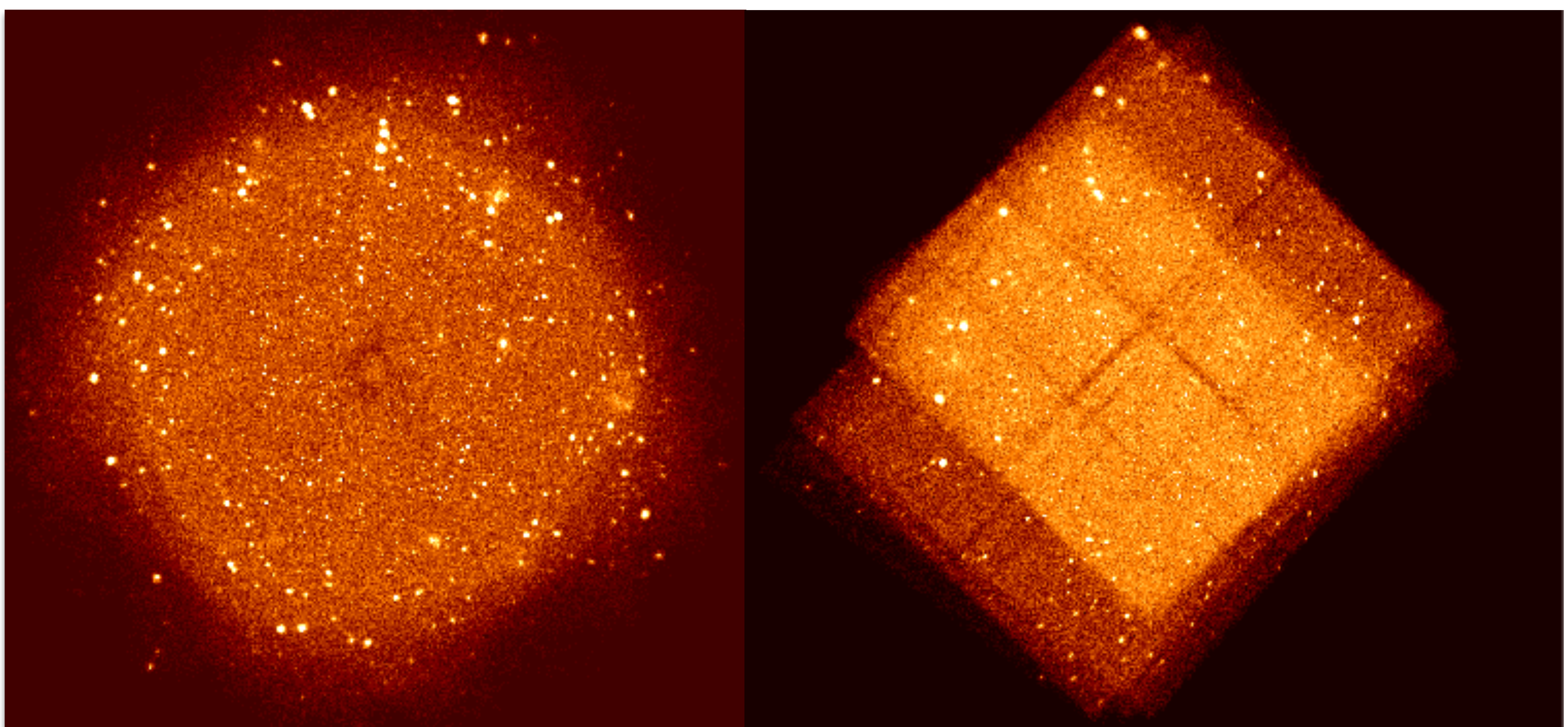
# The $z > 3$ AGN population in the Chandra Deep Fields

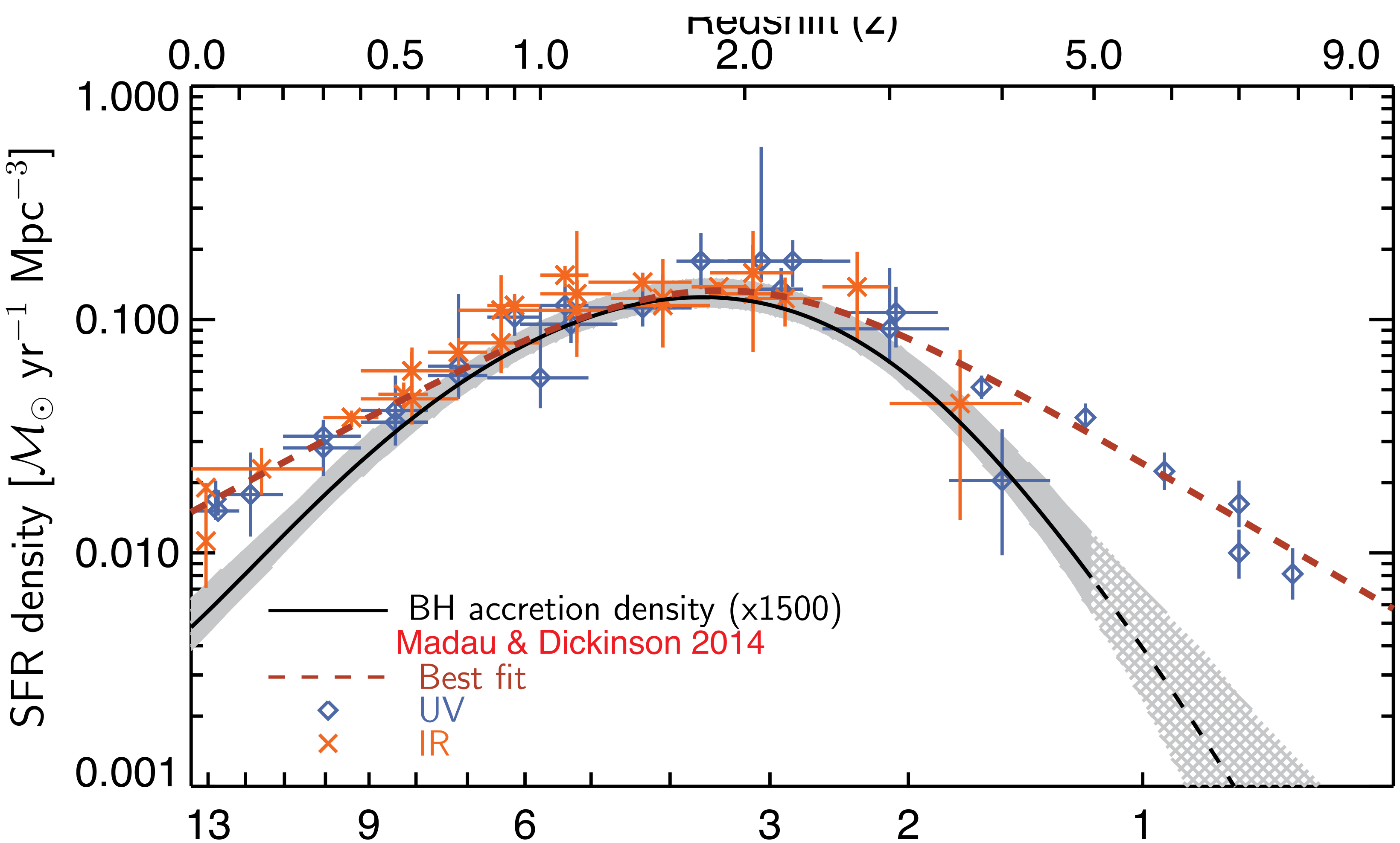

**Fabio Vito**

**Penn State University**

*in collaboration with* W.N. Brandt, G. Yang, R. Gilli, B. Luo, C. Vignali, and the CDF-S Team

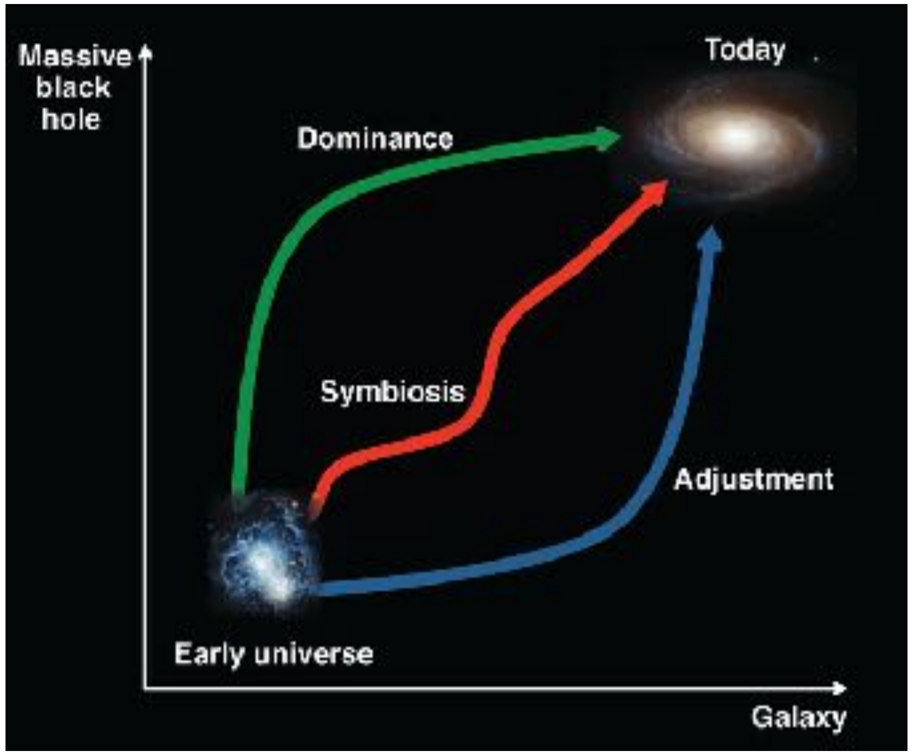
# BH and galaxies co-evolve




Aird+2015

- SFRD and BHAD track each other
- $M_{BH}$ vs $M_{bulge}$ relation
- Downsizing

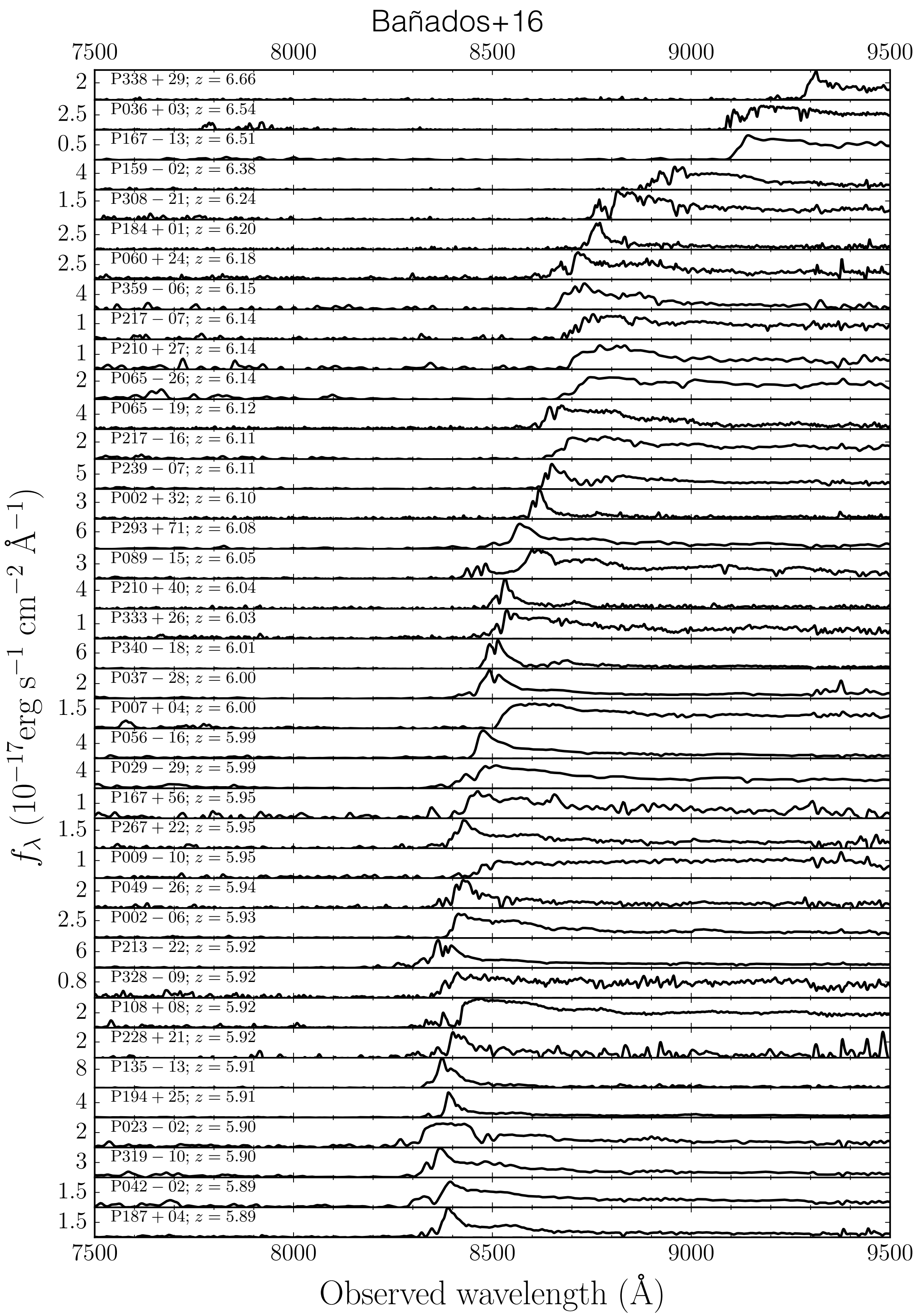
Volonteri+12




Do these relations hold at high redshift?
And how are they established?

e.g. "overmassive" high-M BH (e.g. Walter+04, Wang+13, Barnett+15), "undermassive" low-M BH (from simulations, e.g. Habouzit+16)?

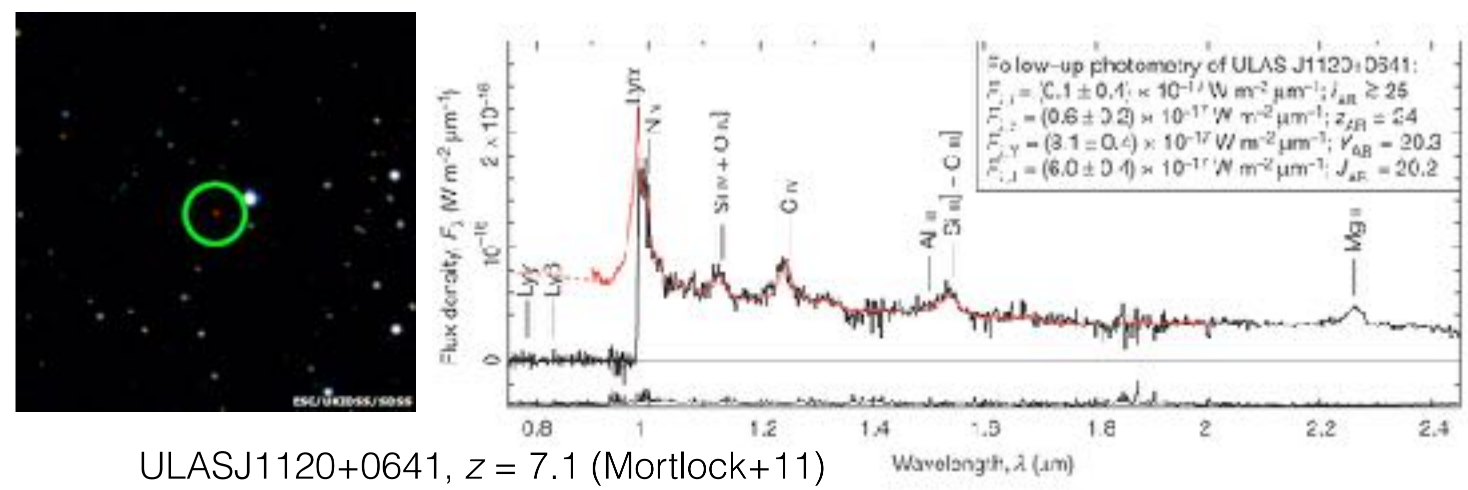
# High-z QSOs




~90 QSOs known at $z$ >6

(SDSS, CFHTQS, PSO, ULAS, ATLAS, VIKING, DES)

with $M_{1450}$≲-25



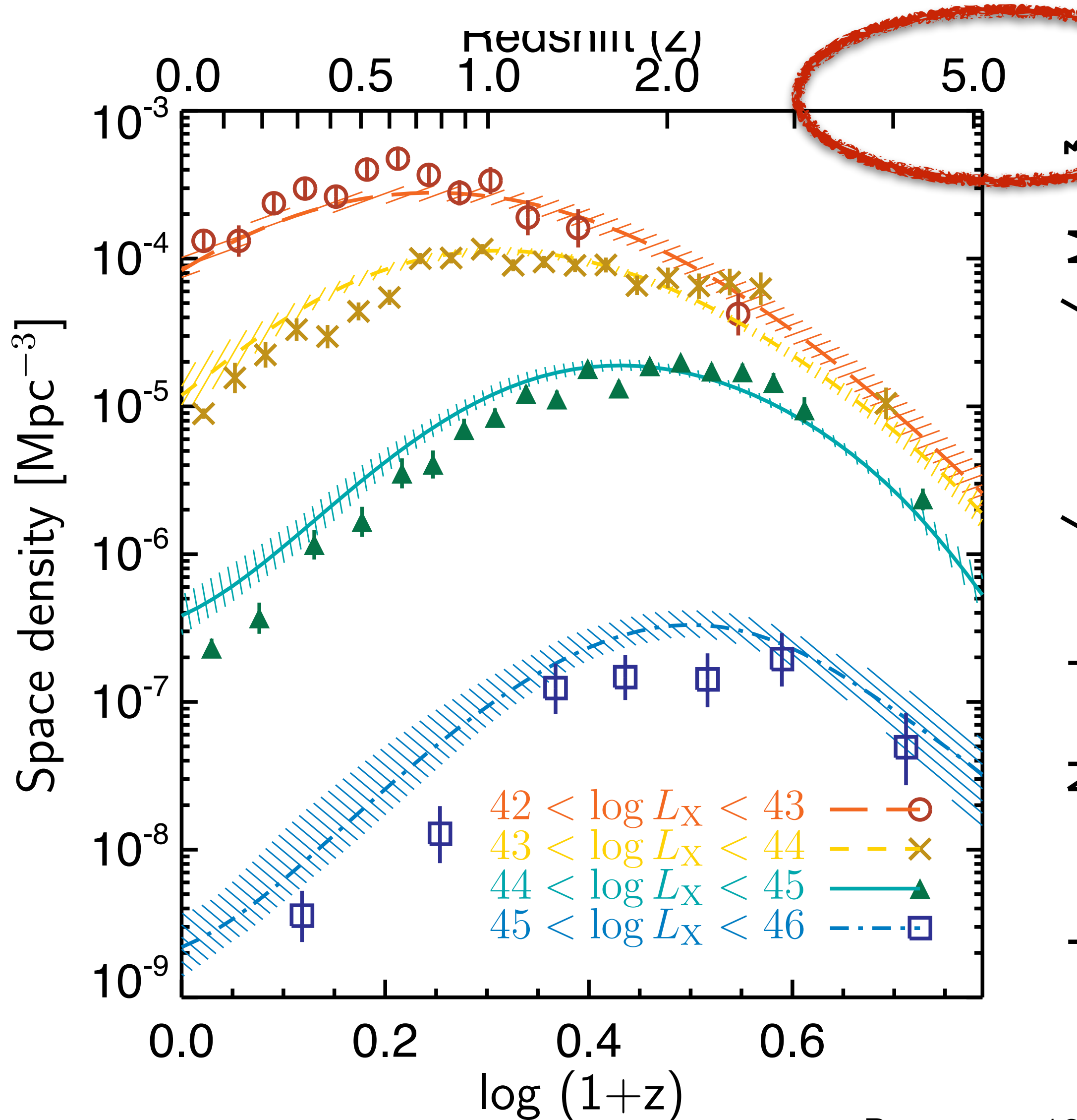

ULASJ1120+0641, $z$ = 7.1 (Mortlock+11)

