GRBs as reionization probes

戸谷友則（TOTANI, Tomonori）
Department of Astronomy, Univ. of Tokyo

Cosmic Shadow 2018
Nov. 24, 2018, Ishigakijima

Talk Plan

- GRBs as a reionization probe: strength and weakness
    - the case of GRB 050904 and some other GRBs

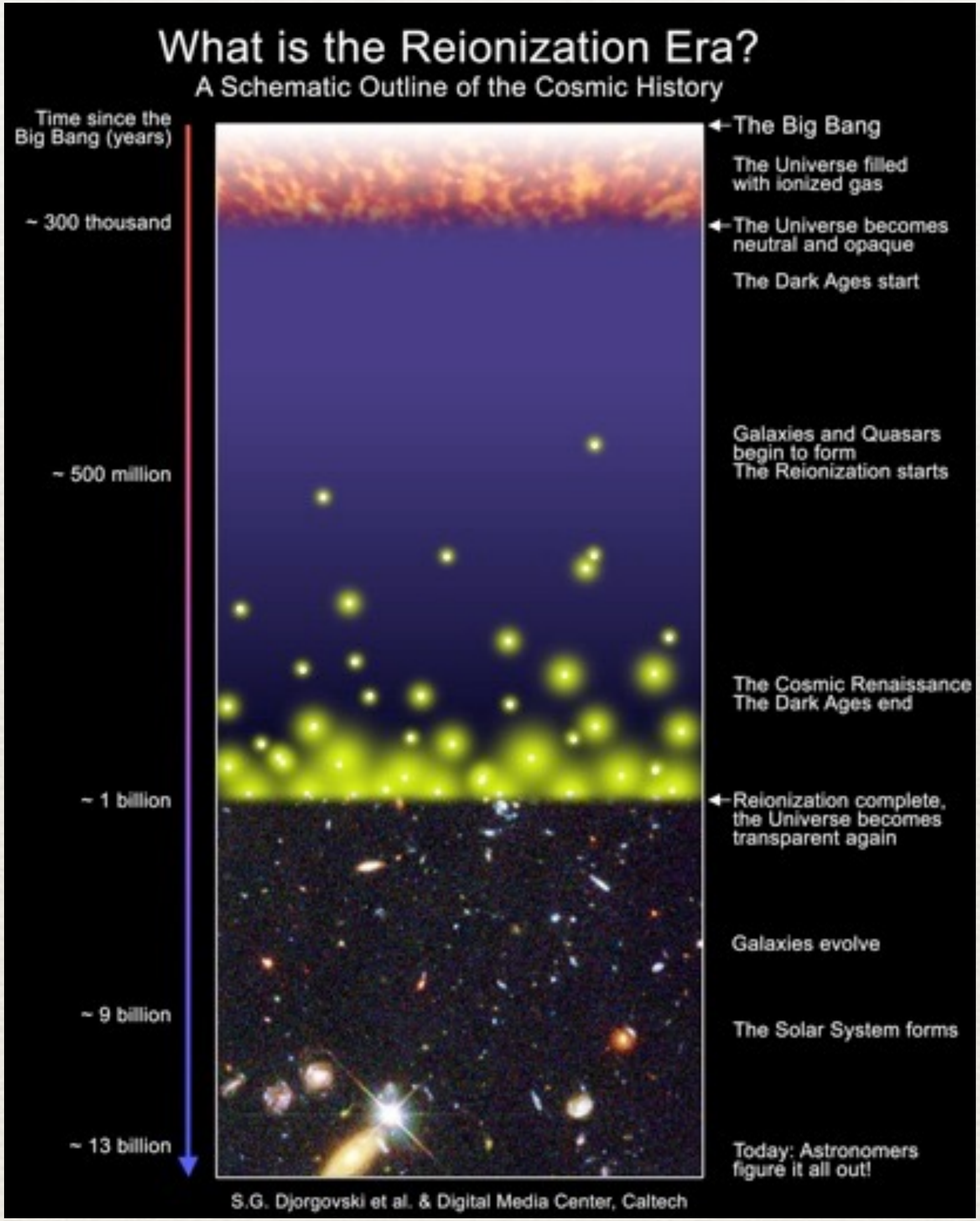
- some stories about GRB 130606A @ z=5.9
    - extremely high-S/N spectra taken, high precision analysis for reionization possible
    - controversy between Gemini/Subaru/VLT?

- On the effect of Lyα cross section formulae (as a function of wavelength) adopted

- Future?
    - prospects of 30m-class telescopes
    - simulating GRB spectra in cosmological reionization simulation

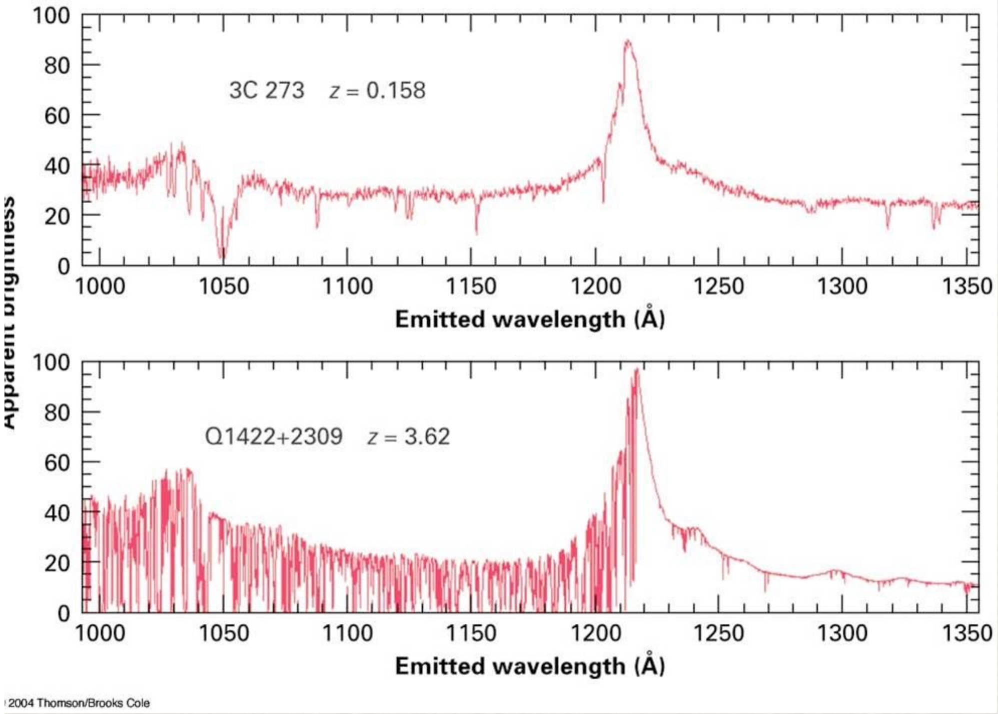
Cosmic Reionization

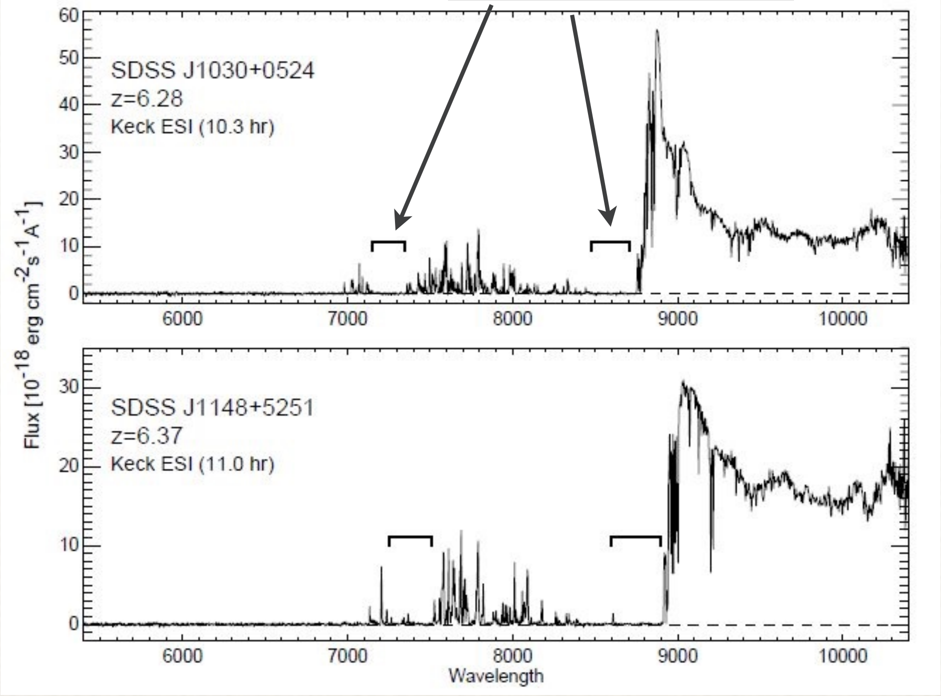
- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination
- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test
- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark to understand galaxy formation



Djorgovski+

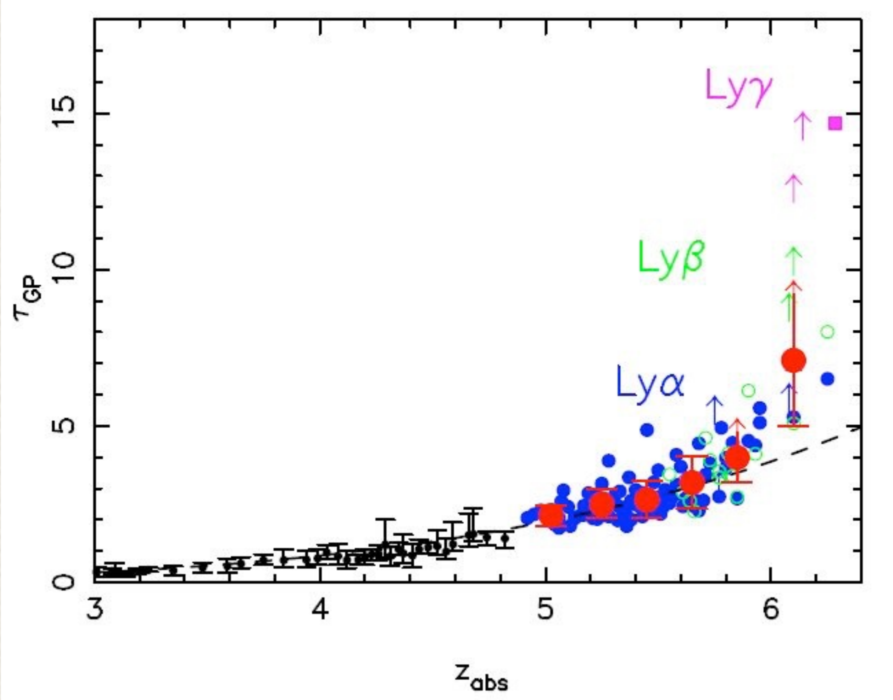
The Gunn-Peterson Test





"GP troughs"

White+'03

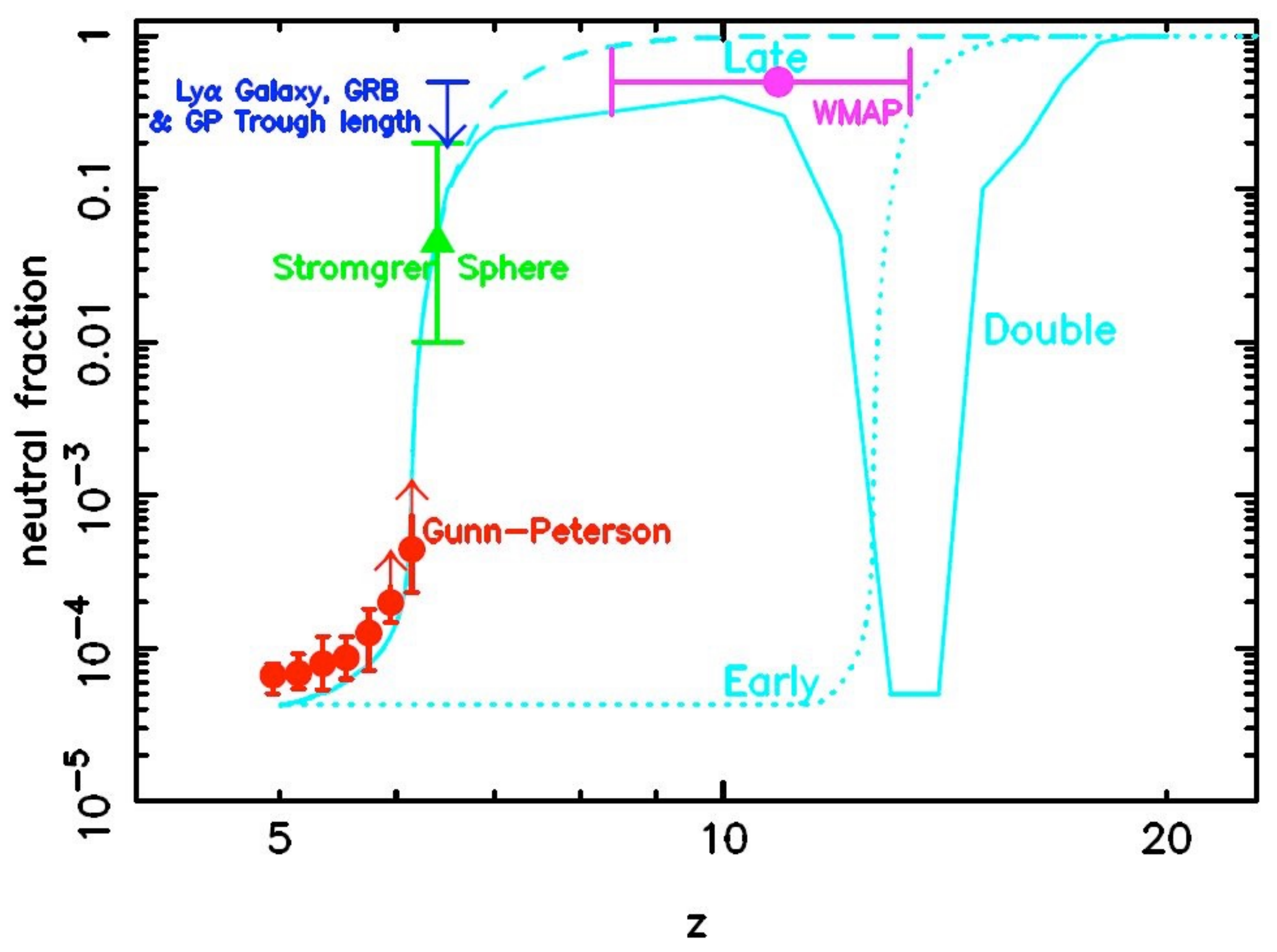


- Ly α absorption features of QSOs indicating that IGM neutral fraction rapidly increasing to z ~ 6
  - close to reionization?

