# Highest-Redshift Quasars – Probing the End of Reionization

Xiaohui Fan

Steward Observatory

The University of Arizona

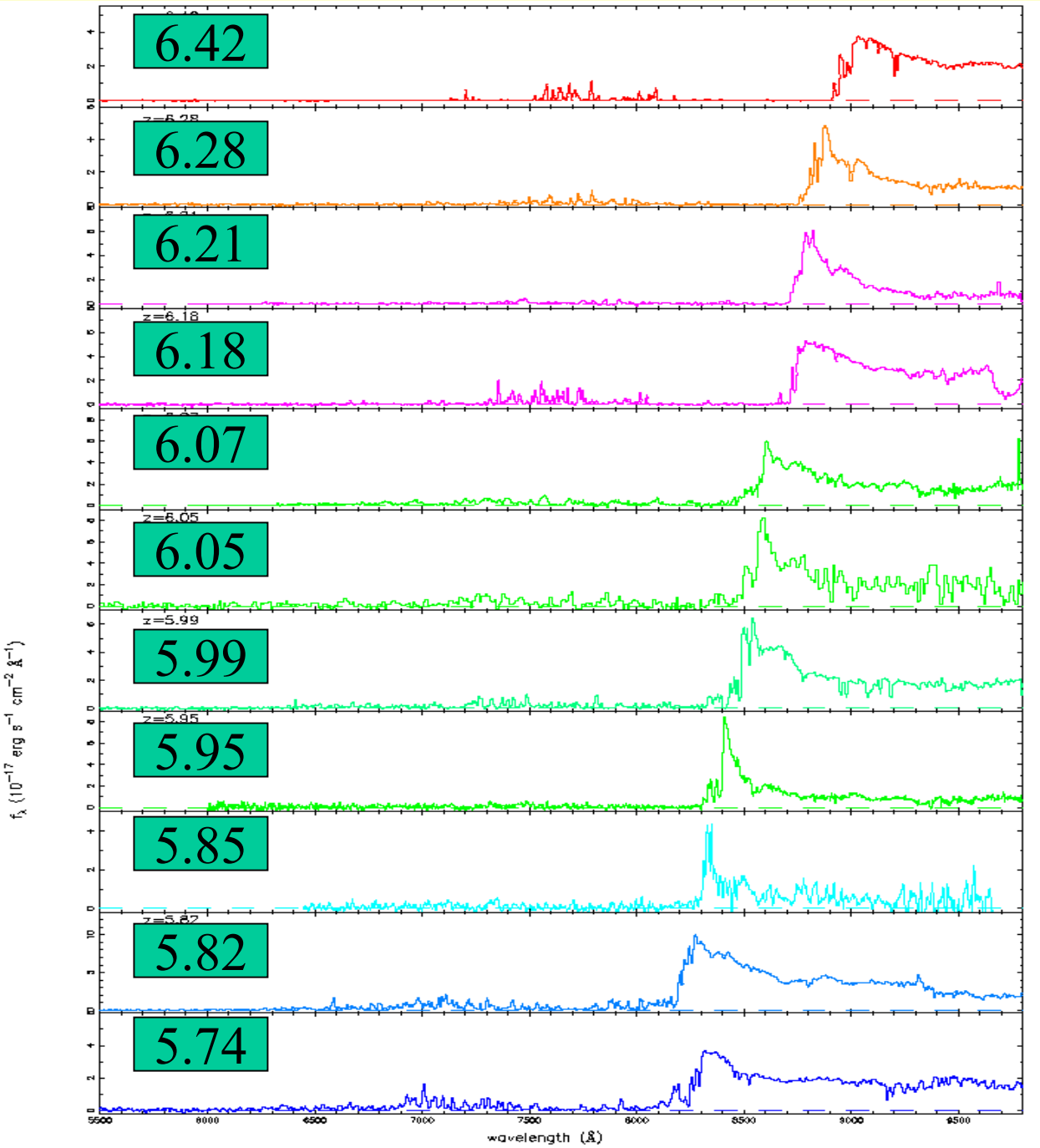
# Introduction

- Highest-redshift Quasars and the End of Dark Ages:
  - Earliest Generation Black Holes and Galaxies
    - The star formation and chemical enrichment in the most massive and biased galaxy environment
    - Role of BH/AGN activity in galaxy formation
  - Ionization State of the IGM
    - Evolution of the UV ionizing background and history of reionization
    - Evolution of IGM metallicity

