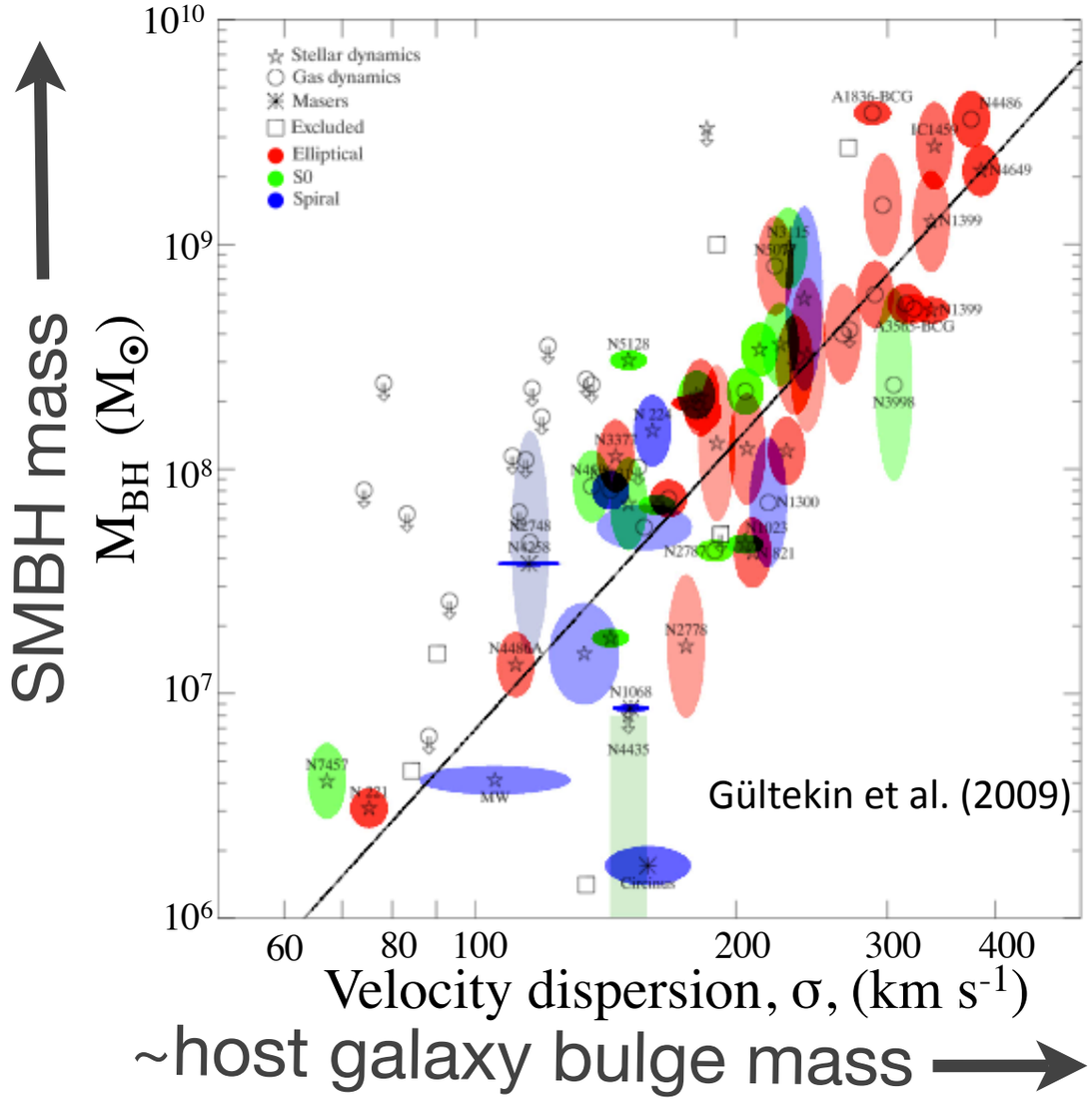
The formation and growth of the earliest supermassive black holes

James Aird & Andrea Comastri

on behalf of Topical Panel 2.1

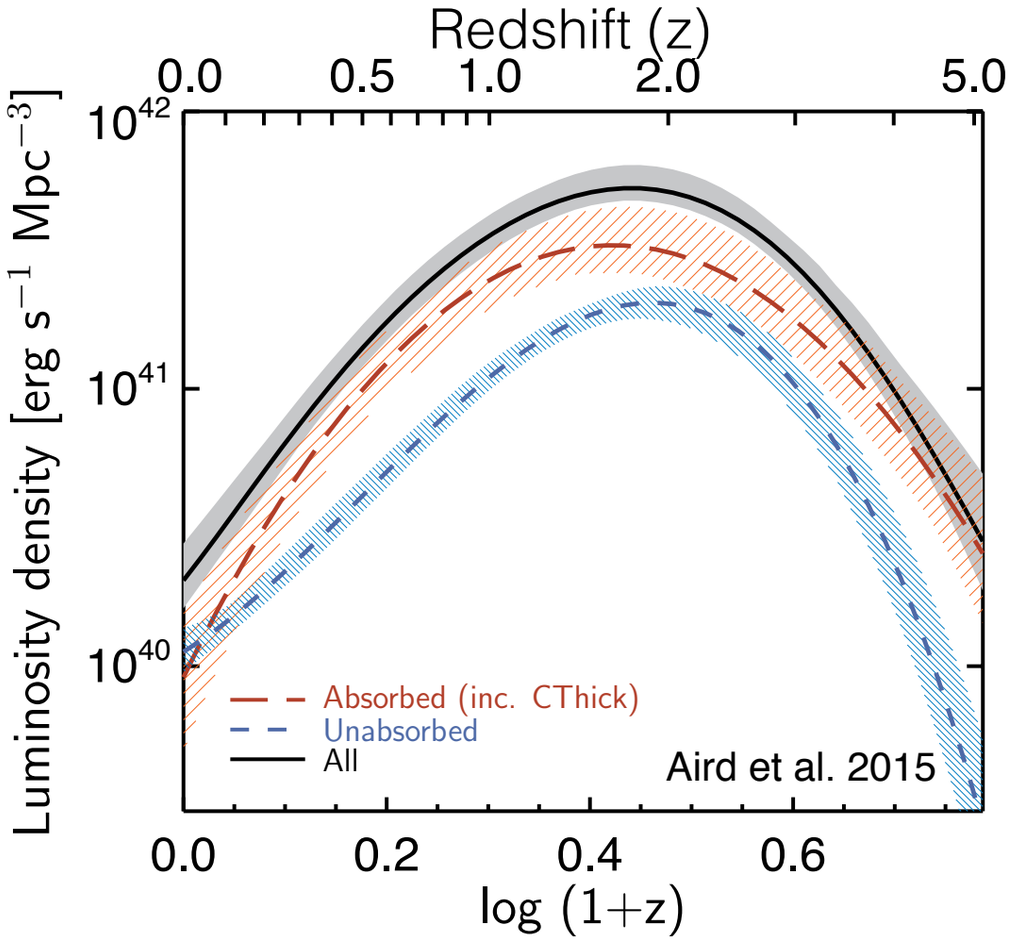
SMBHs in the Universe

SMBHs with M_{BH}~10^6 - 10^{10} $M_\odot$ are found at the centres of most (if not all) galaxies in the local Universe



