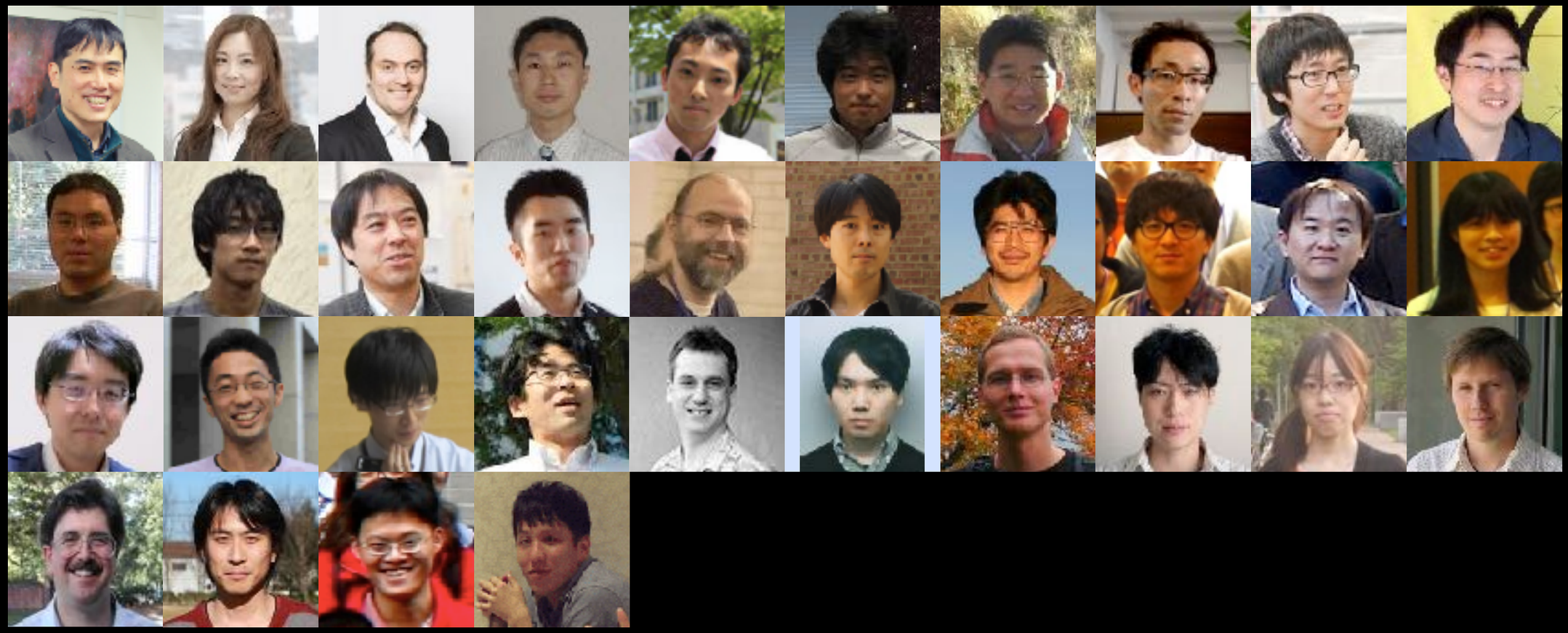
Did low-luminosity quasars reionize the universe?

- A view from the Subaru HSC SSP survey -

Yoshiki Matsuoka (Ehime Univ.)

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

High-z quasars - Unique probe of the early Universe

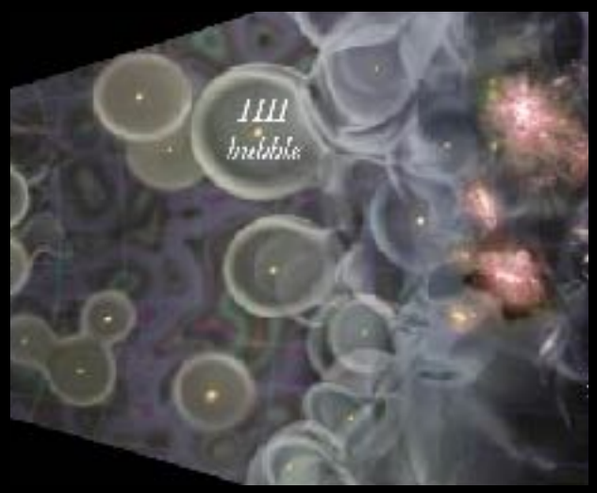
Fundamental questions we aim to answer:

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?

