High-Redshift Quasars in the SDSS

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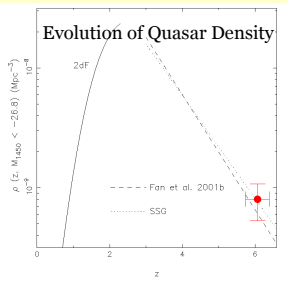
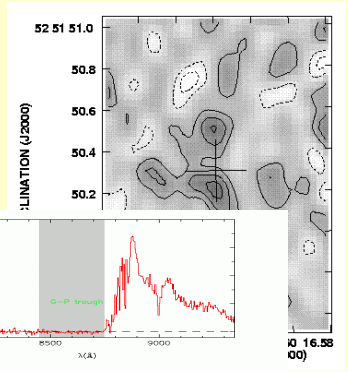
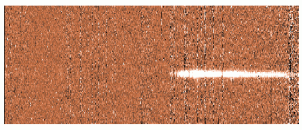
High-redshift Quasars, Black Holes Galaxy Formation and IGM Evolution

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



Resolved CO emission from z=6.42 quasar

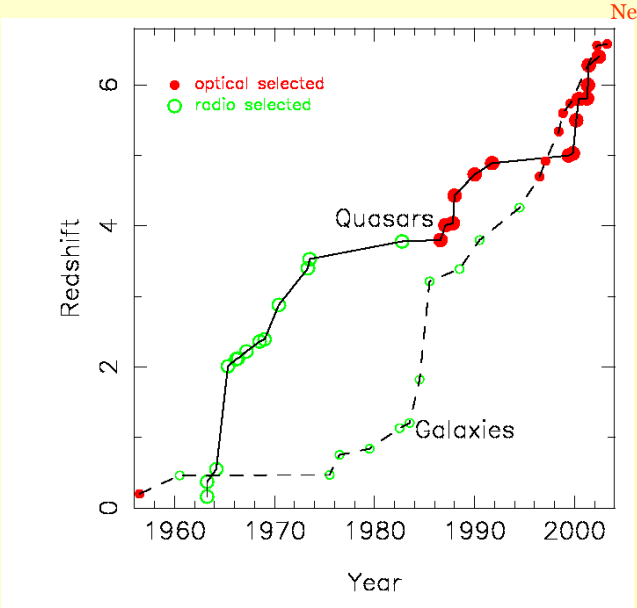




Detection of Gunn-Peterson Trough

