Active Galactic Nuclei:
X-ray surveys and AGN evolution

Astrophysics Laboratory course, AA2021-21

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

✓ Open issues: the first massive black holes and heavily obscured AGN

✓ Integrated AGN emission recorded in the X-ray background (XRB)

✓ X-ray surveys: the deep *Chandra* and XMM-*Newton* exposures in the CDF-S and COSMOS fields. Source demography and redshift distribution.

✓ AGN evolution from X-ray surveys

✓ Insights into the obscuring medium ("torus") from mid-IR and X-ray observations

For **reviews** on the subject, see

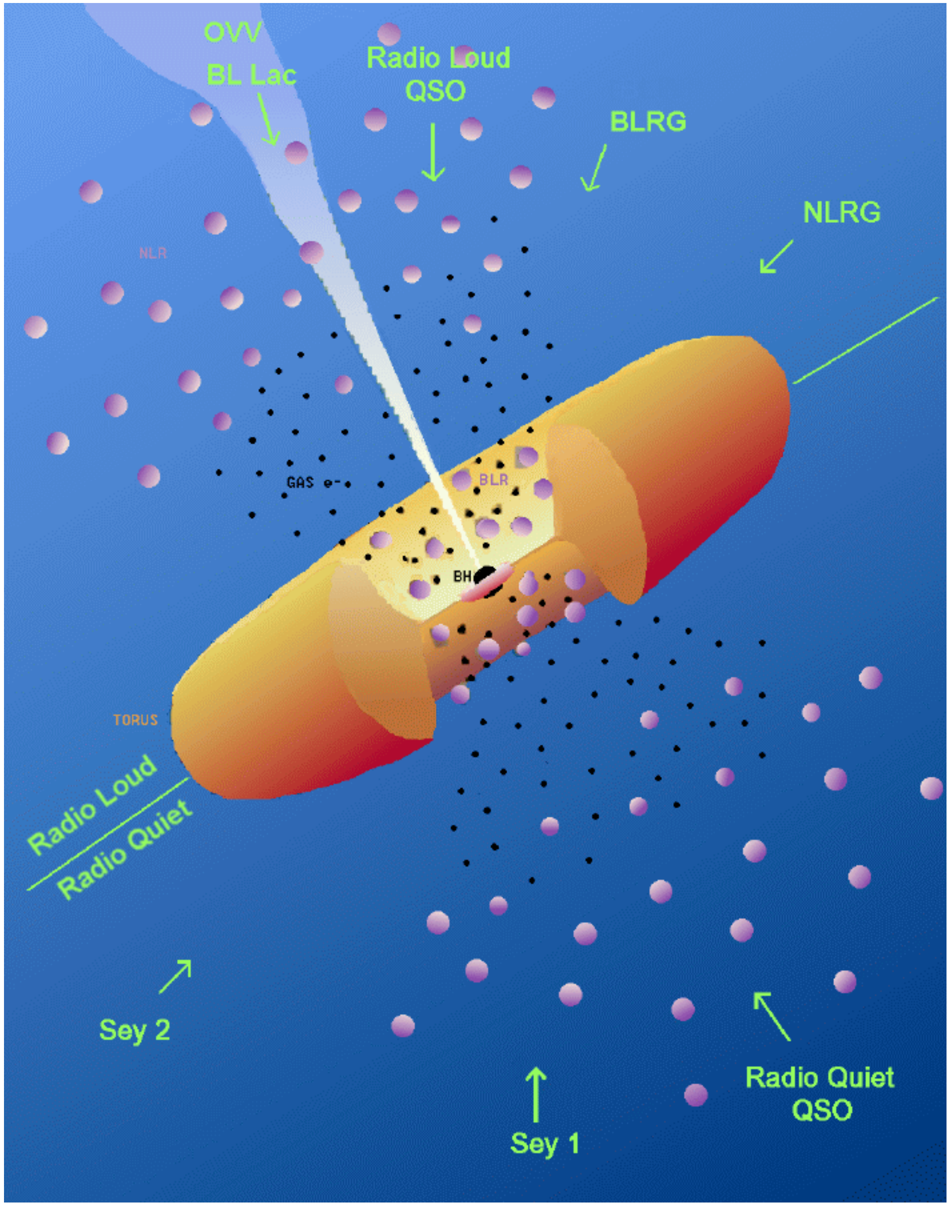
- Alexander & Hickox 2012, New Astronomy Reviews, 56, 93 (arXiv:1112:1949)
- Brandt & Alexander 2015, The Astronomy & Astrophysics Review, 23, 1 (arXiv:1501.01982)
- Hickox & Alexander 2018, ARA&A, 56, 625 (arXiv:1806.04680)

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

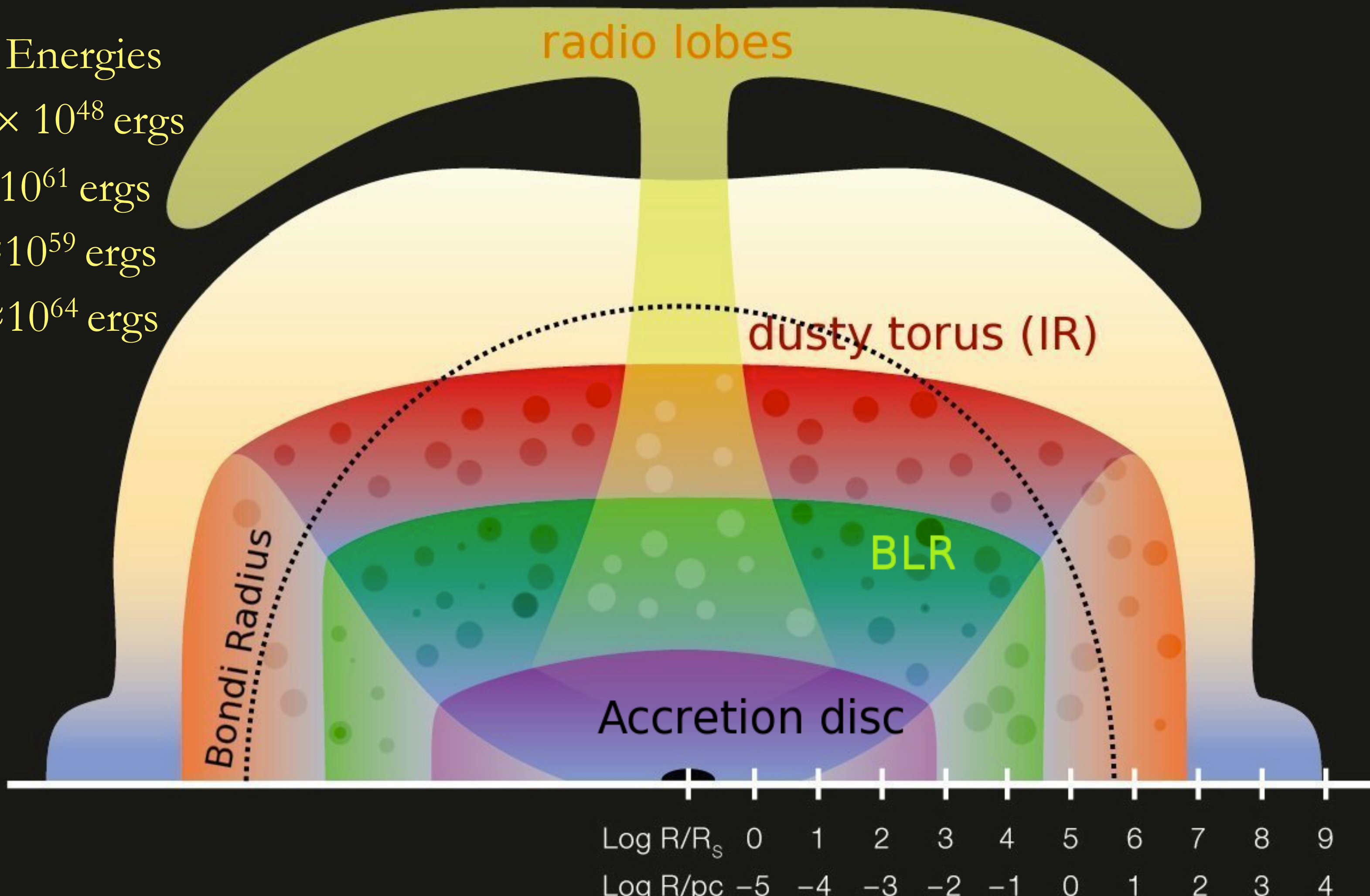
Binding Energies

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

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

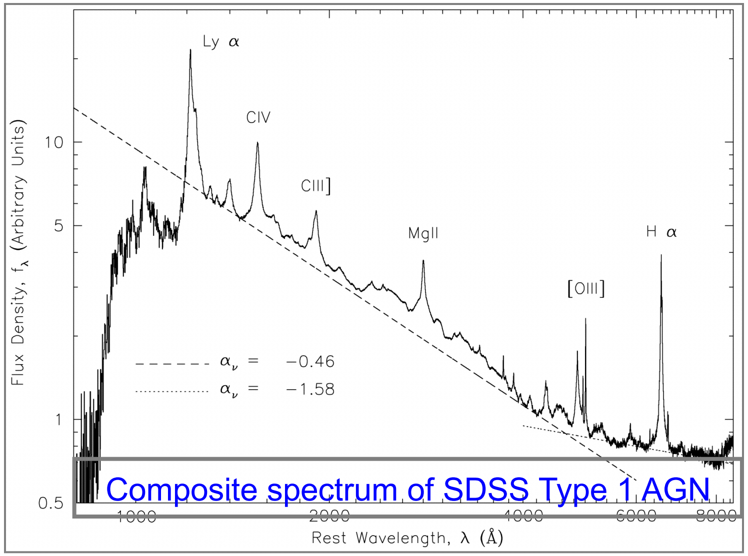
$E_{b,gal,11} \approx 10^{59}$ ergs

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

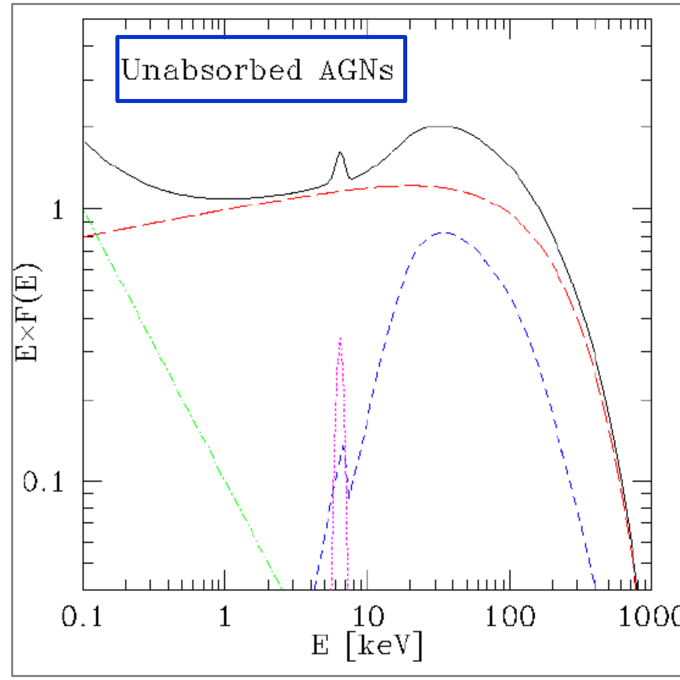


Courtesy of A. Merloni, ESO graphics, 2010

Optical band

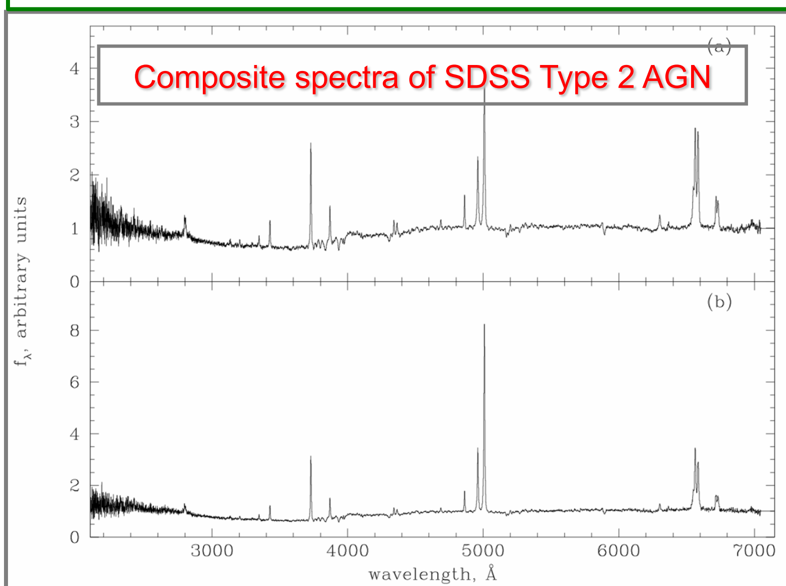


Type 1 AGN

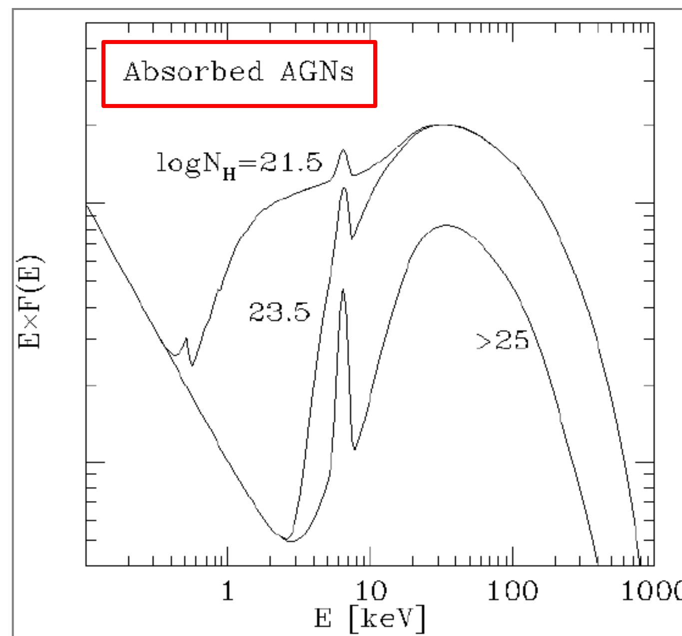


X-ray band

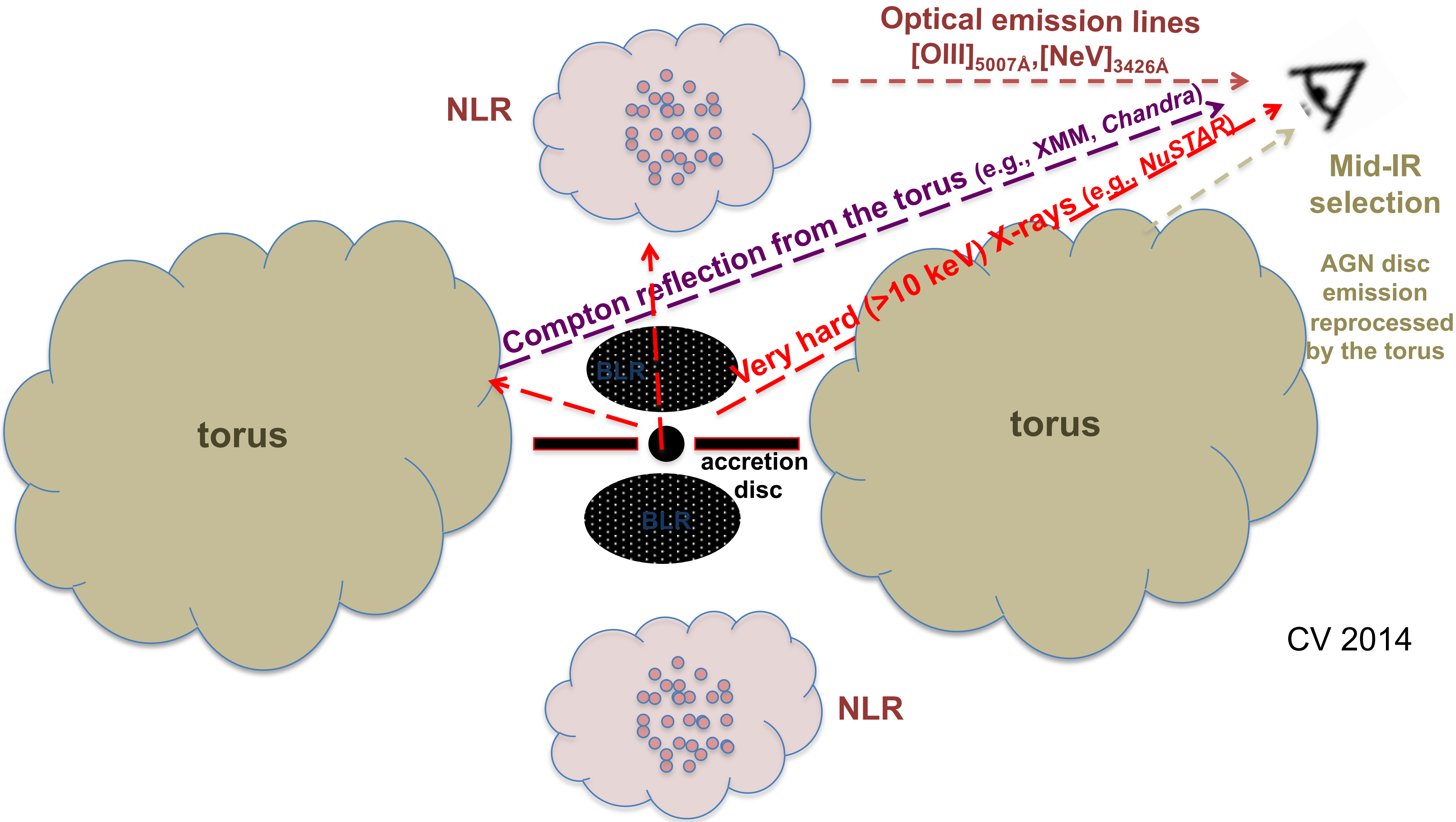
Type 2 AGN easily missed in optical and partly in X-ray surveys



Type 2 AGN



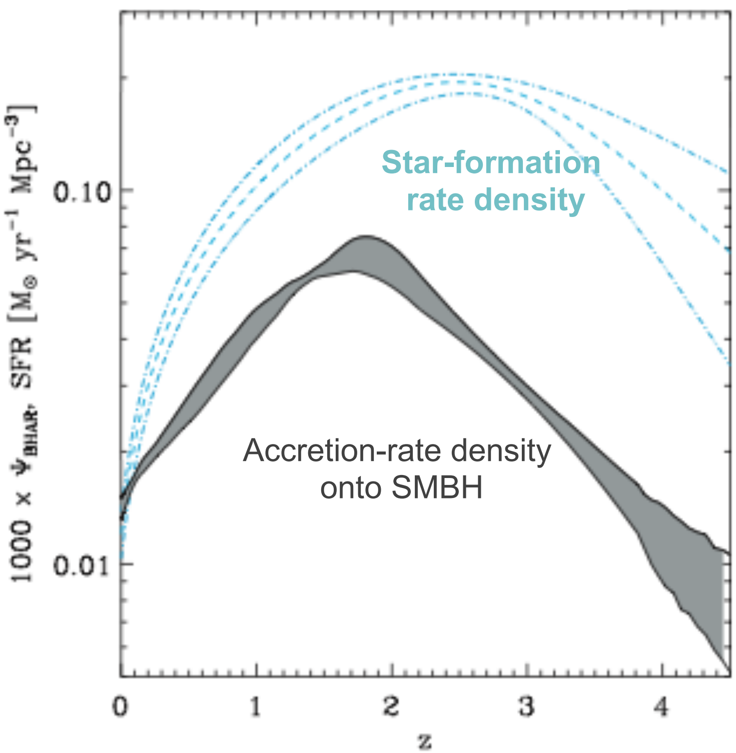
Methods to disclose obscured AGN



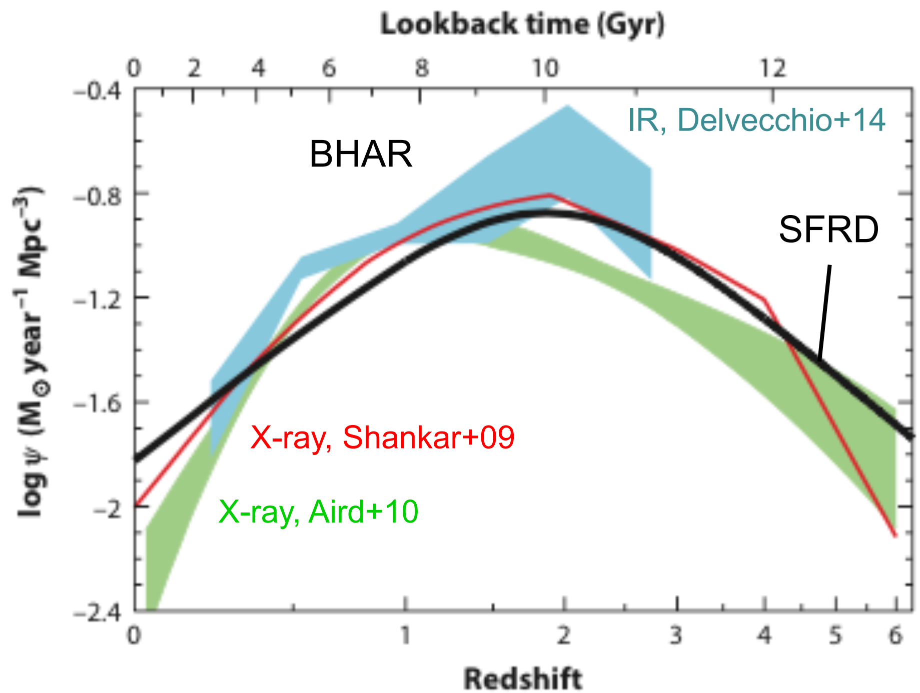
AGN can be found using proxies at other wavelengths also in case of heavy obscuration

