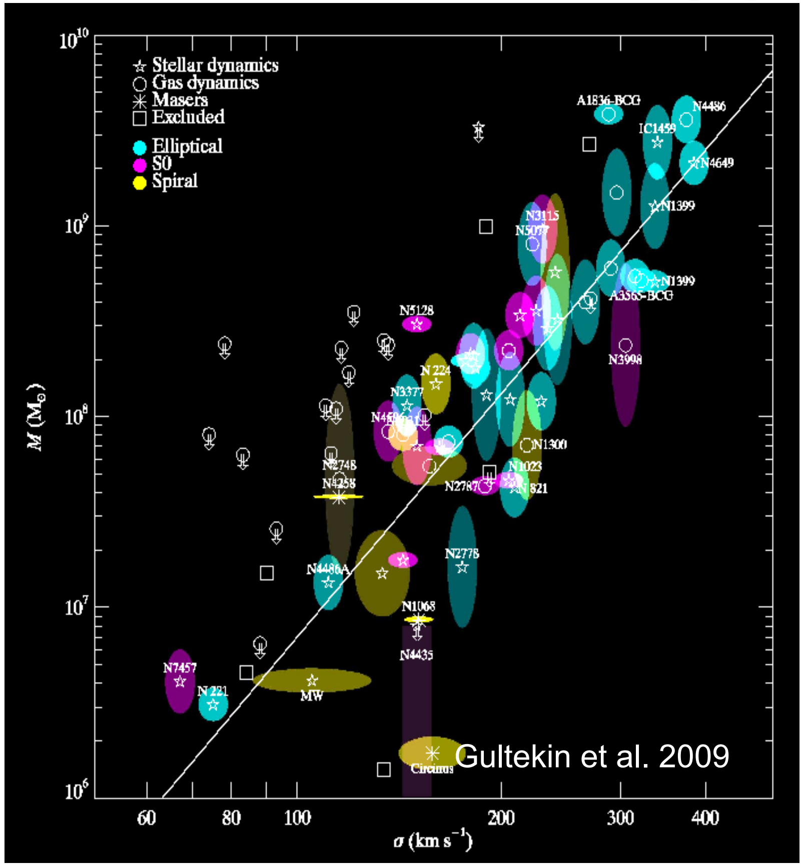
Active Galactic Nuclei − III

X-ray surveys and AGN evolution

AGN−galaxy co-evolution

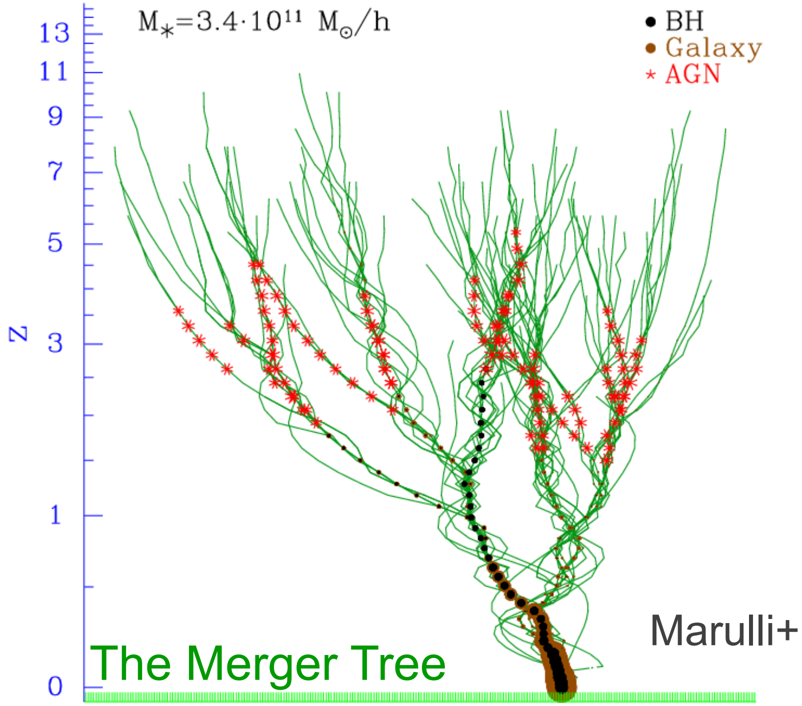
AGN as a key phase of a galaxy lifetime



Scaling relations between **BH mass** and **host galaxy properties** (stellar bulge mass, luminosity, velocity dispersion)

AGN and galaxies closely tied

→ **co-evolution**



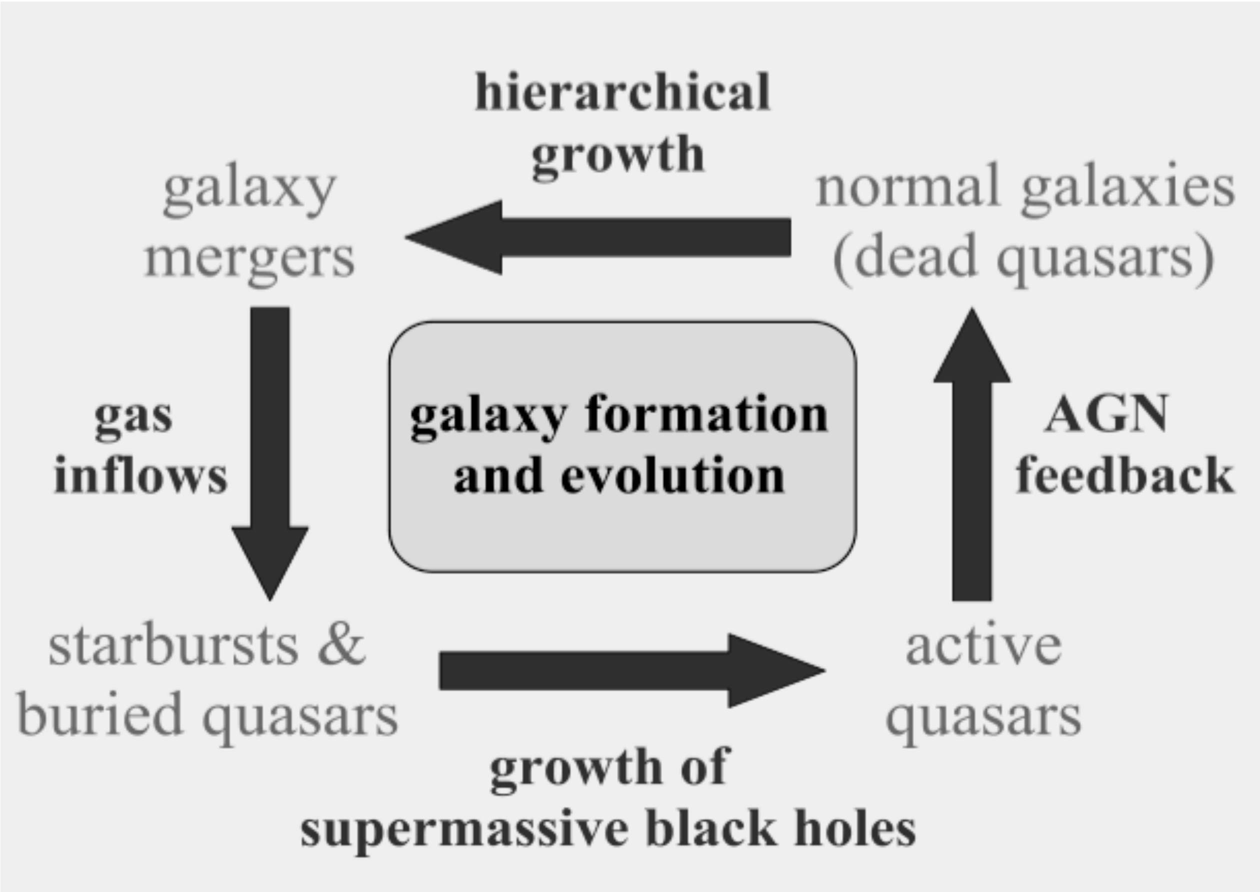
Semi-analytic models of BH/galaxy co-evolution (e.g: Kauffmann+98, Volonteri+06, Salvaterra+06, Rhook&Haehnelt08, Hopkins+08, Menci+08, Marulli+09)

These follow the evolution and merging of Dark Matter Halos with cosmic time and use analytic recipes to treat baryon physics.

<u>Condition: nuclear trigger at merging</u>

The cosmic cycle of galaxy and AGN evolution

(Hopkins et al. 2006)

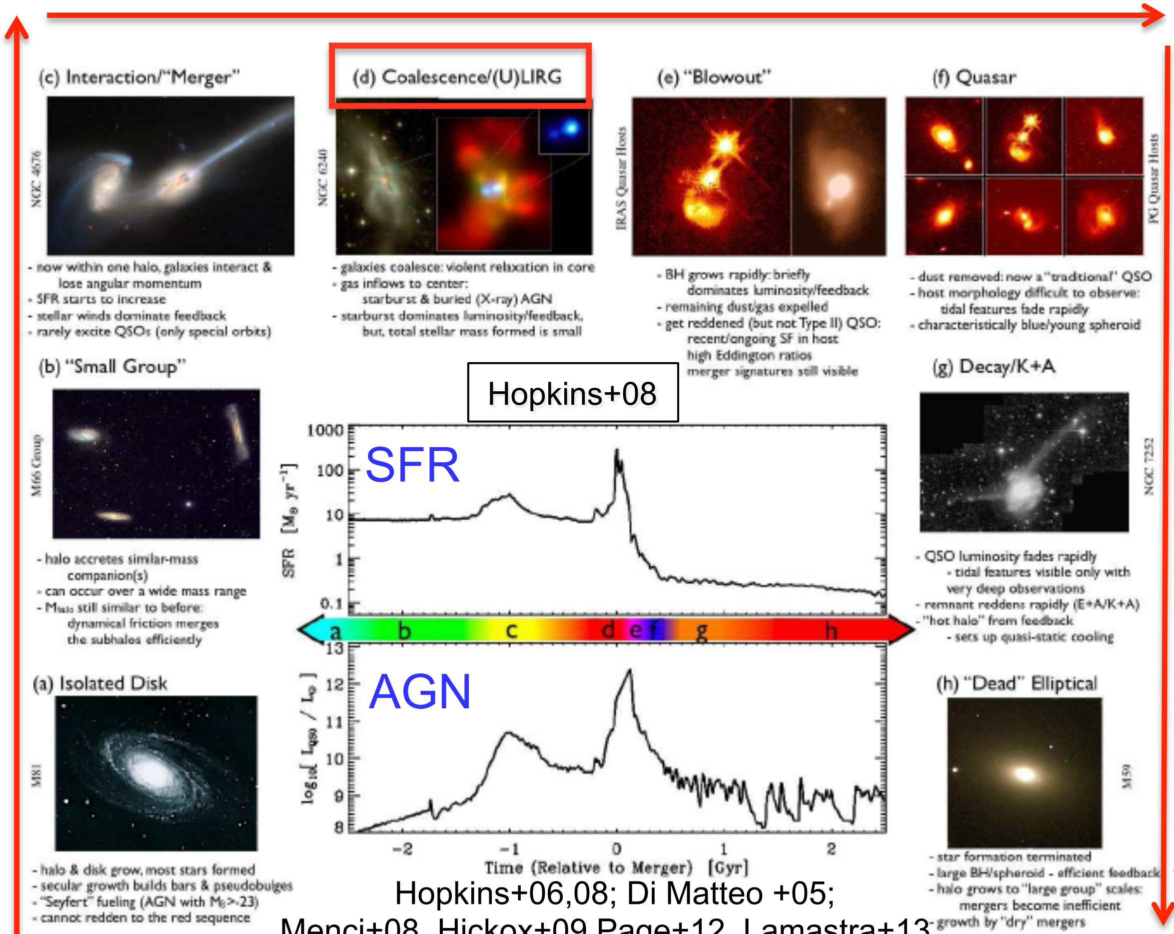


Mergers between gas rich galaxies drive gas which fuel both SF and QSO activity (QSO mode)
Obscured growth (ULIRG, sub-mm phase, 4π covering?)

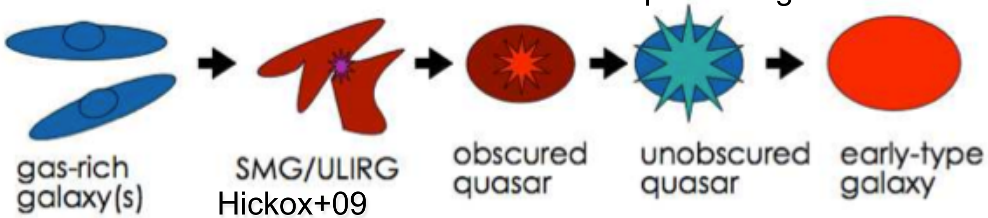
BH feedback expels gas → broad-line QSO

Shut down of BH activity dead quasars (or slowly accreting BH) in red galaxies (radio mode)

The BH/galaxy evolutionary model



Hopkins+06,08; Di Matteo +05;
Menci+08, Hickox+09, Page+12, Lamastra+13..
see also Sanders+88 pioneering work



Hickox+09

mergers

SF/obscured accretion

"clean" accretion (QSO)

transition (green valley) object

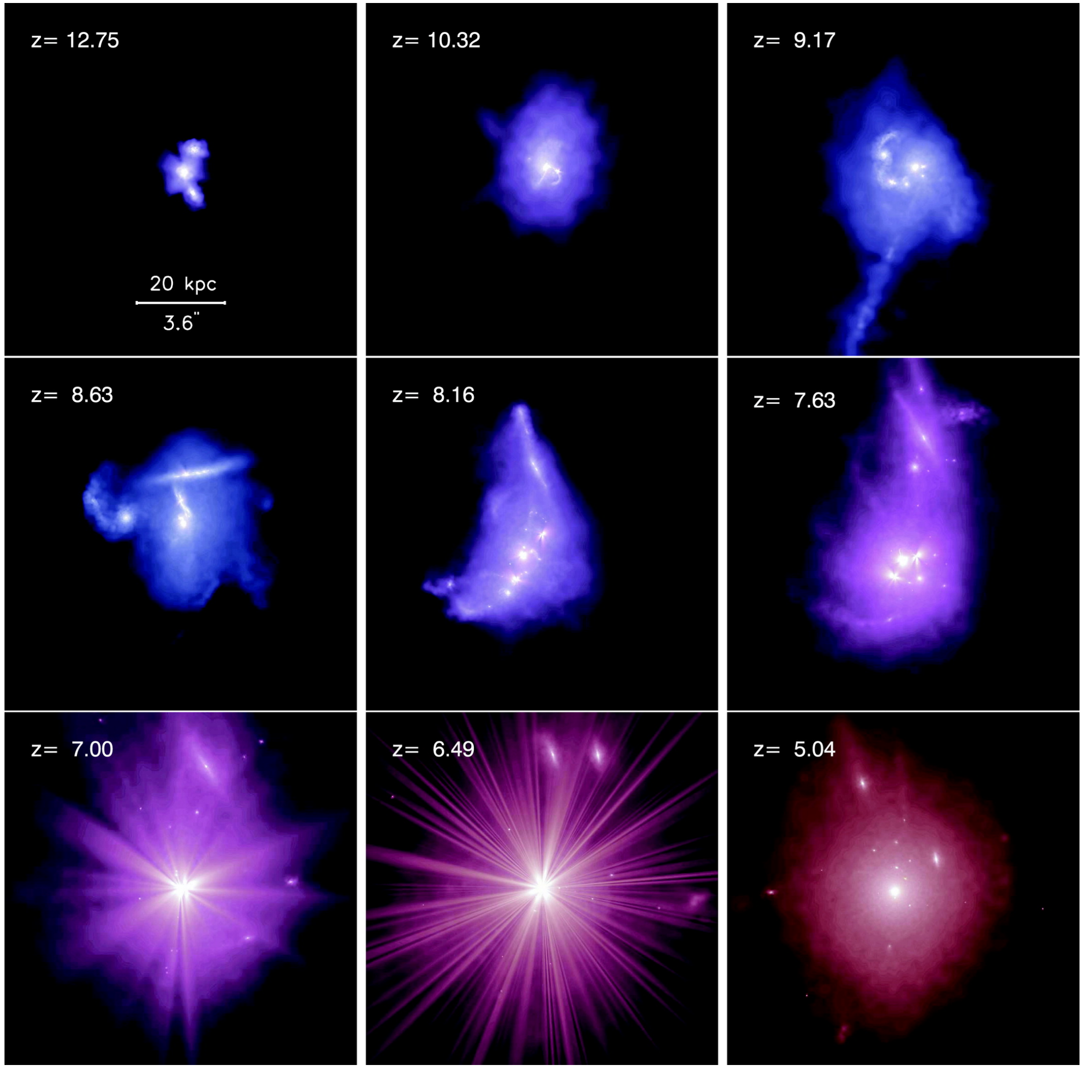
passive red galaxy

SF	Galaxy Morph.	AGN L/L$_{EDD}$	AGN Obsc.
Strong	Disturbed	High	High
Moderate	Coalescing	Lower	Lower
Low	Relaxed	Lower	No

AGN feedback is likely the key to control the evolutionary sequence

Hold mainly (only?) for *luminous AGN*, while secular ("smooth") accretion via cold gas flows and minor mergers is more likely for lower luminosity Seyferts

