The Highest Redshift Quasars:
Early Black Hole Evolution and the End of
Reionization

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Background: 46,420 Quasars from the SDSS Data Release Three
Quest to the Highest Redshift Quasars

- SDSS
- Radio
- APM CCD
- IR survey (UKIDSS, VISTA, LBT)
The Highest Redshift Quasars Today

- $z>4$: >1000 known
- $z>6$: 20
- **SDSS i-dropout Survey:**
  - Completed in June 2006:
    - $7700$ deg$^2$, $z_{AB} < 20$
    - 30 luminous quasars at $5.71 < z < 6.42$
- **CFHT High-$z$ Quasar Survey (CFHTQS, Willott et al.):**
  - 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$^2$, $z_{AB} < 22.5$
  - eight $z\sim6$ quasar at $20 < z_{AB} < 21.5$
  - Goal: quasar LF

- Other on-going $z\sim6$ 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, VISTA,** allows detection up to $z\sim8-9$. 
Outline

• Quasar Evolution and BH Formation at High-Redshift
  – Quasar luminosity function and BH mass
    • Evolution in accretion properties?
  – Quasar SEDs at high-redshift
    • First signs of cosmic evolution?
  – Star-formation and dust in quasar host galaxies
    • Evolution of M-sigma relation?

• Gunn-Peterson Effect and Reionization with High-Redshift Quasars
  – G-P effect premier
  – G-P Observations
  – Measuring IGM neutral fractions
  – Probing the neutral era
What have changed in quasar properties since z~6?

- Luminous, “normal” looking quasars existed at z>6, half Gyr after the first star-formation
  - Timescale for formation of the first billion-$M_{\text{sun}}$ BH?
  - Timescale for the establishment of AGN structure: do quasar spectra at z~6 really look the same as at z~0?
  - Timescale for the establishment of M-sigma relation?
46,420 Quasars from the SDSS Data Release Three

- Lyα
- CIV
- CIII
- MgII
- FeII
- OIII
- Hα

Wavelength: 4000 Å to 9000 Å

Redshift: 0 to 5

Lyα forest
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
  - $M_{BH} \sim 10^{9-10} \ M_{\odot}$
  - $M_{halo} \sim 10^{12-13} \ M_{\odot}$
  - rare, 5-6 sigma peaks at z~6 (density of 1 per Gpc$^3$)
- Assembly of dark matter halos?
- Assembly of supermassive BHs?

Fan et al. 2006
Simulating z~6 Quasars

- The largest halo in Millennium simulation (500 Mpc cube) at z=6.2
  - Virial mass $5 \times 10^{12} \, M_{\text{sun}}$
  - Stellar mass $5 \times 10^{10} \, M_{\text{sun}}$
  - Resembles properties of SDSS quasars
  - Such massive halos existed at z~6, but..

Springel et al. 2005
Formation of z~6 quasars from hierarchical mergers

Li et al. 2007
Virial Mass Estimates

\[ M_{BH} = \frac{v^2 R_{BLR}}{G} \]

- **Low-redshift:**
  - Reverberation Mapping: \( R_{BLR} = c \tau , v_{BLR} \)
- **Radius – Luminosity Relation:** \( R \sim L^\beta \)
- **High-redshift: Scaling Relationships:**
  \[ M_{BH} \propto \text{FWHM}^2 L \beta \]
  - **But what is \( \beta \)?**
    - Photoionization predicts: \( R \sim L^{1/2} \)
Masses of Distant Quasars

- $M_{\text{BH}} \approx 10^9 M_\odot$ at $z \sim 6$
- Standard theory of BH growth:
  - Stellar BH seed of $<100 M_{\odot}$
  - Eddington limited accretion
- Early BH growth:
  - alternative accretion modes?
  - super-Eddington,
  - intermediate mass BH seed?

(Vestergaard et al. in prep)
Constraining Early BH Growth

- **Timescale**
  - At $z\sim6$, the Universe is about $20 \, t_{\text{edd}}$ old (radiative efficiency of 0.1).
  - Enough time to grow $10^9 \, M_\text{sun}$ BH?

