


# **Active Galactic Nuclei: X-ray surveys and AGN evolution**

On the attempt to “replace” the Unified Model for AGN  
by the AGN/galaxy co-evolution prescriptions

## Two main themes in modern high-energy astrophysics

### □ Physics of accretion and ejection in massive black holes

Needs characterization of the X-ray and  $\gamma$ -ray emission from AGN, hence high counting statistics (large effective area) and, possibly, high-resolution X-ray spectra. [Lessons by Dr.ssa P. Grandi/E. Torresi and Dr. M. Cappi]

 Census of SMBHs to “map” the growth of massive structures up to high redshifts: AGN/galaxy co-evolution, feedback processes, etc.

Needs large, well-defined samples of AGN, including the most elusive, heavily obscured ones, and the first SMBHs to form in the Universe. Large source numbers are more important than individual source photon statistics, typically very limited (e.g., in deep X-ray surveys).

# Outline

- ✓ AGN Unified scheme vs. AGN/galaxy co-evolution models
- ✓ The first massive black holes
- ✓ Integrated AGN emission recorded in the X-ray background (XRB) and the role of obscured AGN
- ✓ X-ray surveys: depth vs. coverage
- ✓ New insights into the X-ray absorber (torus) from mid-IR observations

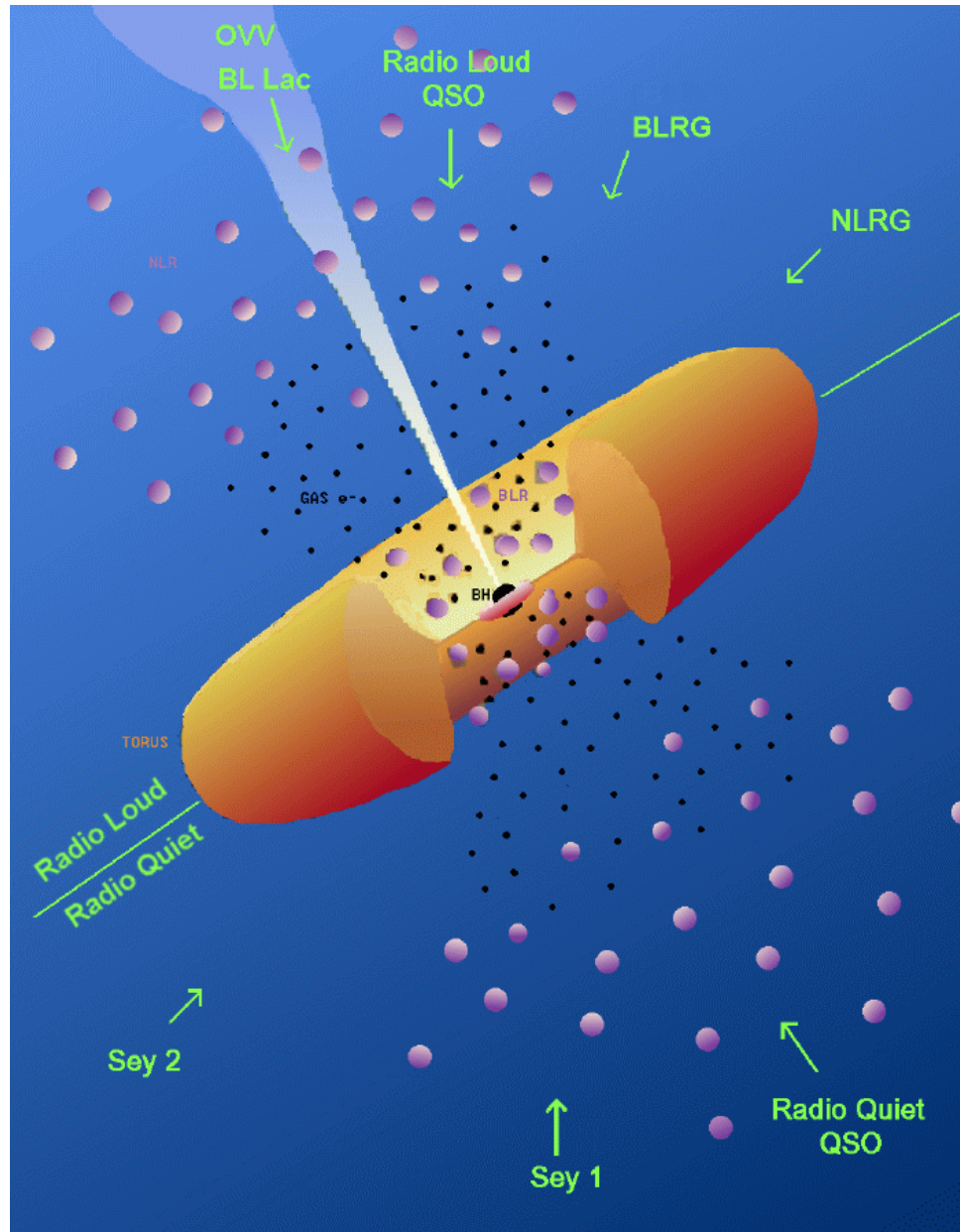
For a recent review on the subject, see Alexander & Hickox 2012, *New Astronomy Reviews*, 56, p. 93 (arXiv:1112:1949) – see also Brandt & Alexander 2015, *The Astronomy & Astrophysics Review*, 23, p.93 (arXiv:1501.01982)

# AGN Unified Model

after Antonucci & Miller 1985;  
Antonucci 1993

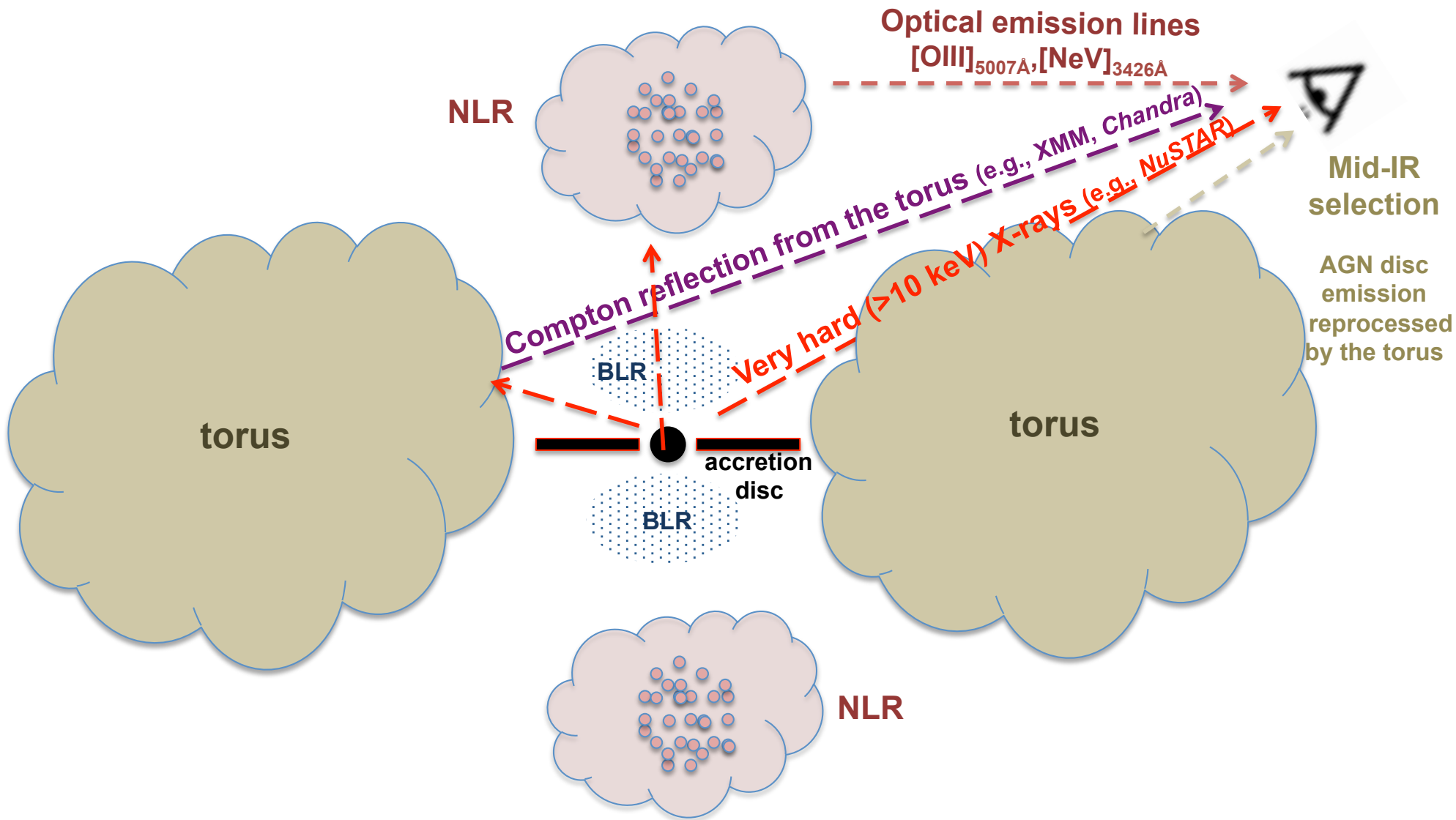
Fine for many AGN as  
a baseline for the  
description of different  
observational  
properties

Probably not the end  
of the story



adapted from Urry  
& Padovani 1995





# A logarithmic view of an AGN

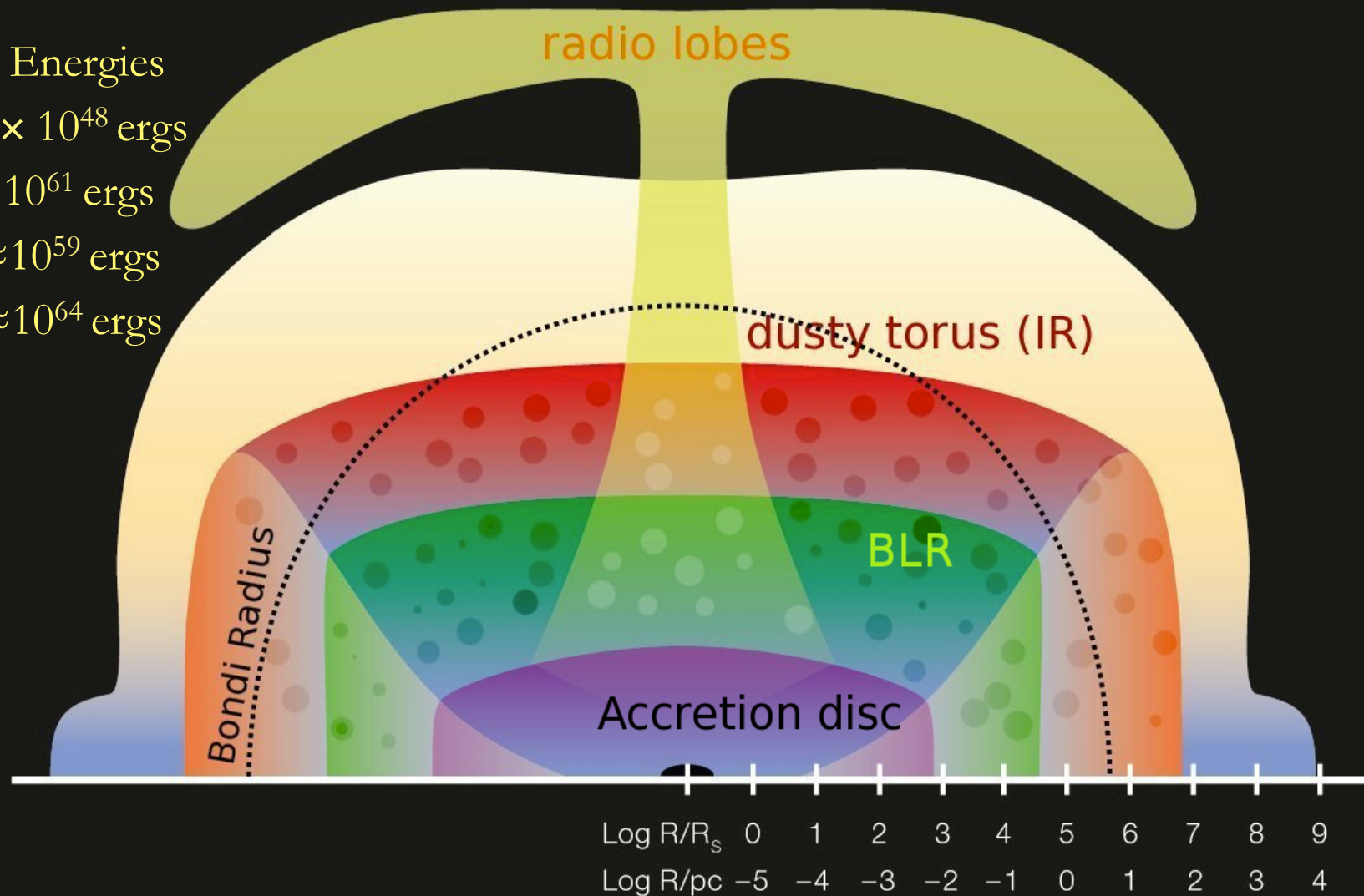
Binding Energies

$$E_{b,\odot} \approx 4 \times 10^{48} \text{ ergs}$$

$$E_{b,BH,8} \approx 10^{61} \text{ ergs}$$

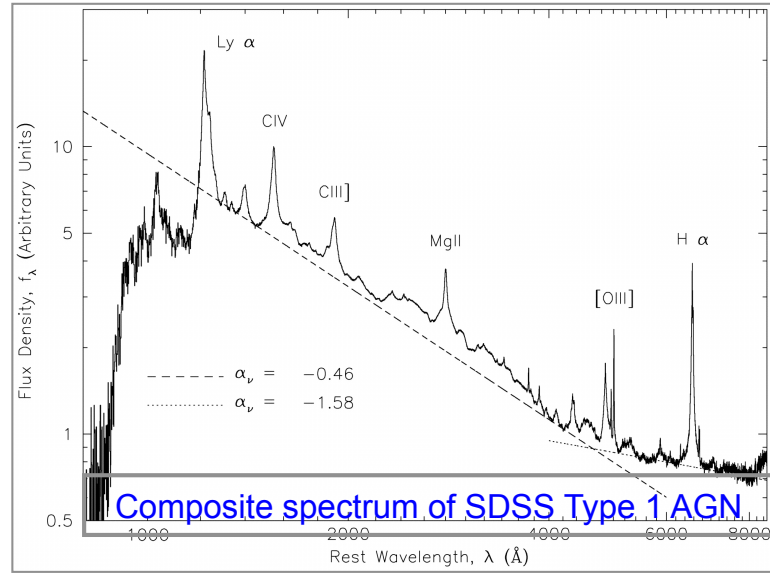
$$E_{b,gal,11} \approx 10^{59} \text{ ergs}$$

$$E_{b,Coma} \approx 10^{64} \text{ ergs}$$

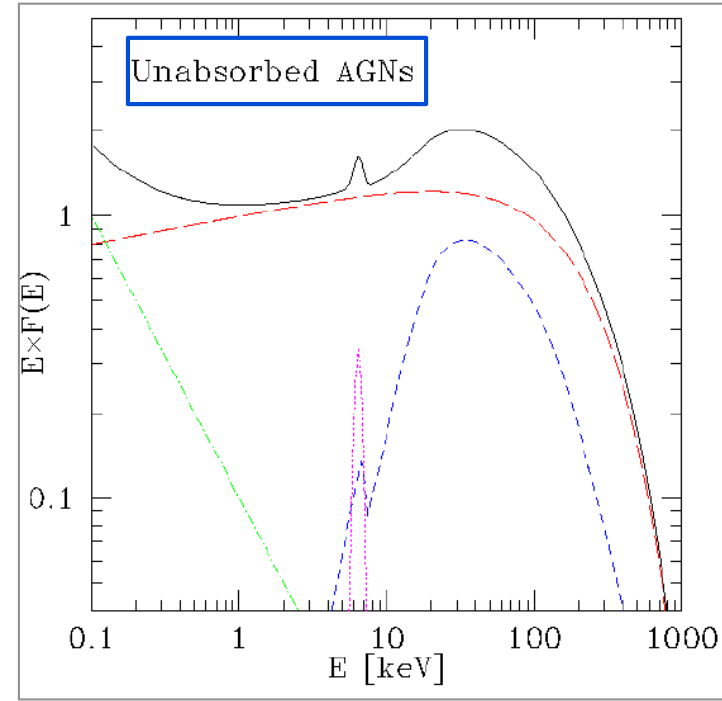


Courtesy of A. Merloni, ESO graphics, 2010

Optical band

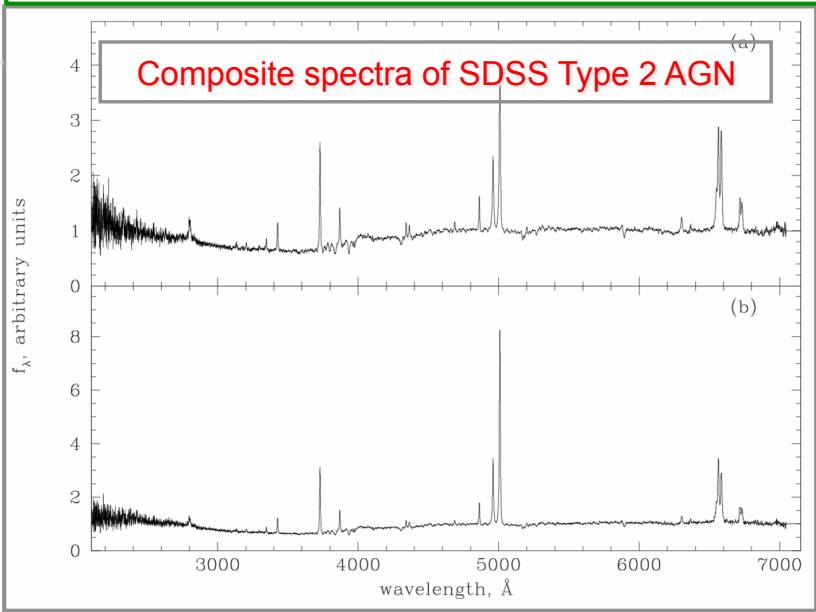


Type 1  
AGN

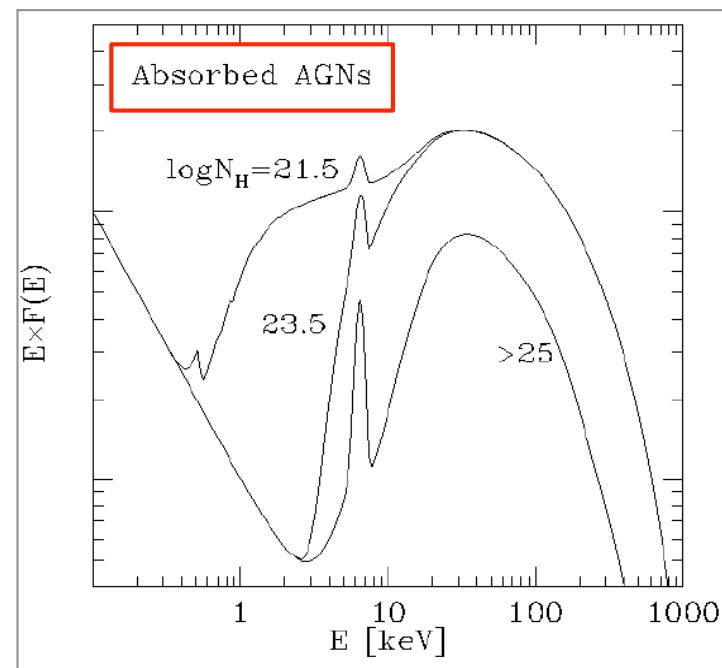


X-ray band

Type 2 AGN easily missed in optical and partly in X-ray surveys

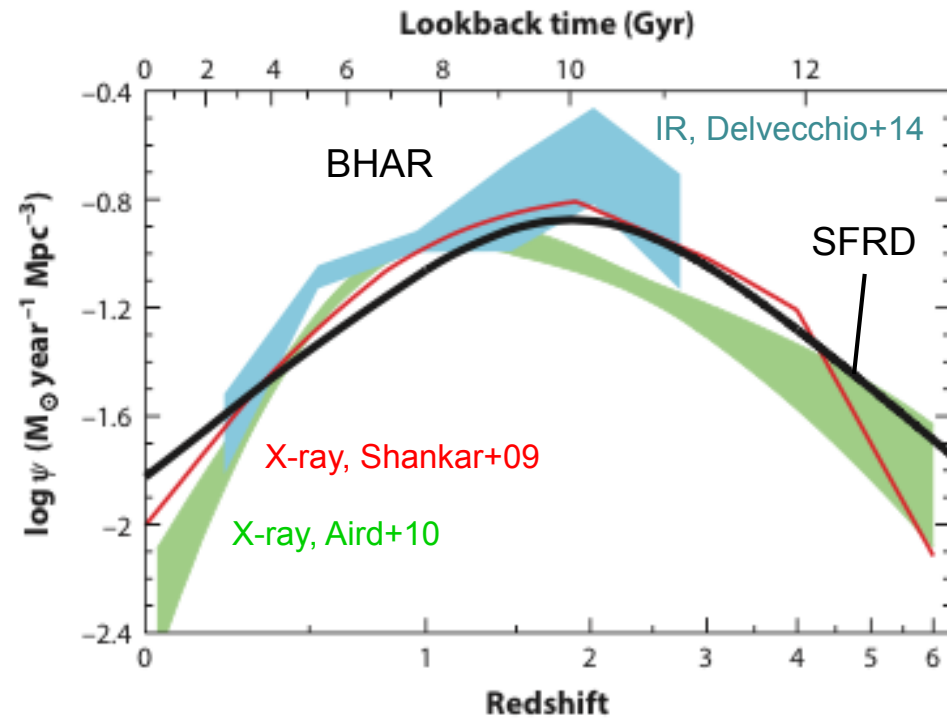
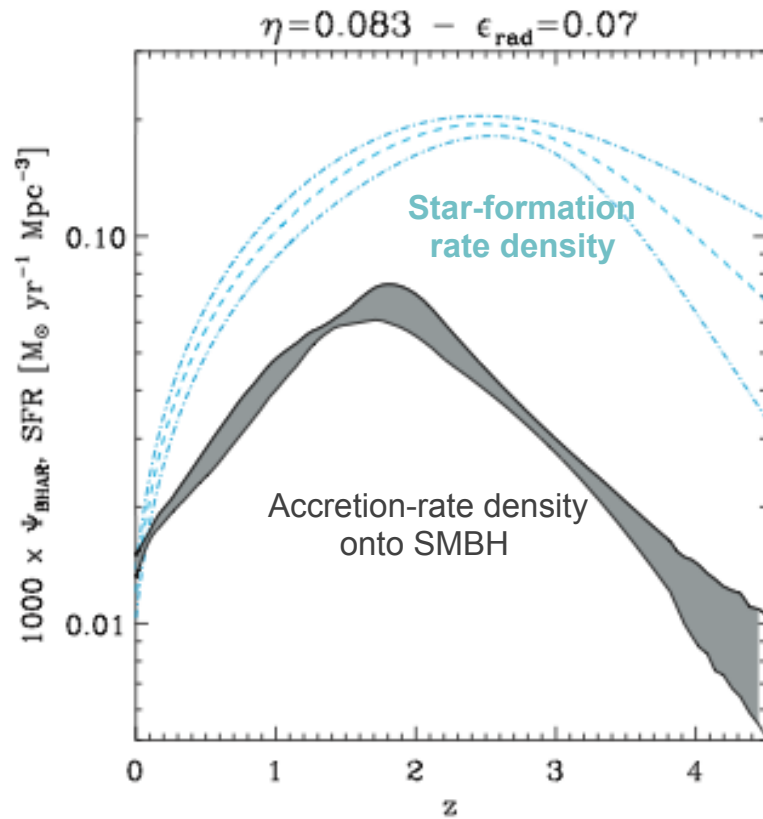


Type 2  
AGN



# AGN-galaxy co-evolution

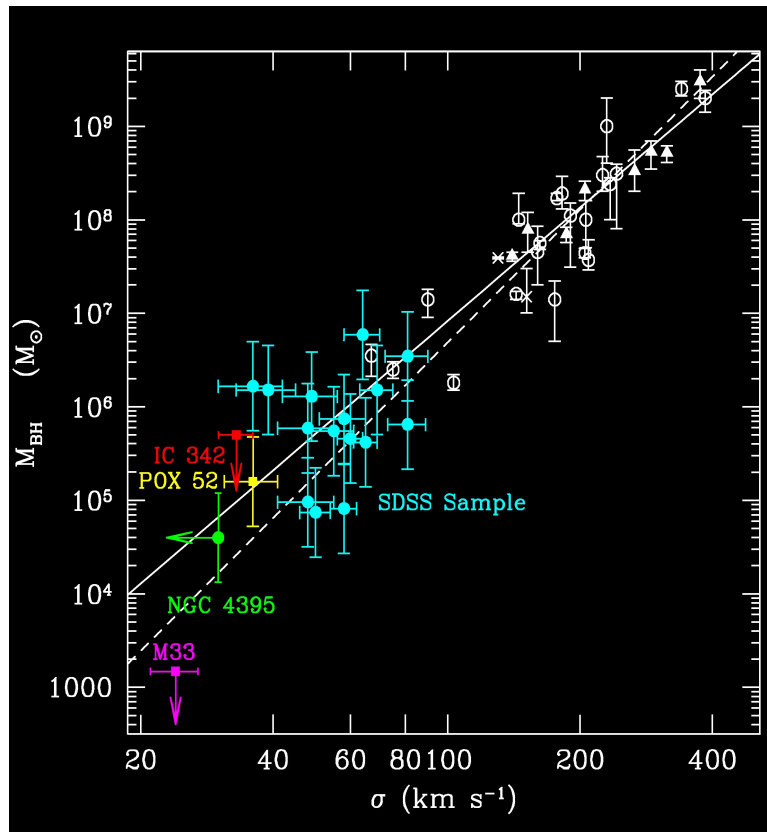
# Accretion and star formation over cosmic