…but they are the extreme tail

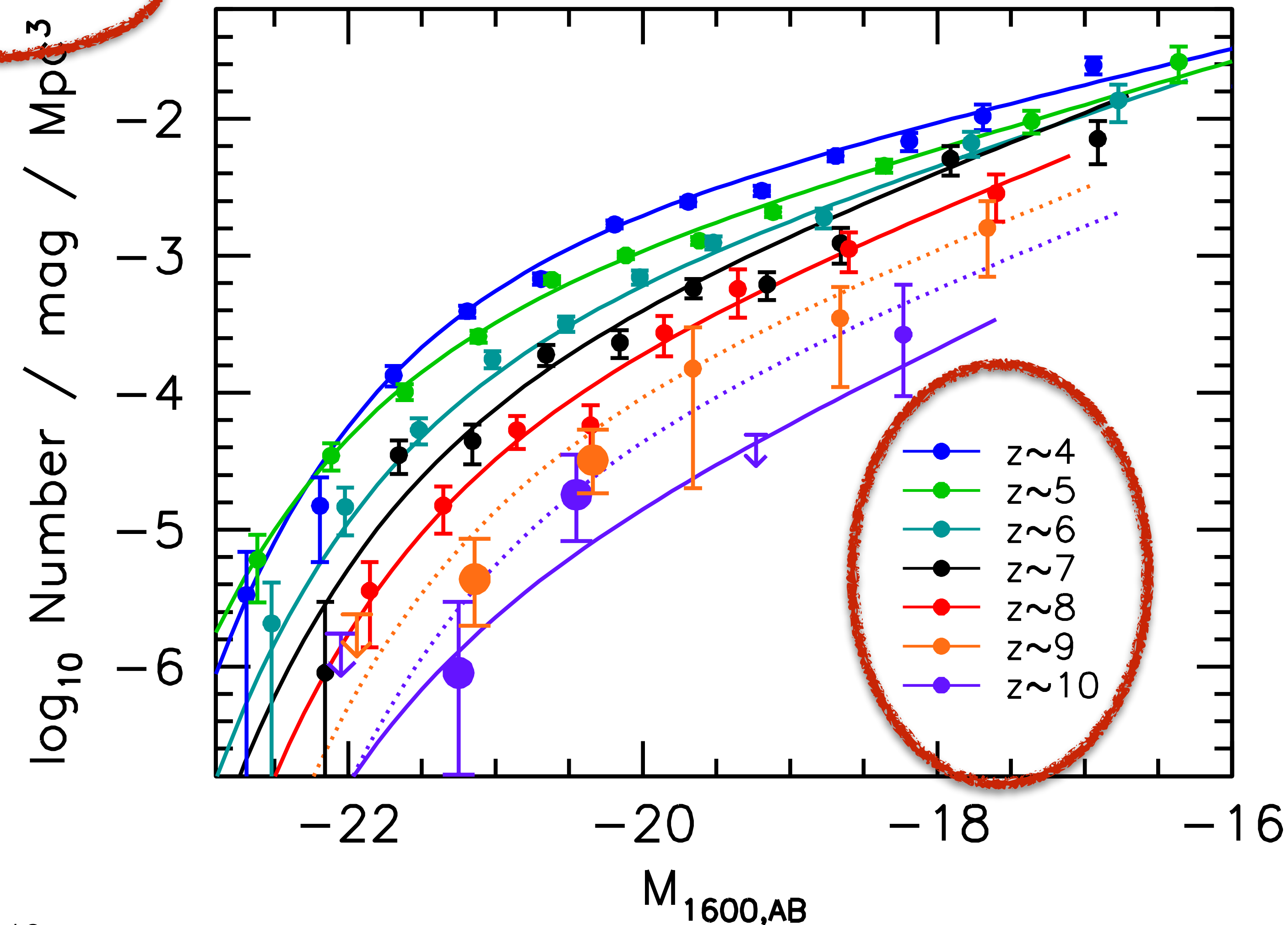
($M_{BH}$=1-10 x$10^9$ M⊙, e.g. Wu+15)

of the underlying population.

# Galaxy vs. AGN luminosity functions




Bouwens+16



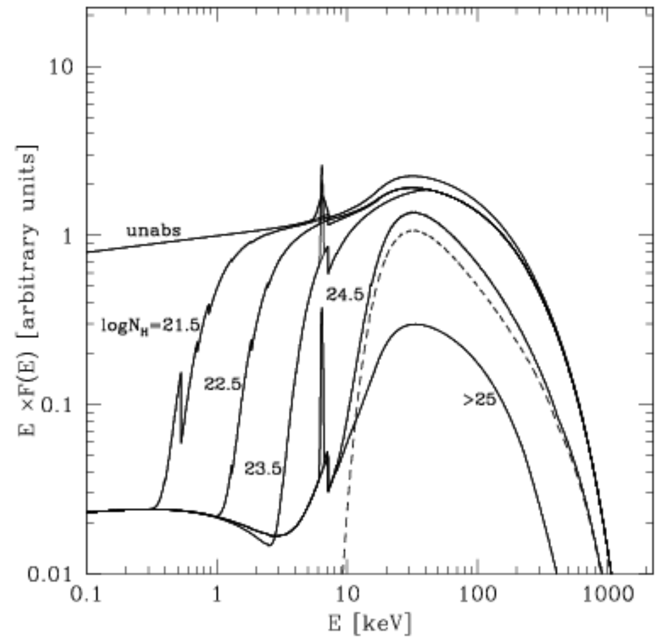

Aird+15

Need to improve our knowledge of AGN at high-z/low-L!

# Why X-rays?

1) Ubiquitous in AGN

2) Obscuration



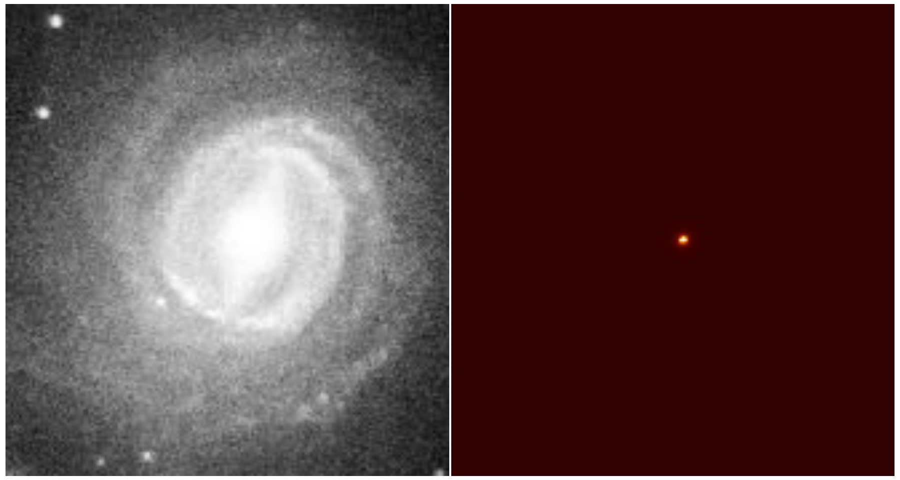

Gilli+07

3) Galaxy dilution

Brandt & Alexander 2015

NGC 3783

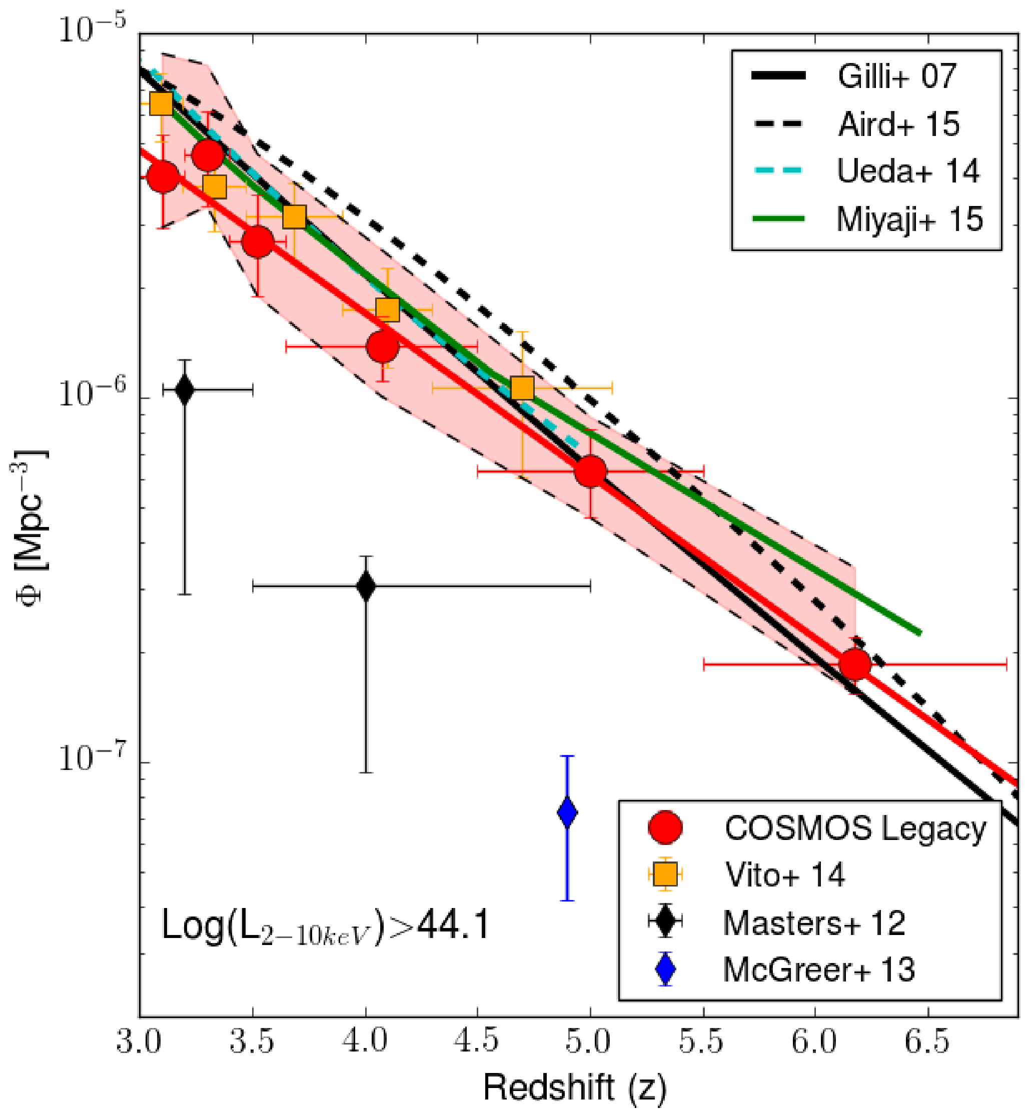
optical X-ray



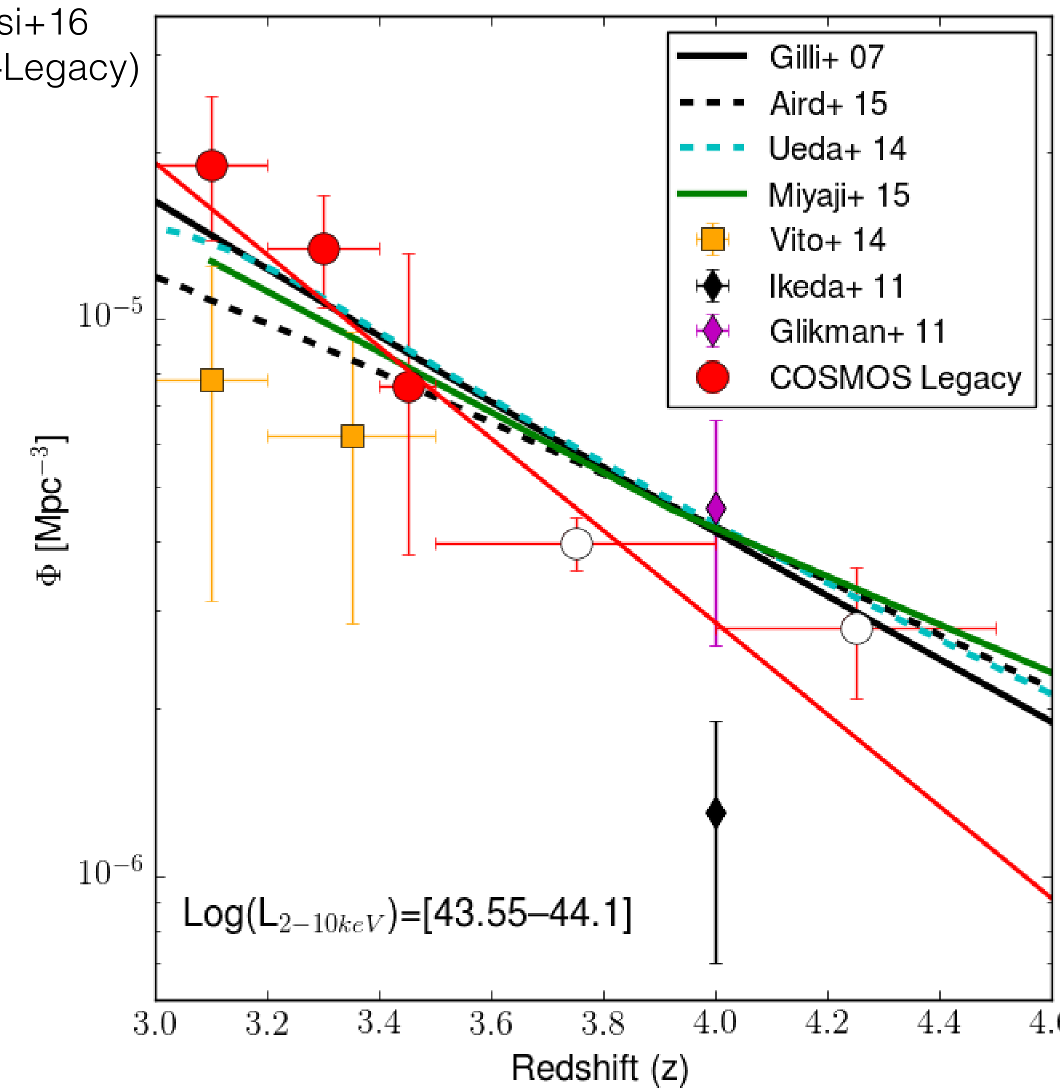
**Clean and less biased selection (especially at high-z)!**

But optical/IR data needed for identification

# High-z (3<*z*<5) AGN in X-ray surveys: space density evolution




Marchesi+16
(COSMOS-Legacy)

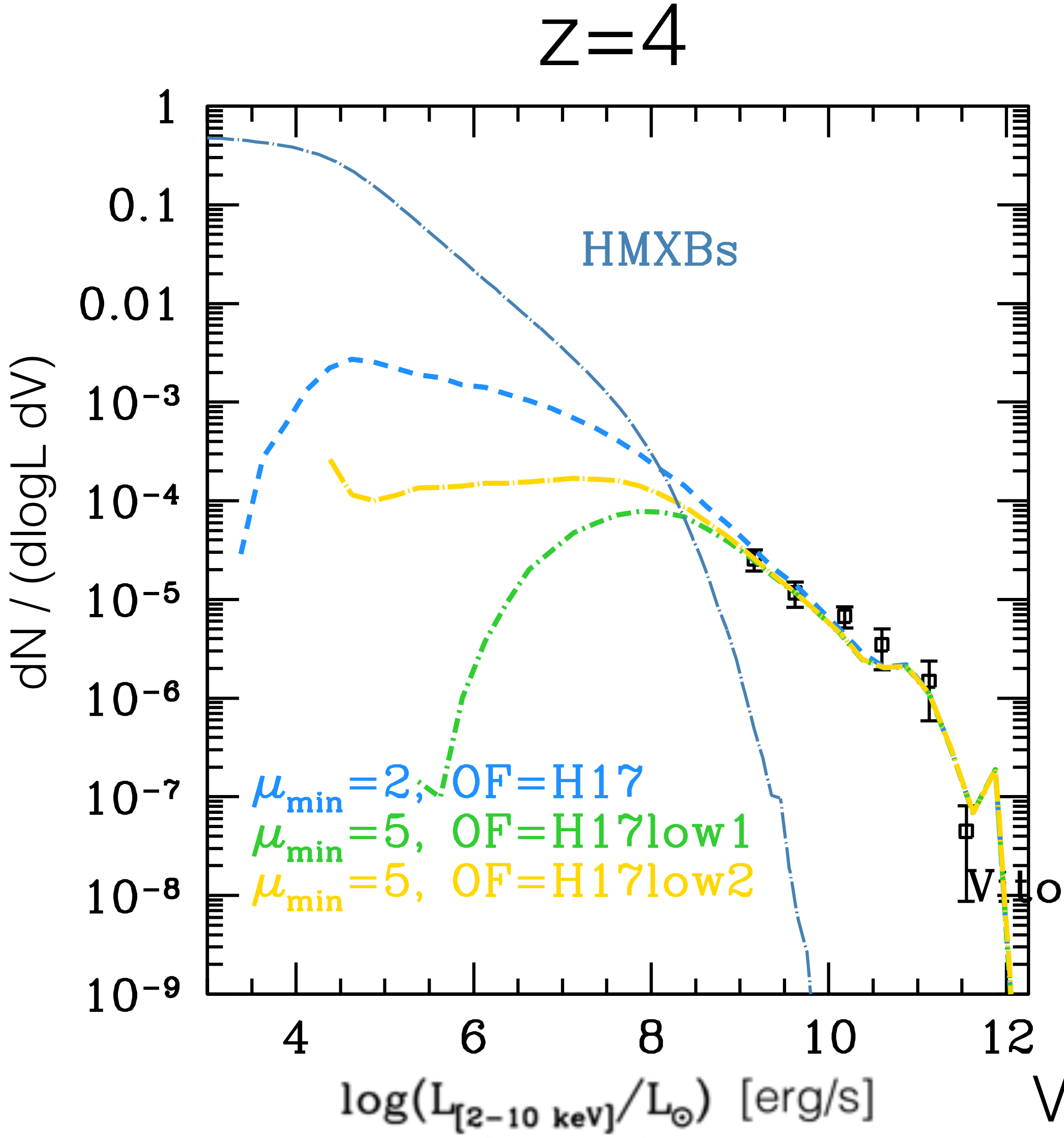



For L≳L$_*$, log$\boldsymbol{\Phi}$ declines as $(1+z)^{-6}$, similarly to optical QSOs (e.g. McGreer+13). At lower luminosities, uncertain evolution.