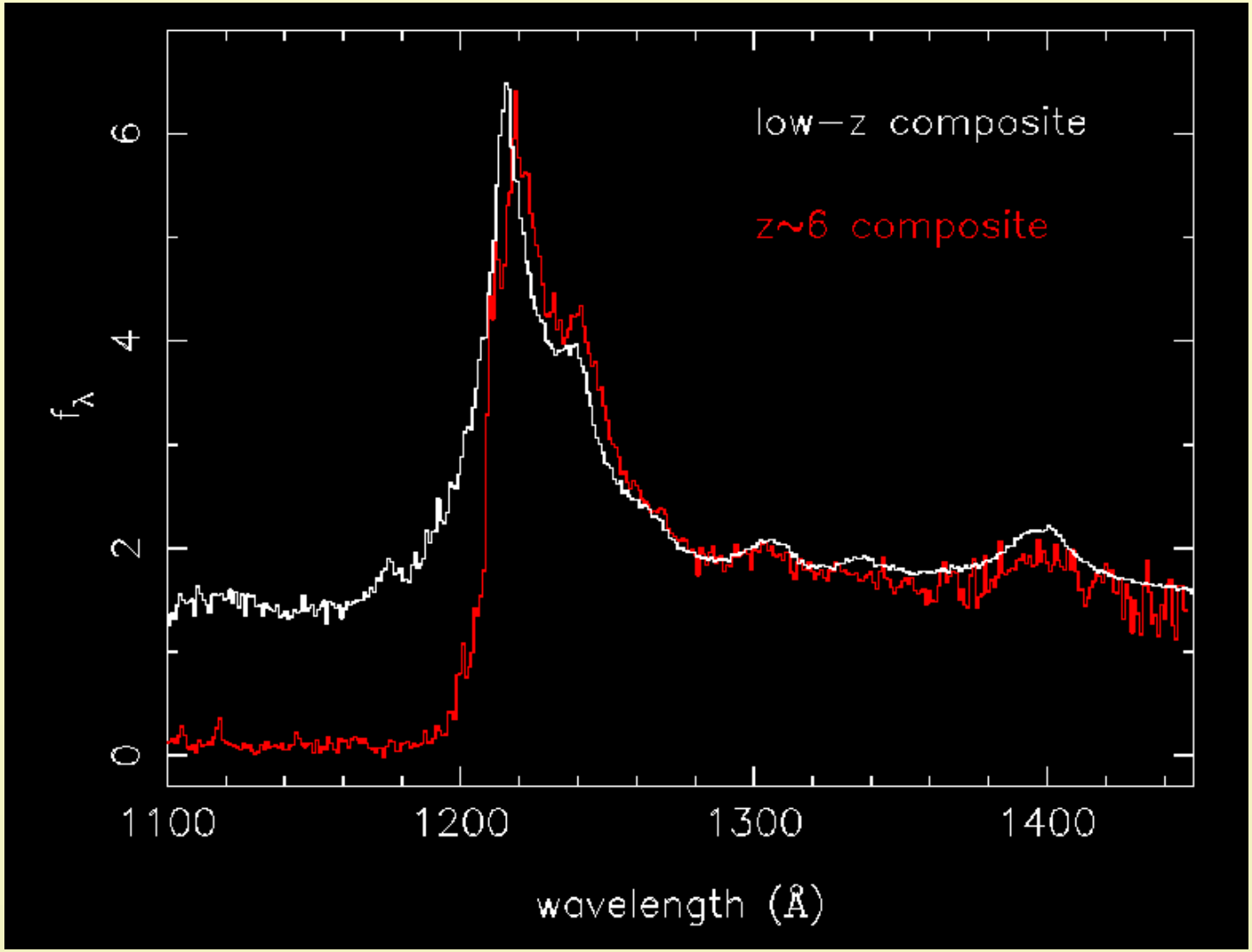
Collaborators: Strauss, Schneider, Becker, White, Pentericci, Rix, Richards, Narayanan, Hennawi et al.

# Highest-Redshift Quasars

- Aug 2003:
  - z>4: ~600 (~400 from the SDSS)
  - z>5: ~30 (~25 from the SDSS)
  - z>6: 6 from the SDSS (highest redshift at z=6.42)
- SDSS i-dropout Survey:
  - By Spring 2003: 4500 $deg^2$ at $z_{AB}<20$
  - Eleven luminous quasars at z>5.7
- 20 – 40 at z~6 expected in the whole survey

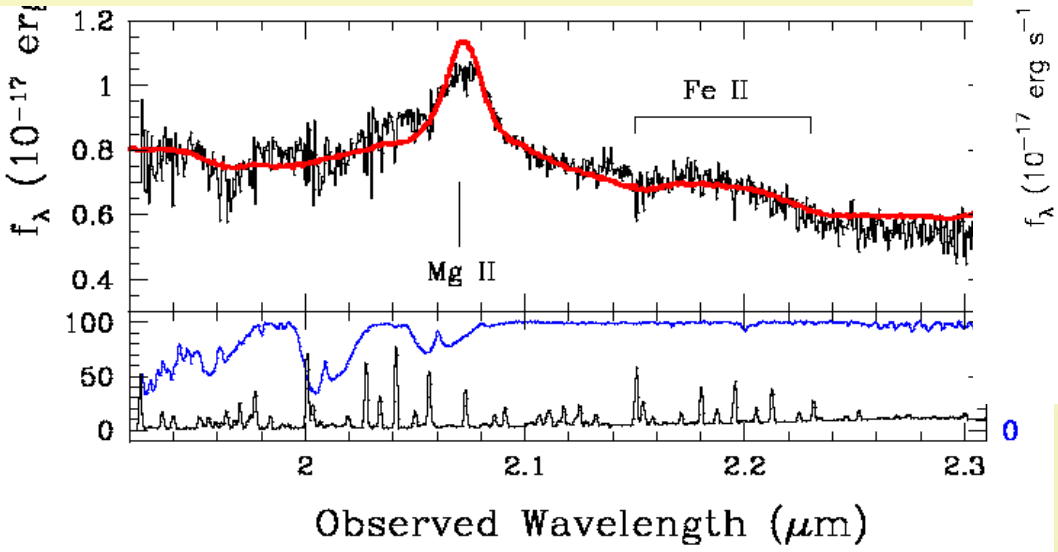

6.42
6.28
6.21
6.18
6.07
6.05
5.99
5.95
5.85
5.82
5.74
z=6.18
z=6.05
z=5.99
z=5.95
z=5.82
wavelength (Å)

