GRBs as reionization probes

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Talk Plan

- concentrate on "Lyα damping wing fitting analysis" to get constraints on IGM neutral fraction

- review on GRBs as a reionization probe: the status before GRB 130606A

- On the results from GRB 130606A @ z=5.9
  - the best opportunity ever for reionization study by GRBs
  - controversy between Gemini/Subaru/VLT? what's the origin?

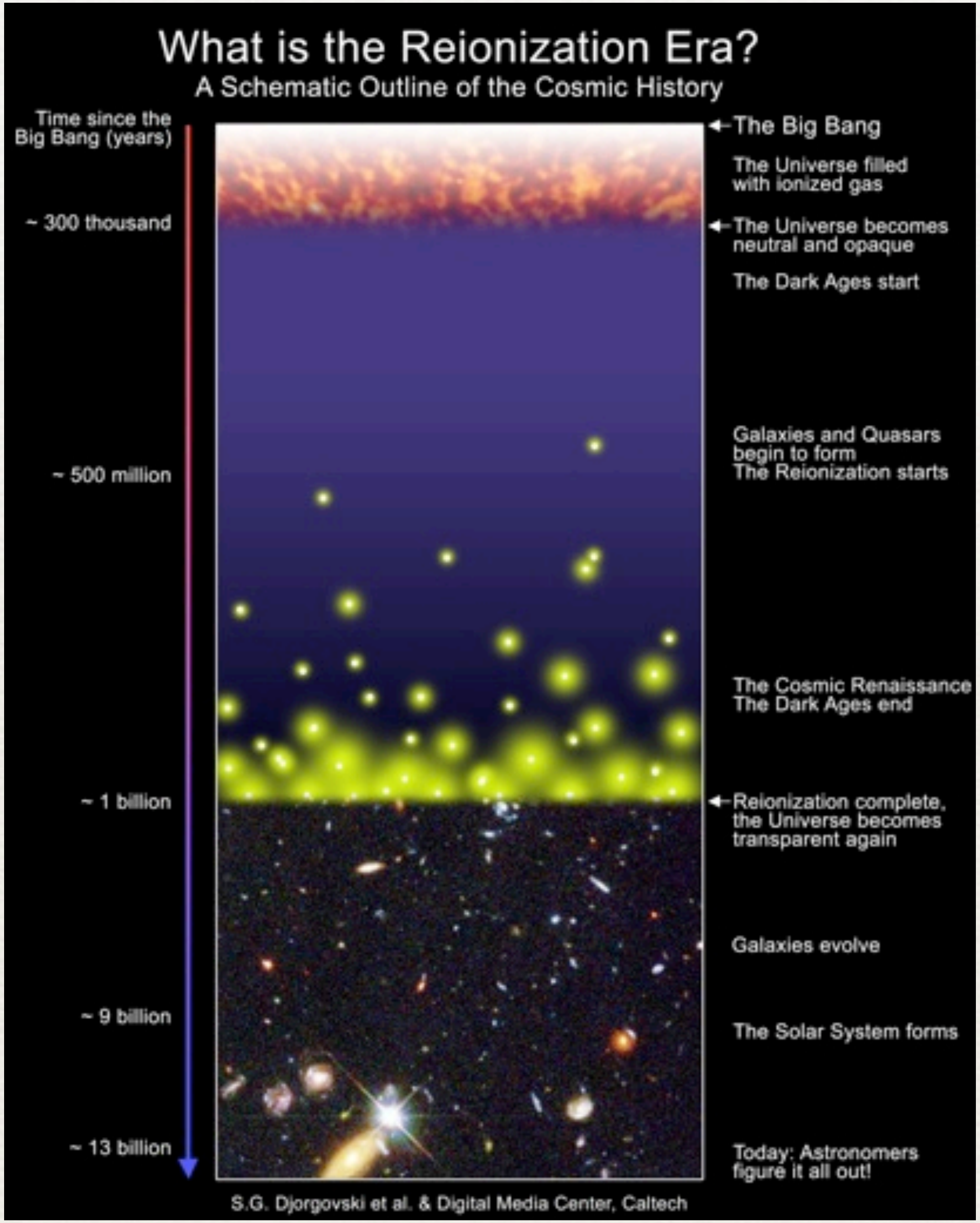
- On the effect of Lyα cross section formulae (as a function of wavelength) adopted
  - need to be careful in the "high precision GRB cosmology era"

Cosmic Reionization

- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination
  - observed as CMB

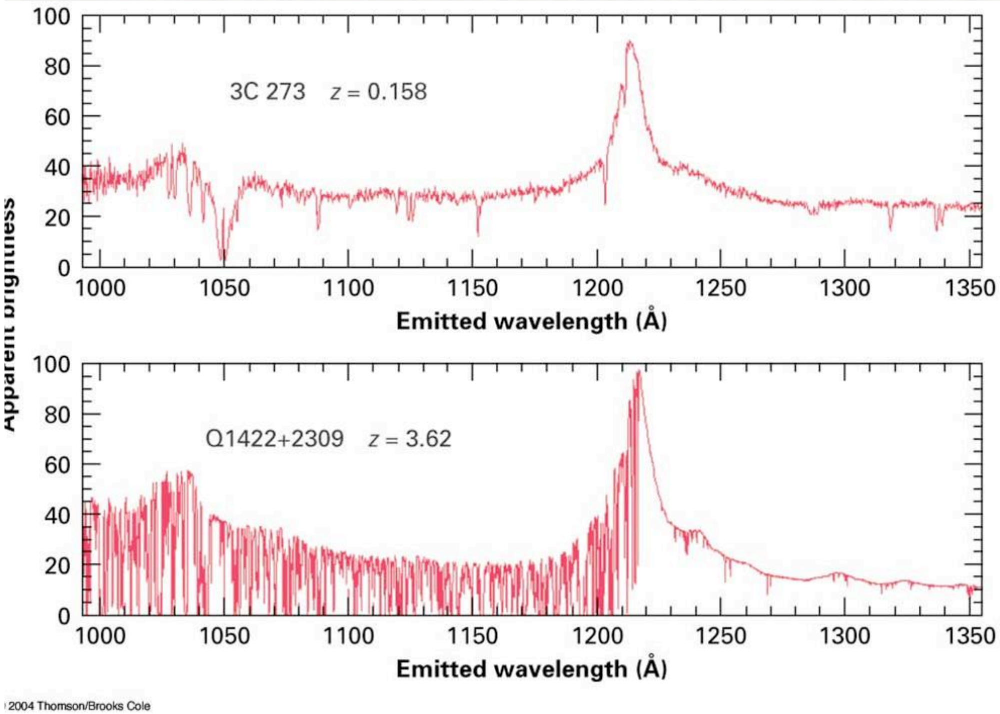
- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test

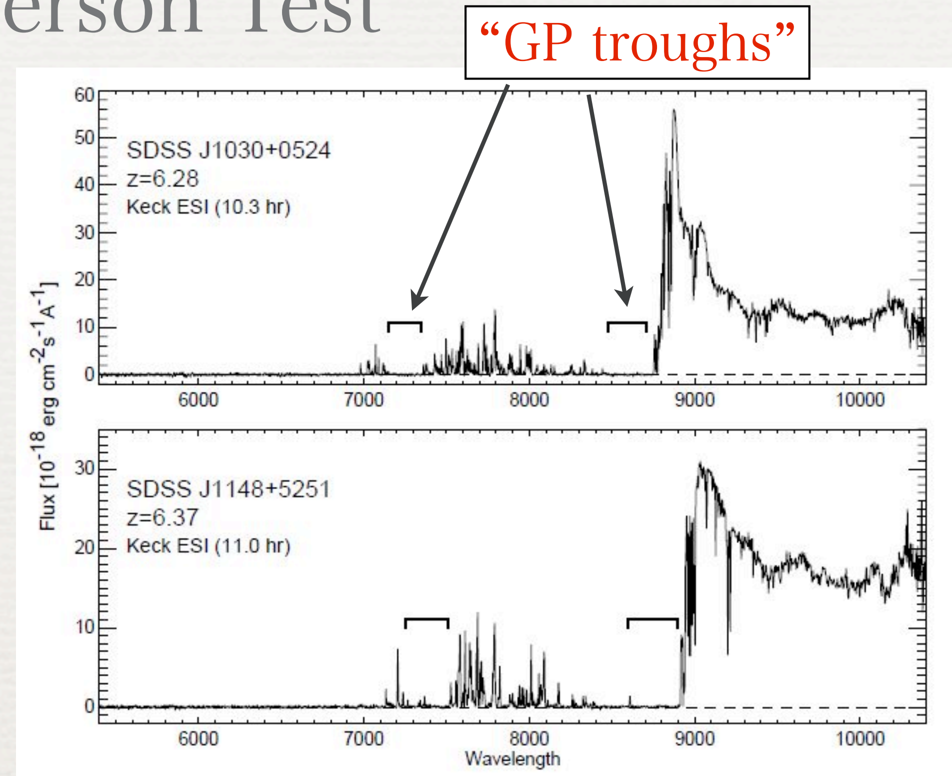
- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark to understand galaxy formation



