High-Redshift Quasars and Reionization

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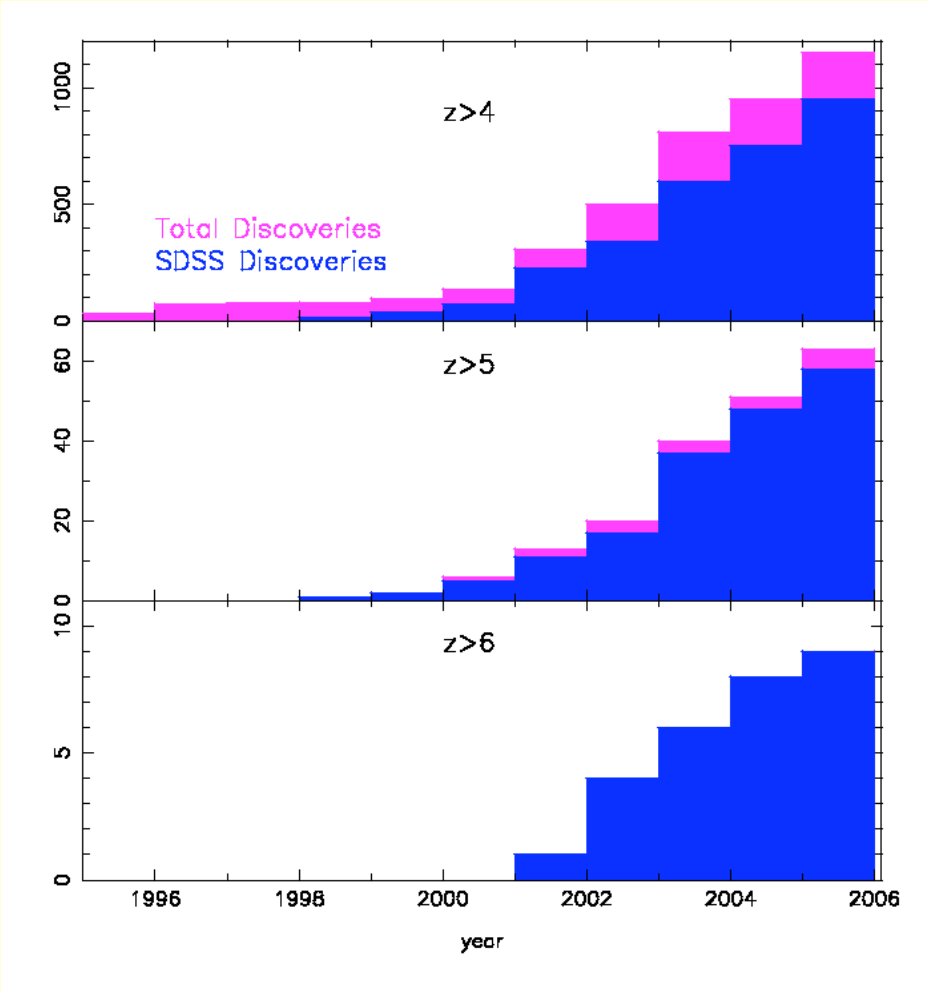
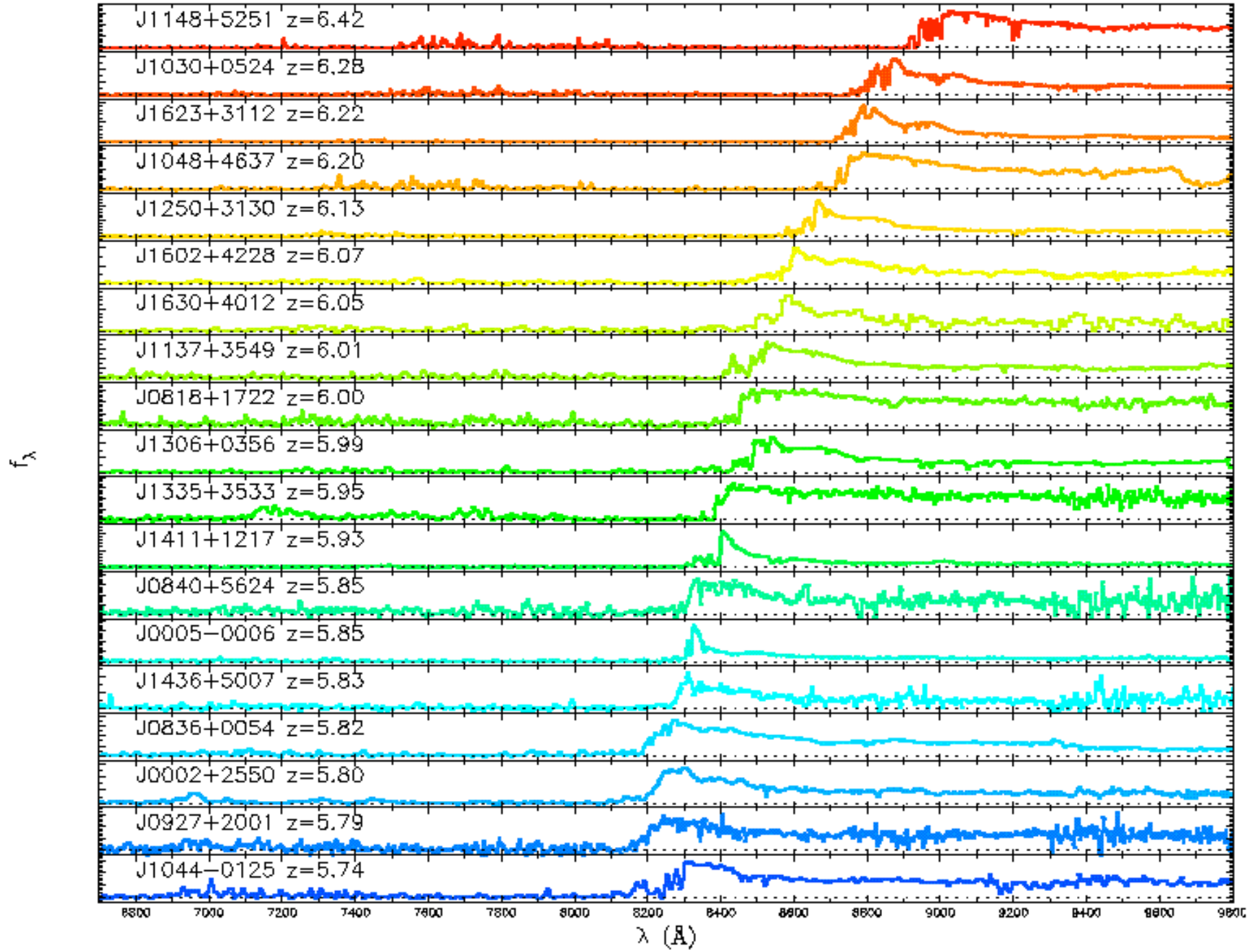
Bertoldi,Omont,Brandt,Vestergaard,Eisenstein,
Cool, Jiang, Diamond-Stanic et al.

