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GRB 130606A 可視残光から得られた宇宙再電離への示唆

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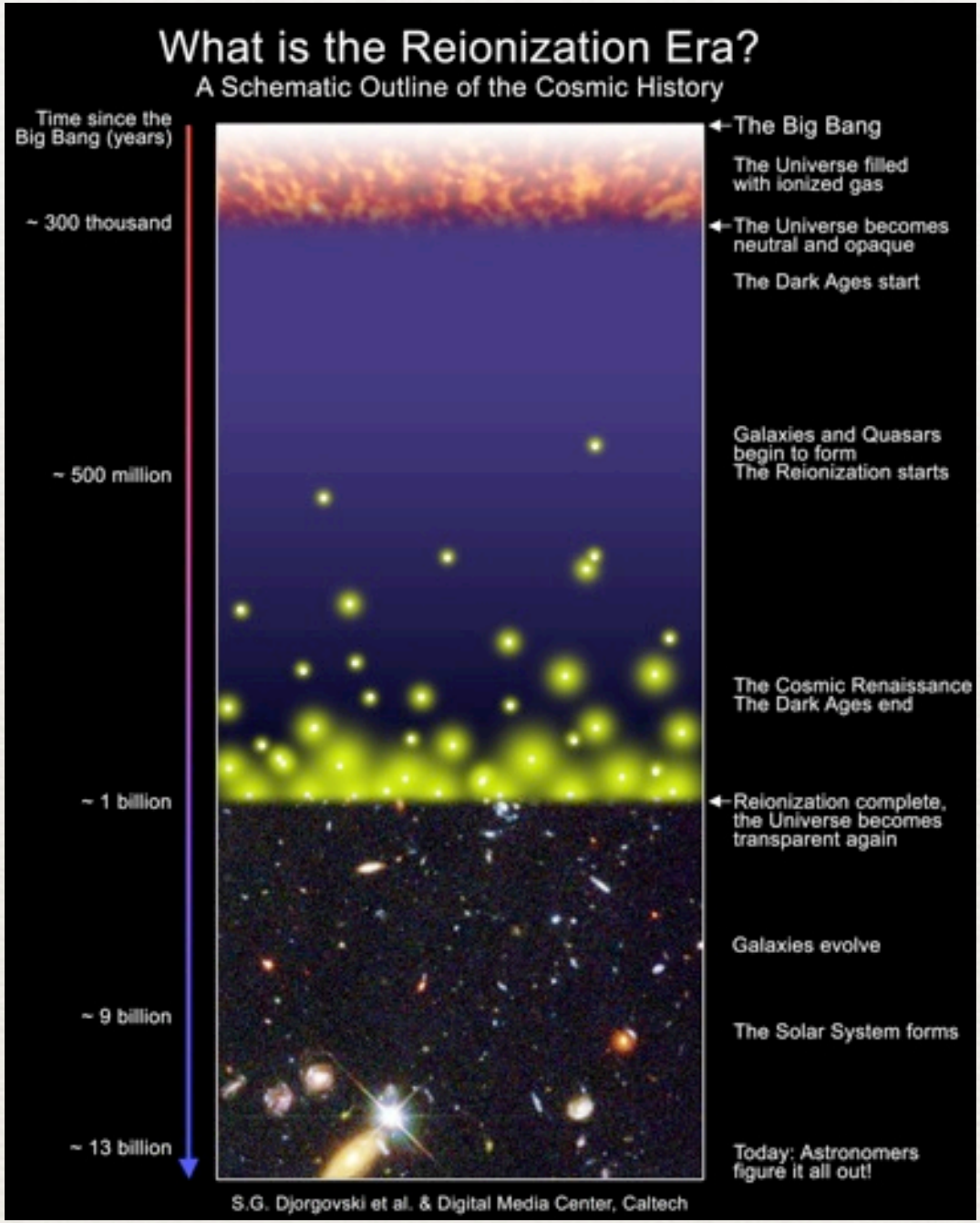
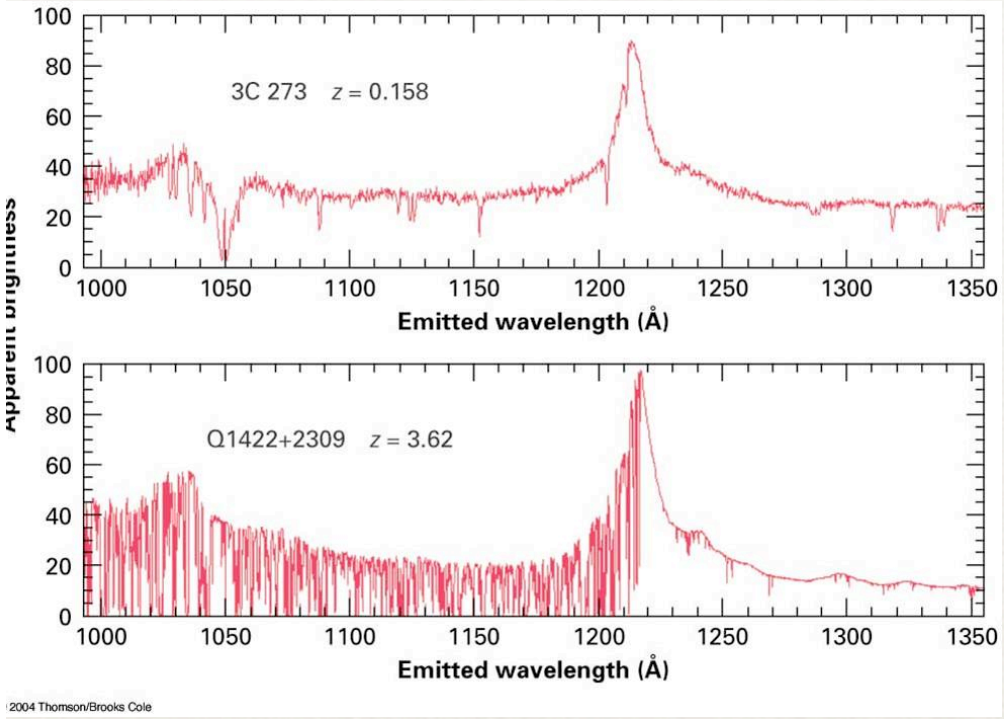
Cosmic Reionization

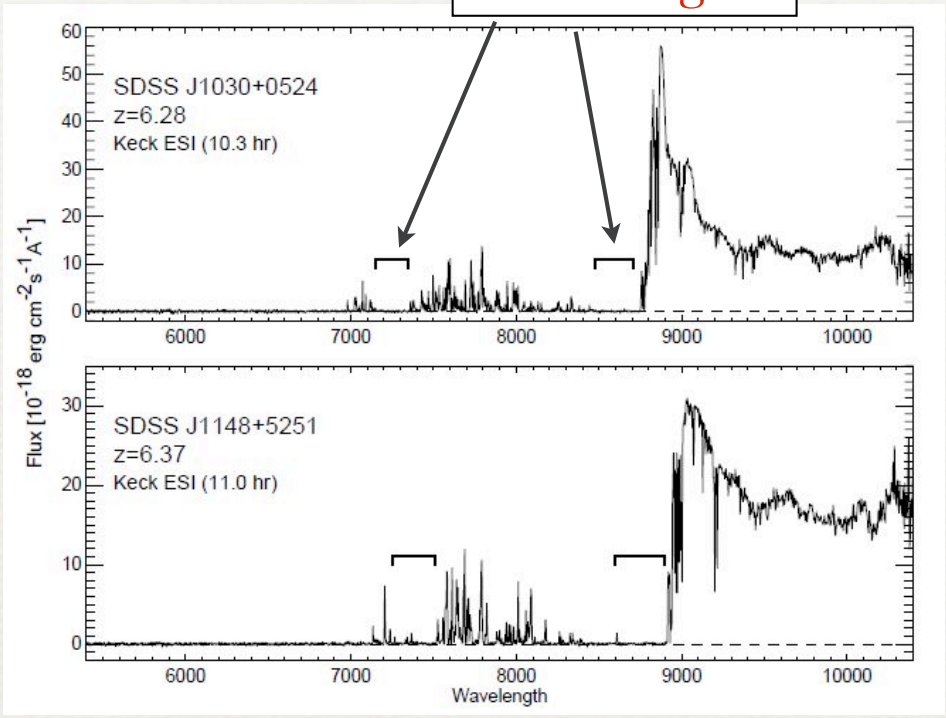
- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination
  - observed as CMB
- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test
- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark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