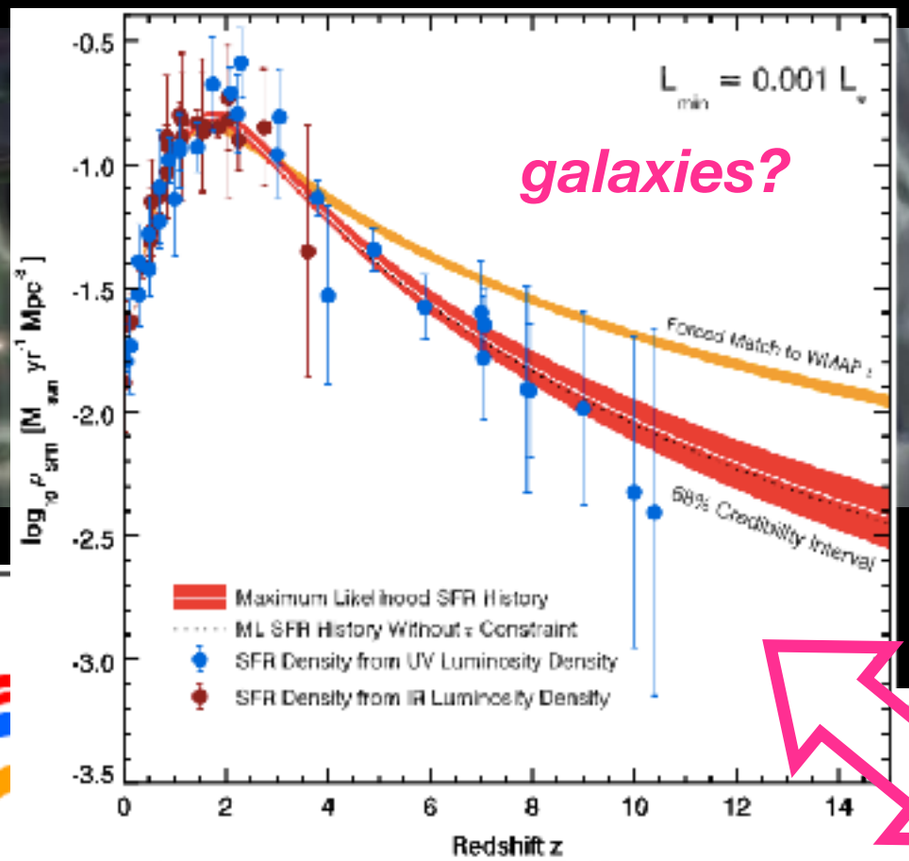


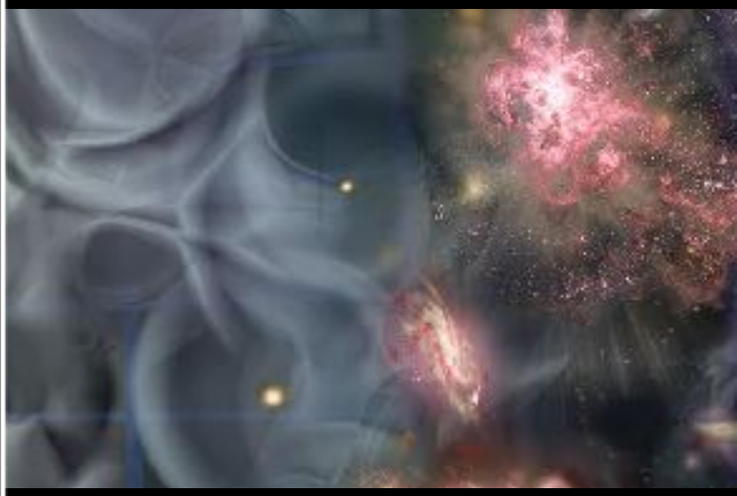
When and how was the Universe re-ionized?

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

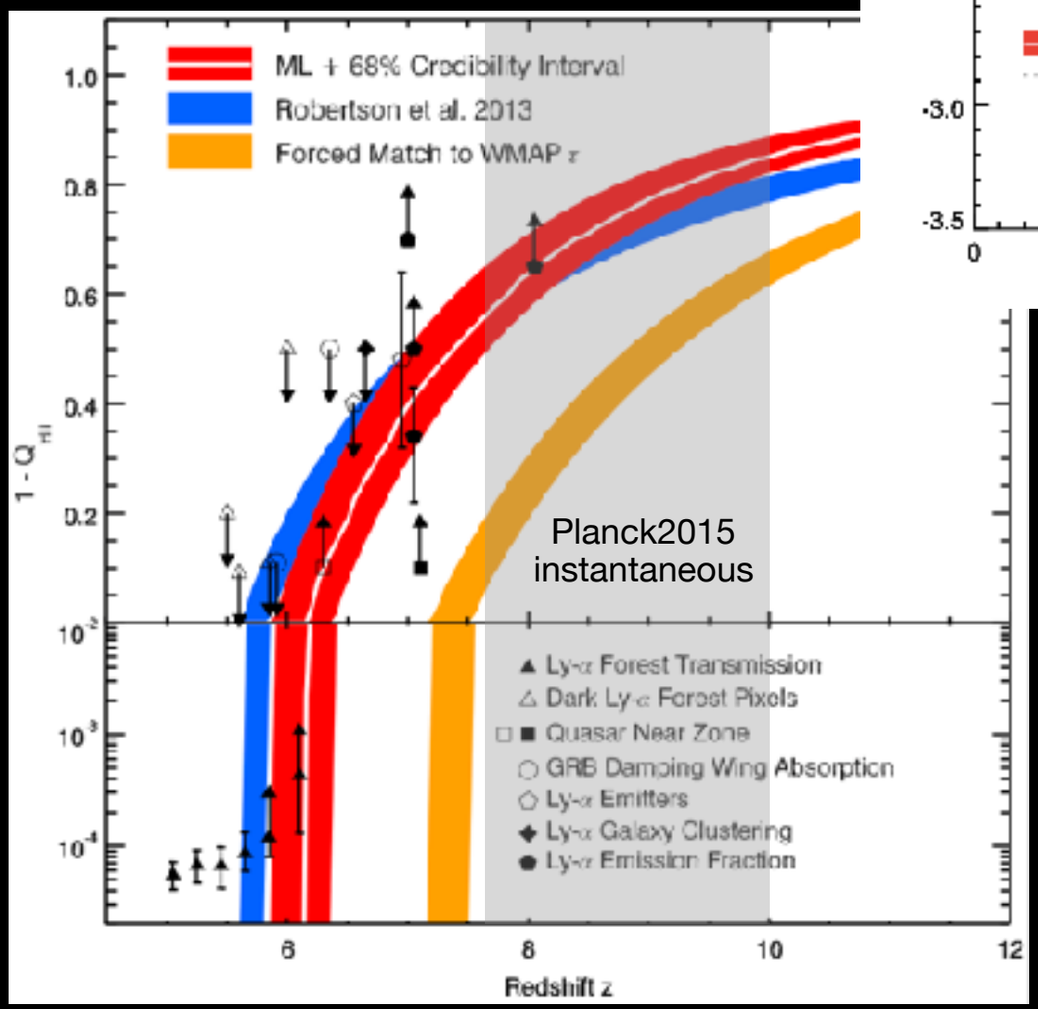
and many more!