# The Lack of Evolution in Quasar Spectral Properties

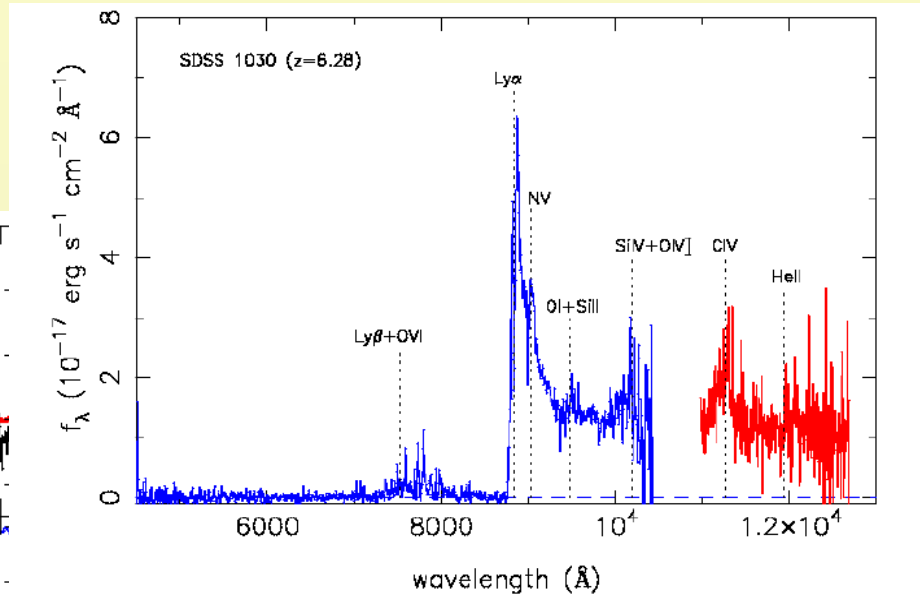


# Chemical Enrichment at z>>6?

- Strong NV emission → consistent with supersolar metallicity
- Fe/alpha unchanged from low-z
- If Fe is mostly made out of Type Ia SN → ~1Gyr delay, not enough time?
- Fe production from Pop III???
- Question: what exactly can we learn from abundance analysis of these most extreme environment in the early universe?




Barth et al. 2003

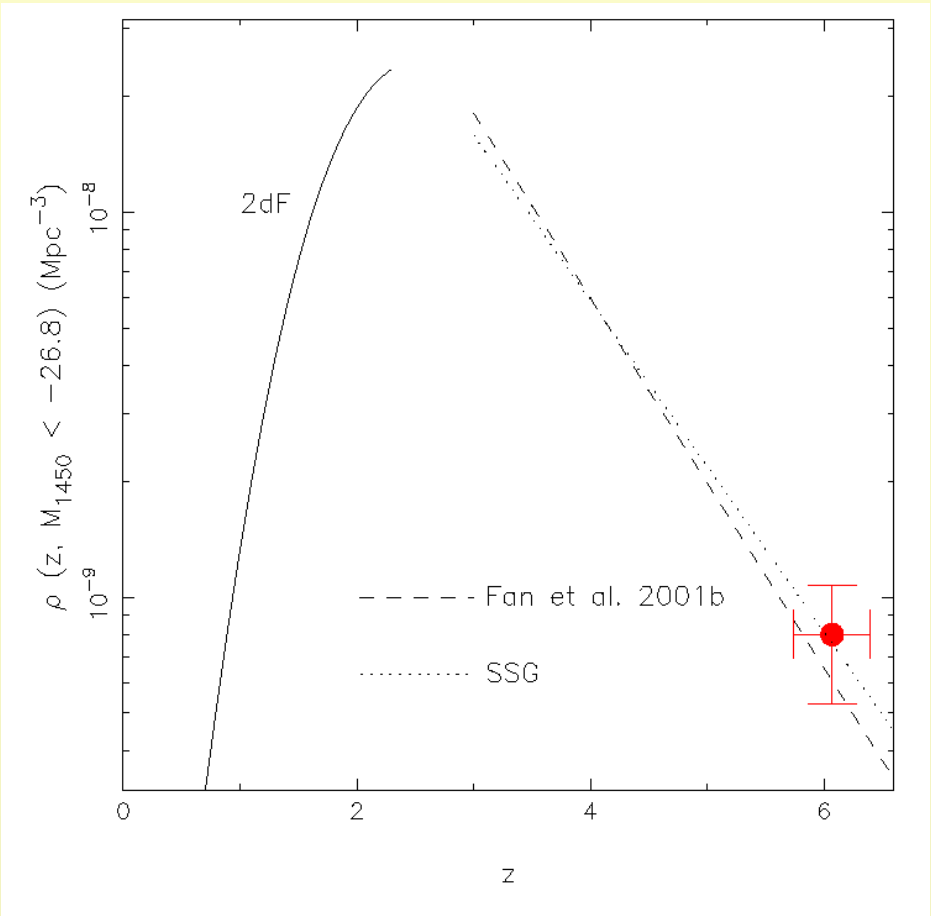



Fan et al. 2001

# Quasar Density at z~6

- Based on nine z>5.7 quasars:
  - Density declines by a factor of ~20 from z~3
  - Number density implies that quasars are unlikely to provide enough UV background if LF is similar to that at low-z → ***first stars ionized the universe!***
- Cosmological implication
  - $M_{BH} \sim 10^{9\text{-}10}\ M_{sun}$
  - $M_{halo} \sim 10^{13}\ M_{sun}$
  - ***How to form such massive galaxies and assemble such massive BHs in less than 1Gyr??***
    - The rarest and most biased systems at early times
    - Using Eddington argument, ***the initial assembly of the system must start at z>>10***