- **Semi-analytic model of early BH growth (Volonteri & Rees 2006)**
  - Traces halo merger and BH accretion/merger history
  - Negative feedbacks slowing down BH growth:
    - Rocket effect from BH mergers (BH kicked out from shallow potential wells)
    - Spin up of BHs
      - Increased radiative efficiency and Eddington timescale
  - Extremely difficult for standard thin-disk, Eddington-limited growth from stellar seed BHs… but still allowed

- **Predictions on BH properties**
  - Only BHs with ideal growth conditions (negative feedback not important) can grow to billion $M_\text{sun}$ at $z\sim6$
  - *Low BH fraction in halos at the high luminosity (mass) end*
    - *Steep quasar luminosity function?*
Quasar Luminosity Function at $z \sim 6$

- Based on:
  - SDSS Wide: 7700 deg$^2$, 17 quasars, $z_{\text{AB}} < 20$
  - SDSS Deep: ~150 deg$^2$, 6 quasars, $20 < z_{\text{AB}} < 21$
  - AGES: 1 quasar in 5 deg$^2$ at $z_{\text{AB}} < 21.5$

- Steepening of LF:
  - $\Phi \propto L^{-3.1}$
  - Comparing to $\Phi \propto L^{-2.4}$ at $z \sim 4$

- At $z \sim 7-8$, quasar growth will severely limited by timescale: intermediate mass seeds and/or super-Eddington accretions may be needed.

Jiang, XF et al. in prep
Outline

• Quasar luminosity function and BH mass
  – Evolution in accretion properties?

• Quasar SEDs at high-redshift
  – First signs of cosmic evolution?

• Star-formation and dust in quasar host galaxies
  – Evolution of M-sigma relation?

• Summary
Structure of a Quasar
Quasar spectral energy distribution

SED of z=6 Quasar (non-evolution)

- BLR
- hot dust
- dust torus
- cool dust in host galaxy

observed wavelength (μm)
The Lack of Evolution in Quasar Emission Line Properties

- Rapid chemical enrichment in quasar vicinity
- Quasar env has supersolar metallicity: no metallicity evolution
- *Does this lack of evolution in rest-frame UV also apply to other wavelength?*

Fan et al. 2004
High Metallicity at high-z

- Strong metal emission $\rightarrow$ consistent with supersolar metallicity
- NV emission $\rightarrow$ multiple generation of star formation from enriched pops
- Fe II emission $\rightarrow$ type II SNe… some could be Pop III?

Barth et al. 2003

Nagao et al. 2006
Quasar Metallicity at z~6

near-IR spectroscopy: Gemini + Keck

Jiang, XF et al. 2007
Quasar spectral energy distribution

![Diagram showing the spectral energy distribution of a z=6 Quasar. Key features include the black hole vicinity (BLR), disk, hot dust, and cool dust in the host galaxy. The diagram is labeled with observational techniques like Chandra/XMM and ground-based observations (RAC, VIPS). The spectral range is marked from 10^-3 to 1000 microns.]
Evolution of Quasar SEDs: X-ray to radio

- To the first order, average SEDs of z~6 quasar consistent with low-z template
- However, detailed analysis might be indicating first signs of SED evolution:
  - Dust properties (Spitzer and extinction)
  - Fraction of radio-loud quasars

Jiang, XF et al. 2006a
Hot dust in z~6 Quasars

- Lack of evolution in UV, emission line and X-ray disk and emission line regions form in very short time scale
- But how about dust? Timescale problem: running out of time for AGB dust
- Spitzer observations of z~6 quasars: probing hot dust in dust torus (T~1000K)
- Two unusual SEDs among 30 objects observed.

Jiang, XF et al. 2006a

No hot dust??
**Disappearance of Dust Torus at z~6?**

- **Quasars with no hot dust**
  - Spitzer SED consistent with disk continuum only
  - Objects with narrowest line width and largest Edd ratio
  - No similar objects known at low-z
  - Age of the universe shorter than lifetime of intermediate mass stars
  - No enough time to form hot dust torus?

