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 and Dr. M. Dadina]

- ✗ 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

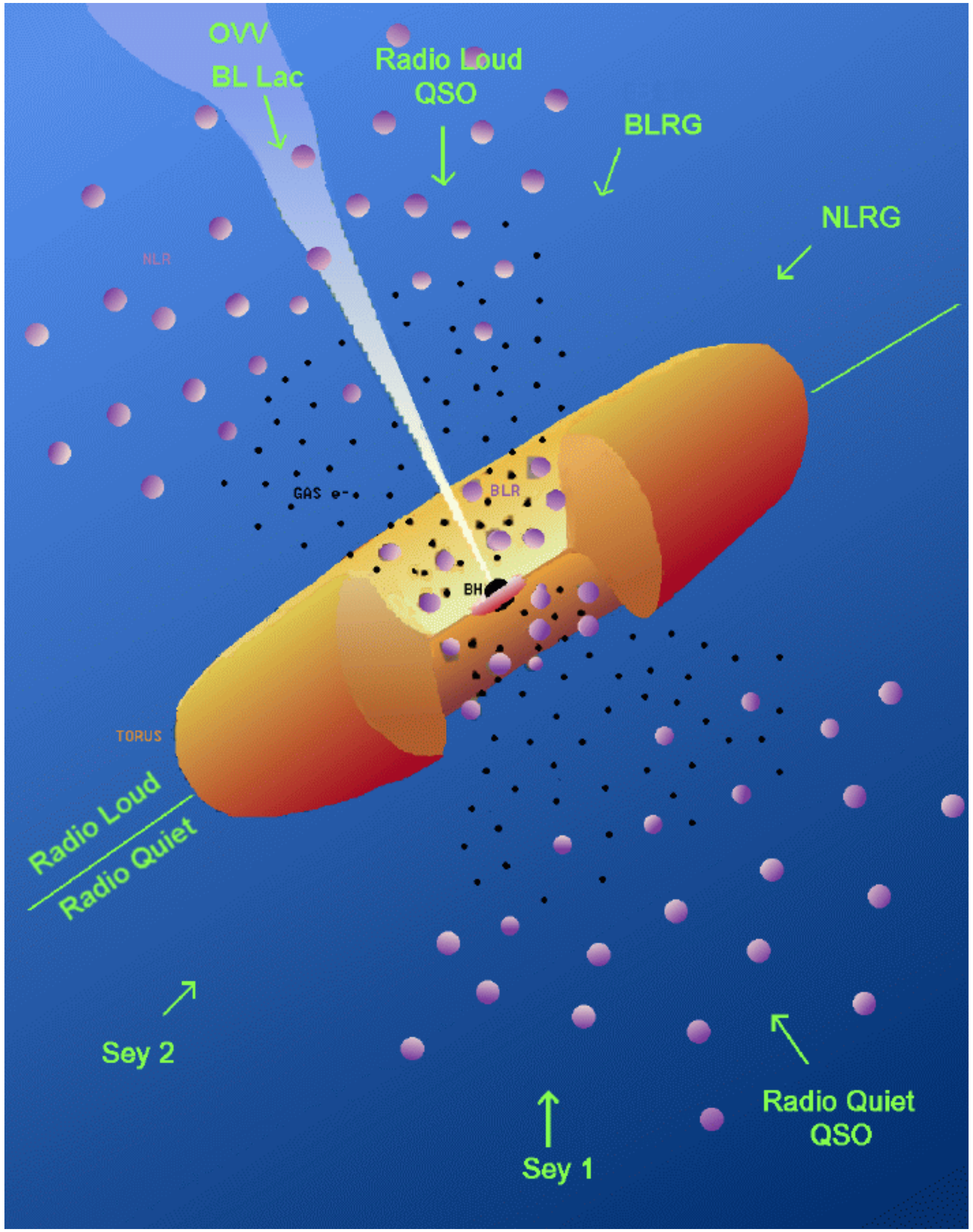
For a recent review on the subject, see Alexander & Hickox 2012, New Astronomy Reviews, 56, p. 93 (arXiv:1112:1949)

AGN Unified Model

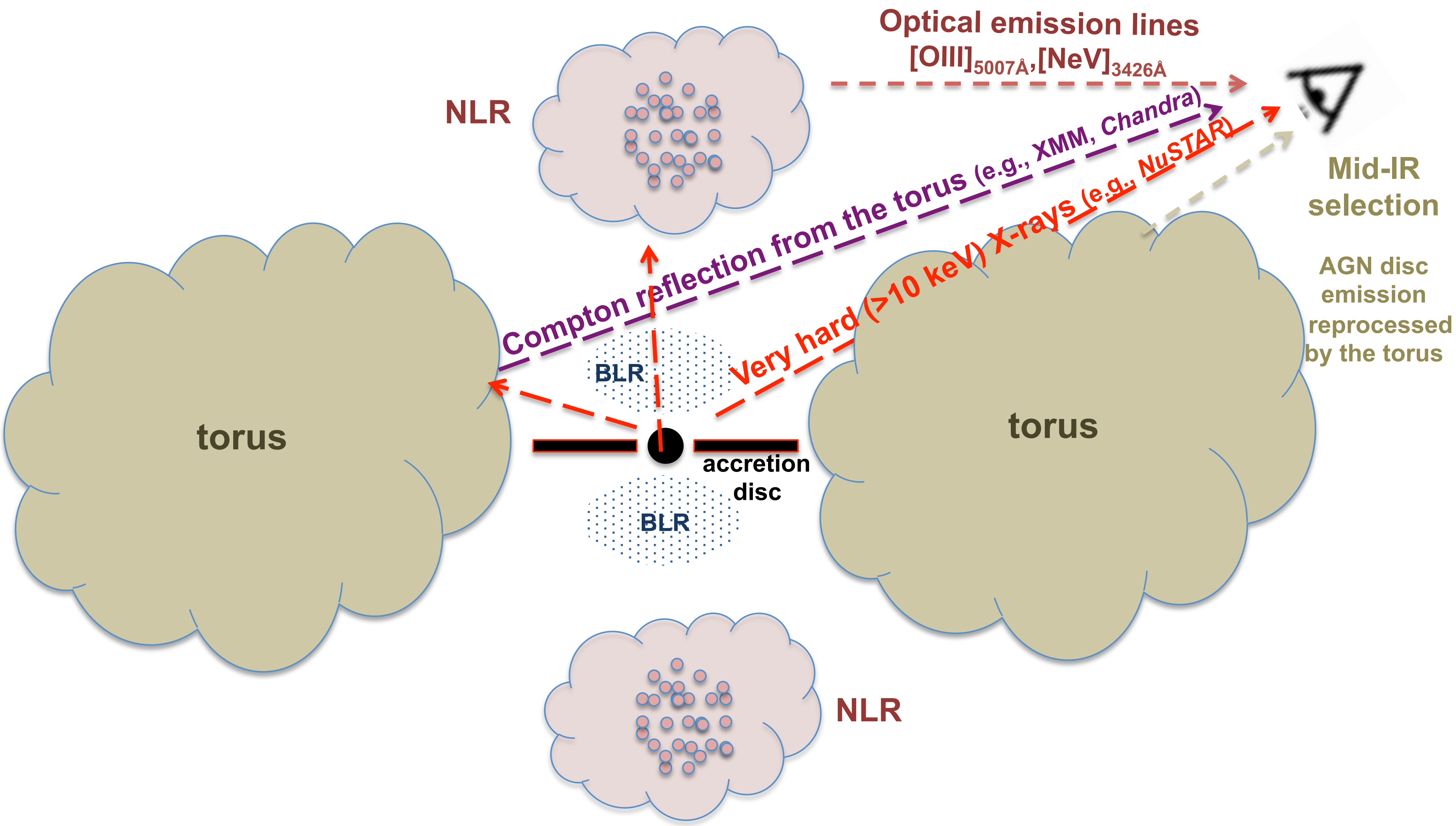
after Antonucci & Miller 1985;
Antonucci 1993

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


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
torus
BLR
accretion disc
BLR
torus
NLR

CV 2014

A logarithmic view of an AGN

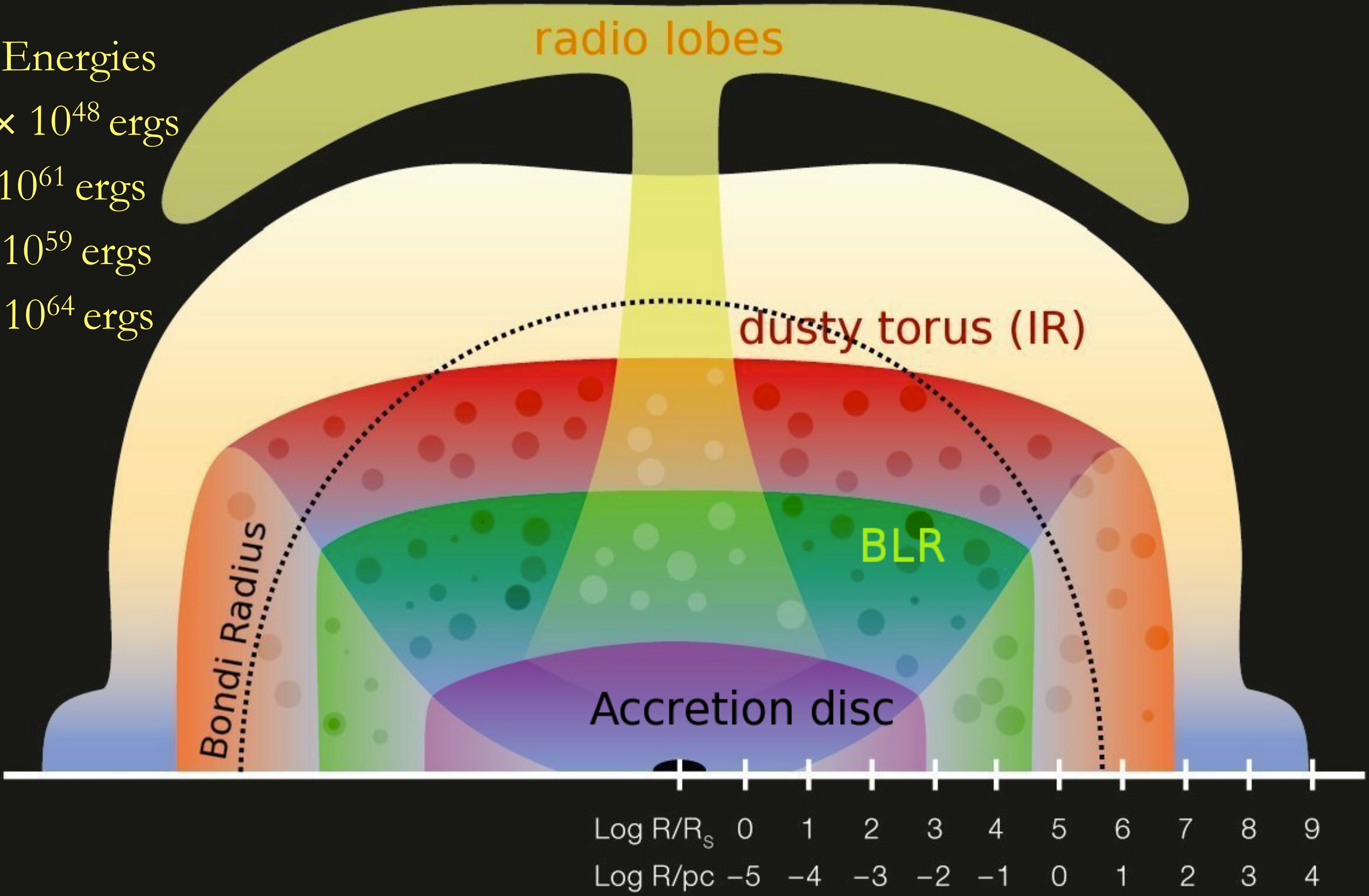
Binding Energies

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

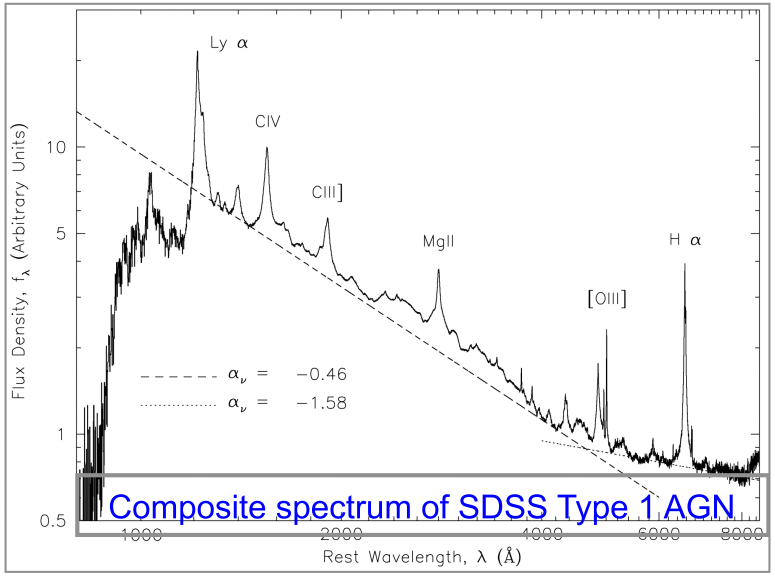
$E_{b,BH,8} \approx 10^{61}$ ergs

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

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

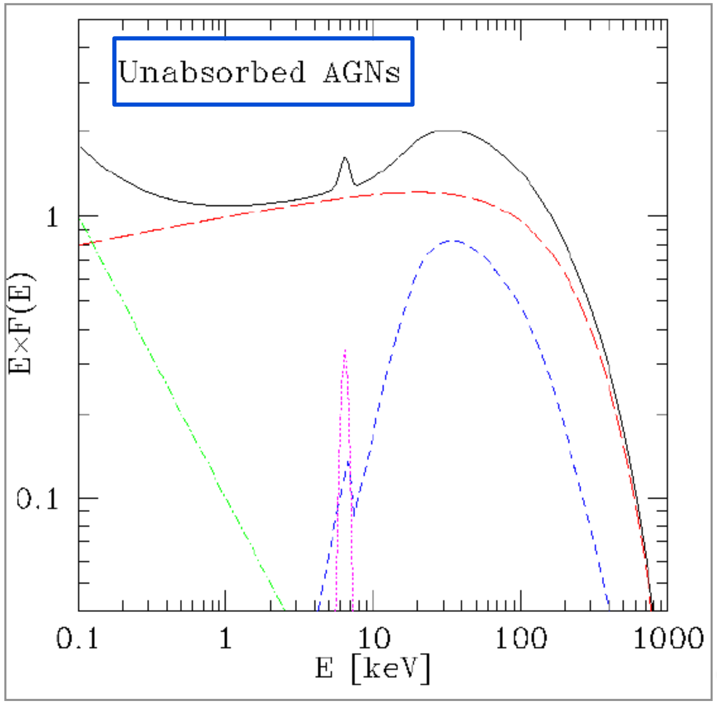


Courtesy of A. Merloni, ESO graphics, 2010



Composite spectrum of SDSS Type 1 AGN

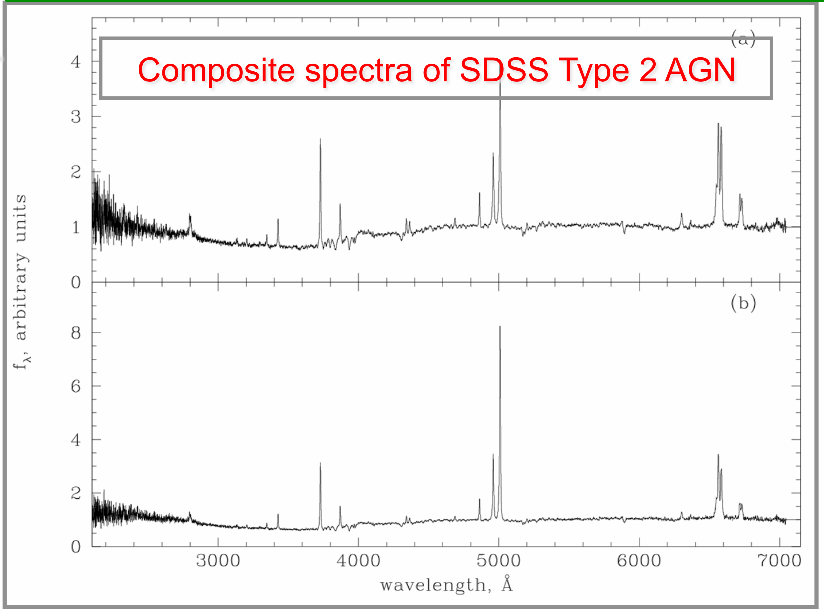
Type 1 AGN



X-ray band

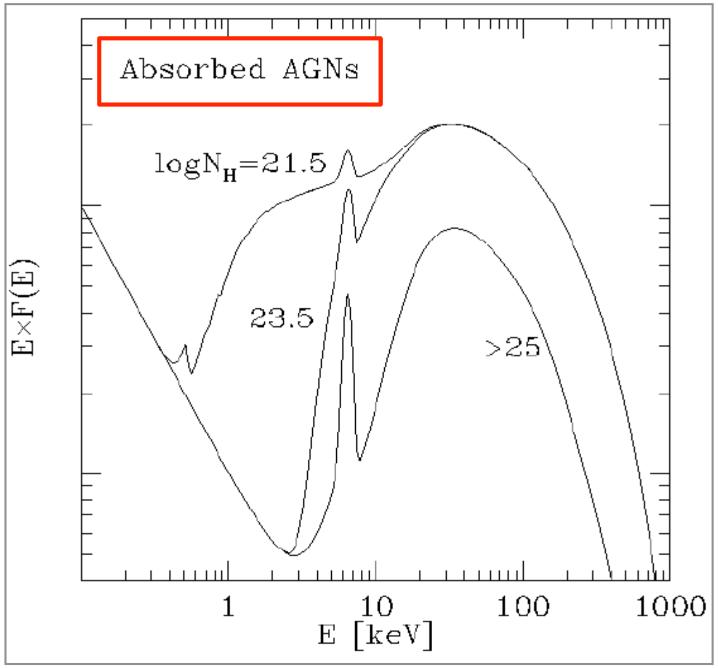
Type 2 AGN easily missed in optical and partly in X-ray surveys

Optical band



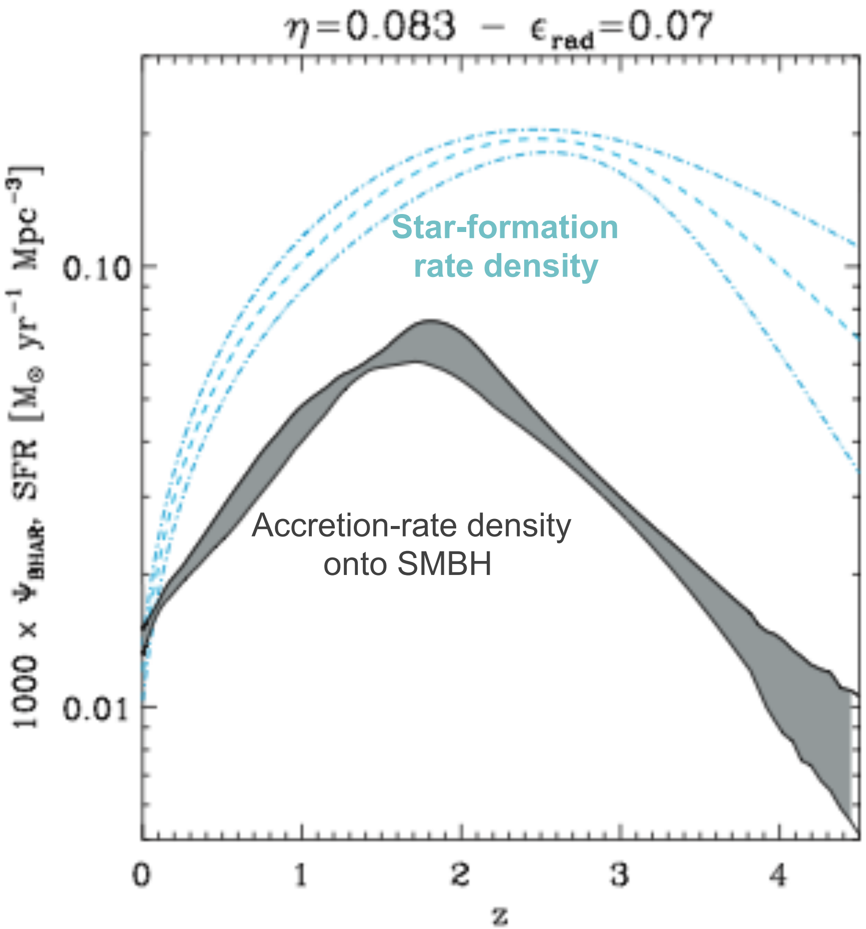
Composite spectra of SDSS Type 2 AGN

Type 2 AGN



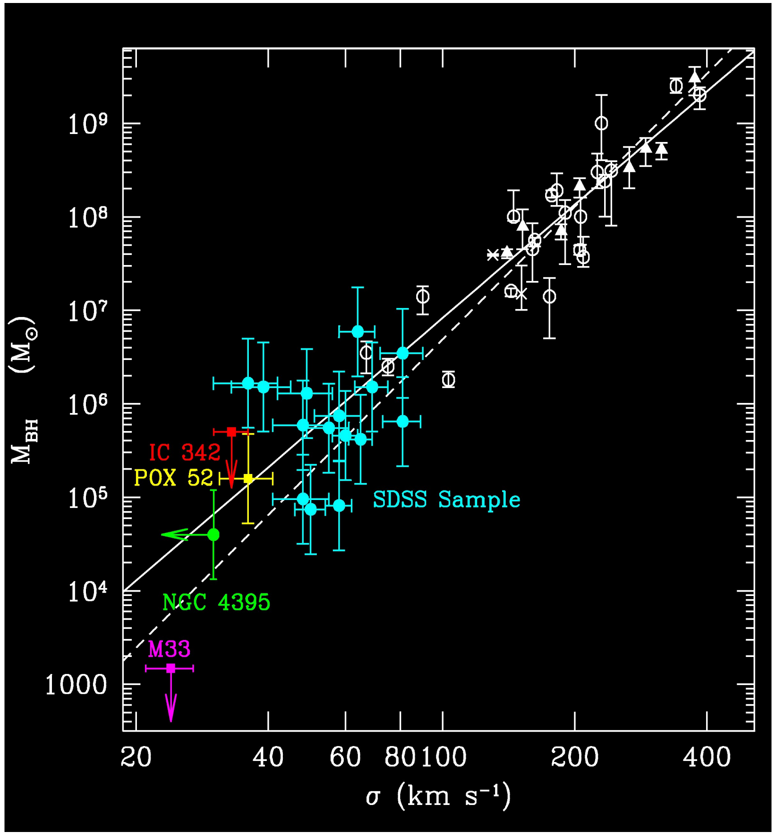
AGN–galaxy co-evolution

Accretion and star formation over cosmic



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

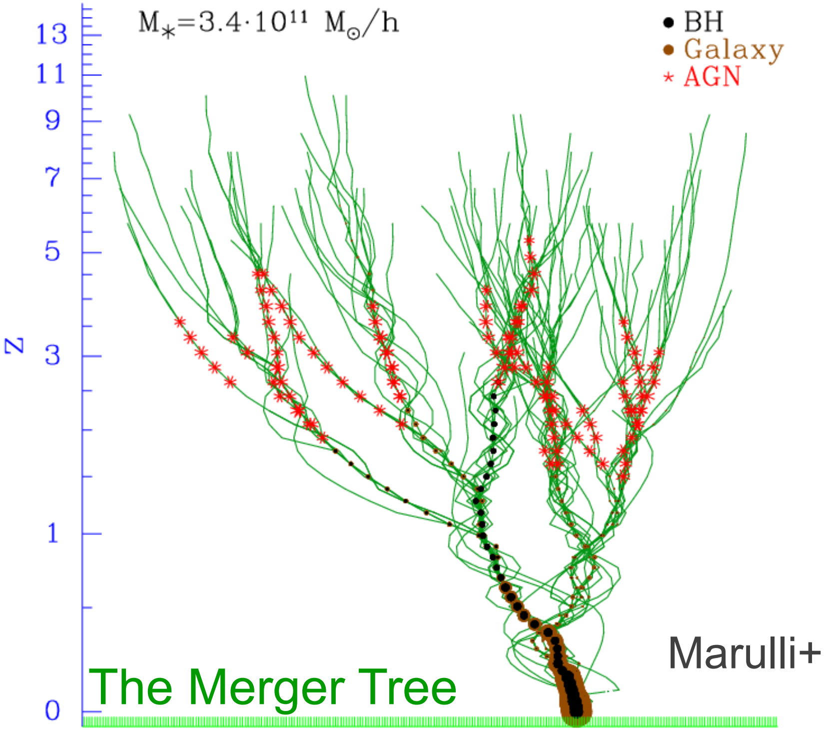
AGN as a key phase of a galaxy lifetime



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

AGN and galaxies closely tied

→co-evolution

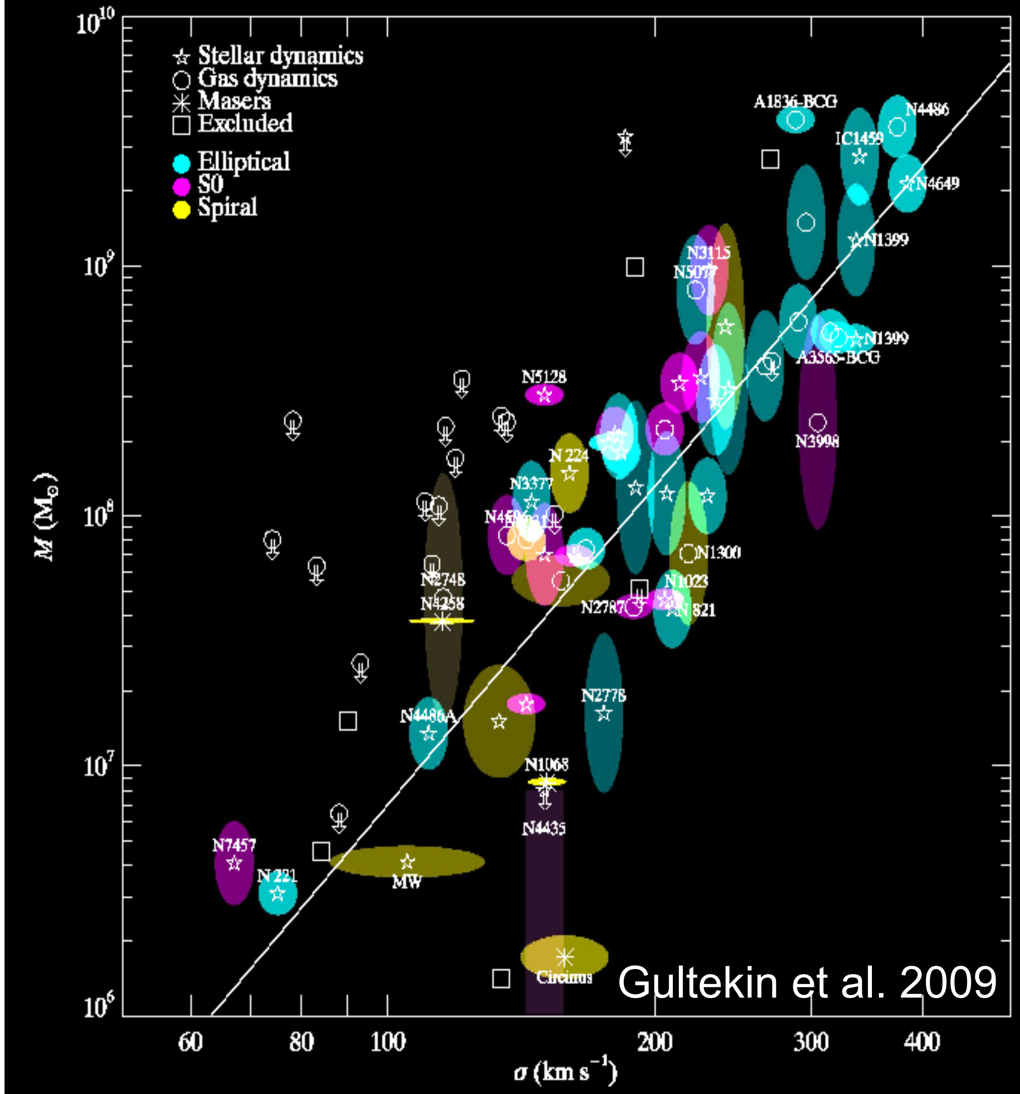


Semi-analytic models of BH/galaxy co-evolution (e.g: Kauffmann+98, Volonteri+06, Salvaterra+06, Rhook&Haehnelt08, Hopkins+08, Menci+08, Marulli+09)