- but saturated GP troughs only gives a lower limit of $n_{HI}/n_H > 10^{-3}$

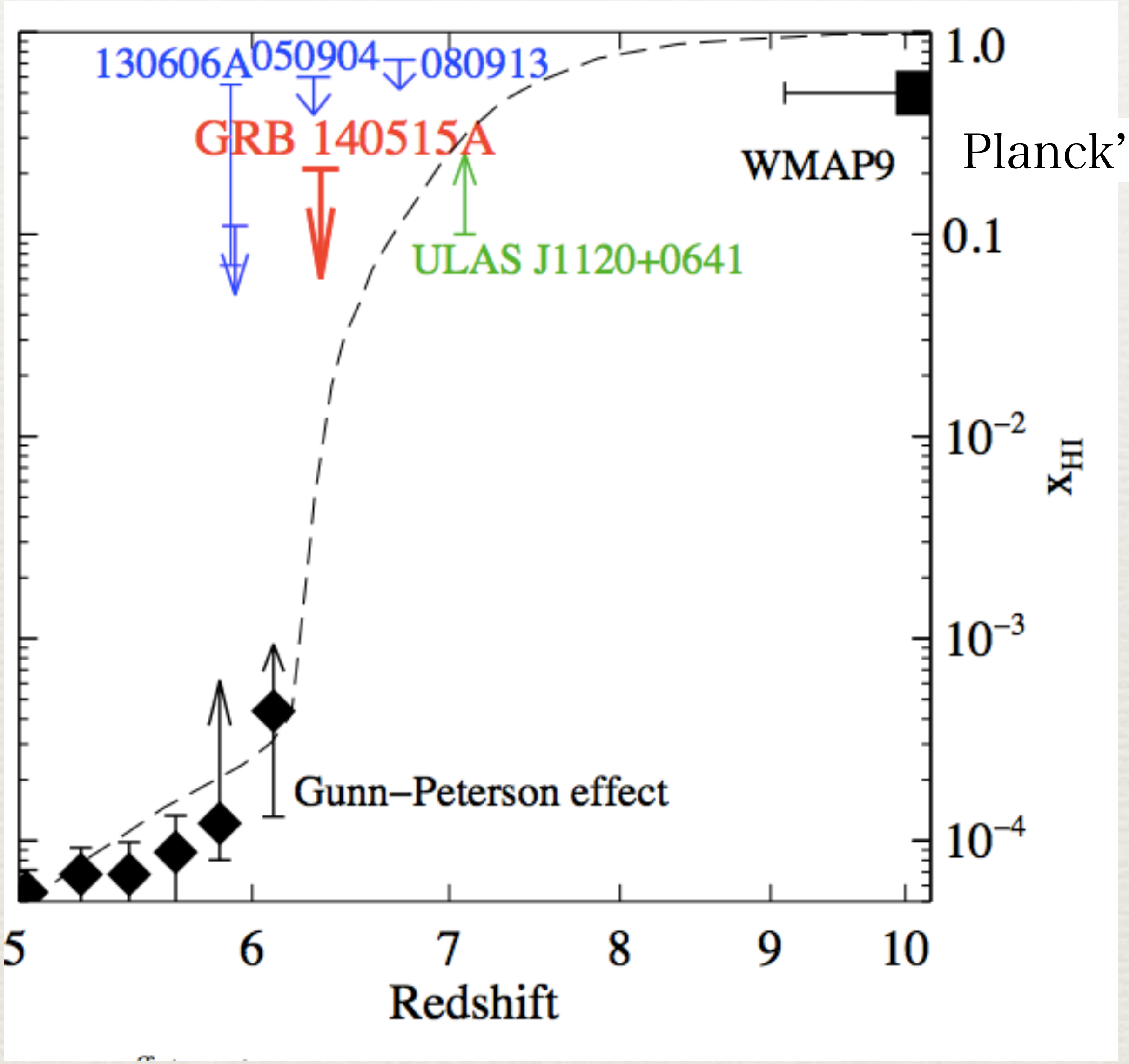
Fan+'05

Observational Constraints on Reionization History



- Fan+ ’06

Observational Constraints on Reionization History

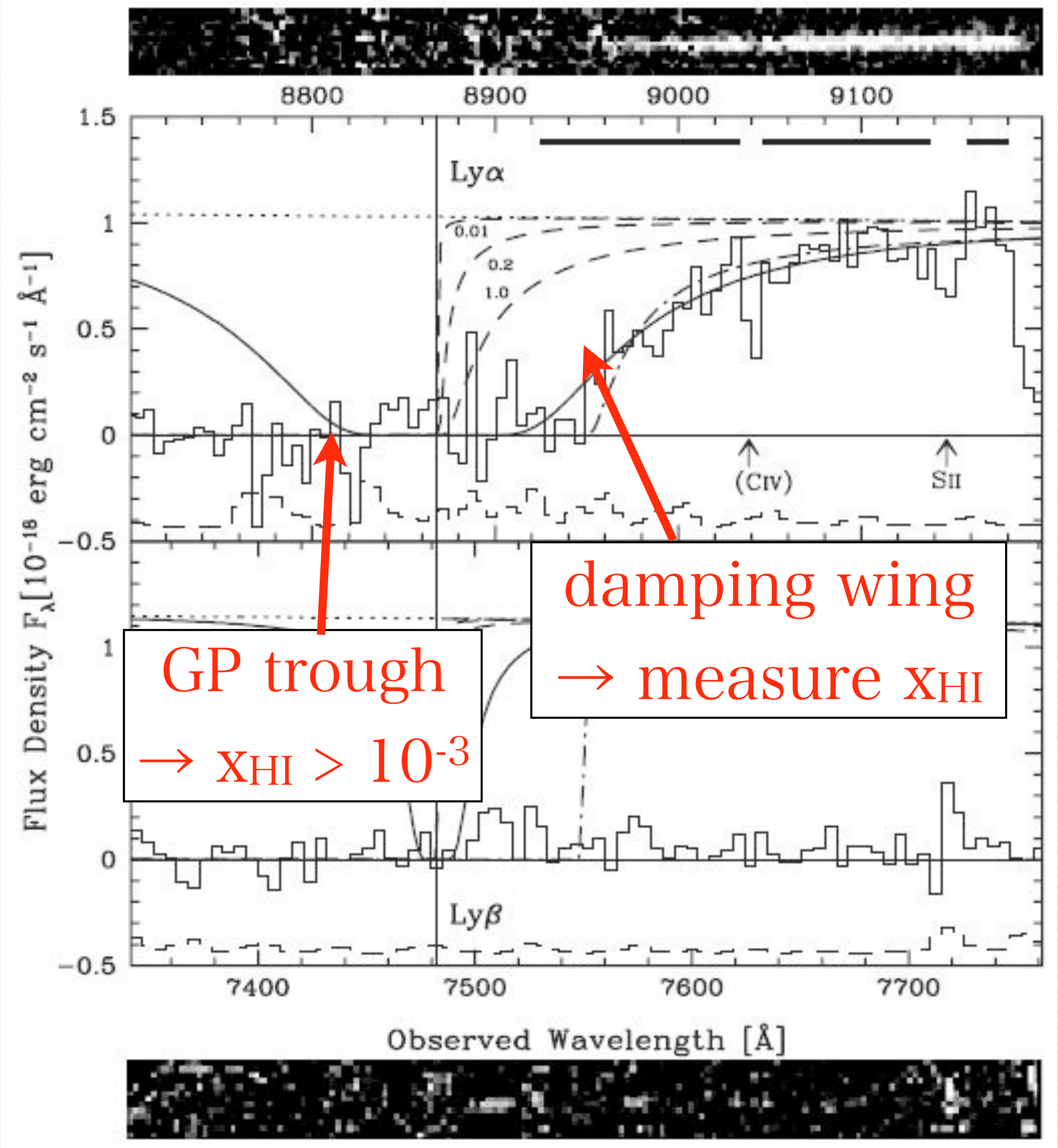


Planck'13: $z_{re} = 11.4^{+4.0}_{-2.8}$

- Chornock+ '14

GRB as a Reionization Probe

- Strengths:
  - GRBs detectable at z >> 6
  - probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - simple power-law spectrum
    - damping wing analysis to precisely measure x_{HI} ($=n_{HI}/n_H$)



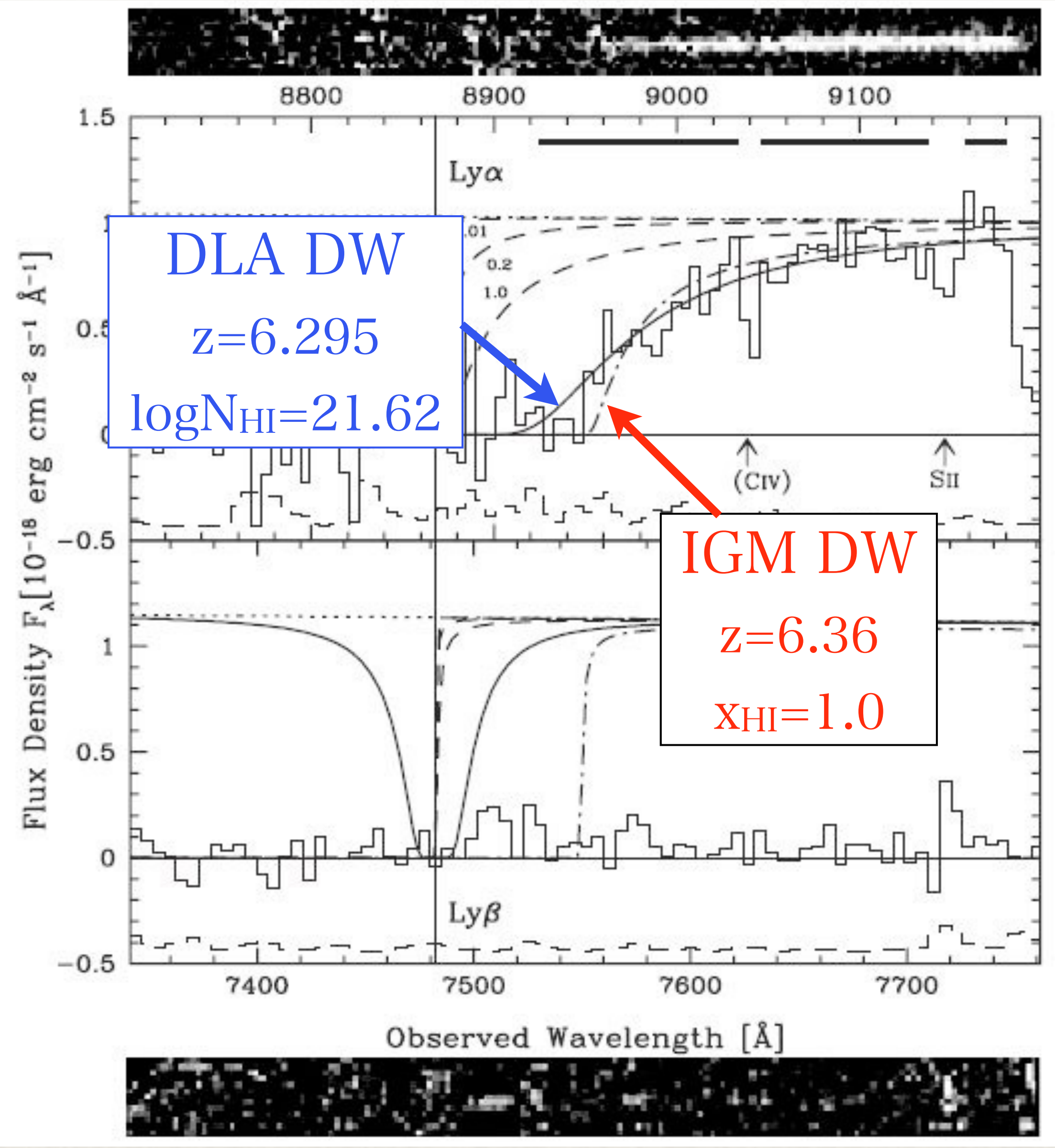
GP trough → $x_{HI} > 10^{-3}$

damping wing → measure x_{HI}

GRB 050904@z=6.3, TT+ '06

GRB as a Reionization Probe (2)