Jiang, XF in prep
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Probing the Host Galaxy Assembly

- **Spitzer**
- **ALMA**
- Dust torus
- Cool Dust in host galaxy
Co-formation of BH/Galaxy at high-z

- Host galaxies of $z \approx 6$ quasars should have ULIRG properties with intense starburst activity

Li et al. astro-ph/0608190
Sub-mm and Radio Observation of High-z Quasars

- Probing dust and star formation in the most massive high-z systems
- Advantage:
  - No AGN contamination
  - Negative K-correction for both continuum and line luminosity at high-z
  - Give measurements to
    - Star formation rate
    - Gas morphology
    - Gas kinematics
Sub-mm Observations of High-z Quasars

- Using IRAM and SCUBA: ~30% 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$_{\odot}$
- If dust heating came from starburst
  - star formation rate of 500 – 2000 M$_{\odot}$/year
- Support for star formation origin of FIR luminosity:
  - z~6 quasars follow starburst galaxy FIR/radio relation
  - No correlation between FIR and UV
  - Heating source still open question

![FIR flux vs. redshift graph](image)
Submm and CO observation of z=6.42 quasar: probing the earliest ISM

- **Strong submm source:**
  - Dust T: 50K
  - Dust mass: $7 \times 10^8 \, M_{\text{sun}}$

- **Strong CO source (multiple transitions)**
  - $T_{\text{kin}} \sim 100K$
  - Gas mass: $2 \times 10^{10} \, M_{\text{sun}}$
  - $n_{\text{H}_2} \sim 10^5$

- Gas/dust, Temp, density typical of local SB

Bertoldi et al.
[CII] detection of $z=6.42$ quasar

• [CII] 158\(\mu\)m line:
  – Brightest ISM line
  – Direct probe of SF region

• J1148 ($z=6.42$)
  – Both [CII] and $L_{\text{FIR}}$ consistent with the brightest local ULIRGs
  – $SFR \sim 10^3 \ M_{\odot}$

Mailino et al. 2005
High-resolution CO Observation of z=6.42 Quasar

• **Spatial Distribution**
  – Radius ~ 2 kpc
  – Two peaks separated by 1.7 kpc
  – CO brightness similar to typical ULIRG SF core.

• **Velocity Distribution**
  – CO line width of 280 km/s
  – Dynamical mass within central 2 kpc: ~ $10^{10} \ M_{\text{sun}}$
  – Total bulge mass ~ $10^{11} \ M_{\text{sun}} < M$-sigma prediction

• **BH formed before complete galaxy assembly?**
M-σ relation at high-z

- Host mass from CO
  - 15 CO detections at z>2
  - Line width all ~200 - 300 km/s
  - Taking at face value:
    - Strong evolution of $M-\sigma \rightarrow BH$ forms early
    - Similar results from HST studies of lensed quasar host (Peng et al.)

- Caveats:
  - Are luminous quasars biased?
  - Are CO observations biased?
  - Need detailed simulations of dust and gas properties of high-z quasar host galaxies

Shields et al. 2006
Summary: High-z vs. Low-z Quasars

• LF and BH mass evolution:
  – Steepening of luminosity/mass functions
  – Billion solar mass BH existed at z~6
  – *Are high-z and low-z quasars accreting differently?*

• Spectral evolution:
  – Little or no evolution in continuum/emission line properties
  – *Strong evolution in radio, Dust and X-ray properties might be evolving as well.*
  – *Approaching the epoch of AGN structure formation?*

• BH/galaxy co-evolution
  – ISM of high-z quasar hosts similar to that of local ULIRGs
  – narrow CO line width
  – *Large BH in small hosts at high-z?*

• Wish list:
  1. *Larger sample and fainter quasars to break degeneracy*
  2. *Better models/observations in dust/gas*
Coffee Break
Outline

• Gunn-Peterson Effect and Reionization with High-Redshift Quasars
  – G-P effect premier
  – G-P Observations
  – Measuring IGM neutral fractions
  – Probing the neutral era
Two Key Constraints:
1. WMAP 5-yr: $z_{\text{reion}} = 11 + \pm 2$
2. IGM transmission: $z_{\text{reion}} > 6$

From Avi Loeb
The end of dark ages: Movie

QuickTime? and a YUV420 codec decompressor are needed to see this picture.
Three stages

Pre-overlap

Overlap

Post-overlap

From Haiman & Loeb

Neutral Hydrogen

Z ~ 30

*First stars and mini-quasars form via H$_2$ Cooling

*H$_2$ destroyed by photons with energies of 11.2-13.6 eV.