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

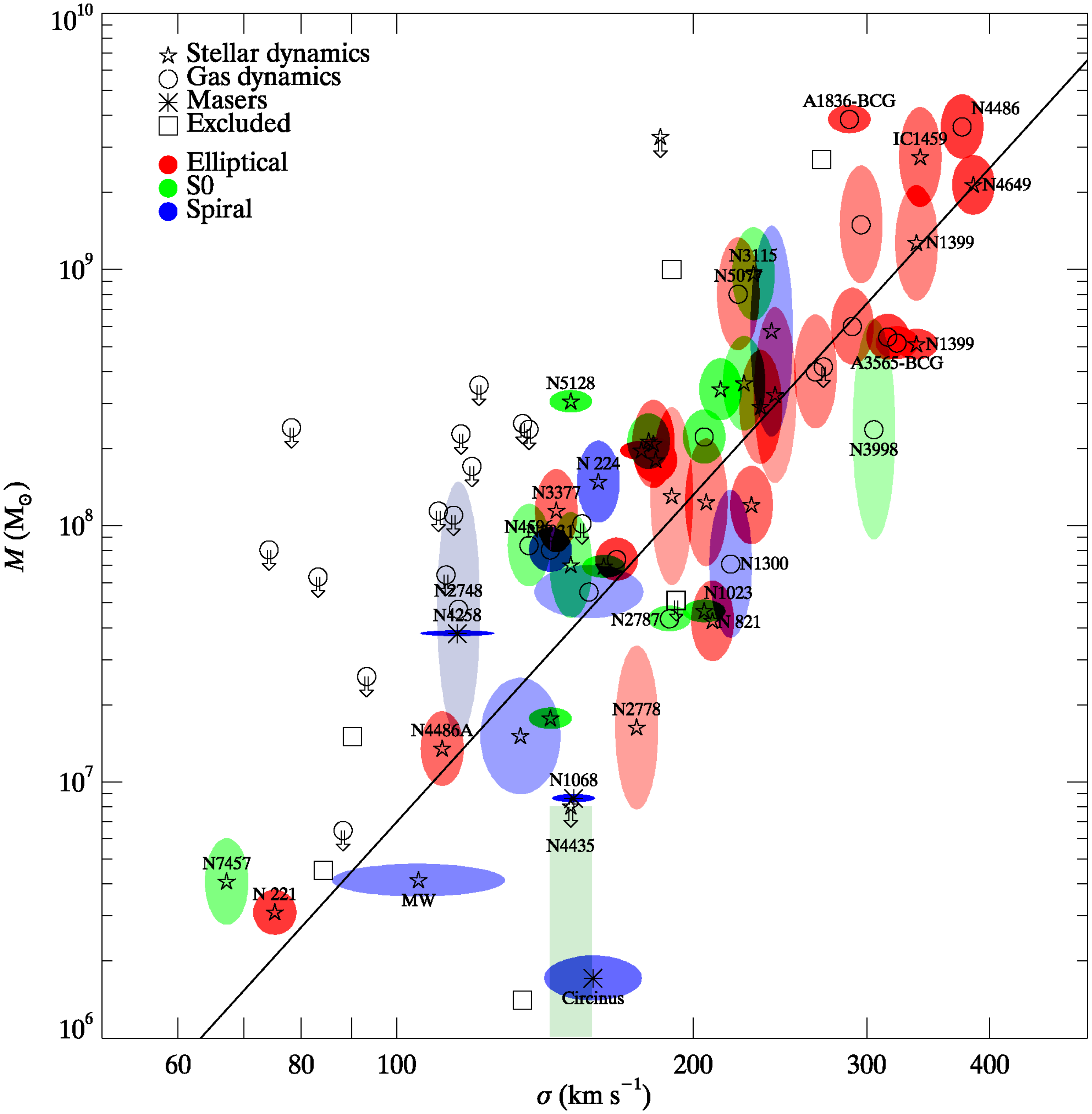
Correlation between BH mass and galaxy velocity dispersion σ

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

No causal connection (now)

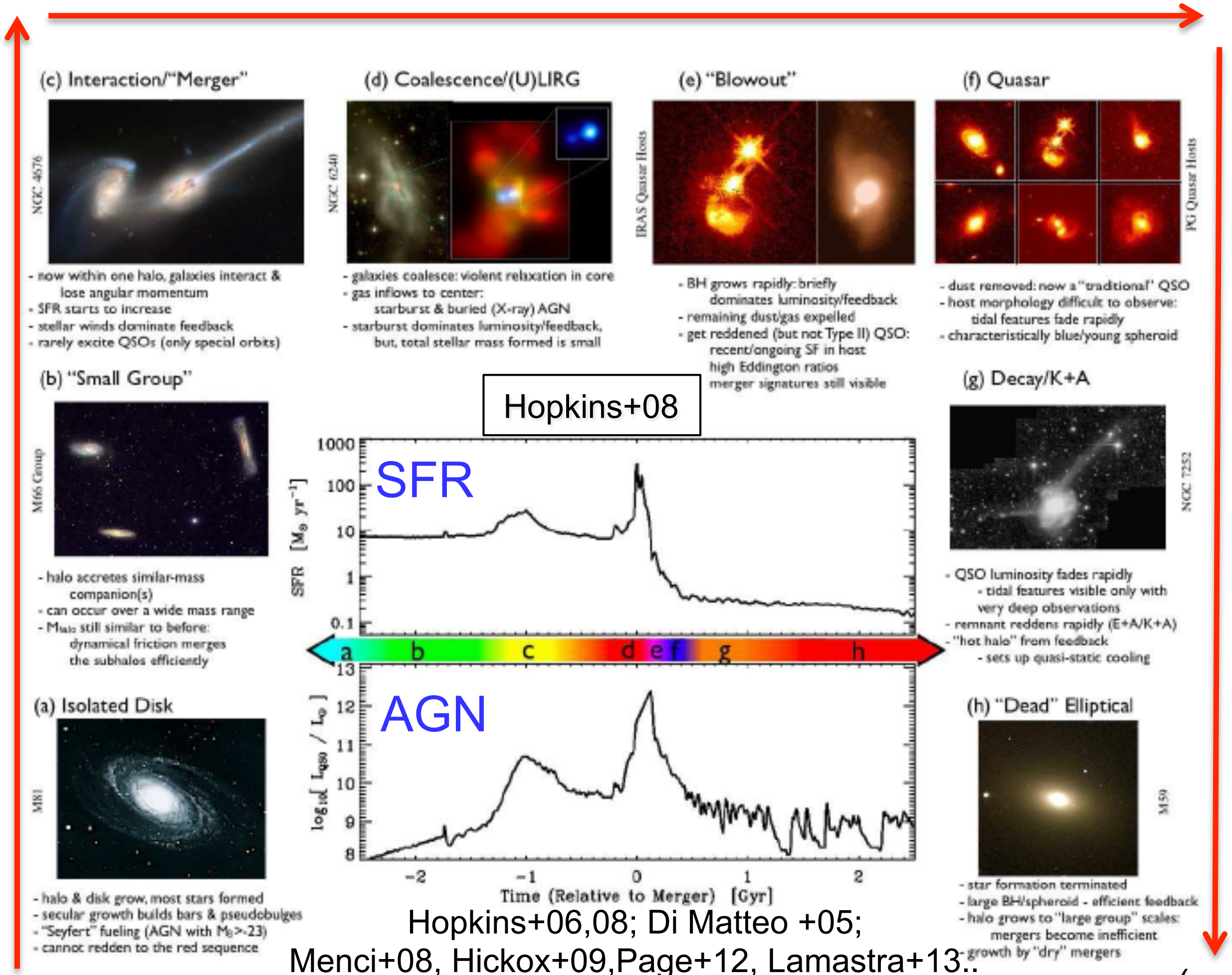
Either coincidence (!) or the result of **common evolution**

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



from Gultekin

The BH/galaxy “evolutionary sequence”

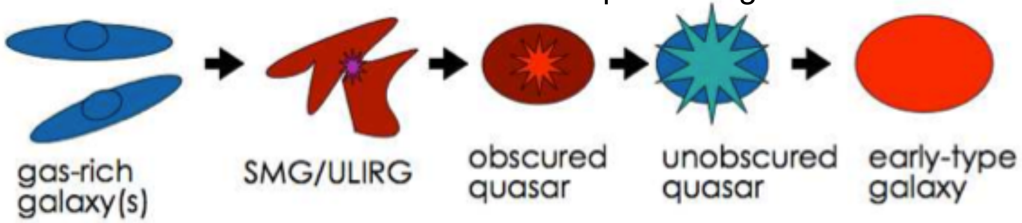


Hopkins+06,08; Di Matteo +05;
Menci+08, Hickox+09,Page+12, Lamastra+13..
see also Sanders+88 pioneering work

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

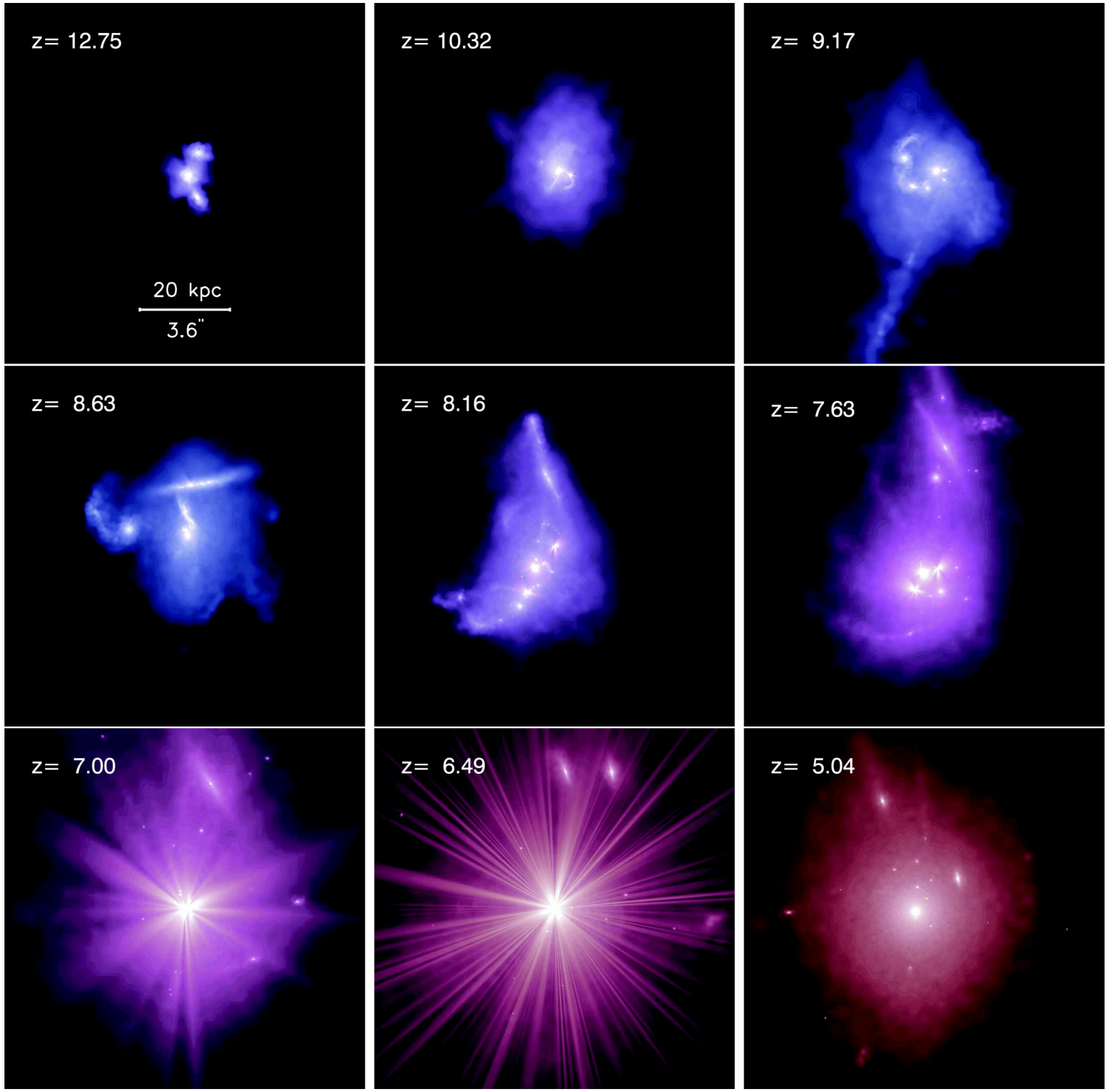
Importance of merger-driven vs.
secular (“smooth”) accretion
(e.g., Elbaz+11, Rodighiero+11, Rovilos+12)

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



Hickox+09

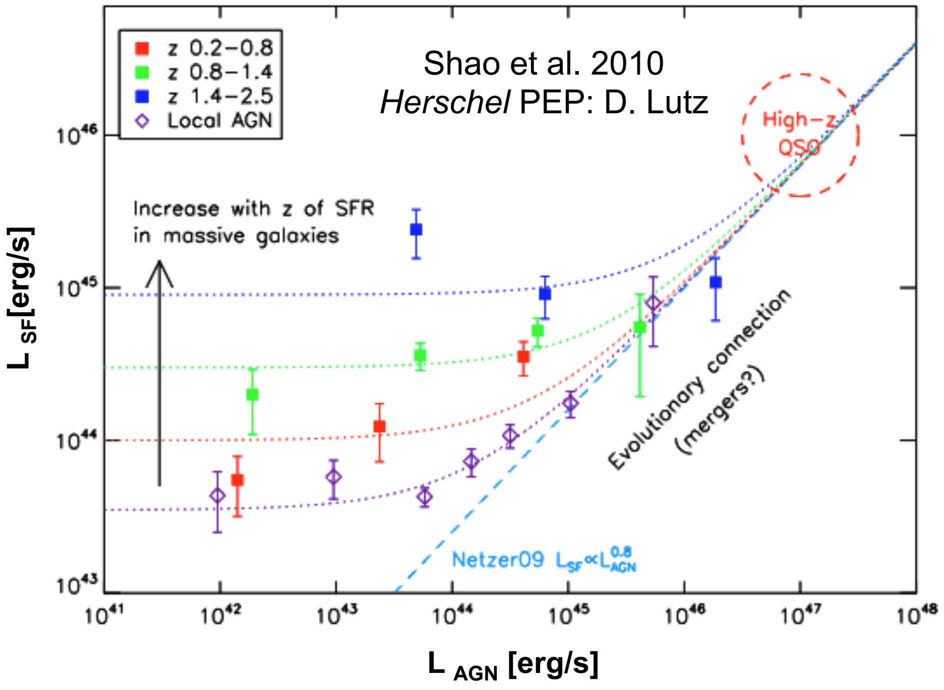
Simulated formation of a ≈10^9 $M_\odot$ BH at high z

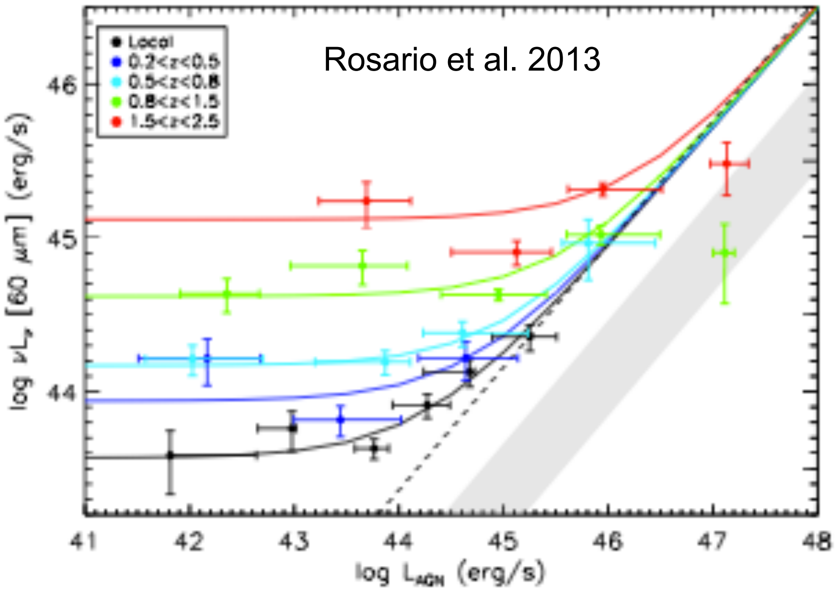


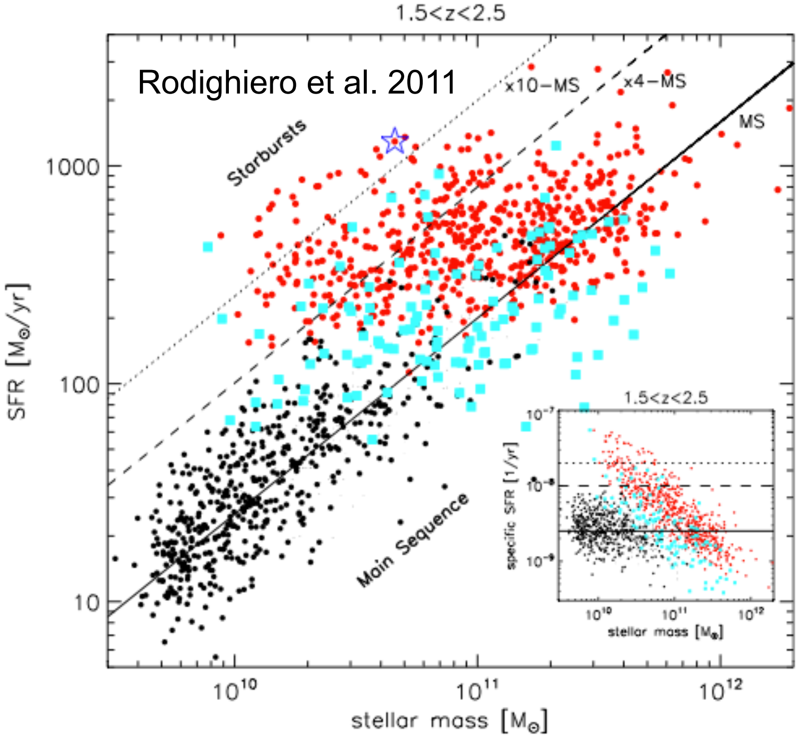
Li+07

- 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?)

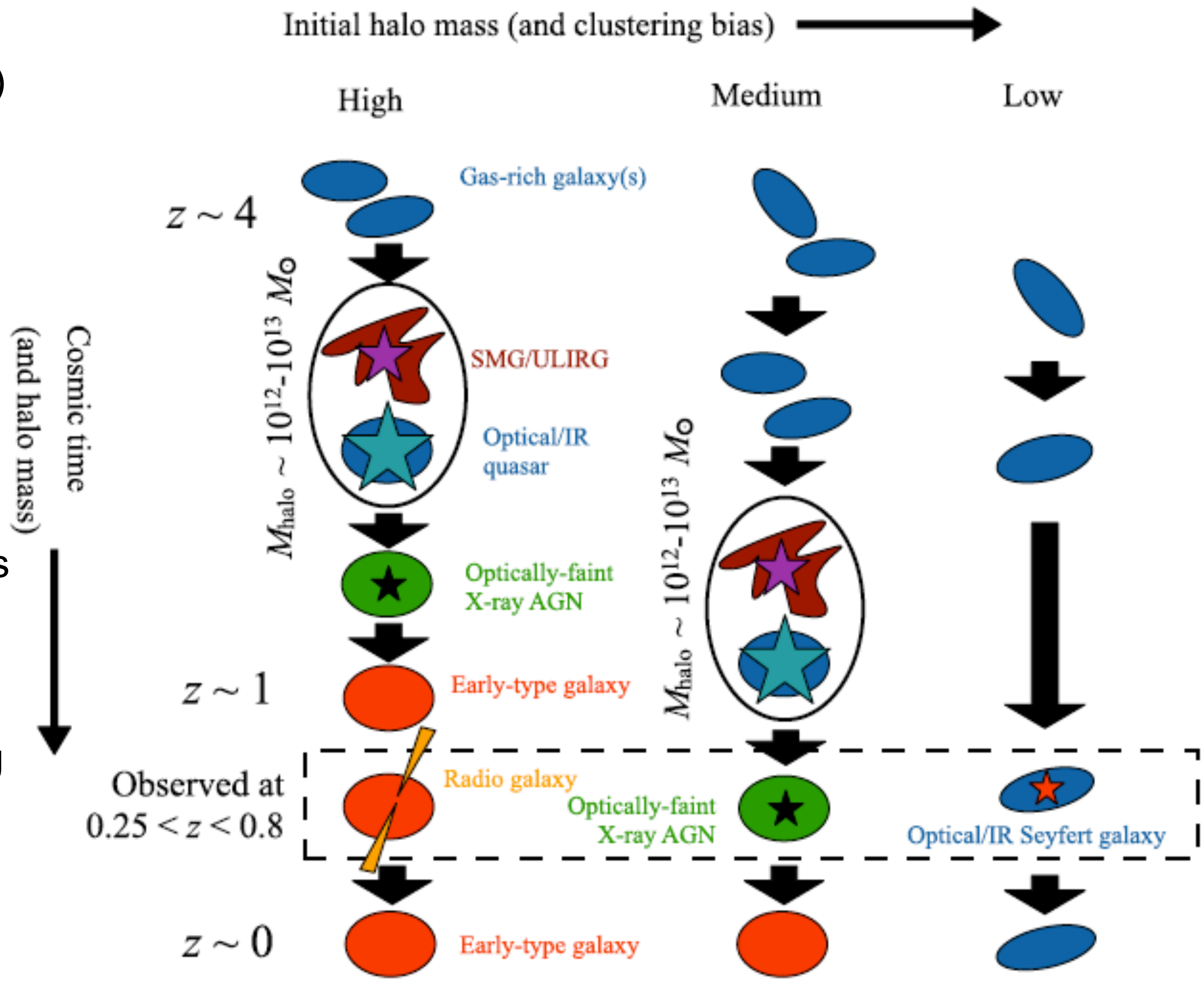
(e.g. Georgakakis+09, Lutz+10, Cisternas+11, Schawinski+11, Elbaz+11, Rodighiero+11,Mullaney+11, Santini+11, Rovilos+12, Rosario+12, …)

The Hickox et al. (2009) cartoon

Threshold halo mass (group mass) to start the galaxy/ AGN co-evolution sequence through mergers

At a given redshift, the evolutionary stage of a galaxy/ AGN depends on the initial halo mass

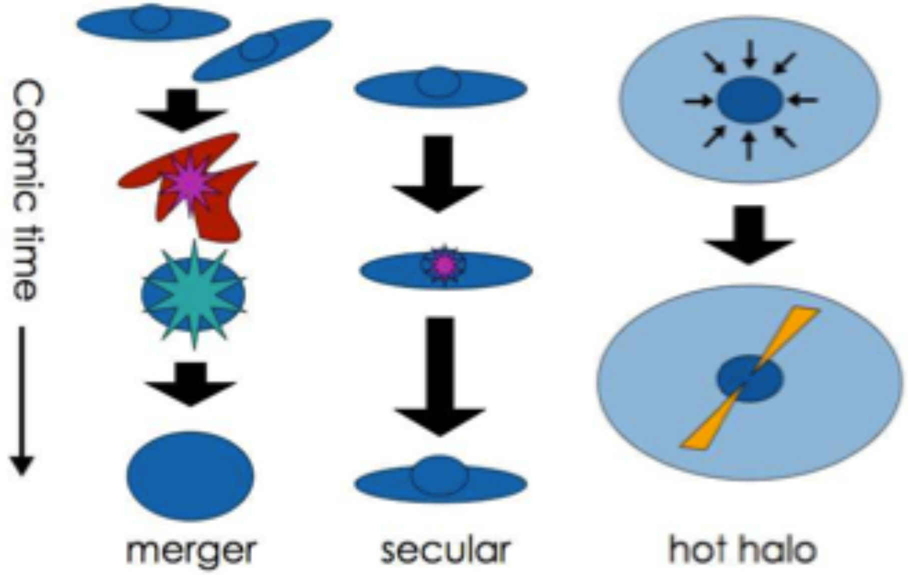
Attempt to link different phases og BH growth with different AGN populations

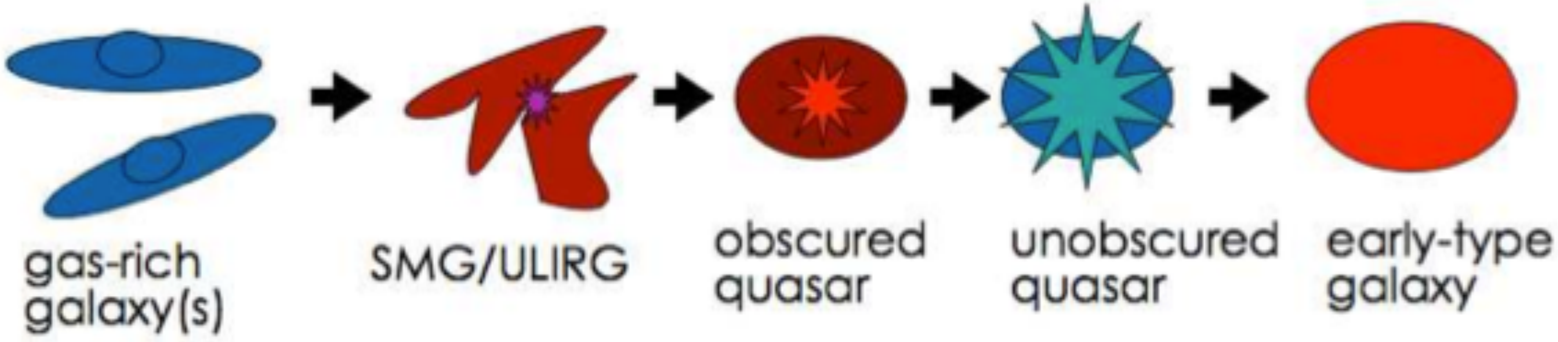


Two modes of accretion:

Mergers ←→ luminous quasars

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

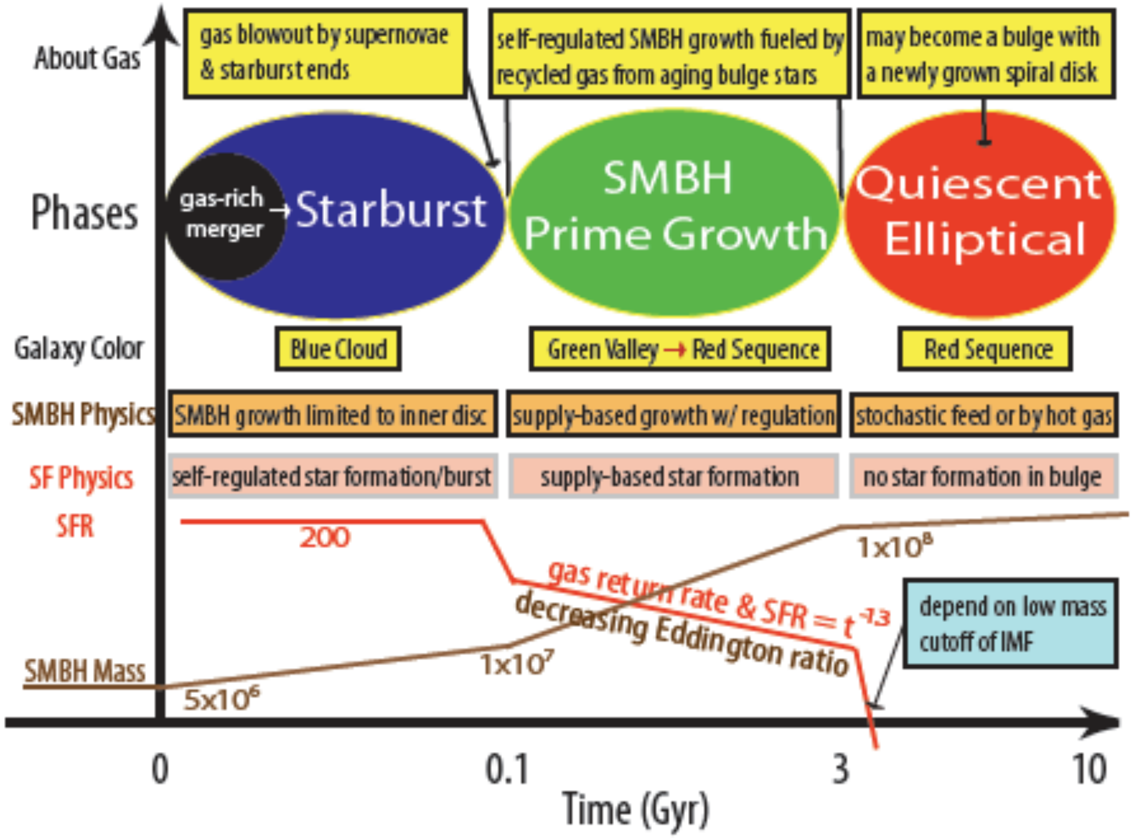




An alternative picture

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

Obscured AGN growth and star formation at z≈2

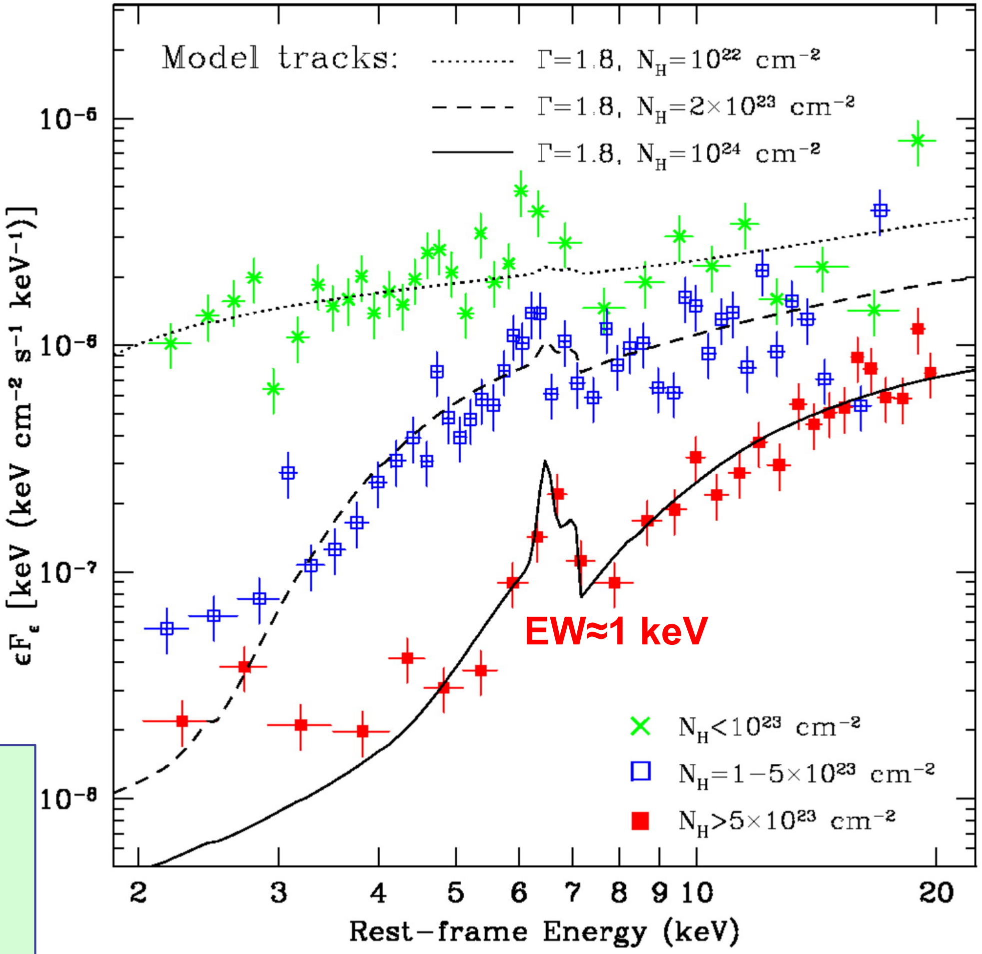
Obscured AGN in sub-mm galaxies

Large reservoir of gas available for accretion and SF

Further indications from mid-IR/ optical selected sources

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

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



Alexander et al. 2005

➔ Needed: census and knowledge of Compton-thick AGN

But …

Two (out of many…) missing pieces:

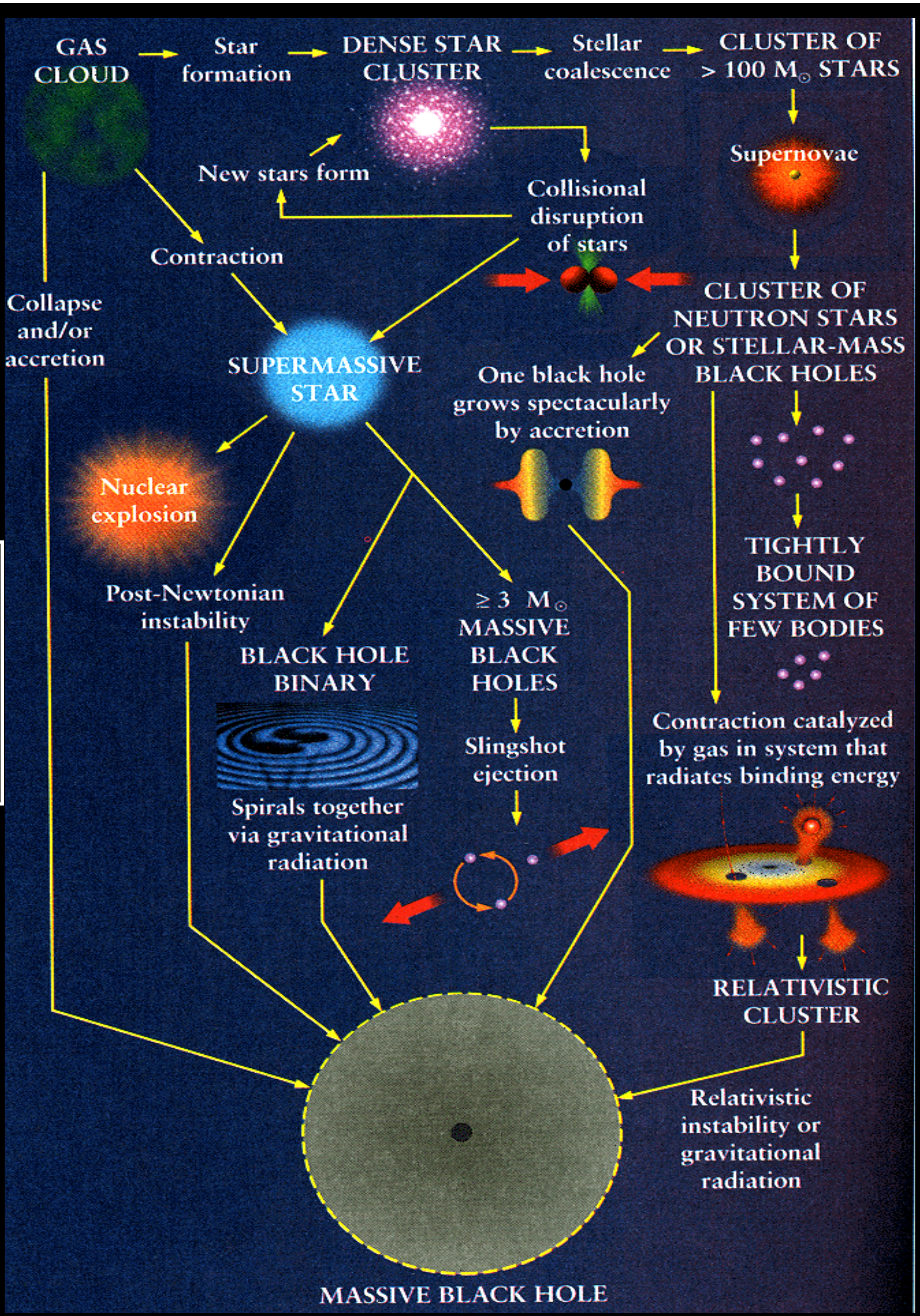
1) BH/galaxy co-evolution is still unconstrained at very high-z (z>6 or so). Already formed luminous QSOs at z=6

2) Heavily obscured accretion mostly unconstrained beyond the local Universe

Requirement: a complete census of AGN activity

Information stored in the X-ray background

The first black holes



GAS CLOUD

Star formation

DENSE STAR CLUSTER

Stellar coalescence

CLUSTER OF > 100 $M_\odot$ STARS

Supernovae

New stars form

Collisional disruption of stars

Contraction

Collapse and/or accretion

SUPERMASSIVE STAR

CLUSTER OF NEUTRON STARS OR STELLAR-MASS BLACK HOLES

One black hole grows spectacularly by accretion

Nuclear explosion

TIGHTLY BOUND SYSTEM OF FEW BODIES

Post-Newtonian instability

≥ 3 $M_\odot$ MASSIVE BLACK HOLES

BLACK HOLE BINARY

Contraction catalyzed by gas in system that radiates binding energy

Slingshot ejection

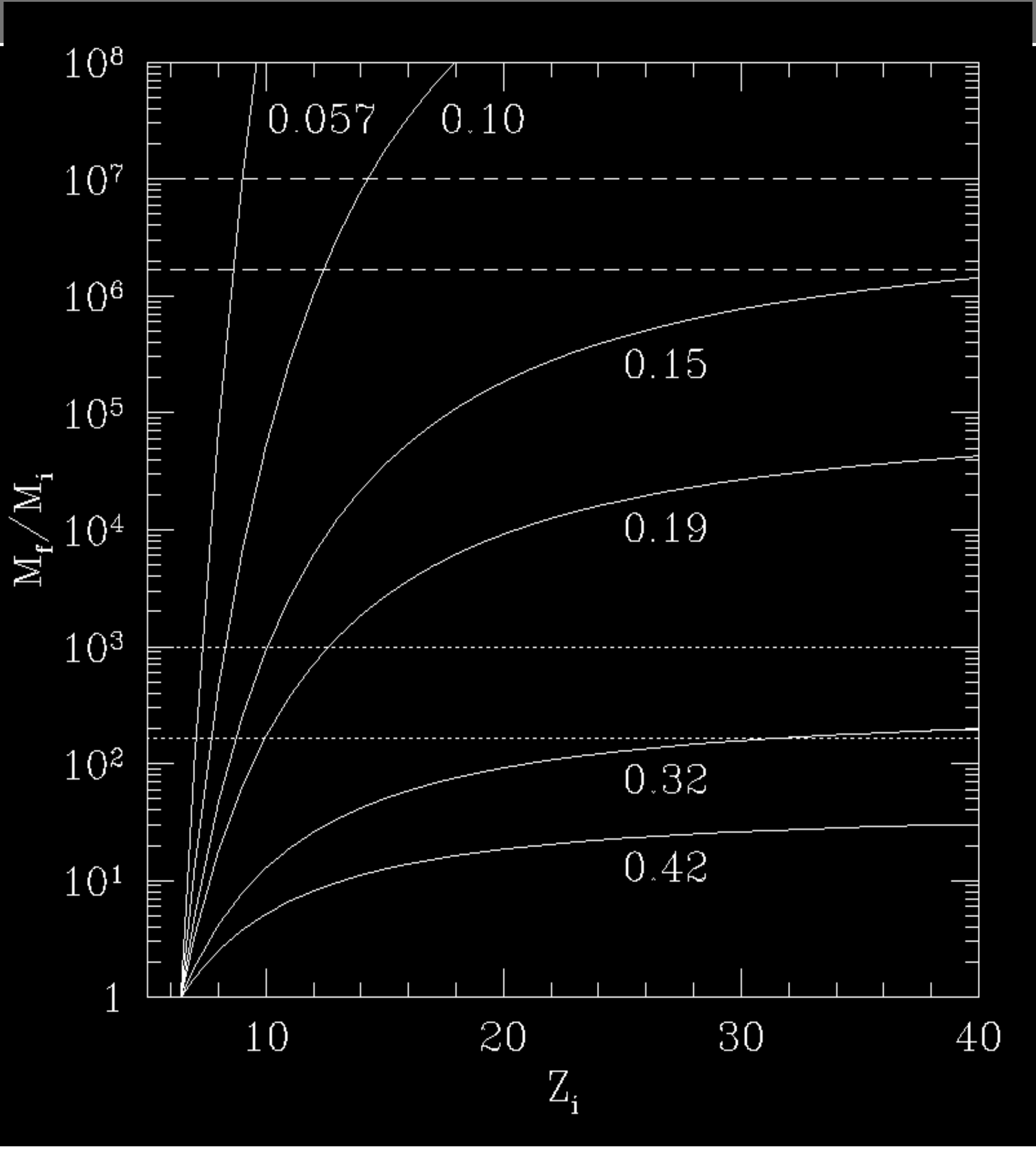
Spirals together via gravitational radiation

RELATIVISTIC CLUSTER

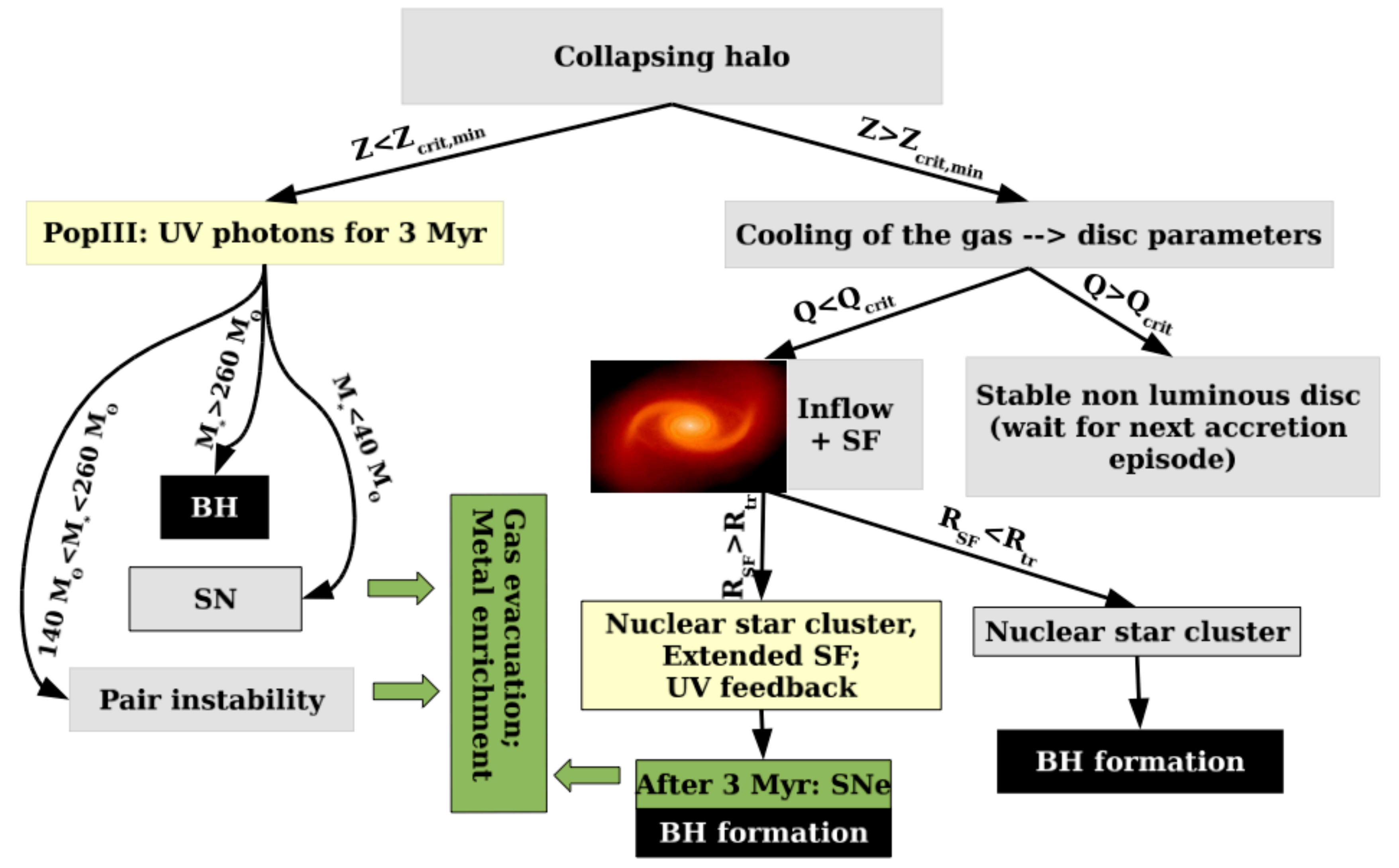
Relativistic instability or gravitational radiation

MASSIVE BLACK HOLE

The highest redshift QSOs: the time problem



Seed black hole formation



Collapsing halo

$Z<Z_{crit,min}$

$Z>Z_{crit,min}$

PopIII: UV photons for 3 Myr

Cooling of the gas --> disc parameters

$140\ M_\odot<M_*<260\ M_\odot$

$M_*>260\ M_\odot$

$M_*<40\ M_\odot$

BH

SN

Pair instability

Gas evacuation;
Metal enrichment

$Q<Q_{crit}$

$Q>Q_{crit}$

Inflow
+ SF

Stable non luminous disc
(wait for next accretion episode)

$R_{SF}>R_{tr}$

$R_{SF}<R_{tr}$

Nuclear star cluster,
Extended SF;
UV feedback

Nuclear star cluster

After 3 Myr: SNe

BH formation

BH formation

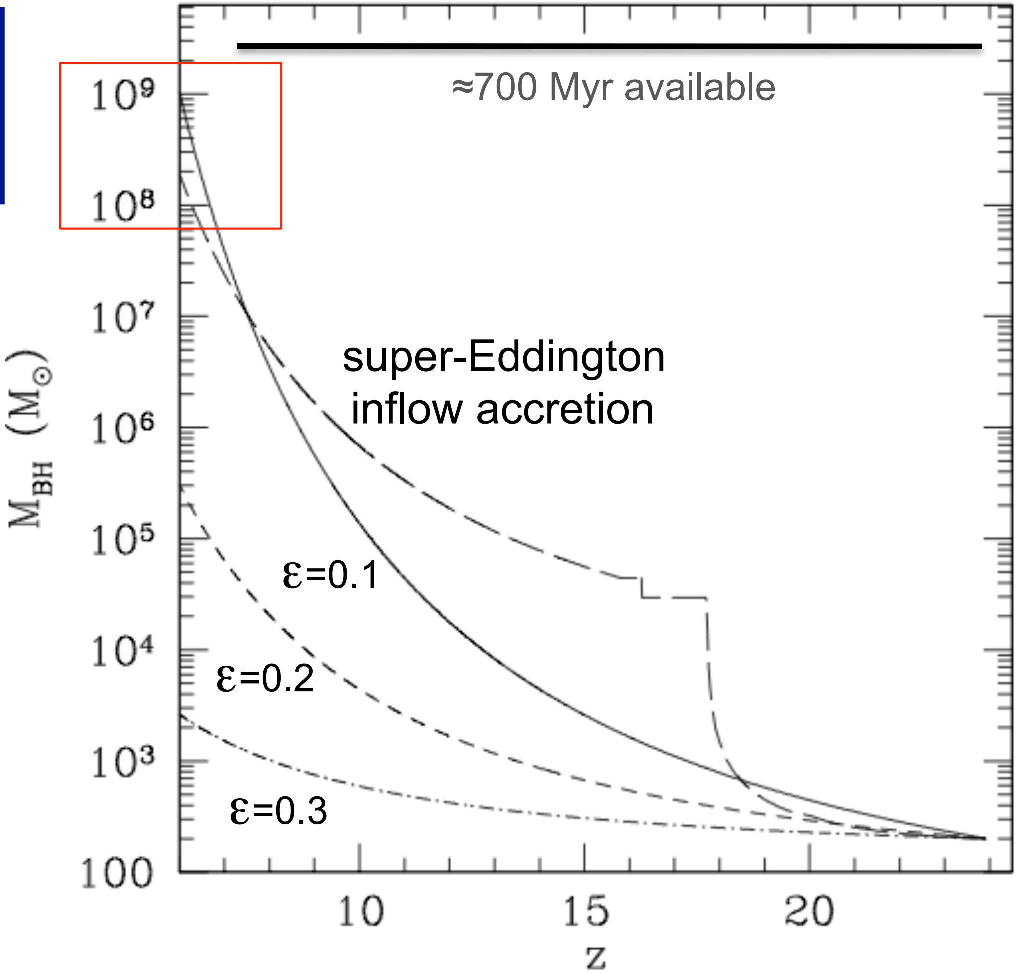
Open issue: time for BH growth at z≈6

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

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

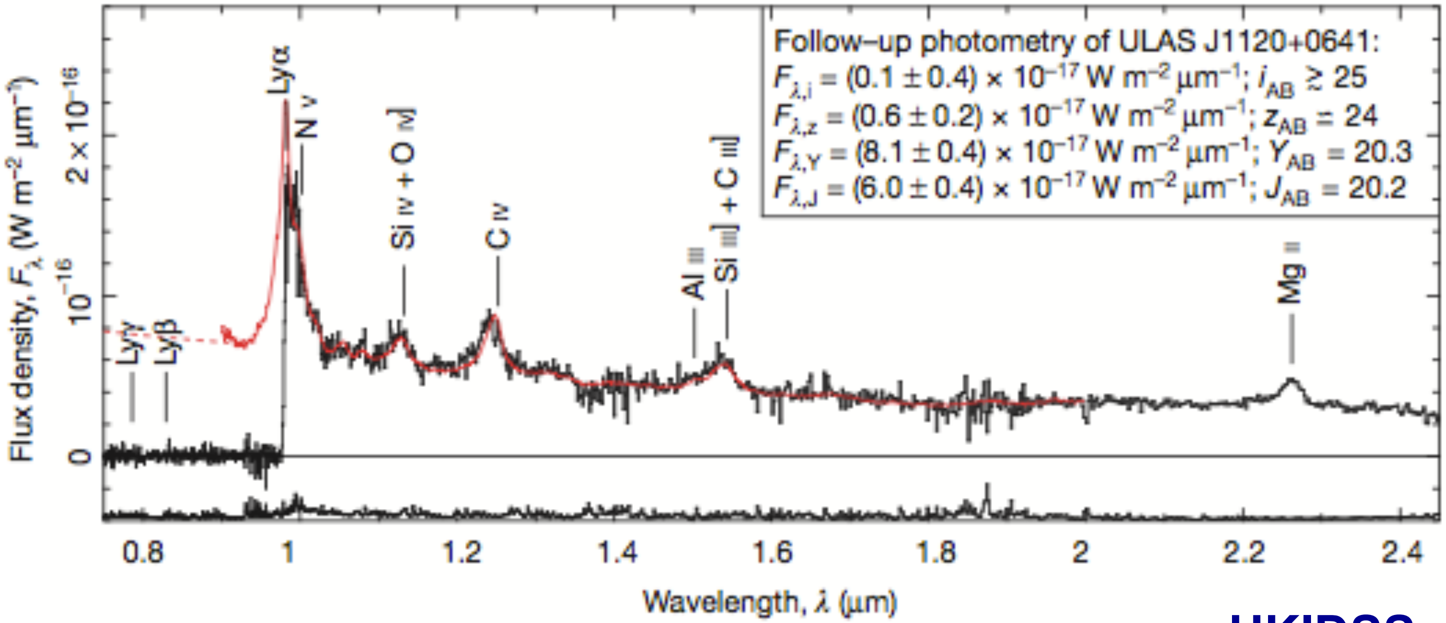
Highest-redshift quasar so far spectroscopically identified: ULASJ1120+0641, z=7.08, M_{BH}≈2×10^9 $M_\odot$ (Mortlock et al. 2011)



Volonteri & Rees 2006

Possible problems with the mass of the “seed” BHs

ULASJ1120+0641, z=7.08



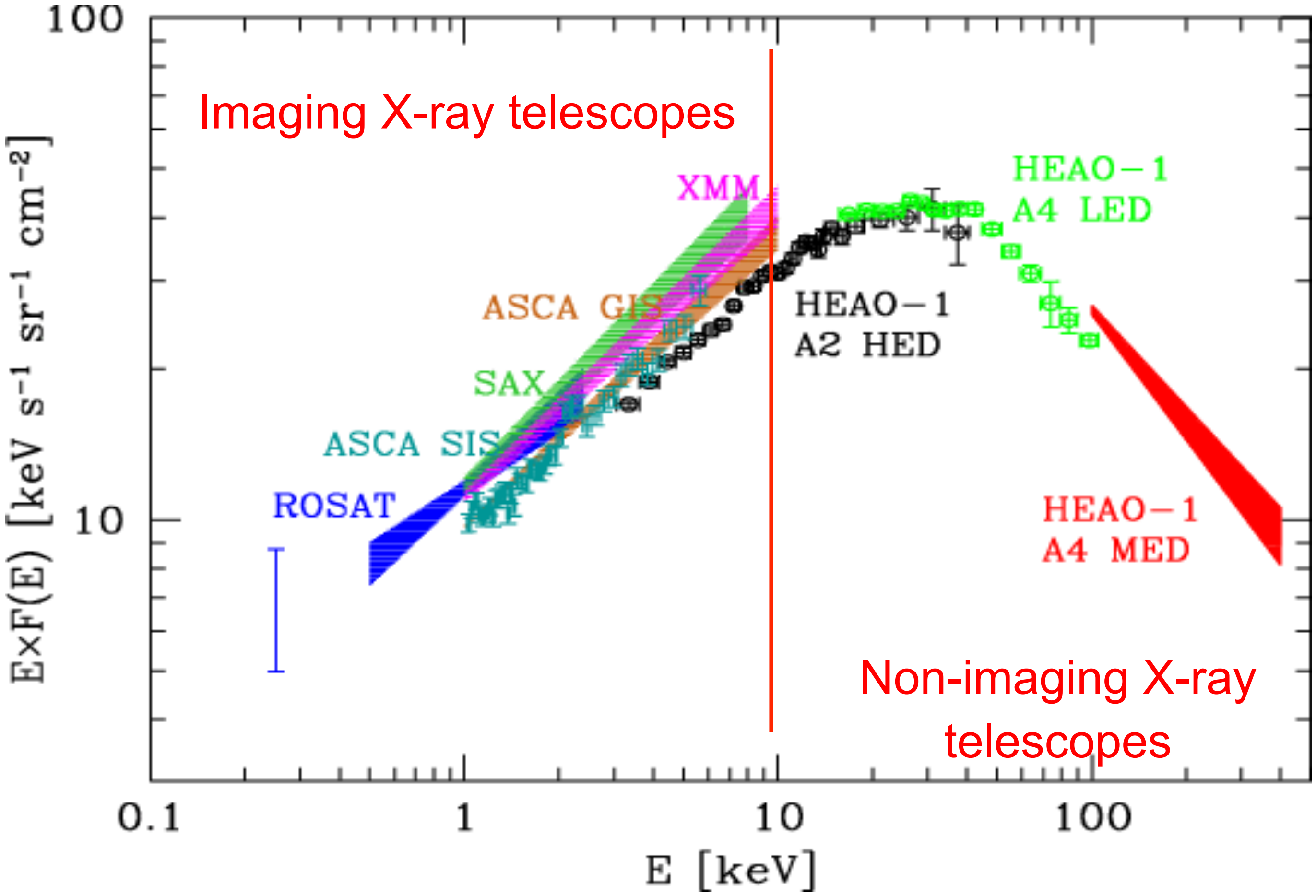
UKIDSS

Mortlock et al. 2011, GNIRS+FORS2, compared to average z~2.5 SDSS QSOs

Fully mature QSOs at high redshift

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:

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

Can a diffuse plasma emission explain the XRB?