Simulated formation of a $\approx 10^9 M_\odot$ BH at high z

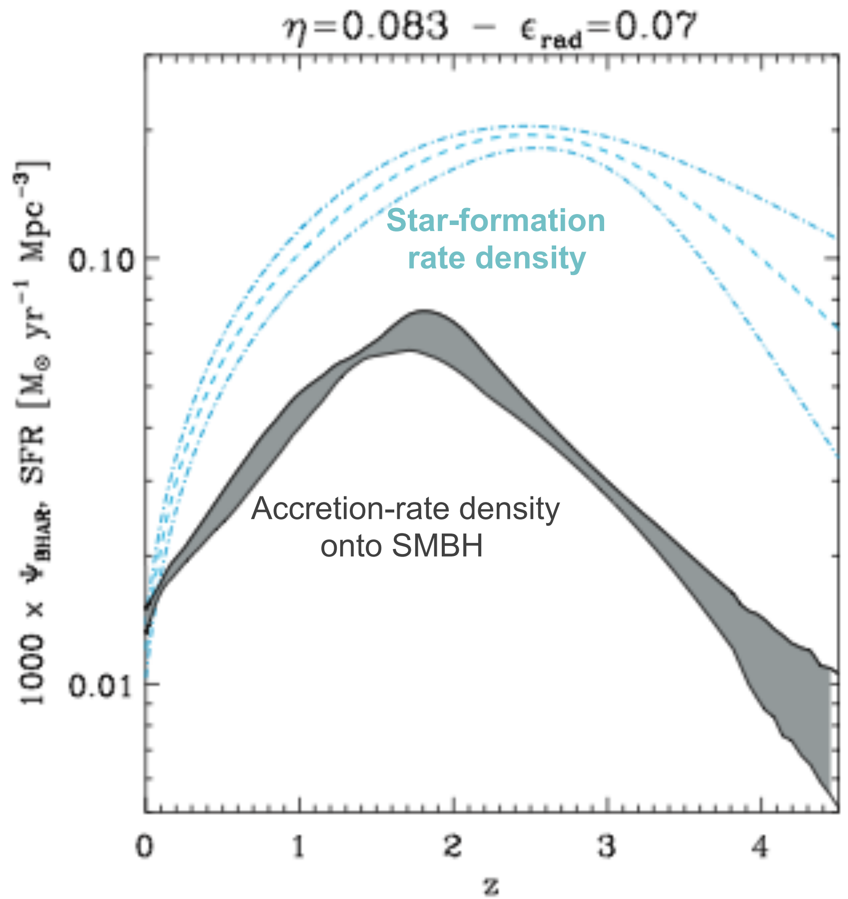


Li+07

- 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
  - outflows as direct evidence for strict QSO/galaxy relation (feedback)
- Later times
  - SF & accretion quenched
  - red spheroid, passive evolution

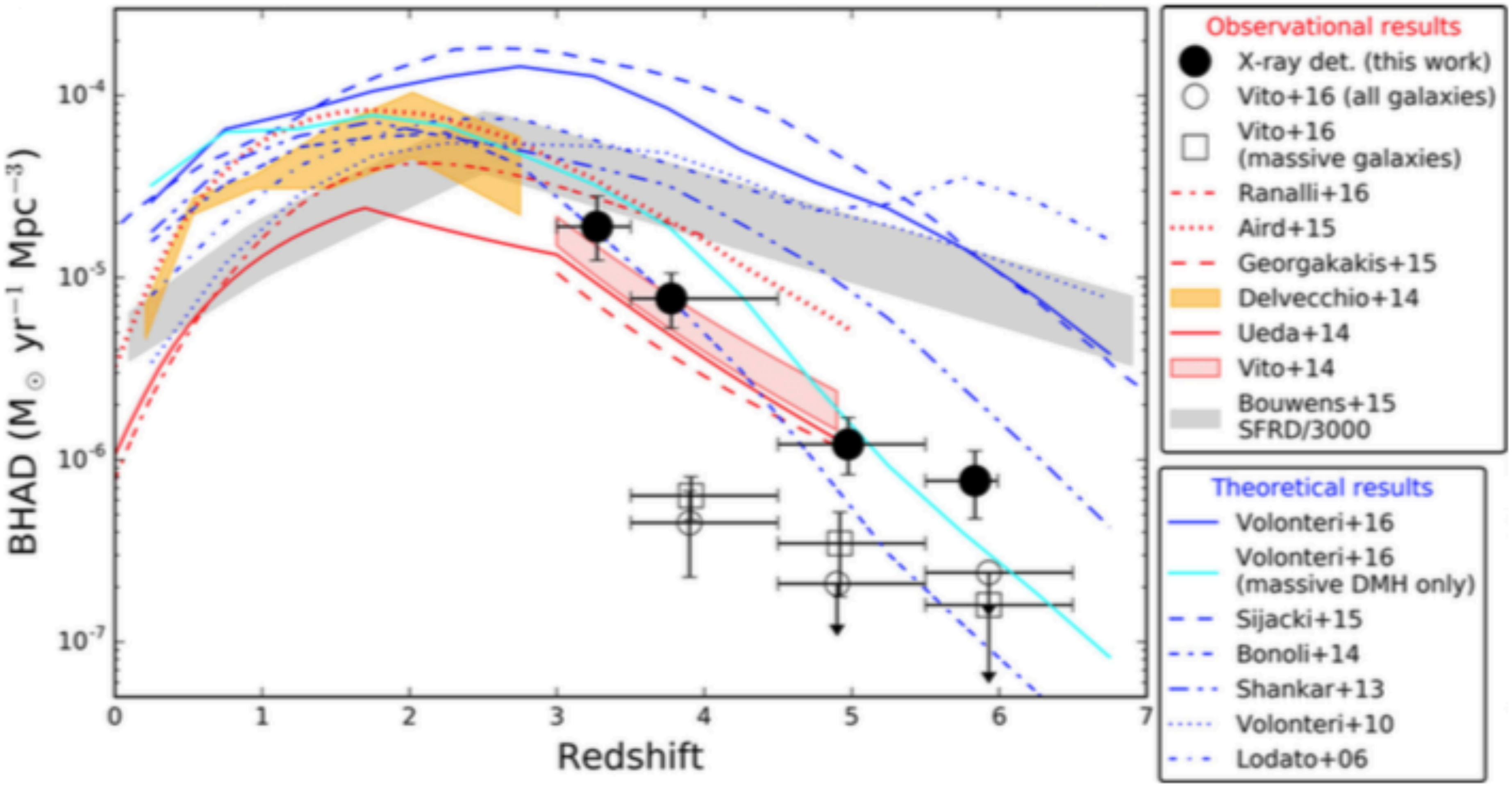
[M_{BH} - σ- M_{Bulge} - … relations]

Accretion and star formation over cosmic



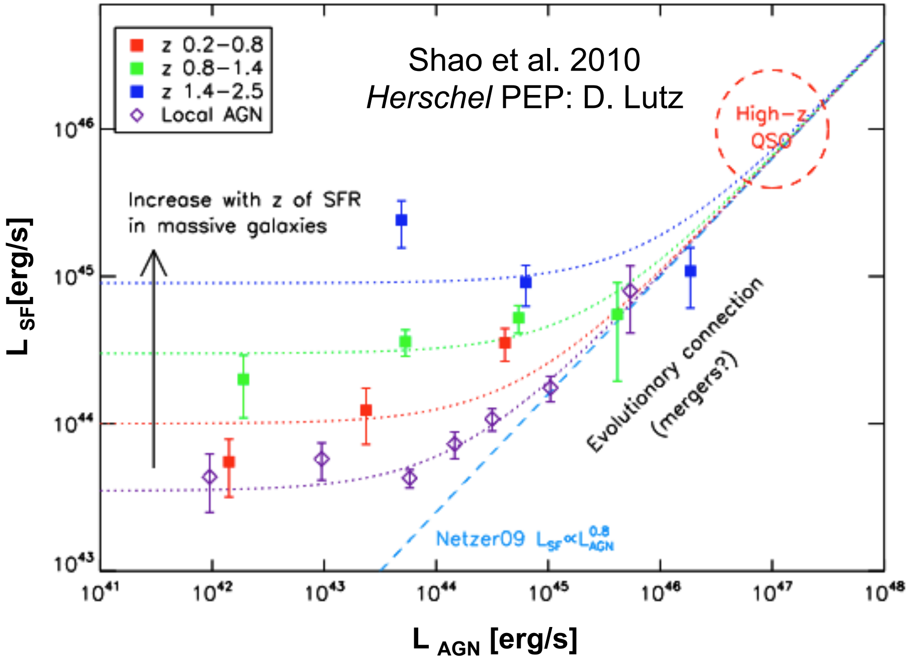
from Merloni & Heinz 2008;
see also Hopkins & Beacom 2006, Gruppioni et al. 2011, Madau et al. 2014

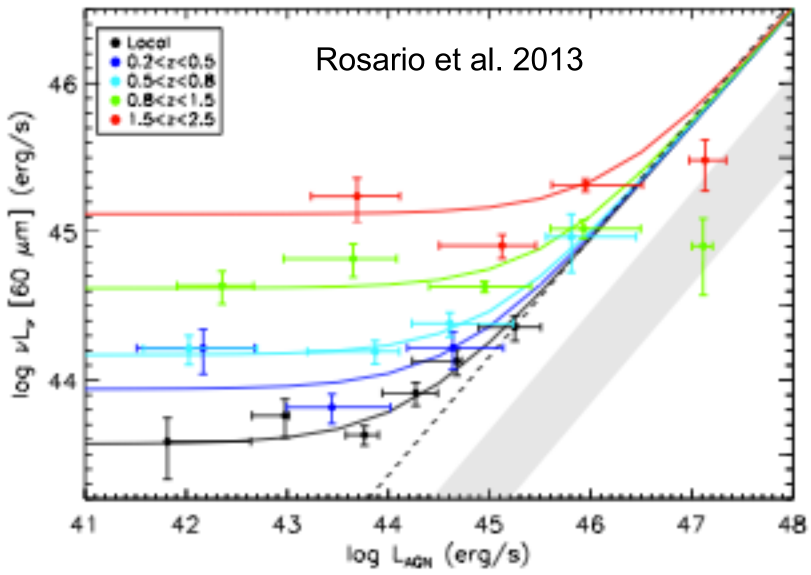
Black hole accretion rate density (BHAD)



Vito et al. (2018)

still large uncertainties and observations vs. model discrepancies



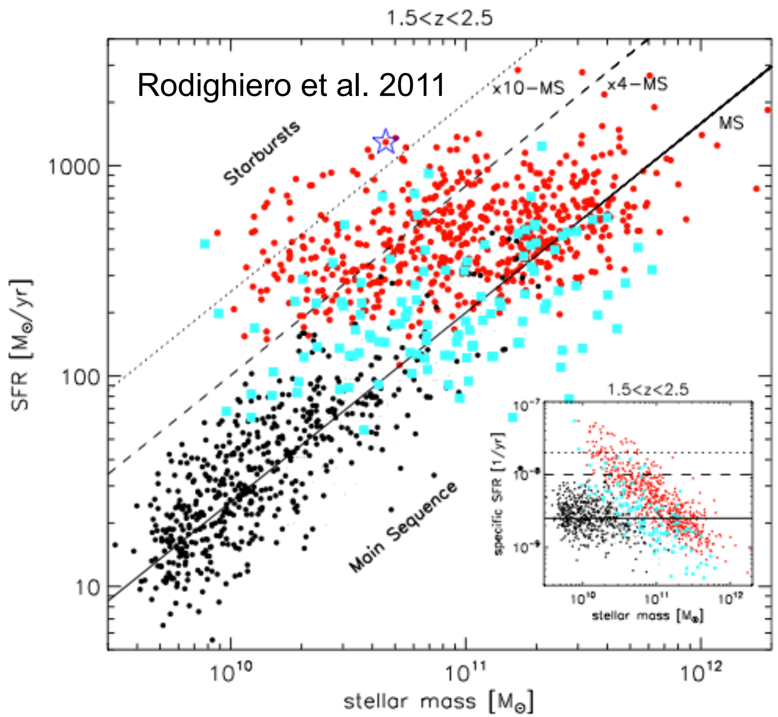


Two paths of AGN/galaxy co-evolution

- At high AGN luminosity, galaxy merging is the driver of accretion and star formation ➔ rapid bursts of activity (~10% population?)

- At lower AGN luminosity, SF has little dependence on AGN luminosity ➔ secular, non-merger driven star formation (~90% pop?)

(e.g. Georgakakis+09, Lutz+10, Cisternas+11, Schawinski+11, Elbaz+11, Rodighiero+11, Mullaney+11, Santini+11, Rovilos+12, Rosario+12, …)



Obscured AGN growth and star formation at z≈2

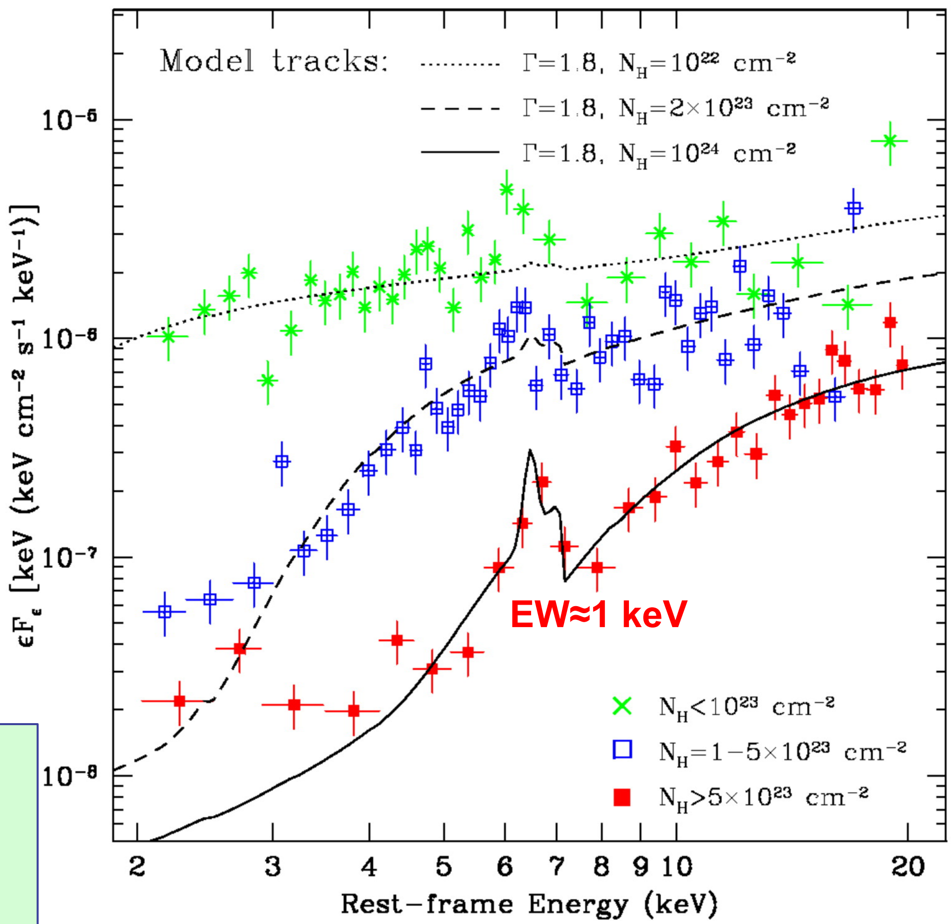
Obscured AGN in sub-mm galaxies

Large reservoir of gas available for accretion and SF

Further indications from mid-IR/ optical selected sources

Deep X-ray fields and stacking techniques needed to estimate average source properties

Obscured accretion = key phase in AGN growth and AGN/galaxy co-evolution ➔ Much of the mass growth of SMBH
occurs during the heavily obscured phase (e.g., Treister+10)



Alexander et al. 2005

➔ Needed: census and knowledge of Compton-thick AGN

Storing the accretion history of the Universe in the XRB

Two main open issues

High-redshift

BH/galaxy co-evolution still unconstrained at very high-z (z>6 or so).
Already formed luminous QSOs at z=6−7

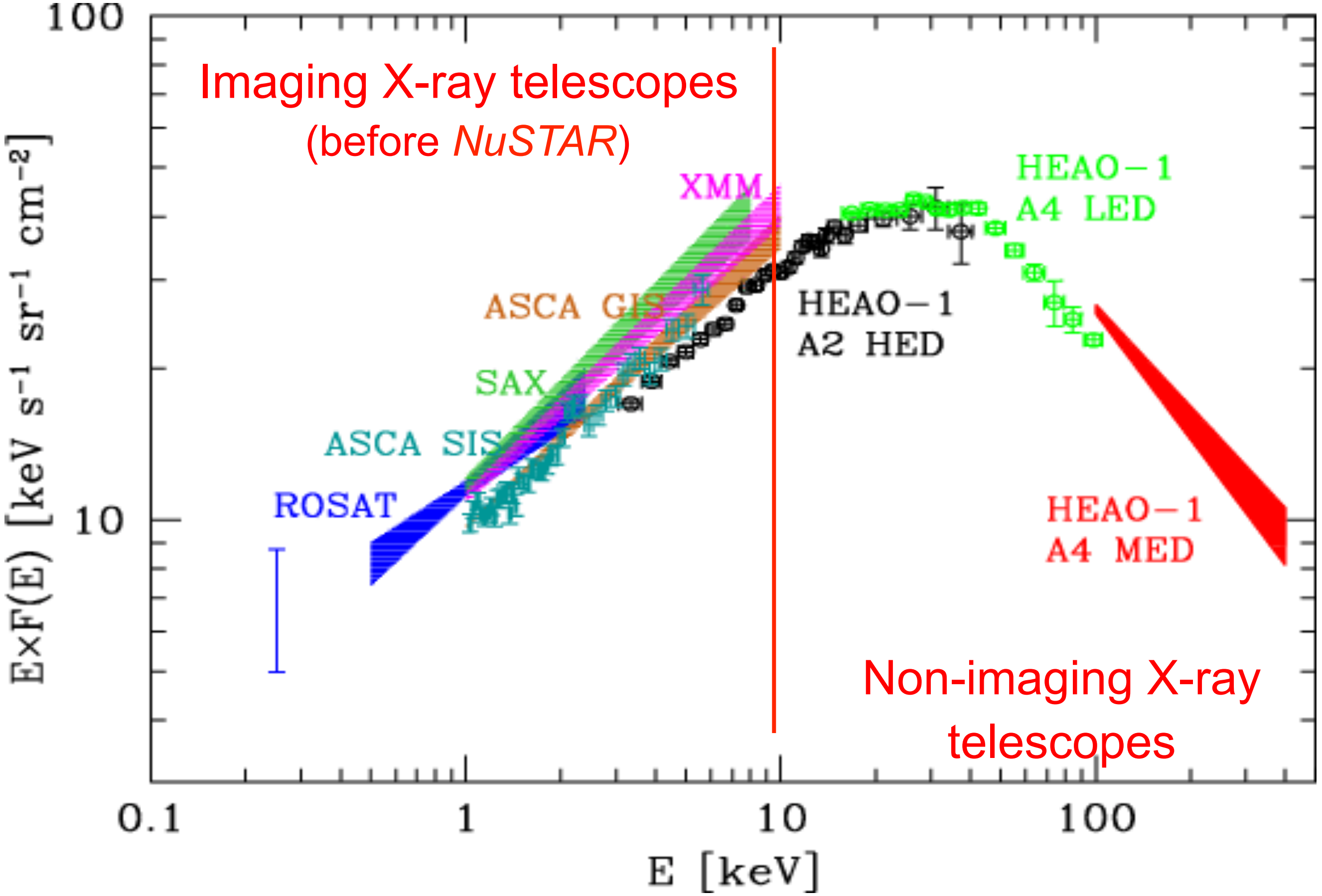
Heavily obscured AGN

Heavily obscured accretion mostly unconstrained beyond the local Universe

Requirement: a complete census of AGN activity

Information stored in the X-ray background

The spectrum of the cosmic XRB



The first spectral data (1980) in the 3-60 keV band could be reproduced accurately by thermal emission from an optically thin plasma: $F(E) \approx E^{-0.29} e^{-E/41\mathrm{keV}}$ (bremsstrahlung)

Can a diffuse plasma emission explain the XRB?

