UNIVERSITY OF LEICESTER

Science & Technology Facilities Council

The cosmic frontier:

Formation and growth of the earliest supermassive black holes

James Aird
(University of Leicester)

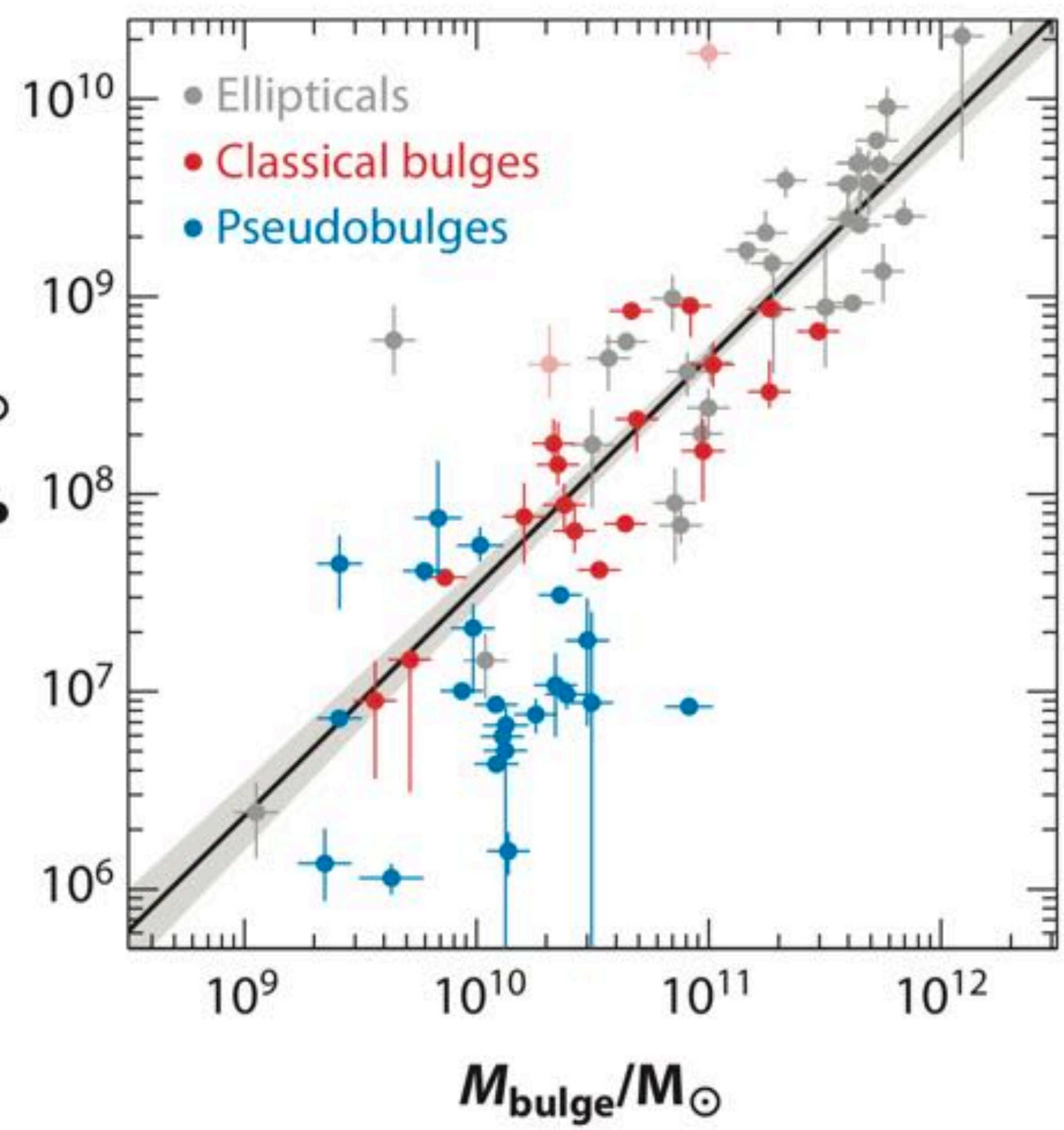
REVIEW + ATHENA

X-ray Astronomy 2019:
current challenges and new frontiers in the next decade
Bologna 8-13 Sept 2019

Cosmic ~~frontier~~ backyard: ubiquity of massive BHs

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

Black hole mass →



Host galaxy bulge mass →

Kormendy & Ho 2013

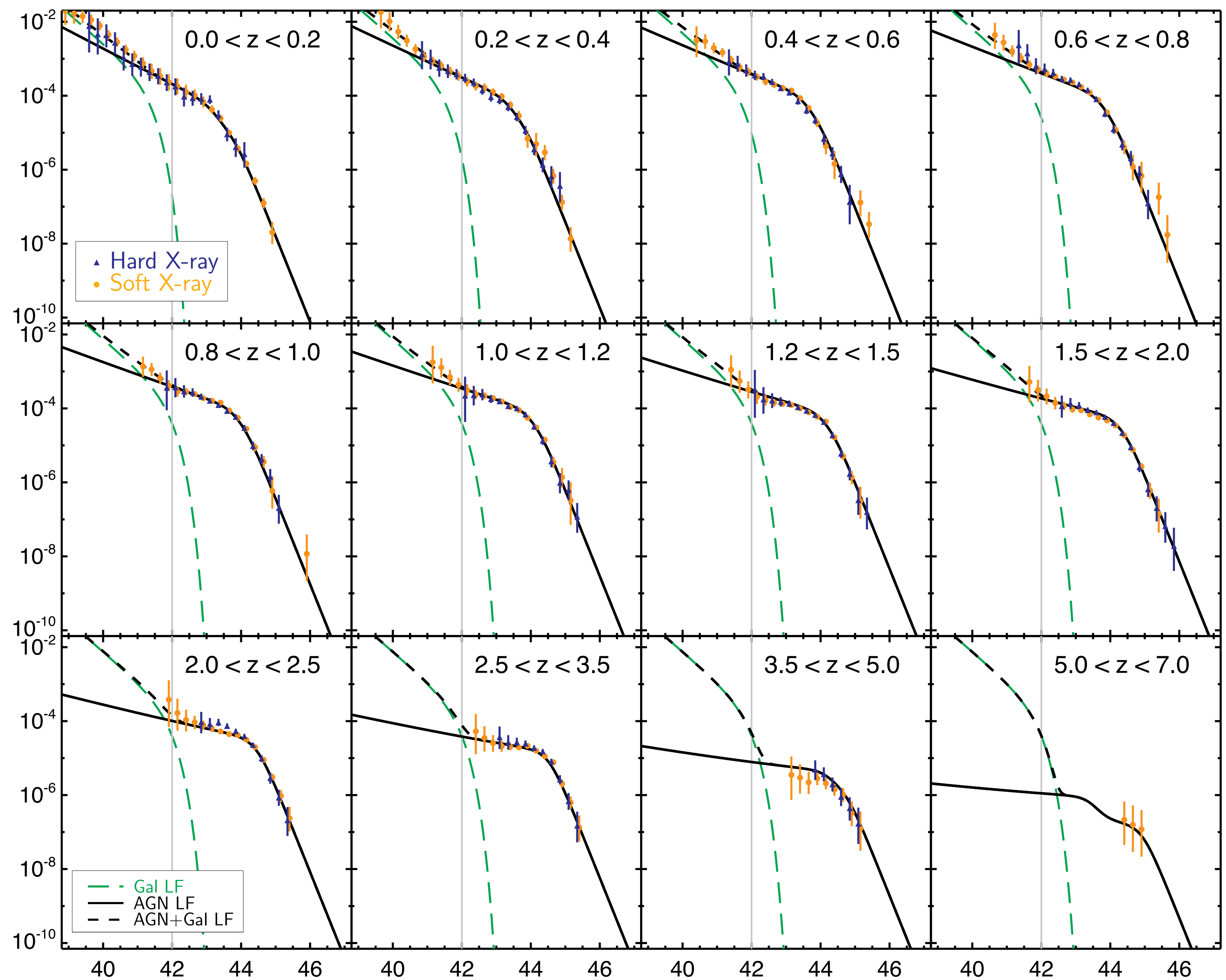
(N.B. Francesco Shankar talk => biased sampling of BHs?)

X-ray surveys (*Chandra* + *XMM-Newton*): track the **growth** of these black holes by accretion

Growth tracked by AGN Luminosity Function

e.g. Aird+15

(see also: e.g. Ueda+14, Buchner+15, Miyaji+15, Fotopoulou+16, Ranalli+16, Georgakakis+17, Ananna+19)



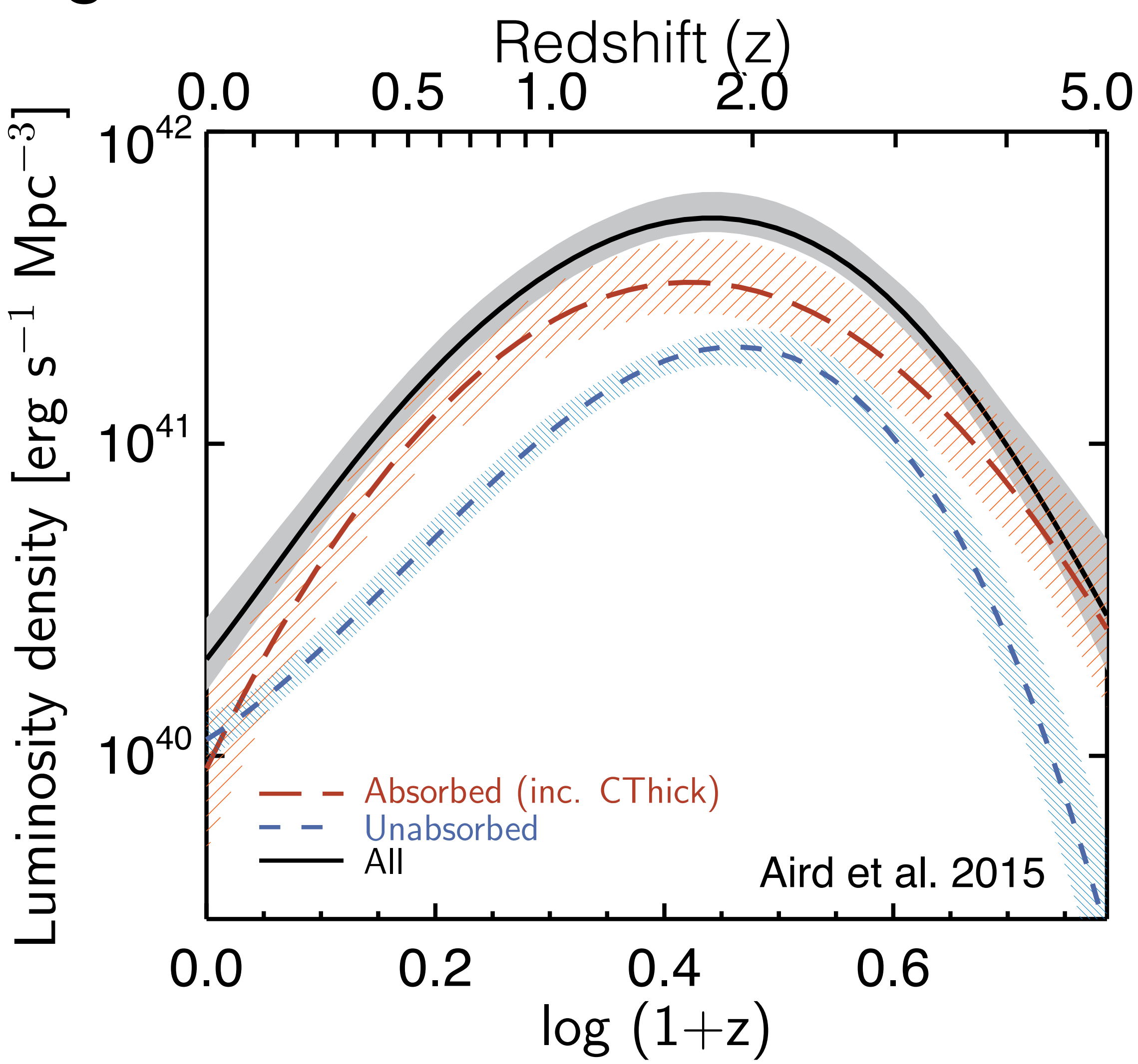
Number density [Mpc^{-3} dex^{-1}]

log L_X [erg s^{-1}]

X-ray surveys (*Chandra* + *XMM-Newton*): track the **growth** of these black holes by accretion