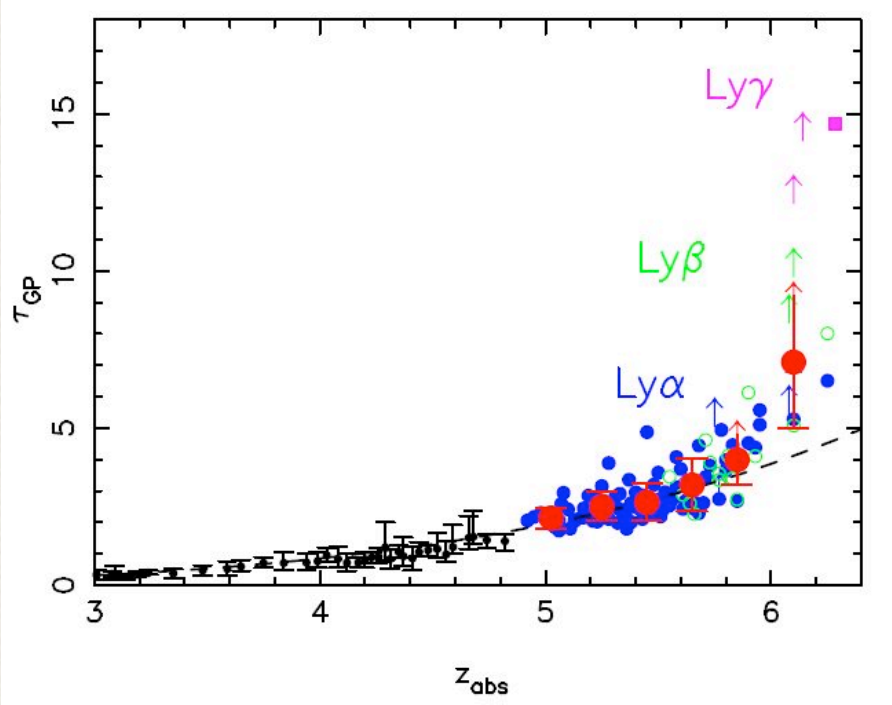
Djorgovski+

The Gunn-Peterson Test





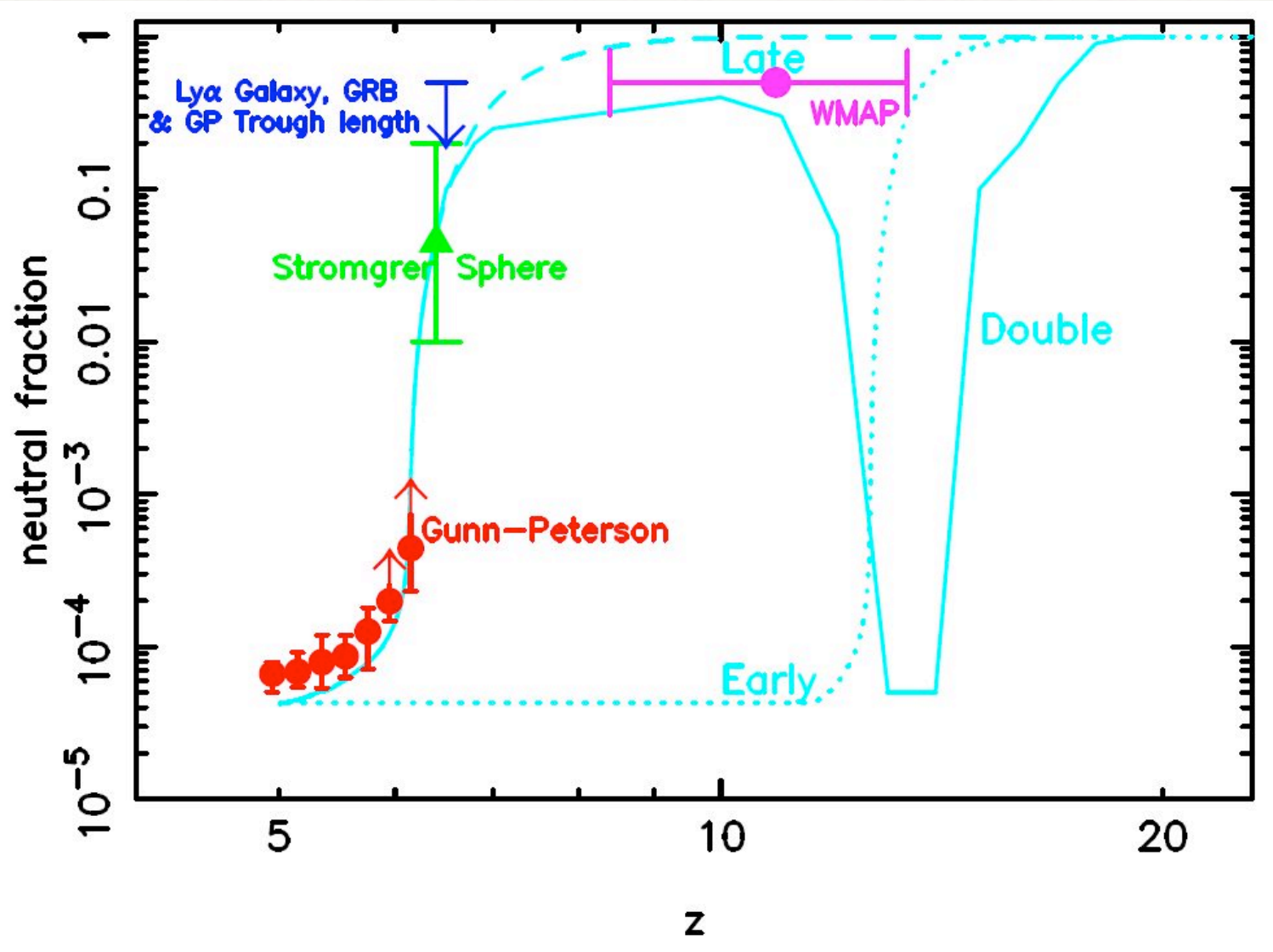
White+'03



- 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

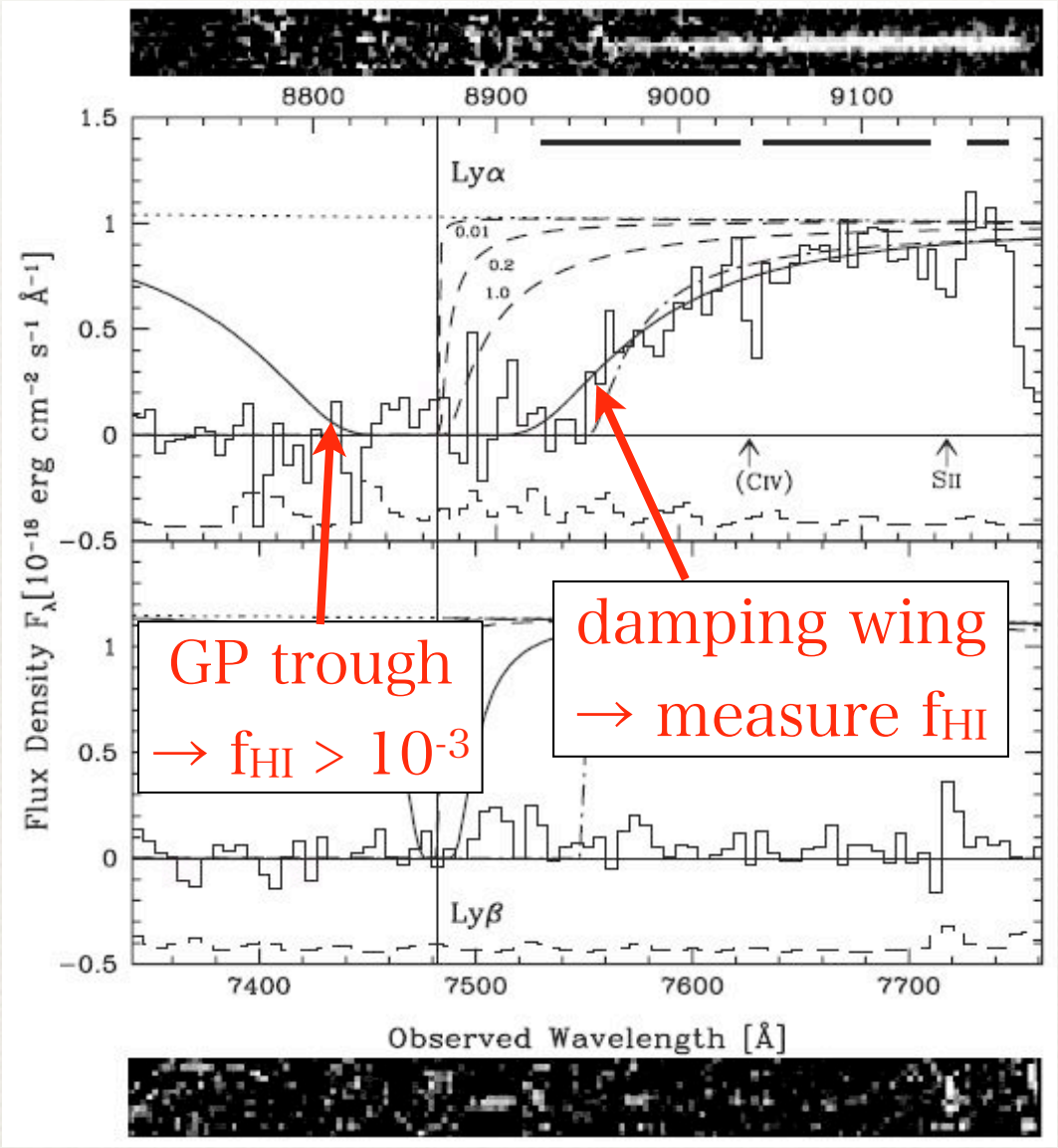
Observational Constraints on Reionization History



- Fan+ ’06

Next Step: Using Ly α Red Damping Wing

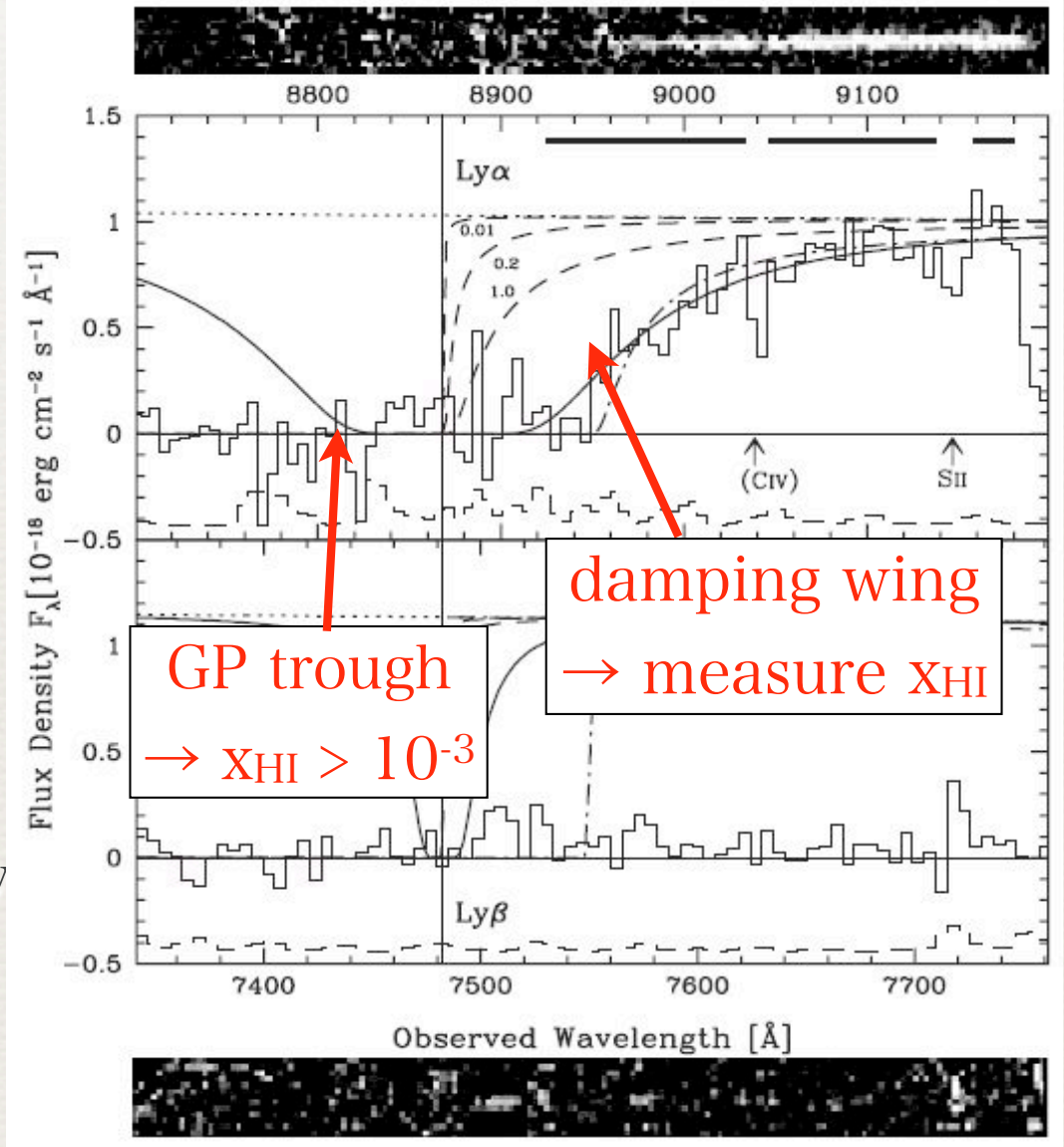
- measurement of $f_{HI}=n_{HI}/n_H$ rather than lower limit is possible, if damping wing feature by neutral IGM is detected!



