Lecture 2.
The Highest Redshift Quasars: how to find them and how did they grow

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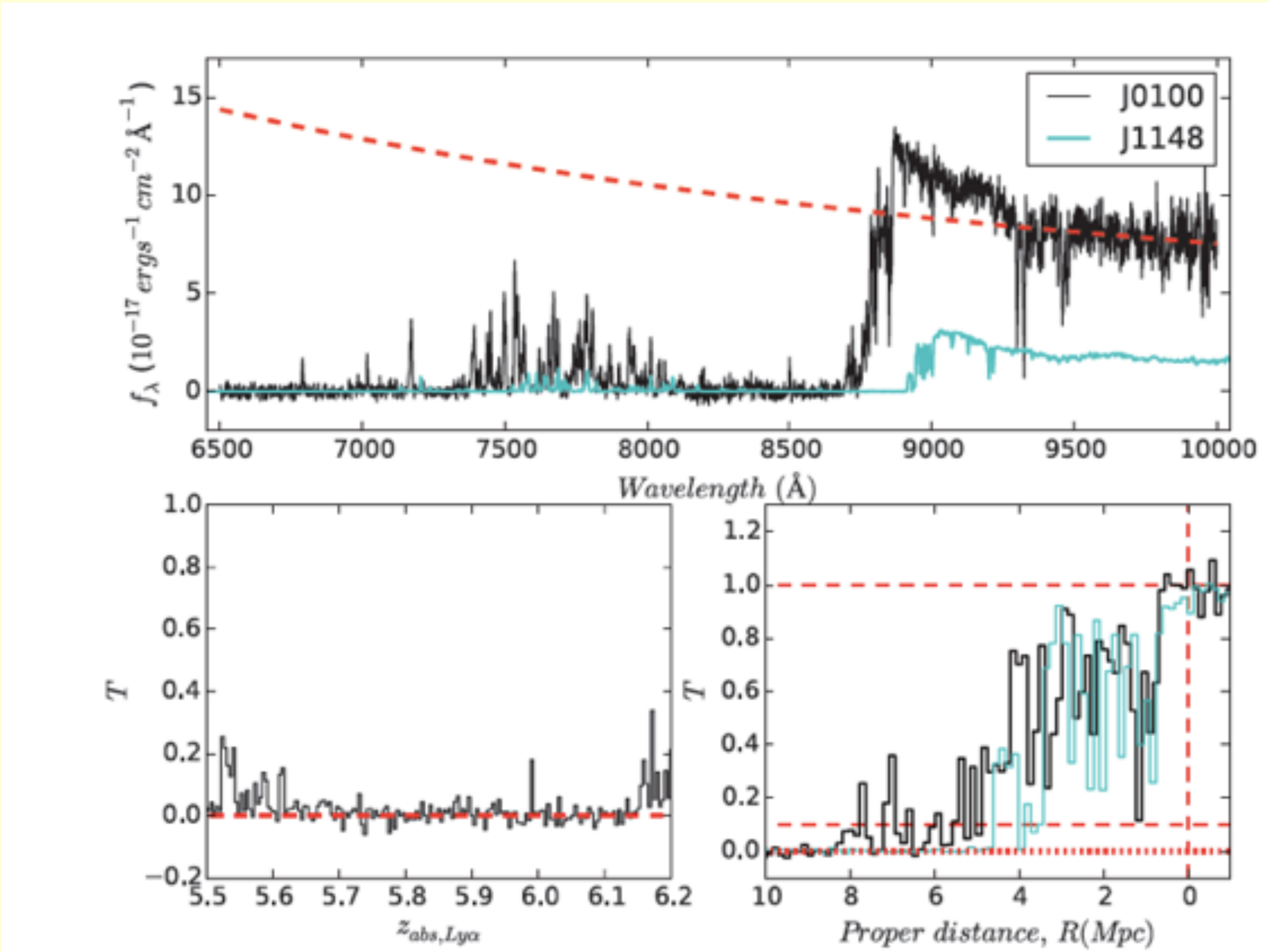
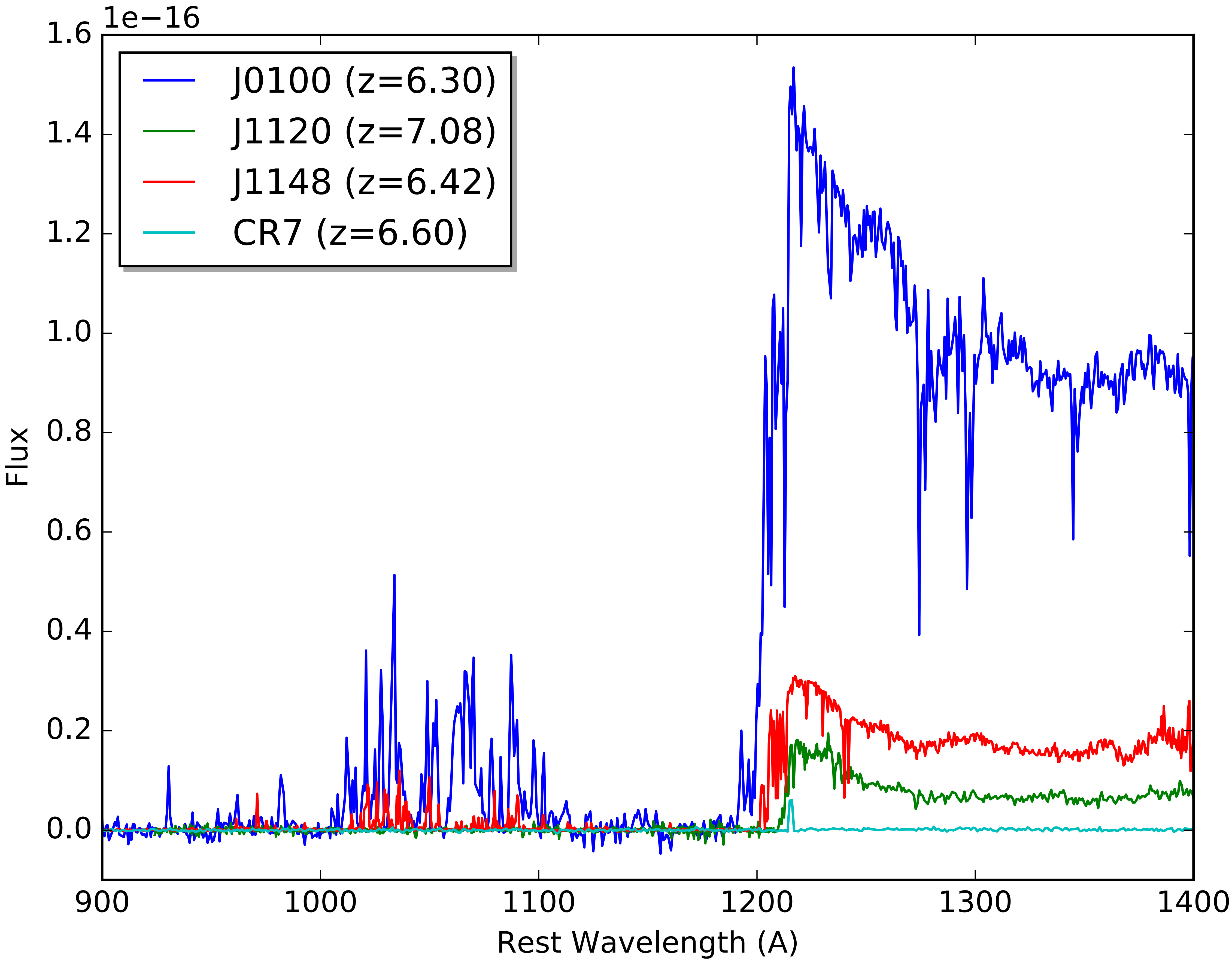
The Story behind the most massive black hole in the early universe



- it is really bright…
  - z_{AB}=18.3, **K=15.2** (detected in 2MASS = 8 sec exposure)
  - the most luminous object known in the observable universe at z>5
  - $L_{bol} = 4 \times 10^{14}\ L_{sun}$

Wu, Wang, Fan et al. 2015
LBT/MODS spectrum



1e−16
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Flux
900
1000
1100
1200
1300
1400
Rest Wavelength (A)
J0100 (z=6.30)
J1120 (z=7.08)
J1148 (z=6.42)
CR7 (z=6.60)

It would … asn't
selected … earches
describe … the i-z
colour o … have
passed t …
--

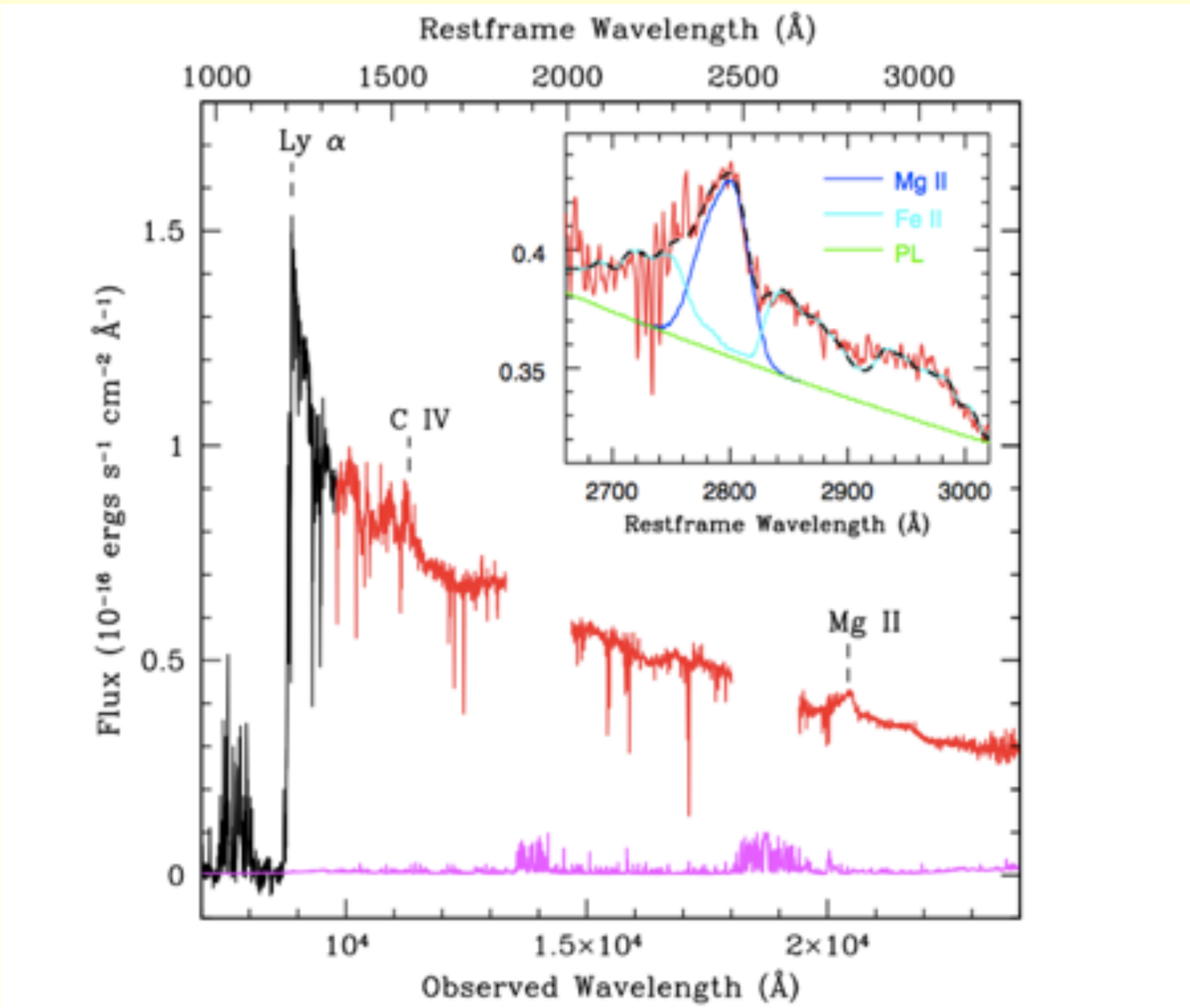
Courtesy of Arizona graduate students

Too Bright: 2MASS sources ignored by selection

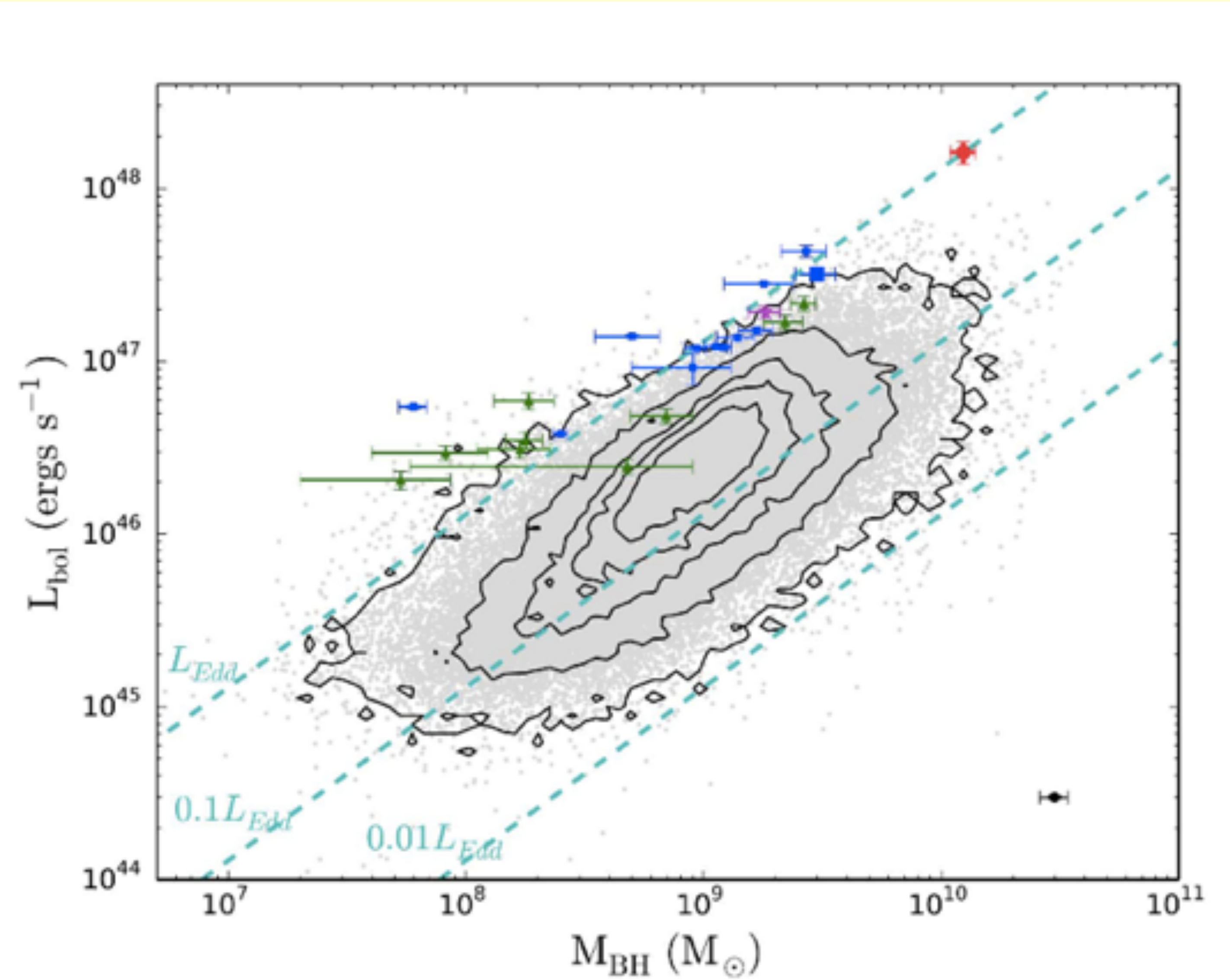
Moral of the story:

