

GRBで探る宇宙再電離

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初代星研究会 平成18年9月4日

国立天文台 三鷹

祝! GRB 050904 本日一周年!



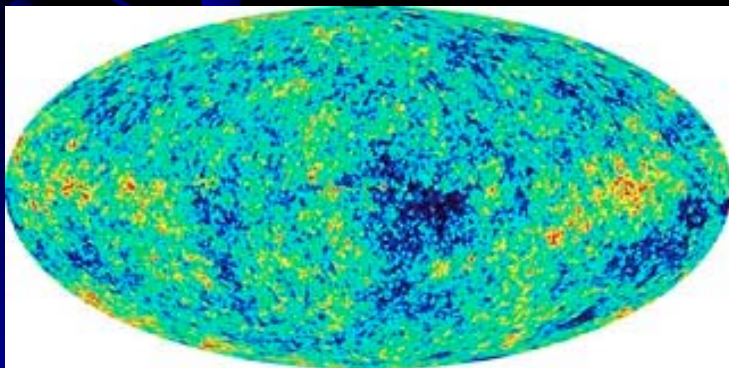
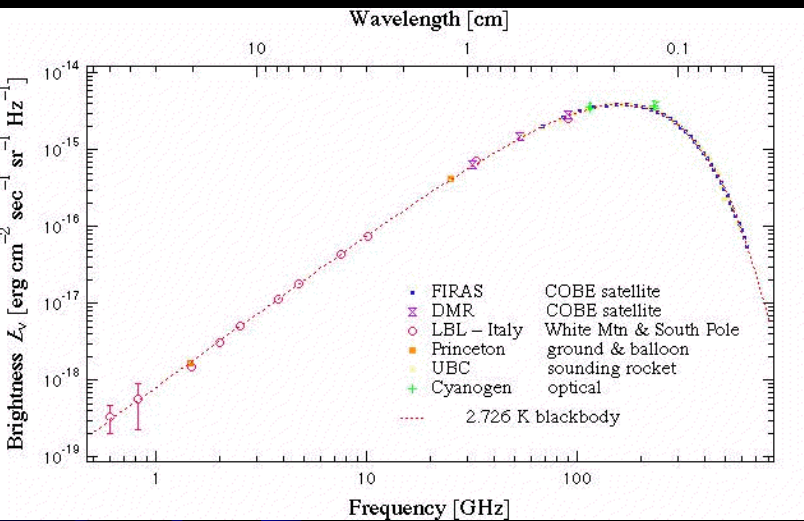
京都大学

宇宙物理学教室

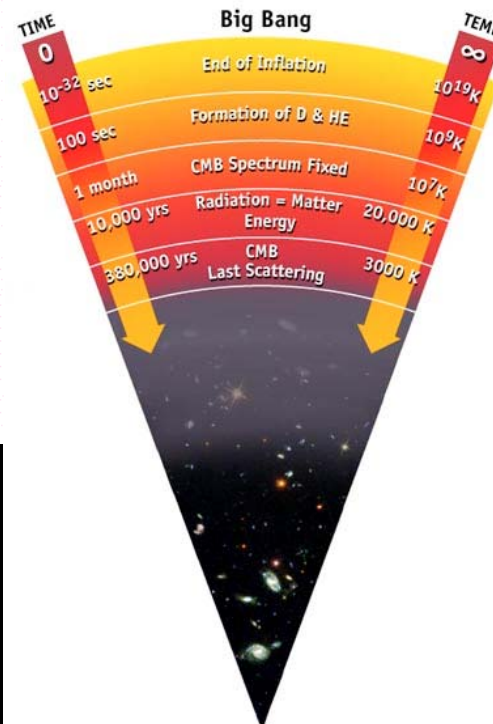
Department of Astronomy
Kyoto University

宇宙再電離研究の現状(1)

- Cosmic Microwave Background (CMB):
 - $z \sim 1100$ で宇宙(水素)が中性化、その時の散乱光

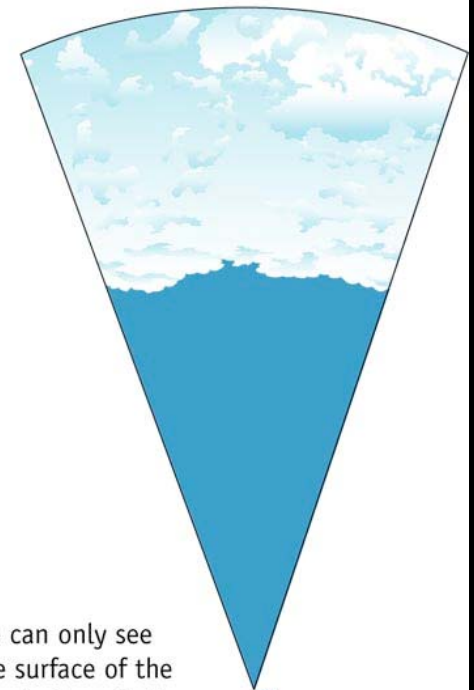


2.7 K の黒体放射、
 10^{-5} の異方性



PRESENT
 13.7 Billion Years
 after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

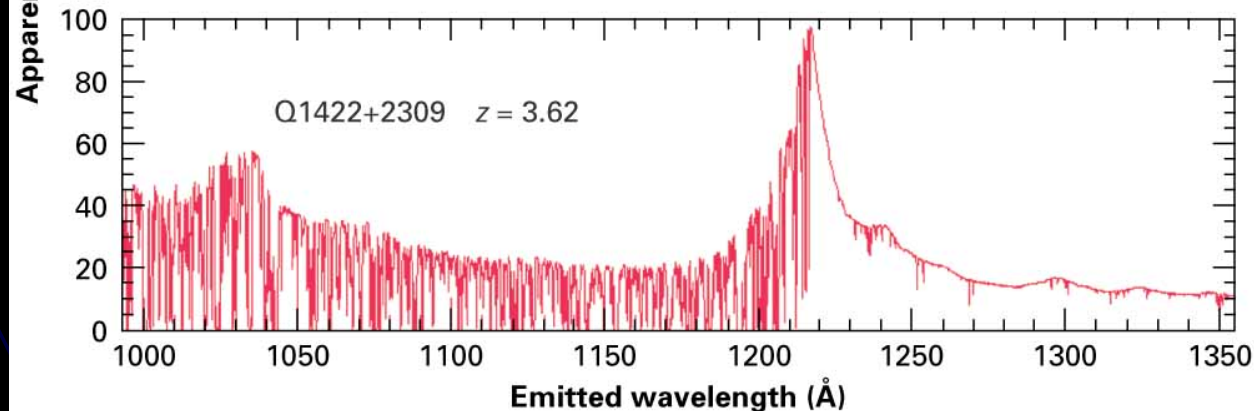
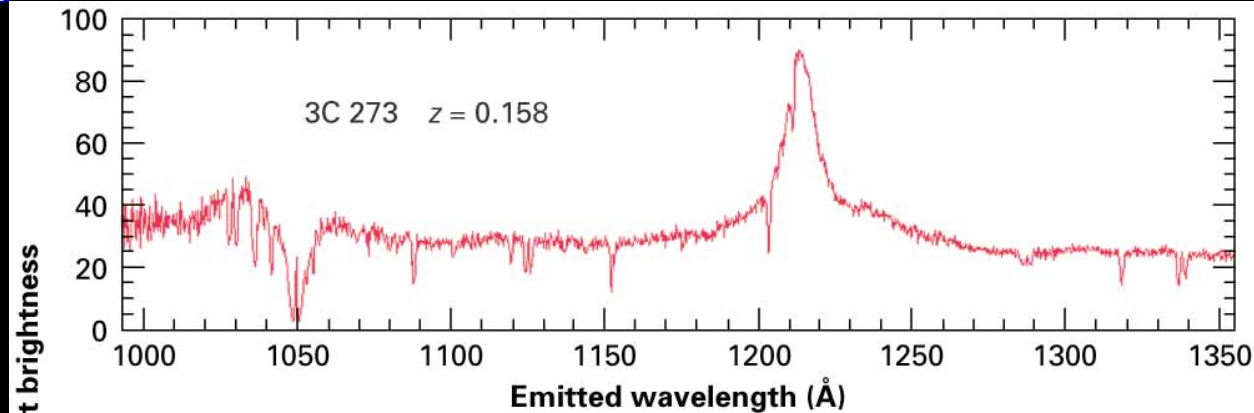


We can only see the surface of the cloud where light was last scattered



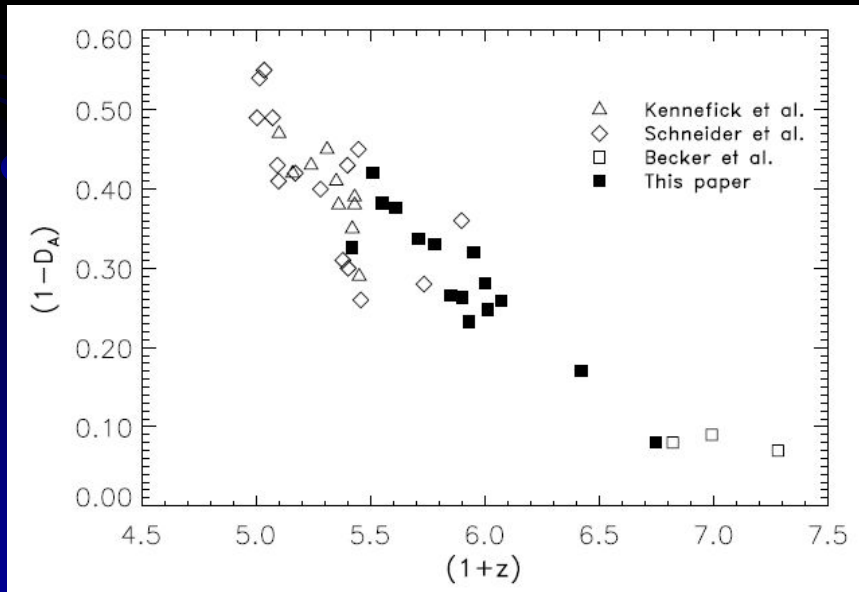
宇宙再電離研究の現状(2)

- 現在の宇宙の銀河間物質 (IGM) はほとんど完全電離
- The Gunn-Peterson Test
 - IGM optical depth for Ly α photons = $2.1 \times 10^4 (1+z)^{3/2} x_{\text{HI}}$
 - $x_{\text{HI}} < \sim 10^{-5}$ for $z \sim 0$
 - ($x_{\text{HI}} \equiv n_{\text{HI}} / n_{\text{H}}$)

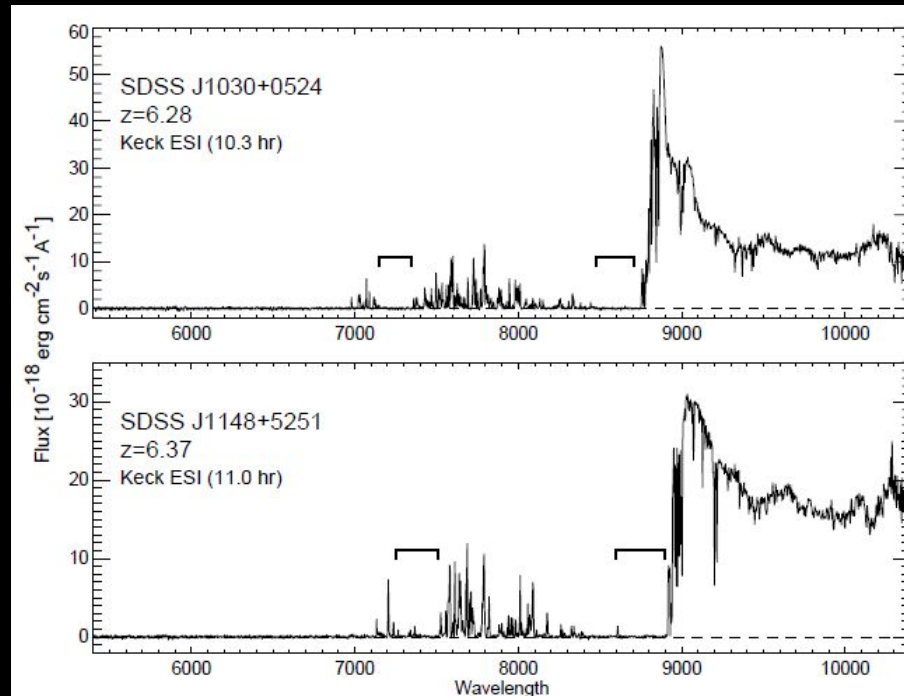


宇宙再電離研究の現状(3)

- IGMは初期天体によって電離された。
 - いつ?どのように? 宇宙論の最重要問題の一つ
 - $z \sim 6-20$, by first stars/quasars?
- 最電離の時期は $z \sim 6$?
 - black “Gun-Peterson trough” found in $z \sim 6$ QSOs
 - しかし、QSO data から言えるのは $x_{\text{H I}} > 10^{-3}$ という事だけ!