- Weakness:
  - Degeneracy between damped Ly α (DLA) of host galaxies and IGM damping wing
    - can be broken by:
      - metal absorption lines
      - Ly β feature
    - $x_{HI} < 0.17$ (68%C.L) or 0.6 (95%C.L.) by fitting to GRB 050904 (dominated by host HI)
    - we need low N_{HI} host galaxy to measure x_{HI} accurately
  - event rate not so high
    - only several GRBs at z > 6 from 2005

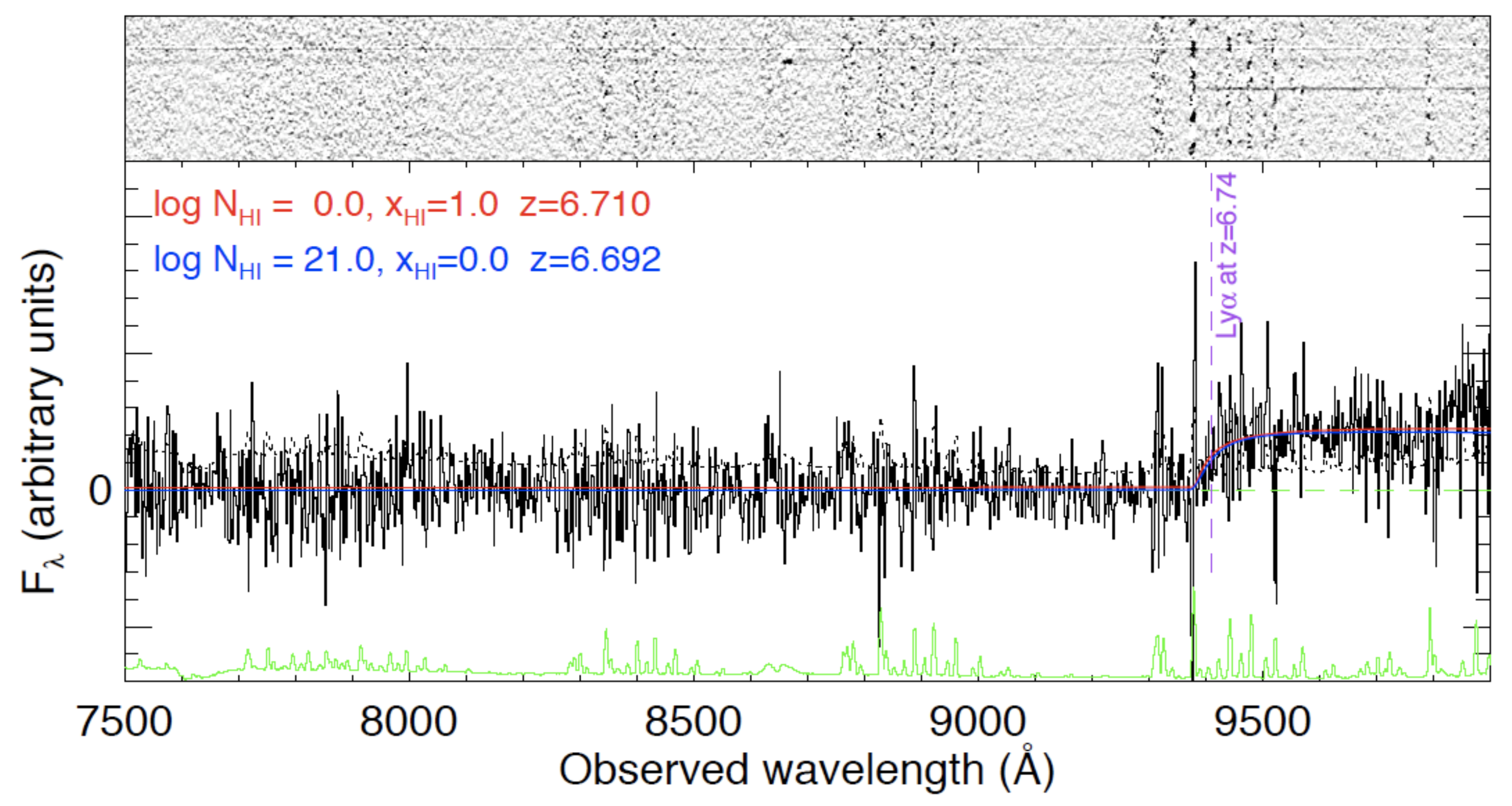


DLA DW
z=6.295
$\log N_{HI}=21.62$

IGM DW
z=6.36
$x_{HI}=1.0$

GRB 050904@z=6.3, TT+ ‘06

GRB 080913 @ z~6.7



(Greiner+'09)

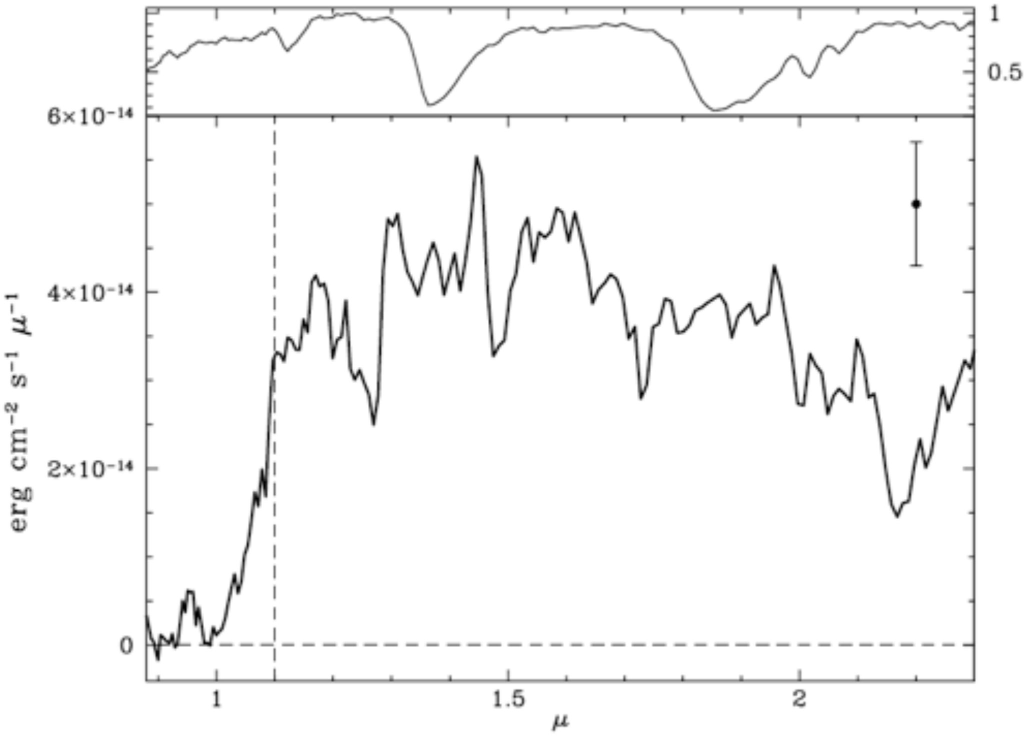
2-3 hrs, z'~24.5(AB), 2400 s exp.

damping wing detected, but difficult to discriminate DLA or IGM

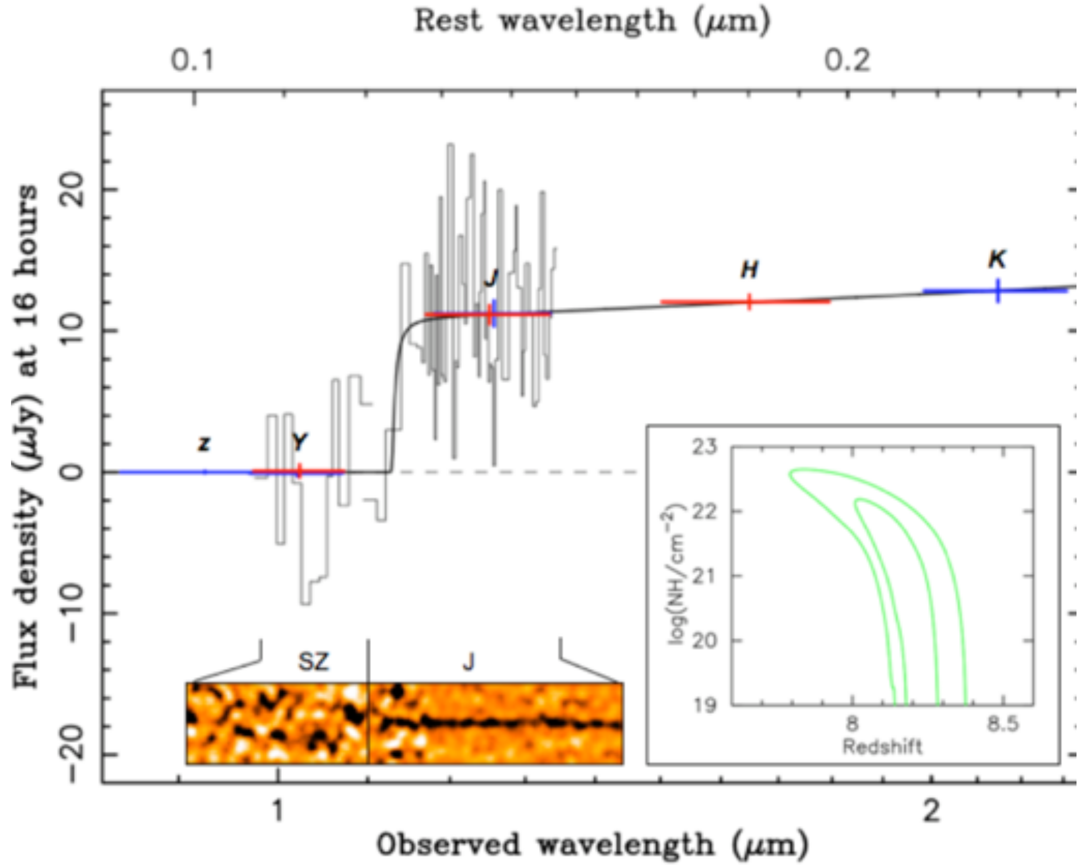
c.f. GRB 050904, z~6.3

3.4 days, z'=23.7(AB), 4 hr exp.