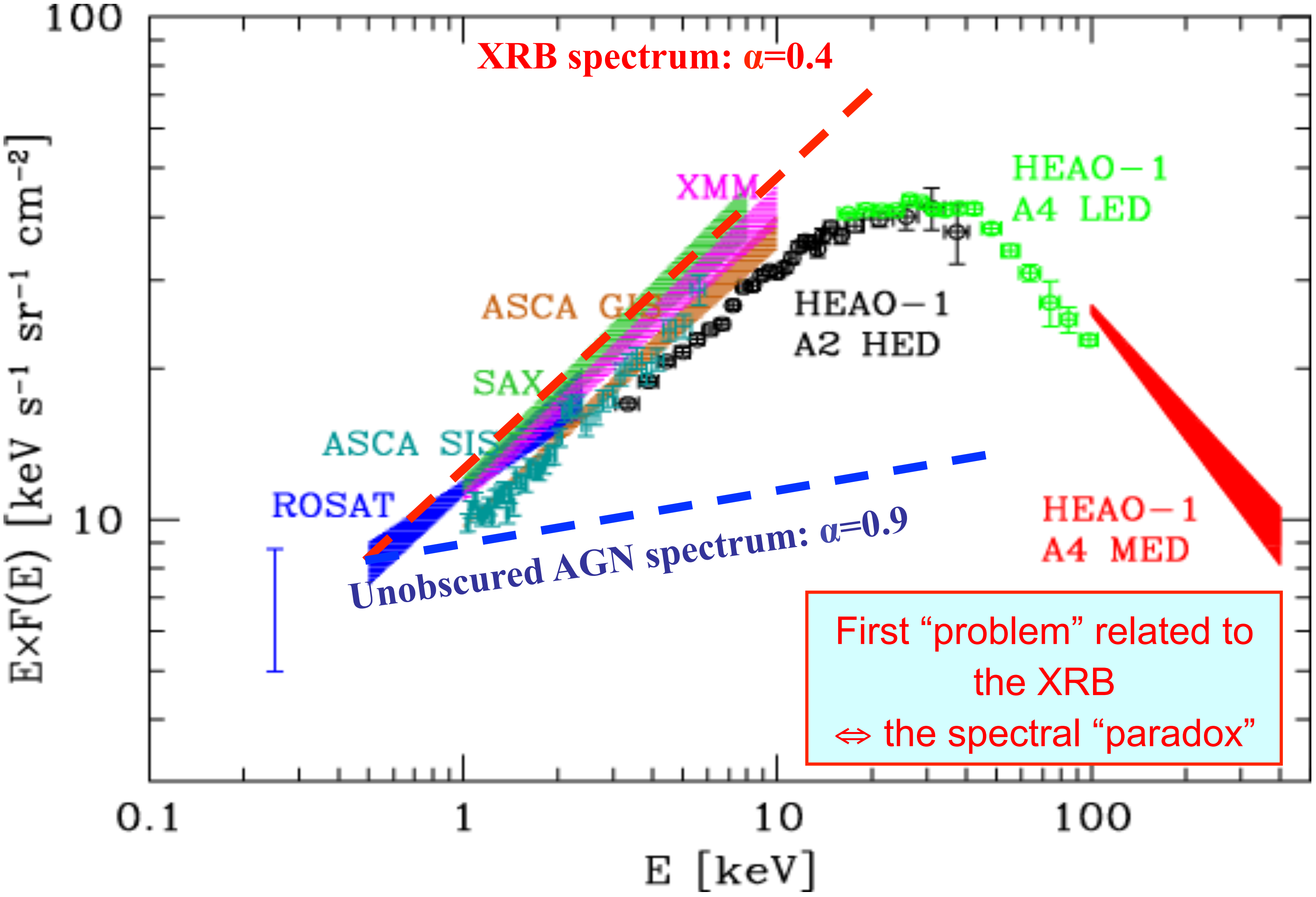
No!

- subtracting AGN implies an XRB spectrum no more compatible with bremsstrahlung emission
- CMB represents a perfect blackbody; hot gas ($T \sim 40$ keV $\approx 4\times10^{8}$ K) would produce distortions by inverse Compton effect (Mather et al. 1994)

⇩

Emission by unresolved, faint individual sources → AGN

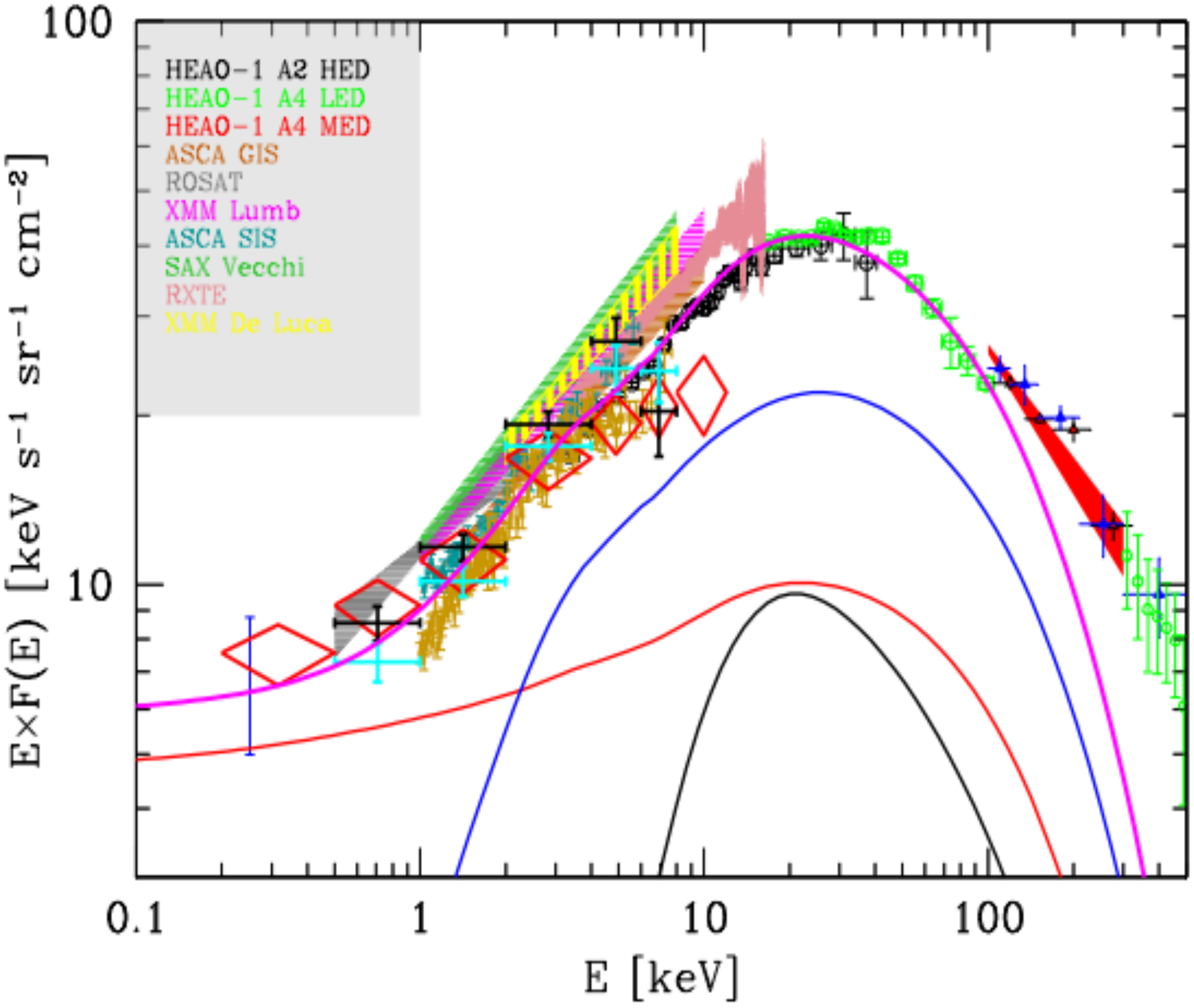
The spectral paradox



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

The spectrum of the cosmic XRB as sum of obscured and unobscured AGN

(following the original idea of Setti & Woltjer 1989)



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

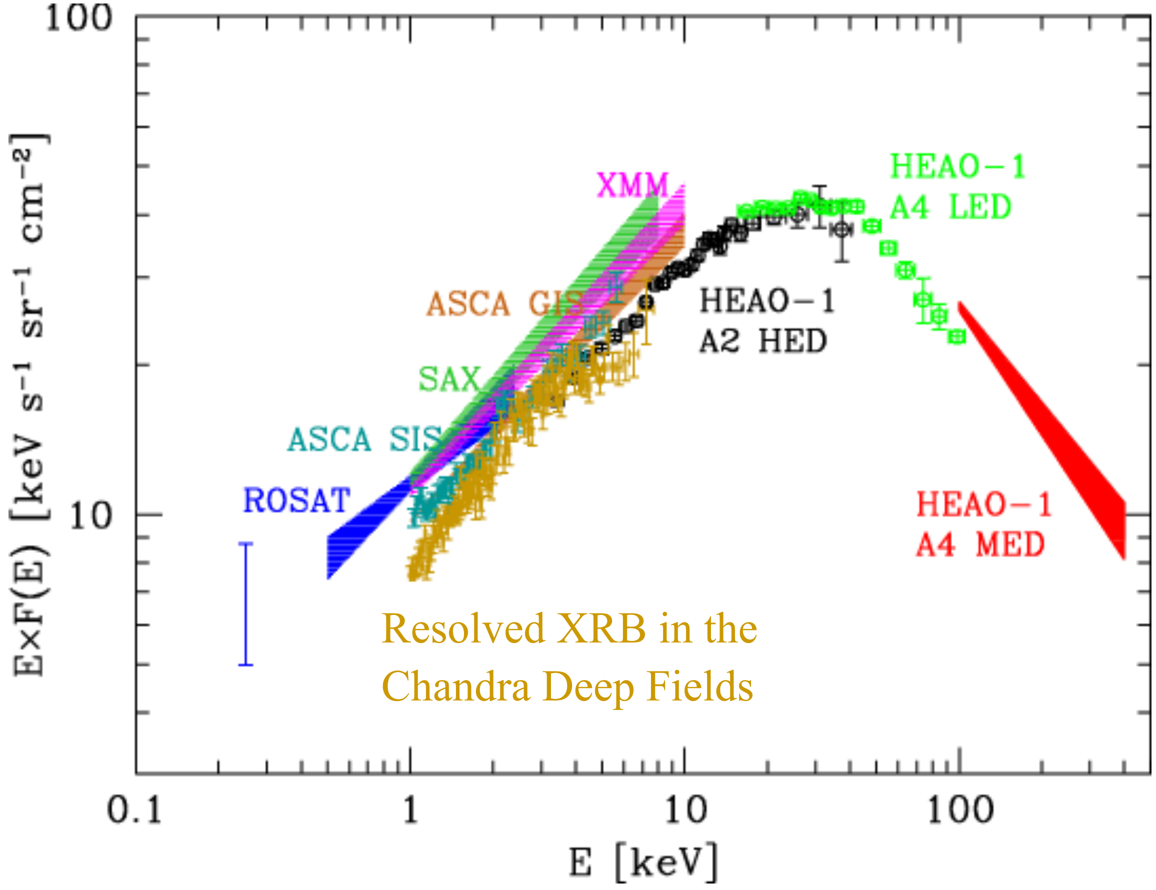
Red ➔ unobscured

Blue ➔ Compton Thin

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

The evolution is folded
in the adopted XLF

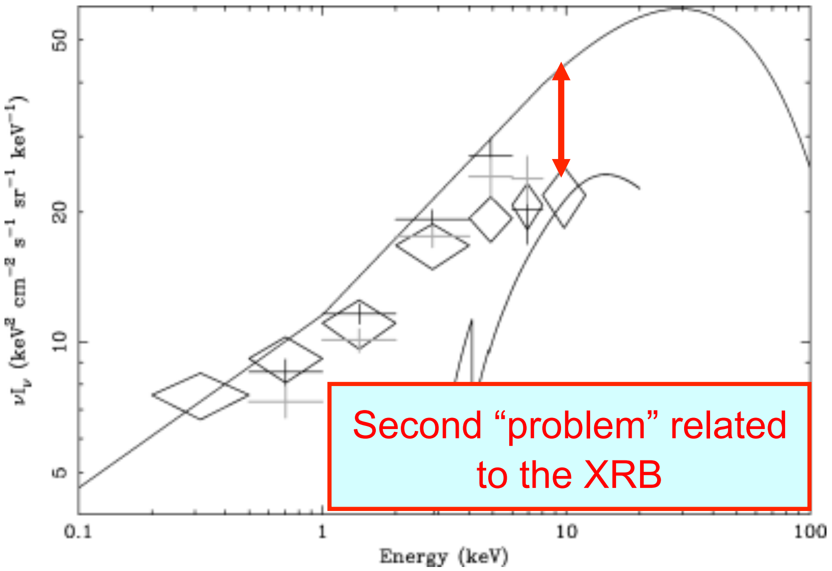
Resolved XRB fraction: still a “missing” population?



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

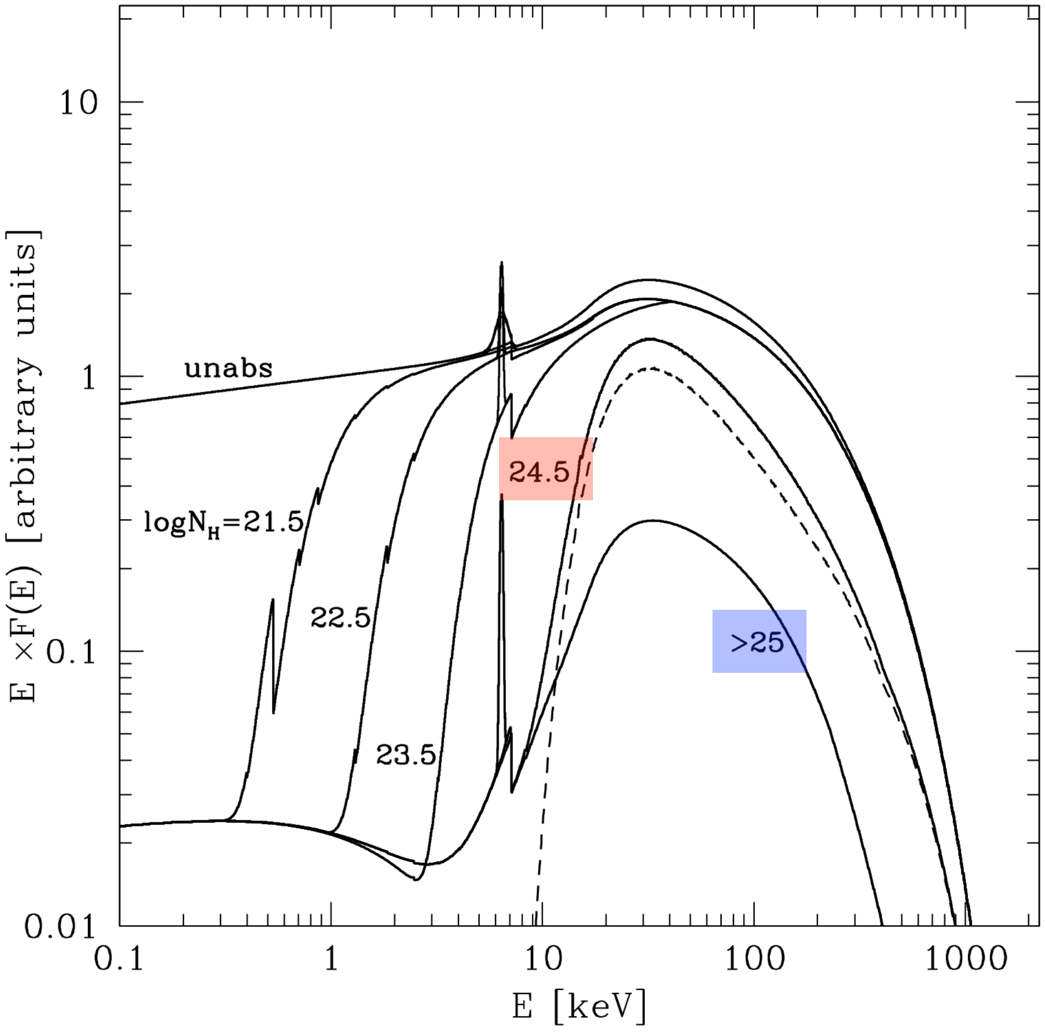
BUT only 50% resolved above 5 keV

Worsley et al. (2005)



Second “problem” related to the XRB

AGN X-ray spectral templates with different N_H

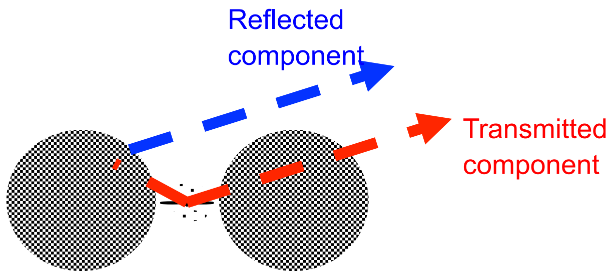


Only ≈40-50 “secure” Compton-thick AGN (≈10 mildly-thick) known at present

Unabsorbed:
$\log N_H < 21$

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

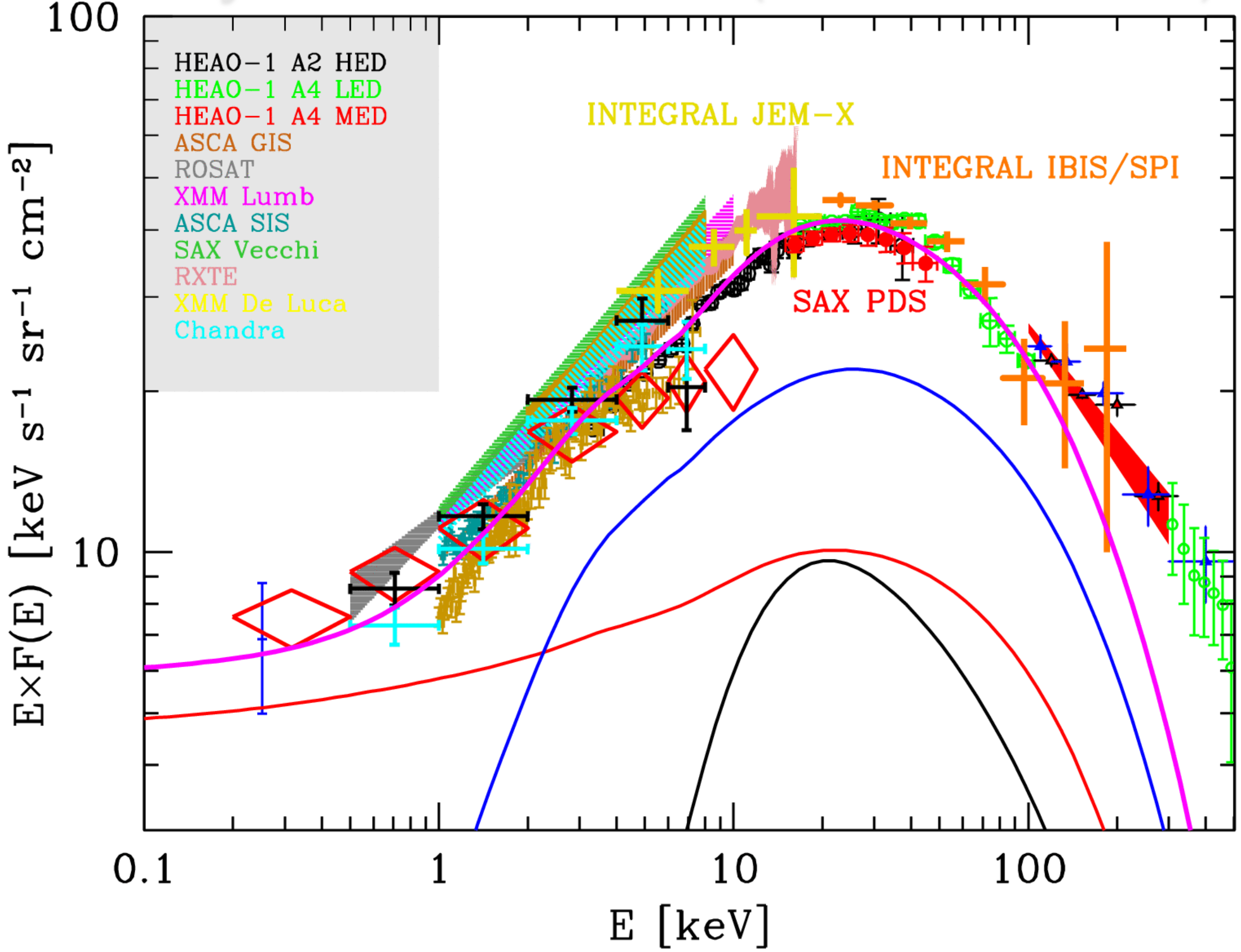
Compton-Thick:
Mildly ($\log N_H = 24\text{-}25$)
Heavily ($\log N_H > 25$)



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

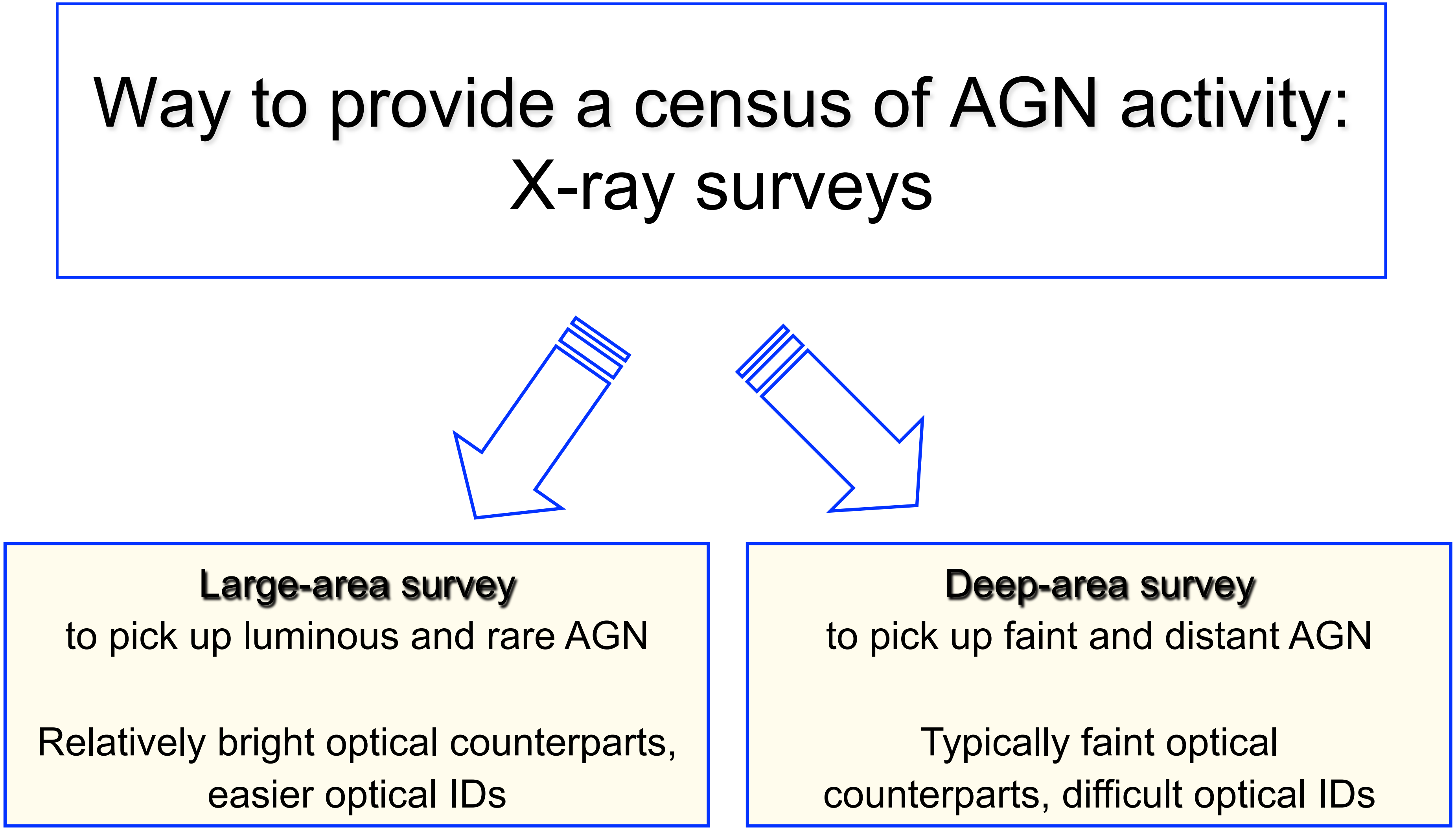
As N_H increases, the spectrum is absorbed towards higher and higher energies.