What reionized the Universe?

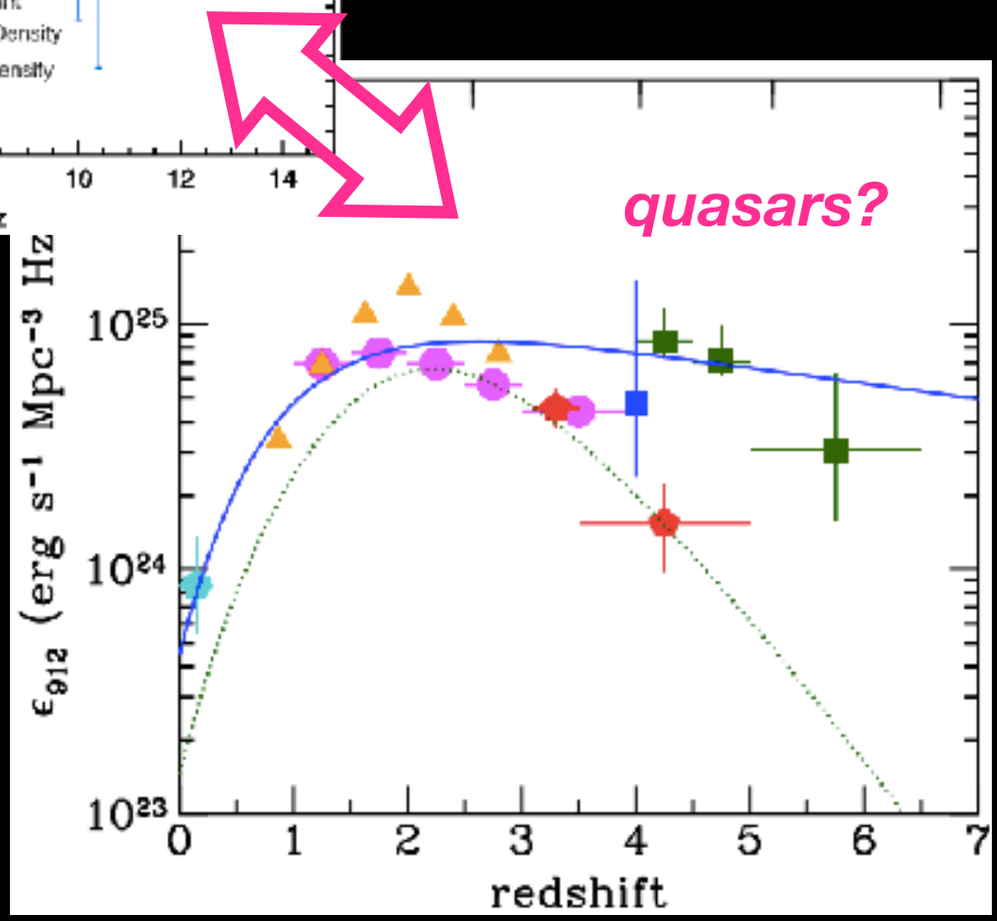




IGM neutral fraction



(Robertson+15)



(Madau+15)

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. (2017)

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**

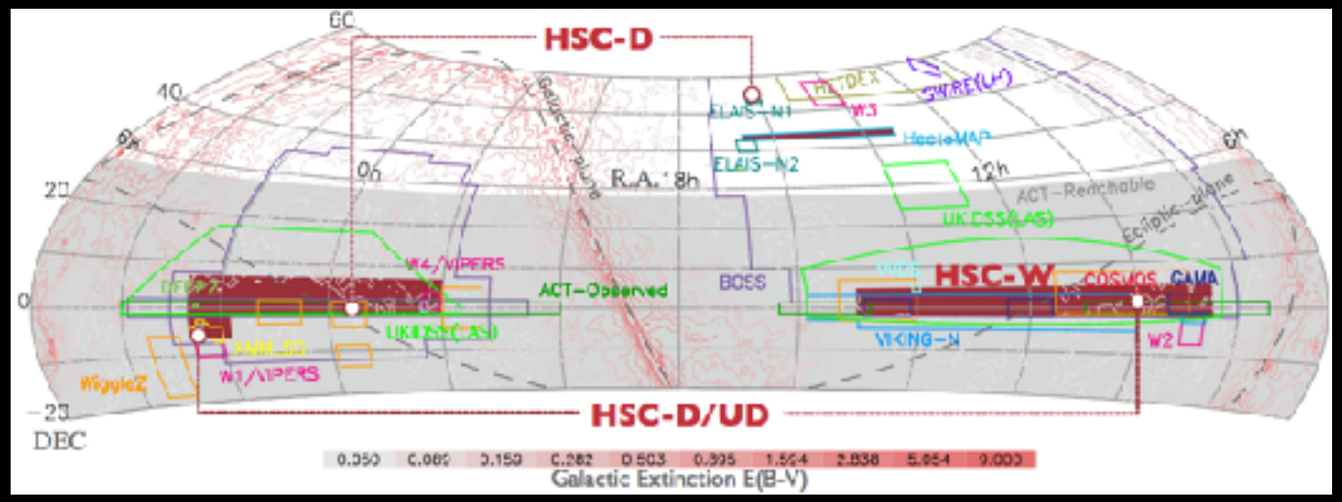


Table 7: Quasar Samples

	Wide (1400 deg^2)				Deep (27 deg^2)			
redshift	3.7–4.6	4.6–5.7	5.9–6.1	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

