Lecture 3. Quasars as First Light Probes: Reionization and Galaxy/SMBH Co-Evolution

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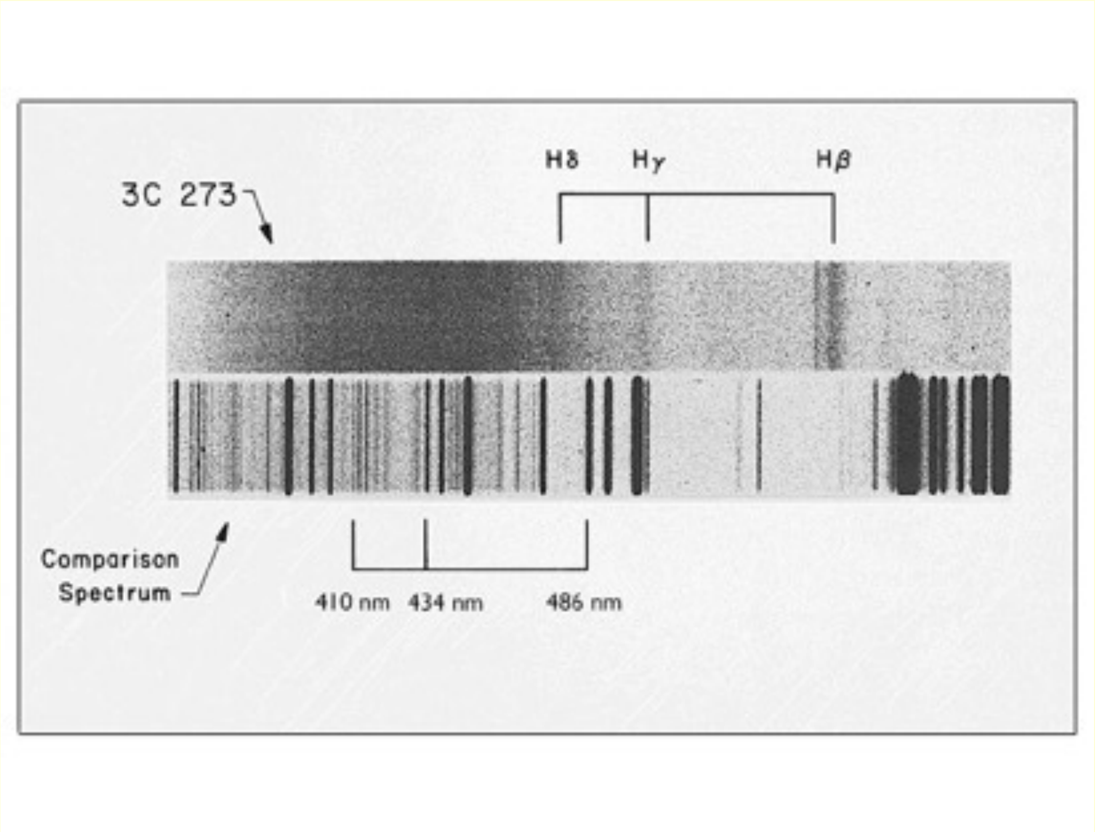
EXPLORING THE EDGE OF THE UNIVERSE
TIME
THE WEEKLY NEWSMAGAZINE
ASTRONOMER
MAARTEN SCHMIDT

The First Quasar Discovered z=0.158 (1963)



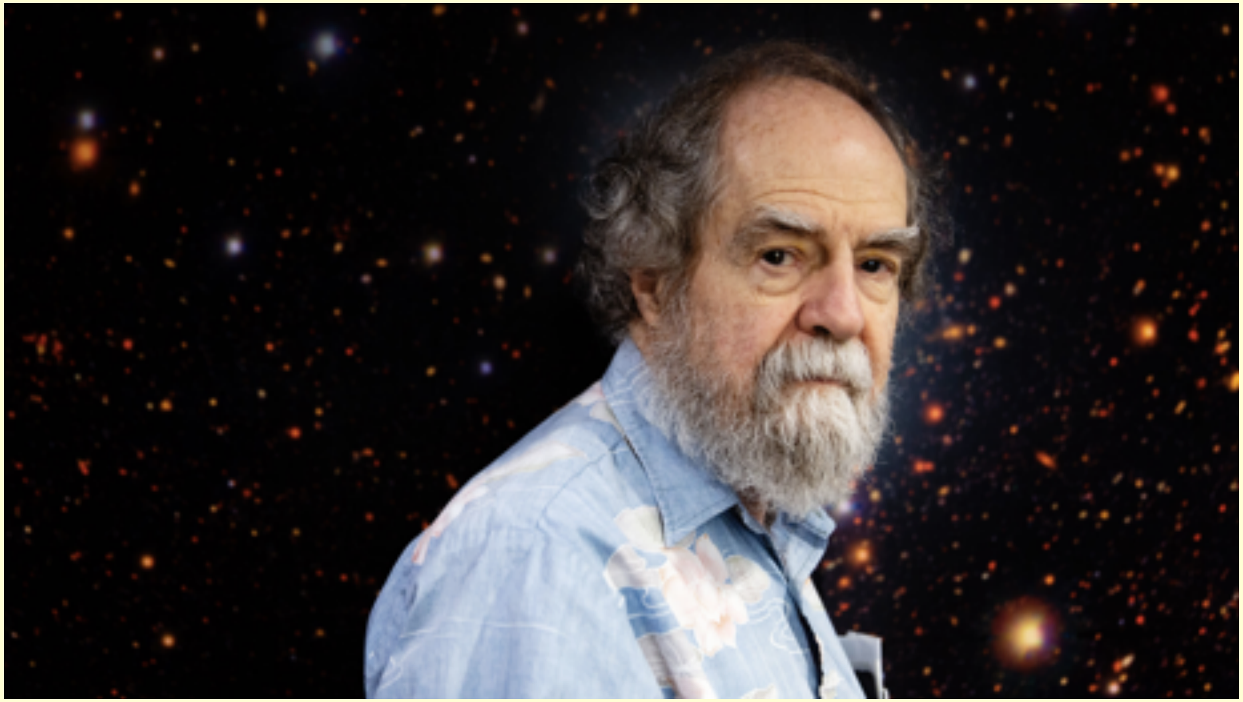
1964: Quasar 3C9 (z=2.01) discovered
first detection of Ly alpha emission

Gunn-Peterson Effect

- 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 5×10^6 of the total mass at that time could have been in the form of intergalactic neutral hydrogen "
- After recombination, the universe was neutral (atomic)
- Absence of G-P trough -> ***the universe highly ionized***

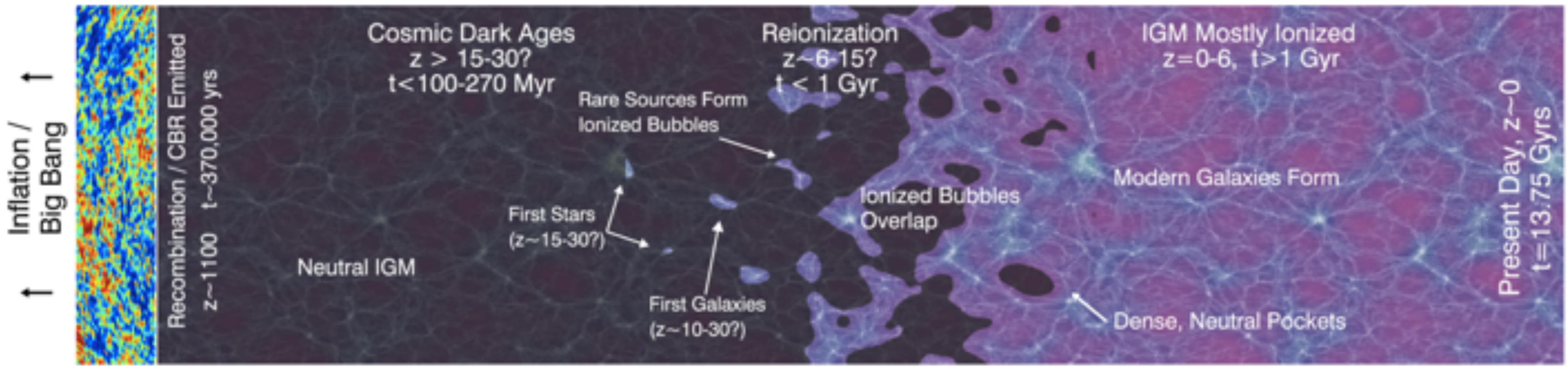
- ***There must be a process of REIONIZATION***

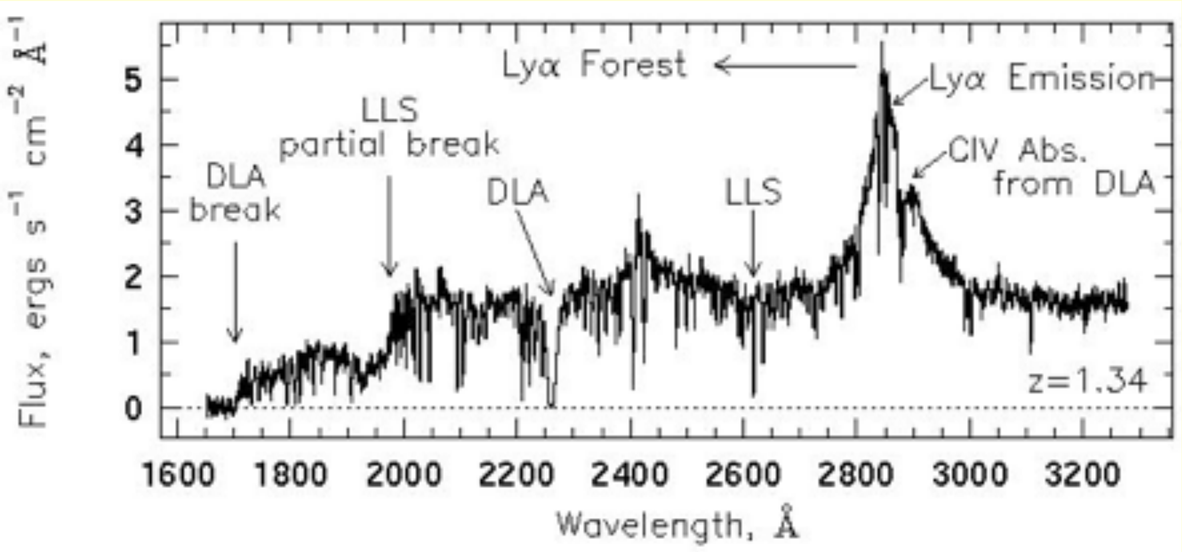
Jim Gunn

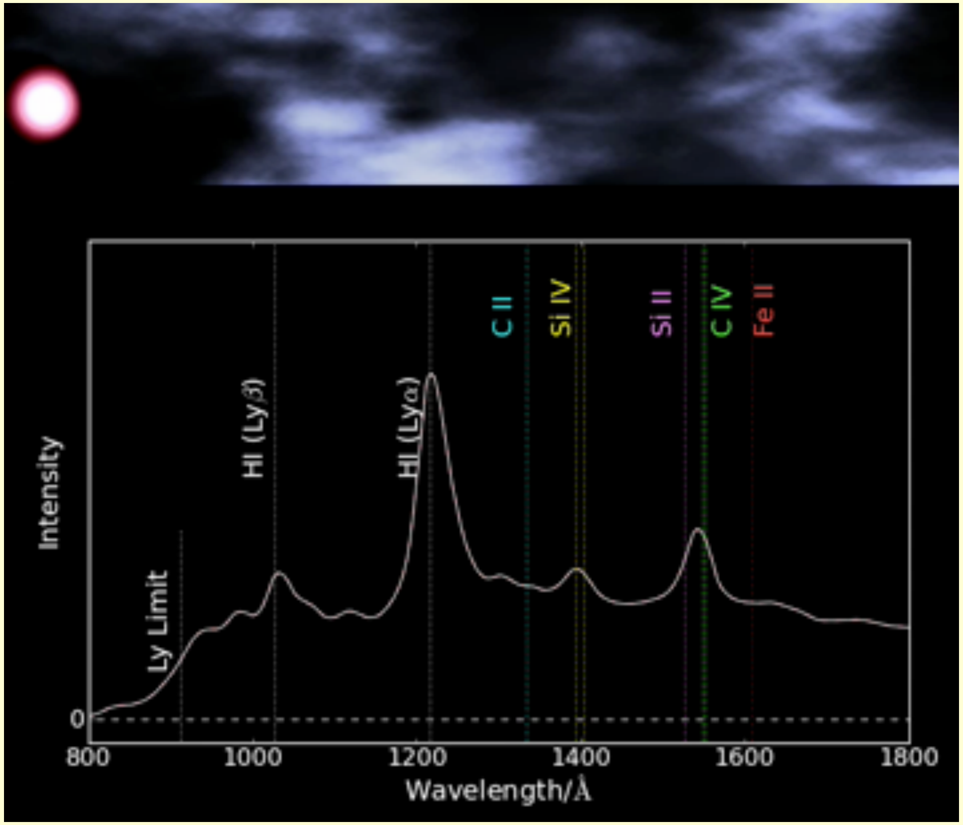


- an observer: Gunn standard star, Gunn filter
- an instrumentalist: WFPC1, SDSS
- a theorist: Gunn-Peterson effect
- and an extraordinary person

Reionization




Lyα Forest
Lyα Emission
LLS
partial break
CIV Abs.
from DLA
DLA
break
DLA
LLS
z=1.34
Flux, ergs s^{-1} cm^{-2} Å^{-1}
Wavelength, Å
0
1
2
3
4
5
1600
1800
2000
2200
2400
2600
2800
3000
3200


C II
Si IV
Si II
C IV
Fe II
HI (Lyβ)
HI (Lyα)
Ly Limit
Intensity
0
800
1000
1200
1400
1600
1800
Wavelength/Å

