# The Final SDSS High-Redshift Quasar Sample: 52 Quasars at z > 5.7 Since 2000


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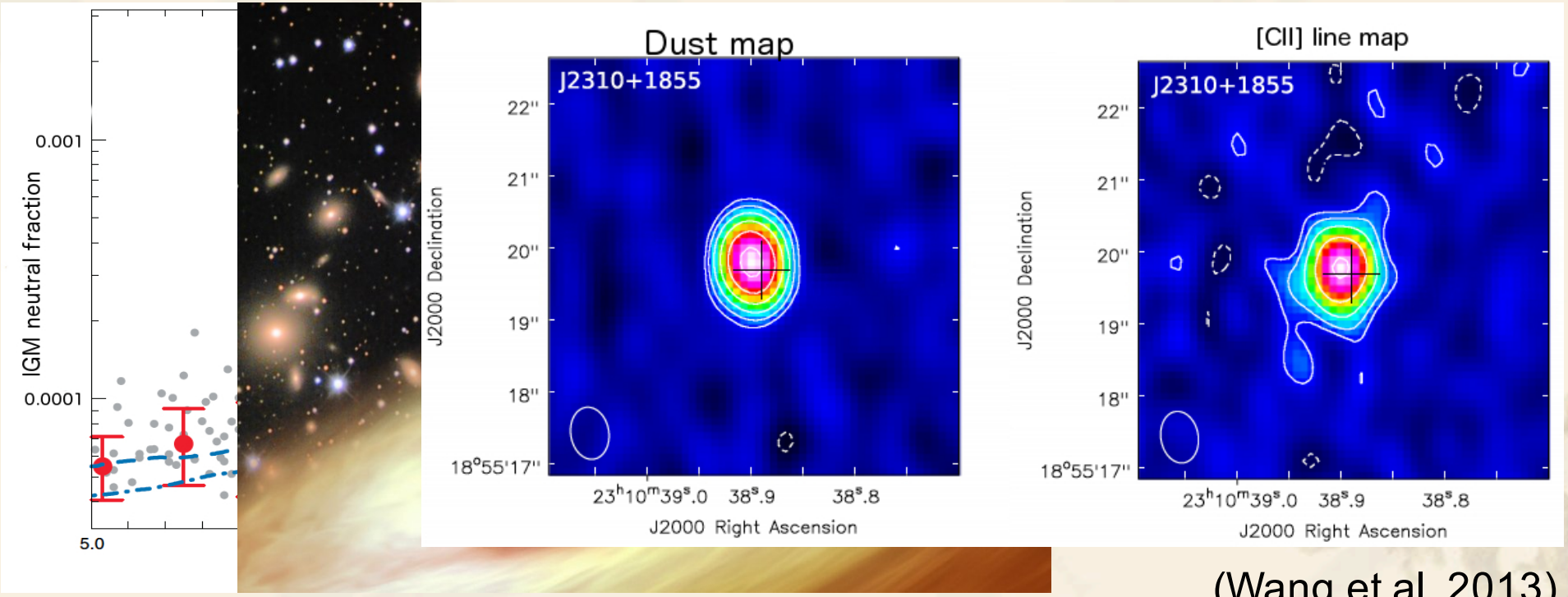
# Outline

- Introduction
- The SDSS survey of z ~ 6 quasars: the final sample
- The quasar luminosity function at z ~ 6
- Future plans and summary

# High-z (z≥6) quasars (See E. Banados's talk)

- Direct evidence: cosmic reionization ends at z~6
- Reionization history, quasar contribution to reionization, etc.
- Birth and growth of early supermassive black holes
- Quasar host galaxies: extreme places to form stars
- Many others




(Wang et al. 2013)

# Current status of quasar surveys

- The first z~6 quasars found in the SDSS (Fan et al. 2000−2006)
- Followed by
  - Deeper SDSS surveys (Jiang et al. 2008, 2009, 2015)
  - CFHTQS (Willott et al. 2005−2010)
  - UKIDSS (Venemans et al. 2007, Mortlock et al. 2009, 2011)
  - Pan-STARRS1 (Morganson et al. 2012, Banados et al. 2014)
  - VISTA (Venemans et al. 2013, 2015)
  - DES (Reed et al. 2015)
  - VST ATLAS (Carnall et al. 2015)
  - SHELLQs (Matsuoka et al. 2016)
- Others like Wu et al. (2015) and Wang et al. (2016)

Note:

- These quasars are not homogeneous
- SDSS quasars: a well-defined $z \geq 6$ quasar sample

