Searching for High-z Faint Quasars with Infrared Medium-deep Survey (IMS)

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working with
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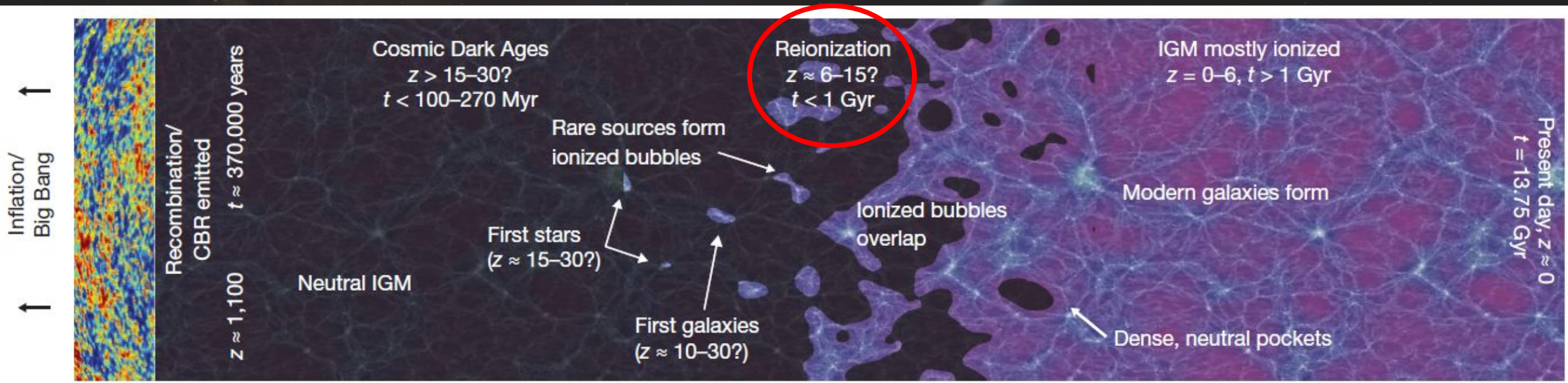
Image Credit: ESO/M. Kornmesser

Introduction

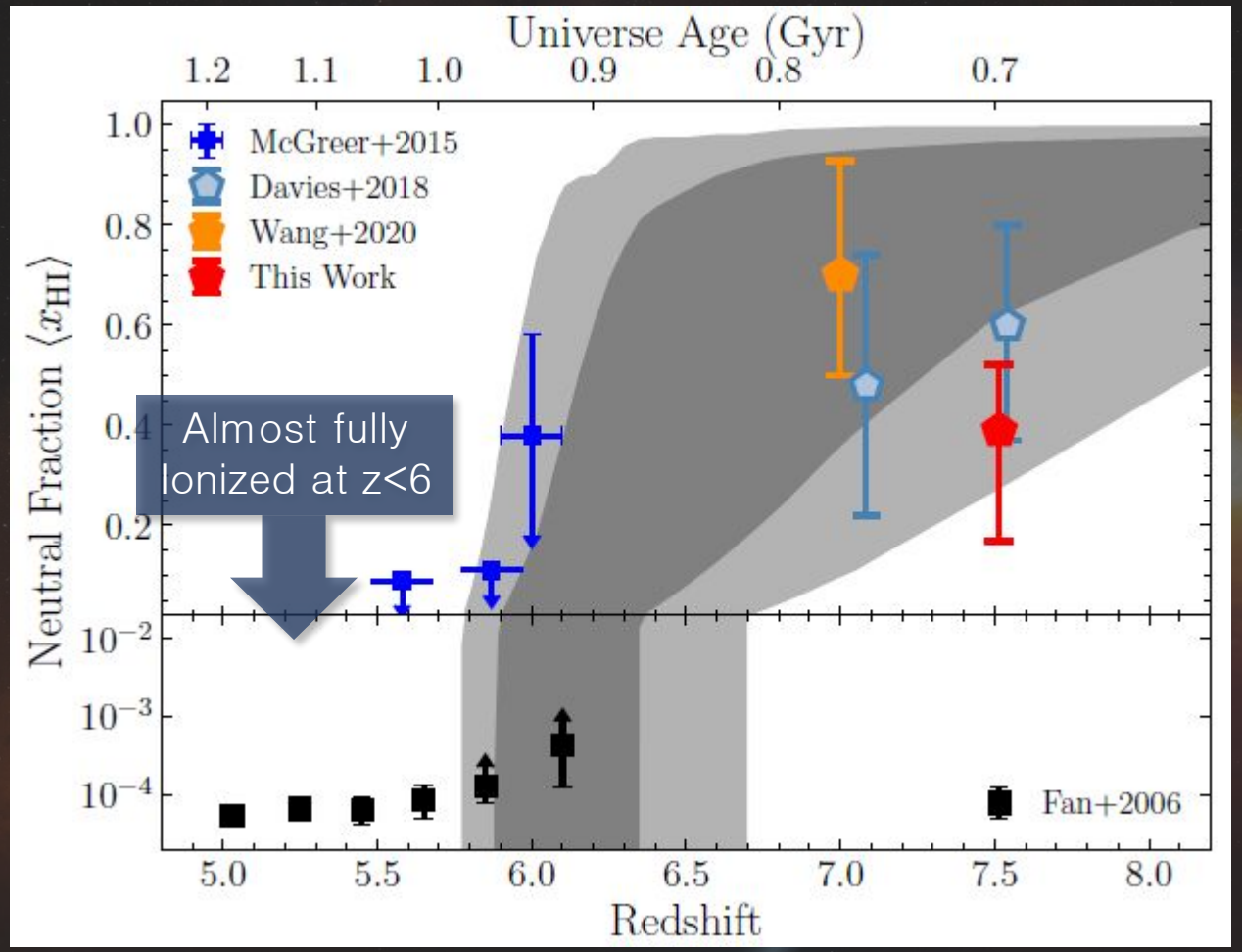
- Cosmic Reionization
  - Cosmic recombination ☐ Neutral hydrogen in the universe
  - Birth of stars & galaxies ☐ A large amount of UV photons
  - Most of hydrogen in the universe is ionized nowadays