Gunn-Peterson Effect

- optical depth along line of sight:

$$\tau = \int_0^{z_0} n(z)\sigma(\nu(1+z))(dl/dz)dz$$

HI density: $n(z) = n_{\rm HI}(1+z)^3$

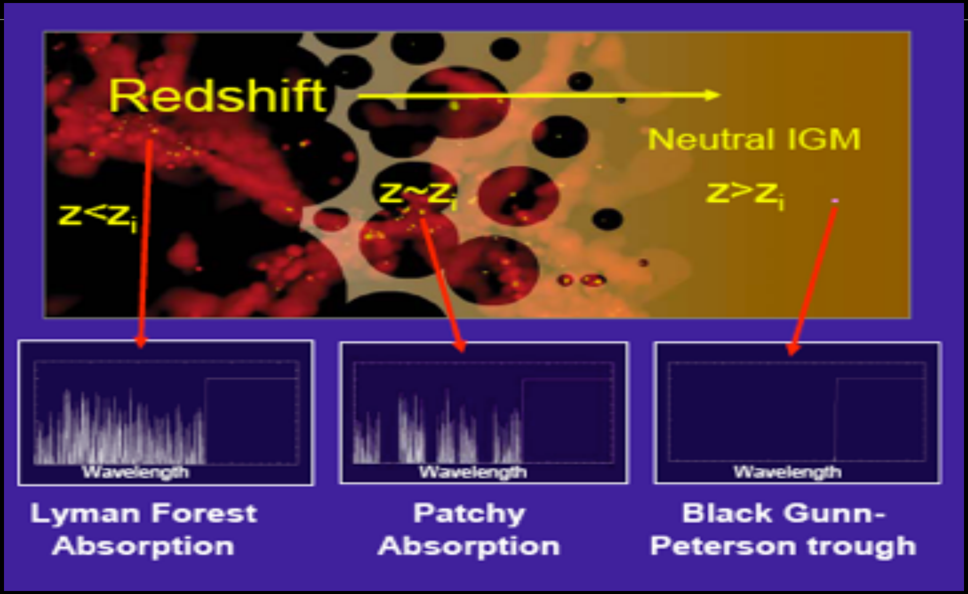
$$dl/dz = c/H(z) = cH_0^{-1}(1+z)^{-3/2}$$

abs. crossing section: $\sigma = \pi e^2 f/m_e c$

$$\tau(z) \approx n_{\rm HI}\sigma(\nu_0(1+z))cH_0^{-1}(1+z)^{3/2}$$

$$\tau = 6.4\times 10^5 h^{-1}\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{1+z}{3}\right)^{3/2}\left(\frac{n_{\rm HI}}{n_{\rm H}}\right)$$

Gunn-Peterson Test

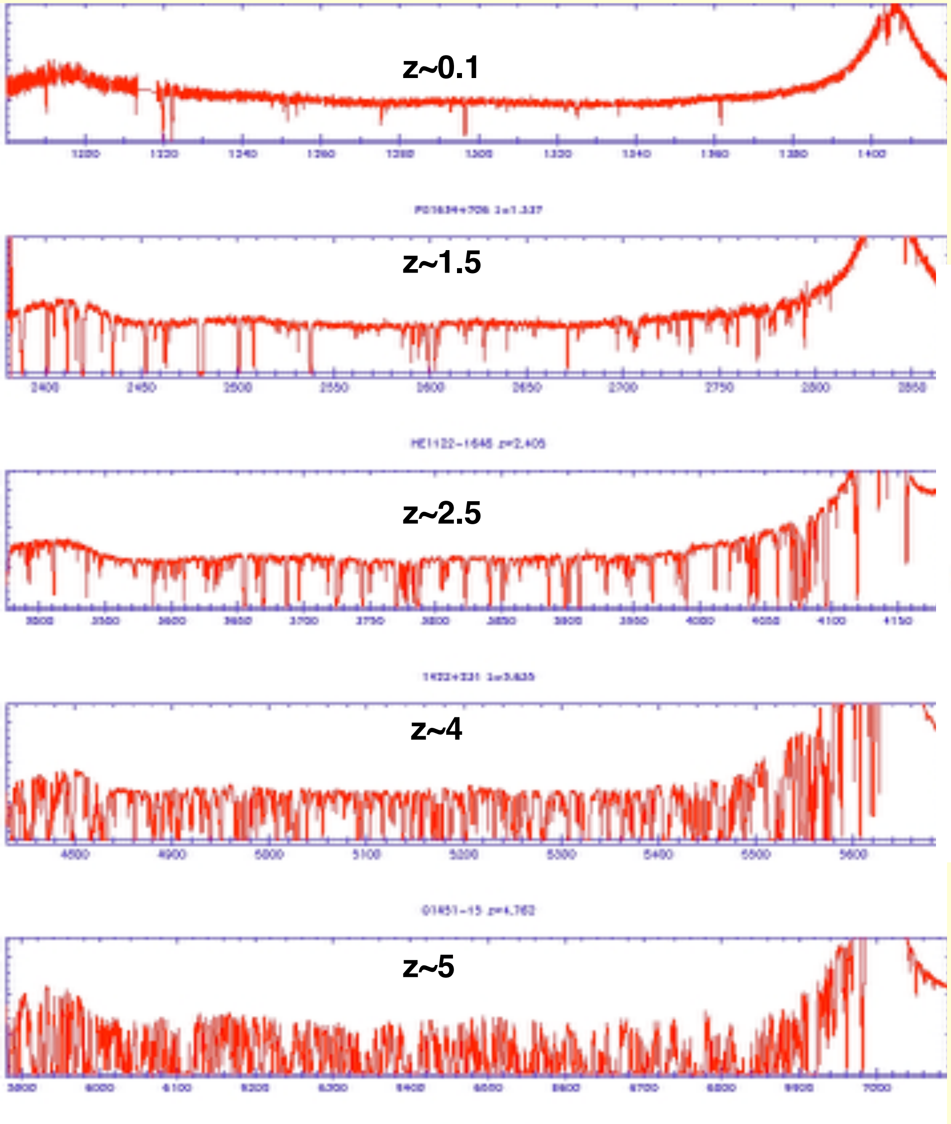


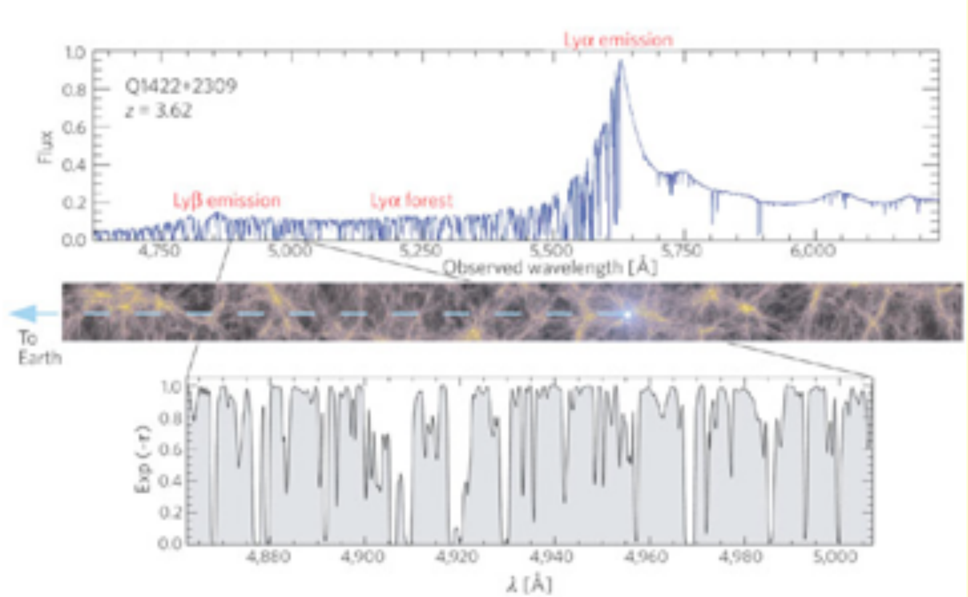
- Classic G-P (1965) effect:

$$\tau_{GP} \sim 10^5 (n_{HI} / n_H)$$

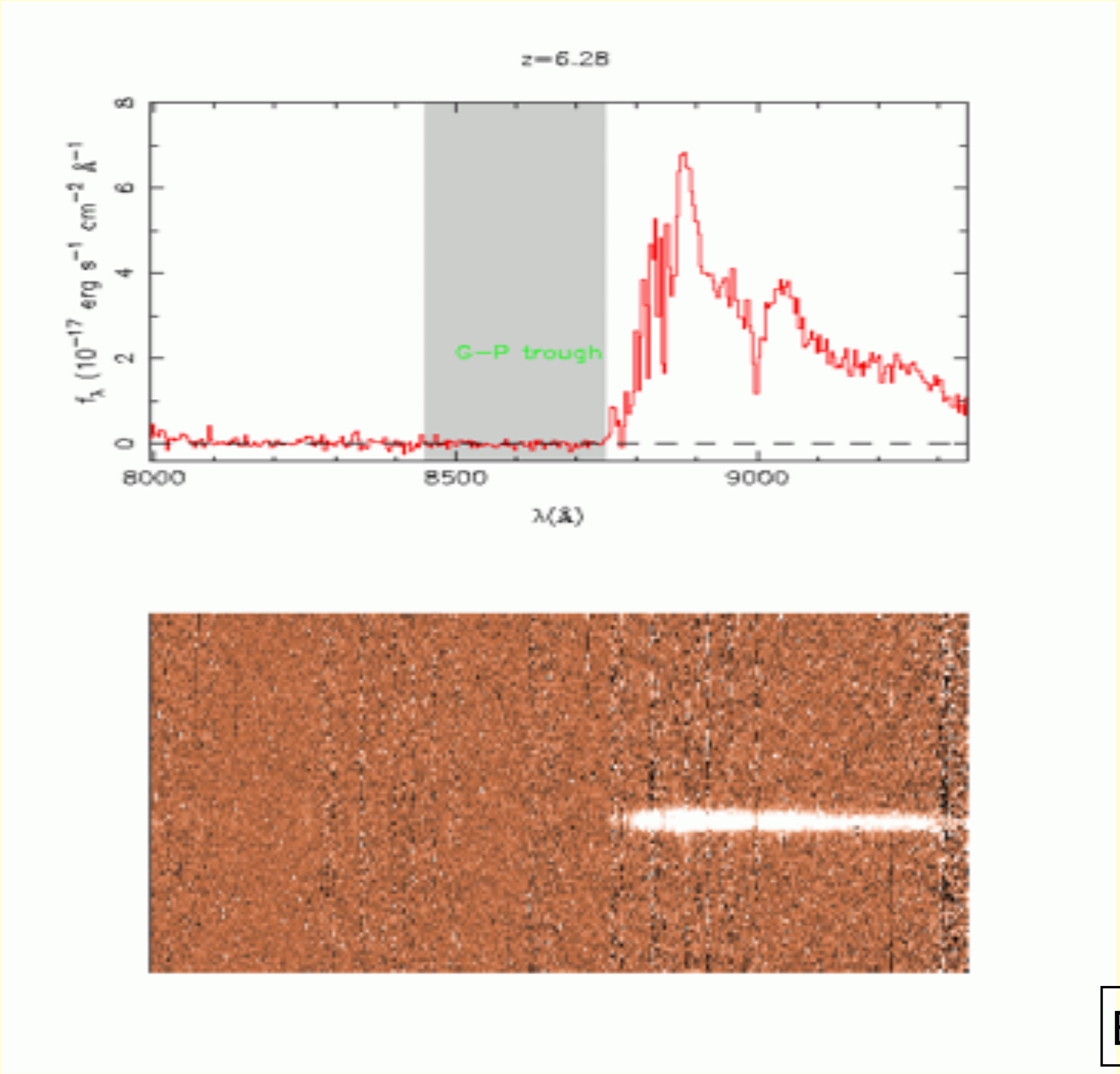
  - Saturates at low neutral fraction

Evolution of Lyman alpha forest absorption





First detection of Gunn-Peterson Effect

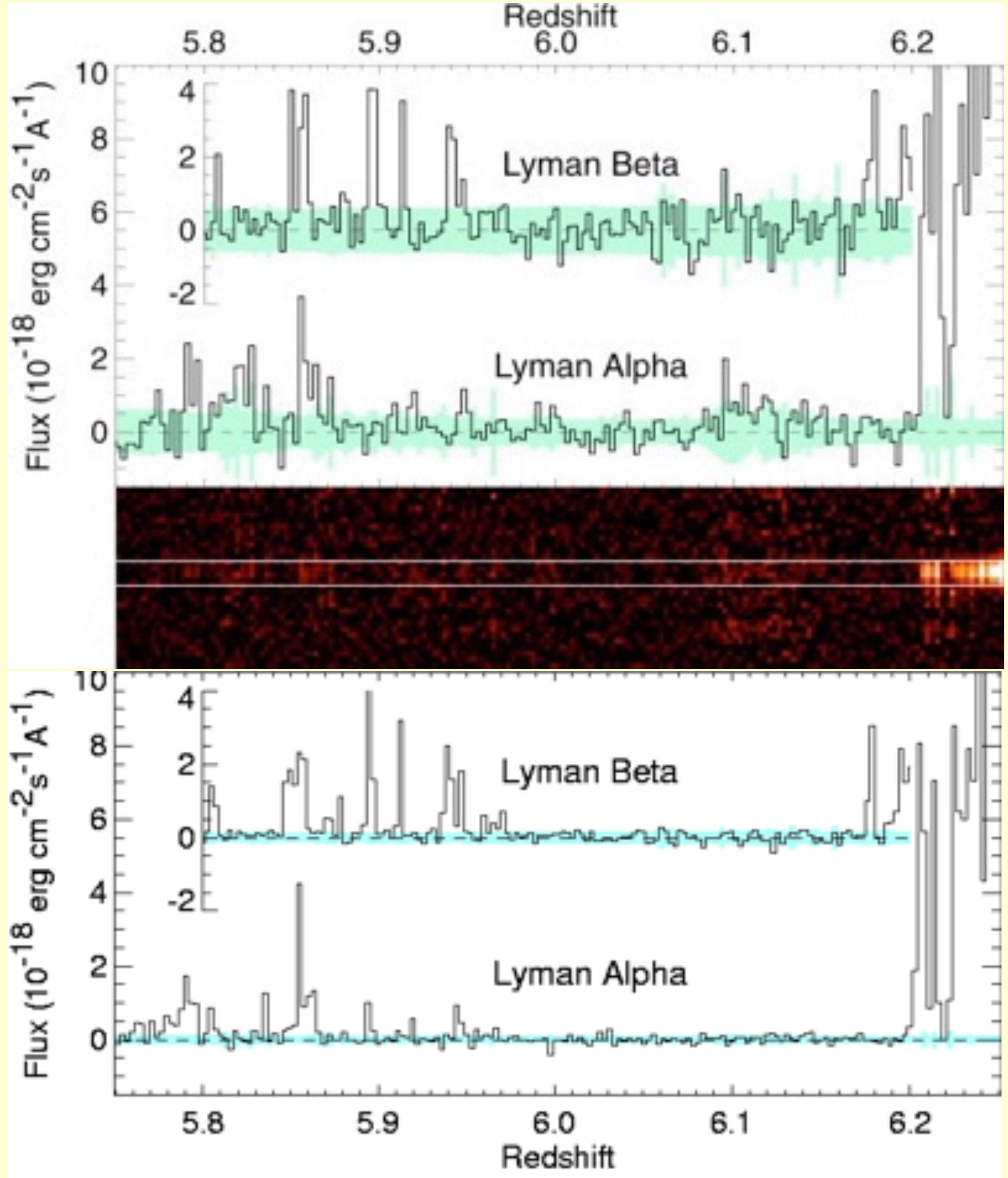


Becker, XF +2002

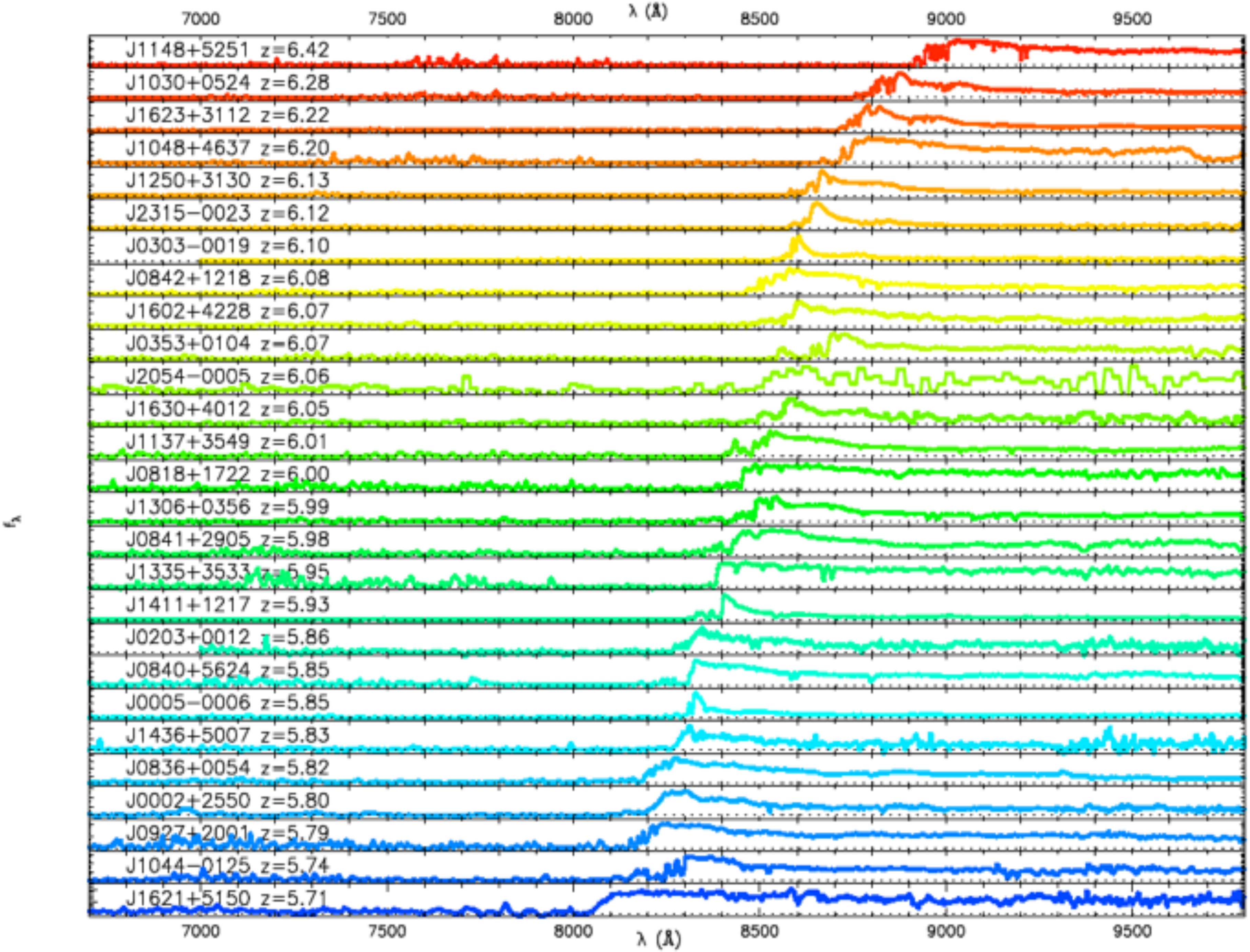
Gunn-Peterson Trough in z=6.28 Quasar

Keck/ESI 30min exposure

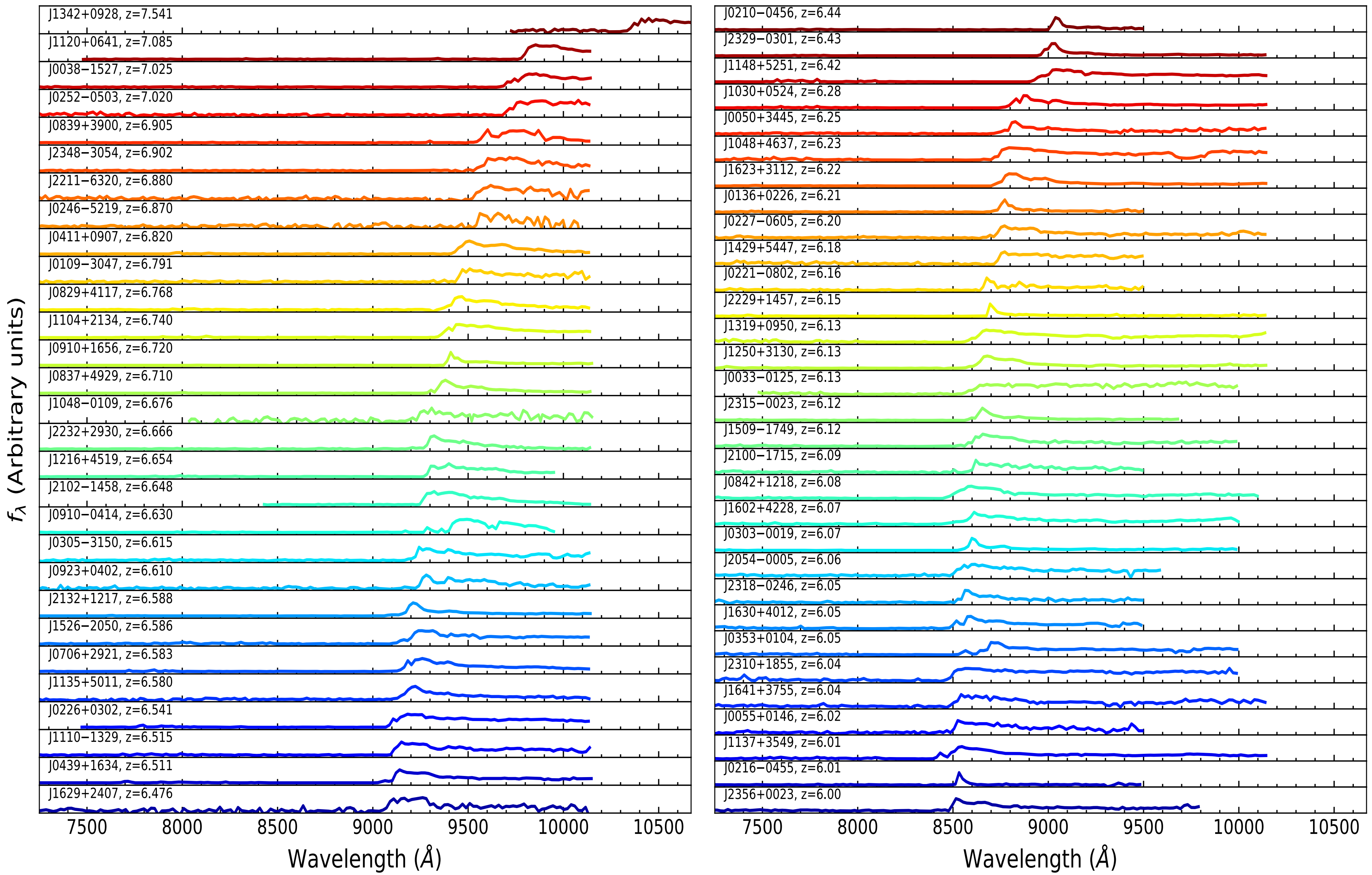
Keck/ESI 10 hour exposure



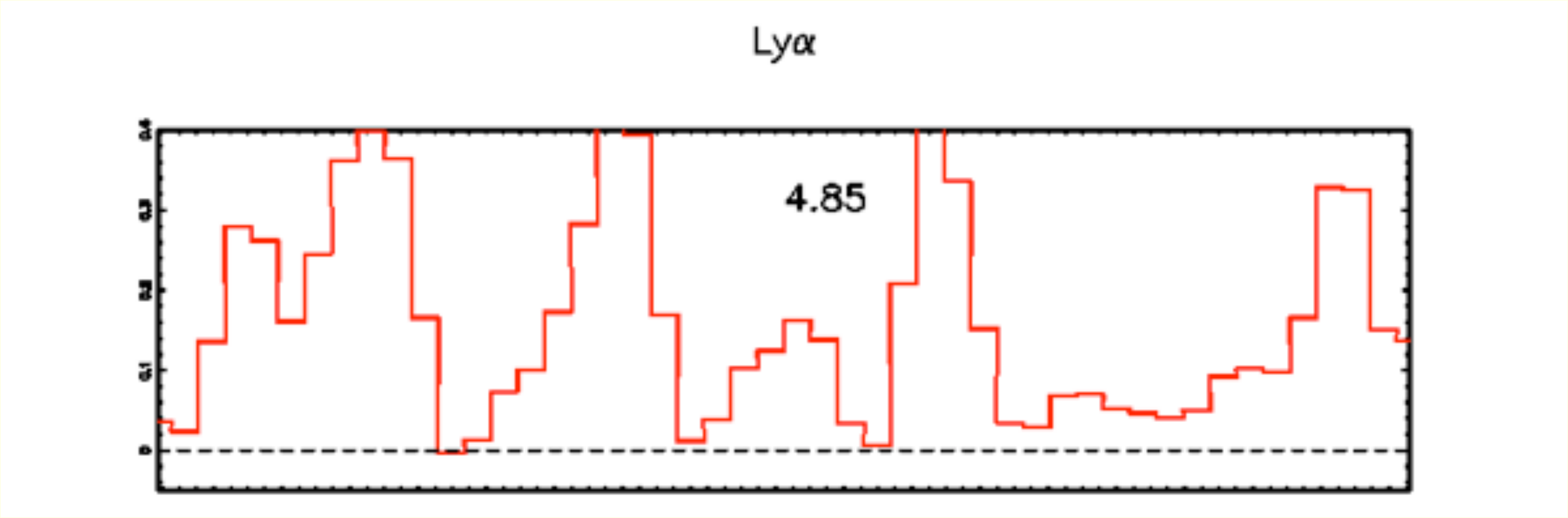
White et al. 2003

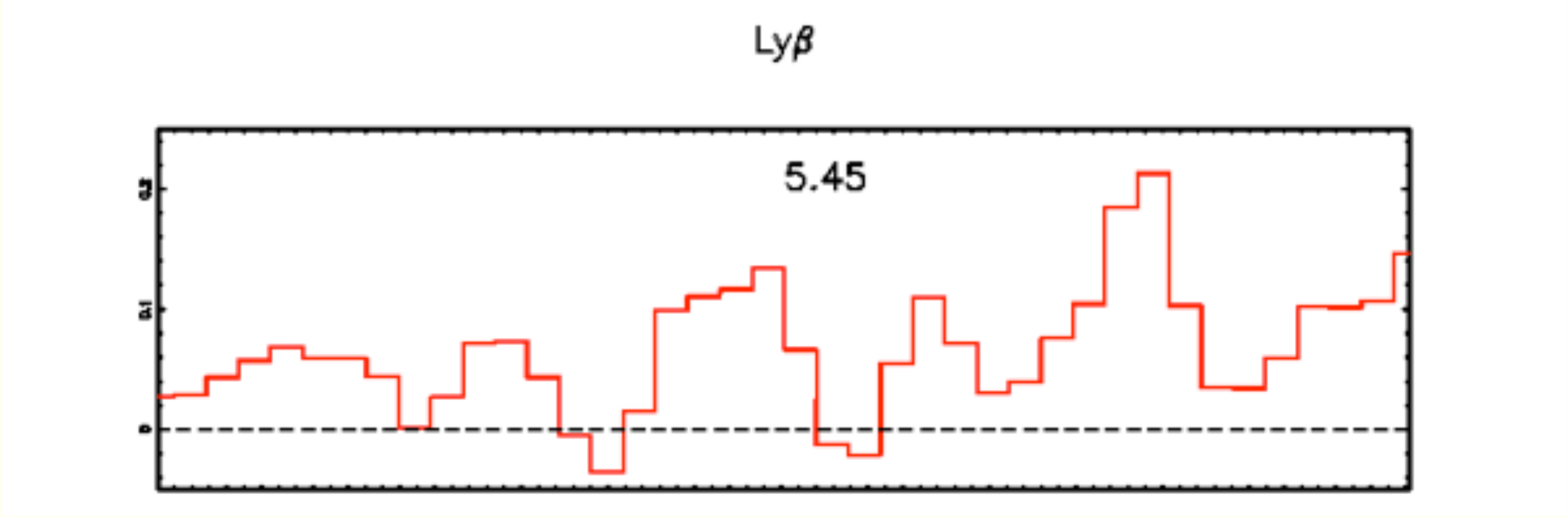


λ (Å)
7000
7500
8000
8500
9000
9500
f_λ
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0303−0019 z=6.10
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J0841+2905 z=5.98
J1335+3533 z=5.95
J1411+1217 z=5.93
J0203+0012 z=5.86
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
J1621+5150 z=5.71


J1342+0928, z=7.541
J1120+0641, z=7.085
J0038−1527, z=7.025
J0252−0503, z=7.020
J0839+3900, z=6.905
J2348−3054, z=6.902
J2211−6320, z=6.880
J0246−5219, z=6.870
J0411+0907, z=6.820
J0109−3047, z=6.791
J0829+4117, z=6.768
J1104+2134, z=6.740
J0910+1656, z=6.720
J0837+4929, z=6.710
J1048−0109, z=6.676
J2232+2930, z=6.666
J1216+4519, z=6.654
J2102−1458, z=6.648
J0910−0414, z=6.630
J0305−3150, z=6.615
J0923+0402, z=6.610
J2132+1217, z=6.588
J1526−2050, z=6.586
J0706+2921, z=6.583
J1135+5011, z=6.580
J0226+0302, z=6.541
J1110−1329, z=6.515
J0439+1634, z=6.511
J1629+2407, z=6.476
J0210−0456, z=6.44
J2329−0301, z=6.43
J1148+5251, z=6.42
J1030+0524, z=6.28
J0050+3445, z=6.25
J1048+4637, z=6.23
J1623+3112, z=6.22
J0136+0226, z=6.21
J0227−0605, z=6.20
J1429+5447, z=6.18
J0221−0802, z=6.16
J2229+1457, z=6.15
J1319+0950, z=6.13
J1250+3130, z=6.13
J0033−0125, z=6.13
J2315−0023, z=6.12
J1509−1749, z=6.12
J2100−1715, z=6.09
J0842+1218, z=6.08
J1602+4228, z=6.07
J0303−0019, z=6.07
J2054−0005, z=6.06
J2318−0246, z=6.05
J1630+4012, z=6.05
J0353+0104, z=6.05
J2310+1855, z=6.04
J1641+3755, z=6.04
J0055+0146, z=6.02
J1137+3549, z=6.01
J0216−0455, z=6.01
J2356+0023, z=6.00
f_λ (Arbitrary units)
7500
8000
8500
9000
9500
10000
10500
Wavelength (Å)