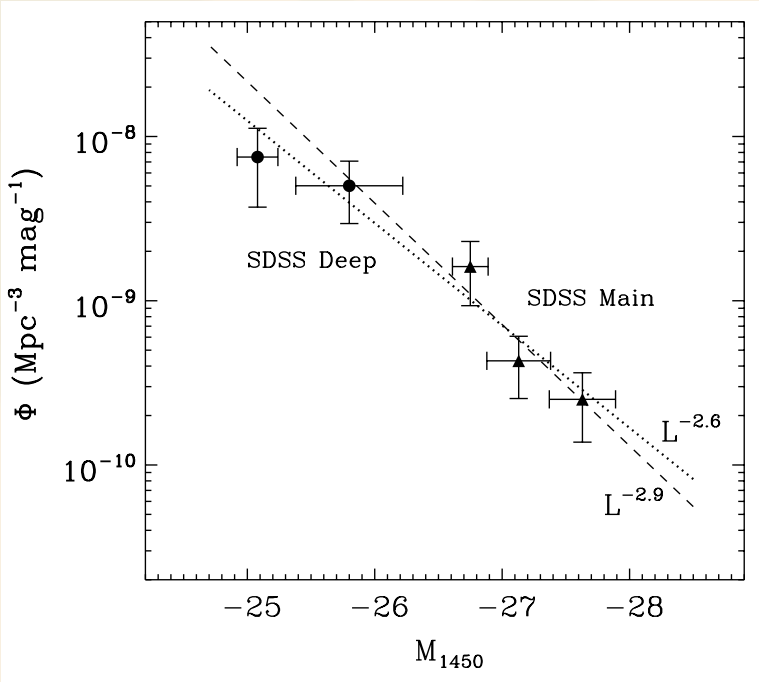
# High-z quasars in the SDSS

- Quasars (z ~ 6) in the SDSS
  - High-z quasars in the SDSS main survey (single-epoch imaging survey)
  - High-z quasars in the SDSS deep survey (Stripe 82)
  - High-z quasars in the SDSS overlap regions (regions with two scans)

- Quasars in the SDSS main survey
  - SDSS: a total of 14555 $deg^2$ of unique sky area (Ahn 2012)
  - 19 quasars in Fan et al. (2000−2006), including 15 with $z_{AB} < 20$ mag in ~7000 $deg^2$ of the main survey

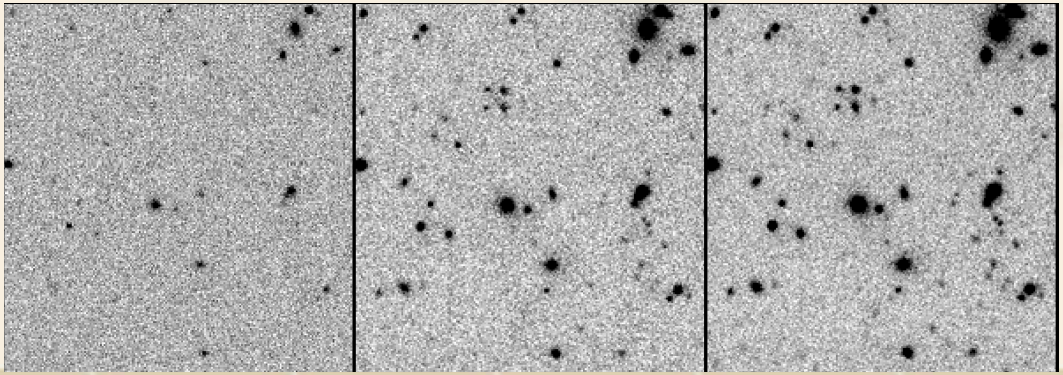
## ➢ Quasars in the SDSS Stripe 82

- Stripe 82: a total of ~300 deg$^2$
- $-60^\circ$ ($20^h$) < RA < $60^\circ$ ($4^h$)
- $-1.26^\circ$ < Dec < $1.26^\circ$
- Repeatedly scanned 70–90 times
- Two mag deeper than single-epoch data
- Depth-optimized co-adds by Jiang et al. (2014)
- 12 quasars published in Jiang et al. (2008, 2009)




SDSS main + deep
(Jiang et al. 2009)