AGN–galaxy co-evolution

Accretion and star formation history

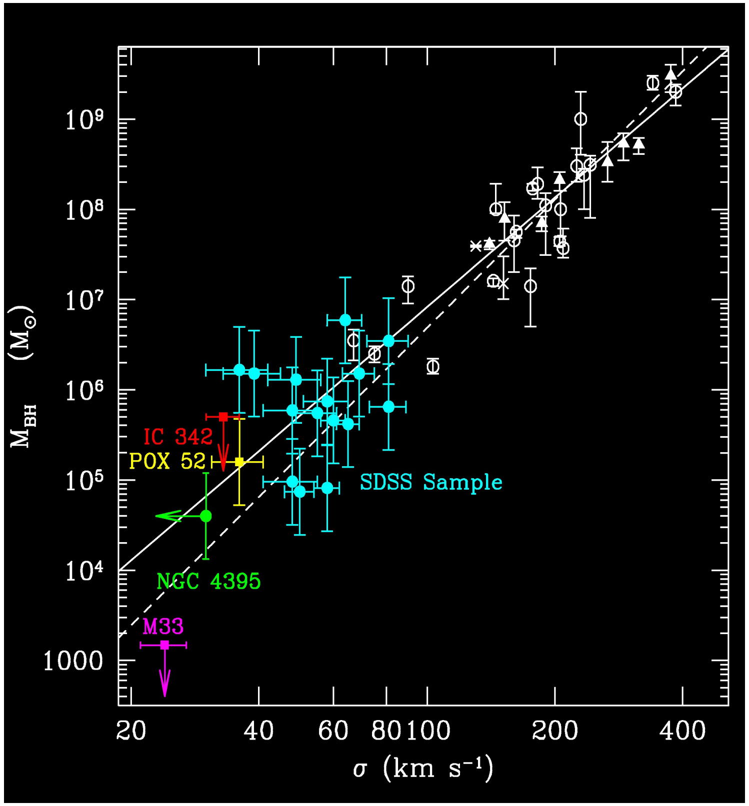


from Merloni & Heinz 2008;
see also Hopkins & Beacom 2006, Gruppioni et al. 2011



from Madau & Dickinson 2014

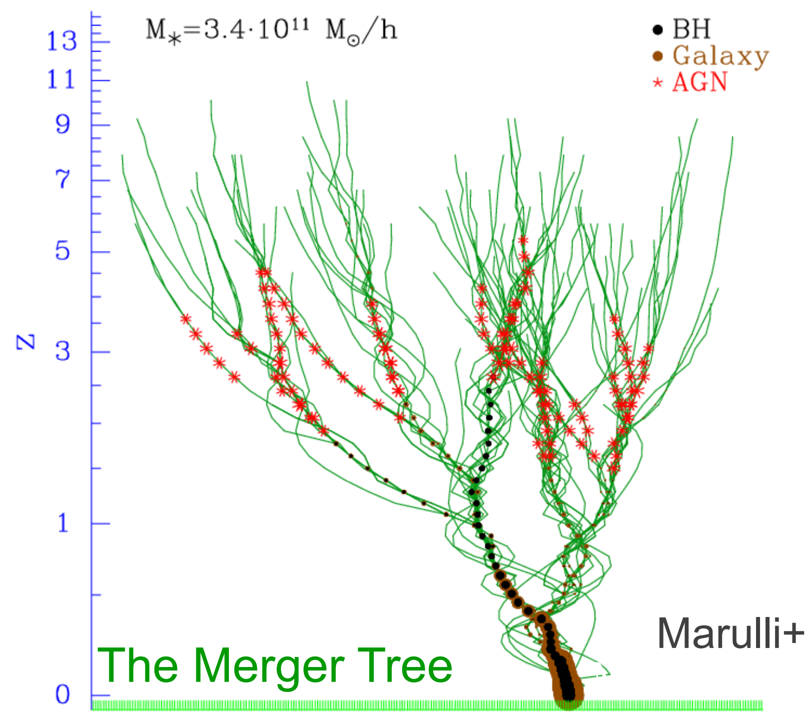
AGN as a key phase of a galaxy lifetime



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

AGN and galaxies closely tied

➔**co-evolution**

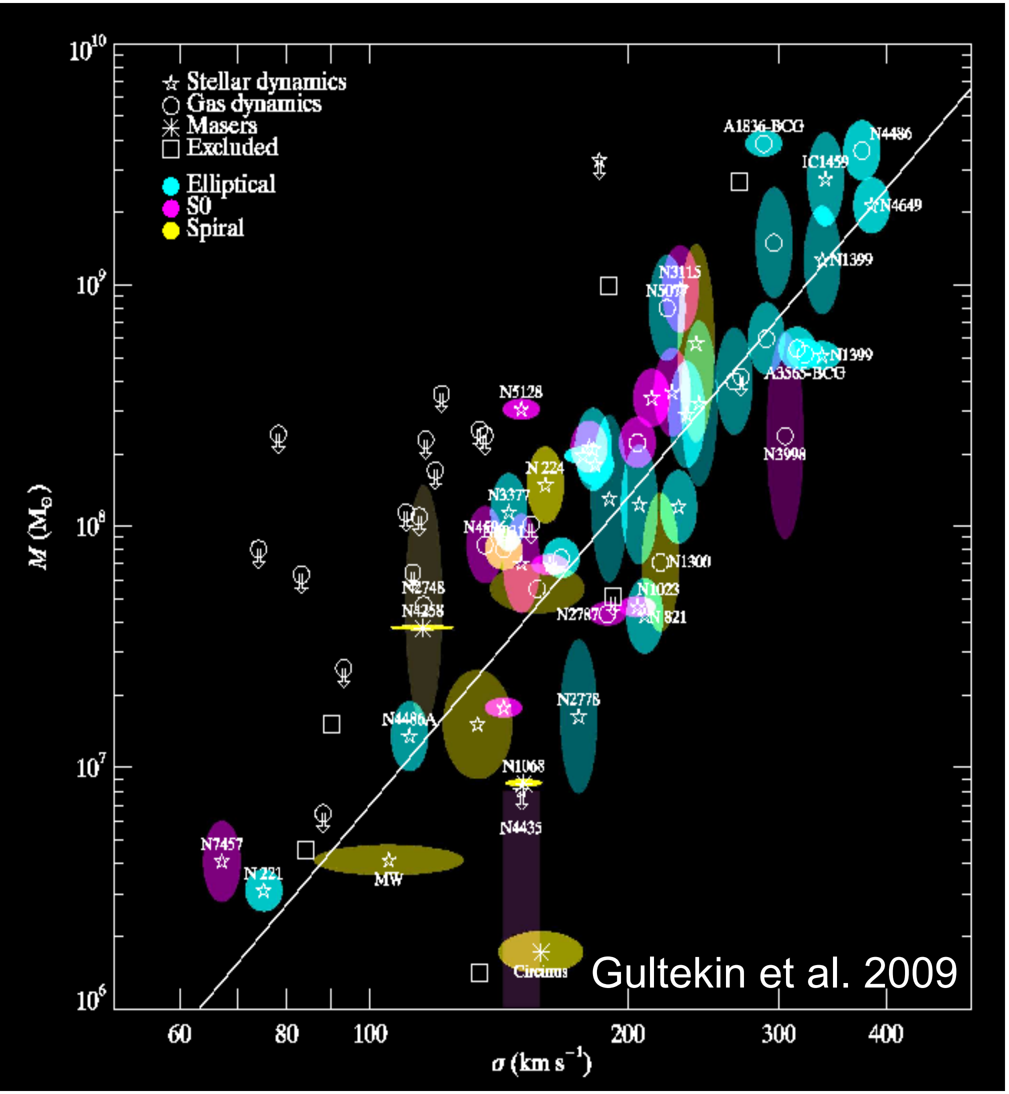


Semi-analytic models of BH/galaxy co-evolution (e.g: Kauffmann+98, Volonteri+06, Salvaterra+06, Rhook&Haehnelt08, Hopkins+08, Menci+08, Marulli+09)

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

BH-galaxy scaling relations



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**

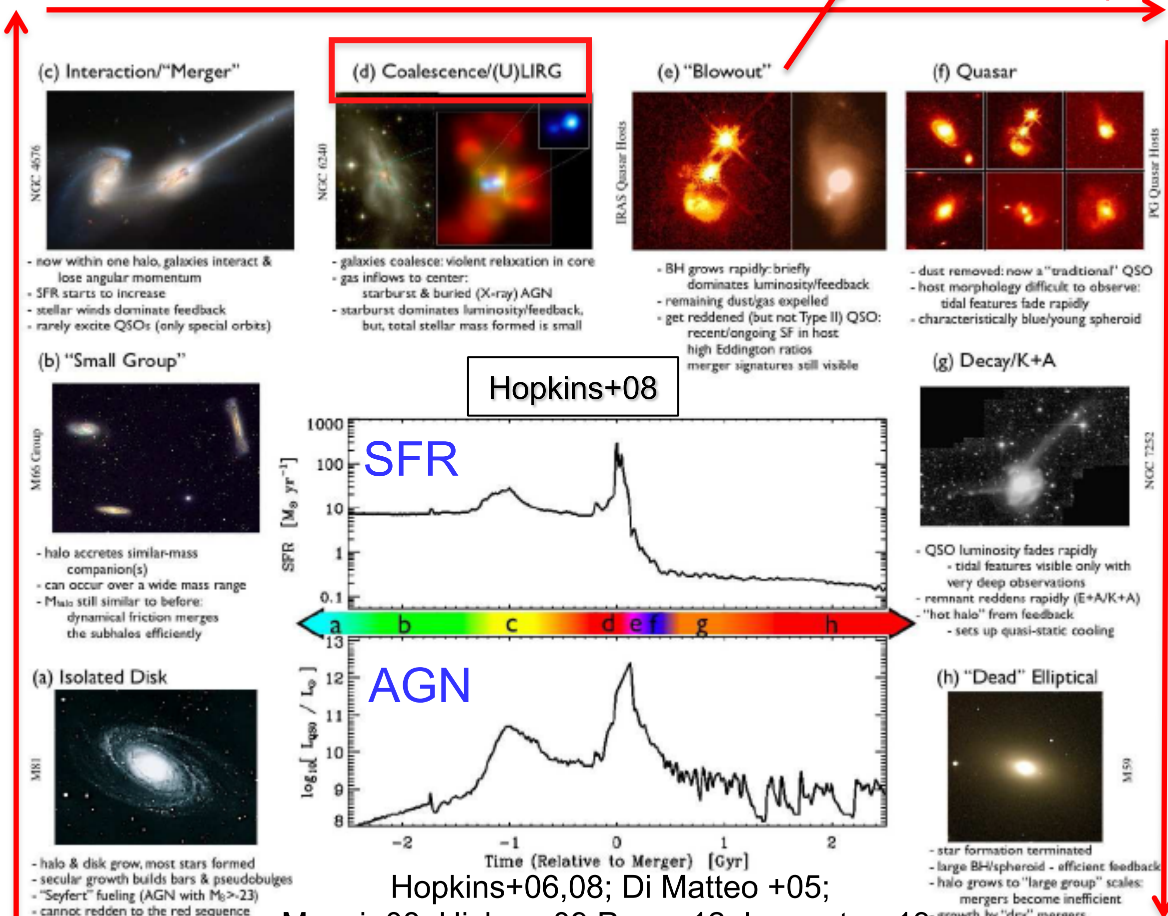
Local MBH-galaxy relations are the result of a balance between AGN activity (L_{Edd}~M_{BH}), which tends to expel gas, and galaxy gravitational attraction (E_{gr}~σ^4 Re), which tends to retain it. The balance is found for M_{BH}~0.001 M_{sph}

see the review by Kormendy & Ho (2013)

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" model (sequence)

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



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

mergers

SF/obscured accretion

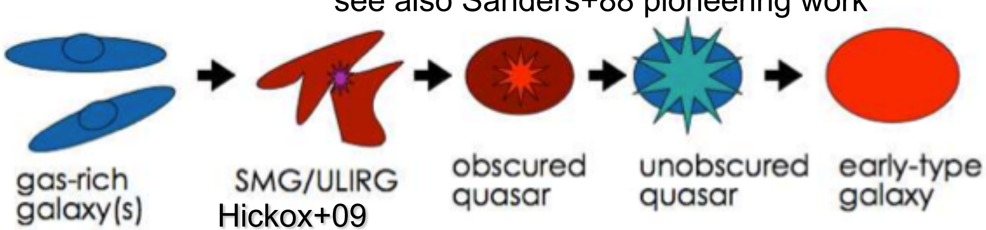
"clean" accretion (QSO)

transition (green valley) object

passive red galaxy

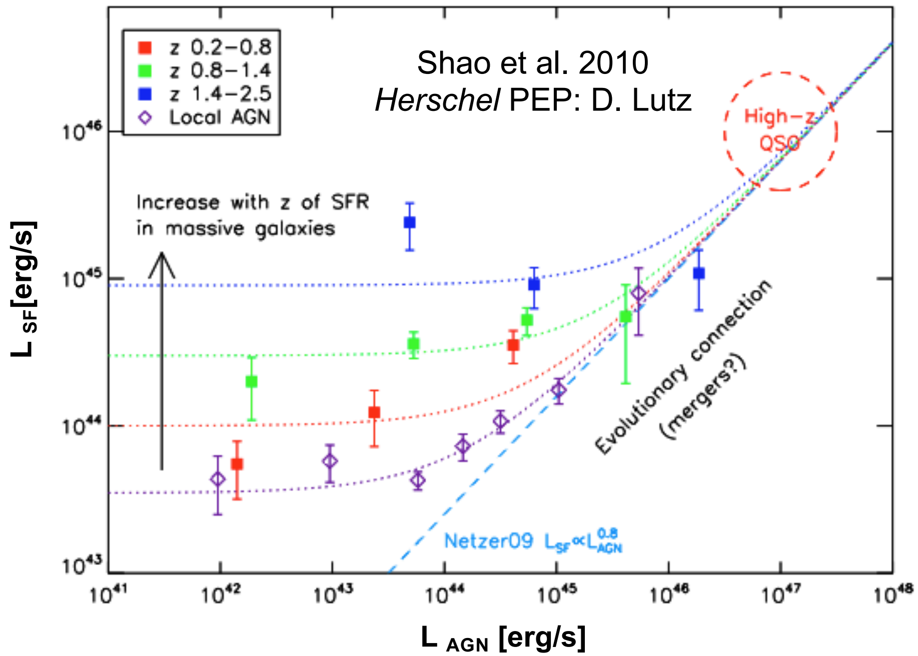
SF	Galaxy Morph.	AGN L/L_{EDD}	AGN Obsc.
Strong	Disturbed	High	High
Moderate	Coalescing	Lower	Lower
Low	Relaxed	Lower	No

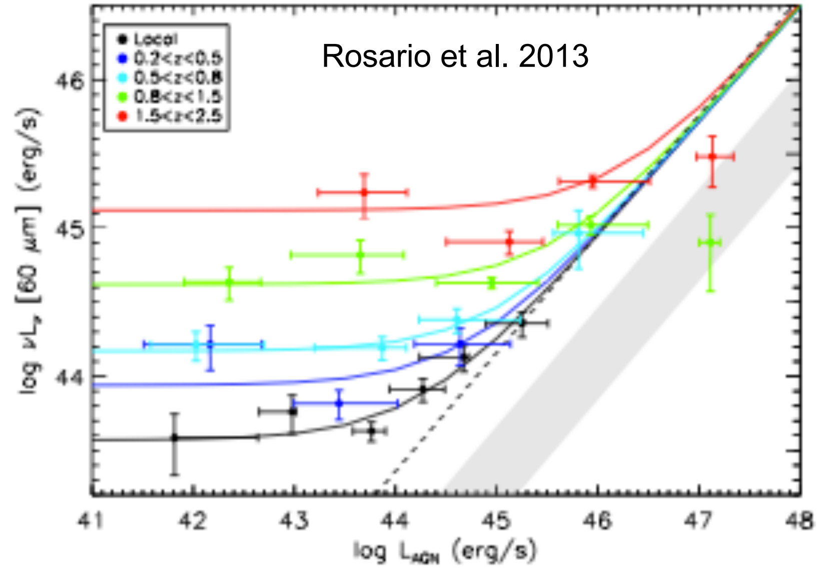
AGN feedback is likely the key to control the evolutionary sequence

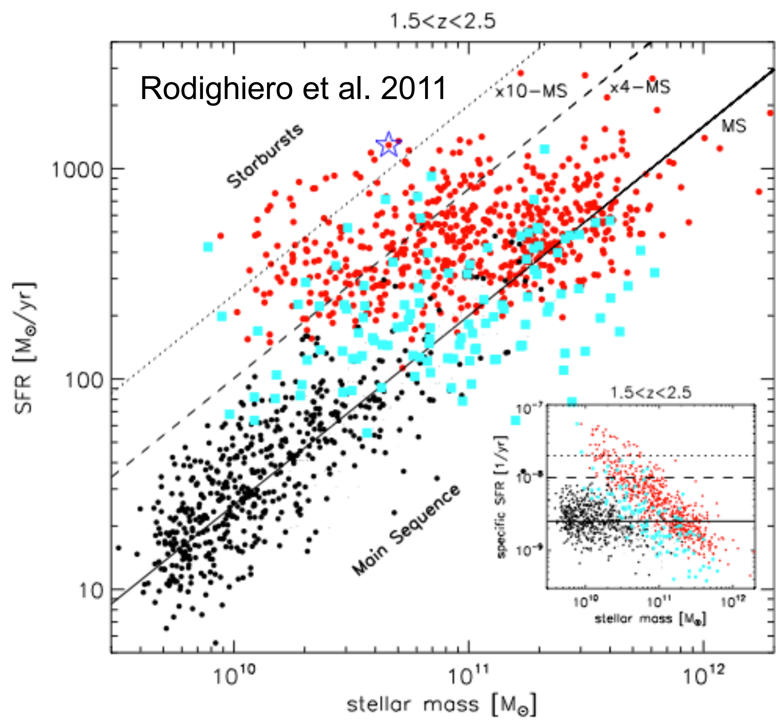


Hickox+09

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







Two paths of AGN/galaxy co-evolution

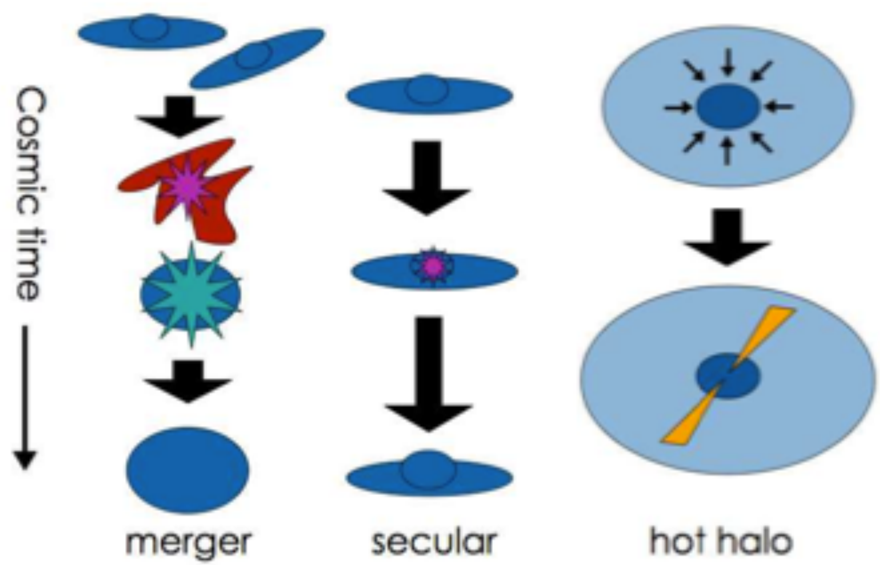
• At high AGN luminosity, galaxy merging is the driver of accretion and star formation ➔ rapid bursts of activity (~10% population?)

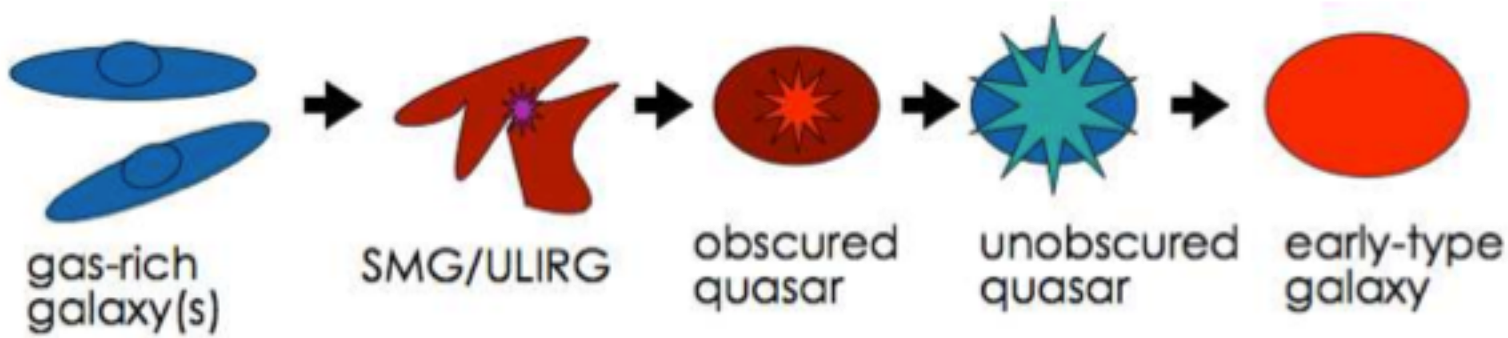
• At lower AGN luminosity, SF has little dependence on AGN luminosity ➔ secular, non-merger driven star formation (~90% pop?)

