Observational Probes of Cosmic Reionization

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TIARA Winter School

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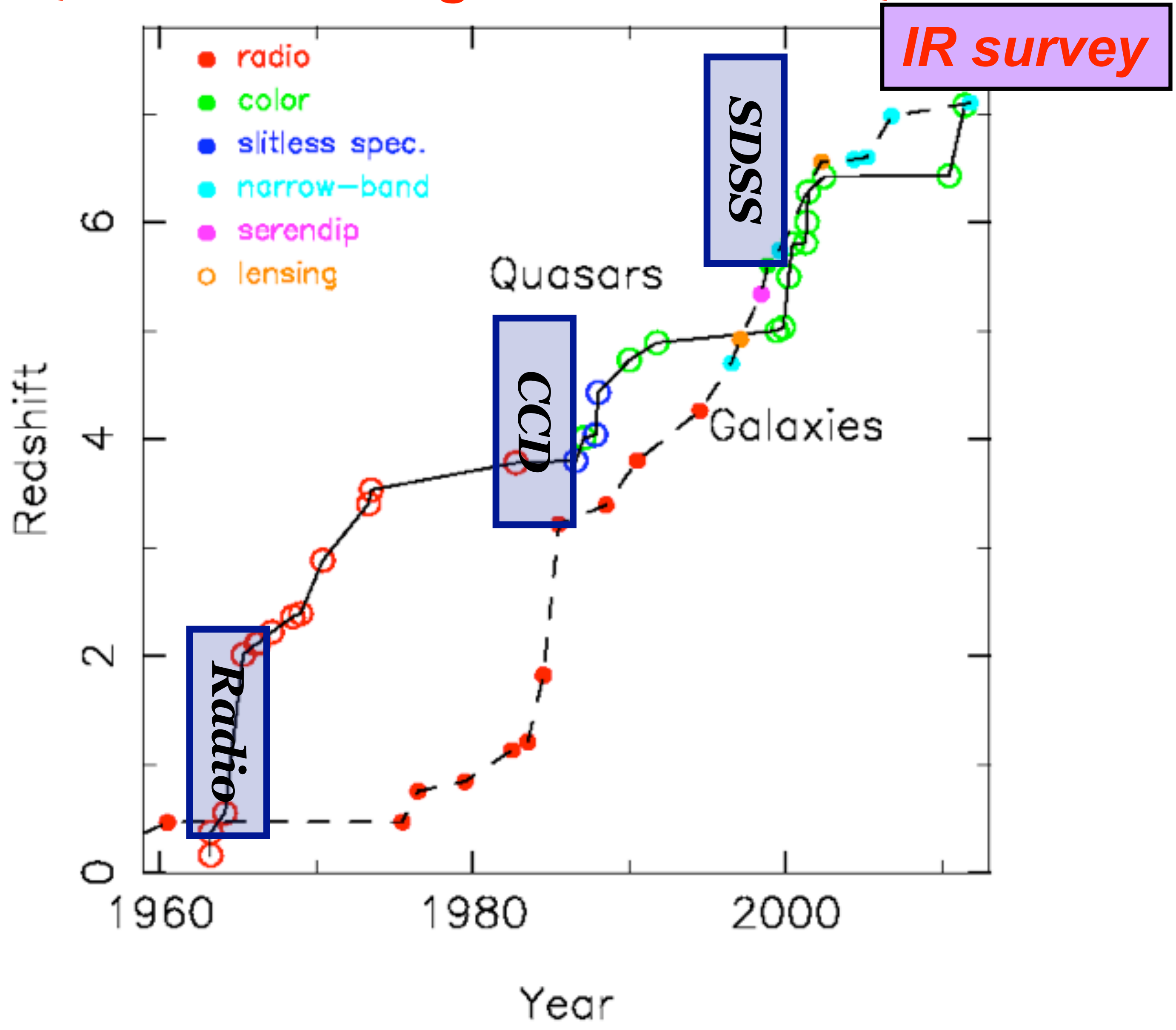
Background: 46,420 Quasars from the SDSS Data Release Three


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

Quest to the Highest Redshift Quasars



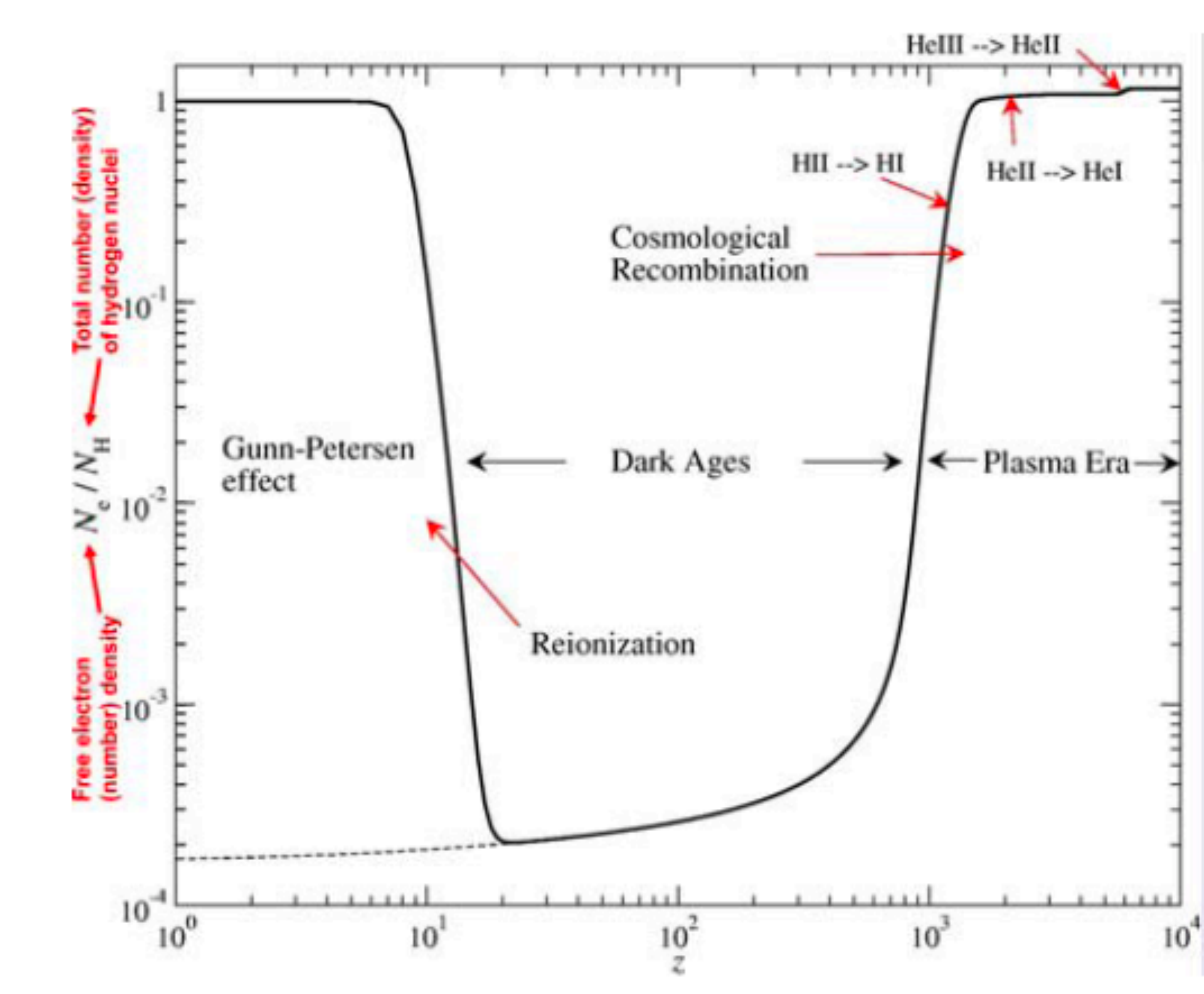
Gunn-Peterson Effect

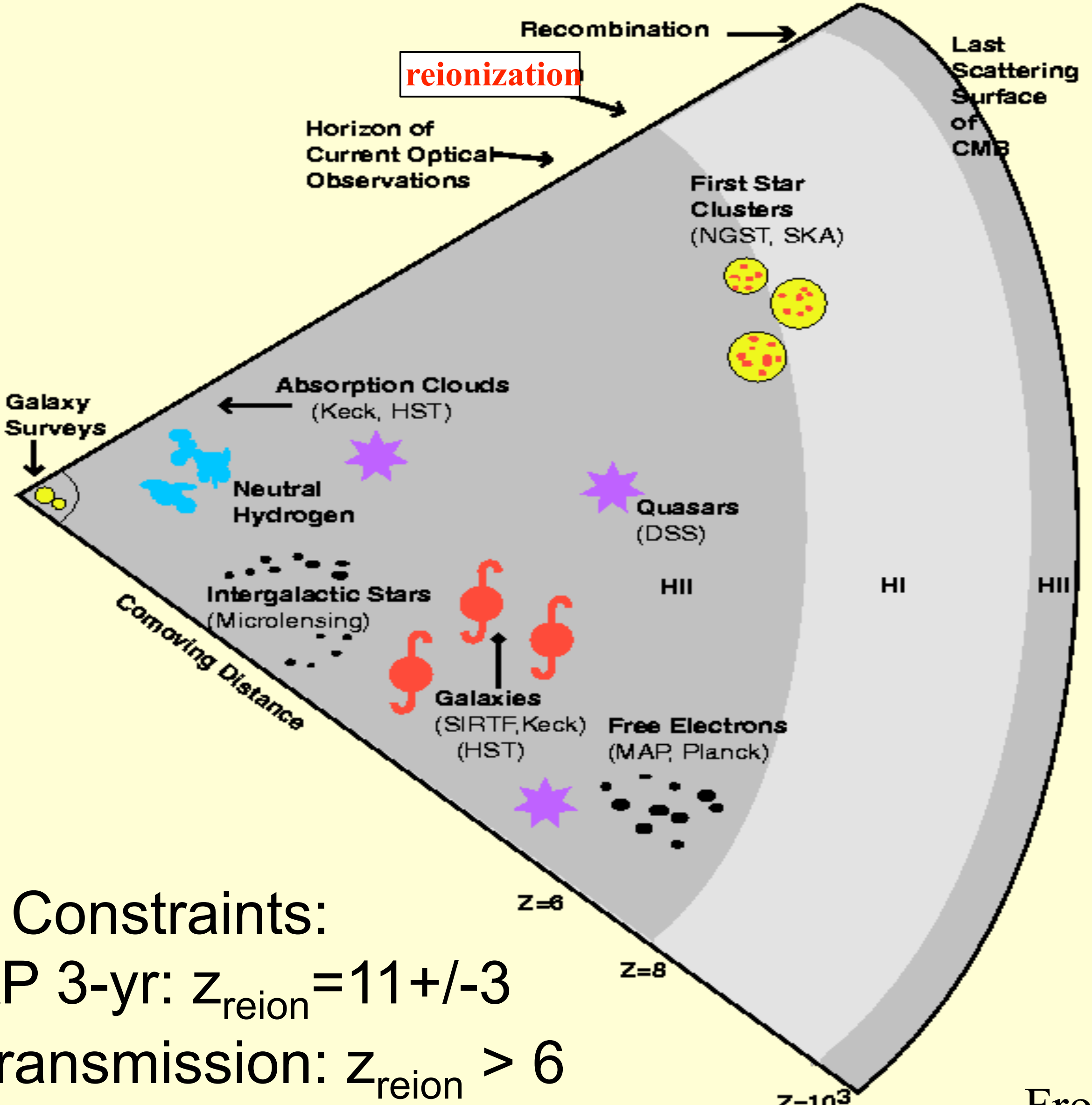
- Gunn and Peterson (1965)
  - "It is observed that the continuum of the source continues to the blue of Ly-α (in quasar 3C9, z=2.01)"
  - "only about one part of $5x10^6$ of the total mass at that time could have been in the form of intergalactic neutral hydrogen "
- After recombination, the universe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

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

Observational Constraints of Reionization

- Reionization at z=6-15 (peak at z ~10)
- Tentative evidence of drastic change in the IGM ionization state at z~7
- IGM most likely ionized by early galaxies but detailed process still highly uncertain
- A major focus of future facilities: IGM, ELTs, SKA etc.


