Probing Reionization by Gamma-Ray Bursts (+Lyα Emitters)

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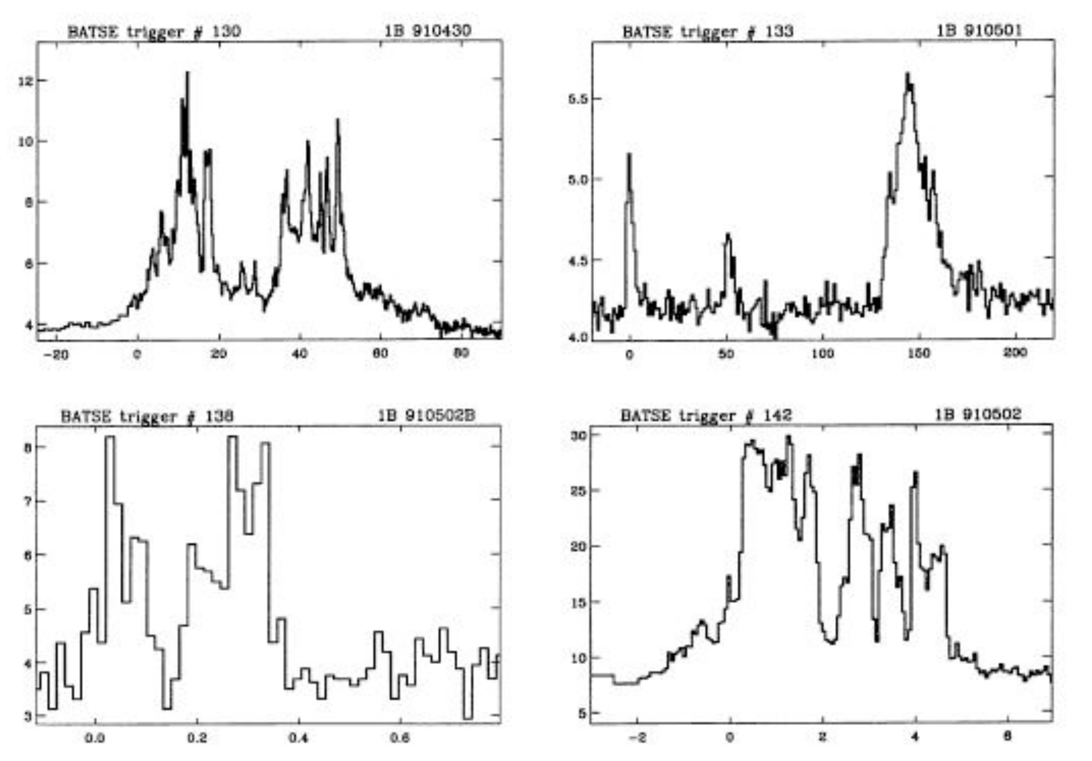
Cosmological Reionization
Feb 16-20 2010, Harris-Chandra Research Inst., Allahabad, India

Talk Outline

- GRBs as a probe of cosmic reionization
  - brief introduction for GRBs
  - present status
  - future prospects
- Theoretical modeling of Lyman α emitters and reionization
  - Kobayashi, TT, & Natashima '10

GRBs: brief introduction



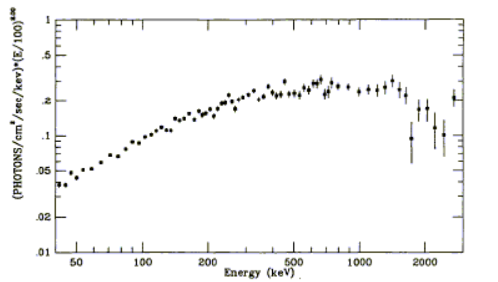


FIG. 11.—Photon spectrum for burst 1B 910503. For additional details, see the caption to Fig. 9.

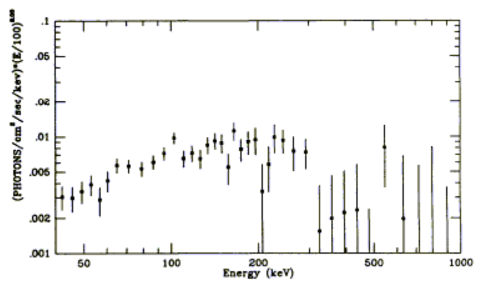
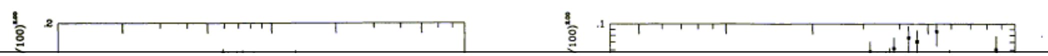
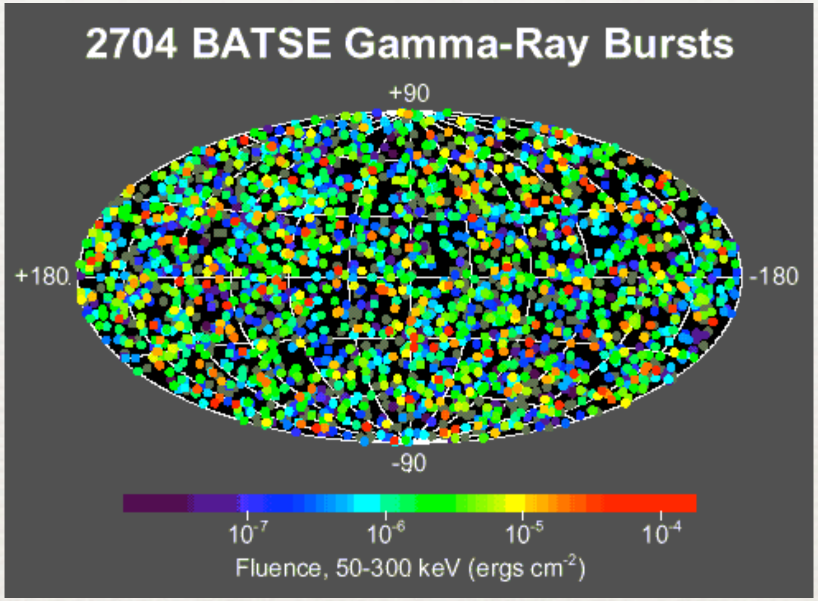


FIG. 12.—Photon spectrum for burst 1B 910507. For additional details, see the caption to Fig. 9.





- event rate ~ 1 / day all sky
- duration ~10 msec - 100 sec
- non-thermal spectra, νF_ν peak around MeV

GRBs: two populations

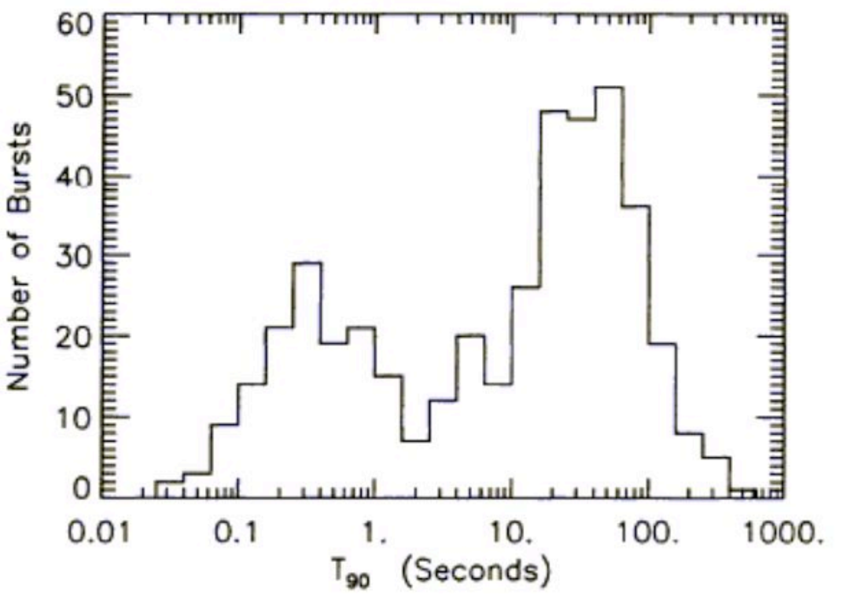


FIG. 11*b*

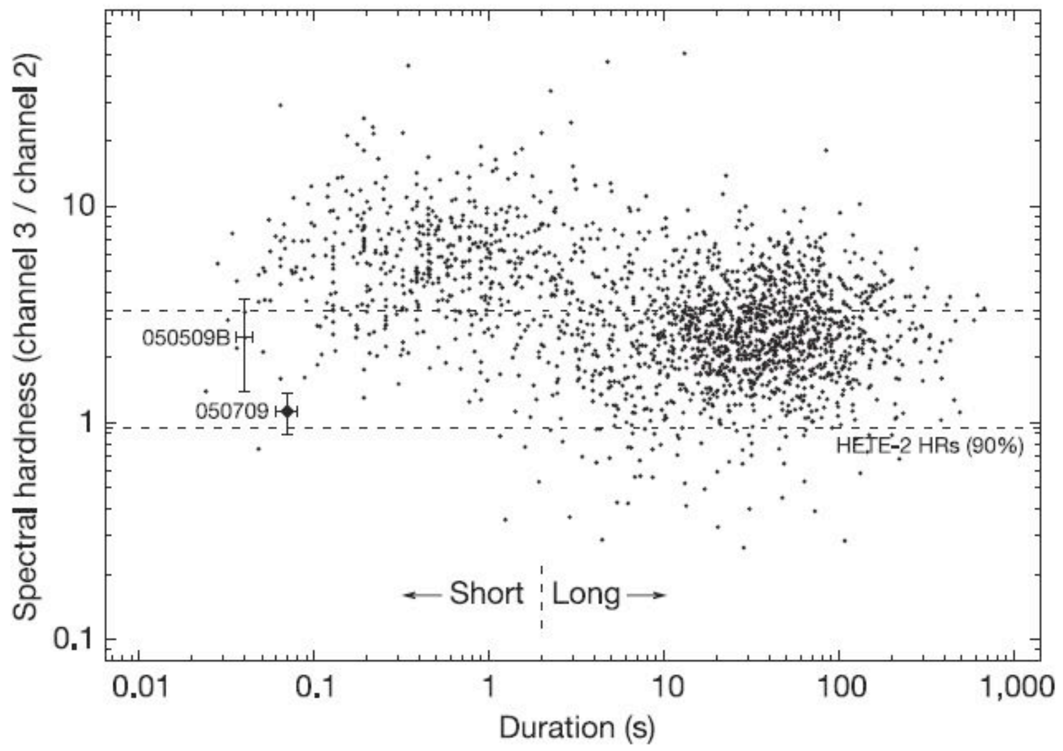
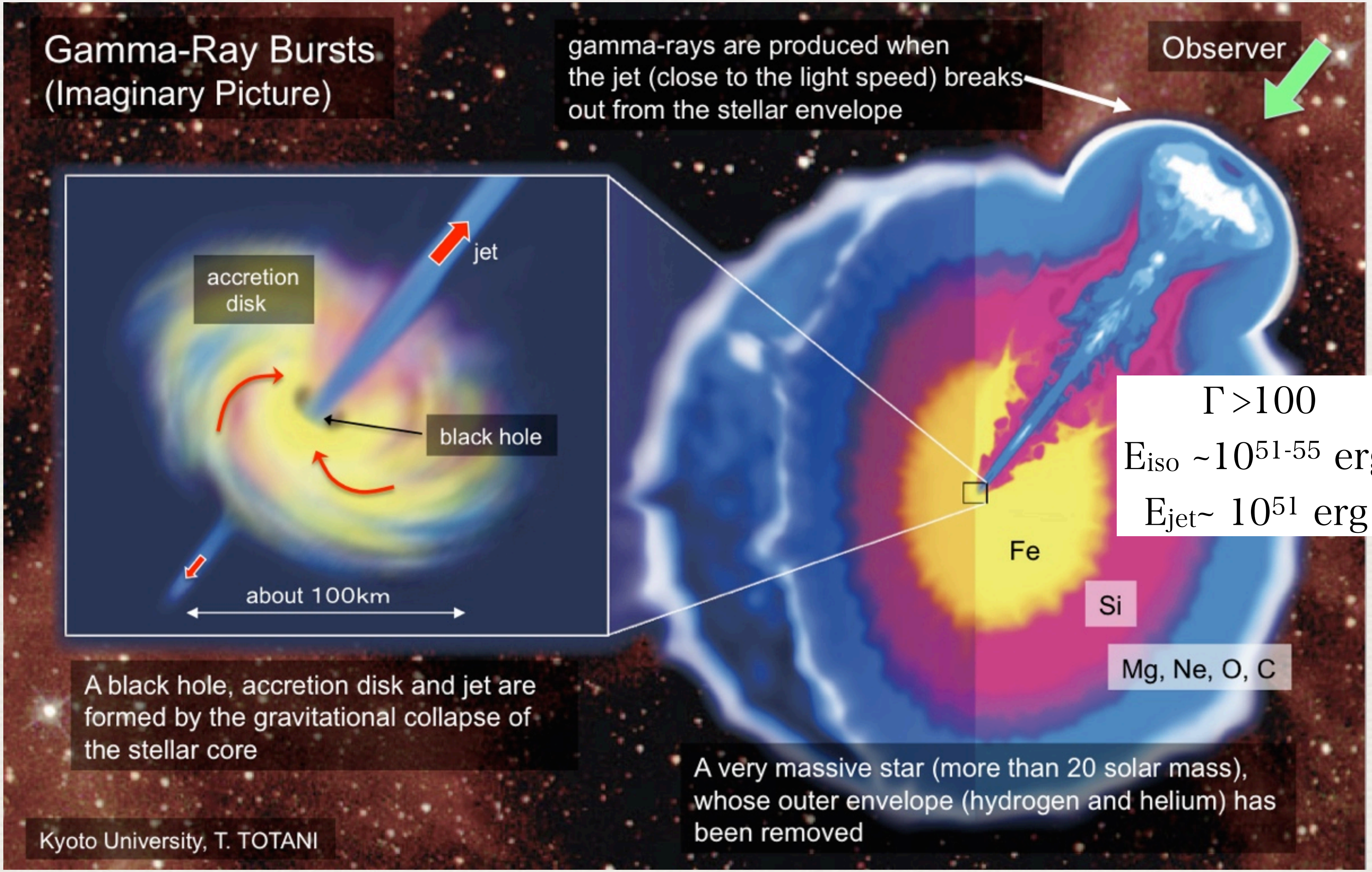


Figure 1 | The classic BATSE duration–spectral hardness diagram[1].

- long-soft GRBs:
  - only in star forming regions: massive star origin
  - luminous, high-z probe
- short-hard GRBs:
  - occur also in elliptical galaxies: NS-NS or NS-BH mergers?
  - relatively underluminous, most are $z < 2$