1. the universe is full of surprises
2. don’t believe everything your advisor says

A Twelve Billion Solar Mass Black Hole at the End of Reionization



Magellan/FIRE spectrum



- BH mass ~12 billion solar masses
- emitting at Eddington limit
- comparable to the most massive BH in the local universe, at z=6.3!!
- Challenge to BH formation and growth

Wu et al. 2015, Nature

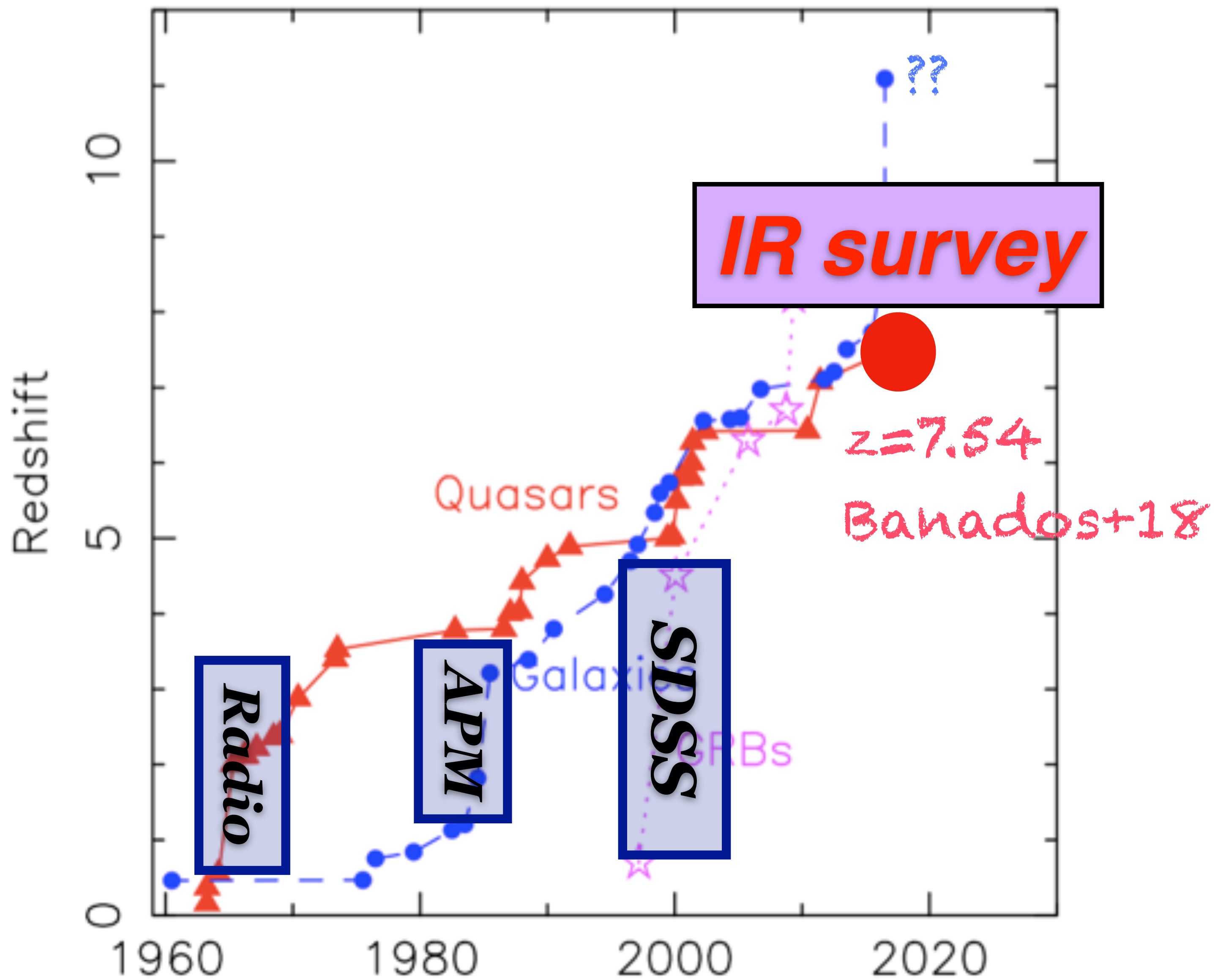
It might yet prove possible to account for the observed high-redshift (z~4) quasar populations with ... conventional cosmic structure formation theory

--- Ed Turner 1991

Topics today

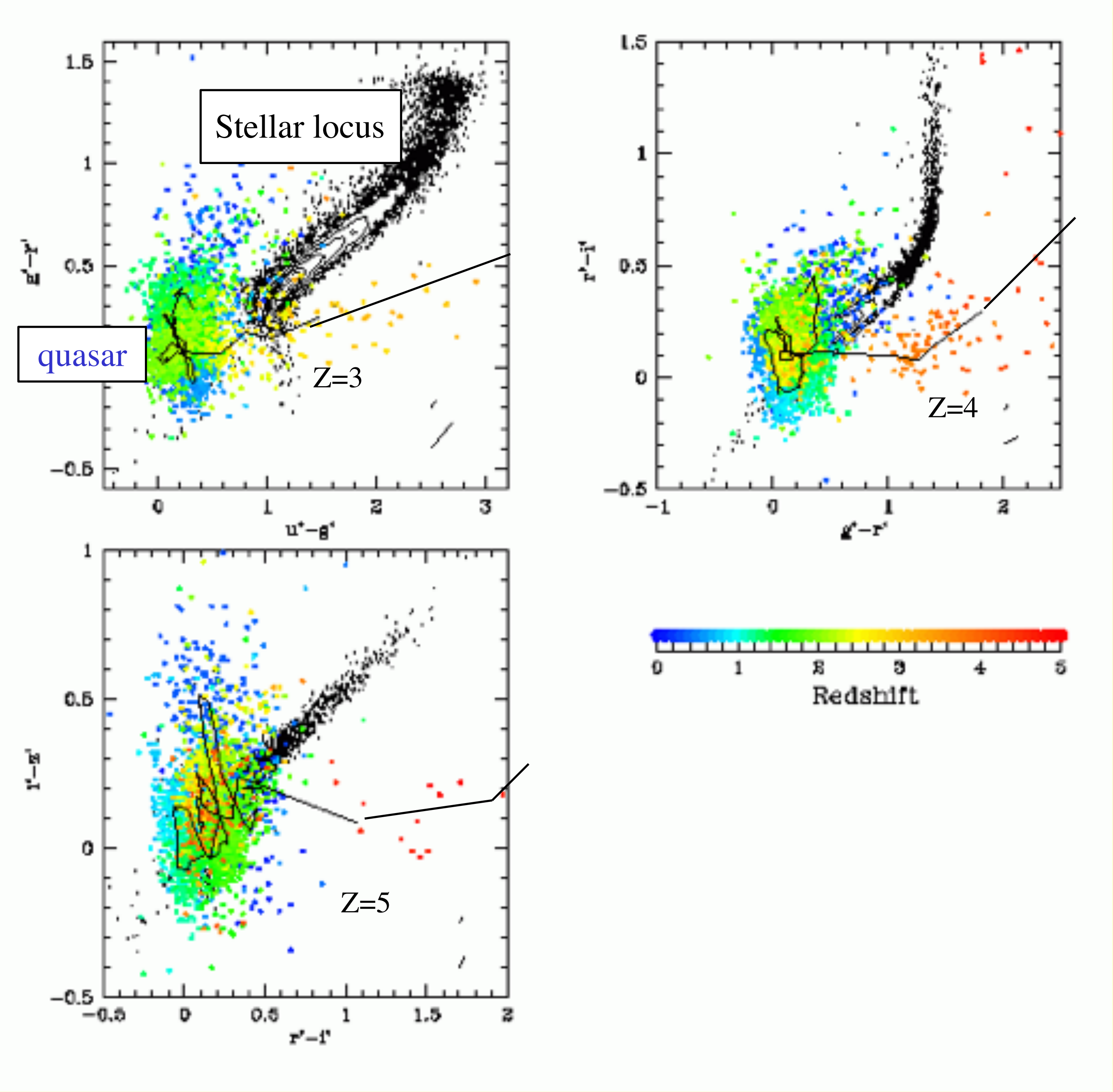
- quasar survey method
- quasar density evolution at the highest redshift
- early black hole growth
- seed black holes

The highest redshift frontier now



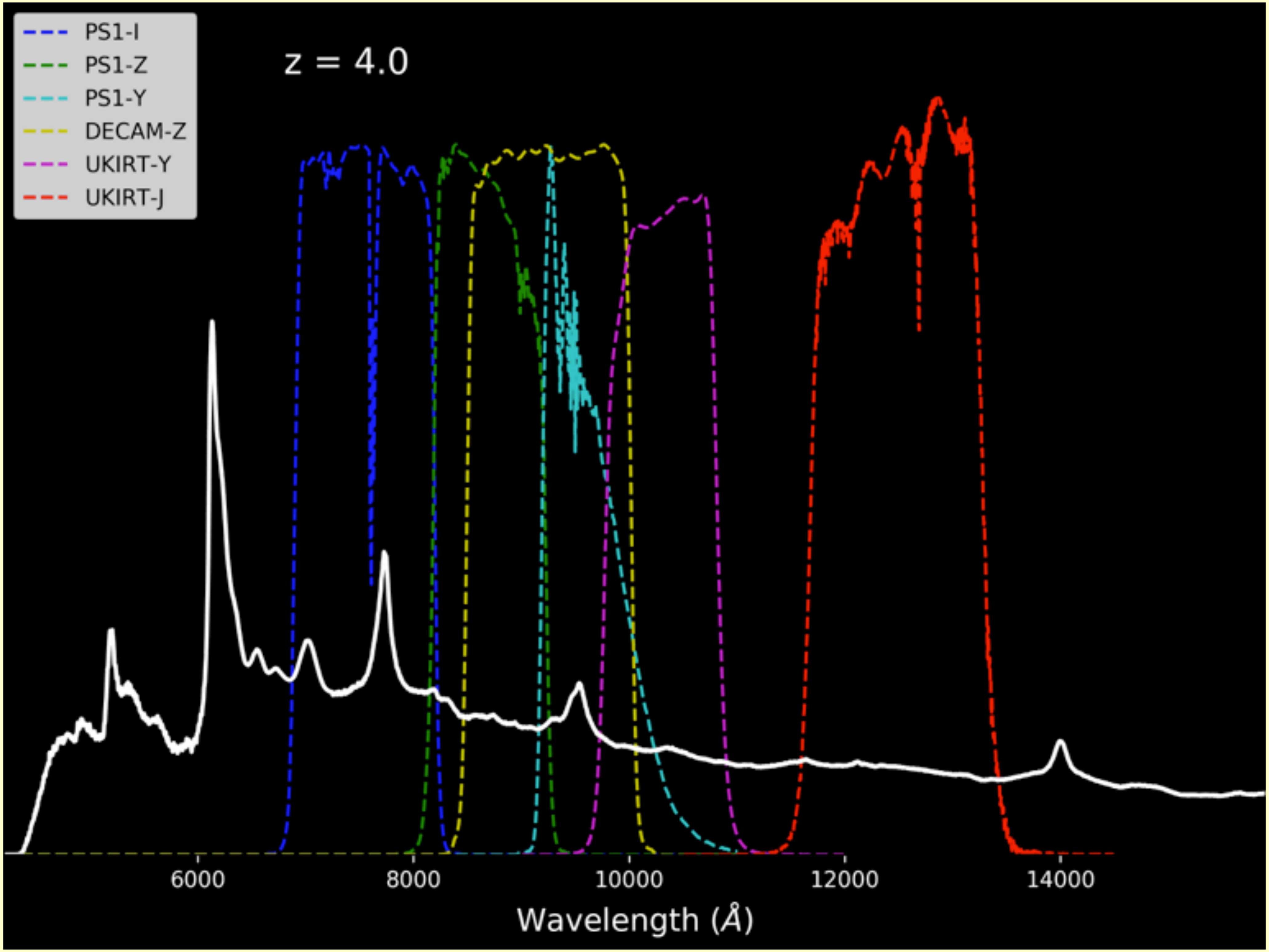
Quasar Color Selection

- Color selection
  - Type-1 quasars
  - Low-z (z<2.5)
    - UV-excess (blue color) from power law continuum; stars have Balmer break
    - Contaminants: white dwarfs
  - High-z (z>2.5)
    - Lyman break (red color) from IGM absorption below Ly alpha
    - Contaminants: late type stars, brown dwarfs
- >95% of known AGNs are color-selected



Richards et al. 2002

Dropout selection at high-z

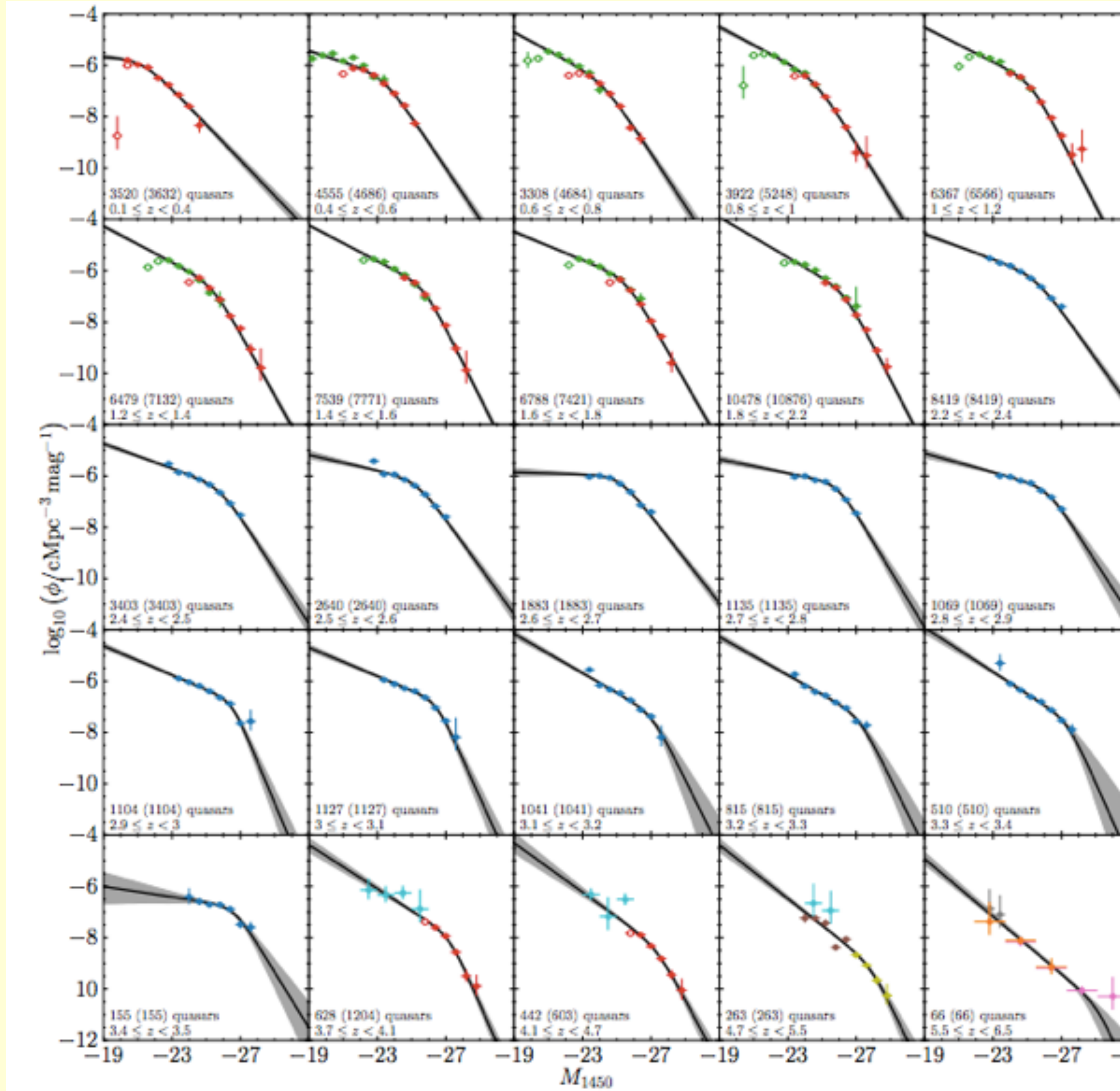


Courtesy: F. Wang

The quasar luminosity function

- How does quasar population evolve at high-redshift?
  - overall density
  - shape and characteristic luminosity (BH mass)
- modeled as double power law:

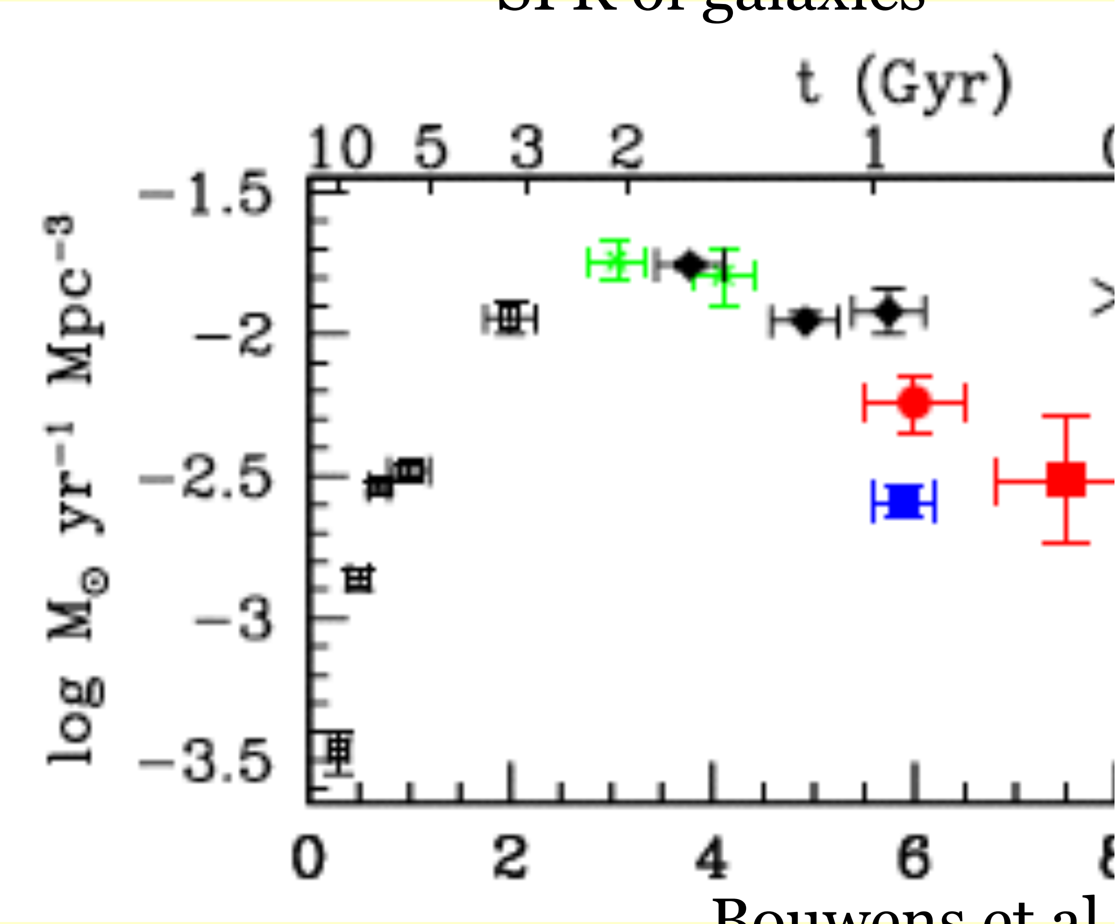
$$\Psi(L) = \frac{\Psi^*}{(L/L^*)^{\beta_h} + (L/L^*)^{\beta_l}}$$



Kulkarni, Worseck and Hennawi 2019

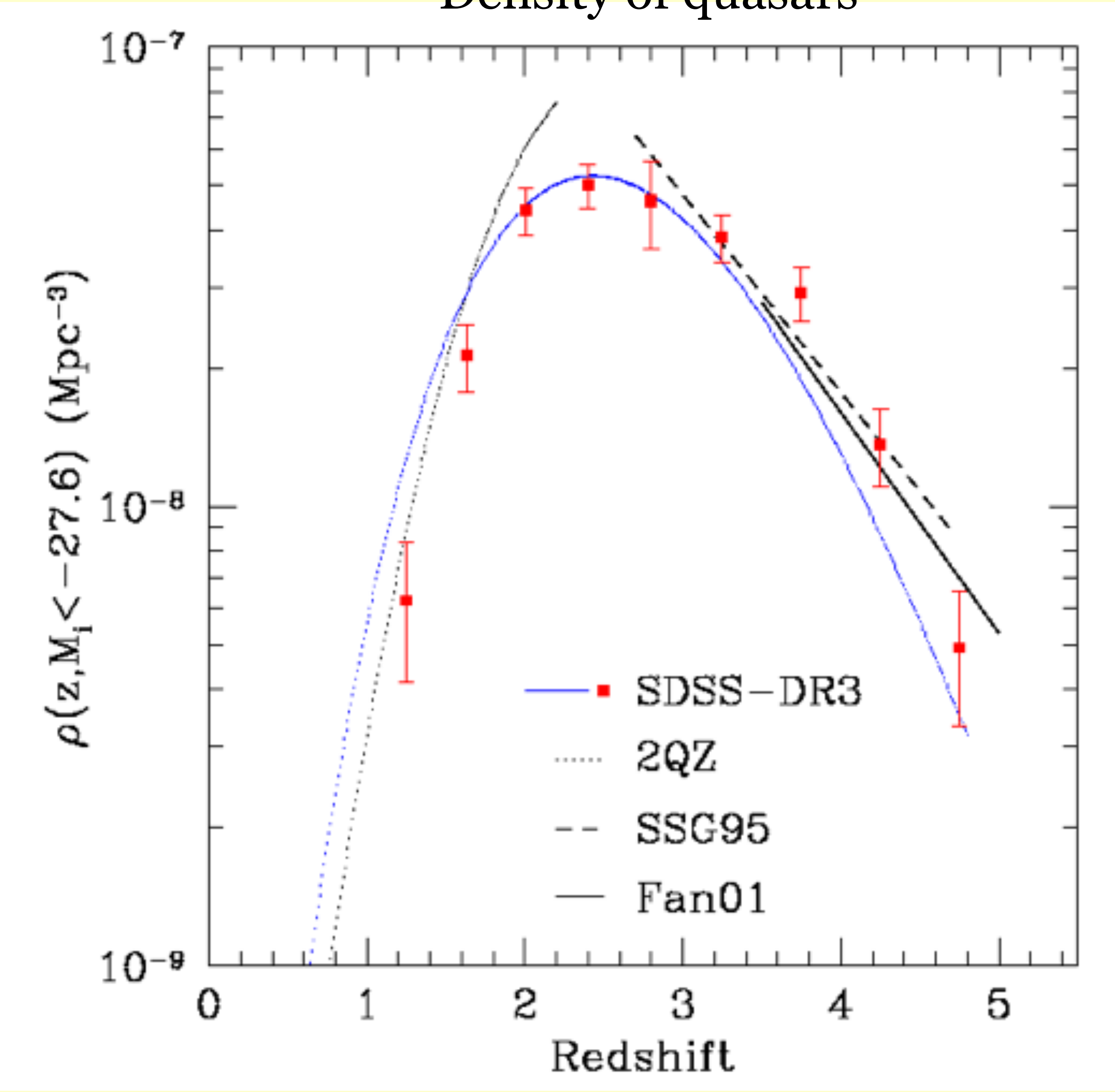
density evolution of luminous quasars

SFR of galaxies



Bouwens et al.

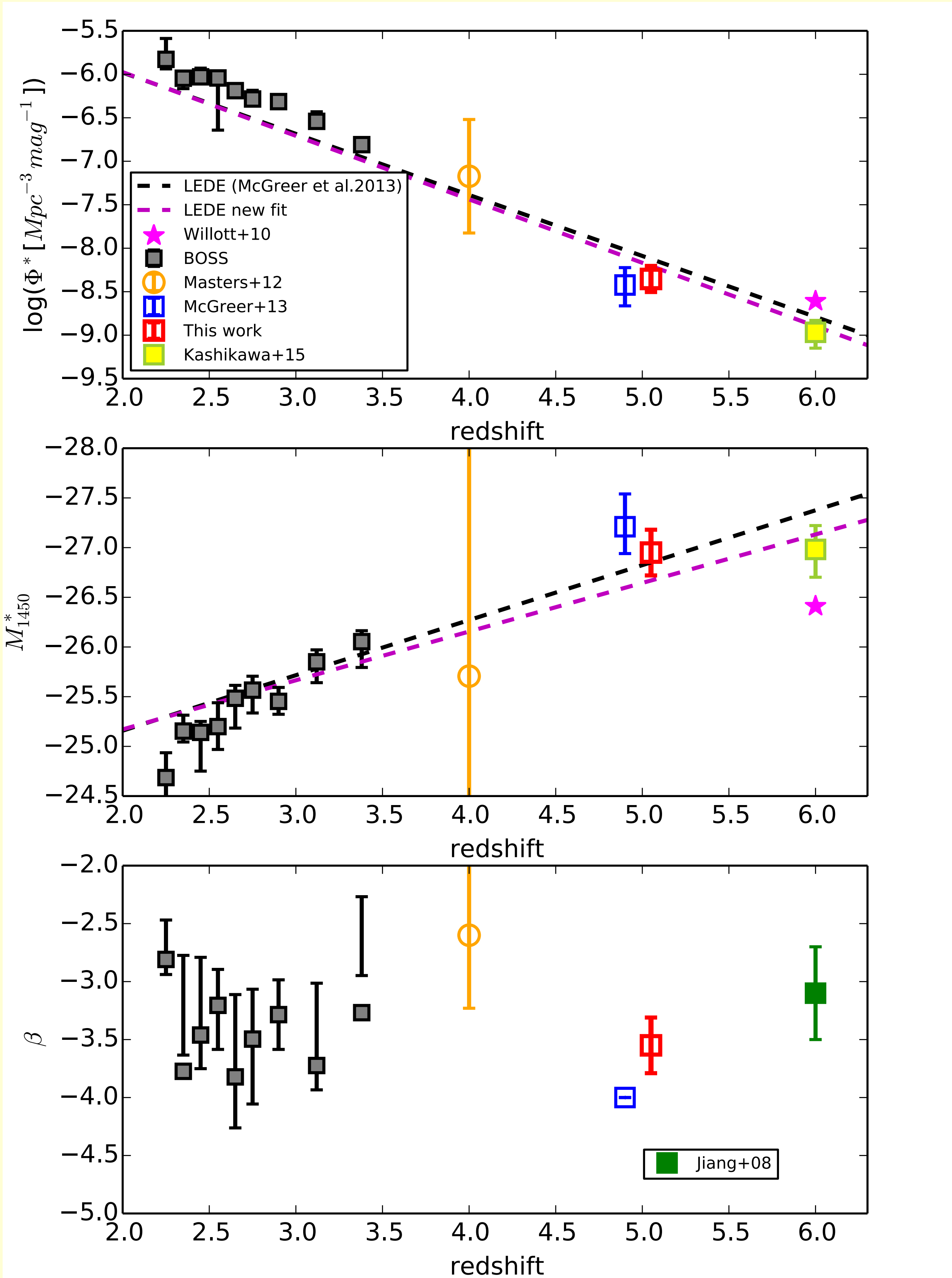
Density of quasars



Exponential decline of quasar density at high redshift, different from normal galaxies

Richards et al. 2006,
Fan e al. 2005

Quasar Evolution at high-redshift



- **Quasar density:** exponential decline
- **characteristic luminosity:** downsizing (large BH form first)
- **shape:** no strong evolution

J. Yang et al. 2016

Putting things together: Soltan's argument

- Soltan's argument: QSO luminosity function $\Psi(L,t)$ traces the accretion history of local remnant BHs (Soltan 1982), if BH grows radiatively

$$\int_0^{\infty} M n_M(M,t_0)\,dM = \int_0^{t_0} \mathrm{d}t \int_0^{\infty} \mathrm{d}L \,\frac{(1-\varepsilon)L_{\mathrm{bol}}}{\varepsilon c^2}\,\psi(L,t);$$

local accreted

$n_M(M,t_0)$: local BH mass function,

$\psi(L,t)$: QSO luminosity function,

ε : efficiency, $\dot{M} = \dfrac{(1-\varepsilon)L_{\mathrm{bol}}}{\varepsilon c^2}$.

Total mass density accreted = total local BH mass density

estimates of BH mass densities

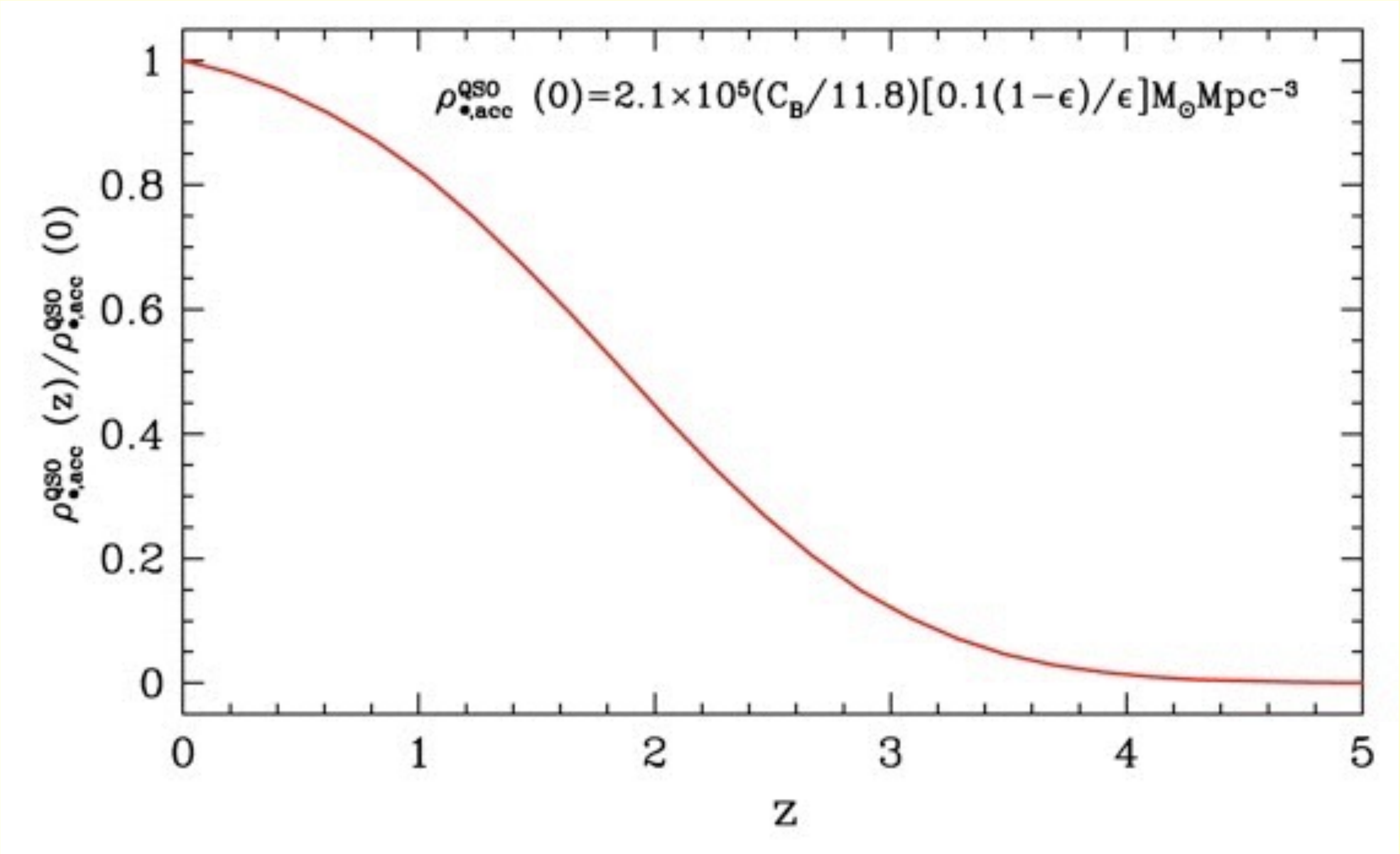
- Total local BH mass density:
  - local BH mass function $n_M(M,t_0)$:
    - SDSS early-type galaxy sample $n_\sigma(\sigma,t_0)$ (Bernardi et al. 2001)
    - the tight $M_\bullet - \sigma$ relation (Tremaine et al. 2002)
  - $\rho_{\bullet,local}=(2.5\pm0.4)\cdot10^5\ M_{sun}/Mpc^3$ (Yu & Tremaine 2002)