The Highest Redshift Quasars Today

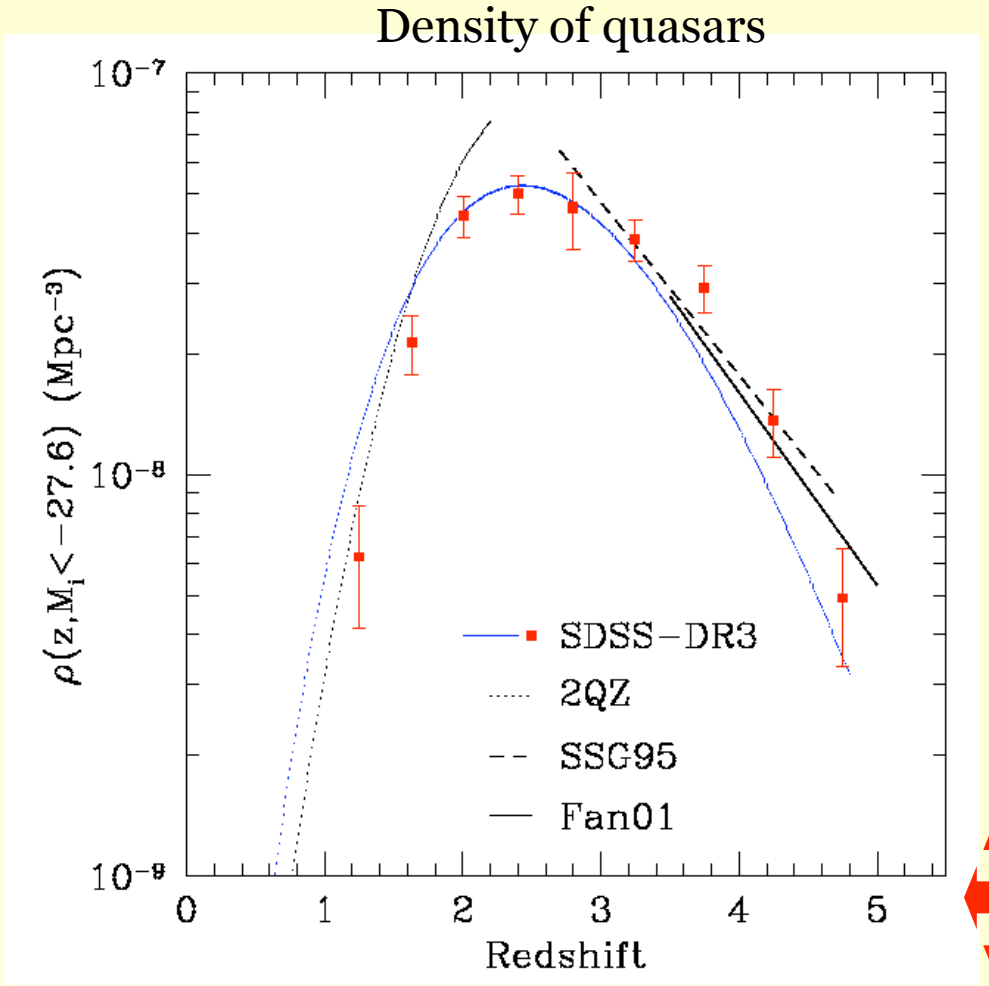
- z>4: >1000 known
- z>5: >60
- z>6: 9
- SDSS i-dropout Survey:
  - By sping 2005: 6600 deg^2 at z_{AB}<20
  - Nineteen luminous quasars at z>5.7
  - Many L and T brown dwarfs
- ~30 at z~6 expected in the whole survey




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
J1602+4228 z=6.07
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J1335+3533 z=5.95
J1411+1217 z=5.93
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
6800
7000
7200
7400
7600
7800
8000
8200
8400
8600
8800
9000
9200
9400
9600
9800
λ (Å)
fλ

Evolution of quasar densities

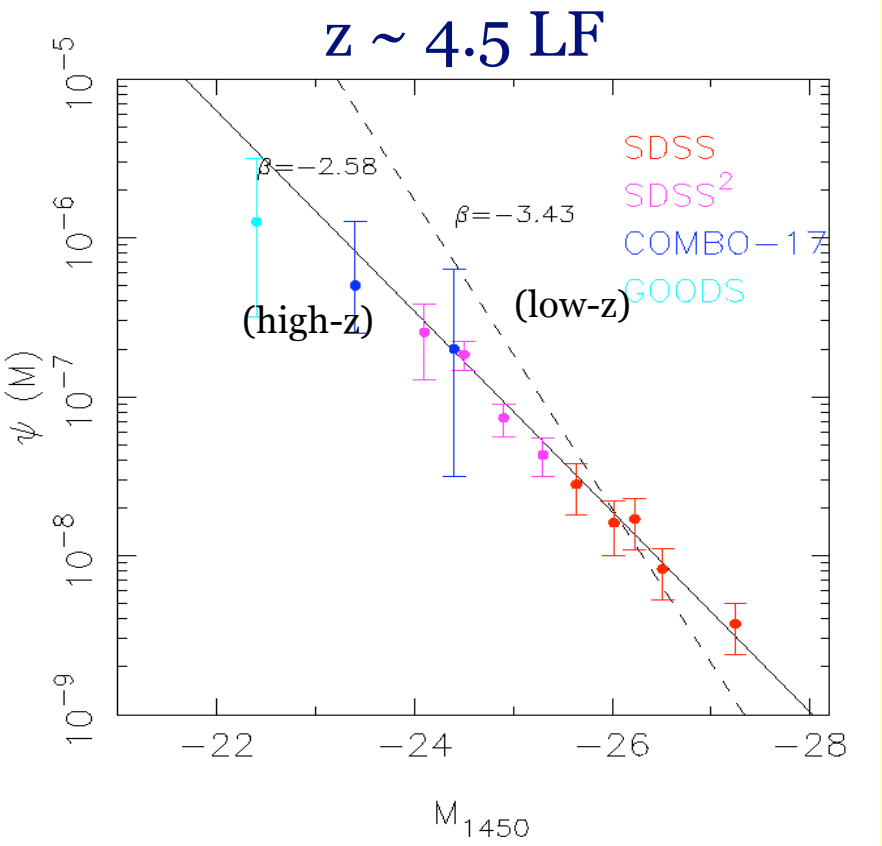
- Quasar density declines by a factor of ~50 from between z~2.5 and z~6
- Implications:
  - $M_{BH} \sim 10^{9\text{-}10}\ M_{sun}$
  - $M_{halo} \sim 10^{12\text{-}13}\ M_{sun}$
  - rare, 5-6 sigma peaks at z~6 (density of 1 per $Gpc^{3)}$
  - Early BH growth and connection to galaxy formation (F. Walter talk)

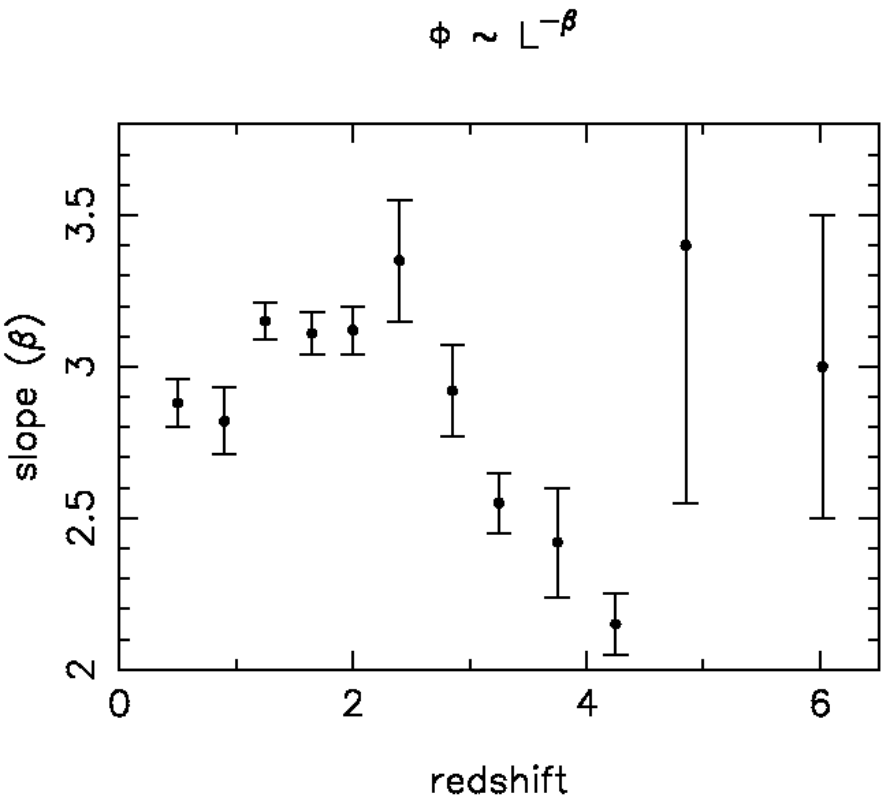


Richards et al. 2005,
Fan e al. 2005

Evolution of Quasar LF

- High-z quasar LF different from low-z
  - High-z LF much flatter
  - Transition at z~3 (where quasar density peaks in the universe)
  - Implies that luminous quasars grow early and more efficiently in the early Universe