Integrating LF =>

Rate of SMBH growth via accretion

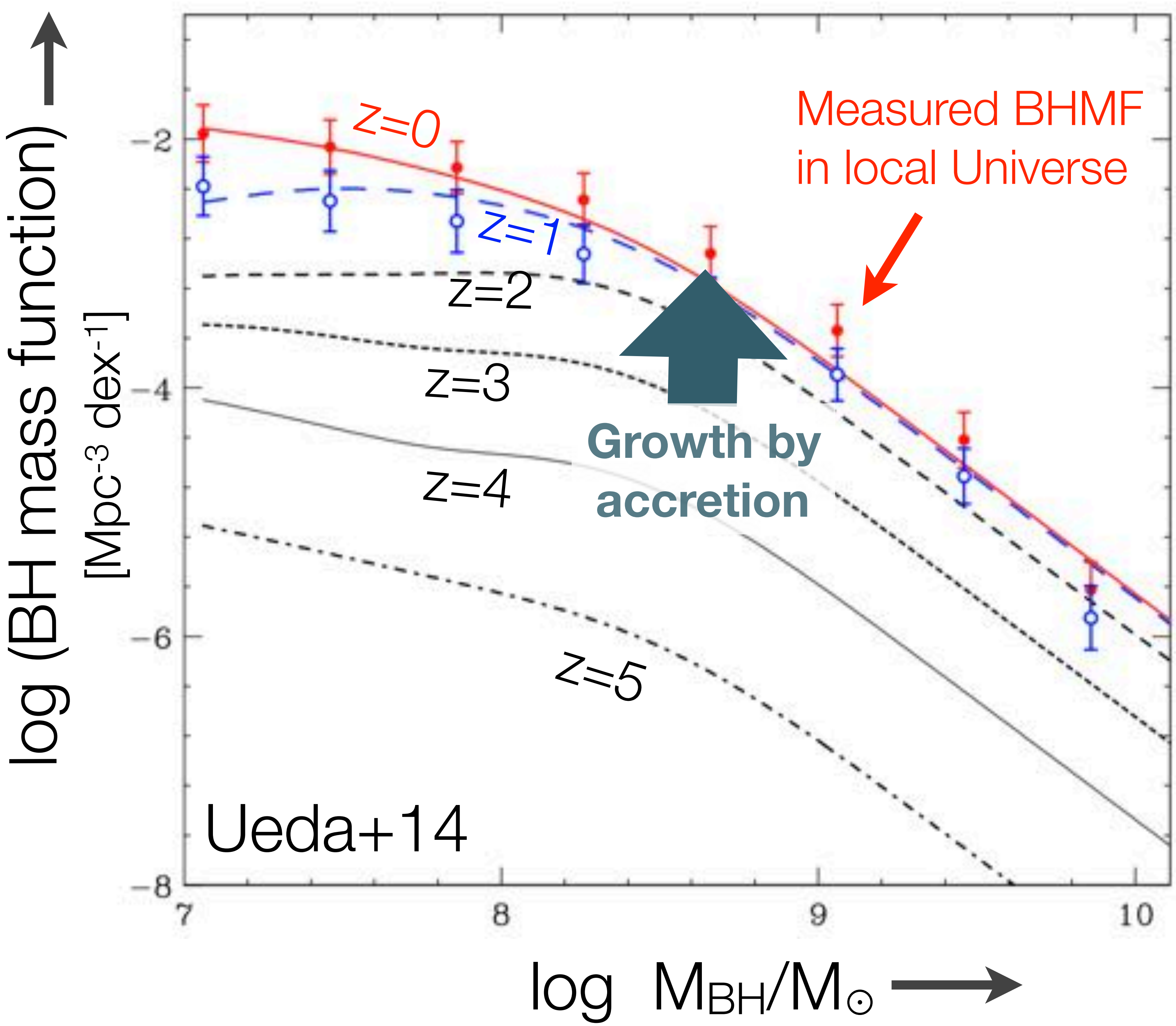


Late (recent) cosmic time

Early cosmic times

Bulk of this growth occurred at **z~1-3**, primarily in moderate-luminosity **obscured** sources (revealed by X-ray observations)

X-ray surveys (*Chandra* + *XMM-Newton*): track the **growth** of these black holes by accretion



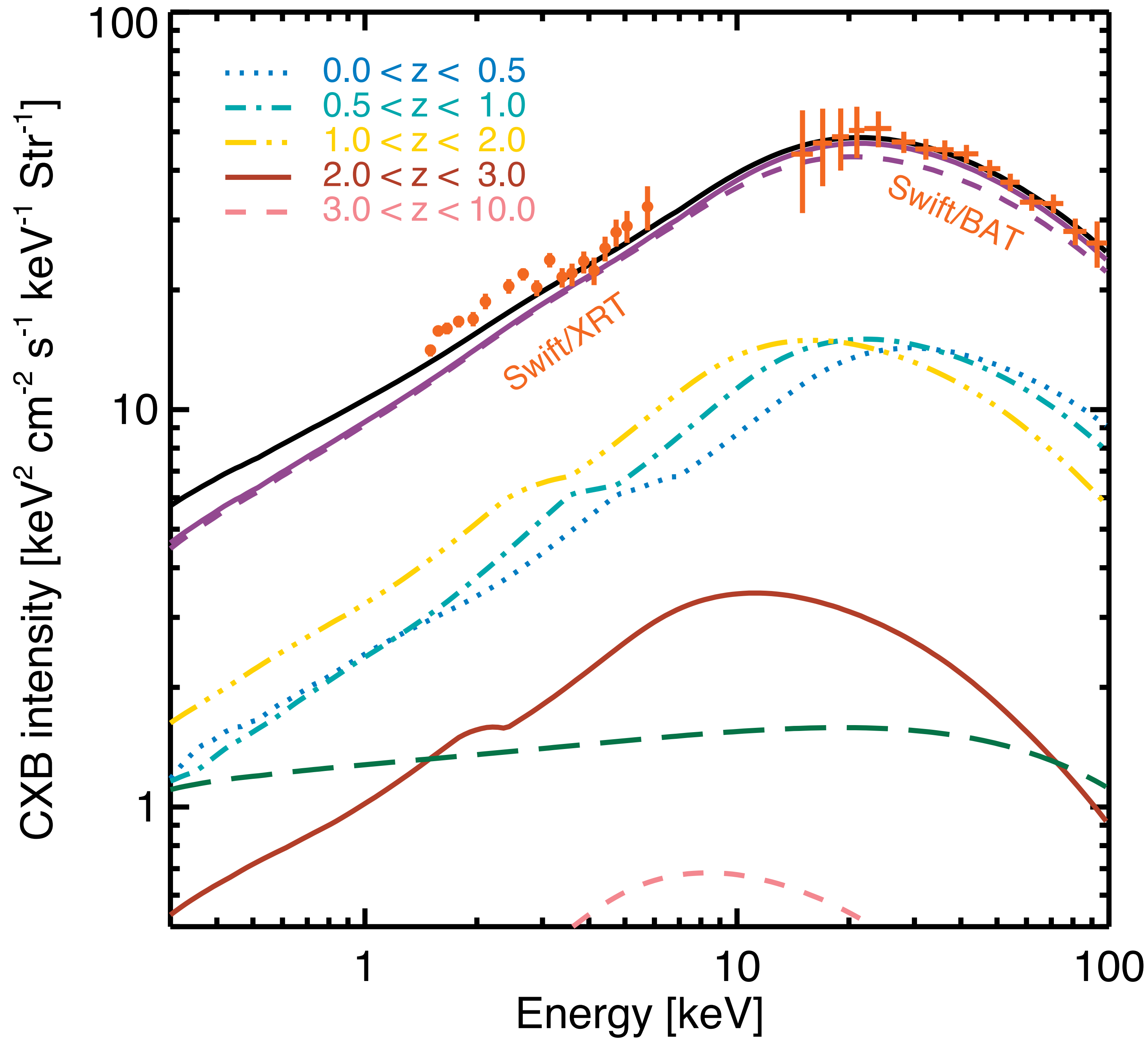
Accretion growth (primarily at z~1-3) accounts for the BH mass density in the local Universe

X-ray surveys (*Chandra* + *XMM-Newton*): track the **growth** of these black holes by accretion

Cosmic X-ray background

(integrated emission from BH growth over the lifetime of the Universe)

- >90% resolved by *Chandra* at soft energies (<2 keV)
- ~35% resolved by NuSTAR at energies >8keV
- Population synthesis models (based on *Chandra/XMM* surveys at 0.5-10keV) =>
    - produced by SMBH accretion, primarily at z<2
    - successfully recover full shape and peak at ~20-30 keV - dominated by **obscured** AGN



Aird+15 (adapted).

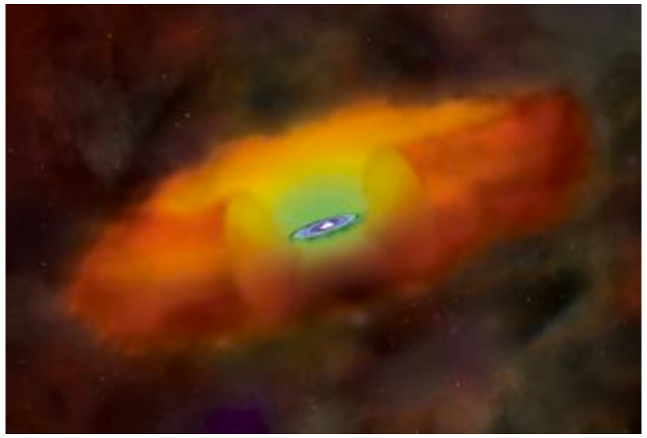
See also e.g. Gilli+07, Triester+09, Ballantyne+11, Akylas+12, Ueda+14, Ananna+19,

Mackenzie Jones talk

Open questions regarding the **bulk** of BH growth

- Connection to **galaxy** properties?
(triggering/fuelling mechanisms, impact of AGN *feedback* on galaxy evolution)

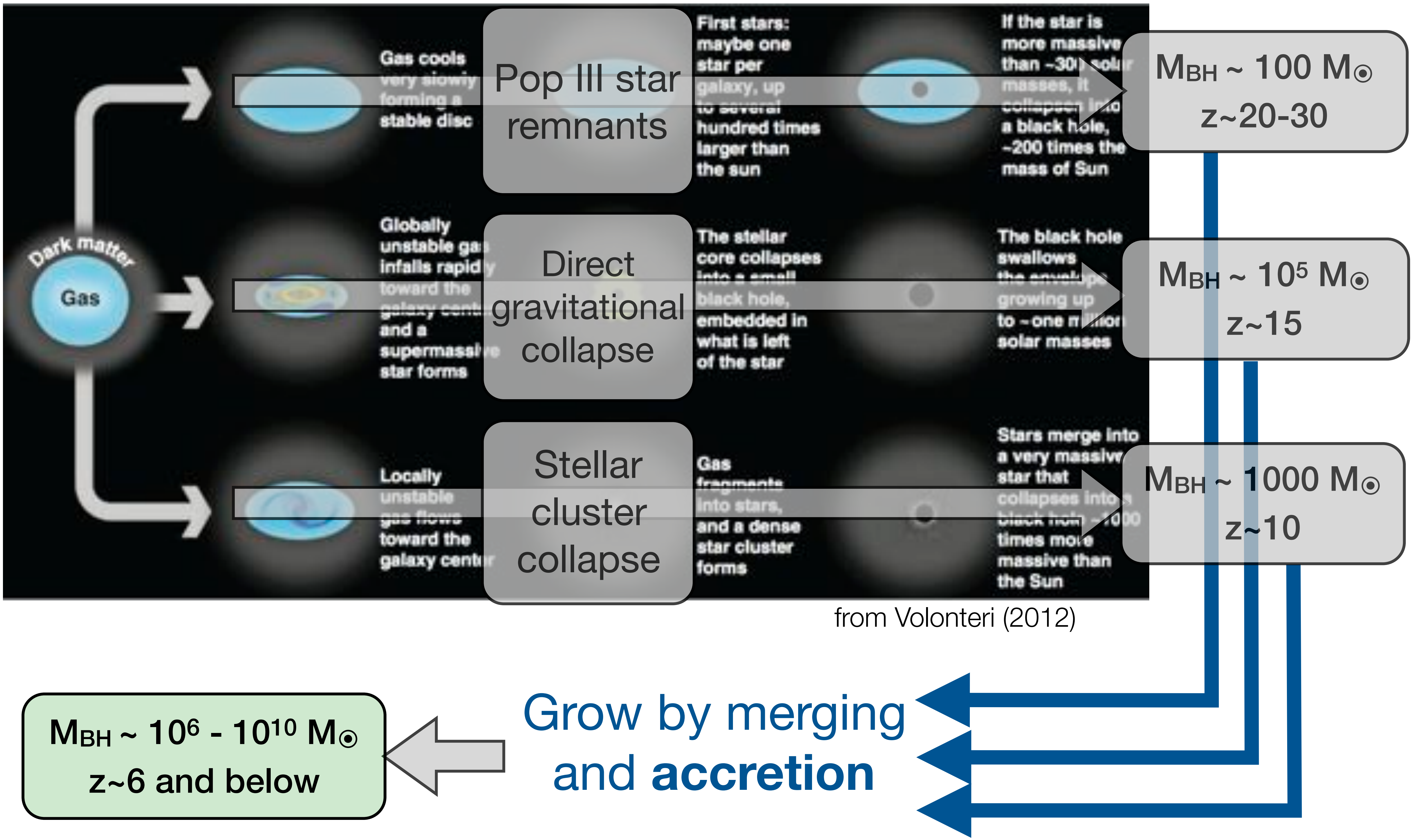
- Contribution of **Compton-thick** AGN?



- **Physics** of the accretion process?
(structure of accretion disk+corona, winds/jets, BH *spin*, super-Eddington accretion)

Where do these supermassive black holes come from?

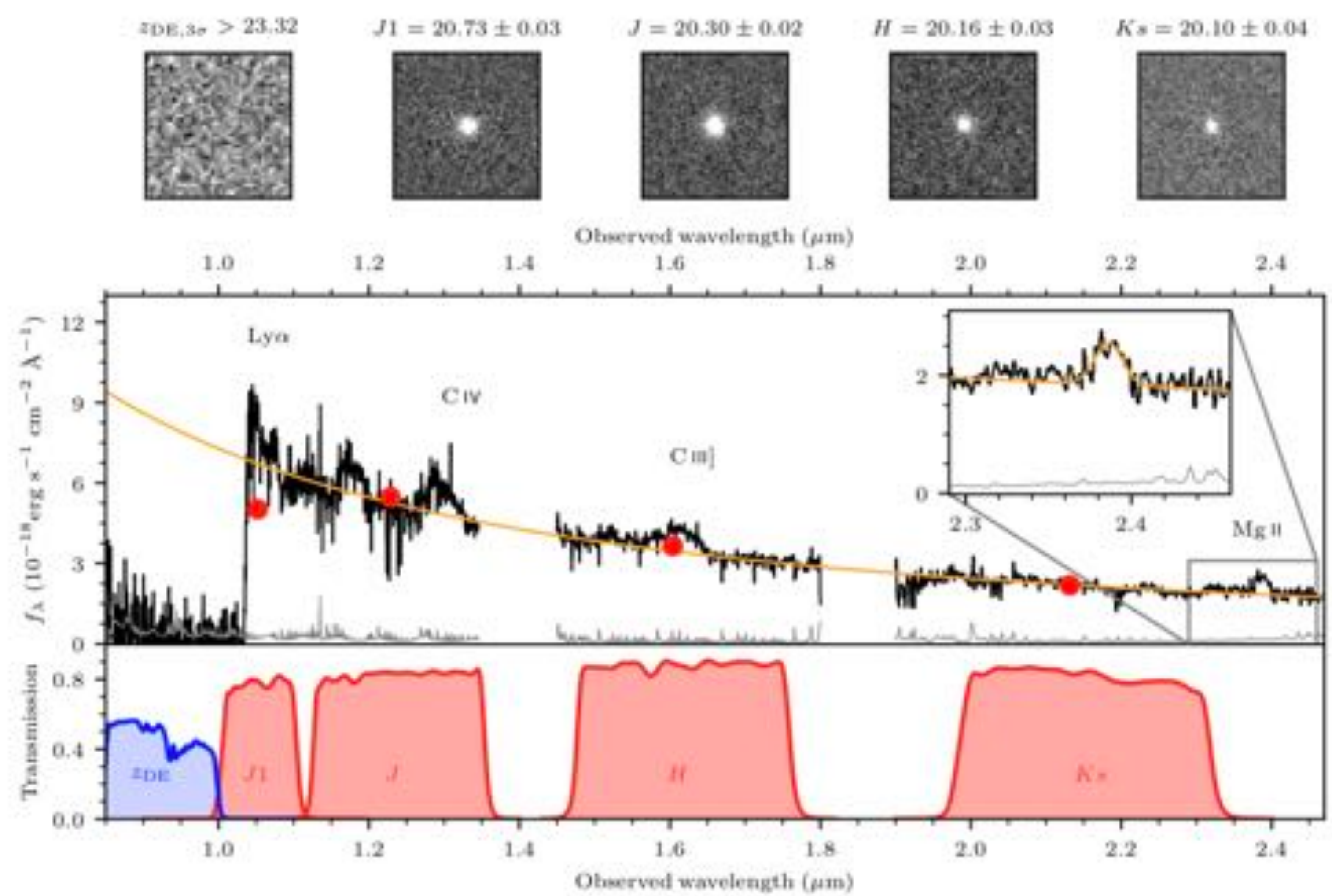
SMBH seed mechanisms



from Volonteri (2012)