- BH mass density accreted due to optically bright QSO phases:
  - $\Psi(L,t)$: 2dF QSO Redshift survey (Boyle et al. 2000)
  - $\rho_{\bullet,acc}=2.1\cdot10^5[0.1(1-\varepsilon)/\varepsilon]\ M_{sun}/Mpc^3$ (Yu & Tremaine 2002)

$$\rho_{\bullet,local} \approx \rho_{\bullet,acc} \quad \text{if} \;\; \varepsilon \approx 0.1$$

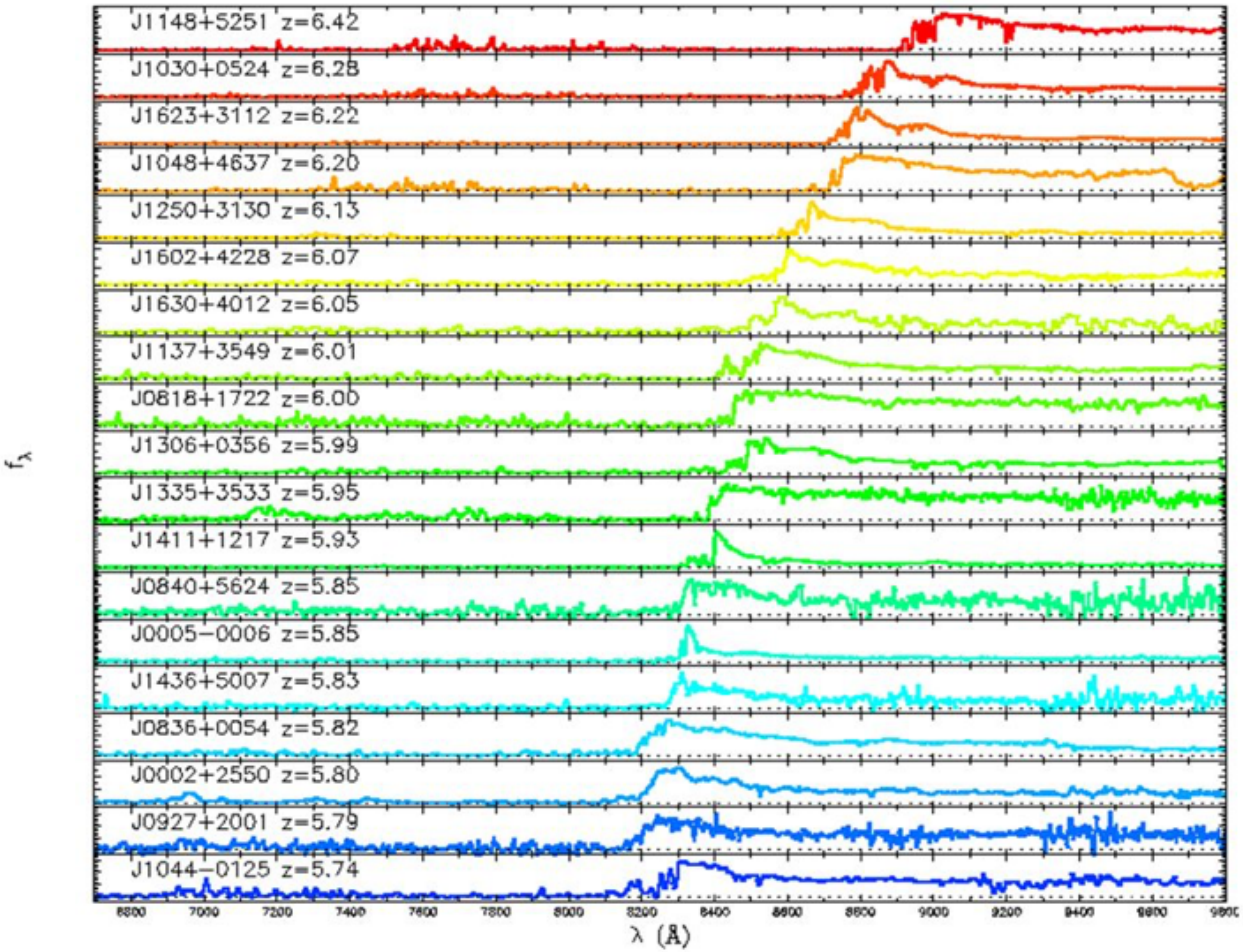
- Bright quasar phase can account for most of the BH mass growth

The history of BH mass density accreted during quasar phase



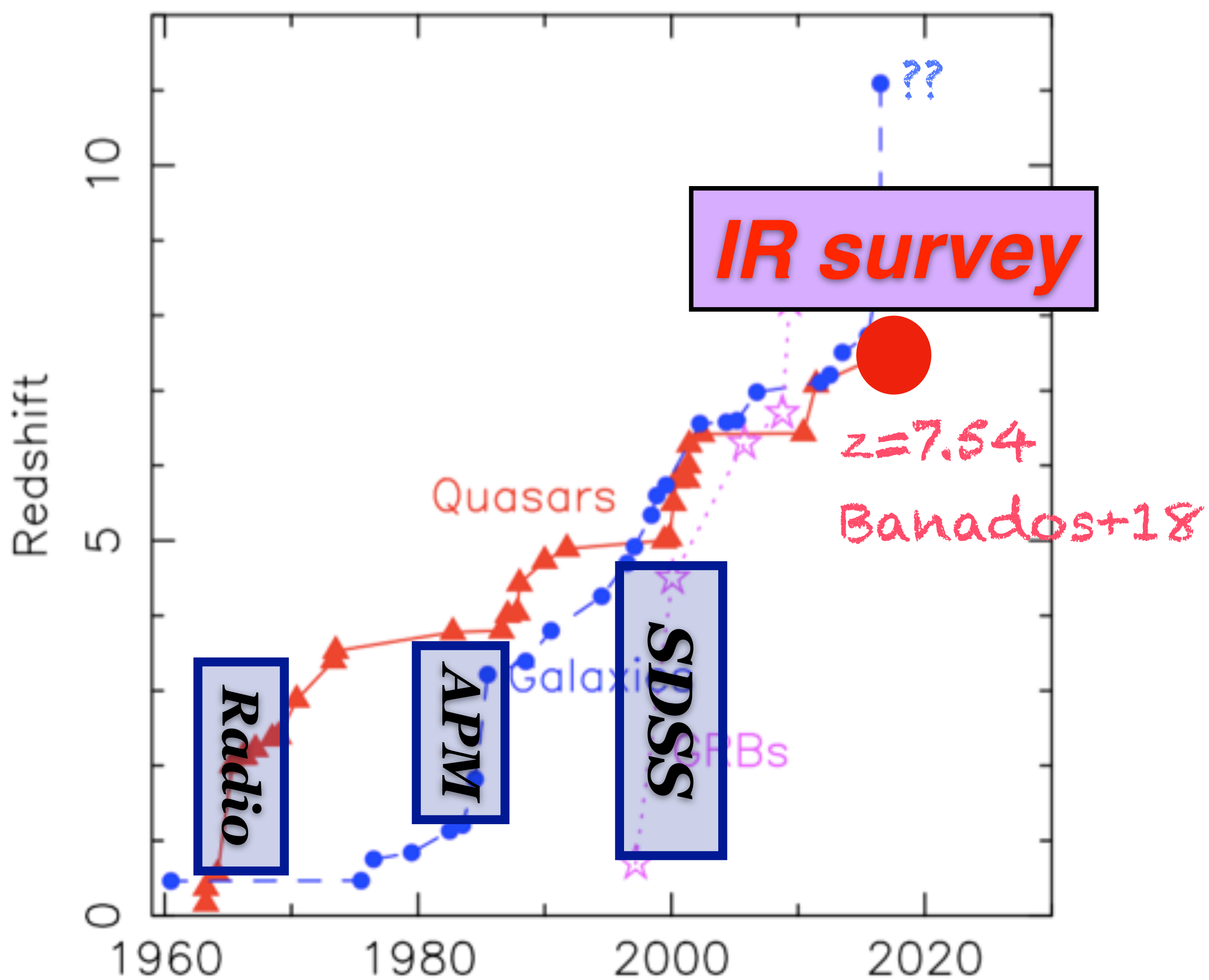
Yu and Tremaine 2002

z~6 quasars: 2006



XF ARAA 2006

The highest redshift frontier now



Eduardo Banados March 10, 2017 at 3:22 AM

To: Fabian Walter, Venemans Bram, Roberto Decarli, Chiara Mazzucchelli, Xiaohui Fan, Feige Wang, and 2 more...

pisco sour quasar

EB

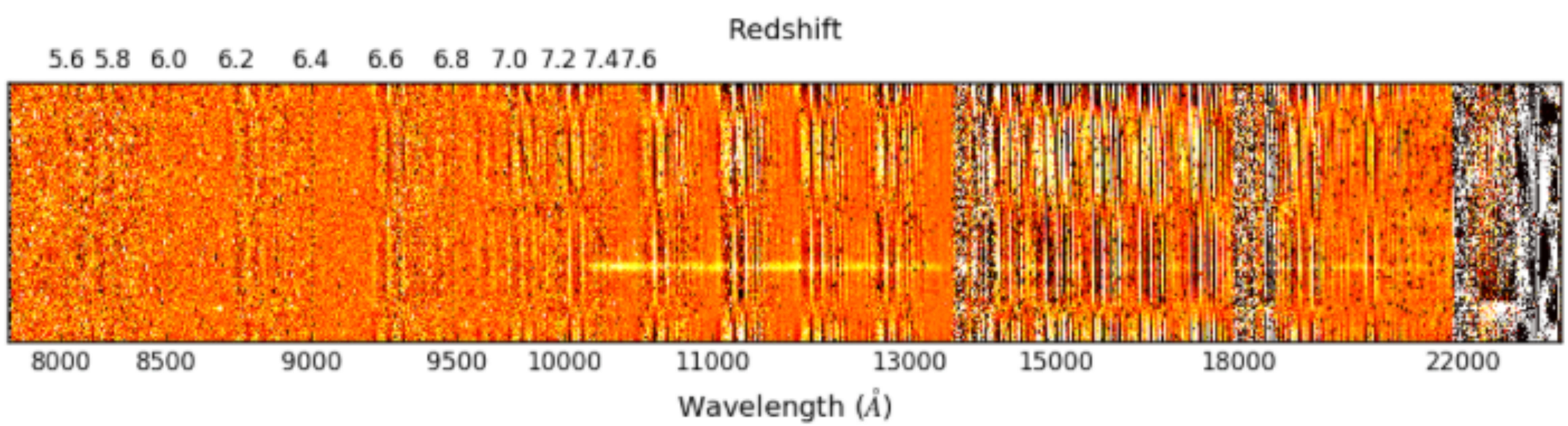
Dear all,

We are concluding the last night at Magellan. We observed more than 100 objects and we are happy to tell you that we have a winner! See attached the 'pisco sour' z>7.2 quasar.

Now is pisco sour time.