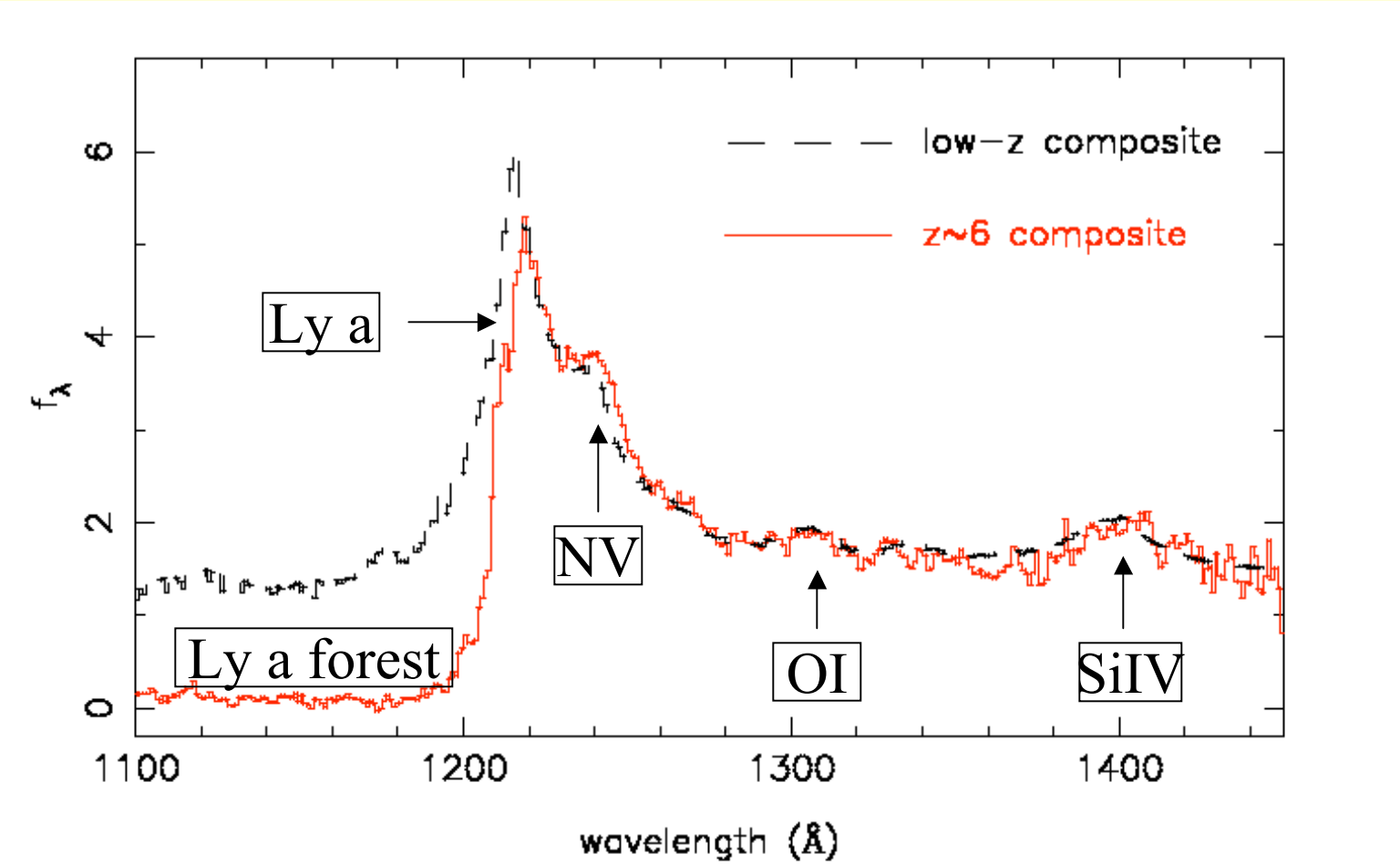




- z>3 quasars also more strongly clustered…
- ***Different formation mechanism at low and high-z?***

Richards, et al.; Fan et al. 2005

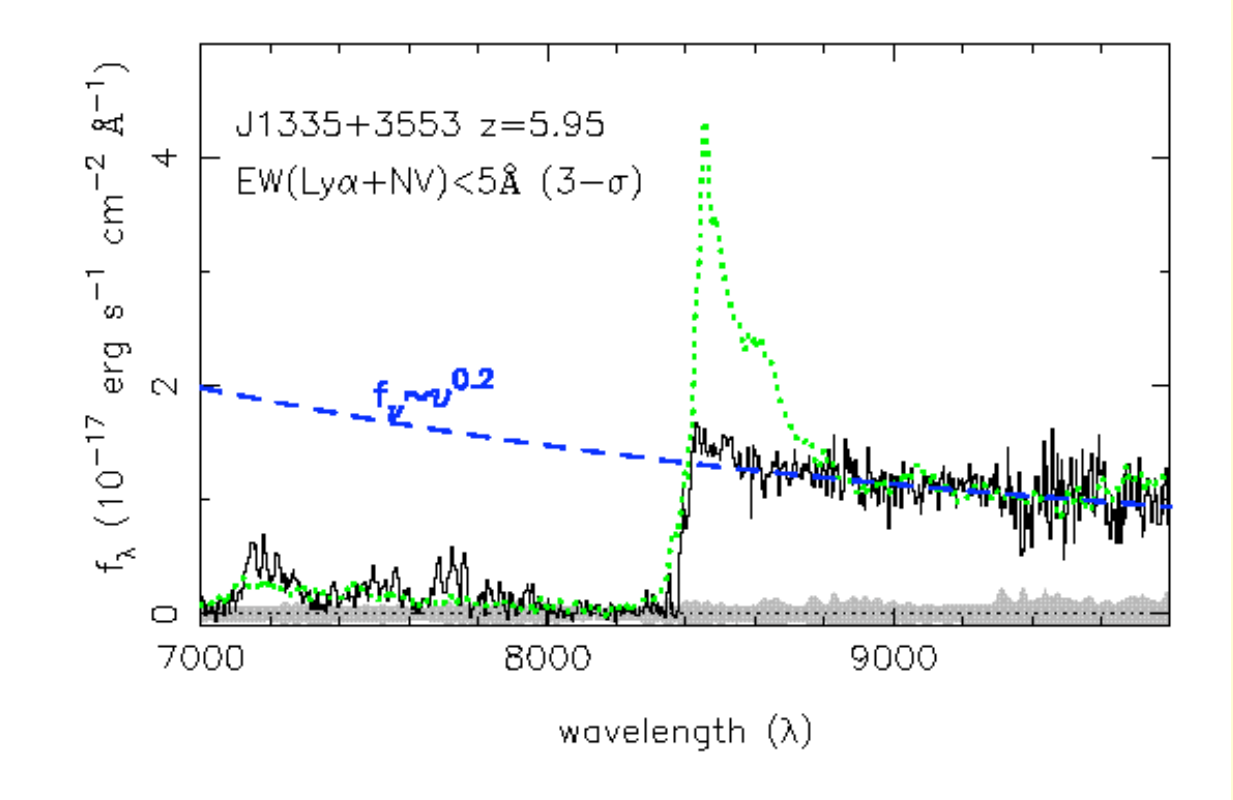
The Lack of Evolution in Quasar Intrinsic Spectral Properties



