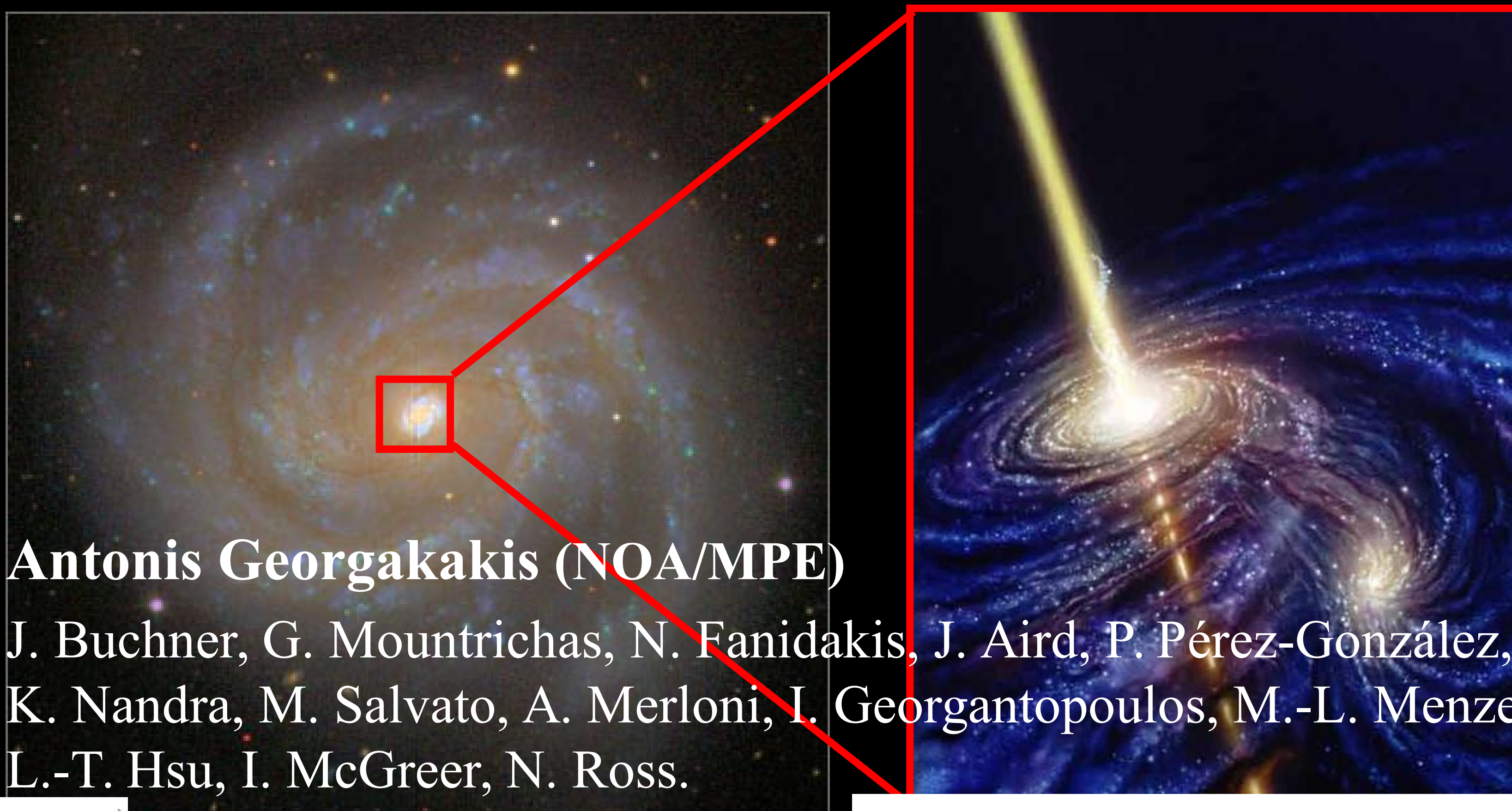
The formation of supermassive black holes across cosmic time



Antonis Georgakakis (NOA/MPE)

J. Buchner, G. Mountrichas, N. Fanidakis, J. Aird, P. Pérez-González, K. Nandra, M. Salvato, A. Merloni, I. Georgantopoulos, M.-L. Menzel, L.-T. Hsu, I. McGreer, N. Ross.

ΘΑΛΗΣ 383549: THE DARK SIDE OF THE ACCRETION HISTORY OF THE UNIVERSE

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY

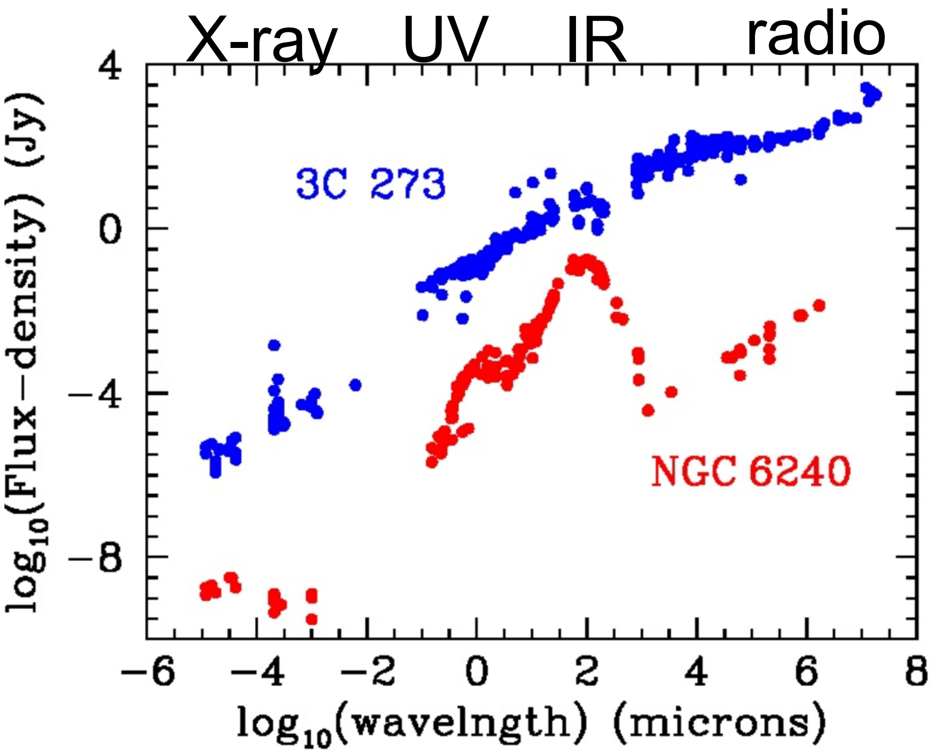
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co-financed by Greece and the European Union

Outline

- **When do SMBH grow their masses?**
  - Demographics of AGN as a function of redshift (AGN luminosity function).
- **How do SMBH grow their masses?**
  - Physical conditions of black hole growth across cosmic time
  - Statistical approach: link black hole accretion properties (e.g. accretion luminosity) to host galaxies properties (e.g. star-formation).

The "When" question: count AGN as a function of redshift



Challenge: Diversity of AGN SEDs

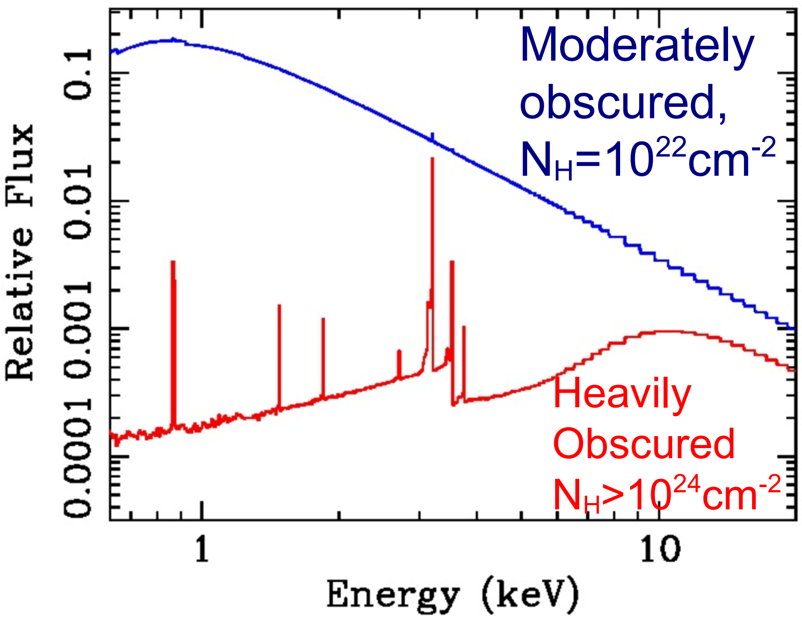
- Obscuration along the line of sight
- Host galaxy contamination
- Accretion physics

AGN luminosity function: Selecting AGN at X-ray wavelengths

- X-rays are least affected by obscuration
- Contamination by AGN host galaxy is unimportant at X-rays
- Sensitive to AGN over a wide Eddington ratio baseline
- Selection function can be accurately quantified

Comastri+11, Brightman & Ueda 2012, Georgantopoulos+13, Lanzuisi+15

Model AGN X-ray spectra at z=1



Obscuration parametrised by N_H, Hydrogen column density along the line-of-sight.

N_H is determined from data (X-ray spectra).

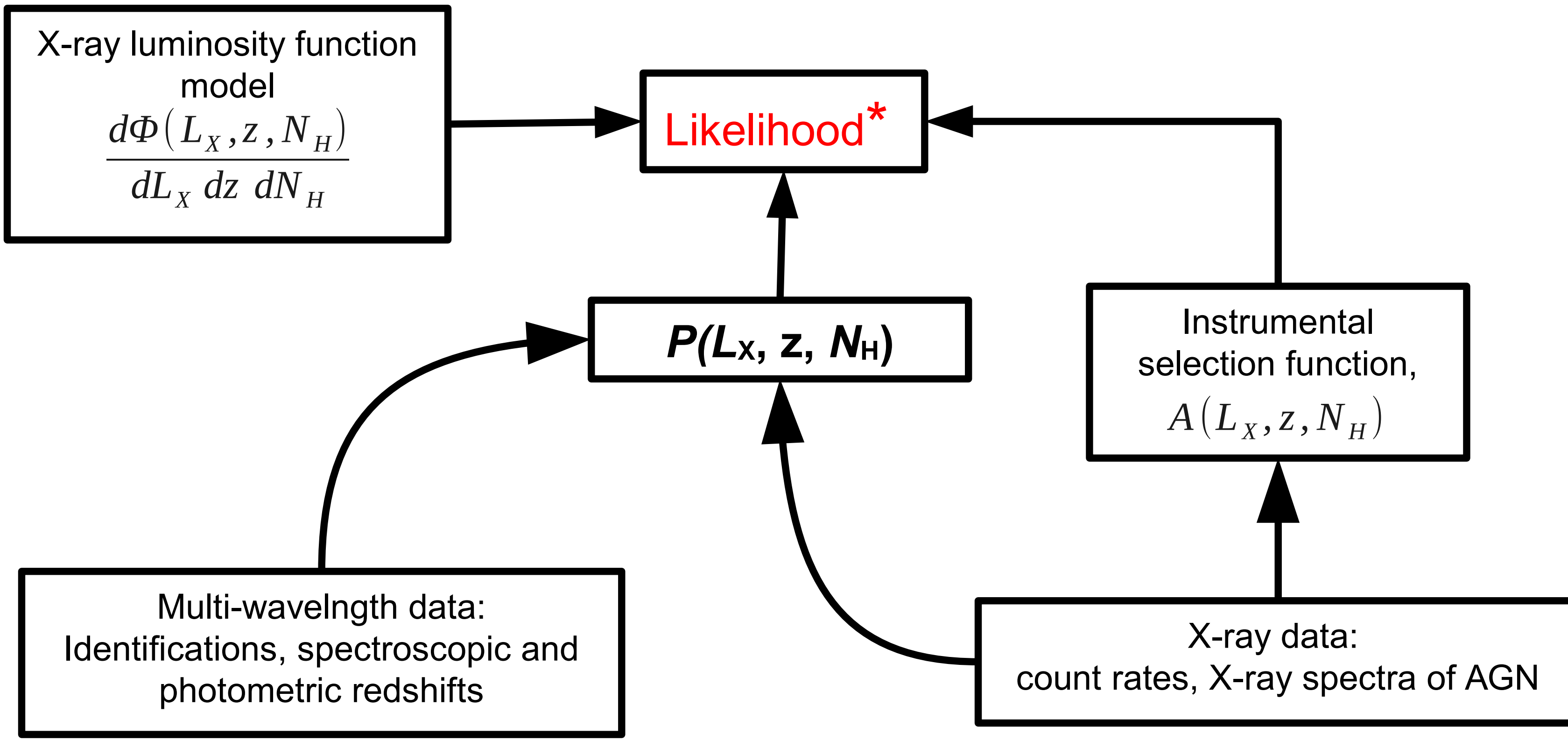
The most heavily obscured AGN (Compton thick, $N_H>10^{24}cm^{-2}$) are represented in X-ray samples, albeit with small numbers.

X-ray luminosity function: open questions

- Space density of obscured AGN, particular deeply shrouded ones (Compton thick)
- Redshift dependence of obscured and Compton thick fraction
- AGN evolution at high redshifts, z>3

Analysis methodology and in partcular accounting for uncertainties in observed quantities is very imporant.

Modeling the X-ray luminosity function



$$* \log(Likelihood) = -\lambda + \sum_i \int \Phi(L_X, z, N_H)\, P(L_X, z, N_H)\, \frac{dV}{dz}\, dz\; dlogL_X\; dlogN_H,$$

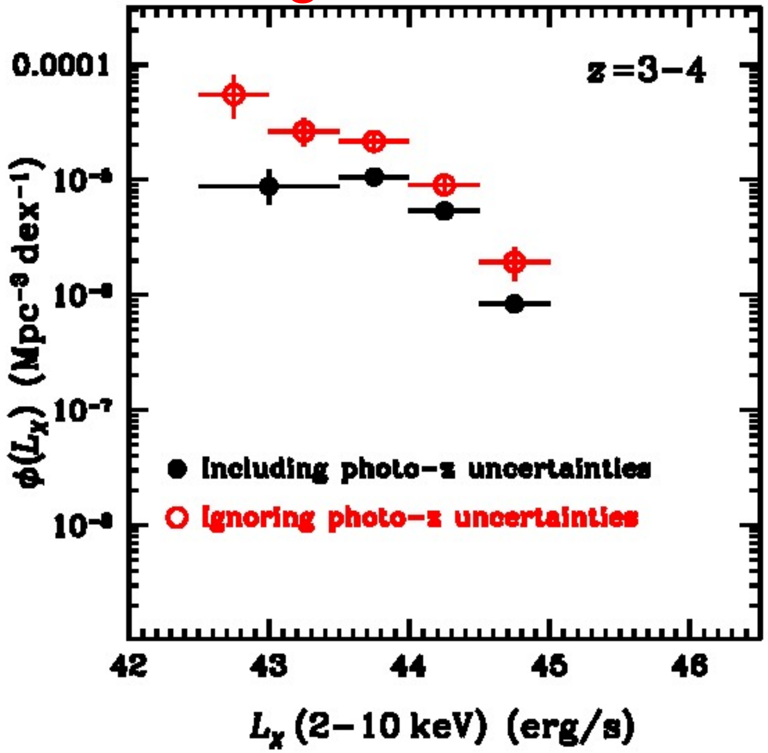
$$where \quad \lambda = \int A(L_X, z, N_H)\, \Phi(L_X, z, N_H)\, \frac{dV}{dz}\, dz\; dlogL_X\; dlogN_H,$$

$$A(L_X, z, N_H) \quad selection \quad function$$

X-ray luminosity function: importance of error propagation

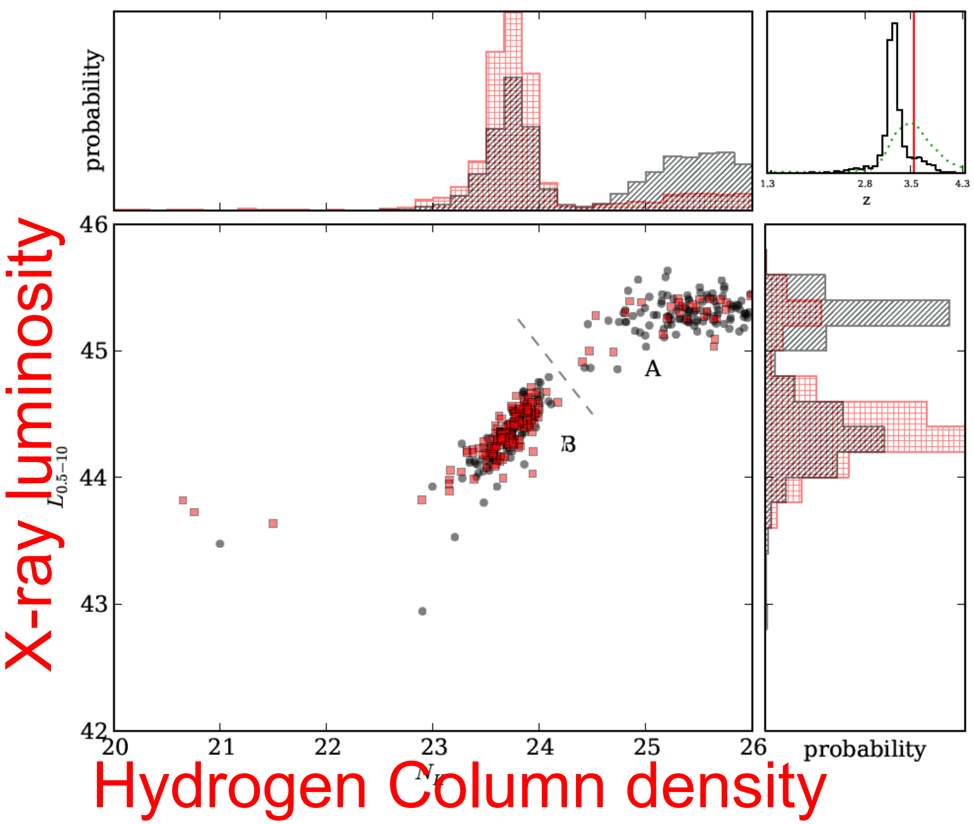
Ignoring uncertainties (e.g. photo-zs) leads to biases in XLF estimation

