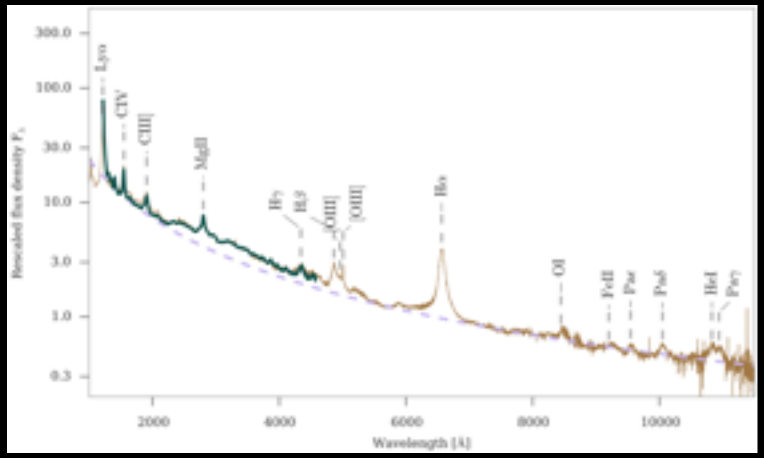
すばるHSC + WFIRSTによる遠方クエーサー探査の可能性

松岡 良樹（国立天文台）

Table 3. Proposed Synergy Programs and required instruments on Subaru

Science Program	Authors	HSC	PFS	IRD	SCE	ULT
Cosmology/Extragalactic Astrophysics						
Cosmology with large-scale structure probes	Takada+	o	o	–	–	–
Quasars in the Reionization Era	Matsuoka+	o	–	–	–	–
Finding and Characterizing high-z Clusters	Oguri	o	–	–	–	–
Searching for Bright Lensed high-z Galaxies	Oguri	o	–	–	–	–
Protoclusters across Cosmic Time	Toshikawa+	o	–	–	–	–
Protoclusters in the Reionization Epoch	Toshikawa+	o	–	–	–	–
Precise photo-z for Weak Lensing	Tanaka+	–	o	–	–	–
Low-Mass Galaxies at up to $z \sim 1.5$	Yabe+	o	o	–	–	–
Galaxy and IGM Co-Evolution	Ouchi+	o	o	–	–	–
Superluminous SNe at Reionization Epoch	Moriya+	o	–	–	–	–
Mass Assembly History of Galaxies since z=4	Kodama+	o	–	–	–	–
Galactic Astrophysics / Local Volume						
Milky Way Disk Flare behind the Bulge	Matsunaga+	–	–	–	–	o
Deep NIR Imaging of the Galactic Bulge	Nakada +	o	o	–	–	–
Hypervelocity Stars in the Galactic Bulge	Nishiyama	–	o	–	–	o
Dark Matter on Dwarf Spheroidal Galaxies	Hayashi+	–	o	–	–	–
Structure of the Galactic Outer Stellar Disk	Toyouchi+	–	o	–	–	–
Stellar Astrophysics						
Low-Mass End of the Initial Mass Function	Tomida	o	o	o	–	–
Bulge Stellar IMF & Low Mass Close Binary	Ita	–	o	–	–	–
Dust Condensation Region around AGB Stars	Ueta+	–	–	–	o	–
Properties of the Bulge Dwarfs by IR Spectra	Fukui+	–	–	o	–	o
Solar System						
Surface Characterization of TNOs	Terai	o	–	–	–	–
Water Ices in the Inner Solar System	Yoshida	o	–	–	–	–
Exoplanets						
Probing Dust Grains in Circumstellar Disks	Muto	–	–	–	o	–
Polarimetry of Planets/Protoplanetary Disks	Murakami+	–	–	–	o	–
Exoplanets Search by Astrometry	Yamaguchi+	–	–	–	o	–
Extinction in WFIRST Microlensing Fields	Suzuki+	o	–	–	–	–
Concurrent Microlensing Observations	Suzuki+	o	–	–	–	–
Imaging of Microlensing Planetary Hosts	Fukui+	–	–	–	o	o
Characterization of Transiting Exoplanets	Narita	–	–	o	–	–
Exoplanets around Late-M Dwarfs	Kuzuhara+	–	–	o	–	–

Note. — SCE and ULT indicate the SCExAO and the ULTIMATE-Subaru, respectively.



Selsing+16

クエーサー／１型AGNは。。

- 多波長測光データから情報を得にくい
  - 静止系紫外 - 可視光は基本的にpower-law continuumに支配される
  - 静止系近赤外線から、トーラスの塵放射の寄与が見えてくる

- 銀河に比べて面密度が小さい
- 銀河に比べて明るい

  ➔ 分光に対する撮像観測のメリットが限定的

- 時間軸を足すと、話は別

Table 3. Proposed Synergy Programs and required instruments on Subaru

Science Program	Authors	HSC	PFS	IRD	SCE	ULT
Cosmology/Extragalactic Astrophysics						
Cosmology with large-scale structure probes	Takada+	○	○	–	–	–
Quasars in the Reionization Era	Matsuoka+	○	–	–	–	–
Finding and Characterizing high-z Clusters	Oguri	○	–	–	–	–
Searching for Bright Lensed high-z Galaxies	Oguri	○	–	–	–	–
Protoclusters across Cosmic Time	Toshikawa+	○	–	–	–	–
Protoclusters in the Reionization Epoch	Toshikawa+	○	–	–	–	–
Precise photo-z for Weak Lensing	Tanaka+	–	○	–	–	–
Low-Mass Galaxies at up to $z \sim 1.5$	Yabe+	○	○	–	–	–
Galaxy and IGM Co-Evolution	Ouchi+	○	○	–	–	–
Superluminous SNe at Reionization Epoch	Moriya+	○	–	–	–	–
Mass Assembly History of Galaxies since z=4	Kodama+	○	–	–	–	–
Galactic Astrophysics / Local Volume						
Milky Way Disk Flare behind the Bulge	Matsunaga+	–	–	–	–	○
Deep NIR Imaging of the Galactic Bulge	Nakada +	○	○	–	–	–
Hypervelocity Stars in the Galactic Bulge	Nishiyama	–	○	–	–	○
Dark Matter on Dwarf Spheroidal Galaxies	Hayashi+	–	○	–	–	–
Structure of the Galactic Outer Stellar Disk	Toyouchi+	–	○	–	–	–
Stellar Astrophysics						
Low-Mass End of the Initial Mass Function	Tomida	○	○	○	–	–
Bulge Stellar IMF & Low Mass Close Binary	Ita	–	○	–	–	–
Dust Condensation Region around AGB Stars	Ueta+	–	–	–	○	–
Properties of the Bulge Dwarfs by IR Spectra	Fukui+	–	–	○	–	○
Solar System						
Surface Characterization of TNOs	Terai	○	–	–	–	–
Water Ices in the Inner Solar System	Yoshida	○	–	–	–	–
Exoplanets						
Probing Dust Grains in Circumstellar Disks	Muto	–	–	–	○	–
Polarimetry of Planets/Protoplanetary Disks	Murakami+	–	–	–	○	–
Exoplanets Search by Astrometry	Yamaguchi+	–	–	–	○	–
Extinction in WFIRST Microlensing Fields	Suzuki+	○	–	–	–	–
Concurrent Microlensing Observations	Suzuki+	○	–	–	–	–
Imaging of Microlensing Planetary Hosts	Fukui+	–	–	–	○	○
Characterization of Transiting Exoplanets	Narita	–	–	○	–	–
Exoplanets around Late-M Dwarfs	Kuzuhara+	–	–	○	–	–

Note. — SCE and ULT indicate the SCExAO and the ULTIMATE-Subaru, respectively.