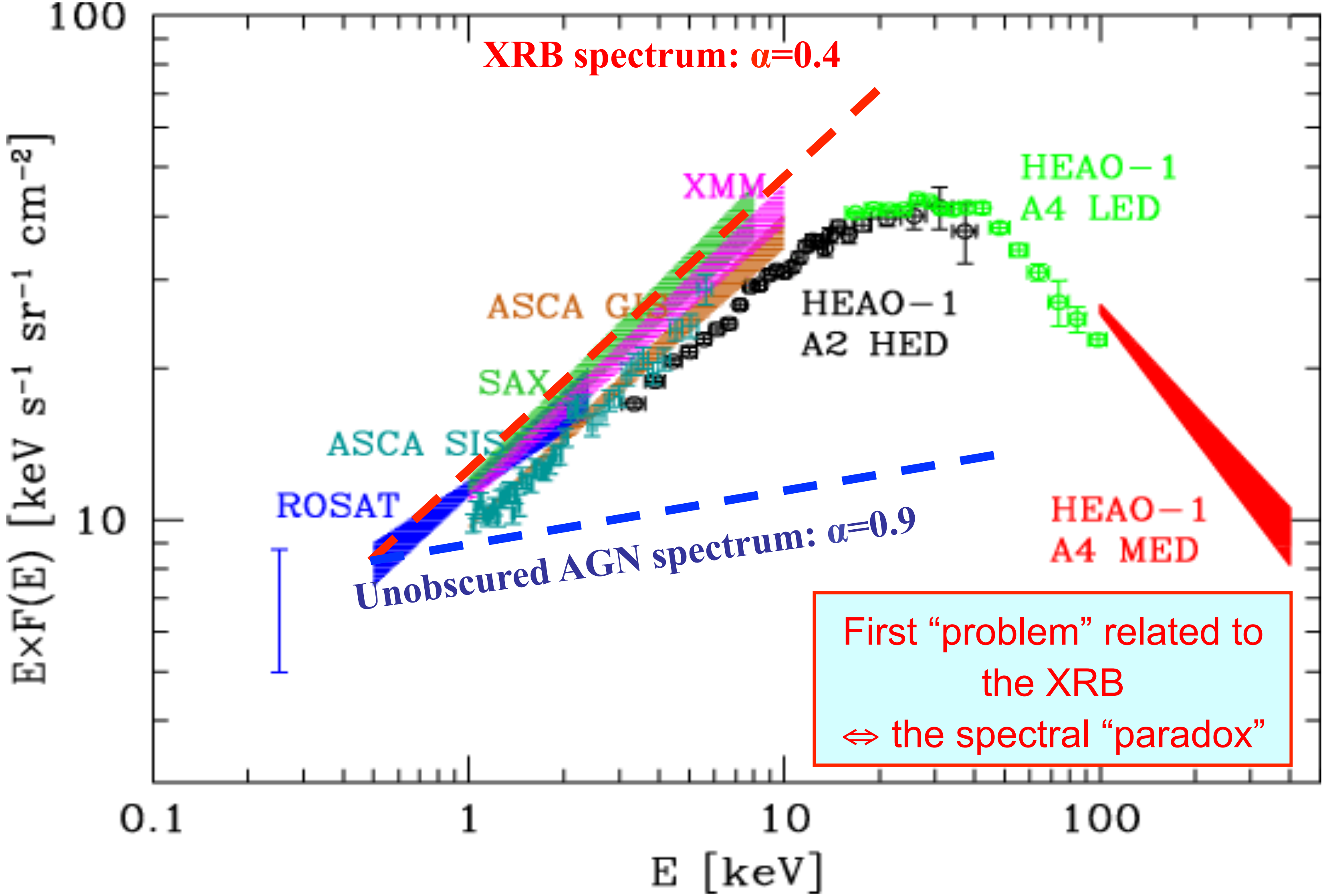
No!

- Subtracting AGN implies an XRB spectrum no more compatible with bremsstrahlung emission
- CMB represents a perfect blackbody; hot gas (T~40 keV ≈ 4×10^8 K) would produce distortions by inverse Compton effect (Mather et al. 1994)

⇩

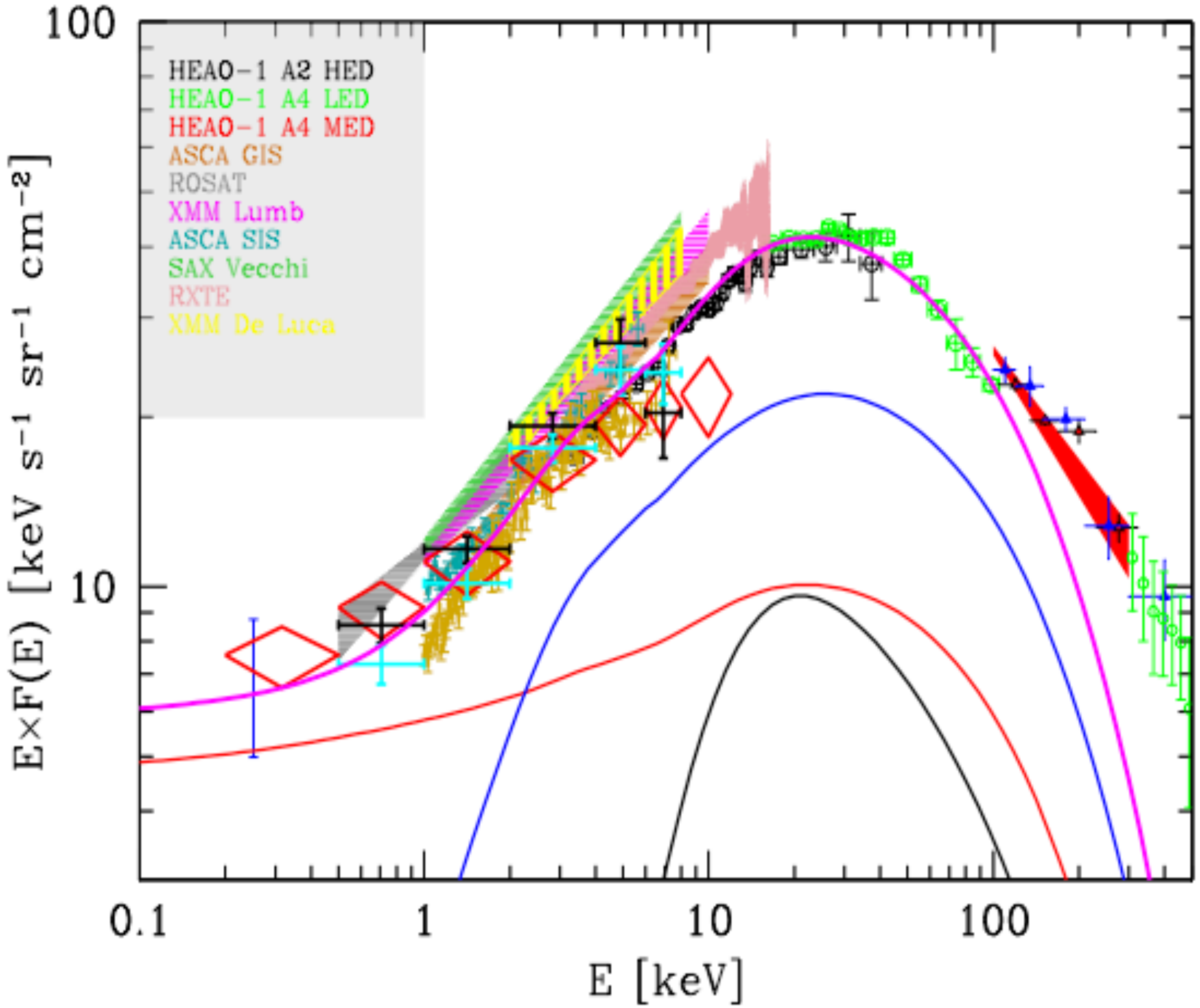
$\boxed{\text{Emission by unresolved, faint individual sources} \rightarrow \text{AGN}}$

The spectral "paradox"



First "problem" related to the XRB
⇔ the spectral "paradox"

The spectrum of the cosmic XRB as sum of obscured and unobscured AGN
(following the original idea of Setti & Woltjer 1989)



The **XRB** synthesis provides an integral constraint (Gilli et al. 2007)

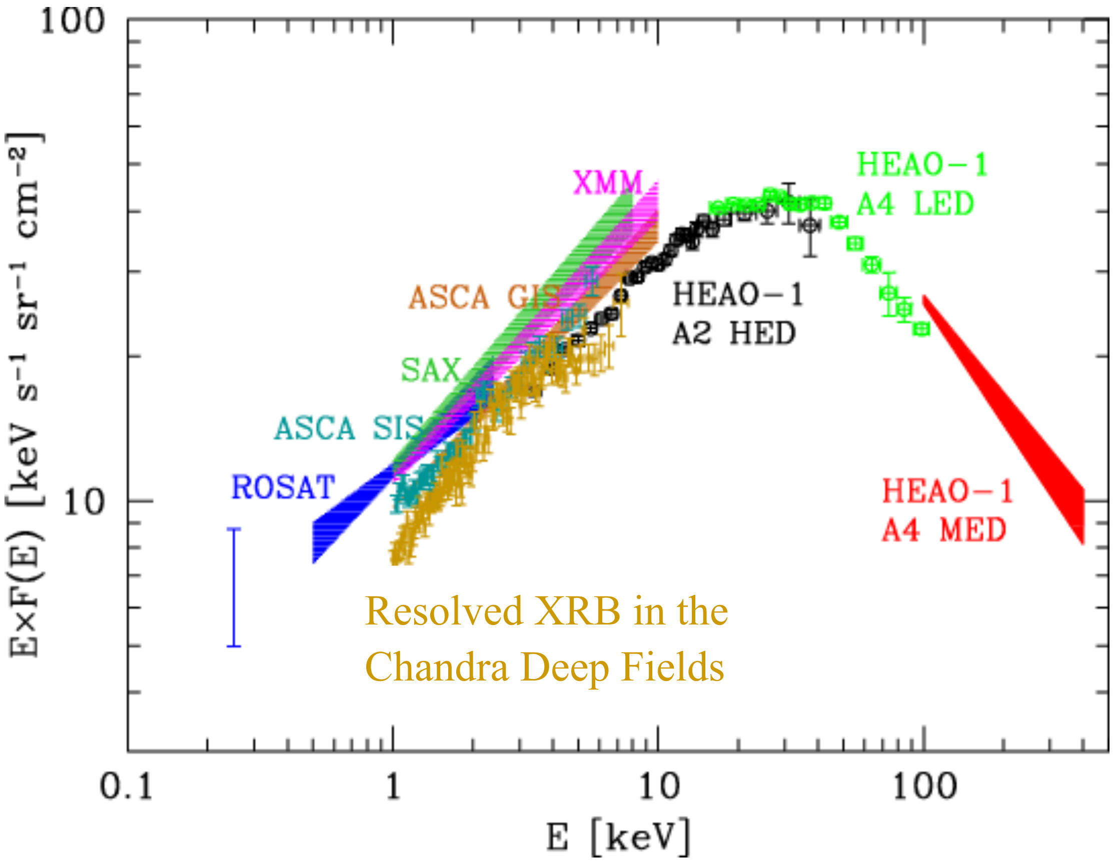
Red ➔ unobscured

Blue ➔ Compton Thin

Black ➔ Compton Thick (N_H>10^{24} cm^{-2})

The evolution is folded in the adopted XLF

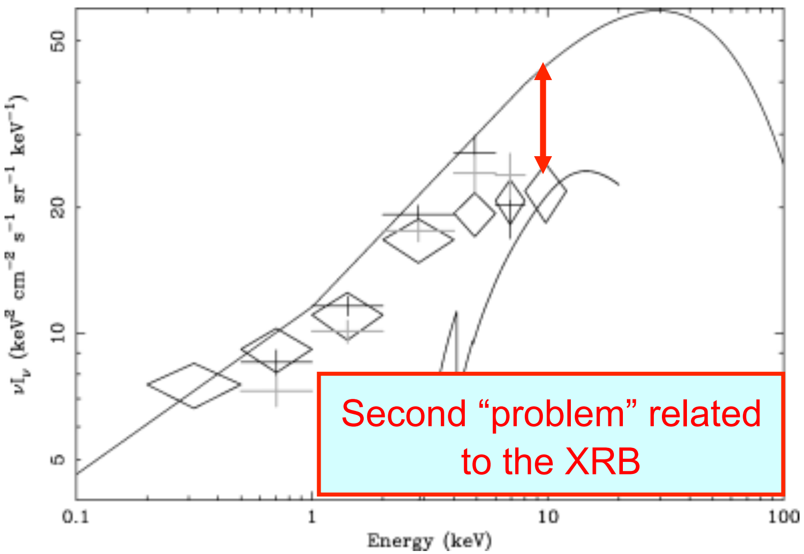
Resolved XRB fraction: still a “missing” population?



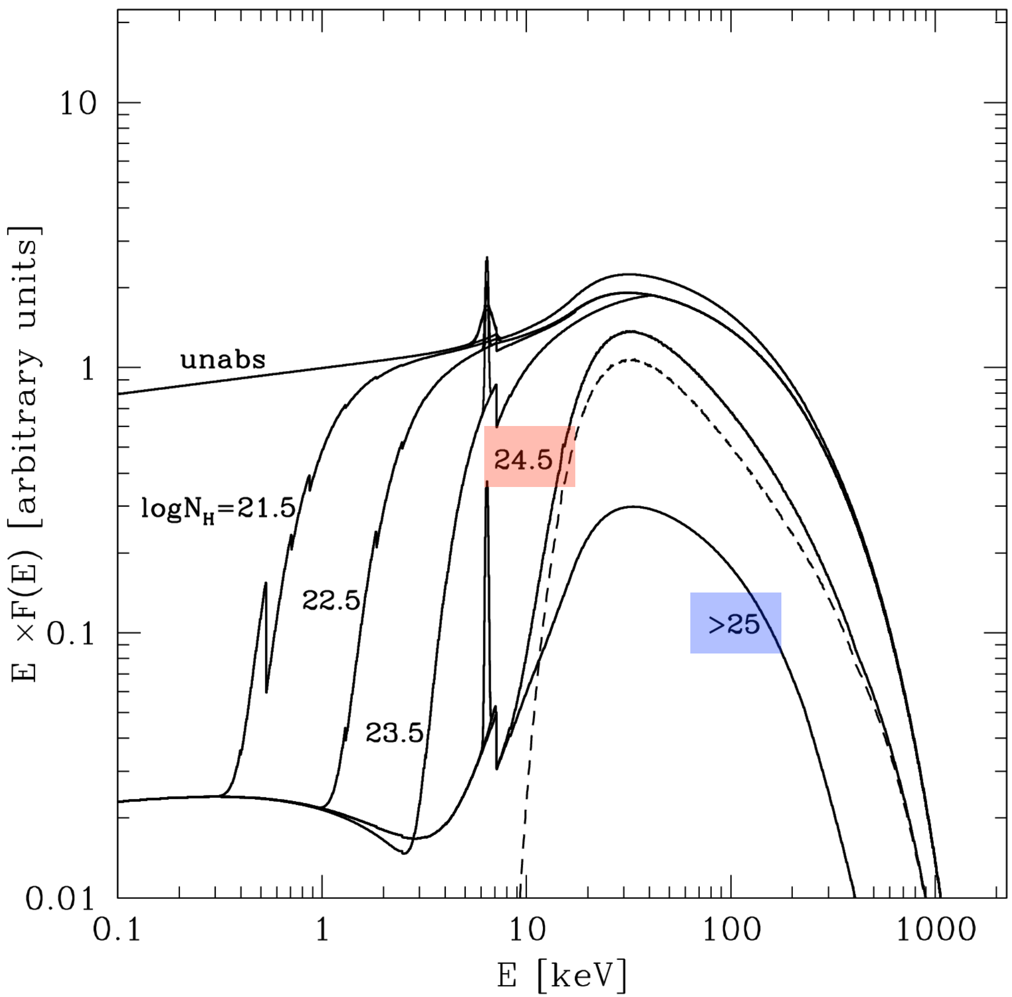
≈50-80% of the XRB being resolved into single sources at E<10 keV

BUT only ≈50% resolved above 5 keV

Worsley et al. (2005)



AGN X-ray spectral templates with different N_H

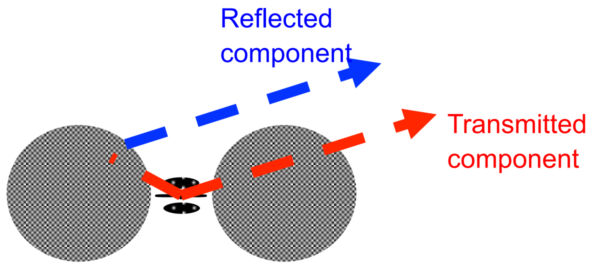


Likely around one hundred “secure” (i.e., with broad-band X-ray data available) Compton-thick AGN known at present. Most of them are local AGN

