Hunting for High-Redshift Quasars with Subaru Hyper Suprime-Cam

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Astrophysics Group in Ehime University

Galaxies & LSS (opt/IR)

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M. Kajisawa
Y. Matsuoka
3 post-docs
10 graduate students

Black Holes (X-ray)

H. Awaki
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1 post-docs
3 graduate students

Plasma Phys (theory)

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K. Kondo
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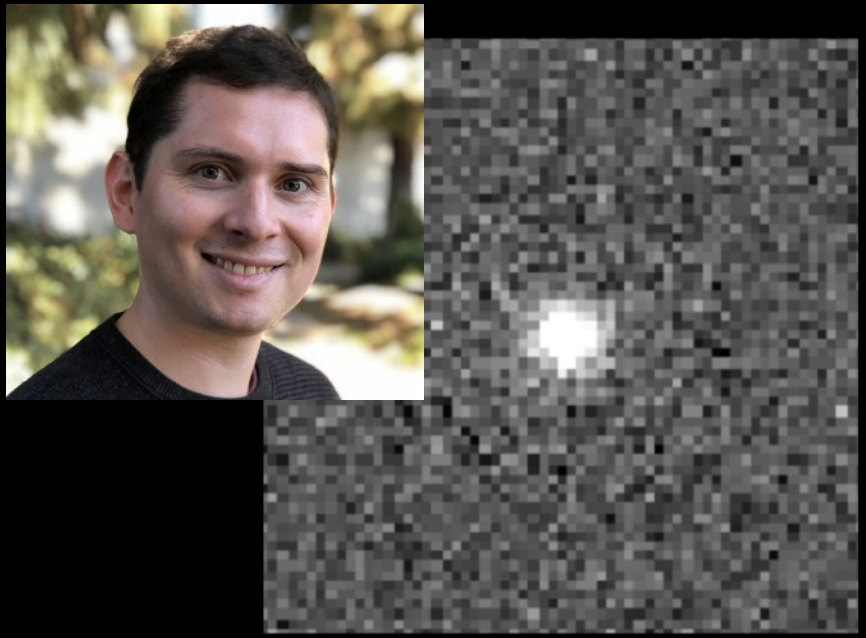
EHIME UNIVERSITY

RCSCE 宇宙進化研究センター
Research Center for Space and Cosmic Evolution

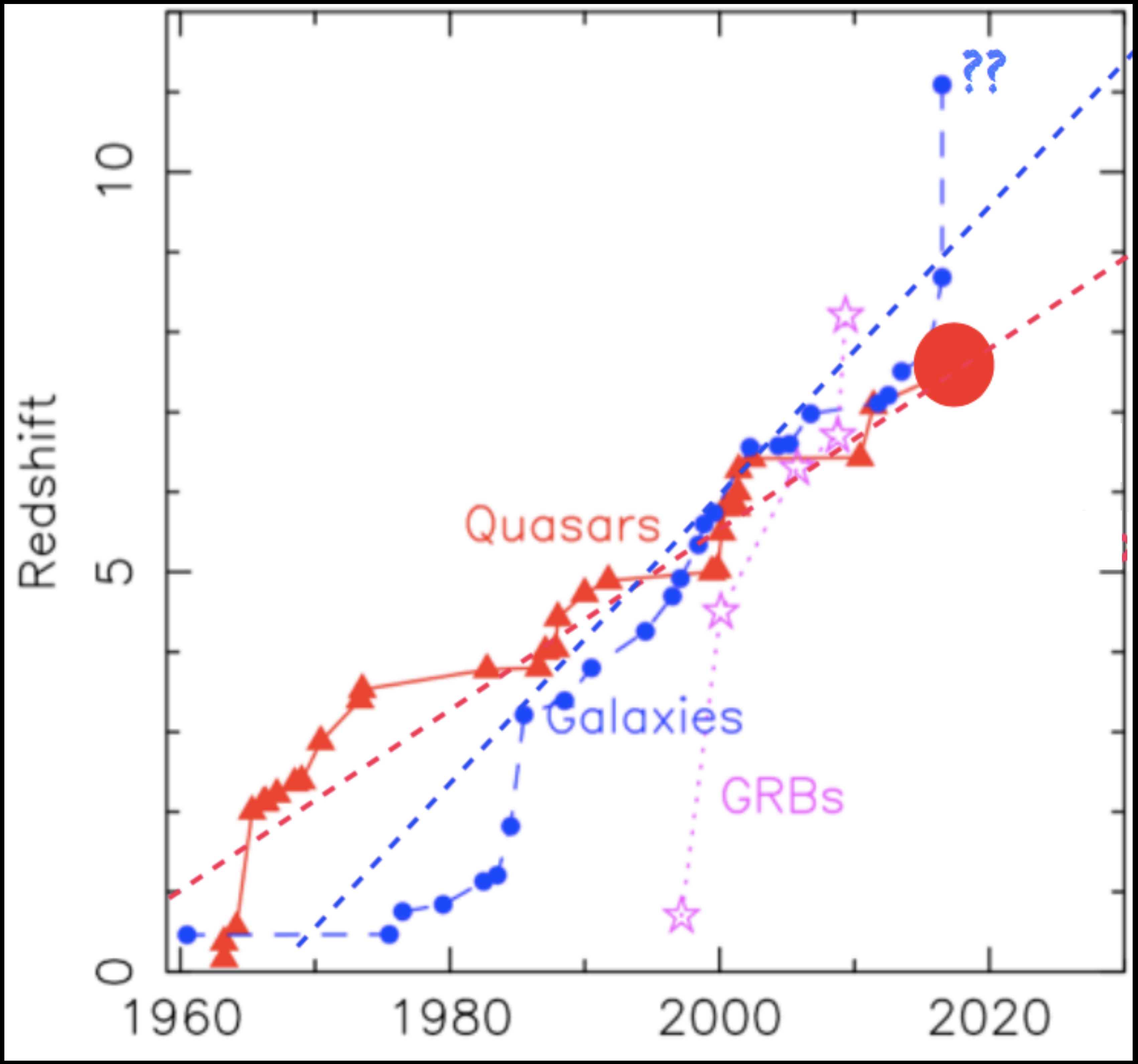
To the farthest reaches of the Universe

✶ z = 0.158 (1963)

✶ z = 7.54 (2018)



Banados+18



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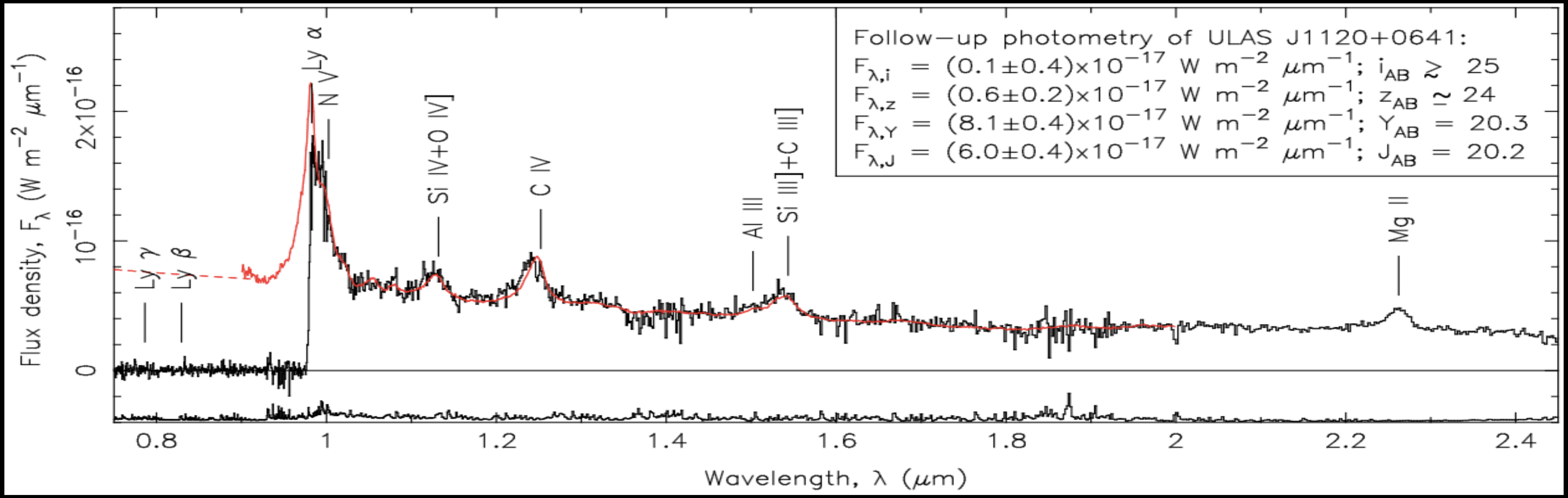
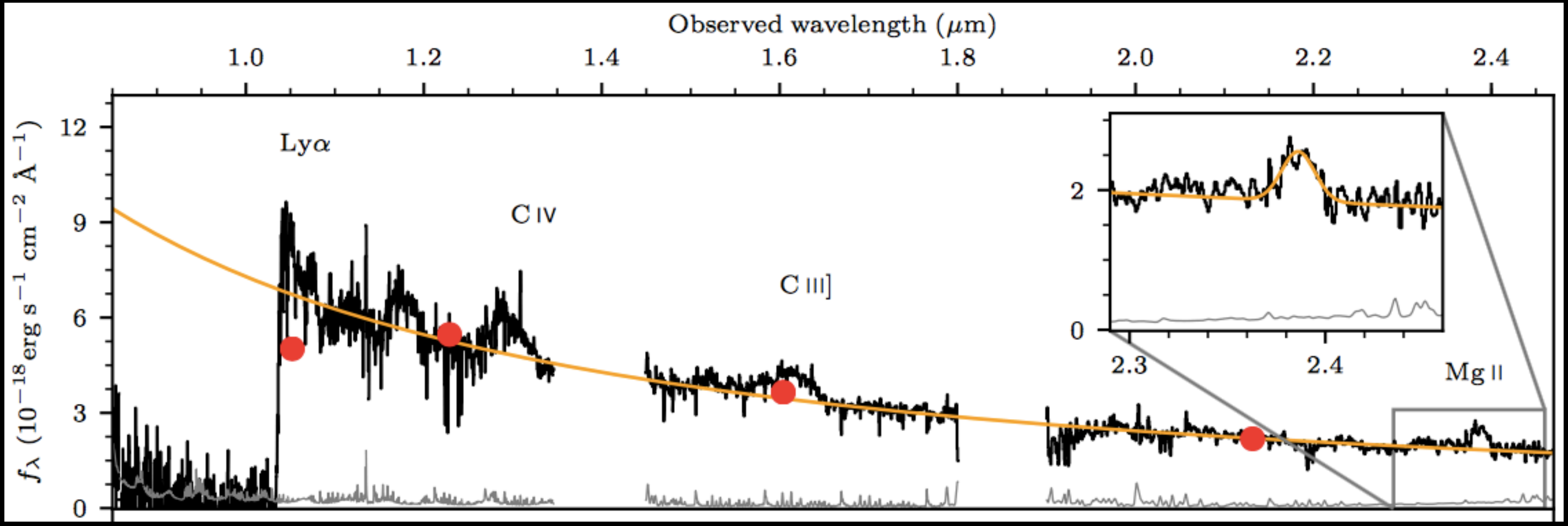
To the farthest reaches of the Universe

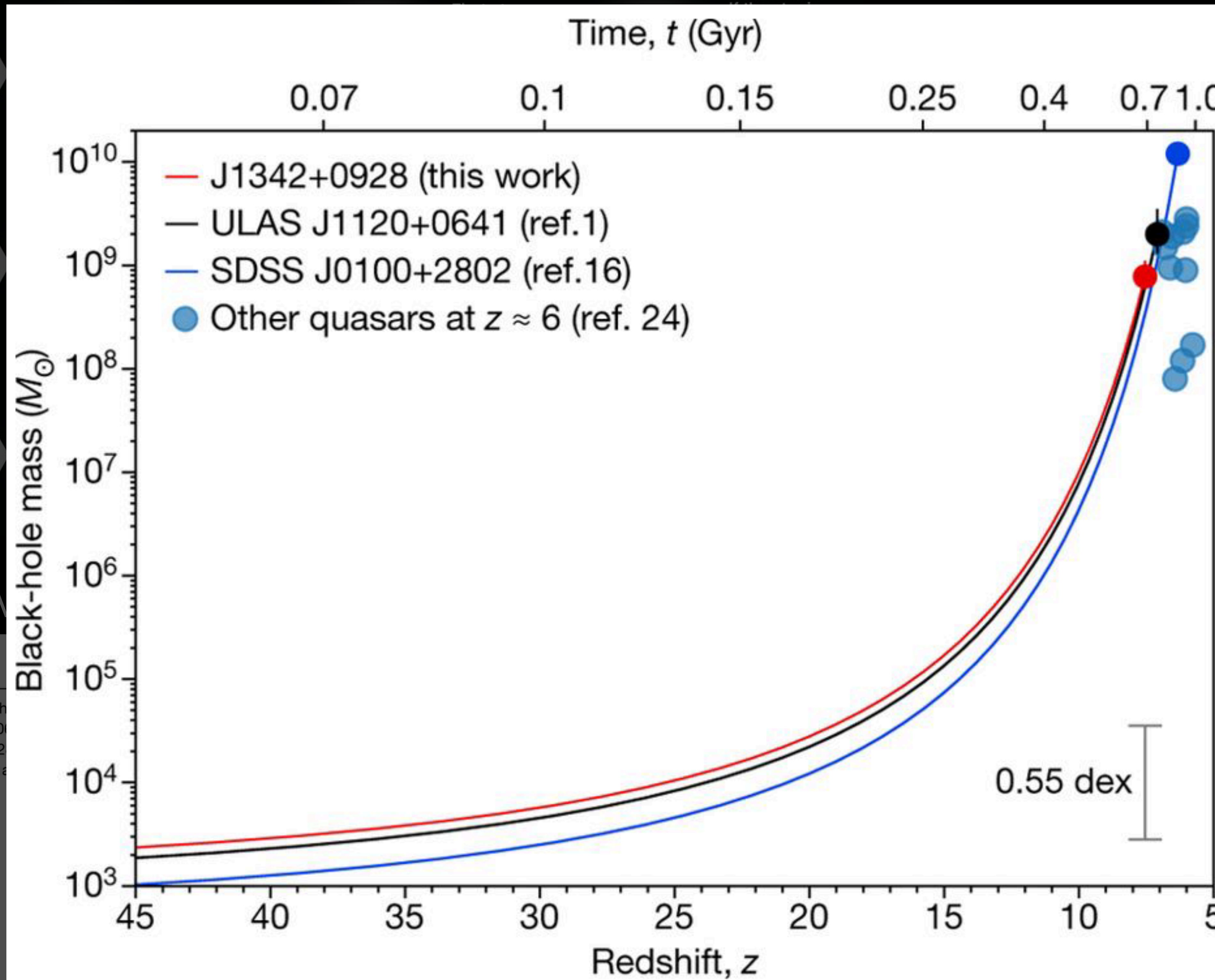
✶ z = 7.085 (Mortlock+11)



✶ z = 7.54 (Banados+18)



The most distant quasars - why do we care?



Maximum

M(t) = M

SMBHs

e seeds?

ey born?

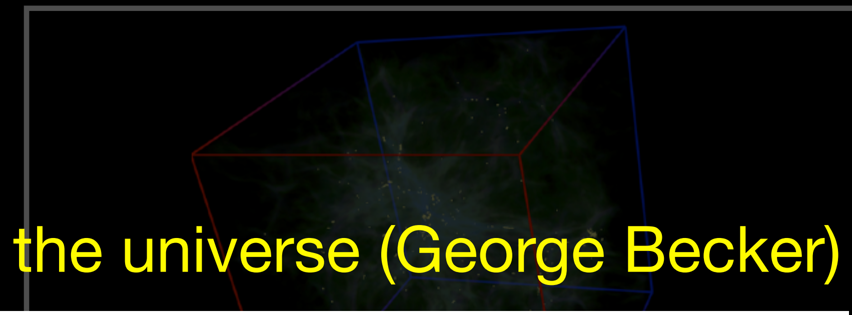
grow?

Banados+18

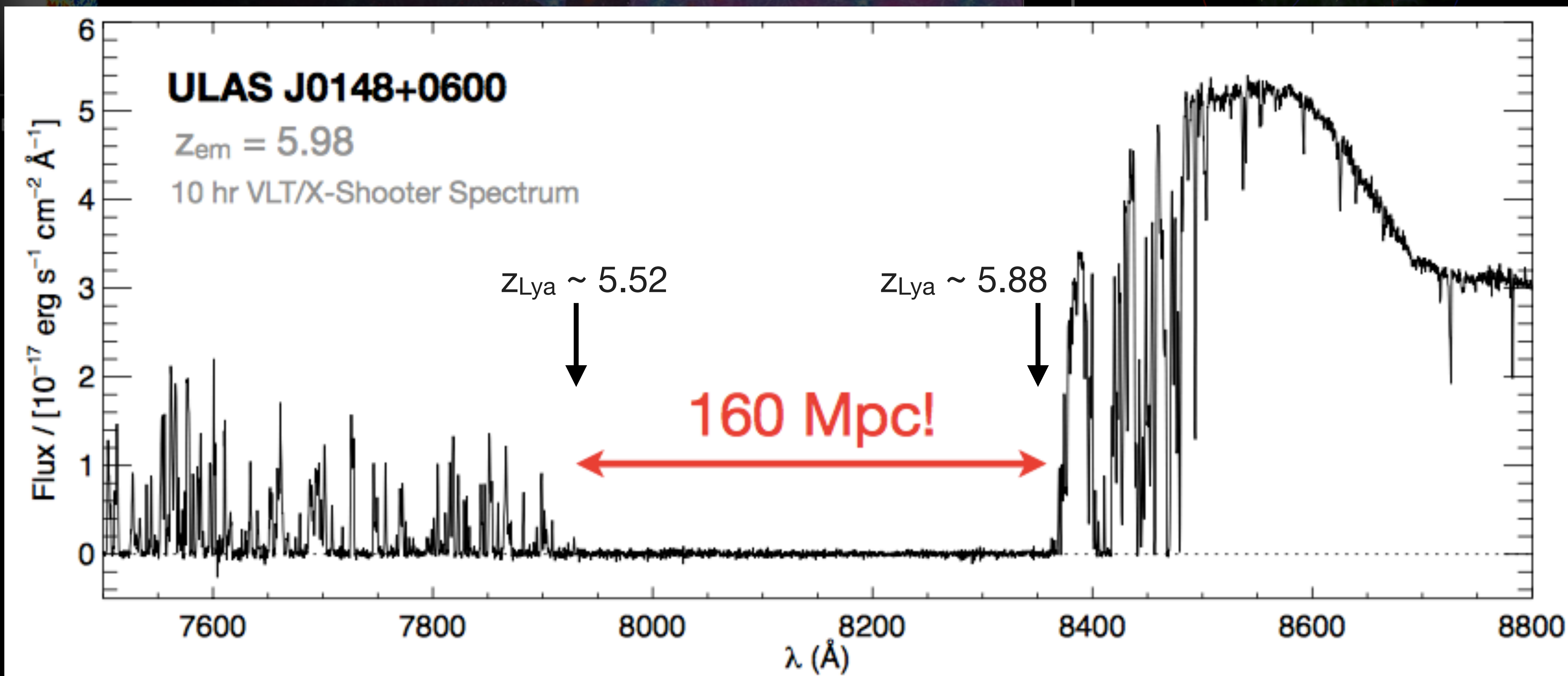
Richards+06

Venemans+13

The most distant quasars - why do we care?