HeIII --> HeII
HII --> HI
HeII --> HeI
Cosmological
Recombination
Gunn-Petersen
effect
Dark Ages
Plasma Era
Reionization
Total number (density)
of hydrogen nuclei
Free electron
(number) density
N_e / N_H
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
z

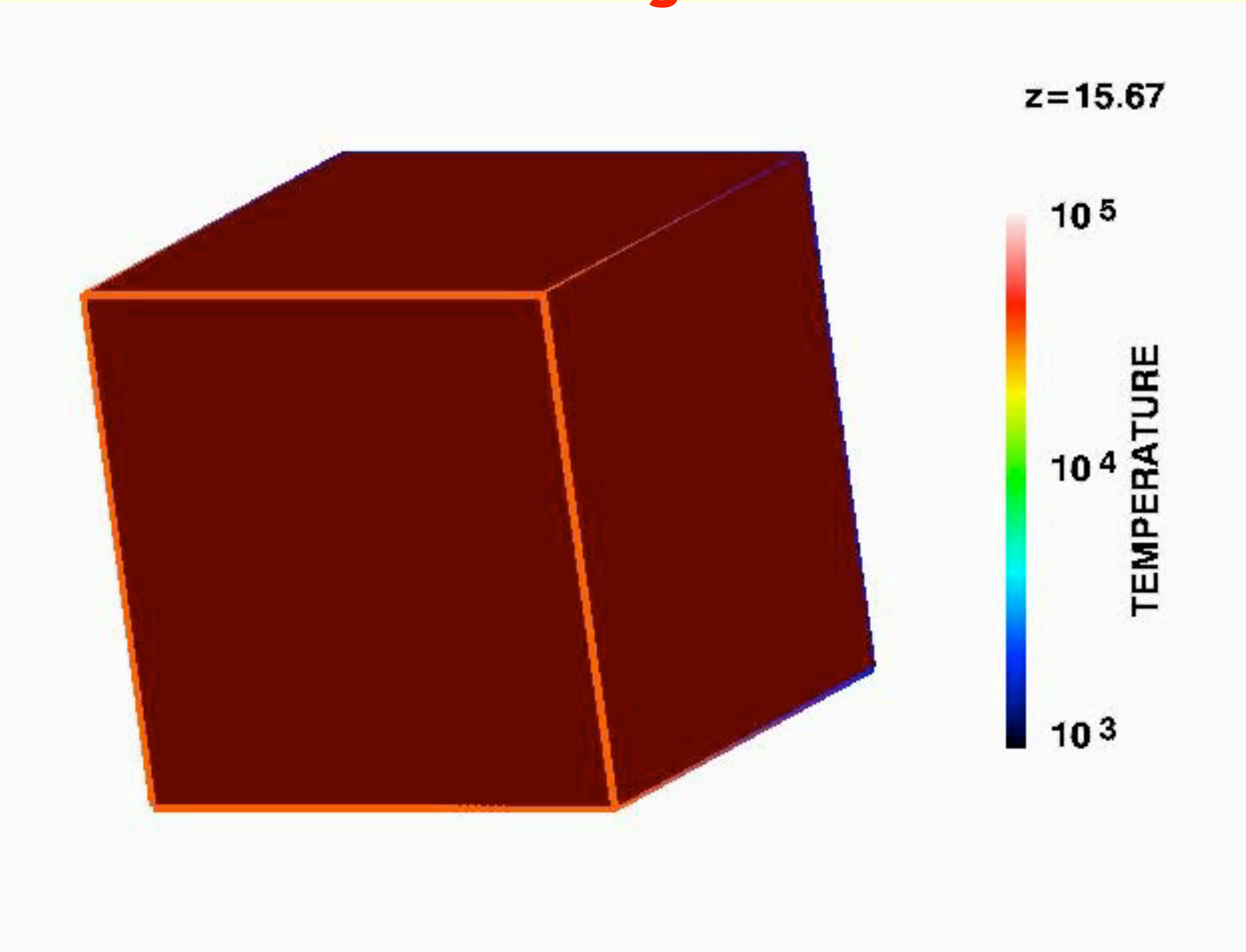


Two Key Constraints:

1. WMAP 3-yr: z_{reion}=11+/-3
2. IGM transmission: z_{reion} > 6

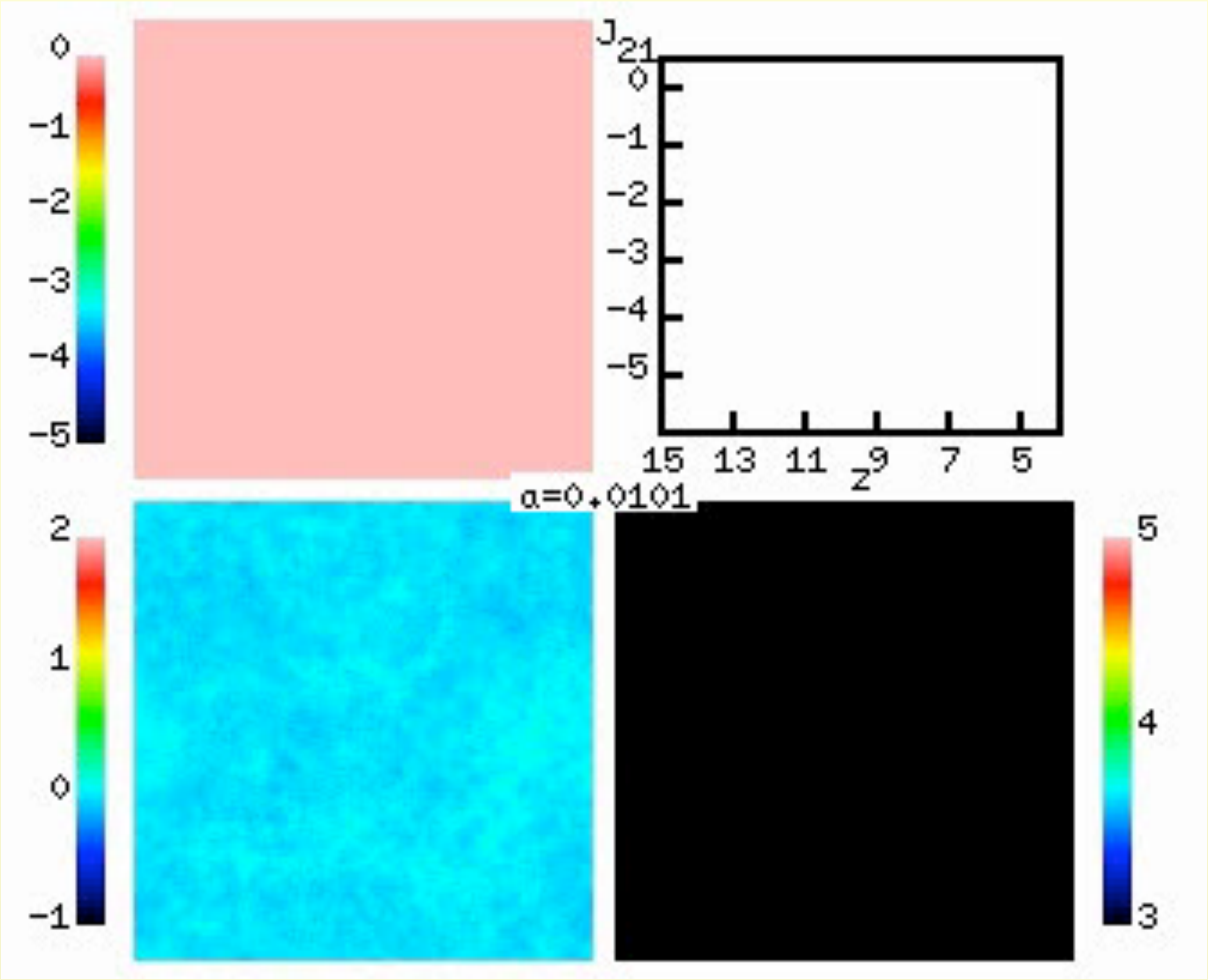
From Avi Loeb

The end of dark ages: Movie



Neutral fraction

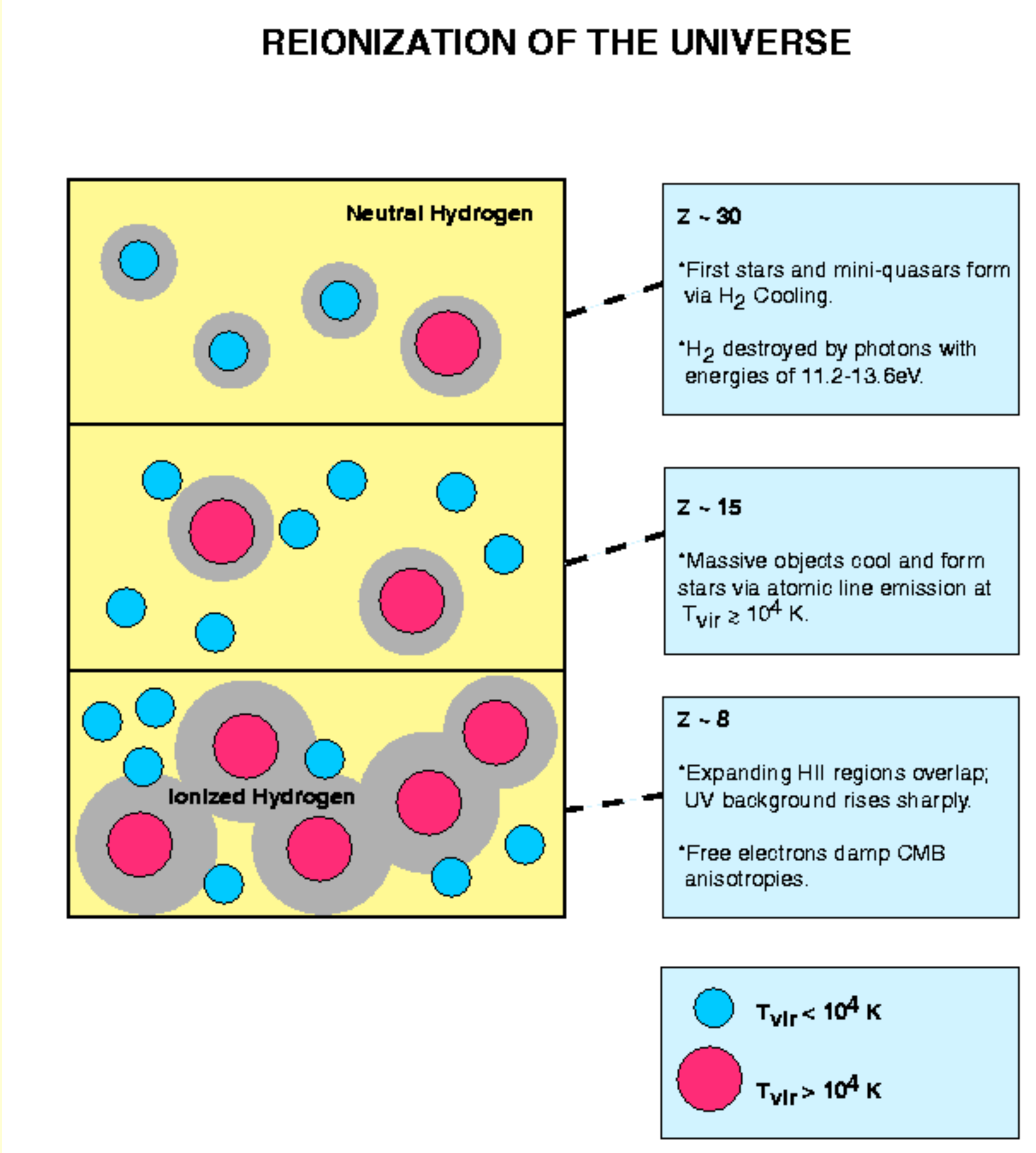
UV background



Gas density

Gas temperature

Gnedin 2000



Three stages

Pre-overlap

↓

Overlap

↓

Post-overlap

From Haiman & Loeb

Open Questions:

- ***When*** did it happen: f_{HI} **vs. z**
  - z~6: late
  - z~15: early
  - Extended or phase transition?
- ***How*** did reionization proceed:
  - Homogeneous or large scatter?
  - Topology of overlap
- ***What*** did it: **ε(gal, qso) vs. z**
  - AGN?
  - Star formation?
  - Decay particles?
- Observational goals
  - Map the evolution and spatial distribution of ionization state
  - Find highest redshift galaxies and quasars: source of reionization

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 5×10^6 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***
- ***First detection of complete G-P trough: SDSS J1030 (z=6.28, Becker et al. 2001)***
- G-P optical depth → evolution of ionizing background and neutral fraction of the IGM

Gunn-Peterson Effect

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

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

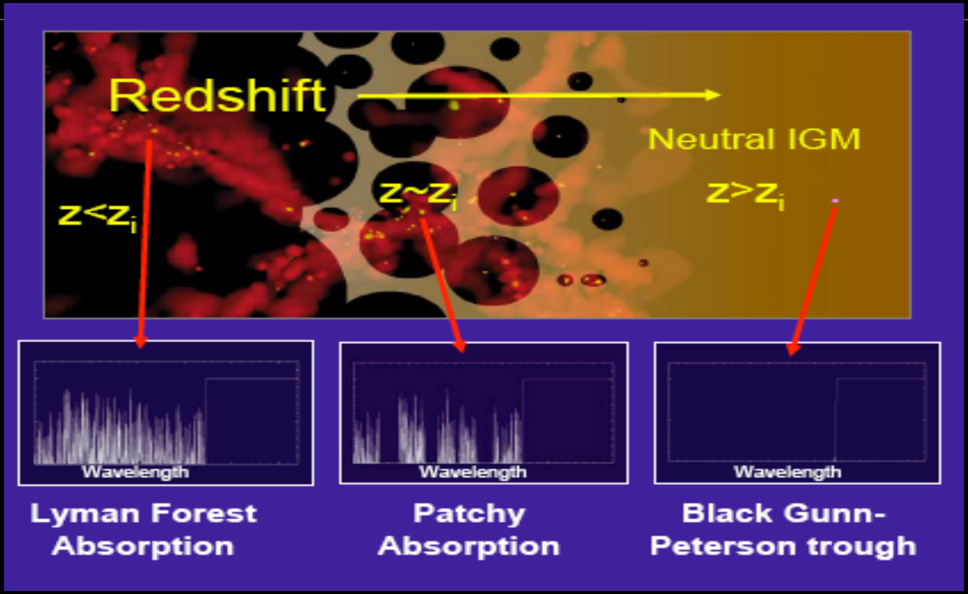
$$dl/dz = c/H(z) = cH_0^{-1}(1+z)^{-3/2}$$