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

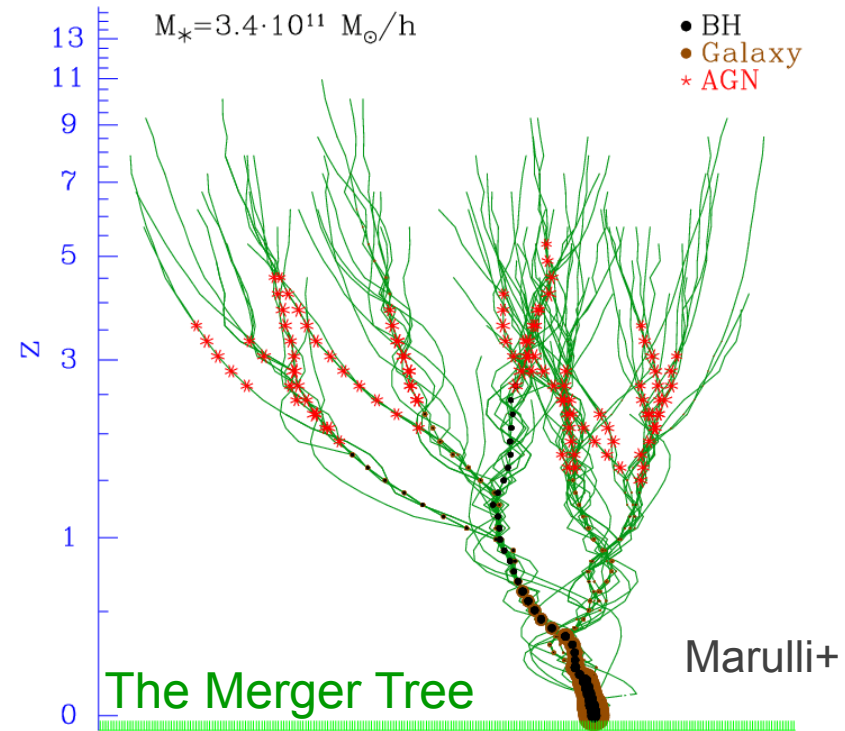
from Madau & Dickinson 2014

# 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

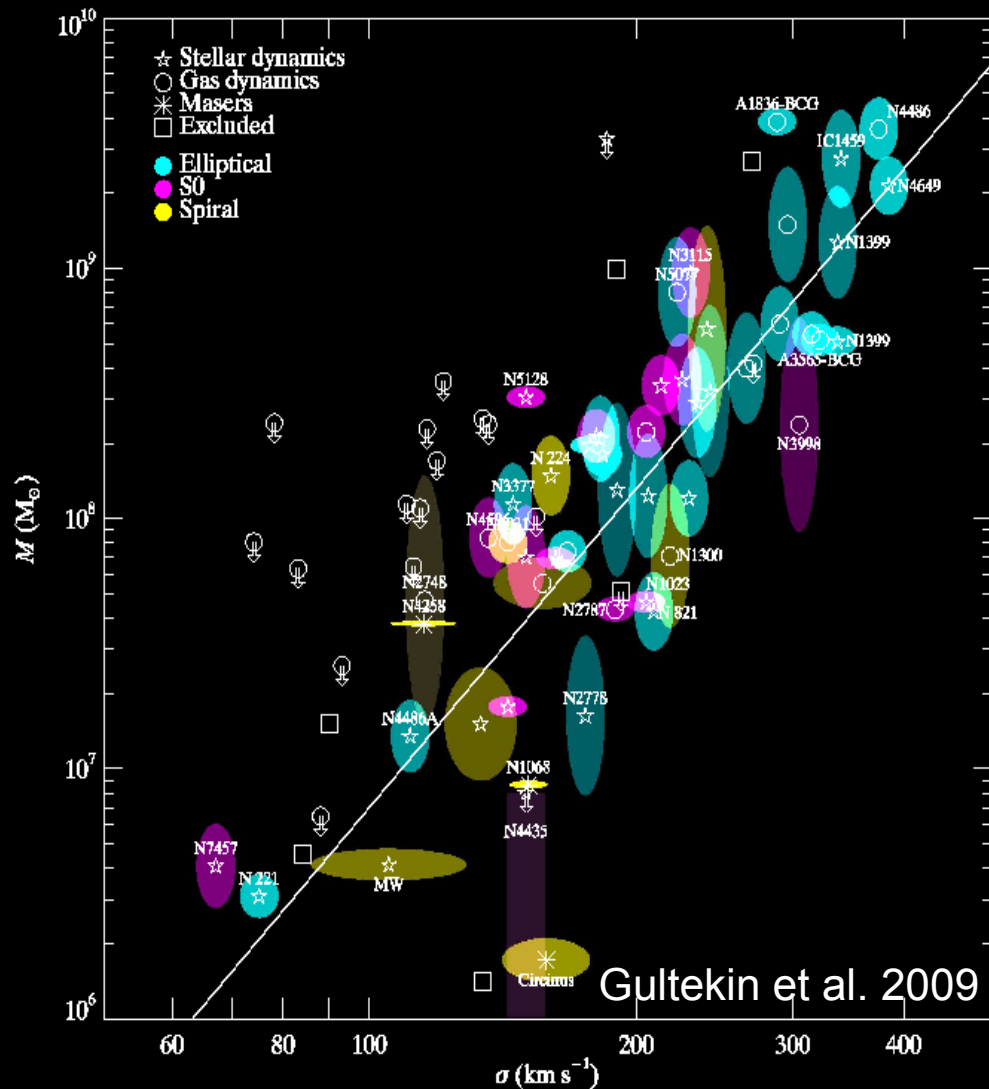
**co-evolution** (e.g: Kauffmann+98, Volonteri+06, Salvaterra+06, Rhook&Haehnelt08, Hopkins+08, Menci+08, Marulli+09)

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

Condition: nuclear trigger at merging



# Black Hole – galaxy scaling relations



Correlation between BH mass and galaxy velocity dispersion  $\sigma$

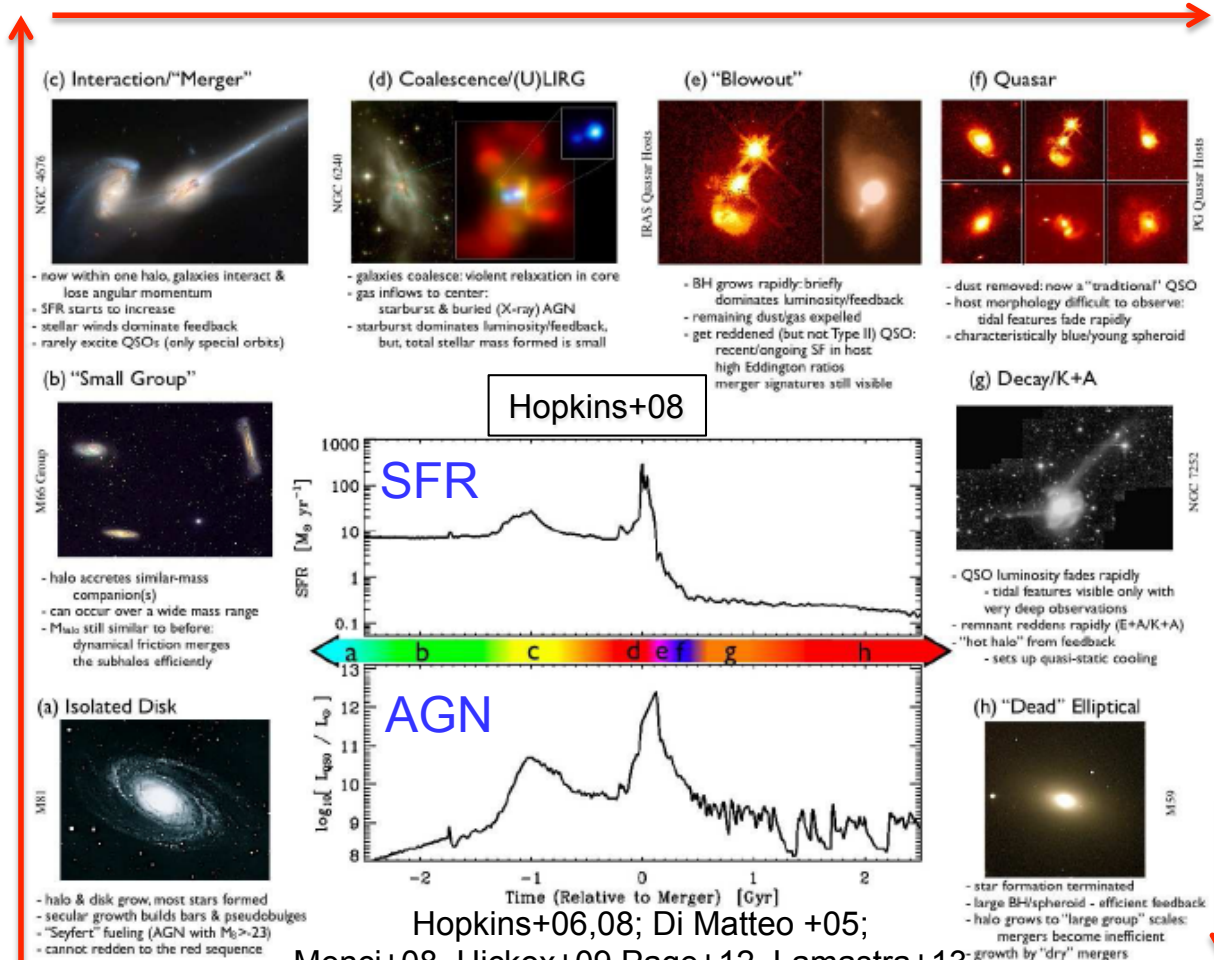
$\sigma$  measured well **outside** the gravitational sphere of influence of the BH

No causal connection (now)

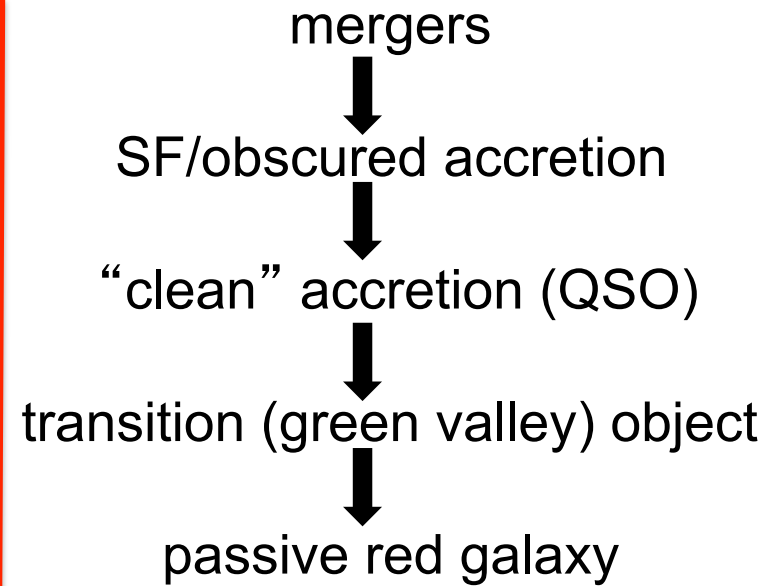
Either coincidence (!) or the result of **common evolution**

Kormendy and Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese et al. 2000; Tremaine et al. 2002; Gultekin et al. 2009; Kormendy & Bender 2012 – see also Jahnke & Maccio' 2011

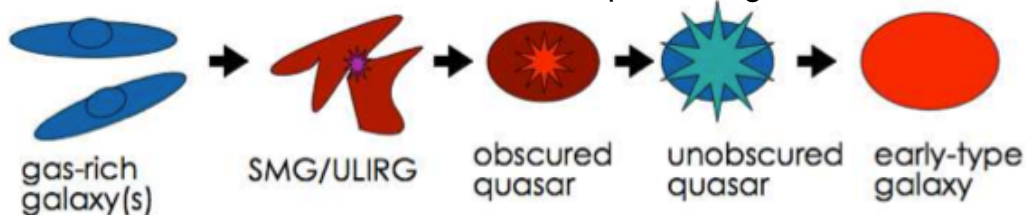
# The BH/galaxy “evolutionary sequence”



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



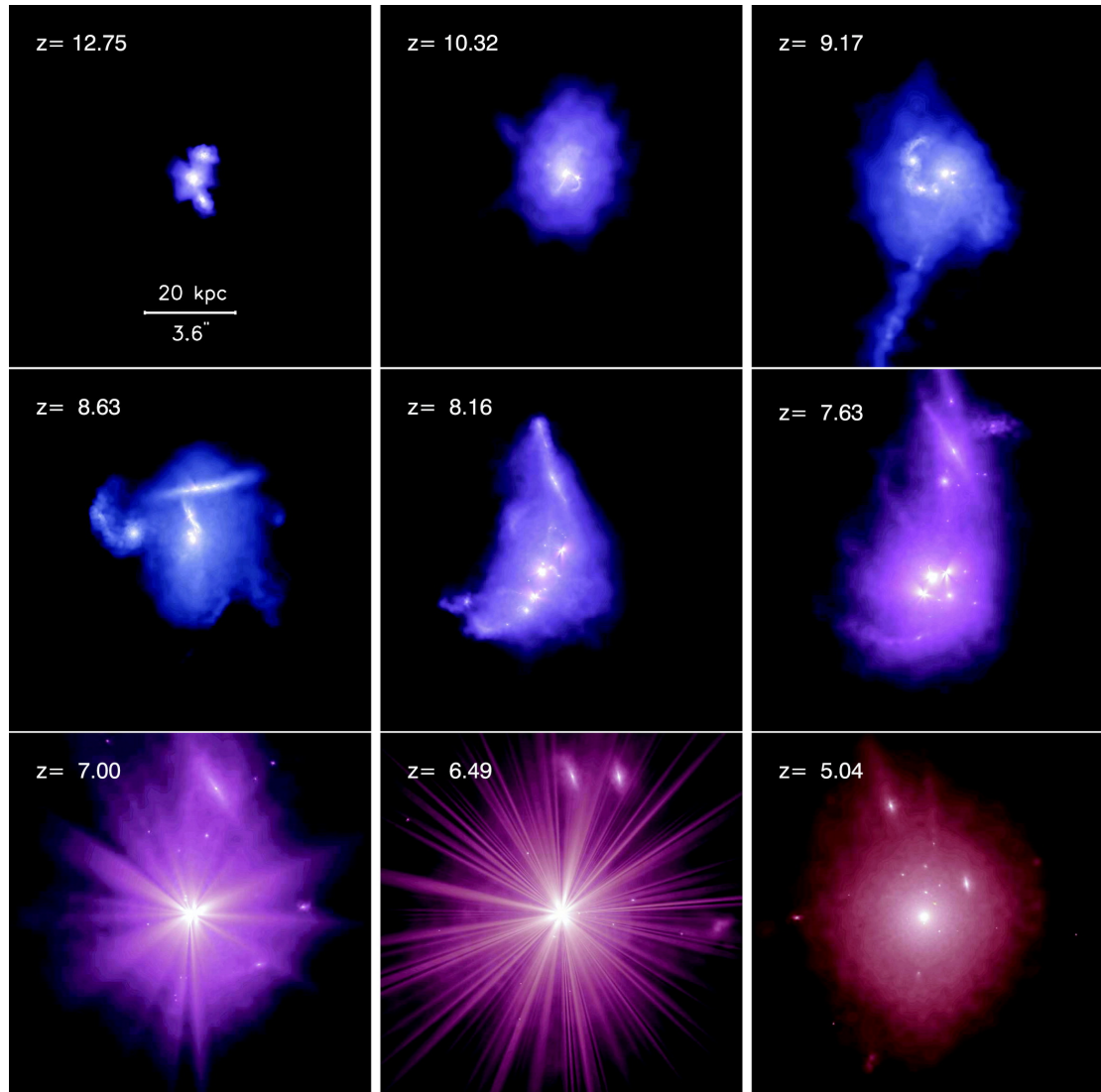
Importance of merger-driven vs. secular (“smooth”) accretion  
 (e.g., Elbaz+11, Rodighiero+11, Rovilos+12)



Hickox+09

Strong winds (=feedback) expected in the “blowout” phase

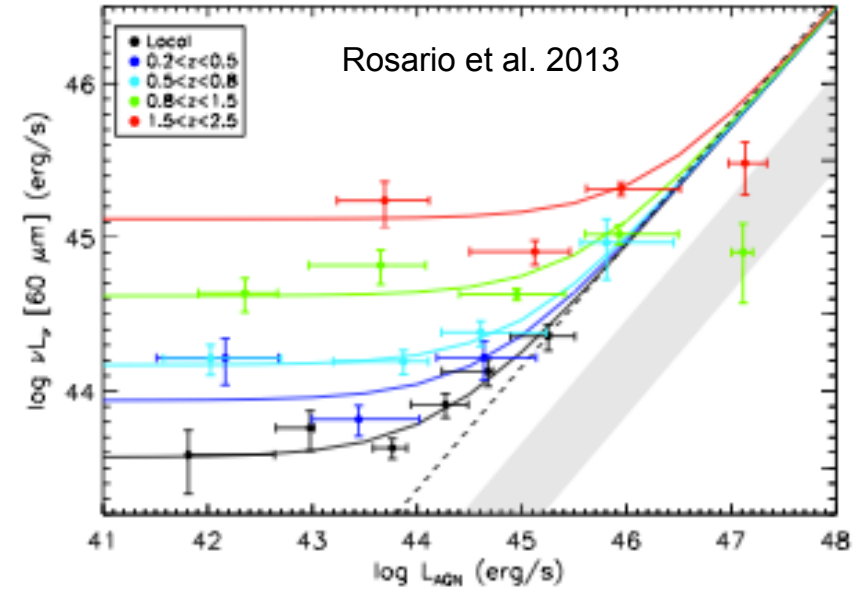
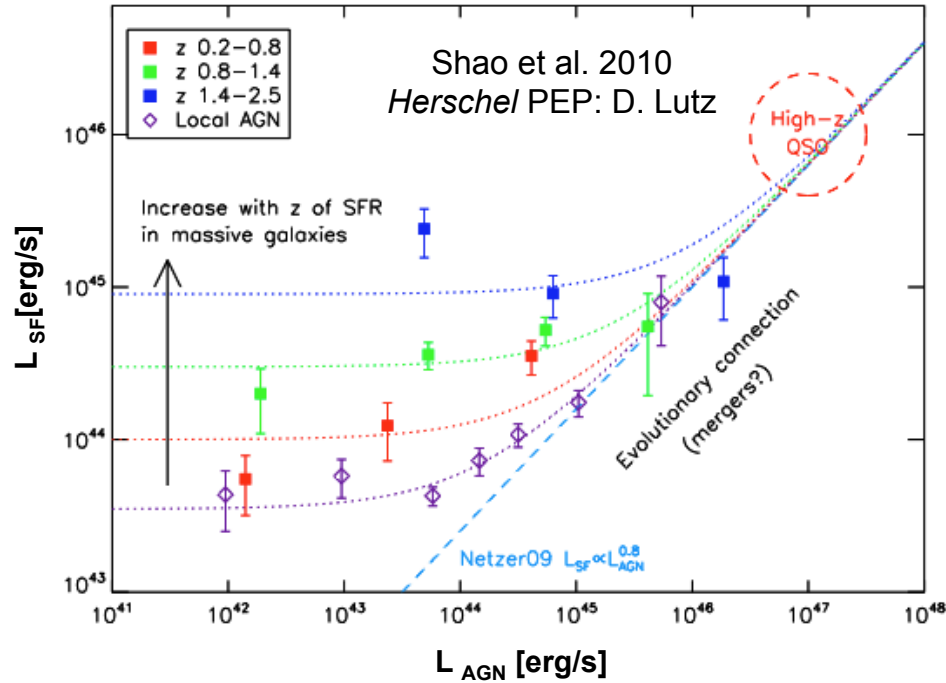
# Simulated formation of a $\approx 10^9 M_{\odot}$ BH at high $z$



- 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

Li+07

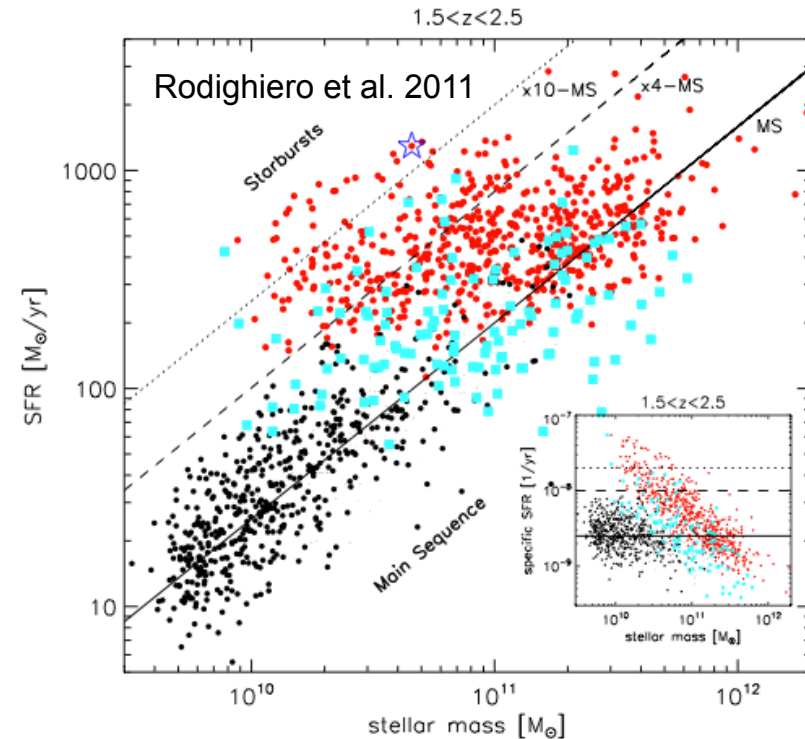
[ $M_{\text{BH}} - \sigma - M_{\text{Bulge}} - \dots$  relations]



### 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?)

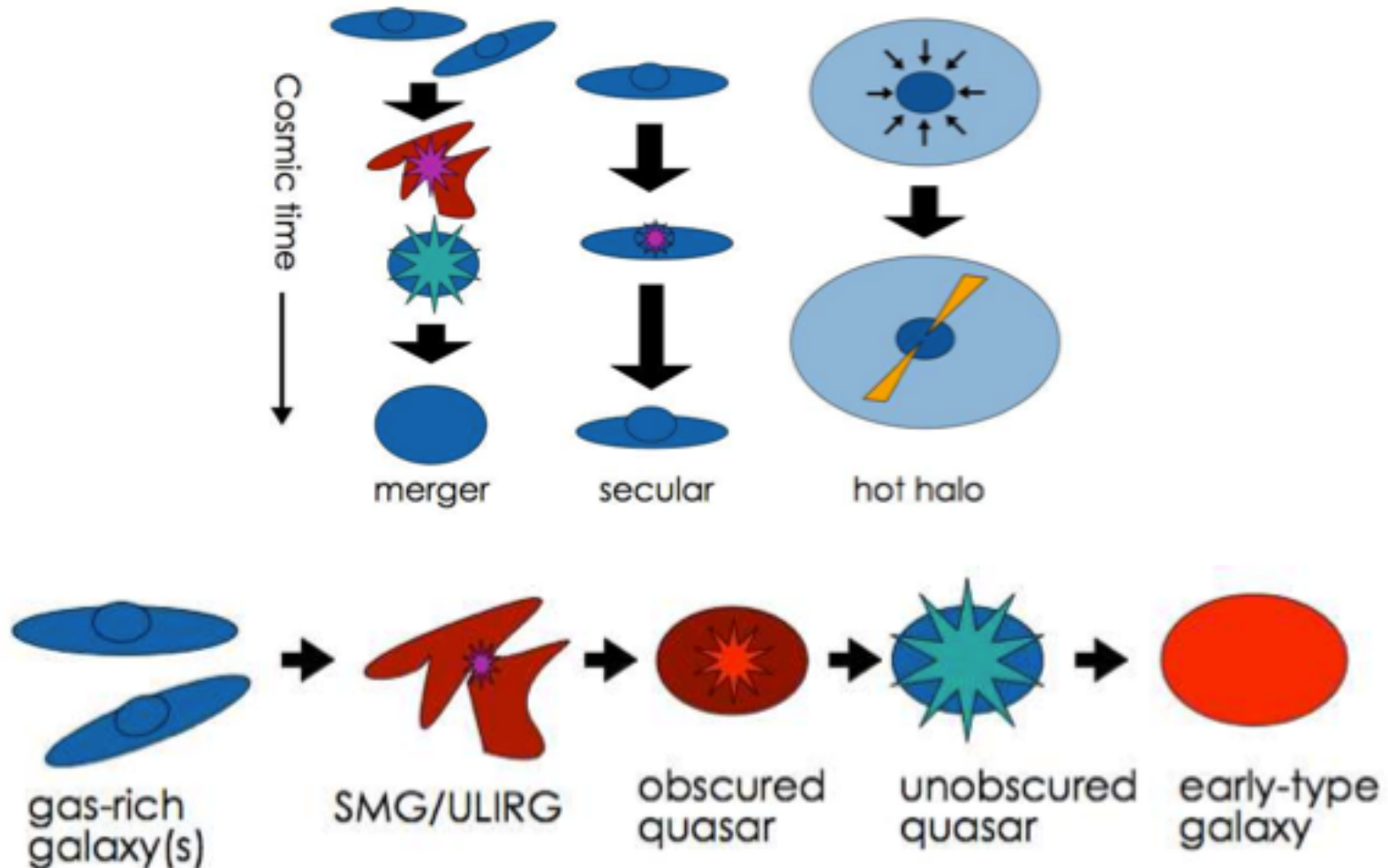
(e.g. Georgakakis+09, Lutz+10, Cisternas+11, Schawinski+11, Elbaz+11, Rodighiero+11, Mullaney+11, Santini+11, Rovilos+12, Rosario+12, ...)



