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 γ-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, heavely 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

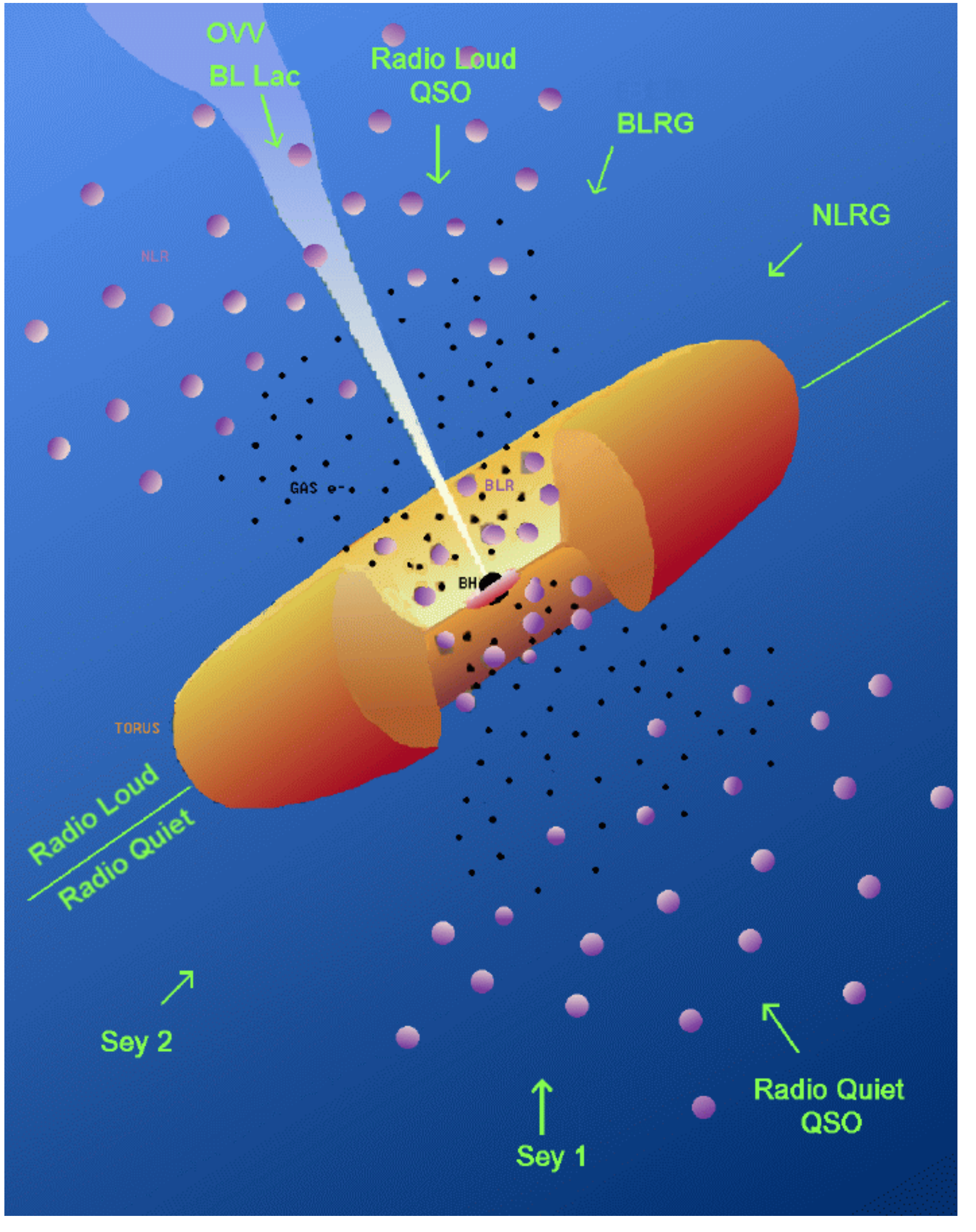
✓ X-ray surveys: depth vs. coverage

✓ 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

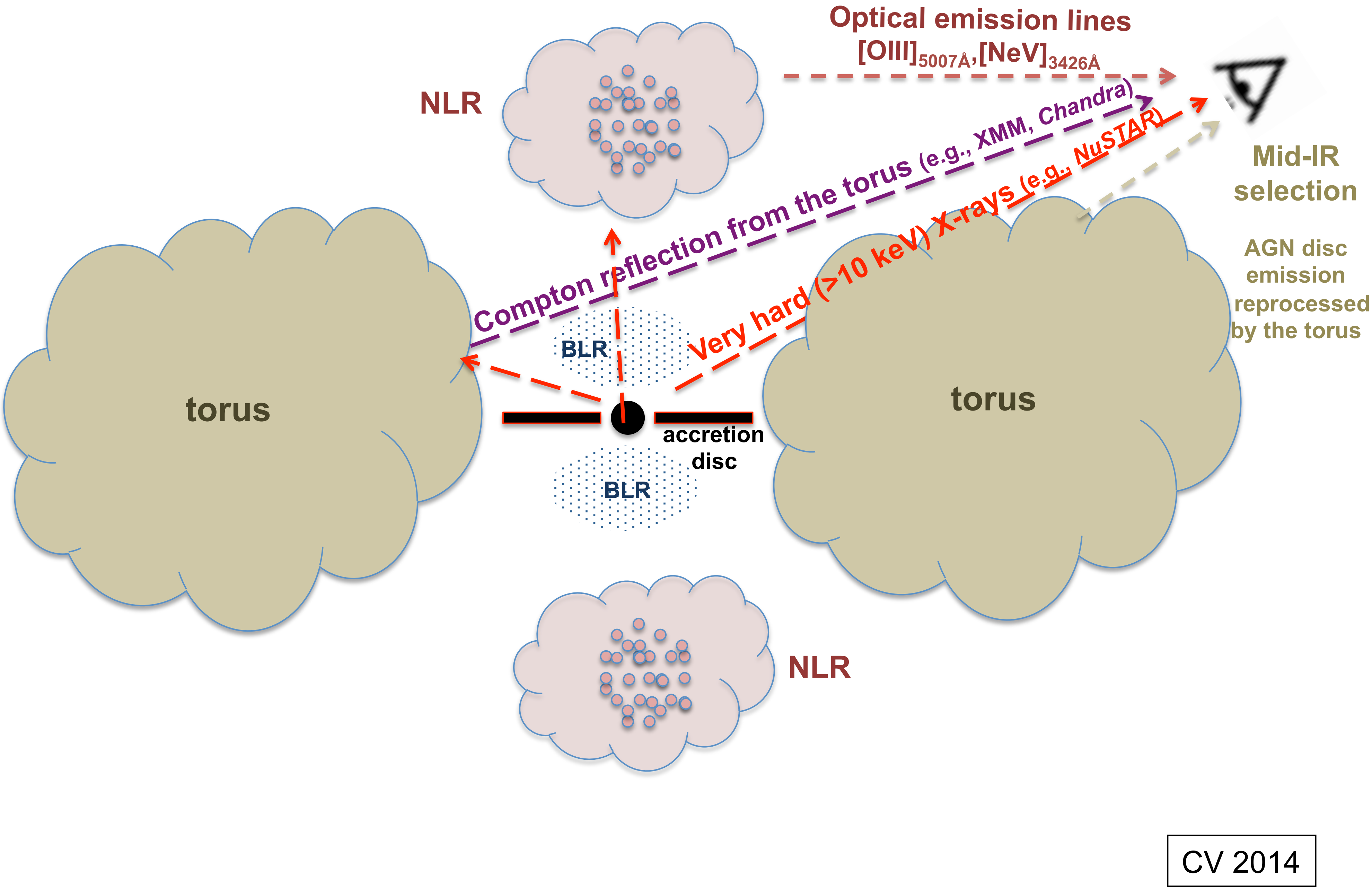
after Antonucci & Miller 1985;
Antonucci 1993



adapted from Urry & Padovani 1995

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

Probably not the end of the story



Optical emission lines
[OIII]5007Å,[NeV]3426Å
NLR
Compton reflection from the torus (e.g., XMM, Chandra)
Very hard (>10 keV) X-rays (e.g., NuSTAR)
Mid-IR selection
AGN disc emission reprocessed by the torus
BLR
torus
accretion disc
BLR
torus
NLR
CV 2014

