Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs)

Yoshiki Matsuoka (NAOJ → Ehime Univ.)

on behalf of
the SHELLQs collaboration

SHELLQs

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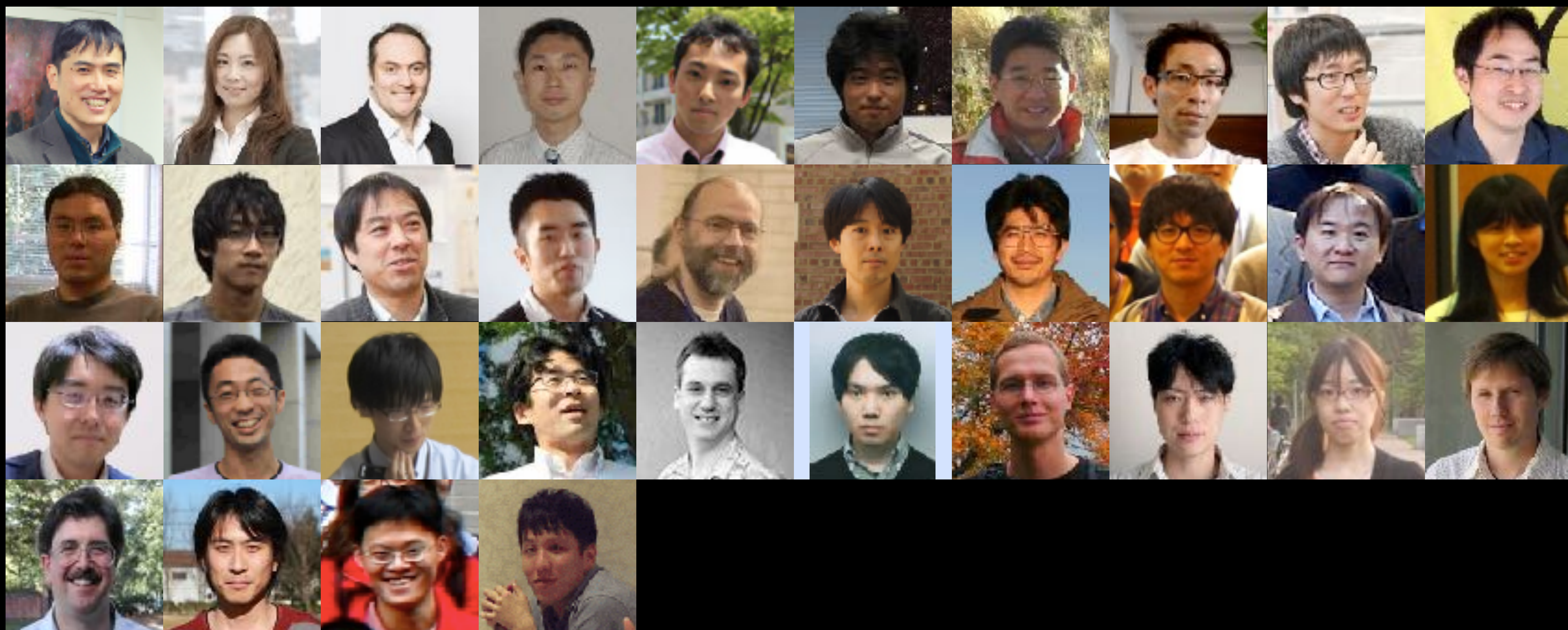

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High-z quasars - Unique probe of the early Universe

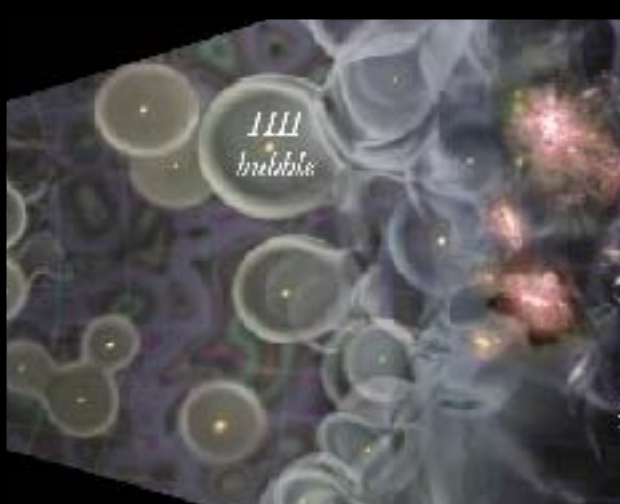
Fundamental questions we aim to answer:

Why do supermassive black holes (SMBHs) exist?

- ✶ When were they born?
- ✶ What were their seeds?
- ✶ How did they grow in the early and late epochs of the cosmic history?

How did the host galaxies form and (co-)evolve?

- ✶ When and how did the first stellar-mass assembly happen?
- ✶ Did SMBHs impact the host galaxy evolution? If so, how?
- ✶ Do they mark the highest density peaks of the DM distribution?



When and how was the Universe re-ionized?

- ✶ When did re-ionization start and complete?
- ✶ How did it proceed, as a function of space and time?
- ✶ What provided the ionizing photons?

and many more!

