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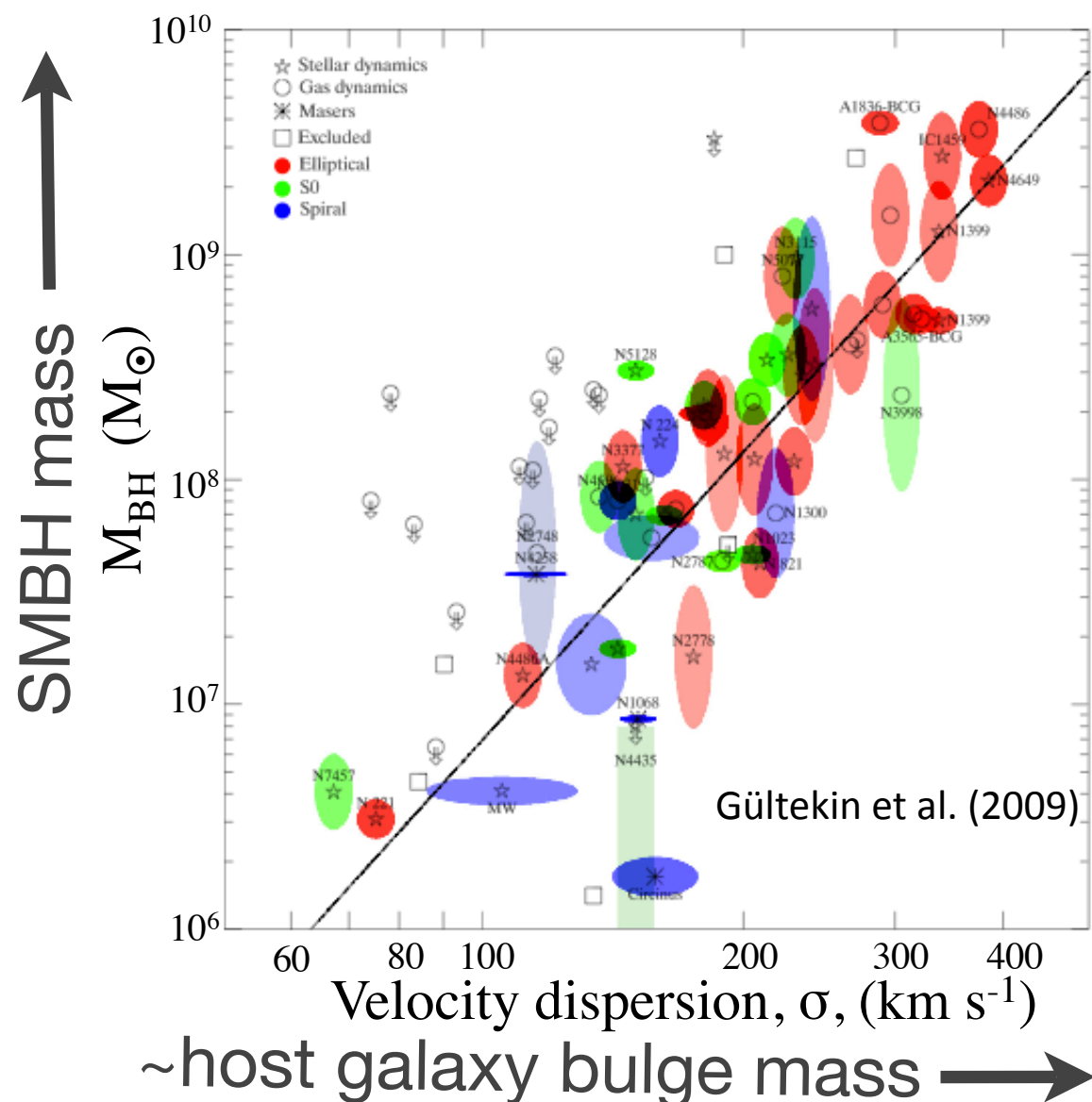
The formation and growth of the earliest supermassive black holes

