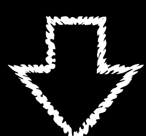
遠方クエーサー探査と宇宙再電離

愛媛大学/宇宙進化研究センター

松岡 良樹

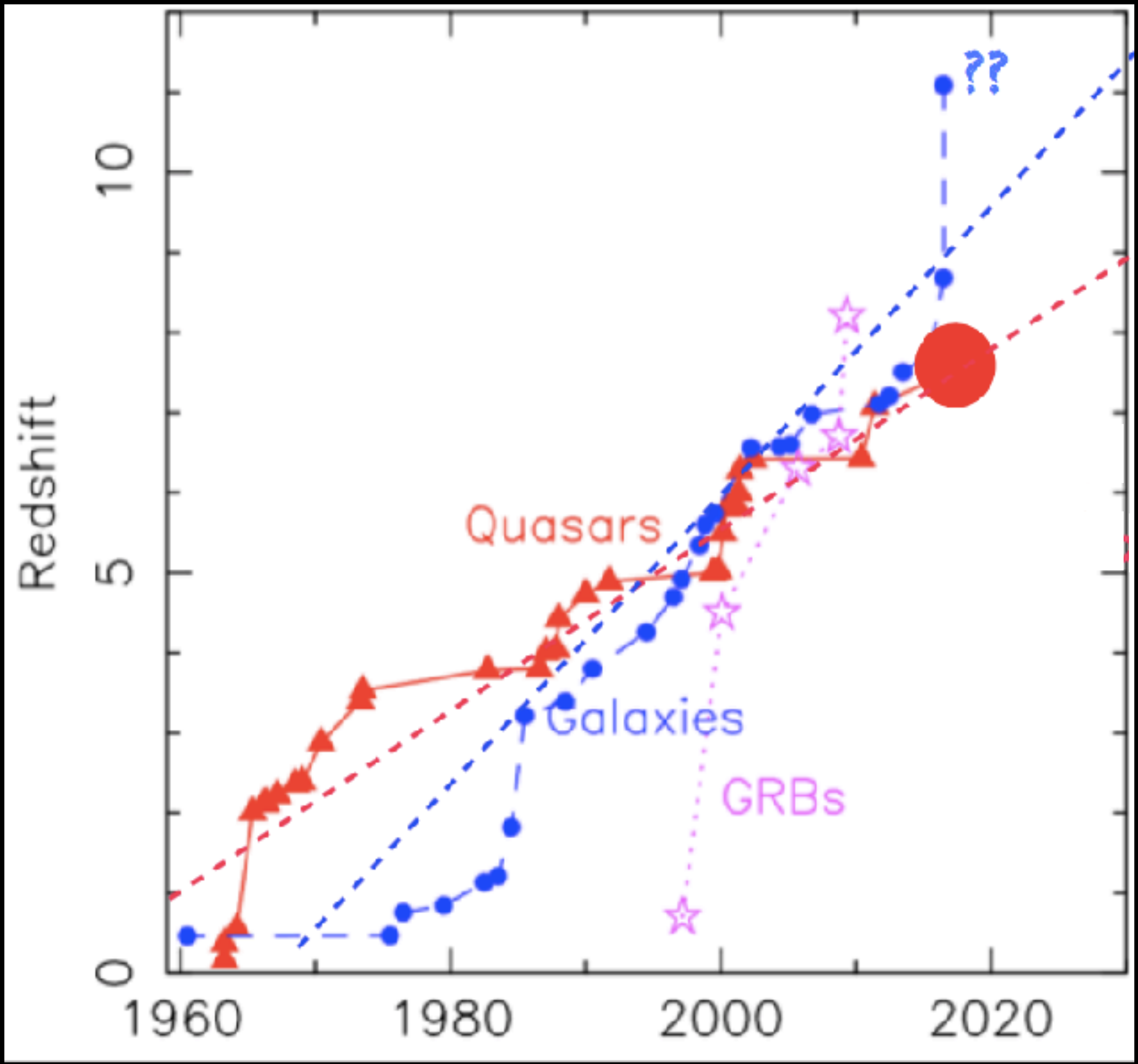
遠くへ

✶ z = 0.158 (1963年)



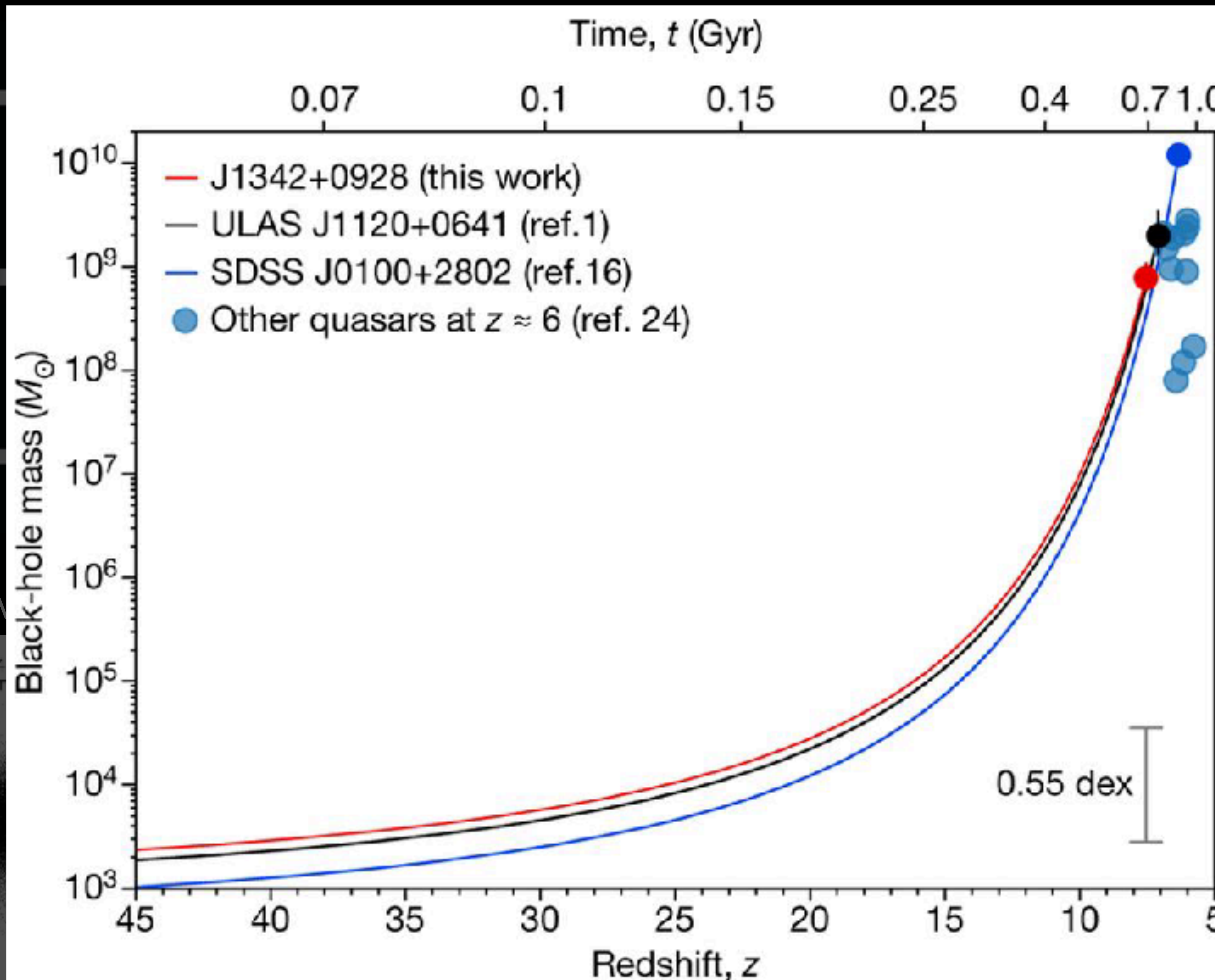
✶ z = 7.54 (2017年)

Banados+17



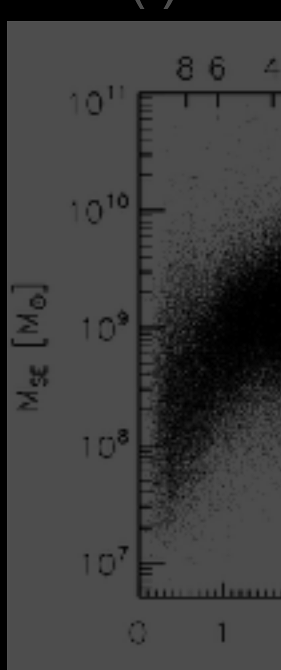
© Xiaohui Fan

遠いクエーサーは、何を教えてくれるのか？

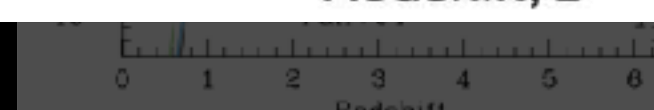


SMBHs
e seeds?
ey born?
grow?

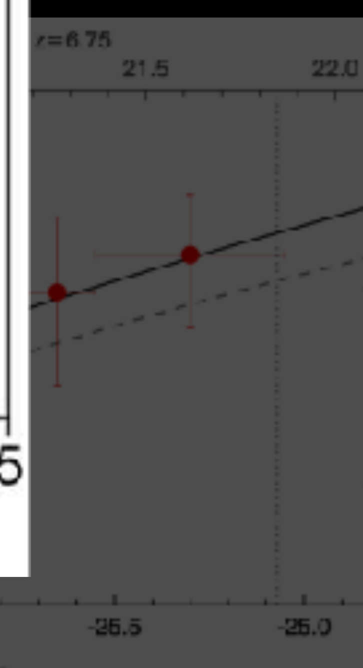
Maximum
M(t) = M
ns



Shen11

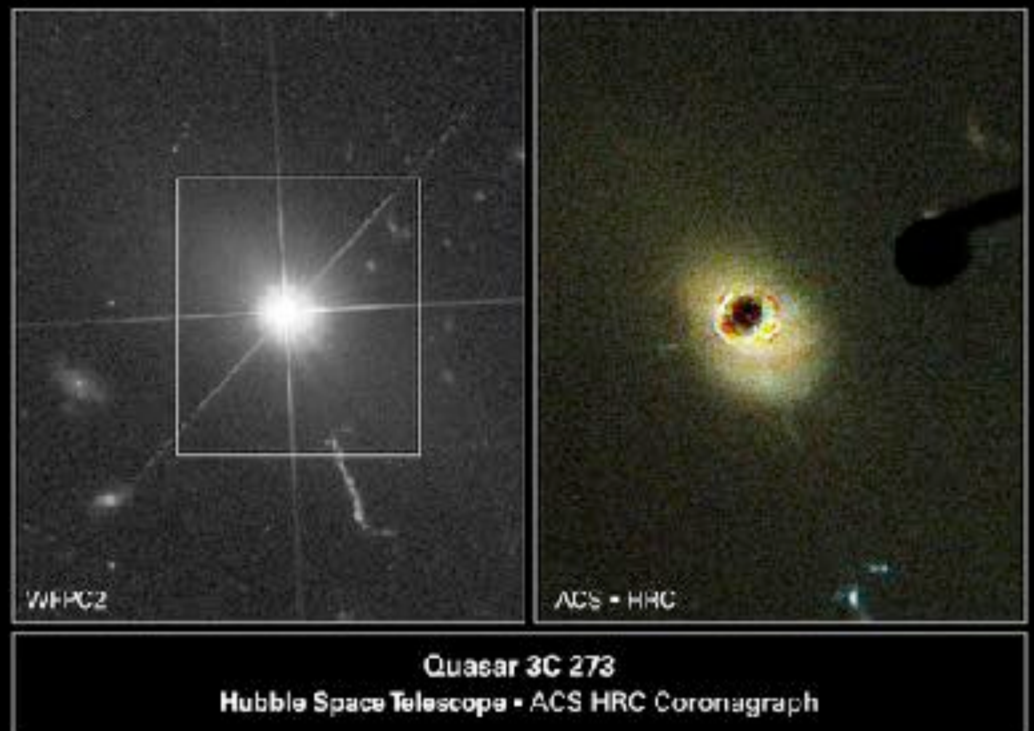


Richards+06



Venemans+13

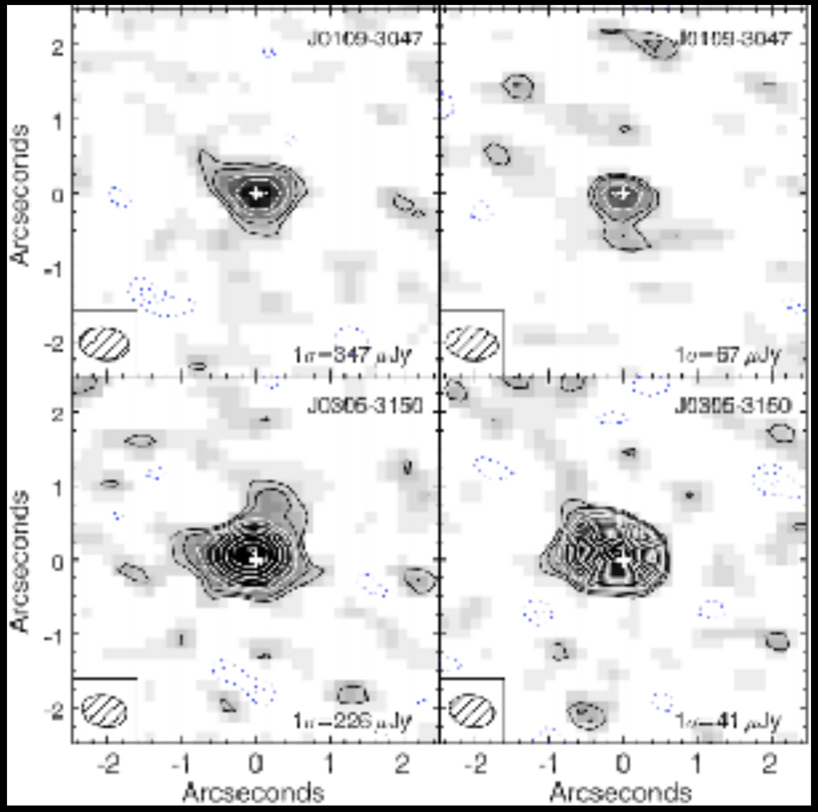
遠いクエーサーは、何を教えてくれるのか？



Host galaxy evolution

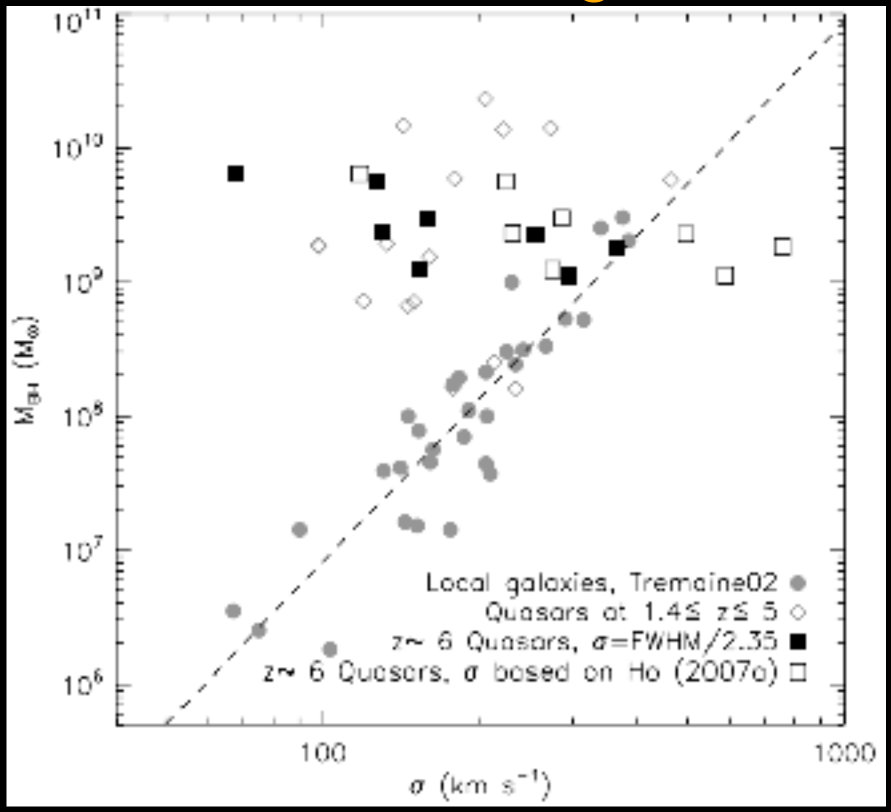
- ✶ Star formation history
- ✶ Quasar feedback?
- ✶ Chemical enrichment