Long-Soft GRBs



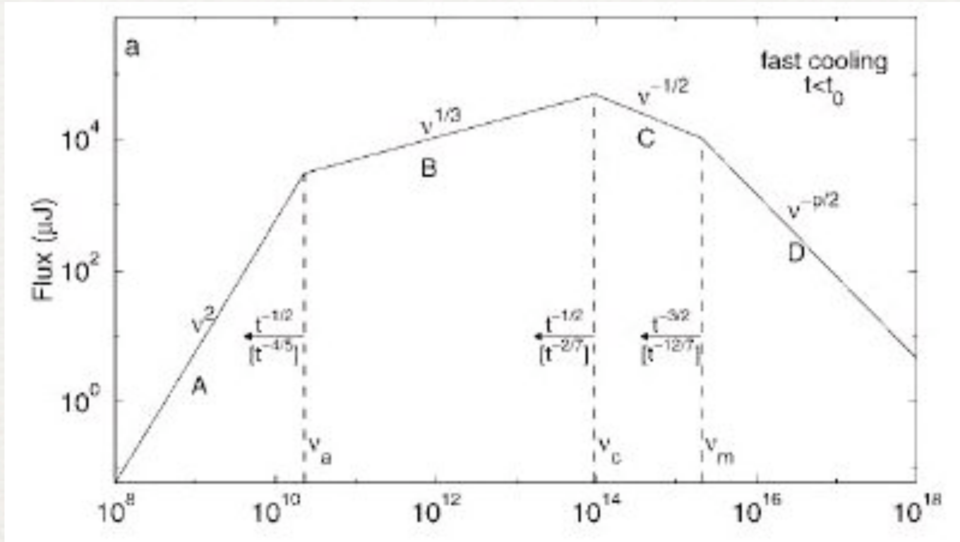
$\Gamma > 100$

$E_{iso} \sim 10^{51\text{-}55}$ erg

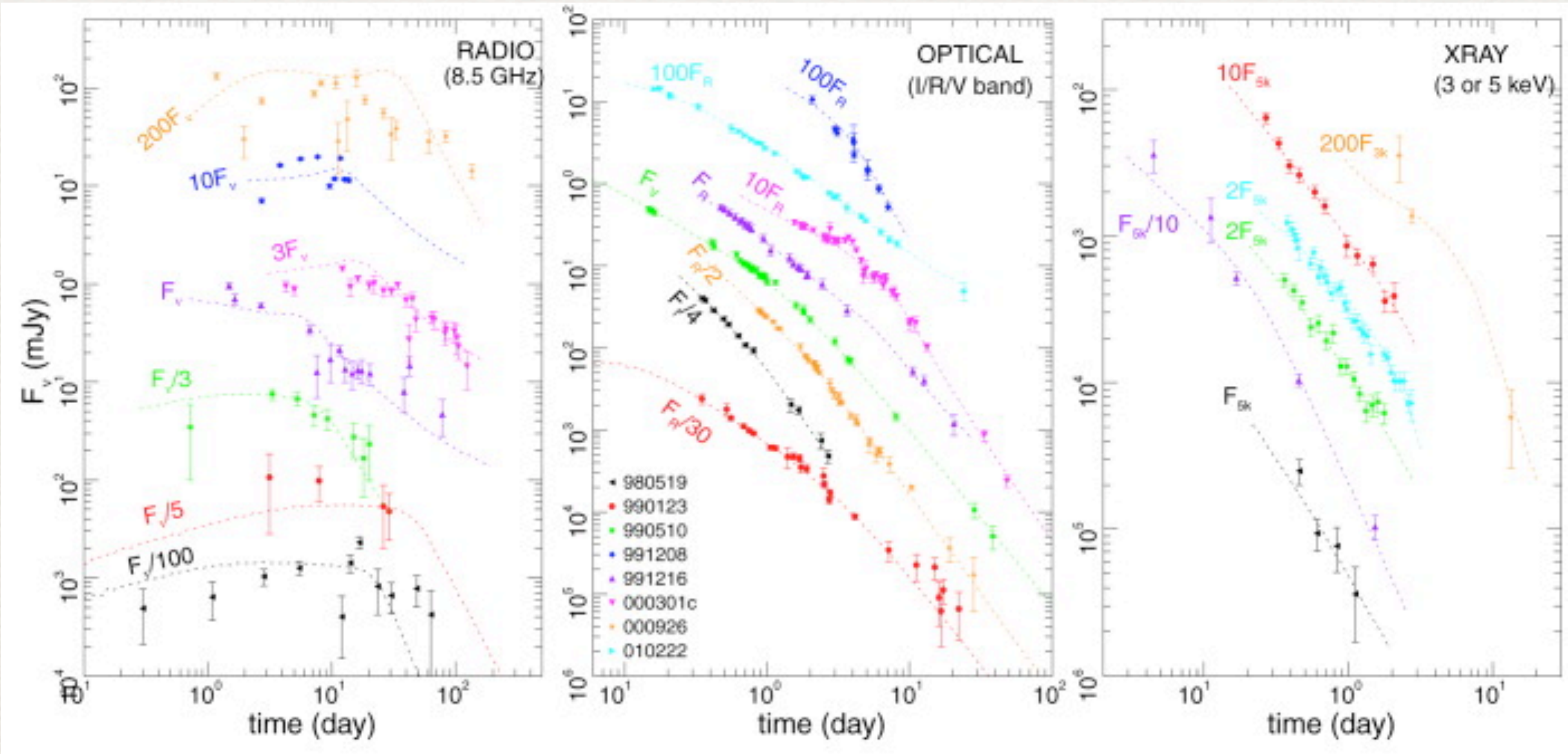
$E_{jet} \sim 10^{51}$ erg

GRB Afterglows

Sari+'98

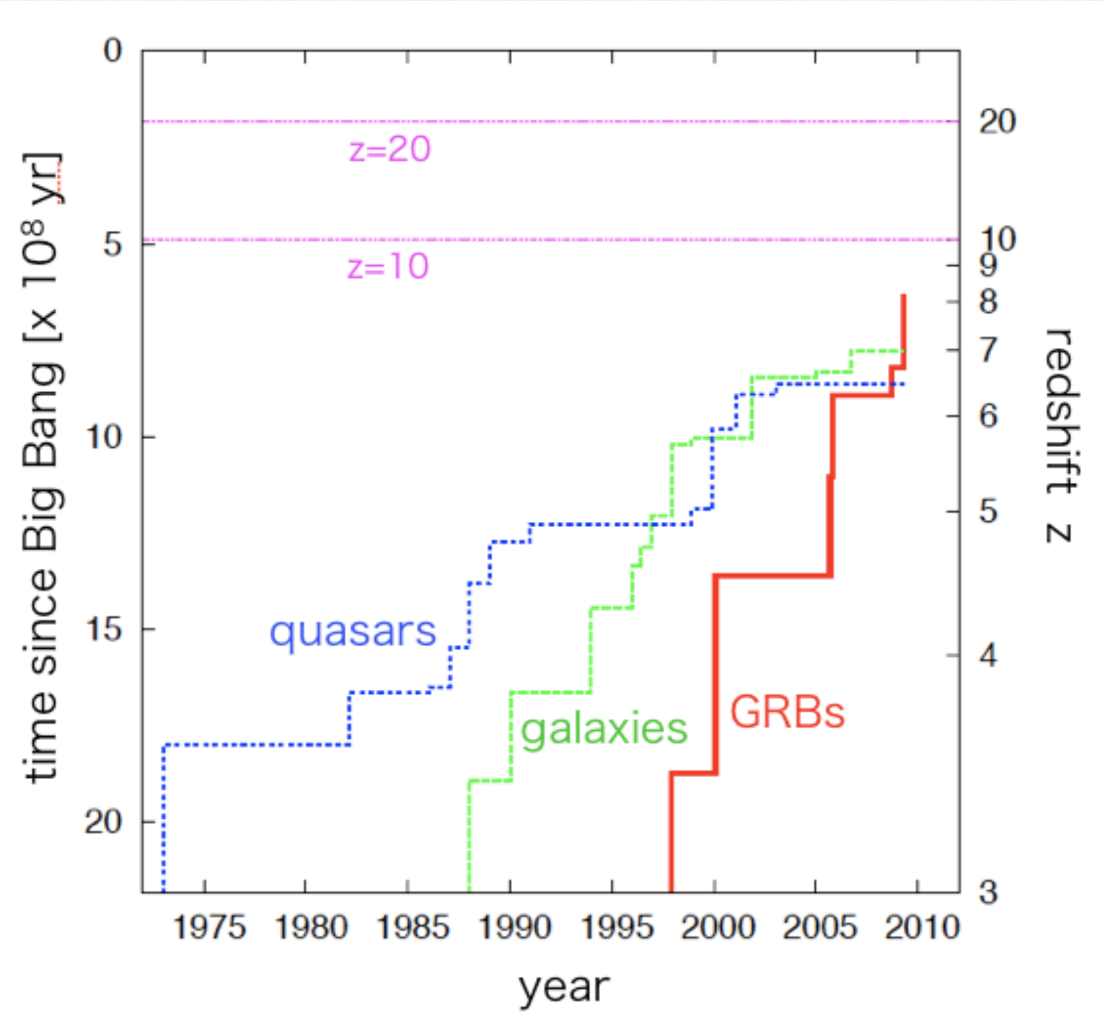


Panaitescu+Kumar'01



GRBs: the high-z probe

- Cosmic SFR evolution unbiased against host galaxy luminosity
- high-redshift host galaxies and IGM
- Reionization



data by Tanvir+Jacobsson '07;
updated by Yamazaki

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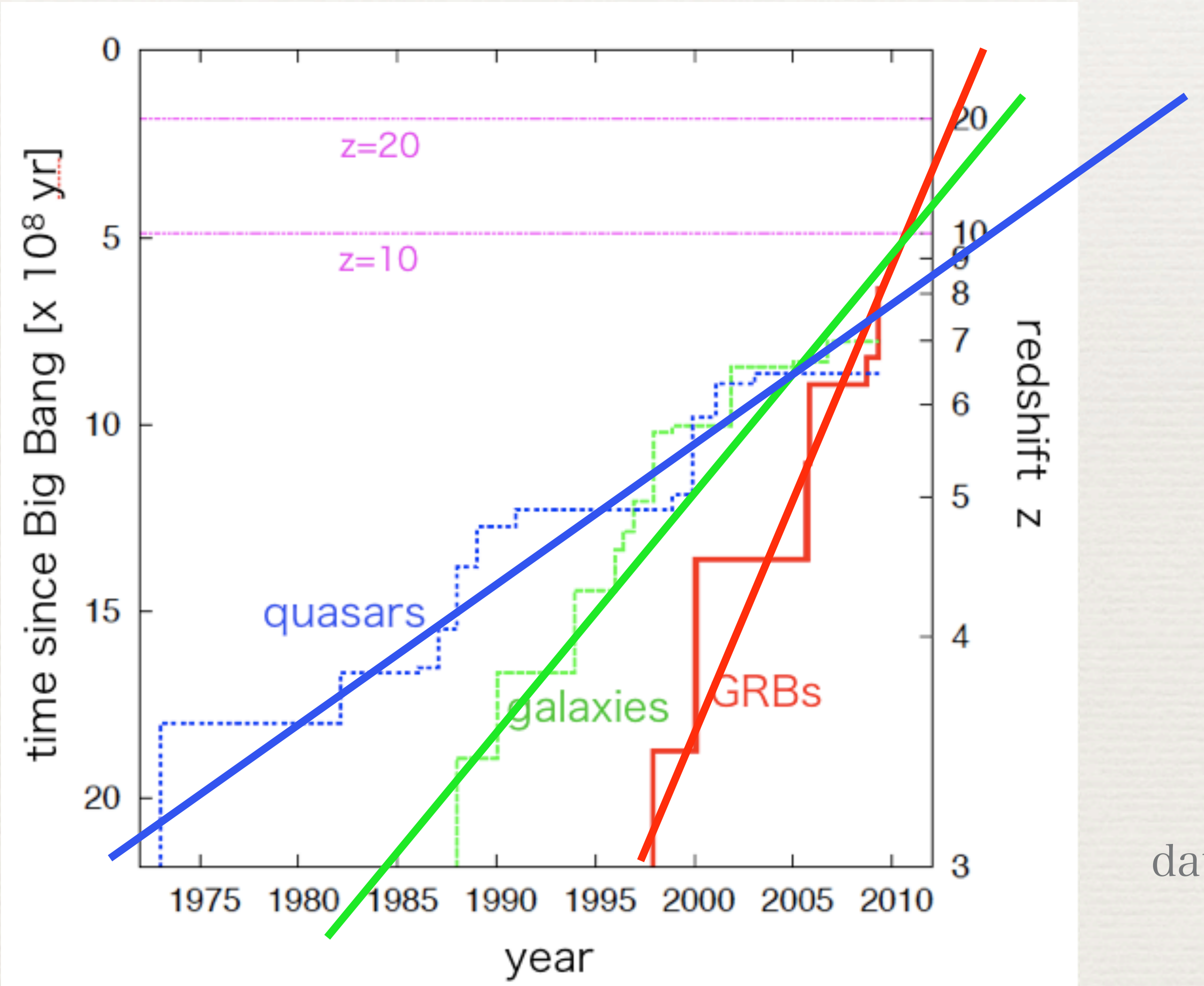

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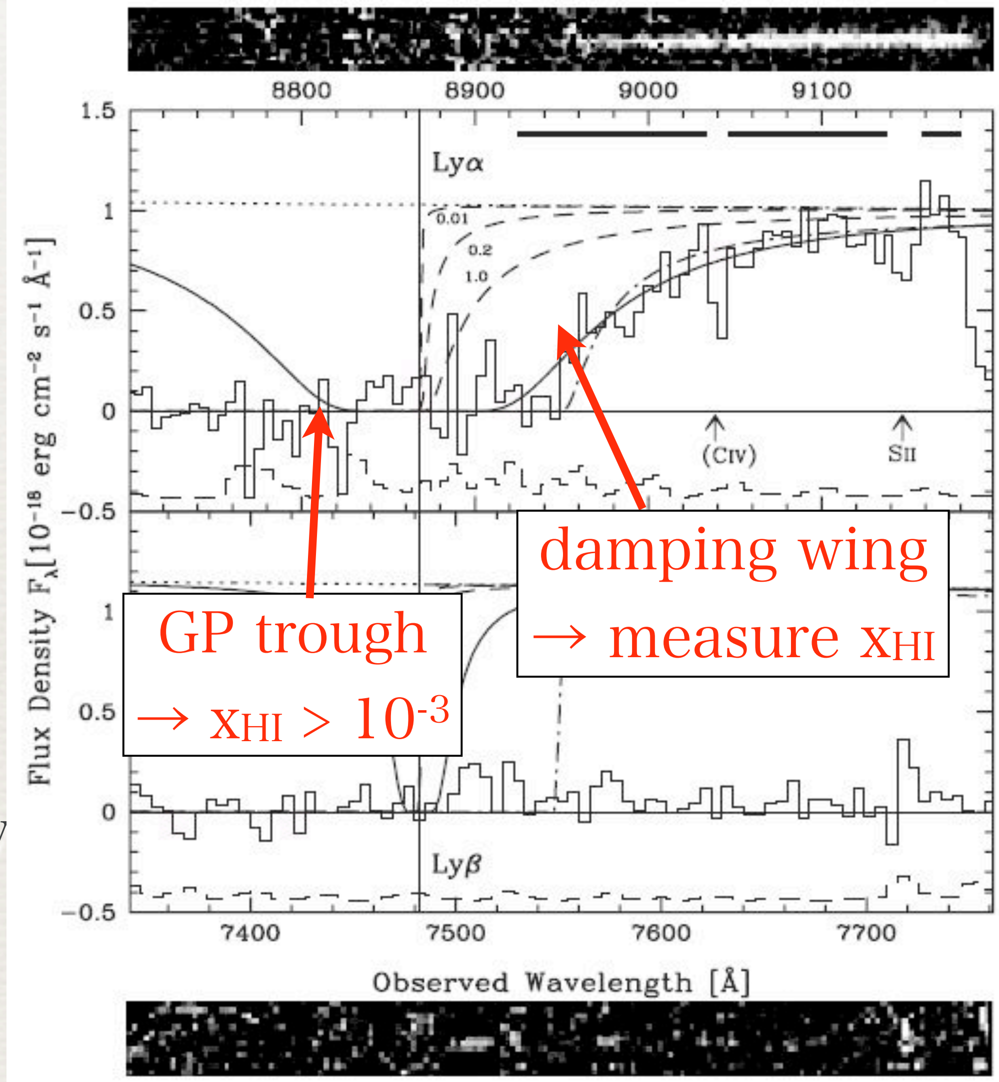
GRB as a Probe of Reionization

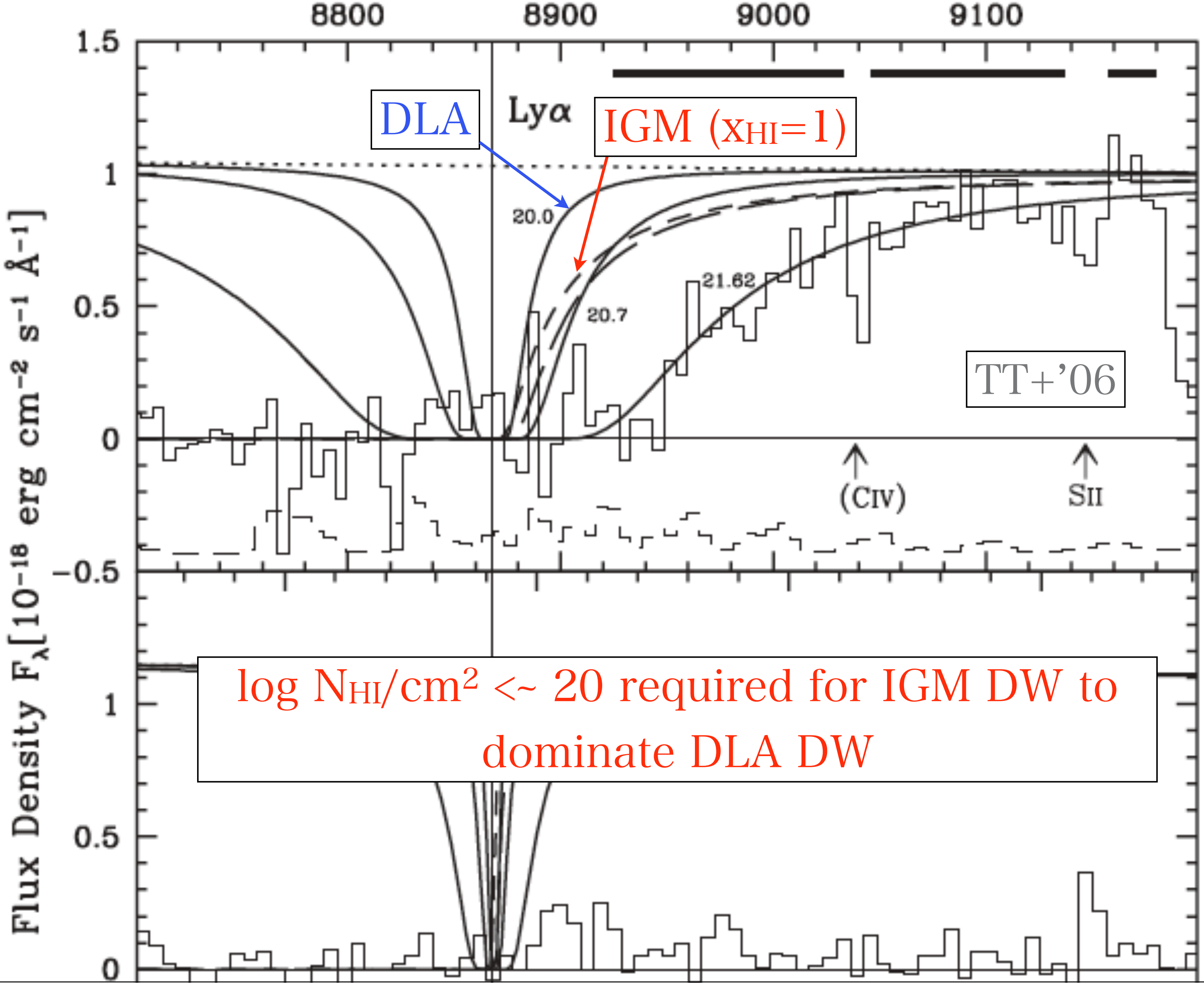
- GRB Strengths:
  - GRBs detectable at z>>6
  - probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - simple power-law spectrum
    - damping wing analysis to precisely measure x_{HI}

$$x_{HI} = n_{HI}/n_H$$



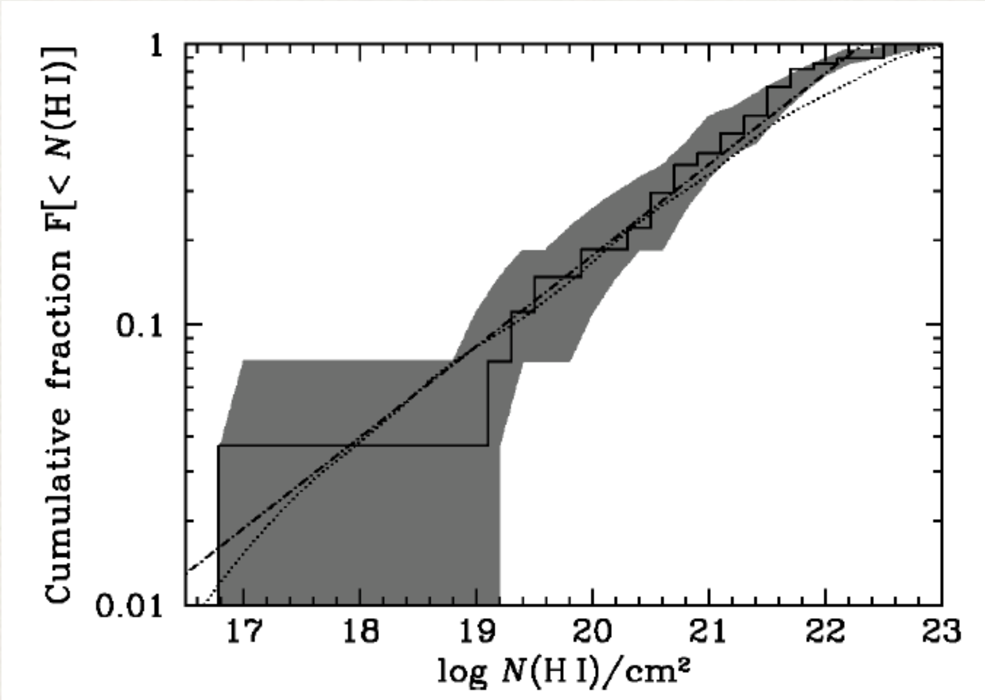
GRB 050904@z=6.3, TT+ '06

How small host-N_{HI} do we need?