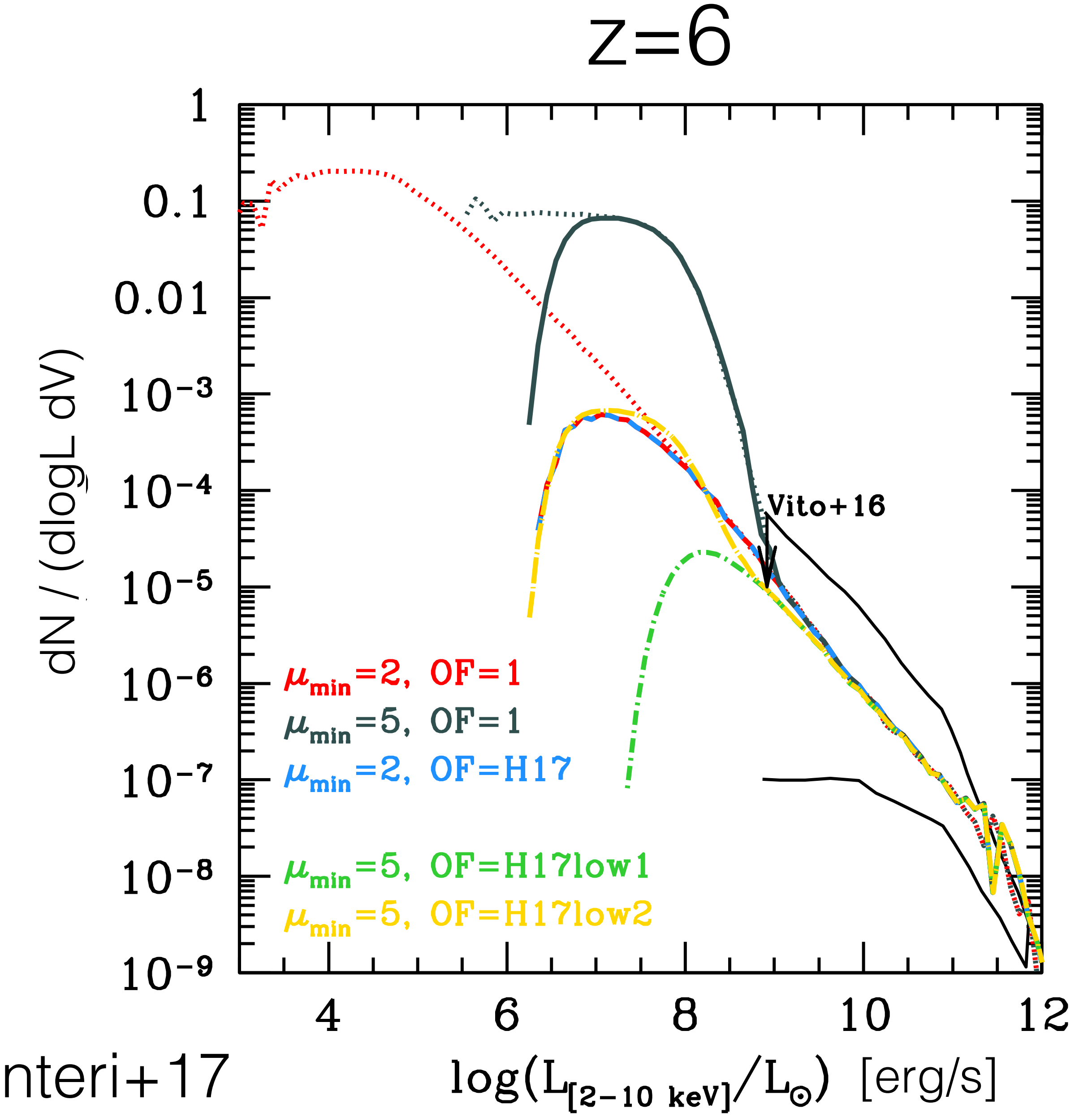
(e.g. Brusa+09, Civano+11, Hiroi+12, Vito+13, Kalfountzou+14, Vito+14, Marchesi+16)

# High-z (3<z<5) AGN in X-ray surveys: faint end of XLF

WHY CARE?



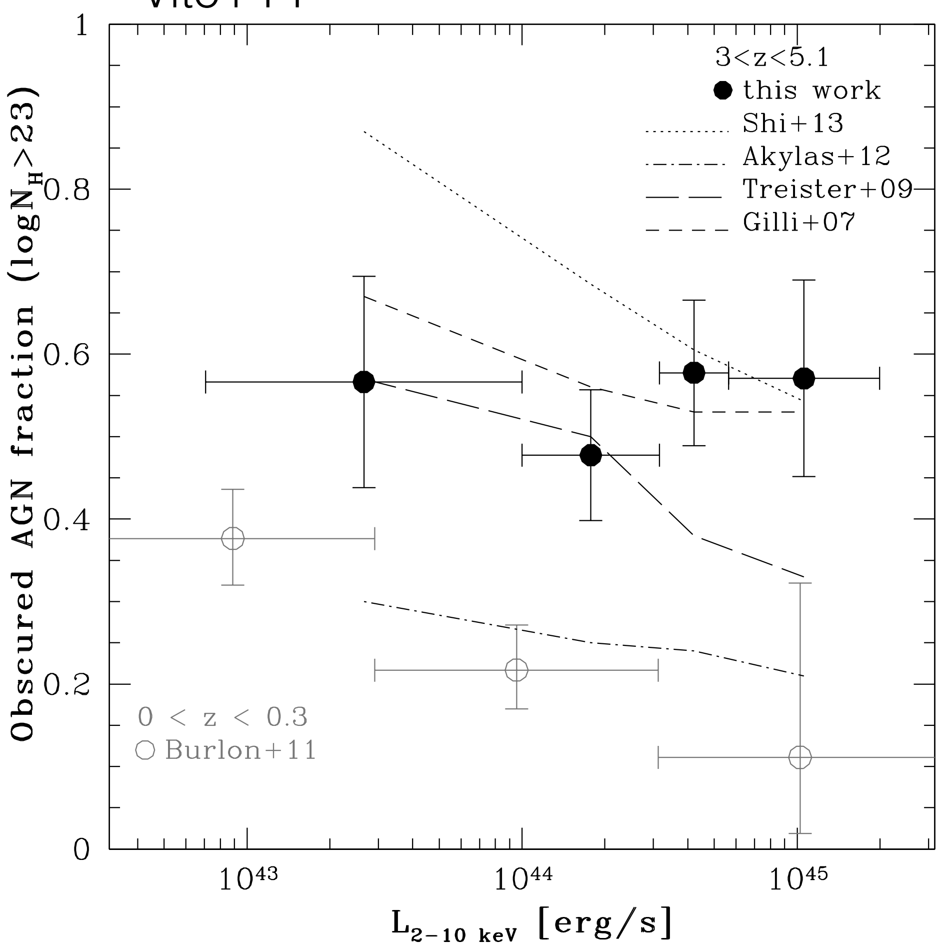

Volonteri+17




Different combinations of the physical parameters driving the formation and growth of BH seeds (e.g. seed mass, occupation fraction, Eddington ratio distribution, etc.) produce different shapes of the AGN XLF faint end!

# High-z (3<z<5) AGN in X-ray surveys: obscured AGN fraction

Vito+14

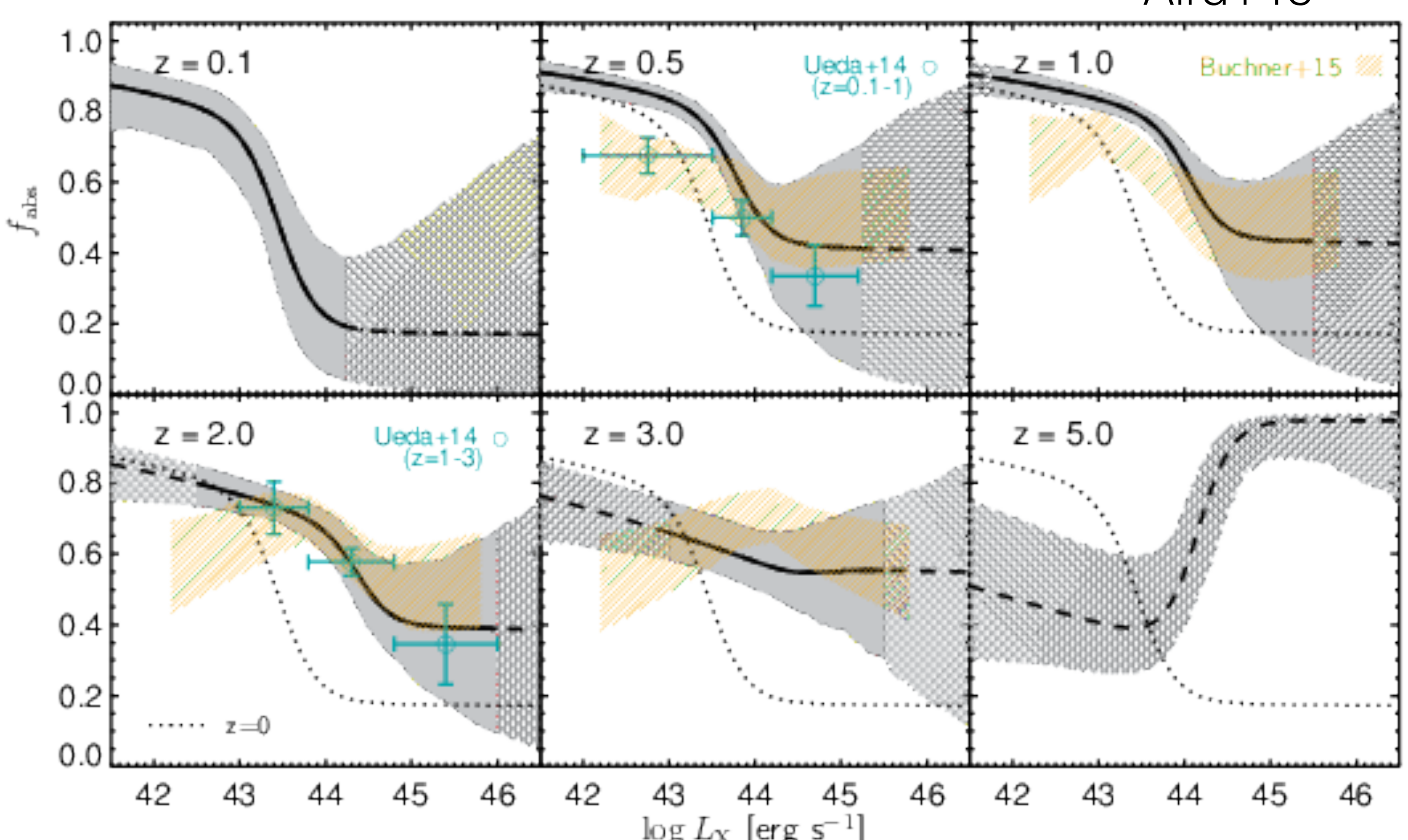



$F_{obs}$ at high-L evolves strongly from low-z to z>3

↓

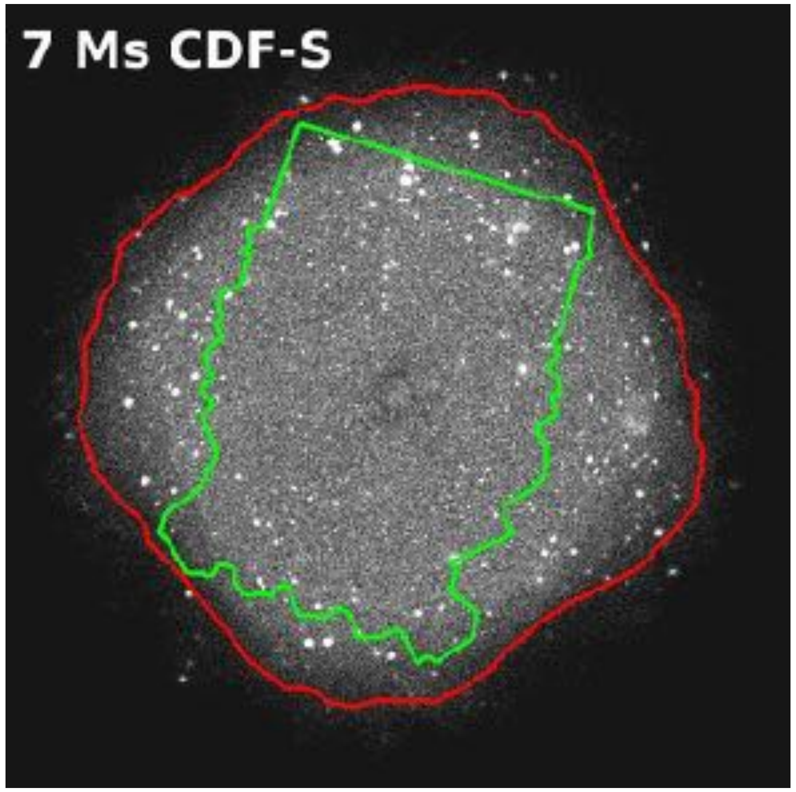
Larger covering angles and/or longer obscured phases due to, e.g., larger gas reservoirs, higher merger rate?

Aird+15



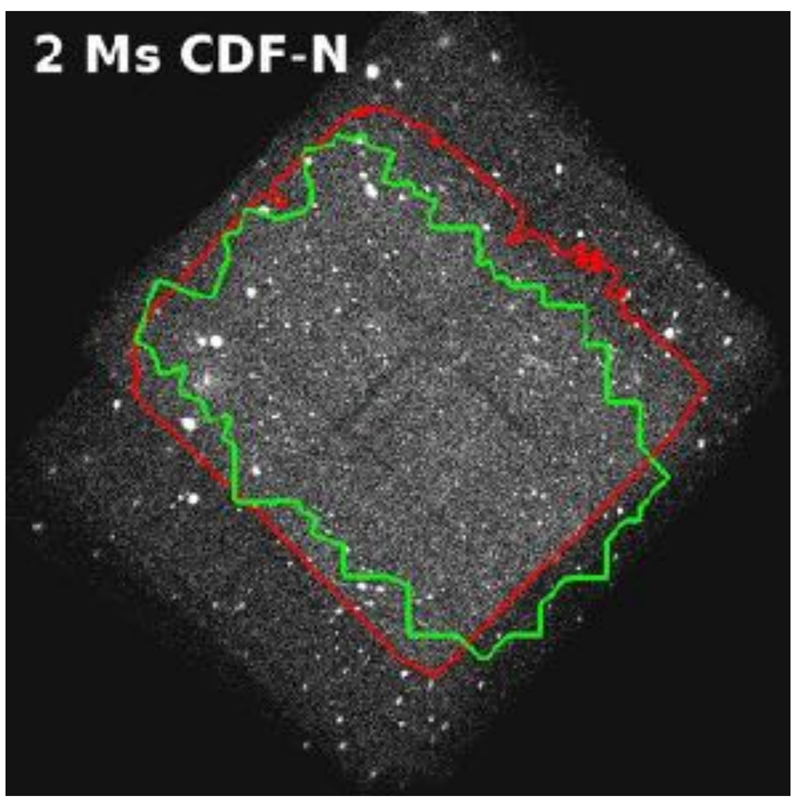

Does the anti-correlation invert at high-z?

# The data-set




## 7 Ms CDF-S (Luo+17)

- **Deepest X-ray survey to date!** $F_{lim}$~6.4 x $10^{-18}$ erg $cm^{-2}$ $s^{-1}$
- A~484 $arcmin^2$
- **Deep radio-UV coverage** (e.g. CANDELS/GOODS-S)
- 1008 X-ray sources
- **~98.5% multi-wavelength identification,**
- **~98% redshift** (~65% spec-z, phot-z from Straatman+16, Santini+15, Hsu+14, Skelton+14, etc.)

