The growth of Supermassive Black Holes across the cosmic time

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Foreword

Active Galactic Nuclei paradigm

Luminous (10^{43-47} erg s^{-1}) nuclei of galaxies

powered by gravitational energy released by *gas* accreting onto Supermassive Black Holes (SMBH)

$L_E = 1.3 \times 10^{38}$ M/M erg s^{-1}

Assuming accretion @ ~ 0.1 Eddington

M > 10^6 M

SMBH ($M > 10^6$ M)

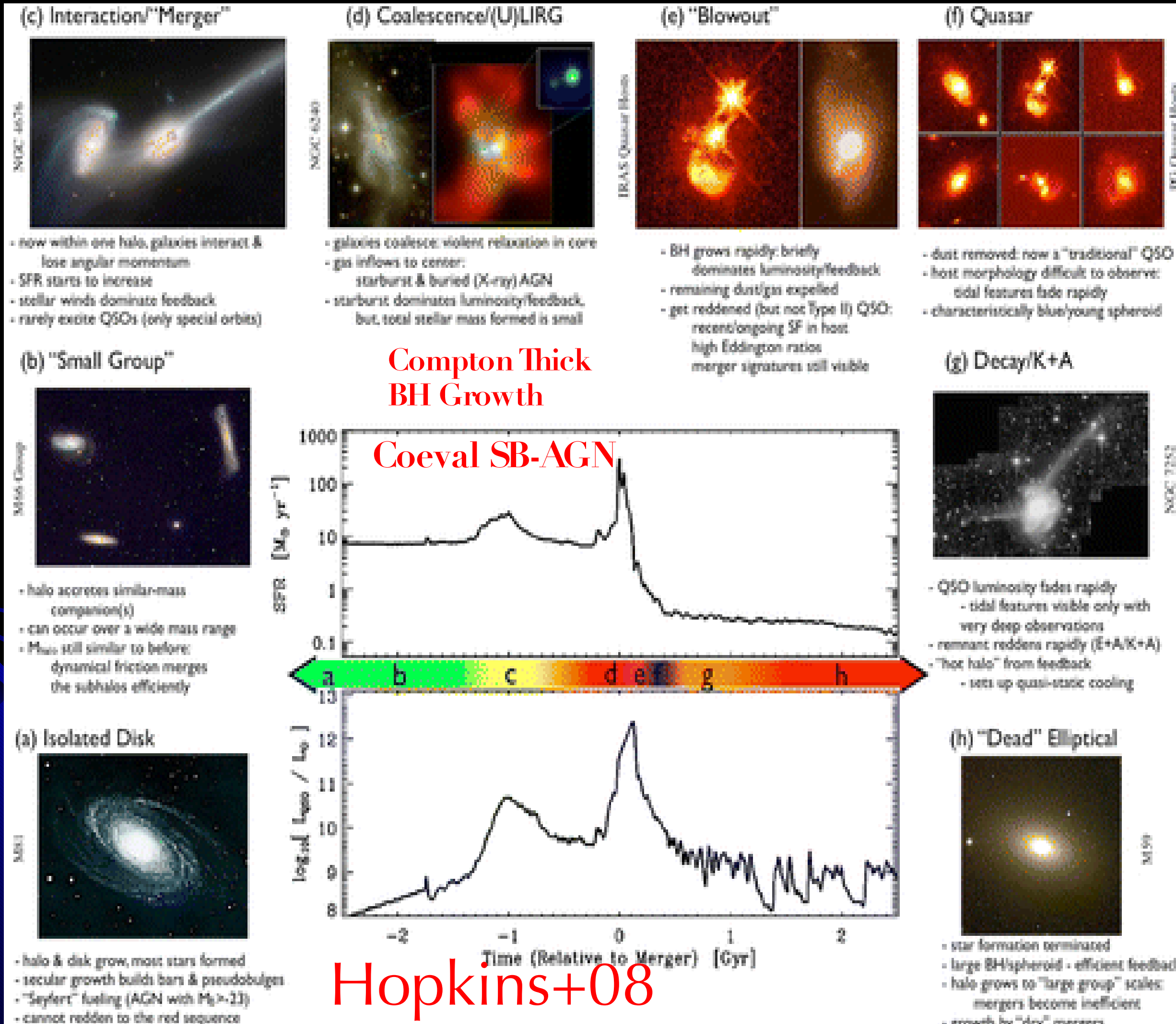
- SMBH are powering high z quasars and reside (ubiquitous) in nearby inactive galaxies [M_{BH} - σ - M_{Bulge} relations]

- SMBH keep the ICM hot (no stationary cooling flows)

- SMBH and galaxy self-regulate growth
(key ingredient in galaxy evolution -> explain high z red passive galaxies)

More in Antonis Georgakakis lecture

AGN and galaxy co-evolution: Unified models revised



- **Early on**
  Strong galaxy interactions= violent star-bursts
  Heavily obscured QSOs
- **When galaxies coalesce**
  accretion peaks
  QSO becomes optically visible as AGN winds blow out gas.
- **Later times**
  SF & accretion quenched
  red spheroid, passive evolution

Timescales of these phases are little constrained (so far)

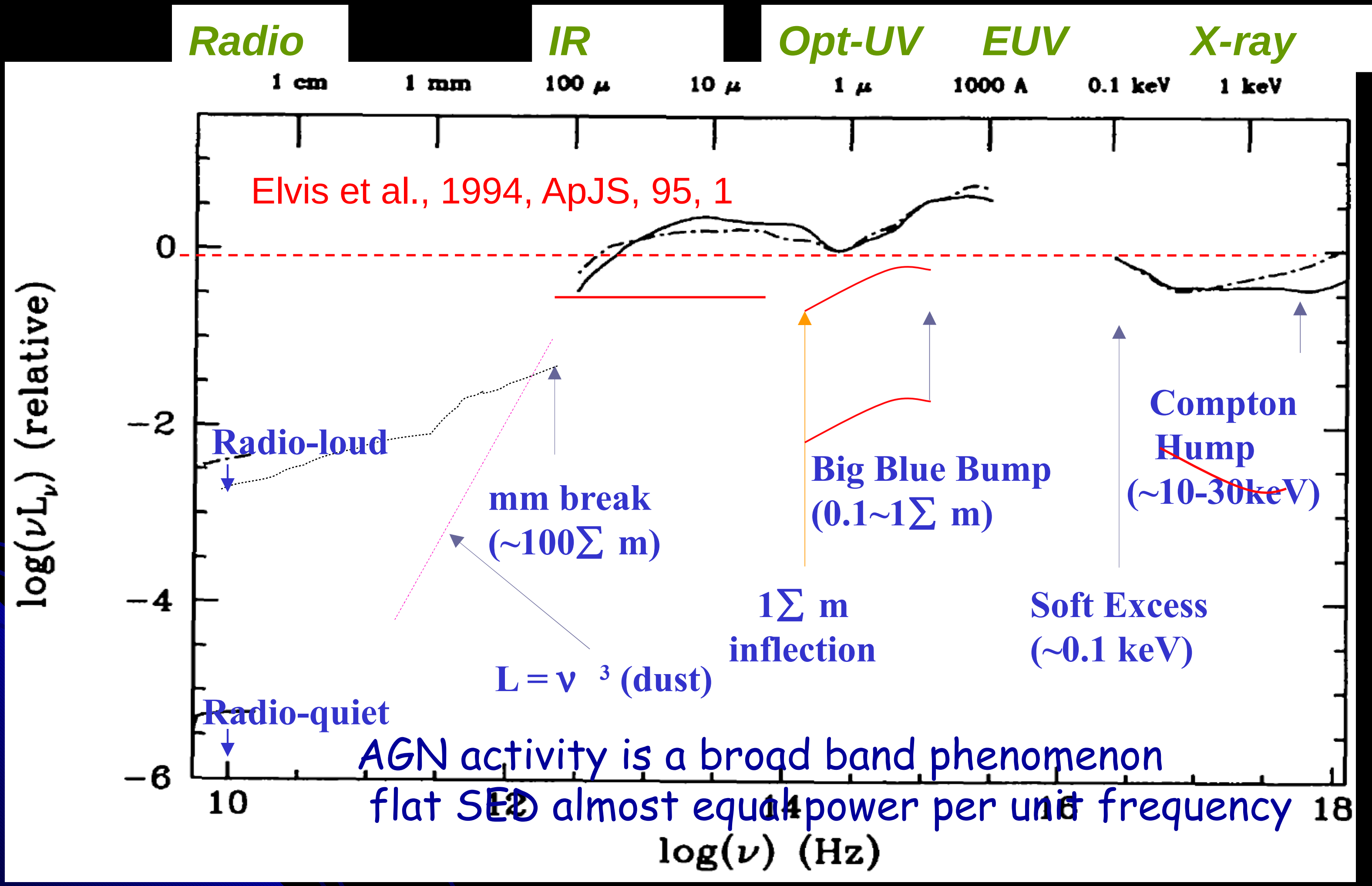
AGN census

- AGN activity is a broad band phenomenon
(flat SED almost equal power per unit frequency)

- Models predict bolometric luminosity/properties
→ bolometric approach is needed for a proper census of SMBH (most of them are obscured or elusive)

- Hard X-ray selection provide an almost unbiased view of obscured AGN

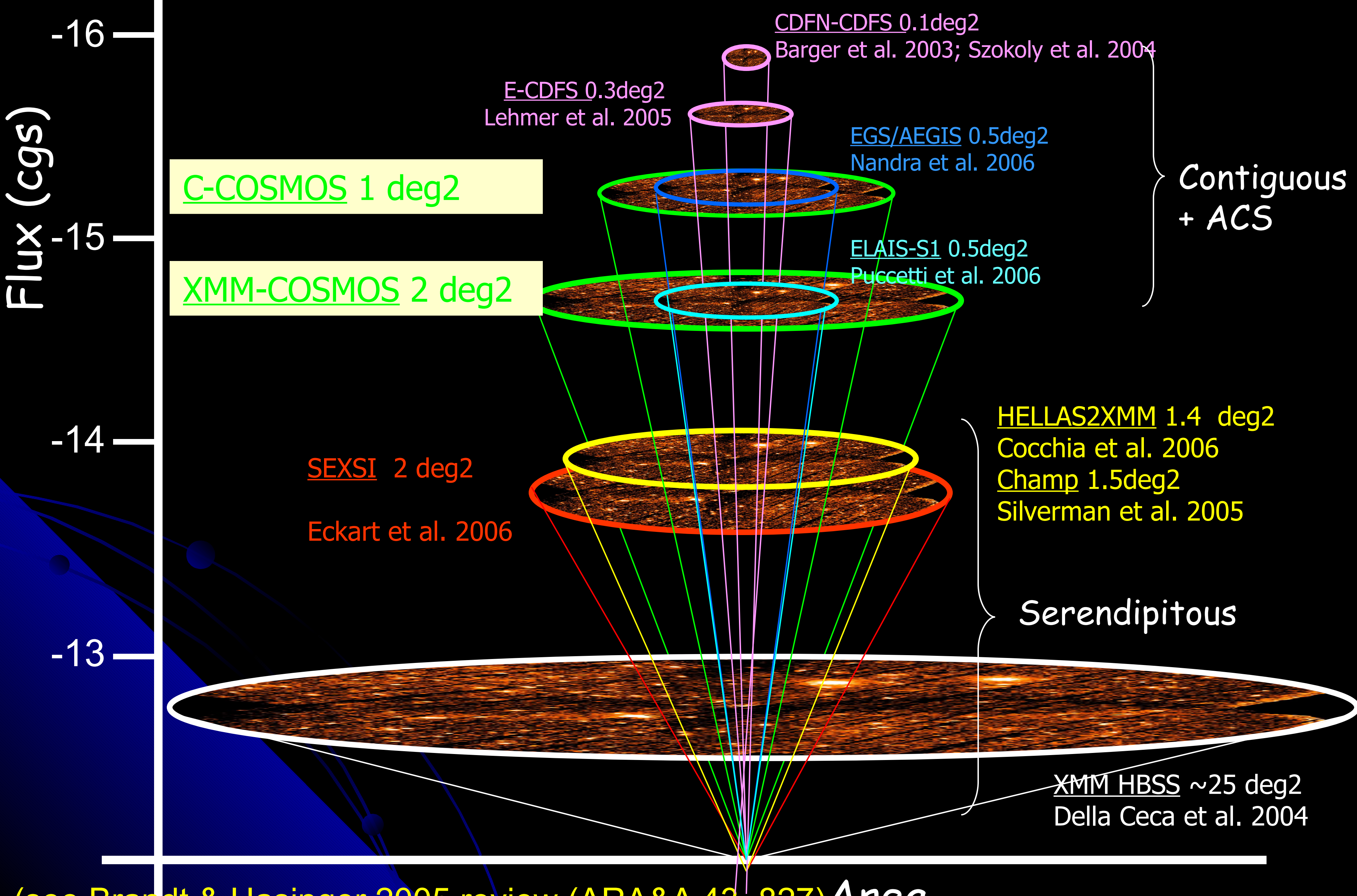
AGN Spectral Energy Distribution



AGN activity is a broad band phenomenon

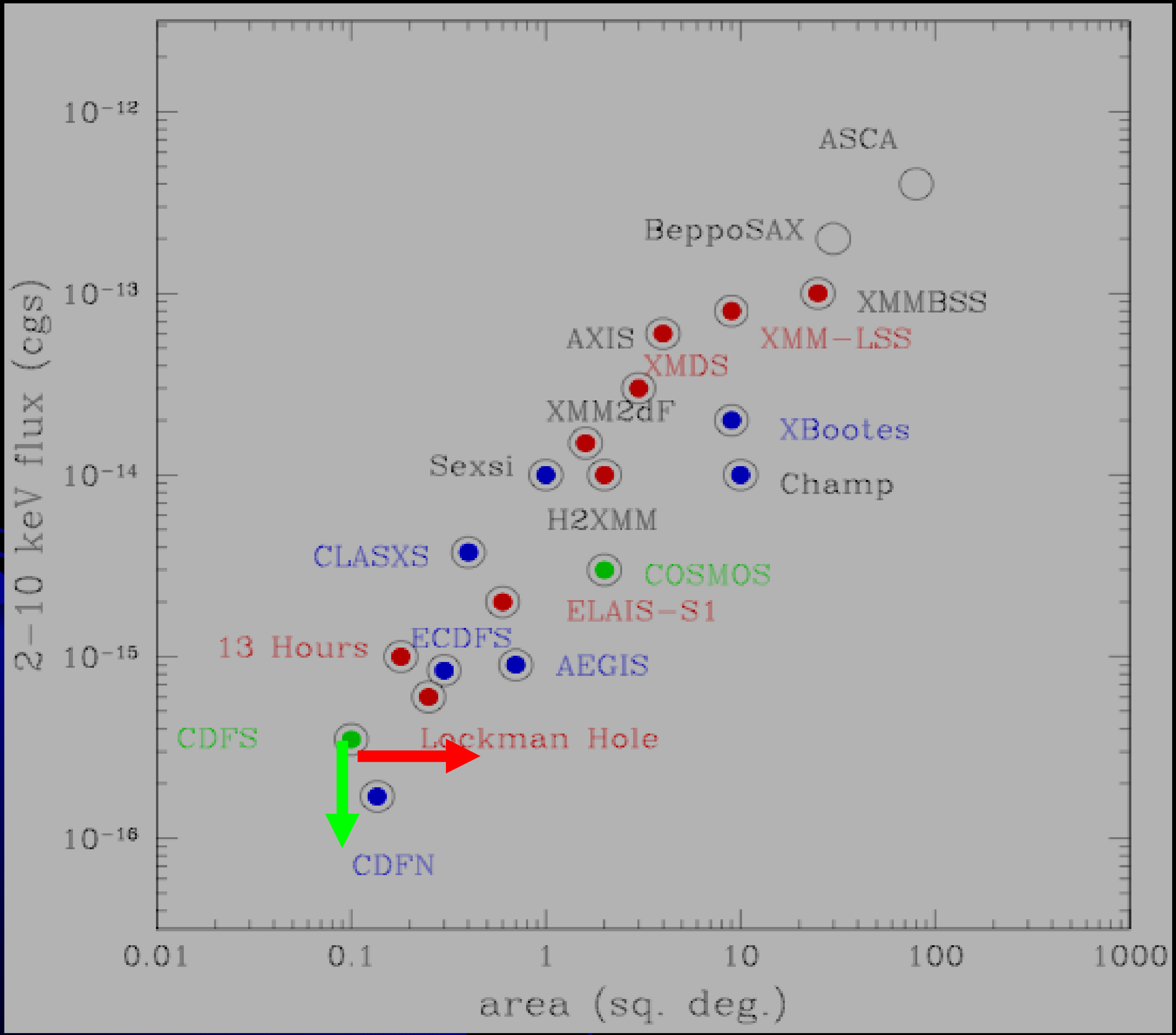
flat SED almost equal power per unit frequency

X-ray Surveys



(see Brandt & Hasinger 2005 review (ARA&A 43, 827)