- Rapid chemical enrichment in quasar vicinity
- Quasar environment has supersolar metallicity
  - Suggests Salpeter IMF (R. Schneider talk)
- *High-z quasars and their environments mature early on*

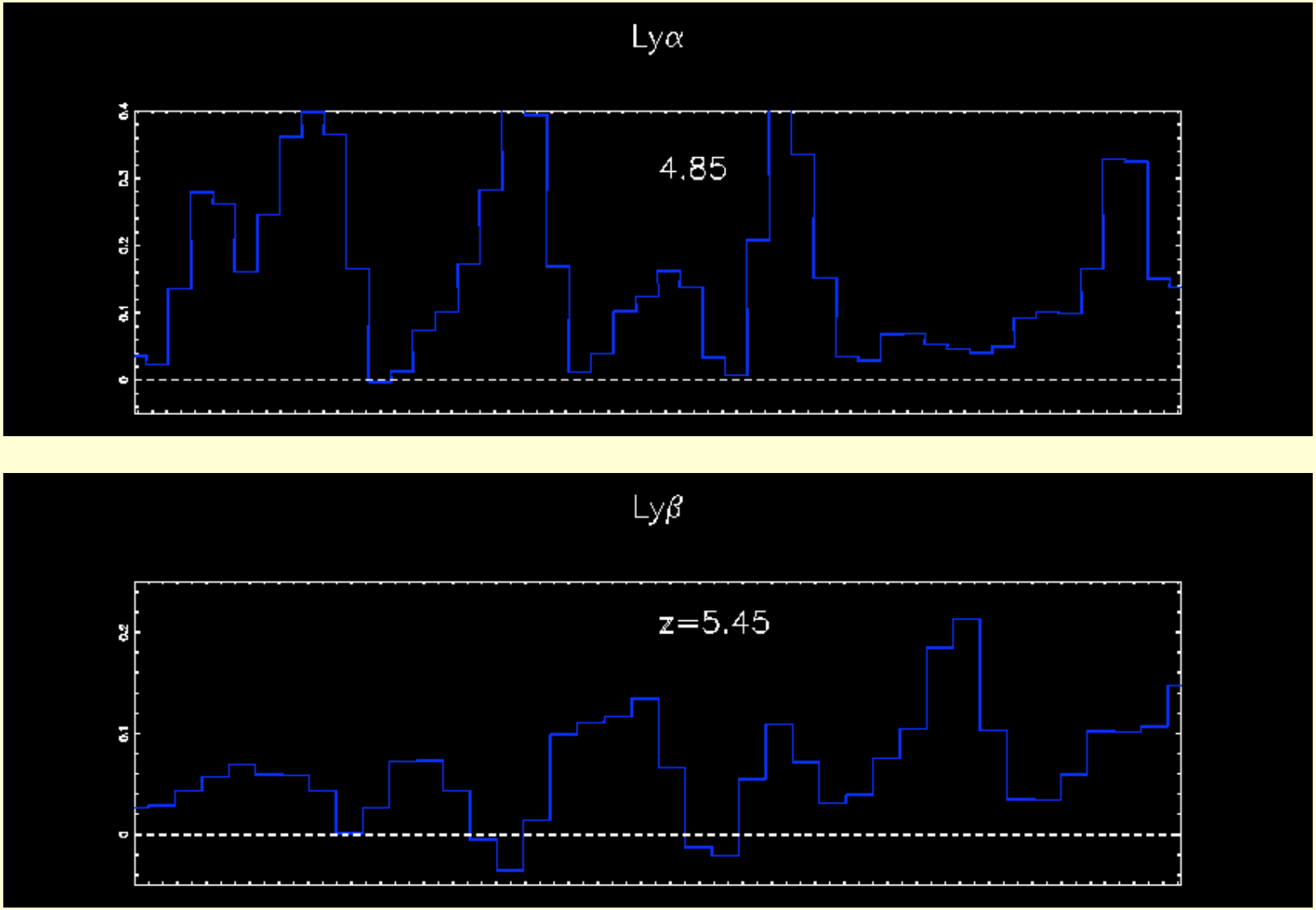
But that's not always the case…

- No emission line, radio-quiet quasars at z>4
  - ~1% of high-z quasars
  - No BL Lac signature
  - A separate population of quasars?
  - See Diamond-Stanic poster