Z ~ 15

*Massive objects cool and form stars via atomic line emission at $T_{Vir} \geq 10^4$ K.

Z ~ 8

*Expanding HII regions overlap, UV background rises sharply

*Free electrons damp CMB anisotropies

Ionized Hydrogen

$T_{vir} < 10^4$ K

$T_{vir} > 10^4$ K
Open Questions:

• **When**: Early or Late
  – $z \sim 6$: late
  – $z \sim 15$: early

• **How** did reionization proceed:
  – Phase transition or gradual?
  – Once or twice?
  – Homogeneous or large scatter?

• **What** did it:
  – AGN?
  – Star formation?
  – Decay particles?

• **Observational goals**
  – Map the evolution of ionization state: neutral fraction ($f_{HI}$) vs. redshift
  – Find highest redshift galaxies and quasars: source of reionization
CMB polarization

- CMB will be polarization by free electrons
  - Signature on the large scale CMB anisotropy
  - Correlation between CMB temperature and polarization
  - Reionization introduces extra free electrons after recombination
    - Affect primary CMB power spectrum (optical depth to last scattering, \( \tau \approx 0.1 \))
    - Affect polarization power spectrum
WMAP: early reionization?

- WMAP fifth year:
  - $\tau = 0.09 +/- 0.02$
  - Larger signal comparing to late reionization model

Page et al., Spergel et al. 2006
WMAP: early reionization

- Inconsistent with a phase transition at $z=6$ at $3\,\sigma$ level
- Reionization could start at $z=10-15$
- IGM could have complex reionization history

$\Rightarrow$ direct observation of high-$z$ sources

Gnedin 2004

Spergel et al. 2006
Searching for Gunn-Peterson Trough

- **Gunn and Peterson (1965)**
  - “It is observed that the continuum of the source continues to the blue of Ly-$\alpha$ (in quasar 3C9, $z=2.01$)”
  - “only about one part of $5 \times 10^6$ of the total mass at that time could have been in the form of intergalactic neutral hydrogen”

- **Absence of G-P trough $\Rightarrow$ the universe is still highly ionized**

- **First detection of complete G-P trough: SDSS J1030 ($z=6.28$, Becker et al. 2001)**

- **G-P optical depth $\Rightarrow$ evolution of ionizing background and neutral fraction of the IGM**
Absorption from HI
Ly α forest

Redshifted Ly alpha resonance absorption!

Thickening of Ly alpha forest towards high-z
Ly alpha absorption from a diffused IGM

Total optical depth along line of sight:

\[ \tau = \int \sigma n_{HI} \, dl \]

Cross section:

\[ \sigma(\nu) = \frac{\pi e^2}{m_e c} f_\alpha \phi(\nu - \nu_\alpha) \]

Integrate all atoms:

\[ \tau(\nu) = \int_0^\infty d\tau = \int n(z) \sigma[\nu(1 + z)] \frac{dl}{dz} \, dz \]

Line element:

\[ \frac{dl}{dz} = c H^{-1} / (1 + z) \]

Gunn-Peterson optical depth:

\[ \tau_{GP} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1} (z) n_{HI} \]

At high-z, for uniform IGM

\[ \tau_{GP}(z) = 1.8 \times 10^5 h^{-1} \Omega_m^{-1/2} \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{1 + z}{7} \right)^{3/2} \left( \frac{n_{HI}}{n_H} \right) \]
Gunn-Peterson Test

- Classic G-P (1965) effect:
  \[ \tau_{GP} \sim 10^5 \left( \frac{n_{HI}}{n_H} \right) \]
  - Saturates at low neutral fraction
- G-P damping wing (Miralda-Escude 1998)
  - Sensitive to neutral IGM
  - Attenuates off-resonance
Outline

• Gunn-Peterson Effect and Reionization with High-Redshift Quasars
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Keck/ESI 30min exposure →

Gunn-Peterson Trough in z=6.28 Quasar

Keck/ESI 10 hour exposure →

White et al. 2003
Evolution of Lyman Absorptions at z=5-6

\[ \Delta z = 0.15 \]
Evolution of Gunn-Peterson Optical Depth

\[ (1+z)^{4.5} \]
Accelerated Evolution at \( z > 5.7 \)

