The formation and growth of the earliest supermassive black holes

James Aird & Andrea Comastri

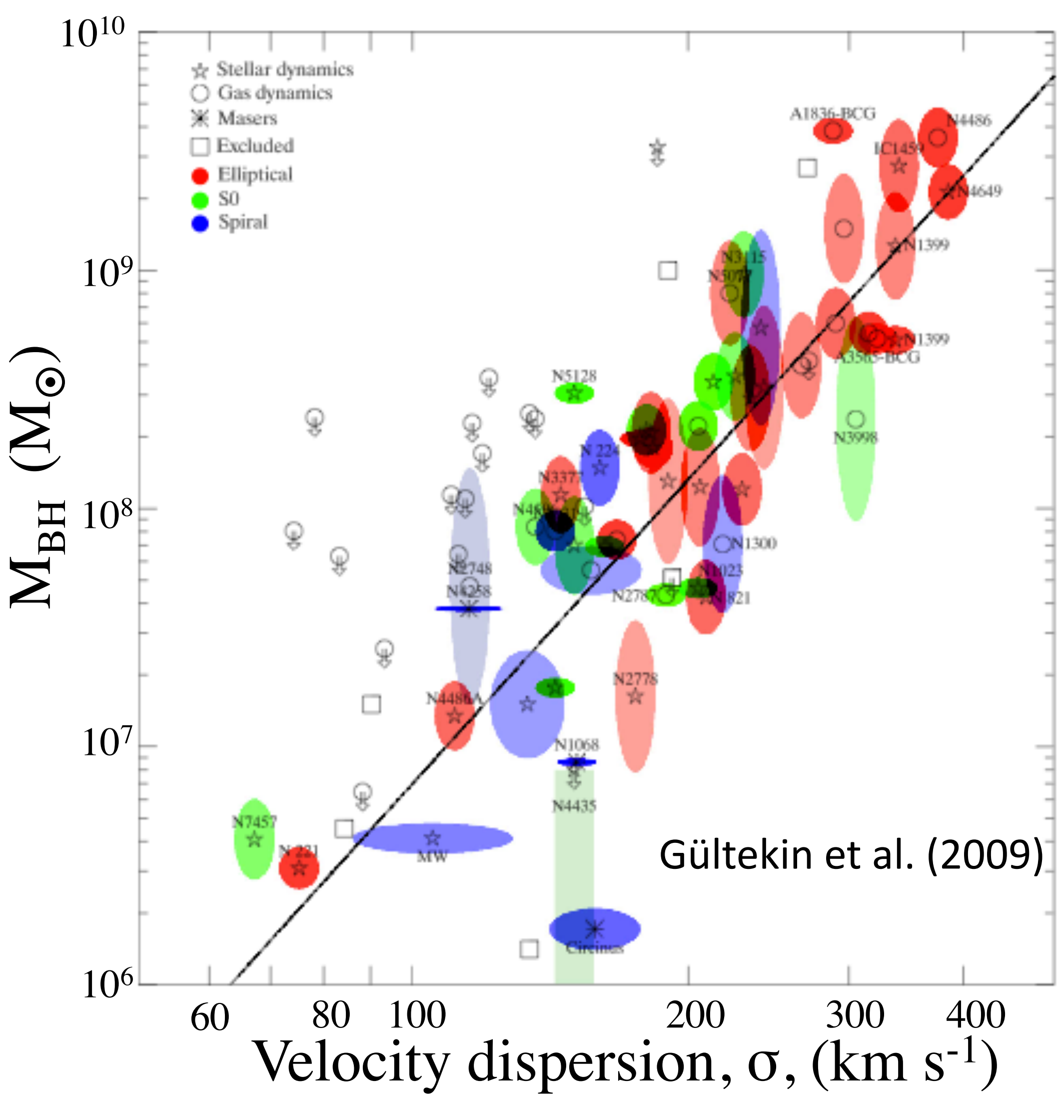
on behalf of Topical Panel 2.1

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

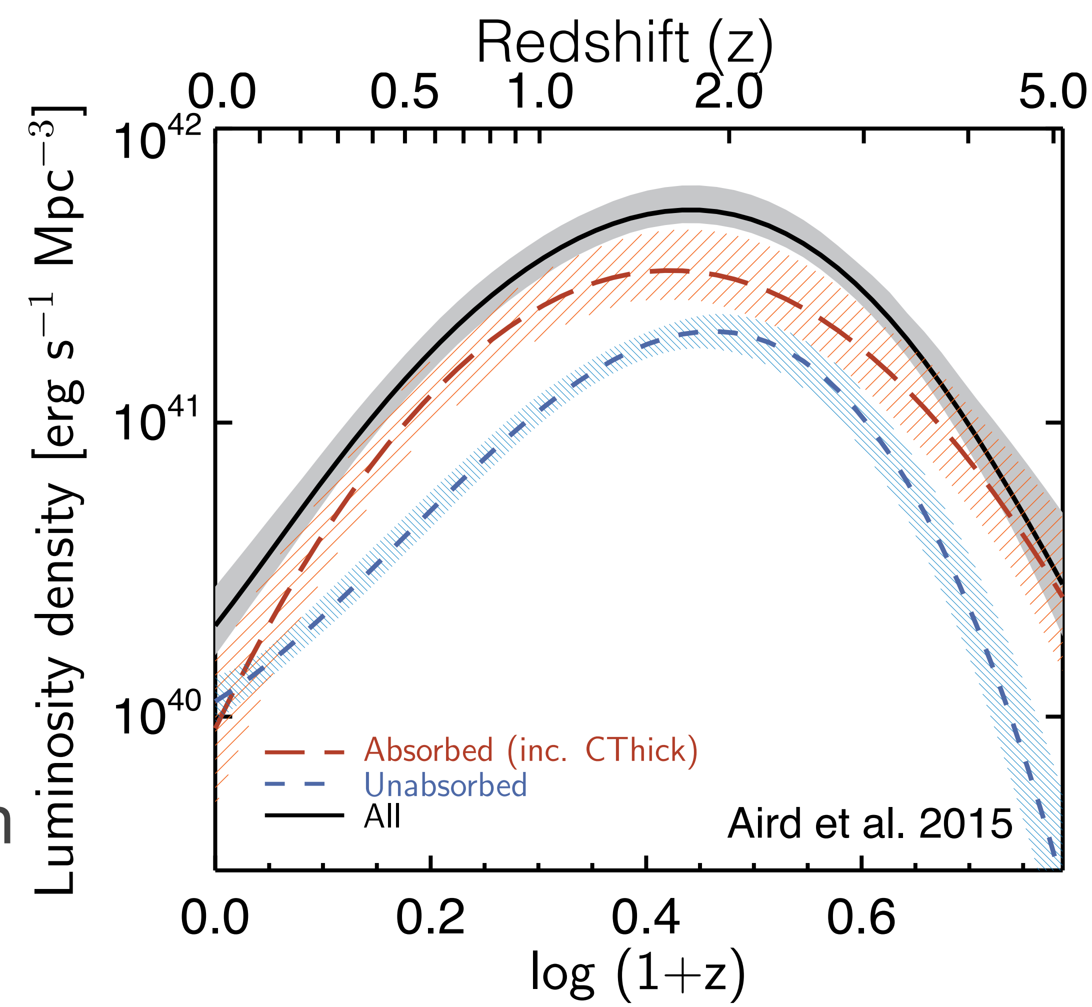
Bulk of SMBH mass is built up via accretion (AGN), peaking at z~1-3