Past and ongoing surveys

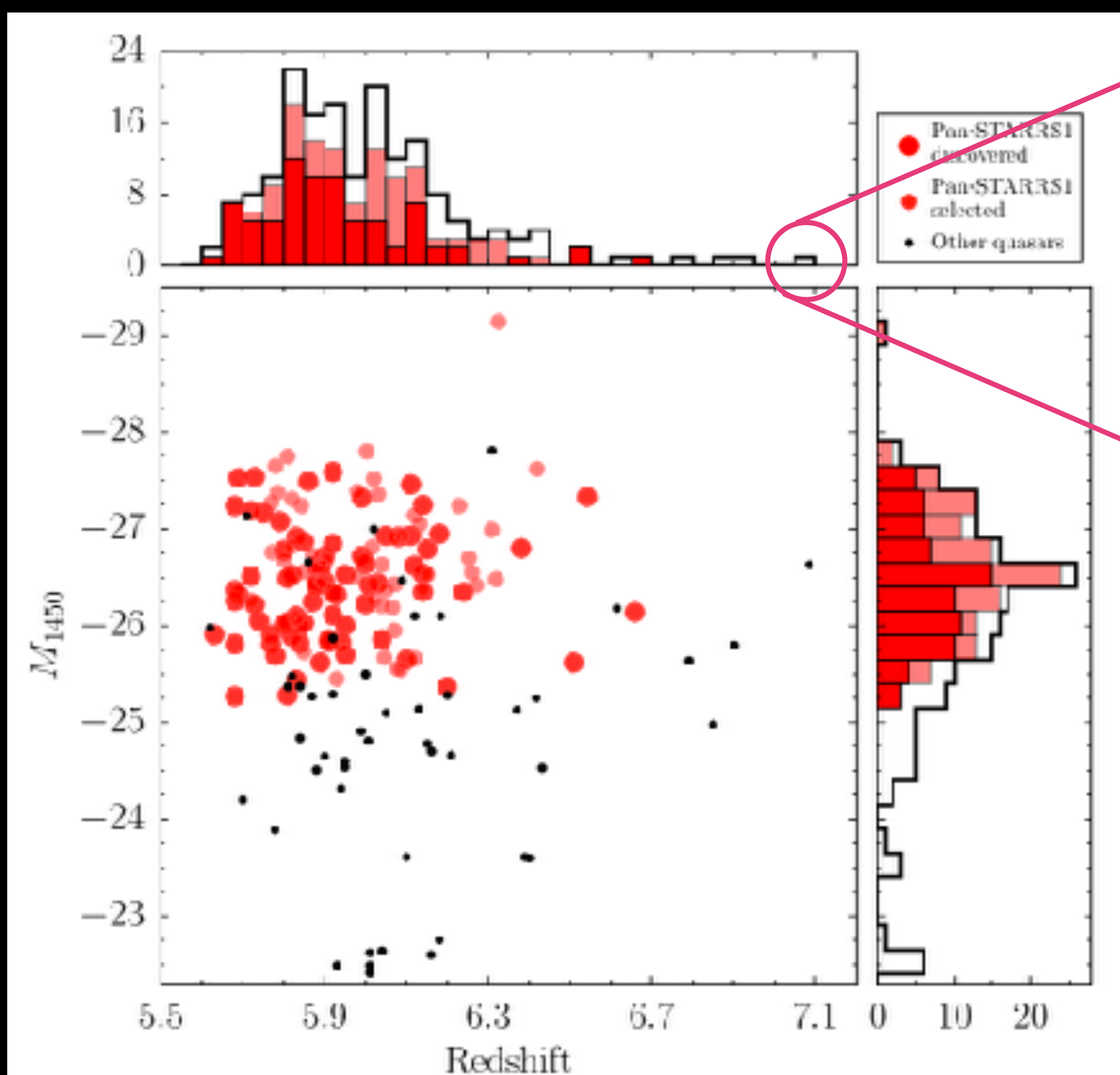
SDSS 2.5m

CFHT 3.6m

UKIDSS/VIKING 4m

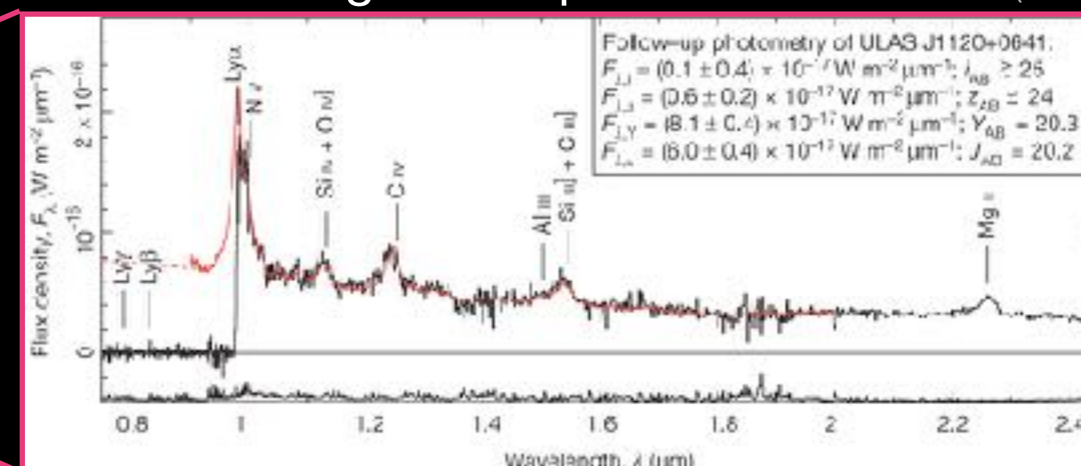
Pan-STARRS1 1.8m

DES 4m

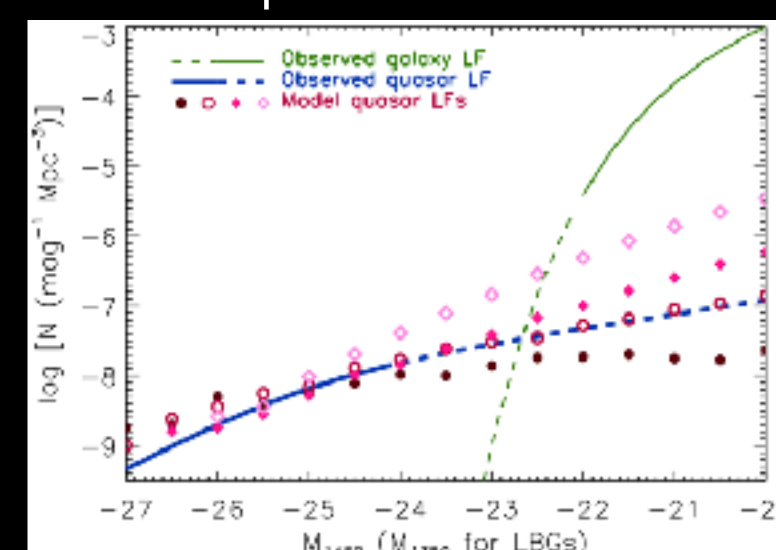


Banados+16

✶ The known highest-z quasar at z = 7.085 (Mortlock+11)



✶ LF model predictions...



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. (2016, in prep.)