James Aird & Andrea Comastri

on behalf of Topical Panel 2.1

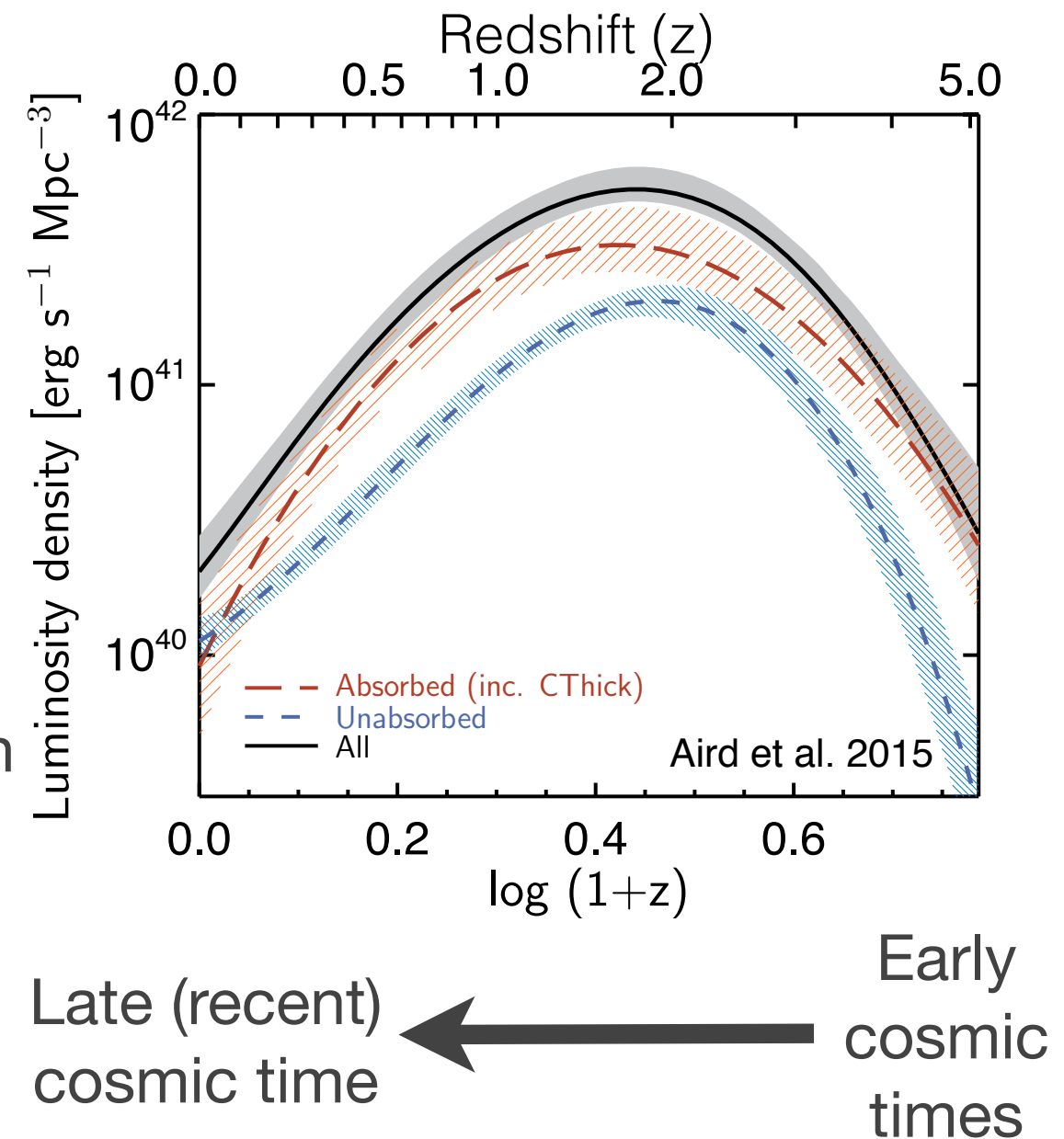
SMBHs in the Universe

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

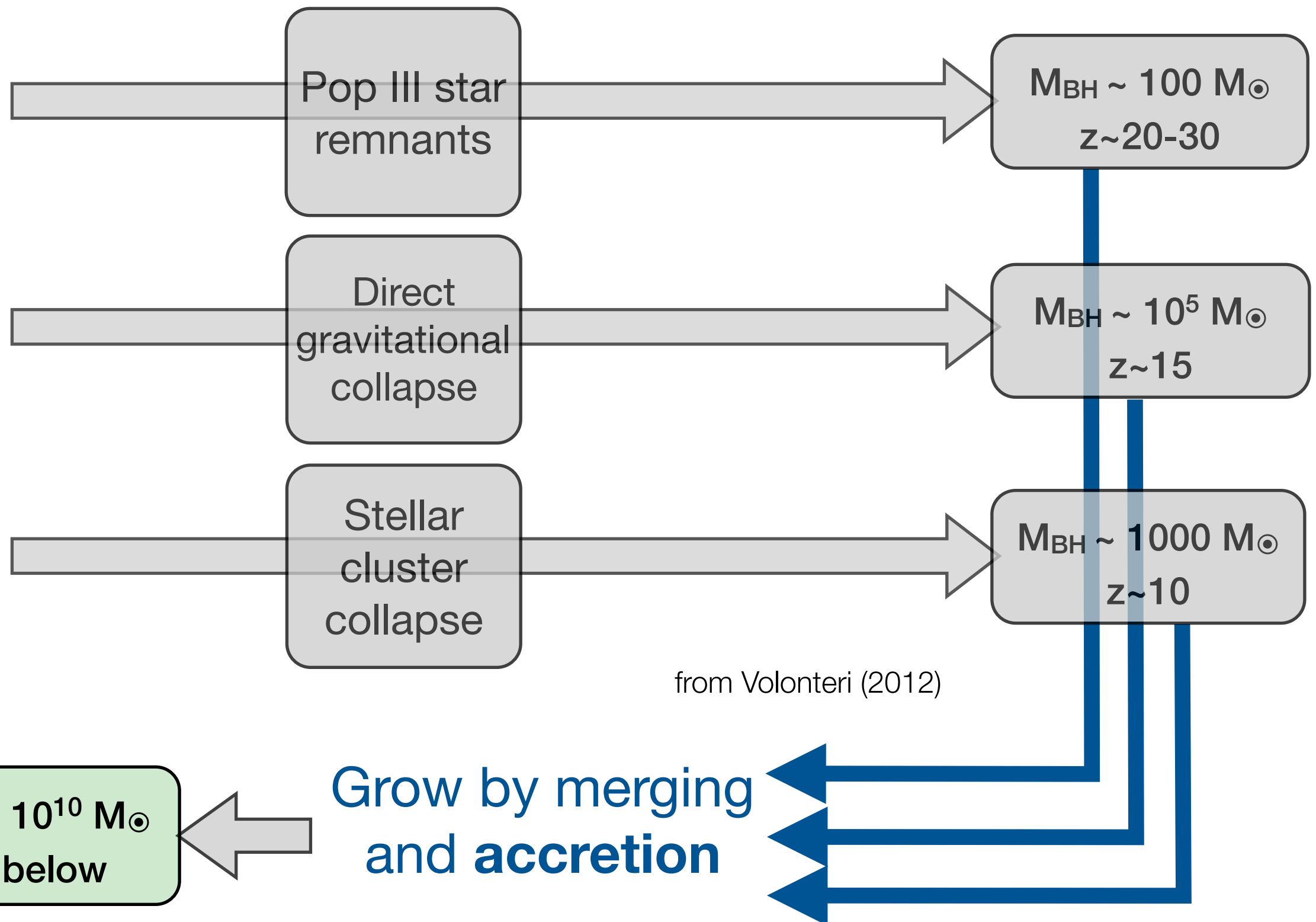


↑ Rate of SMBH growth via accretion

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



SMBH seed formation mechanisms



Athena (level 1) science aims

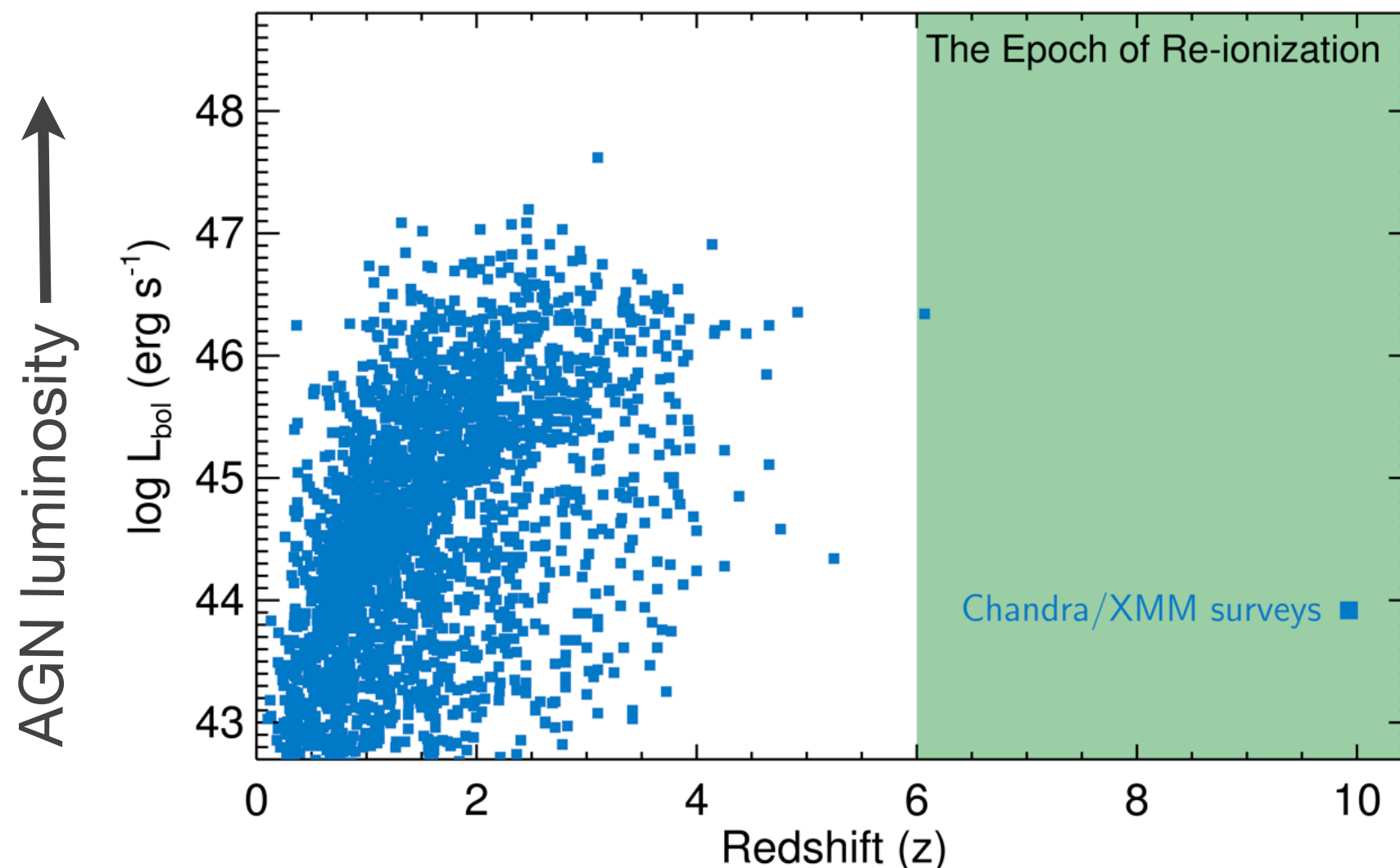