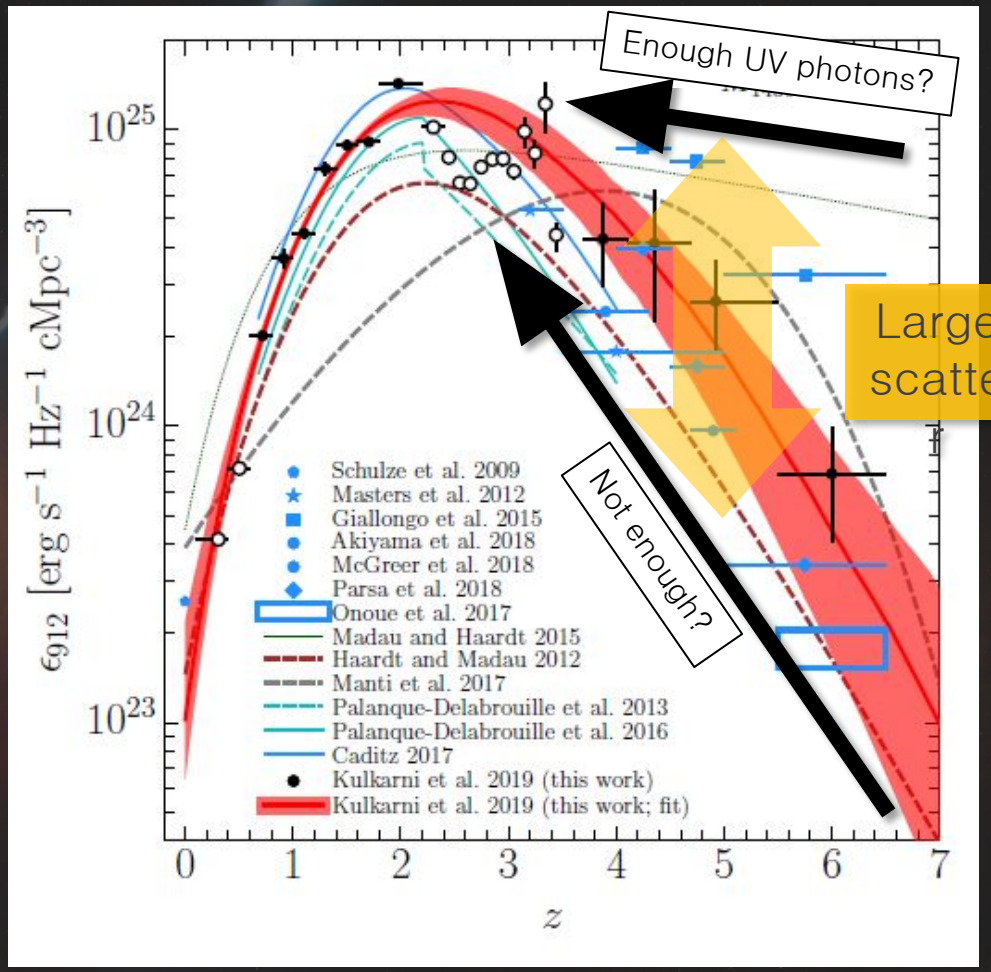
Robertson+10

Introduction

- Ionizing Sources for Intergalactic Medium (IGM) in the Post-reionization Epoch
  - Quasars alone or not?



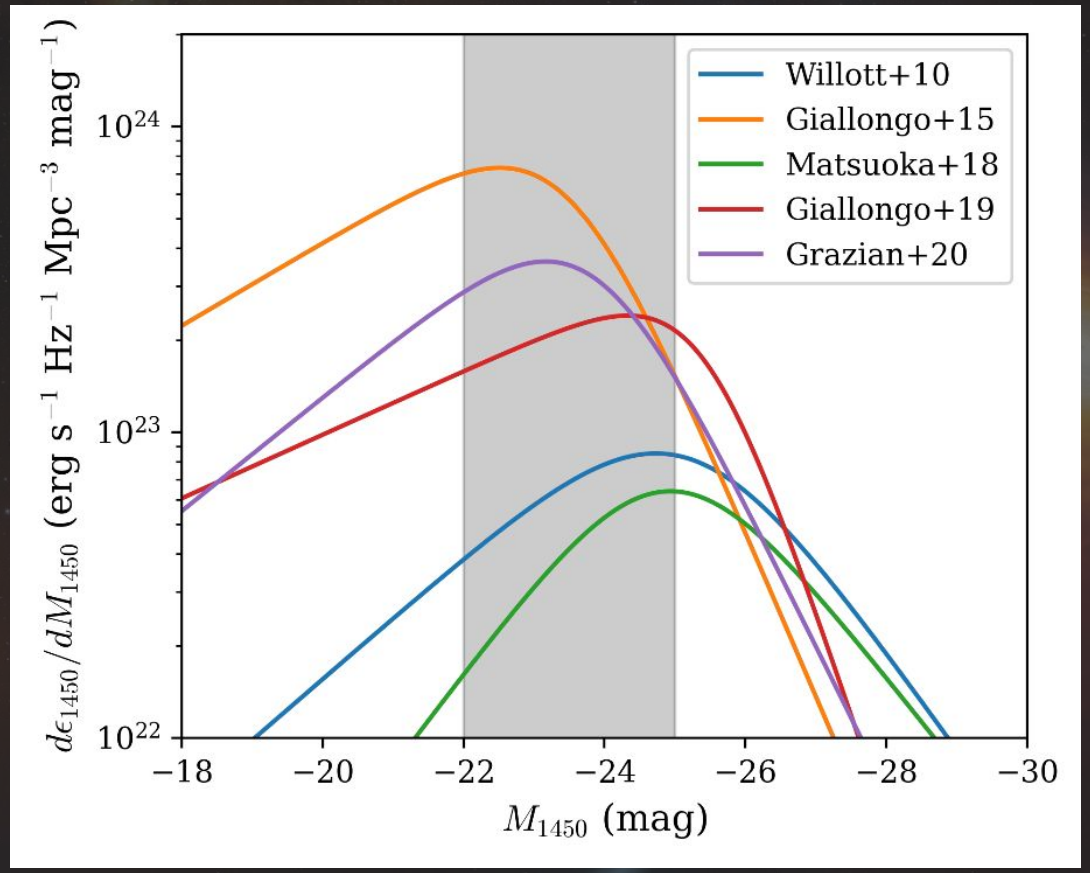
Yang+20

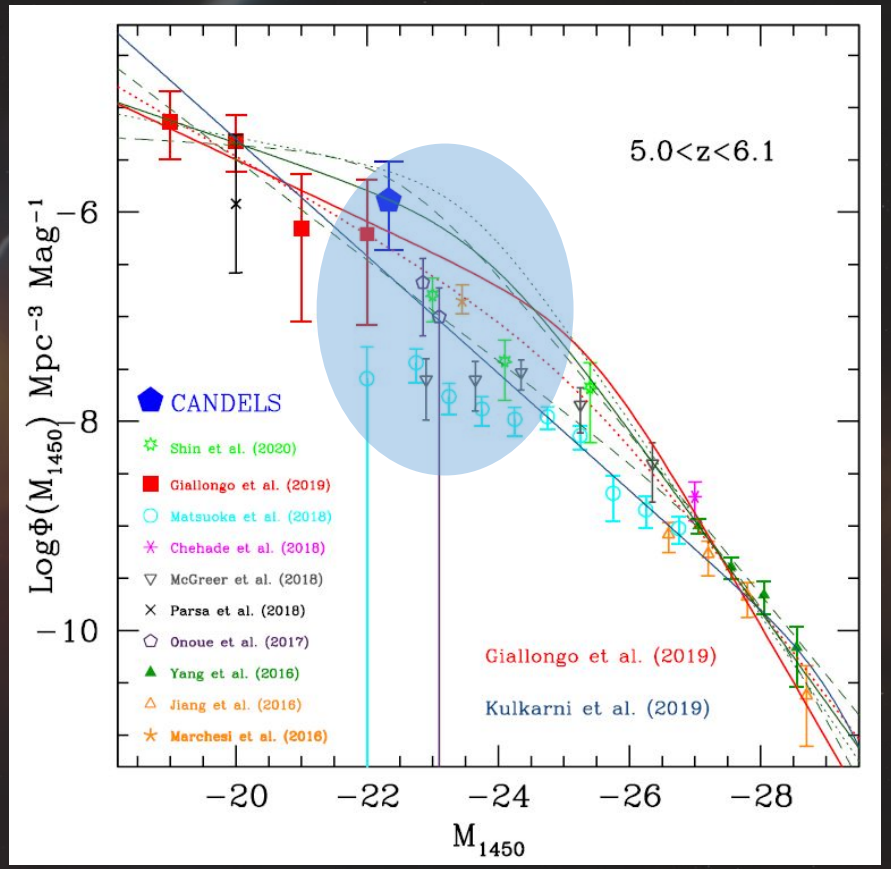


Kulkarni+19

Introduction

- Determination of Quasar Luminosity Function
  - UV emissivity ε_{1450} is proportional to number density & luminosity
    - Maximum at $M_{1450} \sim -23$ mag
  - But number density was not constrained with lack of faint quasars