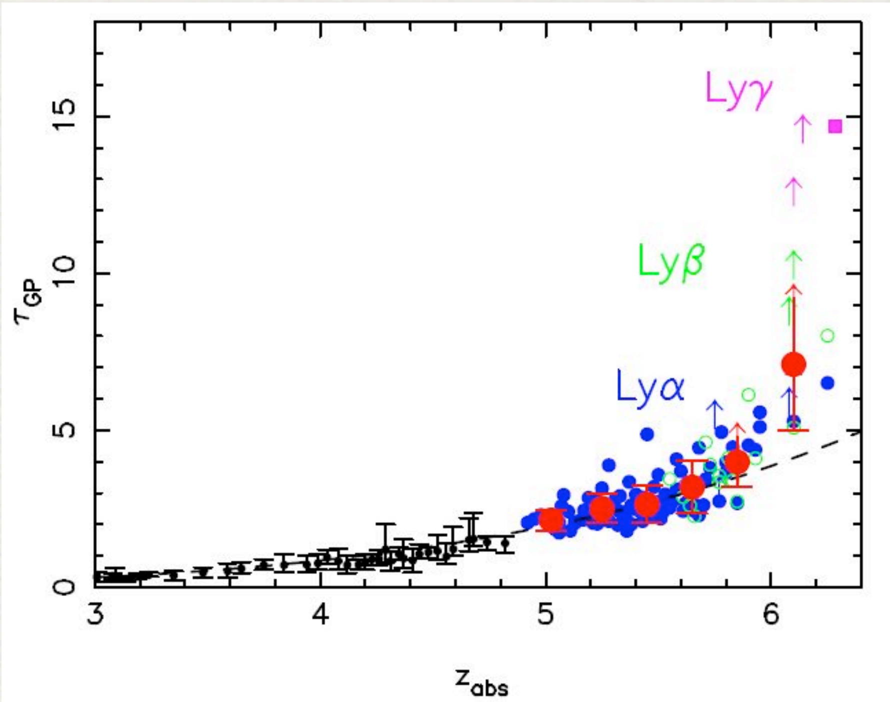
Djorgovski+

The Gunn-Peterson Test





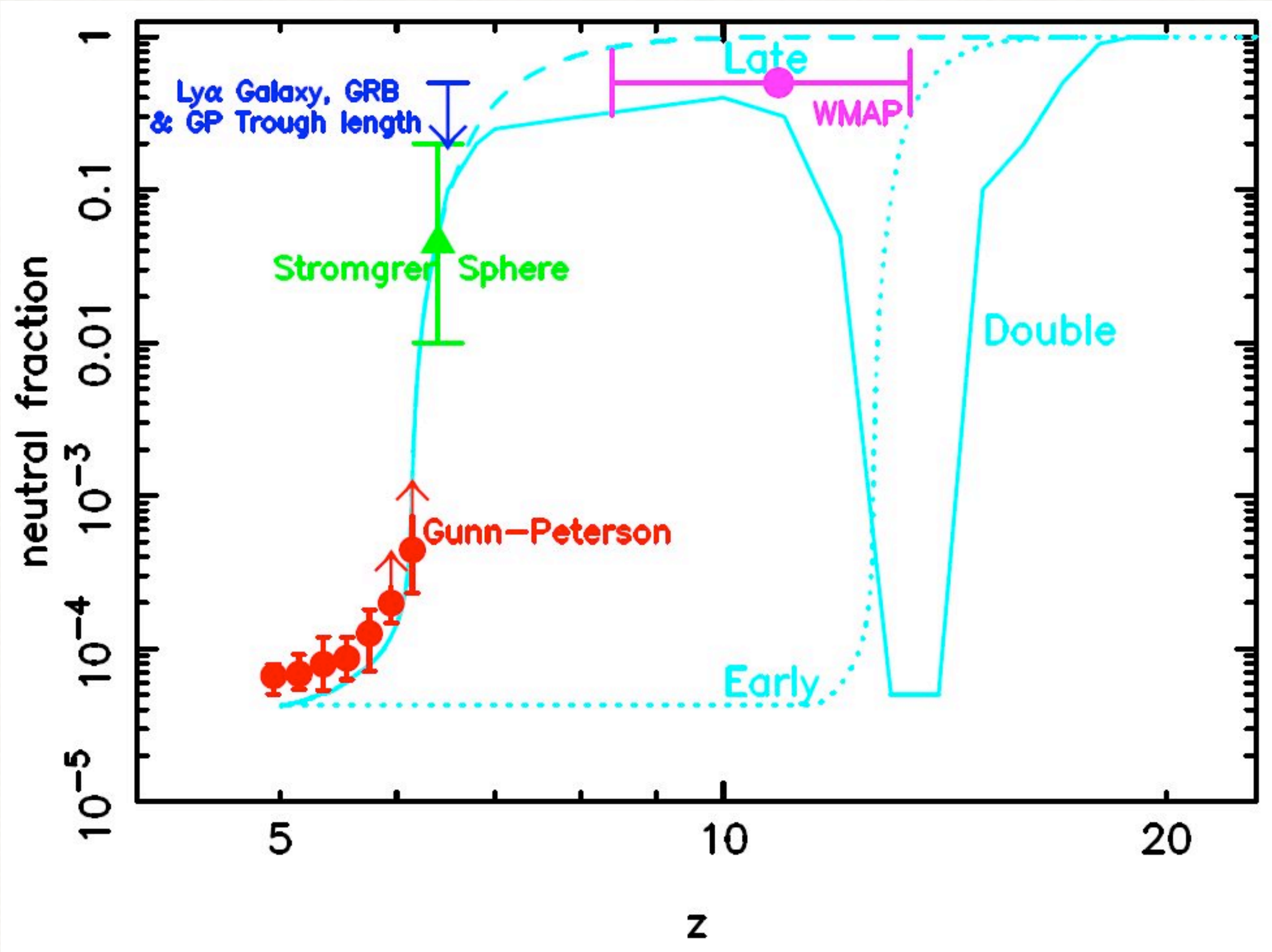
White+'03



- Ly α absorption features of QSOs indicating that IGM neutral fraction rapidly increasing to z ~ 6
  - close to reionization?
- but saturated GP troughs only gives a lower limit of $n_{HI}/n_H > 10^{-3}$

Fan+'05

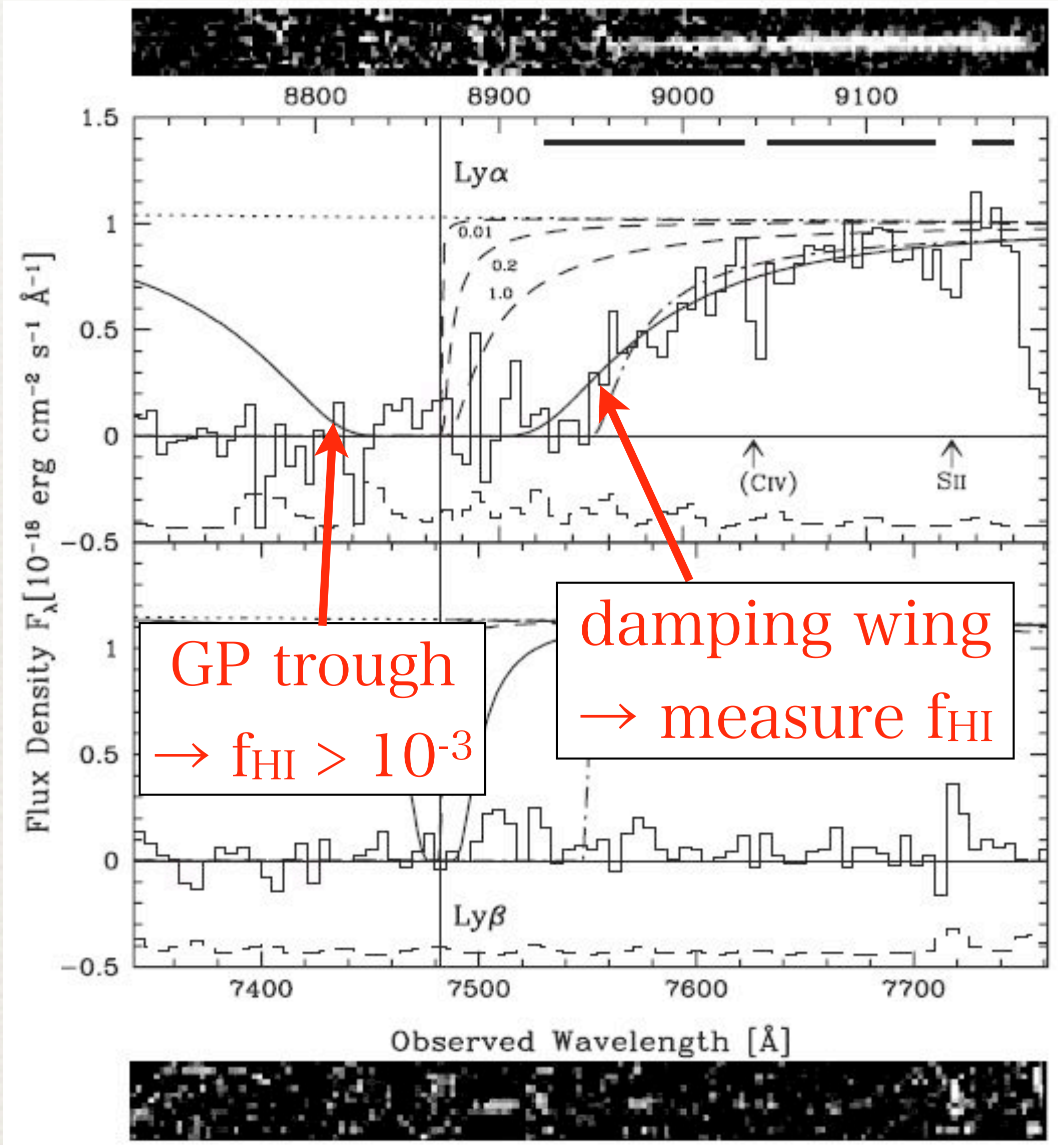
Observational Constraints on Reionization History