Athena shall

- 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

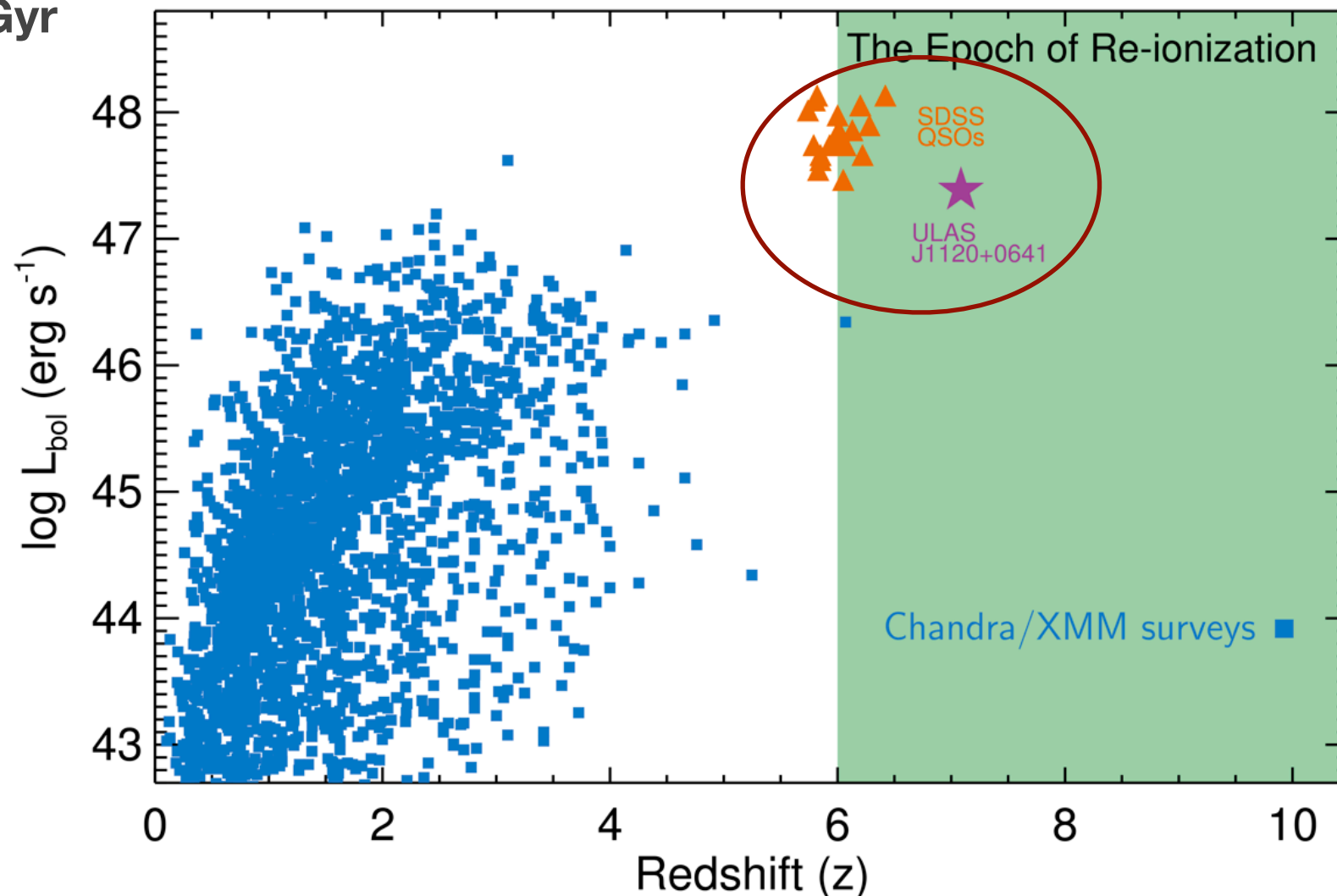
X-ray surveys - *Chandra* and *XMM-Newton*

- 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 $z \sim 5$
- Do not probe $z > 6$: the “epoch of re-ionisation” when the first galaxies and SMBHs form and grow



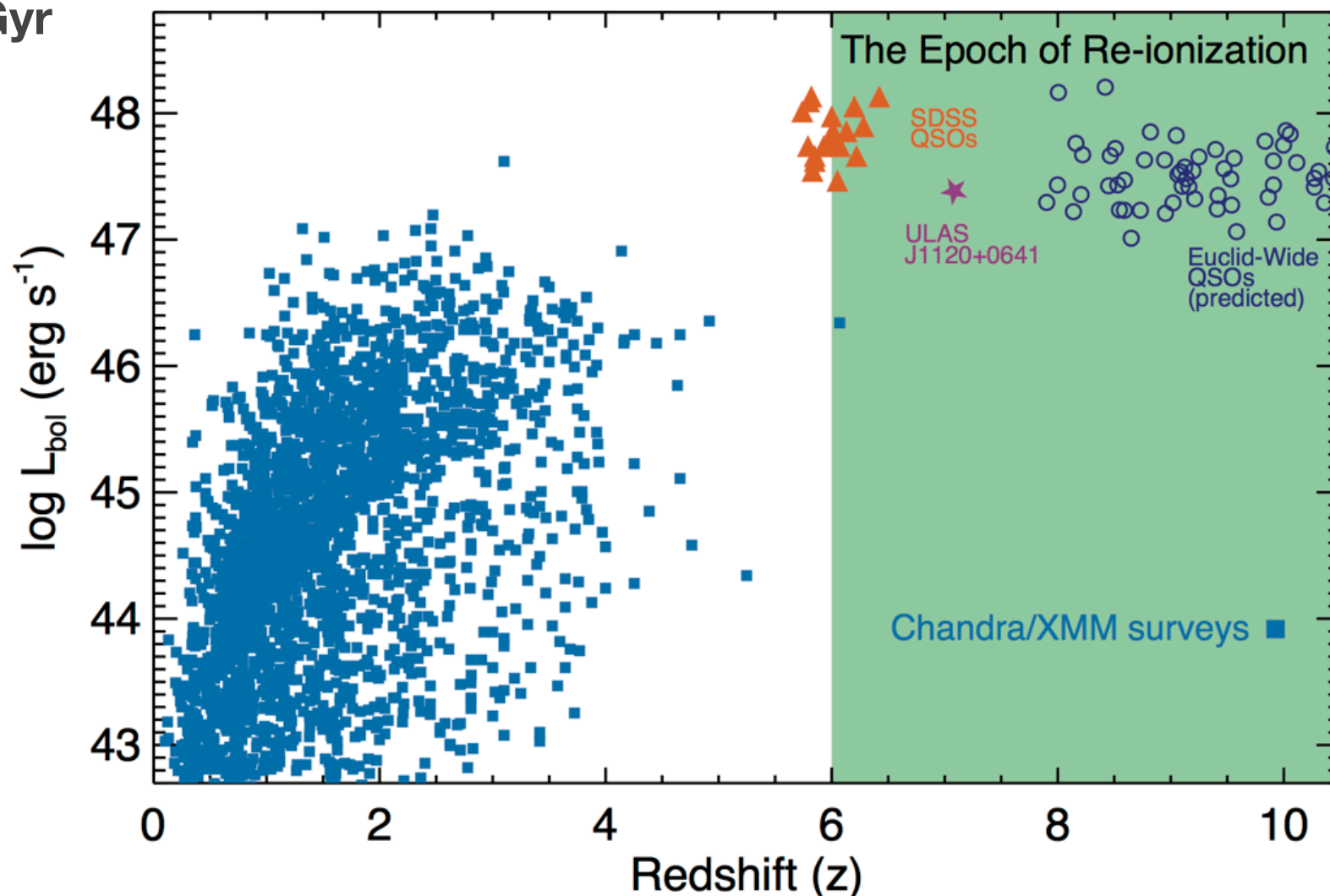
AGN at $z > 6$ - the “tip of the iceberg”