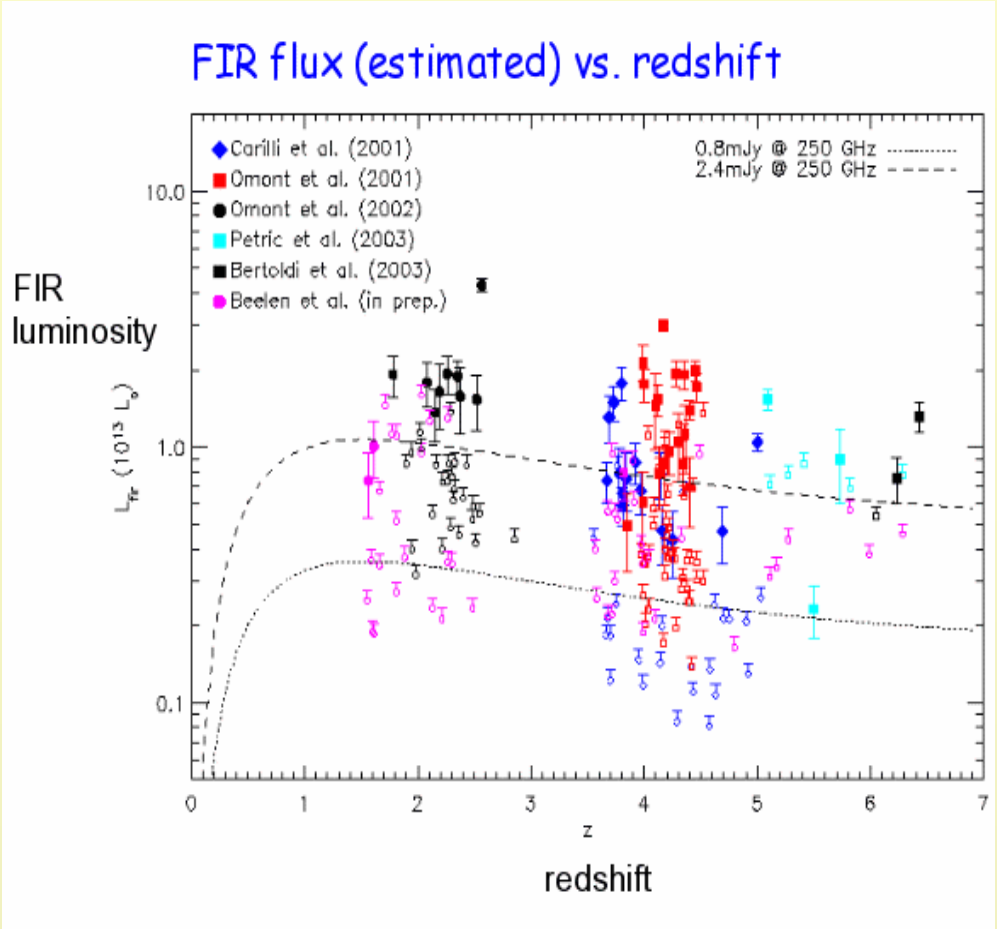
→ ***co-formation and co-evolution of the earliest SBH and galaxies***

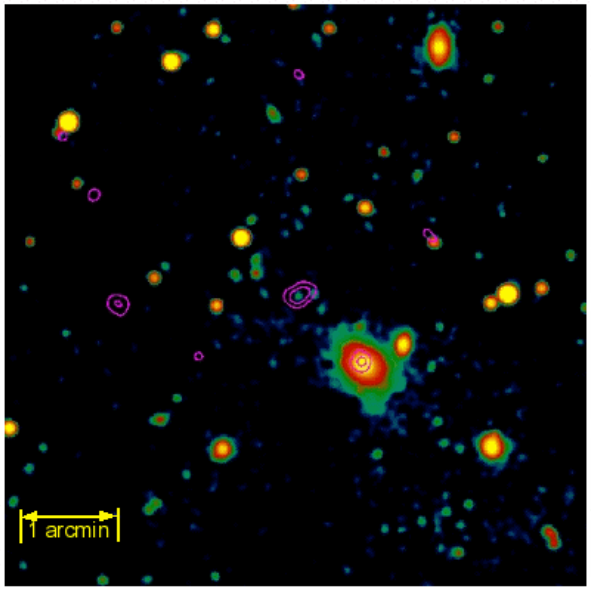



Fan et al. in prep.

# Sub-mm and Radio Observation of High-z Quasars

- Probing dust and star formation in the most massive high-z galaxy
- Using IRAM and SCUBA: ~40% of radio-quite quasars at z>4 detected at 1mm (observed frame) at 1mJy level
- Combination of cm and submm
  → submm radiation in radio-quiet quasars come from thermal dust with mass ~ $10^8$ $M_{sun}$
- If dust heating came from starburst
  → star forming rate of 500 – 2000 $M_{sun}$/year
  →*Quasars are likely sites of intensive star formation*






Bertoldi et al. 2003

**SDSS J1148**

MAMBO 1.2 mm (contour)
S/N on SLOAN z' image.

Dust at z=6.42 !