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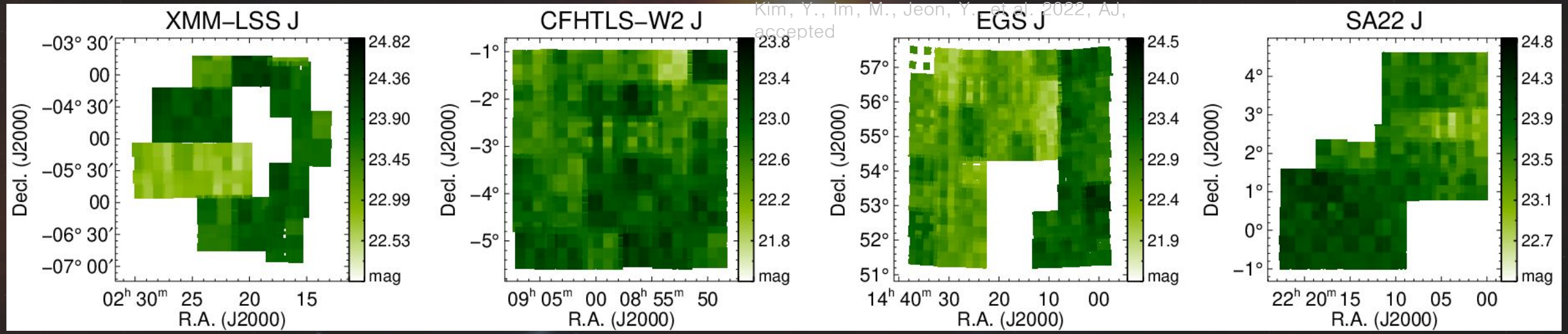
Infrared Medium-deep Survey (IMS)

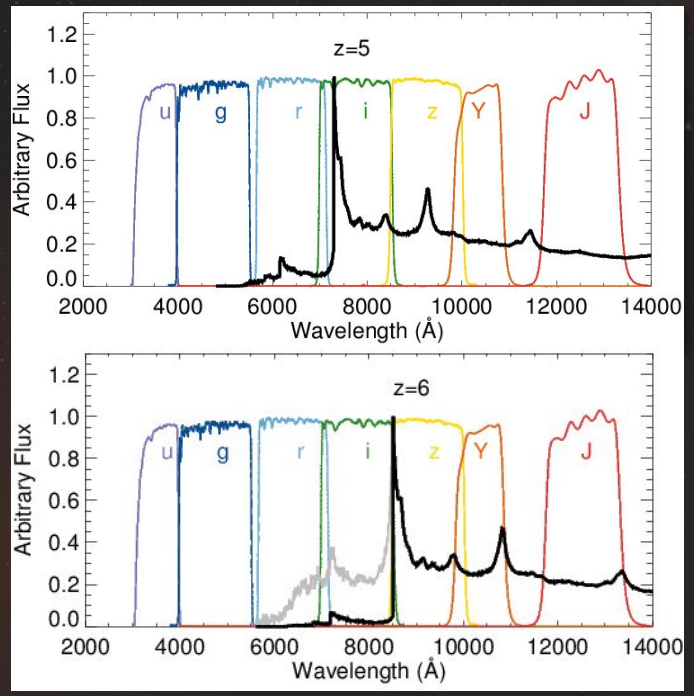
- **Near-infrared Imaging Survey (PI: Myungshin Im)**
  - NIR images obtained with **WFCam** on **UKIRT** (2009-2013)
  - Sky coverage of ~120 deg^2 in Y/J-bands (J_{AB} ~ 23 mag)
- **High-z Quasar Survey with IMS**
  - Combination with Canada-France-Hawaii Telescope Legacy Survey (CFHTLS)
    - Optical images (ugriz down to 25-26 mag)
  - IMS+CFHTLS overlap (86 deg^2)
    - **Targeting faint quasars ($M_{1450} \leq -23$ mag) at z = 5-6**

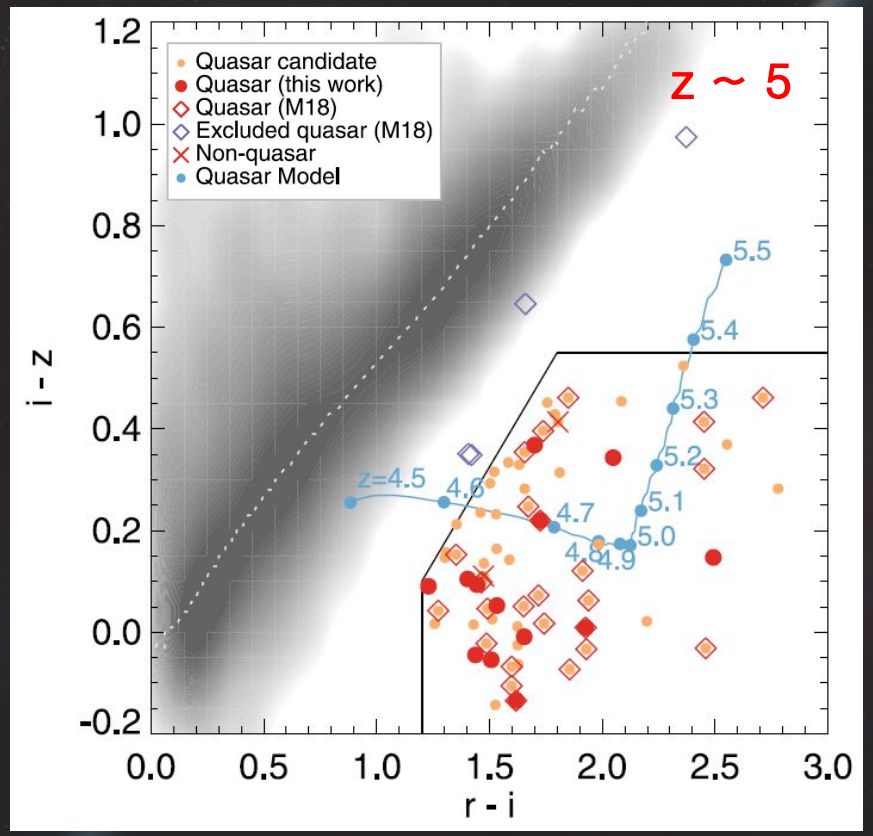
Kim, Y., Im, M., Jeon, Y., et al. 2015, ApJL, 813, L35
Kim, Y., Im, M., Jeon, Y., et al. 2019, ApJ, 870, 86
Kim, Y., Im, M., Jeon, Y., et al. 2020, ApJ, 904, 111
Kim, Y., Im, M., Jeon, Y., et al. 2022, AJ, accepted



Quasar Candidate Selection

- **Traditional Color–Selection Methods**
  - Using red colors from Lyman break due to IGM attenuation
  - Over 86 deg^2 area,
    - 69 z ~ 5 quasar candidates
    - 25 z ~ 6 quasar candidates





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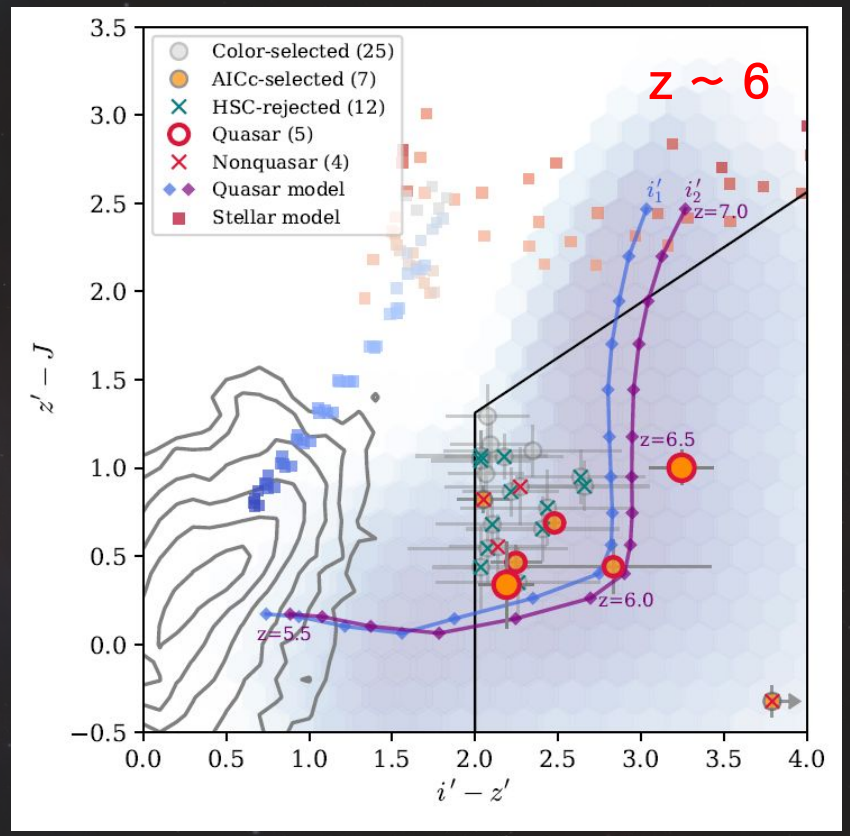