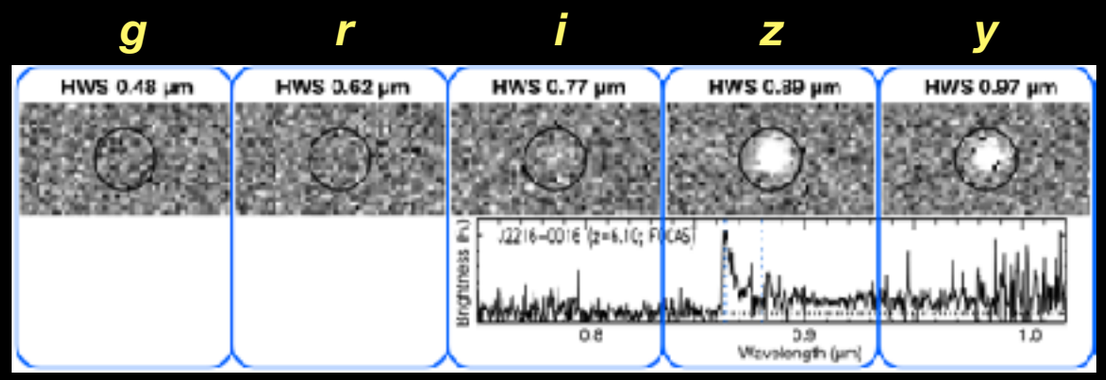
Quasar probability: $P_Q = W_Q/(W_Q+W_D)$

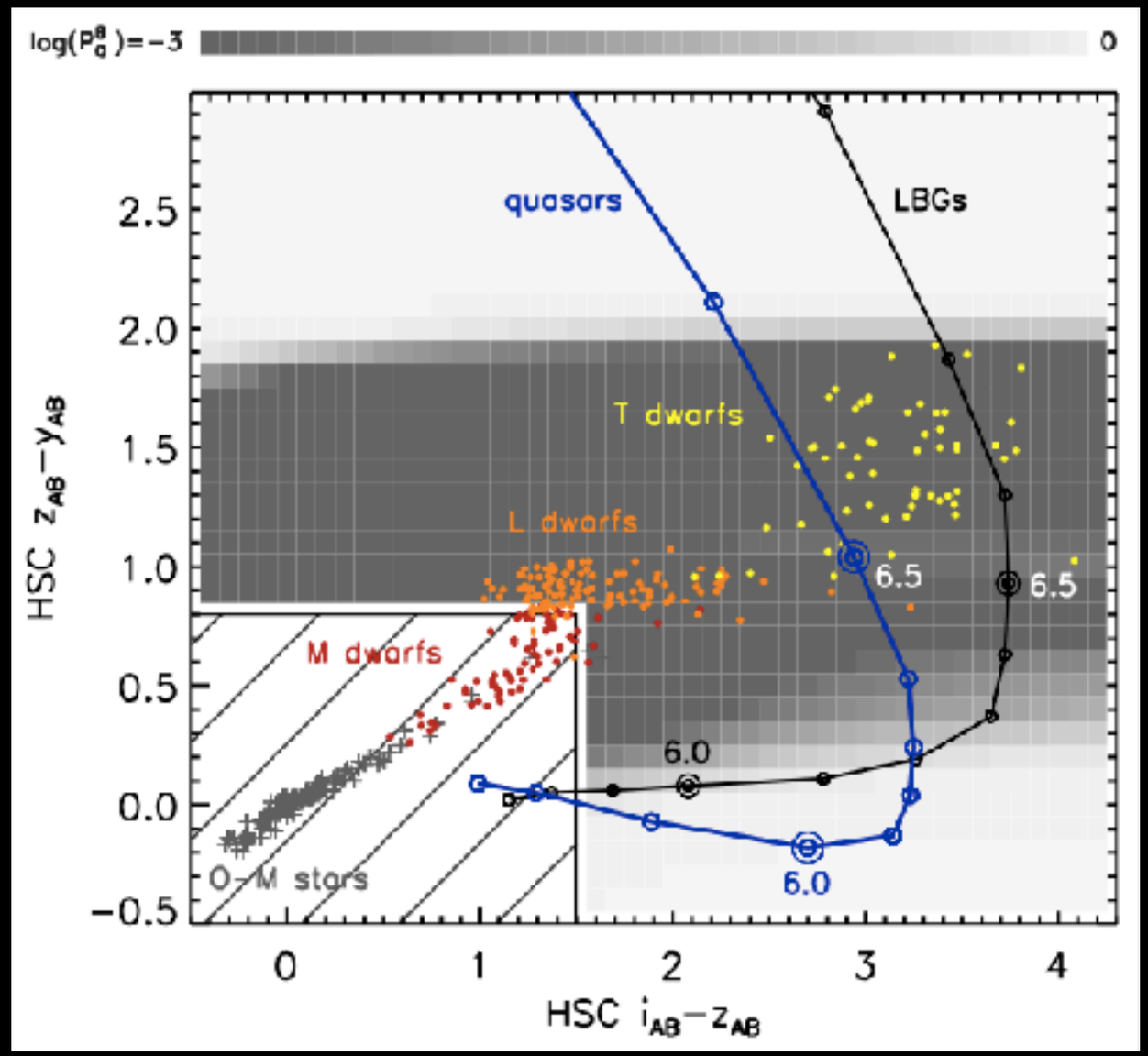
W_Q (**m**, det) = $\int\int \rho_Q (m_{int}, z)$ Pr (det | m_{int}, z) Pr (**m** | m_{int}, z) $dm_{int}\, dz$

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





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

Progress to date

✶ The HSC S16A data release contains ~430 deg^2 of the Wide fields, with more than a single exposures in the *i*, *z*, and *y* bands.