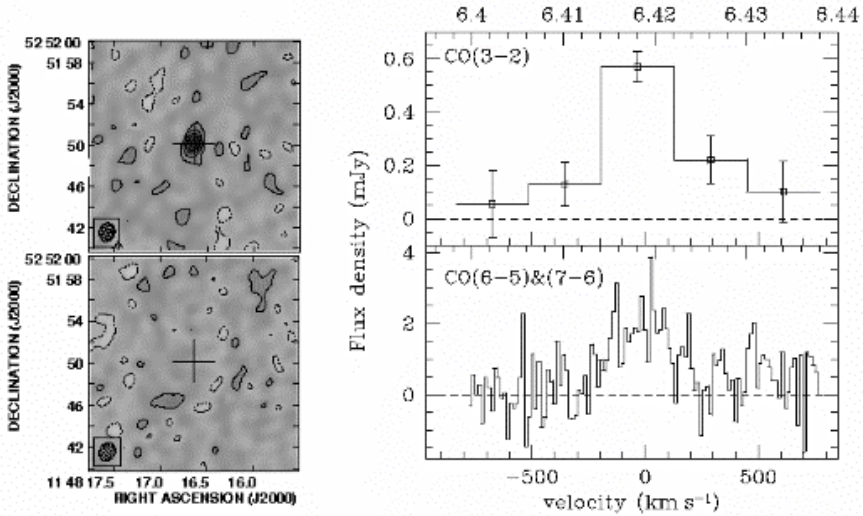
$7 \times 10^8$ $M_{sun}$ in <700 Myr

***Submm and CO detection in the highest-redshift quasar*:**

- Dust mass: 10^8 – 10^9
- H2 mass: 10^10
- Star forming rate: 10^3/yr

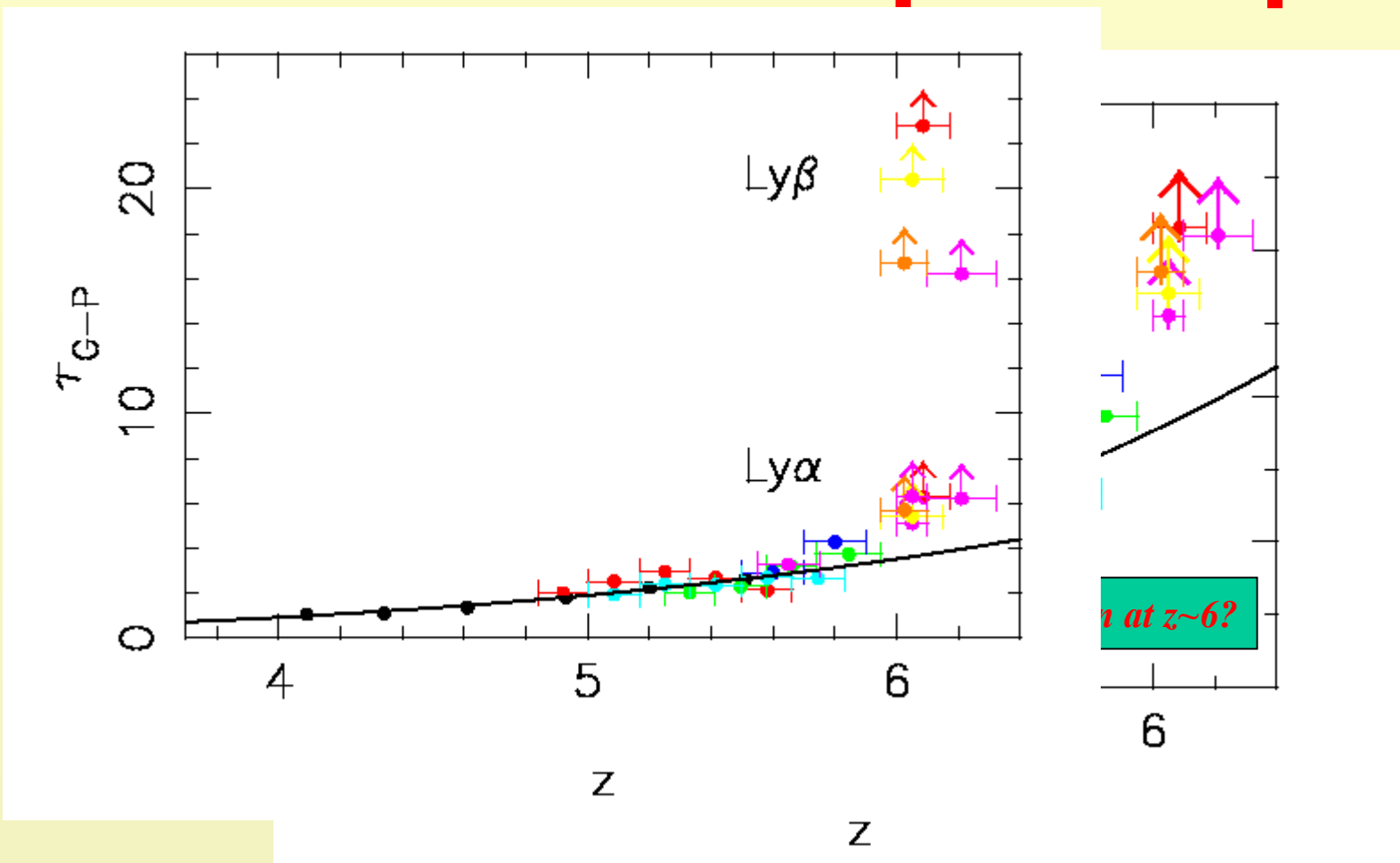
→ *co-formation of SBH and young galaxies*

CO 3-2 (VLA), 6-5, 7-6 (PdBI)