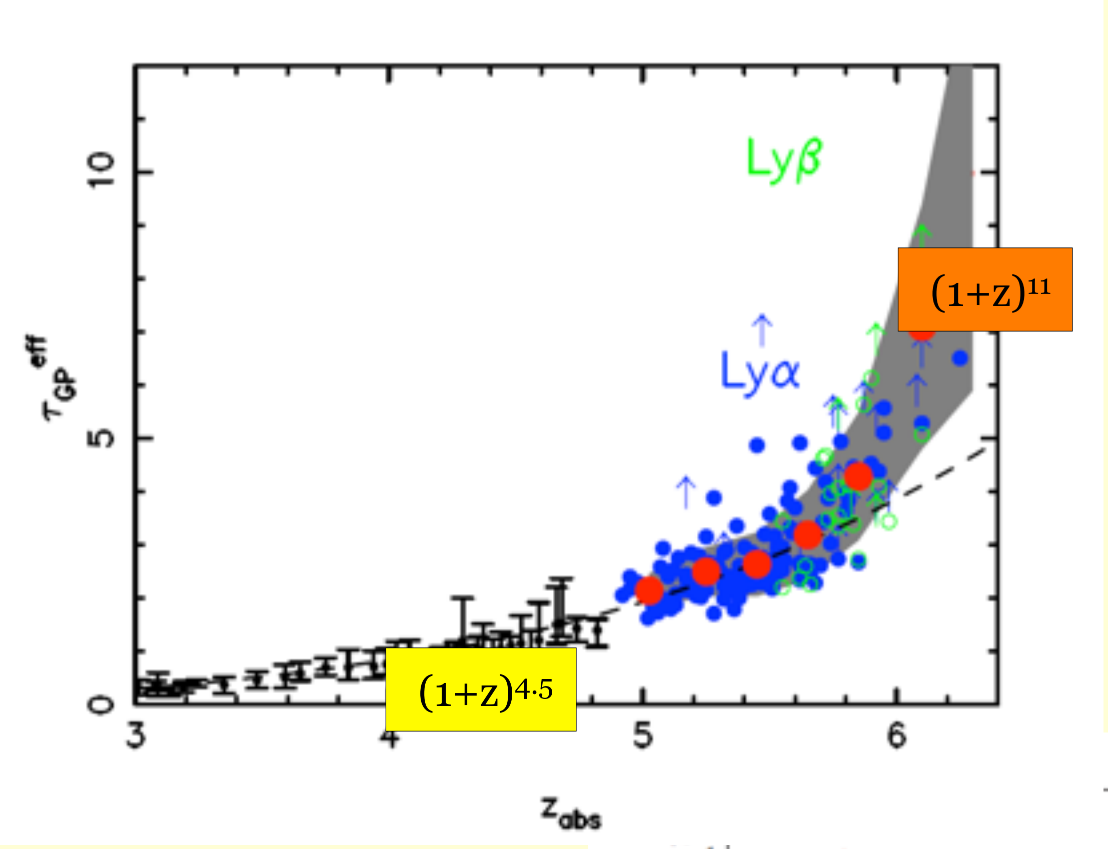
Evolution of Lyman Absorptions at z=5-6





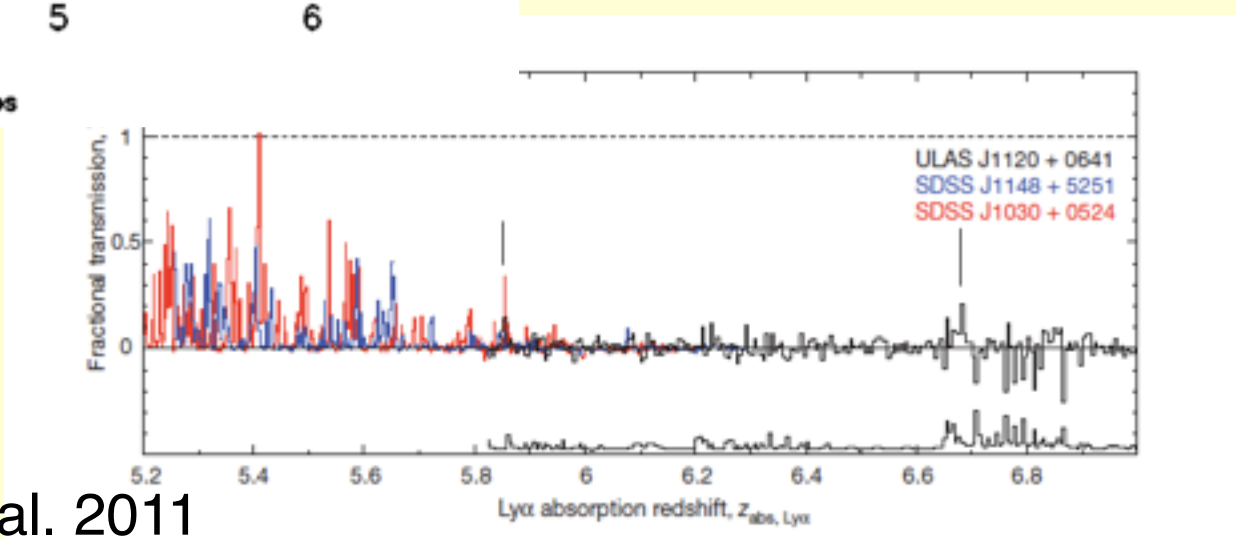
$\Delta z = 0.15$

Accelerated Evolution at z>5.7



- *Optical depth evolution accelerated*
  - $z<5.7$: $\tau \sim (1+z)^{4.5}$
  - $z>5.7$: $\tau \sim (1+z)^{>11}$
  - ***End of reionization?***

XF et al. 2006



Mortlock et al. 2011

G-P optical depth to neutral fraction

- G-P optical depth

$$\tau = 6.4 \times 10^5 h^{-1} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{3}\right)^{3/2} \left(\frac{n_{\rm HI}}{n_{\rm H}}\right)$$

- IGM: photoionization, ionization = recombination

$$n_{\rm HI}\Gamma = n_{\rm HII} n_e \alpha(T),$$

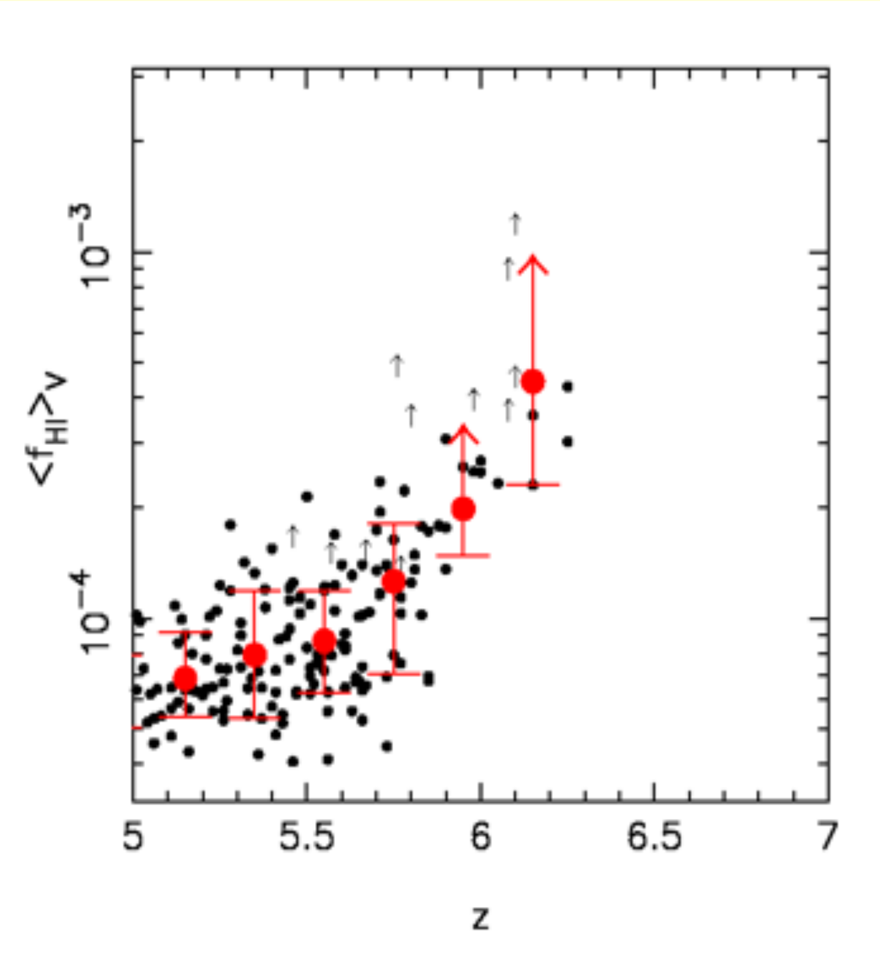
Γ: photoionization rate
α: recombination coeff.

- Assuming IGM mostly ionized: n_HII ~ n_H

$$\tau_{\rm GP} \propto \frac{(1+z)^6 (\Omega_b h^2)^2 \alpha(T)}{\Gamma H(z)} \propto \frac{(1+z)^{4.5} (\Omega_b h^2)^2 \alpha(T)}{h \Gamma \Omega_m^{0.5}}.$$

- Finally, IGM is not uniform: use IGM density distribution from simulation..

Evolution of IGM neutral fraction

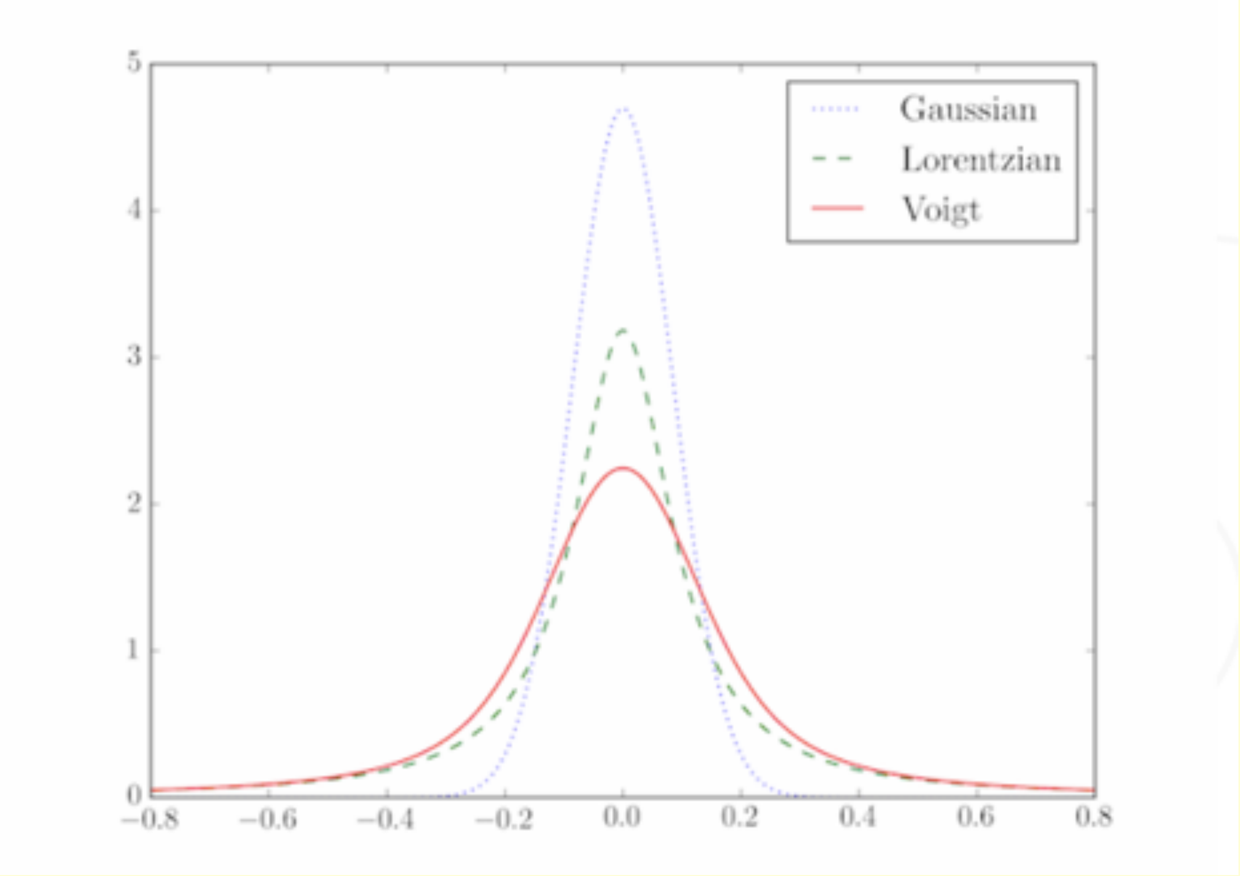


XF et al. 2006

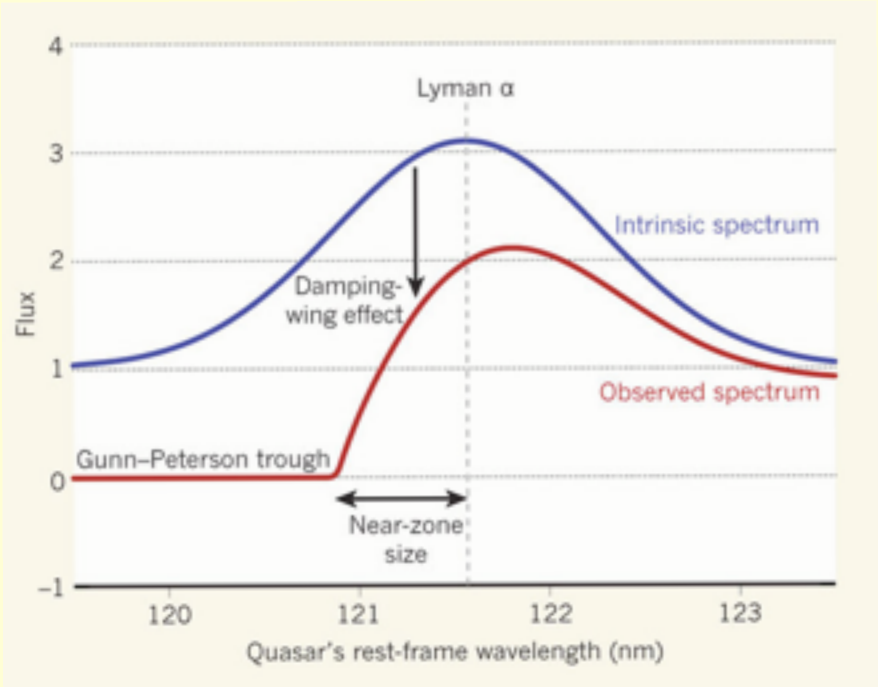
- From GP optical depth measurement, volume averaged neutral fraction increase by >~ order of magnitude from z~5.5 to 6.2
- at z>6: Gunn-Peterson trough saturates