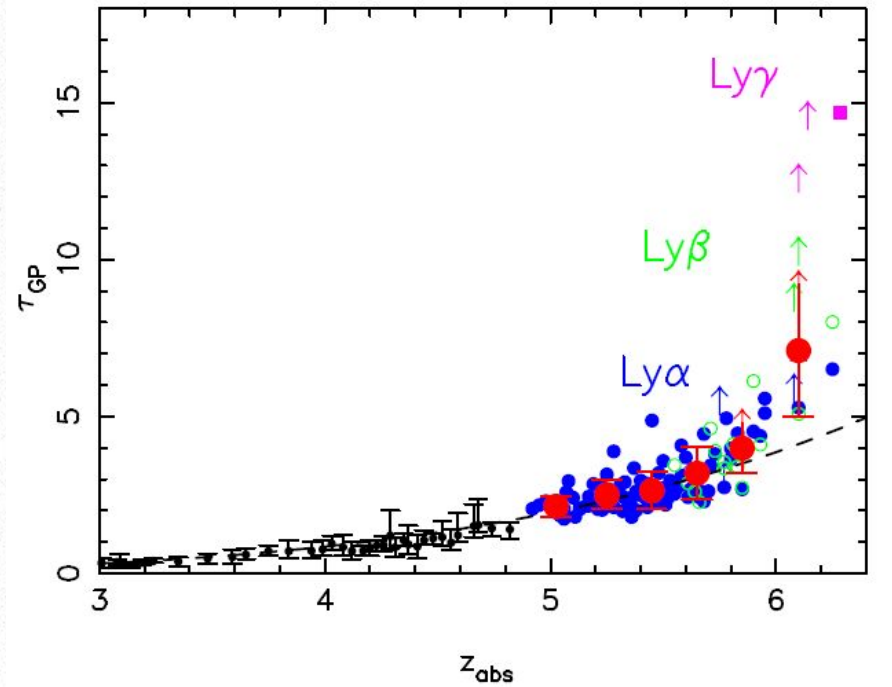
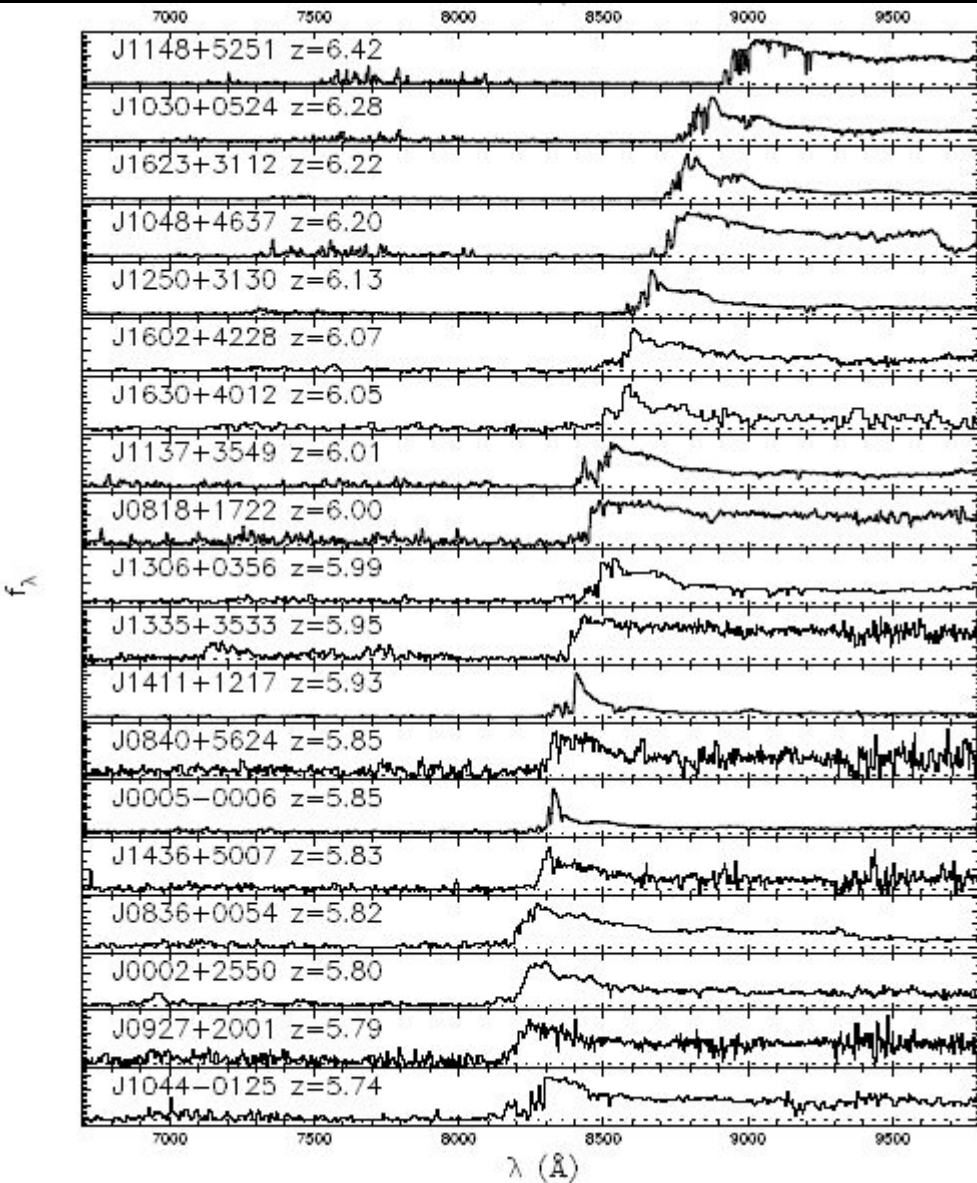


