Probing the End of Dark Ages with High-redshift Quasars

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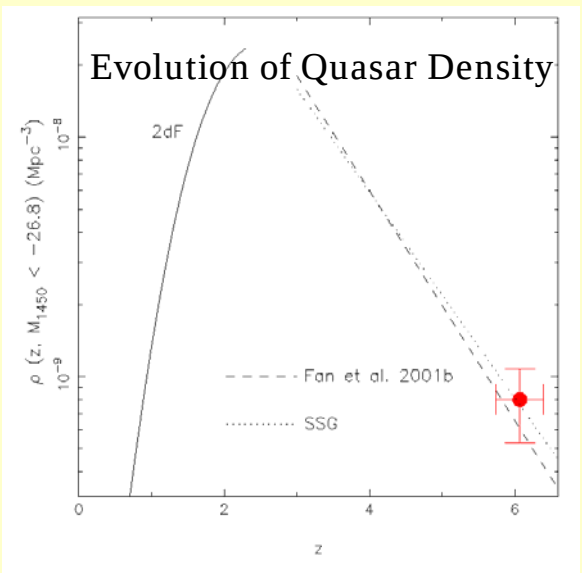
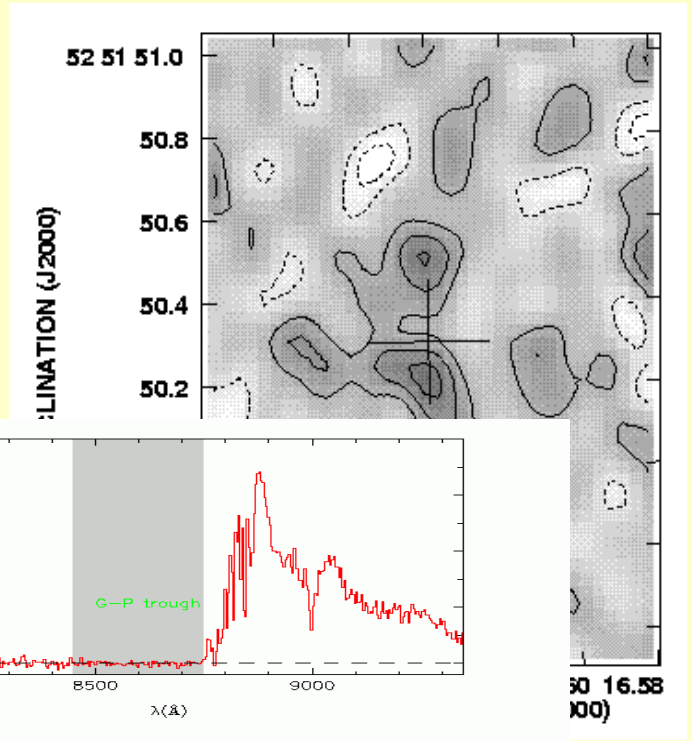
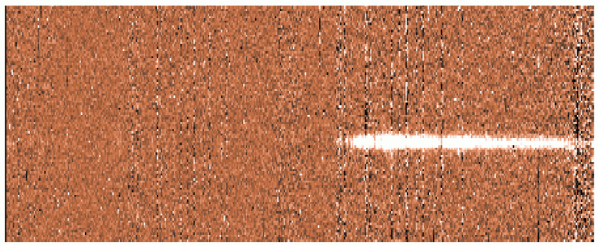
High-redshift Quasars and the End of Cosmic Dark Ages

- Existence of SBHs at the end of Dark Ages
- BH accretion History in the Universe?
- Relation of BH growth and galaxy evolution?
- ***Probing the end of reionization?***