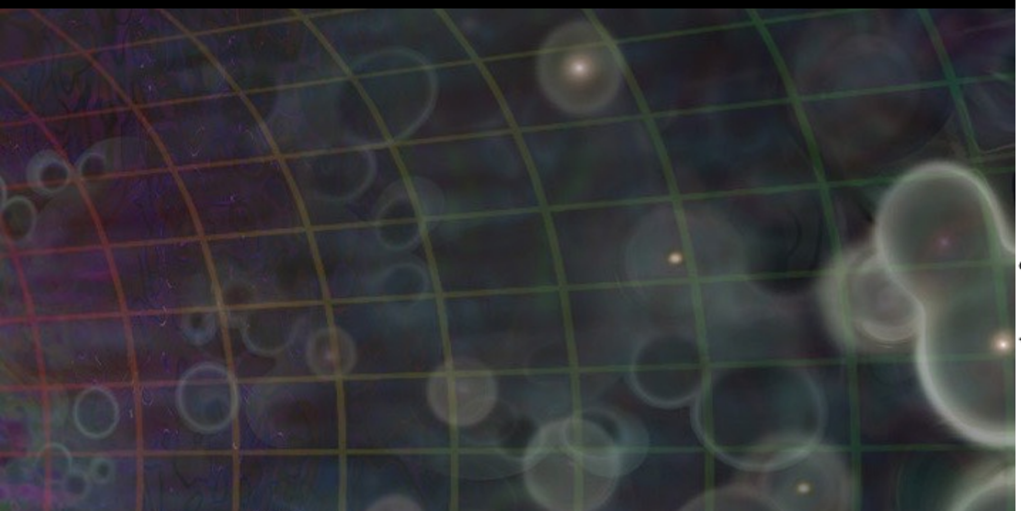


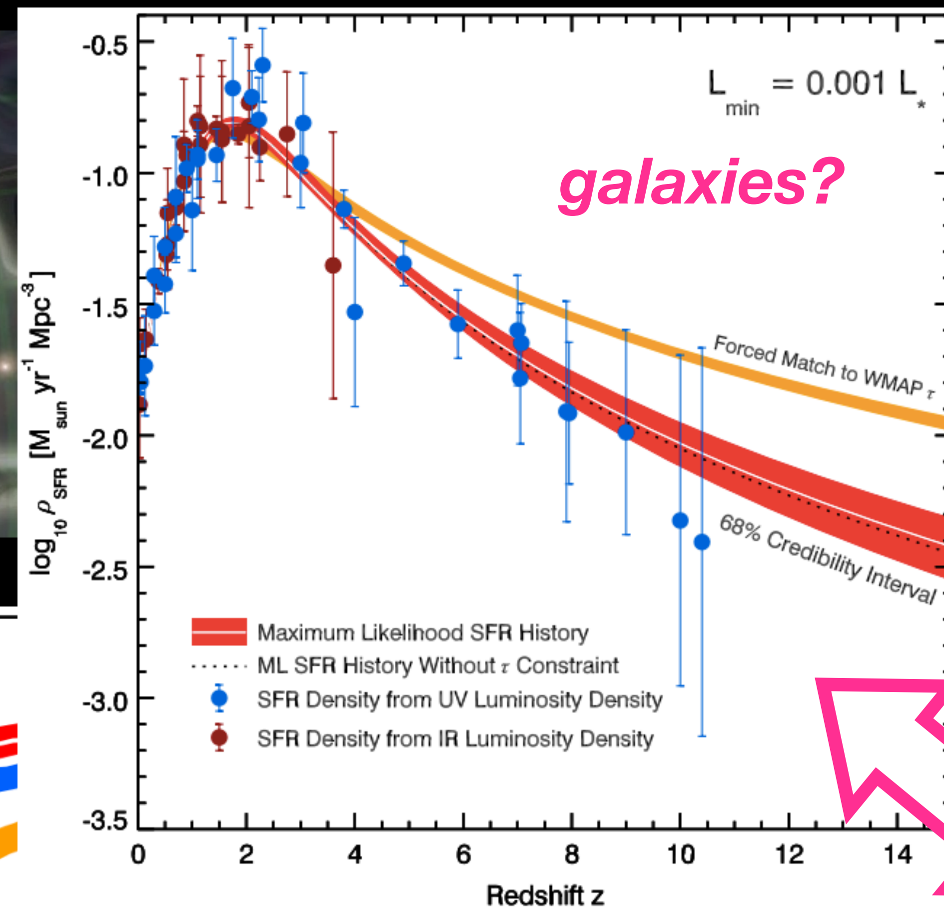
The biggest "thing" in the universe (George Becker)



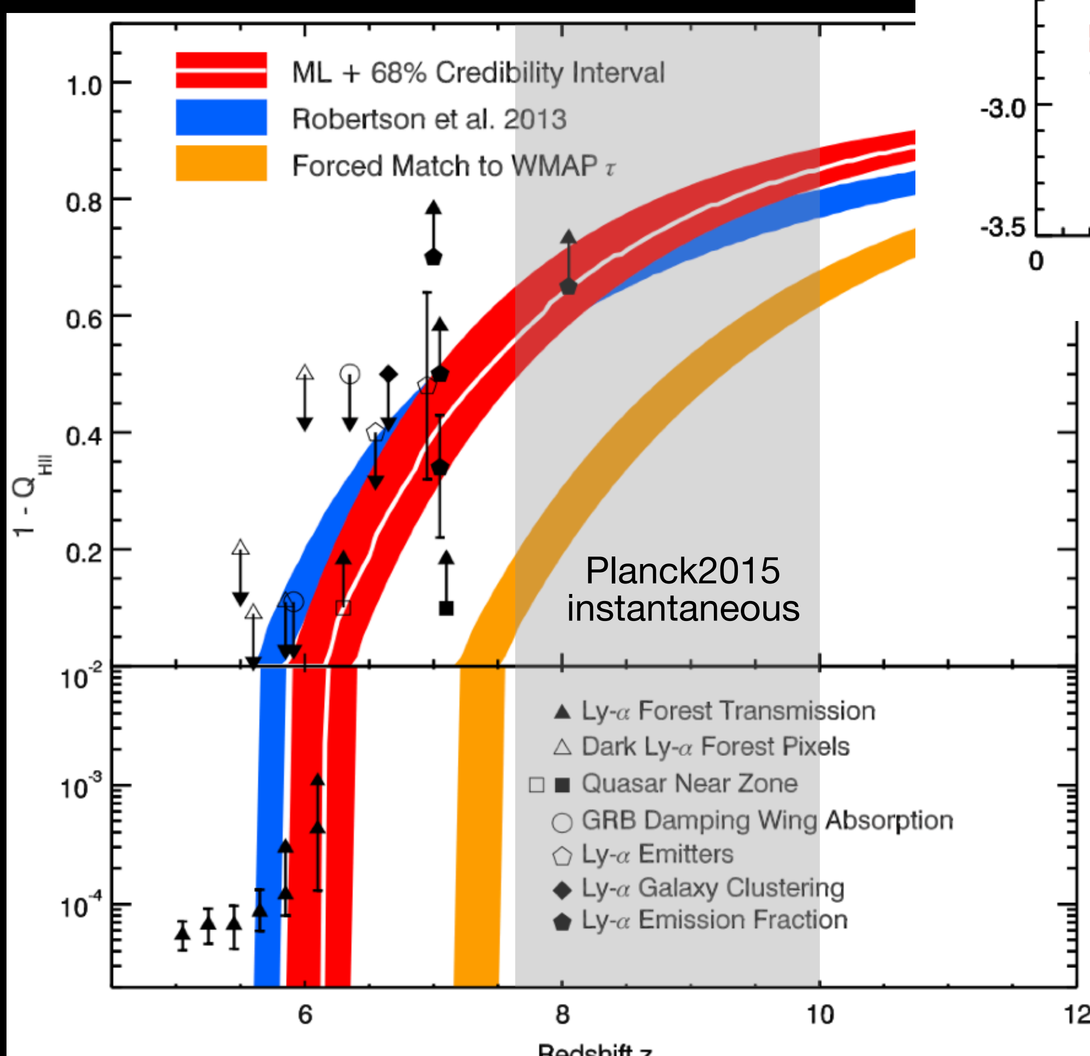
(Robertson+15)

The most distant quasars - why do we care?

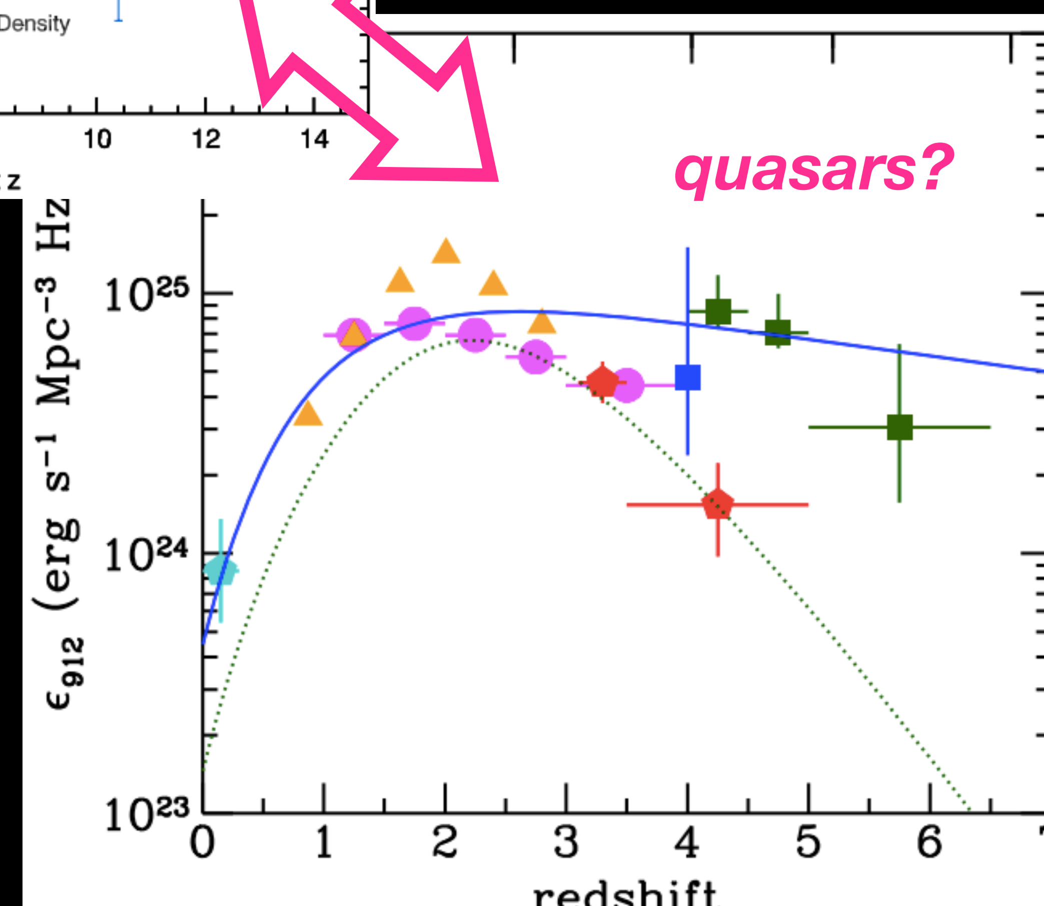




IGM neutral fraction

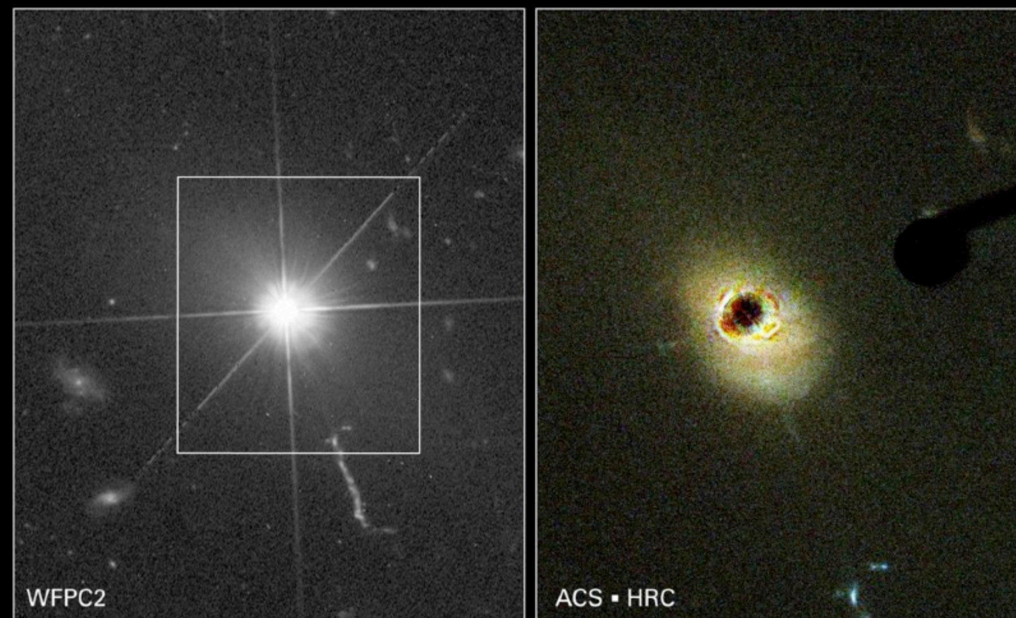


(Robertson+15)



(Madau+15)

The most distant quasars - why do we care?

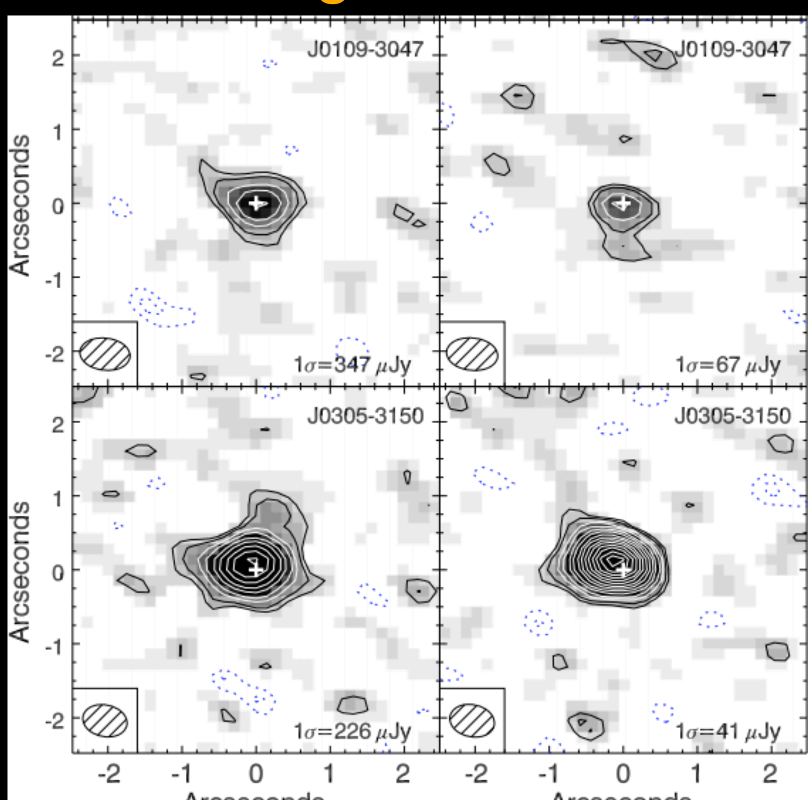


Quasar 3C 273
Hubble Space Telescope • ACS HRC Coronagraph

NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA • STScI-PRC03-03

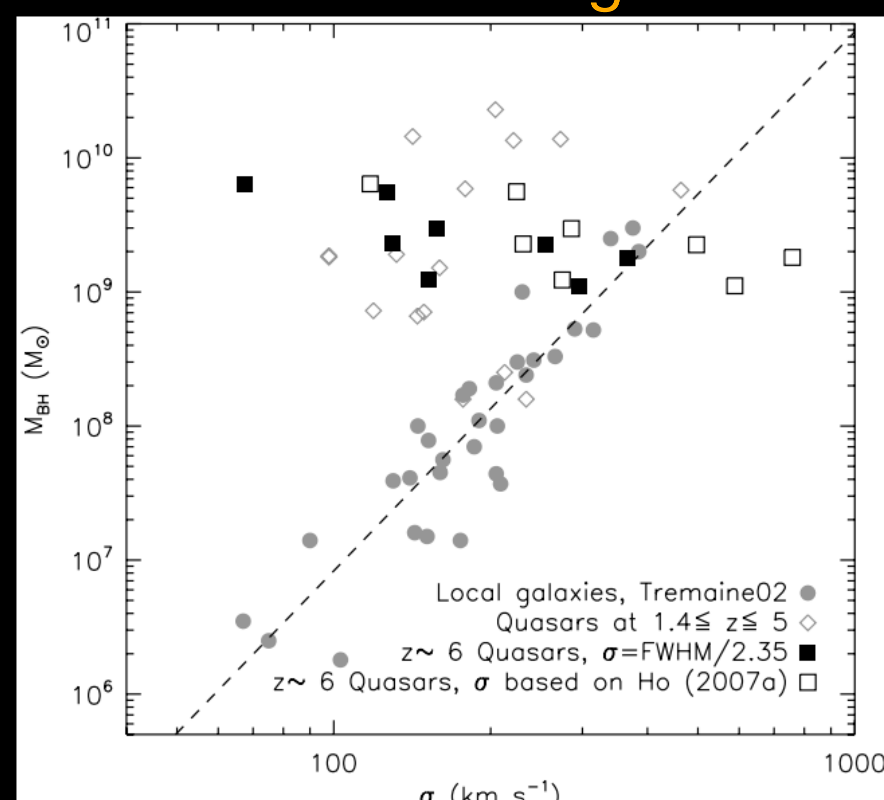
Host galaxy evolution
- ✶ Star formation history
- ✶ Quasar feedback?
- ✶ Chemical enrichment

Stars and gas in the hosts



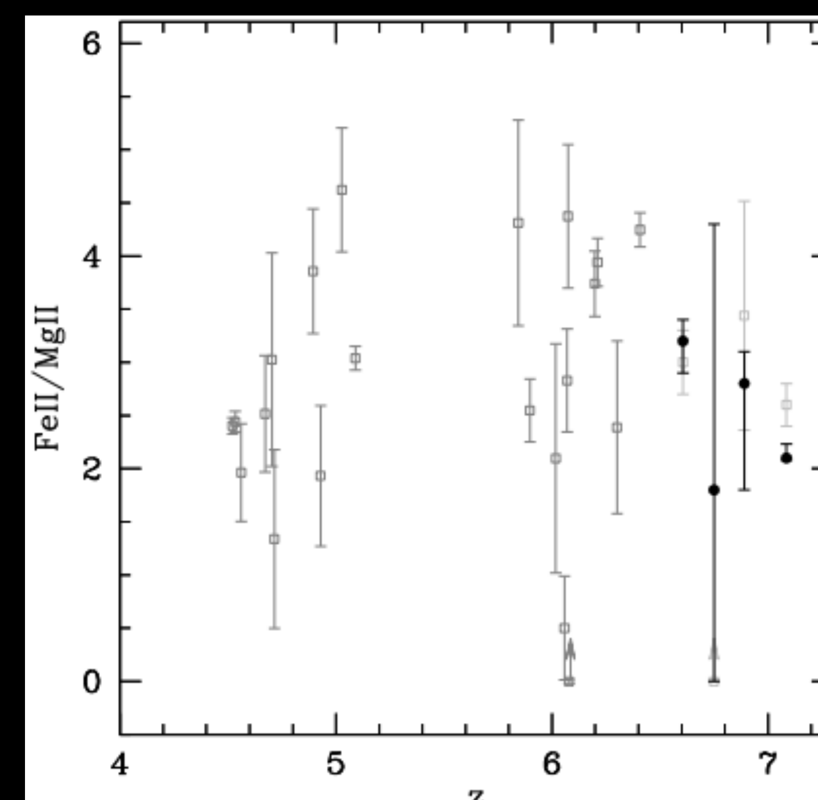
Venemans+16

Scaling relations



Wang+10

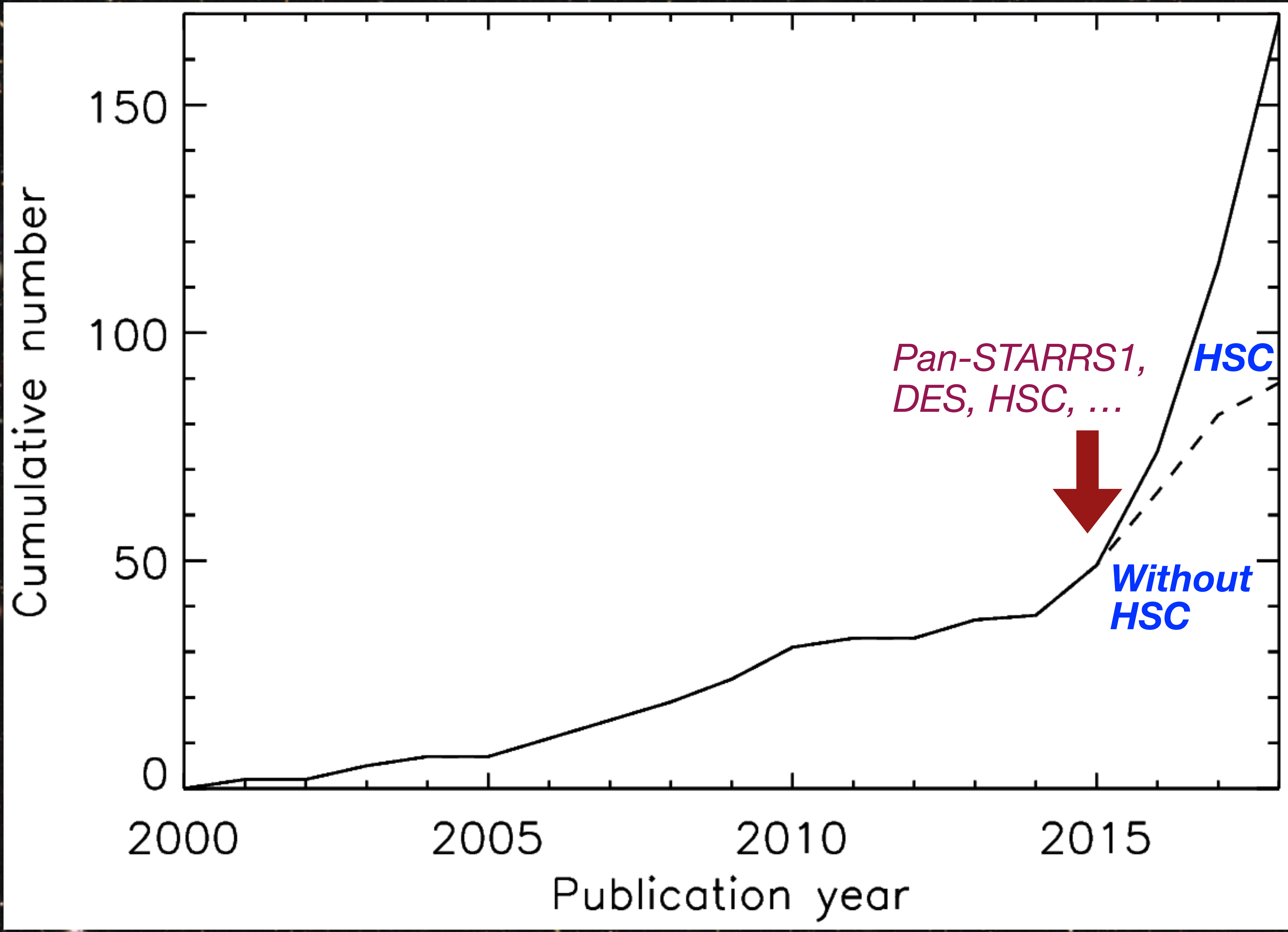
Chemical evolution



De Rosa+14

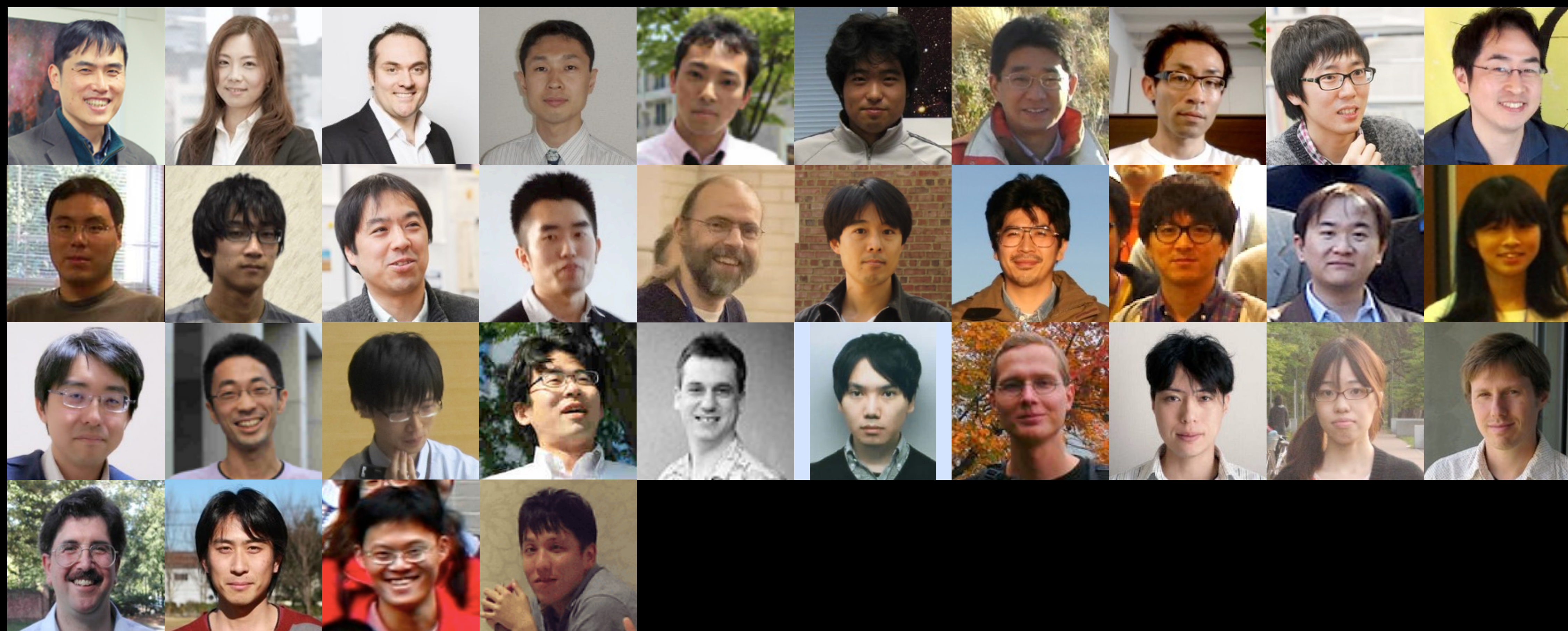
In order to perform these tests, you must FIND quasars first.