GRB 050904@z=6.3, TT+ '06

GRB as a Reionization Probe

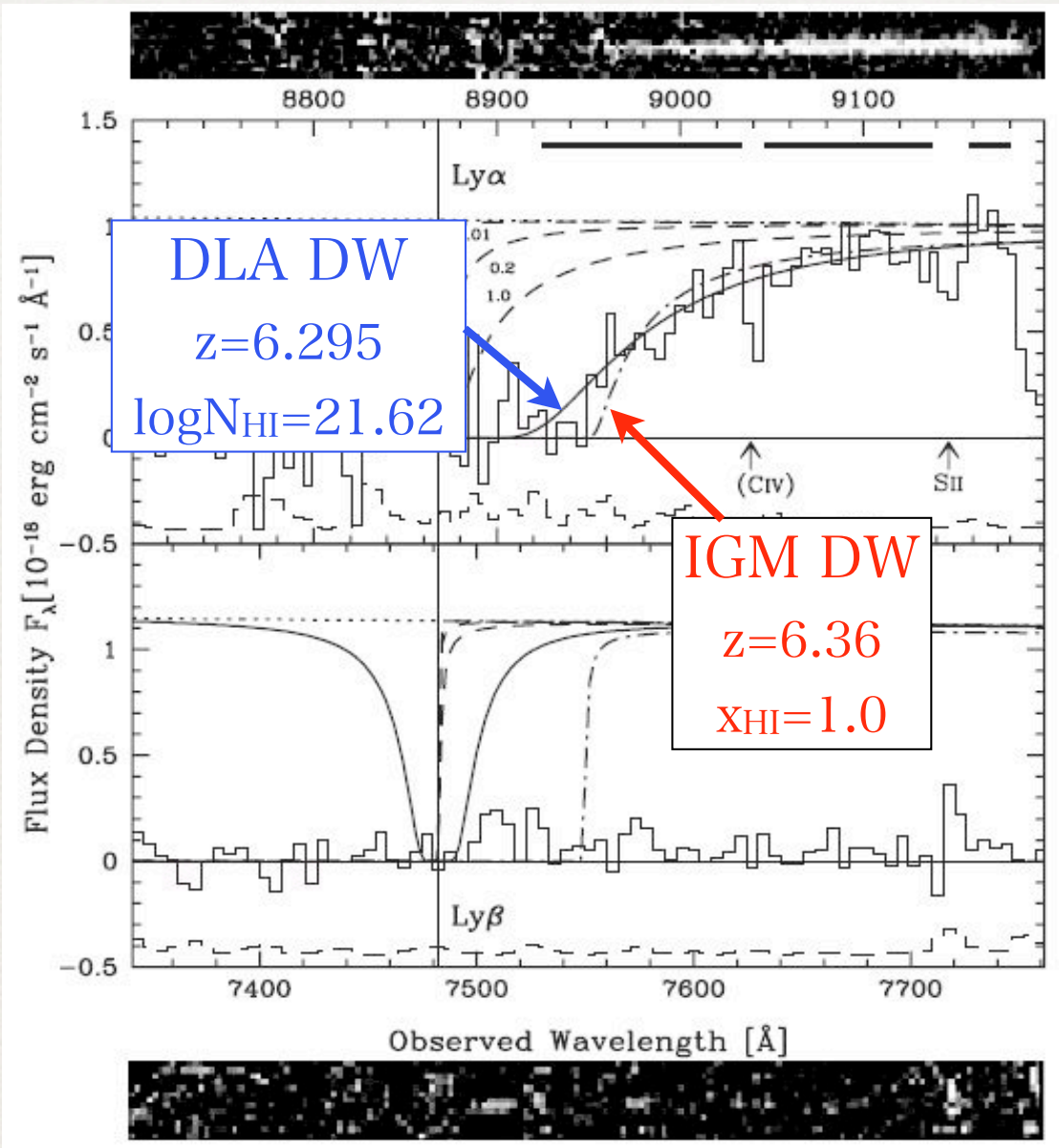
- Strengths:
  - GRBs detectable at z>>6
  - probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - simple power-law spectrum
    - damping wing analysis to precisely measure x_{HI} ($=n_{HI}/n_H$)



GRB 050904@z=6.3, TT+ '06

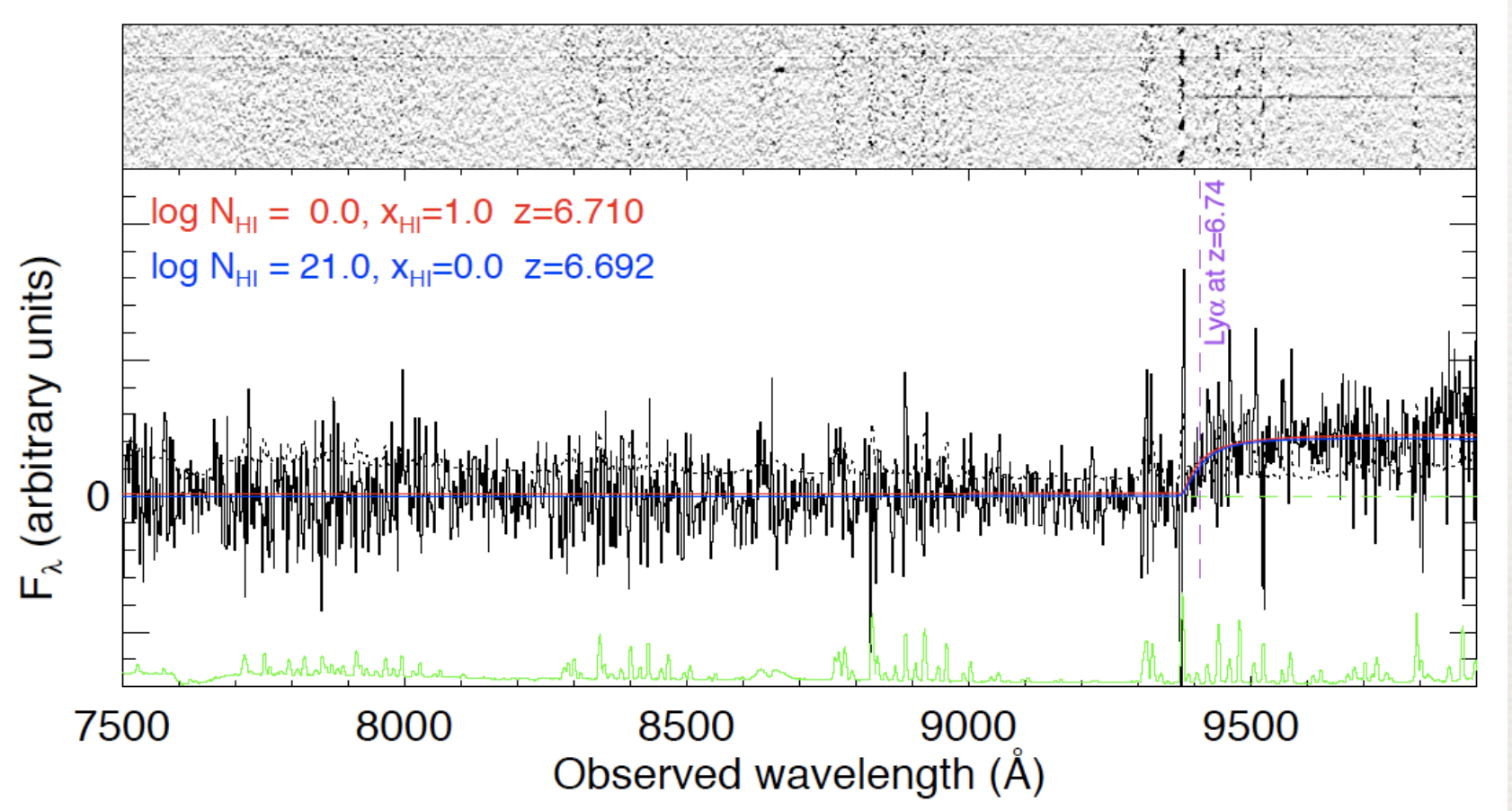
GRB as a Reionization Probe (2)

- Weakness:
  - Degeneracy between damped Ly α (DLA) of host galaxies and IGM damping wing
    - host DLA dominant for GRB 050904
    - can be broken by metal absorption lines / Ly β features
    - we need low N_{HI} host galaxy to measure x_{HI} accurately
  - event rate not so high
    - GRB 050904 has been only one useful constraint on reionization by GRBs since 2005!
    - $x_{HI} < 0.17$ (68%C.L) or 0.6 (95%C.L.) by fitting



GRB 050904@z=6.3, TT+ '06

GRB 080913 @ z~6.7



(Greiner+'09)