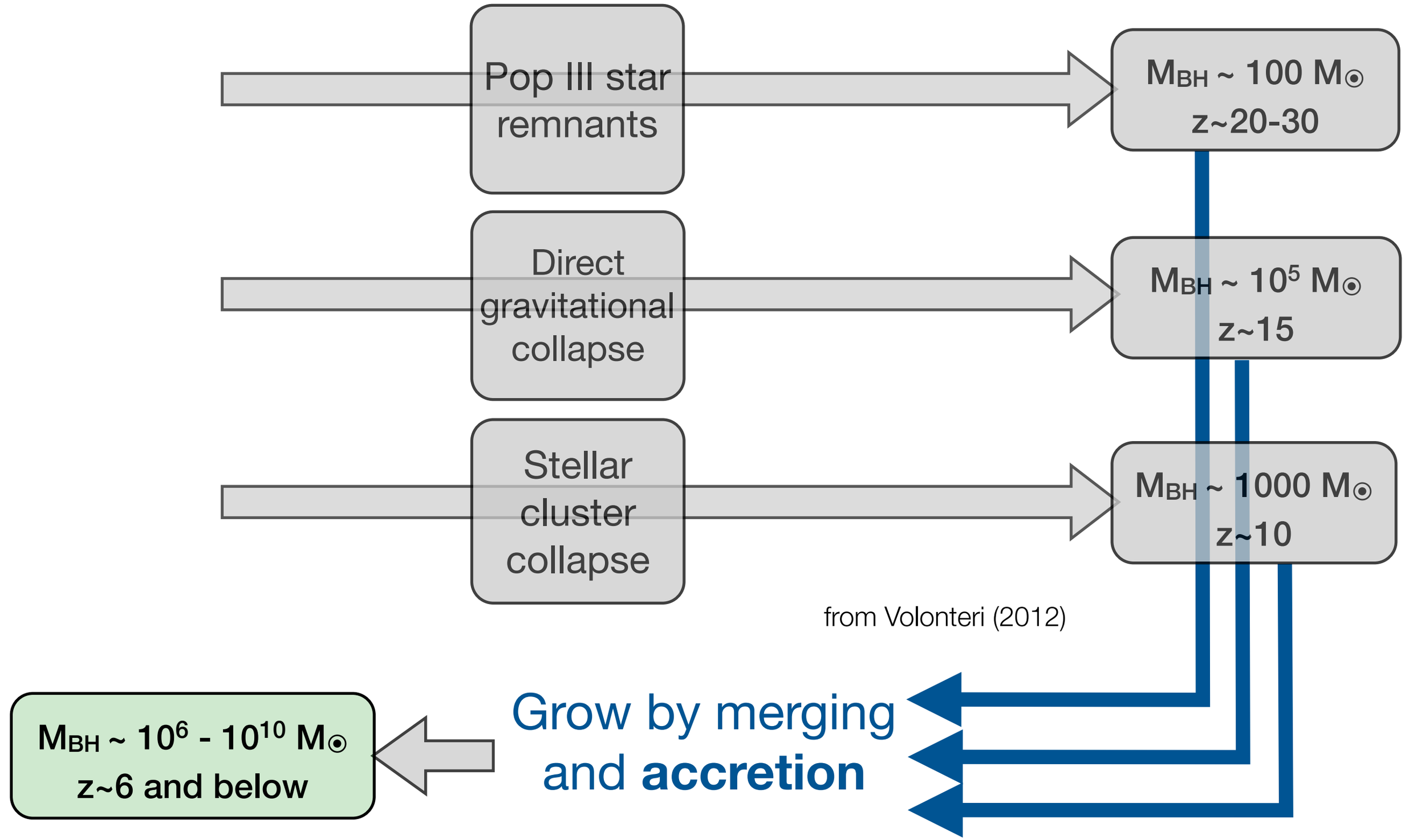
Rate of SMBH growth via accretion

Bulk of SMBH mass is built up via accretion (AGN), peaking at z~1-3



Late (recent) cosmic time ← Early cosmic times

SMBH seed formation mechanisms



Athena (level 1) science aims

Athena shall

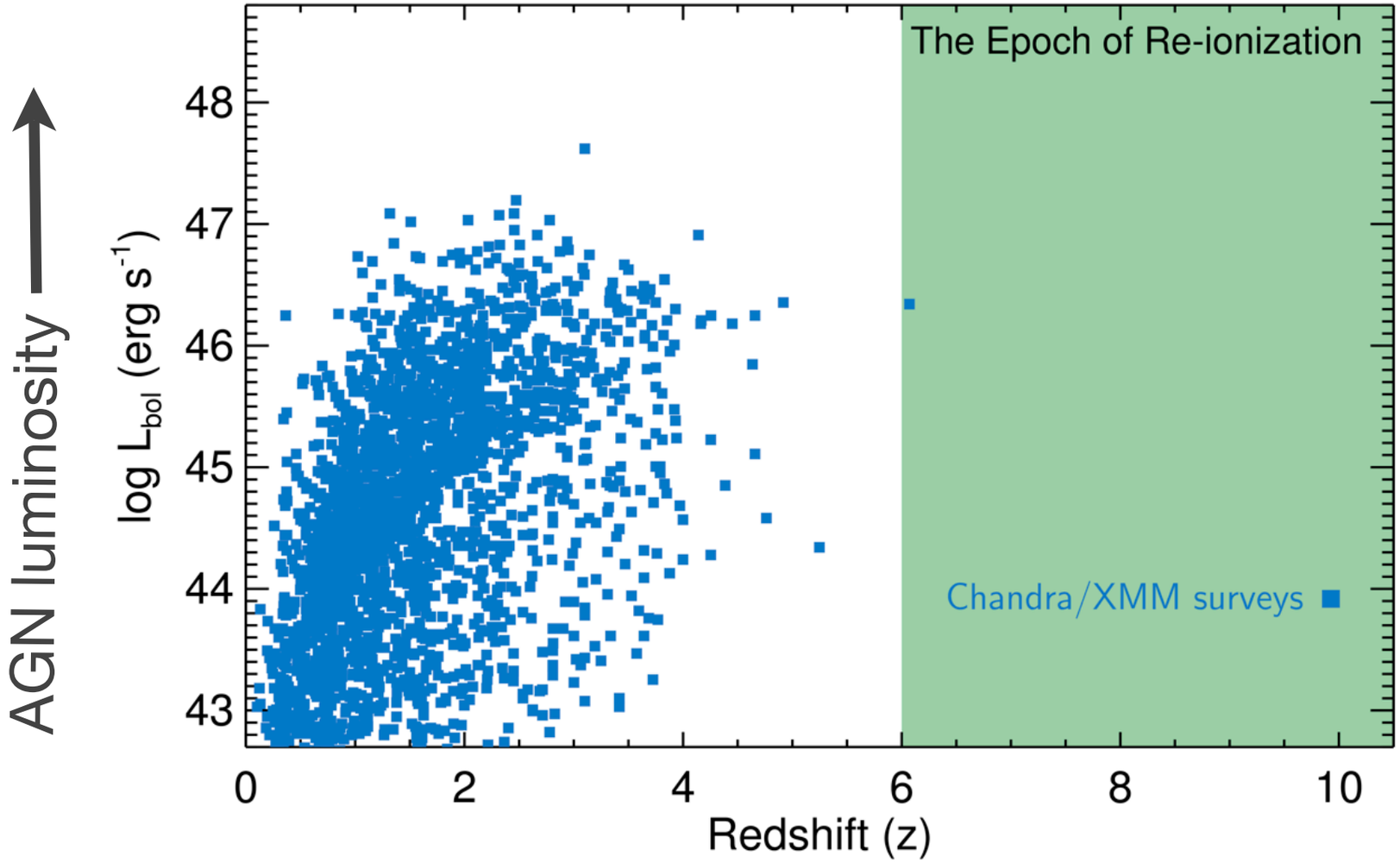
- determine the nature of the seeds of the earliest growing SMBHs (at $z>6$)
- characterise the processes that dominated their early growth
- investigate the influence of accreting SMBHs on the formation of galaxies.

Need to identify large samples of "typical" (low-to-moderate luminosity) AGNs at z>6, probing the epoch when the first galaxies and SMBHs formed and grew

X-ray surveys - *Chandra* and *XMM-Newton*

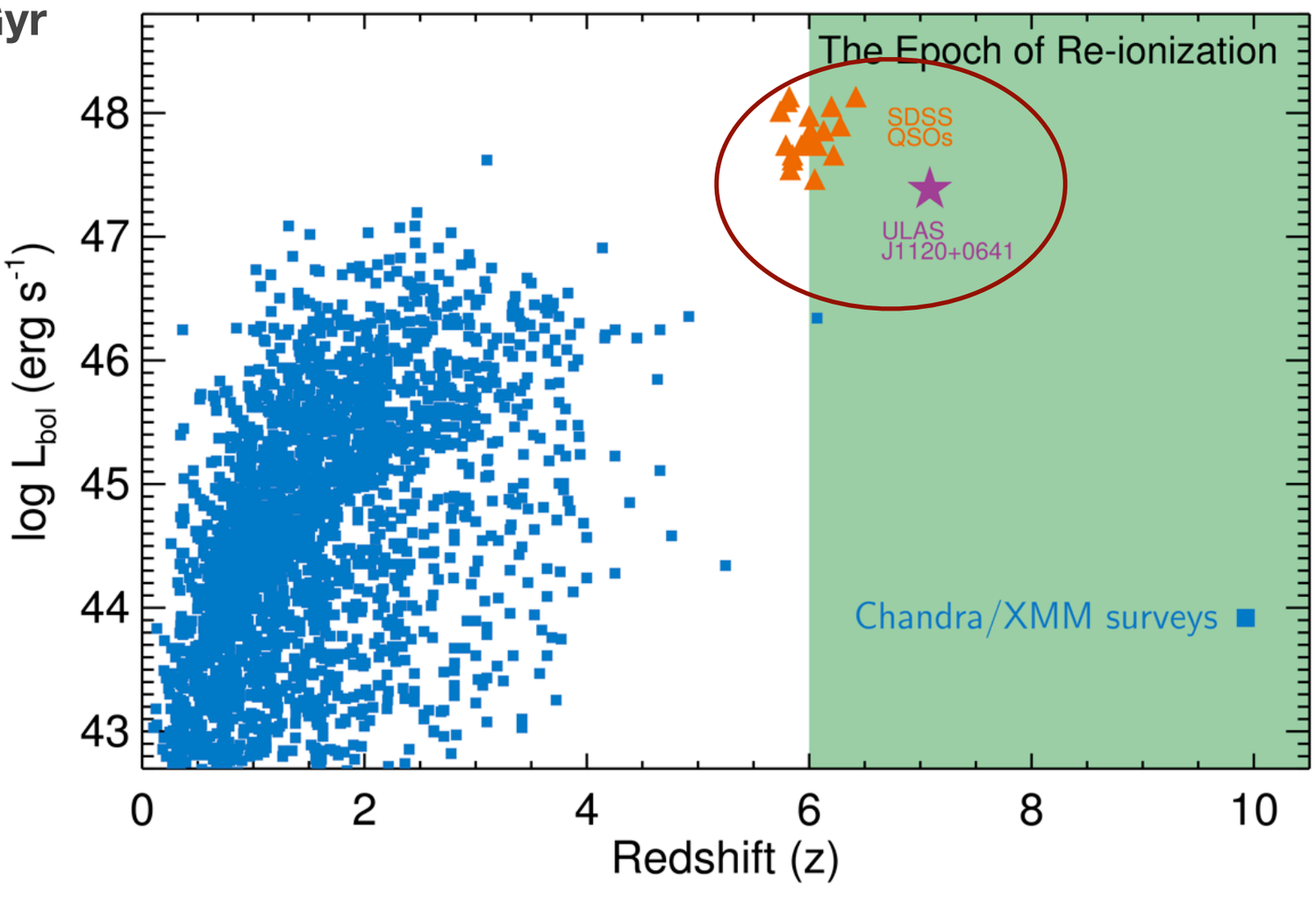
- X-ray surveys are extremely efficient at finding AGN over a wide range of luminosities
- AGN dominate over galaxy X-ray emission
  - find fainter AGN, generally not identified by optical or IR selection
- Less affected by obscuration than optical/UV