Unabsorbed:
$\log N_H < 21$

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

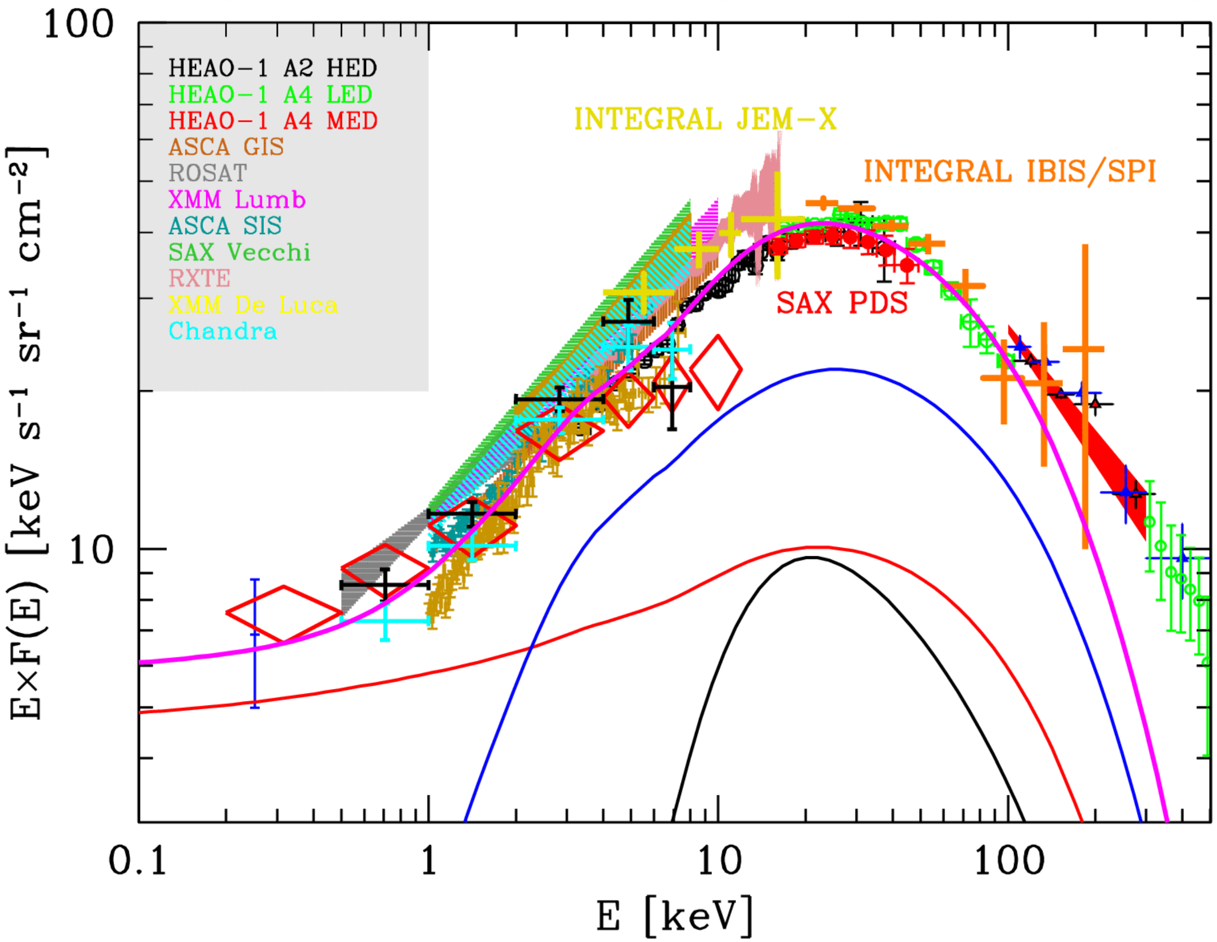
Compton-Thick:
Mildly ($\log N_H$ =24-25)
Heavily ($\log N_H$ >25)



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.

Fitting the XRB with the most up-to-date AGN synthesis model (Gilli et al. 2007)



Now: imaging by *NuSTAR* above 10 keV (limited sens., still limited fraction of resolved XRB)

Number of Compton-thin AGN = Number of Compton-thick AGN at high X-ray luminosities

Compton-thick AGN needed To fill the 30 keV “gap”

Way to provide a census of AGN activity: X-ray surveys

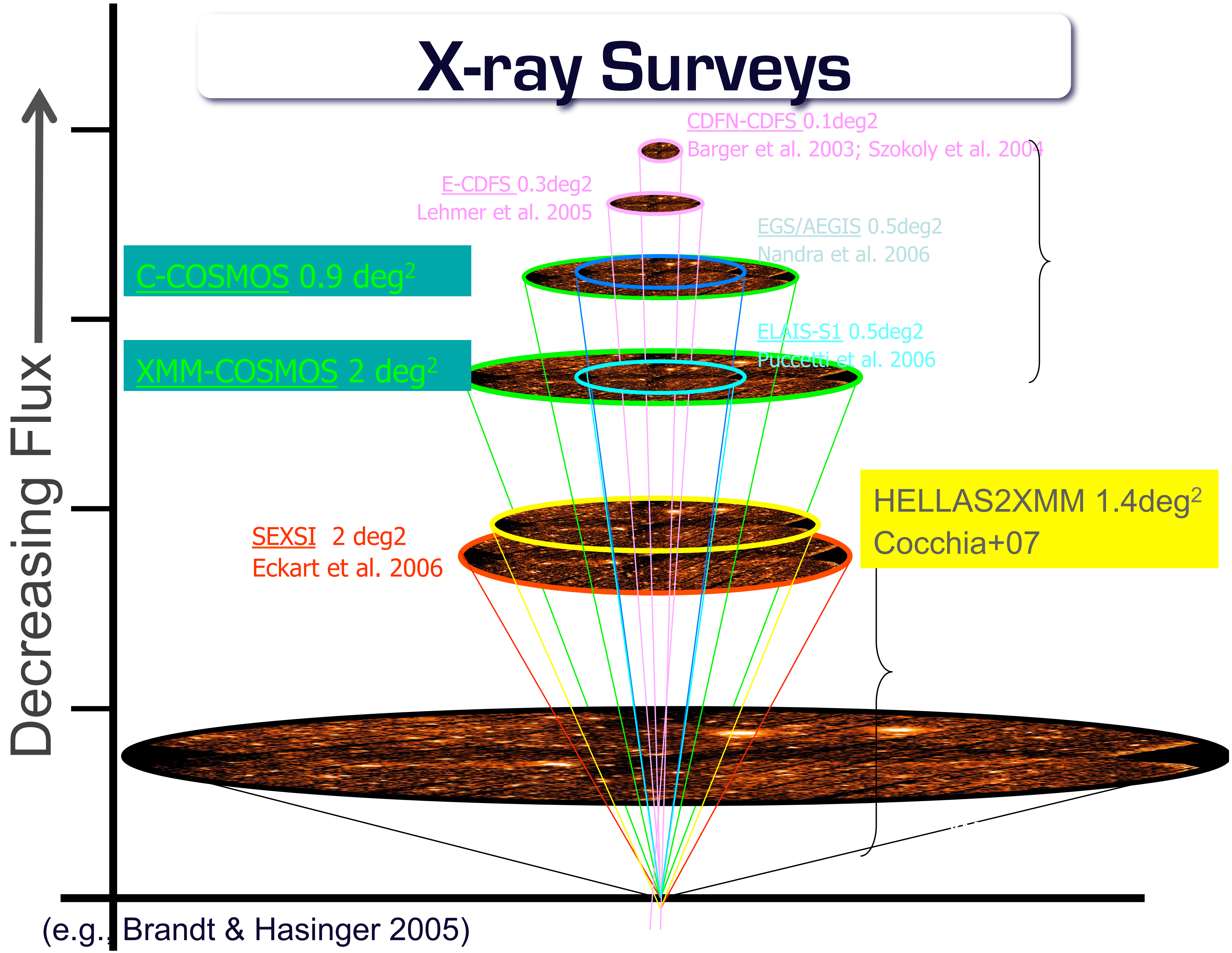
Large-area survey
to pick up luminous and rare AGN

Relatively bright optical counterparts, easier optical IDs

Deep-area survey
to pick up faint and distant AGN

Typically faint optical counterparts, difficult optical IDs

X-ray Surveys



(e.g., Brandt & Hasinger 2005)

What is the best observing strategy for X-ray surveys?

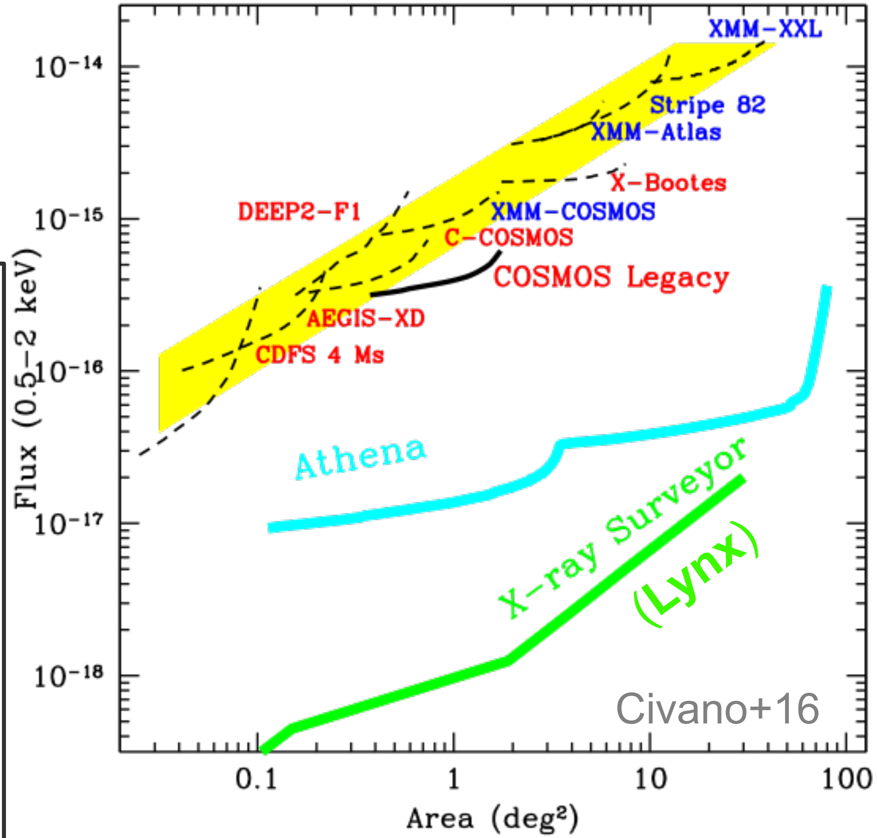
DEEP X-RAY SURVEYS

PROs:

• Ideal to reveal distant sources (because of the depth of the exposure)
• Large number of sources

CONs

• Limited to small areas
• Limited individual photon statistics



Goal: going deep on large area
(BUT huge amounts of exposure time would be needed, so not practicable at present)

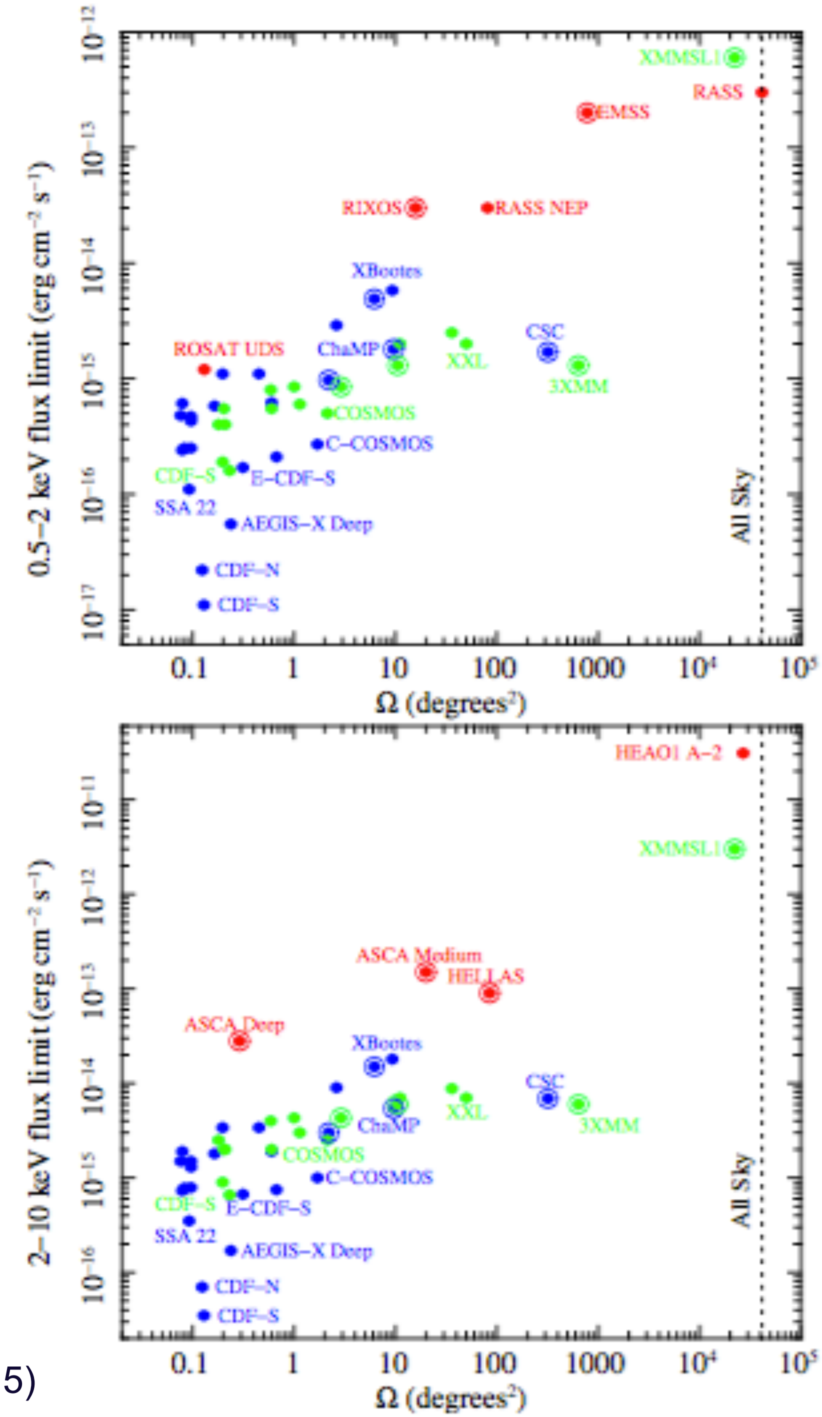
LARGE (and SHALLOW) X-RAY SURVEYS

PROs:

• Ideal to pick up bright and rare X-ray sources
• Possibility to cover large areas of the sky

CONs

• Limited number of sources



RASS: all sky in the soft band

Now: *eROSITA* (German/Russian mission) in the soft and hard band, ALL SKY

(e.g., Brandt & Alexander 2015)

efforts of the last ~20 years with major X-ray facilities

Table 1 Selected extragalactic X-ray surveys with *Chandra*, *XMM-Newton*, and *NuSTAR*

Survey name	Rep. Eff. Exp. (ks)	Solid angle (arcmin^2)	Representative reference
Chandra (0.3–8 keV)			
Chandra Deep Field-South (CDF-S)	3870	465	Xue et al. (2011)
Chandra Deep Field-North (CDF-N)	1950	448	Alexander et al. (2003)
AEGIS-X Deep	800	860	Goulding et al. (2012)
SSA22 protocluster	392	330	Lehmer et al. (2009a)
HRC Lockman Hole	300	900	PI: S.S. Murray
Extended CDF-S (E-CDF-S)	250	1,128	Lehmer et al. (2005)
AEGIS-X	200	2,412	Laird et al. (2009)
Lynx	185	286	Stern et al. (2002)
LALA Cetus	174	297	Wang et al. (2007)
LALA Boötes	172	346	Wang et al. (2004)
C-COSMOS and COSMOS-Legacy	160	6,120	Elvis et al. (2009)
SSA13	101	345	Barger et al. (2001b)
Abell 370	94	345	Barger et al. (2001a)
3C 295	92	274	D'Elia et al. (2004)
ELAIS N1+N2	75	590	Manners et al. (2003)
WHDF	72	286	Bielby et al. (2012)
CLANS (Lockman Hole)	70	2,160	Trouille et al. (2008)
SEXSI[a]	45	7,920	Harrison et al. (2003)
CLASXS (Lockman Hole)	40	1,620	Trouille et al. (2008)
13 h Field	40	710	McHardy et al. (2003)
ChaMP[a]	25	34,560	Kim et al. (2007)
XDEEP2 Shallow	15	9,432	Goulding et al. (2012)
Chandra Source Catalog (CSC)[a]	13	1,150,000	Evans et al. (2010)
Stripe 82X–*Chandra*[a]	9	22,320	LaMassa et al. (2013b)
NDWFS XBoötes	5	33,480	Murray et al. (2005)
XMM-Newton (0.2–12 keV)			
Chandra Deep Field-South (CDF-S)	2820	830	Ranalli et al. (2013)
Lockman Hole	640	710	Brunner et al. (2008)
Chandra Deep Field-North (CDF-N)	180	752	Miyaji et al. (2003)
13 h Field	120	650	Loaring et al. (2005)
ELAIS-S1	90	2,160	Puccetti et al. (2006)
Groth-Westphal	81	730	Miyaji et al. (2004)
COSMOS	68	7,670	Cappelluti et al. (2009)
Subaru *XMM-Newton* Deep Survey (SXDS)	40	4,100	Ueda et al. (2008)
Marano field	30	2,120	Lamer et al. (2003)
HELLAS2XMM[a]	25	10,440	Baldi et al. (2002)
XMM-LSS XMDS	23	3,600	Chiappetti et al. (2005)

(Brandt & Alexander 2015)