Fan et al. 2005

Evolution of Lyman Absorptions at z=5-6

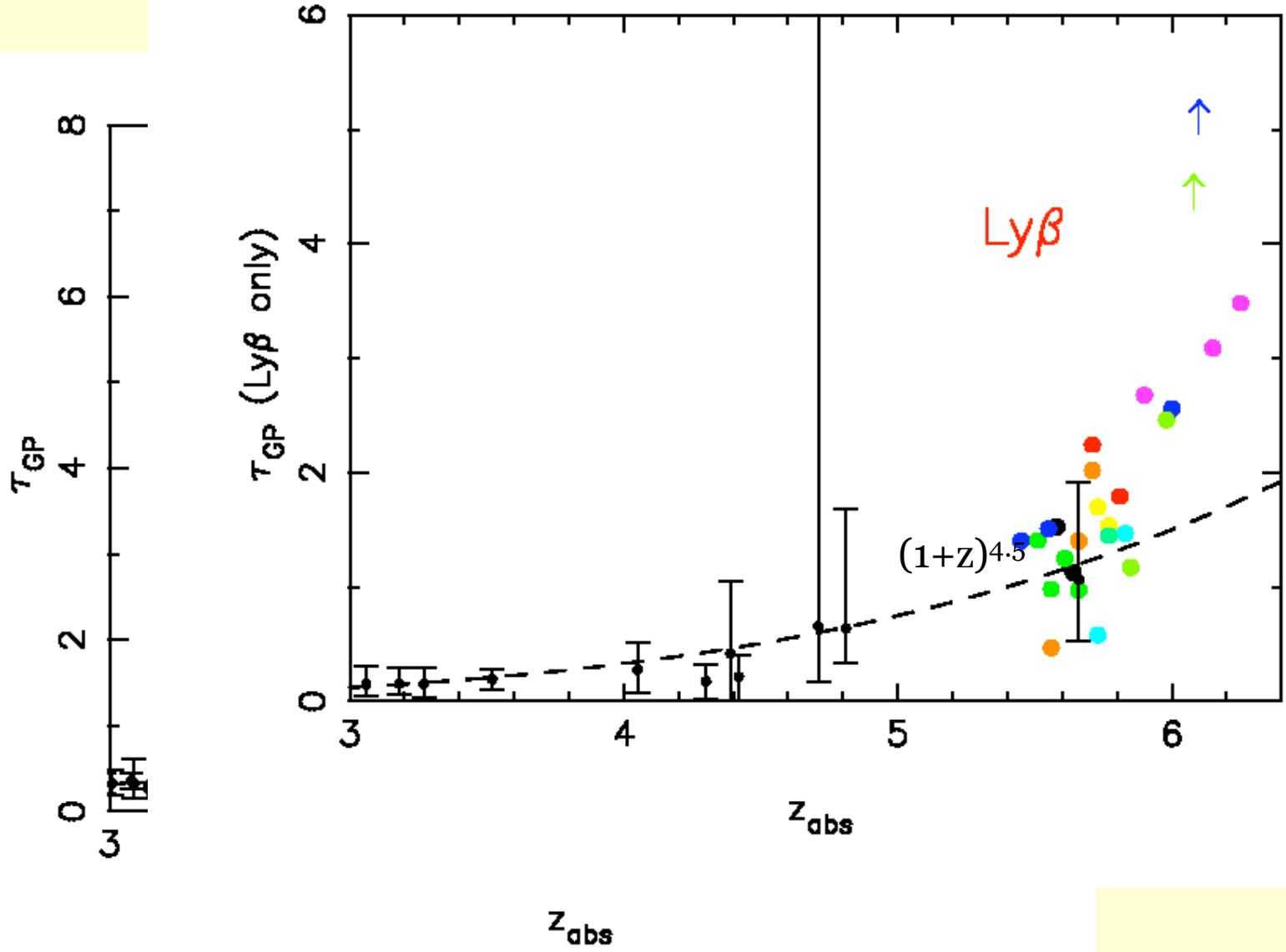


Δz = 0.15

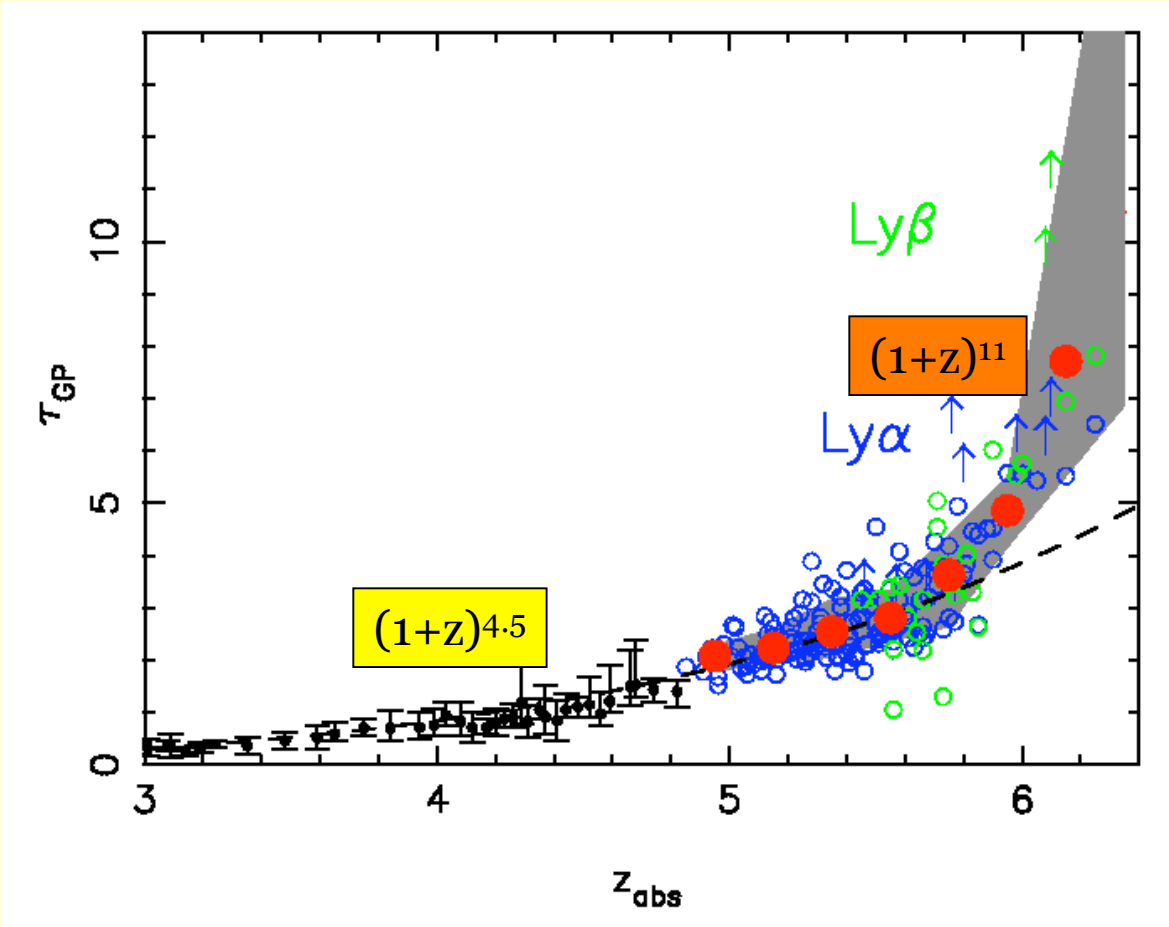
Open Questions

- How fast are the **average and dispersion** of IGM ionization state evolve? ***Is there a break?***
- What's the upper limit of neutral fraction?
- At z>6, Lyα absorption dominated by long gap trough with few transmitted pixels, ***what's the most meaningful statistics?***
- Implication on reionization history?
- Three methods:
  - GP optical depth
  - Dark gap distribution
  - HII region size

Evolution of Gunn-Peterson Optical Depth



Accelerated Evolution at z>5.8

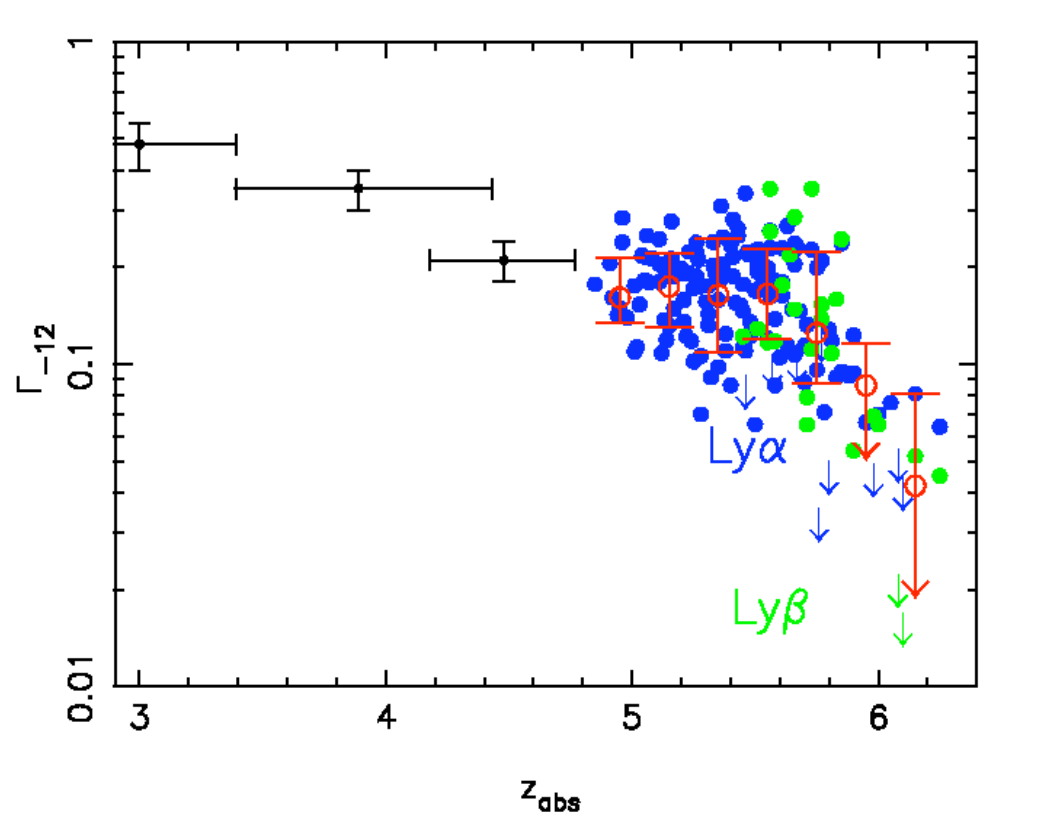


- *Optical depth evolution accelerated*
  - $z<5.7$: $\tau \sim (1+z)^{4.5}$
  - $z>5.7$: $\tau \sim (1+z)^{>10}$
  - But detectable flux in ~50% case at z>6
- *Dispersion of optical depth also increased*
  - $z<5.9$: $\sigma(\tau)/\tau \sim 0.3$ -- 0.5
  - $z>5.9$: $\sigma(\tau)/\tau > 1$
  - Some line of sight have dark troughs as early as z~5.7