## Two modes of accretion:

Mergers  $\leftrightarrow$  luminous quasars

Secular (disk instabilities, bars, minor mergers)  $\leftrightarrow$  low-luminosity AGN

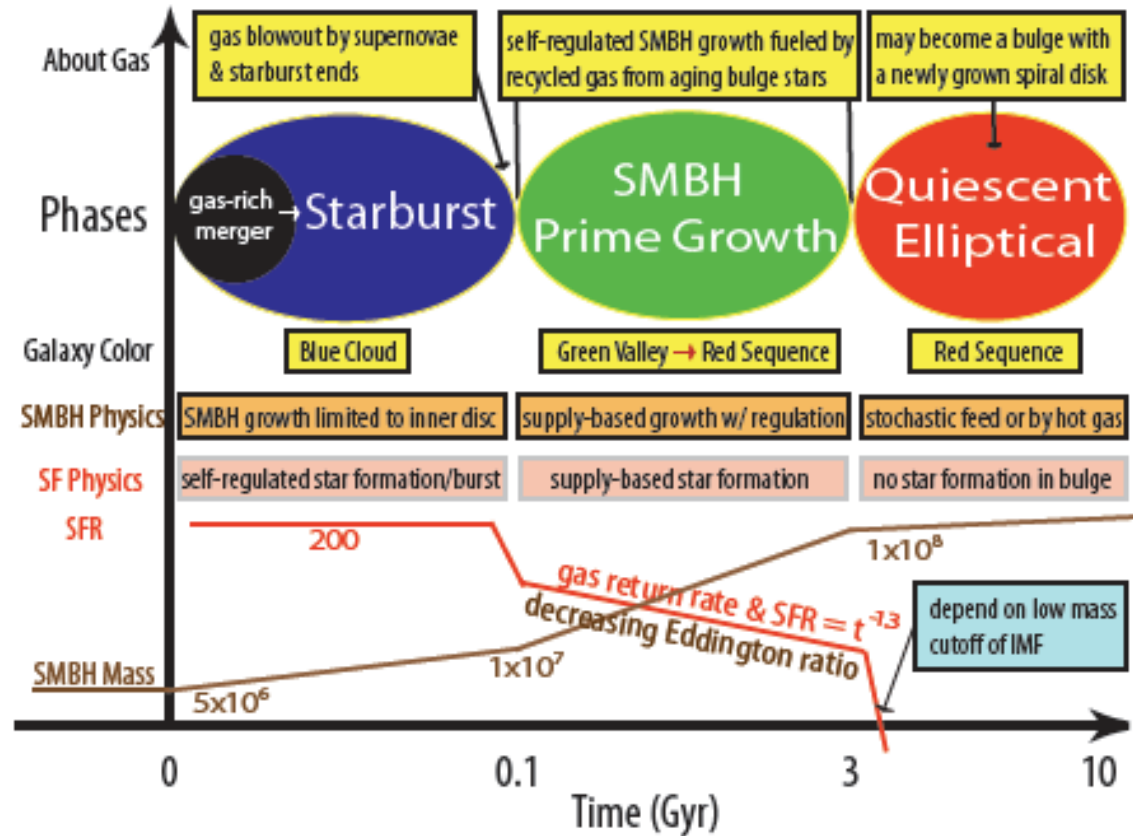




# An alternative picture

STB precedes SMBH growth, lasts 10-100 Myr, and then stops itself (through SN)

Main SMBH growth in the post-starburst phase fueled by recycled gas from inner bulge (old) stars and lasts  $\gg 100$  Myr, albeit at relatively low and diminishing Eddington ratios for most of the time





# Obscured AGN growth and star formation at $z \approx 2$

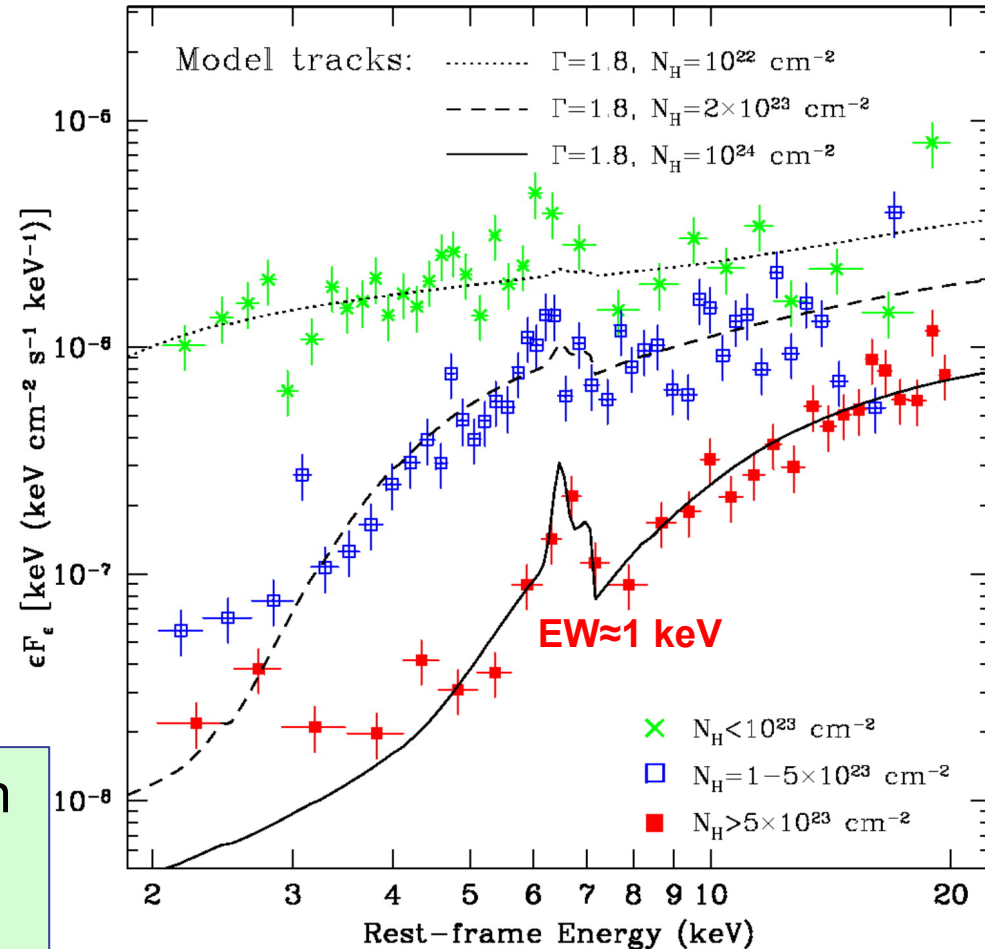
Obscured AGN in sub-mm galaxies

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  $\rightarrow$  Much of the mass growth of SMBH occurs during the heavily obscured phase (e.g., Treister+10)



Alexander et al. 2005

$\rightarrow$  Needed: census and knowledge of Compton-thick AGN

## But ...

Two (out of many...) missing pieces:

- 1) BH/galaxy co-evolution is still unconstrained at very high- $z$  ( $z > 6$  or so). Already formed luminous QSOs at  $z=6$
- 2) Heavily obscured accretion mostly unconstrained beyond the local Universe



**Requirement: a complete census of AGN activity**

**Information stored in the X-ray background**

# Open issue: time for BH growth at $z \approx 6$

$$M(t) = M_0 \exp\left(\frac{1 - \epsilon}{\epsilon} \frac{t}{t_{\text{Edd}}}\right)$$

Larger radiation efficiency  $\epsilon$  means longer times to achieve a given mass

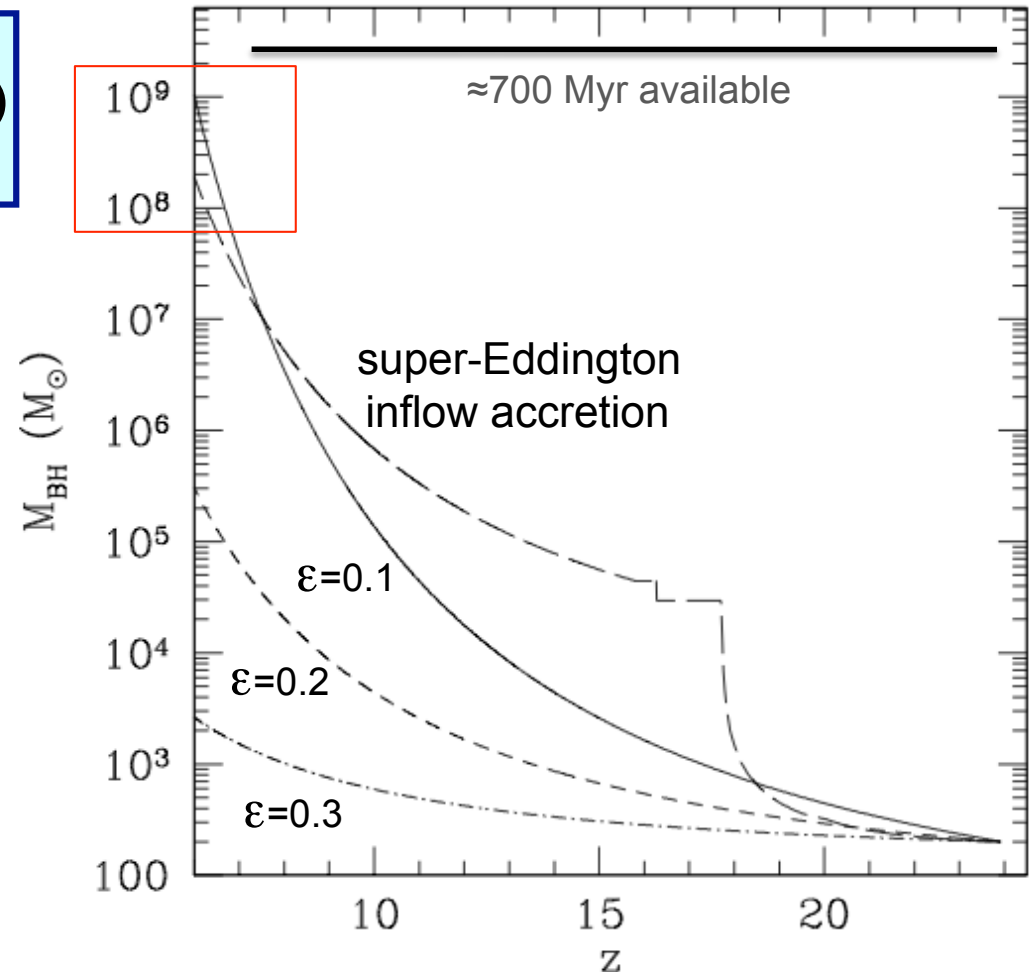
[ $t_{\text{Edd}} = 0.45$  Gyr for  $\epsilon = 0.1$ ]

Rapidly spinning BHs might have problems because of a larger  $\epsilon$

Highest-redshift quasar so far spectroscopically identified:

ULASJ1120+0641,  $z = 7.08$ ,

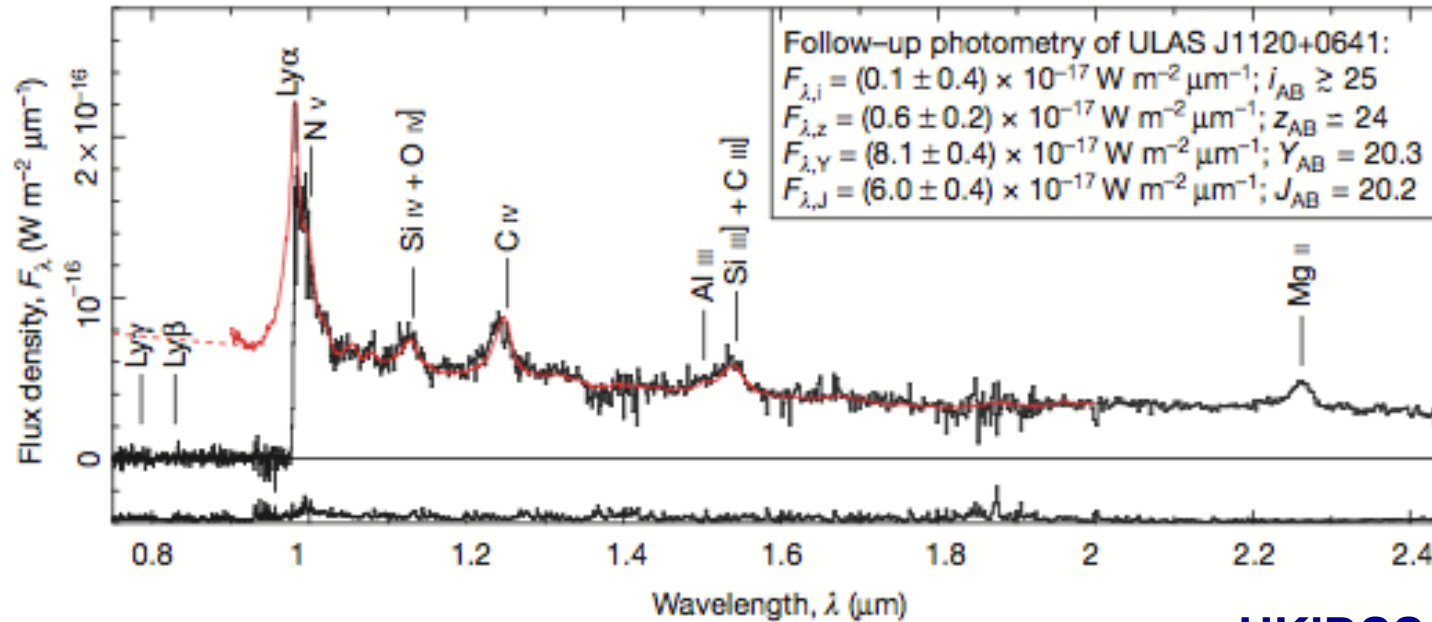
$M_{\text{BH}} \approx 2 \times 10^9 M_{\odot}$  (Mortlock et al. 2011)



Volonteri & Rees 2006

Possible problems with the mass of the “seed” BHs

ULASJ1120+0641,  $z=7.08$



UKIDSS

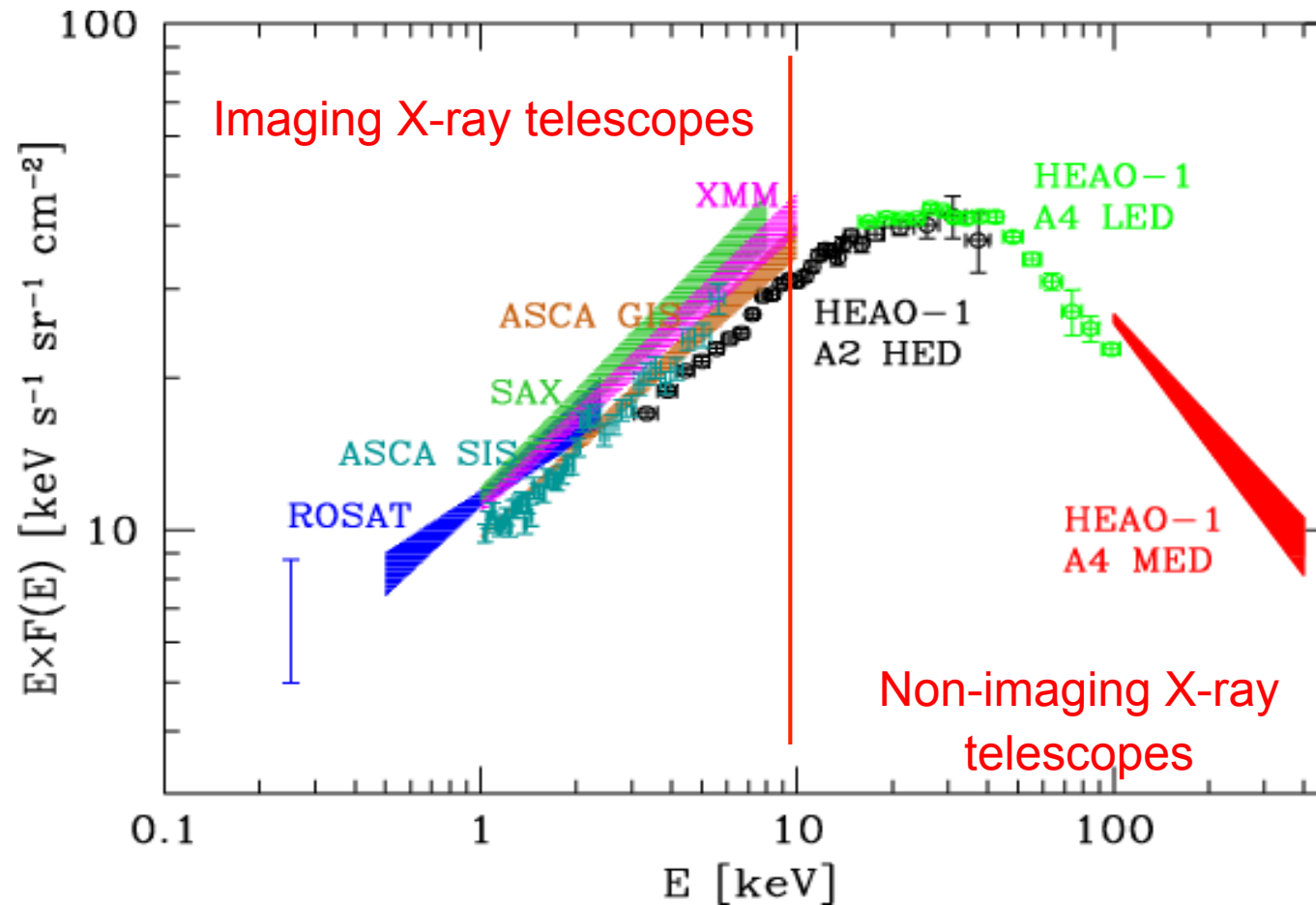
Mortlock et al. 2011, GNIRS+FORS2, compared to average  $z \sim 2.5$  SDSS QSOs  
Fully mature QSOs at high redshift

See lessons on *The high-redshift Universe, and the role of galaxies and AGN to cosmic reionization* at

[http://www.bo.astro.it/~vignali/PhD\\_Lessons/reionization\\_2015/](http://www.bo.astro.it/~vignali/PhD_Lessons/reionization_2015/)

# X-ray background and surveys

# 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:

$$F(E) \approx E^{-0.29} e^{-E/41\text{keV}} \text{ (bremsstrahlung)}$$



# Can a diffuse plasma emission explain the XRB?

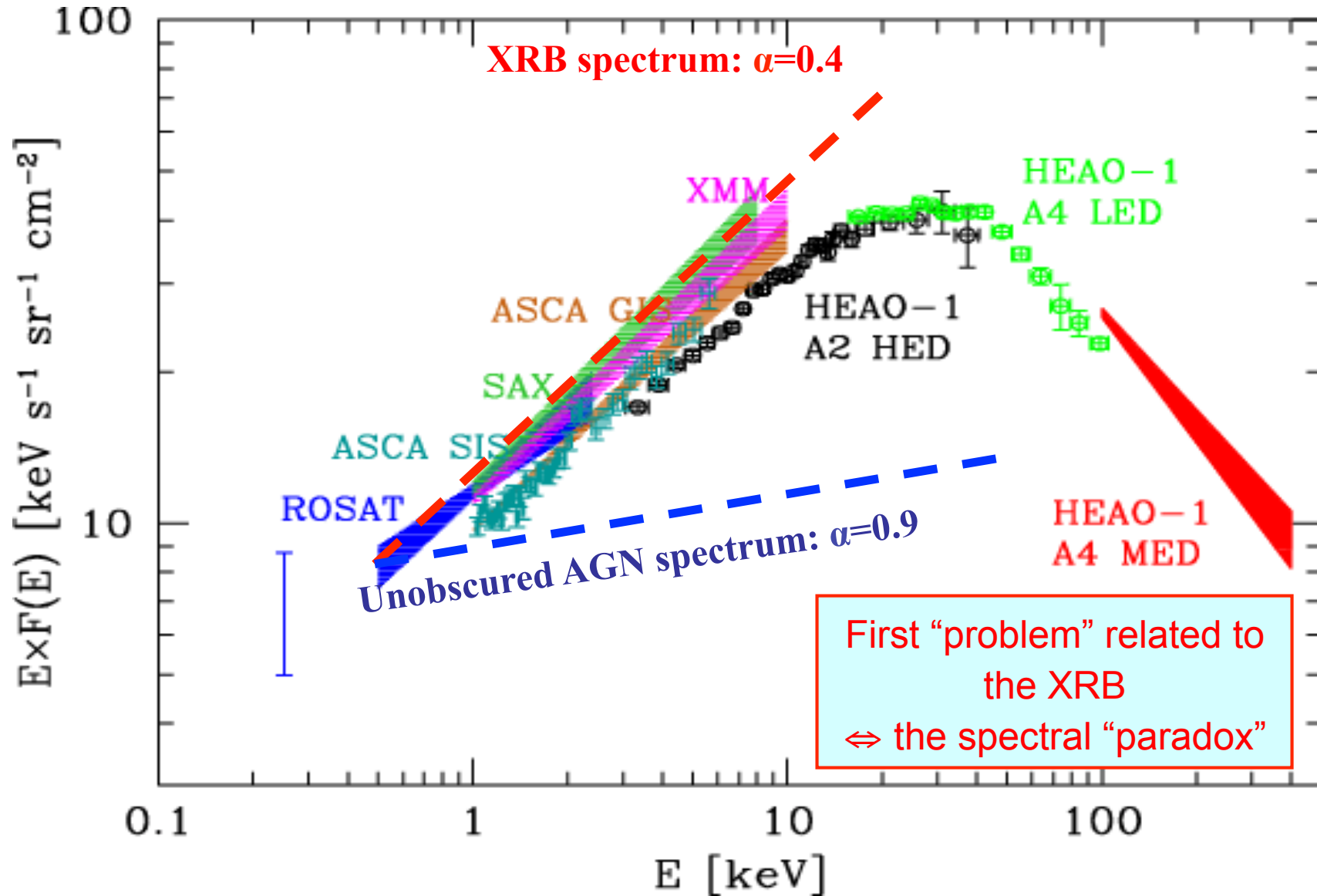
No!