✶ Spectroscopic follow-up is underway: >100 HSC sources have been identified so far.



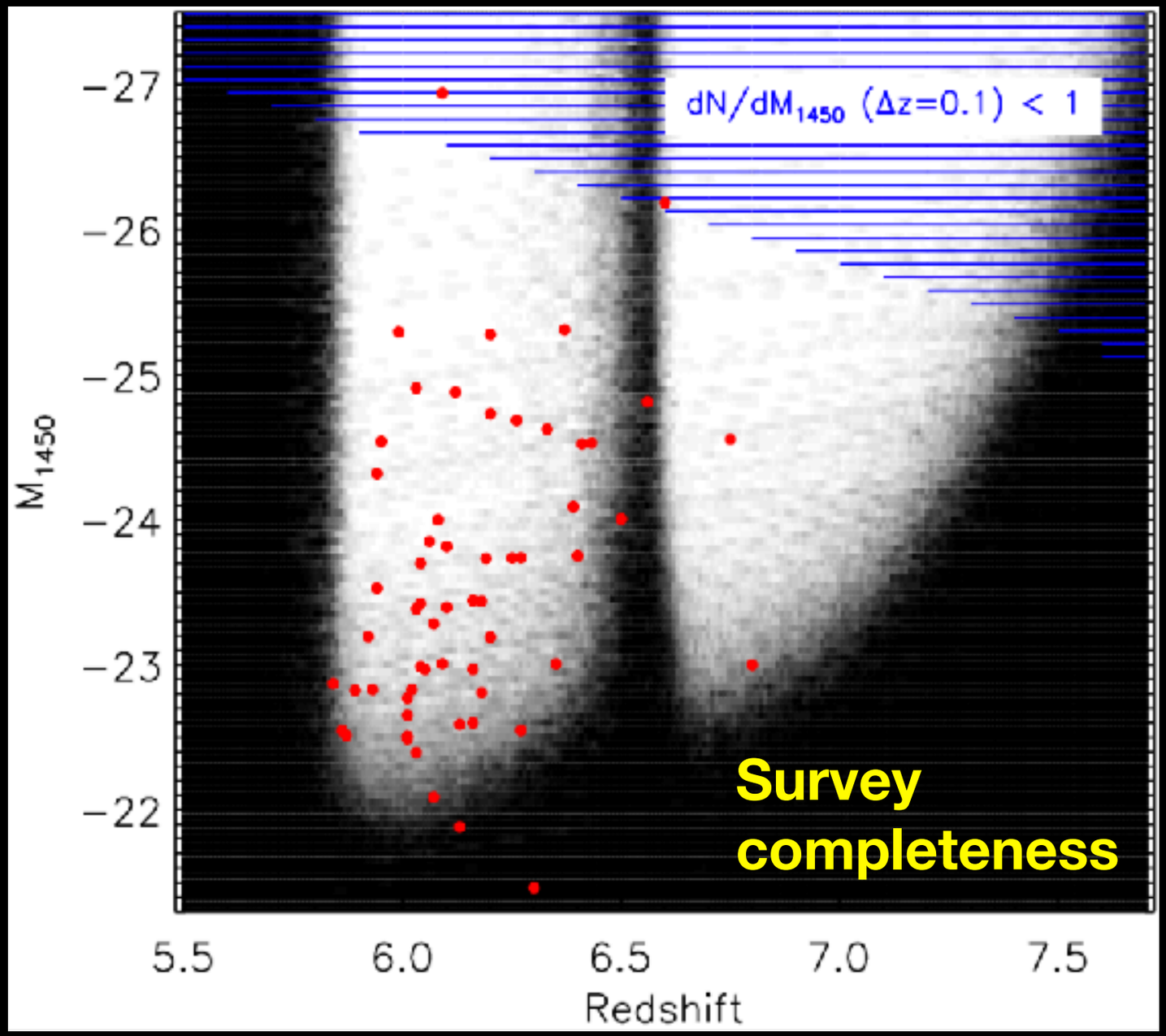
✔ Subaru/FOCAS: 10 nights in S15A-S16A normal programs → ~80% clear