今日の内容

- ✶ 遠方クエーサー探査の目的
- ✶ すばるHSCによる探査の進展
- ✶ 赤方偏移の壁を超えて：
  HSC + WFIRST による新探査の可能性

High-z quasars - Unique probe of the early Universe

Fundamental questions we aim to answer:

Why do supermassive black holes (SMBHs) exist?

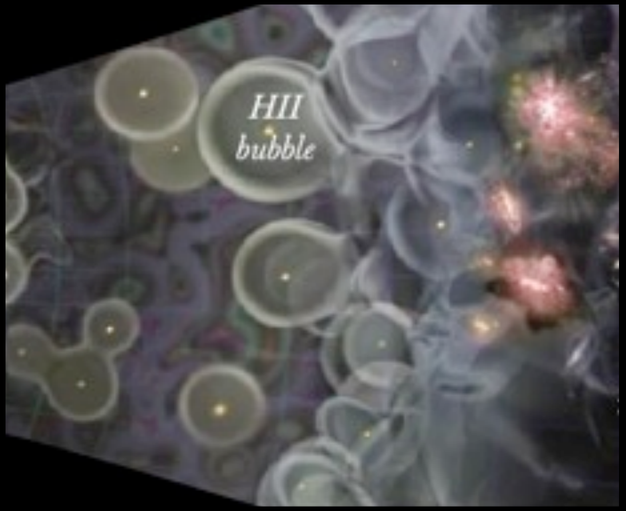
✶ When were they born?
✶ What were their seeds?
✶ How did they grow in the early and late epochs of the cosmic history?

[Observational signatures]
- What are the luminosity/mass functions of quasars/SMBHs?
- Are 10^9 M_{sun}-class SMBHs common or exceptional at $z > 6$?
- How do the luminosity/mass functions evolve towards lower redshift?

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 underlying matter distribution?

[Observational signatures]
- What are the current and past star formation activities, inferred from the amount and kinematics of the gas, current SFR, and chemical enrichment?
- Do we find special (e.g., over-dense) environments around the quasars/host galaxies?



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?

[Observational signatures]
- How does the IGM neutral fraction change along redshift and transverse direction?
- Do low-luminosity quasars emit enough UV photons to re-ionize the Universe?

and many more!

Past/ongoing surveys and their immense legacy value


SDSS 2.5m

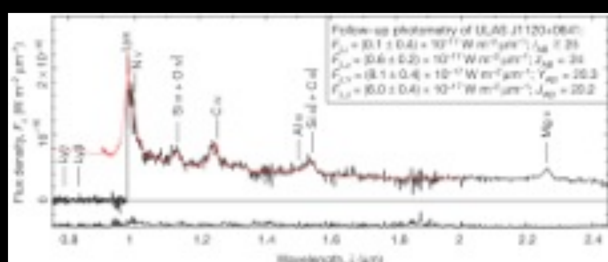

CFHT 3.6m


UKIDSS/VIKING 4m

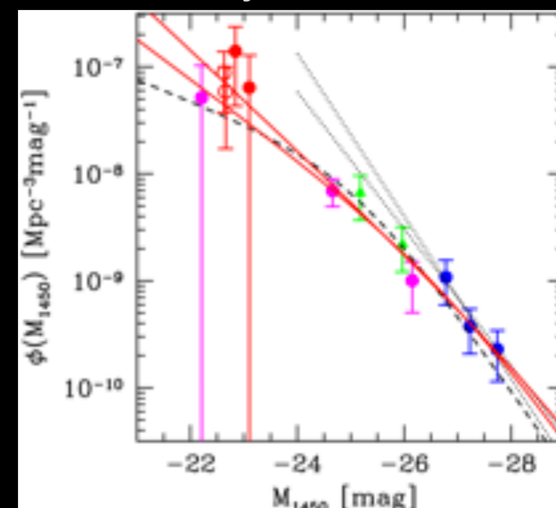

Pan-STARRS1 1.8m


DES 4m

>100 quasars known at z > 5.7:
only several (one) at z > 6.5 (z > 7)
or M_{1450} > −24 mag

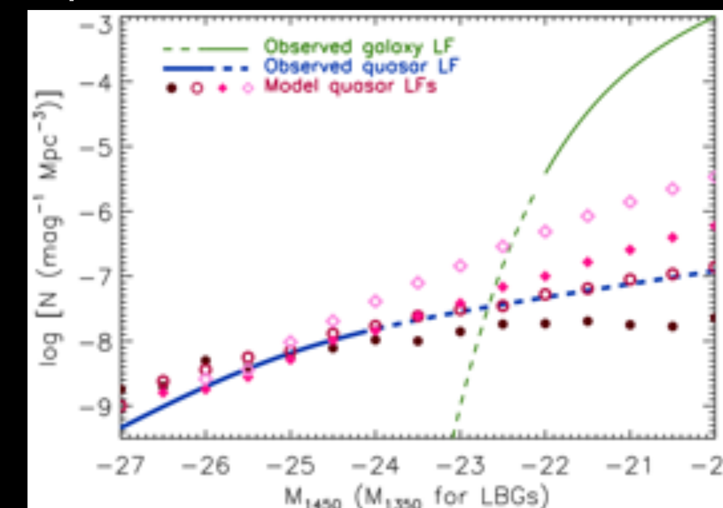

Mortlock+11

Luminosity function



Kashikawa+15

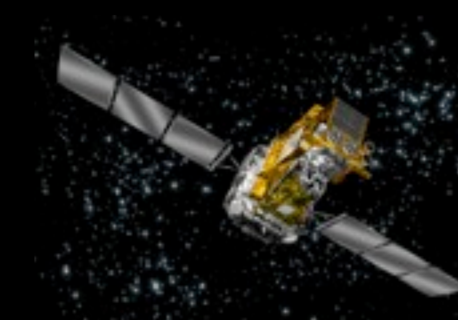
Comparison with theoretical models



A wide variety of follow-up observations with

✶ ALMA for FIR-based SFR, gas and dust masses, gas kinematics, dynamical galaxy mass, ...
✶ Subaru and other large optical/near-IR telescopes (→ELTs) for SMBH mass, metallicity distribution, IGM properties, ...
✶ HST (→JWST) for the morphology, UV-based SFR, etc. in the host galaxies, surrounding ionized gas, ...
✶ Chandra and XMM-Newton (→ATHENA) for intrinsic mass accretion rate, Eddington ratio, absorbers, ...