Georgakakis+15

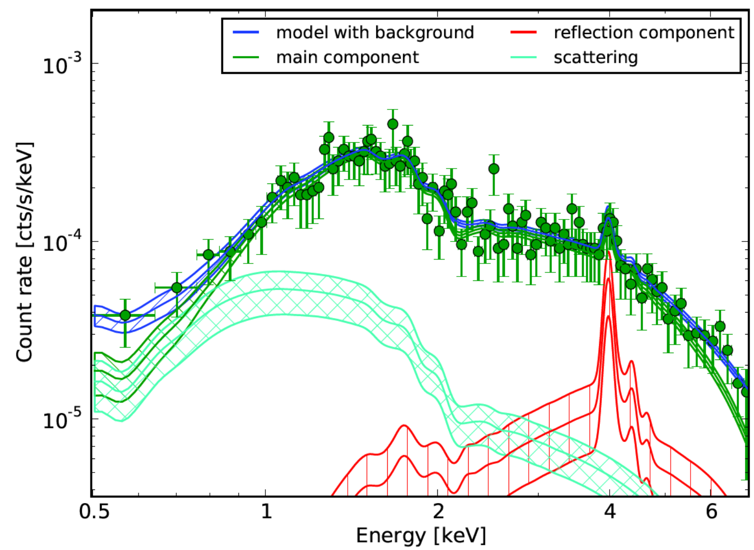


Bayesian X-ray spectral analysis approach

Buchner+14



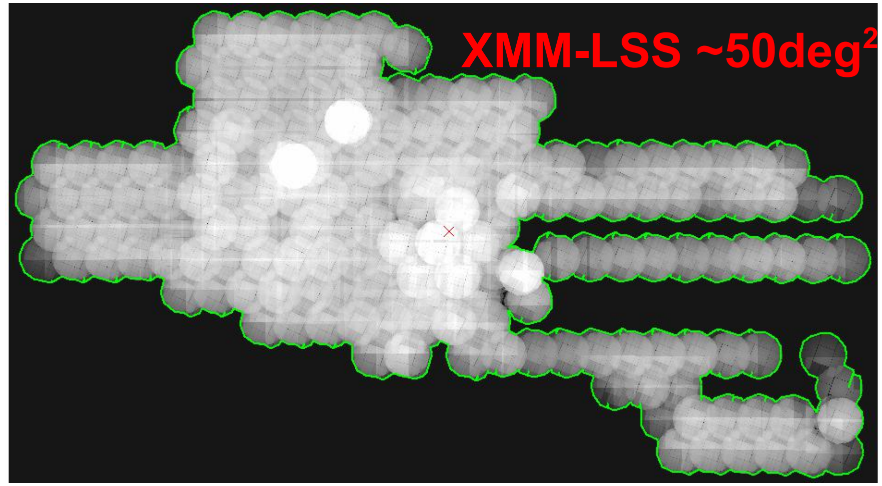
Estimate full probability distribution function of inferred parameters, i.e. N_H, L_X

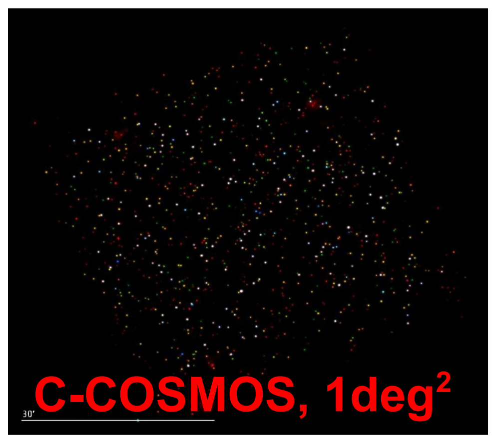


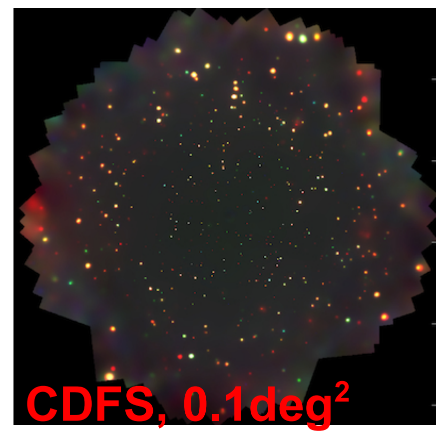
Multi-wavelength surveys

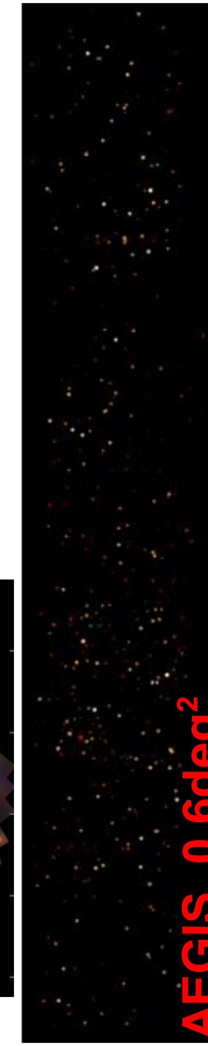
Explosion in quality and quantity of X-ray survey data:

- ✓ Chandra X-ray
- ✓ Optical/near-IR SEDs
- ✓ Large spec-z surveys
- ✓ HST (morphology)
- ✓ Spitzer mid/far-IR
- ✓ Herschel far-IR





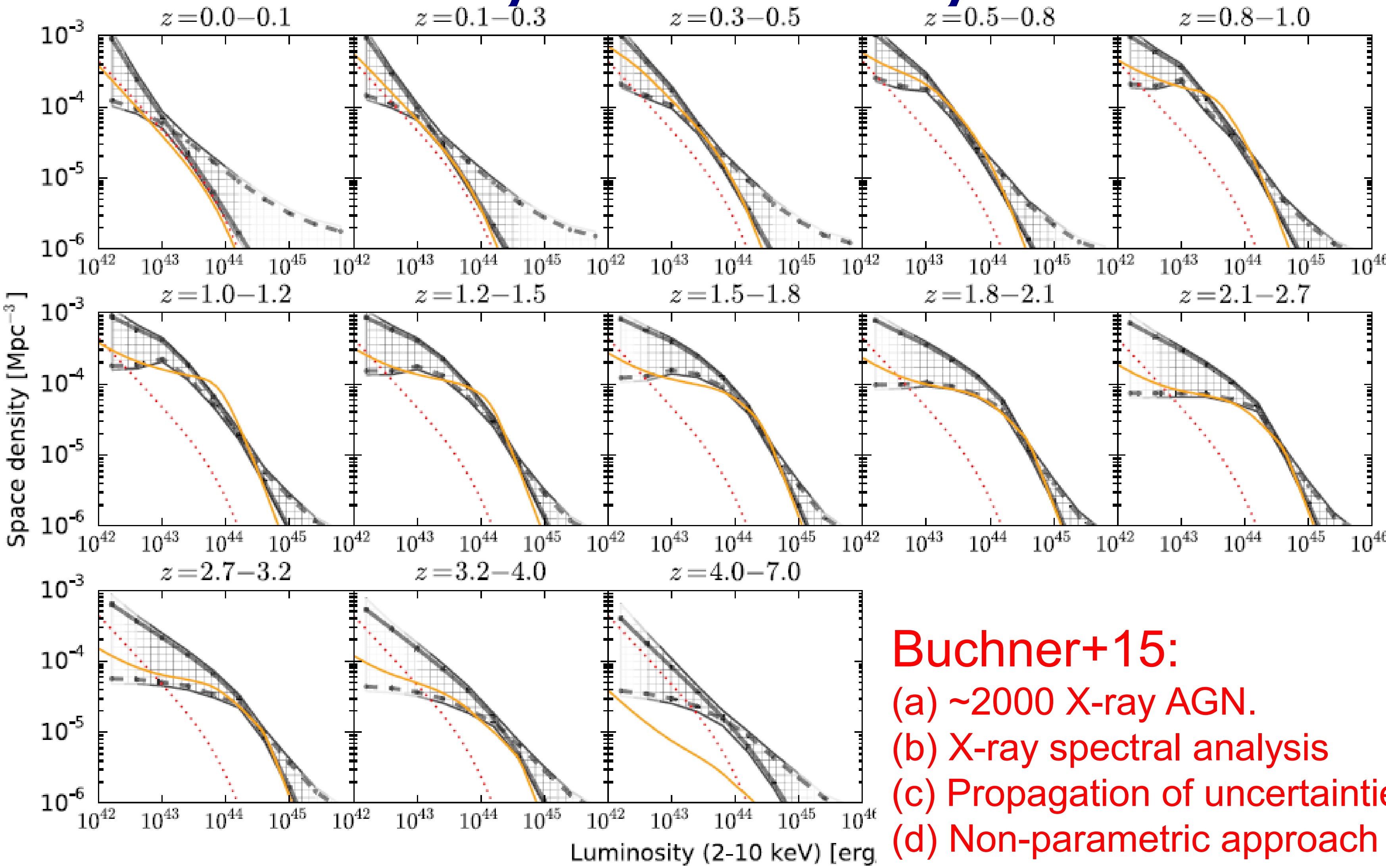




Last comprehensive XLF measurement: Ueda+03

Past year 5 publications on XLF (Ueda et al. 2014, Miyaji et al. 2015, Aird et al. 2015, Buchner et al. 2015, Georgakakis et al. 2015).

Total X-ray luminosity function



Buchner+15:

(a) ~2000 X-ray AGN.

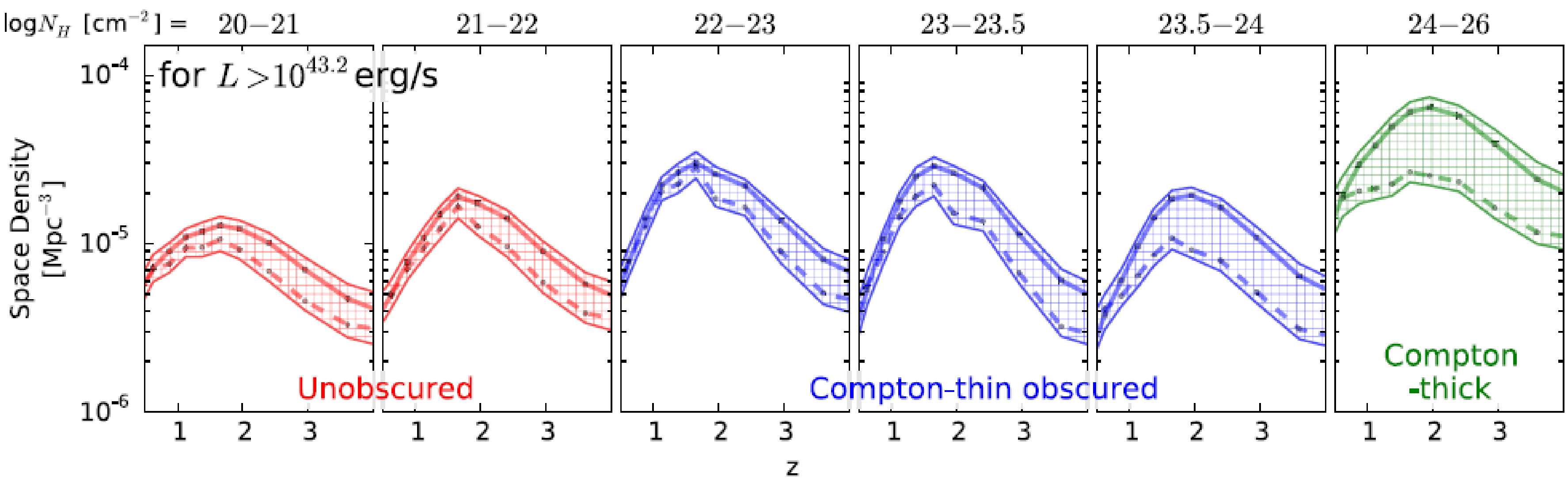
(b) X-ray spectral analysis

(c) Propagation of uncertainties

(d) Non-parametric approach

AGN space density vs obscuration

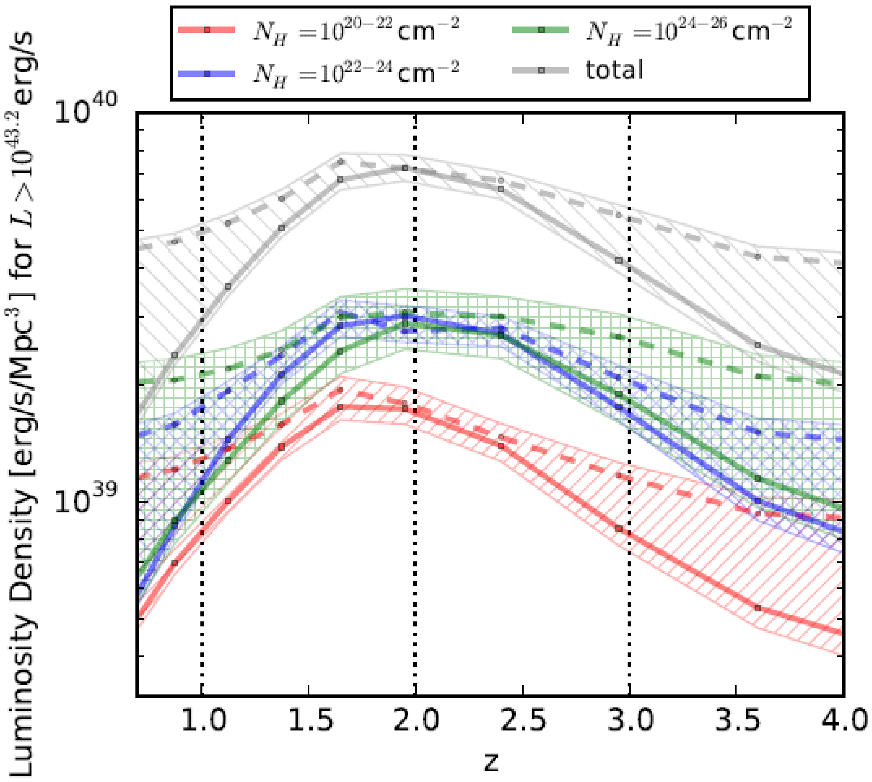
Buchner+15



AGN space density evolution split by the level of obscuration

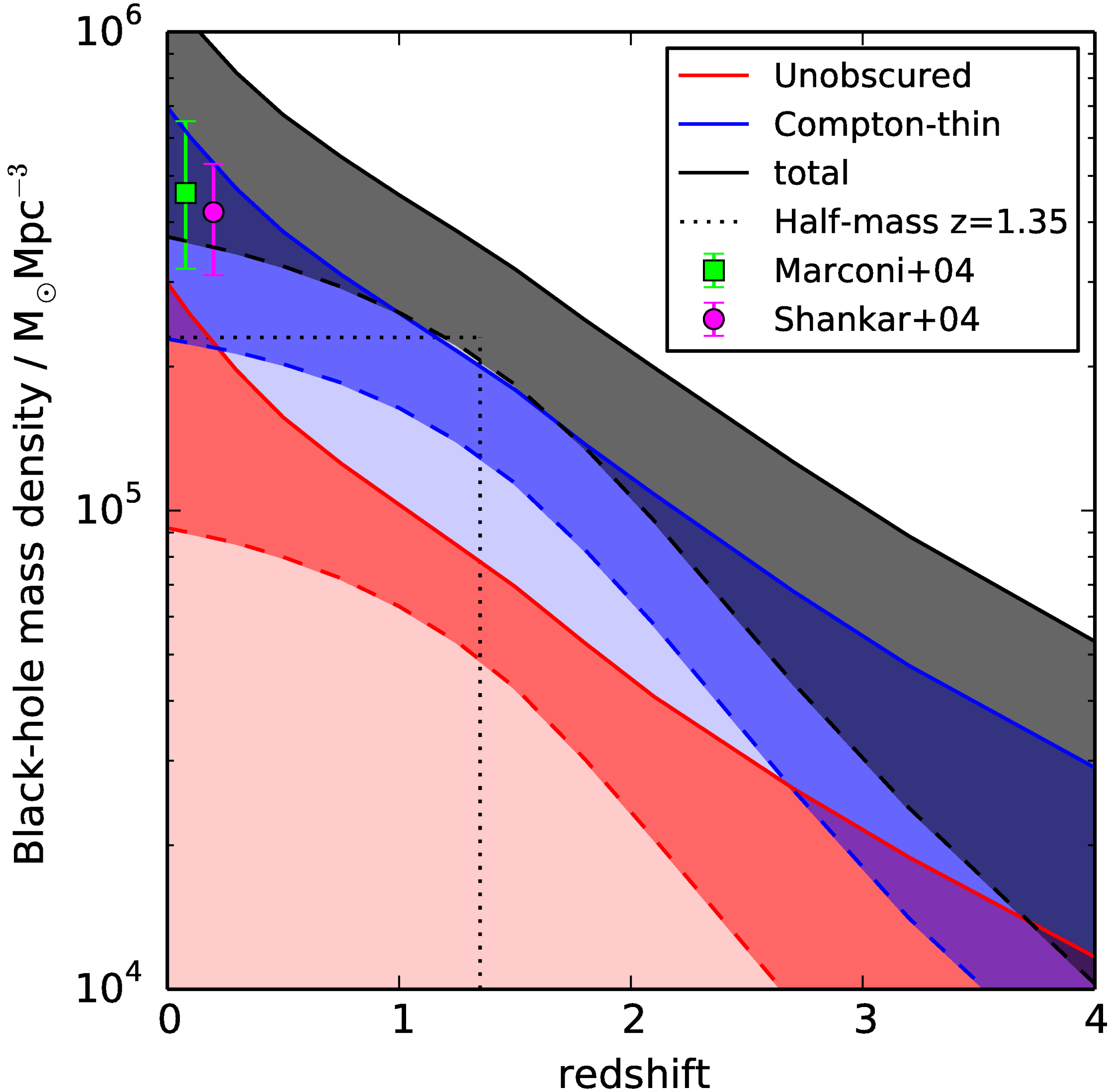
First direct estimate of the Compton Thick AGN evolution