single-epoch 20-30 epochs full depth



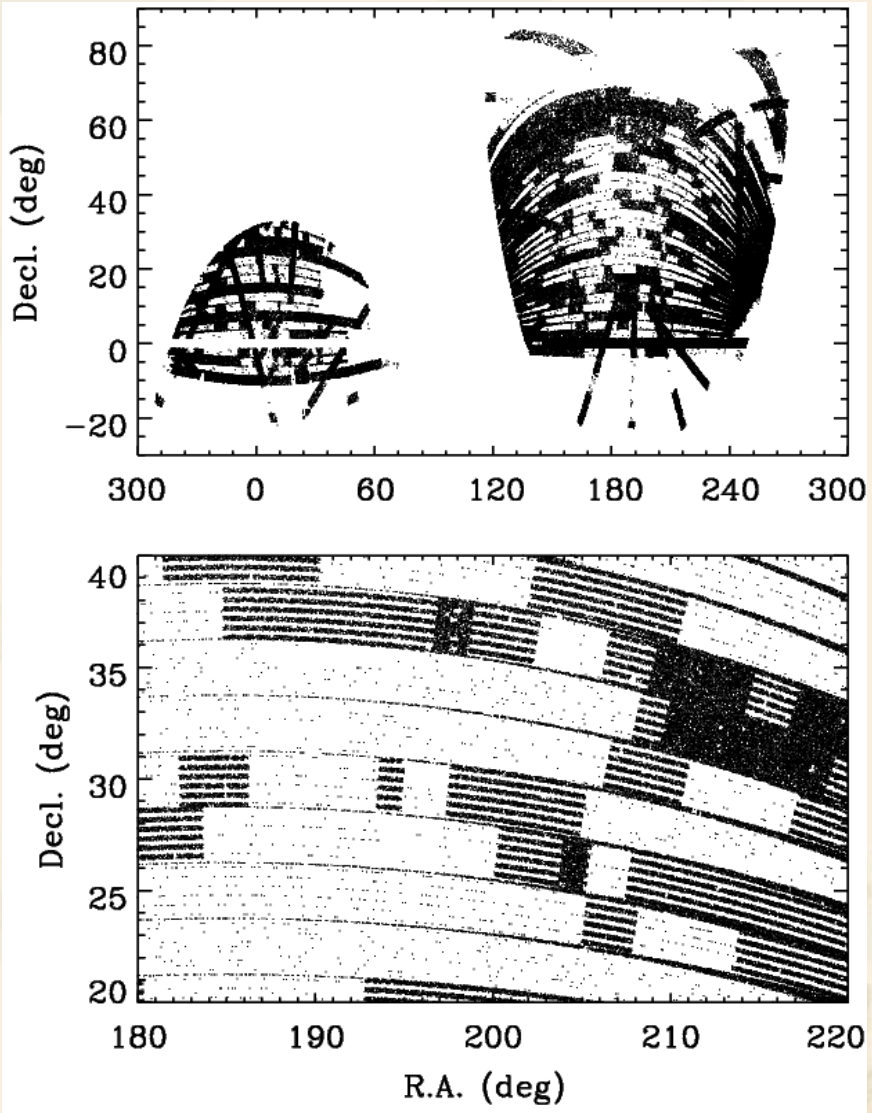
(Jiang et al. 2014)

## ➢ Quasars in the SDSS overlap regions

- SDSS: drift scan along great circles
- A total of >4000 deg$^2$
- Allow selection of quasars ~0.5 mag fainter

In Jiang et al. (2015):