SMBH mass



~host galaxy bulge mass

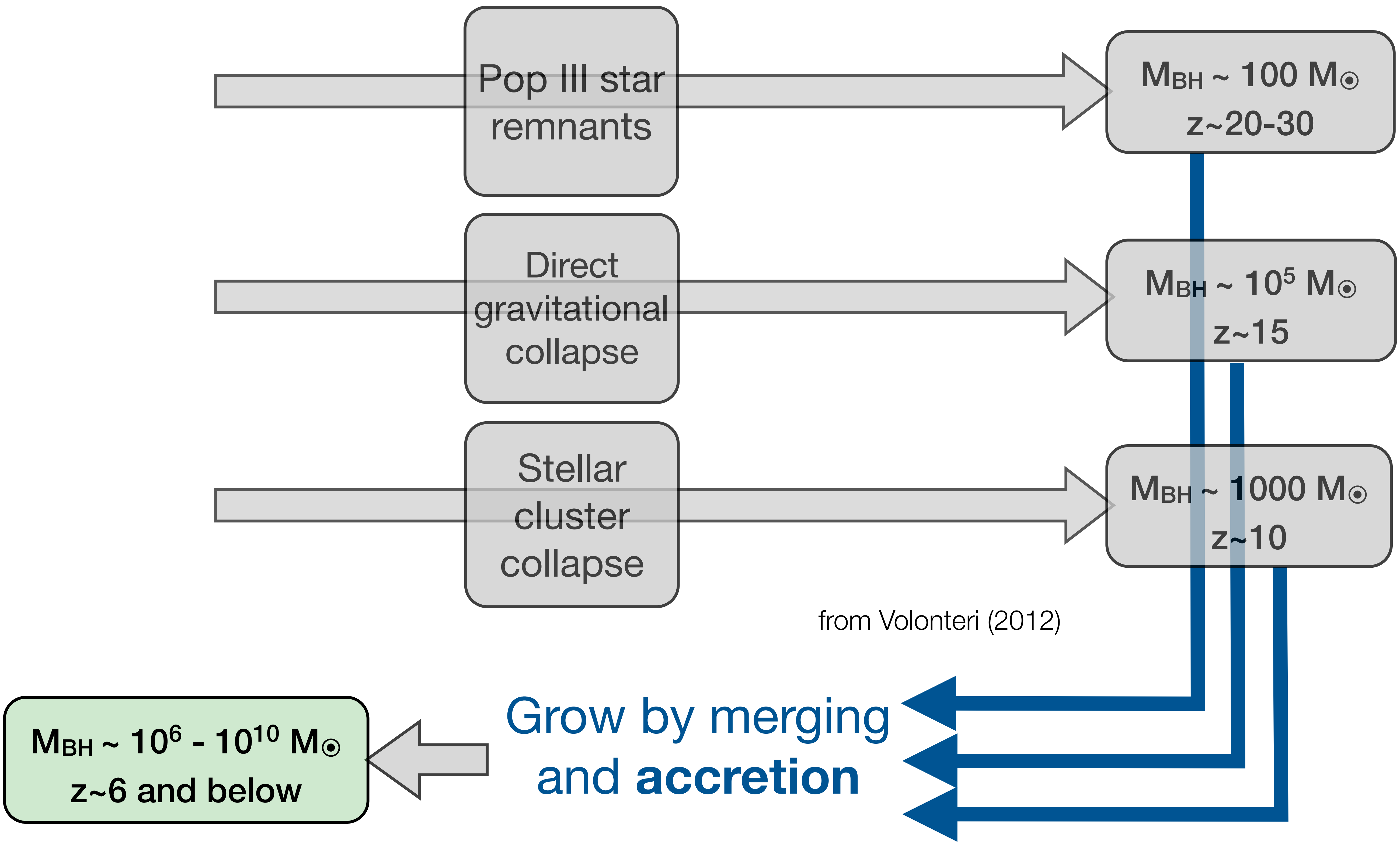
Rate of SMBH growth via accretion



Late (recent) cosmic time

Early cosmic times

SMBH seed formation mechanisms



Athena (level 1) science aims

Athena shall

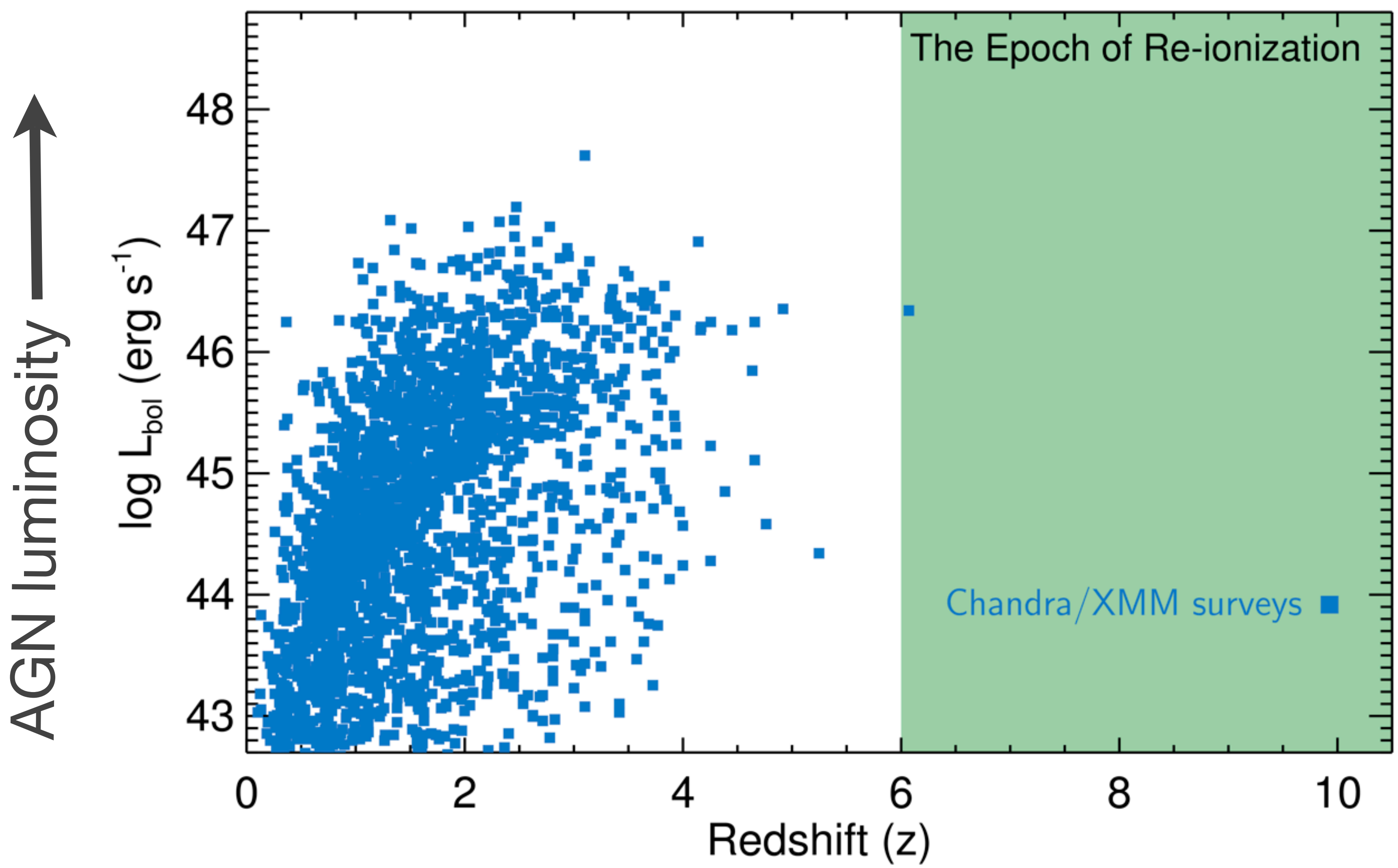
- determine the nature of the seeds of the earliest growing SMBHs (at $z>6$)
- characterise the processes that dominated their early growth
- investigate the influence of accreting SMBHs on the formation of galaxies.