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

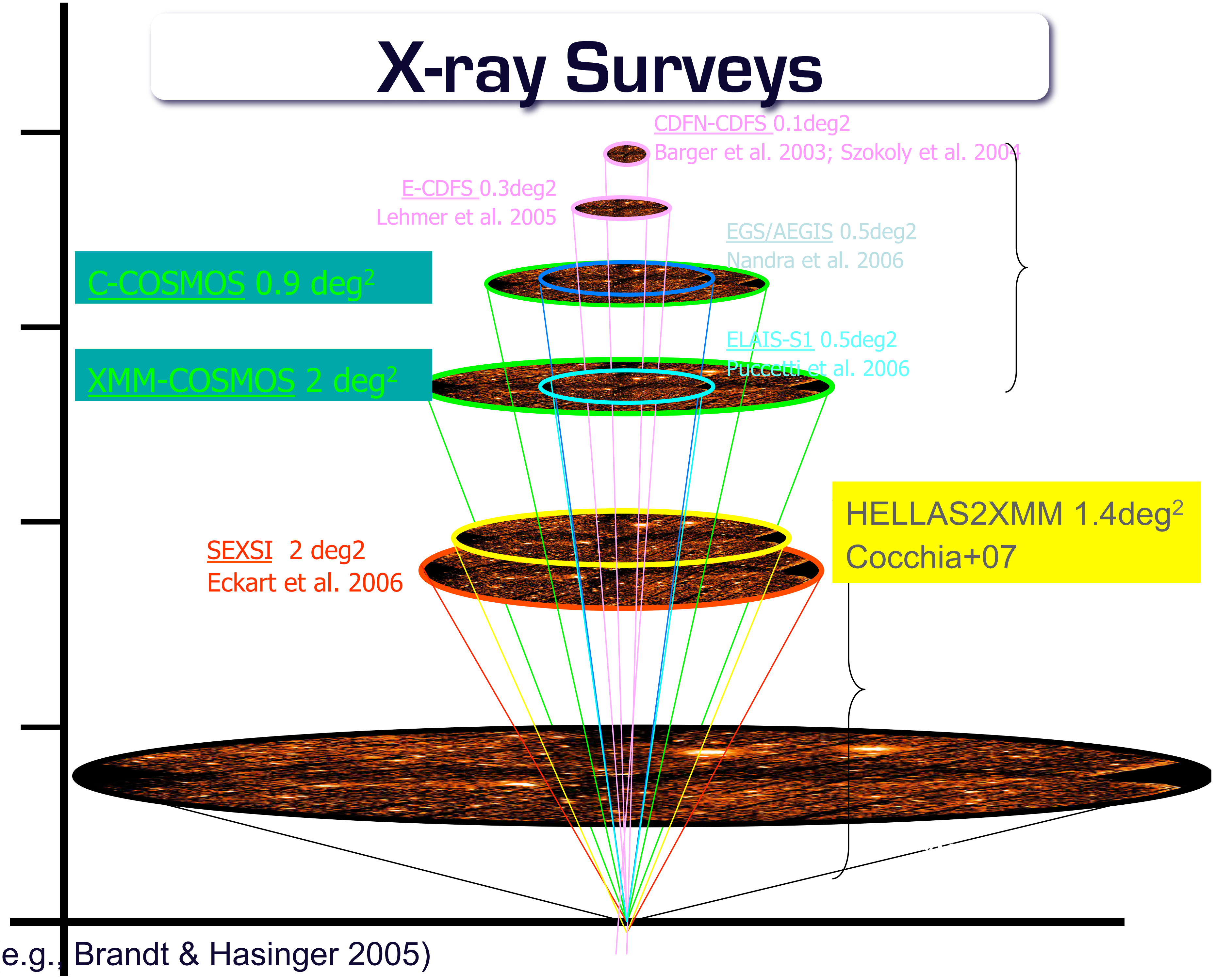
Large-area survey
to pick up luminous and rare AGN

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



CDFN-CDFS 0.1deg2
Barger et al. 2003; Szokoly et al. 2004

E-CDFS 0.3deg2
Lehmer et al. 2005

EGS/AEGIS 0.5deg2
Nandra et al. 2006

C-COSMOS 0.9 deg^2

ELAIS-S1 0.5deg2
Puccetti et al. 2006

XMM-COSMOS 2 deg^2

HELLAS2XMM 1.4deg^2
Cocchia+07

SEXSI 2 deg2
Eckart et al. 2006

(e.g., Brandt & Hasinger 2005)

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

Hickox 2009, adapted from Brandt & Hasinger 2005

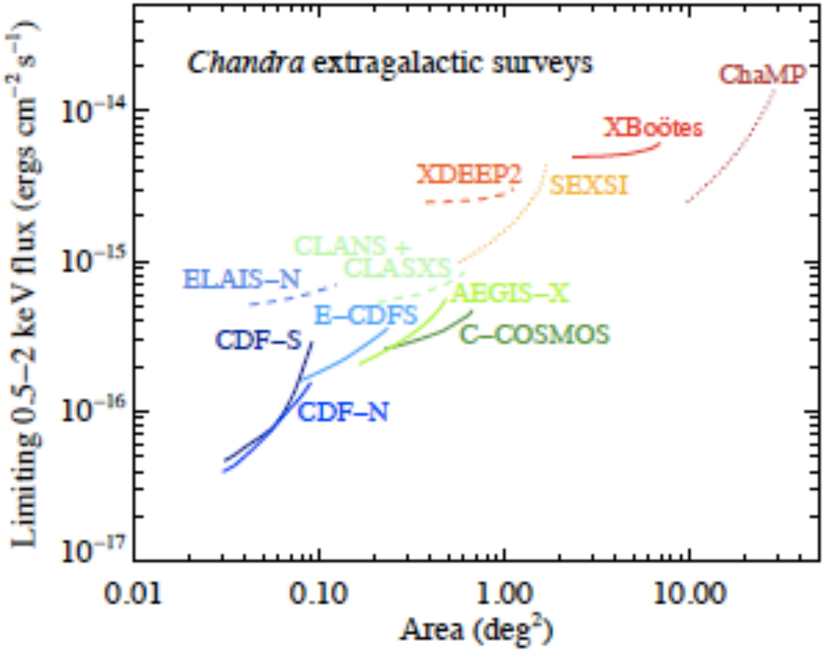
DEEP X-RAY SURVEYS

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:

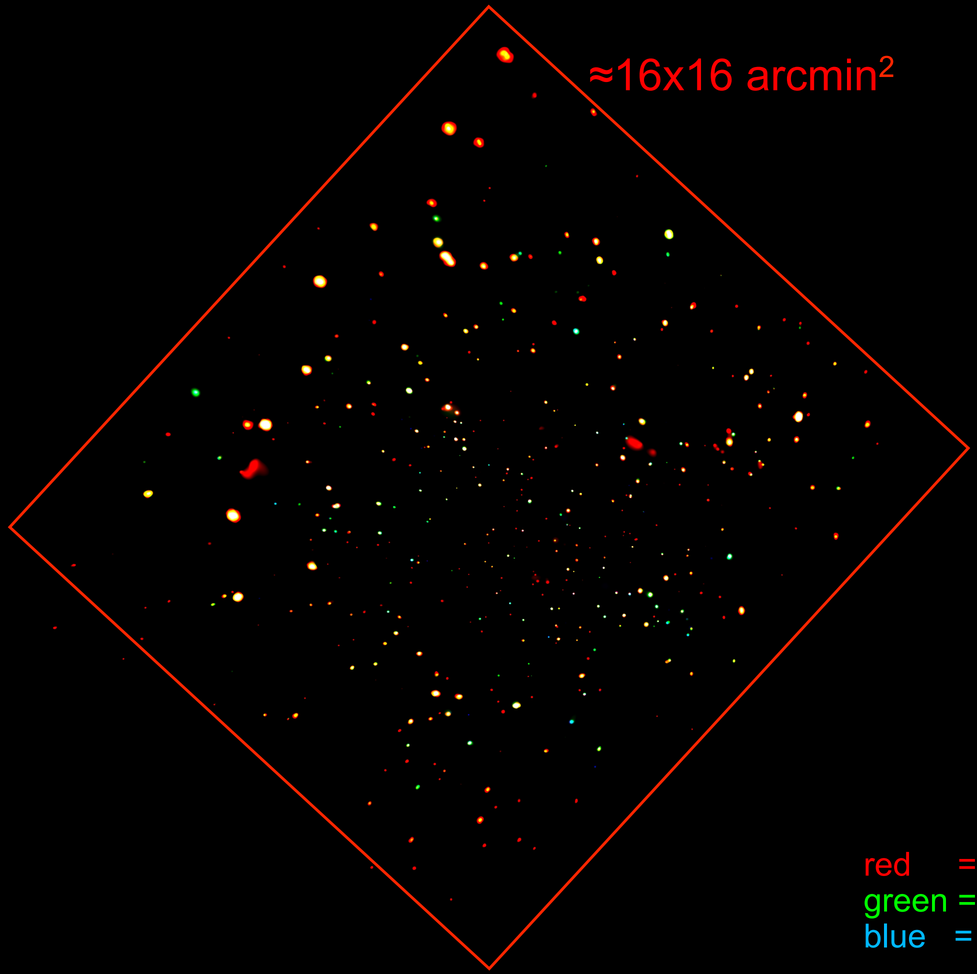
- Ideal to pick up bright and rare X-ray sources
- Possibility to cover large areas of the sky

CONs

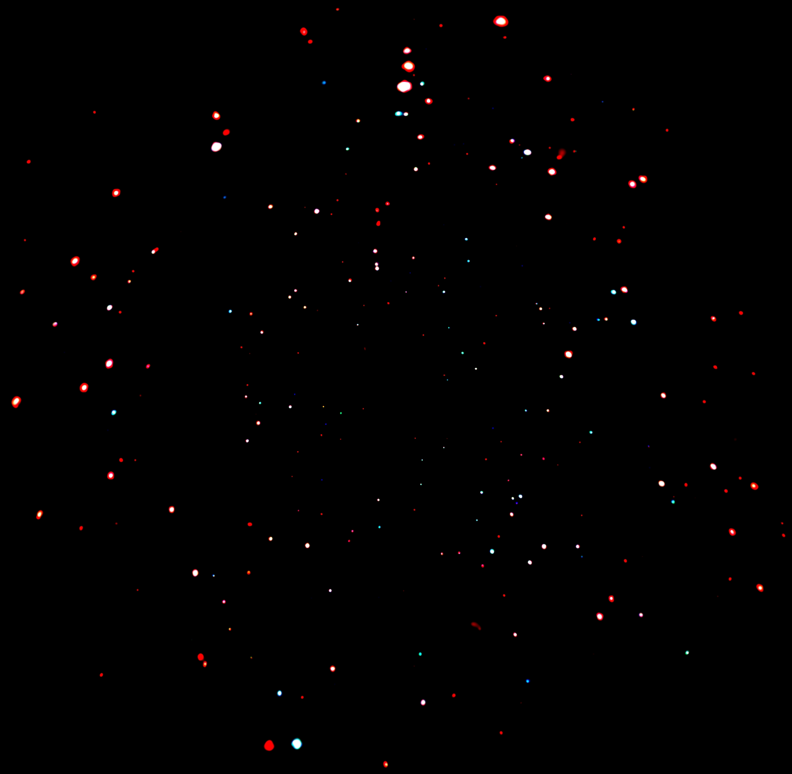
- Limited number of sources

Chandra Deep Fields

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



CDFS (Giacconi+02)



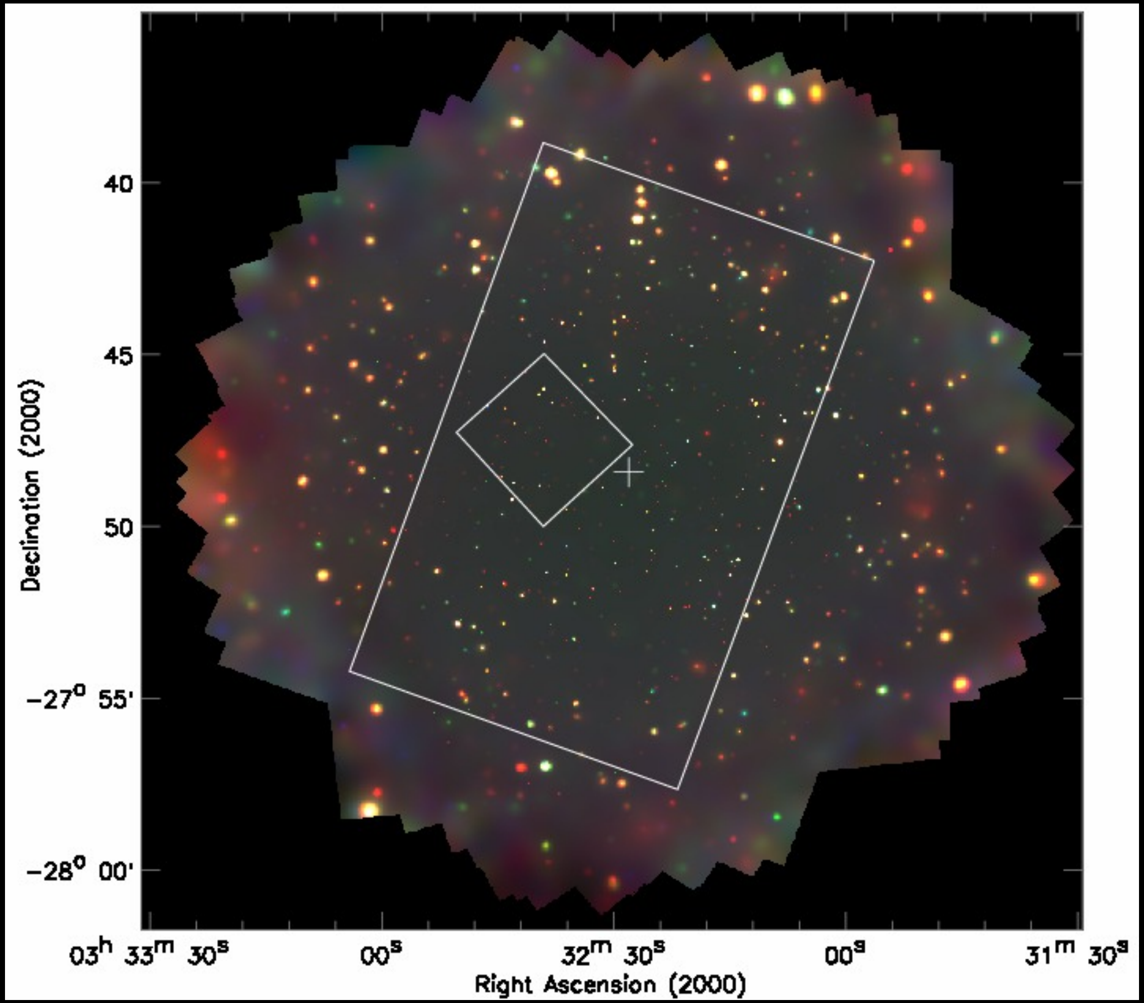
red = 0.5-1 keV
green = 1 - 2 keV
blue = 2 - 8 keV

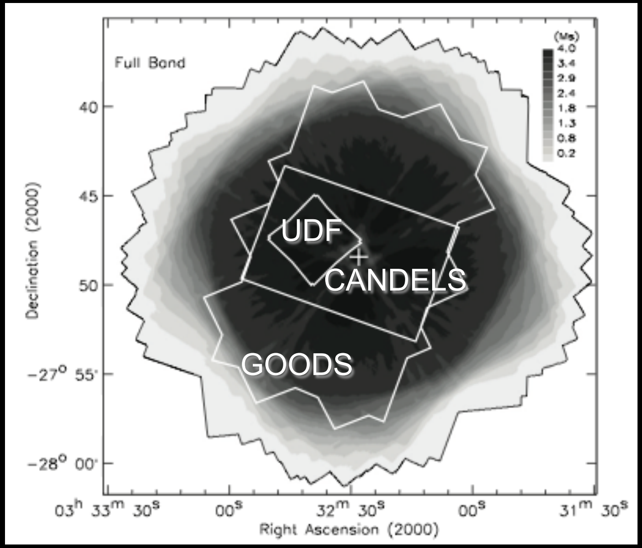
up to the recent 4 Ms exposure in the CDF-S (Xue et al. 2011):

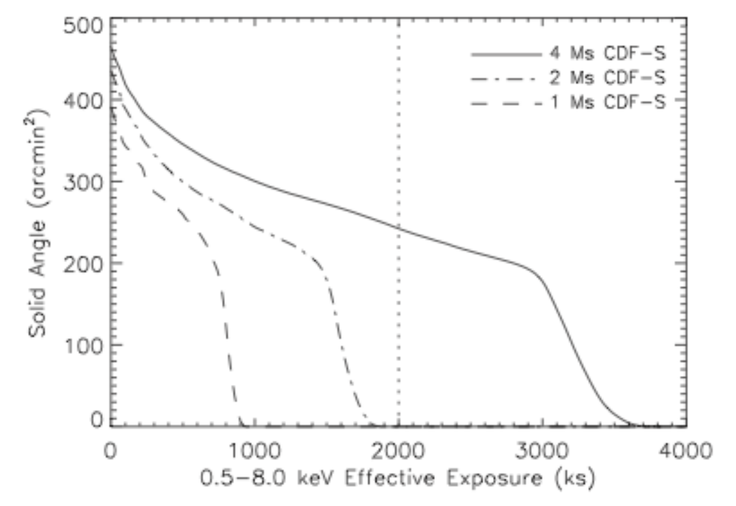
the deepest X-ray exposure ever

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

COMING NEXT: Further 3 Ms

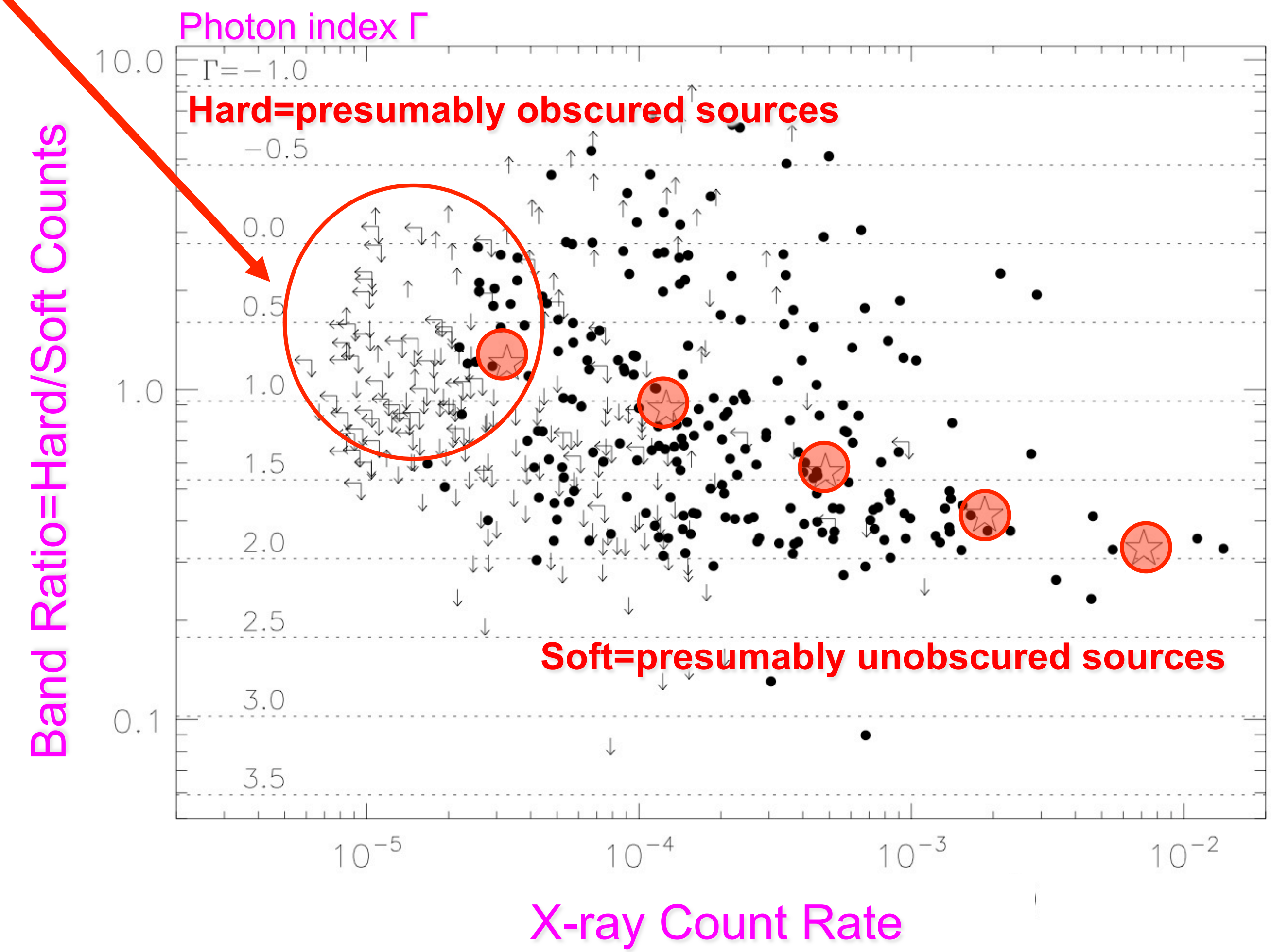






Properties of the 4Ms CDF-S sources (I)

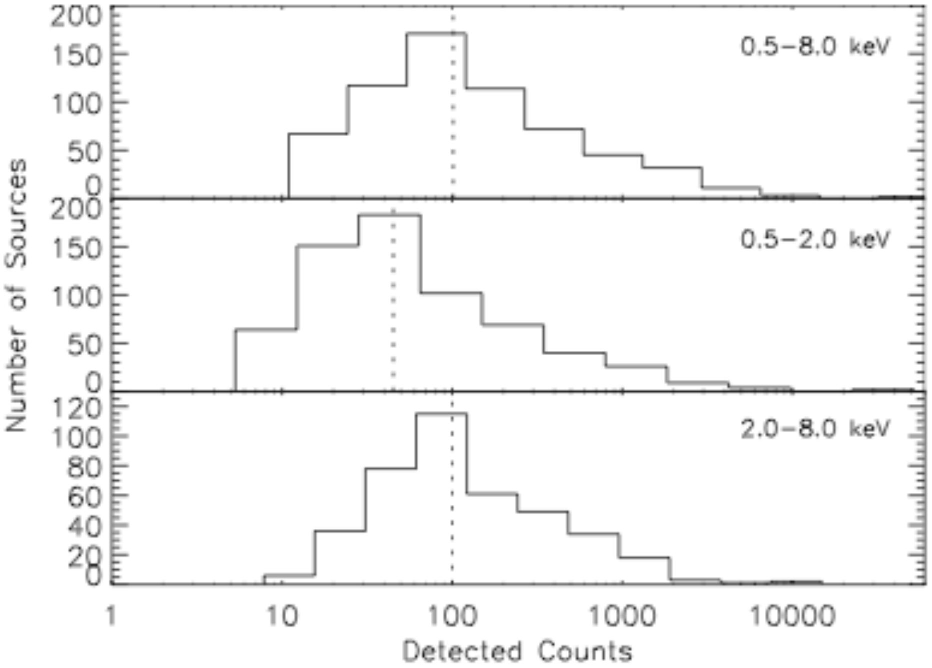
Sources with flatter slopes
(i.e., likely obscured)
at faint X-ray fluxes



Hard=presumably obscured sources

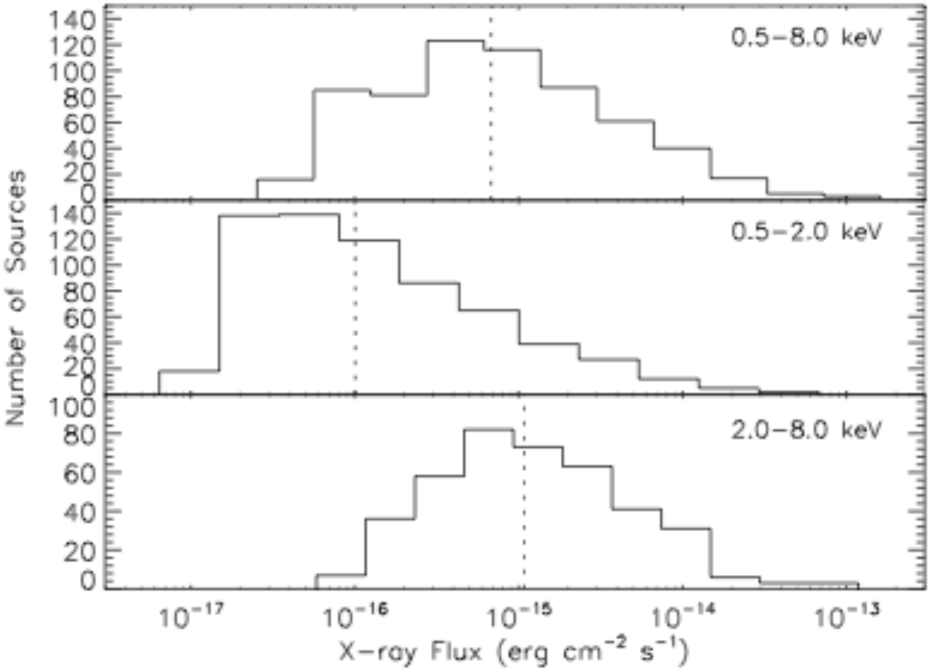
Soft=presumably unobscured sources

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



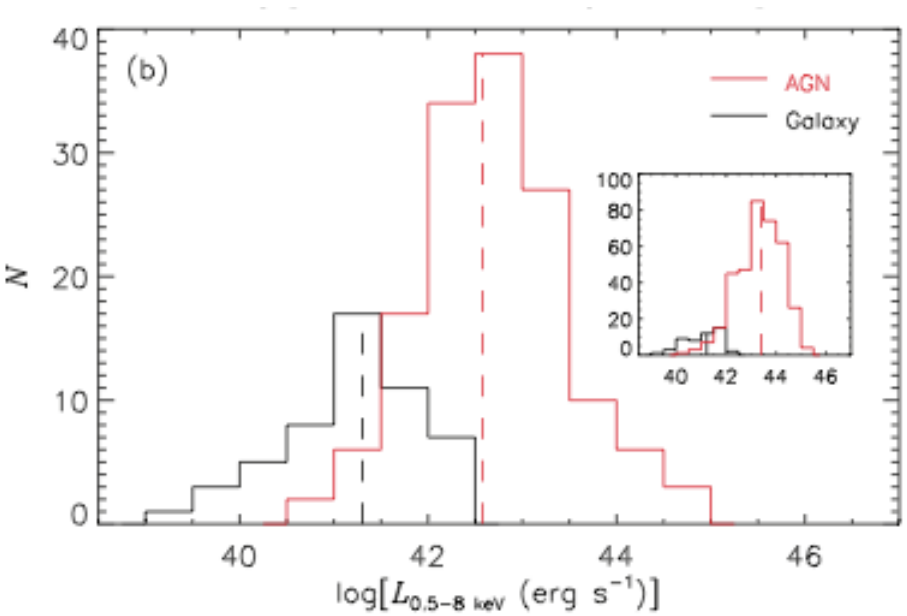
Source net count distribution

X-ray flux distributions



Xue et al. (2011)