Survey of surveys



CHANDRA

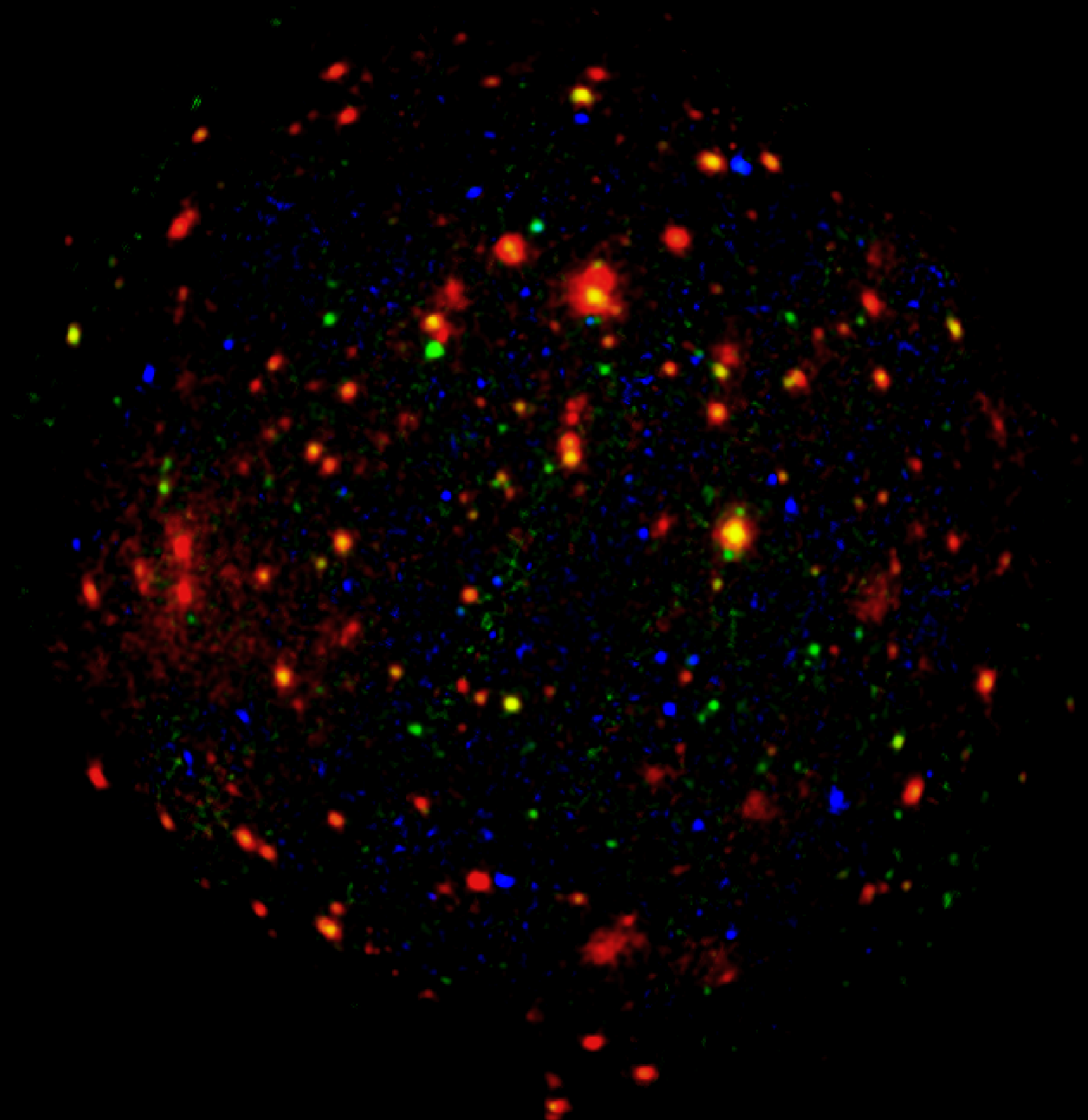
XMM

Both

Encircled Points --> Contiguous

Brandt&Hasinger 2005 ARAA

Deep X-ray surveys

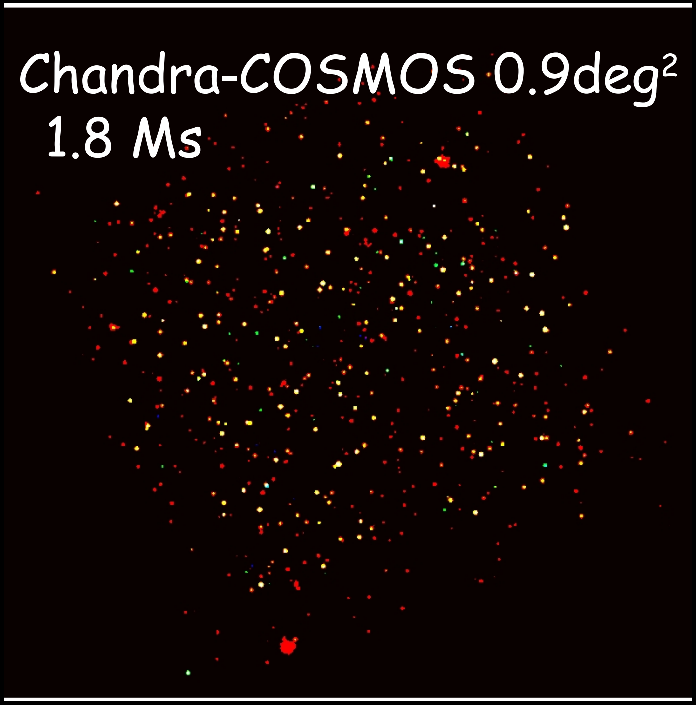


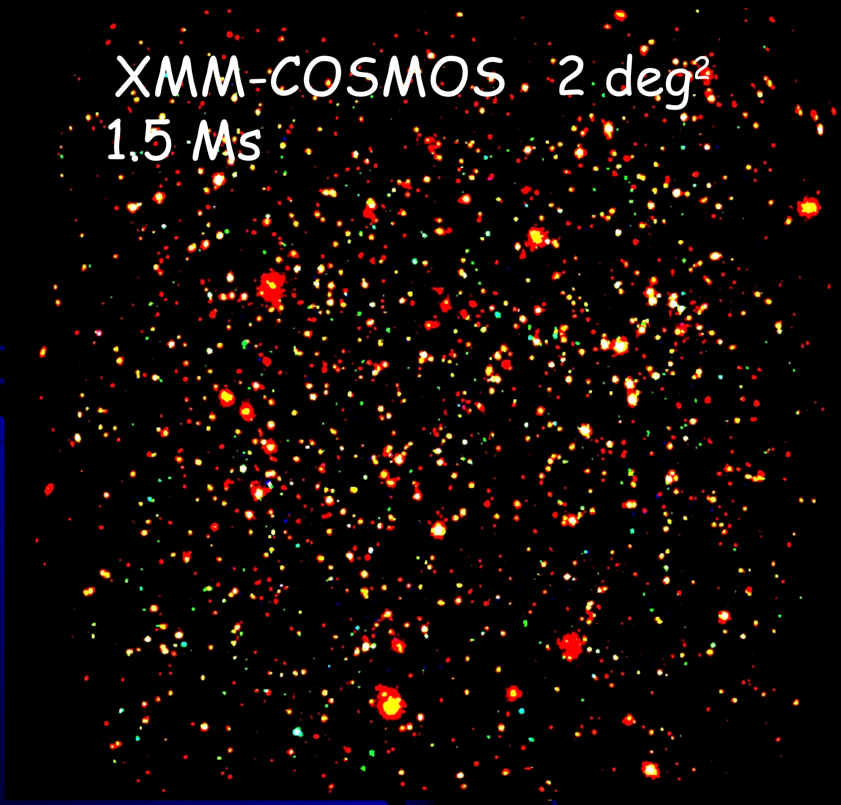
Chandra 2 Ms

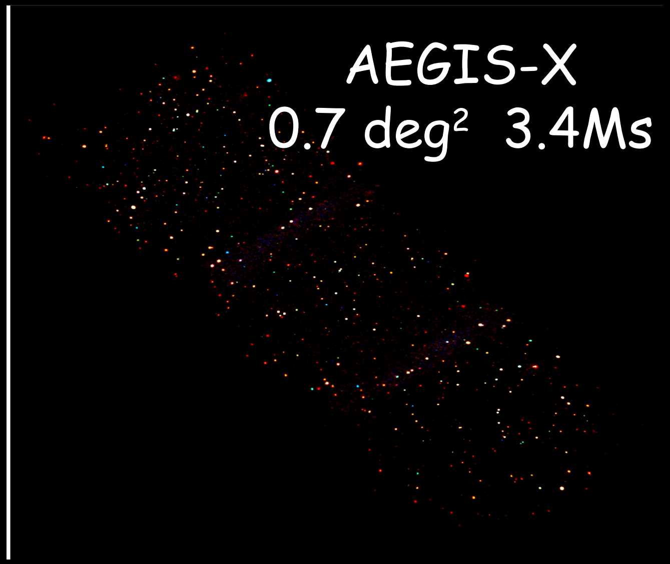
4 Ms (Now !)
Aug. 2010

XMM ~ 1.5 Ms
has reached
~ 2.7-3 Ms

Large area X-ray surveys

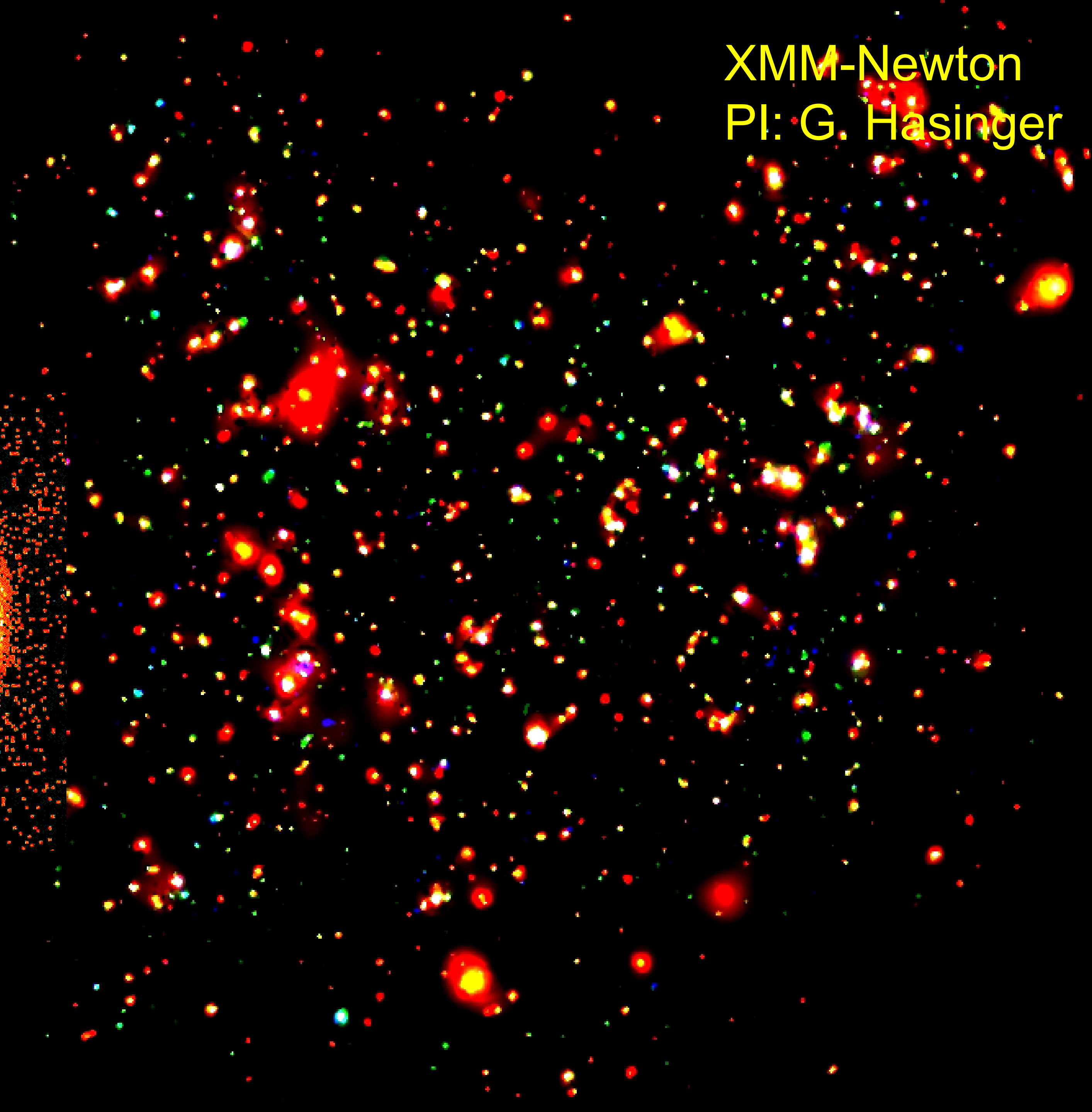


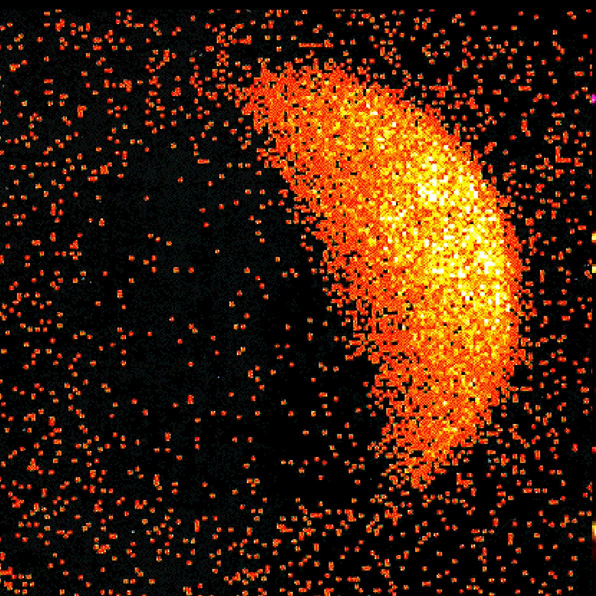


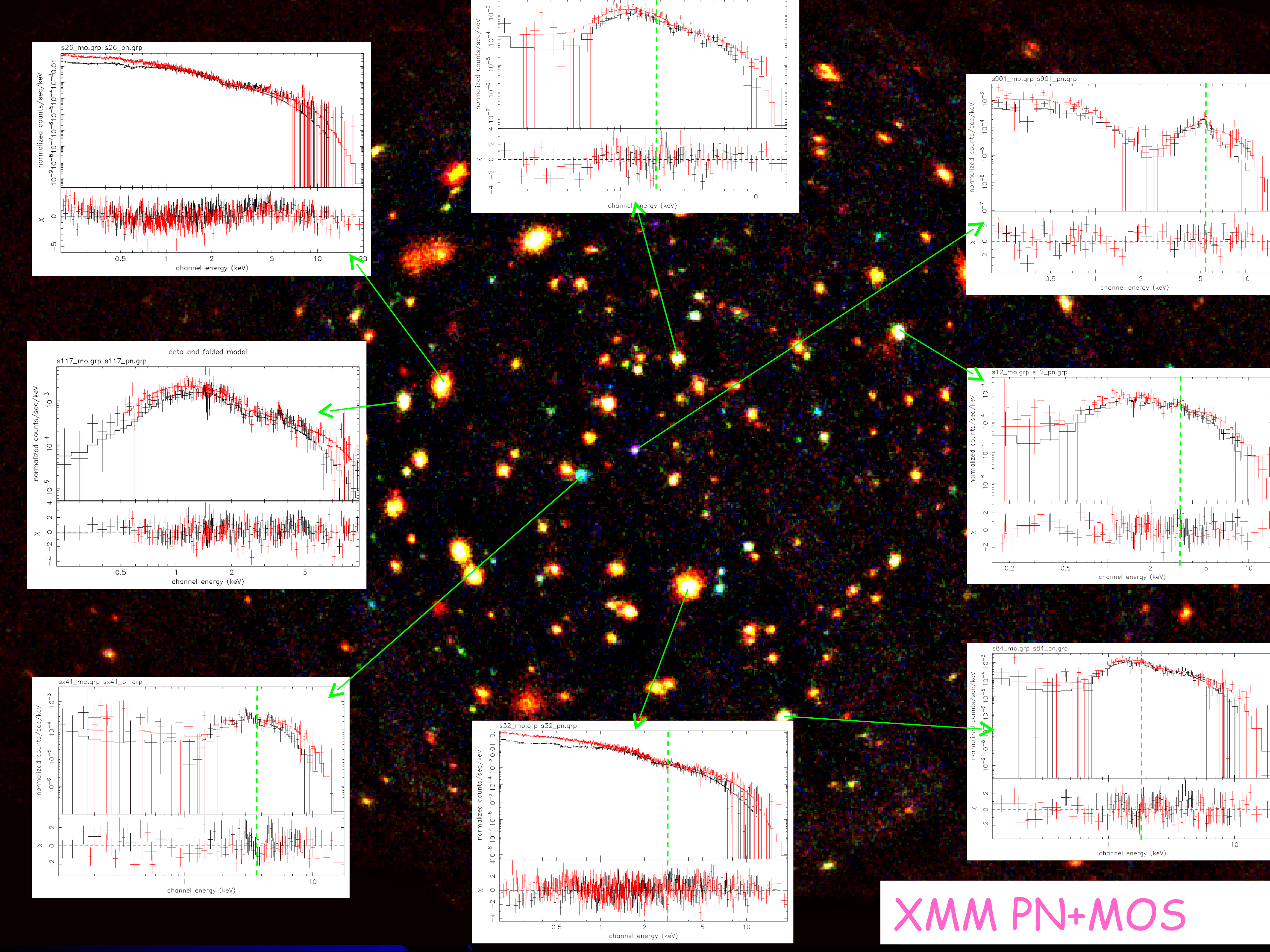


Cosmos Survey

XMM-Newton
PI: G. Hasinger

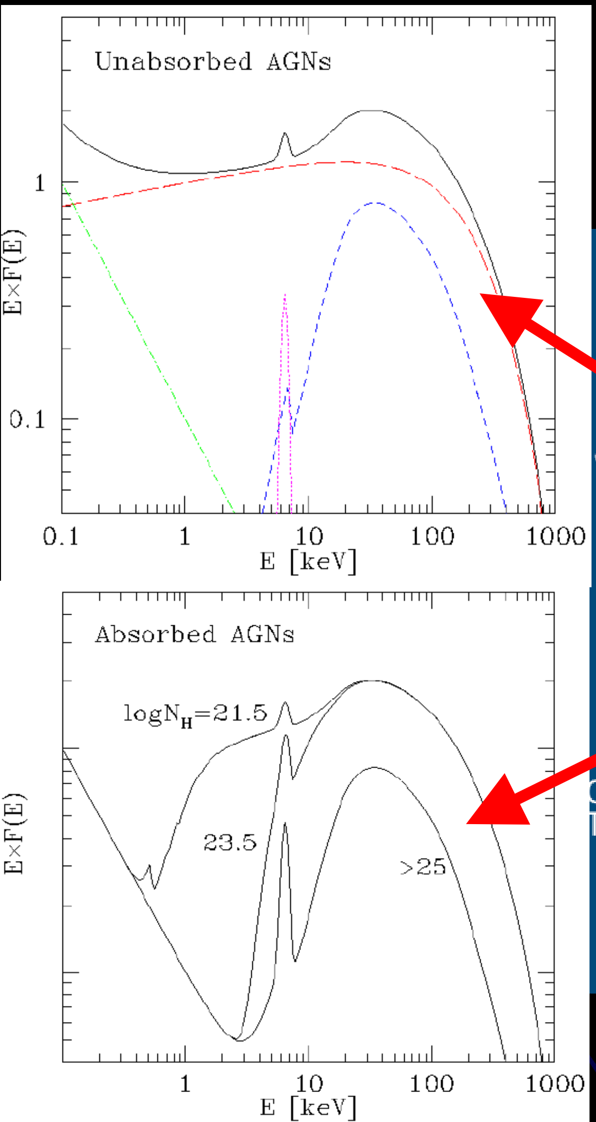




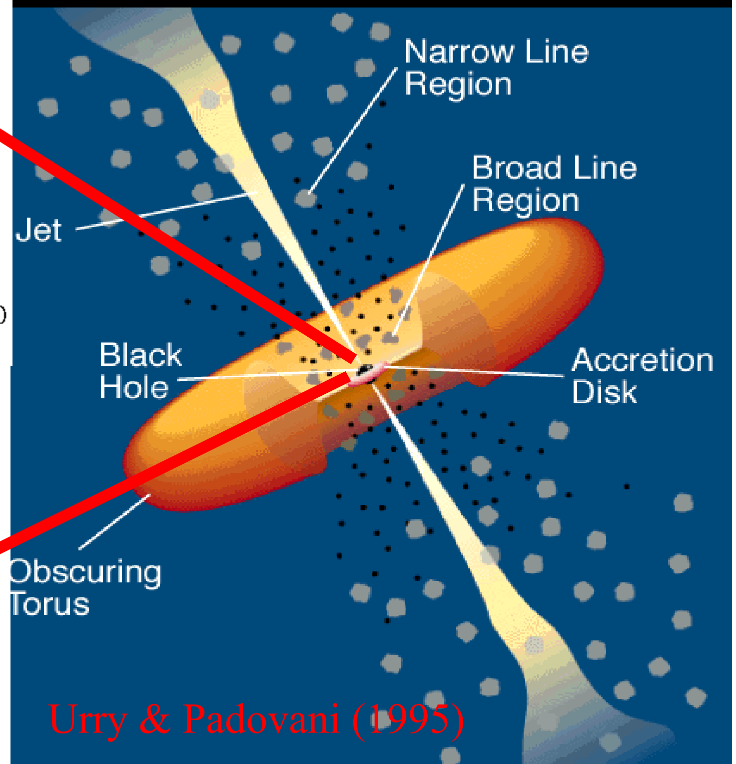


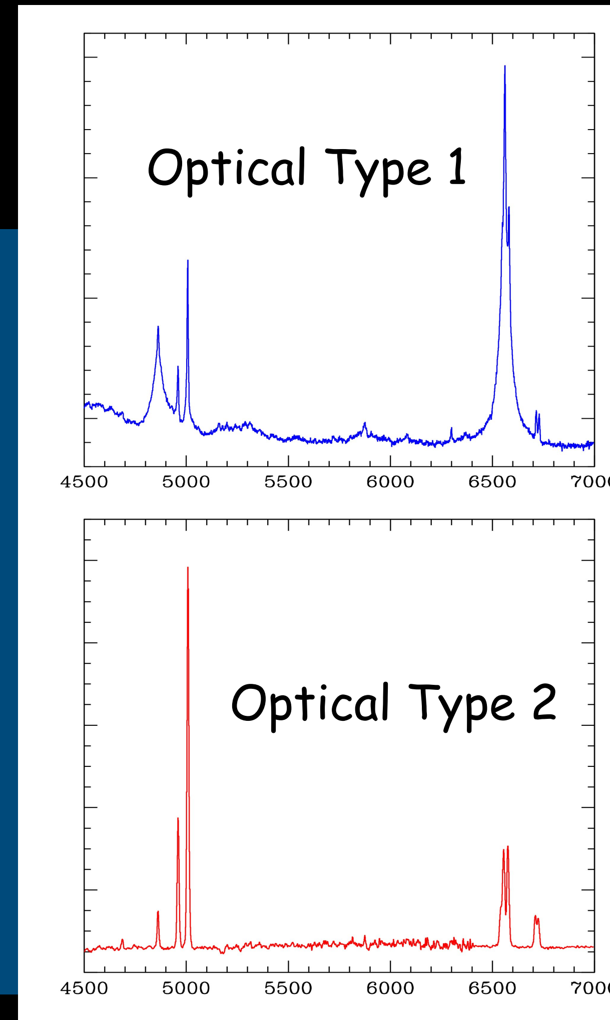
s26_mo.grp s26_pn.grp
data and folded model
s117_mo.grp s117_pn.grp
sx41_mo.grp sx41_pn.grp
s32_mo.grp s32_pn.grp
s901_mo.grp s901_pn.grp
s12_mo.grp s12_pn.grp
s84_mo.grp s84_pn.grp
normalized counts/sec/keV
channel energy (keV)
XMM PN+MOS

The AGN unified model

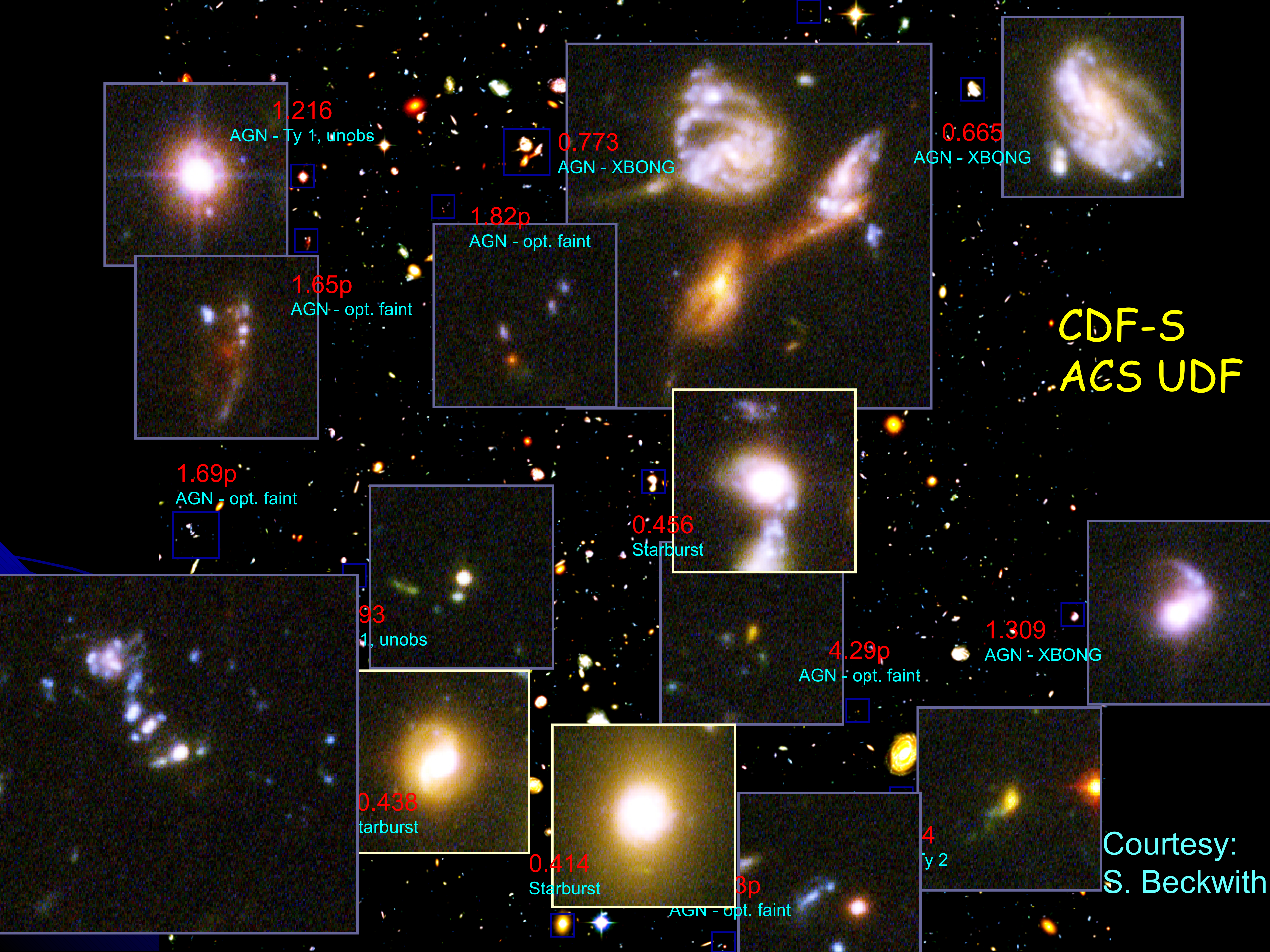


Antonucci & Miller (1985)





In the local Universe it is estimated that absorbed AGN outnumber unobscured ones by a factor of >4
--> about **80-90%** of the local AGN population is obscured.


1.216
AGN - Ty 1, unobs
0.773
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0.665
AGN - XBONG
1.82p
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1.65p
AGN - opt. faint
CDF-S
ACS UDF
1.69p
AGN - opt. faint
0.456
Starburst
93
1, unobs
4.29p
AGN - opt. faint
1.309
AGN - XBONG
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Starburst
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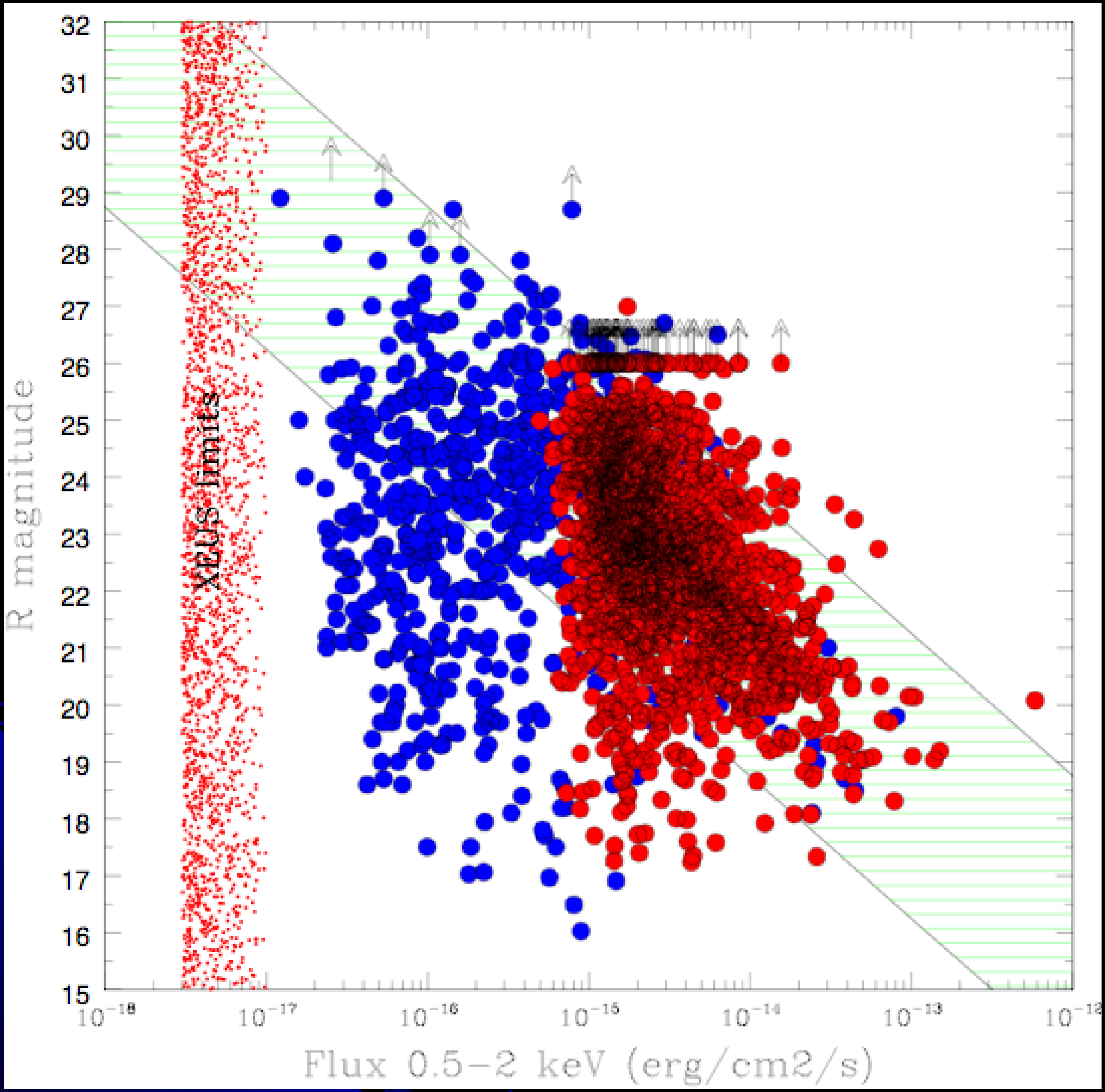
y 2
Courtesy:
S. Beckwith