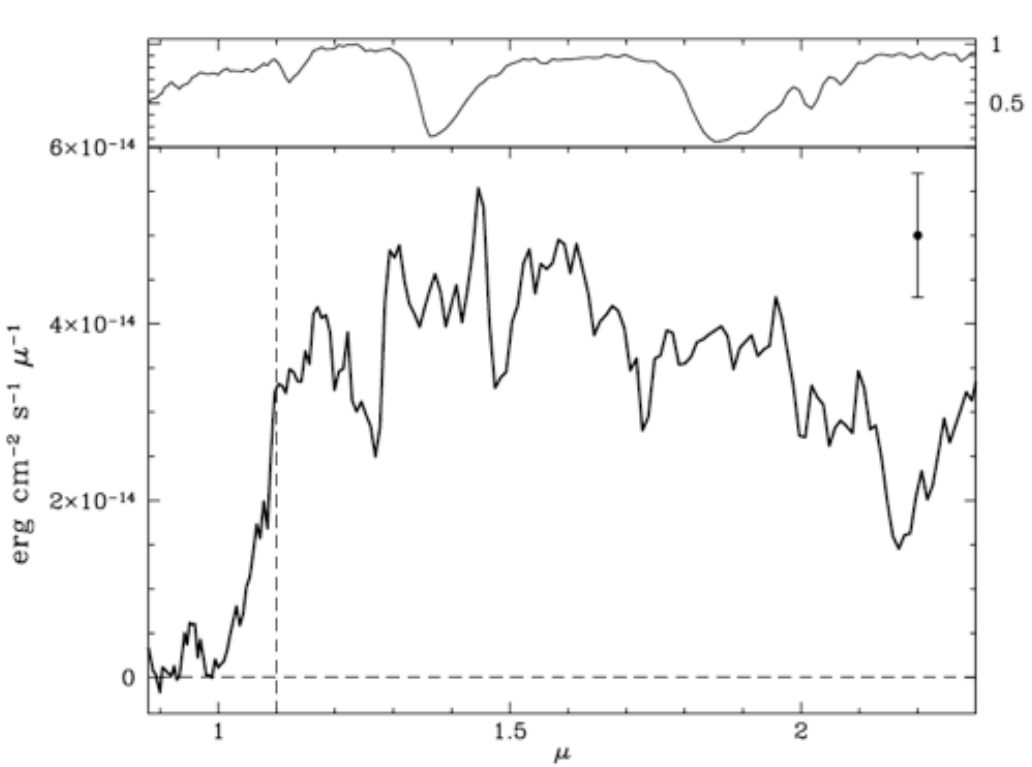
2-3 hrs, z'~24.5(AB), 2400 s exp.

damping wing detected, but difficult to discriminate DLA or IGM

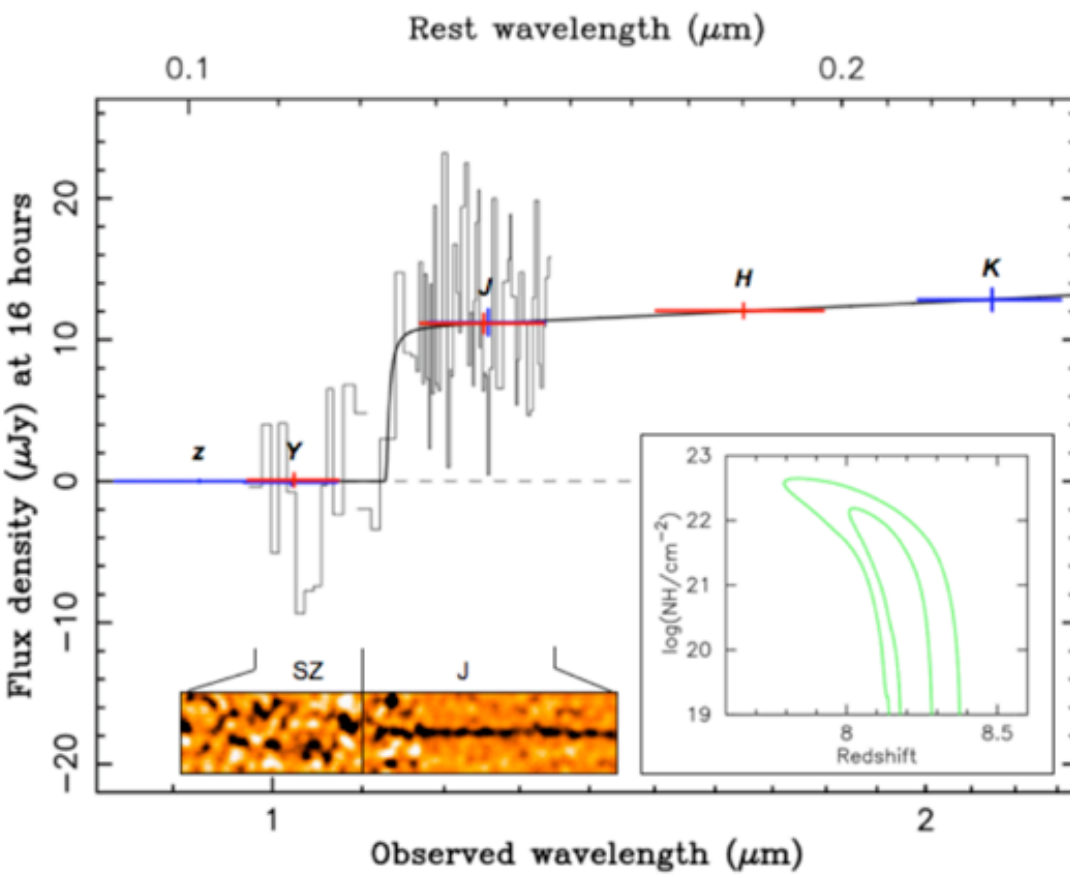
c.f. GRB 050904, z~6.3

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

GRB 090423 @ z~8.2



Salvaterra+'09

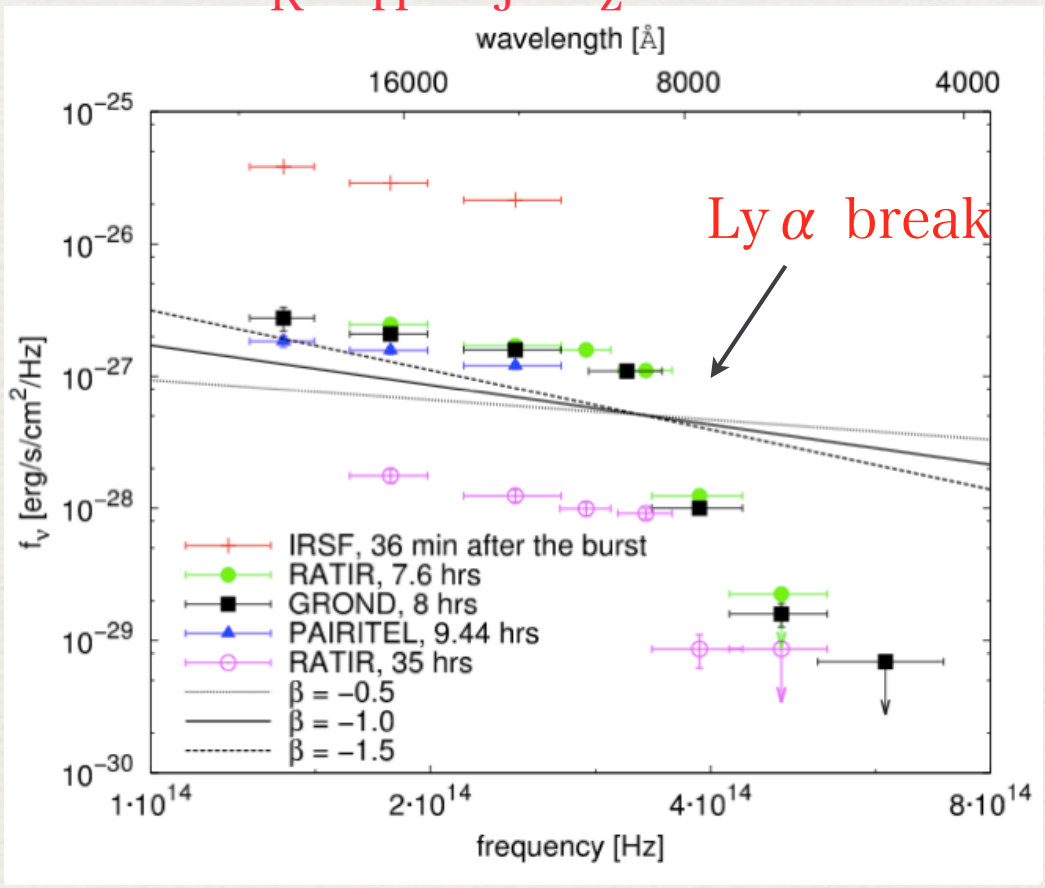


Tanvir+'09, ~20 hr, J~20.8

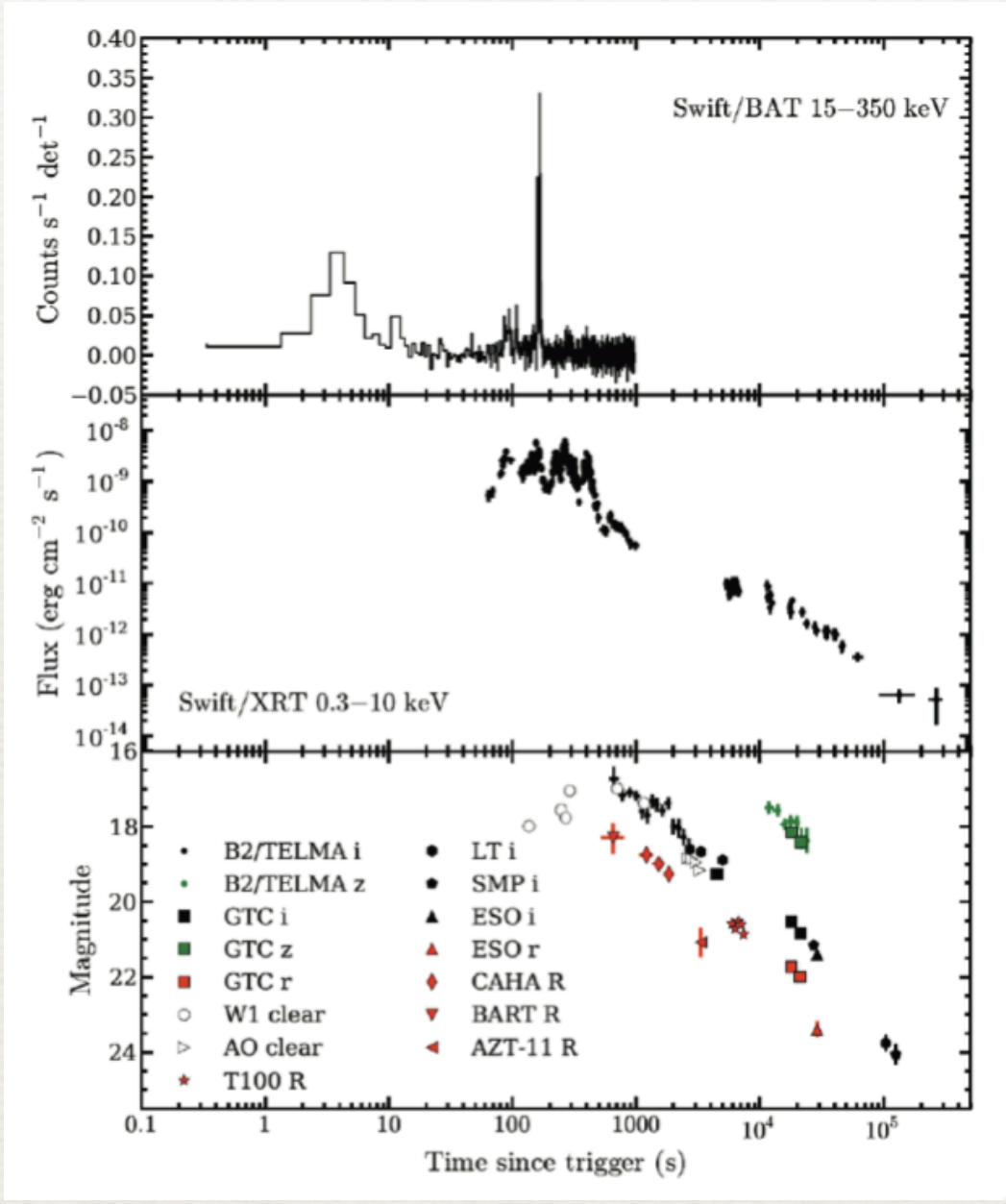
Only upper bound on N_{HI} (=no detection of damping wing)