Massive black holes in the early (z>6) Universe - optical/near-IR searches

- Searches for rare, luminous QSOs at z>6
  - ➡ Require large-area, deep optical + NIR imaging, search for “drop-outs” due to absorption by neutral hydrogen



Bañados et al. 2018

SDSS

Pan-STARRS

UKIDSS

DARK ENERGY SURVEY

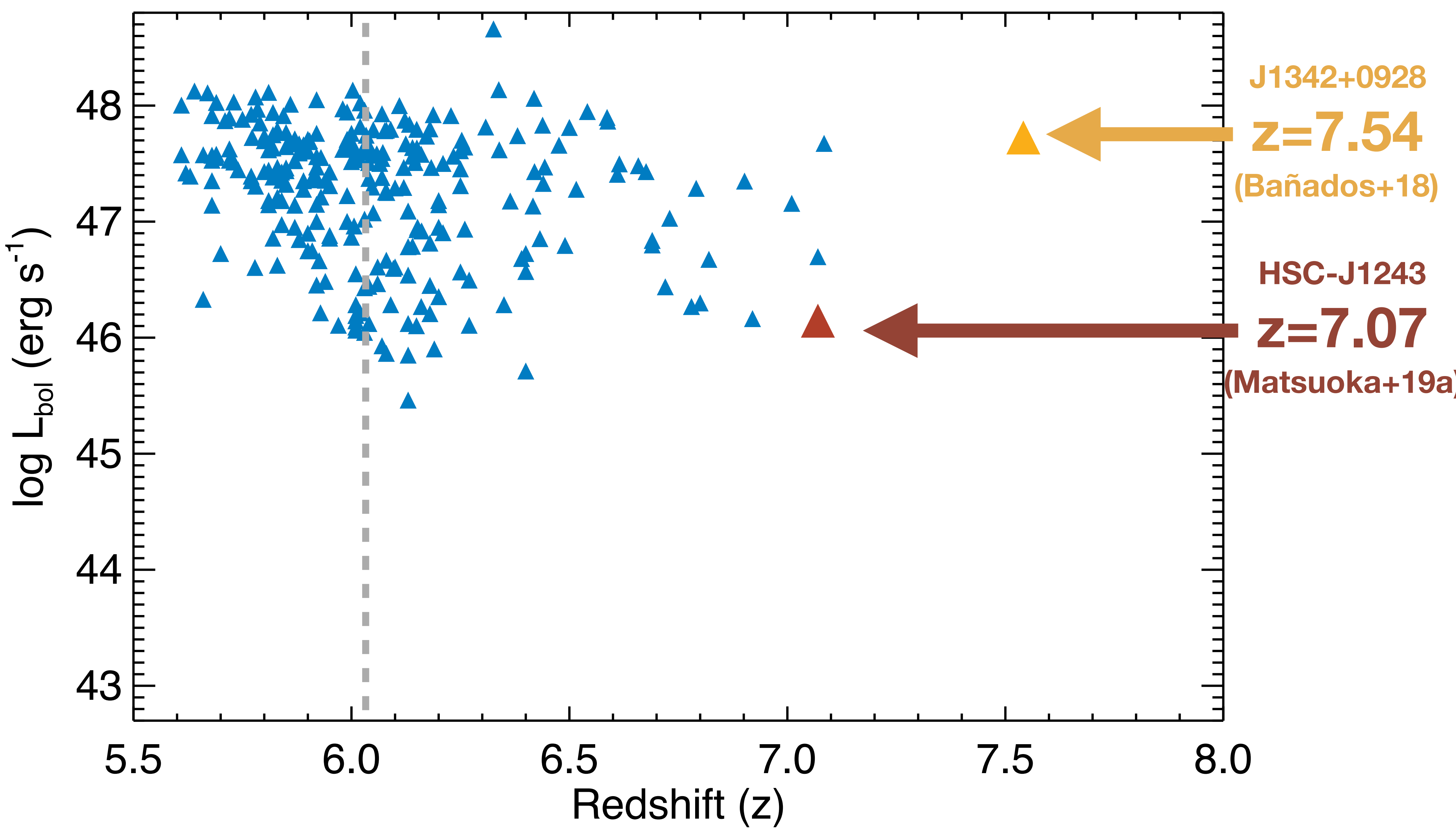
VISTA

SUBARU TELESCOPE

National Astronomical Observatory of Japan

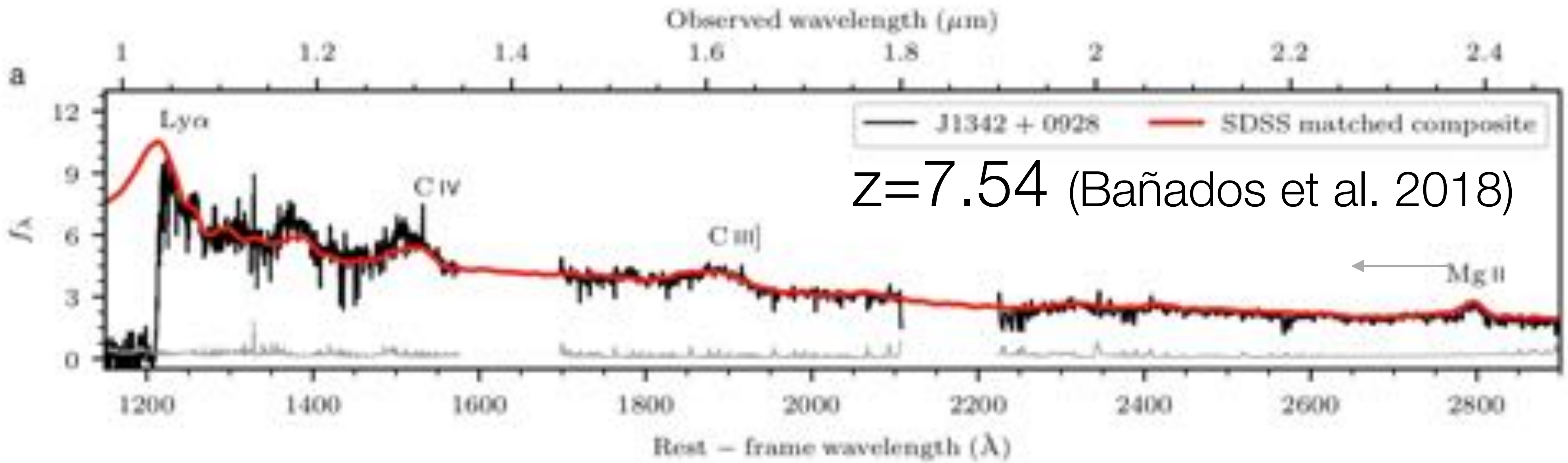
Massive black holes in the early (z>6) Universe - optical/near-IR searches

~146 known quasars at z>6 (4 at z>7)



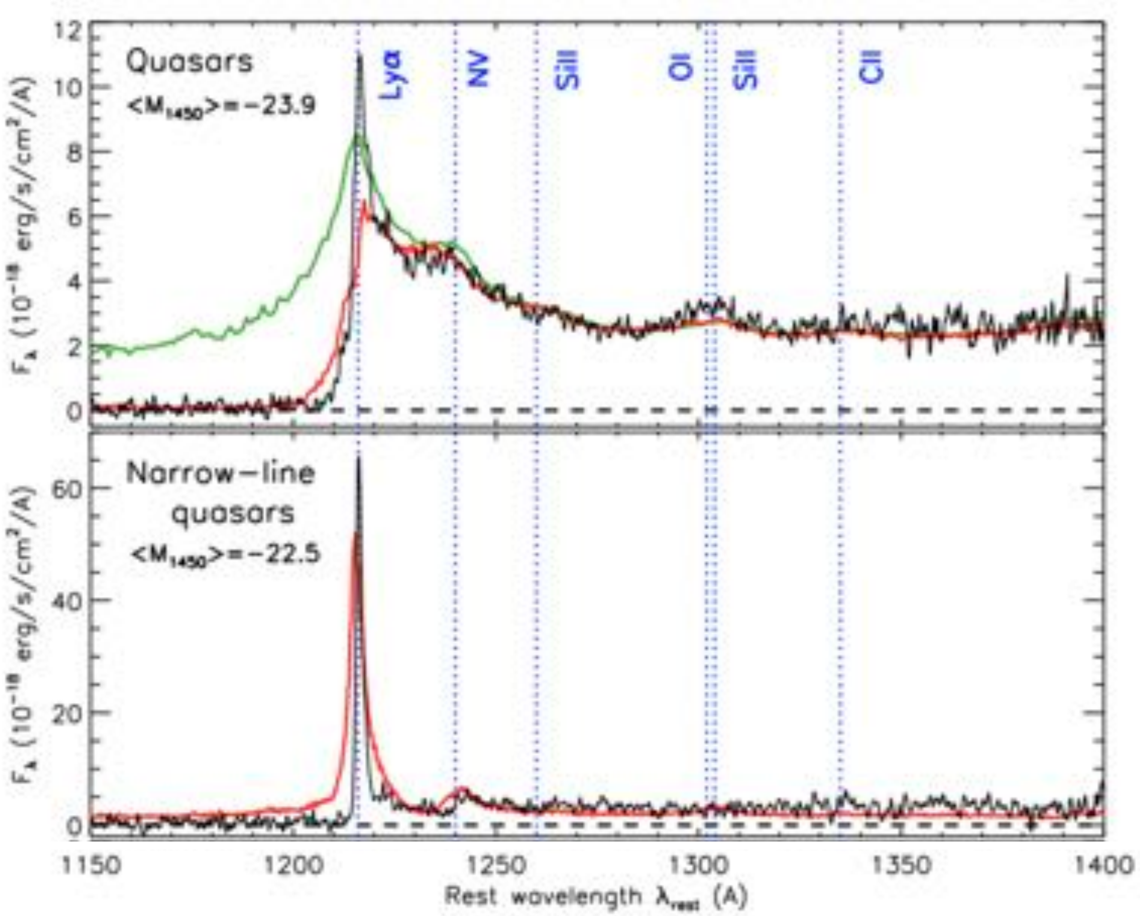
Bañados+16 (and references therein), Mazzucchelli+17, Matsuoka+19a,19b

Optical spectra of luminous *z*>7 quasars



z=7.54 (Bañados et al. 2018)

MgII -> BH mass estimates

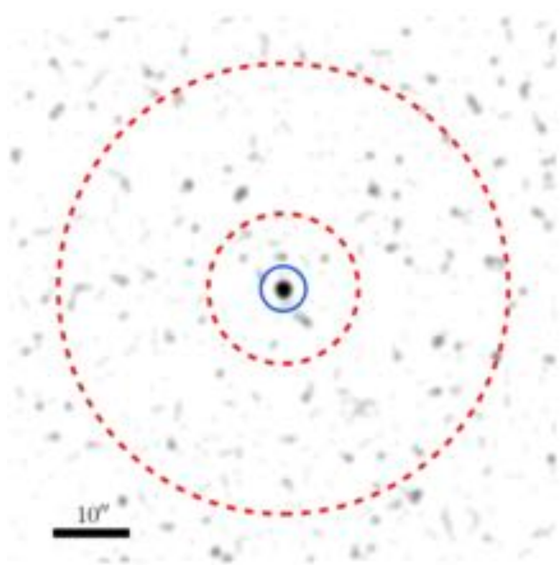


Composites of 75 broad-line and 18 narrow-line quasars at 5.7<*z*<7 from Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs)