(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

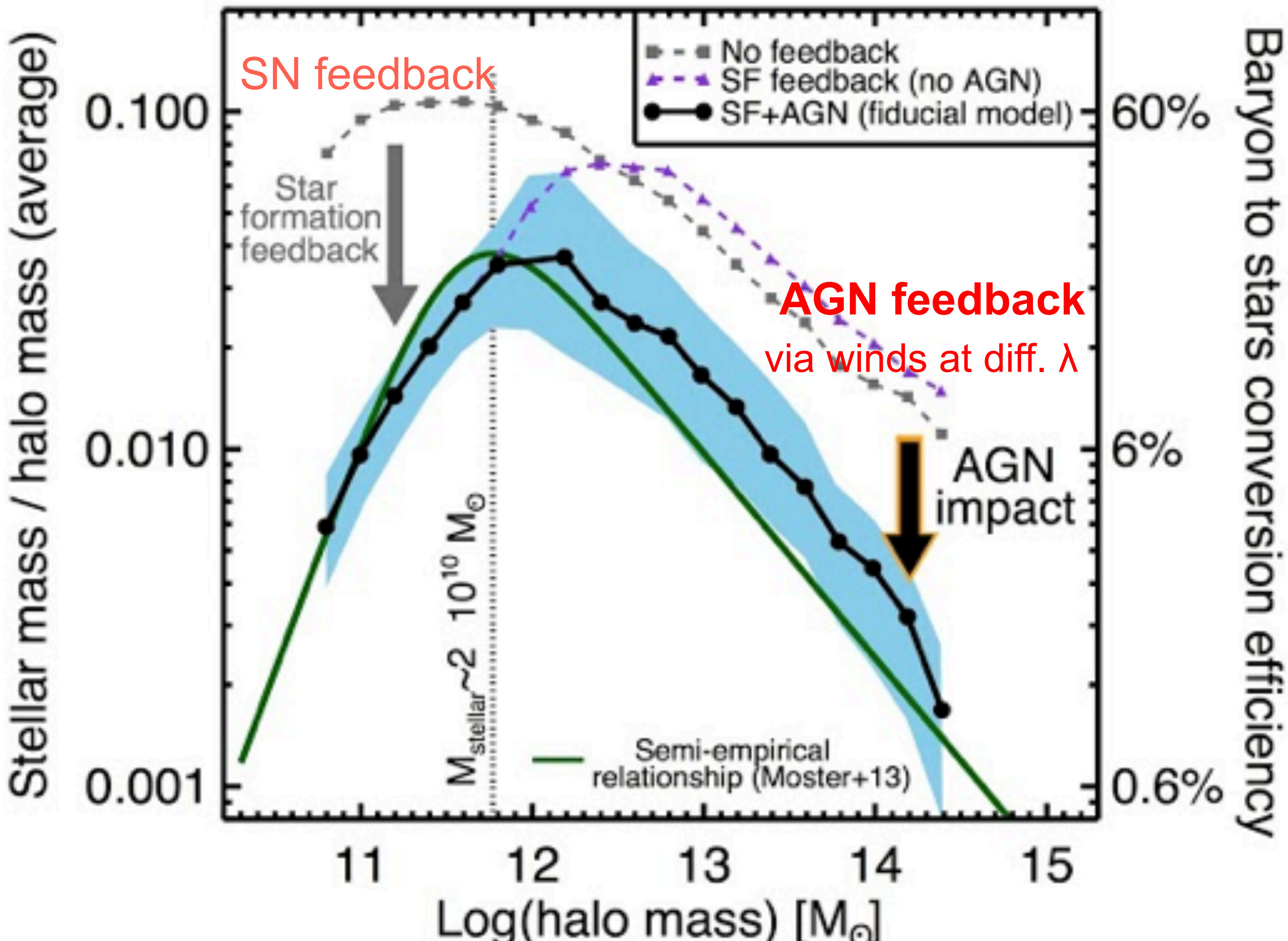
Mergers ←→ luminous quasars
Secular (disk instabilities, bars, minor mergers) ←→ low-luminosity AGN





AGN feedback

AGN feedback is needed to explain the galaxy stellar mass function at high masses

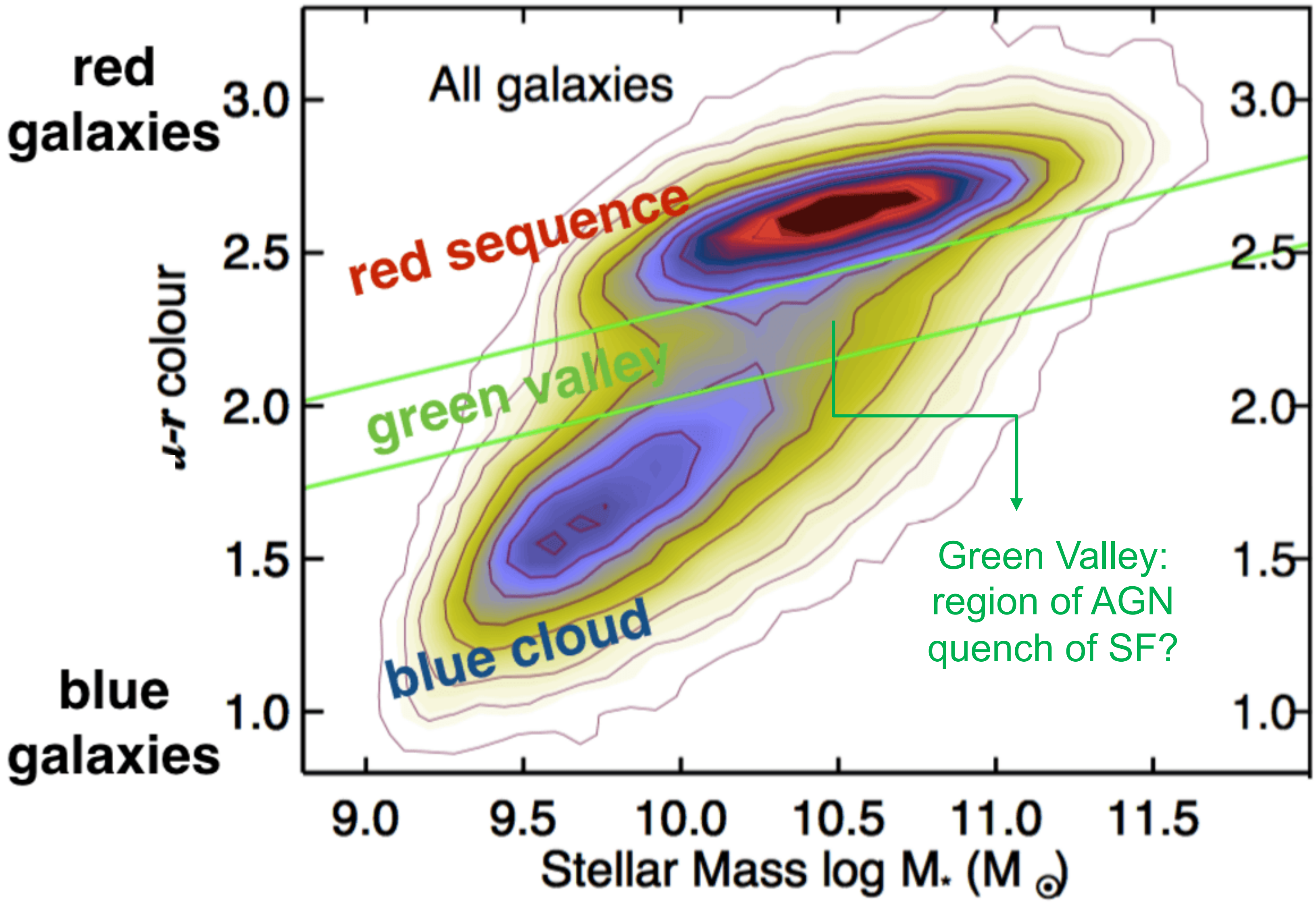


$M_\star/M_{halo} \times f_b$

fb=cosm.baryon fraction

Harrison 2017

Blue vs. red galaxies, and the green valley



Past claims of a higher fraction of AGN activity in the green valley: higher availability of fuel? (Schawinski+10) Then likely quenching of SF → galaxy in the red sequence, mostly dry mergers

Few open issues in AGN studies.
X-ray background models, and the role of X-ray surveys

Two hot topics in AGN demography studies

High-redshift

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

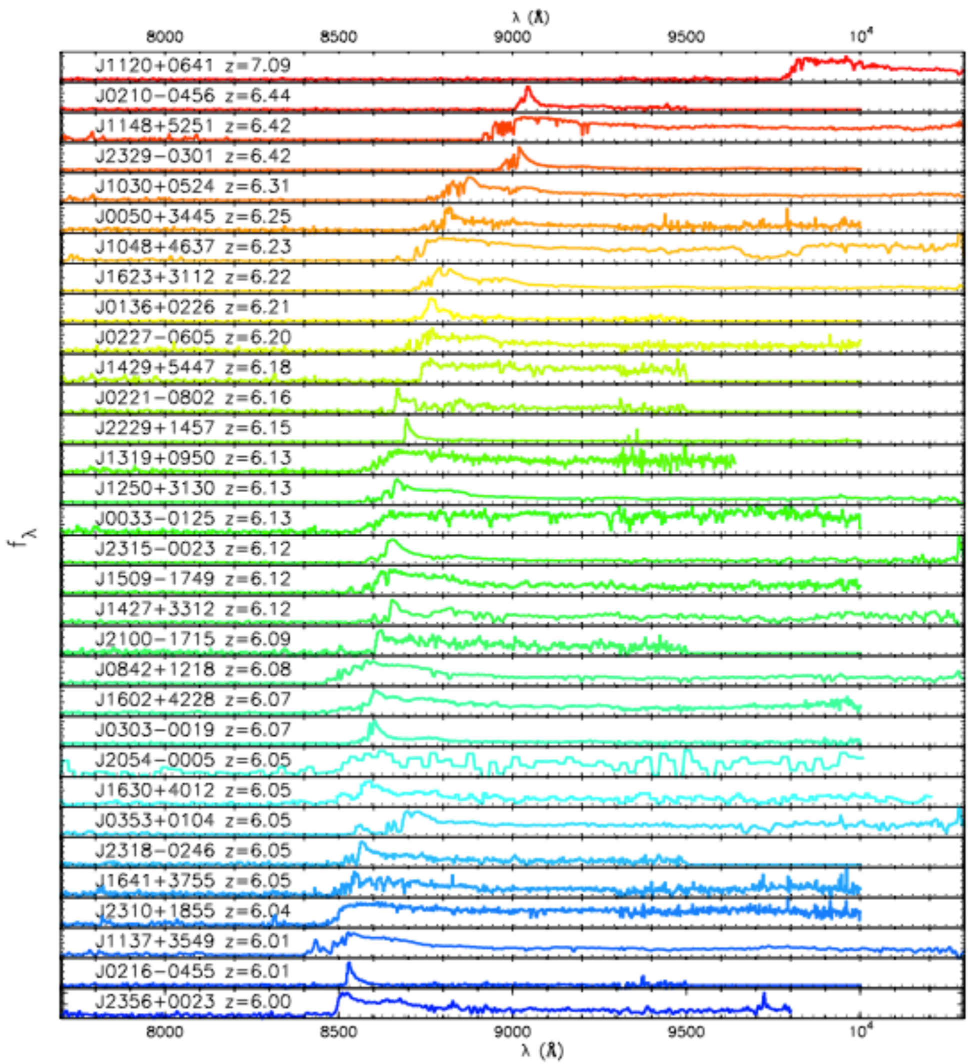
Heavily obscured AGN

Heavily obscured accretion mostly unconstrained beyond the local Universe

Requirement: a complete census of AGN activity across cosmic time

Information stored in the X-ray background

High-redshift quasars: a continuously updating field



Fan+12

continuous update of these numbers
(e.g., Inayoshi+20, ARAA: 197 at z≥6, 6 at z>7)

~310 QSOs at z>5.7 (~200 at z>6, ~50 at z>6.5, ~8 at z>7)

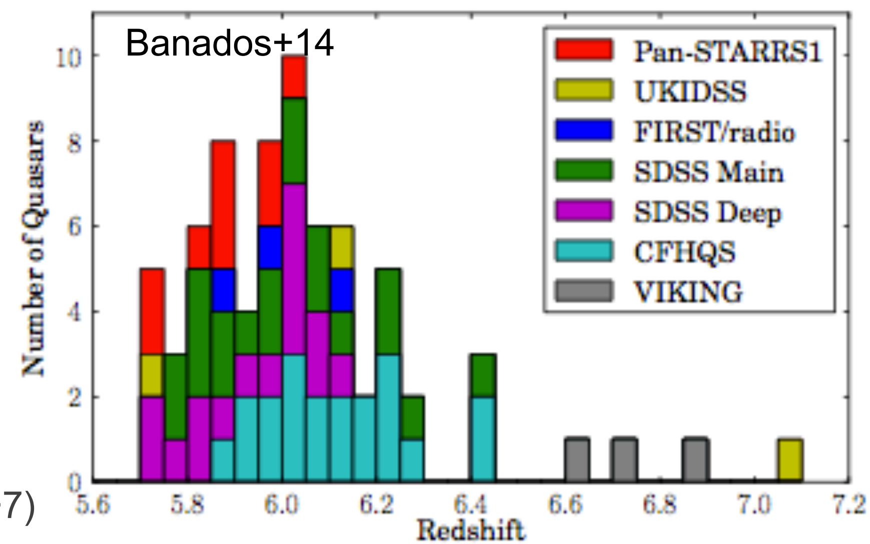
(SDSS, CFHQS, Pan-STARRS1, DES, UKIDSS, VISTA-Viking, HSC) - (Fan+00−06; Jiang+08,09; Willott+07,09,10; Banados+14-16; Mortlock+11; Venemans+13, 15, Matsuoka+16,18,19)

SELECTION: Opt/NIR, 4 radio (McGreer+06, Zeimann+11, Belladitta+20-blazar, …)**, 0 X-ray**

About 1/10 with X-ray coverage, 19 X-ray det.

SDSS traces the most luminous QSOs (logLx~45, $\log L_{bol}$~46.5, M_{1450}=[−24,−28])

Faint end of the LF still to be achieved



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

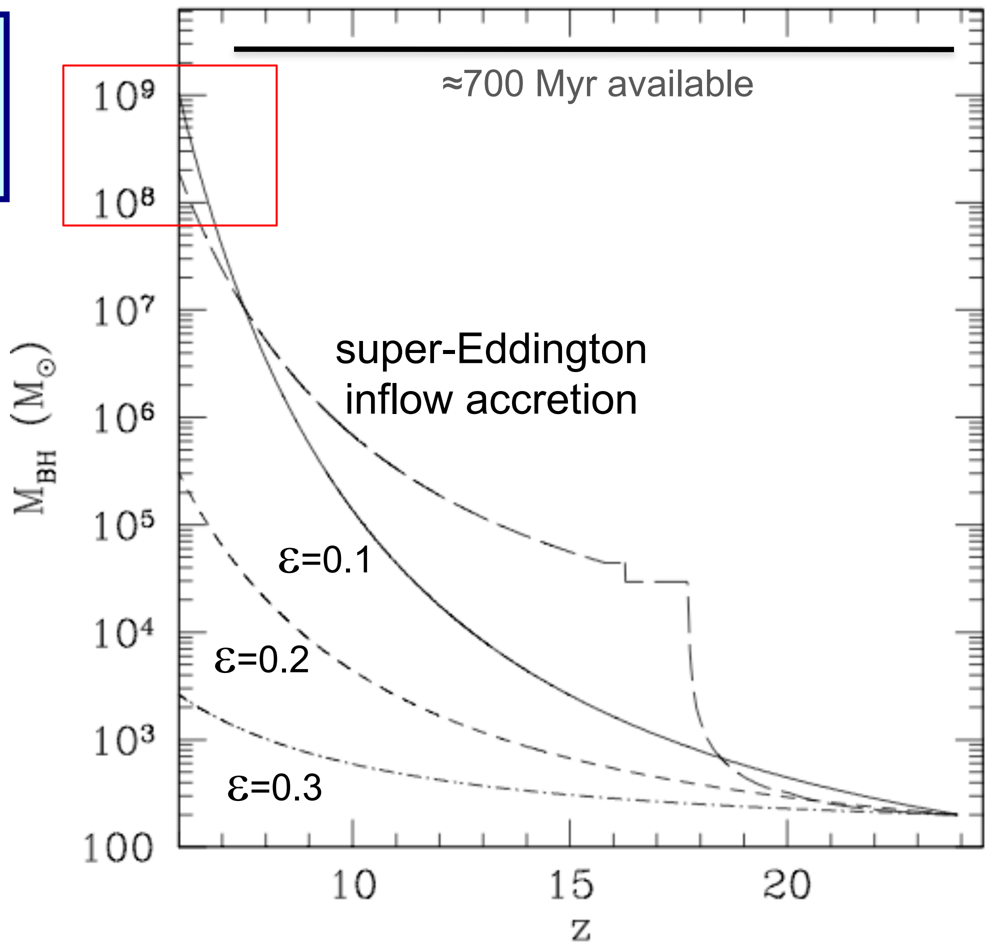
$$M(t) = M_0 \exp\left(\frac{1-\varepsilon}{\varepsilon} \frac{t}{t_{Edd}}\right)$$

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

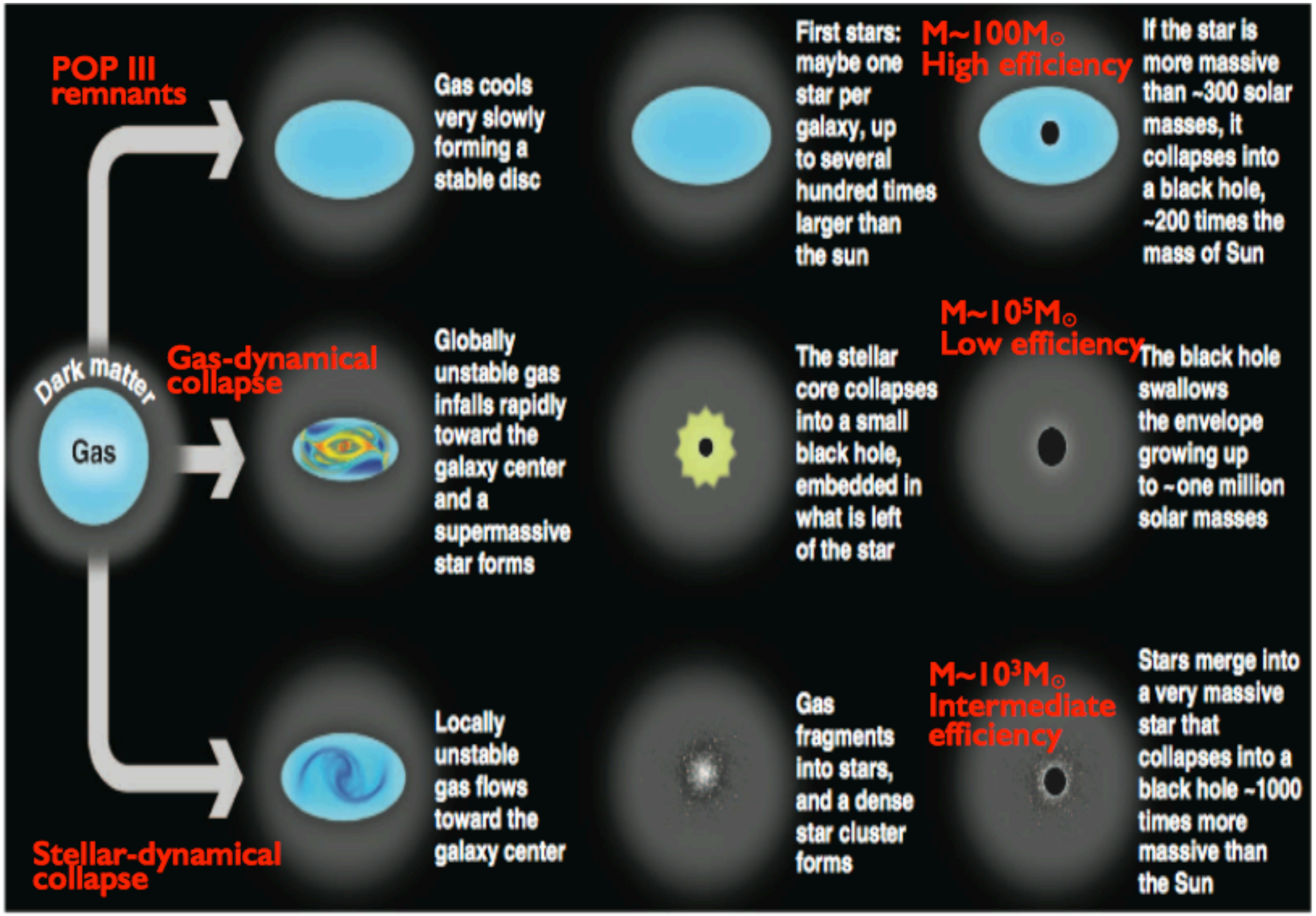
Highest-redshift quasar so far spectroscopically identified: ULASJ1342+0928, z=7.54, $M_{BH} \approx 8 \times 10^8\ M_\odot$ (Banados et al. 2017)



Volonteri & Rees 2006

Possible problems with the mass of the "seed" BHs

BH growth at high redshift: which BH seeds?