- Current surveys only extend to z~5
- Do not probe z>6 : the “epoch of re-ionisation” when the first galaxies and SMBHs form and grow



AGN at z>6 - the “tip of the iceberg”

- The known population of z > 6 consists of extremely luminous QSOs, identified in large area optical/near-infrared surveys (Fan et al. 2003, 2006, Mortlock et al. 2011, Banados et al. 2014, Venemans et al. 2015)
- Powered by SMBHs with $\mathbf{M_{BH} \sim 10^9\ M_\odot}$, comparable to the **most massive** SMBHs in the local Universe, but when the age of the Universe was only **<1Gyr**



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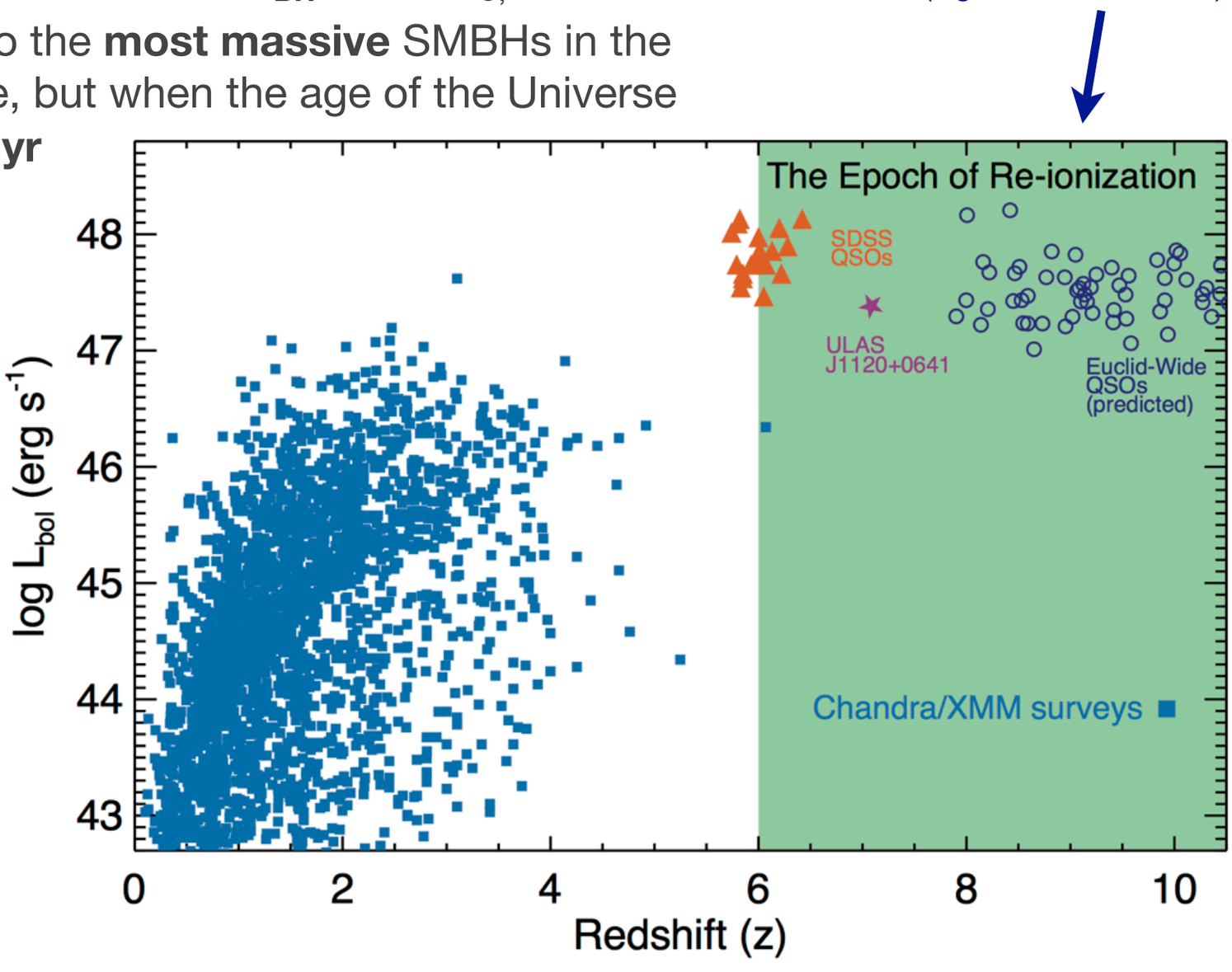
- Euclid surveys are expected to identify AGNs at z ~ 8 – 10 but will still be limited to the most luminous, unobscured sources (e.g. Roche et al. 2012)



Building high redshift QSOs - constraints on growth rates and seed masses

- Assuming Eddington limited growth, black hole mass grows as:

$$M_{\rm BH}(t) = M_0 \exp\left(\frac{1-\epsilon}{\epsilon}\lambda_{\rm Edd}\frac{t}{0.45{\rm Gyr}}\right)$$

seed mass

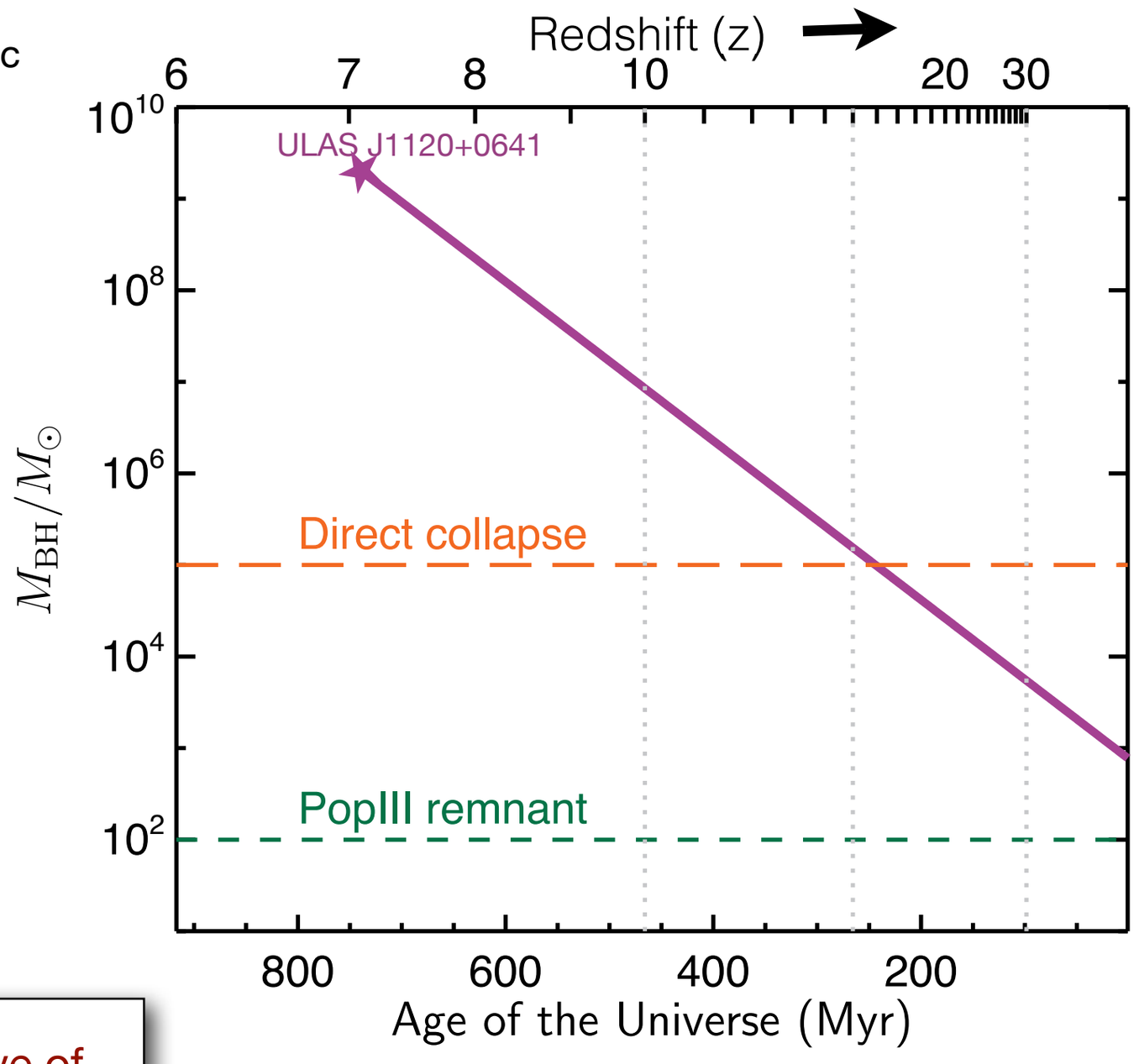
radiative efficiency ~0.1

Eddington ratio ~1

cosmic time

- The seed of ULAS J1120 (z=7.083, $M_{BH} \approx 2 \times 10^9\ M_\odot$) could have formed by direct collapse at z~15, but requires growth at ~Eddington limit for entire lifetime
- Pop III seed requires super-Eddington growth for substantial fraction of age of the Universe