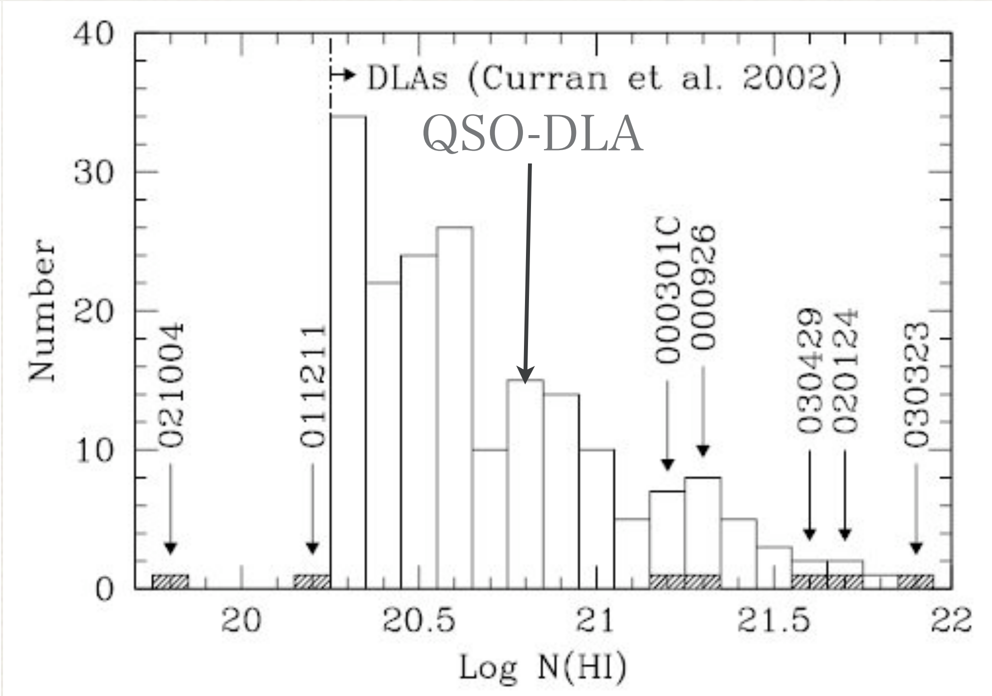


N_{HI} distribution of GRB hosts

- ~20% GRBs have log $N_{HI}/cm^{-2} < 20$

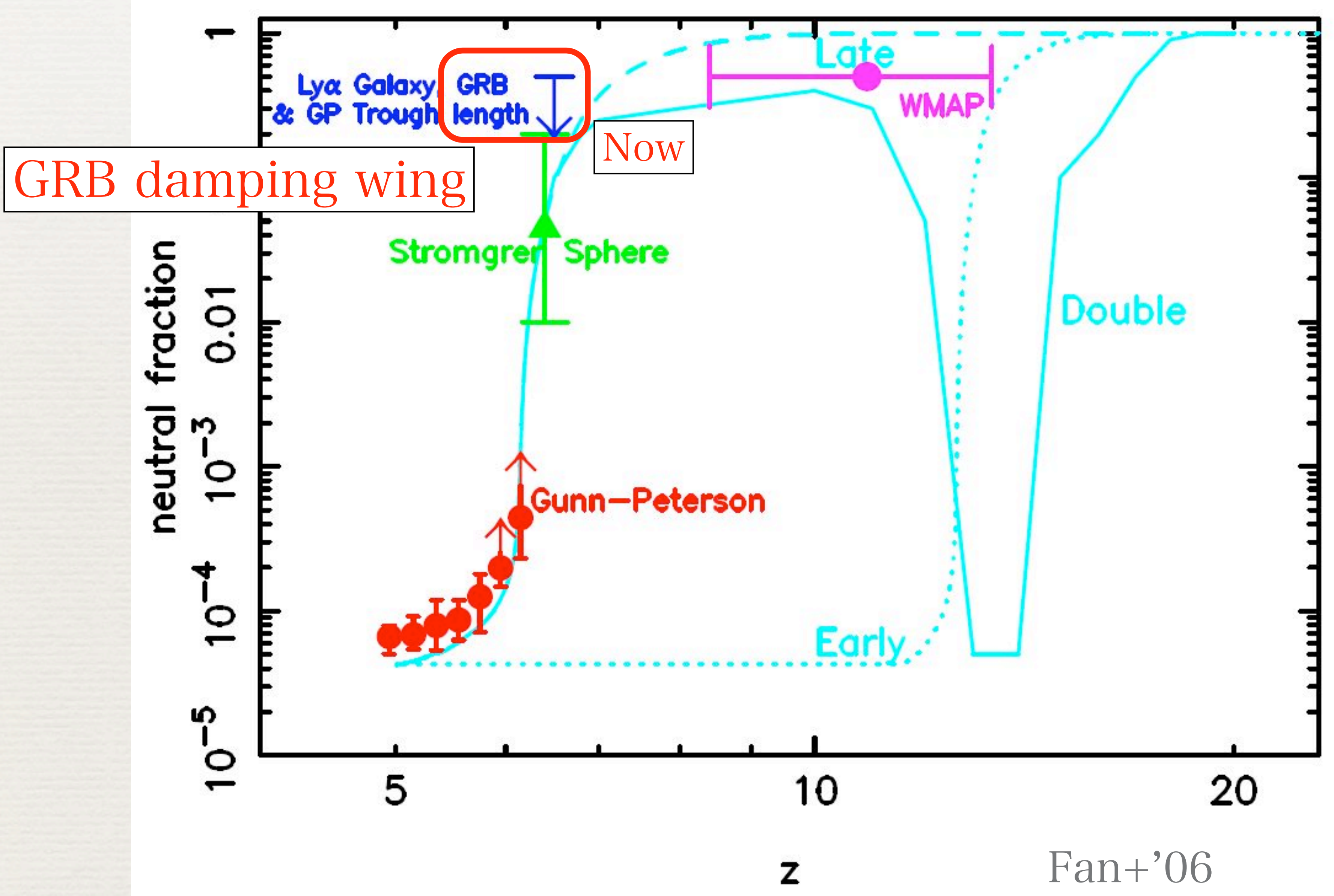


Chen+'07



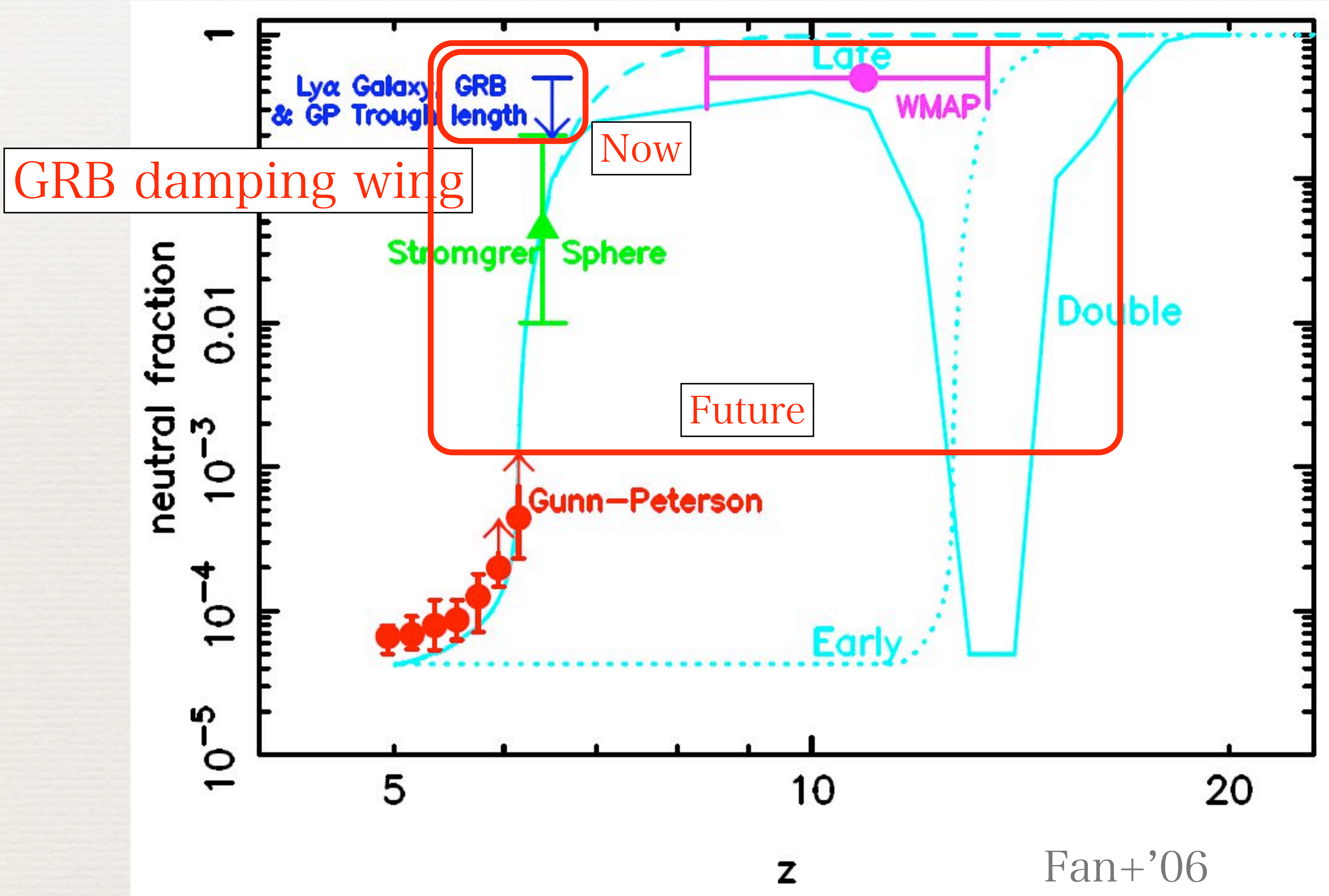
Vreeswijk+'04

GRB and reionization

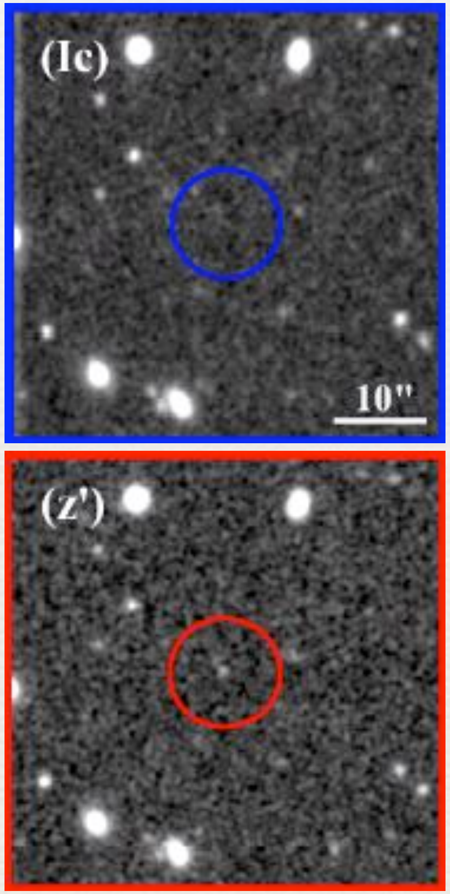


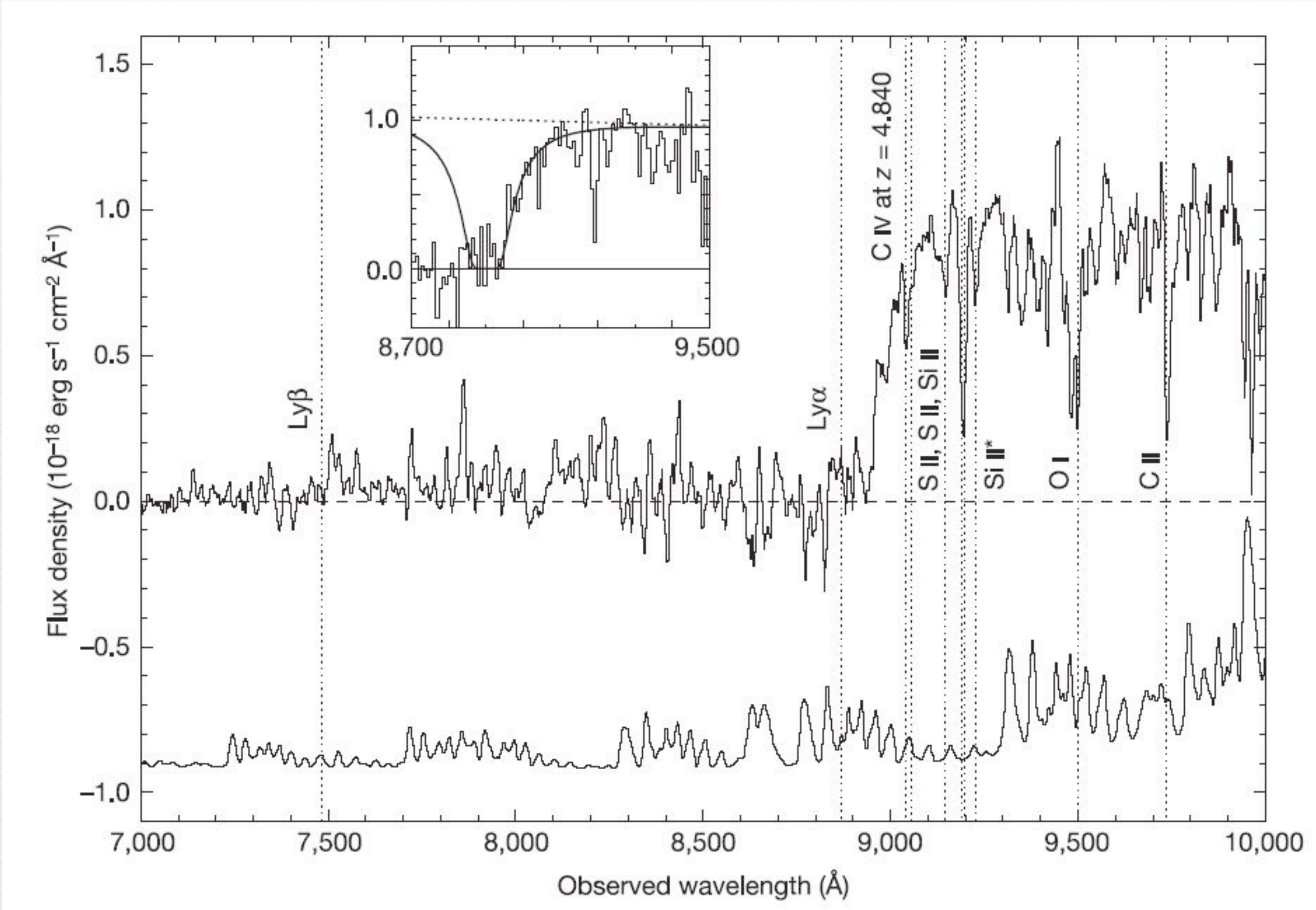
Fan+'06

GRB and reionization



GRB 050904: the first GRB in EoR





- z = 6.295 from metal lines and Ly break
  - Kawai+'06

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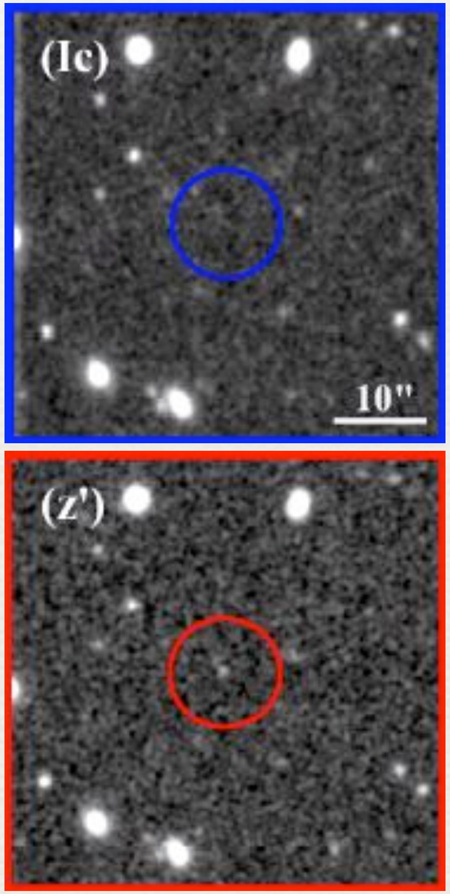
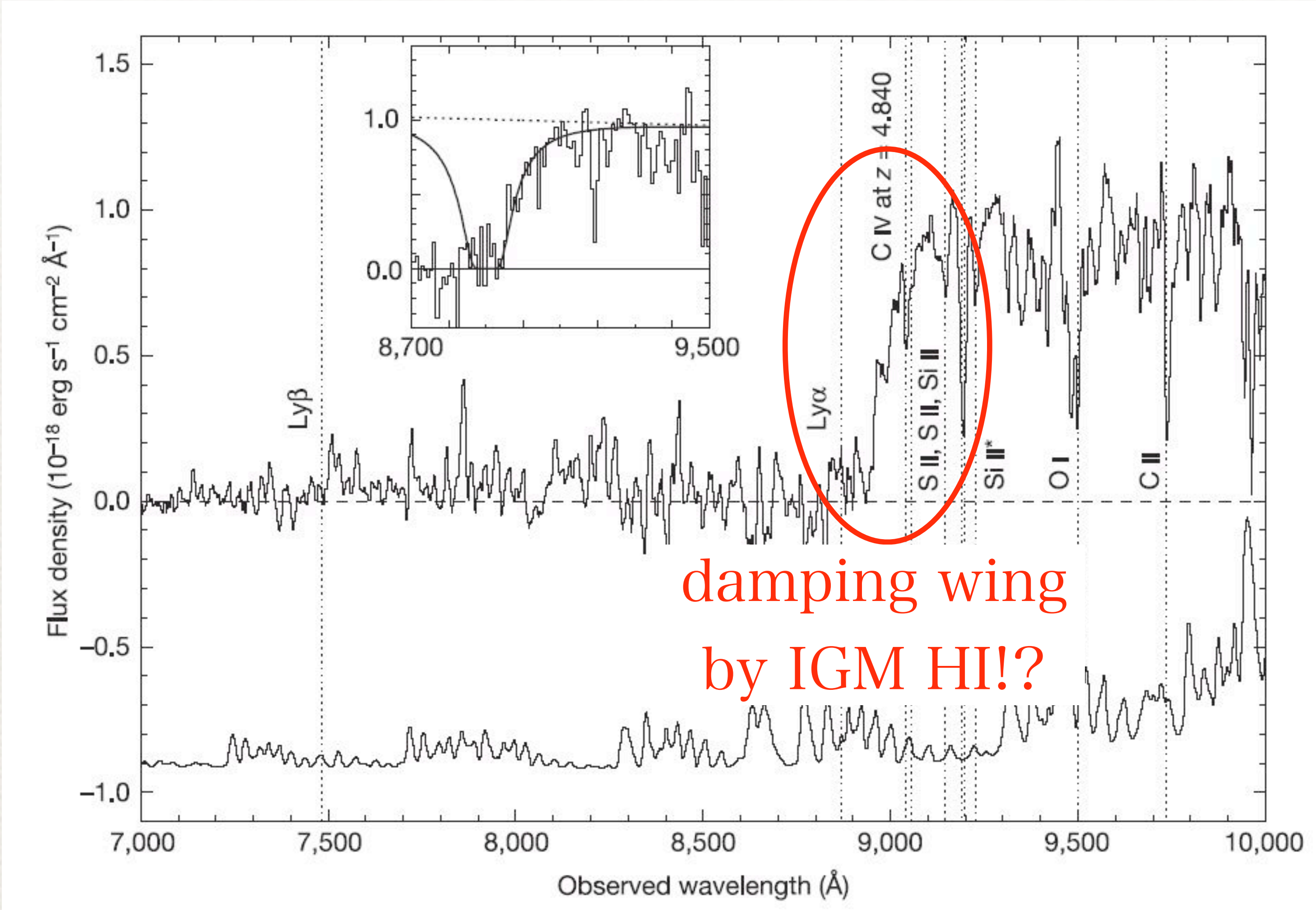
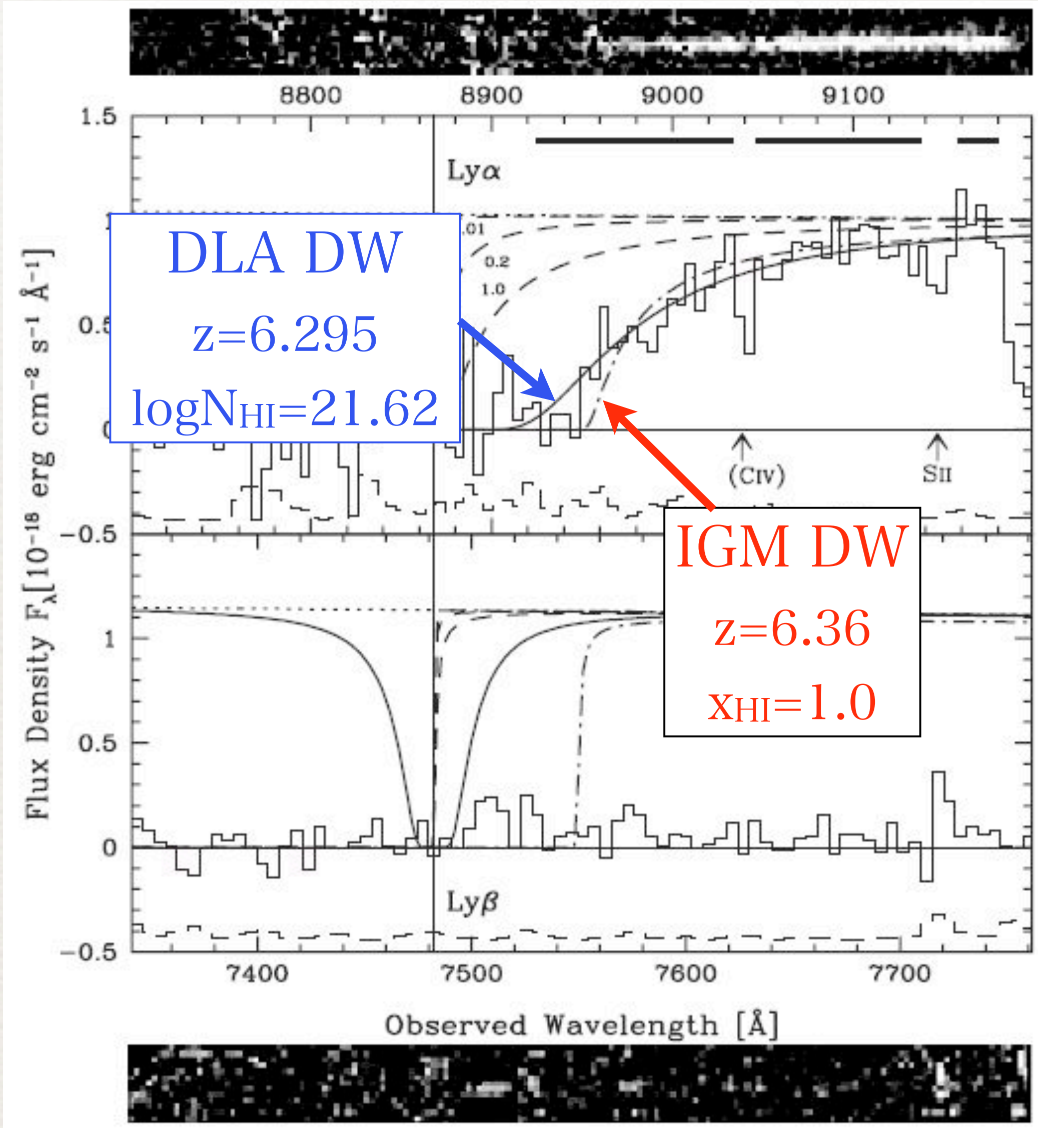