Accretion density of the Universe

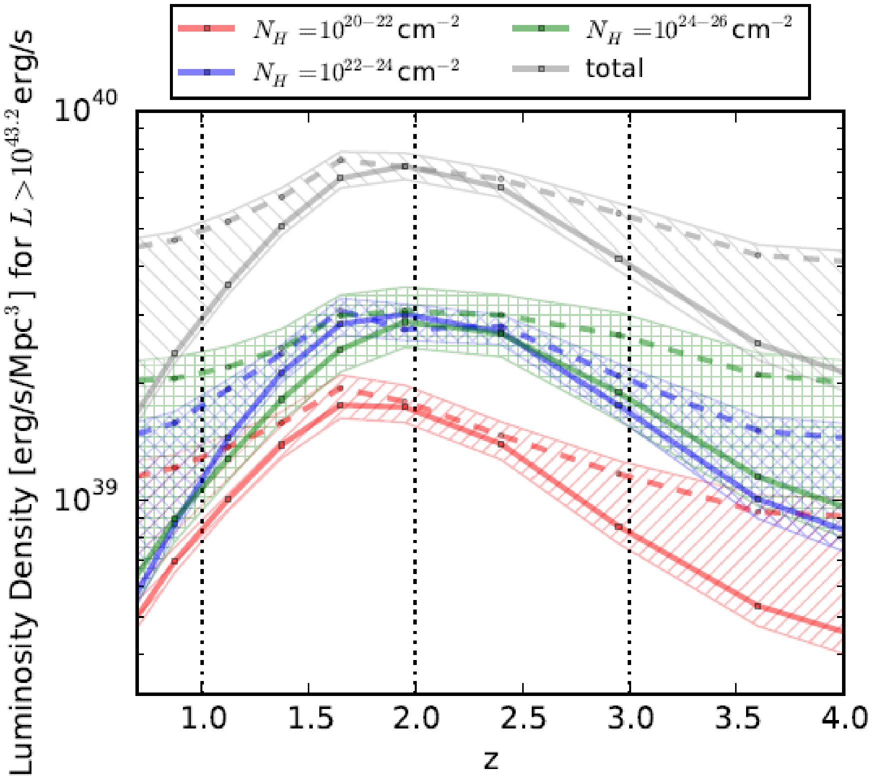


- Rapid decline since *z*~1
- Broad plateau at z~1-3
- Decline at z>3
- Obscured and Compton thick AGN dominate
- Obscured and Compton similar contribution

Black hole mass density vs redshift



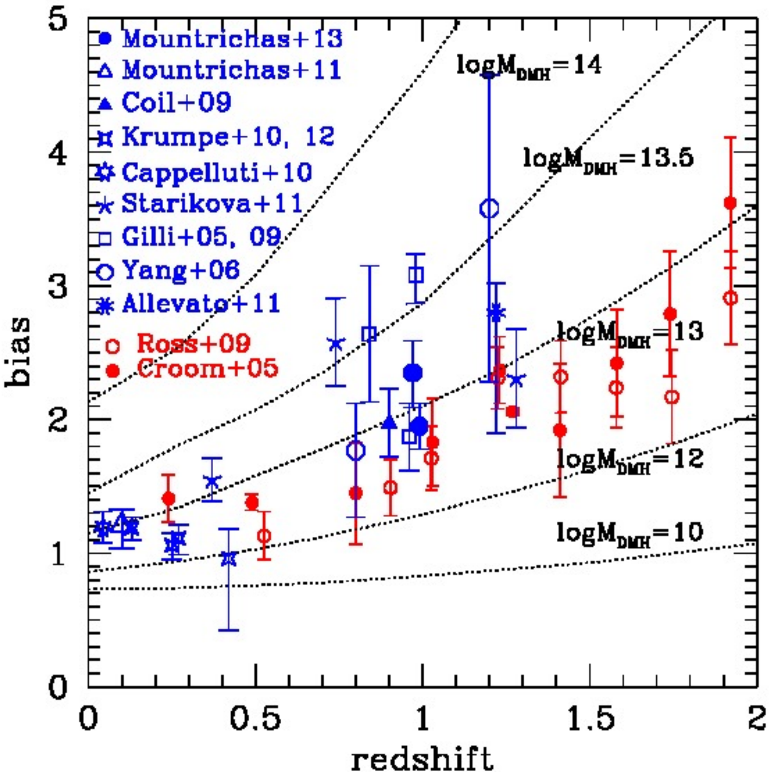
The "How" question: physical conditions black hole growth with cosmic time



- Rapid decline since z~1
- Broad plateau at z~1-3
- Decline at z>3
- What is the physical process driving this evolution?
  - Smaller BHs at lower redshift
  - Decreasing accretion rate
  - Decline of gaseous mergers
  - Different accretion modes at different epochs

Clustering properties of X-ray AGN

Mountrichas+13



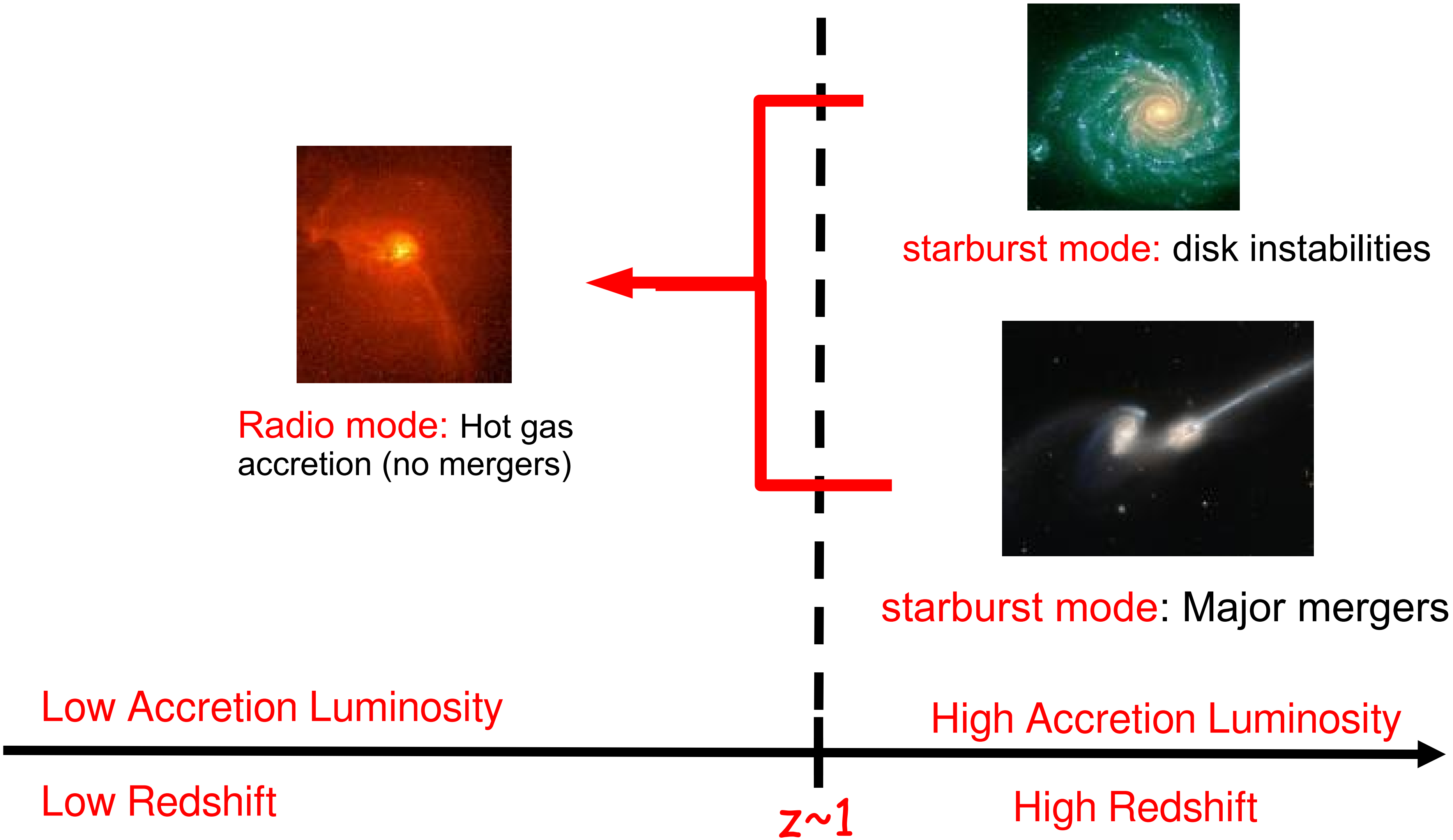
Typical halo mass $\sim 10^{13}$ solar:

- AGN triggering, secular vs mergers.
- Physical conditions of BH growth.

Hickox+09, Allevato+11, Mountrichas+12, 13, Krumpe+12, Koutoulidis+13, Krumpe, Miyaji & Coil+13, Hütsi+14

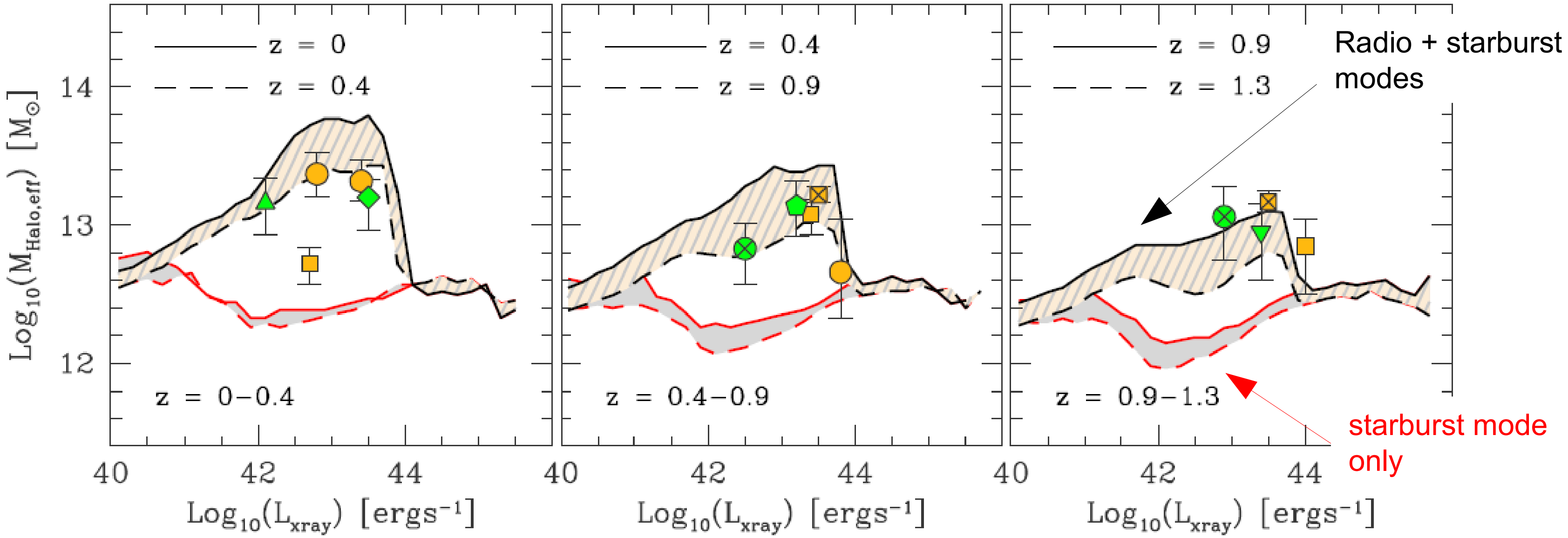
GALFORM Semi-Analytic Model

GALFORM SAM: Bower et al. 2006, Fanidakis et al. 2011



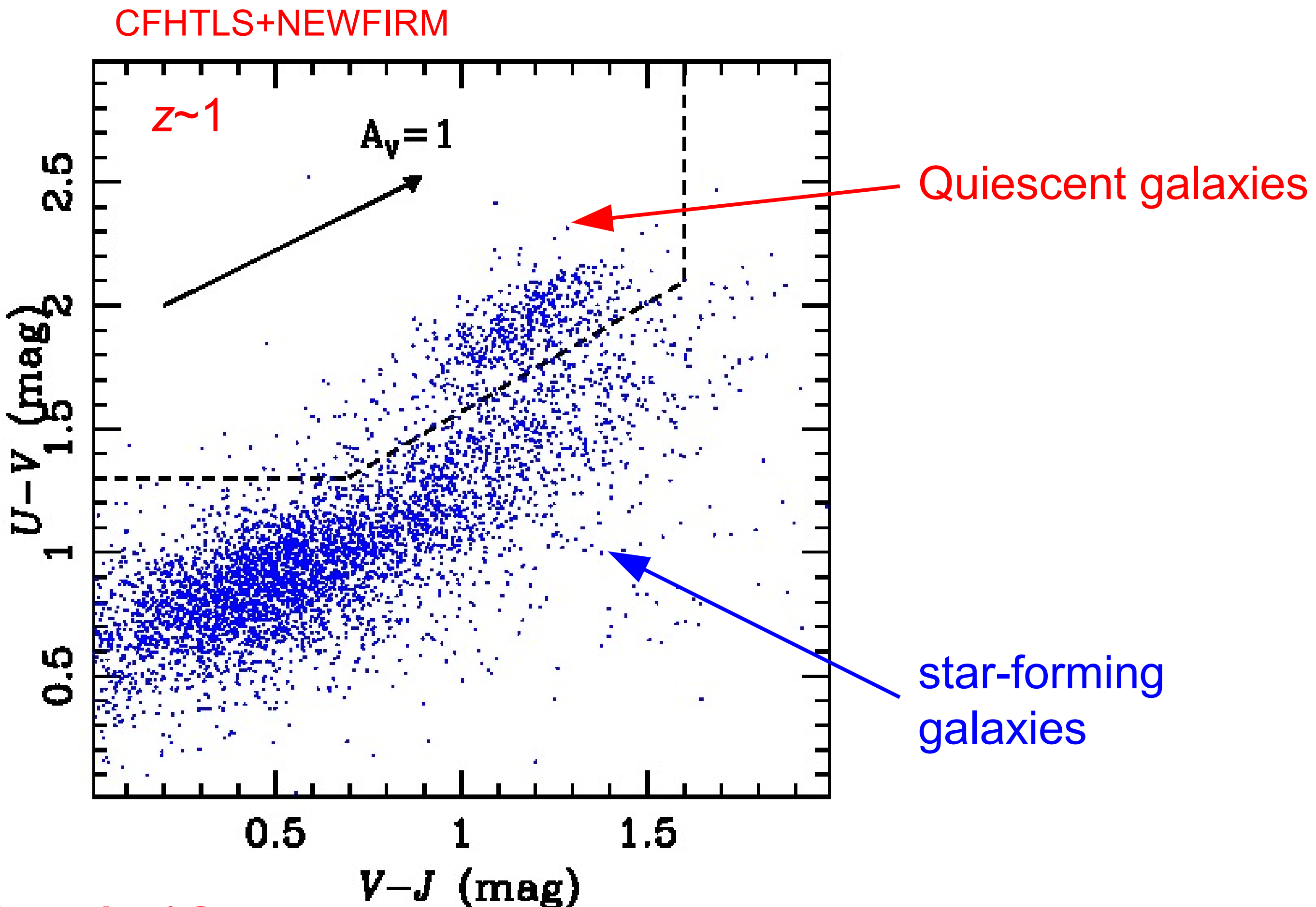
Black hole fuelling modes to z=1: Large Scale Clustering of AGN