- subtracting AGN implies an XRB spectrum no more compatible with bremsstrahlung emission
- CMB represents a perfect blackbody; hot gas ( $T \sim 40 \text{ keV} \approx 4 \times 10^8 \text{ K}$ ) would produce distortions by inverse Compton effect (Mather et al. 1994)

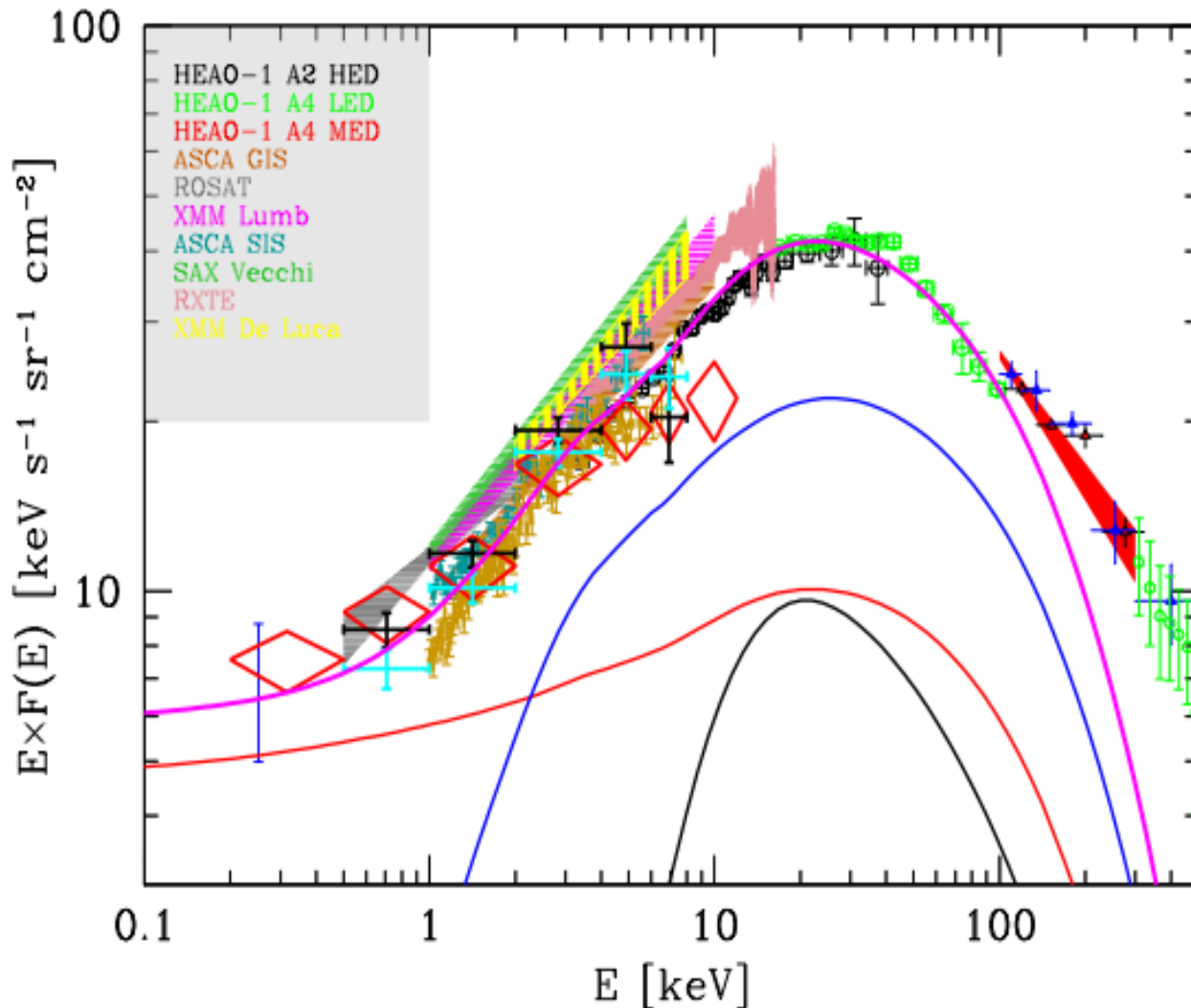


Emission by unresolved, faint individual sources → AGN

# 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)

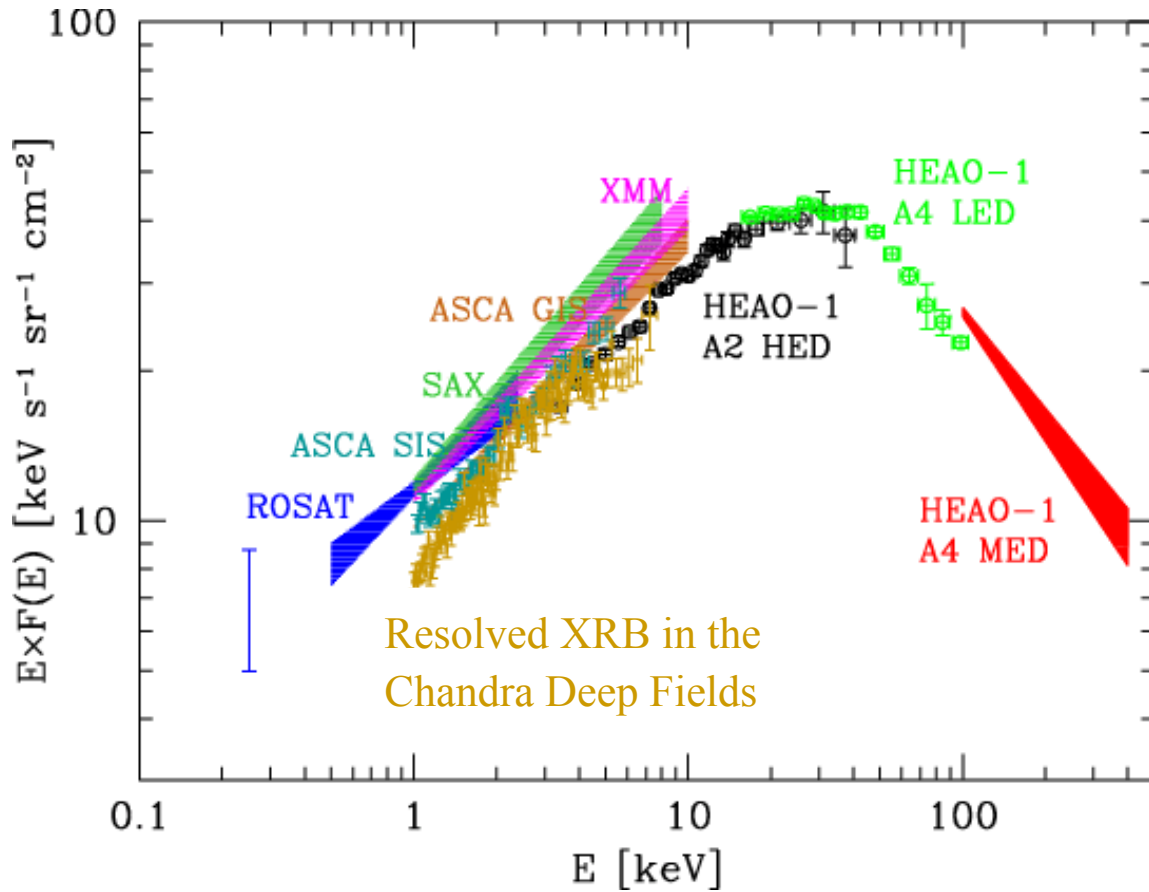
Red → unobscured

Blue → Compton Thin

Black → Compton Thick  
( $N_H > 10^{24}$  cm<sup>-2</sup>)

The evolution is folded in the adopted XLF

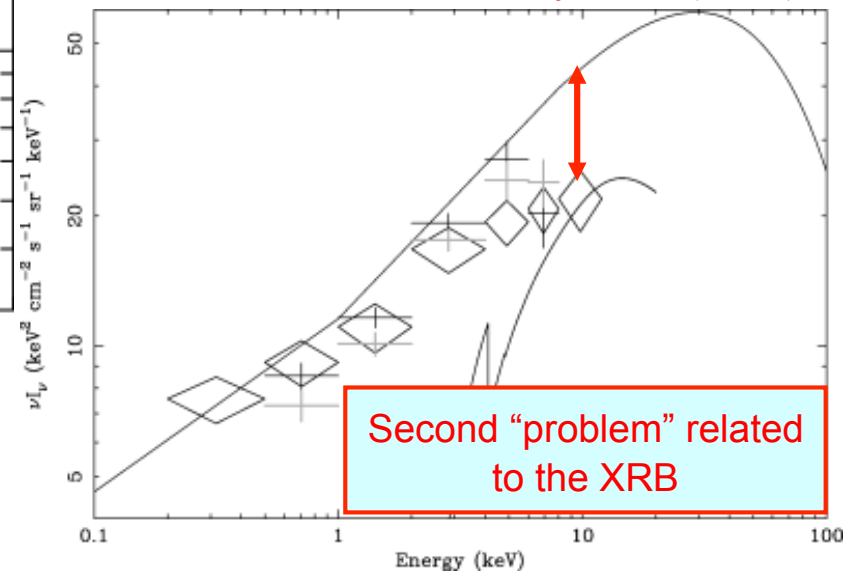
# Resolved XRB fraction: still a “missing” population?



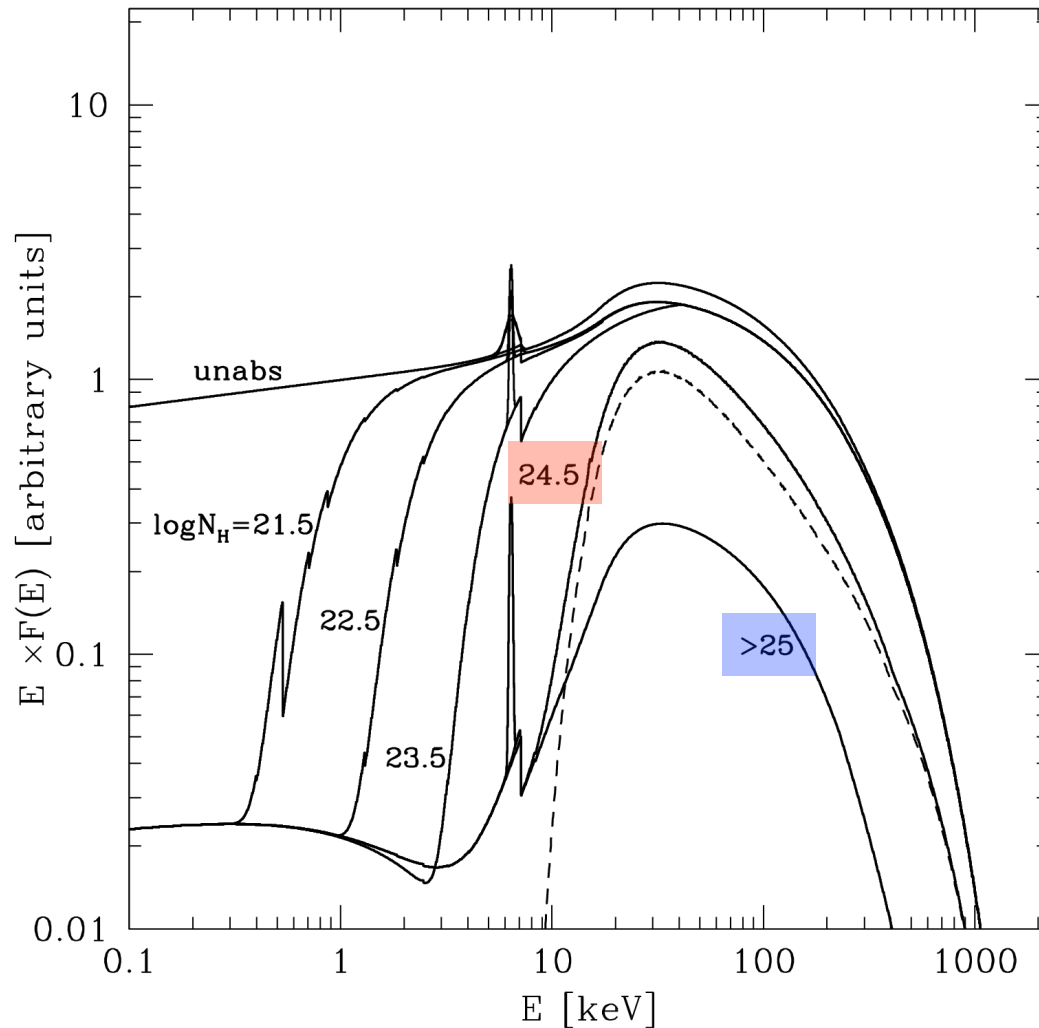
≈50-80% of the XRB being resolved into single sources at  $E < 10$  keV

BUT only 50% resolved above 5 keV

Worsley et al. (2005)



# AGN X-ray spectral templates with different $N_H$

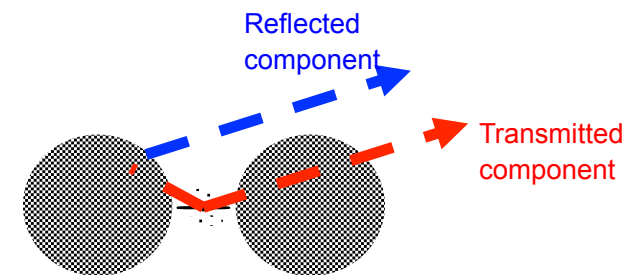


Only  $\approx 40$ -50 “secure” Compton-thick AGN ( $\approx 10$  mildly-thick) known at present

Unabsorbed:  
 $\log N_H < 21$

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

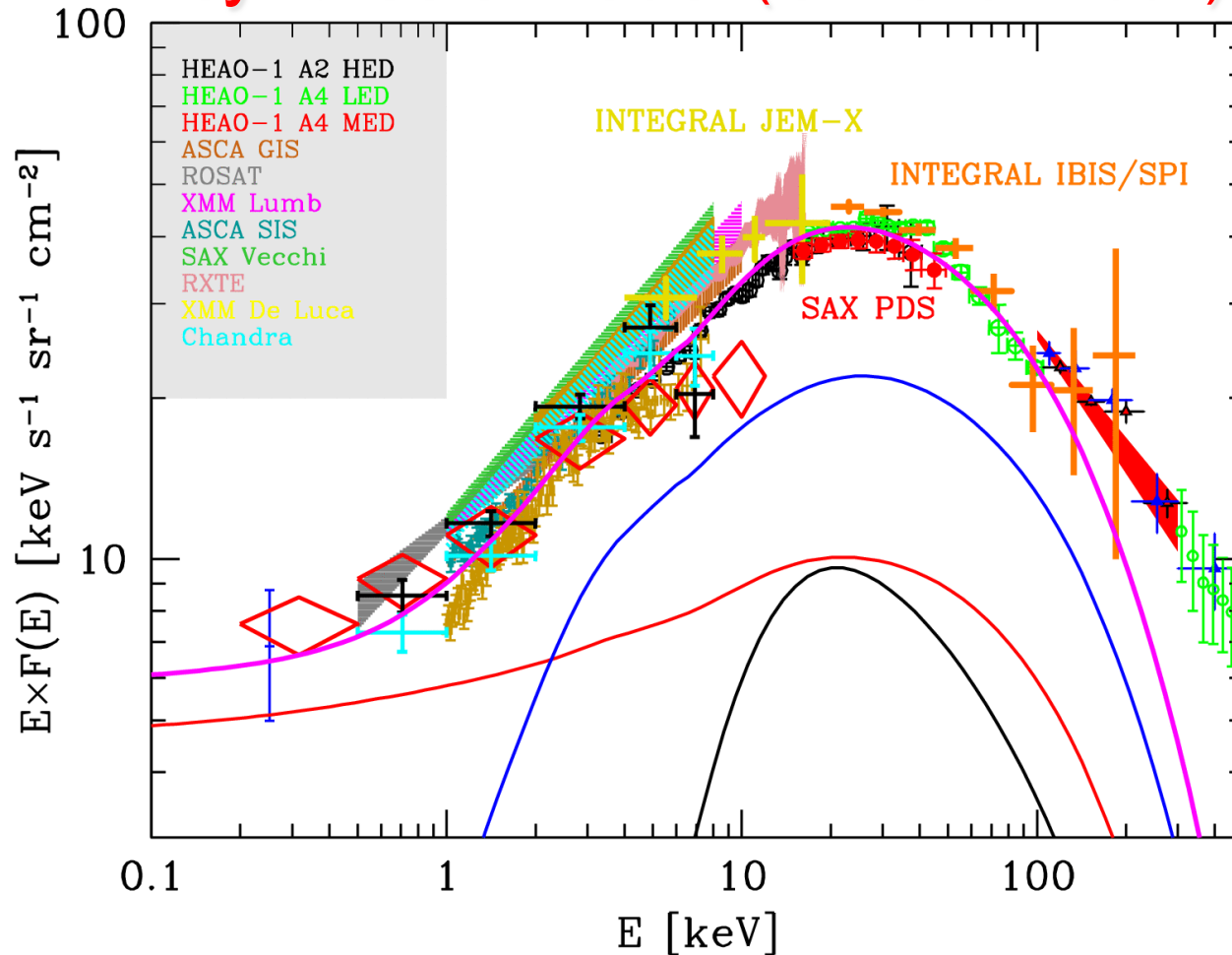
**Compton-Thick:**  
Mildly ( $\log N_H = 24$ -25)  
Heavily ( $\log N_H > 25$ )



The cold gas in the torus contributes to the iron  $K\alpha$  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)

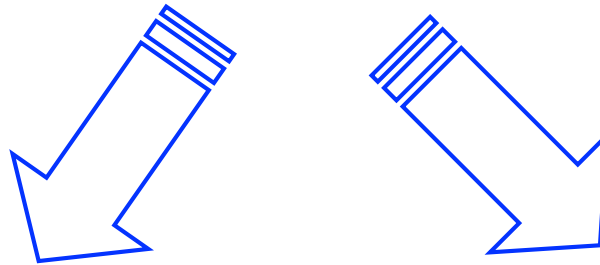


Number of Compton-thin AGN =  
Number of Compton-thick AGN at  
high X-ray luminosities

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

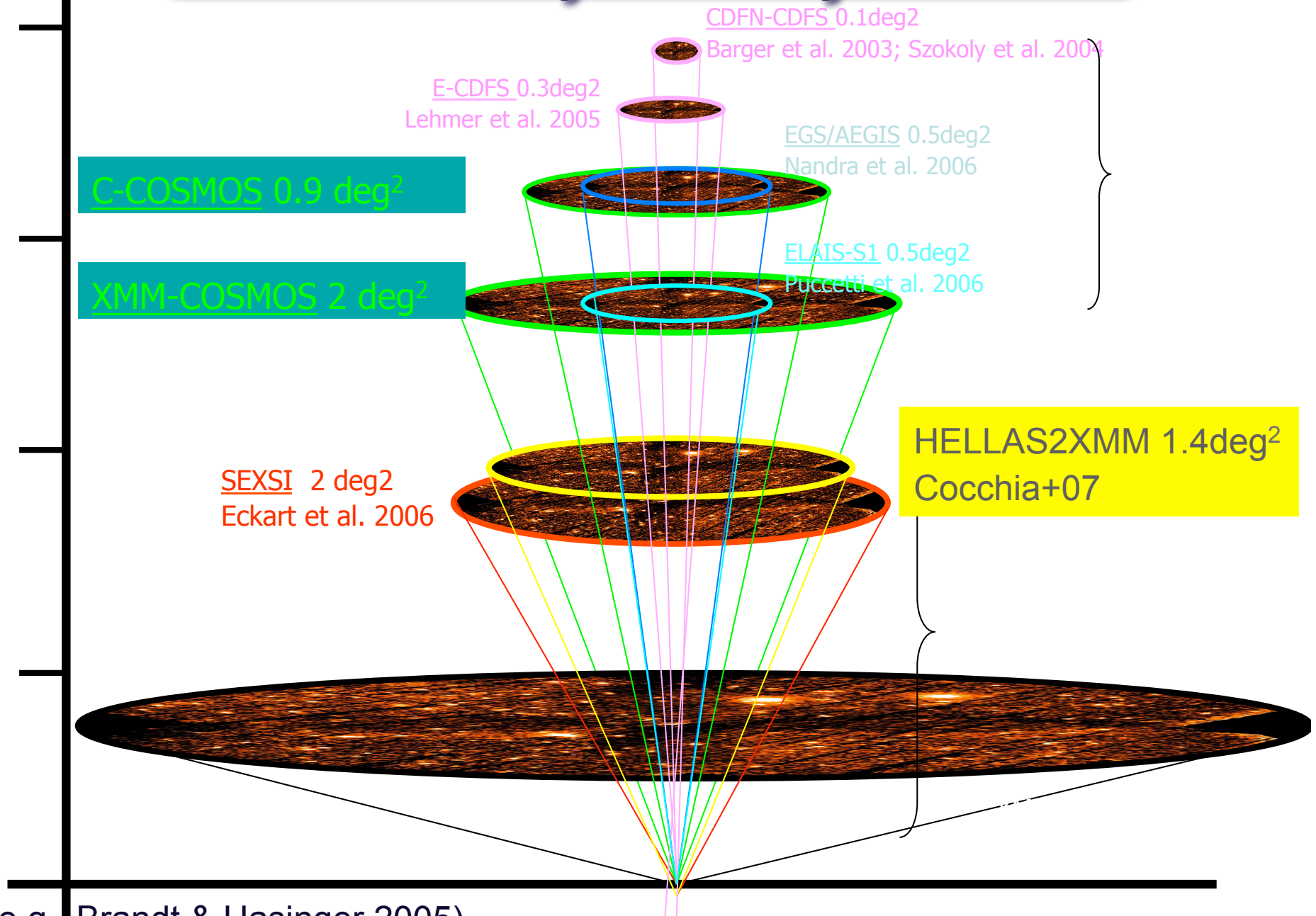
Relatively bright optical counterparts,  
easier optical IDs

## **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?

Hickox 2009, adapted from Brandt & Hasinger 2005

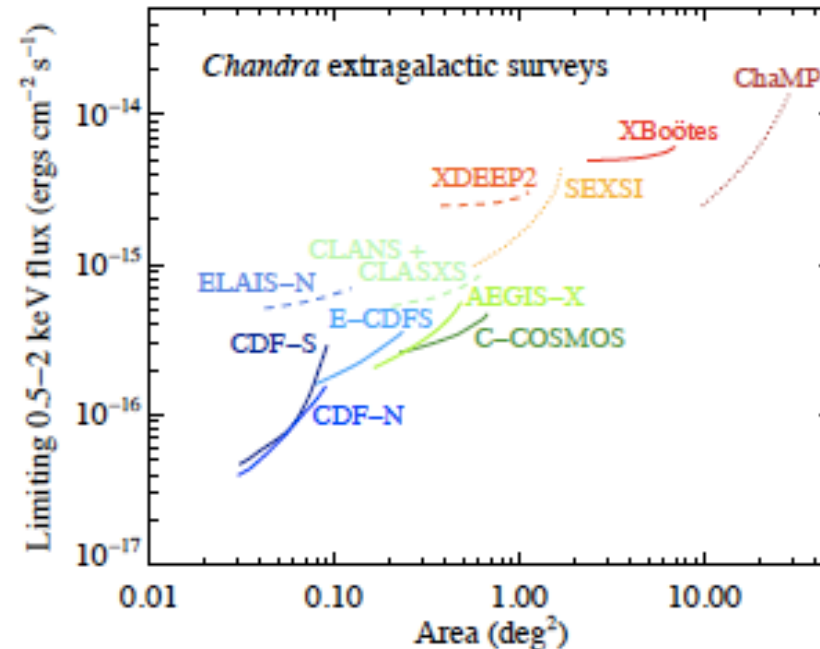
## DEEP X-RAY SURVEYS

### 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



## 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

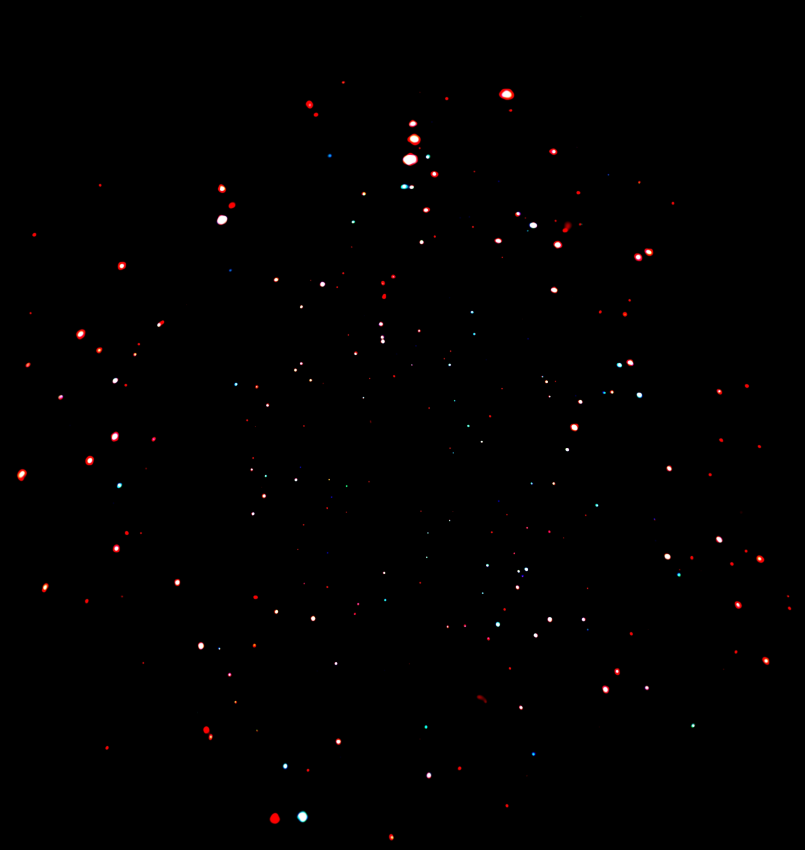
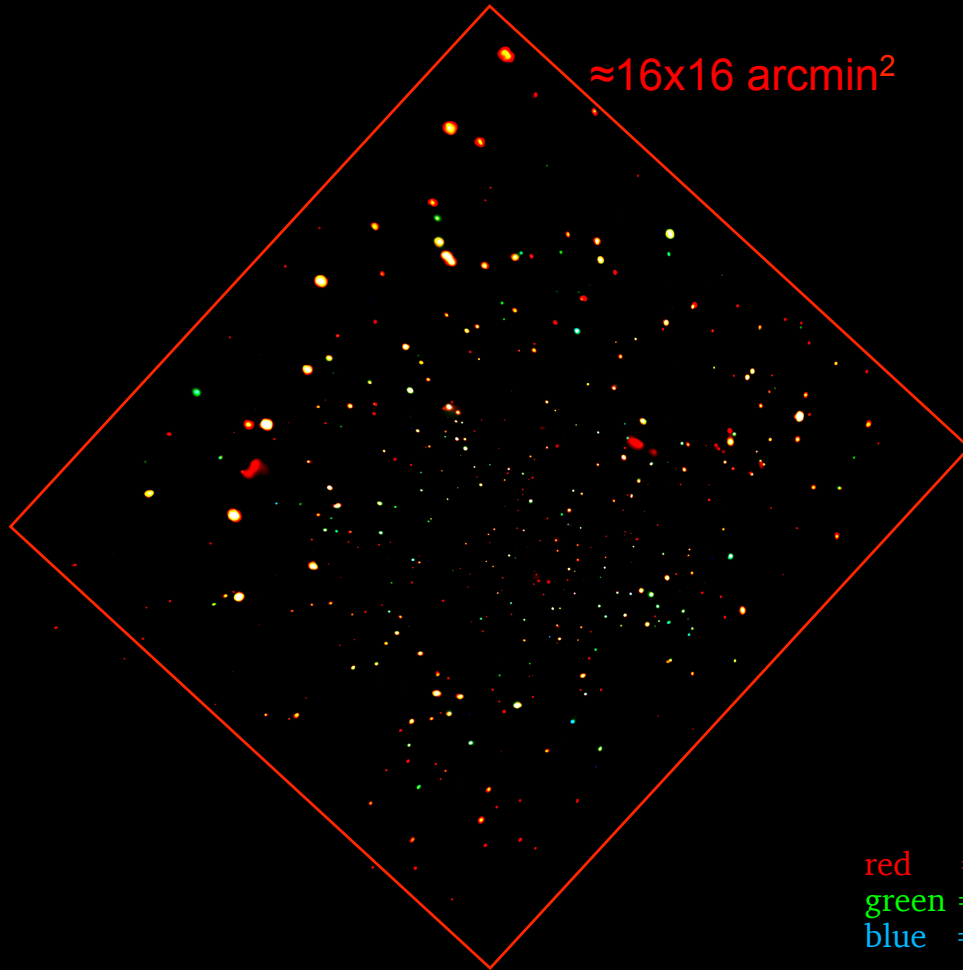
### CONs