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**

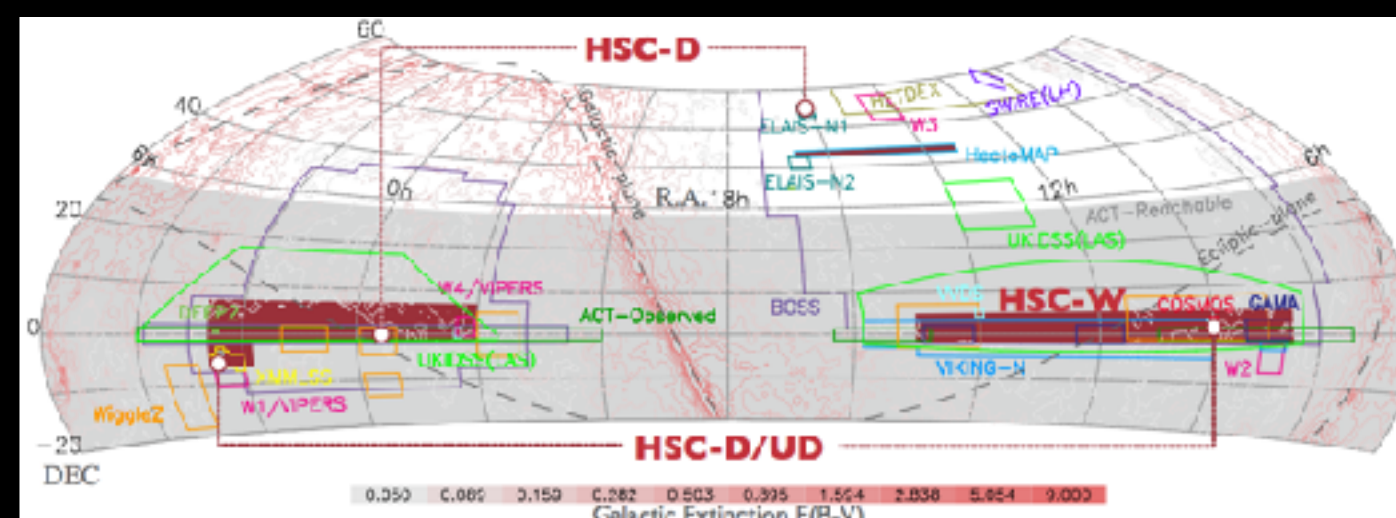
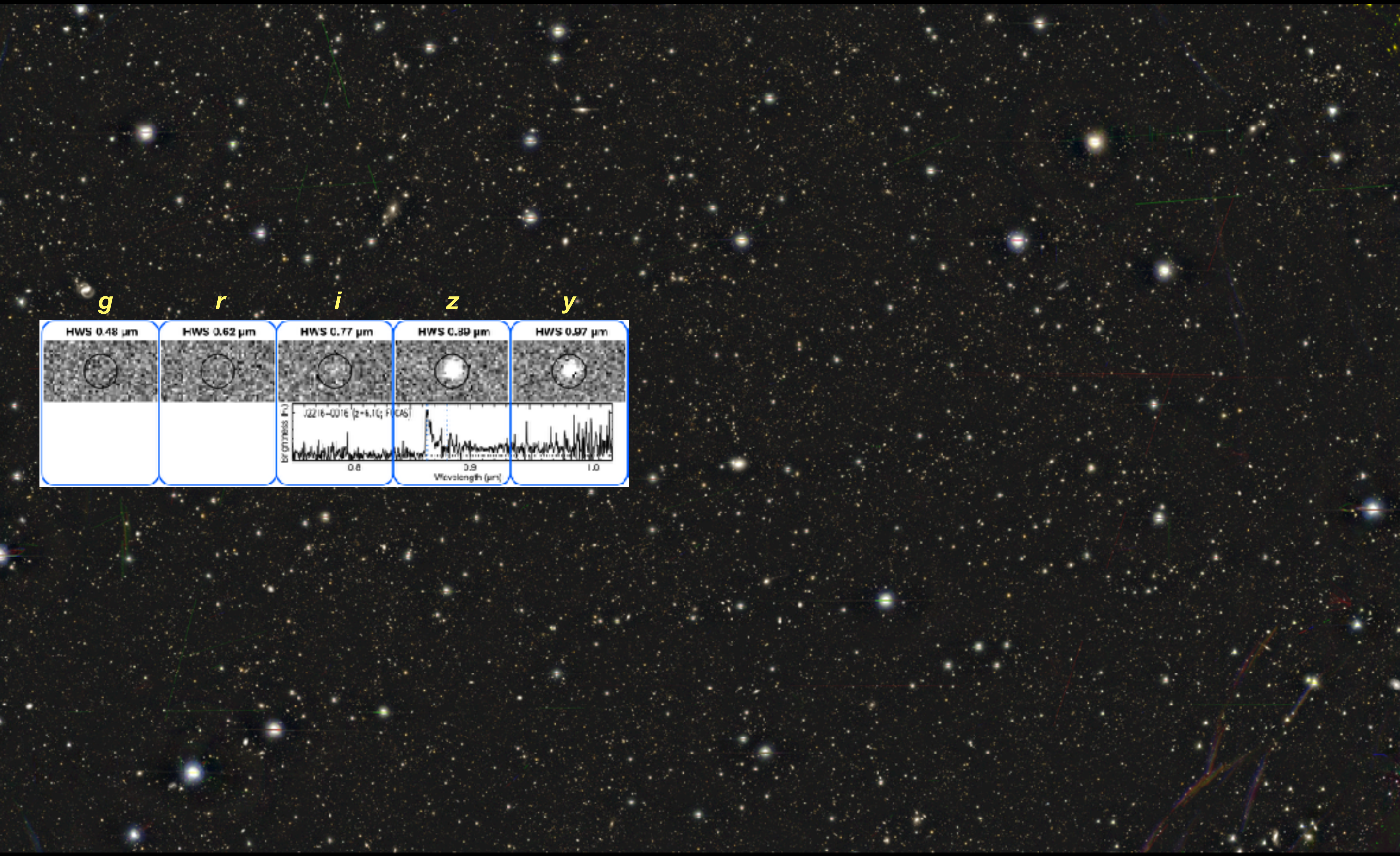


Table 7: Quasar Samples

	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

“Needles in a haystack”



Bayesian probabilistic selection

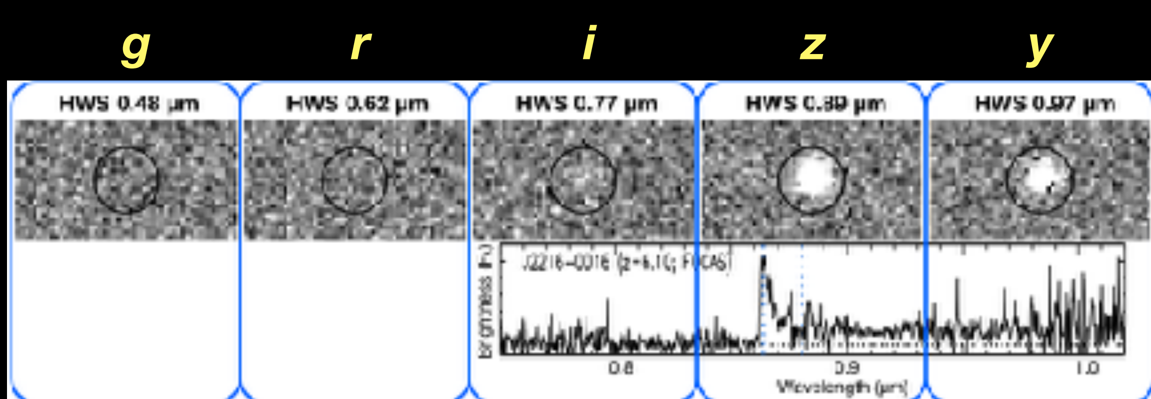
Quasar probability: $P_Q = W_Q/(W_Q+W_D)$

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

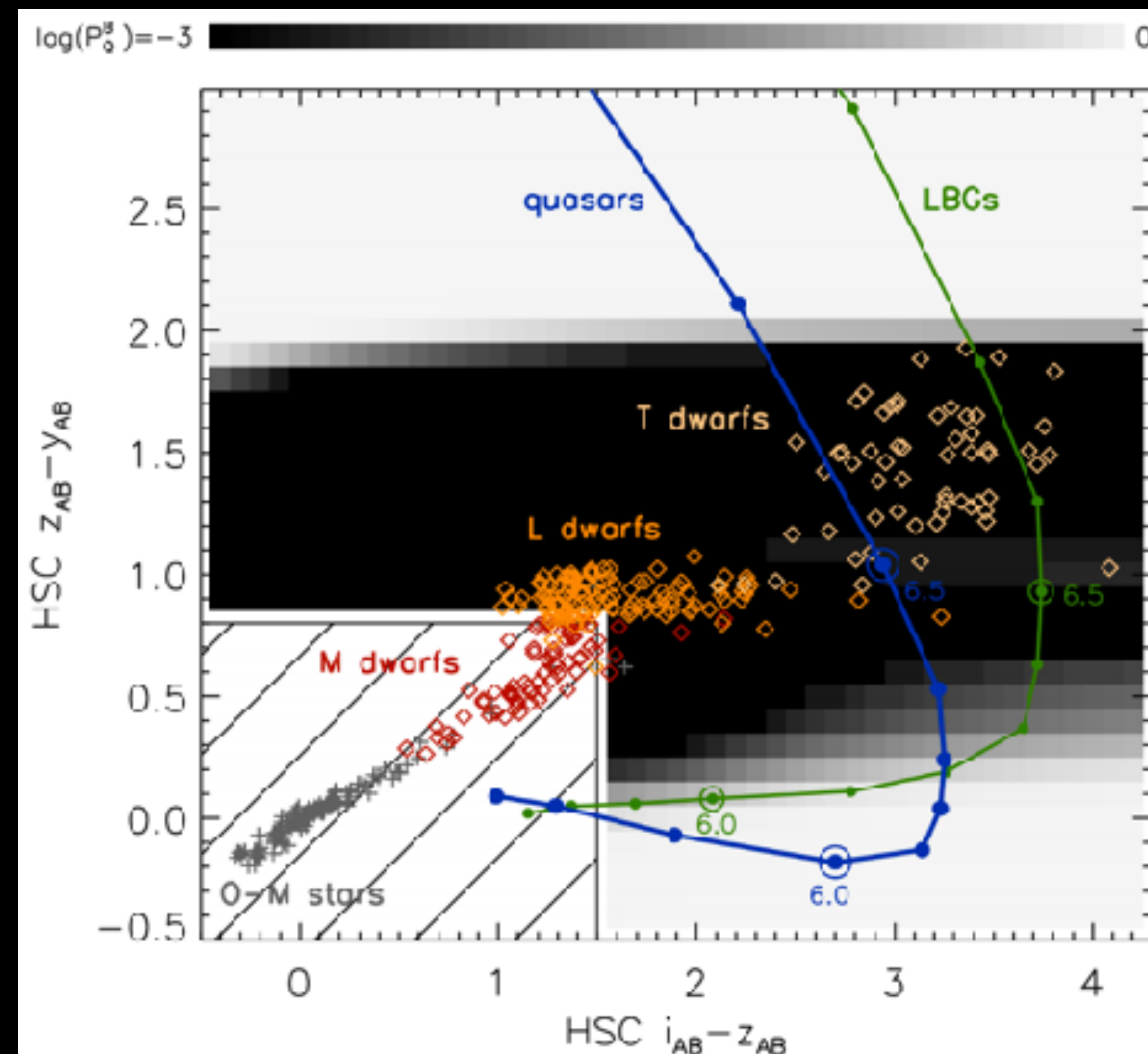
W_D (**m**, det) = $\int\int \rho_D(m_{int}, t_{sp})$ Pr (det | m_{int}, t_{sp}) Pr (**m** | m_{int}, t_{sp}) $dm_{int}\, dt_{sp}$