Songaila & Cowie '02



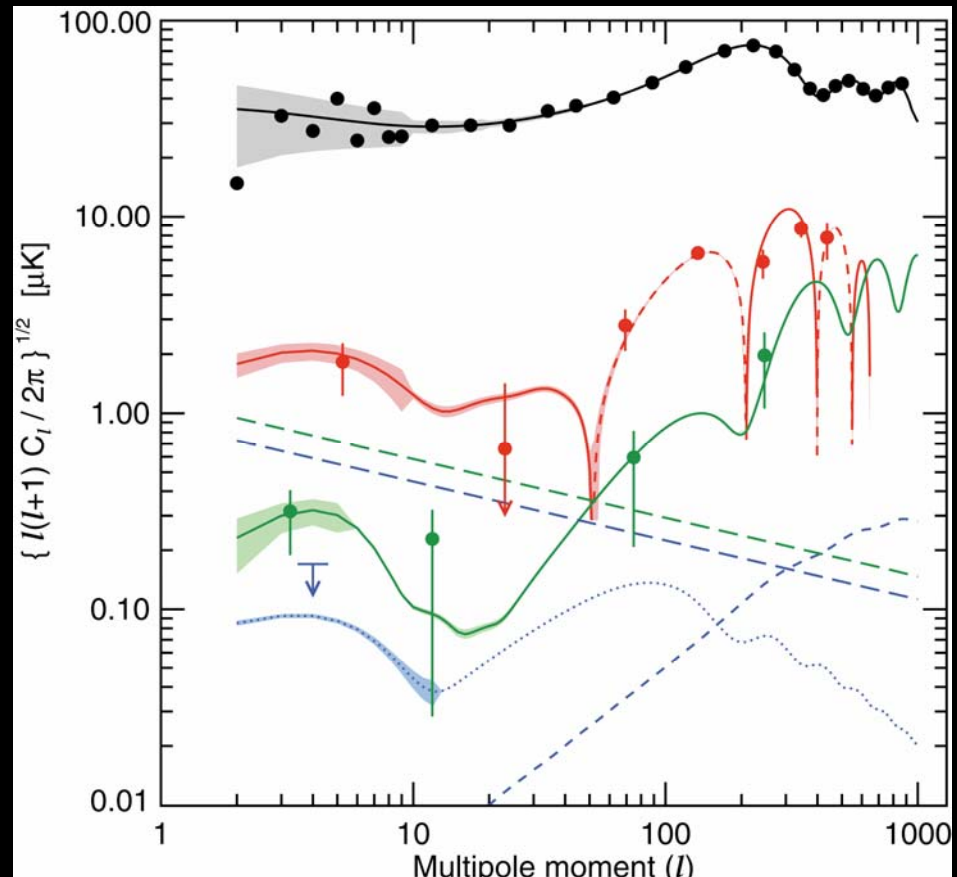
Latest Results from 19 SDSS QSOs

Fan et al. 2005



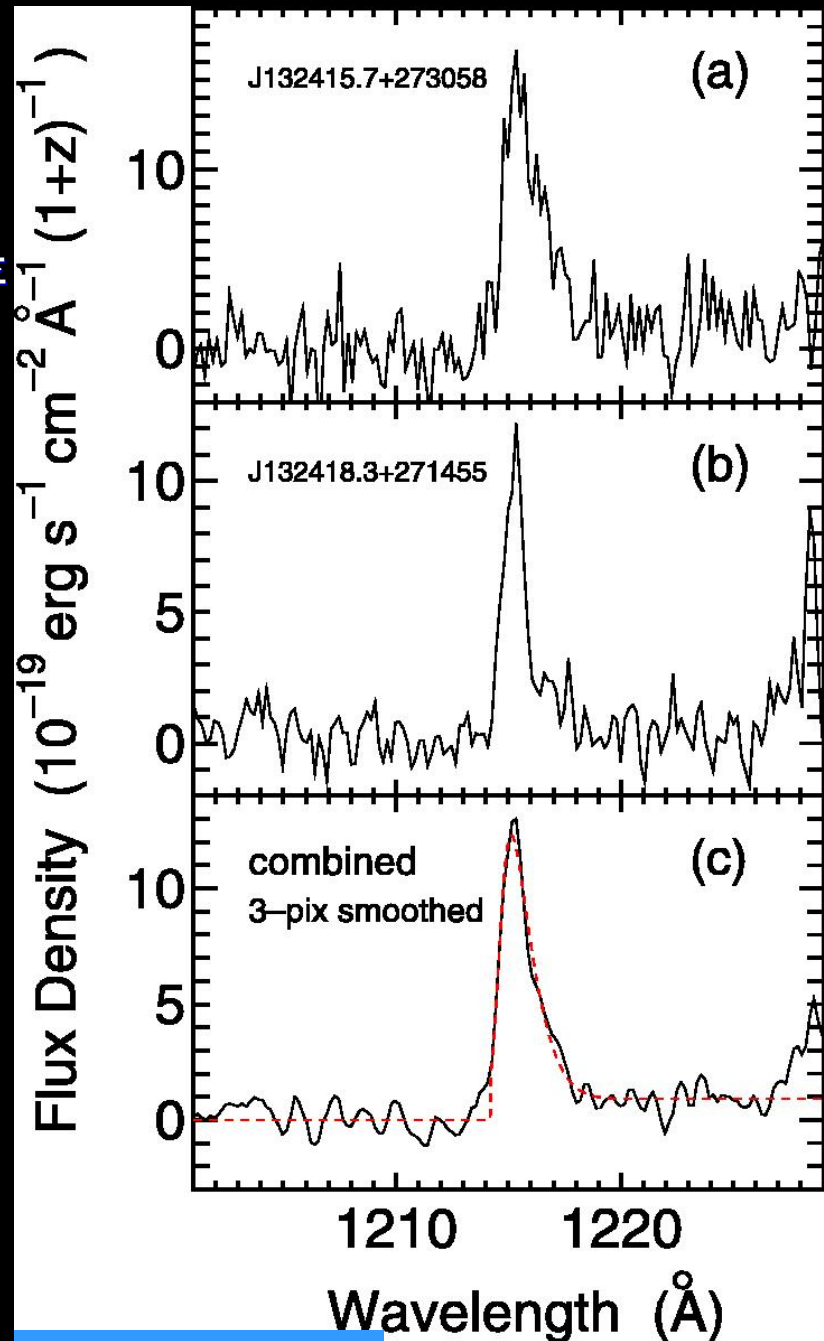
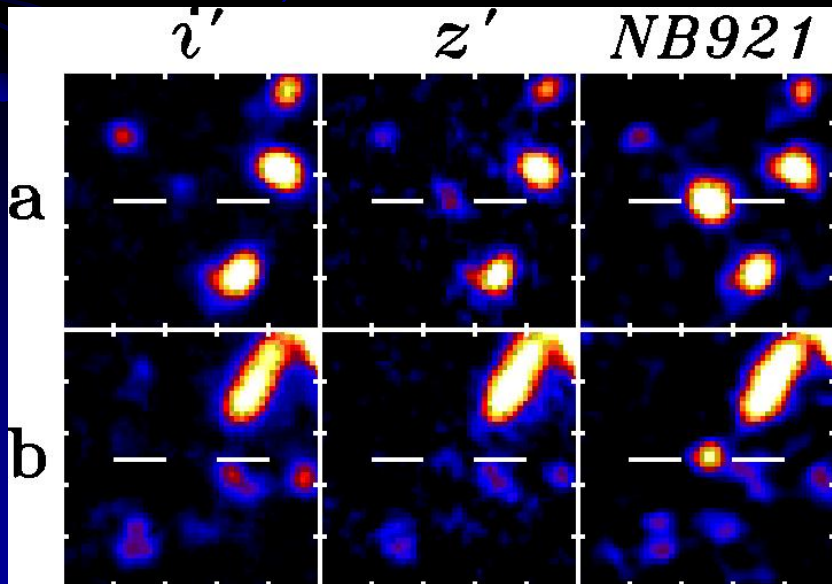
CMB 偏光観測からの制限

- WMAP polarization measurement:
 - reionization at $z=10.9^{+2.7}_{-2.3}$ (Page et al. 2006)
 - the universe reionized twice? (Cen '03; Wyithe & Loeb '03)

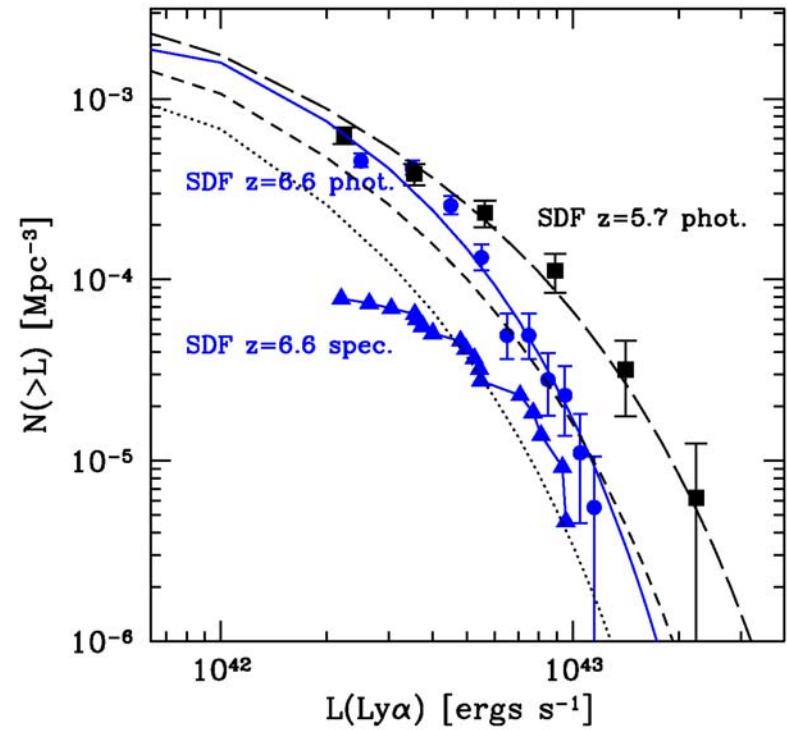
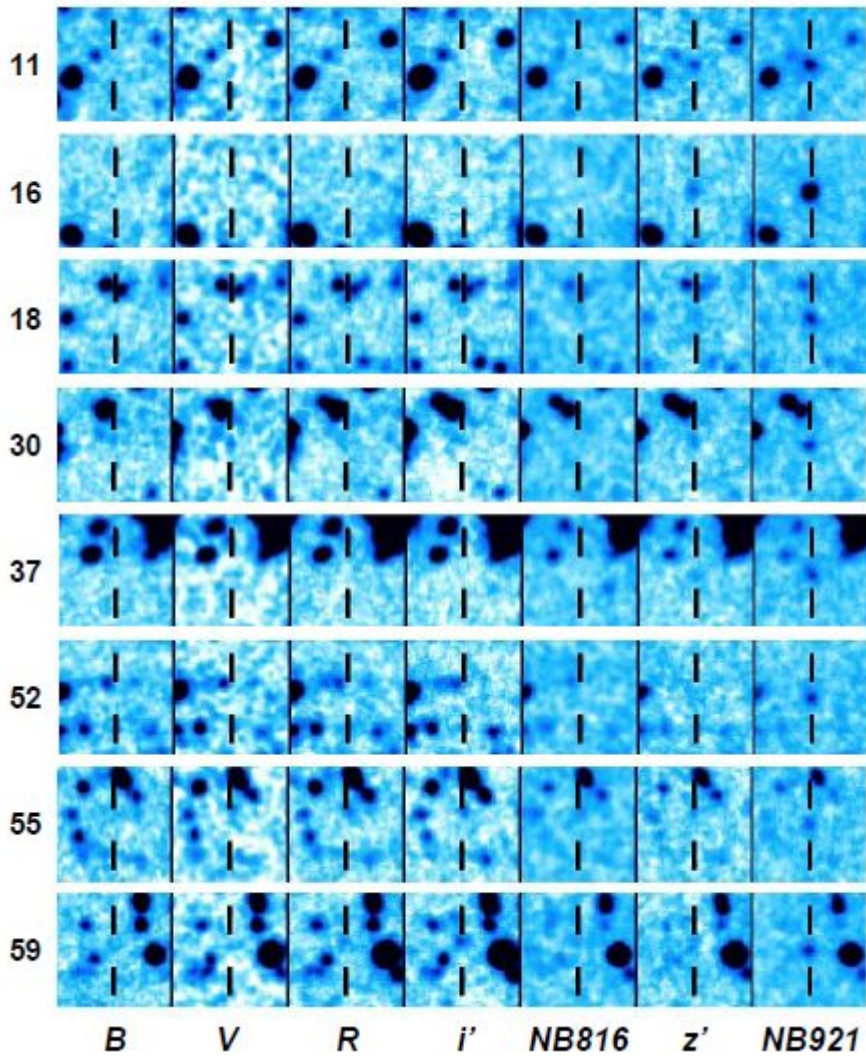


Lyman α Emitters からの制限

- Ly α line emissivity は IGM x_{HI} に強く依存する
- many Ly α emitters at $z > 6$ (e.g. Kodaira et al. '03; Taniguchi et al. '05)
 - already ionized at $z \sim 6.5$? (Malhotra & Rhoads '04; Stern et al. '05)
 - caveat: selection effects, model uncertainties ... (Haiman '02; Wyithe & Loeb '05)