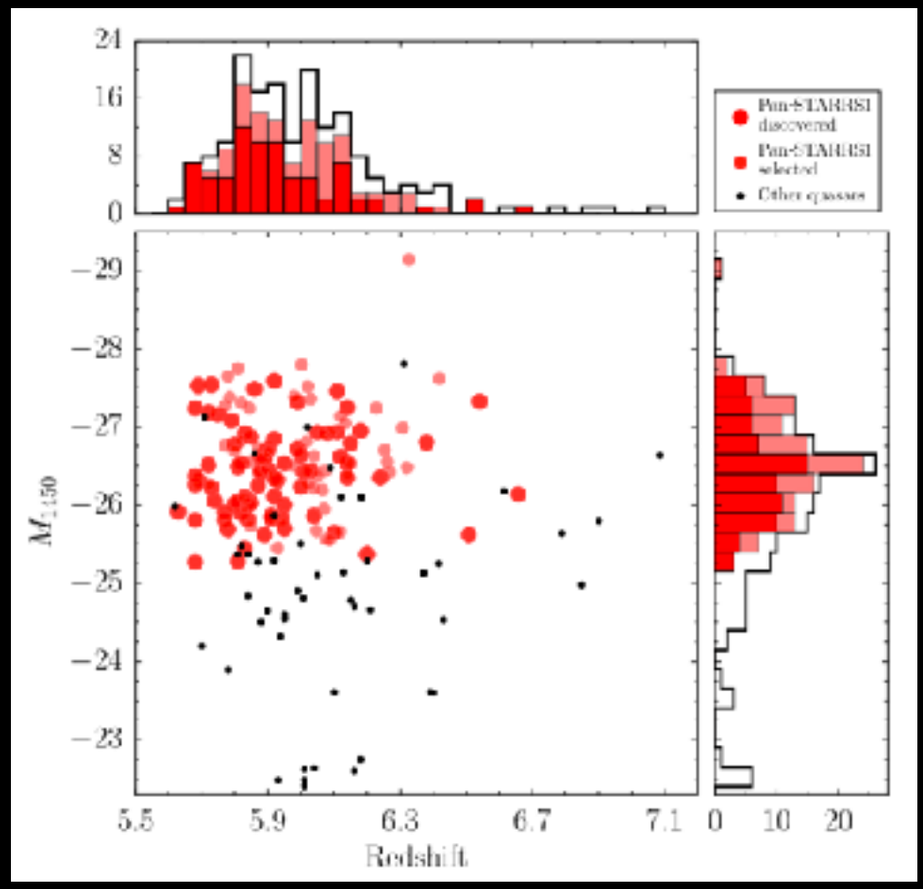
20 nights in S16B-S18A intensive program

- Sep 2016 (2 nights) → ~70% clear
- Dec 2016 (2 nights) → 0% (storm “Curse of Yasuda-san”)
- Jan 2017 (1 night) → ~50% clear
- Mar 2017 (3.5 nights) → 100% clear
- Apr 2017 (1.5 nights) → 0% (wind-screen trouble)
- May 2017 (0.5 night) → 100% clear
- Sep 2017 (5 nights) → 100% clear
- 5 more nights in S18A semester

✔ GTC/OSIRIS and Gemini/GMOS-S: for brighter candidates than FOCAS targets

We are finding A LOT…



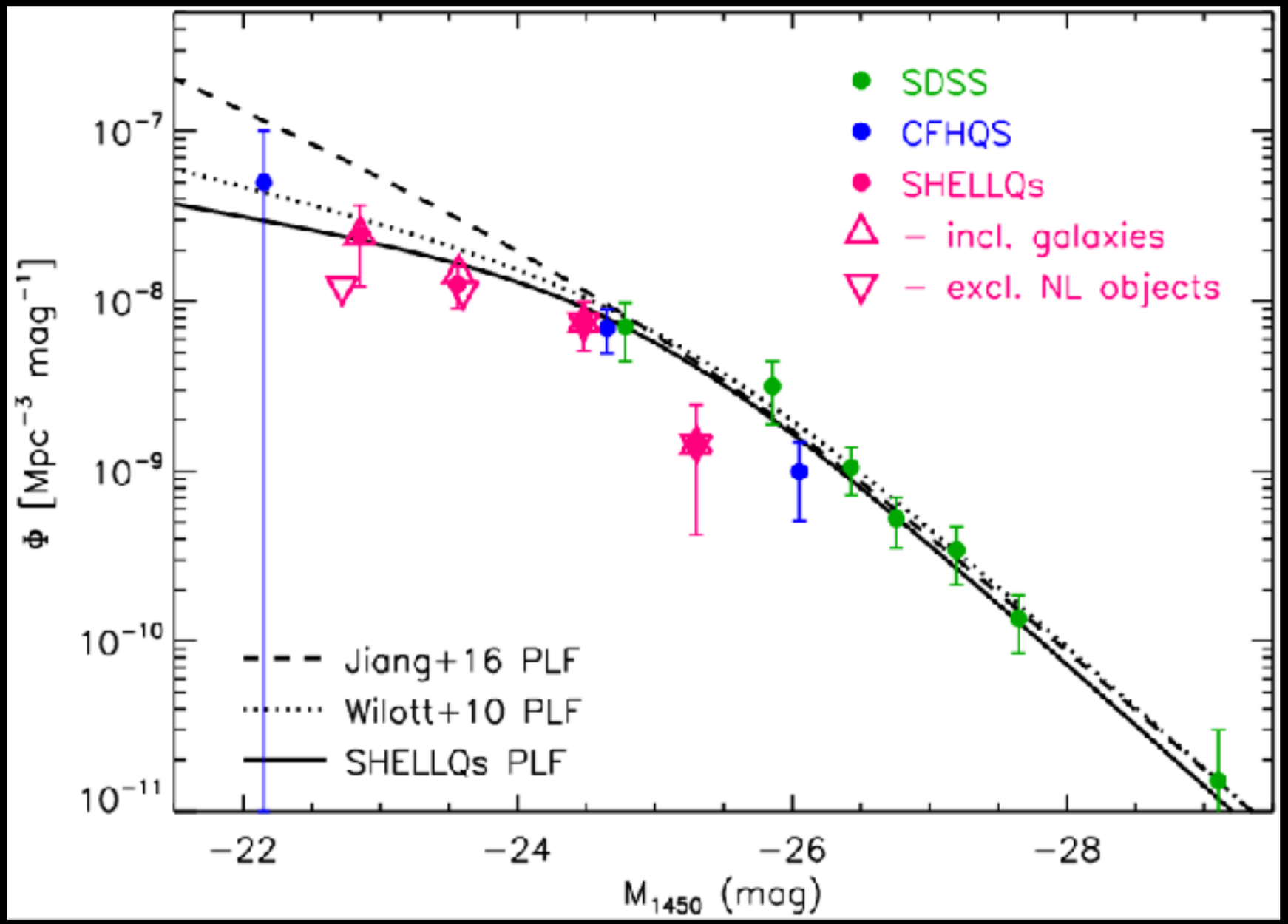


Banados+16

- We discovered ~70 quasars at 5.9 < z < 6.9 so far (Matsuoka+16, 17, in prep).
- 29 quasars with z_{AB} < 24 mag at z < 6.5 constitute our “complete sample” now.
  → luminosity function, and the contribution to cosmic reionization