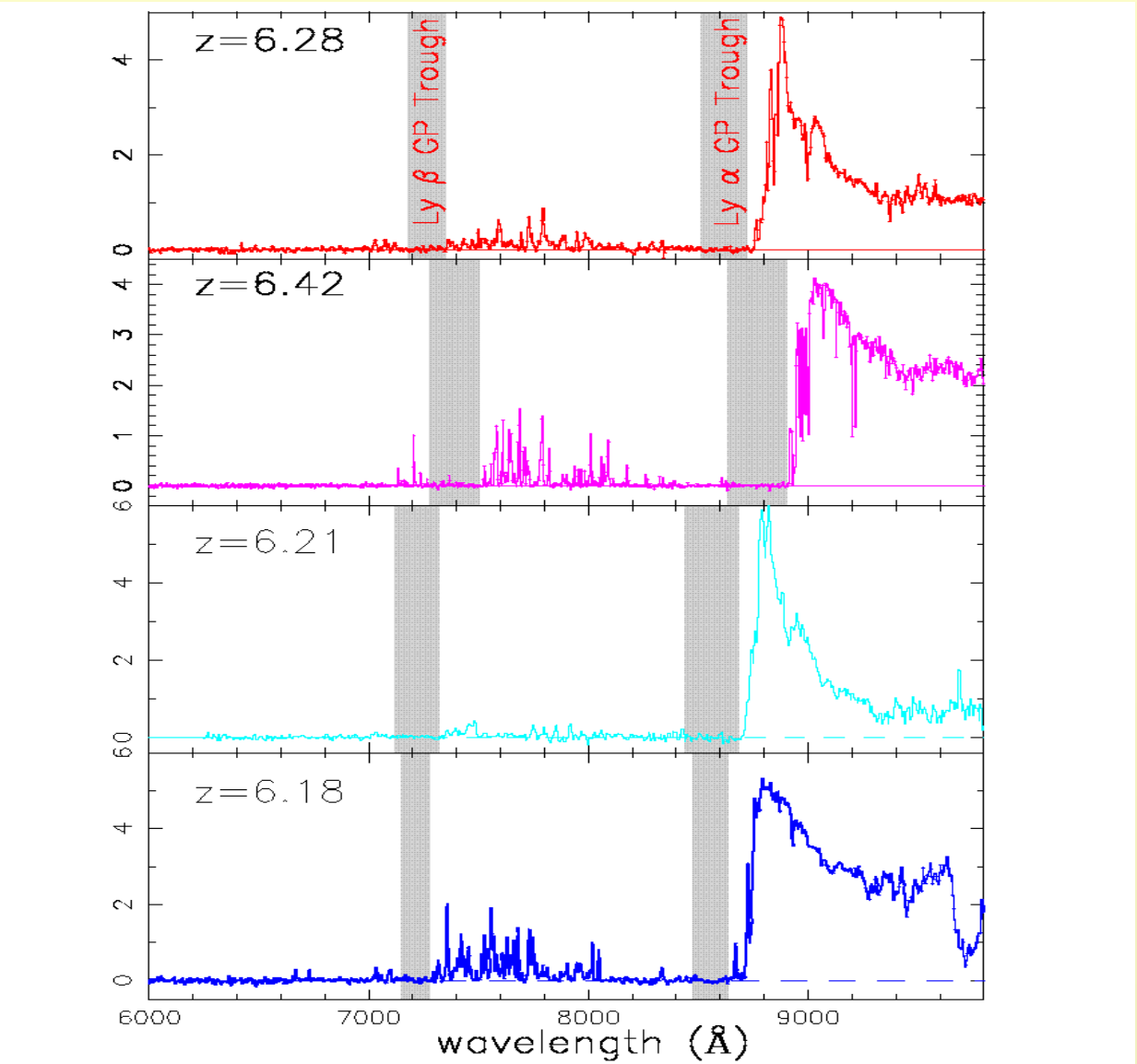

Walter, Bertoldi, Carilli et al. 2003, Nature
Bertoldi, Cox, Neri et al. 2003, A&ALet