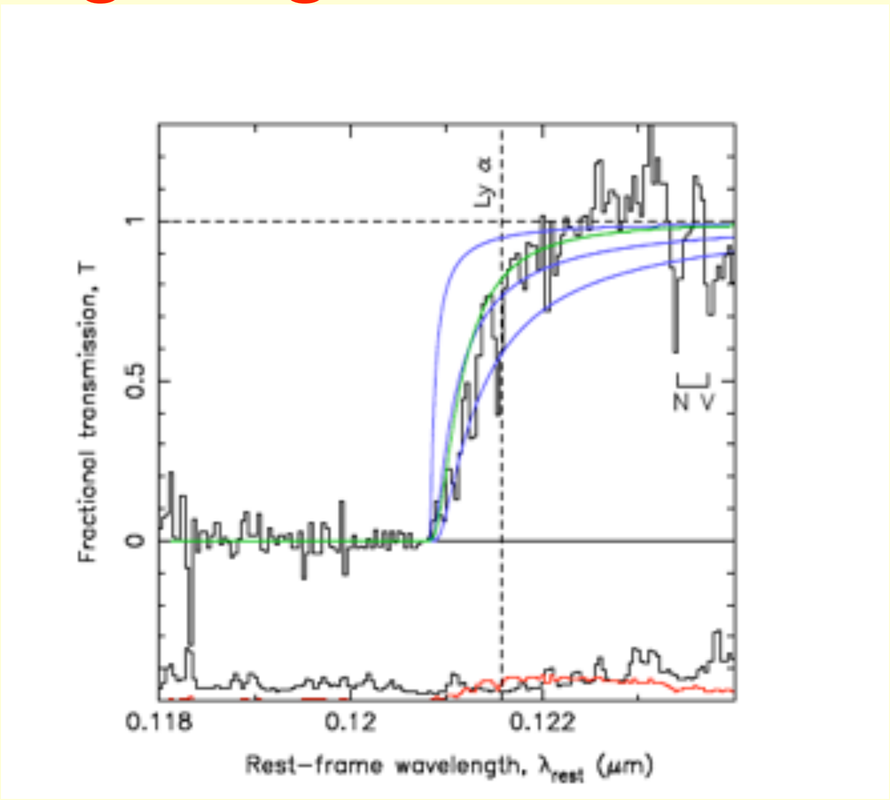
Voigt line profile:
Gaussian core and Lorentzian (damping)wing

$$\tau = \int_0^{z_0} n(z)\sigma(\nu(1+z))(dl/dz)dz$$



z~7 quasar: first IGM damping wing?

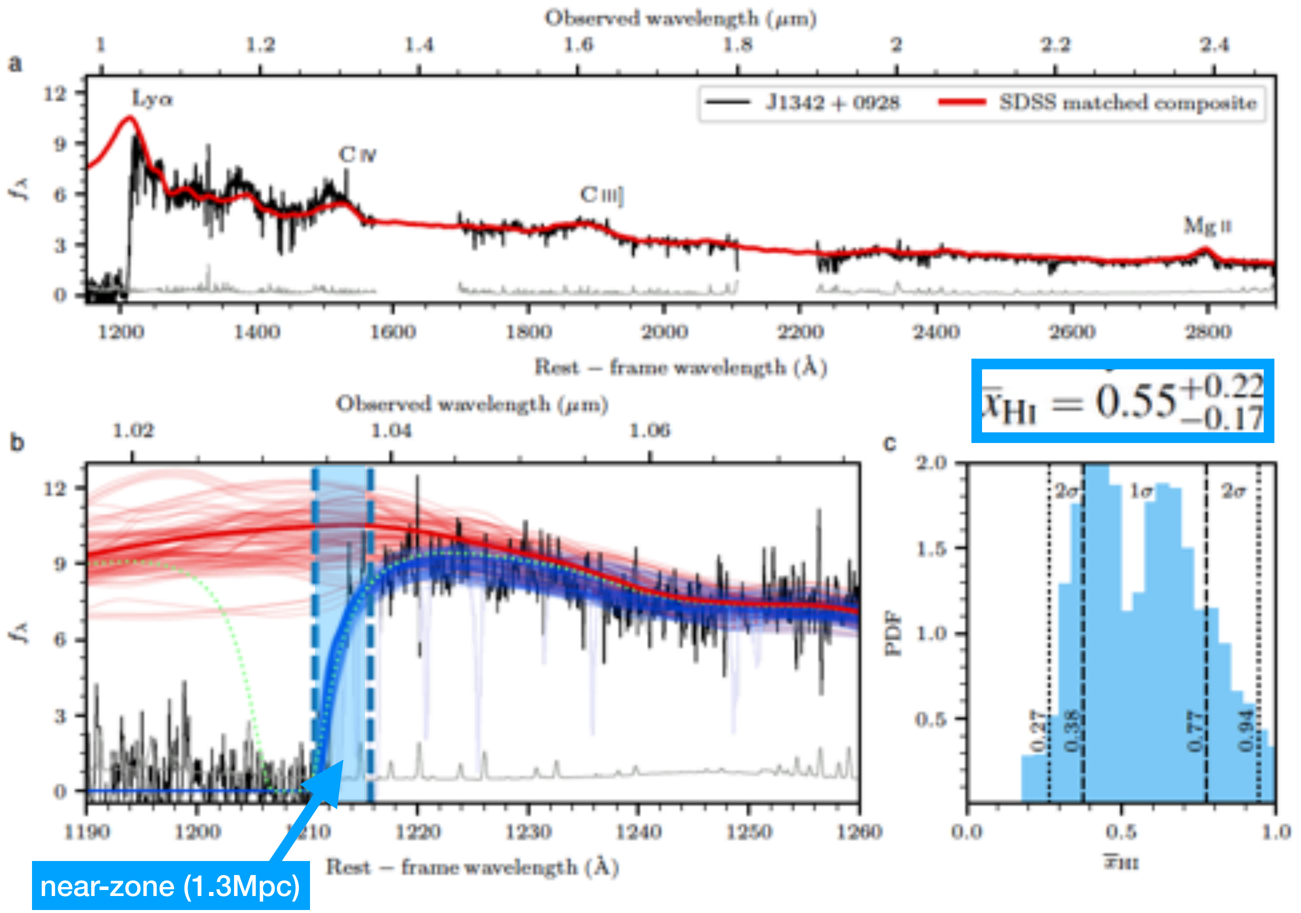




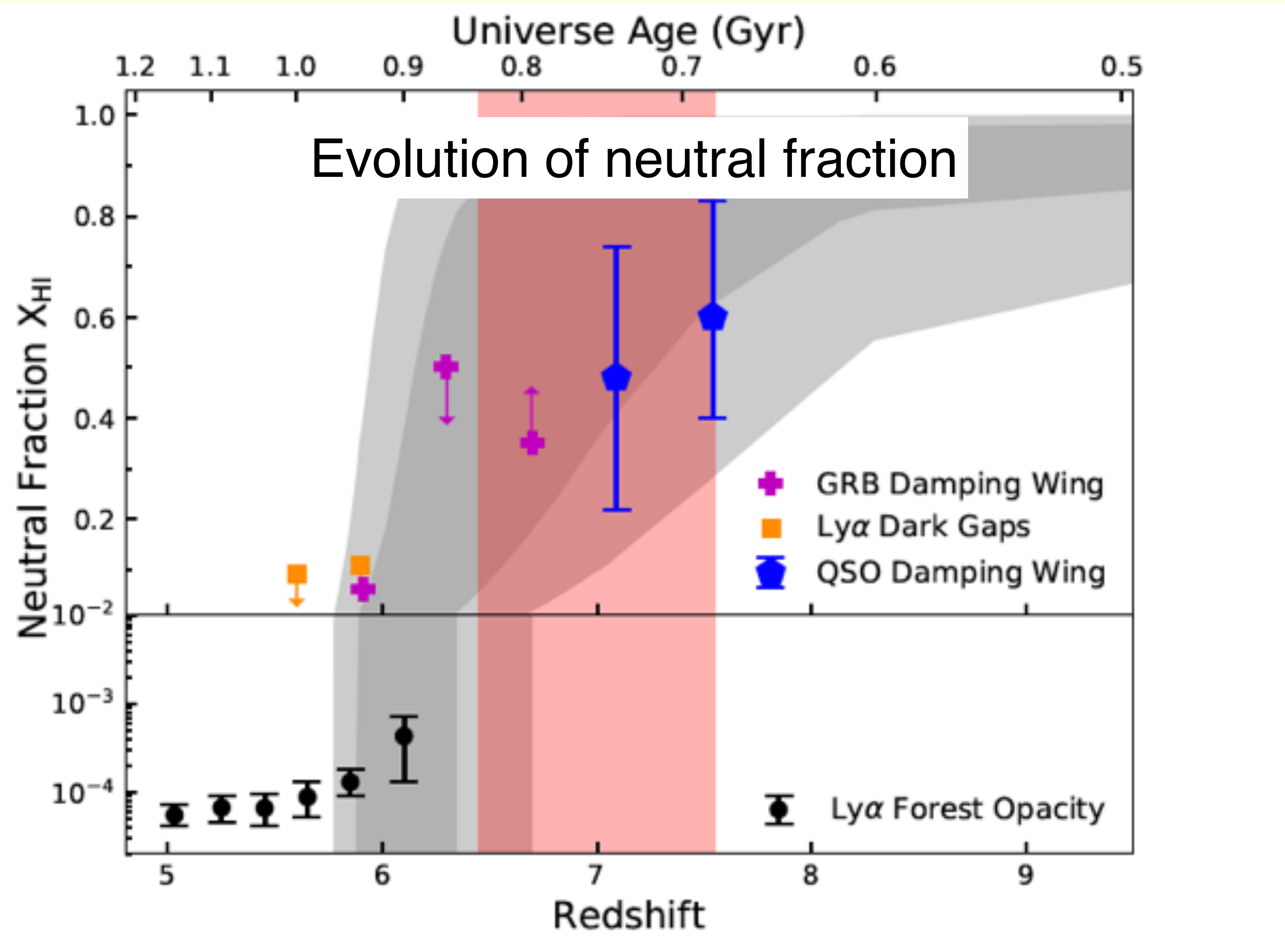
- substantial damping wing: f(HI)>=0.1

Mortlock et al. 2011

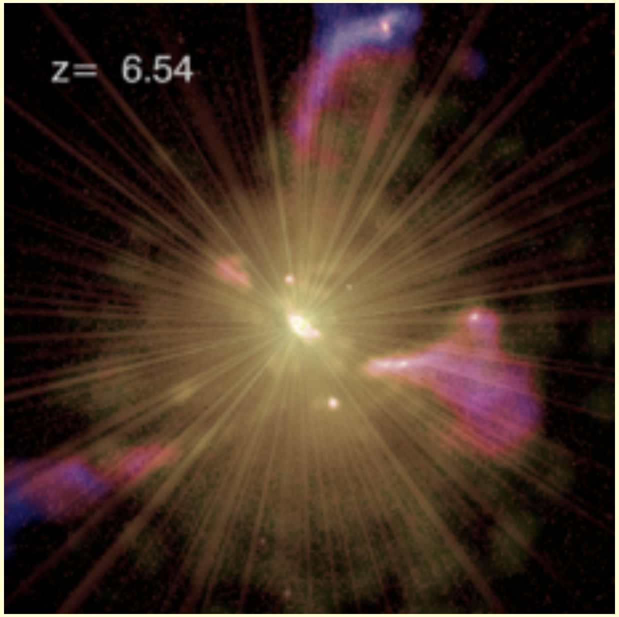
Gunn-Peterson Damping Wing
in z=7.54 Quasar



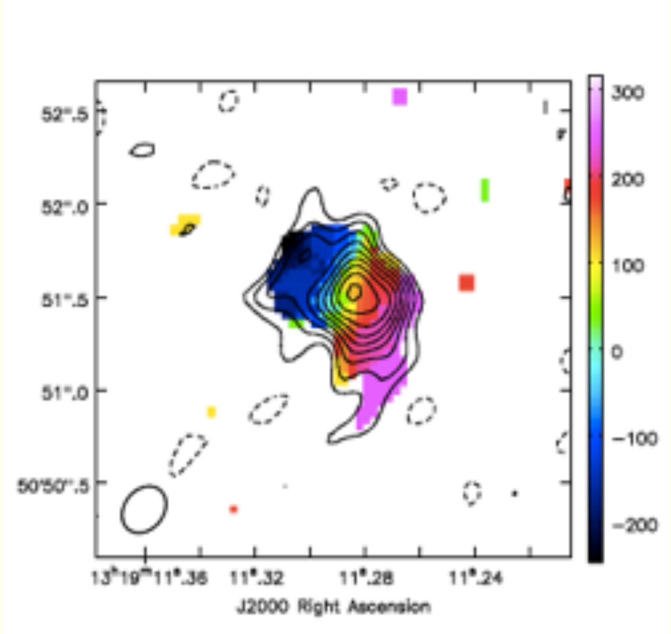
Banados+17


Evolution of neutral fraction
Universe Age (Gyr)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Neutral Fraction X_HI
1.0
0.8
0.6
0.4
0.2
10^-2
10^-3
10^-4
GRB Damping Wing
Lyα Dark Gaps
QSO Damping Wing
Lyα Forest Opacity
5
6
7
8
9
Redshift

Are biggest BHs in the biggest galaxies?



vS.