Stars and gas in the hosts



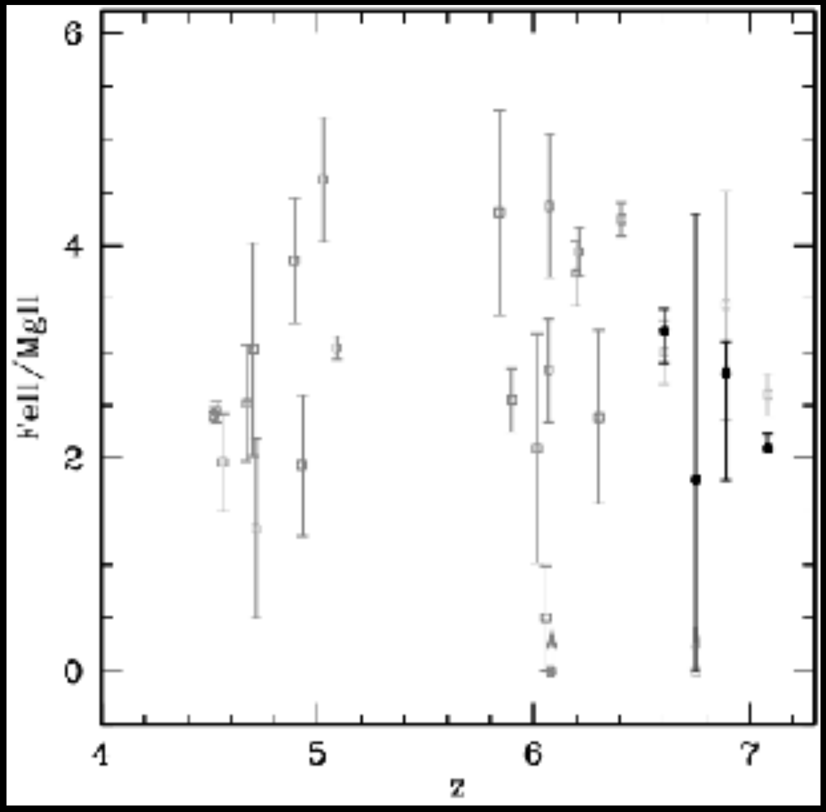
Venemans+16

Scaling relations



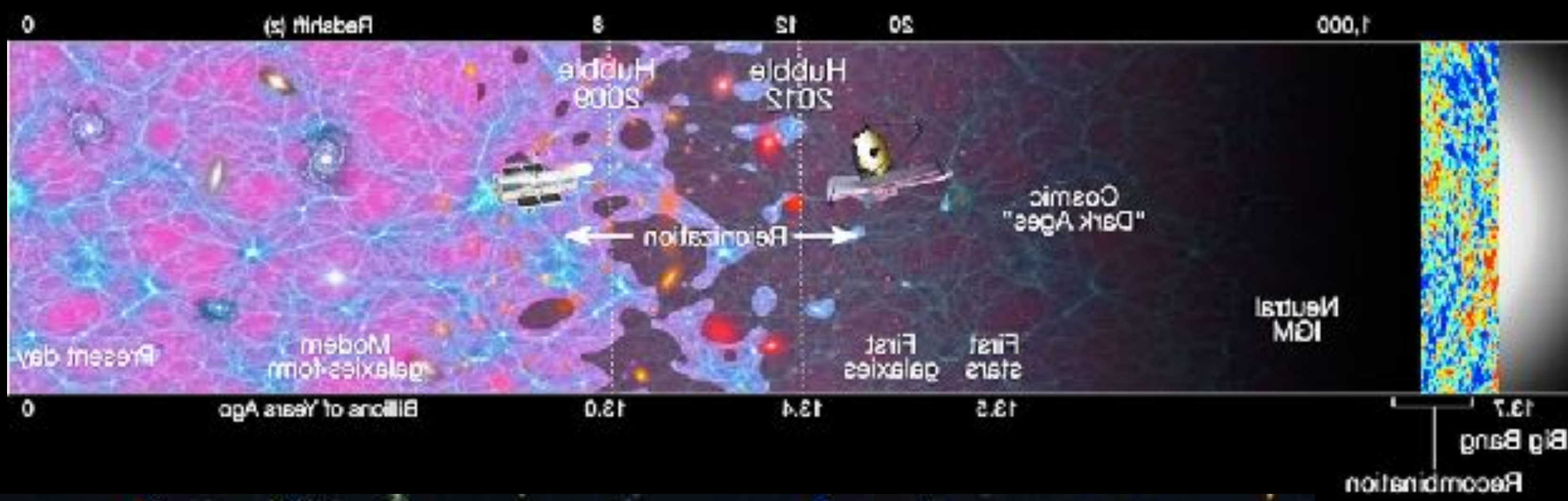
Wang+10

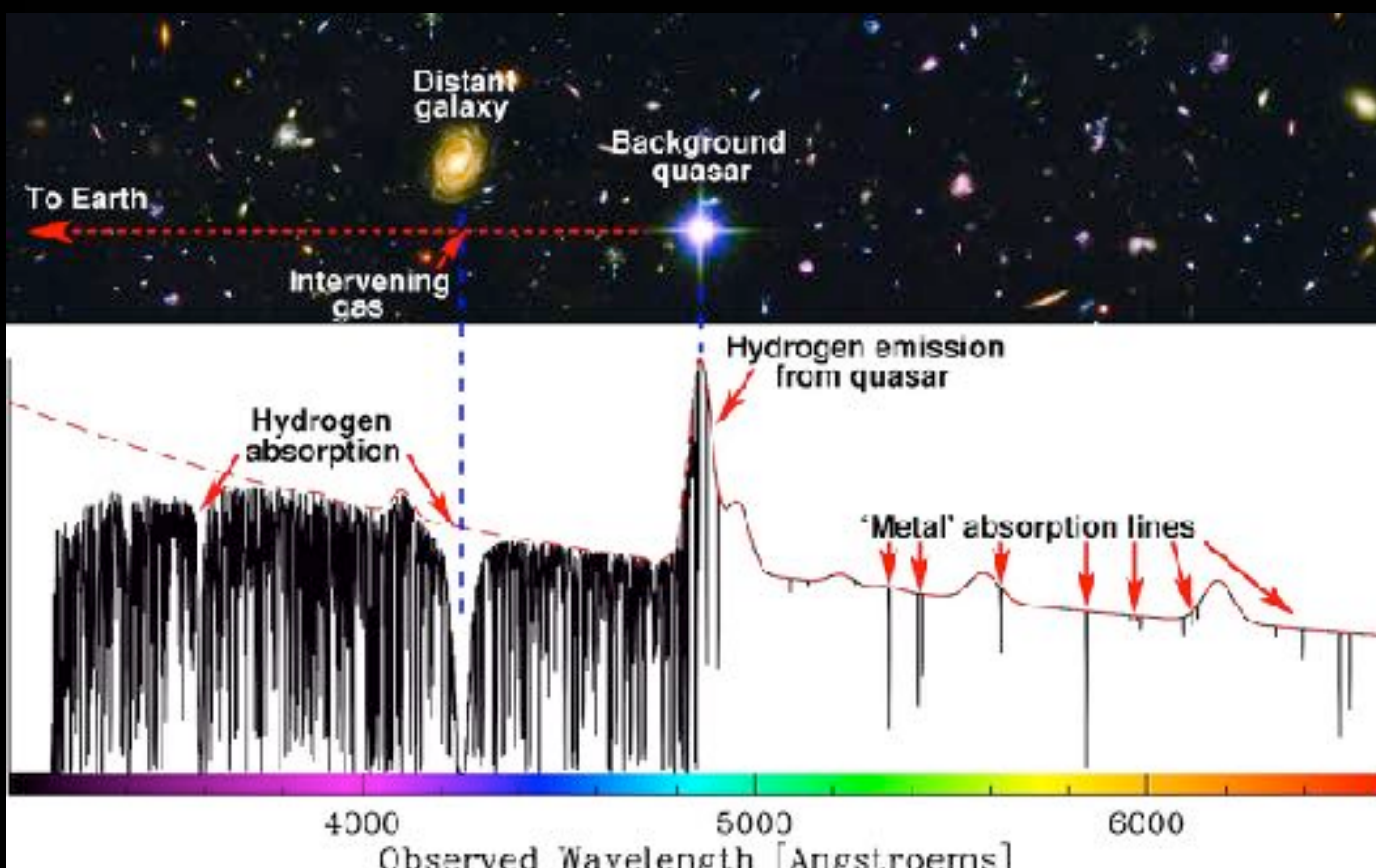
Chemical evolution

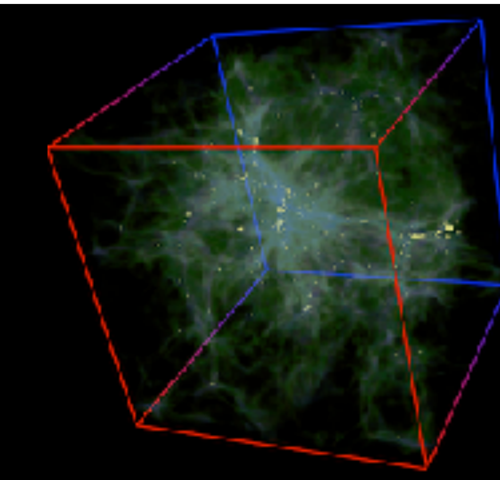


De Rosa+14

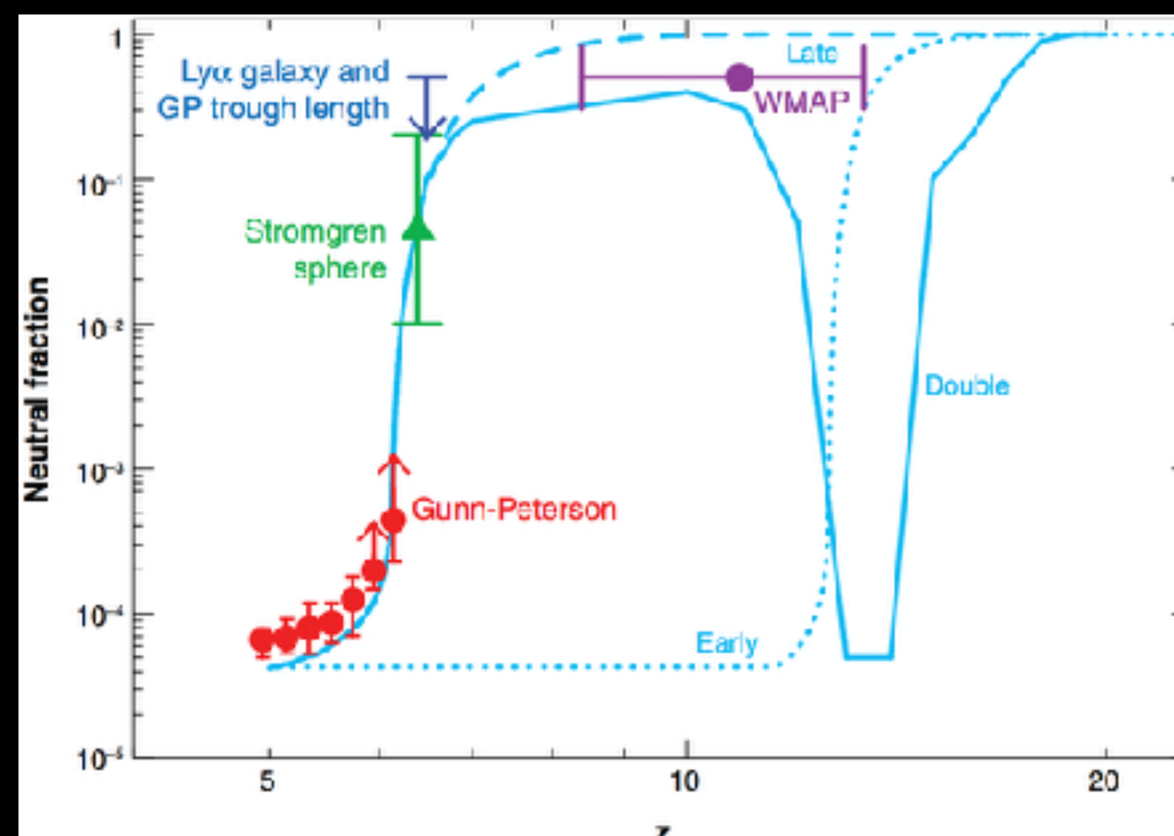
遠いクエーサーは、何を教えてくれるのか？





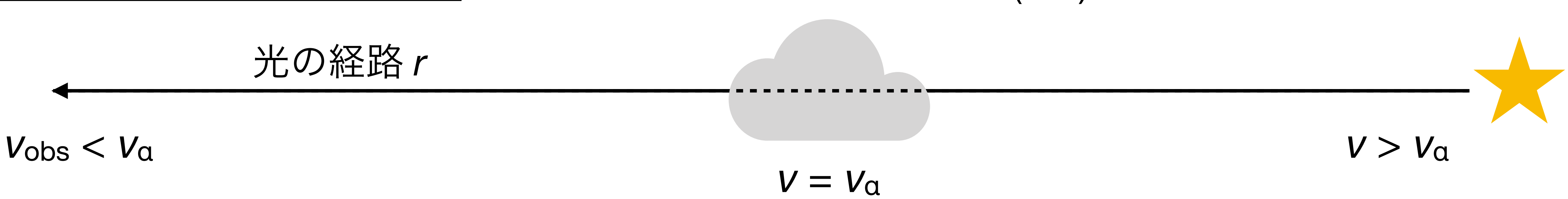


Cosmic Reionization
- ✶ When and where?
- ✶ How did it proceed?
- ✶ Ionizing sources?



Fan+06

✶ IGMにおけるLy α吸収



✓ 観測周波数ν_{obs} の光に対するIGM Ly α吸収の光学的深さは

水素 n = 2 → 1の崩壊率

$$\tau_\alpha = \int dr \sigma_\alpha(r) n_{\rm HI}(r) = \int c \frac{da}{aH} \left[\frac{3\Lambda_\alpha \lambda_\alpha^2}{8\pi} \delta(\nu - \nu_\alpha) \right] [x_{\rm HI} n_{\rm H}(z)]$$

原子のLy α吸収断面積

$$= \frac{3\Lambda_\alpha \lambda_\alpha^2}{8\pi} \int \frac{c}{H} \frac{d\nu}{\nu} \delta(\nu - \nu_\alpha) [x_{\rm HI} n_{\rm H}(z)]$$

$$\nu_{\rm obs} = a\nu$$

$$= \frac{3\Lambda_\alpha \lambda_\alpha^2}{8\pi} \frac{c}{\nu_\alpha} \frac{x_{\rm HI} n_{\rm H}(z_{\rm abs})}{H(z_{\rm abs})}$$

$$\nu_\alpha = \frac{\nu_{\rm obs}}{a_{\rm abs}} = \nu_{\rm obs}(1 + z_{\rm abs})$$

$$\simeq 1.6 \times 10^5 x_{\rm HI} (1 + \delta_{\rm abs}) \left(\frac{1 + z_{\rm abs}}{4} \right)^{\frac{3}{2}}$$

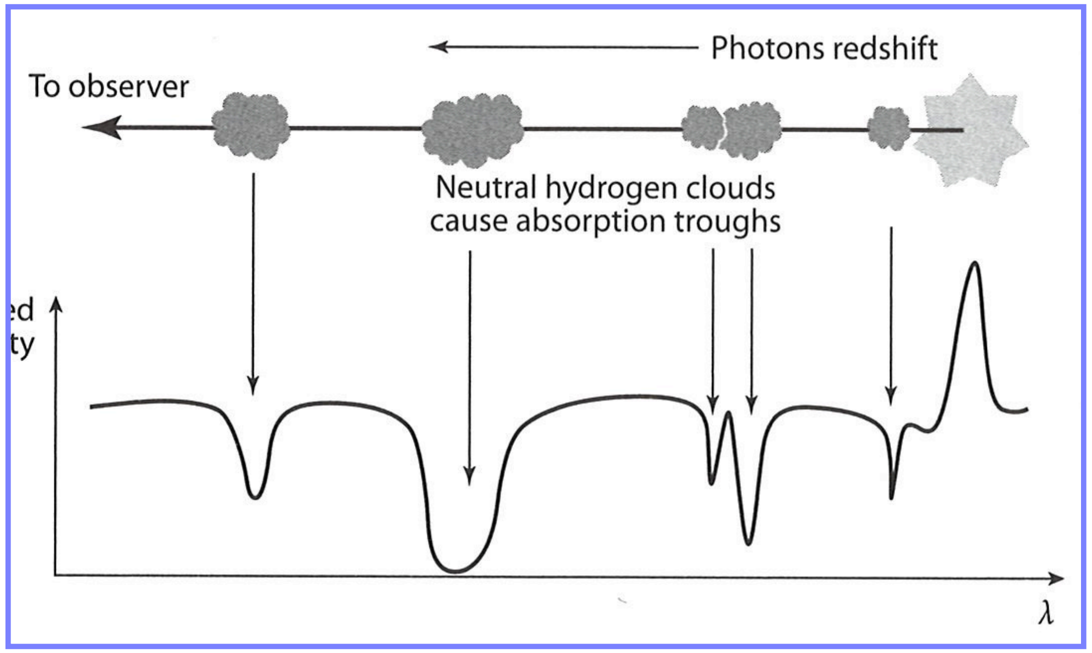
密度揺らぎ

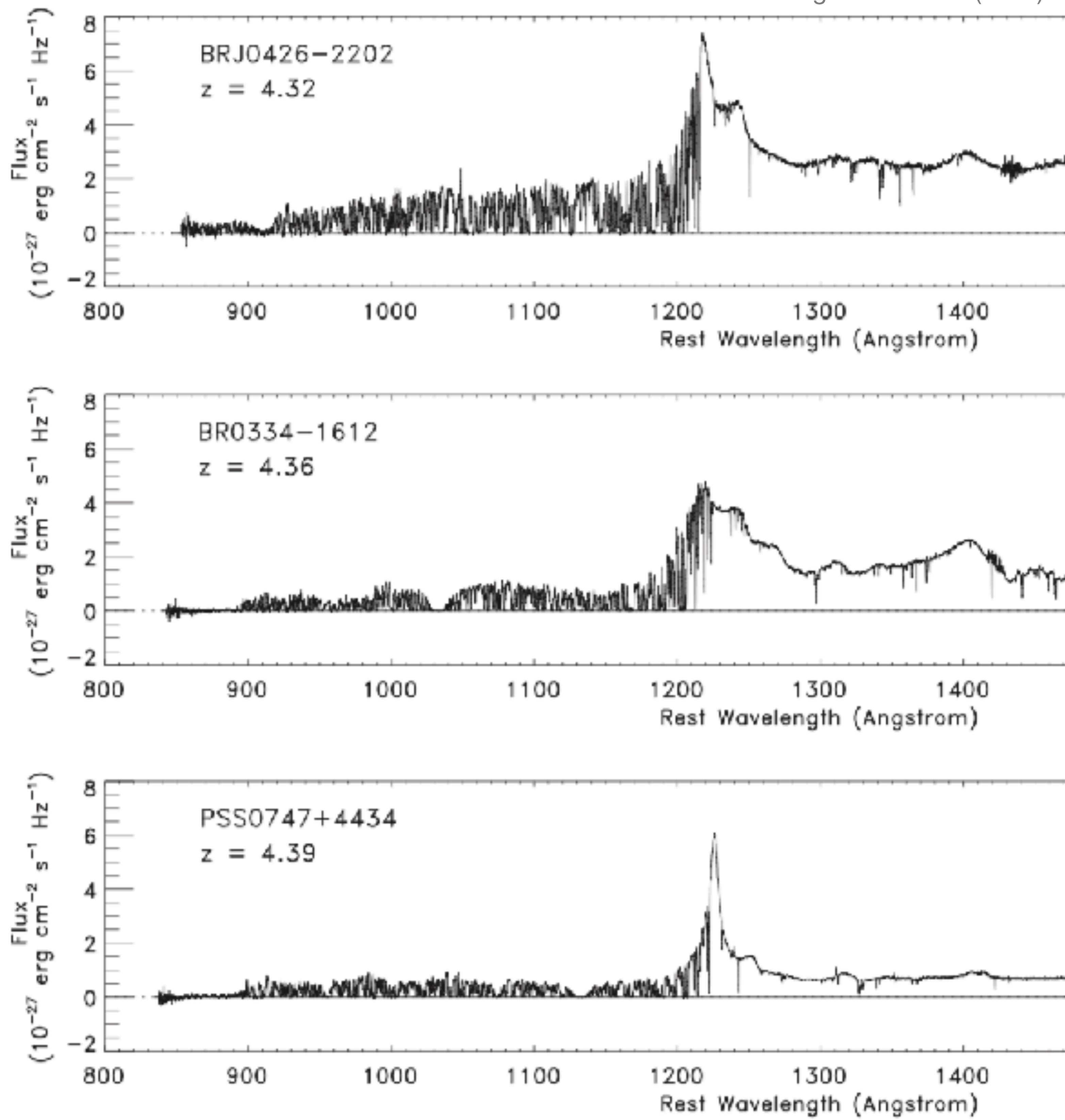
→ わずかな中性水素 (x_{HI} ~ 10^{-4}) によって、IGMはLy αに対して極めて不透明になる

✶ “Lyman-α forest”

Songaila & Cowie (2010)

$$\nu_\alpha = \frac{\nu_{\rm obs}}{a_{\rm abs}} = \nu_{\rm obs}(1 + z_{\rm abs})$$

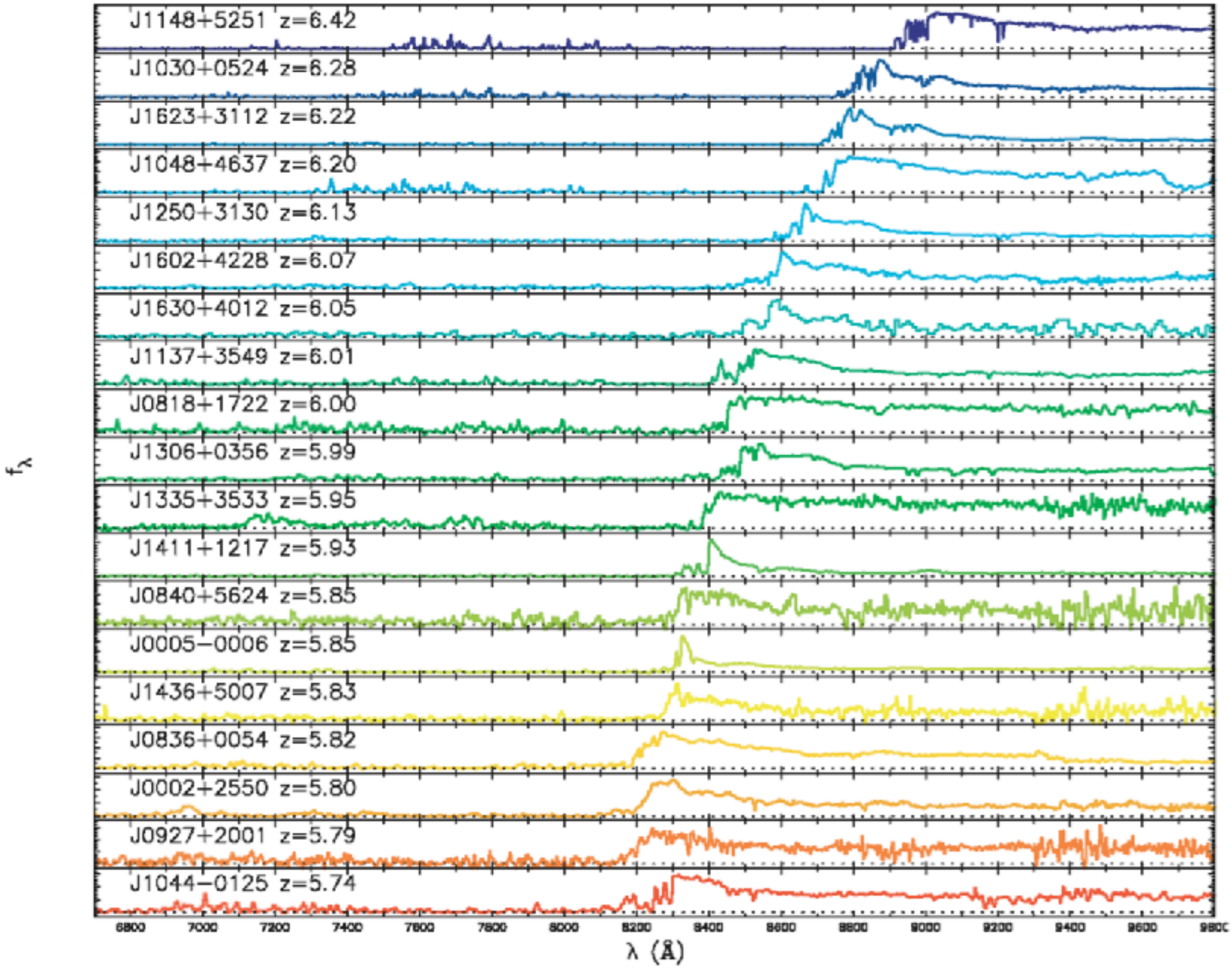




→ 背景光源スペクトルに刻まれる Lyman-α forestから、視線上のIGMの分布を調べられる

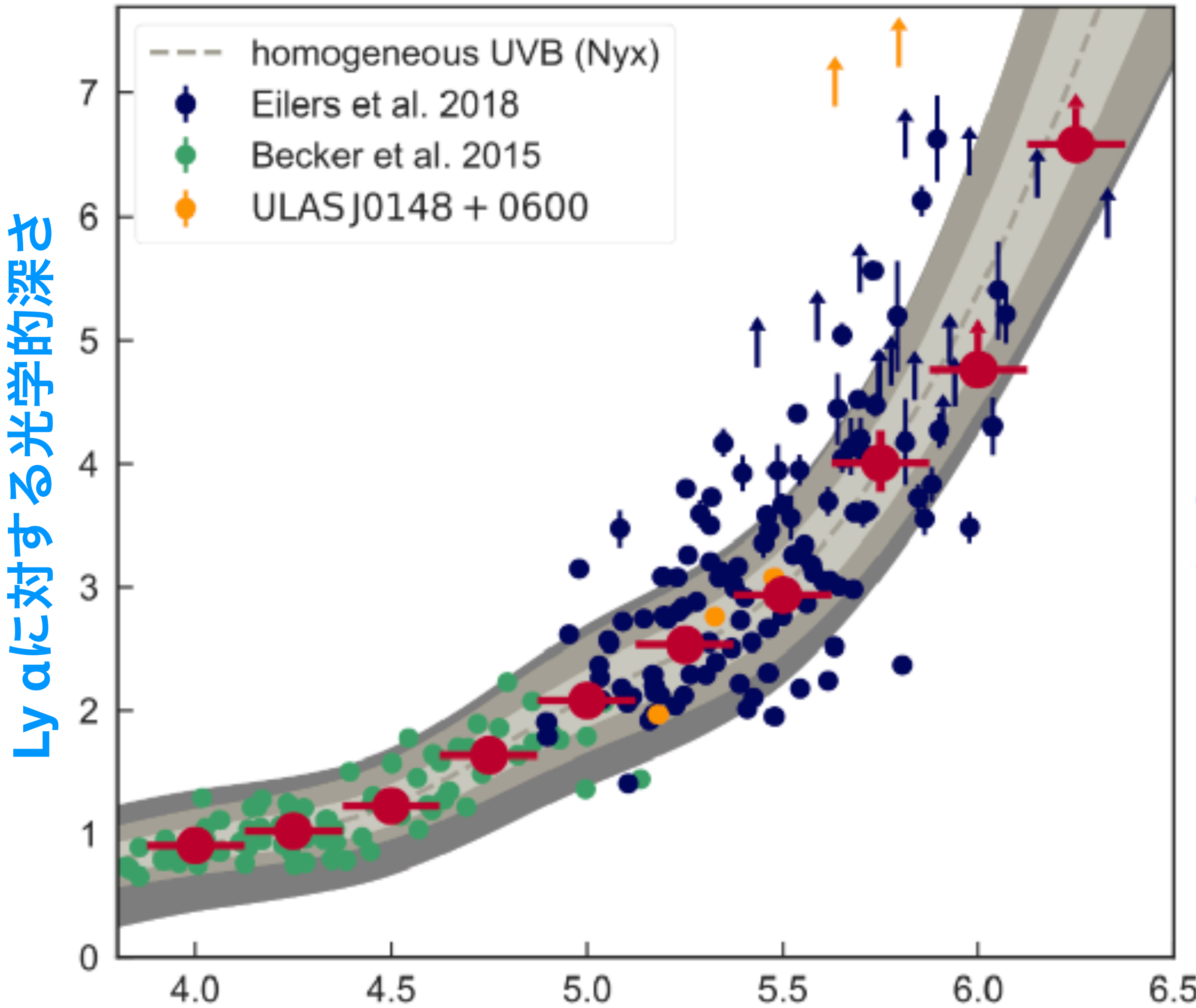
✶ "Gunn-Peterson trough"

Fan et al. (2006)