Subaru Deep Field $z=6.5$ Lyman Alpha Emitters



LF evolution from $z = 6.6$ to 5.7

Kashikawa et al. 2006

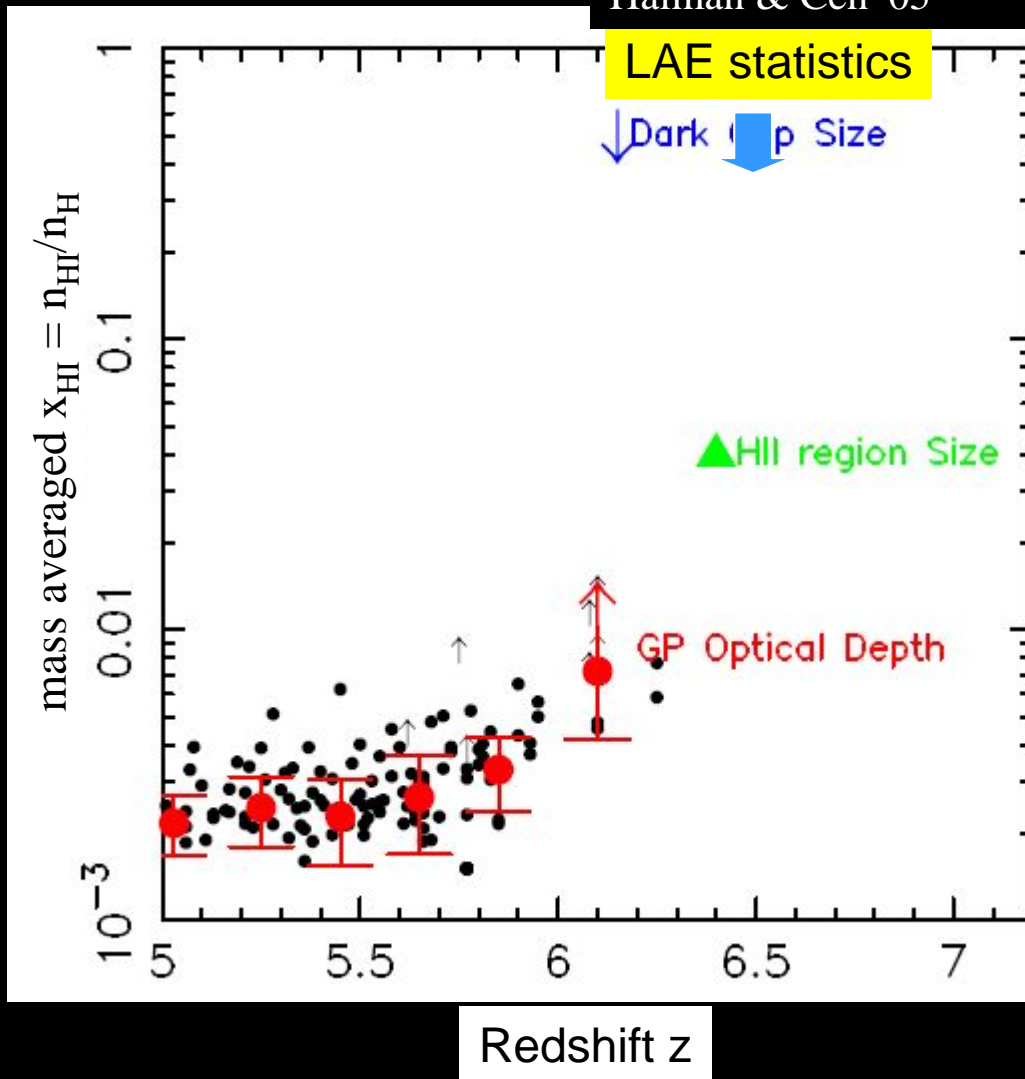
IGM中性度への制限まとめ

Malhotra & Rhoads '05

Stern et al. '05

Haiman & Cen '05

Fan et al. 2005

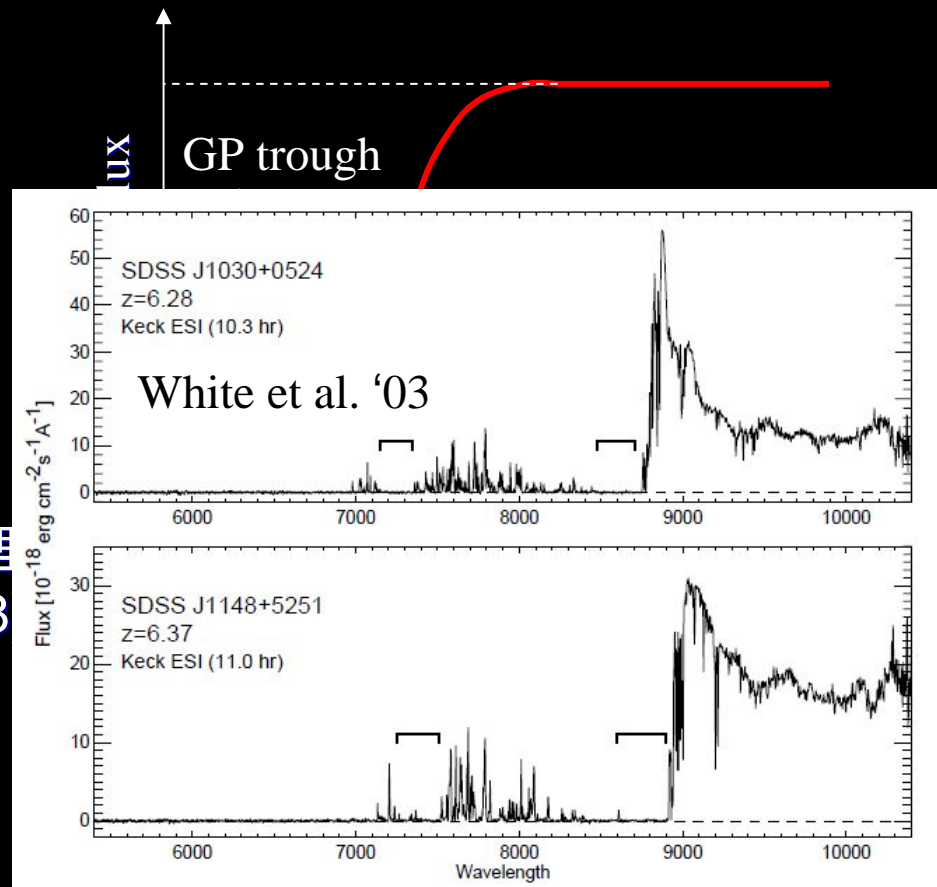


GRB で探る再電離： 多くの利点

- **Brightness**
 - ガンマ線強度は、 $z > \sim 10$ でも観測可能なほど明るい
 - 可視、近赤外残光もクエーサーに匹敵
- **宇宙における「より普通」の場所を探れる**
 - クエーサーは、構造形成の最も進んだ領域の中心にあることが多い
 - GRB は星形成が起きればOK, 母銀河の明るさは関係なし
- **No proximity effect**
 - クエーサーは自らの強い紫外線で周囲を電離してしまう
 - GRBは明るくとも、時間が短いので光子数が少なく、問題にならない
- **Clean spectrum**
 - almost single power-law SED, in contrast to quasars

Probing the Reionization by the Red Damping Wing of the Gunn-Peterson Trough

- クエーサーのGP trough は中性度に対して下限しか与えない
 - $x_{\text{HI}} = n_{\text{HI}}/n_{\text{H}} > \sim 10^{-3}$
 - $\tau_{\text{GP}} = 2.1 \times 10^4 (1+z)^{3/2} x_{\text{HI}}$
- red damping wing が受ければ、 x_{HI} の下限ではない、精密な測定が可能
- GRBs はred damping wing を探す理想的な天体！ (Milarda-Escude 1998)
 - No proximity effect
 - Simple power-law spectrum



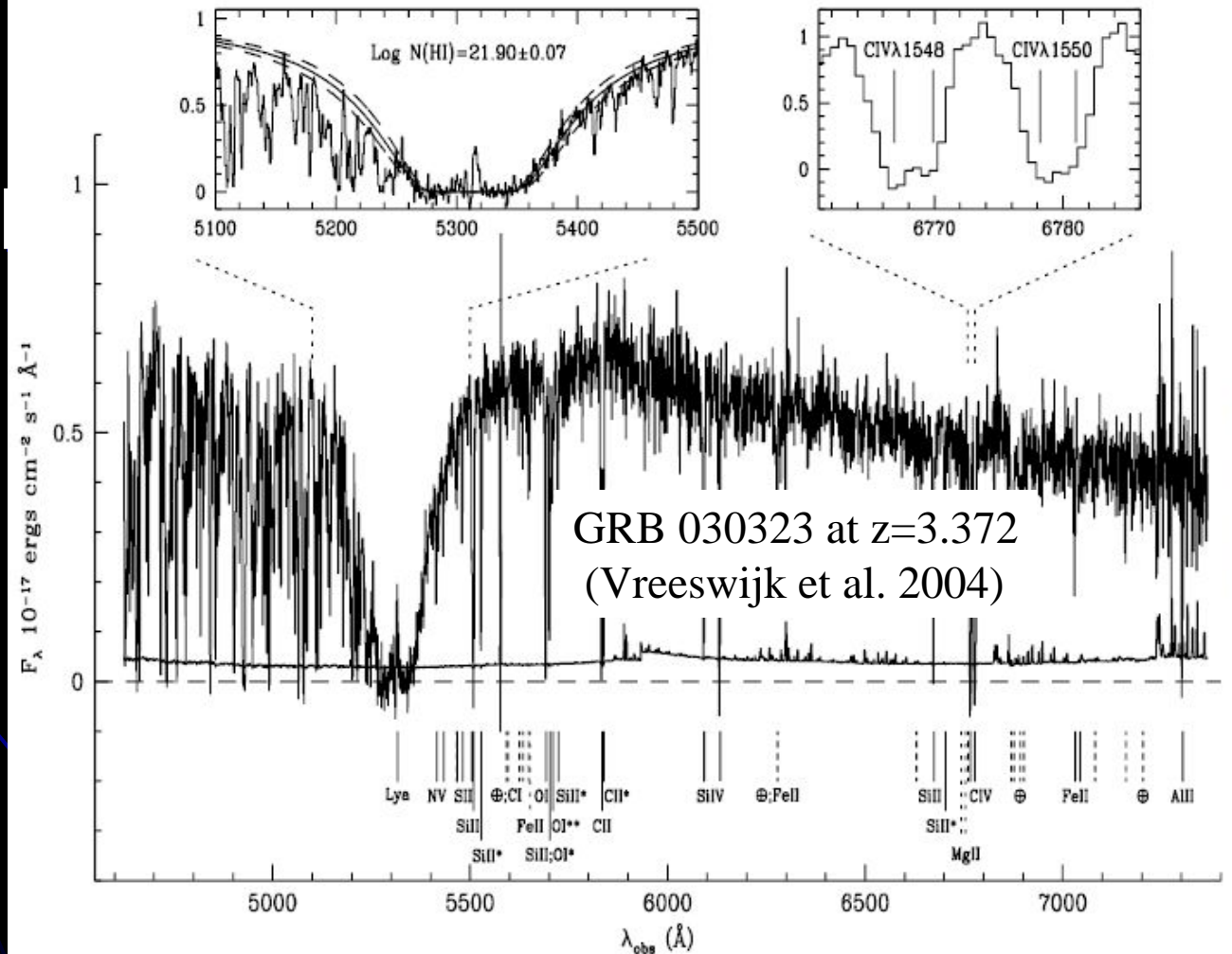
GRB 050904 @ $z=6.3$ GRB による初の再電離への制限

T. Totani et al. 2006, PASJ 54, 485

collaborators: N. Kawai, G. Kosugi, K. Aoki, T.
Yamada, M. Iye, K. Ohta, T. Hattori