N.B. extreme, rare object - not representative of bulk of early SMBHs and their growth



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Latest constraints on evolution of AGNs at $z \sim 0 - 5$
(X-ray luminosity function)

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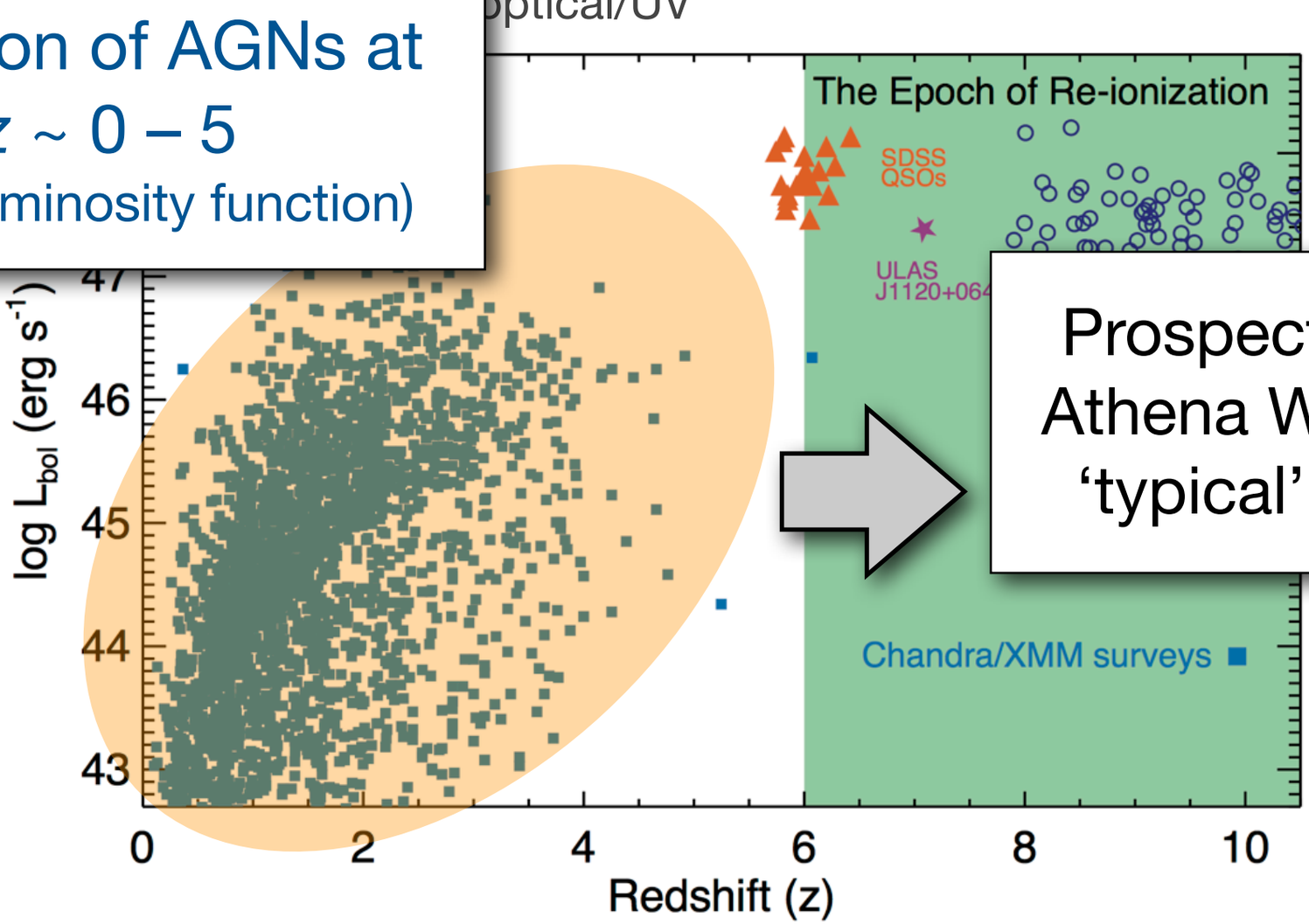
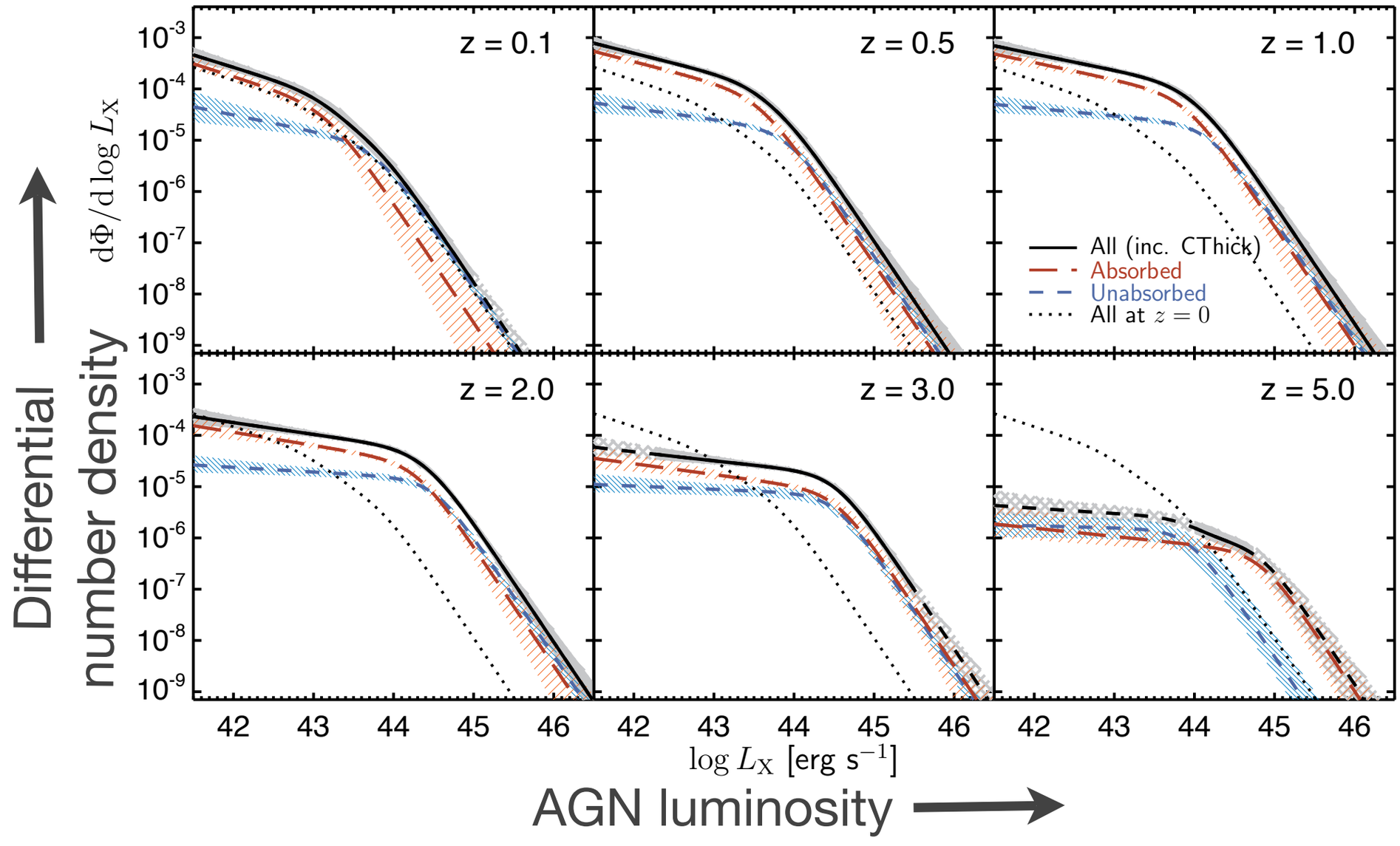


Prospects for a large Athena WFI survey for ‘typical’ AGNs $z > 6$

The evolution of the X-ray luminosity function of AGN from z~0 to z~5

- Number of recently updated studies on the evolution of the XLF of AGN at z~0-5 **- tracking the distribution of SMBH growth via accretion** over the last ~12Gyr
- Enabled by latest deep+wide Chandra surveys (CDFS-4Ms, AEGIS 800ks, C-COSMOS) + new techniques (counterpart IDs, photo-z, N_H correction etc.)