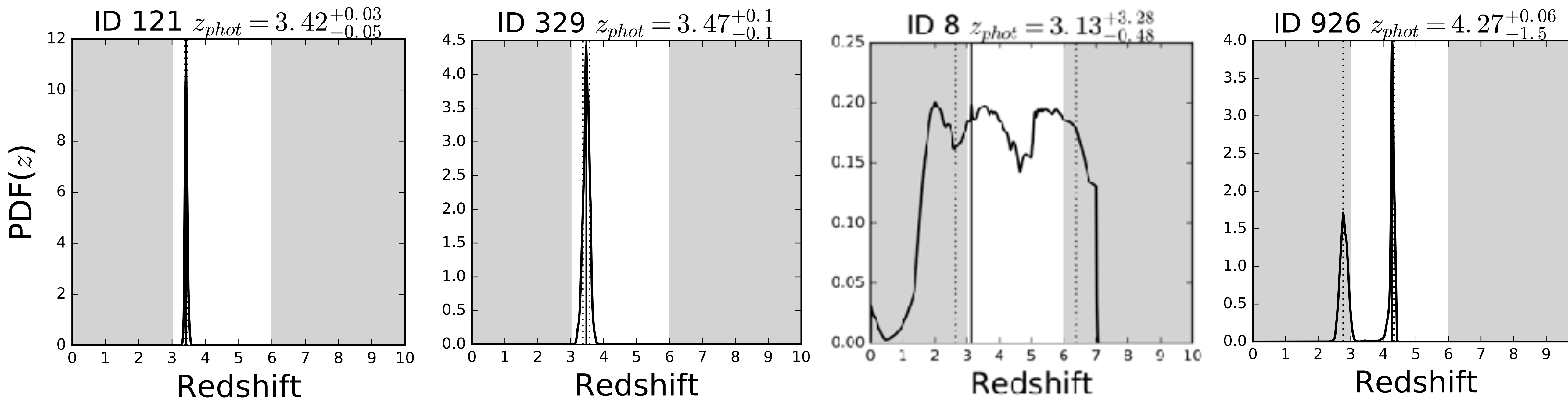


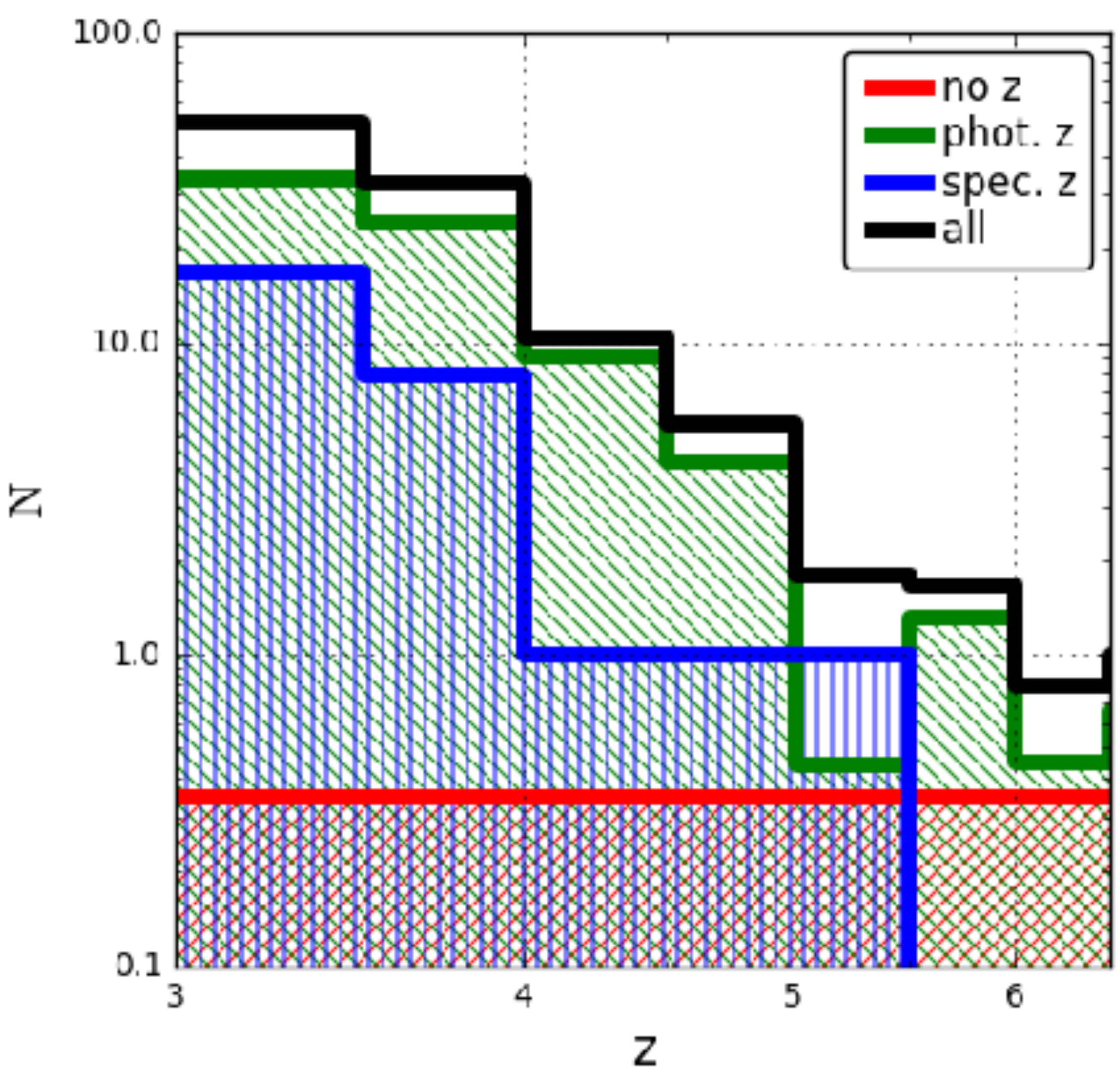

## 2 Ms CDF-N (Xue+16)

- **Second deepest X-ray survey to date!** $F_{lim}$~1.2 x $10^{-17}$ erg $cm^{-2}$ $s^{-1}$
- A~447 $arcmin^2$
- **Deep radio-UV coverage** (e.g. CANDELS/GOODS-N)
- 683 X-ray sources
- **~98% multi-wavelength identification,**
- **>93% redshift** (>50% spec-z, phot-z from Yang+14, Skelton+14, Kodra+ in prep.)

We used only areas (330+215 $arcmin^2$) with >1Ms Chandra exposure

# Redshift distribution




101.6 sources at 3≤z<6

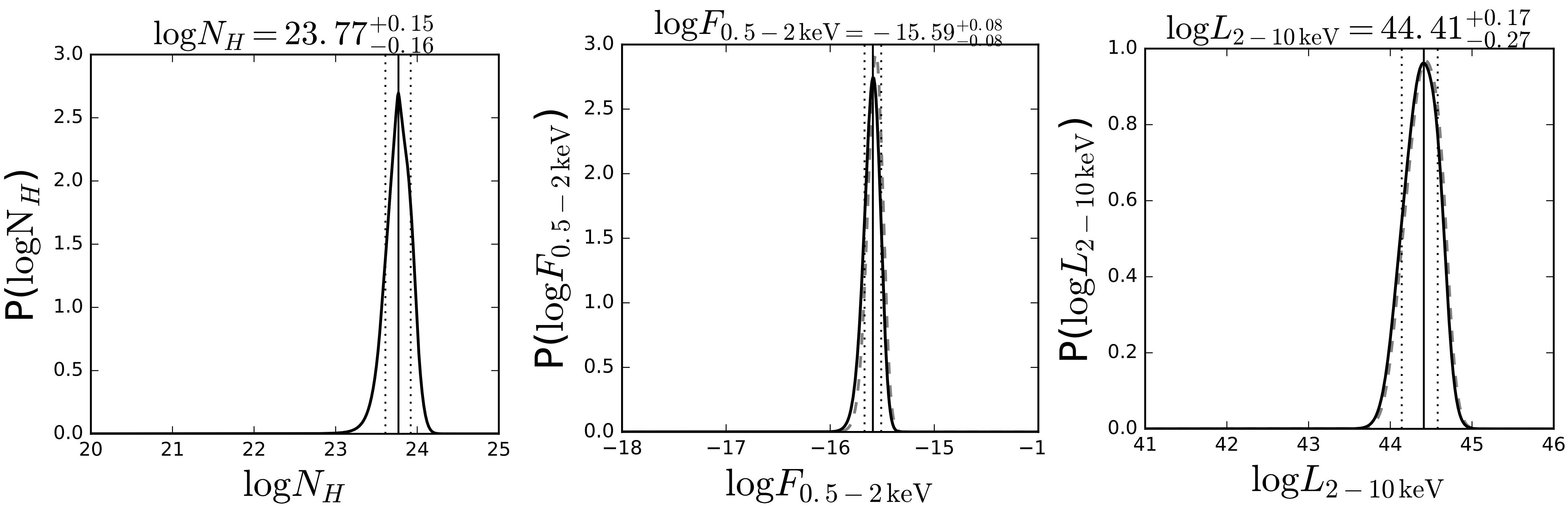
~30% spec. z
(spectroscopic fraction can be increased with future JWST/ELT/ALMA)

# Parameter distributions

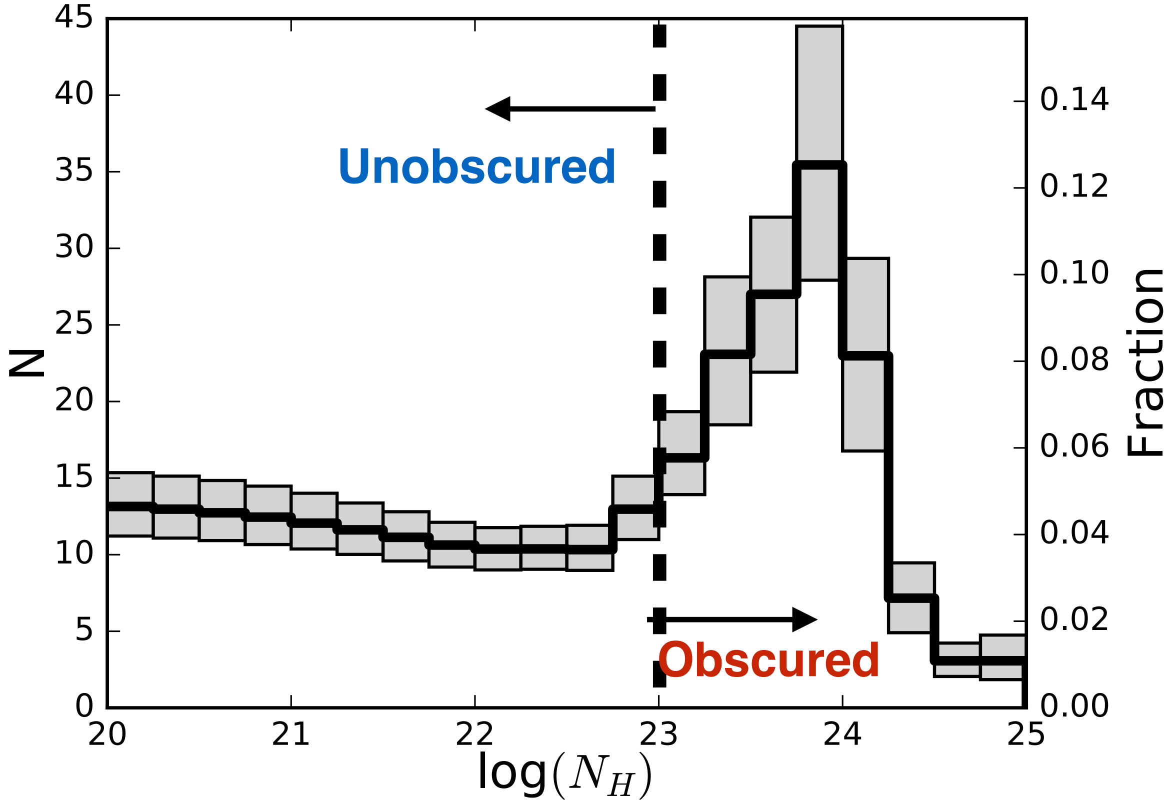
Spectral analysis
(absorbed power-law
with **Γ**=1.8)