Fanidakis, Georgakakis et al. 2013



GALFORM Semi Analytic Model: Fanidakis+11, 12

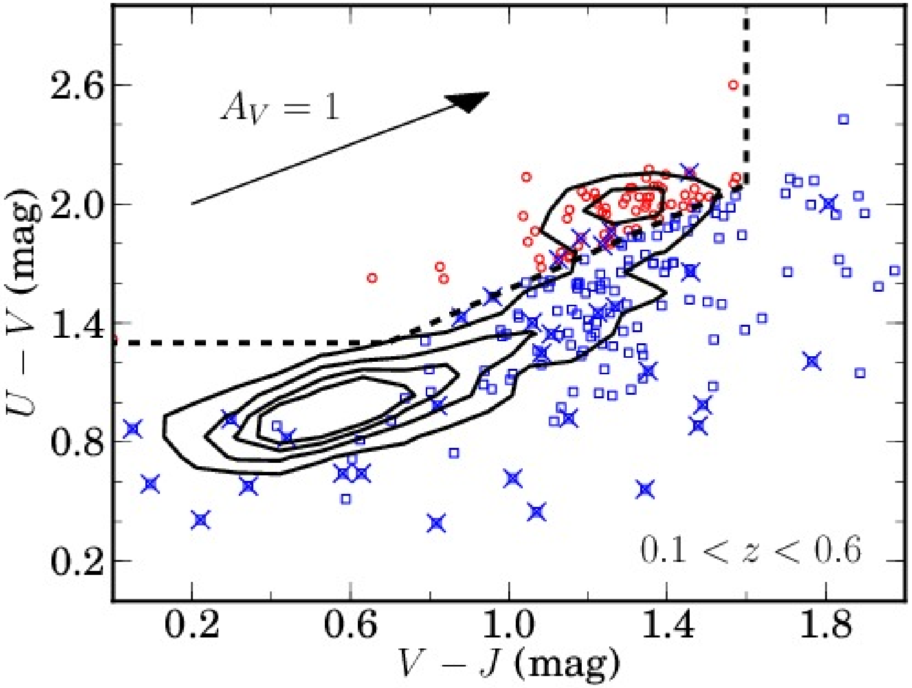
UVJ diagram

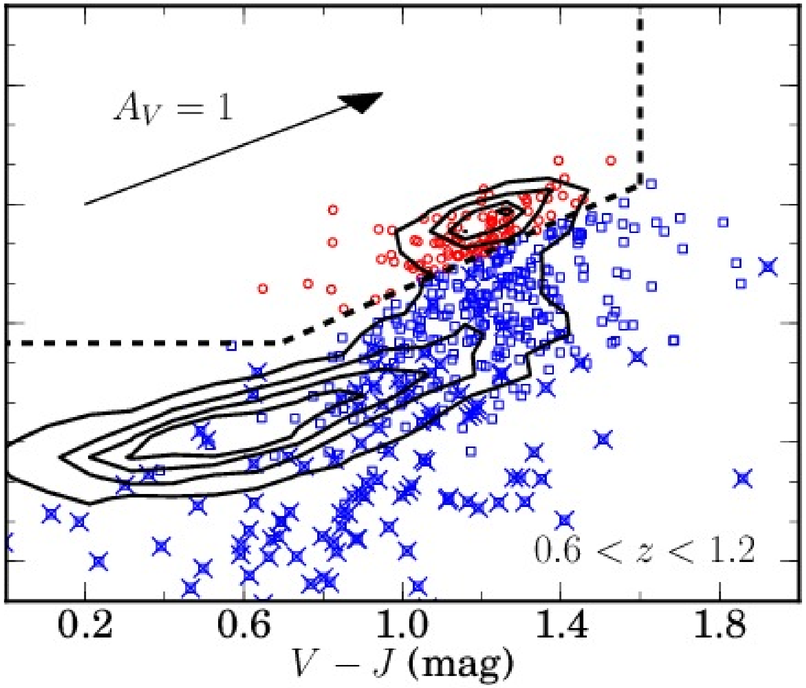


Williams+09, Patel+12

X-ray AGN UVJ diagram

Georgakakis et al., 2014, MNRAS, 440, 339

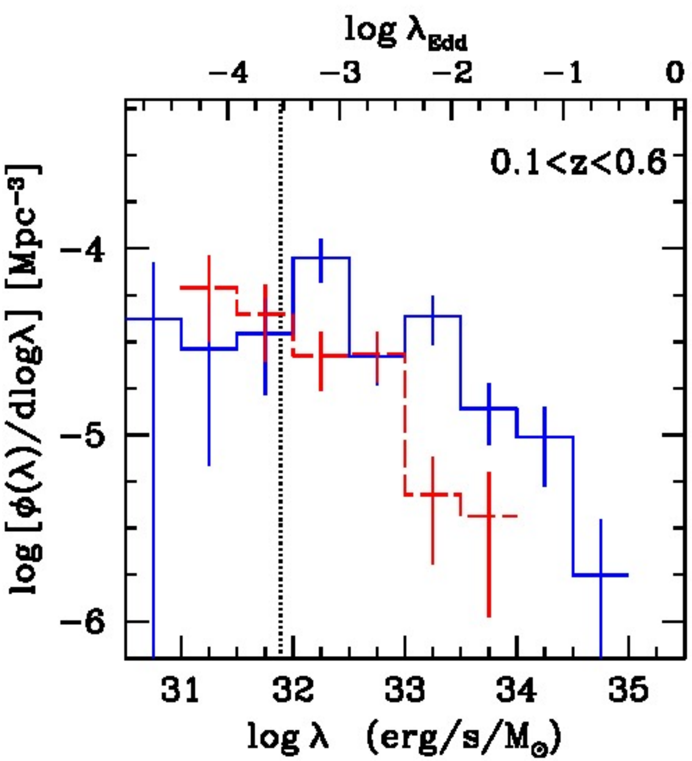


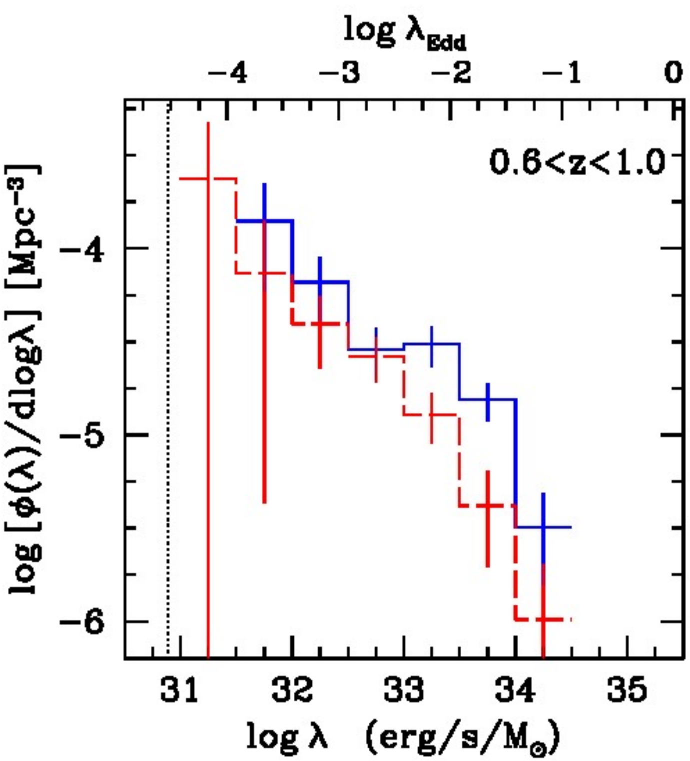


Contours: galaxies
Red symbols: X-ray AGN in passive galaxies
Blue symbols: X-ray AGN in SF galaxies
Crosses: Broad-line AGN

X-ray AGN have diverse SF histories, see also Nandra+07, Silverman+11, Azadi+15, Mullaney+15

Eddington ratio distributions





M_{BH}=0.002*M_{Bulge} (local scaling relation),
M_{bulge}~M_{Star} for bulges
M_{bulge}~0.5*M_{Star} for disks (i.e. typical for Sbc galaxies)

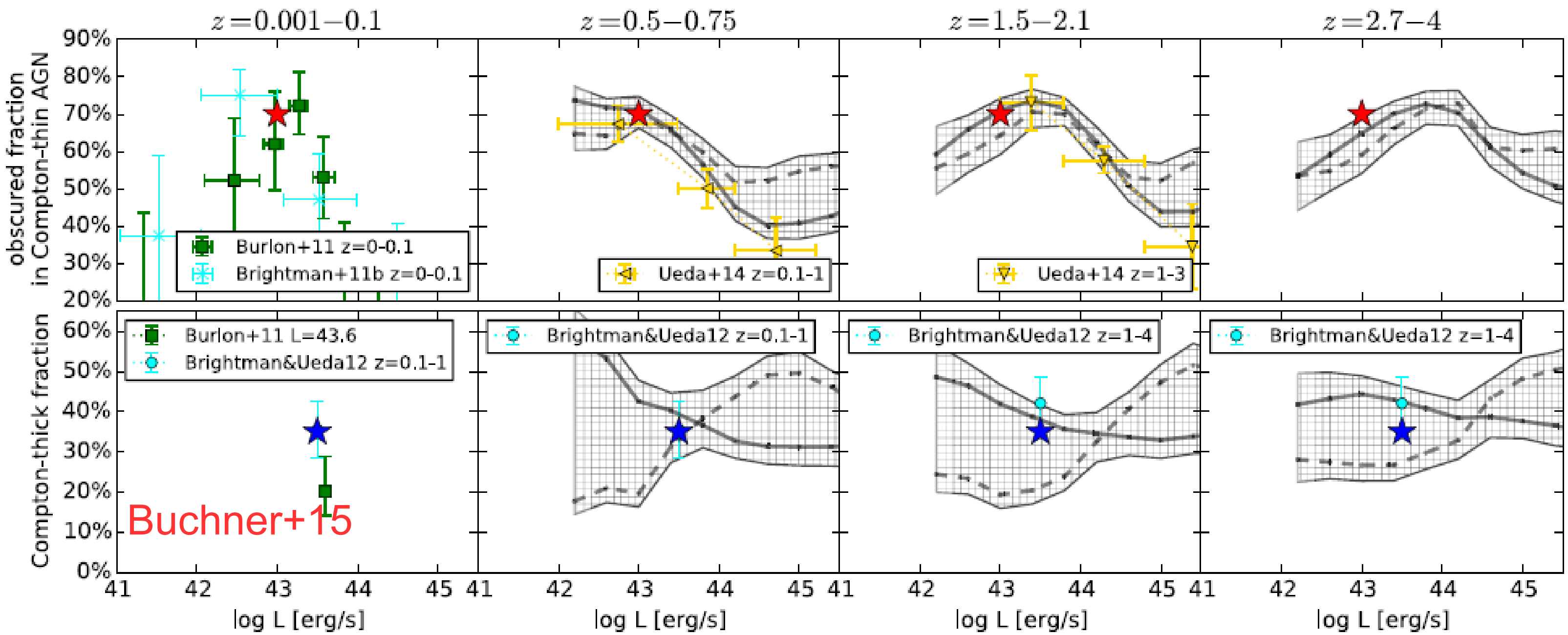
Summary

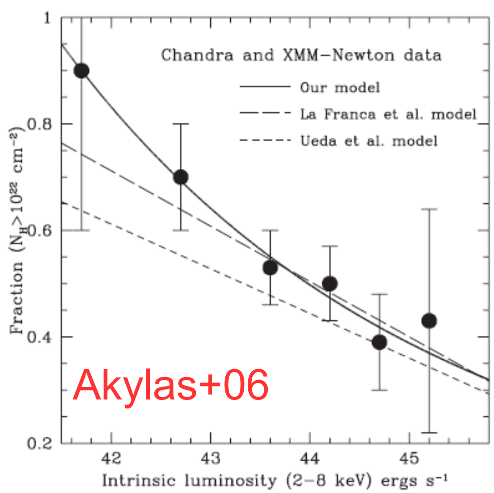
- AGN demographics:
  - Compton thick and obscured sources dominate the growth of black holes in the Universe
  - Nearly half of the accretion density is associated with Compton thick sources
- AGN population properties:
  - AGN hosts have diverse star-formation histories.
  - Evidence for two black hole fueling modes that occur in galaxies with different star-formation histories.

Future prospects

- X-ray AGN demographics and population properties are severely limited by small samples: eROSITA All Sky Survey?
- Toward the Bolometric AGN LF: combination of multi-wavelength AGN selection methods (X-ray, UV, IR)
- Place AGN in the context of galaxy evolution. Type of host galaxies, link to large scale environment: generalise luminosity function models to include host galaxy properties, e.g. $\Phi(L_X, z, N_H, \mathrm{SFR}, M^*)$.

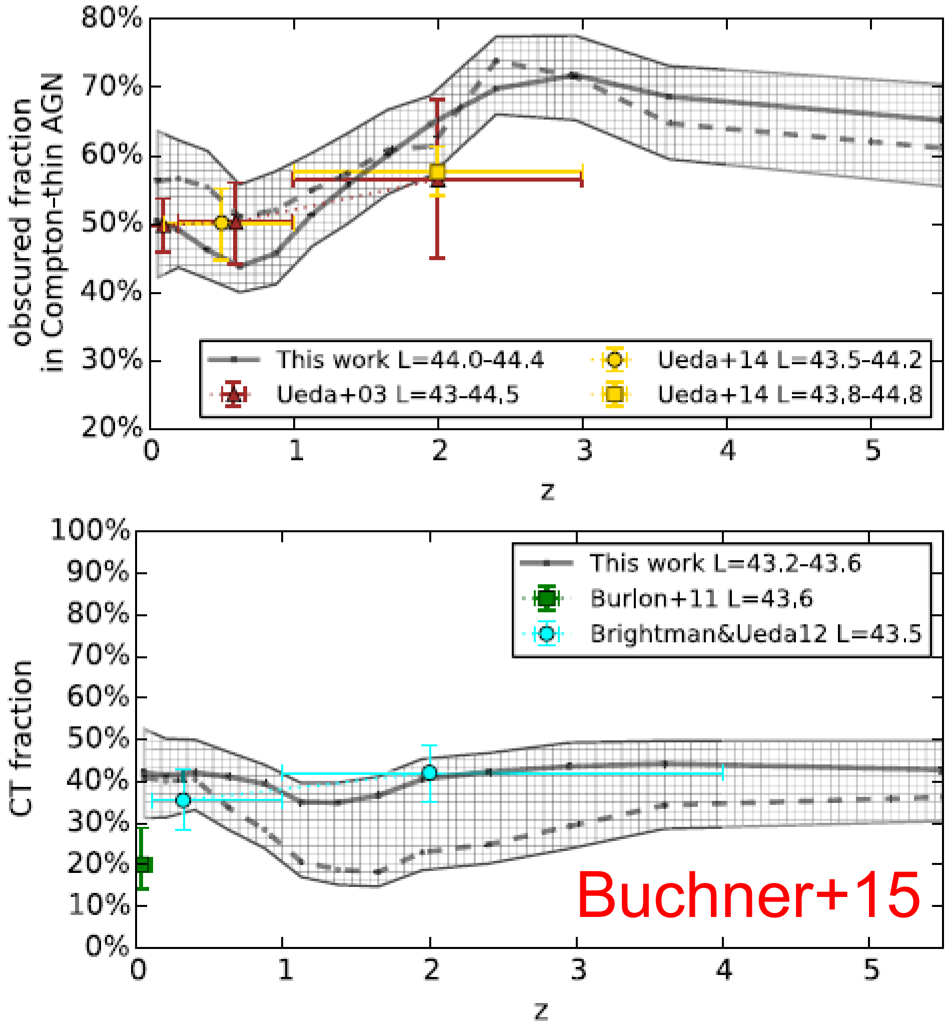
Obscured AGN fraction vs luminosity





- Non-monotonic relation between obscured fraction and luminosity
- Contradicts previous studies (e.g. Ueda+03, Akylas+06)

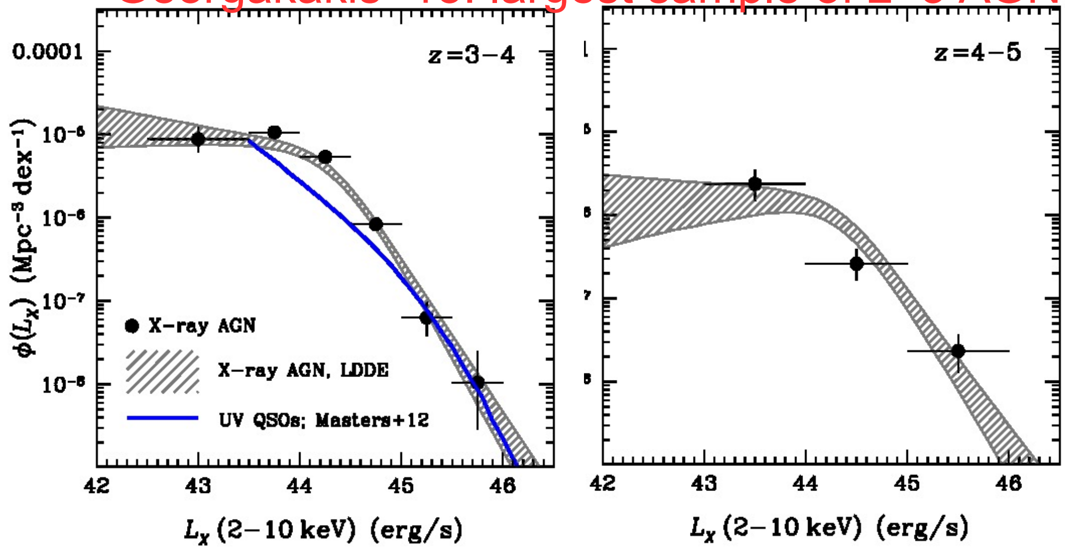
Obscured AGN fraction vs redshift

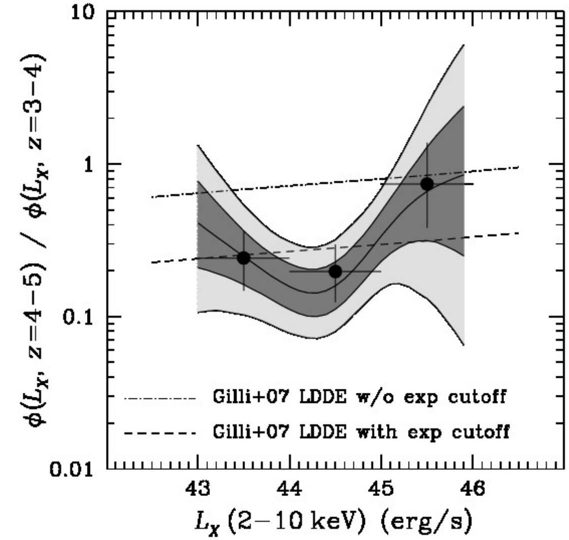


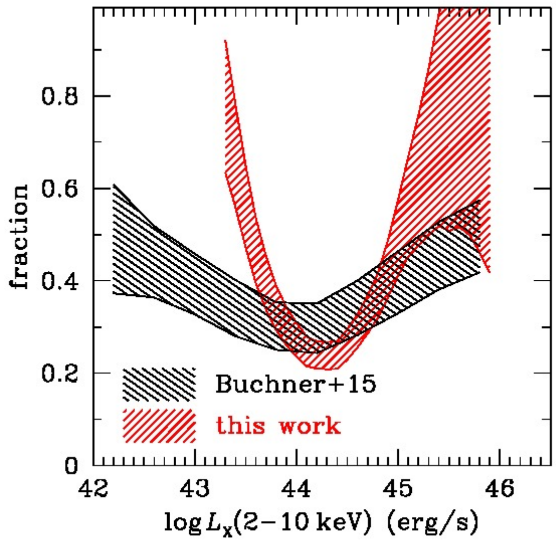
- Obscured AGN fraction increases with redshift
- Compton thick AGN fraction constant with redshift, global average ~40%.