Exploring the Edge of the Universe

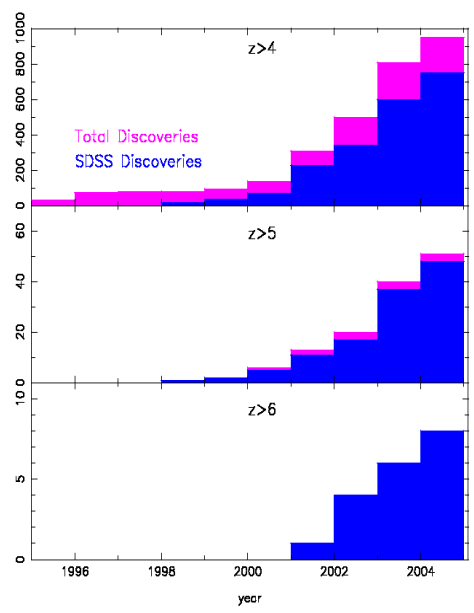
New z~7 galaxies

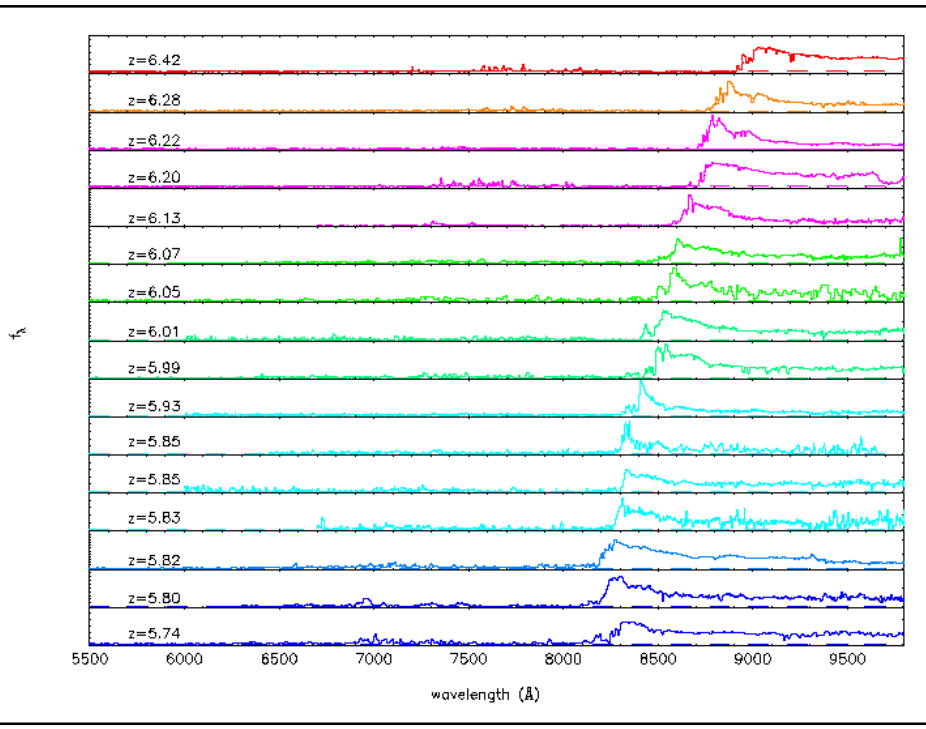


Courtesy of Arizona graduate students

The Highest Redshift Quasars Today

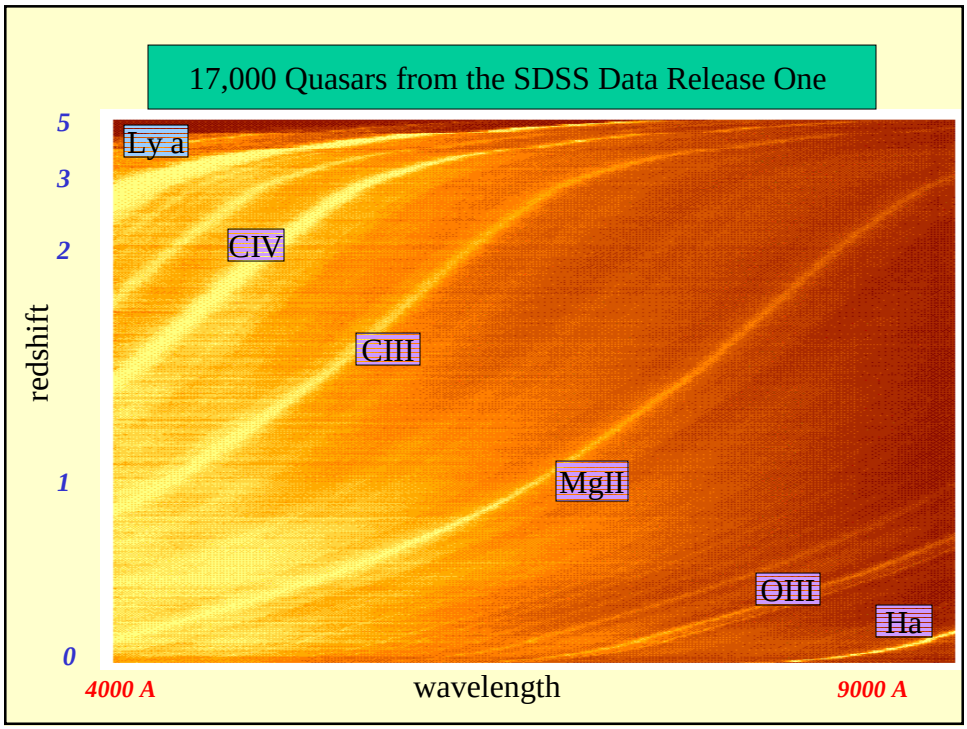
- z>4: >900 known
- z>5: >50
- z>6: 8
- SDSS i-dropout Survey:
  - By Spring 2004: 6000 deg^2 at z_{AB}<20
  - Sixteen luminous quasars at z>5.7
  - Five in the last season
- 30 – 50 at z~6 expected in the whole survey