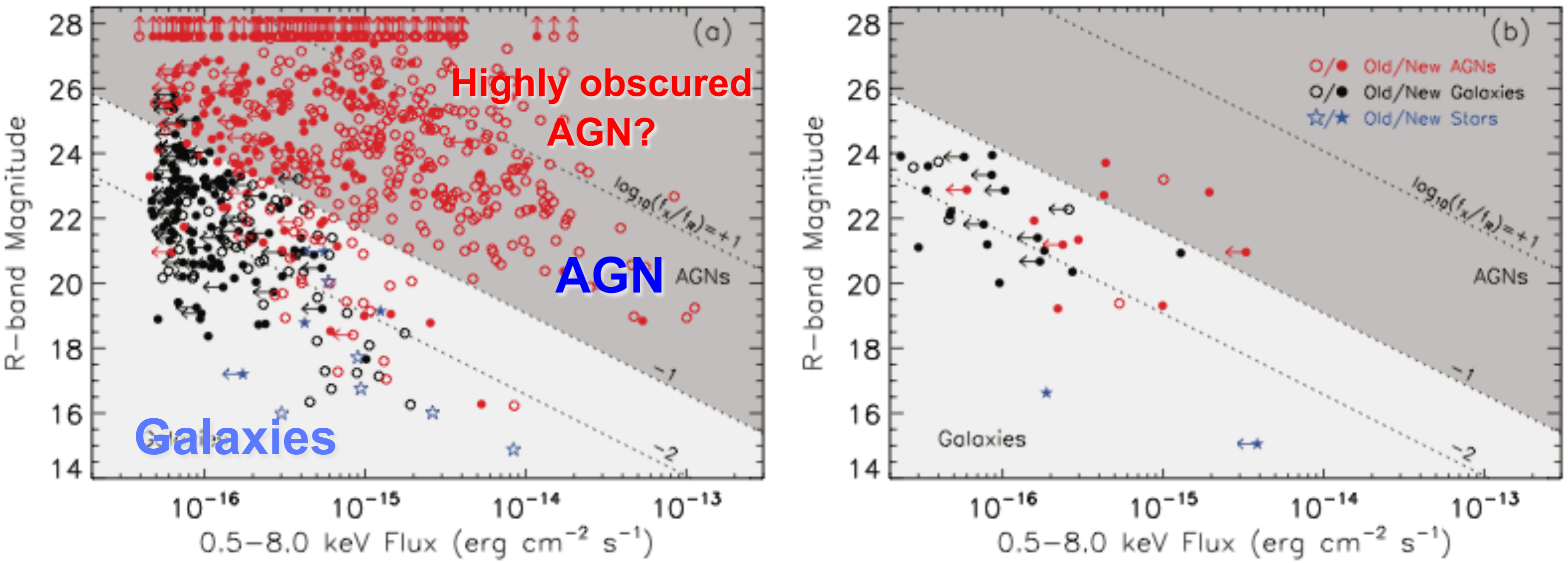
Properties of the 4Ms CDF-S sources (III)



Both AGN and galaxy are detected because of the deep exposure

Xue et al. (2011)

R-band mag vs. X-ray flux

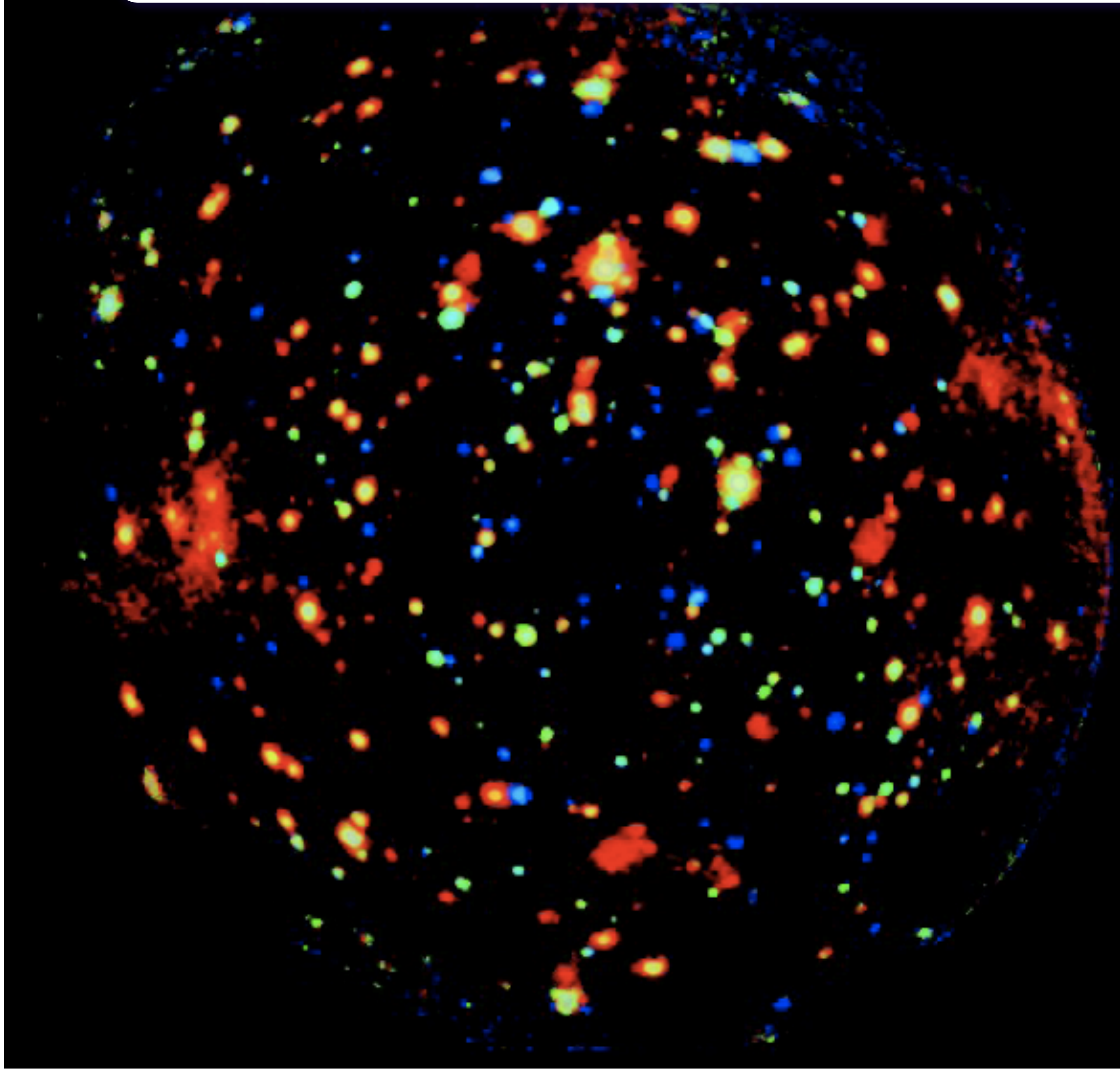


Highly obscured AGN?

AGN

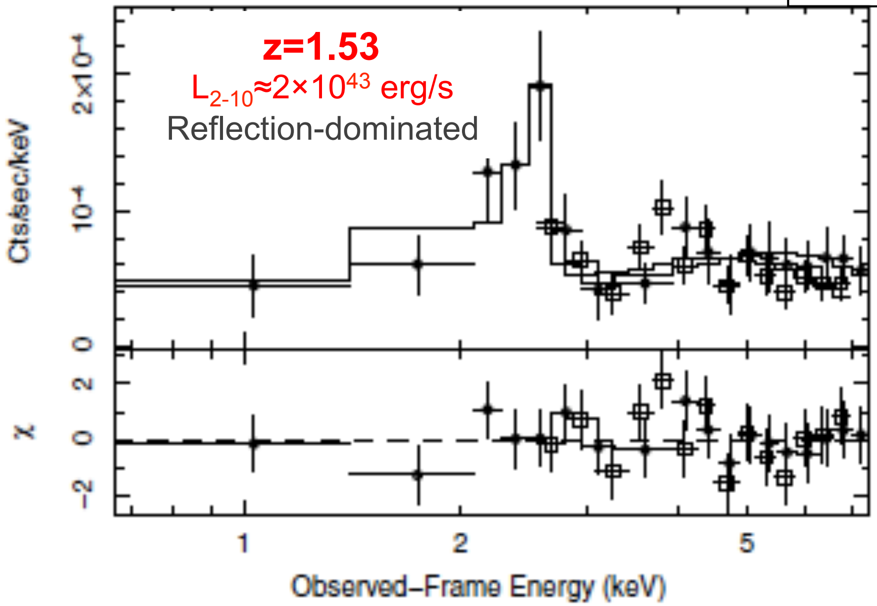
Galaxies

Chandra Deep Field South: XMM 3 Ms exposure



Distant obscured AGN in the CDF-S

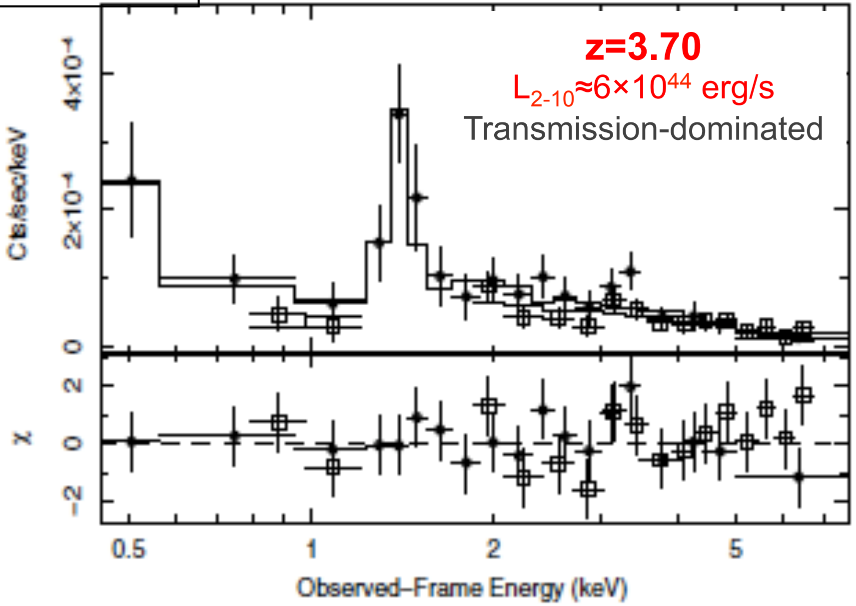
Comastri+11



z=1.53

$L_{2\text{-}10}$≈2×10^{43} erg/s

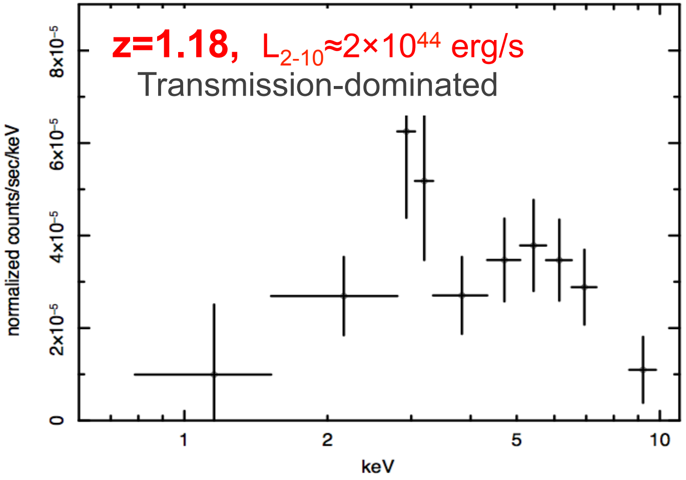
Reflection-dominated



z=3.70

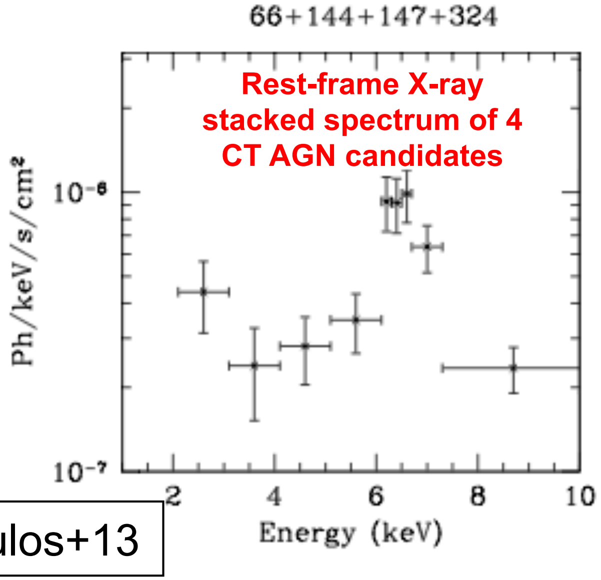
$L_{2\text{-}10}$≈6×10^{44} erg/s

Transmission-dominated



z=1.18, $L_{2\text{-}10}$≈2×10^{44} erg/s

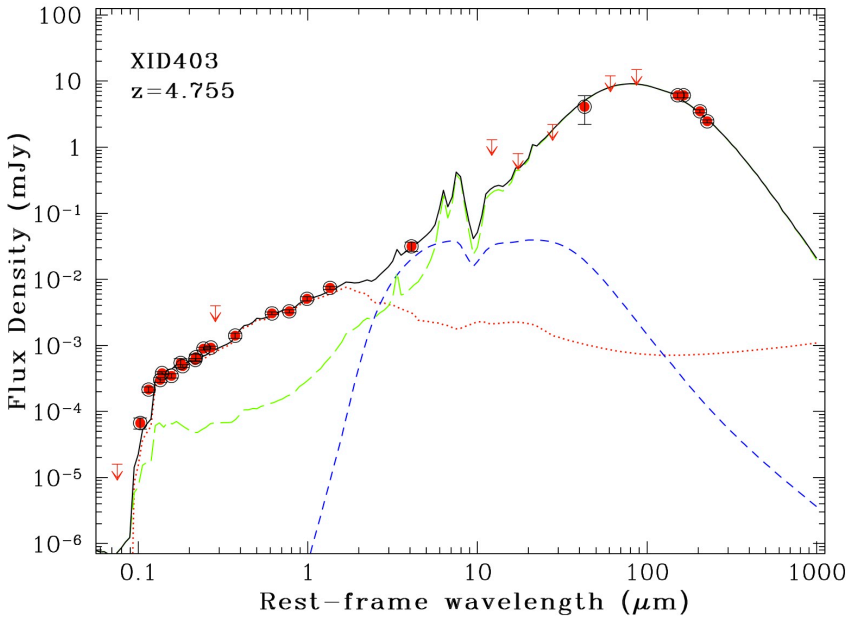
Transmission-dominated

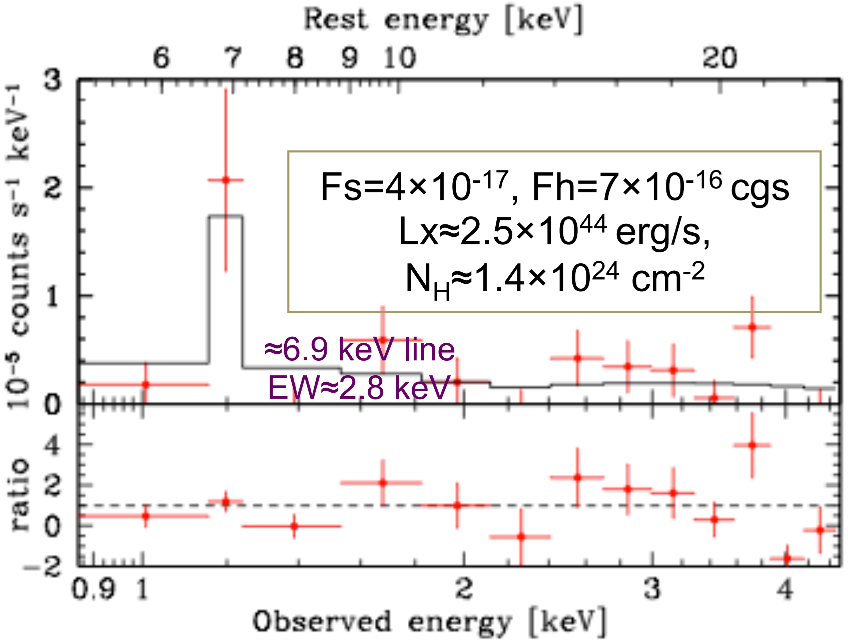


Rest-frame X-ray stacked spectrum of 4 CT AGN candidates

Georgantopoulos+13

Obscured accretion and powerful star formation at z=4.8





Fs=4×10^{-17}, Fh=7×10^{-16} cgs
Lx≈2.5×10^{44} erg/s,
N_H≈1.4×10^{24} cm^{-2}

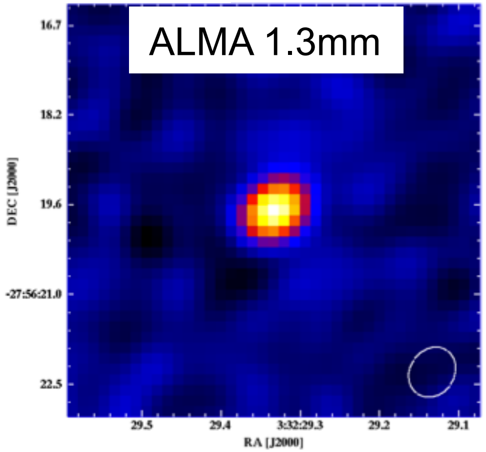
≈6.9 keV line
EW≈2.8 keV

Gilli et al. 2014, 2011

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

Compact starburst, possibly responsible for the X-ray obscuration

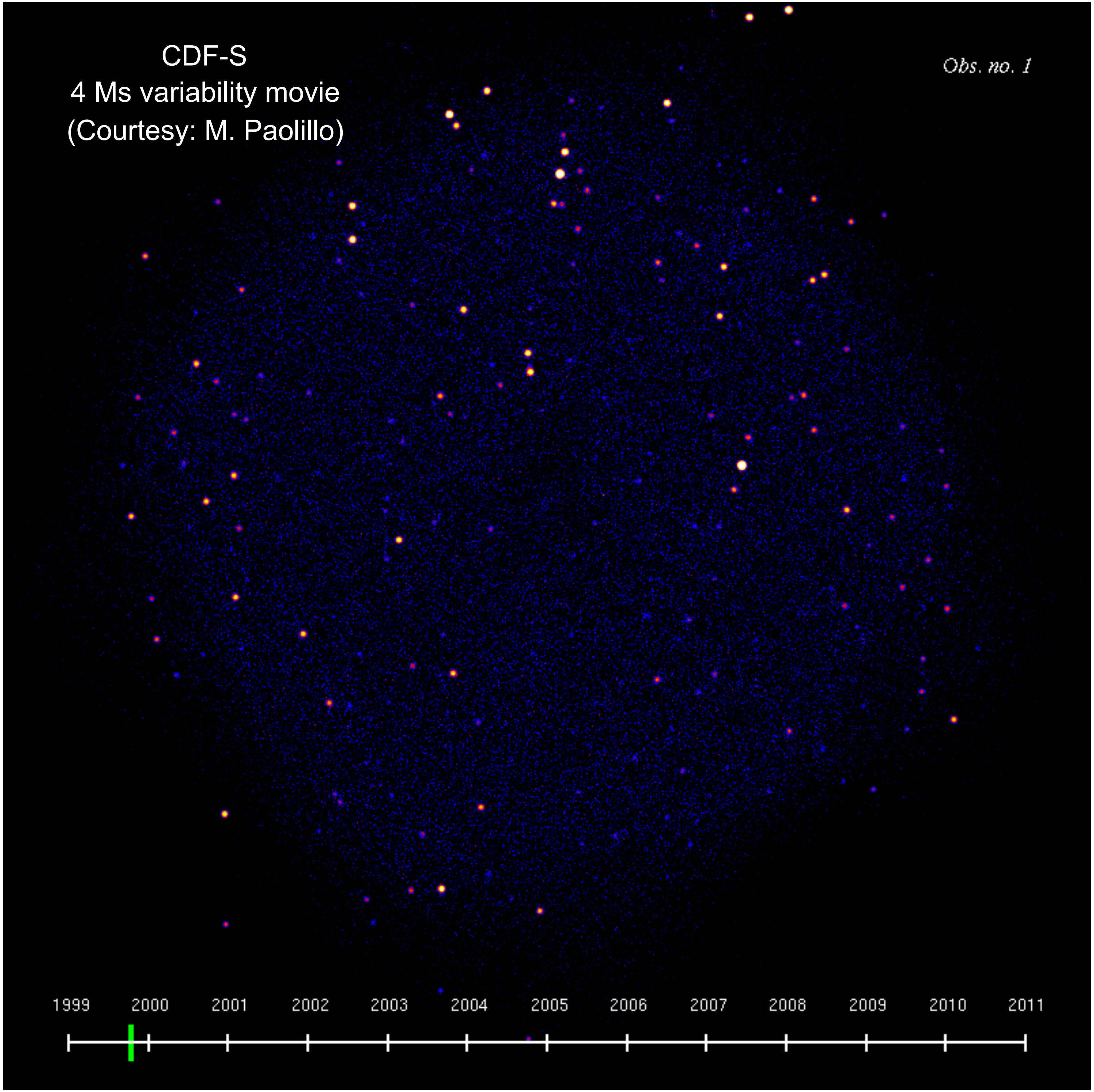
Progenitor of compact quiescent massive galaxies at z≈3



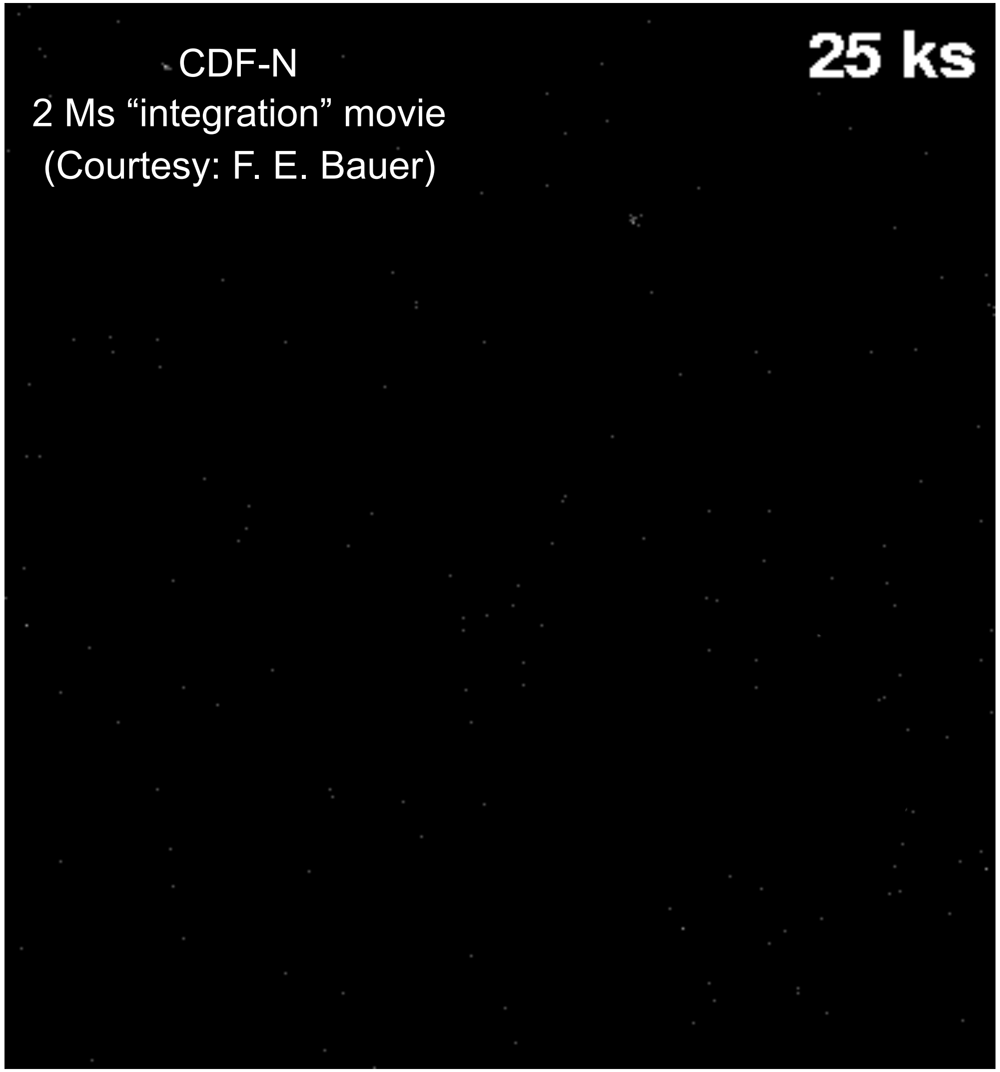
Challenging and time-consuming observations

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

X-ray variability from deep X-ray surveys

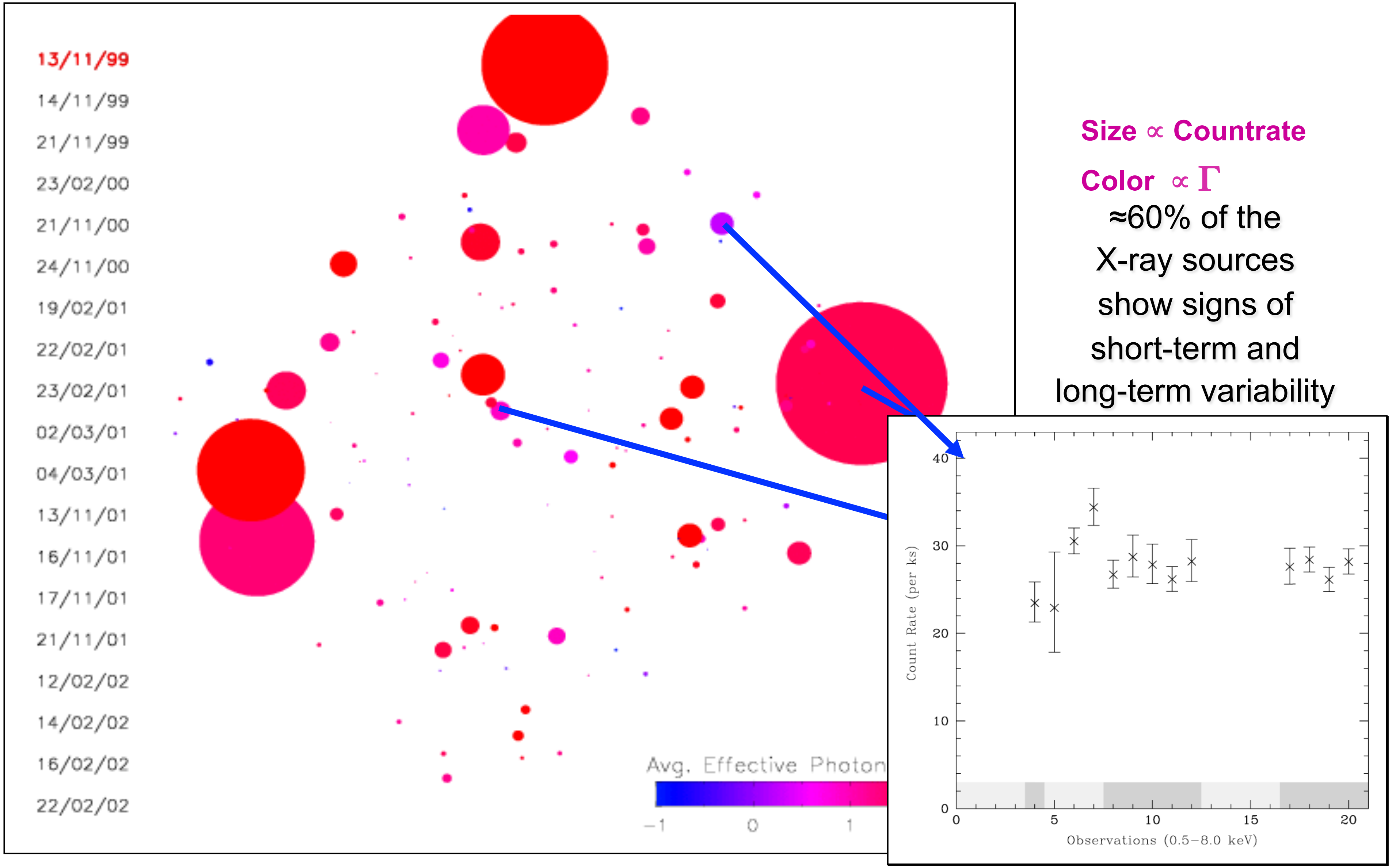


CDF-S
4 Ms variability movie
(Courtesy: M. Paolillo)