# Strong Evolution of Gunn-Peterson Optical Depth



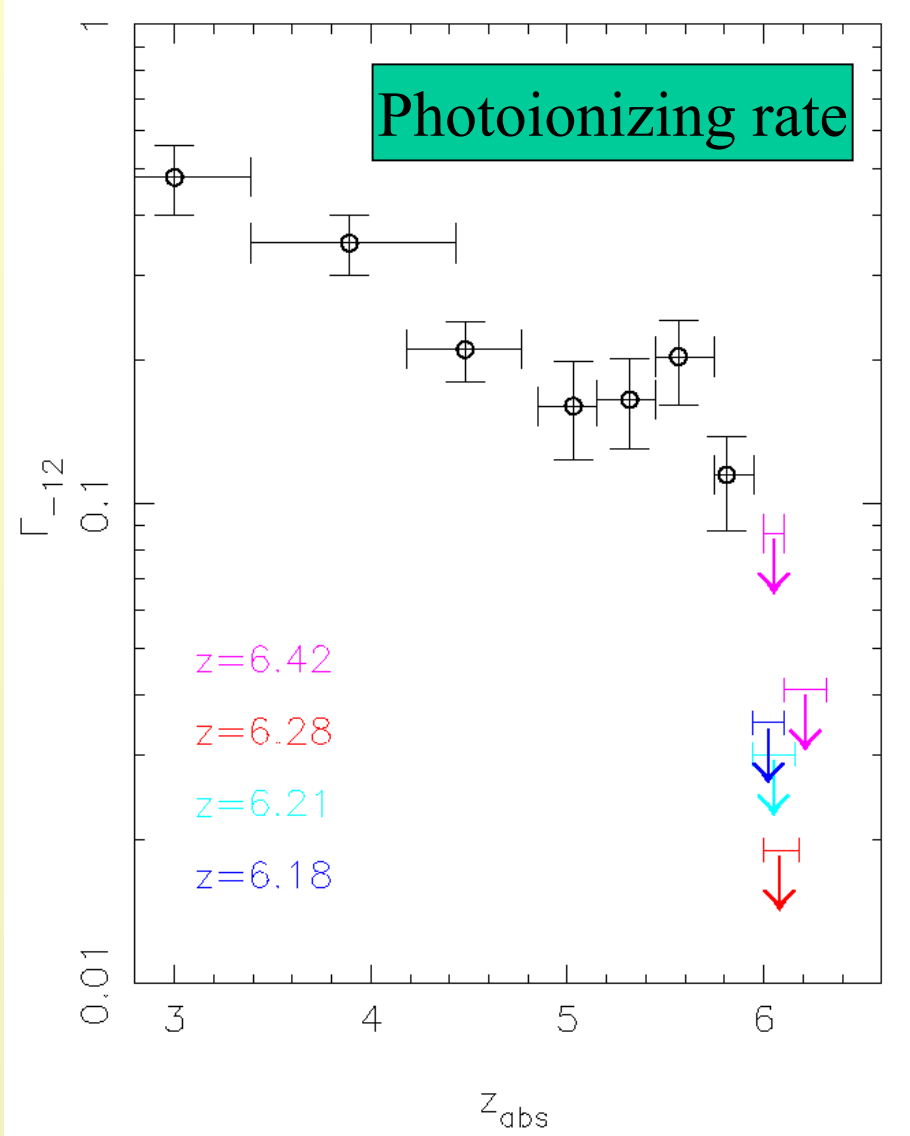

Fan et al. 2003

# Gunn-Peterson troughs confirmed by new z>6 quasars



# Evolution of Ionizing Background

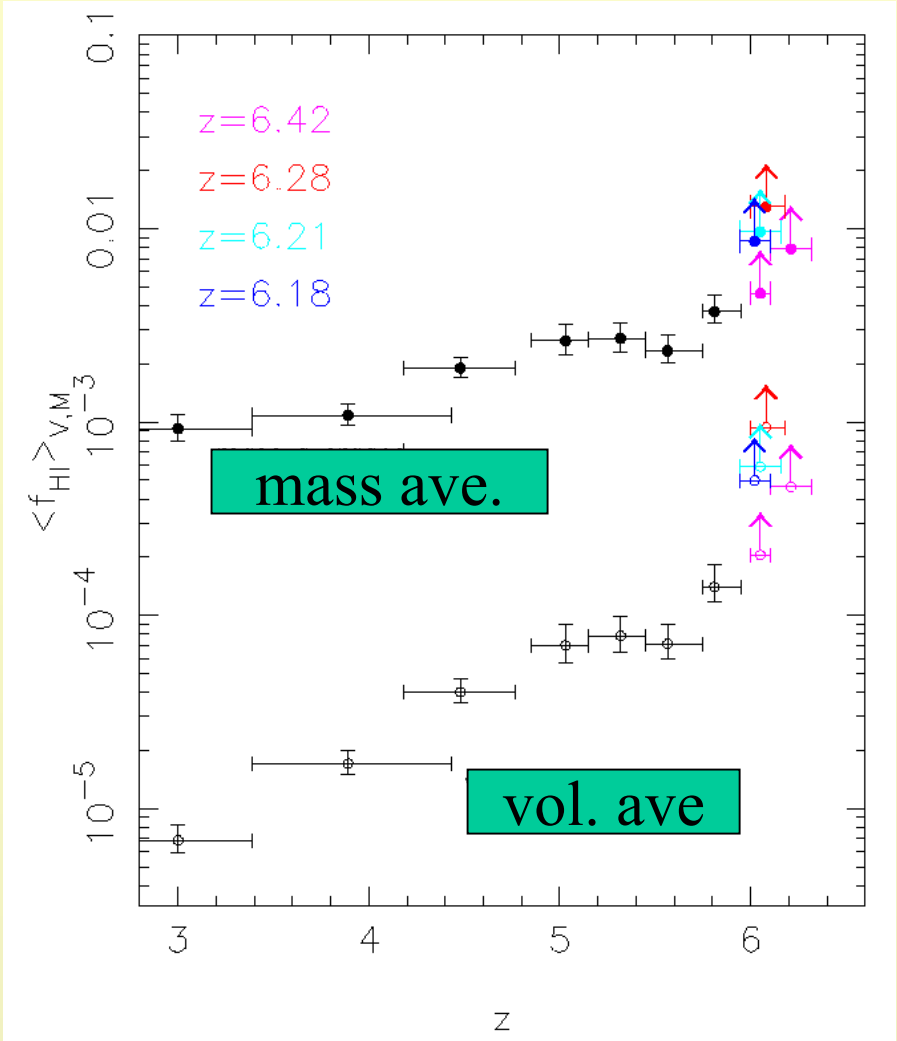
- Ionizing background estimated by comparing with cosmological simulations of Lyman absorption in a LCDM model
  - Stronger constraint from the Lyβ and Lyγ Gunn-Peterson trough
  - Ionizing background declines by a factor of >25 from z~3 to z~6
  - Indication of a sudden change at z~6?




Fan et al. in prep

# Constraining the Reionization Epoch

- Neutral hydrogen fraction
  - Volume-averaged HI fraction increased by >100 from z~3 to z~6
  - Mass-averaged HI fraction > 1%
  - Gunn-Peterson test only sensitive to small neutral fraction and saturates at large neutral fraction
- At z~6:
  - Last remaining neutral regions are being ionized
  - The universe is ~1% neutral
  - ***Marks the end of reionization epoch??***