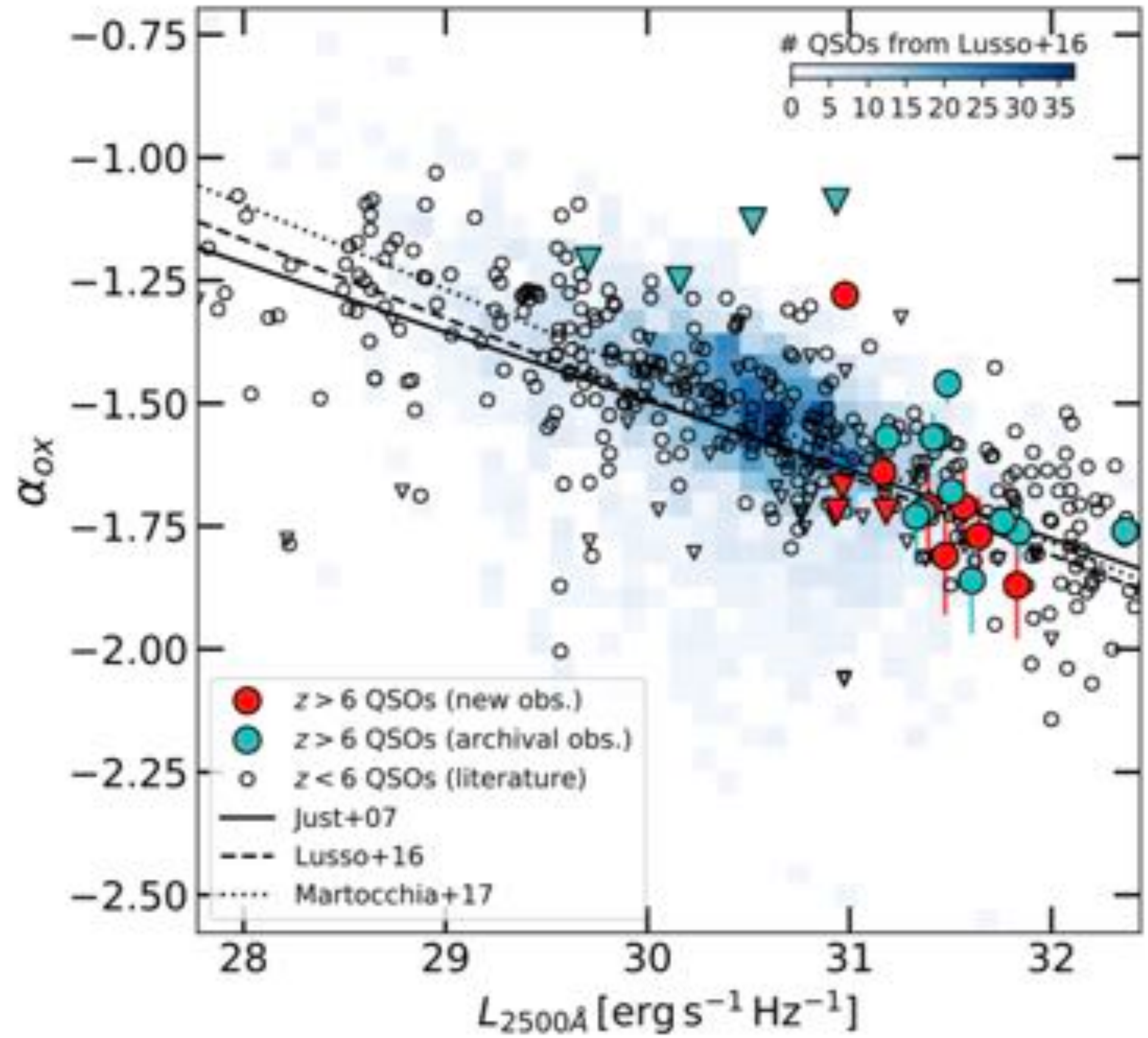
(Matsuoka+19b)

X-ray properties of luminous $z>6$ quasars

Chandra 0.5-7keV image of
J1342+0928, z=7.54
(Bañados et al. 2018b)



Vito et al. 2019



see upcoming talks by Fabio Vito and Ricardo Nanni

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

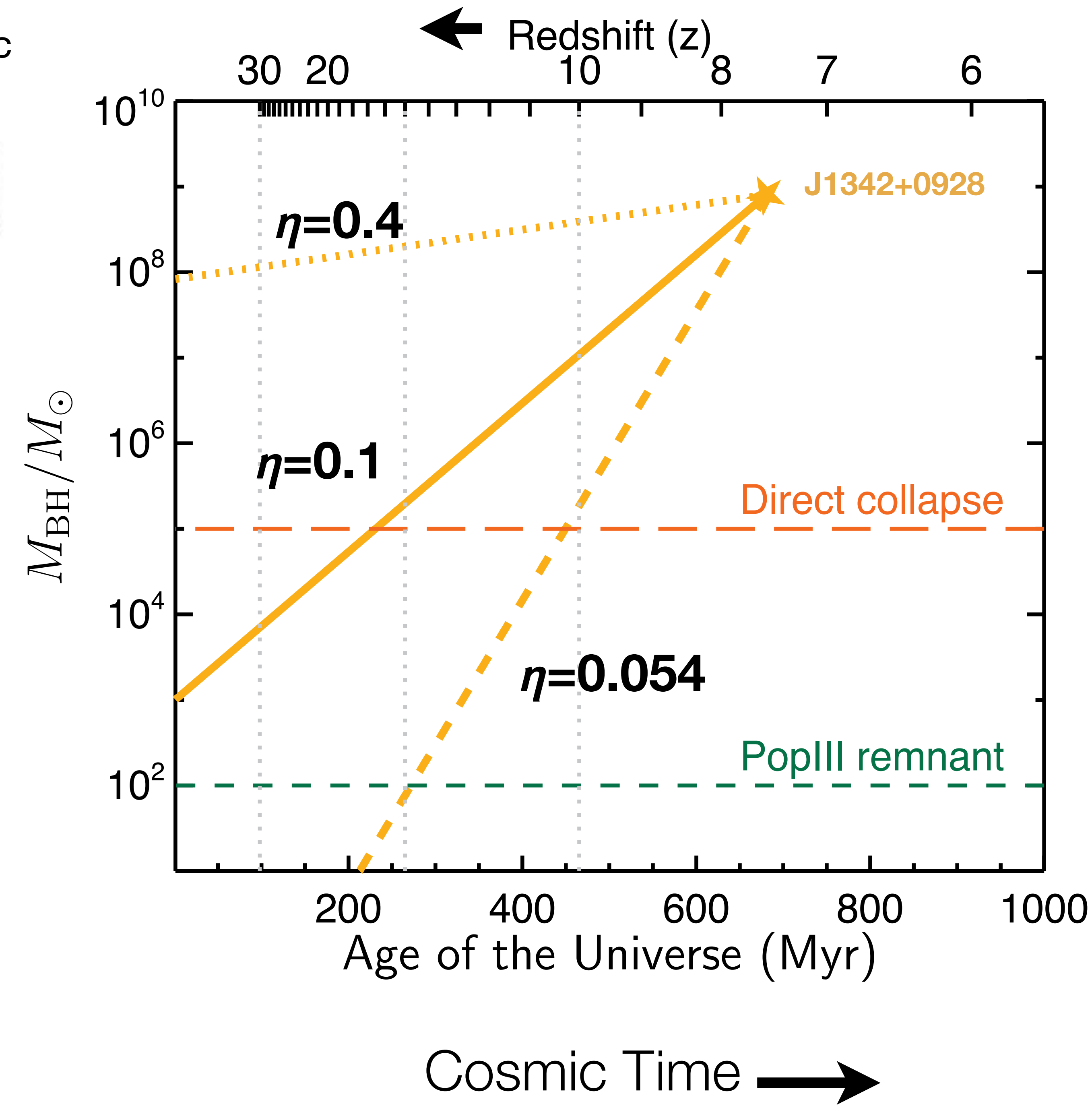
- Black hole mass grows as:

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

seed mass (M_0); radiative efficiency (η); Eddington luminosity ($L_{\rm Edd}$); cosmic time (t)

The seed of J1342 (z=7.54, M_{BH}≈8 x 10^8 $M_\odot$) could have formed by:

- direct collapse at z~15, but requires growth at ~Eddington limit for entire lifetime
- from a PopIII remnant at z<20, but requires growth at ~Eddington limit for entire lifetime and low radiative efficiency (maintain low spin = chaotic accretion?)



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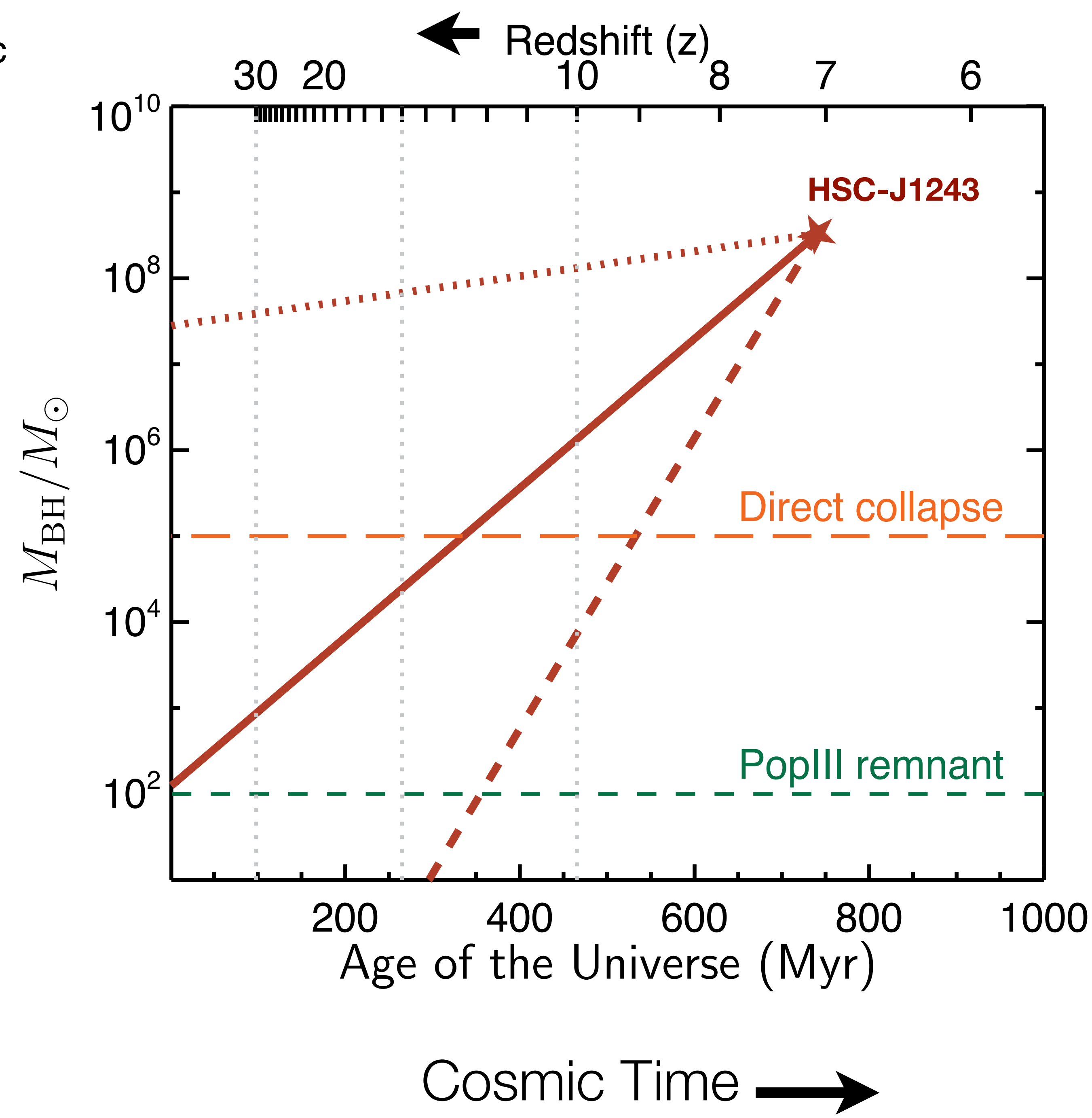
HSC-J1243 (z=7.07, M_{BH}≈3.3 x 10^8 $M_\odot$):

- also consistent with direct collapse or PopIII **if** accreting at Eddington limit



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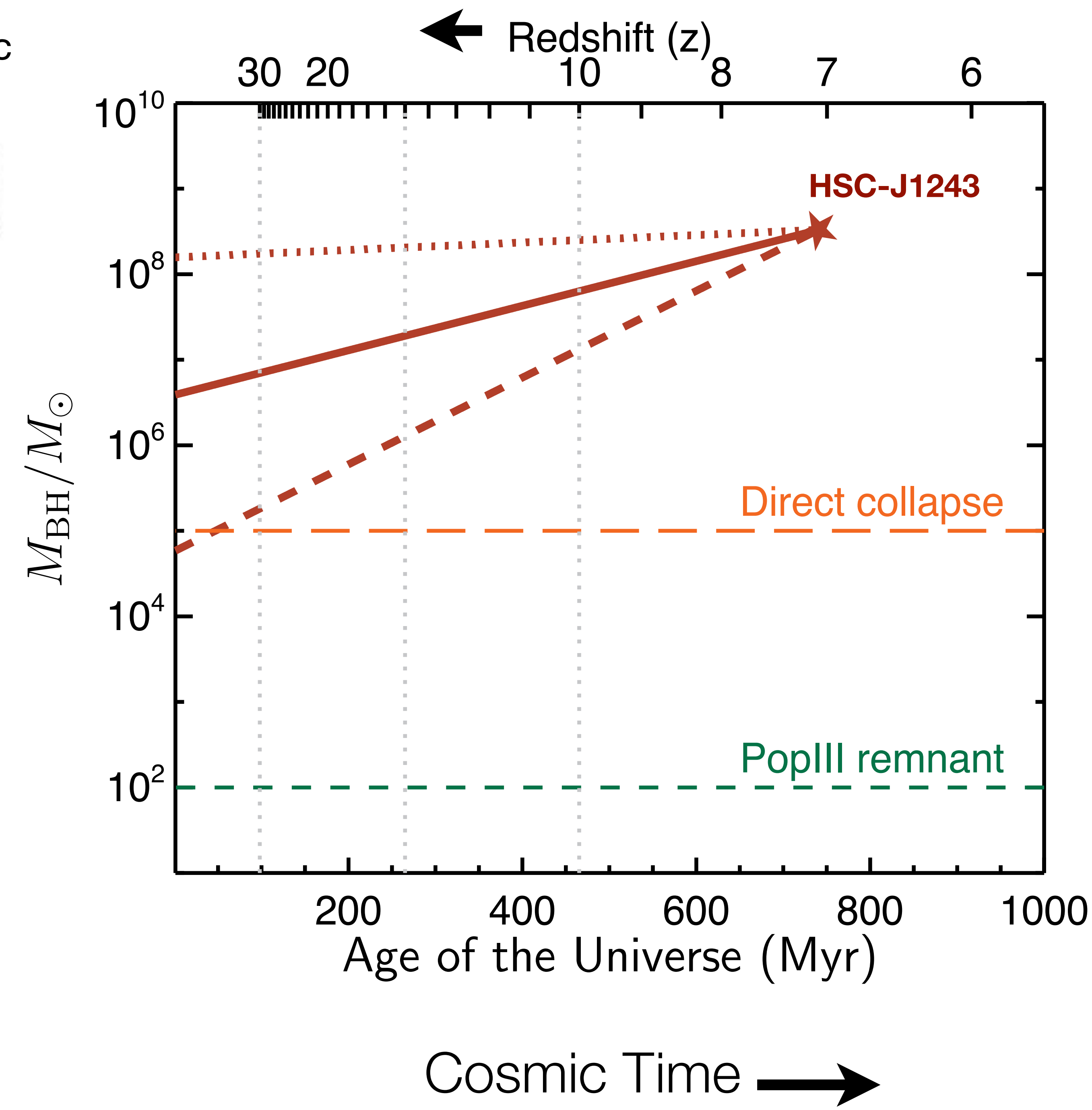
cosmic time

seed mass

radiative efficiency

Eddington luminosity



HSC-J1243 (z=7.07, M_{BH}≈3.3 x 10^8 $M_\odot$):