✦ Fan+ '06

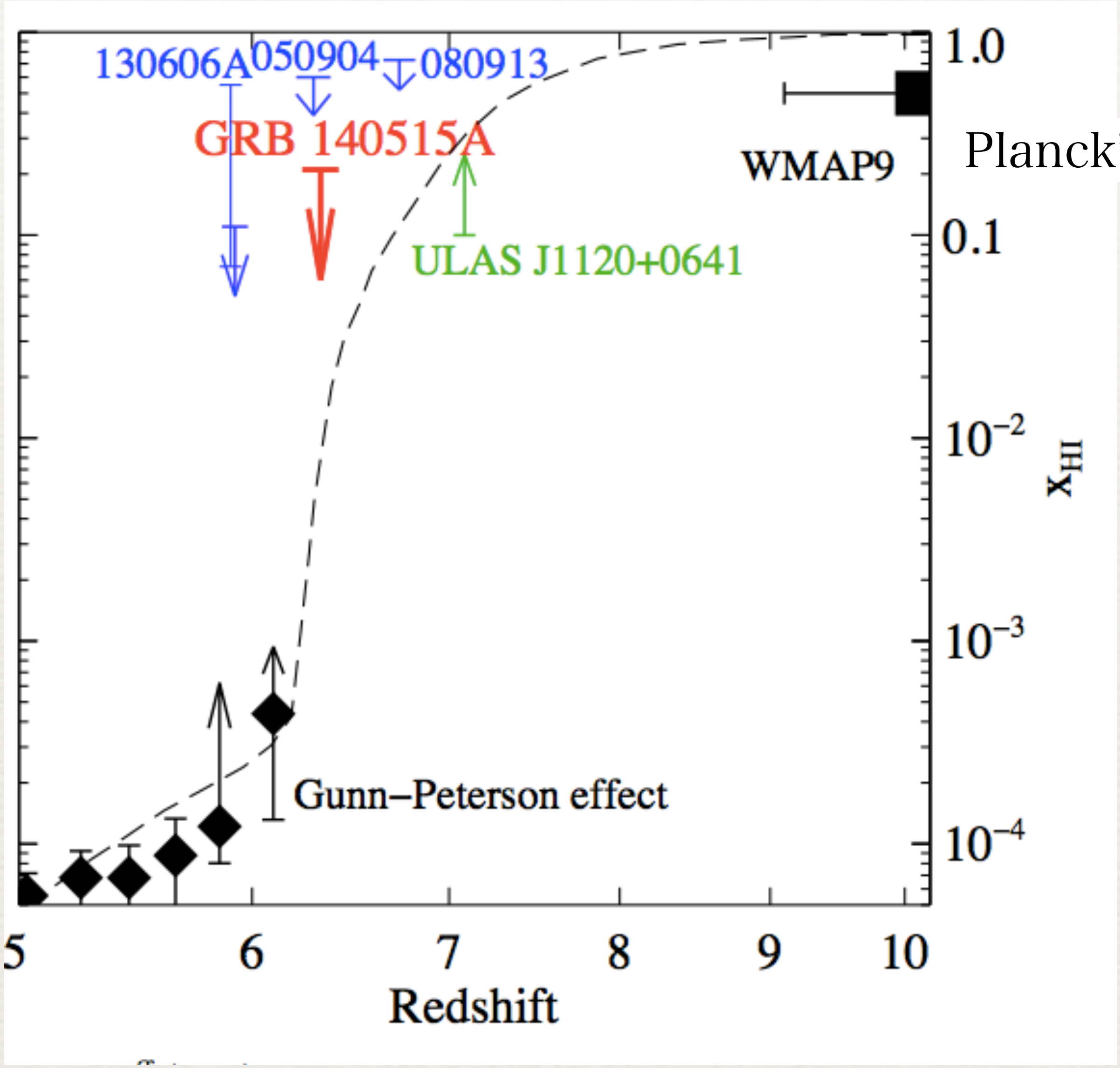
A Next Step: Using Ly α Red Damping Wing

- measurement of $f_{HI}=n_{HI}/n_H$, rather than lower limit, is possible if damping wing feature by neutral IGM is detected!
- GRBs especially powerful:
  - simple power-law unlike quasars
  - no proximity effect
  - more normal regions than quasars
- Obstacles:
  - low event rate of high-z GRBs
  - contamination by HI in host galaxies
- GRB 050904: the first meaningful constraint
  - 95% C.L. upper limit $f_{HI} < 0.6$ (TT +'06)



GRB 050904@z=6.3, TT+ '06

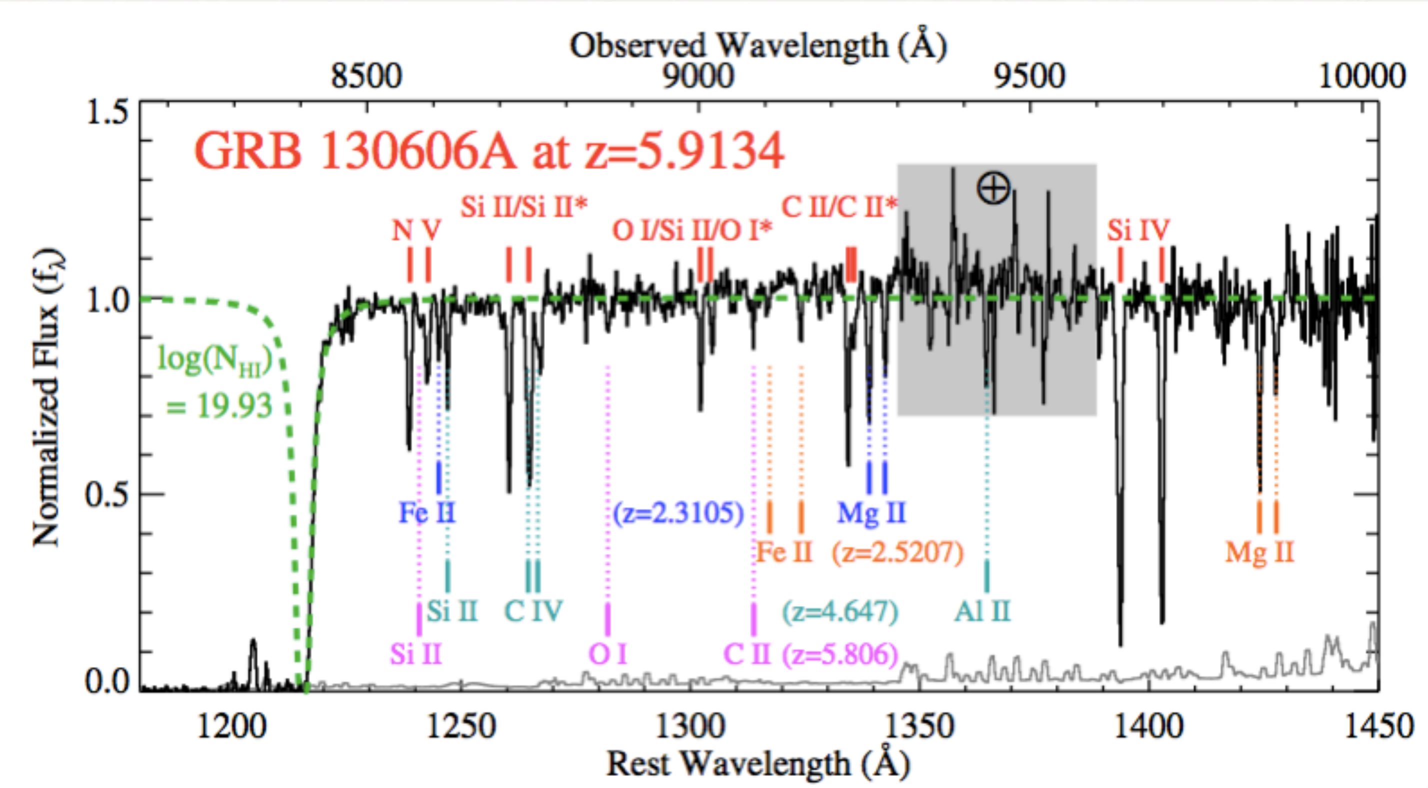
Observational Constraints on Reionization History