COSMOS

CDFS/N

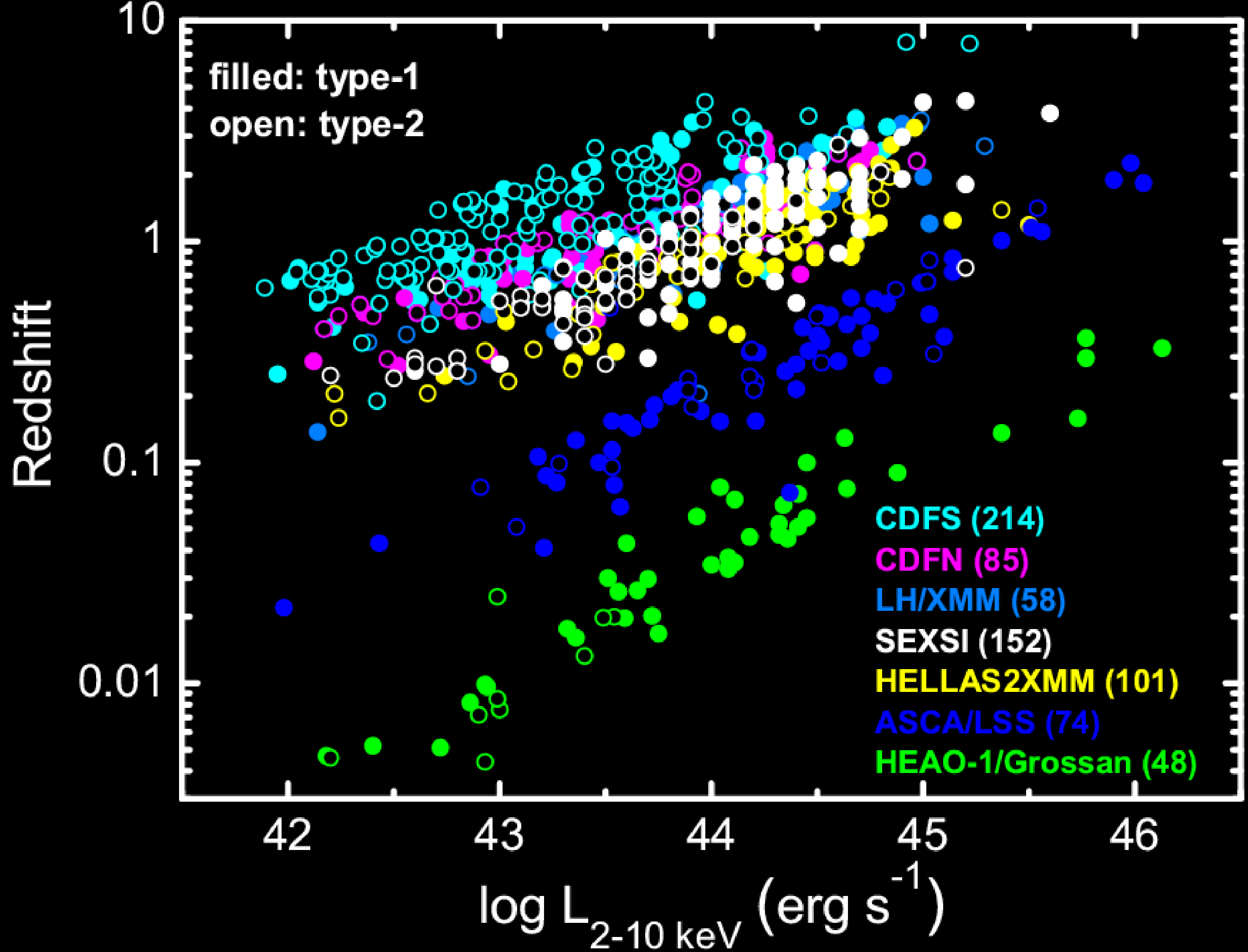
On average optically faint

For a given X-ray Flux a large Spread in optical Mag is observed

Optically identified hard samples

Type-1: opt. BLAGN, or galaxy with L_X>42, HR<-0.2 soft

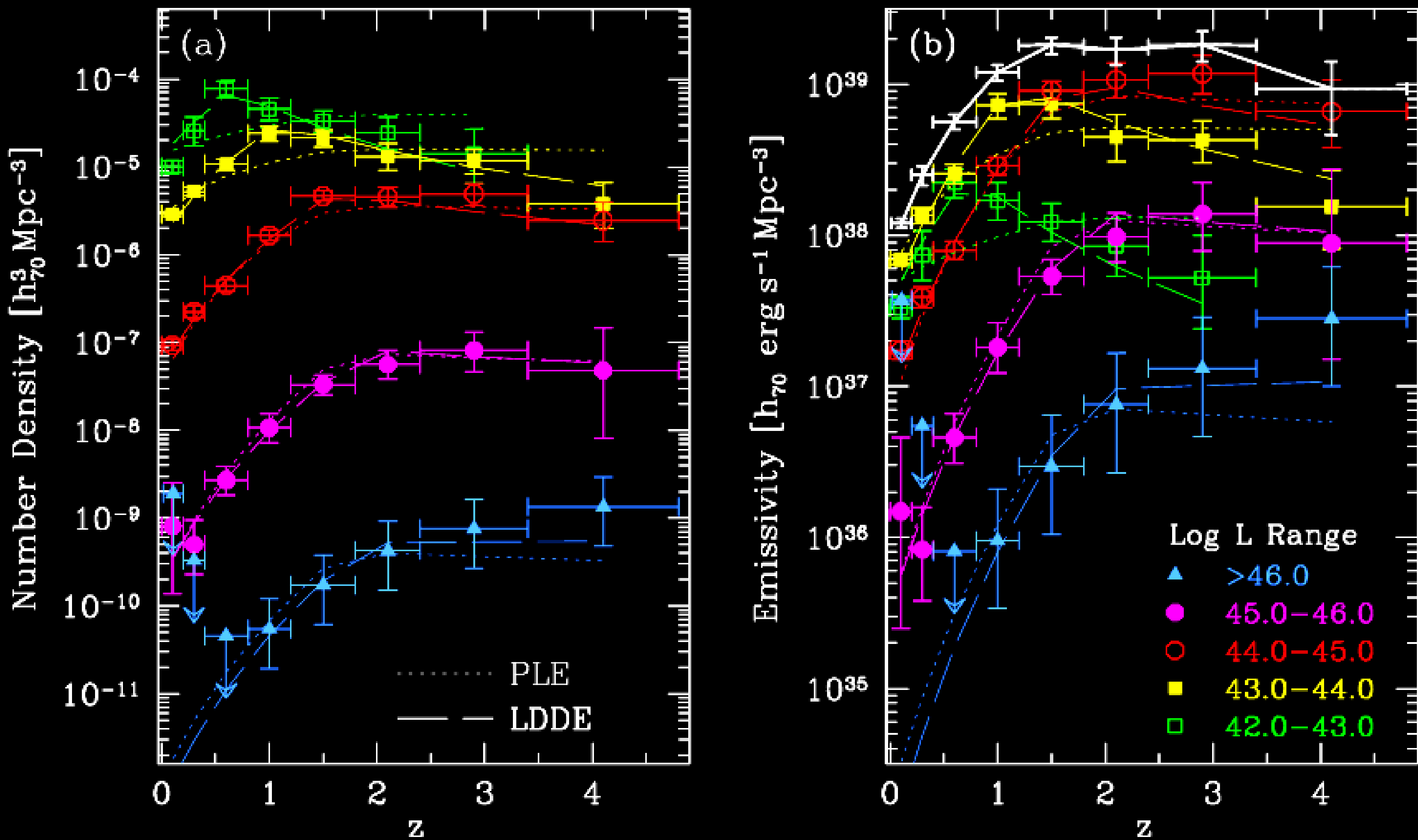
Type-2: opt. NLAGN, or galaxy with L_X>42, HR>-0.2 hard



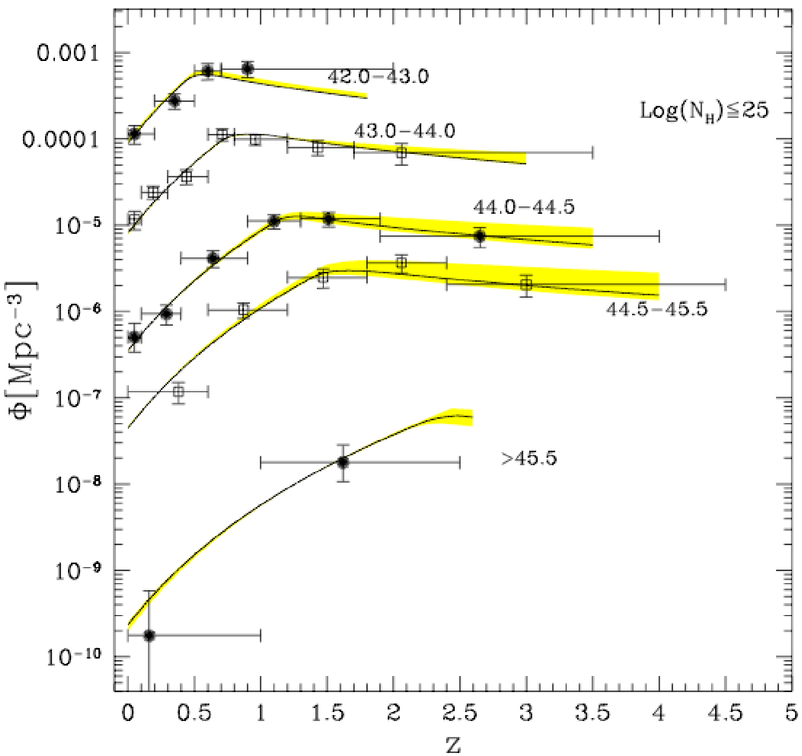
Ueda + 03
La Franca + 05
Hasinger + 05
Silverman+08
Ebrero+09
Yencho+09
Aird+10 …

> 1000 objects optical/NIR completeness ~80-90% Including photo-z

Space/Luminosity density evolution



Hasinger, Miyaji & Schmidt, 2005; Ueda et al. 2003; La Franca et al. 2005; etc etc



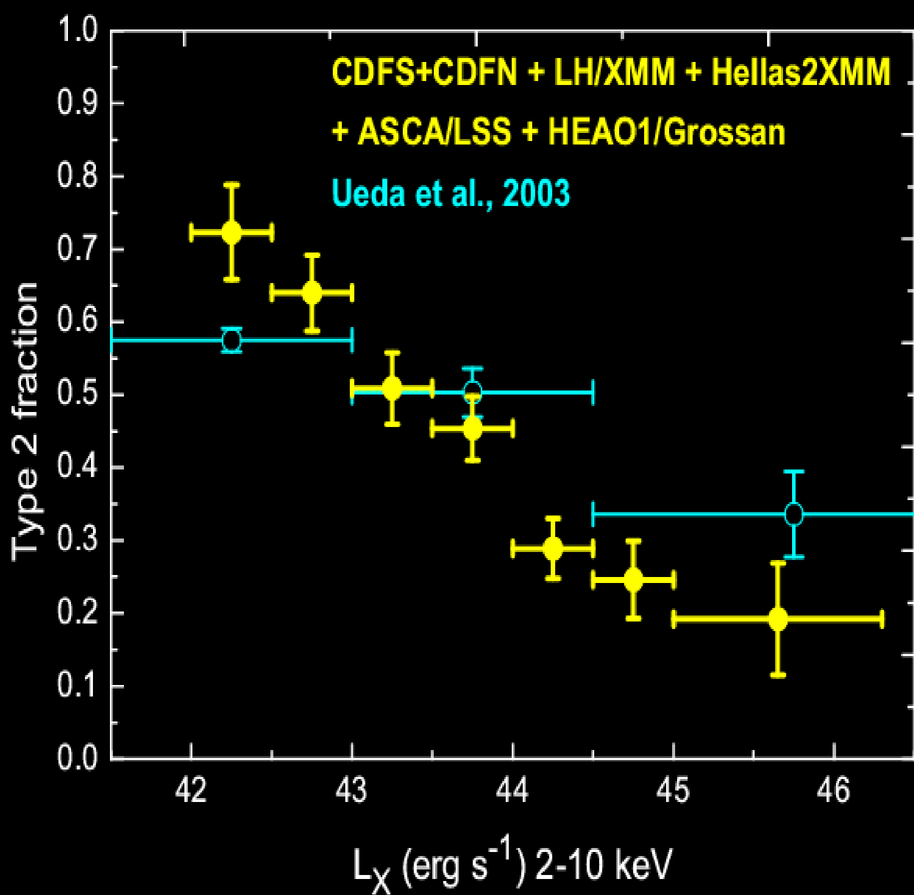
Space density of
hard X-ray selected
AGN (Ueda+03,
La Franca+05, …Aird+10)

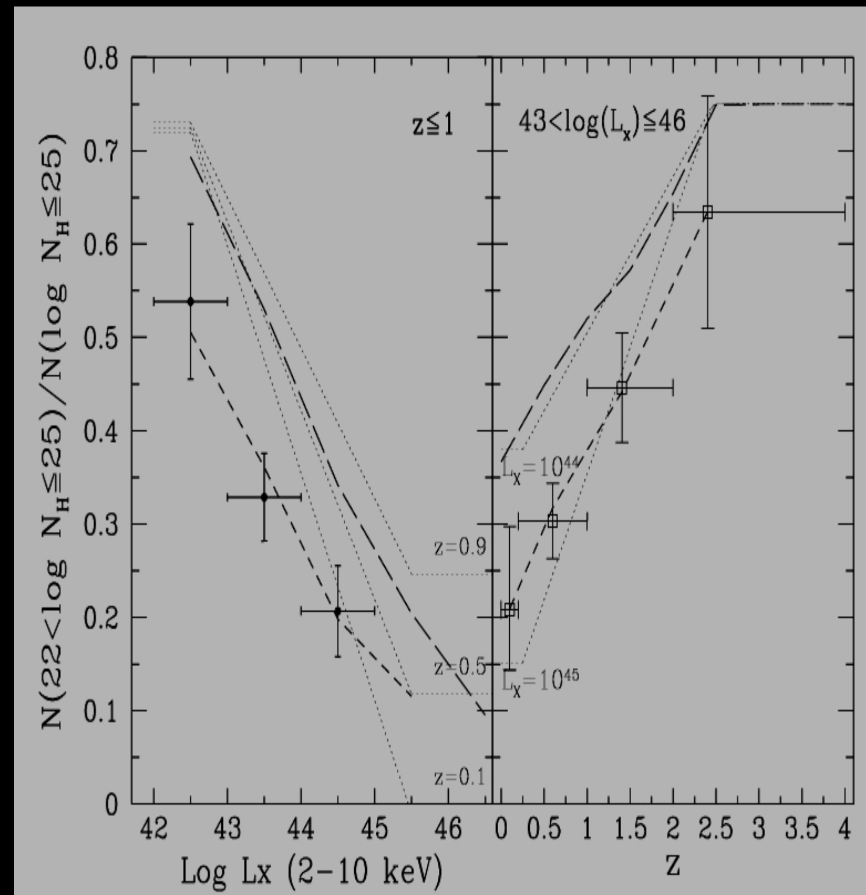
> 500 X-ray sources

Similar behavior of soft
X-ray selected samples

The peak of AGN space
Density shifts to lower z
For decreasing X-ray
Luminosity.

Absorption is L and z(?) dependent





Gilli+07 ; La Franca+05 Hasinger+05

WHAT HAVE WE LEARNED FROM X-RAY SURVEYS ?

- Few keV (< 5) XRB mostly resolved into AGN
- Unobscured and Compton Thin fairly sampled up to moderate z (~ 3)
- Rapid evolution up to a Lum. Dep. redshift (z ~ 1 for Seyferts z ~ 2-3 for QSO)
- Type 2/1 fraction decreases with L_X
- The type 2/1 fraction increases with *z (?)*
- Lot of work on galaxy colors / morphologies / SFR / clustering properties
- …

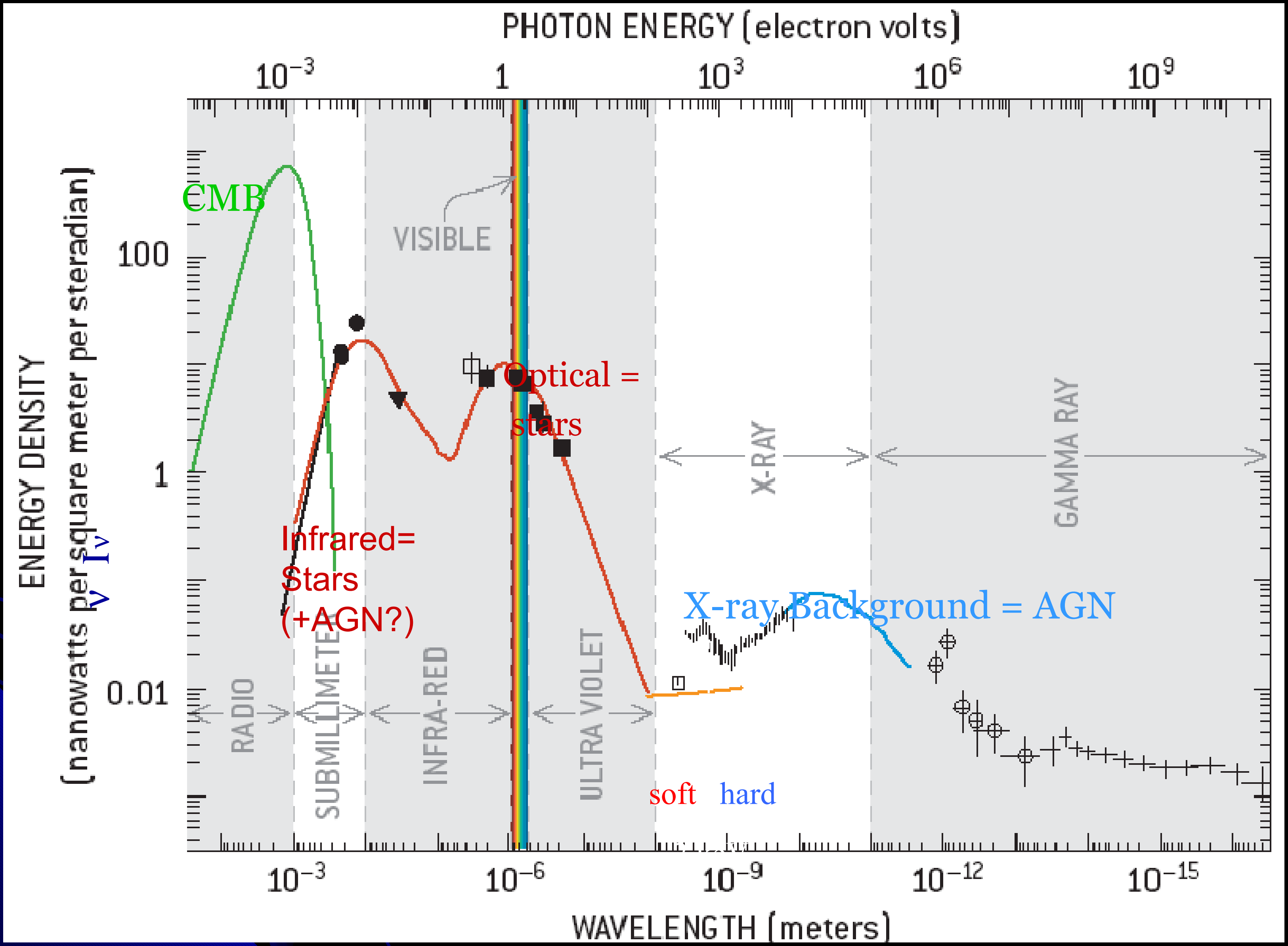
SMBH Census and evolution

Two (out of many..) missing pieces after 10+ years of X-ray and multi-wavelength surveys :

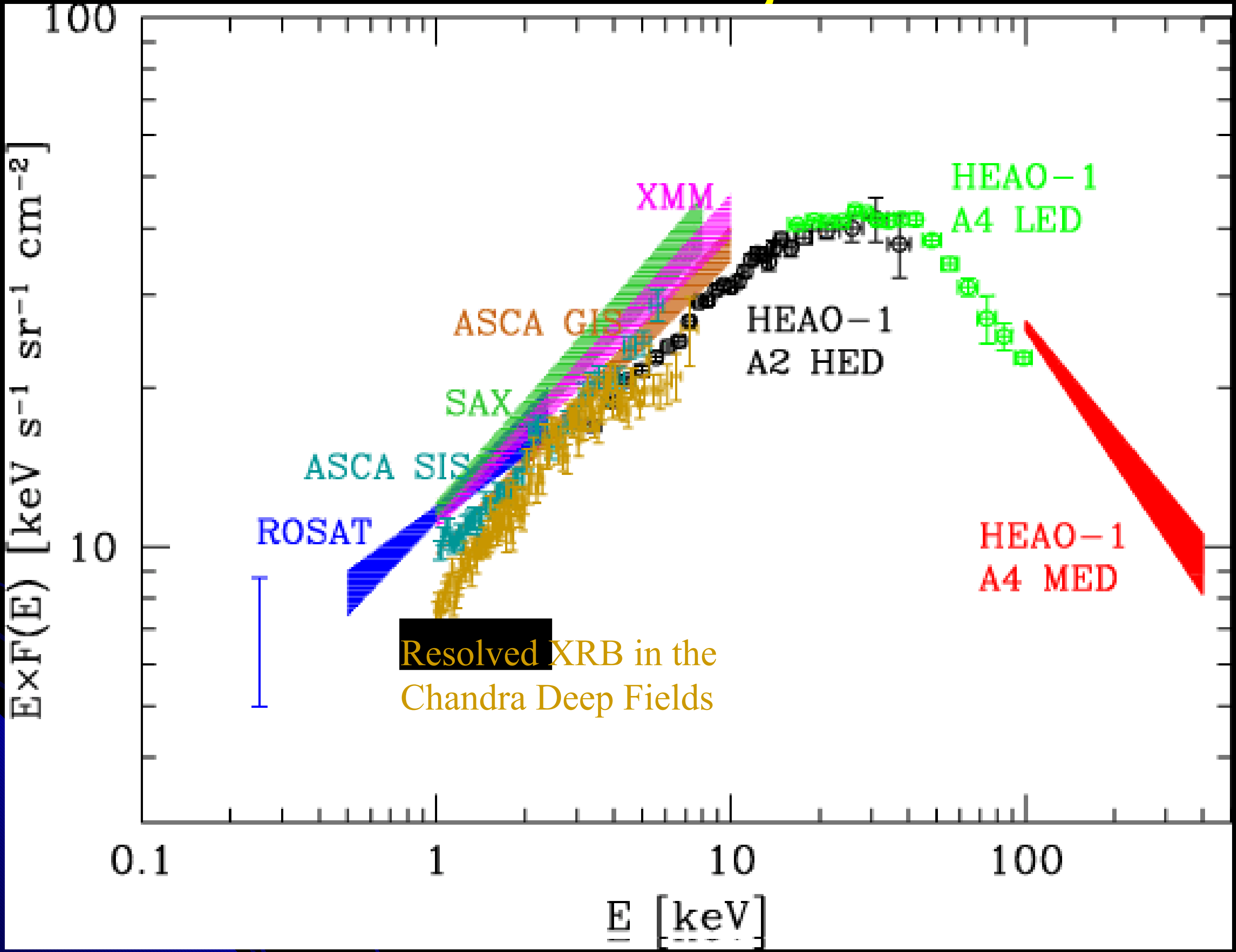
1) Heavily obscured accretion mostly unconstrained beyond the local Universe

2) BH/galaxy co-evolution is still unconstrained at very high-z ($z > 6$ or so) and poorly known at $z > 4$

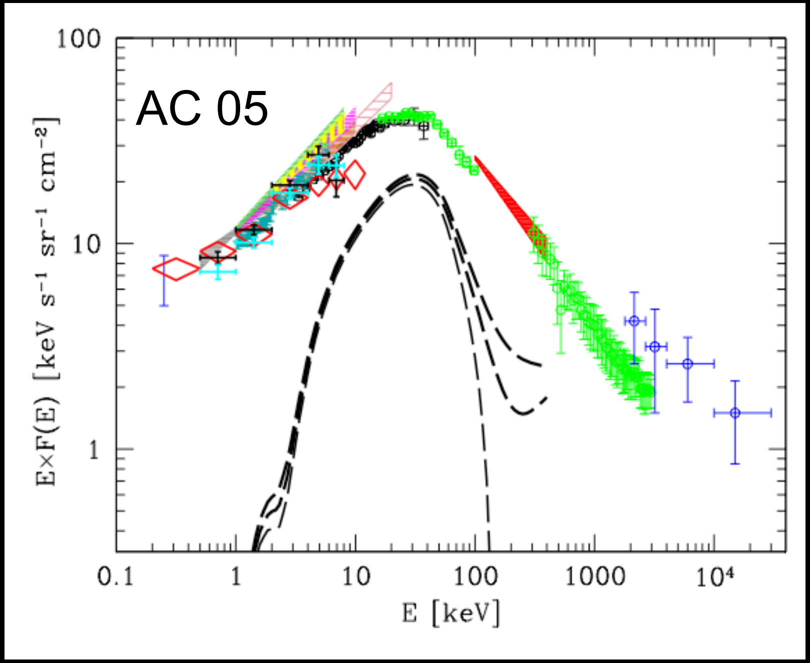
Cosmic backgrounds at different wavelengths