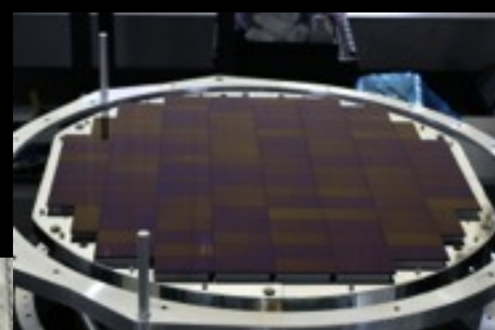


Subaru Hyper Suprime-Cam SSP survey

Hyper Suprime-Cam (HSC)

- ✶ 116 2K x 4K Hamamatsu FD CCDs (104 CCDs are used for science exposures)
- ✶ Circular FoV of 1°.5 diameter
- ✶ Installed on the Subaru 8.2-m telescope
- ✶ 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

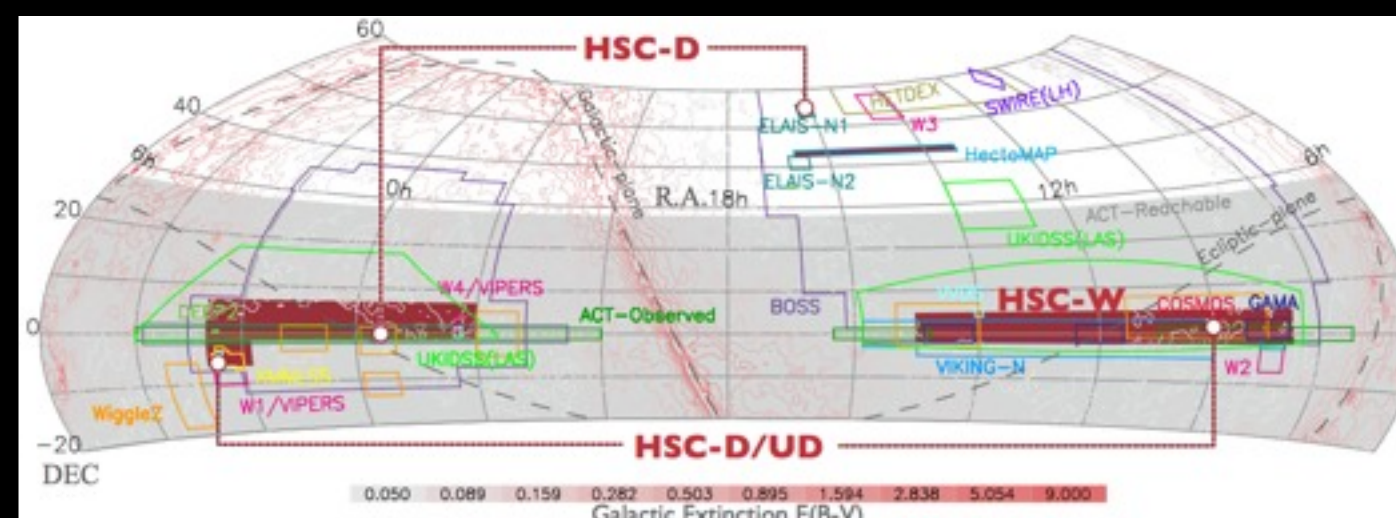


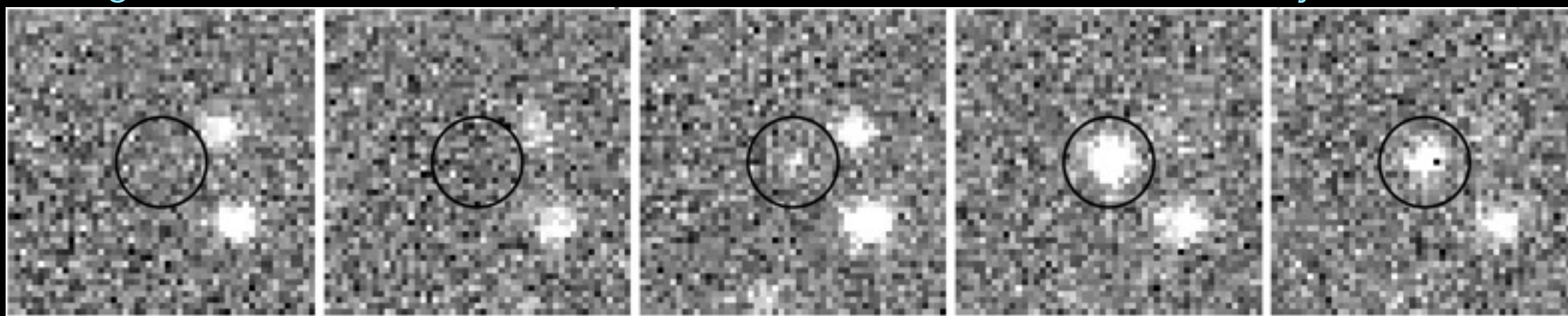