- Limited number of sources

# Chandra Deep Fields

CDFN (Alexander+03; Luo+ 08,10)

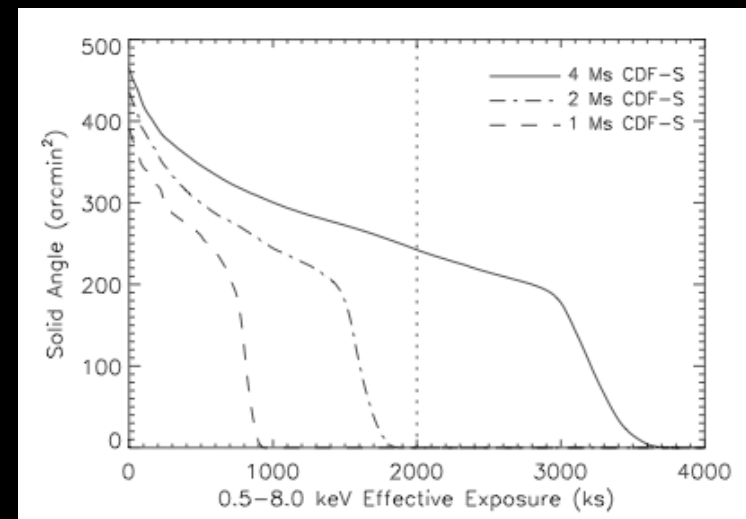
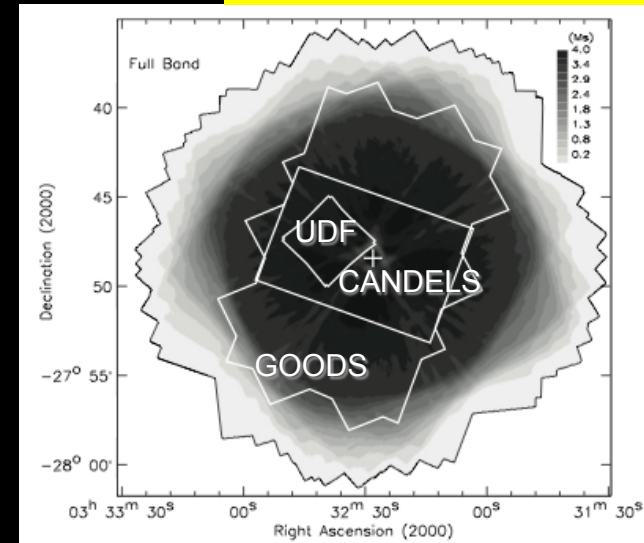
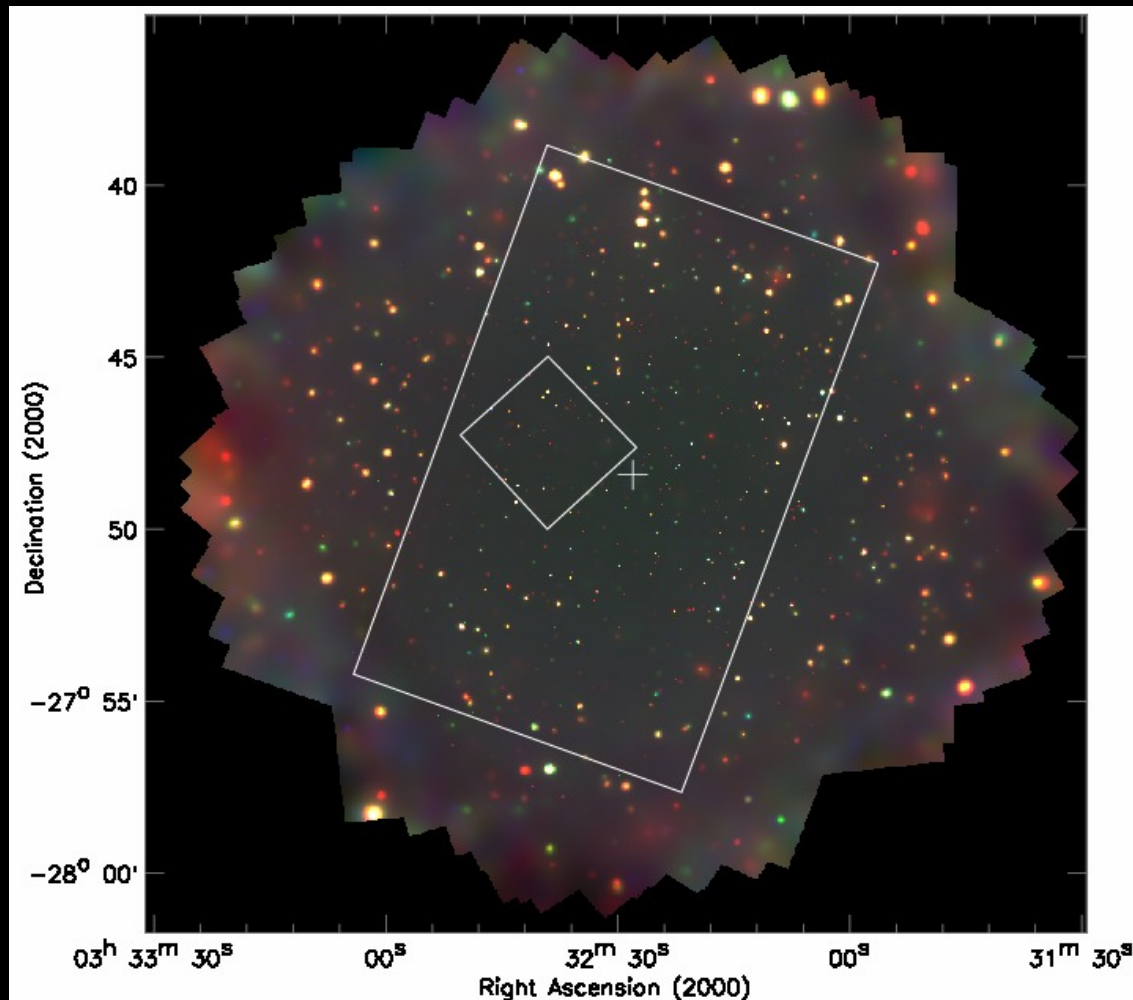
CDFS (Giacconi+02)



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

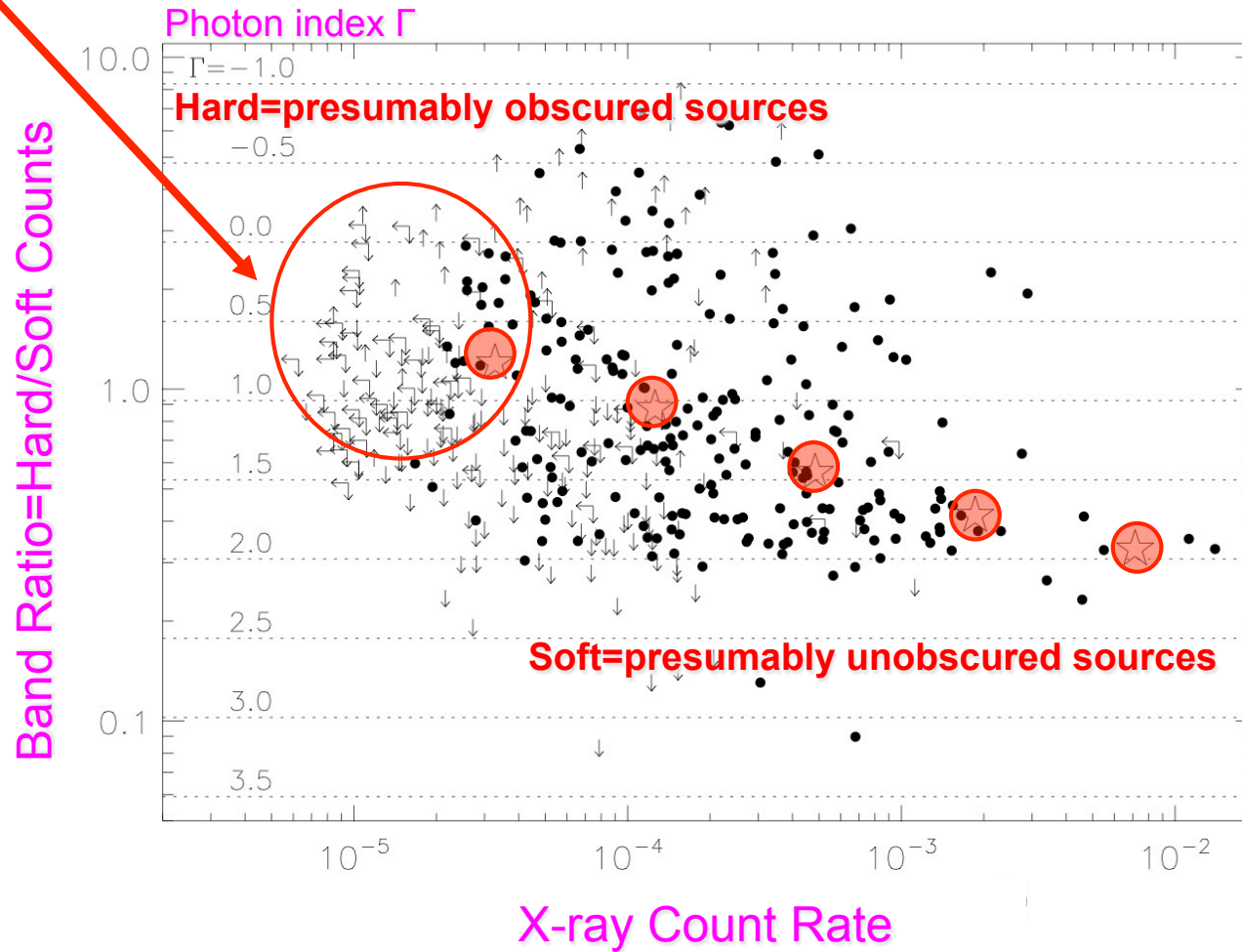
**COMING NEXT  
(end 2015):  
Further 3 Ms**

up to the recent 4 Ms exposure in the CDF-S (Xue et al. 2011):  
the deepest X-ray exposure ever  
740 X-ray sources ( $\approx 60\%$  with spec. redshift)

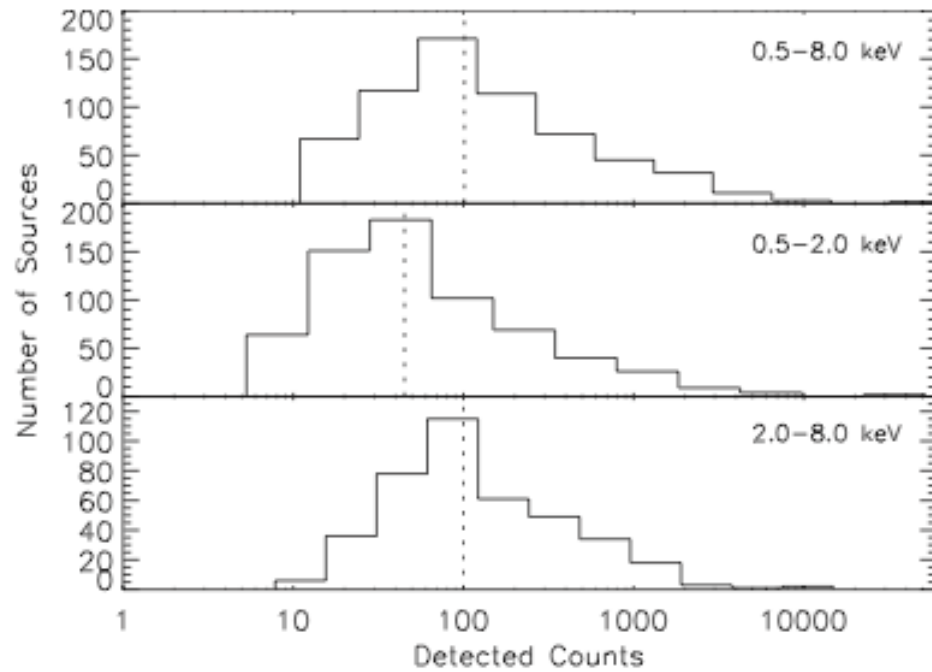


Sources with flatter slopes  
(i.e., likely obscured)  
at faint X-ray fluxes

## Properties of the 4Ms CDF-S sources (I)

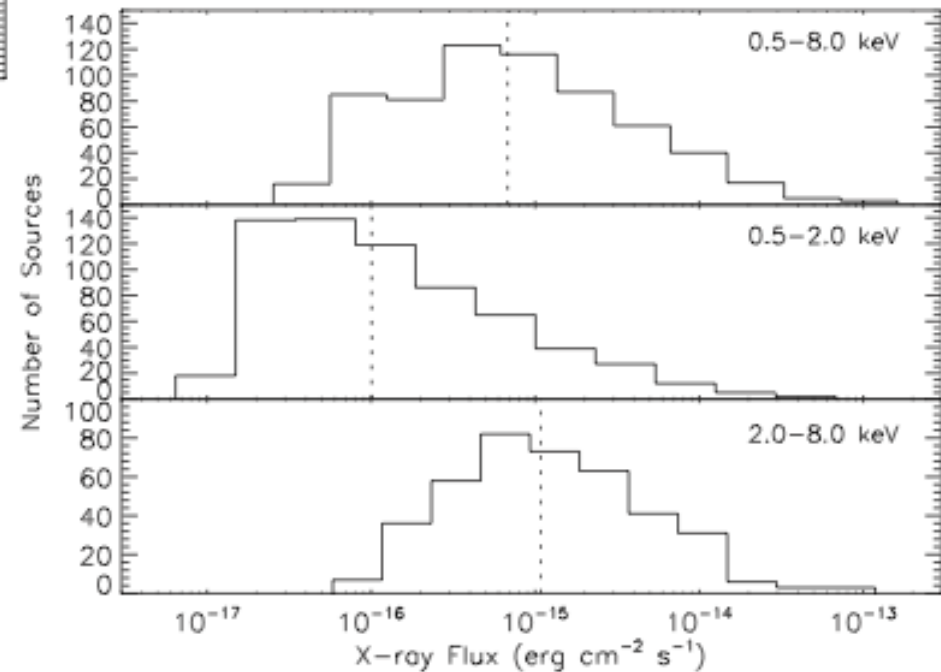


# Properties of the 4Ms CDF-S sources (II)



Source net count distribution

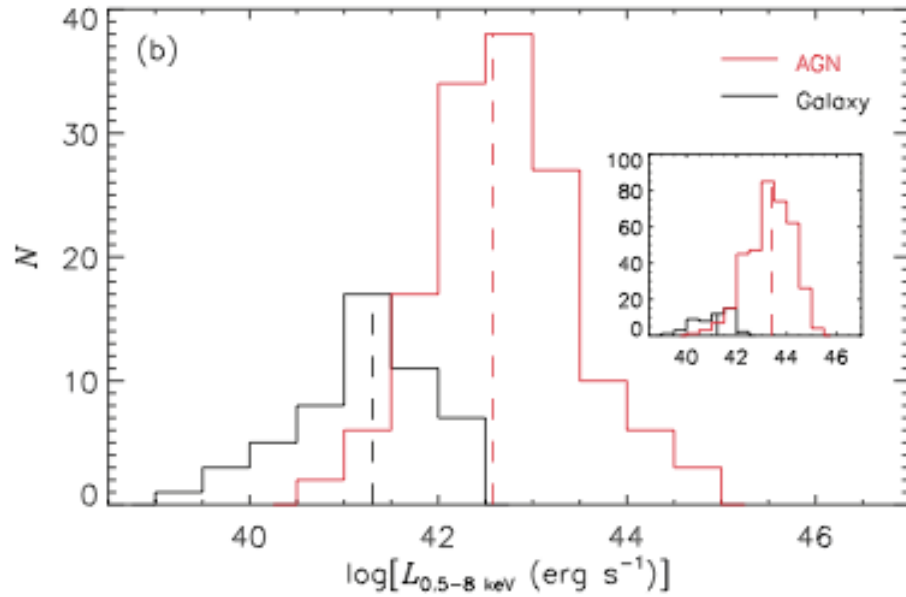
X-ray flux distributions



Xue et al. (2011)



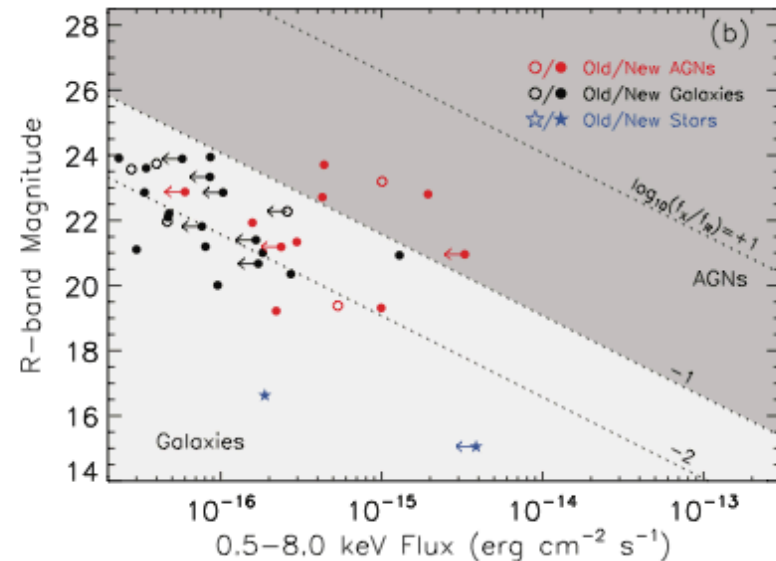
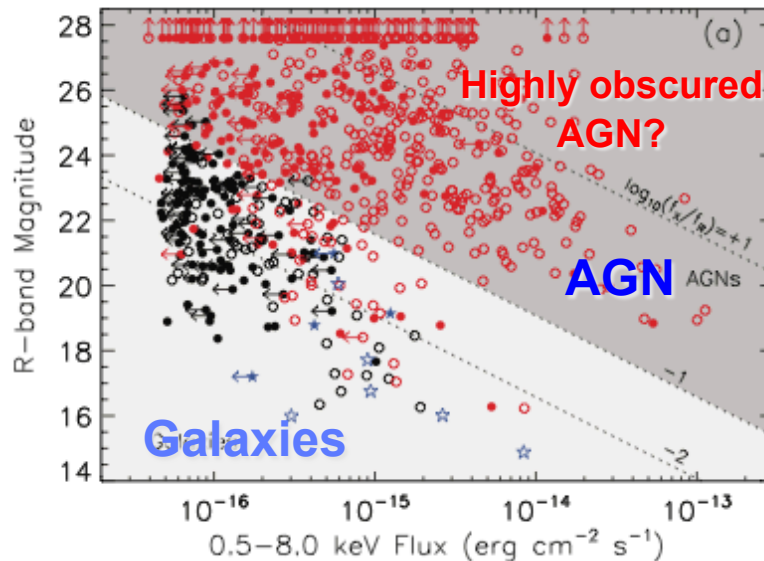
# Properties of the 4Ms CDF-S sources (III)



Both AGN and galaxy are detected because of the deep exposure

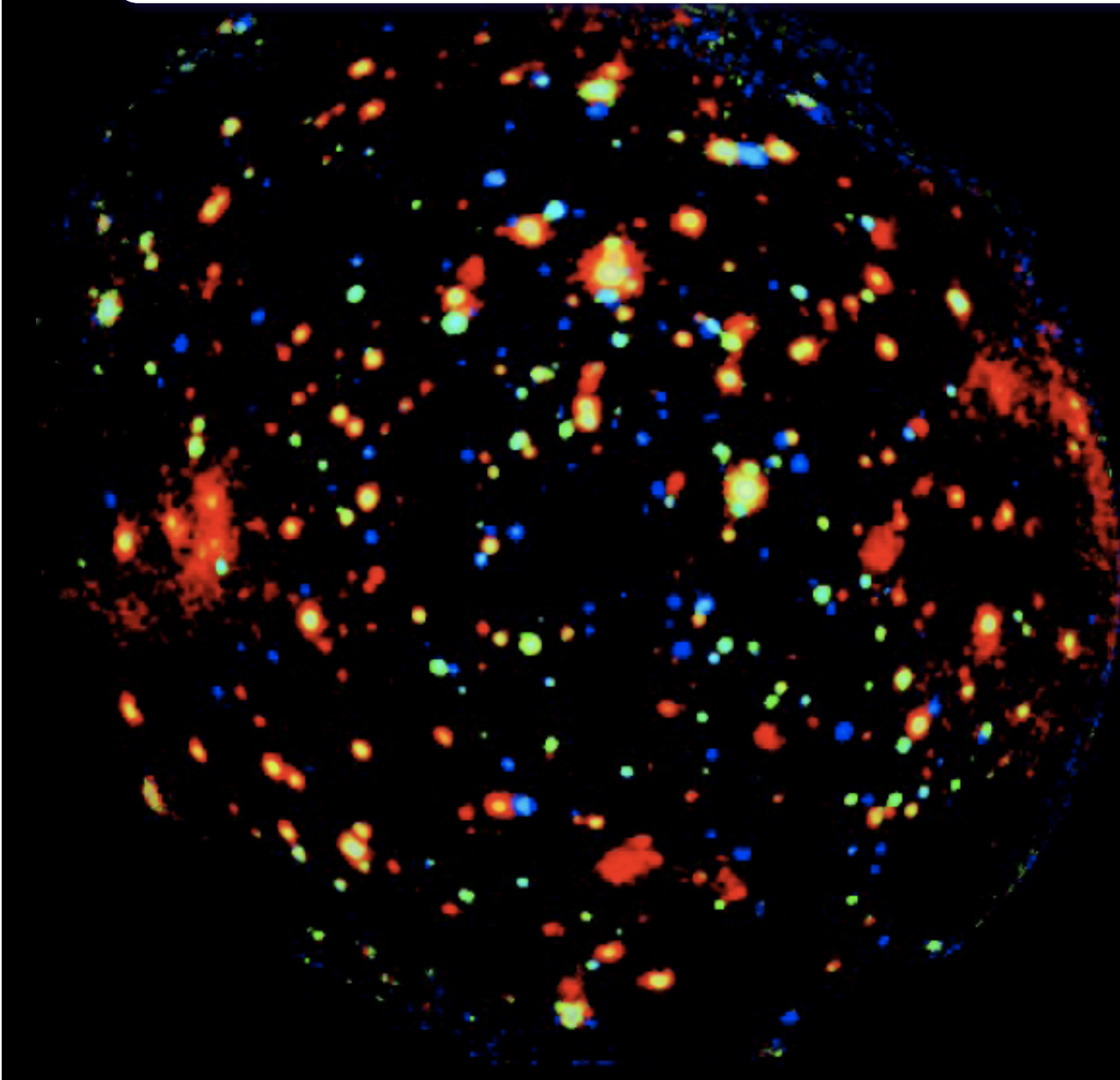
Xue et al. (2011)