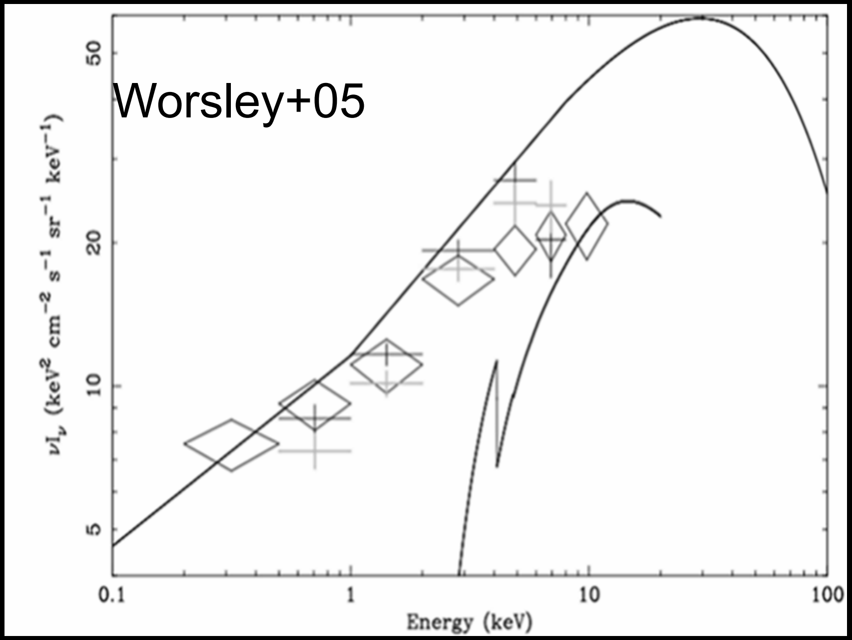


Most (50-80%) of the E < 10 keV XRB is resolved into single sources



LIMITS OF X-RAY SELECTION



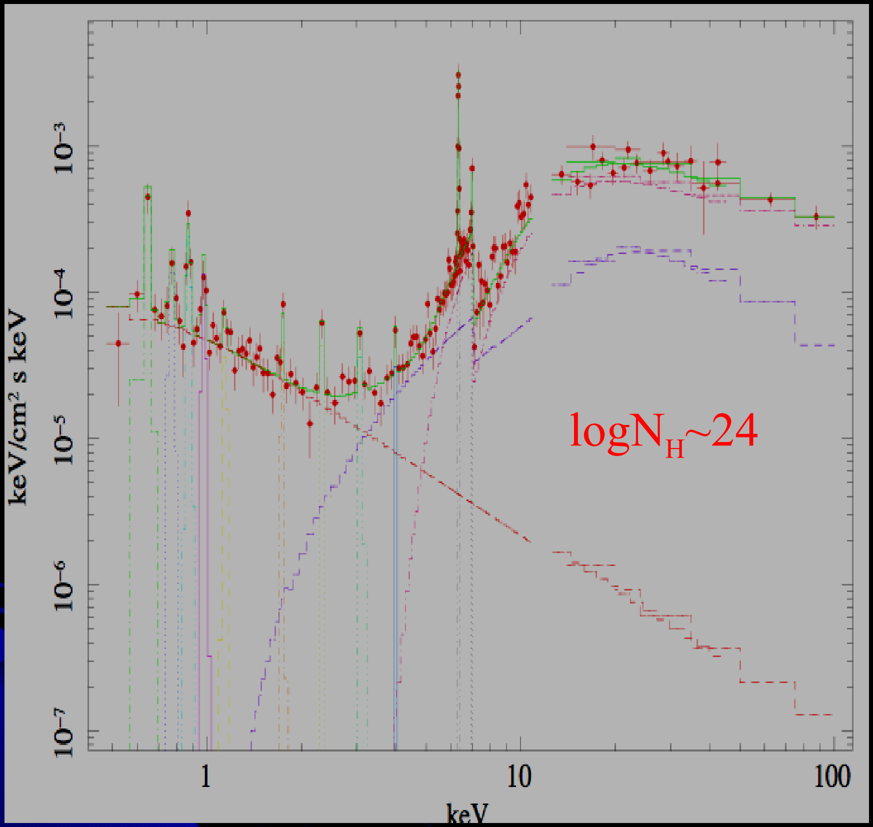


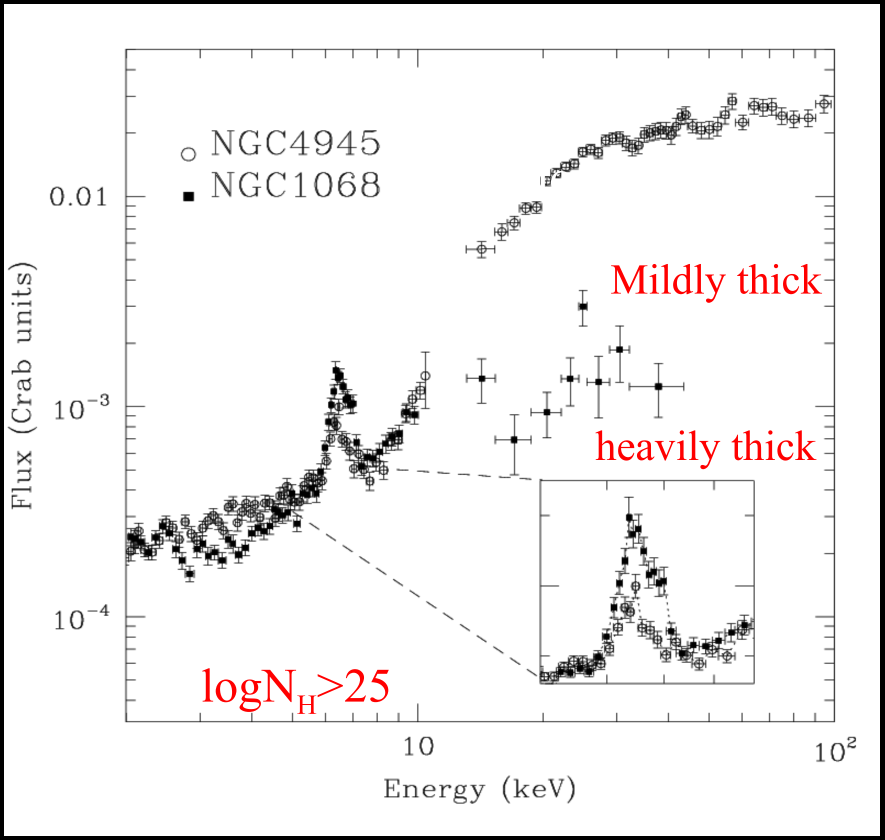
Hard X-ray surveys still miss the most obscured sources (do not sample the 25-30 keV peak of the XRB)

Missing population: (numerous) moderate luminous, log NH > 23, z = 0.5-2 (Worsley+04,05, AC 04,05) and Compton Thick AGN (log NH > 24)

[see e.g. Fiore et al. 2003, Koekemoer et al. 2004, Mignoli et al. 2004, Brusa et al. 2005, Mainieri et al. 2005, Maiolino et al. 2006, Rigby et al. 2006, Georgakakis et al. 2006, and many others

Obscured Compton-thick AGN in the nearby Universe





Seyfert 2 NGC5728 : logN_H~24 ➔ reflection + Transmission+ warm scattering

Seyfert 2 NGC4945 : logN_H~24 ➔ reflection + transmission

Seyfert 2 NGC1068 : logN_H>25 ➔ only reflection

Synthesis of the XRB

$$I(E) = \frac{1}{4\pi}\int_0^{z_{max}} \frac{1+z}{4\pi {d_L}^2}\,\frac{dV}{dz}dz\int_{L_{min}(z)}^{L_{max}(z)} f[E(1+z)]\,\rho[L(z),z]\,L(z)dL(z)$$

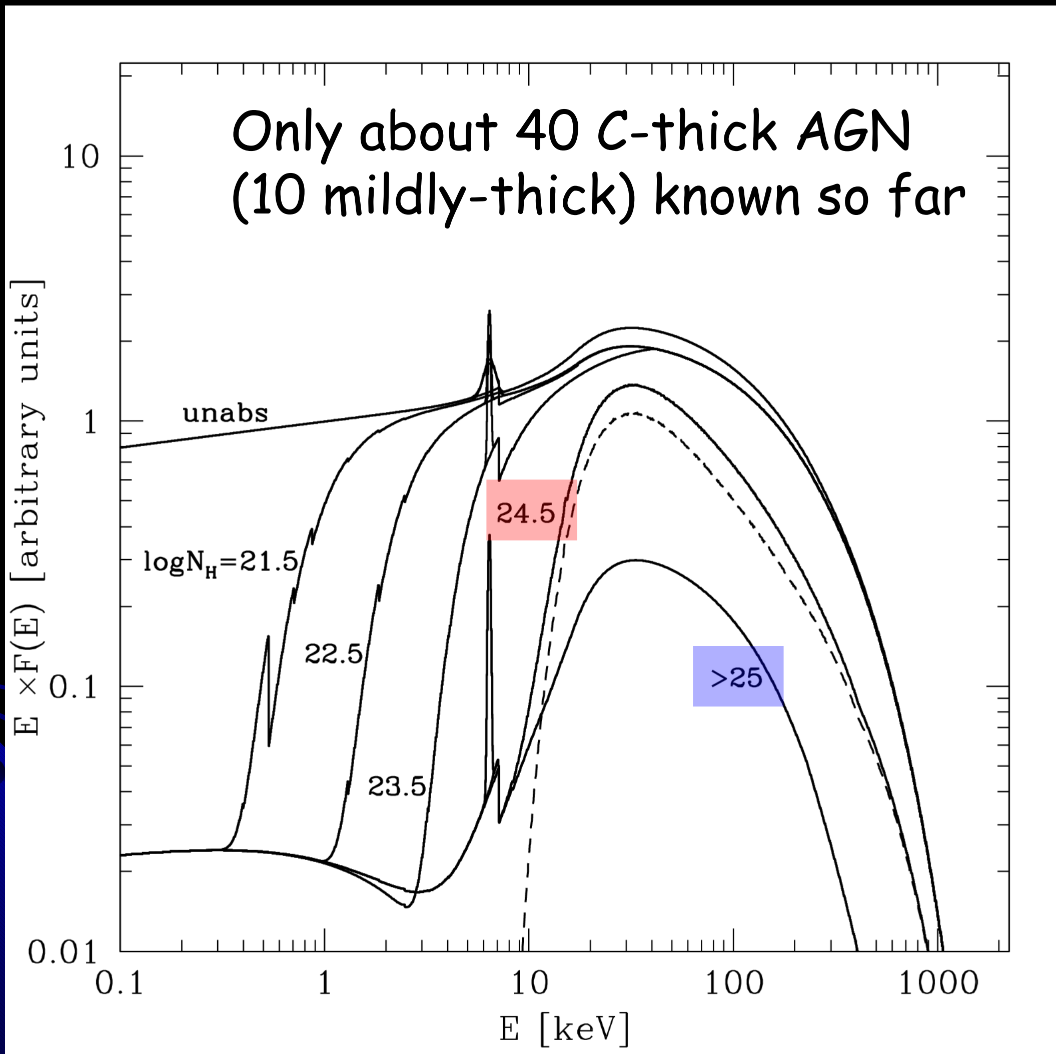
X-ray spectrum

X-ray luminosity function

$I(E)$=cosmic XRB intensity . Usually in units of keV/cm^2/s/sr/keV

The XRB synthesis provides an integral constraint

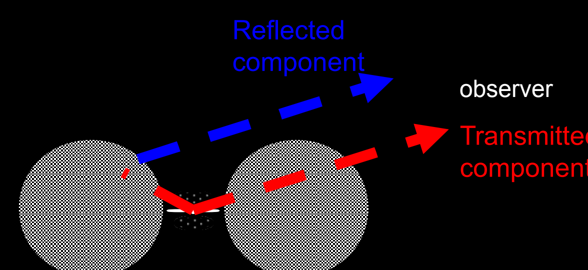
AGN X-ray spectral templates with different N_H



Unabsorbed:
$\log N_H < 21$

Compton-Thin:
$21 < \log N_H < 24$

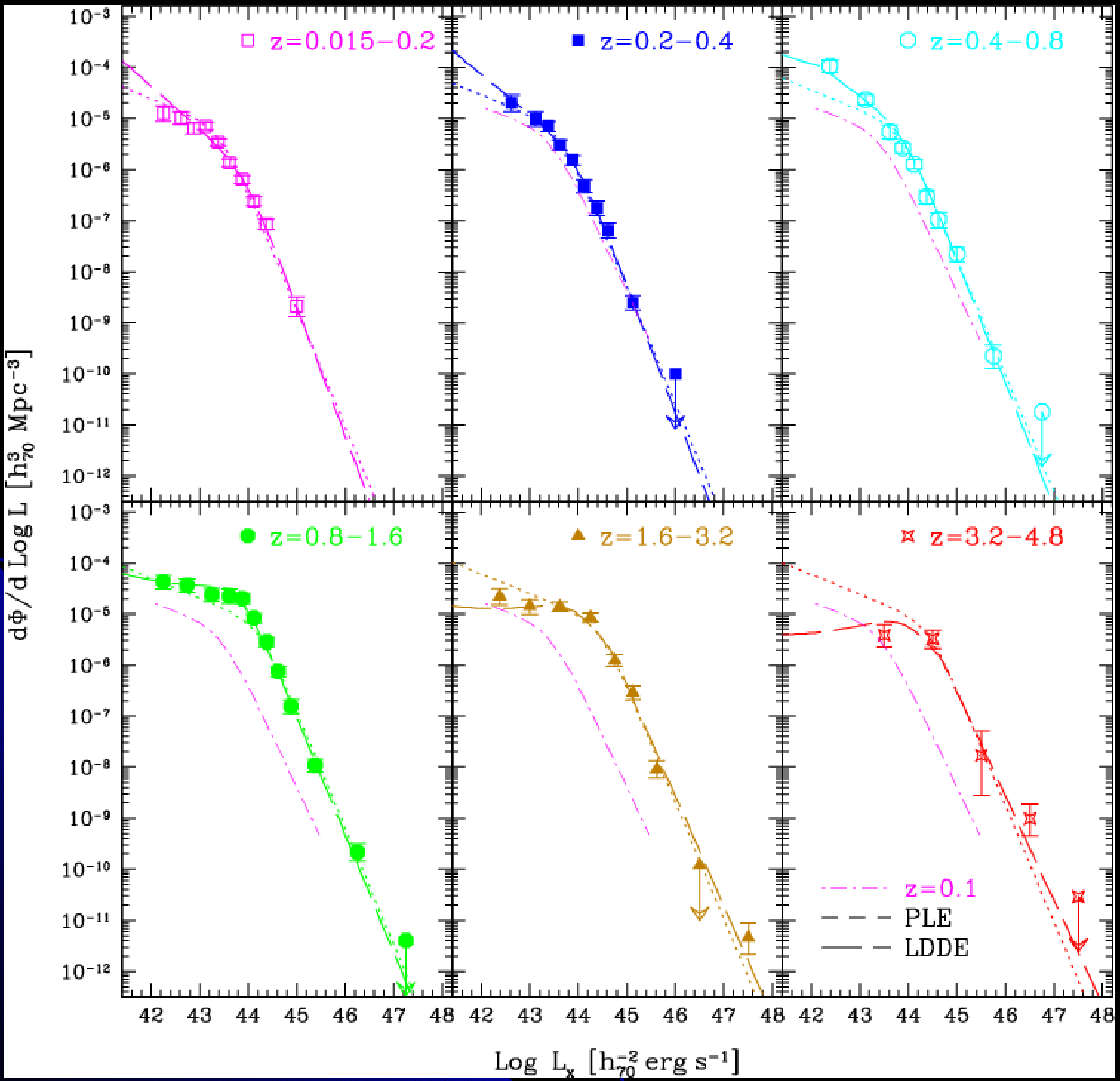
Compton-Thick:
Mildly ($\log N_H$ =24-25)
Heavily ($\log N_H$ >25)



The cold gas in the torus contributes to the iron Kα line emission.

As N_H increases, the spectrum is absorbed towards higher and higher energies.

AGN luminosity function in the soft band (unobscured AGN only)

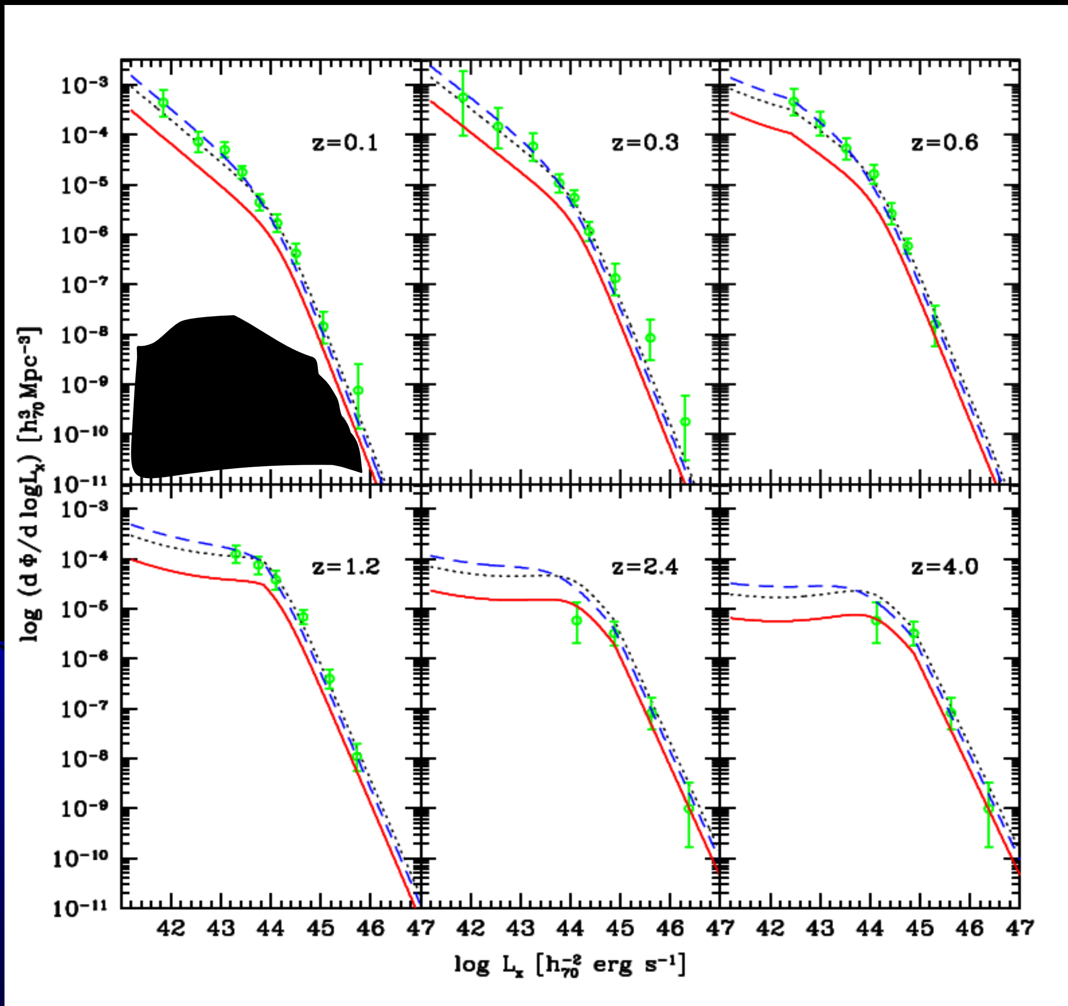


Luminosity dependent density evolution (LDDE): evolution rate is higher for high luminosity objects

From

Hasinger, Miyaji & Schmidt (2005)

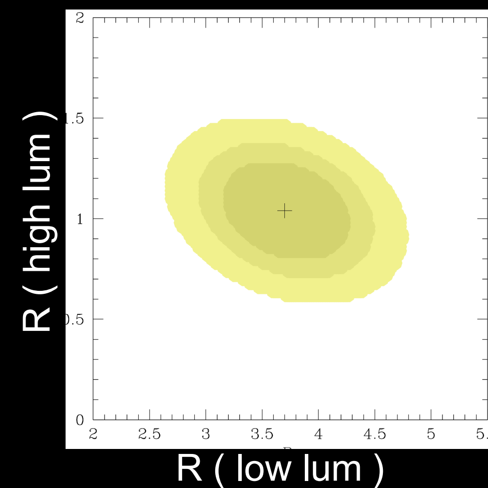
Hard band (2-10 keV) LF: unabs + Compton-thin AGN



Unabsorbed AGN (from soft XLF)

Total Compton-thin AGN (abs/unabs ratio decreasing with increasing Lx)

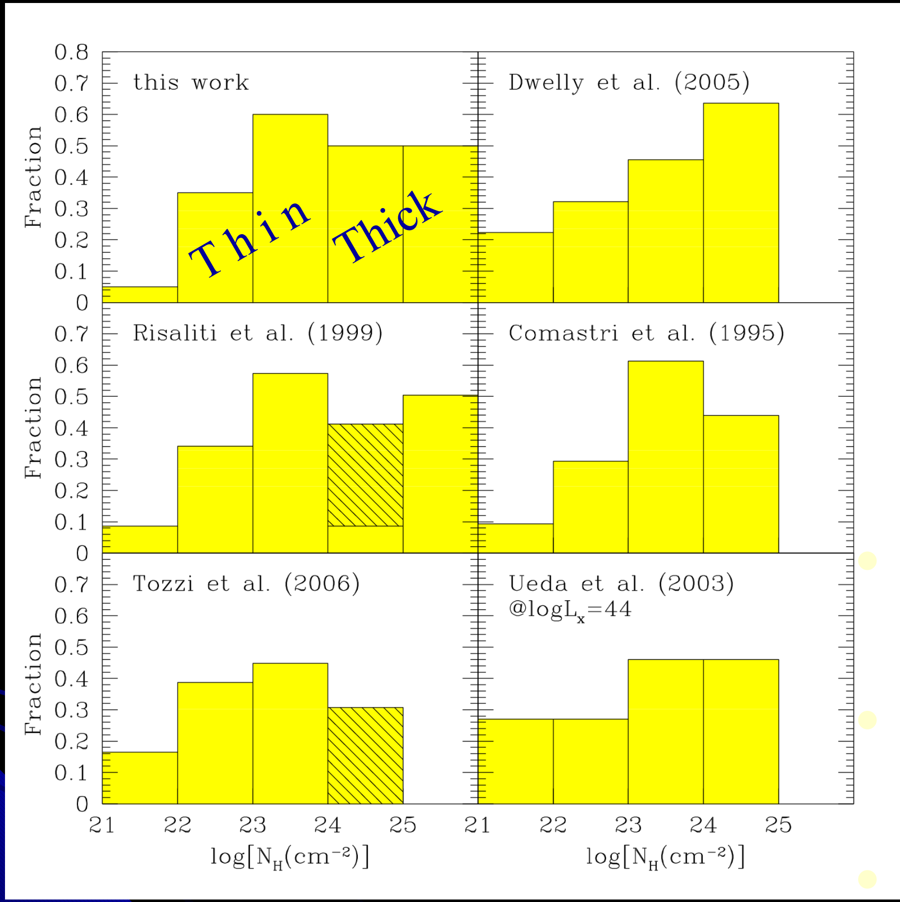
Total Compton-thin AGN (constant abs/unabs ratio)

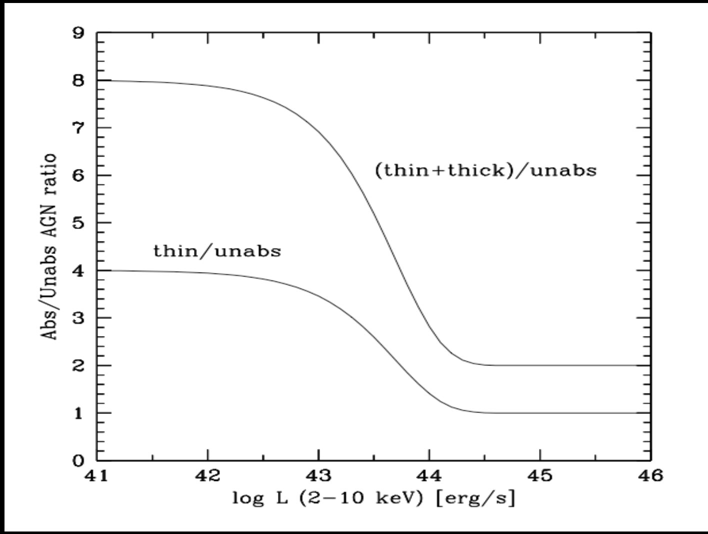


Best fit thin/unabs ratios: ~ 4 for Log Lx ~ 42 erg/s

~ 1 for Log Lx ~ 45 erg/s

Absorption distr. (L and z depen.)