observed magnitudes in HSC + NIR bands

source detection



P_Q distribution in a color subspace (*i-z* vs. *z-y*)



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

- Subaru/FOCAS, GTC/OSIRIS, Gemini/GMOS-S

Progress to date

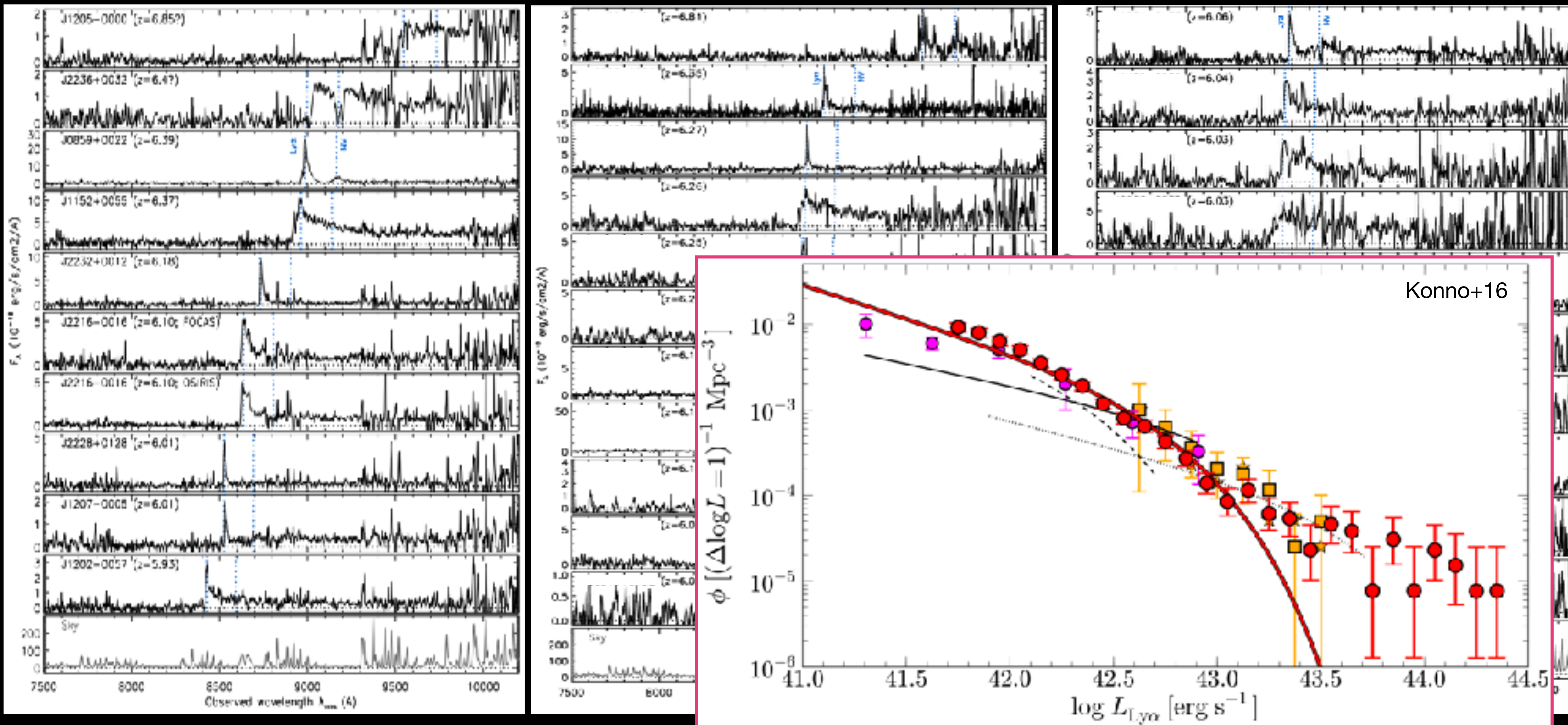
- ✶ The HSC survey has imaged ~250 deg^2 (full color, full depth) of the planned Wide fields, as of Jan 2017. Most of our candidates have come from this Wide layer so far.
- ✶ Spectroscopic follow-up is underway: ~50 objects have been identified so far.

✔ Subaru/FOCAS: 1 night in S15A... weathered out
4 nights in S15B... mostly clear
5 nights in S16A... perfectly clear
20 nights in S16B-S18A ("intensive")... 2.5/5 successful so far

✔ GTC/OSIRIS and Gemini/GMOS-S: observe brighter objects than do FOCAS

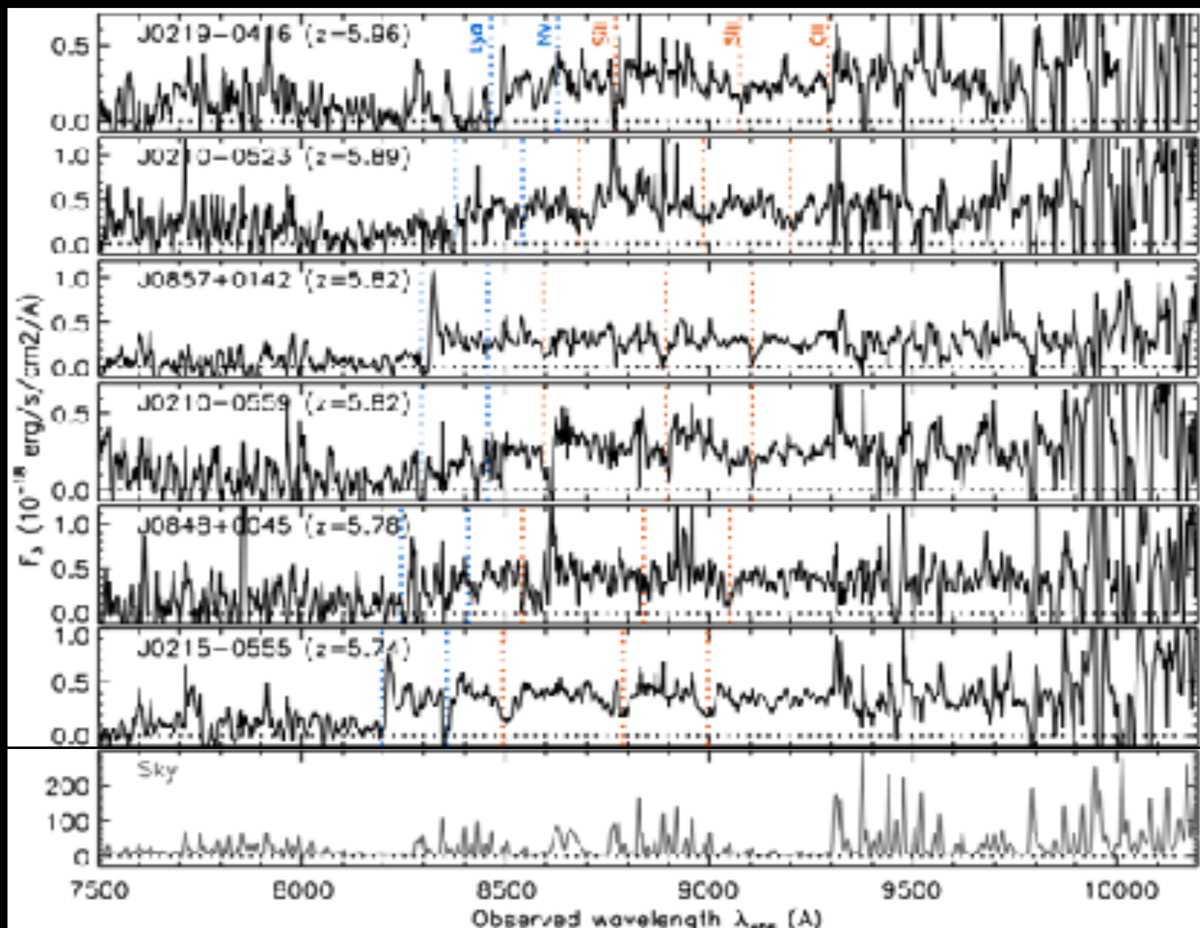
- ✶ Multi-wavelength follow-up observations are planned/underway.
- ✶ First discovery paper published (Matsuoka et al. 2016, ApJ, 828:26).