- z = 6.295 from metal lines and Ly break
  - Kawai+'06

A Difficulty to Study Reionization by GRBs

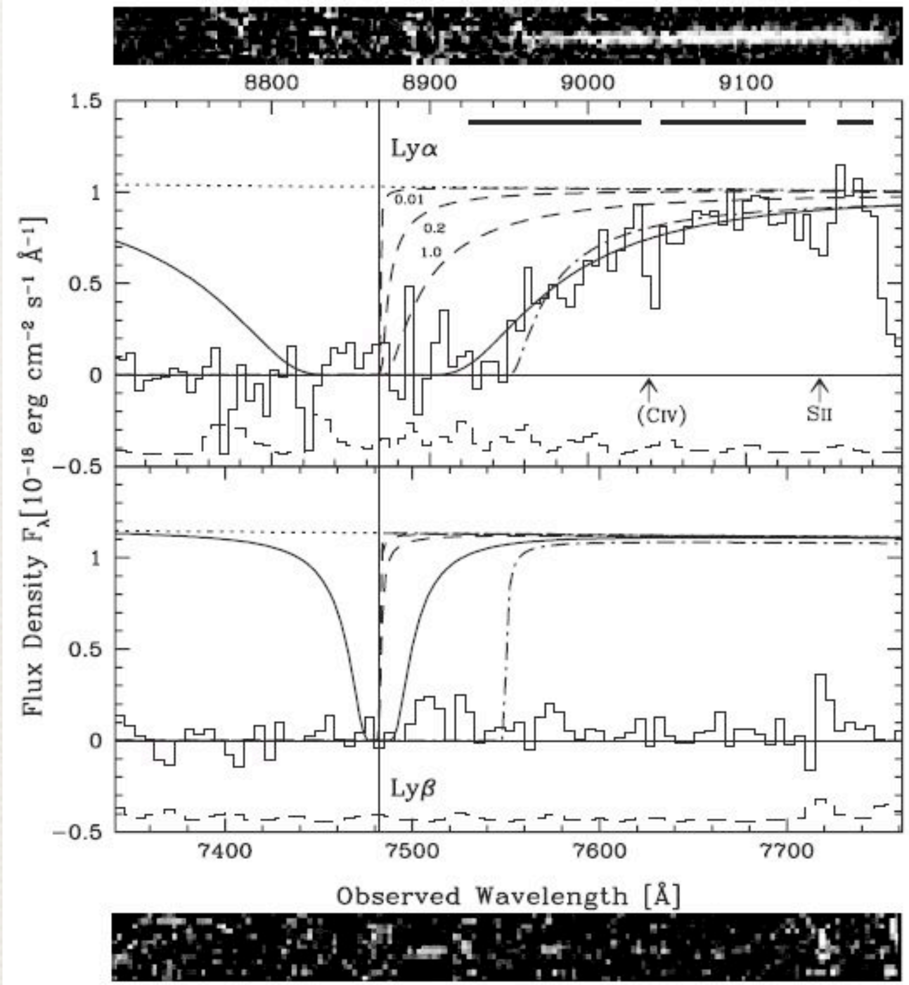
- Degeneracy between:
  - Damped Ly α (DLA) of host galaxies with log N_{HI}/cm^2 ~ 21.5
  - IGM damping wing by x_{HI}~1 at slightly higher redshift



TT+ '06

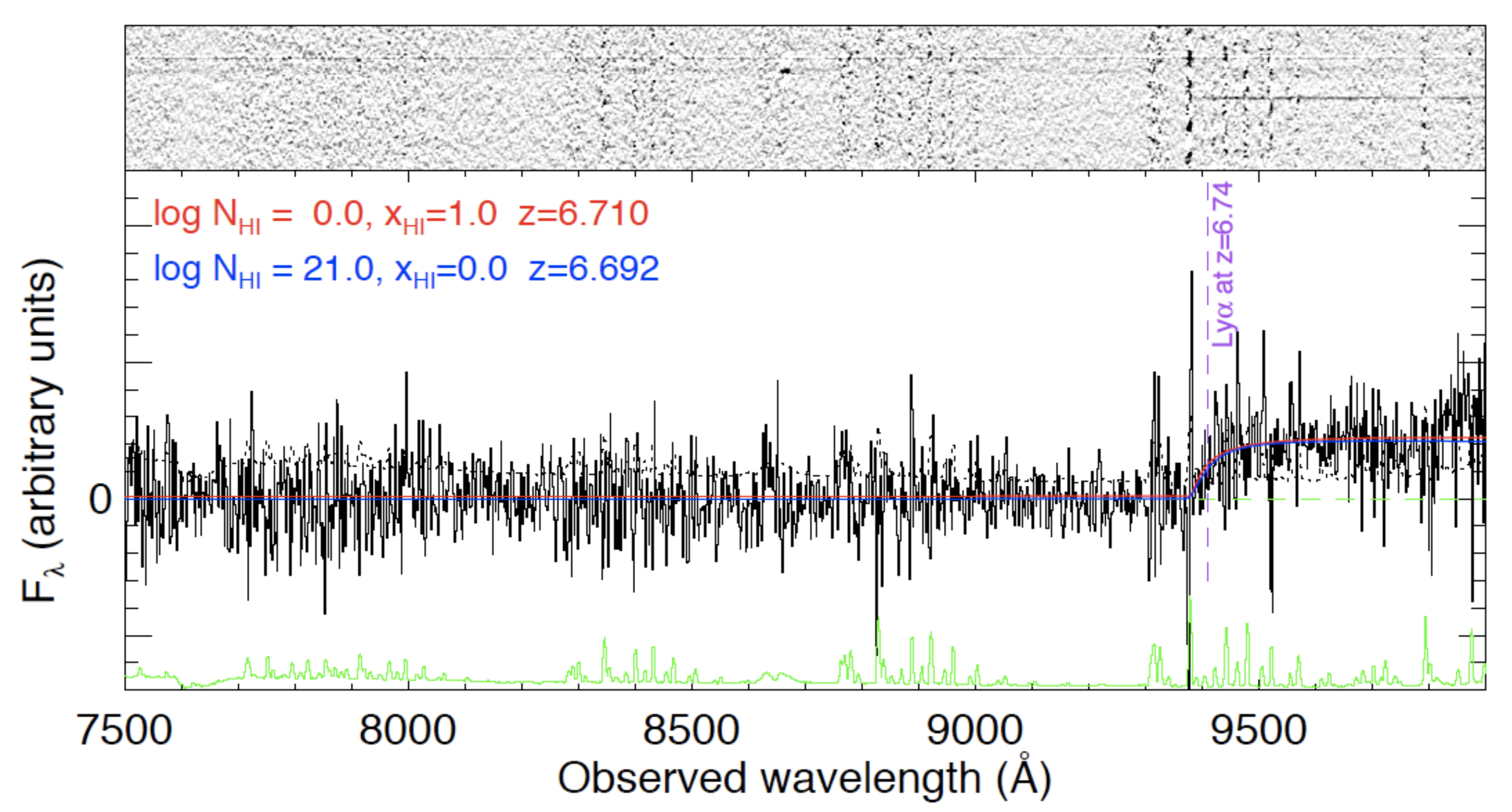
Lessons from GRB 050904 @ z=6.295

- Keys to break the degeneracy:
  - metal absorption lines
    - favors host galaxy HI
    - but be careful about systematic velocity shifts from the rest-frame of host galaxy
  - Ly β feature
    - robustly including IGM case
- DLA dominant for GRB 050904
  - DLA log N_{HI}/cm^2 ~ 21.6
  - still, upper limit on IGM HI
  - $n_{HI}/n_H < 0.17$ (68%CL) or 0.60 (95%CL) at z=6.3
  - complementary to quasar GP tests



TT+ '06

GRB 080913 @ z~6.7



(Greiner+'09)

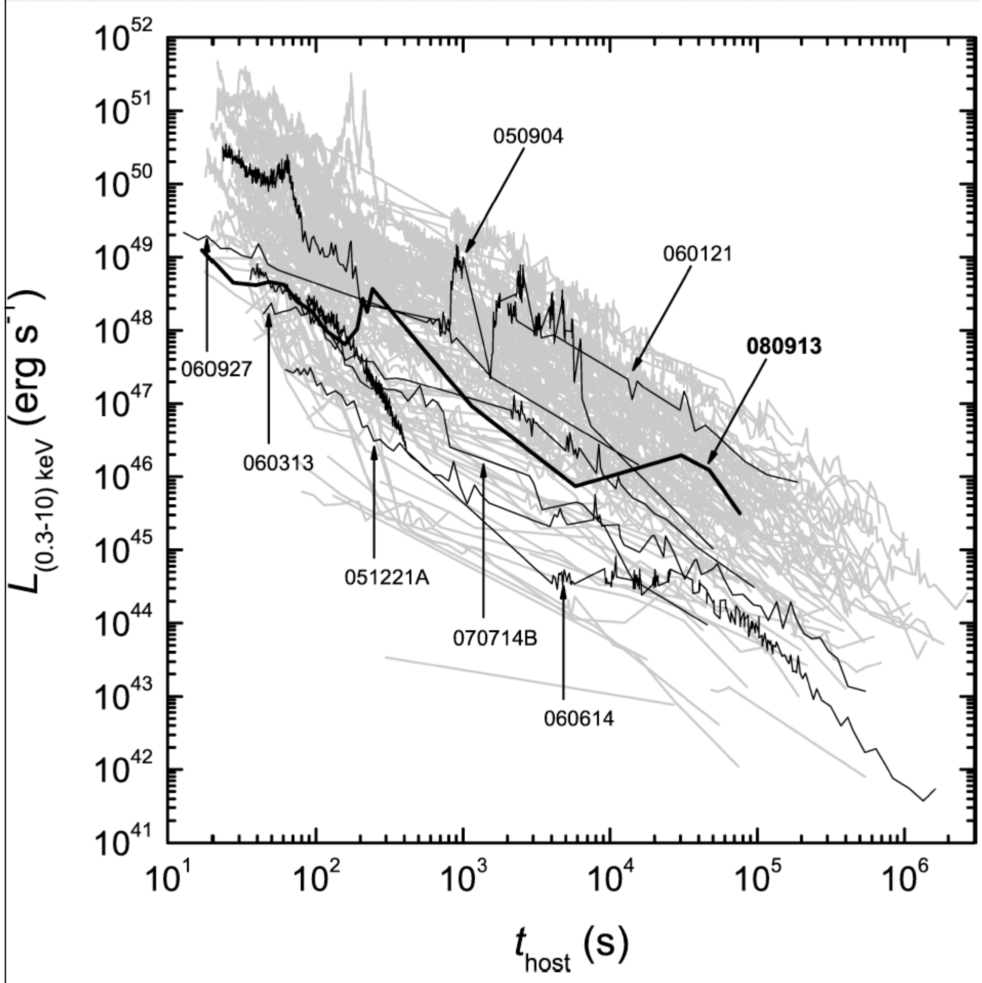
2-3 hrs, z'~24.5(AB), 2400 s exp.