GRB 090423 @ z~8.2



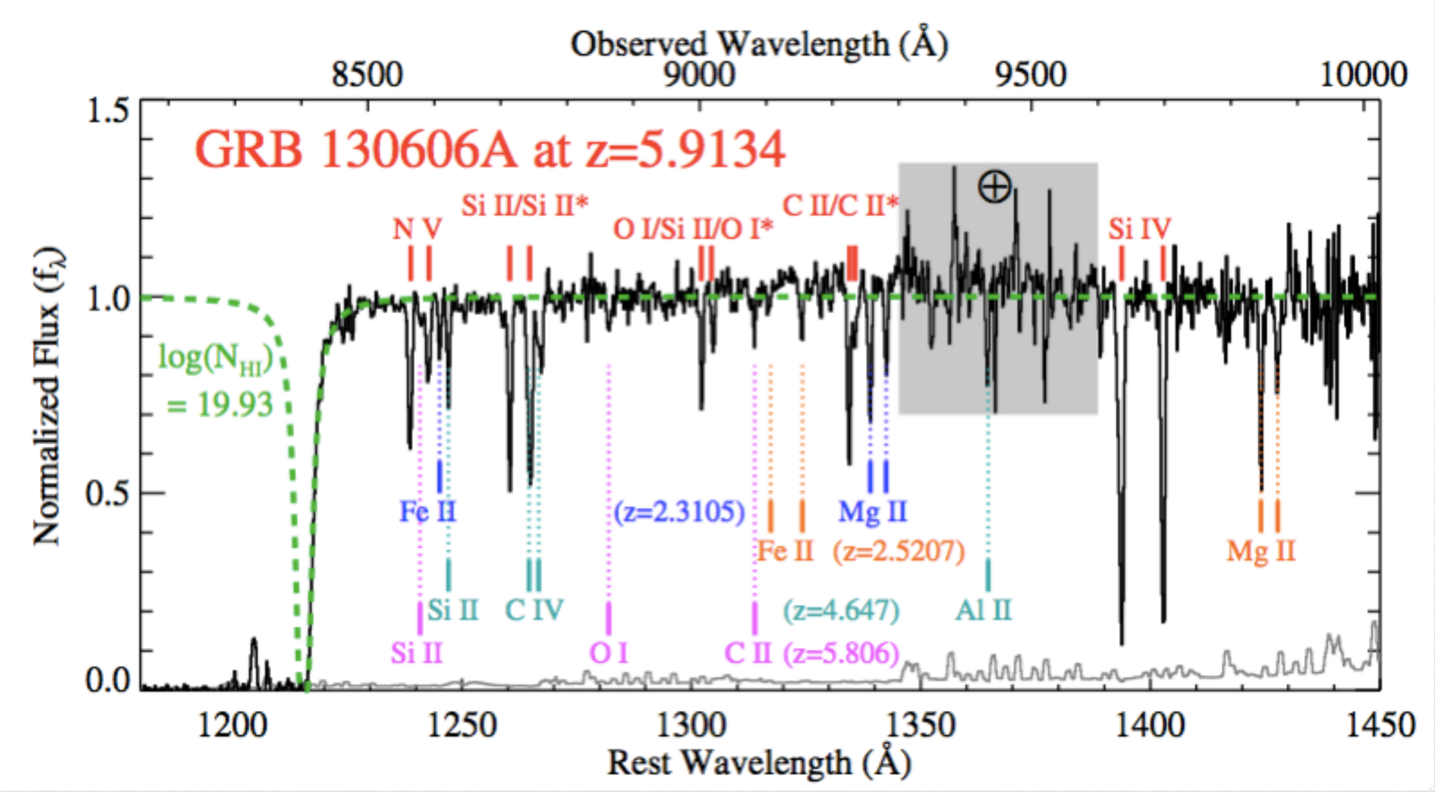
Salvaterra+’09

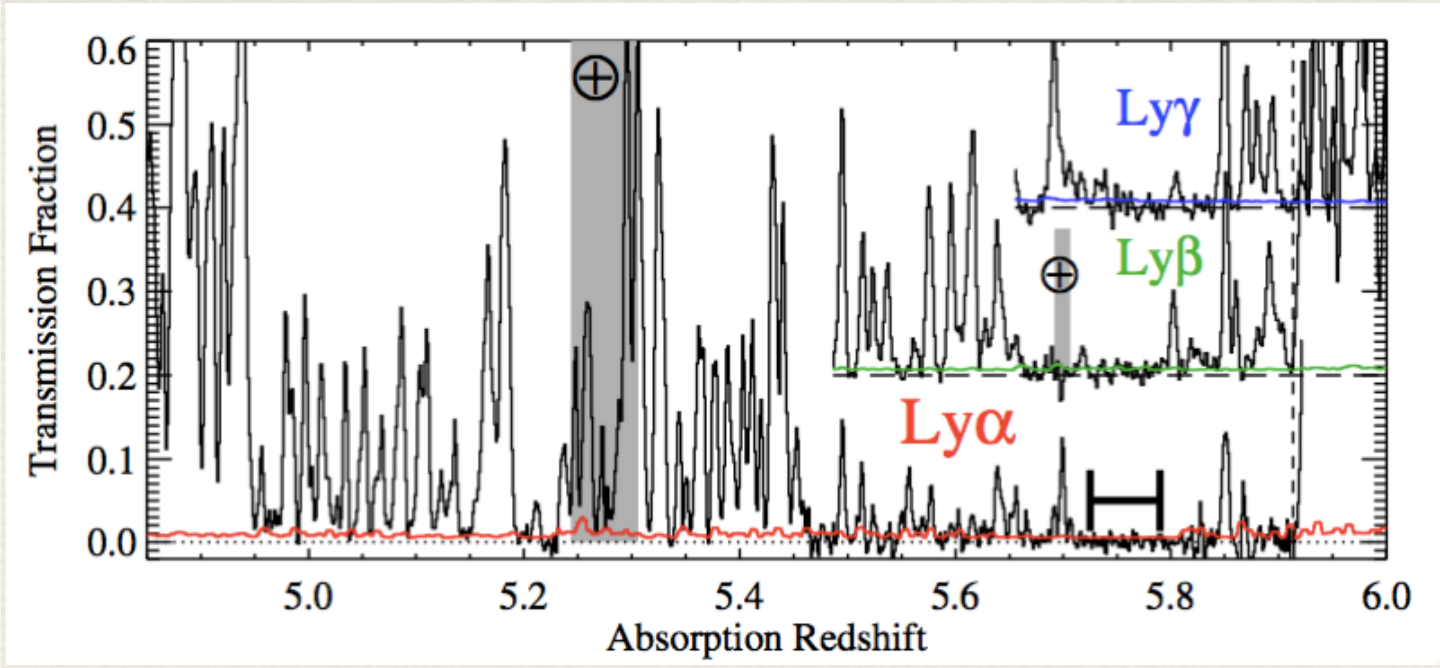


Tanvir+’09, ~20 hr, J~20.8

Only upper bound on N_{HI} (=no detection of damping wing)

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

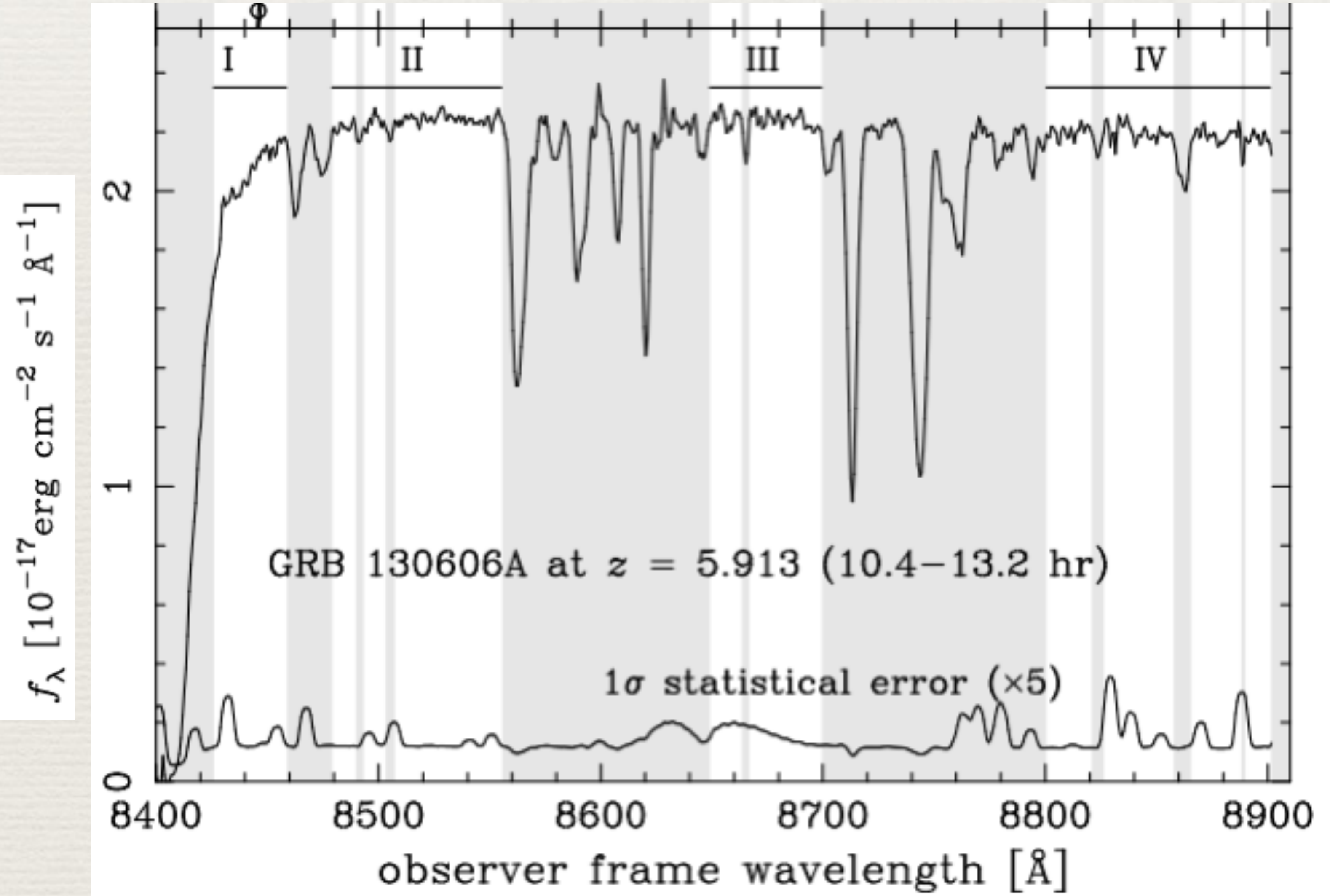
- Chornock et al. 2013 (Gemini, ApJ, 774, 26)
  - no evidence for IGM HI by damping wing analysis
  - $f_{HI} < 0.11$ (2σ)
  - spectral index $\beta = -1.99$ ($f_\nu \propto \nu^\beta$), very different from $\beta \sim -1$ found by more recent studies

- Totani et al. 2014 (Subaru, PASJ, 66, 63)
  - ~3σ preference for IGM HI, with
    - $f_{HI} \sim 0.09$ if $z_{IGM,u} = zGRB = 5.913$ ($\beta = -0.93$)

- Hartoog et al. 2015 (VLT, A&A 580, 139)
  - $\beta = -1.02$ 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
- strong absorption regions excluded from analysis