A logarithmic view of an AGN

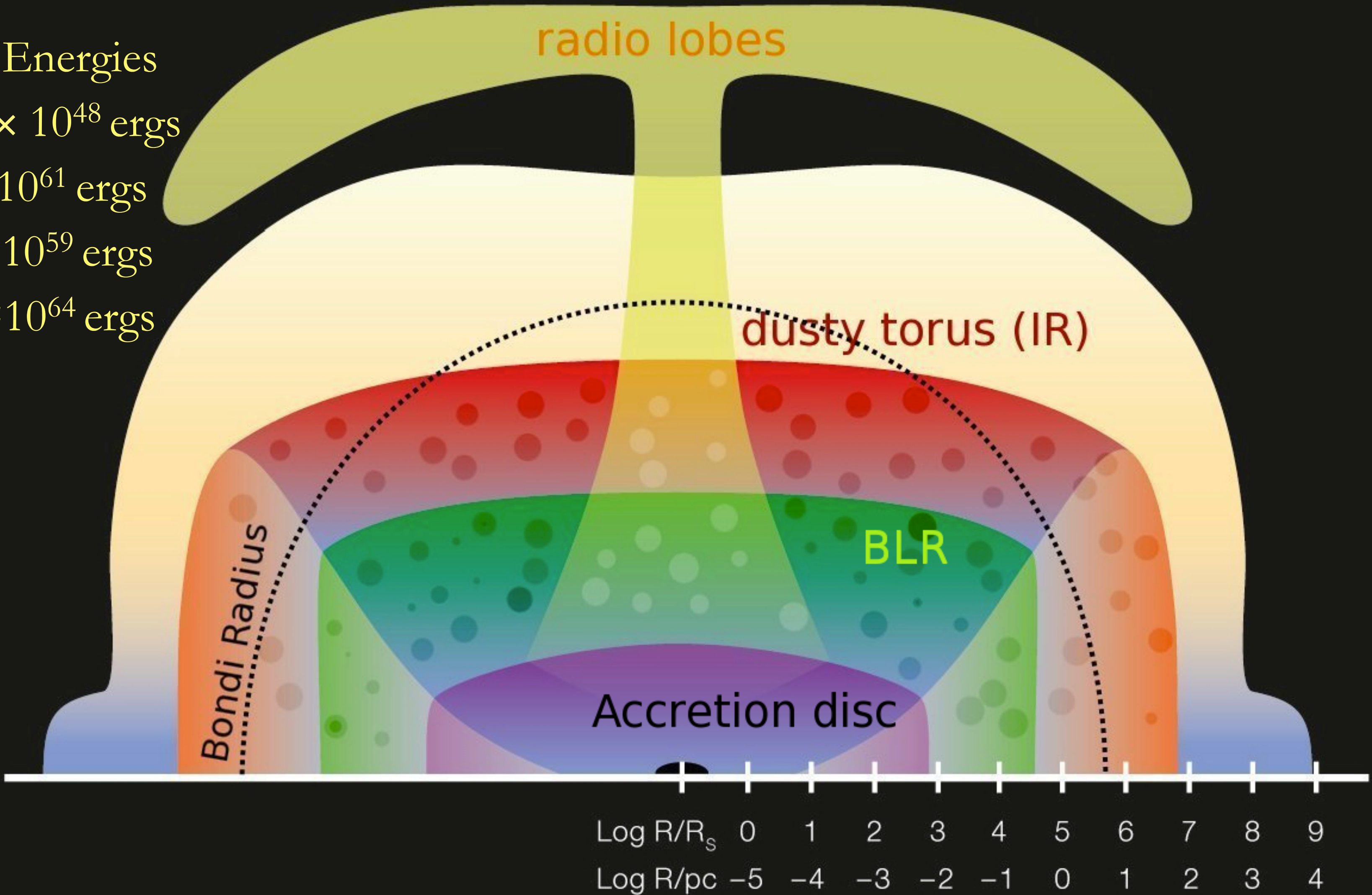
Binding Energies

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

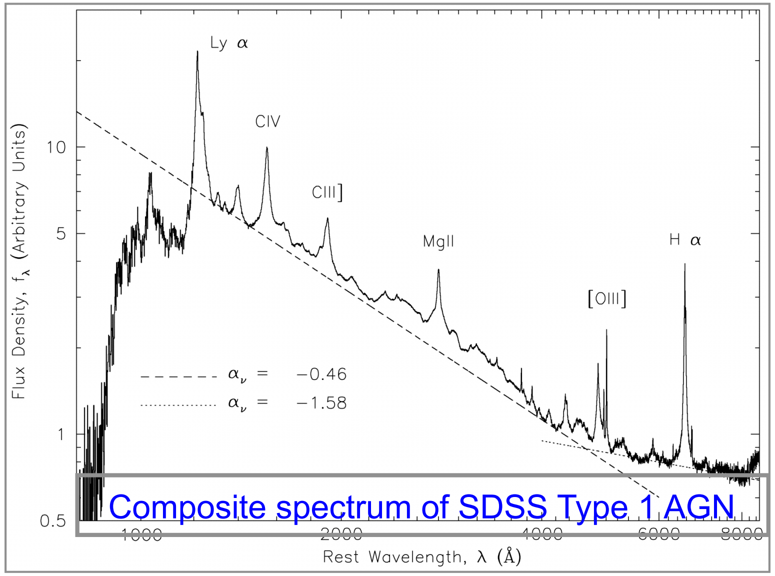
$E_{b,BH,8} \approx 10^{61}$ ergs

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

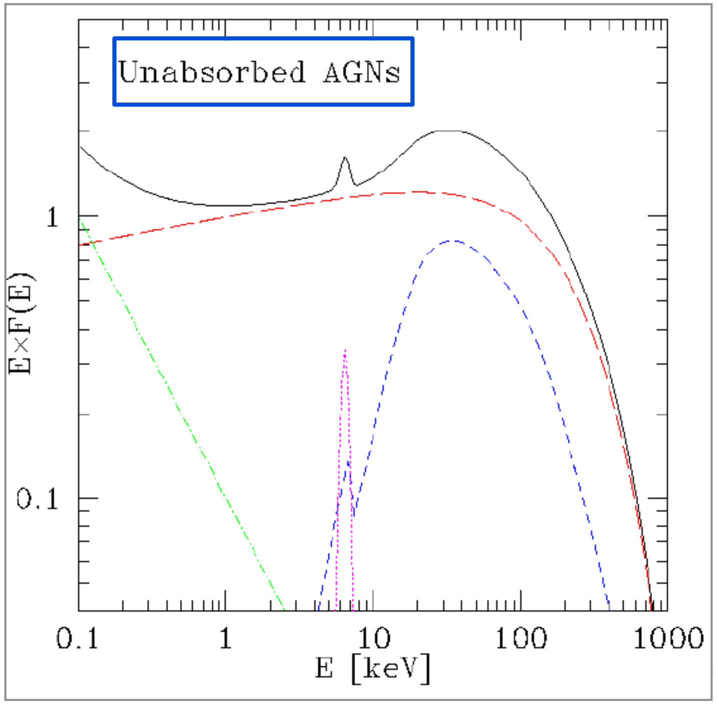
$E_{b,Coma} \approx 10^{64}$ ergs



Courtesy of A. Merloni, ESO graphics, 2010



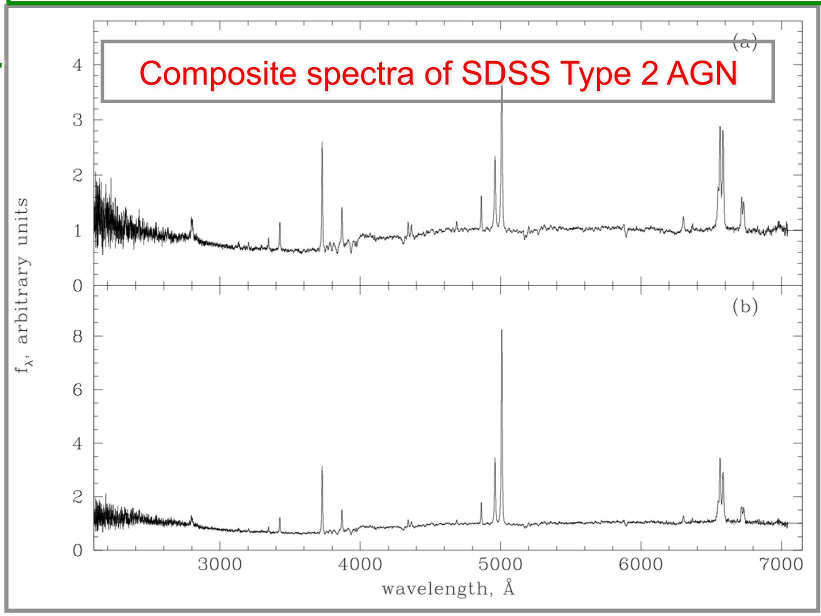
Type 1 AGN



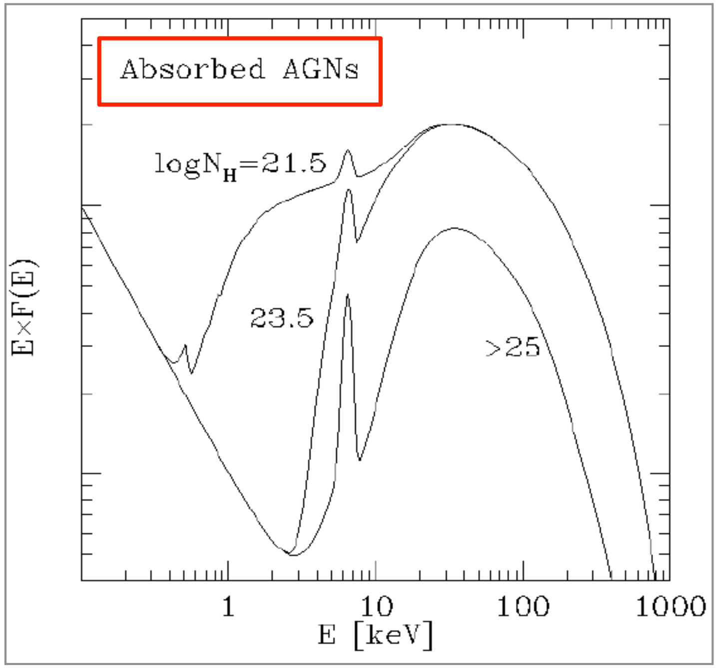
Optical band

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

X-ray band

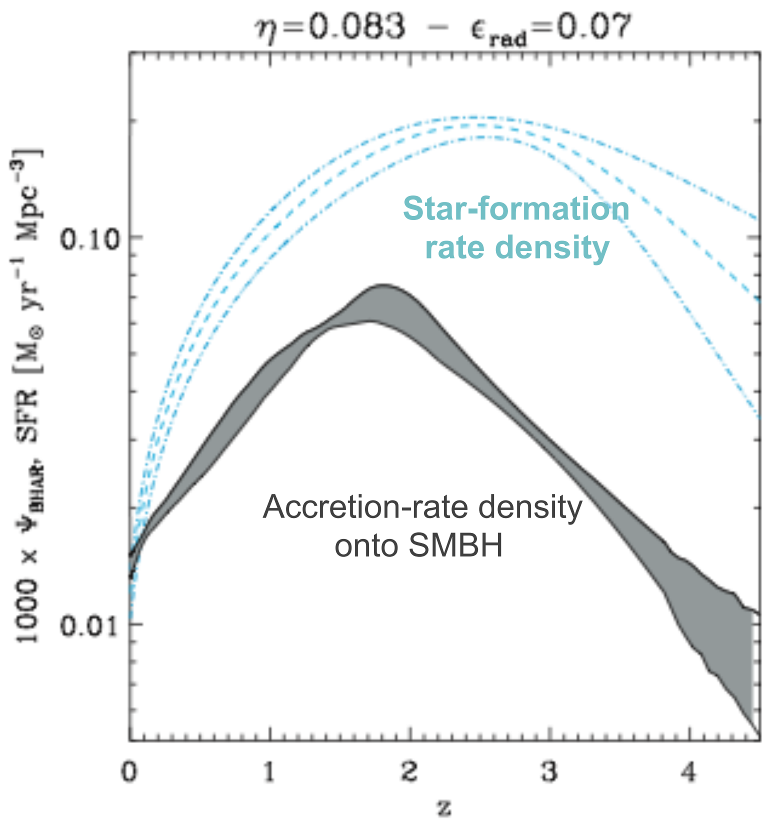


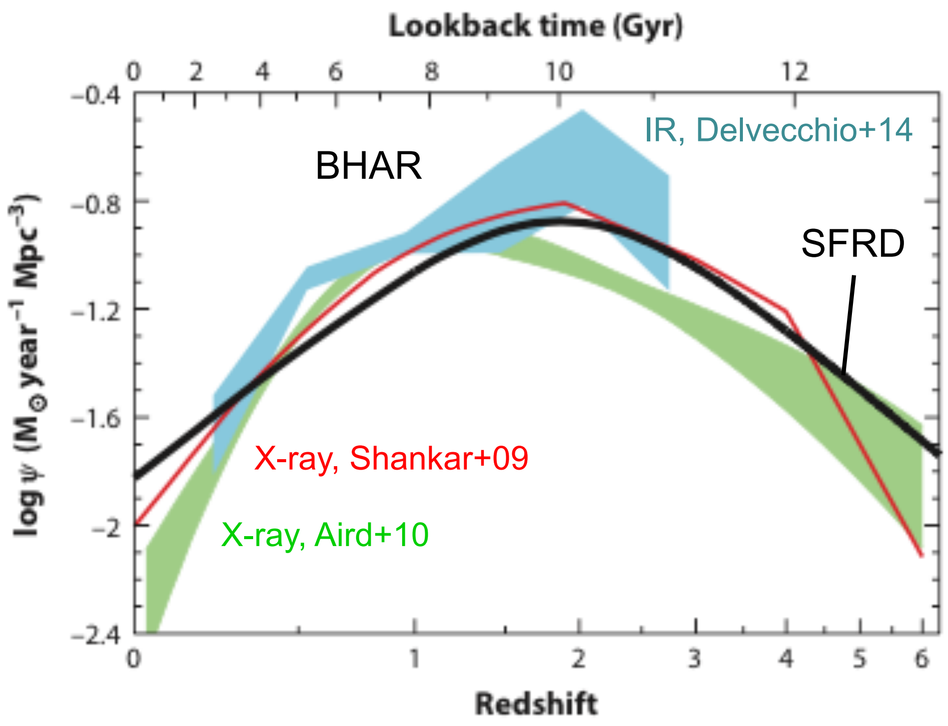
Type 2 AGN



AGN–galaxy co-evolution

Accretion and star formation over cosmic

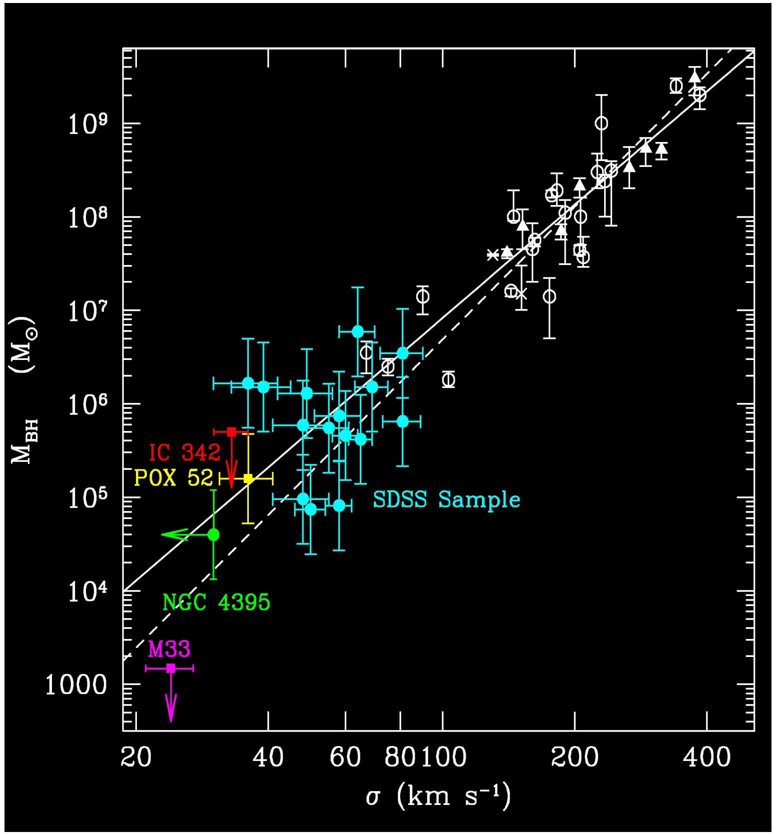




from Merloni & Heinz 2008;
see also Hopkins & Beacom 2006, Gruppioni et al. 2011

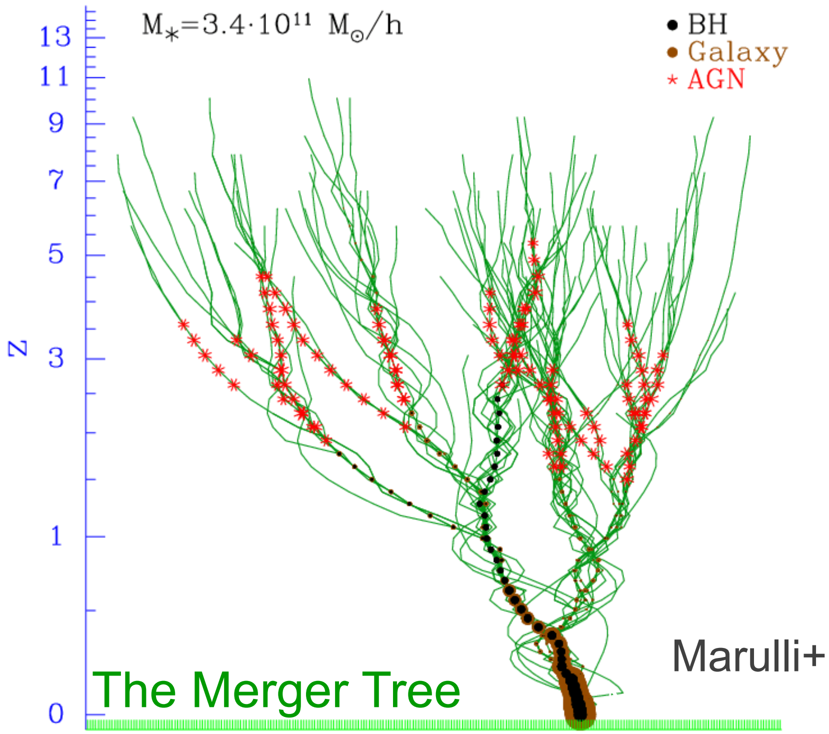
from Madau & Dickiinson 2014

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**

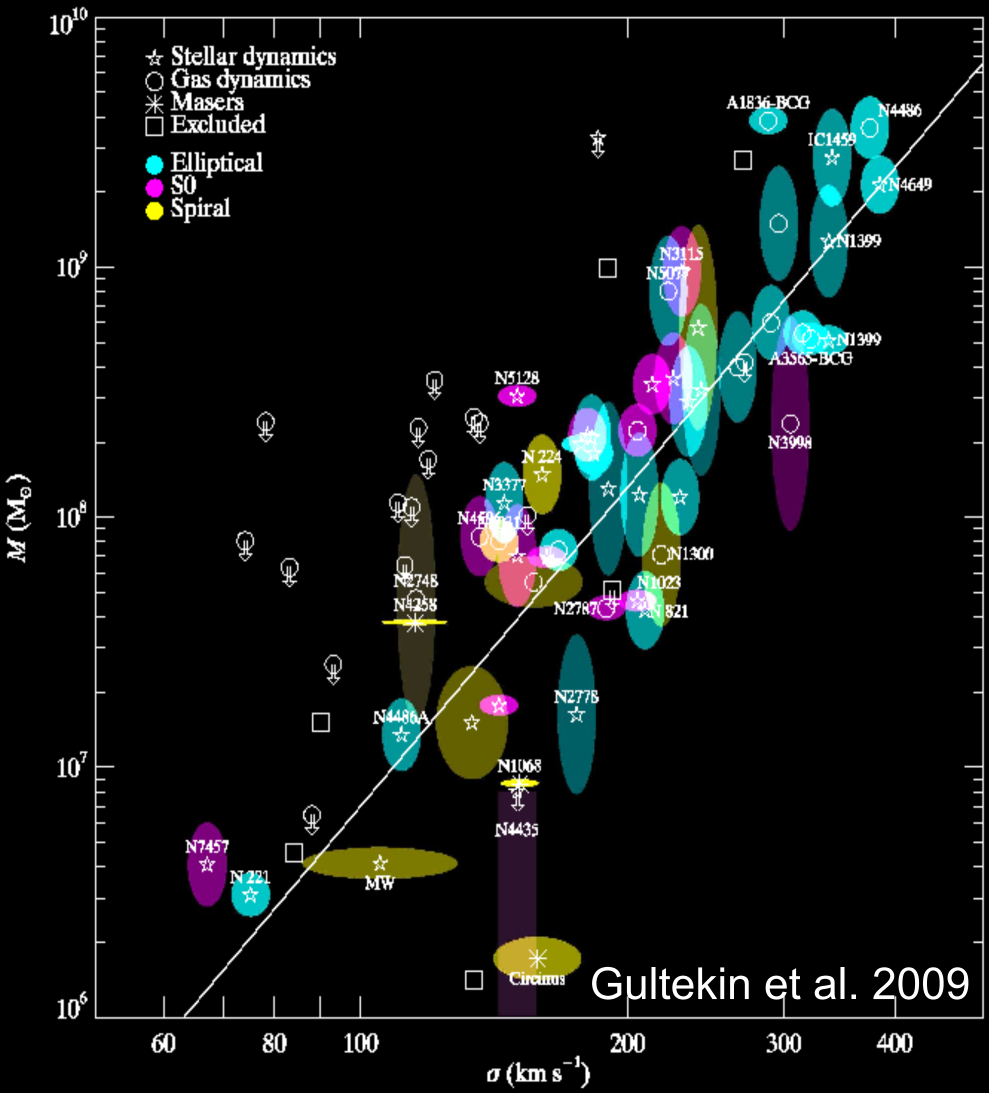


Semi-analytic models of BH/galaxy co-evolution (e.g: Kauffmann+98, Volonteri +06, Salvaterra+06, Rhook&Haehnelt08, Hopkins+08, Menci+08, Marulli+09)

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



Gultekin et al. 2009

Correlation between BH mass and galaxy velocity dispersion σ

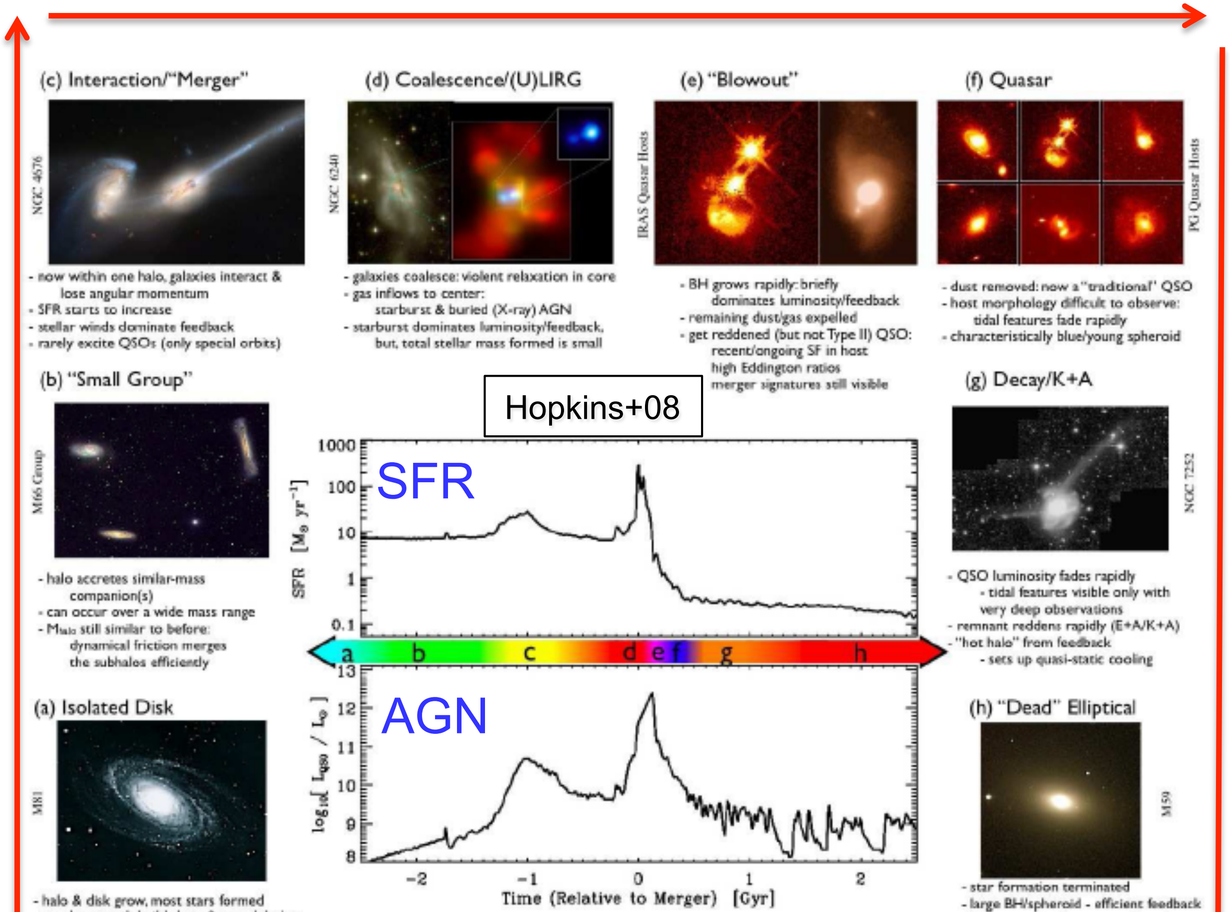
σ measured well **outside** the gravitational sphere of influence of the BH

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

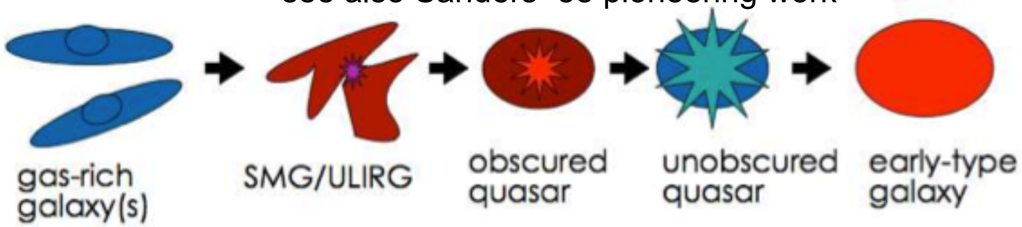
The BH/galaxy "evolutionary sequence"



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

mergers
↓
SF/obscured accretion
↓
"clean" accretion (QSO)
↓
transition (green valley) object
↓
passive red galaxy

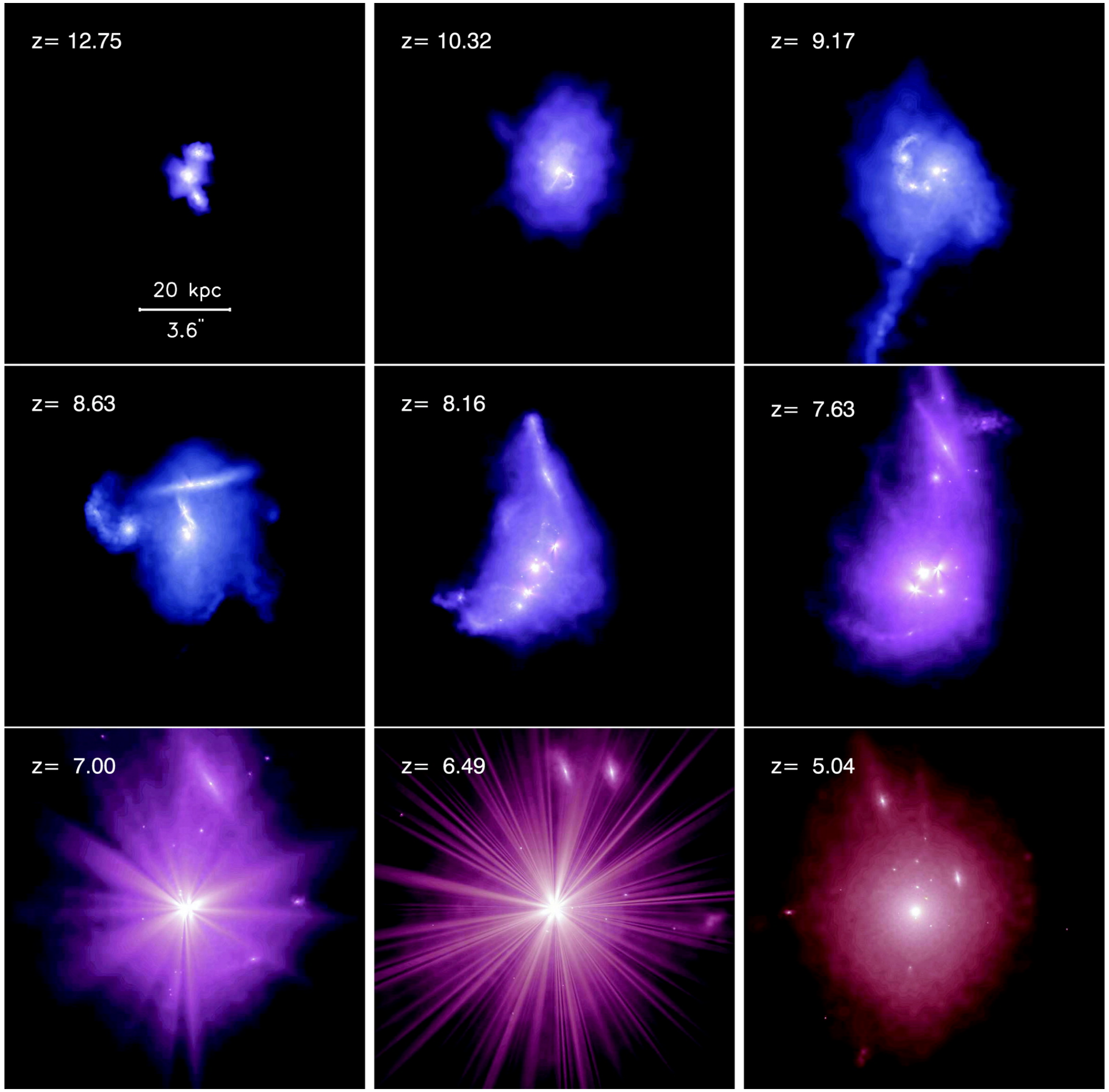
Importance of merger-driven vs. secular ("smooth") accretion
(e.g., Elbaz+11, Rodighiero+11, Rovilos+12)



Hickox+09

Strong winds (=feedback) expected in the "blowout" phase

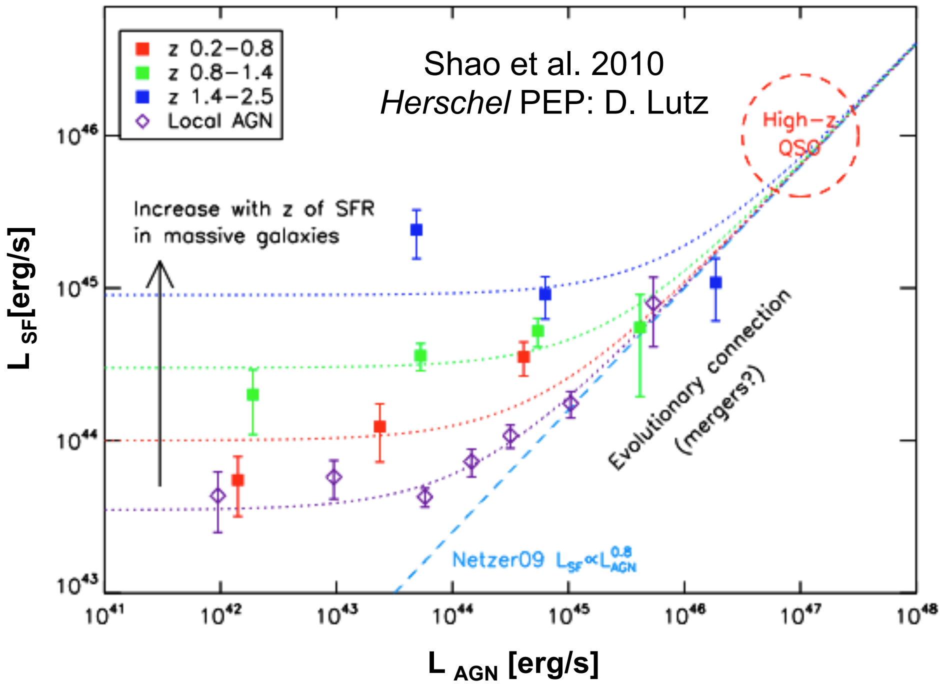
Simulated formation of a ≈10^9 $M_\odot$ BH at high z

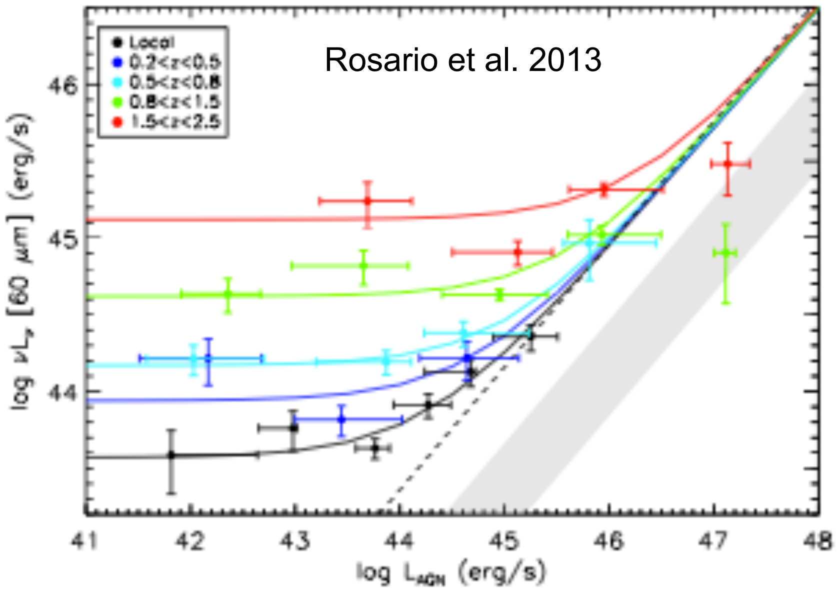


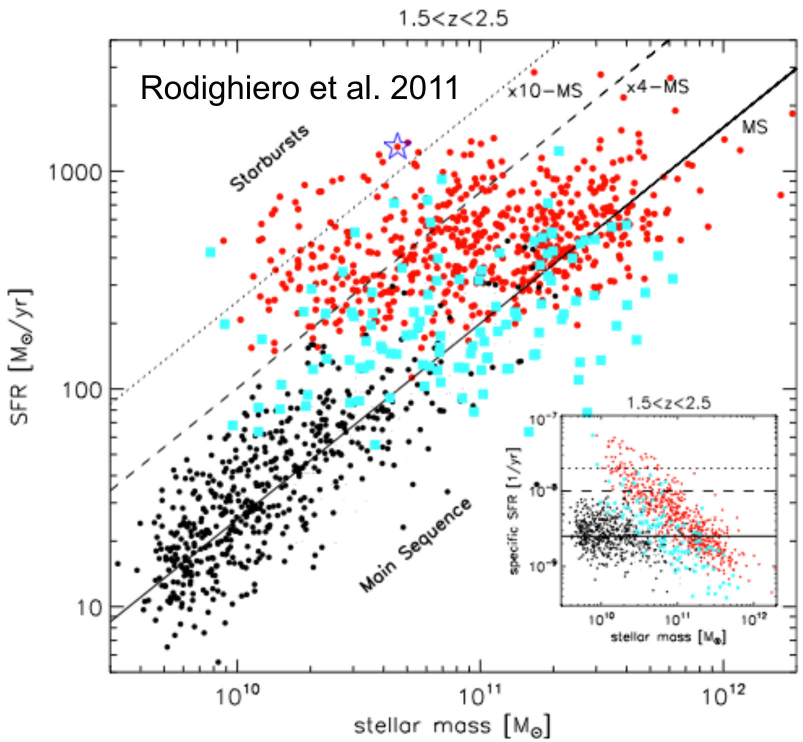
Li+07

- 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]







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?)

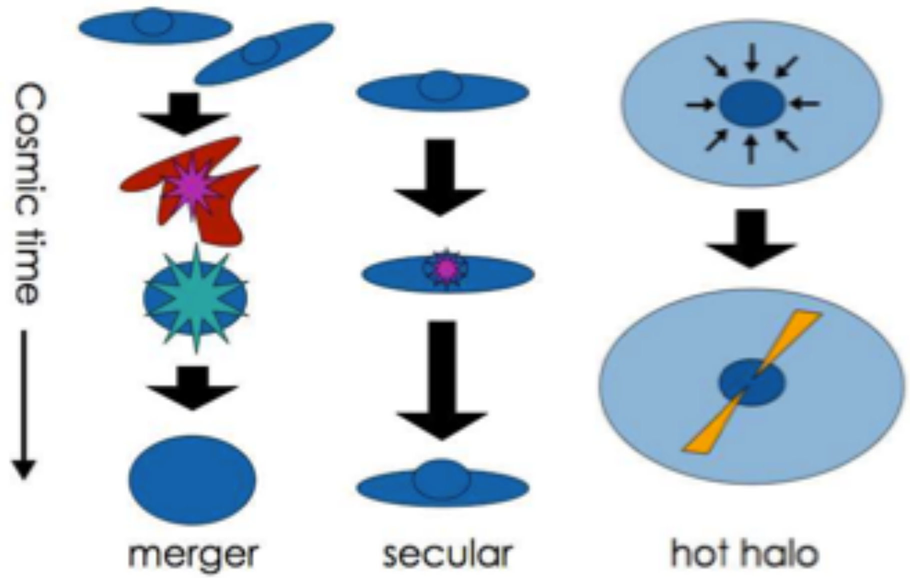
• At lower AGN luminosity, SF has little dependence on AGN luminosity ➔ secular, non-merger driven star formation (~90% pop?)

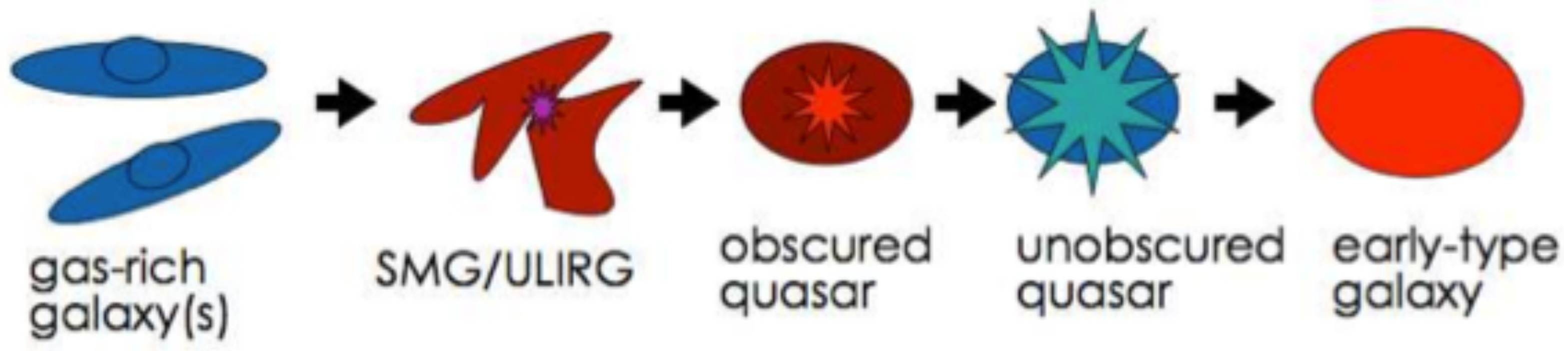
(e.g. Georgakakis+09, Lutz+10, Cisternas+11, Schawinski+11, Elbaz+11, Rodighiero+11,Mullaney+11, Santini+11, Rovilos+12, Rosario+12, …)

Two modes of accretion:

Mergers ←→ luminous quasars

Secular (disk instabilities, bars, minor mergers) ←→ low-luminosity AGN

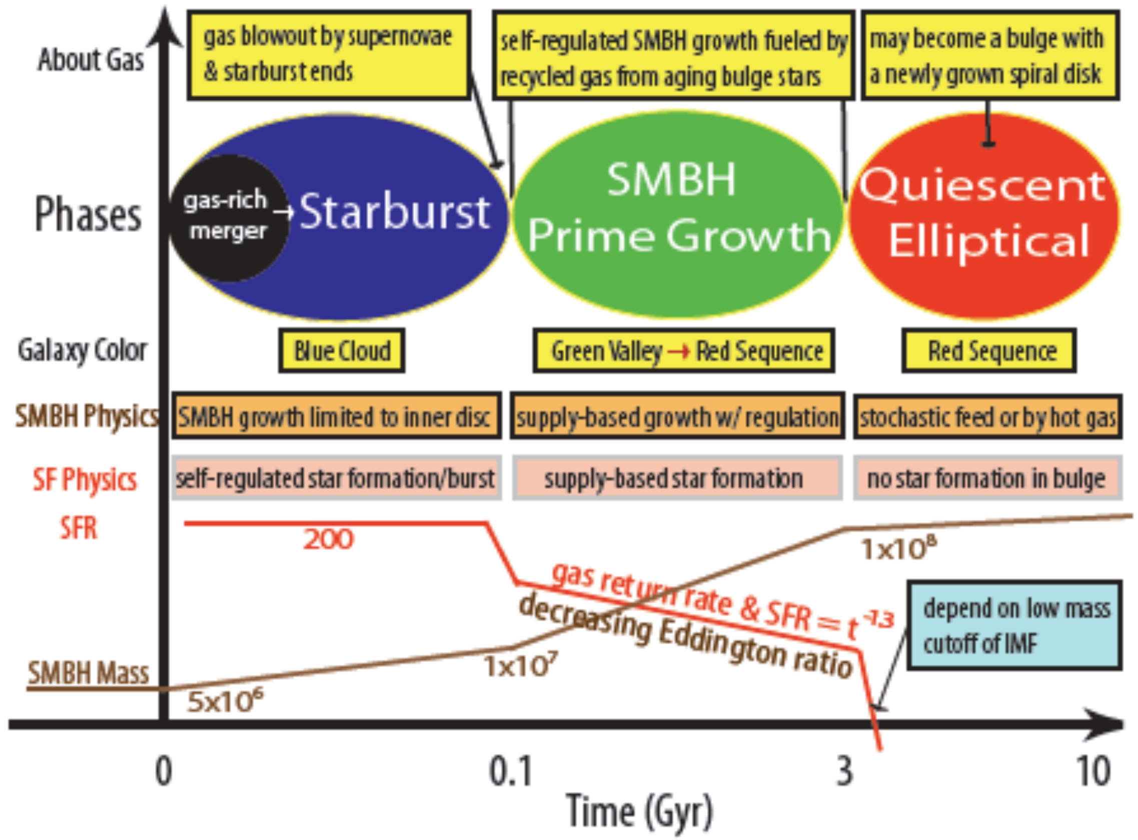




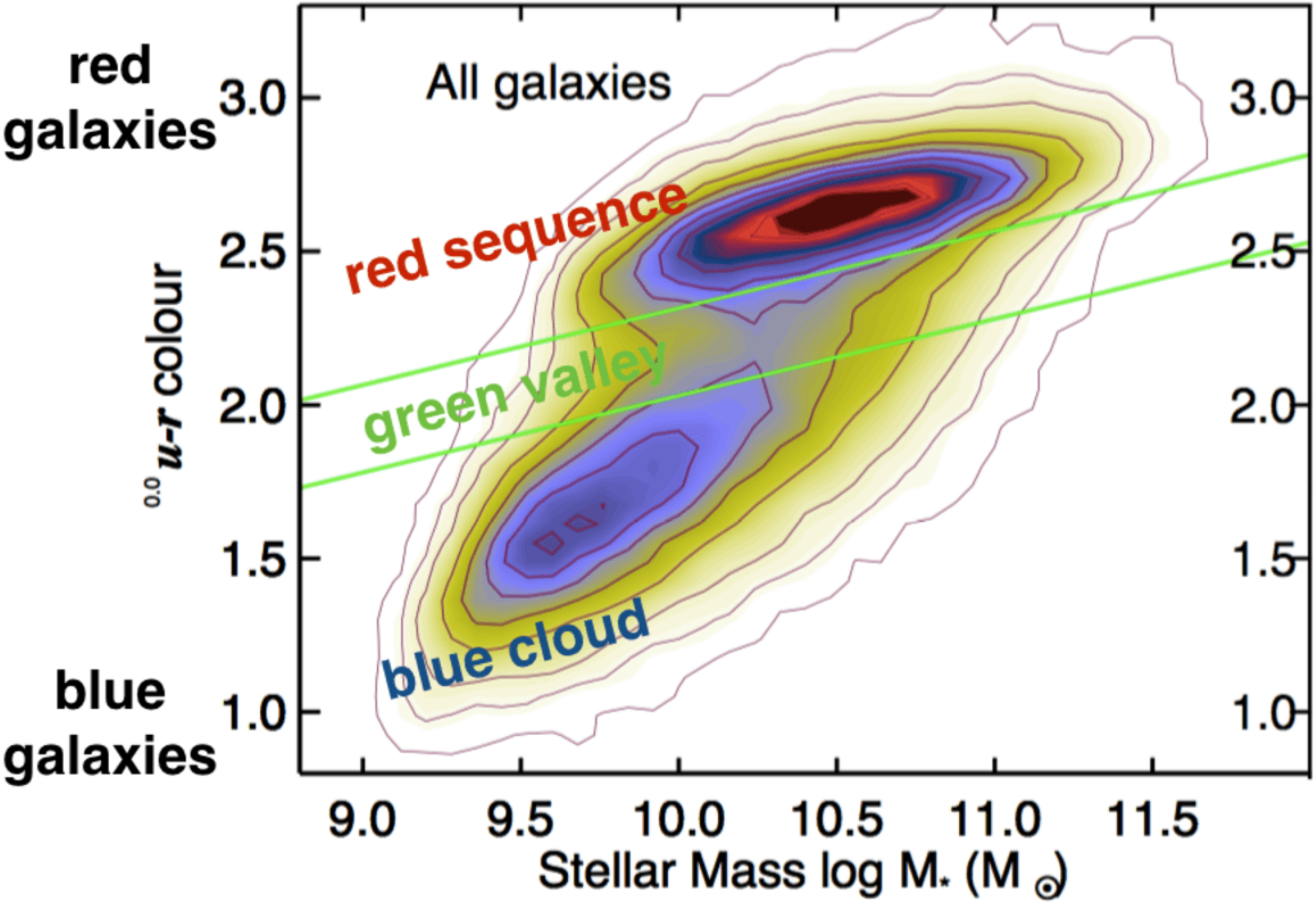
An alternative picture

STB preceeds 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 >>100 Myr, albeit at relatively low and diminishing Eddington ratios for most of the time



Cen 2011



Claims of a higher fraction of AGN activity in the green valley: higher availability of fuel?

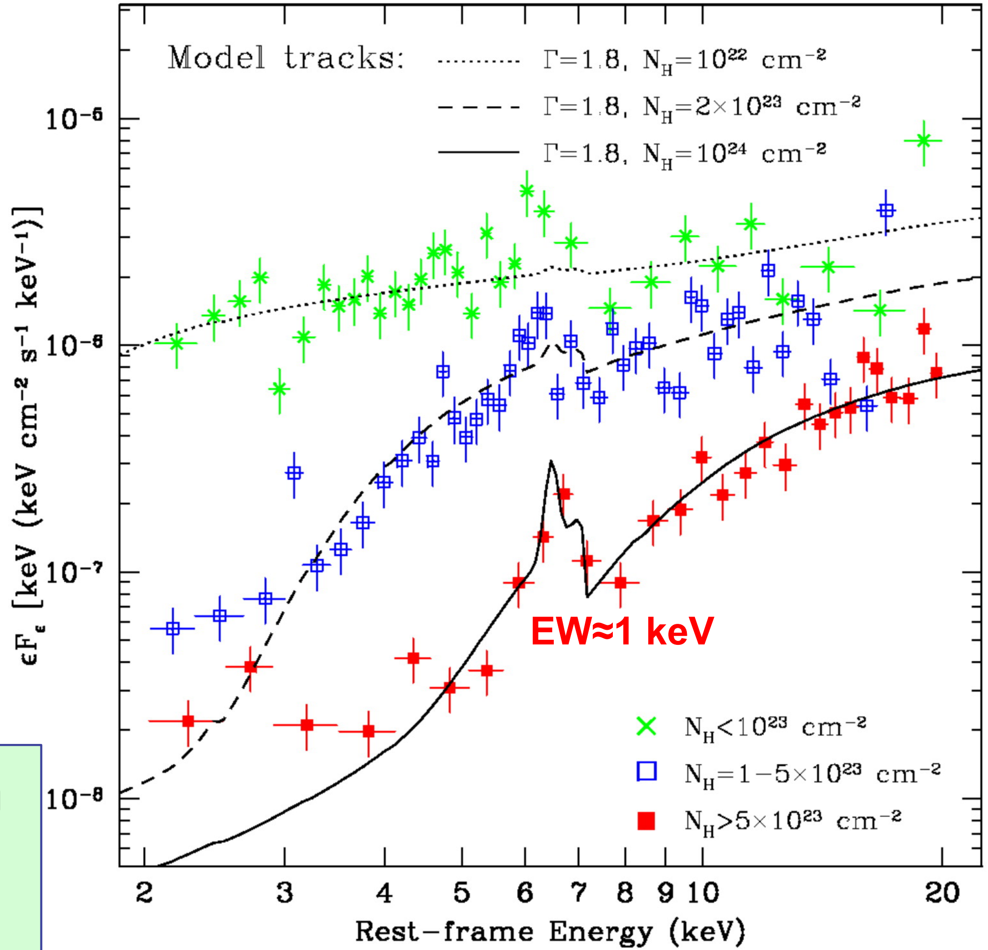
Obscured AGN growth and star formation at z≈2

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



Alexander et al. 2005

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)

➔ Needed: census and knowledge of Compton-thick AGN

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

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

Open issue: time for BH growth at z≈6

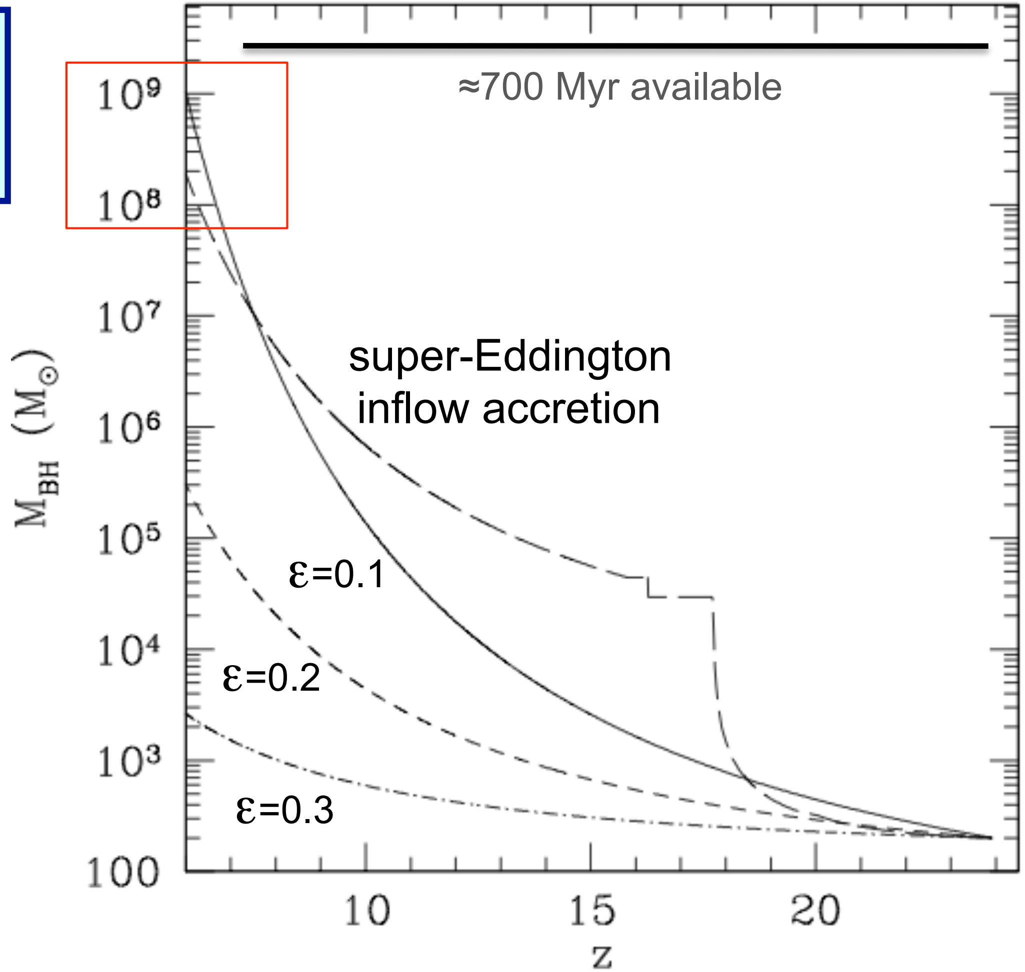
Growth of BHs: trade-off between the gas “converted” into radiation and that accreted onto the SMBH

$$M(t) = M_0 \exp\left(\frac{1-\varepsilon}{\varepsilon}\,\frac{t}{t_{\rm Edd}}\right)$$

Larger radiation efficiency ε means longer times to achieve a given mass
[t_{Edd}=0.45 Gyr for ε=0.1]

Rapidly spinning BHs might have problems because of a larger ε

Highest-redshift quasar so far spectroscopically identified: ULASJ1120+0641, z=7.08, $M_{BH} \approx 2\times10^9\ M_\odot$ (Mortlock et al. 2011)



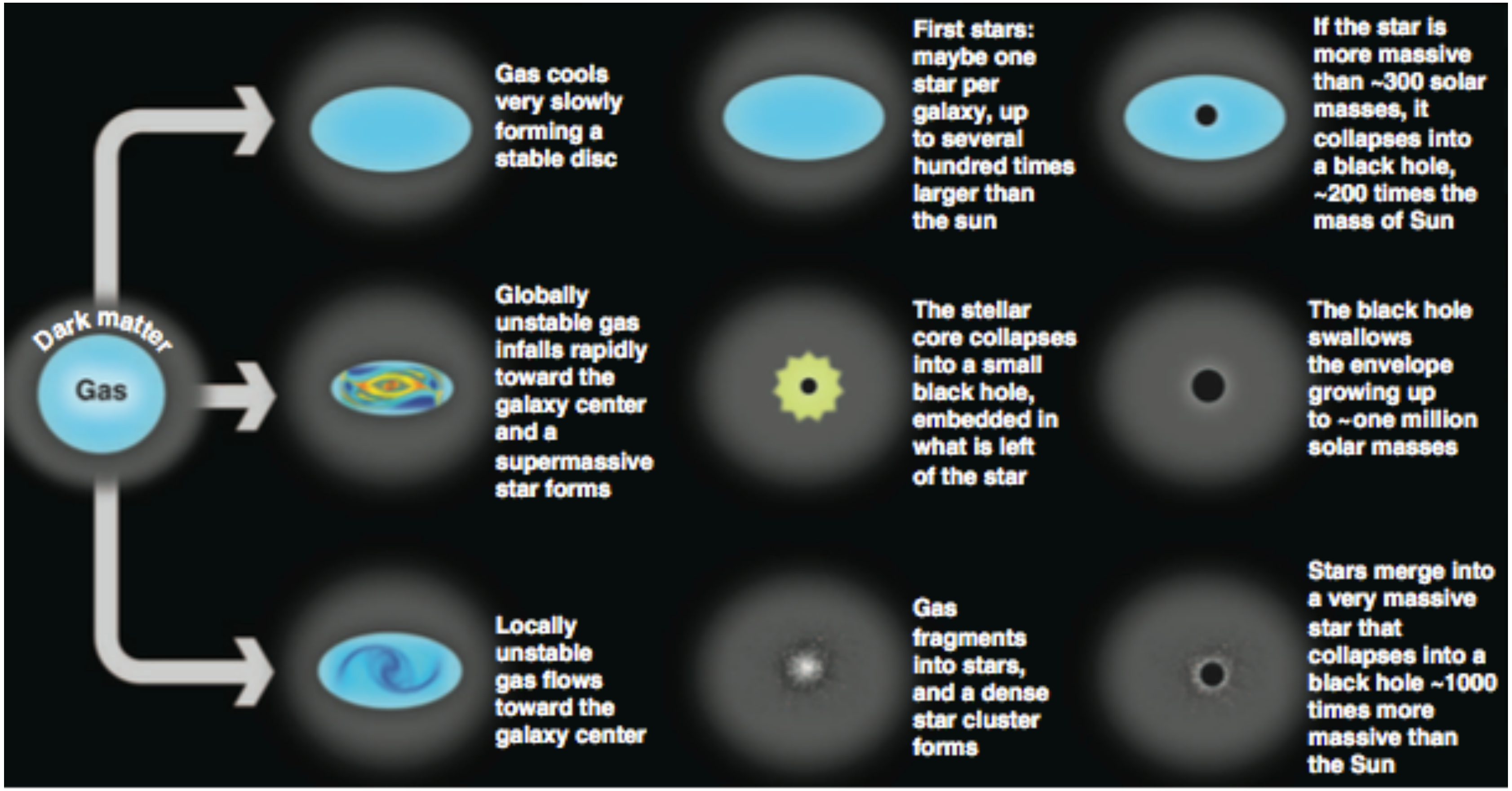
Volonteri & Rees 2006

Possible problems with the mass of the “seed” BHs

The first Black Holes

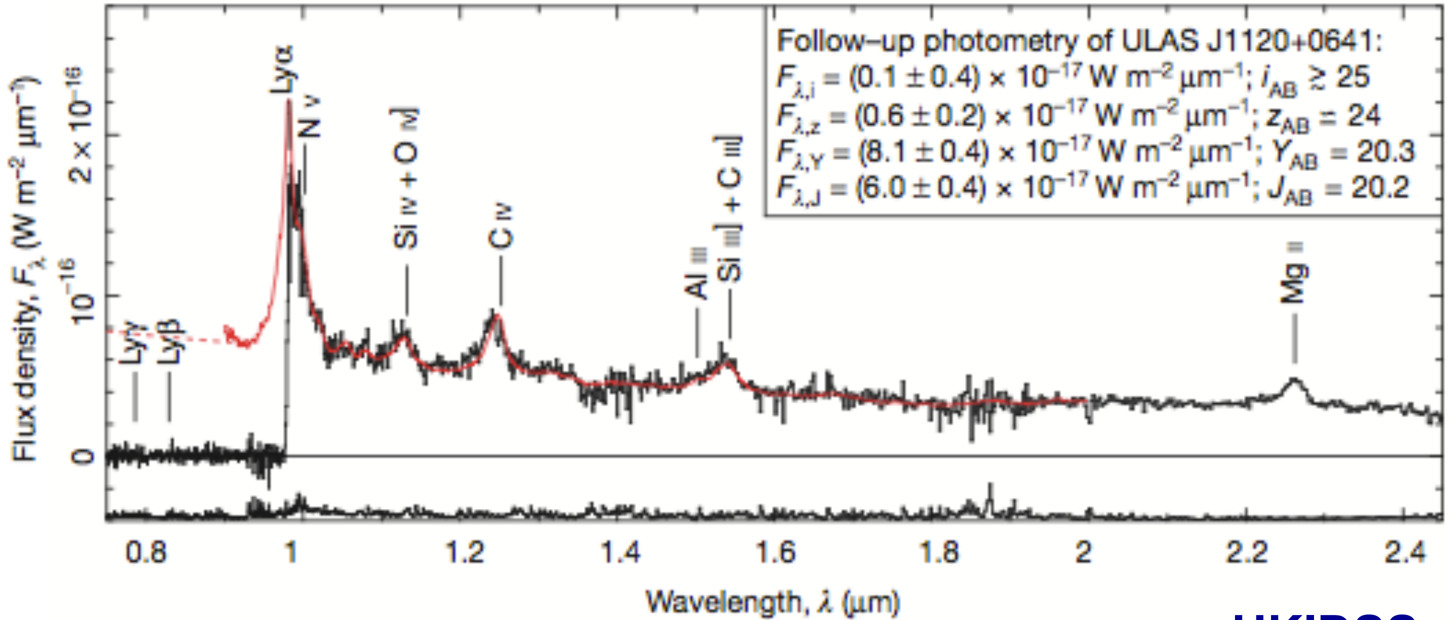
Black hole seeds

- Population III stars ($10^2\ M_\odot$)
- Direct collapse of gas clouds ($10^{4\text{-}5}\ M_\odot$)
- Stellar mergers in dense clusters ($10^{4\text{-}5}\ M_\odot$)



Volonteri 2010

ULASJ1120+0641, z=7.08



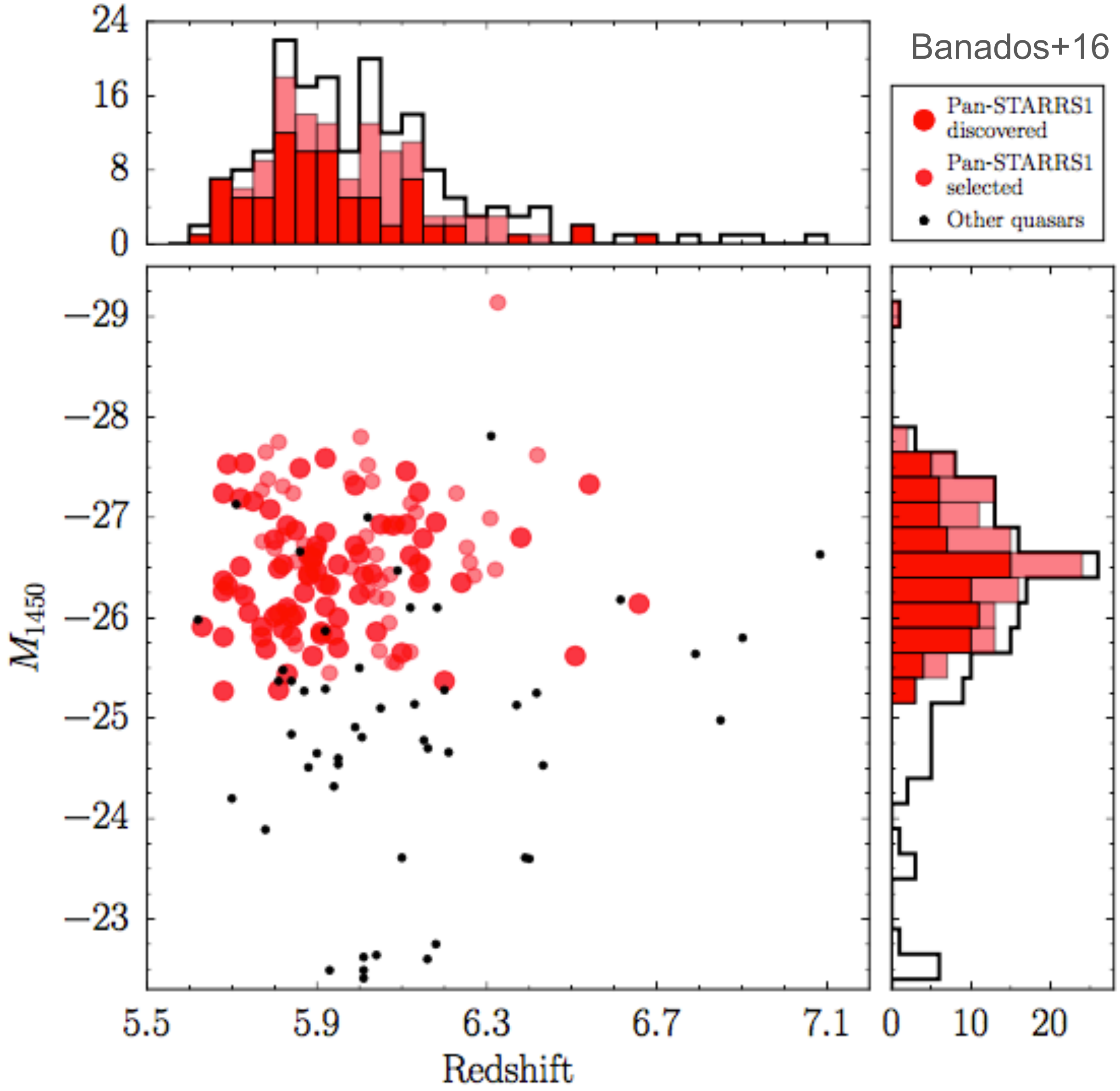
UKIDSS

Mortlock et al. 2011, GNIRS+FORS2, compared to average z~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/

High-redshift quasars



Situation as of Sept. 2016

173 quasars known at
z>5.6
(≈80 at z>6; 7 at z>6.5)

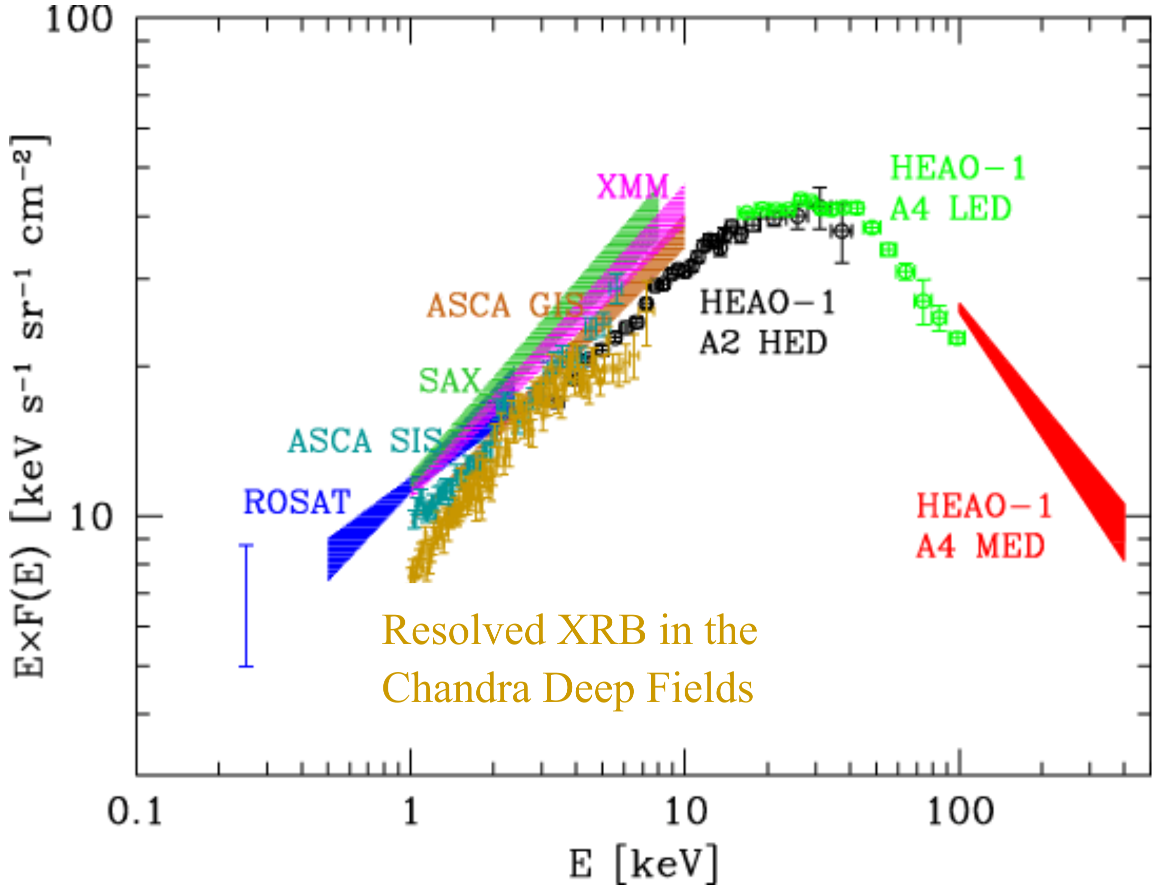
172 optical-near-IR selected
(Fan+00-06; Jiang+08-15; Willott+07-10; Banados+14-16; Mortlock+11; Venemans +13-15; Matsuoka+16)

1 radio selected
(Zeimann+11)

0 X-ray selected

X-ray background, and the role of X-ray surveys

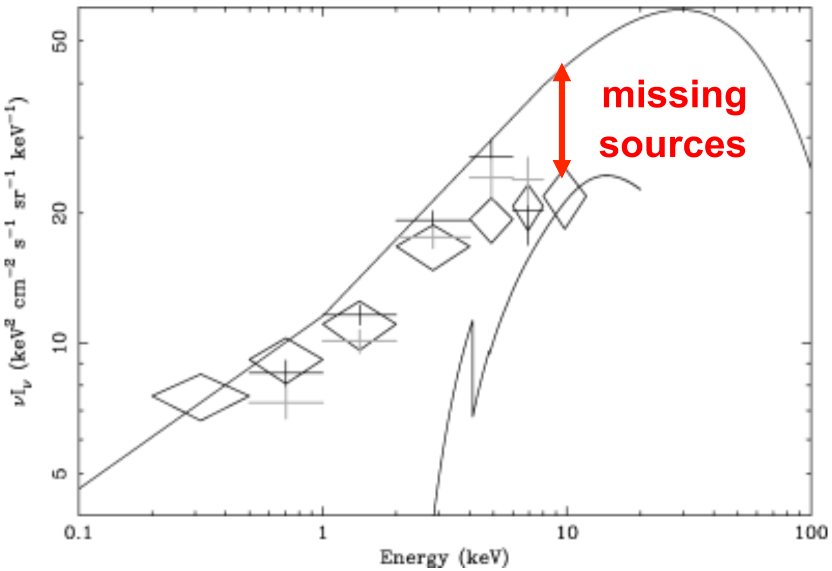
Resolved XRB fraction: still a "missing" population?