Outline

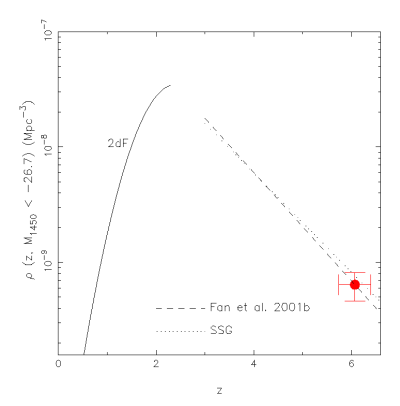
- The first quasars
  - Evolution of faint quasars
- Reionzation
  - G-P trough updates
  - Quasar's role in reionization
- Quasar Environment and Black growth
  - Metallicity and chemical Evolution
  - Is there an upper limit on the BH mass?
- Probing the growth of host galaxies
  - Dust, gas and star-formation
- Collaborators: Strauss,Schneider,Richards,Gunn, Becker,White,Rix,Pentericci,Walter,Carilli,Cox,Omont ,Brandt,Vestergaard,Eisenstein,Cool,Jiang,plus many SDSS collaborators



Quasar Density at z~6

- Based on 6000 sq. deg of SDSS i-dropout survey:
  - Density declines by a factor of ~40 from between z~2.5 and z~6
  - It traces the growth of the earliest supermassive BHs in the Universe
- Cosmological implication
  - $M_{BH} \sim 10^{9\text{-}10}\ M_{sun}$
  - $M_{halo} \sim 10^{12\text{-}13}\ M_{sun}$
  - ***How to form such massive galaxies and assemble such massive BHs in less than 1Gyr??***
    - The rarest and most biased systems at early times
    - ***The initial assembly of the system must start at z>>10***

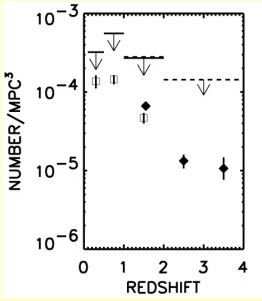
→ ***co-formation and co-evolution of the earliest SBH and galaxies***



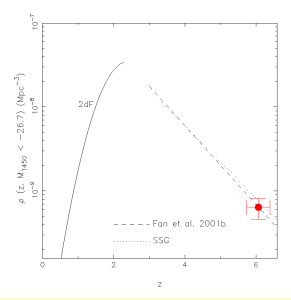
Fan et al. 2004

Evolution of LF shape

- At low-z:
  - 2dF: LF is well fit by double power law with pure luminosity evolution → downsizing of BH activities
- What about high-redshift?
  - Does the shape of quasar LF evolve?
  - Do X-ray and optically-selected samples trace the same population?
  - ***Key: how does faint quasars at high-z evolve?***



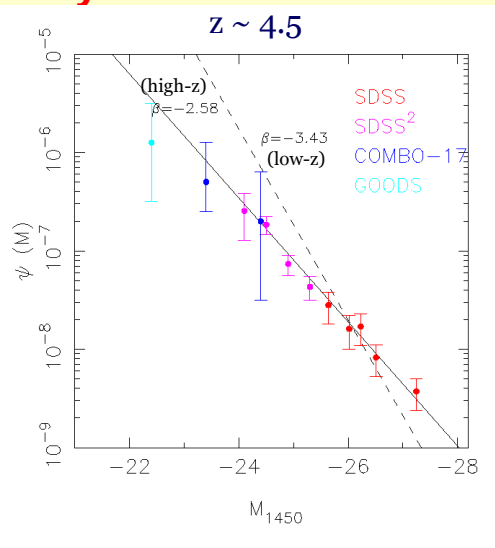
X-ray, low-luminosity



Optical, high-luminosity

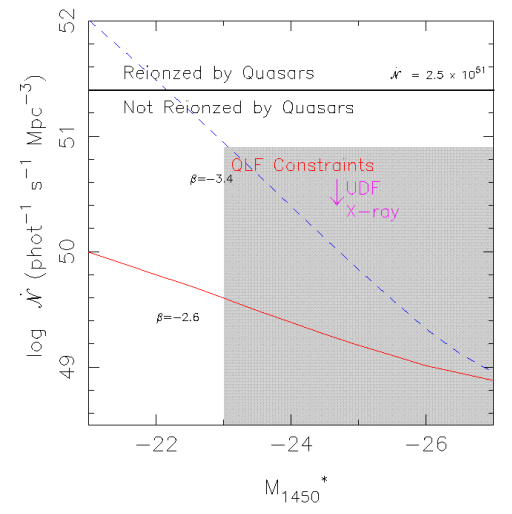
High-z QLF from SDSS Deep Stripe Survey

- High-z quasar LF different from low-z
  - High-z LF much flatter
  - Different triggering mechanism at low and high-z?
  - Constrain quasar contribution to the reionization