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*

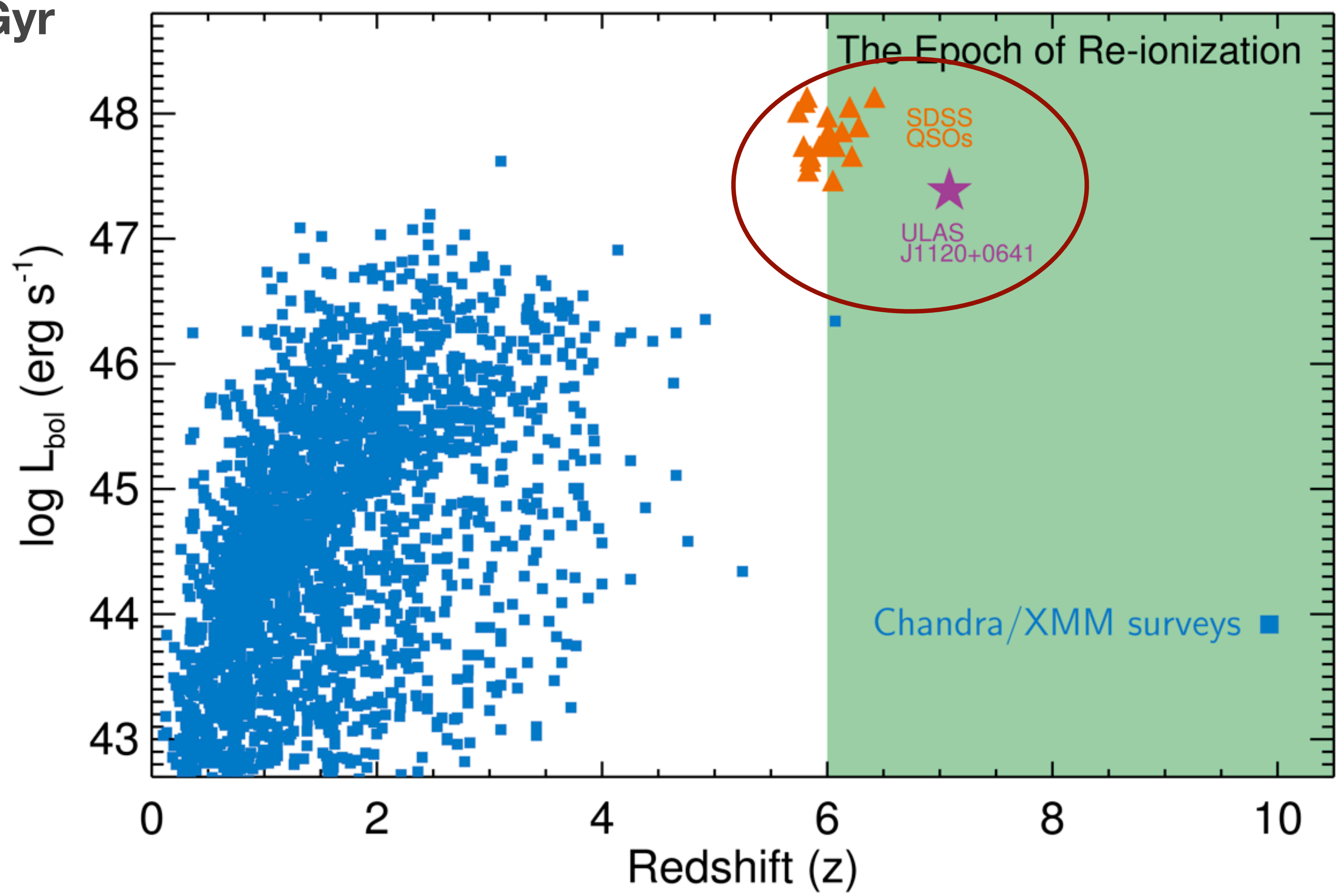
- X-ray surveys are extremely efficient at finding AGN over a wide range of luminosities
- AGN dominate over galaxy X-ray emission
  - find fainter AGN, generally not identified by optical or IR selection
- Less affected by obscuration than optical/UV

- 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 **$M_{BH} \sim 10^9\ M_\odot$**, comparable to the **most massive** SMBHs in the local Universe, but when the age of the Universe was only **<1Gyr**



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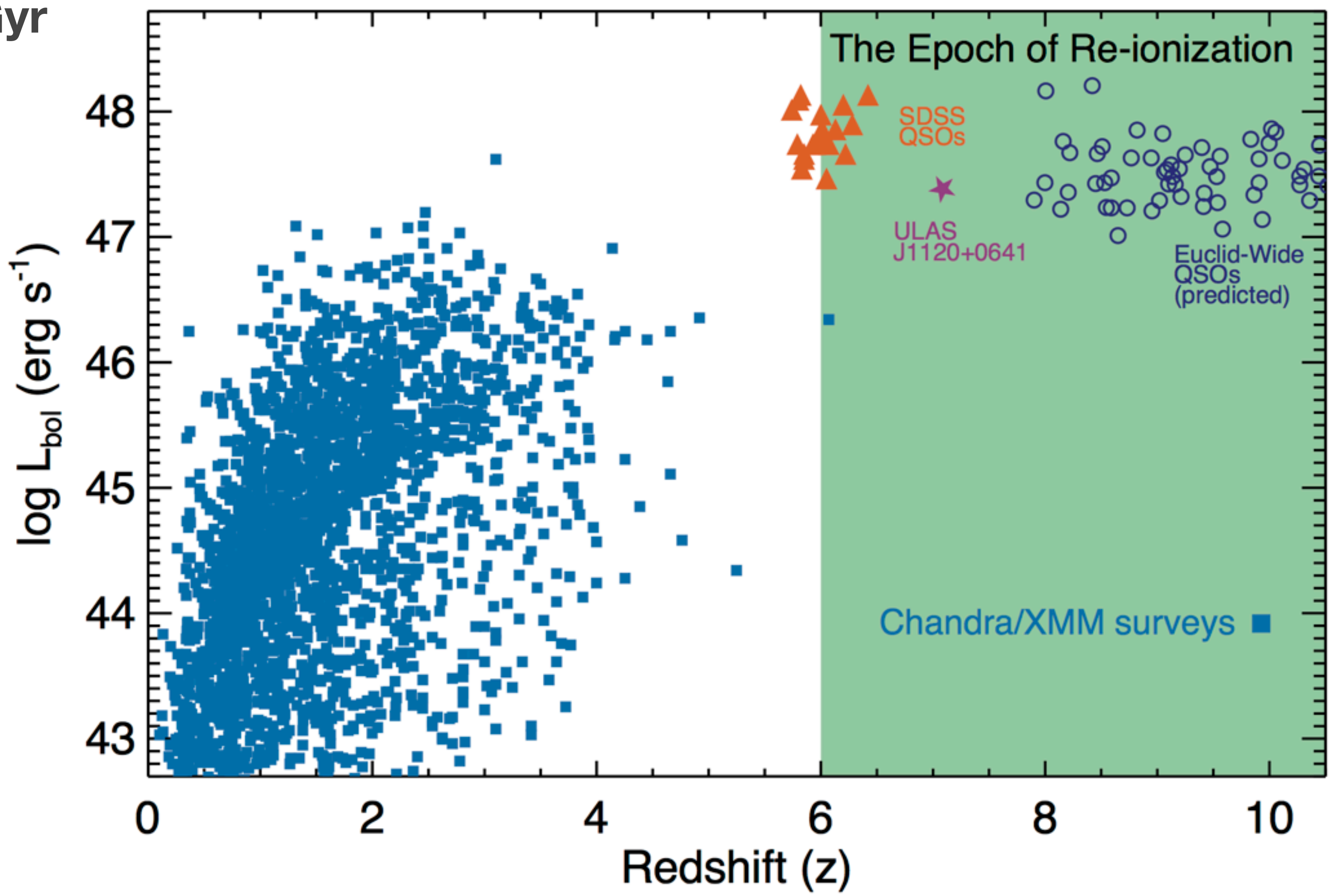
- Euclid surveys are expected to identify AGNs at z ~ 8 – 10 but will still be limited to the most luminous, unobscured sources (e.g. Roche et al. 2012)