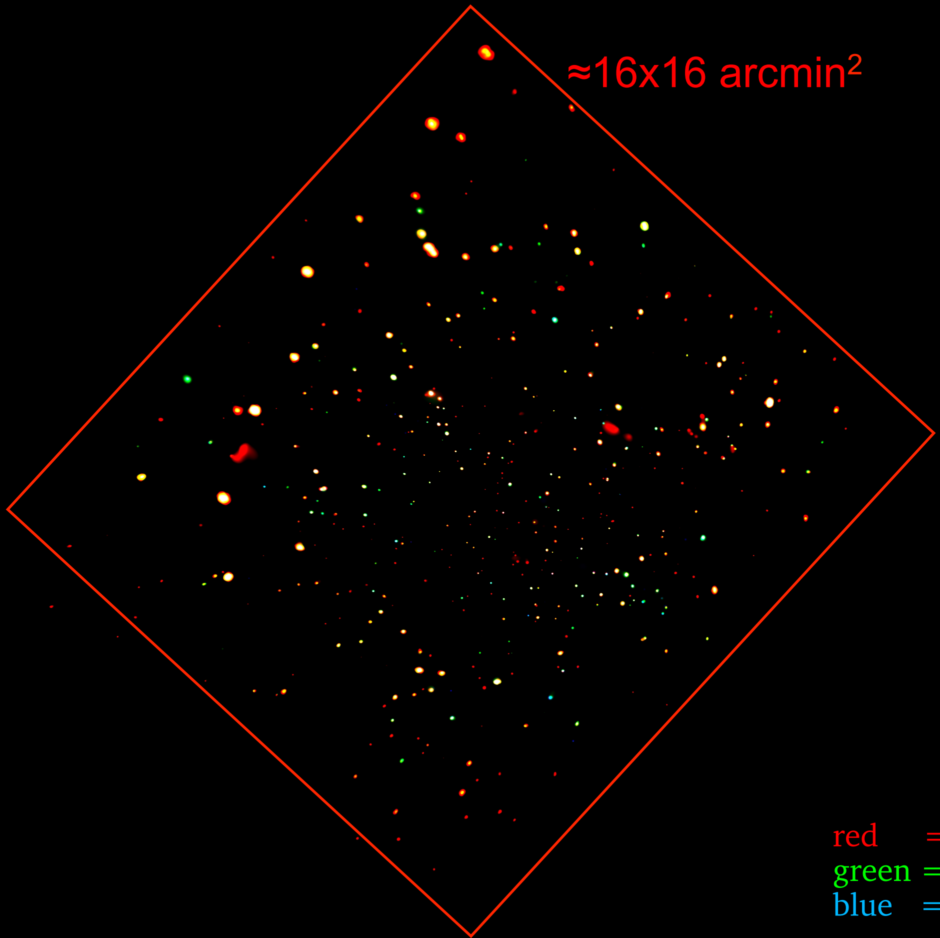
Table 1 continued

Survey name	Rep. Eff. Exp. (ks)	Solid angle (arcmin^2)	Representative reference
3XMM[a]	15	2,300,000	Watson (2012)
Stripe 82X–*XMM-Newton*[a]	15	37,800	LaMassa et al. (2013a)
XMM-LSS	10	39,960	Chiappetti et al. (2013)
XMM-XXL	10	180,000	Pierre (2012)
Stripe 82X–*XMM-Newton* Targeted	8	129,600	PI: C.M. Urry
XMM-Newton Slew Survey (XMMSL1)[a]	0.006	8×10^7	Warwick et al. (2012)
NuSTAR (3–24 keV)			
Extended CDF-S (E-CDF-S)	200	1,100	Mullaney et al, in prep
AEGIS-X	270	860	Aird et al, in prep
COSMOS	65	6,120	Civano et al, in prep
Serendipitous survey[a]	22	19,000	Alexander et al. (2013)

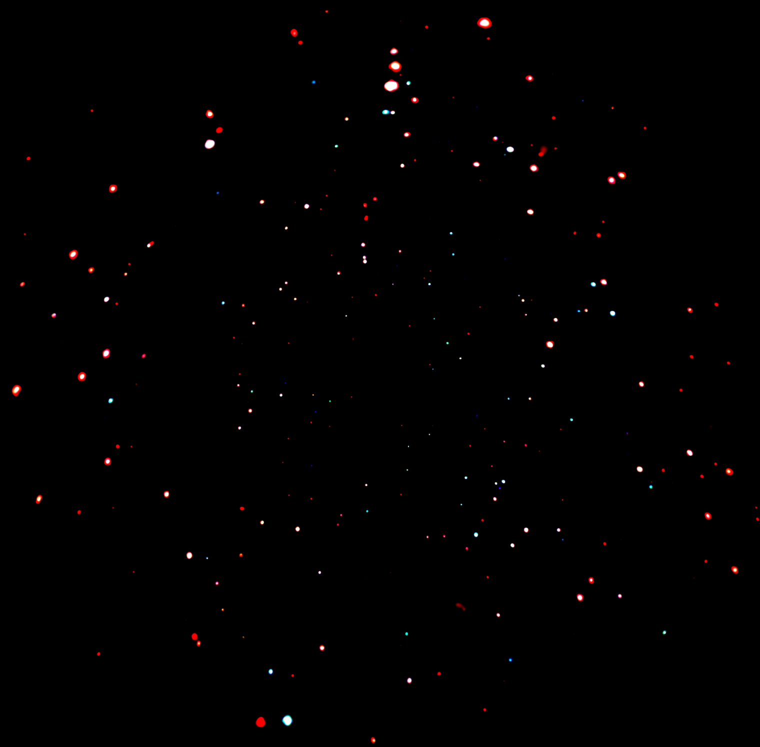
[a] Serendipitious survey; see Sect. 2.1 for brief discussion regarding such surveys

Chandra Deep Fields

CDFN (Alexander+03; Luo+ 08)



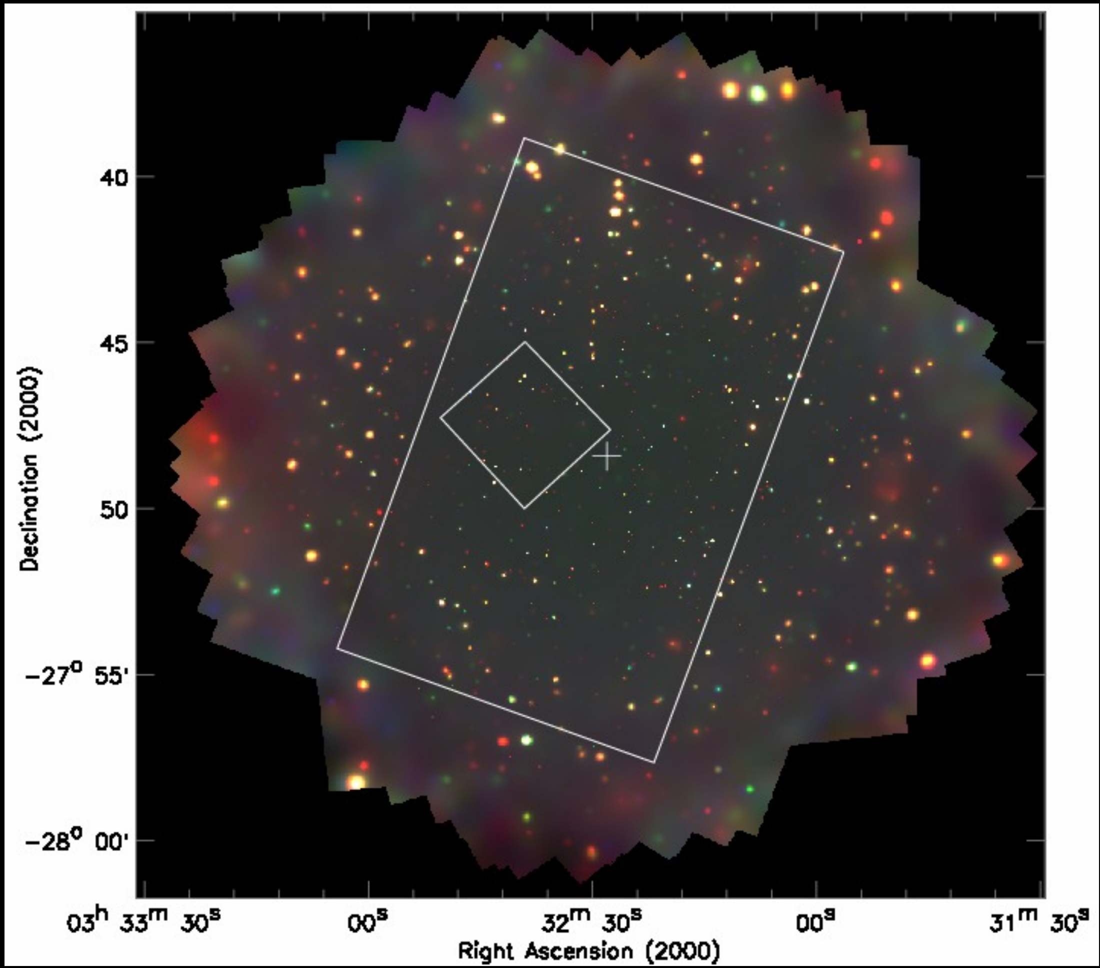
CDFS (Giacconi+02)

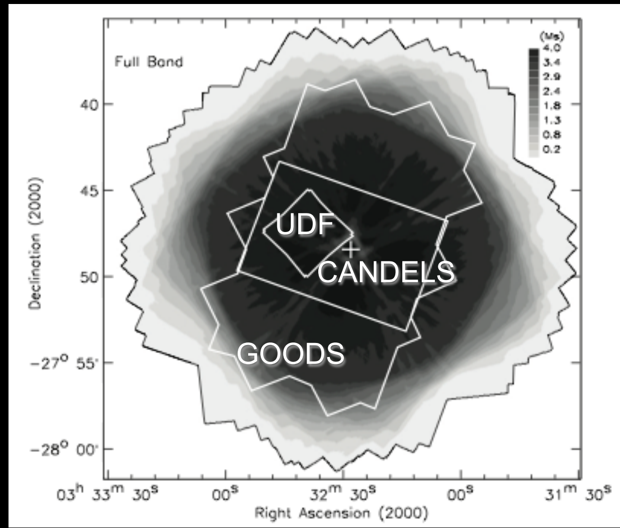


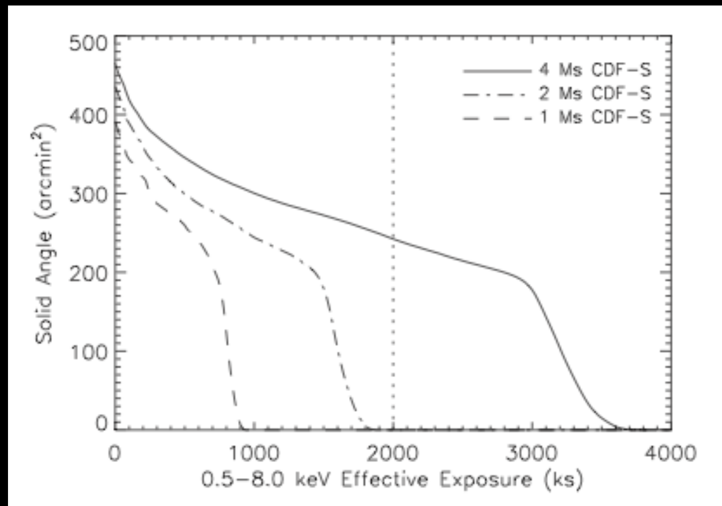
red = 0.5-1 keV
green = 1 - 2 keV
blue = 2 - 8 keV

up to the 4 Ms exposure in the CDF-S (Xue et al. 2011):

740 X-ray sources (≈60% with spec. redshift)

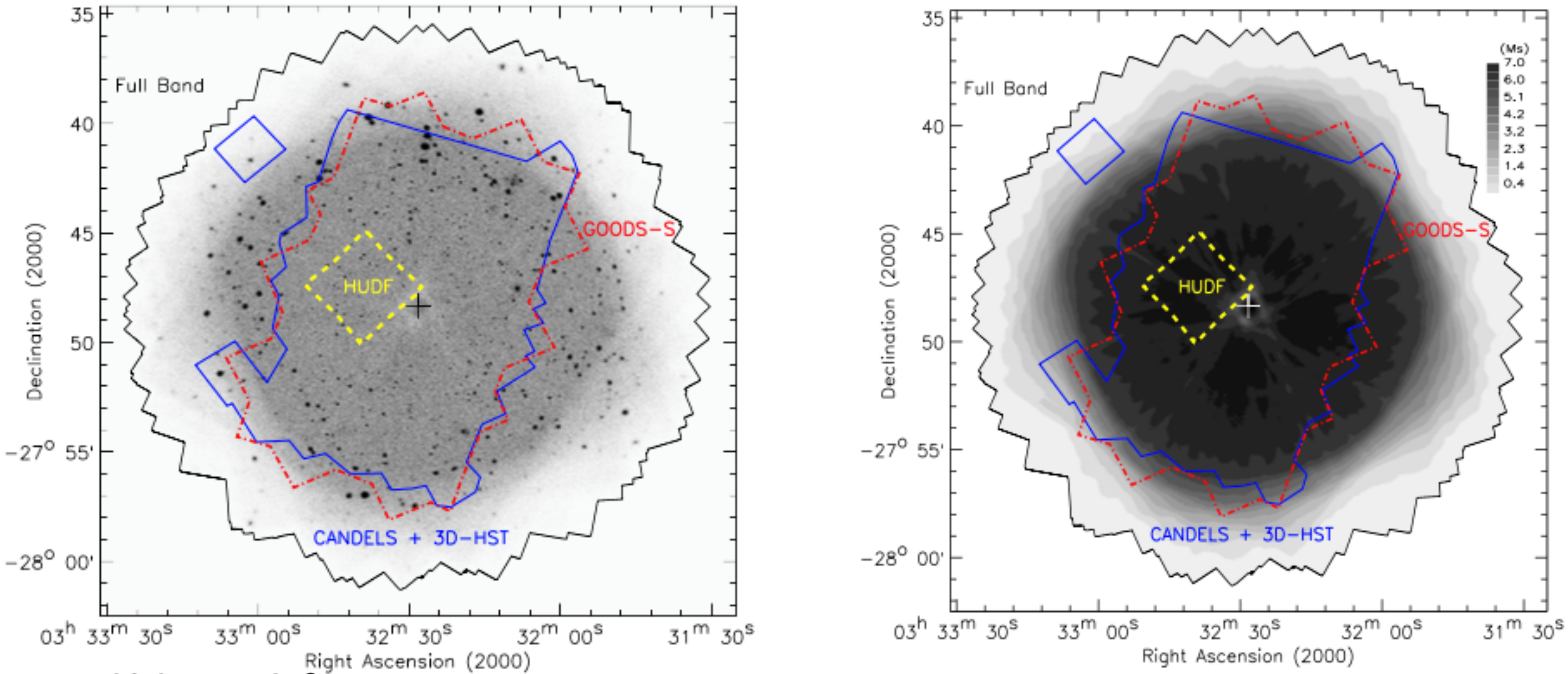






The 7Ms *Chandra* Deep Field South. I.

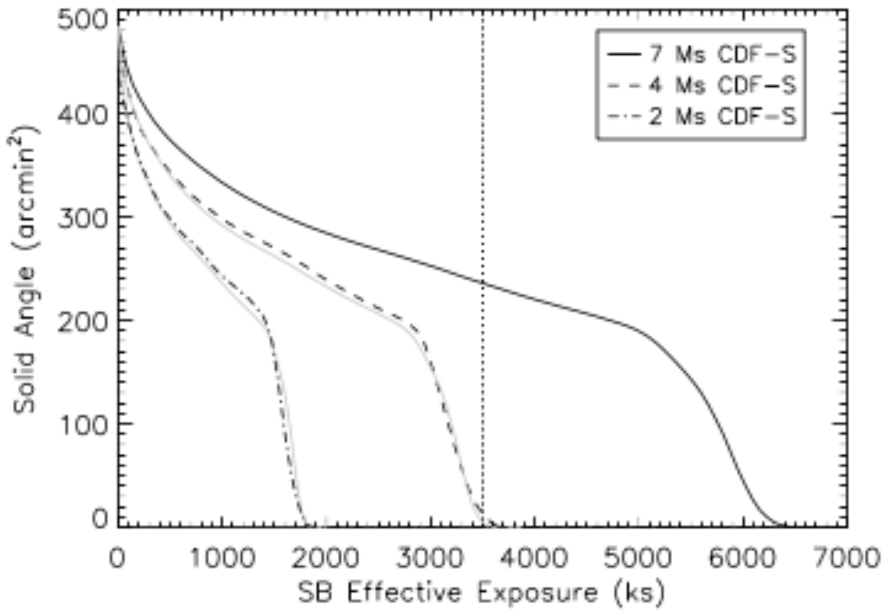
The deepest X-ray exposure ever



Luo+ 2017

- 484 arcmin^2
- 1008 X-ray sources (992 with counterpart, ≈66% with spec. redshift)
- At least 70% are classified as AGN (the remaining are galaxies and stars)
- Inner 1 arcmin region: $F_{[0.5-7keV]}=1.9\times10^{-17}$ erg/cm^2/s
  $F_{[0.5-2keV]}=6.4\times10^{-18}$ erg/cm^2/s
  $F_{[2-7keV]}=2.7\times10^{-17}$ erg/cm^2/s

The 7Ms *Chandra* Deep Field South. II.

