High-redshift Quasars as Probes to the End of Reionization

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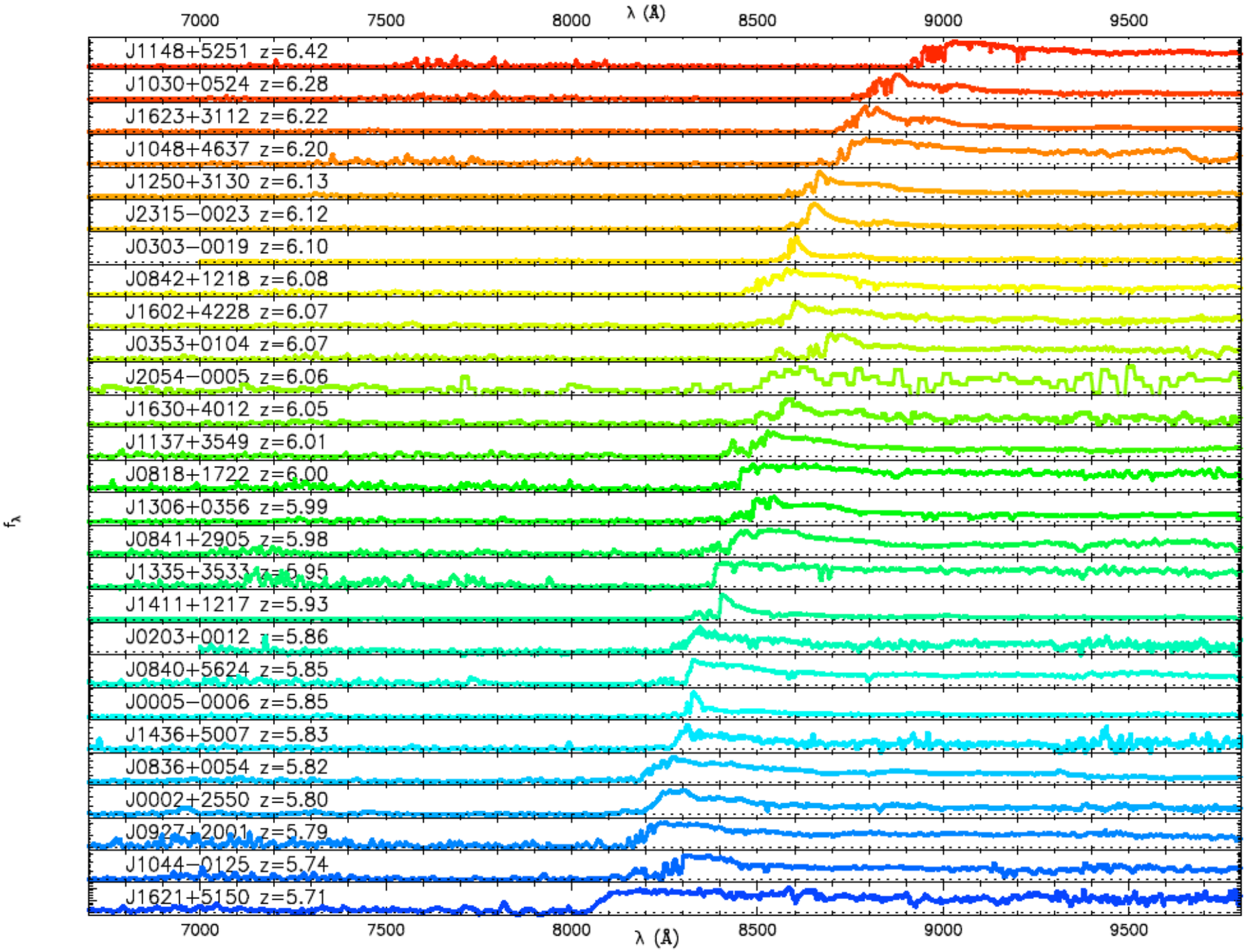
Background: 46,420 Quasars from the SDSS Data Release Three

The Highest Redshift Quasars Today

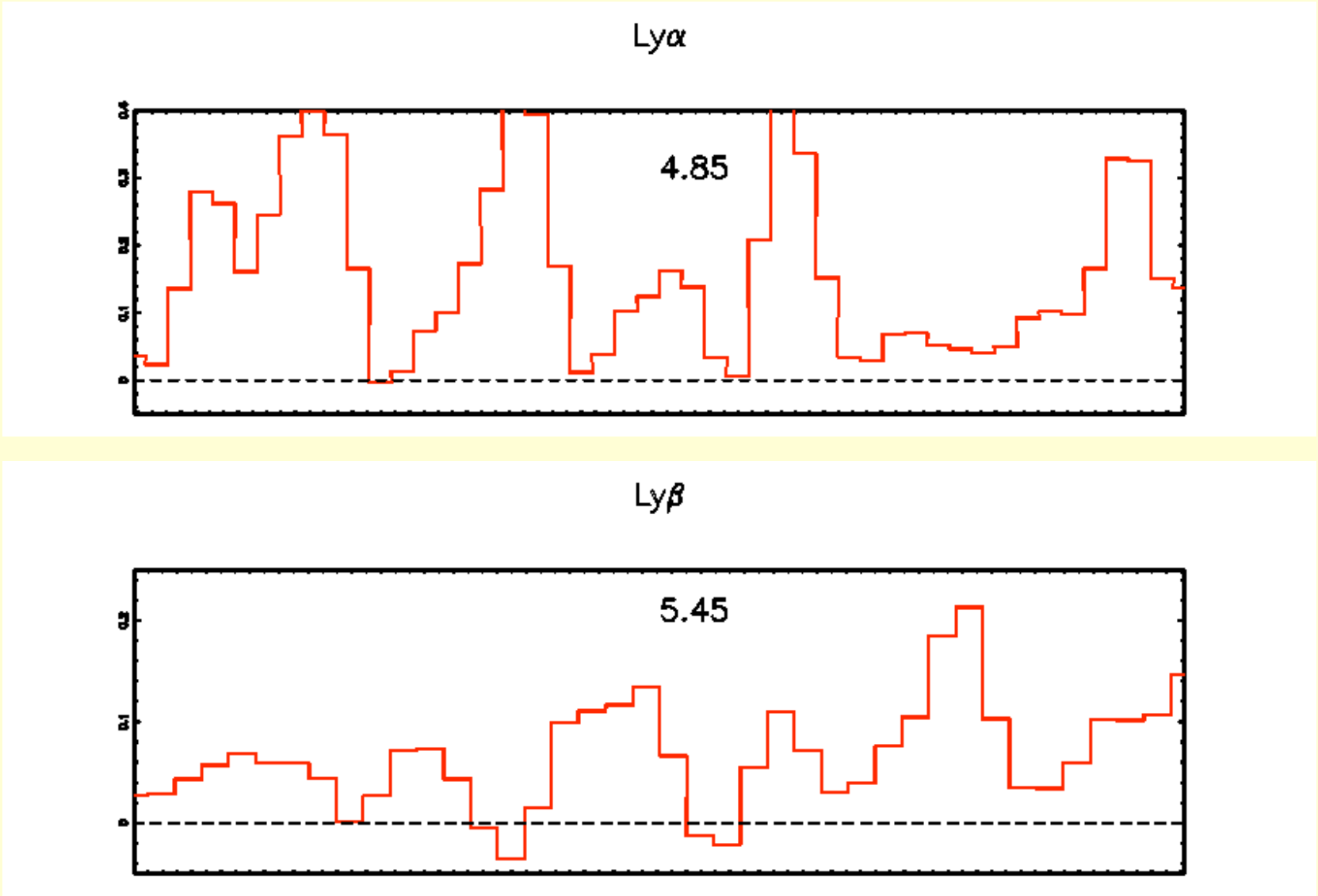
- z>4: >1000 known
- z>6: 19
- SDSS i-dropout Survey:
  - Completed in June 2006:
    - ***7700 deg^2, z_{AB} < 20***
    - ***27 luminous quasars at 5.71<z<6.42***
- ***CFHT High-z Quasar Survey (CFHTQS, Willott et al. astro-ph/0706091)***
  - ***Goal: 400 deg^2, z_{AB}<22.5***
  - ***4 quasars at z>6***
  - ***New highest-z quasar at z=6.43***
- ***SDSS Faint Quasar Survey (SFQS)***:
  - **faint quasars in the deep SDSS stripe (Jiang, XF et al.),**
  - **300 deg^2, z_{AB} < 22.5**
  - **six z~6 quasar at 20 < z_{AB} < 21**
  - **Goal: quasar LF**
- Other on-going z~6 quasar surveys:
  - ***AGES*** *(Cool et al.): Spitzer selected, one quasar at z=5.8*
  - ***FIRST-Bootes*** *(Becker et al.): radio selected, one quasar at z=6.1*
  - ***QUEST:*** *i-dropout surveys similar to SDSS*
  - *IR-based survey:* ***UKIDSS, (z=5.83), VISTA****, allows detection up to z~8-9.*