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

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

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

cosmic time

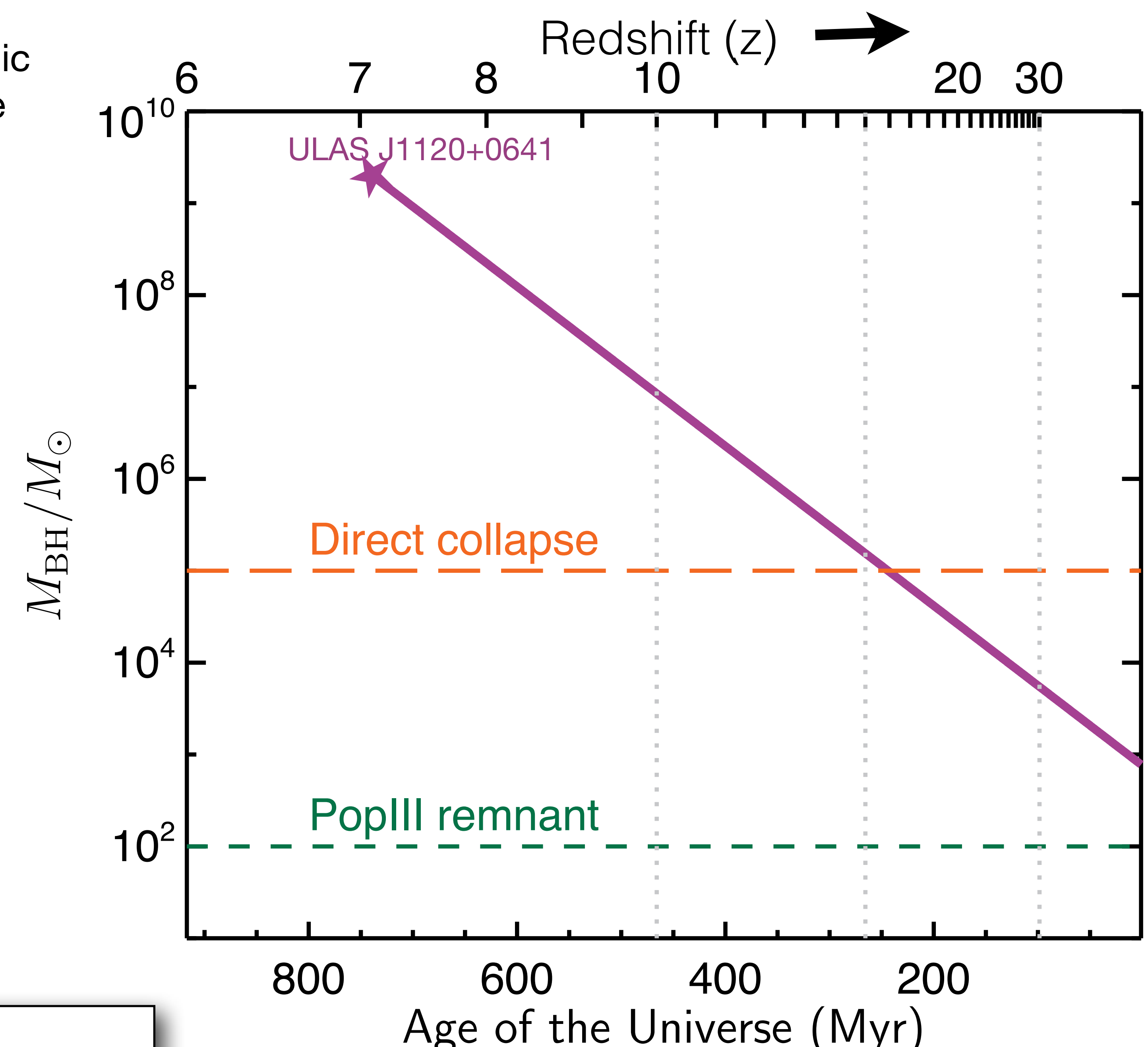
seed mass

radiative efficiency ~0.1

Eddington ratio ~1

- The seed of ULAS J1120 (z=7.083, M_{BH}≈2 x 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



Cosmic Time

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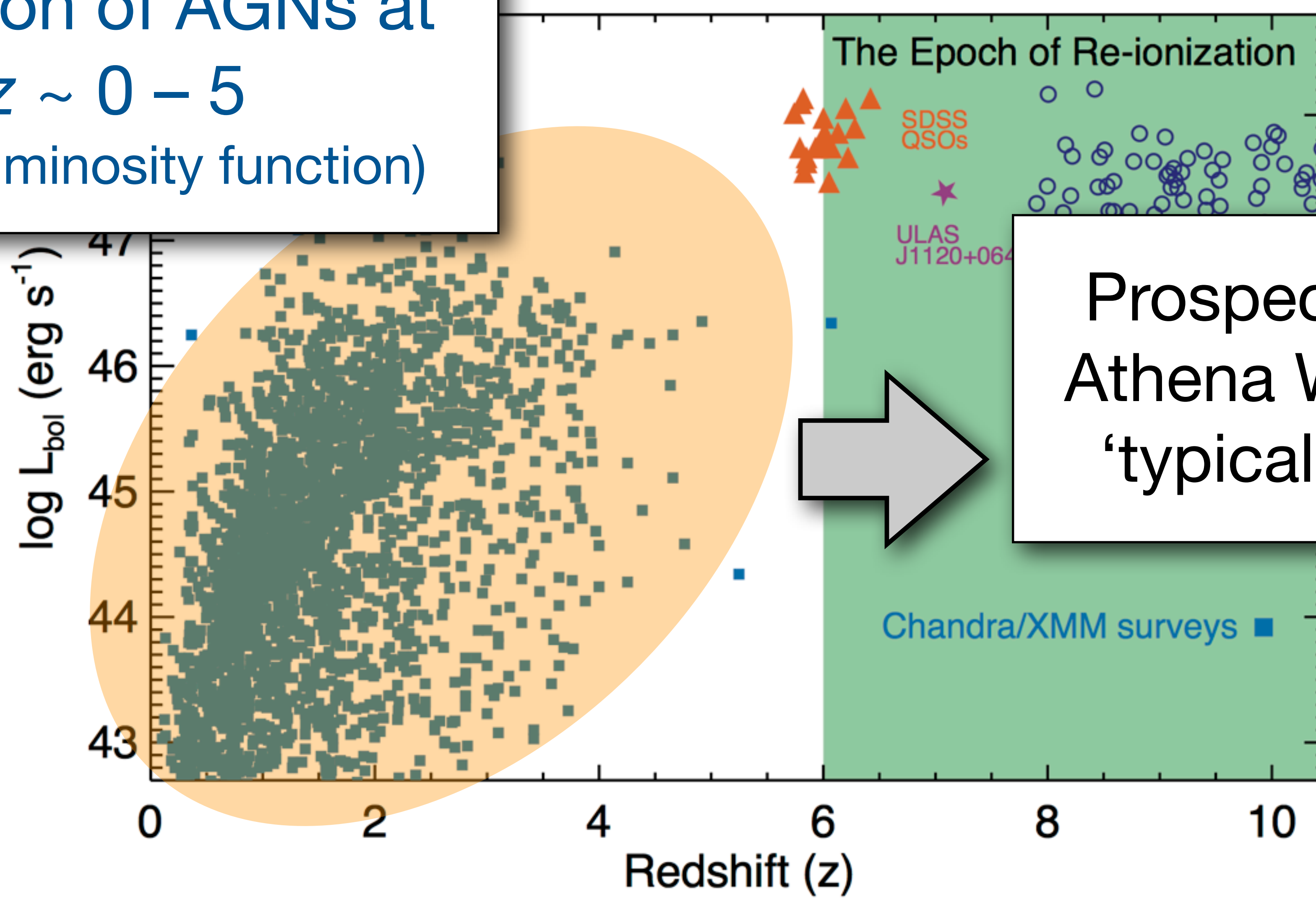
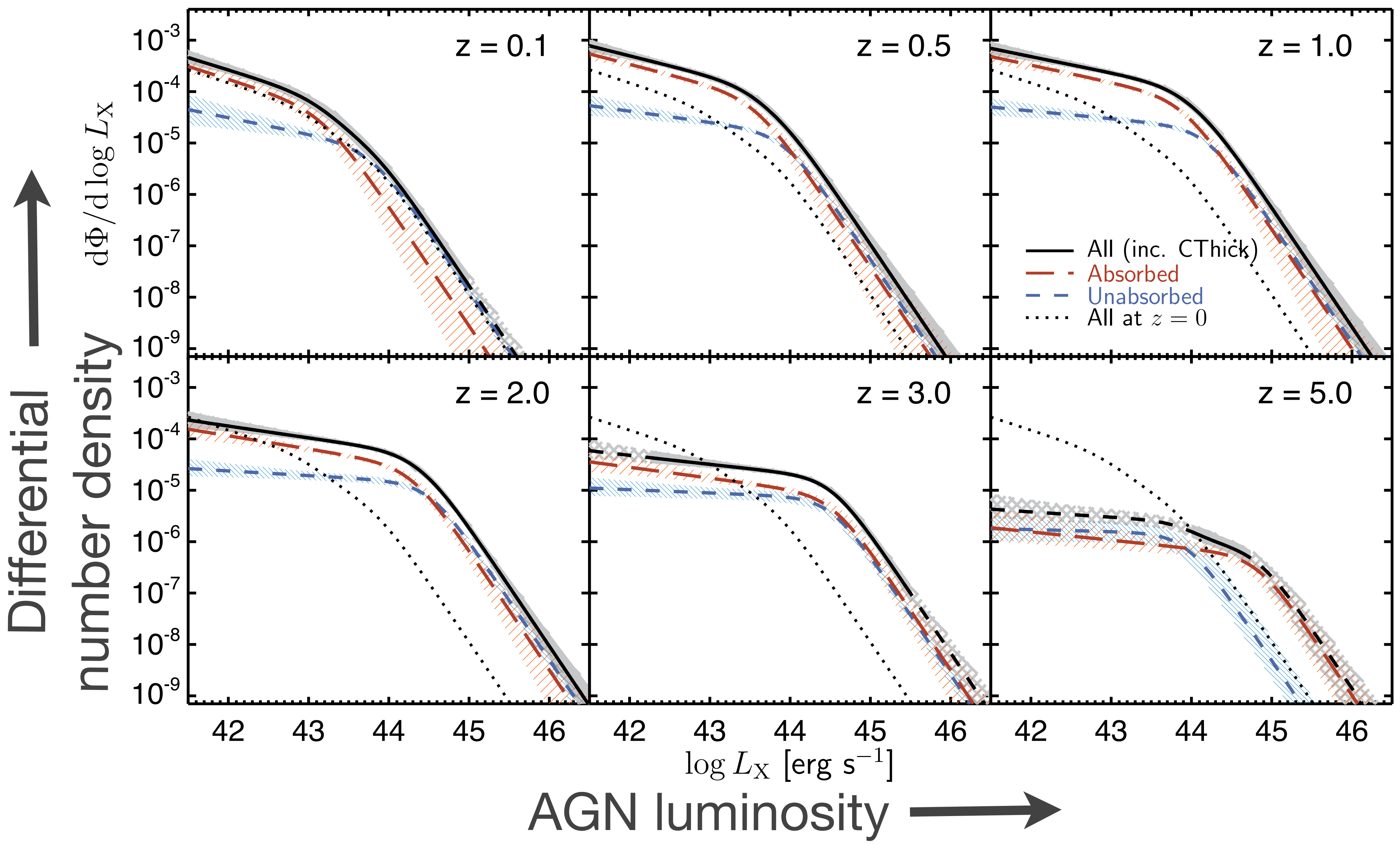
Latest constraints on evolution of AGNs at $z \sim 0 - 5$
(X-ray luminosity function)