damping wing detected, but difficult to discriminate DLA or IGM

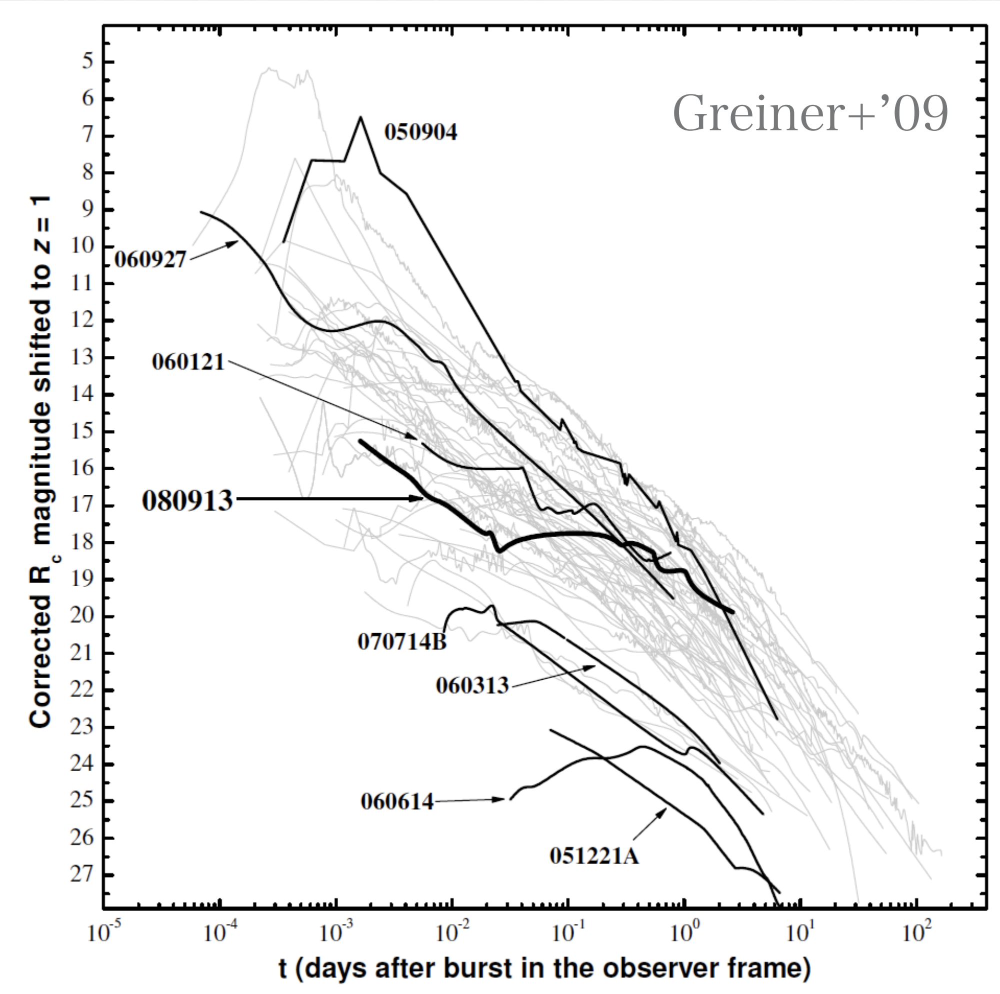
c.f. GRB 050904, z~6.3

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

GRB afterglow luminosities

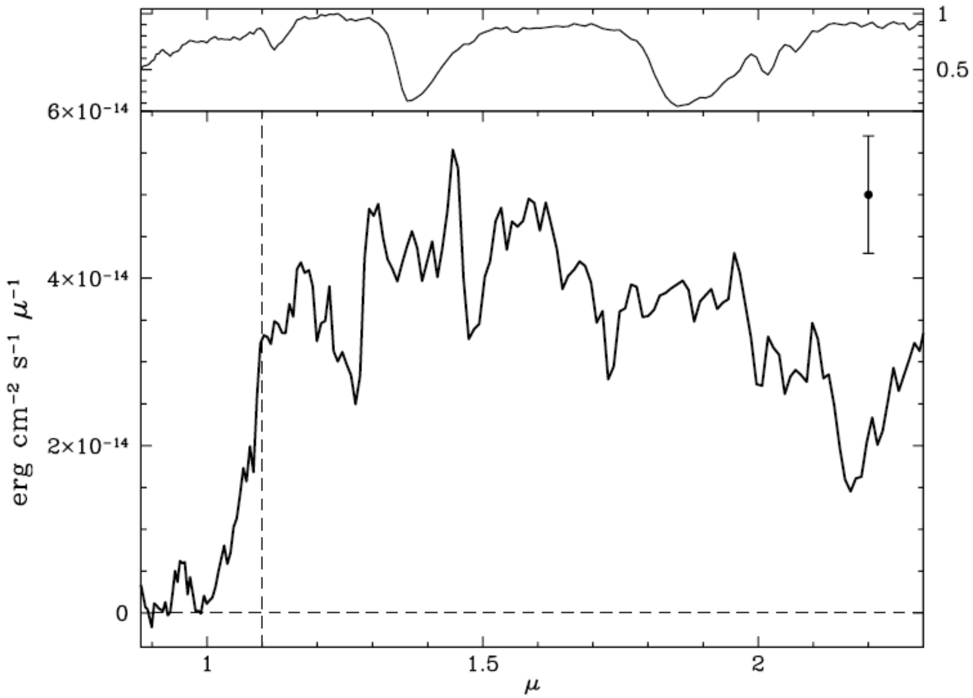


X-ray

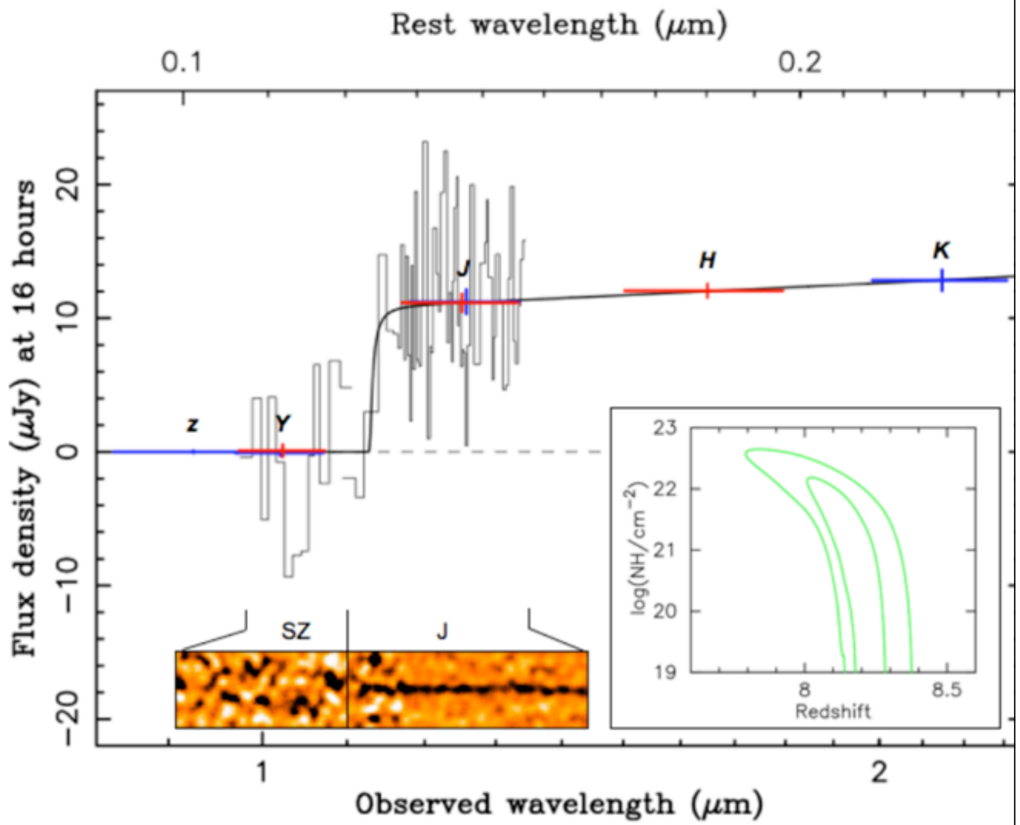


optical

GRB 090423 @ z~8.2



Salvaterra+'09



near-IR spectrograph required

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

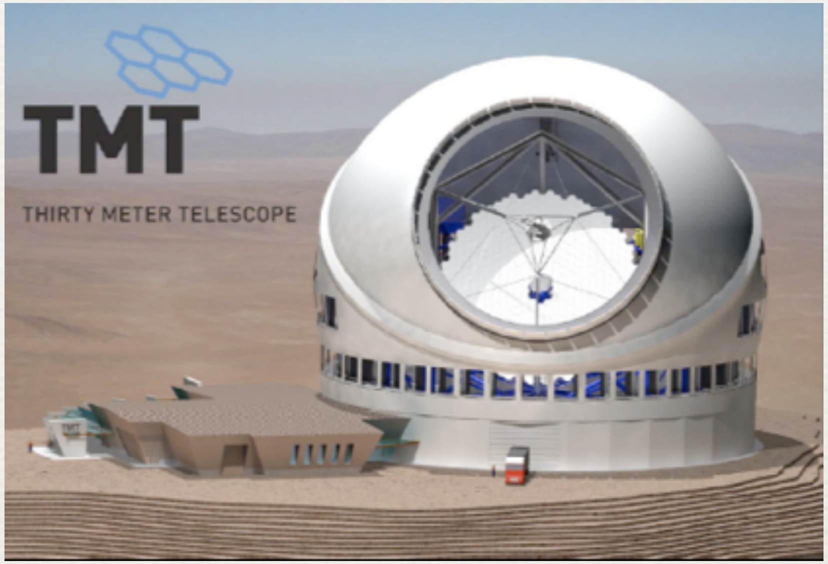
Only upper bound on N_{HI} (=no detection of damping wing)

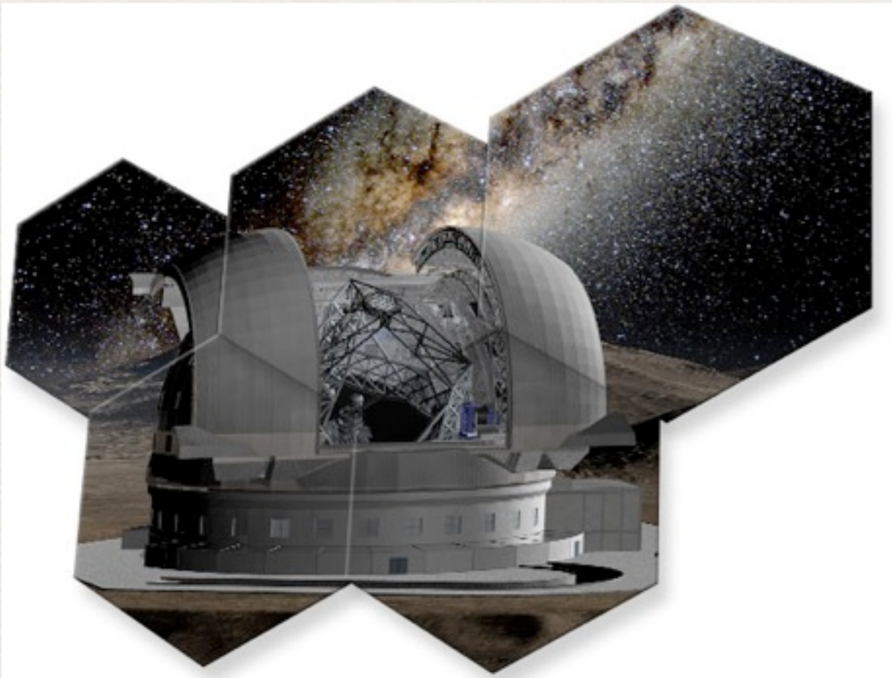
What's the hindrance now?

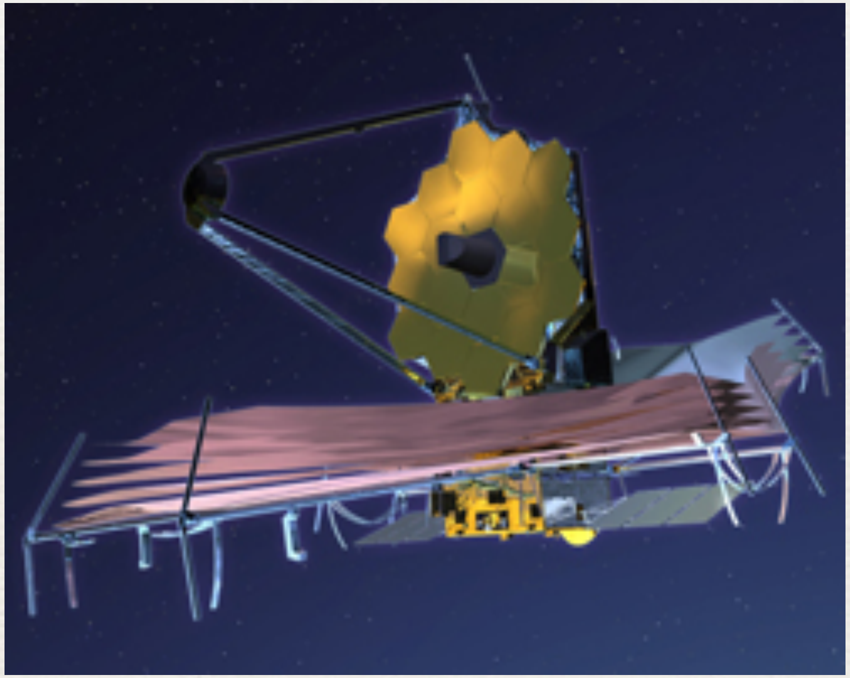
- More sensitive NIR spectrograph
  - LGS-AO by 8m telescopes
  - 30m-class telescopes / JWST
  - Note: optical spectroscopy still important up to z~7.3 (obs. 8500A) to see the Lyβ feature

- Increase the event rate
  - Especially important to find low N_{HI} GRB
  - quicker follow-ups by more sensitive detectors
  - but ultimately limited by high-z GRB rates

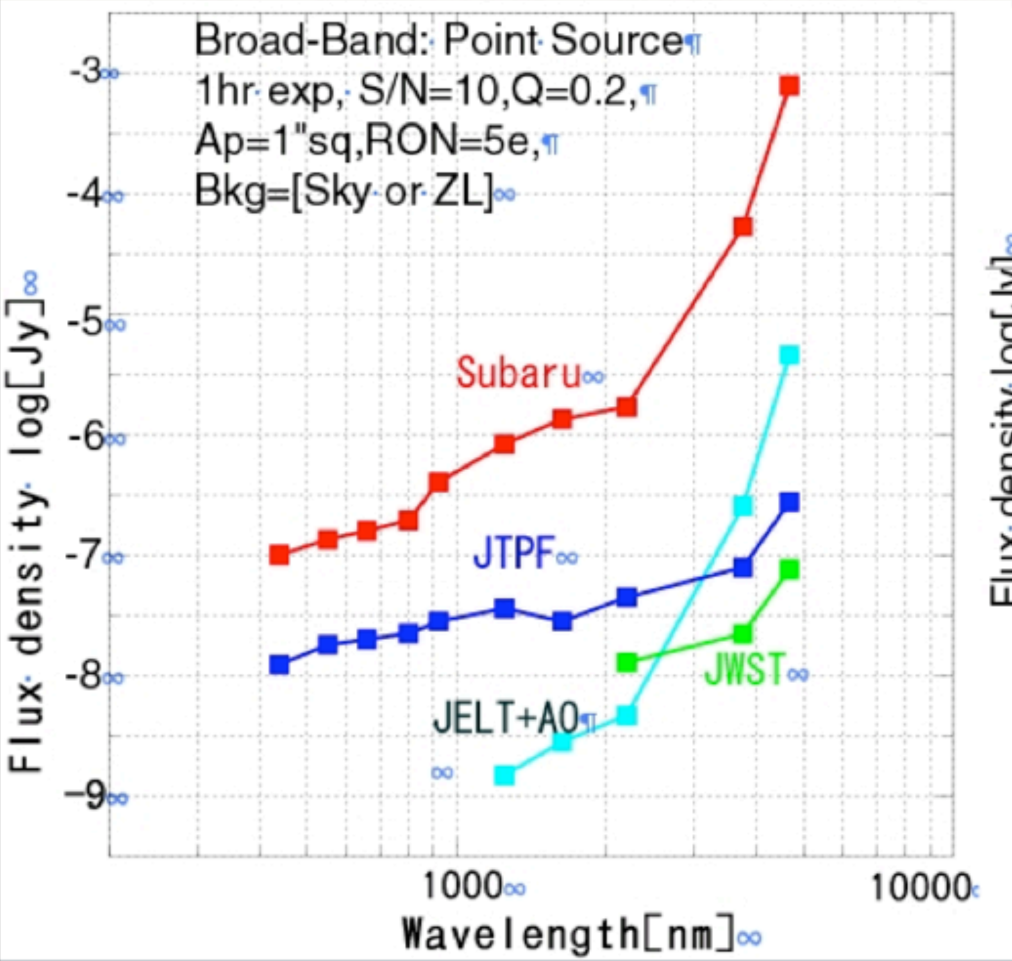
30m/JWST

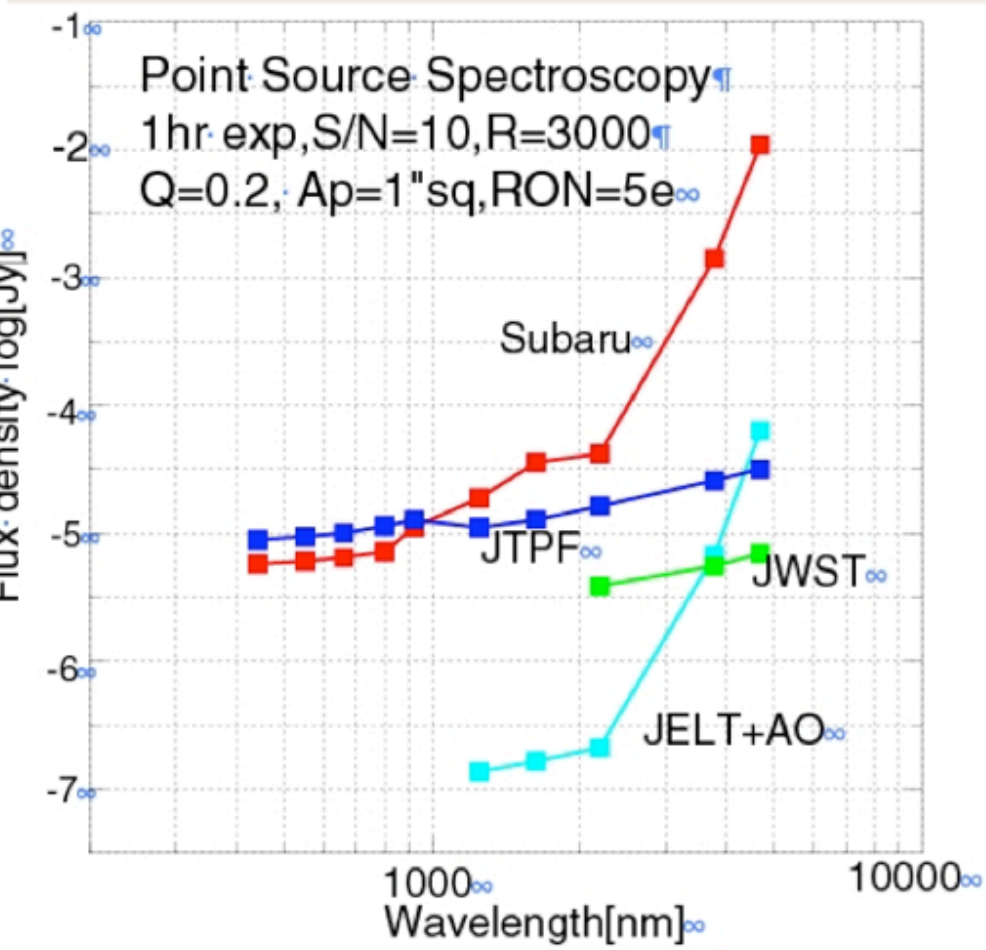






30m/JWST sensitivity

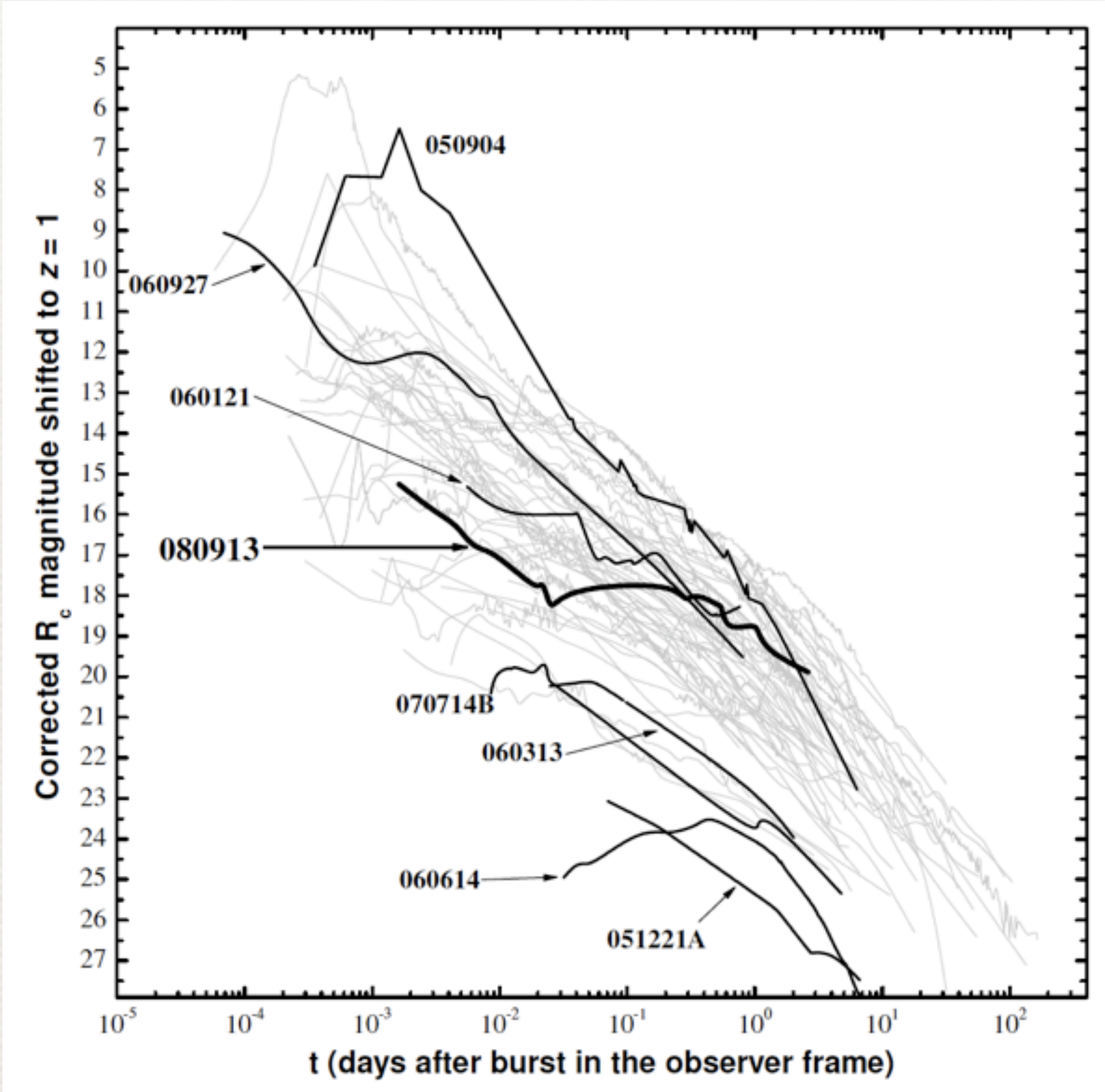




from M. Iye

30m/JWST 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



(Greiner+'09)