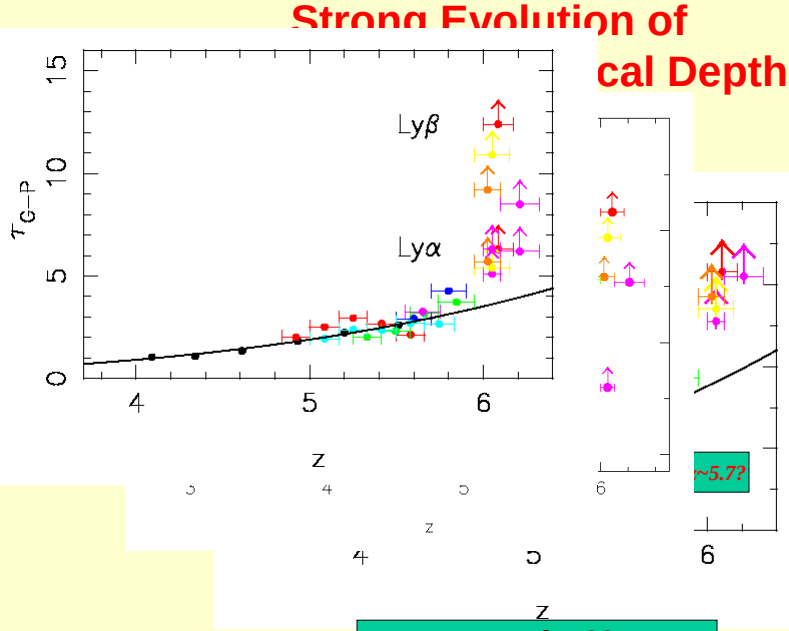


What Reionized the Universe?

- Based on SDSS quasar luminosity function:
  - ***UV photons from luminous quasars and AGNs are not the major sources that ionized the universe***
  - Consistent with limit from X-ray stacking of Lyman break galaxies in the UDF
  - Star-formation? Soft X-ray from mini-quasars?



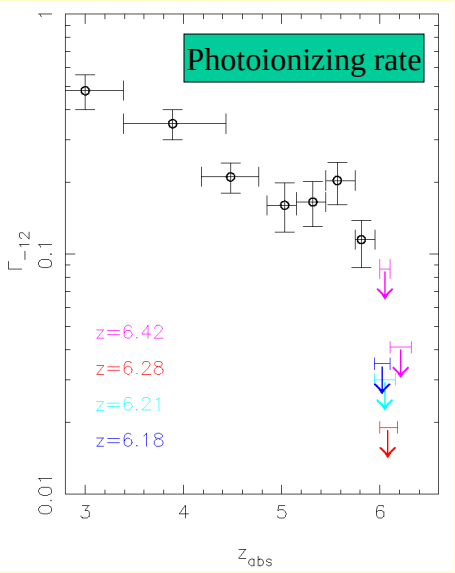
Strong Evolution of cal Depth



Fan et al. 2004

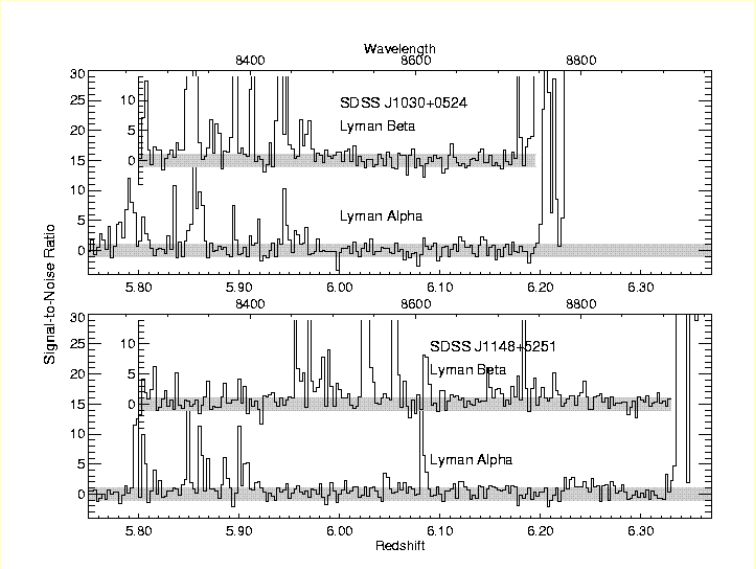
Evolution of Ionizing Background

- 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?