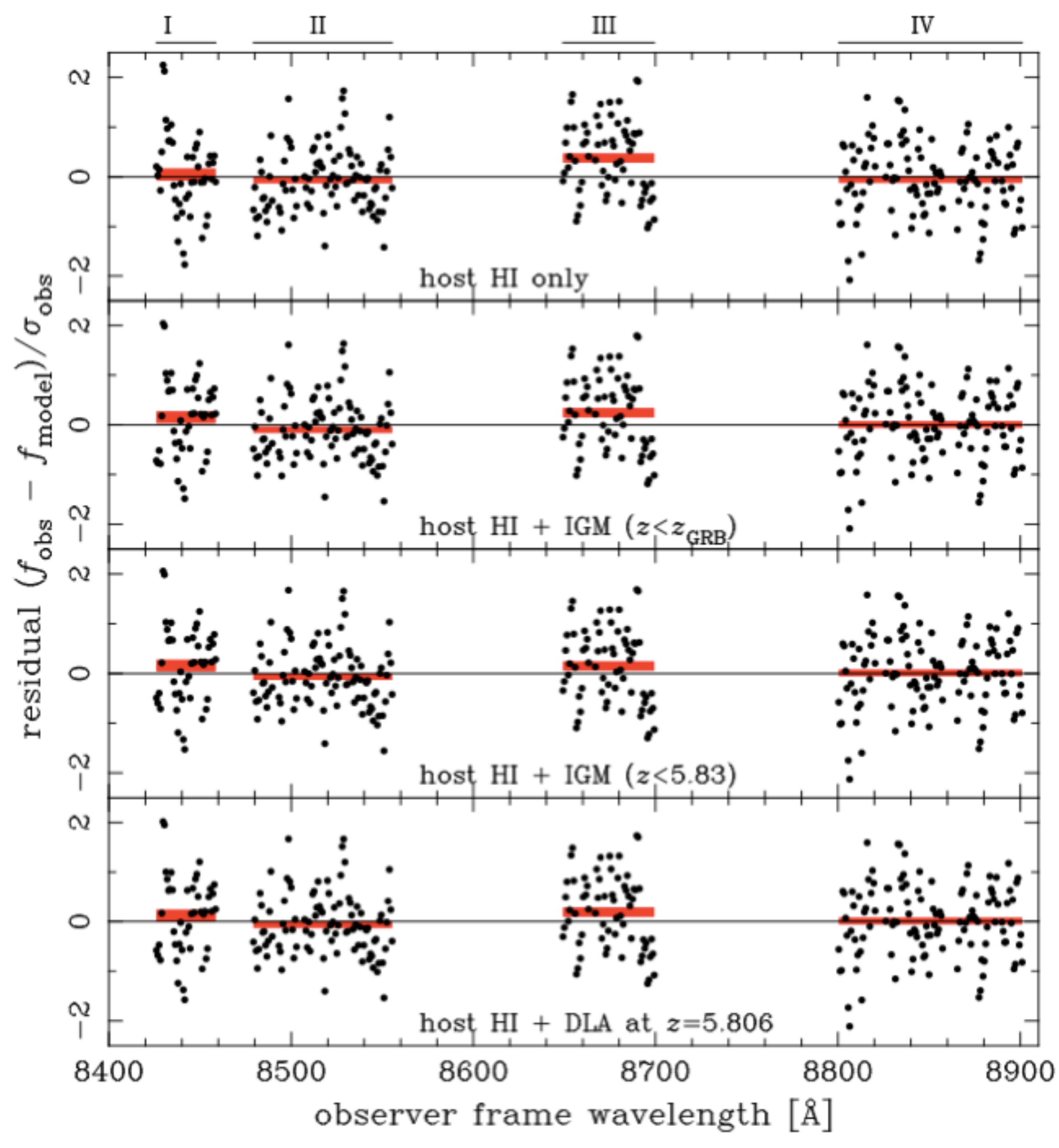


TT+'14

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

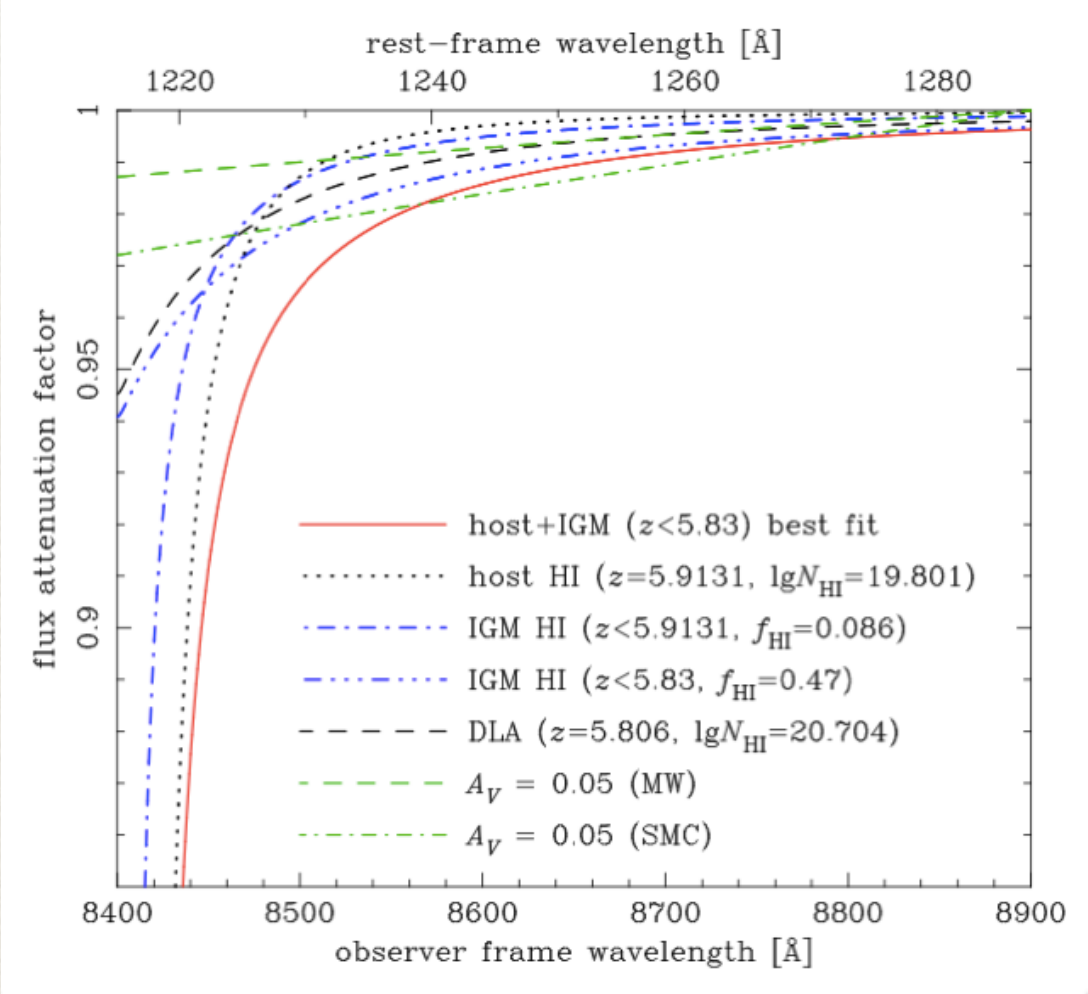
- diffuse IGM HI can reduce the residual by about 3 sigma statistics
  - IGM extending to $z_u = z_{GRB} = 5.913$, with f_{HI} ~ 0.1
  - IGM extending to z_u ~ 5.8, with f_{HI} ~ 0.4
    - corresponding to dark GP troughs to this sightline



TT+'14

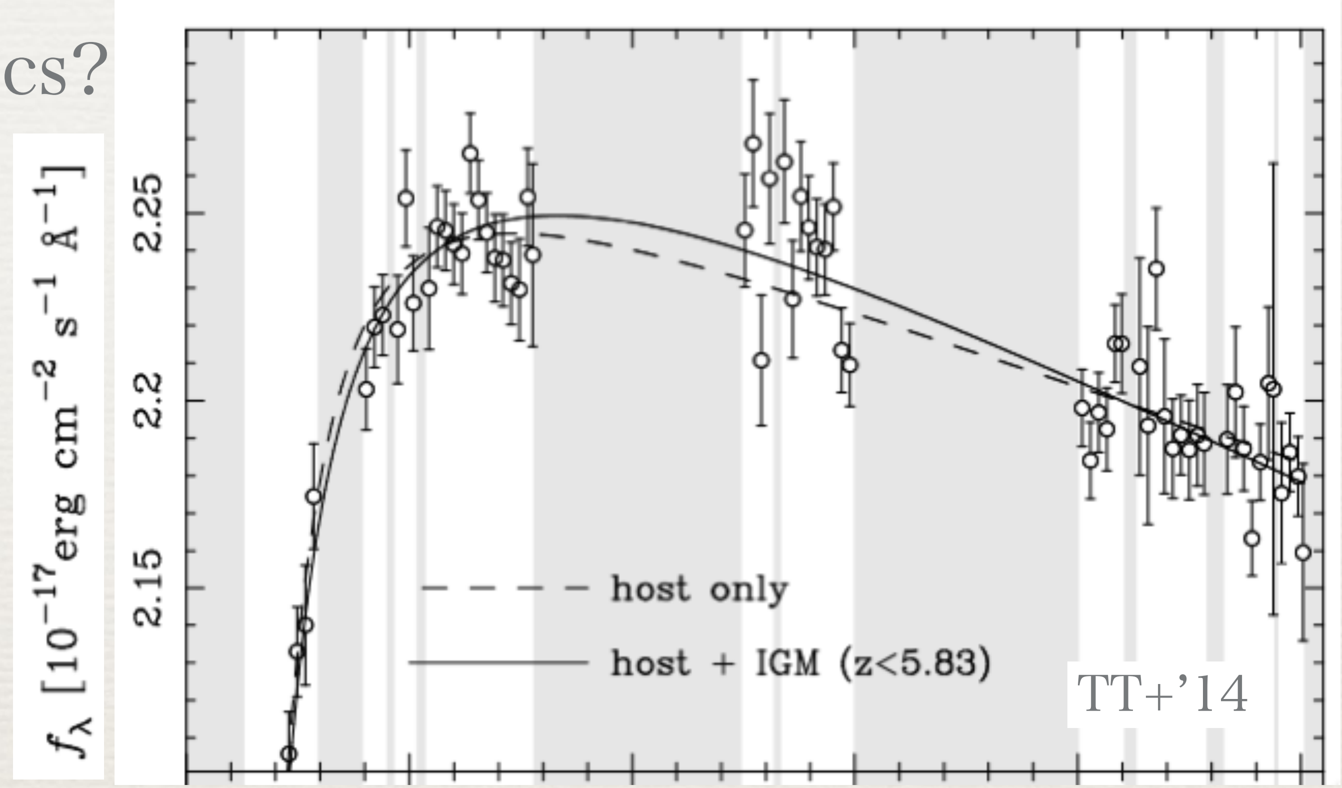
DW from various components

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



TT+'14

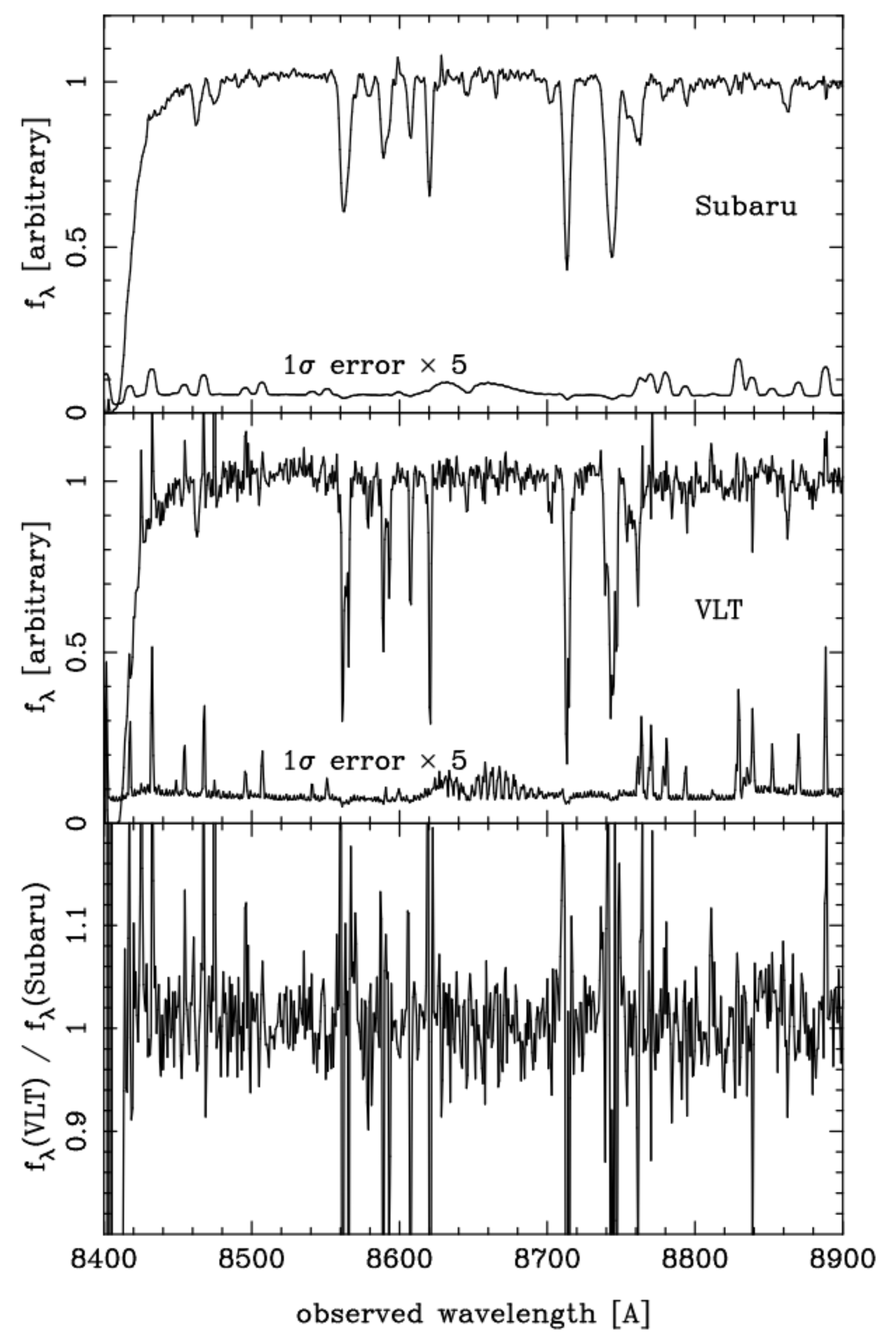
Very subtle! systematics?



- 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?