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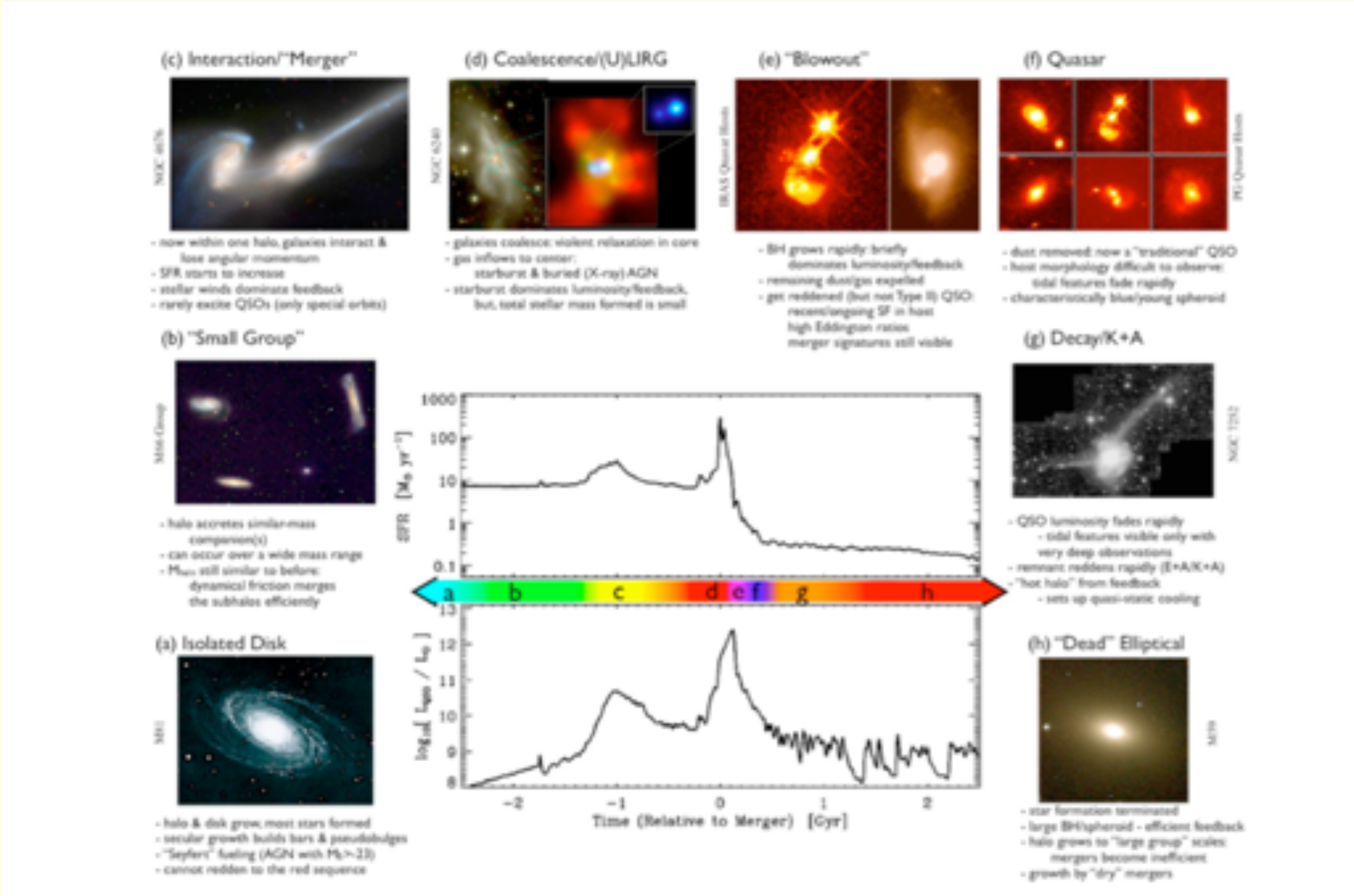
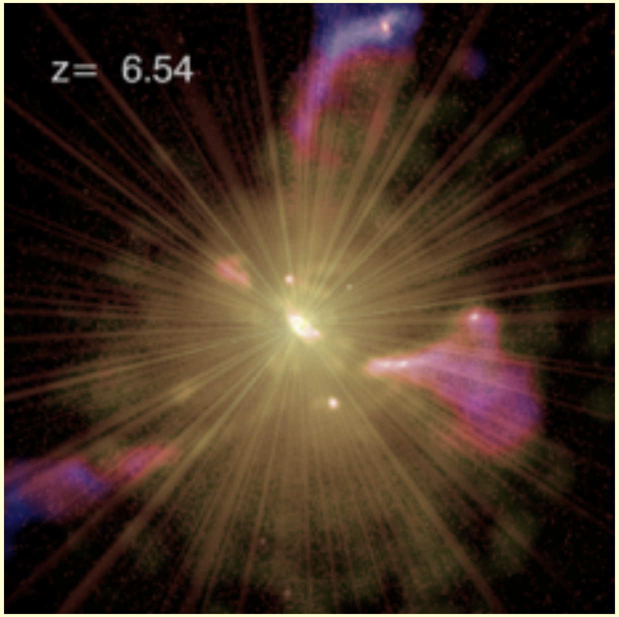
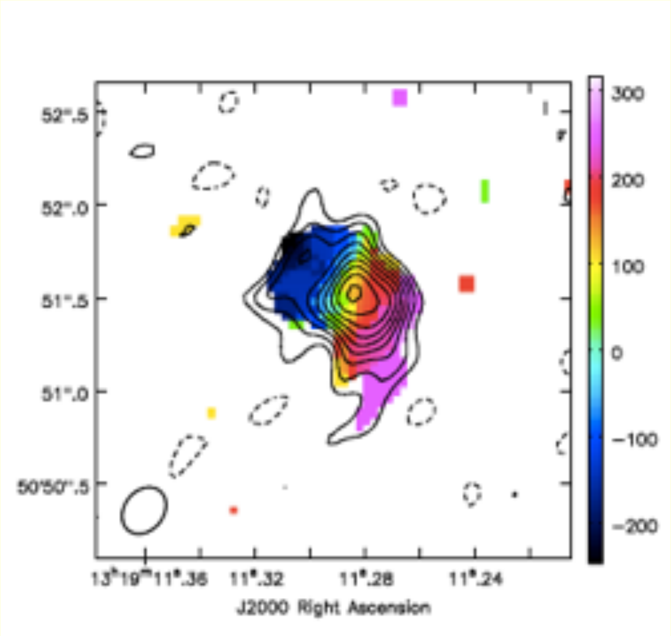


- **In merger driven galaxy evolution sequence, the most luminous quasars are:**
  - in the most massive halos
  - have high SFR
  - after the ULIRG/SMG phase
  - providing energy for galaxy feedback through winds/outflows

Co-Evolution of supermassive black holes and galaxies in the early universe



vs.

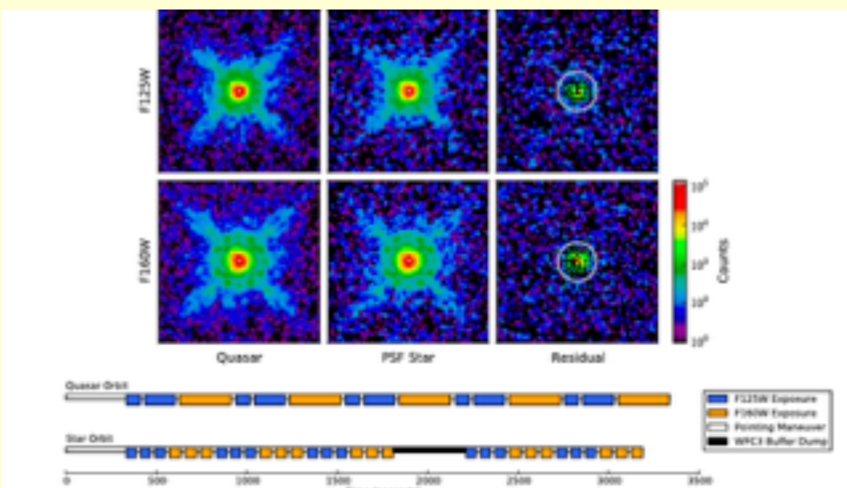


- Needs to measure:
  - BH mass
  - and the properties of quasar host galaxies

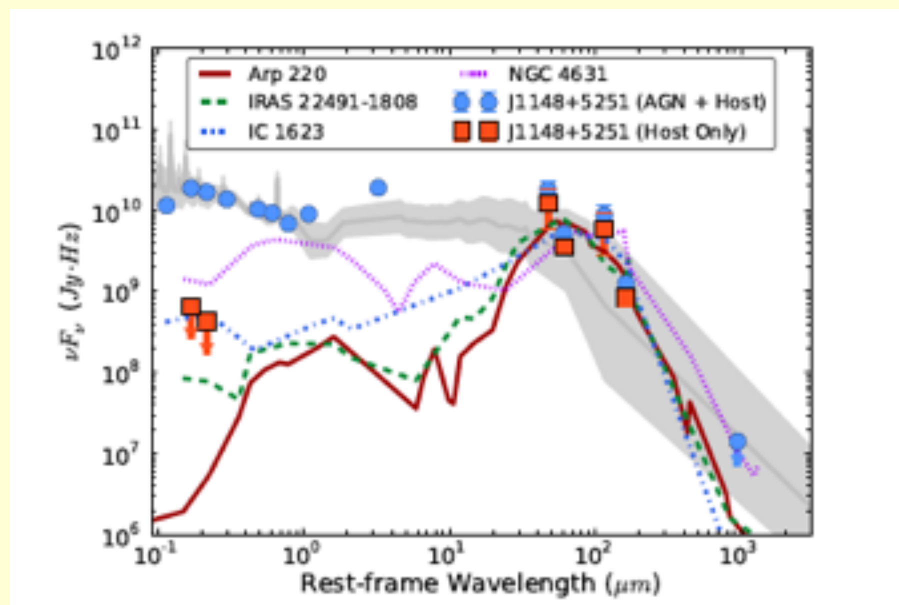
Rest-frame UV imaging of high-z quasar host galaxies with HST

- quasars outshine hosts by >100
- cosmological surface brightness:$(1+z)^{-4}$
- non reliable detection of stellar light so far

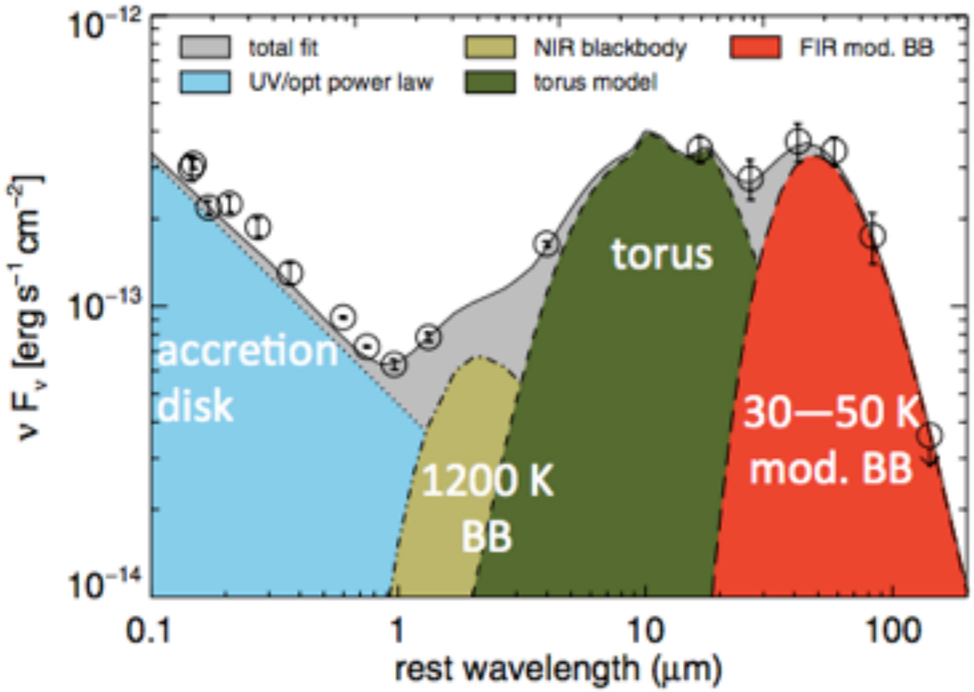
z=6.42, HST WFP3



Metchley et al. 2002



Spectral energy distribution

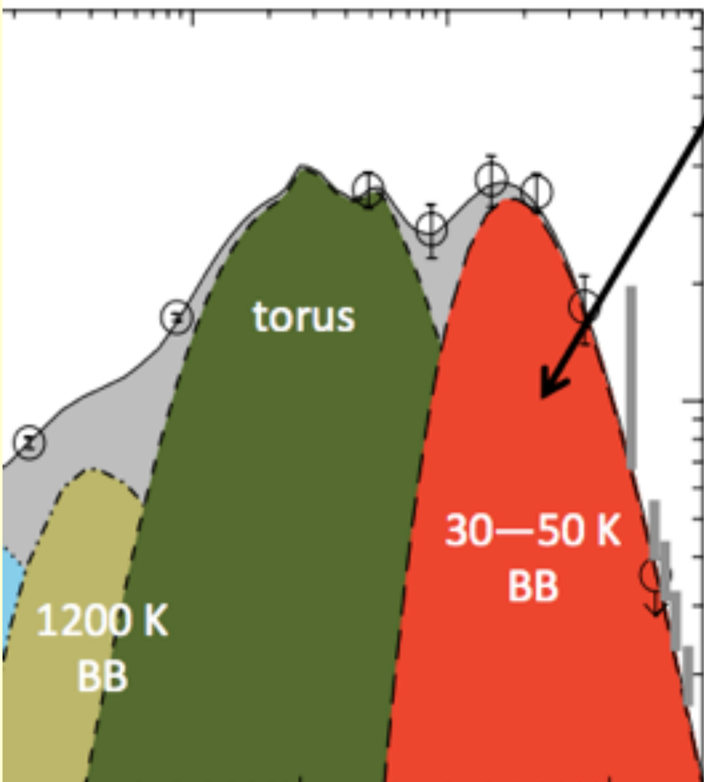


Spectral energy distribution

- UV/optical: accretion disk
- mid-infrared: hot dust and torus
- far-infrared: cold dust → host galaxy

Slide from Bram Venemans

(sub-)mm observations of quasars



Ground-based (sub-)mm observations (ALMA, NOEMA):

- **dust continuum**
  - star-formation (SF) tracer
  - ISM mass
- **[C II] 158 μm line**
  - main ISM coolant
  - strongest line in FIR
  - SF tracer
- **CO lines:**
  - ISM tracer
  - cold gas supply for SF

Slide from Bram Venemans

(sub-)mm observations of quasars

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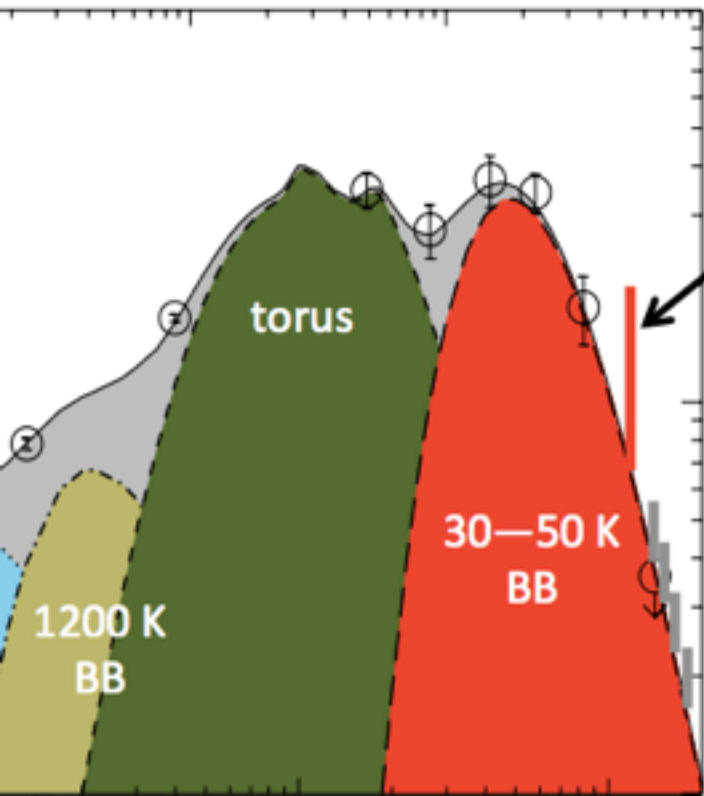