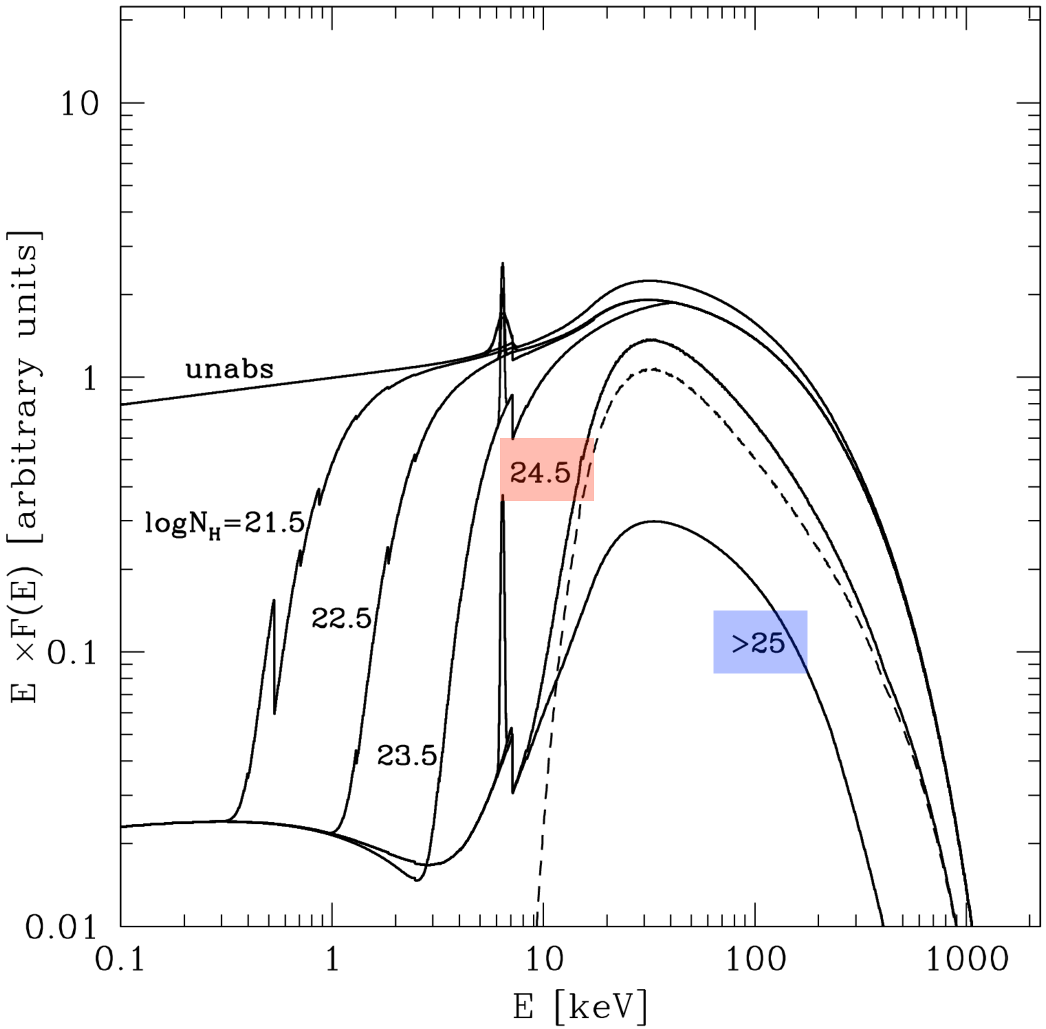
≈80-95% of the XRB being resolved into single sources at E<a few keV

BUT only 50% resolved above 5 keV

Worsley et al. (2005)



AGN X-ray spectral templates with different N_H

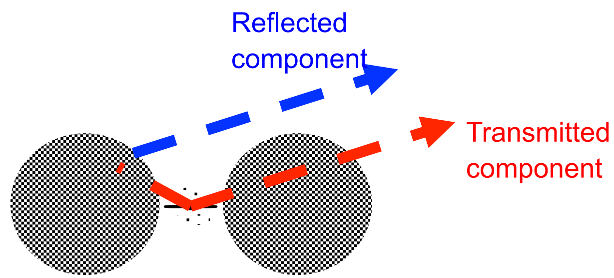


Only ≈40-50 "secure" Compton-thick AGN (≈10 mildly-thick) known at present

Unabsorbed:
$\log N_H < 21$

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

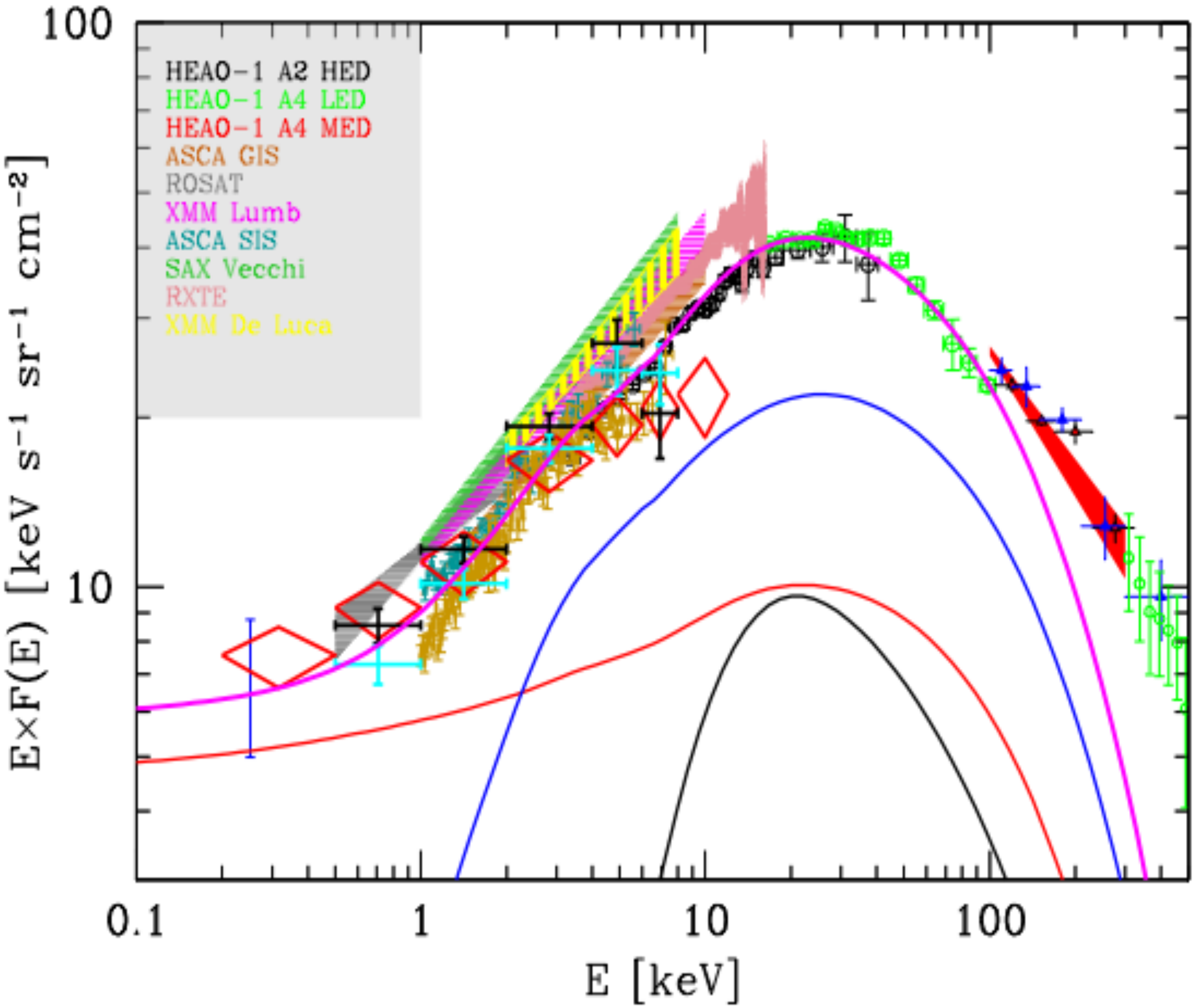
Compton-Thick:
Mildly ($\log N_H = 24\text{-}25$)
Heavily ($\log N_H > 25$)



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.

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)

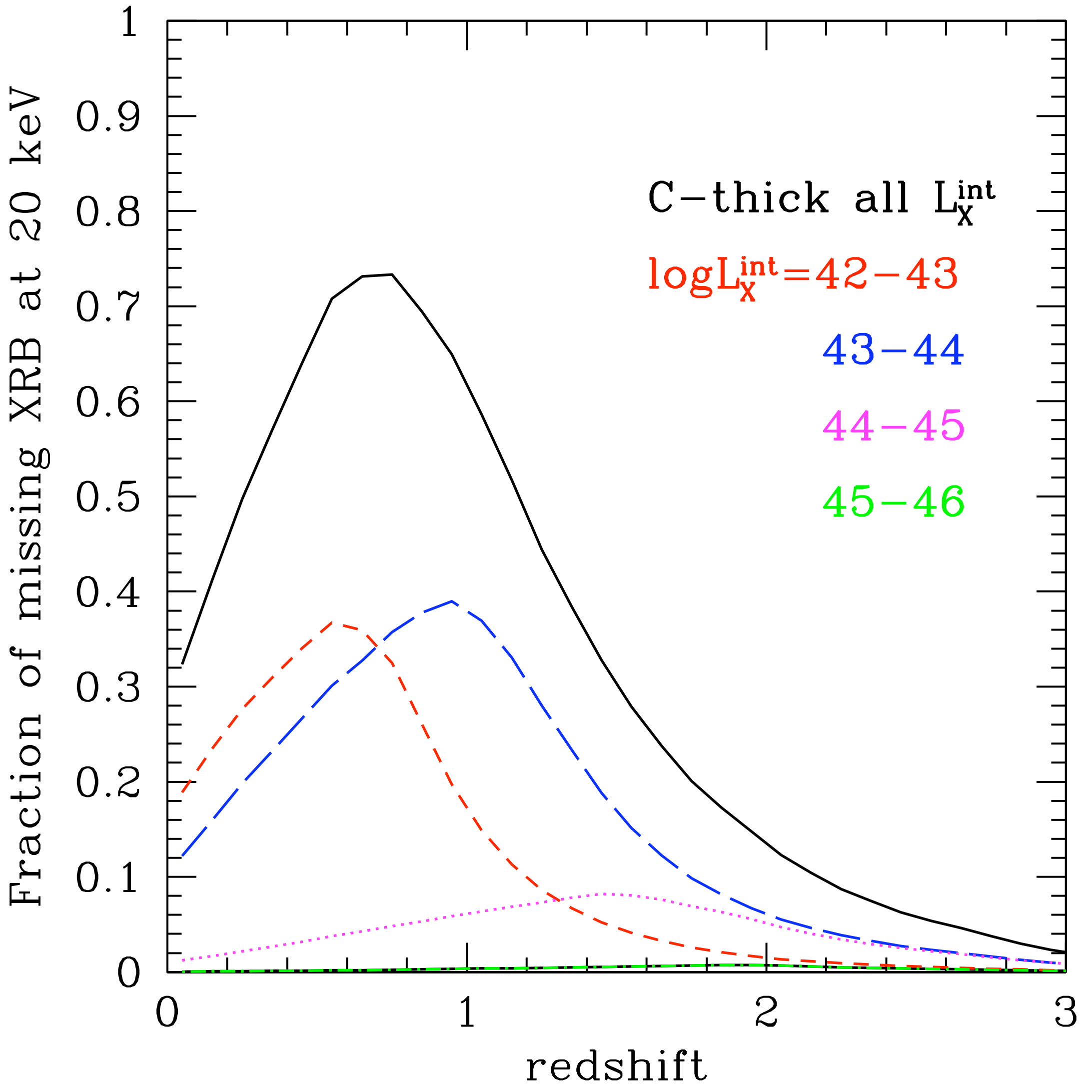
Red ➔ unobscured

Blue ➔ Compton Thin

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

The evolution is folded in the adopted XLF

When the “missing” XRB was emitted?

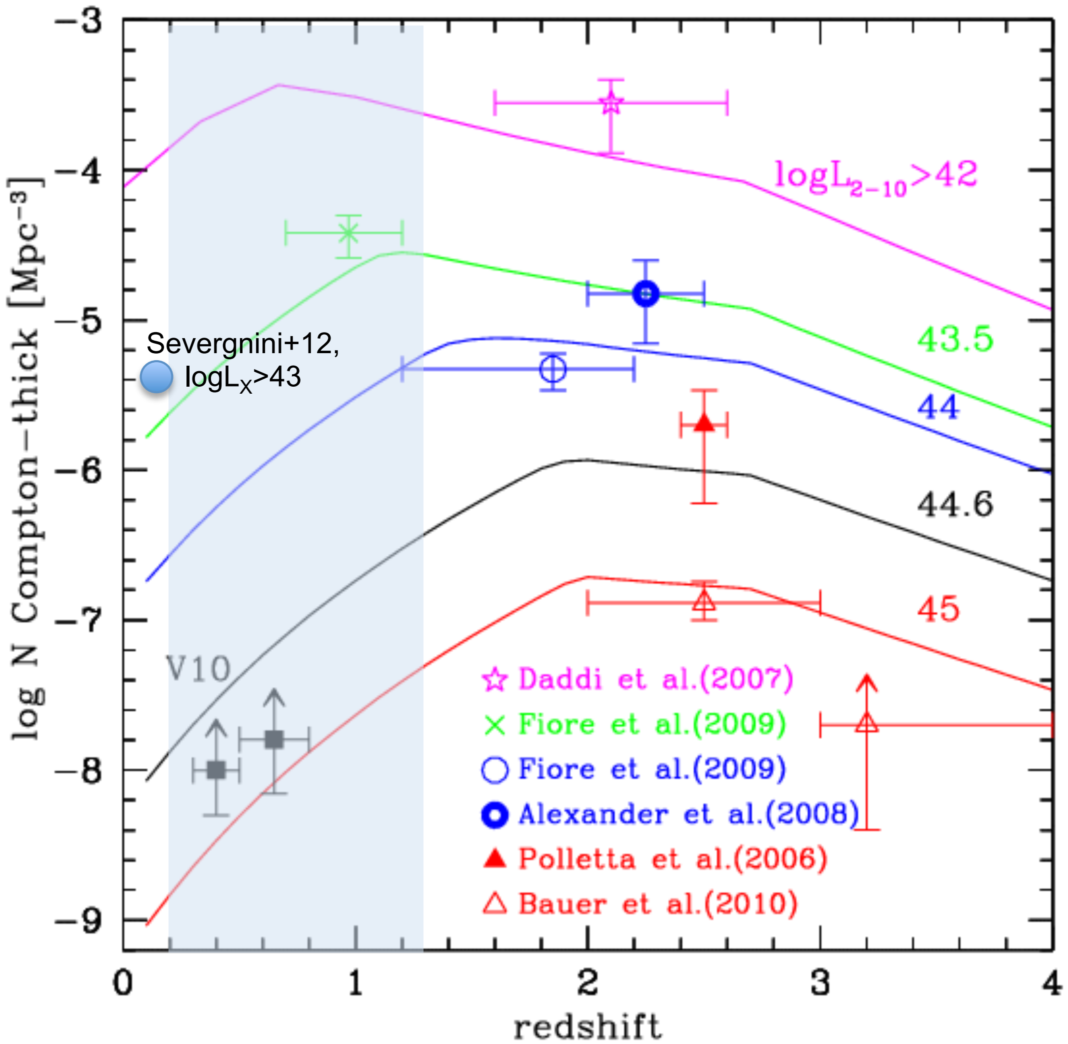


Predicted peak at z≈0.7-0.8

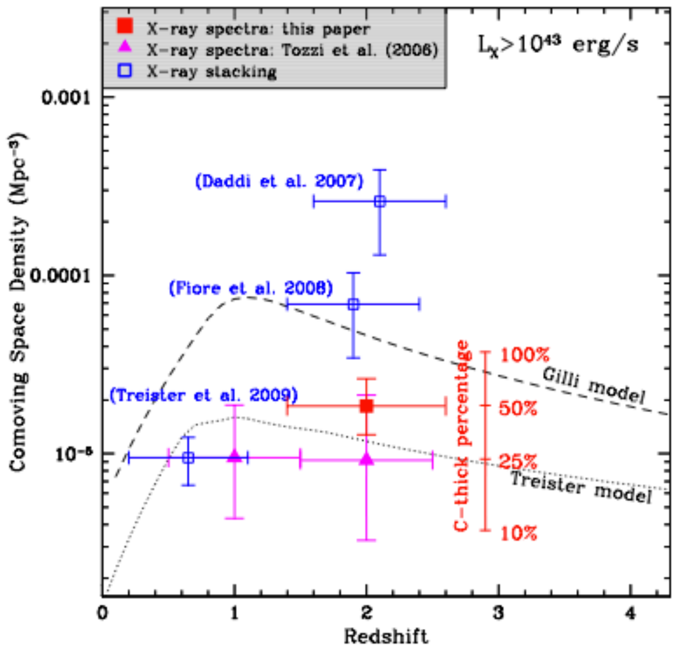
Mostly at L_x~10^{42-44} erg/s

Gilli 2013

The space density of Compton-thick AGN



Vignali+10



Alexander+11;
see also Bauer+10, …

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

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

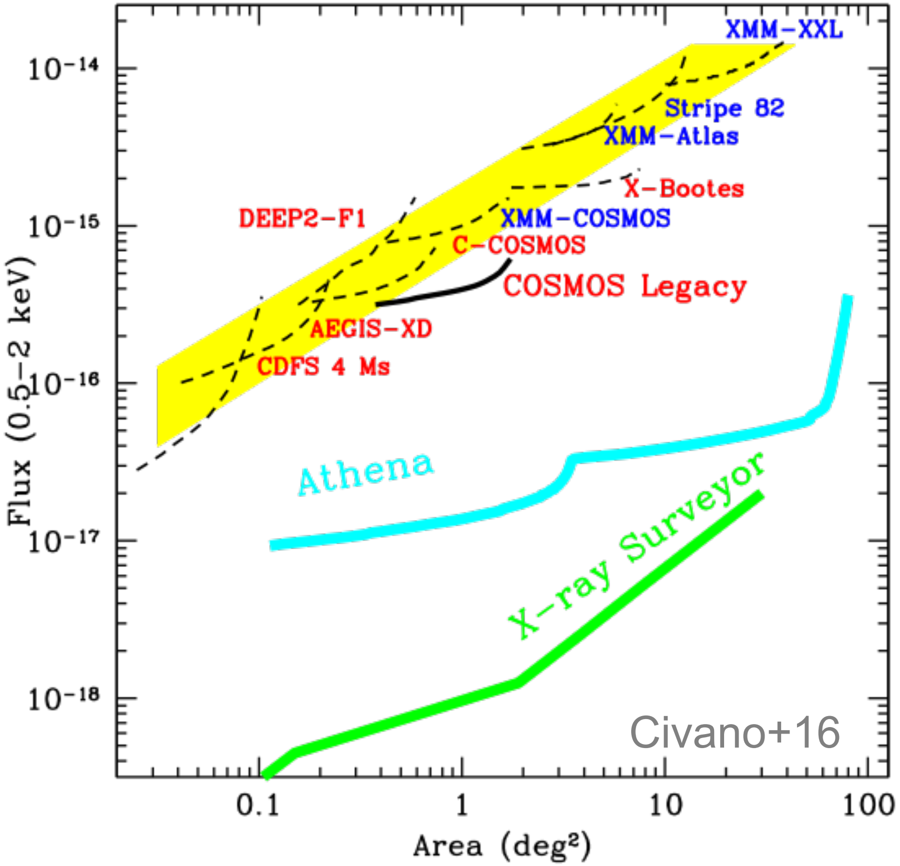
DEEP X-RAY SURVEYS

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



LARGE (and SHALLOW) X-RAY SURVEYS

PROs:

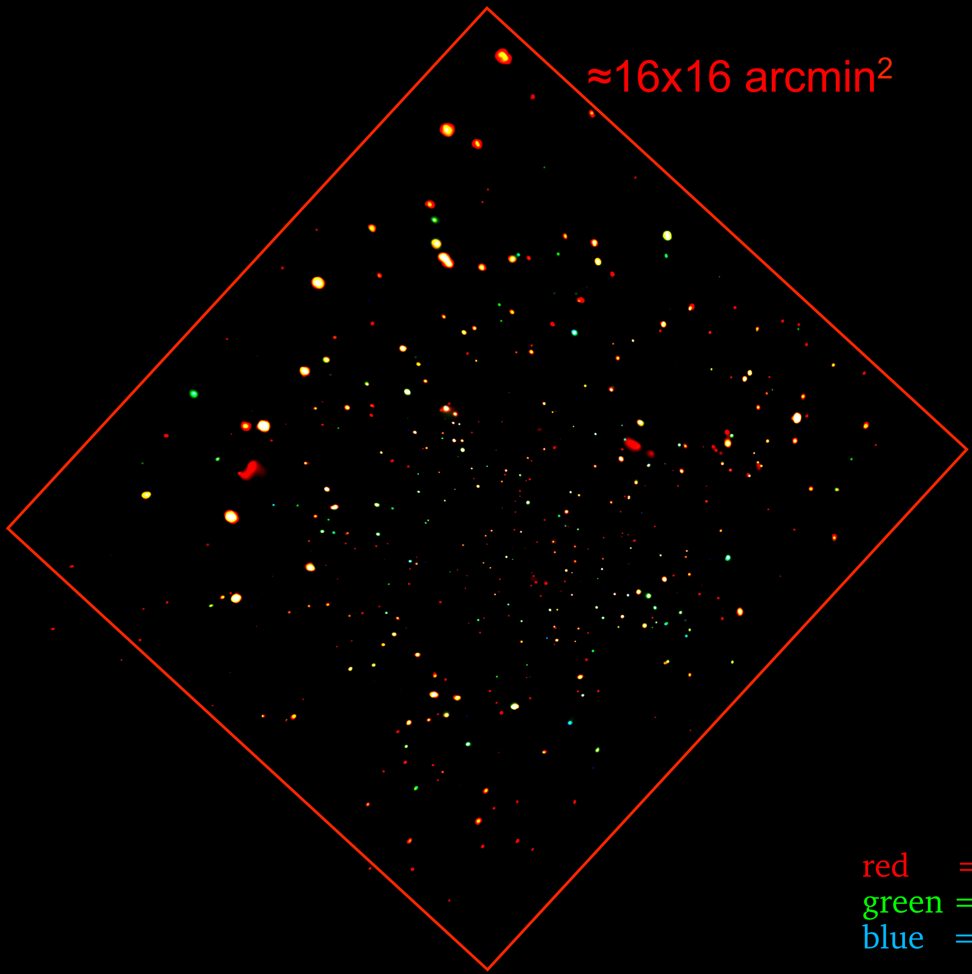
- Ideal to pick up bright and rare X-ray sources
- Possibility to cover large areas of the sky