$$\sigma = \pi e^2 f/m_e c$$

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

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

Gunn-Peterson Test

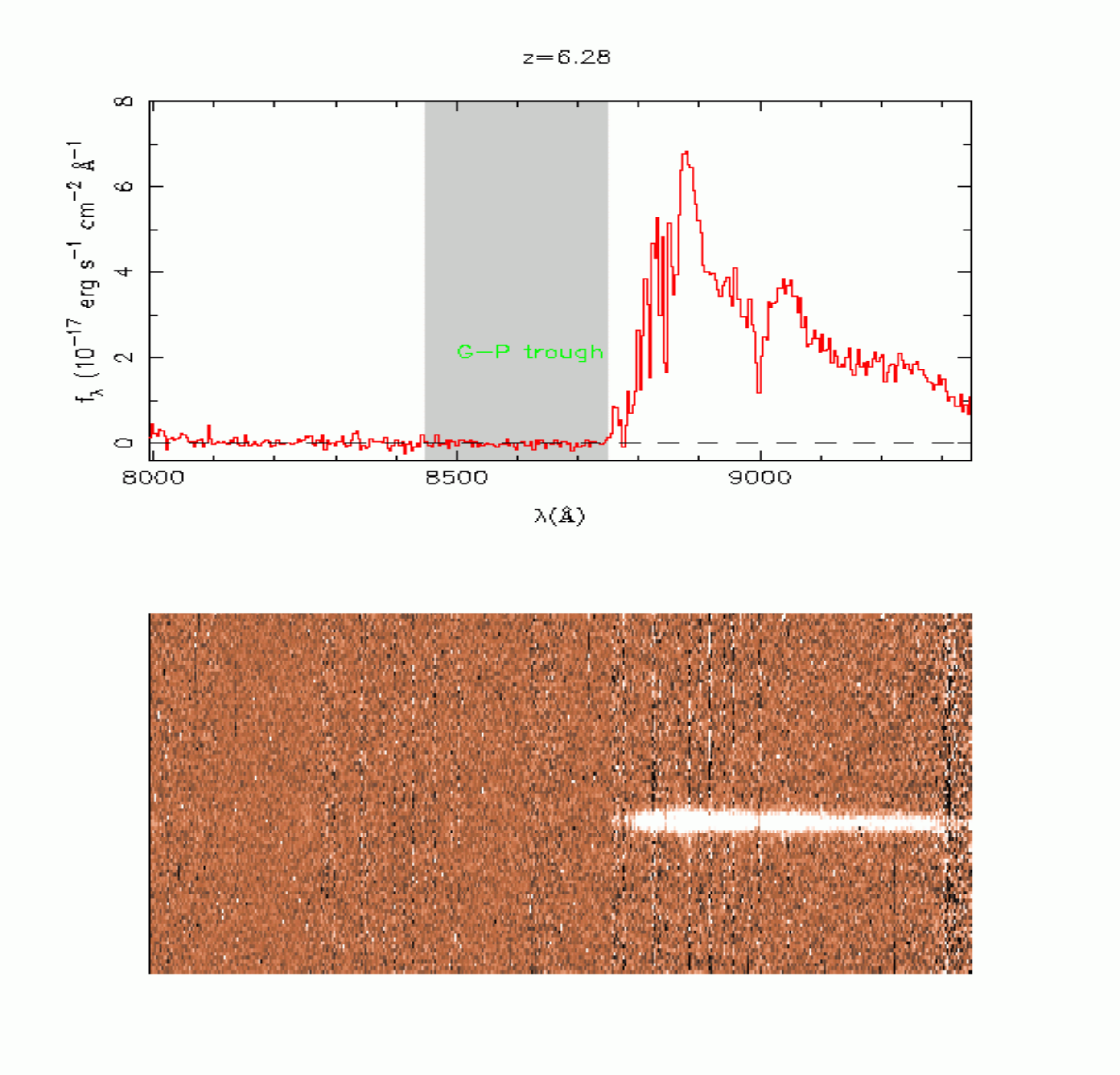


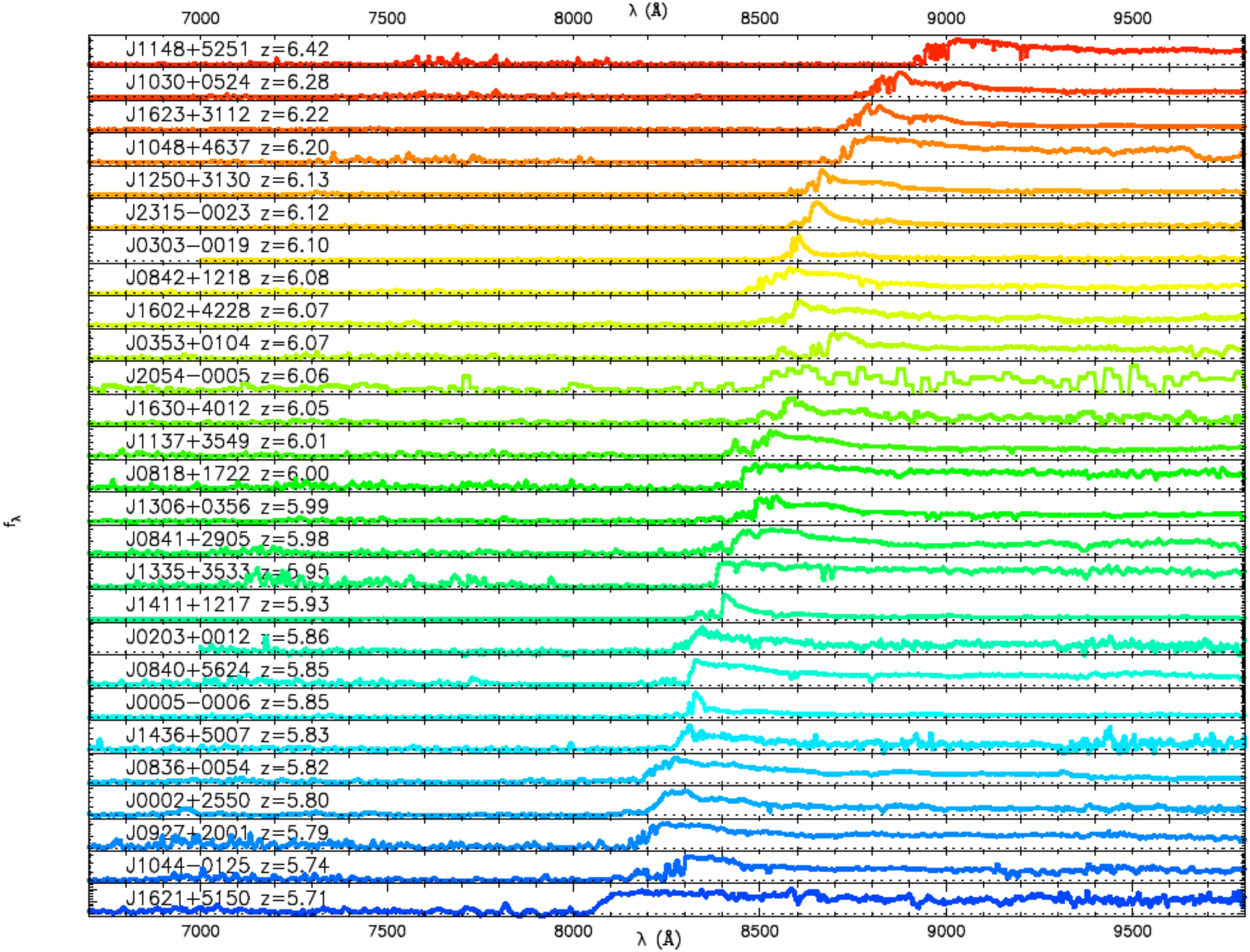
- Classic G-P (1965) effect:

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

  - Saturates at low neutral fraction

First detection of Gunn-Peterson Effect



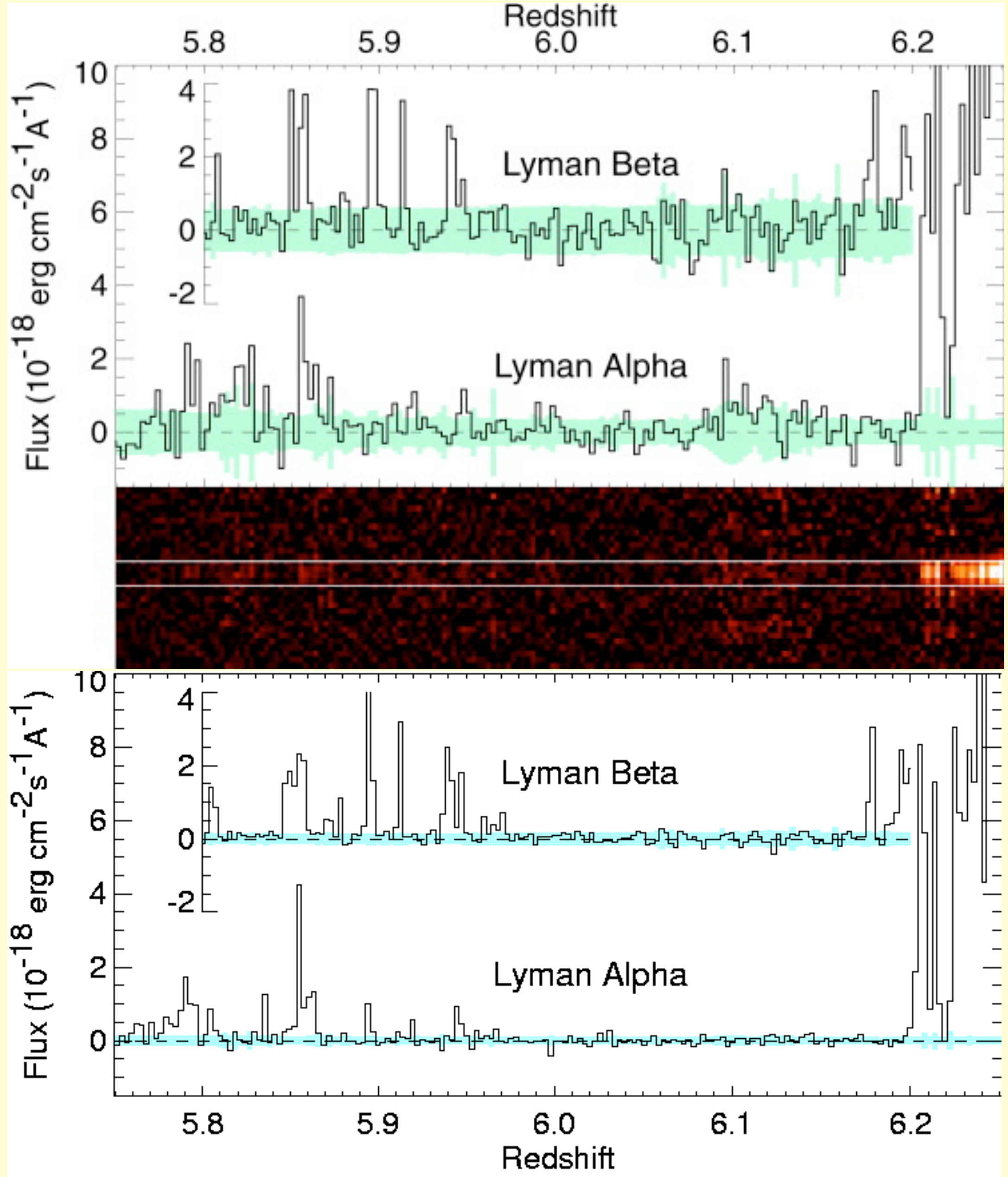


λ (Å)
7000
7500
8000
8500
9000
9500
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0303−0019 z=6.10
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
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
f_λ
7000
7500
8000
8500
9000
9500
λ (Å)