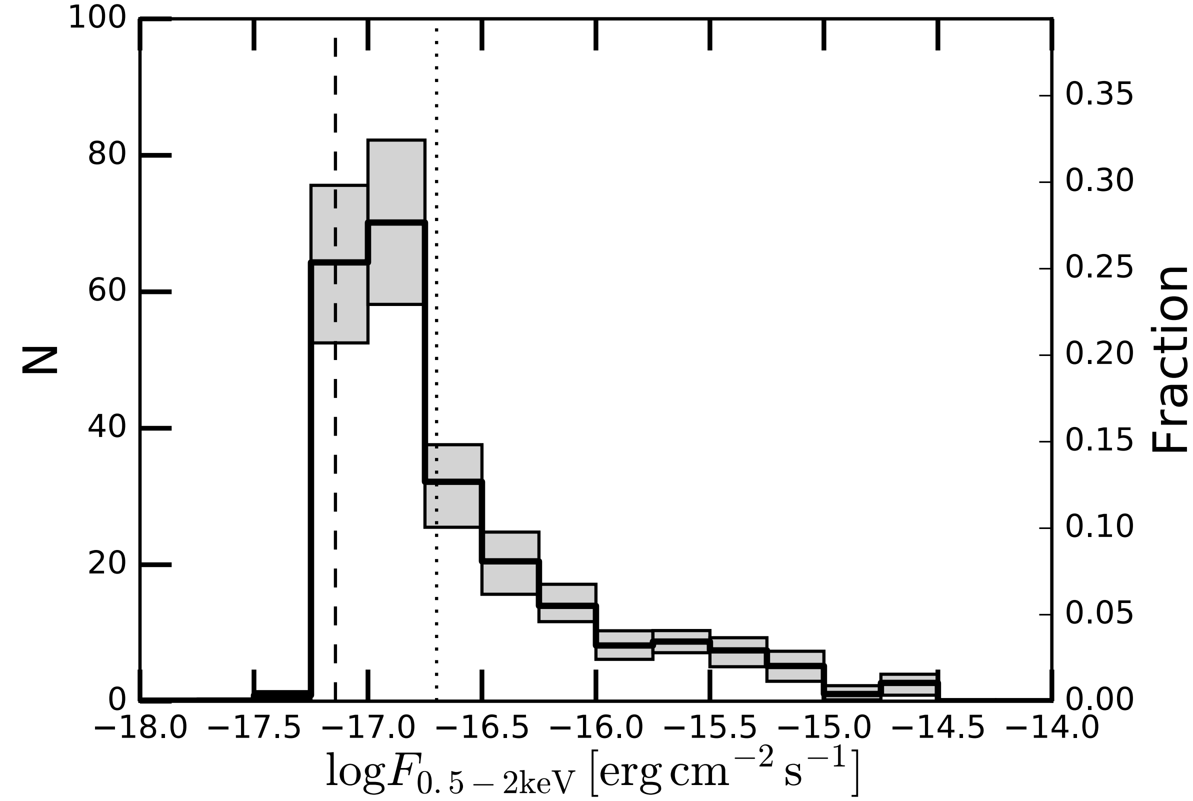
\+

Eddington bias correction



# Parameter distributions

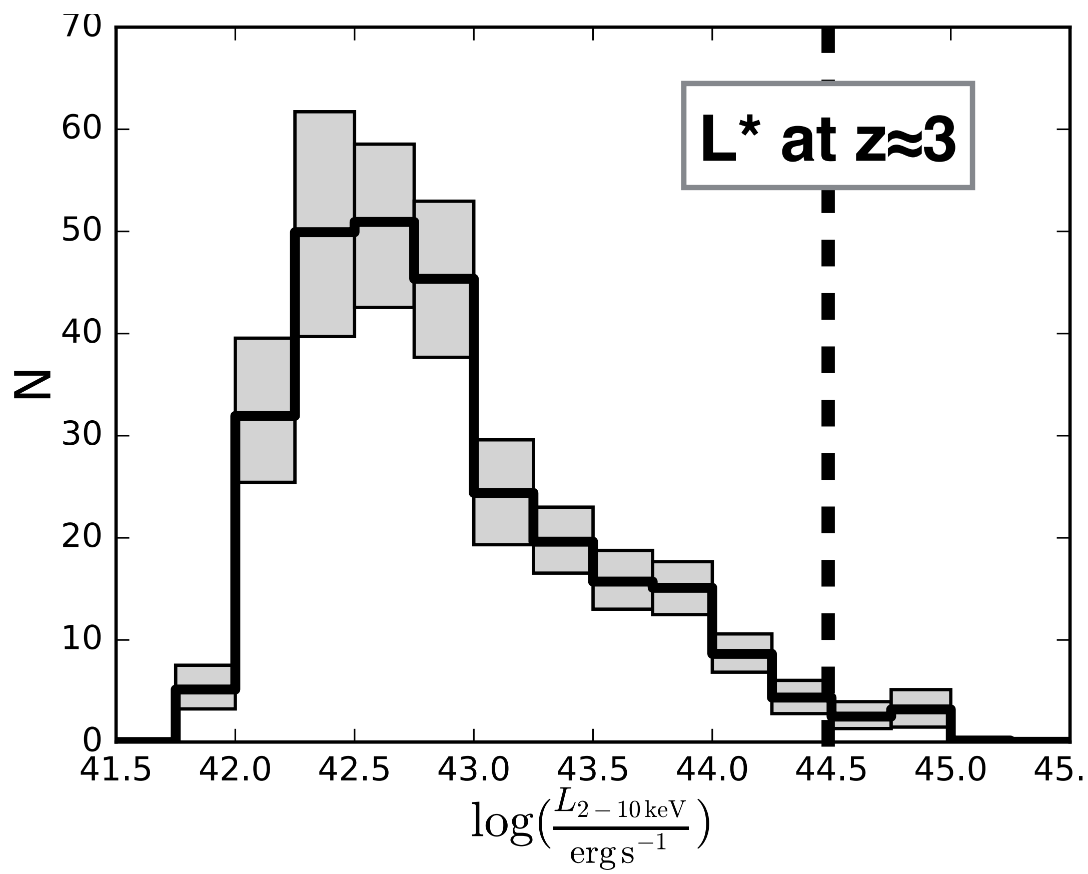


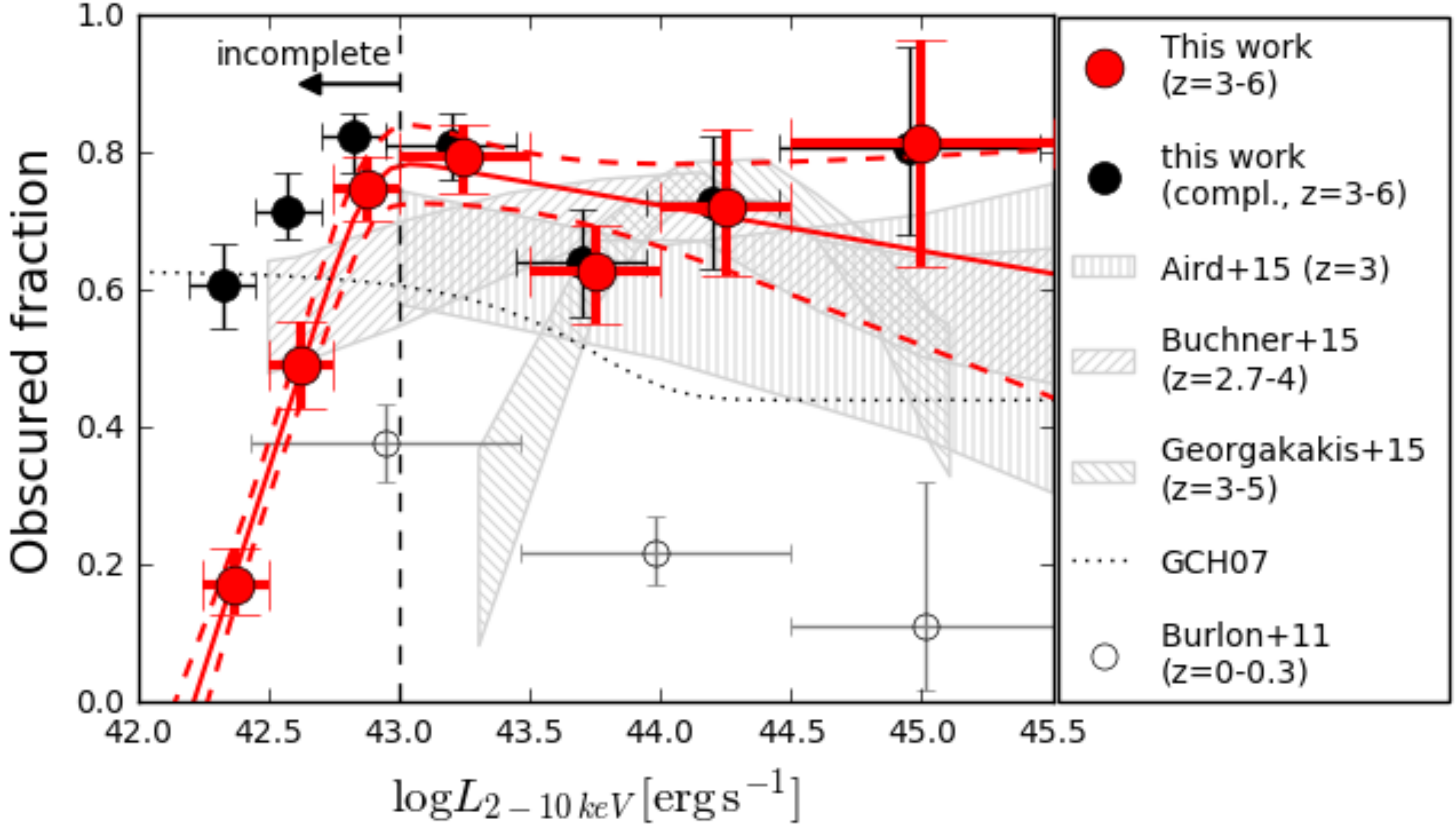

observed
0.5-7 keV

↓

Rest-frame
2-40 keV
at z=3-6

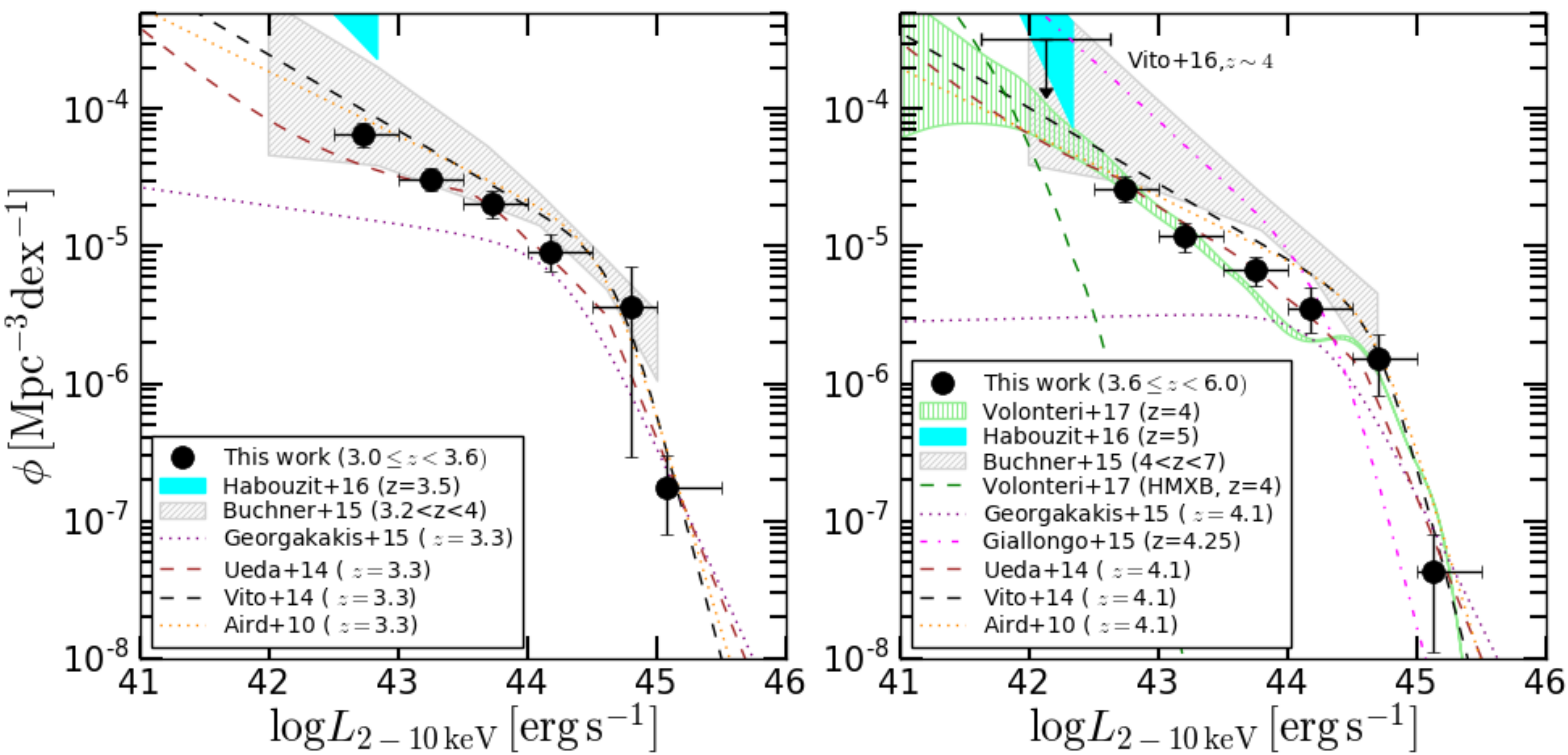


# Obscured fraction ($F_{obsc}$) vs $L_X$

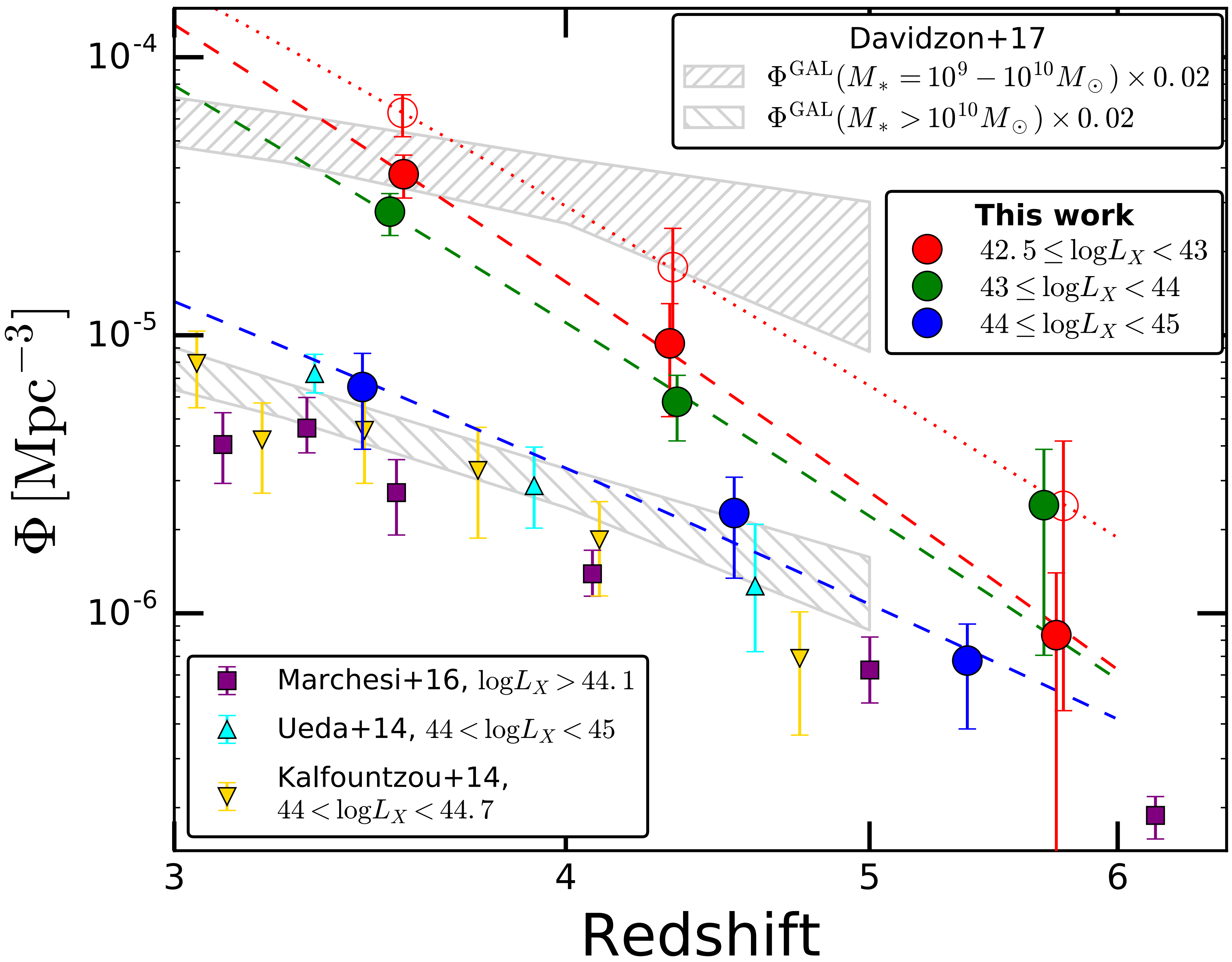



Strong evolution from low z, especially at high L

# AGN X-ray luminosity function



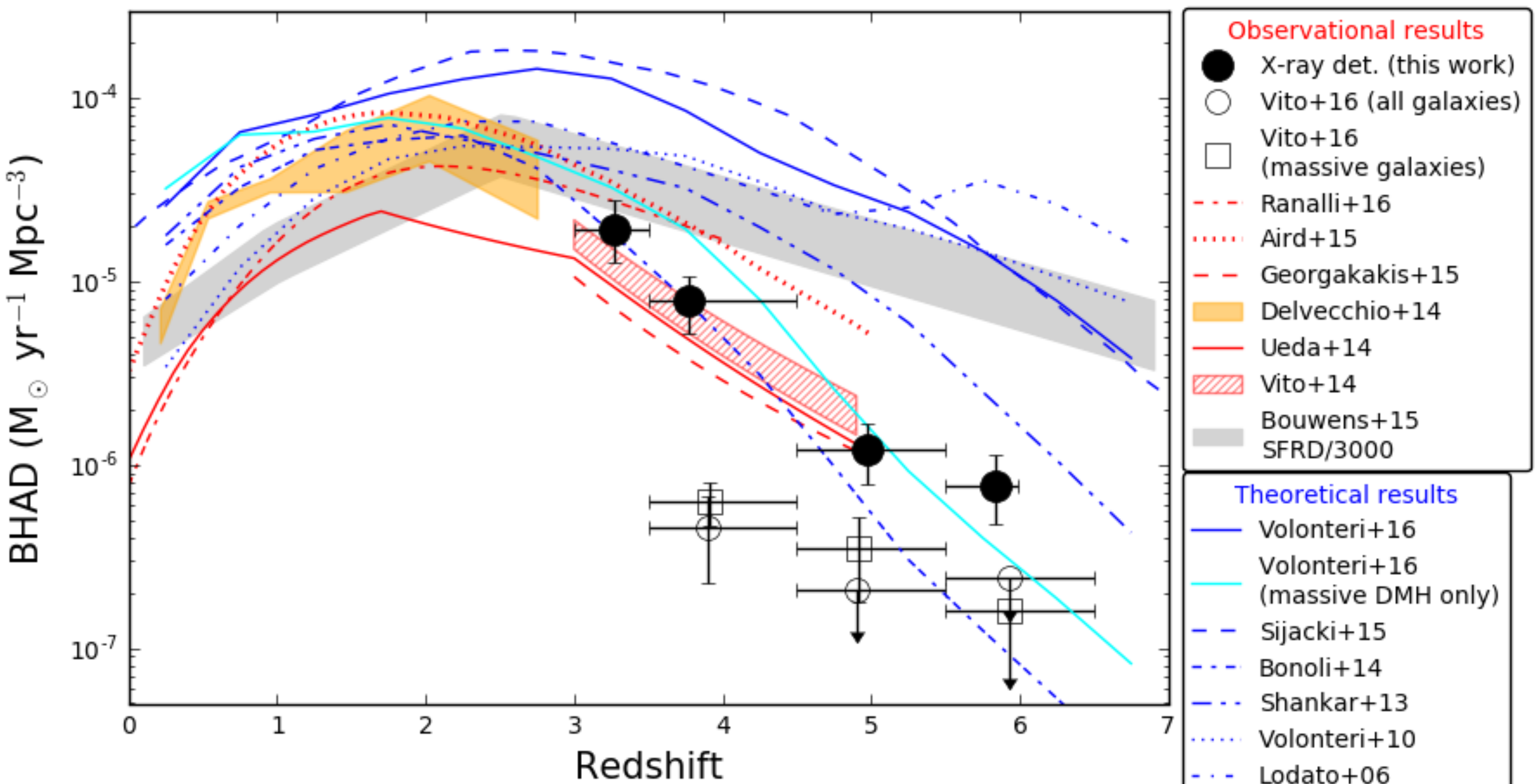
# AGN space density




Decline at high-L driven by evolution of number of massive galaxies?

Hints for steepening at low-L (not matched by low-mass galaxies): change of the accretion parameters (Eddington ratio, occupation fraction, etc.)?