Cheers,

Eduardo & Dan



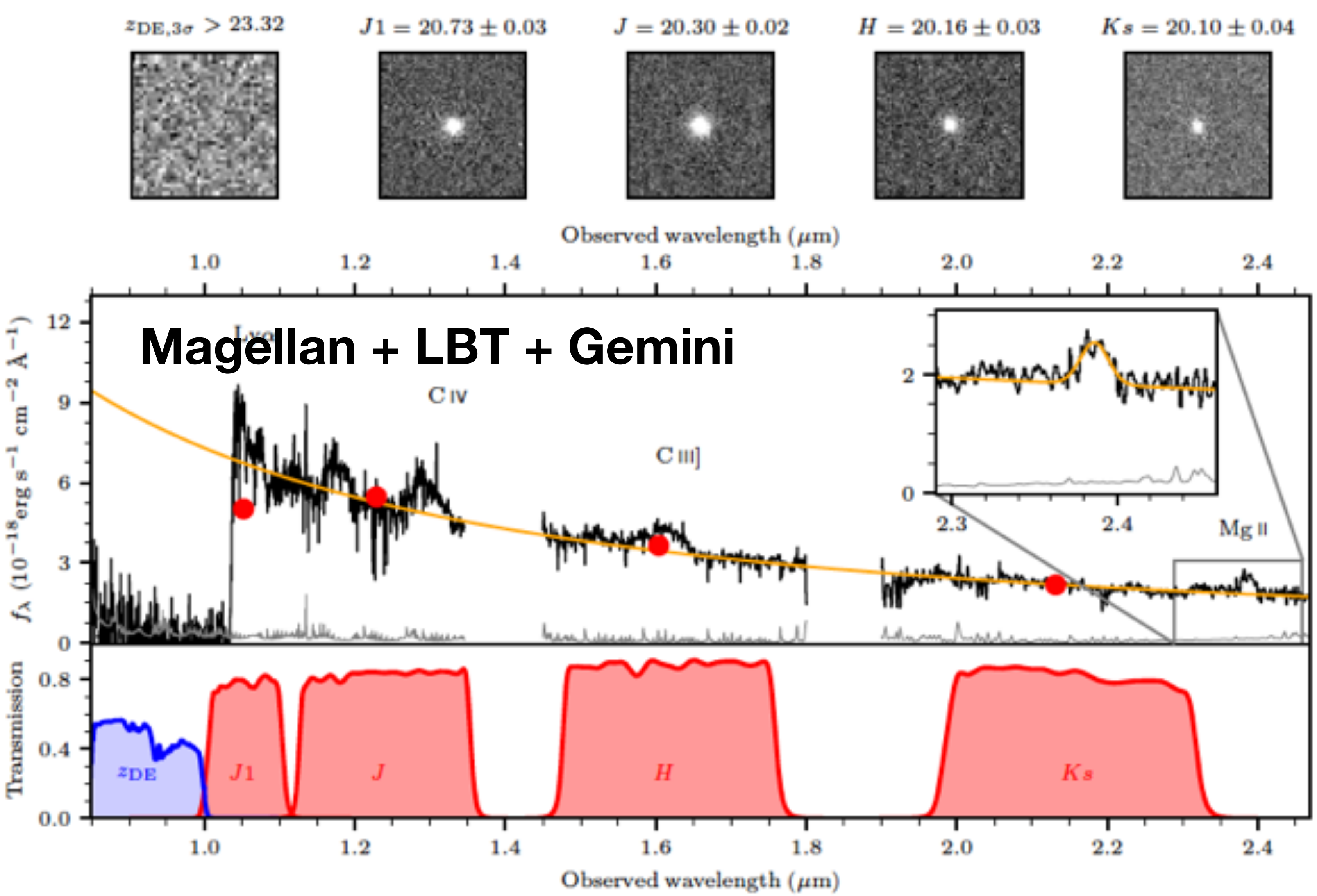
What does it takes to make a pisco sour

(1) photometric selection

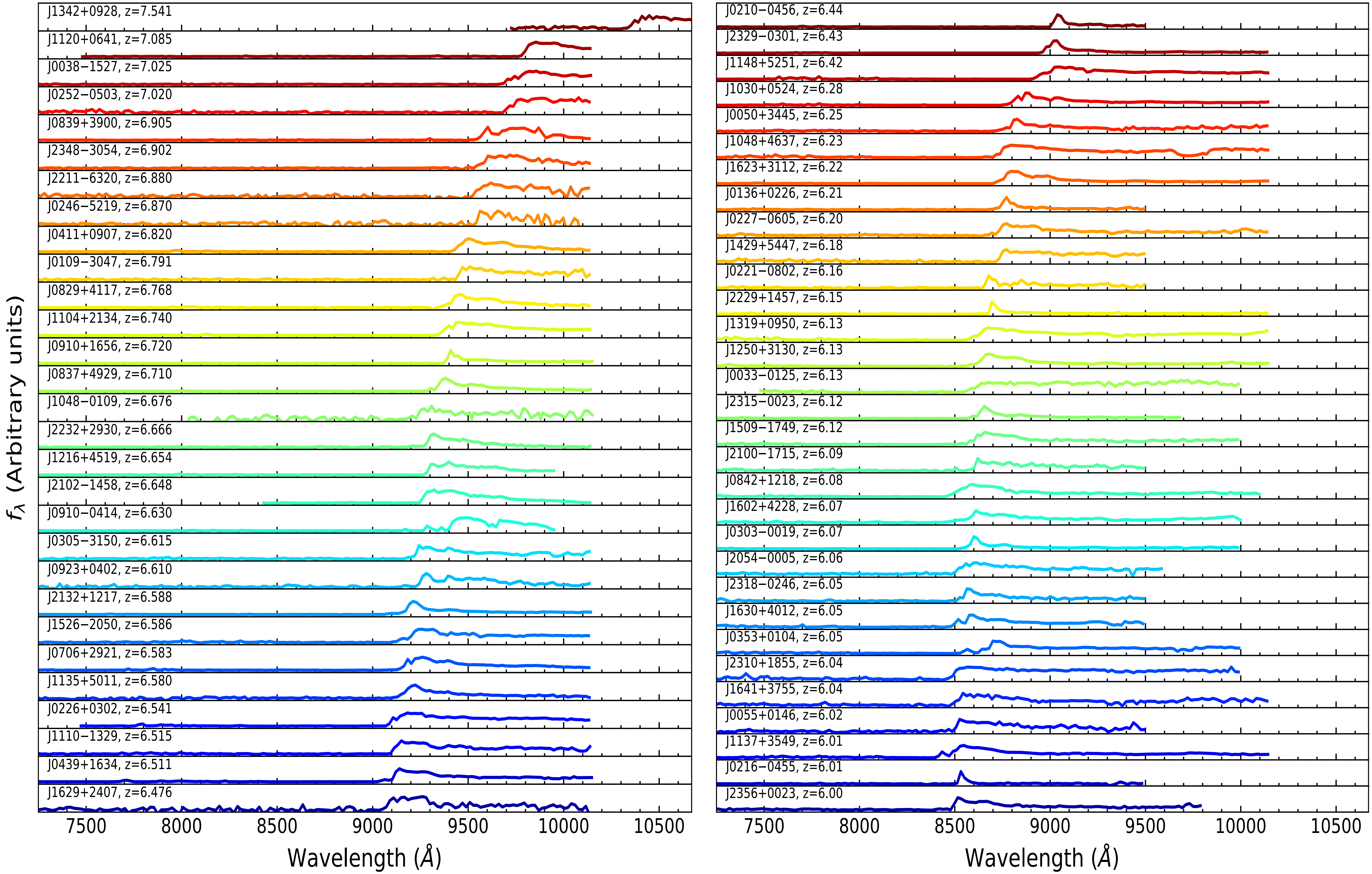
Survey	AB magnitudes	
DECaLS	$z_{DE,3\sigma} > 23.32$	
UKIDSS	$Y = 21.47 \pm 0.19$	$J = 20.75 \pm 0.11$
	$H = 20.02 \pm 0.02$	$K = 20.03 \pm 0.12$
WISE	$W1 = 20.17 \pm 0.15$	$W2 = 20.11 \pm 0.29$

(2) spec identification

(3) redshift determination: z=7.54 from millimeter observations of C[II]



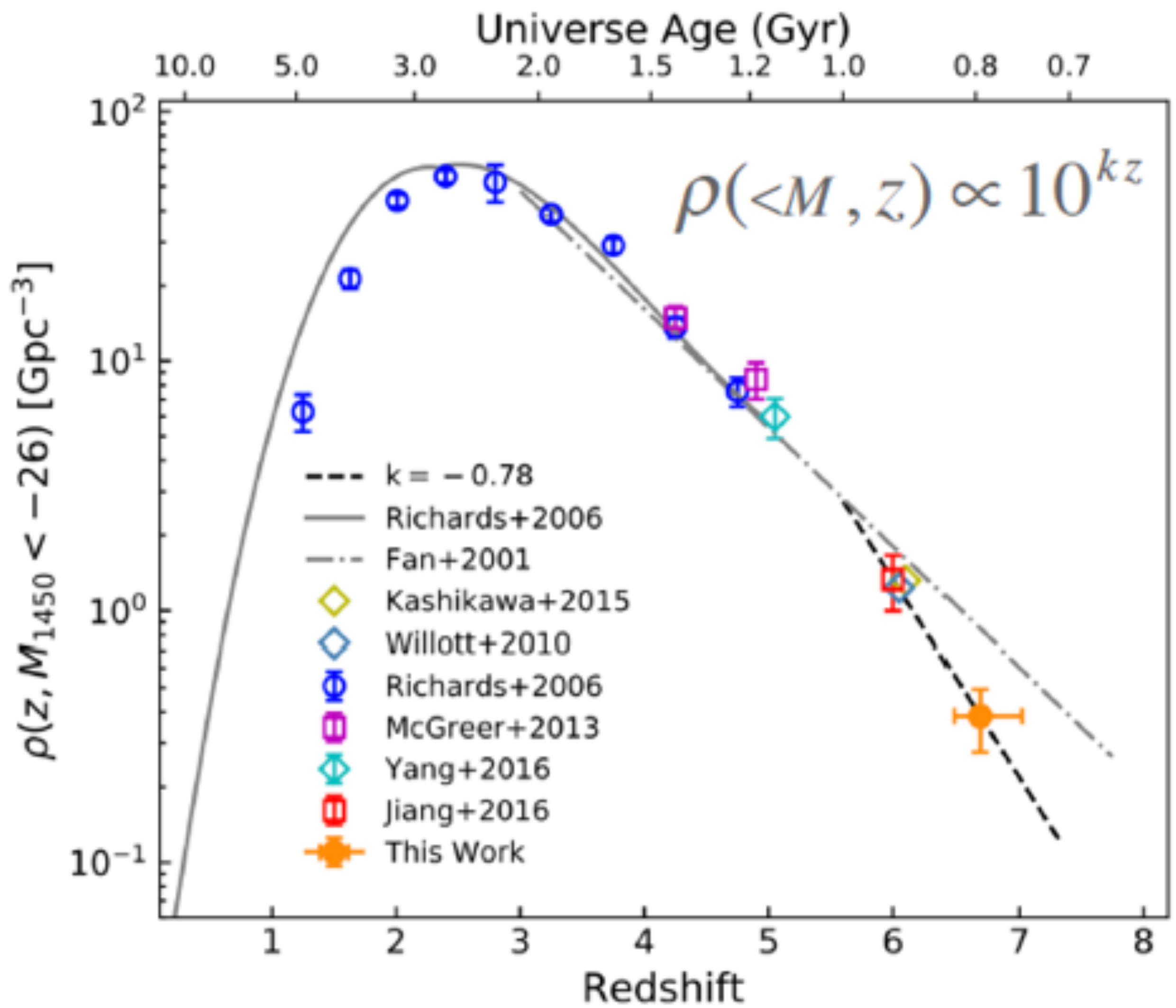
Now…



>500 at z>5; ~200 at z>6; >=6 at z>7

closing in to the era of first quasars

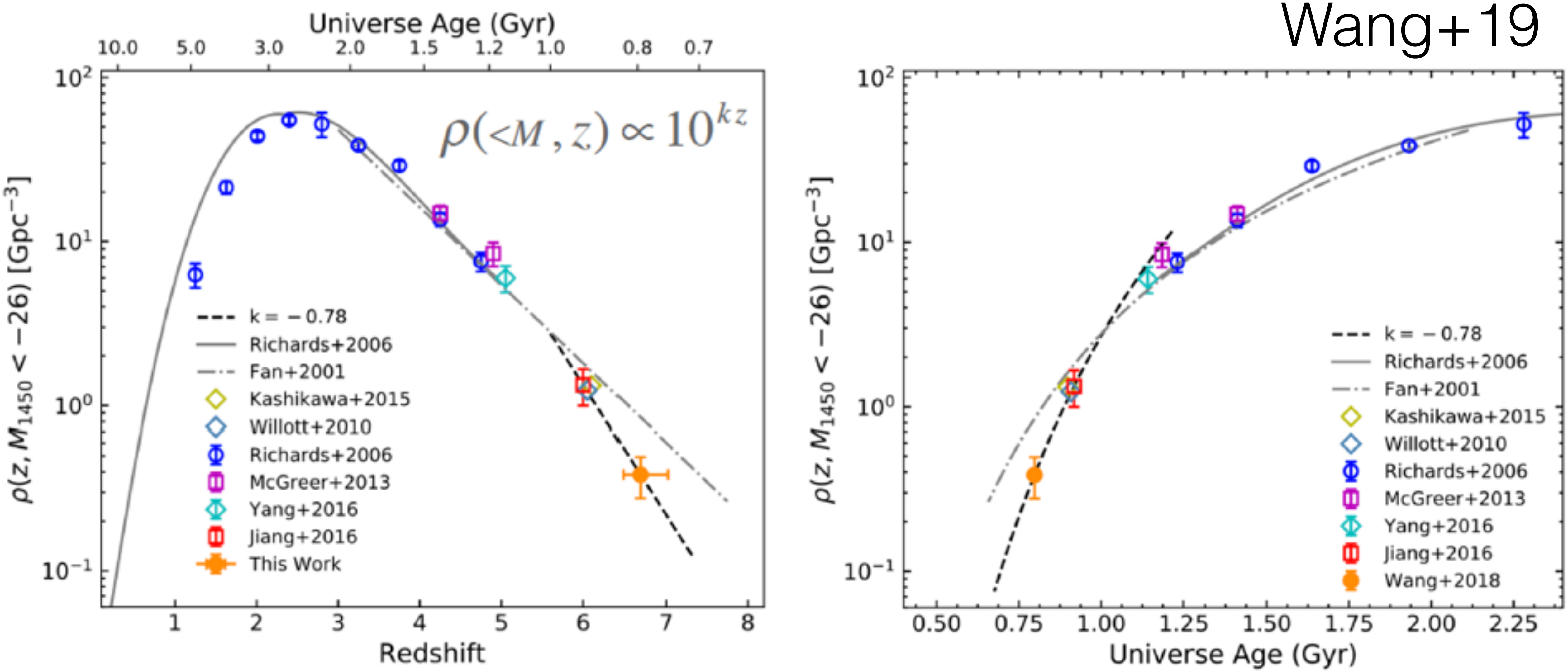
Wang+19



- **first determination of quasar luminosity function at z~7**
- quasar density evolution accelerated at z>6
- e-folding time for quasar density growth: 80 Myr (delta z = 0.6)
- comparable to Eddington timescale (45 Myr)
- **quasar BH growth is accretion-limited**