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

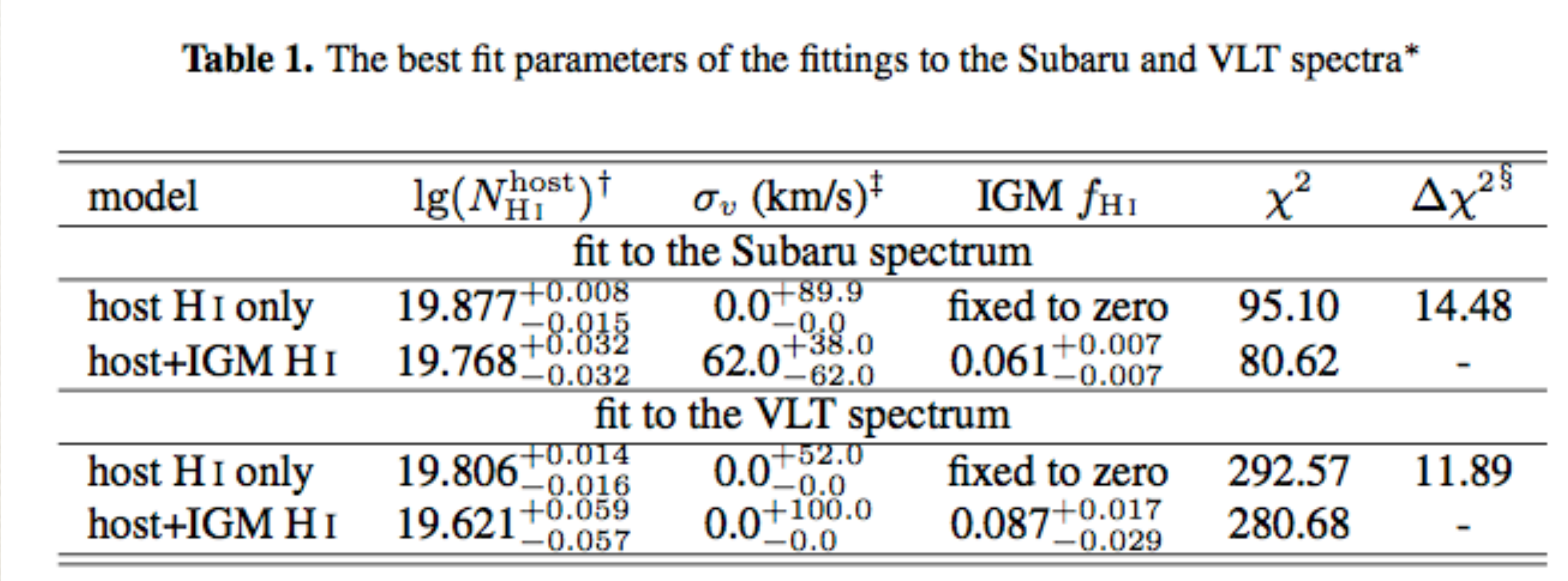


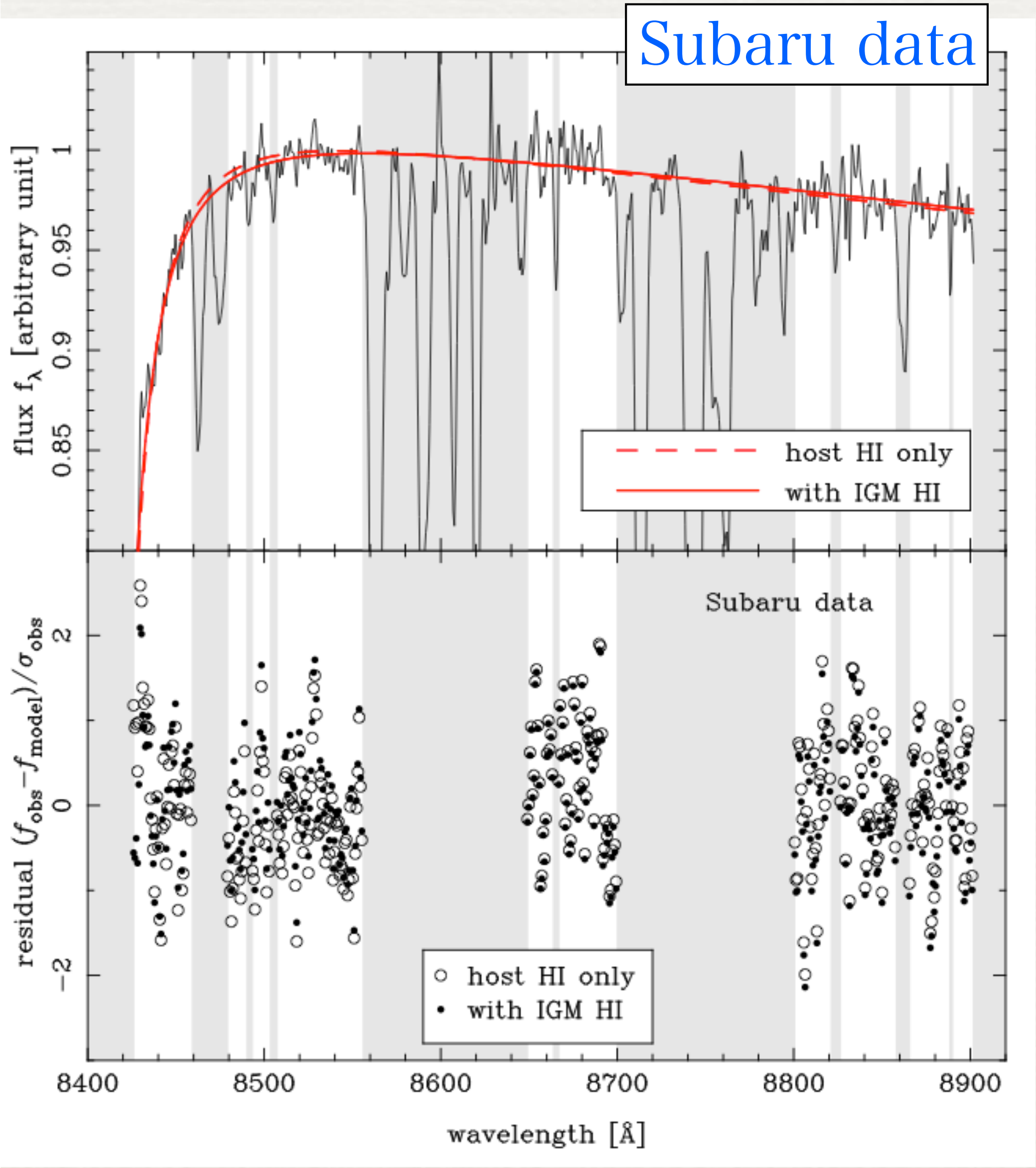
Table 1. The best fit parameters of the fittings to the Subaru and VLT spectra*

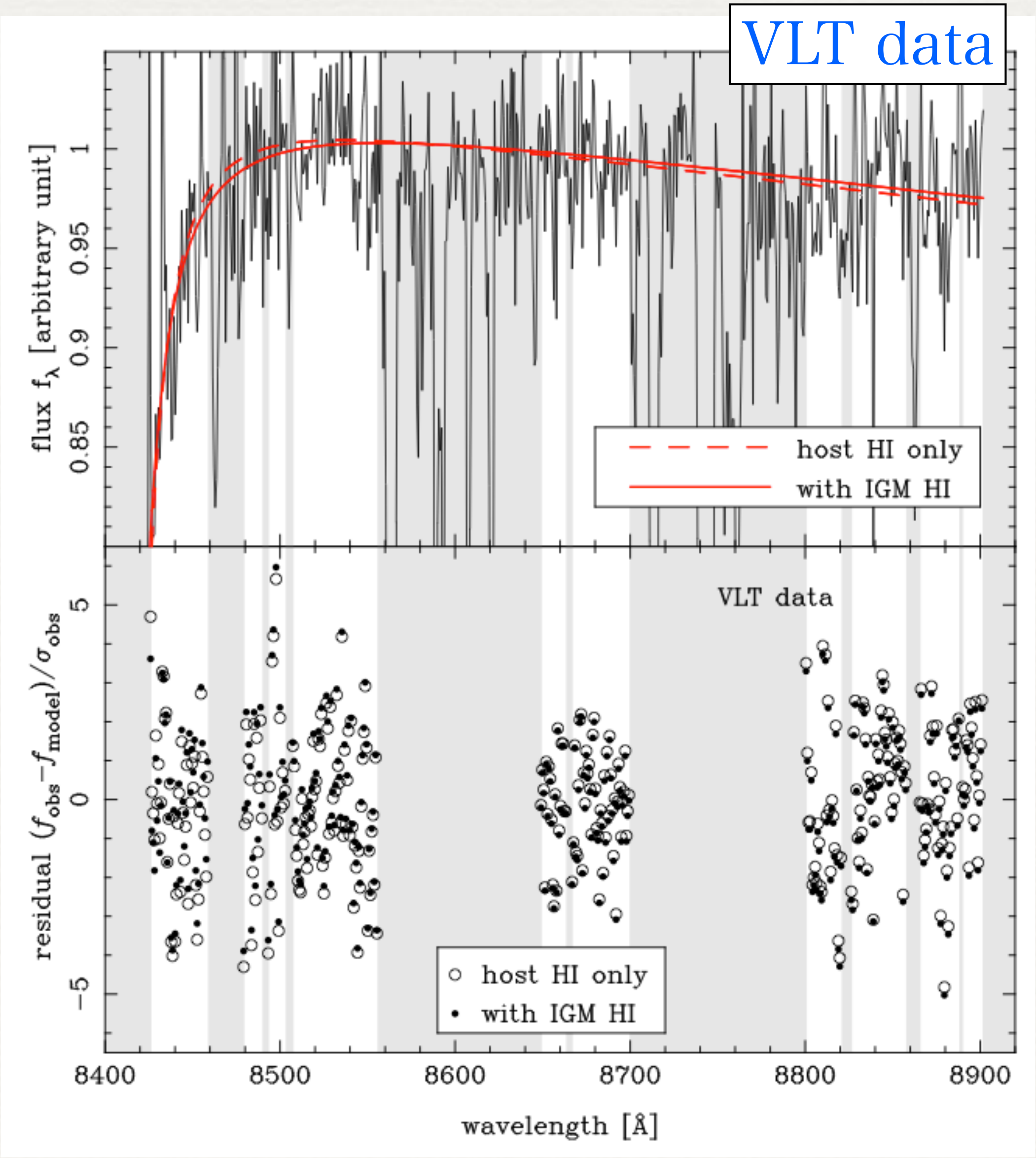
model	$\lg(N_{\rm H\,I}^{\rm host})^{\dagger}$	σ_v (km/s)‡	IGM $f_{\rm H\,I}$	χ^2	$\Delta\chi^{2\,\S}$
fit to the Subaru spectrum					
host H I only	$19.877^{+0.008}_{-0.015}$	$0.0^{+89.9}_{-0.0}$	fixed to zero	95.10	14.48
host+IGM H I	$19.768^{+0.032}_{-0.032}$	$62.0^{+38.0}_{-62.0}$	$0.061^{+0.007}_{-0.007}$	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

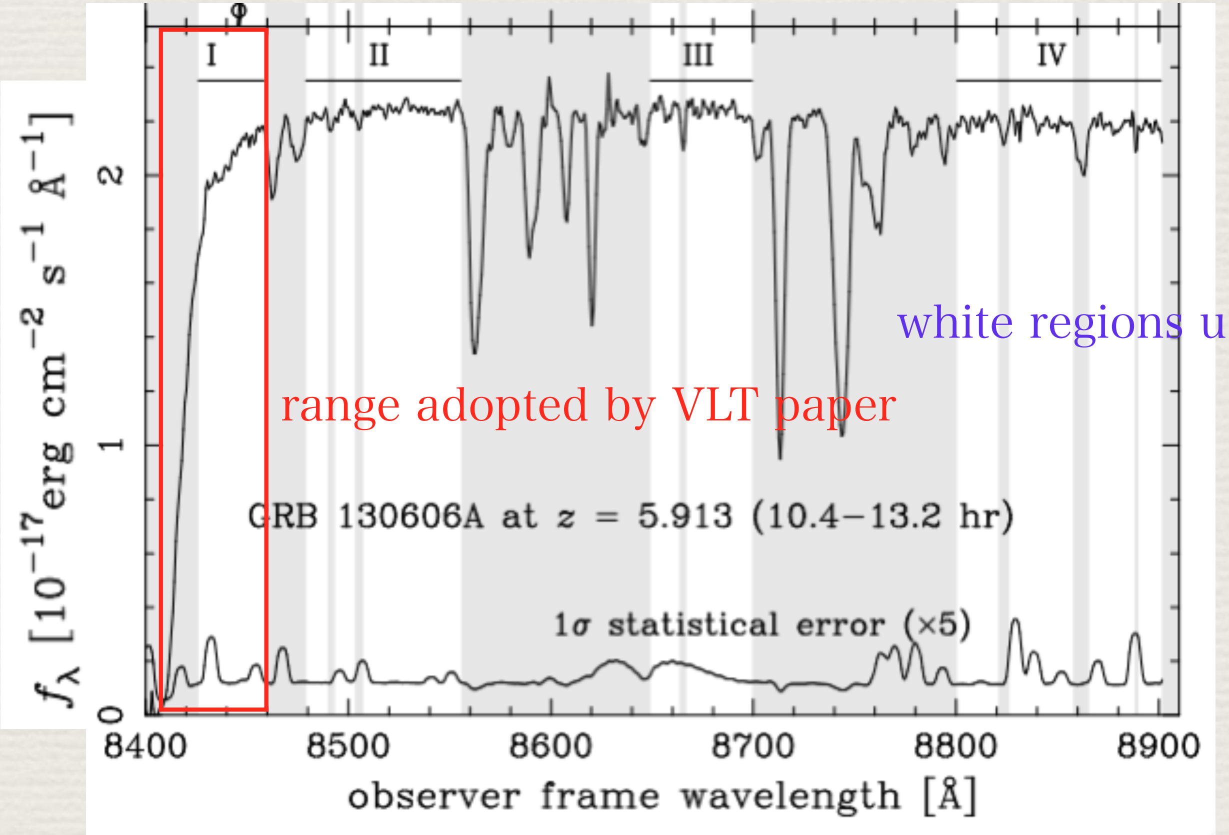




- the same trend for the fit residuals by no IGM HI model

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 (<8426 Å 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
  - $\sigma_v = 61.8 \pm 3.3$ km/s by our fit result
  - systematics about unknown realistic velocity distribution is a worry



white regions used in Subaru paper

range adopted by VLT paper

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)