Table 7: Quasar Samples

	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

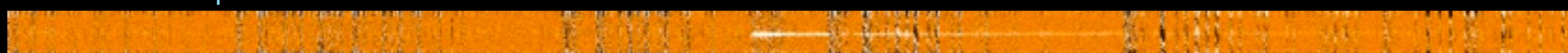
The first outcome

Discovered in September 2015, by the first GTC/OSIRIS observations

HSC g r i z y

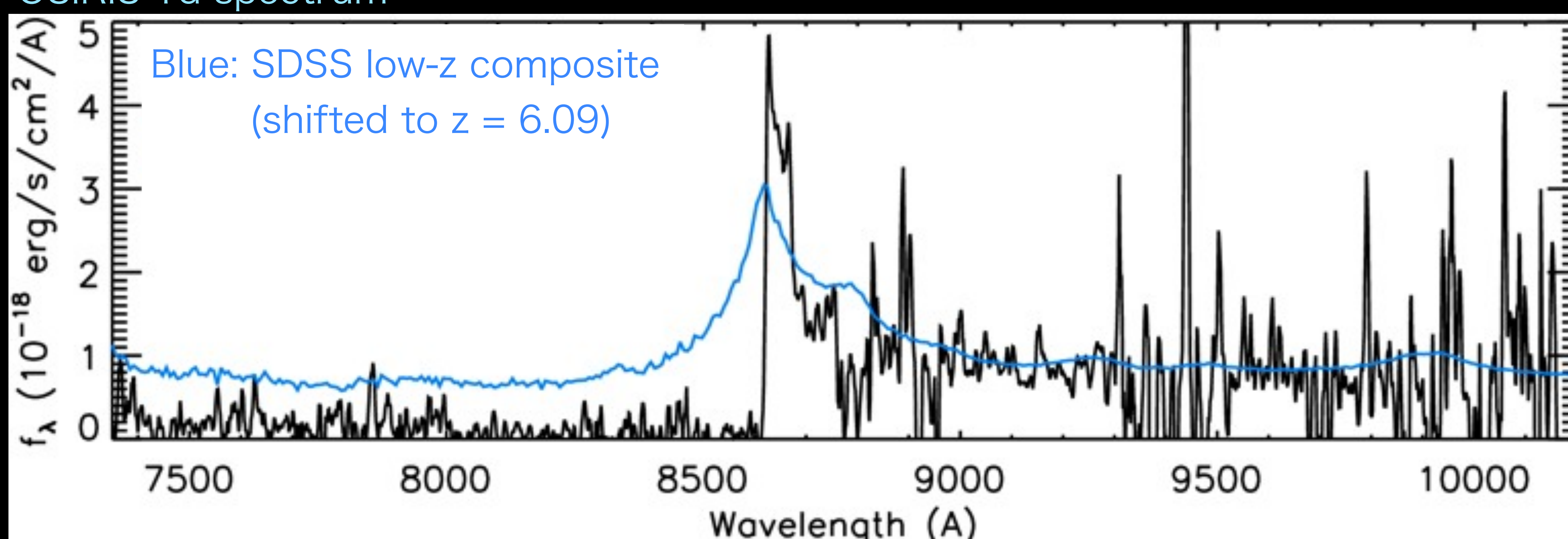


OSIRIS 2d spectrum

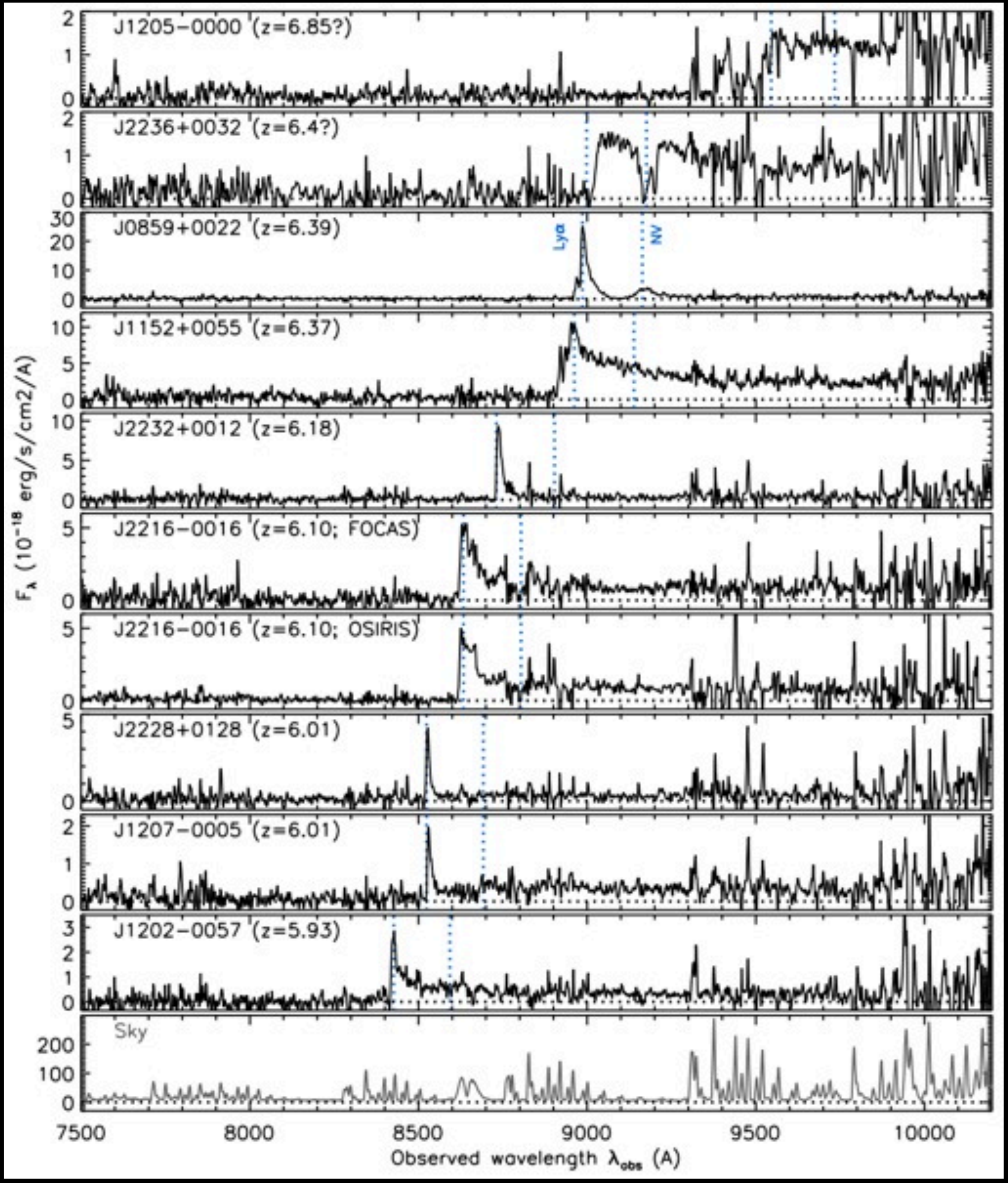


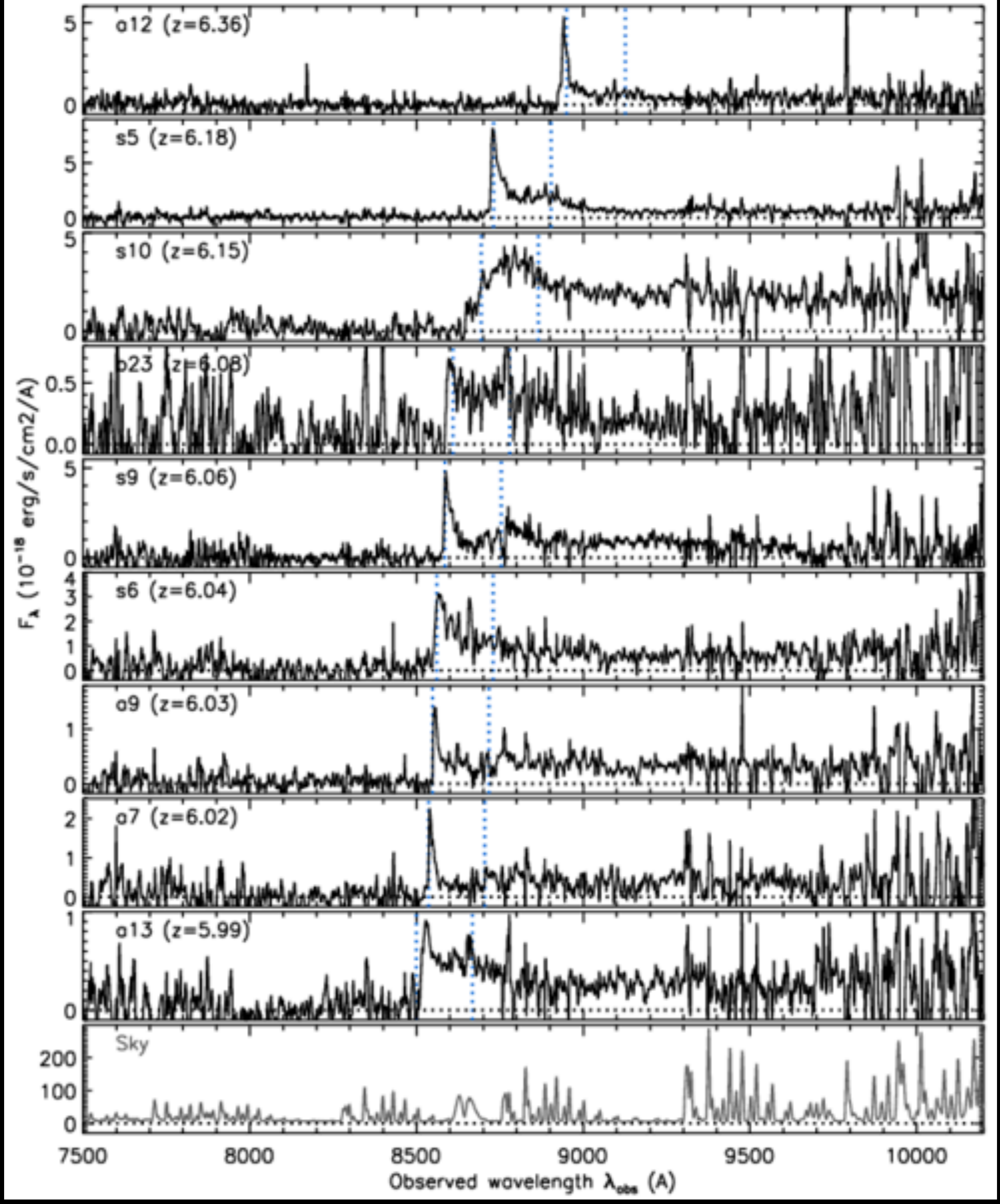
Blue (~7300 A) Red (~10200 A)