Cumulative number of z > 6 quasar discovery



SHELLQs

Subaru High-z Exploration of Low-Luminosity Quasars



Members

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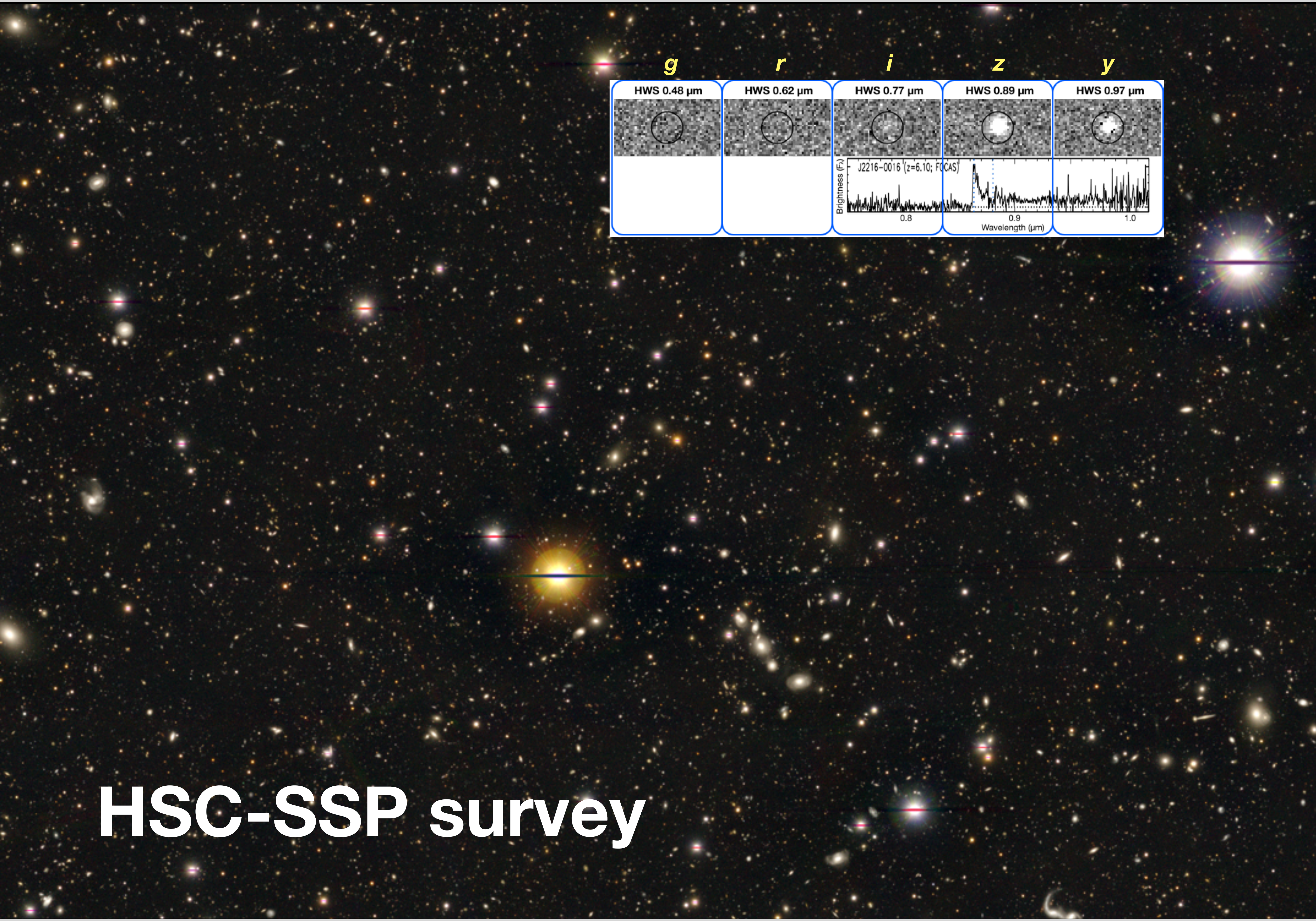


HSC-SSP survey

Subaru Hyper Suprime-Cam SSP survey

Hyper Suprime-Cam (HSC)

- ✶ 116 2K x 4K Hamamatsu FD CCDs (104 CCDs for science exposures)
- ✶ Circular FoV of 1°.5 diameter
- ✶ Miyazaki et al. (2018)

The HSC SSP (Subaru Strategic Program) survey

- ✶ 300 Subaru nights over 5 years, started in early 2014.
  - **Wide**: r_{AB} < 26.1 mag over 1400 deg^2
  - **Deep**: r_{AB} < 27.1 mag over 27 deg^2
  - **UDeep**: r_{AB} < 27.7 mag over 3.5 deg^2
- ✶ Filters: (*g, r, i, z, y*) in **Wide**, + NBs in **Deep** & **UDeep**

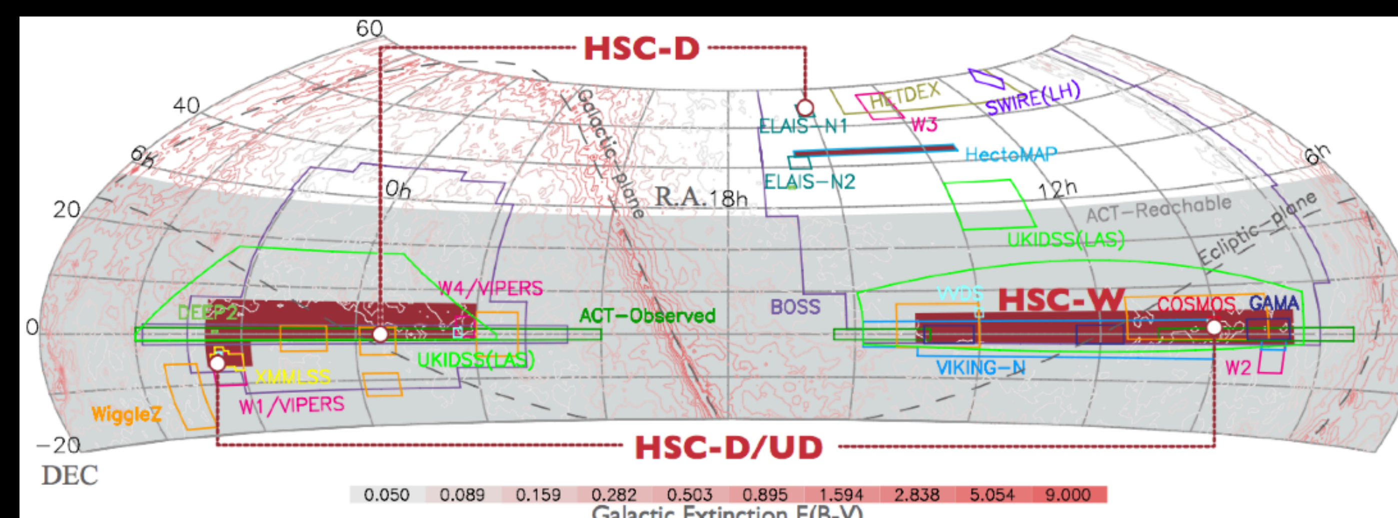
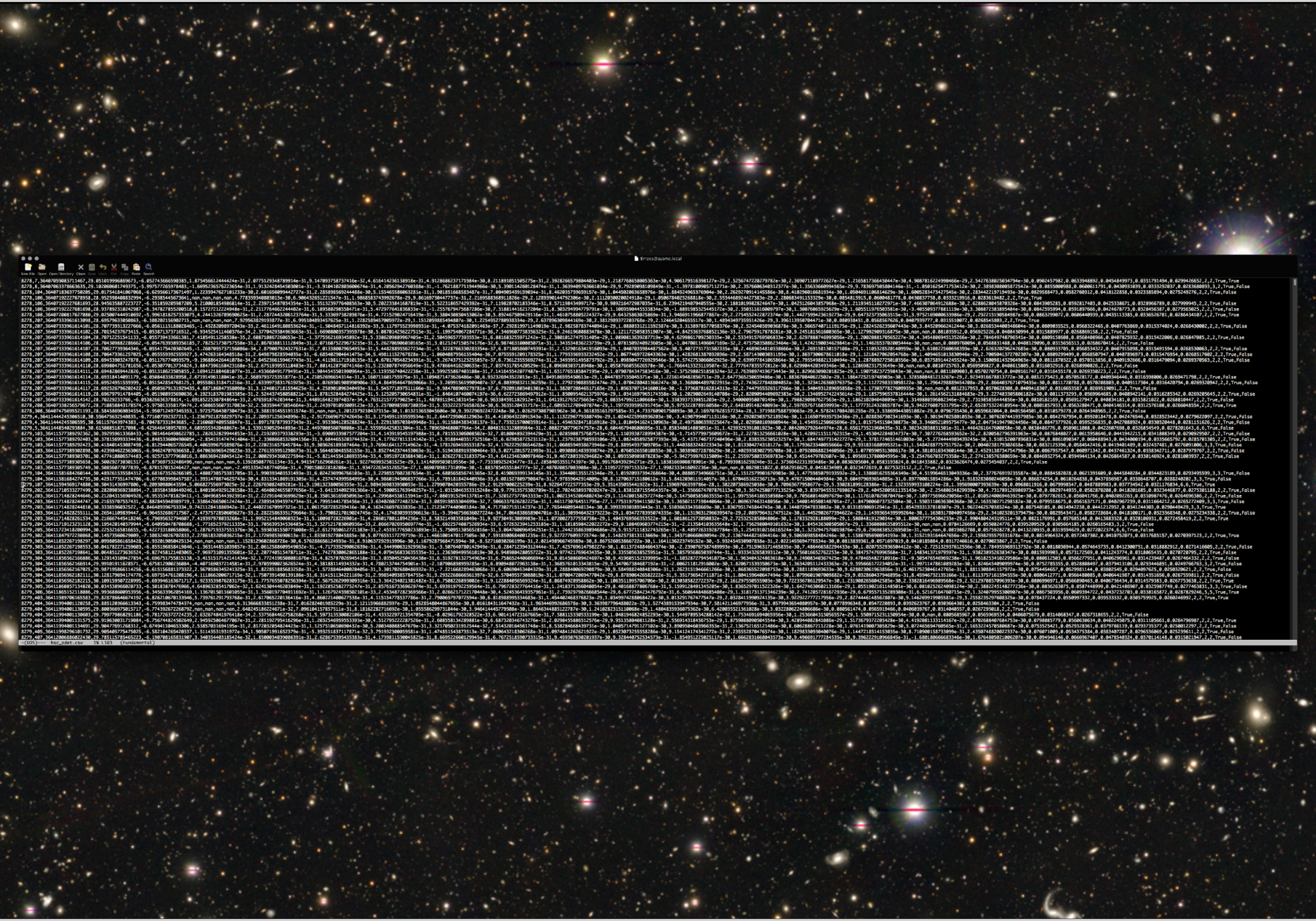


Table 7: Quasar Samples

	Wide (1400 deg^2)				Deep (27 deg^2)			
redshift	3.7–4.6	4.6–5.7	5.9–6.4	6.6–7.2	< 1	3.7–4.6	4.6–5.7	6.6–7.2
mag. range	$r < 23.0$	$i < 24.0$	$z < 24.0$	$y < 23.4$	$i < 25.0$	$i < 25.0$	$i < 25.0$	$y < 25.3$
number	6000	3500	280	50	2000	200	50	3



Bayesian probabilistic selection

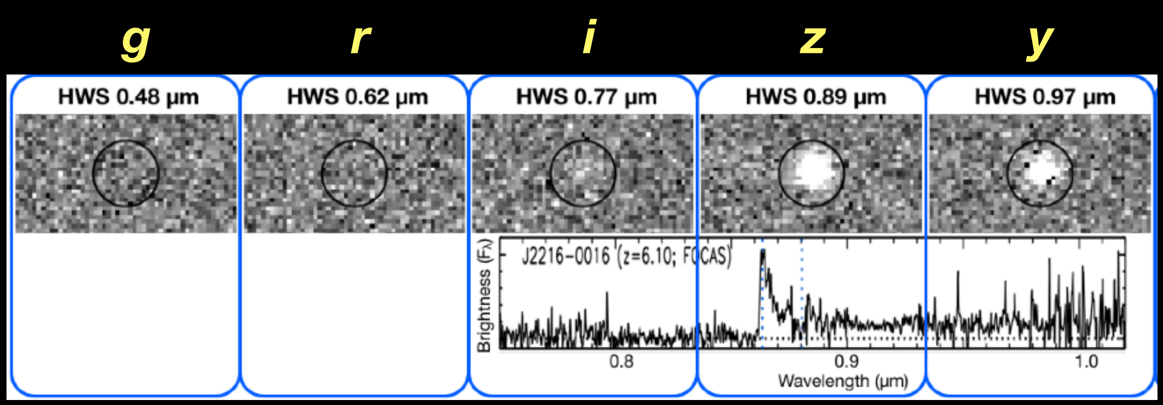
Quasar probability: $P_Q = W_Q/(W_Q+W_D)$

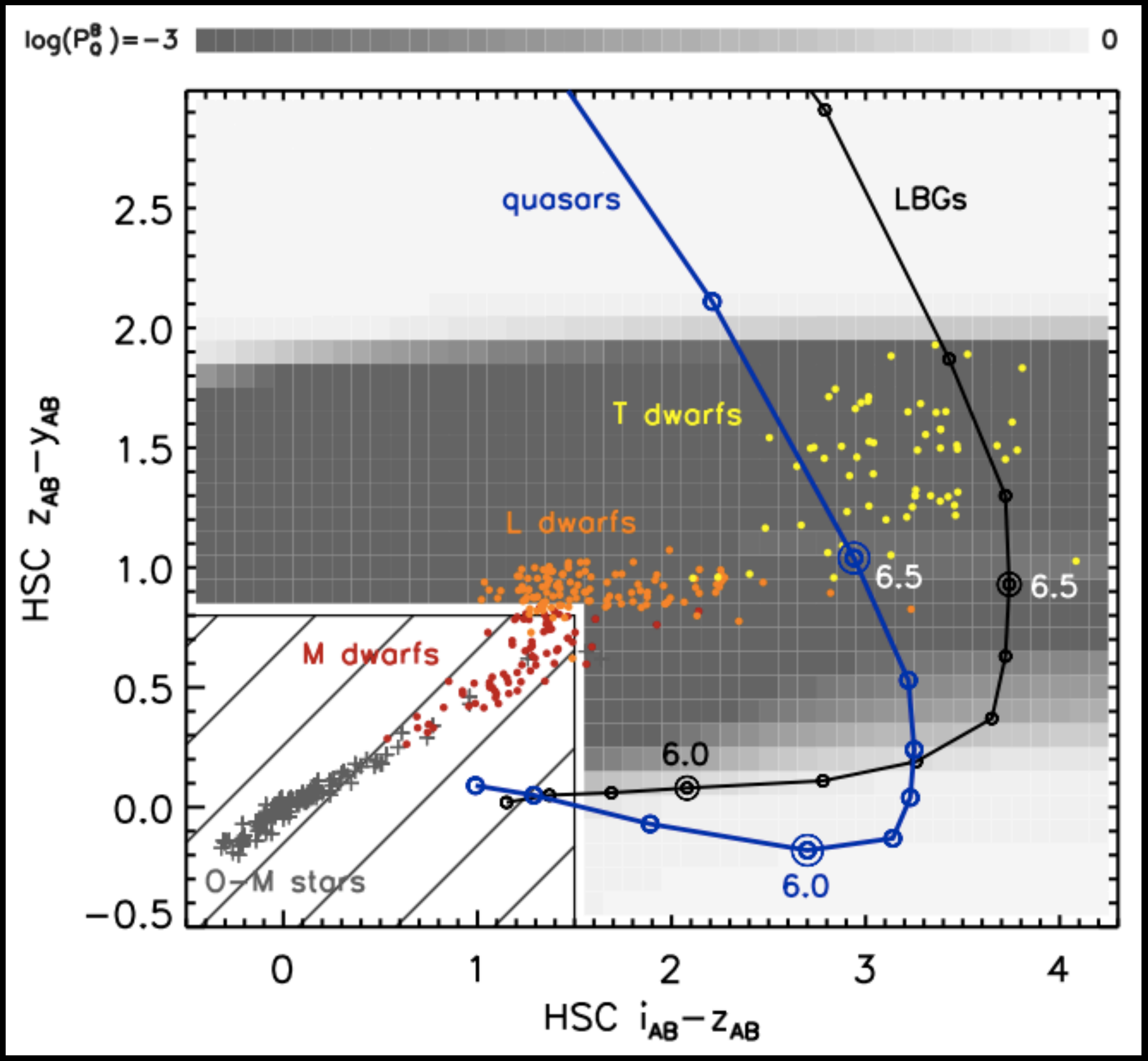
W_Q (**m**, det) = $\int\int \rho_Q(m_{int}, z)\ \Pr(det \mid m_{int}, z)\ \Pr(\mathbf{m} \mid m_{int}, z)\ dm_{int}\ dz$

W_D (**m**, det) = $\int\int \rho_D(m_{int}, t_{sp})\ \Pr(det \mid m_{int}, t_{sp})\ \Pr(\mathbf{m} \mid m_{int}, t_{sp})\ dm_{int}\ dt_{sp}$

observed magnitudes in HSC + NIR bands

source detection





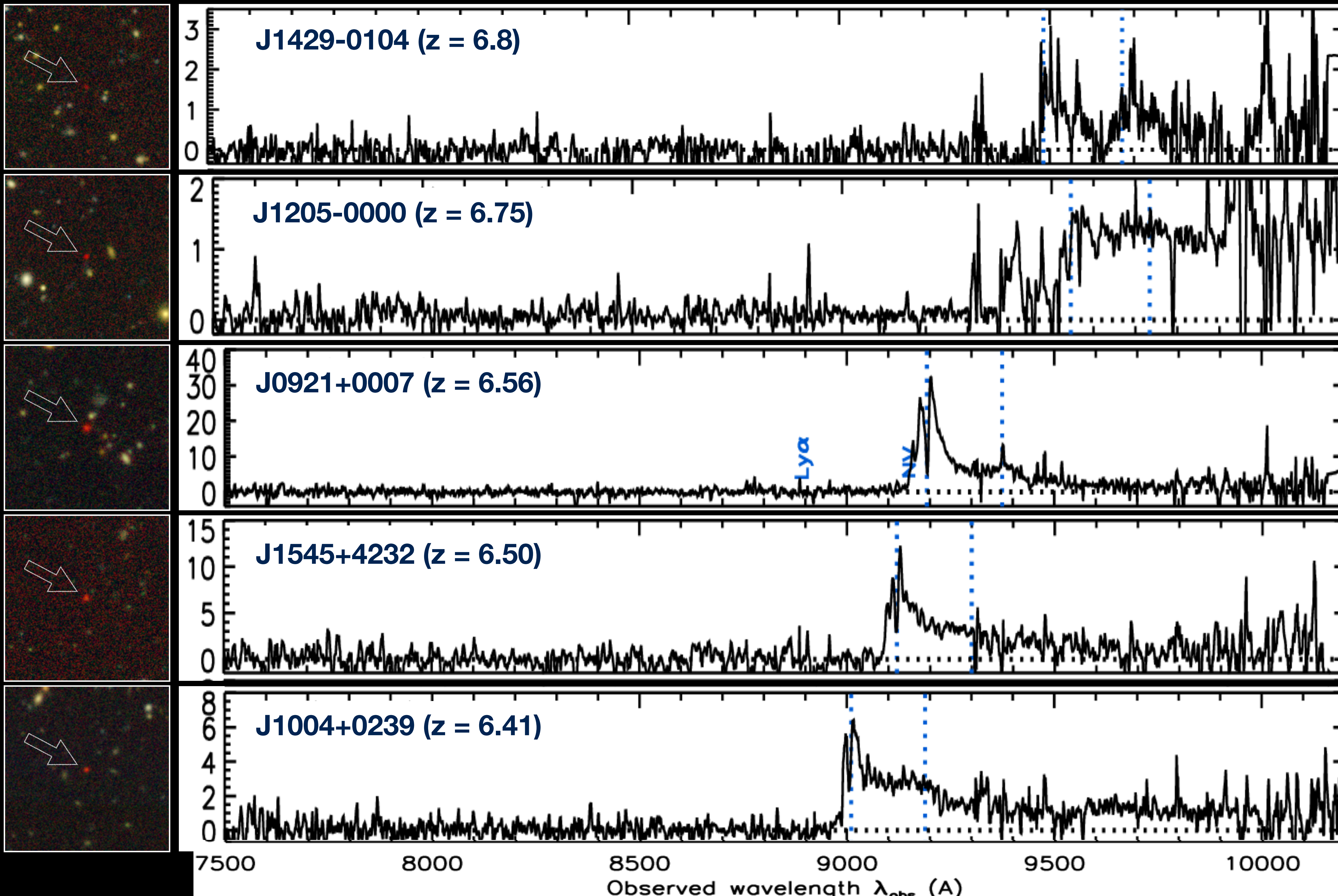
→ Spectroscopic follow-up of all the photometric candidates with $P_Q > 0.1$