Two possibilities for the origin of the damping wing

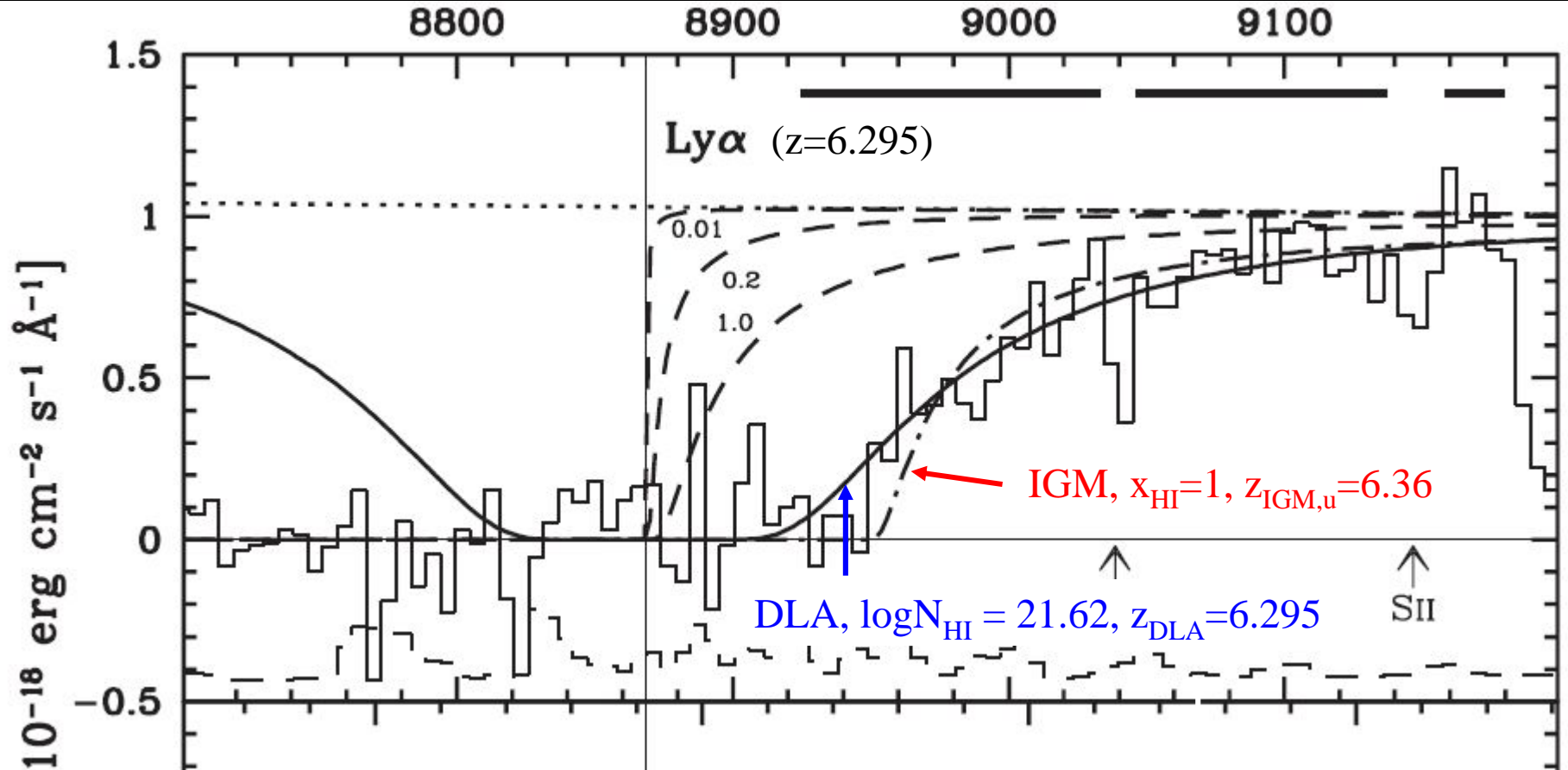
- 中性IGMの
- 母銀河に付



Model Fitting by IGM and DLA

- Intrinsic GRB afterglow spectrum
 - $\beta = -1.25 \pm 0.25$ power-law ($F_\nu \propto \nu^{-\beta}$)
 - ~0.5 day observations of NIR colors by Haislip et al., Tagliaferri et al.
- Absorptions by DLA and IGM
 - 4 model parameters: $z_{\text{DLA}}, N_{\text{HI}}, z_{\text{IGM,u}}, X_{\text{HI}}$
 - DLA: $\tau = N_{\text{HI}} \sigma [(1+z) \nu_{\text{obs}}]$
 - damping width \gg reasonable velocity dispersion ($< \sim 200$ km/s)
 - IGM: Formula of Miralda-Escude 1998
 - uniform IGM distributed from $z_{\text{IGM,l}}$ to $z_{\text{IGM,u}}$
 - $z_{\text{IGM,l}} = 6.0$ assumed in the baseline model

Fitting to the Damping Wing

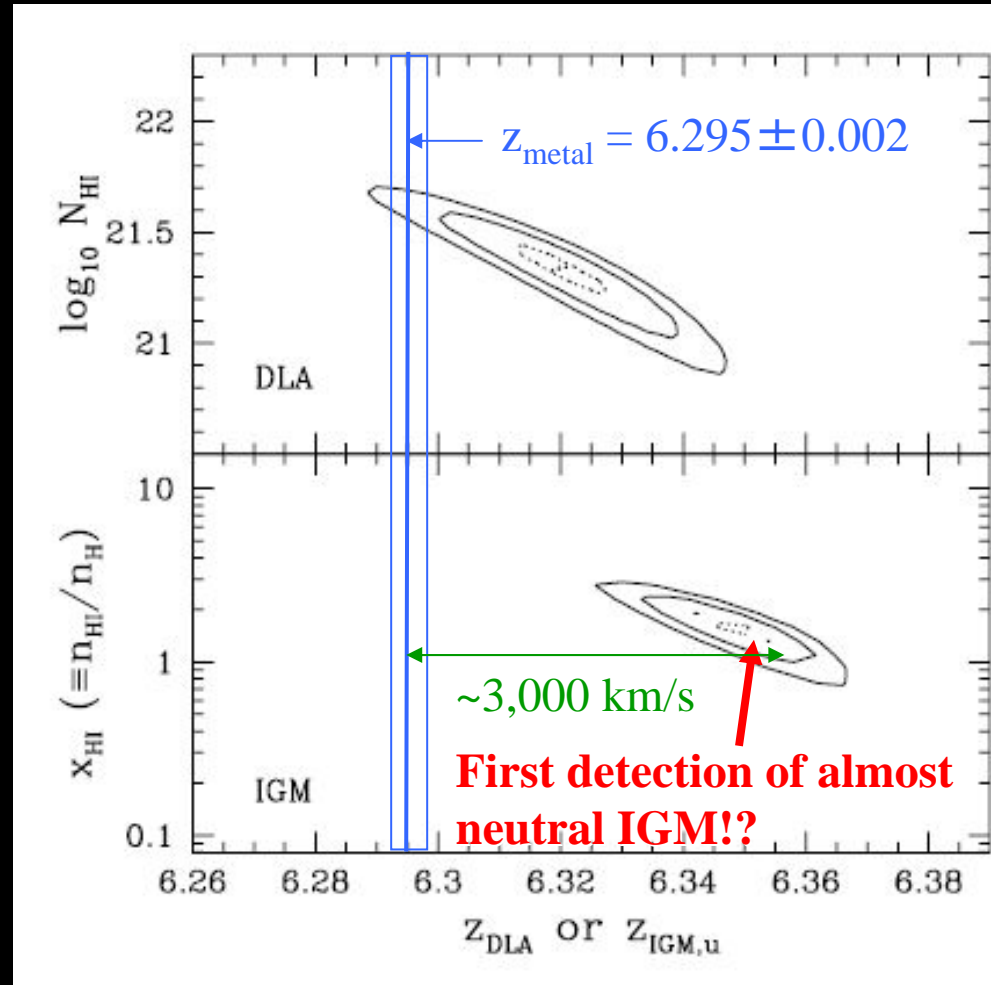


Wavelength [\AA]

Separate Fitting of IGM and DLA

- DLA でも IGM でも damping wing は説明できる(degeneracy!)

- marginally $z_{\text{DLA}} = z_{\text{metal}}$ allowed for DLA
- If IGM:
 - $x_{\text{HI}} \sim 1$ (neutral IGM!)
 - z_{metal} must be blueshifted by about 3,000 km/s
 - possible in GRBs



Possible Deviations of z_{DLA} and $z_{\text{IGM,u}}$ from z_{metal}

- 以下の効果はほとんど効かない

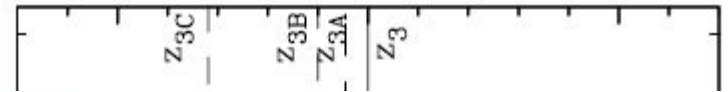


Table 1 | Absorption lines detected in the spectrum of the optical afterglow of GRB 050904

Observed wavelength (Å)	Equivalent width (Å)	Column density log (cm ⁻²)	Line identification (element, Å)	Redshift, z
9,041.0 ± 0.8	4.5 ± 1.0	14.44 ^{+0.14} _{-0.16}	C IV, λ = 1,548.2 (N V, λ = 1,238.8)	4.840 ± 0.001 (6.298 ± 0.001)
9,055.9 ± 1.7	1.7 ± 1.0	14.21 ^{+0.25} _{-0.46}	C IV, λ = 1,550.8 (N V, λ = 1,242.8)	4.840 ± 0.001 (6.287 ± 0.001)
9,146.4 ± 1.8	3.8 ± 1.1	15.60 ^{+0.14} _{-0.17}	S II, λ = 1,253.8	6.295 ± 0.001
9,188.7 ± 2.6	6.1 ± 3.7	16.20 ^{+1.67} _{-0.92}	S II, λ = 1,259.5	6.295 ± 0.002
9,195.9 ± 1.2	8.3 ± 2.7	14.29 ^{+0.57} _{-0.39}	Si II, λ = 1,260.4	6.296 ± 0.001
9,225.8 ± 1.8	3.9 ± 1.1	13.63 ^{+0.13} _{-0.16}	Si II*, λ = 1,264.7	6.295 ± 0.001
9,499.1 ± 0.9	10.3 ± 1.9	15.85 ^{+0.39} _{-0.28}	O I, λ = 1,302.2	6.295 ± 0.001
9,737.2 ± 1.1	12.3 ± 2.4	15.41 ^{+0.30} _{-0.26}	C II, λ = 1,334.5	6.296 ± 0.001

The wavelengths and equivalent widths were derived by fitting a single gaussian. The column densities of lines were estimated by the standard curve of growth analysis²⁵. The equivalent widths in the table are observed ones, that is, not converted to the rest-frame. The quoted uncertainties are 1σ statistical errors. Most of the absorption lines are consistent with being at a single redshift of $z = 6.295 \pm 0.002$ within the statistical uncertainties. The absorption lines at $\lambda = 9,041.0 \text{ \AA}$ and $9,055.9 \text{ \AA}$ could be identified as N V $\lambda = 1,238.8 \text{ \AA}$, $\lambda = 1,242.8 \text{ \AA}$, if they are at a redshift similar to that of the other absorption lines. However, the derived redshifts of these two lines are significantly inconsistent with each other. Another possible identification is C IV $\lambda = 1,548.2 \text{ \AA}$, $\lambda = 1,550.8 \text{ \AA}$ in an intervening system at $z = 4.840$, which we think is more likely.

しかし....