CONs

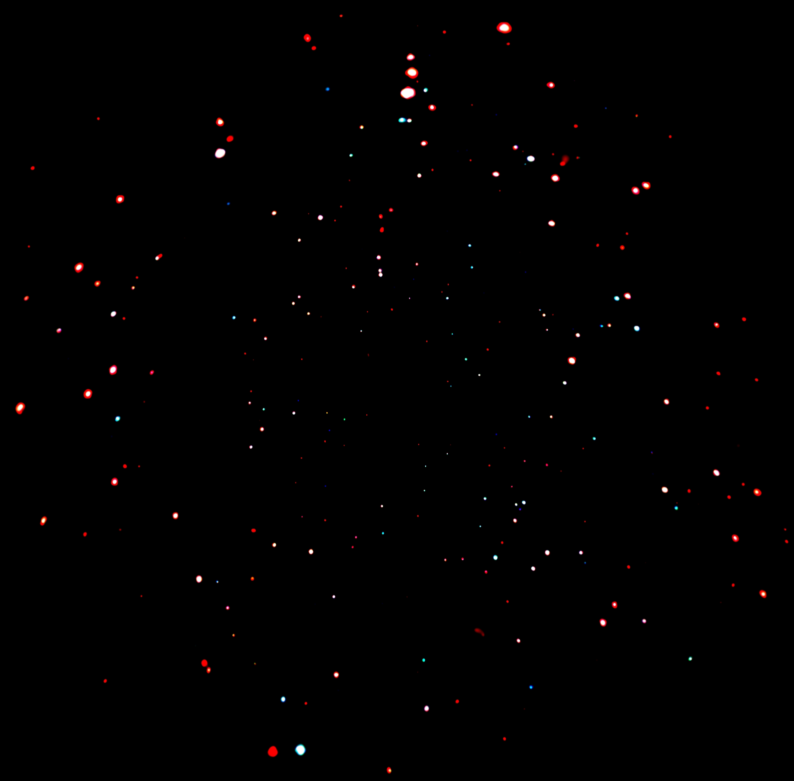
- Limited number of sources

Chandra Deep Fields

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



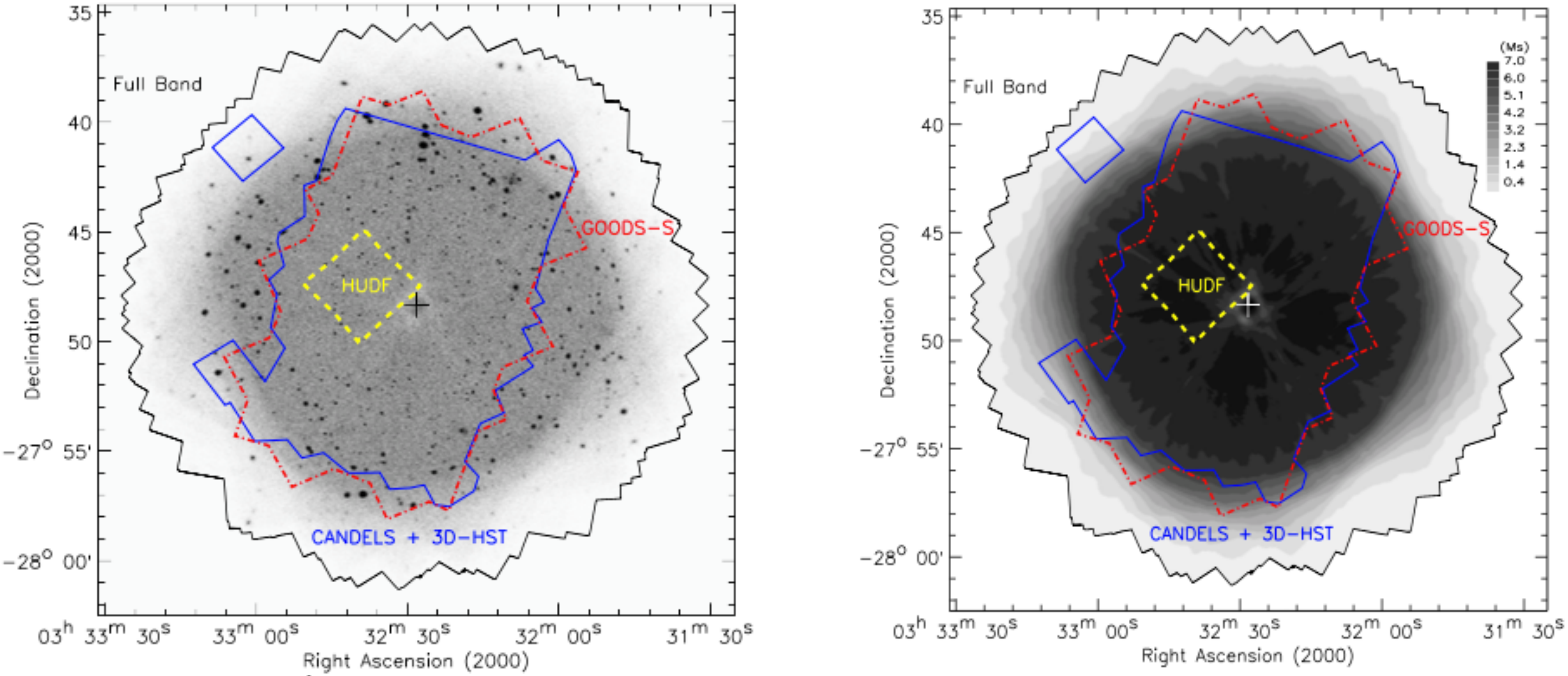
CDFS (Giacconi+02)



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

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

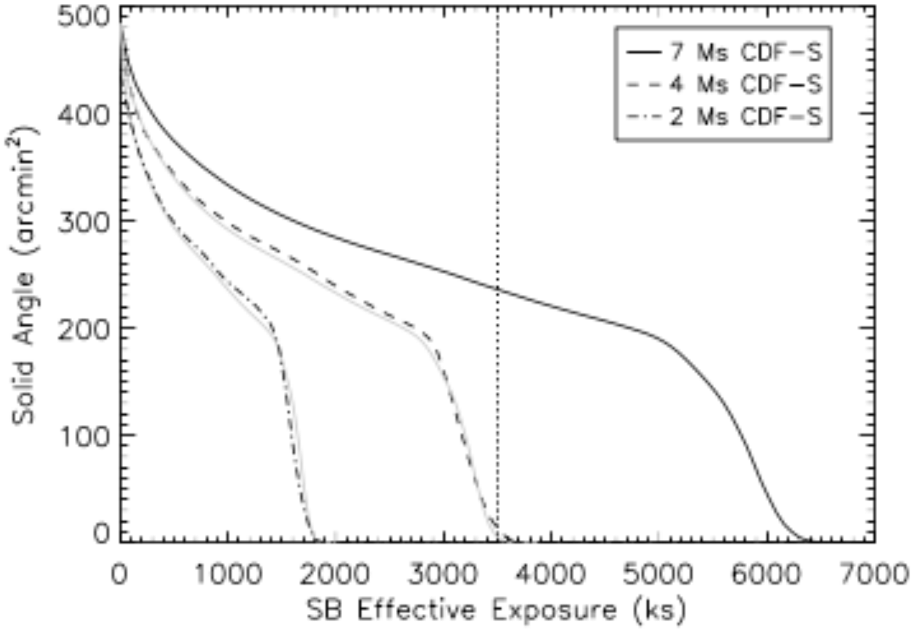
The deepest X-ray exposure ever



Luo+17

- 484 arcmin^2
- 1008 X-ray sources (992 with counterpart, ≈66% with spec. redshift)
- At least 70% are classified as AGN
- 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.

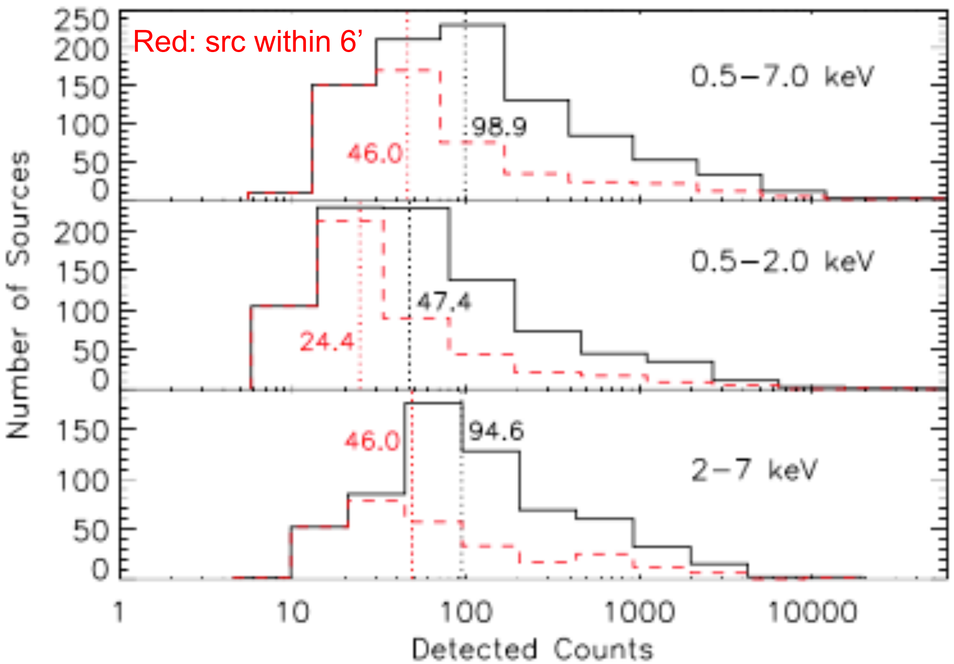


Solid angle vs. exposure time

Motivations behind going deeper

Number of counts

Median values around 100 (still low)

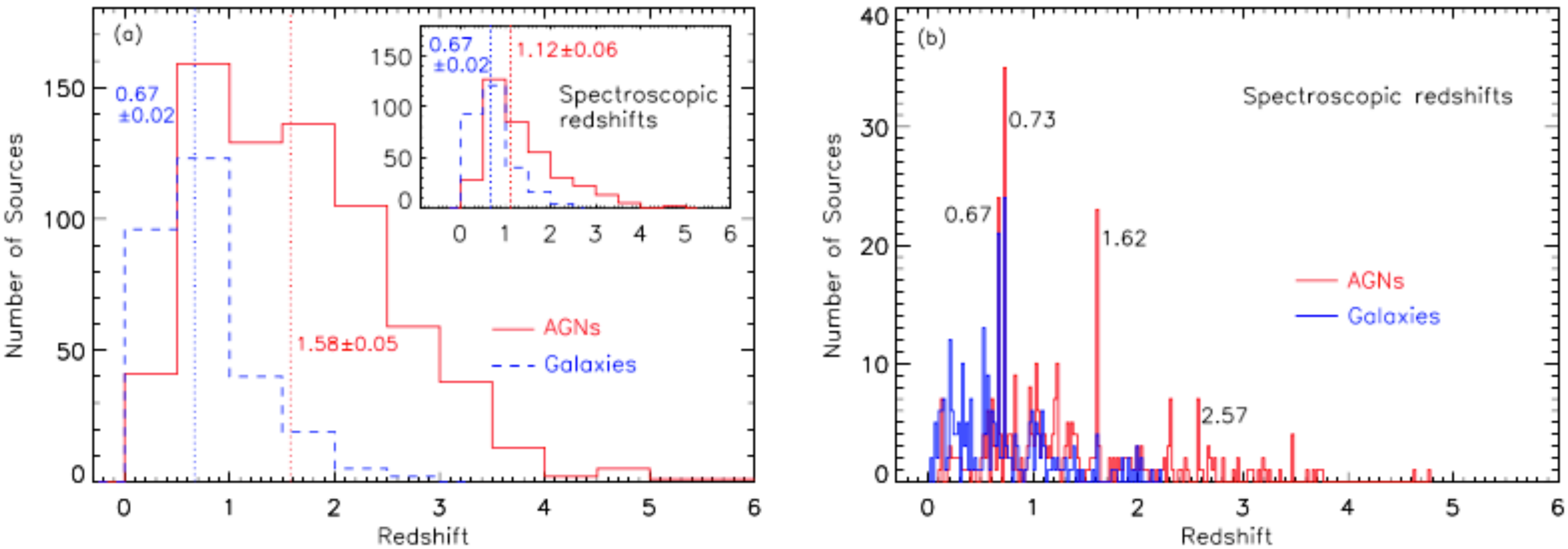


Luo+17

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

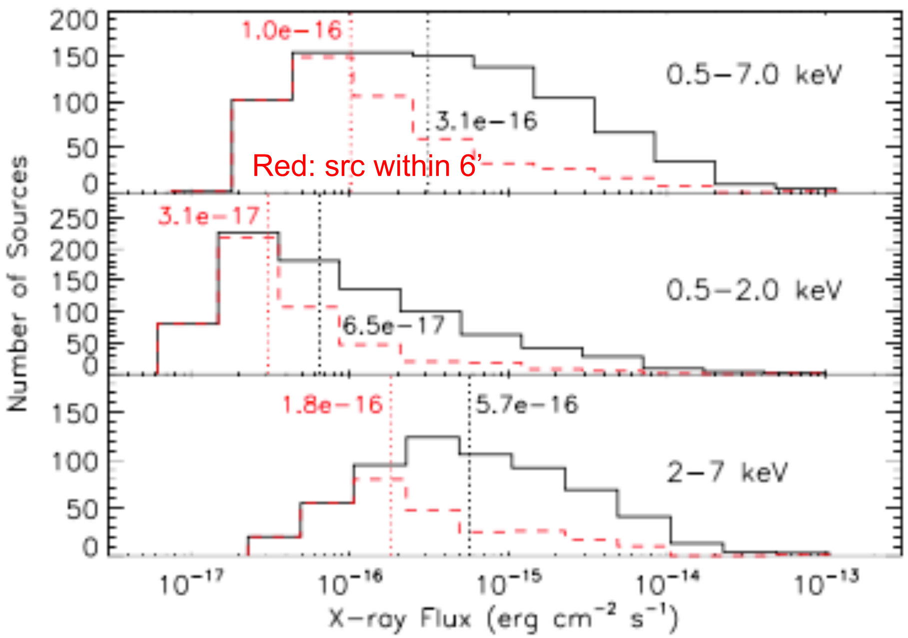
Redshift distribution

AGN vs. Galaxies



Luo+17

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

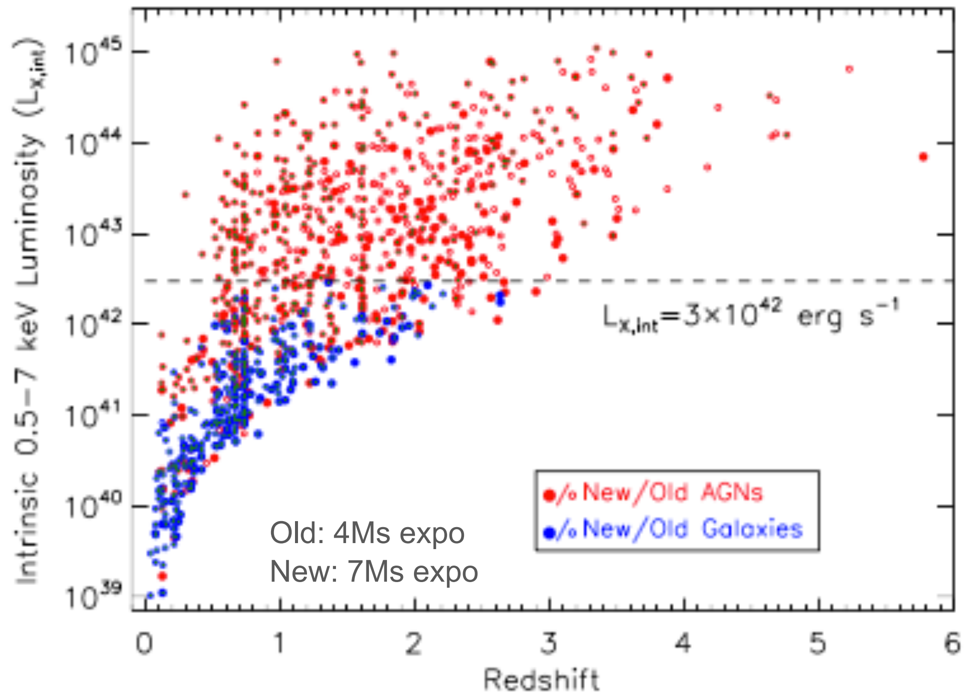


Flux distribution

Inner region vs. whole field

Luminosity distribution

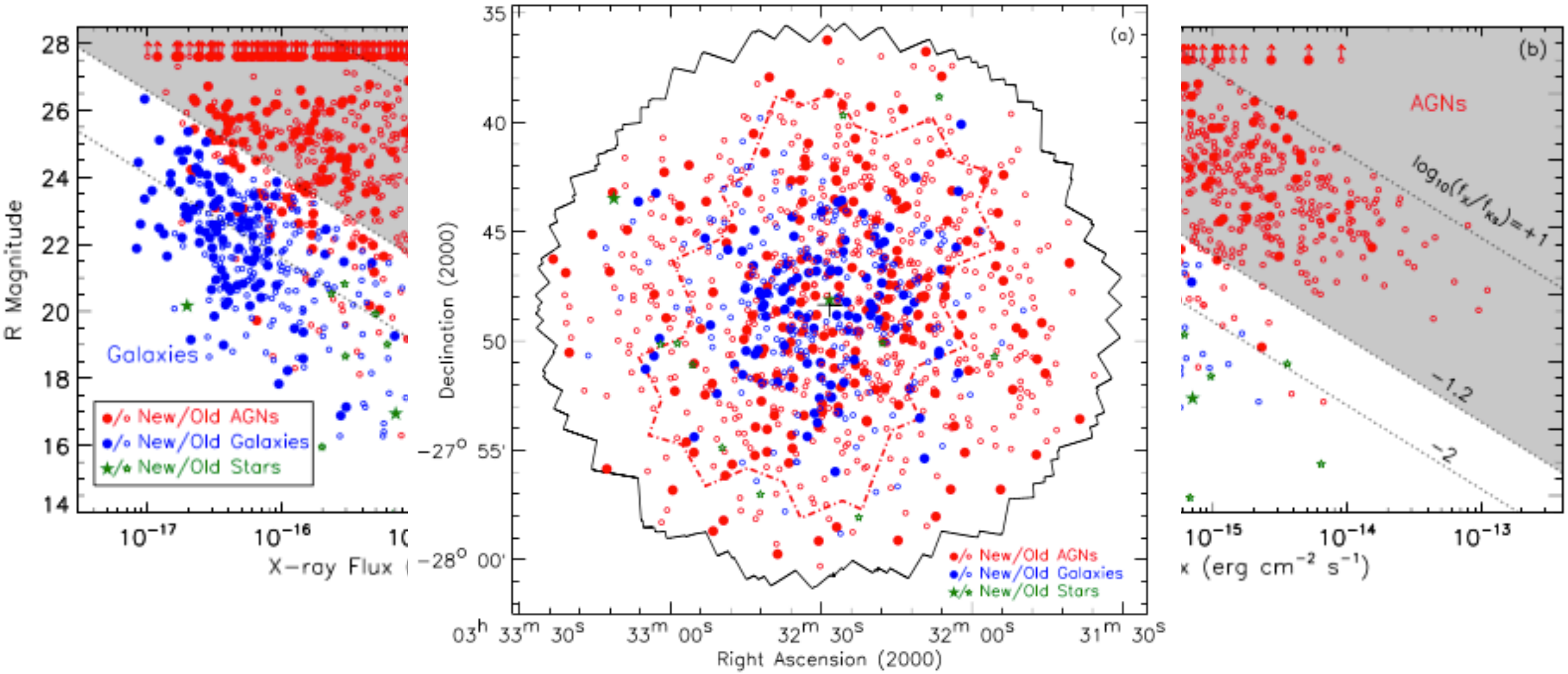
AGN vs. Galaxies



Luo+17

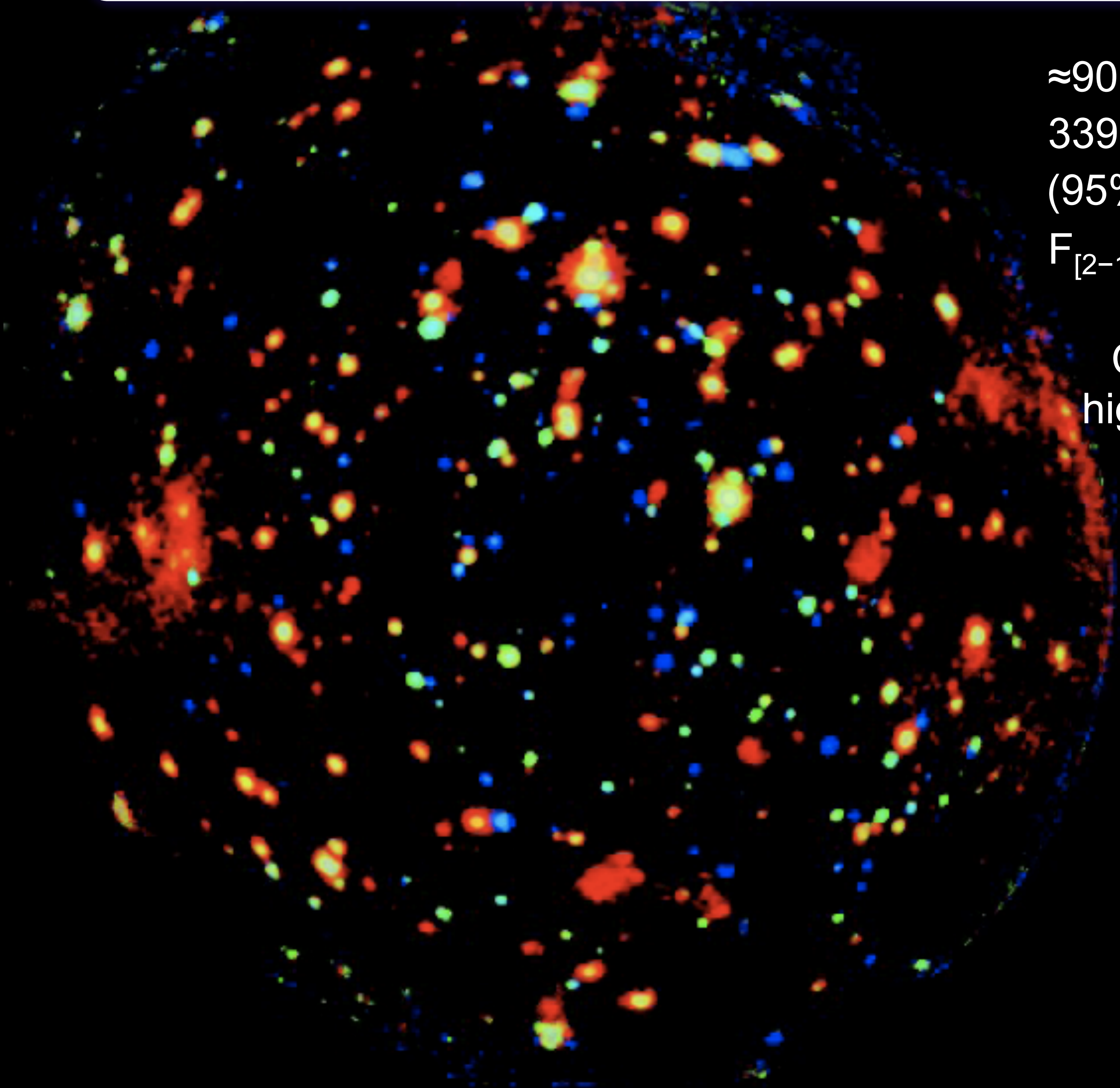
The 7Ms *Chandra* Deep Field South. V.