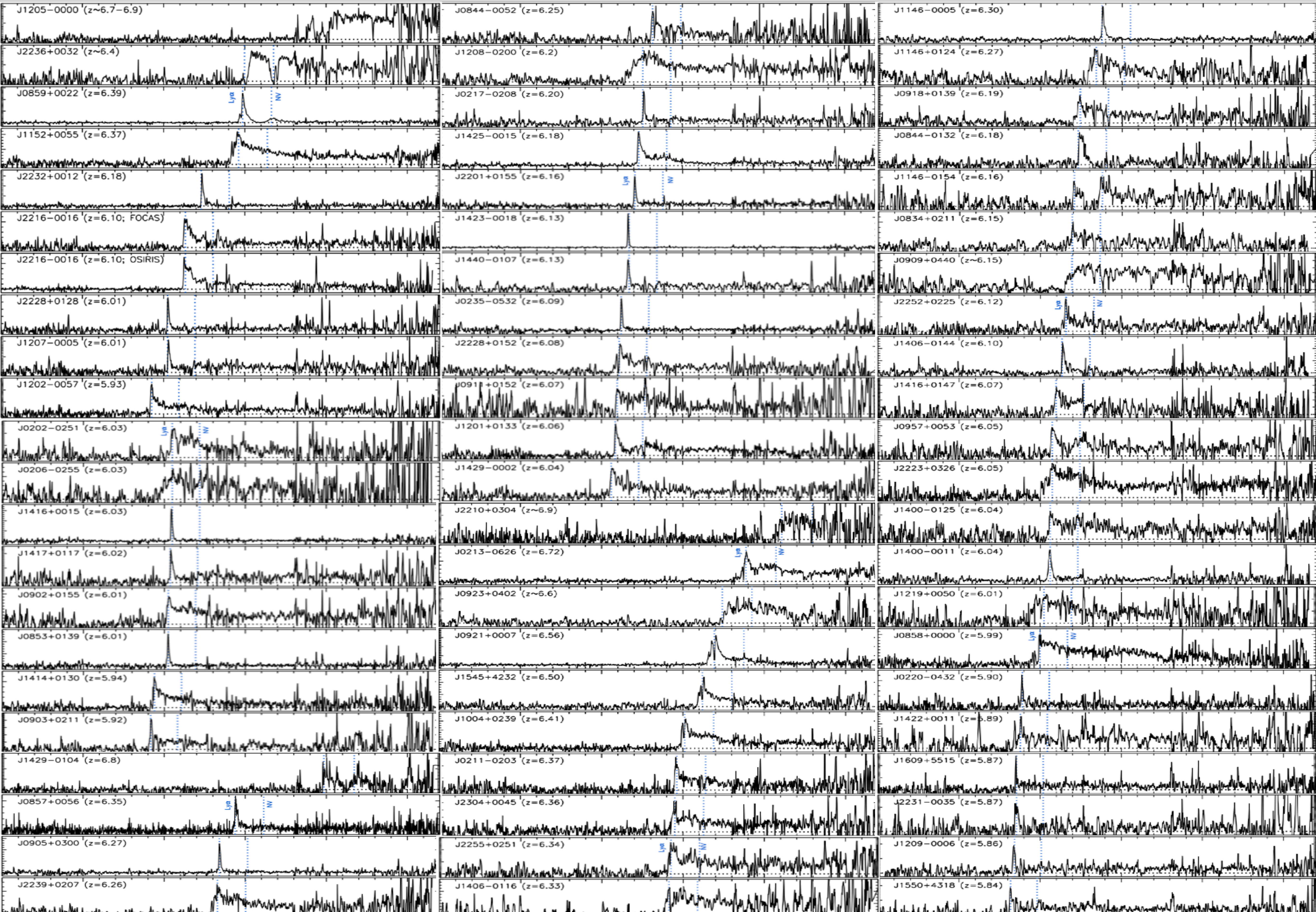
Brief summary of the SHELLQs progress

- ✶ HSC-SSP survey: the previous, S17A data release contains ~650 deg^2 of the Wide fields, with more than a single exposures in the *i*, *z*, and *y* bands.
- ✶ Candidate selection: ~300 candidates with ($z_{AB} < 24.5$ or $y_{AB} < 24.0$) & $P_Q > 0.1$.
- ✶ Spectroscopic follow-up is underway, with Subaru, Gemini, and GTC. In particular, we were allocated 60 Subaru nights in total, including two "intensive program"s.

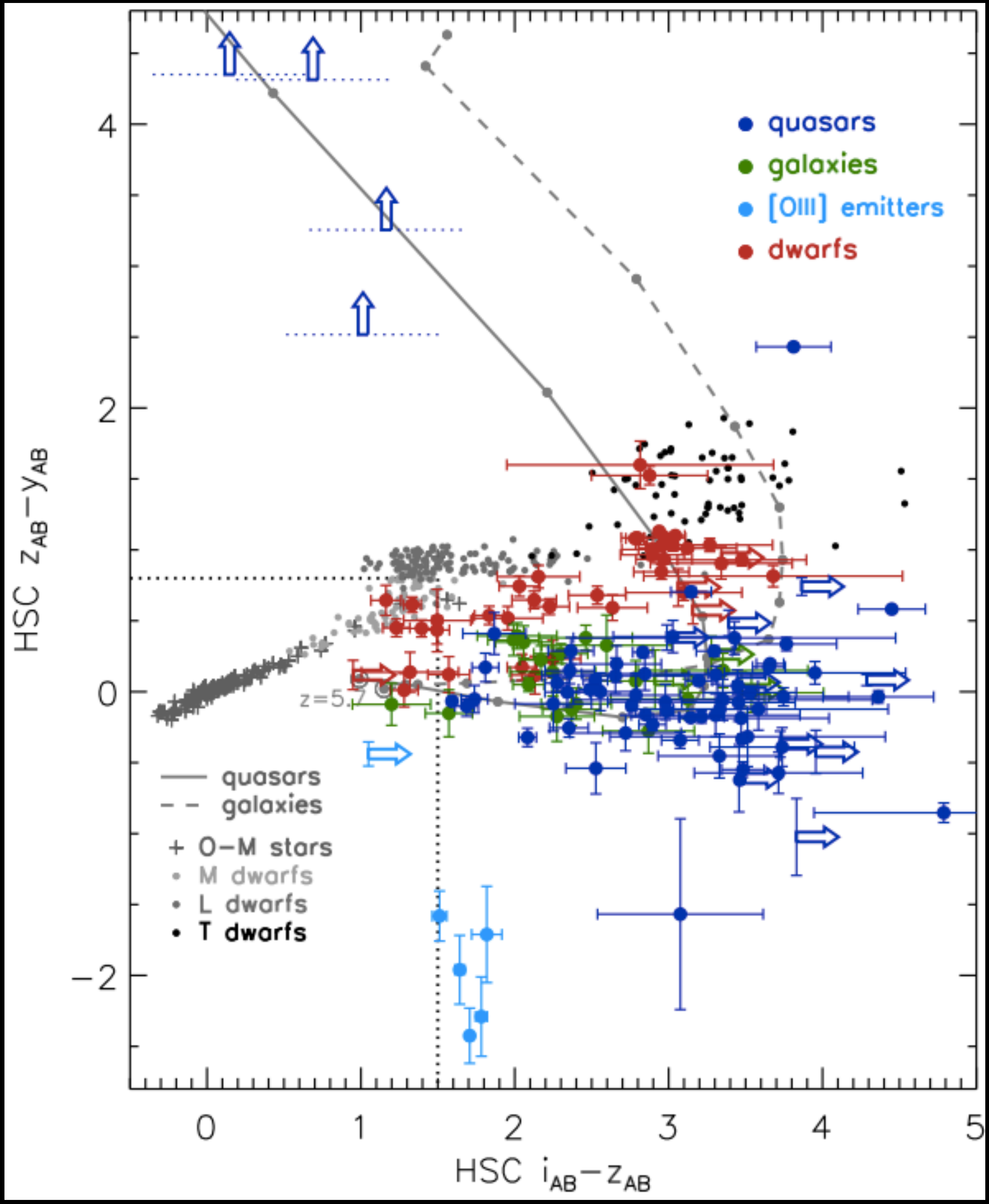
- ✶ We have identified 163 candidates so far, which include 80 high-z quasars, 25 high-z galaxies, 6 [O III] emitters at z~0.8, and 53 brown dwarfs.
- ✶ A series of publications:
  - Paper I (Matsuoka+16): initial discovery of 9 quasars
  - Paper II (Matsuoka+18): more discovery of 24 quasars
  - Paper III (Izumi+18): ALMA follow-up
  - Paper IV (Matsuoka+18): more discovery of 31 quasars
  - Paper V (Matsuoka+18, submitted): quasar luminosity function at z = 6

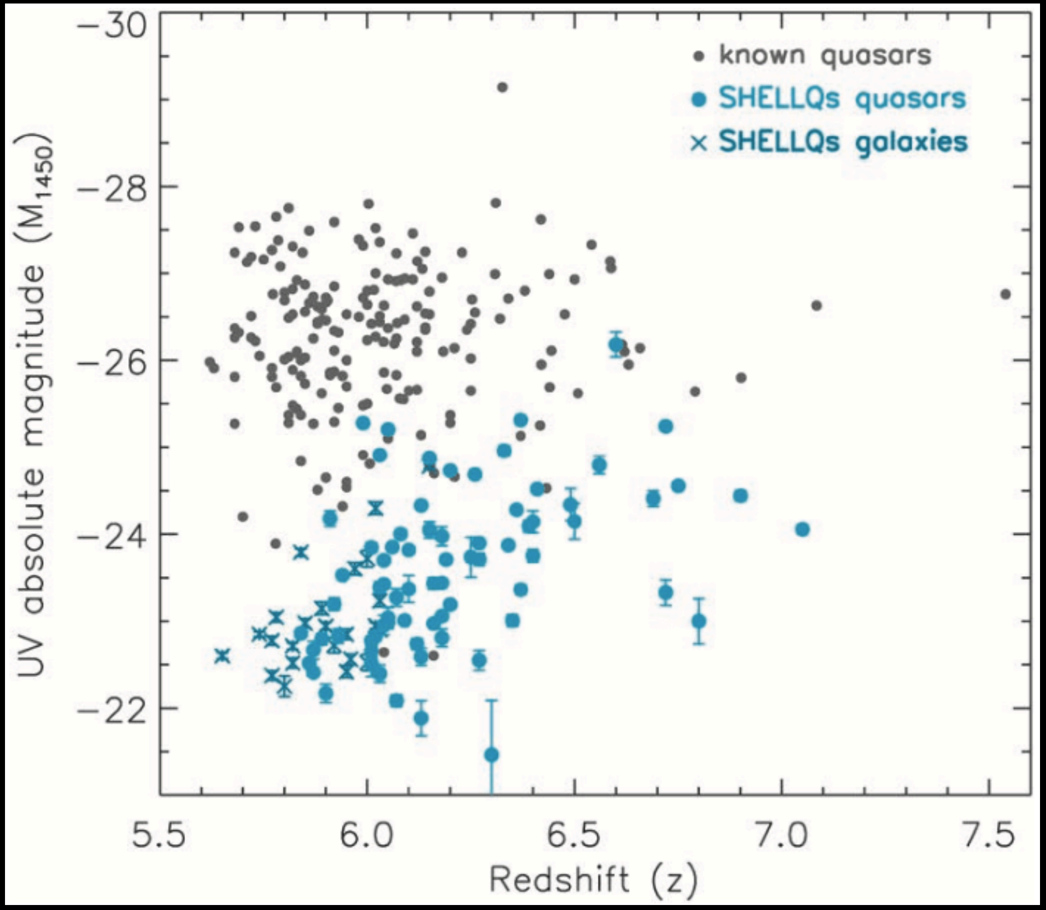
Examples of the discovery images and spectra

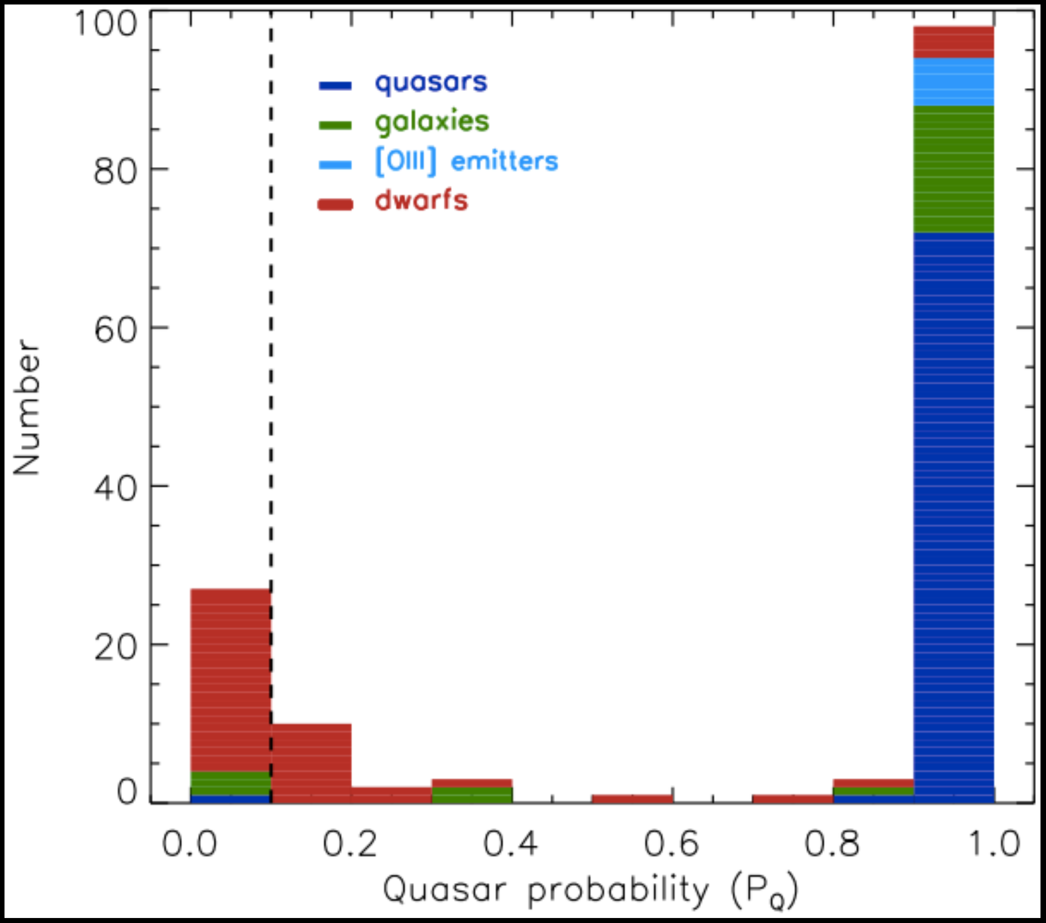



J1205−0000 (z~6.7−6.9)
J2236+0032 (z~6.4)
J0859+0022 (z=6.39)
Lyα
NV
J1152+0055 (z=6.37)
J2232+0012 (z=6.18)
J2216−0016 (z=6.10; FOCAS)
J2216−0016 (z=6.10; OSIRIS)
J2228+0128 (z=6.01)
J1207−0005 (z=6.01)
J1202−0057 (z=5.93)
J0202−0251 (z=6.03)
J0206−0255 (z=6.03)
J1416+0015 (z=6.03)
J1417+0117 (z=6.02)
J0902+0155 (z=6.01)
J0853+0139 (z=6.01)
J1414+0130 (z=5.94)
J0903+0211 (z=5.92)
J1429−0104 (z=6.8)
J0857+0056 (z=6.35)
J0905+0300 (z=6.27)
J2239+0207 (z=6.26)
J0844−0052 (z=6.25)
J1208−0200 (z=6.2)
J0217−0208 (z=6.20)
J1425−0015 (z=6.18)
J2201+0155 (z=6.16)
J1423−0018 (z=6.13)
J1440−0107 (z=6.13)
J0235−0532 (z=6.09)
J2228+0152 (z=6.08)
J0911+0152 (z=6.07)
J1201+0133 (z=6.06)
J1429−0002 (z=6.04)
J2210+0304 (z~6.9)
J0213−0626 (z=6.72)
J0923+0402 (z~6.6)
J0921+0007 (z=6.56)
J1545+4232 (z=6.50)
J1004+0239 (z=6.41)
J0211−0203 (z=6.37)
J2304+0045 (z=6.36)
J2255+0251 (z=6.34)
J1406−0116 (z=6.33)
J1146−0005 (z=6.30)
J1146+0124 (z=6.27)
J0918+0139 (z=6.19)
J0844−0132 (z=6.18)
J1146−0154 (z=6.16)
J0834+0211 (z=6.15)
J0909+0440 (z~6.15)
J2252+0225 (z=6.12)
J1406−0144 (z=6.10)
J1416+0147 (z=6.07)
J0957+0053 (z=6.05)
J2223+0326 (z=6.05)
J1400−0125 (z=6.04)
J1400−0011 (z=6.04)
J1219+0050 (z=6.01)
J0858+0000 (z=5.99)
J0220−0432 (z=5.90)
J1422+0011 (z=5.89)
J1609+5515 (z=5.87)
J2231−0035 (z=5.87)
J1209−0006 (z=5.86)
J1550+4318 (z=5.84)