- GRB、あるいは親星の活動性による吸収によって、大きな Δz による吸収
- $\Delta z \sim 0.05$ ($\sim 3,000 \text{ km/s}$) possible

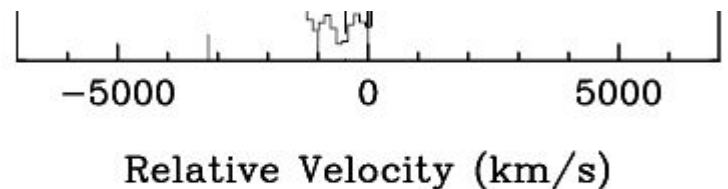
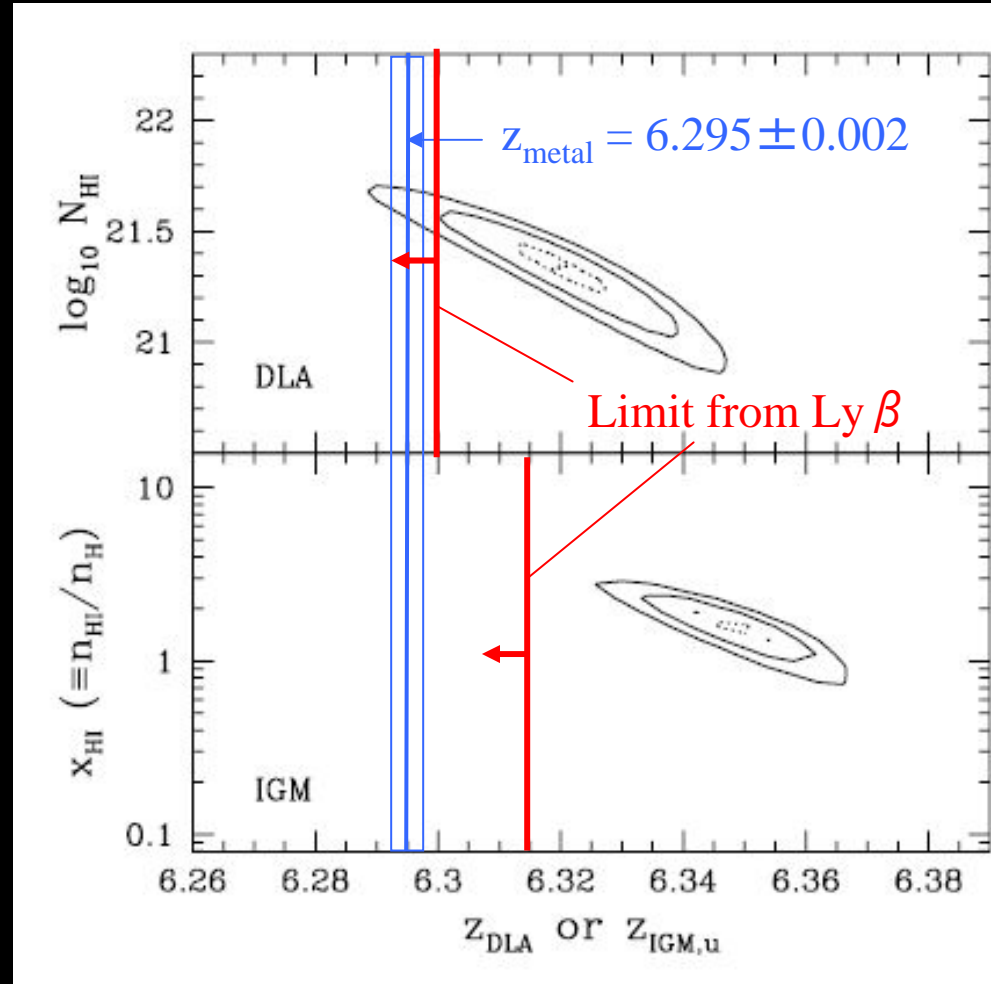


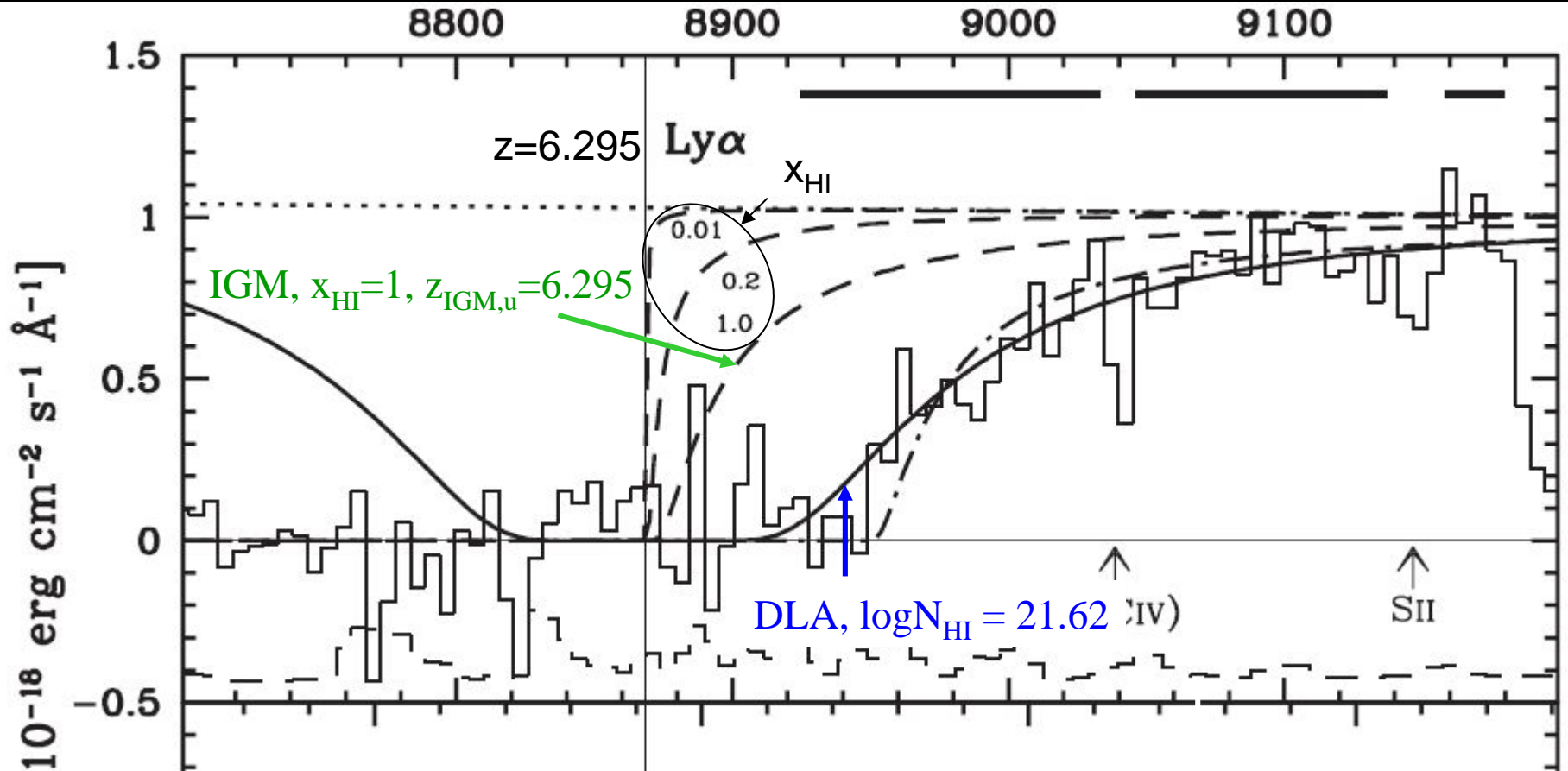
FIG. 7.—Blueshifted Ly α , Ly β , Si IV, and C IV absorbers in the GRB 021004 afterglow spectrum plotted in velocity space. As zero velocity we use the systemic redshift $z_3 = 2.328$. The dashed lines indicate blueshifted absorbers at $z_{3A} = 2.323$, $z_{3B} = 2.317$, and $z_{3C} = 2.293$. [See the electronic edition of the Journal for a color version of this figure.]

Breaking the degeneracy by Ly β Feature

- IGM model は完全に棄却
 - upper limit $z_{\text{IGM,u}} < 6.314$
- DLA model は良く合う
- the plausible model:
 - $z_{\text{DLA}} = z_{\text{IGM,u}} = z_{\text{metal}} = 6.295$
 - DLA dominates the damping wing
 - $\log N_{\text{HI}} \sim 21.6$
 - $x_{\text{HI}} \sim 0$



Constraint on x_{HI} ?