The New Opportunity: GRB 130606A

- a bright, otherwise normal long GRB at z = 5.913

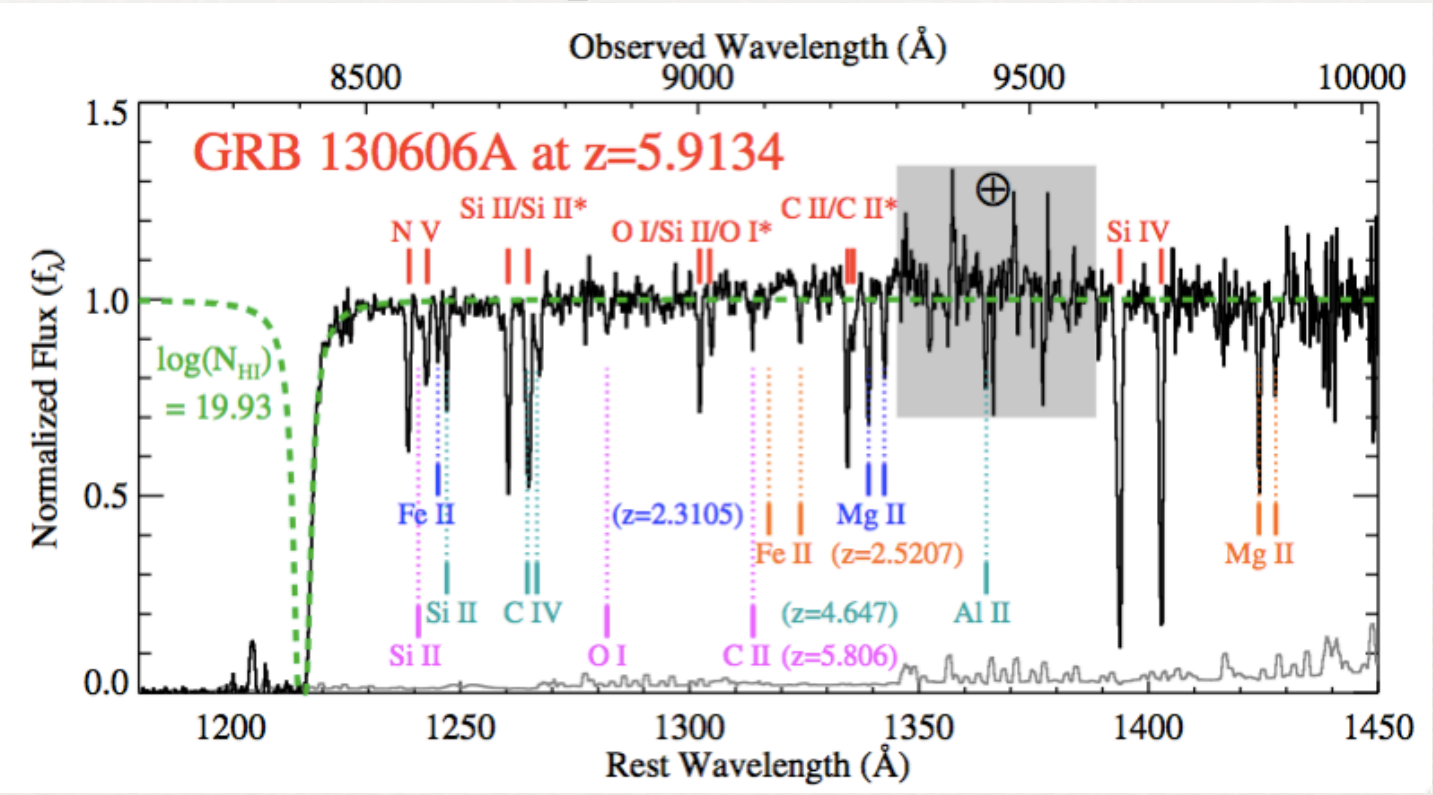


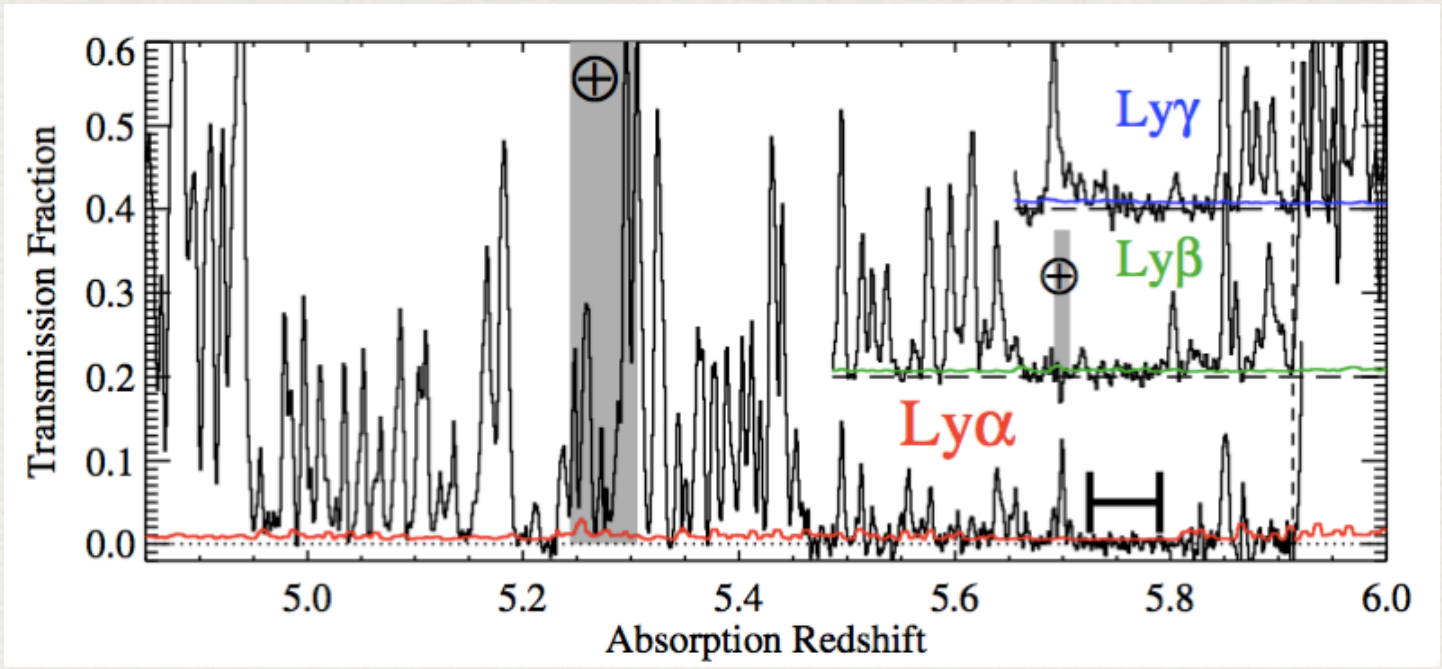
Totani+'13, fig. created by Y. Niino



Castro-Tirado+'13

Spectrum of GRB 130606A



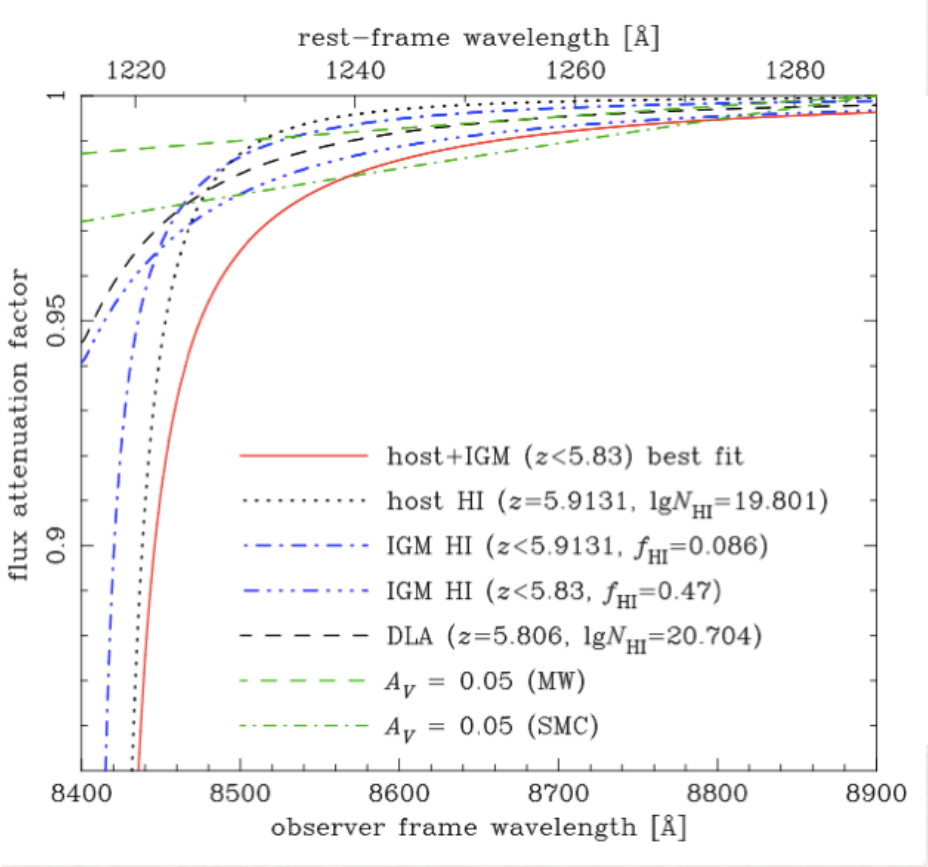


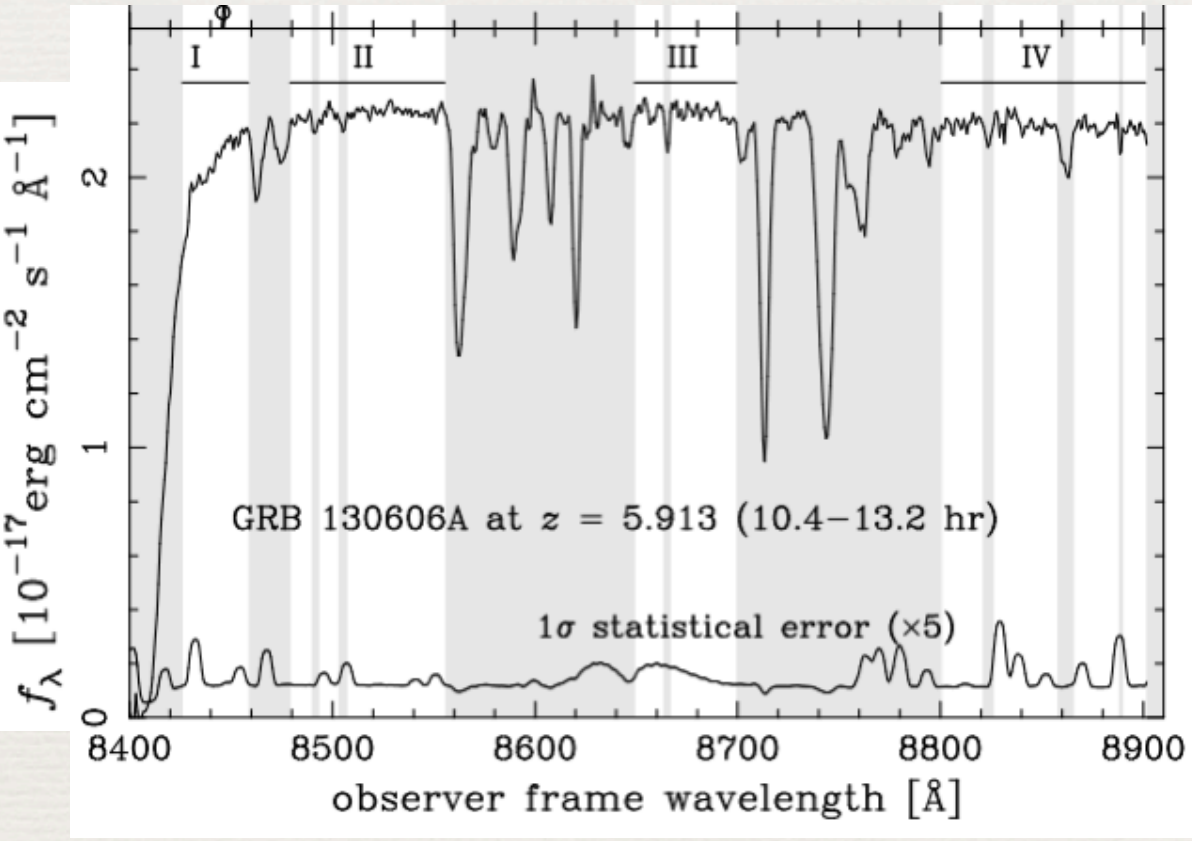
- ultra-high S/N spectra taken by Gemini, GTC, Magellan, Subaru, ...
- host HI at most $\log(N_{HI})<$ 19.8, good for IGM study!
  - c.f. 21.6 for GRB 050904

Chornock+'13

Damping Wing Analysis

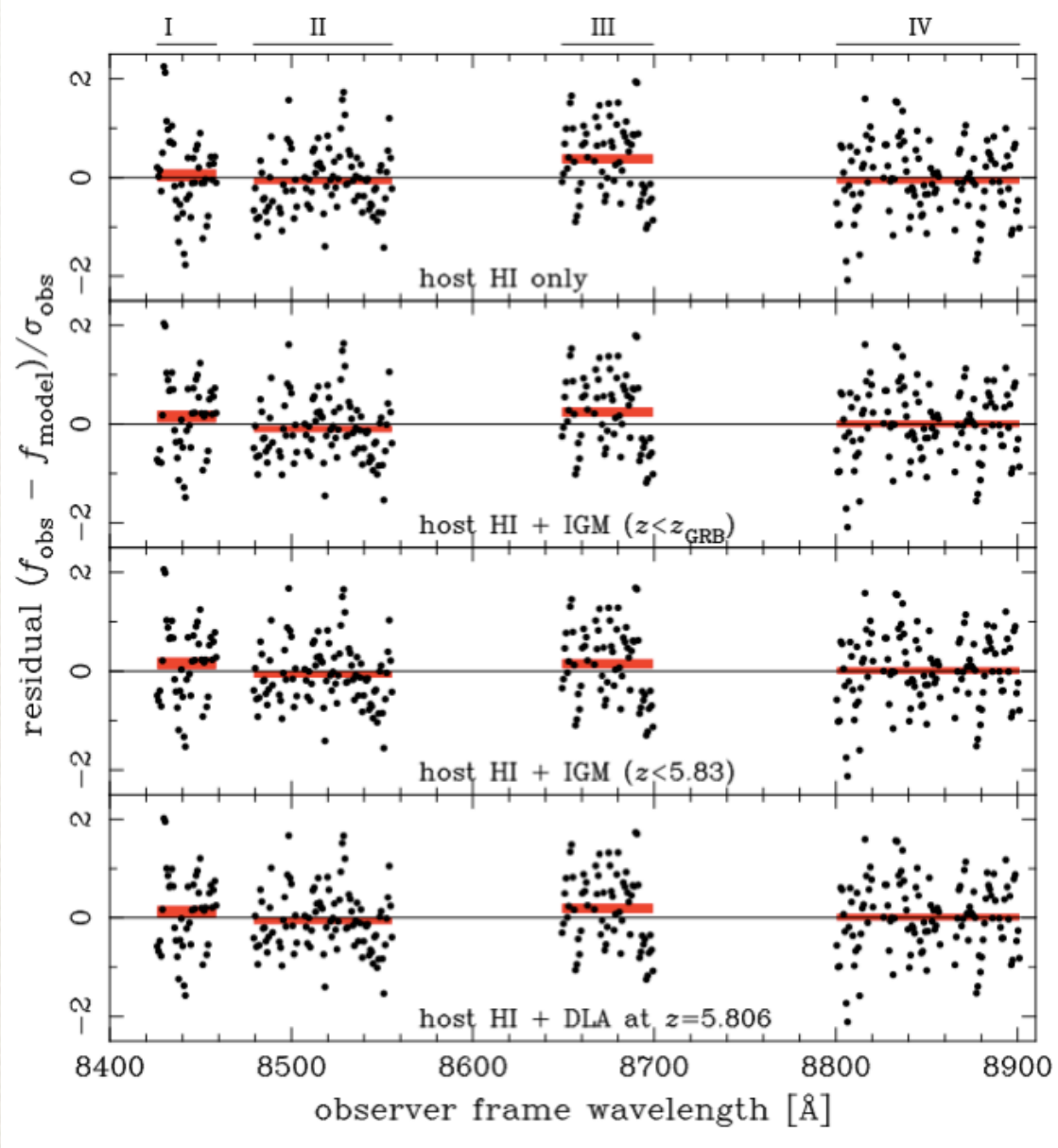
- Subaru/FOCAS spectrum in 10.4-13.2 hr after the burst
- S/N=100 per pixel (0.74A)!