X-ray luminosity function: z>3 evolution

Georgakakis+15: largest sample of z>3 AGN to date

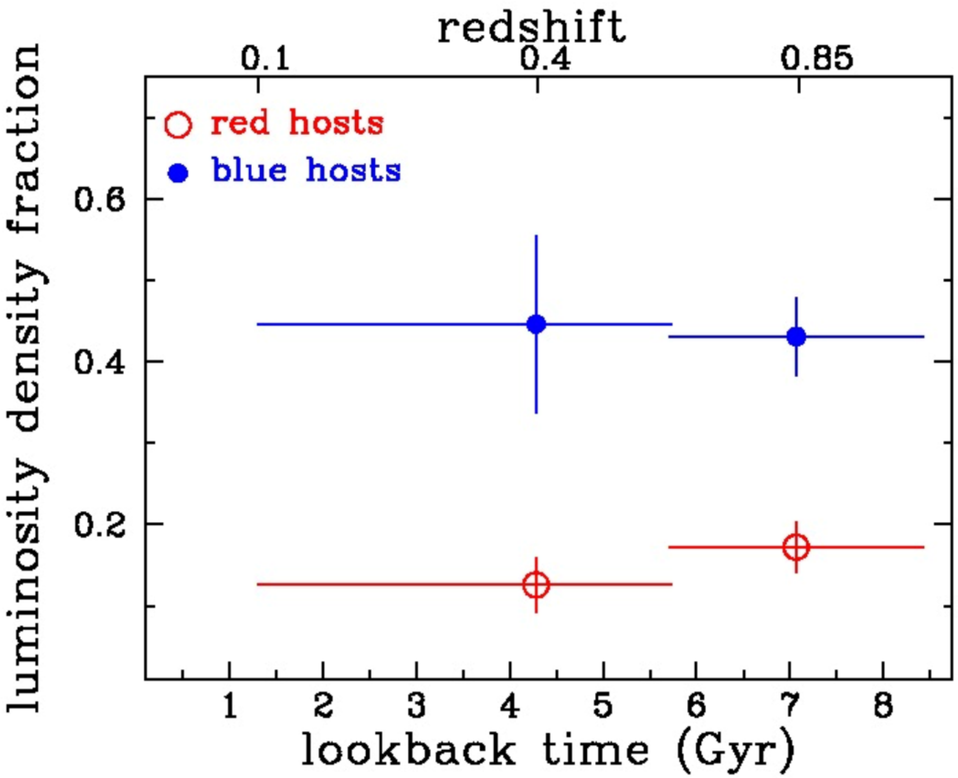






- Rapid evolution of AGN population between z=3 and z=5. Nearly 1dex in space density
- The luminosity dependence of the Type-I AGN fraction at z>3 is non-monotonic

Accretion density split into quiescent and star-forming hosts



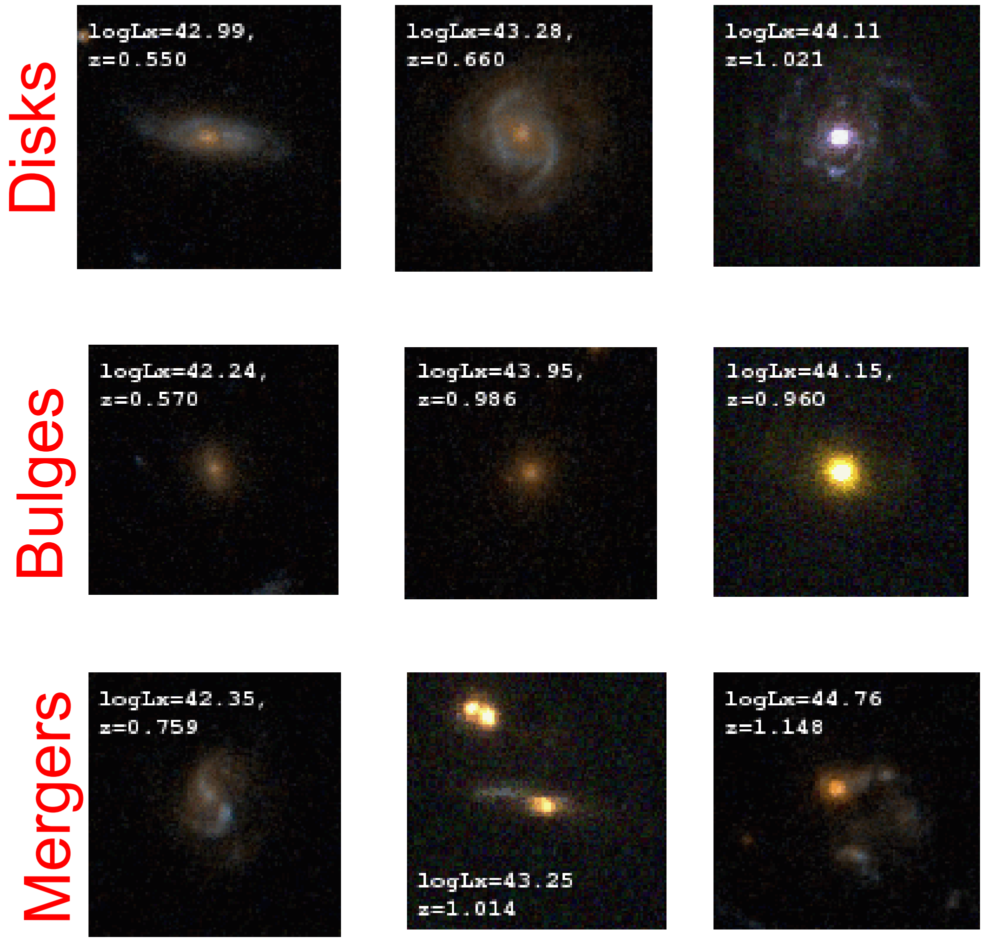
Bulk of accretion density associated with star-formation

Quiescent hosts: 15-20% of accretion density independent of redshift

Georgakakis et al., 2014, MNRAS, 440, 339

Morphology of AGN hosts at *z*~1

Georgakakis et al. 2009

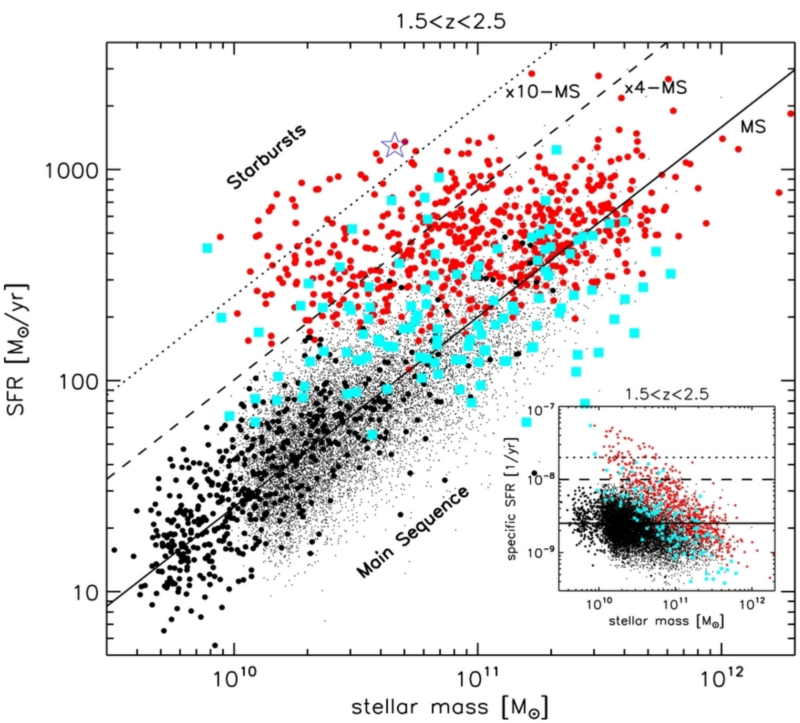


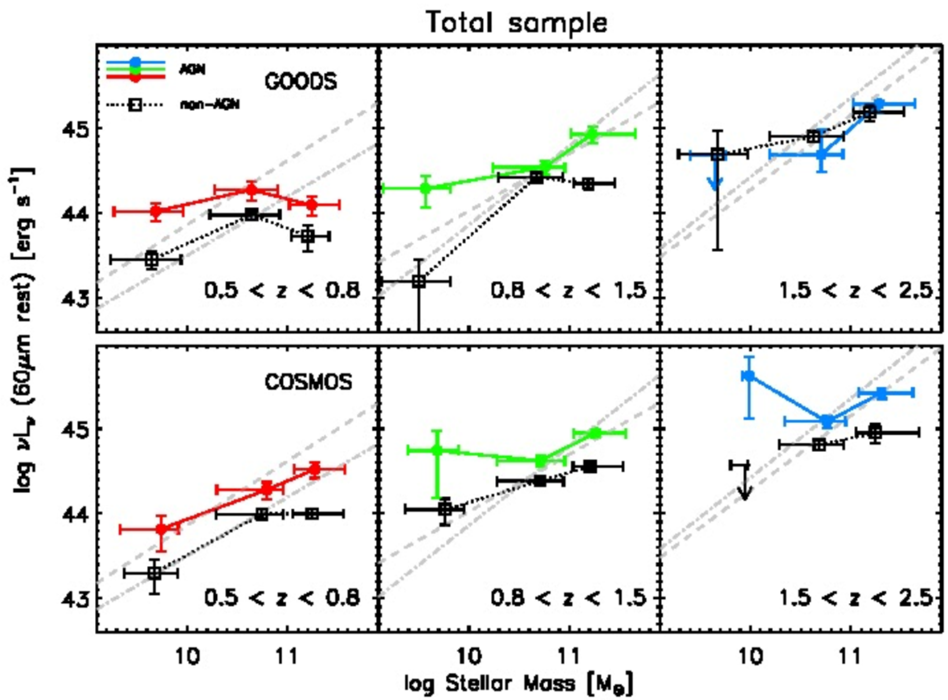
- AEGIS, CDF-North and South
- Morphological classification of AGN hosts at z~1:

30% of AGN in disk galaxies (NOT mergers)

Also: Pierce+07, Cisternas+11, Kocevski+12, Villforth+14

AGN hosts lie on average on the main sequence of SF



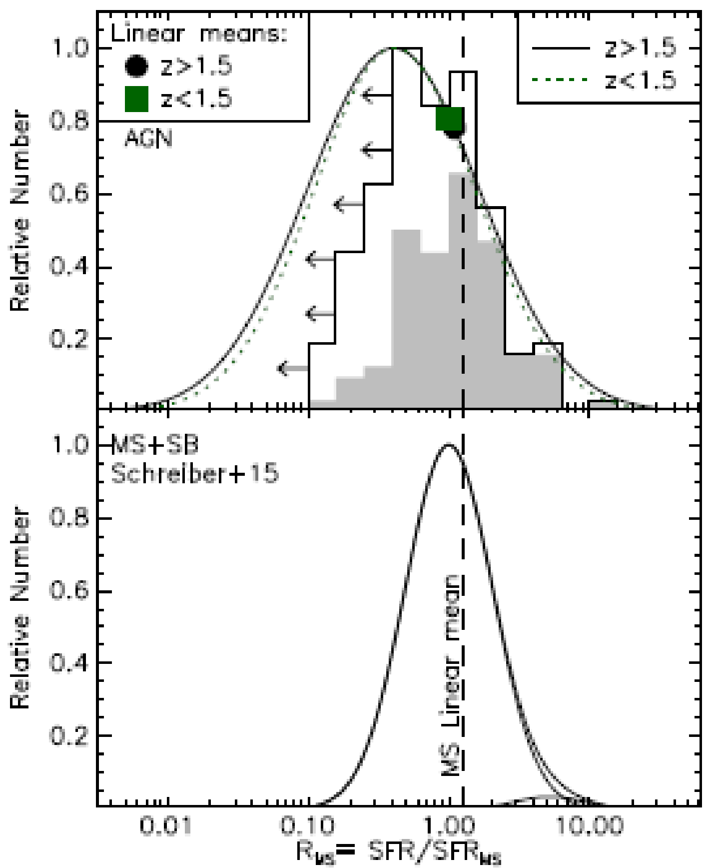


Main Sequence: Rodighiero+11

Santini+09

also, Rosario+11, Rosario+13, Mullaney+12

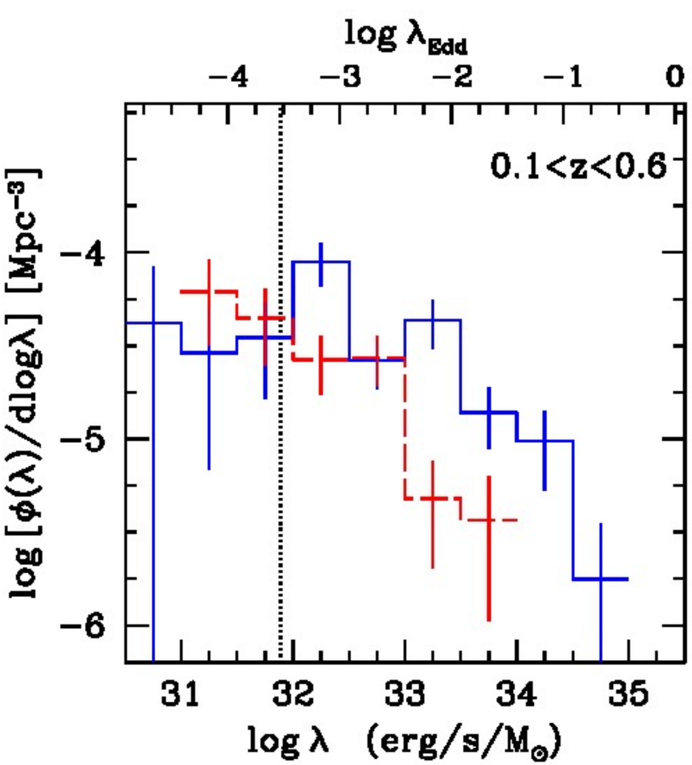
Revisiting Herschel results on X-ray AGN SF properties

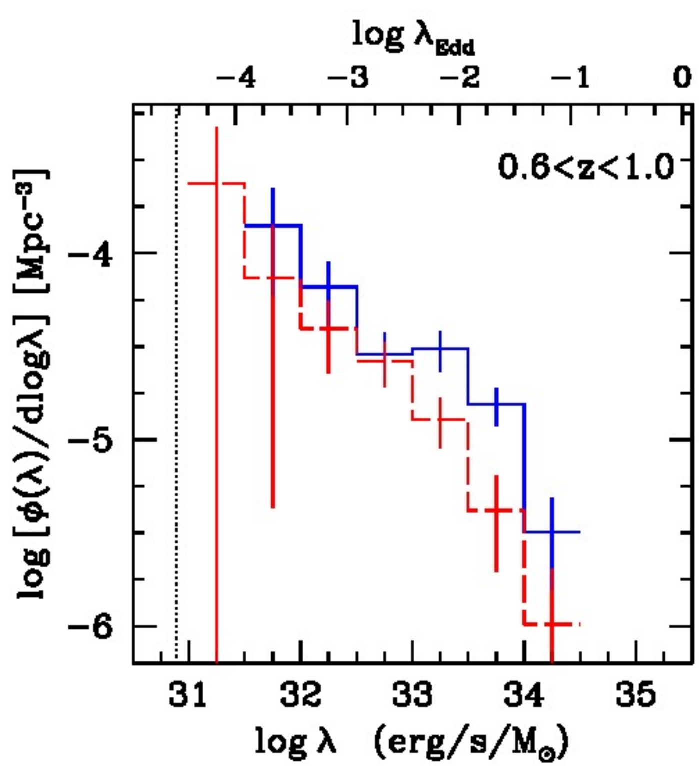


- Herschel stacking results biased to high values.
- SF properties of X-ray AGN hosts broad

Mullaney+15, arXiv:1506.05459

Eddington ratio distributions





M_{BH}=0.002*M_{Bulge} (local scaling relation),

M_{bulge}~M_{Star} for bulges

M_{bulge}~0.5*M_{Star} for disks (i.e. typical for Sbc galaxies)