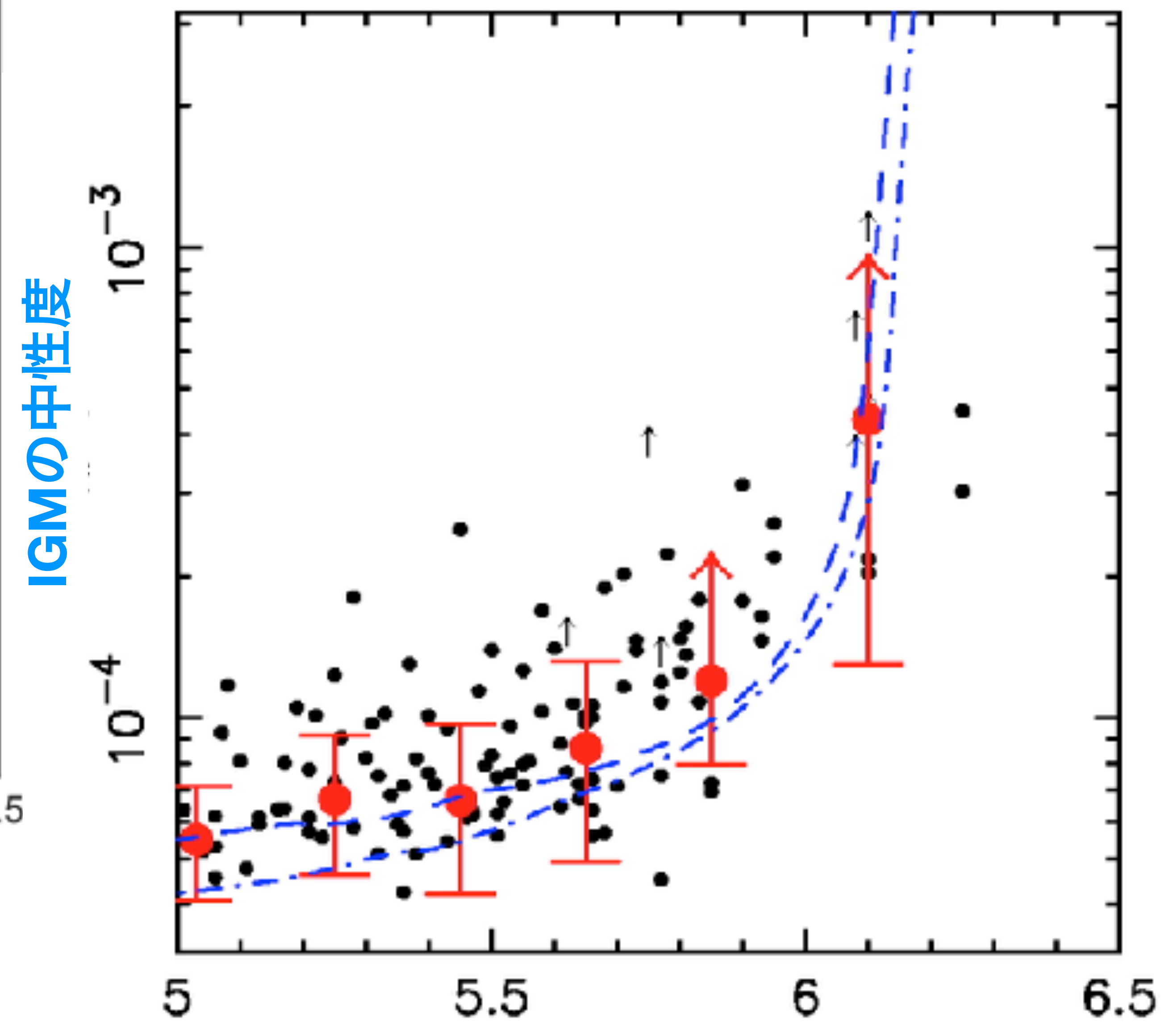


✶ “Gunn-Peterson trough”

$$\tau_\alpha \simeq 1.6 \times 10^5 x_{\rm HI} (1+\delta_{\rm abs}) \left(\frac{1+z_{\rm abs}}{4}\right)^{\frac{3}{2}}$$

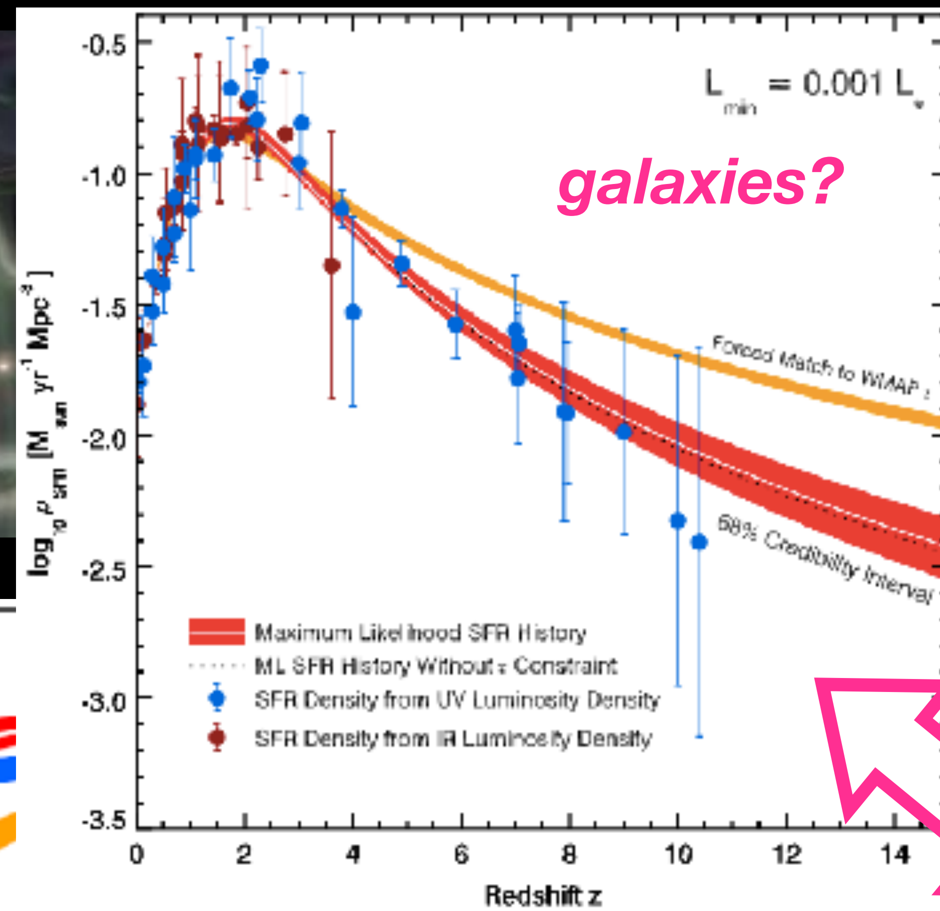


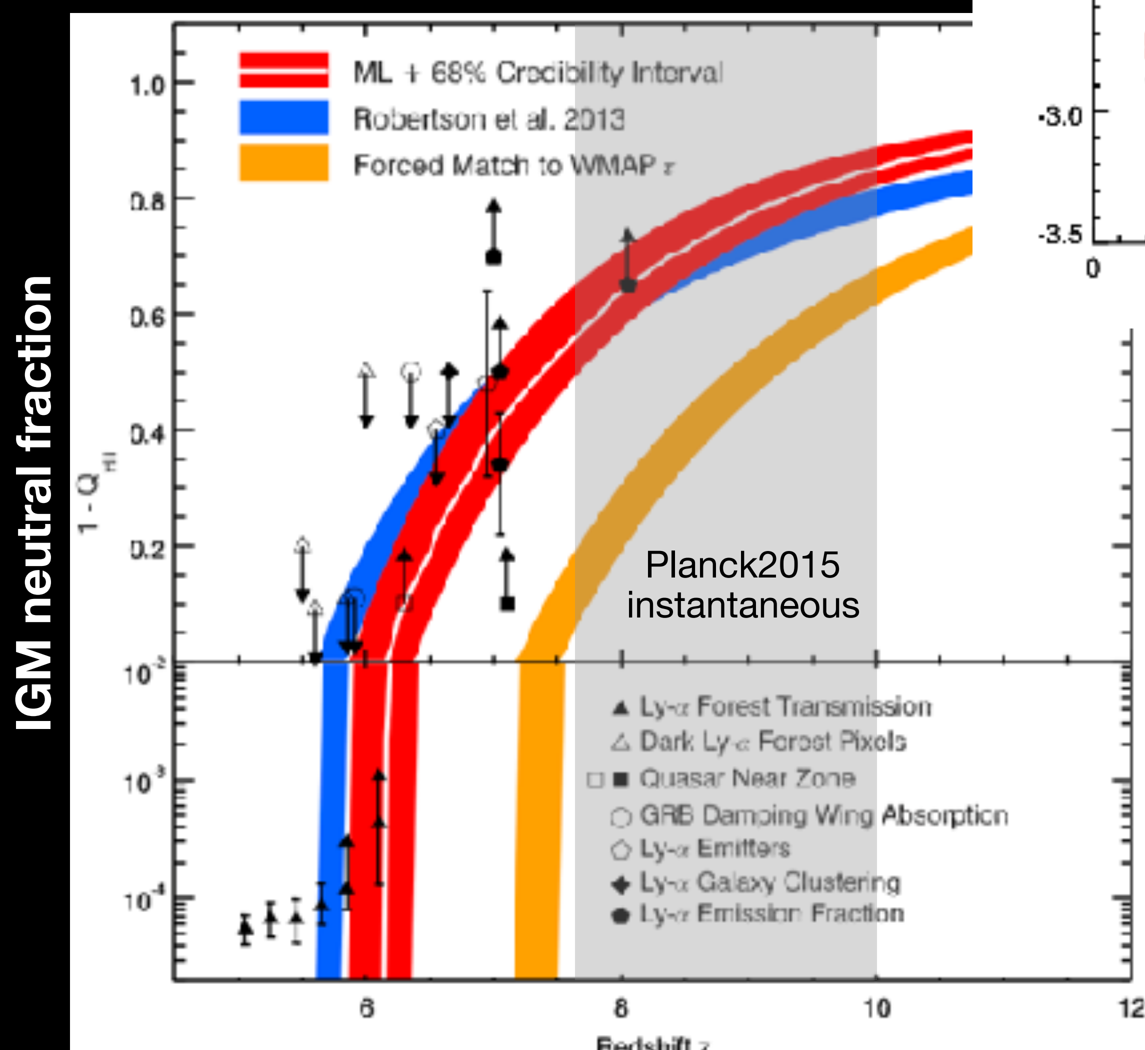
Eilers et al. (2018)



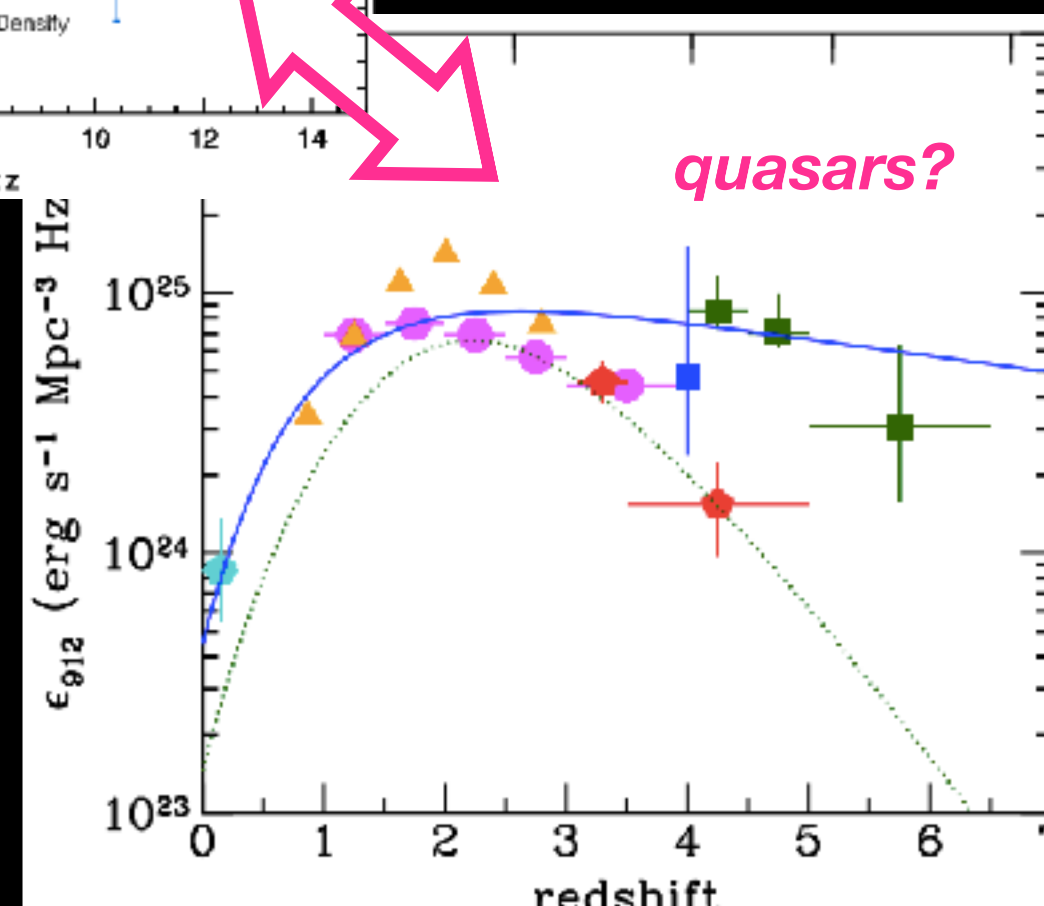
Fan et al. (2006)

遠いクエーサーは、何を教えてくれるのか？





(Robertson+15)



(Madau+15)

Past/ongoing high-z quasar surveys

SDSS 2.5m

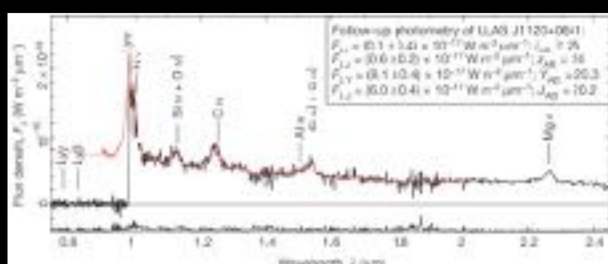
CFHT 3.6m

UKIDSS/VIKING 4m

Pan-STARRS1 1.8m

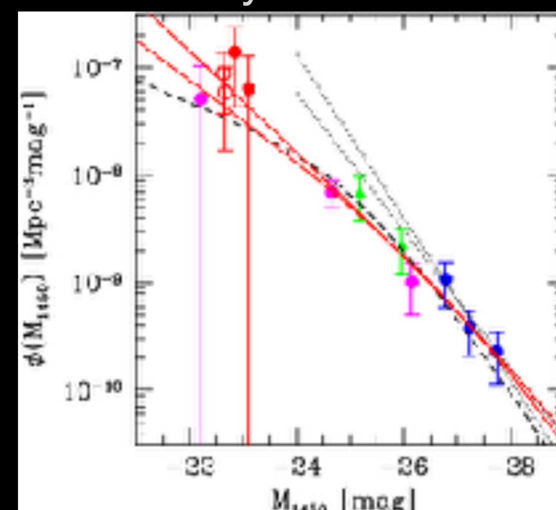
DES 4m

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



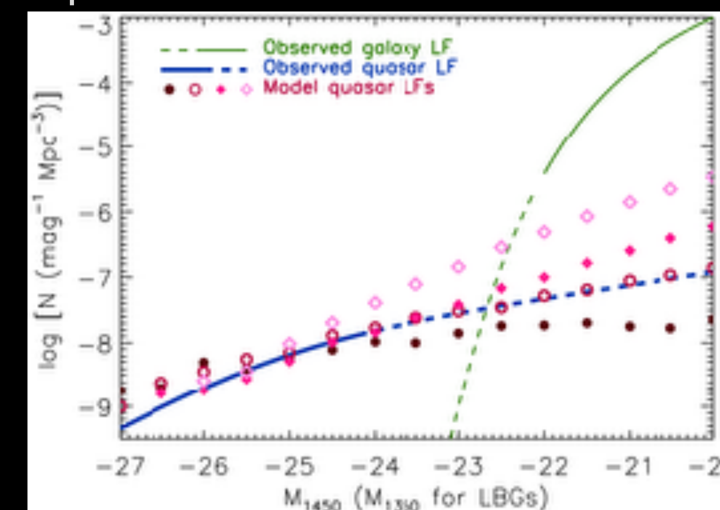
Mortlock+11

Luminosity function



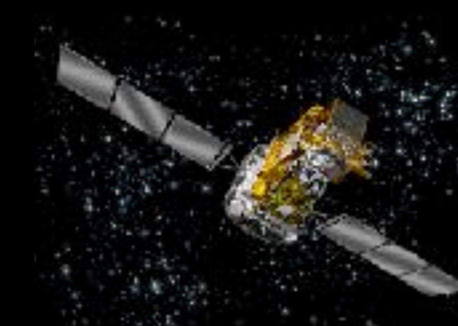
Kashikawa+15

Comparison with theoretical models

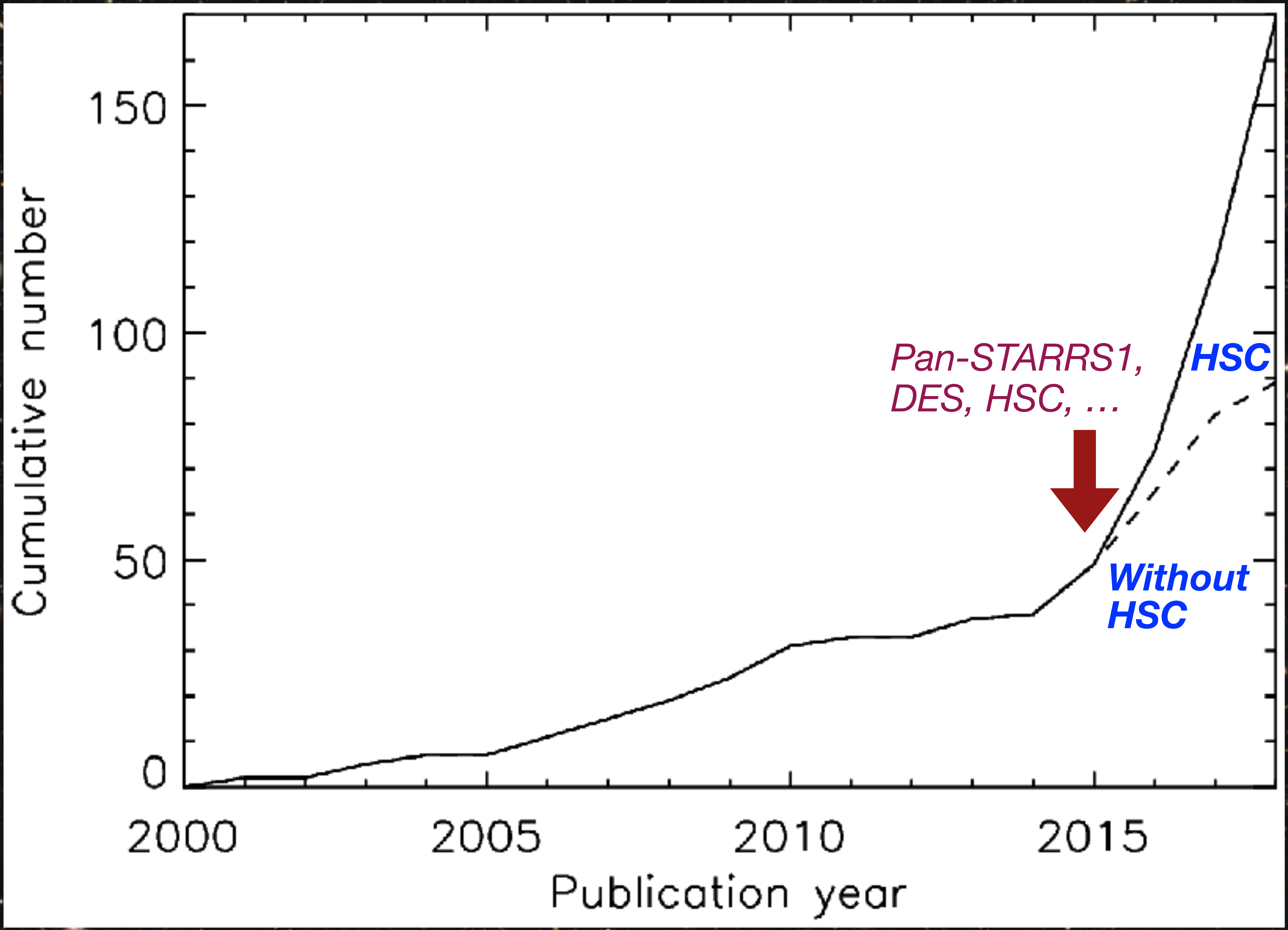


A wide variety of follow-up observations with

✶ 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, ...