- also consistent with direct collapse or PopIII **if** accreting at Eddington limit
- **Observed f_{Edd}=0.3** - if accreting at this rate (on average) requires direct collapse

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

- Black hole mass grows as:

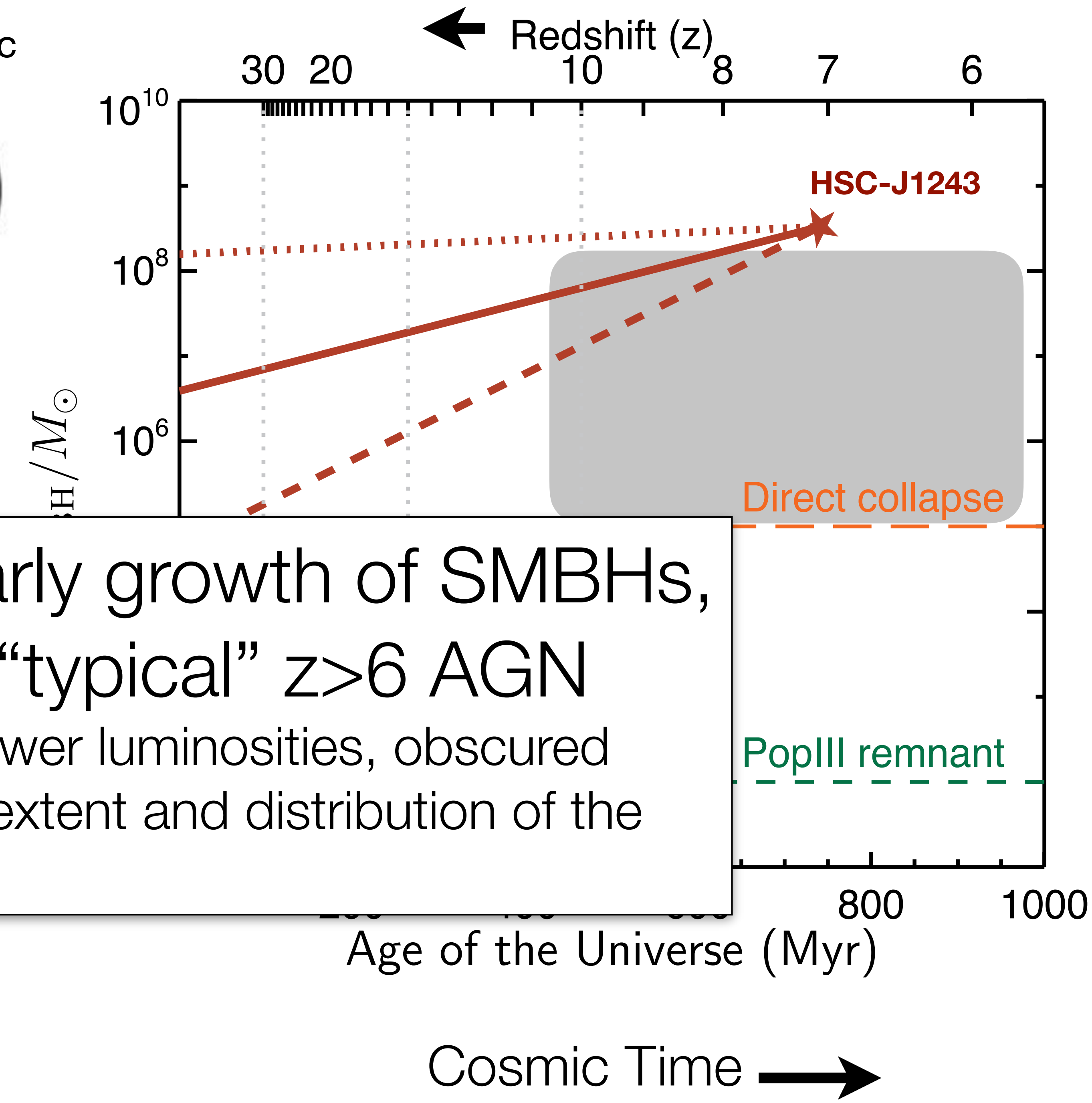
$$M_{\rm BH}(t) = M_0 \exp\left(\frac{1-\eta}{\eta}\frac{L_{\rm bol}}{L_{\rm Edd}}\frac{t}{0.45{\rm Gyr}}\right)$$

cosmic time

seed mass

radiative efficiency

Eddington luminosity



To constrain the early growth of SMBHs, need to probe the "typical" z>6 AGN

(lower mass black holes, lower luminosities, obscured sources => determine the extent and distribution of the bulk of early BH growth)

HSC-J1243

M☉):

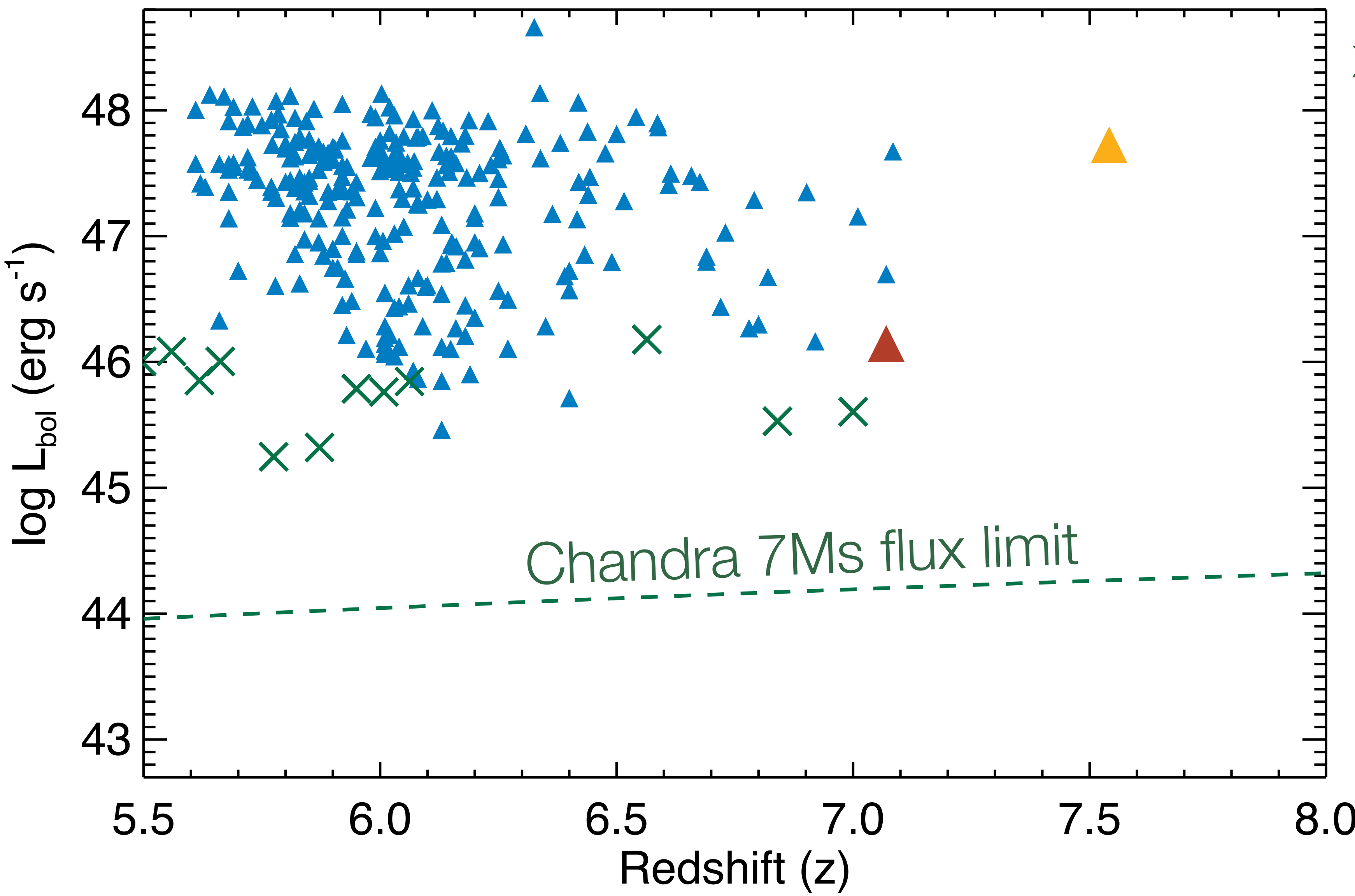
- also c
collapse or PopIII if accreting at Eddington limit

- **Observed $f_{\rm Edd}$=0.3** - if accreting at this rate (on average) requires direct collapse

Current X-ray searches for early AGN

X-ray surveys:

- probe a broad range in luminosity
- find fainter AGN, generally not identified by optical or IR selection
- identify obscured AGN



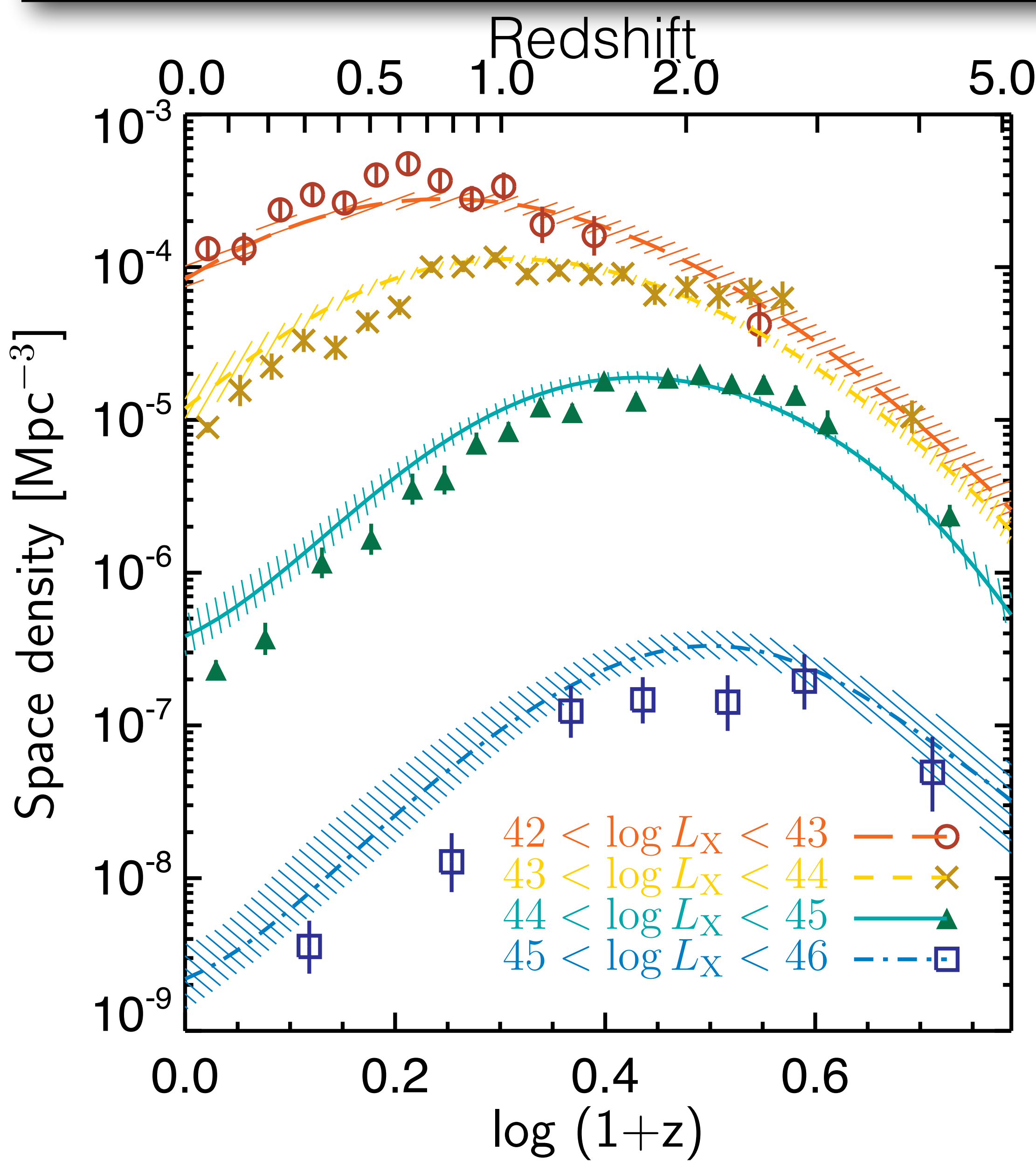
x Chandra detections

CDFS 7Ms (Luo+ 17)
COSMOS Legacy (Marchesi+16)
AEGIS (Nandra+15)