- 8400-8900 A which is the most sensitive to IGM HI signature
- avoid strong absorption



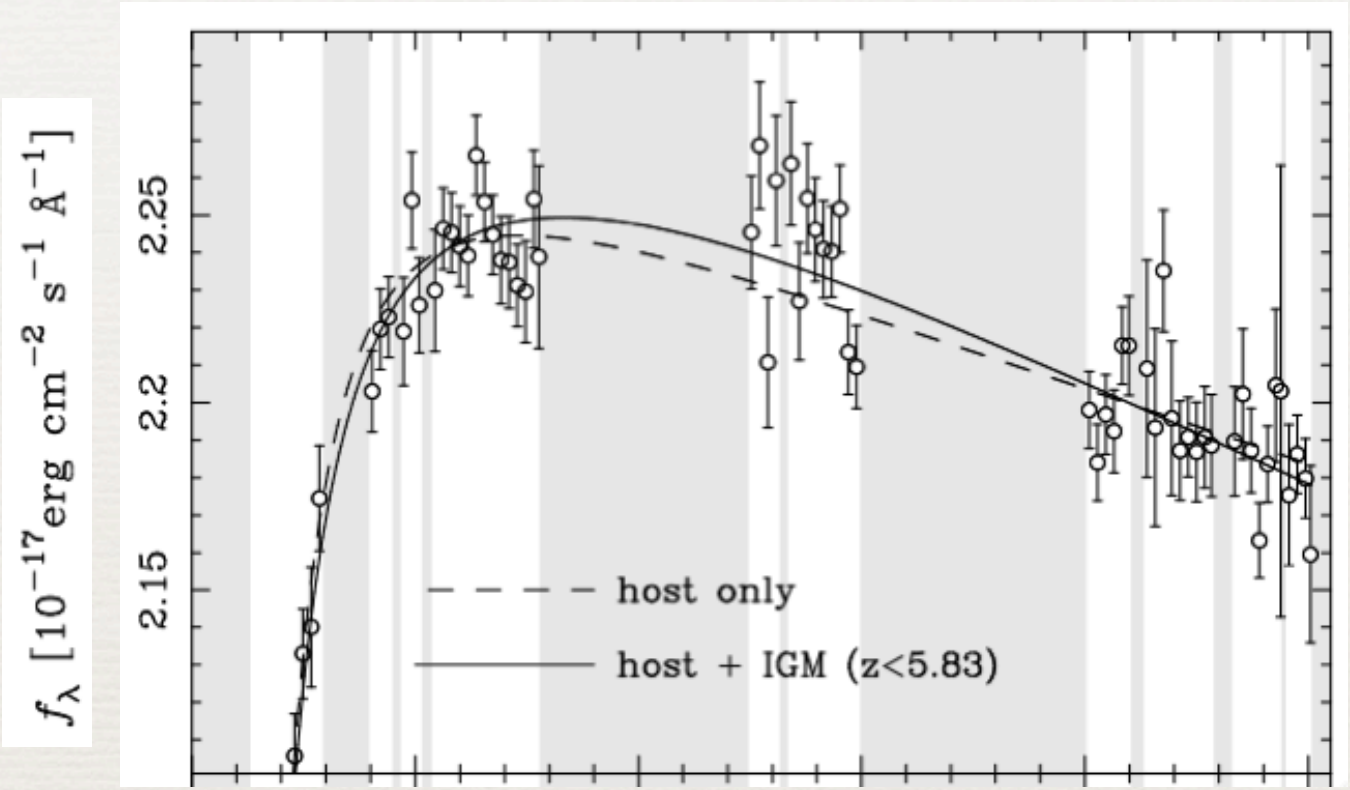


Fitting Residuals

- power-law + host HI only
  - showing curved systematic residual
  - amplitude ~ 0.6% of continuum flux
- 3 models of intervening HI can reduce the residual by about 3 sigma statistics
  - IGM extending to $z_u = z_{GRB} = 5.913$
  - IGM extending to z_u ~ 5.8
    - corresponding to dark GP troughs to this sightline
  - a DLA at z = 5.806
    - a metal absorption system found here
    - $\log(N_{HI}/cm^{-2})$ ~ 20.7 required



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
  - extinction at host
  - intrinsic curvature in afterglow spectrum?