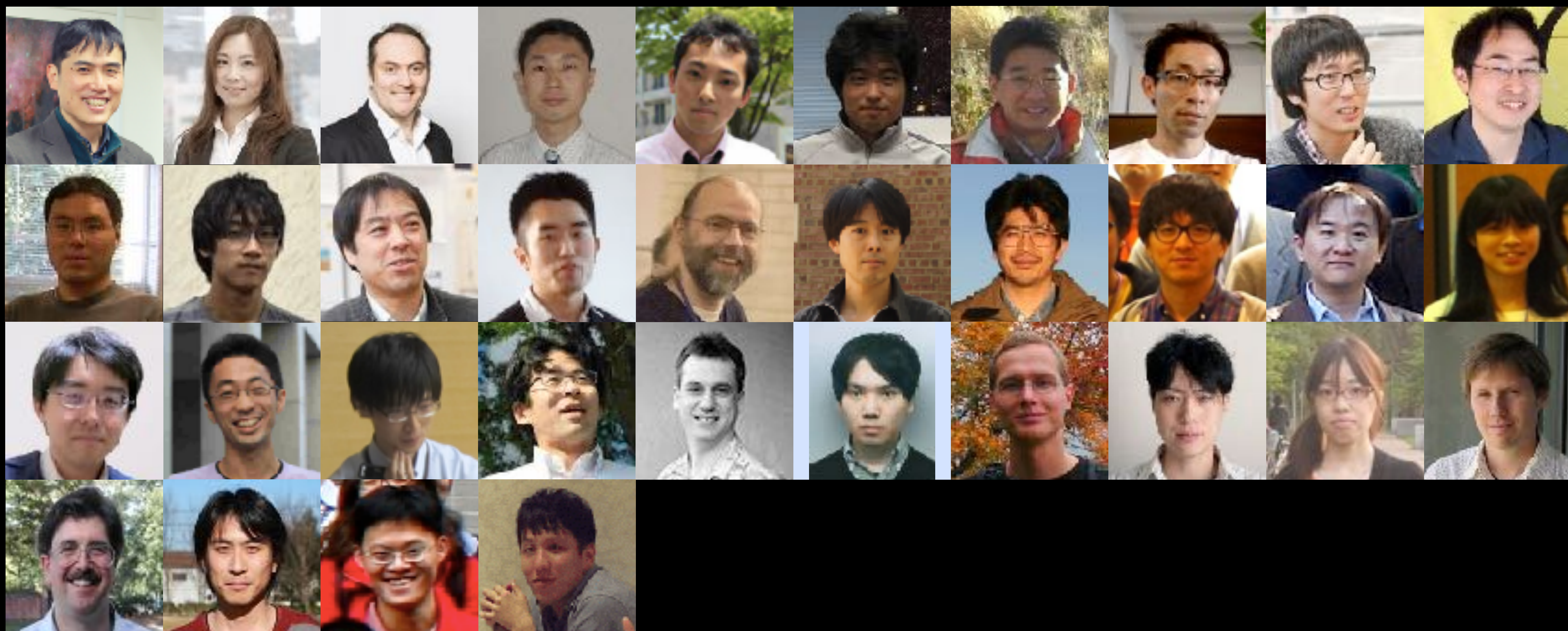


z > 6クエーサーの積算発見数



SHELLQs

Subaru High-z Exploration of Low-Luminosity Quasars

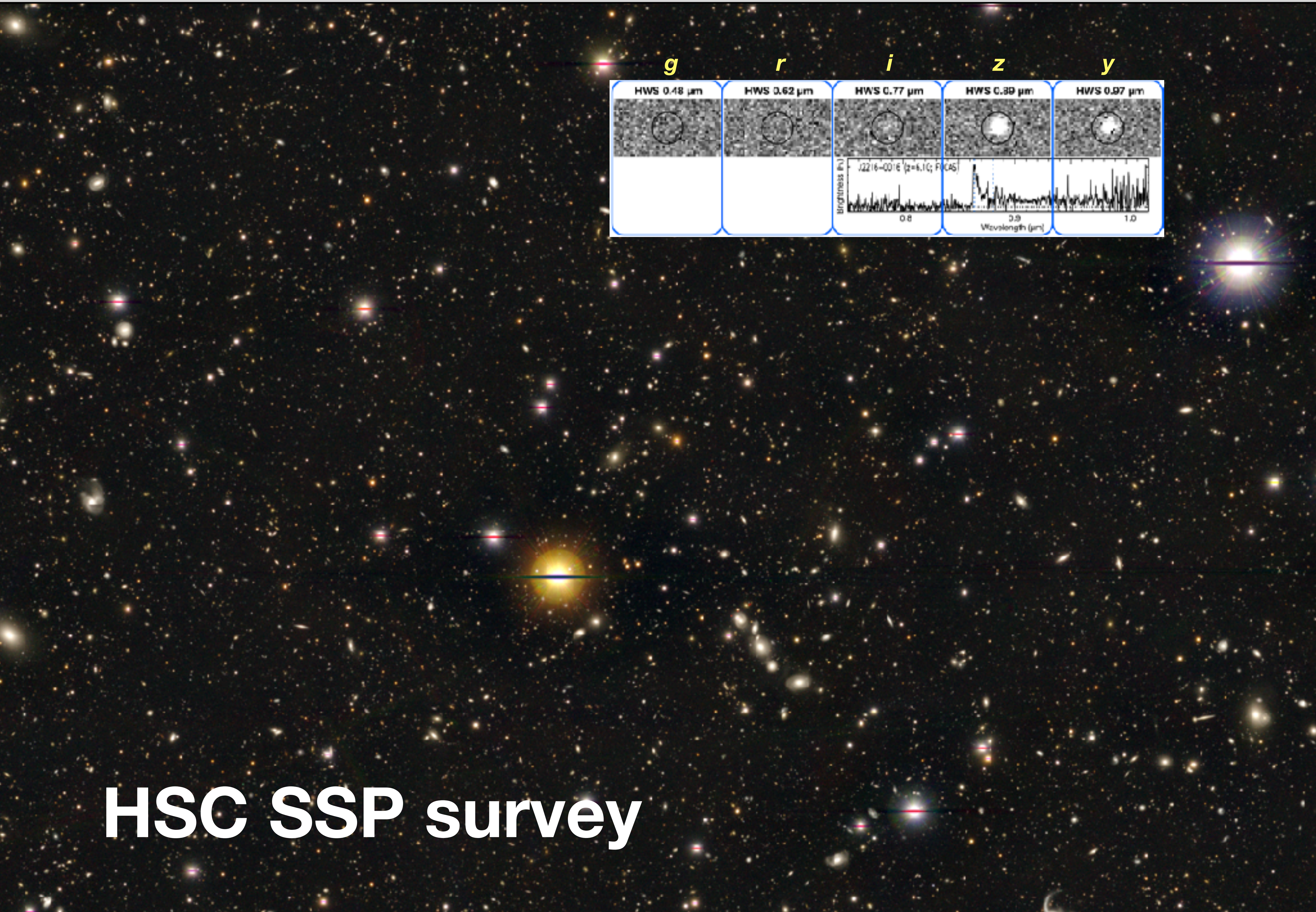


Members

Y. Matsuoka[1] (PI)

M. Akiyama[2], N. Asami[3], S. Foucaud, T. Goto[4], Y. Harikane[5], H. Ikeda[1], M. Imanishi[1], K. Iwasawa[6], T. Izumi[5], N. Kashikawa[1] T. Kawaguchi[7], S. Kikuta[1], K. Kohno[5], C.-H. Lee[1], R. H. Lupton[9], T. Minezaki[5], T. Morokuma[5], T. Nagao[8], M. Niida[8], M. Oguri[5], Y. Ono[5], M. Onoue[1], M. Ouchi[5], P. Price[9], H. Sameshima[10], A. Schulze[5], T. Shibuya[5], H. Shirakata[11], J. D. Silverman[5], M. A. Strauss[9], M. Tanaka[1], J. Tang[12], Y. Toba[8]

[1]NAOJ, [2]Tohoku, [3]JPSE, [4]Tsinghua, [5]Tokyo, [6]Barcelona, [7]Sapporo Medical, [8]Ehime, [9]Princeton, [10]Kyoto Sangyo, [11]Hokkaido, [12]ASIAA

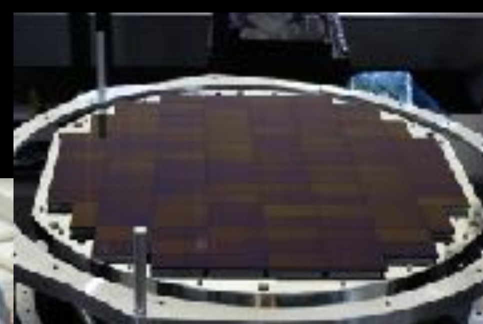


HSC SSP survey

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**

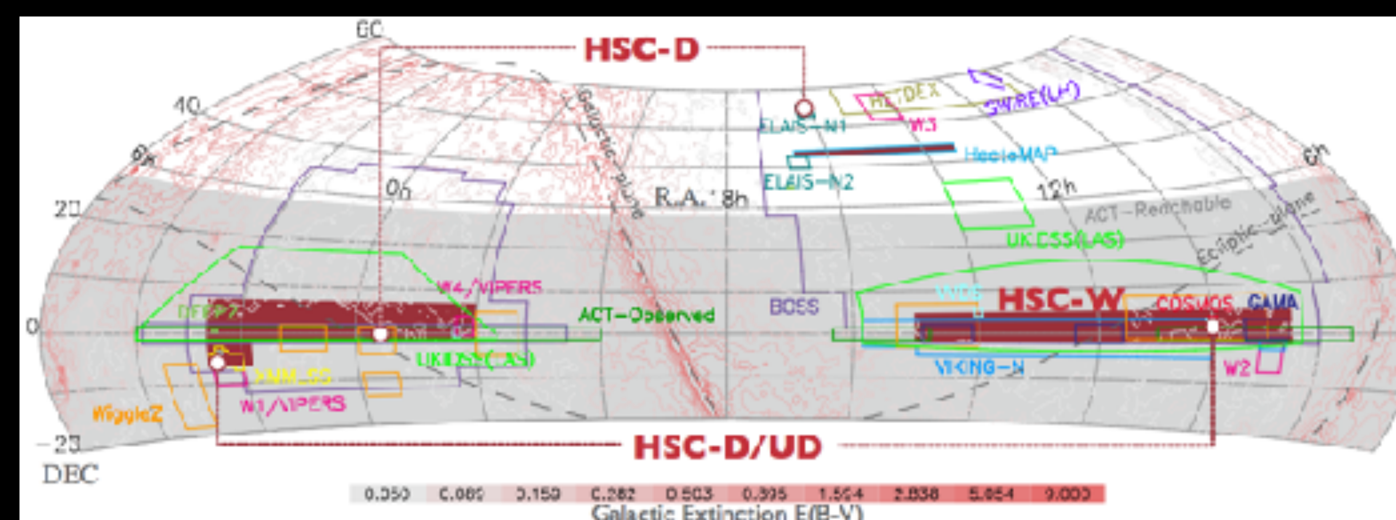


Table 7: Quasar Samples

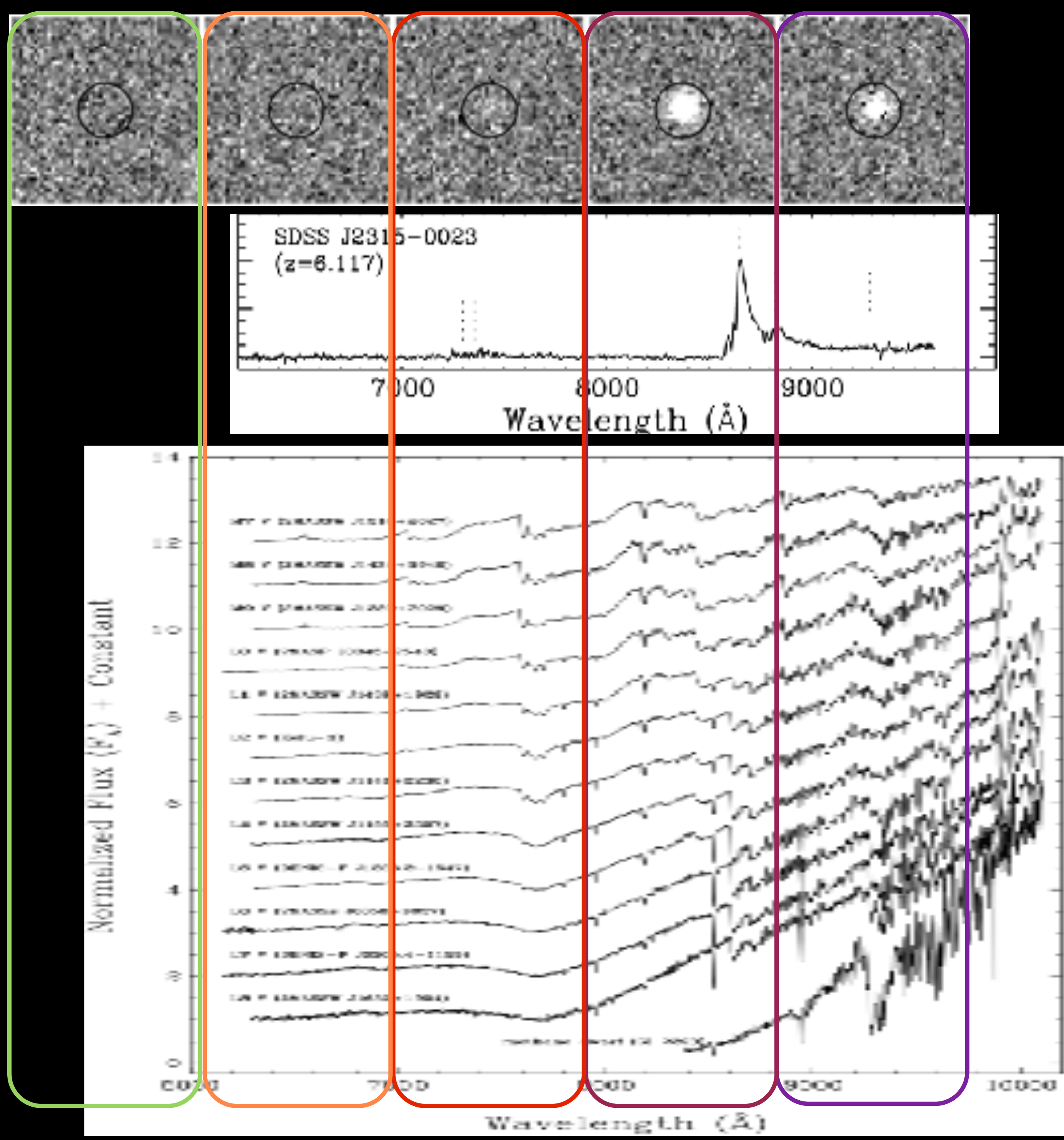
	Wide (1400 deg^2)				Deep (27 deg^2)			
redshift	3.7–4.6	4.6–5.7	5.9–6.4	6.6–7.2	< 1	3.7–4.6	4.6–5.7	6.6–7.2
mag. range	$r < 23.0$	$i < 24.0$	$z < 24.0$	$y < 23.4$	$i < 25.0$	$i < 25.0$	$i < 25.0$	$y < 25.3$
number	6000	3500	280	50	2000	200	50	3


“Needle in a haystack”

Survey strategy

1. Look for red point sources in the HSC catalog
   (+ UKIDSS/VIKING catalog)

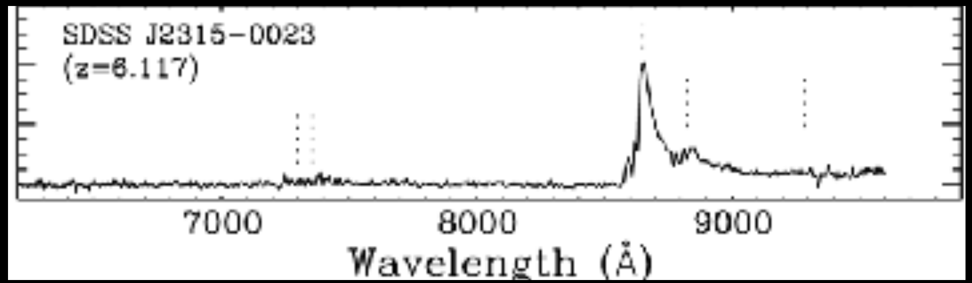
g r i z y



(2. Follow-up photometry)

3. Follow-up spectroscopy

4. Discovery



Bayesian probabilistic selection

Prioritization of the candidates with the probabilistic approach:

P_Q = the Bayesian probability of being a high-z quasar rather than a Galactic brown dwarf

= $W_Q/(W_Q+W_D)$ where $W_{Q/D}$ is the weighted evidence of being a quasar/dwarf.

observed magnitudes

the fact of detection

(model) magnitude and redshift

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

(1) Quasar LF and its evolution (Willott+10)

0 if $m_{int} > m_{limit}$

1 if $m_{int} < m_{limit}$

(2) Mean quasar colors from ~340 SDSS quasars at z~3 with the Songaila (2004) IGM opacity

(3) multi-D Gaussian error function with $\sigma = \mathbf{m}_{err}$

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

(4) Galactic brown-dwarf distribution model (Caballero+08)

(5) SpeX and CGS4 spectral library

Bayesian probabilistic selection

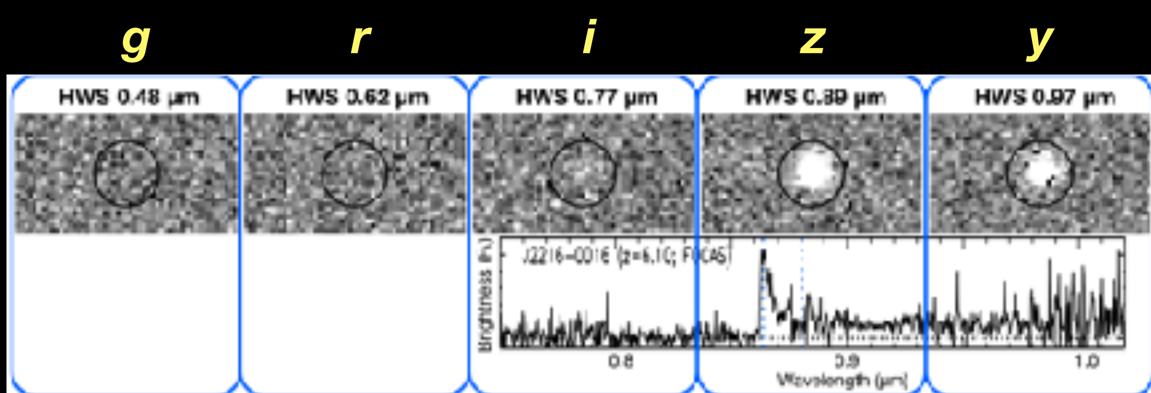
Quasar probability: $P_Q = W_Q/(W_Q+W_D)$

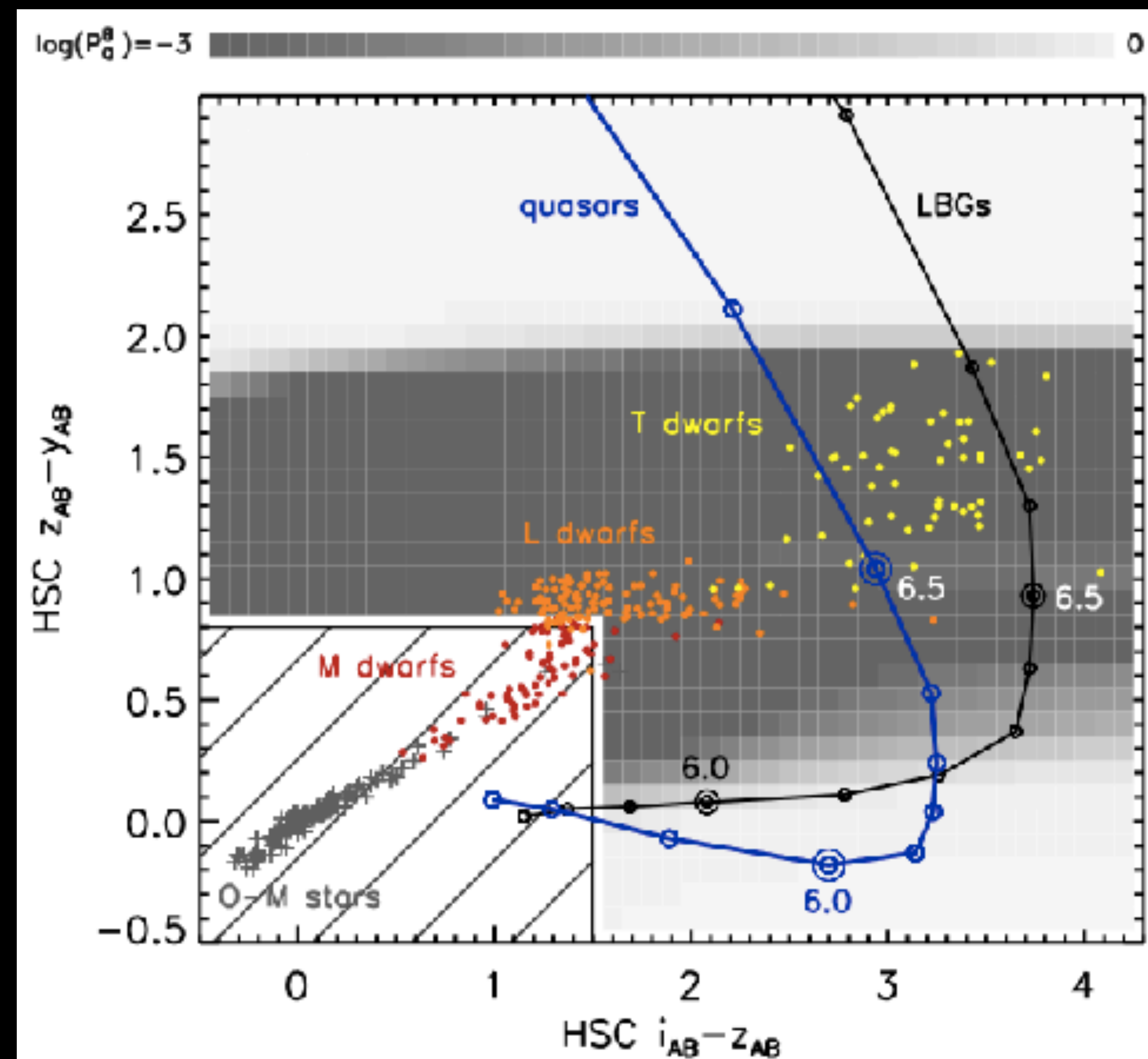
$W_Q(\mathbf{m}, det) = \int\int \rho_Q(m_{int}, z)\, Pr(det \mid m_{int}, z)\, Pr(\mathbf{m} \mid m_{int}, z)\, dm_{int}\, dz$

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

observed magnitudes in HSC + NIR bands (→ **m**)

source detection (→ det)





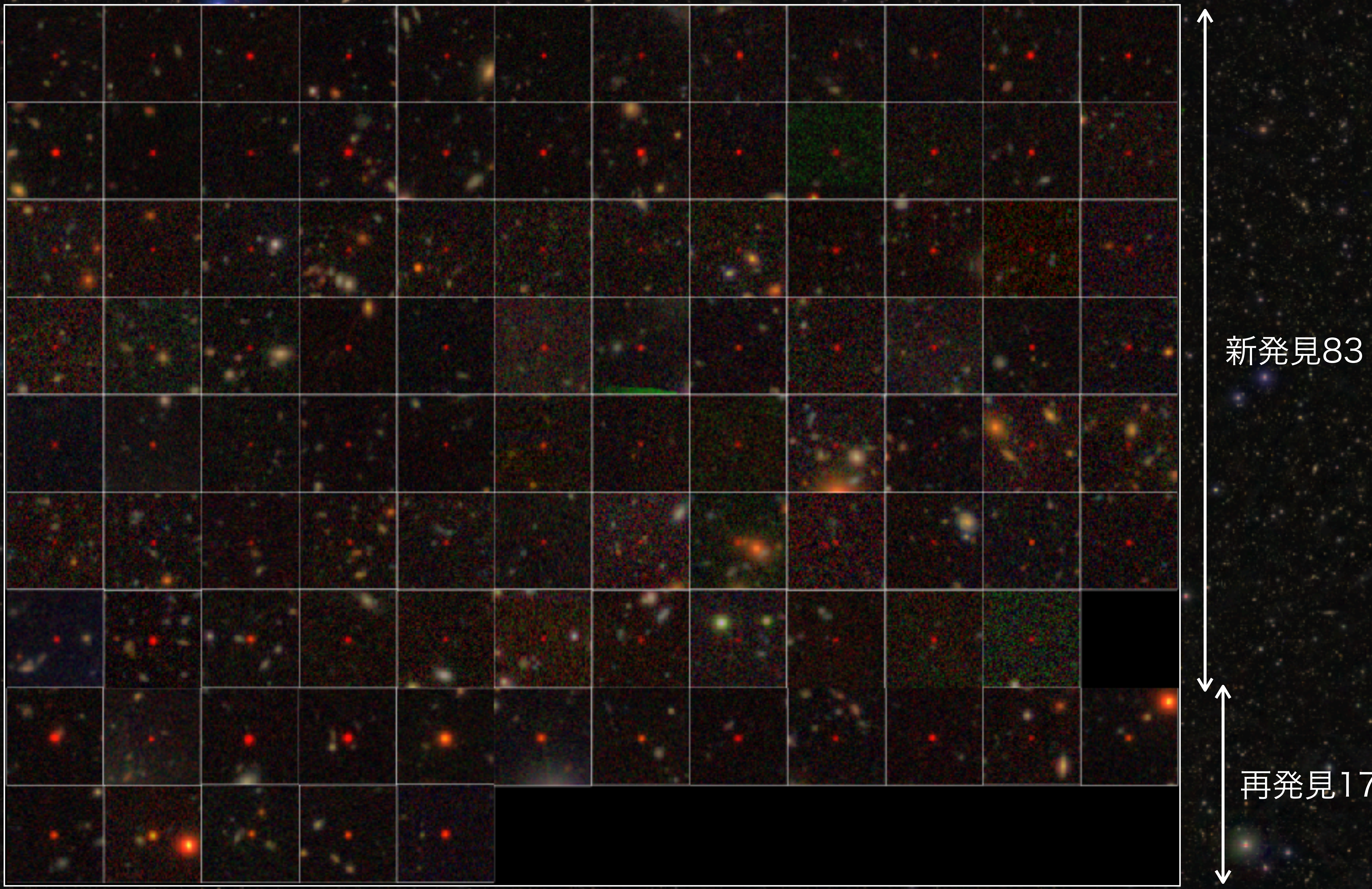
→ Spectroscopic follow-up of all the photometric candidates with $P_Q > 0.1$