SHELLQs luminosity function

Preliminary!



$$\Phi(M_{1450}, z) = \frac{10^{k(z-6)}\Phi(M^*_{1450})}{10^{0.4(\alpha+1)(M_{1450}-M^*_{1450})} + 10^{0.4(\beta+1)(M_{1450}-M^*_{1450})}}$$

Double power-law

Fixed:

- ✶ Bright-end slope
  $\beta = -2.8$ (Willott+10, Jiang+16)
- ✶ Redshift evolution
  $k = -0.7$ (Jiang+16)

Determined:

- ✶ Faint-end slope
  $\alpha = -1.35 \pm 0.35$
- ✶ Characteristic Mag
  $M_{1450}^* = -24.9 \pm 0.5$
- ✶ Characteristic Φ
  $\Phi^* = 10^{-7.9 \pm 0.3}$ [Mpc^{-3} mag^{-1}]

Contribution to cosmic 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:

$$Q_{\rm HII}(t) = 1, \ \frac{dQ_{\rm HII}(t)}{dt} \geq 0 \ \rightarrow \ \dot{n}_{\rm ion} \geq \frac{\langle n_{\rm H} \rangle}{t_{\rm rec}} = 10^{49.8} C_{\rm HII} \left(\frac{1+z}{6} \right)^3 \ [{\rm s}^{-1} \ {\rm Mpc}^{-3}]$$

(Madau+99, Bolton & Haehnelt07)

✶ *Total quasar emissivity of ionizing photons*

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

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}

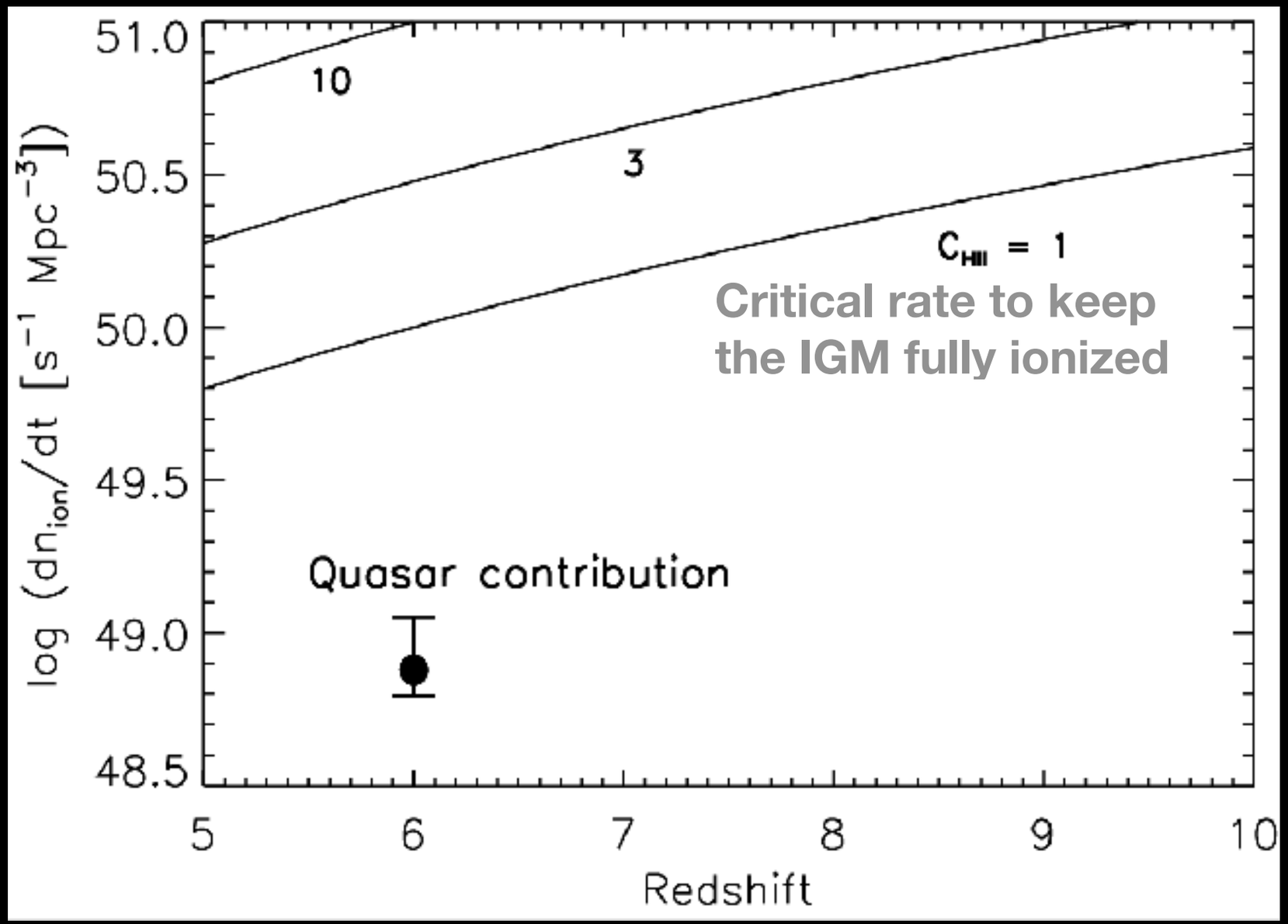
$$\xi_{\rm ion} \ [{\rm s^{-1} \ (erg \ s^{-1} \ Hz^{-1})^{-1}}] = (L_{\nu 1450})^{-1} \int_{\nu {\rm LL}}^{4\nu {\rm LL}} \frac{L_\nu}{h\nu} \, d\nu$$

Contribution to cosmic reionization

Preliminary!