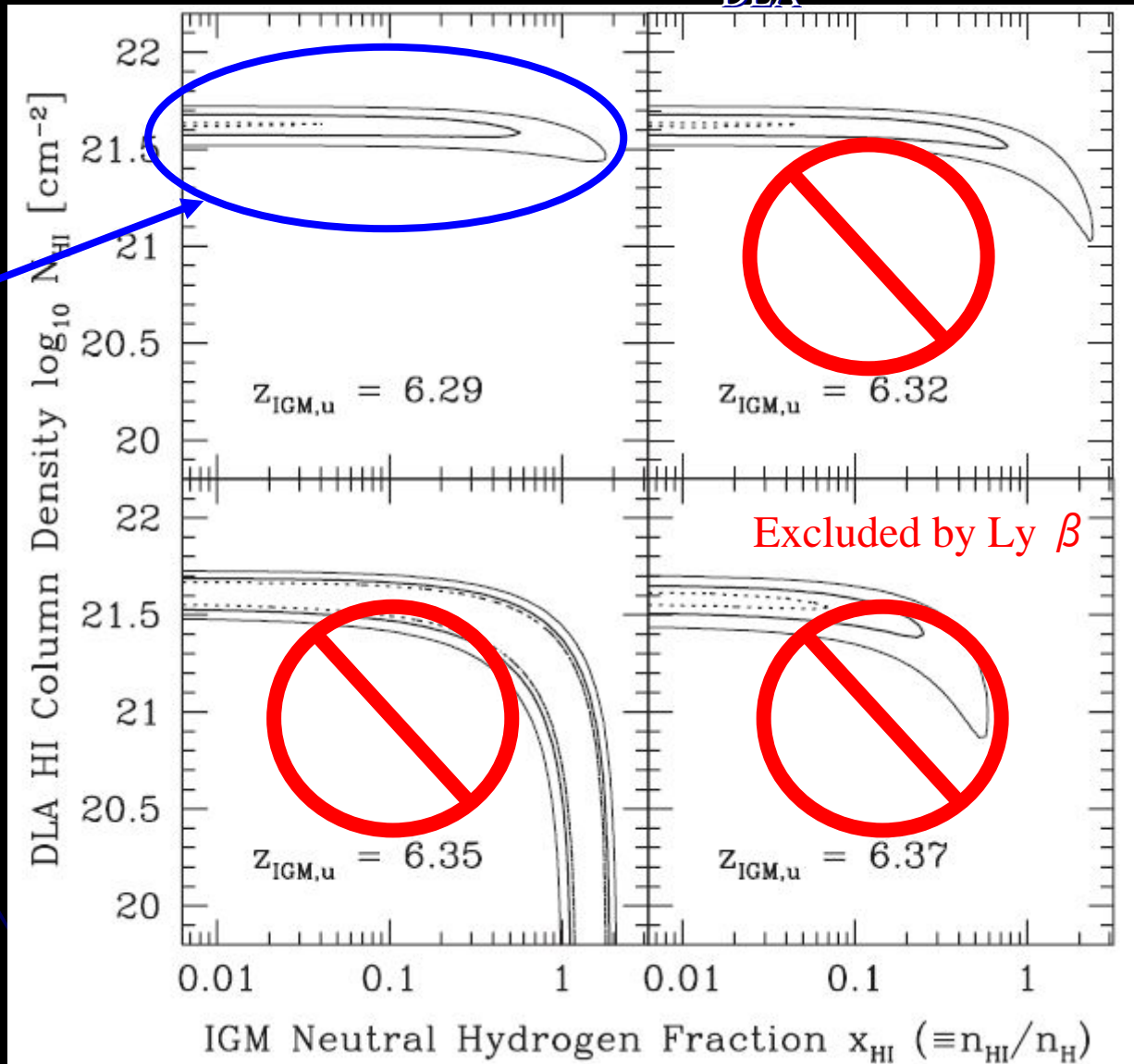


中性IGMは damping wing の支配的成分ではないが、
 $x_{\text{HI}} \sim 1$ ならその形に影響を与える

DLA-IGM Joint Fit

$$z_{\text{DLA}} = 6.295$$

Preference for smaller x_{HI}



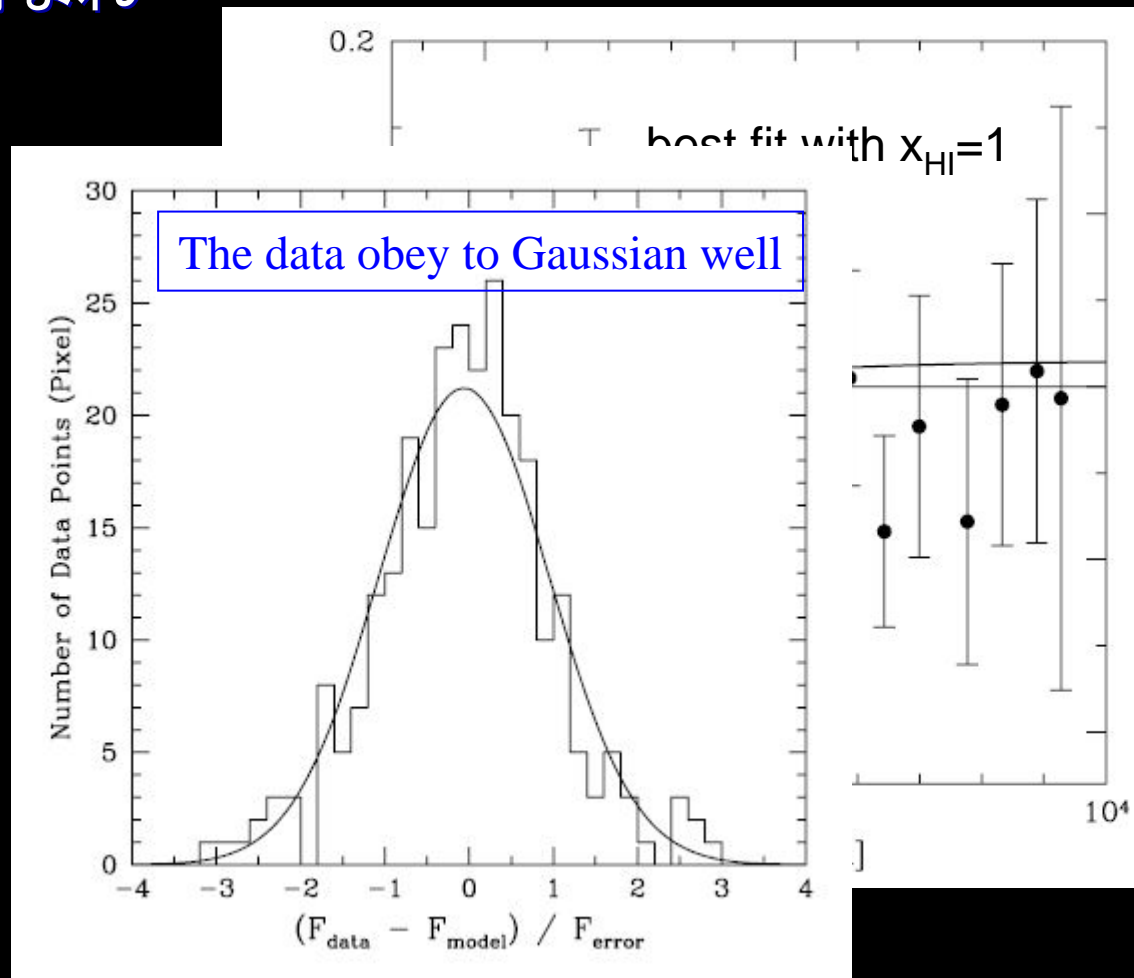
Smaller x_{HI} Favored

- N_{HI} をフリーにしたとき、好まれる x_{HI} は？

- $z_{\text{IGM,u}} = z_{\text{DLA}} = 6.295$
- **best fit $x_{\text{HI}} = 0.00$**
- **$x_{\text{HI}} < 0.17$ (68 % C.L.)**
0.60 (95% C.L.)

- Systematics?

Flux residual from the $x_{\text{HI}} = 0$ model



Uncertainty Check

- checks done for: **intrinsic spectral index, dust in host galaxy, redshift parameters, weak unidentified absorption lines, and time variability**

Table 1. Constraint on x_{HI} for various models.

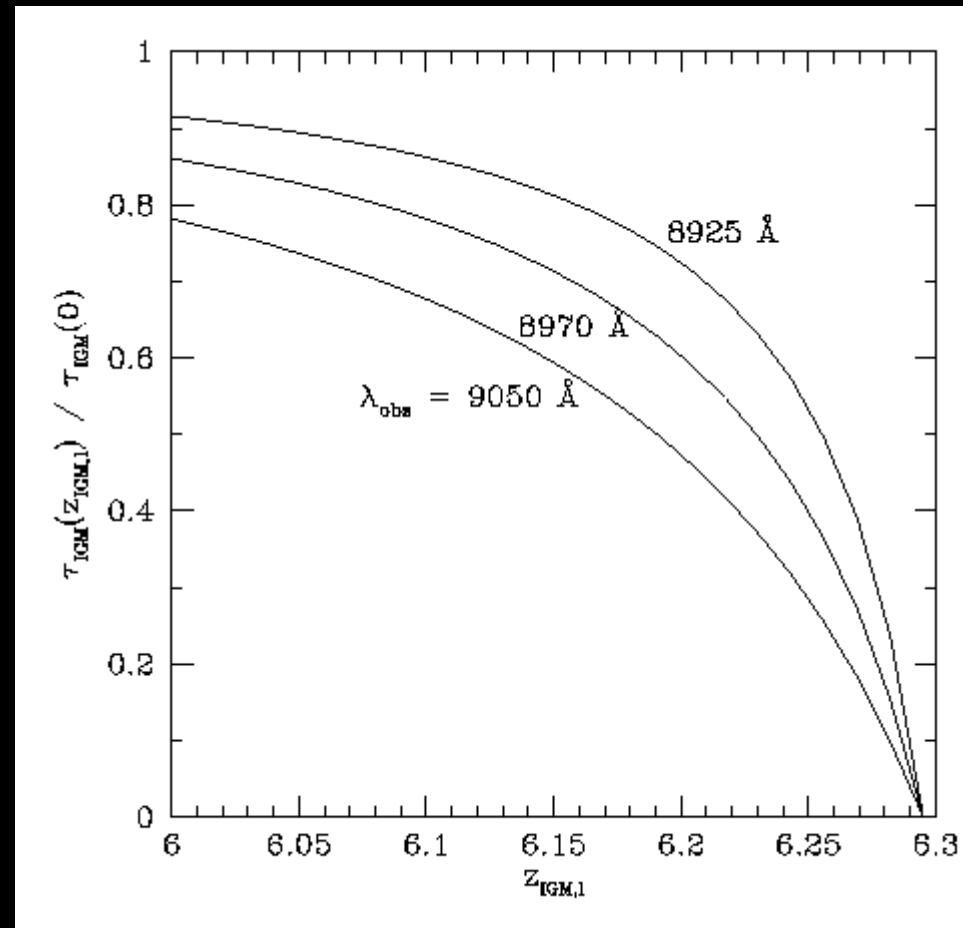
Models	$\chi^2_{\text{min}}^*$	$\chi^2(x_{\text{HI}} = 1)$	$\Delta\chi^2(x_{\text{HI}} = 1)$	Confidence level (%) [†]	Upper limits on x_{HI}^{\ddagger} (% confidence level)		
					68	95	99
Baseline [§]	277.29	284.12	6.84	99.1	0.17	0.60	0.98
$\beta_0 = -1/-1.5$	273.86/281.10	280.07/288.75	6.21/7.65	98.7/99.4	0.18/0.15	0.66/0.52	1.08/0.88
$A_V = 0.45/0.17^{\parallel}$	316.93/283.18	329.72/291.12	12.80/7.94	99.97/99.5	0.09/0.15	0.32/0.52	0.54/0.85
$z_{\text{IGM,u}} = 6.27/6.314$	277.29/277.29	283.55/283.21	6.27/5.93	98.8/98.5	0.19/0.19	0.63/0.68	1.06/1.12
$z_{\text{IGM,l}} = 5.5/6.2$	277.29/277.29	286.70/280.07	9.41/2.78	99.8/90.5	0.13/0.38	0.45/1.36	0.74/2.22
$z_{\text{DLA}} = 6.29/6.314^{\#}$	281.47/266.41	288.49/271.25	7.03/4.83	99.2/97.2	0.16/0.27	0.57/0.84	0.96/1.27
Lines included	796.03	802.53	6.50	98.9	0.17	0.63	1.02
Variability check	283.98	289.54	5.56	98.2	0.20	0.71	1.18

* In all models...
 † Exclusion...
 ‡ See section...
 § The baseline... models when some parameter...
 ‖ The spectral index is changed into $\beta_0 = -0.75$ to keep the expected NIK colors consistent with the observed ones for the MW/SMC extinction curves, respectively.
 # The IGM redshift parameter $z_{\text{IGM,u}}$ is kept to be the same as z_{DLA} .

許されるモデルパラメータ範囲内で、 x_{HI} への上限值はほとんど変わらない

redshift range of IGM contributing the damping wing at $z \sim 6.3$

- our constraint, $x_{\text{HI}} < 0.6$ applies for $6 < z_{\text{IGM}} < 6.3$
 - $z_{\text{IGM,l}}$ set to be 6
- optical depth の半分以上は $z > 6.2$ の水素による

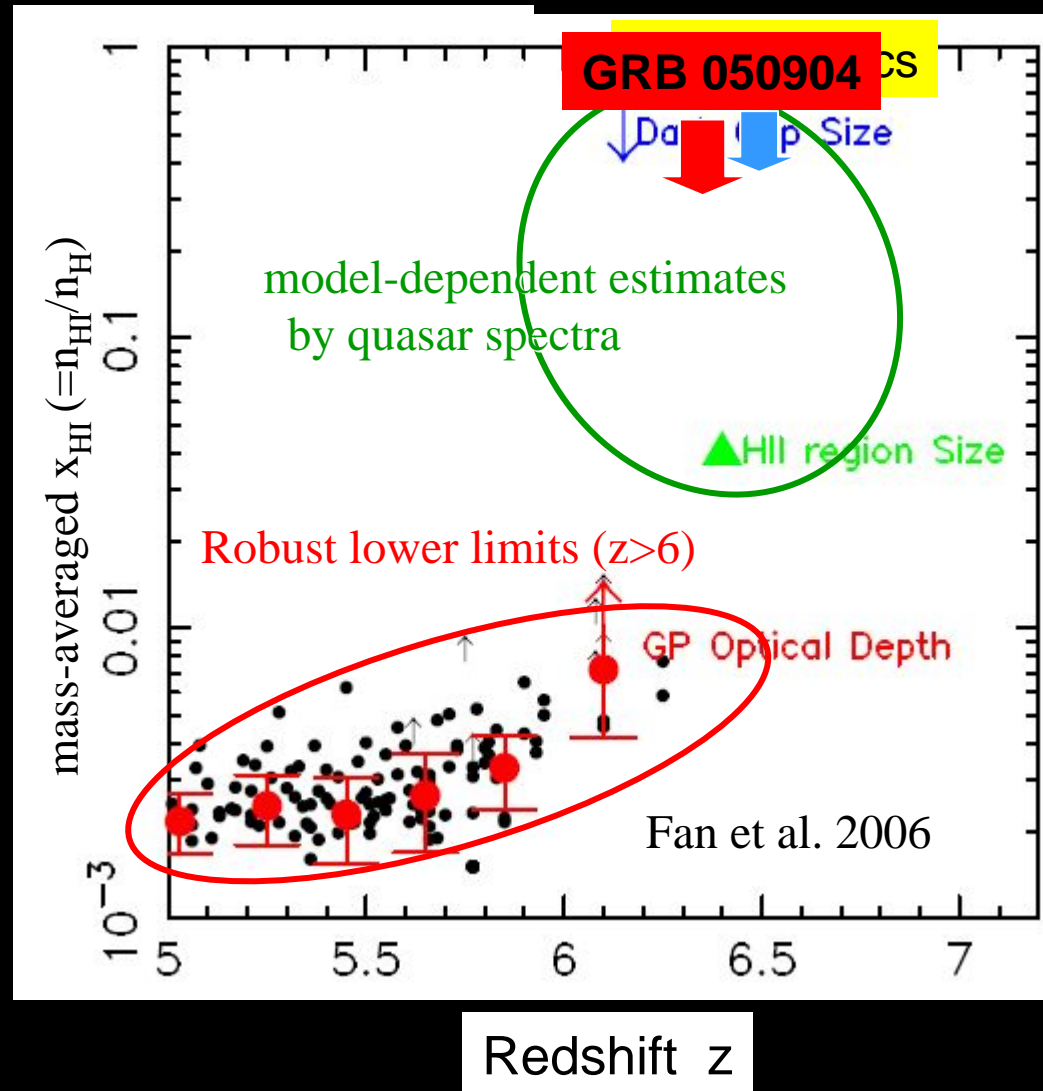


$$(z_{\text{IGM,u}} = 6.3)$$

Comparison with other constraints

Malhotra & Rhoads '05
Stern et al. '05
Haiman & Cen '05
see also Kashikawa-san's talk