Aird et al. (2015)

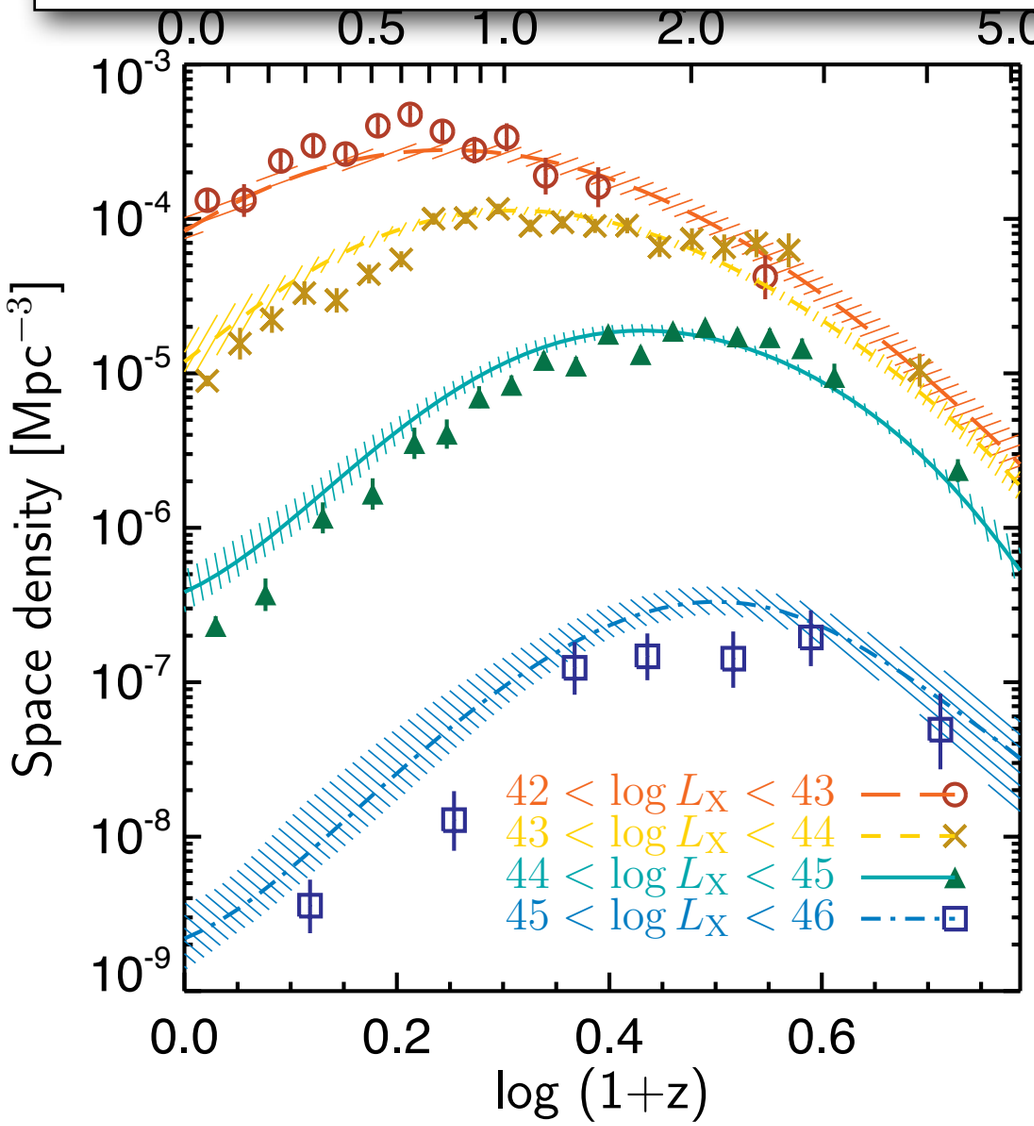
Evolution of the XLF is due to combination of:

- strong luminosity and density evolution of both absorbed and unabsorbed AGN
- changing mix of absorbed and unabsorbed populations

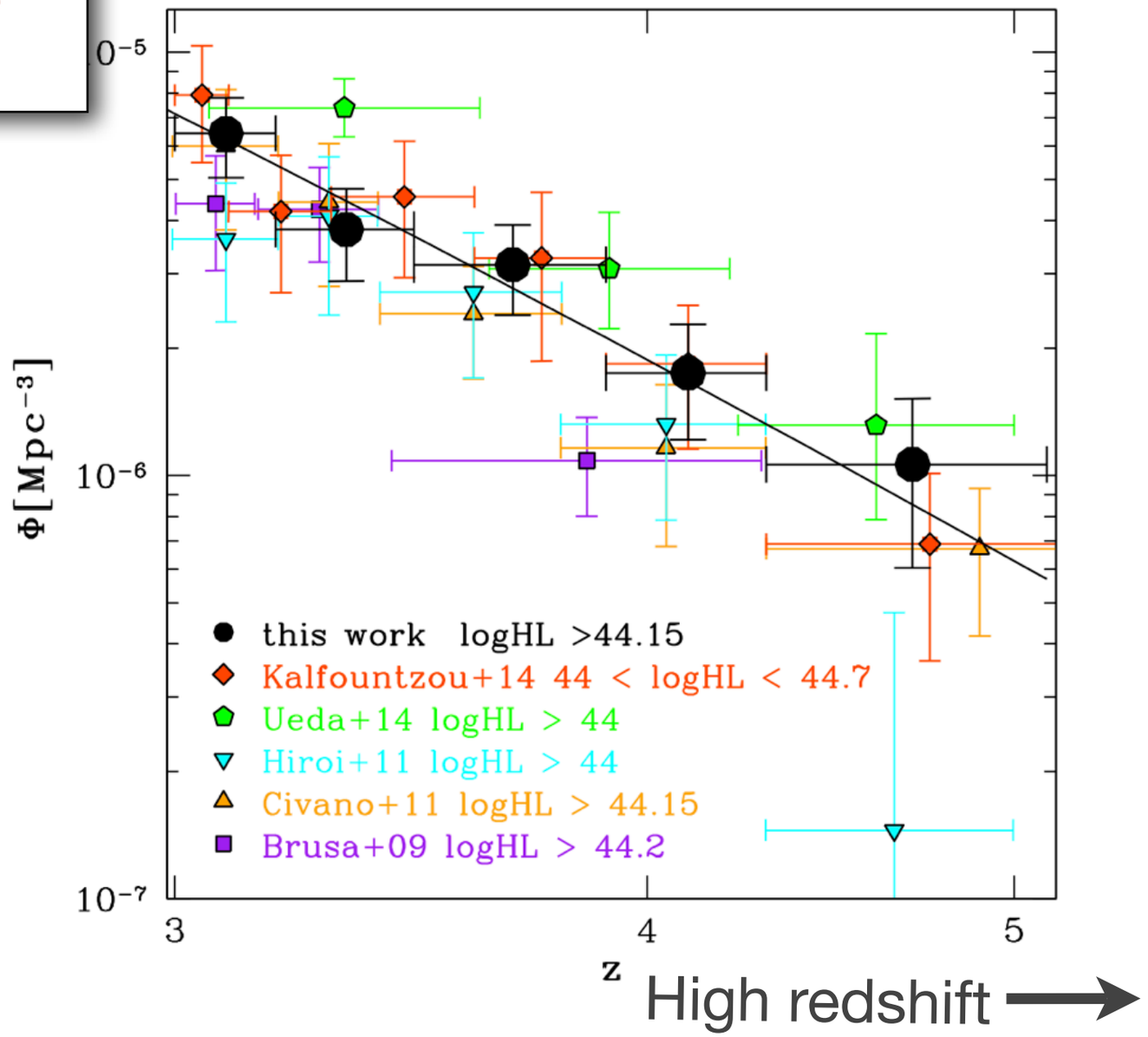
see also
Ueda et al. (2014),
Miyaji et al. (2015),
Buchner et al. (2015)

The evolution of the **space density** of AGN from z~0 to z~5

- **Luminosity-dependent** evolution
- Strong decline in space densities at $z > 3$ for **all** luminosities



Data points= Miyaji et al. (2015)
Lines+shading = Aird et al. (2015)