7000
7500
8000
λ (Å)
8500
9000
9500
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0303−0019 z=6.10
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J0841+2905 z=5.98
J1335+3533 z=5.95
J1411+1217 z=5.93
J0203+0012 z=5.86
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
J1621+5150 z=5.71
7000
7500
8000
λ (Å)
8500
9000
9500

Quasars as Probes to the End of Reionization

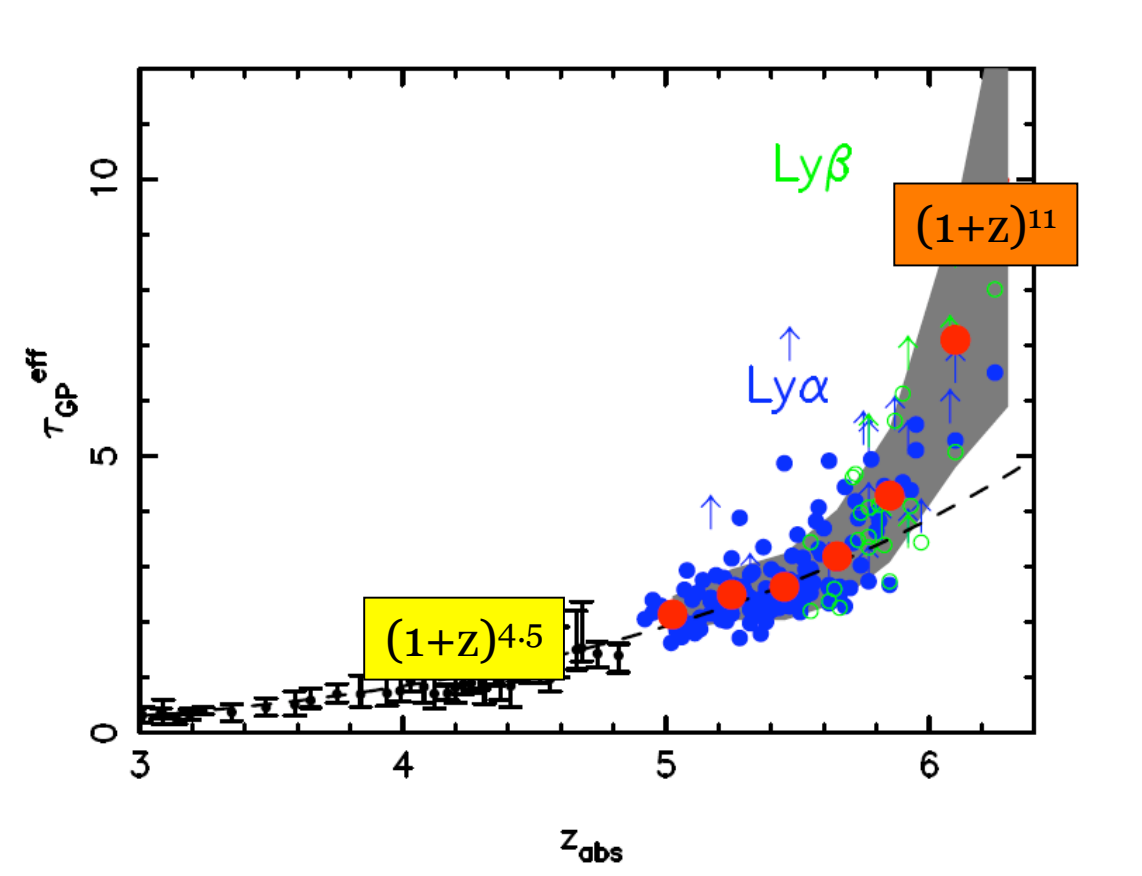
- What's the Status of IGM at z~6?
  - Measurements of Gunn-Peterson optical depth
  - Evolution of UV background
  - Constraints on IGM neutral fraction
- Was the Universe mostly neutral by z~6-8?
  - Distribution of dark gaps and transmission peaks
  - HII region size distribution
- What is the source of reionization?
  - AGN or galaxy