Volonteri10 review

"light" seeds
(pop III star remnants)
$M_{BH} \approx 100-600\ M_{\odot}$
$z \approx 20-50$
Madau & Rees 01
Volonteri+03

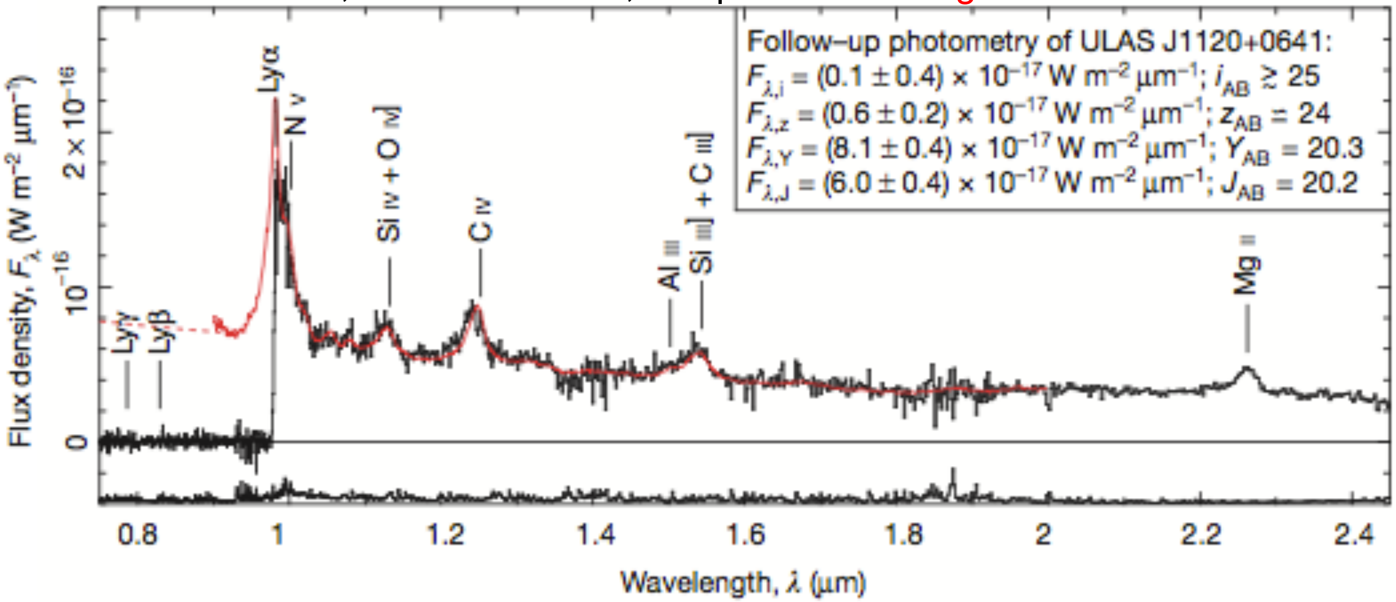
"heavy" seeds
DCBHs
$M_{BH} \approx 10^4-10^6\ M_{\odot}$
$z \approx 5-10$
Volonteri+08, Agarwal+13, Yue+13

intermediate seeds
$M_{BH} \approx 10^3\ M_{\odot}$, $z \approx 10-15$
Runaway stellar mergers in high-z clusters
Devecchi & Volonteri09

Needed: very low metallicity (otherwise fragmentation)

Fully “mature” quasars at high redshift

Mortlock+11, GNIRS+FORS2, compared to average z~2.5 SDSS QSOs



UKIDSS

ULAS J1120 z=7.08

$M_{1450}=-26.6$
$M_{BH}=2.4\times10^9\ M_\odot$
$L_{bol}\approx2.4\times10^{47}$ erg/s

see also J1007+2115 at z=7.52, Yang+20

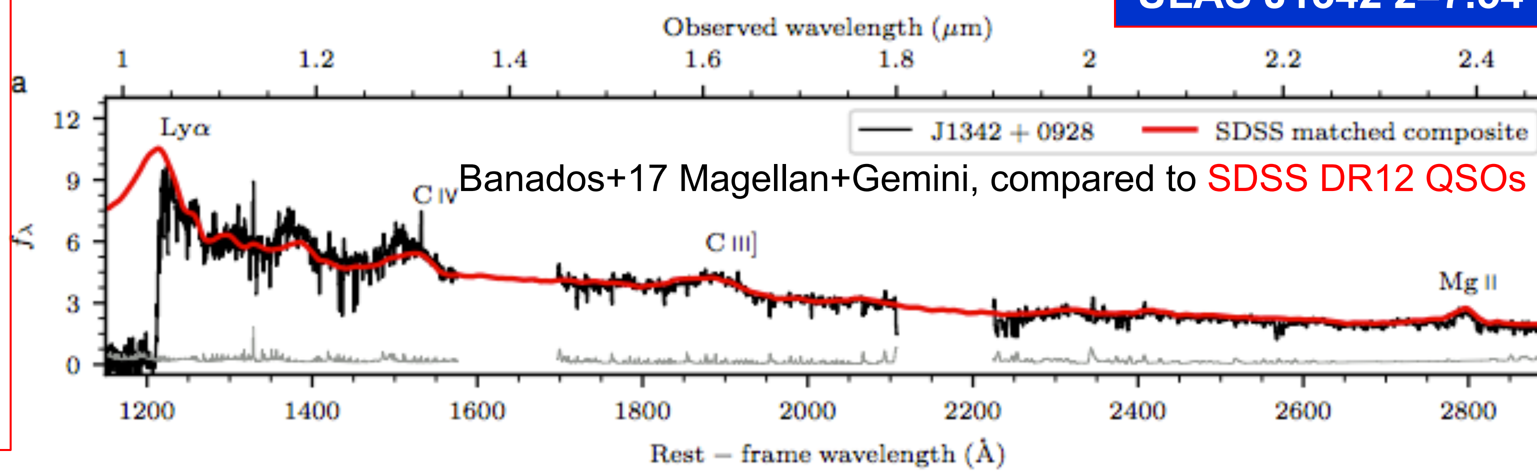
$M_{1450}=-26.8$
$M_{BH}=8.0\times10^8\ M_\odot$
$L_{bol}\approx1.5\times10^{47}$ erg/s

ULAS J1342 z=7.54

Metallicity of high-z QSOs is similar to that of low-z QSOs

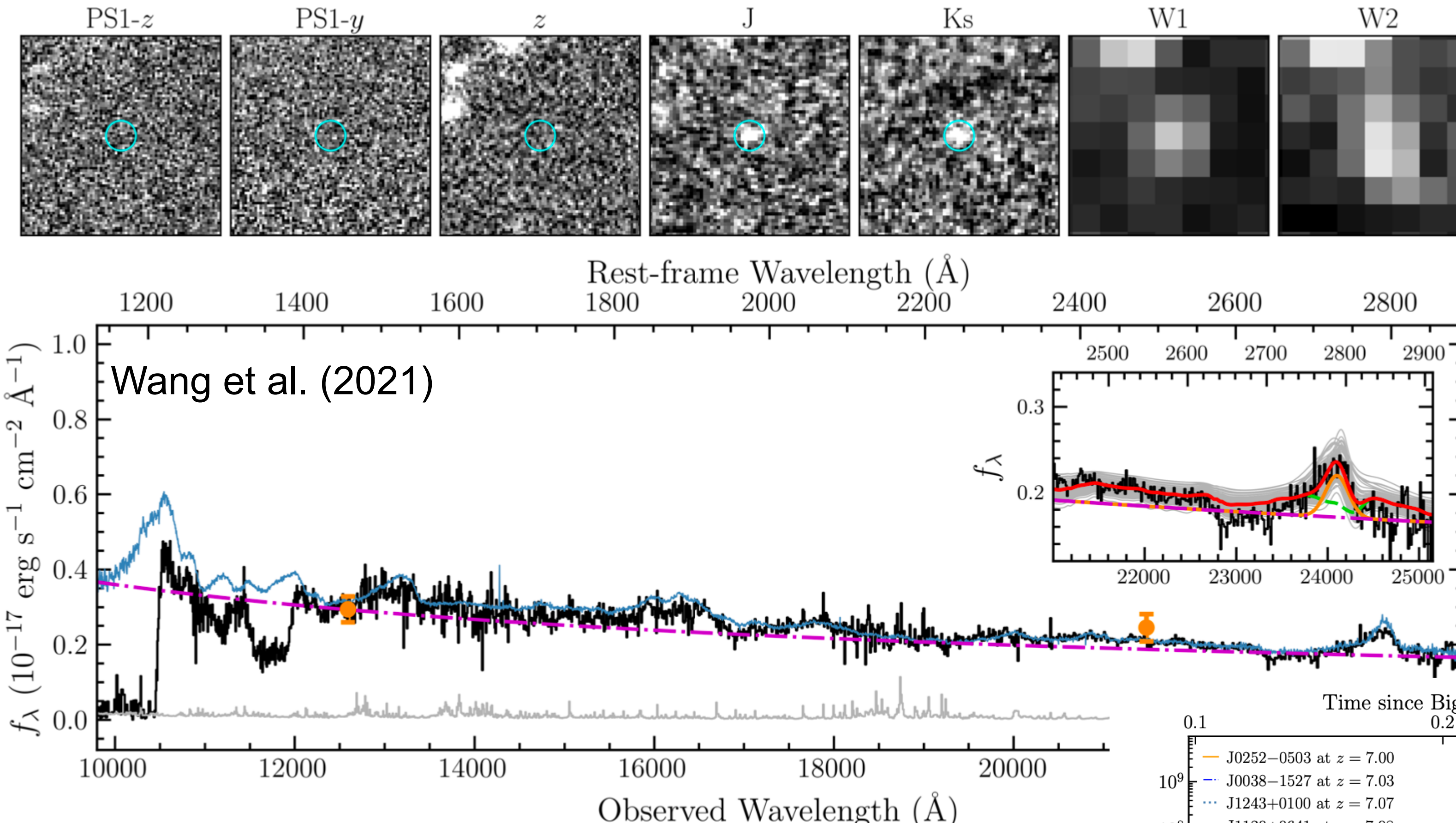
→ the nuclear regions are metal rich

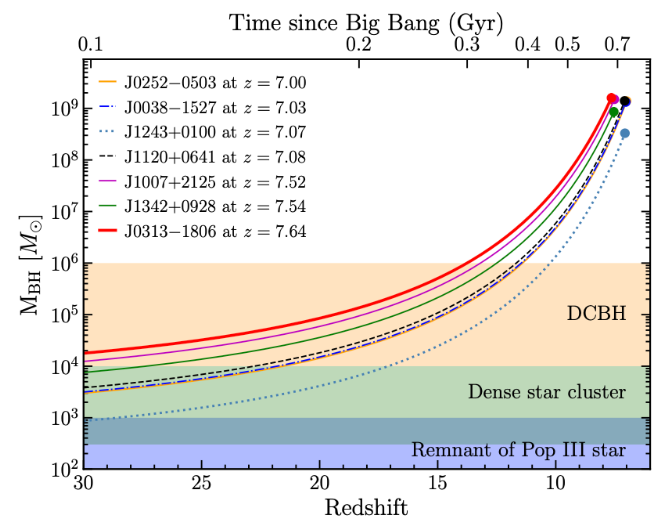
→ major episode of chemical enrichment in their hosts at t_U<1 Gyr



Banados+17 Magellan+Gemini, compared to SDSS DR12 QSOs

The newly discovered highest redshift quasar





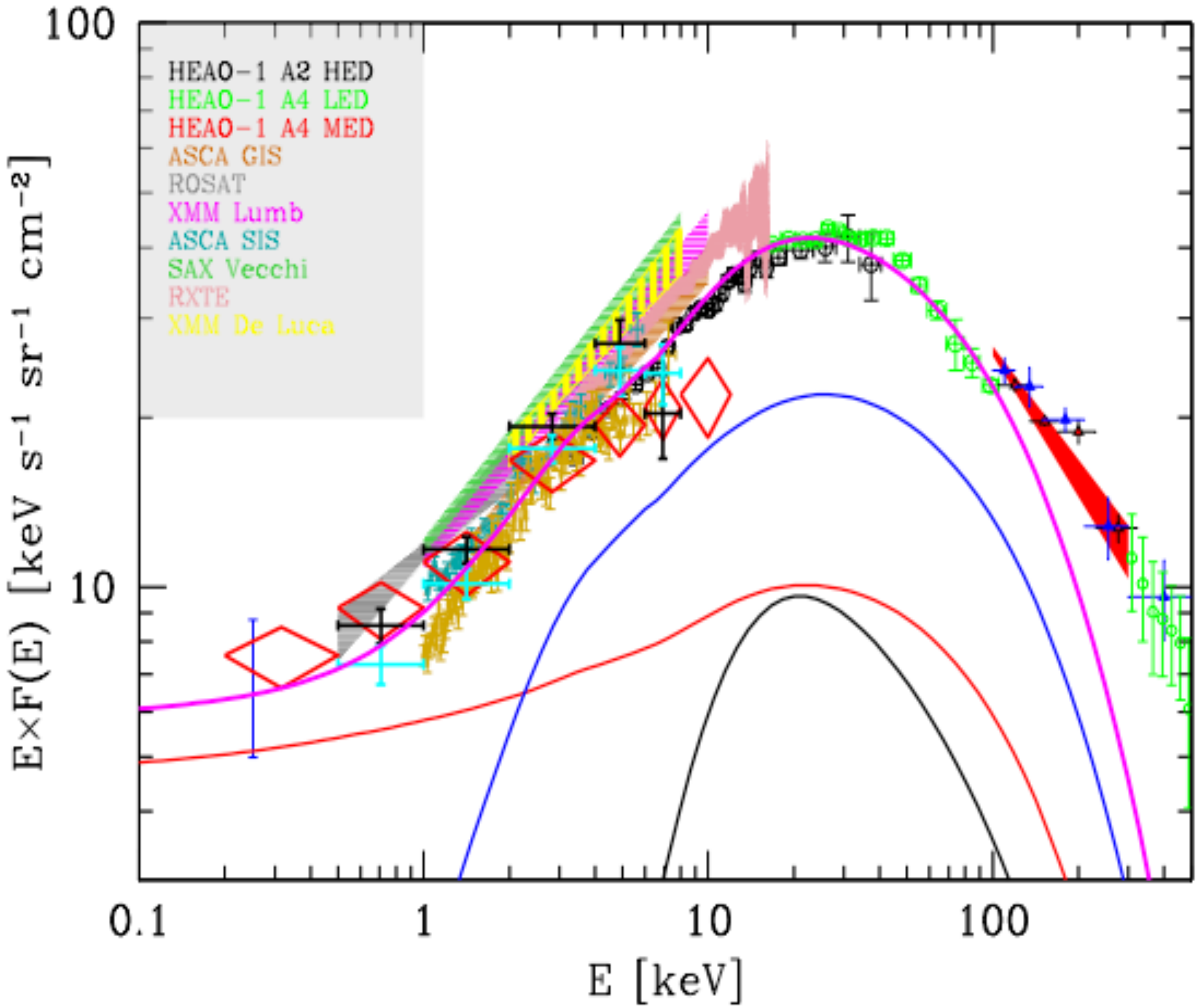
Pan-STARRS1

ULAS J0313-1806 z=7.642

M_{1450}=−26.1
M_{BH}=1.6 × 10^9 $M_\odot$
L_{bol}≈1.4 × 10^{47} erg/s

The spectrum of the cosmic XRB

XRB as the ‘sum’ of obscured and unobscured AGN – currently, many models for the XRB, following the original idea of Setti & Woltjer 1989



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

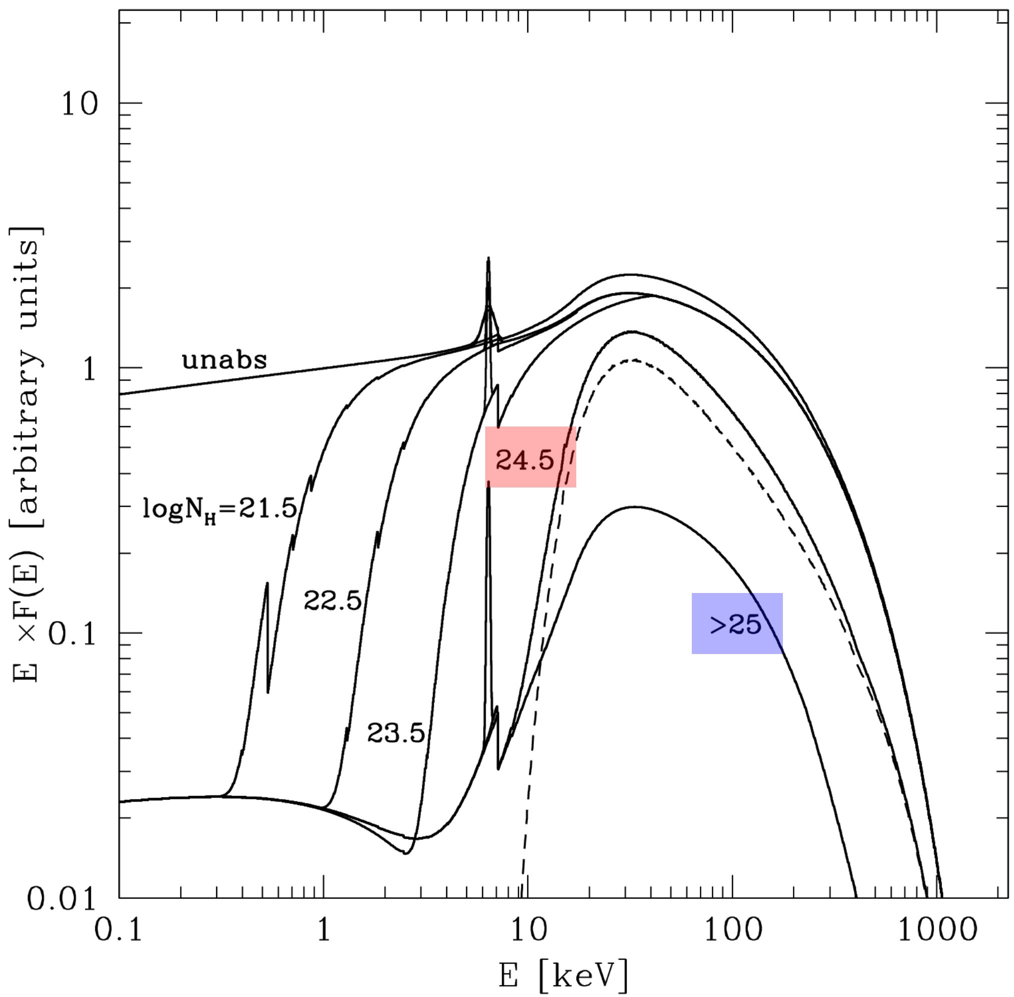
Red → unobscured

Blue → Compton Thin

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

The evolution is folded in the adopted XLF

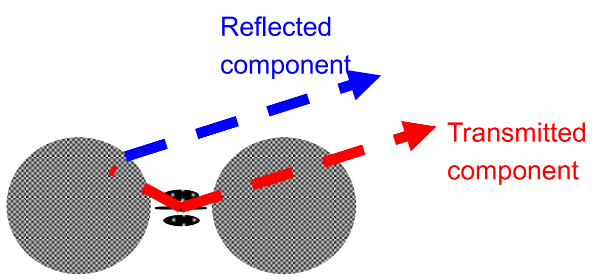
AGN X-ray spectral templates with different N_H



Unabsorbed:
$\log N_H < 21$

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

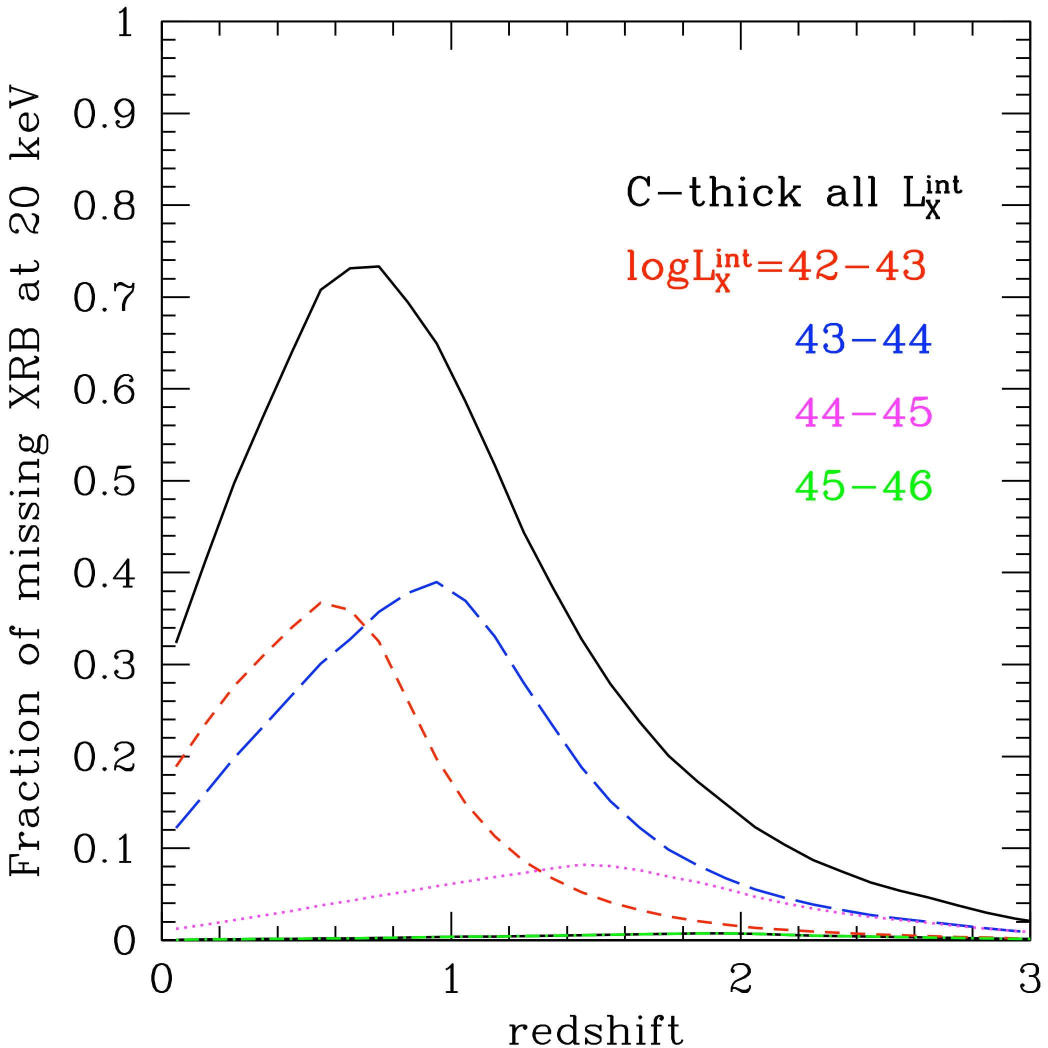
Compton-Thick:
Mildly ($\log N_H = 24\text{-}25$)
Heavily ($\log N_H > 25$)



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

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.

When the “missing” XRB was emitted?



Predicted peak at z≈0.7-0.8

Mostly at $L_x \sim 10^{42-44}$ erg/s

Gilli 2013

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

Large-area surveys
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?