CDF-N
2 Ms “integration” movie
(Courtesy: F. E. Bauer)

Long-term X-ray variability



Size ∝ Countrate

Color ∝ Γ

≈60% of the X-ray sources show signs of short-term and long-term variability

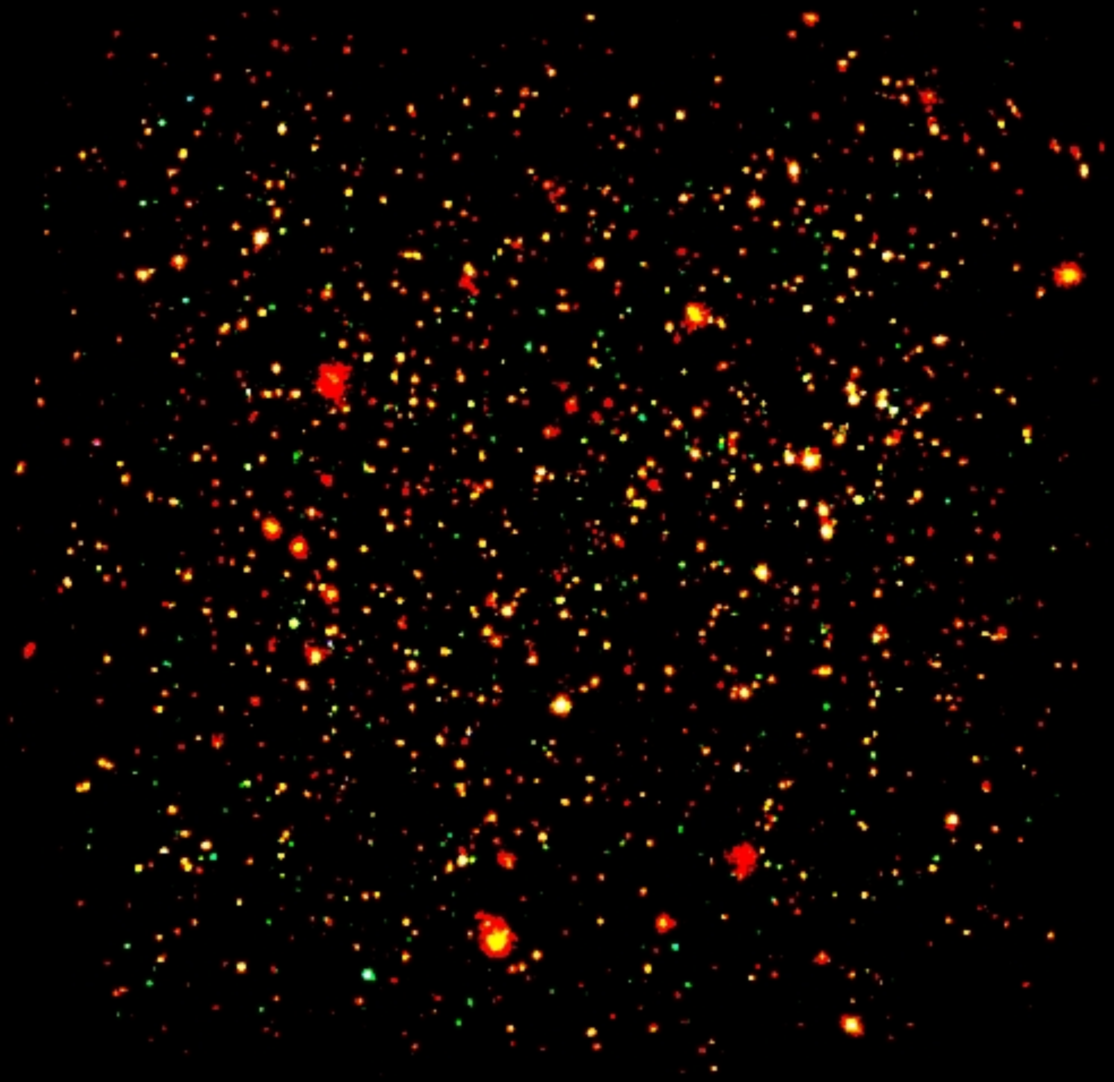
X-raying the COSMOS

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



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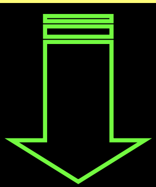
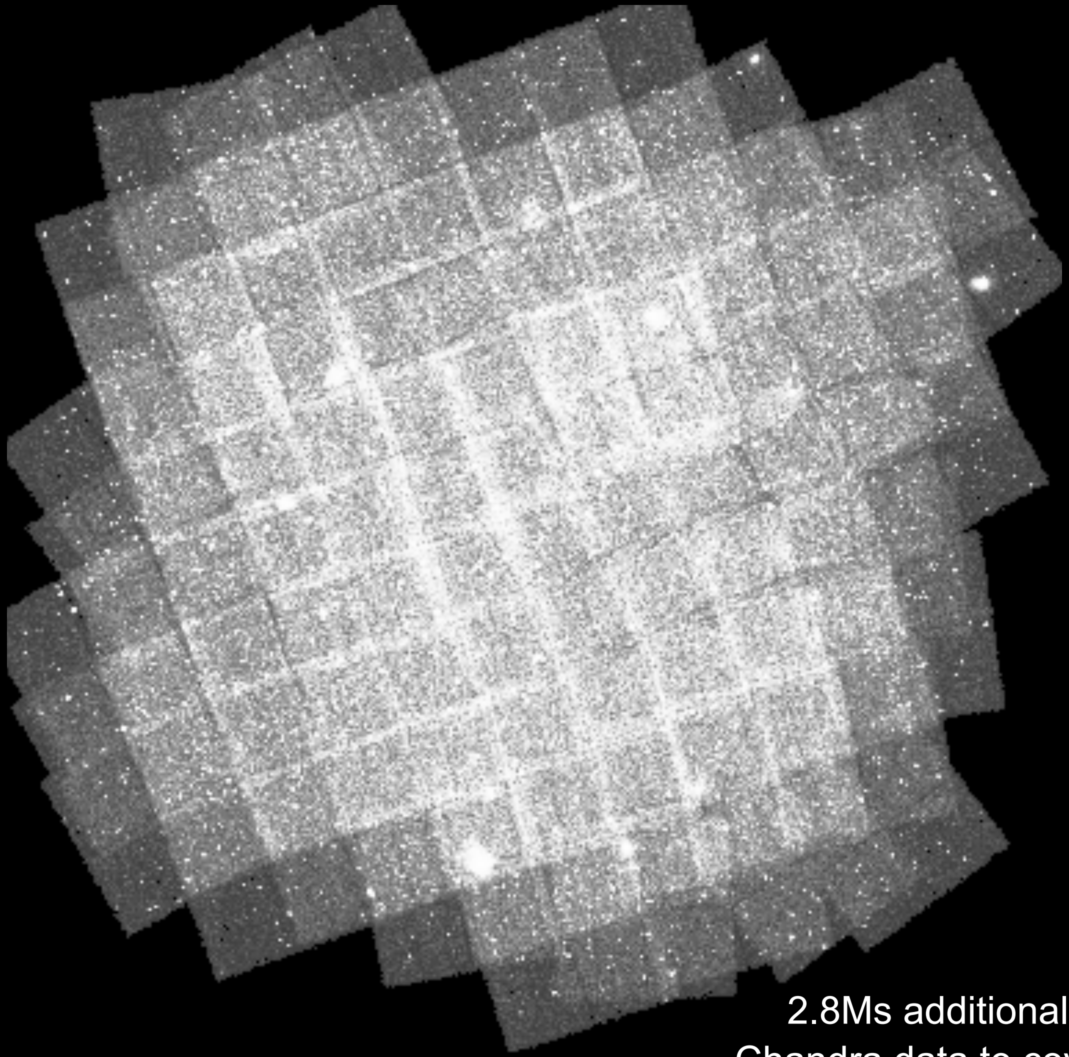


Larger area of the sky surveyed at brighter flux limits

XMM-Newton
1.55 Ms
1822 sources



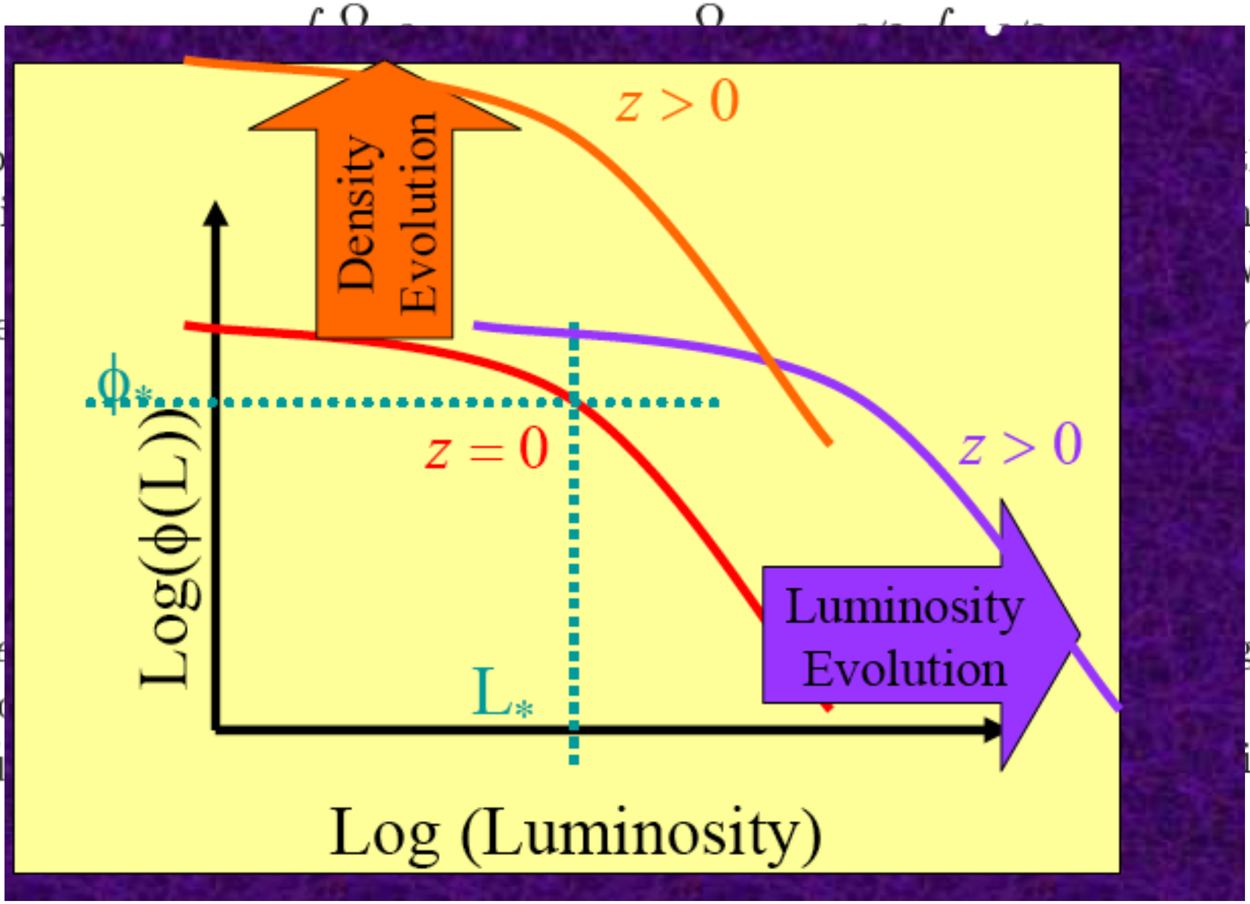
2.8Ms additional Chandra data to cover the entire ~2 deg^2 (going deep)

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)



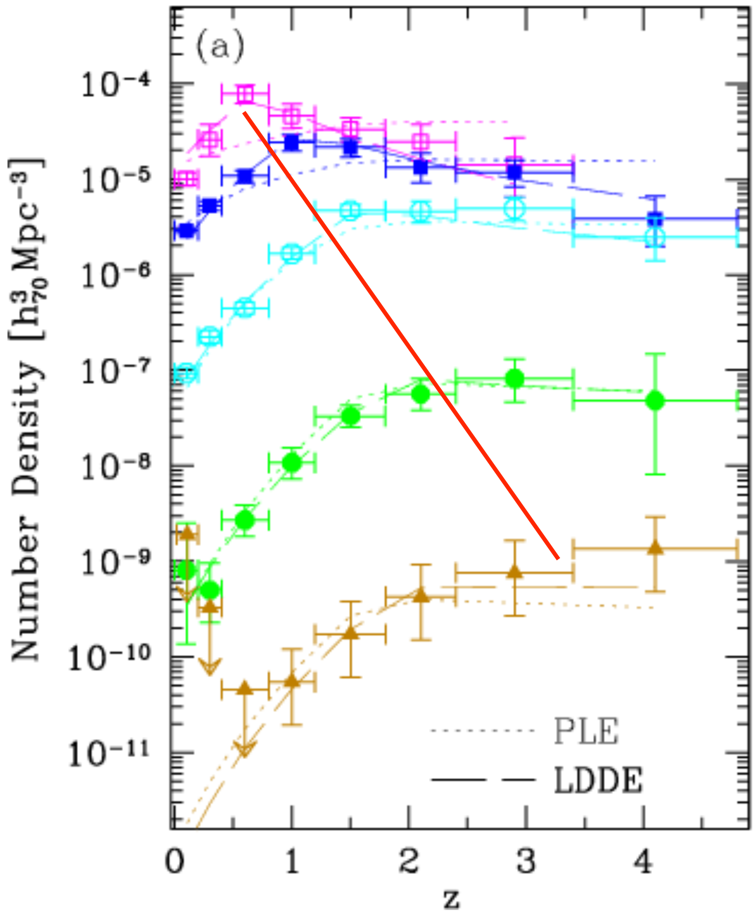
Thus, indep he determination of a normalizati on-evolving class of sources in a $(> S)/d\log S =$ $-3/2$ (if we use $= 0.6$).

(2)

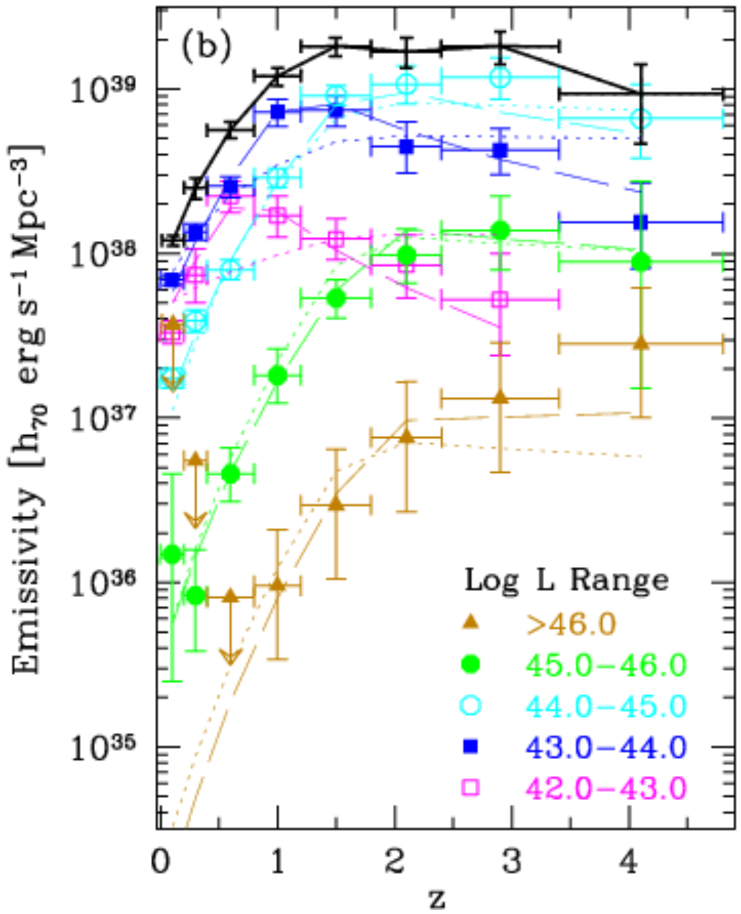
In the *pure* number density of sources is co *density evolution* *(PDE)* case (*f* ity varies.

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**

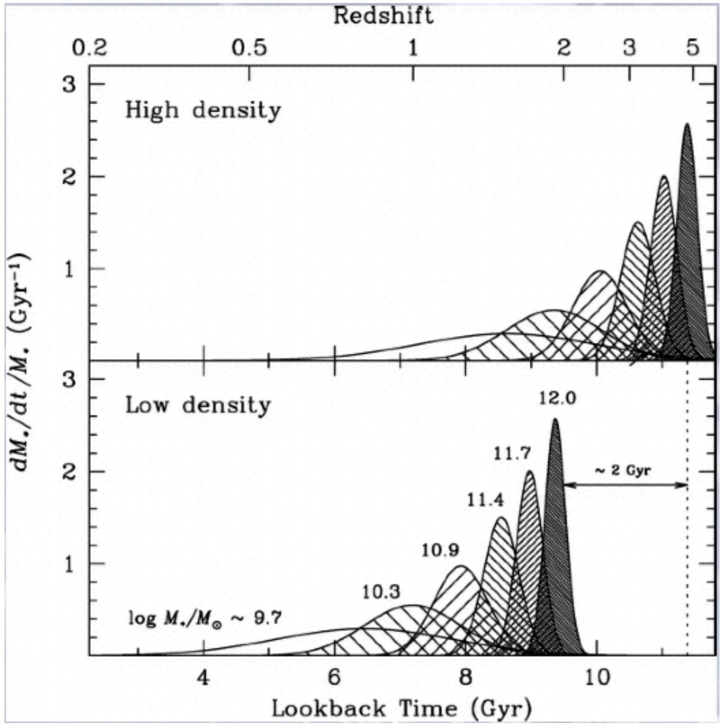
QSOs peak at z≈2-3, AGN at z≈0.5-1

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

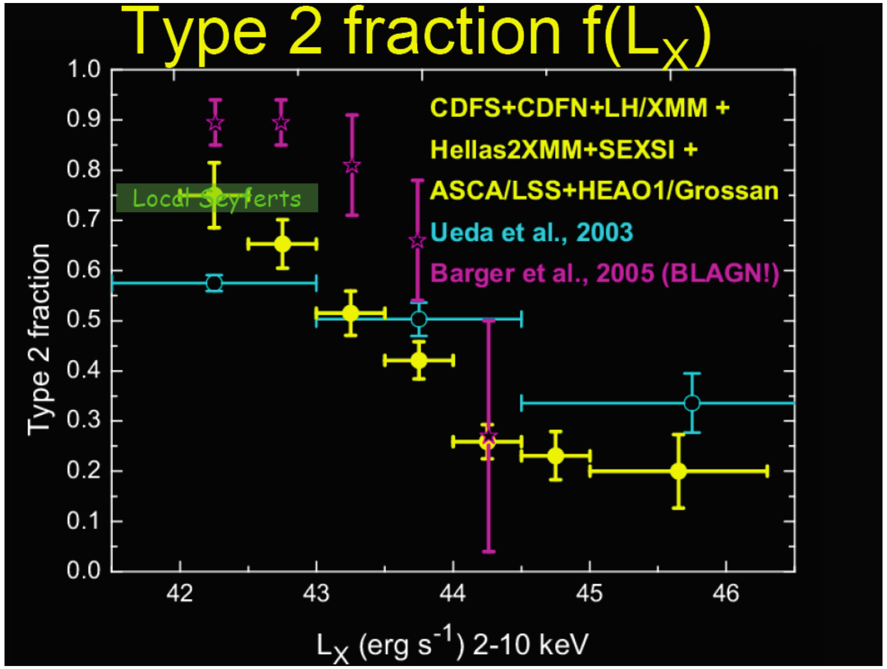


Thomas+2005

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

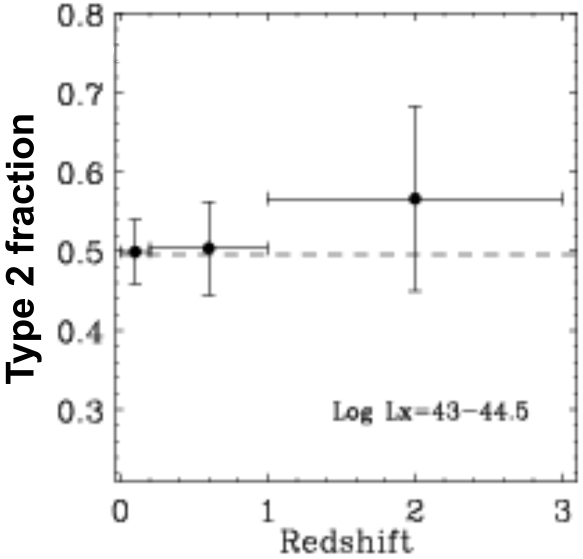
AGN and galaxies seem to share a similar behavior in terms of evolution

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

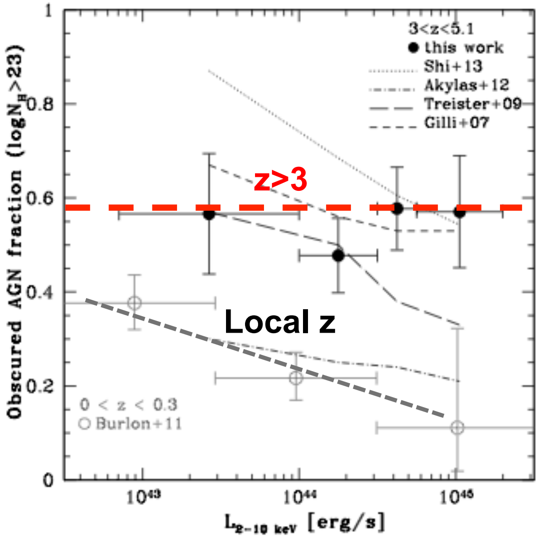


Broad consensus for an obscured AGN fraction declining towards high intrinsic luminosities ➔ receding torus model (Lawrence 1991, Simpson 2005; see also Lusso et al. 2013)