Evolution of Lyman Absorptions at z=5-6



$\Delta z = 0.15$

Accelerated Evolution at z>5.7

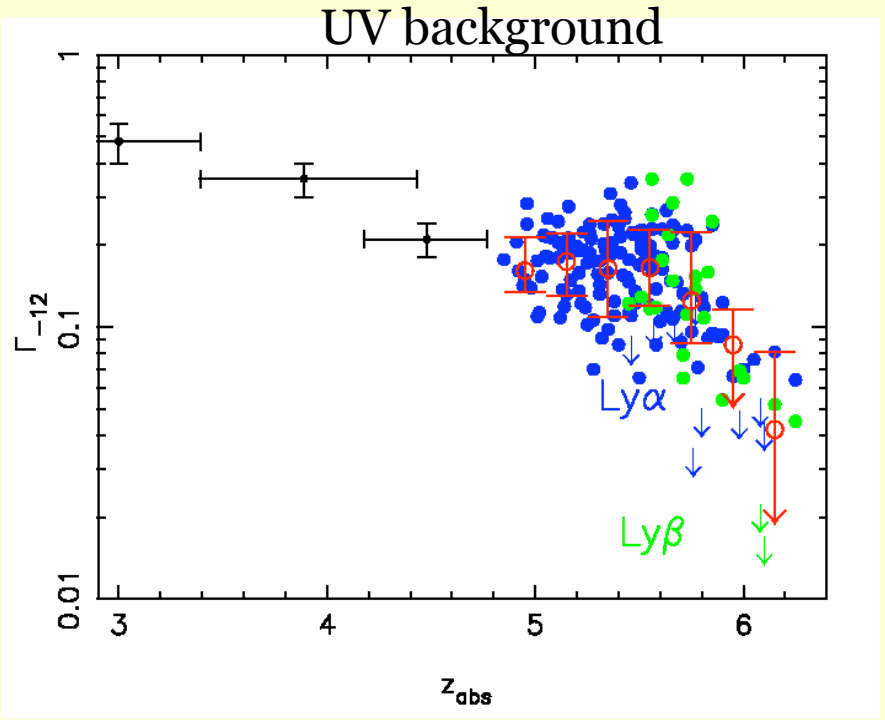


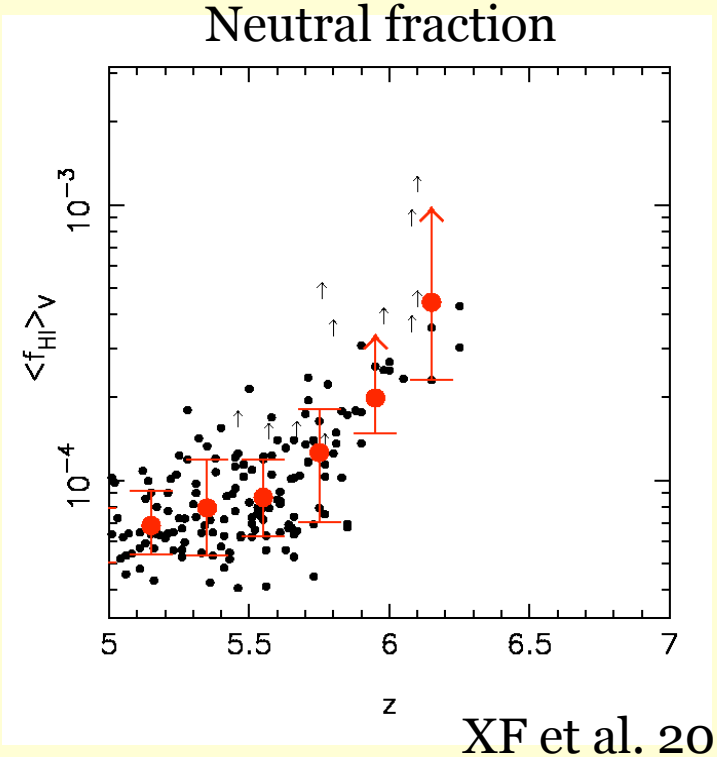
XF et al. 2006

- *Optical depth evolution accelerated*
  - $z<5.7$: $\tau \sim (1+z)^{4.5}$
  - $z>5.7$: $\tau \sim (1+z)^{>11}$
  - ***End of reionization?***
- *Dispersion of optical depth also increased*
  - Some line of sight have dark troughs as early as z~5.7
  - But detectable flux in ~50% case at z>6
  - ***End of reionization is not uniform, but with large scatter***

Evolution of Ionization State

- UV Ionizing background:
  - Assuming photoionization and model of IGM density distribution
  - UV background declines by close to an order of magnitude from z~5 to 6.2
  - ***Increased dispersion suggests a highly non-uniform UV background at z>5.8***



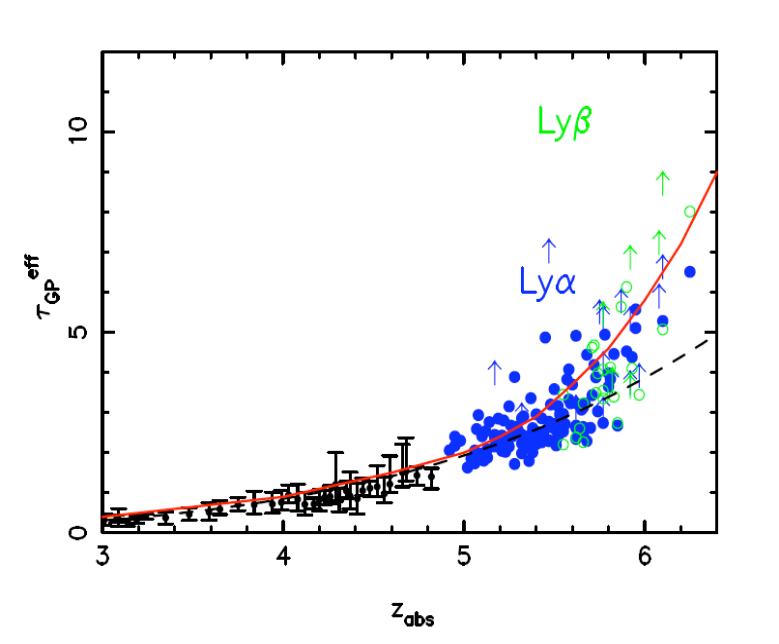


XF et al. 2006

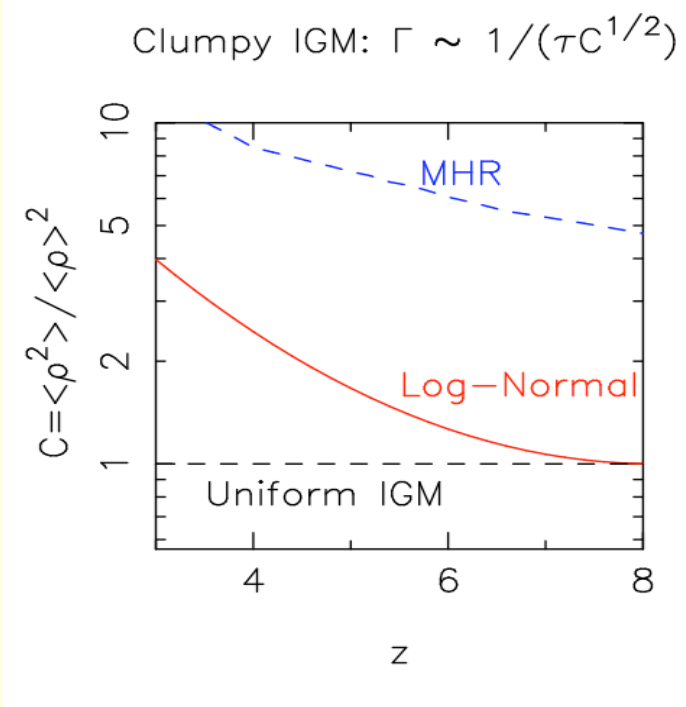
- From GP optical depth measurement, volume averaged neutral fraction increase by >~ order of magnitude from z~5.5 to 6.2