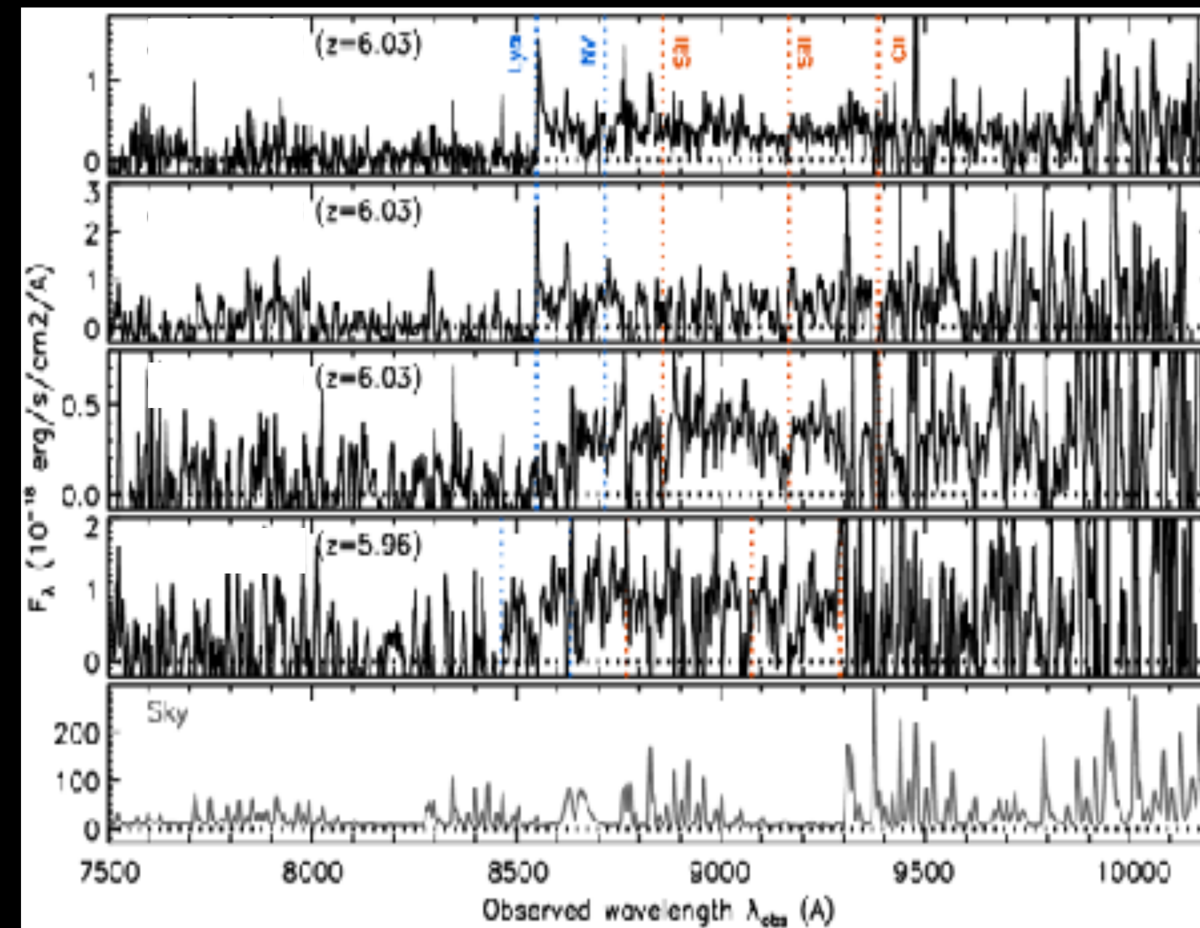
Quasars



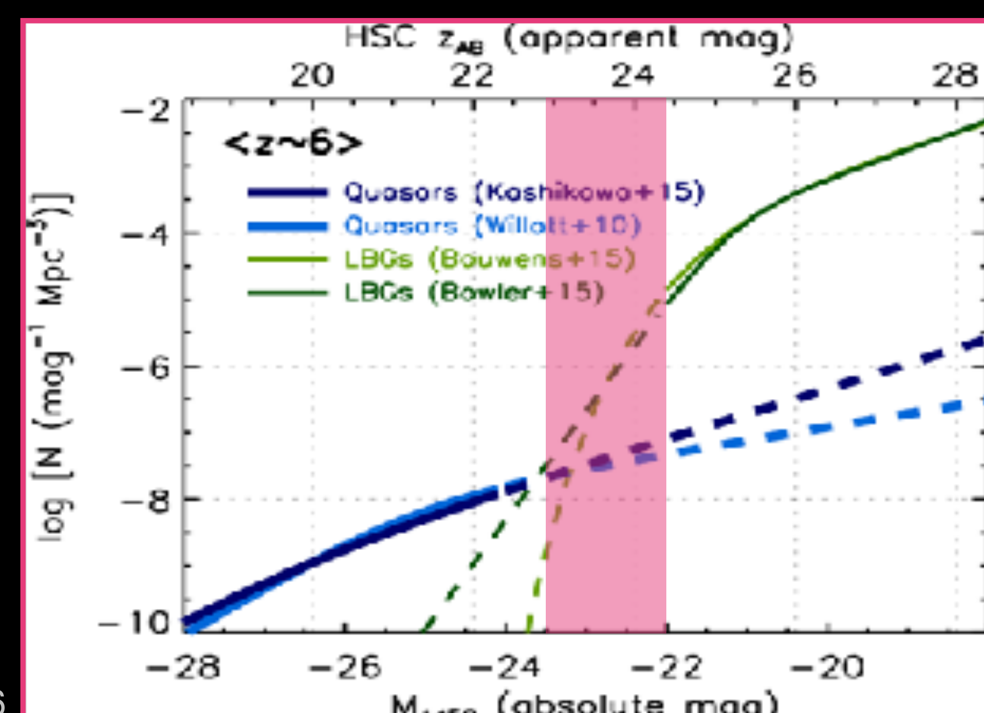
- ✶ 30 new quasars at $5.9 < z < 6.9$ (+ 5 quasars recovered) over ~100-150 deg^2.
- ✶ Increasing fraction of absorption features toward higher-z and lower-L?
- ✶ Quasar/galaxy separation is not trivial, even with spectra.
  We tentatively classify all the objects with L(Ly α) > 10^{43} erg/s or FWHM(Ly α) > 500 km/s (uncorrected for IGM absorption) as AGNs or possible AGNs.