The Obscured/Unobscured ratio is luminosity dependent

(4:1 --> 1:1) Gilli, AC, Hasinger 07

Compton Thick (log NH > 24)

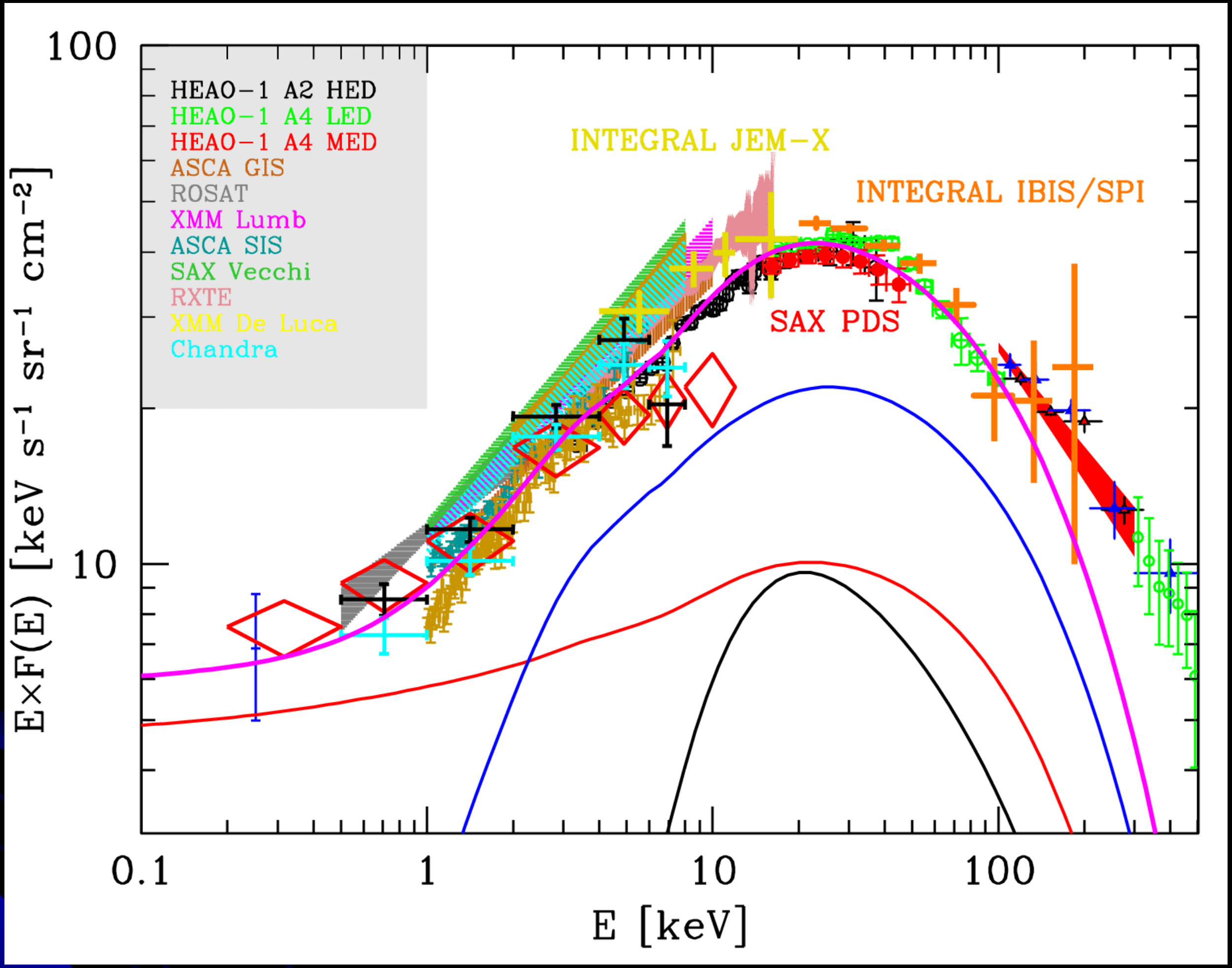
are as numerous as Compton Thin (8:1 --> 2:1)

The heavily Compton Thick AGN

(log NH > 25 i.e. NGC 1068)

are unconstrained even by XRB models --> though BH mass density arguments could help

The fit to the XRB spectrum

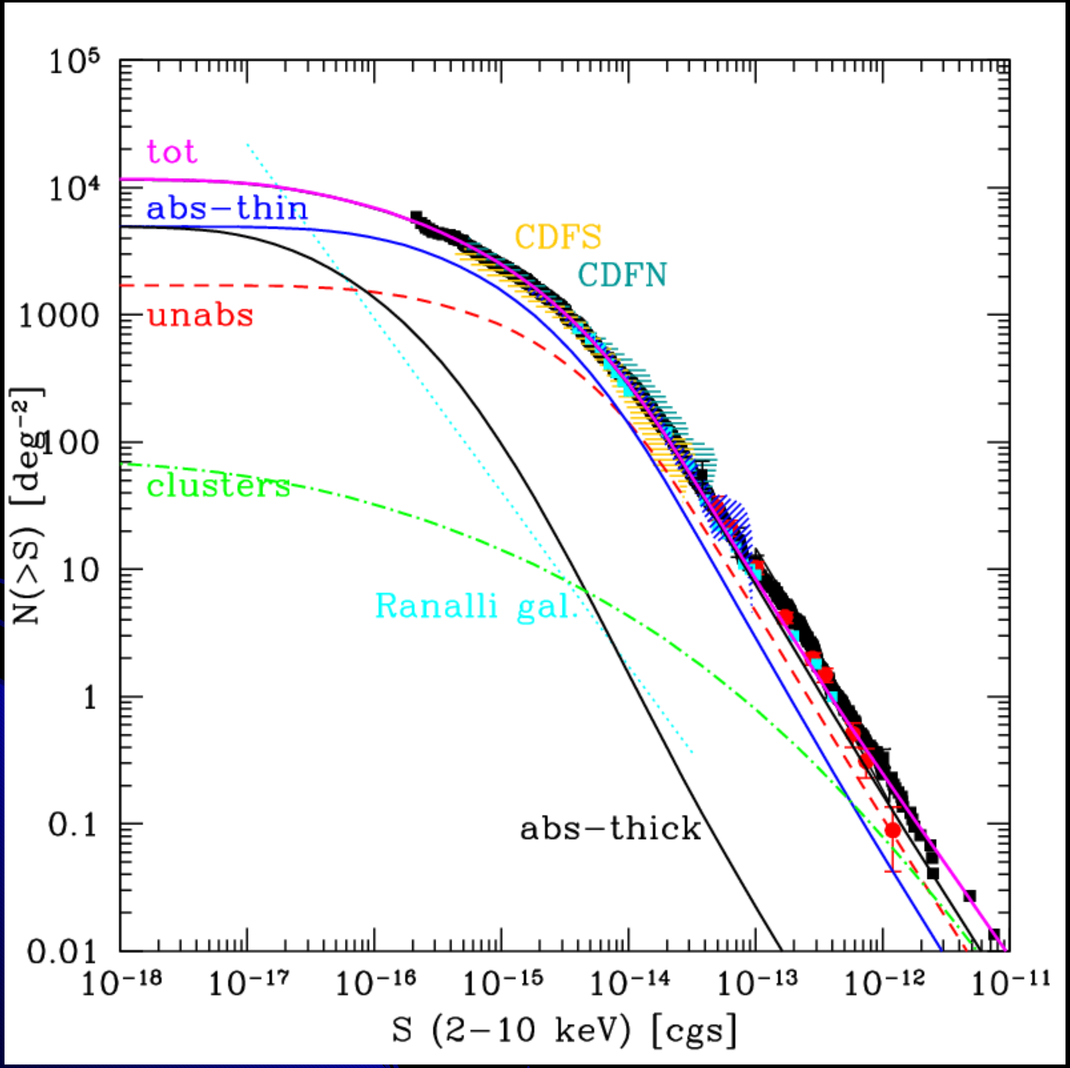


COMPTON-THICK AGN NECESSARY TO FILL THE 30 KEV GAP

INTEGRAL: Churazov et al. 2007; SAX PDS: Frontera et al. 2007

AGN number counts

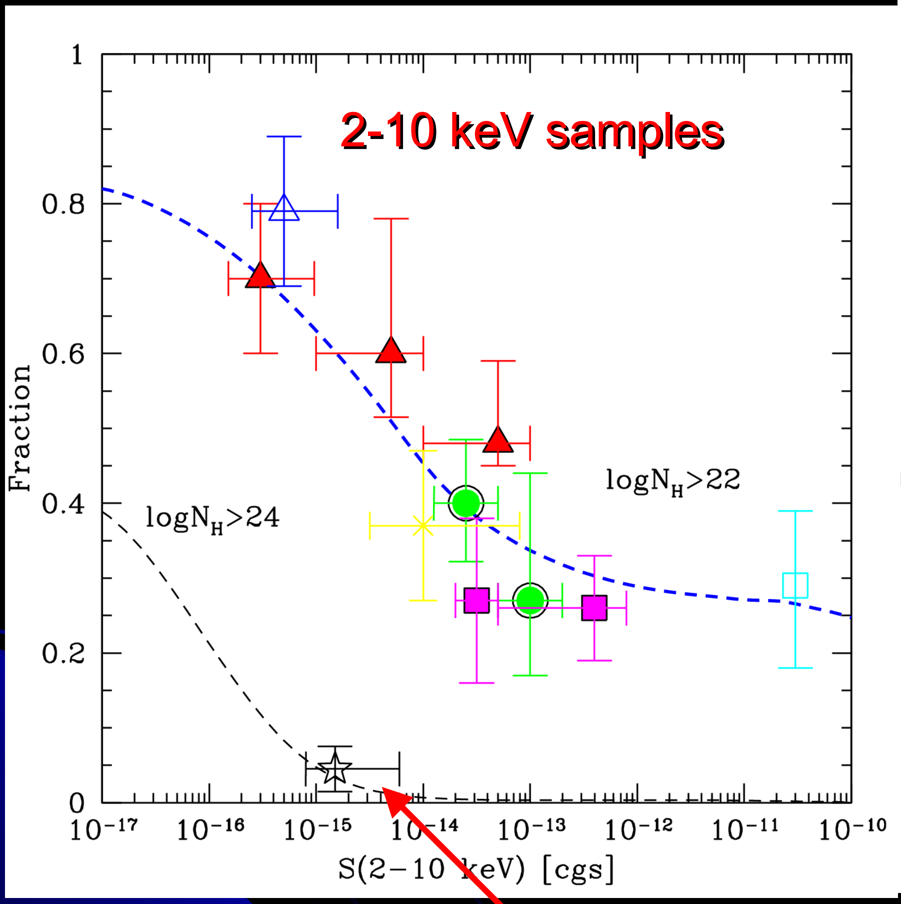
logN-logS relation: source counts above a given flux S. At bright fluxes unobscured AGN dominates, while the contribution from obscured sources increases towards fainter fluxes.

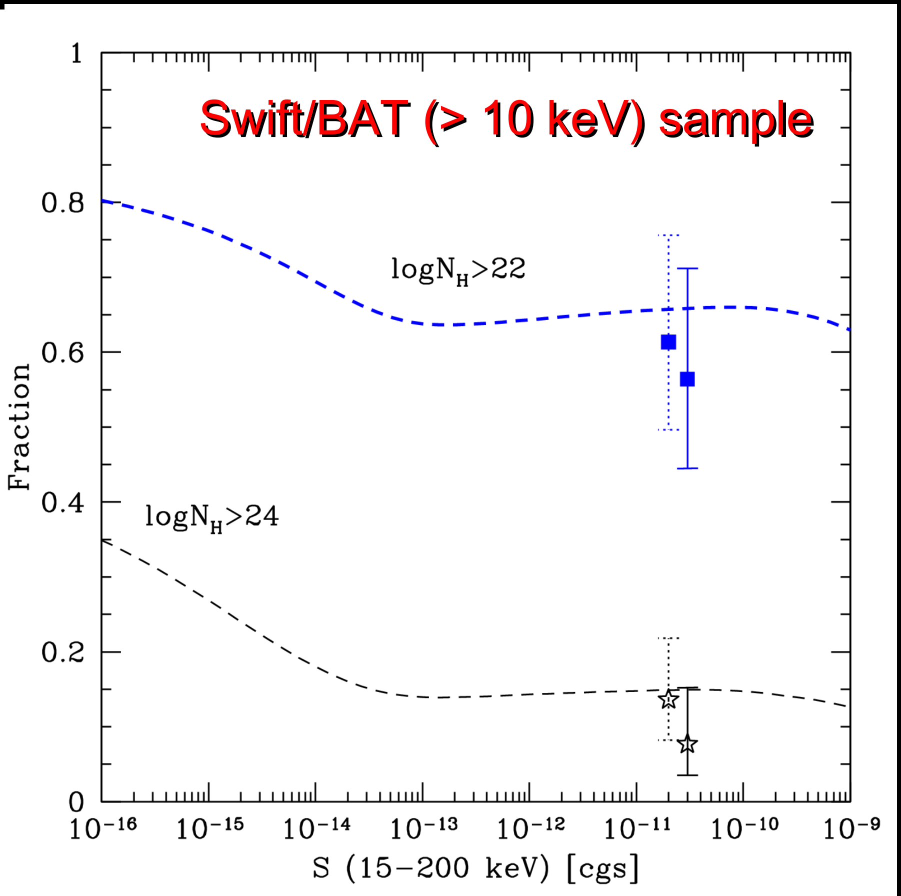


For a Euclidean Universe:
$N(>S) \sim S^{-1.5}$

[cgs] = erg/cm^2/s

Obscured AGN fraction vs sample limiting flux

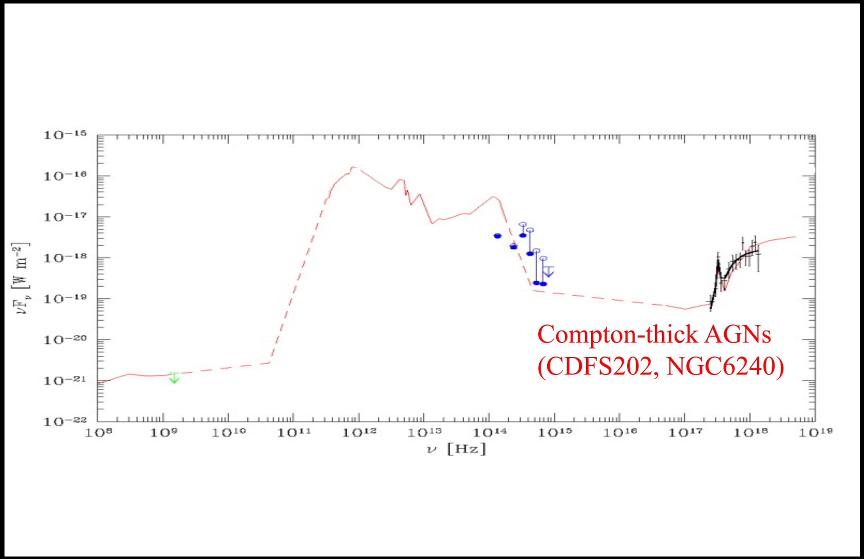




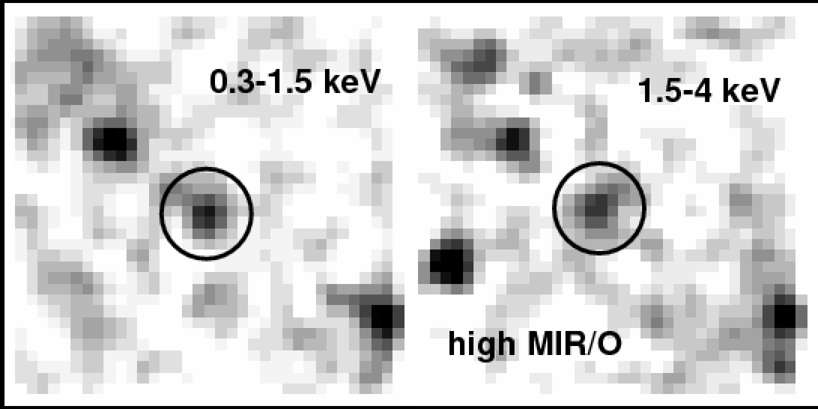
Compton-thick candidates in the CDFS (Tozzi et al. 2006)

Compton-thick AGN are present in very small numbers in current samples

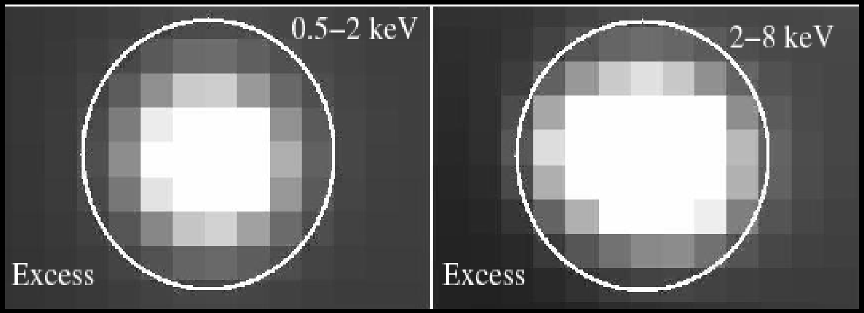
Where to look for Compton-thick AGN (IR?)



From Norman et al. (2002)



From Fiore et al. (2007)

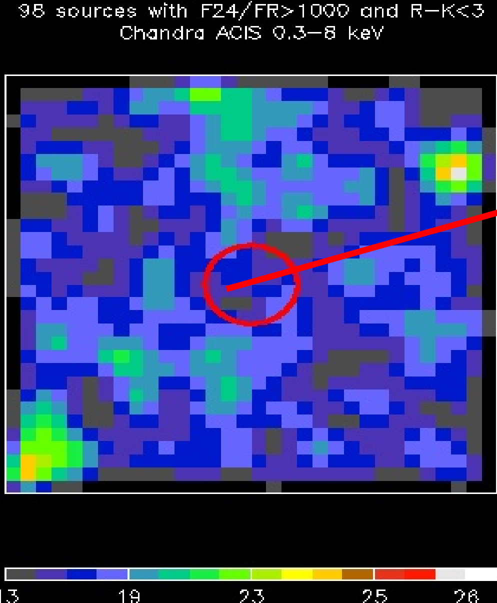


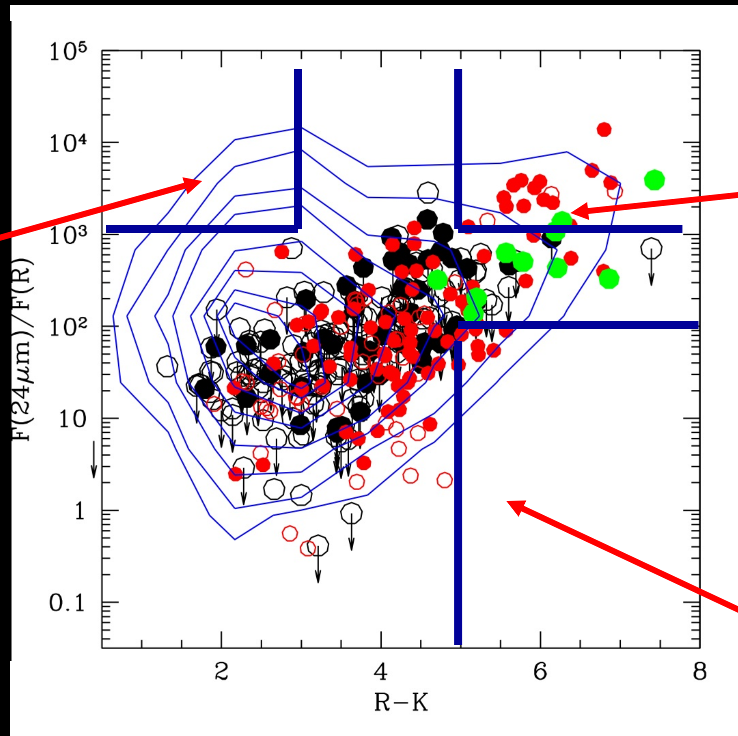
From Daddi et al. (2007)

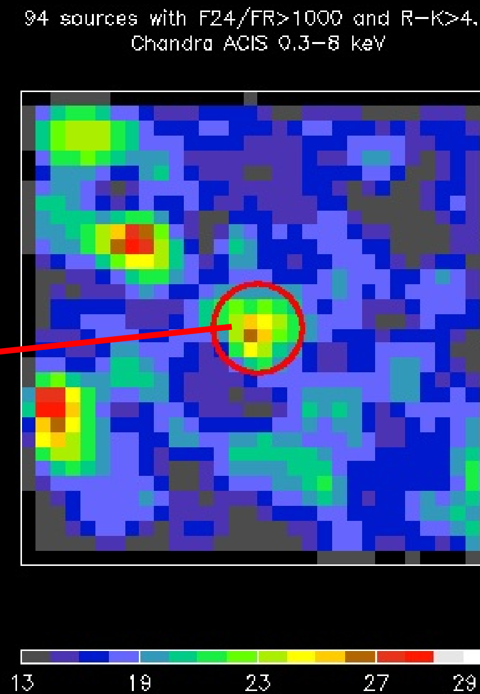
Radiation absorbed by the torus re-radiated in the IR band: X-ray stacking of sources which are not detected individually in the X-rays but show a mid-IR excess wrt to stellar emission

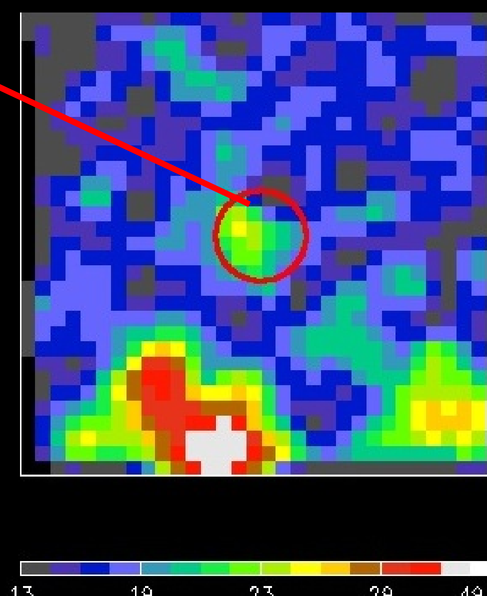
Large population of C-thick AGN candidates at z~2 (N thick ≥ N thin)

MIR AGNs


98 sources with F24/FR>1000 and R−K<3
Chandra ACIS 0.3−8 keV
13 19 23 25 26

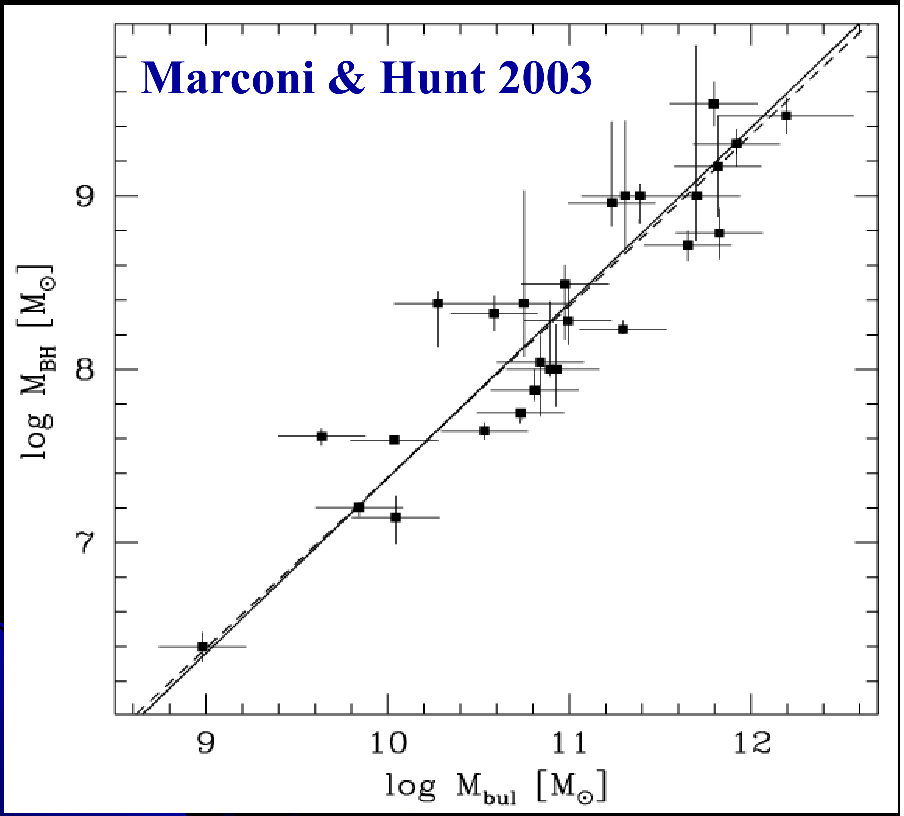

10^5
10^4
10^3
10^2
10
1
0.1
F(24μm)/F(R)
2 4 6 8
R−K

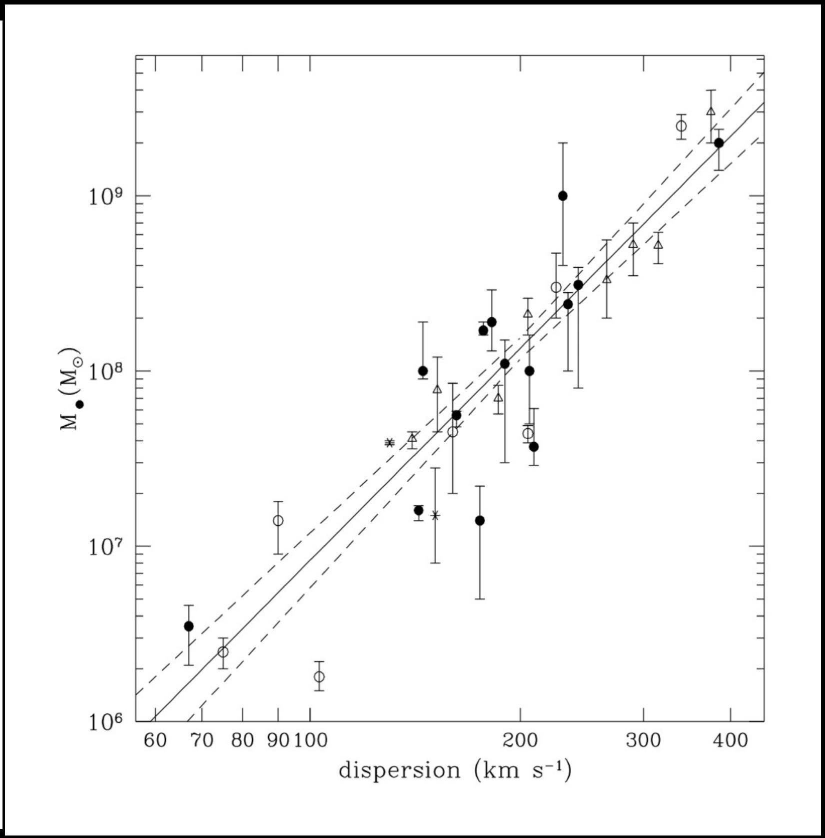

94 sources with F24/FR>1000 and R−K>4.5
Chandra ACIS 0.3−8 keV
13 19 23 27 29


13 19 23 29 49


CAMERA
CAFÉ

M_{BH} vs M_{bul}





- Tight correlation between M_{BH} and virial bulge mass ($\approx R_e\ \sigma_e^2$) with *rms* 0.25 (all 0.5).
- Linear slope (0.96+/-0.07), average ratio $M_{BH}/M_{bul} \simeq \Sigma$ 0.002.