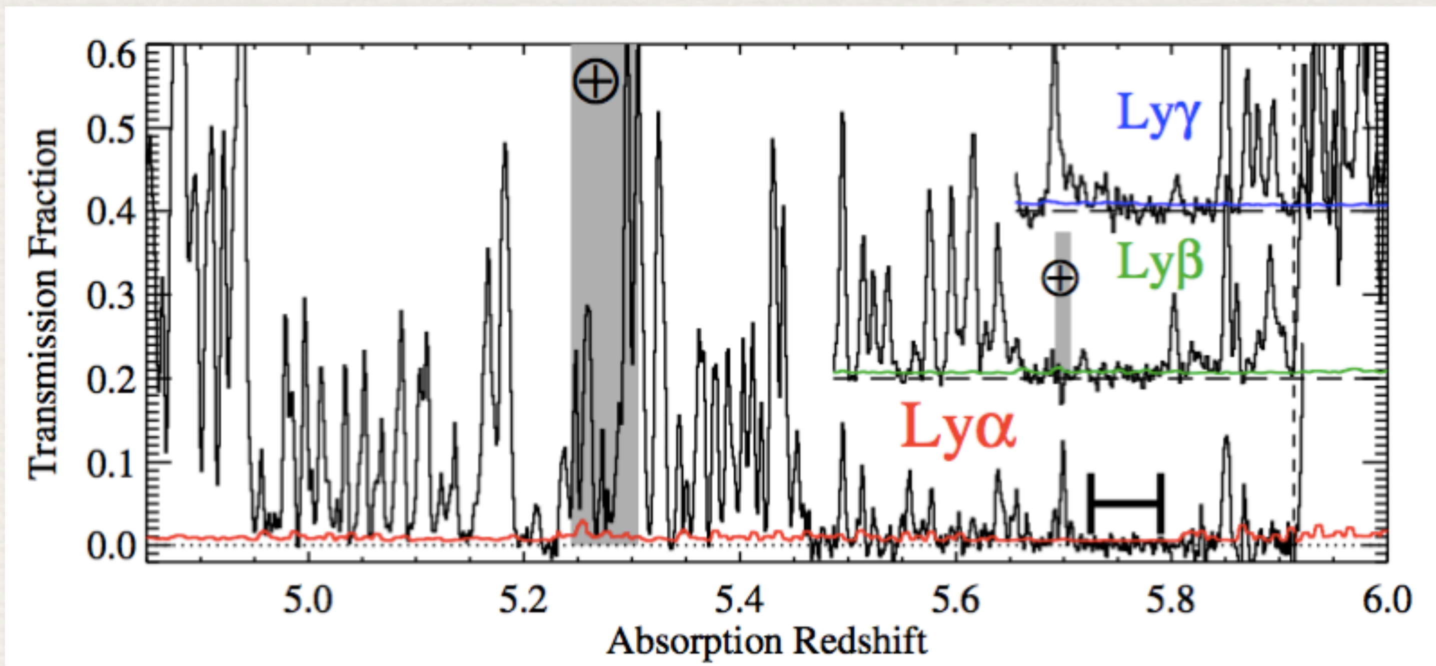


Planck'13: $z_{re} = 11.4^{+4.0}_{-2.8}$

- Chornock+ '14

The best opportunity ever: GRB 130606A





- exceptionally bright afterglow
- ultra-high S/N spectra taken by Gemini, GTC, Magellan, Subaru, VLT, ...
- host HI at most $\log(N_{HI}) < 19.8$, good for IGM study!
  - c.f. 21.6 for GRB 050904

Chornock+'13

Gemini vs. Subaru vs. VLT

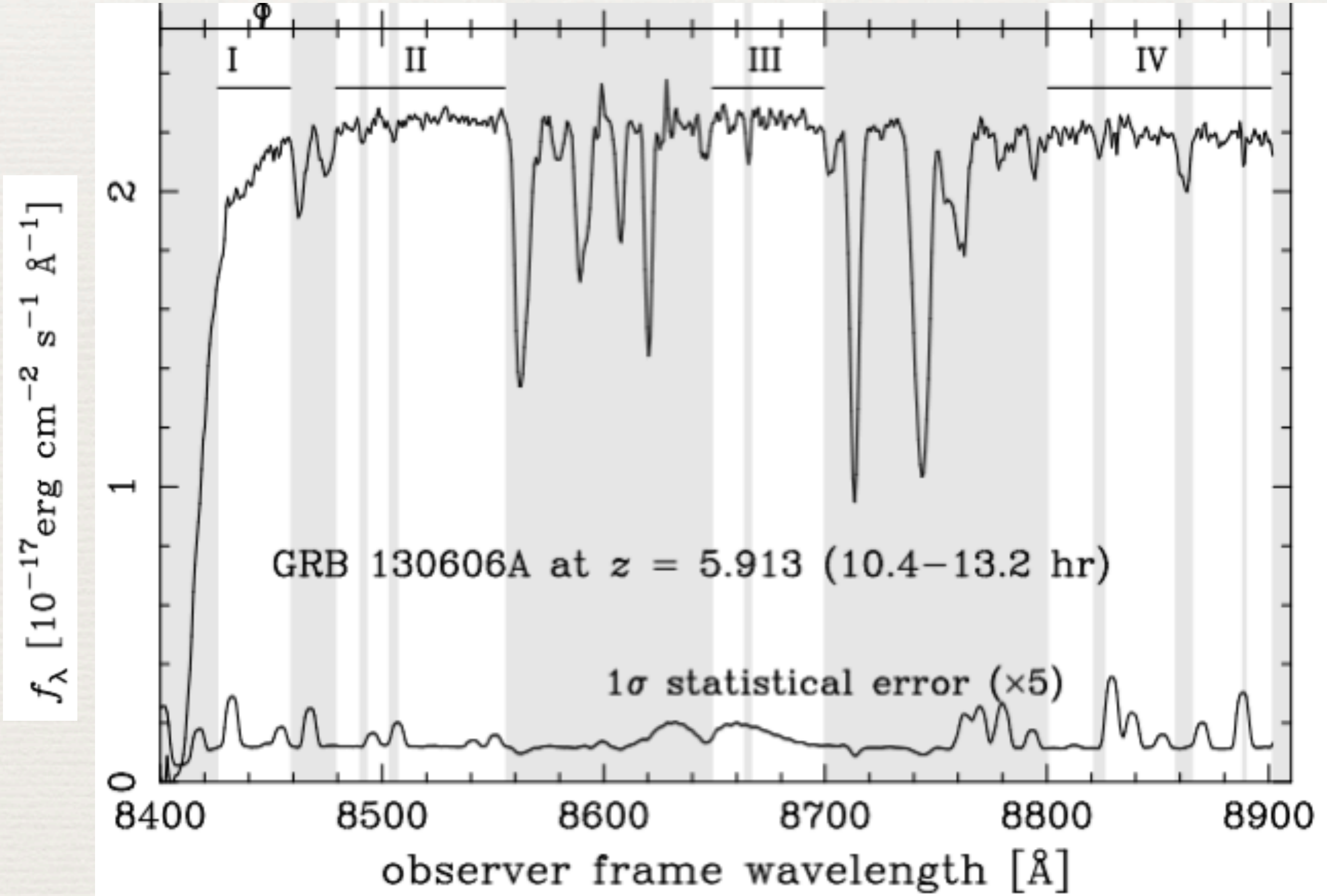
- Chornock et al. 2013 (Gemini, ApJ, 774, 26)
  - no evidence for IGM HI by damping wing analysis
  - $f_{HI} < 0.11$ (2σ)
  - spectral index $\beta = -1.99$ ($f_\nu \propto \nu^\beta$), very different from $\beta \sim -1$ found by more recent studies

- Totani et al. 2014 (Subaru, PASJ, 66, 63)
  - ~3σ preference for IGM HI, with
    - f_{HI} ~ 0.09 if $z_{IGM,u}$ = zGRB = 5.913 ($\beta = -0.93$)
    - f_{HI} ~ 0.4 if $z_{IGM,u} = 5.83 < 5.913$ ($\beta = -0.74$) ← now disfavored from VLT measurement of β

- Hartoog et al. 2014 (VLT, arXiv:1409.4804)
  - $\beta = -1.02$ from optical-NIR spectrum
  - no evidence for IGM HI, $f_{HI} < 0.03$ (3σ)

Damping Wing Analysis for Subaru Data

- Subaru/FOCAS spectrum in 10.4-13.2 hr after the burst
- S/N=100 per pixel (0.74A)!
- 8400-8900 A which is the most sensitive to IGM HI signature
- avoid strong absorption