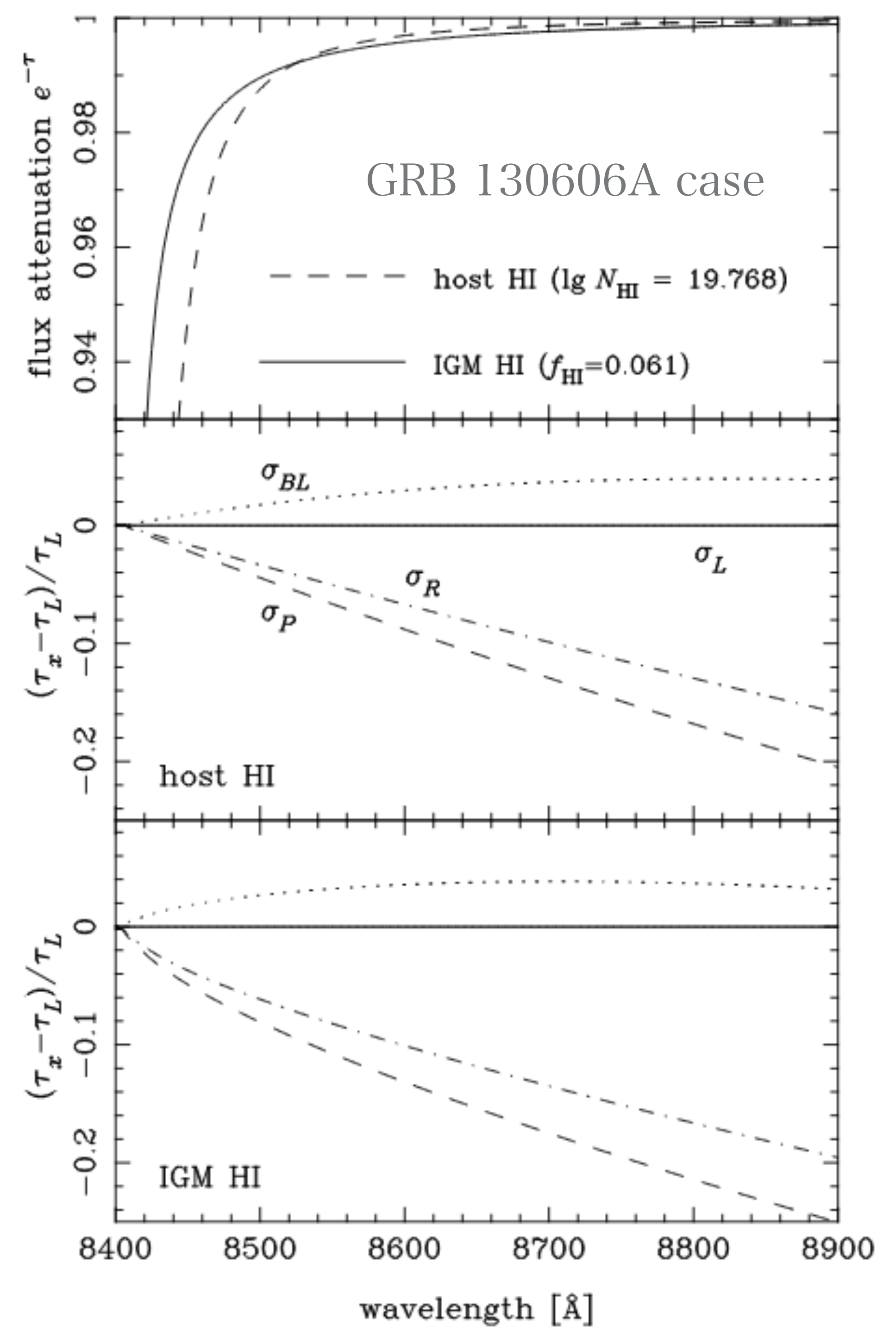
$$\sigma(\omega) = \sigma_{\mathrm{L}} \frac{4\,(\omega/\omega_0)^4}{(1+\omega/\omega_0)^2}\,[1 + f(\omega)].$$

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

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

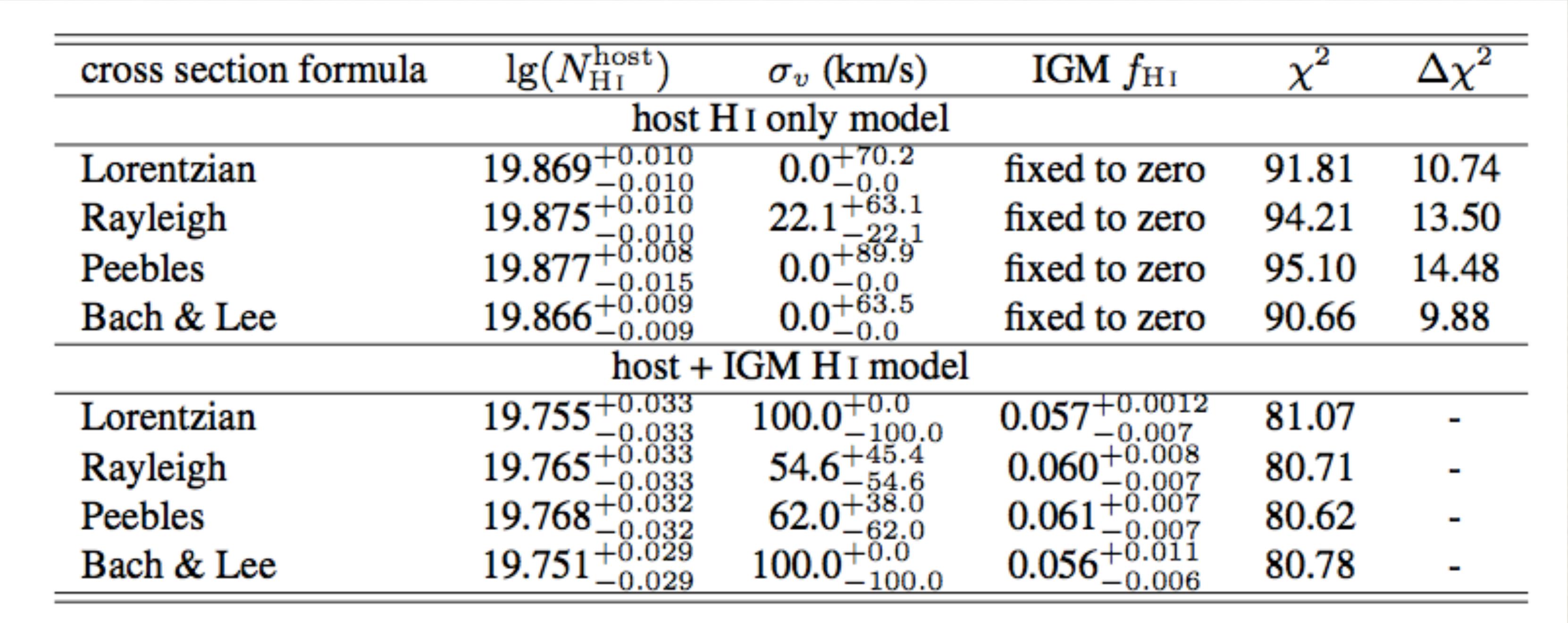
effect on HI opacity by Lyα cross section formulae

- ~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 Lyα cross section formula
- preference to IGM HI by ~3-4σ unchanged



cross section formula	$\lg(N_{\rm H\,I}^{\rm host})$	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	-

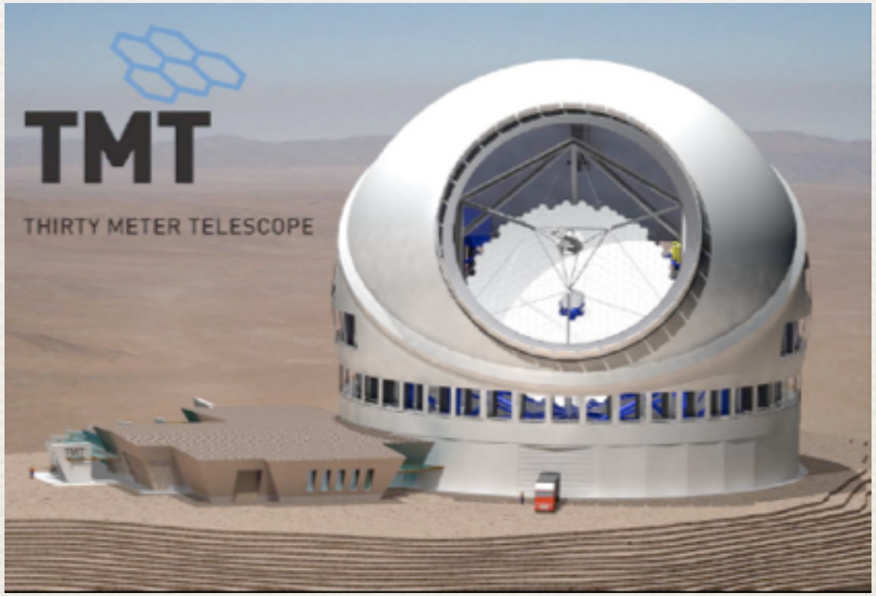
What do we need to increase the rate of GRBs useful for reionization?

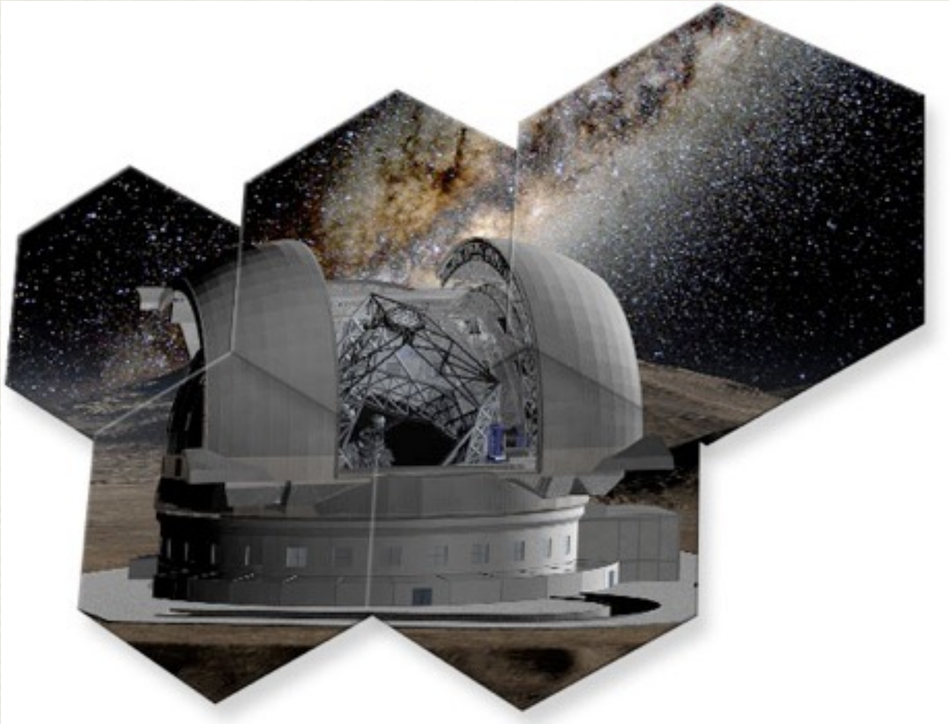
- GRB rate study indicate that >1% of GRBs are at z>6
    - e.g. Elliott+'12

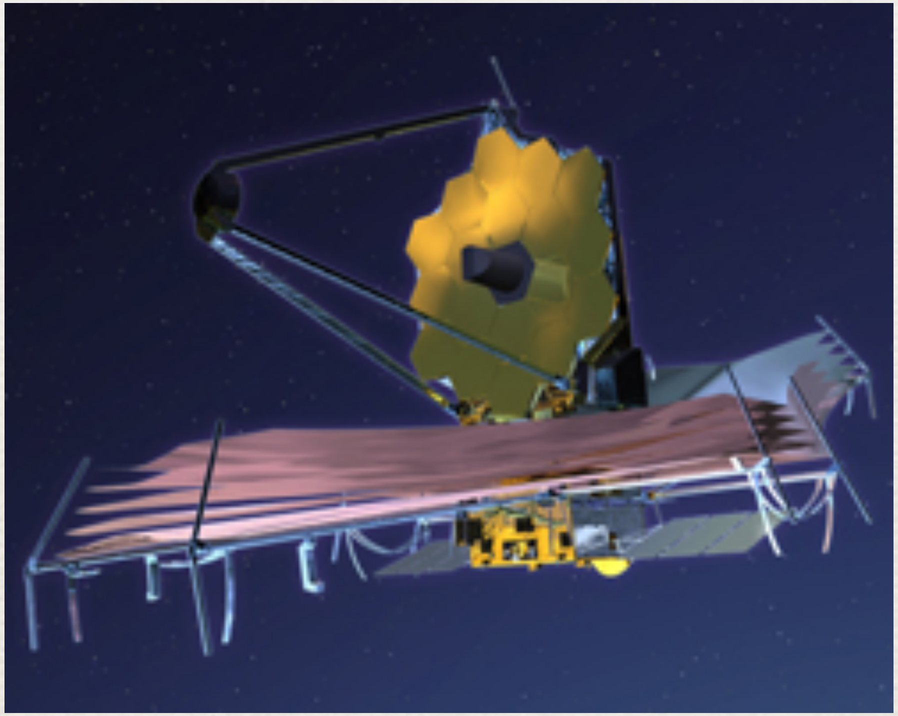
- Current 8m telescopes are not sufficient to measure the damping wing for typical GRB luminosities
    - GRB 050904/130606A was exceptionally bright!