Galaxies



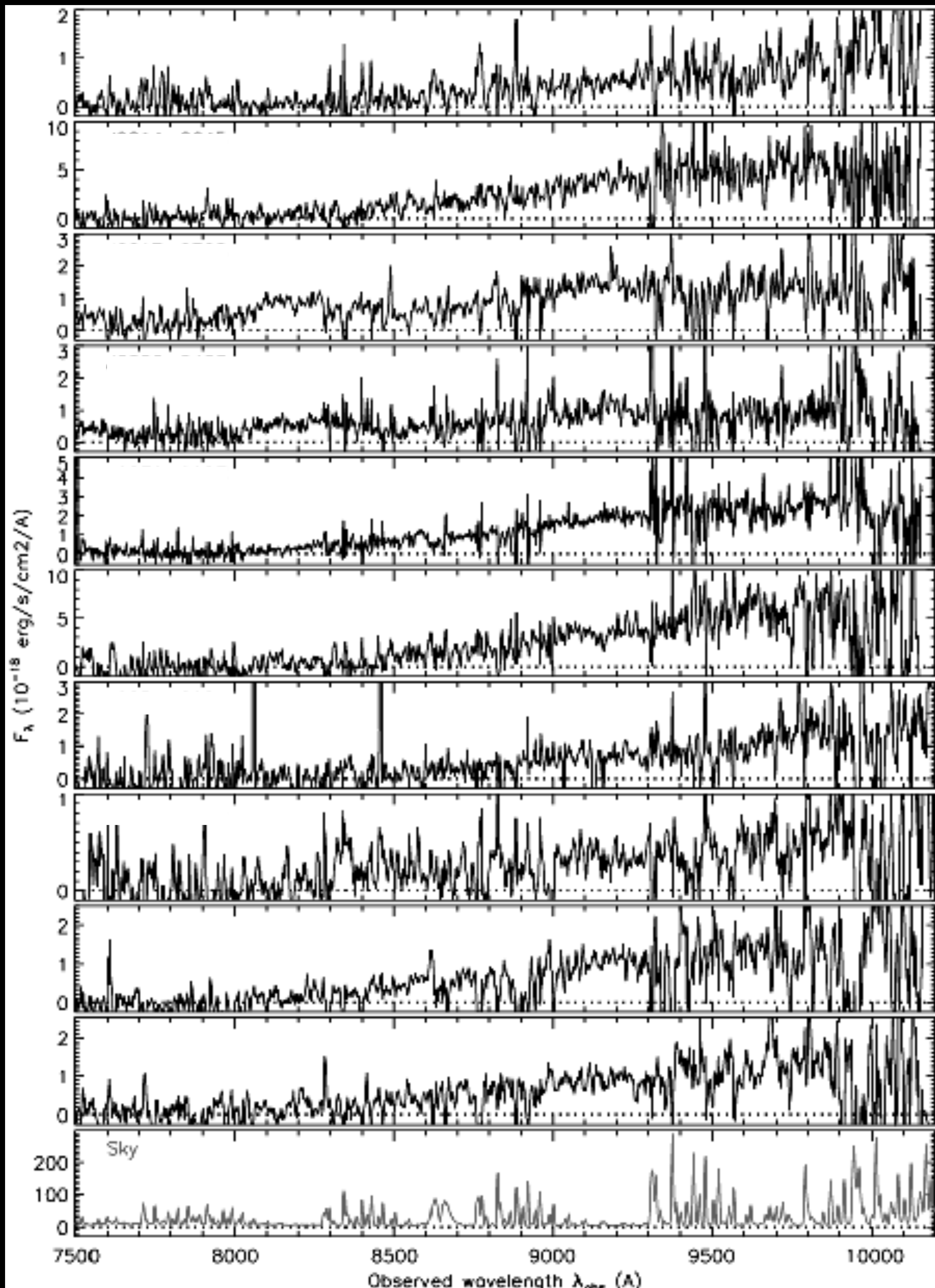


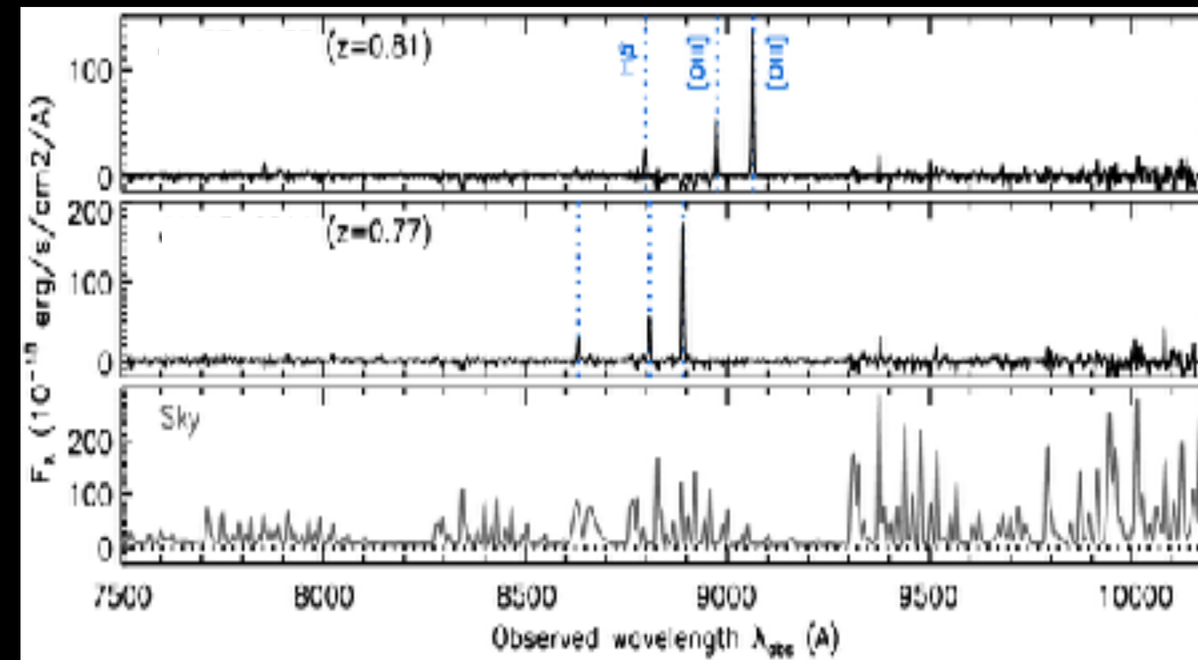
- ✶ 9 luminous galaxies at $5.7 < z < 6.1$, with $-23.5 < M_{1350} < -22$ mag.
- ✶ We excluded extended sources from our selection, so this result gives us the lower limit of the number density of high-z luminous galaxies.