closing in to the era of first quasars

Wang+19



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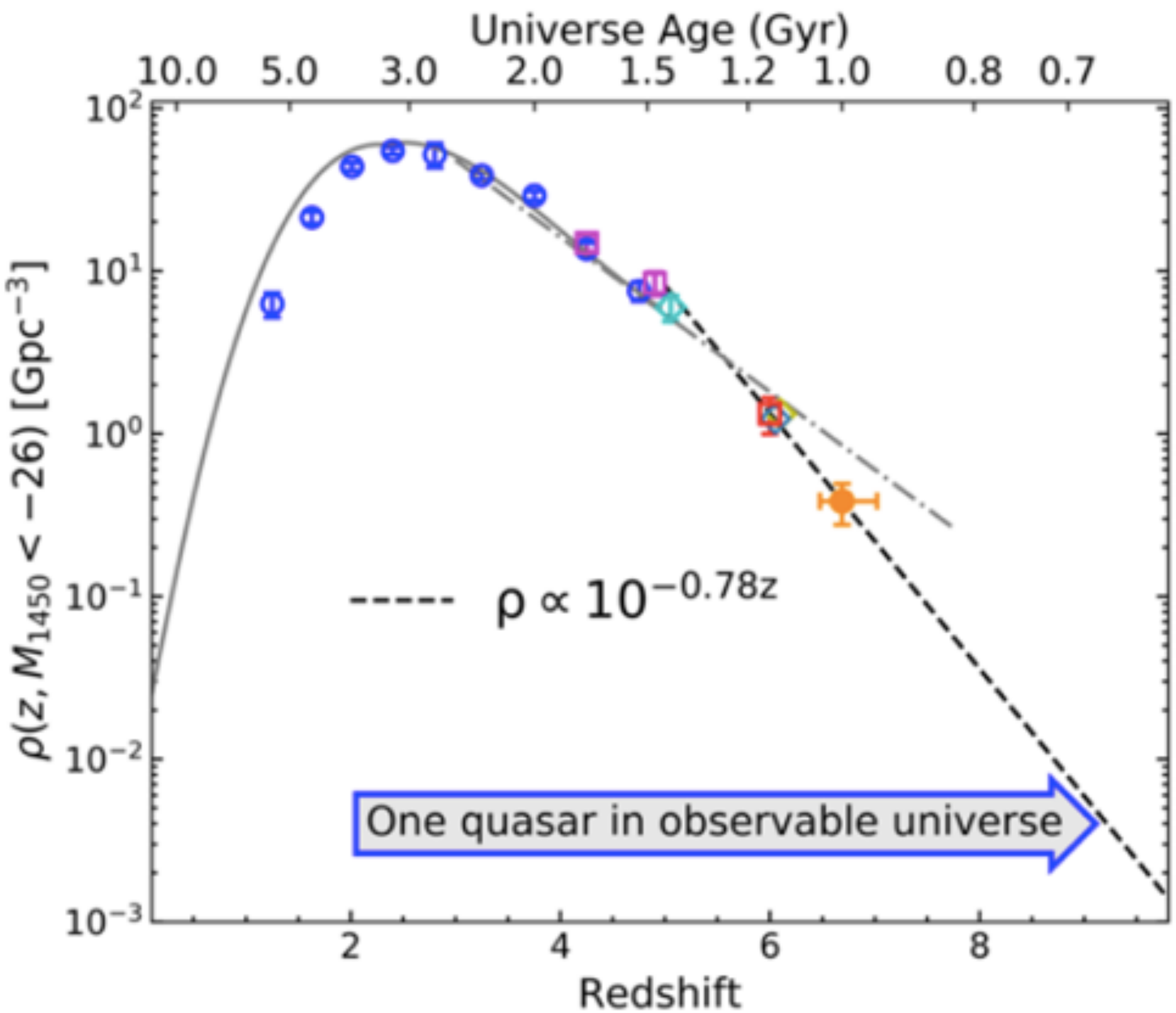
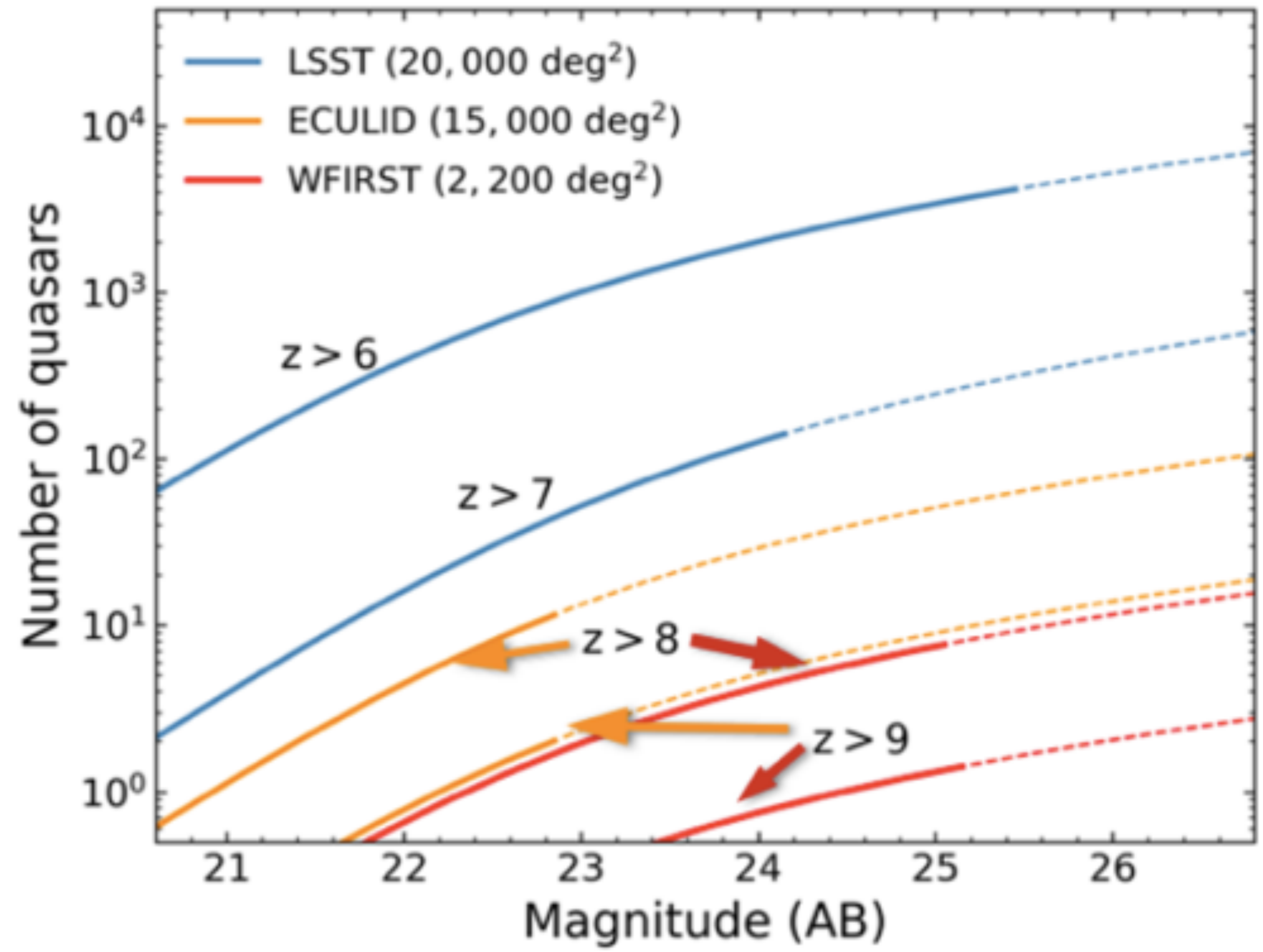
The First Quasar?

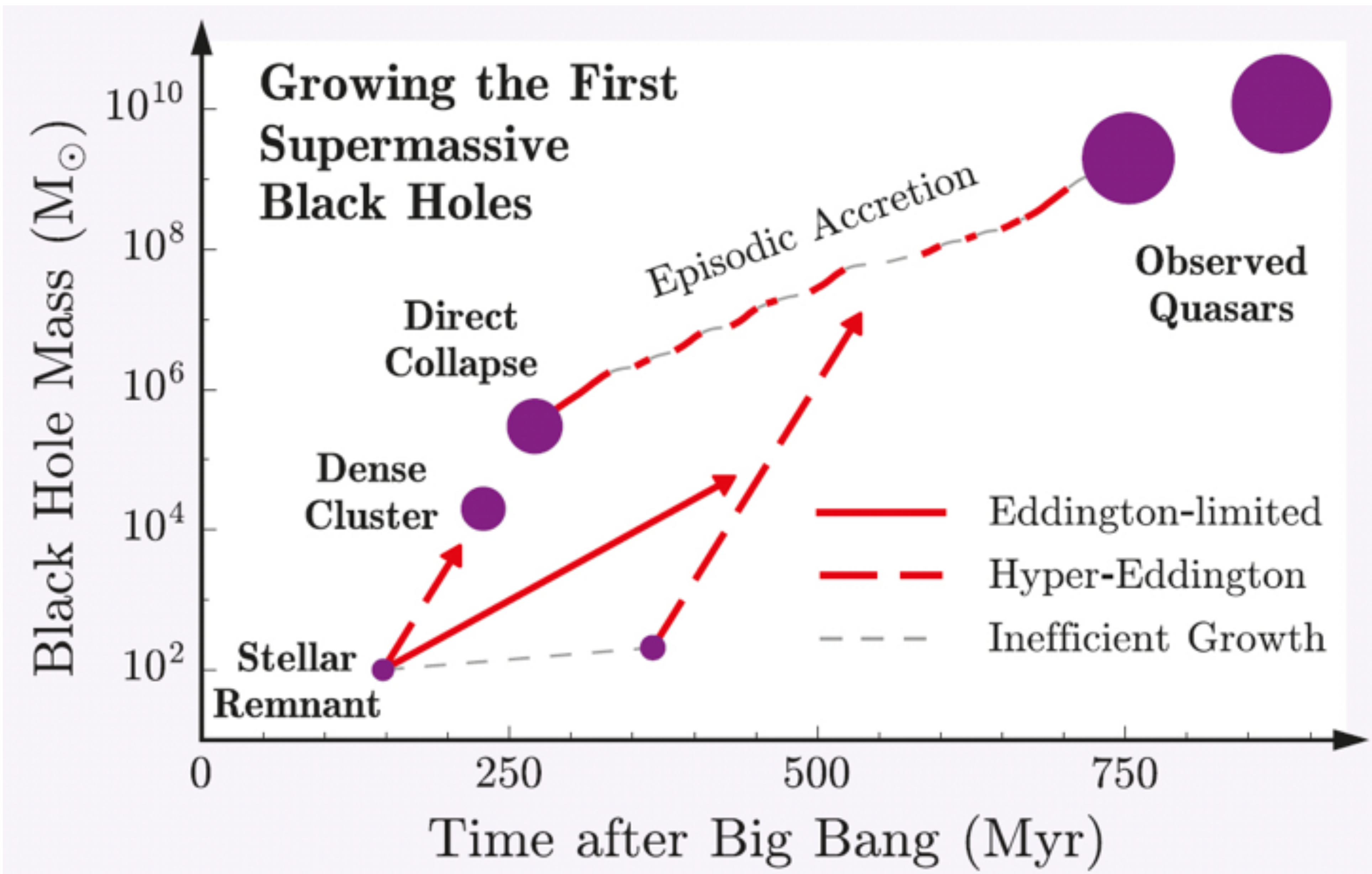




- **only ~1 quasar with billion M_sun BH (M<-26) at z>9 in the observable universe -> the first quasars**
- **find them? Euclid + LSST**
- **identify them? need spectroscopic identification of faint (AB~23-25) in IR -> JWST? ELTs?**