- We need more sensitive NIR spectrograph
    - 30m-class telescopes / JWST

30m/JWST

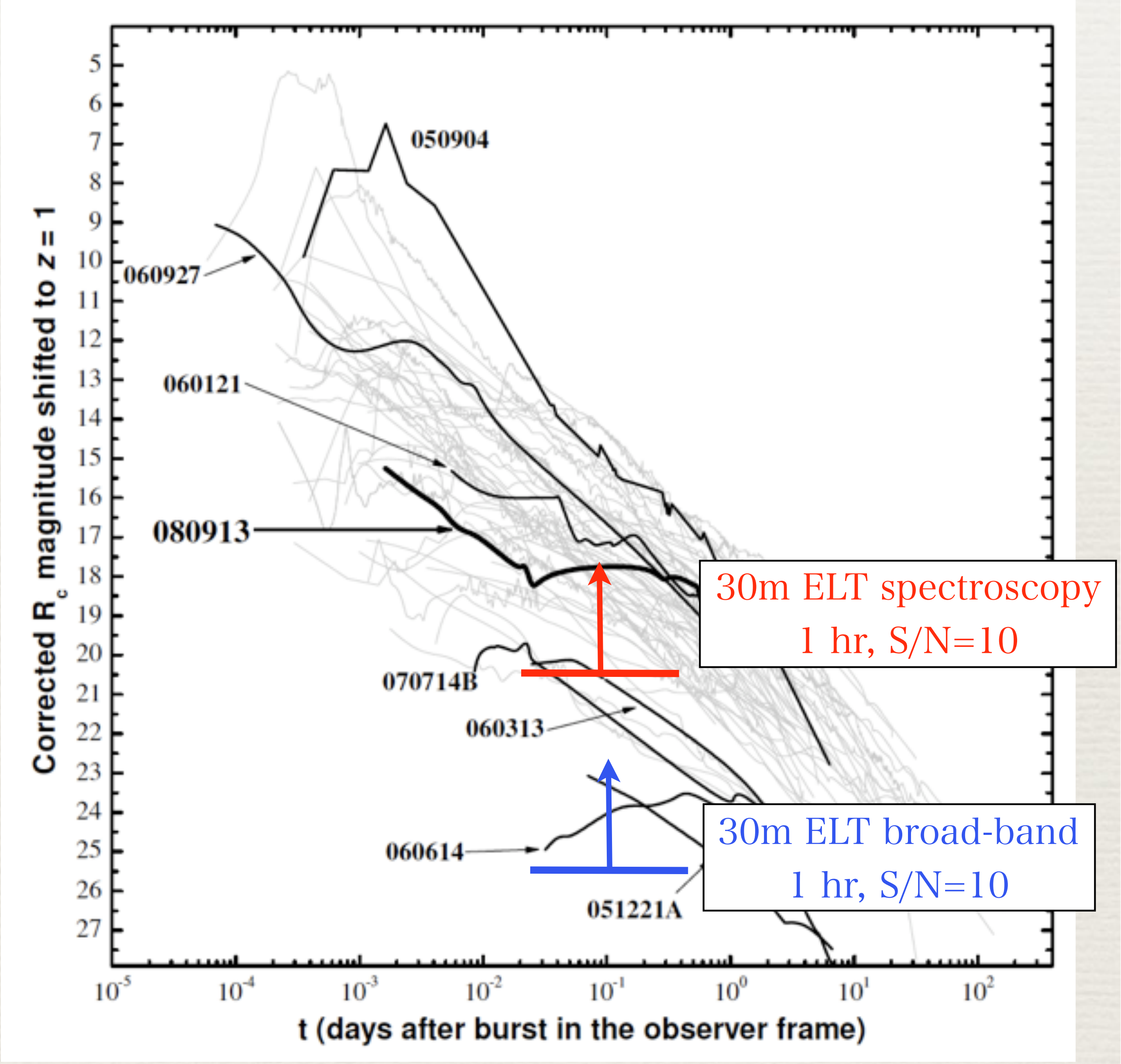






30m telescope sensitivity vs. GRBs

- convert into R mag, z=1
  - $F_\nu \propto t^{-1} \nu^{-1}$
  - observe at 1 day after z=10 burst → ~0.1 day for z=1



30m ELT spectroscopy
1 hr, S/N=10

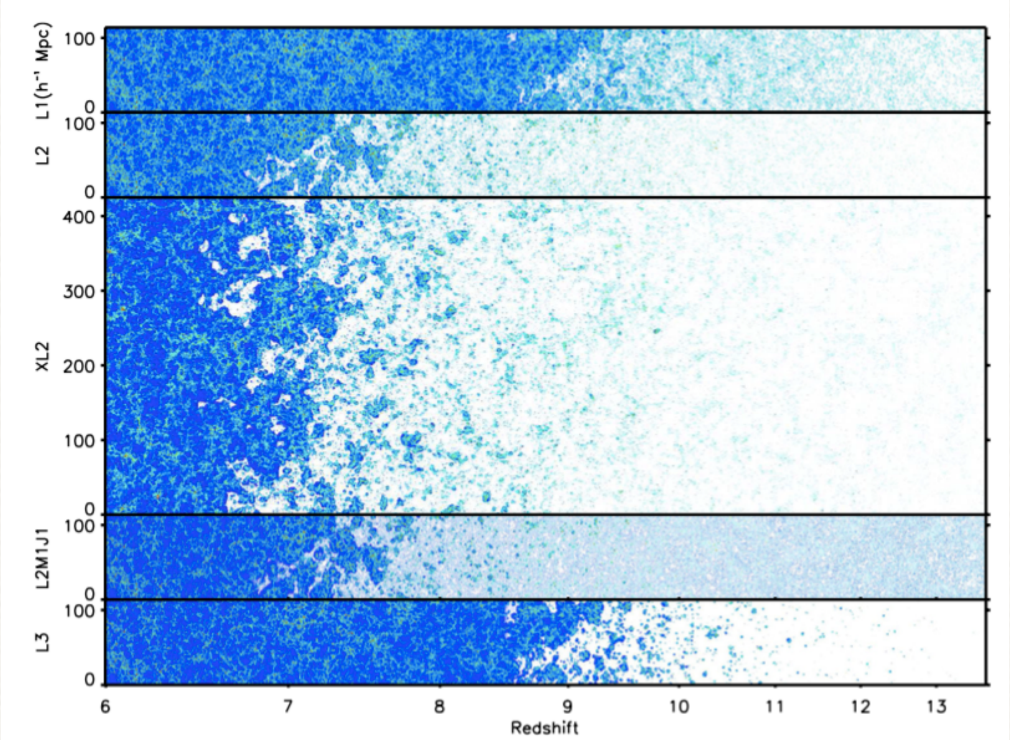
30m ELT broad-band
1 hr, S/N=10

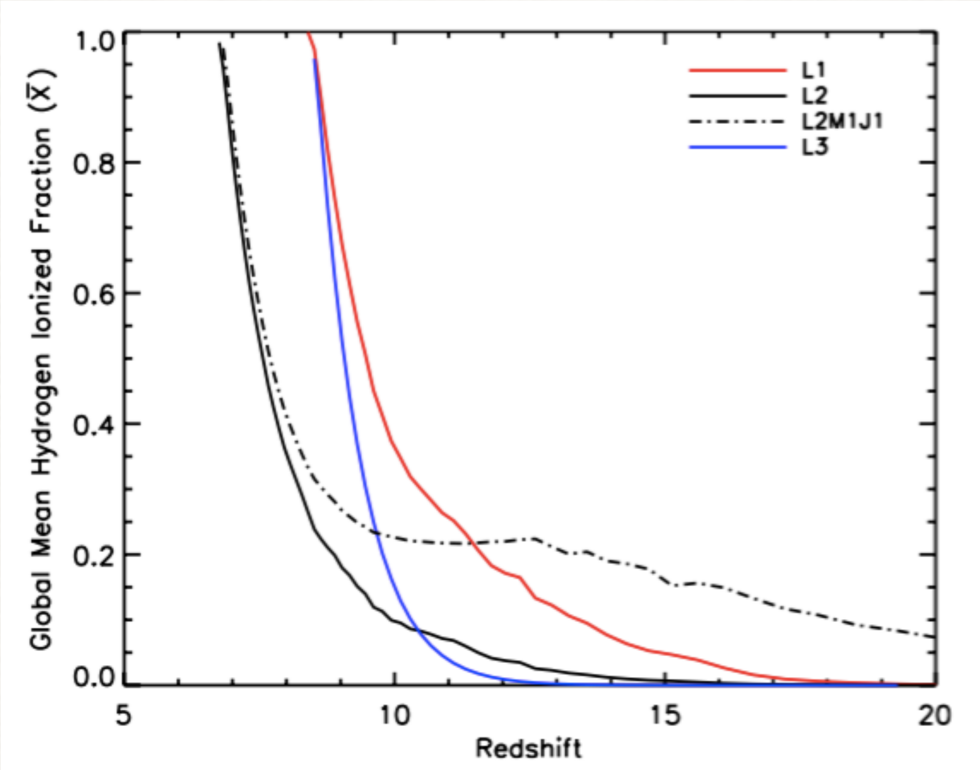
(original figure from Greiner+'09)

simulating GRB spectra with reionization simulation

- ongoing work by Ryota Baba, TT, Naoki Yoshida, and Hyunbae Park
- calculating “real” Ly α damping wing in inhomogeneous density and ionization degree
- how would it be observed by “model fitting” assuming homogeneous IGM?
- relation between mean f_{HI} in simulation vs. f_{HI} distribution from fits to GRBs?

reionization simulation by Park+’13

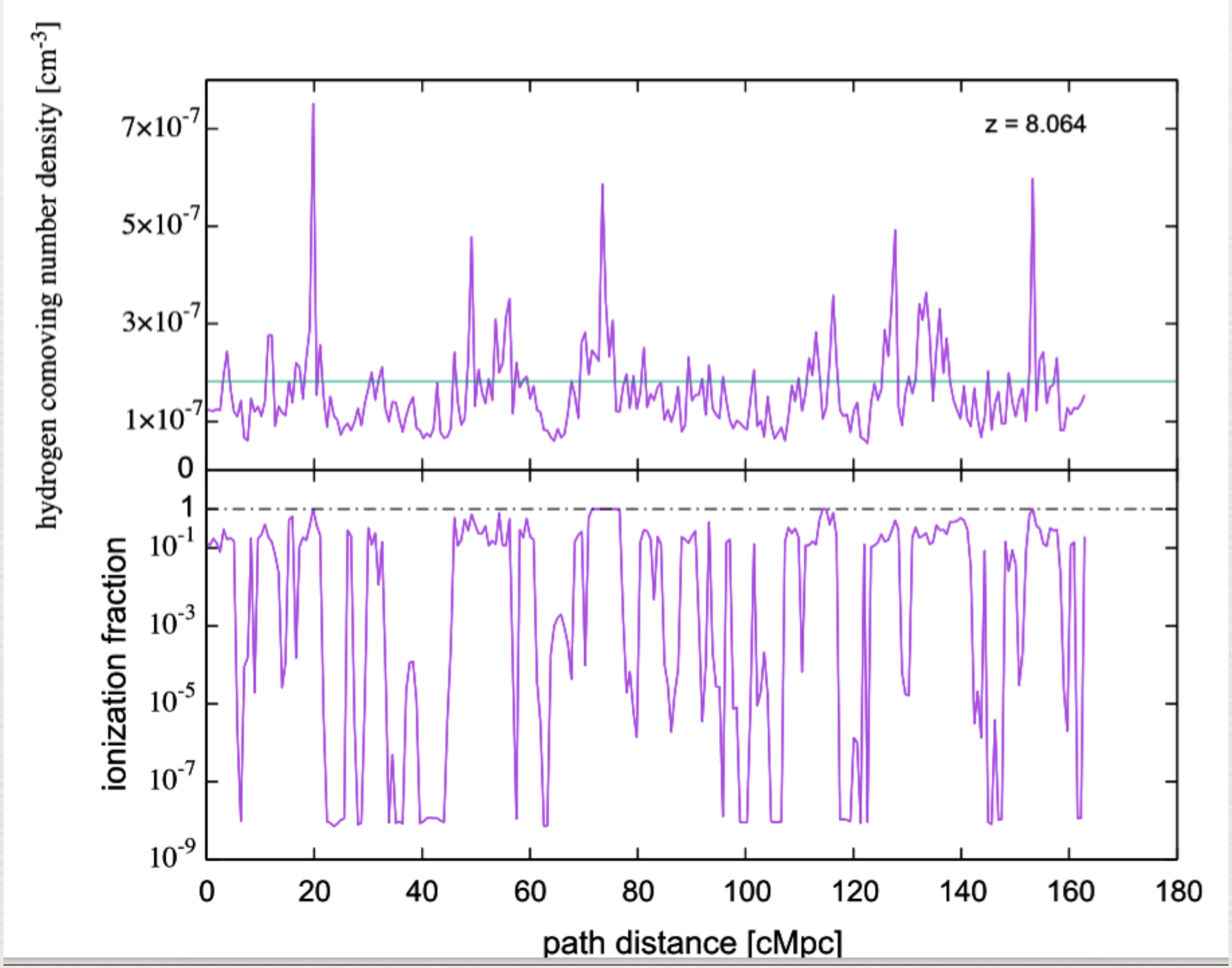




contour: density×ionization fraction

simulating GRB spectra with reionization simulation

- density and ionization degree along a path in the simulation



Conclusions

- GRBs are a unique probe of reionization
    - less biased than quasars
    - damping wing on pure power-law spectrum, avoiding GP trough saturation

- high precision damping wing analysis indeed possible (e.g. GRB 130606A)
    - but systematics must be carefully treated

- strong constraints on reionzation history hampered by low event rate of high-z and bright GRB afterglows

- future 30m class telescopes will change the status