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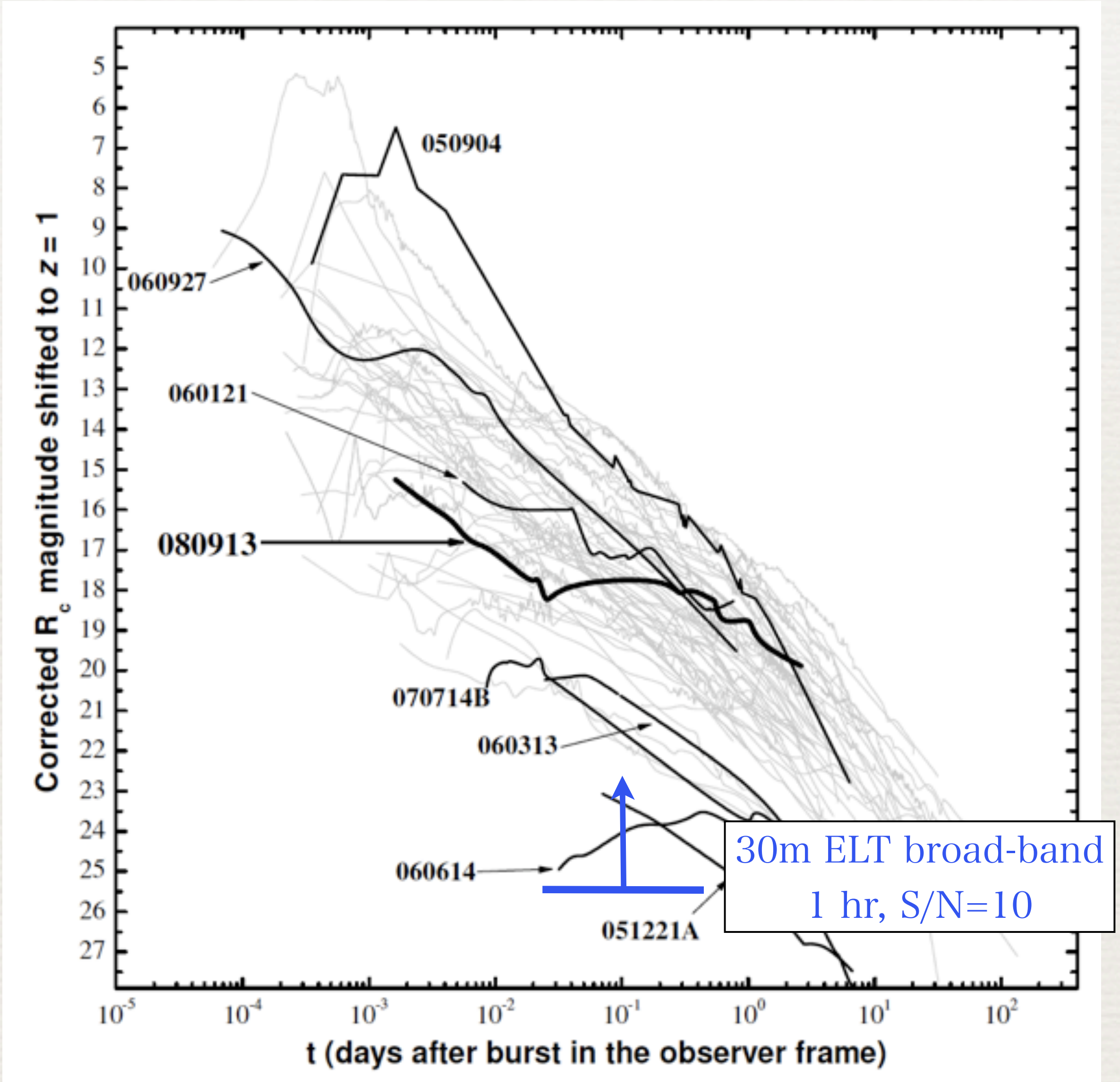

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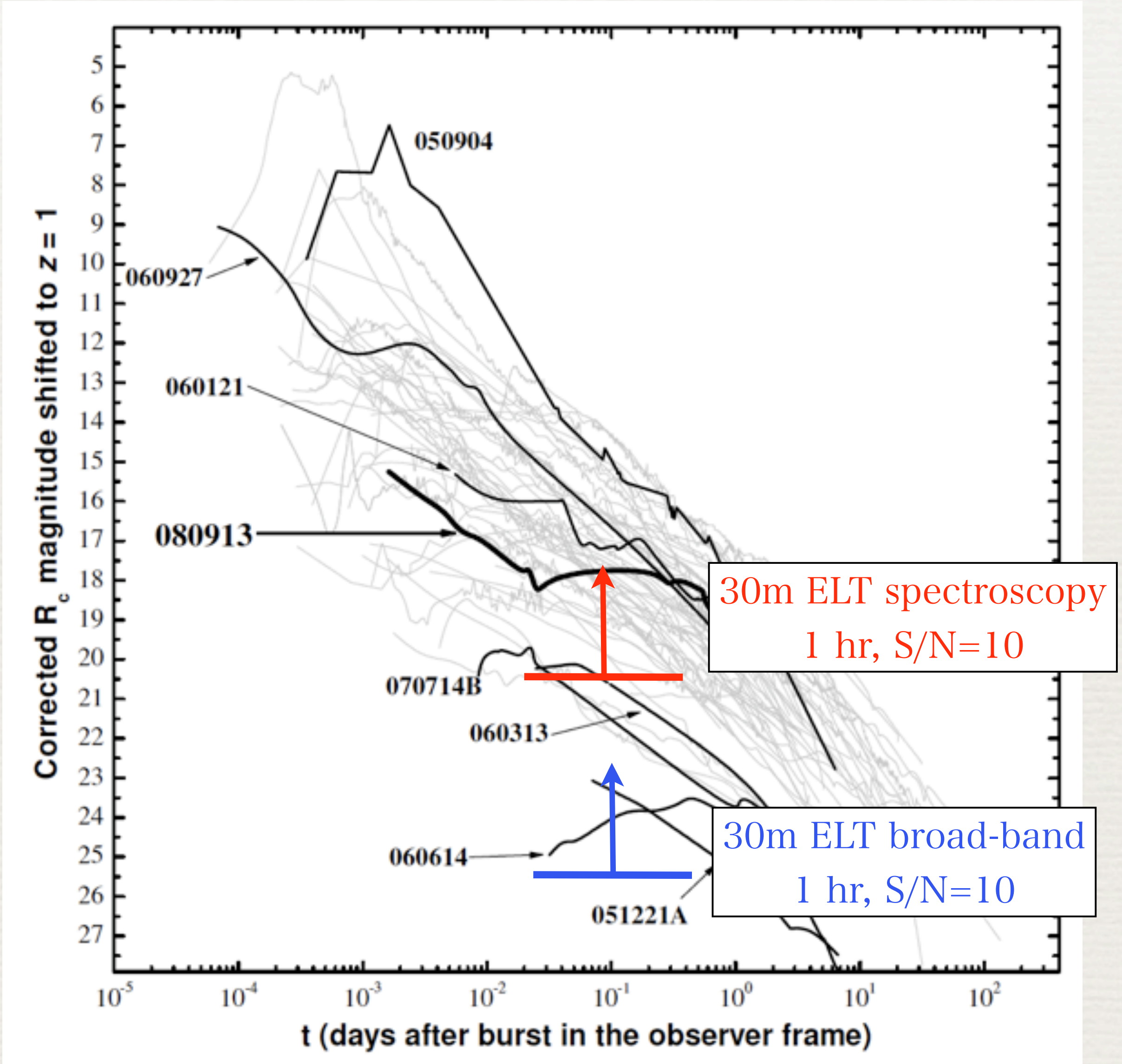
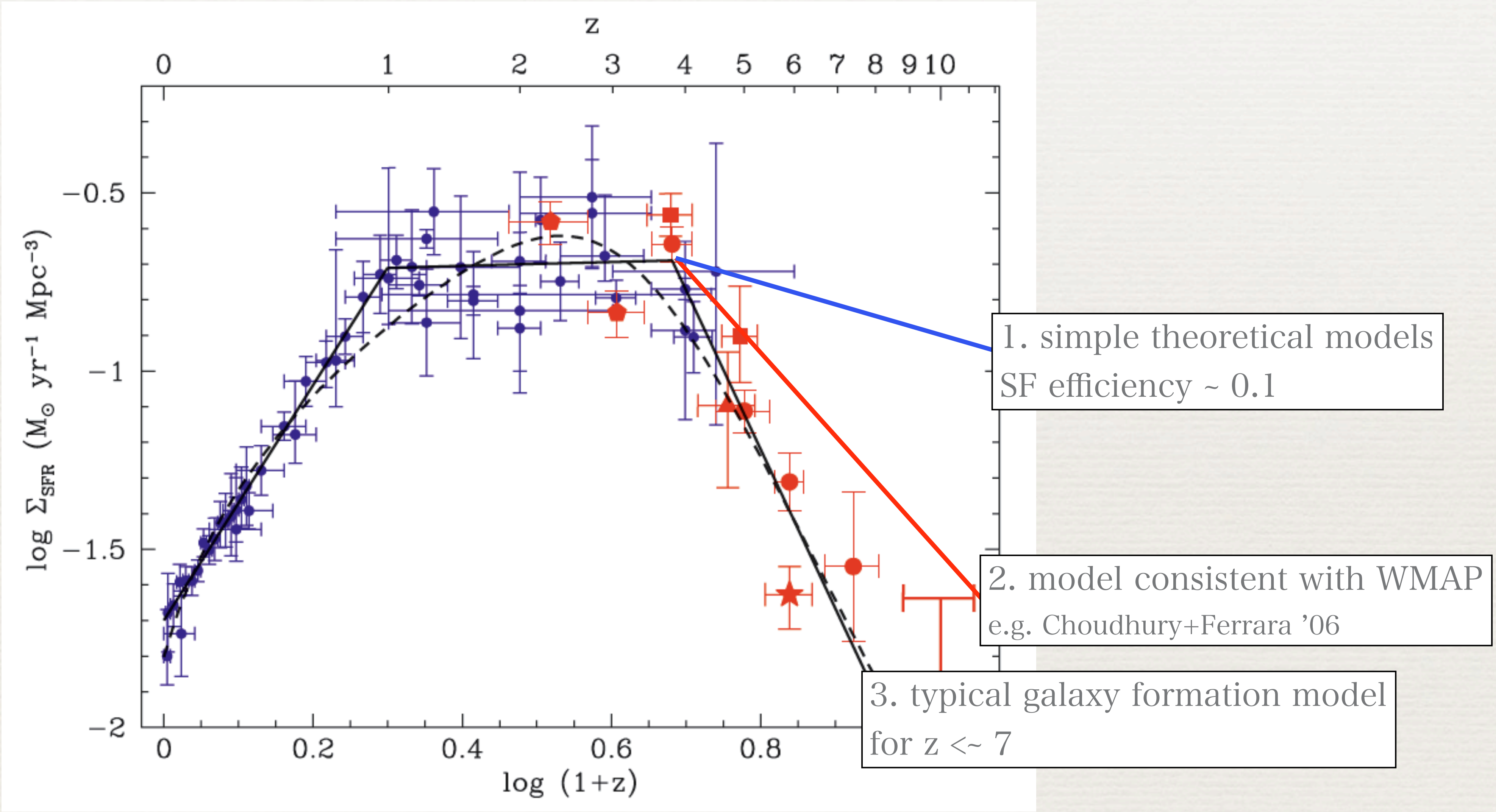


(Greiner+'09)

Event rate: vs SFR evolution



Li '08

The Fraction of z>10 GRBs

- (No flux limit: z>~10 may seriously be flux limited by Swift sensitivity)

- If GRB $\propto$ SFR
  - case 1: 0.06%
  - case 2: 0.7%
  - case 3: 8%

- If GRB/SFR $\propto (1+z)^1$
  - (case 2 + this assumption roughly consistent with a GRB @z=8.25: Kistler+'09)
  - case 1: 0.3%
  - case 2: 2%
  - case 3: 26%

- ~1% seems a reasonable estimate for z>10 GRBs

Then how many eventually?

- my personal estimate that I believe reasonable:
  - ~1% of GRBs at $z > 10$
  - ~20% of GRBs have $\log N_{HI}/cm^{-2} < 20$
  - → 0.2% of GRBs can be used to measure x_{HI} at z~10
  - 500 GRBs required! We need to be patient…
- further reducing factors:
  - dark GRBs (hopefully not important at very high-z)
  - gamma-ray sensitivity (Swift marginal)
  - afterglow not bright enough (ELT/JWST will be OK)
- high sensitivity, high event-rate GRB mission desirable in the ELT/JWST era
  - even one GRB with clear IGM damping wing will have very strong impact on reionization study!

Topic 2

- Lyα emitters in hierarchical galaxy formation
  - Kobayashi, TT, Nagashima ’07, ’10

Lyman α Emitters

- powerful method to find high-z galaxies by strong Ly α emission
  - including highest-z galaxies at z=6.96
- When and how galaxies become LAEs?
- A probe of reionization
  - Ly α lines absorbed by IGM HI damping wing

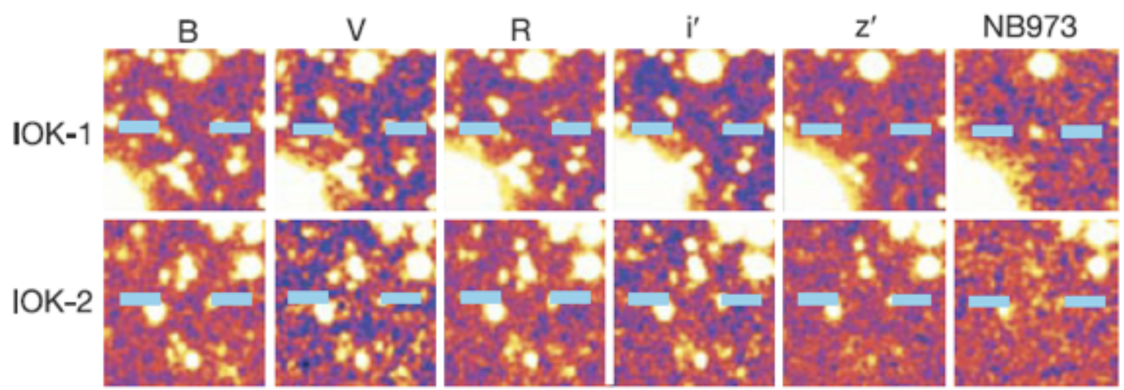


Figure 1 | Multi-waveband 20″ × 20′ images of the z = 6.96 Lyman α emitter IOK-1 and the unidentified candidate IOK-2. Deep broadband

Iye+'06

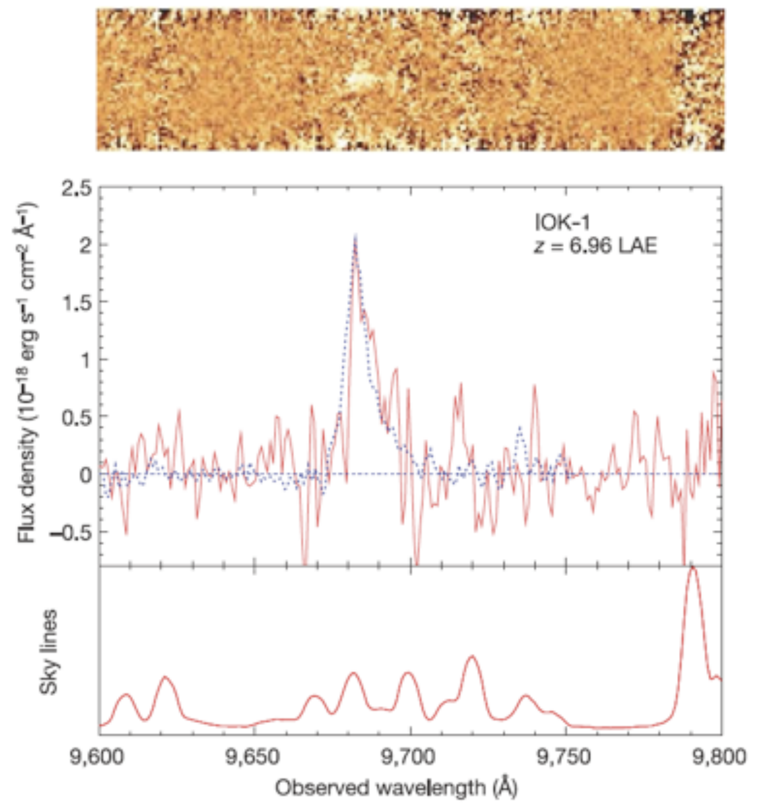
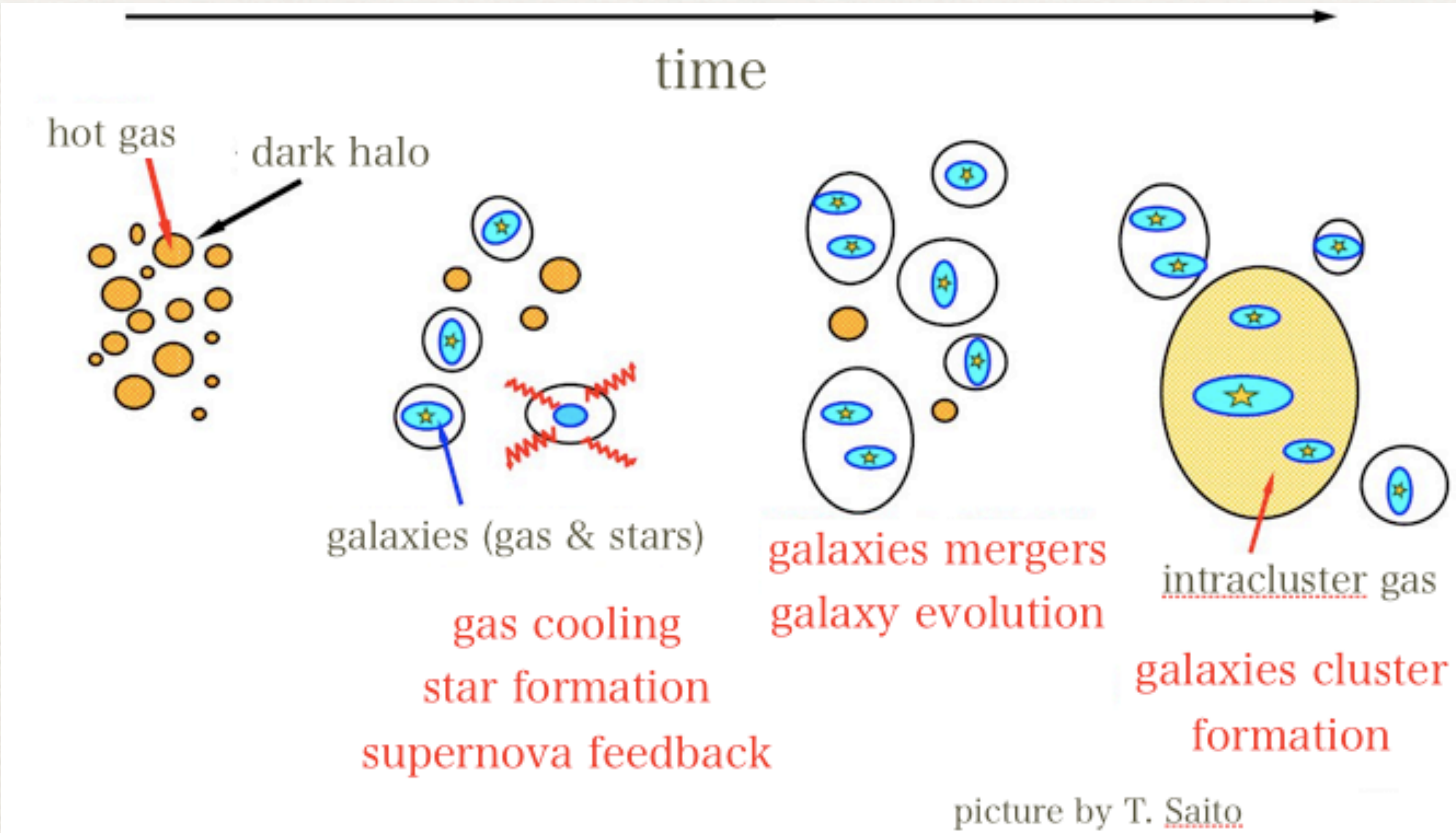


