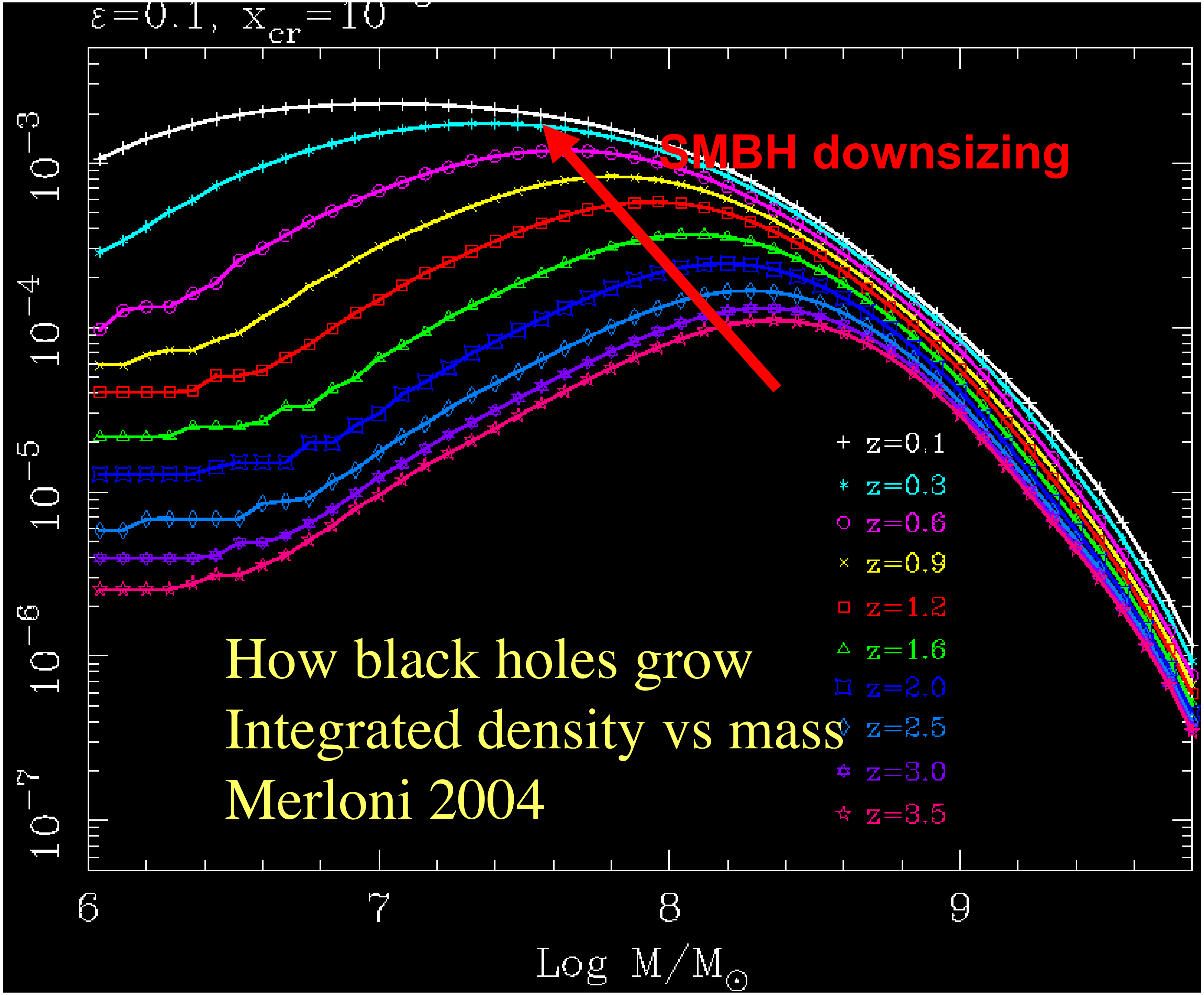
However this argument is sensitive to

1) evolution of the luminosity function
2) bolometric correction- how to transform from the observation in some band to the total luminosity