OSIRIS 1d spectrum

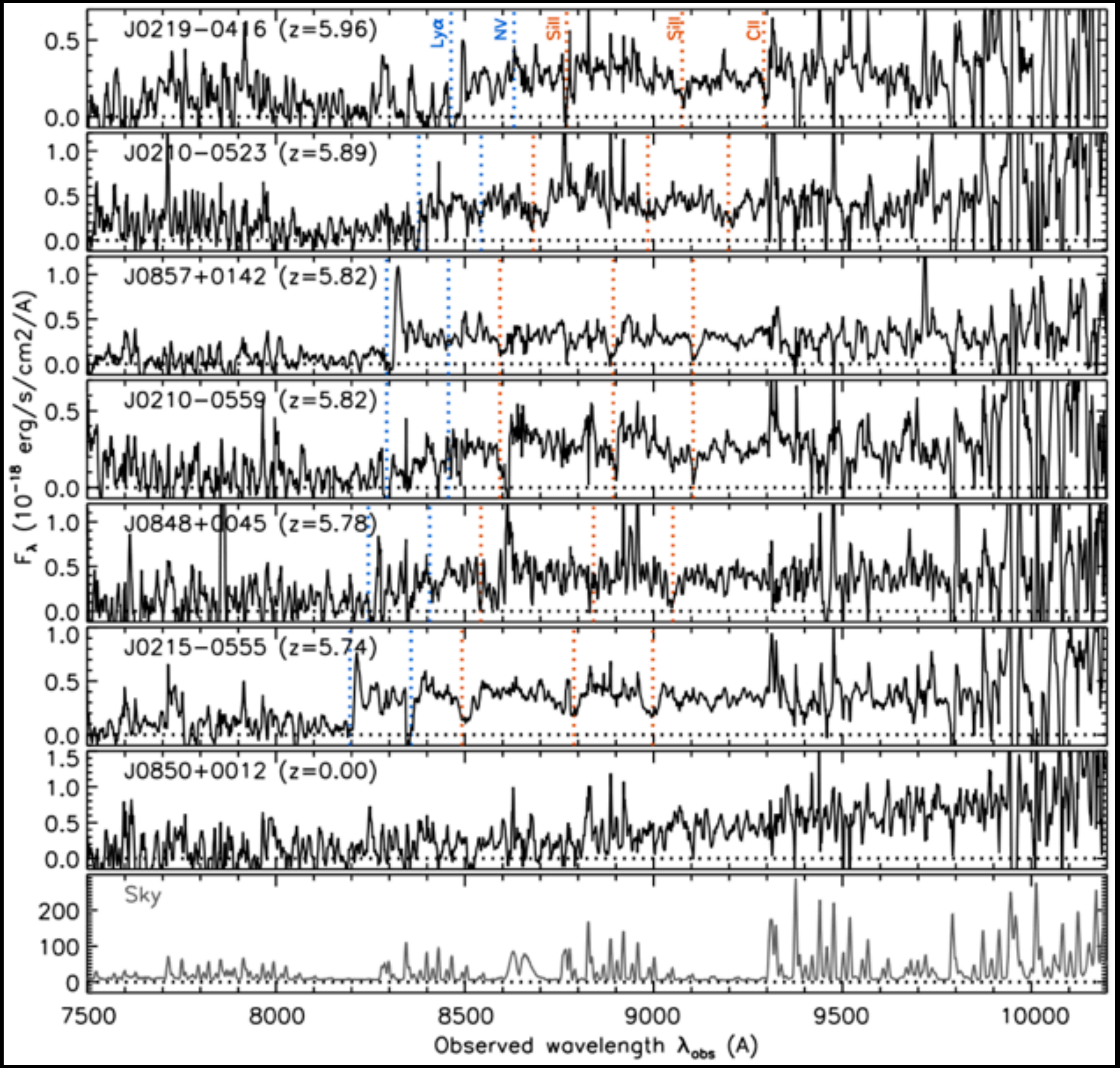


Discovery continues





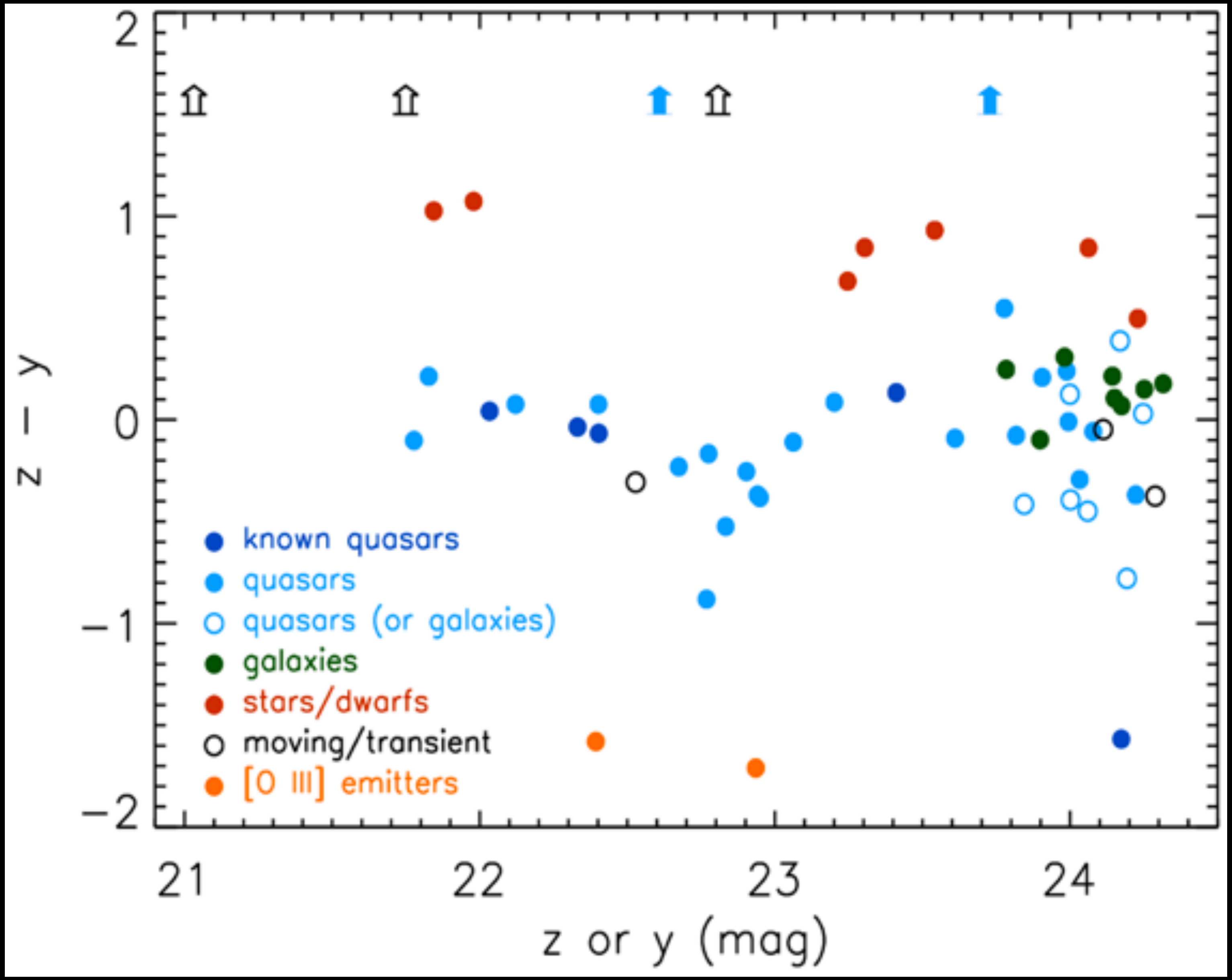
Surprisingly...



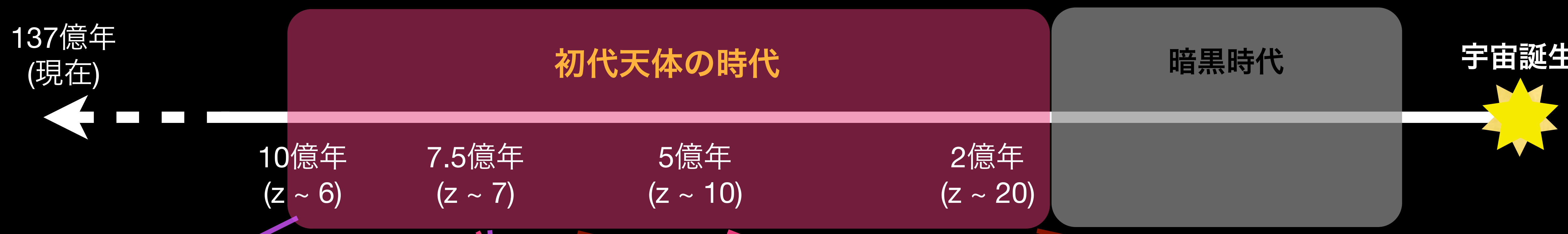
Our score sheet

- Spectroscopic identification as of 2016 Sep 2

Candidates (z_{AB} < 24.5, y_{AB} < 24.0)	80
Known z ≥ 6 quasars	5
Spectroscopy done	55
Quasars at z ≥ 6	31
Galaxies at z ~ 6	8
[O III] emitters at z ~ 0.8	2
Brown dwarfs	8
Moving/transient	6

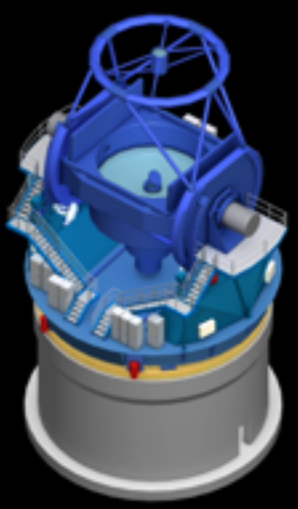


赤方偏移の壁を越えて：HSC + WFIRSTによる新探査の可能性



すばる望遠鏡 (HSC探査)

東京大学アタカマ天文台 (TAO)
6.5m望遠鏡



ATHENA

WFIRST

& more future space missions

地上可視光探査
(2014 ～ 2020年)

⇨

地上近赤外線探査
(2018 ～ 2025年)

⇨

スペース近赤外線・X線探査
(2024年～)

WFIRST-AFTA SDT 2015 Report
Table 2-1
(High-Latitude Survey; HLS)

Characteristic	Y	J	H	F184
λ_{min} (μm)	0.927	1.131	1.380	1.683
λ_{max} (μm)	1.192	1.454	1.774	2.000
PSF ½ light radius	0.12”	0.13”	0.13”	0.14”
Exposure time (s)	5x174	6x174	5x174	5x174
5σ depth AB pt src	26.56	26.70	26.54	25.76
5σ depth AB (exp. prof. $r_{1/2}$=0.3”)	25.39	25.56	25.44	24.71
WL n_{eff} (gal/am^2)	N/A	32.8	35.2	19.0
(combined filters)		44.8		