Matsuoka+16

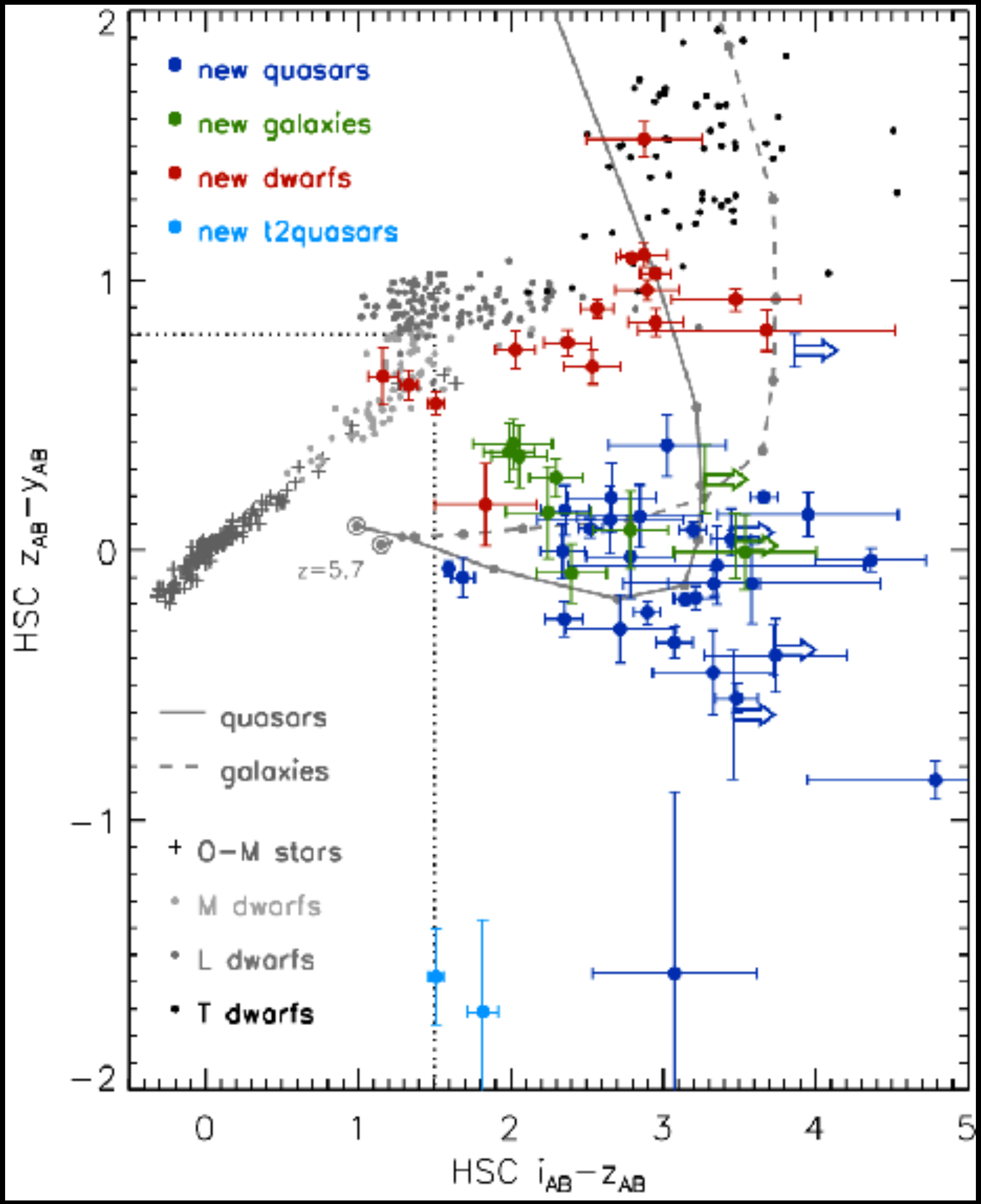
Brown dwarfs and low-z [O III] emitters

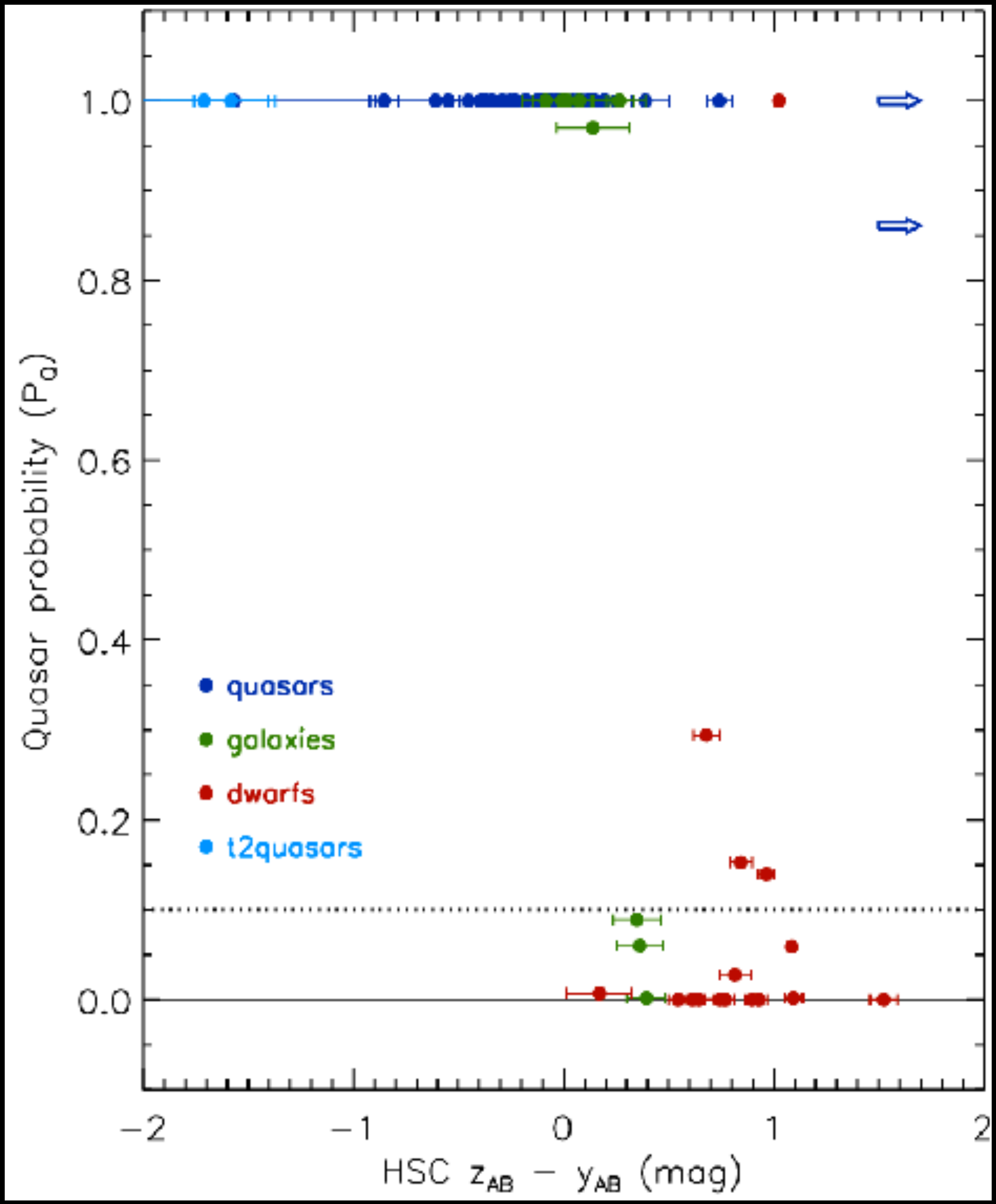




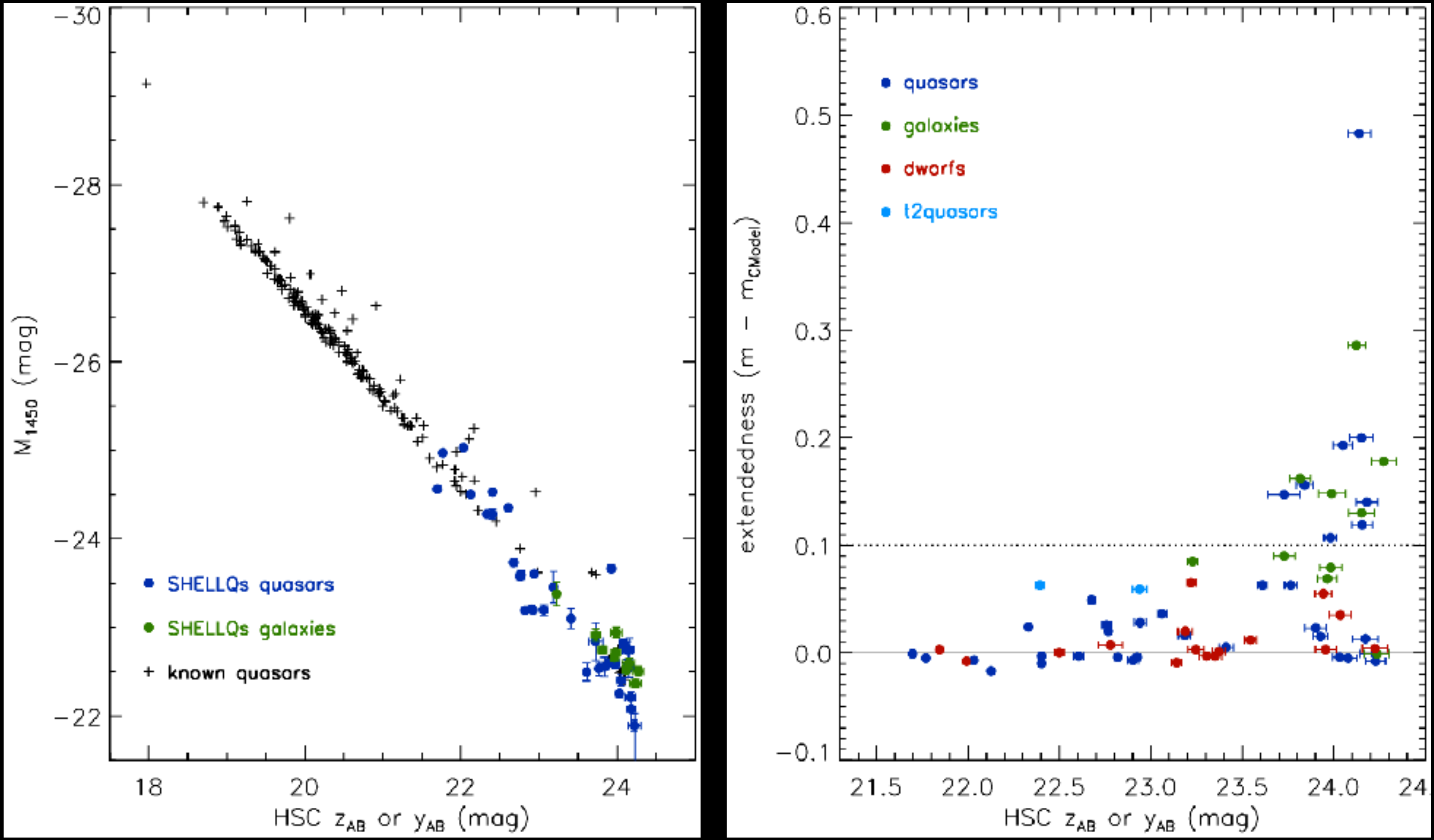
- ✶ Small number of contaminating brown dwarfs. Most of these objects have low quasar probability P_Q.
- ✶ 2 type-II quasars or low-metallicity star-forming galaxies at z ~ 0.8, with $L_{[OIII]}$ ~ $10^{42.5}$ erg/s. The strong [O III] lines mimic Ly α at z ~ 6.

Some sample characteristics





Some sample characteristics



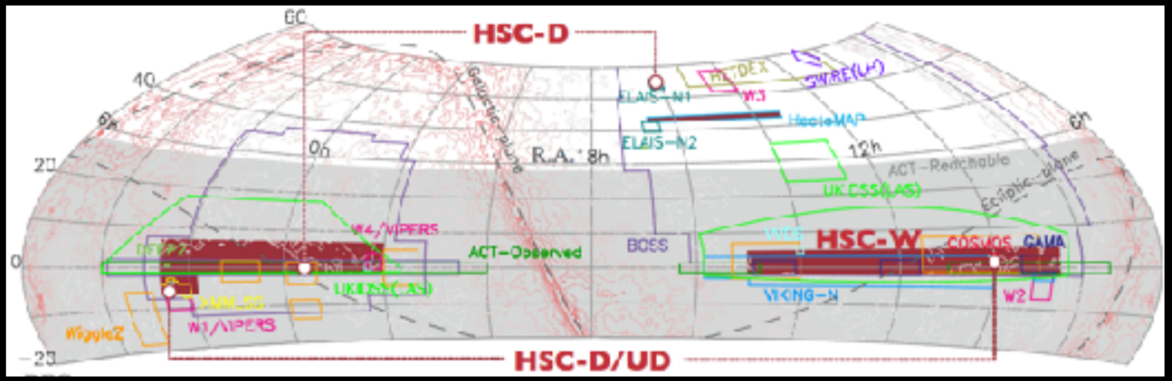
Multi-wavelength follow-up efforts

- ✶ "X-SHOOTER spectroscopy of low-luminosity quasars at z > 6.4" (Onoue+)
  VLT/X-shooter NIR spectroscopy of 3 quasars (IGM, SMBH mass, and metallicity)
- ✶ "Measuring the SMBH mass of a low-luminosity quasar at z = 6.26" (Onoue+)
  Gemini/GNIRS NIR spectroscopy of 1 quasar (IGM, SMBH mass, and metallicity)
- ✶ "Probing the star formation nature and co-evolutionary relations of low-luminosity quasars at z > 6" (Izumi+)
  ALMA observations of 4 quasars (SFR, dust/gas mass, M_{BH} - σ relation)
- ✶ "On the submm nature of the low-luminosity BAL quasars at z ~ 6-7 discovered by Subaru/HSC" (Izumi+)
  ALMA observations of 2 quasars (redshift, SFR, dust/gas mass, outflows)