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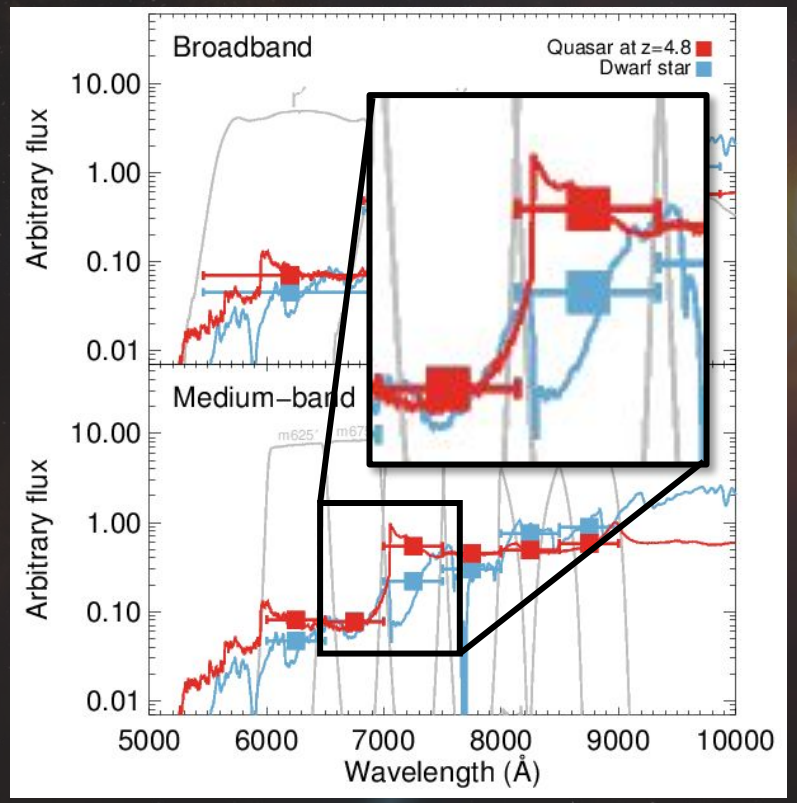
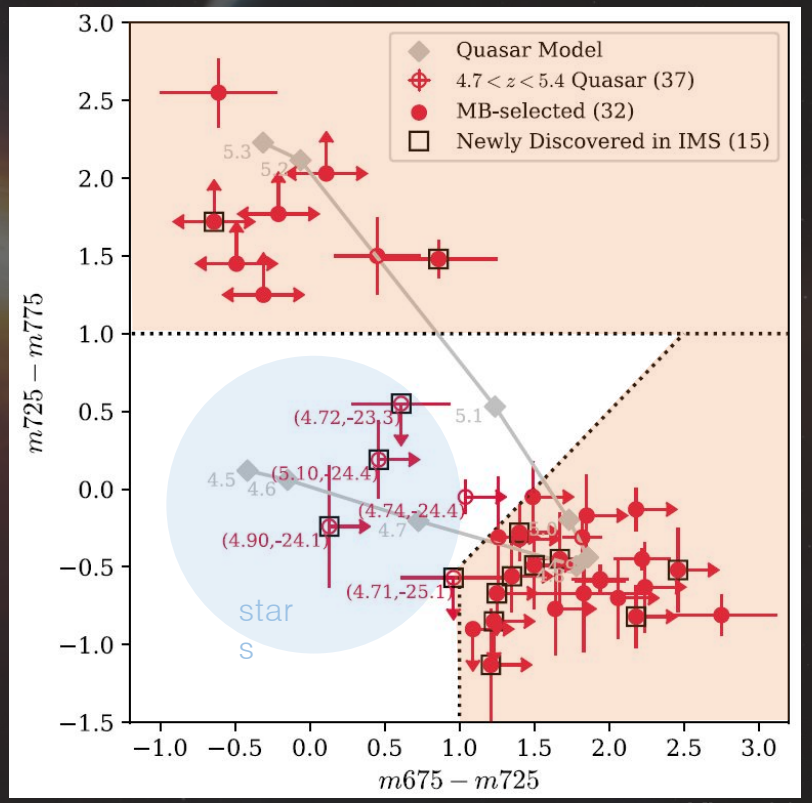
Quasar Candidate Selection

- Medium-band-based Approach with SQUEAN
  - To improve success rate of quasar identification
  - SED Camera for QUasars in the EArly uNiverse (SQUEAN) on Otto Struve 2.1 m Telescope, McDonald Observatory
  - Medium-band Follow-up
    - Bandwidth of 500 Å
    - For $z \sim 5$ quasars, m675/m725/m775 bands are useful ☐ 33/69 candidates satisfy color criteria





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Quasar Candidate Selection

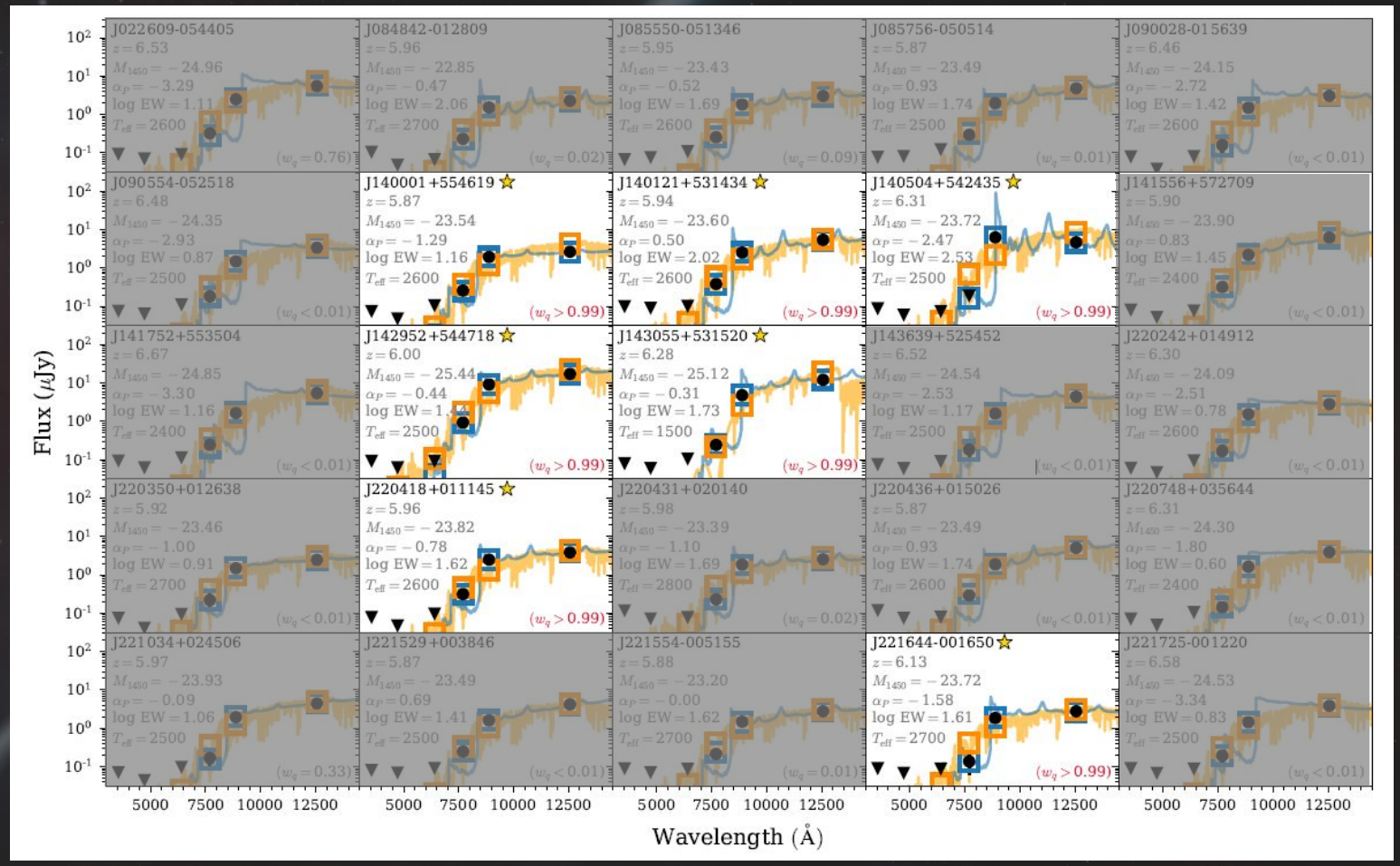
- AICc Selection Method to Find z ~ 6 Quasars
  - Corrected Akaike Information Criterion (AICc; Akaike 1974; Sugiura 1978)
    - Weights between High-redshift quasar model vs late-type star model
    - 7/25 candidates with $w_q > 0.99$