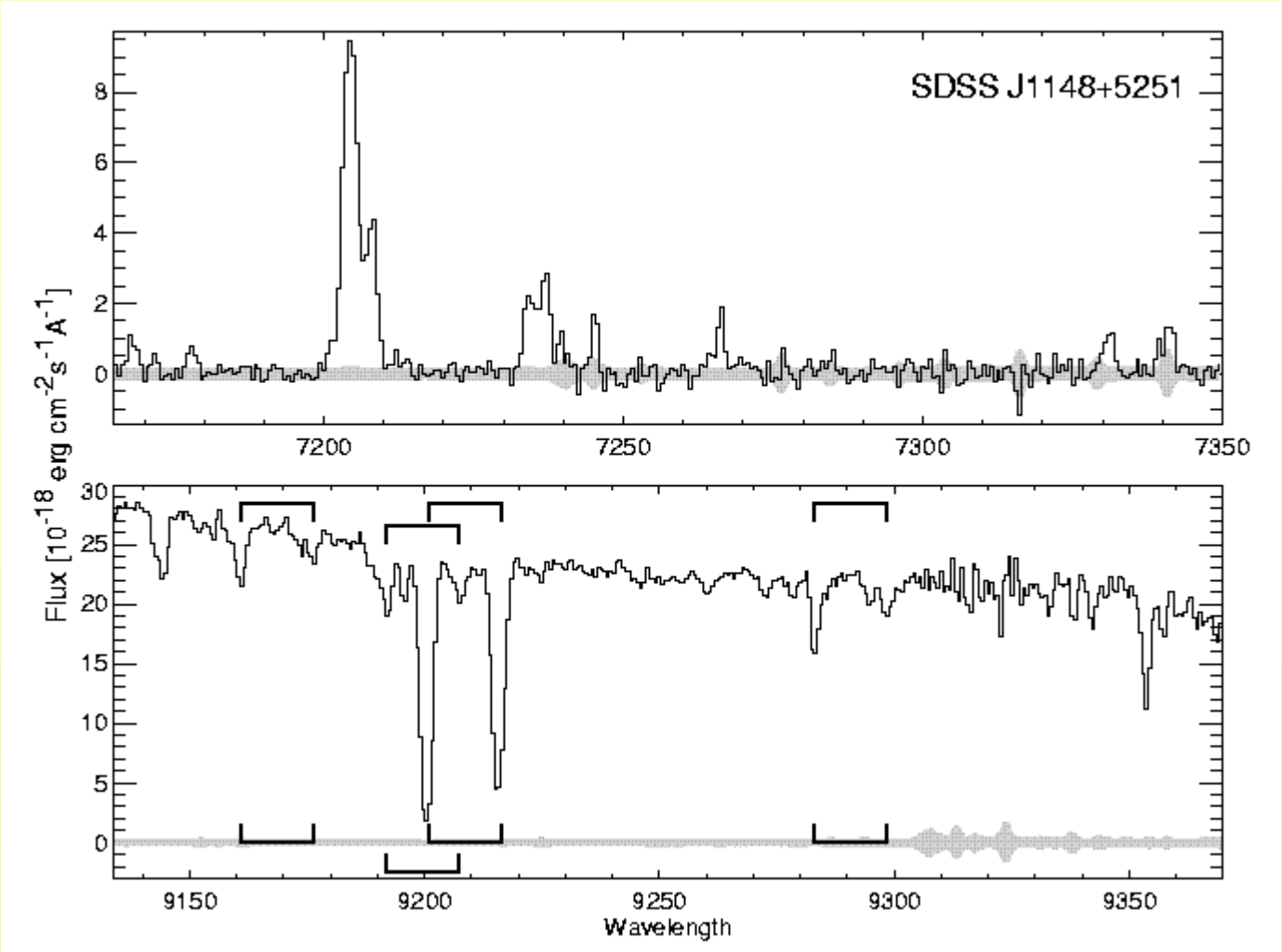



Fan et al. in prep

# Reionization History: Combining GP test with CMB

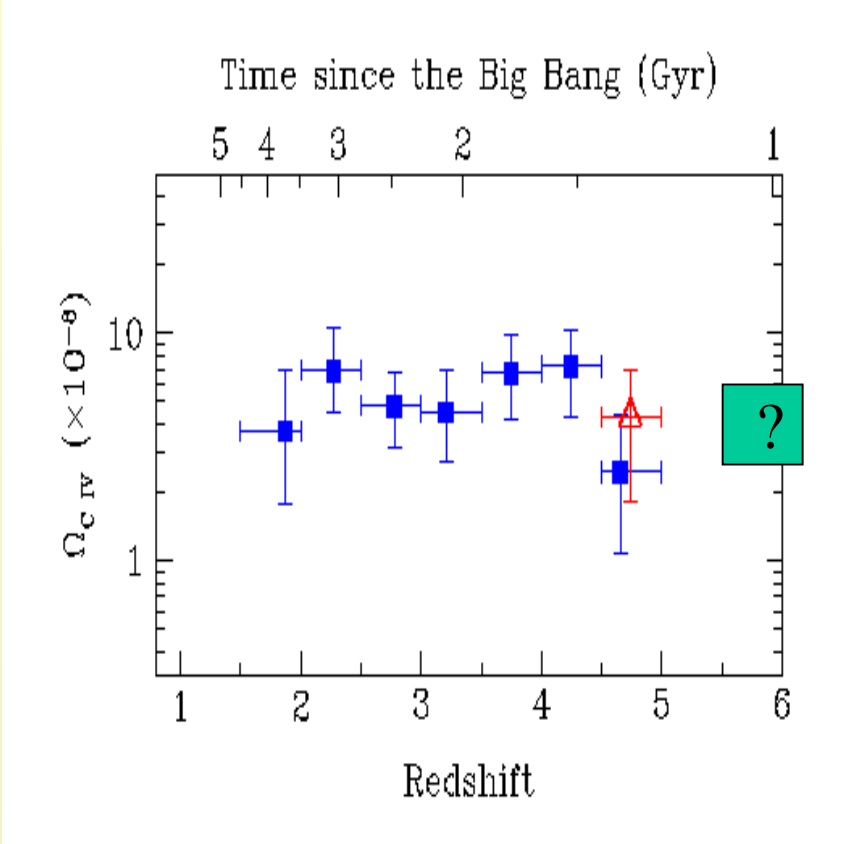
- G-P test shows: at z~6, the IGM is about 1% neutral → ***the tail end of the reionization process***
- Discovery of three G-P troughs in the three highest redshift quasars known → ***end of reionization at z~6 with small dispersion among different lines of sight***
- CMB polarization shows: substantial ionization by z~17:
- Combining GP with CMB → *reionization history:*
  - *Reionization seems to be more complicated by the simplest theory*
  - *Reionization is not a phase transition*
  - *Reionization last from 20 to 6? (600 million years) ?*
- What's Next?
  - More quasars: understanding the topology of the reionization from multiple lines of sights
  - More sensitive to large neutral fraction: GRBs? 21cm?

# Probing the first metals?



# Evolution of IGM CIV density

- No redshift evolution of CIV density from z~2 to 5
- IGM enriched in metal at z>>5
- First massive stars as the source of earliest metal enrichment?
- Future observations:
  - Near IR spectroscopy: metals at z~6
  - Absorption from different ions → abundance and ionization state of the IGM




Pettini et al. 2003

# Summary

- High-redshift quasars evolve strongly with redshift:
  - not likely to be sources of reionization → *first stars ionized the universe?*
- High-redshift quasars are sites of spectacular star formation:
  - *Co-formation of the first galaxies and first black holes?*
- High-redshift quasars probe the end of reionization epoch:
  - Metal lines: early IGM enrichment by the first stars?
  - At z~6: ionizing background much lower, neutral fraction >1%,

**→ it marks the end of the reionization epoch when the last remaining HI in the IGM is being ionized**

**→ combining with CMB results: revealing the reionization history**