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



Luo+17

Chandra Deep Field South: XMM 3 Ms exposure

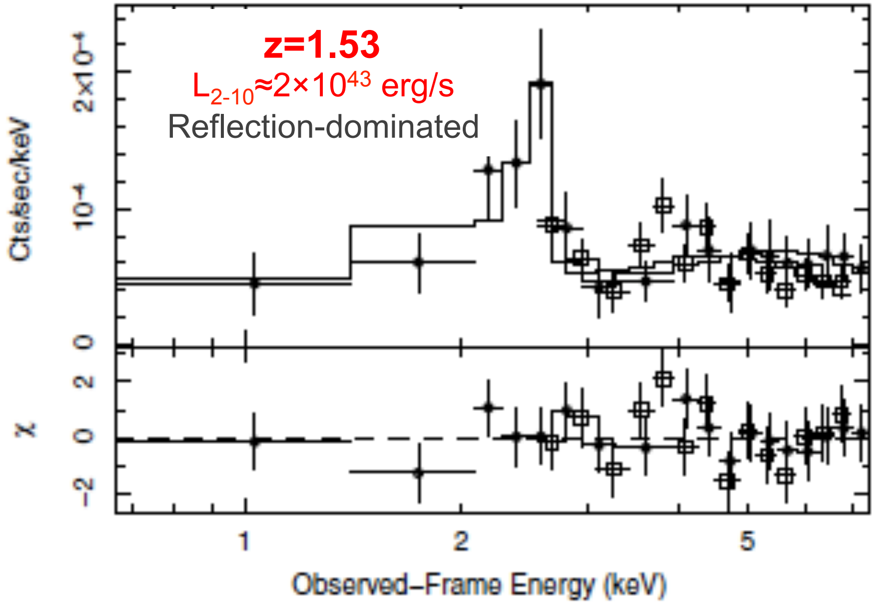


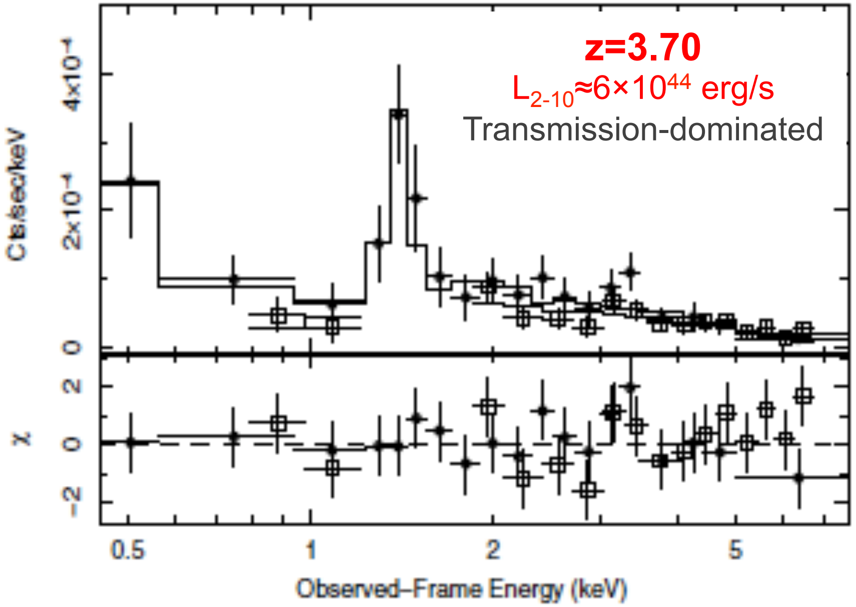
≈900 $arcmin^2$
339 hard (2−10 keV) sources
(95% with spec/photo-z)
$F_{[2-10keV]}=6.6\times10^{-16}$ $erg/cm^2/s$

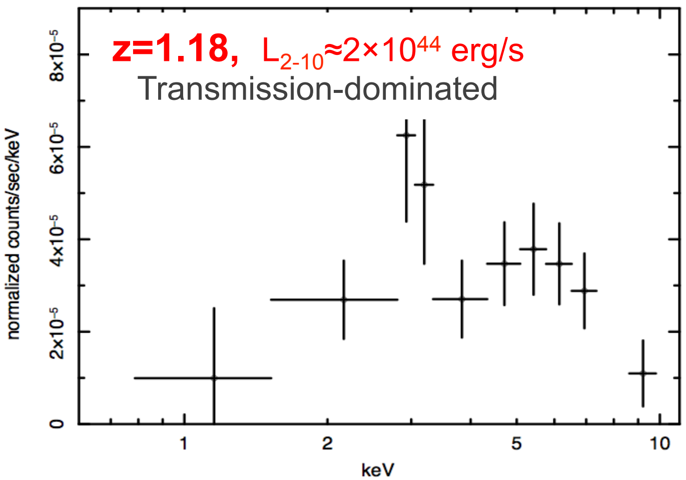
Capable of probing the high-z Universe with good photon statistics

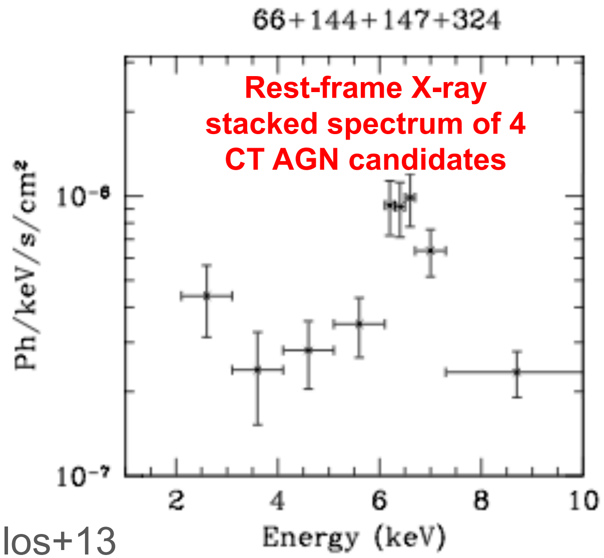
Distant obscured AGN in the CDF-S

Comastri+11



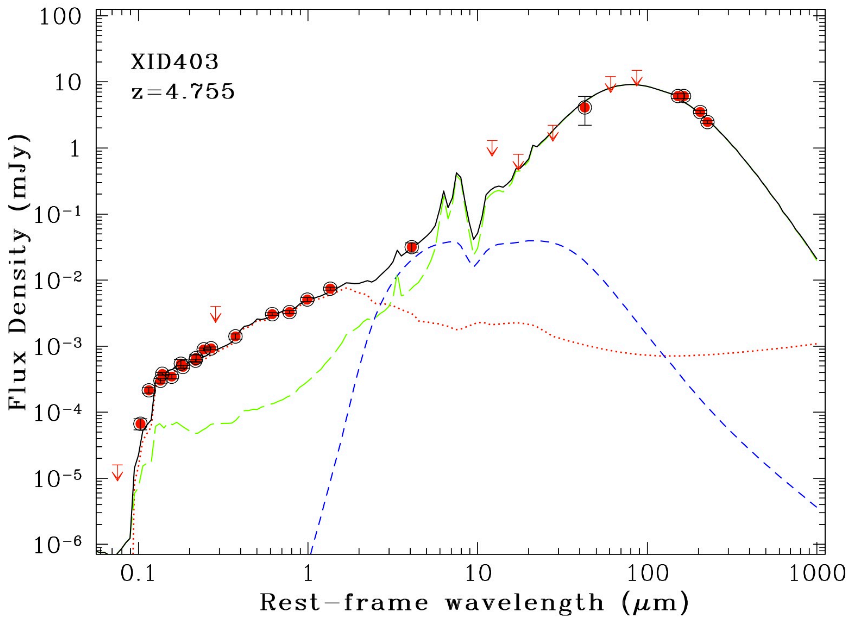


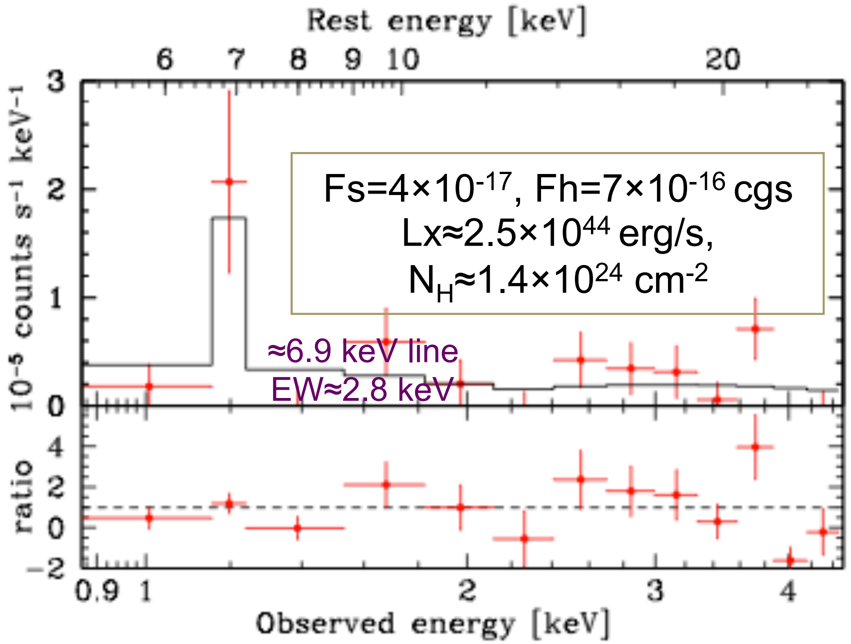




Georgantopoulos+13

Obscured accretion and powerful star formation at z=4.8

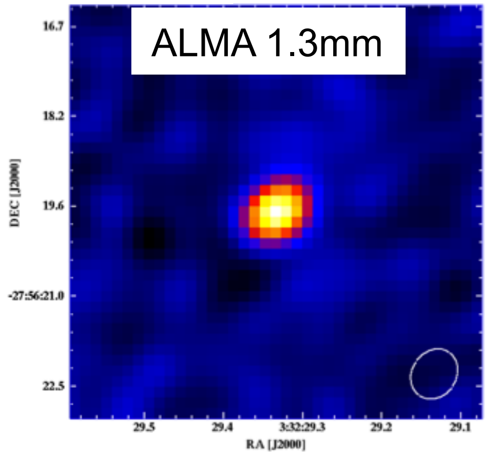




SFR≈1000 $M_\odot$/yr
Σ_{SFR}> 26 $M_\odot$/yr/kpc^2

Compact starburst, possibly responsible for the X-ray obscuration

Progenitor of compact quiescent massive galaxies at z≈3



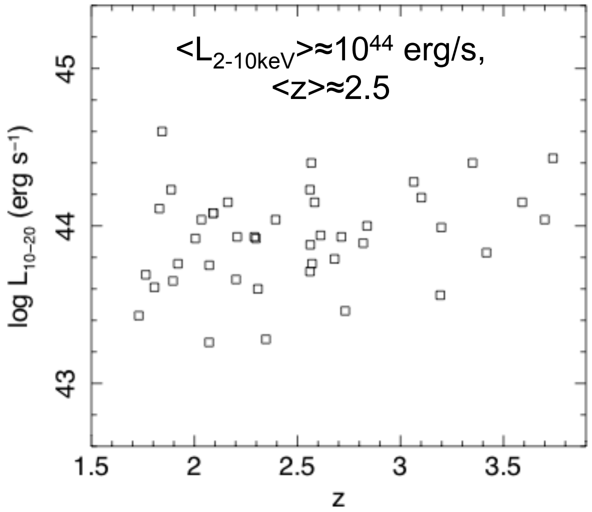
Gilli et al. 2014, 2011

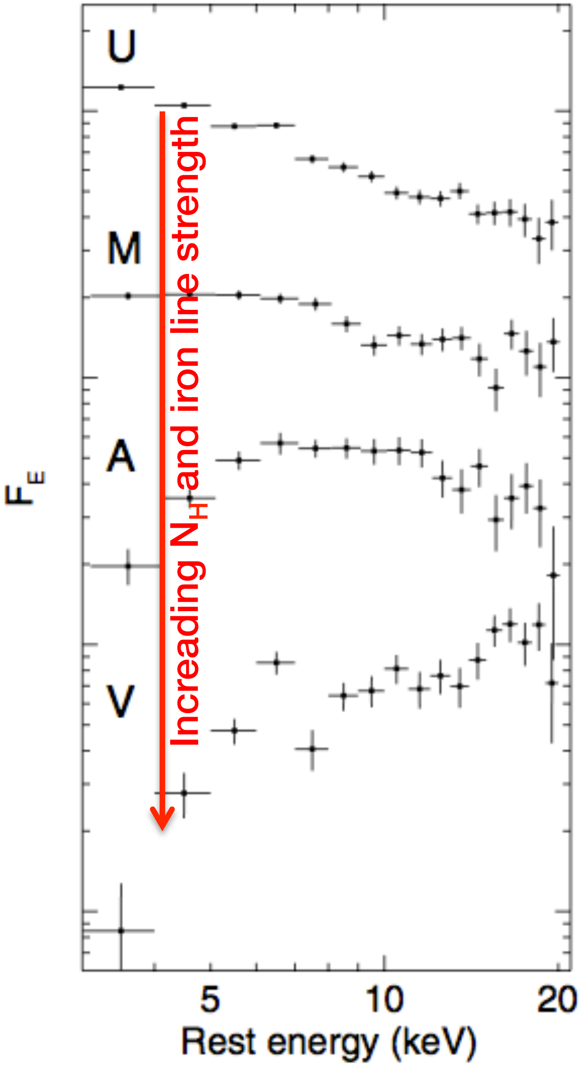
Challenging and time-consuming observations

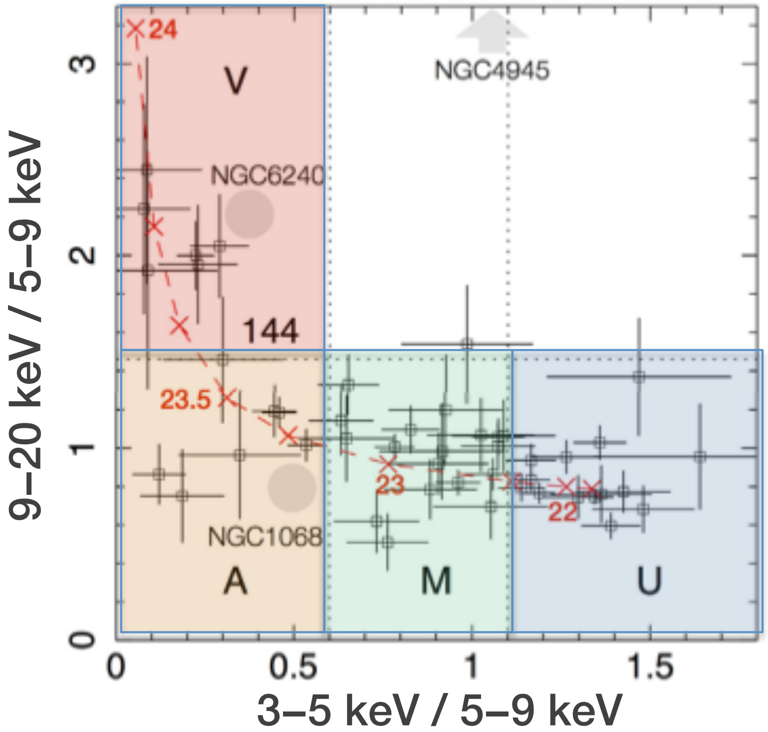
This kind of studies are possible only with deep (>Ms) *Chandra* exposures

X-ray stacking to probe high-redshift sources

At **z>1.7**, the rest-frame 10−20 keV band enters the XMM-*Newton* bandpass ➔ search for obscured AGN using the hard (>10 keV) excess − 44 AGN in the 2−10 keV source catalog







Iwasawa+12

X-ray variability from deep X-ray surveys

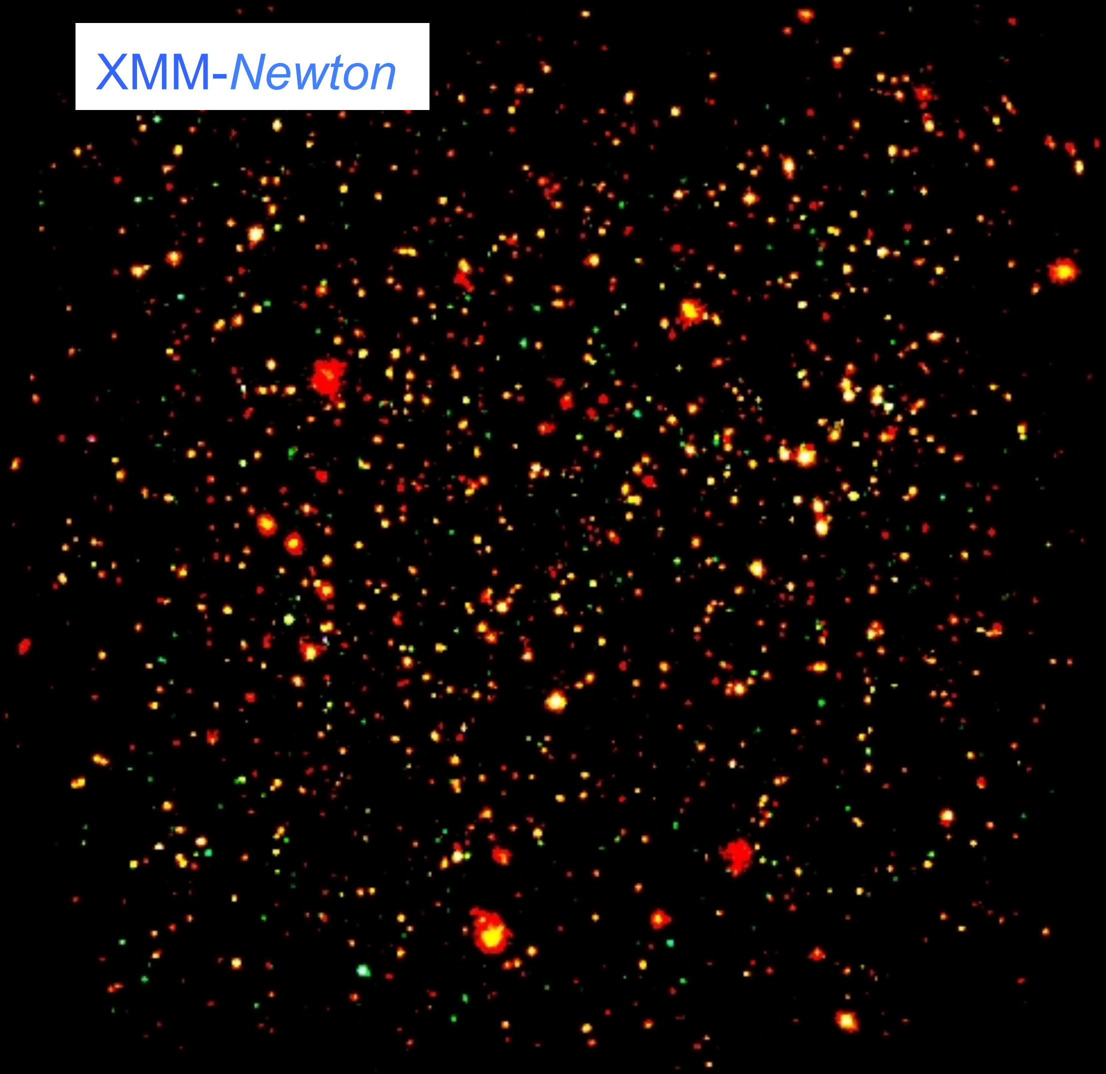
X-raying the COSMOS

XMM-*Newton*
1.55 Ms
1822 sources

Large area, 2 deg^2, good photon statistics
Background and PSF size main limitations

Chandra
1.8 Ms
1761 sources

Guarantees depth on an area initially of 0.9 deg^2



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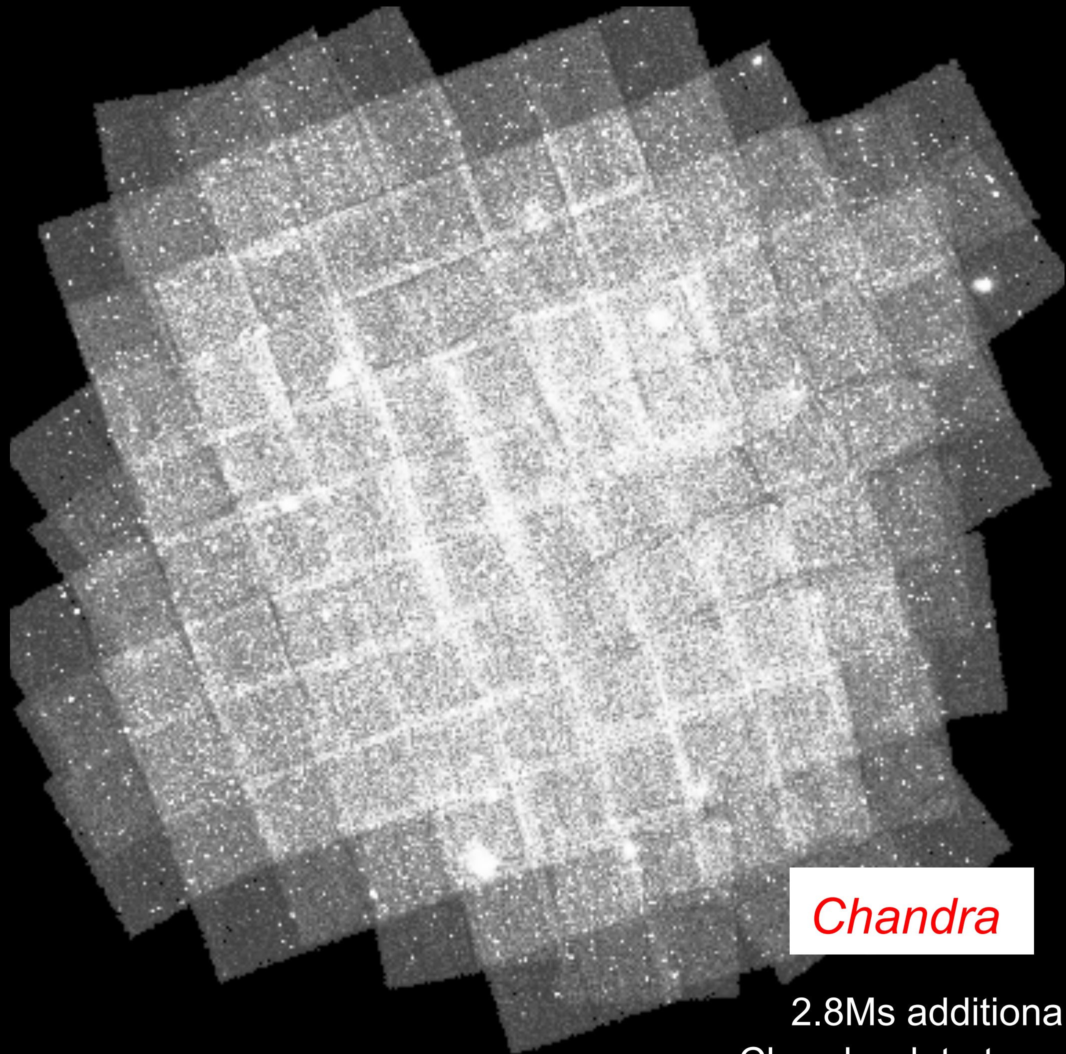
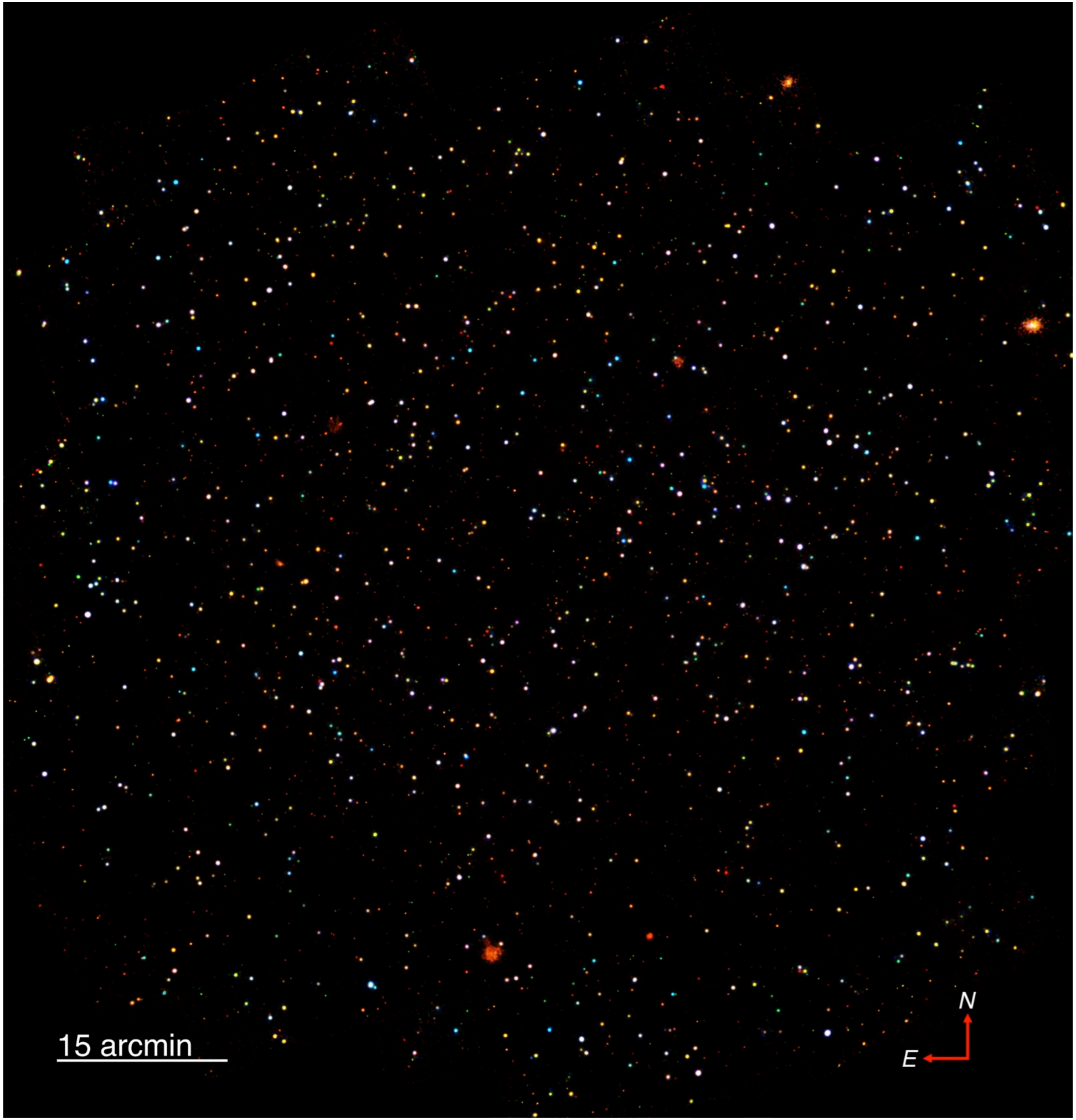