Resolved CO emission from z=6.42 quasar

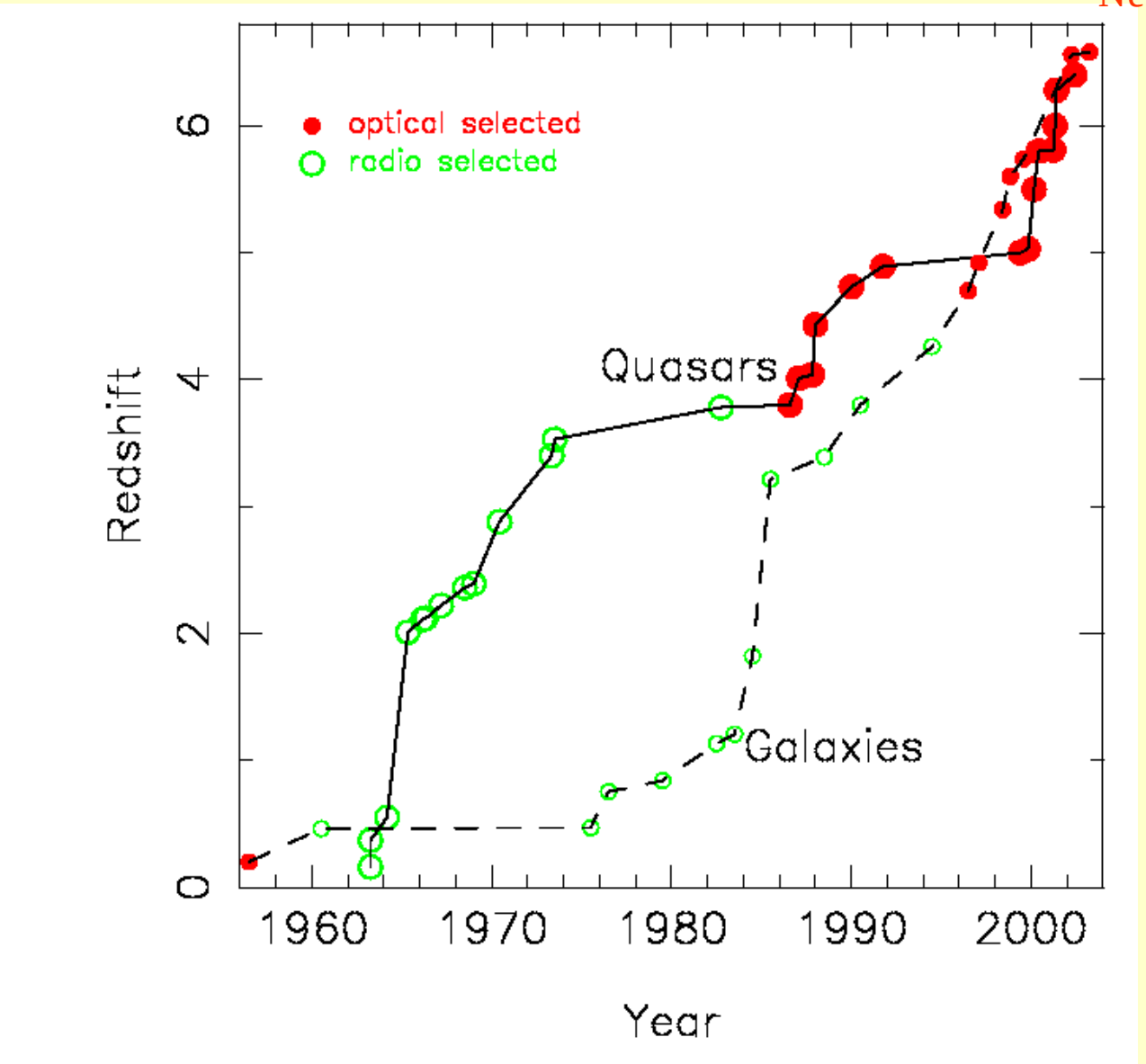




Detection of Gunn-Peterson Trough

Exploring the Edge of the Universe

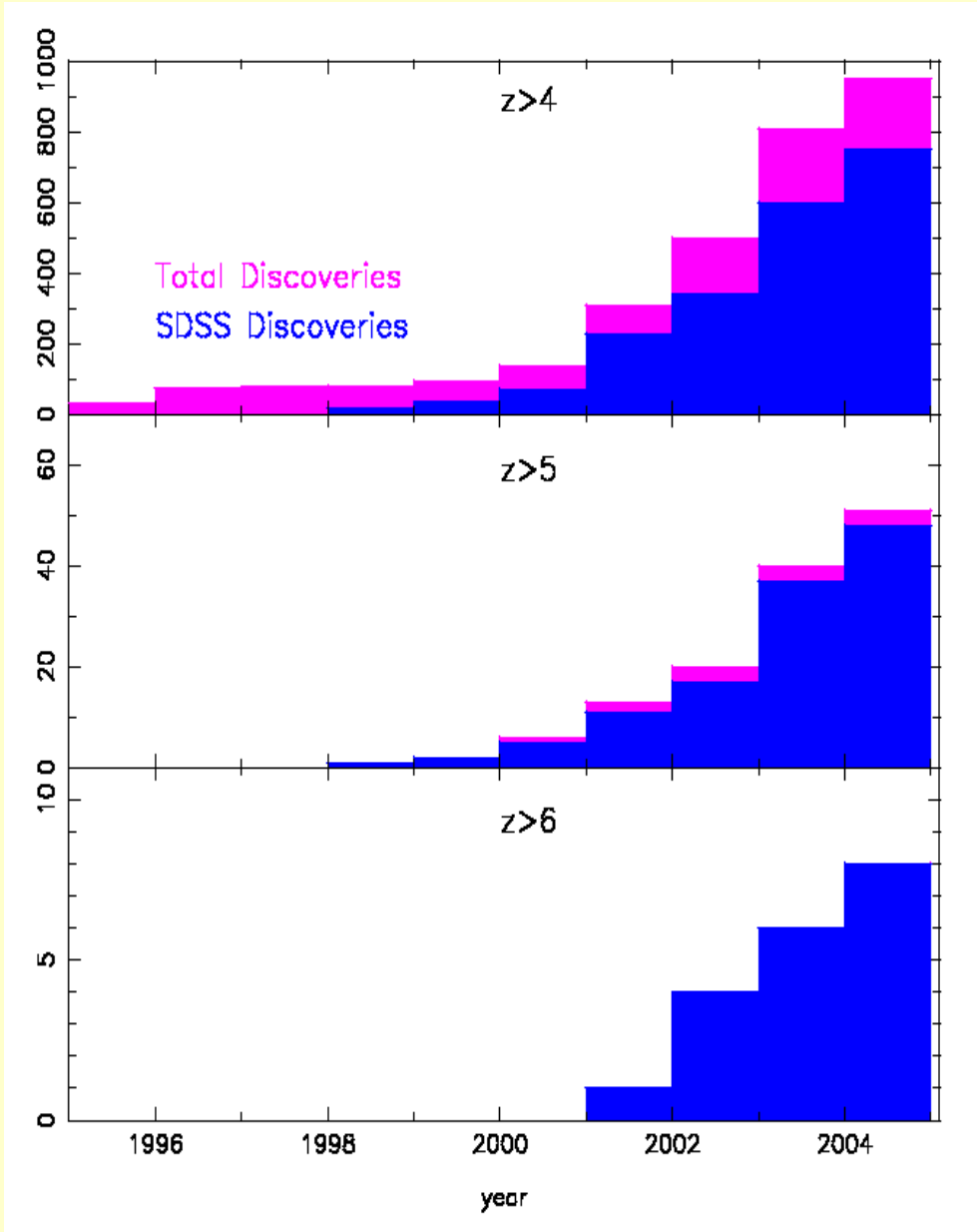
New z~7 galaxies

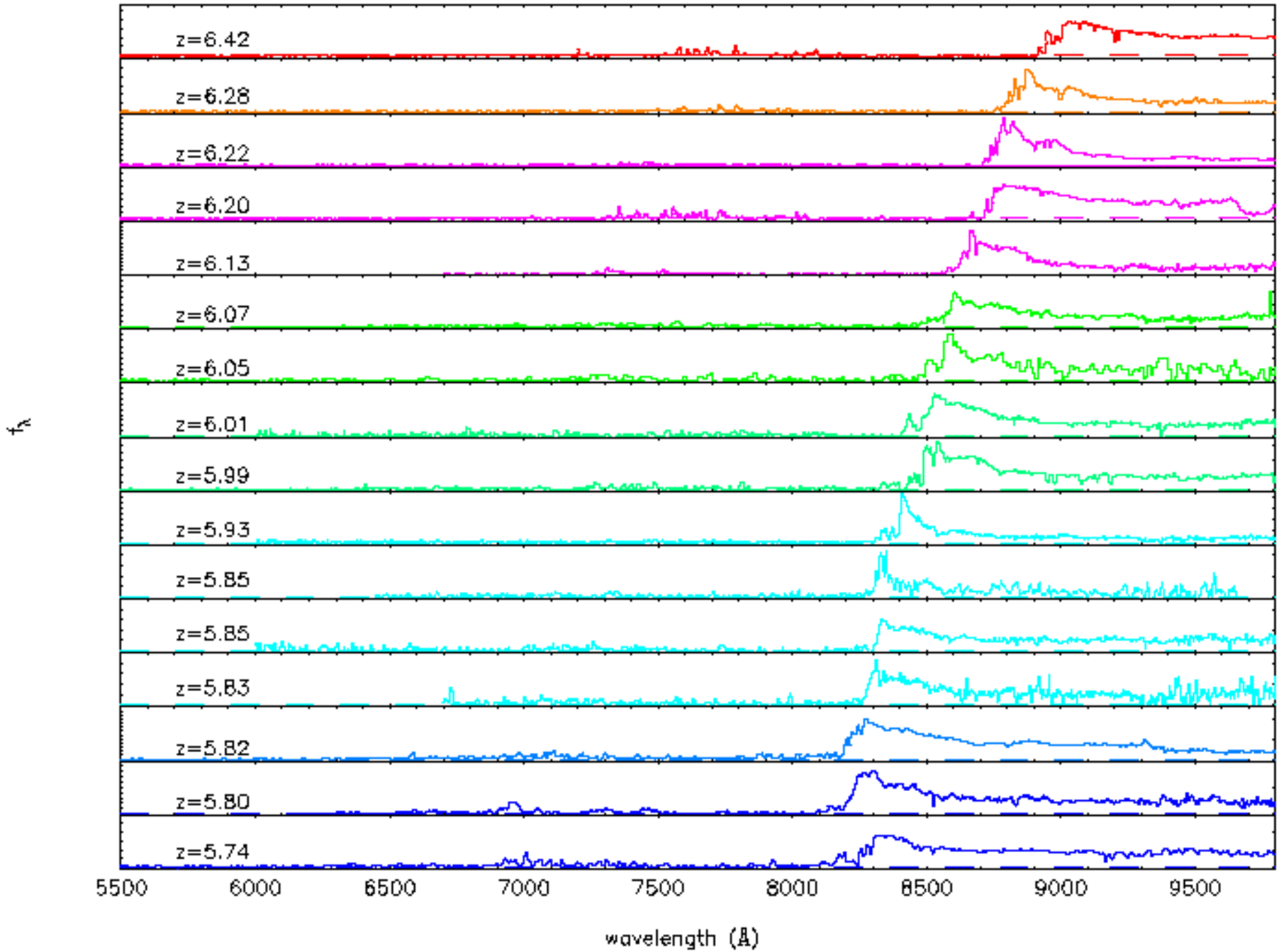


Courtesy of Arizona graduate students

The Highest Redshift Quasars Today

- z>4: >900 known
- z>5: >50
- z>6: 8
- SDSS i-dropout Survey:
  - By Spring 2004: 6000 deg^2 at z_{AB}<20
  - Sixteen luminous quasars at z>5.7
  - Five in the last season
- 30 – 50 at z~6 expected in the whole survey