- $x_{\text{HI}} < 0.6$ at $z=6.3$ という制限は QSO (HII region size etc.) や LAE statistics から得られたものと矛盾しない



GRBからの制限のユニークな点

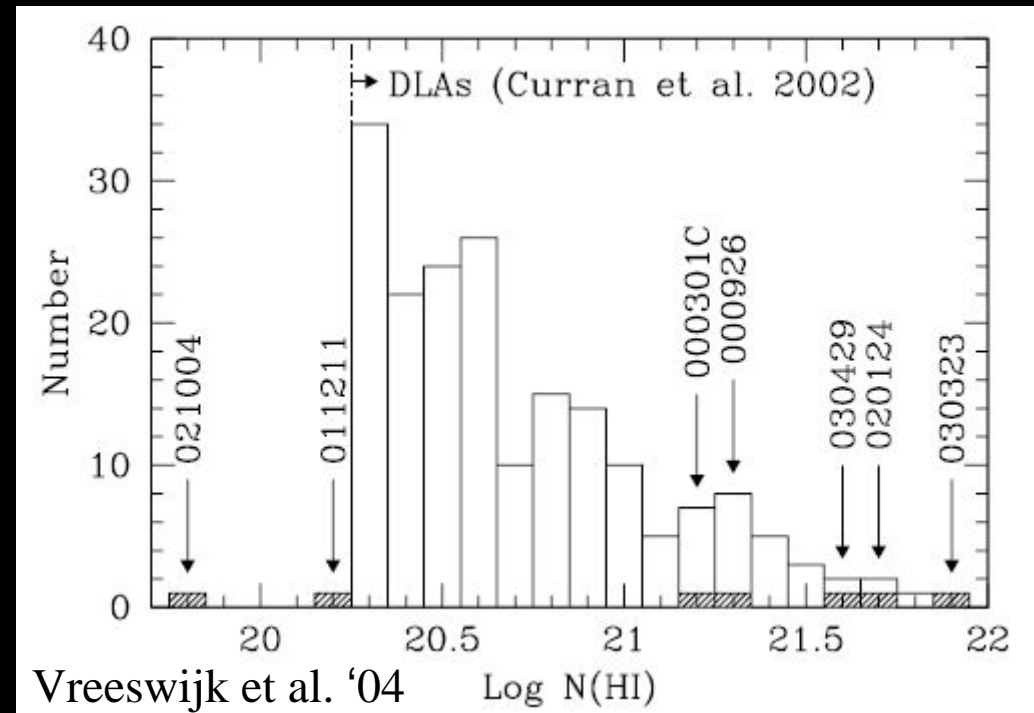
- **the first quantitative upper bound on x_{HI} at $z > 6$**
 - 水素の吸収を直接的に見ている、「直接的方法」
 - モデル不定性がほとんどない
- damping wing は optical depth $\lesssim 1$
 - **$z \sim 6$ から $z = 6.3$ の視線上の全ての水素に対して感度**
 - **IGM clumpiness に影響されない**

$$\text{sight - line averaged } x_{\text{HI}} : \quad \langle x_{\text{HI}} \rangle = \frac{\int n_{\text{HI}} dl}{\int n_{\text{H}} dl}$$

今後の展望

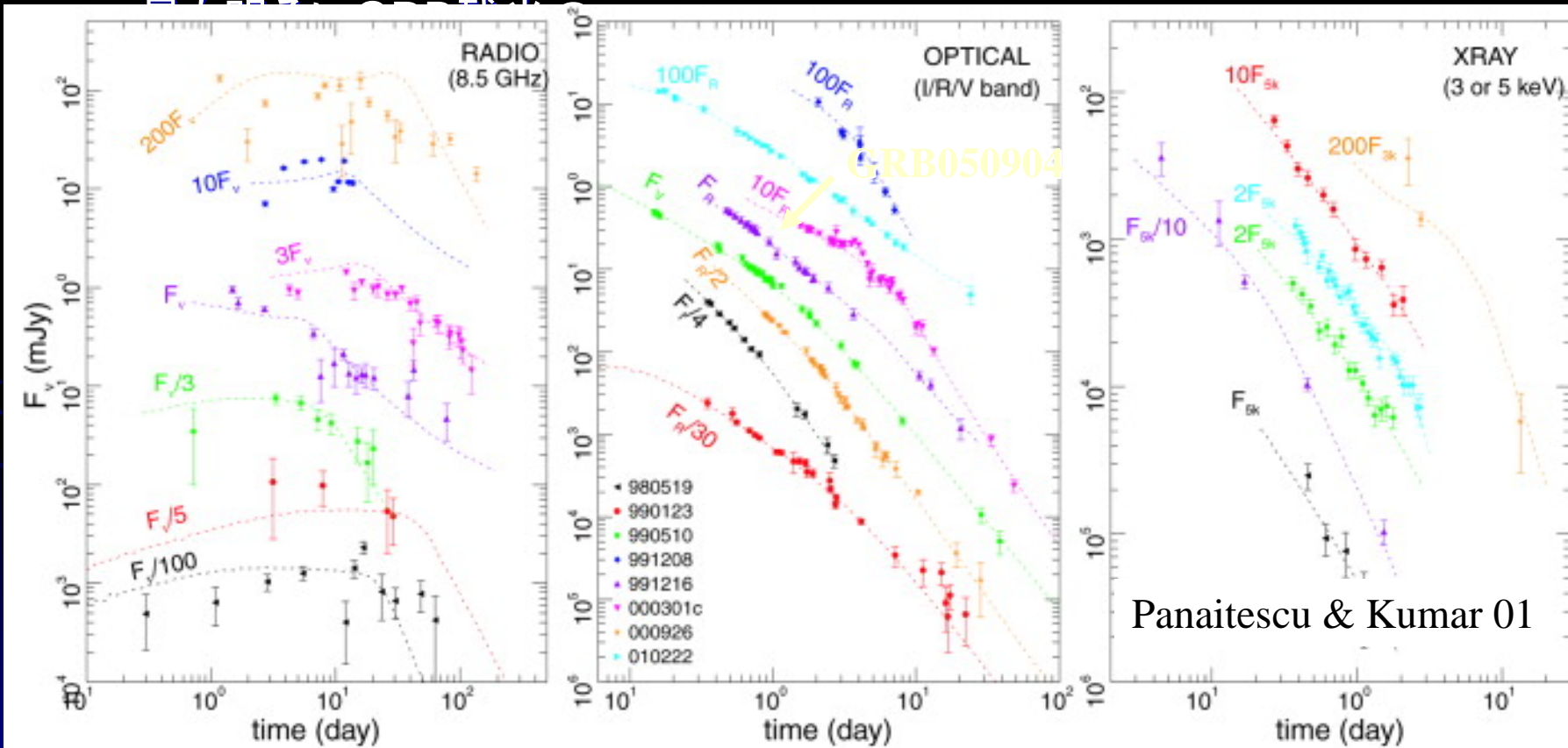
- low N_{HI} GRBs?

- only weak constraint on x_{HI} when $\log N_{\text{HI}} > 21.5$
- しかし、 $\log N_{\text{HI}} < \sim 20$ のGRBも存在する
- promising chance for a better constraint on x_{HI} by IGM damping wing

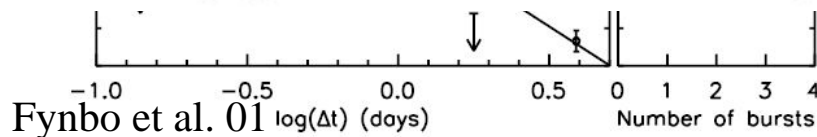


今後の展望(2)

- GRB 050904のような現象の頻度? $< \sim 1 \text{ yr}^{-1}$?
 - GRB 050904 は3.4 日後の分光. 0.5 日後なら10倍明るかった
 - If GRB 050904 occurred at $z=1$, $R=17.9$, $F \sim 0.2 \text{ mJy}$ at 1 day \rightarrow



Panaitescu & Kumar 01



Fynbo et al. 01 $\log(\Delta t)$ (days)

Number of bursts

Conclusions

- GRB によって初めて再電離への制限が得られた
 - GRB 宇宙論の新時代の幕開け
- $z \sim 6.3$ で、宇宙はほぼ電離されていることが判明
 - $x_{\text{HI}} < 0.17$ (68% C.L.) and < 0.60 (95% C.L.)
for $\sim 6 < z < 6.3$
 - The first quantitative upper limit on x_{HI} at $z > 6$ by a “direct” method
 - for a more “normal” region than quasars
 - モデル不定性やIGM clumpinessへの依存性が少ない

Identified Absorption Lines

Kawai et al. 2006

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9,499.1 ± 0.9	10.3 ± 1.9	15.85 ^{+0.39} _{-0.28}	O I, λ = 1,302.2	6.295 ± 0.001
9,737.2 ± 1.1	12.3 ± 2.4	15.41 ^{+0.30} _{-0.26}	C II, λ = 1,334.5	6.296 ± 0.001

The wavelengths and equivalent widths were derived by fitting a single gaussian. The column densities of lines were estimated by the standard curve of growth analysis²². The equivalent widths in the table are observed ones, that is, not converted to the rest-frame. The quoted uncertainties are 1σ statistical errors. Most of the absorption lines are consistent with being at a single redshift of $z = 6.295 \pm 0.002$ within the statistical uncertainties. The absorption lines at $\lambda = 9,041.0 \text{ \AA}$ and $9,055.9 \text{ \AA}$ could be identified as N V $\lambda = 1,238.8 \text{ \AA}$, $\lambda = 1,242.8 \text{ \AA}$, if they are at a redshift similar to that of the other absorption lines. However, the derived redshifts of these two lines are significantly inconsistent with each other. Another possible identification is C IV $\lambda = 1,548.2 \text{ \AA}$, $\lambda = 1,550.8 \text{ \AA}$ in an intervening system at $z = 4.840$, which we think is more likely.