Keck/ESI 30min exposure →

Gunn-Peterson Trough in z=6.28 Quasar

Keck/ESI 10 hour exposure →

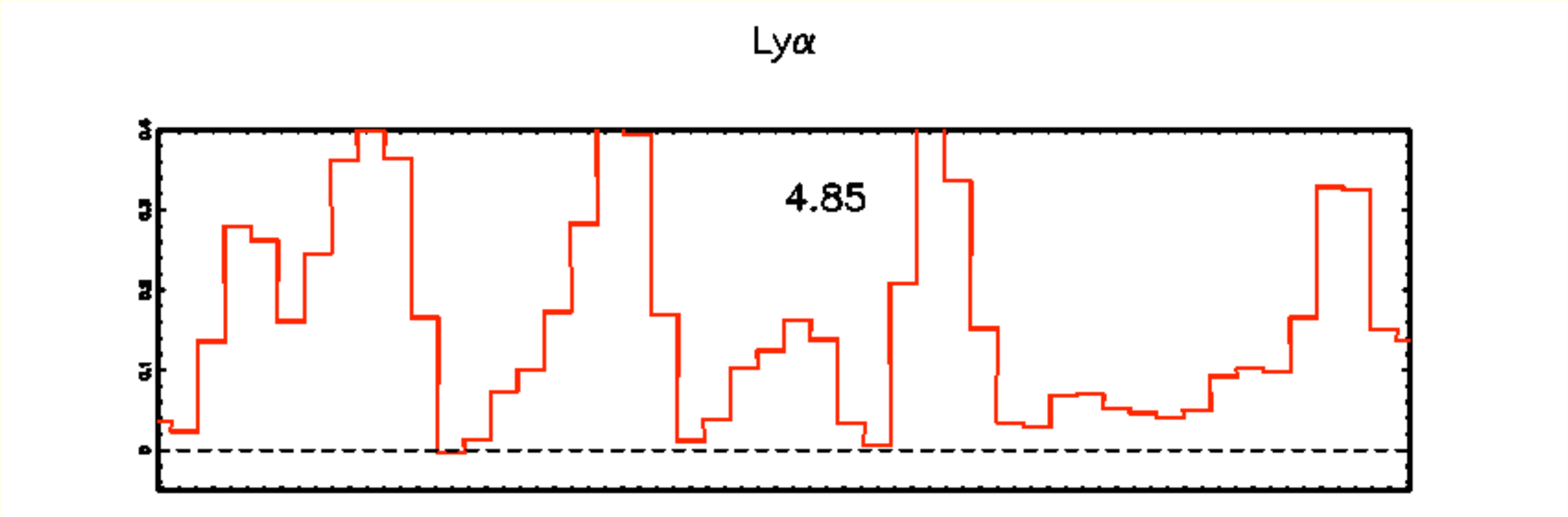


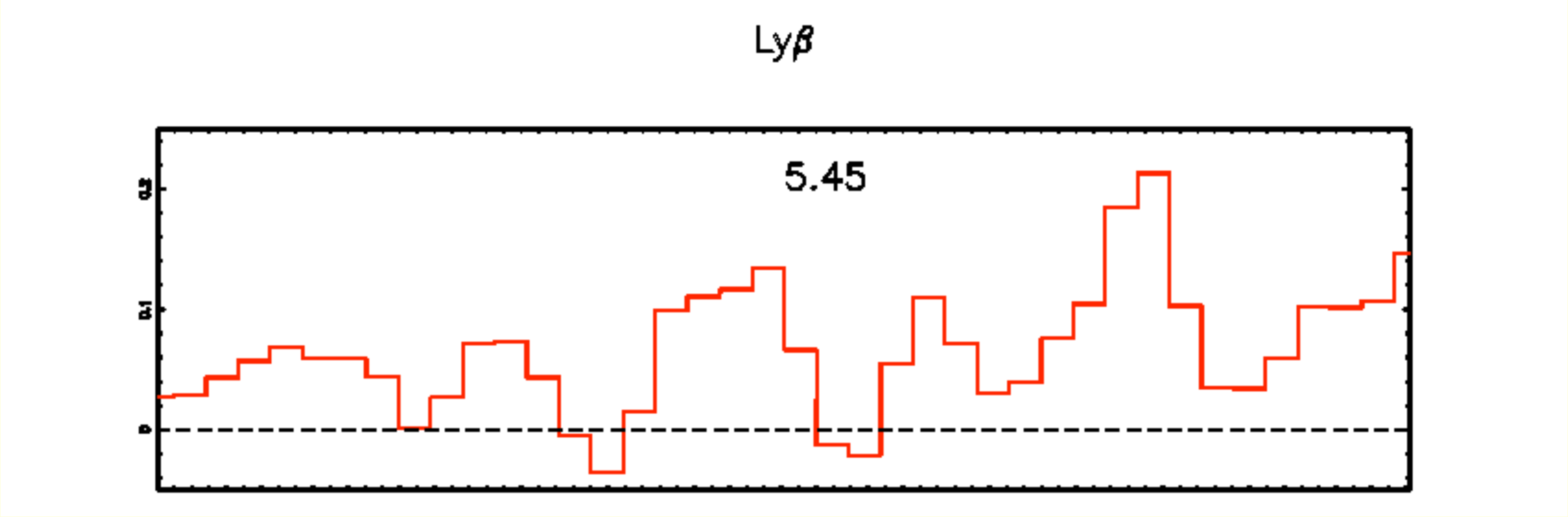
White et al. 2003

Evolution of Lyman Absorptions at z=5-6

$\Delta z = 0.15$

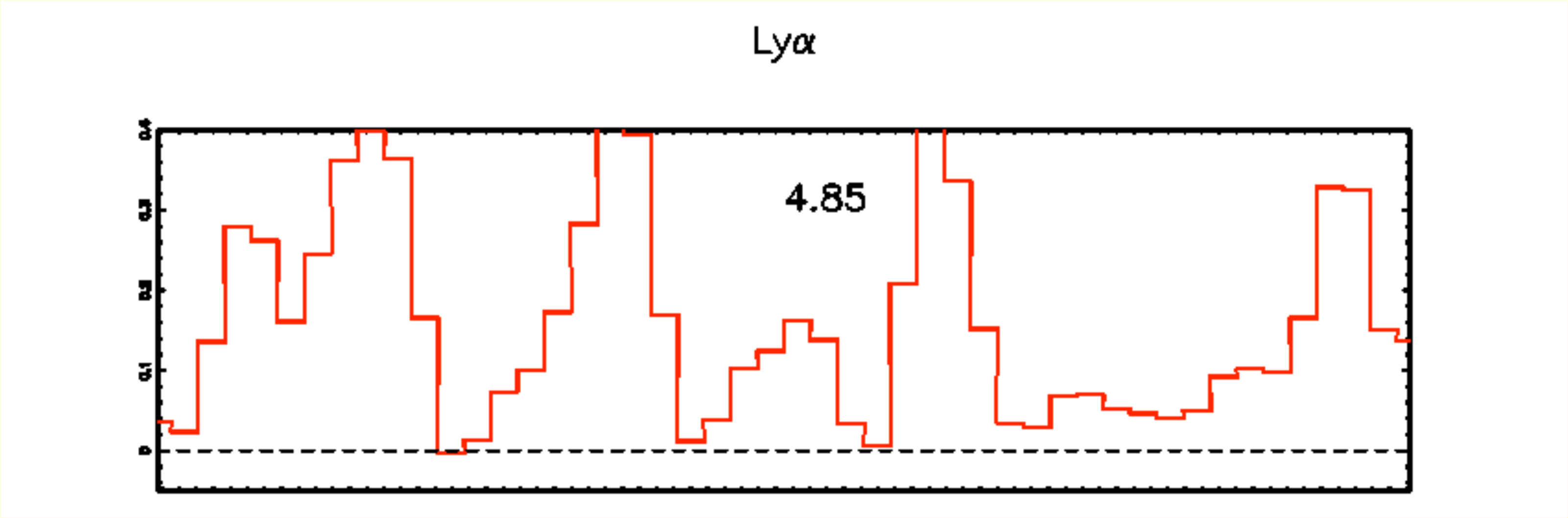
Evolution of Lyman Absorptions at z=5-6

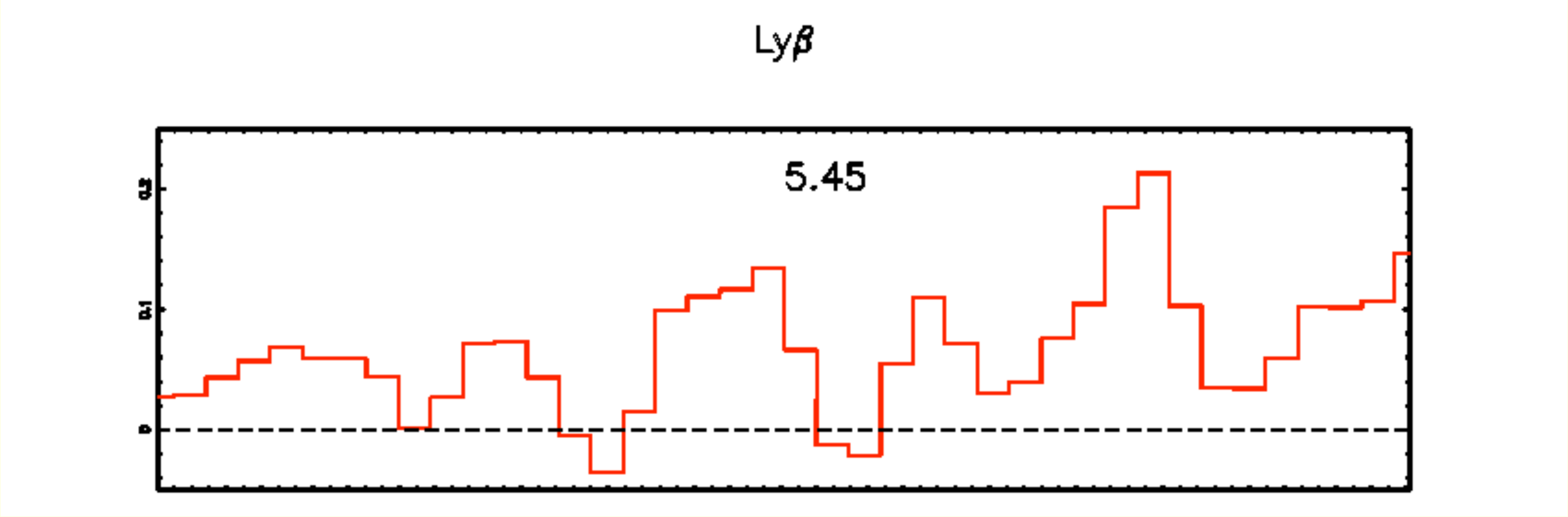




Δz = 0.15

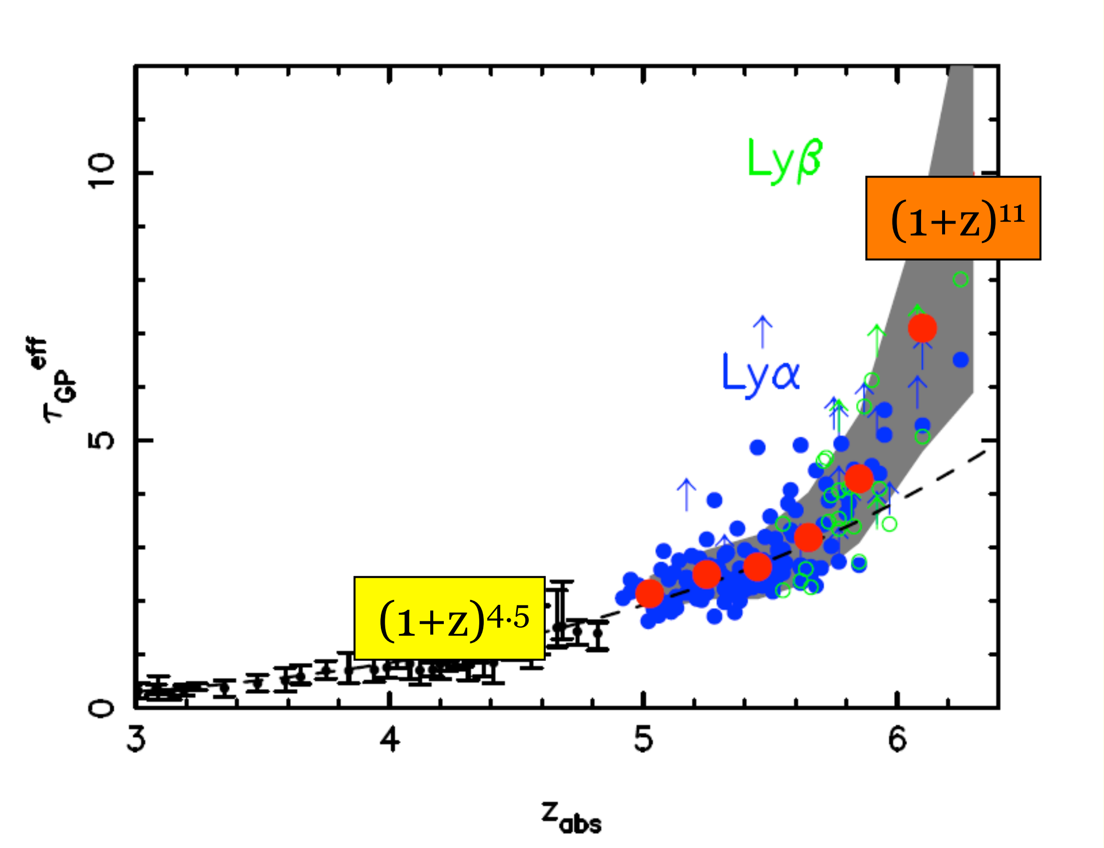
Evolution of Lyman Absorptions at z=5-6





$\Delta z = 0.15$

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

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

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

- Assuming IGM mostly ionized: n_HII ~ n_H

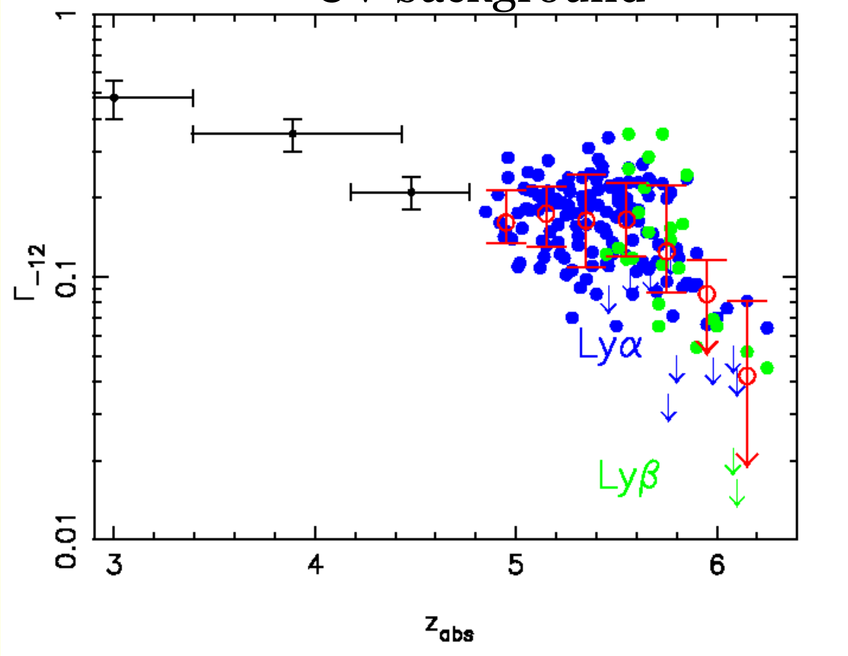
$$\tau_{\rm GP} \propto \frac{(1+z)^6 (\Omega_b h^2)^2 \alpha(T)}{\Gamma H(z)} \propto \frac{(1+z)^{4.5} (\Omega_b h^2)^2 \alpha(T)}{h \Gamma \Omega_m^{0.5}}.$$