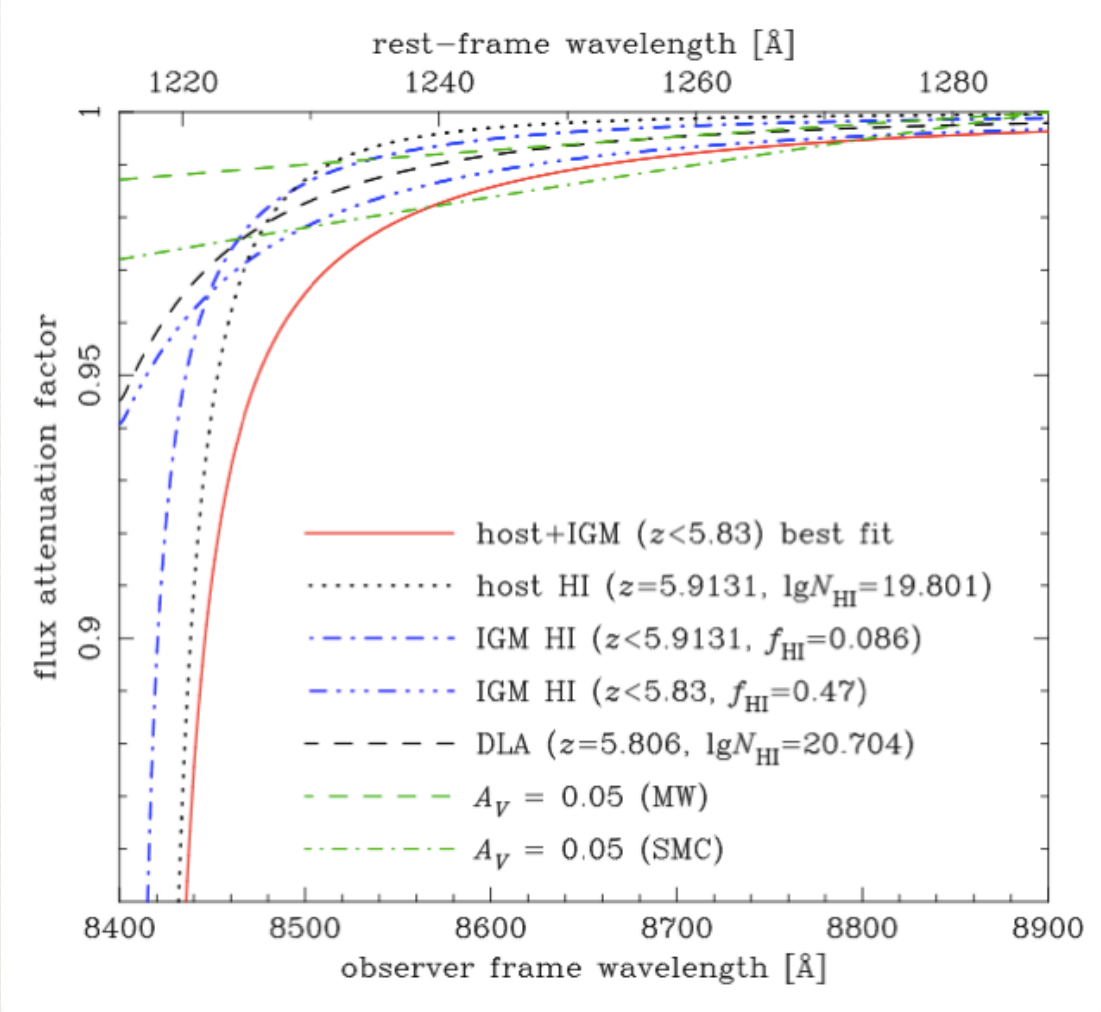
Systematics in Spectrum Reduction

- spectrum calibration by standard stars
  - HST spectral standard library (CALSPEC)
  - a white dwarf Feige 34 taken on the same day
  - the primary pure-hydrogen WD GD153 taken one day before
  - two reduced spectra agree within ~0.2%
- slit/aperture loss
  - should not produce 0.6%-level “curvature” in 8400-8900 A
- removal of absorption lines
  - results insensitive to inclusion/removal of marginally detected absorption lines

Extinction at the Host Galaxy?

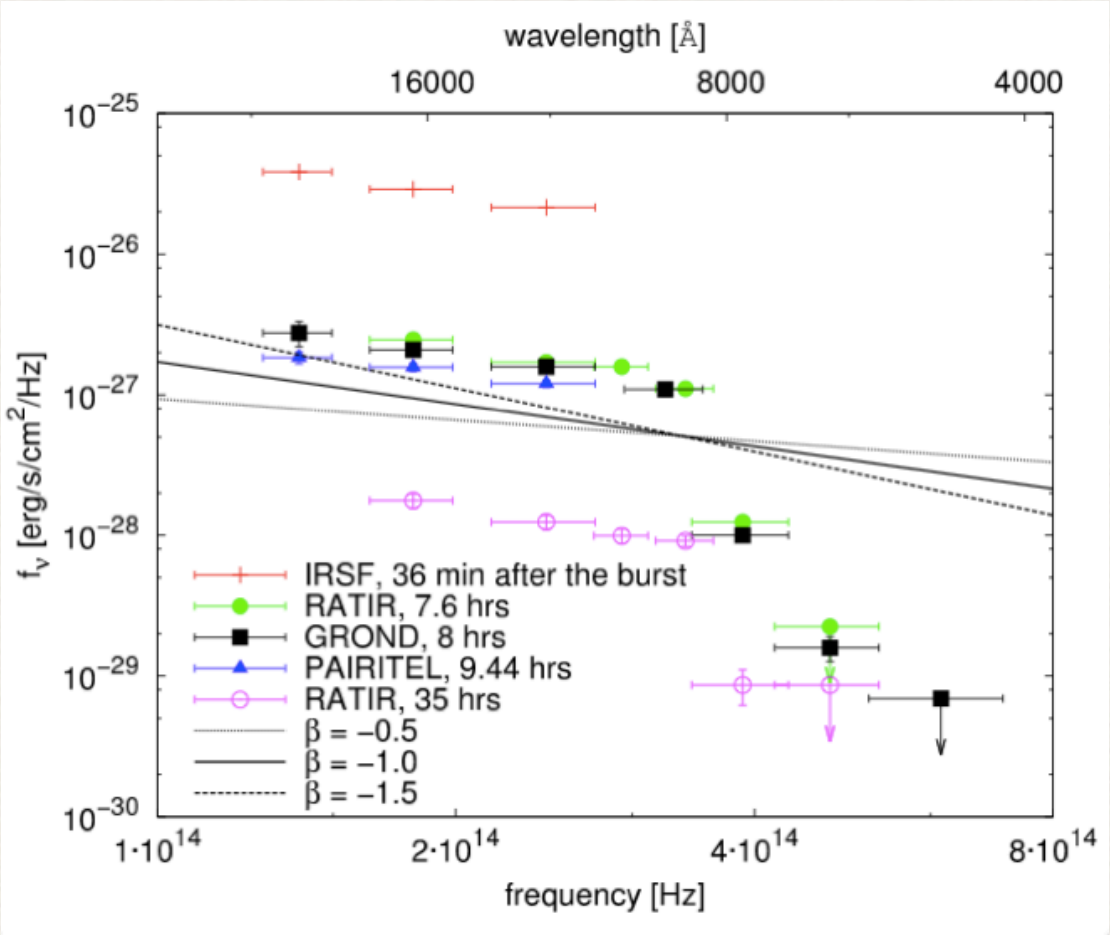
- using standard extinction curves (MW/SMC), the reddening is linear in 8400-8900 A, does not produce "curvature"

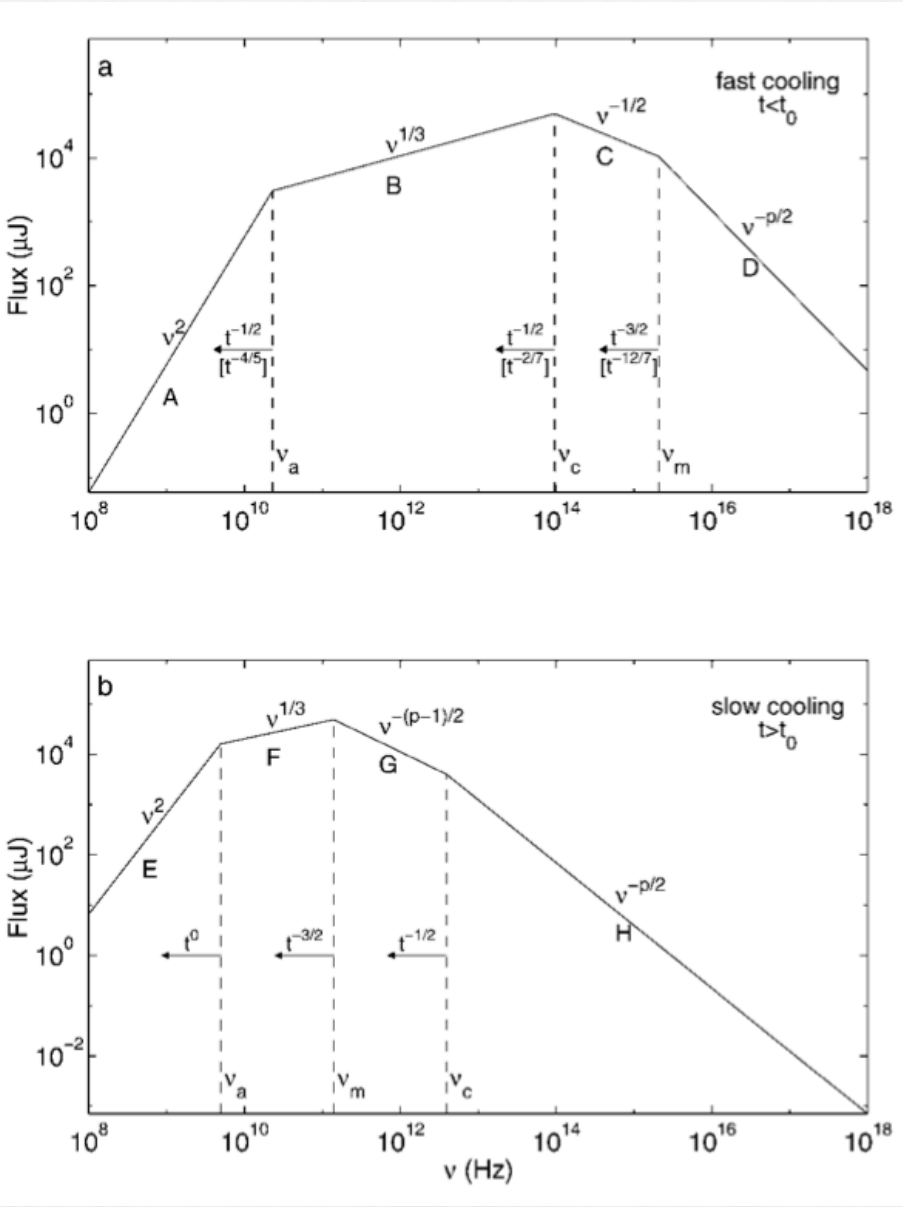
- from N_{HI} and Z inferred for the host, A_V should be <~ 0.01



Curvature in the GRB Afterglow Spectrum?