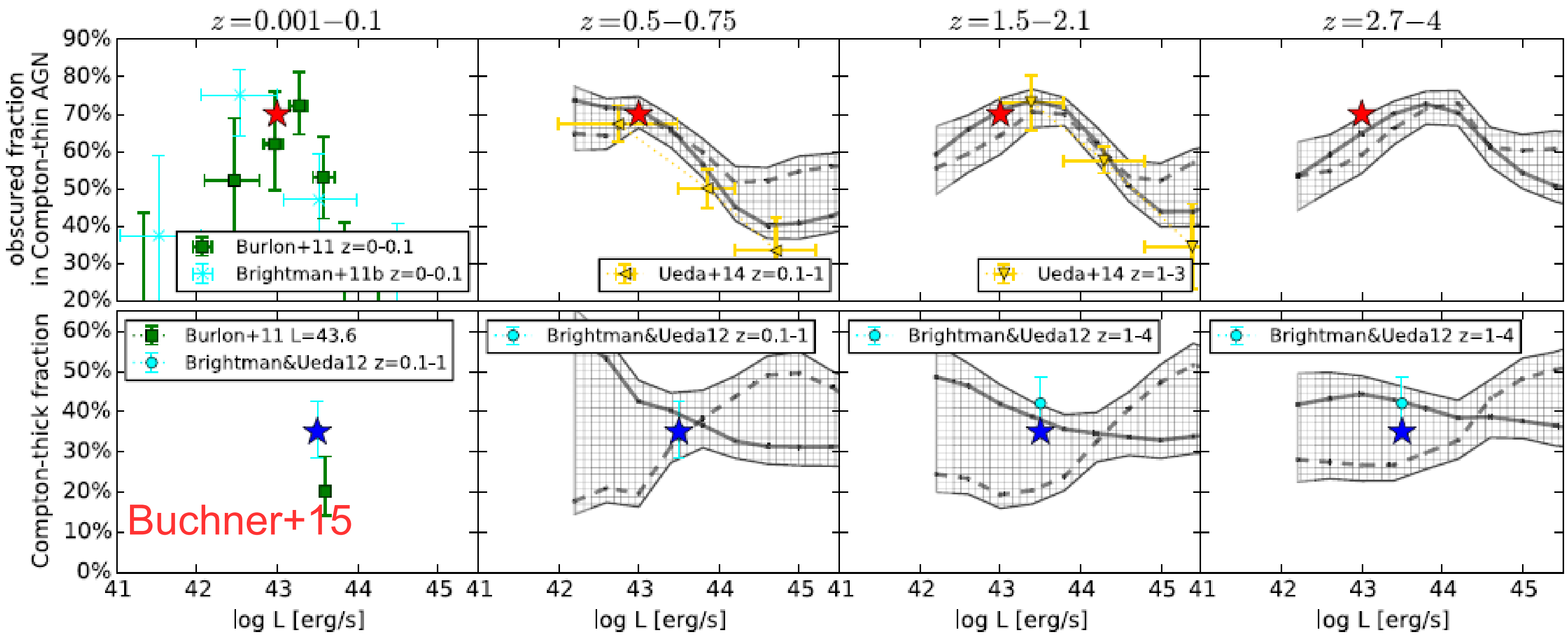
Summary

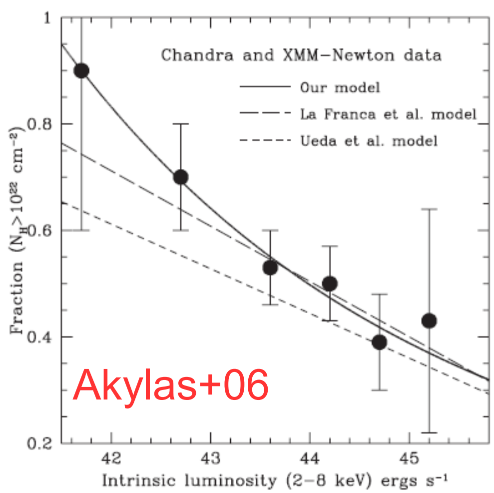
- AGN demographics:
  - Obscured AGN fraction increases with redshift
  - Compton thick AGN fraction is ~40% independent of redshift.
  - Nearly half of the accretion density is associated with Compton thick sources
- AGN population properties:
  - AGN hosts have diverse star-formation histories.
  - Evidence for two black hole fueling modes that occur in galaxies with different star-formation histories.

Future prospects

- X-ray AGN demographics and population properties are severely limited by small samples: eROSITA All Sky Survey?
- Toward the Bolometric AGN LF: combination of multi-wavelength AGN selection methods (X-ray, UV, IR)
- Place AGN in the context of galaxy evolution. Type of host galaxies, link to large scale environment.
  - Generalise luminosity function models to include host galaxy properties, e.g. $\Phi(L_X, z, N_H, \mathrm{SFR}, M^*)$.

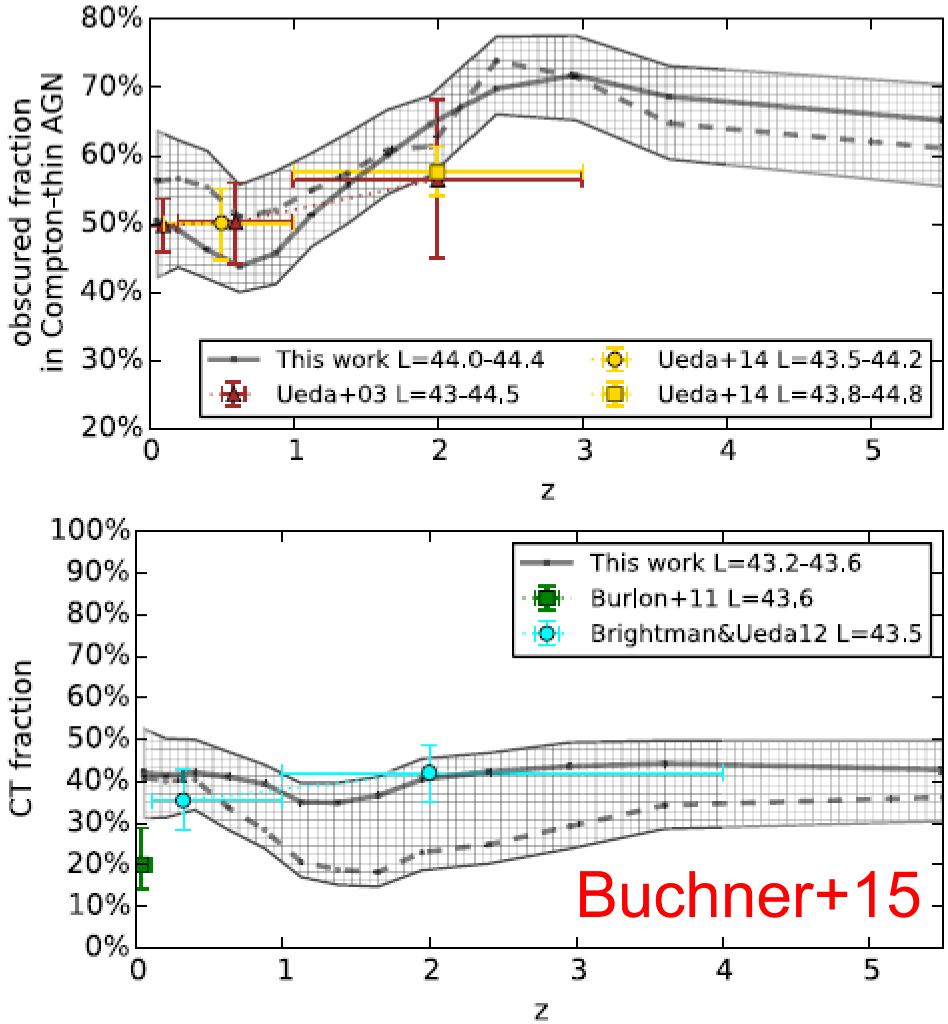
Obscured AGN fraction vs luminosity





- Non-monotonic relation between obscured fraction and luminosity
- Contradicts previous studies (e.g. Ueda+03, Akylas+06)

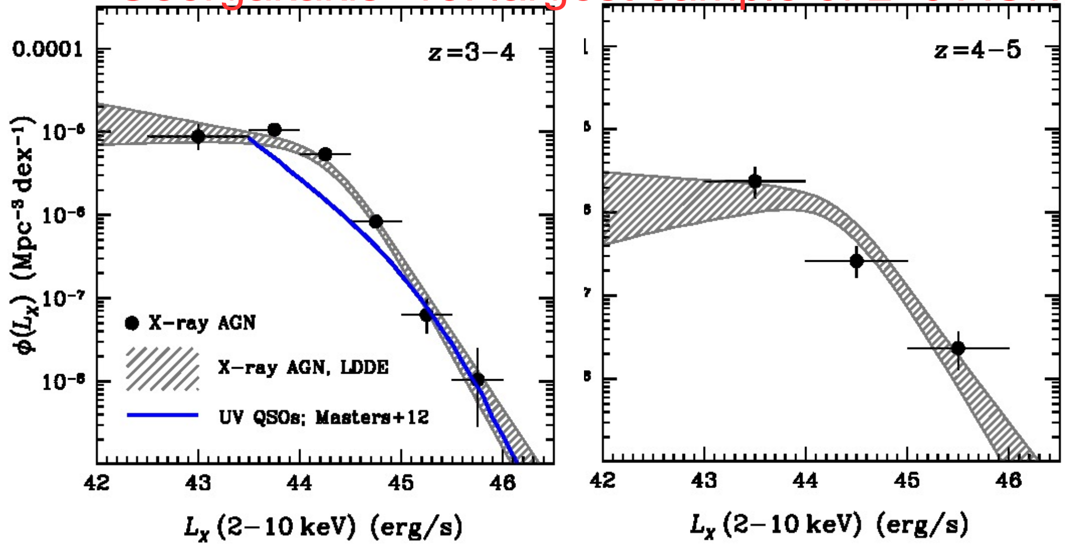
Obscured AGN fraction vs redshift

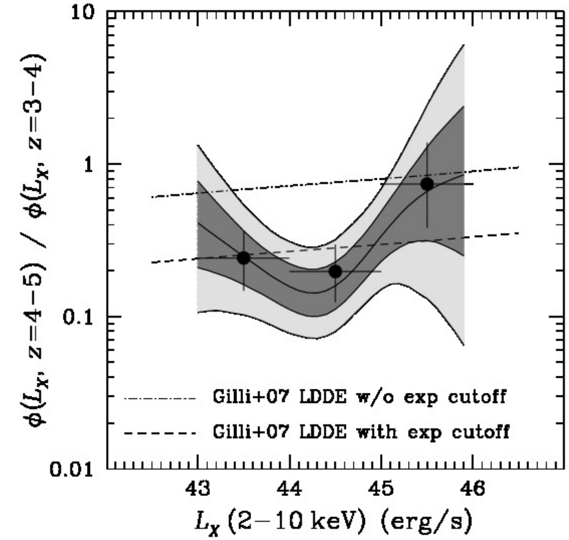


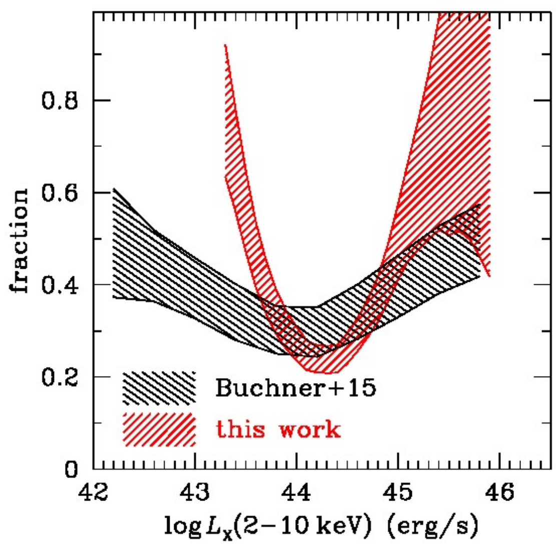
- Obscured AGN fraction increases with redshift
- Compton thick AGN fraction constant with redshift, global average ~40%.

X-ray luminosity function: z>3 evolution

Georgakakis+15: largest sample of z>3 AGN to date

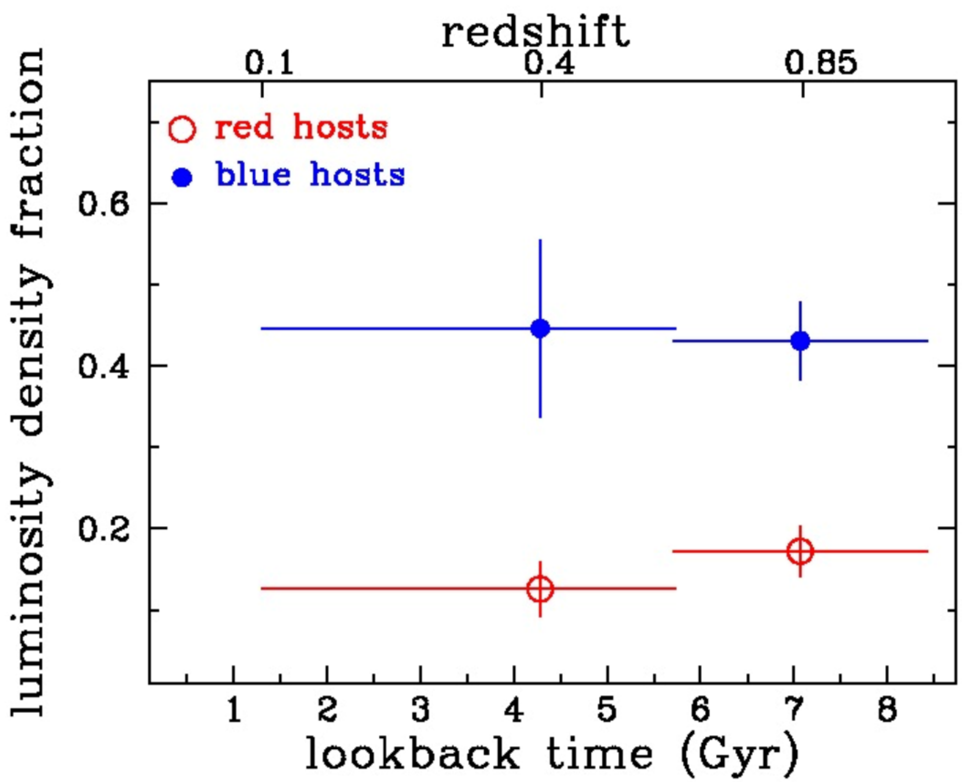






- Rapid evolution of AGN population between z=3 and z=5. Nearly 1dex in space density
- The luminosity dependence of the Type-I AGN fraction at z>3 is non-monotonic

Accretion density split into quiescent and star-forming hosts



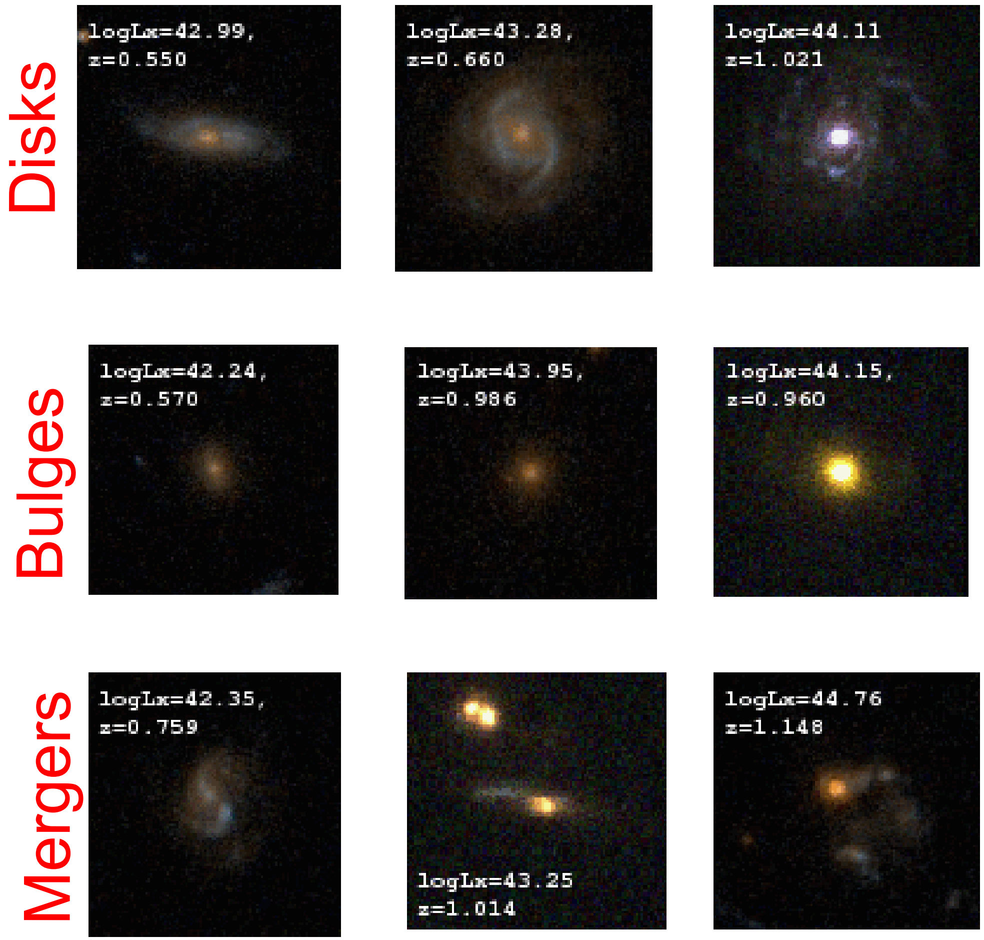
Bulk of accretion density associated with star-formation