R-band mag vs. X-ray flux



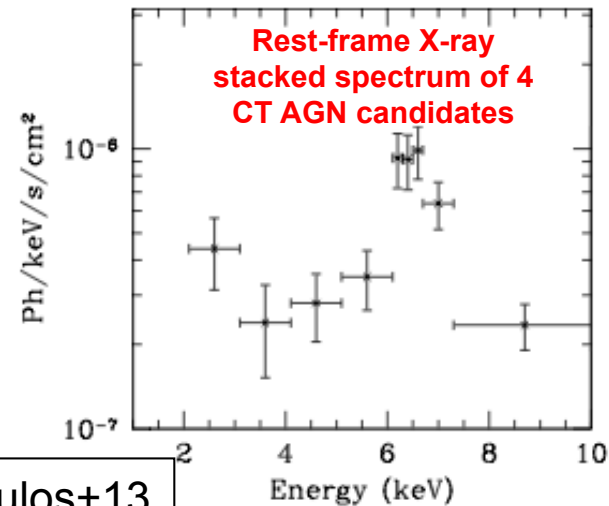
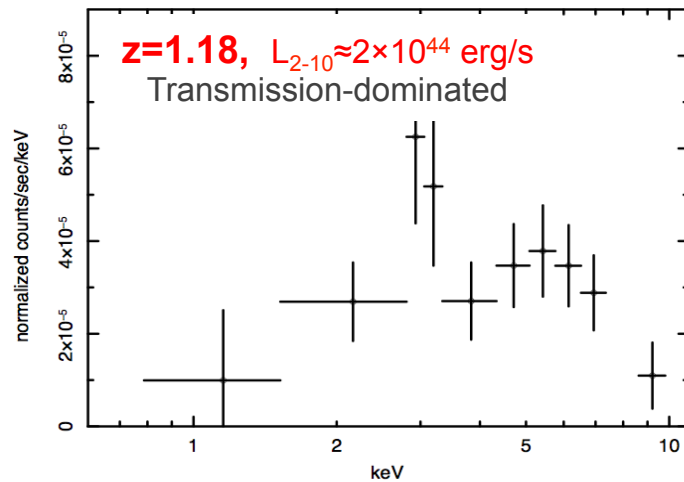
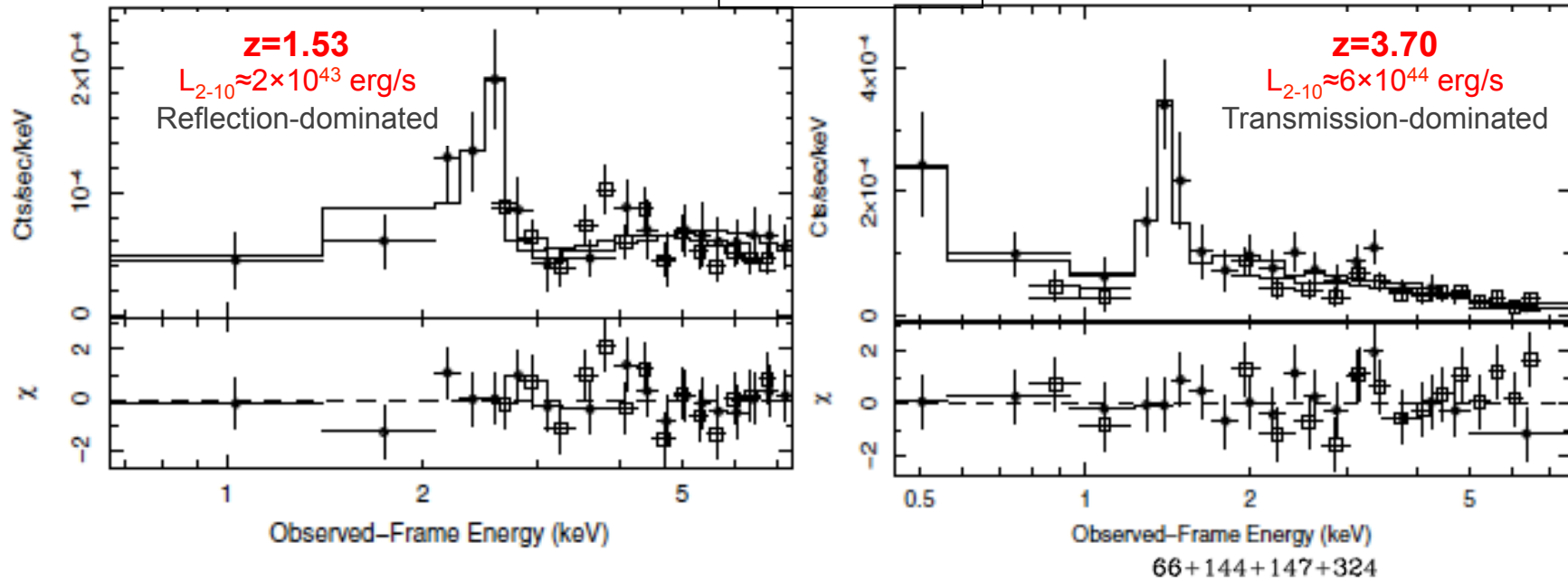


# Chandra Deep Field South: XMM 3 Ms exposure



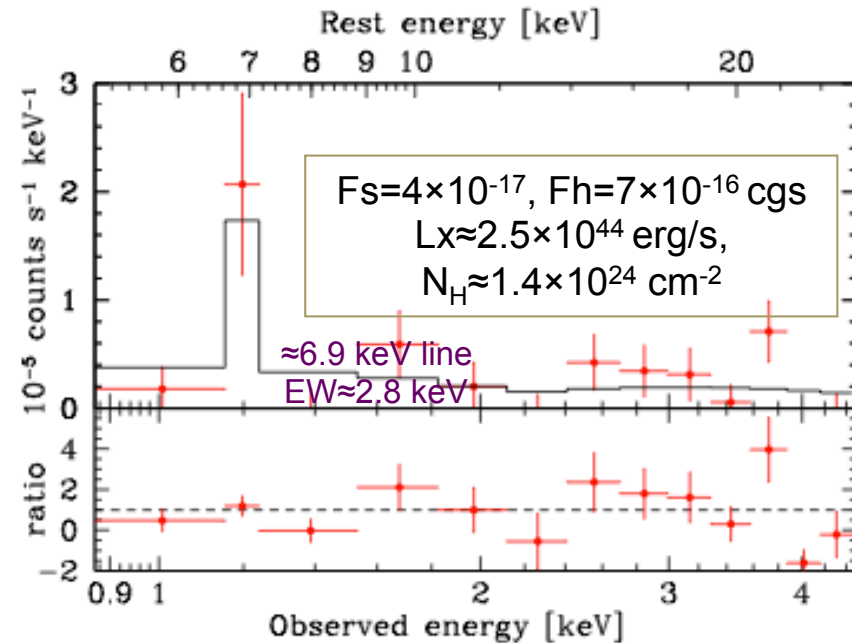
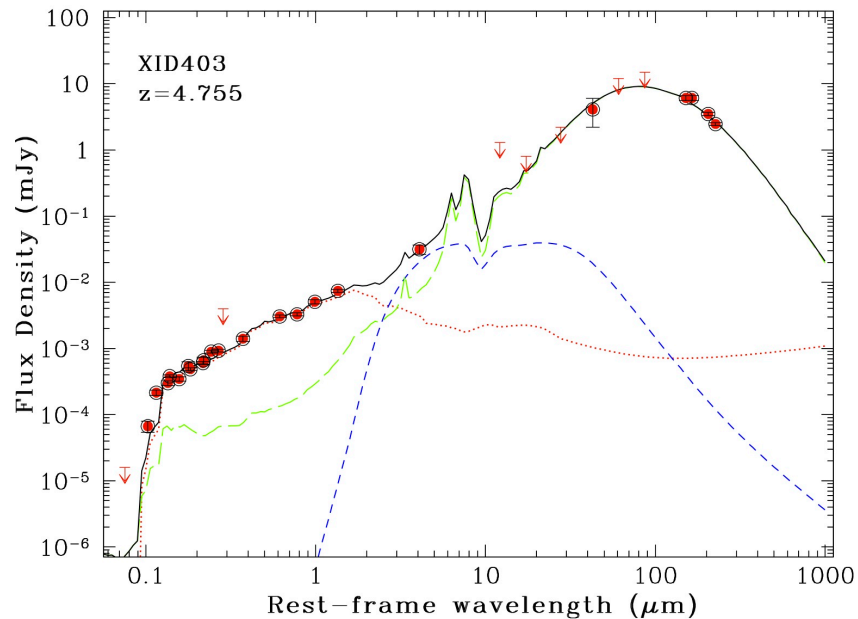
# Distant obscured AGN in the CDF-S

Comastri+11



Georgantopoulos+13

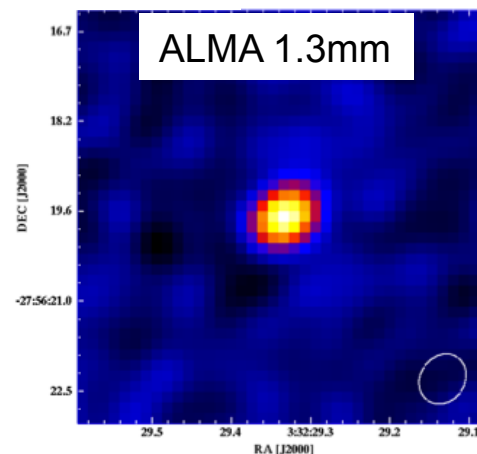
# Obscured accretion and powerful star formation at $z=4.8$



$SFR \approx 1000 M_{\odot}/yr$   
 $\Sigma_{SFR} > 26 M_{\odot}/yr/kpc^2$

Compact starburst, possibly  
responsible for the X-ray  
obscuration

Progenitor of compact quiescent  
massive galaxies at  $z \approx 3$



Gilli et al. 2014, 2011

Challenging and time-consuming  
observations

This kind of studies are possible only  
with deep ( $>Ms$ ) *Chandra* exposures

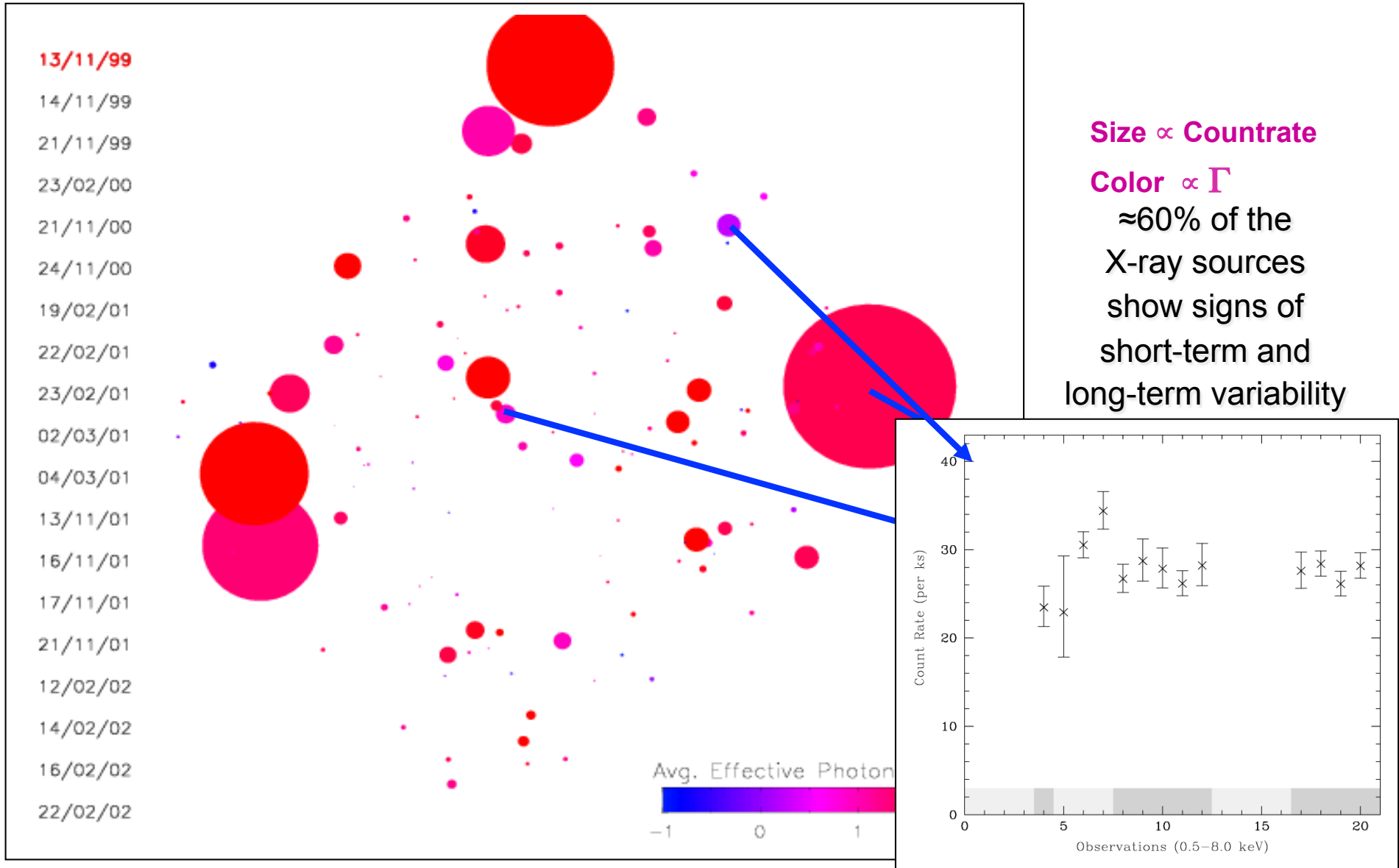
# X-ray variability from deep X-ray surveys

CDF-N

**25 ks**

2 Ms "integration" movie  
(Courtesy: F. E. Bauer)

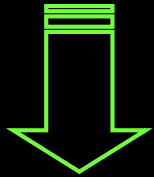
# Long-term X-ray variability



# X-raying the COSMOS

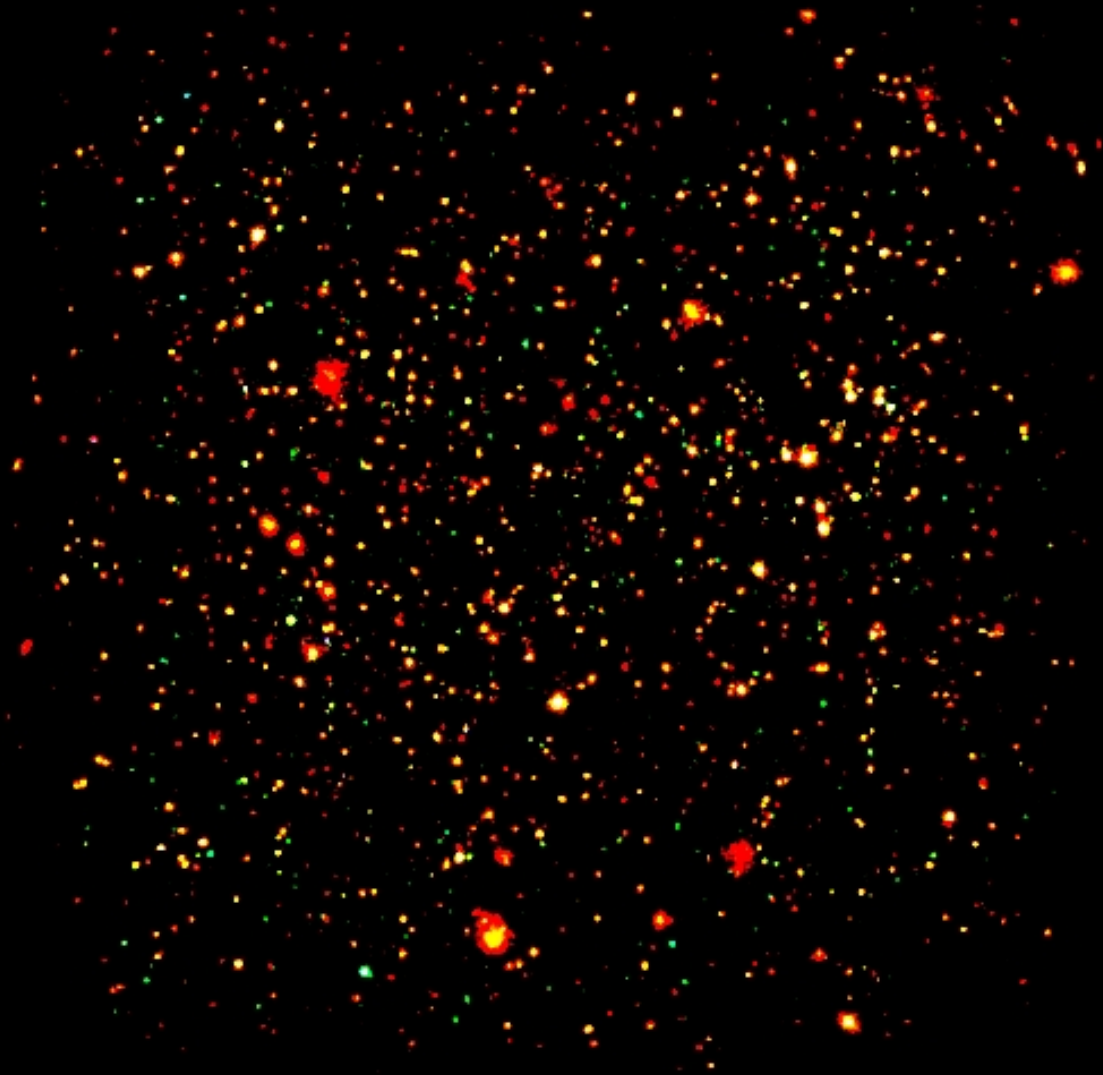
Need to overcome  
the problems related  
to the limited size of  
the explored region

**Chandra**  
**1.8 Ms**  
**1761 sources**



Larger area of the sky  
surveyed at brighter  
flux limits

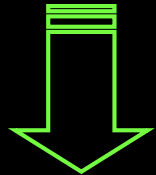
**XMM-Newton**  
**1.55 Ms**  
**1822 sources**



# X-raying the COSMOS

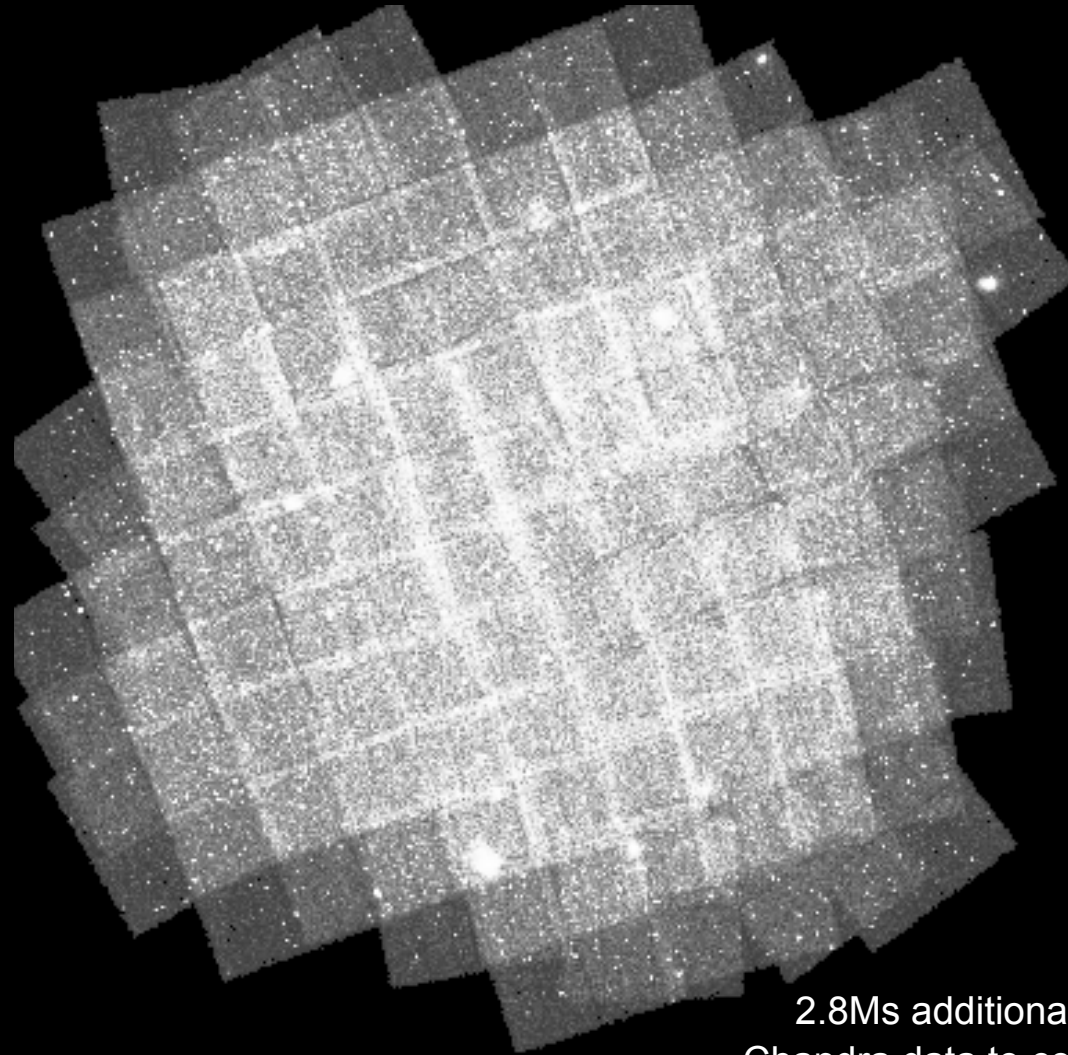
Need to overcome  
the problems related  
to the limited size of  
the explored region

**Chandra**  
**1.8 Ms**  
**1761 sources**



Larger area of the sky  
surveyed at brighter  
flux limits

**XMM-Newton**  
**1.55 Ms**  
**1822 sources**



2.8Ms additional  
Chandra data to cover  
the entire  $\sim 2.2 \text{ deg}^2$  (going deep)  
4016 point-like X-ray sources



# AGN Evolution

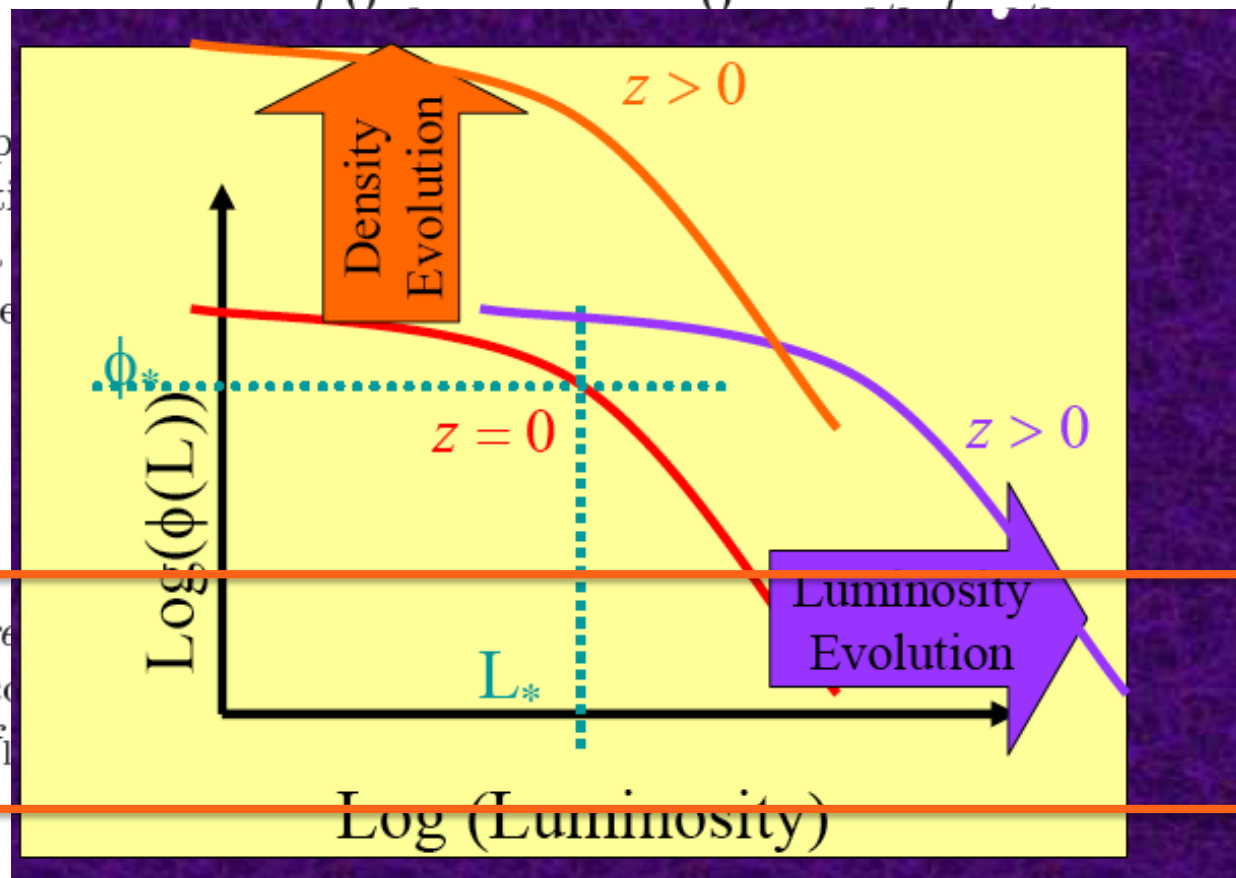
# AGN surveys, basic definitions

The space density of sources of different intrinsic luminosities,  $L$ , is described by the *luminosity function* (LF),  $\phi(L)$ , so that  $dN = \phi(L)dL$  is the number of sources per unit volume with luminosity in the range  $L$  to  $L + dL$ . Let us consider, for simplicity, the local or nearby (Euclidean) universe uniformly filled with sources with LF  $\phi(L)$ . If  $S$  is the limiting flux that we can detect, sources with luminosity  $L$  can be observed out to a distance  $r = (L/4\pi S)^{1/2}$ . The number of sources over the solid angle  $\Omega$ , observable down to the flux  $S$  are:

$$\int_{L_{\min}}^{L_{\max}} \phi(L) \Omega r^2 dL \quad (1)$$

Thus, independent of a normalization of sources in a  $\Omega$  of  $-3/2$  (if we use

the determination of a non-evolving class  $N(> S)/d \log S = \phi(L) \Omega r^2$  ( $n = 0.6$ ).