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

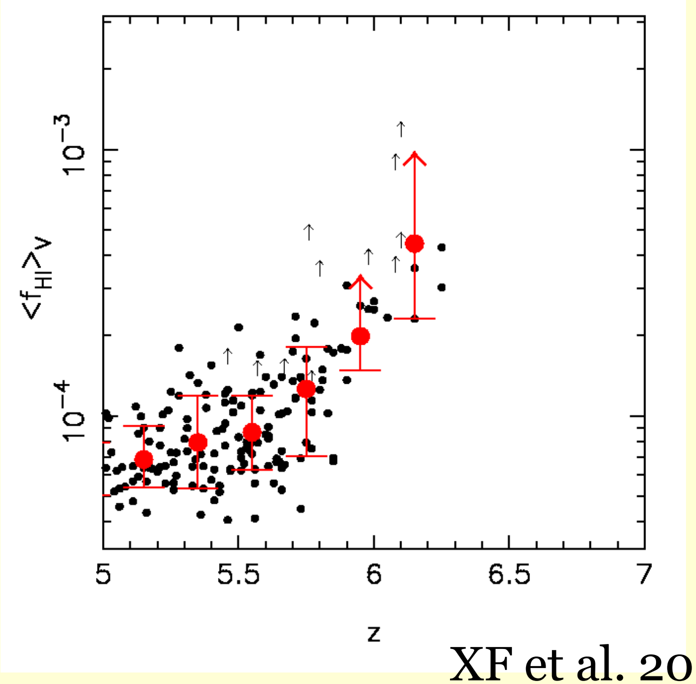
Evolution of Ionization State

- 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***

UV background



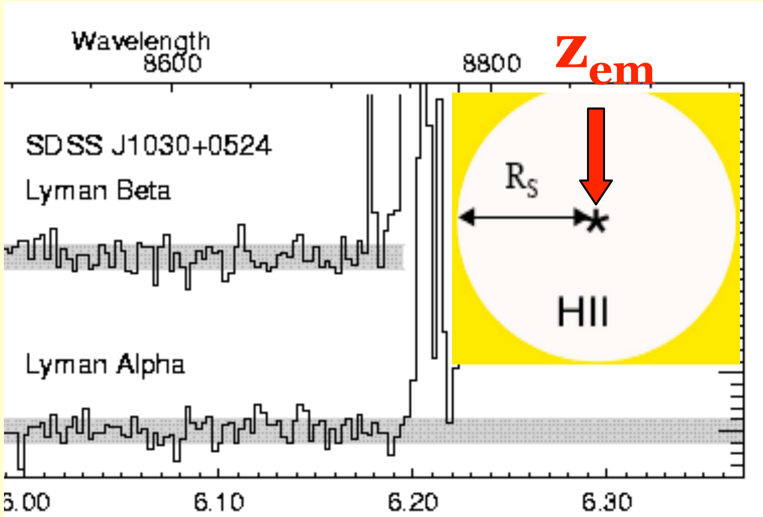
Neutral fraction



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

HII Region Sizes

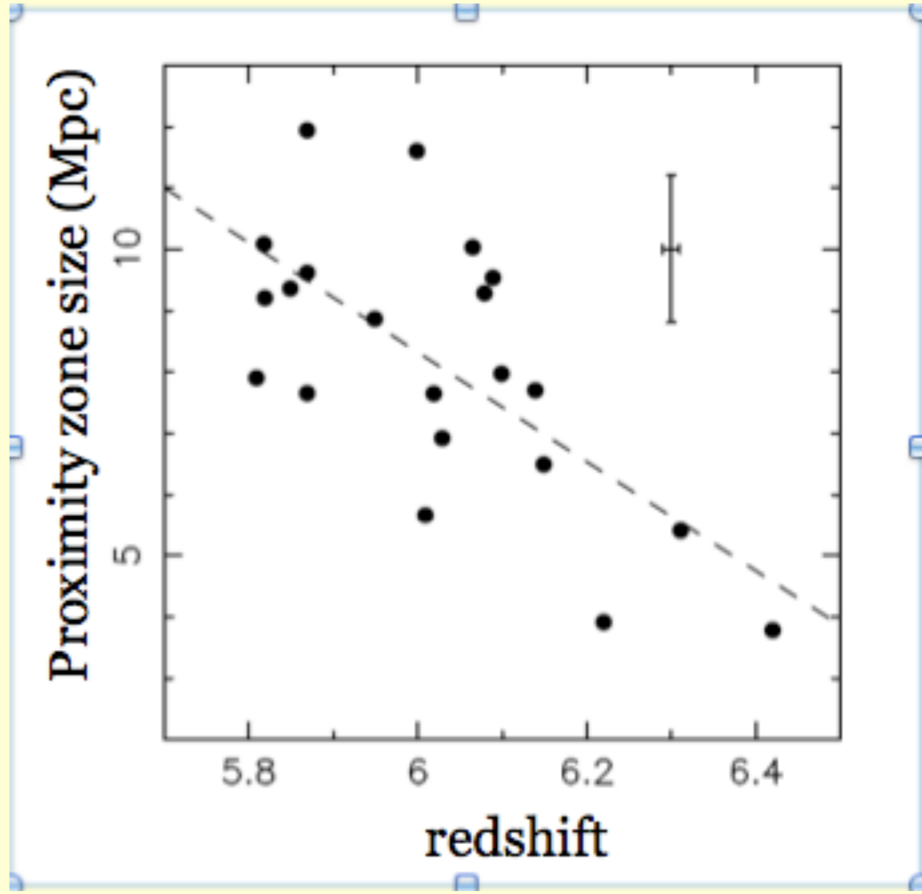


Shapiro, Haiman, Mesinger, Wyithe, Loeb, Bolton, Haehnelt, Maselli et al.

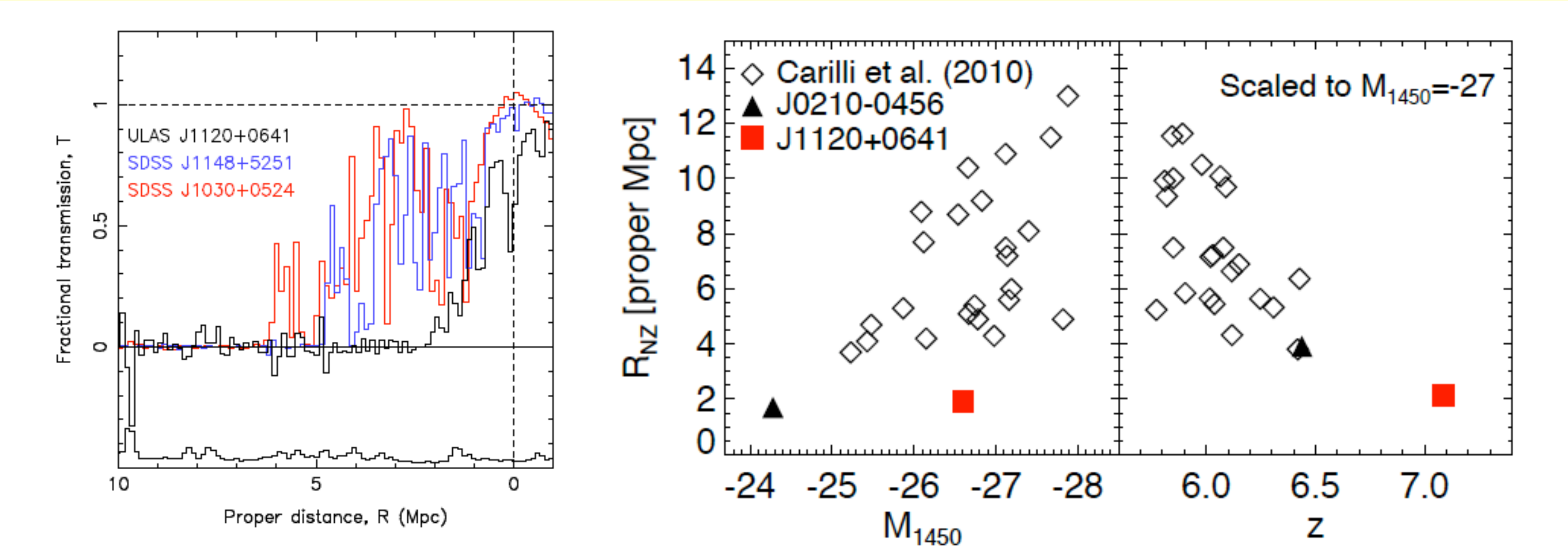
- Size of HII region

$$R_s \sim (L_Q\, t_Q \,/\, f_{HI})^{1/3}$$

- **Best estimate: f_{HI} ~ a few percent at z~6**
- **Can be applied to higher z and f_{HI} with lower S/N data**



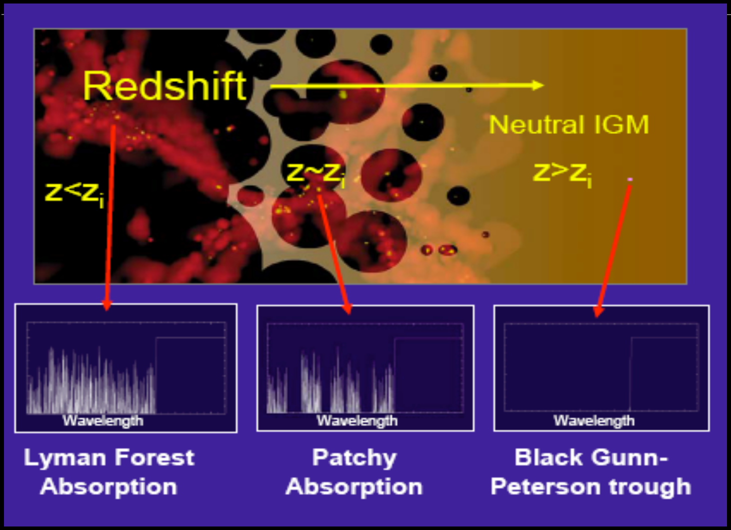
z~7 quasar HII region



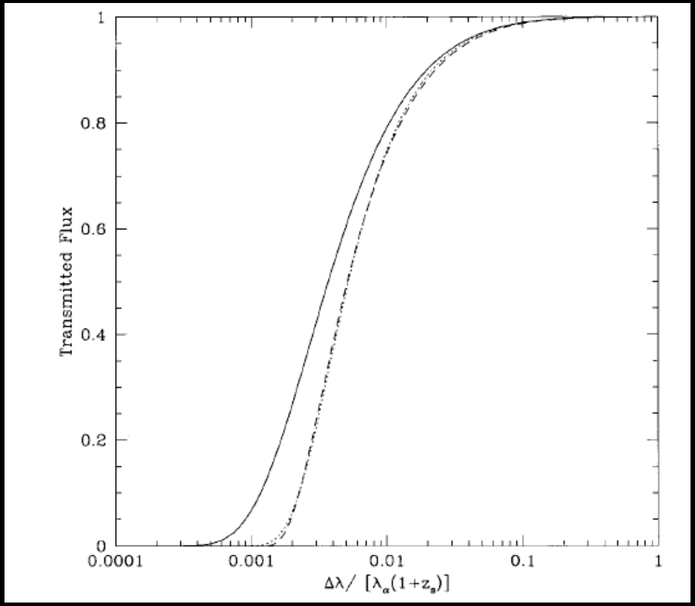
- HII region size much smaller at z~7
- f(HI) >=0.1