Brief summary of the SHELLQs progress

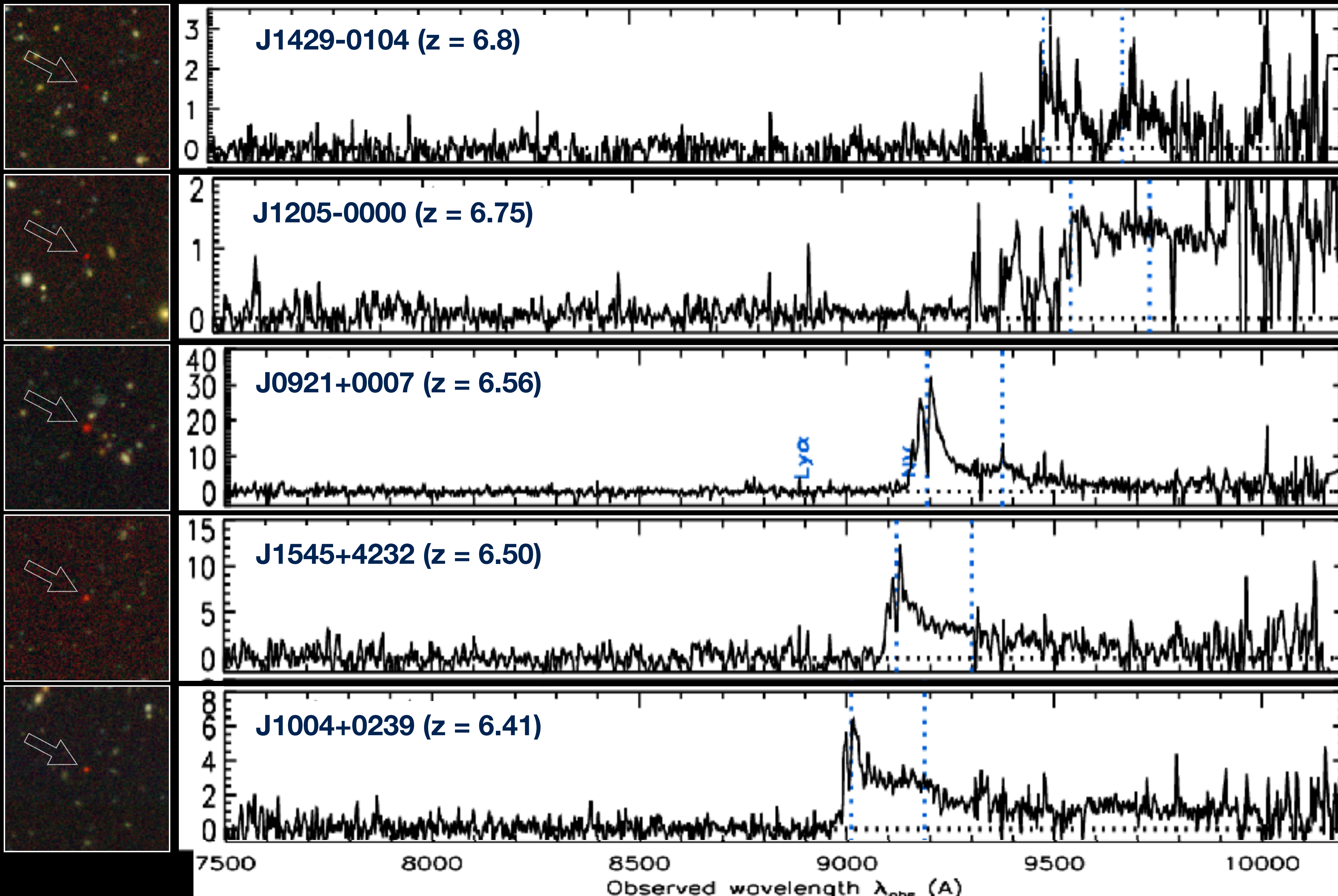
- ✶ HSC-SSP survey: the latest, S18A data release contains ~1 billion objects over ~900 deg^2 (>1 exposures in *i*, *z*, and *y*) in the Wide fields.
- ✶ Candidate selection: ~300 candidates with ($z_{AB} < 24.5$ or $y_{AB} < 24.0$) & $P_Q > 0.1$.
- ✶ Spectroscopic follow-up is underway, with Subaru, 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 83 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+18a): more discovery of 24 quasars
  - Paper III (Izumi+18): ALMA follow-up
  - Paper IV (Matsuoka+18b): more discovery of 31 quasars
  - Paper V (Matsuoka+18c): quasar luminosity function at z = 6
  - Paper VI (Onoue+, in prep.): black-hole mass measurements
  - Paper VII (Matsuoka+19): discovery of a z = 7.07 quasar

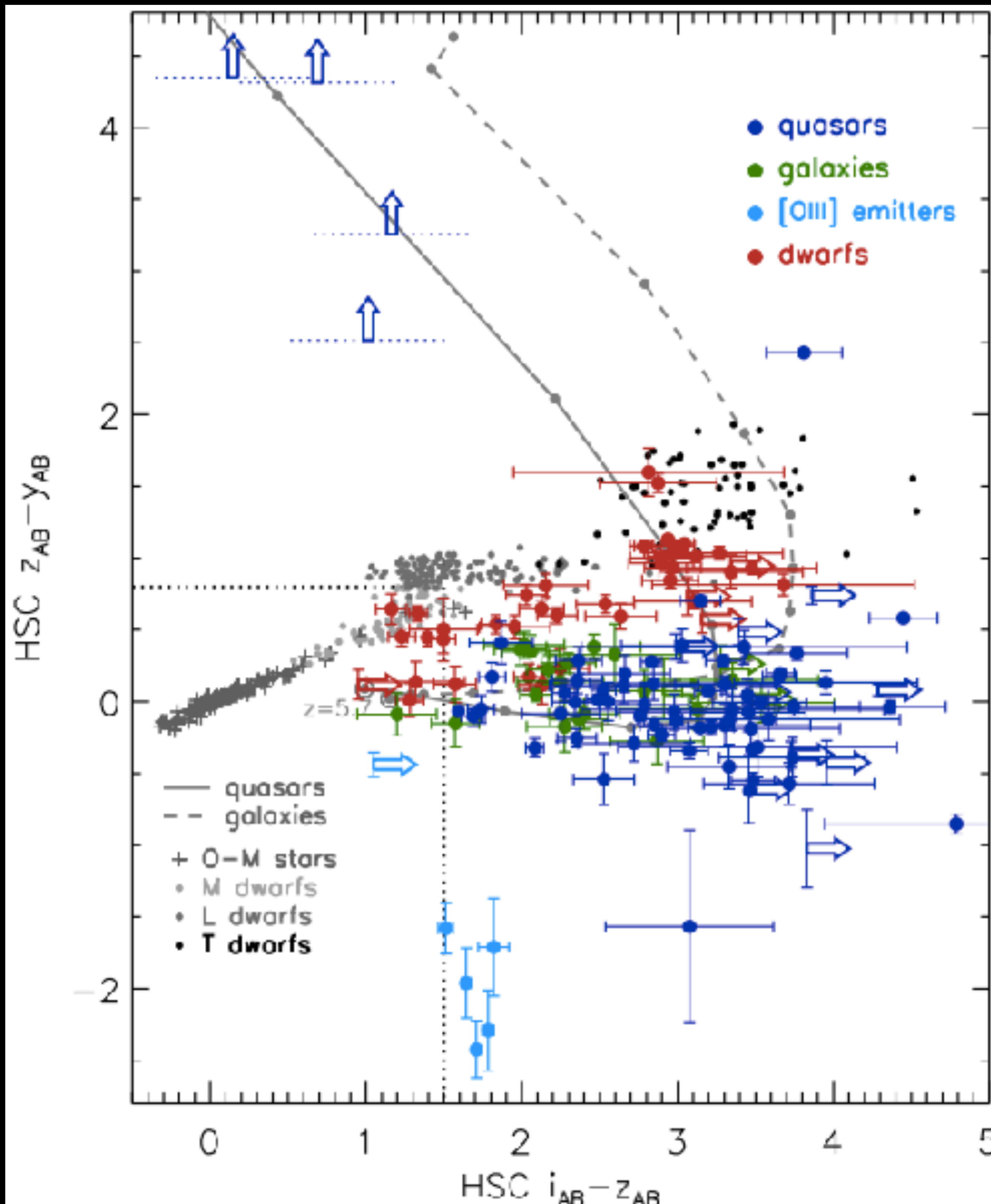
発見された遠方クエーサー群

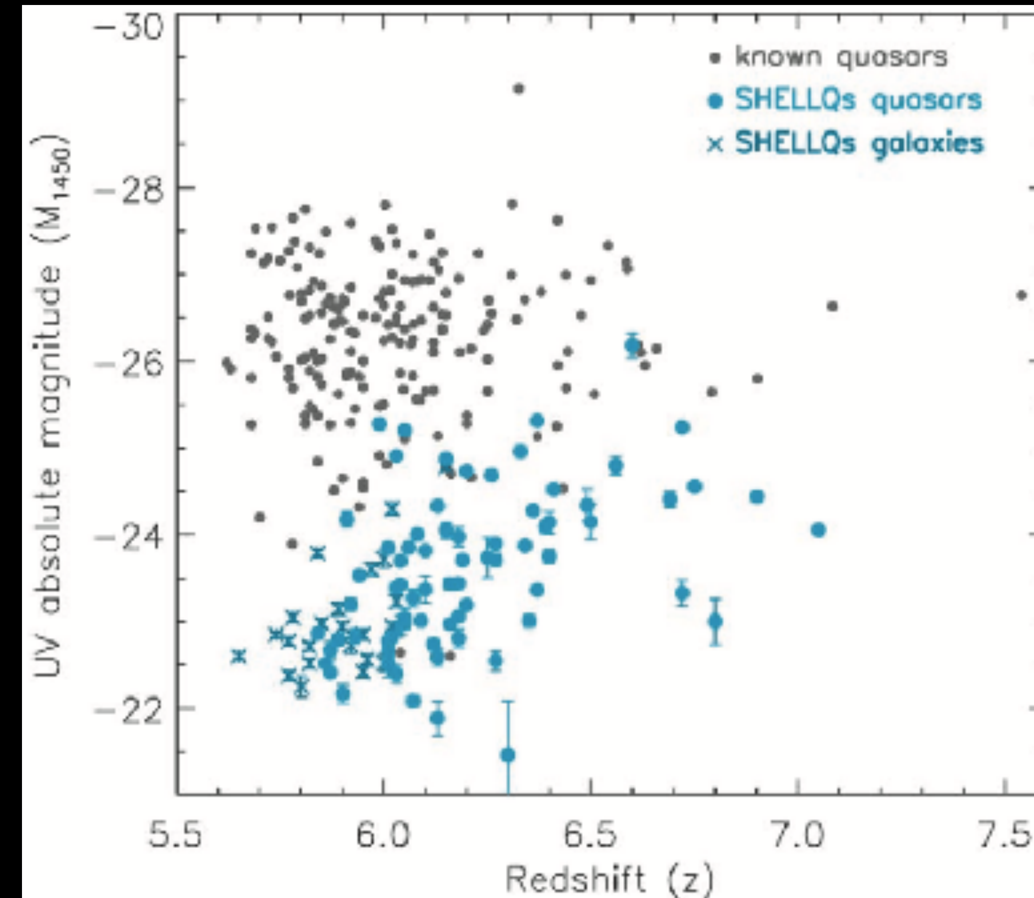


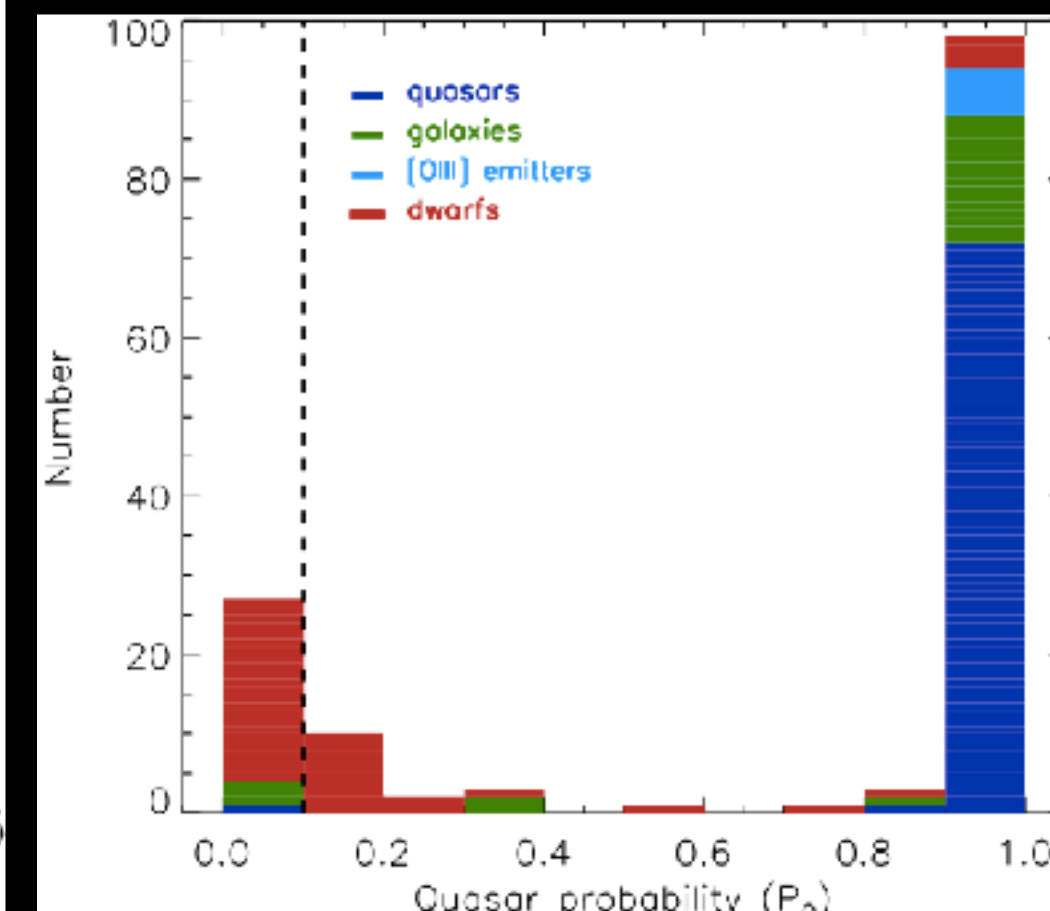
発見天体の例


J1429-0104 (z = 6.8)
J1205-0000 (z = 6.75)
J0921+0007 (z = 6.56)
Lyα
J1545+4232 (z = 6.50)
J1004+0239 (z = 6.41)
7500
8000
8500
9000
9500
10000
Observed wavelength λobs (A)

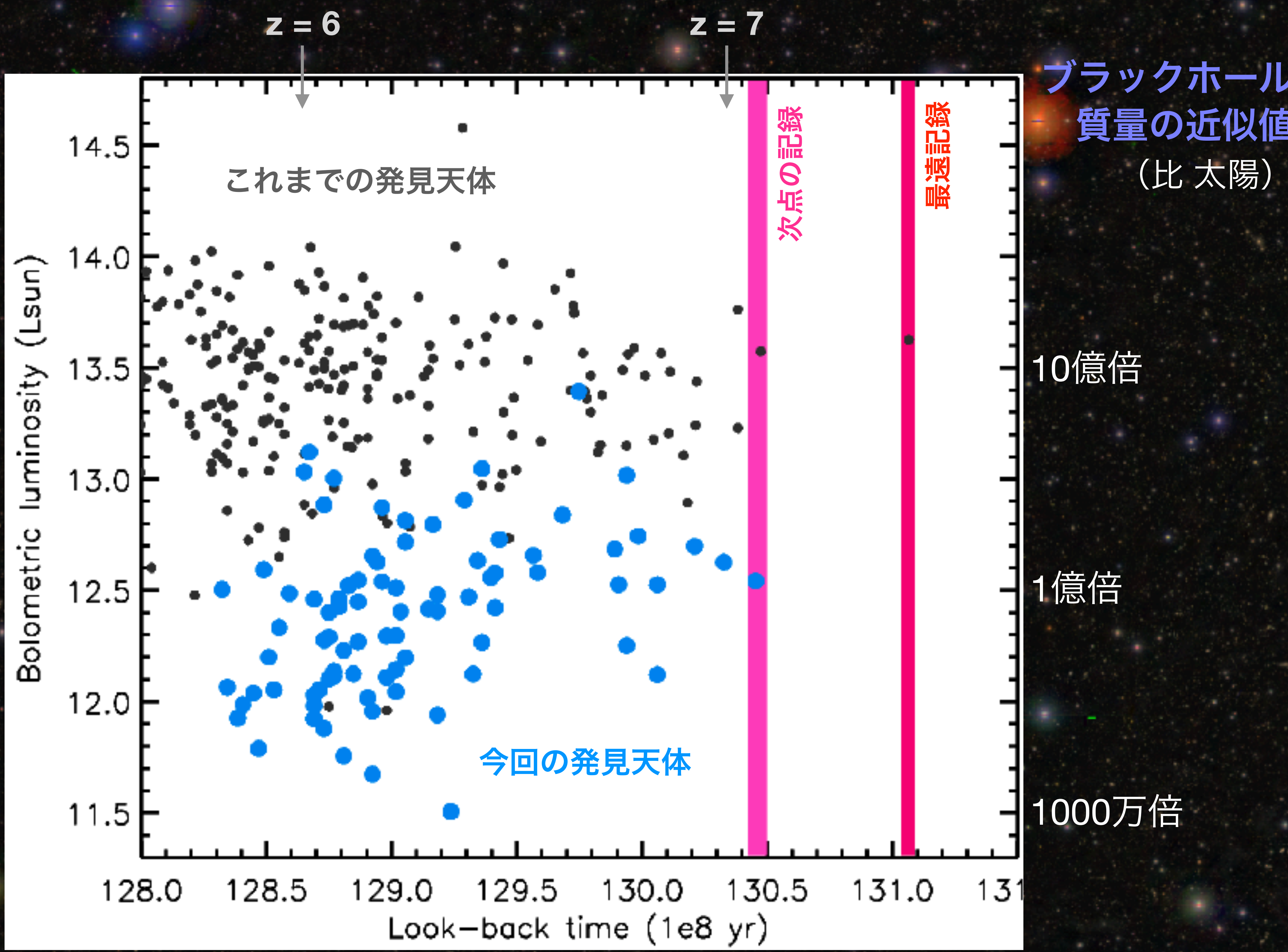
Highlight (1/5): Sample statistics





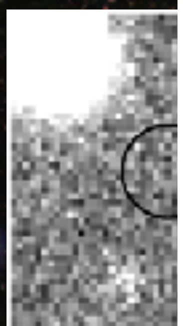


SHELLQs in a Nutshell



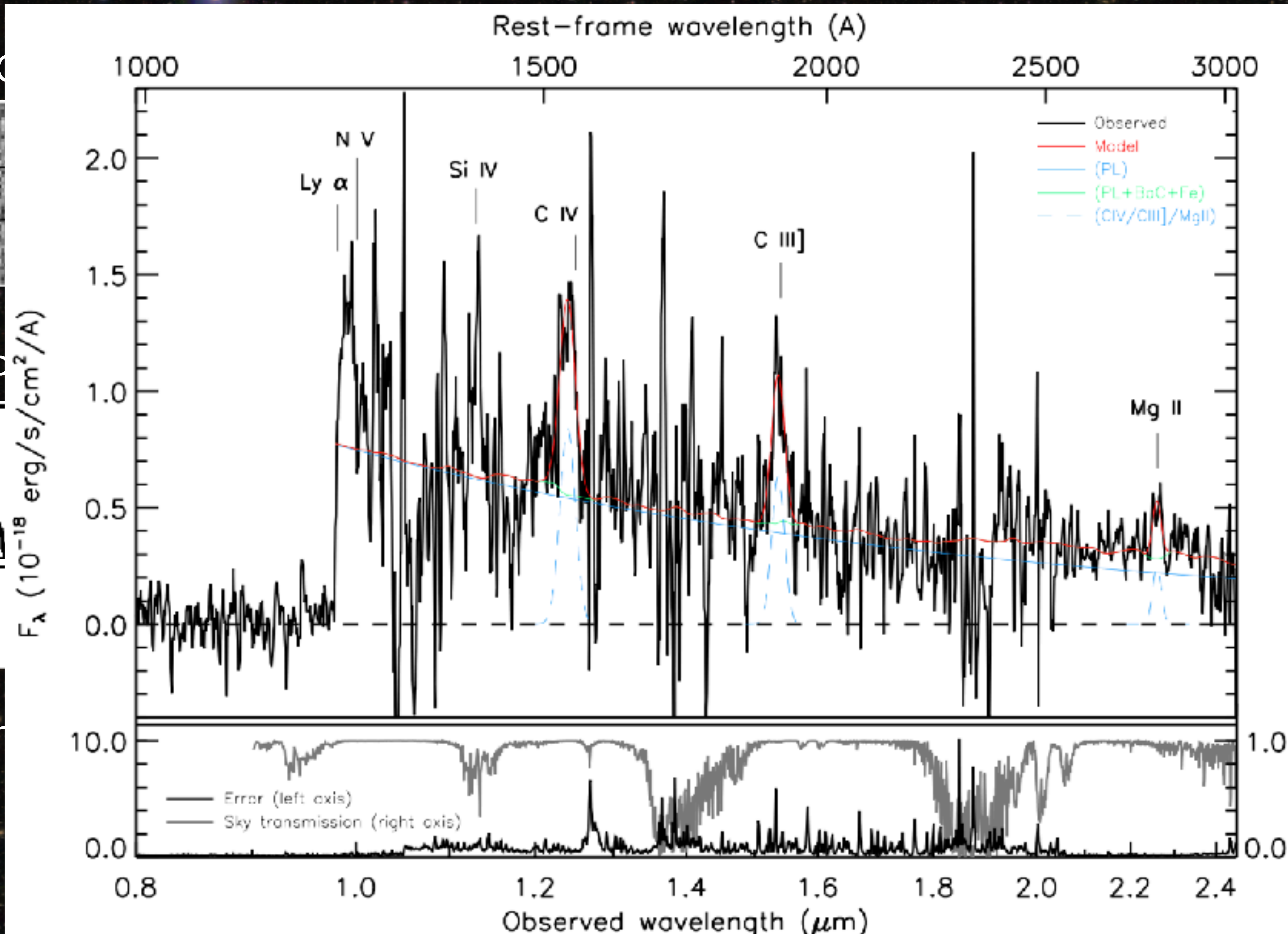
Highlight (2/5) : the first low-L quasar at z > 7