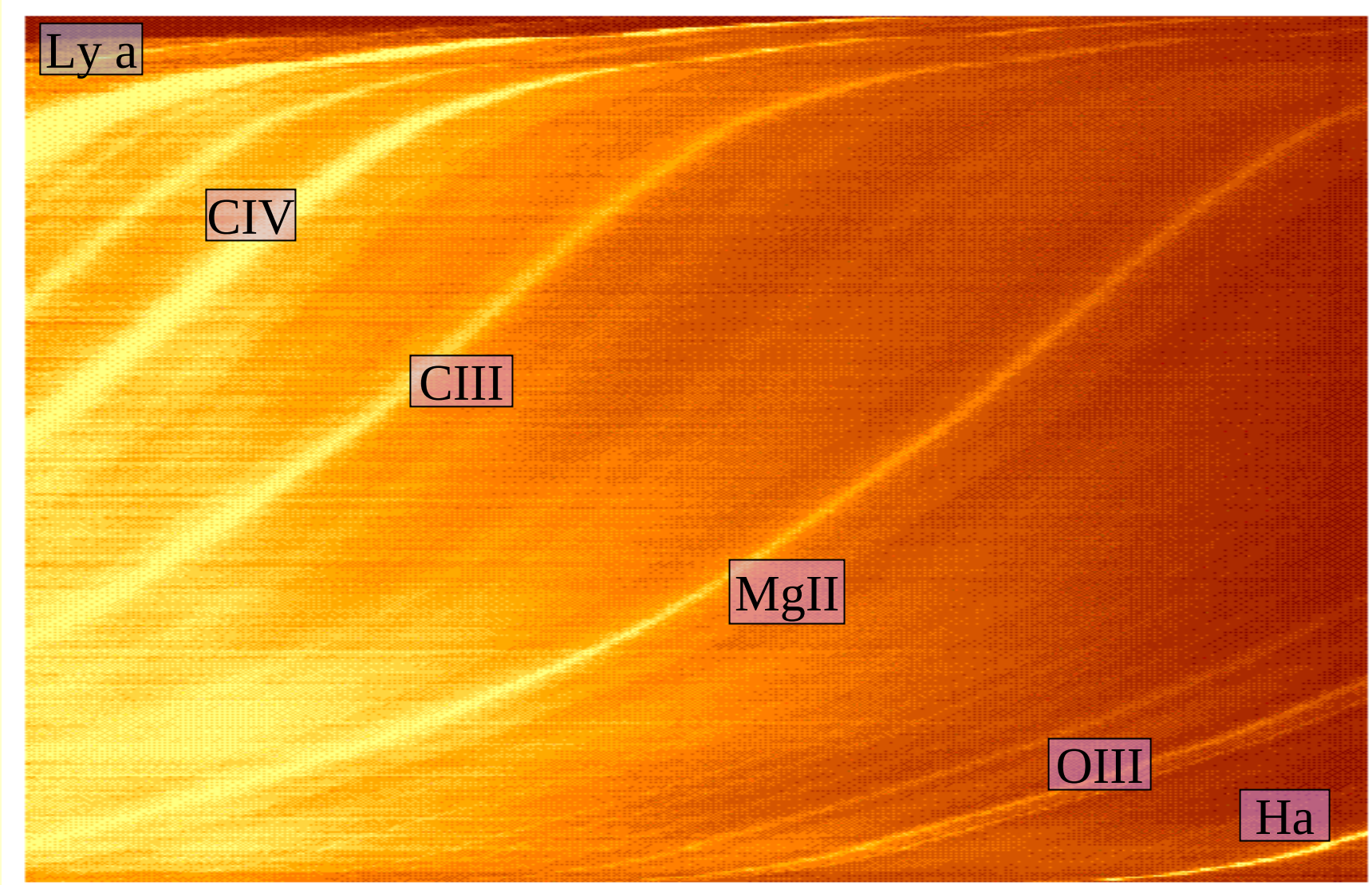



z=6.42
z=6.28
z=6.22
z=6.20
z=6.13
z=6.07
z=6.05
z=6.01
z=5.99
z=5.93
z=5.85
z=5.85
z=5.83
z=5.82
z=5.80
z=5.74
f_λ
5500
6000
6500
7000
7500
8000
8500
9000
9500
wavelength (A)

Outline

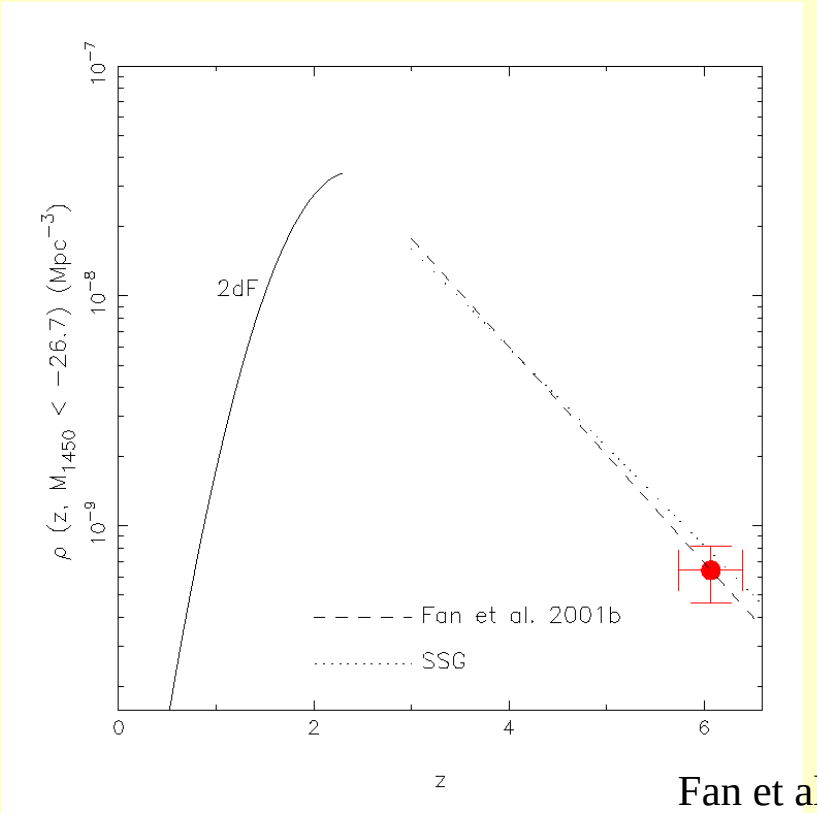
- The Earliest Quasars and Supermassive Massive Black Holes
  - Evolution of z>6 quasars
  - Chemical Enrichment in the Quasar Environment
  - Co-evolution of Supermassive BHs and host galaxies at z~6
- The End of Reionzation
  - G-P troughs in the highest redshift quasars
  - Inhomogeneous reionization
- Collaborators: Strauss, Schneider, Richards, Gunn, Becker, White, Rix, Pentericci, Walter, Carilli, Cox, Omont, Brandt, Vestergaard, Eisenstein, Cool, Jiang, plus many SDSS collaborators

17,000 Quasars from the SDSS Data Release One



Quasar Density at z~6

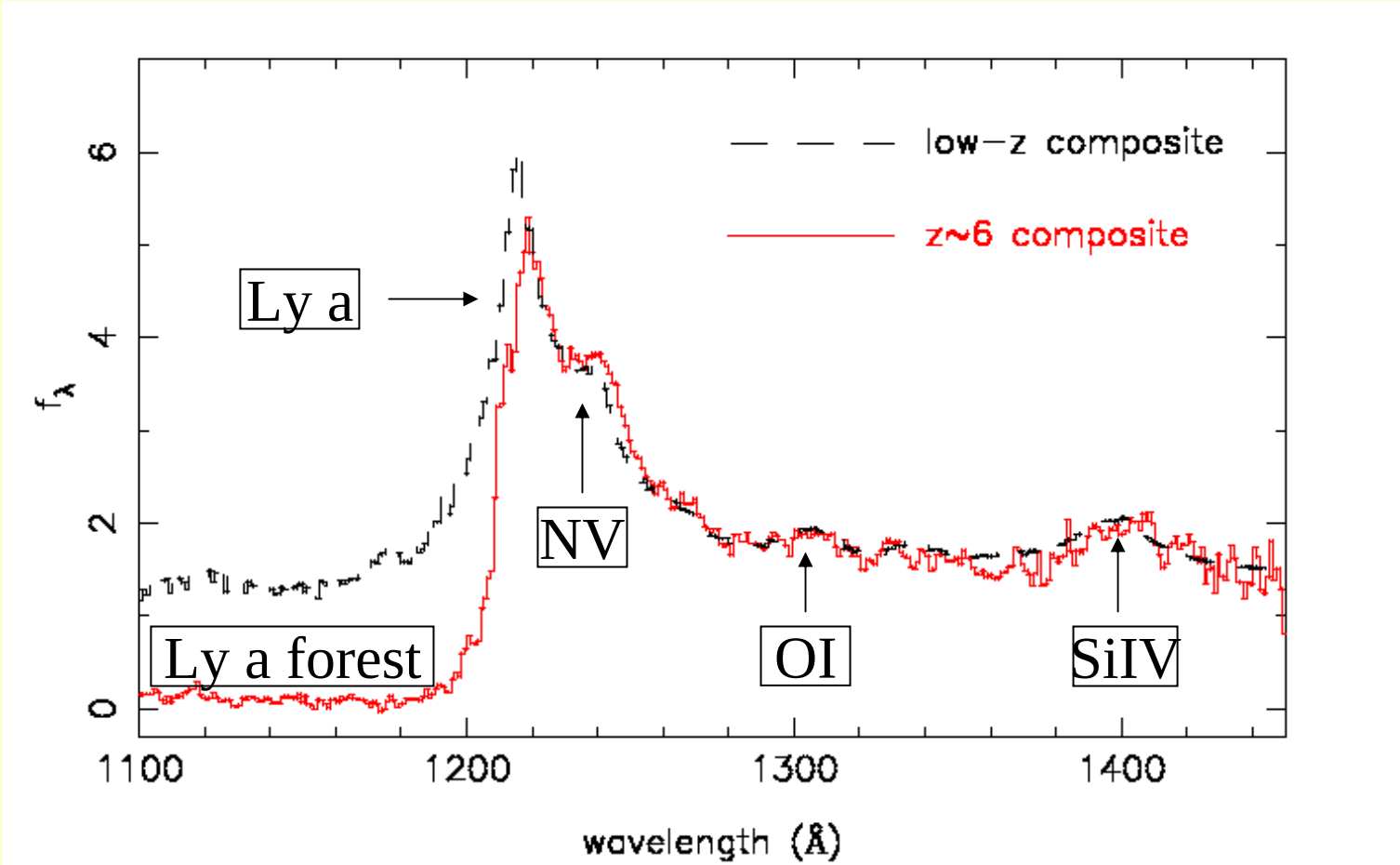
- From SDSS i-dropout survey
  - Density declines by a factor of ~40 from between z~2.5 and z~6
- Cosmological implication
  - $M_{BH} \sim 10^{9\text{-}10}\ M_{sun}$
  - $M_{halo} \sim 10^{12\text{-}13}\ M_{sun}$
  - 5-6 sigma peaks at z~6 → number density consistent with CDM prediction with reasonable duty cycle and M-sigma assumptions
  - ***not a problem for structure formation as far as DM is concerned***



Fan et al. 2004

- ***How to form assemble such massive BHs and "mature" galaxies in less than 1Gyr??***
  - ***The initial assembly of both gal and BH must start at z>>10***
  - Implication on (lack of negative?) feedback for the formation of these monsters?