# BHAD in AGN vs galaxy

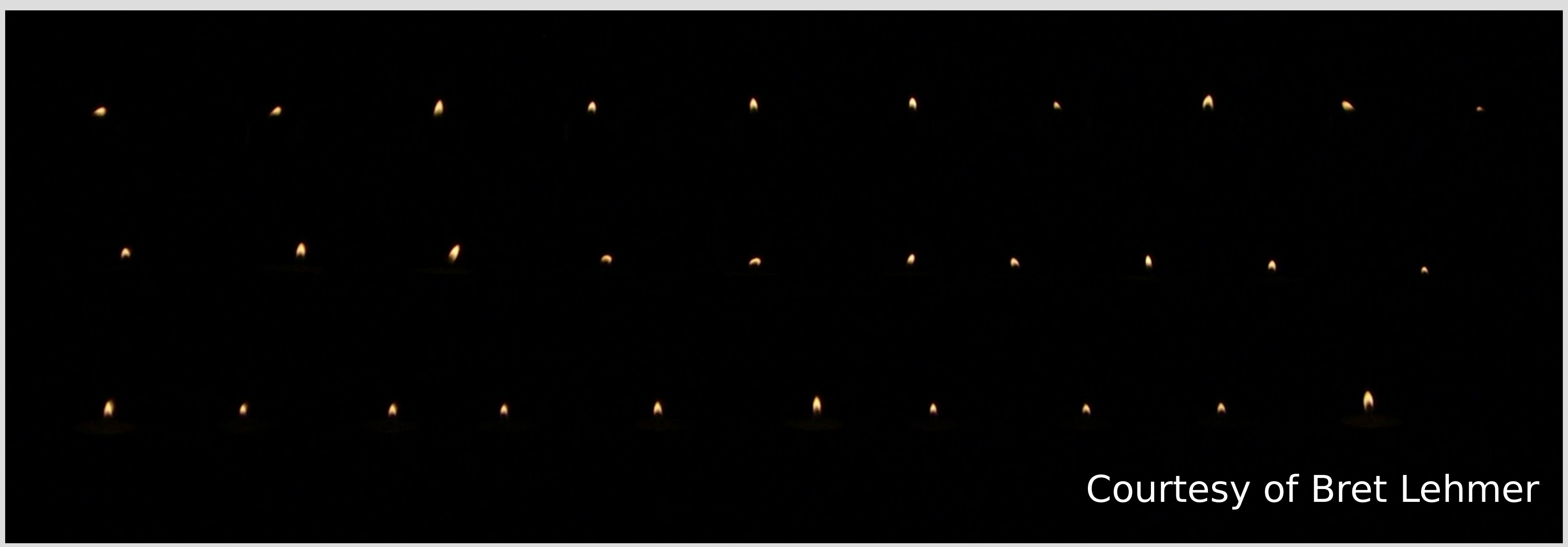


# Enhancing *Chandra* sensitivity: stacking analysis

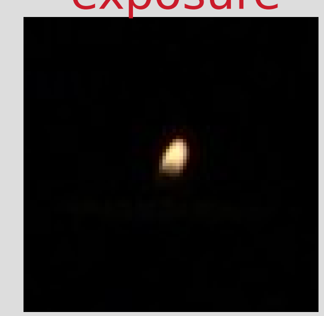
Credits: B. Lehmer

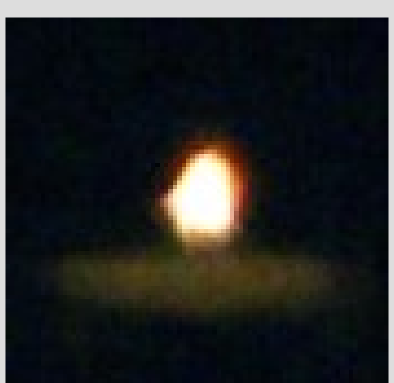
## Stacking: A Romantic Example

3 / 100 second exposure




1 / 1000 second exposure



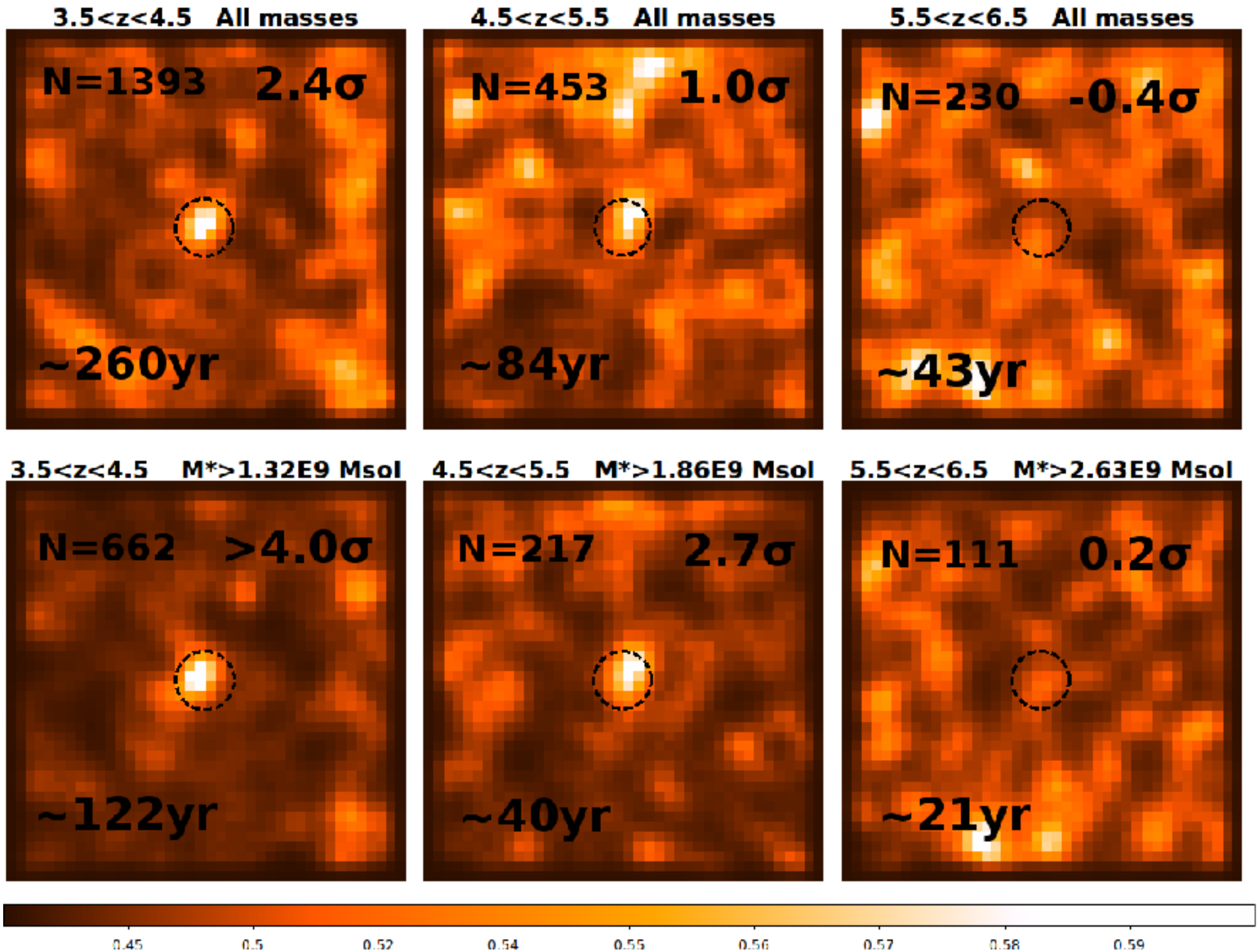


Stacked image of 30 candles with 1 / 1000 sec exposure.

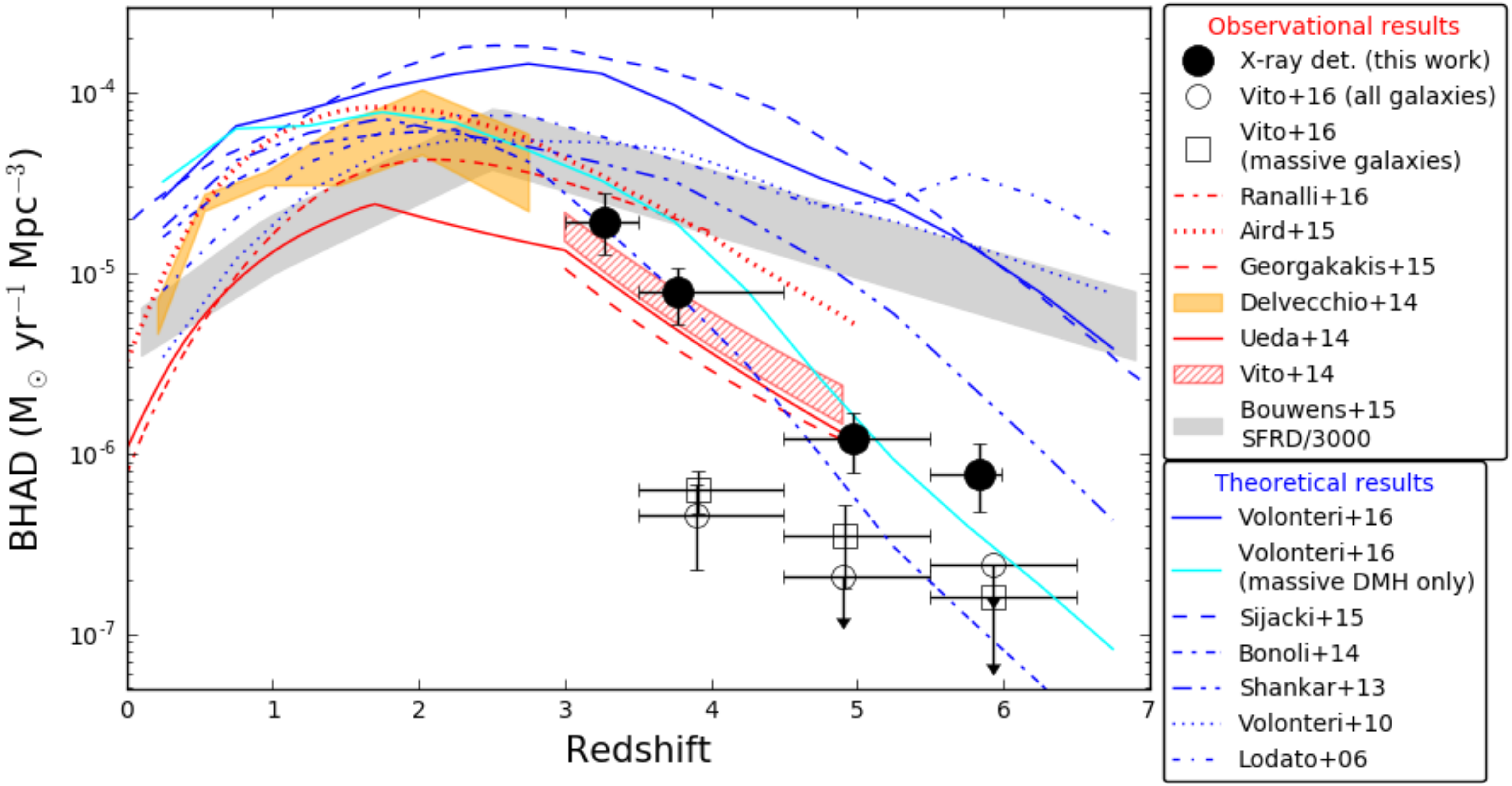
Effective stacked exposure of (30× 1/ 1000 sec) = 3 / 100 sec.

# Results from stacking analysis

Vito+16



# BHAD in AGN vs galaxy



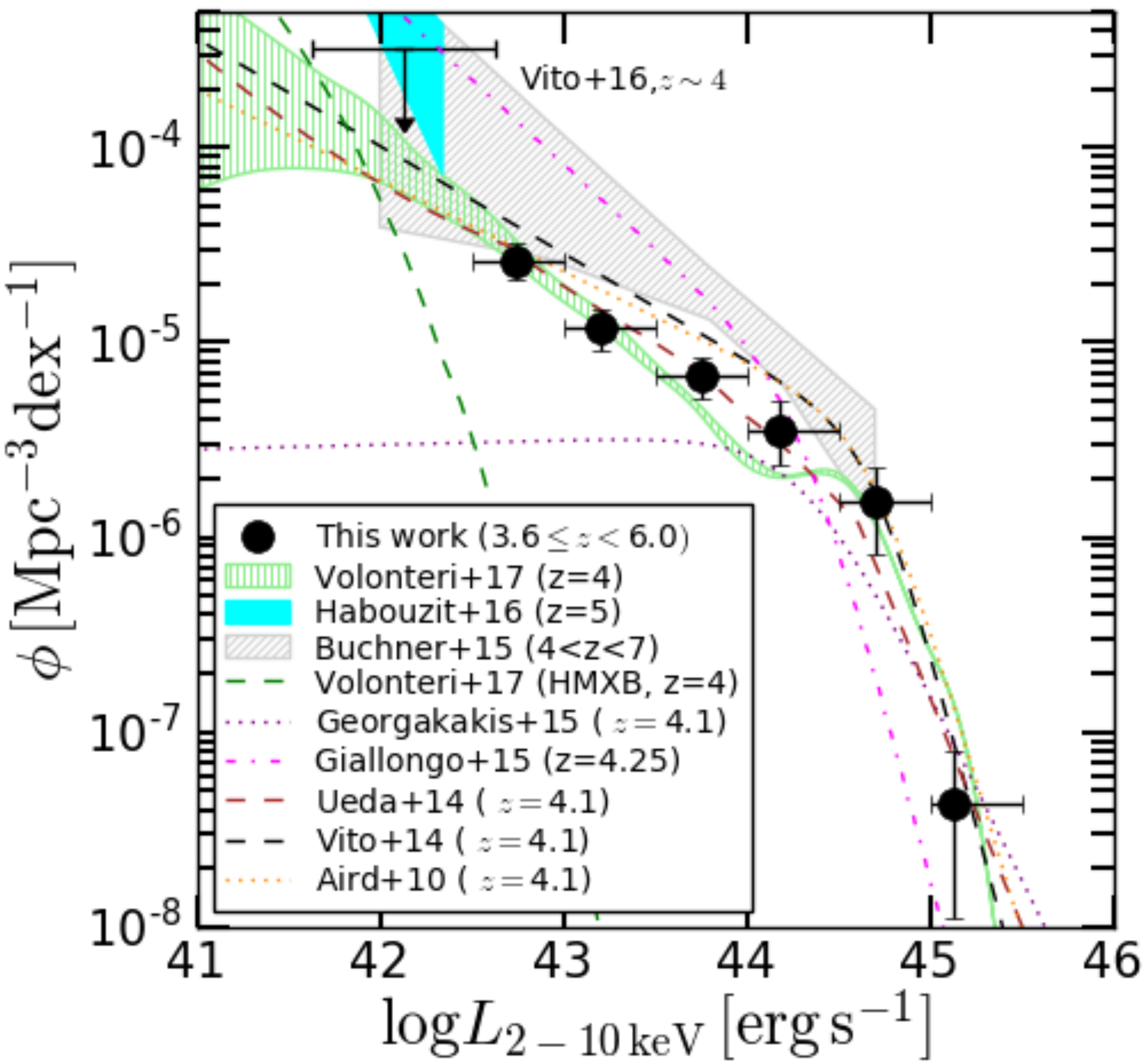

BHAD dominated by X-ray detected AGN: most of the BH growth happens during the "bright" AGN phase

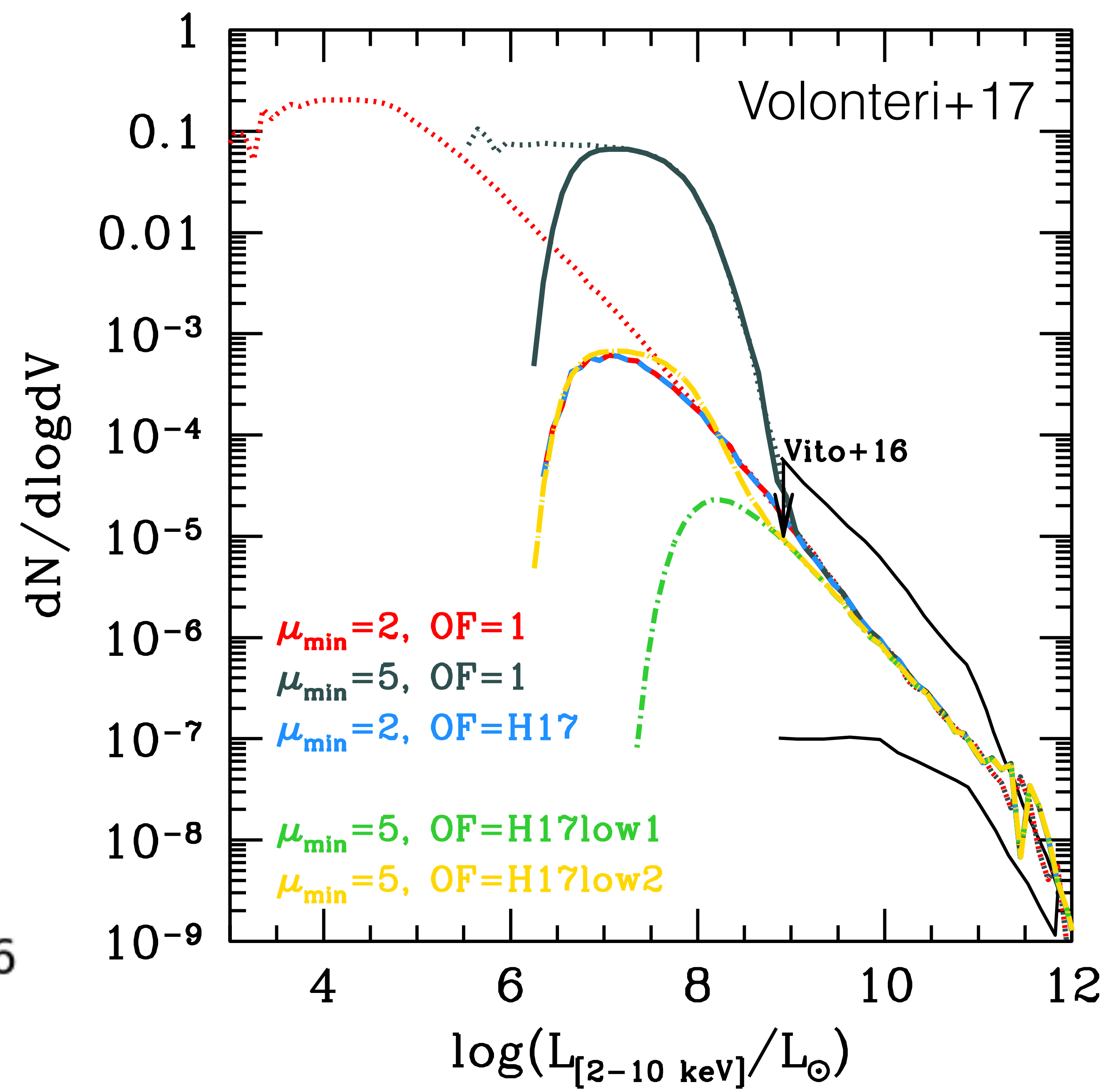
Low-rate accretion not enough for observations to match simulations

What causes the different slopes of BHAD and SFRD?

(see also Aird+15; complex combination of parameters, e.g., occupation fraction, duty cycle, Eddington ratio distribution, etc…)

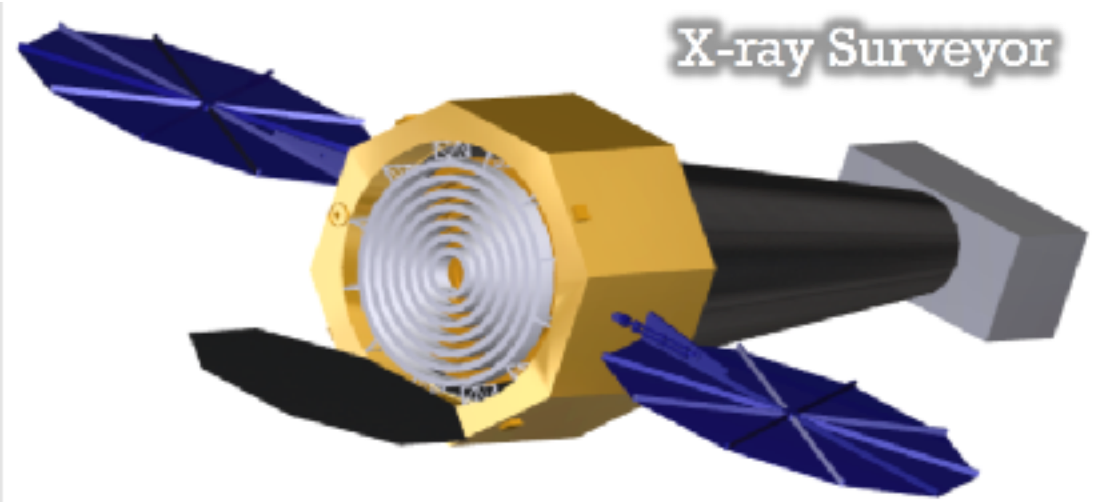
# XLF faint end at high-z as a tool to study BH seed formation and growth




**Need to push at lower-L and higher-z! E.g. *Lynx***

# *Lynx* (Weisskopf et al. 2015)




- *Chandra*-like spatial resolution
- 10x f.o.v.
- 50x sensitivity

Credits: Alexey Vikhlinin

| | |
|---|---|
| Detection threshold @ 4Msec (0.5-2 keV) (for known locations) | $3.0\times10^{-19}$ erg/s/cm^2 ($1.1\times10^{-19}$) |
| 2–10 keV luminosity at z=10 assuming $\Gamma=1.7$ | $3.7\times10^{41}$ erg/s ($1.35\times10^{41}$) |
| Bolometric luminosity at z=10, assuming 10% correction | $3.7\times10^{42}$ erg/s ($1.35\times10^{42}$) |
| Black Hole Mass assuming Eddington rate | 29,000 Msun (11,000 Msun) |

# *Lynx* sensitivity

Credits: Alexey Vikhlinin

| | |
|---|---|
| Detection threshold @ 4Msec (0.5-2 keV)<br>(for known locations) | $3.0\times10^{-19}$ erg/s/cm^2<br>($1.1\times10^{-19}$) |
| 2–10 keV luminosity at z=10 assuming $\Gamma$=1.7 | $3.7\times10^{41}$ erg/s<br>($1.35\times10^{41}$) |
| Bolometric luminosity at z=10, assuming 10% correction | $3.7\times10^{42}$ erg/s<br>($1.35\times10^{42}$) |
| Black Hole Mass assuming Eddington rate | 29,000 Msun<br>(11,000 Msun) |