Highlight (1/5): Sample statistics

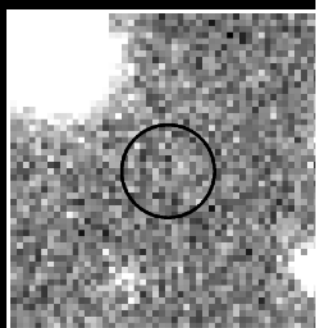




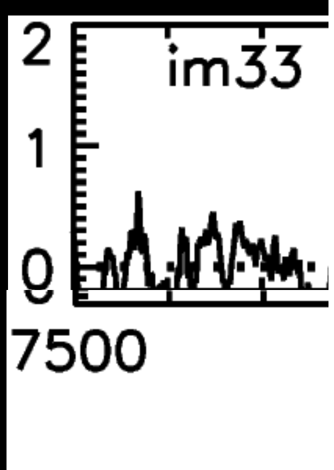


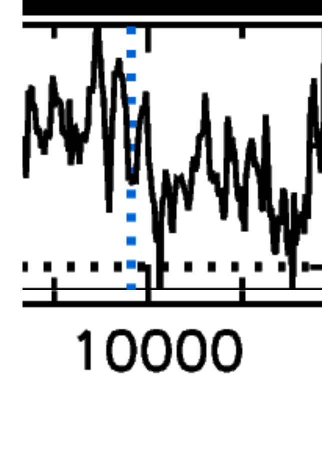
Highlight (2/5) : the 3rd z > 7 quasar

- HSC pho

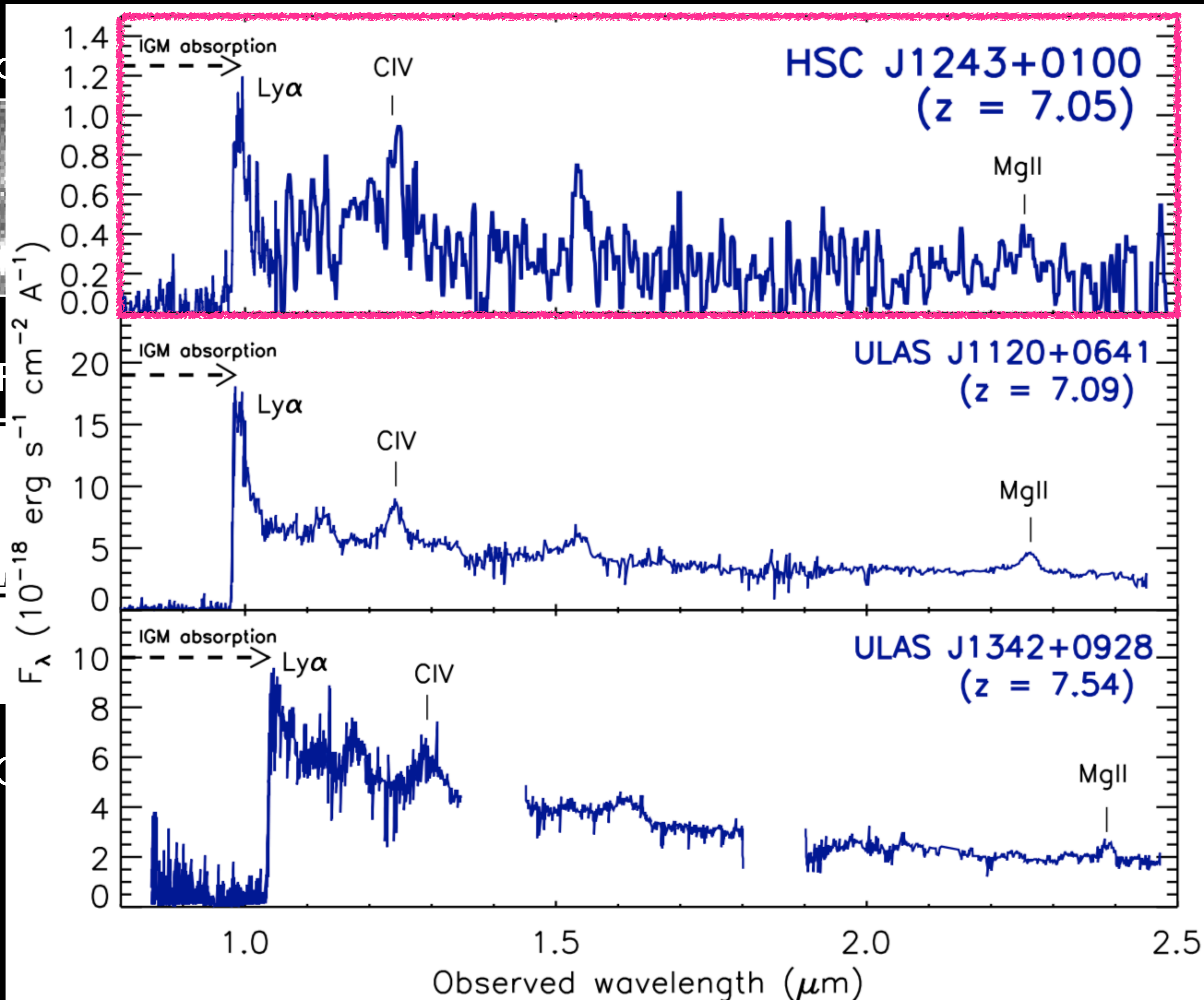


- Subaru/F



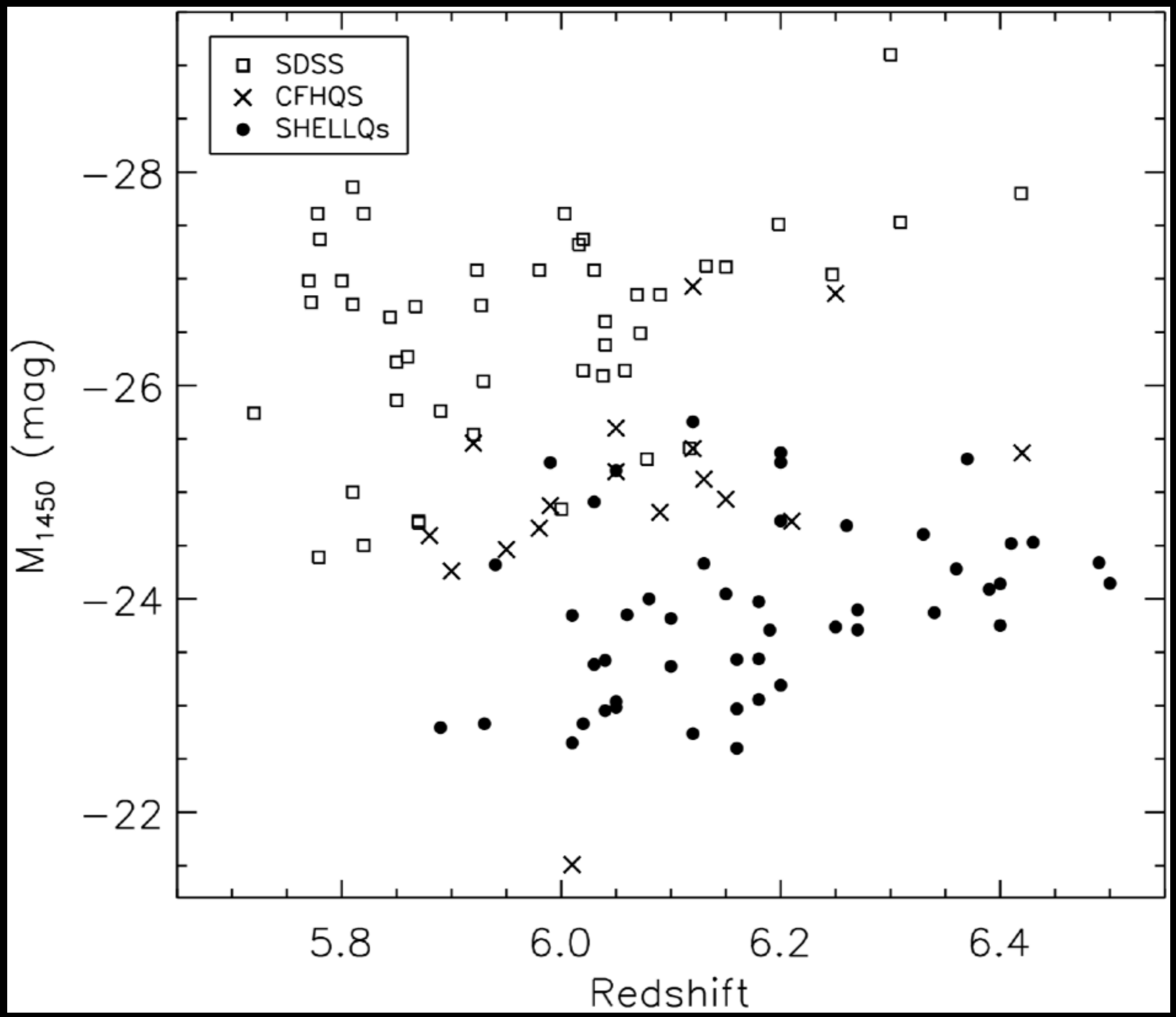


- Gemini/G



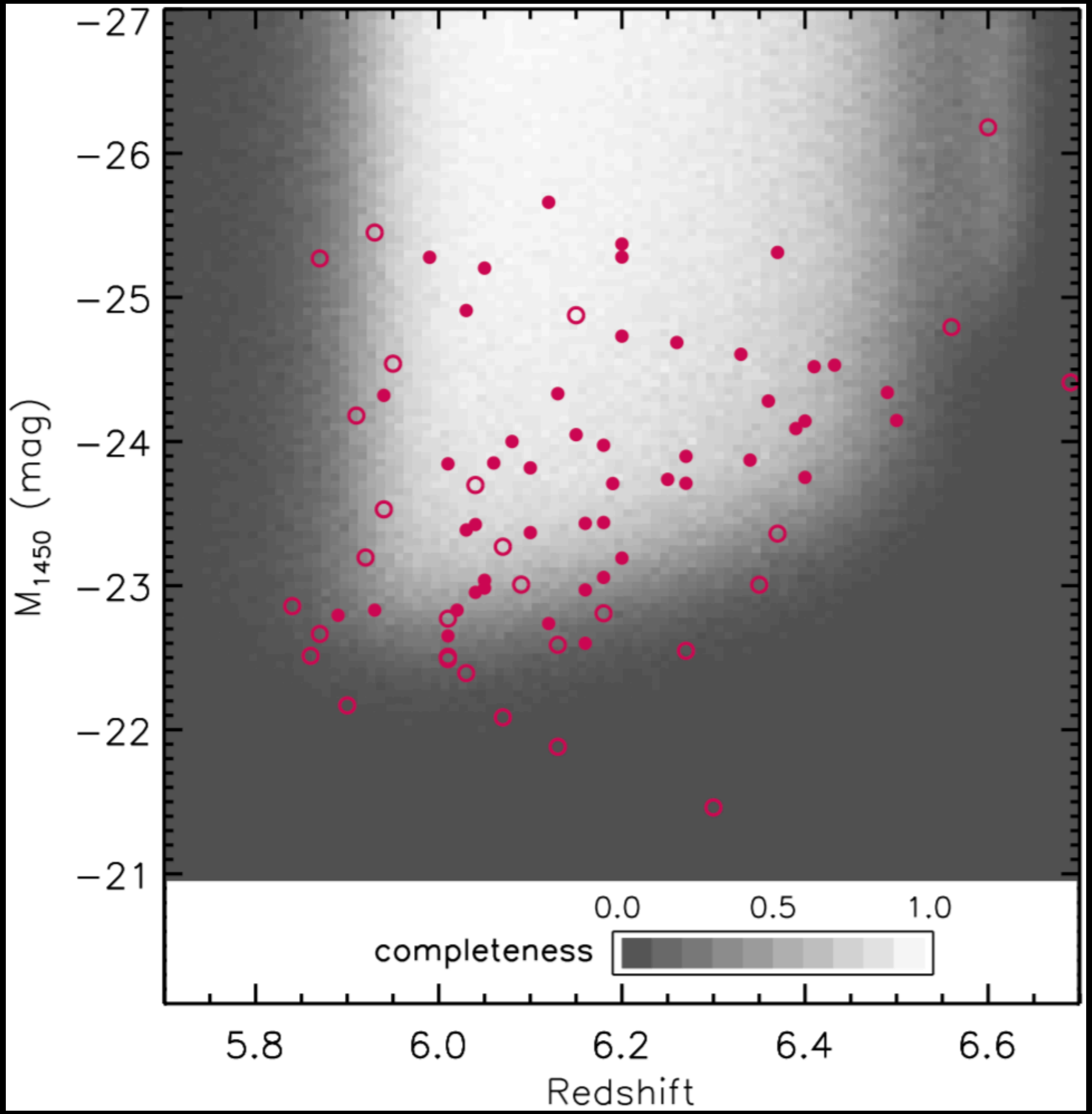
Highlight (3/5): Luminosity function at z = 6

✶ 110 complete sample of quasars from SDSS, CFHQS, and SHELLQs

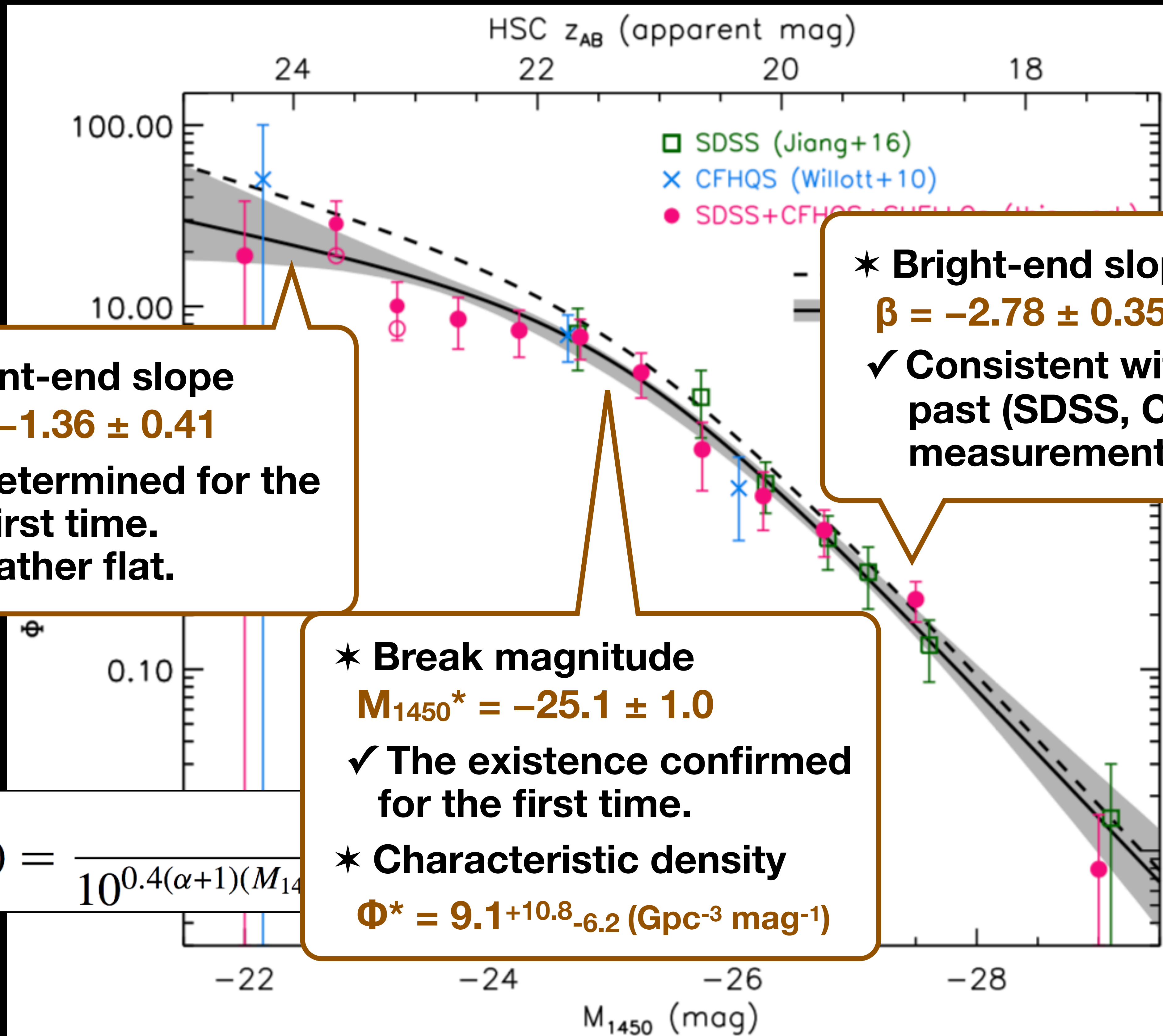


✶ SHELLQs survey completeness

… estimated by adding artificial sources to the HSC images, and recovering them.



Highlight (3/5): Luminosity function at z = 6



✶ **Faint-end slope**

α = −1.36 ± 0.41

✓ **Determined for the first time.**

✓ **Rather flat.**

✶ **Break magnitude**

M_{1450}^{*} = −25.1 ± 1.0

✓ **The existence confirmed for the first time.**

✶ **Characteristic density**

$\Phi^{*} = 9.1^{+10.8}_{-6.2}$ (Gpc^{-3} mag^{-1})

✶ **Bright-end slope**

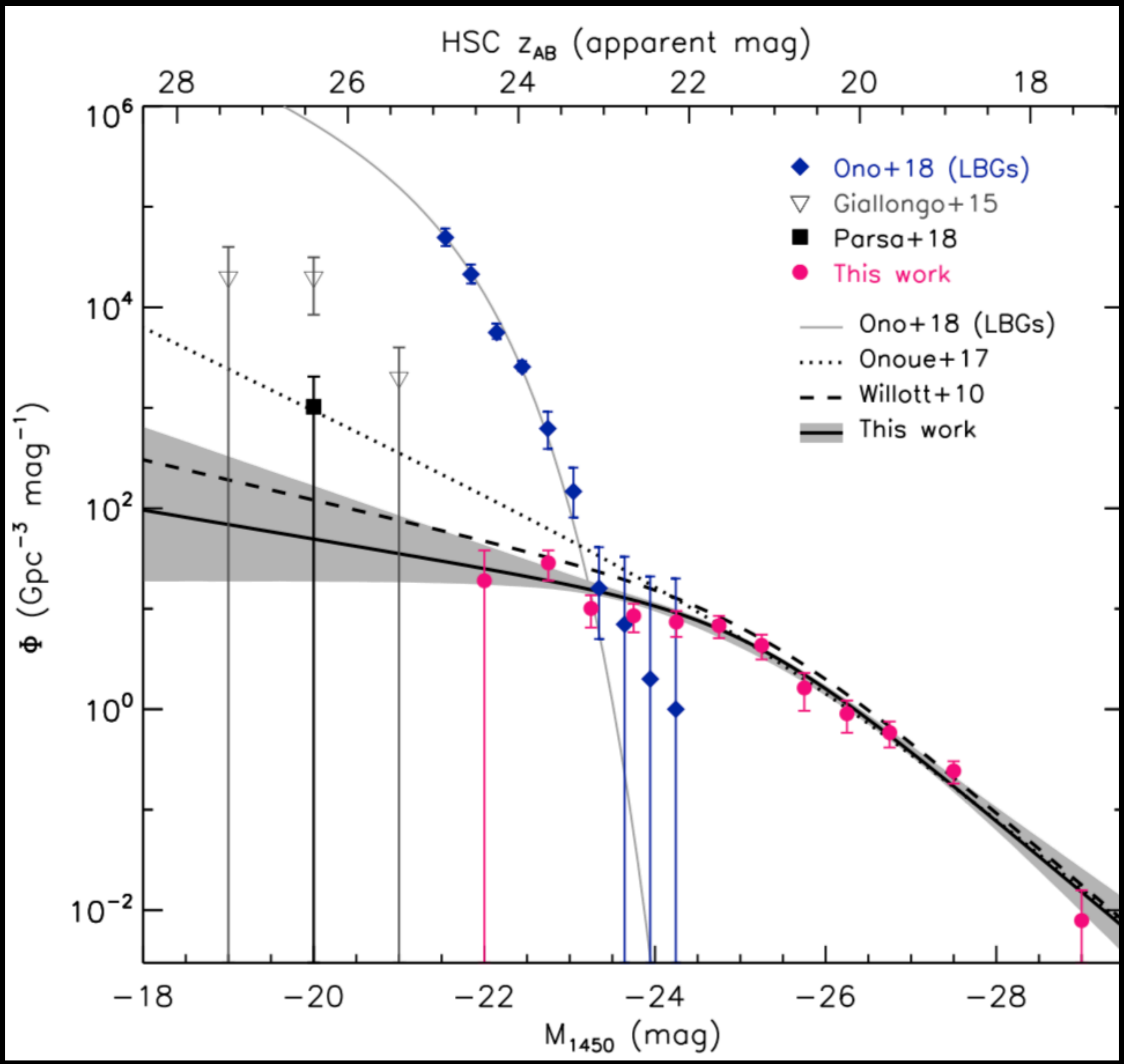
β = −2.78 ± 0.35

✓ **Consistent with the past (SDSS, CFHQS) measurements.**

$$\Phi(M_{1450}, z) = \frac{}{10^{0.4(\alpha+1)(M_{14}}}$$

Highlight (3/5): Luminosity function at z = 6

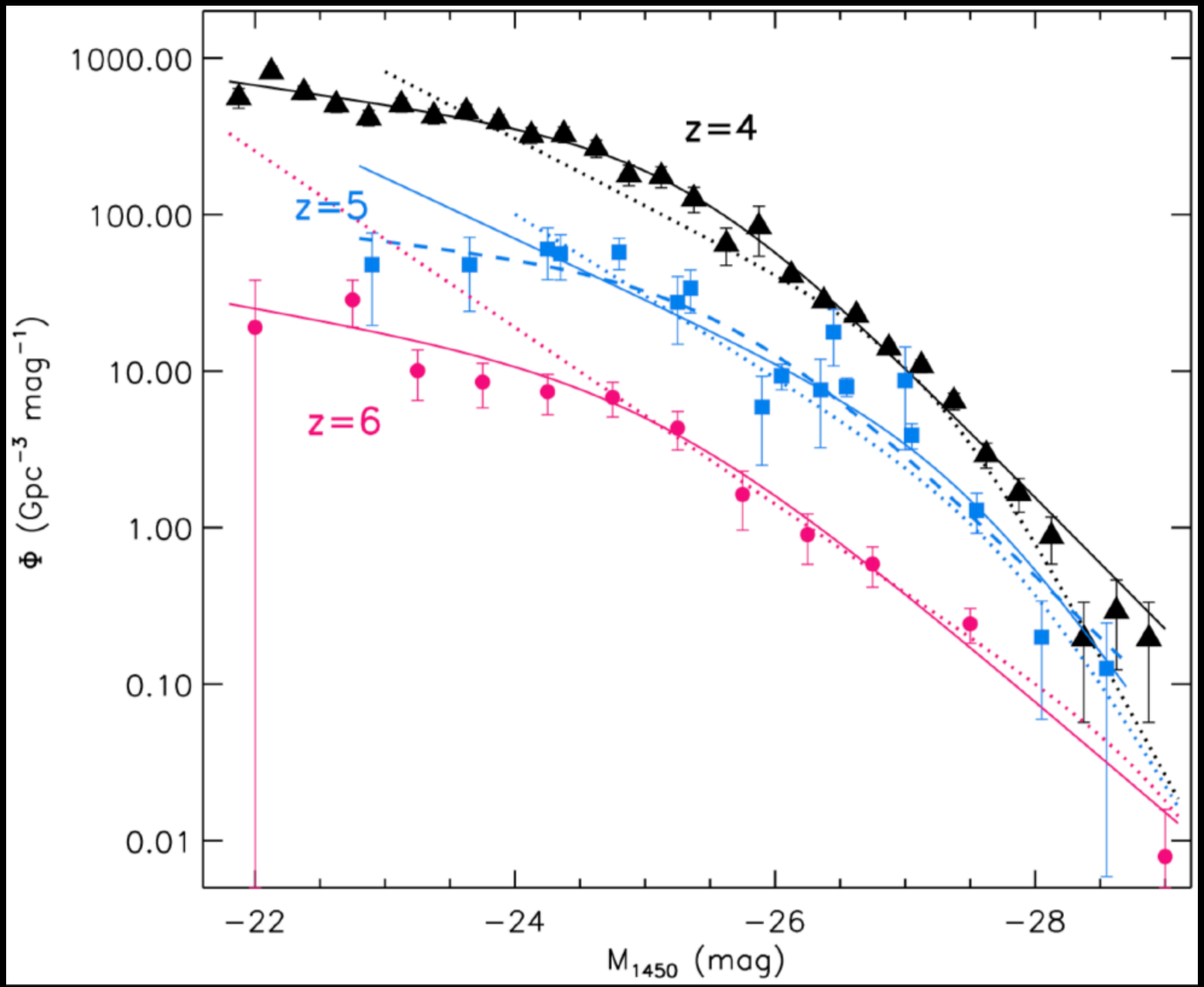
✶ Comparison with other measurements



→ Galaxies outnumber at $M_{1450} > -23$ mag

→ contradicts with the previous claim of "numerous faint AGNs dominating cosmic reionization"