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

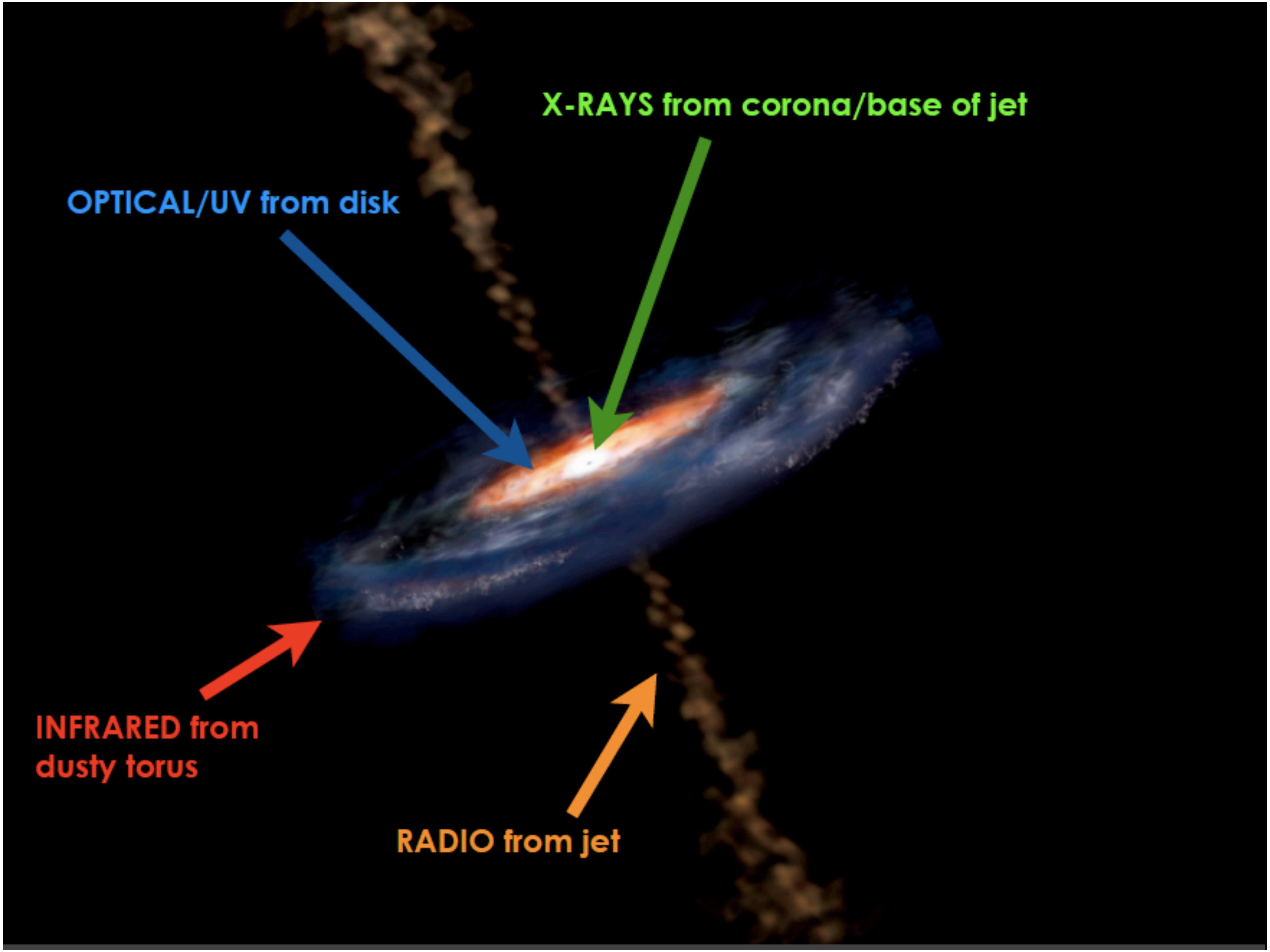


No evolution with z



Evolution with z

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



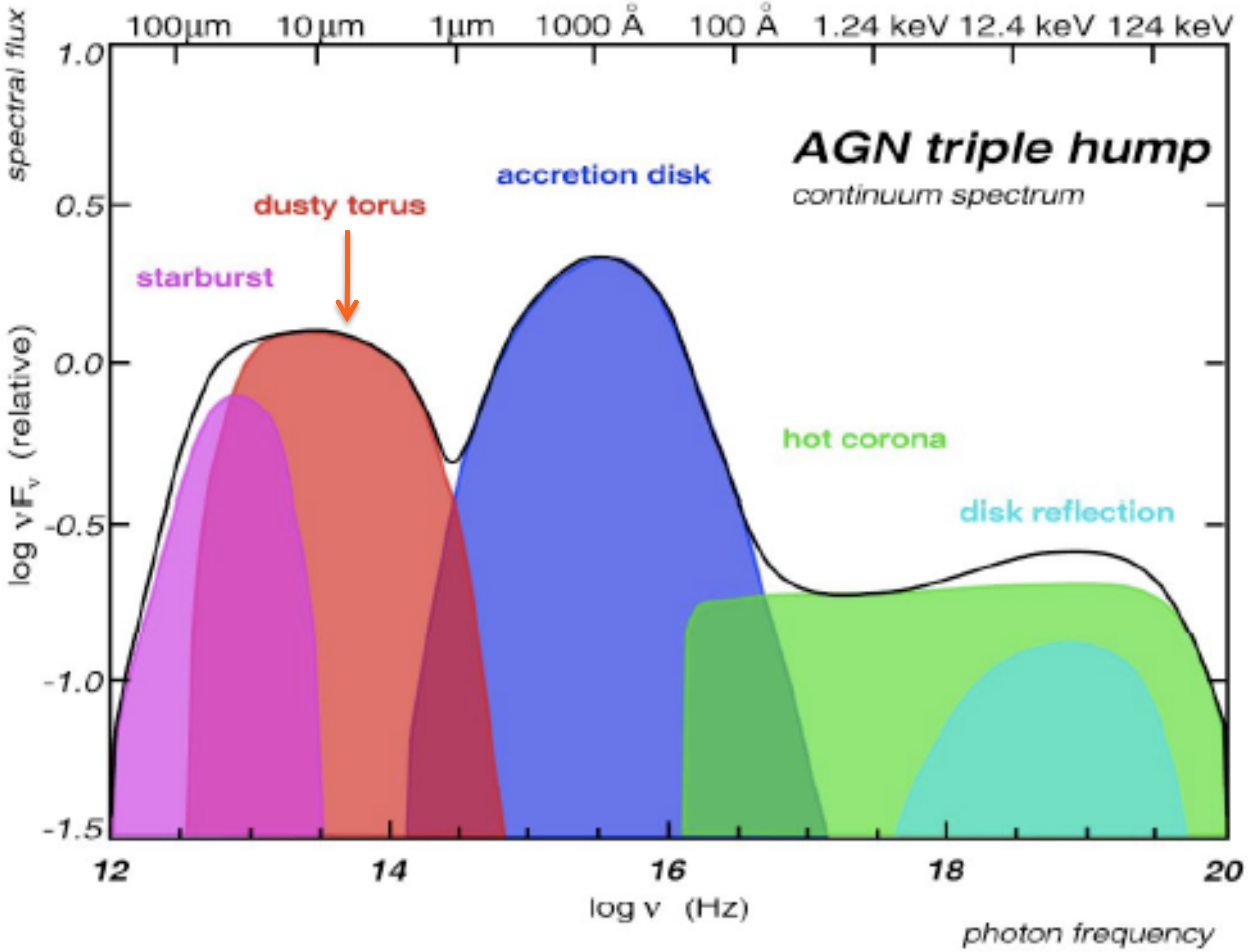
X-RAYS from corona/base of jet

OPTICAL/UV from disk

INFRARED from
dusty torus

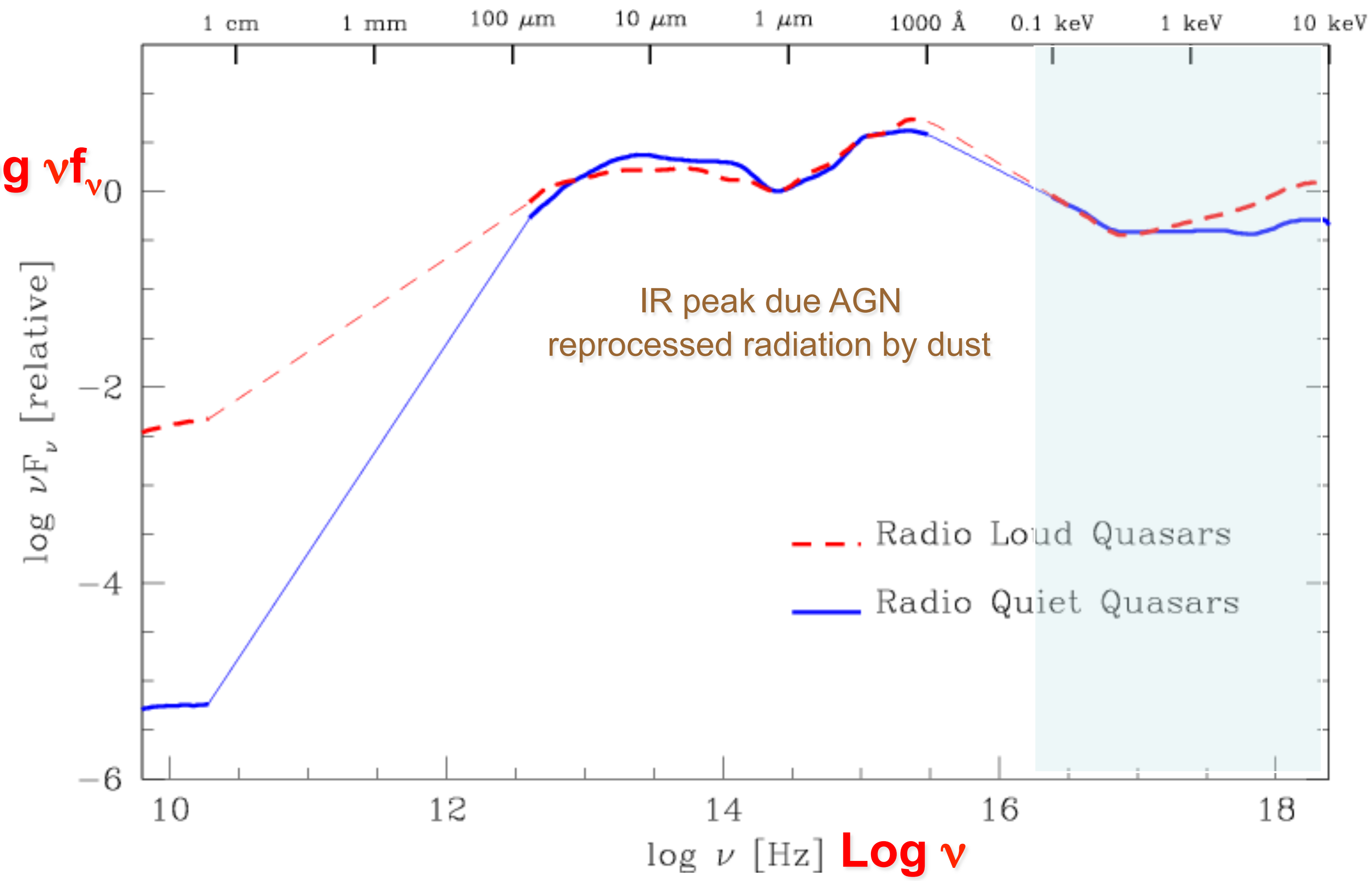
RADIO from jet

Broad-band spectral energy distribution of AGN (I)



Broad-band spectral energy distribution of AGN (II)

Log νf$_\nu$



IR peak due AGN reprocessed radiation by dust

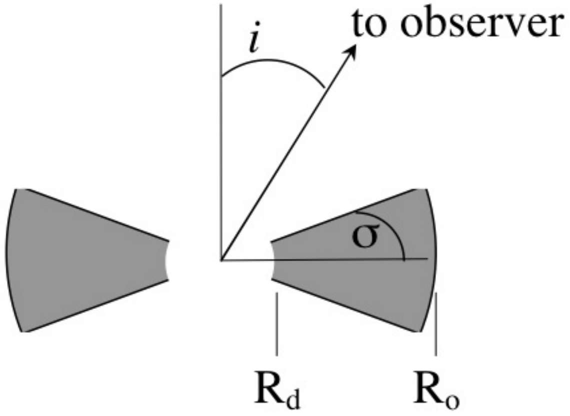
Log ν

Elvis et al. 1994

Models for the infrared emission of AGN (I)

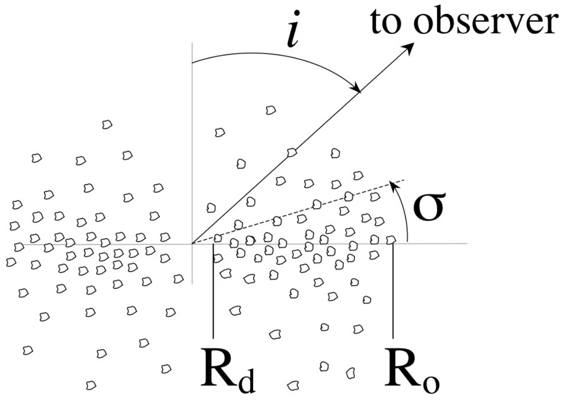
Smooth dust distribution

dust grains around a central source (AGN) in a smooth distribution (e.g., Pier & Krolik '92, '93)



Clumpy models

dust grains in clouds (not uniform distribution)
A Type 2 AGN can be seen also at large inclination angles over the equatorial plane
(e.g., Nenkova et al. '02, '08)

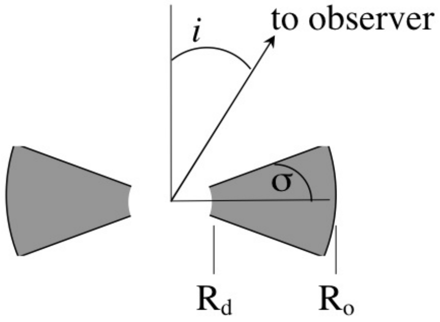


Models for the infrared emission of AGN (II)

Smooth dust distribution: main properties

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

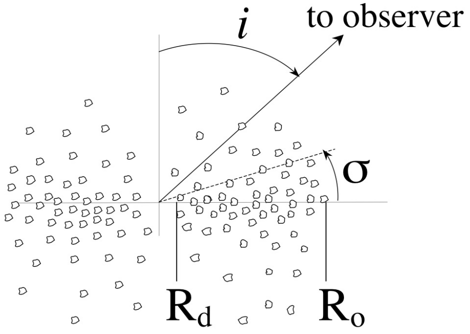
- Dust temperature is a function of the distance from the source of the radiation field



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)

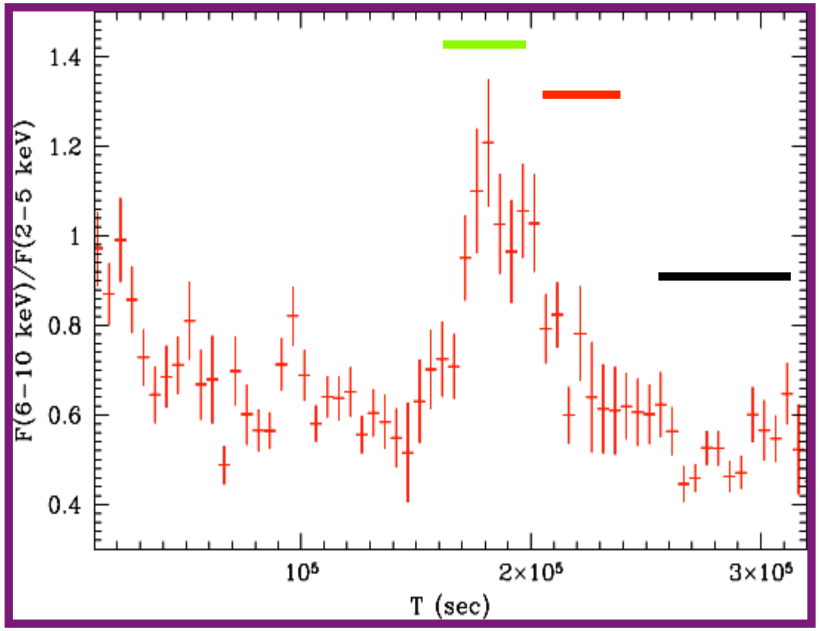
Indications from X-ray observations of local Seyferts

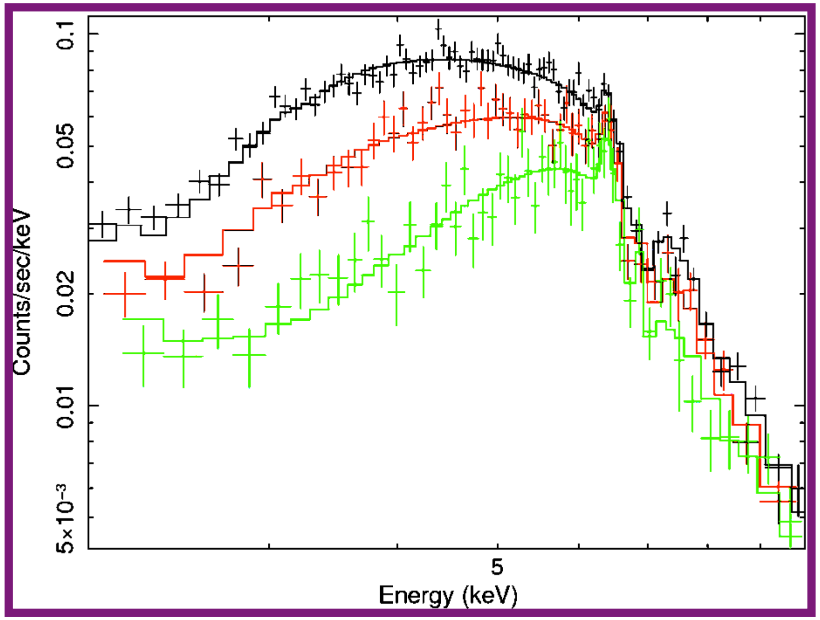
Eclipses of the X-ray source are COMMON in nearby AGN:
$\Delta N_H \sim 10^{23}\text{-}10^{24}\ \mathrm{cm}^{-2}$

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

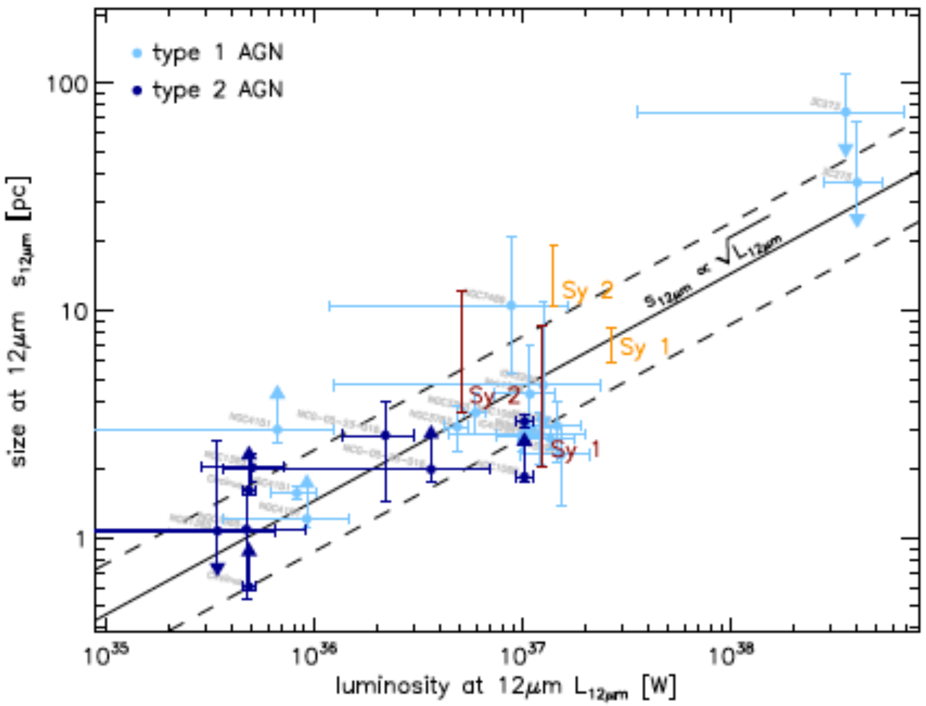
X-ray absorber "made" of BLR clouds on scales<pc-scale (torus)

Risaliti et al., 2007, 2010…





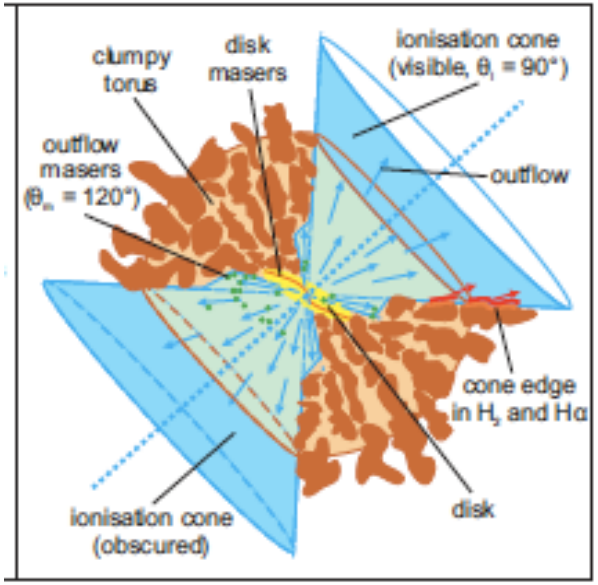
High-resolution mid-IR observations of Seyferts



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

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

- No significant Sey1/Sey2 difference



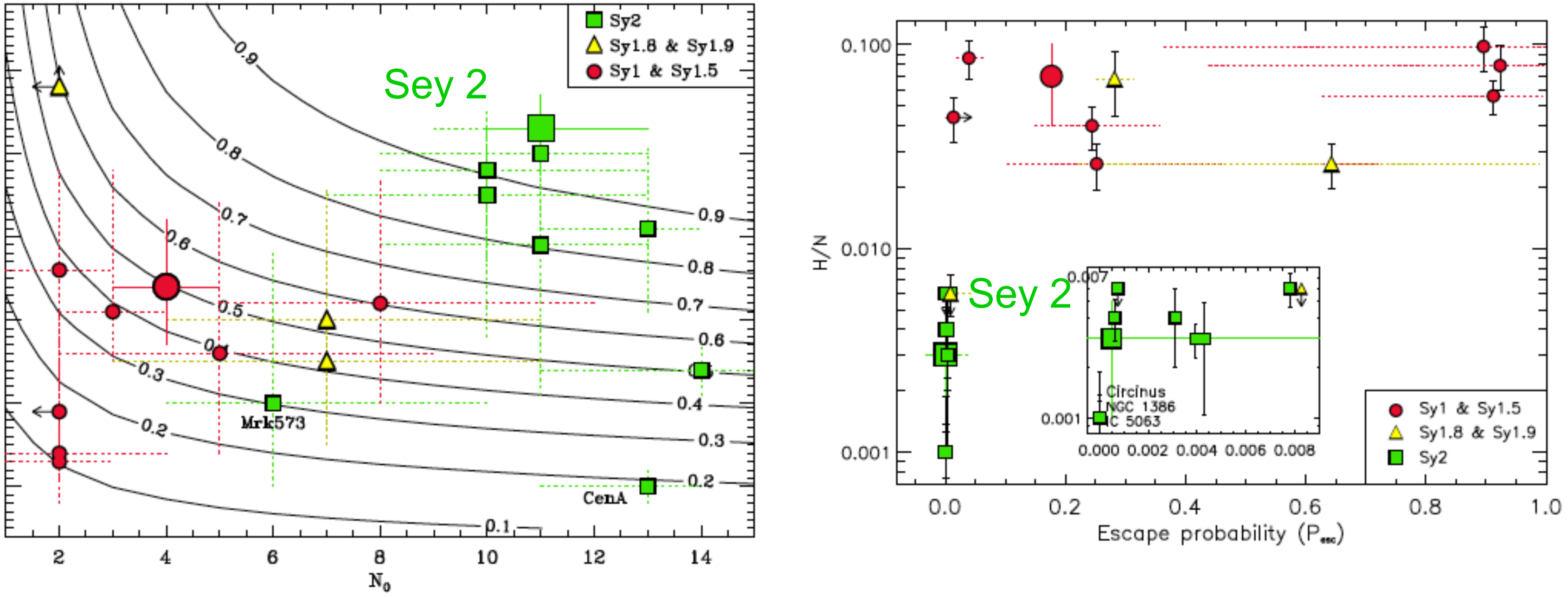
Tristram+07 - Circinus

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

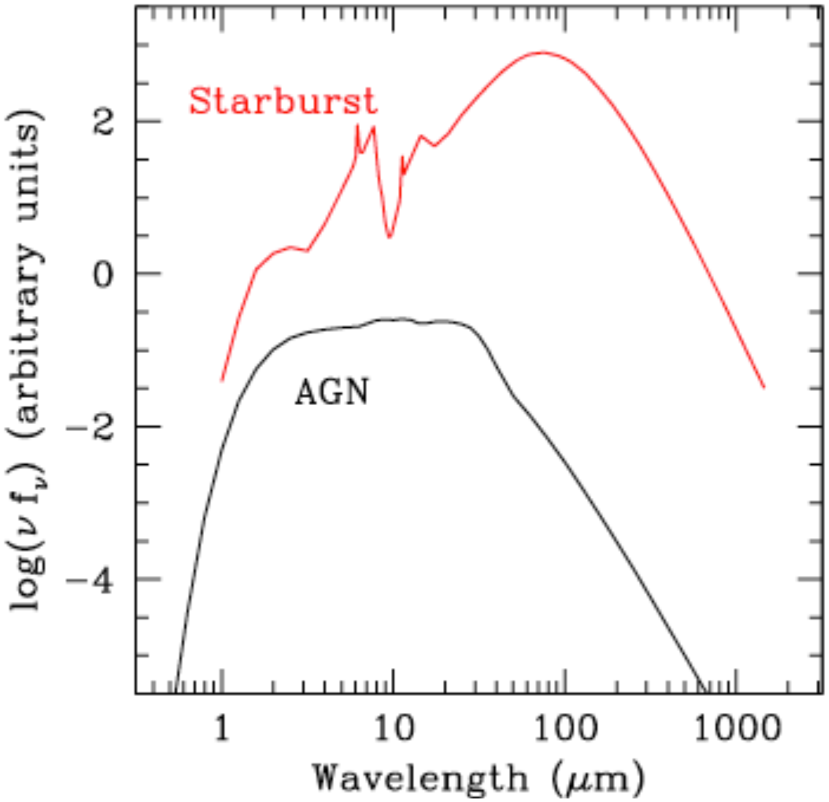
✓ Same dust temperatures can be observed at different distances from the AGN

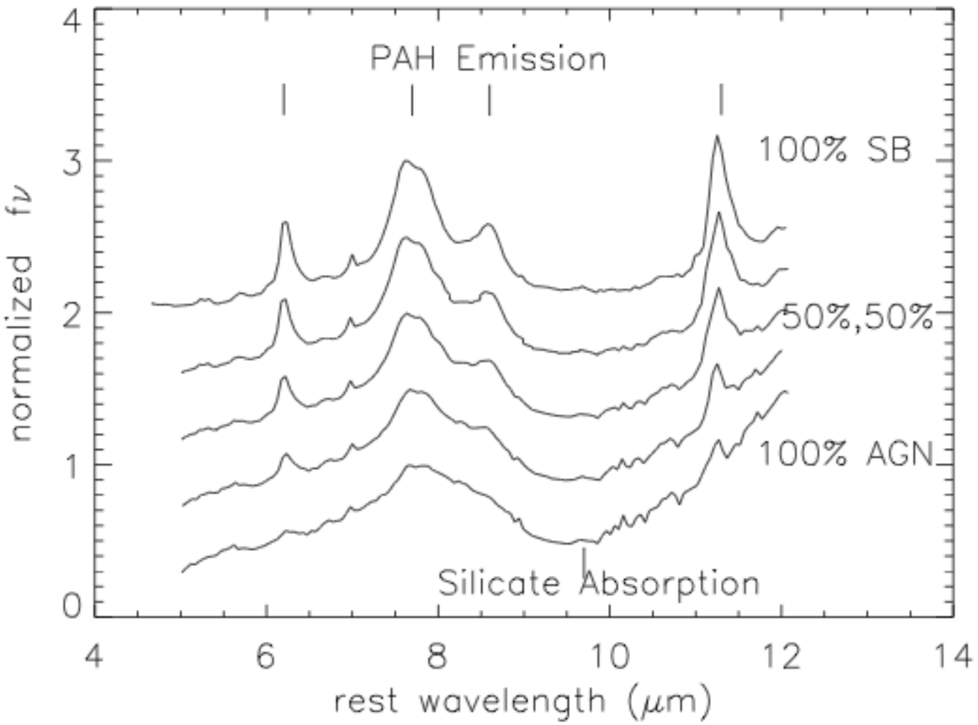
➔ Type 2 AGN: larger number of clouds and lower P_{esc} for the photons to escape



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

Infrared spectra of AGN

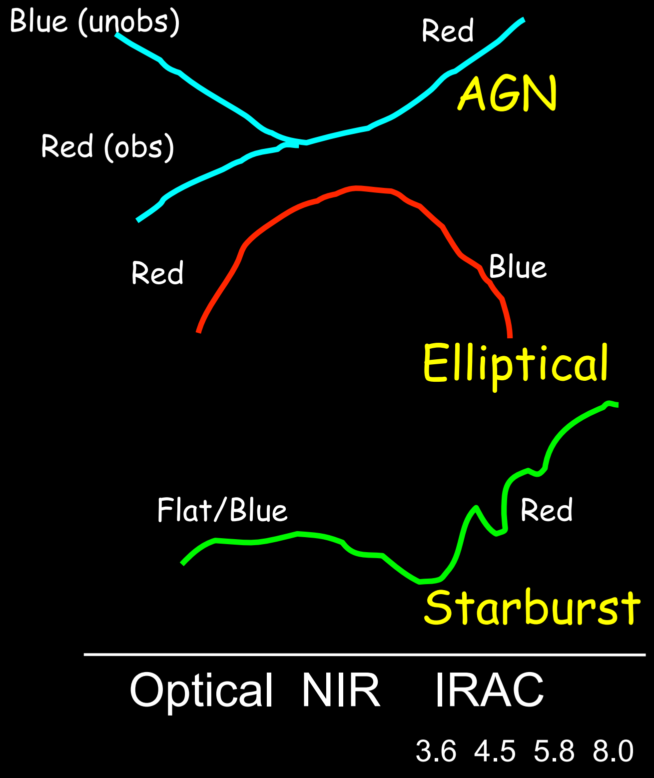
- AGN (unobs and obs) are expected to have warm power-law sed at >1micron (≠ from elliptical/starburst)

AGN (both type 1 and 2) can be isolated in NIR/MIR diagrams and they are ~ same order of magnitude of X-ray selected obscured AGN

(Lacy et al. 2004, Hatziminaouglou et al. 2005, Stern et al. 2005, Donley et al.2008, Pope et al. 2008, Fiore et al. 2008, Luo et al. 2011)

Main issues:

reliability (are only AGN selected?)
completeness (are all AGN selected?)



Courtesy of M. Brusa

The End