Quiescent hosts: 15-20% of accretion density independent of redshift

Georgakakis et al., 2014, MNRAS, 440, 339

Morphology of AGN hosts at *z*~1

Georgakakis et al. 2009



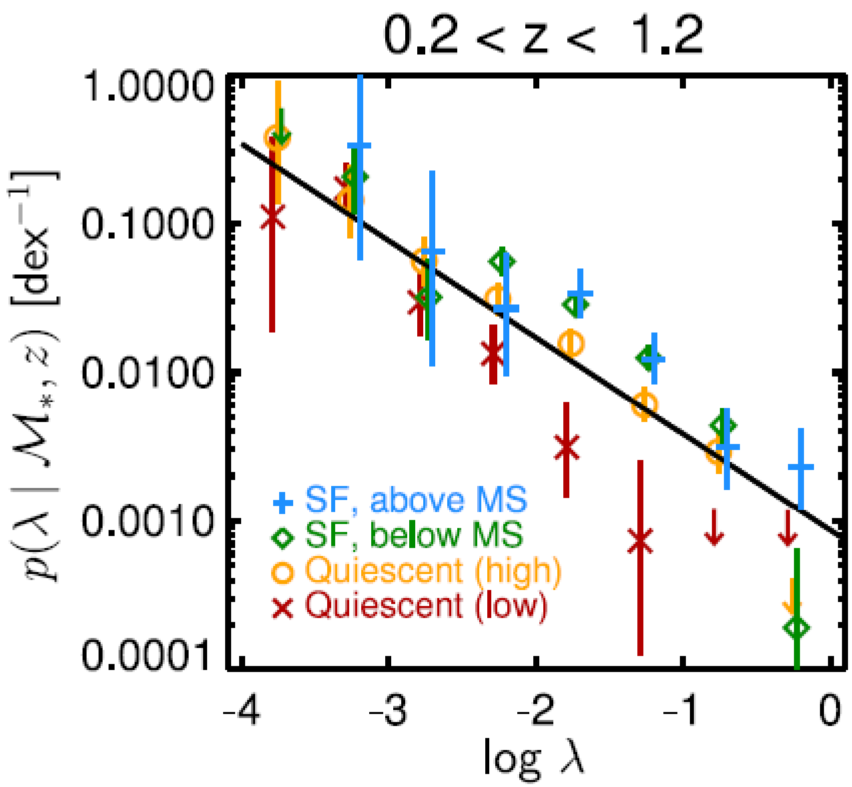
- AEGIS, CDF-North and South
- Morphological classification of AGN hosts at z~1:

↓

30% of AGN in disk galaxies (NOT mergers)

Also: Pierce+07, Cisternas+11, Kocevski+12, Villforth+14

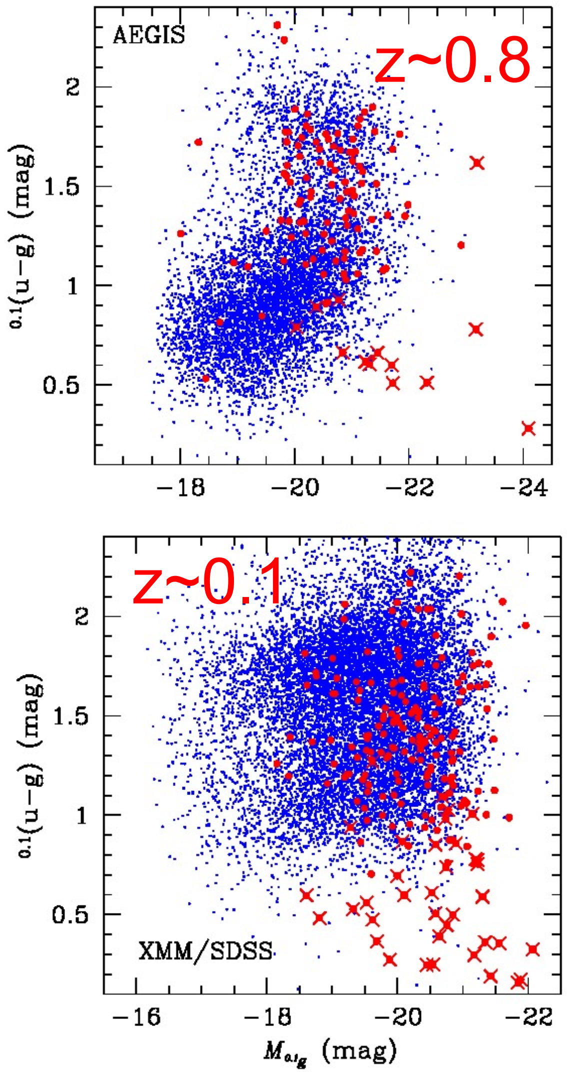
Eddington ratio distributions



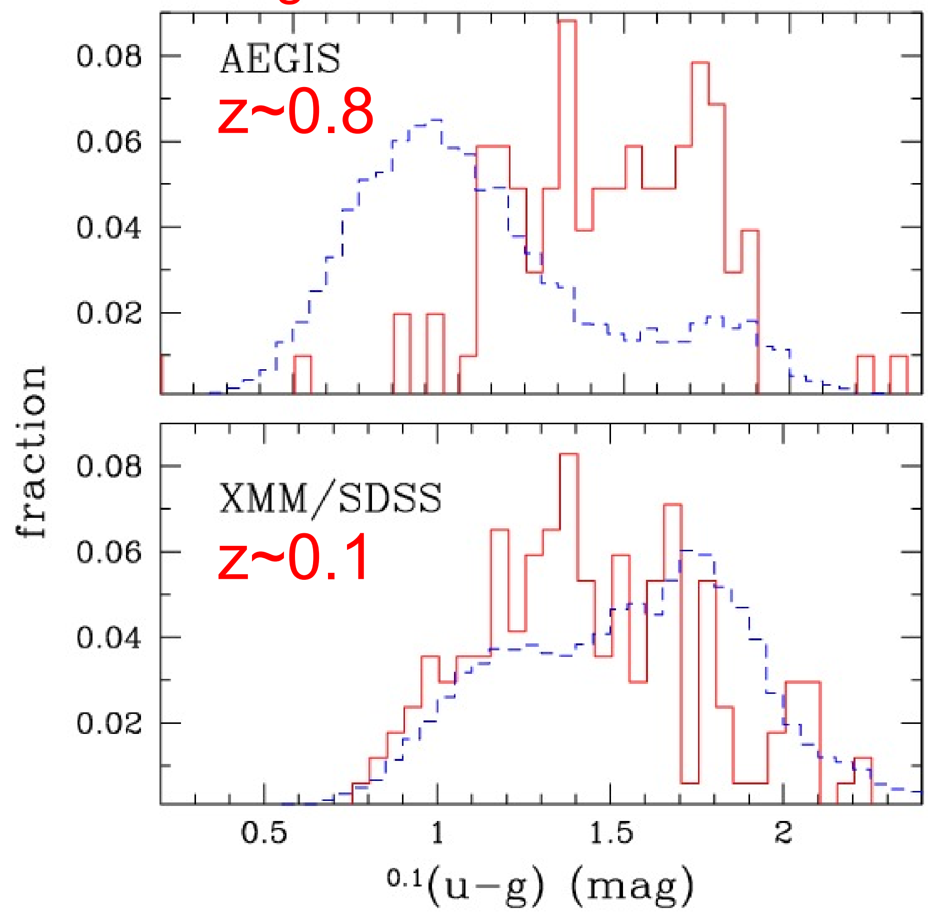
Azadi+15

- Quiescent galaxies: probability of hosting high-λ AGN lower compared to SF galaxies
- BUT, all AGN hosts PL distribution at low accretion rates.

X-ray AGN colour-magnitude diagram



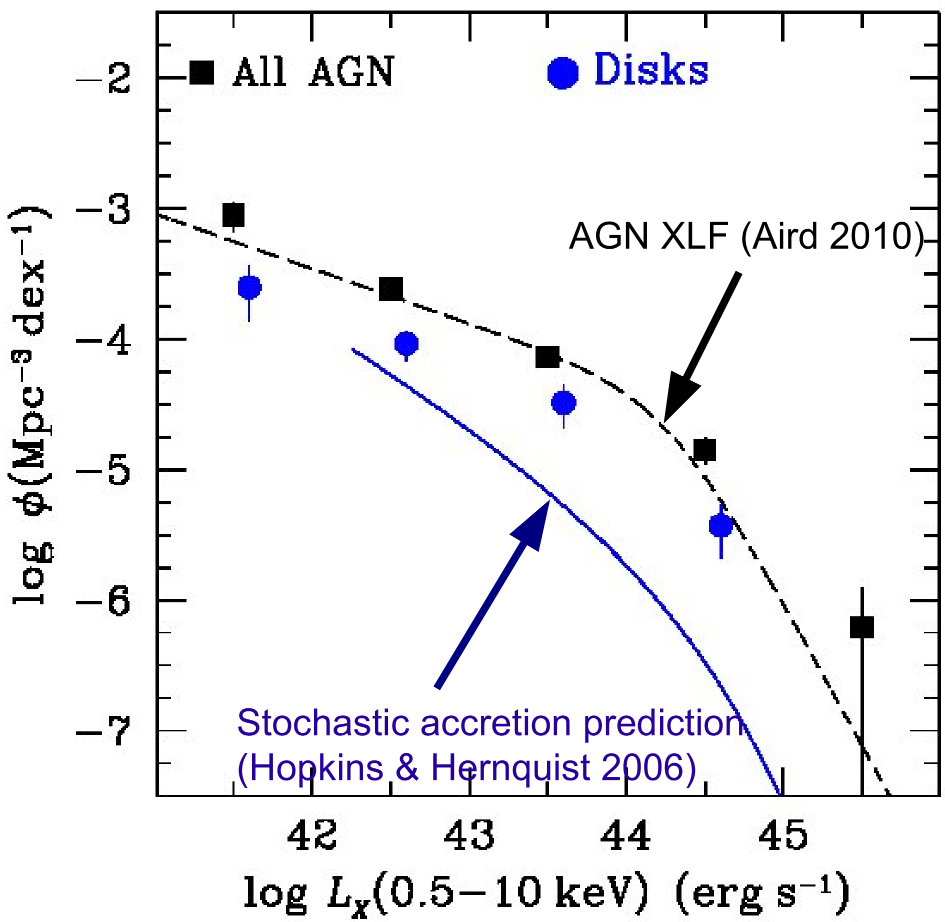
Georgakakis & Nandra 2011



Nandra+07, Silverman+09, Schawinski+09, Xue+10, Aird+12, Azadi+14

Morphology of AGN hosts at *z*~1

Georgakakis et al. 2009



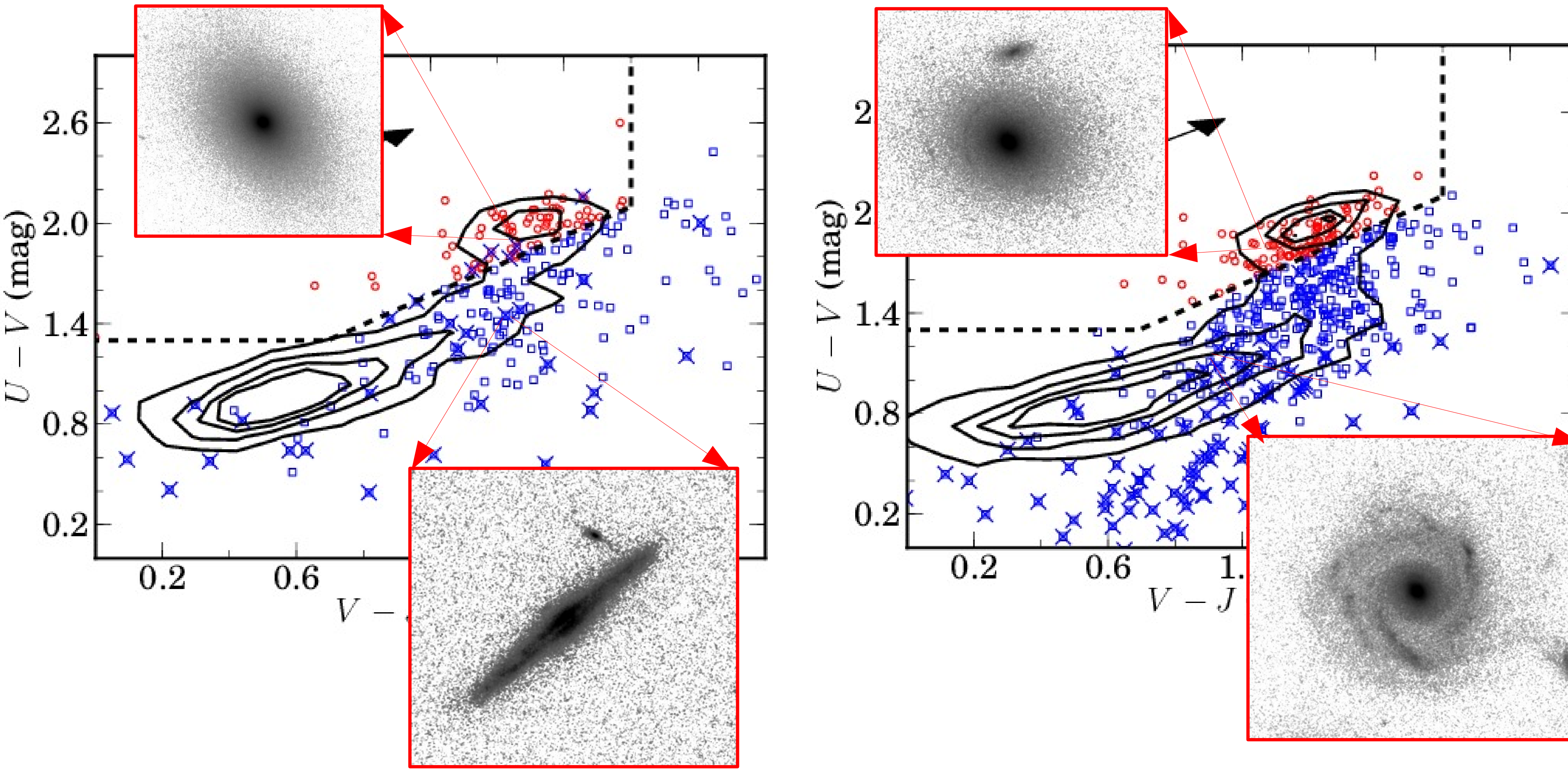
- AEGIS, CDF-North and South
- Morphological classification of AGN hosts at z~1:

BH growth due to disk instabilities is underestimated

Also: Pierce+07, Cisternas+11, Kocevski+12, Villforth+14

X-ray AGN UVJ diagram

Quiescent AGN hosts: mostly bulges



Star-forming AGN hosts: 50% disks

Georgakakis et al., 2014, MNRAS, 440, 339

Future prospects

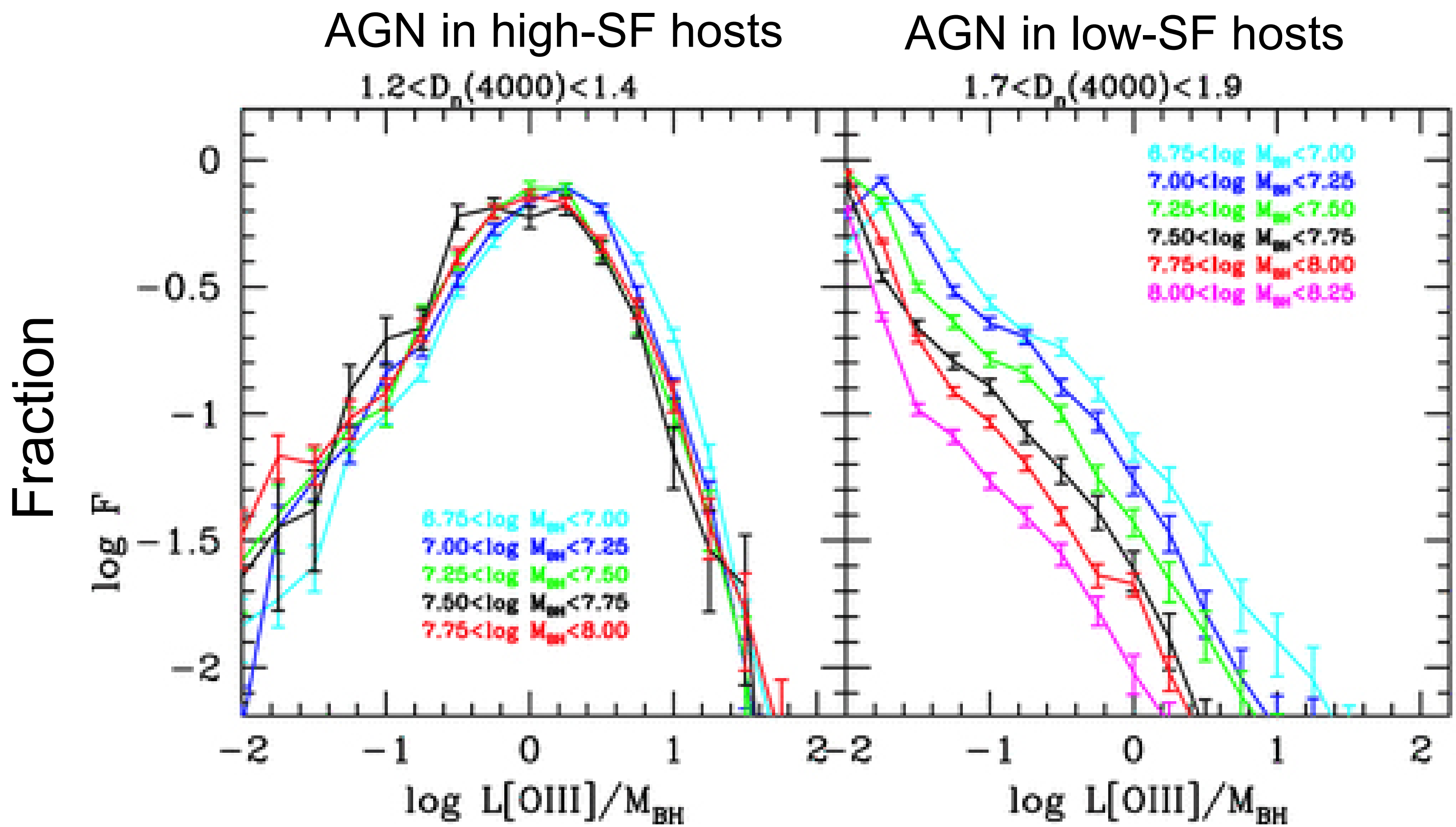
- X-ray AGN demographics and population properties are severely limited by small samples: eROSITA All Sky Survey?
- Toward the Bolometric AGN LF: combination of multi-wavelength AGN selection methods (X-ray, UV, IR)
- Eddington ratio distribution vs host galaxy properties. Apply Bayesian methods developed for LF calculation.