✶ LF evolution over $4 \leq z \leq 6$

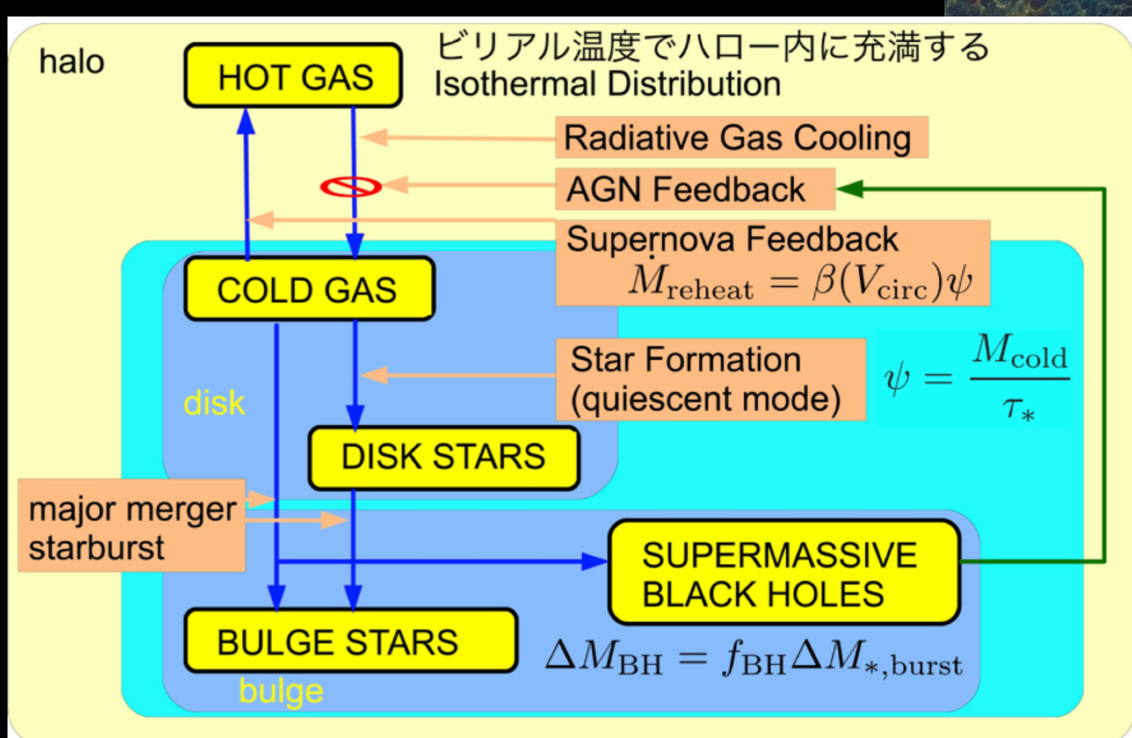


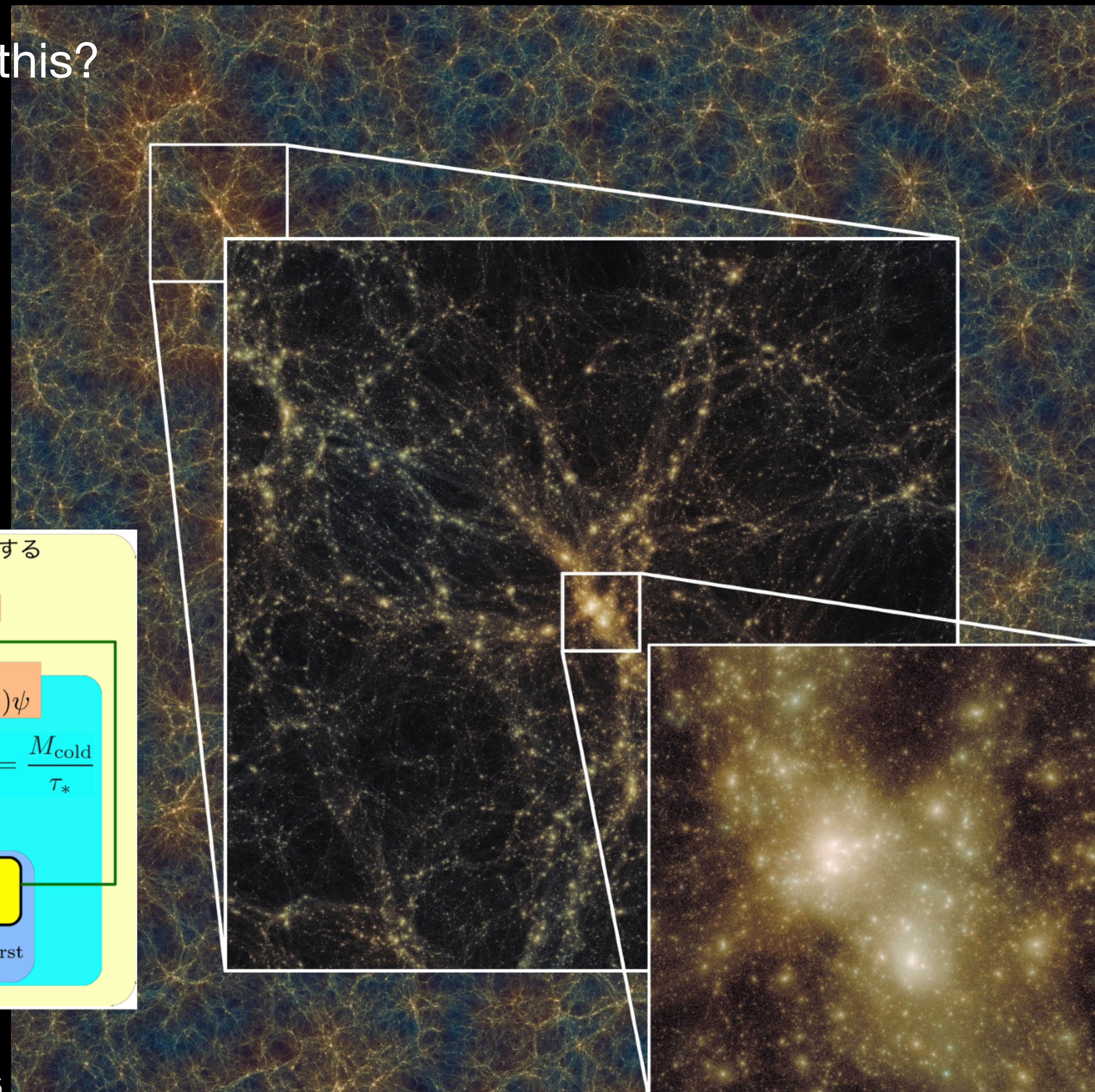
→ Similar overall shape

→ Strong decline in the number densities

Highlight (3/5): Luminosity function at z = 6

- ✶ So, how do we interpret this?
  - → Theoretical models…



Ishiyama+15

Highlight (4/5): Contribution to reionization

★ *Evolution of the HII volume-filling factor*

$$\frac{dQ_{\rm HII}(t)}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm HII}(t)}{t_{\rm rec}}$$

→ In order to keep the IGM fully ionized:

$$Q_{\rm HII}(t) = 1, \ \frac{dQ_{\rm HII}(t)}{dt} \geq 0 \ \rightarrow \dot{n}_{\rm ion} \geq \frac{\langle n_{\rm H} \rangle}{t_{\rm rec}} = 10^{50.0} C_{\rm HII} \left(\frac{1+z}{7} \right)^3 ({\rm s}^{-1}{\rm Mpc}^{-3})$$

(Madau+99, Bolton & Haehnelt07)

★ *Total quasar emissivity of ionizing photons*

$$\dot{n}_{\rm ion} \ [{\rm s}^{-1} \ {\rm Mpc}^{-3}] = f_{\rm esc} \ \epsilon_{1450} \ \xi_{\rm ion}$$

luminosity function

EUV SED (Lusso+15)

where

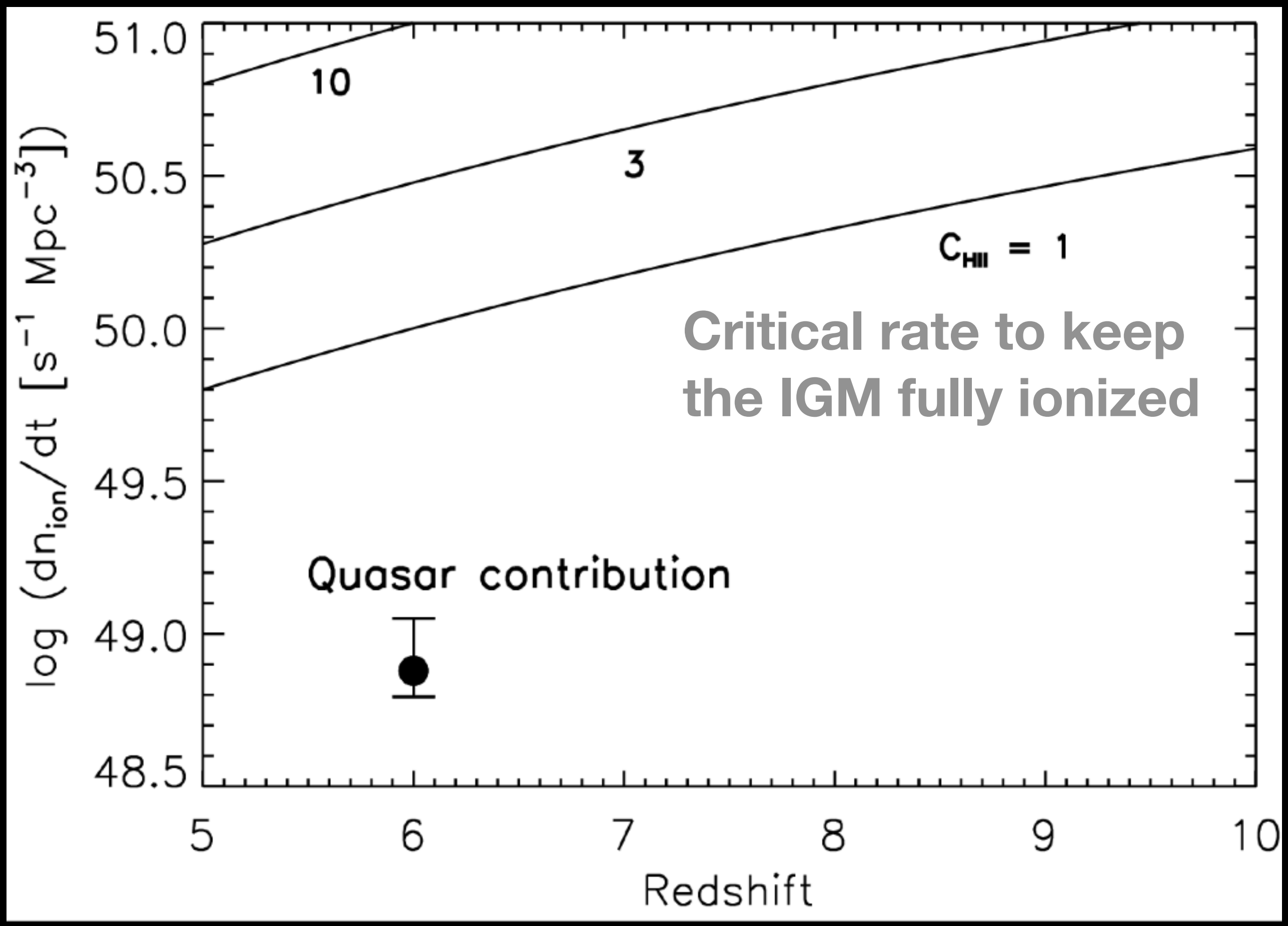
- total emissivity at 1450 A

$$\epsilon_{1450} \ [{\rm erg \ s^{-1} \ Hz^{-1} \ Mpc^{-3}}] = \int \Phi(M_{1450}, z) \ L_{\nu 1450} \ dM_{1450}$$

- Number of ionizing photons per L_{1450}

$$\xi_{\rm ion} \ [{\rm s}^{-1} \ ({\rm erg \ s^{-1} \ Hz^{-1}})^{-1}] = (L_{\nu 1450})^{-1} \int_{\nu {\rm LL}}^{4 \nu {\rm LL}} \frac{L_\nu}{h\nu} d\nu$$

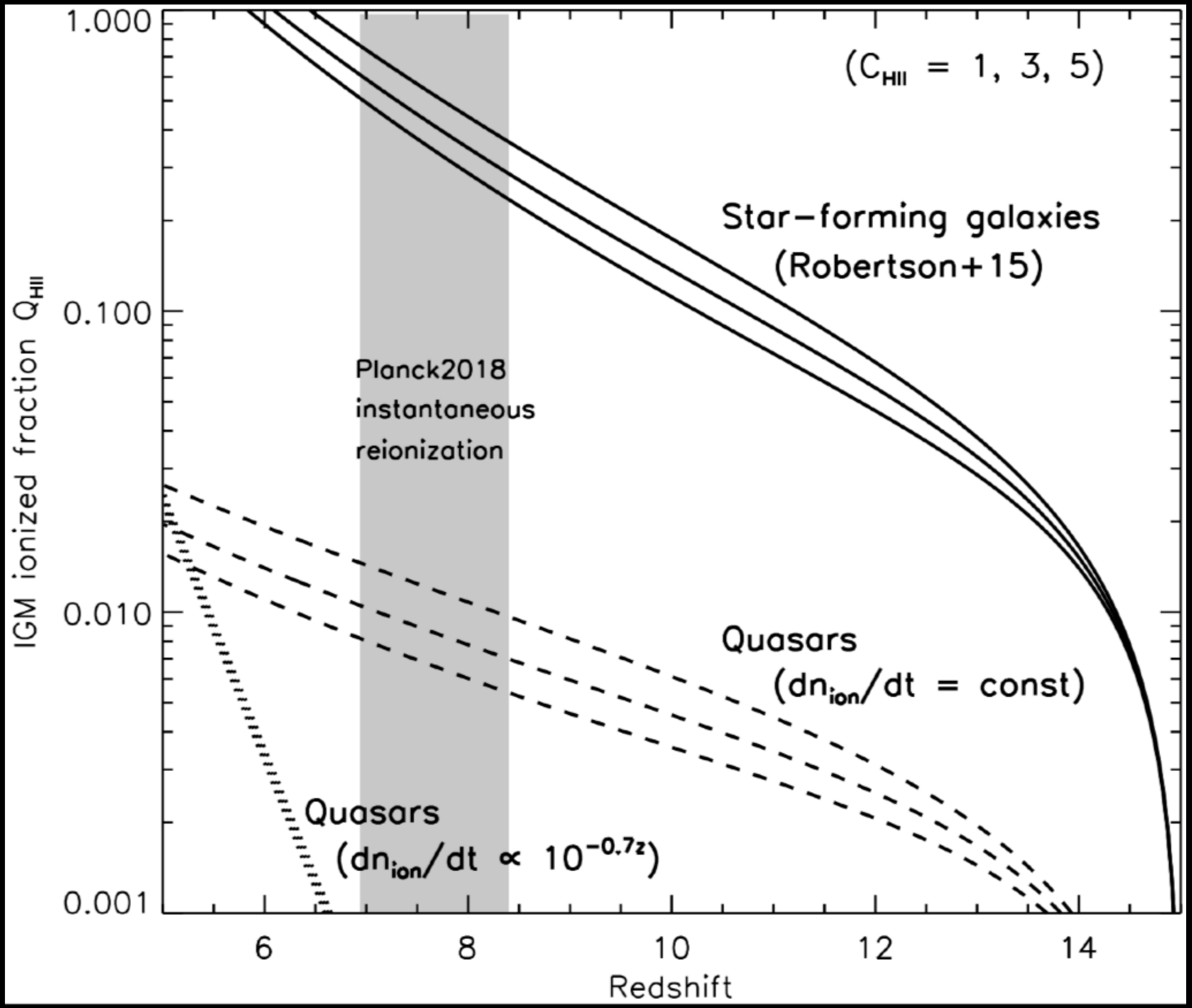
Highlight (4/5): Contribution to reionization



→ Integrating the luminosity function over -18 < M_{1450} < -30 mag gives the ionizing photon density:

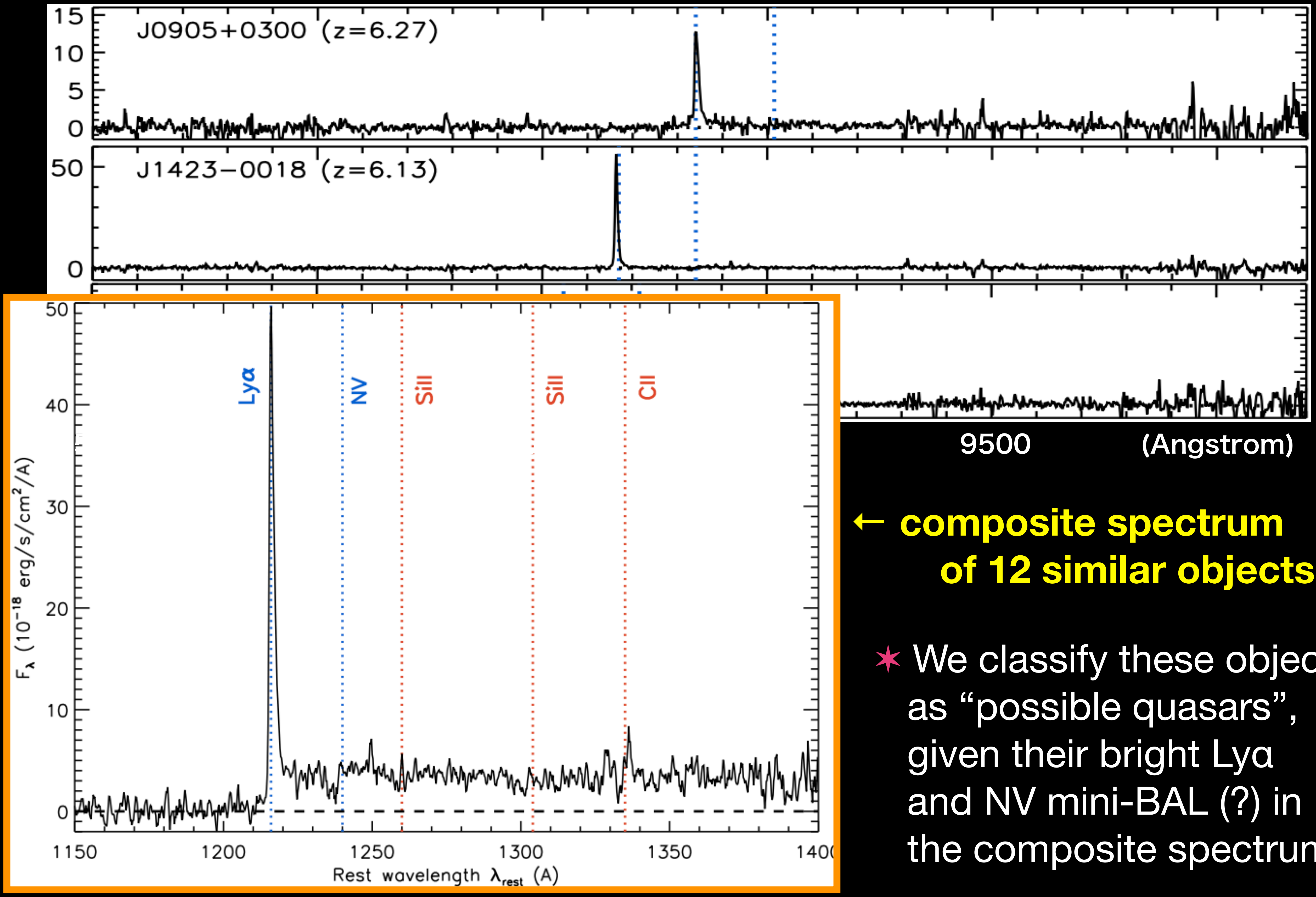
$\dot{n}_{ion} = 10^{48.9 \pm 0.2}$ (s^{-1} Mpc^{-3})

→ <10 % of the density necessary to keep the IGM fully ionized



→ Quasars alone cannot reionize the Universe. They contribute <10 % of the photons necessary to keep the IGM fully ionized.