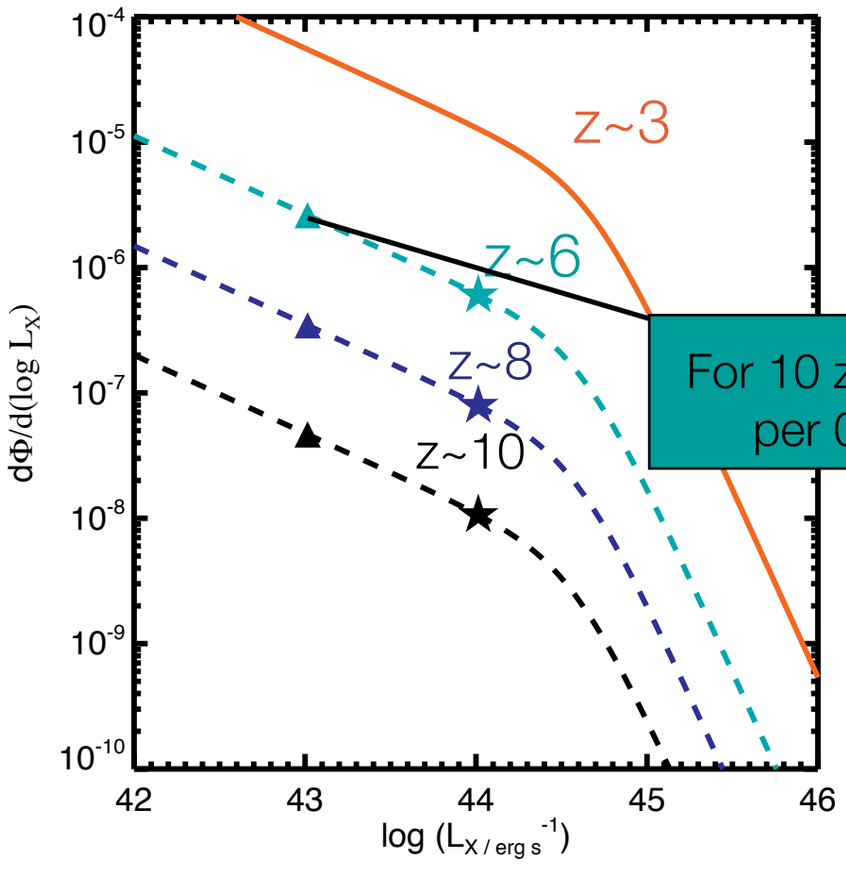


Vito et al. (2014)
see also Georgakakis et al. (2015), Weigel et al. (2015)

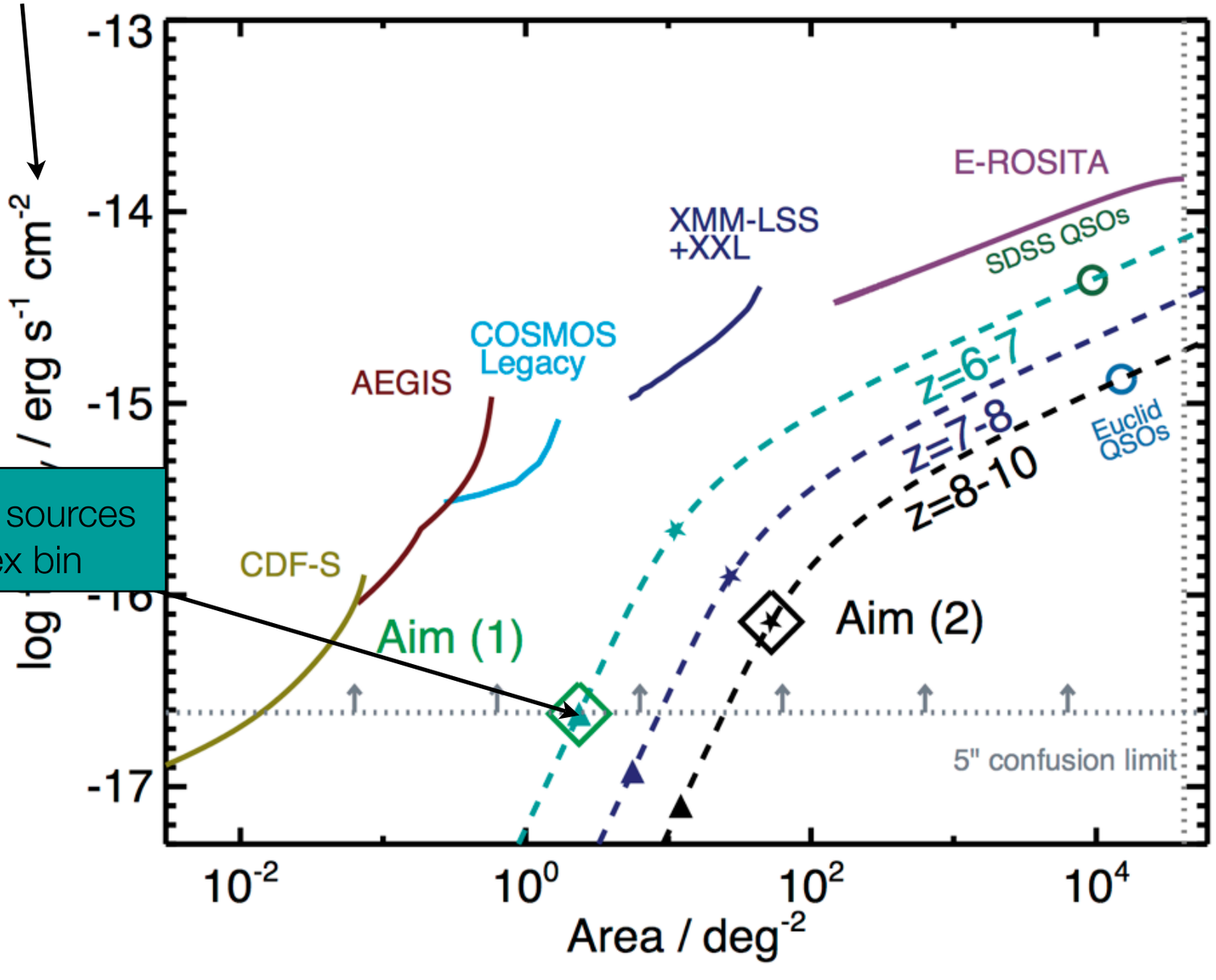
Detecting X-ray AGN at the highest redshifts

Soft (0.5-2 keV) band

Scaling z~3 XLF assuming strong density evolution



For 10 z=6-7 sources per 0.5 dex bin



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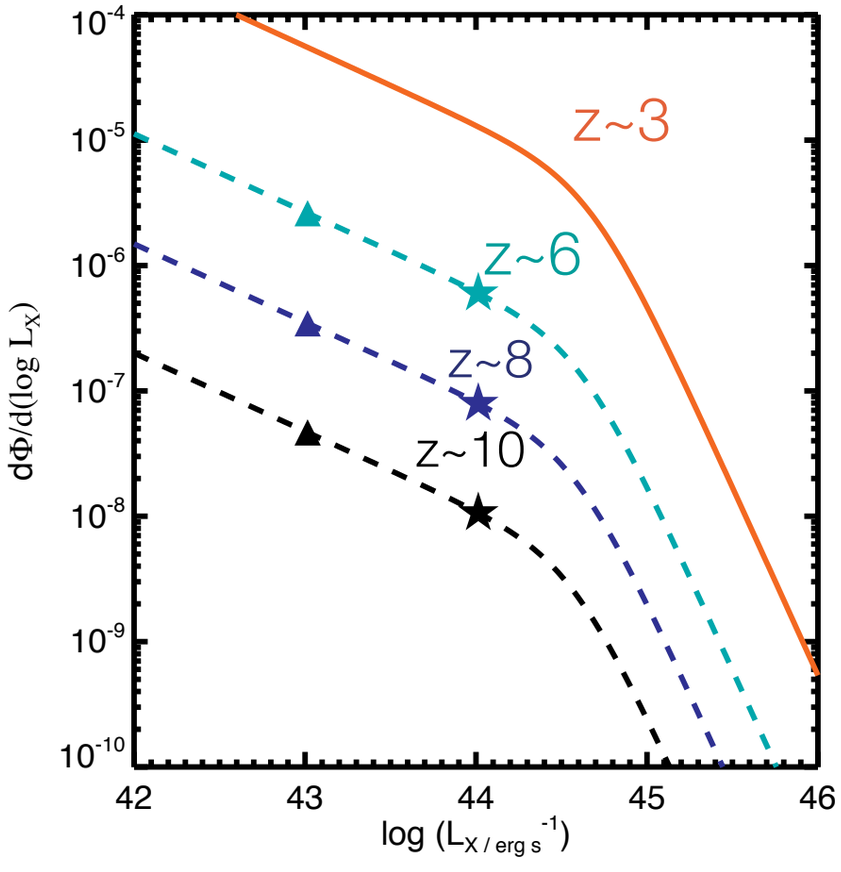