Figure 2 | Combined spectrum of z = 6.96 galaxy, IOK-1. The bottom panel

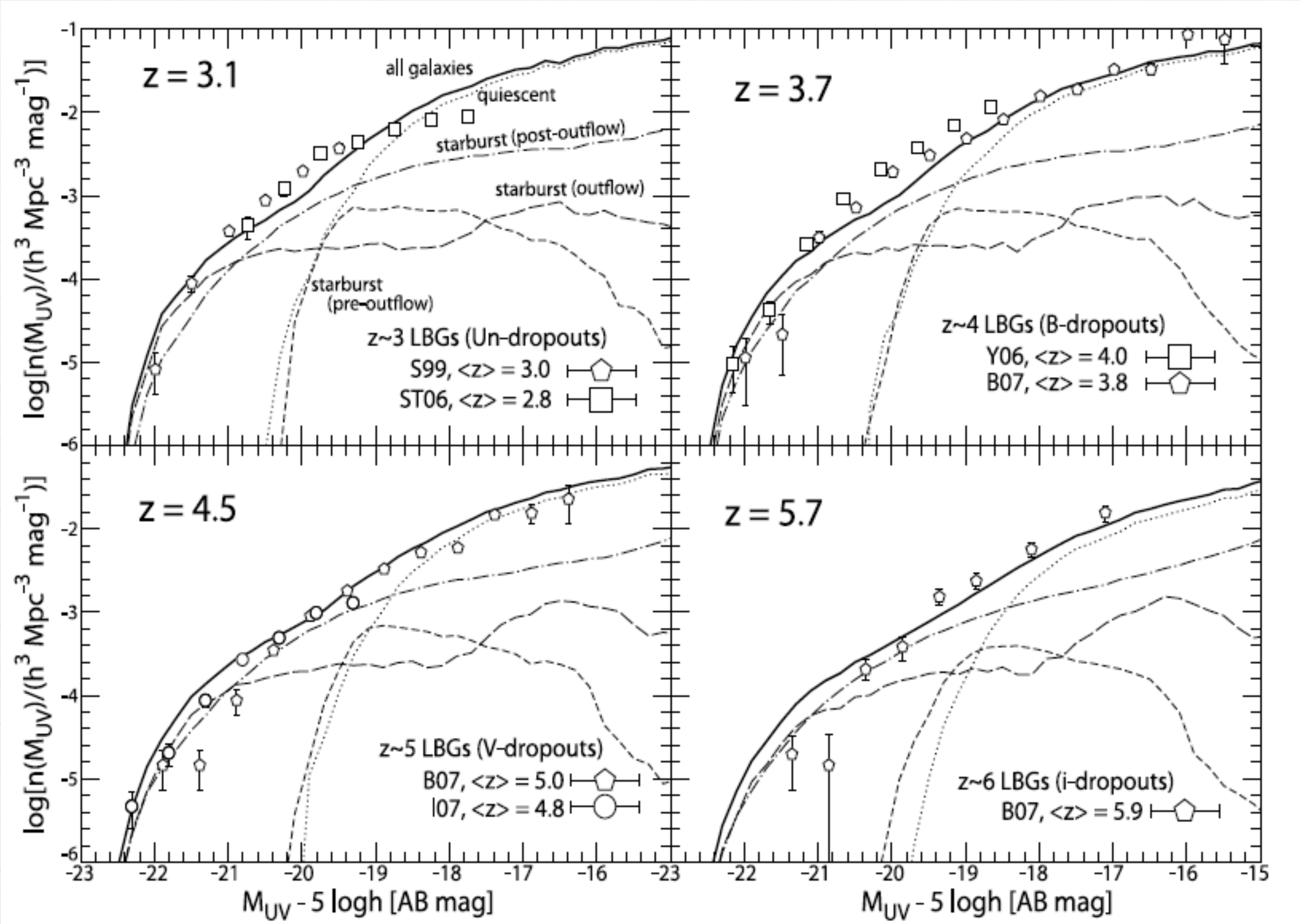
Hierarchical Galaxy Formation

- galaxy formation in hierarchical clustering universe has been modeled well by e.g.,
  - numerical simulations
  - semi-analytic models



obs. vs. model for Ly-break galaxies

- predictions by a semi-analytic model of Nagashima et al.

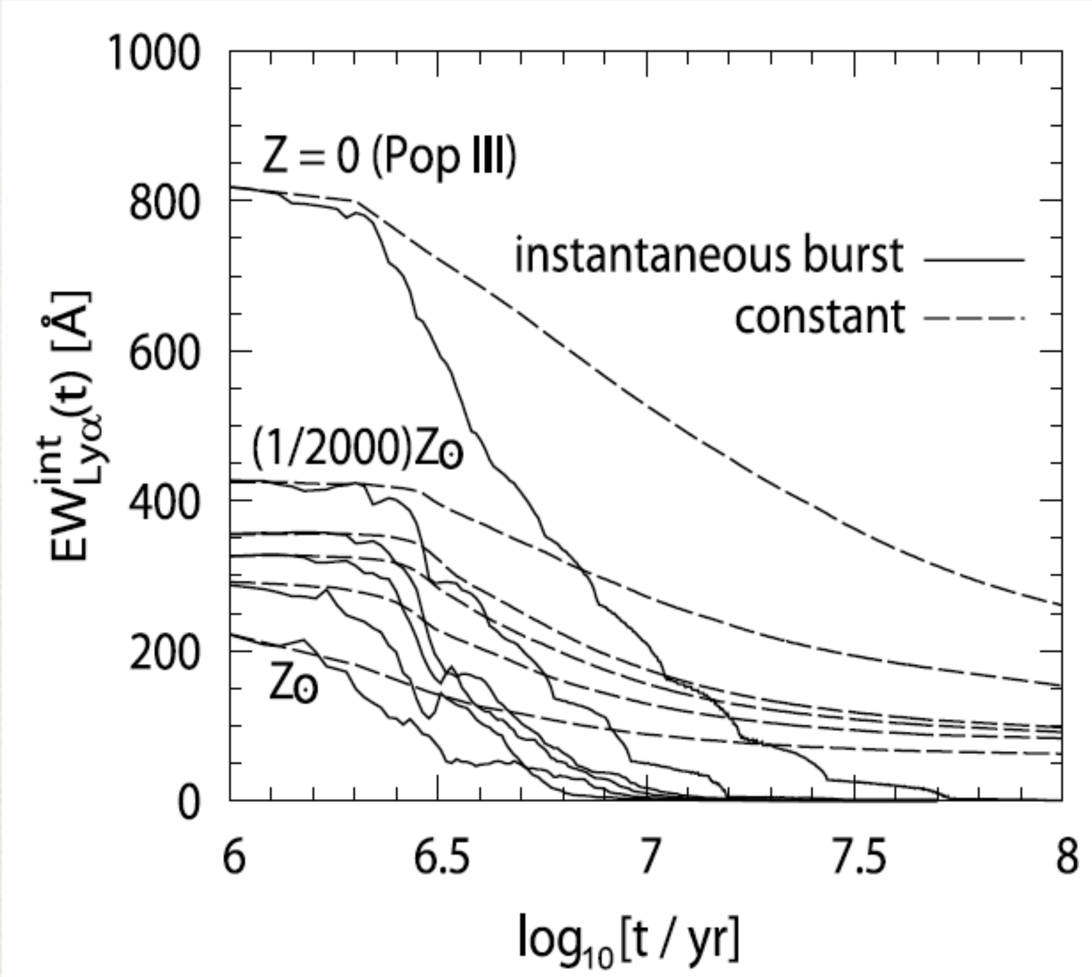


Modeling Lyα emitters

- Predicting Lyα statistics (luminosity function etc.) by cosmological galaxy formation theories
  - Koyayashi+'07, '10
    - ionizing photon calculation including metallicity dependence and chemical evolution
    - detailed comparison with Lyα LF, UV-continuum LF, EW distribution at z~3-6
    - LAE selection criteria carefully considered for each survey
  - see also for other approaches:
    - Le Delliou+'06; Mao+'07; Dayal+'08,09; Orsi+'08; Barton +'04; Nagamine+'08; Samui+'09

Ionizing Photon Production

- "intrinsic" Ly α luminosity and EW calculated by stellar population synthesis models
  - Schaerer '03 here
- sensitive to metallicity and stellar population ages
- intrinsic Ly α luminosity and EW assuming case B recombination



Kobayashi, TT, Nagashima'09

Lyα photon escape fraction from galaxies

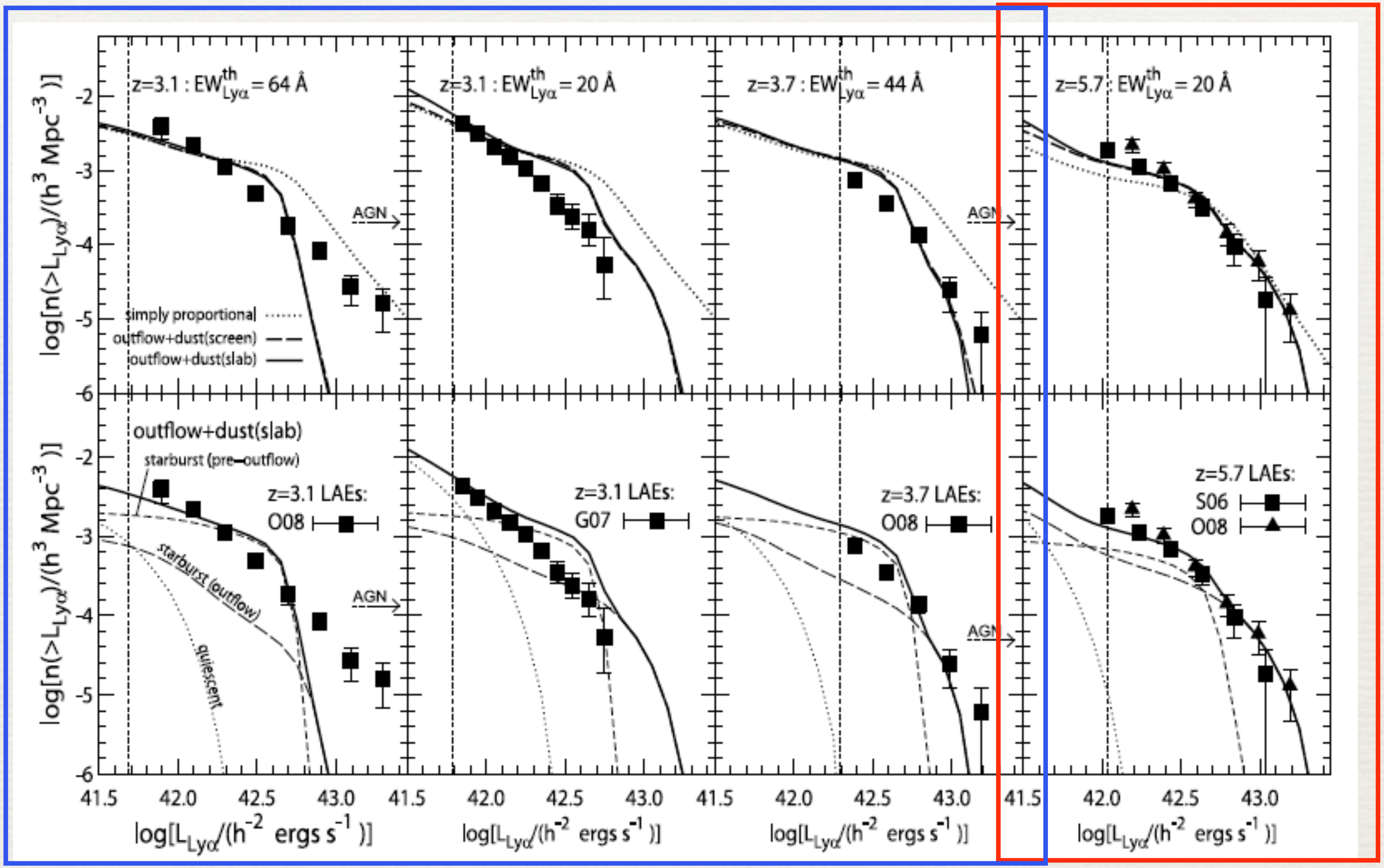
- So much uncertainties!
  - especially resonant Lyα scatterings causing random walk

- A simple phenomenological approach (essentially 2 parameters)
  - a universal factor f_0
  - dust attenuation τ_d for Lyα (**different** from that for UV cont)

$$f_{\rm esc}^{\rm Ly\alpha} = f_0 \frac{1-\exp(-\tau_d^{\rm Ly\alpha})}{\tau_d^{\rm Ly\alpha}}$$

  - determined by fit to Lyα LF at z=5

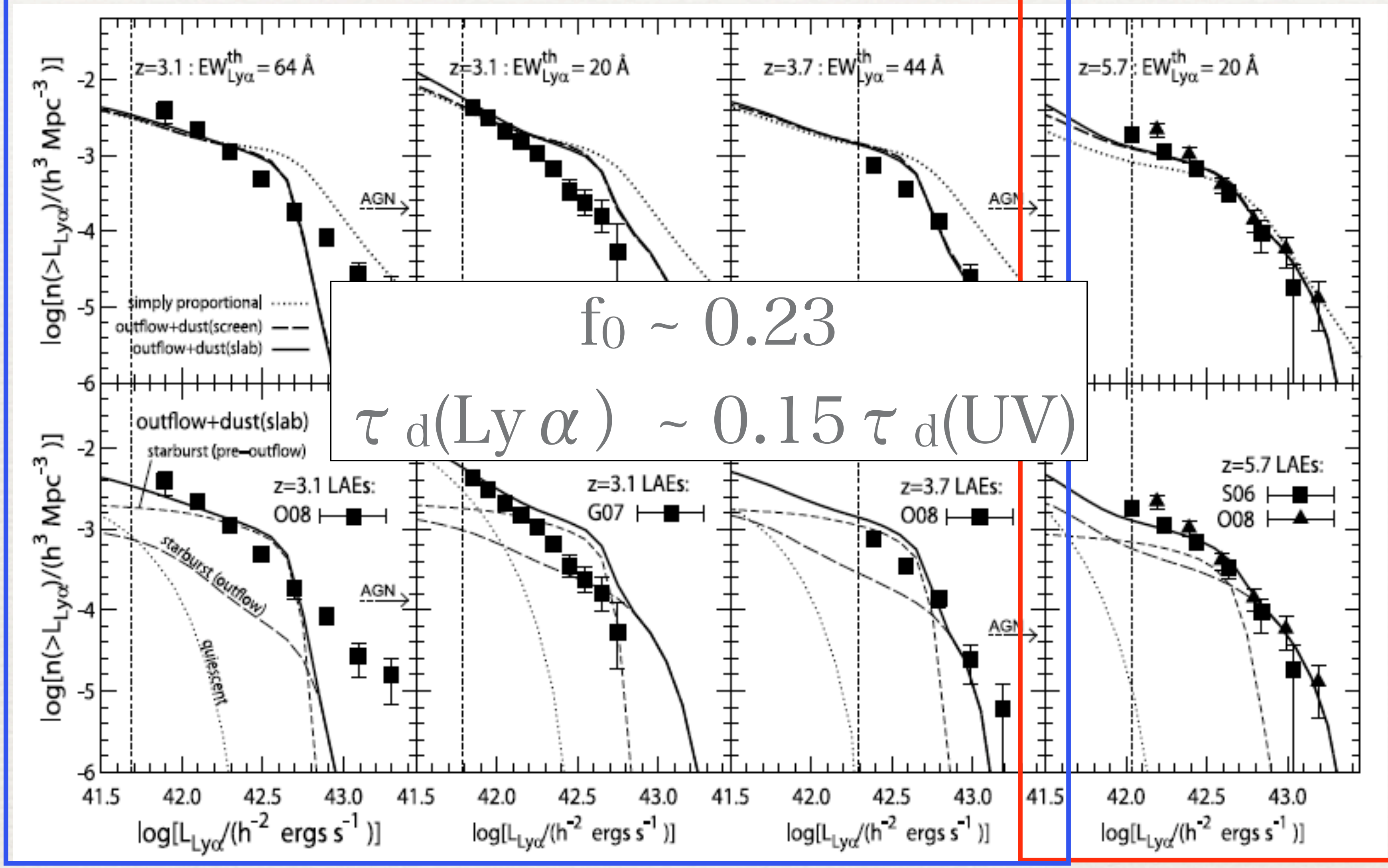
LAE Lyα Luminosity Function



Prediction

Fit

LAE Lyα Luminosity Function



$f_0 \sim 0.23$

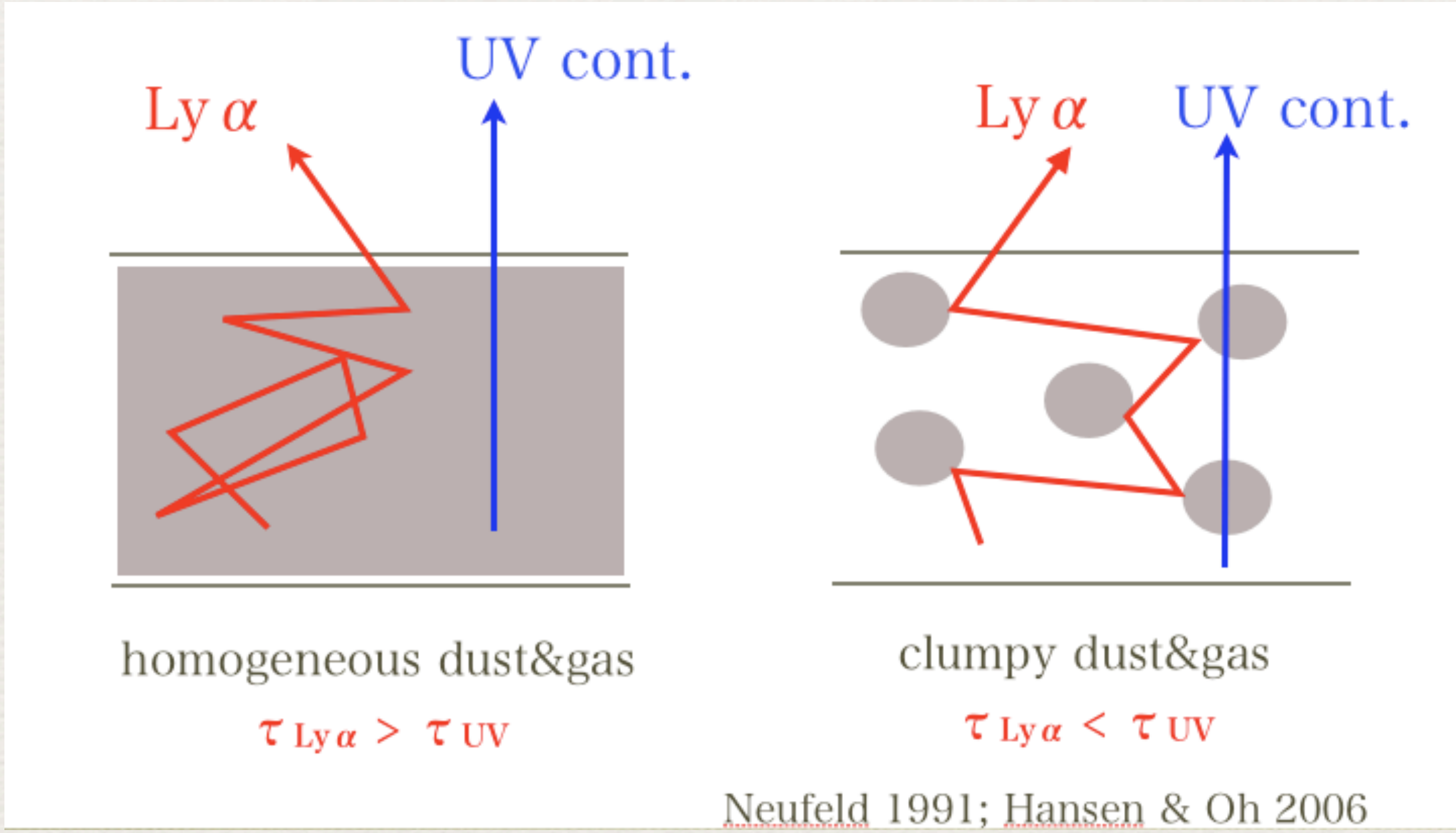
$\tau_d(\mathrm{Ly}\alpha) \sim 0.15\,\tau_d(\mathrm{UV})$