For a given model j,
k_j: # of free parameters
n: # of data
L_j: likelihood function

$$\mathrm{AICc}_j = 2k_j - 2\ln \mathcal{L}_j + \frac{2k_j(k_j+1)}{n-k_j-1}$$

$$w_j = l_j/(l_q + l_s)$$

$$l_j = \exp\left(-1/2\,(\mathrm{AICc}_j - \mathrm{AICc}_{\min}\right)$$



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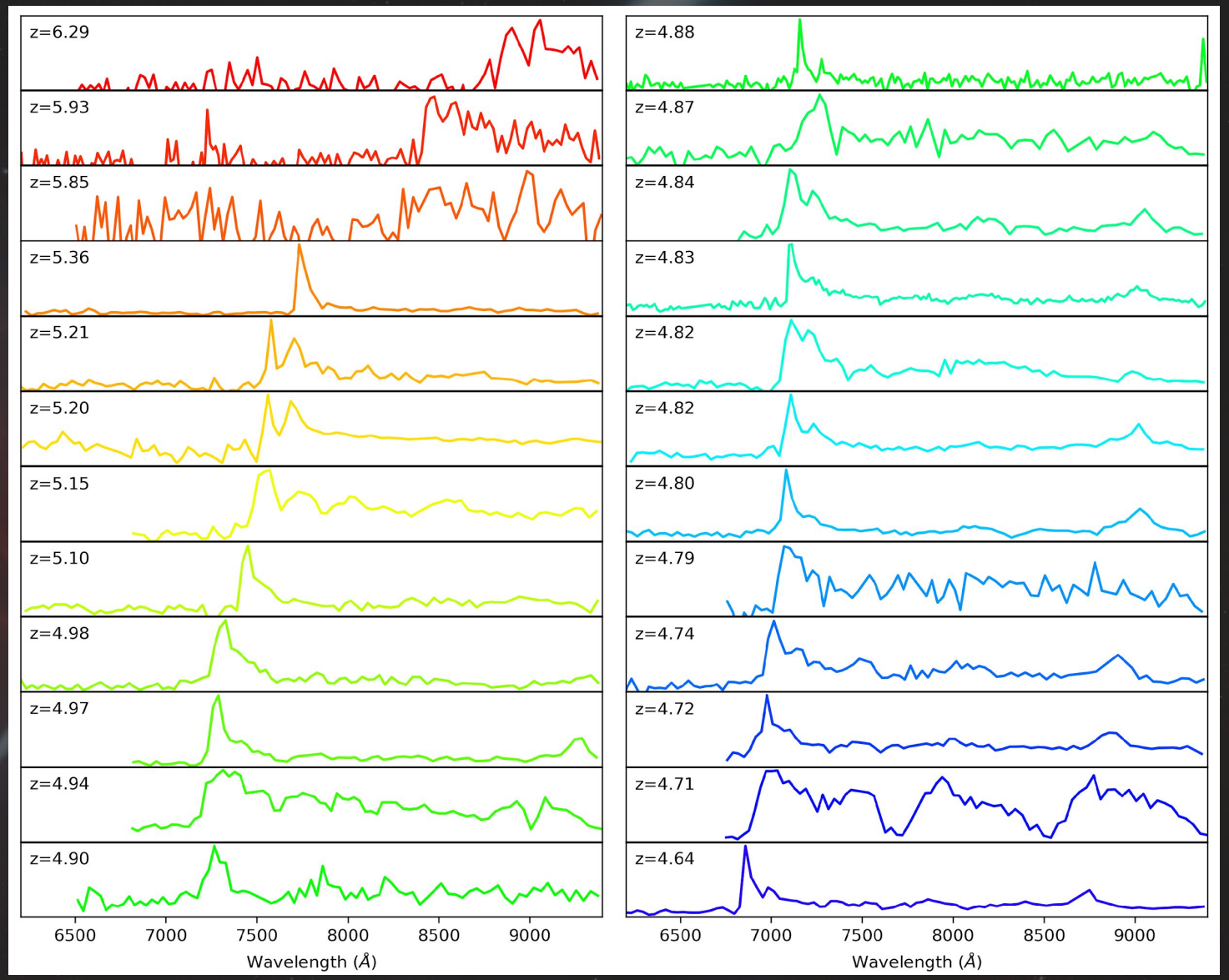
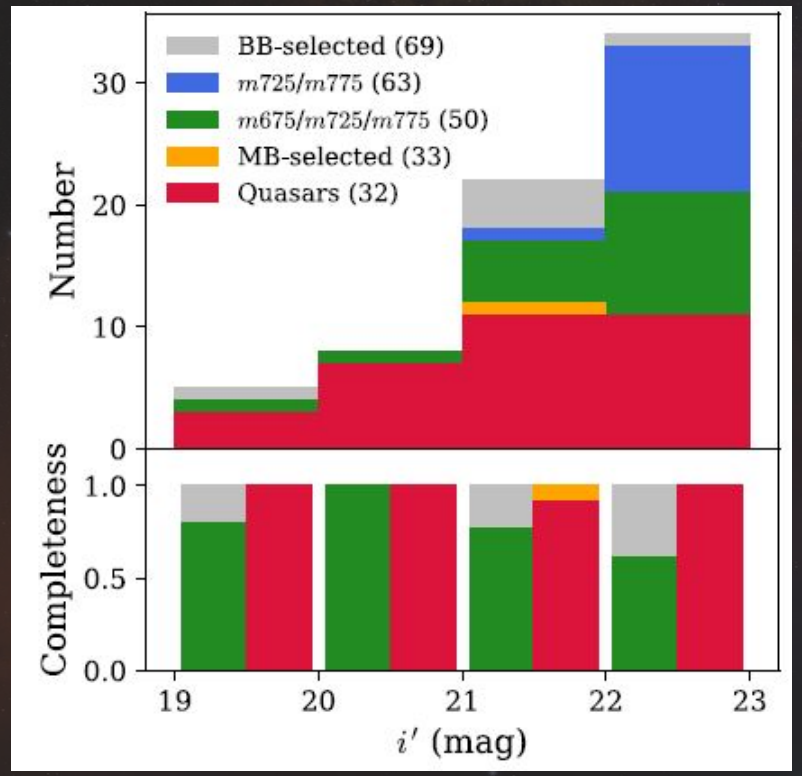
Discovery of New Quasars with Spectroscopy

- Gemini GMOS-N/S Observations
  - Supported by K-GMT Science Group at KASI
  - 19 & 1 quasars at z ~ 5 & 6
- Magellan IMACS Observations
  - Supported by CEOU at SNU
  - 2 quasars at z ~ 5
- P200 DBSP Observations
  - Supported by TAP Program in China
  - 2 quasars at z ~ 6