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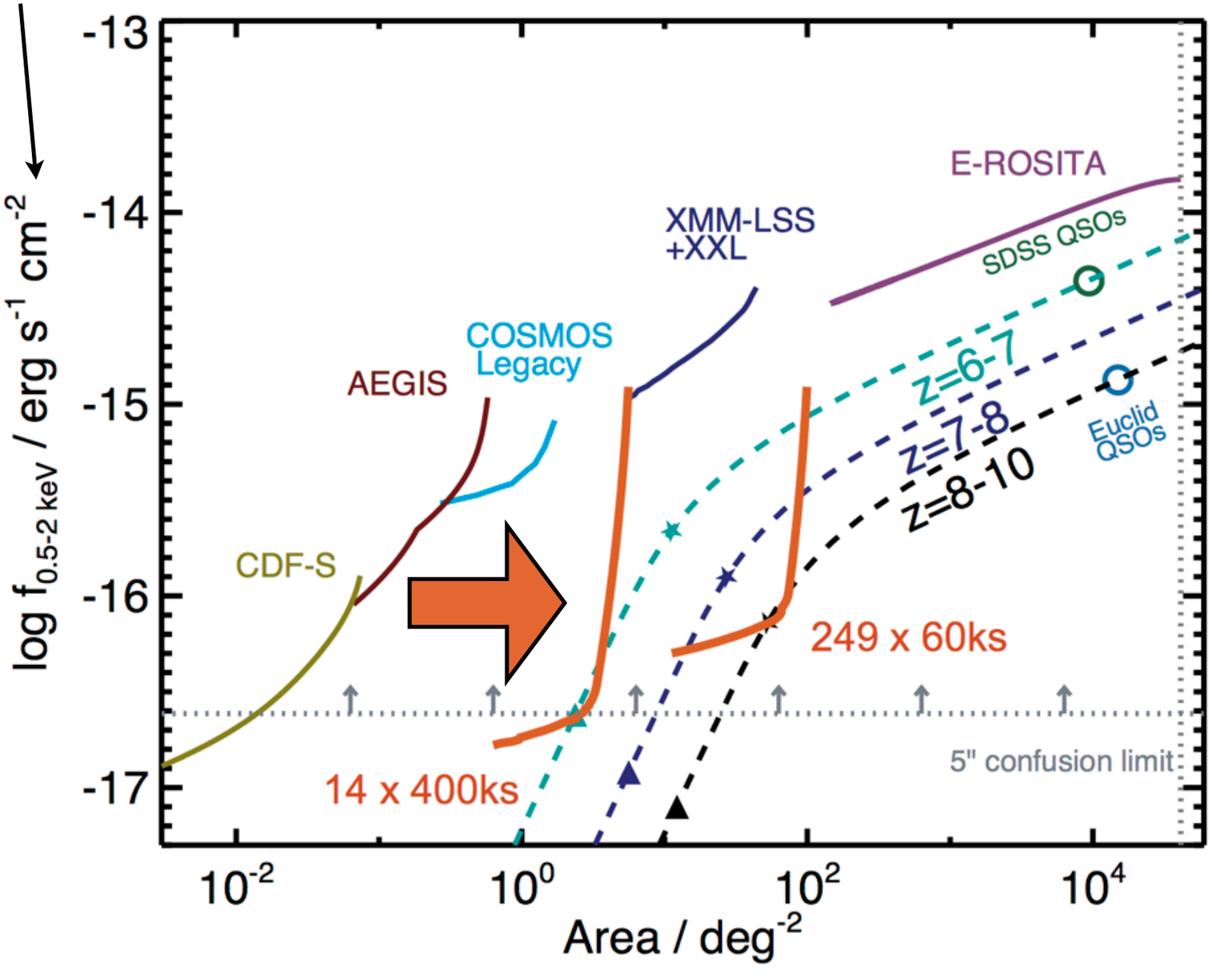
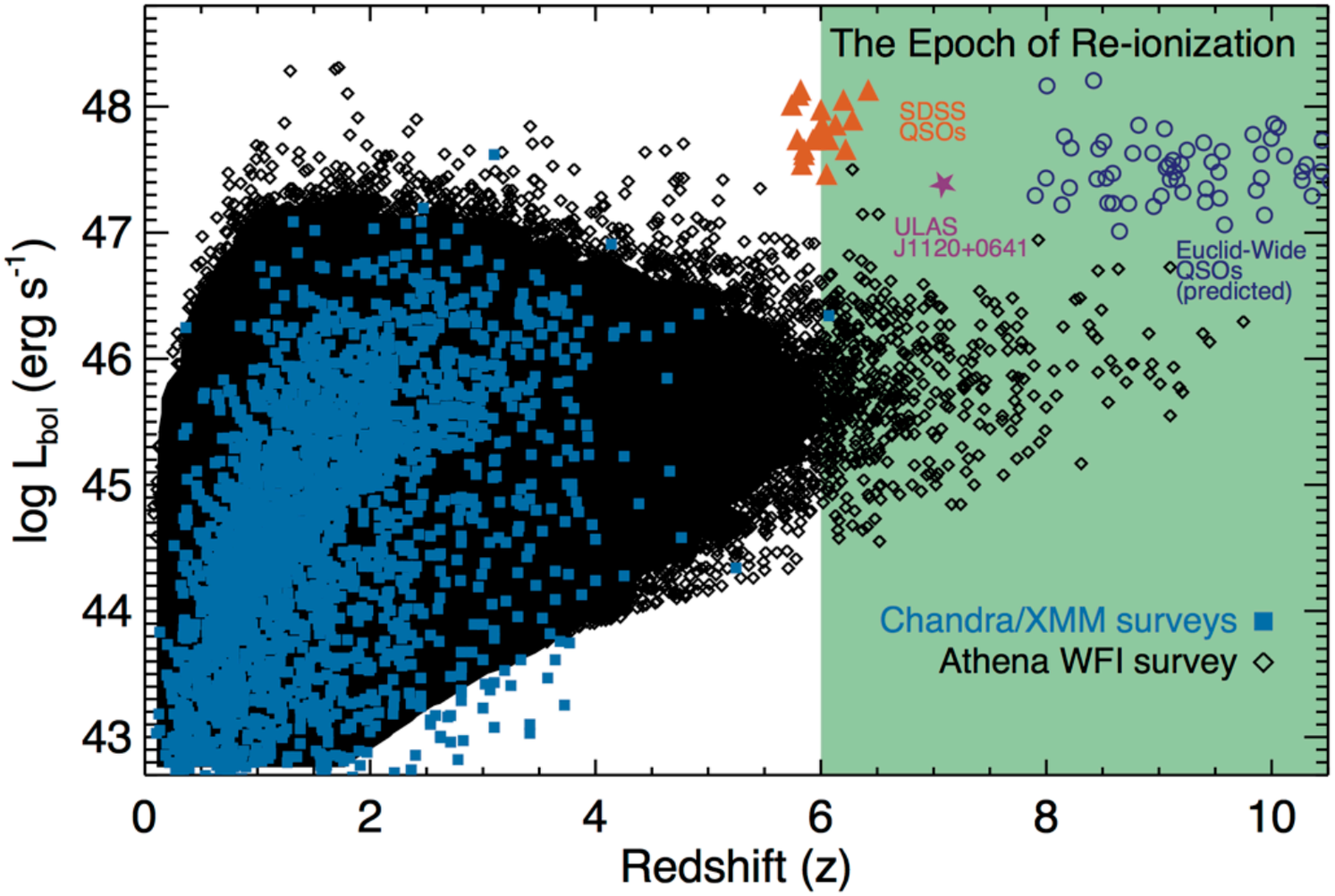


Athena WFI survey **~100** times faster than Chandra or XMM

Athena WFI survey for z>6 AGNs

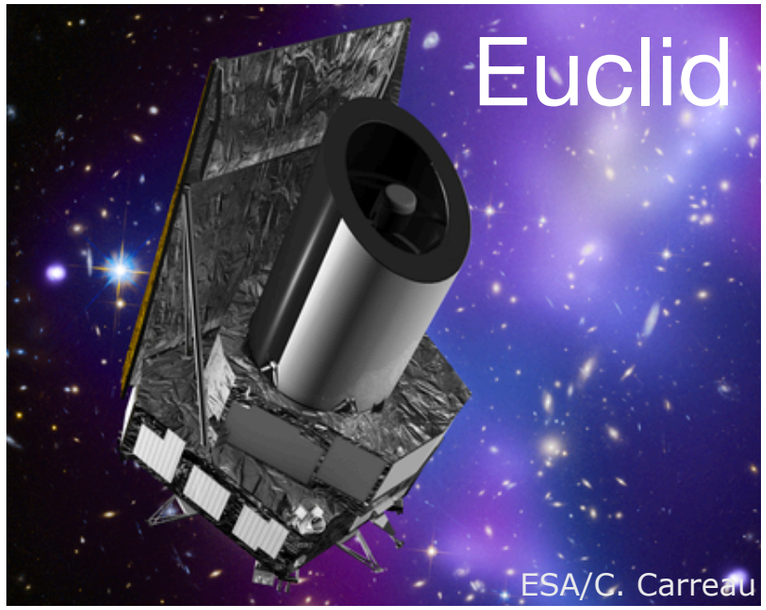
- A multi-layered Athena WFI survey, taking ~25 Ms will identify >600,000 AGNs, **including >400 AGNs at z>6**

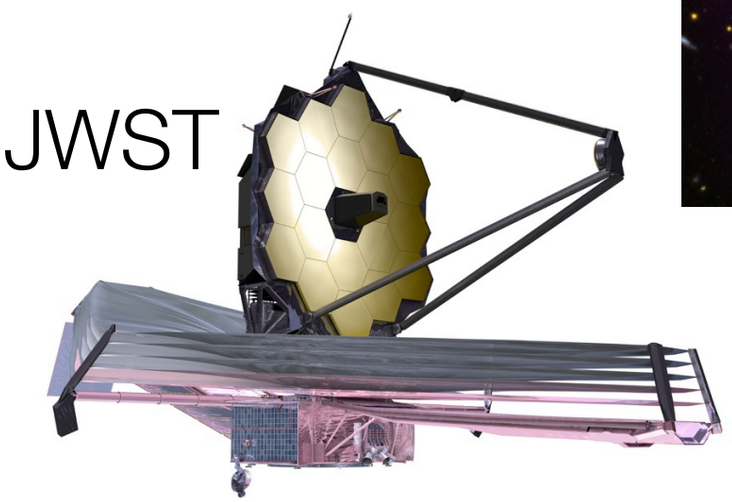
➔ Key challenge: identifying multiwavelength counterparts to Athena X-ray detections and estimating their redshifts