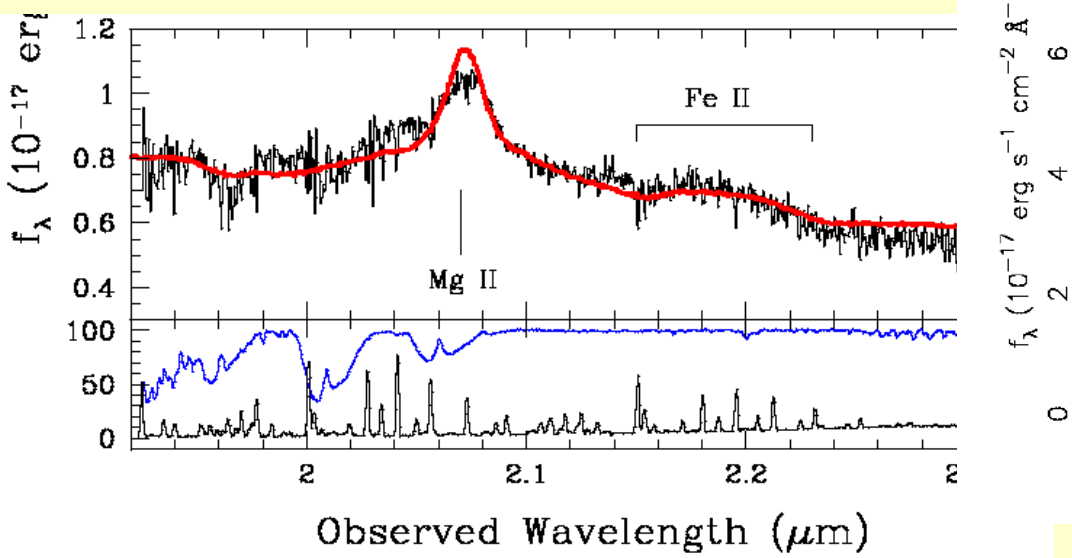
The Lack of Evolution in Quasar Intrinsic Spectral Properties



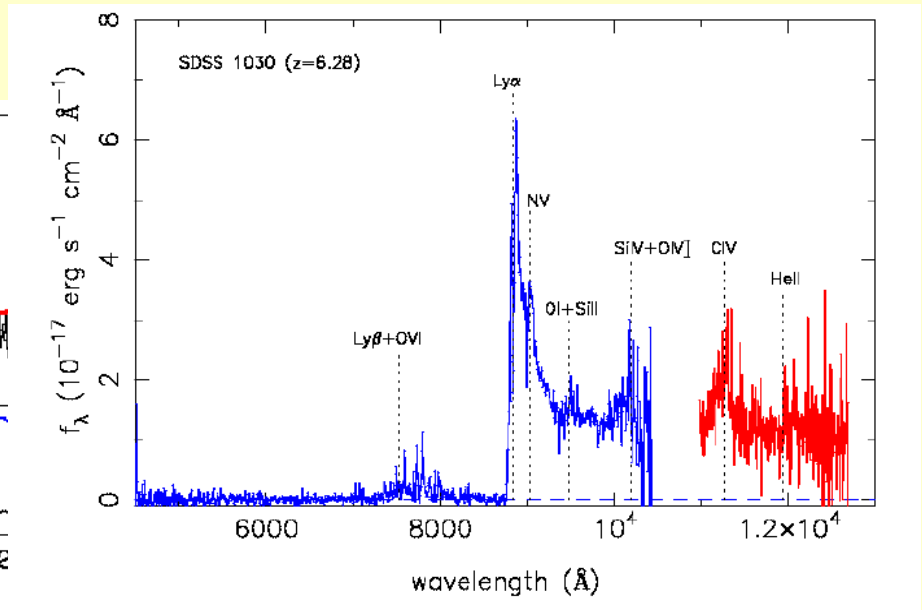
- Rapid chemical enrichment in quasar vicinity
- High-z quasars and their environments mature early on

Chemical Enrichment at z>>6?

- Strong metal emission → consistent with supersolar metallicity
- NV emission → multiple generation of star formation from enriched pops
- Fe II emission → could have Pop III contribution
- Question: what exactly can we learn from abundance analysis of these most extreme environment in the early universe?

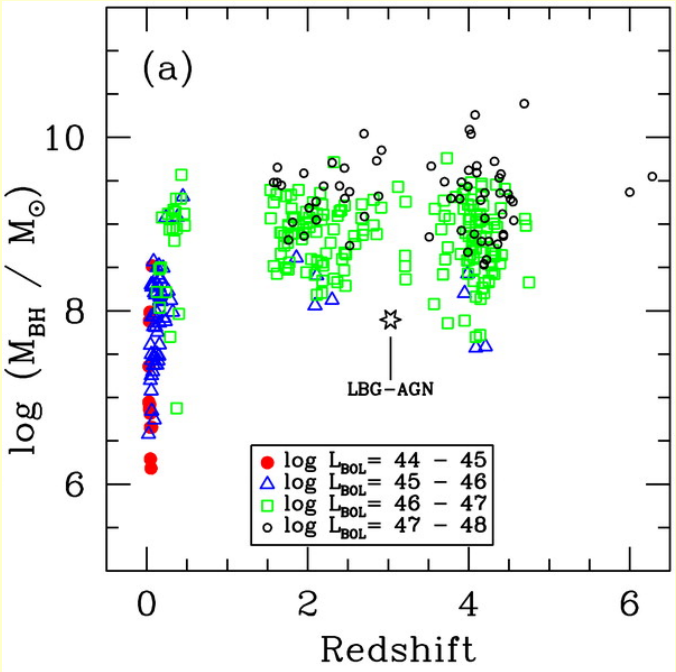


Barth et al. 2003



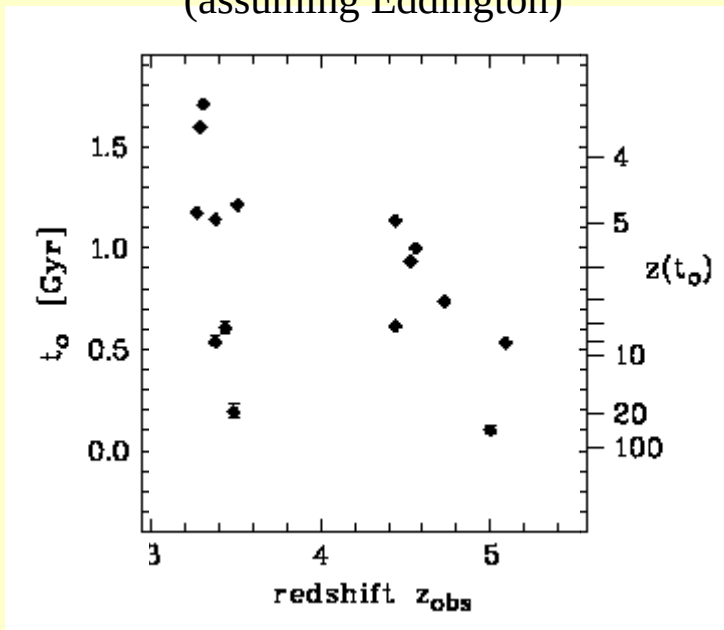
Fan et al. 2001

Early Growth of Supermassive Black Holes



Vestergaard 2004

Formation timescale
(assuming Eddington)



Dietrich and Hamann 2004

Lack of spectral evolution in high-redshift quasars → quasar BH estimate valid at high-z