- Optical depth evolution accelerated
  - \( z < 5.7 \): \( \tau \sim (1+z)^{4.5} \)
  - \( z > 5.7 \): \( \tau \sim (1+z)^{11} \)
  - > Order of magnitude increase in neutral fraction of the IGM

\( \Rightarrow \) End of Reionization

- Dispersion of optical depth also increased
  - Some line of sight have dark troughs as early as \( z \sim 5.7 \)
  - But detectable flux in \( \sim 50\% \) case at \( z > 6 \)
  - End of reionization is not uniform, but with large scatter

Fan et al. 2006
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Ionization State of the IGM

- G-P optical depth at z~6:
  \[ \tau_{GP} \sim 10^5 \left( \frac{n_{HI}}{n_H} \right) \]
  - Small neutral fraction needed for complete G-P trough
  - *By itself not indication that the object is beyond the reionization epoch*
- The evolution of G-P optical depth:
  - Tracking the evolution of UV background and neutral fraction of the IGM (McDonald & Mirada-Escude 2000)
  - IGM is highly non-uniform:
    - Needs to take into account the IGM density distribution to derive neutral fraction
Optical depth in a clumpy IGM

• What we actually observe?
  – Average transmitted flux, or effective optical depth:

\[ F = e^{-\tau_{\text{eff}}} = \left< e^{-\tau} \right> = \int_0^\infty e^{-\tau(\Delta)} p(\Delta) d(\Delta) \]

  – \( p(\Delta) \) is the probability distribution function of the IGM overdensity
  – Need to calculate optical depth in each region of the IGM, then average their respective transmitted flux
  – Average is done on flux space, not optical depth space:

\[ \left< e^{-\tau} \right> \neq e^{-\left< \tau \right>} \]
Optical depth of Photoionization

- Assuming photoionization equilibrium:

\[ n_{\text{HI}} \Gamma = n_{\text{HI}} n_e \alpha(T) \]

- For mostly ionized uniform IGM:

\[ \tau_{\text{GP}} \propto \frac{(1 + z)^6 (\Omega_b h^2)^2 \alpha(T)}{\Gamma H(z)} \]

- For a region of IGM with density \( \Delta \):

\[ \tau(\Delta) \propto \frac{(1 + z)^{4.5} (\Omega_b h^2)^2 \alpha[T(\Delta)]}{h \Gamma(\Delta, z) \Omega_m^{0.5}} \Delta^2 \]
From optical depth to IGM characteristics

1. Assuming IGM PDF (from simulation)
2. Adjusting ionizing background $\Gamma$ so that the transmitted flux, averaged over the entire IGM density distribution, matches the observed flux
3. Calculate HI density and neutral fraction as a function of IGM density
4. Derive “volume-averaged” and “mass-averaged” neutral fractions
5. Infer photon mean-free-path from neutral fraction and density distribution
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

- From GP optical depth measurement, volume averaged neutral fraction increase by >~ order of magnitude from z~5.5 to 6.2
Reionization overlap at $z\sim 6-7$?

- Comparing G-P observations with high-resolution reionization simulation:
  - Overlap redshift $\sim 6.2$
  - Current simulation does not resolve earliest star formation to predict an accurate CMB polarization optical depth

Gnedin and Fan 2006
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Evolution of Proximity Zone Size Around Quasars

- Size of Proximity Zone region
  \[ R_p \sim \left( \frac{L_Q t_Q}{f_{HI}} \right)^{1/3} \]
- Size of quasar proximity zone decreases by a factor of \( \sim 2.4 \) between \( z=5.8 \) and 6.4 (Fan et al. 2006)
- Consistent with neutral fraction increased by a factor of \( \sim 15 \) over this narrow redshift range
- But see eg Bolton and Haehnelt (2006) for complications in this interpretation

Haiman, Mesinger, Wyithe, Loeb et al.