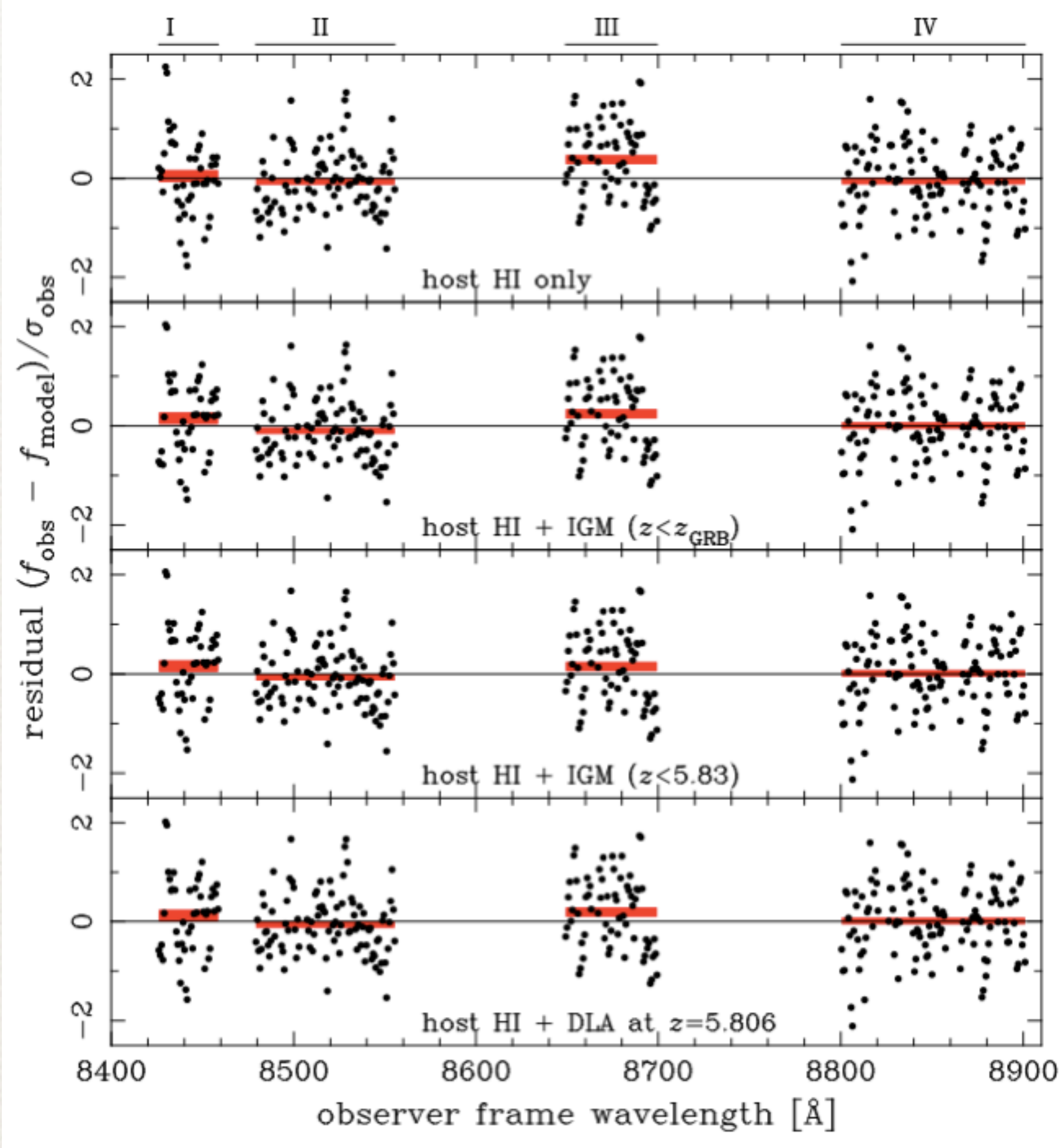


TT+'14

Fitting Residuals

- power-law + host HI only
  - free parameters: power-law index, N_{HI}, σ_v
  - showing curved systematic residual
  - amplitude ~ 0.6% of continuum flux

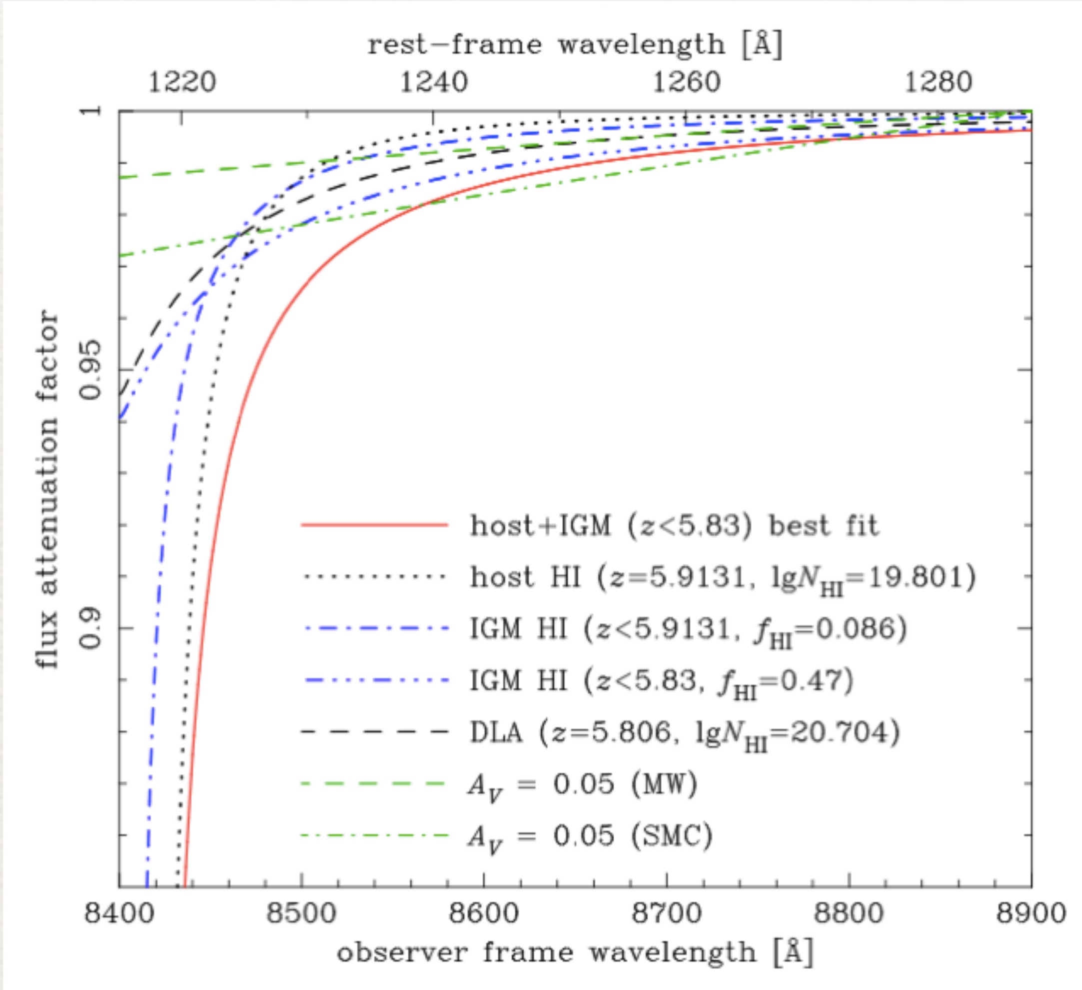
- diffuse IGM HI can reduce the residual by about 3 sigma statistics
  - f_{HI} ~ 0.1, if IGM extending to $z_u = z_{GRB} = 5.913$



TT+'14

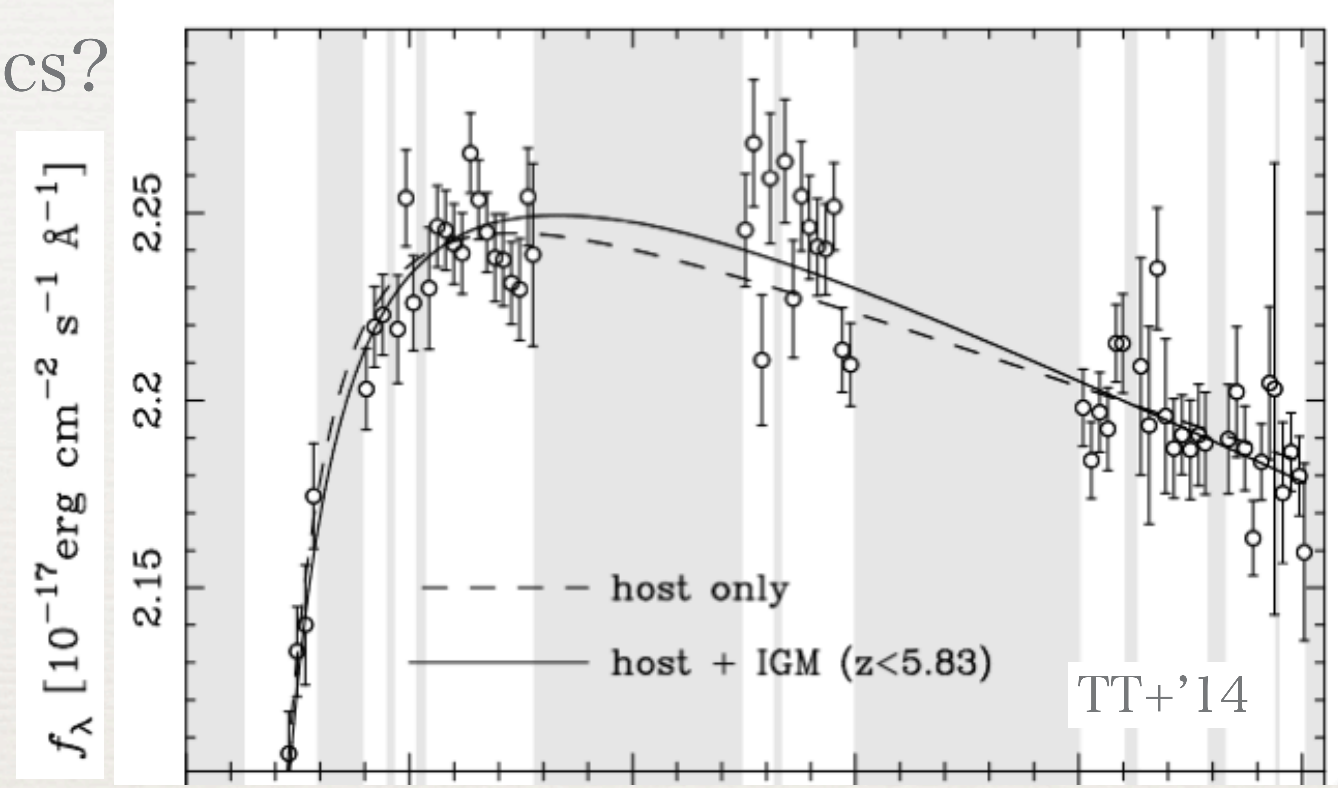
DW from various components

- wavelength close to Lyα center is dominated by HI in the host galaxy
- IGM HI becomes relatively important at wavelength far from Lyα
- wavelength range choice is a crucial issue in the damping wing analysis for reionzation!