Relation between optical depth and neutral fraction highly model-dependent

- Becker et al. (2006)
  - optical depth evolution could be consistent with a smooth evolution of ionizing background for a **strongly-evolving log-normal density distribution** of the IGM

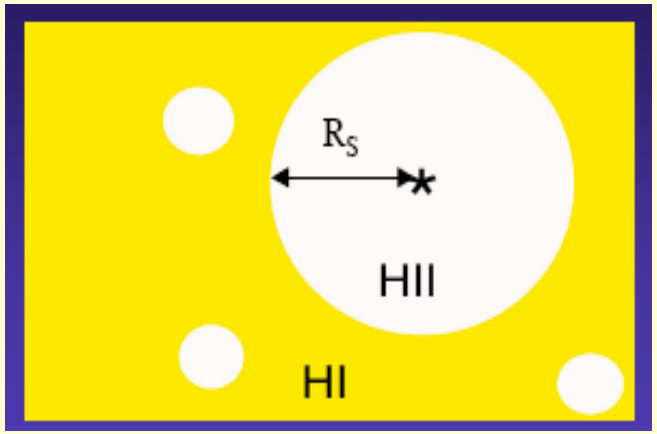


Becker et al. 2006



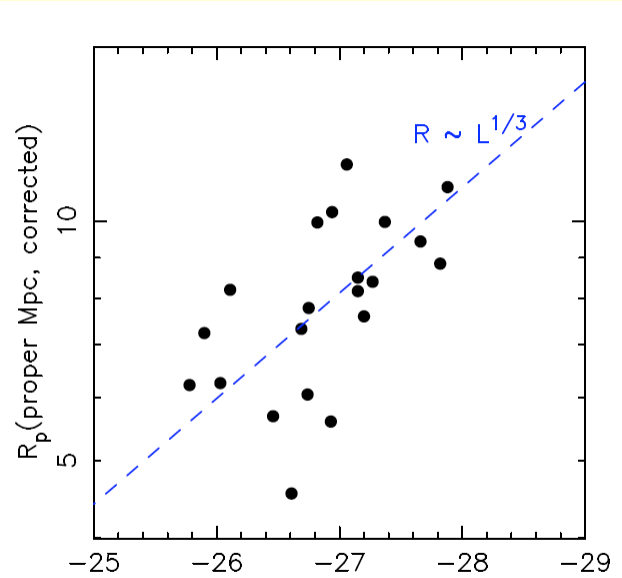
- Relation between Γ and τ dependent on IGM clumpiness
  - Simulation results: clumpiness ~ 5 - 30, no strong evolution at z~6
    - Optical depth evolution driven by an decreasing background towards high-z

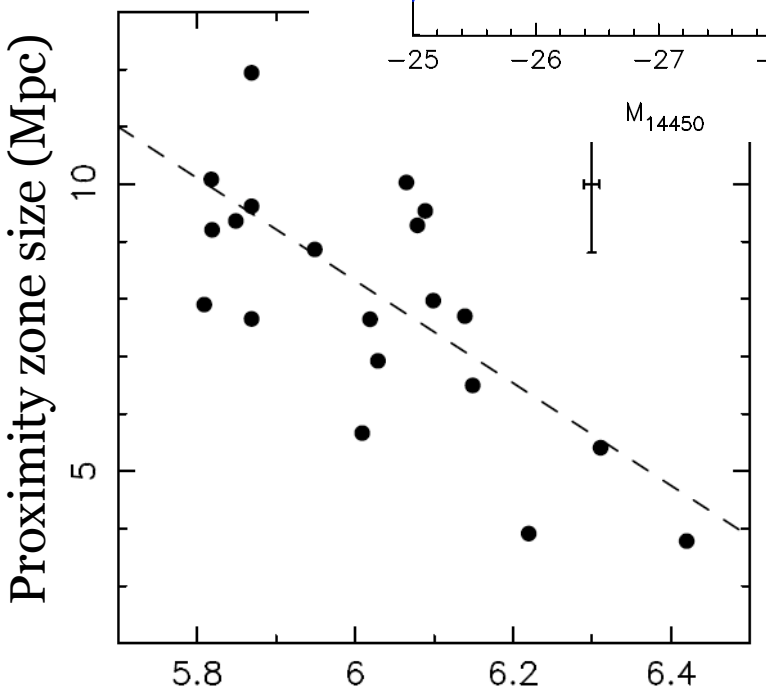
Evolution of Proximity Zone Size Around Quasars



Shapiro, Haiman, Mesinger, Wyithe, Loeb et al.

- Size of Proximity Zone region
  $R_p \sim (L_Q\, t_Q / f_{HI})^{1/3}$
- Size of quasar proximity zone decreases by a factor of ~2.4 between z=5.8 and 6.4 (Fan et al. 2006)
- **Consistent with neutral fraction increased by a factor of ~15 over this narrow redshift range**
- **Can be applied to higher z and f_{HI} with lower S/N data**
- Actual size of proximity zone dependent on details of radiative transfer and quasar model...