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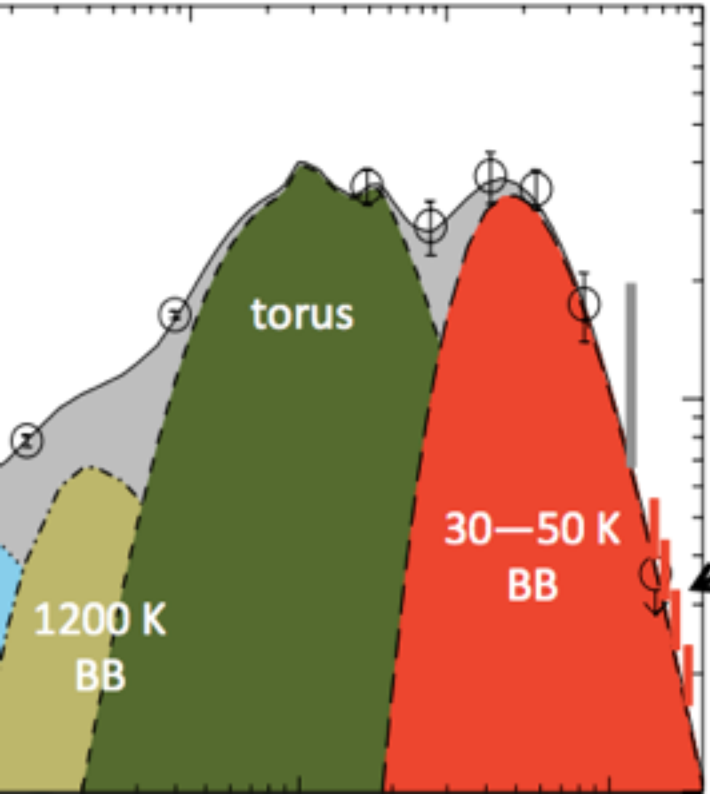
(sub-)mm observations of quasars



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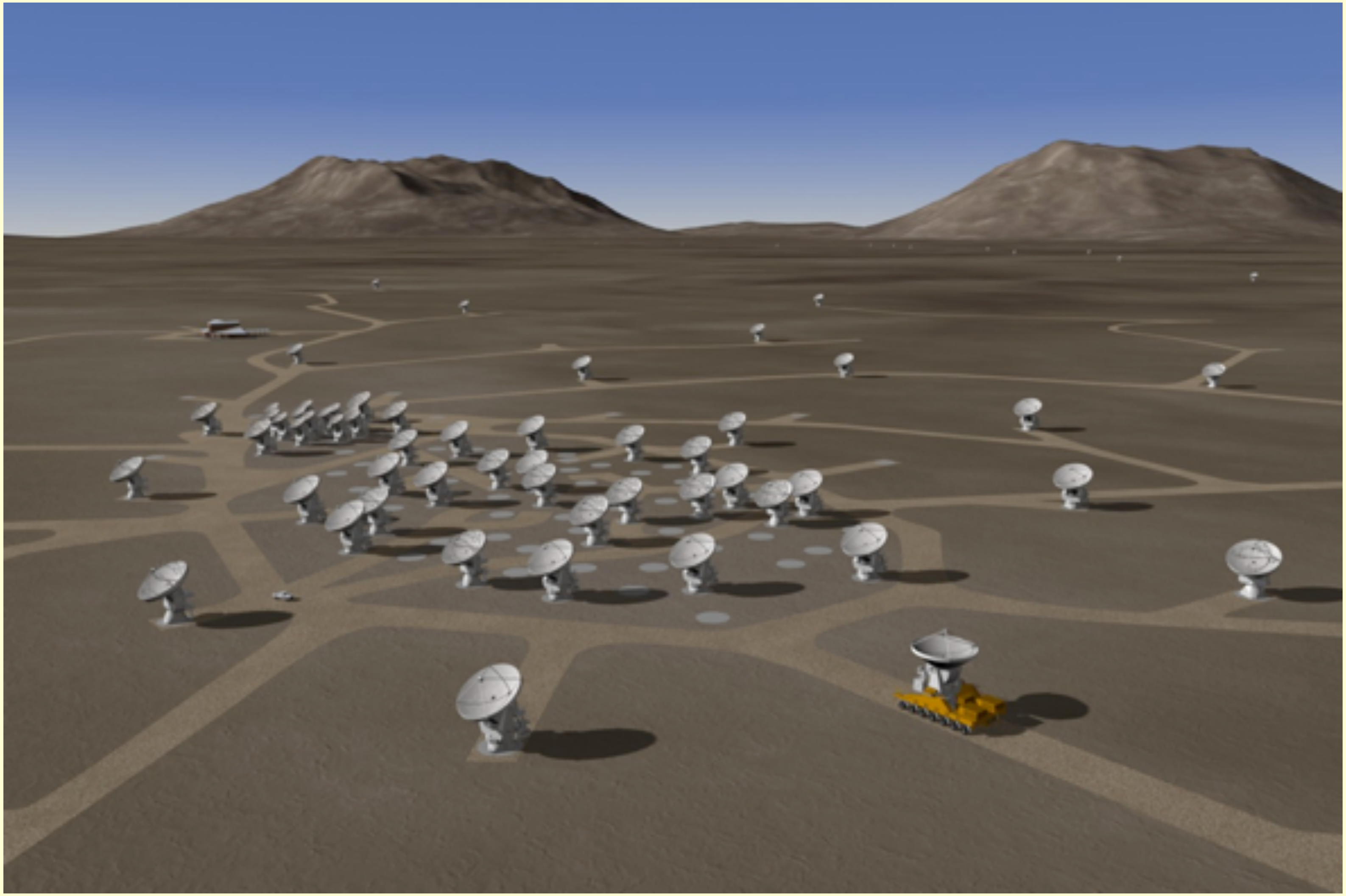
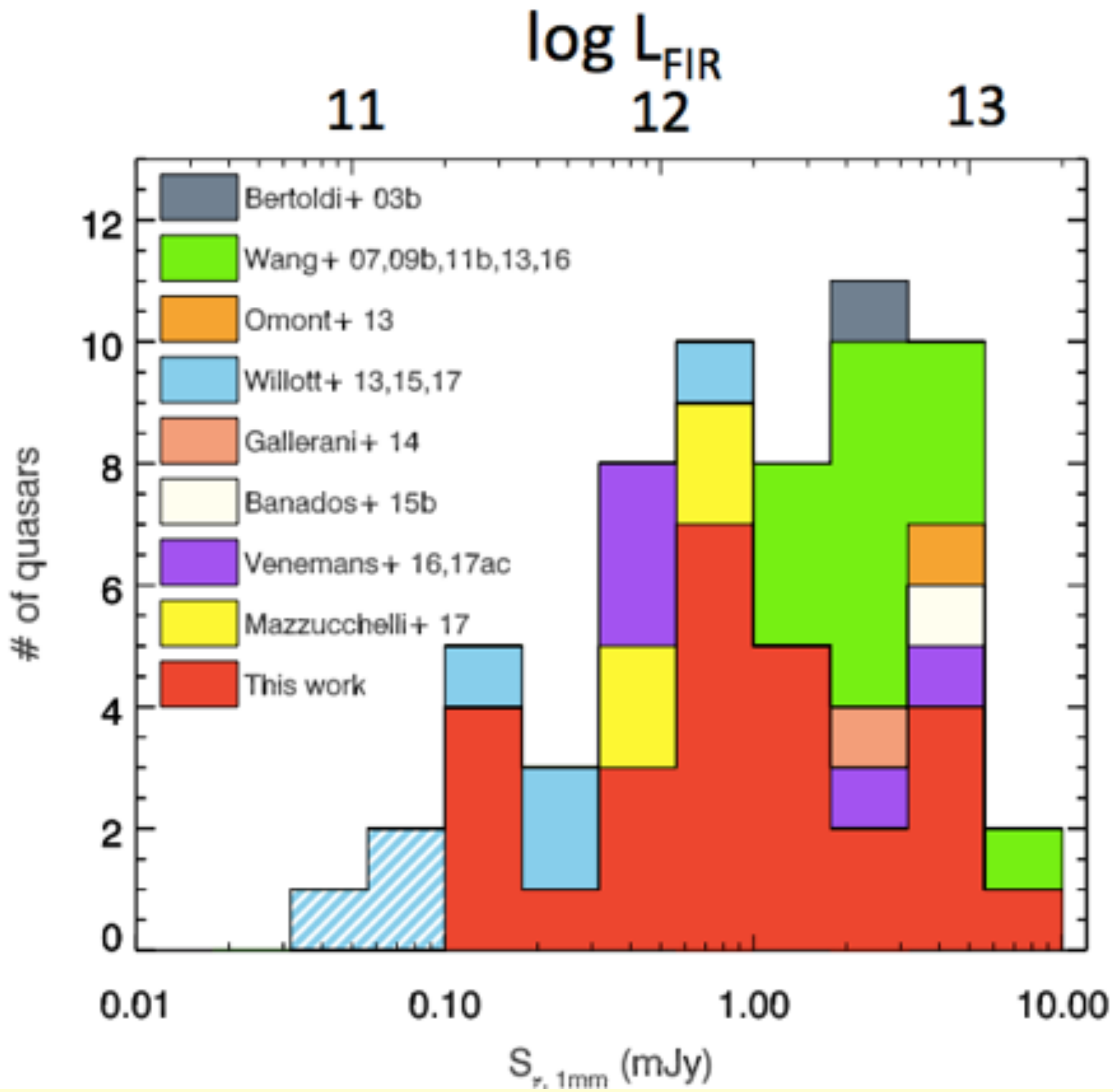
ALMA



Dust continuum observations



A very large fraction of z>6 quasar hosts detected in the FIR

Decarli+ 18
BV+ 18

Slide from Bram Venemans

Properties of z>6 quasar host galaxies

- Sizes around 1 – 3 kpc
- SFRs: 100 – 1500 M_{sun}/yr
- Dust masses: $10^7 - 10^9$ M_{sun}
- SFRD: 50 – 400 $M_{sun}/yr/kpc^2$

→ Orion-like SFRDs, over kpc scales

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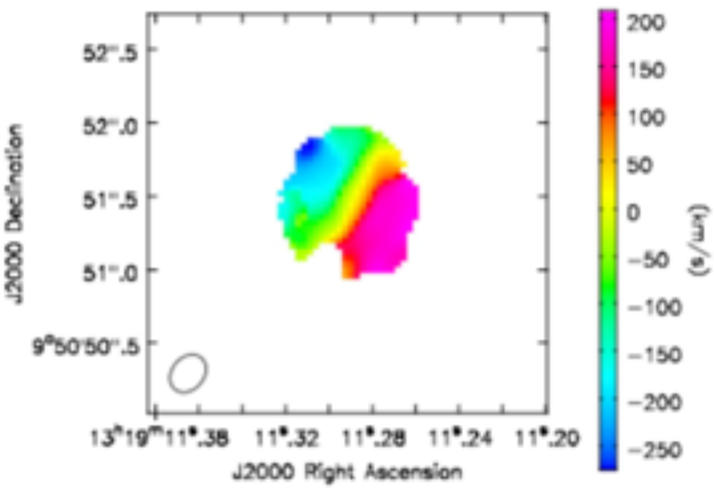
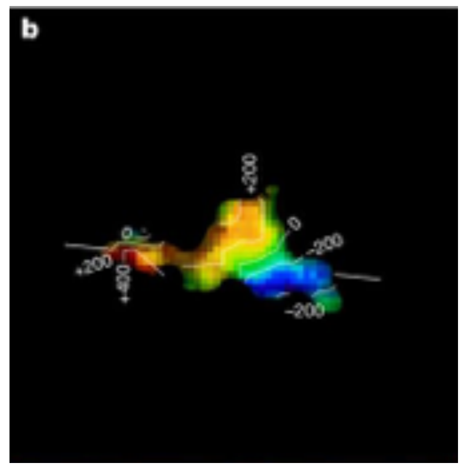
Diversity of the host galaxies of reionization-era quasars environment revealed by ALMA

rotation



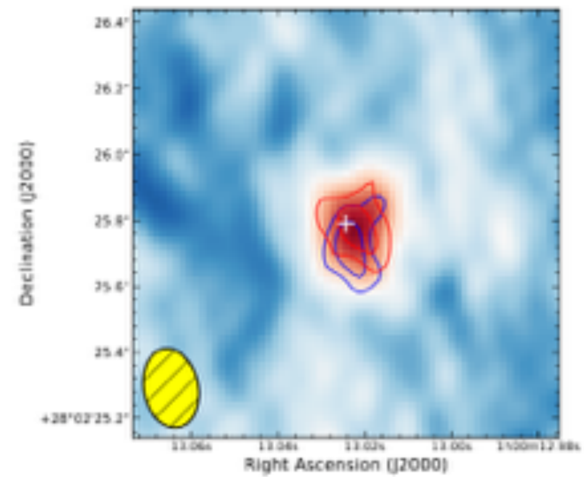
Shao et al.2018

merger



Decarli et al. 2018

no ordered motion



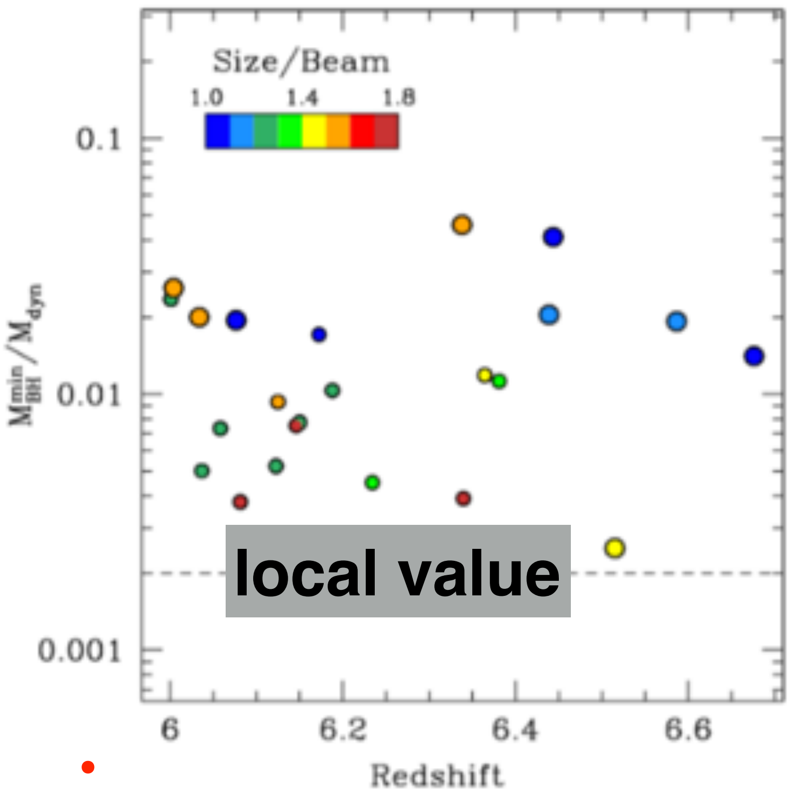
Wang et al. 2019

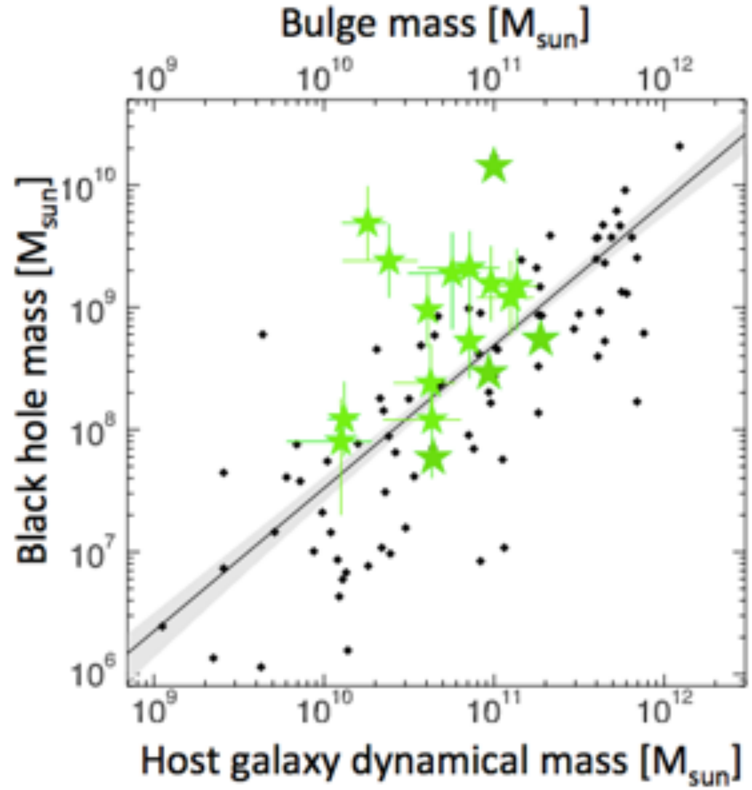
- bright submm sources: warm dust -> SFR >100 solar mass/year
- bright CO emission: cool gas -> 10^10 solar mass H2 mass
- enhanced merger rate
- formation of the most massive galaxies in early universe