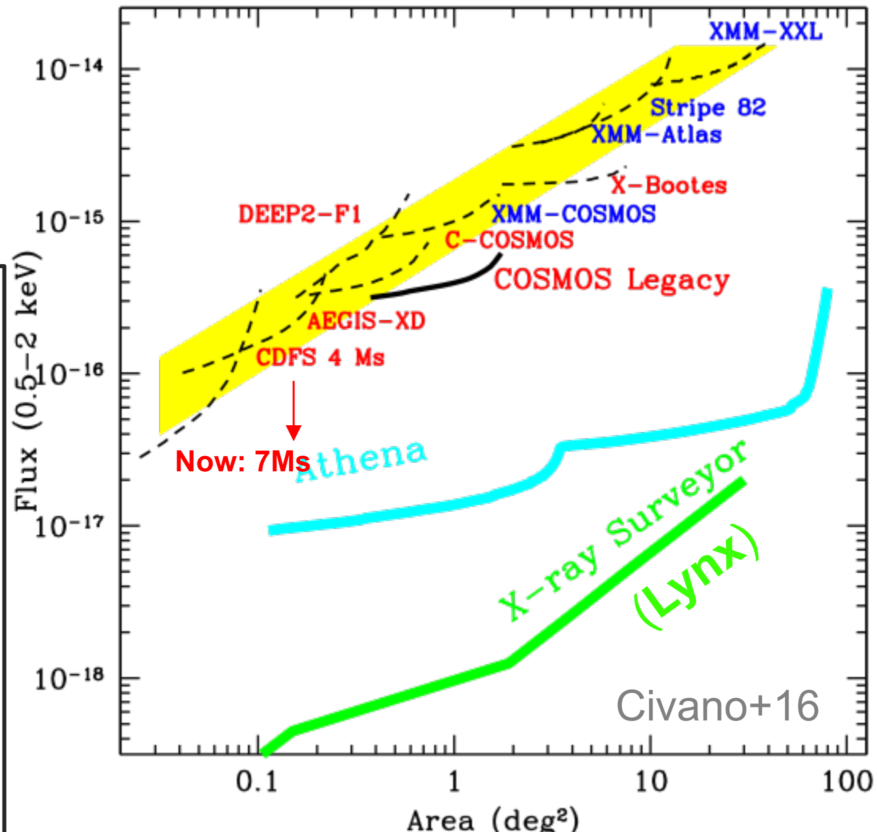
DEEP X-RAY SURVEYS

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



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:

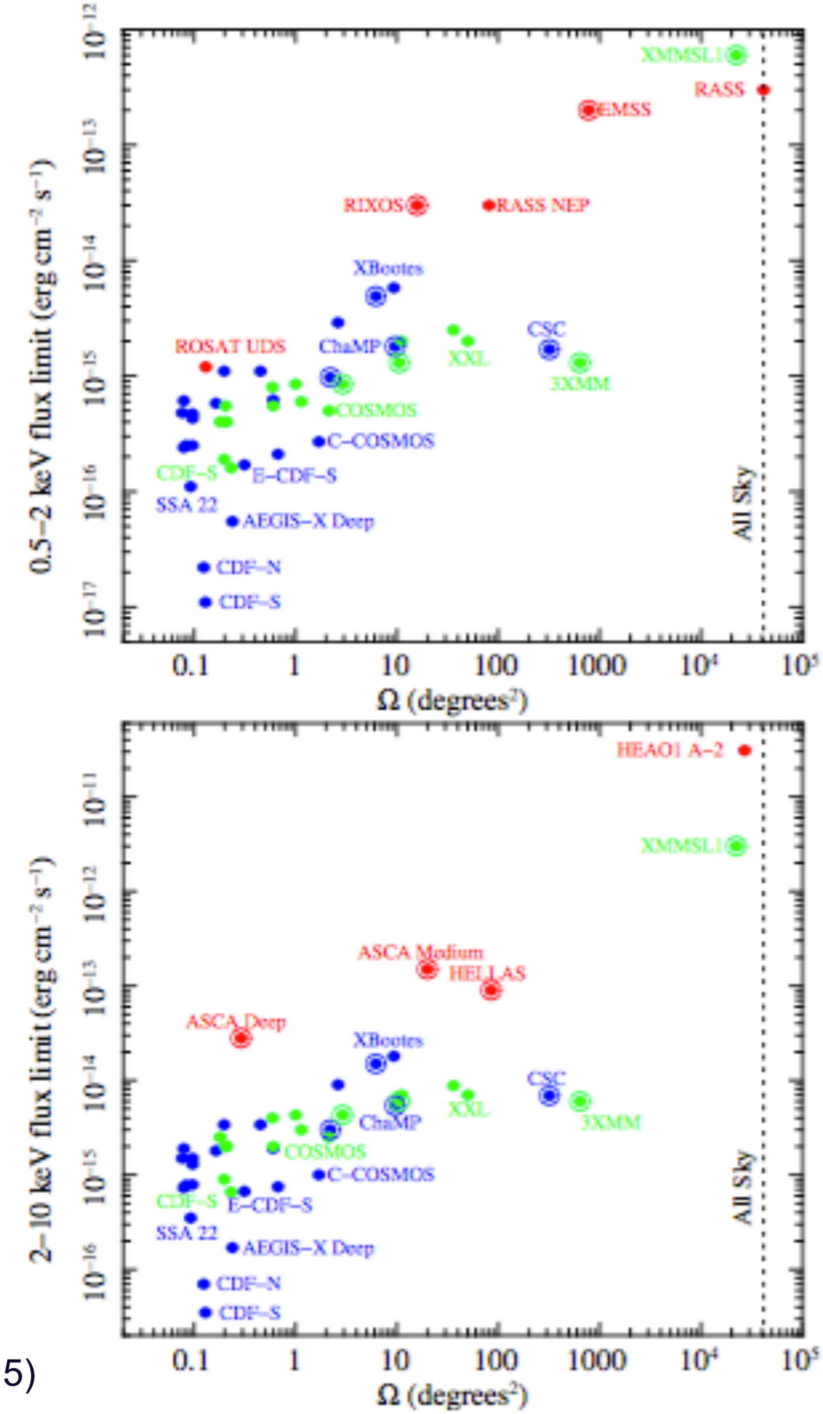
- Ideal to pick up bright and rare X-ray sources
- Possibility to cover large areas of the sky

CONs

- Limited number of sources

0.5−2 keV
flux limit
vs. Area

2−10 keV
flux limit
vs. Area



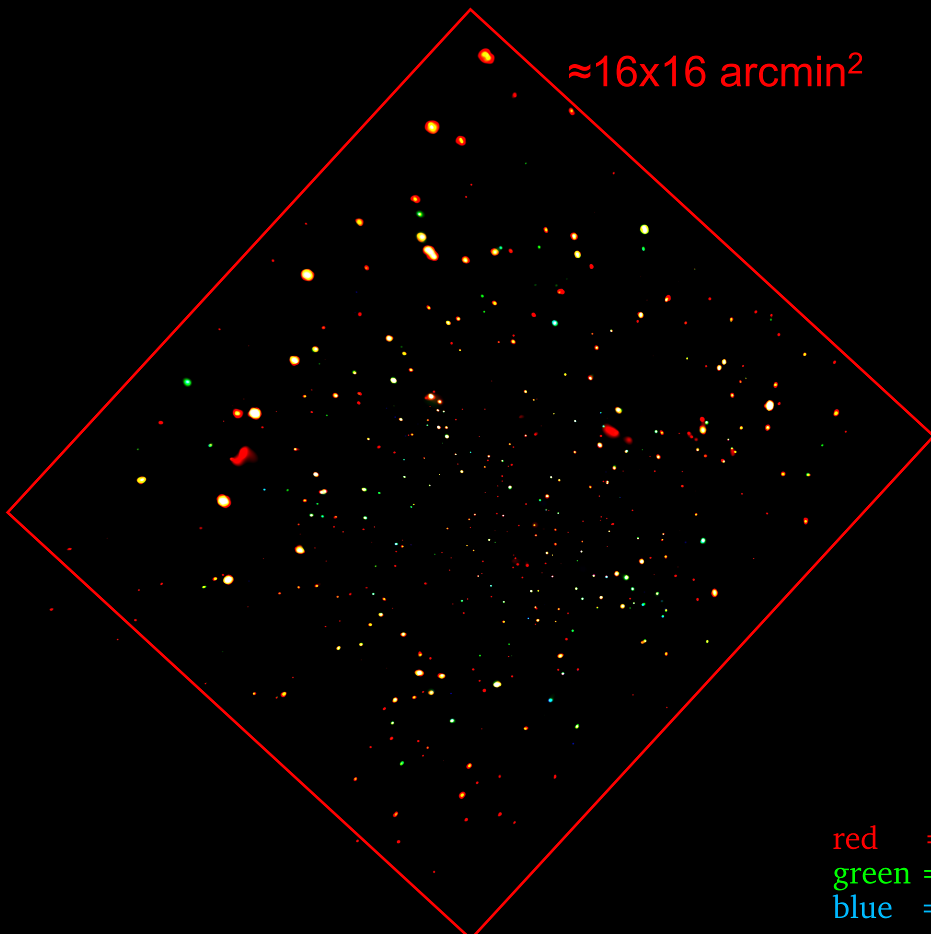
RASS: all sky in the soft band

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

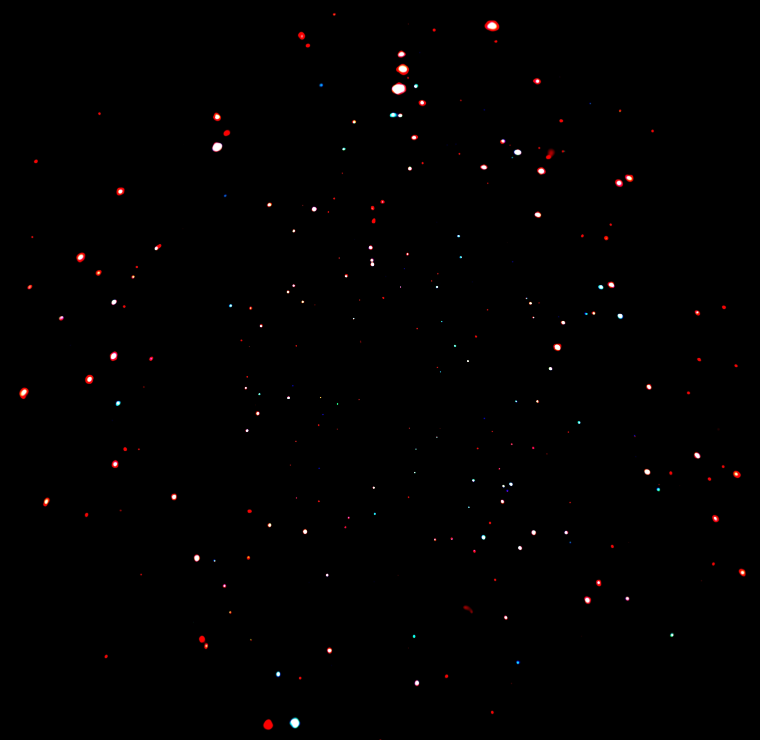
(e.g., Brandt & Alexander 2015)

Chandra Deep Fields: where all begun in modern times

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



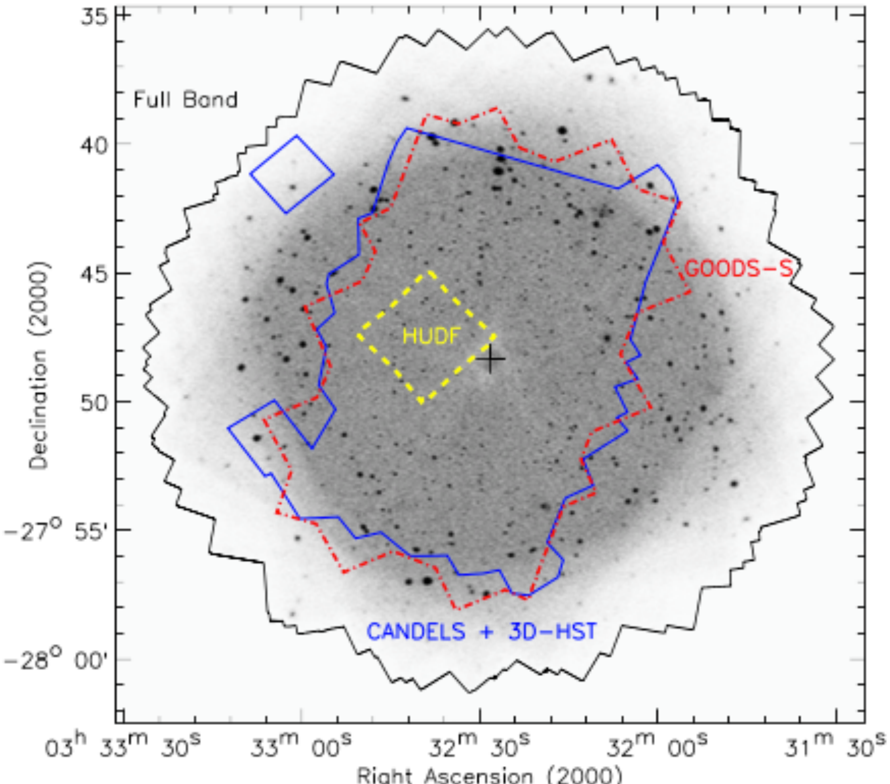
CDFS (Giacconi+02)

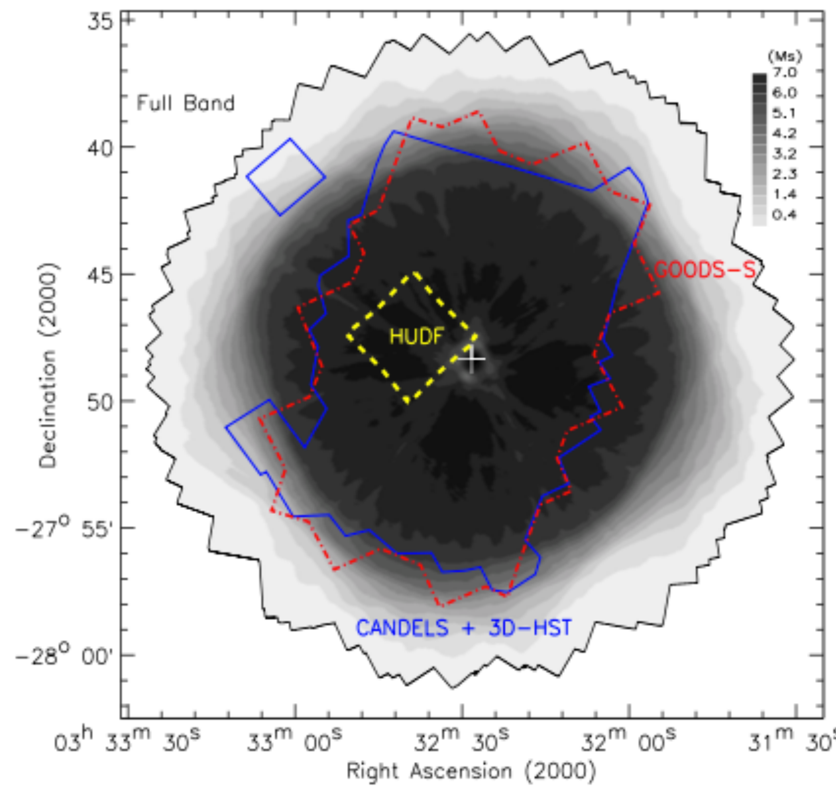


red = 0.5-1 keV
green = 1 - 2 keV
blue = 2 - 8 keV

The 7Ms Chandra Deep Field South. I

The deepest X-ray exposure ever

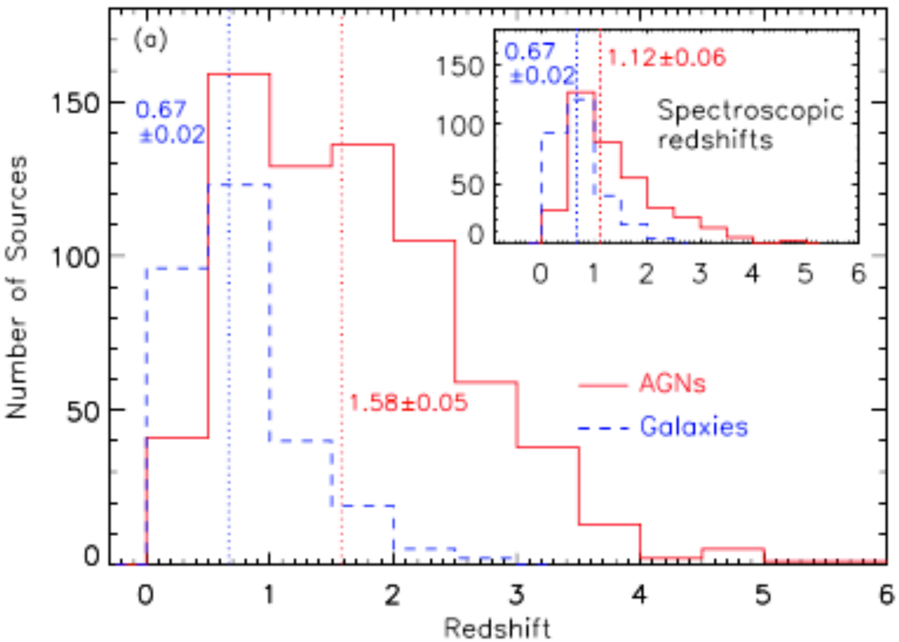




Luo+17

- 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: $F_{[0.5-7keV]} = 1.9 \times 10^{-17}$ erg/cm^2/s
  $F_{[0.5-2keV]} = 6.4 \times 10^{-18}$ erg/cm^2/s
  $F_{[2-7keV]} = 2.7 \times 10^{-17}$ erg/cm^2/s

The 7Ms Chandra Deep Field South. II

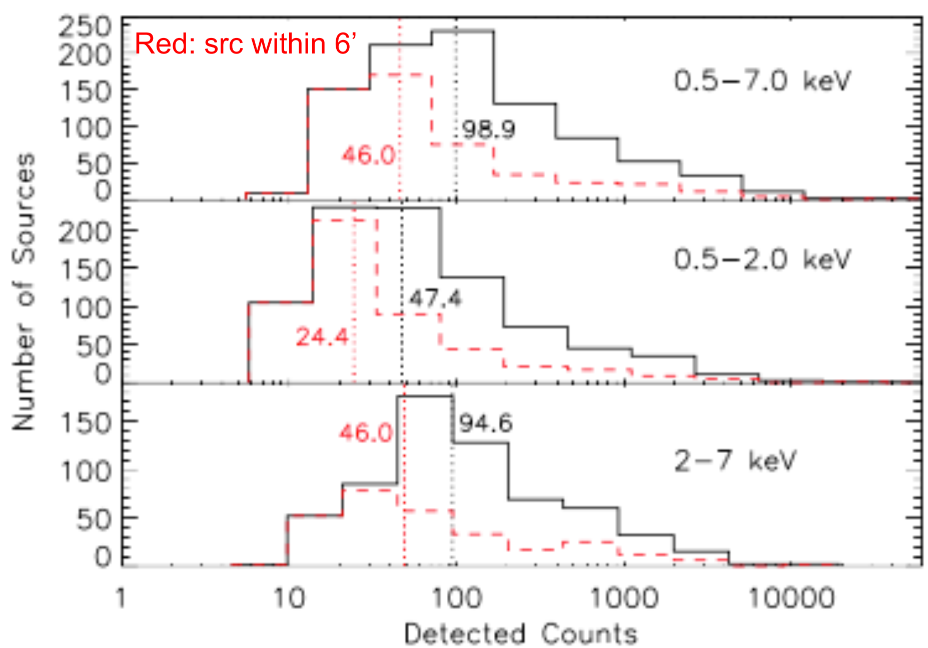


Redshift distribution

AGN vs. Galaxies (X-ray from SF)

Number of counts

Median values around 100 (still low)



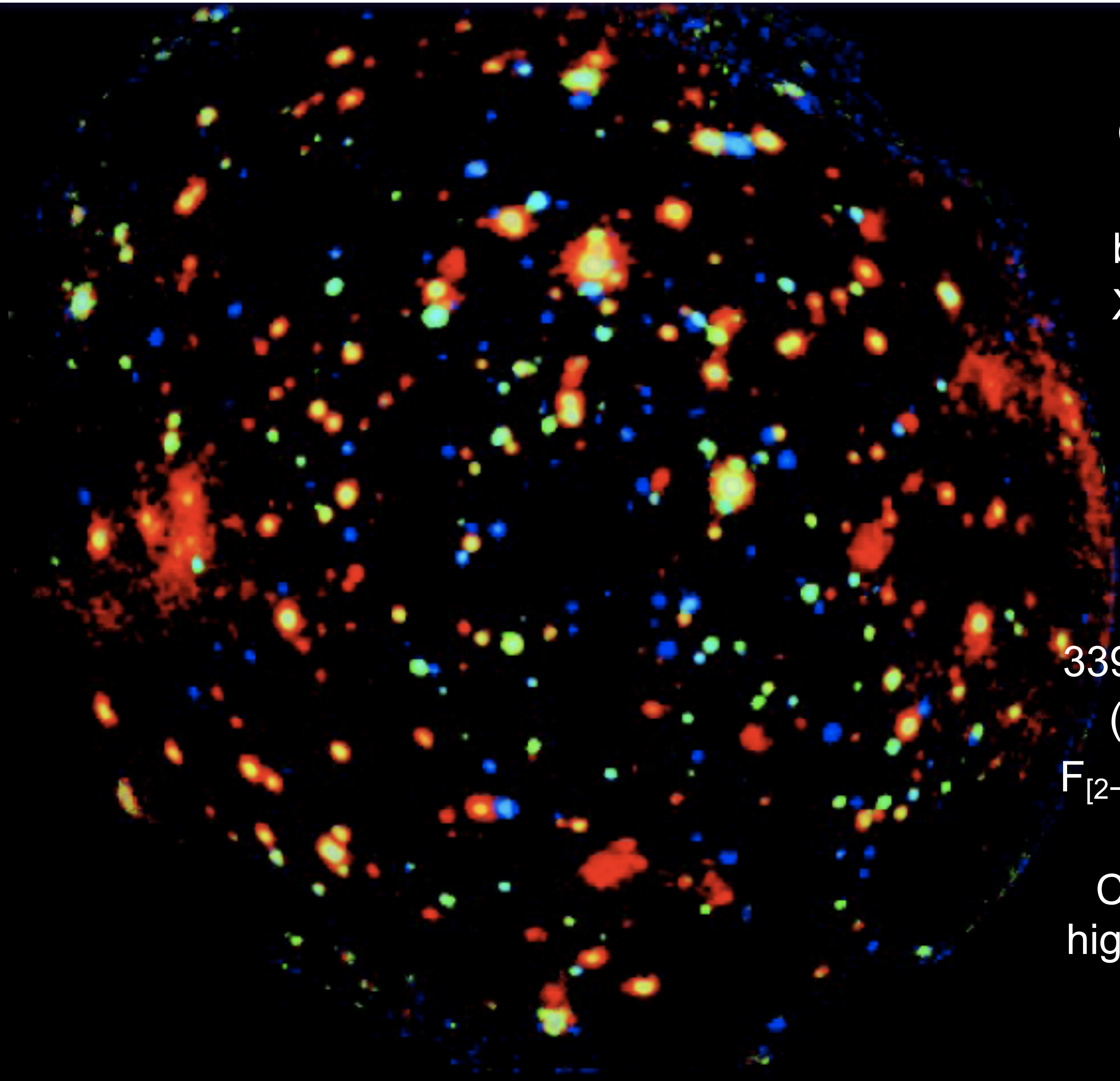
About 90% of the 0.5−2 keV XRB resolved into discrete sources in the CDF-S

About 60% of spec-z identifications (remaining: photo-zs)

Probing low fluxes translates into an increasing number of detected obscured AGN and galaxies

Luo+17

Chandra Deep Field South: the 3Ms XMM-Newton view

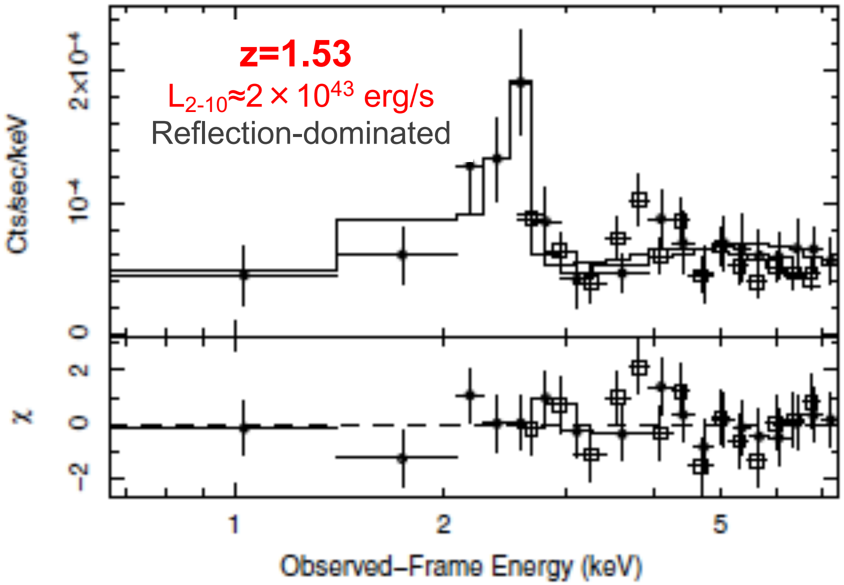


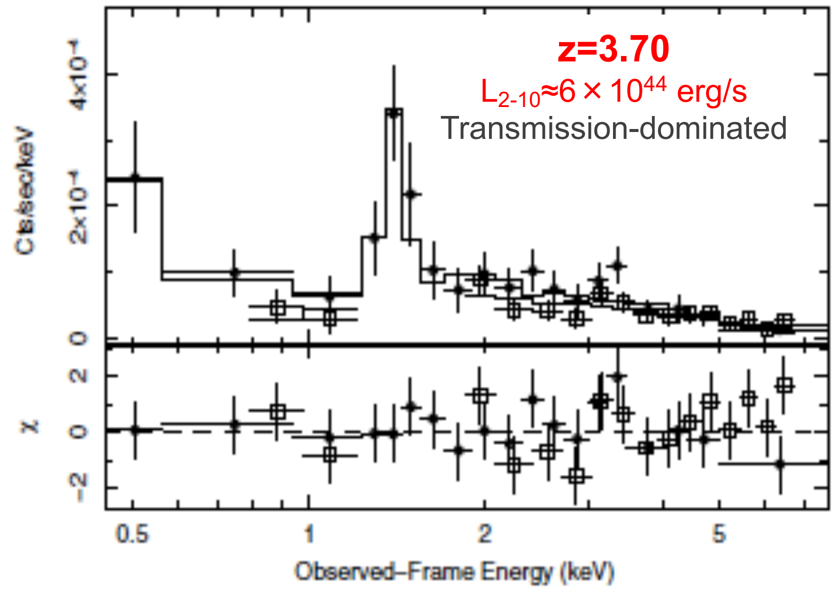
Larger field-of-view than Chandra, larger effective area, worst PSF, higher background → good for X-ray spectral analysis of relatively X-ray bright sources