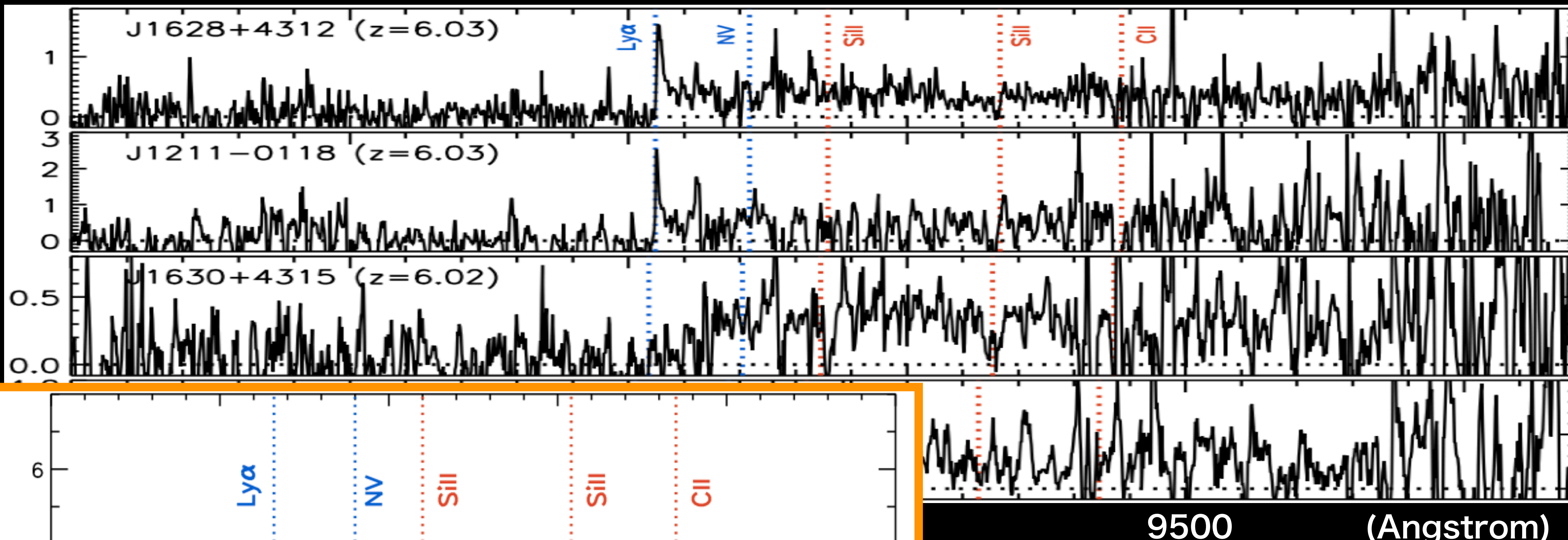
Highlight (5/5): different classes of objects

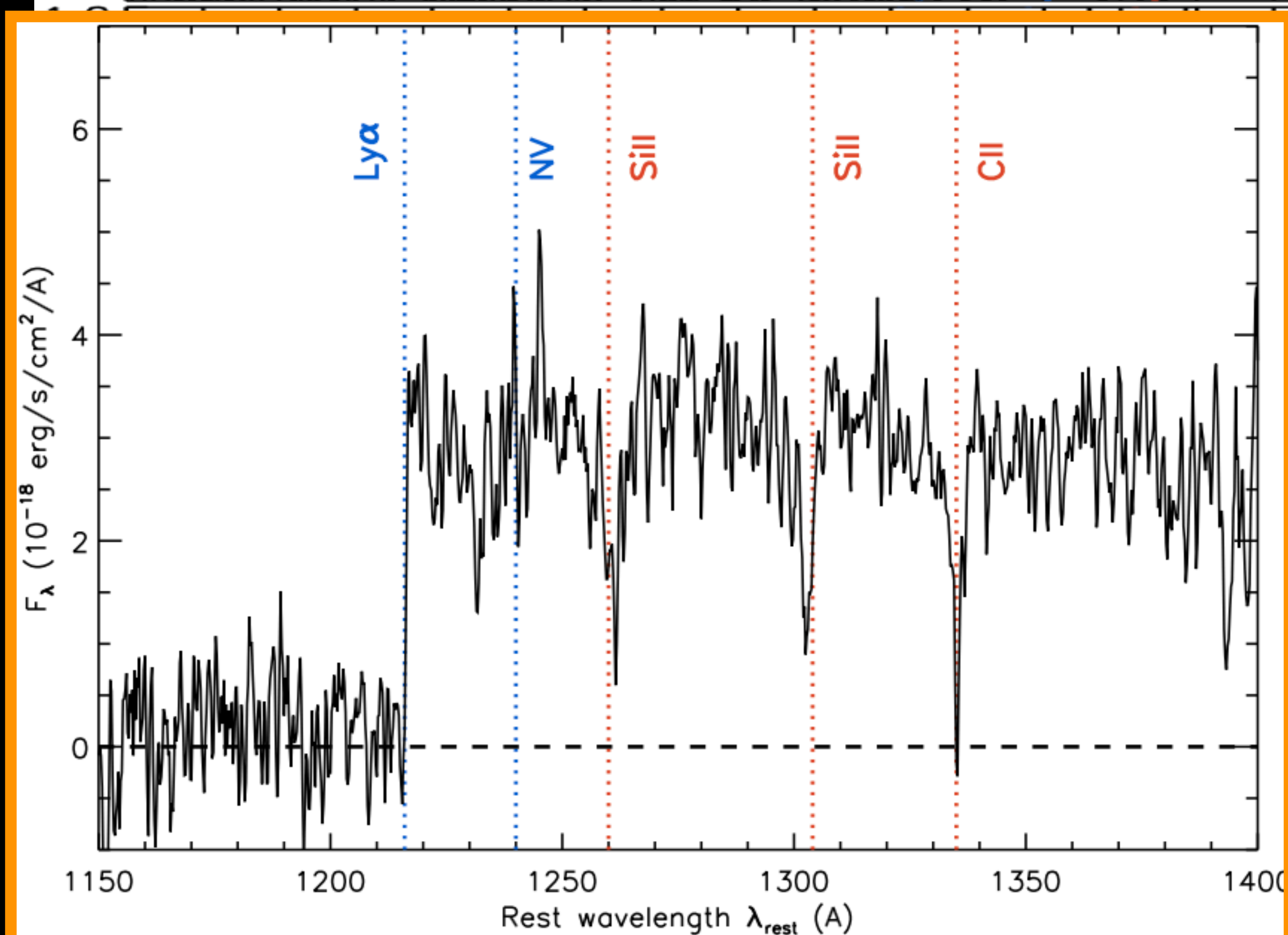


← **composite spectrum of 12 similar objects**

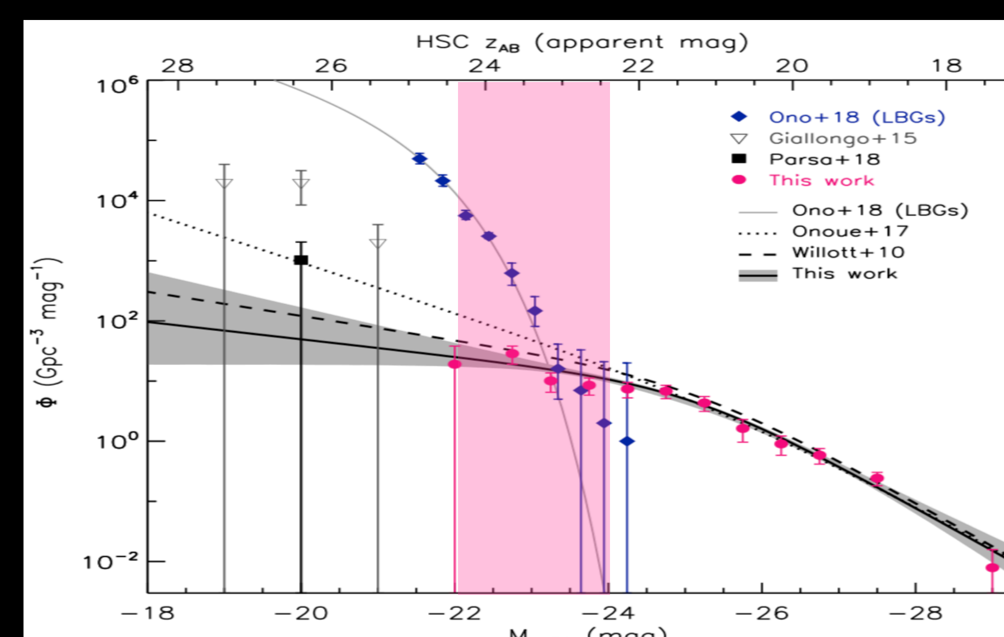
- We classify these objects as "possible quasars", given their bright Lyα and NV mini-BAL (?) in the composite spectrum.

Highlight (5/5): different classes of objects

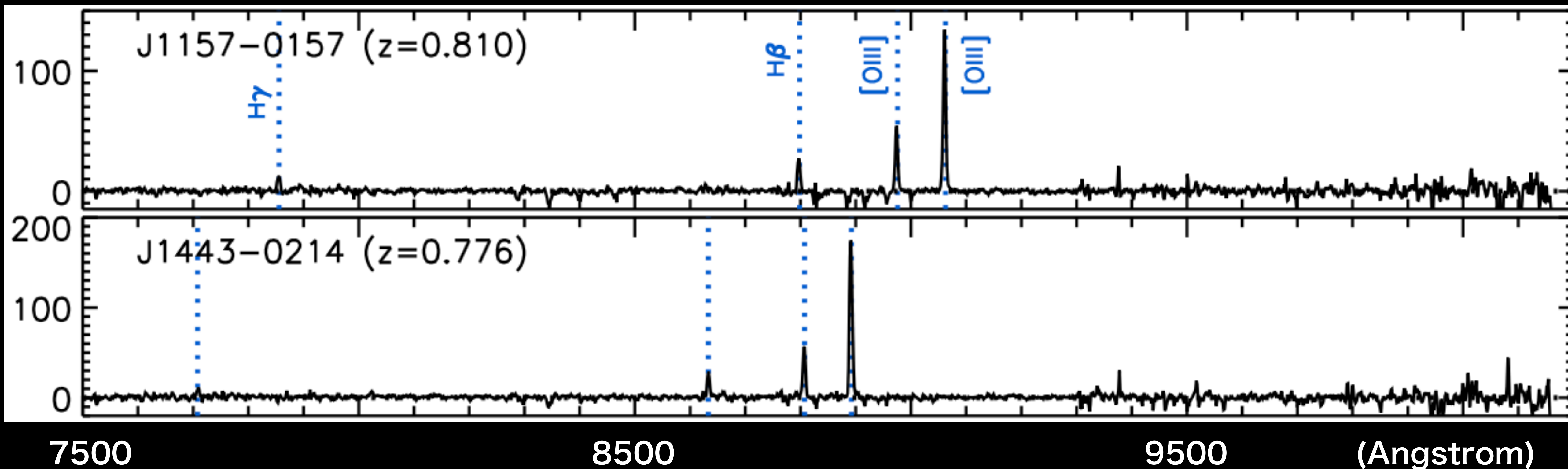


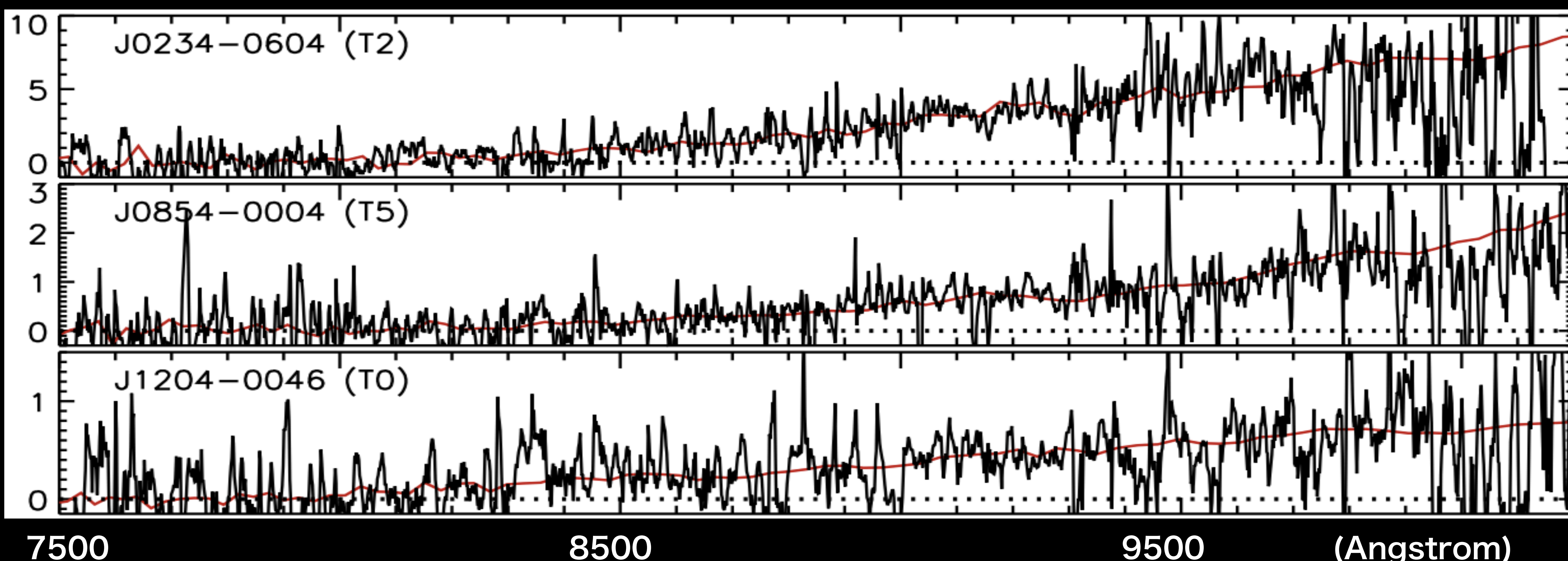


← **composite spectrum of 14 high-z galaxies**



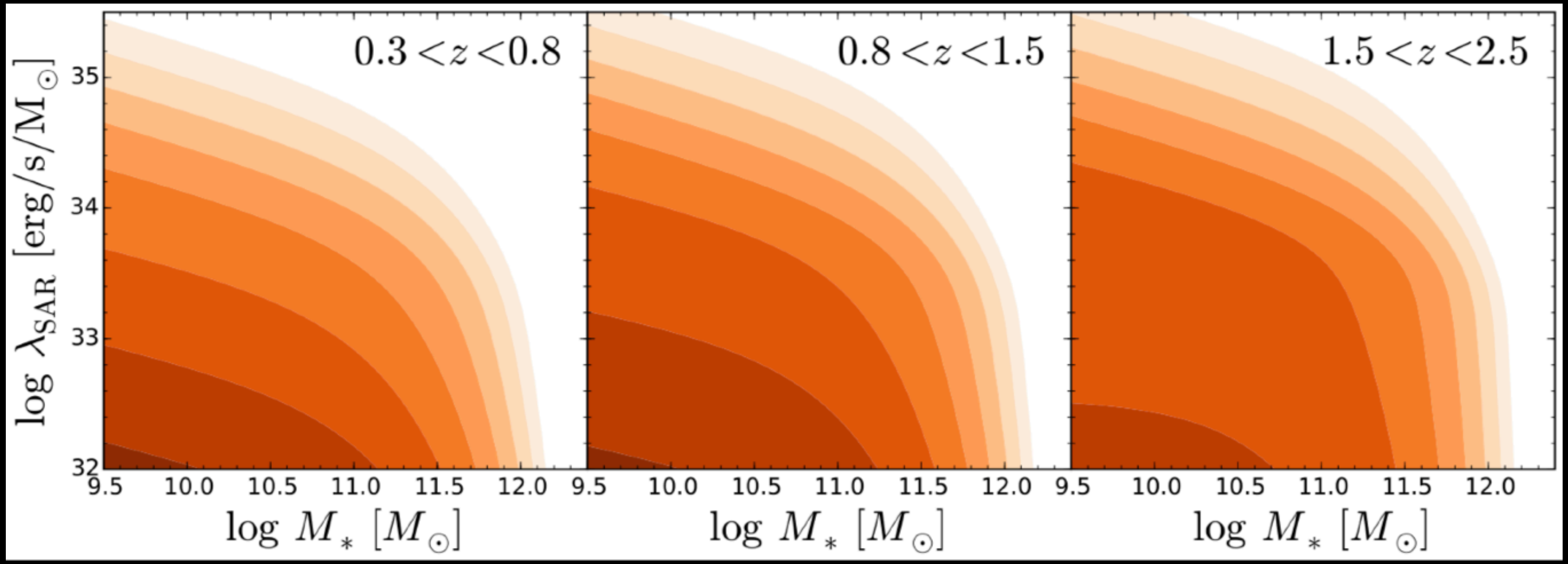
Highlight (5/5): different classes of objects





Multi-wavelength follow-up (1/2): near-IR

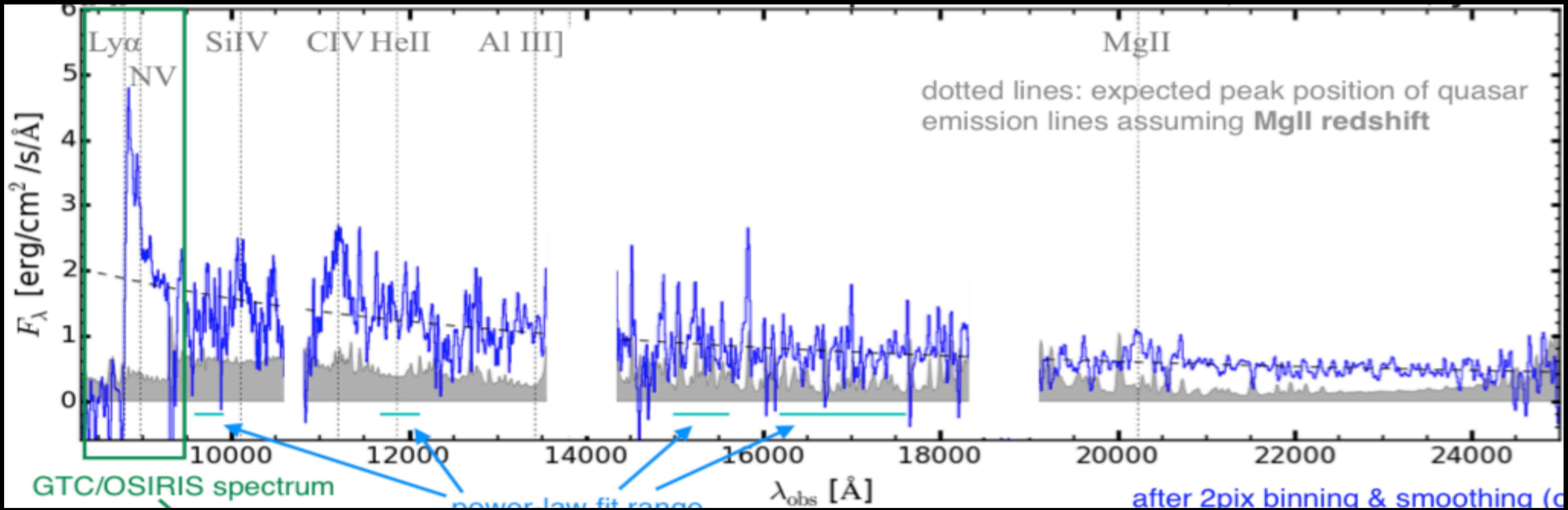
✶ *Luminosity function = BH mass function x Eddington ratio function*



Bongiorno+16

→ **BH mass measurements with Mg II λ2800 line in near-IR** (Onoue+, in prep)

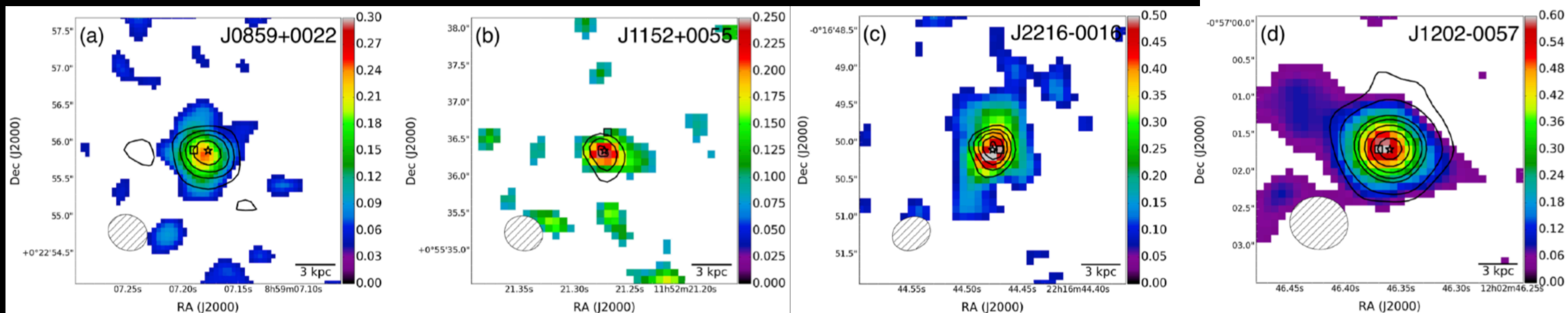
… 9 objects observed so far with Subaru/MOIRCS, VLT/X-Shooter, Gemini/GNIRS