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



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



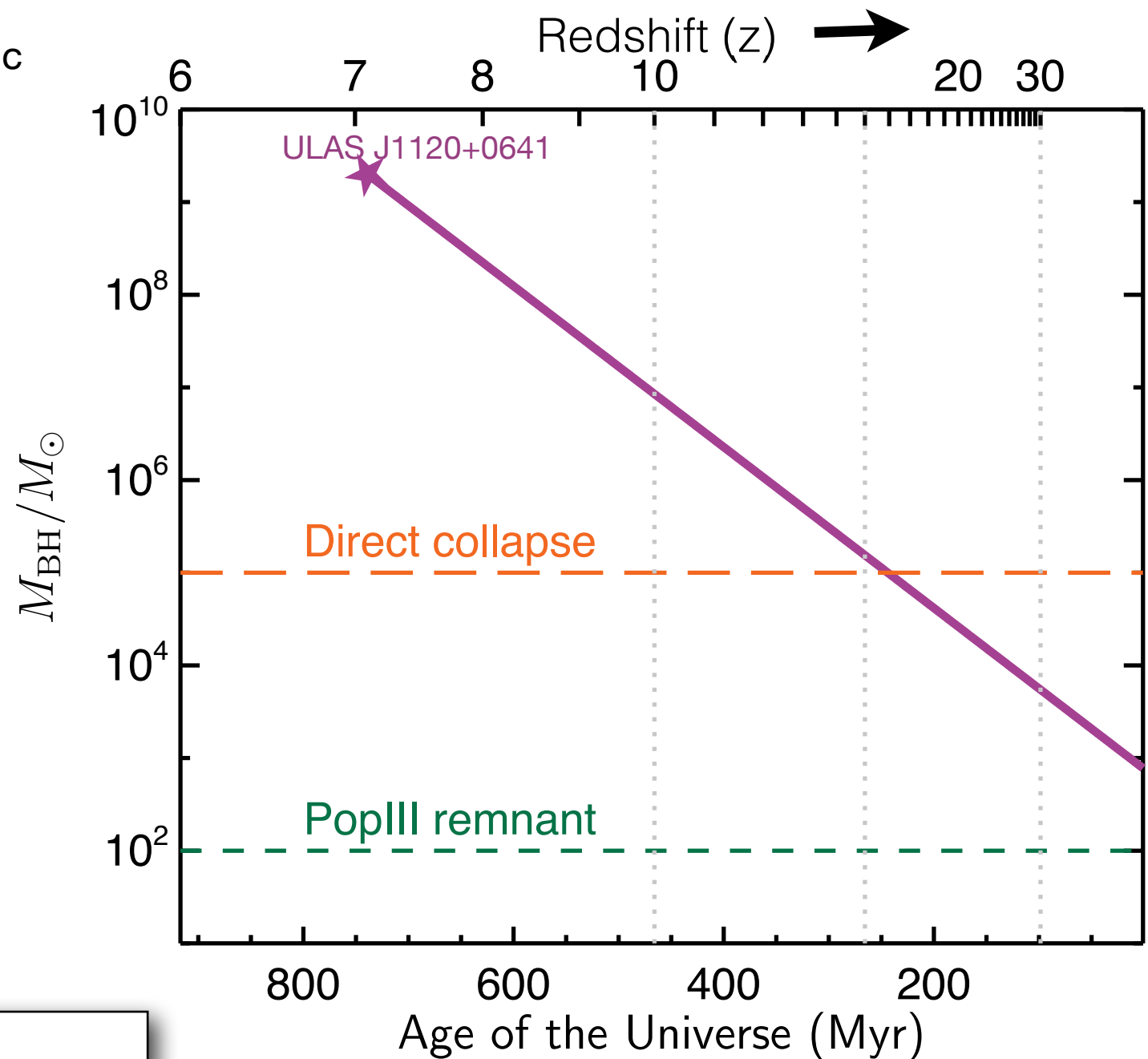
Building high redshift QSOs - constraints on growth rates and seed masses

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

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

seed mass $\uparrow$ M_0 $\uparrow$ $\frac{1 - \epsilon}{\epsilon}$ radiative efficiency ~ 0.1 $\uparrow$ λ_{Edd} Eddington ratio ~ 1 $\uparrow$ t cosmic time

- The seed of ULAS J1120 ($z=7.083$, $M_{\text{BH}} \approx 2 \times 10^9 M_{\odot}$) could have formed by direct collapse at $z \sim 15$, but requires growth at $\sim$ 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

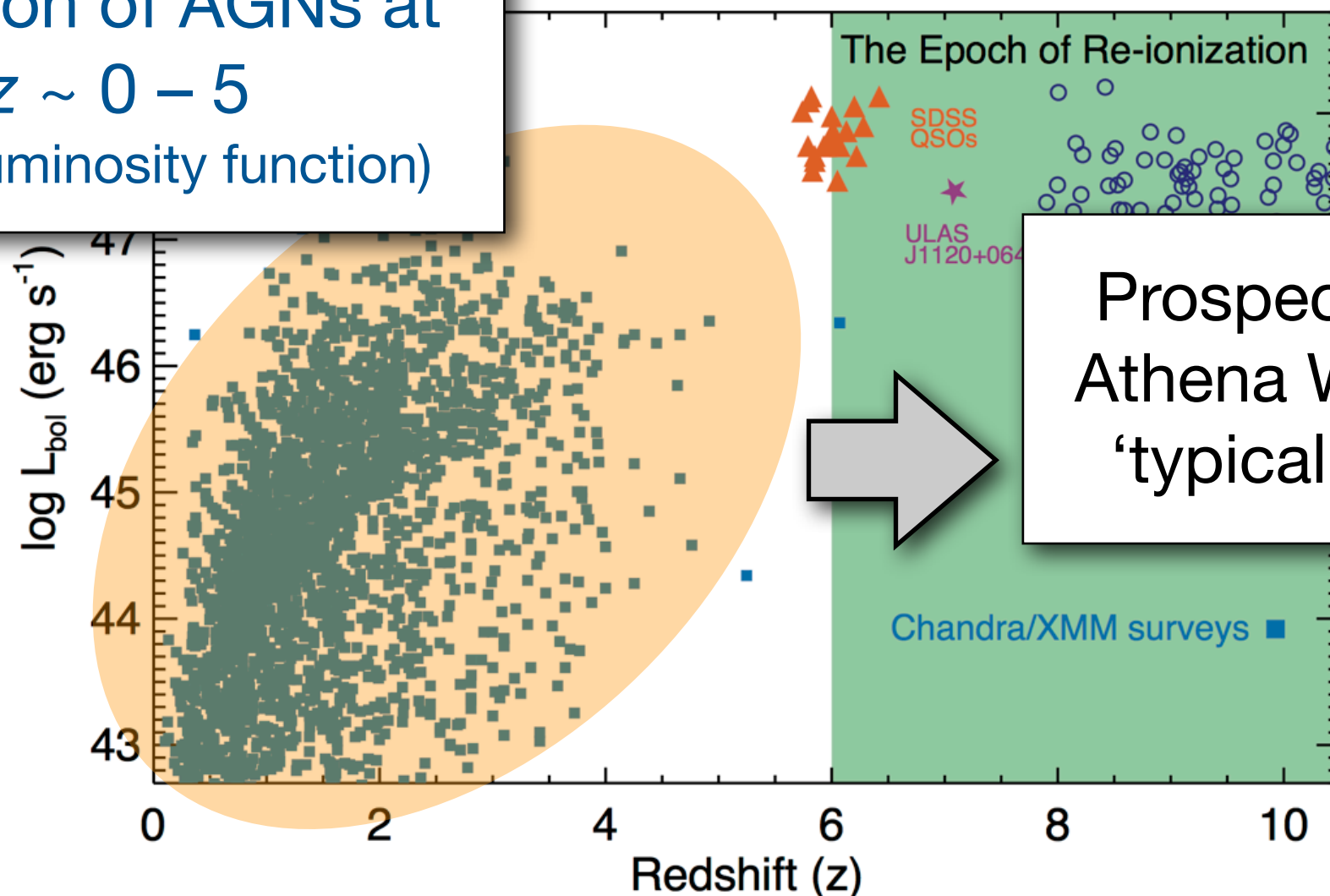
← Cosmic Time

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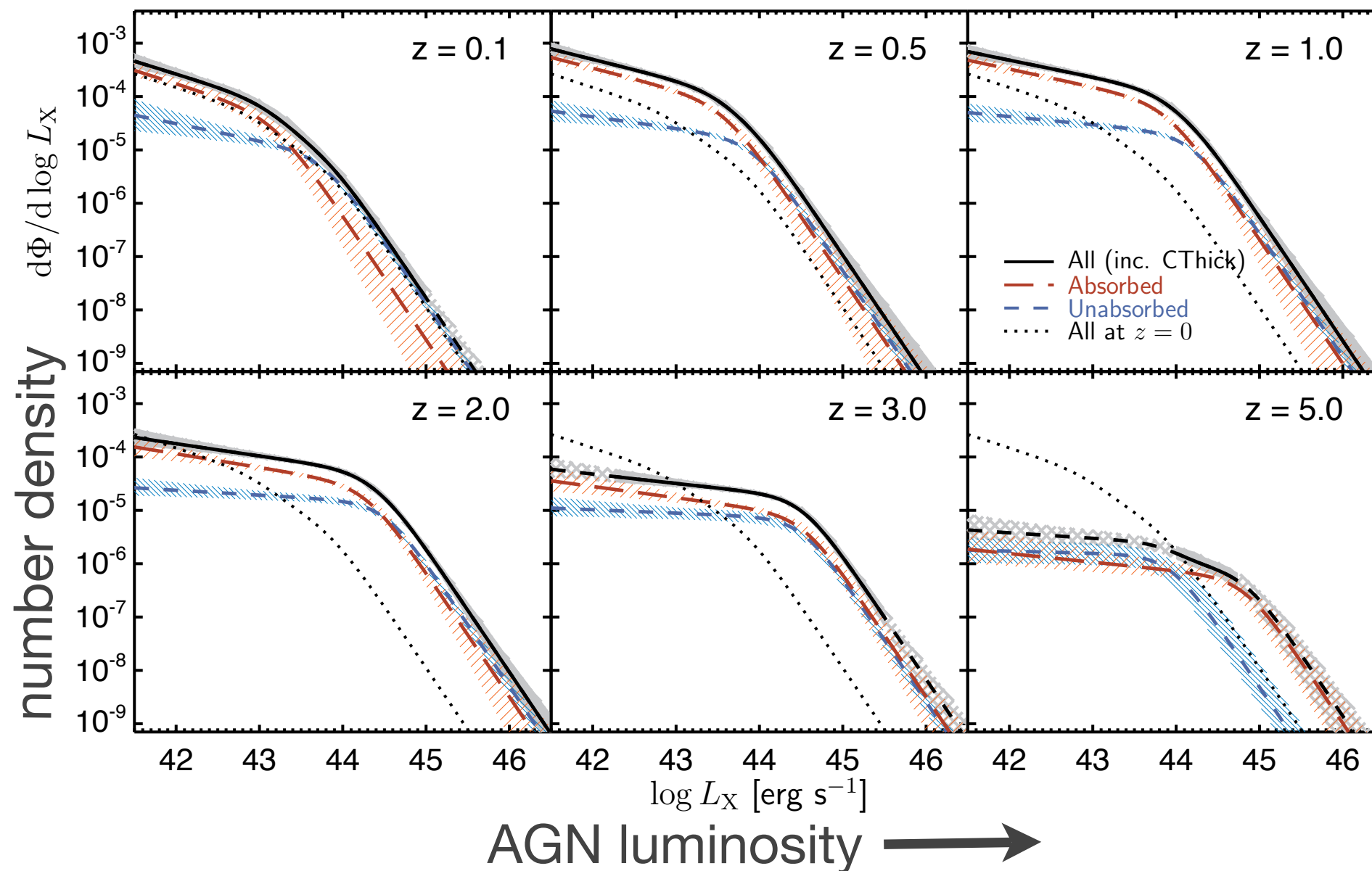
Latest constraints on
evolution of AGNs at
 $z \sim 0 - 5$
(X-ray luminosity function)