Mortlock et al. 2011
Bolton et al. 2011

Gunn-Peterson Test



Damping wing

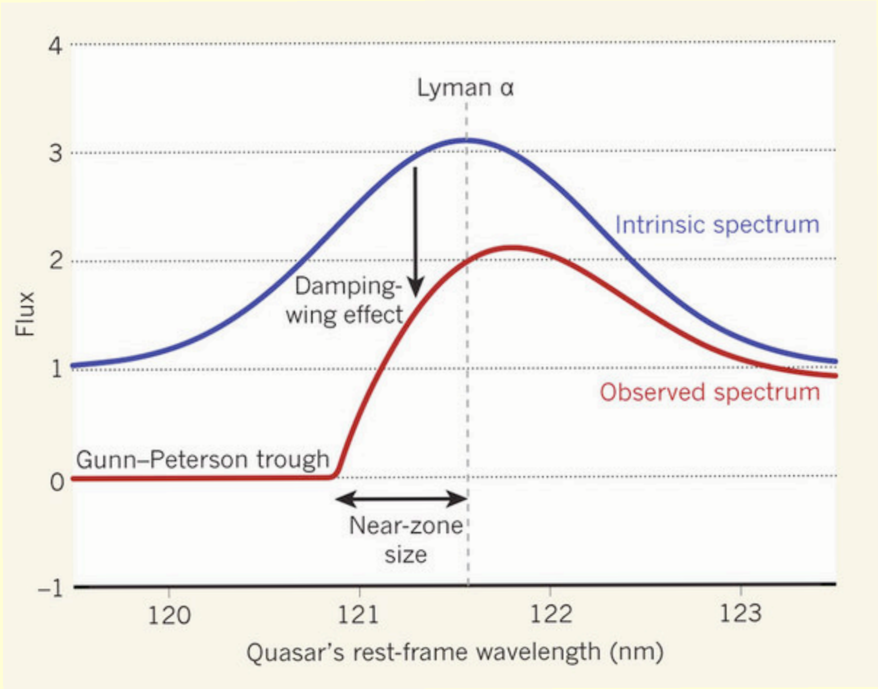


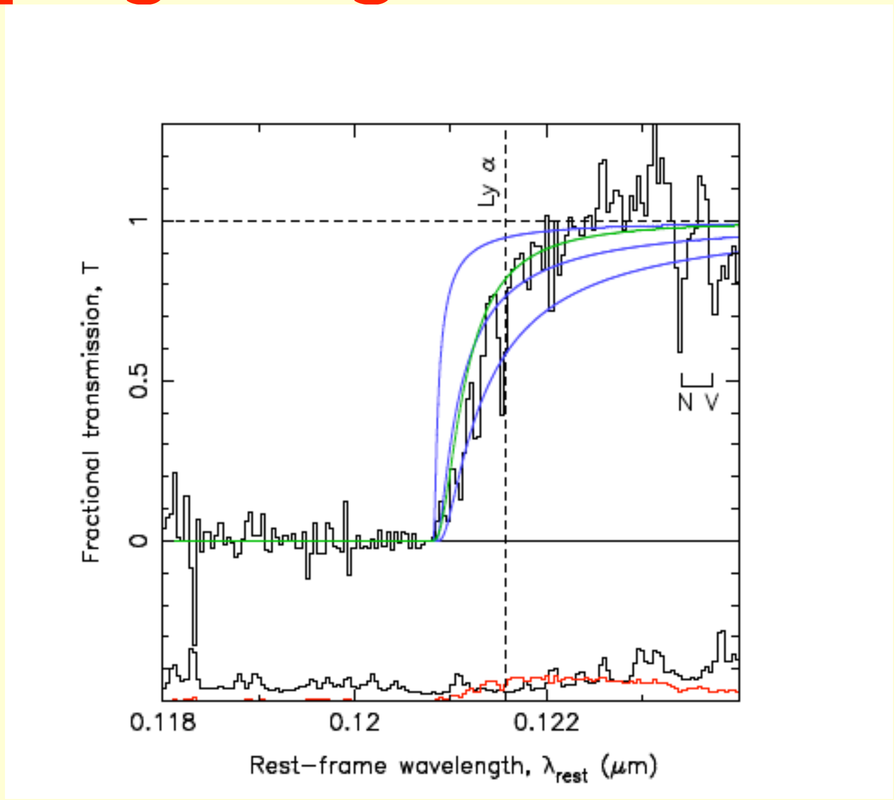
- Classic G-P (1965) effect:

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

  - Saturates at low neutral fraction
- G-P damping wing (Miralda-Escude 1998)
  - Sensitive to neutral IGM
  - Attenuates off-resonance

z~7 quasar: first IGM damping wing?

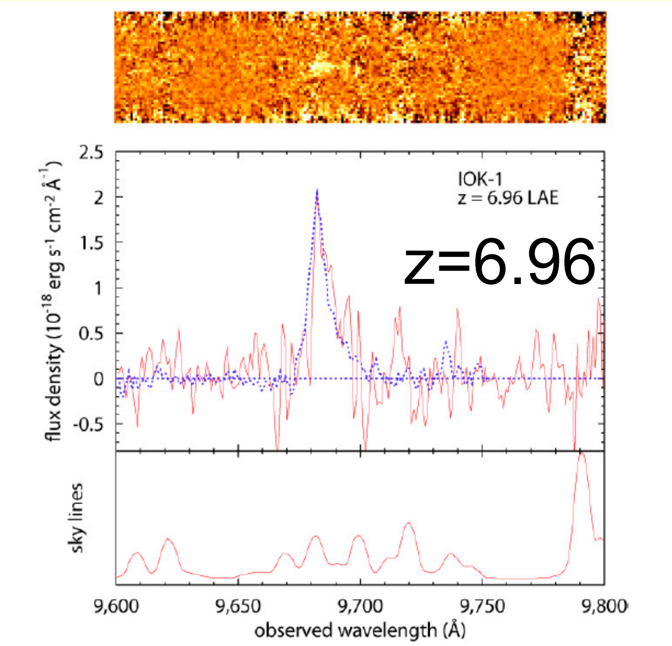




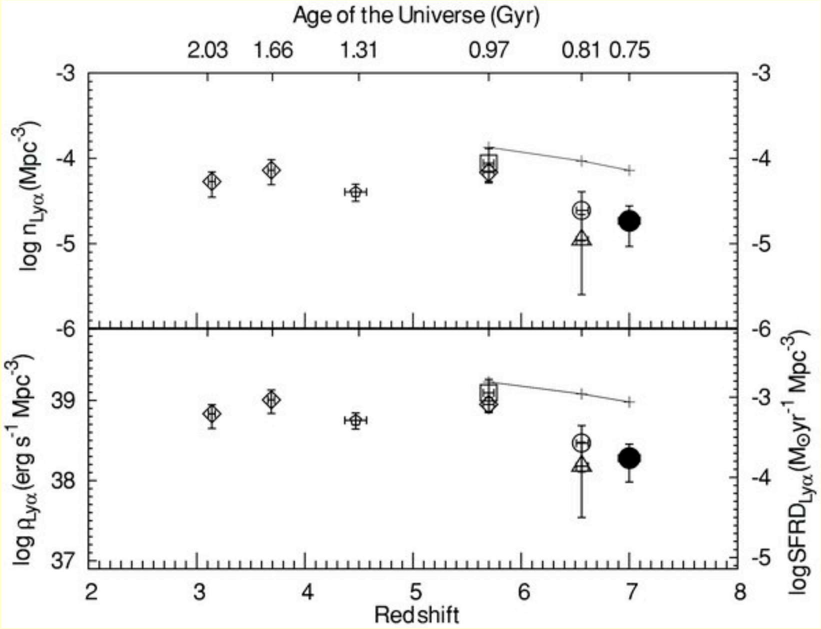
- substantial damping wing: f(HI)>=0.1

Mortlock et al. 2011

Ly α Galaxy LF at z>6



Iye et al. 2006
Kashikawa et al. 2006
Ota et al. 2007, 2010

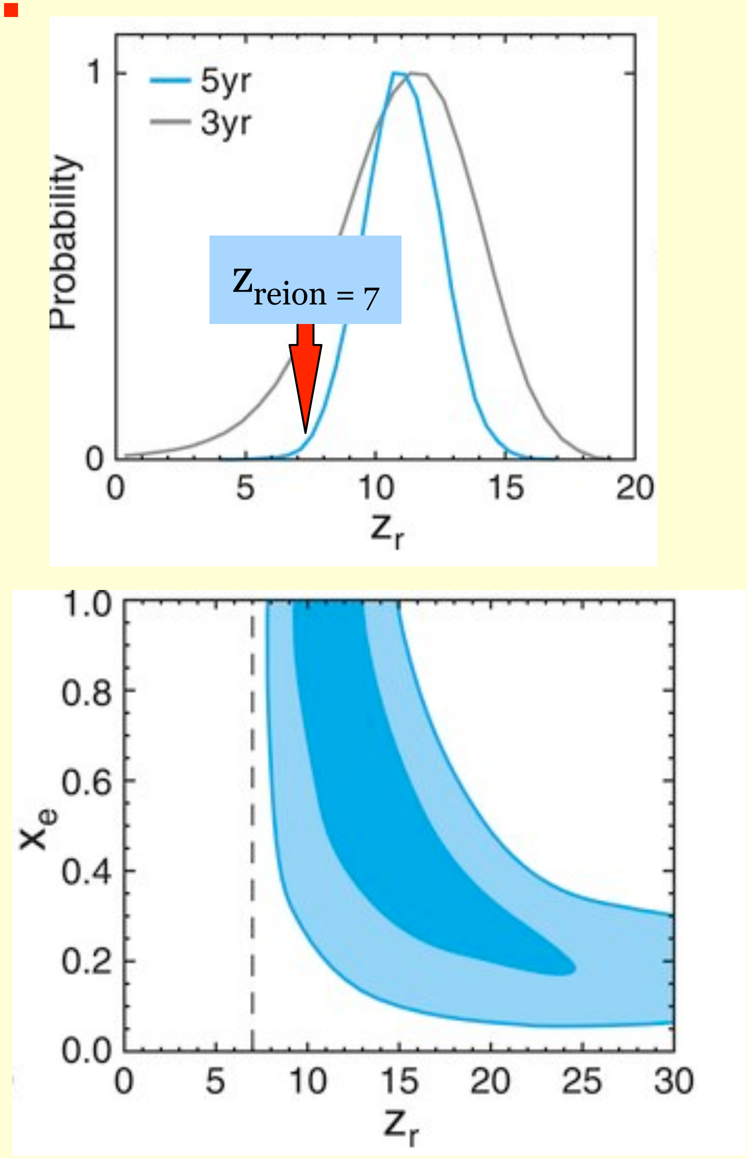


- Neutral IGM has extended GP damping wing → attenuates Ly α emission line
- Detectability of Ly α galaxies as markers of IGM optical depth
  - Reionization not completed by z~6.5
  - **f_{HI} ~ 0.3 - 0.6 at z~7**
  - **Overlapping at z=6-7?**

WMAP: early reionization?

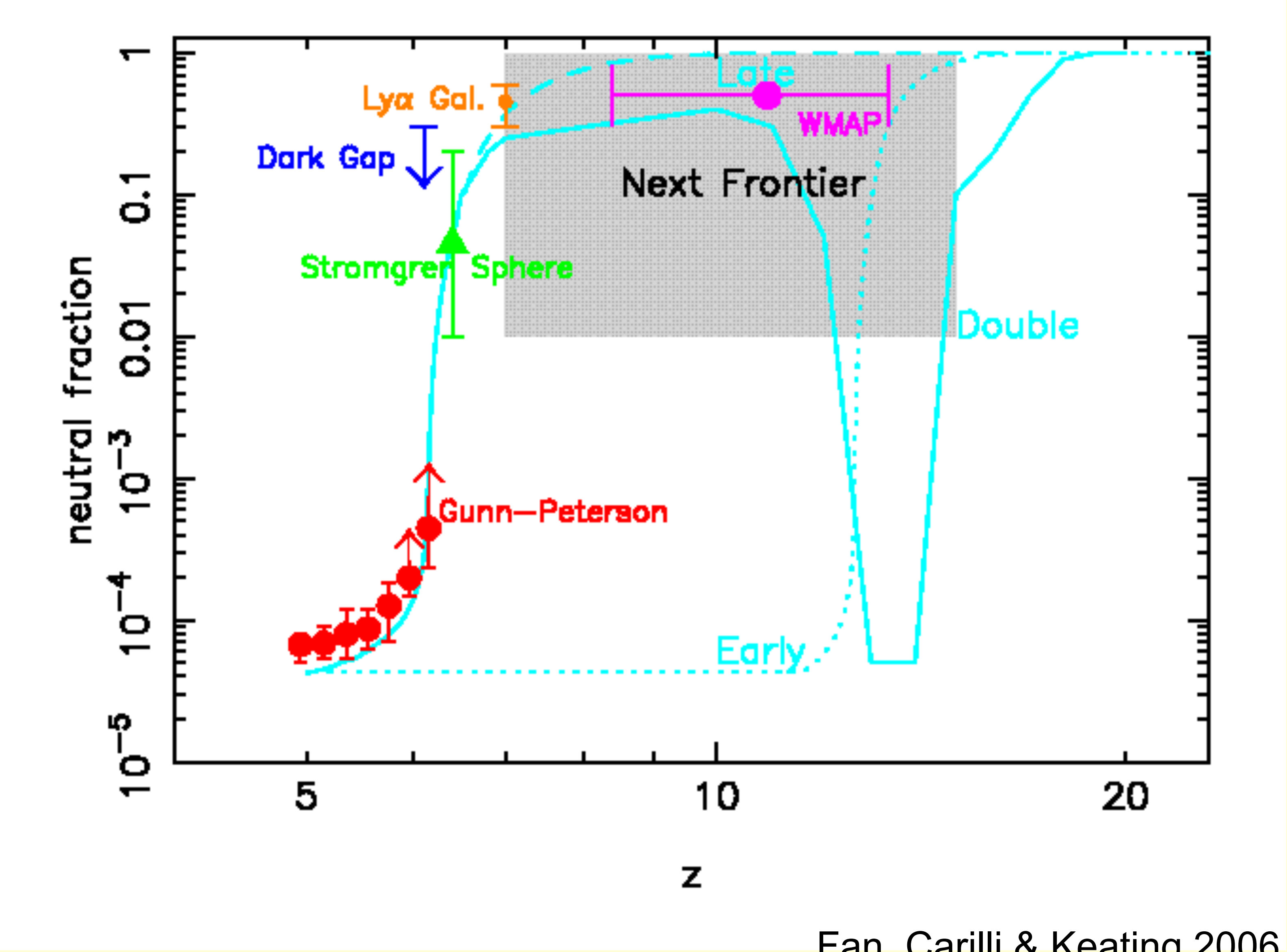
- WMAP seventh-year:
  - τ = 0.088+/- 0.014 z=10.5+/-1.2
  - Larger signal comparing to late reionization model (but marginally consistent!)
- However, no direct conflict to Gunn-Peterson result, which is sensitive only to ~1% neutral IGM
- Overlapping could still be at z~6
- IGM could have complex reionization history

⇒ ***direct observation of high-z sources***



Dunkely+ 2009, Komatsu+2010

Probing Reionization History



Fan, Carilli & Keating 2006

Next Generation Quasar Surveys

- Optical surveys: limited to $z<7$
- New generations of red-sensitive CCD devices
  - Improved QE at 1 micron (Y band)
  - SUBARU/Princeton (2010+): a few hundred deg, Y<25;?
  - Pan-Starrs (2008+): 3π: Y<22.5; 1000 deg^2: Y<24; 30 deg^2: Y<26
  - LSST (2013+): 3π: Y< 25
  - Discovery of large number of quasars at $z<7.5$
- New generation of Near-IR surveys:
  - Ground-based surveys: J_AB<22? 10,000+ sq. deg
  - ECULID/WFIRST: 20,000 sq. deg, J_AB ~ 24
  - Discovery of large number of quasars at z=7-10