LSST Science Book v.2

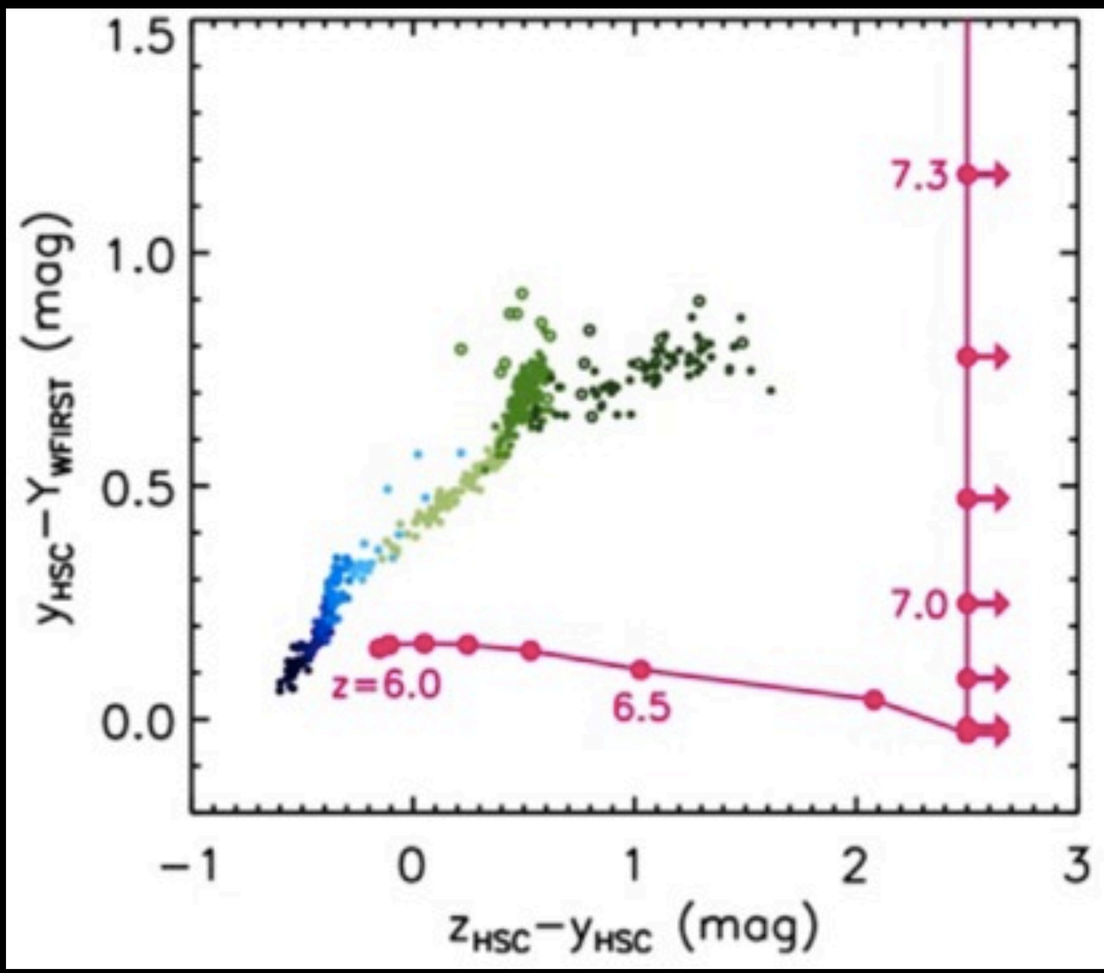
System Capability	
Single-visit depths (point sources; 5σ)	u: 23.9 g: 25.0 r: 24.7 i: 24.0 z: 23.3 y: 22.1 AB mag
Baseline number of visits over 10 years	u: 70 g: 100 r: 230 i: 230 z: 200 y: 200
Coadded depths (point sources; 5σ)	u: 26.3 g: 27.5 r: 27.7 i: 27.0 z: 26.2 y: 24.9 AB mag
Photometry accuracy (rms mag)	repeatability: 0.005; zeropoints: 0.01
Astrometric accuracy at $r = 24$ (rms)	parallax: 3 mas; proper motion: 1 mas yr^{-1}

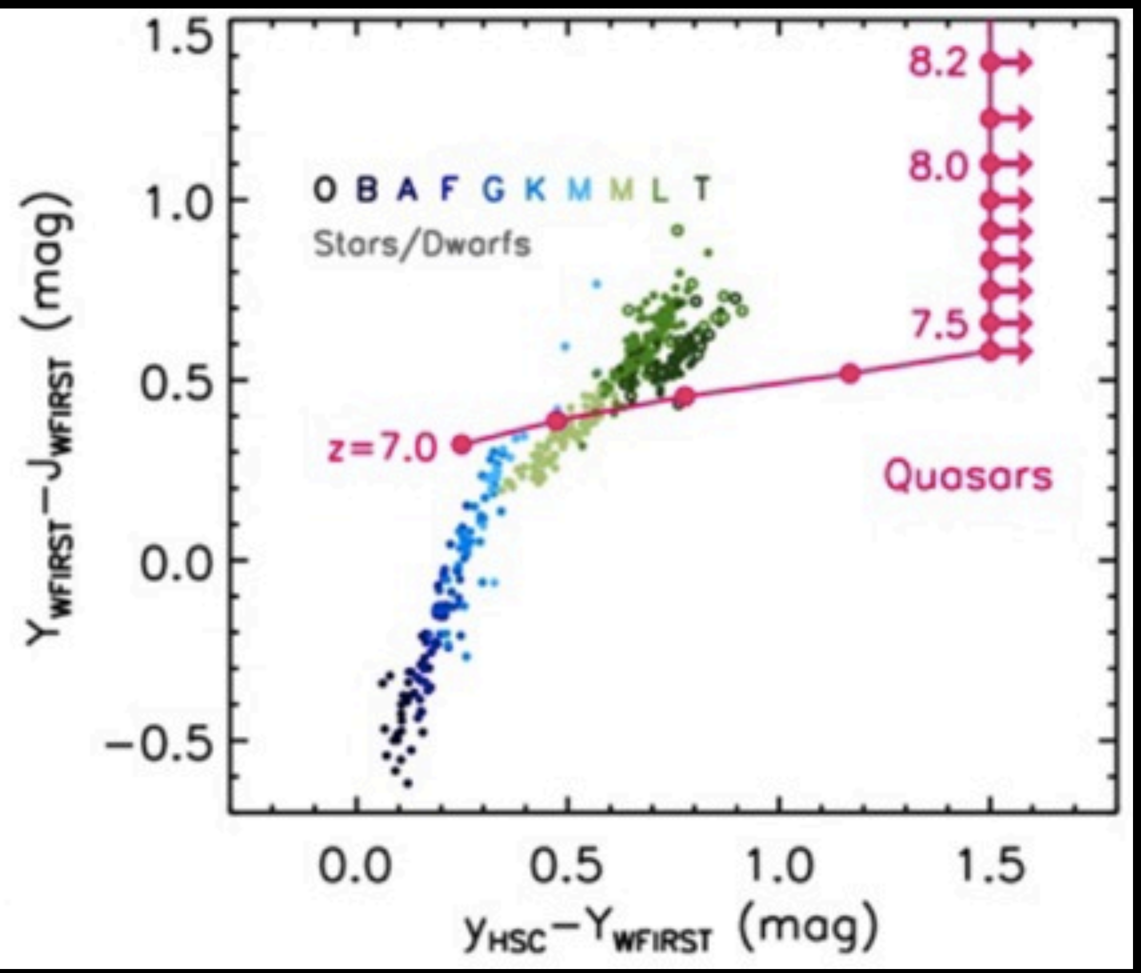
Table 1.1: LSST System Parameters

Prospect for HSC + WFIRST

For example...