- spectral break が付近に来ているなら SED が時間変動するはずだが、兆候なし
- 8400-8900A で 0.6% の歪みは、波長が7%変化しただけで power-law index が 1 変化するレベル （afterglow の break としては激しすぎる？）

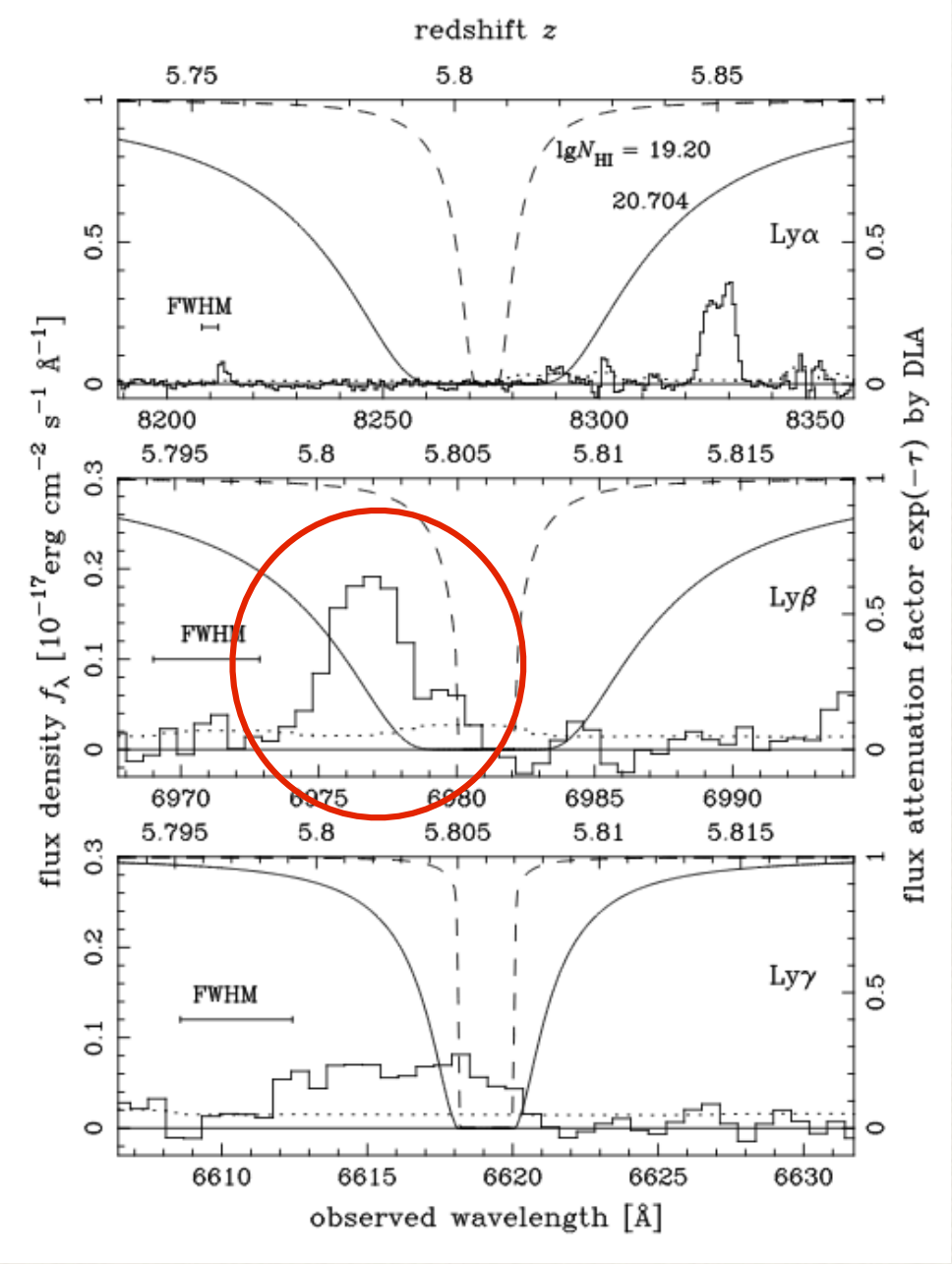




Sari+'98

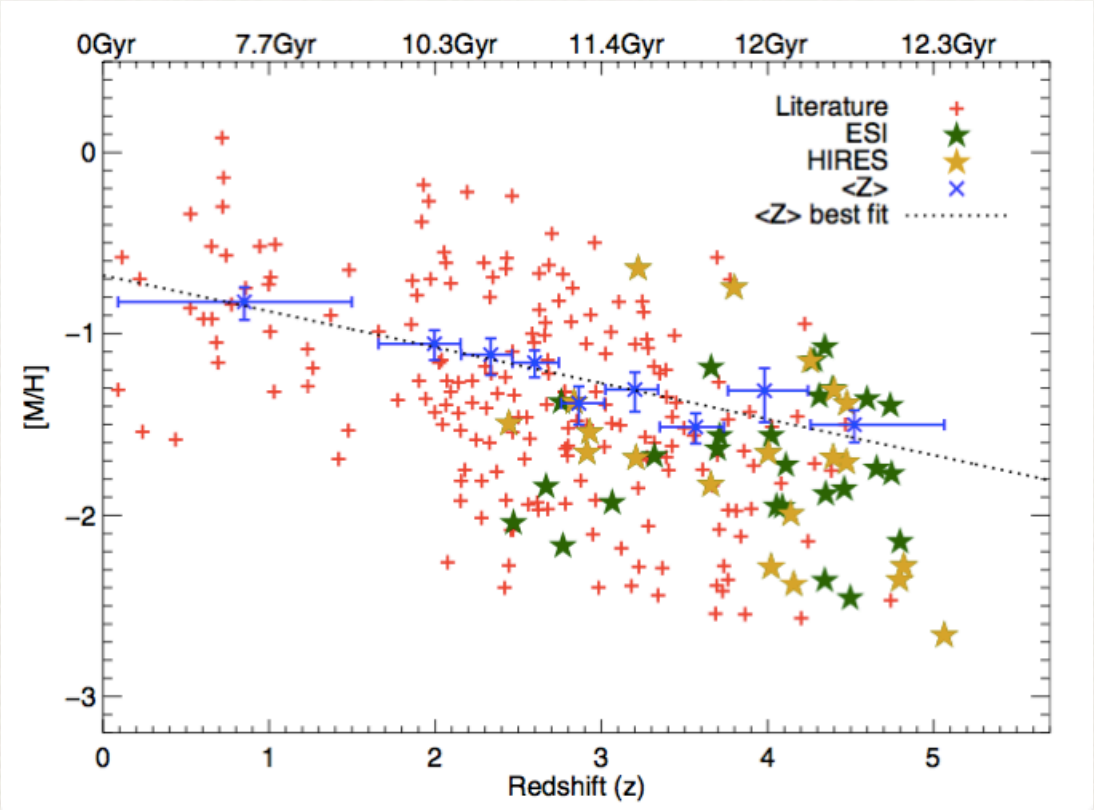
diffuse IGM vs. DLA? (1) Ly β constraint

- the only metal absorption system close to the GRB host is at z=5.806
  - if the DLA is located at this redshift, $\log(N_{HI}/cm^2) = 20.7$ required, much larger than in GBR host (19.7)
- chance probability of finding such a DLA is low (~3%) from DLA statistics at $z < 5$
- the case of z=5.806 & $\log(N_{HI}/cm^2) = 20.7$ is excluded by the profile around Ly β feature



diffuse IGM vs. DLA? (2) metallicity

- the case of z=5.806 & $\log(N_{HI}/cm^2)$ = 20.7 indicates [Si/H] < -3.5
  - the lowest Z DLA known: -2.7
- even lower Z required if the DLA is not at z=5.806



Rafelski+'12

Discussion

- Chornock et al. 2013 でも damping wing 解析をしていて、f_{HI} <~ 0.1 (2σ) という結果を主張
  - 詳細は論文に書いていないが、多分 zu=zGRB=5.913の結果
  - 我々はその場合、f_{HI} ~ 0.1 なので、矛盾はない
  - Chornock et al. は、afterglow spectral index $\beta = -2.0$ で、我々の $\beta = -1.0$ と全く合わない
    - 自信もって言いますが、彼らが間違っています
      - 我々の結果は、NIR photometric data と一致
    - IGM HI に影響を受けた波長域を power-law fit していそう
    - fit した波長域、吸収線の除去、など詳しいことが全く書いてない

- z=5.9 では電離しているのじゃないの！？
  - quasar vs. GRB で環境は異なりうる
  - z~6 付近の quasar 解析から、z~6 ではまだ再電離は完全ではないという主張もある(e.g. Mesinger 2010)

Conclusions

- GRB 130606A gives the second opportunity to probe reionization by GRBs, next to GRB 050904
- simple power-law + host HI does not give a good fit, and intervening HI outside the host improves the fit by about $3\,\sigma$
  - n_{HI}/n_H ~ 0.1 if $z_{IGM,u}$ ~ z_{GRB} ~ 5.913
  - n_{HI}/n_H ~ 0.5 if $z_{IGM,u}$ ~ 5.8 (dark GP trough region, 5 proper Mpc away from GRB)
  - the first evidence for intervening HI to GRB sightlines
- Known systematics or an intervening DLA seem unlikely
- diffuse IGM HI remains as a plausible explanation
  - highly neutral IGM hidden in GP trough regions?
  - indicating that the reionization not yet complete at z~6
- demonstrated the great power of GRBs to study reionization!