- Billion solar mass BH indicates very early growth of BHs in the Universe

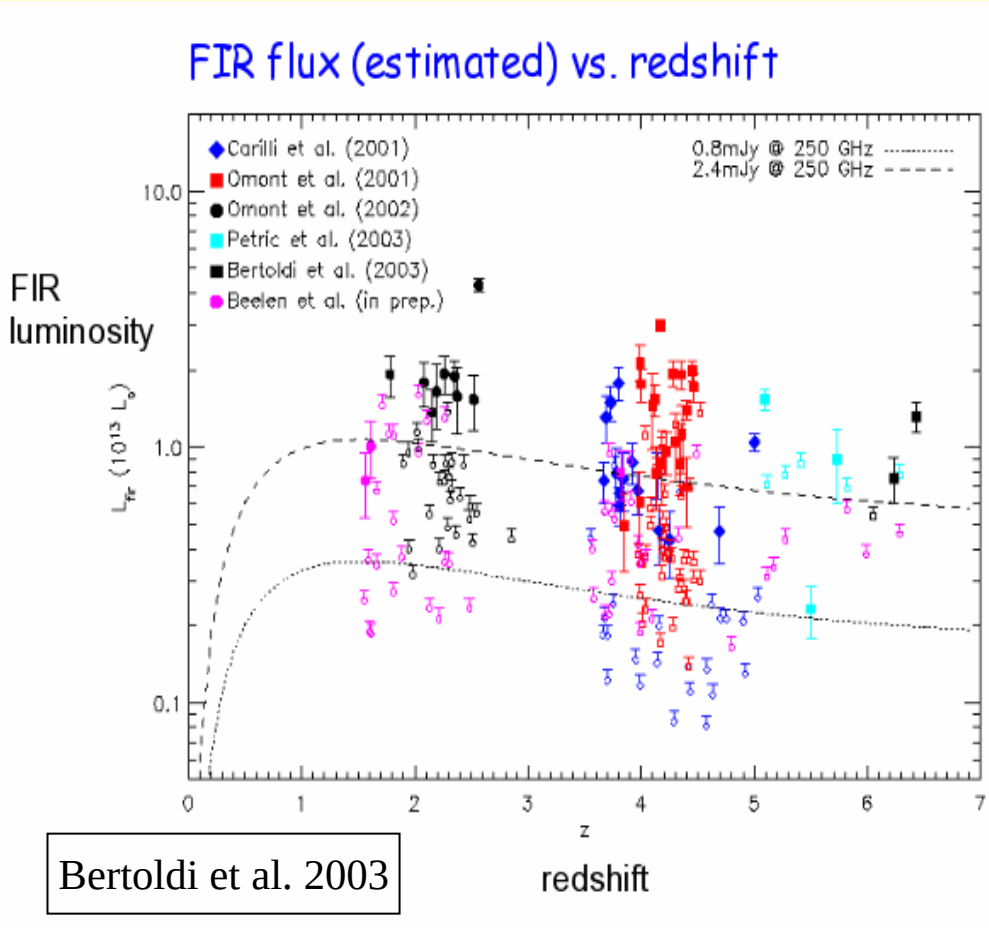
Sub-mm and Radio Observation of High-z Quasars

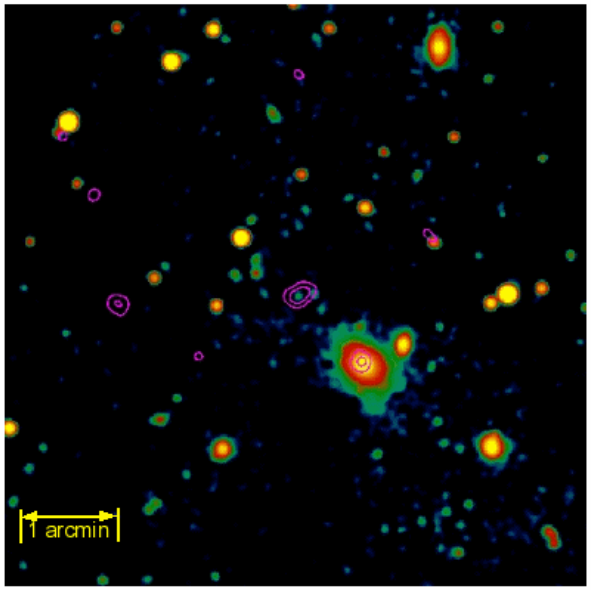
- Probing dust and star formation in the most massive high-z systems
- Using IRAM and SCUBA: ~40% of radio-quiet quasars at z>4 detected at 1mm (observed frame) at 1mJy level

  → submm radiation in radio-quiet quasars come from thermal dust with mass ~ 10^8 M_{sun}
- If dust heating came from starburst

  → star formation 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 !

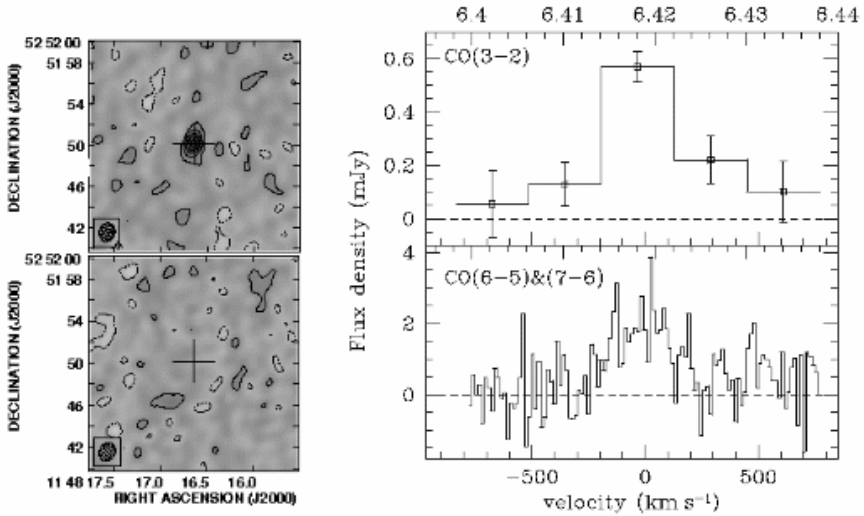
7×10^8 M_{sun} in <700 Myr

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

- Dust mass: $10^8 - 10^9 M_{sun}$
- H_2 mass: $10^{10} M_{sun}$
- Star formation 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

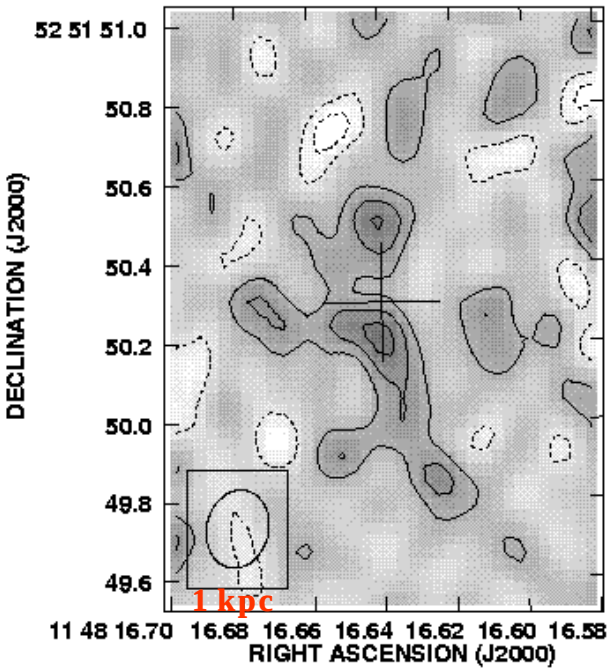
High-resolution CO Observation of z=6.42 Quasar

- Spatial Distribution
  - Radius ~ 2 kpc
  - Two peaks separated by 1.7 kpc
- Velocity Distribution
  - CO line width of 280 km/s
  - Dynamical mass within central 2 kpc: ~ 10^{10} M_sun
  - Total bulge mass ~ 10^{11} M_sun

  < M-sigma prediction

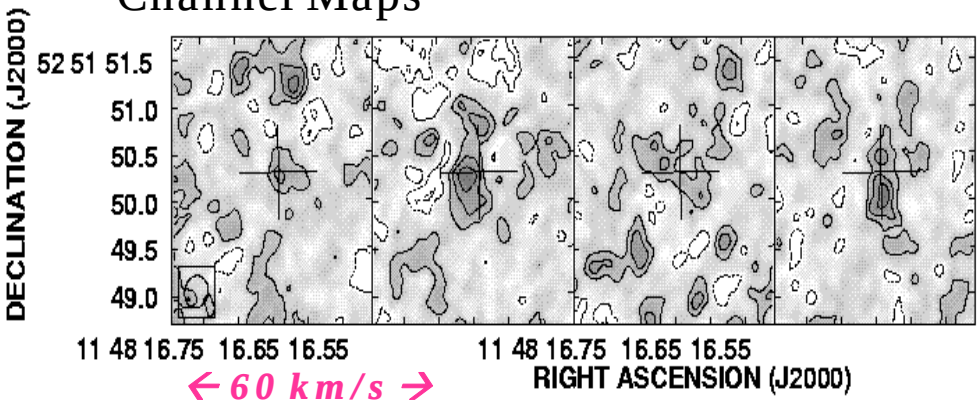
- ***BH formed before complete galaxy assembly?***