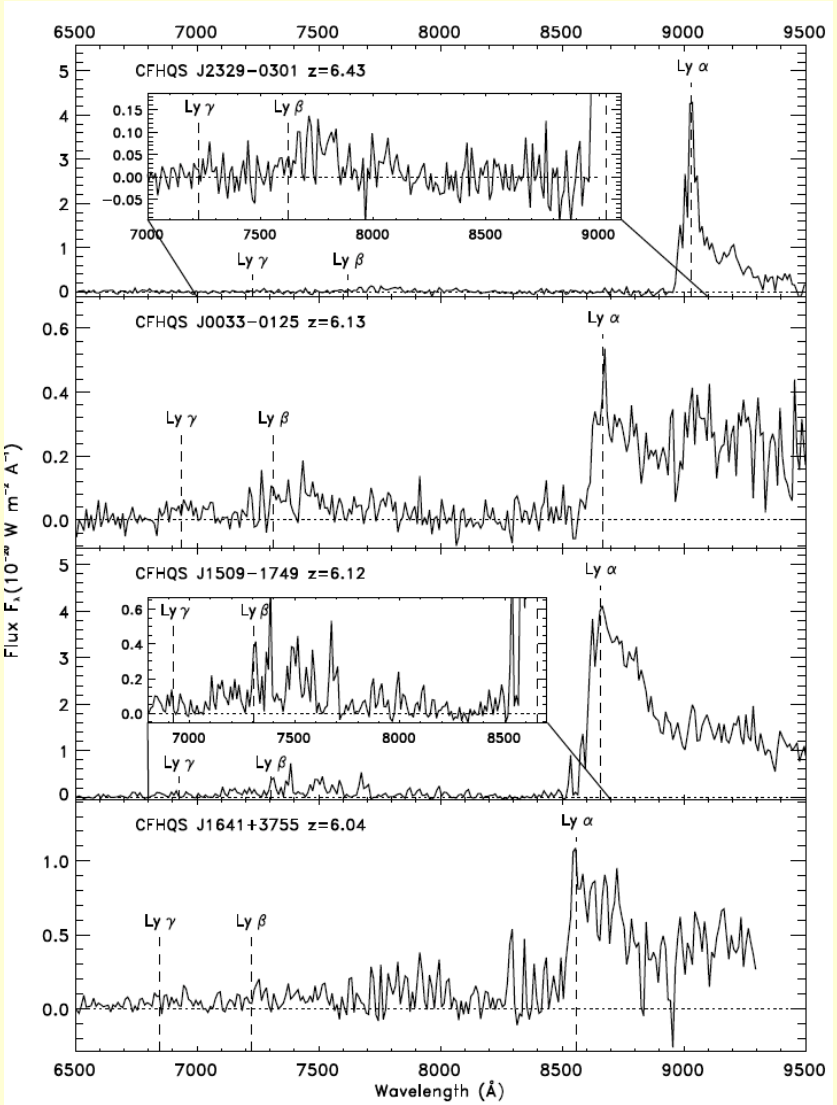




XF et al. 2006

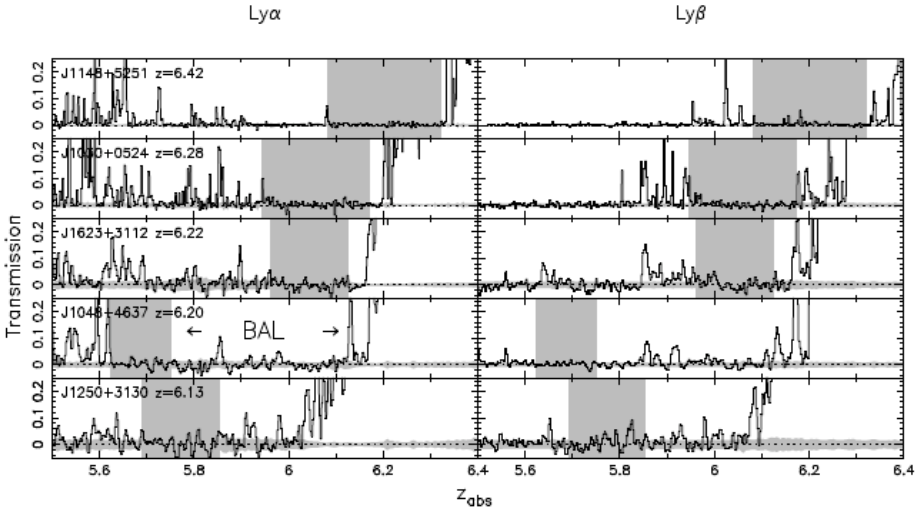
CFHTQS results (Willott et al. 2007)

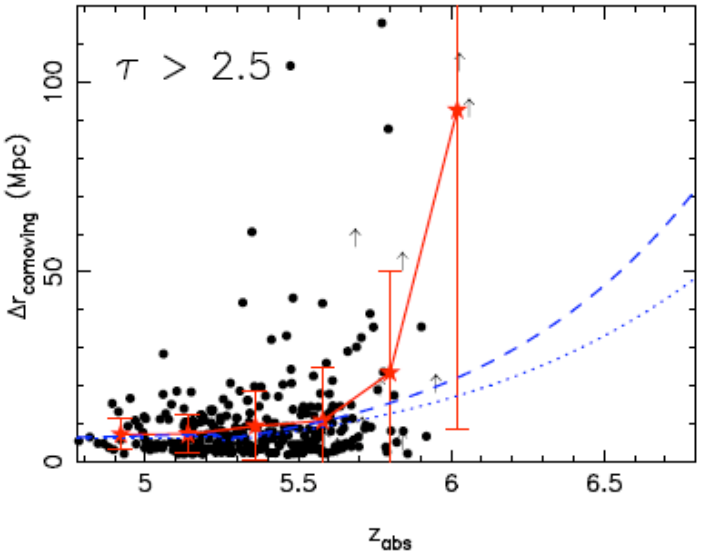
- Strong evolution in τ_{GP} seen at z>5.5, but low S/N
- Scaled near-zone size 6-11 Mpc at z>6
  - Consistent with a low f_{HI}
  - But uncertainties in z_{em} based on Lyα
  - **Caution: using Lyα redshift could introduce large uncertainty in HII region size; but true systematic redshift difficult for faint quasars at z>6**



Dark Gap Distributions

- Dark gap statistics (Songaila & Cowie 2002)
  - Gaps: regions where all pixels have $\tau > 2.5$
- Gaps among z~6 quasars
  - Average length shows the most dramatic increase at z>5.8 → IGM is dominated by long, dark gaps
    - Consistent with overlap at z~6-8?
  - Dispersions
    - Even at z>6, gap lengths are still finite
- Upper limit on neutral fraction
  - If IGM largely neutral, GP damping wing will wipe out all HII region transmissions
  - ***Existence of transmission at z>6 places an upper limit of average neutral fraction <30%***
  - Independent upper limit on neutral fraction