**on behalf of the Lynx "first accretion light" working group:**

Under reasonable assumptions on space density

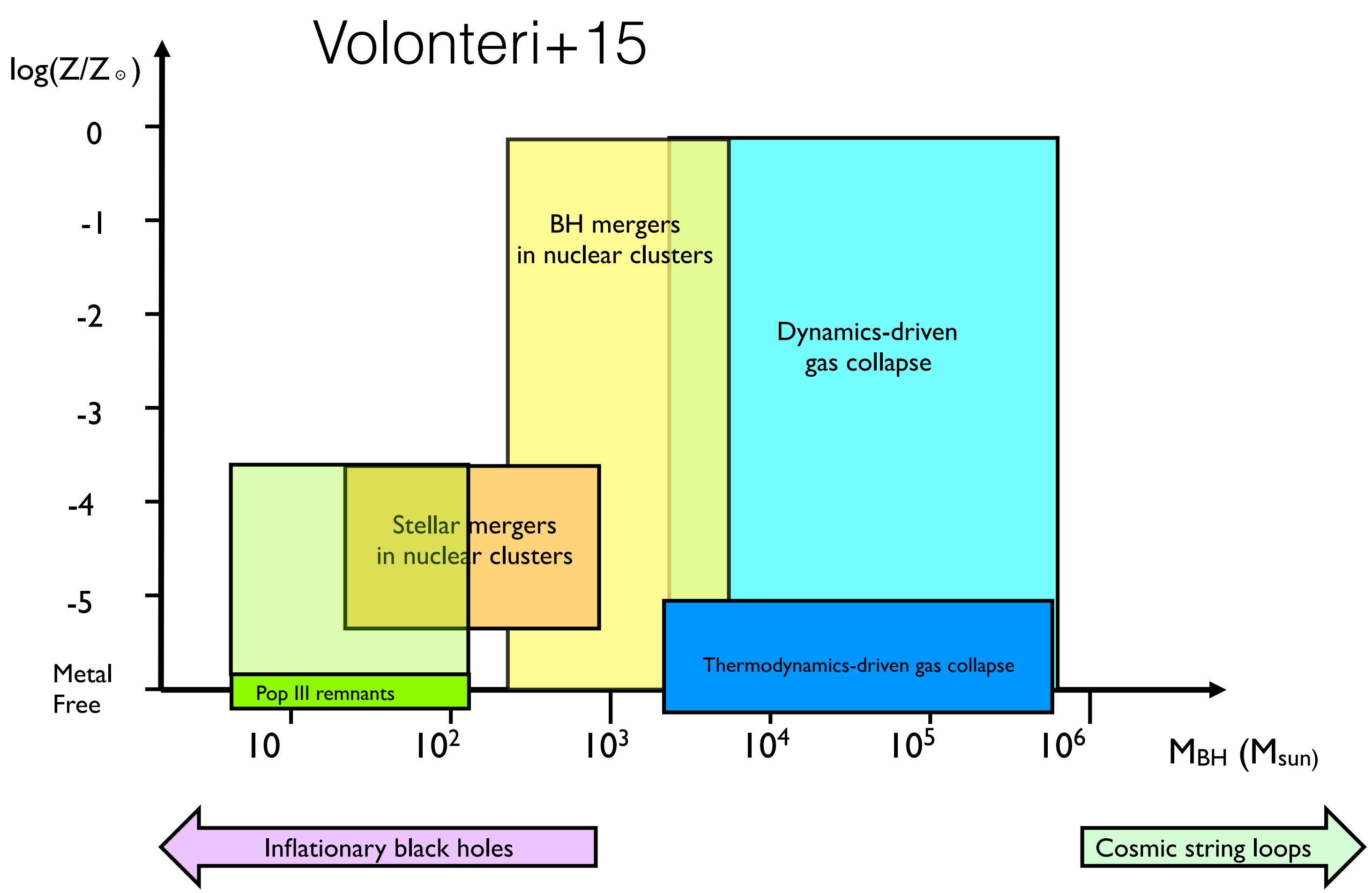
(from Habouzit+16 and Volonteri+17 or from DM halo arguments)

and physical parameters ($\lambda_{Edd}$=1, $K_{bol}$=10%), we expect to detect **~1000 accreting BH at z=8-9 with $\log L_x \gtrsim 41$ and $\log(M_{BH}/M_\odot) \gtrsim 4$ in ~ 1 deg$^2$**

# ~1000 accreting BH at z=8-9 with $\log L_X \gtrsim 41$ and $\log(M_{BH}/M_\odot) \gtrsim 4$ in ~ 1 deg$^2$

Enough to sample accurately the XLF and place tight constraints to physical parameters regulating BH seed formation and growth

(e.g. Volonteri+12,+16, Haiman+13, Johnson&Haardt+16, and references therein)




1. seed mass distribution (light or heavy seeds?)
2. occupation fraction
3. $\lambda_{Edd}$ distribution
4. feedback
5. etc.

Multi-$\lambda$ data can help breaking the degeneracies (e.g. Pacucci+15,Natarajan+17)

**~1000 accreting BH at z=8-9**
**with $\log L_X \gtrsim 41$ and $\log(M_{BH}/M_\odot) \gtrsim 4$ in ~ 1 $deg^2$**

Enough to sample accurately the XLF and place tight constraints to physical parameters regulating BH seed formation and growth

But significant uncertainties due to…

1. modelling
   (e.g. factors of several in space density)
2. XRB contribution/confusion
3. ancillary data
   (i.e. NIR/MIR with JWST/WFIRST, we need rest-frame UV m~30)

**Work in progress here!**

https://wwwastro.msfc.nasa.gov/lynx/

# Conclusions

- Largest sample of $3<z<6$ X-ray detected AGN with $L<L_*$, thanks to the use of the deepest *Chandra* surveys
- Large fraction of obscured AGN at $\log L_X>43$ ($F_{obsc}$~0.6-0.8), less clear at low-L
- Strong evolution of $F_{obsc}$ from low-z
- Best constraints on the $L<L_*$ AGN XLF at $z>3$
- Space density of luminous AGN evolves similarly to (is caused by?) that of massive galaxies
- Hints for a steeper evolution of the space density of low-L AGN than high-L AGN, while flattening of density of low-mass galaxies: evolution of accretion parameters (duty cycle, Eddington ratio,etc)?
- BHAD due mostly to luminous AGN, and steeper evolution than SFRD: higher BH-to-galaxy mass ratio at high z?
- *Lynx* will probe the AGN population down to $\log M_{BH}$~4 up to $z$~10

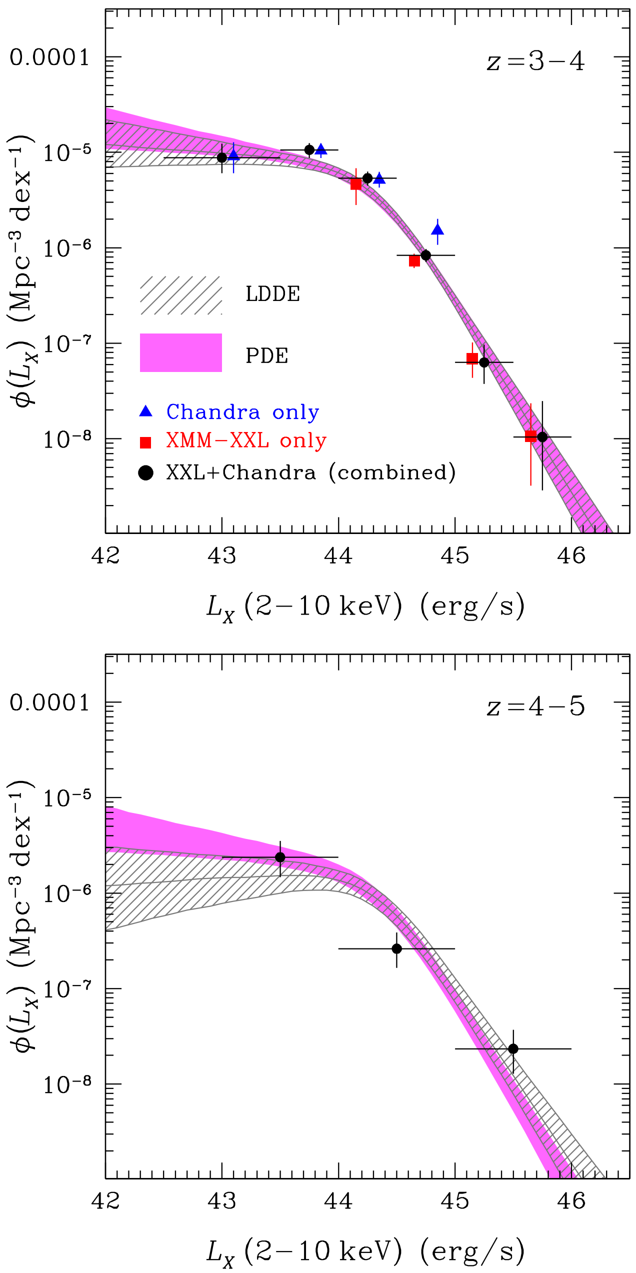
# Back-up slides

# High-z (3<z<5) AGN in X-ray surveys: faint end of XLF

## LDDE?

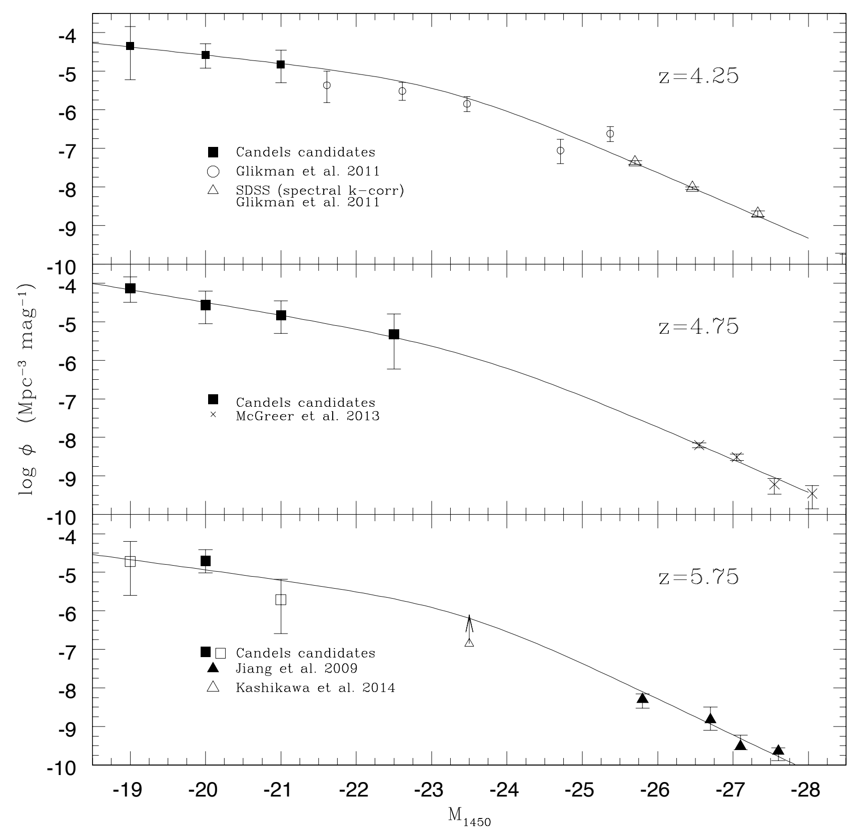
### Flattening?

(e.g. Georgakakis+15)




### Steepening?

(e.g. Fiore+12, Giallongo+15)

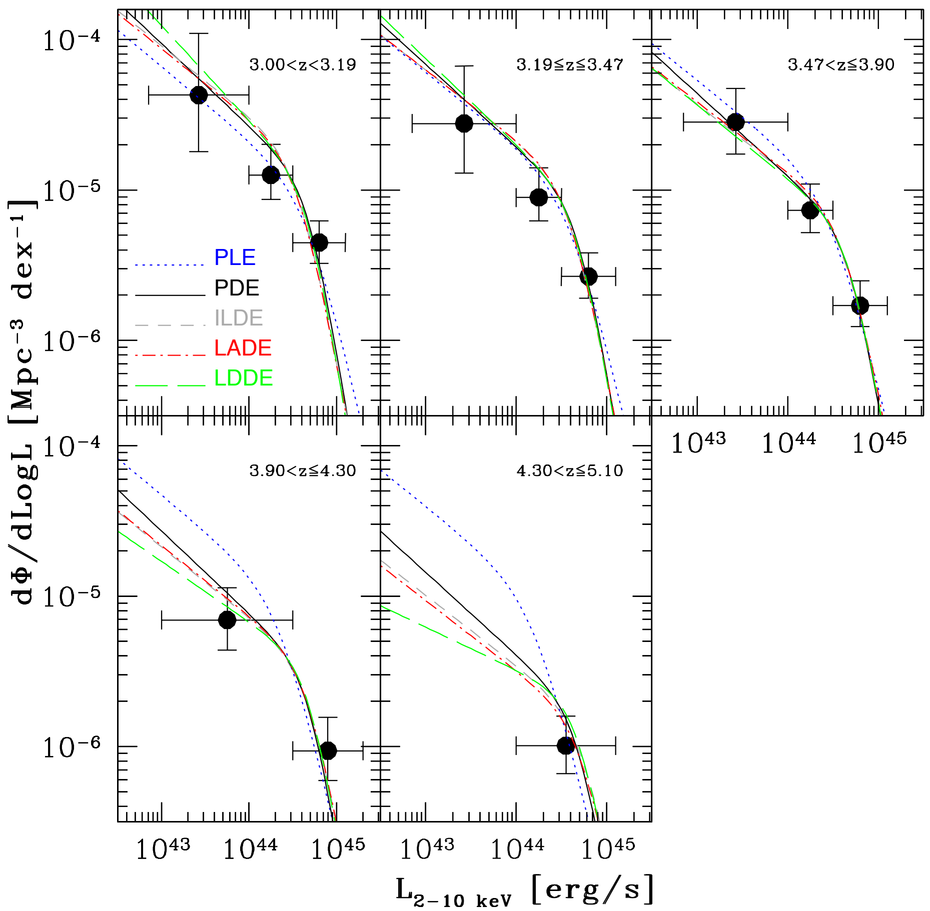



(possible high AGN contribution to cosmic reionization)

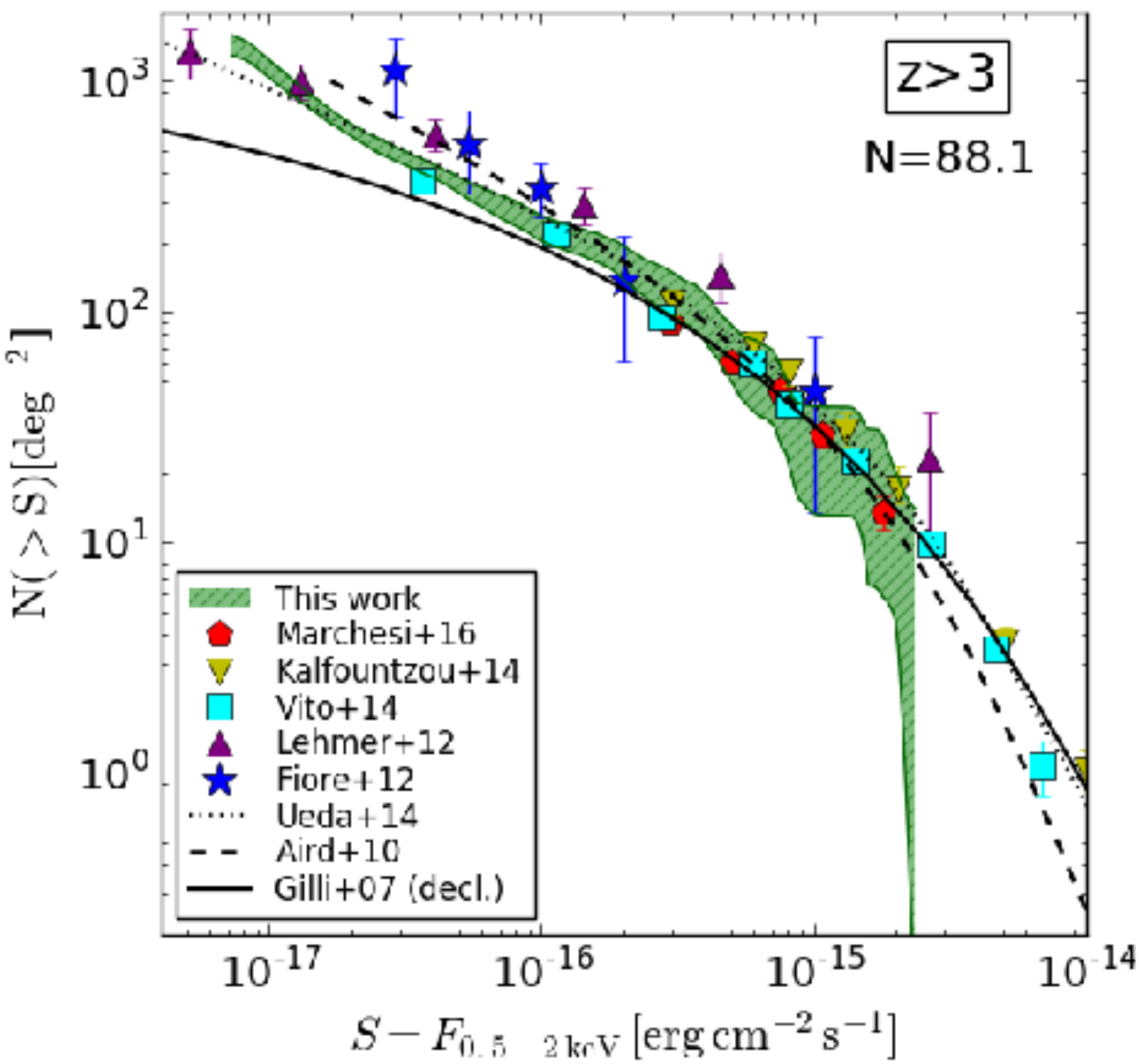
## PDE?