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 $k_{bol}^B \simeq 15$

$2.2\times10^5\ M_\odot\ Mpc^{-3}$ (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 $k_{bol}^X \simeq 30$

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

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

Optical counts and pre Chandra/XMM estimates of the BH mass density

Lower limit = only UNOBSCURED objects

All hard X-ray sources (accretion dominated)

Main assumptions in estimate from the XRB intensity:

- Redshift distribution ($\langle z \rangle$)
- Efficiency (η)
- Bolometric correction (k_{bol})

BH mass density from "recent" luminosity function and z distribution

(i.e. Marconi+04)

$$\rho_{\bullet} \sim 4\text{-}5 \times 10^{5}\ M_{\odot}\ \mathrm{Mpc}^{-3}$$

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)

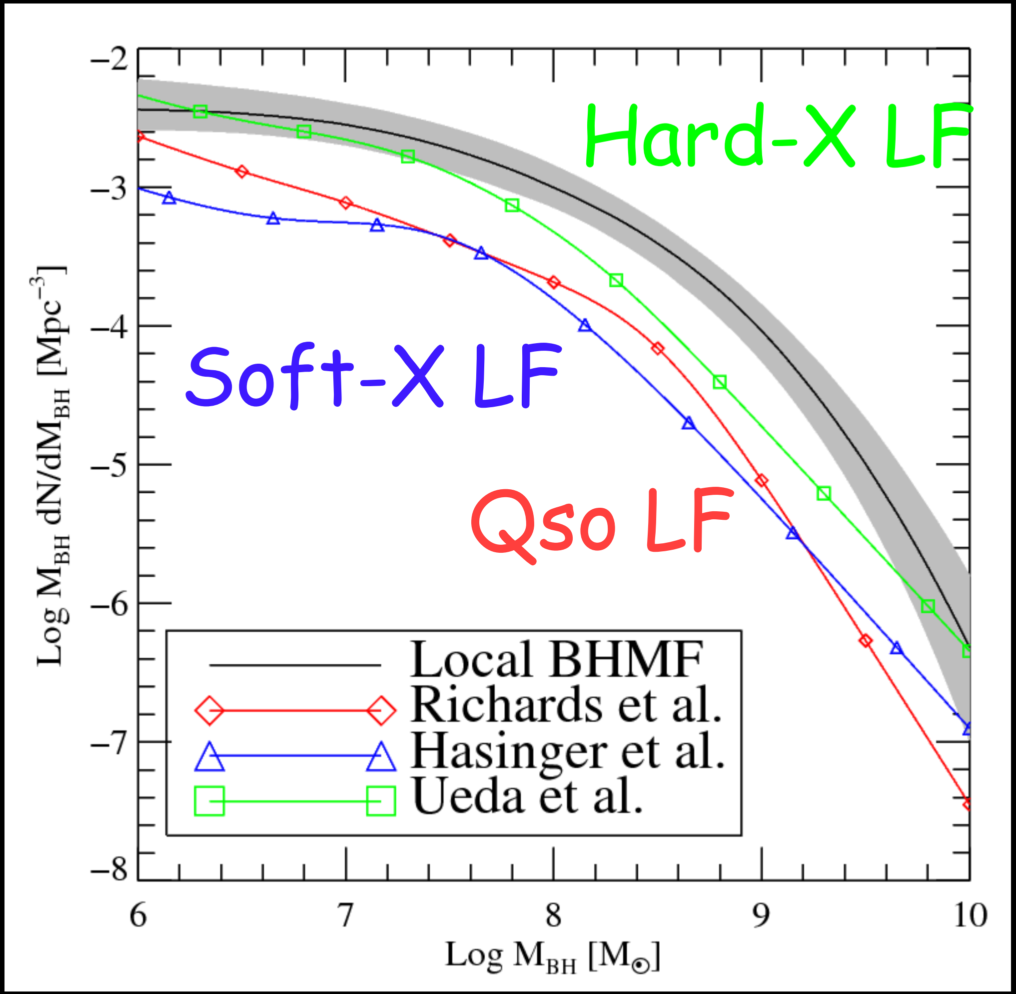
Good agreement between local BH mass density
and AGN BH mass density
Little room for inefficient accretion …

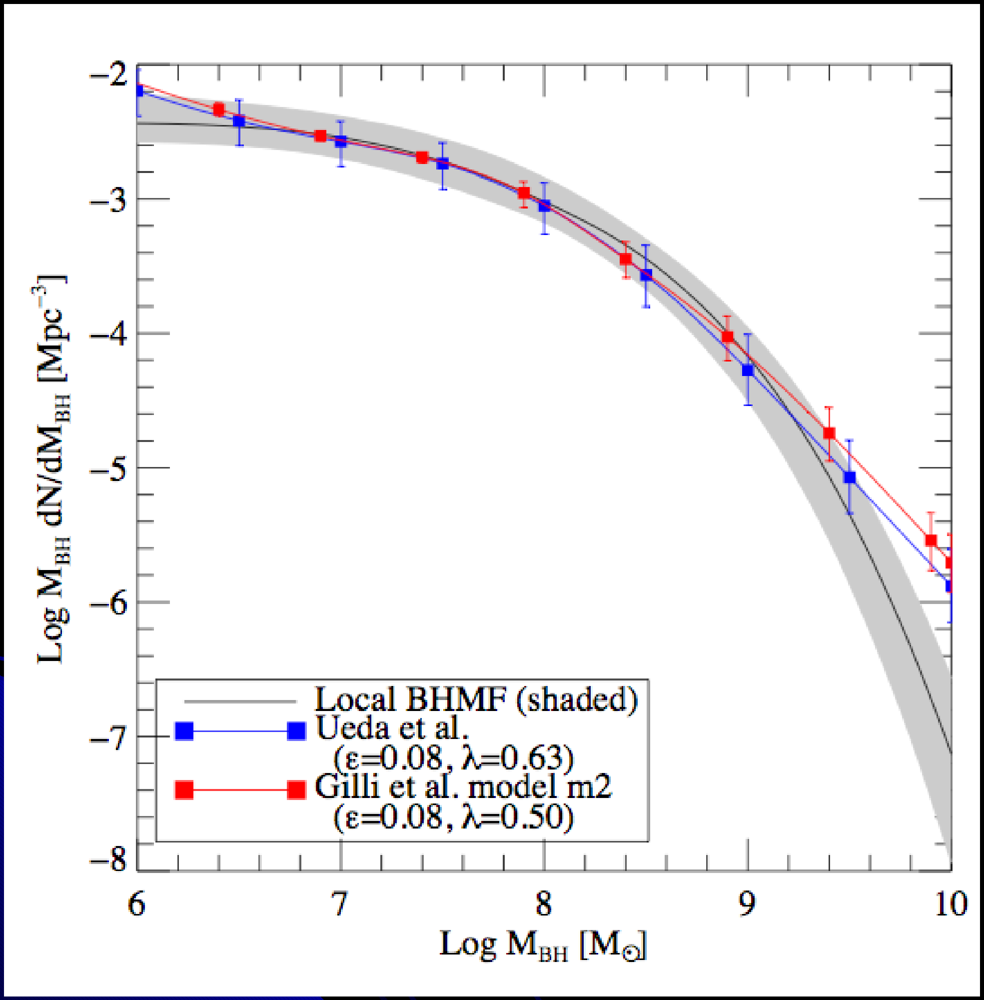
Local Black Holes and AGN relics

- Marconi et al. 2004 have shown that local BHs are relics of AGN activity by comparing:
  - the local BH mass function (from galaxy L/σ functions and M_{BH}-L_{bul}/M_{BH}-σ_e)
  - the relic BHMF (from AGN luminosity function and continuity equation)

Importance of AGN LF: even the hard (2-10 keV) XLF does not sample the whole AGN population.

Heavily obscured Compton-thick AGN are missing ...





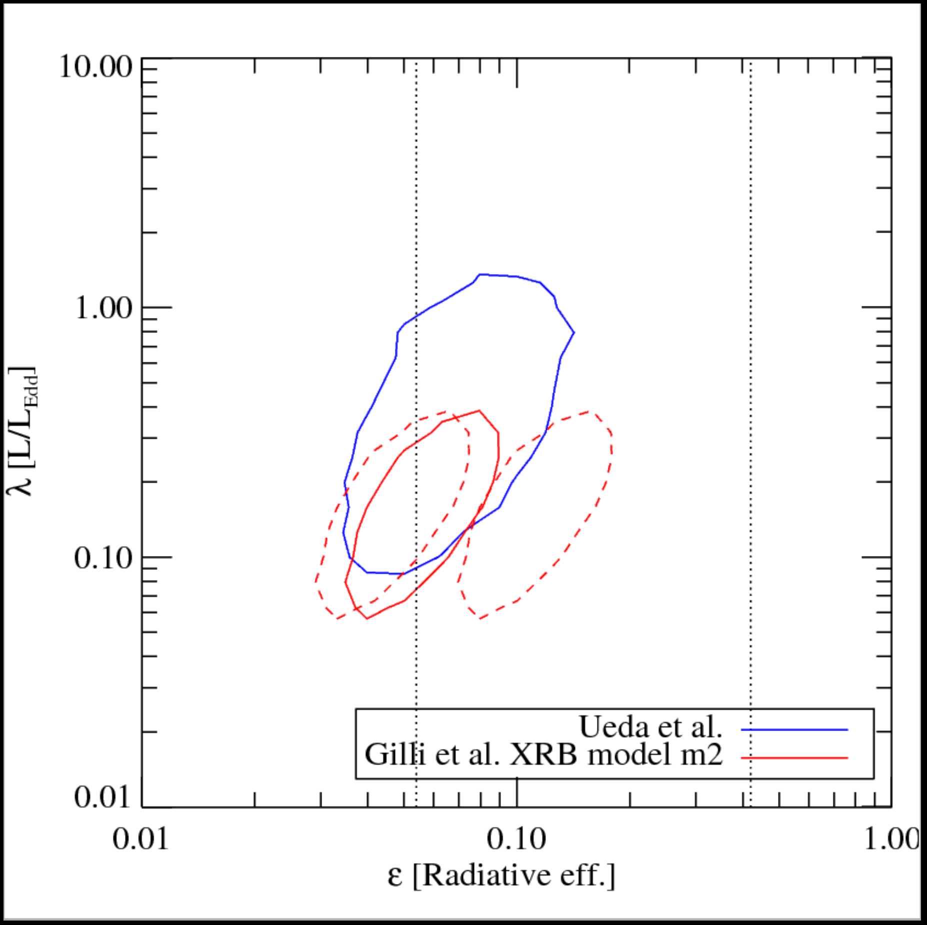
- Correction for Compton-Thick sources from XRB models whole AGN pop. Considered
- The only free parameters are the accretion efficiency and Eddington ratio

$$L = \epsilon \, dM/dt \, c^2$$

$$L = \lambda L_{Edd}$$

Radiative Efficiency and Eddington ratio

- Determine locus in ε-λ plane where there is the best match between local and relic BHMF!
- ε=0.04-0.10 λ=0.08-0.5 which are consistent with common 'beliefs' on AGNs



SMBH Census and evolution

Two (out of many..) missing pieces after 10+ years of X-ray and multi-wavelength surveys :

1) Heavily obscured accretion mostly unconstrained beyond the local Universe

2) BH/galaxy co-evolution is still unconstrained at very high-z ($z > 6$ or so) and poorly known at $z > 4$

The high-z Universe: open issues

Future facilities (ALMA,LOFAR, JWST…) will investigate high-z galaxies and AGN in many bands.

How and when do early BHs form and grow?
What triggers nuclear activity?
How do accretion modes evolve? [radiative efficiency, L/L_{Edd}, SED(α_{ox})]

What formed first, BH or galaxy?
Some evidence for larger BH per fixed stellar mass at z~0.3-0.6 (Treu+06,Woo+08).
Also, suggestions for M_{BH}/M_{*}~0.1-0.3 in bright QSOs at z>4 (Walter+04, Maiolino+07)
How do they co-evolve ? (obscured growth, feedback, bright QSO sequence ?)
What is the high-z BH mass function?

SDSS selected MASSIVE (> 10^9 M_{SUN}) QSO at z > 6 ARE THE TIP OF THE ICEBERG … --> MUST BE A POPULATION …

Semi analytic models of BH growth

Merging of Dark Matter Halos with cosmic time (LCDM) + recipes for the baryon physics. Press-Schechter formalism or Millenium Simulations to get halo merger trees.
(Volonteri+06, Rhook&Haehnelt08, Menci+08, Marulli+08, Volonteri+10 review)

Common assumption: nuclear trigger at merging

Free parameters:

- BH seeds
  Direct Collapse : Heavy Seeds
  Runaway Merging : Intermediate Seeds
  Pop III : Light Seeds

- recipes for accretion ➔ Eddington ratio, AGN duty cycle, efficiency, …
- relation between initial BH mass and halo mass (e.g. bias)
- SED (e.g. obscuration) and Bolometric Luminosity
- room for accretion due to internal processes (i.e. not related to mergers)
- Probably many more …

Is there enough time to form Black Holes ?

$$M(t) = M(t_0) \exp\{ \varepsilon_L \ (1 - \varepsilon_M) / \varepsilon_M \ * \ (t - t_0) / \tau_E \}$$

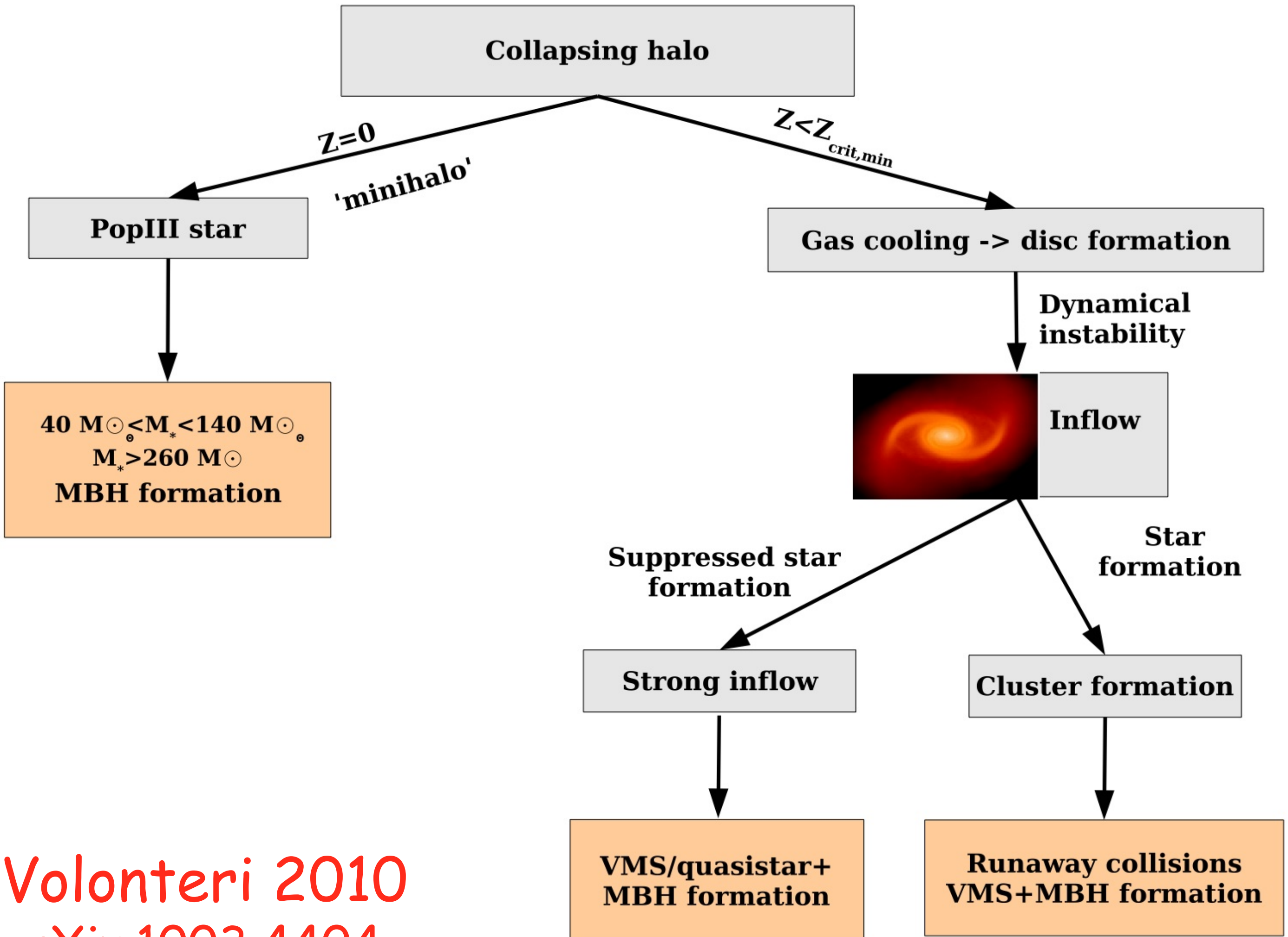
$\tau_E = 0.45$ Gyr $\quad \varepsilon_L = L / L_E \quad \varepsilon_M = L / M c^2$

The highest z QSO (z = 6.43) has a mass of ~ 10^9 M

A likely candidate for a seed BH is the remnant of Pop III Star with M >~ 300 M

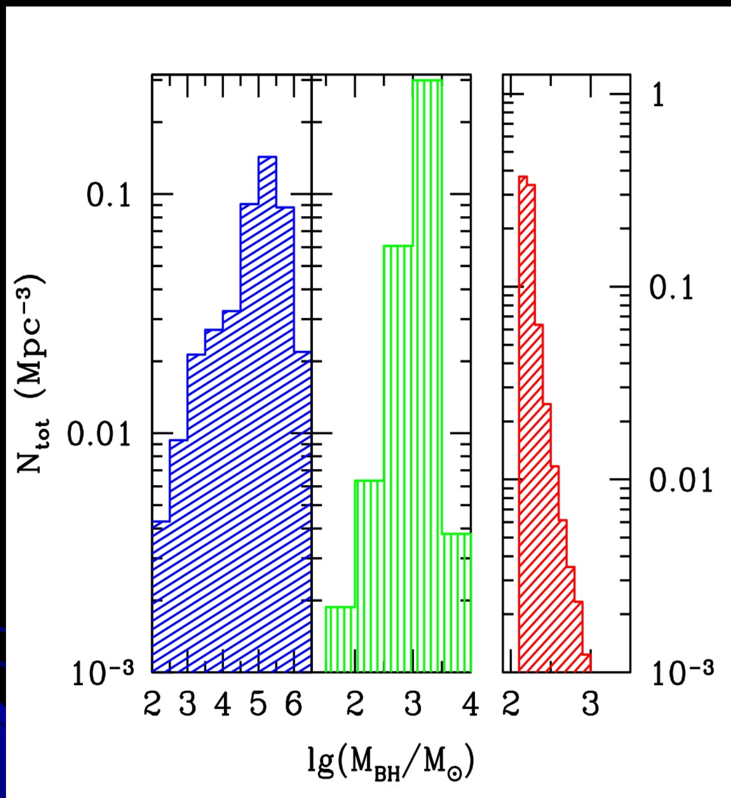
The higher the efficiency (ε_M) the longer is the time needed to grow. If accretion is via a thin disc the BH is efficiently spin up and ε_M reach 0.3-0.4 requiring about 2 Gyrs to reach the "observed" mass

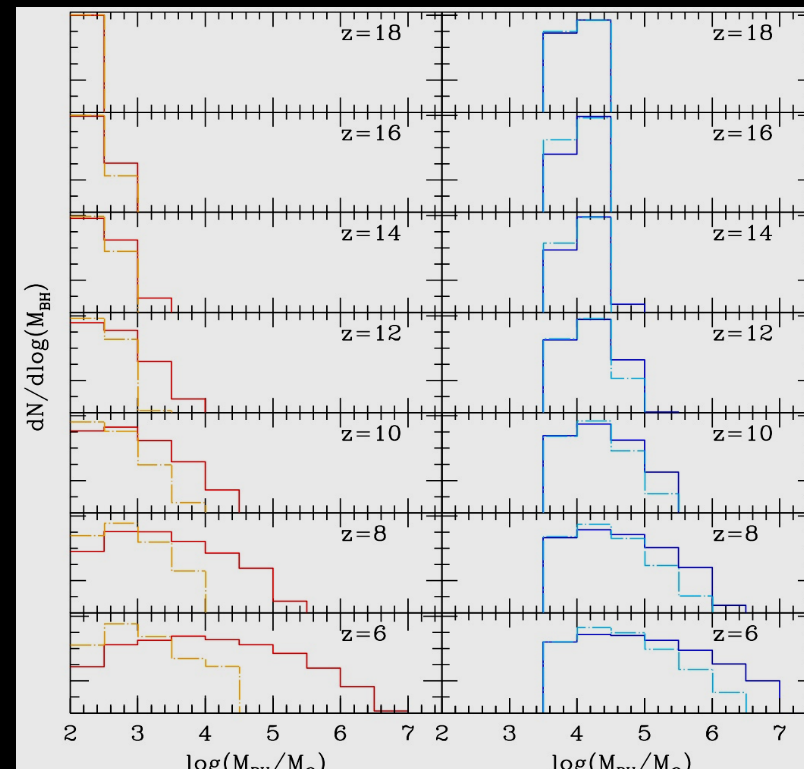
"Rees flow chart"



Volonteri 2010
arXiv.1003.4404

Seed Mass function"