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)

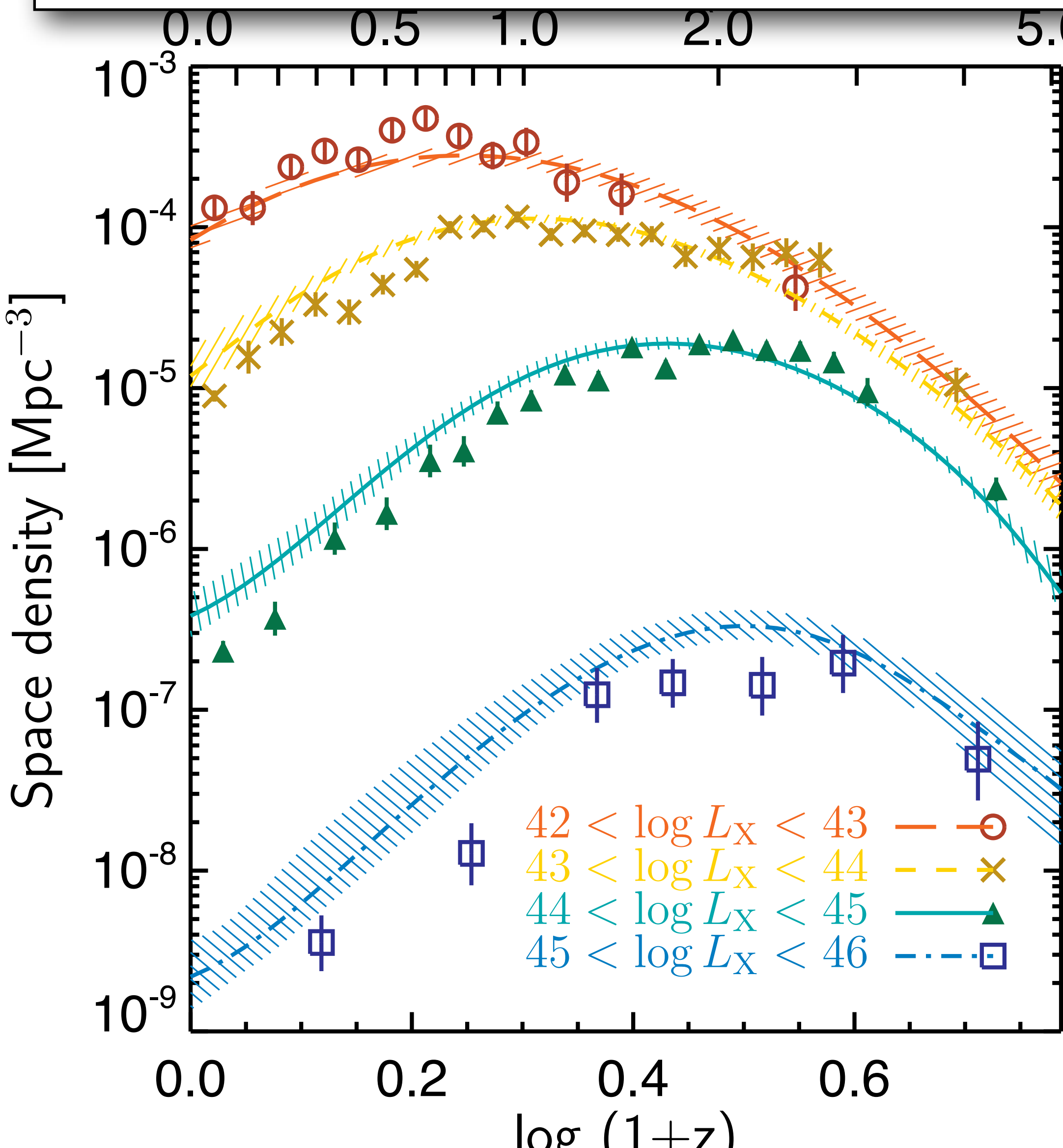
Evolution of the XLF is due to combination of:

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

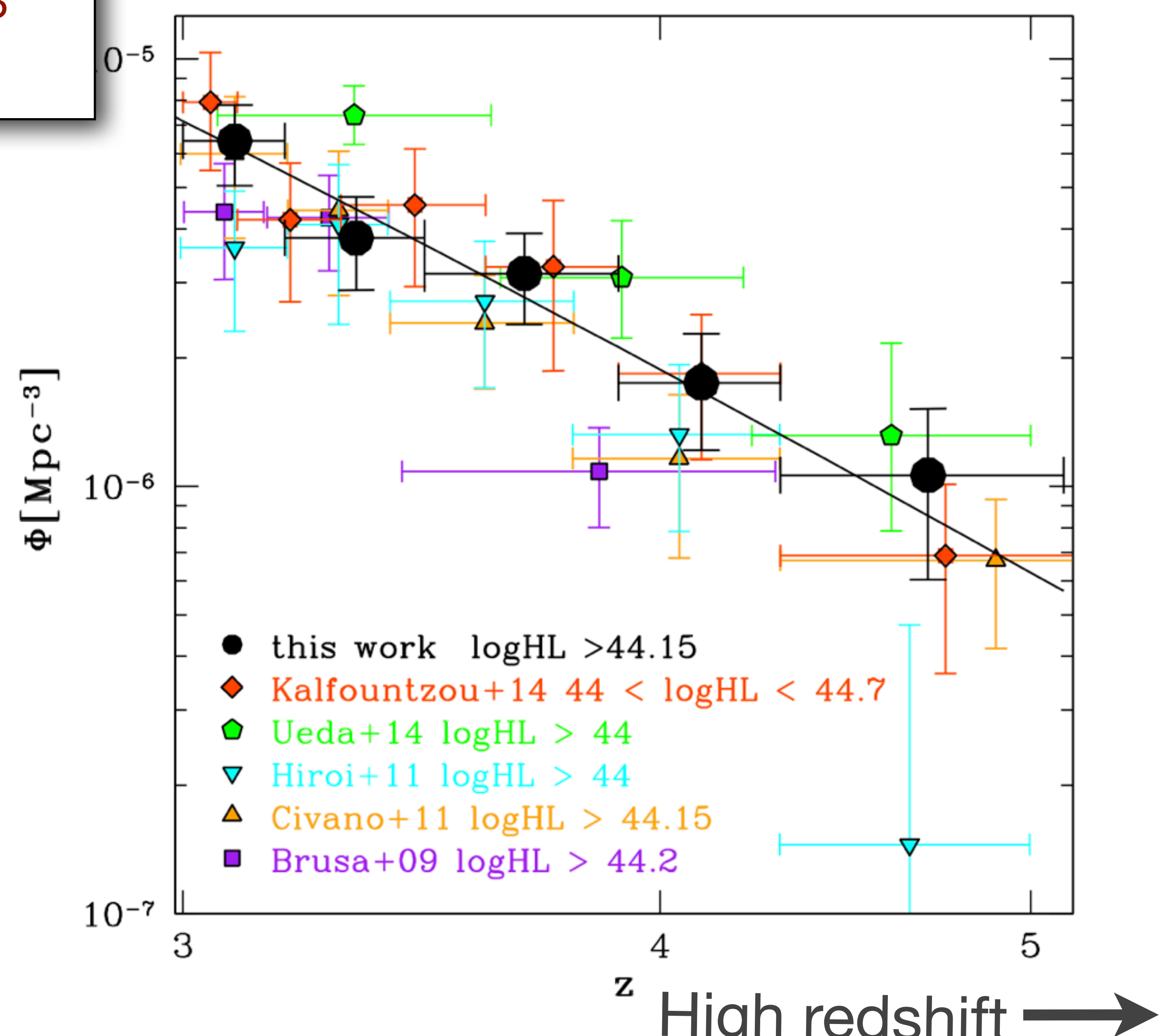
see also
Ueda et al. (2014),
Miyaji et al. (2015),
Buchner et al. (2015)