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

The evolution of the X-ray luminosity function of AGN from $z \sim 0$ to $z \sim 5$

- Number of recently updated studies on the evolution of the XLF of AGN at $z \sim 0-5$
- **tracking the distribution of SMBH growth via accretion** over the last ~ 12 Gyr
- 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:

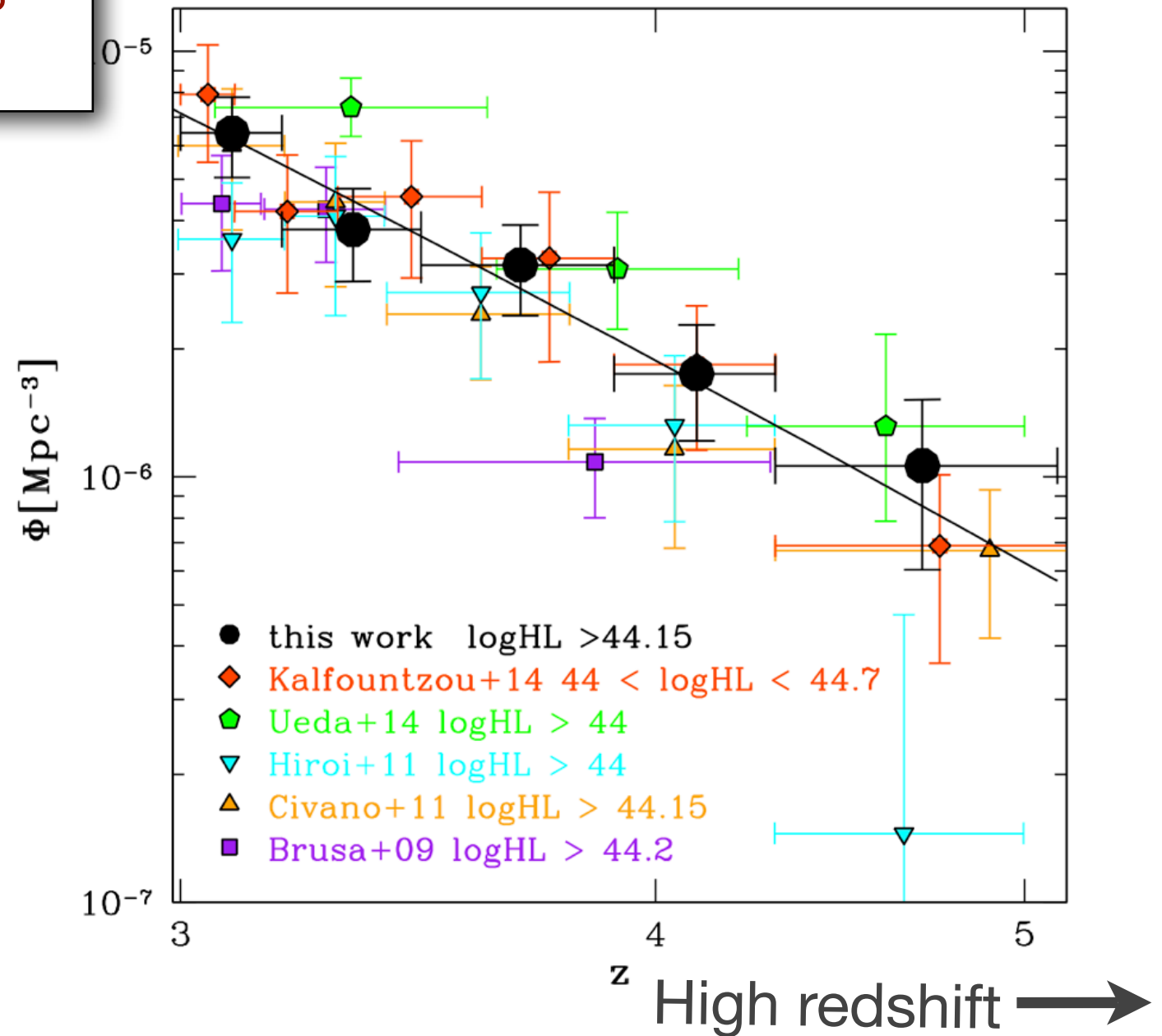
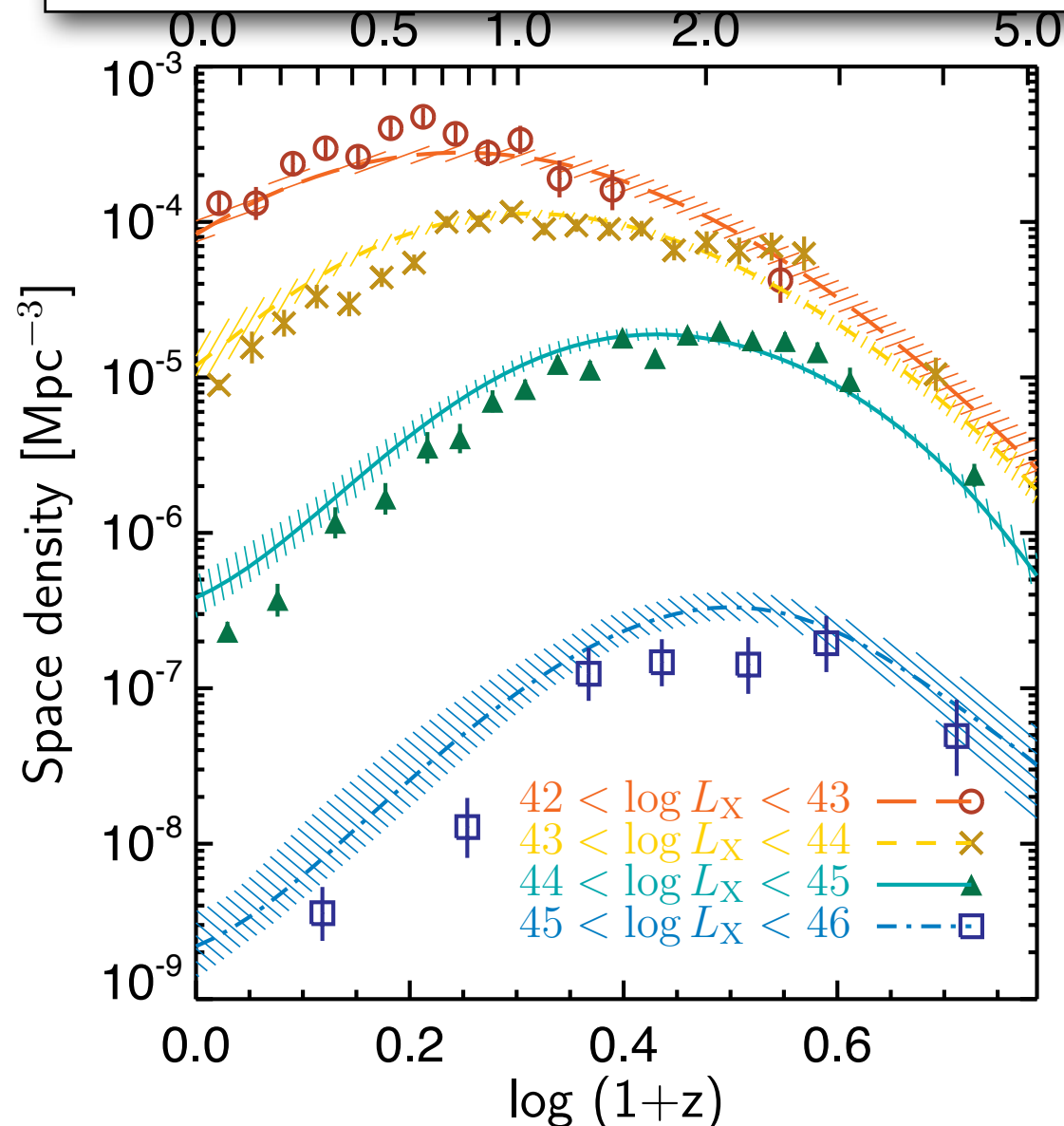
- strong luminosity and density evolution of both absorbed and unabsorbed AGN
- changing mix of absorbed and unabsorbed populations