Anti-Hierarchical BH growth
Marconi 2006



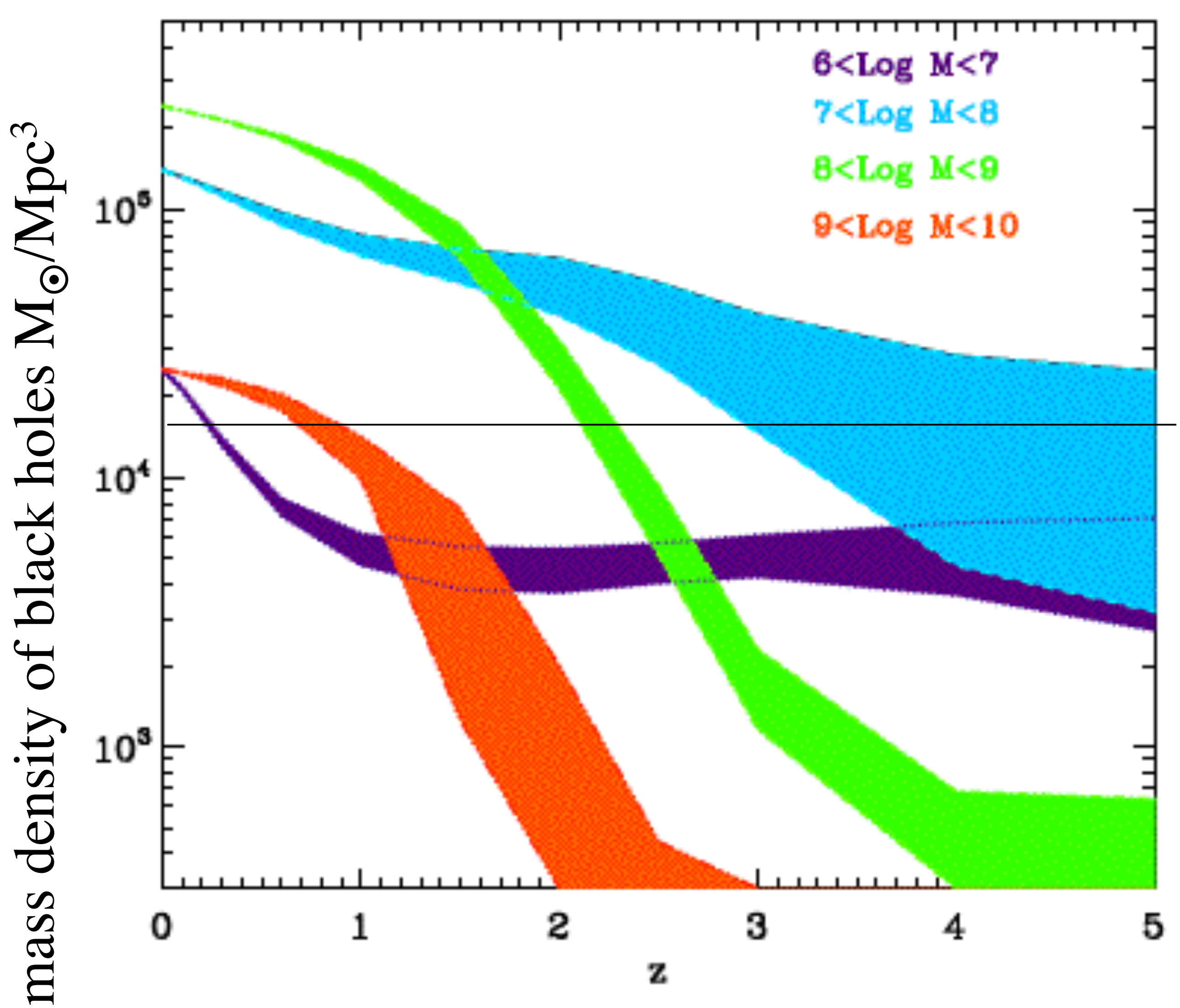
- Big BHs form in deeper potential wells ⇨ they form first.
- Smaller BHs form in shallower potential wells -they form later and take more time to grow.(Merloni 2004.)



ε=0.1, x_cr=10
SMBH downsizing
+ z=0.1
z=0.3
z=0.6
z=0.9
z=1.2
z=1.6
z=2.0
z=2.5
z=3.0
z=3.5
How black holes grow
Integrated density vs mass
Merloni 2004
Log M/M☉

How Black holes grow
Merloni 2009

- Most of the mass in BHs today is in the 10^8-10^9 $M_\odot$ range
- BH in mass range 10^6-10^7 $M_\odot$ are growing rapidly today



Summary

- Majority of AGN in the universe are not like optically selected AGN
- Most of these sources are "optically dull" and radio quiet , obtaining optical redshifts is difficult
- z~1 is the peak epoch of AGN where the energy density peaks, consistent with the peak in the integral star formation
- AGN evolve very rapidly to z~1, consistent with pure luminosity evolution- at higher z the evolution changes ***sign***
- total energy radiated is consistent with the present day mass of black holes if efficeincy of accretion is ~0.05-0.1
  - Observed x-ray sources can produce "all" of the mass of z~0 black holes via accretion
- Optically selected AGN (broad line objects) are a subset of x-ray selected objects
- The data are consistent with many of the non-broad line objects (the dominant population) having high column densities- but not a unique solution.
- The data point to downsizing- massive luminous systems dominate at high z, low mass lower luminosity at lower z.
- Simple unified model is not correct- there are almost no low luminosity broad line objects (Steffen effect)