Fan et al. 2002, 2004

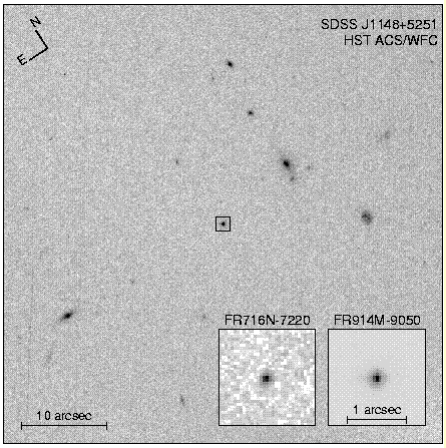
Line of Sight Difference…

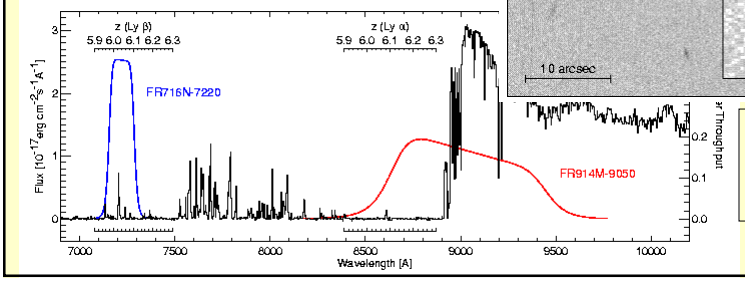


Leaky IGM at z~6

- Deep narrow band ACS imaging
  - Lyβ transmission point-like, coincides with quasar position

  → IGM transmission at z~6, not intervening galaxies, not lensed…

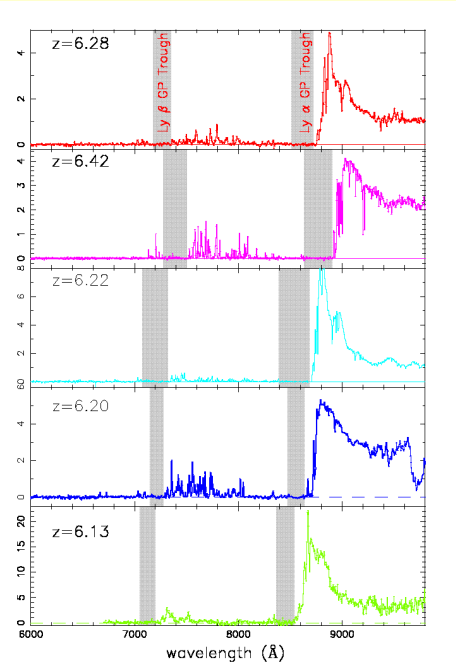




White, Beck, Fan and Strauss 2004

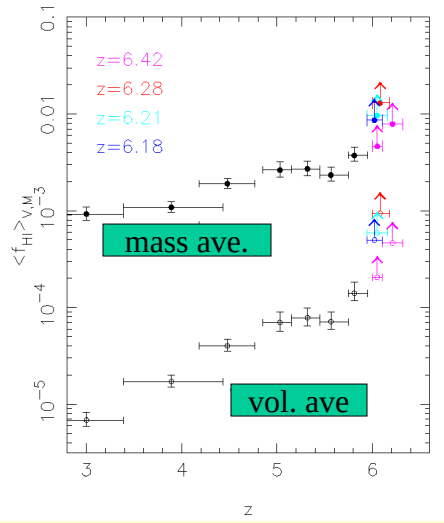
Gunn-Peterson Troughs in the Highest-redshift Quasars

- 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?