Improved Quasar Candidate Selection Methods

- Medium-band Follow-up
  - 32/33 MB-selected candidates were identified as z ~ 5 quasars
    - Five quasars are missed but due to detection limit
  - Higher accuracy of photometric redshift determination ($\Delta z \sim 1-2\%$)
    - Prospects for future medium-band surveys (e.g., 7DS)



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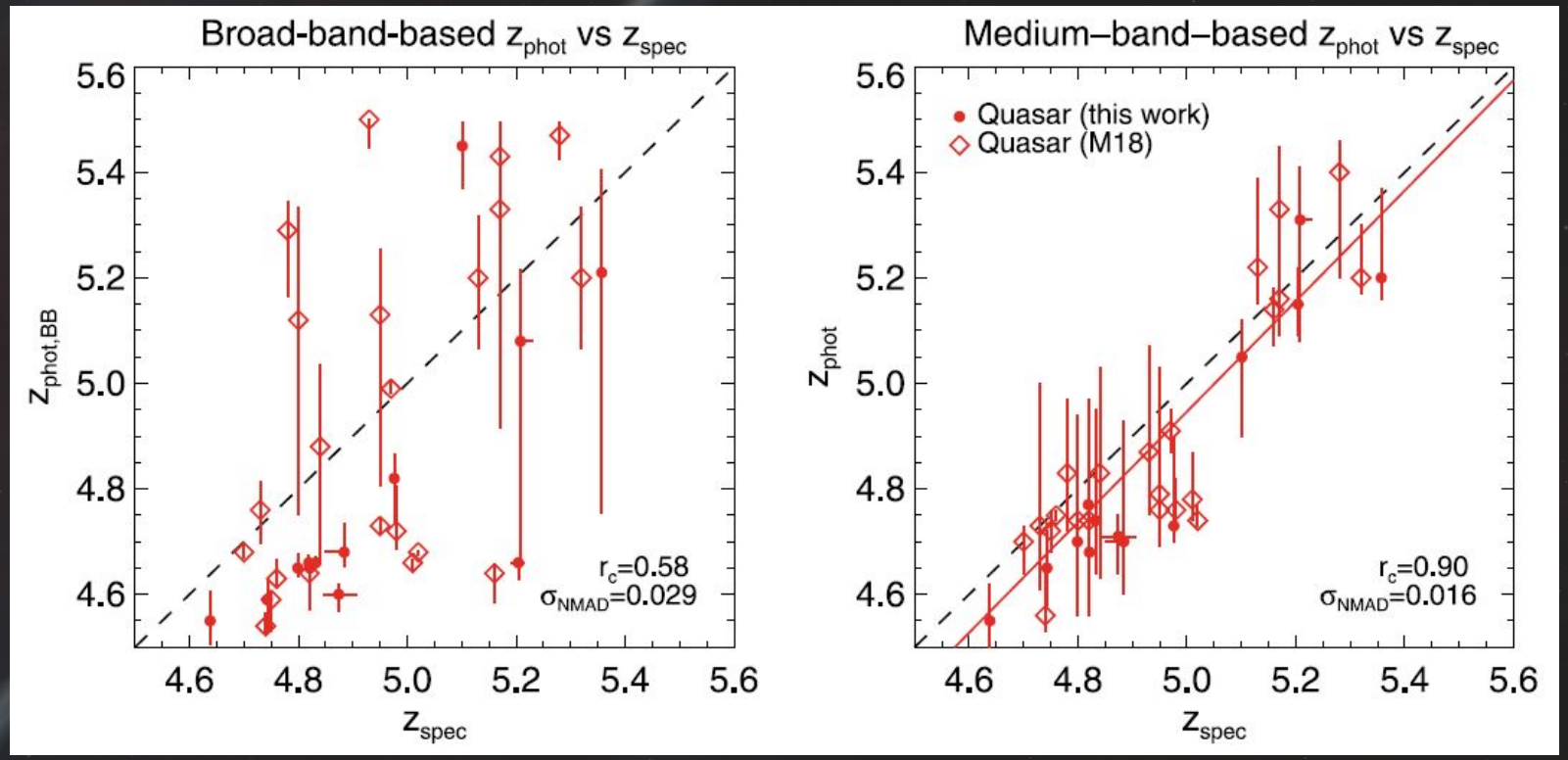

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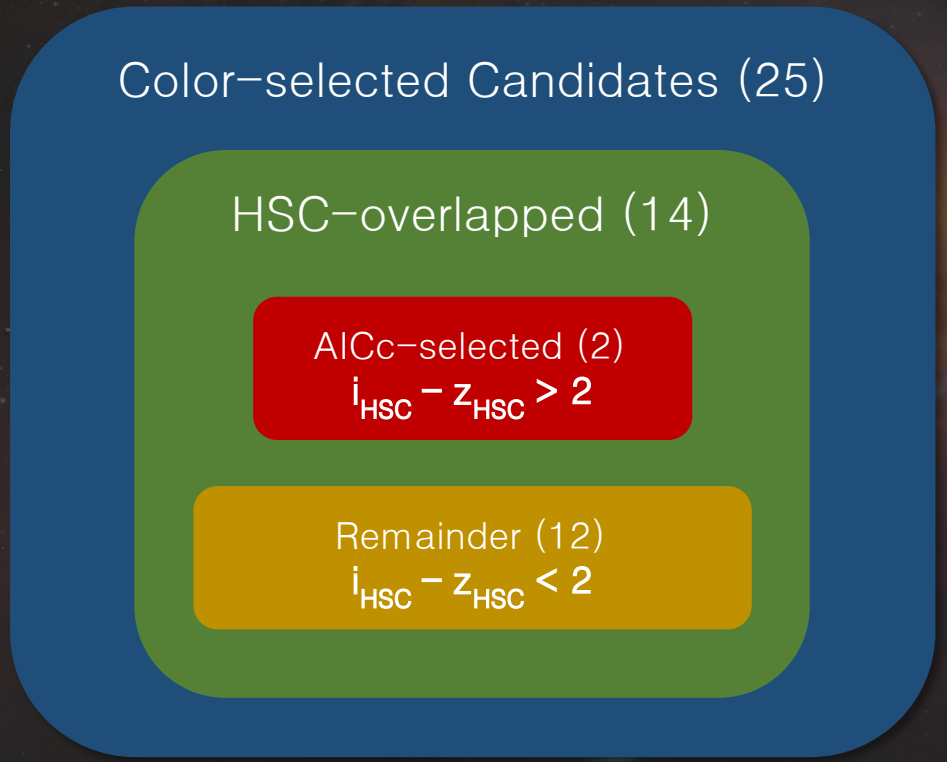
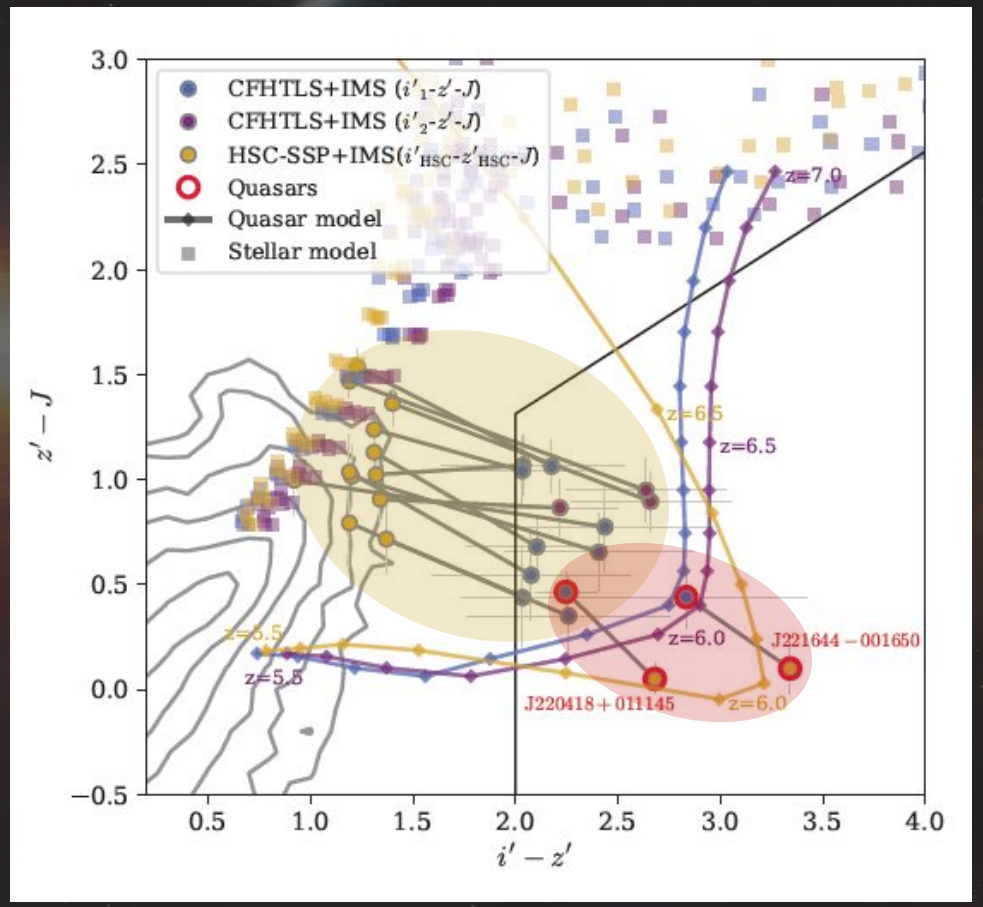
Improved Quasar Candidate Selection Methods