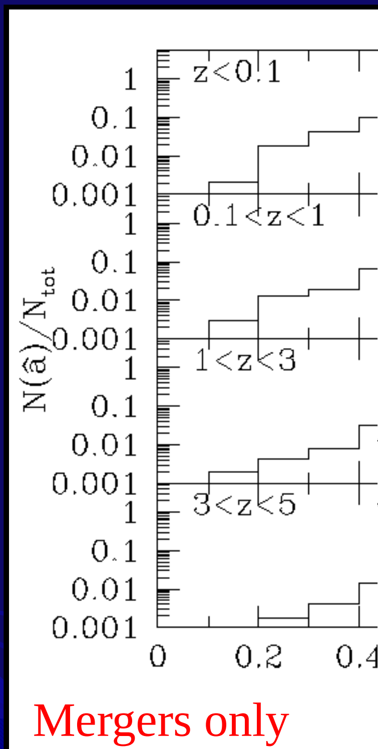


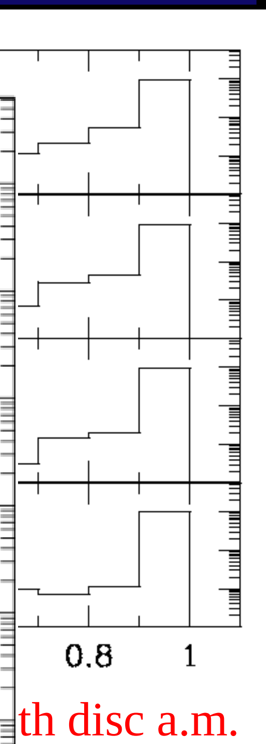


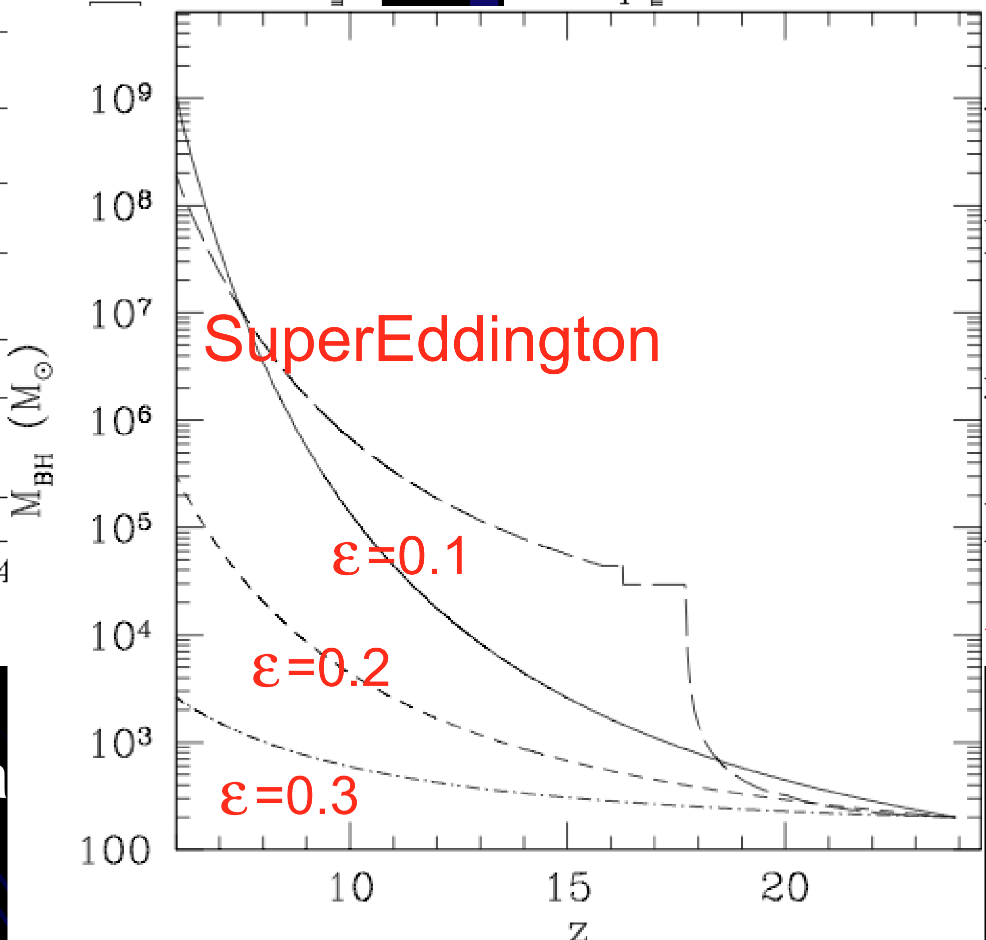
Heavy -------> light

Small Seeds -------> Large Seeds
Solid=Eddington - Dotted=Edd. Ratio Distr.

Evolution of BH Spins

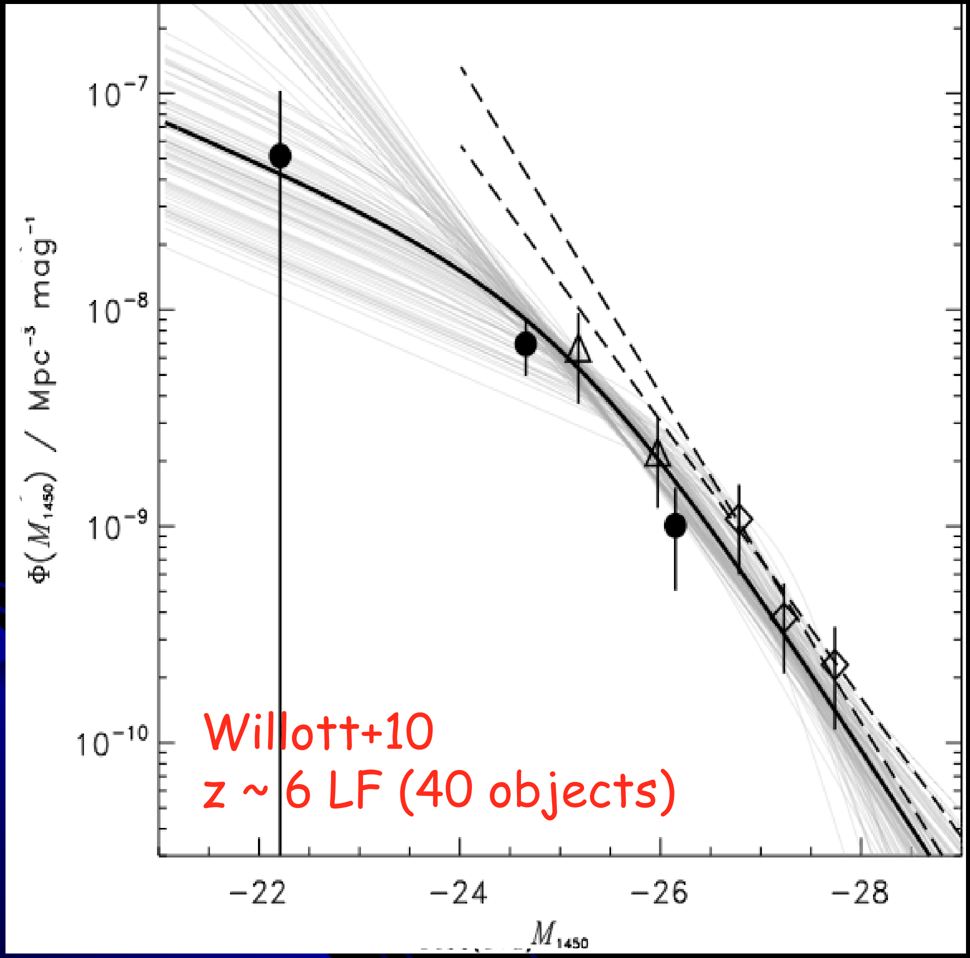






Volonteri Ha

Optically selected vs X-ray selected



The number of high-z AGN detected so far

	SDSS	X-ray sel.$
z > 3	8000	~100
z > 4	1500	~ 15
z > 5	150	~ 3-4
z ~6	40	~ 0

$ see eg. compilations by Silverman+08, Hasinger08; Brusa+09; Civano+10;

X-rays from high-z QSO predictions

Two possible ways to make predictions on the high-z Universe:

1) extrapolate from known XLF towards high-z and low luminosities

(e.g. La Franca+05; Gulli+07; Silverman+08; Ebrero+09; Yencho+09; Aird+10; …)

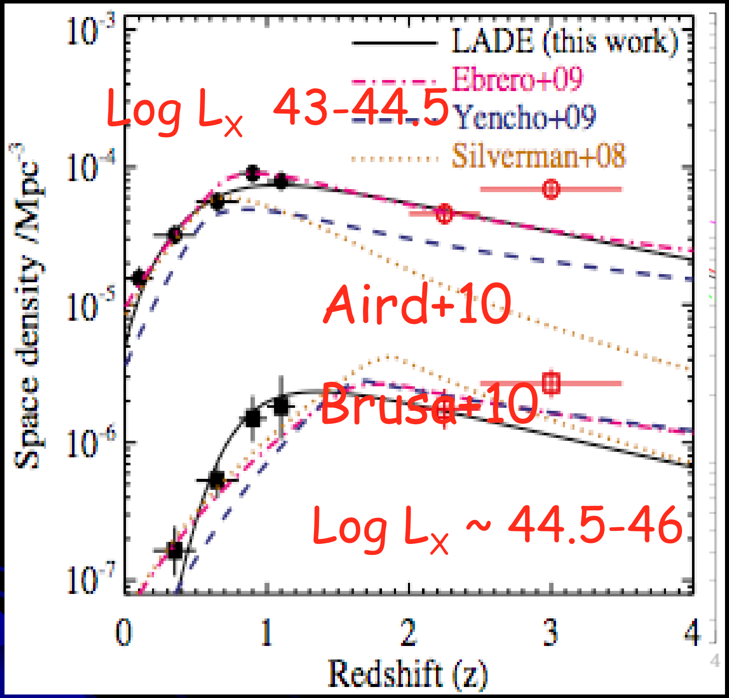
2) use semi-analytic models of BH/galaxy coevolution

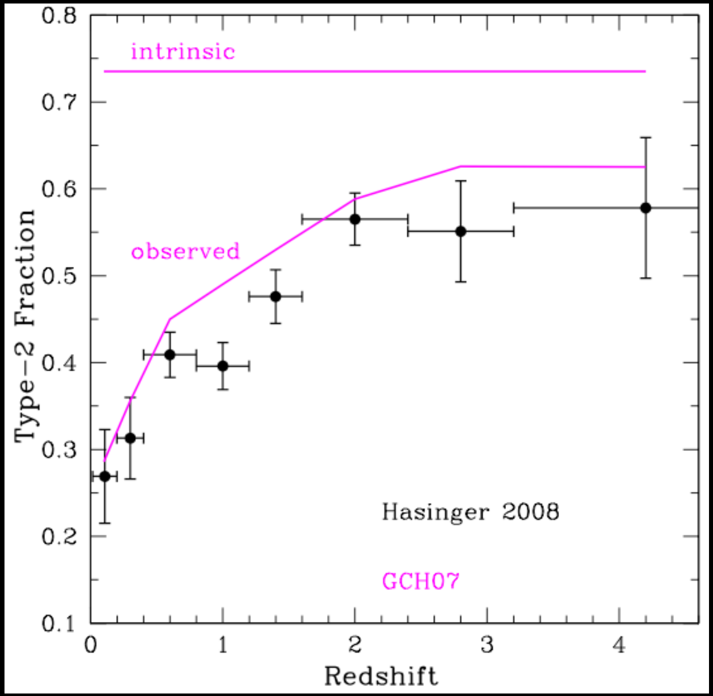
(e.g. Kauffmann&Heanhelt00, Volonteri+06, Salvaterra+07, Rhook&Haehnelt08, Menci+08,Marulli+09, Lamastra+10, …)

a large number of free parameters

(BH seeds; BH abundance/location; AGN lightcurves; obscuration etc.)

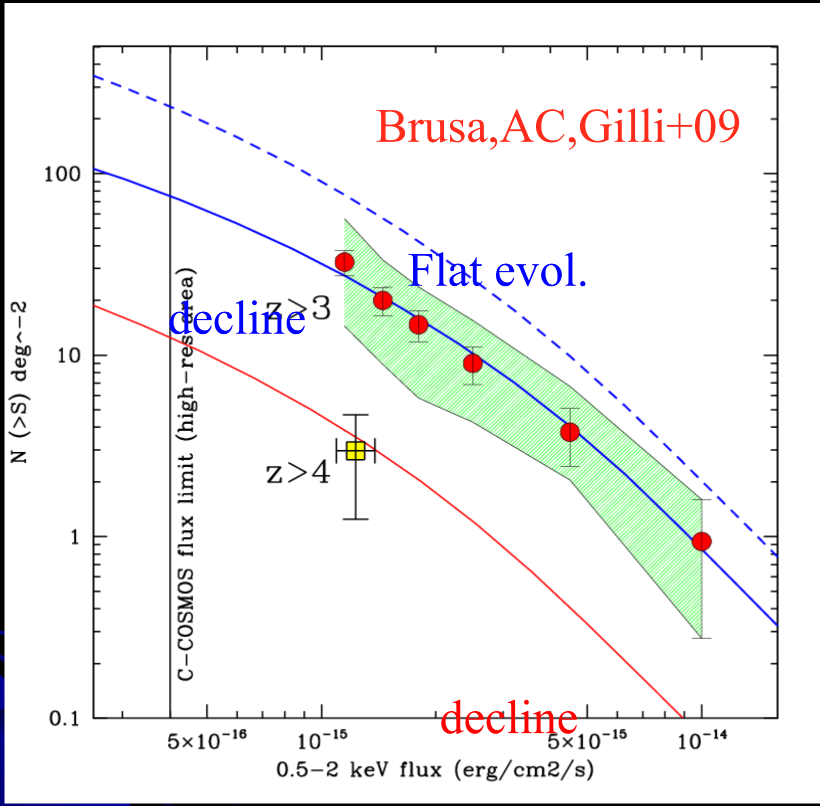
X-ray luminosity function





expected/predicted in feedback models (i.e. Menci+08)
Seen in (some) data [e.g. La Franca+05, Treister+06, Hasinger08], not seen in others (Ueda+03, Dwelly&Page 2006), not needed in XRB models (Gilli+07)

High-z Counts



High fluxes (>5x10-16 cgs):
data and predictions robust

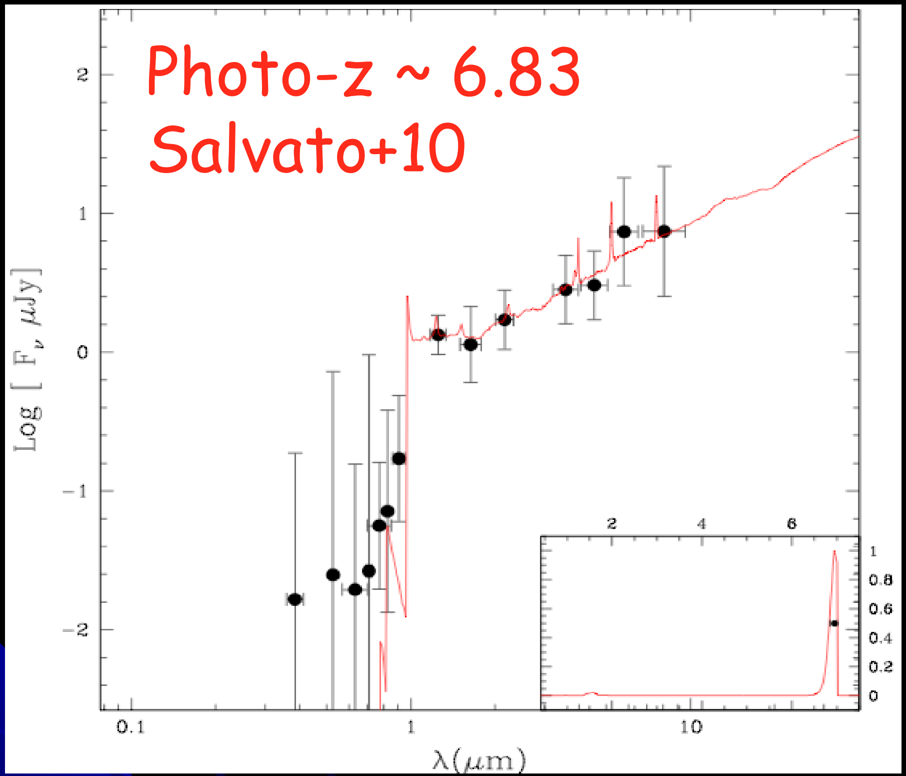
data from COSMOS survey
Brusa+09 (XMM), Civano+10 in prep. (Chandra)
~70 objects, 50% specz

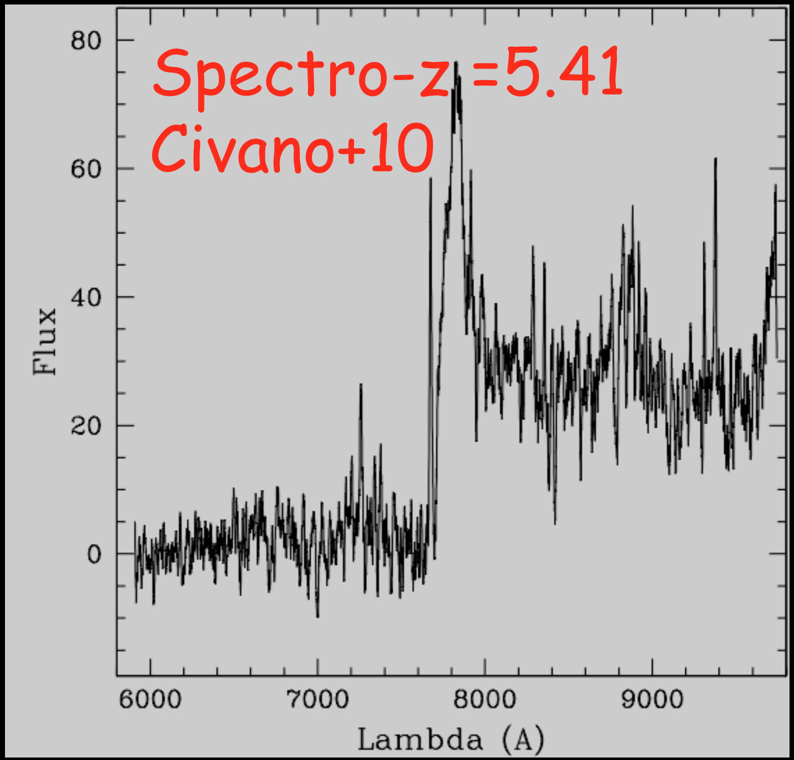
http://www.bo.astro.it/~gilli/counts.html

Low fluxes (<10-16cgs) and high-z:
photoz more uncertain

data: 2Ms CDFS (Luo+10 catalog)
- 40 z>3
- 8 z>4 (ONLY photoz!)
- 4 z>5 (ONLY photoz!)

The highest z QSO ?

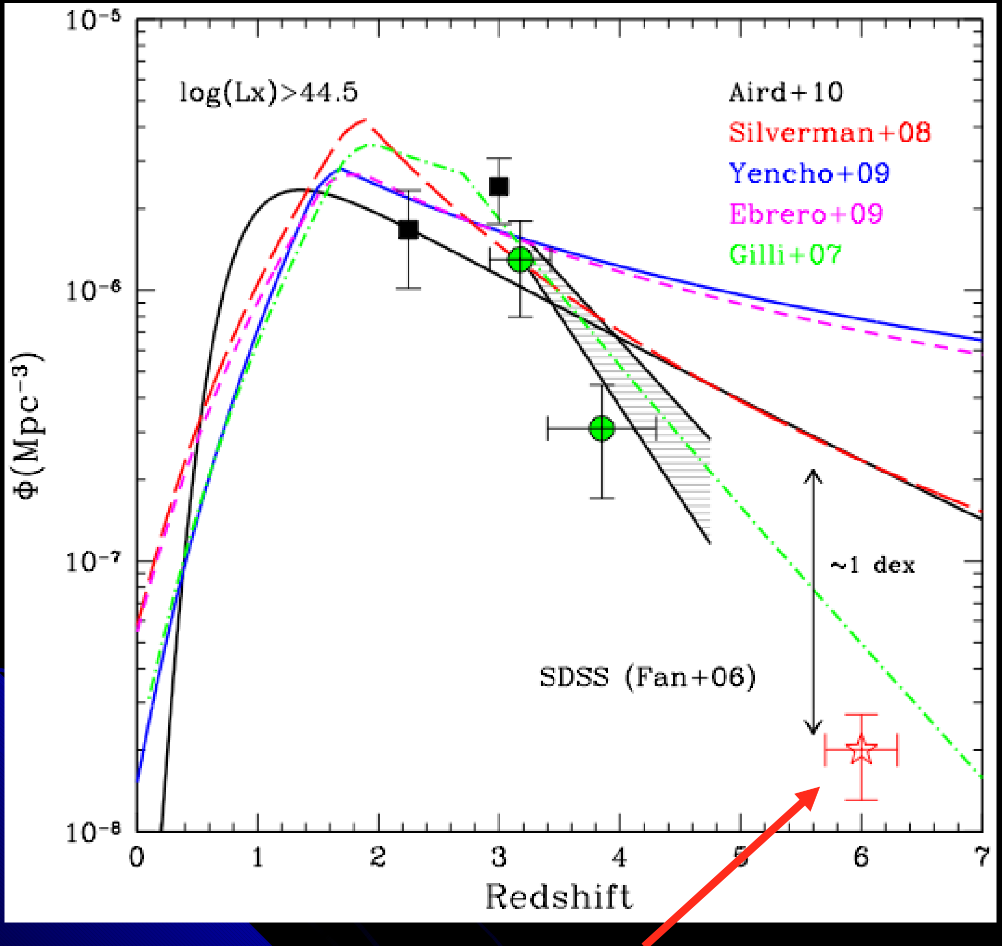


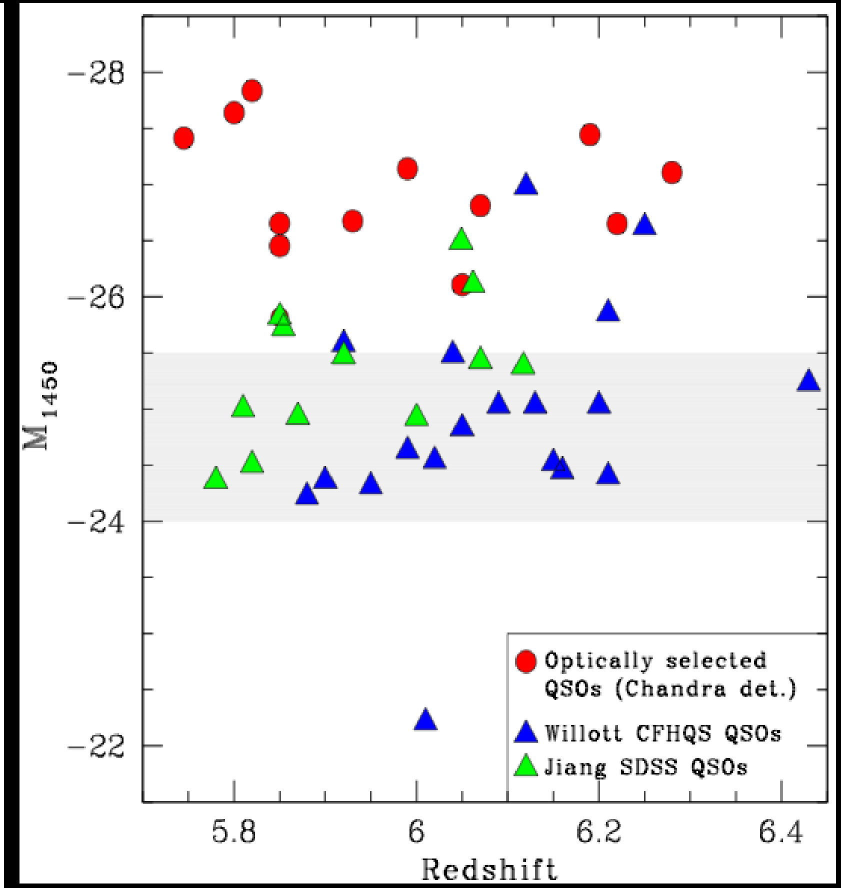


$L_{2\text{-}10\ keV} \sim 10^{44}$ cgs
z ~ 25.4
J ~ 23.6

$L_{2\text{-}10\ keV} \sim 3 \times 10^{44}$ cgs
z ~ 22

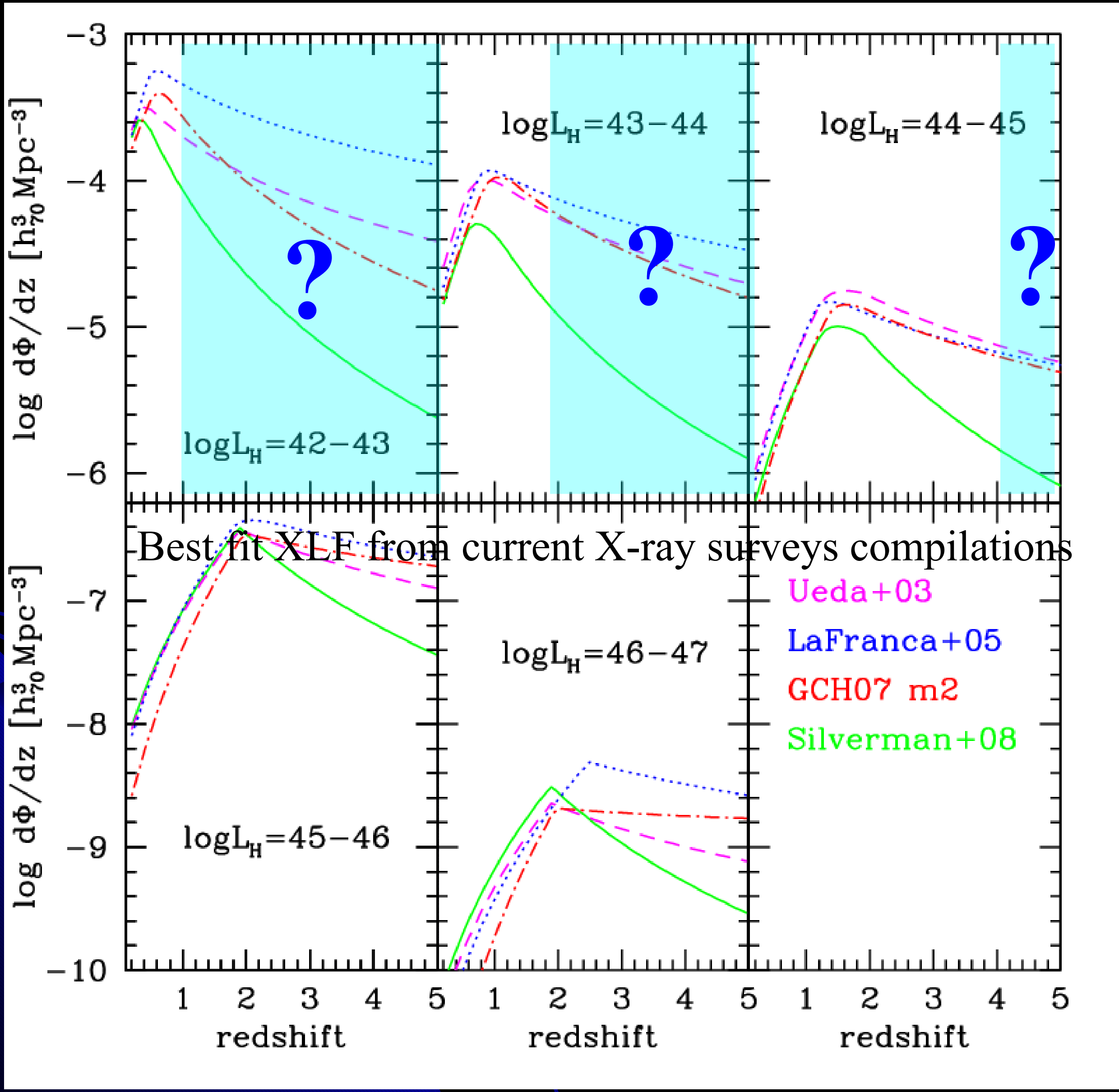
Searching for z ~ 6 QSO





Estimated space density of Type 1 AGN from optical LF and narrow α_{OX} distribution centered at 1.6. (No obscured AGN)

What's the density of low L_X, high-z AGN?