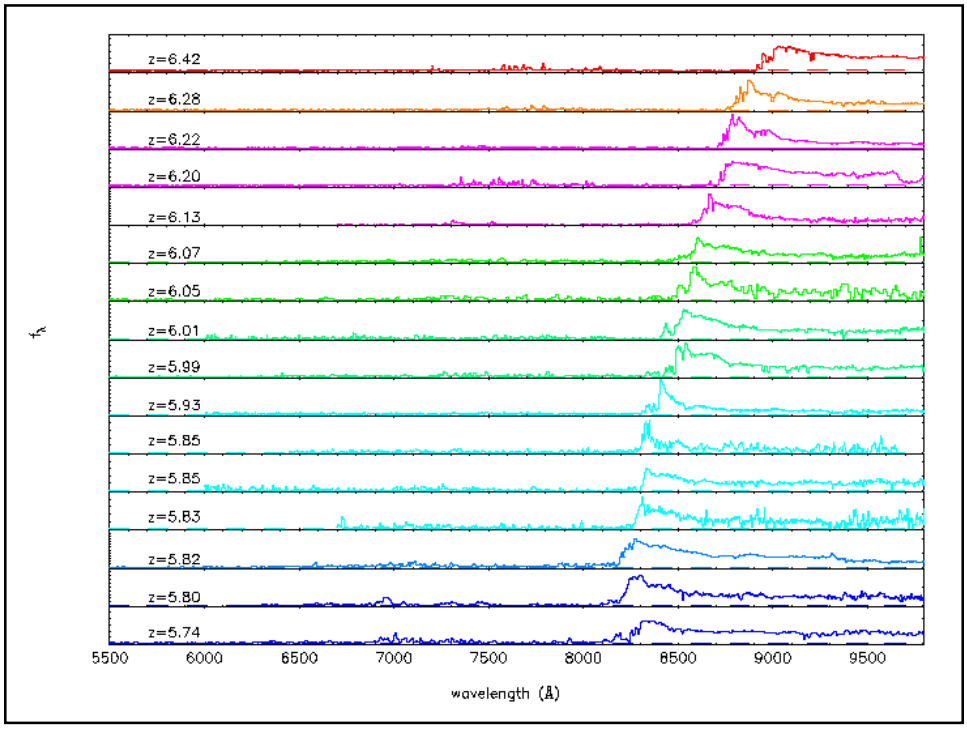


Constraining the Reionization Epoch

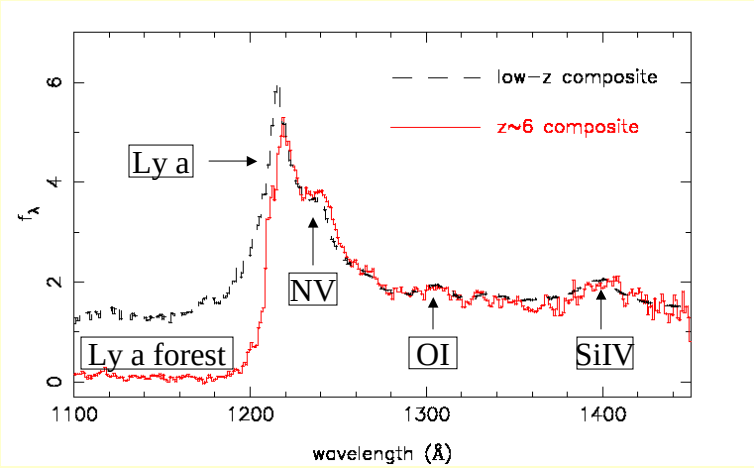
- Neutral hydrogen fraction
  - Volume-averaged HI fraction > 0.1% at z~6
- From G-P alone:
  - There is still a long way to go from τ>10 to τ~100,000
  - Gunn-Peterson test only sensitive to small neutral fraction and saturates at large neutral fraction
  - Was H 50% neutral at z~6.5 or z~8.5 or z~15.5?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



Fan et al. in prep



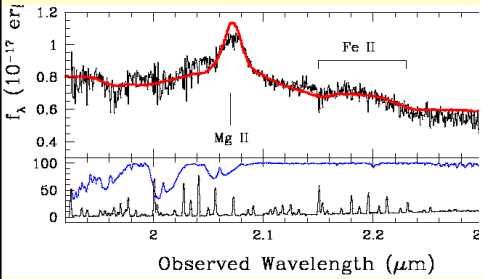
The Lack of Evolution in Quasar Intrinsic Spectral Properties



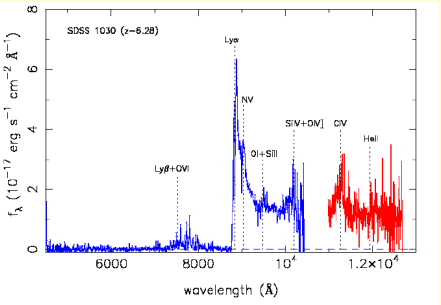
- Rapid chemical enrichment in quasar vicinity
- High-z quasars and their environments mature early on

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?