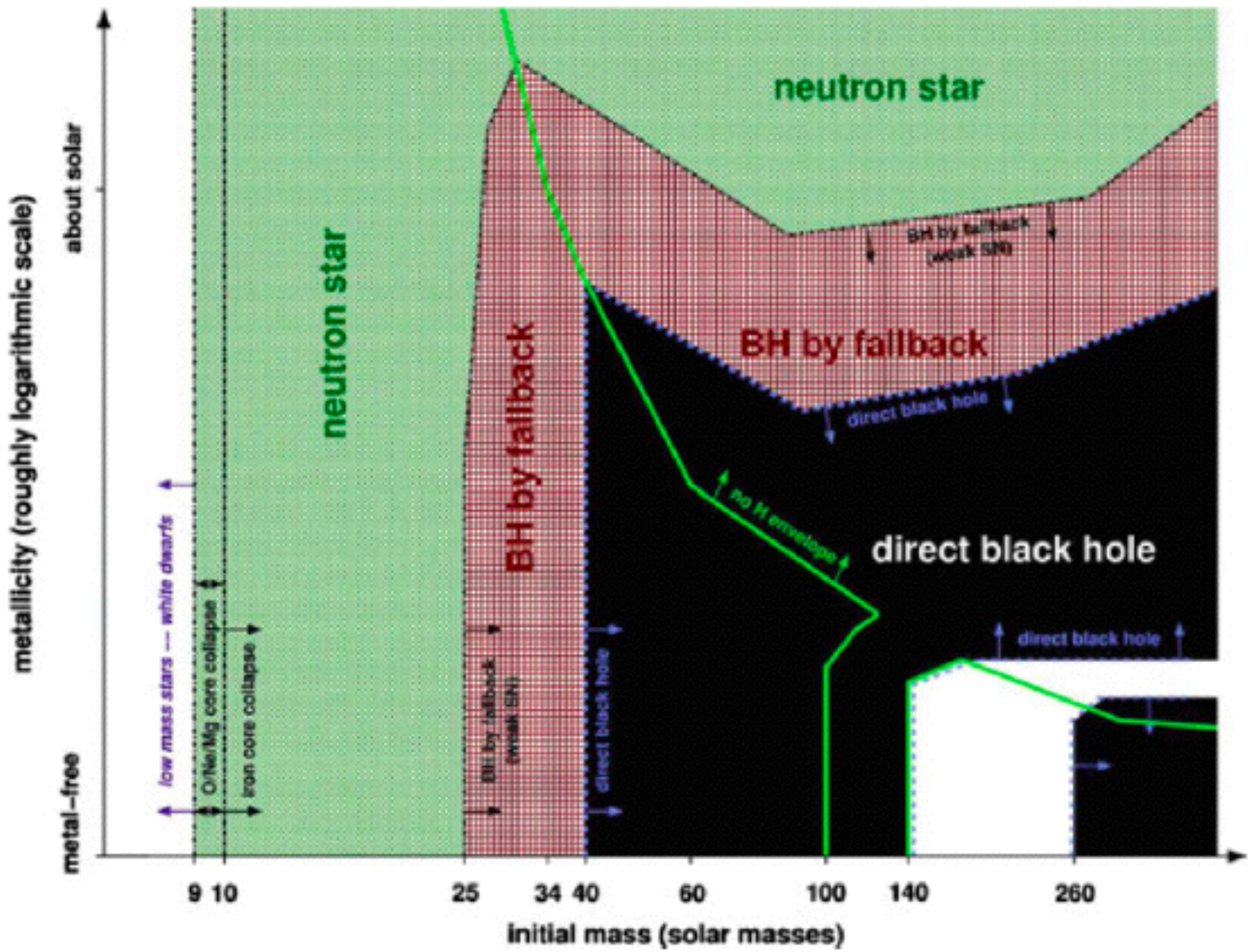
XF+, astro2020 White paper

growing the first SMBHs: seed and accretion rate

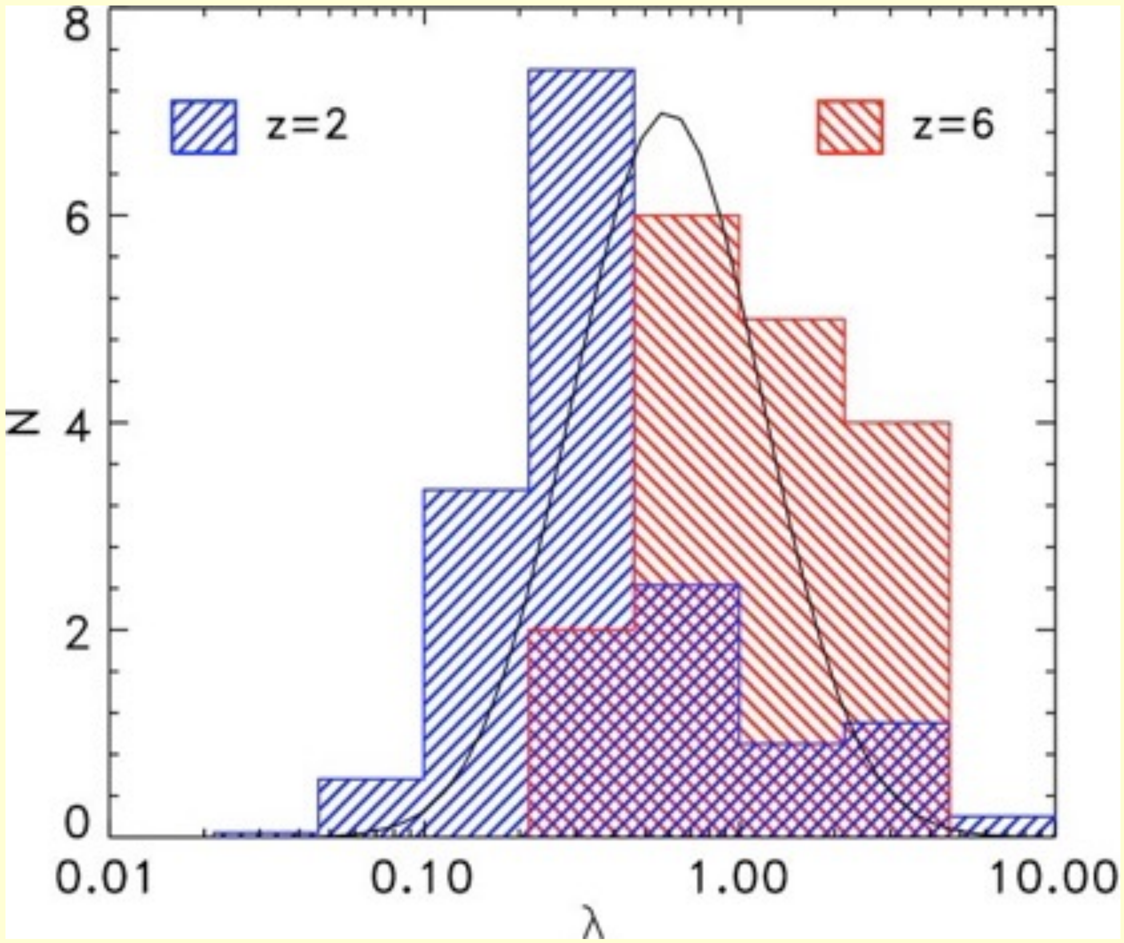


Smith+17

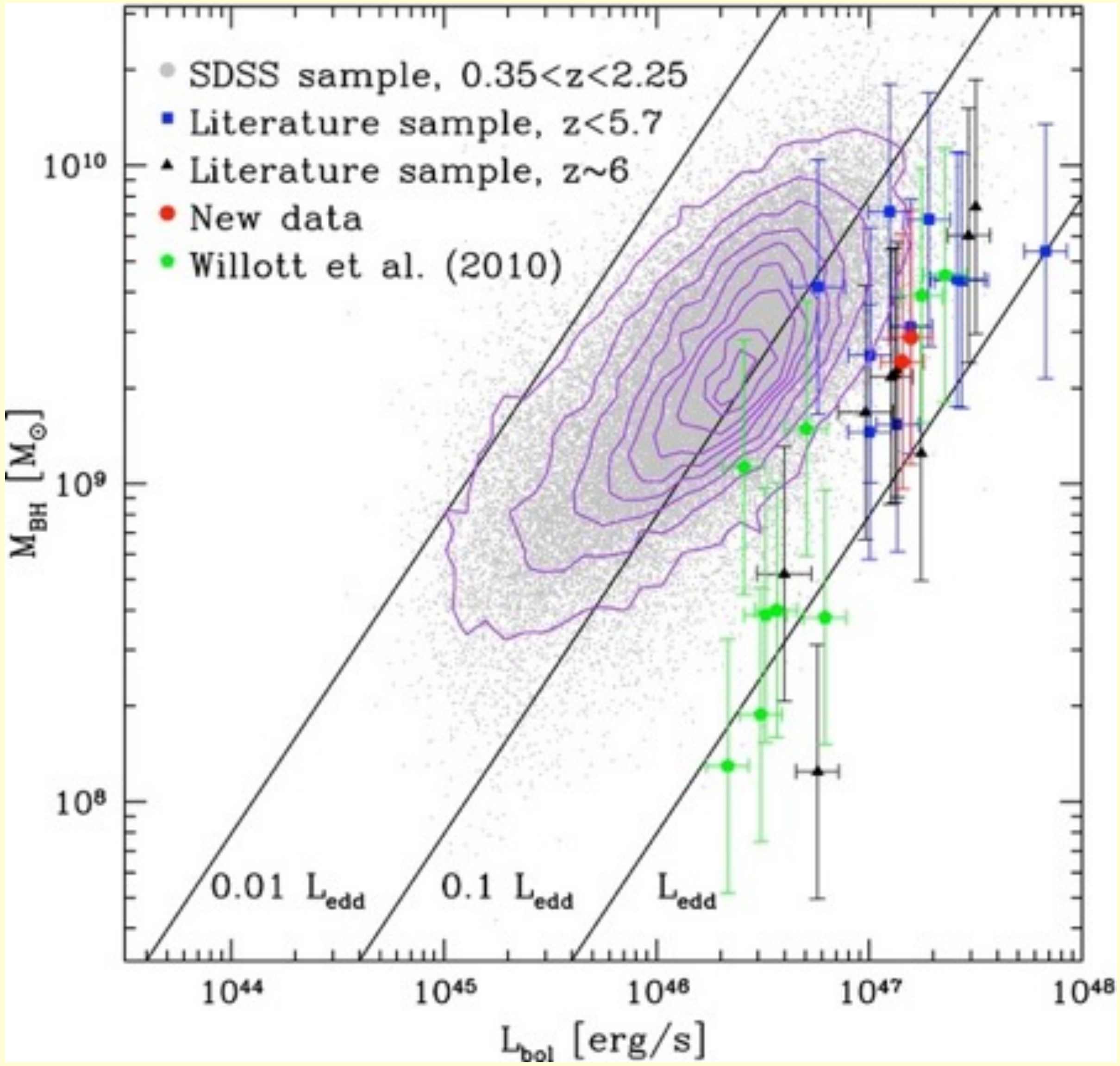
First BH Seeds:
collapse of Pop III stars with BH mass of ~100M_sun



Quasars are accreting at close to Eddington limit at z~6



Willott et al. 2010



de Rosa et al. 2011

- $M_{BH} \sim (FWHM)^2 L^{0.5}$ based on MgII line

Eddington-limited accretion growth

» radiative efficient growth

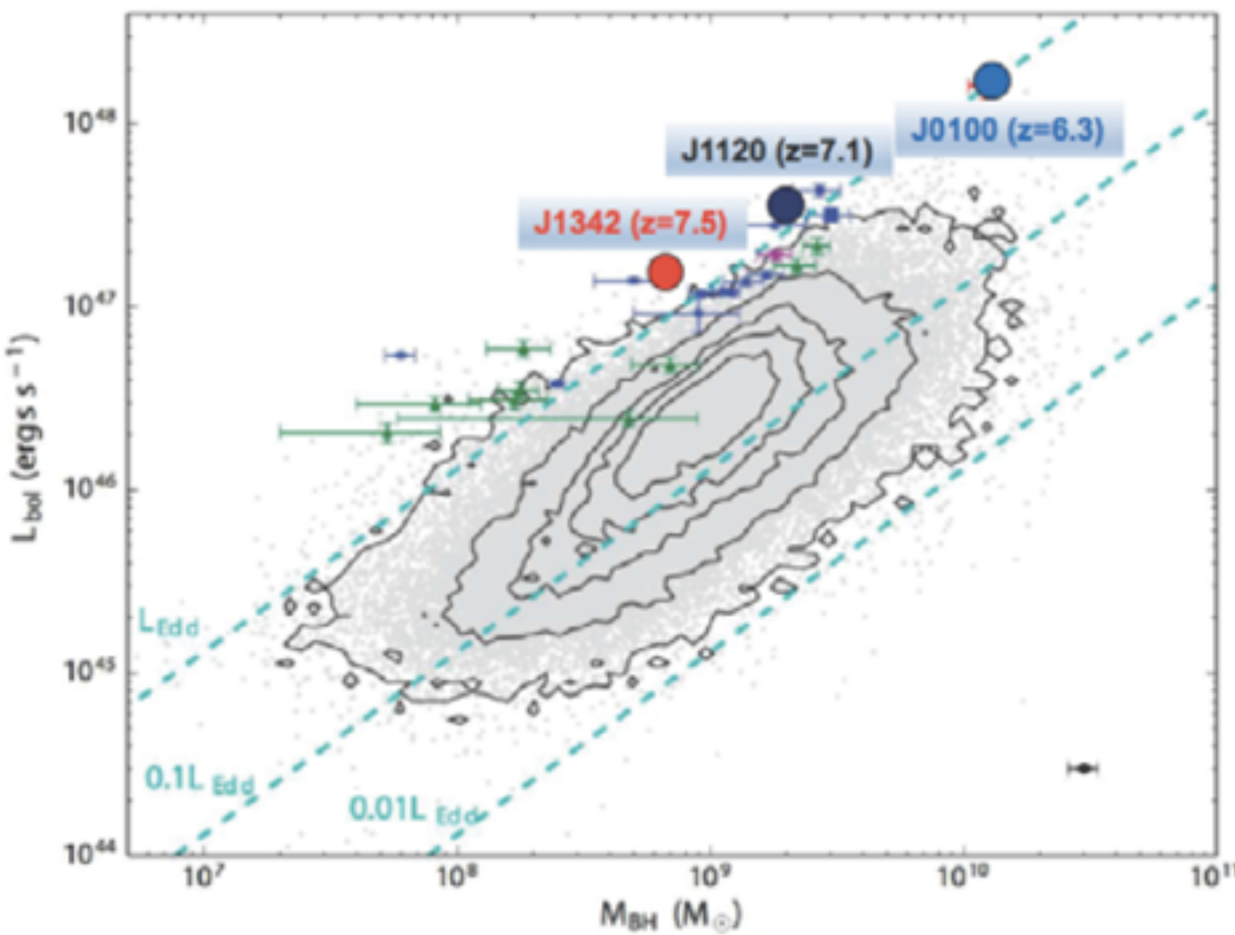
$$L = c^2 \frac{\epsilon}{1-\epsilon} \dot{M}_{\rm BH},$$

» grow from seed black hole, with e-folding time of ~45 Myrs (t_Edd)

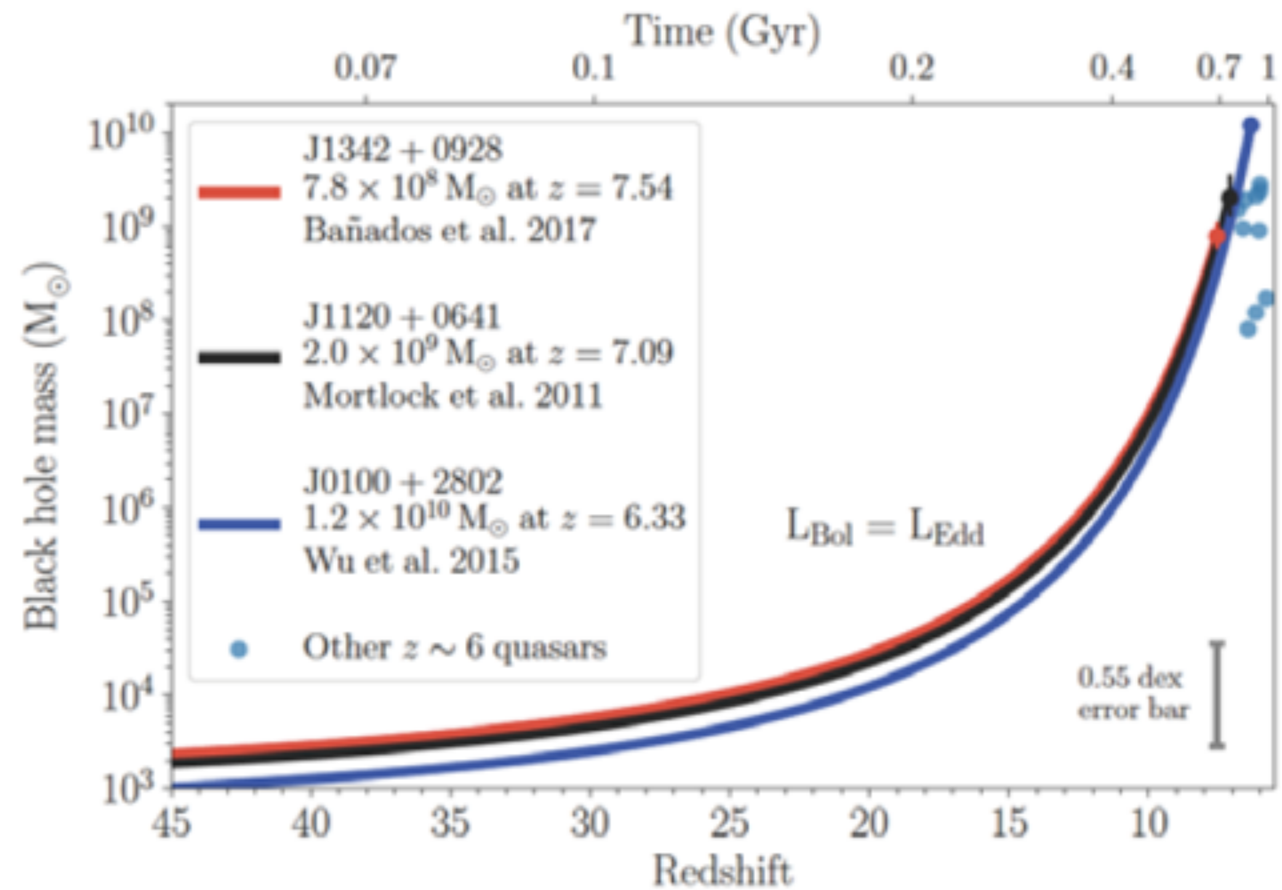
$$M_{\rm BH}(t) = M_{\rm BH}(0)\, \exp\left(\frac{1-\epsilon}{\epsilon}\frac{\rm t}{\rm t_{Edd}}\right),$$

How to form 12 billion solar mass BH at z=6.3?

- Black Holes do not grow arbitrarily fast
  - Accretion onto BHs dictated by Eddington Limit
  - E-folding time of **maximum** supermassive BH growth: 40 Myr
  - At z=6.3: age of the universe: 880 Myr = **maximum** 20 e-folding
- 12 Billion solar mass BH at z>6
  - Non-stop, maximum accretion from 100 solar mass BHs at z~30 (collapse of first stars in the Universe?)
  - **Theoretically difficult for formation of 12 billion solar mass BHs by z=6**
  - possibilities?
    - Direct collapse of "intermediate" mass BHs (10^{4-5} M_{sun})?



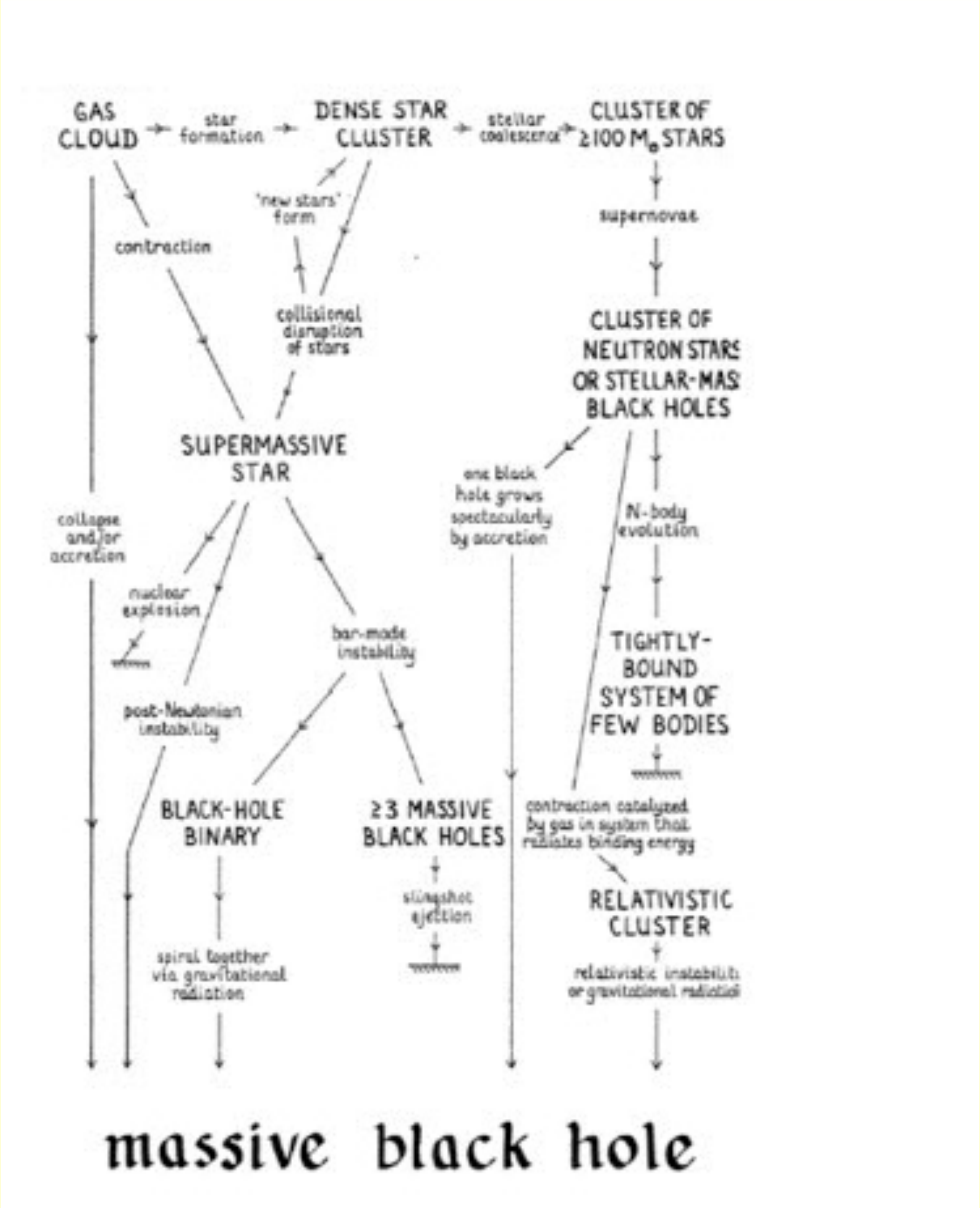
J0100 (z=6.3)
J1120 (z=7.1)
J1342 (z=7.5)
L_{Edd}
$0.1L_{Edd}$
$0.01L_{Edd}$
L_{bol} (ergs s^{-1})
M_{BH} ($M_\odot$)



Time (Gyr)
0.07
0.1
0.2
0.4
0.7
1
J1342 + 0928
$7.8 \times 10^8\ M_\odot$ at $z = 7.54$
Bañados et al. 2017
J1120 + 0641
$2.0 \times 10^9\ M_\odot$ at $z = 7.09$
Mortlock et al. 2011
J0100 + 2802
$1.2 \times 10^{10}\ M_\odot$ at $z = 6.33$
Wu et al. 2015
Other $z \sim 6$ quasars
$L_{Bol} = L_{Edd}$
0.55 dex
error bar
Black hole mass ($M_\odot$)
Redshift

BH growth: an old question

Rees 1984



Direct Collapse Black Holes (DCBHs) as Seeds of the Most Massive SMBHs in the Early Universe?