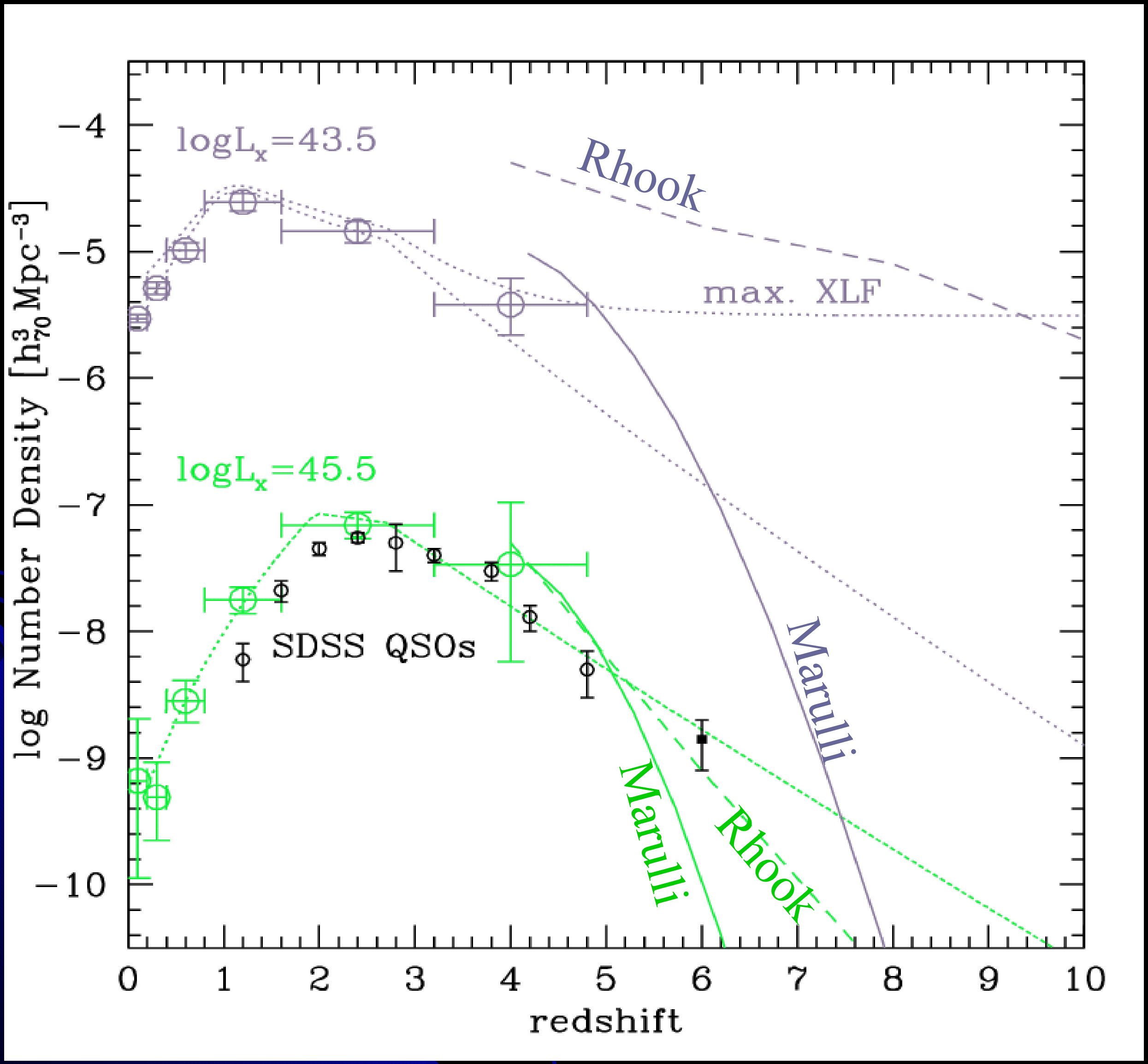
Evolution of the bulk of the AGN population still to be determined at moderate to high-z.

Flatter evolution or decline as for high luminosity?

Sensitivity needed for high-z AGN census

<u>What do we expect?</u>

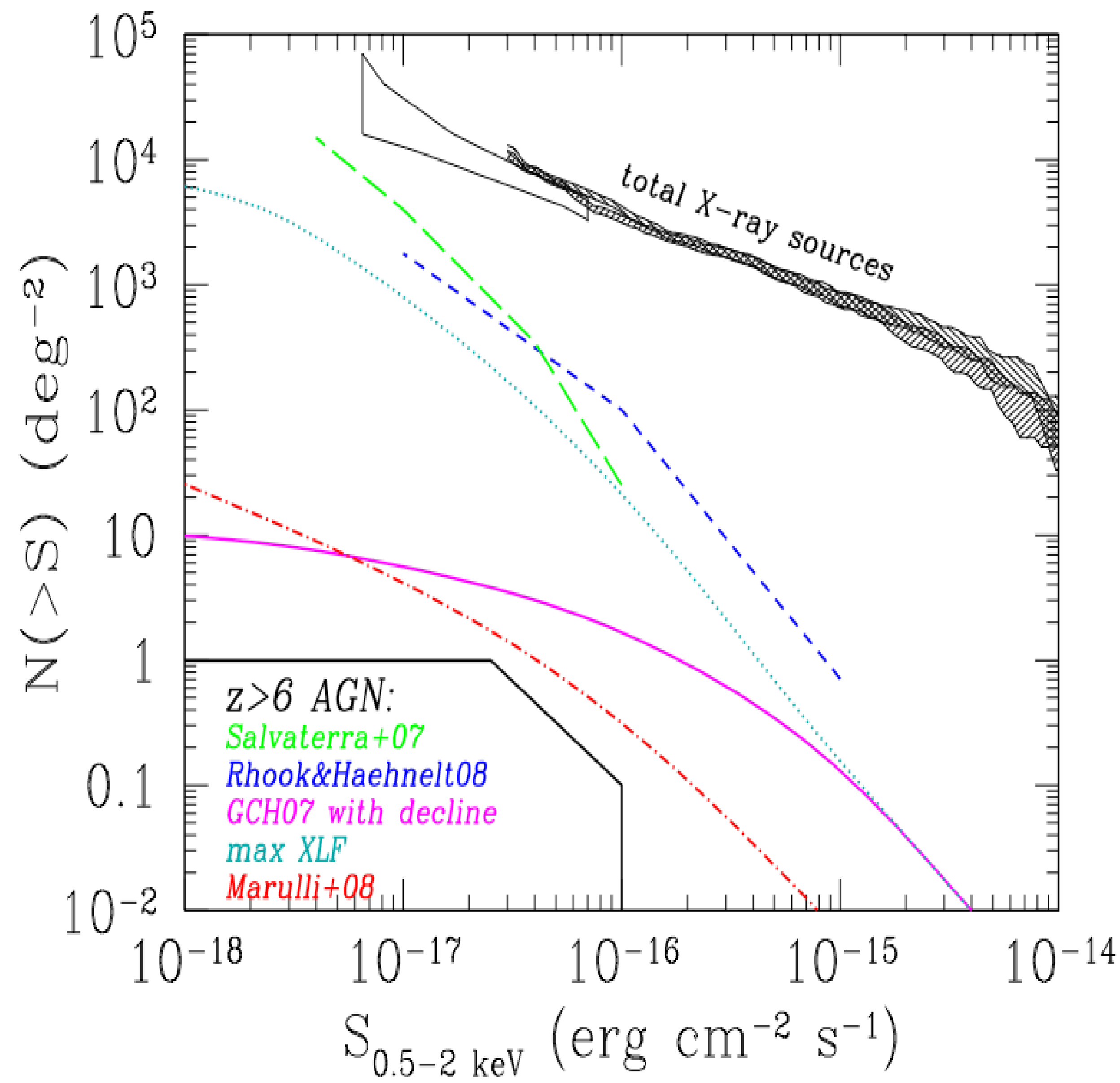
High-z AGN space density predictions



Very, Very uncertain …

max. XLF:

XLF that predicts the maximum number of high-z AGN while being in agreement with current “low-z” XLF.



Confusion

at N(>S) ~ 2×10^{4} deg^{-2},
i.e. S ~ 10^{-17} $erg/cm^{2}/s$

in ~1 Msec (depending on the bkg level)

XLF @ z > 6
would constrain the physics of early BH formation, seeds mass function, accretion mechanisms etc.

Future Perspectives

Nustar (NASA)/Astro-H (JAXA) /NHXM(ESA?-Italy)

Imaging survey in the 10 - 70 keV energy range

Goals : resolve the sources of the hard X-ray background

WFXT

Large FOV (~ 1 deg^2) uniform sensitivity

Goals: Large area surveys, high-z and obscured QSO.

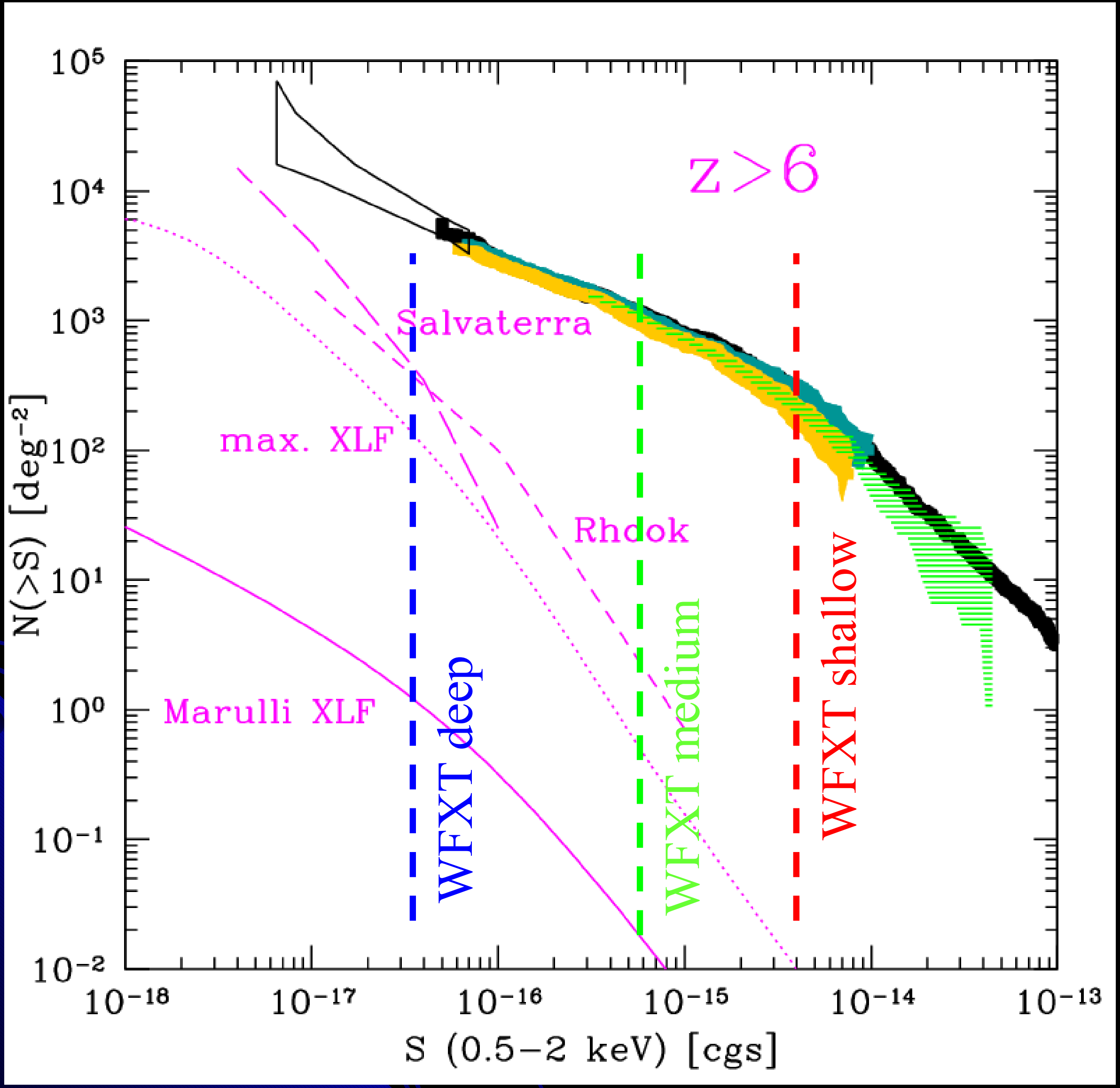
IXO

NASA-ESA-JAXA proposal(ranked 4 in the Decadal, competing for ESA CV 2015-2025

Large collecting area (3 m^2 @ 1 keV)), deep imaging (5″ PSF) high resolution spectroscopy, variability, polarimetry

Goals: deep Universe spectroscopy, first lights

AGN at $T_{Universe}$ < 1 Gyr



Very wild range of predictions for z>6 AGN:

Observations of significant samples at z>6 would constrain the physics of early BH formation disentangling between several scenarios

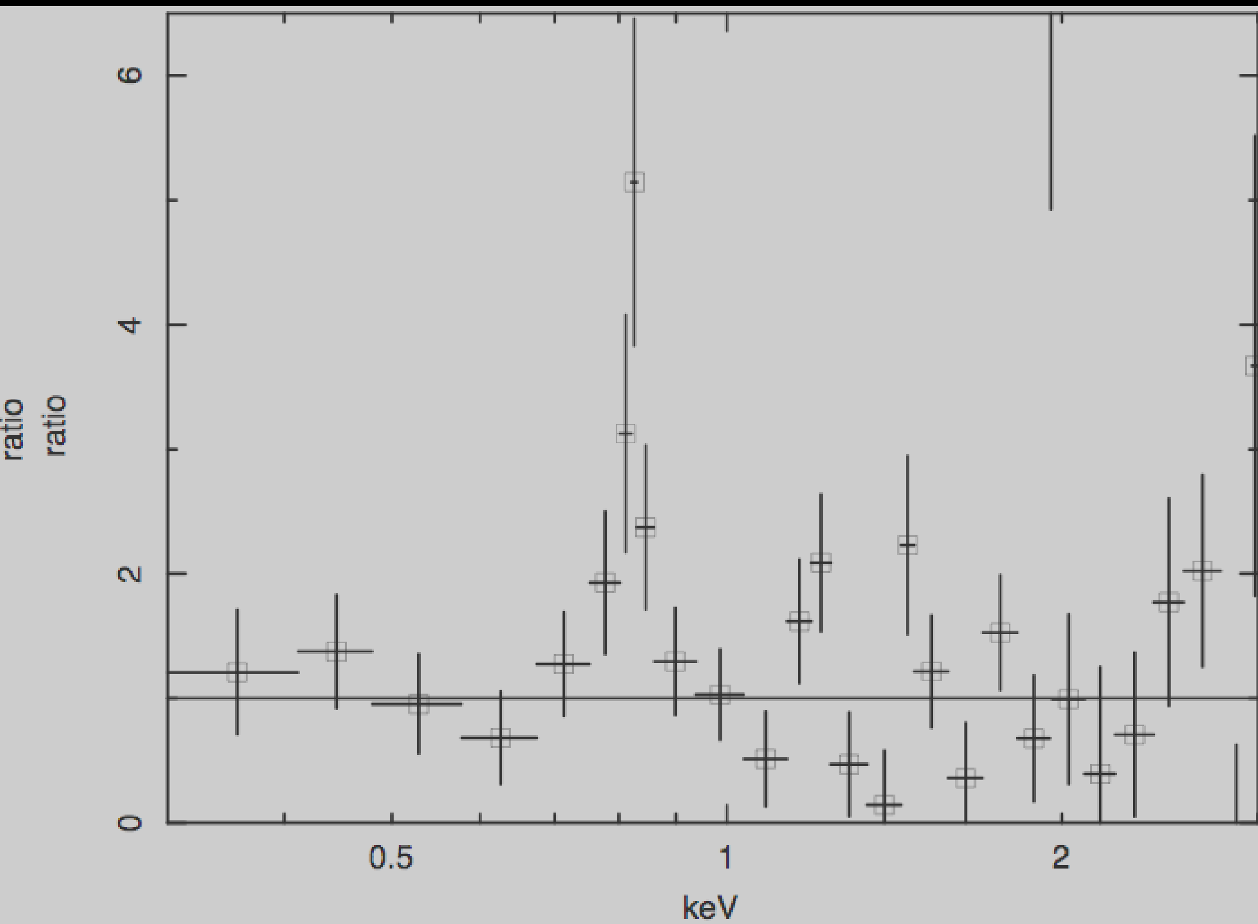
How many WFXT will see?

The expected number of high-z AGN

Sample	Shallow	Medium	Deep	Total
z>4 decline	30600	38000	6100	74700
z>4 maxlf	31300	54100	43600	1.3e5
z>4 SAM	55600	84000	34600	1.7e5
z>6 decline	660	1350	310	2320
z>6 maxlf	680	3650	11950	16280
z>6 SAM	30	105	110	245
z>8 decline	22	59	19	100
z>8 maxlf	20	400	3270	3690
z>8 SAM	2e-5	4e-4	3.6e-3	4e-3

Statistics large enough to determine the XLF of z>6 AGN

IXO X-ray Spectra



WFI simulation of a SDSS like QSO at z = 6, $L_X \sim 3 \times 10^{44}$ cgs - $F_X \sim 10^{-15}$ cgs line EW ~ 40 eV (obs-frame) .

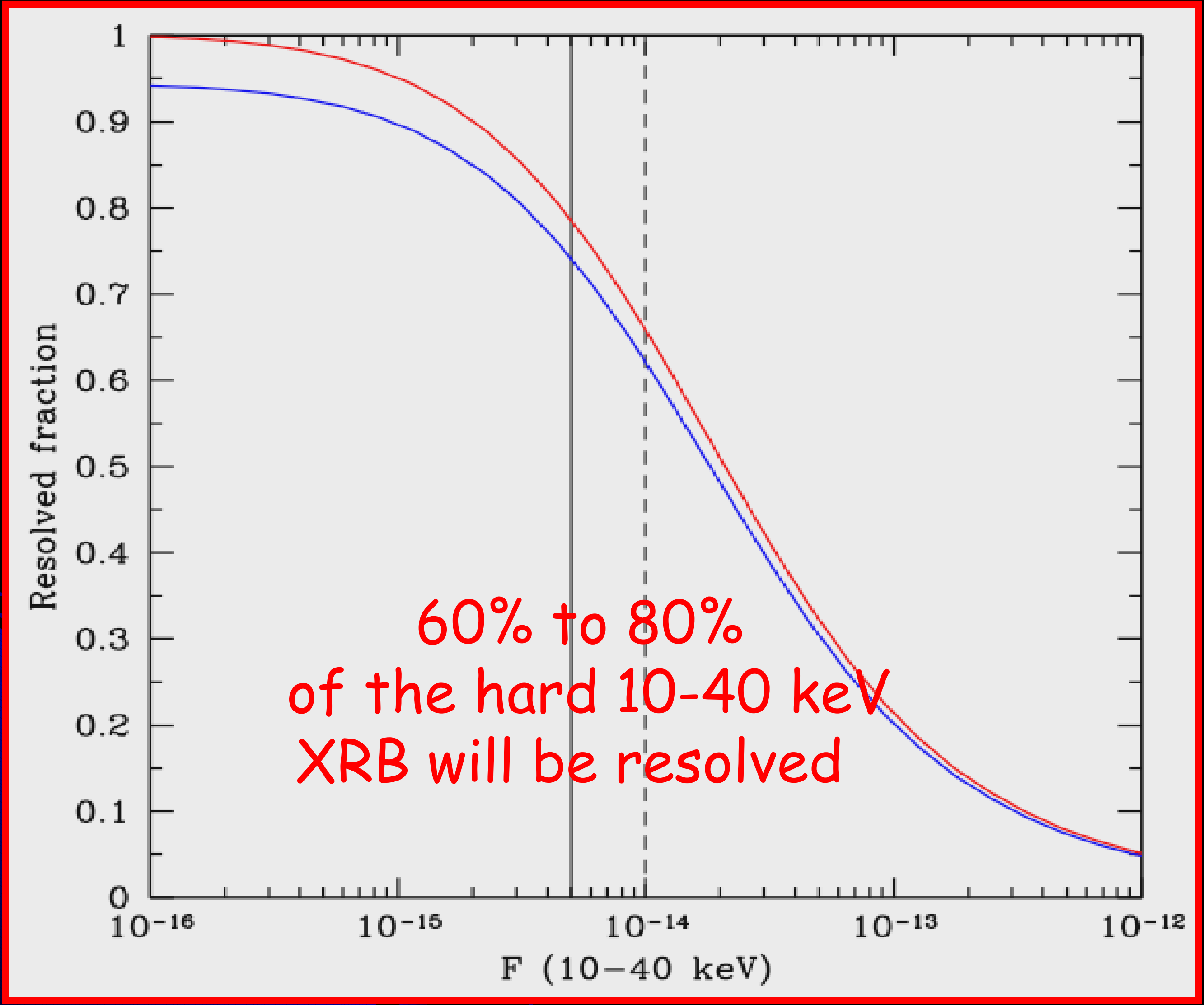
100 ks (back. included)

Obscured AGN at z = 7 ($L_X \sim 10^{43}$ cgs - $F_X \sim 10^{-16}$ cgs, line EW ~ 1.2 keV (rest-frame)

1 Ms (back included)

Redshift determination accuracy +- 0.2

HARD X-RAY (> 10 keV) IMAGING



NUSTAR
(NASA)
Feb 3, 2012

Astro-H
(JAXA)
2013-2014

NHXM ?
(ESA-ASI, …)
2018 ?

Summary

Ultra deep plus wide area XMM / Chandra observations will reveal heavily obscured SMBH up to moderate to high redshifts and start to detect first (z ~ 5-6) QSOs

Hard X-ray (> 10 keV) imaging (NuStar, Astro-H, NHXM) -> sources of the XRB 30 keV peak or bulk of the Universe accretion power

Large area (eROSITA, WFXT) needed for a census of SMBH at high (> 6) redshifts

IXO surveys for the physics and evolution of first QSOs