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

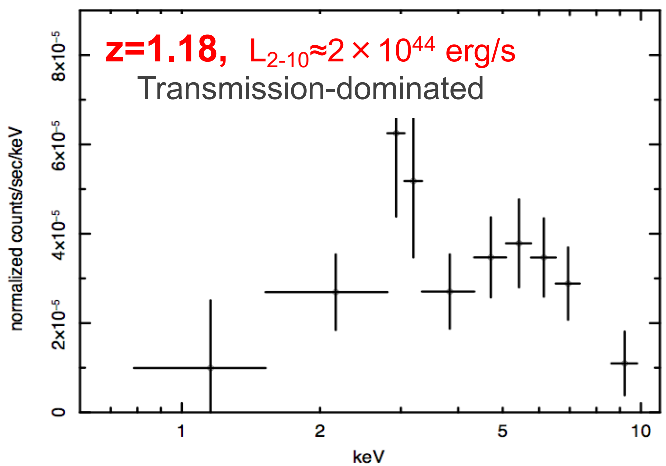
Capable of probing the high-z Universe with good photon statistics

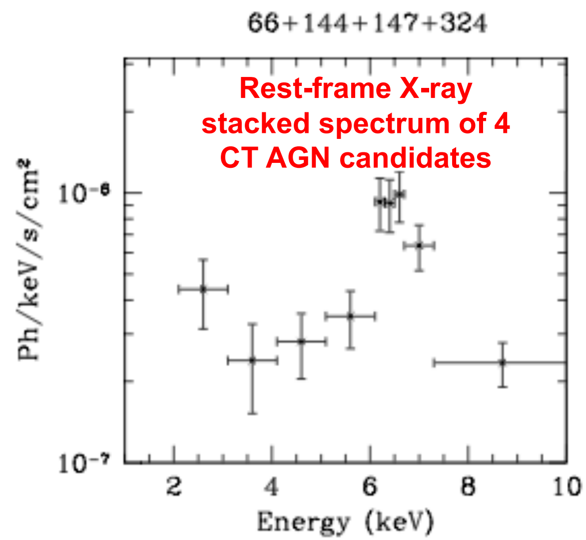
The 3 Ms XMM-Newton Survey in the CDF-S. I





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



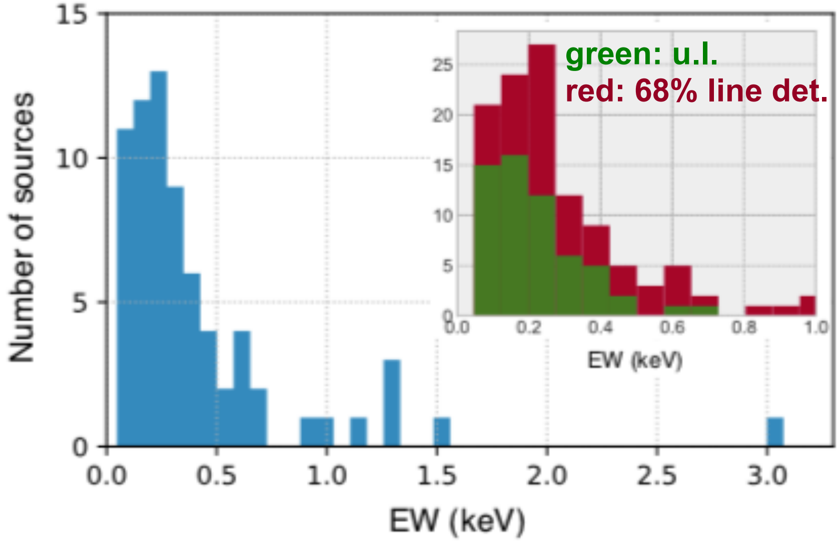


Observed flat X-ray spectra → reflection/transmission dominated, strong iron Kα line

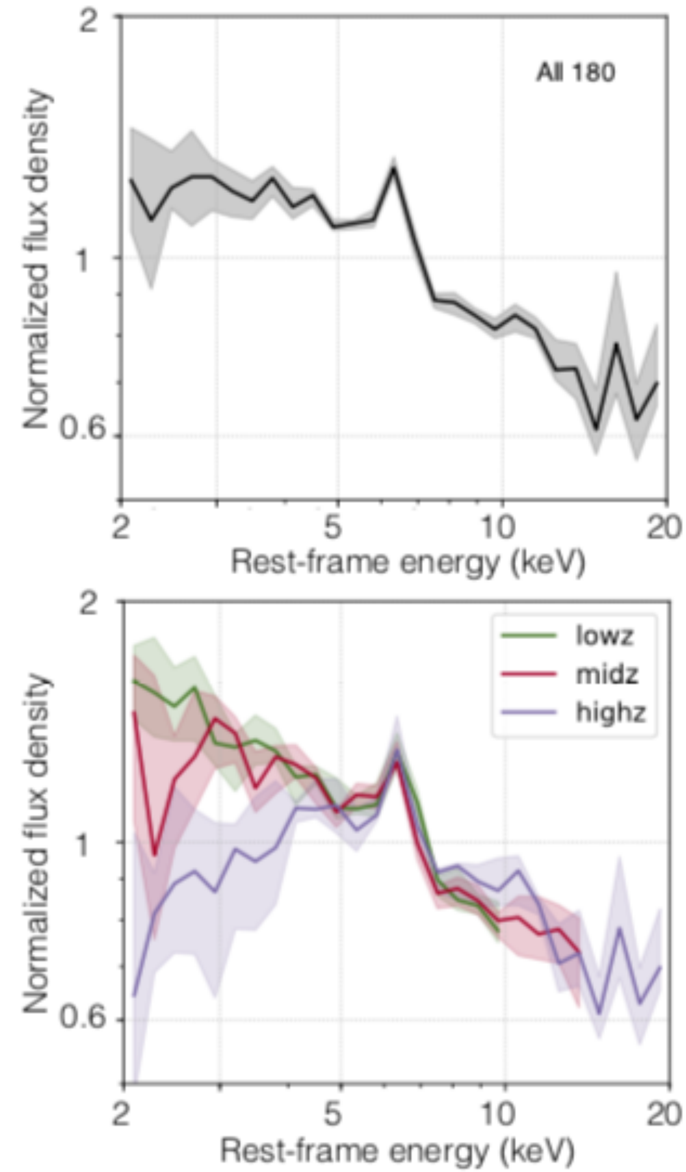
Georgantopoulos+13

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

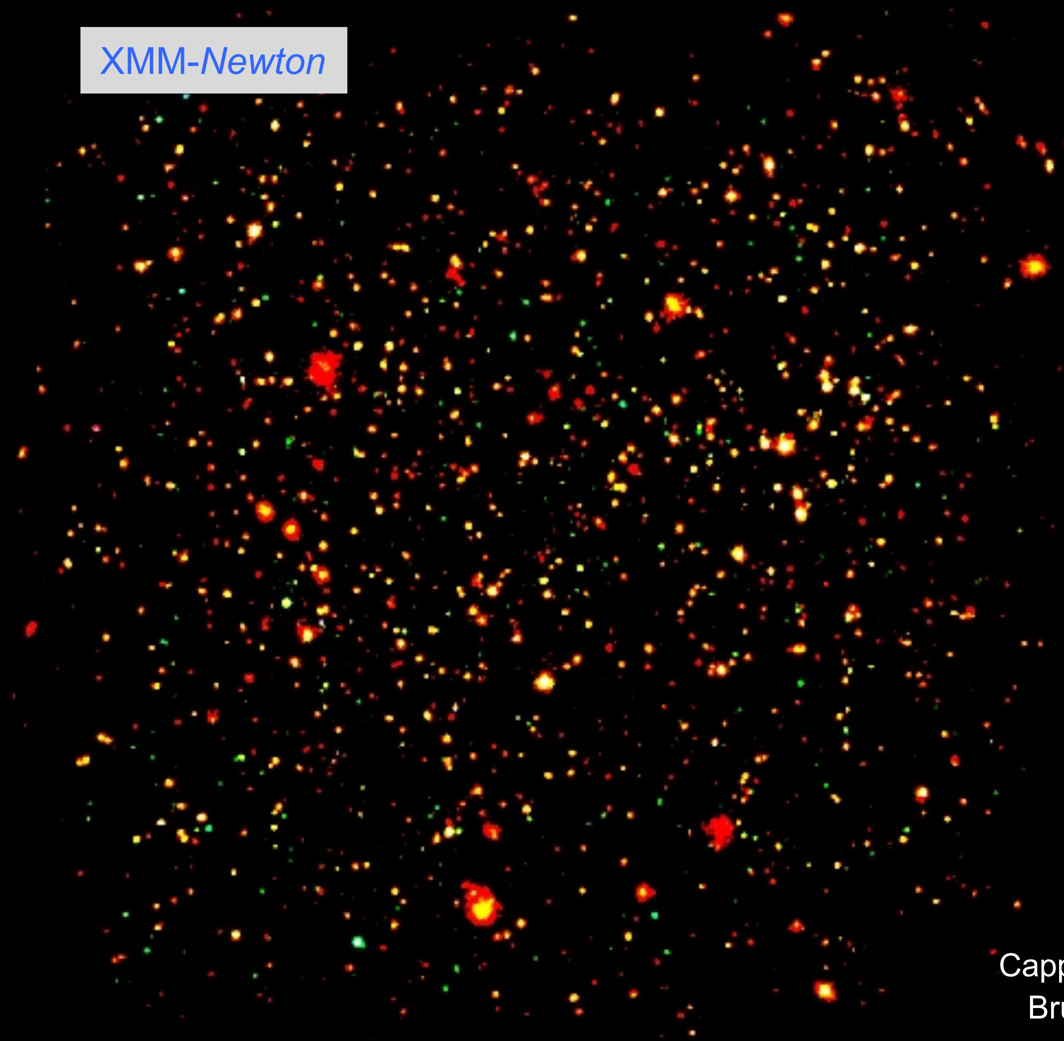


Iwasawa et al. (2020)

X-raying the COSMOS Field

XMM-*Newton*
1.55 Ms
1822 sources

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



Cappelluti+09
Brusa+10

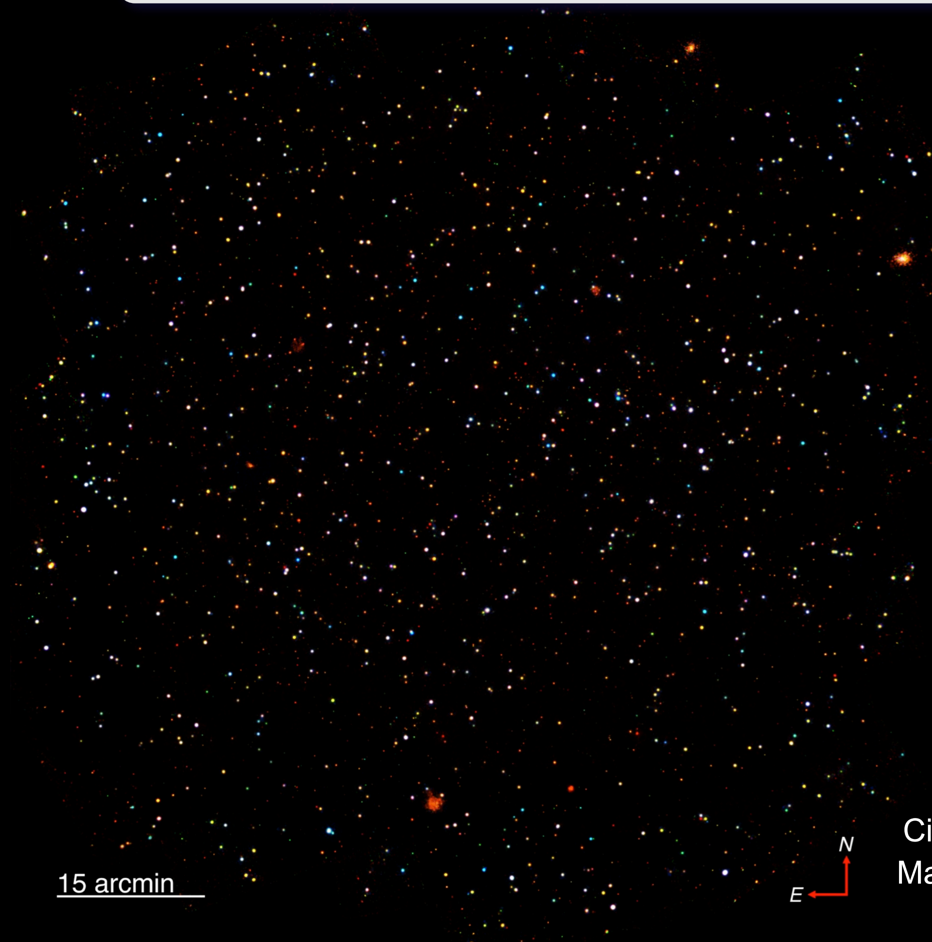
X-raying the COSMOS Field

XMM-*Newton*
1.55 Ms
1822 sources

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

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

The final COSMOS-Legacy Field



Civano+16, Marchesi+16

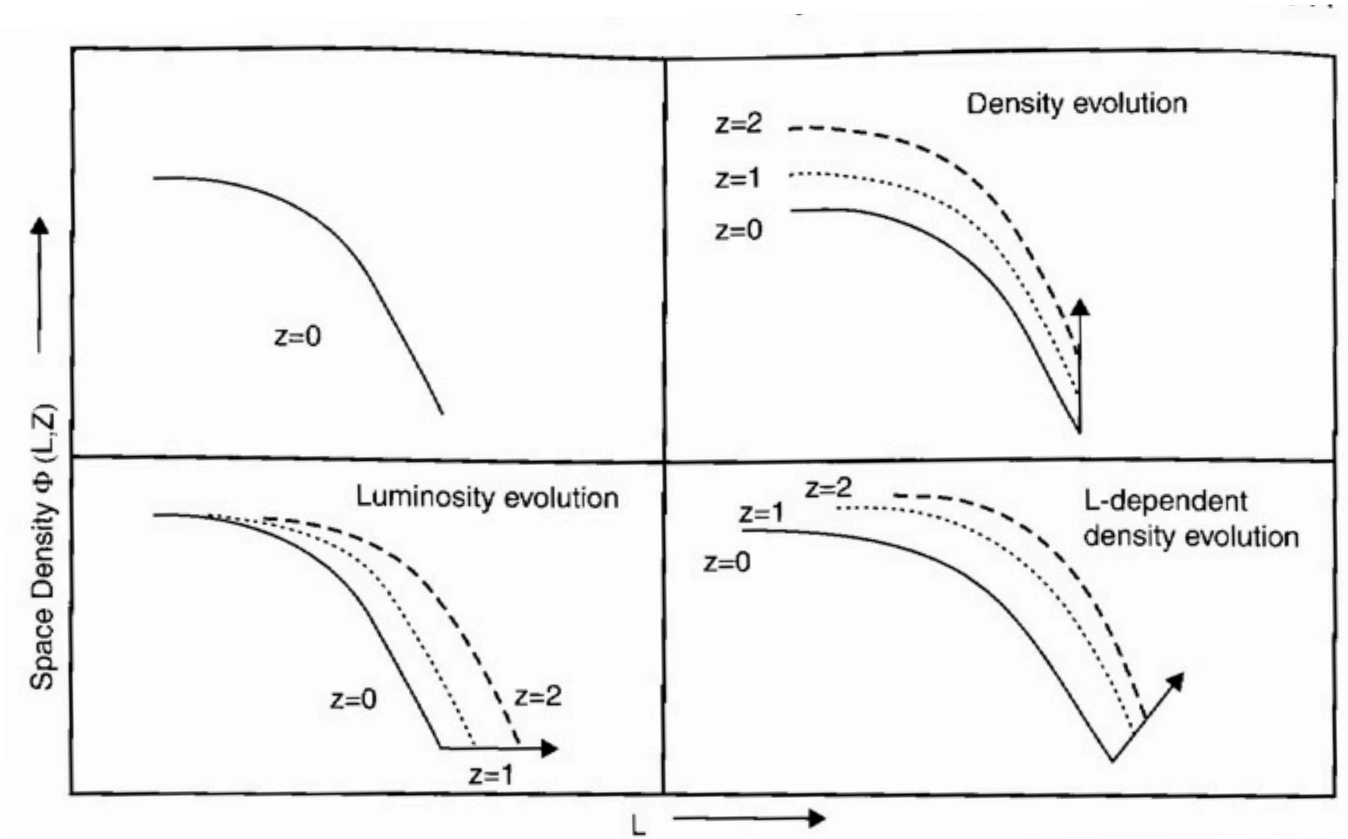
Chandra

AGN evolution from X-ray surveys

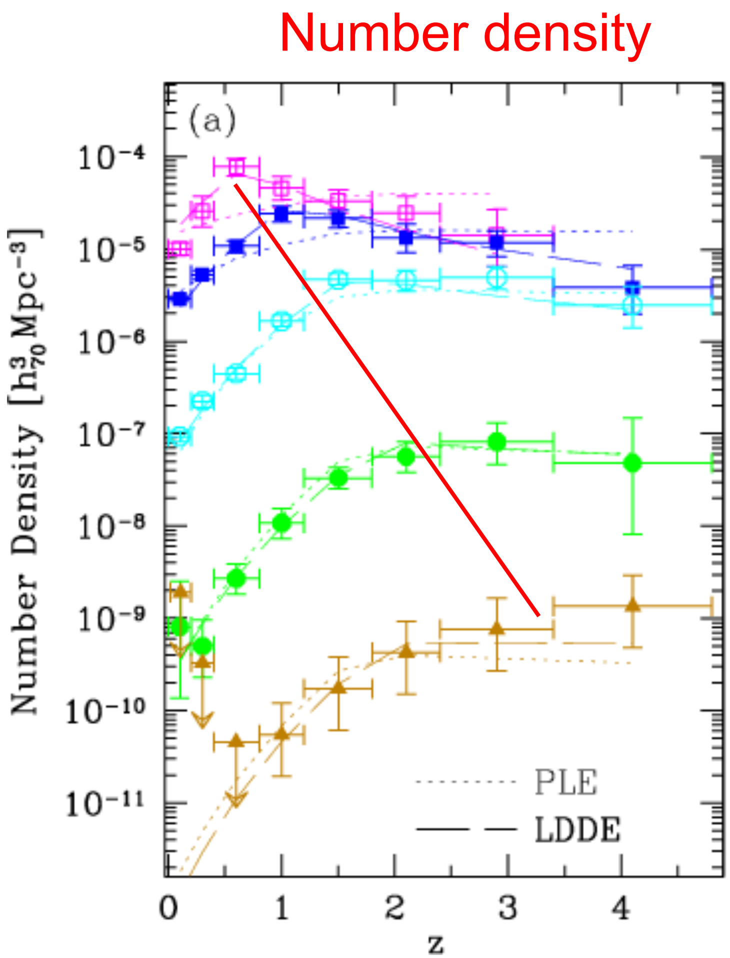
Luminosity Evolution:
AGN more luminous in the past

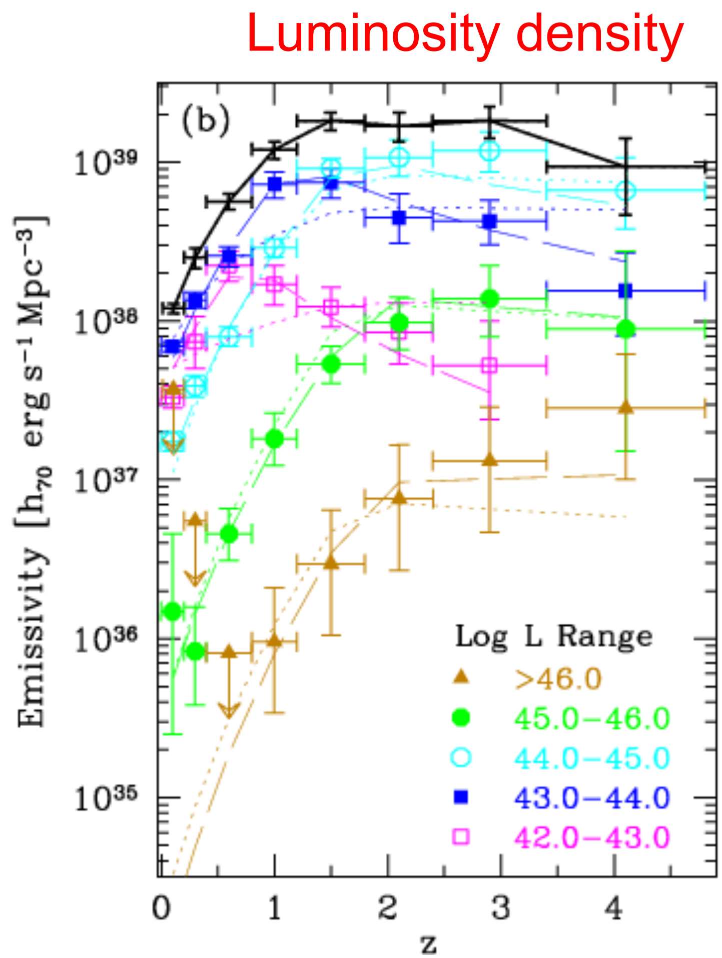
Density Evolution:
AGN more numerous in the past