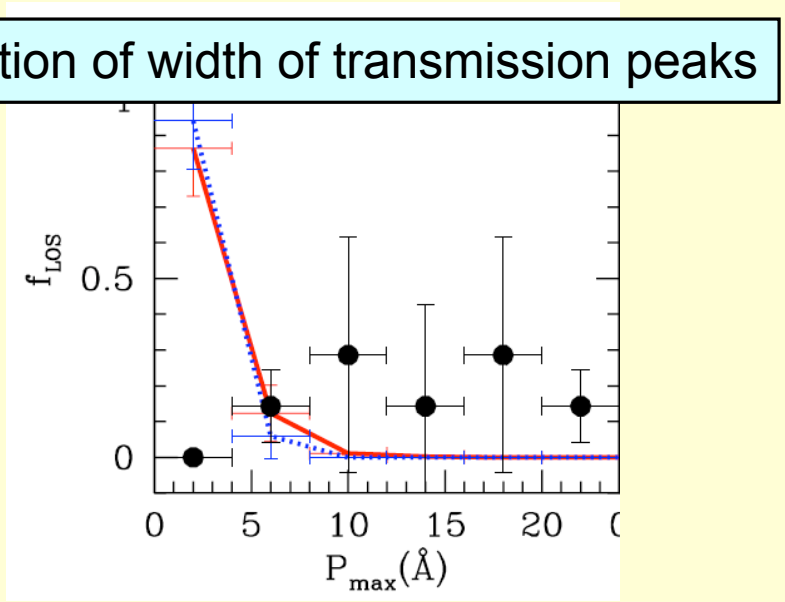


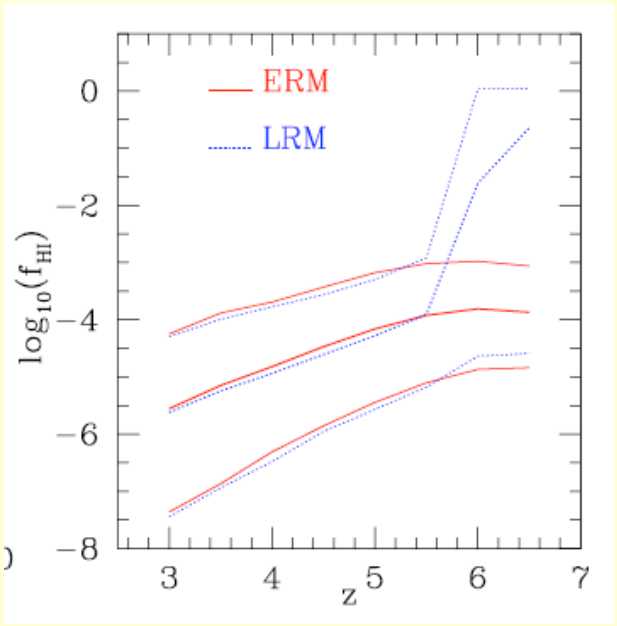
XF et al. 2006

Dark Gap Statistics: Comparison with Simulations

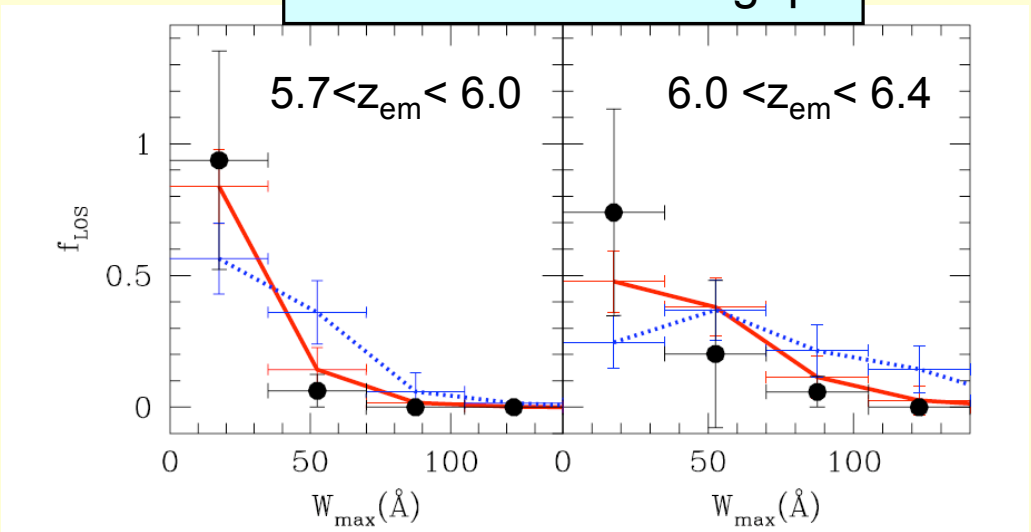
- Gallerani et al. (2006, 2007)
  - Early reionization ($z_{overlap}$ ~15)
  - Late reionization ($z_{overlap}$ ~7)
  - Significant difference in gap distribution at z~6
  - f_{HI}<0.3 at z~6
  - ***But observed transmission peaks too wide compared to simulations***