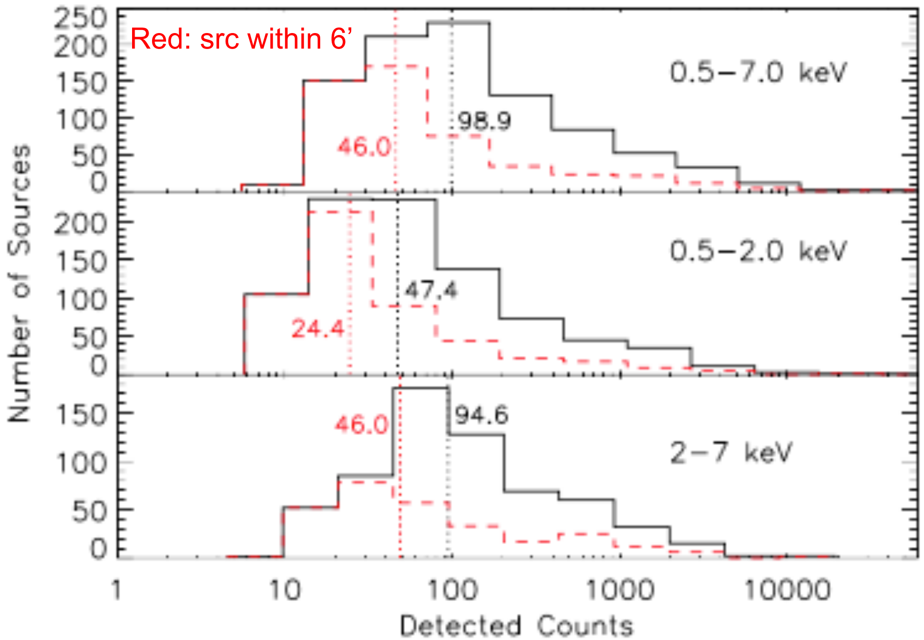


Solid angle vs. exposure time

Motivations behind going deeper

Number of counts

Median values around 100 (still low)



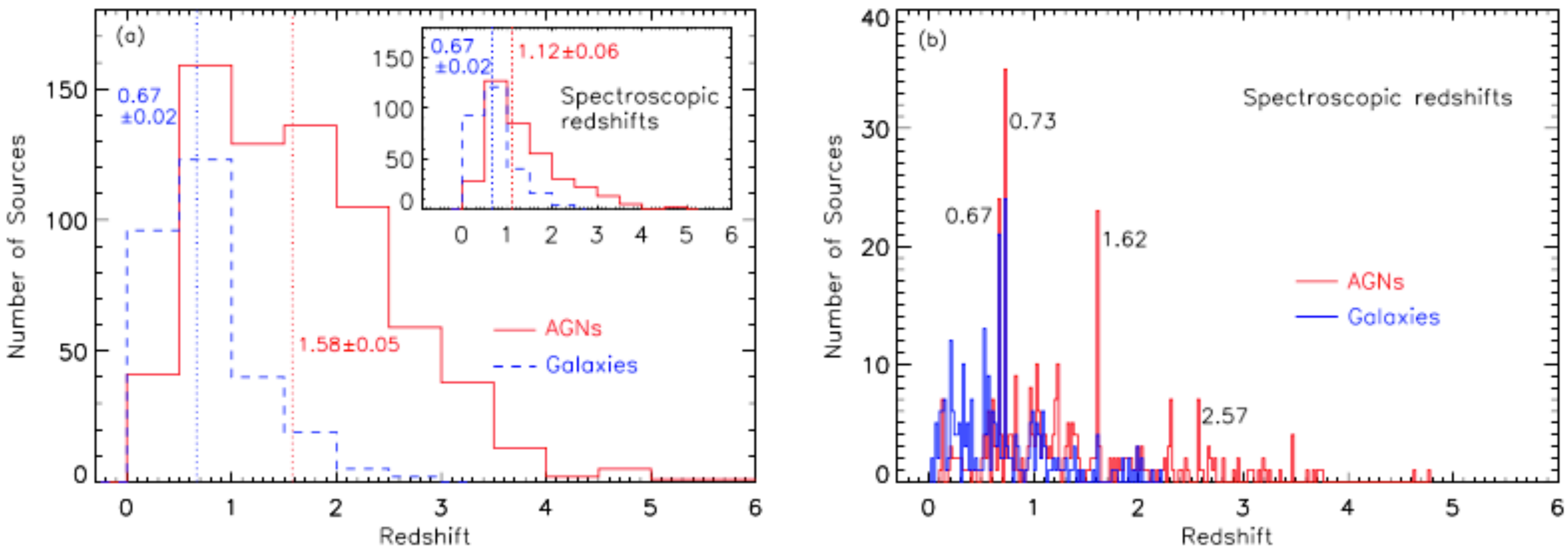
About 90% of the 0.5−2 keV XRB resolved into discrete sources in the CDF-S

Luo+ 2017

The 7Ms *Chandra* Deep Field South. III.

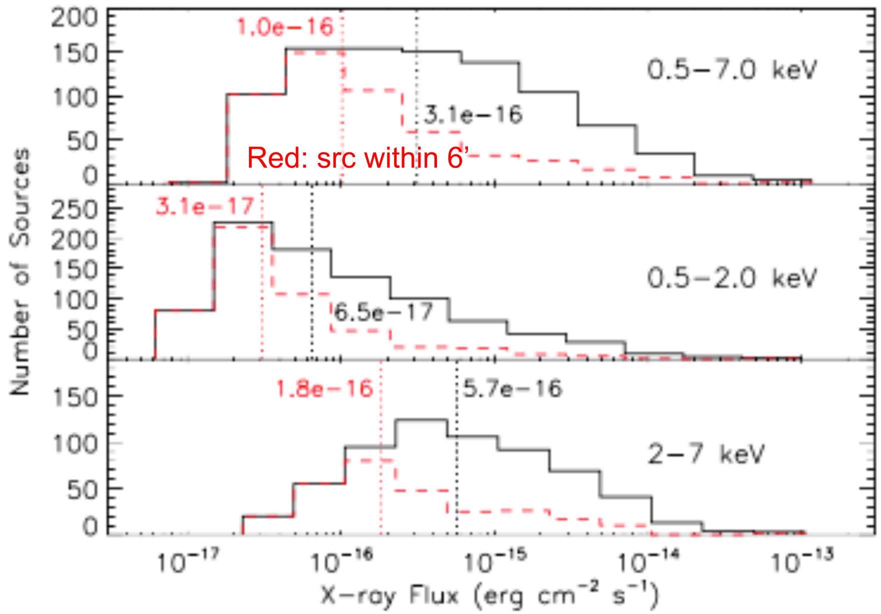
Redshift distribution

AGN vs. Galaxies



Luo+ 2017

The 7Ms *Chandra* Deep Field South. IV.

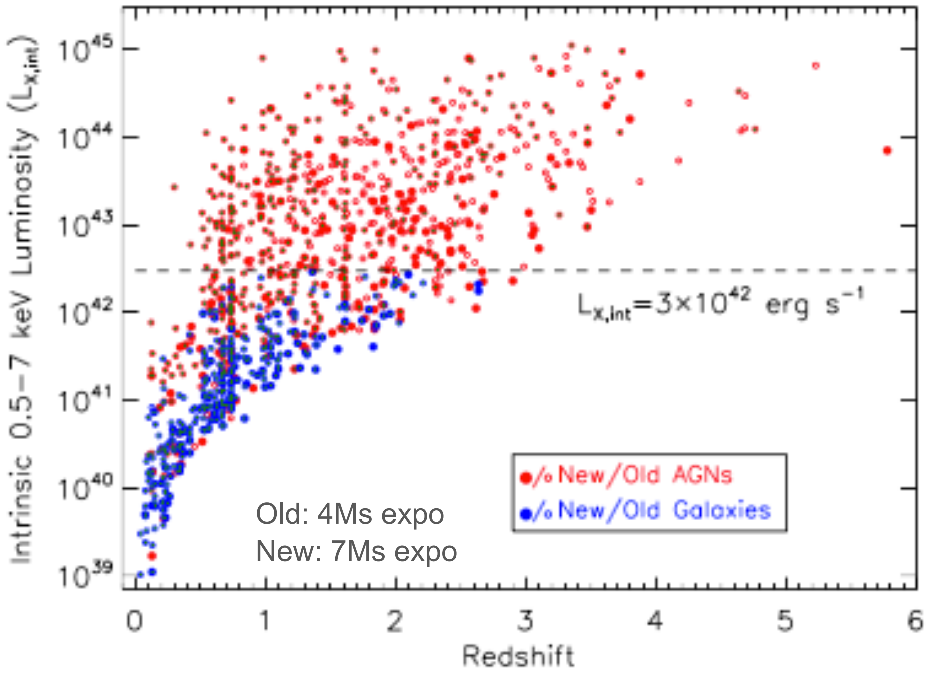


Flux distribution

Inner region vs. whole field

Luminosity distribution

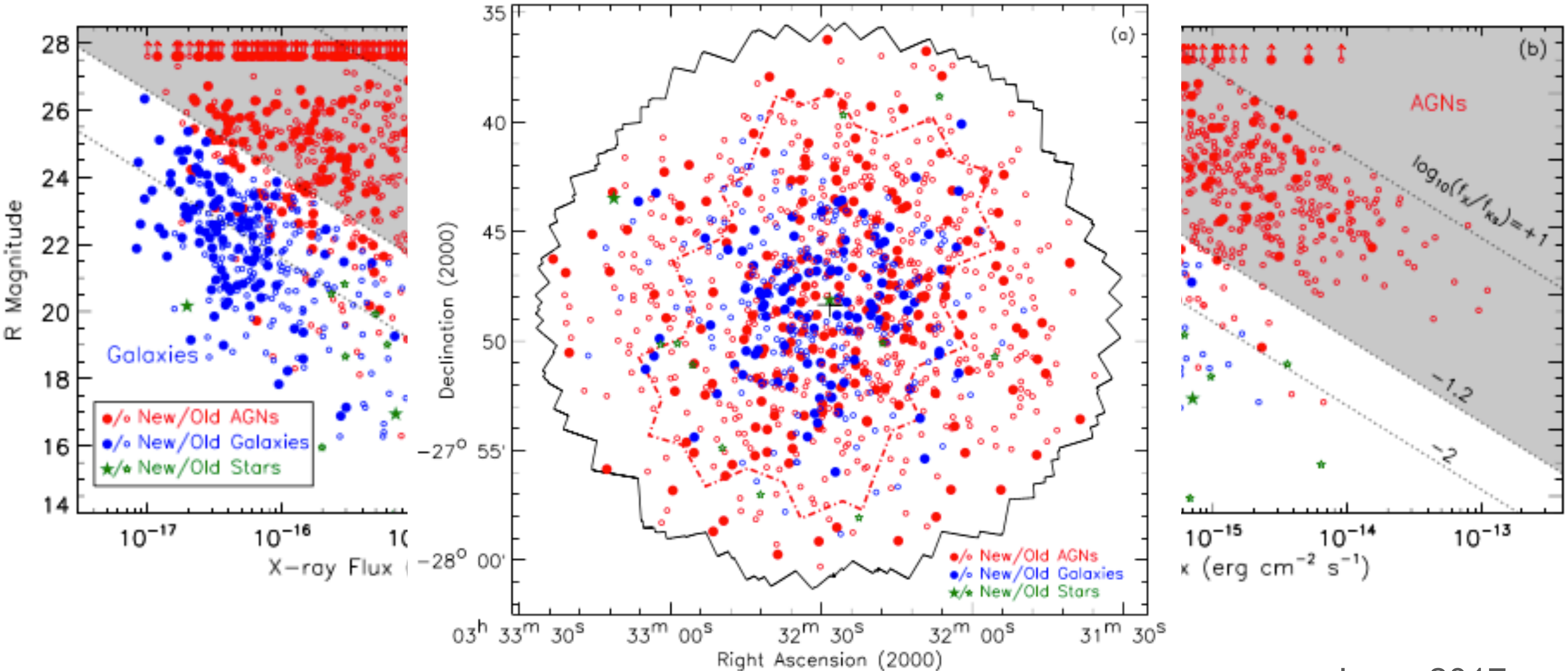
AGN vs. Galaxies



Luo+ 2017

The 7Ms *Chandra* Deep Field South. V.

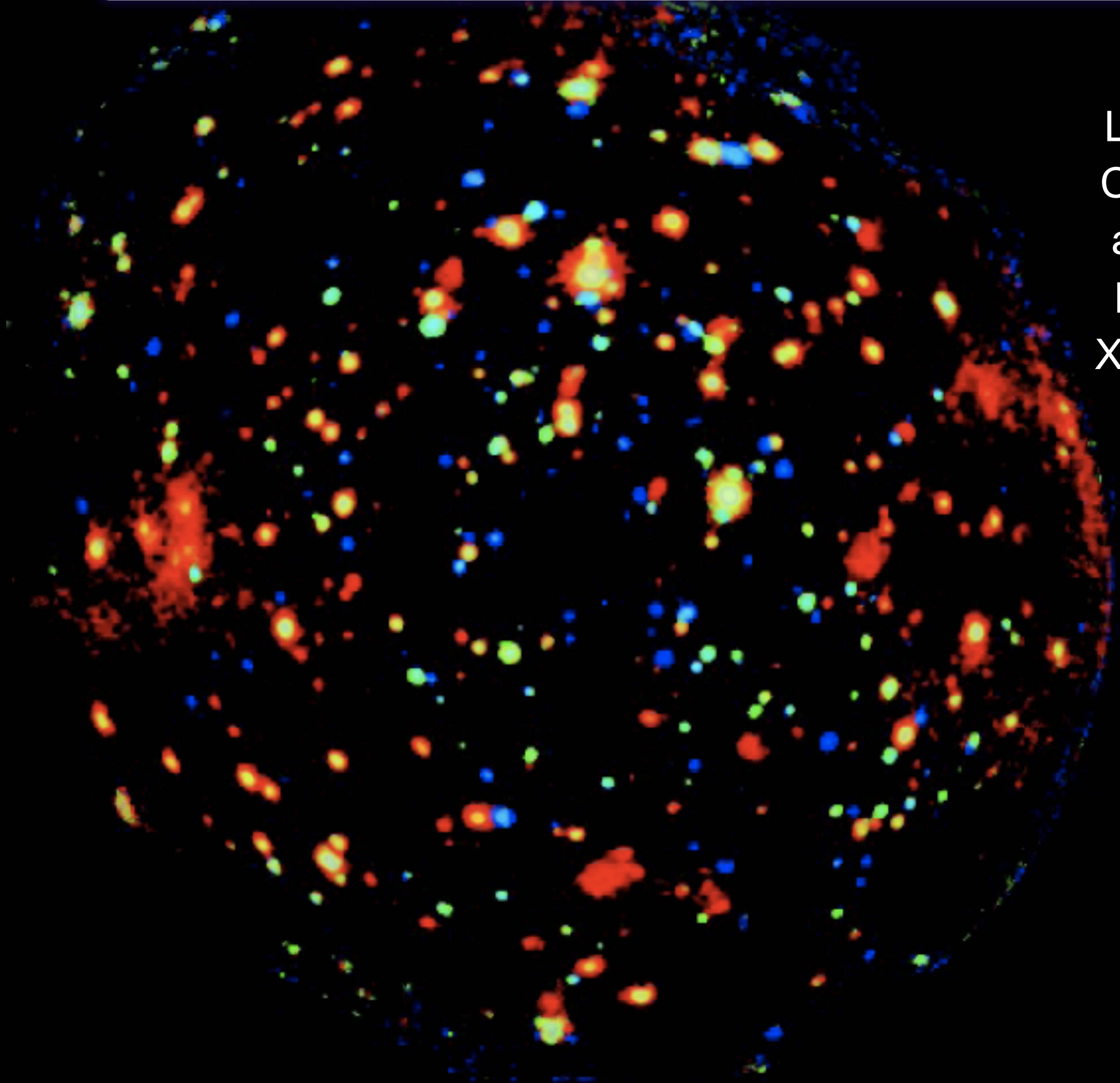
R- (*left panel*) and K_S-band (*right panel*) mag vs. X-ray Flux



Luo+ 2017

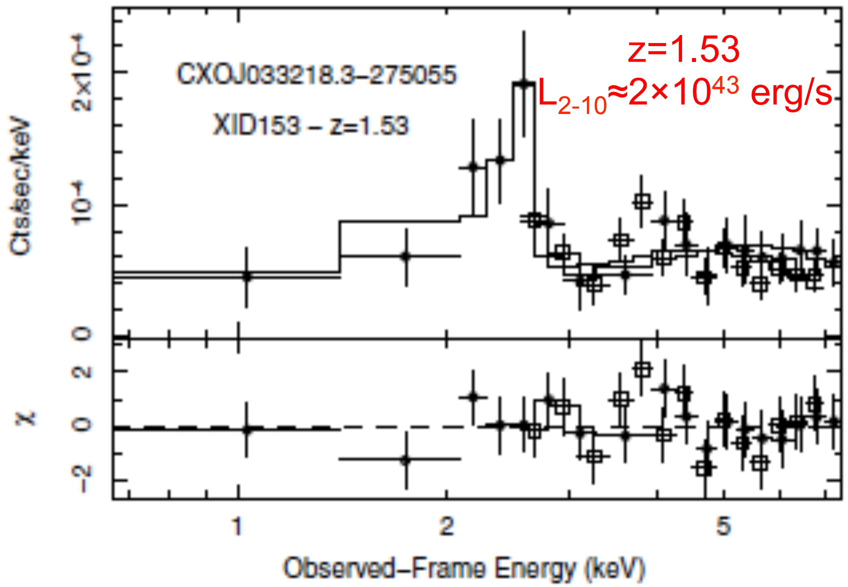
Source statistics fundamental to populate luminosity and redshift bins and study AGN evolution and demographics

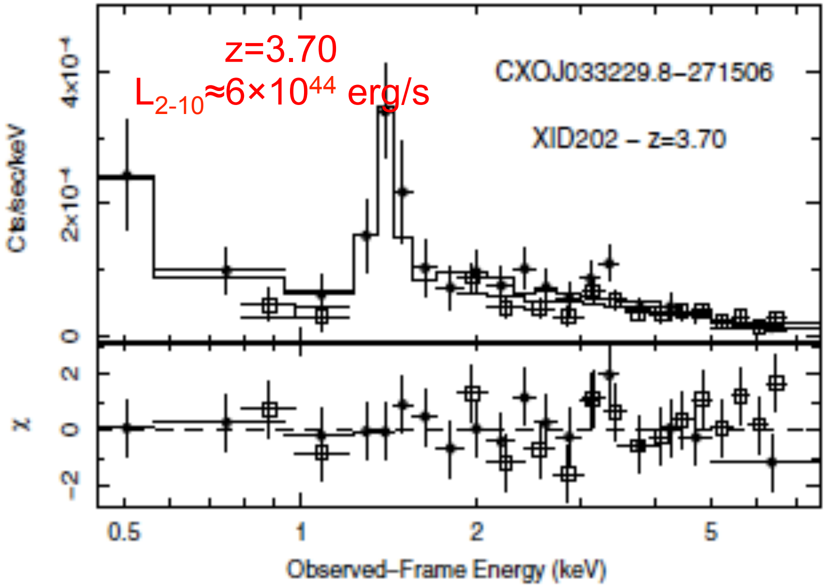
Chandra Deep Field South: XMM 3 Ms exposure