✶ Our QLF indicates:

$\dot{n}_{\rm ion} = 10^{48.9\pm0.2}$ [s^{-1} Mpc^{-3}] at z ~ 6

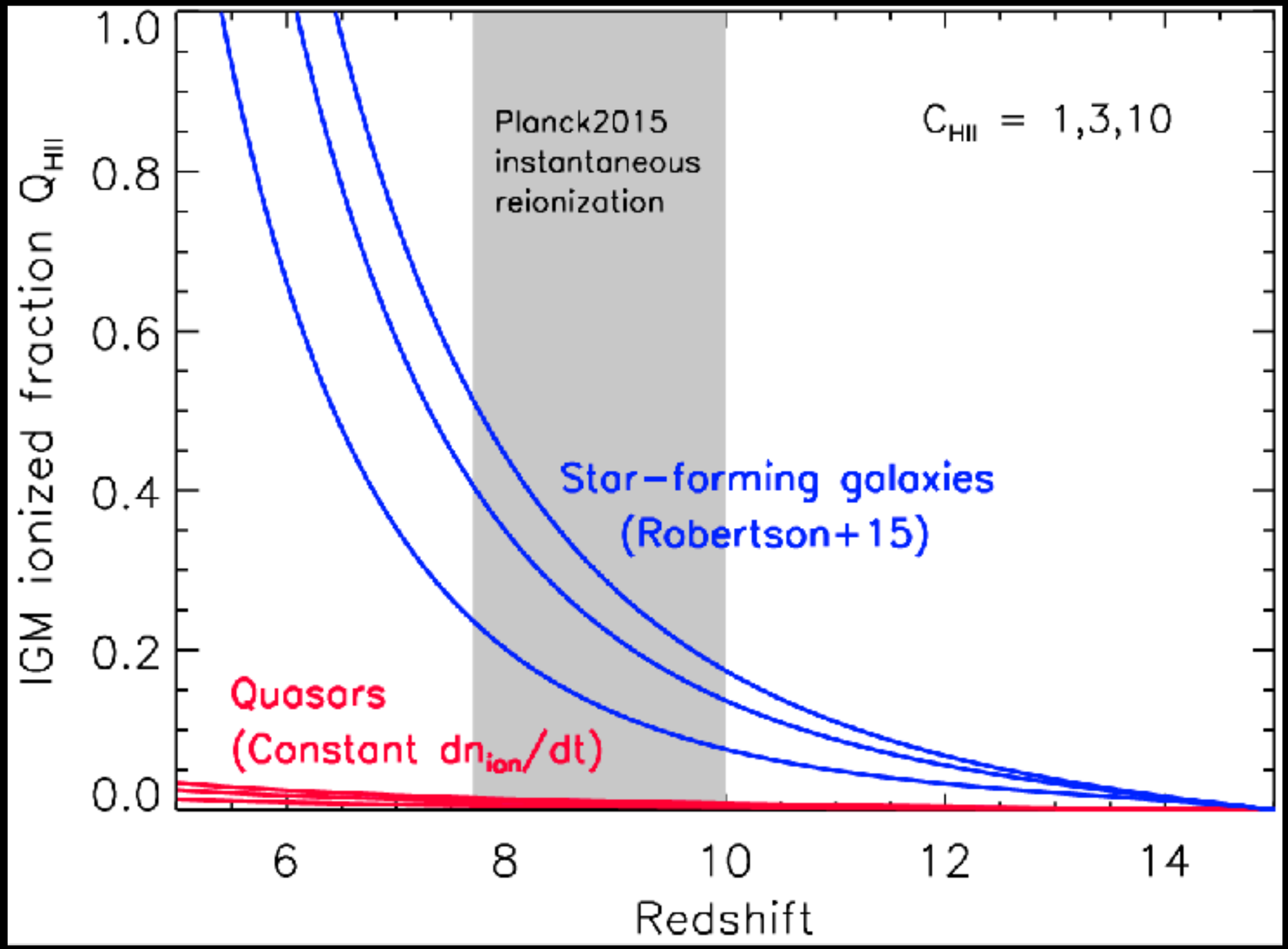


→ Quasars alone cannot reionize the Universe.

Contribution to cosmic reionization

Evolution of Q_{HII}, for constant quasar $\dot{n}_{ion}$ at $5 < z < 15$ (which is unlikely)

Preliminary!



Future Prospects

✶ In the short term…

✓ Multi-λ follow-up observations (ALMA, Gemini/GNIRS, VLT/X-shooter)
- some data already delivered (ALMA Cycle 4, GNIRS, …)
- more data coming soon, and more proposals submitted

✓ Continue to identify new high-z objects

✓ Luminosity function

✶ In the longer term…

✓ IGM absorption → reionization

✓ BH mass/Eddington ratio functions

✓ Host galaxy properties: metallicity, star formation, dust, ionized halo, …

✓ PFS! We will target all (remaining) HSC high-z quasar candidates in the planned PFS-SSP survey.