Distribution of width of transmission peaks



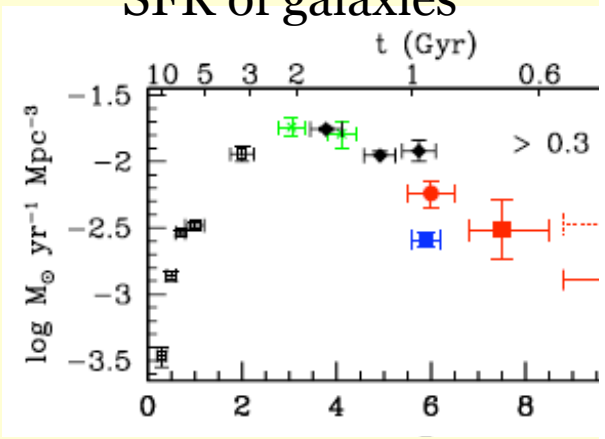


Distribution of dark gaps

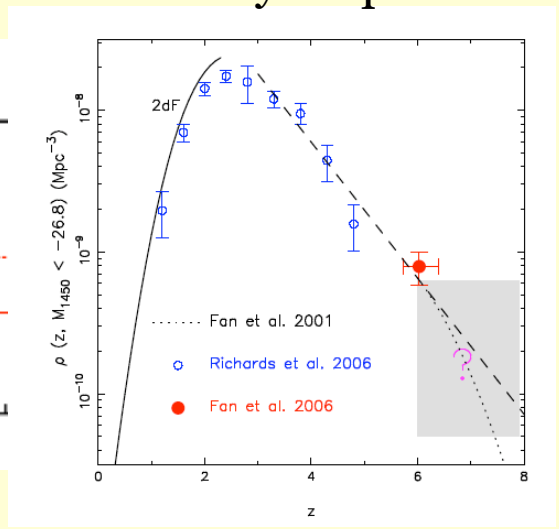


What Ionized the Universe? AGNs or Galaxies

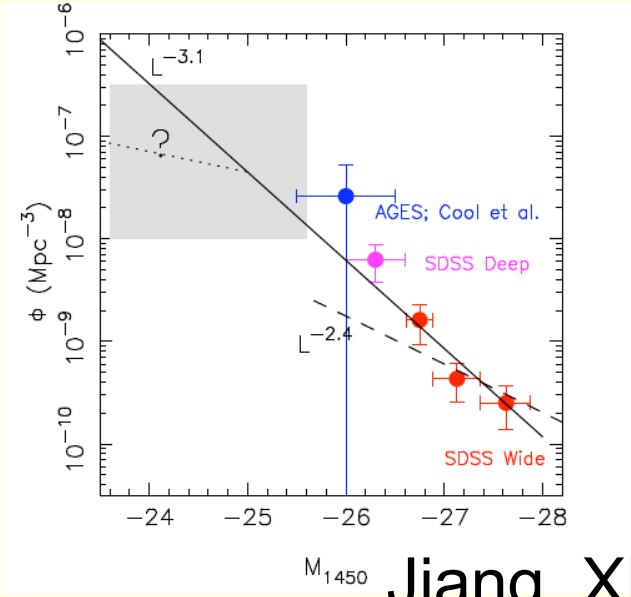
SFR of galaxies



Density of quasars



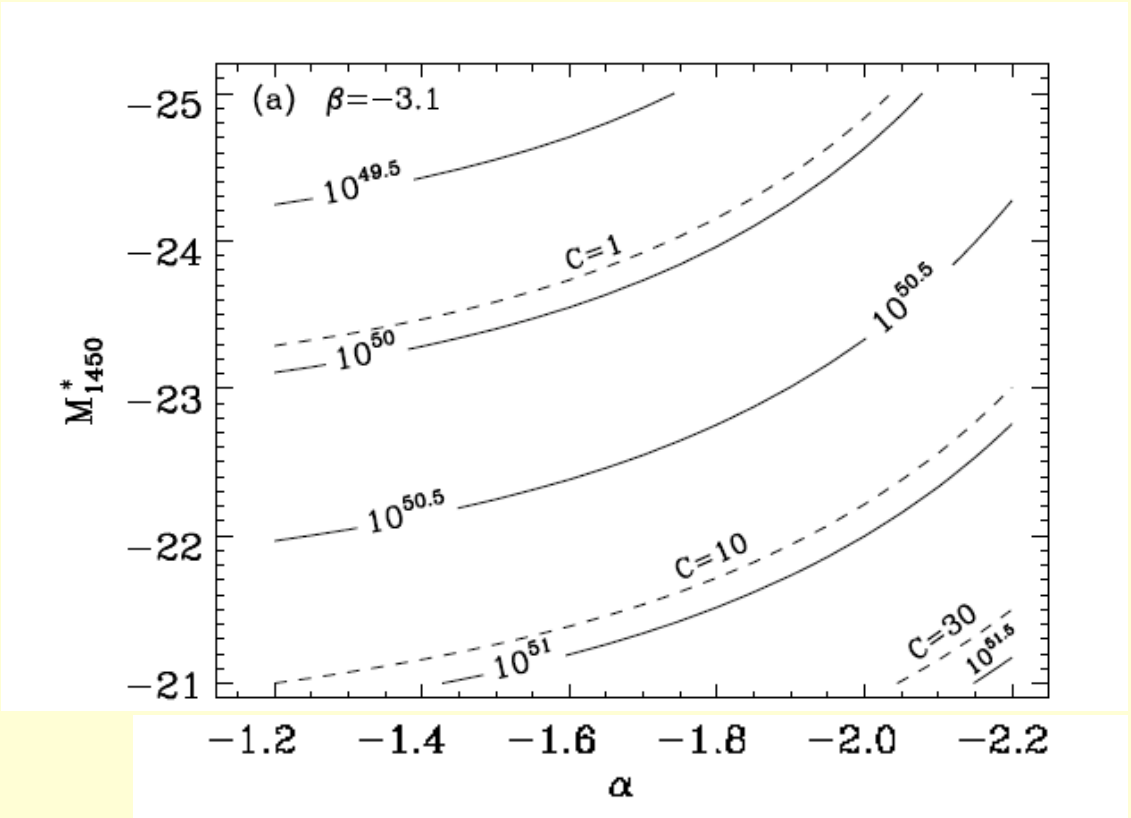
- **Quasar LF at z~6:**
  - SDSS Wide: 7700 deg^2, 17 quasars, z_{AB} <20
  - SDSS Deep: ~150 deg^2, 6 quasars, 20<z_{AB}<21
  - AGES: 1 quasar in 5 deg^2 at z_{AB}<21.5
- **Steeppening of LF:**
  - $\Phi \propto L^{-3.1}$
  - *Comparing to $\Phi \propto L^{-2.4}$ at z~4*



Jiang, XF et al. 2007

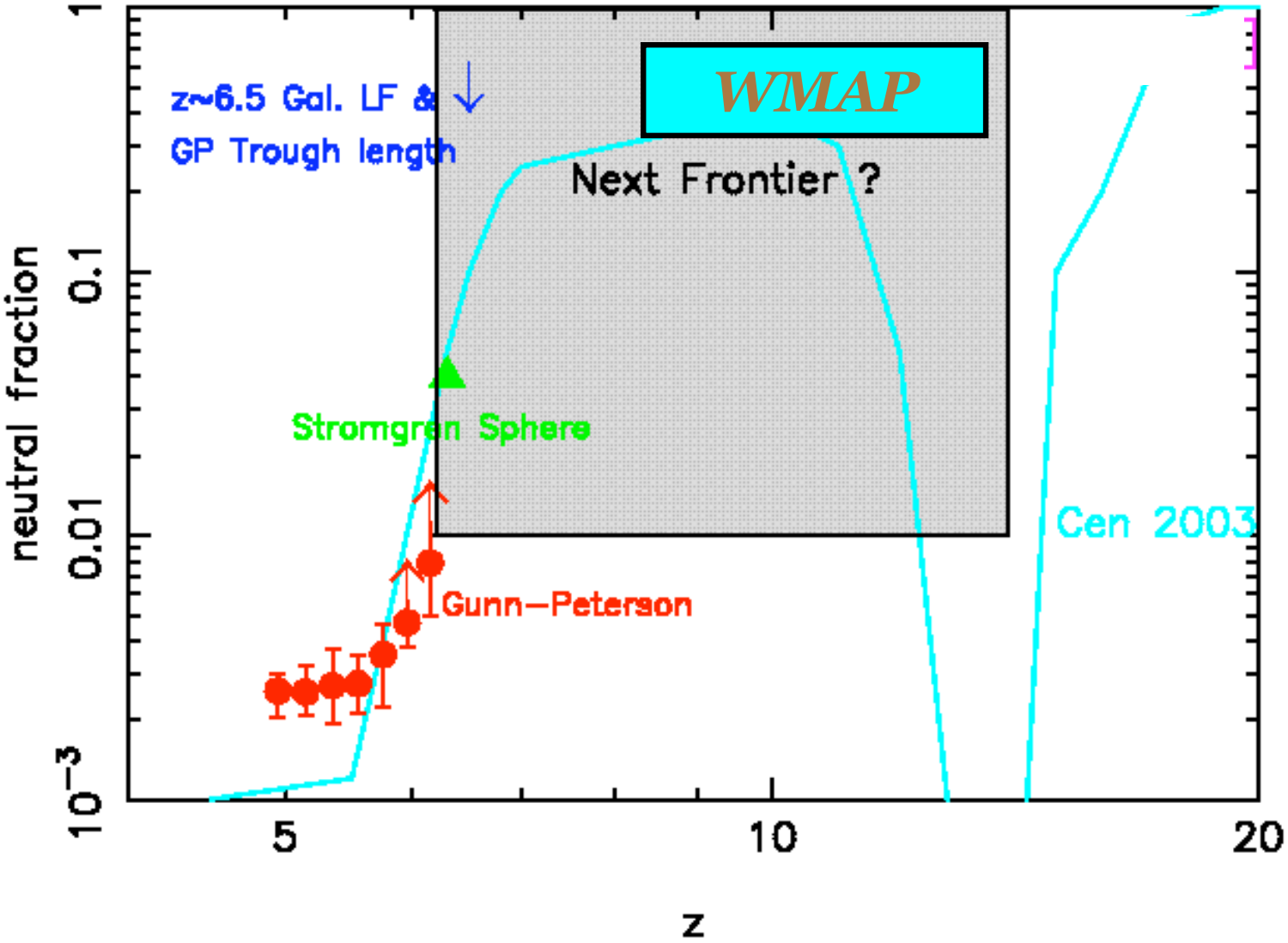
Reionization by AGNs?