- HSC *z*- and *y*-band imaging over 50 deg^2 of the WFIRST-HLS fields.
- HSC (z_{AB}, y_{AB}) < (26.5, 26.0) mag combined with WFIRST-HLS Y_{AB} < 26.5 mag (5σ).
- cf. LSST coadd 5σ depth (z_{AB}, y_{AB}) ~ (26.2, 24.9) mag.
- >10 quasars at z ~ 7 with y_{HSC} < 25.0 mag, $z_{HSC} - y_{HSC}$ > 1.5.
- Several quasars at z ~ 8 with Y_{WFIRST} < 25.0 mag, $y_{HSC} - Y_{WFIRST}$ > 1.0.
- Quasars at z > 8 can be searched for with the WFIRST colors alone as Y_{WFIRST} dropouts.
- The above HSC survey will require 50 nights each in the *z* and *y* band, including overheads and weather factor (scaled from the HSC-SSP survey).





Quasars in the Reionization Era

Yoshiki Matsuoka (NAOJ; yk.matsuoka@nao.ac.jp), Masayuki Akiyama (Tohoku), Tomotsugu Goto (Tsing Hua), Hiroyuki Ikeda (NAOJ), Masatoshi Imanishi (NAOJ), Takuma Izumi (Tokyo), Nobunari Kashikawa (NAOJ), Kotaro Kohno (Tokyo), Tohru Nagao (Ehime), Mana Niida (Ehime), Masafusa Onoue (GUAS)

The era from the birth of the first stars to cosmic reionization is one of the key subjects in astronomy and astrophysics today. While the formation of the first stars is observationally out of reach at present, the epoch of reionization is being explored by several different approaches, such as measurements of the cosmic microwave background, evolving galaxy luminosity function, and neutral fraction of the intergalactic medium (IGM) seen against background quasars. The main source of ultraviolet photons that reionized the Universe is still under debate, while the latest Planck measurements imply that faint star-forming galaxies may have made a major contribution. Although active galactic nuclei (AGNs) are a possible additional source of ionizing photons, this population is still poorly explored in the reionization era at $z > 6$.

High-z quasars are a key population to understand the formation and evolution of supermassive black holes (SMBHs) as well. Since the age of the Universe at $z \sim 6$ is comparable to the time necessary for a SMBH to grow to a billion solar masses (depending on the seed mass), which is commonly observed at $z \leq 6$, the mass function at higher redshift convey critical information about the population(s) of the seed black holes and the mode of subsequent growth. In addition, high-z quasars might be a signpost of galaxies and high density peaks in dark matter distribution in the early Universe. The stellar and gaseous properties in and around the host galaxies can be studied across the whole electromagnetic spectrum, giving a unique probe of galaxies in its early evolution phase. The chemical enrichment, and thus the preceding star formation history, can be measured with strong metal emission lines arising from ionized gas around the quasar nuclei.

Coordinated WFIRST and Subaru/HSC observations will provide a unique opportunity to search for quasars at $6 < z < 8$, where the IGM rapidly transitions from neutral to ionized state. A characteristic spectral break of these quasars, caused by strong IGM absorption, is identifiable with extremely red colors in the z_{HSC}, y_{HSC}, and Y_{WFIRST} bands (see Figure 1). Contamination from Galactic stars and dwarfs will be eliminated effectively by this color selection technique. In addition, the exquisite image quality of the WFIRST will help identify contaminating galaxies at all redshifts. Spectroscopic confirmation of the quasars will be performed with the WFIRST grism or with Thirty Meter Telescope (TMT) from the ground. It is particularly important for us to find those high-z quasars in the northern sky, which will allow for further follow-up studies with the unique capability of TMT.

Based on the quasar luminosity function at $z \sim 6$ and its extrapolation into lower luminosity and higher redshifts, more than several quasars are expected each at $z \sim 7$ and $z \sim 8$, for $Y_{WFIRST} < 25$ mag over 50 deg^2. In order to identify those quasars, we would need HSC depth of (z_{HSC}, y_{HSC}) = (26.5, 26.0) mag; this would be achieved with 50 nights survey each in the z_{HSC} and y_{HSC} band, if we scale the estimates in the HSC-SSP survey, including the weather factor and overheads. Quasars at $z > 8$ are practically invisible in the Y_{WFIRST} and bluer bands, and can be searched for with WFIRST colors alone.

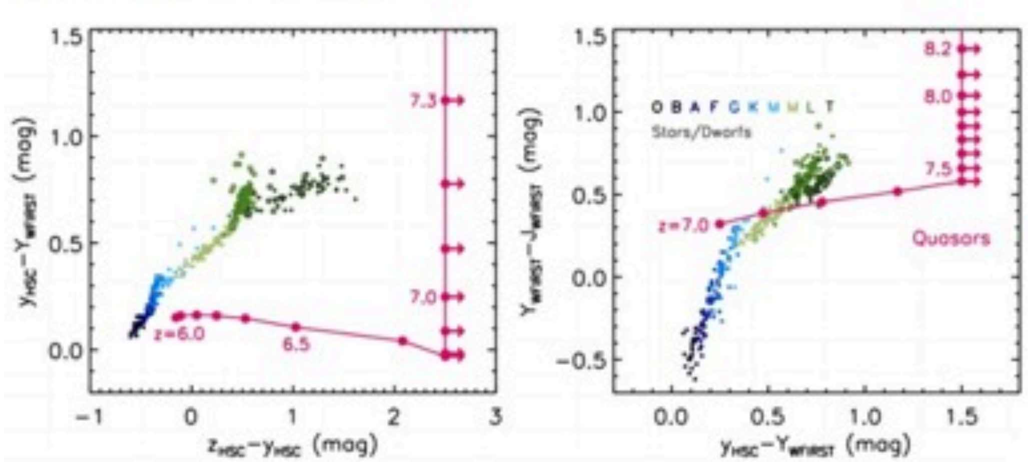


Figure 1: Predicted colors of high-z quasars and Galactic stars/dwarfs measured in the WFIRST and Subaru/HSC bands. The color coding is indicated in the right panel.