Larger field-of-view than Chandra, larger effective area, worst PSF, higher background ➔good for X-ray spectral analysis of relatively X-ray bright sources

The 3 Ms XMM-*Newton* Survey in the CDF-S. I



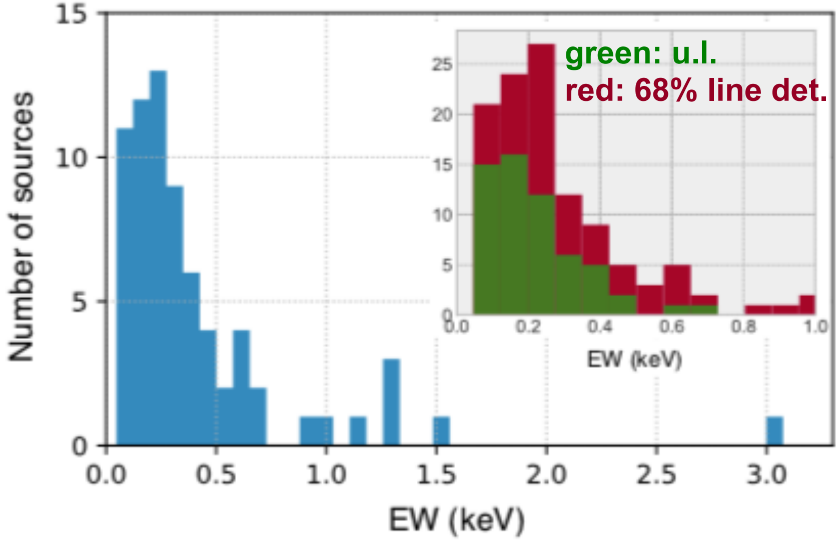


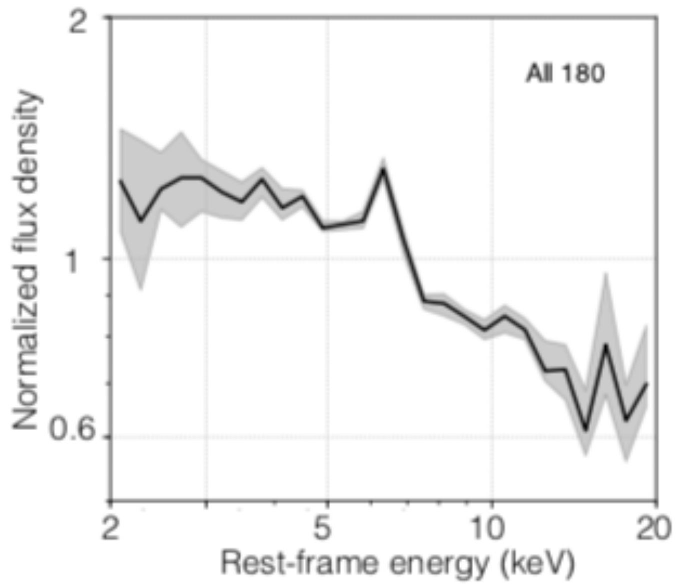
Comastri et al. (2011)
see also Iwasawa et al. (2020)

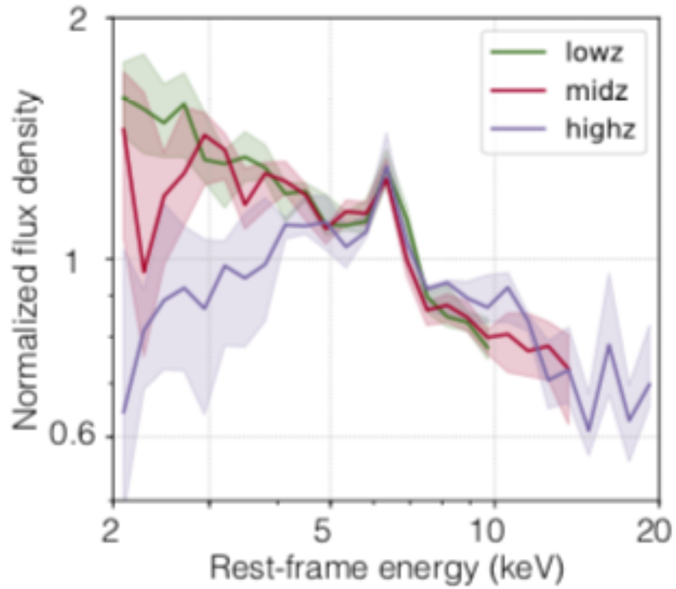
Observed flat X-ray spectra ➔ reflection/transmission dominated, strong iron Kα line

The 3 Ms XMM-*Newton* Survey in the CDF-S. II

iron Kα EW analysis





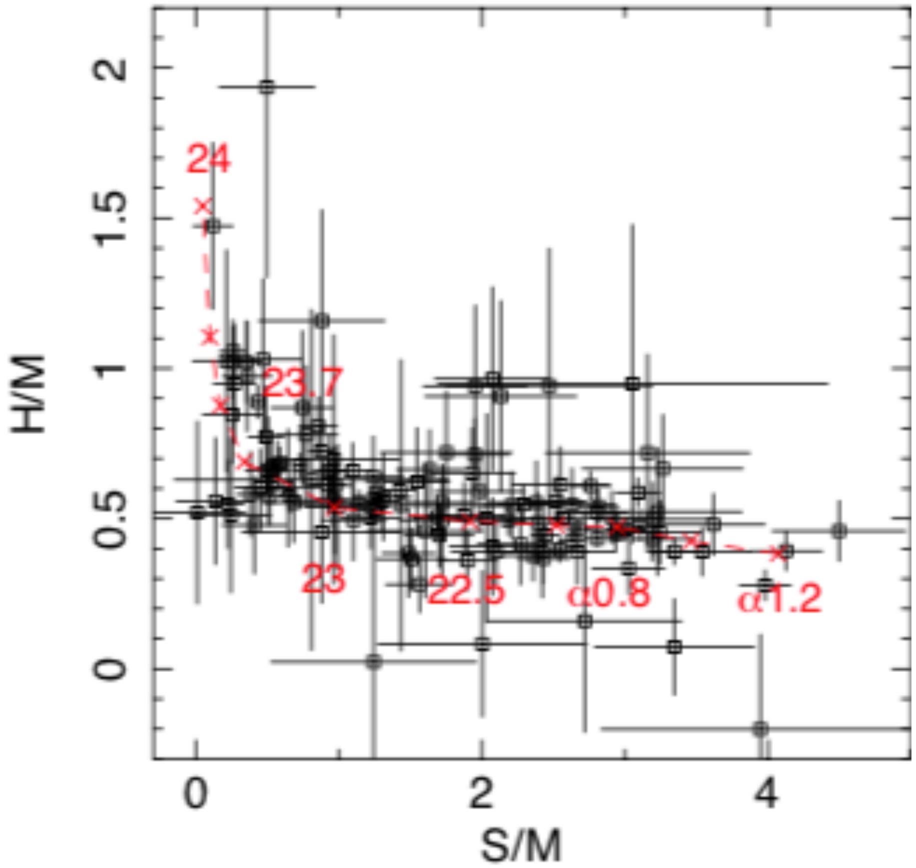


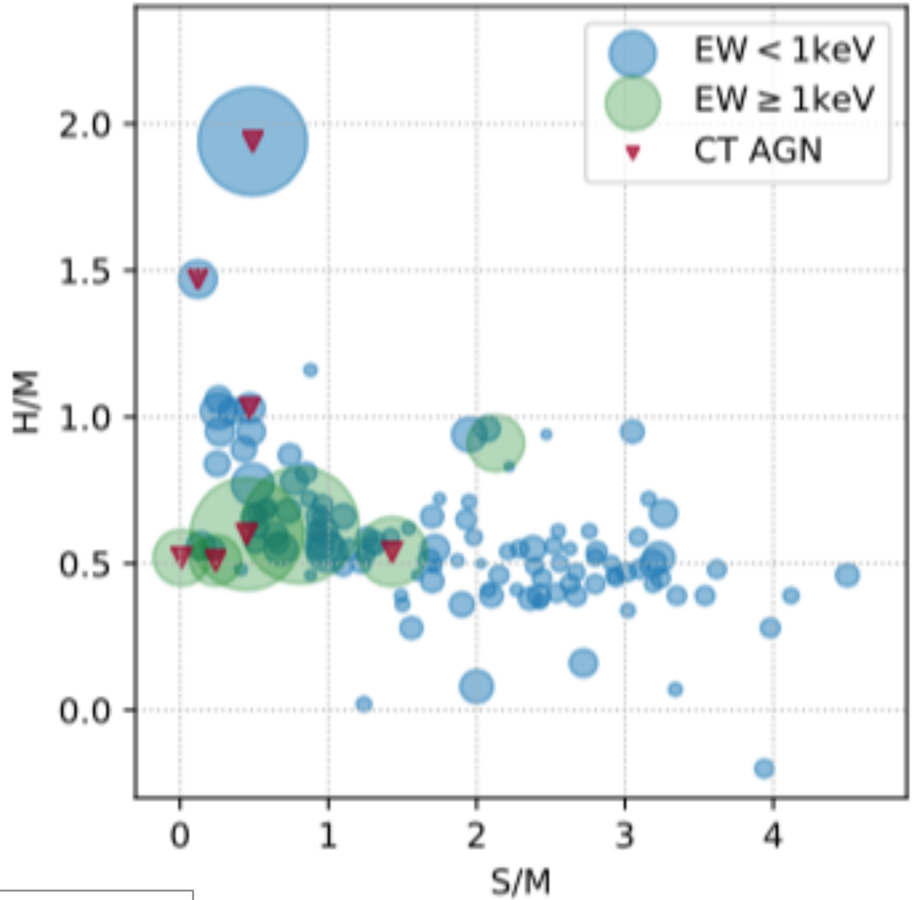
composite spectra:
180 X-ray sources at z=0.4−3.8

Iwasawa et al. (2020)

The 3 Ms XMM-*Newton* Survey in the CDF-S. III

combining hardness ratio (HR) + iron Kα EW analysis to pick up obscured sources





S=2−5 keV r.f.
M=5−9 keV r.f.
H=9−14 keV r.f.

Iwasawa et al. (2020)

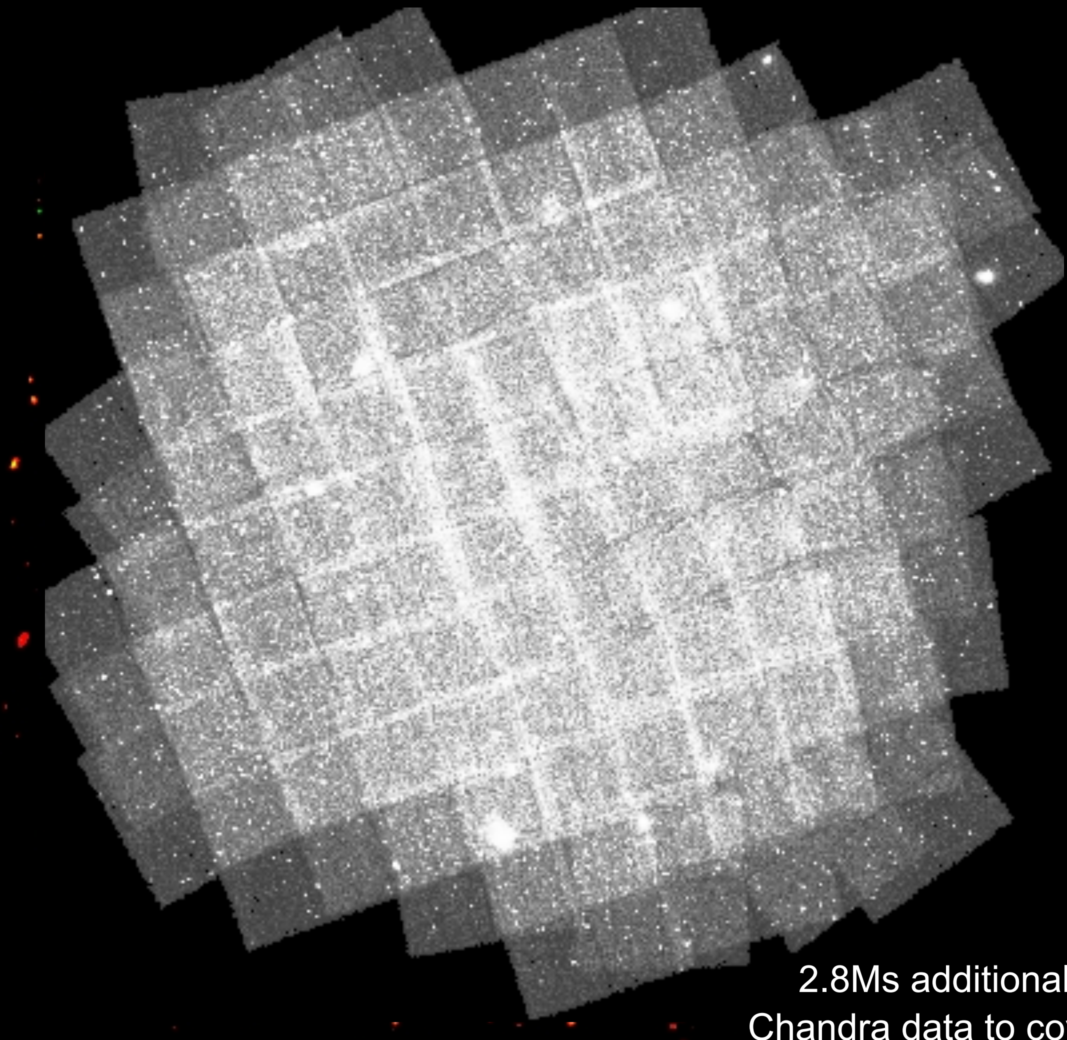
X-raying the COSMOS

Large area of sky (≈2 deg^2) surveyed at bright flux limits

XMM-*Newton*
1.55 Ms
1822 sources

Sampling X-ray fainter fluxes going deeper on a smaller region

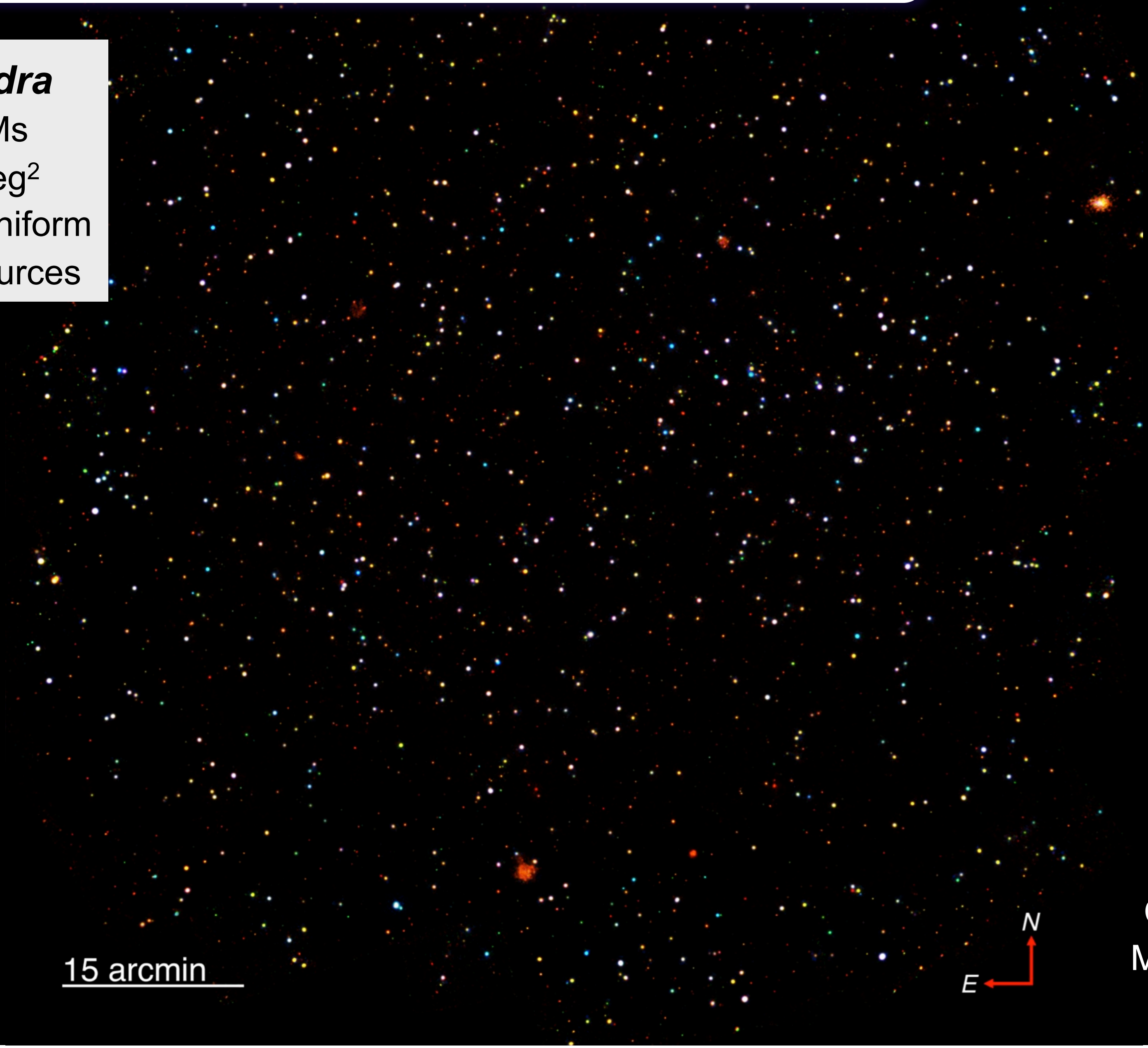
Chandra
1.8 Ms
1761 sources



2.8Ms additional Chandra data to cover the entire ~2 deg^2 (going deep)