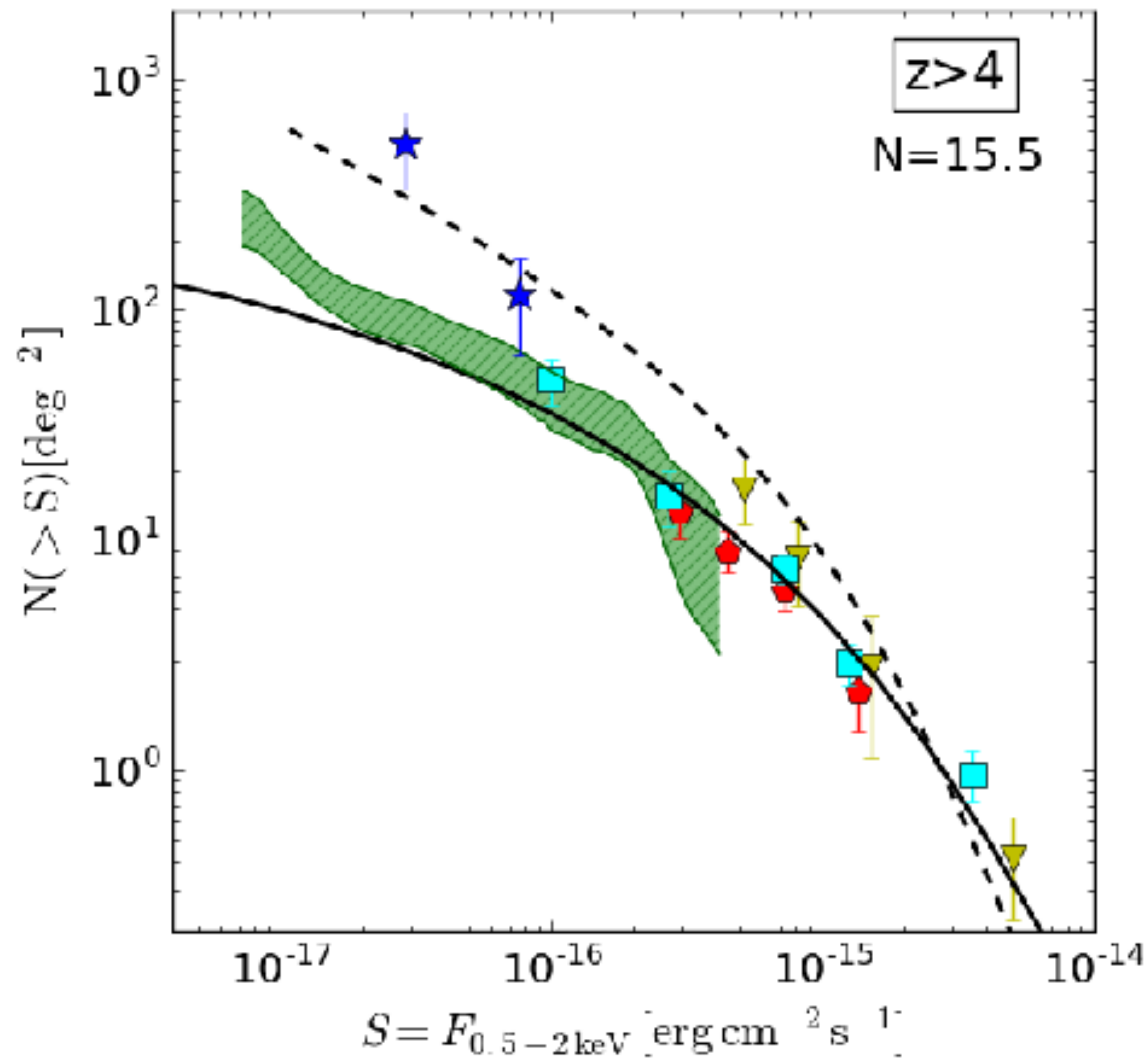
### No slope evolution?

(e.g. Vito+14)



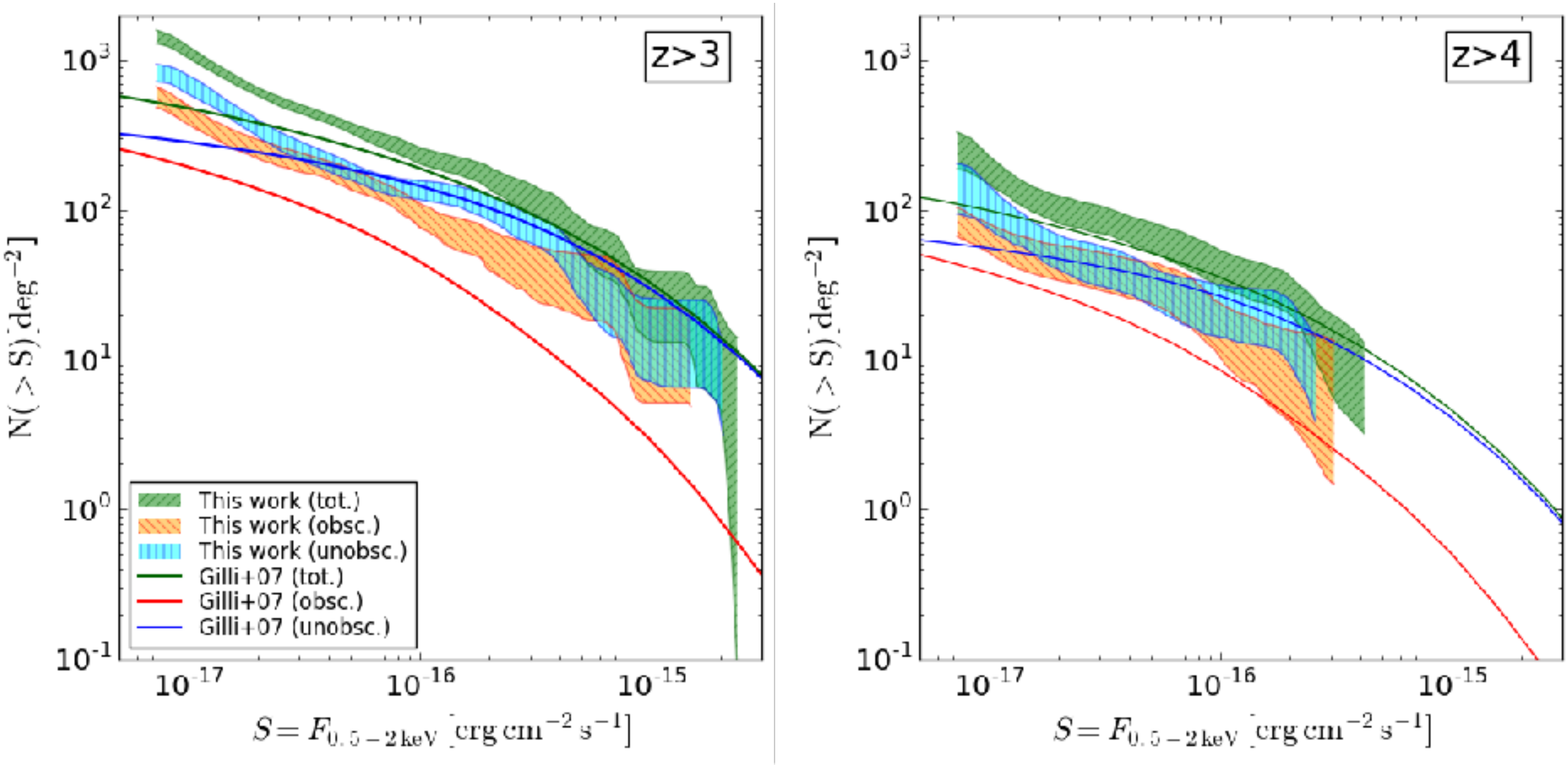
# AGN number counts at high-z



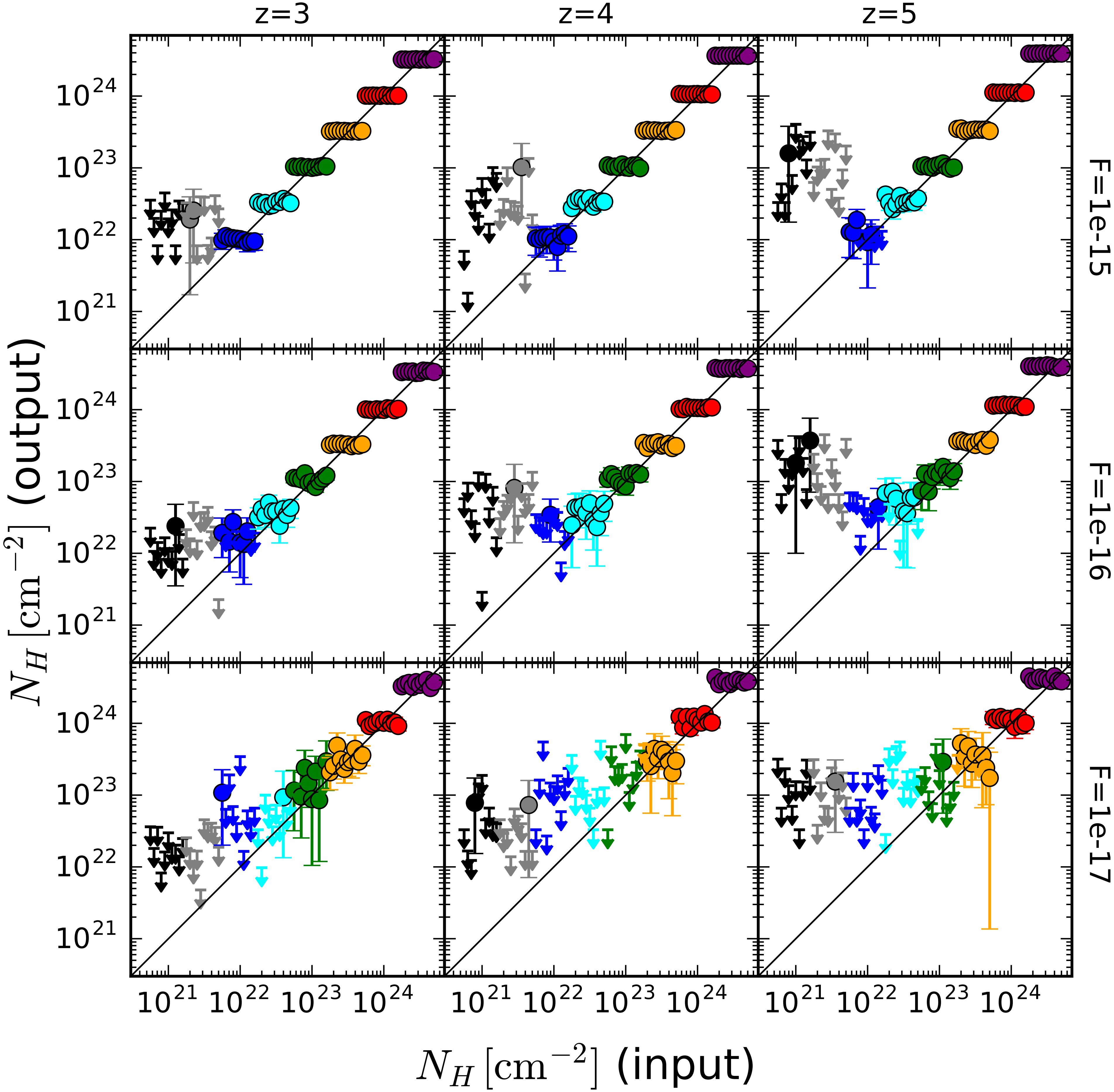




Soft-band detected sources only

# AGN number counts at high-z

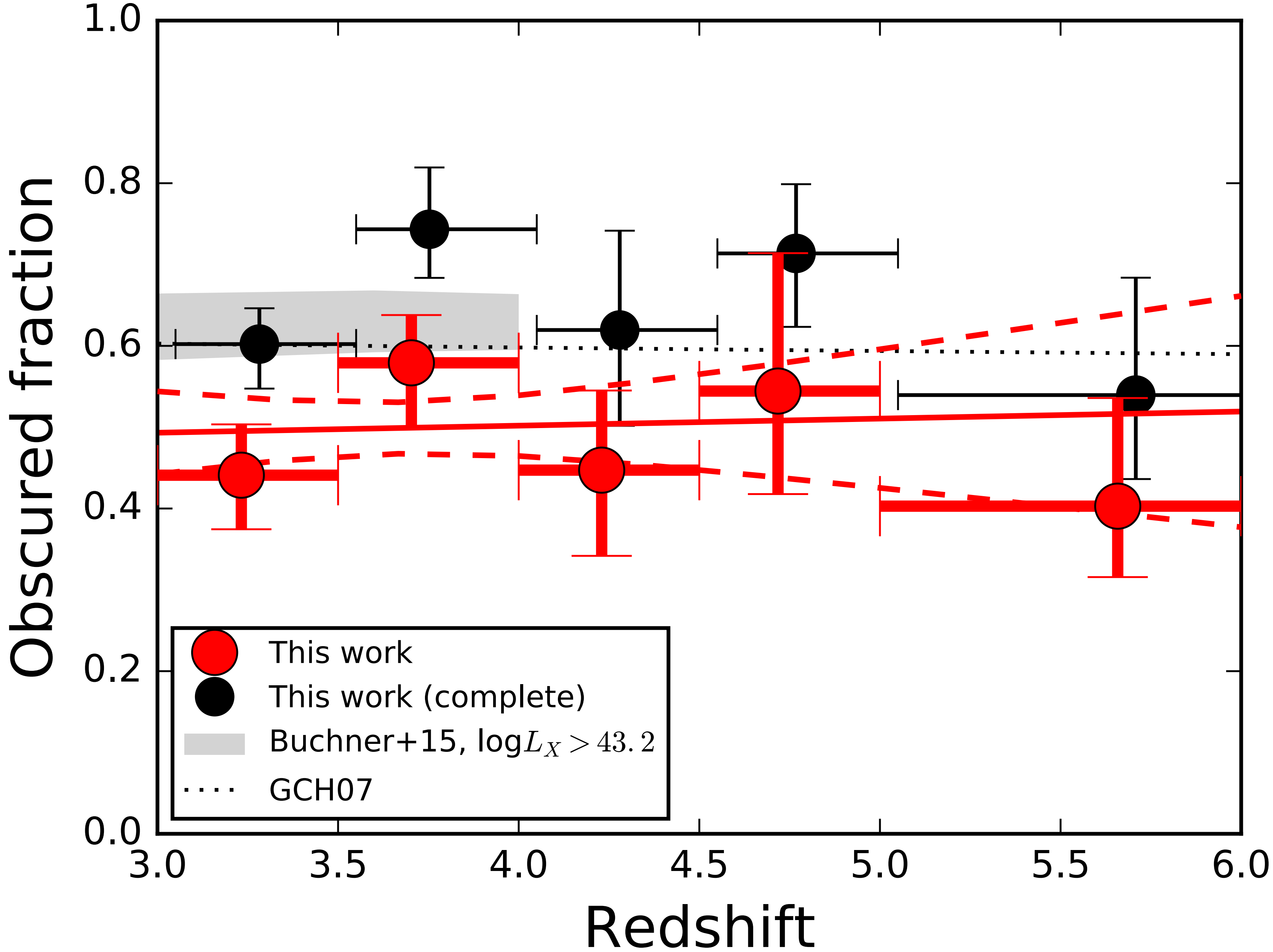



Larger population of obscured AGN than expected!



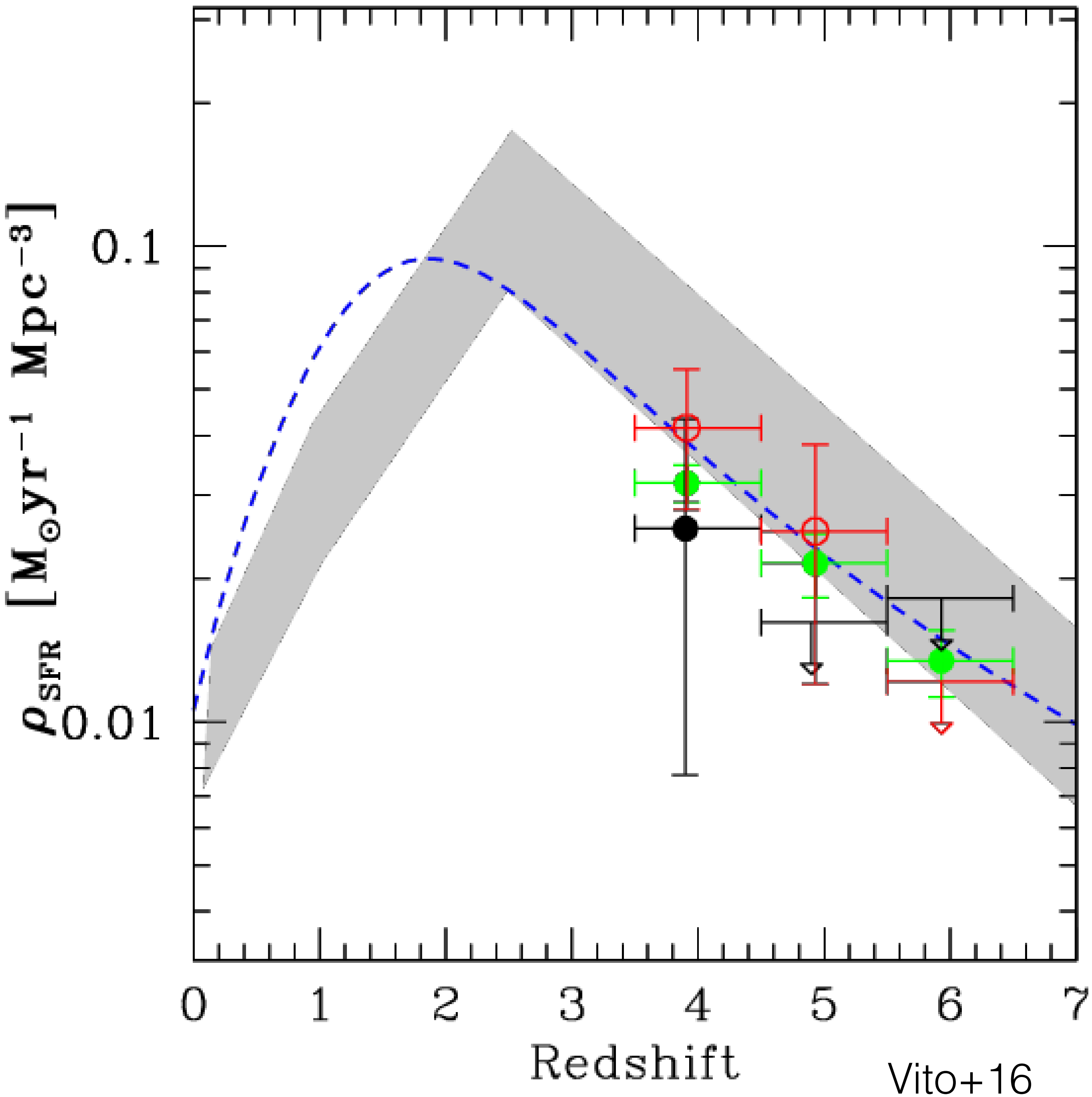
z=3
z=4
z=5
F=1e-15
F=1e-16
F=1e-17
$10^{21}$
$10^{22}$
$10^{23}$
$10^{24}$
$N_H\,[\mathrm{cm}^{-2}]$ (output)
$N_H\,[\mathrm{cm}^{-2}]$ (input)

# Obscured fraction ($F_{obsc}$) vs z




No significant evolution from z=3 to z=6

# Stacked X-ray emission dominated by XRB?




Vito+16

Stacked emission consistent with being produced ~entirely by XRB