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



AGN cosmological evolution. I





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

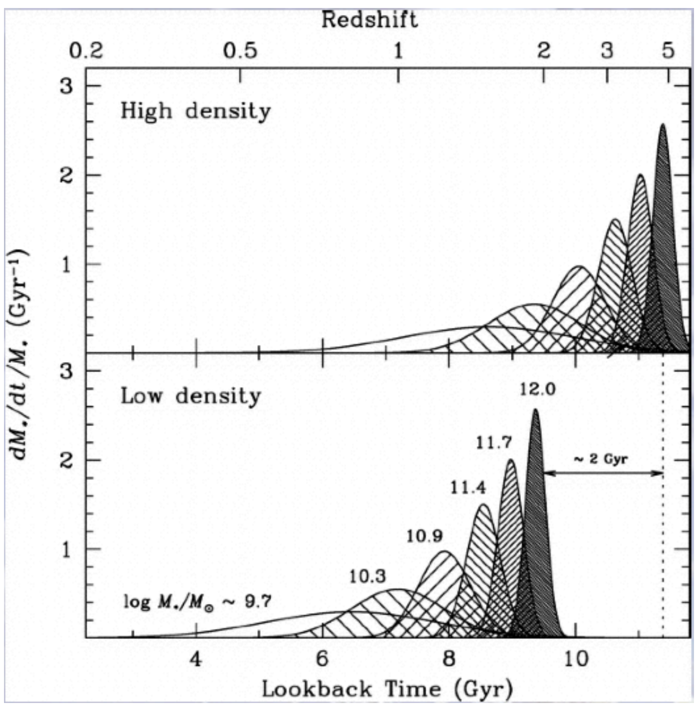
QSOs peak at z≈2-3, AGN at z≈0.5-1

AGN cosmological evolution. II

- 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)

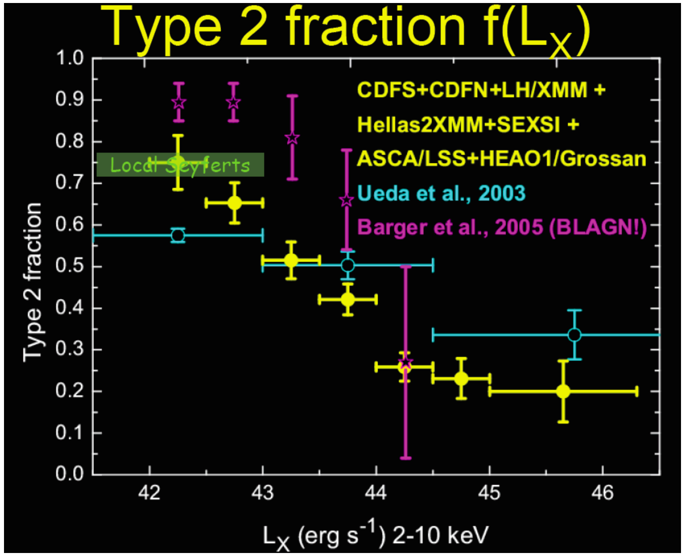


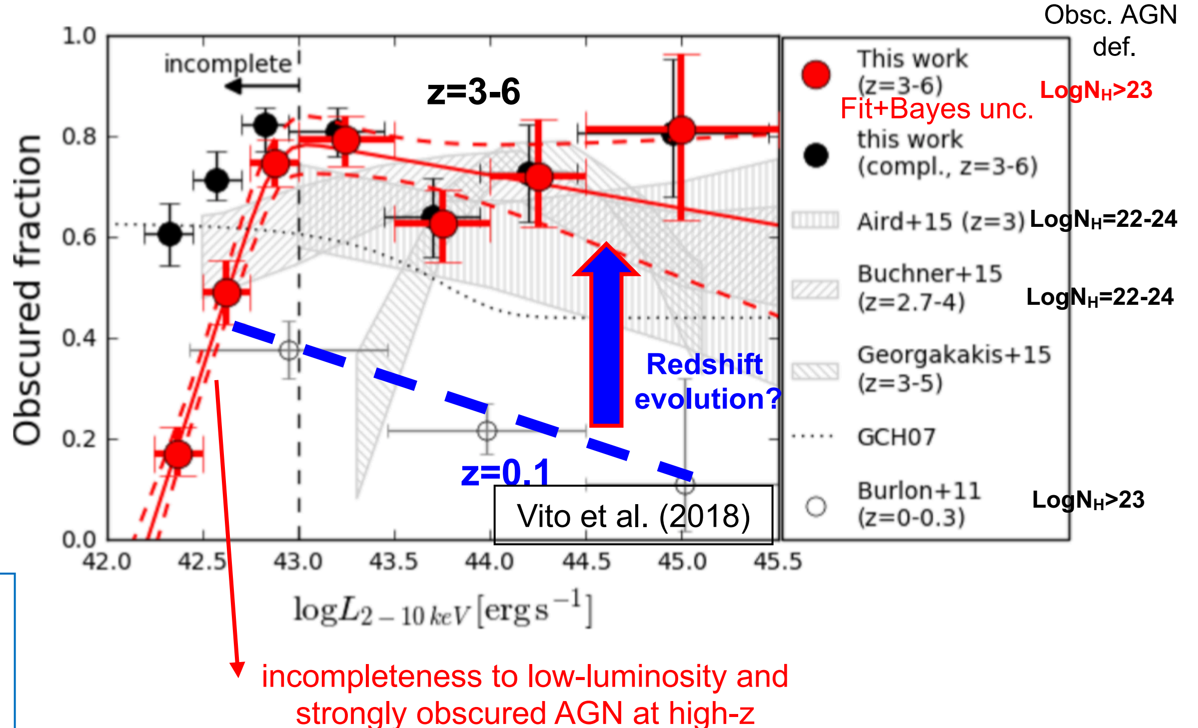
Thomas+2005

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

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



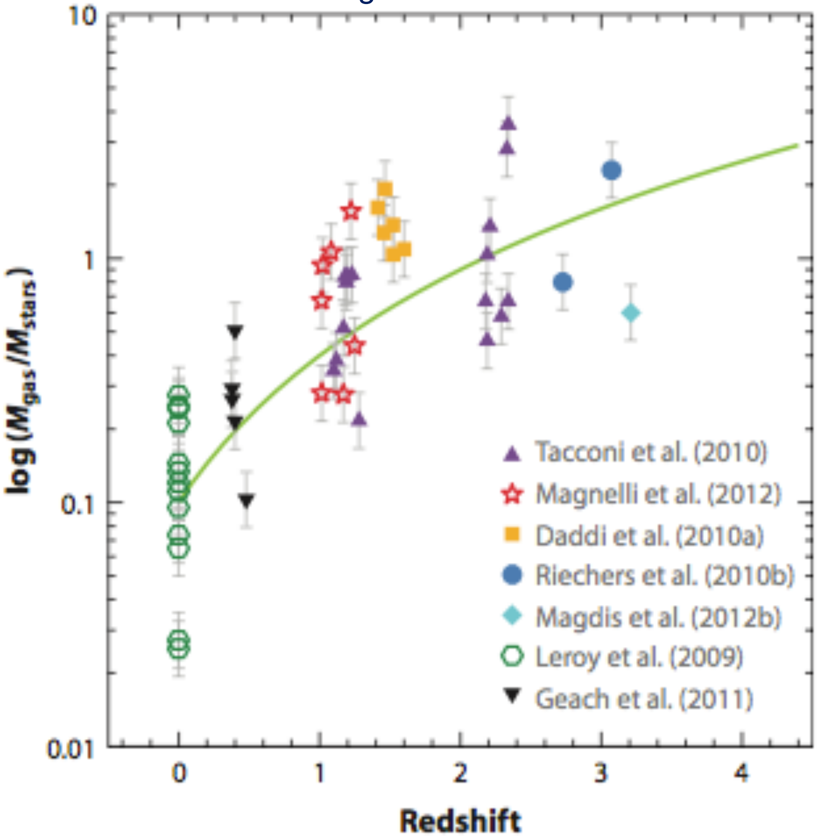


Broad consensus for an obscured AGN fraction declining towards high intrinsic luminosities, consistently with the **receding torus model** (Lawrence 1991, Simpson 2005; see also Lusso et al. 2013)
Behavior with z still debated (see e.g. La Franca et al. 2005; Treister & Urry 2009; Iwasawa et al. 2012; Vito et al. 2013, 2014, Buchner et al. 2015; likely increasing with z)

z>3 AGN: ≈70−80% with $N_H > 10^{23}$ cm^{-2}
see also Iwasawa et al. (2012) – CDFS, 3Ms, z=1.7−3.7

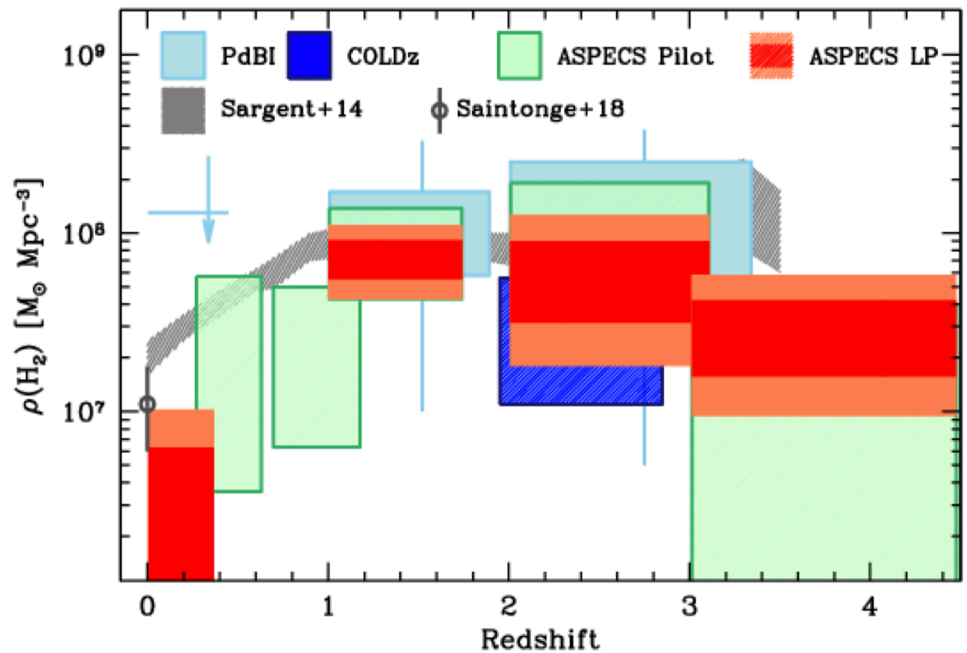
Obscured AGN fraction increases with redshift, especially at high luminosity
More gas available, more mergers, …

$M_{gas}/M_{\star}$ vs. z



Carilli & Walter (2013)

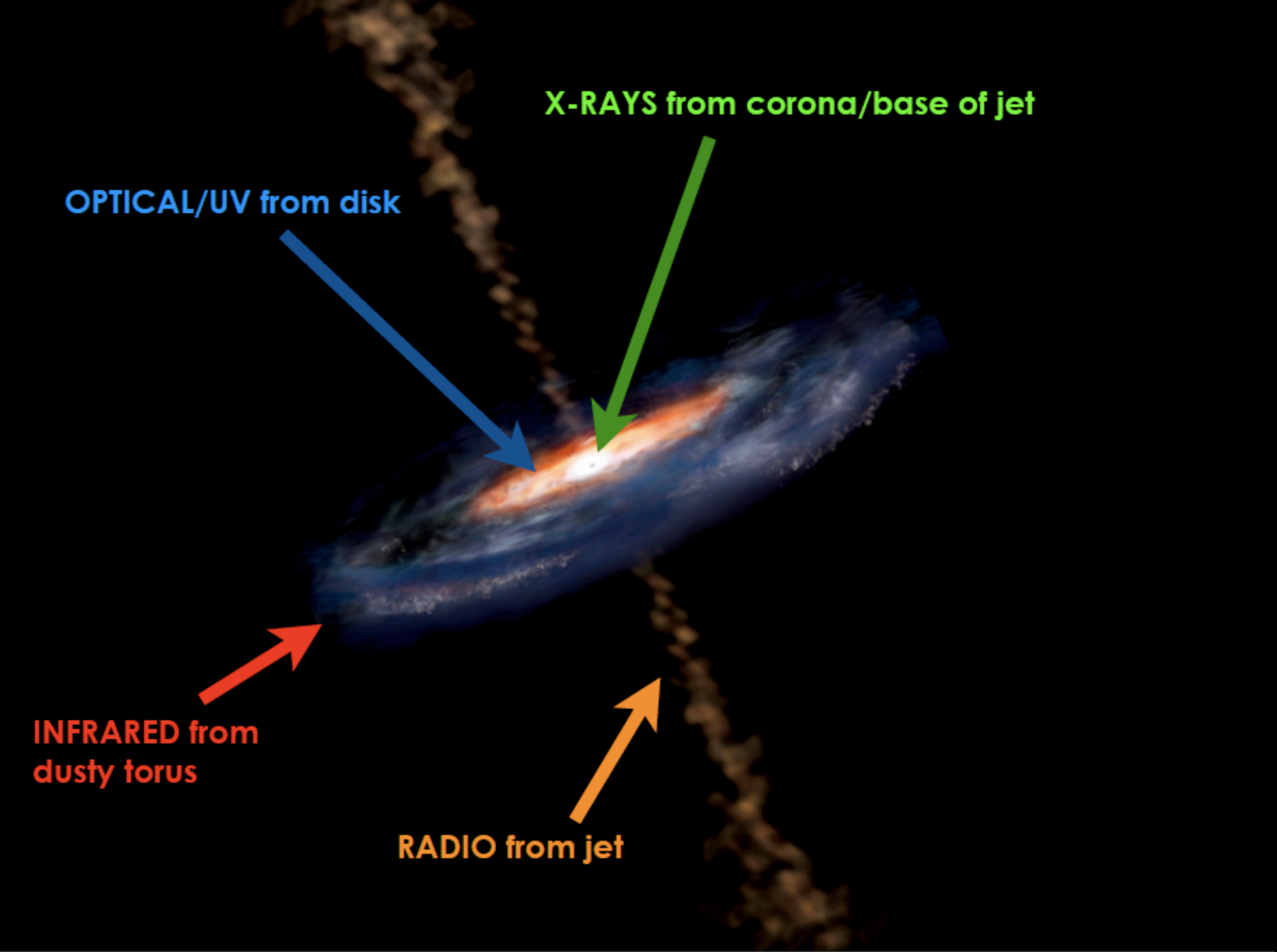
ϱ_{gas} vs. z



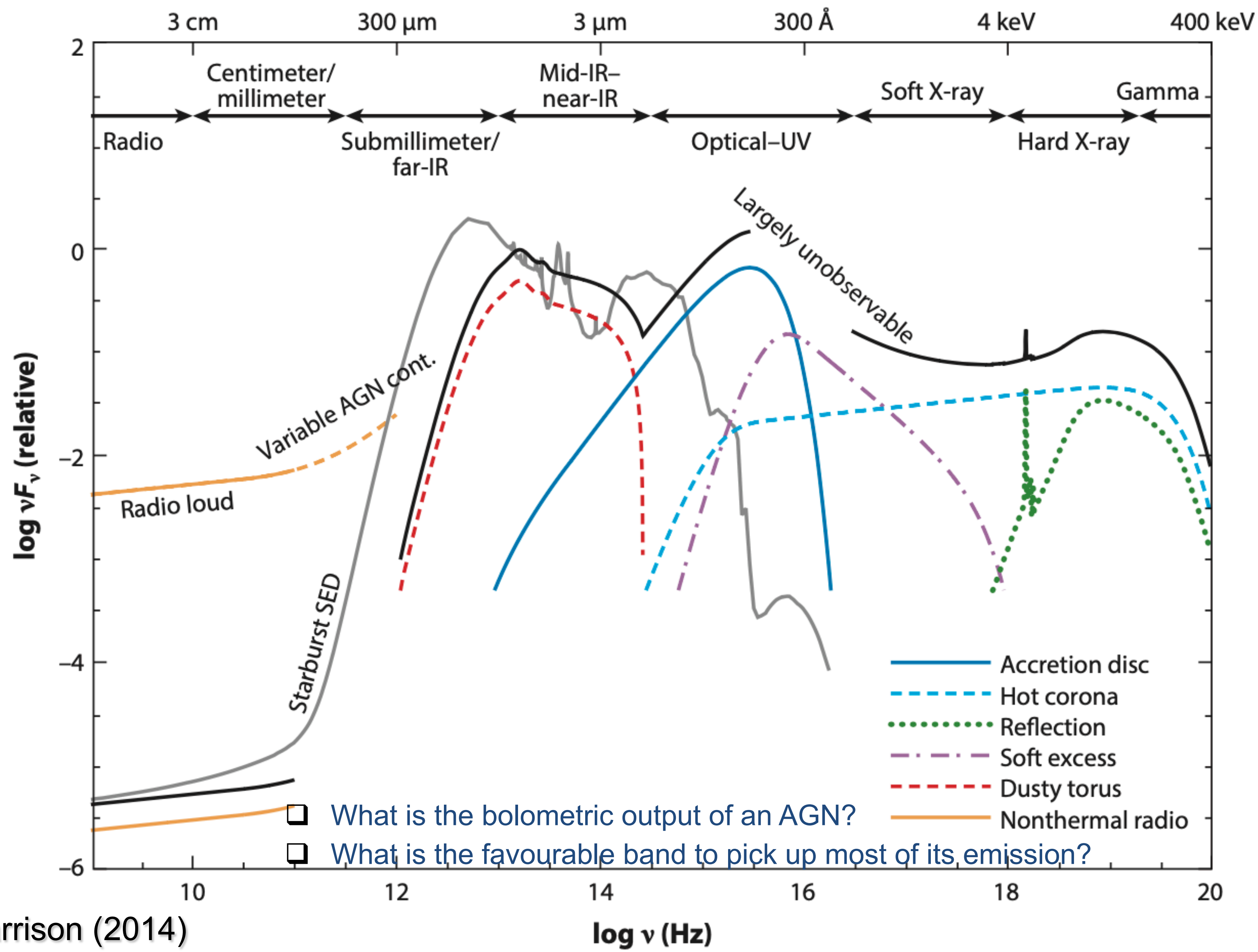
Decarli et al. (2019)

- Large quantity of gas available at high redshift
- Higher merger rate and more gas available for the accreting SMBHs at high redshift; larger covering factors? The same gas sustaining strong SF at high redshift may be responsible for the obscuration – more on high-z AGN lesson

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

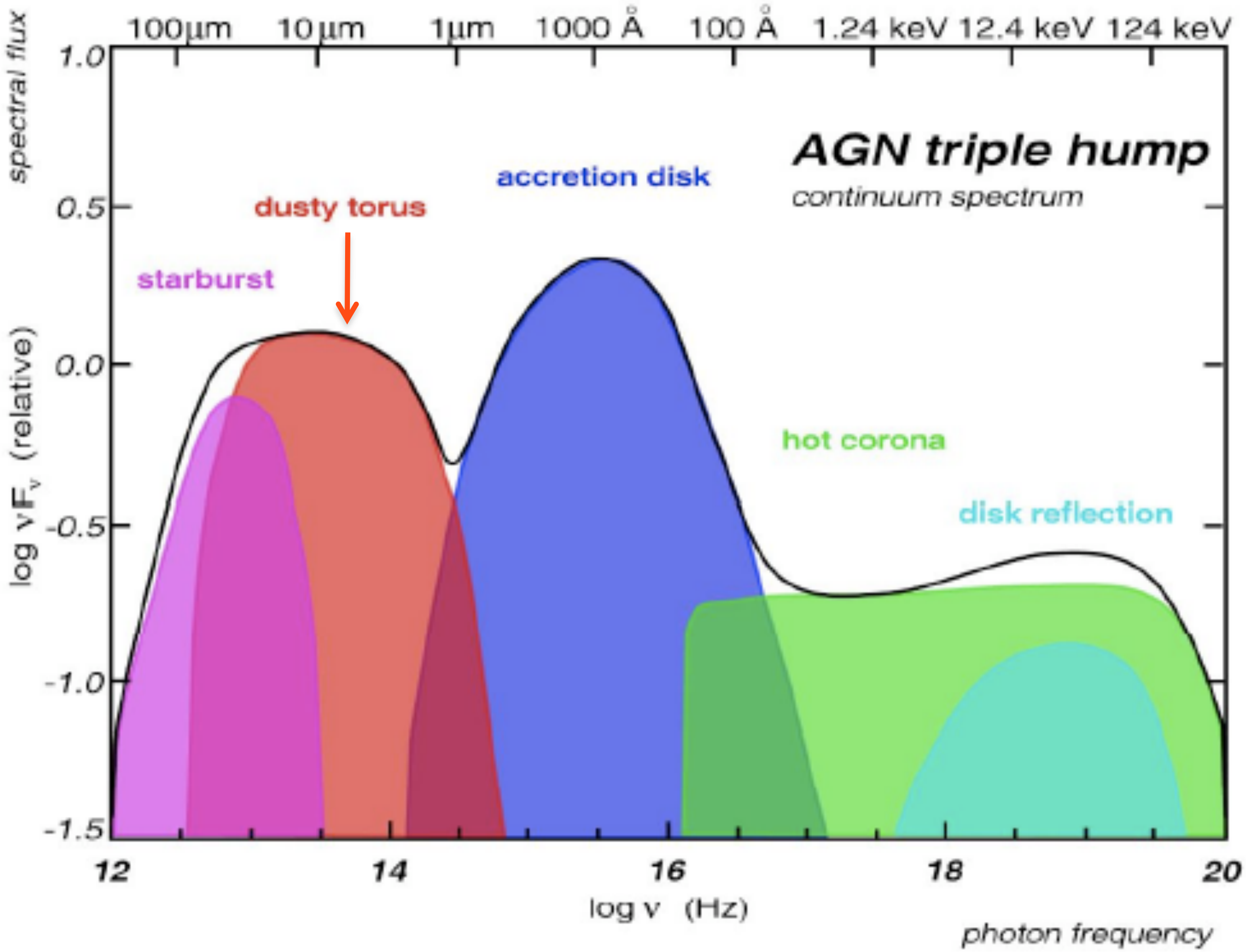
AGN Spectral Energy Distribution. I



- ❑ What is the bolometric output of an AGN?
- ❑ What is the favourable band to pick up most of its emission?