✶ HSC



✶ Sub

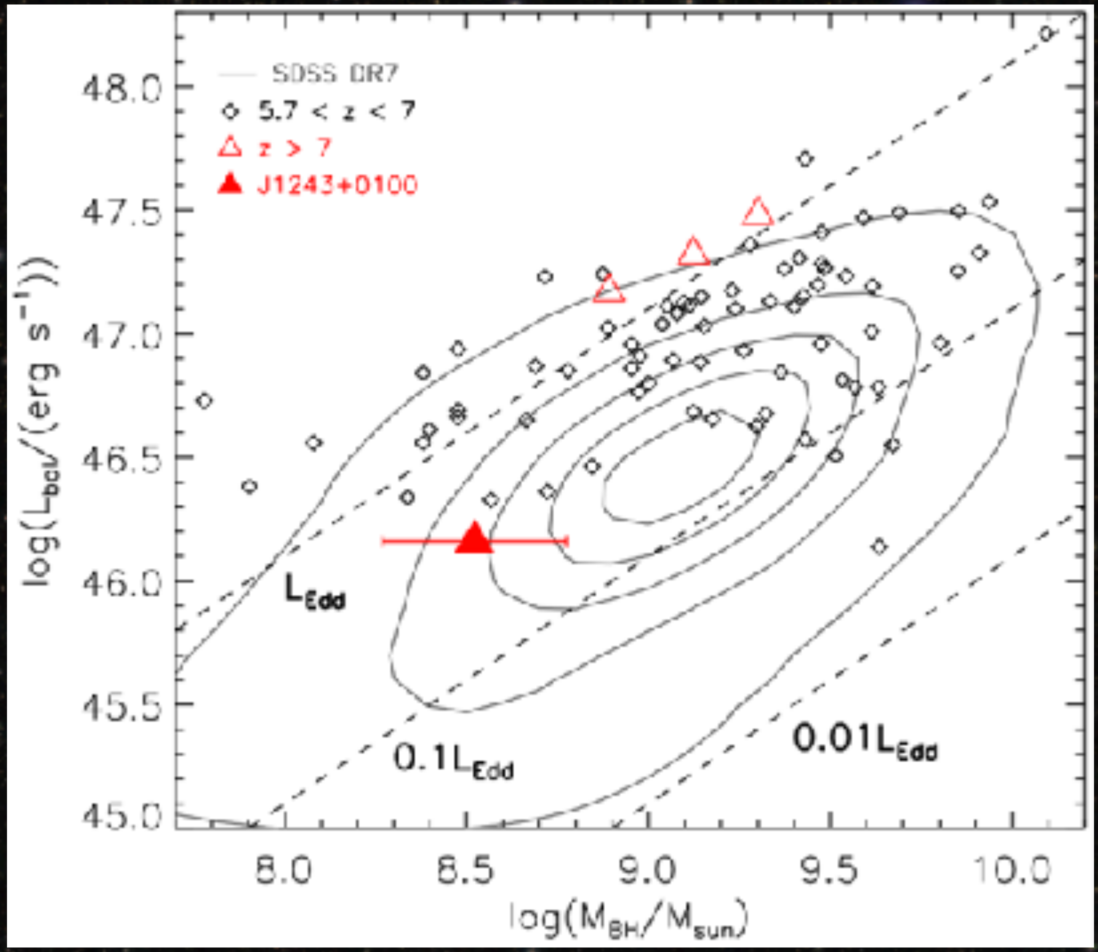
✶ Gen



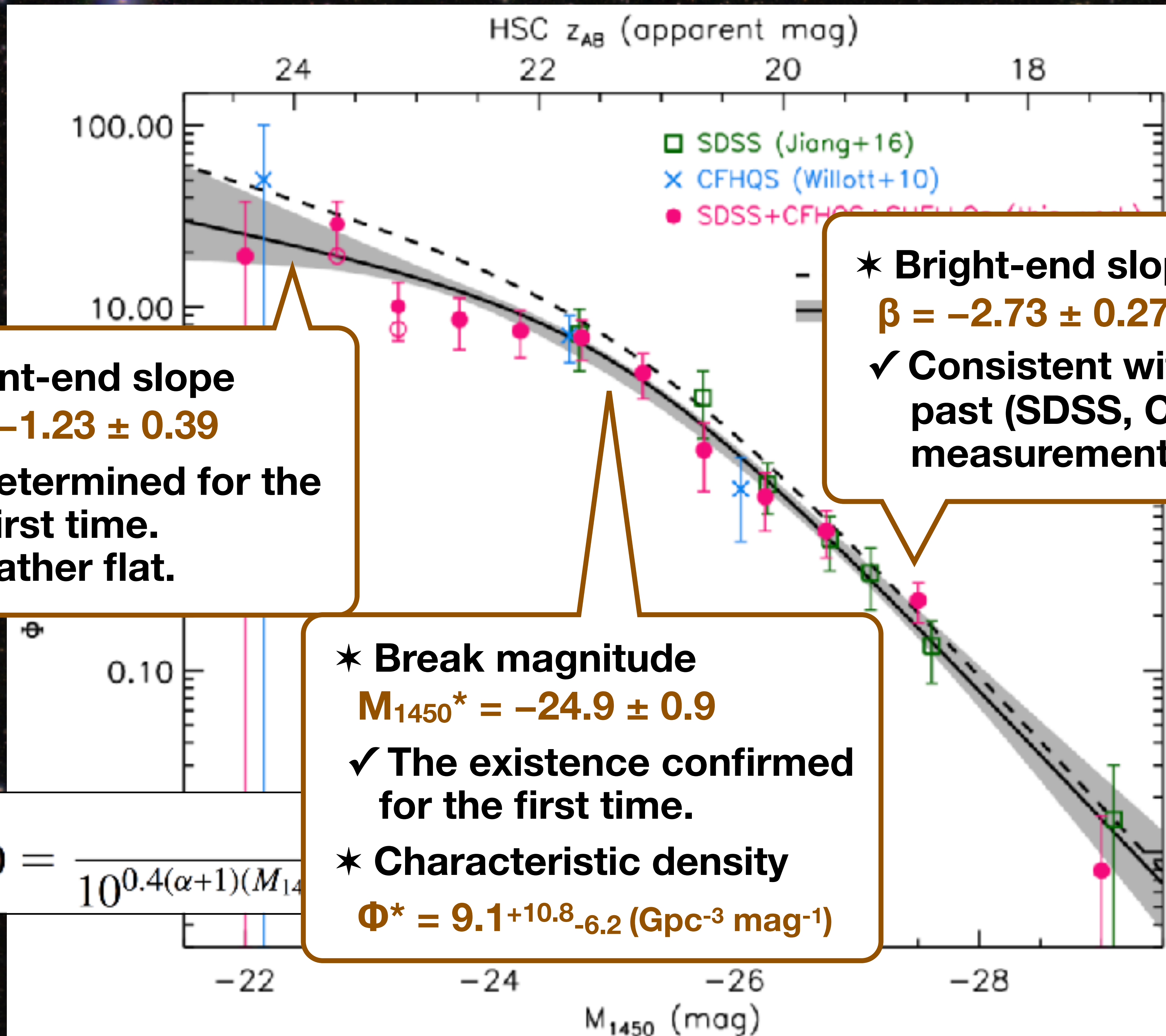
Highlight (2/5) : the first low-L quasar at z > 7

	Lyα + N V λ1240	C IV λ1549	C III] λ1909	Mg II λ2800
Redshift	...	...	...	7.07 ± 0.01
Velocity Offset (km s^{-1})	...	−2400 ± 500	−800 ± 400	...
Flux (erg s^{-1} cm^{-2})	(9.6 ± 0.4) × 10^{-17}	(2.1 ± 0.4) × 10^{-16}	(1.6 ± 0.5) × 10^{-16}	(6.2 ± 1.9) × 10^{-17}
Rest-frame Equivalent Widths (Å)	16 ± 1	48 ± 10	51 ± 15	35 ± 11
FWHM (km s^{-1})	...	5500 ± 1300	4600 ± 1500	3100 ± 900
M_{BH} ($M_\odot$)	...	...	...	(3.3 ± 2.0) × 10^8
λ_{Edd}	...	...	...	0.34 ± 0.20

R.A.	$12^h43^m53^s.93$
Decl.	+01°00′38″.5
g_{AB} (mag)	<26.7 (2σ)
r_{AB} (mag)	<26.5 (2σ)
i_{AB} (mag)	<26.7 (2σ)
z_{AB} (mag)	<25.8 (2σ)
y_{AB} (mag)	23.57 ± 0.08
m_{1450} (mag)	22.82 ± 0.08
M_{1450} (mag)	−24.13 ± 0.08
L_{bol} (erg s^{-1})	(1.4 ± 0.1) × 10^{46}



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



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

✶ **Faint-end slope**

α = −1.23 ± 0.39

✓ **Determined for the first time.**

✓ **Rather flat.**

✶ **Bright-end slope**

β = −2.73 ± 0.27

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

✶ **Break magnitude**

M_{1450}^{*} = −24.9 ± 0.9

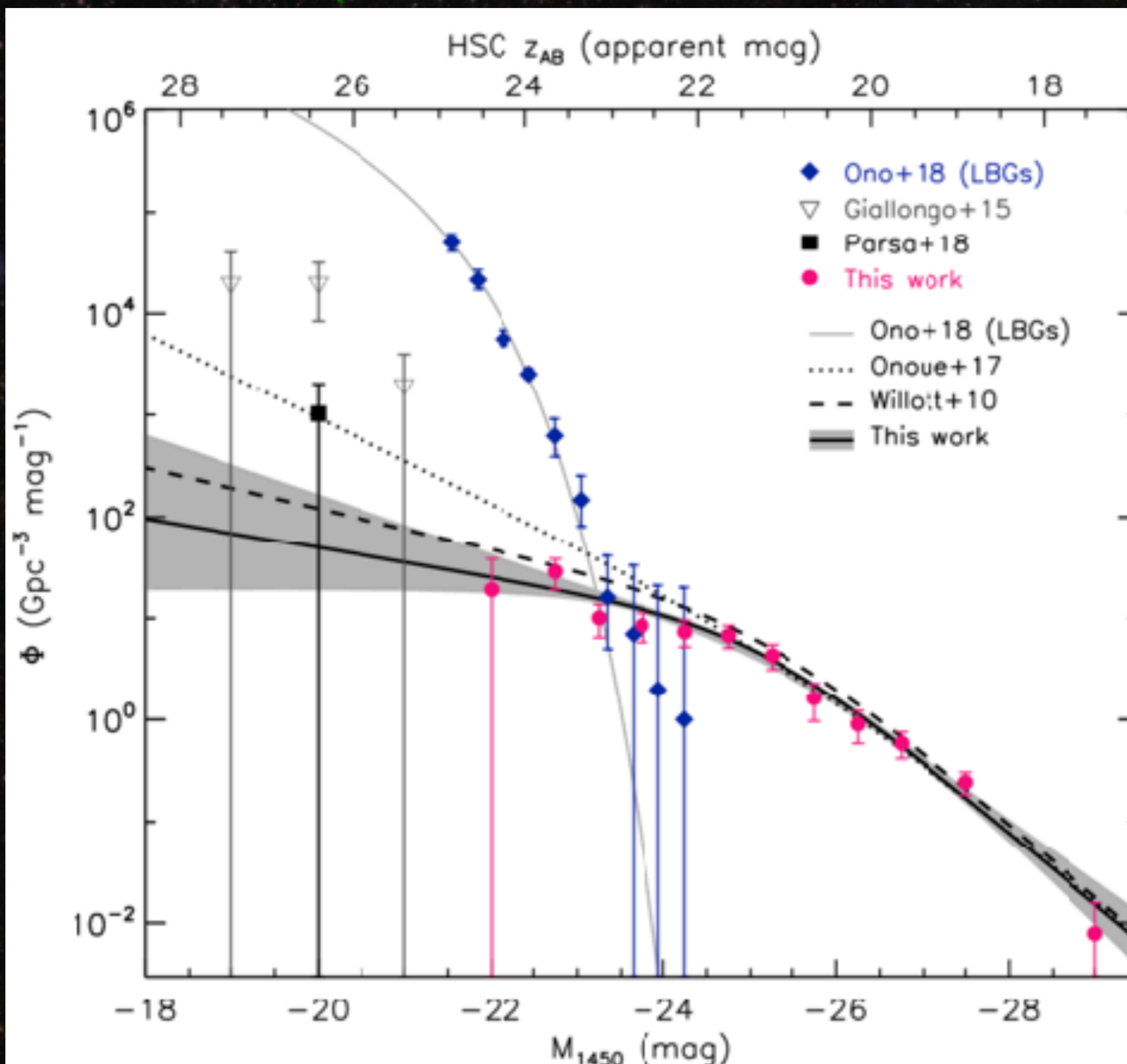
✓ **The existence confirmed for the first time.**

✶ **Characteristic density**

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

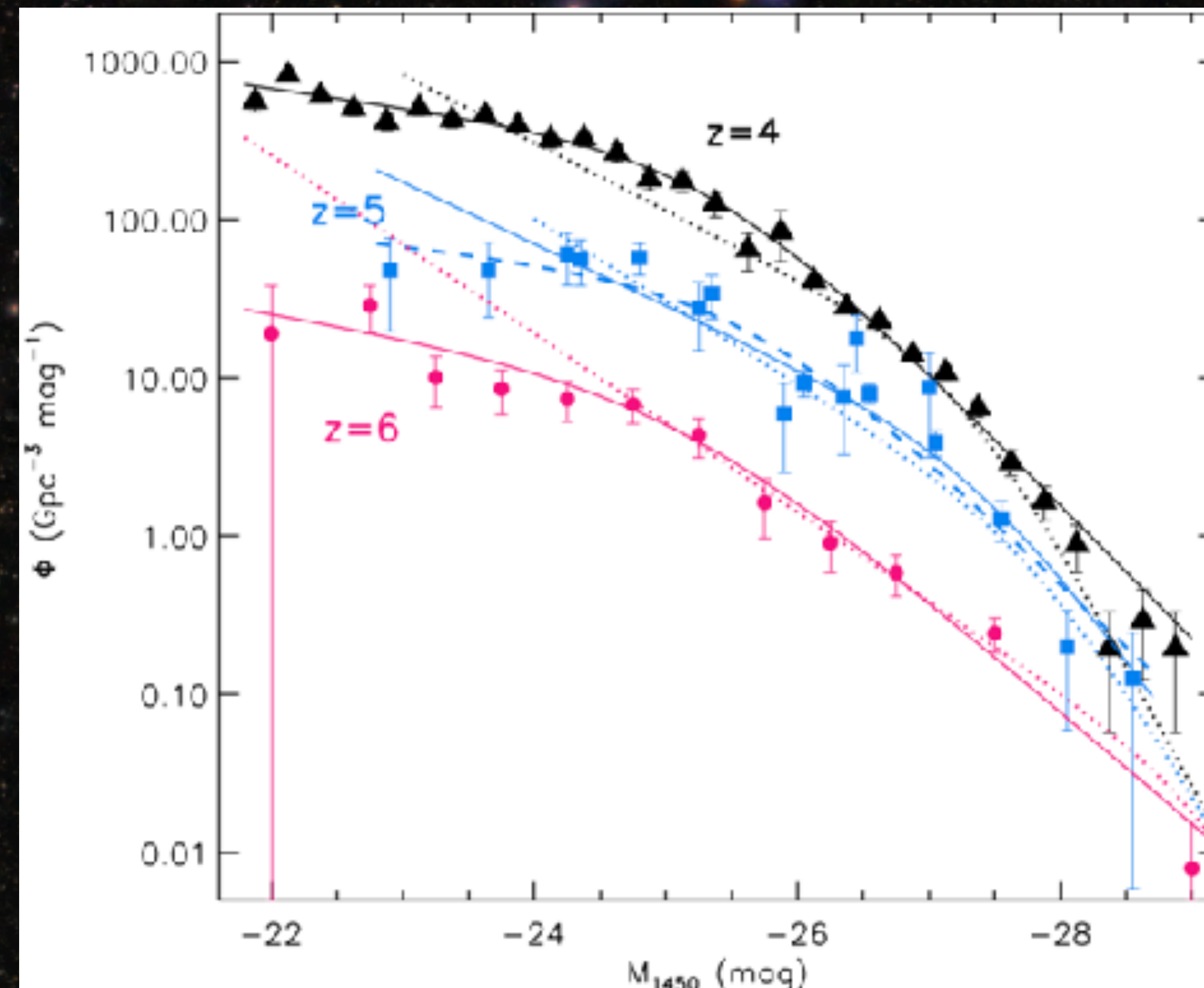
Highlight (3/5): Luminosity function at z = 6

✶ Comparison with other measurements



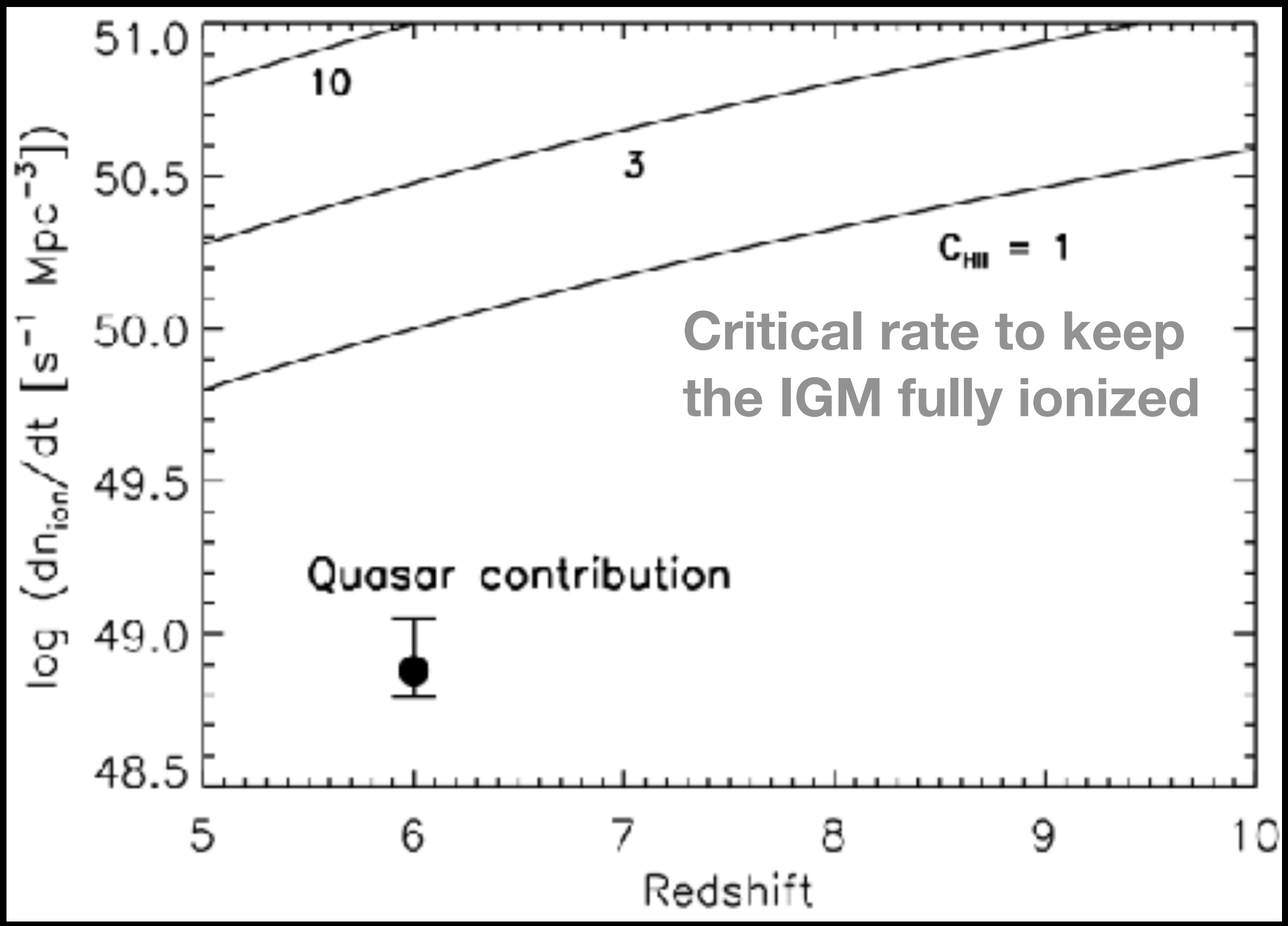
→ Galaxies outnumber at $M_{1450} > -23$ mag
→ contradicts with the previous claim of "numerous faint AGNs dominating cosmic reionization"

✶ LF evolution over $4 \leq z \leq 6$



→ Similar overall shape
→ Strong decline in the number densities

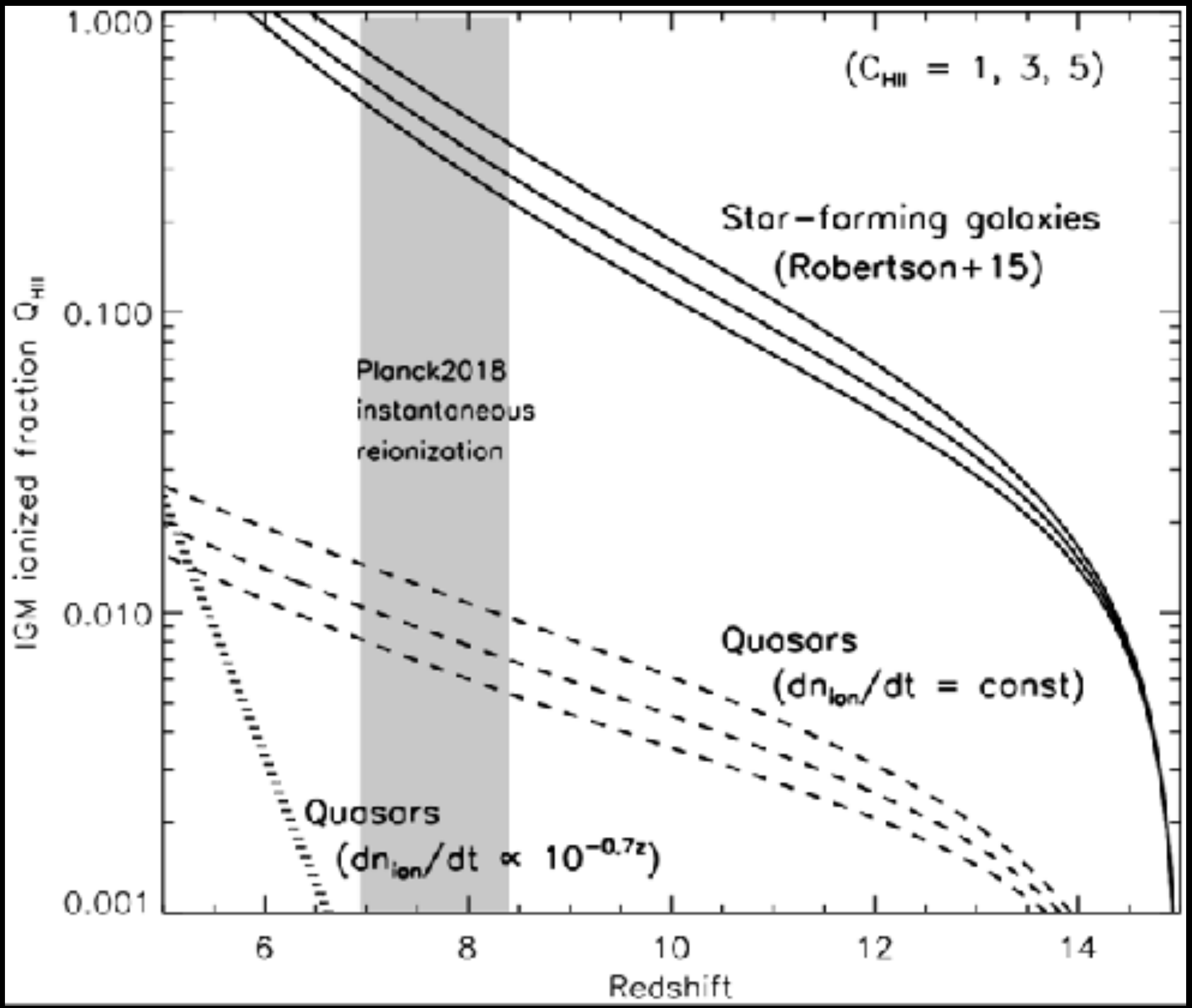
Highlight (4/5): Contribution to reionization