VLA CO 3—2 map



Walter et al. 2004

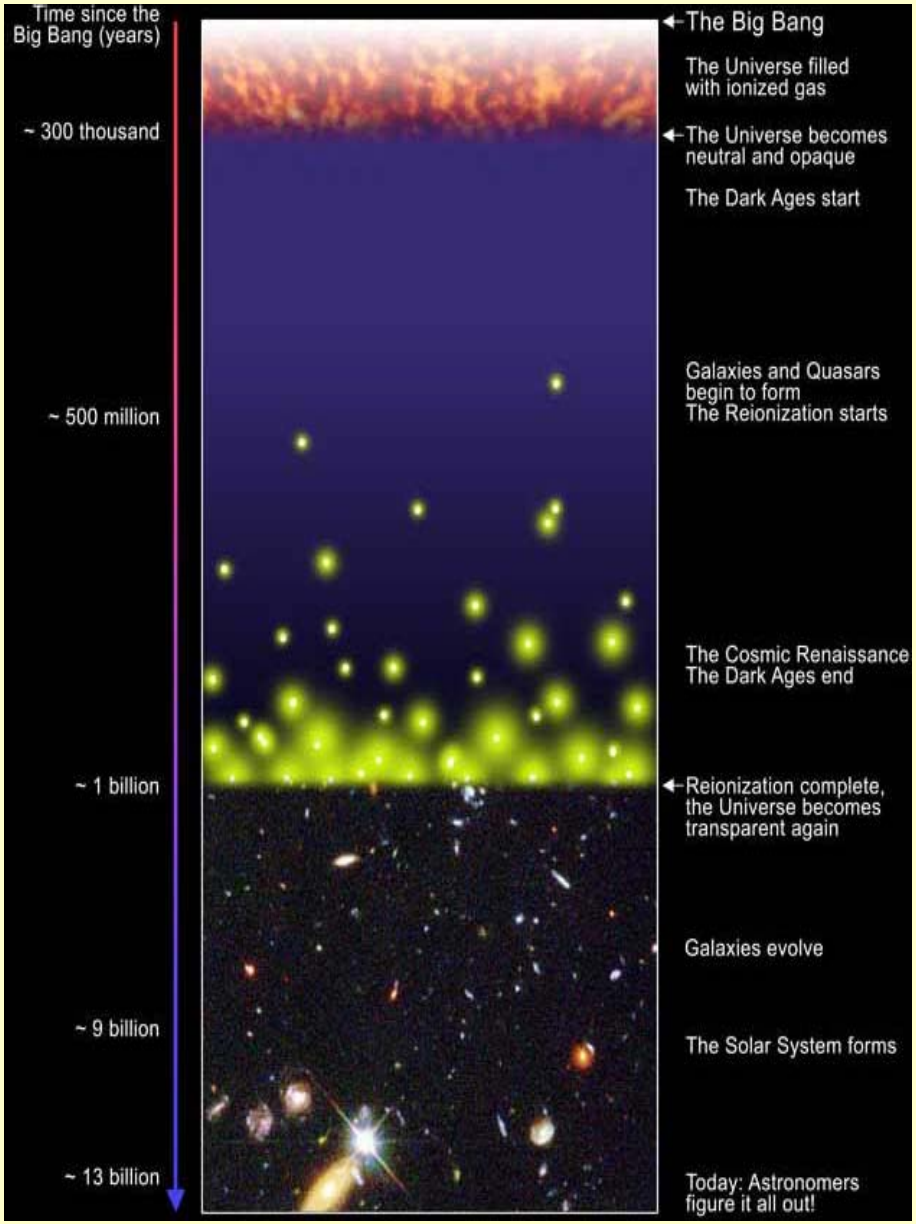
Channel Maps



Searching for Gunn-Peterson Trough

- Gunn and Peterson (1965)
  - "It is observed that the continuum of the source continues to the blue of Ly-α (in quasar 3C9, z=2.01)"
  - "only about one part of $5x10^6$ of the total mass at that time could have been in the form of intergalactic neutral hydrogen "
- Absence of G-P trough → ***the universe is still highly ionized***

A brief cosmic history



←recombination

←Cosmic Dark Ages: no light
no star, no quasar; IGM: HI

←First light: the first galaxies
and quasars in the universe

←Epoch of reionization: radiation from the first object lit up and ionize IGM : HI → HII

←HII regions overlap,
reionization completed,
the universe is transpartent and
the dark ages ended

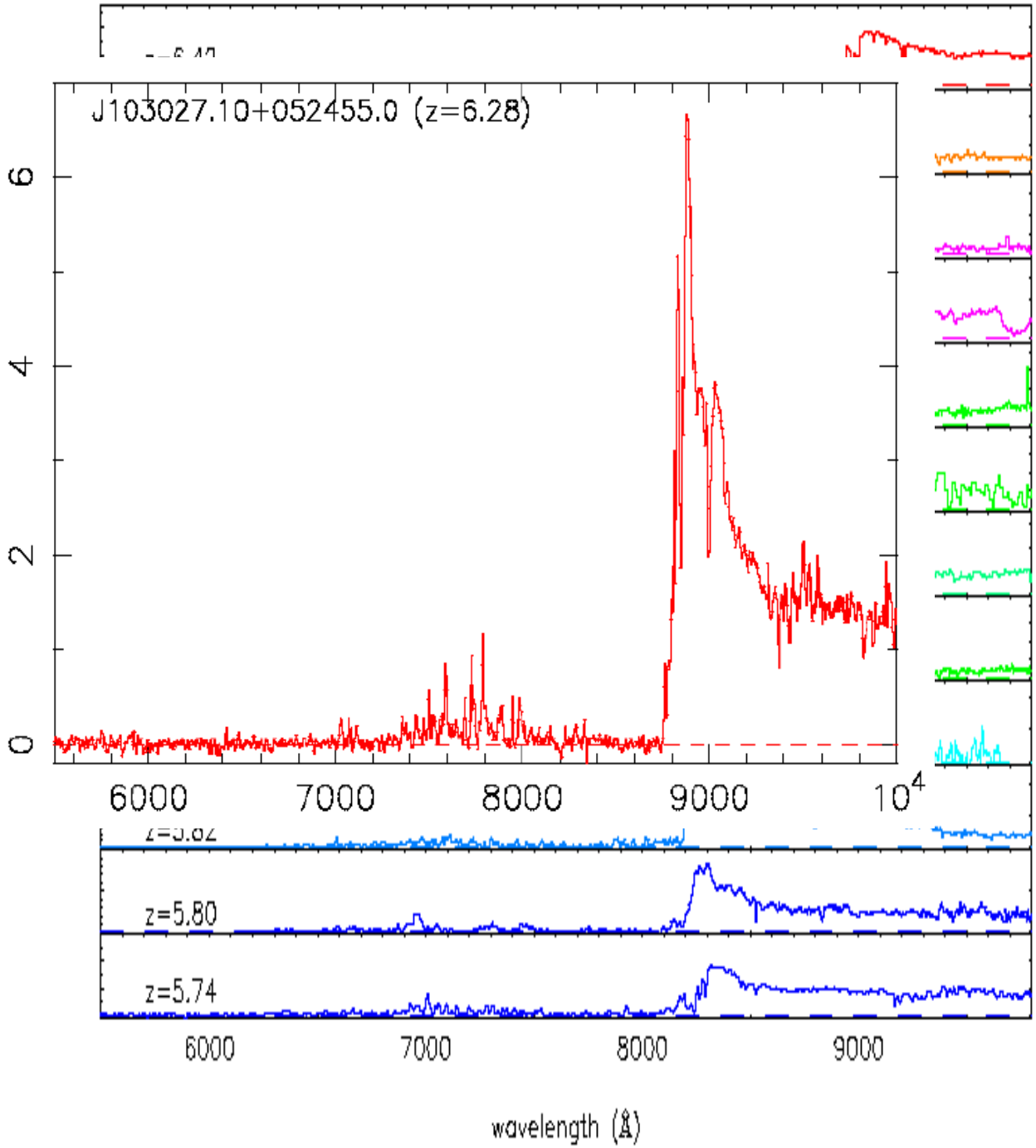
← today

Increasing Lyα absorption with redshift:

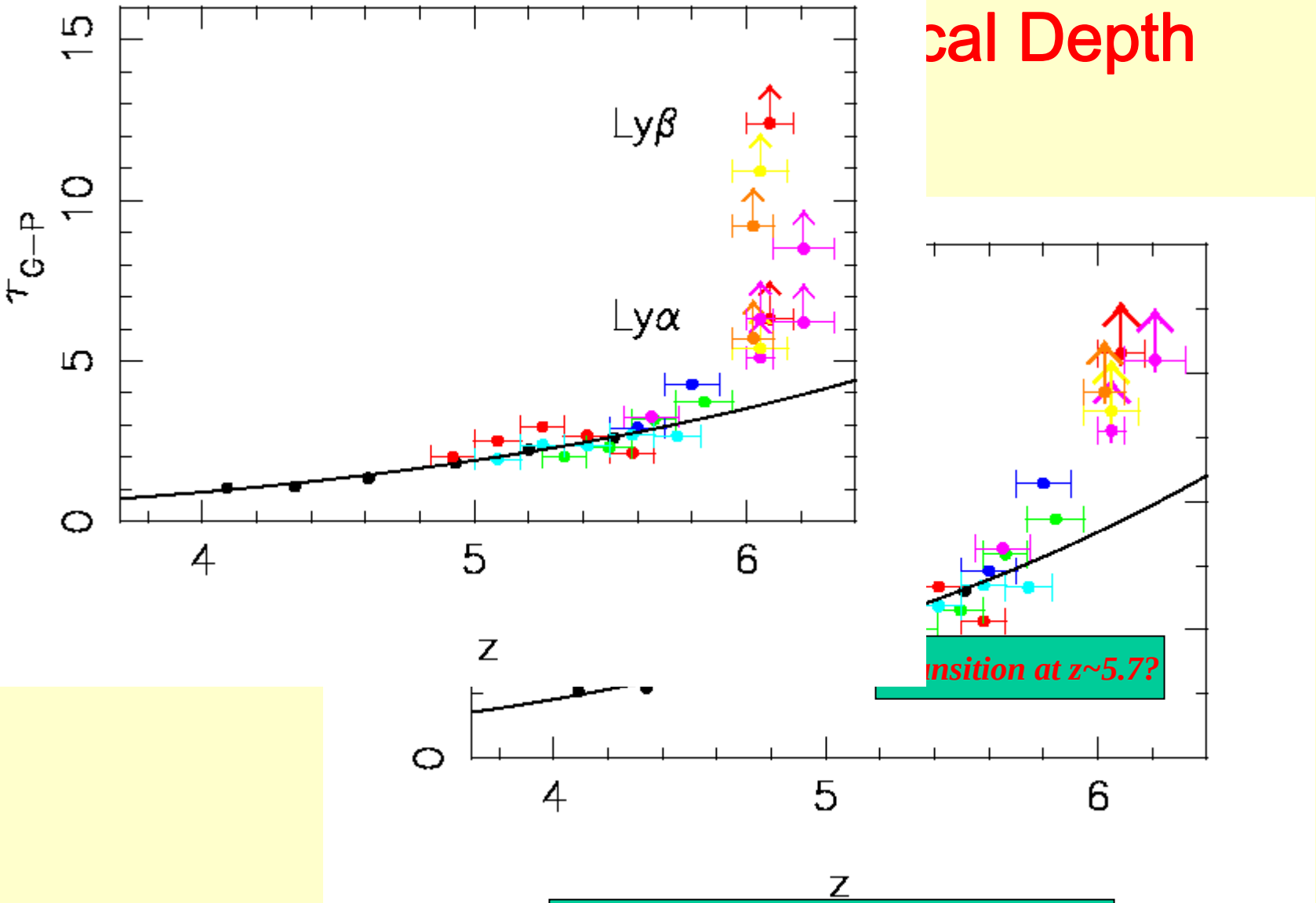
z_{abs}	f_{obs}/f_{con}
~5.5	0.10
~5.7	0.05
~6.0	<0.002

Zero flux over 300Å immediately blueward of Lyα emission in z=6.28 quasar → Detection of complete Gunn-Peterson Trough: τ>>1 over large region of IGM

Becker et al. 2001



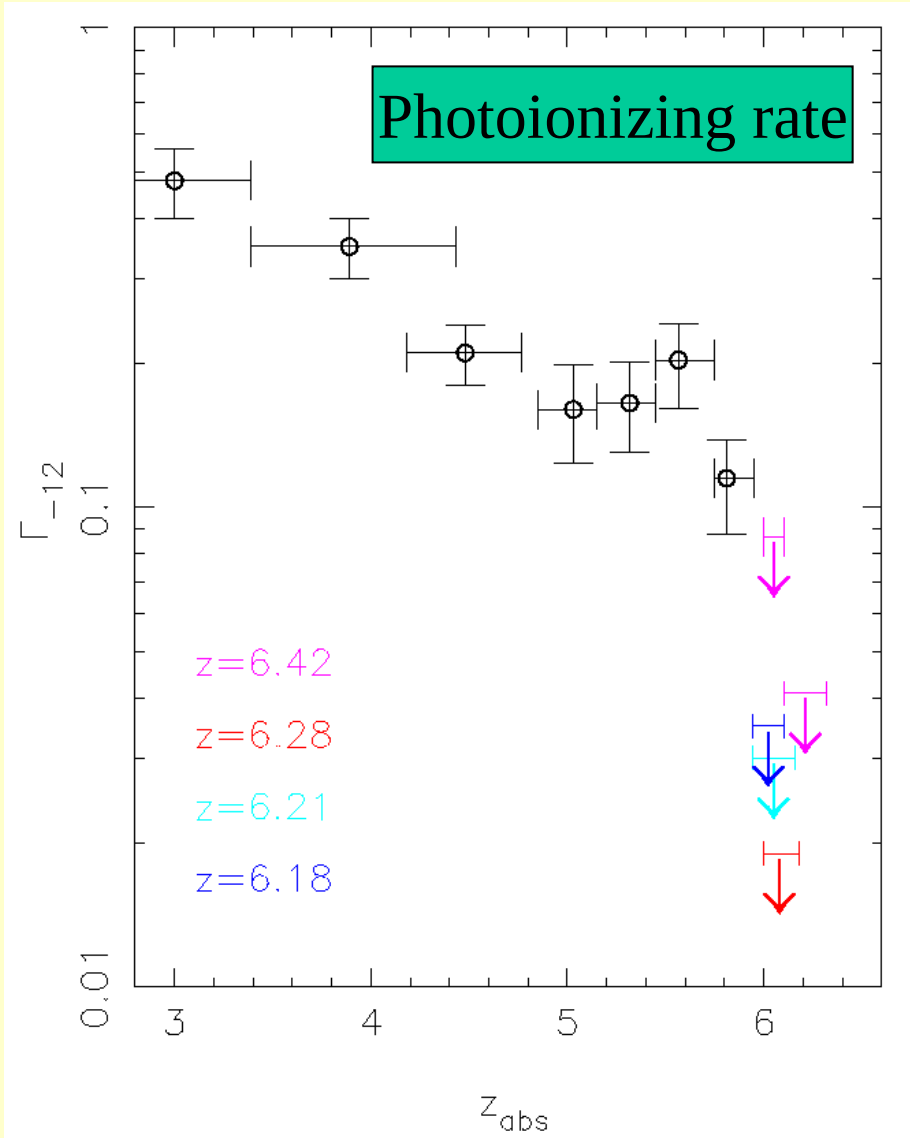
Strong Evolution of
cal Depth



Fan et al. 2004

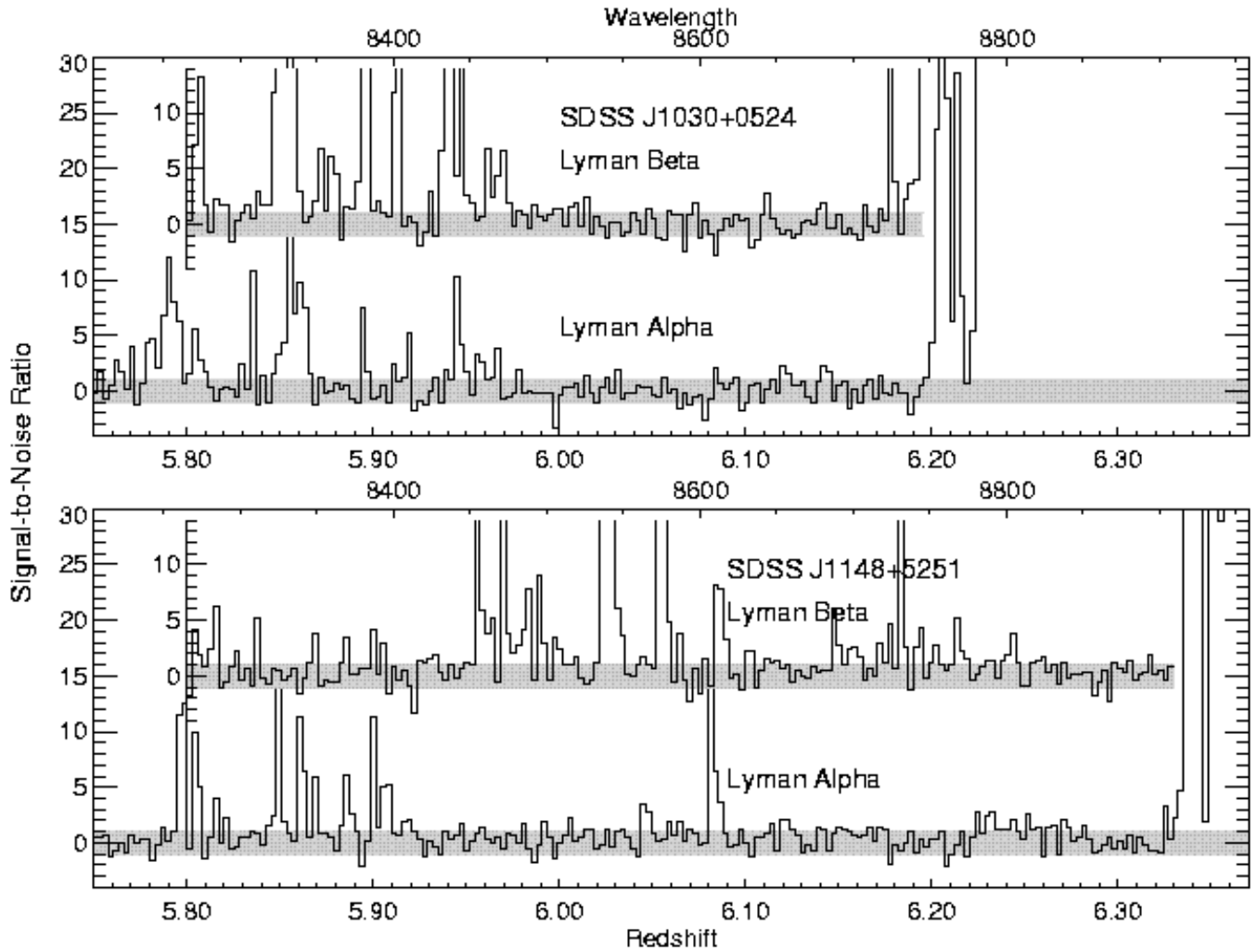
Evolution of Ionizing Background

- Ionizing background estimated by comparing with cosmological simulations of Lyman absorption in a LCDM model
  - Ionizing background declines by a factor of >25 from z~3 to z~6
  - Indication of a rapid decline at z>5.7?
  - The end of reionization – overlapping of individual HII regions – at z~6