TT+'14

Very subtle! systematics?

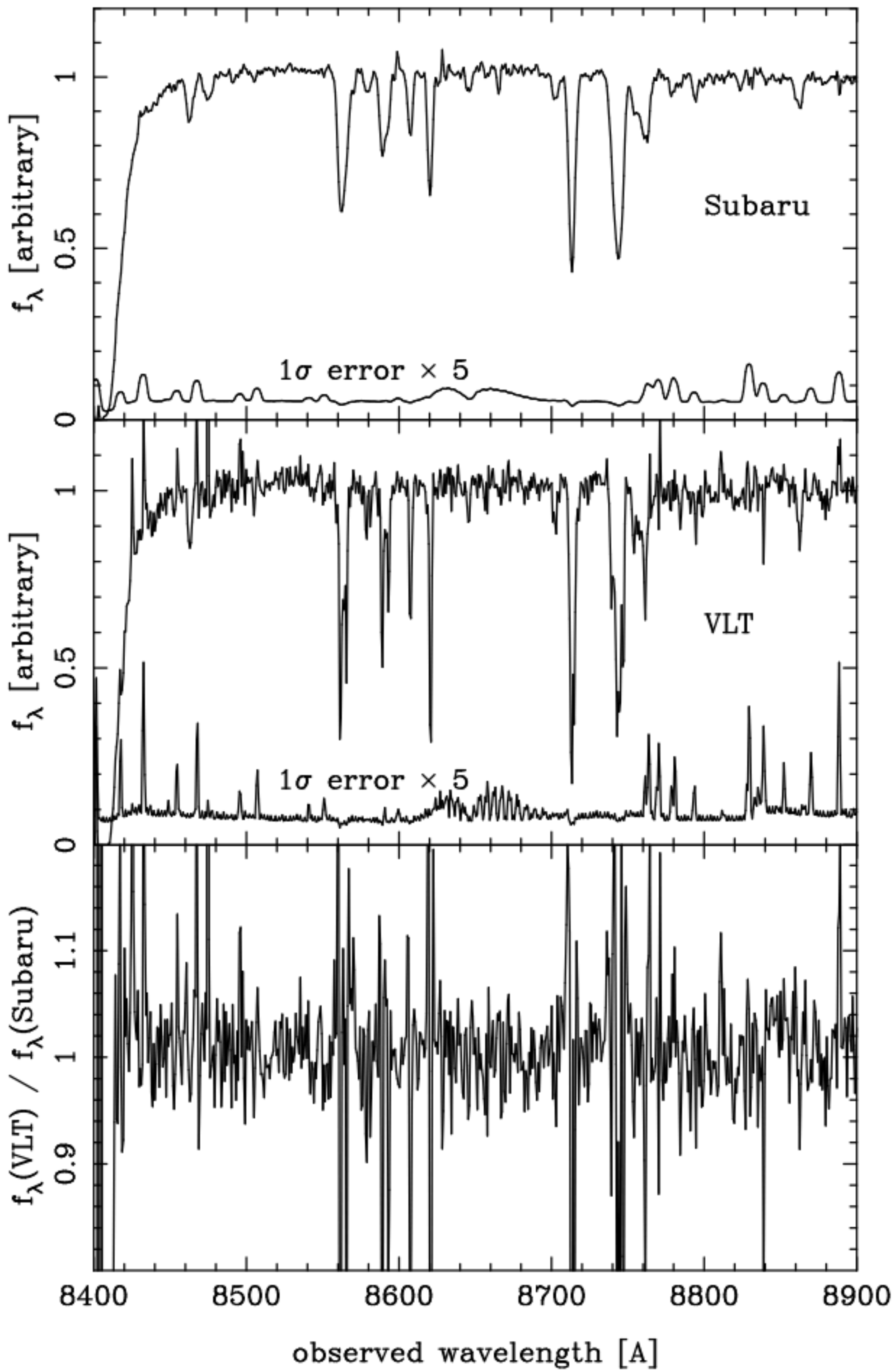


- various sources of systematics examined, but unlikely to explain the 0.6% curvature in the narrow range of 8400-8900 A
  - spectrum reduction, calibration
    - calibration accuracy is < 0.2%
    - no known systematics can explain the observed curvature
  - extinction at host
    - extinction does not explain the strong curvature in the short wavelength range
  - DLAs on the sightline
    - disfavored from Lyβ and metal absorption

what's the origin of Subaru/VLT controversy?

- To reveal this, the Subaru and VLT spectra have been exchanged by the two teams
  - I thank the VLT team for kindly agreeing with this exchange
- VLT spectrum averaged on the Subaru spectrum grids
  - VLT has a better spectral resolution
  - S/N similar per wavelength
- no systematic trend on > 100 Å scale
- how about adopting the same Subaru analysis code on the VLT spectrum?

TT+'15



Result of TT's-code on VLT spectrum. 1

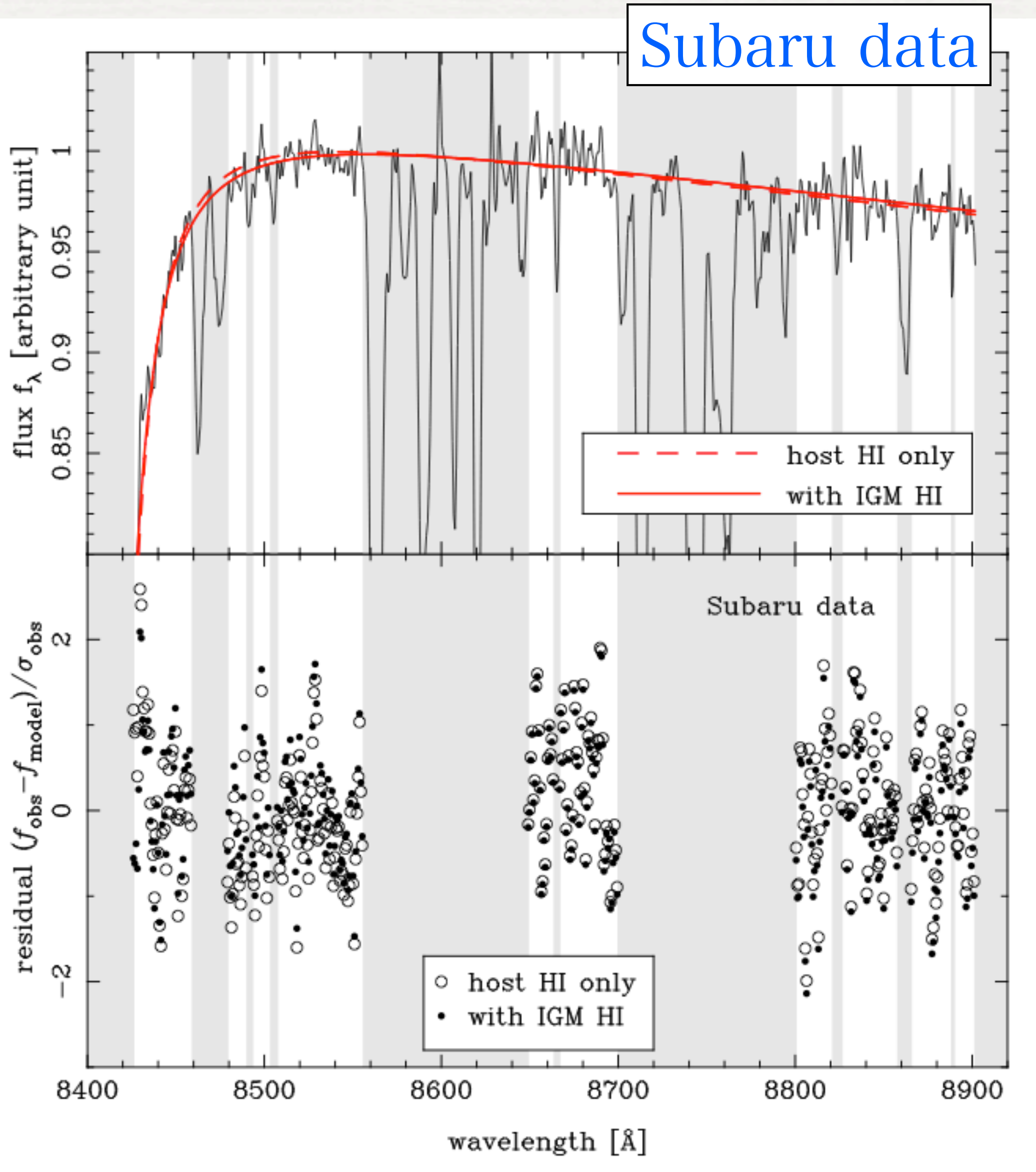
Table 1. The best fit parameters of the fittings to the Subaru and VLT spectra*