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

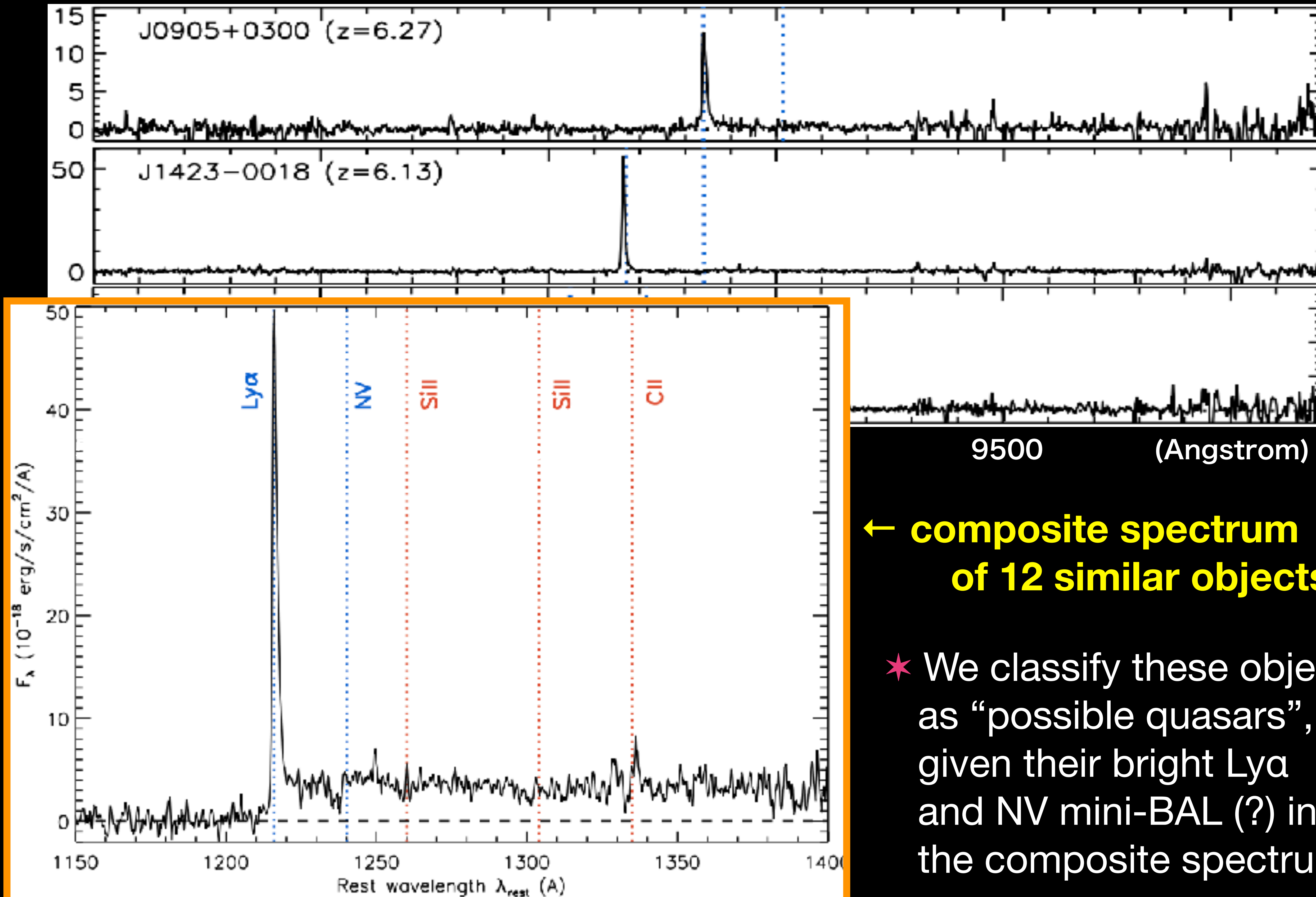
$\dot{n}_{ion} = 10^{48.9\pm0.2}$ (s^{-1} Mpc^{-3})

→ <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.

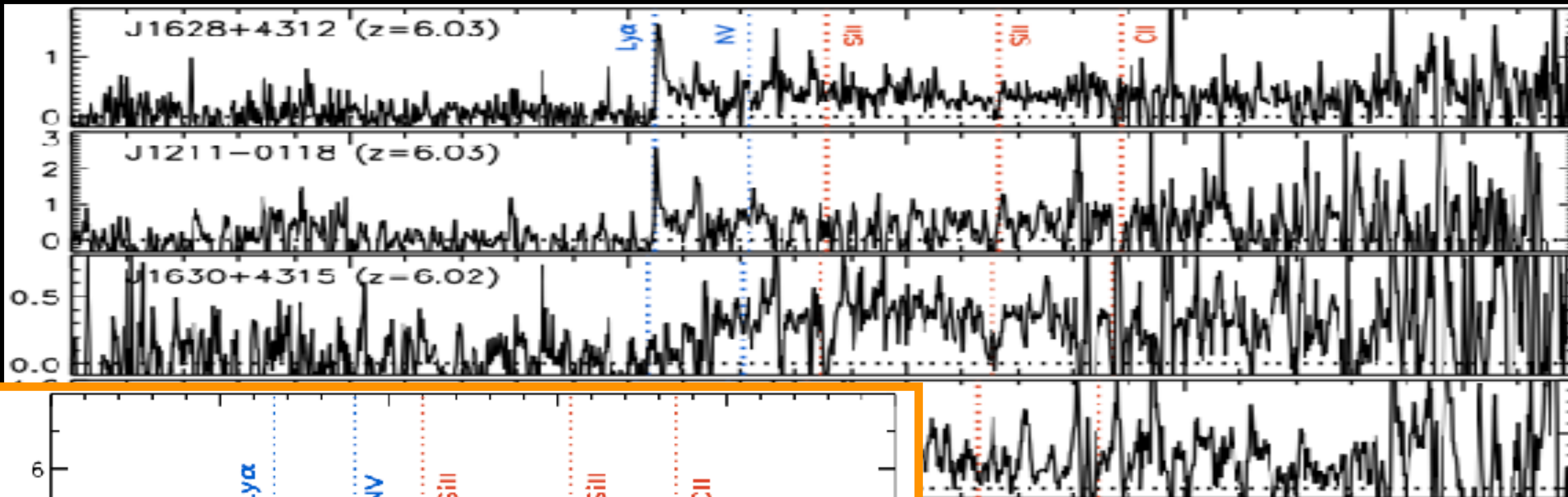
Highlight (5/5): different classes of objects

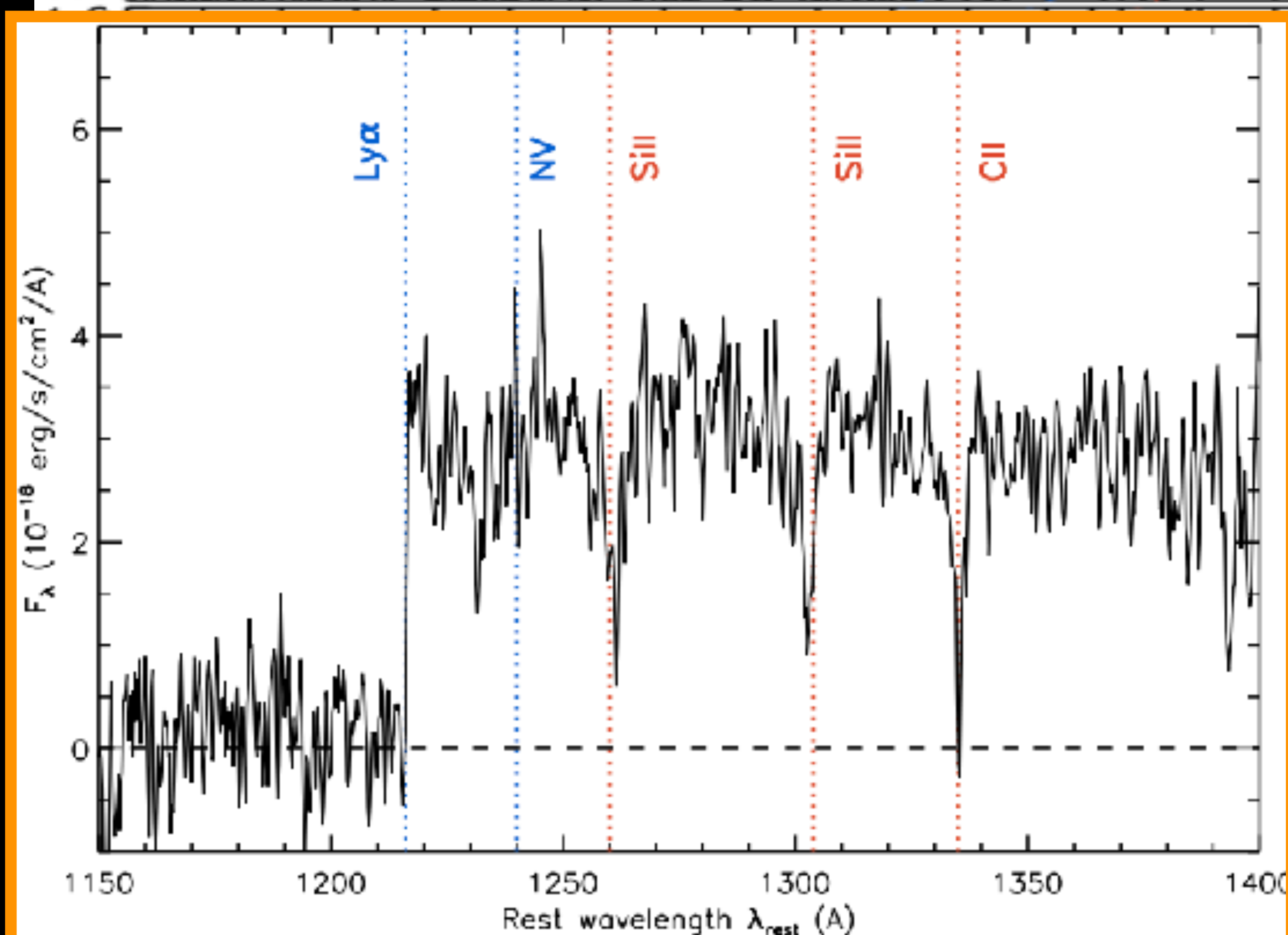


← **composite spectrum of 12 similar objects**

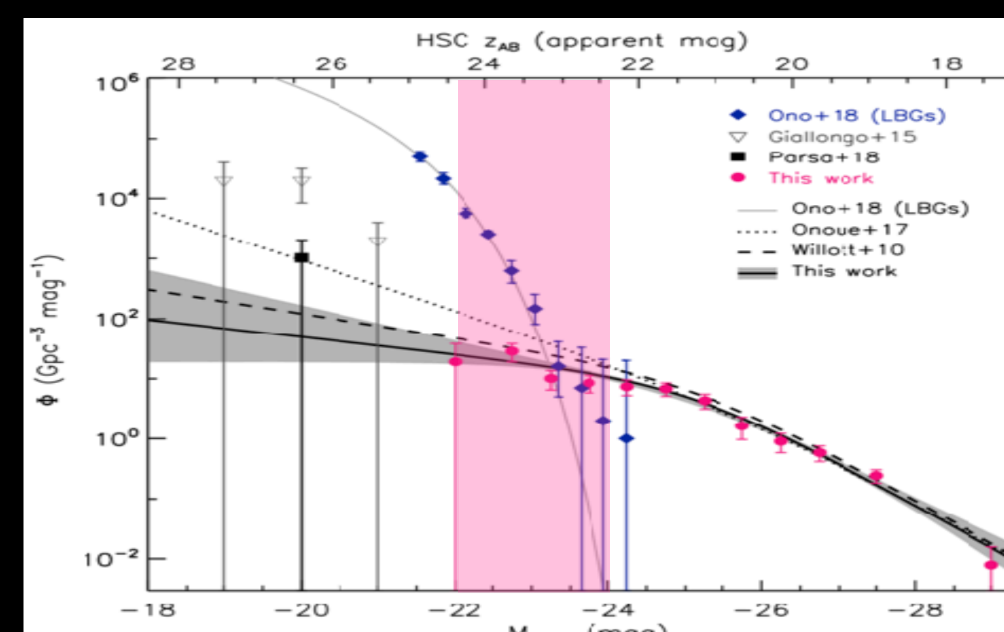
✶ We classify these objects as "possible quasars", given their bright Lyα and NV mini-BAL (?) in the composite spectrum.

Highlight (5/5): different classes of objects

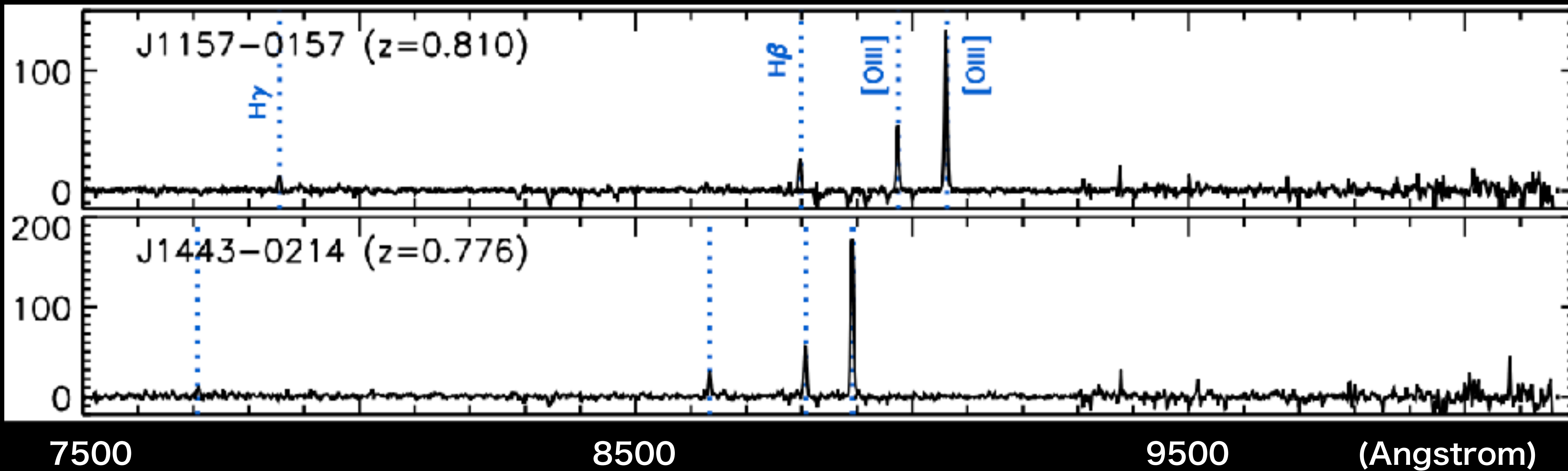


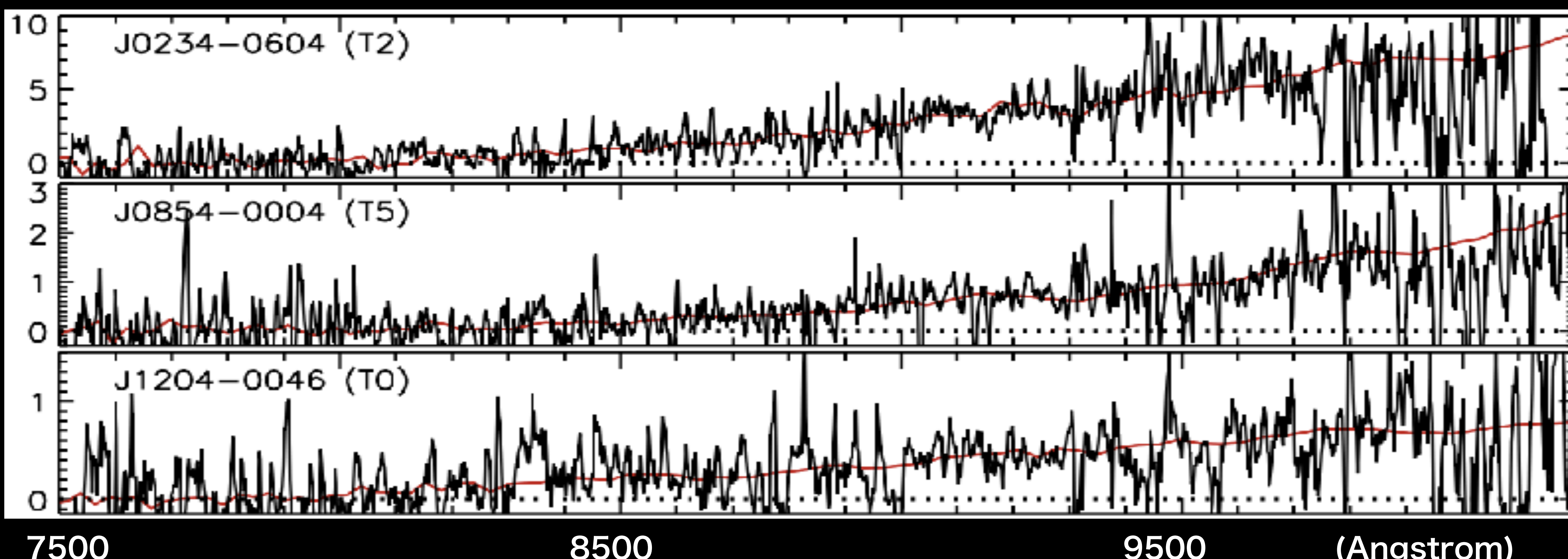


← composite spectrum
of 14 high-z galaxies



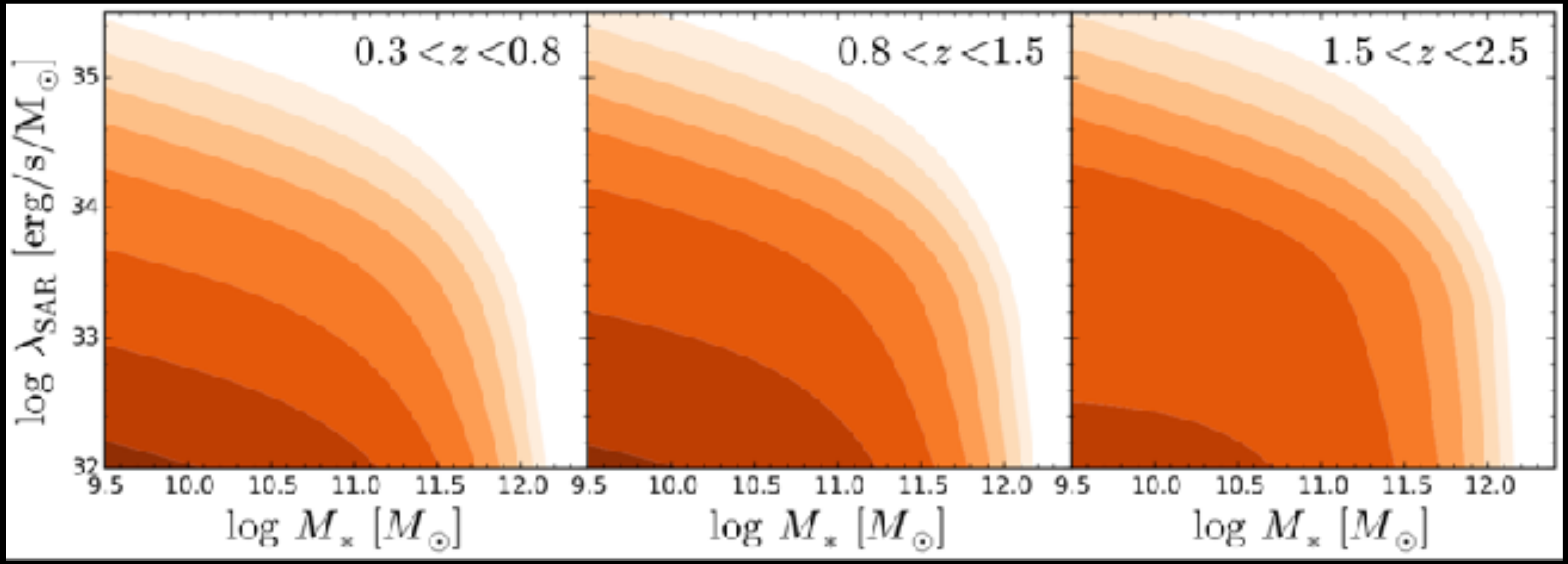
Highlight (5/5): different classes of objects





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

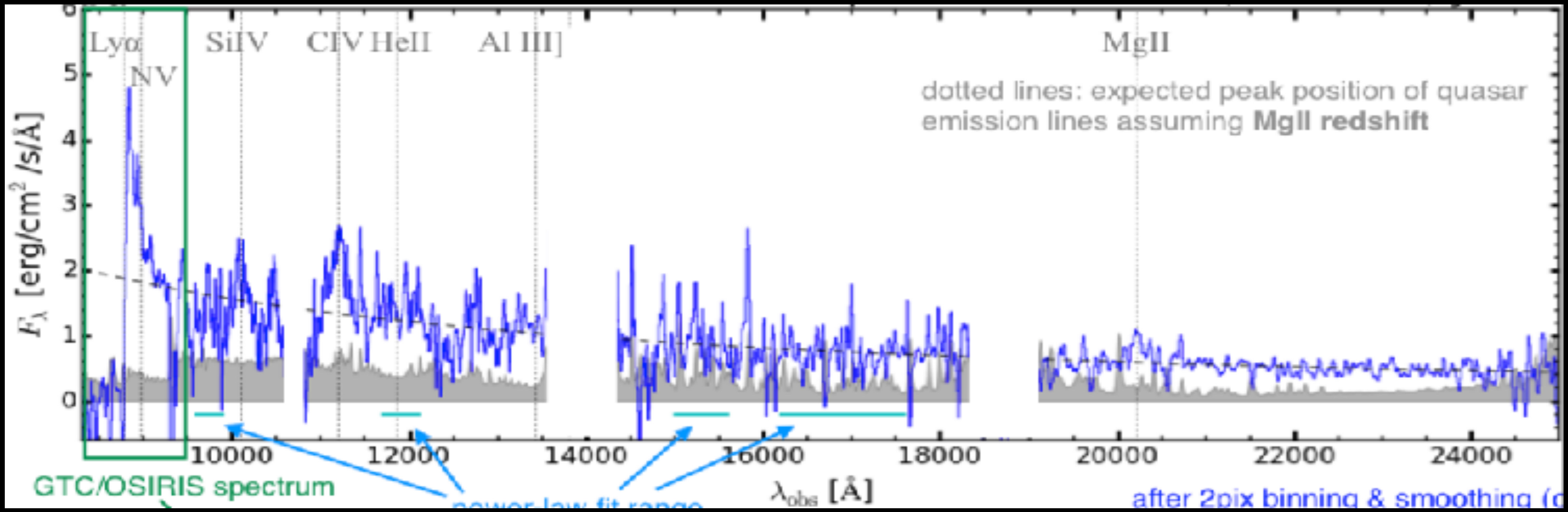
✶ *Luminosity function = BH mass function x Eddington ratio function*