The final COSMOS-Legacy Field

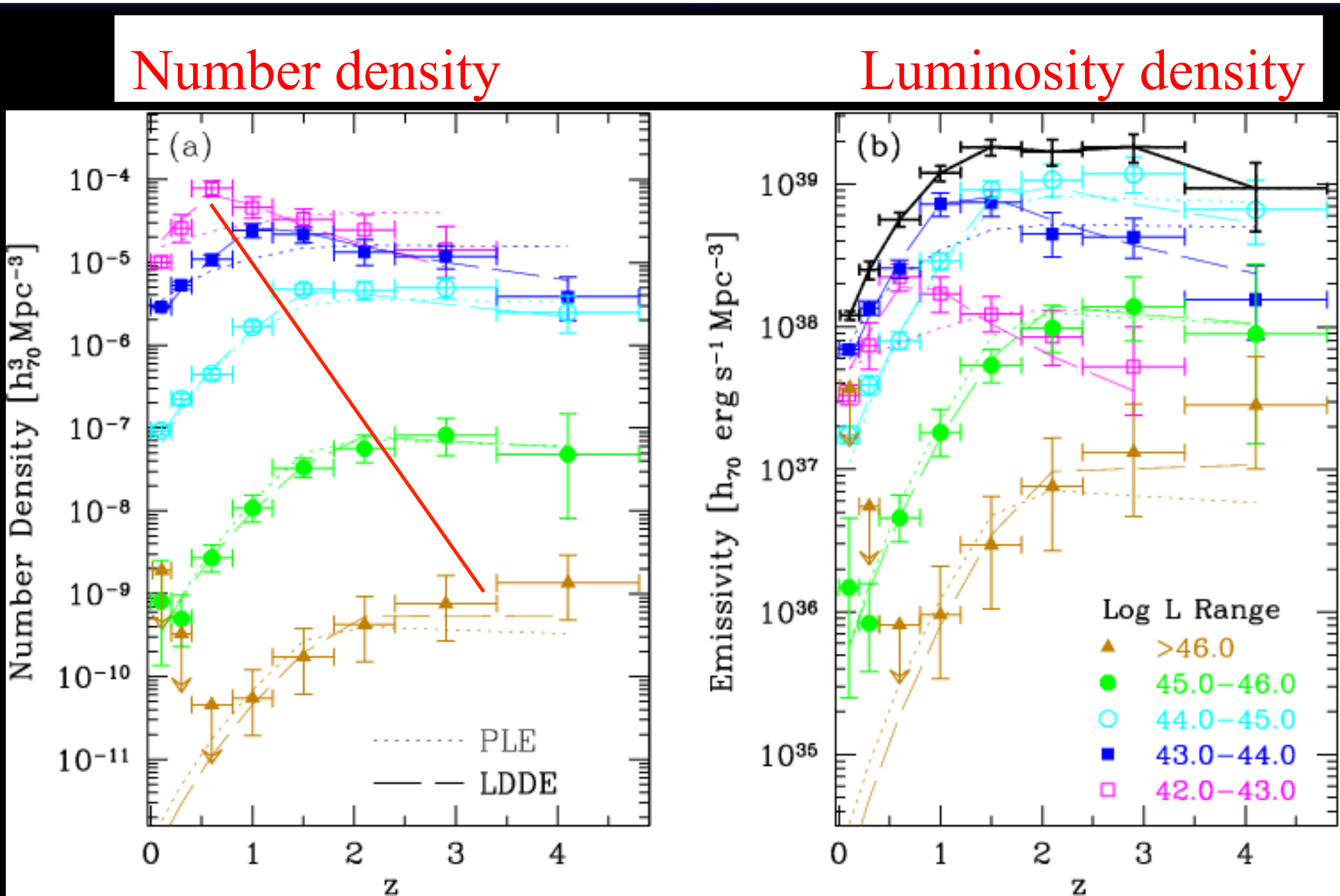
Chandra
4.6 Ms
2.2 deg^2
150 ks uniform
4016 sources



Civano+16, Marchesi+16

AGN Evolution

AGN cosmological evolution



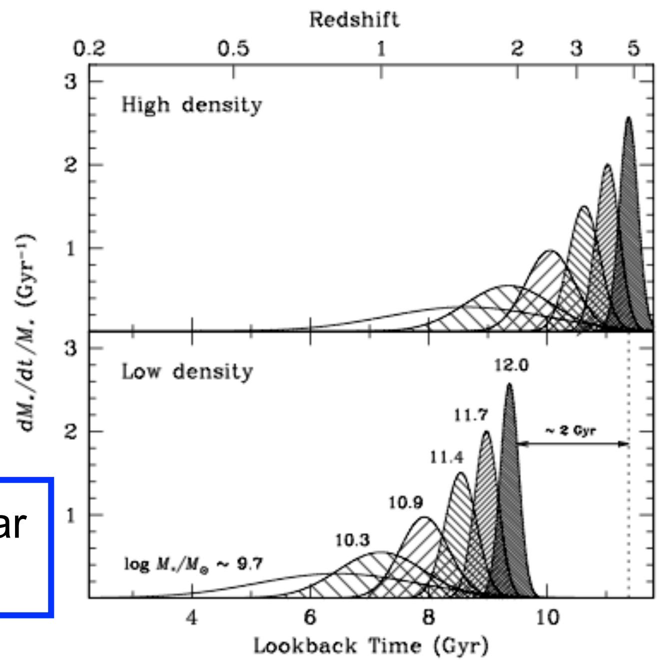
Objects with lower luminosity peak at lower redshift, similar to what observed for SFR in galaxies ⇒ **cosmic downsizing**

QSOs peak at z≈2-3, AGN at z≈0.5-1

➢ The number density of AGN evolves differently for sources of varying luminosities ➔ LDDE (luminosity-dependent density evolution) is the current, widely accepted parameterization of AGN evolution in X-rays

➢ The density of the most luminous AGN peaks earlier in cosmic time than for less luminous objects, which likely implies that large black holes are formed earlier than their low-mass counterparts

➢ Similar behavior for galaxies: massive galaxies tend to form stars earlier and faster than less massive galaxies (*downsizing*, Cowie+96)



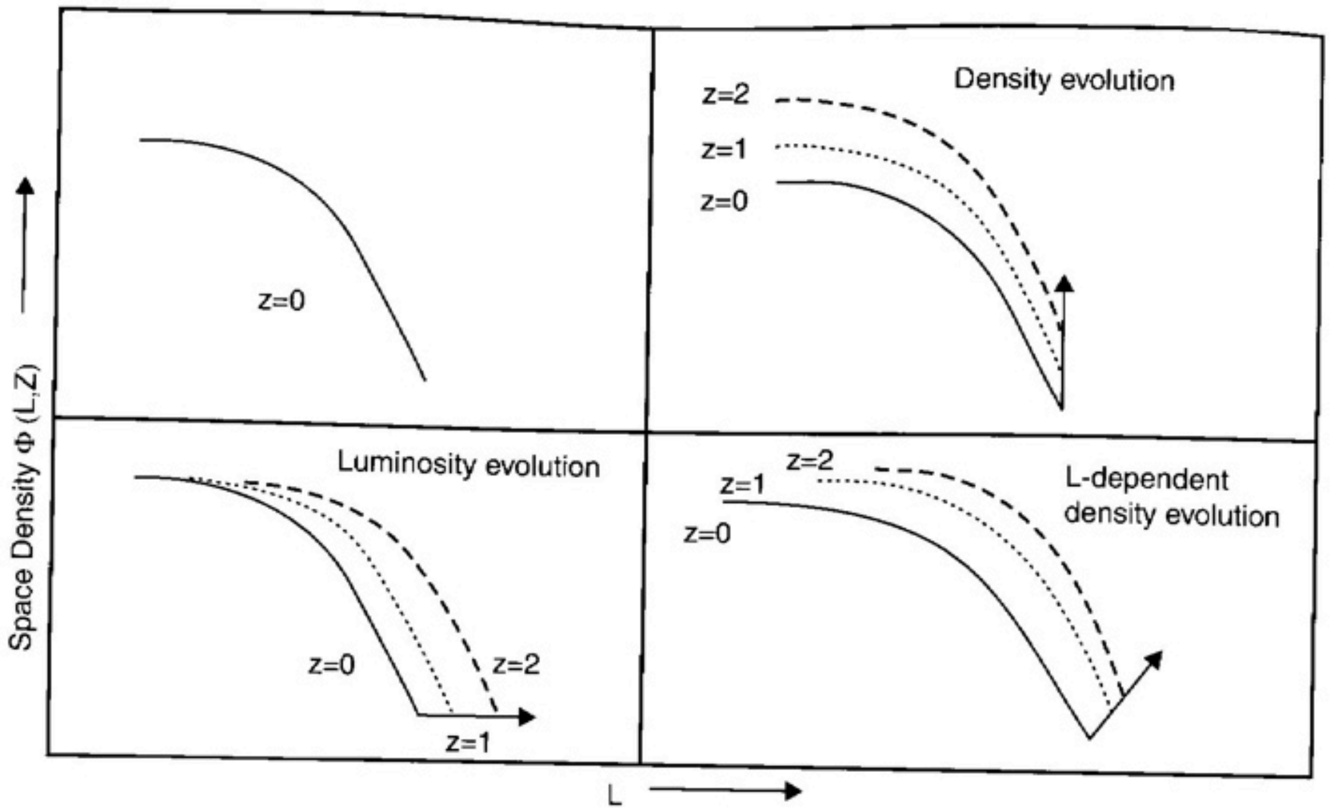
Thomas et al. 2005

AGN and galaxies seem to share a similar behavior in terms of evolution

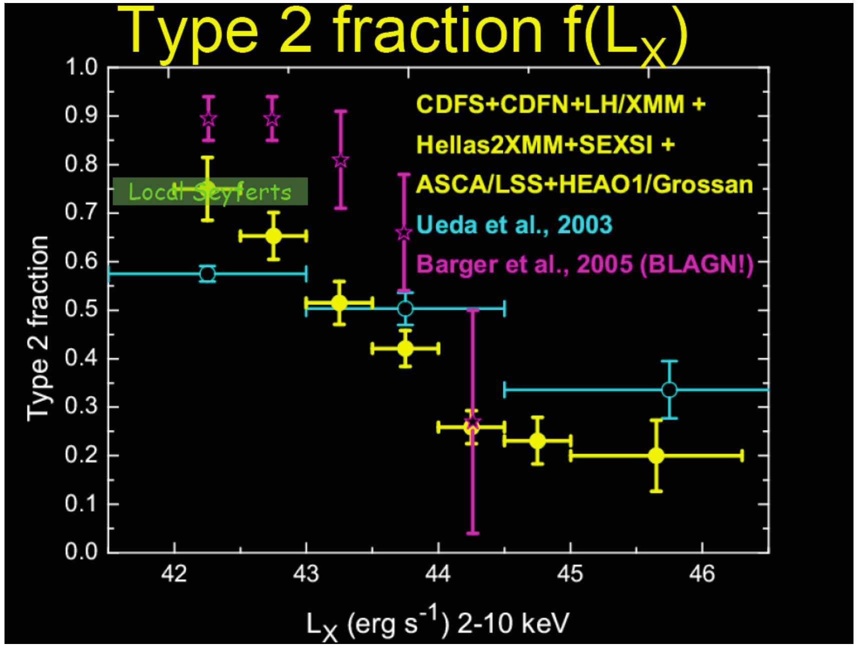
Luminosity Evolution:
AGN more luminous in the past

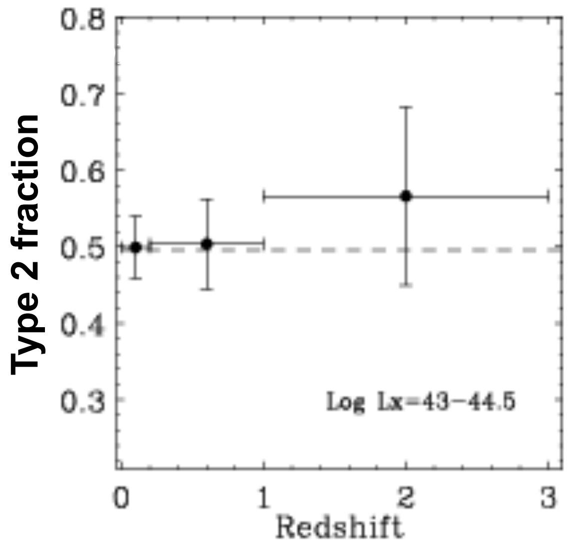
Density Evolution:
AGN more numerous in the past

Luminosity-dependent Density Evolution:
Evolution in density dependent on AGN luminosity

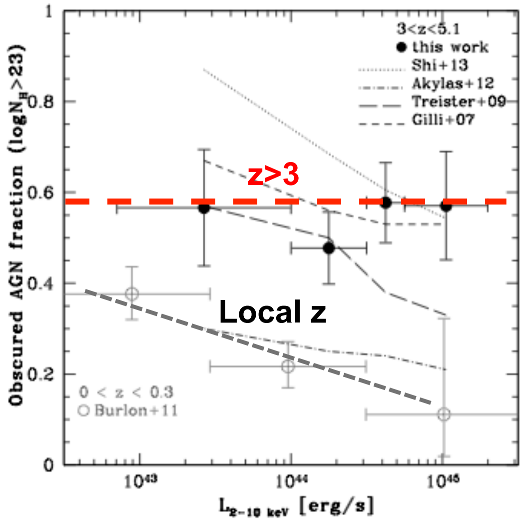


Dependence of the obscured AGN fraction on X-ray luminosity and redshift





No evolution with z



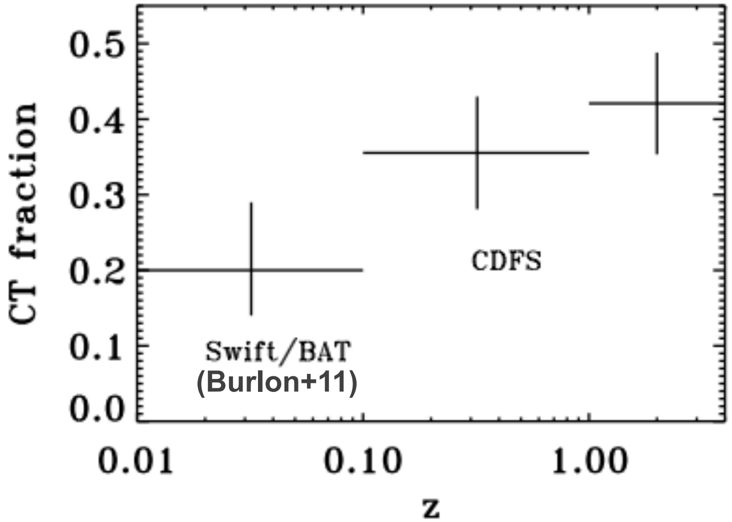
Evolution with z

Broad consensus for an obscured AGN fraction declining towards high intrinsic luminosities ➔ receding torus model (Lawrence 1991, Simpson 2005; see also Lusso et al. 2013)

Behavior with z still debated (see e.g. La Franca et al. 2005; Treister & Urry 2009; Iwasawa et al. 2012; Vito+13, 14) – see also Buchner+15

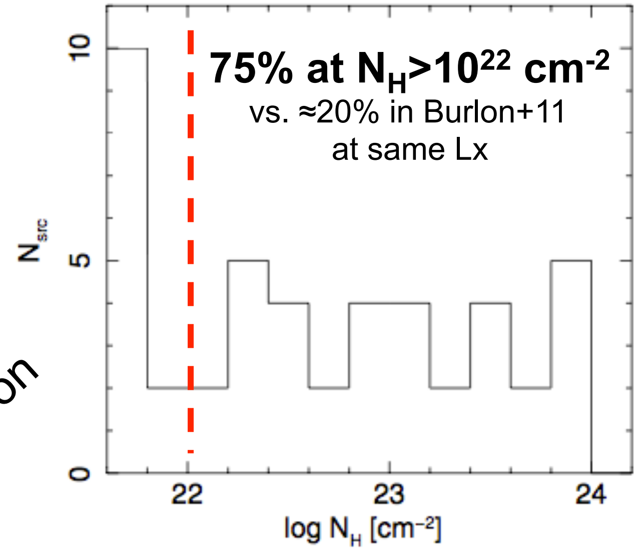
High obscured AGN fraction at high redshift

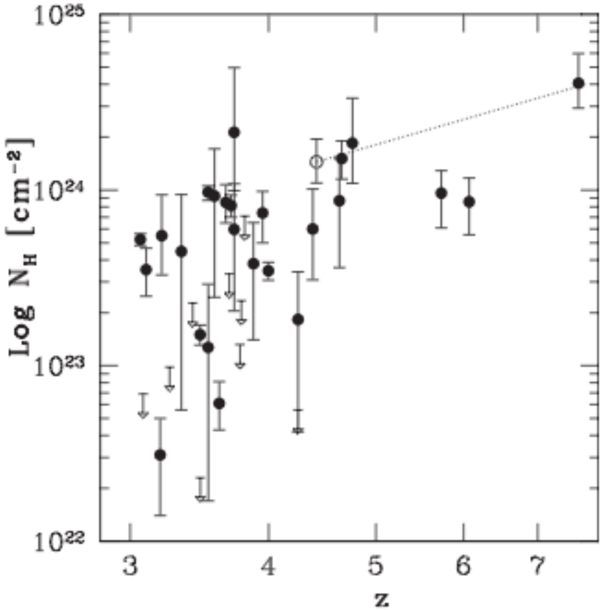
The evolution of the obscured AGN fraction over cosmic time has been a debated issue since almost a decade (Ueda, La Franca, Gilli, Hasinger, Treister, …) − see also Merloni+14



Compton-thick ($N_H > 10^{24}$ cm^{-2}) AGN,
CDF-S, 4Ms (normalized to LogL_X=43.5)
Brightman & Ueda 2012

XMM-CDFS, 3Ms, **z=1.7−3.7**
Iwasawa+12





CDF-S, 4Ms, **z>3** AGN
65% with $N_H > 10^{23}$ cm^{-2}
Vito+13

more on this in the high-redshift AGN lesson

Higher merger rate and more gas available for the accreting SMBHs at high redshift

X-ray spectral analysis and stacking are fundamental tools, but we need photons and low background