- 8 new quasars
- Recovered 8 known quasars

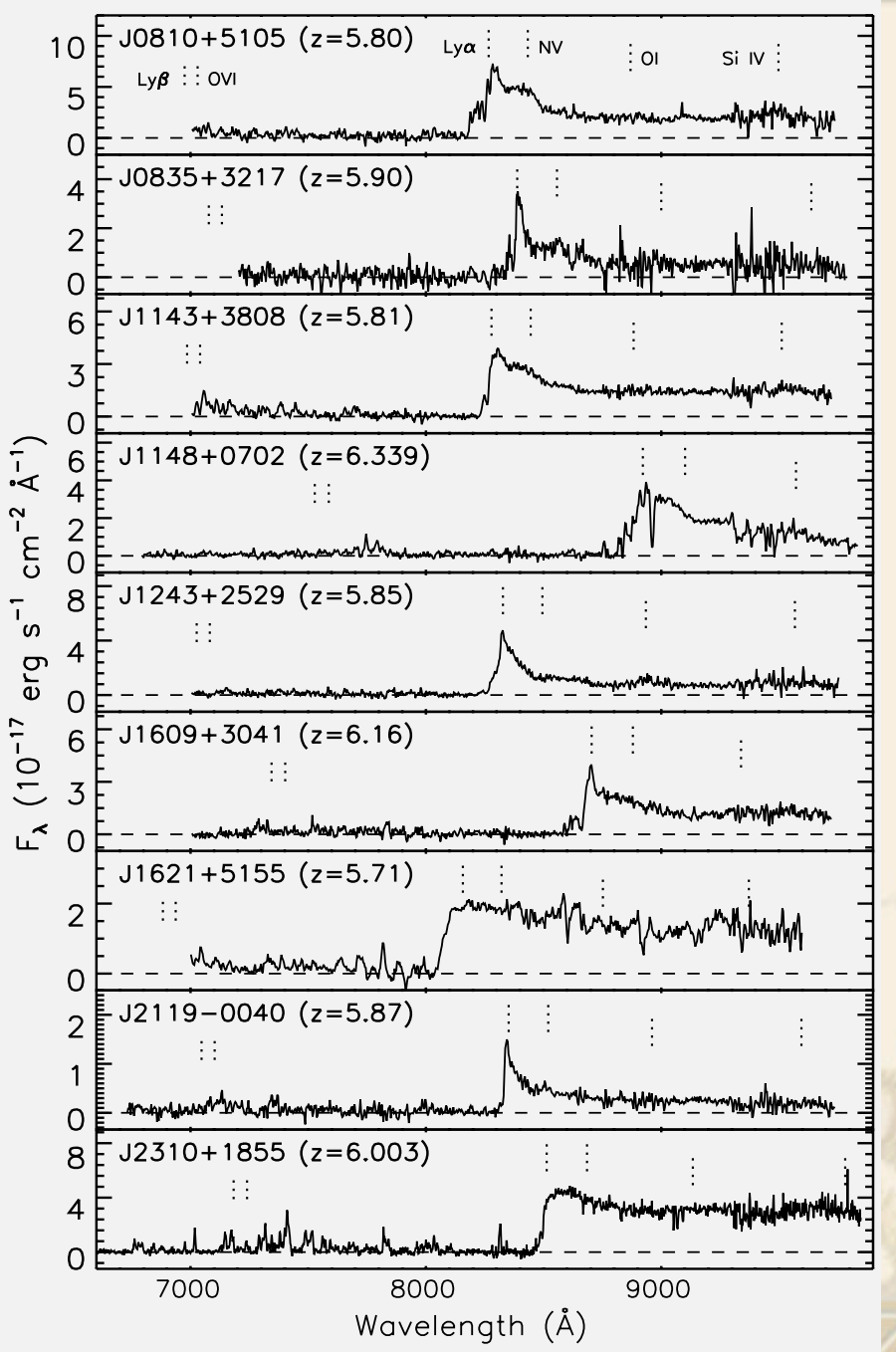



|b|>30deg

(Jiang et al. 2015)

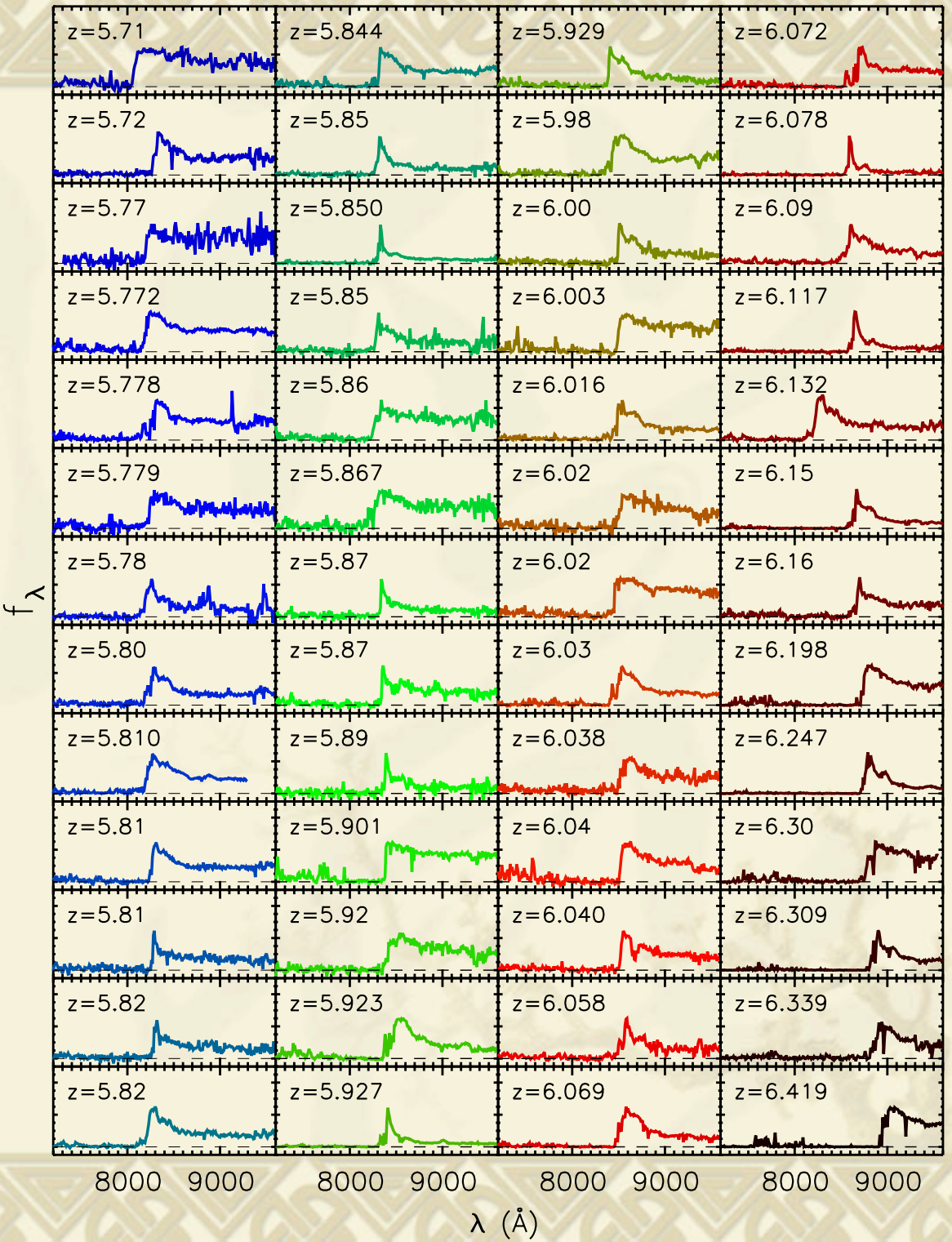
- New quasars in the SDSS
  - 9 quasars (Jiang et al. in prep.)
  - 7 in the main survey
  - 1 in Stripe 82
  - 1 in overlap regions
- All quasars in the SDSS
  - 19 from Fan et al. 2000, 2001, 2003, 2004, 2006
  - 28 from Jiang et al. 2008, 2009, 2015, 2016 (in prep.)
  - 1 from Goto et al. 2006
  - 1 from Mortlock et al. 2009
  - 1 from X. Wu et al. 2015
  - 2 from F. Wang et al. 2016

(Jiang et al. in prep.)