Harrison (2014)

AGN Spectral Energy Distribution. II
A simplified view

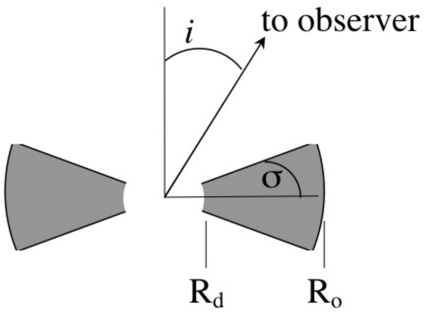


Models for the infrared emission of AGN

Smooth dust distribution: main properties

• The source is obscured if radiation intercepts the torus, hence obscuration is related to geometrical issues

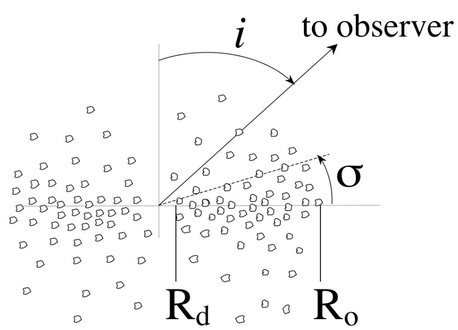
• Dust temperature is a function of the distance from the source of the radiation field



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

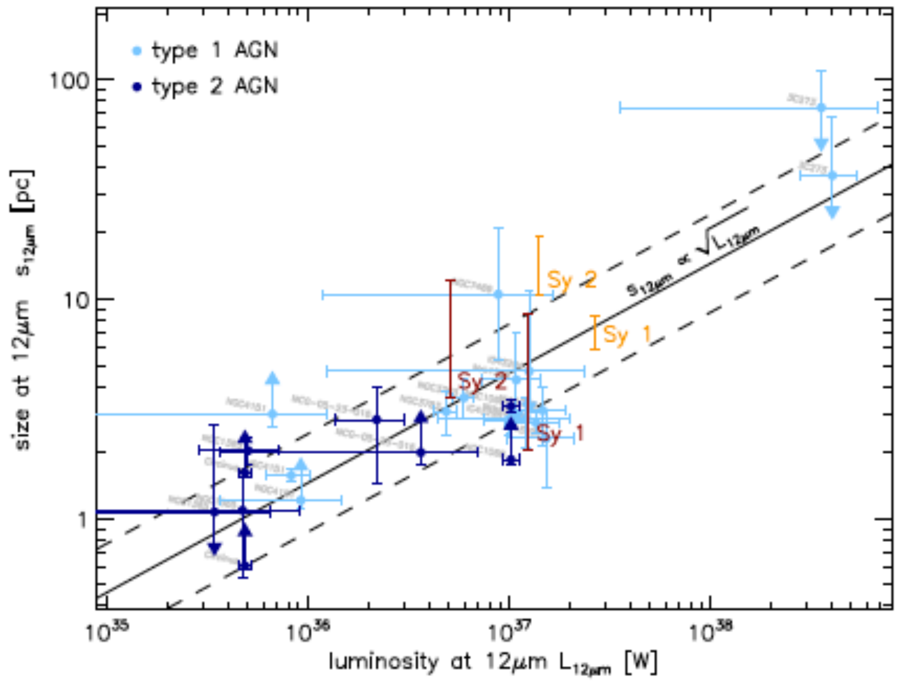


AGN type is a viewing-dependent probability

Alternative modeling: hydromagnetic disk wind

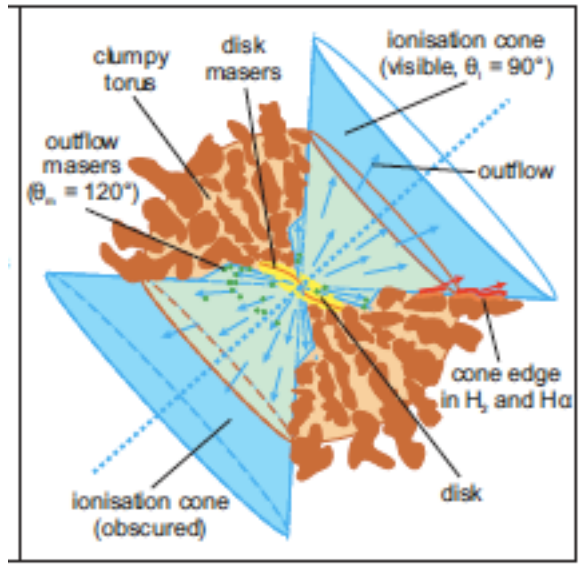
• Torus=toroidal region of a wind, structured in outflowing clouds. The acceleration is provided by magnetic field lines anchored in the disc (Blandford & Payne ‘82; Elitzur ‘08)

High-resolution mid-IR observations of Seyfert galaxies
(reverberation-mapping technique, time lags)



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



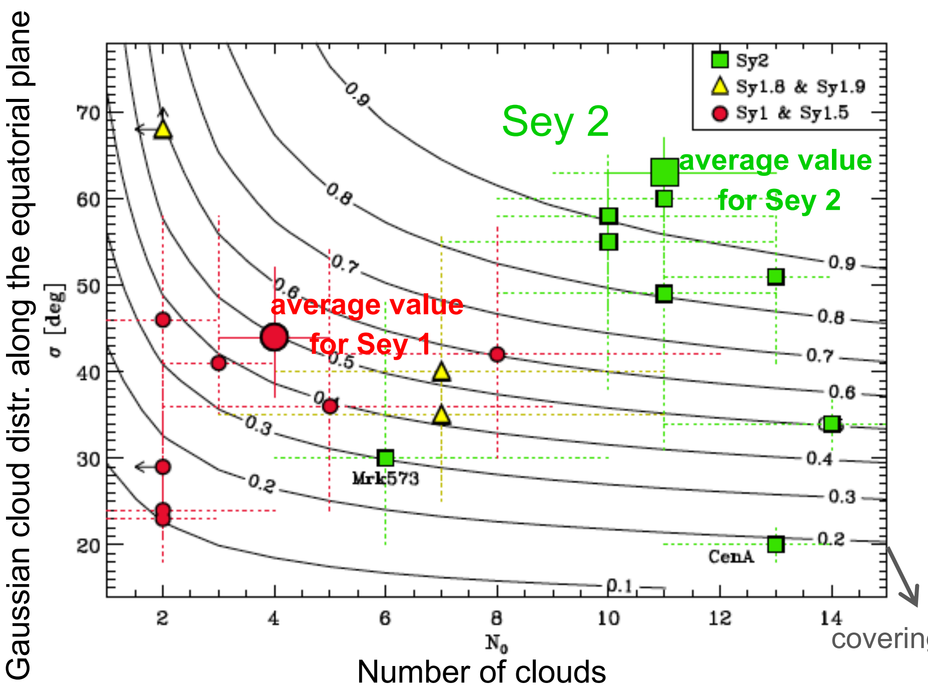
Tristram+07 - Circinus

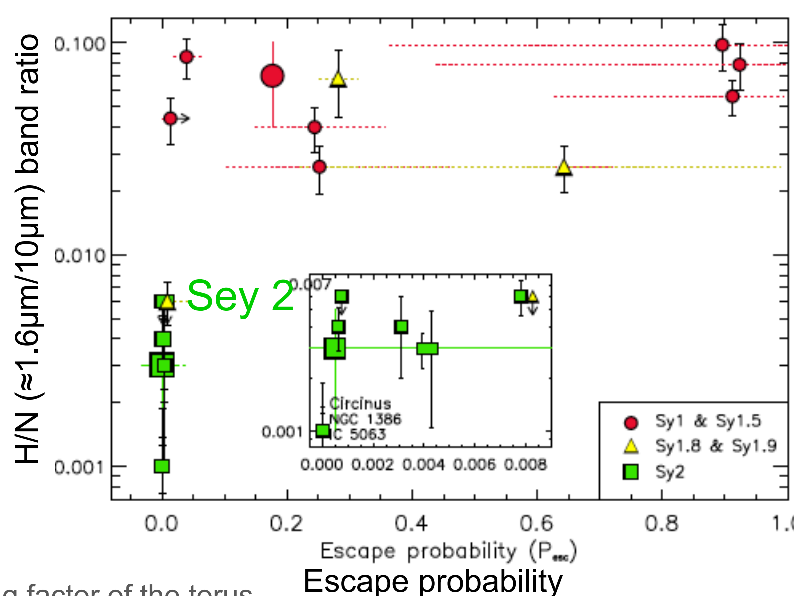
$$R_{K=2.2\mu m} \sim 0.4\ L_{46}^{1/2}\ pc$$ (Koshida et al. 2014)

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





covering factor of the torus

Ramos-Almeida+11; see also Garcia-Bernete+19

X-ray observations of local Seyfert galaxies: absorbing clouds within the BLR?

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

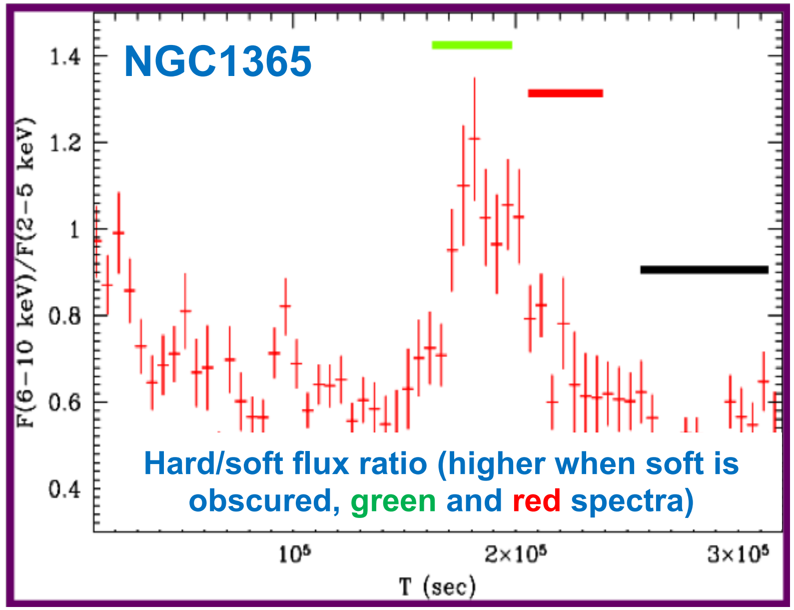
↓

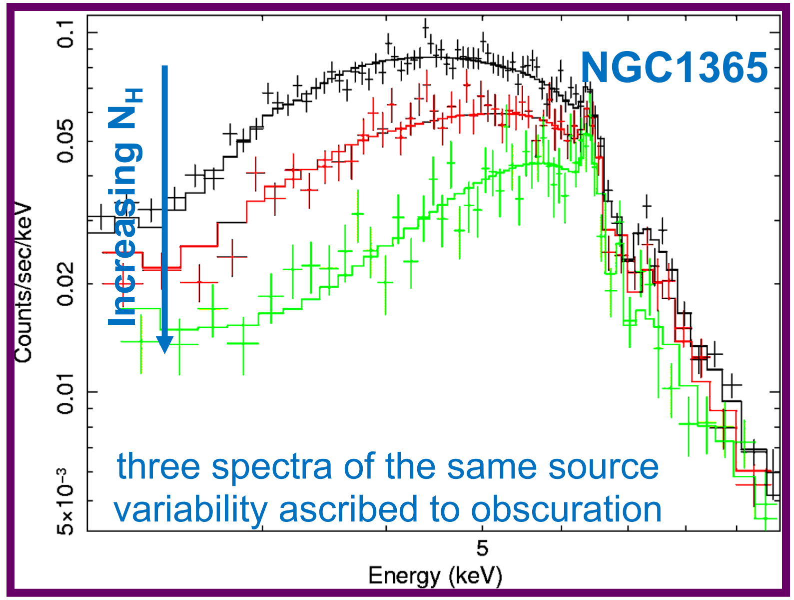
size X-ray src $<10^{14}$ cm
D $< 10^{16}$ cm

↓

X-ray absorber "made" of BLR clouds

Risaliti et al. 2007, 2011; see also Torricelli-Ciamponi et al. 2014

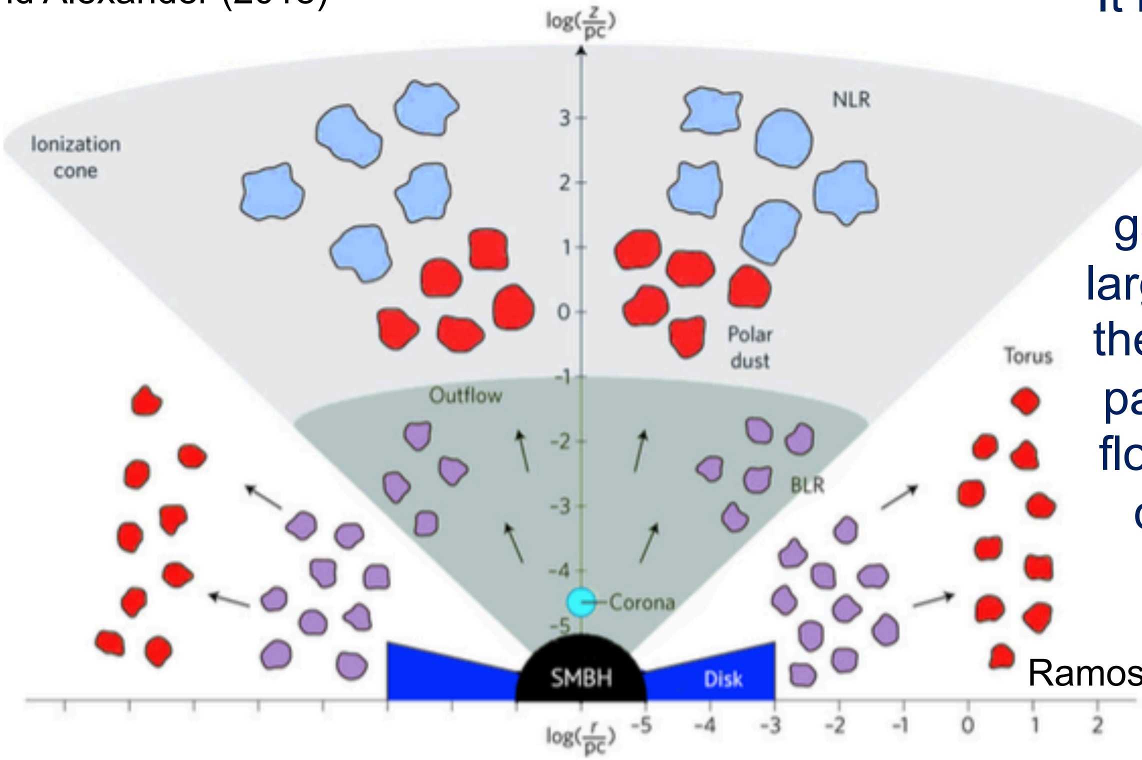




What is not fitting into AGN Unified Model picture in its basic form

- Presence of obscured broad-line AGN
- Presence of unobscured narrow-line AGN (called 'true' Type 2 AGN)

see also Hickox and Alexander (2018)



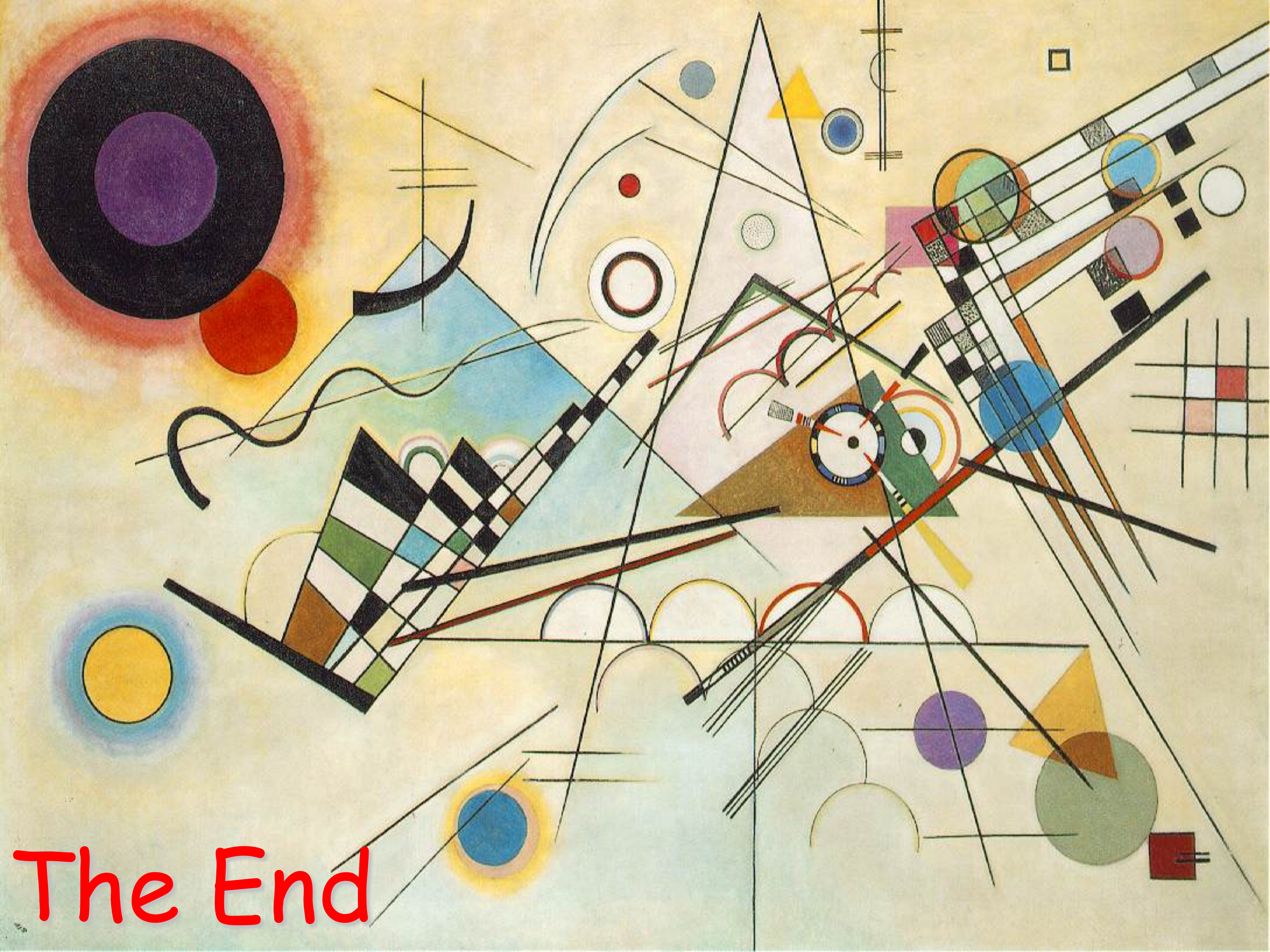
Ramos-Almeida & Ricci (2017)

It is often assumed that the torus material is gas inflow from the galaxy along with larger-scale flows in the galaxy plane → part of the general flow that continues down to the BH accretion disc

The **absorber/reprocessing material** is most likely **cloudy** and **filamentary** (e.g., Jaffe+04, Burtscher+13; Ramos-Almeida+11, Alonso-Herrero14, Garcia-Bernete+17,19)

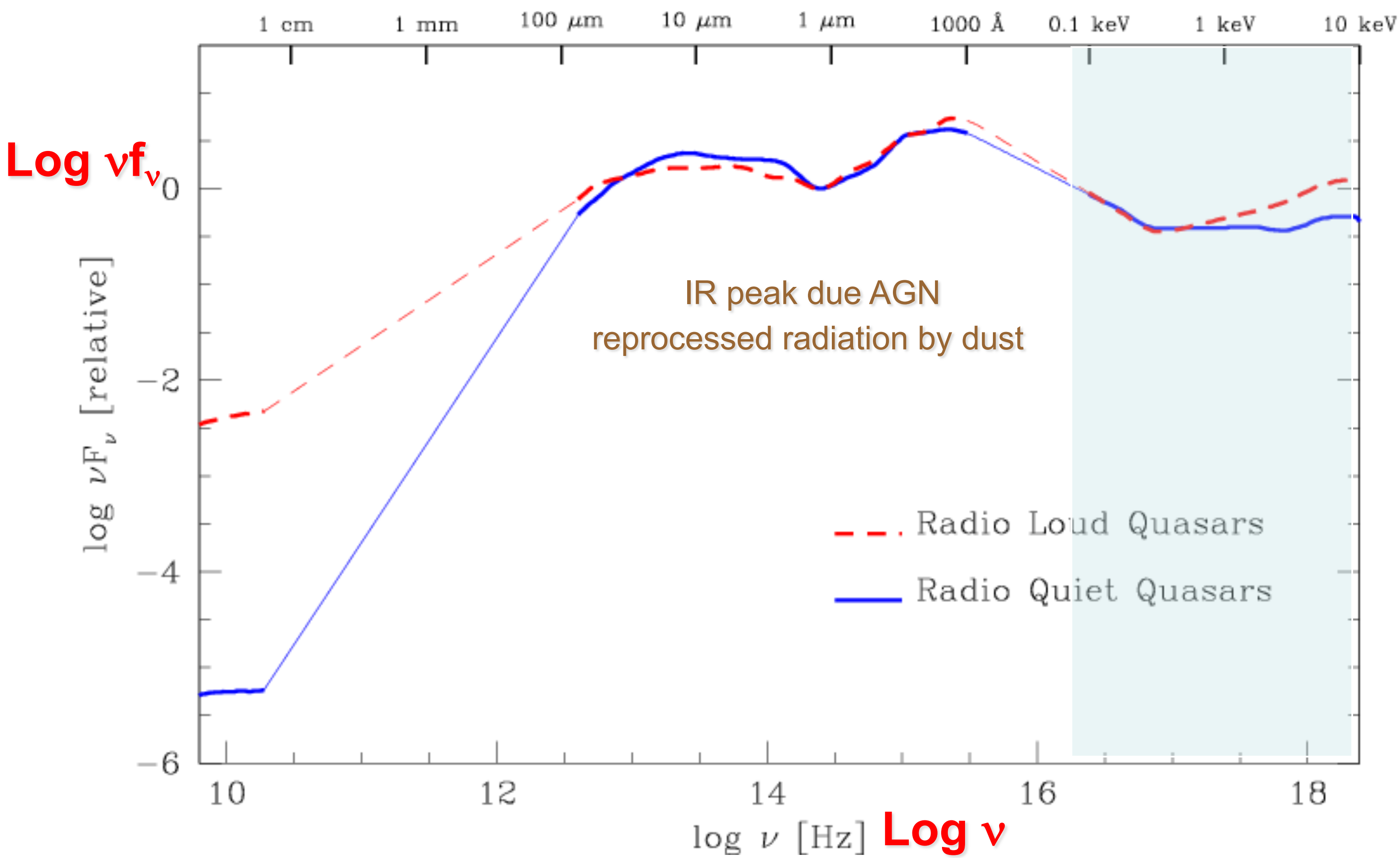
Combes+18 – ALMA results, tori are disk-like on scales of ~10-30 pc + resonant rings at 100-pc scales; AGN non necessarily in the center

Recent studies to link the mid-IR properties of the torus with those from X-ray observations



The End

Broad-band spectral energy distribution of AGN



Elvis et al. 1994