see also

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

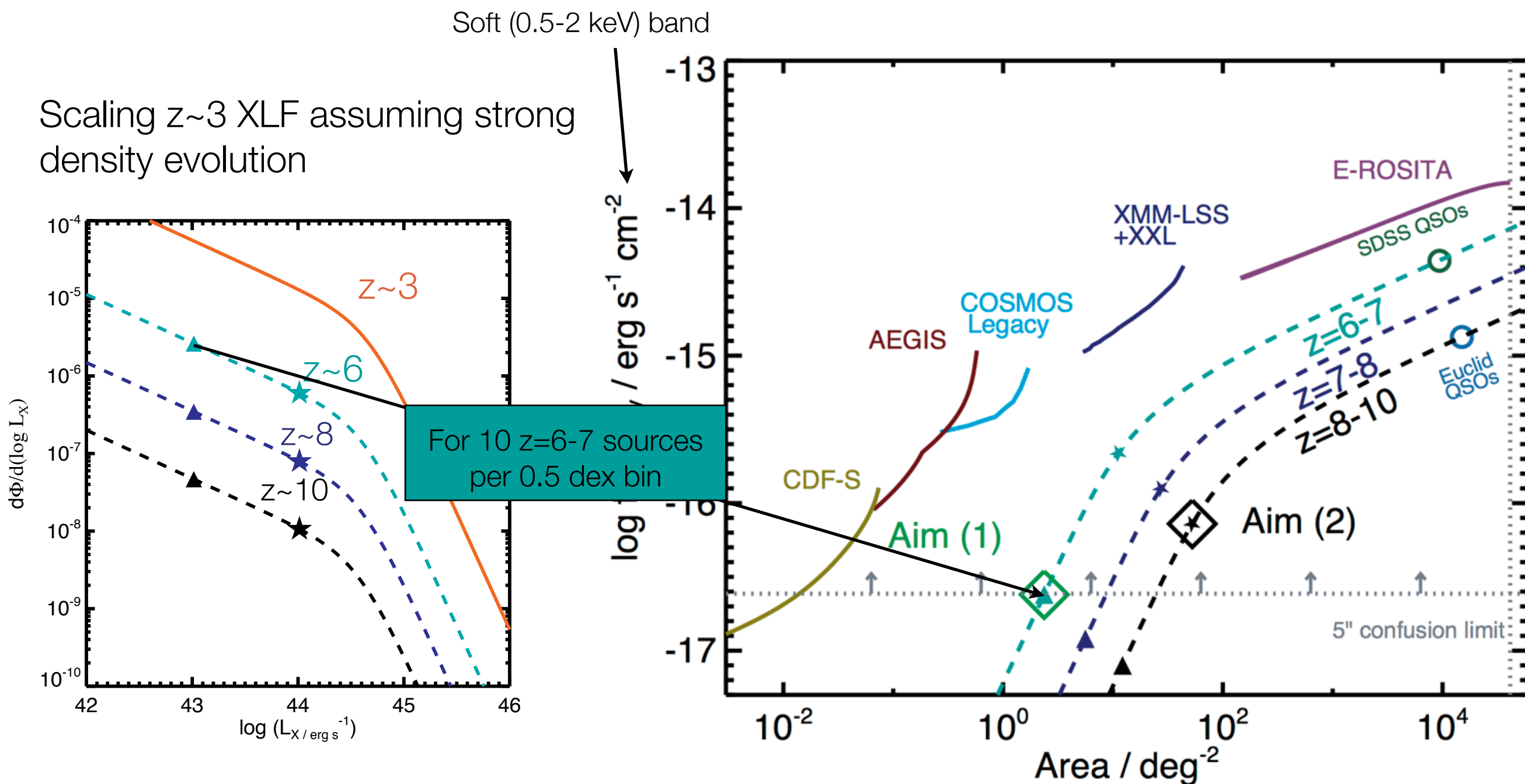
The evolution of the space density of AGN from $z \sim 0$ to $z \sim 5$