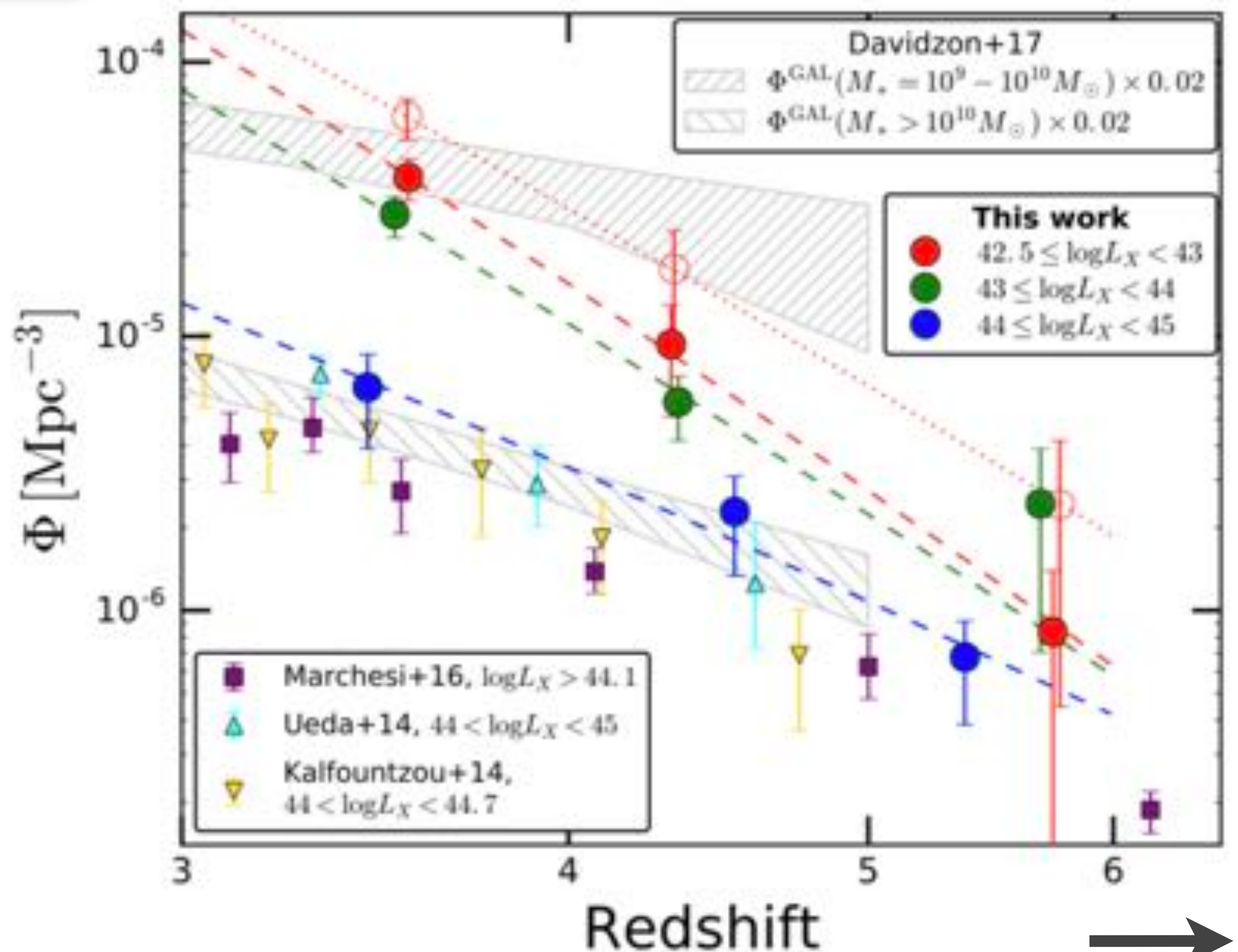
- only a handful at z>5
- faint counterparts, uncertain photo-z

The evolution of the **space density** of X-ray detected AGN

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



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



High redshift

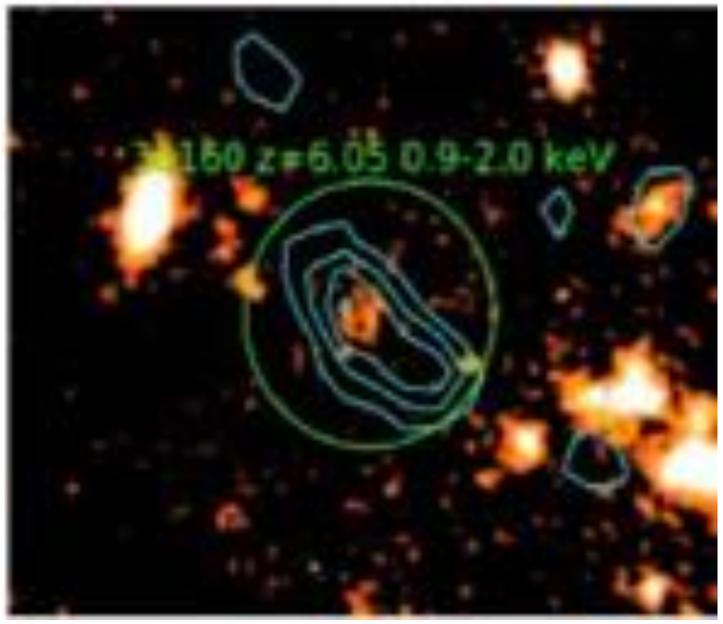
Vito et al. (2018)
(see also Brusa+09, Civano+12, Ueda+14, Vito+14, Weigel+15, Georgakakis+15, Khorunzhev+18)

X-ray searches for the earliest SMBHs

- “sub-threshold” detections

- deep NIR+optical imaging (HST/CANDELS) provides moderate samples of *galaxies* at $z>5$
    - **Attempt to improve X-ray source identification using galaxy positions**

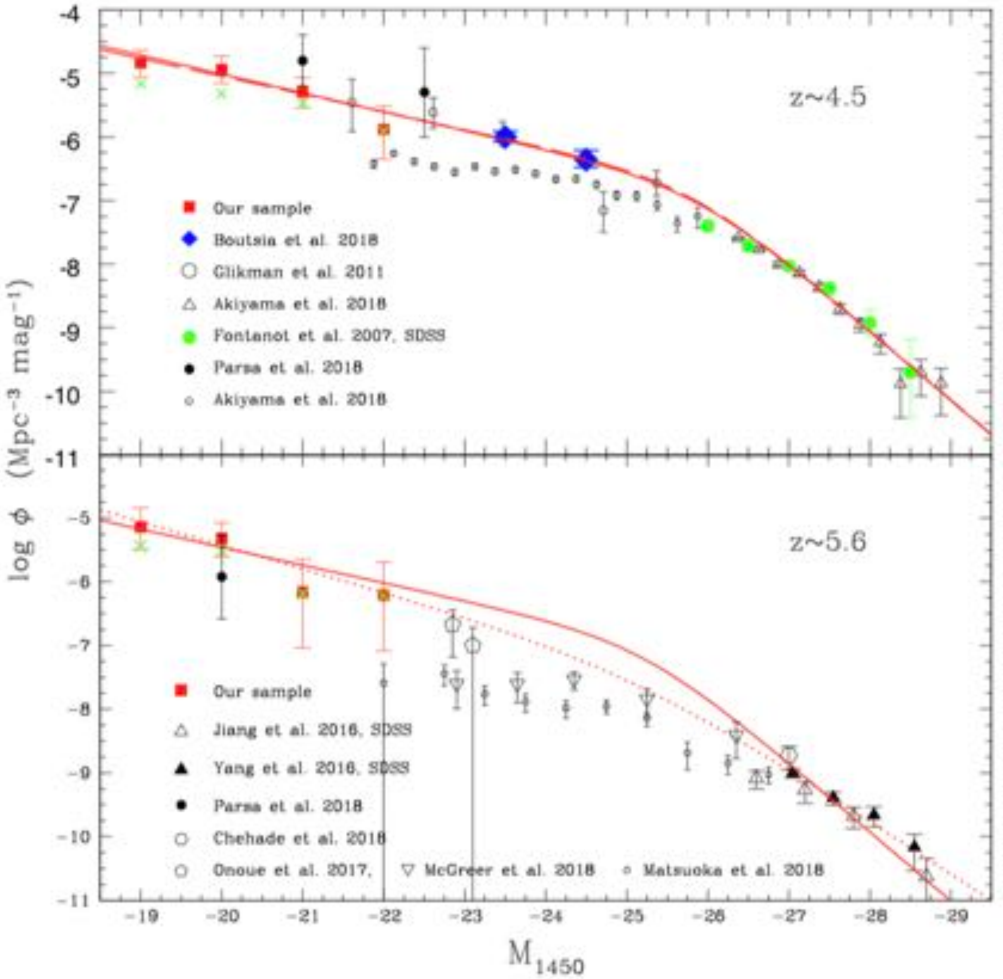
Giallongo et al. (2019)



H-band image + X-ray contours

identifies additional AGN =>

- constraints on faint end of UV luminosity function (connection to opt+IR selected quasars)
- role of AGN in re-ionization,)

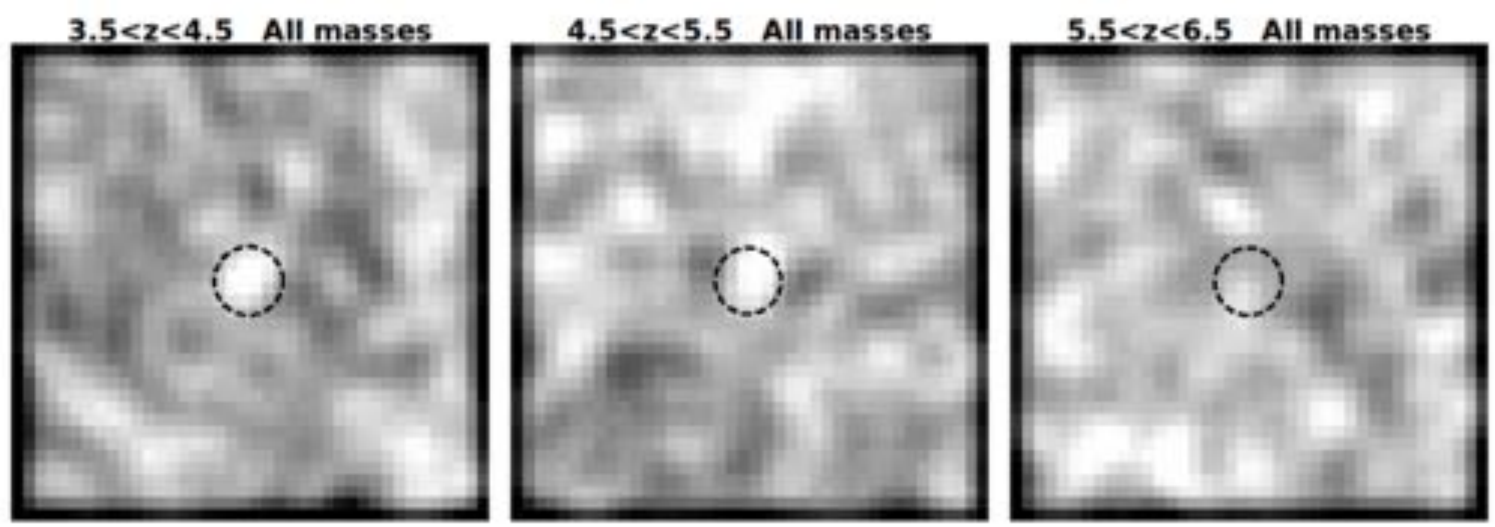


- see also Fiore+12, Giallongo+15, Cappelluti+16

X-ray searches for the earliest SMBHs

- stacking

- deep NIR+optical imaging (HST/CANDELS) provides moderate samples of *galaxies* at *z*>5
  - **Stack the X-ray data at the galaxy positions**



e.g. Vito+16

- X-ray signal likely dominated by star formation processes
- Places upper limits on BH accretion density due to low-L_X AGN in these very high-z galaxies

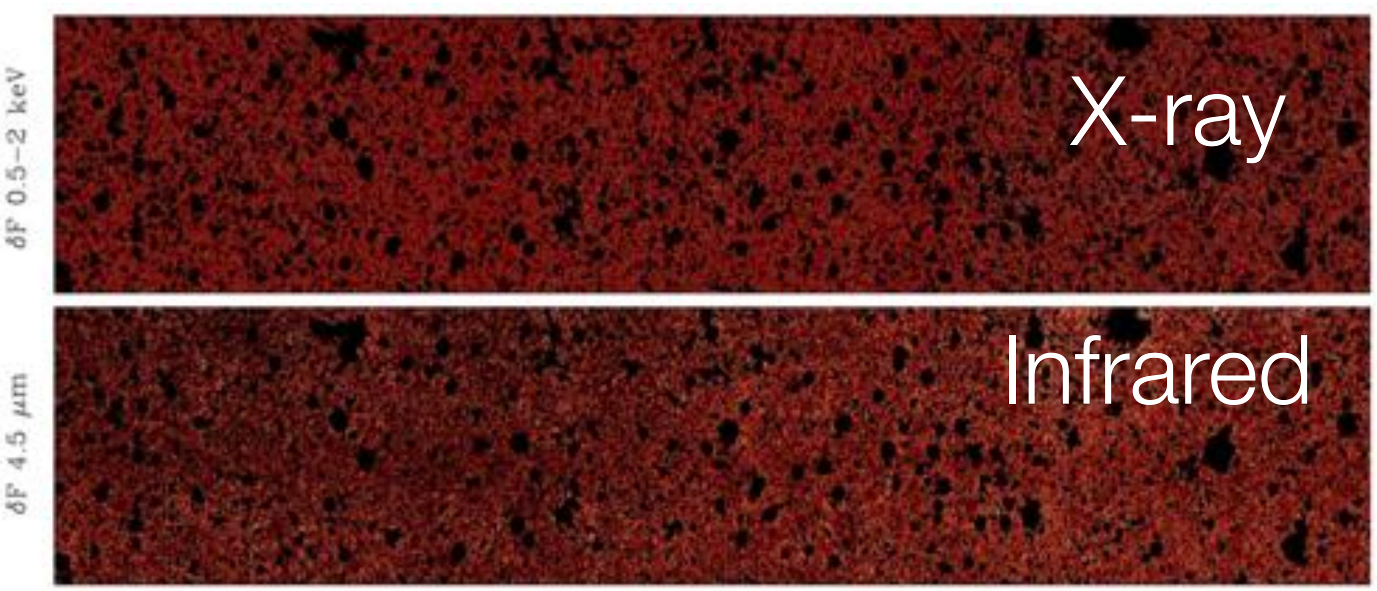
X-ray searches for the earliest SMBHs

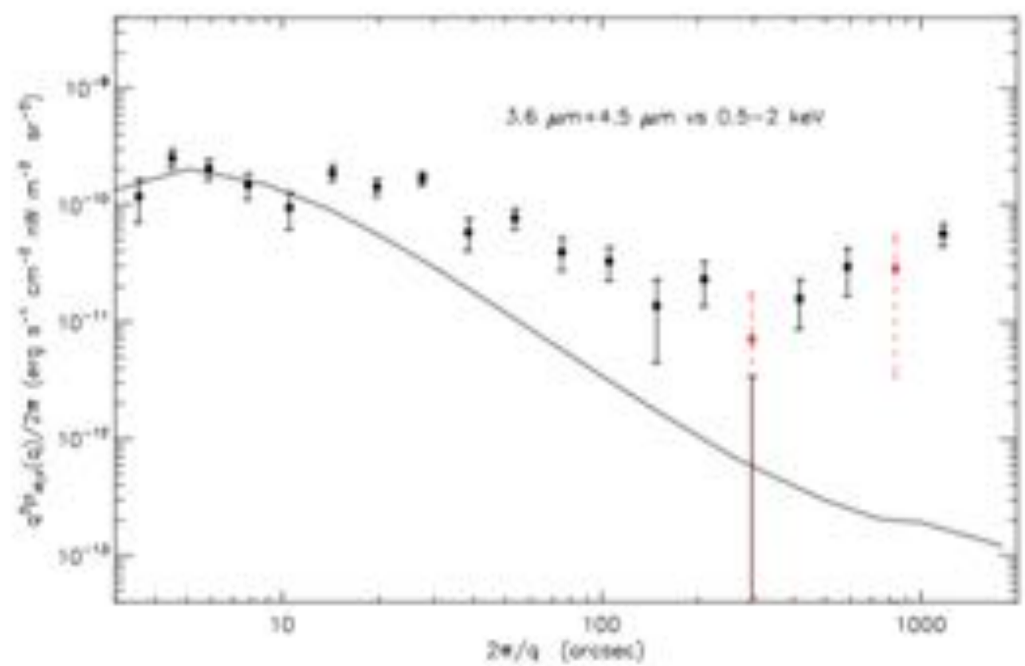
- what's left…?