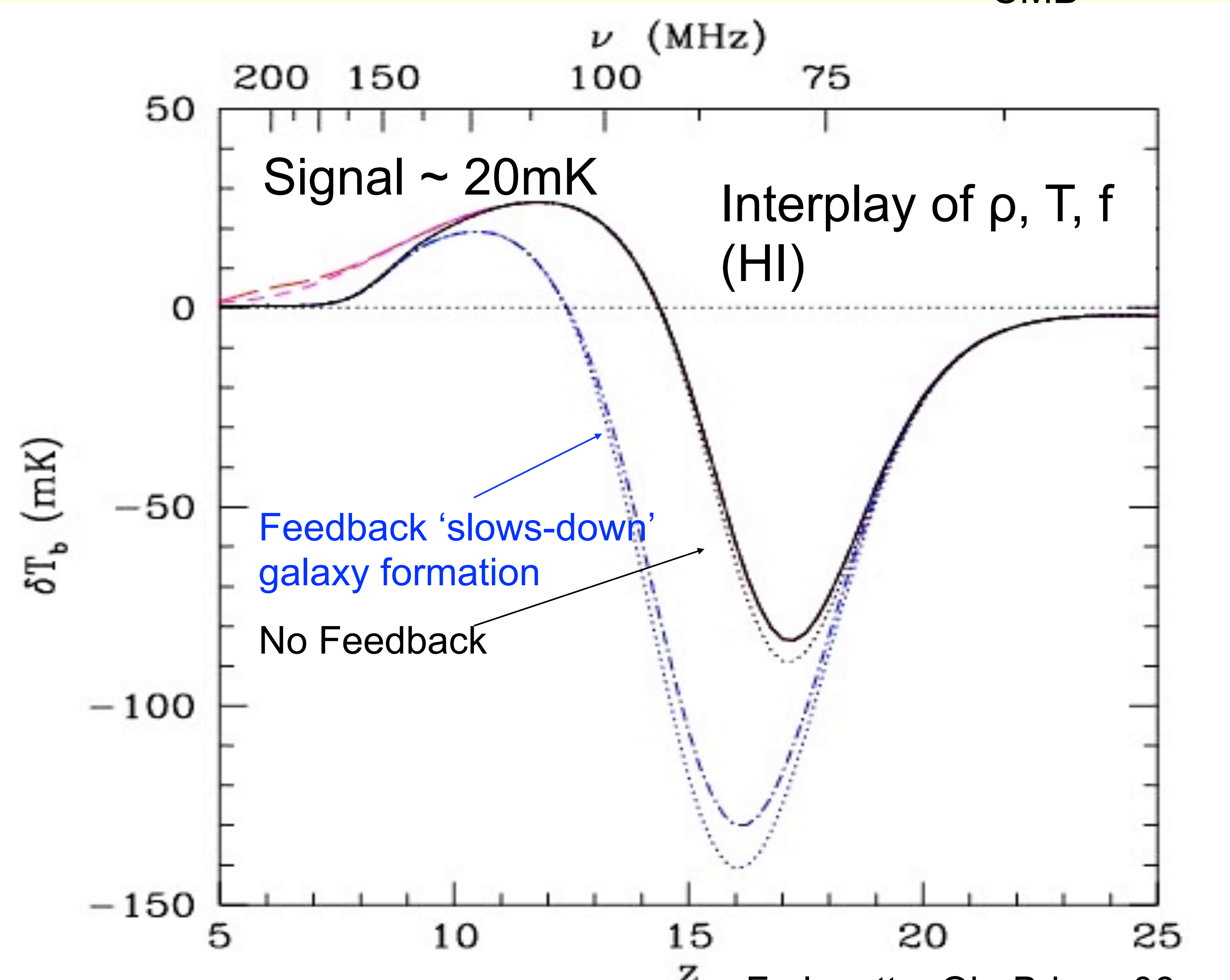
21cm probe of reionization

- Analog of Gunn-Peterson effect, with HI 21cm transition
- If HI spin temperature is different from CMB temperature

$$T_B \approx \frac{T_S - T_{\rm CMB}}{1+z}\tau \approx 7(1+\delta)x_{HI}(1-\frac{T_{CMB}}{T_S})(1+z)^{1/2}\ {\rm mK},$$

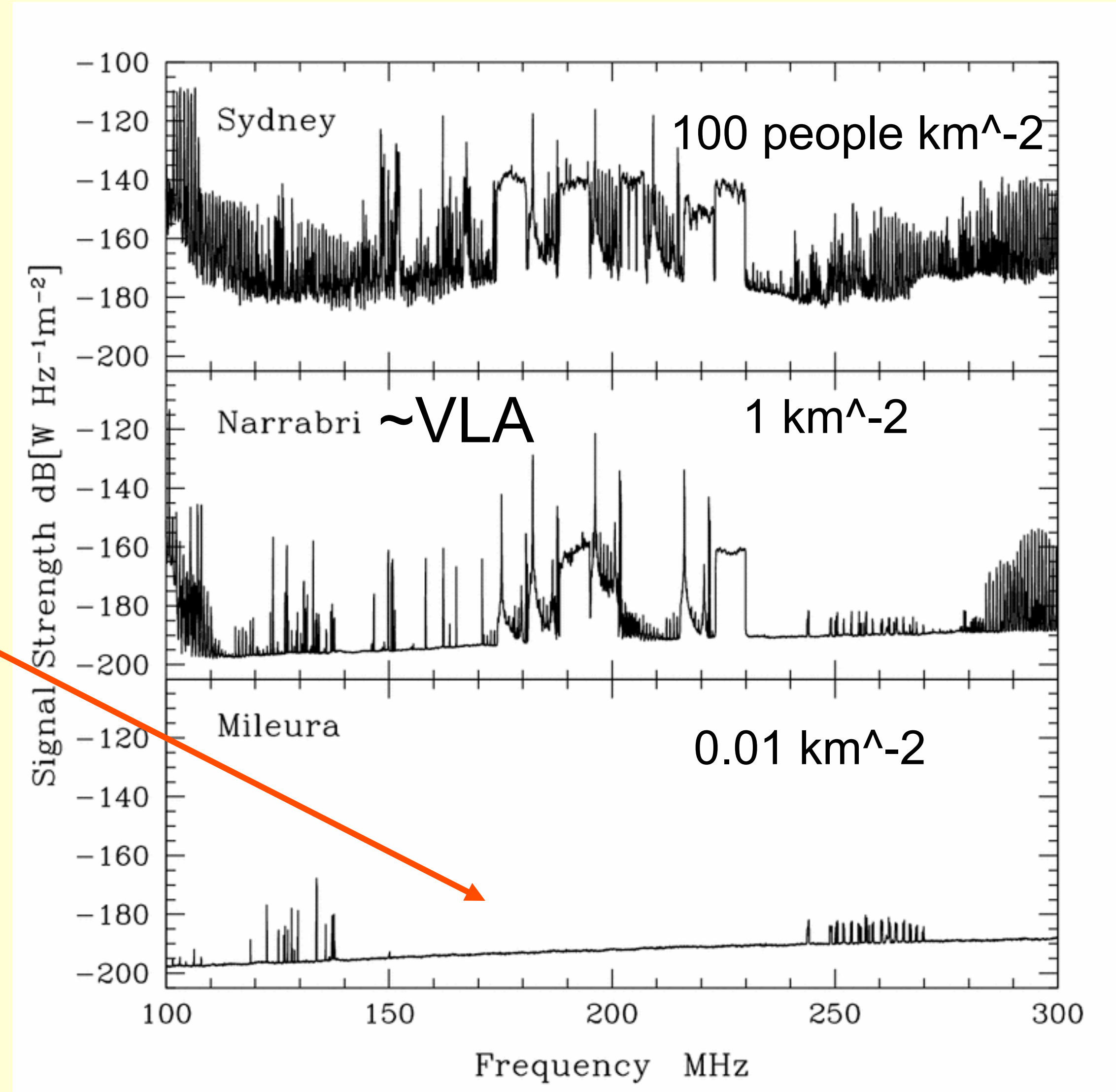
- Advantages:
  - doesn't saturate (unlike Ly alpha G-P)
  - probe 3-D structure (unlike CMB)
- Disadvantage
  - tiny signal on top of CMB
  - with large radio interference

Global (all sky) emission (eg. T_{CMB})

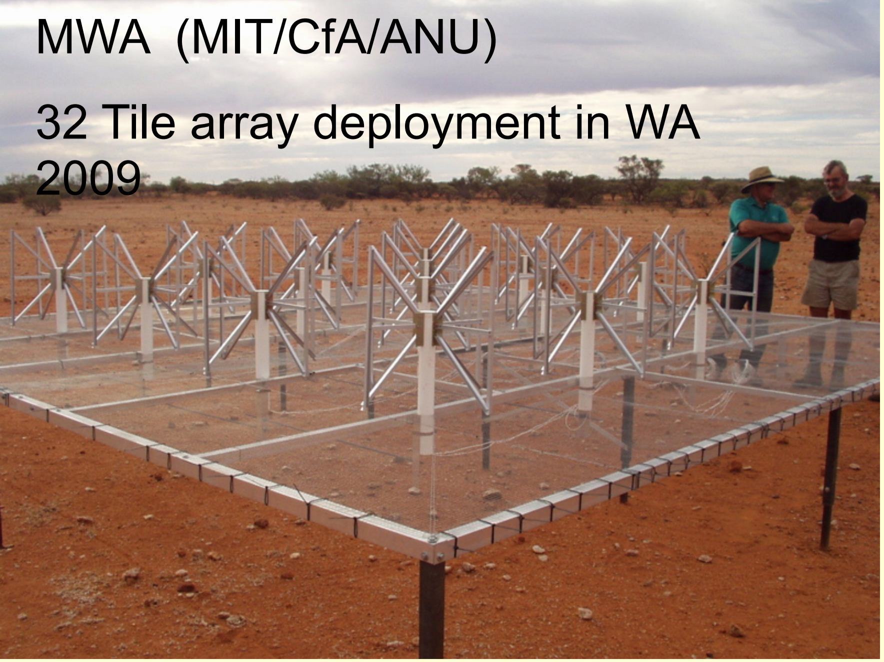


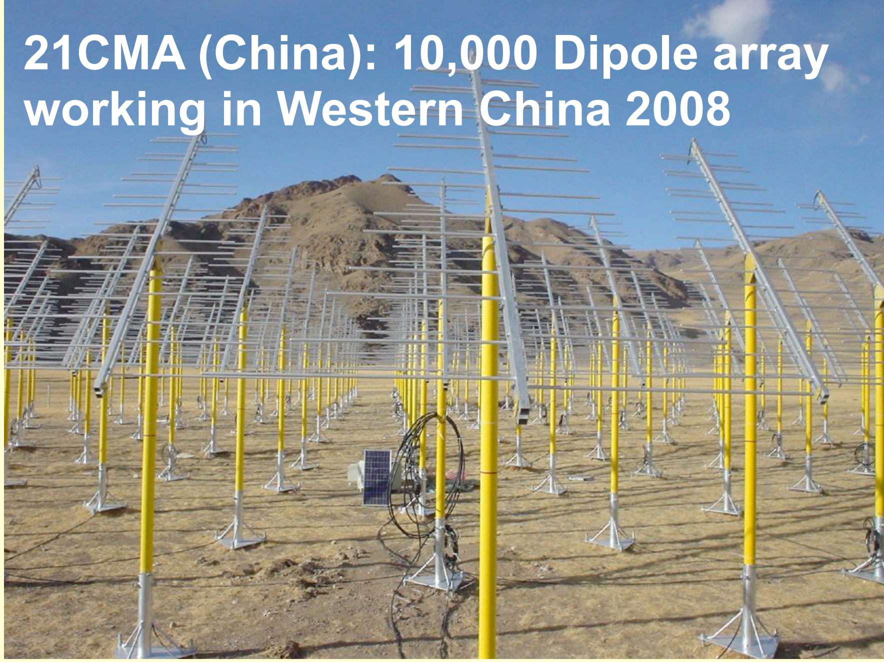
Furlanetto, Oh, Briggs 06

RFI mitigation: location, location location...



Chippendale & Beresford 2007





Pathfinders: 1% to 10% of a square kilometer array

	Site	Type	Freq MHz	Area m^2	Goal	Date
GMRT	India	Parabola	150-165	4e4	CSS	2009
21CMA	China	Dipole	70-200	1e5	PS	2008
PAPER	GB/Oz/SA	Dipole	110-200	5e3	PS/CSS	2009
MWAdemo	Oz	Aperture	80-300	1e4	PS/CSS	2009
LOFAR	NL	Aperture	115-240	1e5	PS/CSS	2010
SKA	??	Aperture	30-300	1e6	Imaging	??