- Lyα and Lyβ conversion:
  - Calibrated with photoionization model and empirically
  - $\tau(\alpha)/\tau(\beta)$ ~2.5 (instead of 6.2)

Evolution of Ionizing Background

- UV background estimation:
  - assuming photoionization and realistic IGM density distribution
  - Similar to optical depth: strong evolution in average and dispersion at z>5.8
  - 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***



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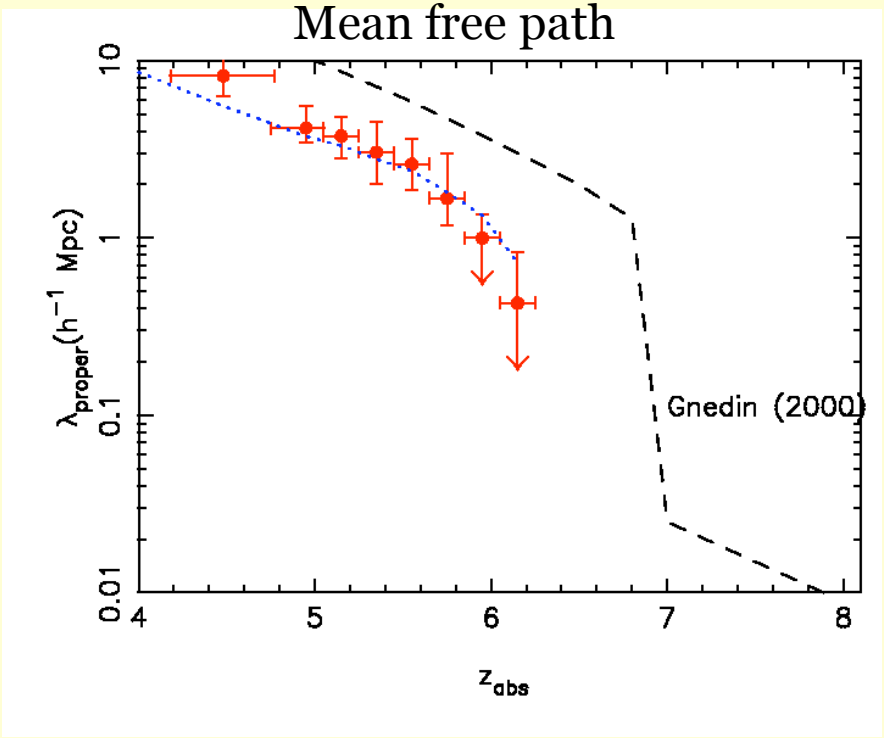
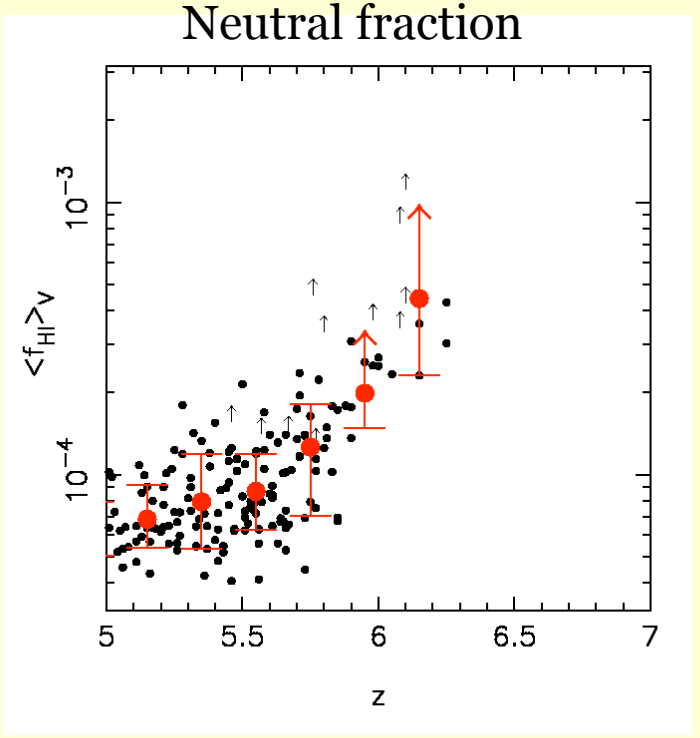
Evolution of Ionization State