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



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

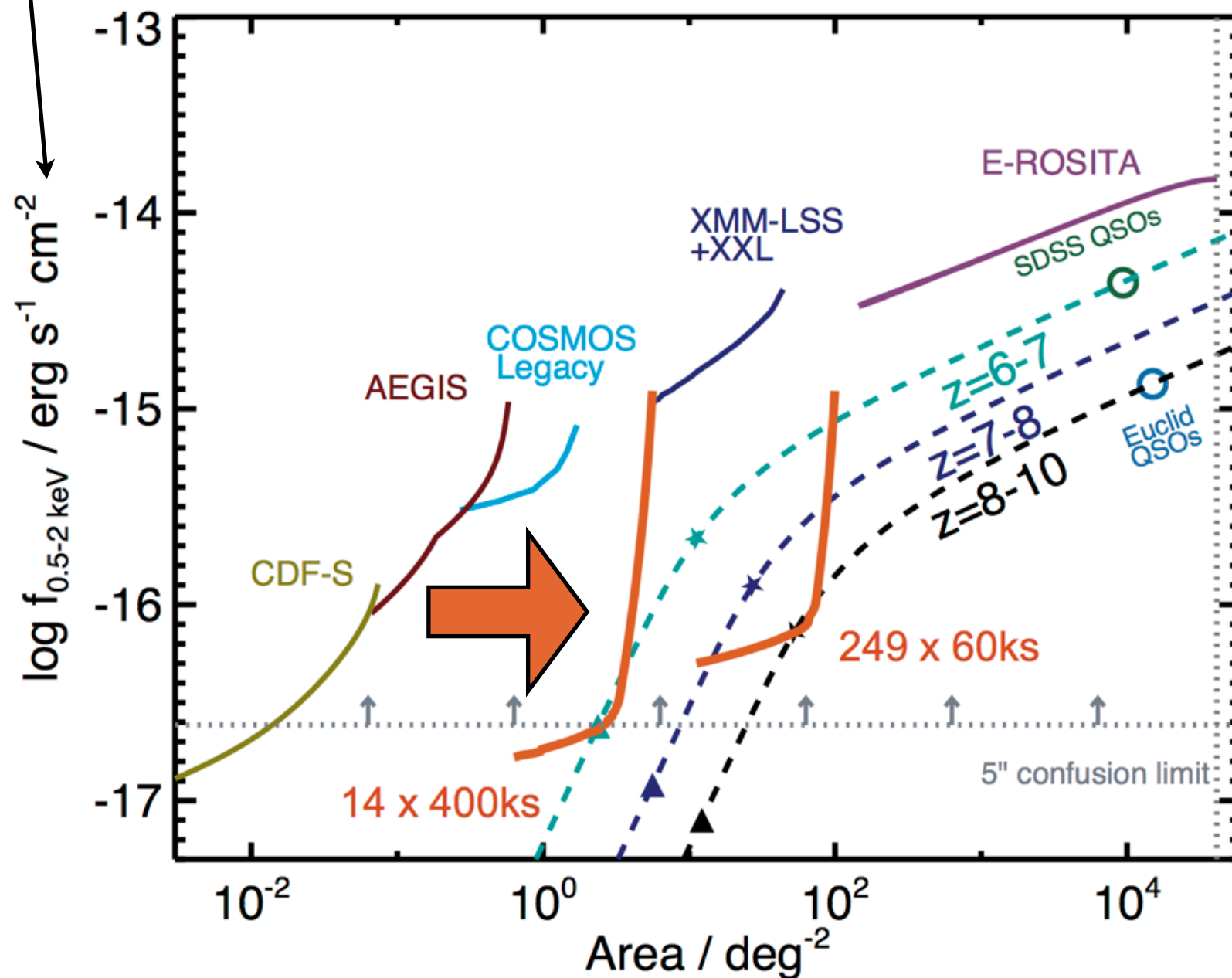
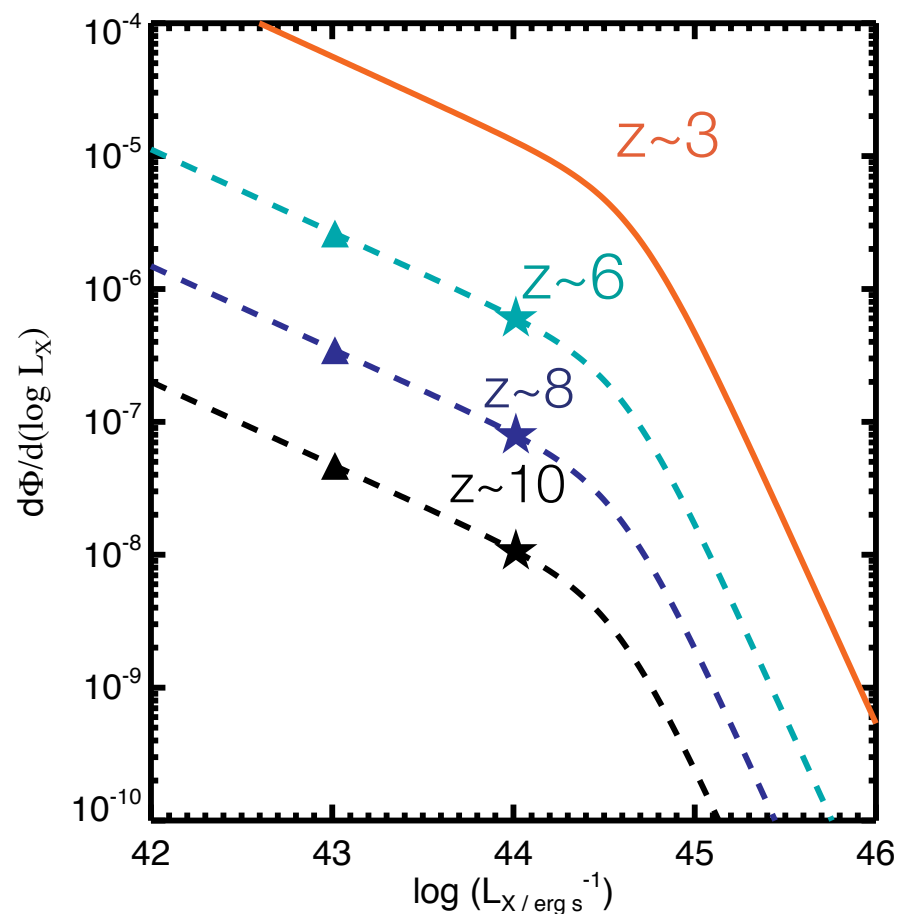
Detecting X-ray AGN at the highest redshifts