- ✶ "Uncovering cold ISM of very massive galaxies at z ~ 6 discovered by the extensive large-area deep Subaru/HSC survey" (Harikane+)
  ALMA observations of 4 galaxies (SFR, dust mass, outflows, link to Lyα properties)



Future Prospects

- ✶ The HSC-SSP survey will continue to observe the planned 1,400 deg^2 in the Wide component, until 2019-2020.
- ✶ We will continue our high-z quasar survey, keeping pace with the HSC survey.
- ✶ We are starting to look at the Deep (27 deg^2) and the UDeep (3.5 deg^2) fields, but severer galaxy contamination would be a critical issue.



- ✶ We will keep efforts to get sufficient amount of spectroscopic time.
  - ✓ "Subaru Intensive program" has been approved for our project; 20 nights in 2016B - 2018A.

- ✶ Various follow-up studies are underway.
  - ✓ luminosity function
  - ✓ IGM neutral fraction through GP and damping-wing measurements
  - ✓ SMBH mass and Eddington ratio distributions
  - ✓ metallicity and chemical evolution
  - ✓ star formation, dust, and gas in the host galaxies
  - ✓ ionized (Ly α) halos

- ✶ Subaru Prime Focus Spectrograph (PFS) will come on stage at ~2019, and will start a massive spectroscopic survey over the HSC survey area.