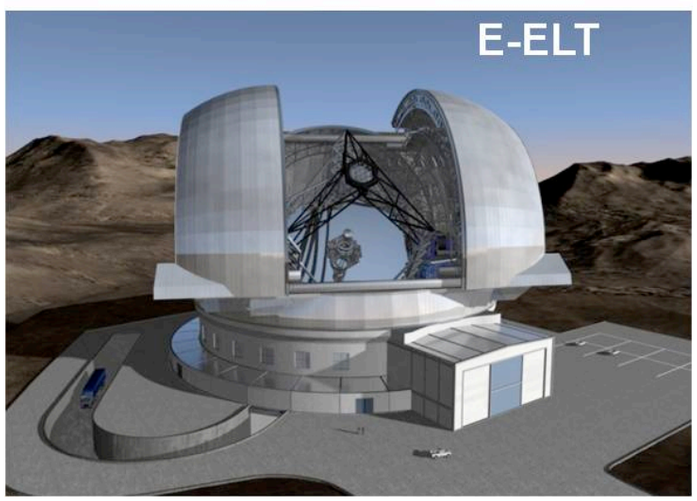


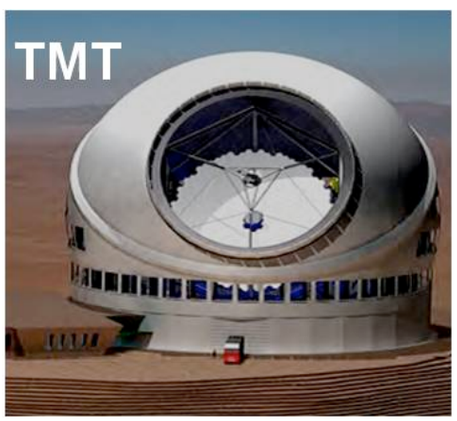
Counterparts to Athena X-ray sources (in the late 2020s)

- ~50 deg^2 Athena 'shallow' (~60ks) surveys will be well matched in depth/area to forthcoming deep optical/near-infrared surveys (e.g. Euclid, HyperSuprimeCam, LSST)
- JWST imaging required to identify counterparts in deep Athena surveys (~2 deg^2, 400ks)?
- *Athena* will pinpoint (low-L/obscured) AGNs within samples of early (z>6) galaxies - efficiently tracing SMBH **accretion** activity
- Further follow-up with ELTs, ALMA, JWST for
  - spectroscopic redshifts
  - host properties (stellar mass, star formation rates, dust masses etc.)









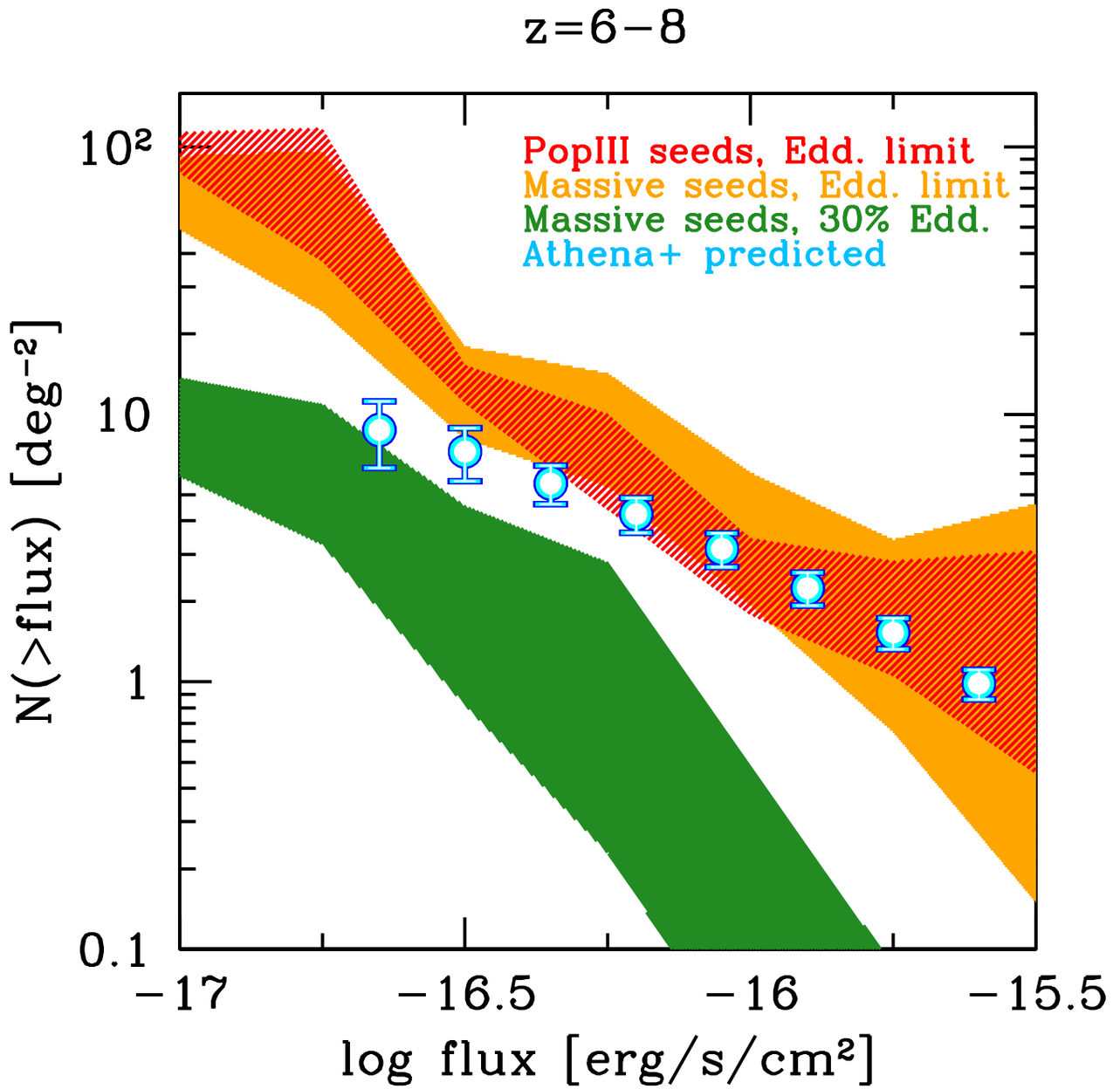
Constraints on seed formation and early growth?

- Detection of an AGN with $L_X = 10^{43}$ erg s^{-1} at z = 6
  => $M_{BH} >\sim 2 \times 10^6 M_{sun}$
  (assuming ~Eddington limited)

- Detection of an AGN with $L_X = 10^{44}$ erg s^{-1} at z = 8
  => $M_{BH} >\sim 2 \times 10^7 M_{sun}$
  (assuming ~Eddington limited)

Athena will **not** identify SMBH seeds immediately after their formation

but samples **will** constrain the extent of early mass growth and possible seed mechanisms



Next steps for Athena: (1) scientific challenges

- How do we expect the (moderate-luminosity) AGN population to evolve in the early (z>6) universe?
    - Theoretical framework?
    - What can we learn **now** from lower redshift (z~0-5) sources?
    - What can we learn **now** from the high-luminosity z>6 QSO population?

- What can we learn about the environment/types of galaxies where early black hole growth takes place from the multiwavelength information?

- What constraints can *Athena* place on seed formation/early growth mechanisms?

- How else can we study early SMBH formation/growth with Athena? e.g.
    - Low-luminosity AGN in dwarf galaxies at later times: a more direct tracer of seed SMBHs and their formation environments?
    - X-ray spectroscopic studies of known high-z QSOs **(see Brandt talk)**

Next steps for Athena: (2) technical challenges

- Optimised survey strategy - field-of-view, overlap, chip gaps, dither pattern
  see poster 4.03 by Fabio Vito
- Confusion limit - source detection and deblending techniques for a 5” PSF
- Counterpart identification
  - Optical/IR imaging requirements, photo-z techniques
  - spectroscopic follow-up campaigns
  - Host galaxy properties
- X-ray spectral information for z>6 sourc
  (see also Francisco
- Full end-to-end simulations of WFI surve
  multiwavelength data?)

TP 2.1 meeting,
lunchtime on Thursday
in the “Printing room”

Take home points

- *Athena* WFI surveys will identify >400 ‘typical’ AGNs at z >6
    - ~100 times faster survey power than *Chandra* or *XMM-Newton*.

- *Athena* will thus trace the growth of early SMBHs at $z > 6$ and place constraints on their formation and growth mechanisms

- *Athena* is well-matched and complementary to next generation of optical/near-IR photometric surveys. A large WFI survey will pinpoint AGN accretion activity within samples of high-z galaxies.

- Ongoing work to develop scientific and technical expertise in preparation for the *Athena* era