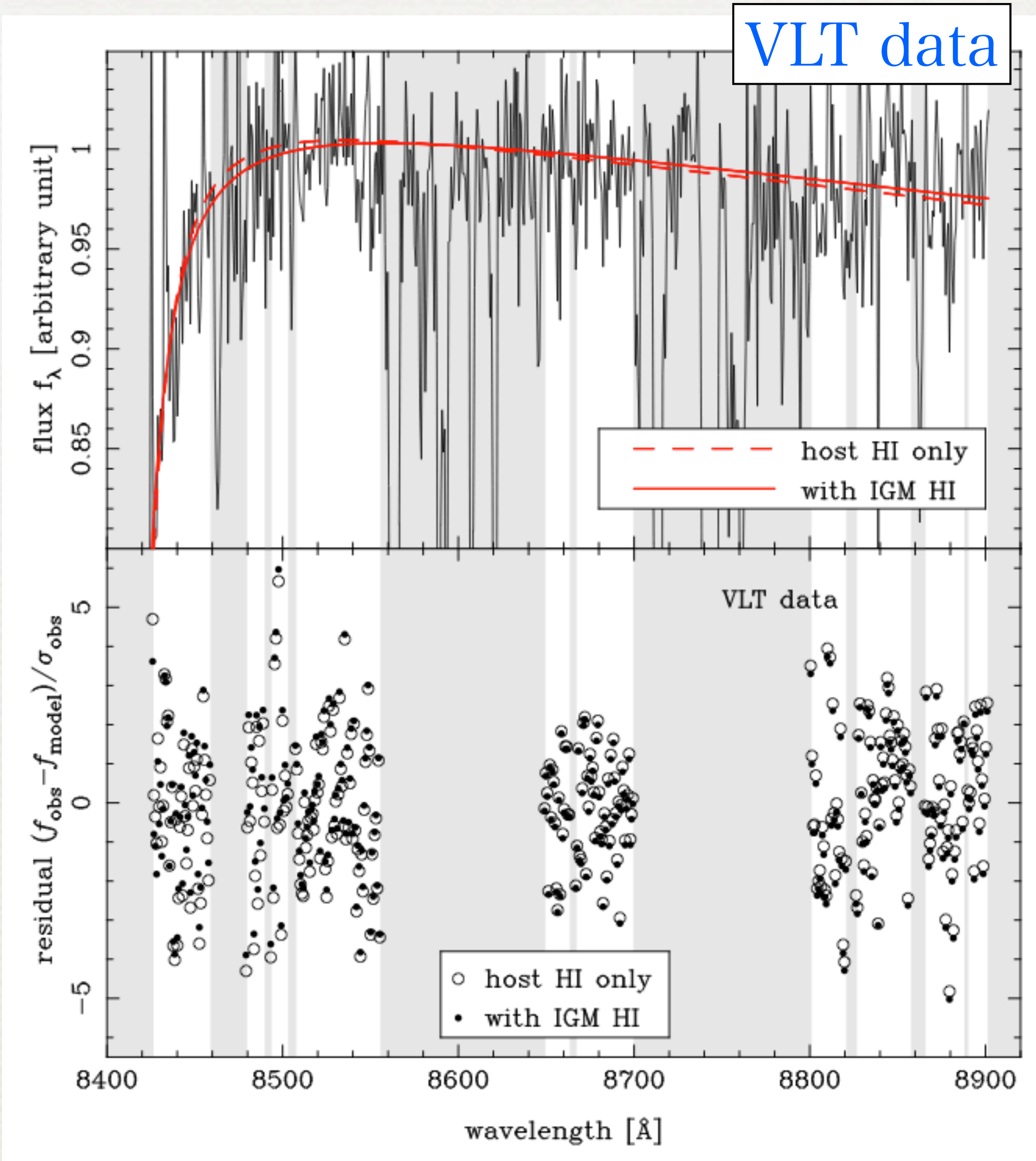
model	$\lg(N_{\rm H\,I}^{\rm host})^{\dagger}$	σ_v (km/s)‡	IGM $f_{\rm H\,I}$	χ^2	$\Delta\chi^{2\,\S}$
fit to the Subaru spectrum					
host H I only	$19.877^{+0.008}_{-0.015}$	$0.0^{+89.9}_{-0.0}$	fixed to zero	95.10	14.48
host+IGM H I	$19.768^{+0.032}_{-0.032}$	$62.0^{+38.0}_{-62.0}$	$0.061^{+0.007}_{-0.007}$	80.62	-
fit to the VLT spectrum					
host H I only	$19.806^{+0.014}_{-0.016}$	$0.0^{+52.0}_{-0.0}$	fixed to zero	292.57	11.89
host+IGM H I	$19.621^{+0.059}_{-0.057}$	$0.0^{+100.0}_{-0.0}$	$0.087^{+0.017}_{-0.029}$	280.68	-

- β fixed at −1.02 as measured by VLT
- IGM HI extends to $z_{\rm GRB,u} = z_{\rm GRB} = 5.913$

- The original Subaru result (~3 σ preference for IGM HI) confirmed using VLT spectrum

Result of Subaru-code on VLT spectrum. 2

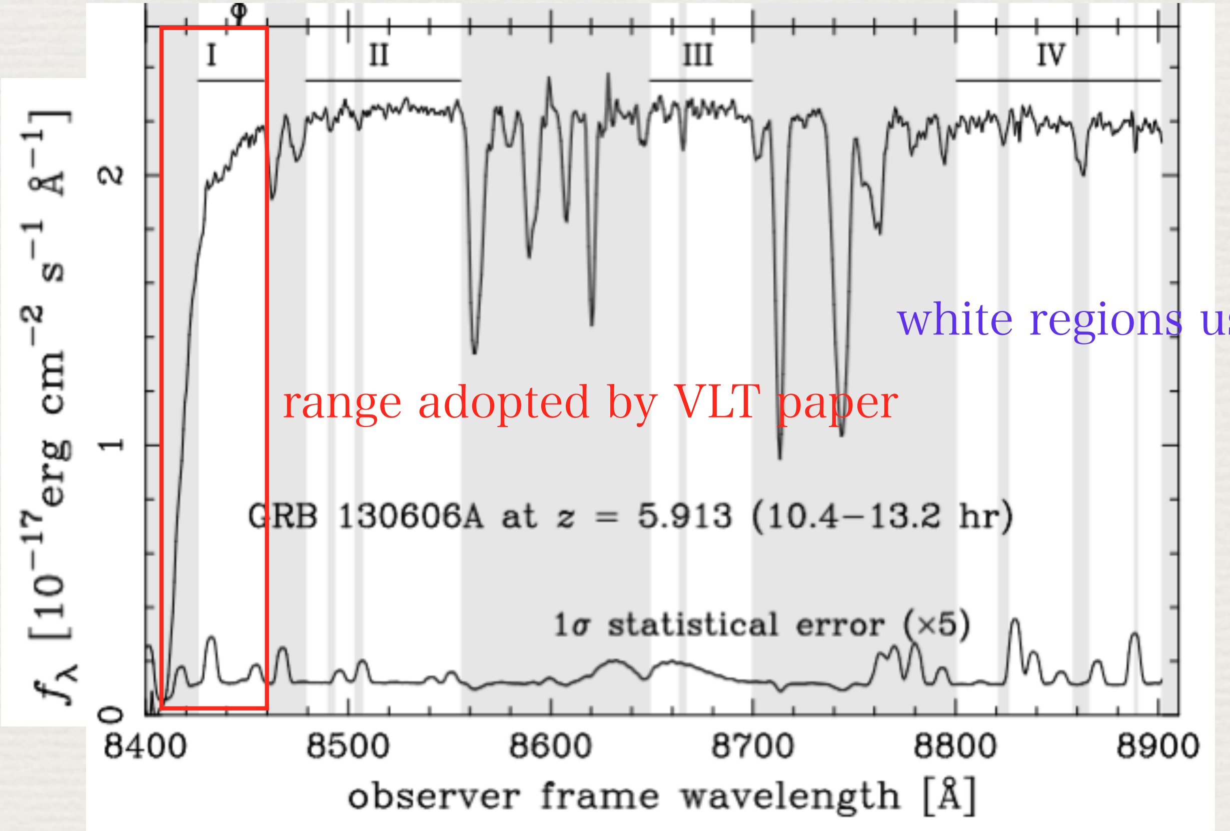




- the same trend for the fit residuals by no IGM HI model

What's the origin of discrepancy?