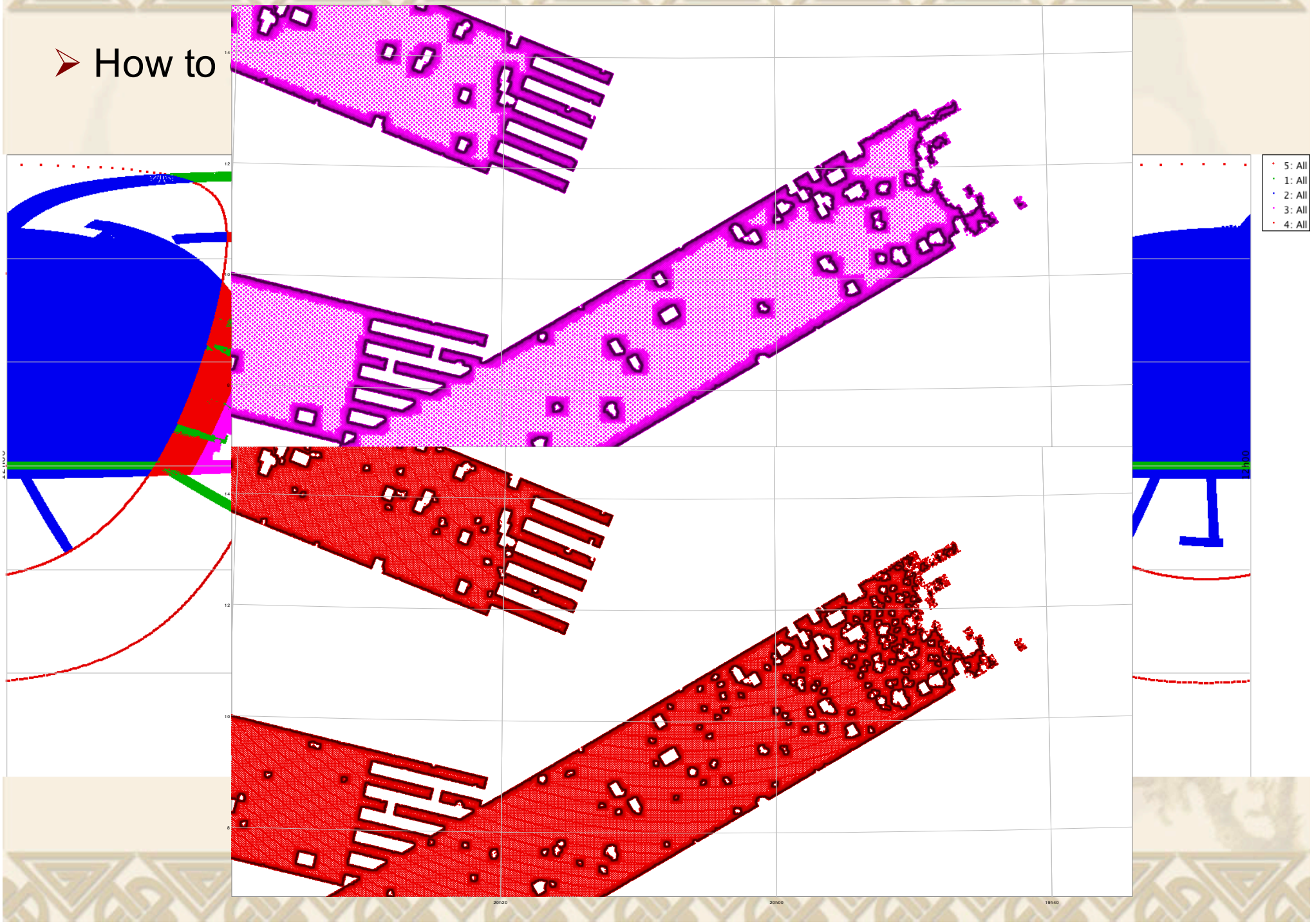


# A final SDSS sample of 52 quasars at z > 5.7

- Main survey:
  - 11,128 deg$^2$
  - 24 (or 29) quasars (1/460 deg$^2$ )
  - $z_{AB}$ ~20 mag
- Overlap regions:
  - 4022 deg$^2$
  - 10 (or 17) quasars
  - 20< $z_{AB}$ <20.5 mag
- Stripe 82:
  - 275 deg$^2$
  - 13 quasars (1/21 deg$^2$ )
  - $z_{AB}$ ~22 mag