$$\Phi(L_X, z) = \int d\log L_X \frac{dV}{dz} dz \int d\log M_{BH}\, \varphi(M_{BH}, z)\, \lambda(L_X, M_{BH}, z)$$

$$\text{where} \quad \varphi(M_{BH}, z) \ \text{is BH mass function,}$$

$$\lambda(L_X, M_{BH}, z) \ \text{is Eddington ratio distribution}$$

Black hole fuelling modes at z=0



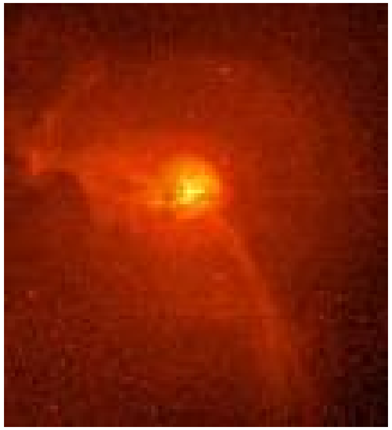
Kauffmann & Heckman 2009

But not at z~1 (Aird+12, Bongiorno+12, Azadi+14)

AGN fueling/triggering modes: population properties of X-ray AGN host galaxies

Disk instabilities

Cold gas accretion
low mass BHs, high *M*dot
spiral morphology
young stars
low density regions



Radio mode accretion

Hot gas accretion
Massive BHs, low *M*dot
Massive ellipticals
evolved stars
high density regions

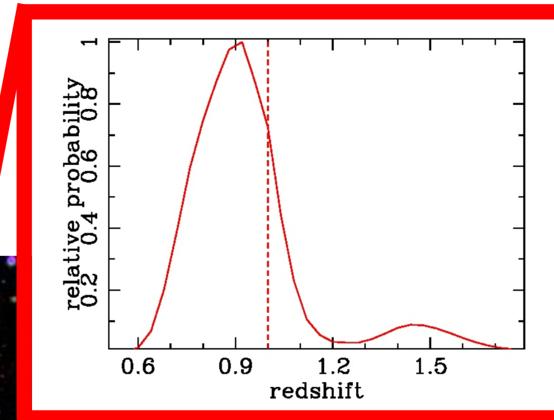
Major mergers

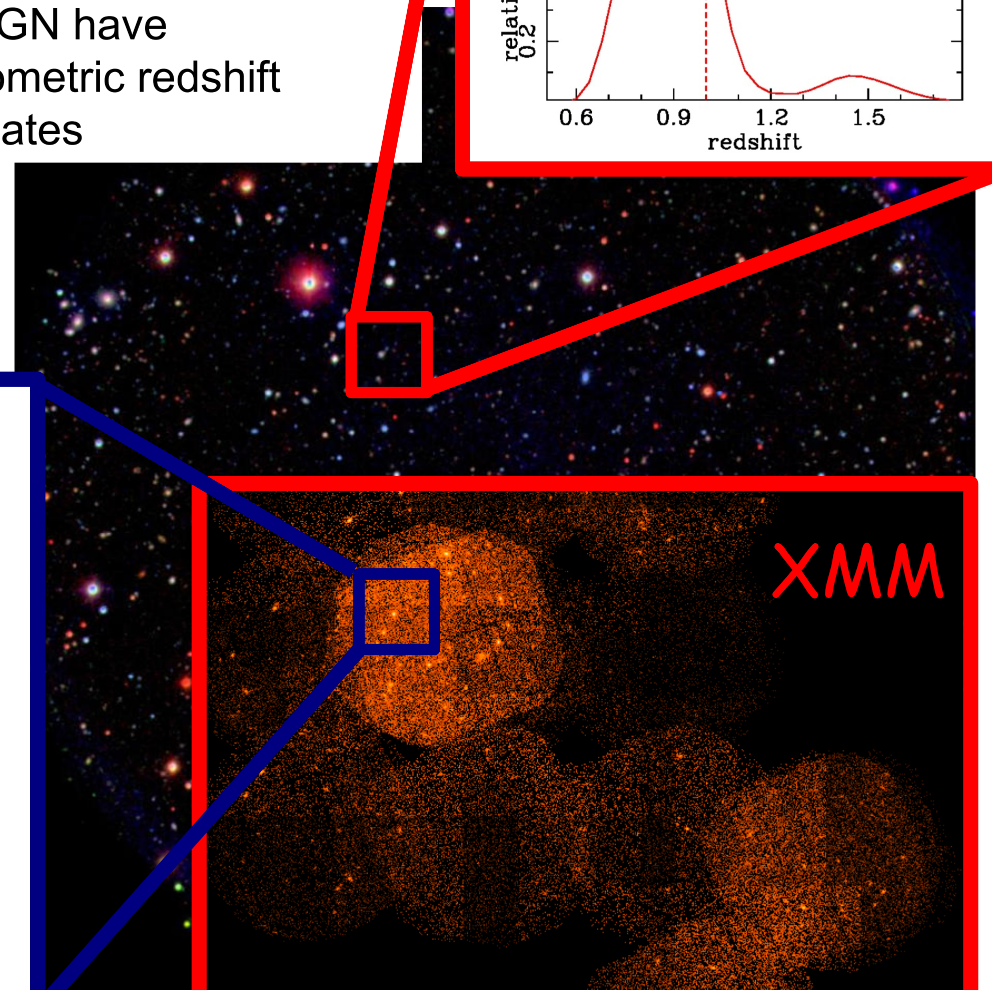
cold gas accretion
disturbed morphology
ongoing star-formation
Moderate density regions

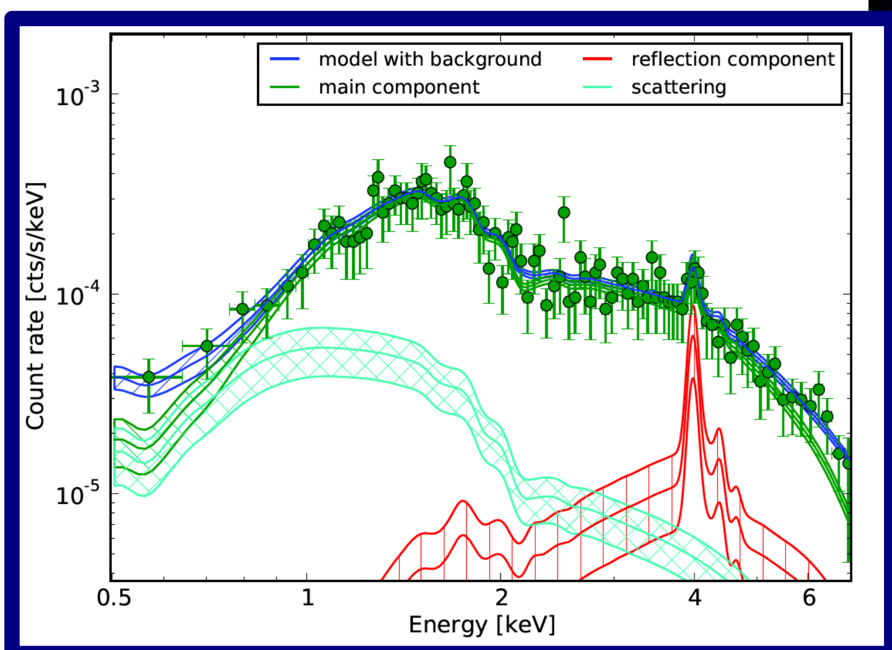
X-ray survey data: observational challenges

Poisson nature of X-ray spectra: derived quantities (N_H, L_X) have complex and correlated uncertainties

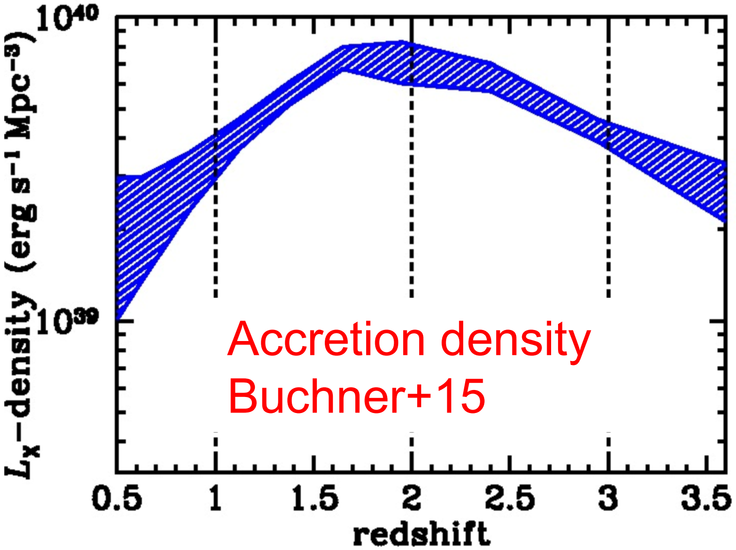
Typically ~50% of the X-ray AGN have photometric redshift estimates

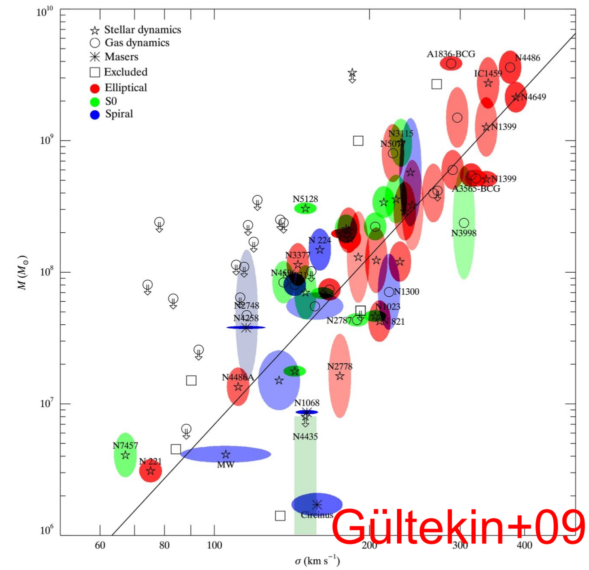


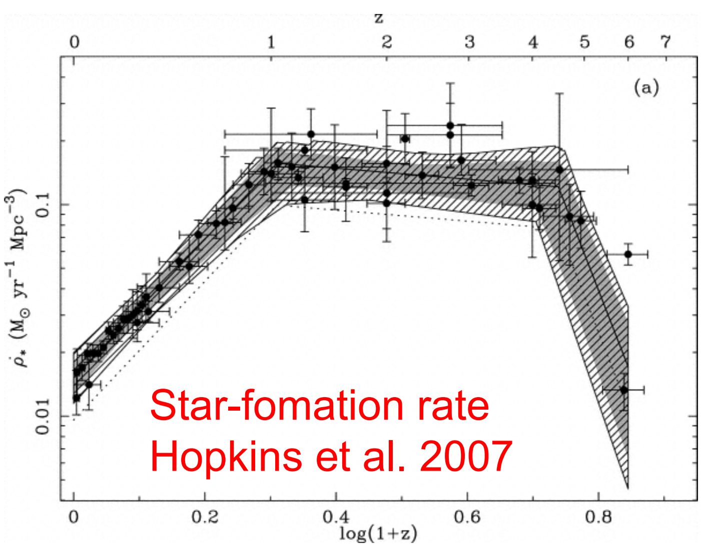


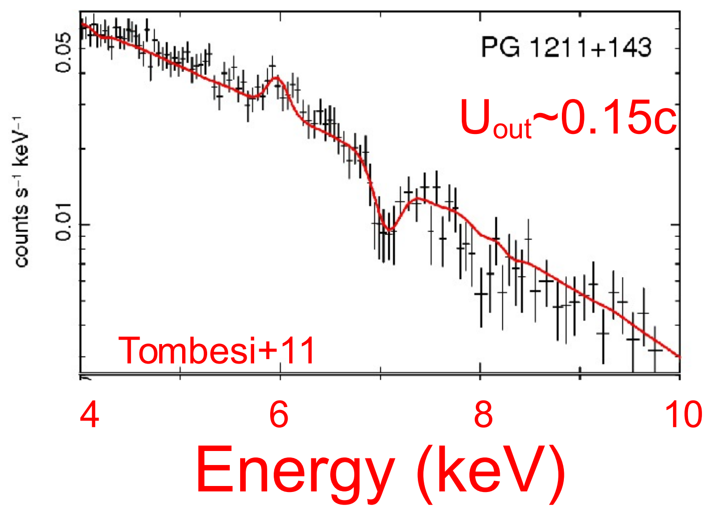


Relevance of AGN activity to the evolution of galaxies

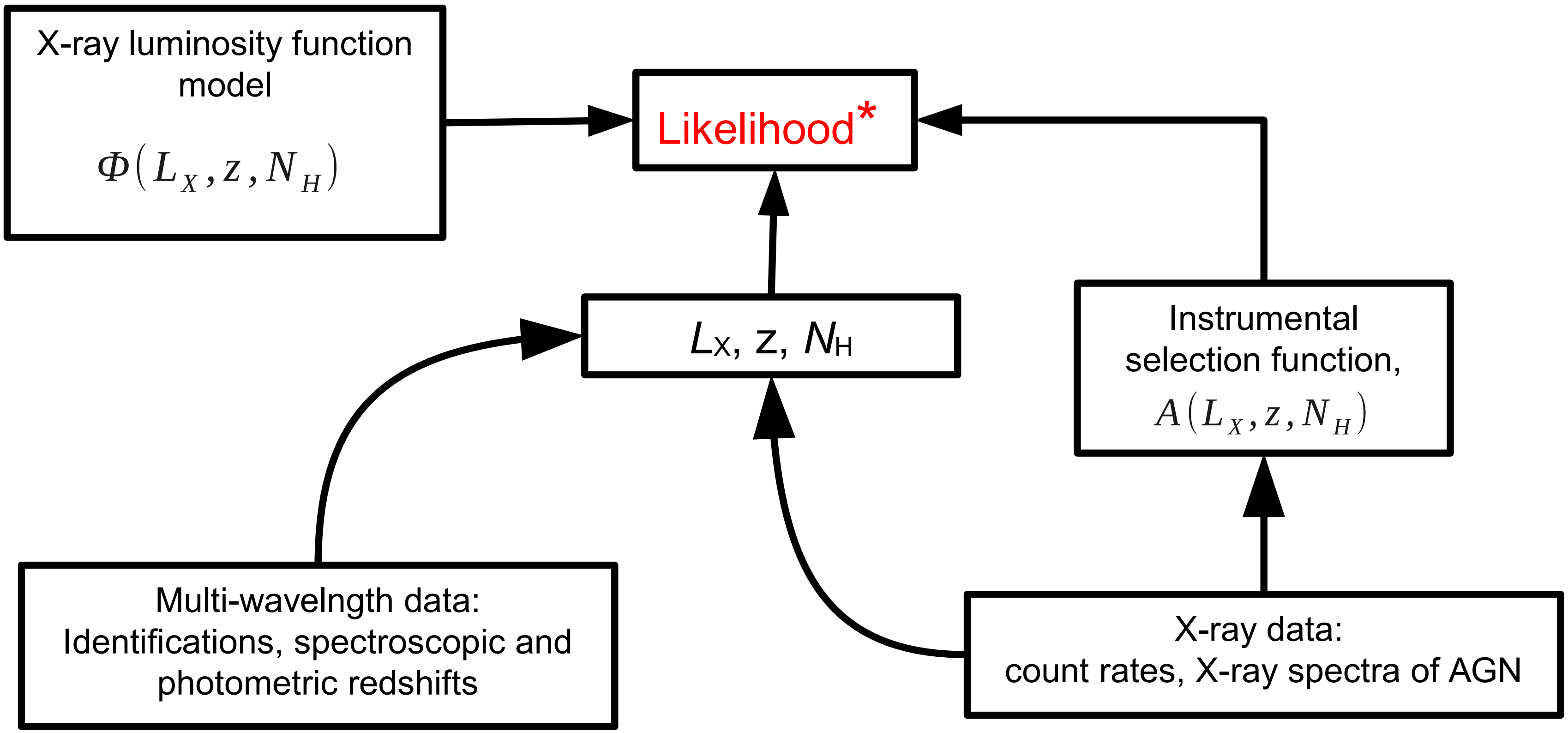








Modeling the X-ray luminosity function



$$* \quad \log(Likelihood) = -\lambda + \sum_i \int \Phi(L_X, z, N_H) \frac{dV}{dz} \, dz \, d\log L_X \, d\log N_H,$$

$$where \quad \lambda = \int A(L_X, z, N_H) \, \Phi(L_X, z, N_H) \frac{dV}{dz} \, dz \, d\log L_X \, d\log N_H,$$

$$A(L_X, z, N_H) \quad selection \quad function$$