Chandra

2.8Ms additional Chandra data to cover the entire ~2.2 deg^2 (going deep)
4016 point-like X-ray sources

COSMOS Legacy Survey



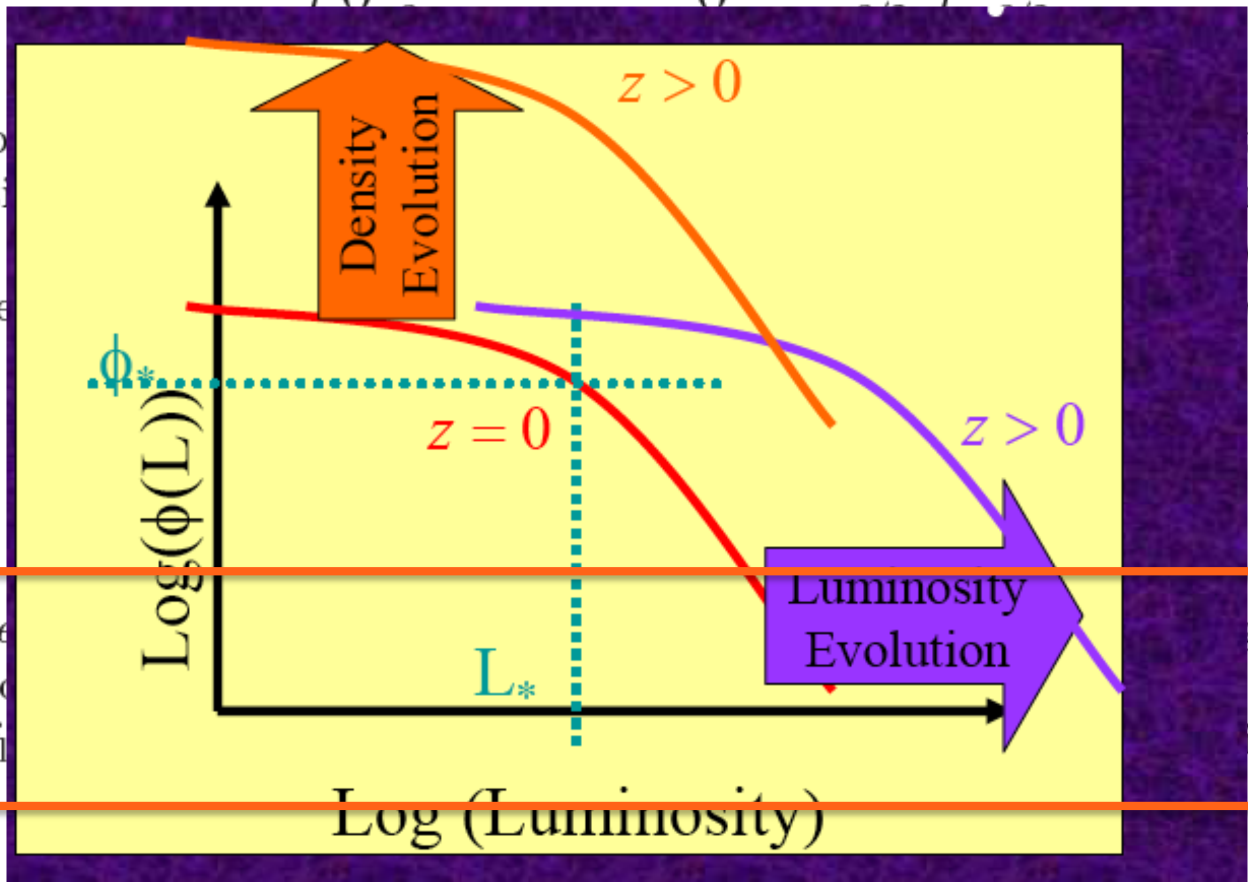
Courtesy of the Chandra COSMOS Legacy collaboration

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 Ω, observable down to the flux S are:

(1)



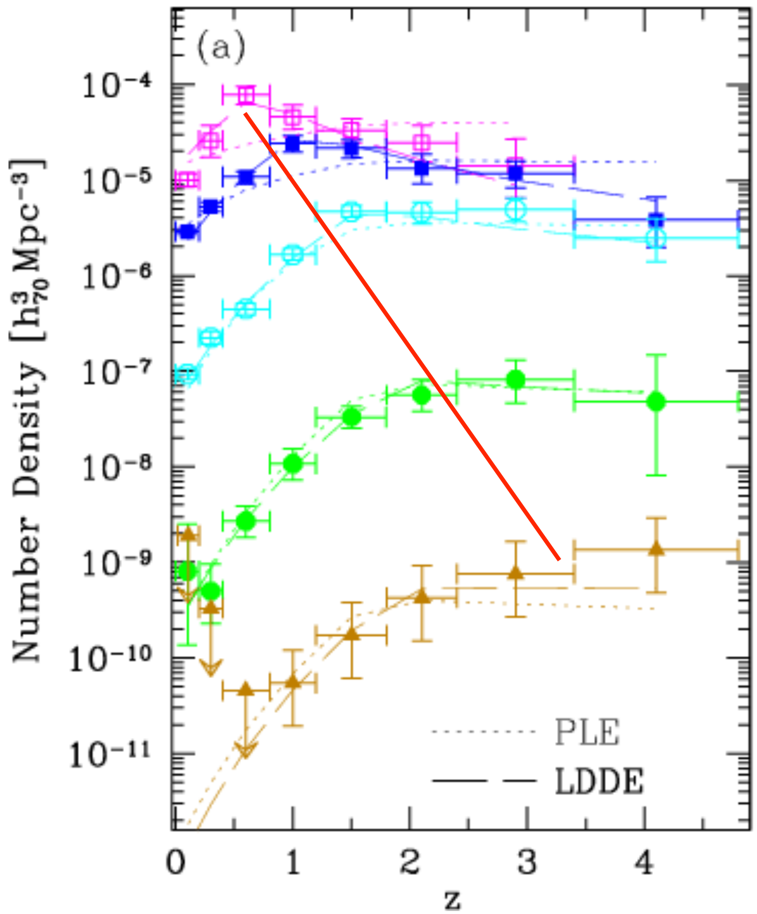
Thus, indep … he determination of a normalizati … on-evolving class of sources in a … $/(> S)/d\log S =$ $-3/2$ (if we use … $= 0.6$).

(2)

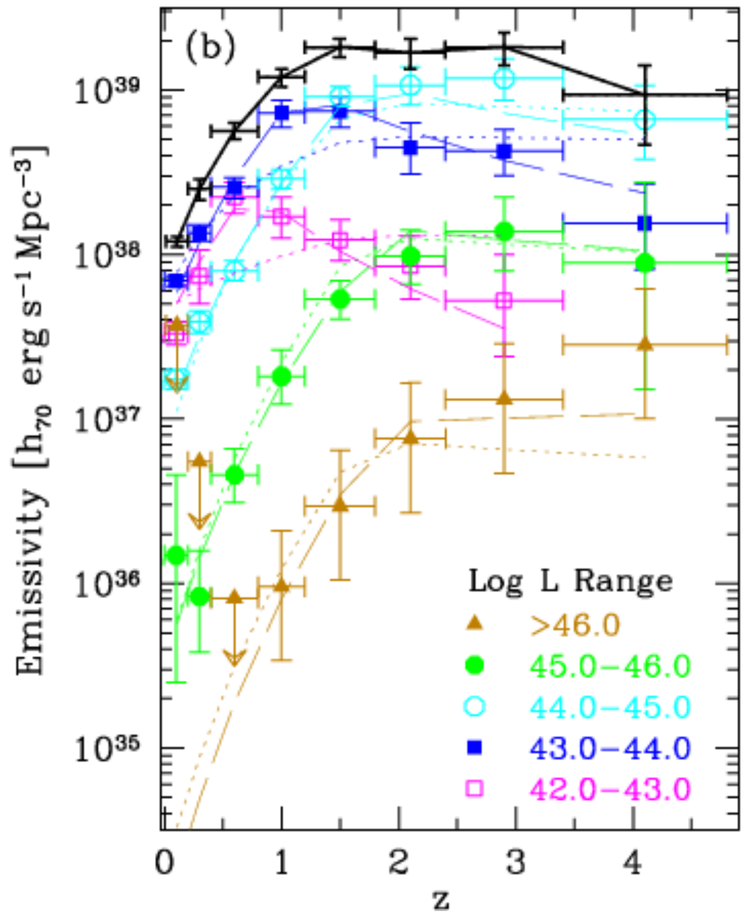
In the *pur* … number density of sources is c … *density evolution (PDE)* case (f … ity varies.

AGN cosmological evolution

Number density



Luminosity density



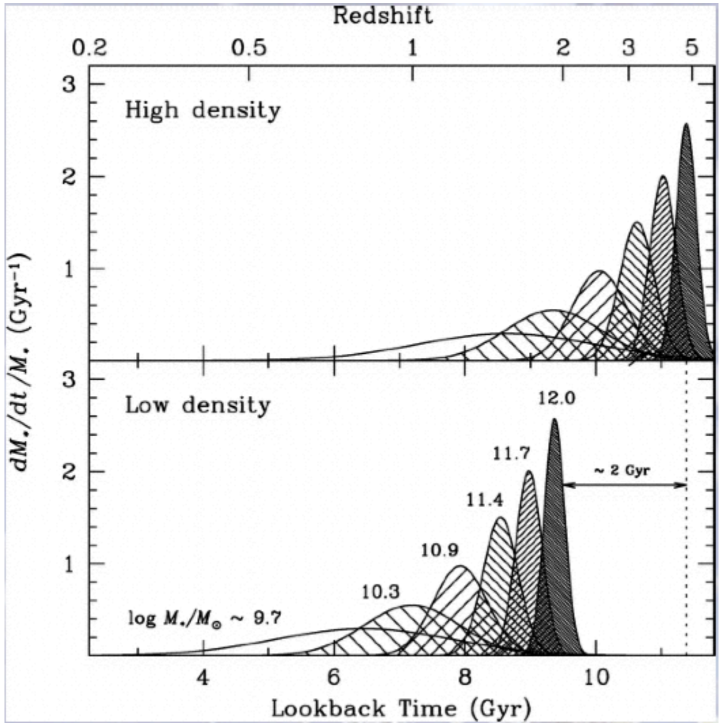
Objects with lower luminosity peak at lower redshift, similar to what observed for SFR in galaxies ⇒ **cosmic downsizing**

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



Thomas+2005

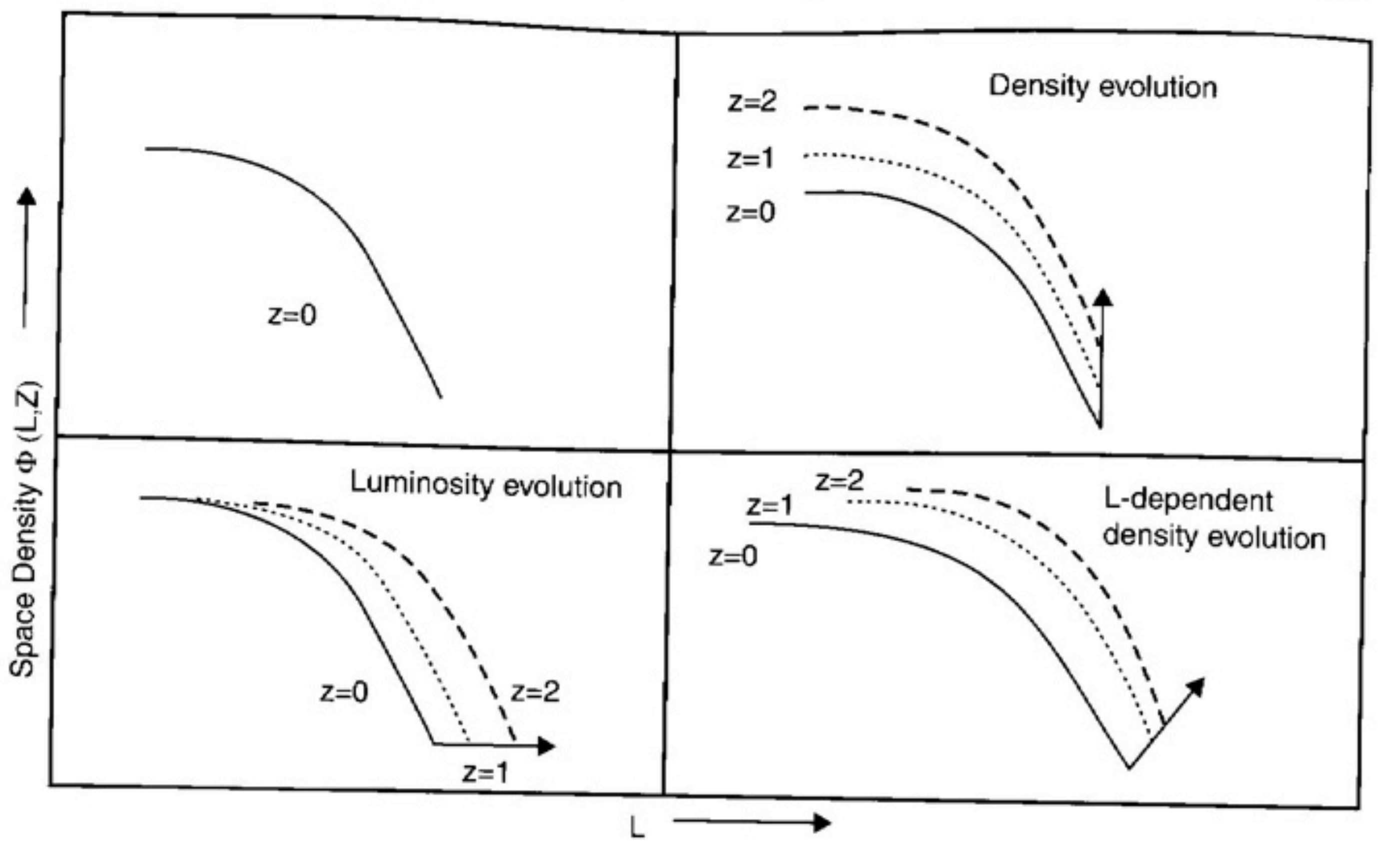
Galaxy formation took place in "downsizing", with more massive galaxies forming at higher redshift (Cowie+96)

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

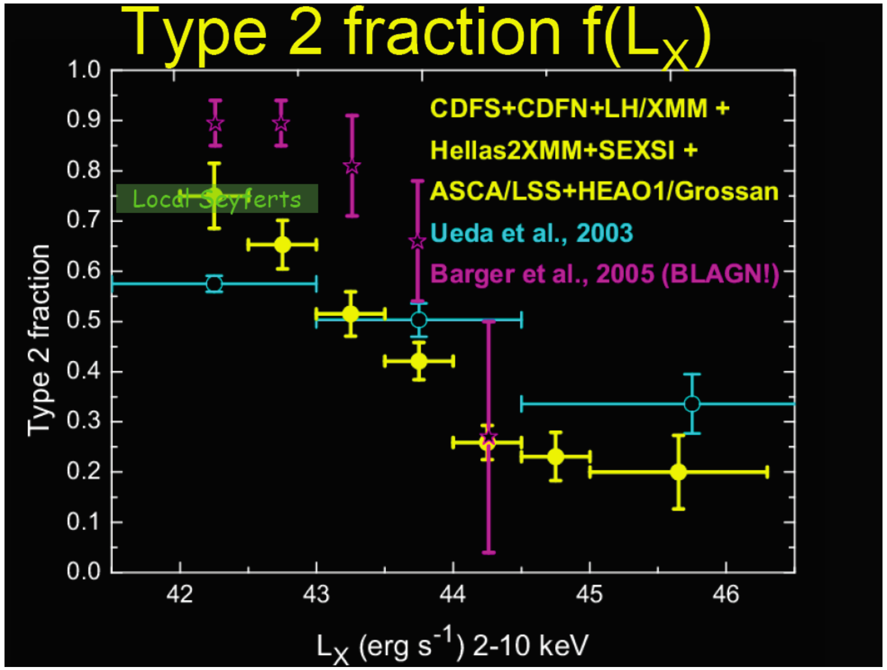
Luminosity Evolution:
AGN more luminous in the past

Density Evolution:
AGN more numerous in the past

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

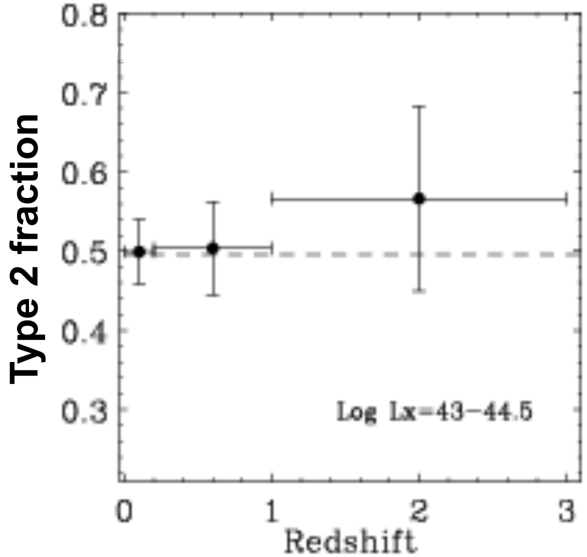


Dependence of the obscured AGN fraction on X-ray luminosity and redshift

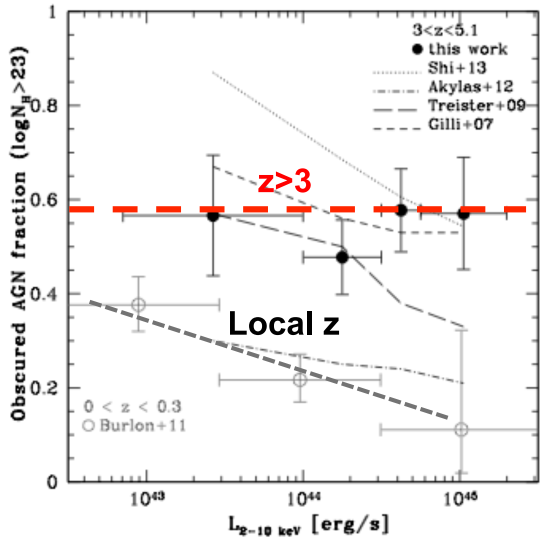


Broad consensus for an obscured AGN fraction declining towards high intrinsic luminosities ➔ *receding torus model* (Lawrence 1991, Simpson 2005; see also Lusso et al. 2013)