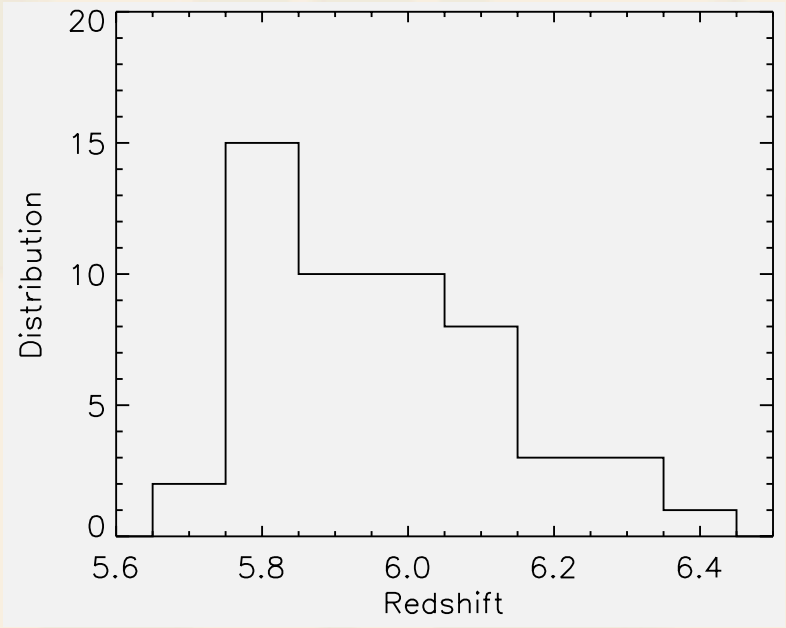


- How to

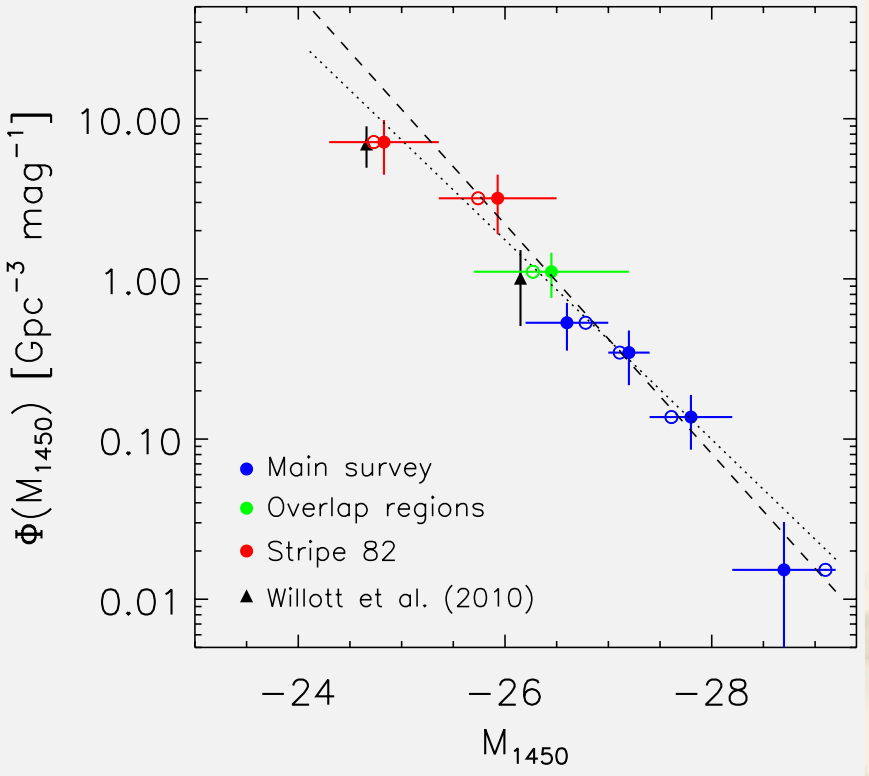


# Quasar luminosity function at z ~ 6

- From our well-defined SDSS quasar sample




Redshift distribution



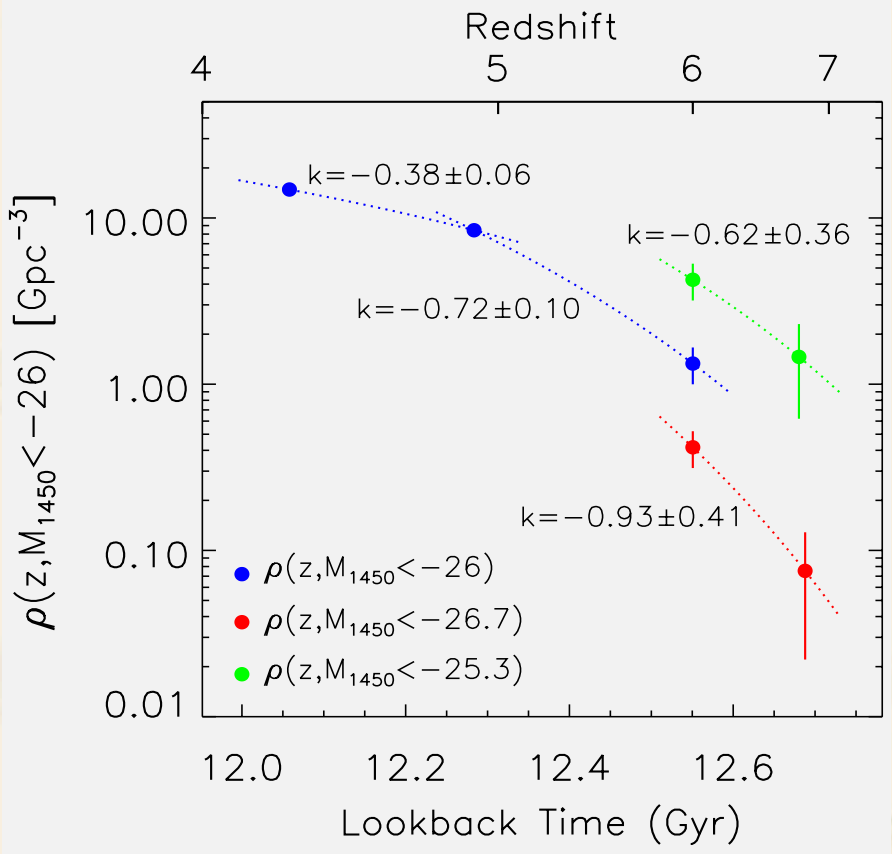

Bright end of the QLF at z ~ 6;
Steep slope β ~ −2.80±0.18

## ➢ Density evolution of luminous quasars at high redshift

- $$\rho(<M,z) = \int_{-\infty}^{M} \Phi(M',z)\, dM'$$
- Densities at z ~ 4 and 5 from McGreer et al. 2013
- Densities at z ~ 6 from our sample