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



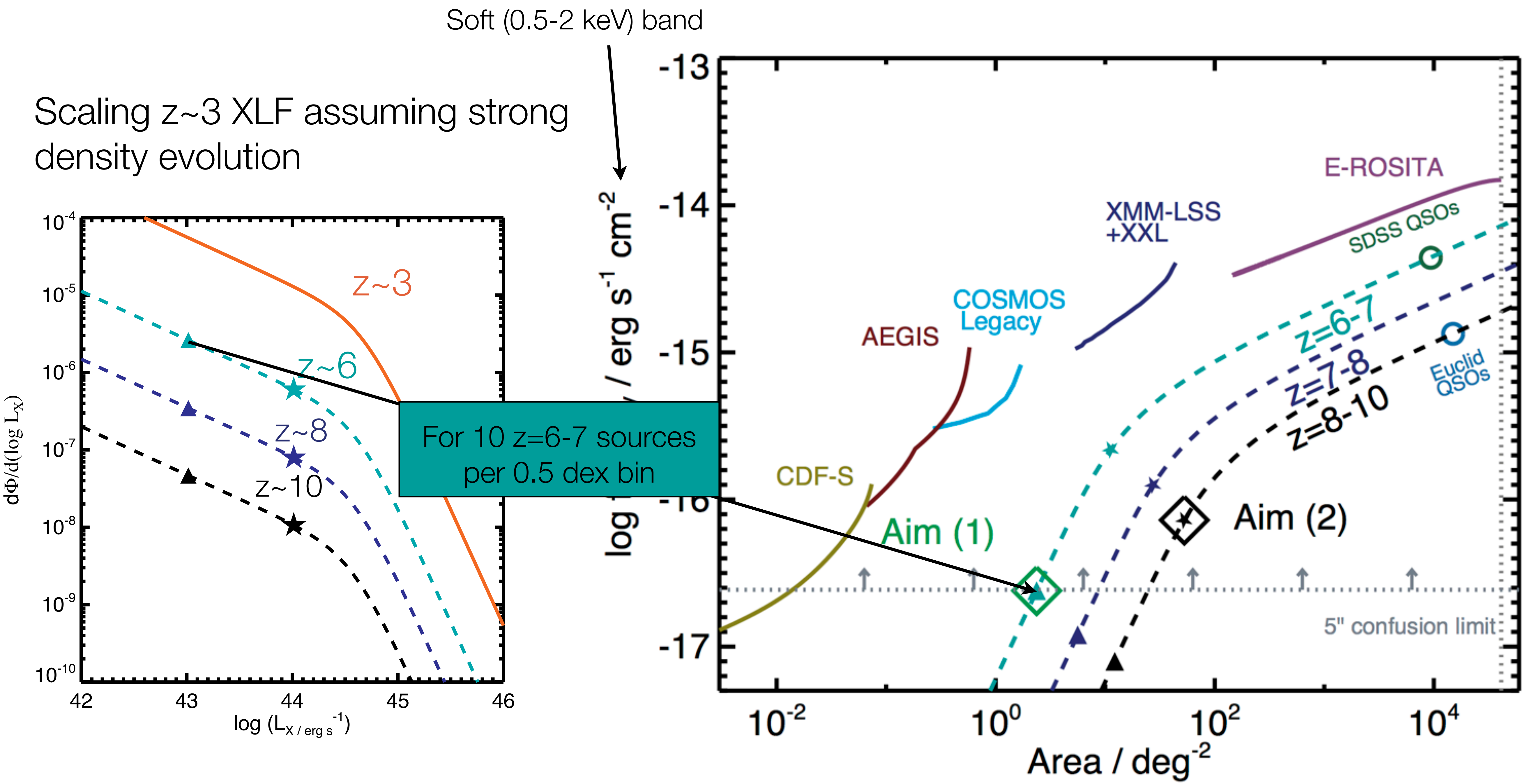
Data points= Miyaji et al. (2015)
Lines+shading = Aird et al. (2015)