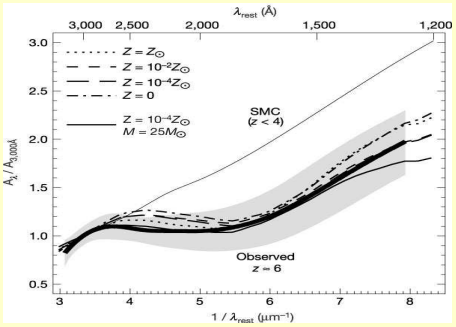
Barth et al. 2003

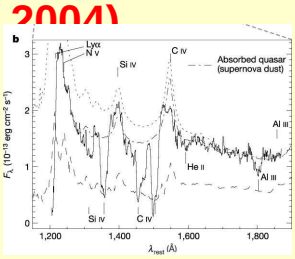


Fan et al. 2001

Supernova Dust in z~6 quasar? (Maiolino et al. 2004)

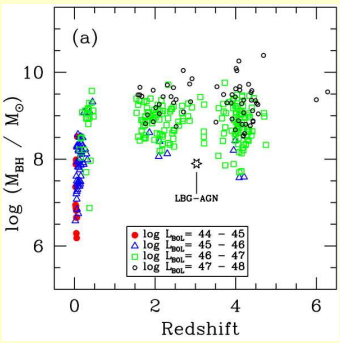
- SDSS J1148 (z=6.2)
  - Highest-z Low-BAL
  - SED suggesting unusual dust extinction





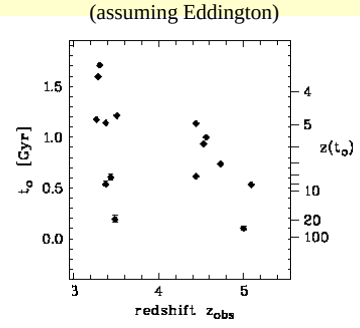
- Age of the universe < 1Gr
  - No time for AGB dust…
- Dust extinction produced by SN dust fits the data
- Implications on AGN obscuration model at high-z, submm radiations, star-formation rate estimates and extinction corrections for high-z galaxies

Early Growth of Supermassive Black Holes



Vestergaard 2004

Formation timescale (assuming Eddington)

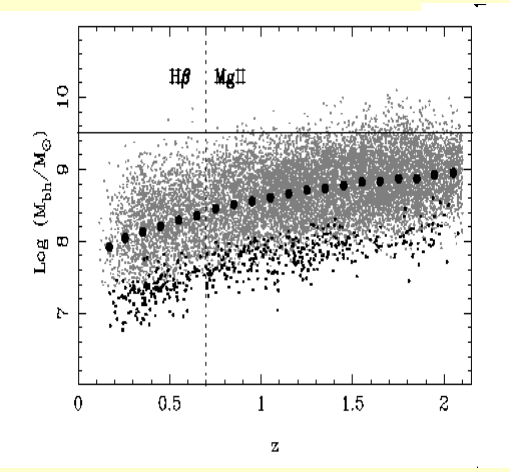


Dietrich and Hamann 2004

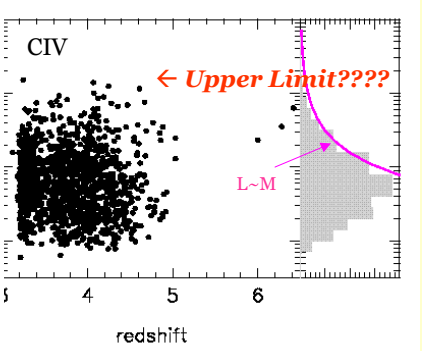
Lack of spectral evolution in high-redshift quasars → quasar BH estimate valid at high-z