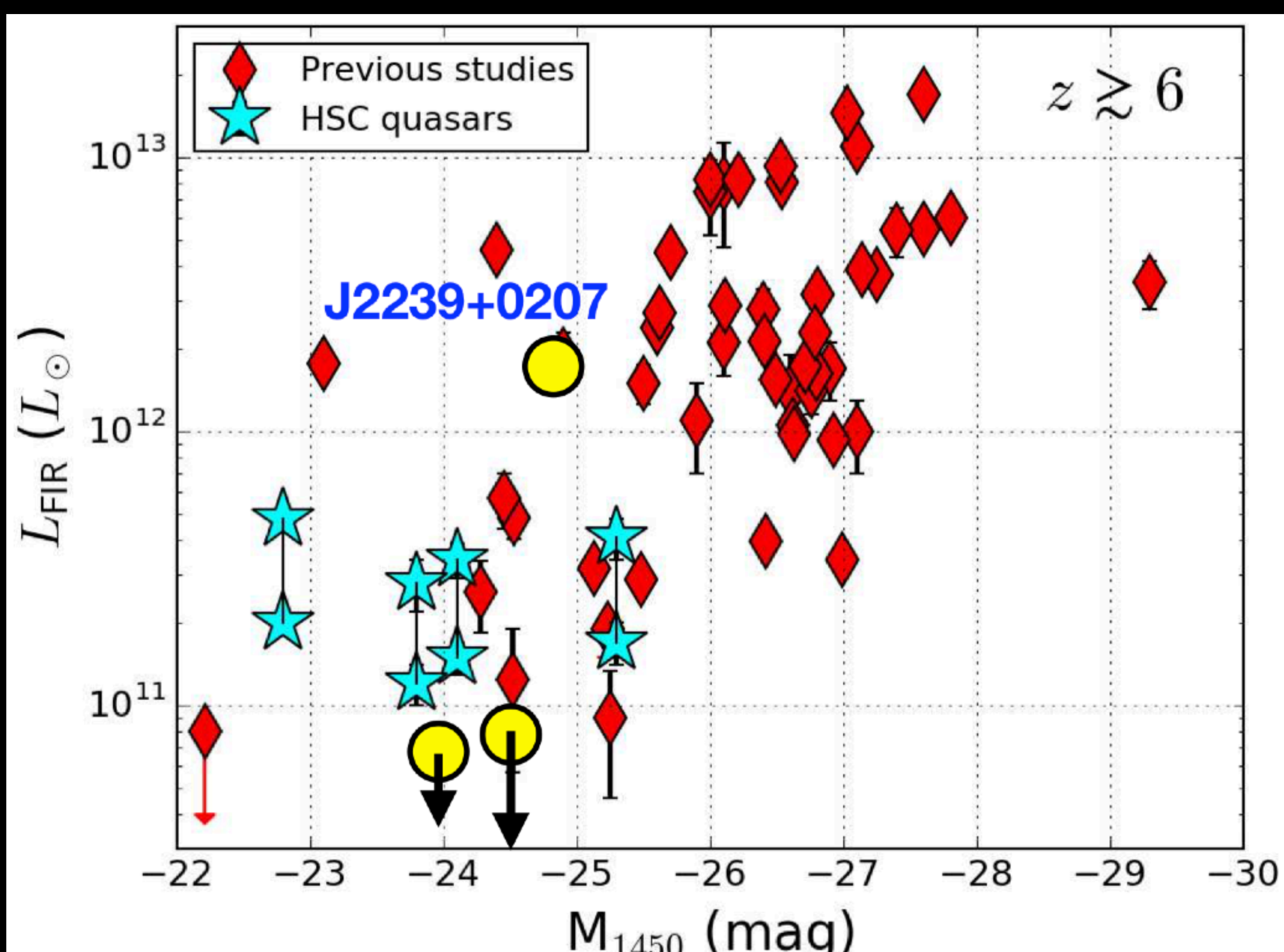


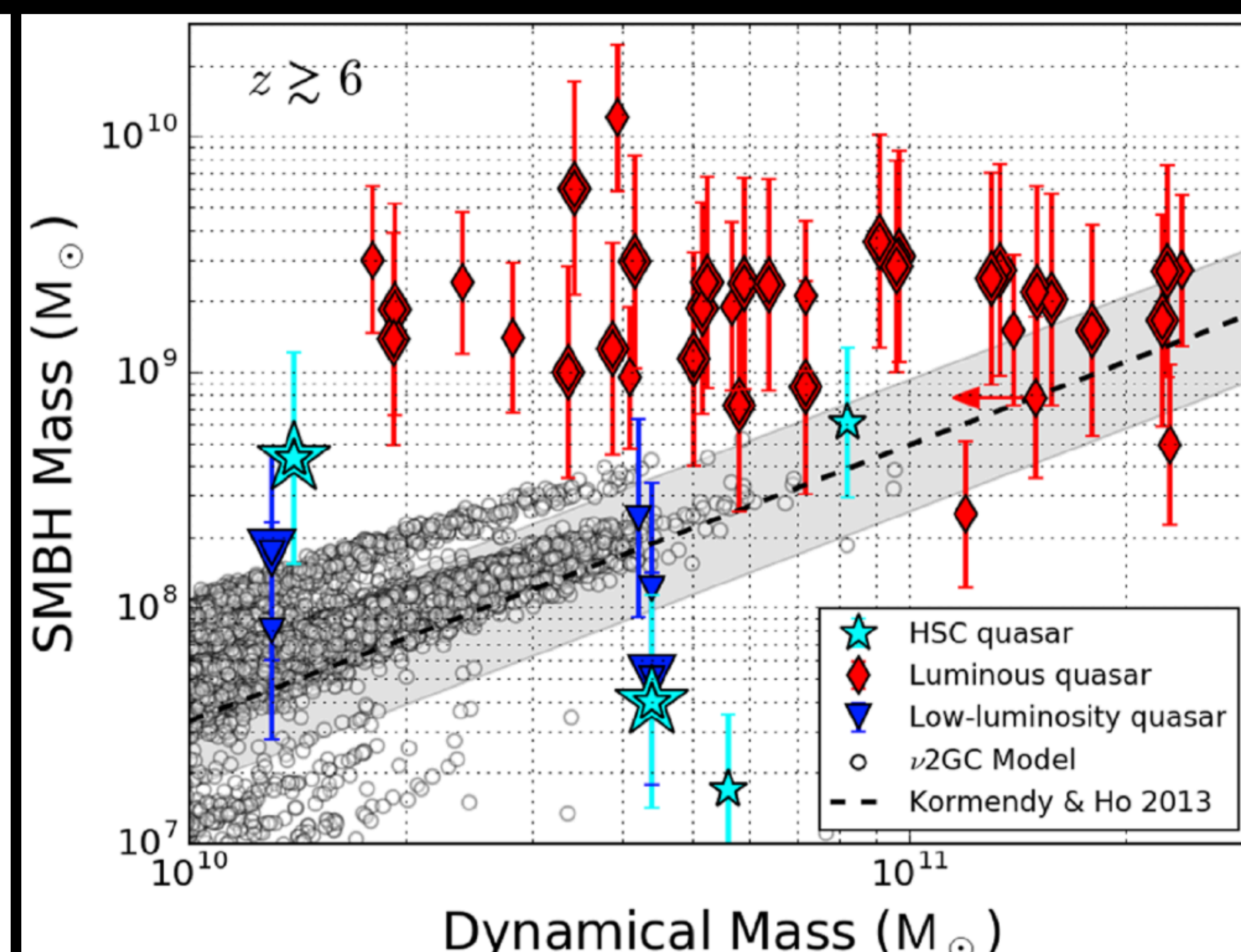
Multi-wavelength follow-up (2/2): ALMA

- 7 quasars observed in Cycles 4 & 5 (Band 6)

Color = [CII] integrated intensity
Contour = FIR continuum

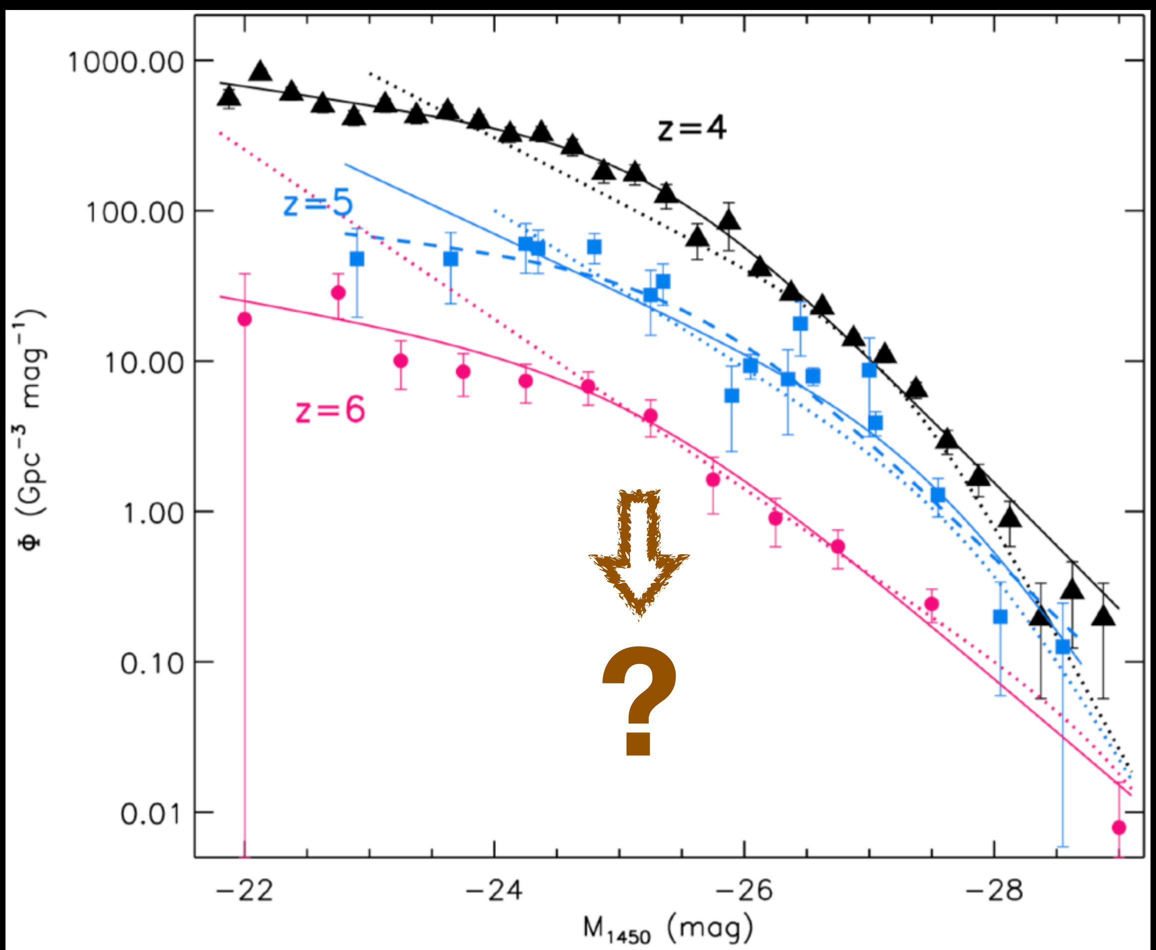


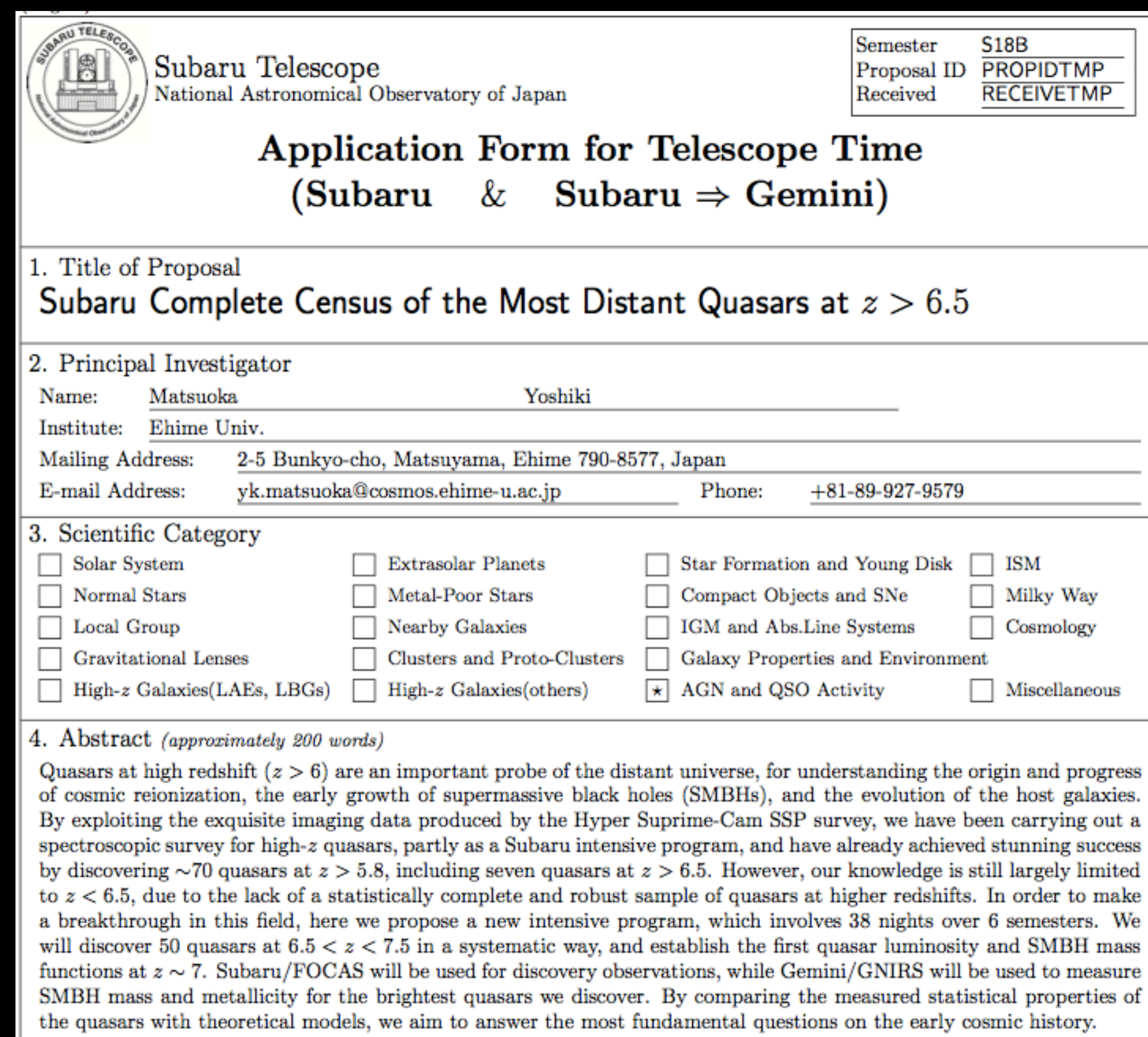




Izumi+18; Izumi+ in prep

To the farthest reaches of the Universe (future prospects)





Subaru Telescope
National Astronomical Observatory of Japan

Semester	S18B
Proposal ID	PROPIDTMP
Received	RECEIVETMP

Application Form for Telescope Time
(Subaru & Subaru ⇒ Gemini)

1. Title of Proposal

Subaru Complete Census of the Most Distant Quasars at $z > 6.5$

2. Principal Investigator

Name: Matsuoka Yoshiki
Institute: Ehime Univ.
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3. Scientific Category

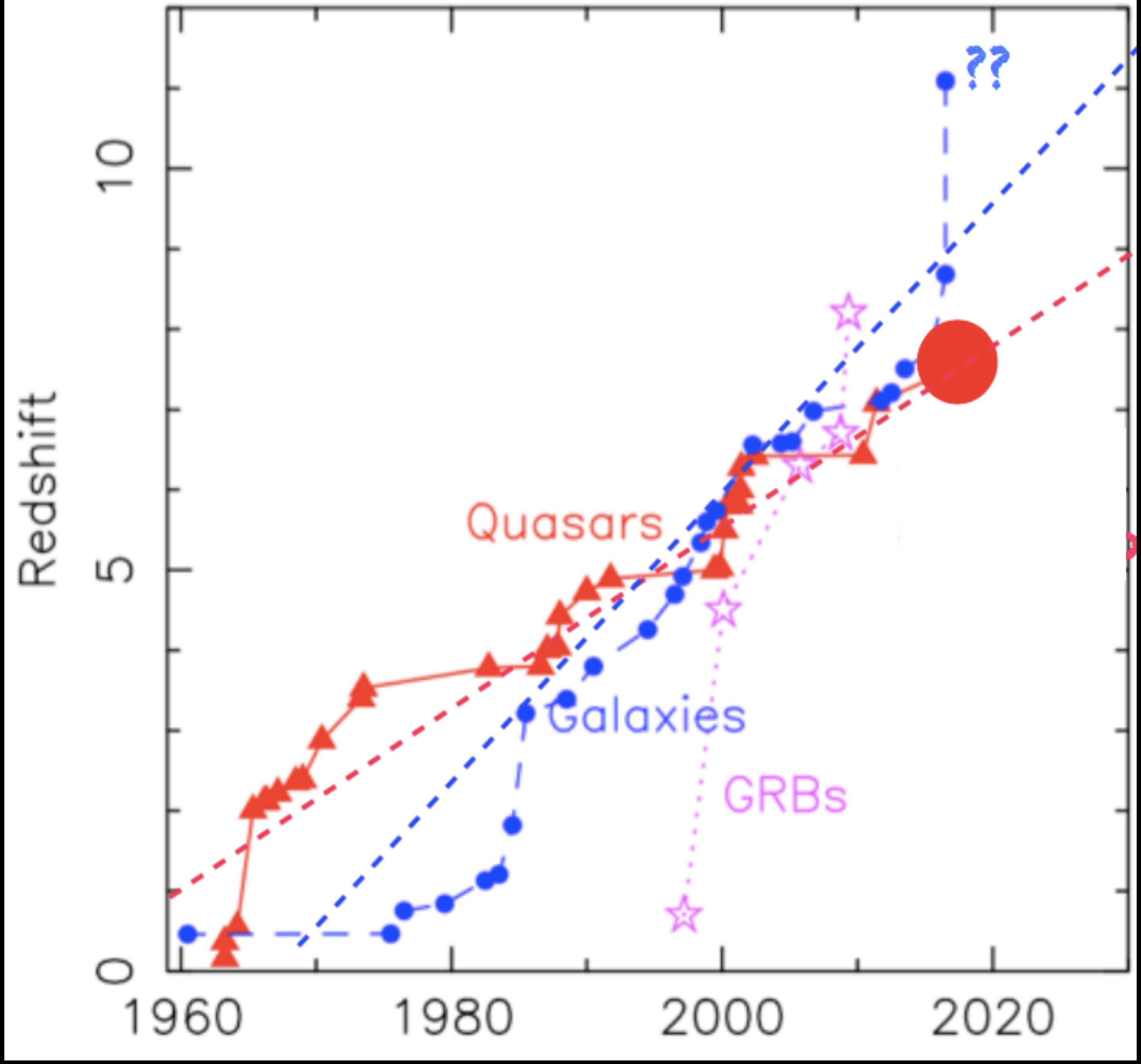
- ☐ Solar System
- ☐ Normal Stars
- ☐ Local Group
- ☐ Gravitational Lenses
- ☐ High-z Galaxies(LAEs, LBGs)
- ☐ Extrasolar Planets
- ☐ Metal-Poor Stars
- ☐ Nearby Galaxies
- ☐ Clusters and Proto-Clusters
- ☐ High-z Galaxies(others)
- ☐ Star Formation and Young Disk
- ☐ Compact Objects and SNe
- ☐ IGM and Abs.Line Systems
- ☐ Galaxy Properties and Environment
- ☒ AGN and QSO Activity
- ☐ ISM
- ☐ Milky Way
- ☐ Cosmology
- ☐ Miscellaneous

4. Abstract *(approximately 200 words)*

Quasars at high redshift ($z > 6$) are an important probe of the distant universe, for understanding the origin and progress of cosmic reionization, the early growth of supermassive black holes (SMBHs), and the evolution of the host galaxies. By exploiting the exquisite imaging data produced by the Hyper Suprime-Cam SSP survey, we have been carrying out a spectroscopic survey for high-z quasars, partly as a Subaru intensive program, and have already achieved stunning success by discovering ~70 quasars at $z > 5.8$, including seven quasars at $z > 6.5$. However, our knowledge is still largely limited to $z < 6.5$, due to the lack of a statistically complete and robust sample of quasars at higher redshifts. In order to make a breakthrough in this field, here we propose a new intensive program, which involves 38 nights over 6 semesters. We will discover 50 quasars at $6.5 < z < 7.5$ in a systematic way, and establish the first quasar luminosity and SMBH mass functions at $z \sim 7$. Subaru/FOCAS will be used for discovery observations, while Gemini/GNIRS will be used to measure SMBH mass and metallicity for the brightest quasars we discover. By comparing the measured statistical properties of the quasars with theoretical models, we aim to answer the most fundamental questions on the early cosmic history.

30 nights with Subaru/FOCAS through 2021A

To the farthest reaches of the Universe (future prospects)



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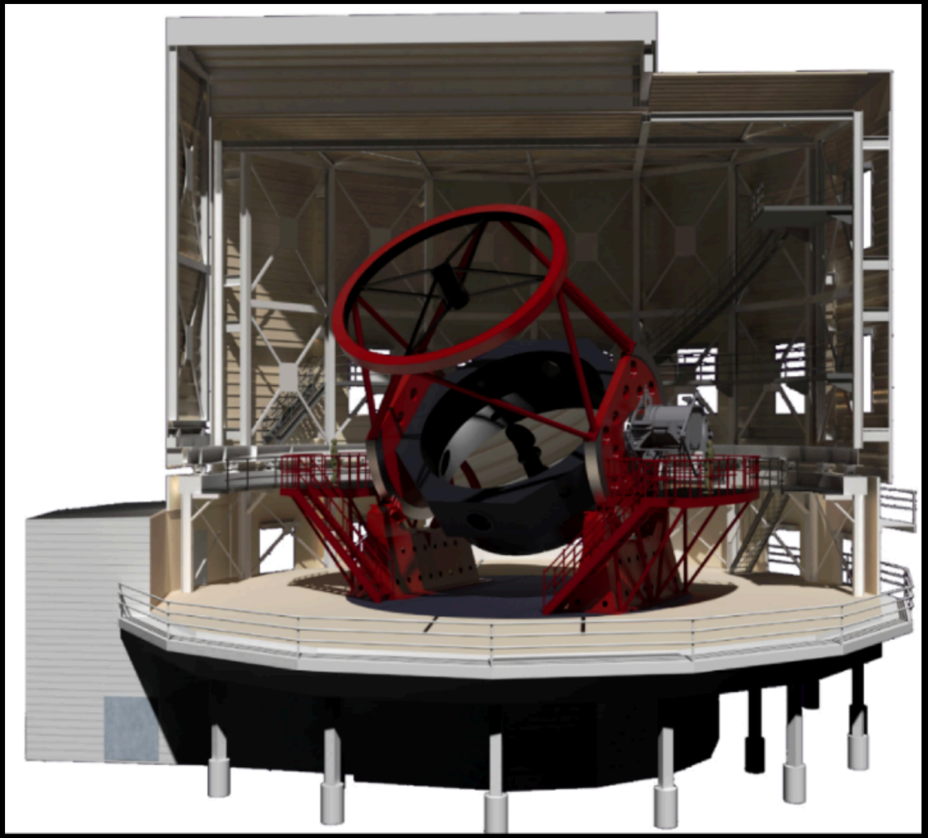
★ TAO



★ WFIRST

Thank you for your attention.