Detecting X-ray AGN at the highest redshifts

Soft (0.5-2 keV) band

Scaling $z \sim 3$ XLF assuming strong density evolution

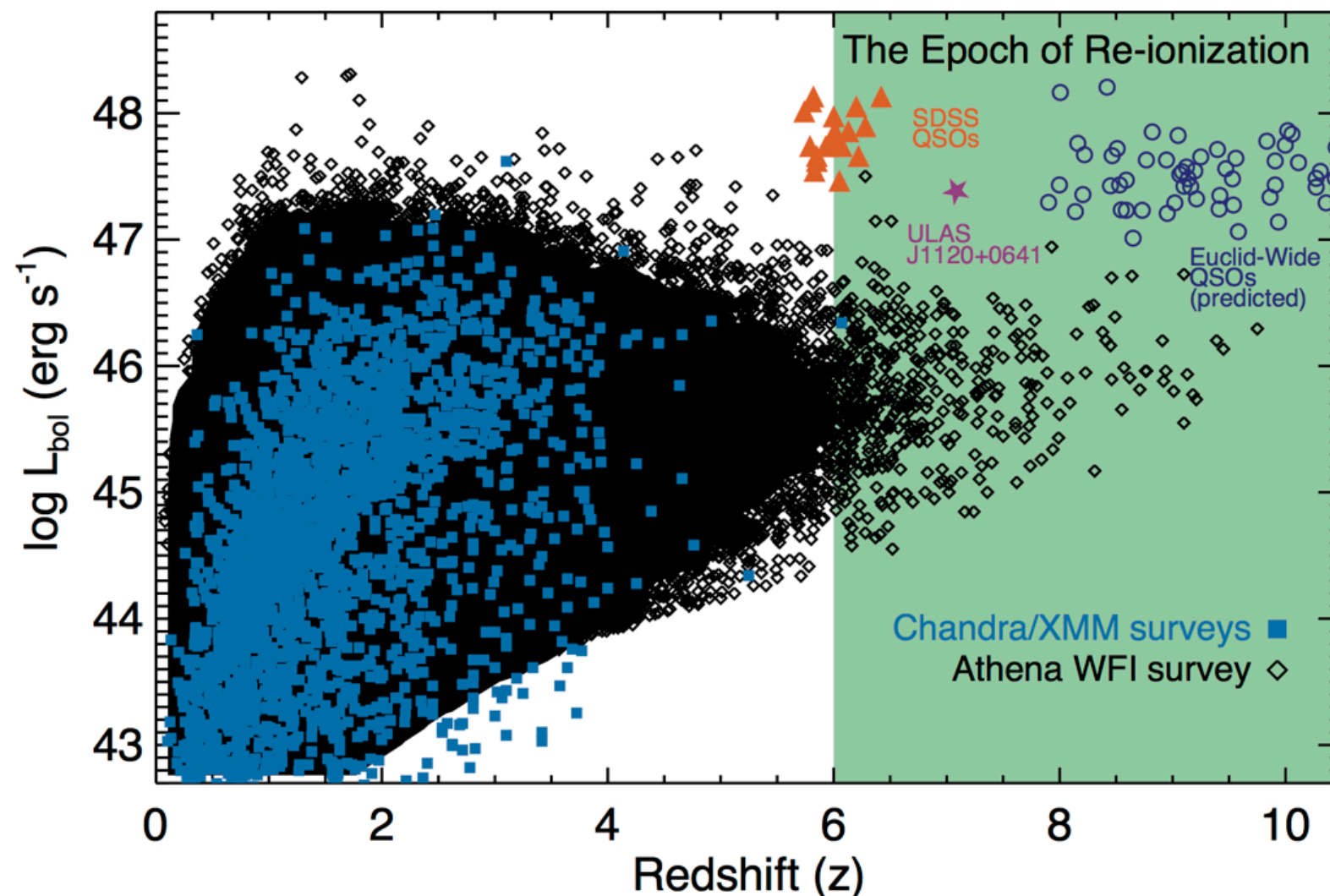


Athena WFI survey **~100** times faster than Chandra or XMM

Athena WFI survey for $z > 6$ AGNs

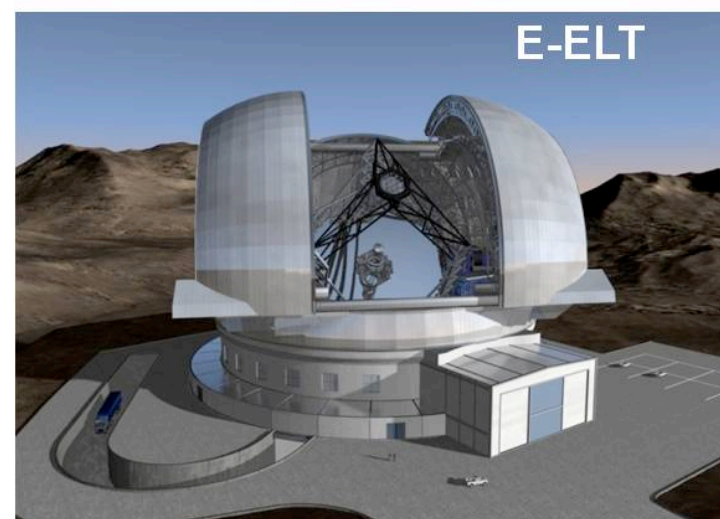
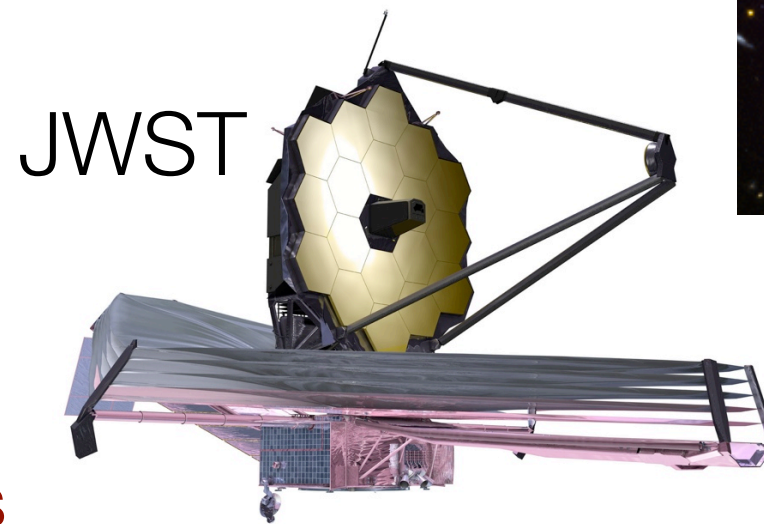
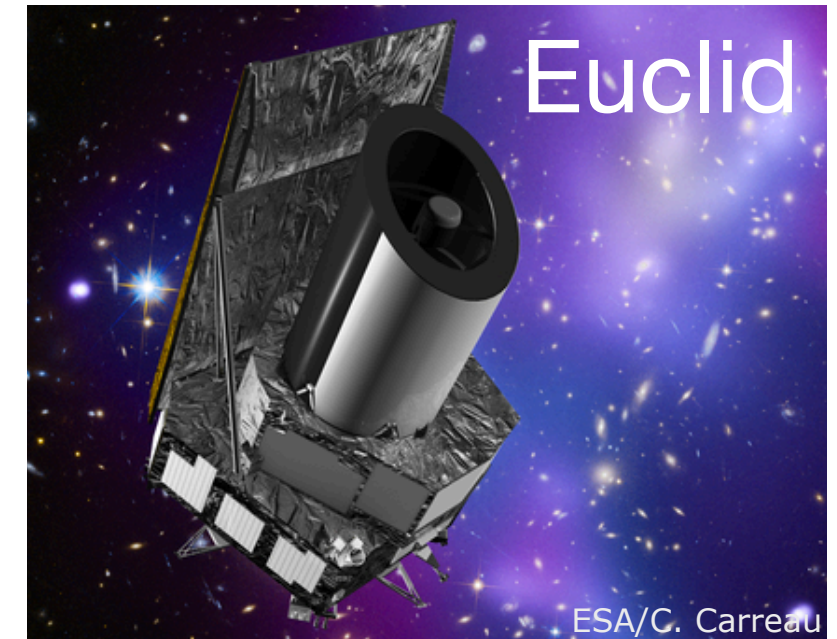
- A multi-layered Athena WFI survey, taking ~ 25 Ms will identify $> 600,000$ AGNs, **including > 400 AGNs at $z > 6$**

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



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

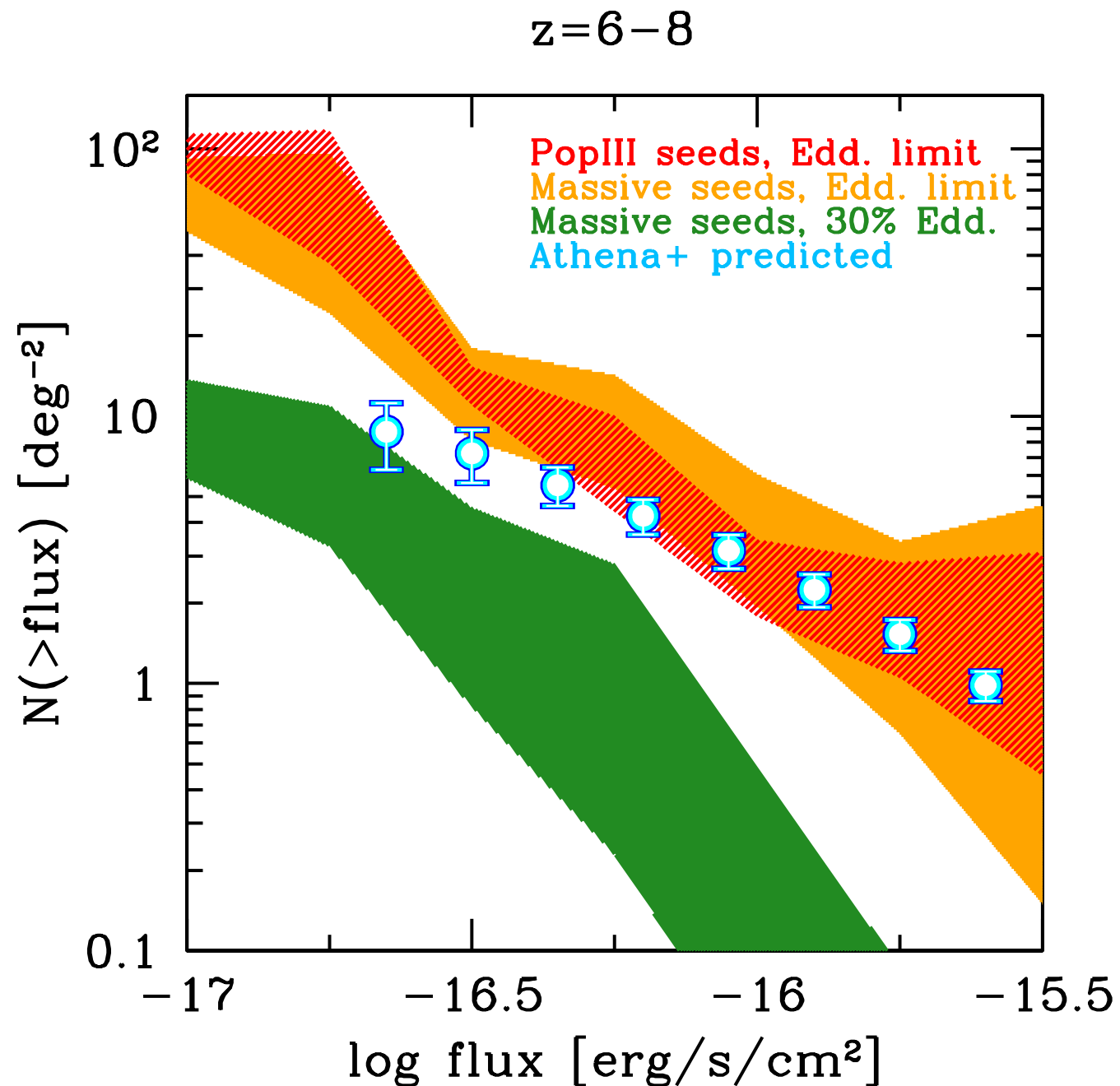
- $\sim 50 \text{ deg}^2$ Athena 'shallow' ($\sim 60\text{ks}$) surveys will be well matched in depth/area to forthcoming deep optical/near-infrared surveys (e.g. Euclid, HyperSuprimeCam, LSST)
- JWST imaging required to identify counterparts in deep Athena surveys ($\sim 2 \text{ deg}^2$, 400ks)?
- *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 $L_X = 10^{43} \text{ erg s}^{-1}$ at $z = 6$
 $\Rightarrow M_{\text{BH}} > \sim 2 \times 10^6 M_{\text{sun}}$
(assuming $\sim$ Eddington limited)
- Detection of an AGN with $L_X = 10^{44} \text{ erg s}^{-1}$ at $z = 8$
 $\Rightarrow M_{\text{BH}} > \sim 2 \times 10^7 M_{\text{sun}}$
(assuming $\sim$ 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 ($z \sim 0-5$) 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 $z > 6$ sources
(see also Francisco)
- Full end-to-end simulations of WFI survey 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