- AICc Selection
  - 5/7 candidates were identified as z ~ 6 quasars
  - Crosscheck with Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; ~1 mag deeper than CFHTLS)
    - Candidates with blue color in HSC data are rejected well!
    - Spec-identified quasars are selected well
  - Effective for searching at survey detection limits





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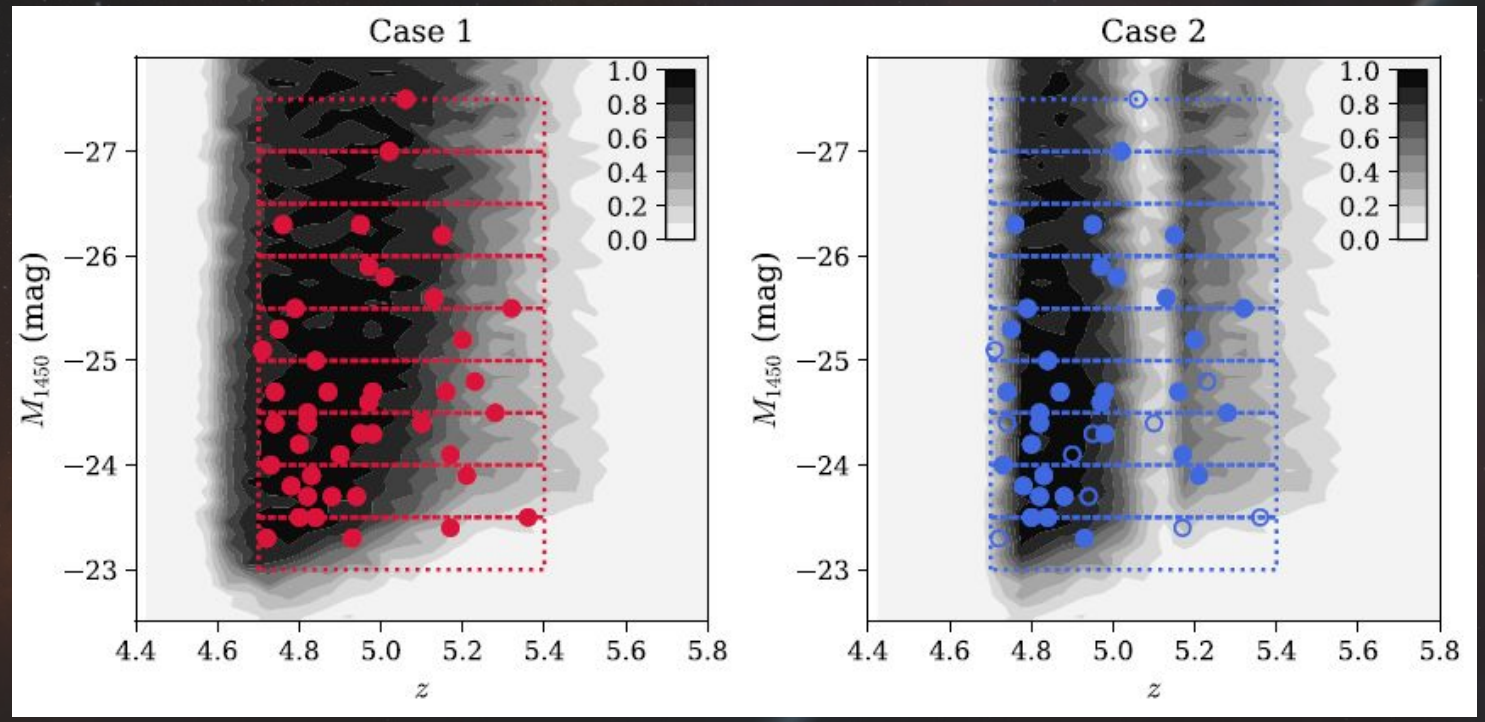
Quasar Luminosity Functions

- Survey Completeness and Selection Functions
  - Photometric and spectroscopic completeness
  - Selection functions with our selection methods
    - Calculated based on our high-redshift quasar model (Kim+19)
    - At z ~ 5, divided into two cases
      - Case 1: Broadband selection
      - Case 2: Broadband+Medium-band selection



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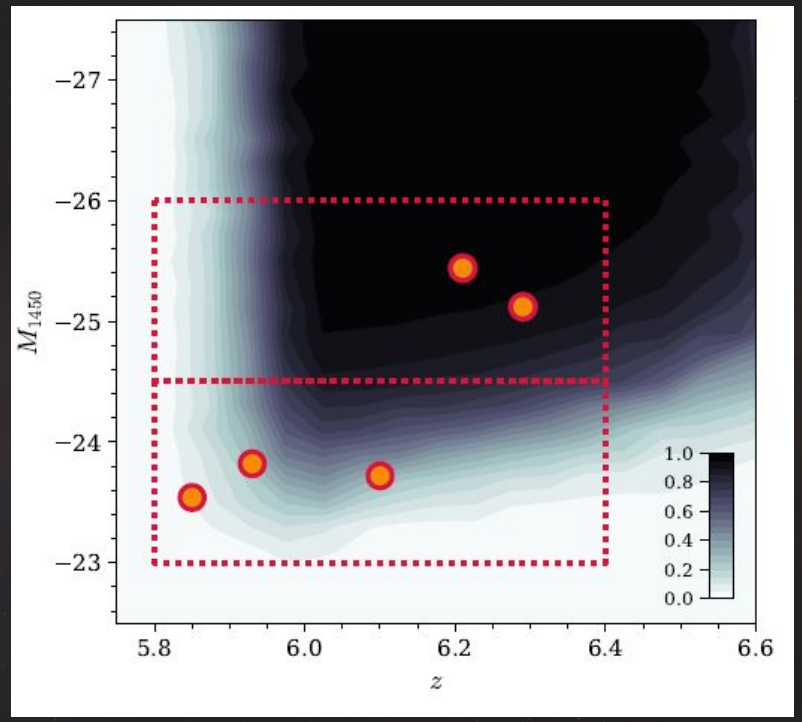