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

BH mass distribution



McLure et al. SDSS DR 1



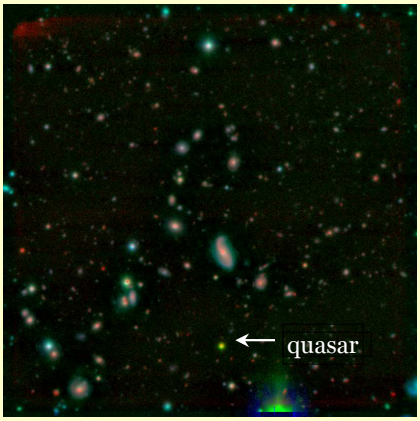
Fan et al. >1000 quasars at z>3

There might be an upper envelop of BH Mass at M_{BH} ~ few x 10^{10} M_solar

How does BH accretion history trace host galaxy assembly??

Environment of a z=6.3 quasar

- Deep VLT i-z-J imaging
- 19 i-dropout candidates
  in 38 sq. arcmin at z<25.6
- >6 times higher than in
  GOODS etc.
- No host galaxy detected
  → J>22, below the M_BH
  vs. M_Bulge relation
  assuming young stellar age…

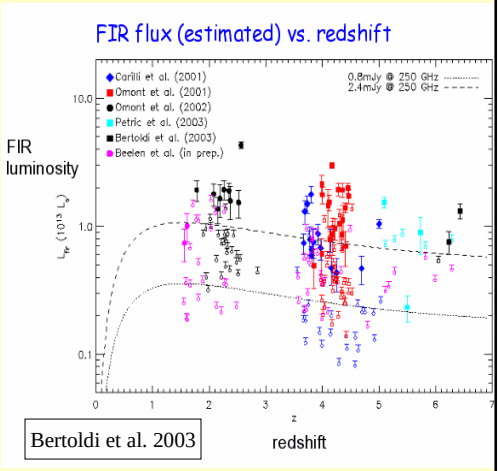


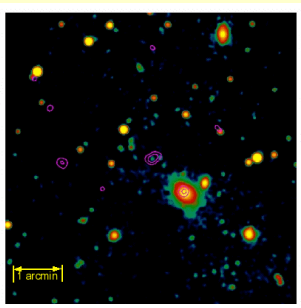
izJ composite (z_lim =26)

Pentericci et al.

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***





SDSS J1148
MAMBO 1.2 mm (contour)
S/N on SLOAN z' image.

Dust at z=6.42 !

7×10^9 M_{sun} in <700 Myr

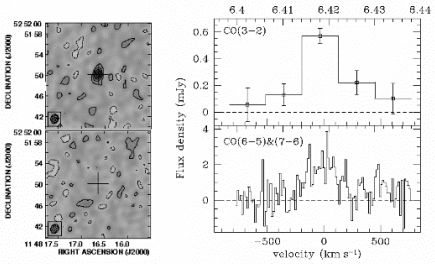
Bertoldi et al. 2003

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

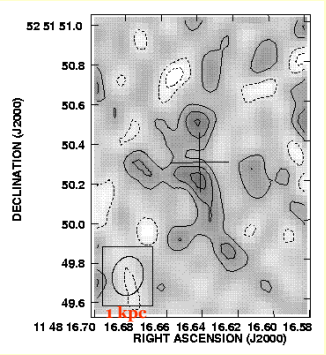
High-resolution CO Observation of z=6.42 Quasar

- 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

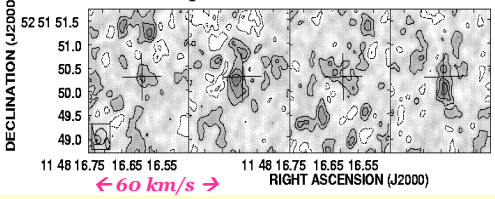
- ***BH formed before complete galaxy assembly?***

VLA CO 3—2 map



Walter et al. 2004

Channel Maps



Summary

- Quasar Luminosity Function
  - Strong evolution from z~3 to 6
  - Relatively flat LF at high-redshift
- Reionization
  - Neutral fraction rises dramatically at z>5.7
  - But with considerable scatter
  - UV photons from quasars not important to reionization
- Lack of quasar spectral evolution
  - Quasar environment matured very early, with rapid chemical enrichment
  - Black hole mass estimates at high-z reliable
  - 10^{10} M_sun BH existed at z>6
  - But is there a real upper limit?
- 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?