Proximity zone size (Mpc) vs. redshift

Fan et al. 2006
Uncertainties in interpretation of proximity zone sizes

  - Observed size of proximity zone much smaller than true HII region size
  - Neutral fraction $\sim$ a few percent
  - Consistent with G-P constraints

- Mesinger et al. (2004), Wyithe et al. (2005)
  - Neutral fraction $\sim$10-30%

- Better models and simulated spectra needed…

Maselli et al. 2006

Bolton & Haehelt 2006
• Classic G-P (1965) effect:
  \[ \tau_{GP} \sim 10^5 (n_{HI}/n_H) \]
  – Saturates at low neutral fraction
• G-P damping wing (Miralda-Escude 1998)
  – Sensitive to neutral IGM
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Dark Gap Distributions

- Dark gap statistics (Songaila & Cowie 2002)
  - Gaps: regions where all pixels have \( \tau > 2.5 \)
  - Sensitive to the topology of reionization

- Gaps among z~6 quasars
  - dramatic increase in gap length:
    - Consistent with overlap at z~6-8

- 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% (Gallerani et al. 2007)

Gallerani et al.

XF et al. 2006
Ly α Galaxy LF at $z>6$

- Neutral IGM has extended GP damping wing $\rightarrow$ attenuates Ly α emission line
- New Subaru results
  - Declining density at $z\sim6$-$7$ (2-3σ result)
  - Reionization not completed by $z\sim6.5$
  - Neutral fraction could be as high as a few tenths but strongly model-dependent
  - cf. Malhotra & Rhoads, Hu et al.: lack of evolution in Ly α galaxy density
Probing Reionization History

Fan, Carilli, Keating 2006
Quest to the Highest Redshift

The graph shows the progression of redshift over time, with markers indicating different observational methods: lensing, serendip, narrow-band, slitless spec., color, and radio. The categories of Quasars and Galaxies are also highlighted.
LBT Search for z~7 Quasars

- Using the Large Binocular Camera on LBT
  - Red sensitive CCD for Y band survey
  - Six nights in Spring to survey 9 deg NOAO Deep-Wide Bootes Field (with Spitzer data)
  - 0.5” images
  - 1-3 quasars at z~7 (stay tuned)
Next Generation Quasar Surveys

- Optical surveys: limited to $z<7$
- New generations of red-sensitive CCD devices
  - Improved QE at 1 micron (Y band)
  - LBT/LBC (2008+): tens of deg, $Y<23.5$
  - SUBARU/Princeton (2010+): a few hundred deg, $Y<25$?
  - Pan-Starrs (2008+): $3\pi$: $Y<22.5$; 1000 deg$^2$: $Y<24$; 30 deg$^2$: $Y<26$
  - LSST (2013+): $3\pi$: $Y<25$
  - Discovery of large number of quasars at $z<7.5$
- New generation of Near-IR surveys:
  - UKIDSS (2005-2012?): 4000 deg$^2$: $J_{AB}<21$
  - VISTA/VHS (2008+): 20000 deg$^2$: $J_{AB}<21$
  - VISTA/VIKING (2008+): 1500 deg$^2$: $J_{AB}<22$
  - VISTA/VIDEO (2008+): 15 deg$^2$: $J_{AB}<24.5$
  - Discovery of a handful of quasars at $z=7-9$
Will there be enough quasars?

- For $z>9$ (assuming quasar LF evolution has not steepened)
  - Bright ($AB<22.5$): $0.2/100 \text{ deg}^2$
  - Faint ($AB<24.5$): $1-10/100 \text{ deg}^2$

- difficult for current or planned ground-based IR surveys to find enough quasars for JWST reionization probes…
  - Wide-area near-IR space surveys
Probing the Neutral Era with JWST
Quasar Spectroscopy

- Measuring G-P optical depth
  - $R \sim 100$ mode for faint AGNs
  - Insensitive to neutral era
- Measuring HII region sizes
  - $R \sim 1000$ mode
  - Sensitive to high $f_{\text{HI}}$
  - Radiative transfer effects causing large scatter for individual object
  - Modest S/N but require large sample
  - $J_{\text{AB}} < 24.5$ (deep surveys)

- Probing reionization using dark gap distribution and metal lines
  - $R \sim 2700$ mode
  - Sensitive to overlap topology
  - $J_{\text{AB}} < 22.5$ (wide surveys!)