- Density at z ~ 7 from UKIDSS and Venemans et al. 2013

### Strong density evolution:

- $\rho(M_{1450} < -26, z) = \rho(z=6)\, 10^{k(z-6)}$
- k= −0.38 for z = 4.2 – 4.9
- k= −0.72 for z = 4.9 – 6.0
- k= −0.80 for z = 6.0 – 6.8 from a joint fit

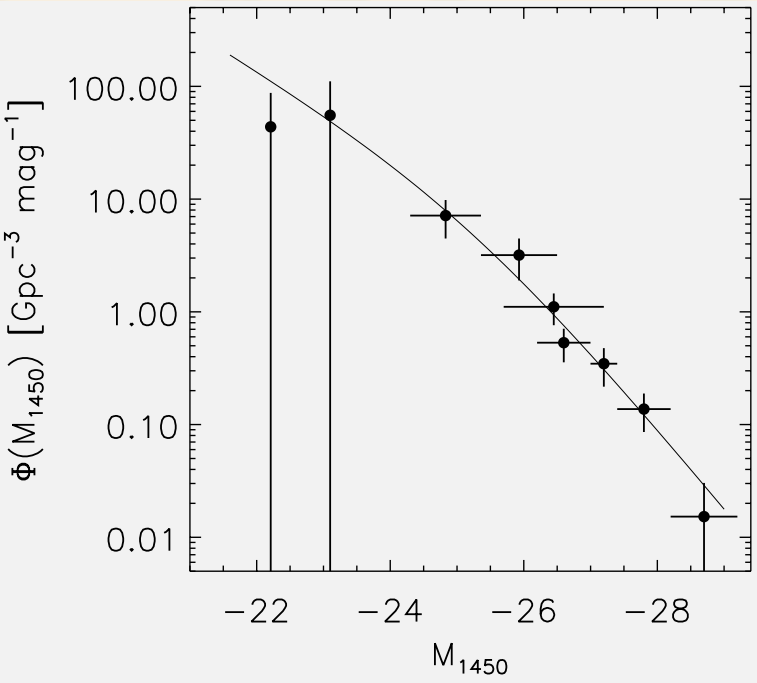


# Quasar luminosity function at z ~ 6

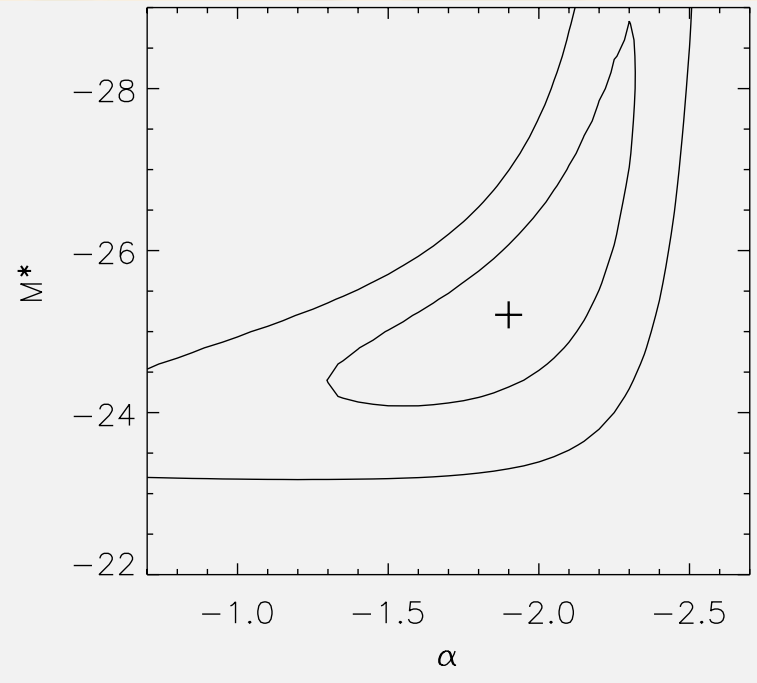
- Double power-law QLF

$$\phi(M_{1450}) = \phi^* / (10^{0.4(\alpha+1)(M_{1450}-M_{1450}^*)} + 10^{0.4(\beta+1)(M_{1450}-M_{1450}^*)})$$