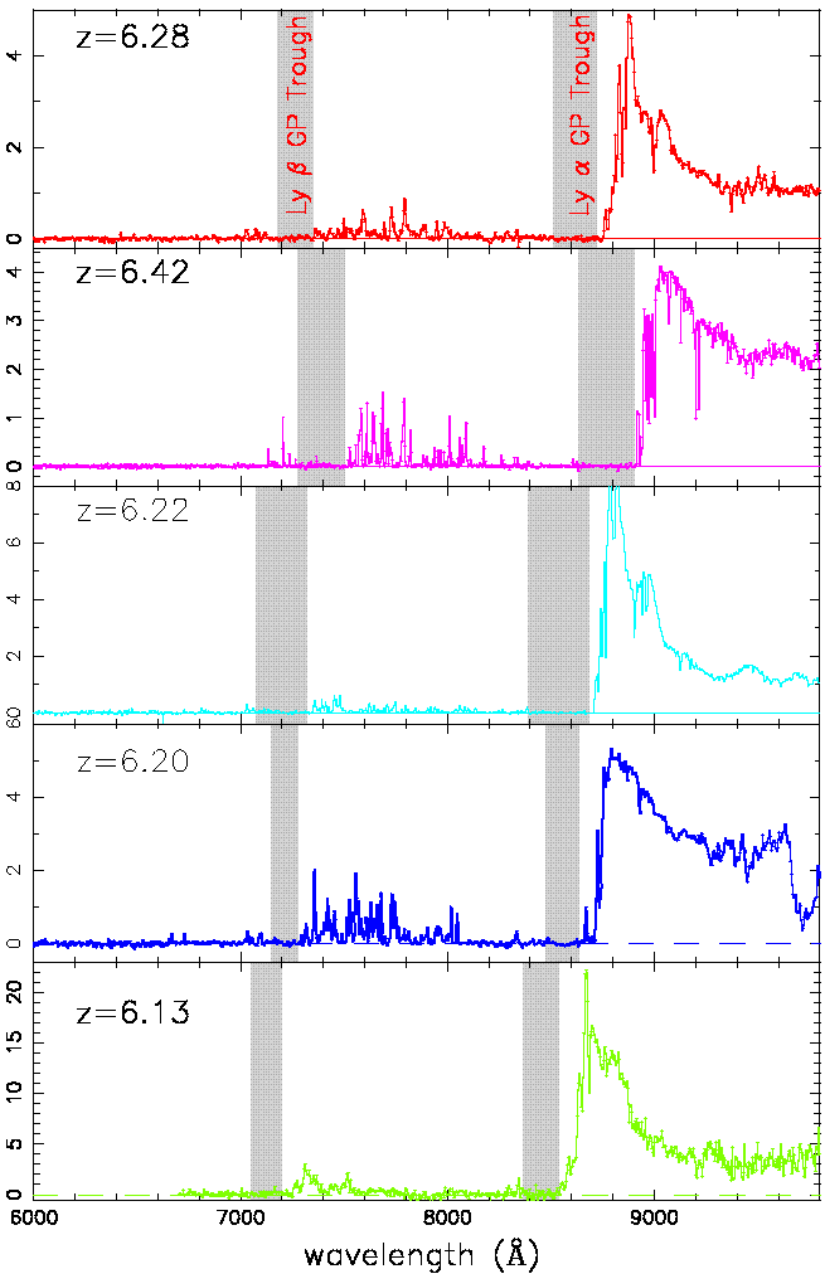
Fan et al. 2002, 2004

Line of Sight Difference…



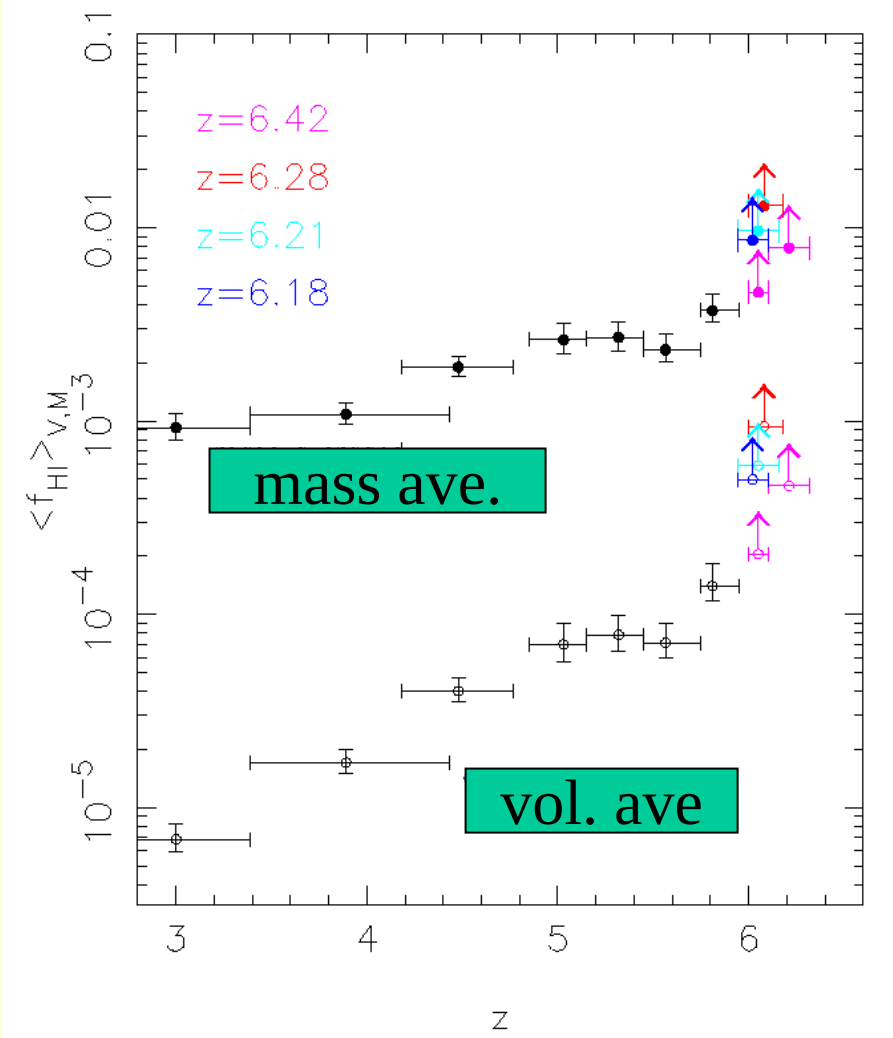
Gunn-Peterson Troughs in the Highest-redshift Quasars

- Five quasars known at z>6.1
- Strong, complete Lyα and Lyβ absorption in all five objects immediately blueward of Lyα emission…
- But LOS variation is significant
  - The "last transmitting" redshift ranges from 5.85 to 6.15
  - Patchy reionzation?
  - Non-uniform radiation field?
  - Gradual transition to neutral?



Constraining the Reionization Epoch

- Neutral hydrogen fraction
  - Volume-averaged HI fraction > 0.1% at z~6
- From G-P alone:
  - There is still a long way to go from τ>10 to τ~100,000
  - Gunn-Peterson test only sensitive to small neutral fraction and saturates at large neutral fraction
  - Was H 50% neutral at z~6.5 or z~8.5 or z~15.5? With what scatter? Need powerful test, e.g. HII region, damping wing, LAE…
  - Combined with WMAP results → a more complex reionization history?



Fan et al. in prep

Summary

- Quasar Luminosity Function
  - Strong evolution from z~3 to 6
- Quasar spectral evolution
  - Quasar environment matured very early, with rapid chemical enrichment
  - 10^{10} M_sun BH existed at z>6
- Radio and sub-mm probes of host galaxies
  - High-redshift quasars are sites of spectacular star-formation: 1000 M_sun/yr
  - First resolved z~6 host galaxy: BH growth before galaxy assembly?
- Reionization
  - Neutral fraction rises dramatically at z>5.7
  - Marking the end of reionization
  - But with considerable scatter
  - A complex reionization history?