- Background fluctuations!

- correlation between infrared and X-ray background fluctuations
  => tracer of early BHs

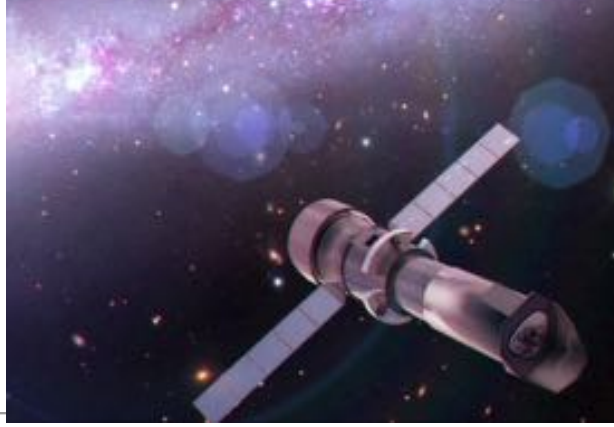
Cappelluti+13,16





see next talk by Nico Cappelluti

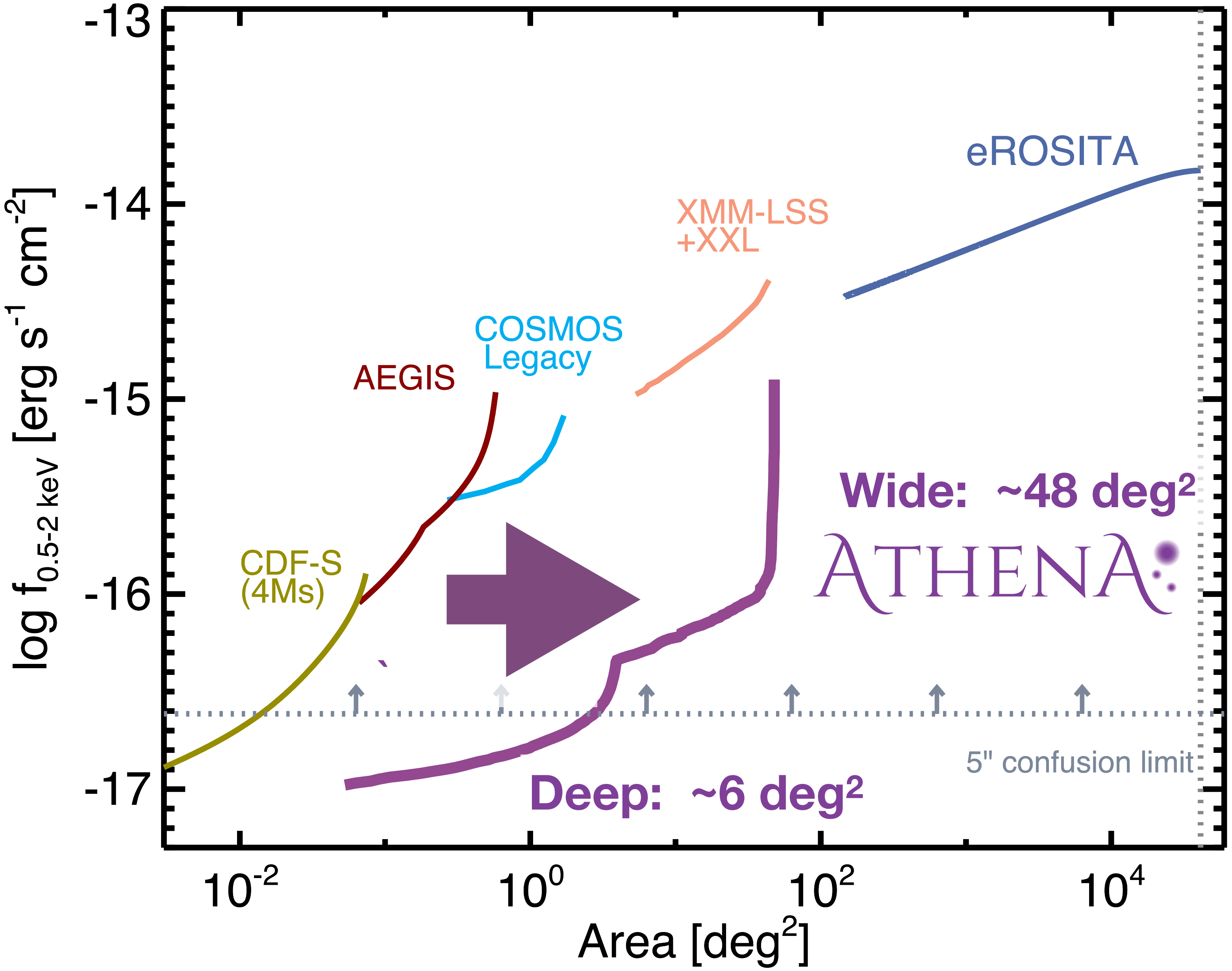
Tracking the early growth of SMBHs with *Athena*



- Current surveys (Chandra) have the sensitivity to detect low-to-moderate L_X AGN ($10^{43\text{-}44}$ erg s^{-1}) at z>6, but lack the area coverage

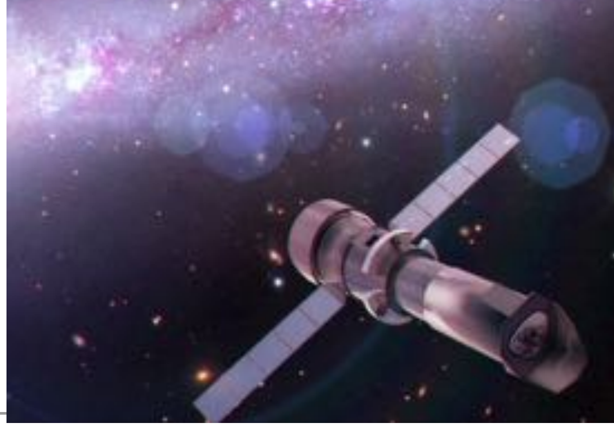
➡ Athena:

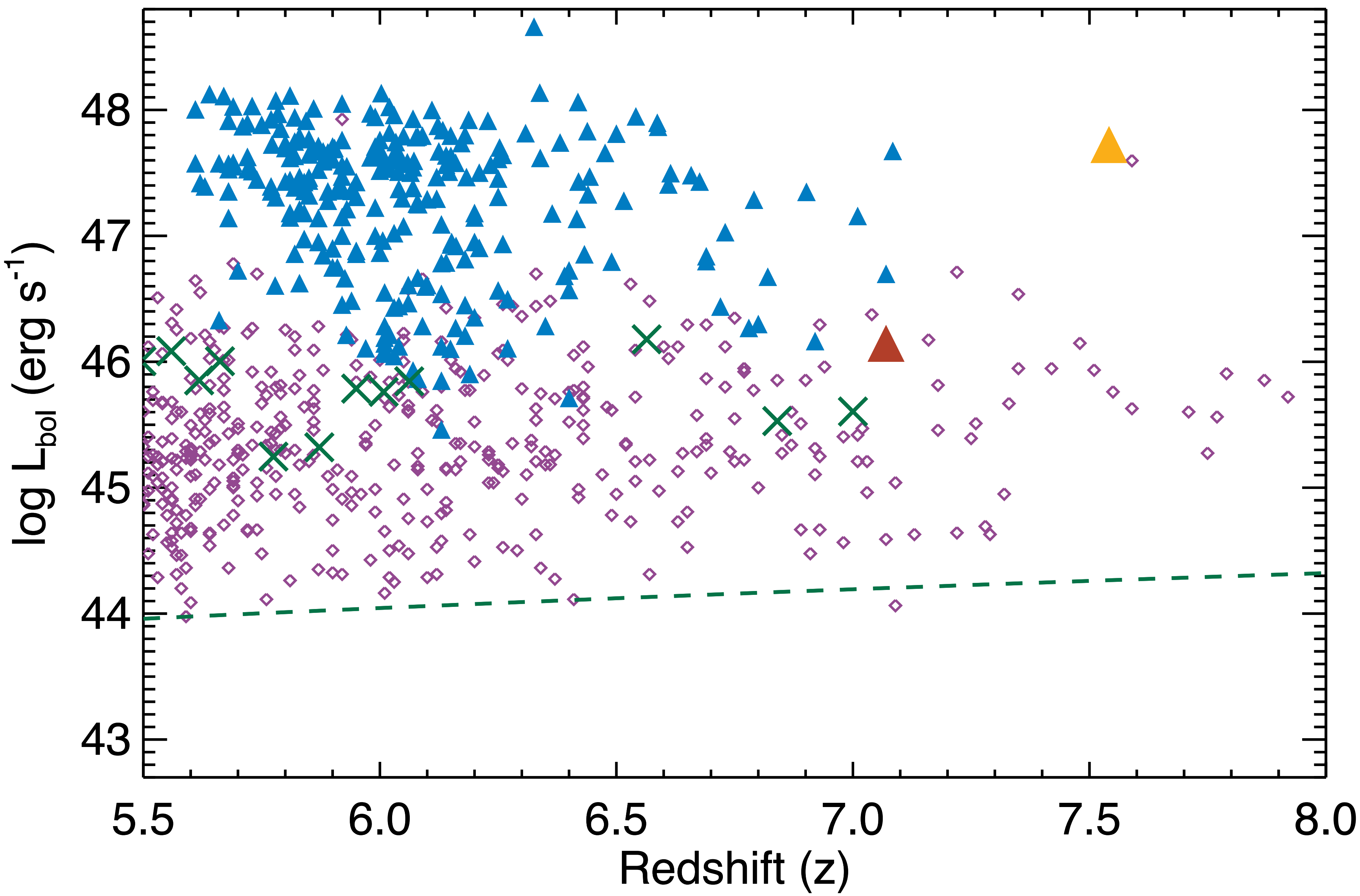
- large-collecting area (1.4m²)
- large field-of-view (40'x40')
- PSF ~5" HEW **across the FOV**
- **survey speed up to 100 times faster than Chandra**



~22.5 Ms survey programme (tentative plan): 4x1.3Ms + 8x950ks + 108x90ks

Tracking the early growth of SMBHs with *Athena*





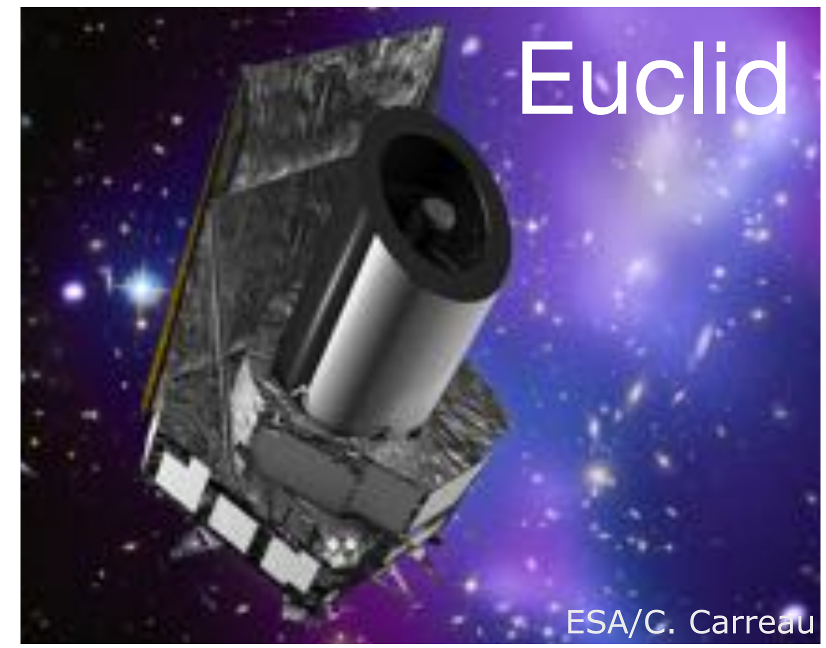
x Chandra detections

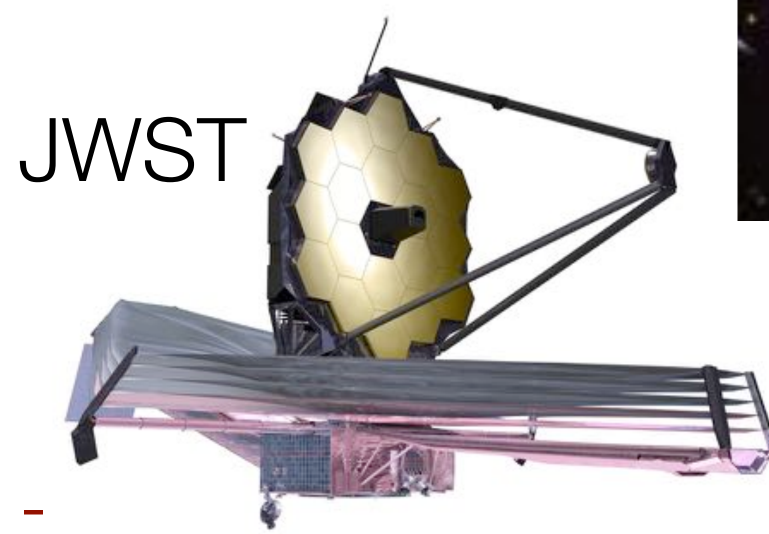
CDFS 7Ms (Luo+ 17)
COSMOS Legacy (Marchesi+16)
AEGIS (Nandra+15)

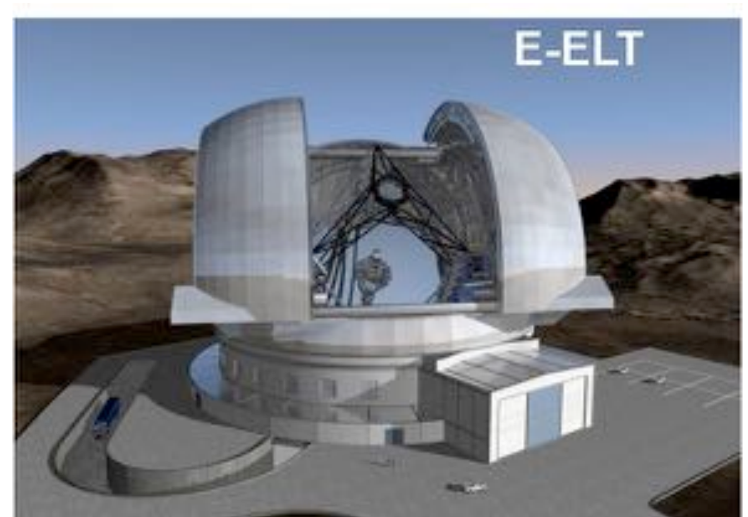
◇ **Athena predicted high-z detections**
(~25Ms multi-tiered survey)

Counterparts to Athena X-ray sources (in the early 2030s)

- ~50 deg^2 Athena 'shallow' (~90ks) 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 (~6 deg^2, 950ks)
- *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.)