- Can quasars do it?
  - Too few quasars unless QLF remains to be steep to AGN luminosity
- Can low-luminosity AGNs ionize the IGM by z~6?
  - Stacking X-ray image of LBGs in UDF… too few faint AGNs
- Can accretion to seed BHs ionize the IGM by z~15?
  - **Dijkstra, Haiman & Loeb (2004)**
  - **Soft X-ray background overproduced if quasars produce ~10 photons/H atom**
  - **'Preionization' to f(HI)~50% by X-rays is still allowed (e.g. Ricotti et al.)**

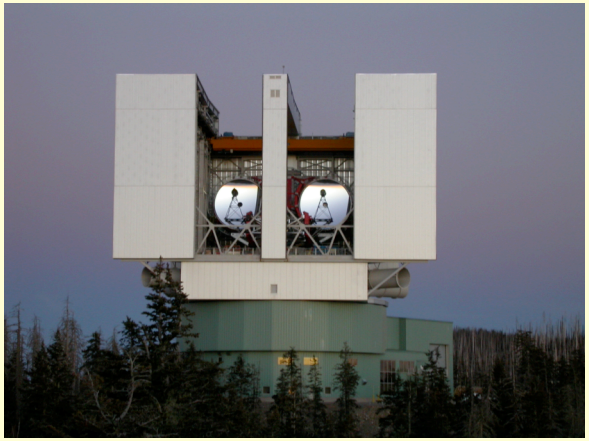


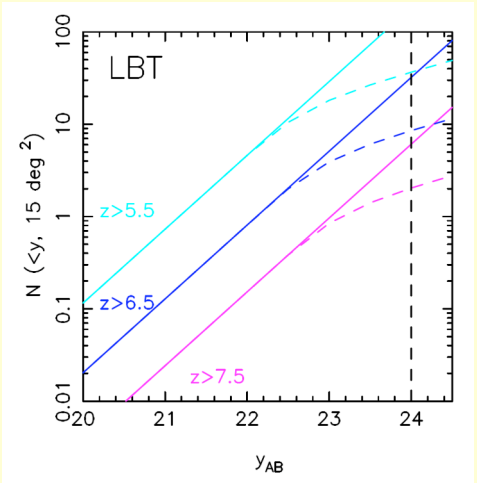
Jiang, XF et al. 2007

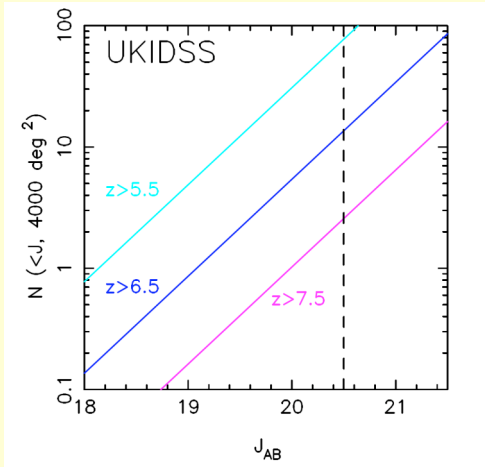
Probing Reionization History



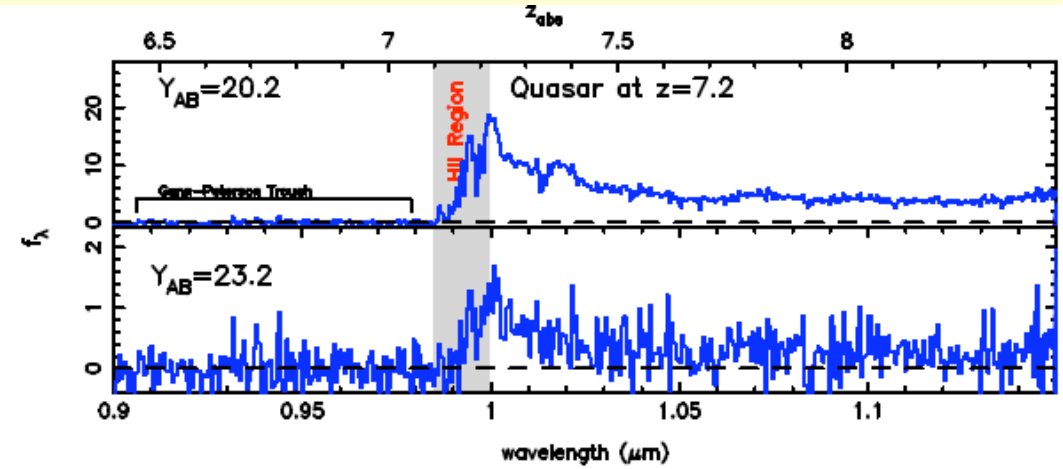
Surveys of quasars at z~7







LBT: LBC-Red
i-z-Y selection (1 deg^2/night)



UKIDSS: YJHK photometry