- wavelength ranges used are very different for Subaru and VLT papers
  - 8406-8462 Å by VLT
  - 8426-8900 Å by Subaru (<8426Å avoided because of strong dependence on host HI velocity distribution)
- when the TT's-code adopted on the VLT spectrum, I confirmed the VLT paper result (no evidence for host HI)
- the VLT-paper range is highly sensitive to velocity distribution of HI in the host
  - σ_V = 61.8±3.3 km/s by our fit result
  - systematics about unknown realistic velocity distribution is a worry



On the Ly α cross section formulae

- classical Rayleigh scattering

$$\sigma_{\mathrm{R}}(\omega) = \sigma_{\mathrm{T}} \frac{f_{12}^2 \omega^4}{(\omega_0^2 - \omega^2)^2 + \Gamma_{2p}^2 \omega^2},$$

- Lorentzian

$$\sigma_{\mathrm{L}}(\omega) = \sigma_{\mathrm{T}} \left(\frac{f_{12}}{2} \right)^2 \frac{\omega_0^2}{(\omega_0 - \omega)^2 + \Gamma_{2p}^2 / 4}$$

- Peebles' two-level approximation

$$\sigma_{\mathrm{P}}(\omega) = \frac{3\lambda_0^2}{8\pi} \frac{\Gamma_{2p}^2 (\omega/\omega_0)^4}{(\omega_0 - \omega)^2 + \Gamma_{2p}^2 (\omega/\omega_0)^6 / 4}.$$

- second order perturbation theory for fully quantum mechanical scattering (Bach+'14)

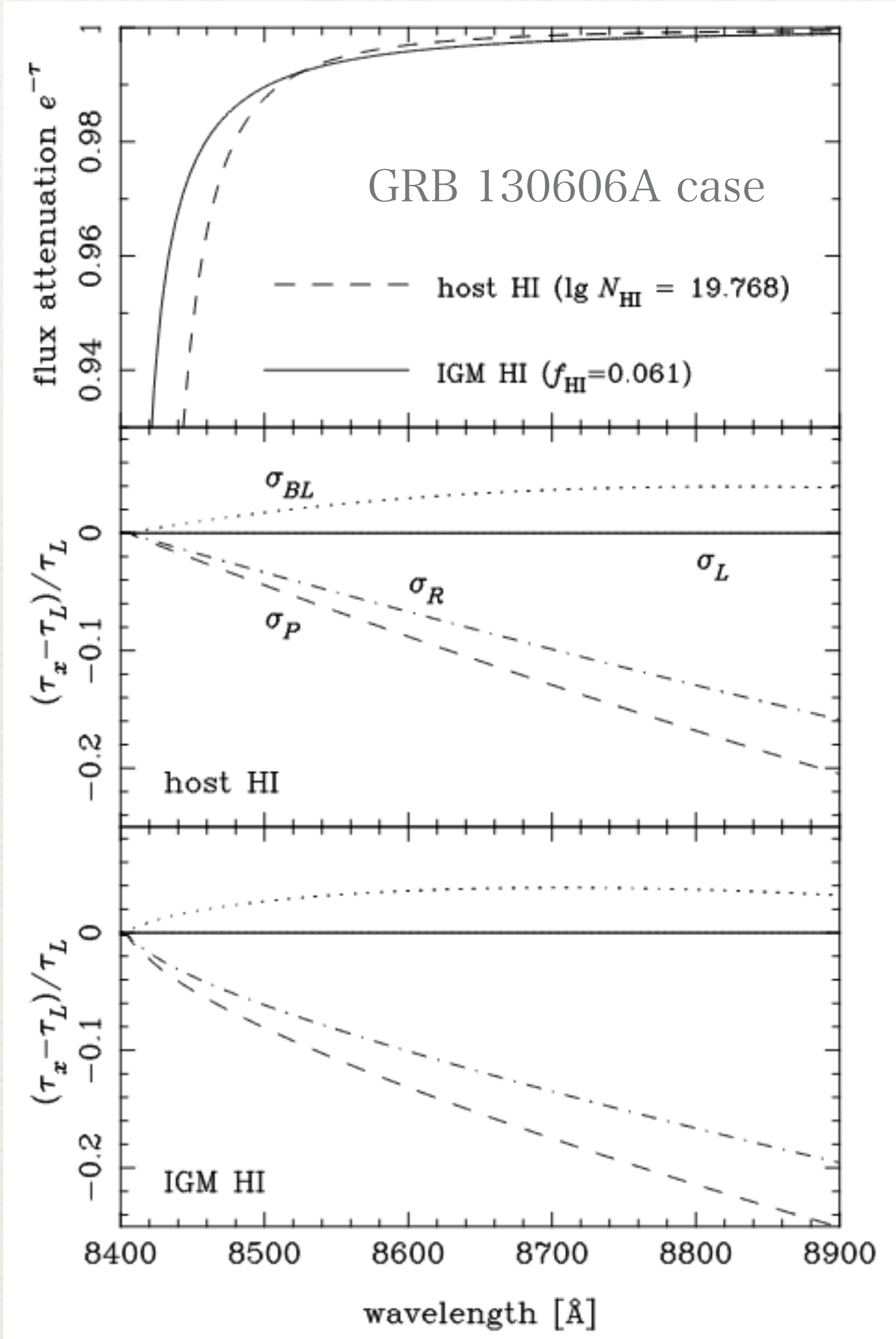
$$\sigma(\omega) = \sigma_{\mathrm{L}} \frac{4 (\omega/\omega_0)^4}{(1 + \omega/\omega_0)^2} [1 + f(\omega)].$$

$$f(\omega) = a \left(1 - \mathrm{e}^{-bx}\right) + cx + dx^2$$

$$\begin{cases} a = 0.376 \\ b = 7.666 \\ c = 1.922 \\ d = -1.036, \end{cases}$$

effect on HI opacity by Lyα cross section formulae

- ~10% difference in cross section / HI opacity
- The Peebles' formulae often used shows the largest deviation from BL (Bach-Lee) formula
- How much is the effect on the damping wing fitting results?
  - perhaps the evidence for IGM HI reported by TT+'14 just an artifact by using inaccurate cross section formula?



Fitting results dependence on cross section formulae

- on the Subaru data of the GRB 130606A spectrum
- with the fitting method of TT+'14, only changing Ly α cross section formula
- preference to IGM HI by ~3-4 σ unchanged

cross section formula	$\lg(N_{\rm HI}^{\rm host})$	σ_v (km/s)	IGM $f_{\rm H\,I}$	χ^2	$\Delta\chi^2$
		host H I only model			
Lorentzian	$19.869^{+0.010}_{-0.010}$	$0.0^{+70.2}_{-0.0}$	fixed to zero	91.81	10.74
Rayleigh	$19.875^{+0.010}_{-0.010}$	$22.1^{+63.1}_{-22.1}$	fixed to zero	94.21	13.50
Peebles	$19.877^{+0.008}_{-0.015}$	$0.0^{+89.9}_{-0.0}$	fixed to zero	95.10	14.48
Bach & Lee	$19.866^{+0.009}_{-0.009}$	$0.0^{+63.5}_{-0.0}$	fixed to zero	90.66	9.88
		host + IGM H I model			
Lorentzian	$19.755^{+0.033}_{-0.033}$	$100.0^{+0.0}_{-100.0}$	$0.057^{+0.0012}_{-0.007}$	81.07	-
Rayleigh	$19.765^{+0.033}_{-0.033}$	$54.6^{+45.4}_{-54.6}$	$0.060^{+0.008}_{-0.007}$	80.71	-
Peebles	$19.768^{+0.032}_{-0.032}$	$62.0^{+38.0}_{-62.0}$	$0.061^{+0.007}_{-0.007}$	80.62	-
Bach & Lee	$19.751^{+0.029}_{-0.029}$	$100.0^{+0.0}_{-100.0}$	$0.056^{+0.011}_{-0.006}$	80.78	-

Conclusions (1/2)

- GRB 130606A gives the best ever opportunity to probe reionization by GRBs
- ~3 σ evidence for IGM HI is found by the damping wing analysis of Subaru spectrum
  - f_{HI} ~ 0.1 if $z_{IGM,u} = z_{GRB} = 5.913$
  - robust against known systematics (spectrum, extinction, intervening DLA)
  - the first evidence for intervening HI to GRB sightlines
  - suggesting that the reionization not yet complete at z~6, but needs more sightlines to examine inhomogeneity
- discrepant result from VLT (Haartoog et al. 2014)?
  - data consistent with each other, and the same result confirmed when the same analysis is done on the two different spectra
    - high precision damping wing analysis indeed possible!
  - discrepancy comes from different wavelength ranges
    - need to be careful for systematics in analysis methods!
    - systematics about host HI velocity distribution seems serious when using range close to Ly α resonance

Conclusions (2/2)

- Now we are in the era of “GRBs as a high precision reionzation probe”
  - sensitive to f_{HI} ~ 0.1 at z~6!
  - systematics must be carefully treated

- Choice of Lyα cross section formulae is important in a high-precision analysis such as GRB 130606A
  - but preference to IGM HI reported by TT+’14 unchanged

- current limitation of GRBs as a reionization probe:
  - low event rate of sufficiently bright GRBs at z>~6
  - this situation will be improved by 30m-class telescopes
  - future GRB missions in synergy with 30m-class telescopes will be crucial
  - good data for many GRBs would reveal not only the mean but also inhomogeneity of reionization history