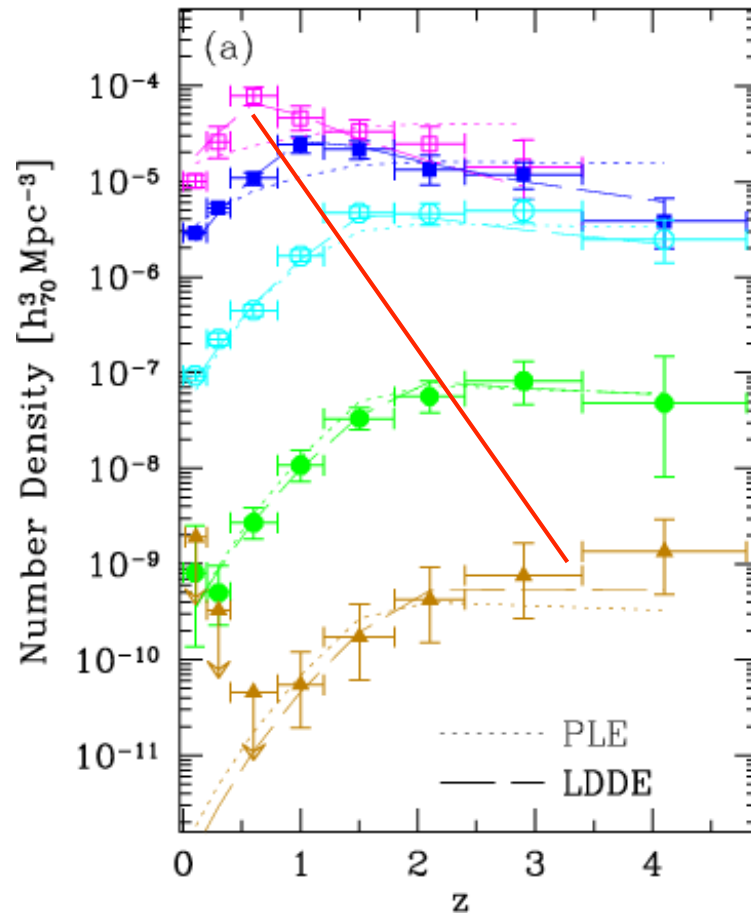
(1)

(2)

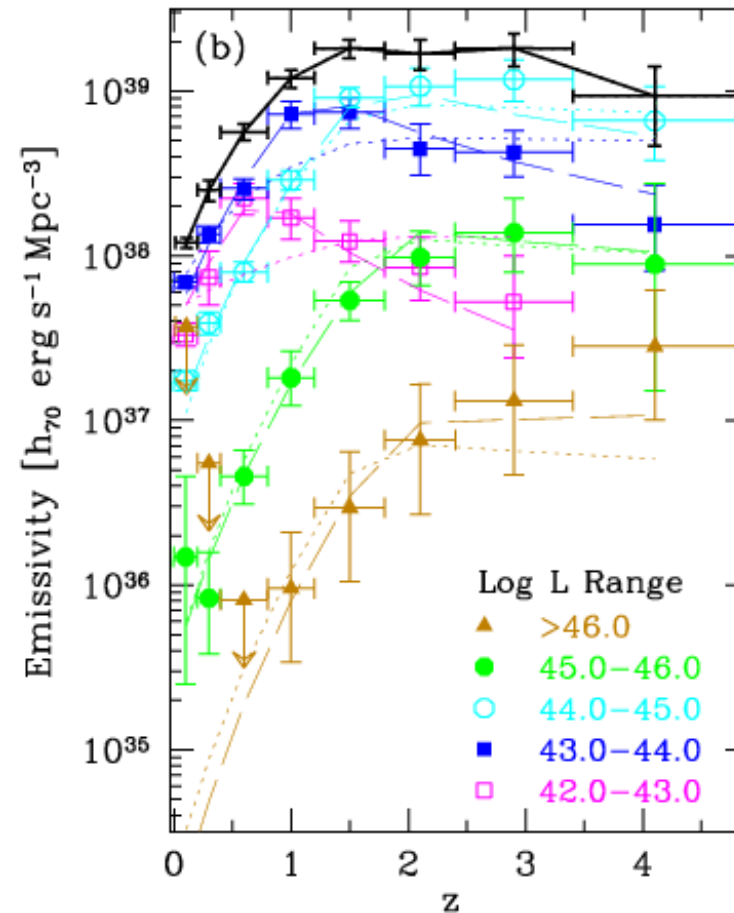
In the *pure* of sources is co (PDE) case (f) g number density density evolution ity varies.

# AGN cosmological evolution

## Number density



## Luminosity density

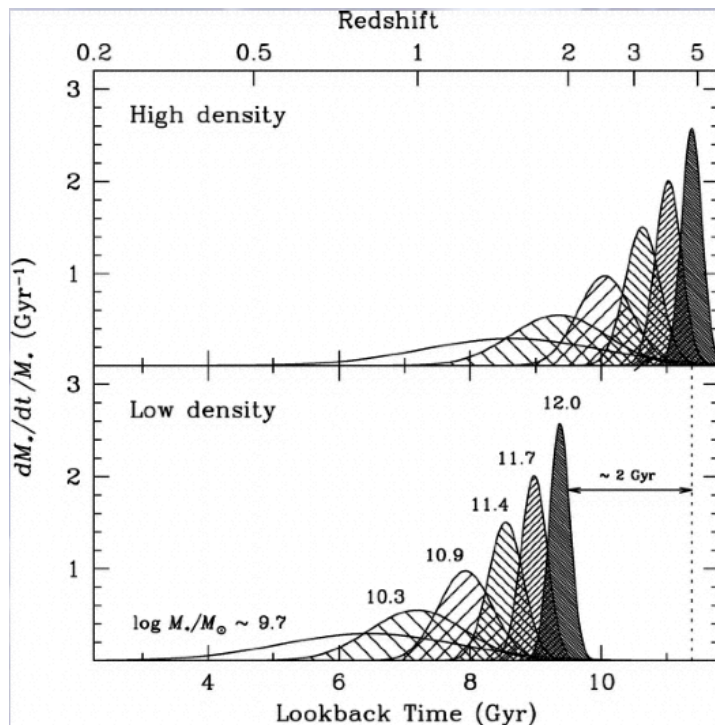


Objects with lower luminosity peak at lower redshift, similar to what observed for SFR in galaxies  $\Rightarrow$  **cosmic downsizing**  
**QSOs peak at  $z \approx 2-3$ , AGN at  $z \approx 0.5-1$**

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



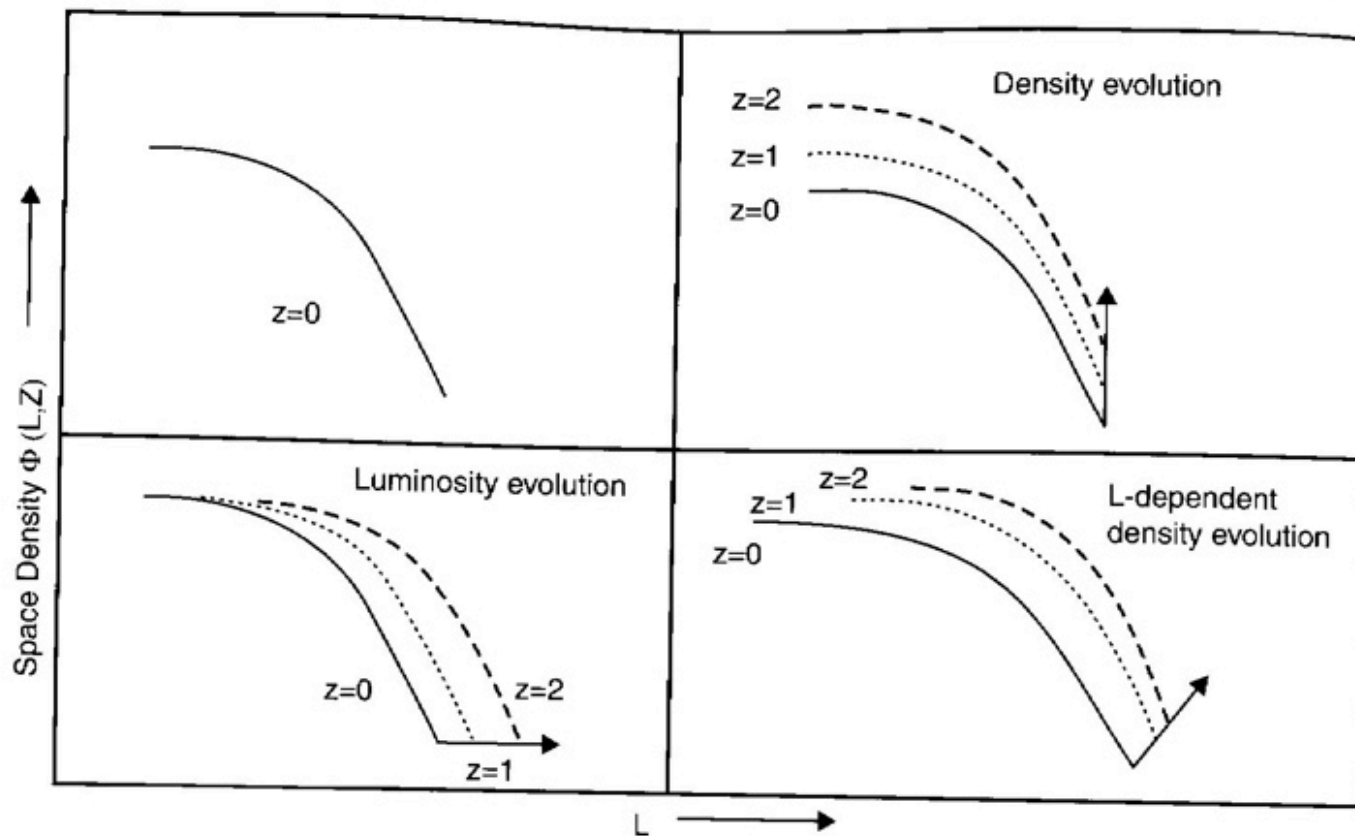
**Galaxy formation took place in “downsizing”, with more massive galaxies forming at higher redshift (Cowie+96)**

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

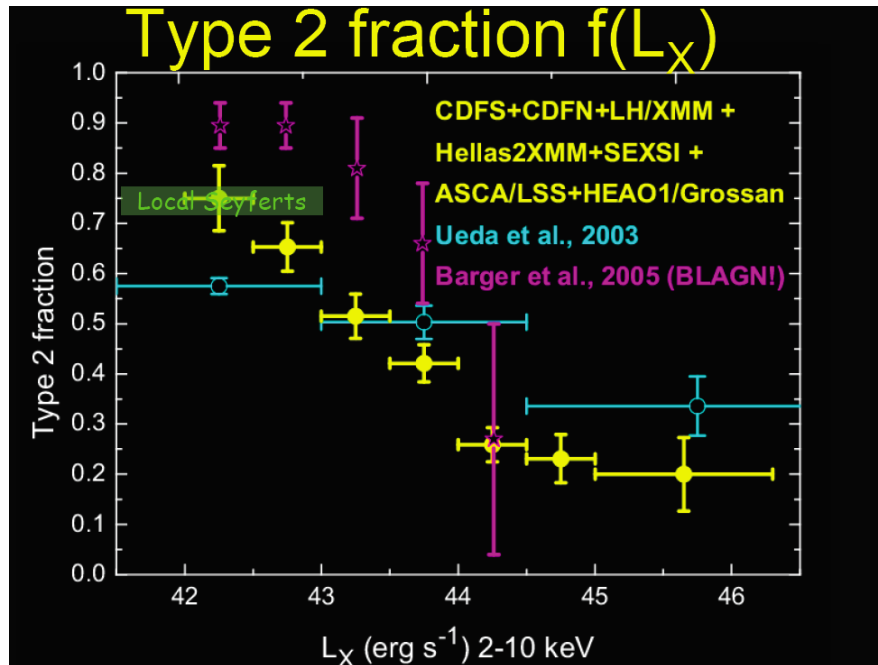
Luminosity Evolution:  
AGN more luminous in the past

Density Evolution:  
AGN more numerous in the past

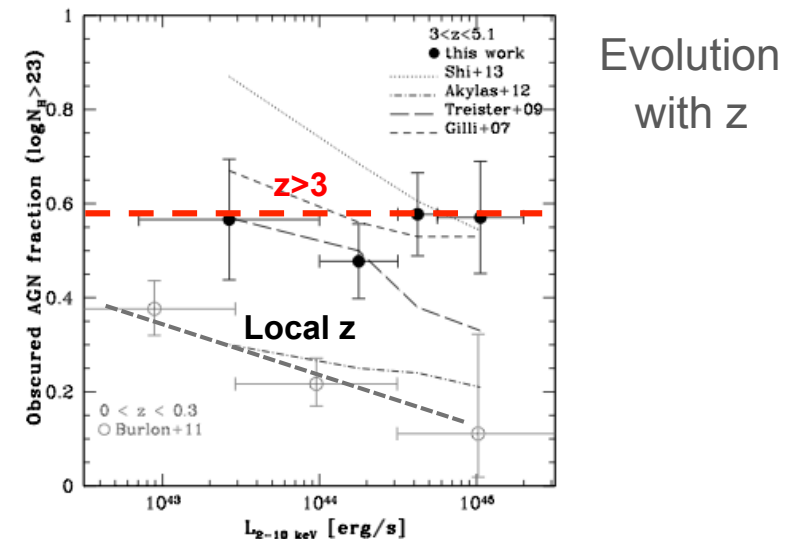
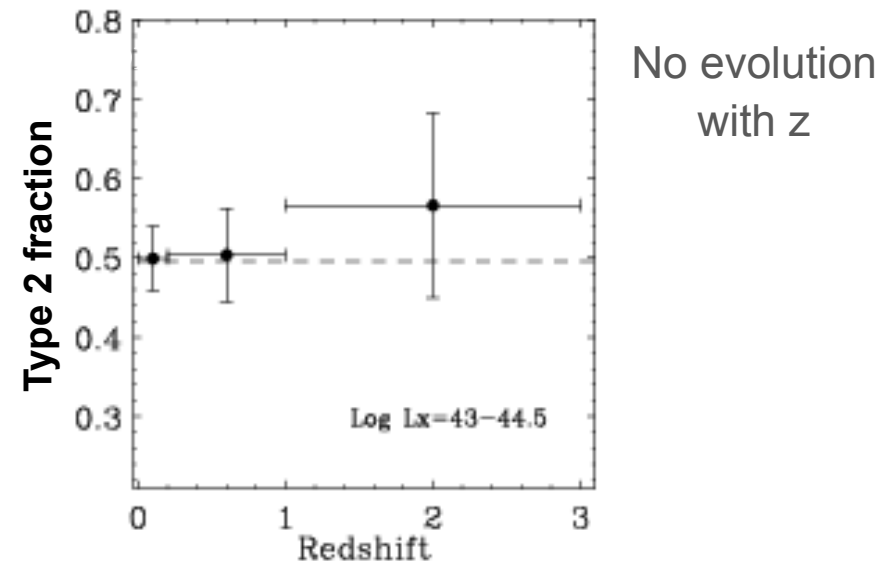
Luminosity-dependent Density  
Evolution:  
Evolution in density dependent on  
AGN luminosity



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



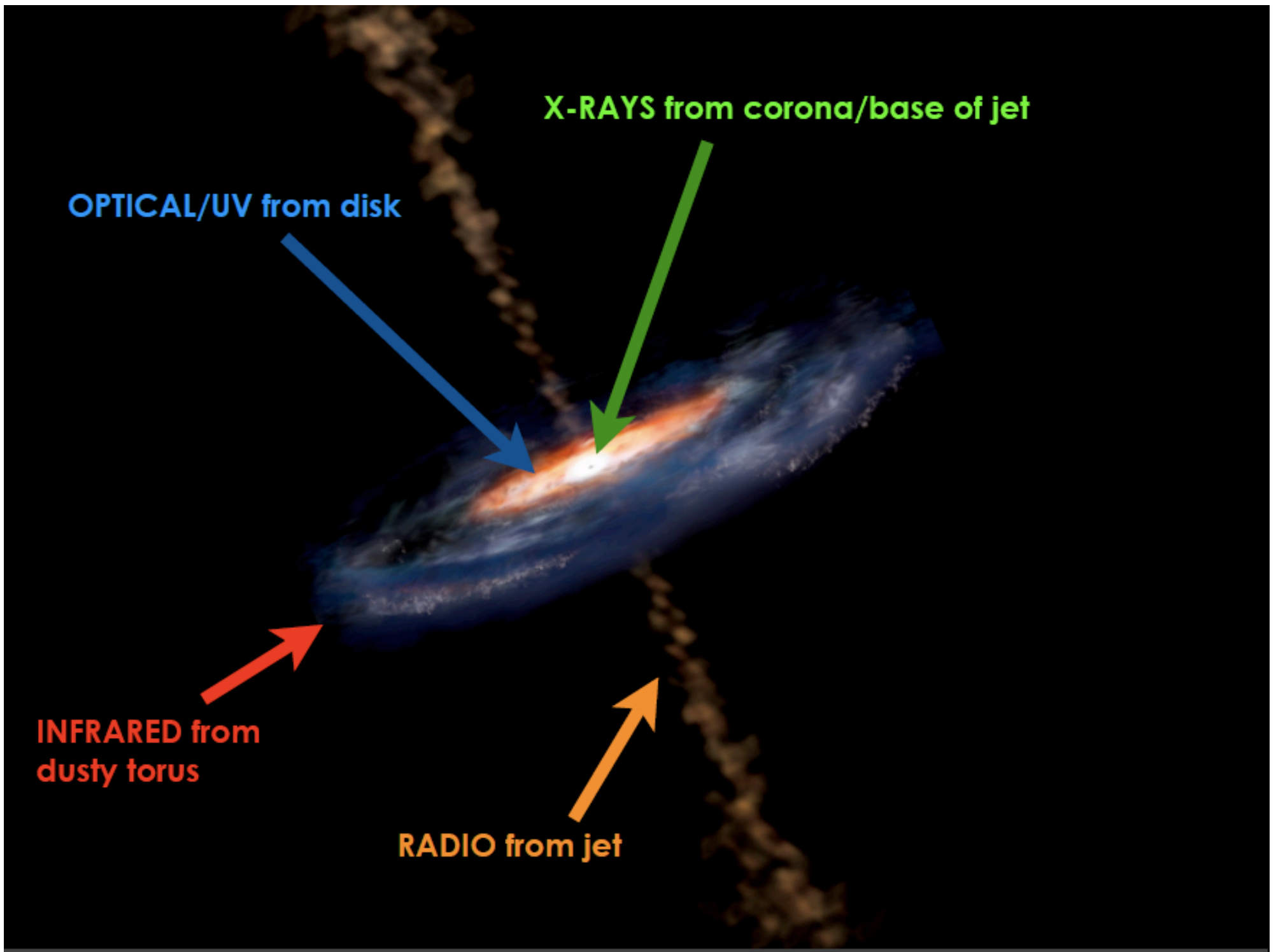
Broad consensus for an obscured AGN fraction declining towards high intrinsic luminosities → receding torus model (Lawrence 1991, Simpson 2005; see also Lusso et al. 2013)  
 Behavior with  $z$  still debated (see e.g. La Franca et al. 2005; Treister & Urry 2009; Iwasawa et al. 2012; Vito+13, 14)



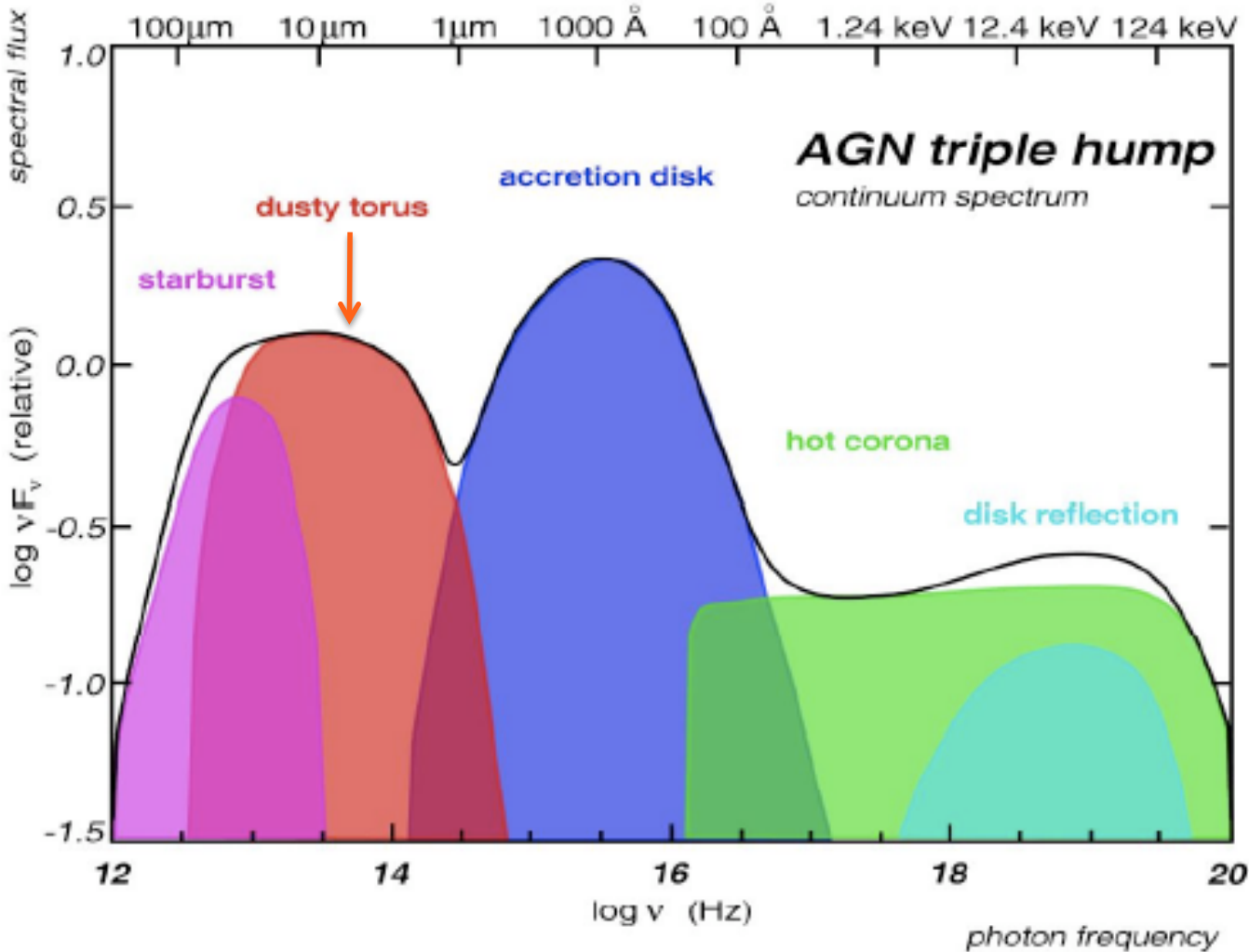
## AGN Spectral Energy Distributions.