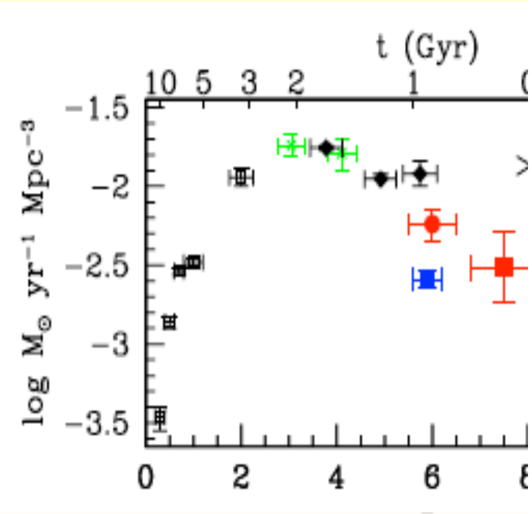
What Ionized the Universe? AGNs or Galaxies

Reionization Budget

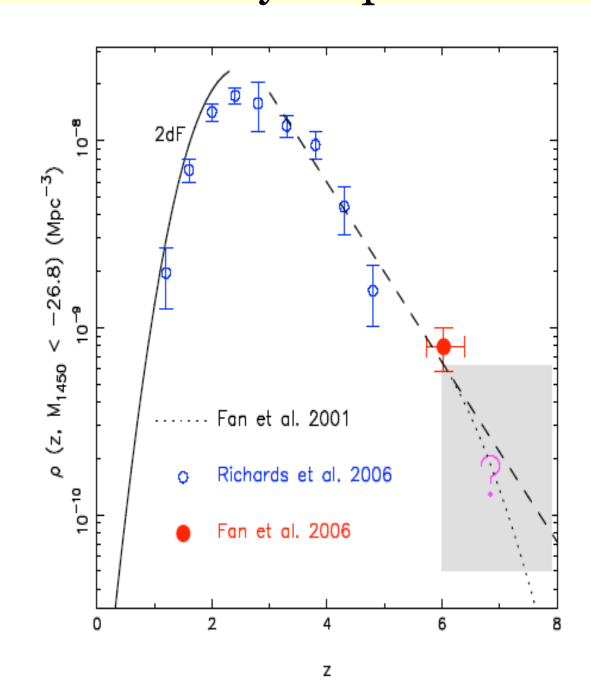
$$\dot{N}_{ion} \propto \rho^{L}_{912\mathrm{A}} f_{esc} C_{IGM}$$

- Depends on:
  - Luminosity density:
    - Detailed LF and IMF
  - Escape fraction of ionizing photons to the IGM:
    - Quasar: f_{esc}~1
    - Galaxies??
  - Clumpiness of the IGM
- Can quasars do it? ***Not likely***
  - **Too few quasars unless QLF remains to be steep to AGN luminosity**

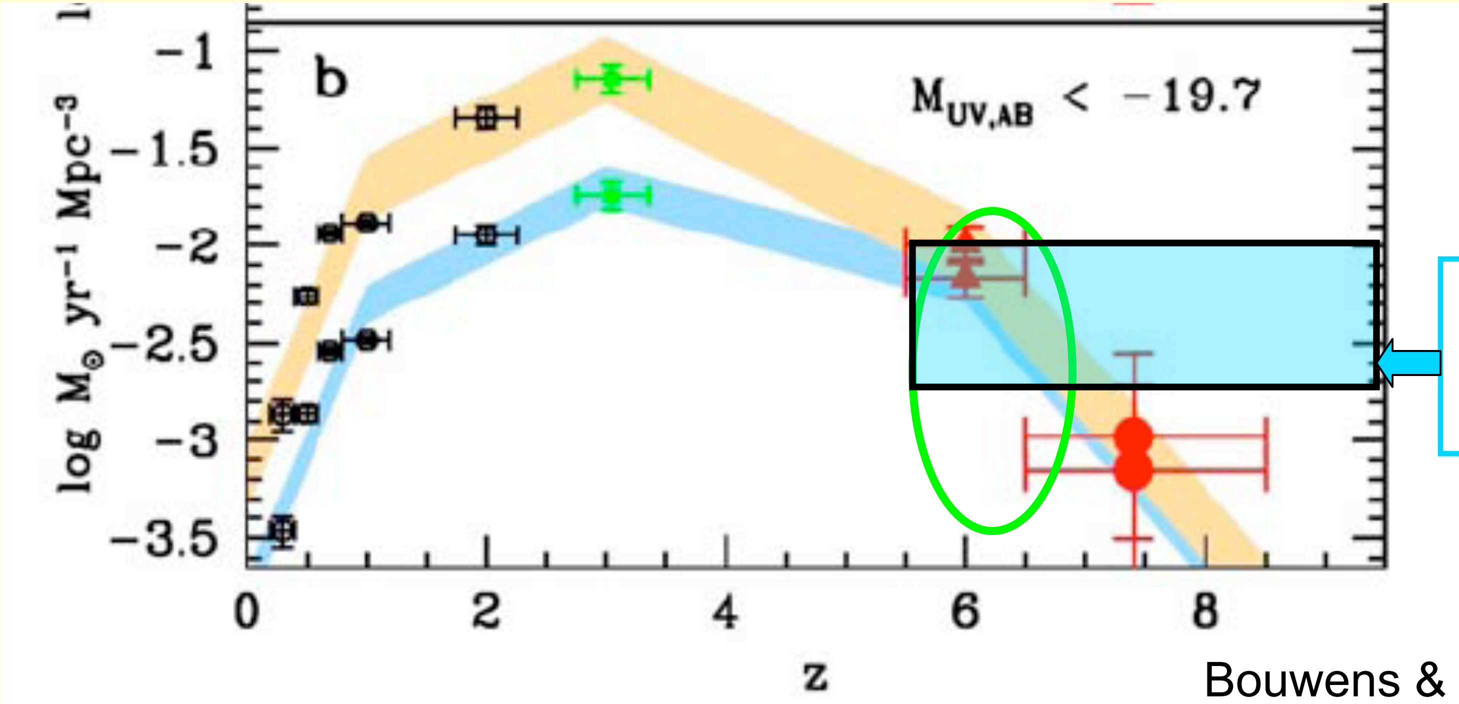
SFR of galaxies



Density of quasars



Reionization by stellar sources?



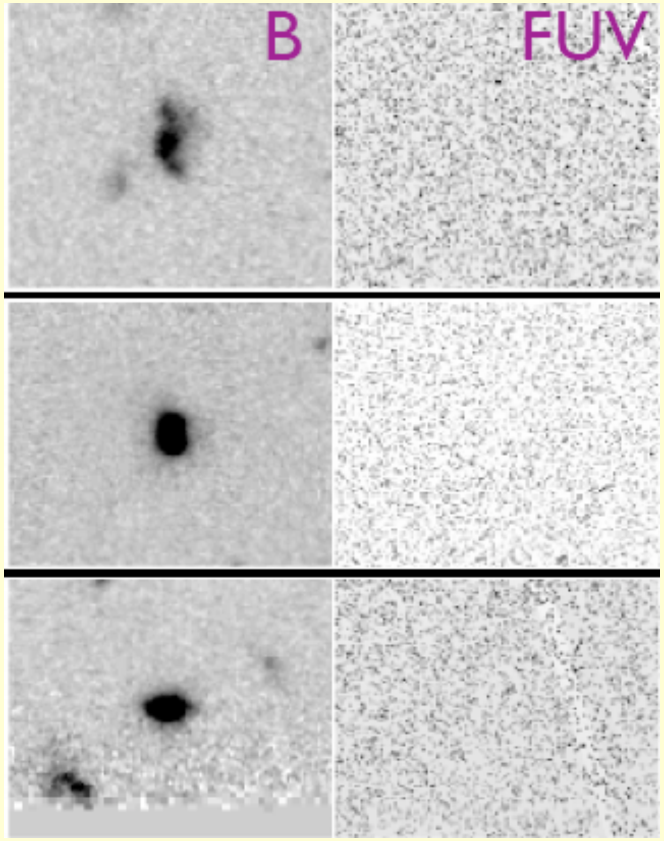
Necessary for reionization 6<z<9 (Stiavelli et al 2003)

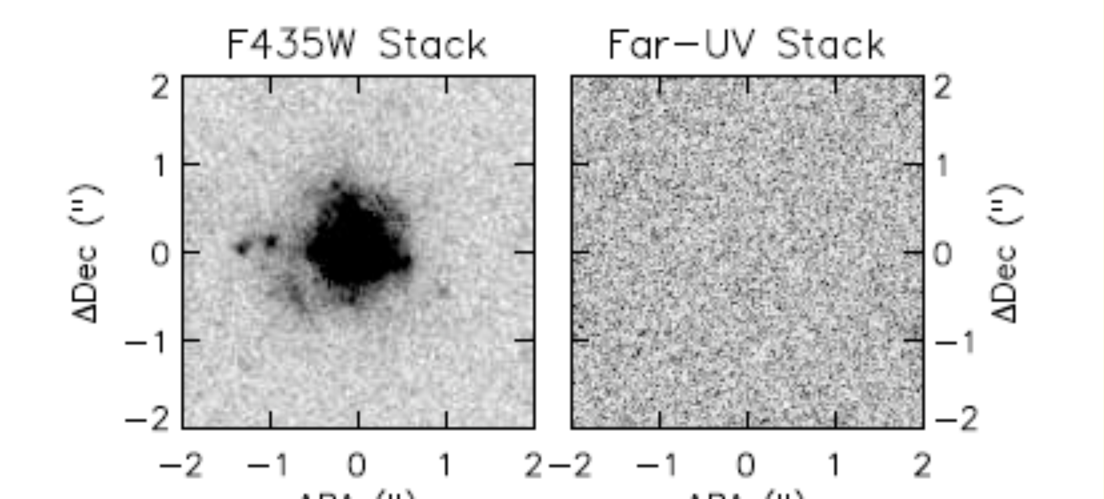
Bouwens & Illingworth; Bunker et al. ; Gnedin Yan and Windhorst

- Large uncertainties in reionization photon budget:
  - IGM clumpiness; IMF; escape efficiency
  - Large cosmic (sample) variance in deep field data
  - Galaxy luminosity function at high-z
- ***Sources of reionization have not been identified!***
  - ***Most likely dwarf galaxies***

Escape Fraction: A Key Uncertainty

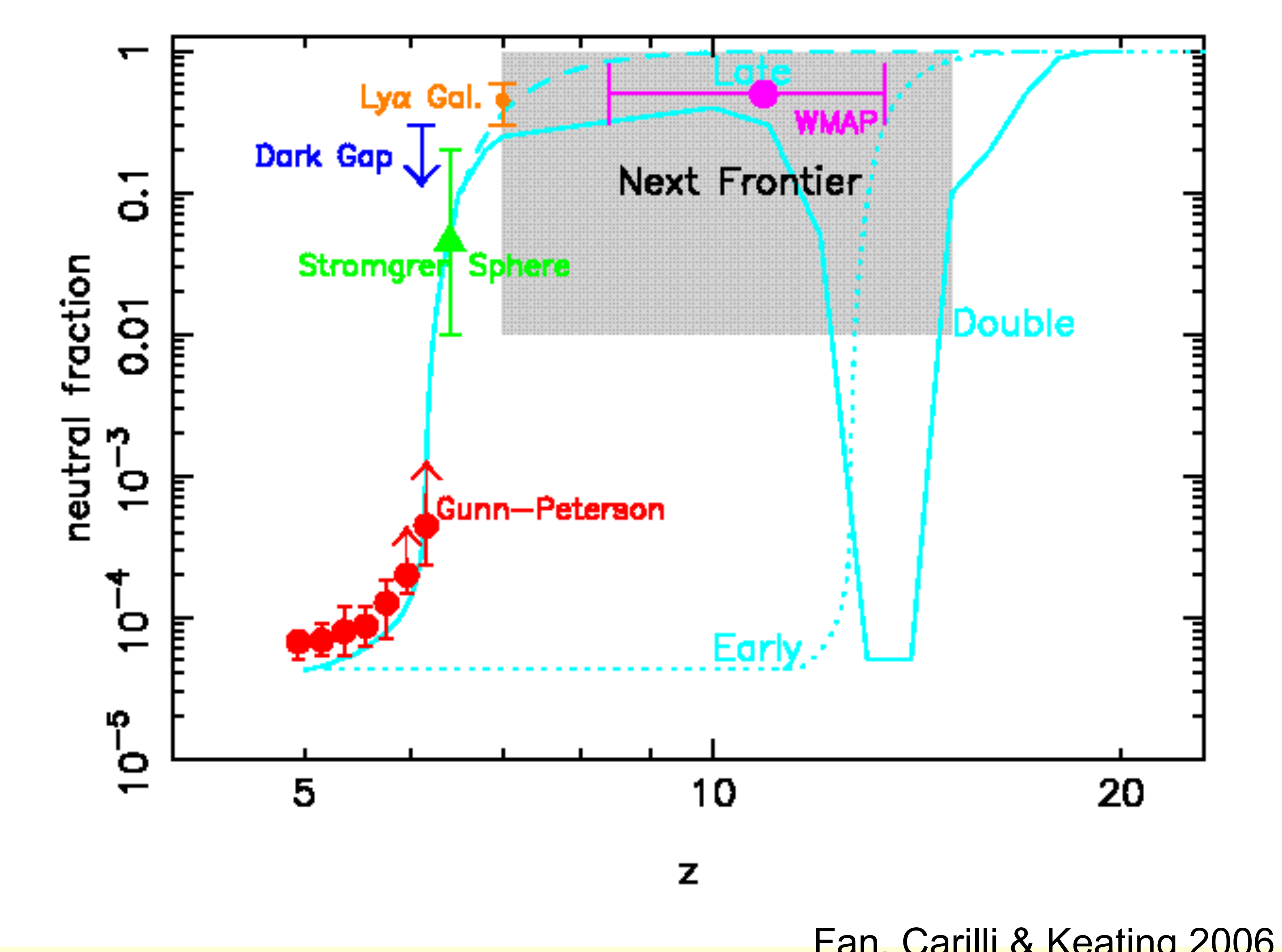
- Escape fraction (as a function of z, L, age) affects:
  - Total reionization budget
  - HII region sizes
  - Lyα emitter probe
- Current measurements extremely uncertain
  - Shapley et al. at z~3: 2/14 detections
  - Siana et al. at z~1: f_{esc} <0.02; **evolution?**
  - Large HST surveys underway
- But how to measure it at z>6???





Siana et al. 2007, 2010

Probing Reionization History



Fan, Carilli & Keating 2006

Synergetic survey of the reionization era

ALMA