What about host galaxy mass

- assume: dynamical mass = bulge mass
- line and size comes from [CII] or CO
- with rotation curve: fit dynamical model
- without rotation curve: M sin(i) ~ FWHM^2 x radius

Evolution of M-sigma relation?





-
- M_{BH}/M_{dyn} ~ 0.002 - 0.05
- local relation: ~1.4 x 10^{-3}
- average: one order of mag higher ratio at z~6 vs. z~0

Caveats

- selection bias: targeting brightest quasar
- uncertainty in black hole mass
- uncertainly in host galaxy dynamical mass
- this is not what simulation shows

- evolution of M-sigma relation still an open question

What we know about high-z quasar evolution and black hole growth

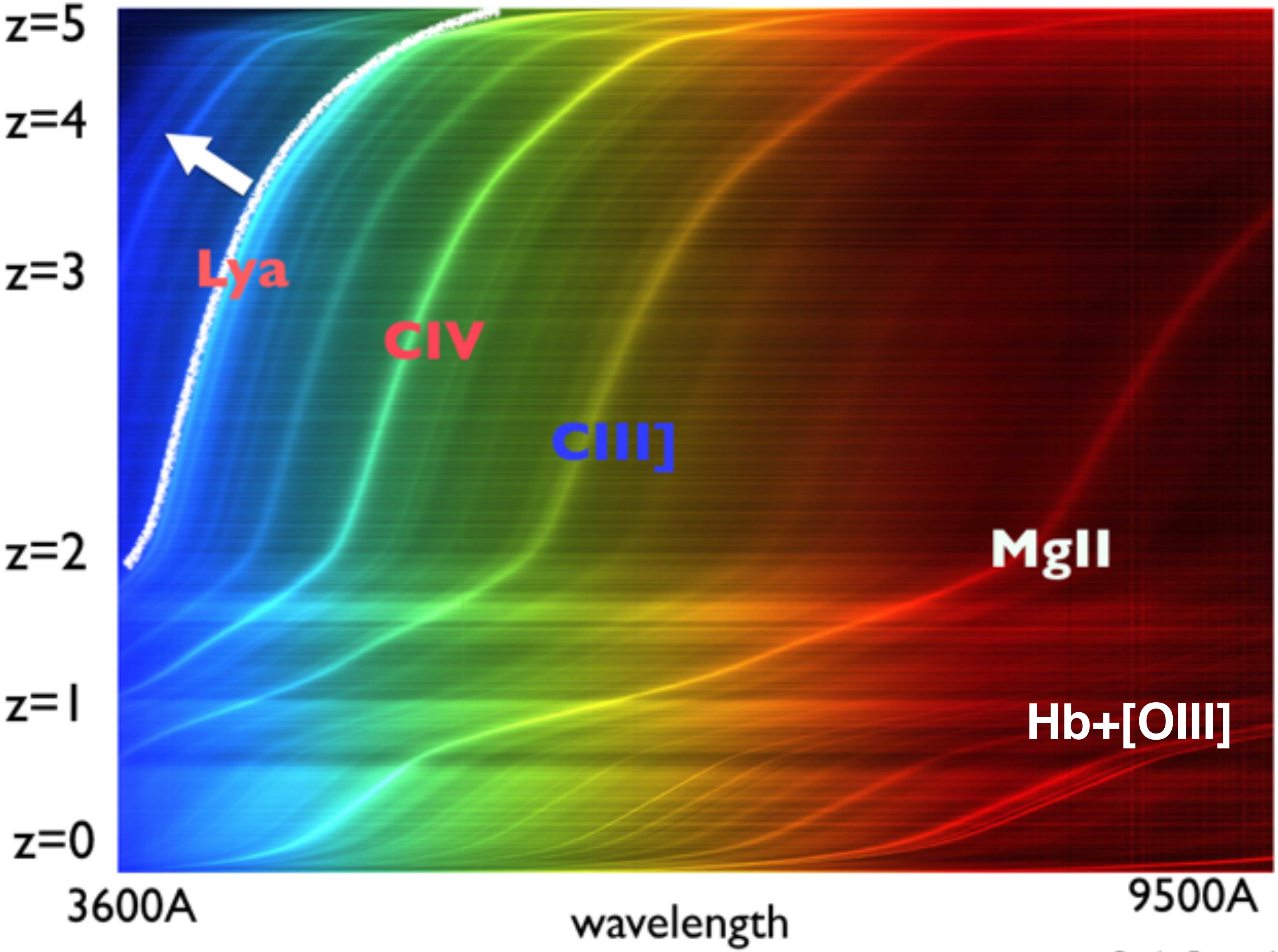
- luminous quasars have been discovered at z>7
- they are powered by billion solar mass black holes
- they are among the rarest objects in the universe and their density declines rapidly towards higher redshift
- they are hosted by galaxies with strong star formation activities and abundance molecular gas
- high-z quasar spectra show a rapid increase of neutral hydrogen fraction in the IGM at z>6 — end of reionization.

what are the open questions?

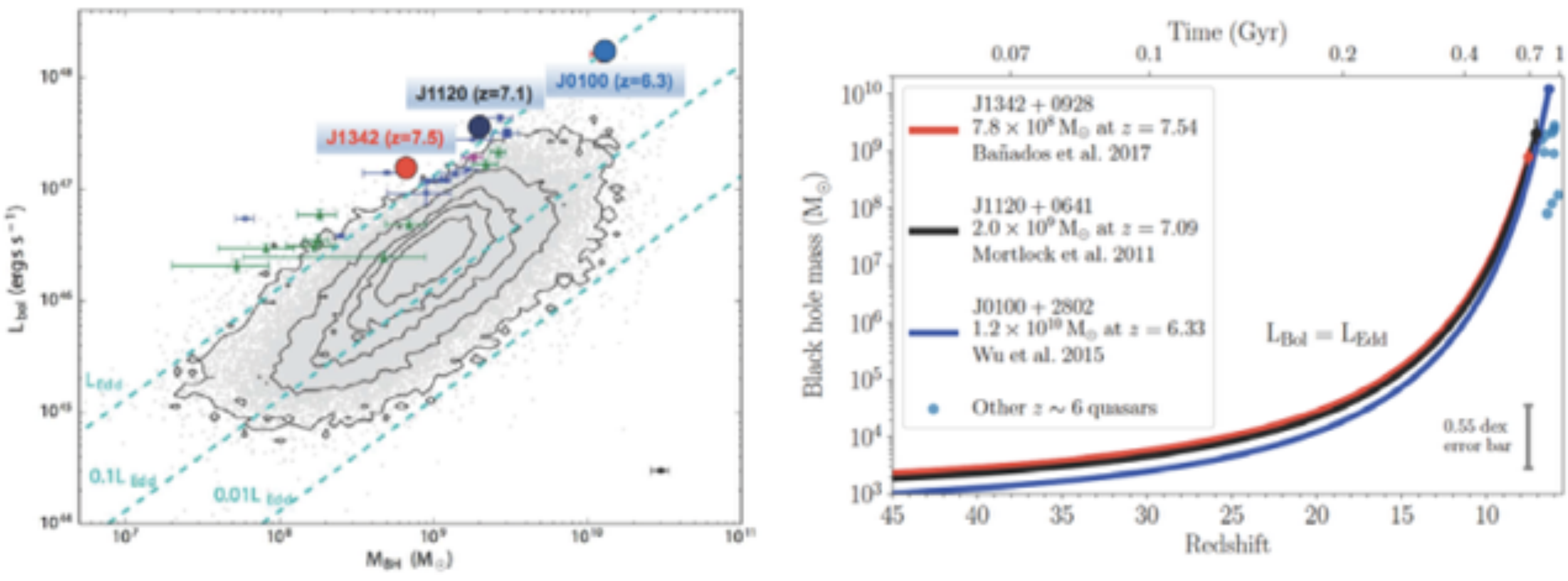
- how to push the redshift limit beyond z~8
- how to efficiently search for low-luminosity quasars/smaller BHs at z>7
- do we really need massive seed or different accretion mode to grow billion solar mass BHs?
- are hosts of luminous quasars massive? and do they live in dense environment?
- is the IGM about half neutral by z~7

summary: three plots to remember

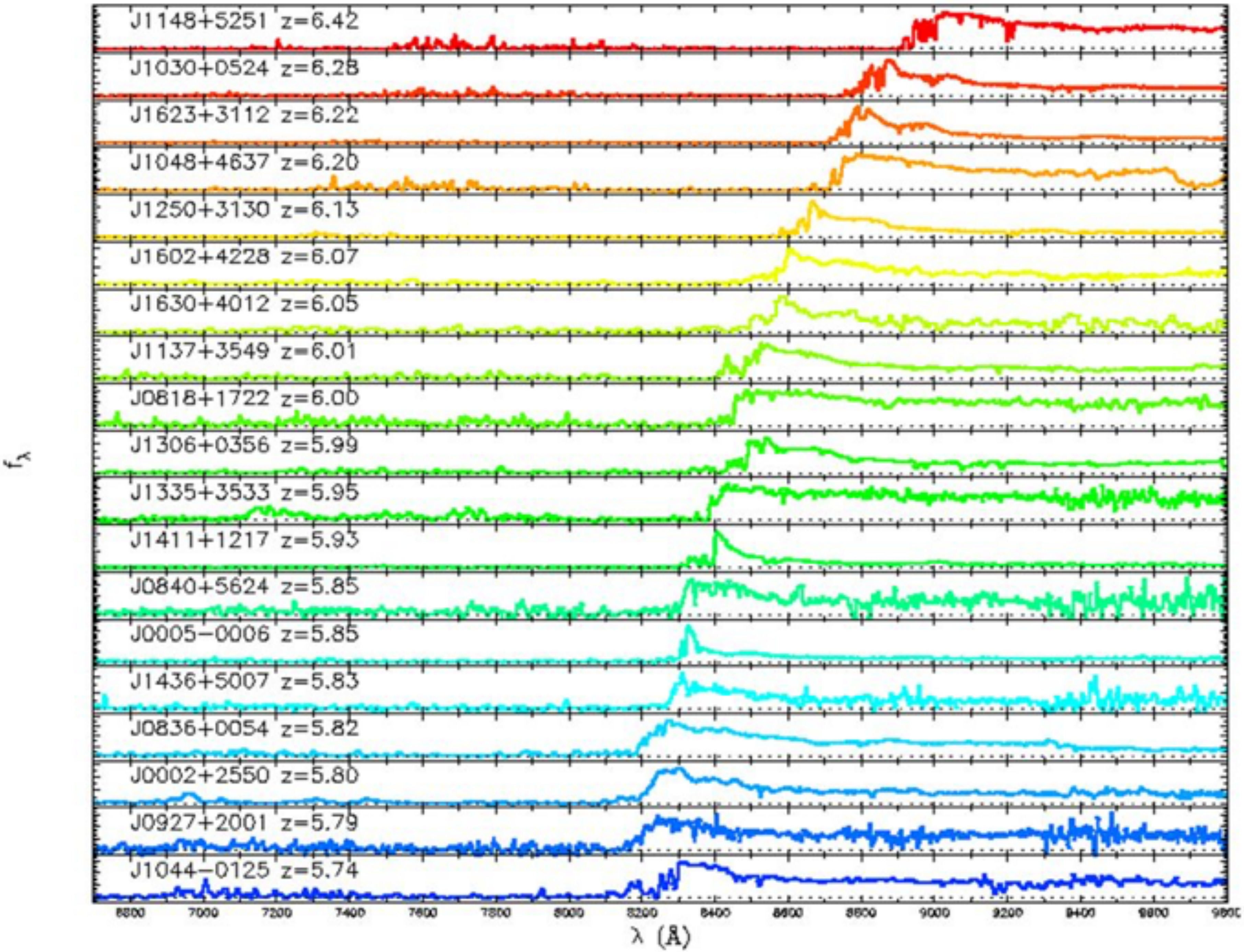
SDSS DR12 (2016) : 300,000 quasars



Credit: Franco Alberti



J0100 (z=6.3)
J1120 (z=7.1)
J1342 (z=7.5)
L_{Edd}
$0.1L_{Edd}$
$0.01L_{Edd}$
L_{bol} (ergs s^{-1})
M_{BH} ($M_\odot$)
Time (Gyr)
0.07
0.1
0.2
0.4
0.7
1
J1342 + 0928
$7.8 \times 10^8\,M_\odot$ at $z = 7.54$
Bañados et al. 2017
J1120 + 0641
$2.0 \times 10^9\,M_\odot$ at $z = 7.09$
Mortlock et al. 2011
J0100 + 2802
$1.2 \times 10^{10}\,M_\odot$ at $z = 6.33$
Wu et al. 2015
Other $z \sim 6$ quasars
$L_{Bol} = L_{Edd}$
0.55 dex error bar
Black hole mass ($M_\odot$)
Redshift
45
40
35
30
25
20
15
10


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
f_λ
λ (Å)