Mean free path

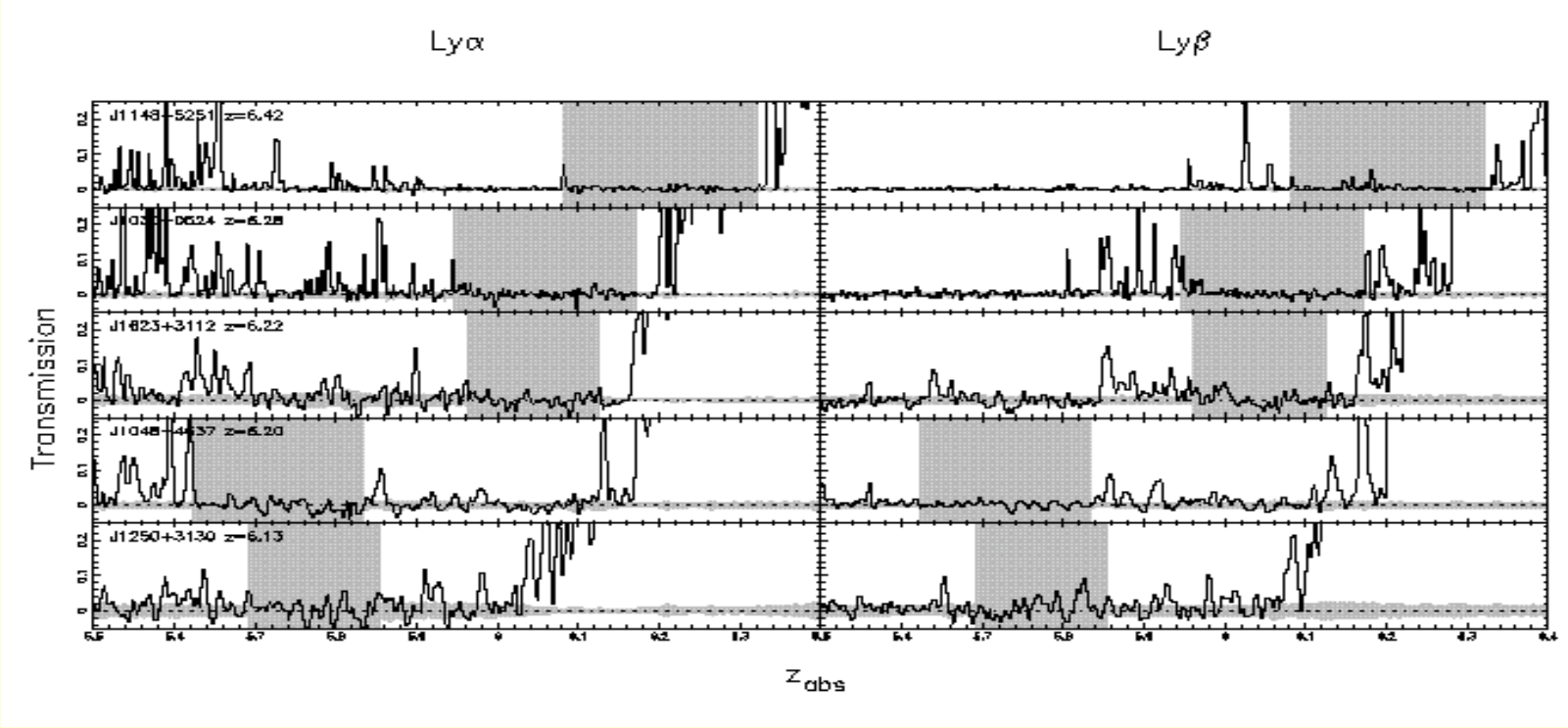


Neutral fraction



- Mean free path of UV photons < 1 proper Mpc at z>6
  - Comparable to correlation length of star-forming galaxies
  - ***Large scale variation in UV background and ionization state expected***
- From GP optical depth measurement, volume averaged neutral fraction increase by ~ order of magnitude from z~5.5 to 6.2

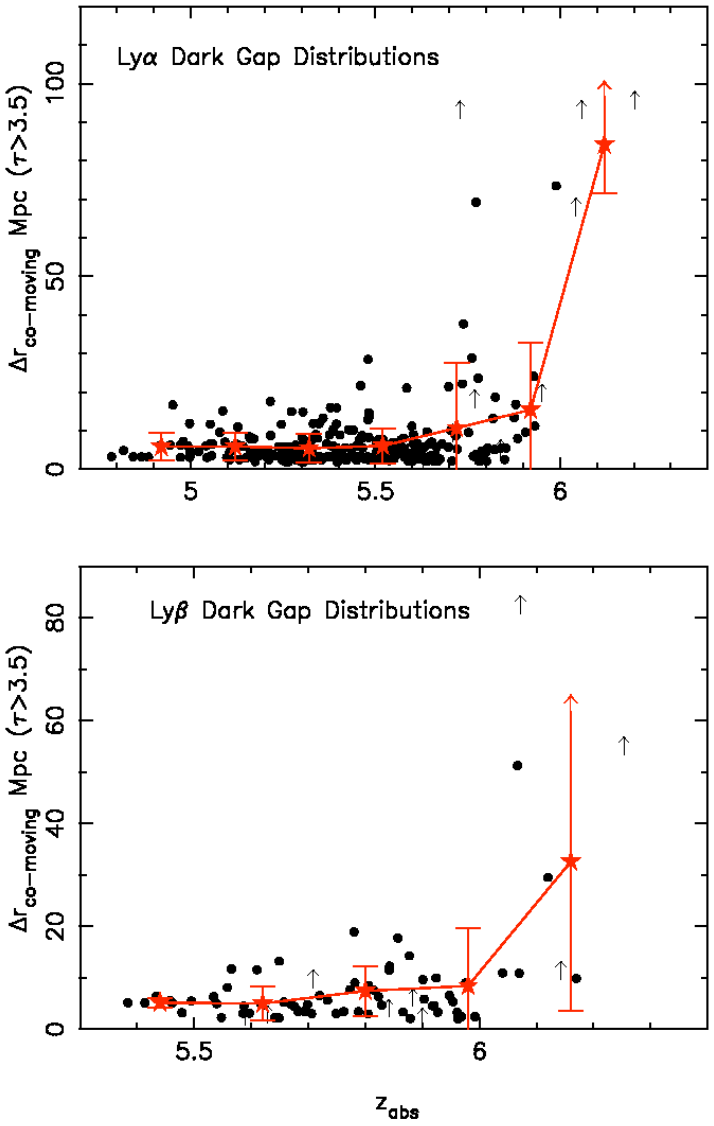
Gunn-Peterson Troughs



- Appearance of GP troughs show large line of sight variations
  - J1148 (z=6.42): detectable flux in α, β, γ: IGM highly ionized
  - J1030 (z=6.28): no flux in α, β, γ
  - J1623 (z=6.22): no flux in α, β, γ
  - Some dark troughs starts to appear at z~5.6, although not as deep or as long

Dark Gap Distributions

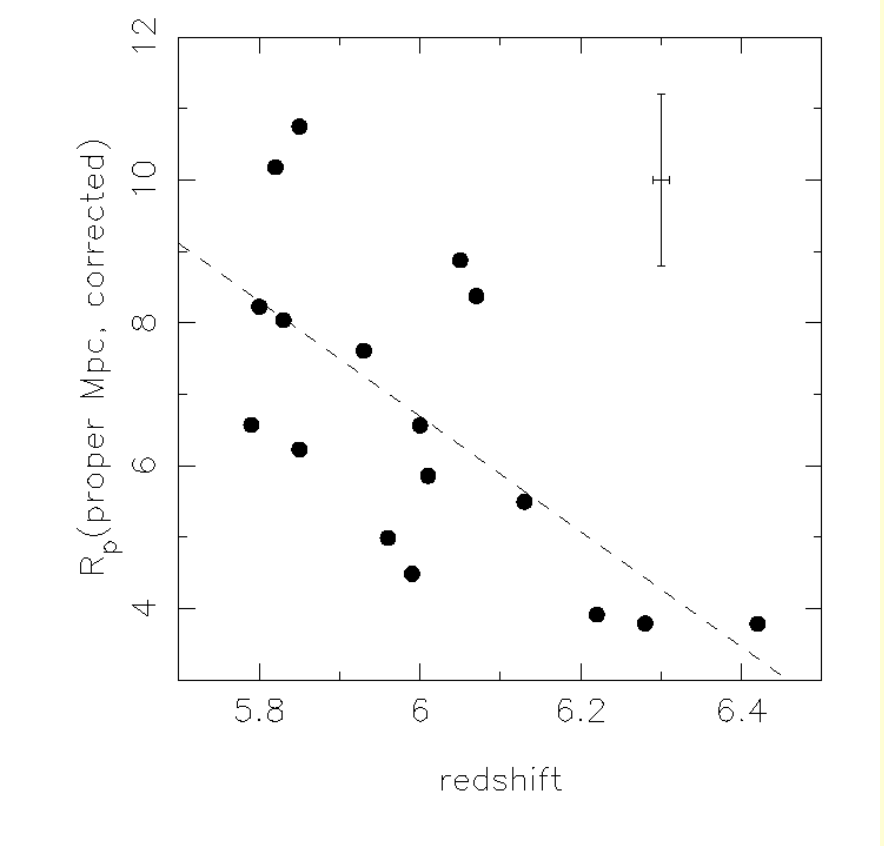
- Length of gaps
  - Defined as regions where all pixels have $\tau>3.5$
  - Average length shows the most dramatic increase at $z>5.8 \rightarrow$ IGM is dominated by long, dark gaps
- Dispersions
  - Some dark gaps appear at lower z
  - Even at z>6, gap lengths are still finite
- Upper limit on neutral 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