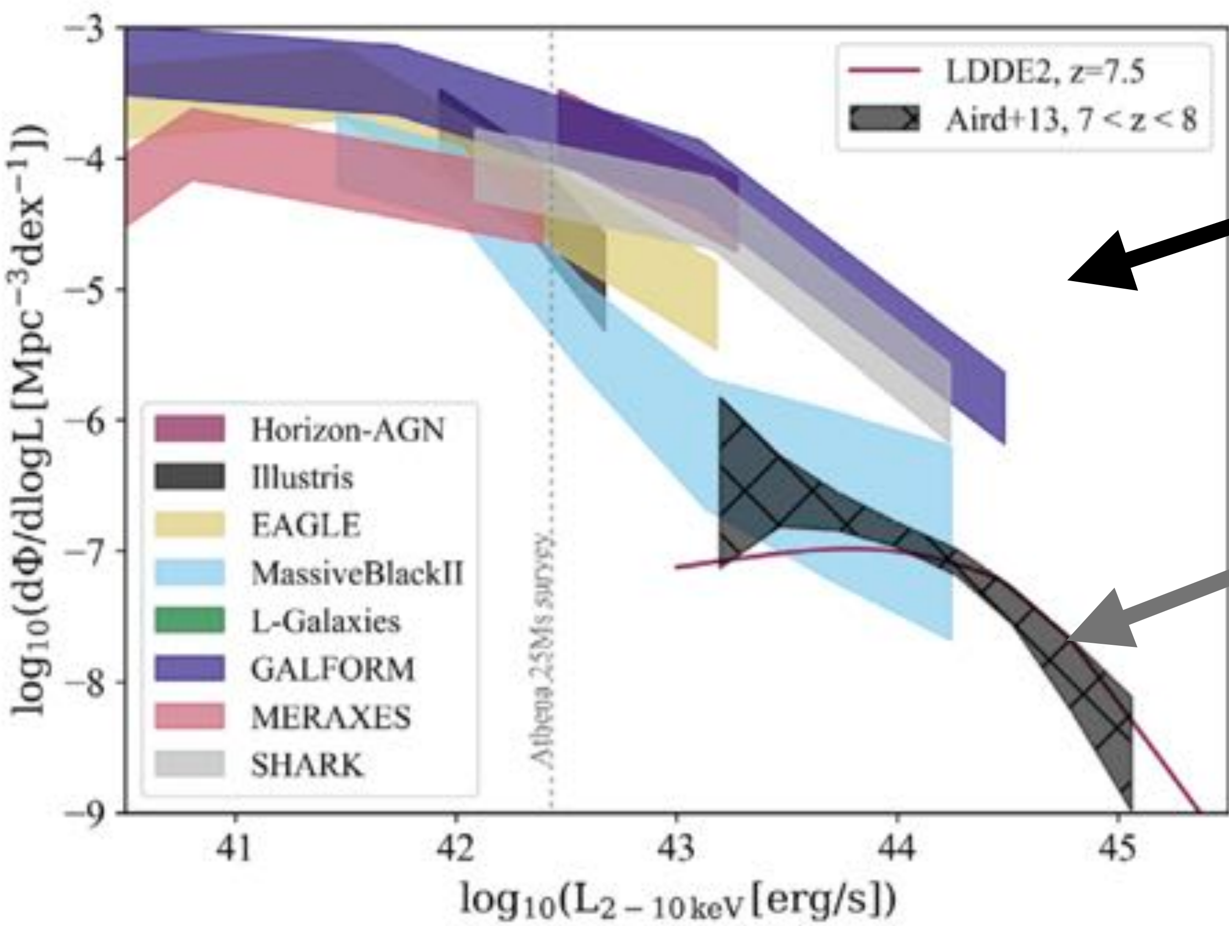






Athena constraints vs. models

Amarantidis+19



see also: Ricarte+18, Valiante+18, DeGraf+19, Griffin+19

Comparison of the high-z AGN luminosity function from a range of hydrodynamic and semi-analytic simulations

vs. predicted *Athena* constraints

- models often high vs. empirical predictions (extrapolations) - also true at lower z!
- order of magnitude differences between models - Athena will provide vital constraints!
- some models do not extend to highest L_X - volume limitations?

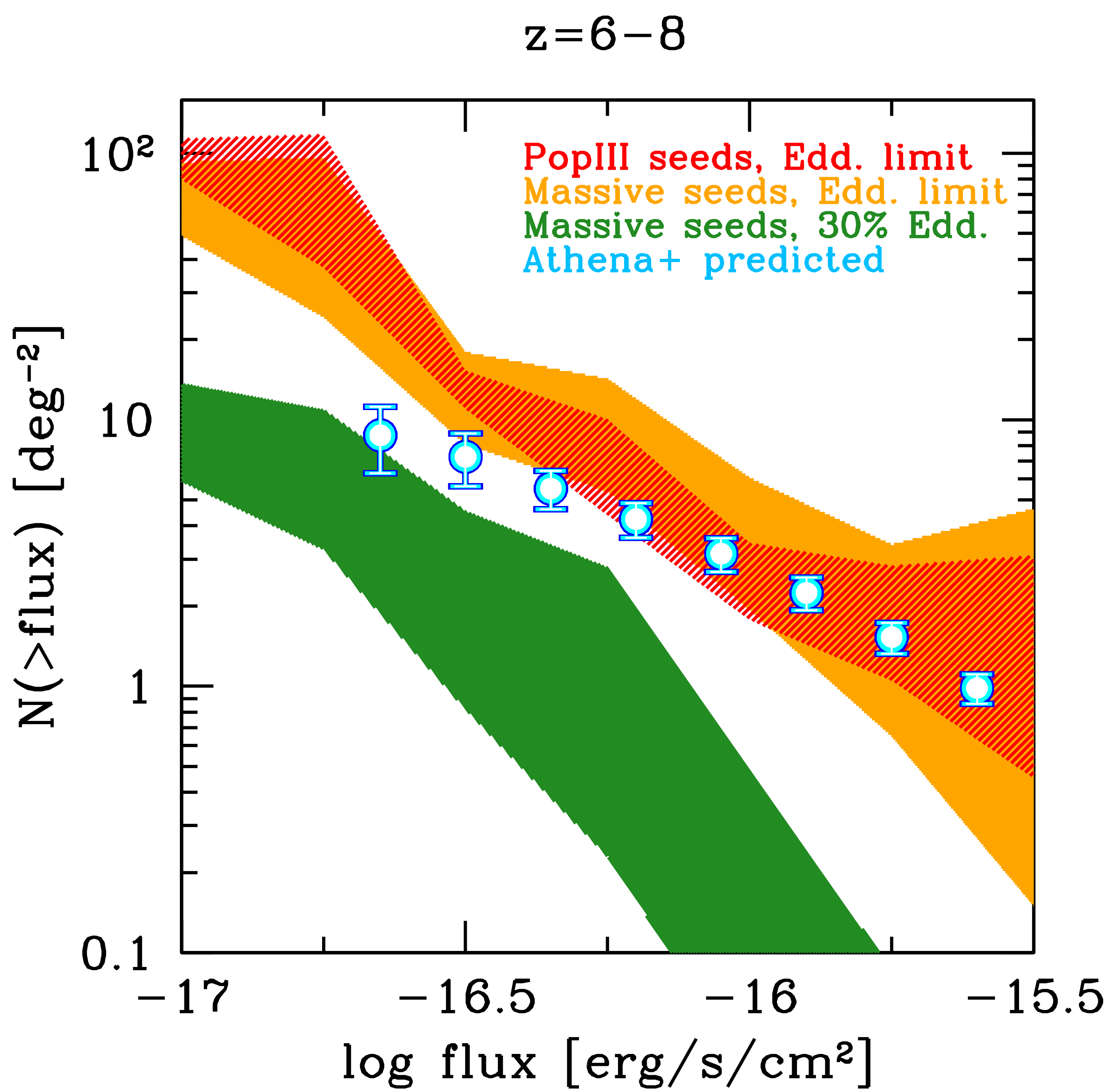
Athena constraints vs. models

- 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

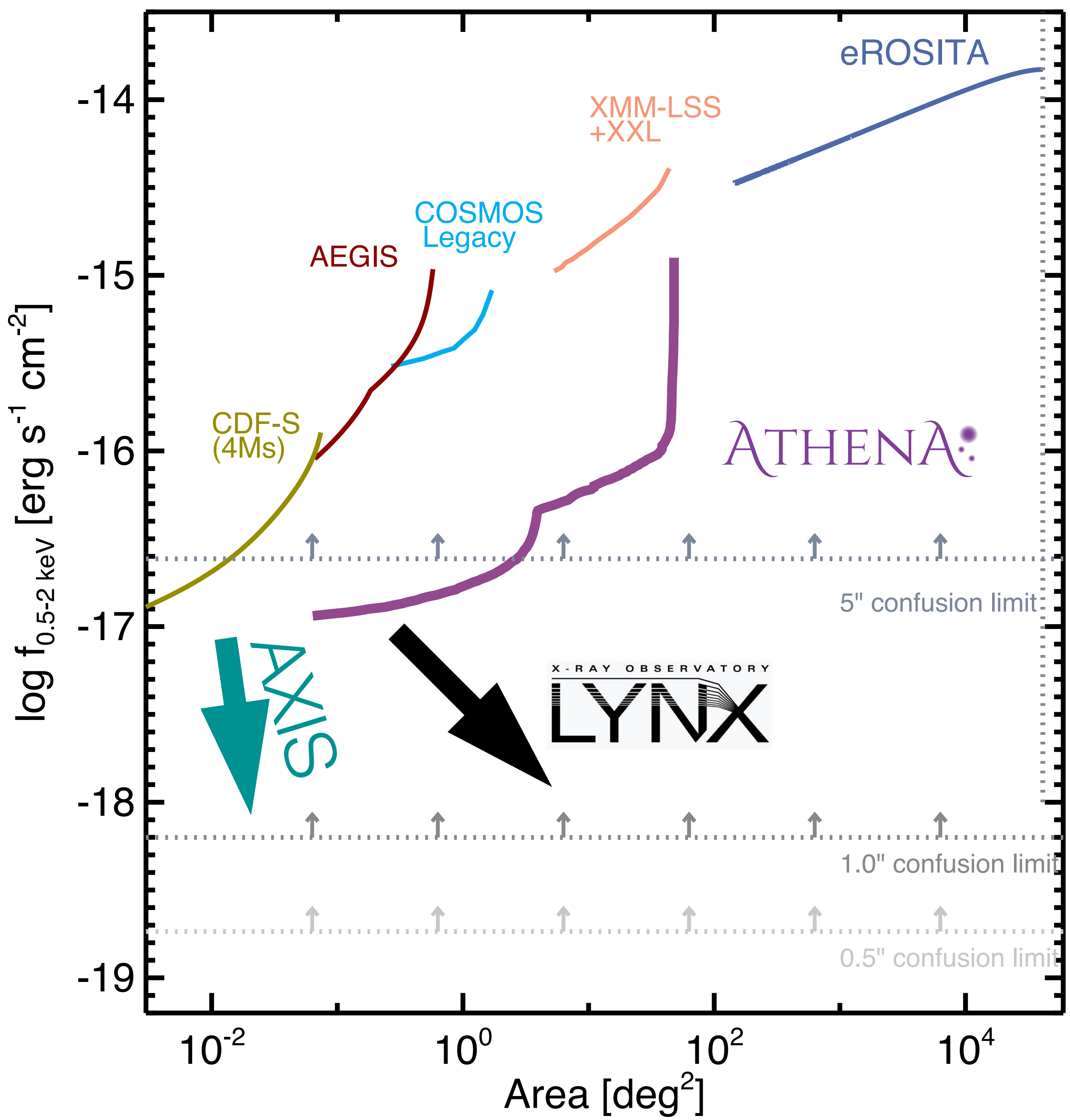
but samples **will** constrain the extent of early mass growth, where this growth occurs within the *z*>6 galaxy population, and the *possible* seed mechanisms, ruling out certain classes of models



Aird, Comastri et al. 2013, models by Marta Volonteri

Beyond *Athena*: AXIS and Lynx

To detect accreting ~$10^{4-5}\,M_{\odot}$ black holes in the z~6-10 Universe, requires ~1" resolution



Summary

- Bulk of the mass growth of supermassive black holes is due to accretion at $z<3$ and is well-characterised
- But initial *seeds* likely formed in particular environments at very high $z>10$, with subsequent growth by merging but (mostly) accretion

- Latest optical/NIR surveys starting to sample *quasar* population at z>6 - challenges for seed models to build most massive black holes
- Current X-ray surveys reveal strong drop in space density of AGN at all luminosities at z>3 - very few sources found at z>5 *even though Chandra* has the sensitivity to detect them

- To characterise early growth need to reach deepest Chandra flux limits over large sky areas (6-50 deg^2) coverage => ATHENA
- To directly see the initial growth of $\sim 10^{4-5} M_{\odot}$ black holes requires order of magnitude improvement in sensitivity *and* wide-area coverage => X-RAY OBSERVATORY LYNX