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

Detecting X-ray AGN at the highest redshifts

Scaling z~3 XLF assuming strong density evolution



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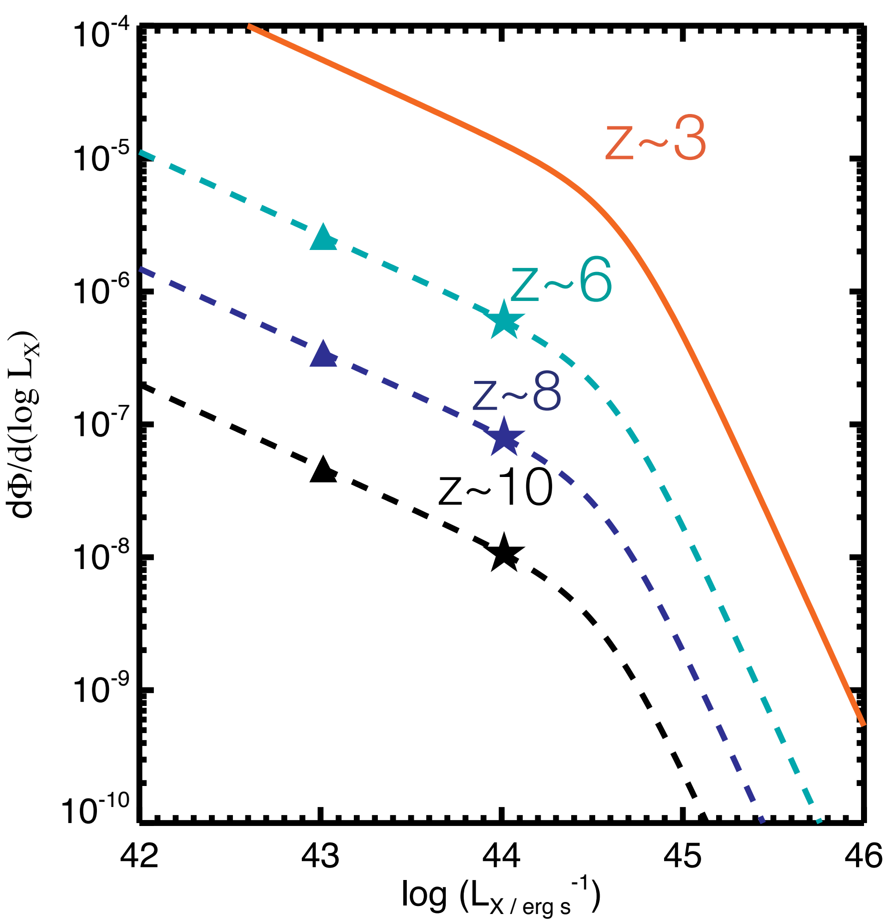
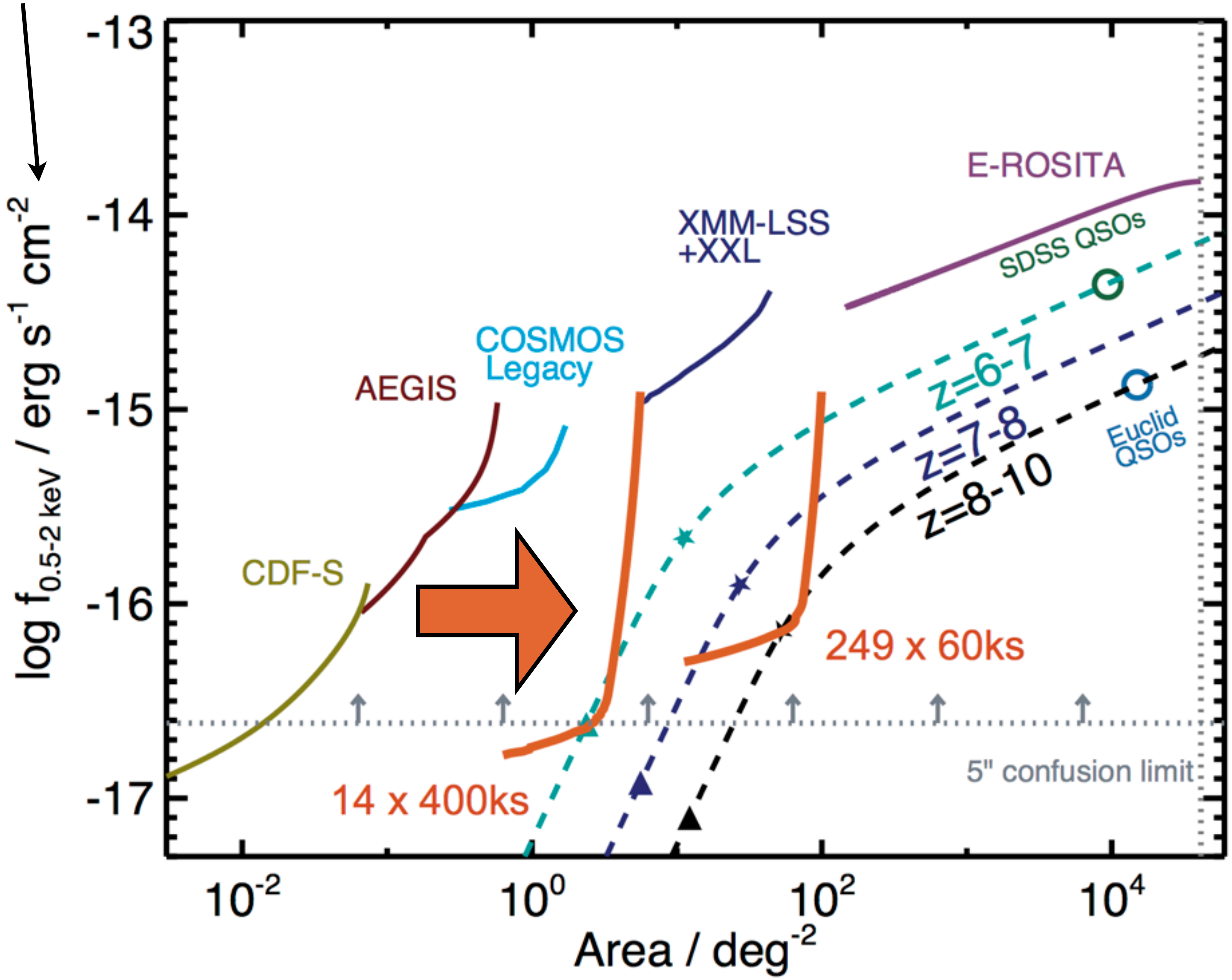