Prediction

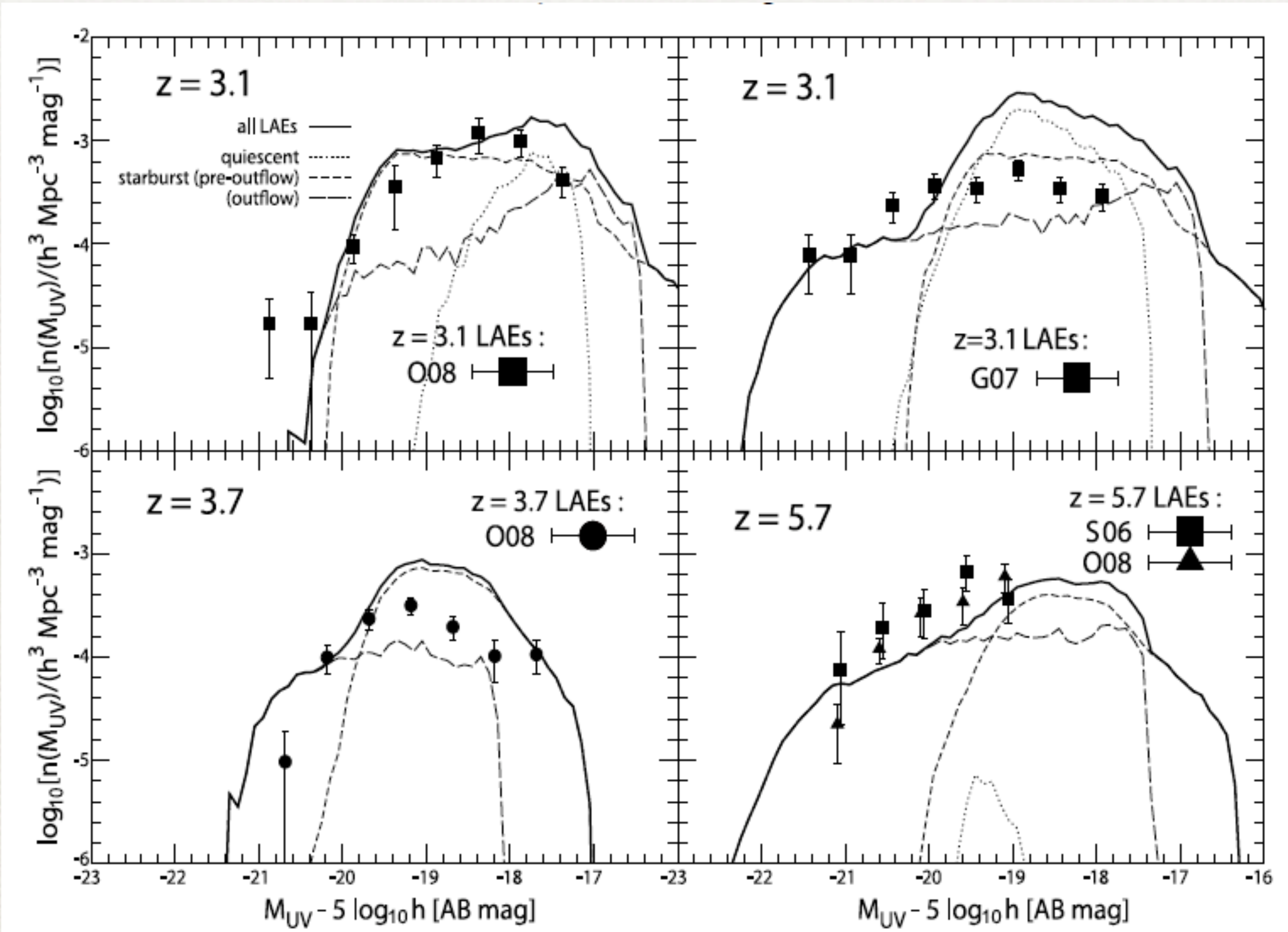
Fit

Dust in Clumpy ISM!?

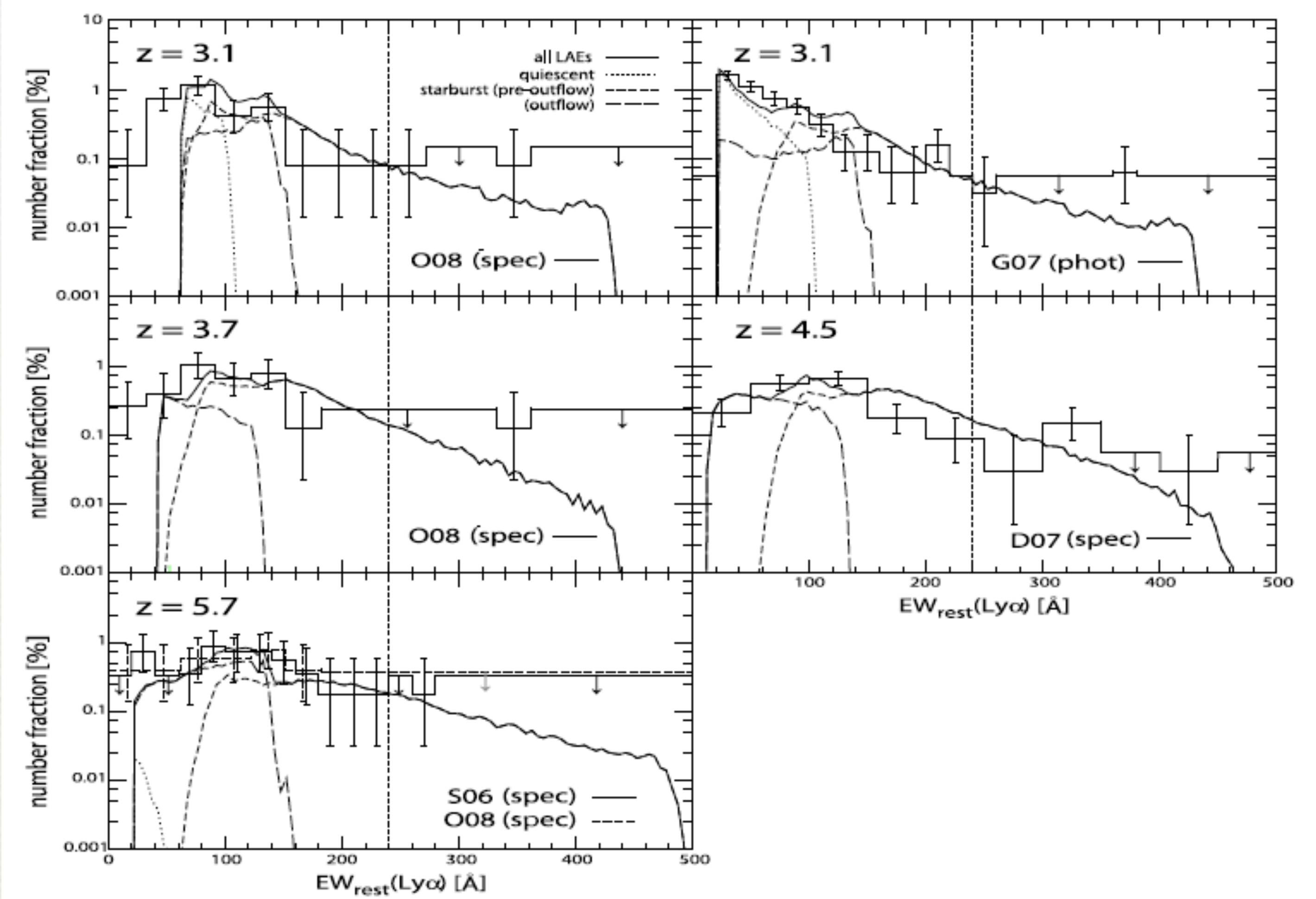
- random walk by resonant scattering by neutral hydrogen
- dust extinction in two possible opposite ways
  - EW decrease by homogeneous dust
  - EW increase by dust in clumpy ISM



UV continuum LF of LAEs



Equivalent Width Distribution

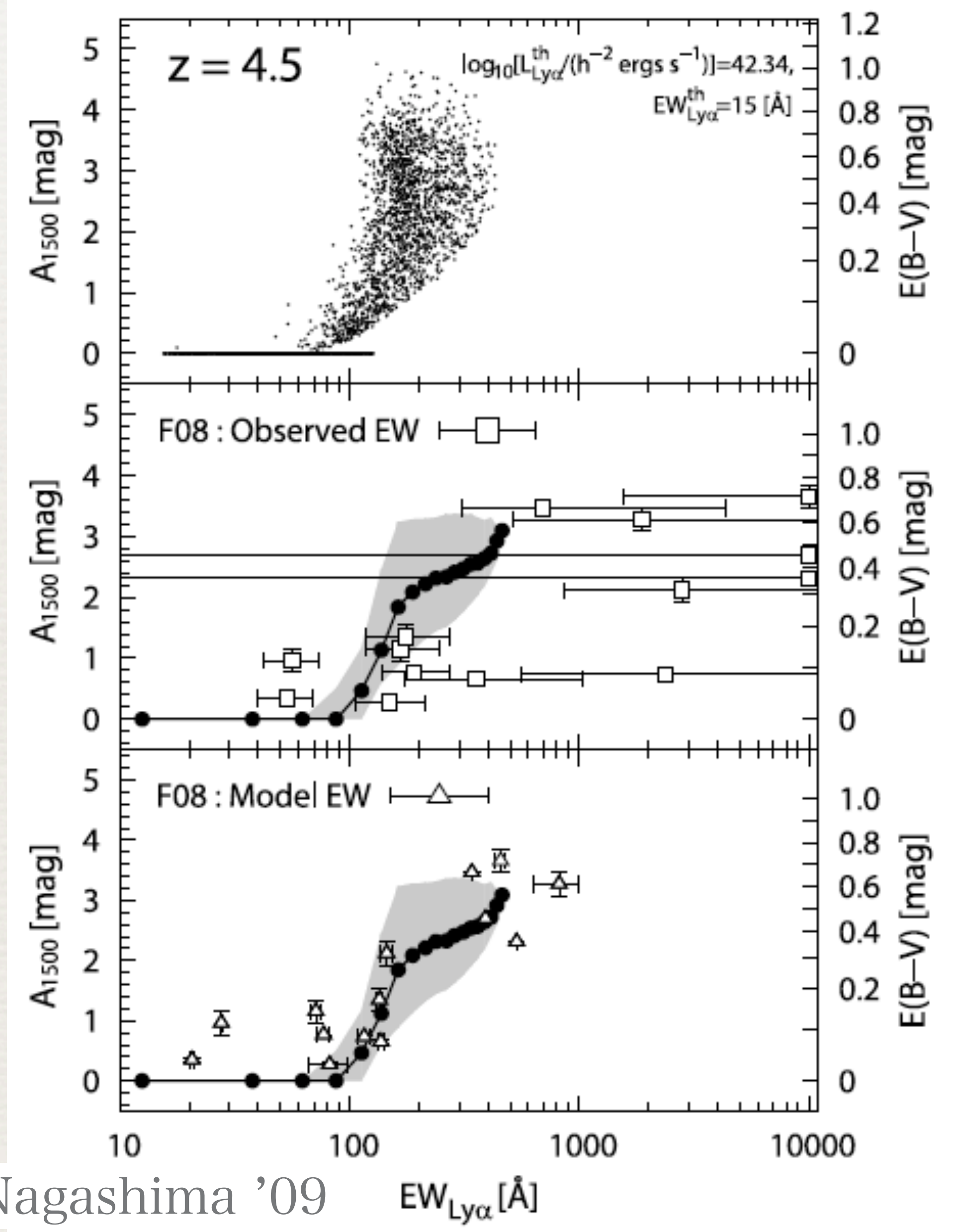


- EW > 240 A possible without significant Pop III or top heavy IMF
- Thanks to:
  - young and low-metallicity stellar population
  - EW enhancement by clumpy ISM dust

clumpy ISM dust?

- favored in KTN model to reproduce data
  - Ly α LF
  - large EW LAEs (> 240A)

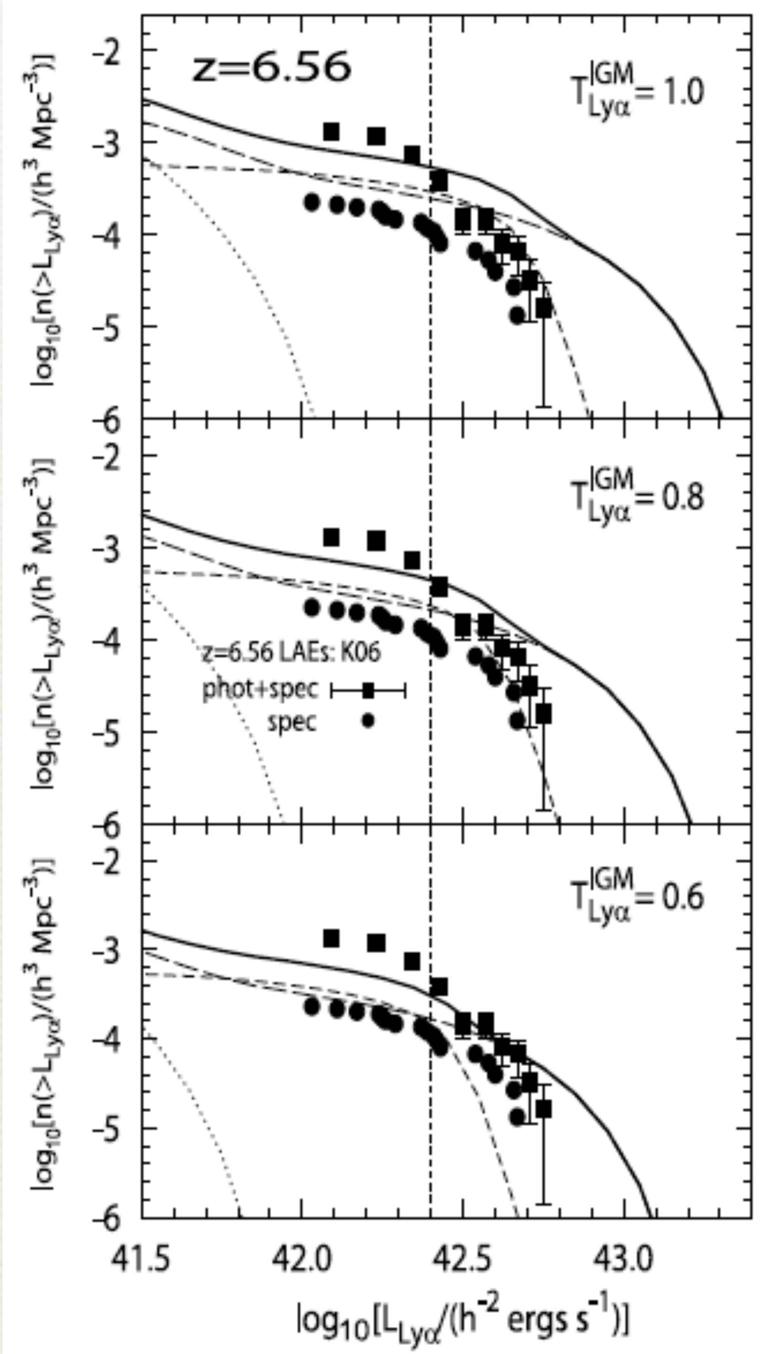
- Independently suggested from observation by Finkelstein et al.
  - Ly α EW - extinction correlation



Kobayashi, TT, Nagashima ’09

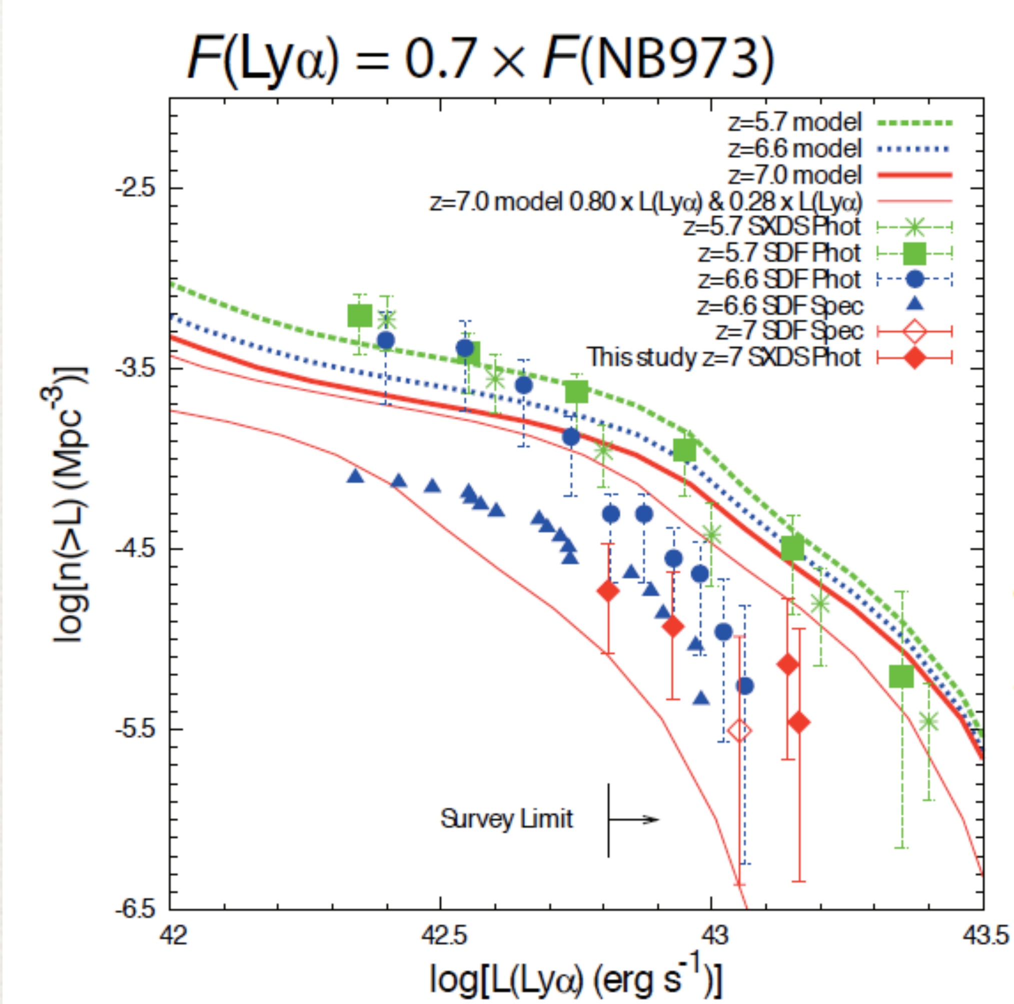
Implications for Reionization

- observed Lyα LF suddenly drops compared with the model at z >~6.5
  - (good match at z~5.7)
- implies Lyα attenuation by a factor of ~0.6
- Evidence for EoR?
  - large uncertainties in conversion to n_{HI}/n_H



The New Subaru Result

- SXDS (Subaru-XMM Newton Deep Field) imaging with new red-sensitive CCD of Suprime-Cam
- 0.5 mag deeper than the previous SDF search that found z=6.96 LAE
- 3 LAE candidates, upper limit on LAE LF
- deficit of z~7 LAEs compared with z-6 confirmed
  - IGM transmission ~0.5 at z~7?
- Ota+'10, submitted to ApJ



Conclusions

- GRB and reionization
  - GRB is a unique tool to measure IGM neutral fraction by damping wing
  - currently hampered by small even rate and insufficient sensitivity in NIR spectroscopy
    - 30m telescopes / JWST will have sufficient sensitivities
    - event rate would be the ultimate limitation of the power of this method: high event-rate GRB mission favorable!
- Lyα Emitters
  - clumpy ISM dust inferred LF, EW, and EW-A_V
  - evidence for significant attenuation of Lyα at $z > 6.5$: EoR?

GRBs: the high-z probe