Evolution of Proximity Zone Size Around Quasars

- Size of quasar HII region

  $R_s \sim (N_Q\, t_Q / x_{HI})^{1/3}$
- Size of proximity zone decreases by a factor of ~2.4 between z=5.8 and 6.4 (after correcting for different luminosity)
- **Neutral fraction increased by a factor of ~14 over this narrow redshift range**



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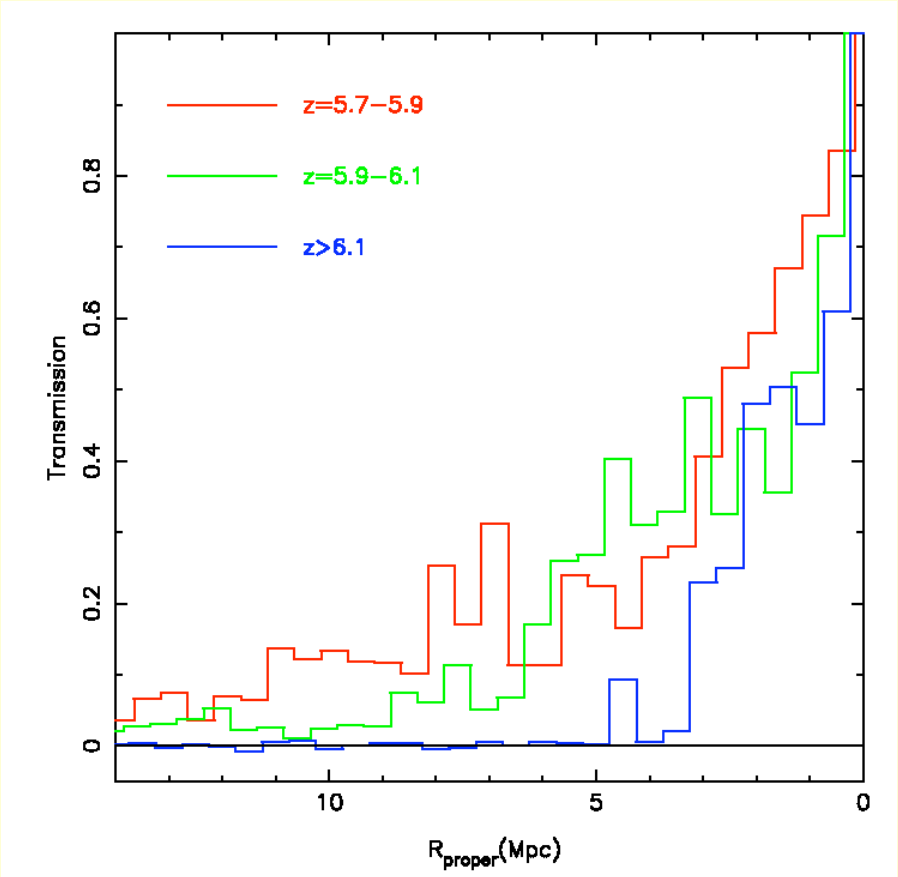
Evolution of Transmitting Profiles



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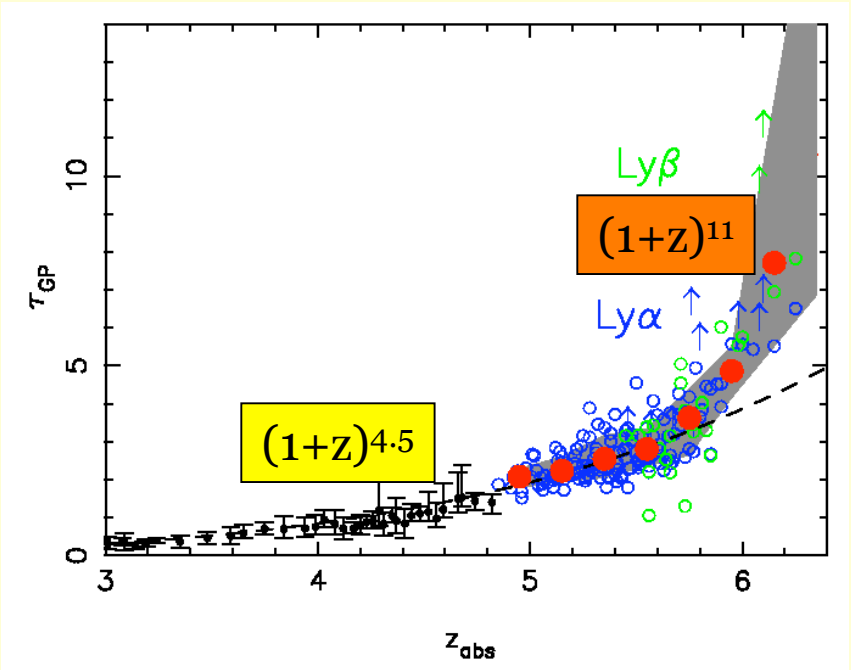
z>6 transmitting profile much narrow:
consistent with quasar HII region expanding into increasing neutral IGM

Summary

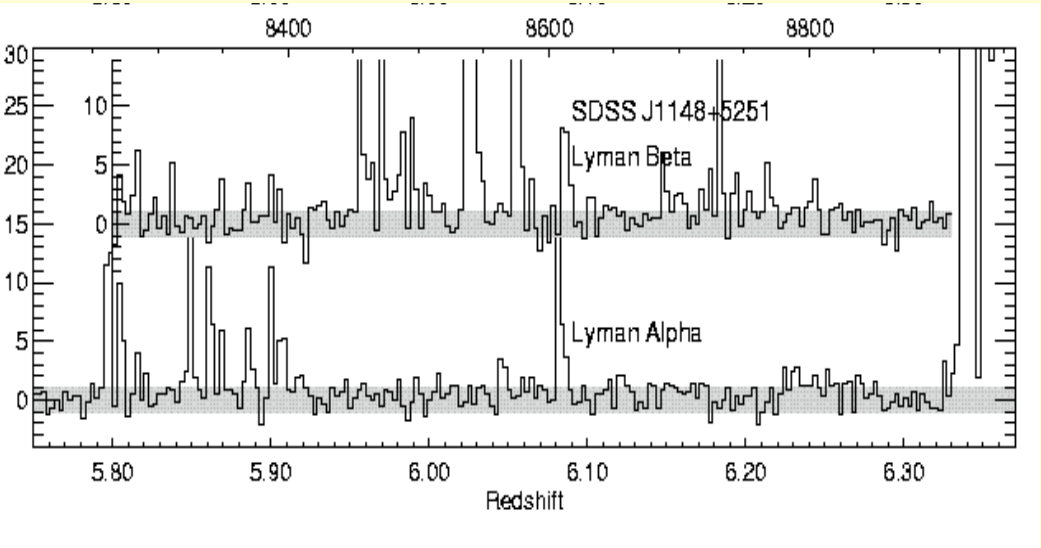
- How fast are the **average and dispersion** of IGM ionization state evolve? ***Is there a break?***
  - At z>5.8: IGM evolution accelerated
  - Accompanied by large variations that are likely result of highly non-uniform background
  - The neutral fraction likely increased by ~order of magnitude at z=5.8 to 6.4
  - But too early to tell whether it is anything like a phase transition



Summary

- At z>6, Lyα absorption dominated by long gap trough with few transmitted pixels, ***what's the most meaningful statistics?***
  - z<6: GP optical depth easy to interpret
  - z>6: gap distribution statistics robust to observational uncertainties and is sensitive
  - HII region size sensitive to large neutral fraction but affected by systematics

- What's the upper limit of neutral fraction?
  - Transmitted pixels at z>6: IGM not mostly neutral
  - But ~30% neutral can't be ruled out



Reionization History?