On the properties, location and structure of the X-ray absorber

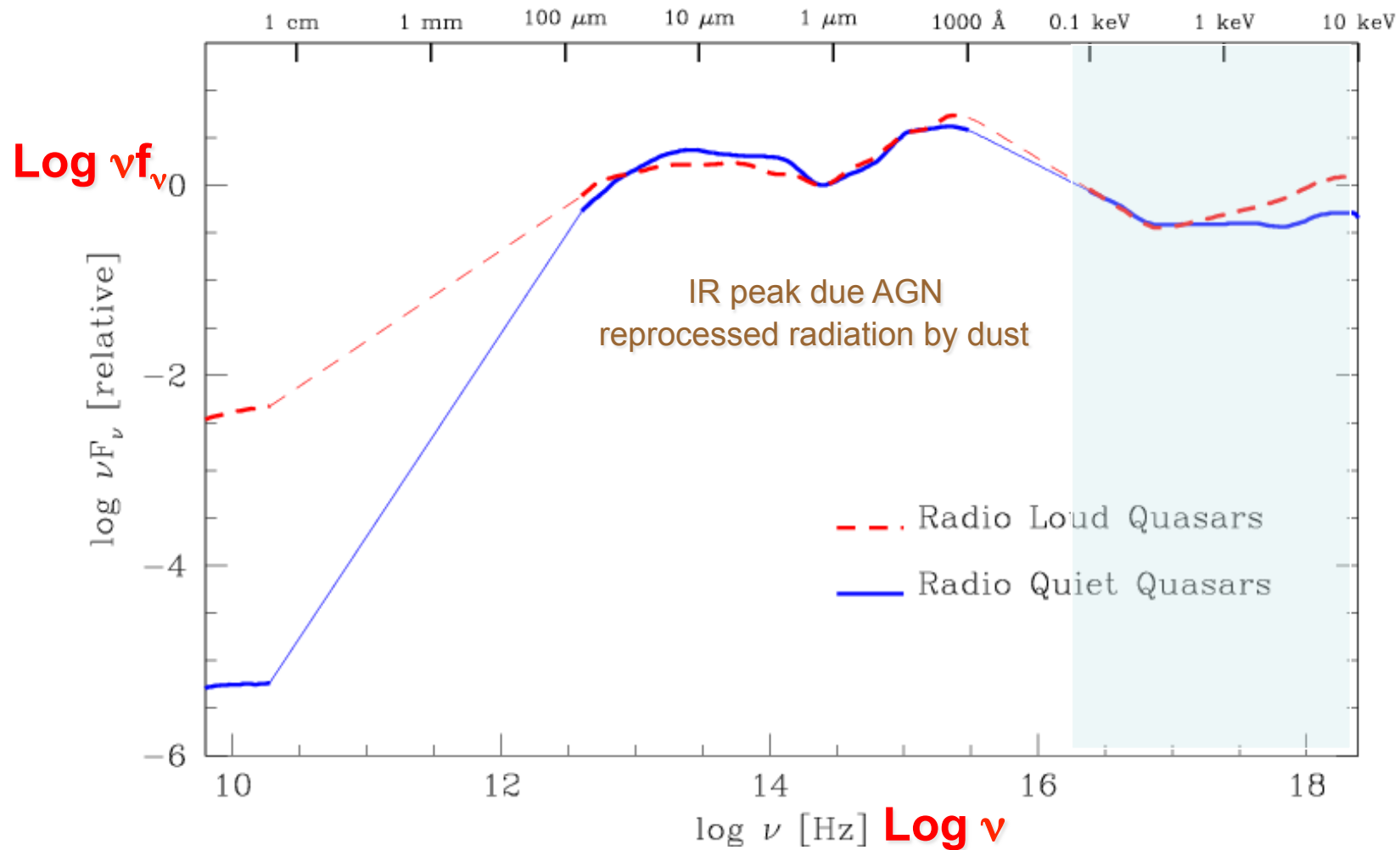




# Broad-band spectral energy distribution of AGN (I)



# Broad-band spectral energy distribution of AGN (II)

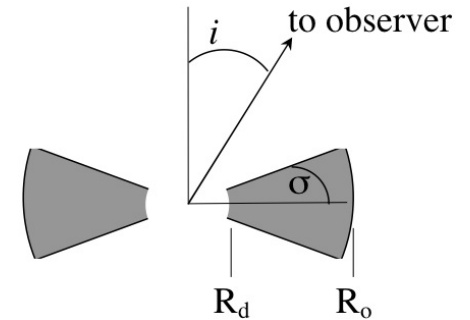


Elvis et al. 1994

# Models for the infrared emission of AGN (II)

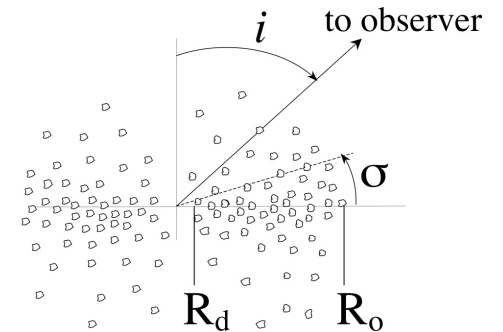
## Smooth dust distribution: main properties

- The source is obscured if radiation intercepts the torus, hence obscuration is related to geometrical issues
- Dust temperature is a function of the distance from the source of the radiation field



## Clumpy models: main properties

- The probability of direct viewing of the AGN decreases away from the axis, but is always finite
- Different dust temperatures coexist at the same distance from the radiation source, and the same dust temperature occurs at different distances



AGN type is a viewing-dependent probability

## Alternative modeling: hydromagnetic disk wind

- Torus=toroidal region of a wind, structured in outflowing clouds. The acceleration is provided by magnetic field lines anchored in the disc (Blandford & Payne '82; Elitzur '08)

# Indications from X-ray observations of local Seyferts

Eclipses of the X-ray source are  
COMMON in nearby AGN:  
 $\Delta N_H \sim 10^{23} - 10^{24} \text{ cm}^{-2}$

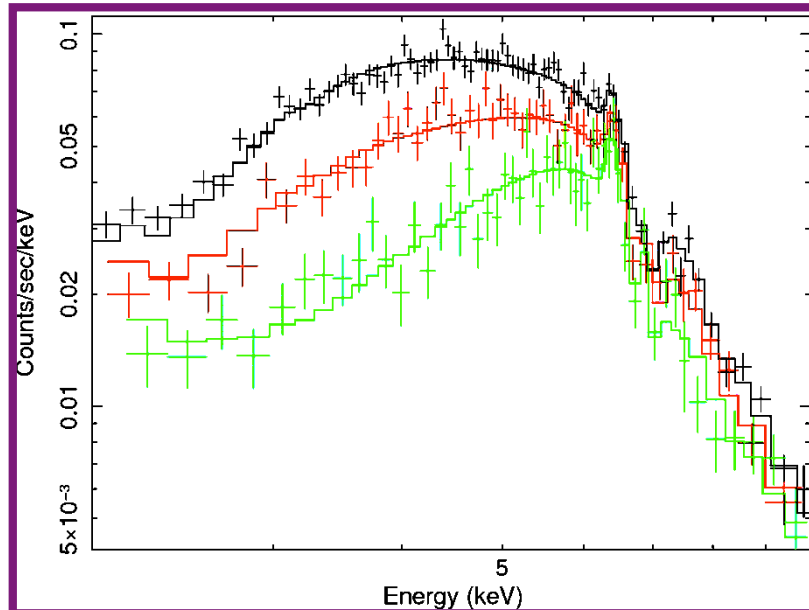
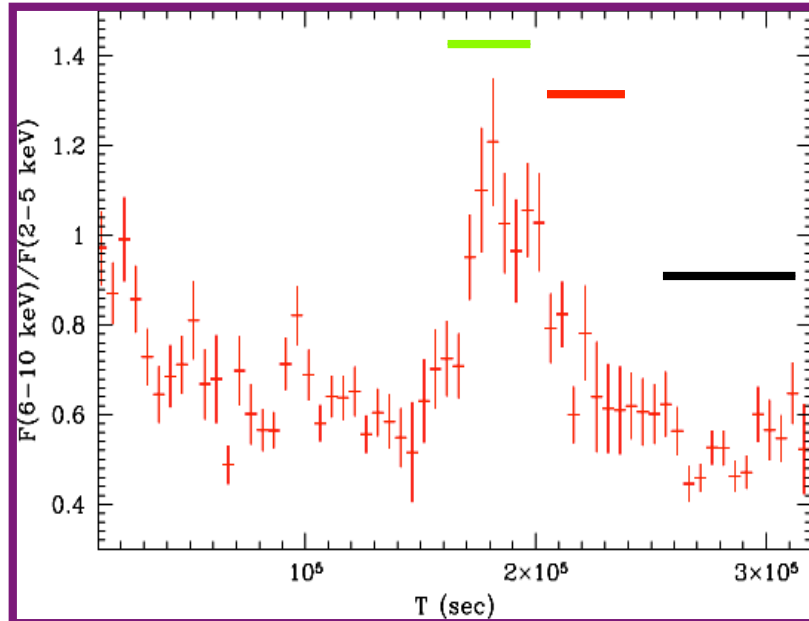


size X-ray src  $< 10^{14} \text{ cm}$   
 $D < 10^{16} \text{ cm}$

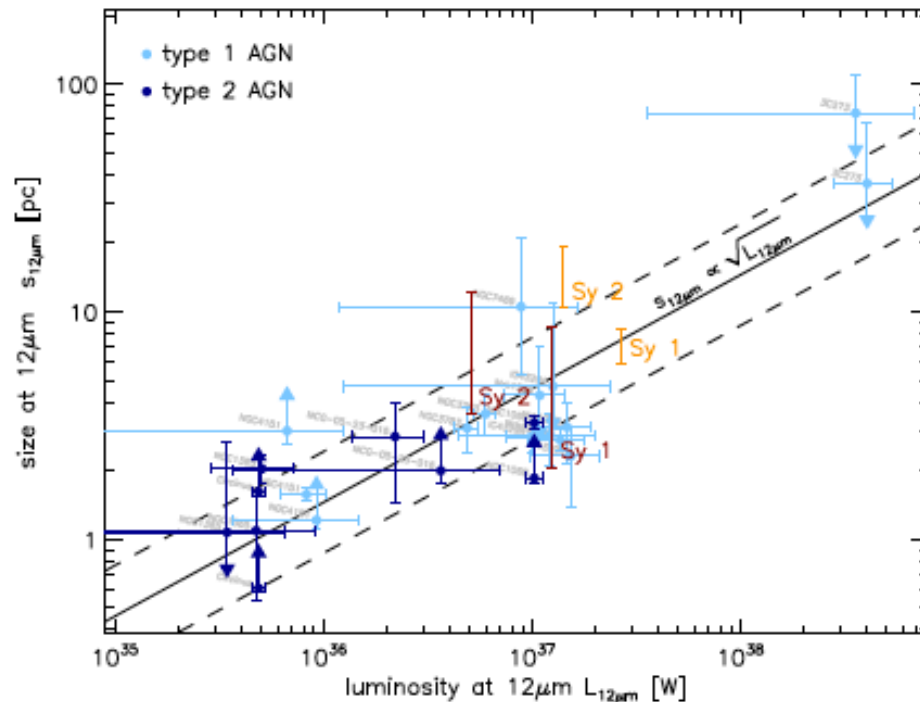


X-ray absorber “made” of BLR  
clouds on scales  $< \text{pc-scale}$  (torus)

Risaliti et al., 2007, 2010...



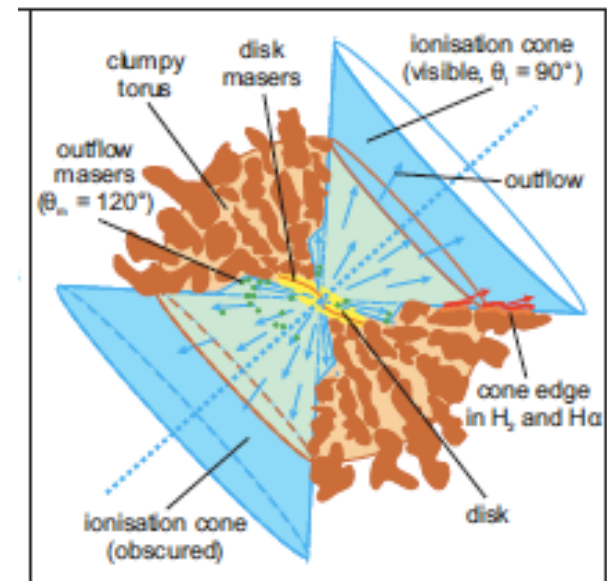
# High-resolution mid-IR observations of Seyferts



Tristram & Schartmann 2011  
 (see also Jaffe+04; Meisenheimer+07;  
 Tristram+07; Tristram+09, Burtscher+13)

- Compact (a few pc) tori with a clumpy/filamentary dust distribution (warm disk + geom. thick torus)

- No significant Sey1/Sey2 difference

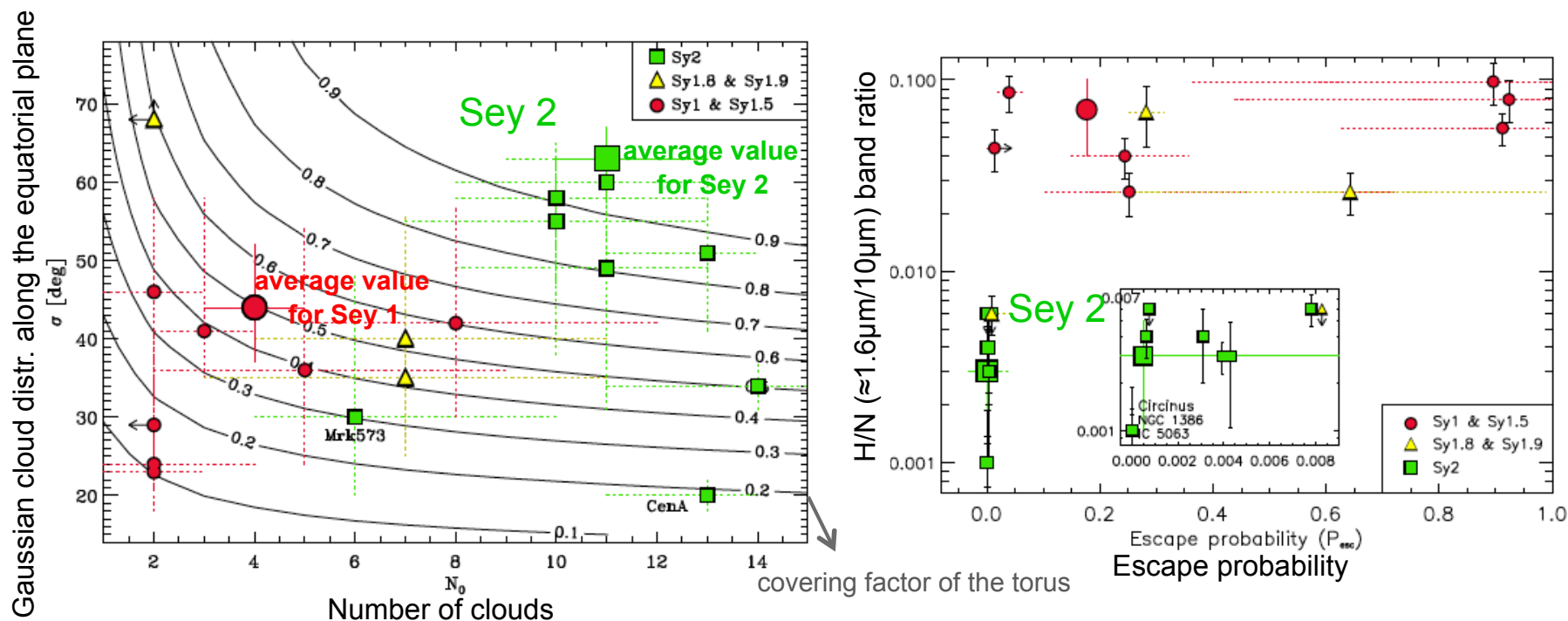


Tristram+07 - Circinus

# Modeling the mid-IR emission with “clumpy” torus

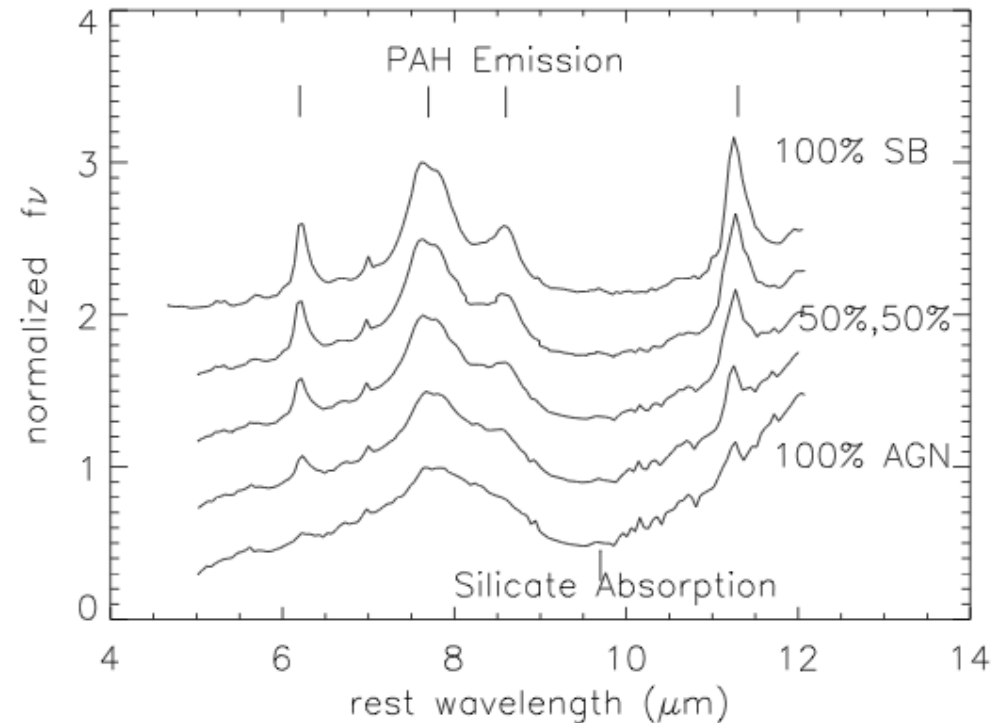
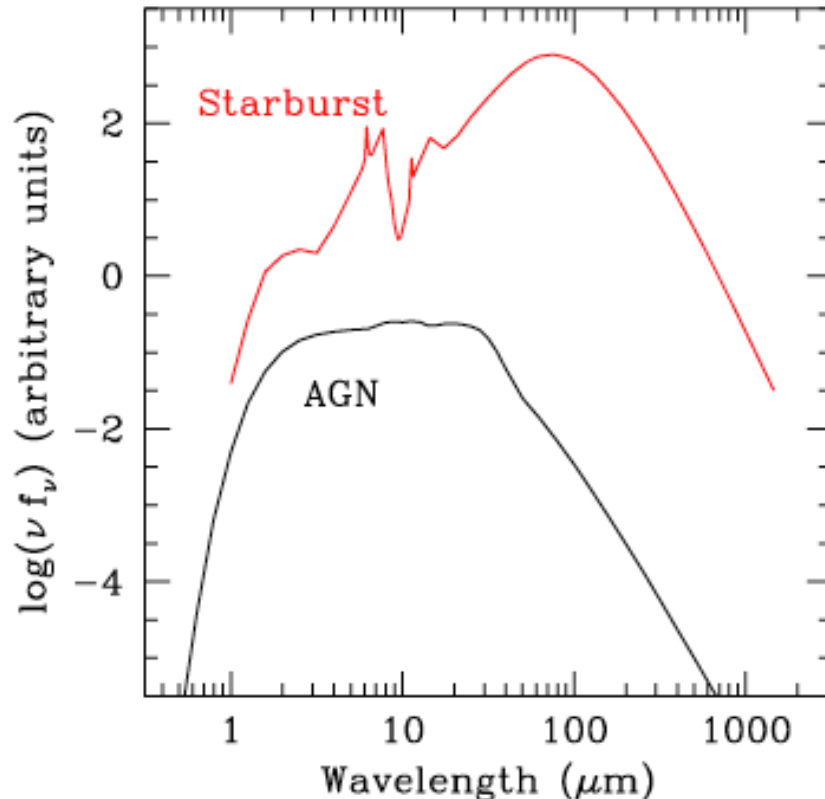
- ✓ Type 1 vs. Type 2 AGN difference: it is a function of the number of clouds along the line of sight, i.e., of the escape probability
- ✓ Same dust temperatures can be observed at different distances from the AGN

➔ Type 2 AGN: larger number of clouds and lower  $P_{\text{esc}}$  for the photons to escape





# SED fitting: stellar vs. accretion processes

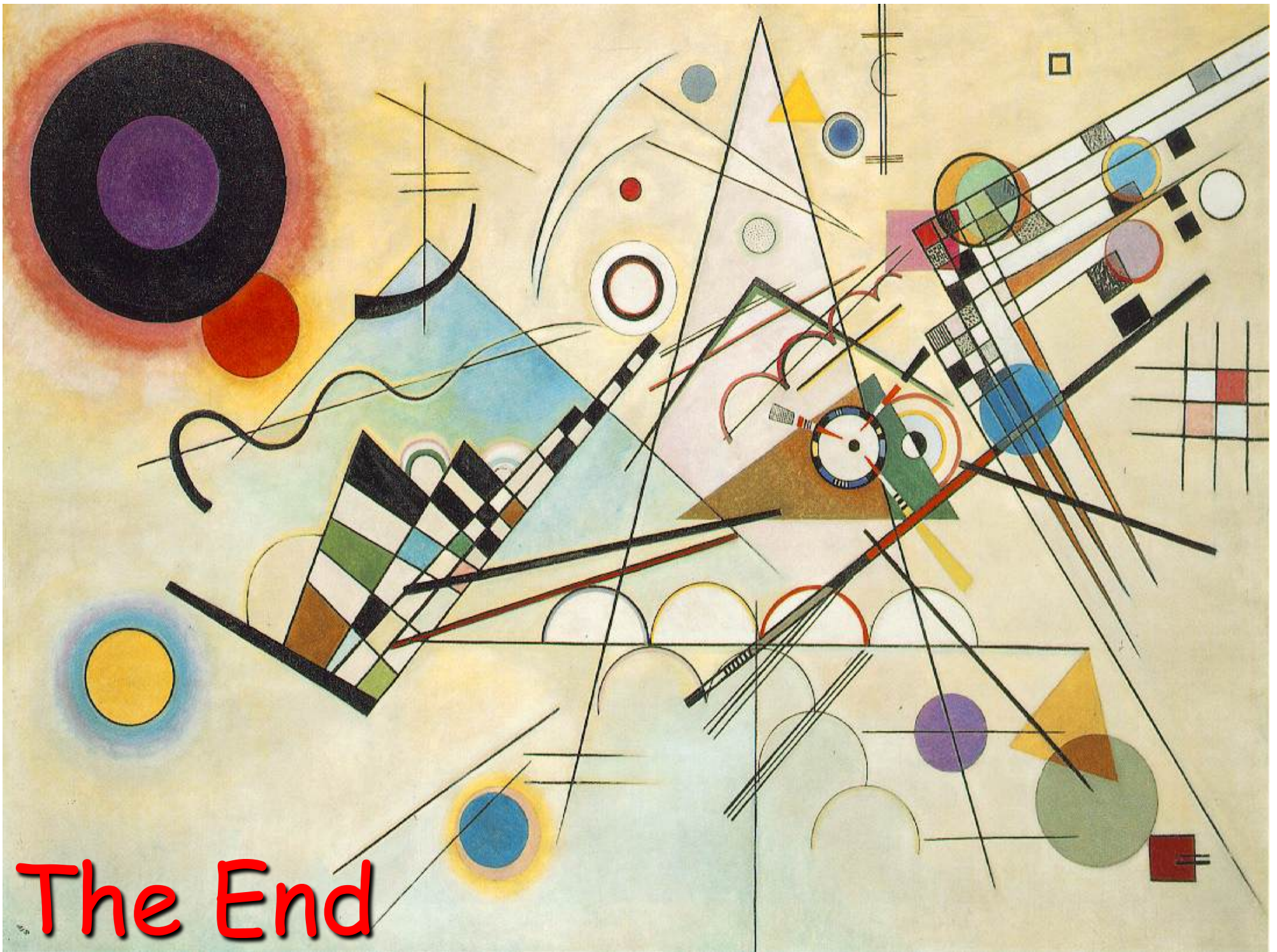


BROAD-BAND SED fitting: common problem to all torus models:  
Need to separate the galaxy contribution from that due to the AGN

AGN reprocessed emission and starburst SED peak at different wavelengths

MID-IR continuum vs. PAH features

→ need to decouple the activity due to accretion from that related to stellar processes



The End