- Supermassive stars can form via atomic hydrogen cooling to 10^4 M_sun
  - Agarwal, Begelman, Johnson, Latif, Omukai, Regan, Volonteri, etc.

- current observations only detect the “end products” at billion solar mass level
- key is to observe the earlier growth (10^4 - 10^6 M_sun)

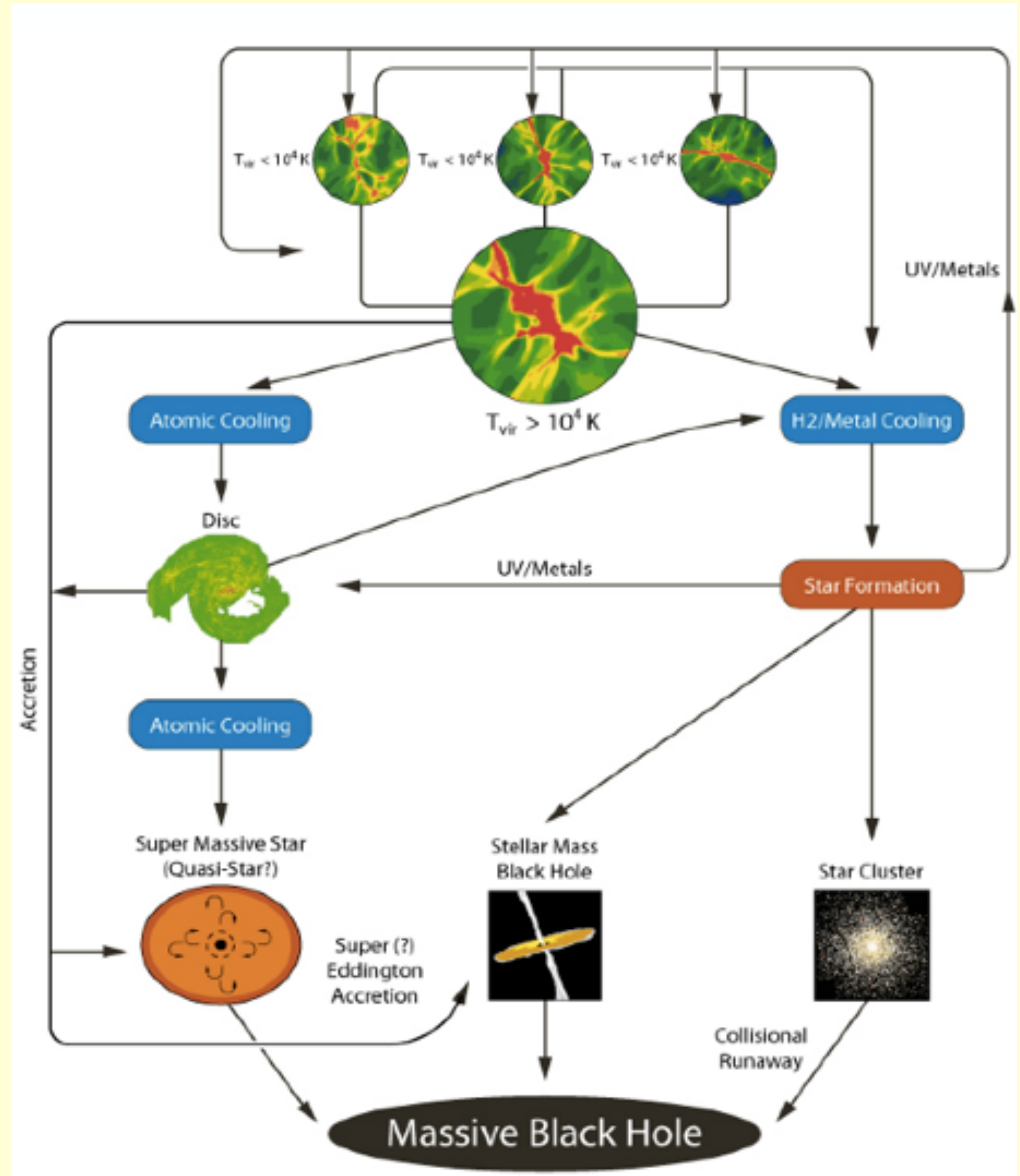
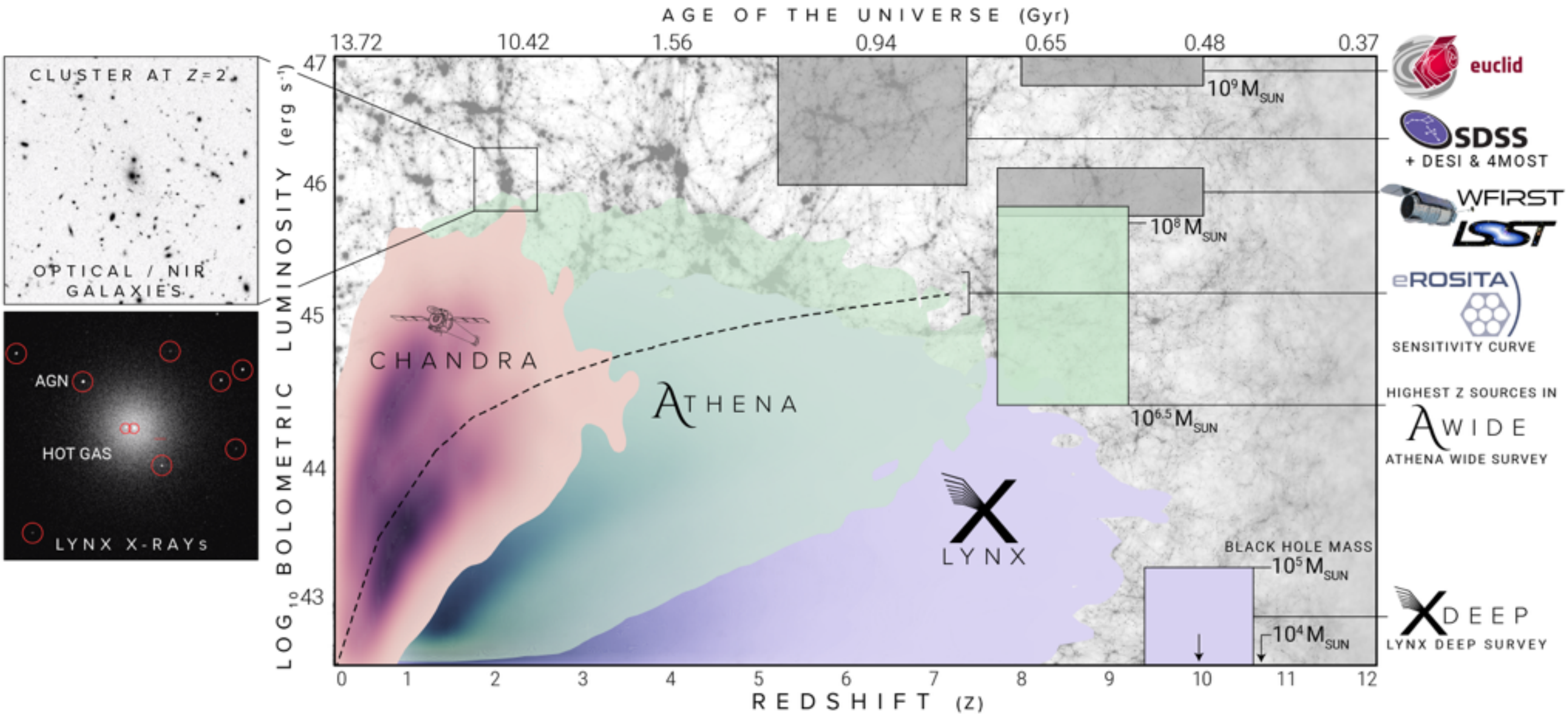


Image credit Regan et al 2009

Power of X-ray surveys



Civano+, astro2020 White paper

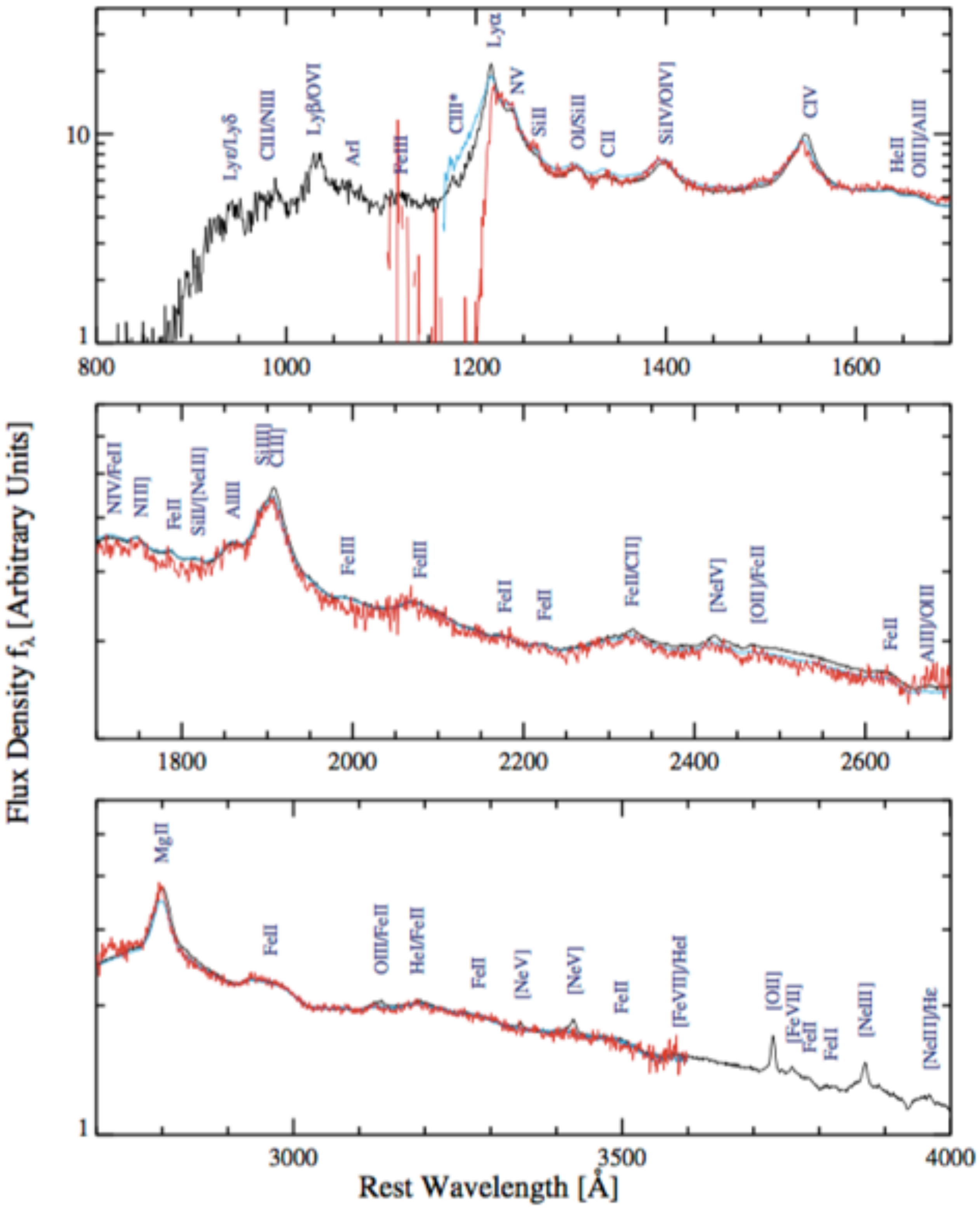
Detecting the Dawn of Black Holes

Future Observatory	Importance for Seeds
JWST (launch: 2021)	• Detect peak emission of typical seeds • Detect heavily obscured seeds
Athena (planned: 2031)	• Larger field of view for surveys • Detect Compton-thin sources
Lynx (concept study)	• Higher angular resolution • Detect heavily Compton-thick sources
LISA (planned: 2034)	• Unequivocally determine main formation channel of seeds

Pacucci+, astro2020 White paper

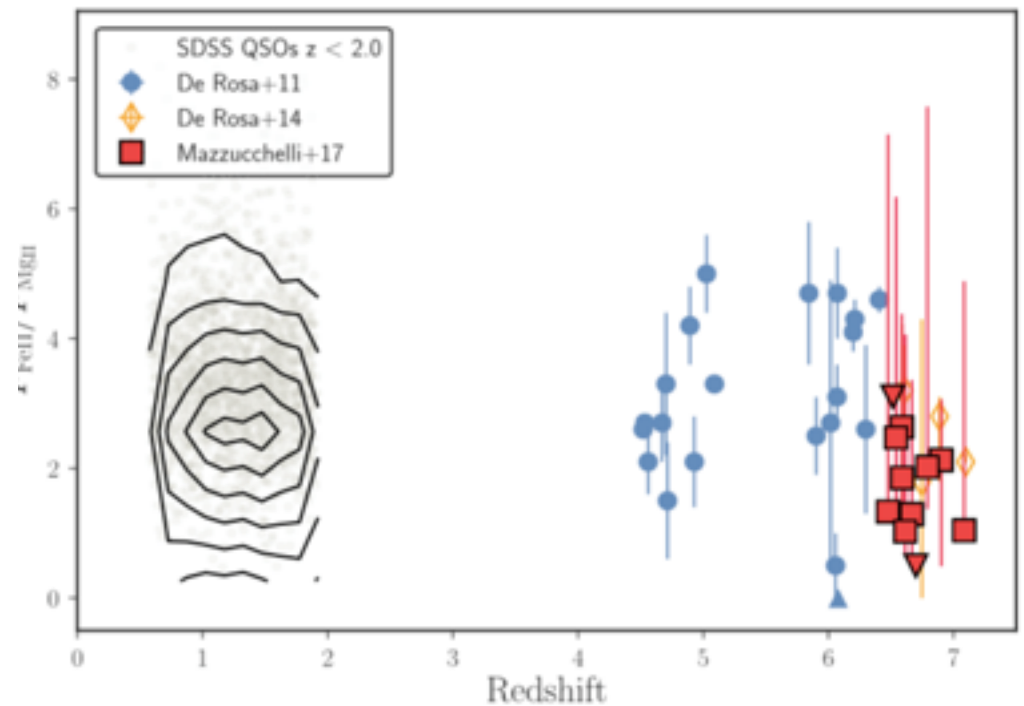
High-redshift quasar spectra are boring…

z~6 vs z~2



Shen+19

Fe at the highest redshift



Mazzucchelli+17

Lack of spectral evolution

- mature luminous quasars at the highest redshift
- **where are the "young" quasars?**