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

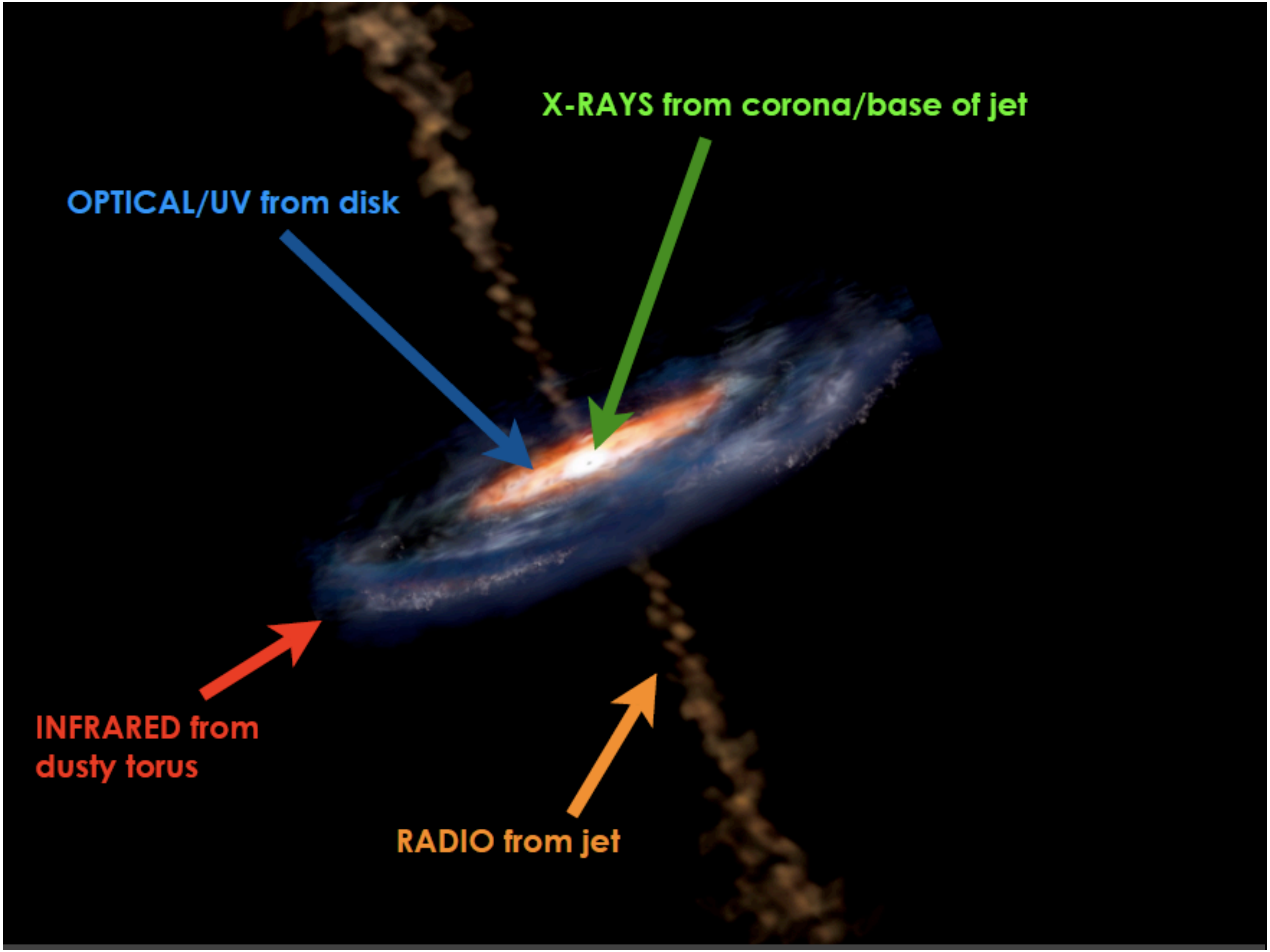


No evolution with z

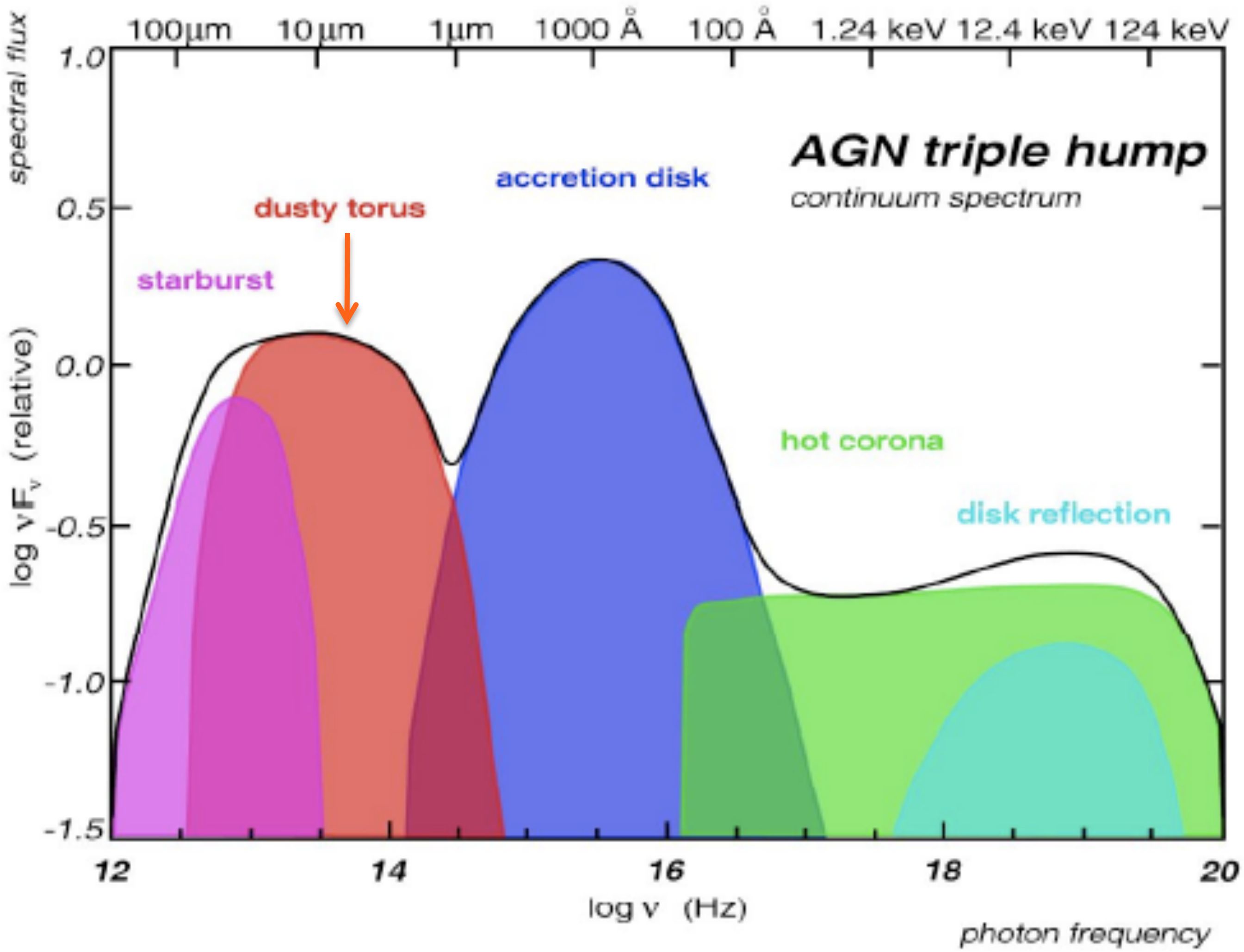


Evolution with z

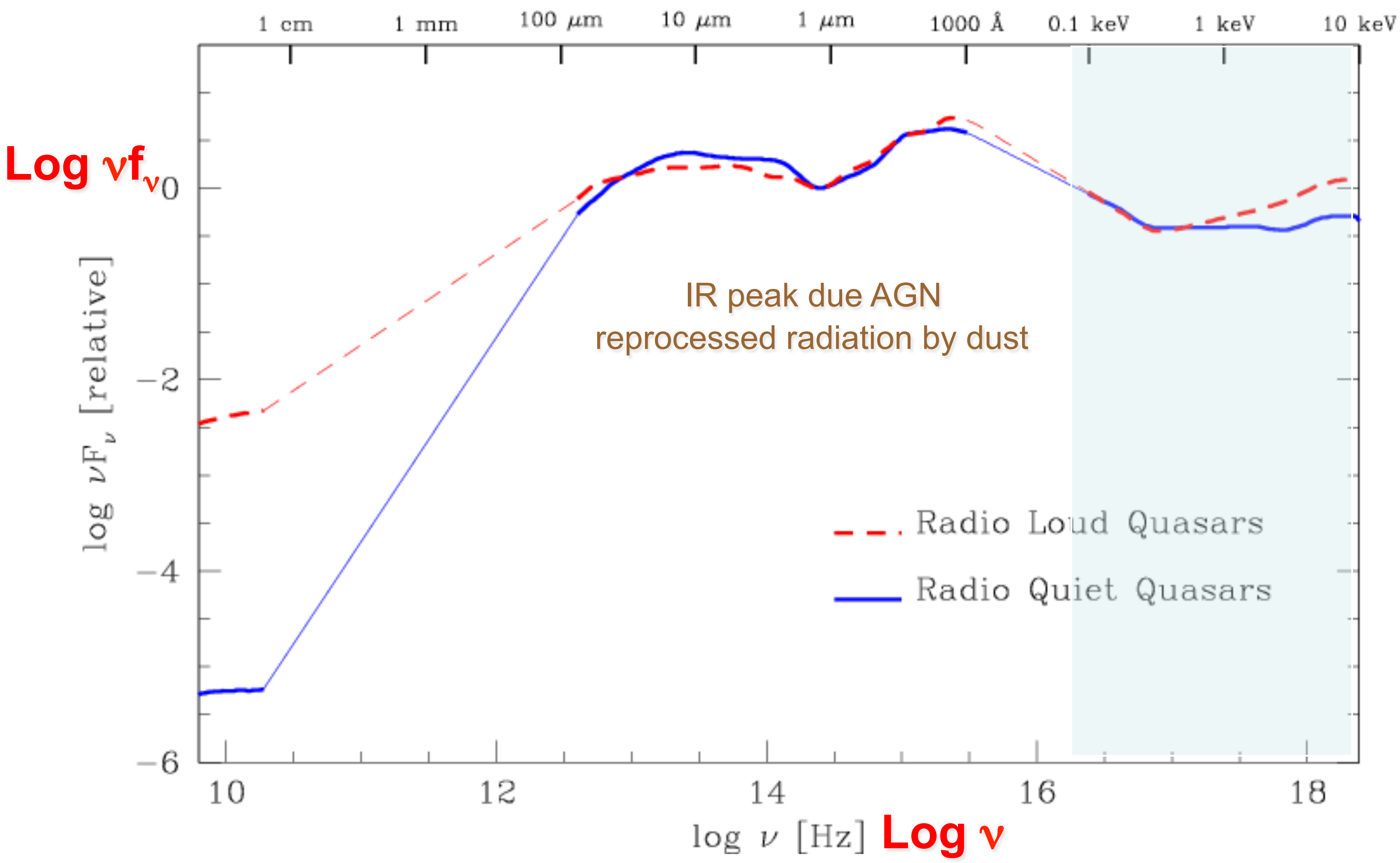
AGN Spectral Energy Distributions.
On the properties, location and structure of the X-ray absorber


X-RAYS from corona/base of jet
OPTICAL/UV from disk
INFRARED from
dusty torus
RADIO from jet

Broad-band spectral energy distribution of AGN (I)



Broad-band spectral energy distribution of AGN (II)



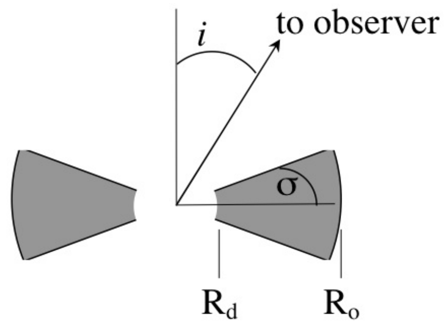
Elvis et al. 1994

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

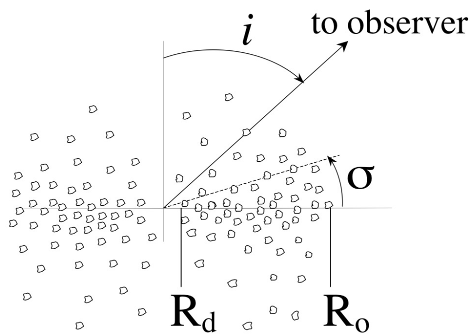
• Dust temperature is a function of the distance from the source of the radiation field



Clumpy models: main properties

• The probability of direct viewing of the AGN decreses 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:
$\Delta N_H \sim 10^{23}\text{-}10^{24}\ \mathrm{cm^{-2}}$

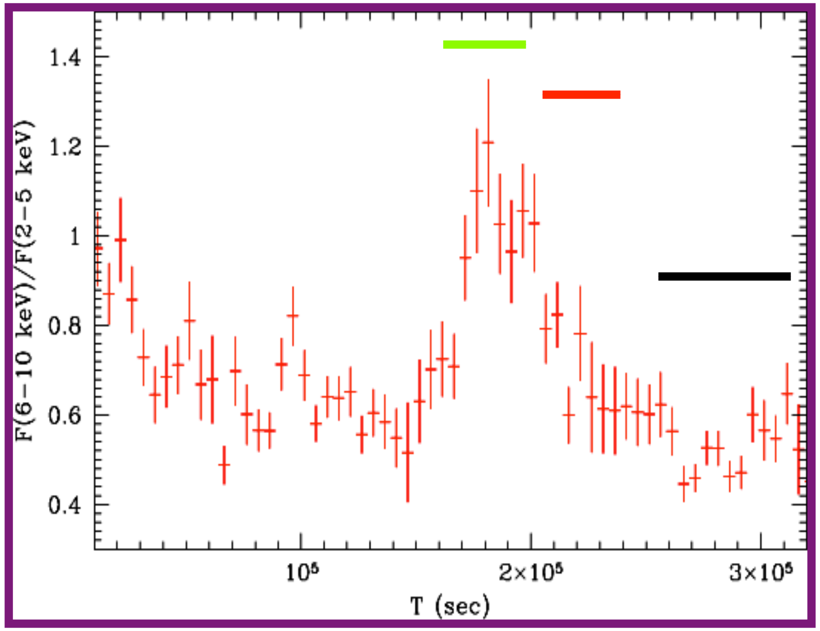
↓

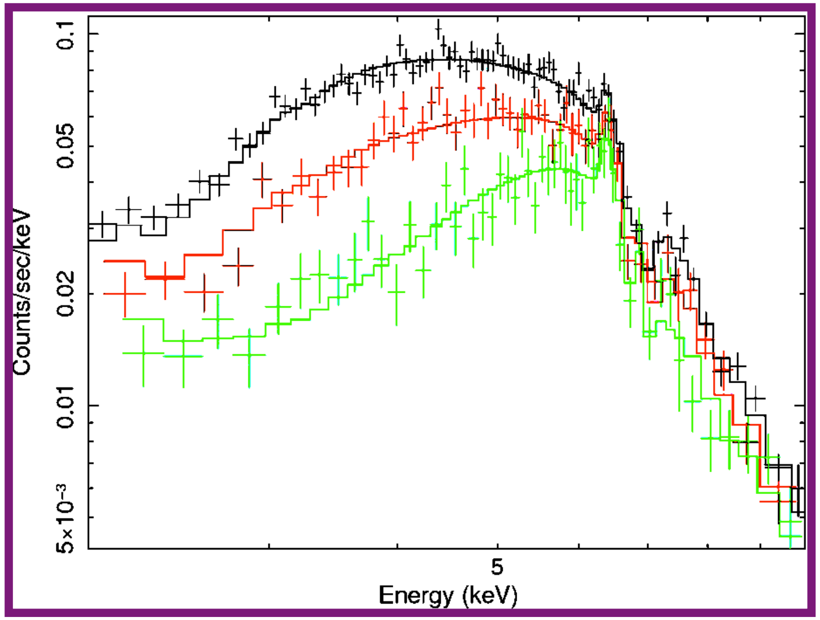
size X-ray src $<10^{14}$ cm
$D < 10^{16}$ cm

↓

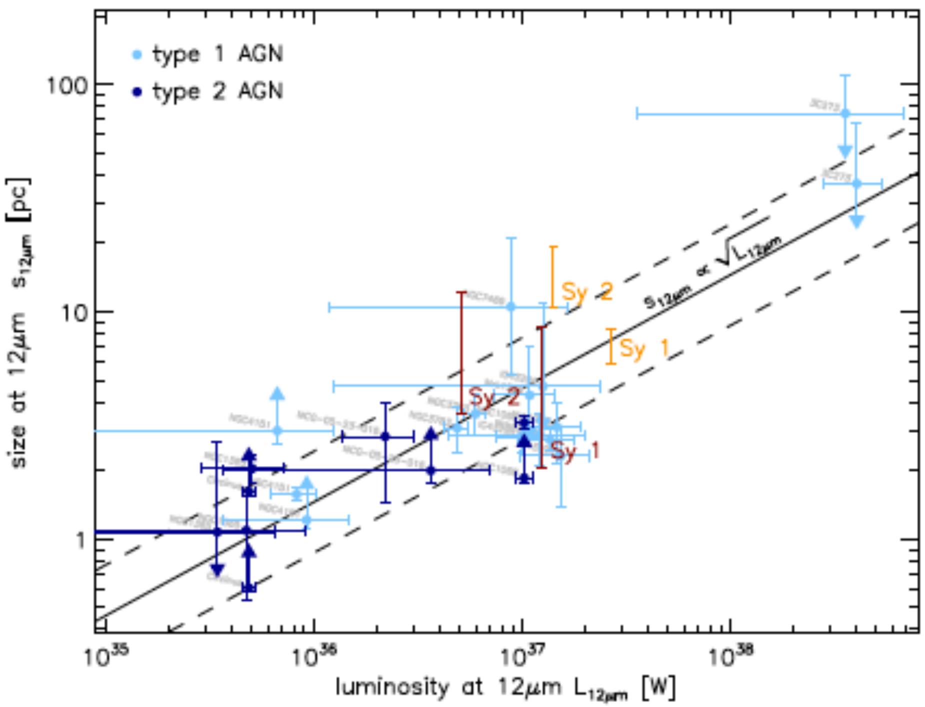
X-ray absorber "made" of BLR clouds on scales<pc-scale (torus)

Risaliti et al., 2007, 2010…





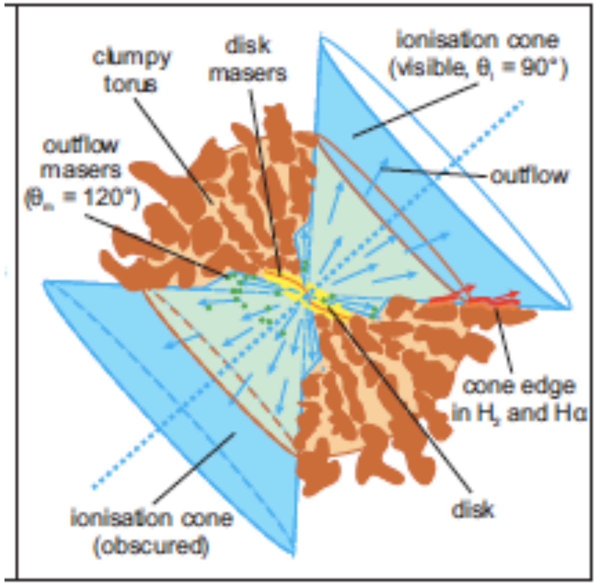
High-resolution mid-IR observations of Seyferts



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

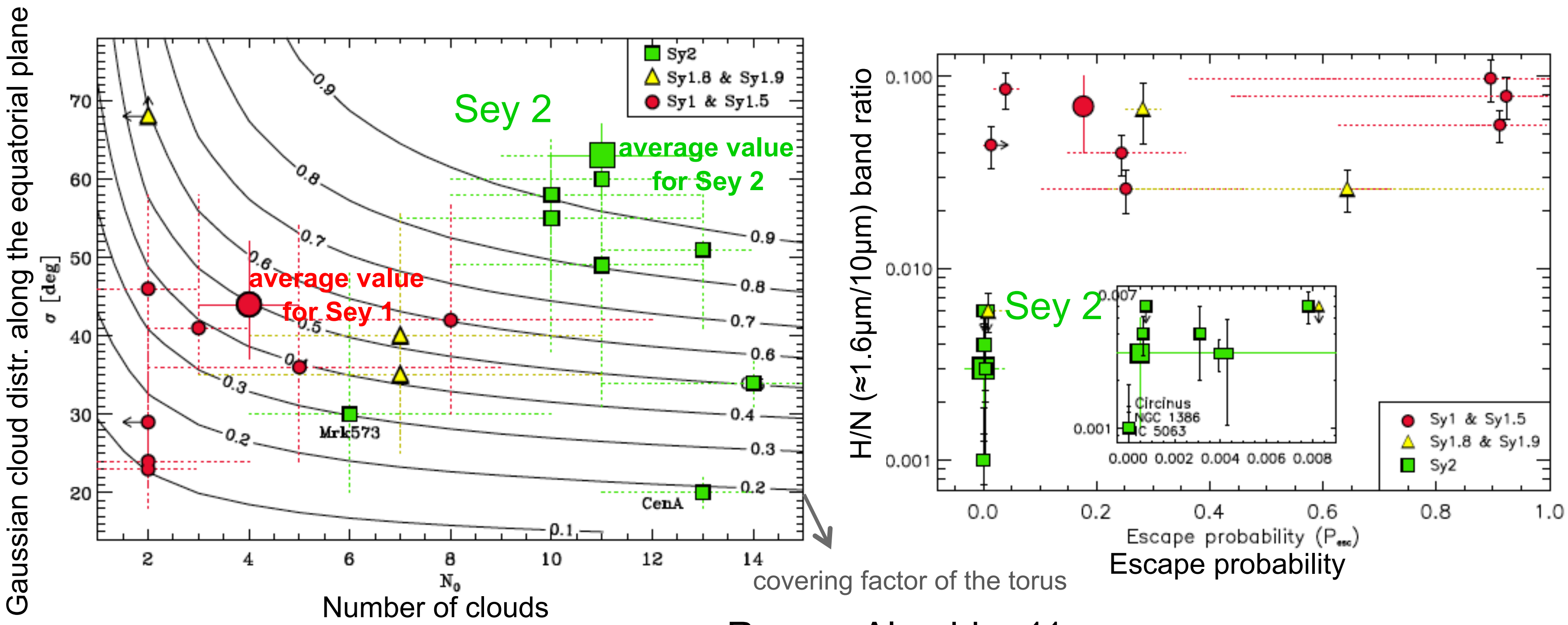


Tristram+07 - Circinus

Modeling the mid-IR emission with "clumpy" torus

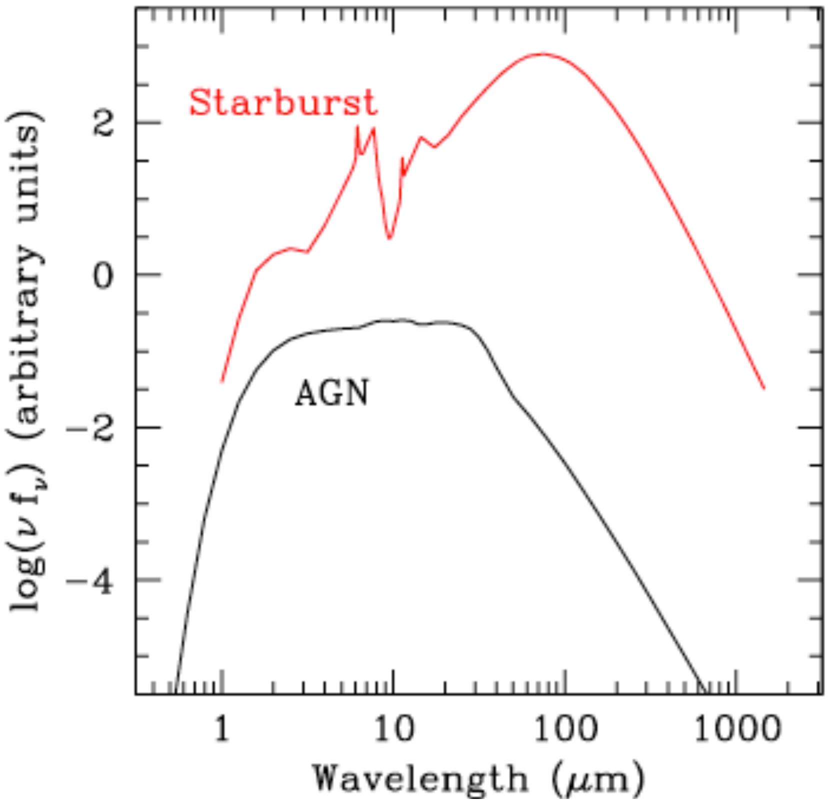
✓ Type 1 vs. Type 2 AGN difference: it is a function of the number of clouds along the line of sight, i.e., of the escape probability
✓ Same dust temperatures can be observed at different distances from the AGN

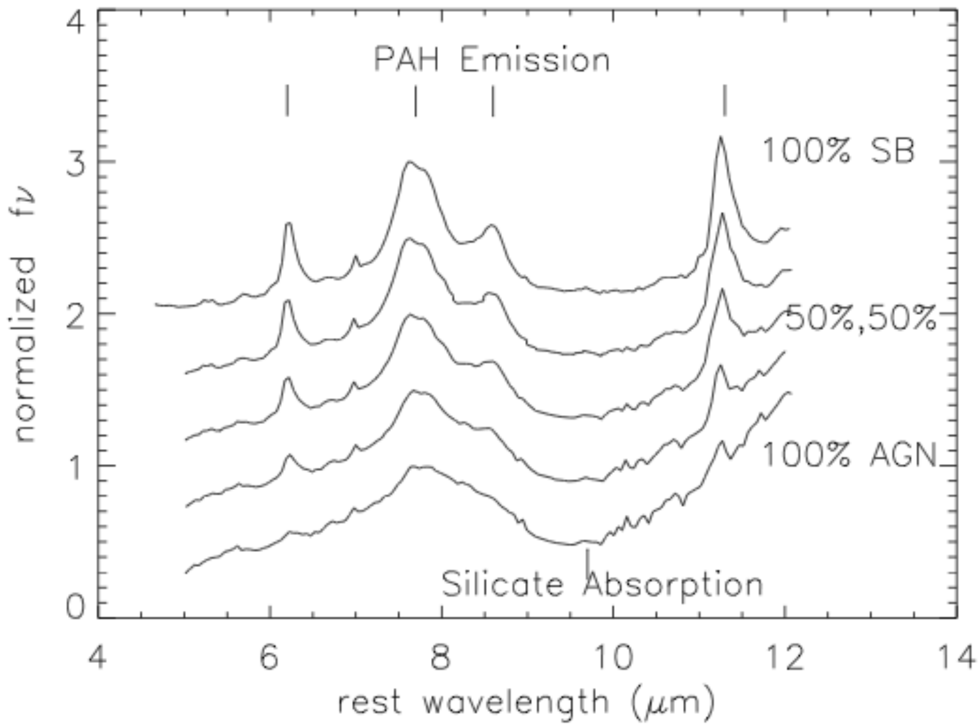
➔ Type 2 AGN: larger number of clouds and lower P_{esc} for the photons to escape



Ramos-Almeida+11

SED fitting: stellar vs. accretion processes



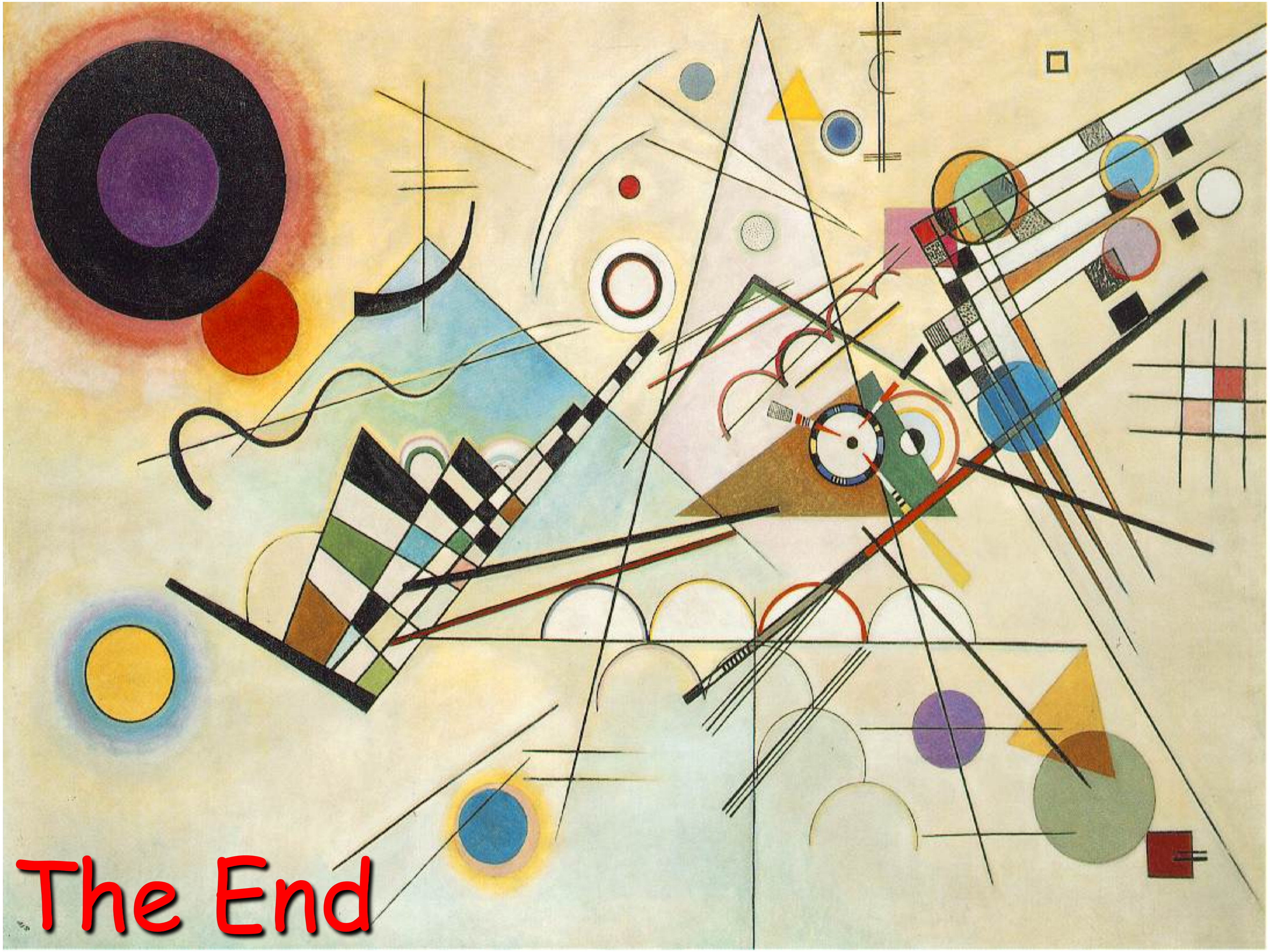


BROAD-BAND SED fitting: common problem to all torus models:
Need to separate the galaxy contribution from that due to the AGN

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