- Two faintest points from Willott et al. 2010 and Kashikawa et al. 2015
- Best-fitting results: $\alpha=-1.9$, $M_{1450}^*=-25.2$, $\beta=-2.8$ (fixed), $k=-0.7$(fixed)




QLF at z ~ 6




α - $M_{1450}^*$ correlation

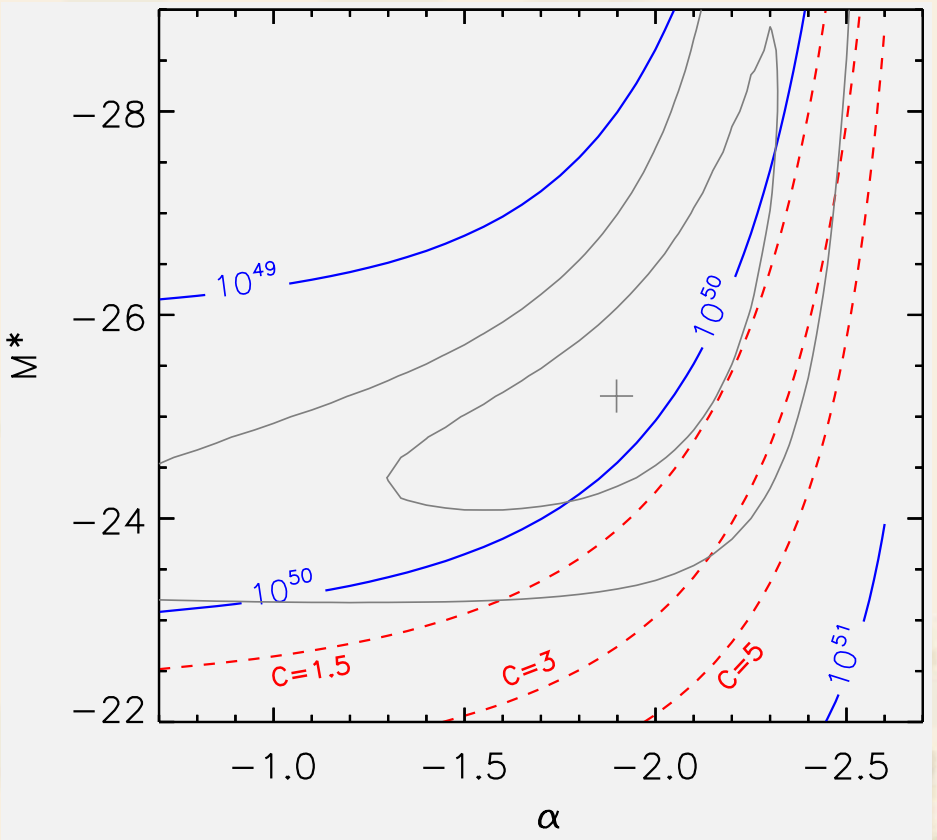
# Quasar contribution to the UV background:

- Required number of photons calculated from Madau 1999
- Luminosity range $M_{1450}$= [−30, −18]
- IGM clumping factor *C* = 1.5, 3, 5

Results:

- The quasar contribution strongly depends on M*, α, and *C*
- For *C*=3, quasars/AGN cannot provide enough photons to ionize the z~6 IGM (at 90% confidence)
- For *C*=3, quasars can, only if α is very steep, and/or M* is very low, and/or the IGM is homogeneous

(see also e.g. Giallongo 2015, Madau 2015, Mitra 2016)



# Near future plans

## ➢ Near-IR spectroscopy

- A large Gemini/GNIRS program for ~50 SDSS quasars
- Wavelength coverage: near-IR from 0.9 to 2.5 um
- Science goals: basic UV properties, BH masses, BLR metallicity, etc.
- Half of the quasars have been observed

## ➢ Survey of fainter quasars

- Imaging data: Next Generation Virgo Cluster Survey (NGVS)
- 100+ $deg^2$ from CFHT
- Three bands: g,i,z; depth: g=26.5, i=26, z=24.5 AB mag (5σ)
- Already identified two quasars at z ~ 6
- To constrain the faint end of the QLF at z ~ 6 (also HSC survey)

## Summary

- High-z quasars are a powerful tool to probe the distant universe
- We have built a fundamental sample of 52 quasars at $z \sim 6$ identified in the SDSS footprint
- These quasars are being used to study various quasar properties and their implications for cosmic reionization
- Future plans: near-IR spectroscopy, fainter quasars, etc.