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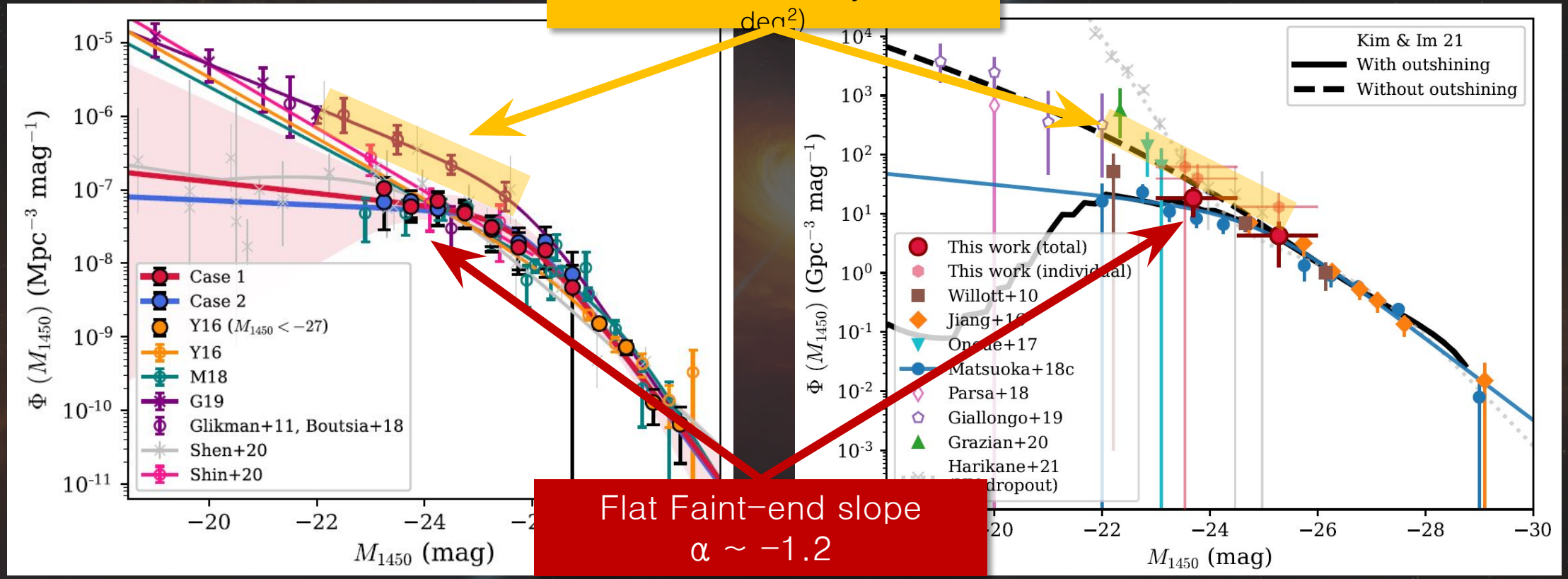
Quasar Luminosity Functions

- **Binned and Parametric QLFs**
  - Binned: $1/V_{max}$ method (Avni & Bahcall 80)
    - Number density corrected by selection functions
  - Parametric: Maximum likelihood method ($S = -\ln \mathcal{L}$; Marshall+83)
    - Double power-law form (only at z ~ 5)

Lower than results from small-area surveys (< 10 deg^2)



Flat Faint-end slope
$\alpha \sim -1.2$

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Contribution to Ionizing Background

- **UV Emissivity**
  - Assuming DPL quasar UV spectra (Lusso+15)

$$\epsilon_{1450} = \int_{-30}^{-18} \Phi_{par}(M_{1450})\, 10^{-0.4(M_{1450}-51.6)} dM_{1450}$$

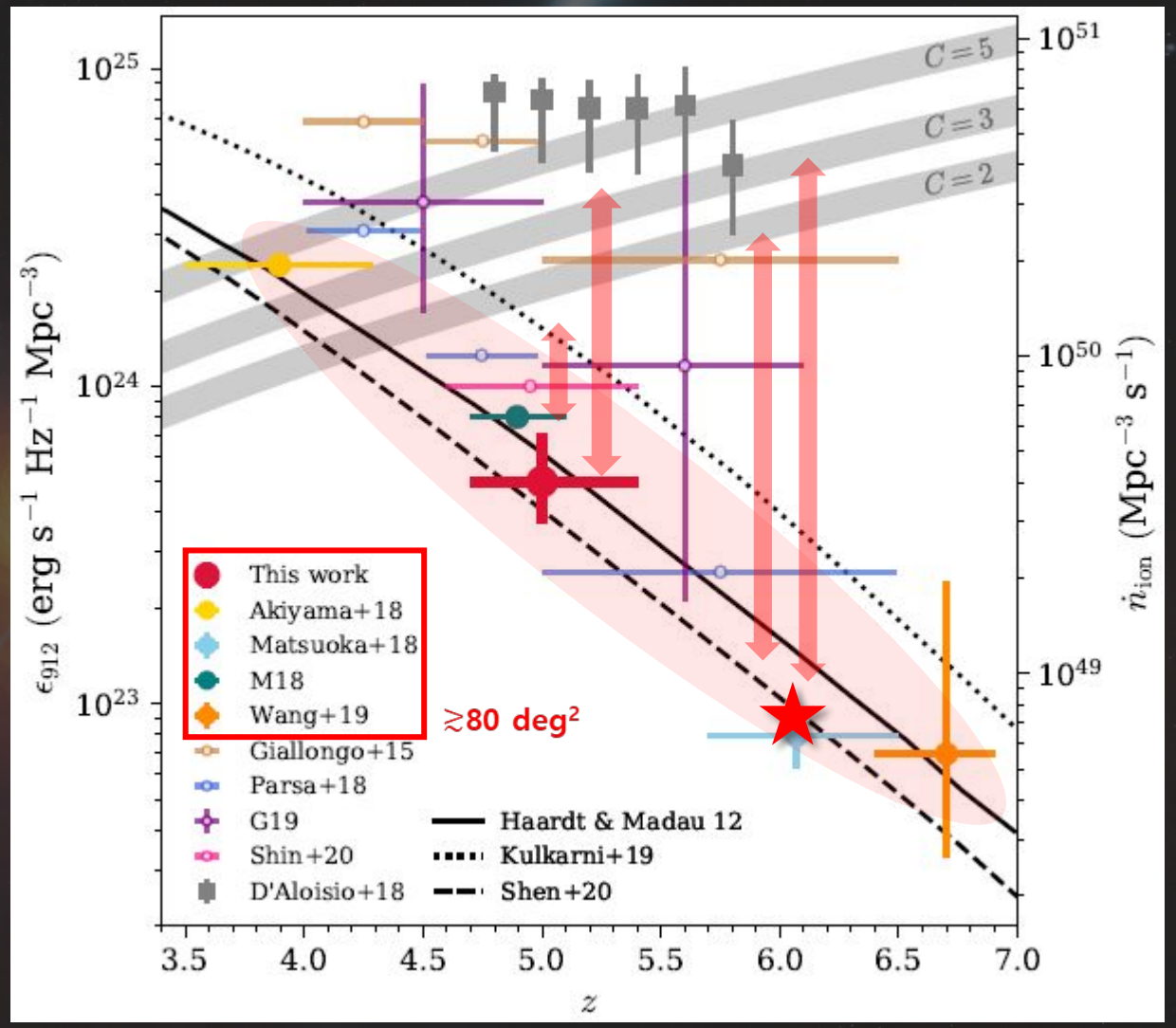
$$\epsilon_{912} = \epsilon_{1450} \times \left(\frac{912}{1450}\right)^{0.61}$$

- **Ionizing Photon Density**
  - Assuming f_{esc} = 1

$$\dot{n}_{\rm ion} = f_{\rm esc}\epsilon_{1450}\xi_{\rm ion}$$

- **Compared to Required $\dot{n}_{\rm ion}$**
  - Balance with H recombination? (e.g., Madau+99)
  - Match to transmitted Lyα flux? (e.g., D'Aloisio+18)

  → **Quasars alone couldn't have ionized IGM!**



Summary

- **High-redshift Quasar Survey with IMS**
  - Traditional broadband color selection +
    - Medium-band color selection
    - AICc selection
  - Newly discovered 24 quasars at $4.6 \leq z \leq 6.3$
    - 20 of them have been identified by Gemini Telescopes
  - Quasar luminosity functions
    - Space number densities down to M1450 ~ -23 mag
    - Very flat faint-end slope
  - Implication for UV Ionizing Background
    - Low UV emissivity and ionizing photon density
    - Quasars alone could not have ionized intergalactic medium after reionization epoch