Bongiorno+16

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

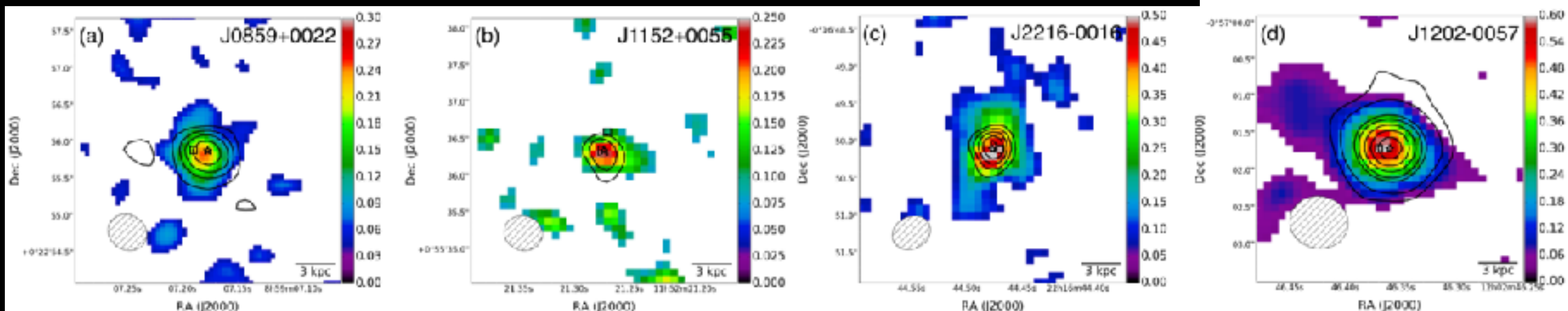
… 9 objects observed so far with Subaru/MOIRCS, VLT/X-Shooter, Gemini/GNIRS

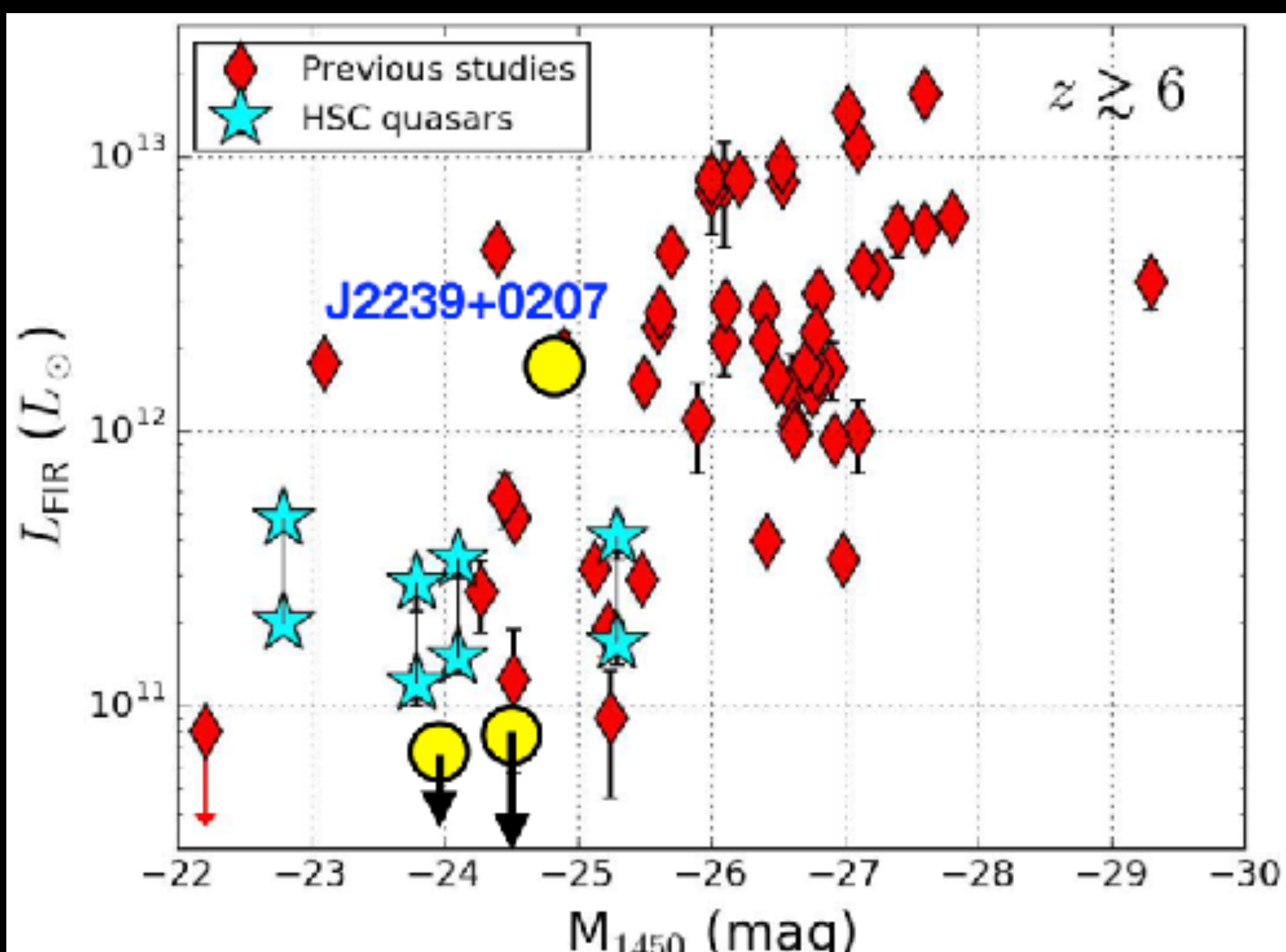


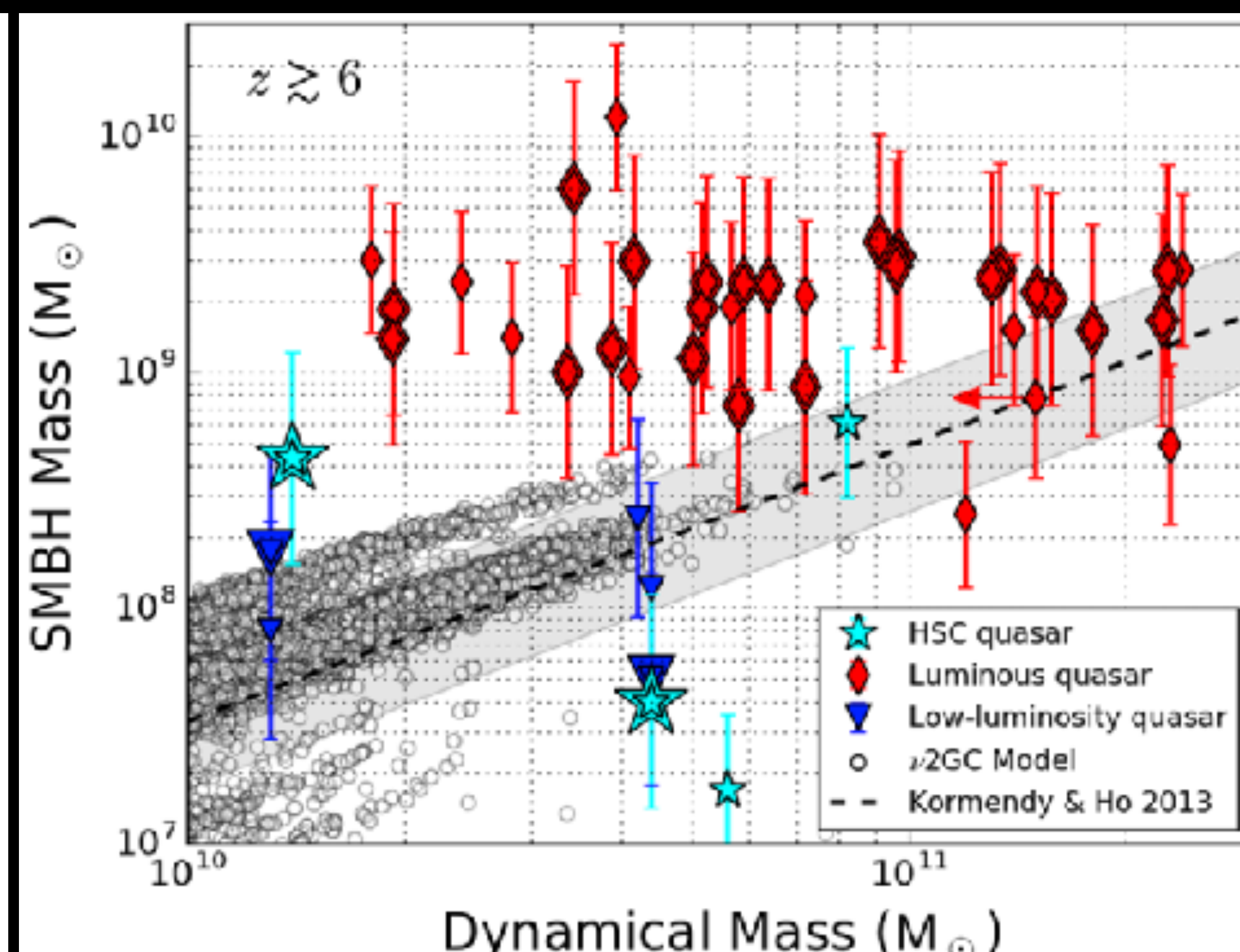
Multi-wavelength follow-up (2/2): ALMA

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

Color = [CII] integrated intensity
Contour = FIR continuum

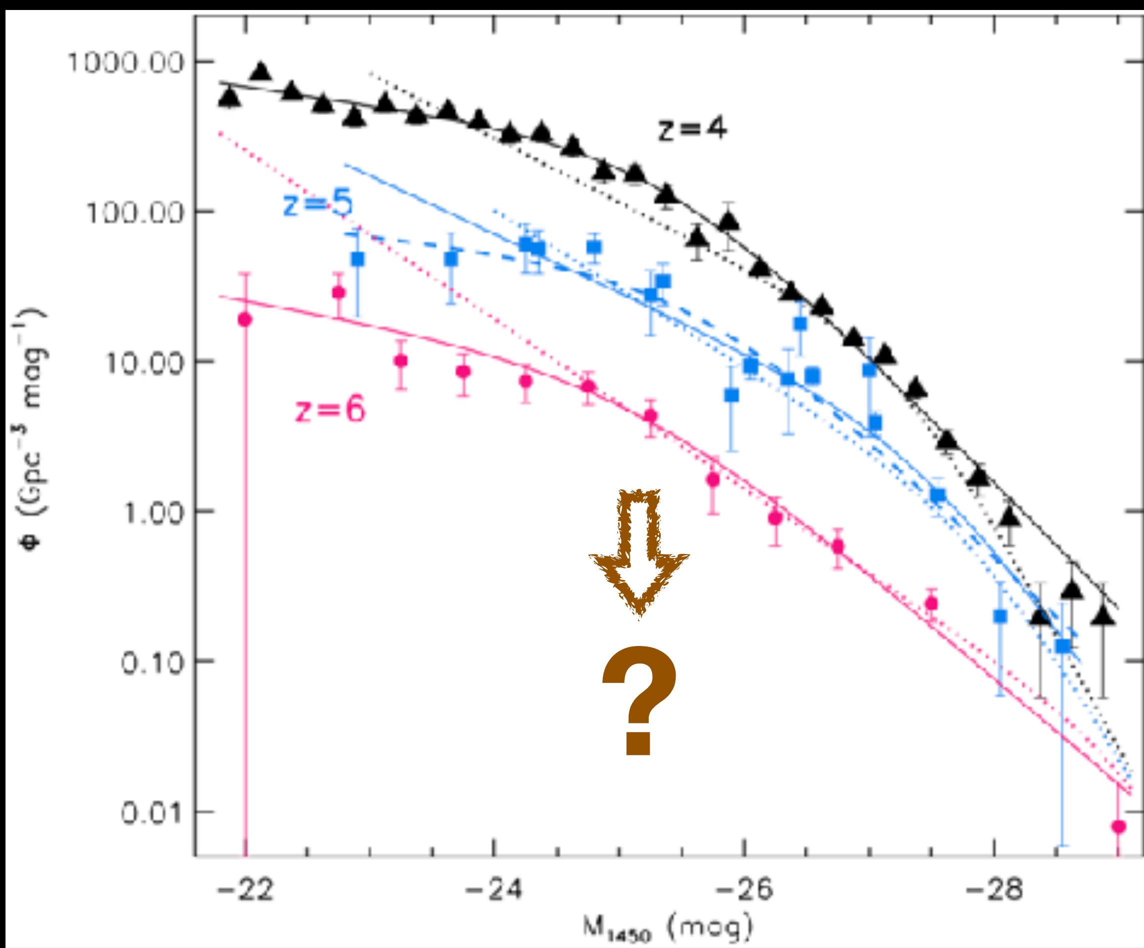






Izumi+18; Izumi+ in prep

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.
Mailing Address: 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577, Japan
E-mail Address: yk.matsuoka@cosmos.ehime-u.ac.jp Phone: +81-89-927-9579

3. Scientific Category

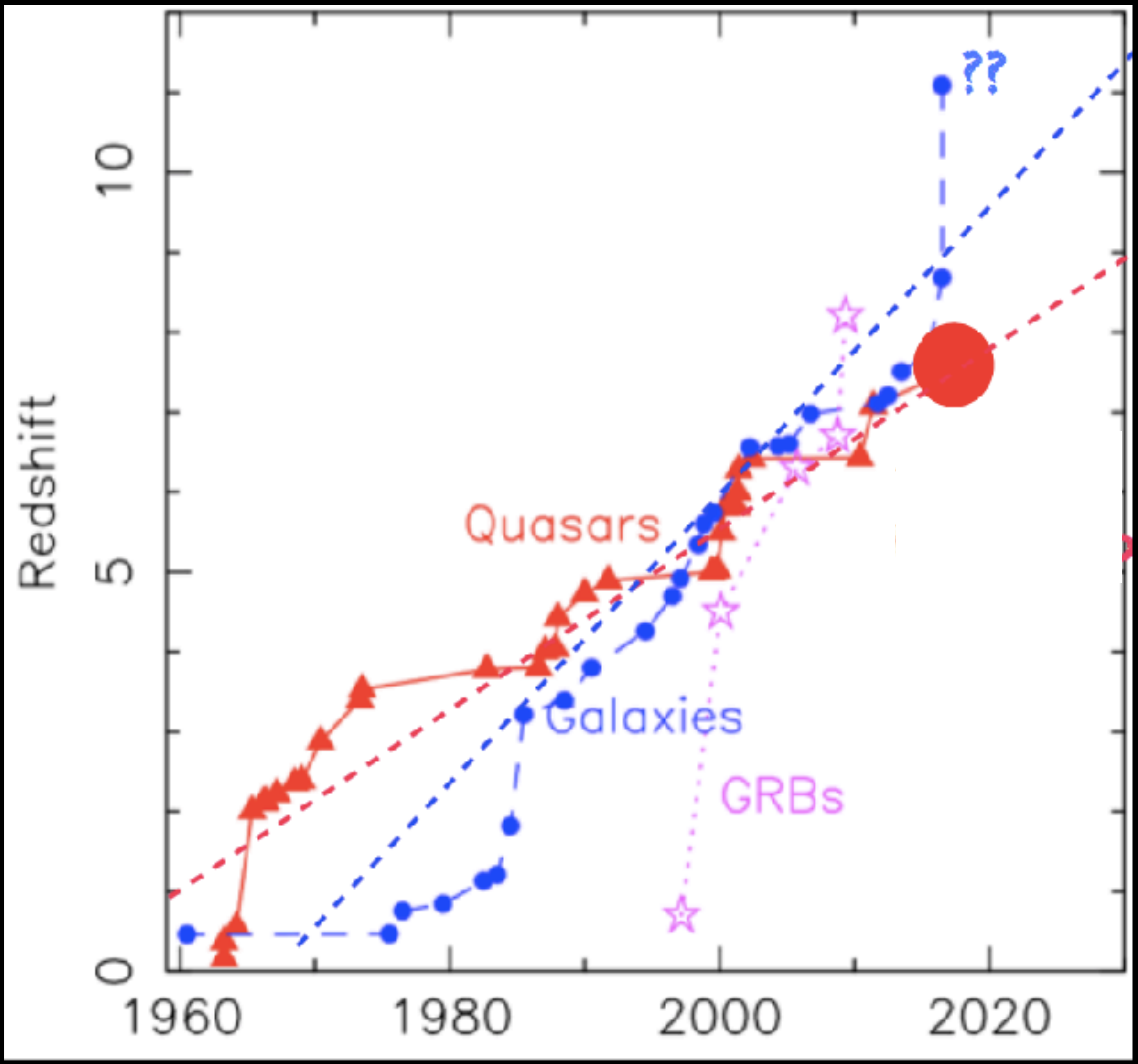
- [ ] Solar System
- [ ] Extrasolar Planets
- [ ] Star Formation and Young Disk
- [ ] ISM
- [ ] Normal Stars
- [ ] Metal-Poor Stars
- [ ] Compact Objects and SNe
- [ ] Milky Way
- [ ] Local Group
- [ ] Nearby Galaxies
- [ ] IGM and Abs.Line Systems
- [ ] Cosmology
- [ ] Gravitational Lenses
- [ ] Clusters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

4. Abstract *(approximately 850 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.

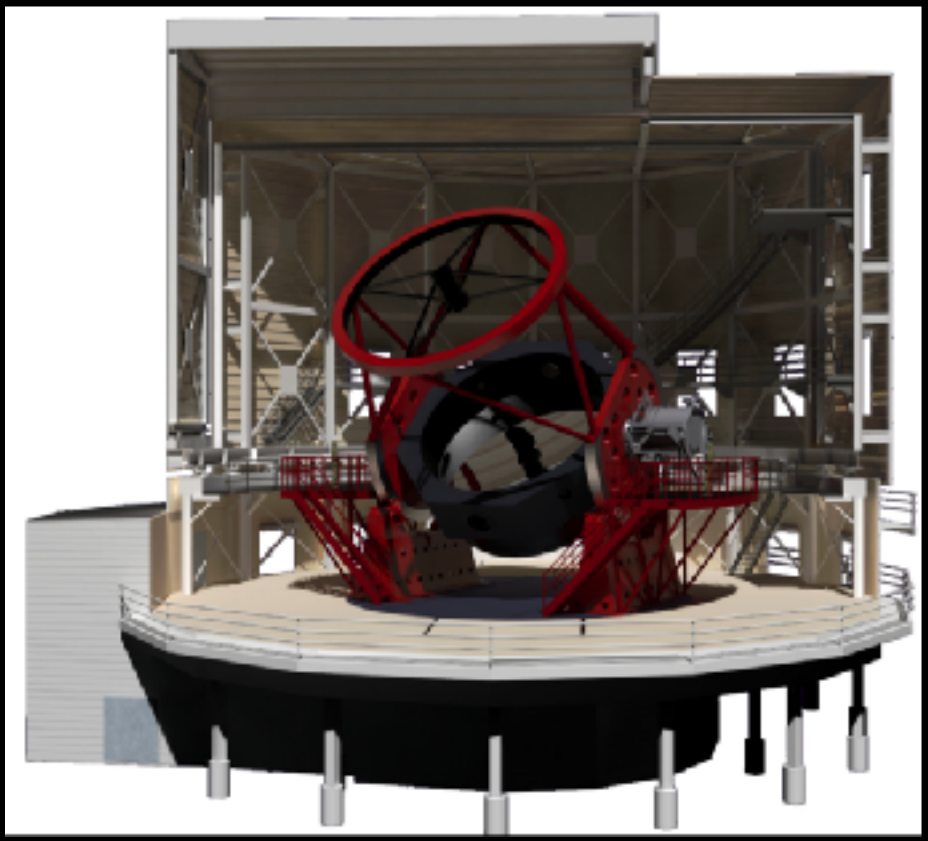
30 nights with Subaru/FOCAS
through 2021A

To the farthest reaches of the Universe (future prospects)



© Xiaohui Fan

★ TAO



★ WFIRST

✶ Lyman-α 遷移によるIGM観測の限界

(1) わずかな中性水素があるだけで、IGMは非常に不透明になる

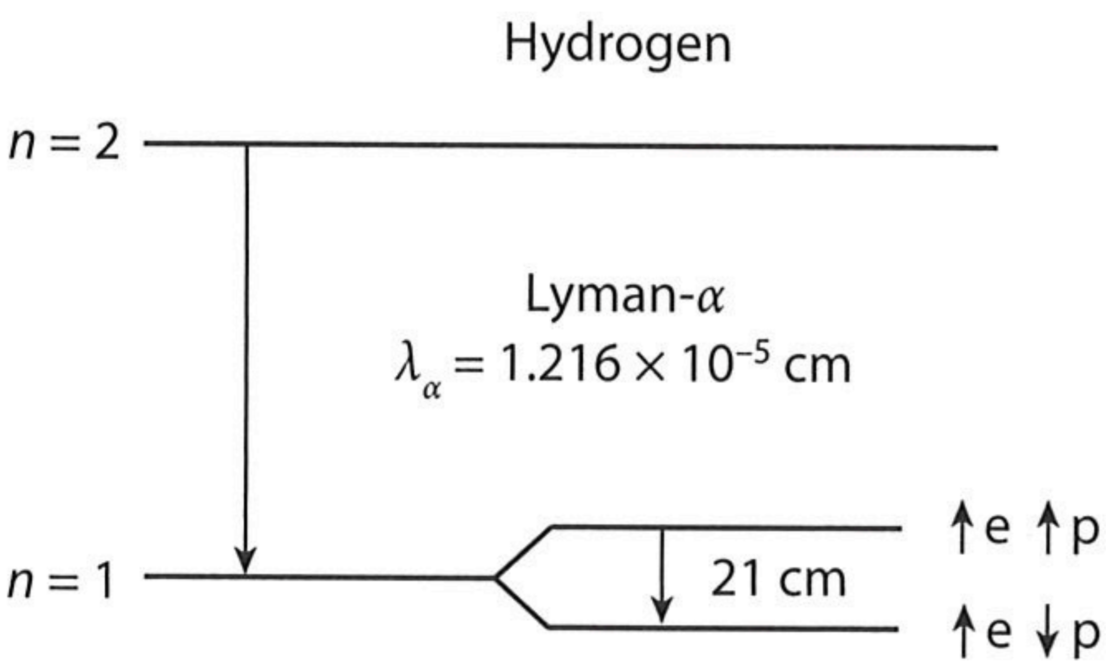
$$\tau_\alpha \simeq 1.6 \times 10^5 x_{\rm HI}(1+\delta_{\rm abs})\left(\frac{1+z_{\rm abs}}{4}\right)^{\frac{3}{2}}$$

→ 再電離の完了に近い時期より昔を見ることができない

(2) 宇宙初期には極めて稀な、明るい紫外線背景光源が必要

(3) 再電離前のIGMは低温であり、熱衝突によってLyman-α励起を起こせないことから、（たとえ(1)の問題がなくても）再電離期前の観測には使えない

水素21cm輝線とSKA



(c) SPDO/TDP/DRAO/Swinburne Astronomy Productions