Soft (0.5-2 keV) band

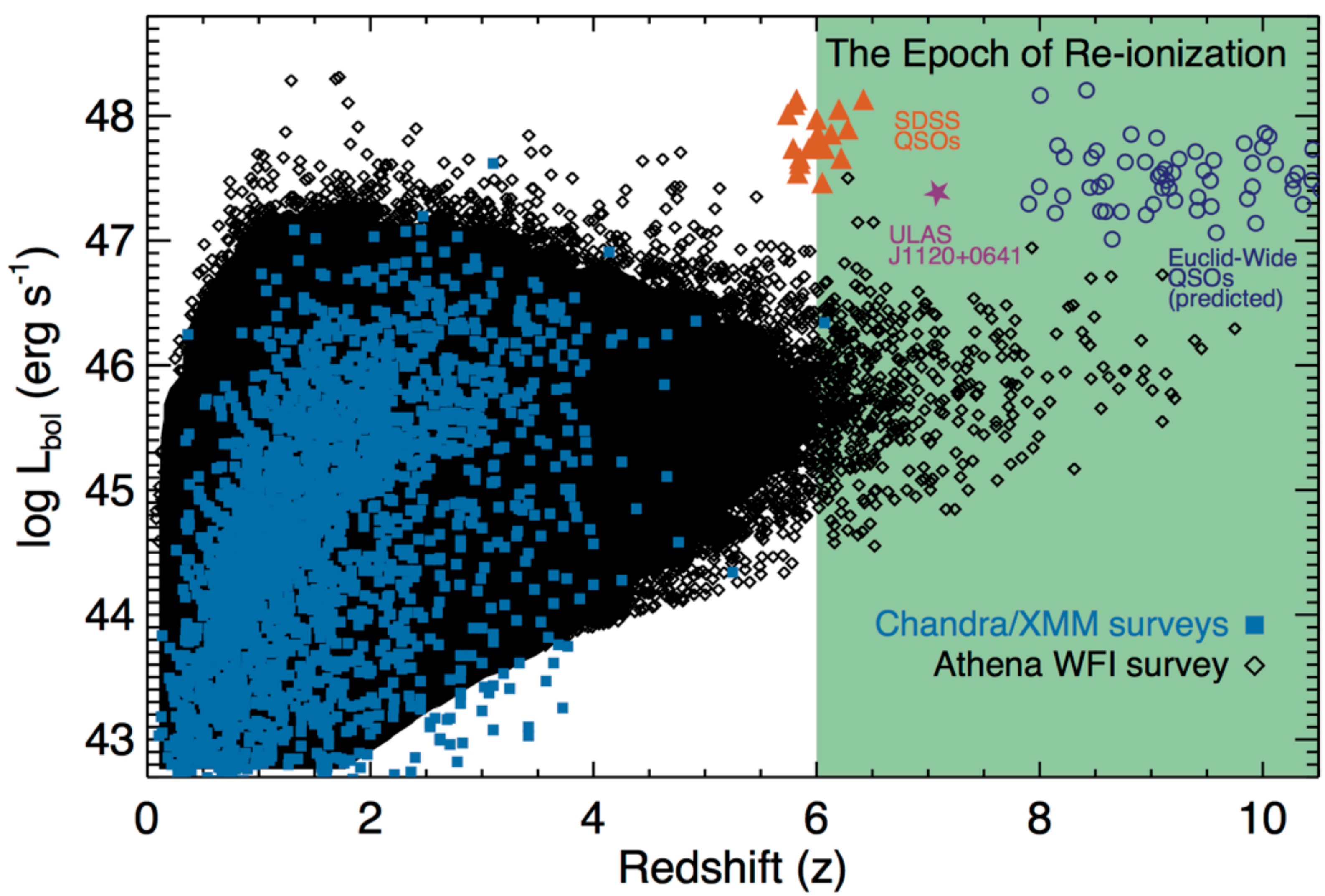


Athena WFI survey **~100** times faster than Chandra or XMM

Athena WFI survey for z>6 AGNs

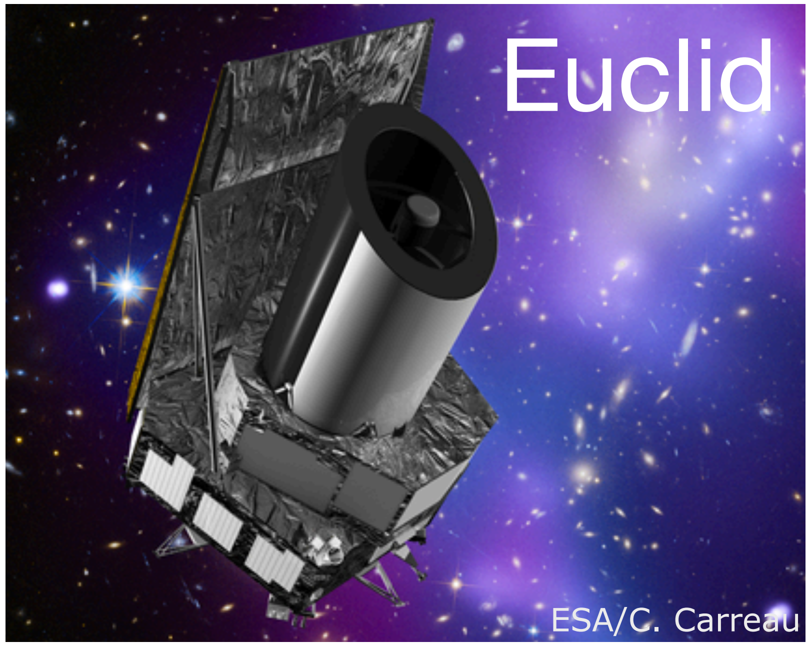
- A multi-layered Athena WFI survey, taking ~25 Ms will identify >600,000 AGNs, **including >400 AGNs at z>6**

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

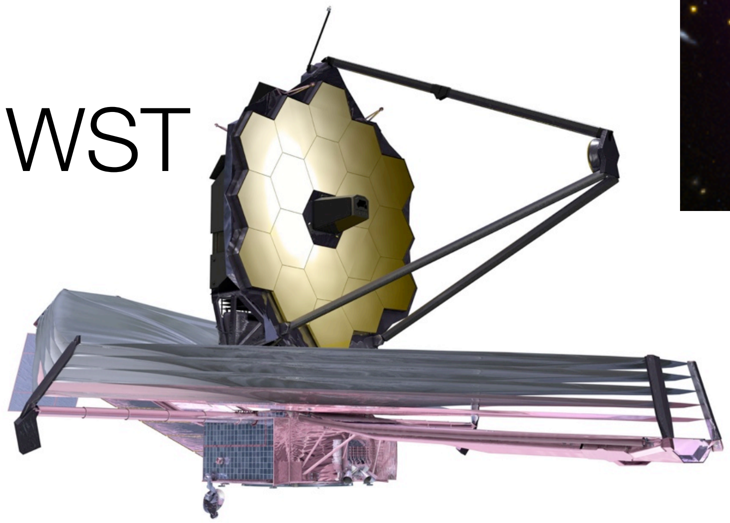


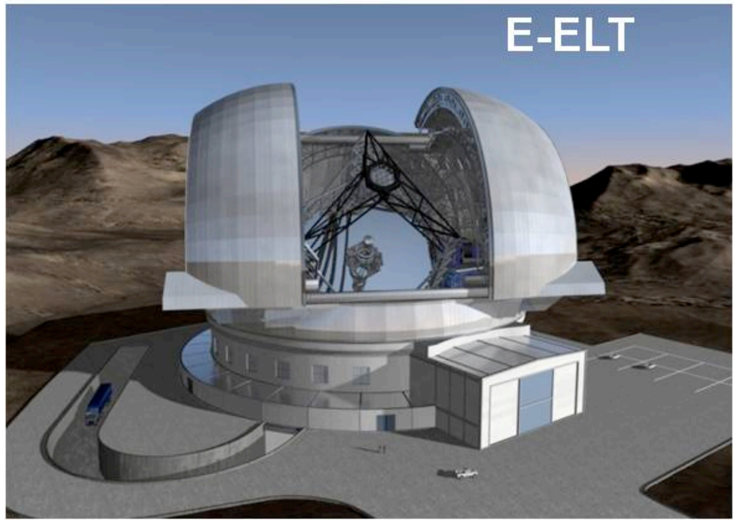
Counterparts to Athena X-ray sources (in the late 2020s)

- ~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.)



JWST





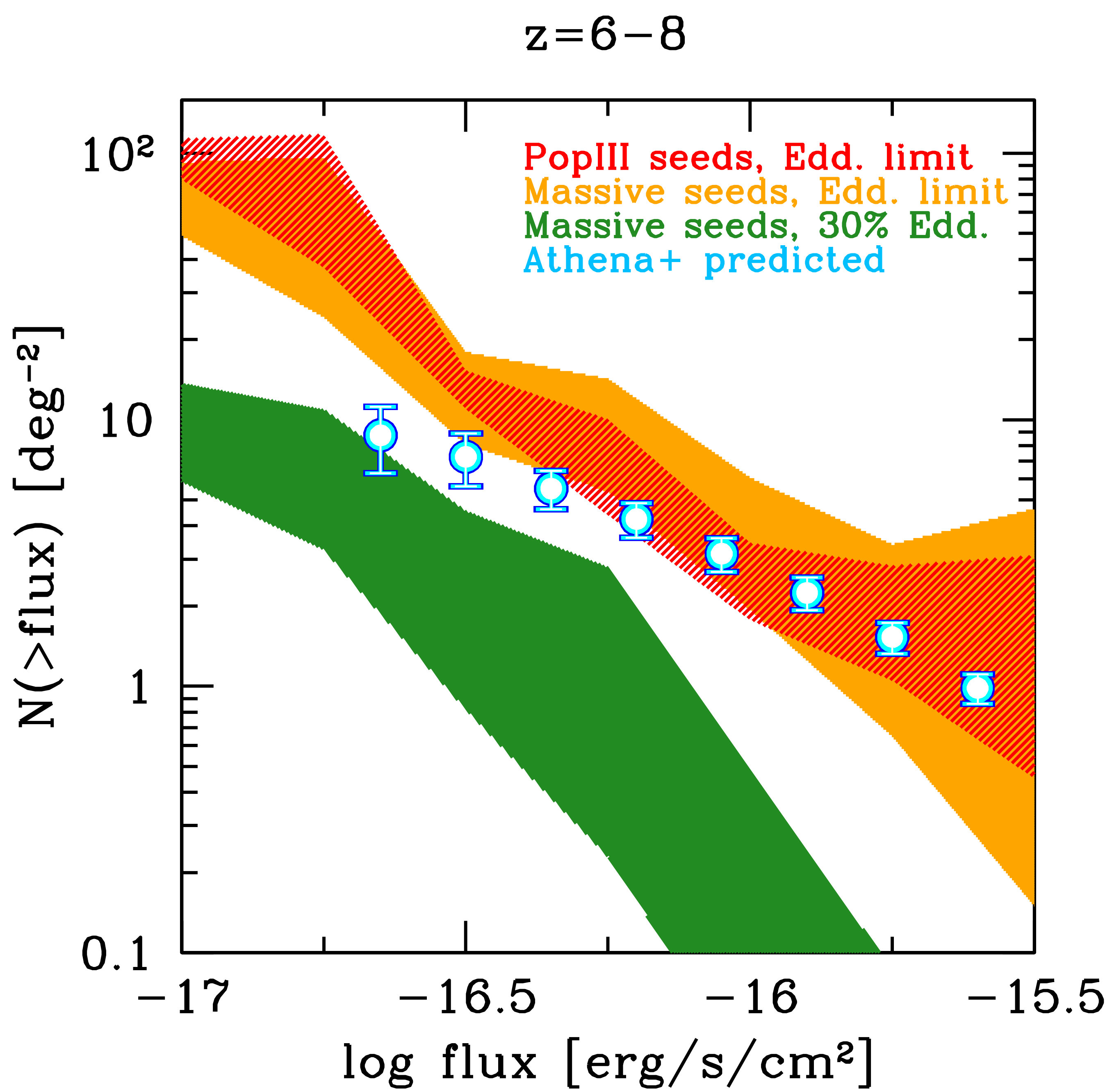
Constraints on seed formation and early growth?

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

- Detection of an AGN with $L_X = 10^{44}$ erg s^{-1} at $z = 8$
  => M_{BH} >~ 2×10^{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