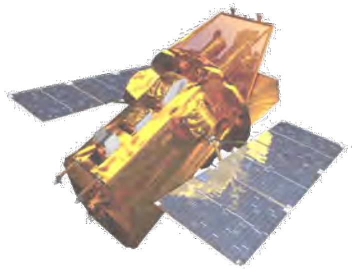
Absorption Line Spectroscopy of Gamma-Ray Burst Afterglows

- Introduction to long GRBs
- GRB 050904
- GRB-DLA vs. QSO-DLA
- GRB 130606A

GRBs in the high redshift universe
Metallicity of GRB host galaxies
Velocity fields of gas in high-z galaxies
GRB environment in high-z galaxies

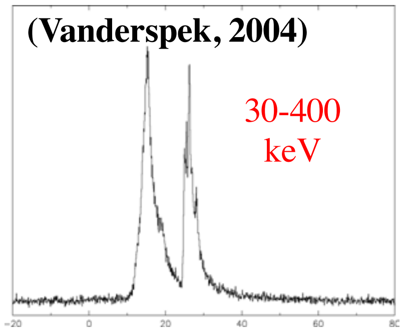
Nobuyuki Kawai (Tokyo Tech)

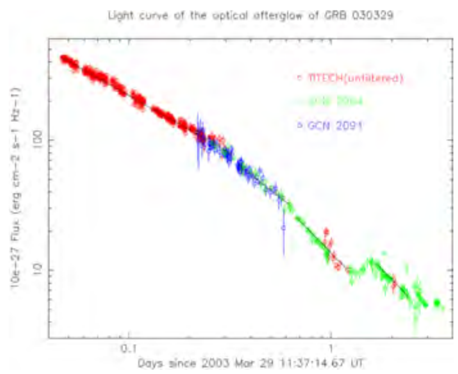
河合誠之　（東工大）

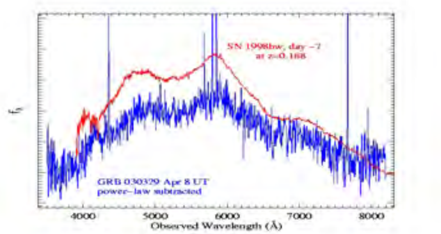


Gamma-ray bursts (GRBs)

- Luminous explosion from the distant Universe
  - ◆ Average redshift ~2, highest observed z~9.4
  - ◆ Observable out to ~130 Gyr (redshift ~10)
- Gamma-ray prompt emission
  - ◆ a few — 100's seconds
- followed by wideband afterglows
  - ◆ radio–IR–optical–X-ray
  - ◆ Days—100's of days







Stanek et al. (2003)

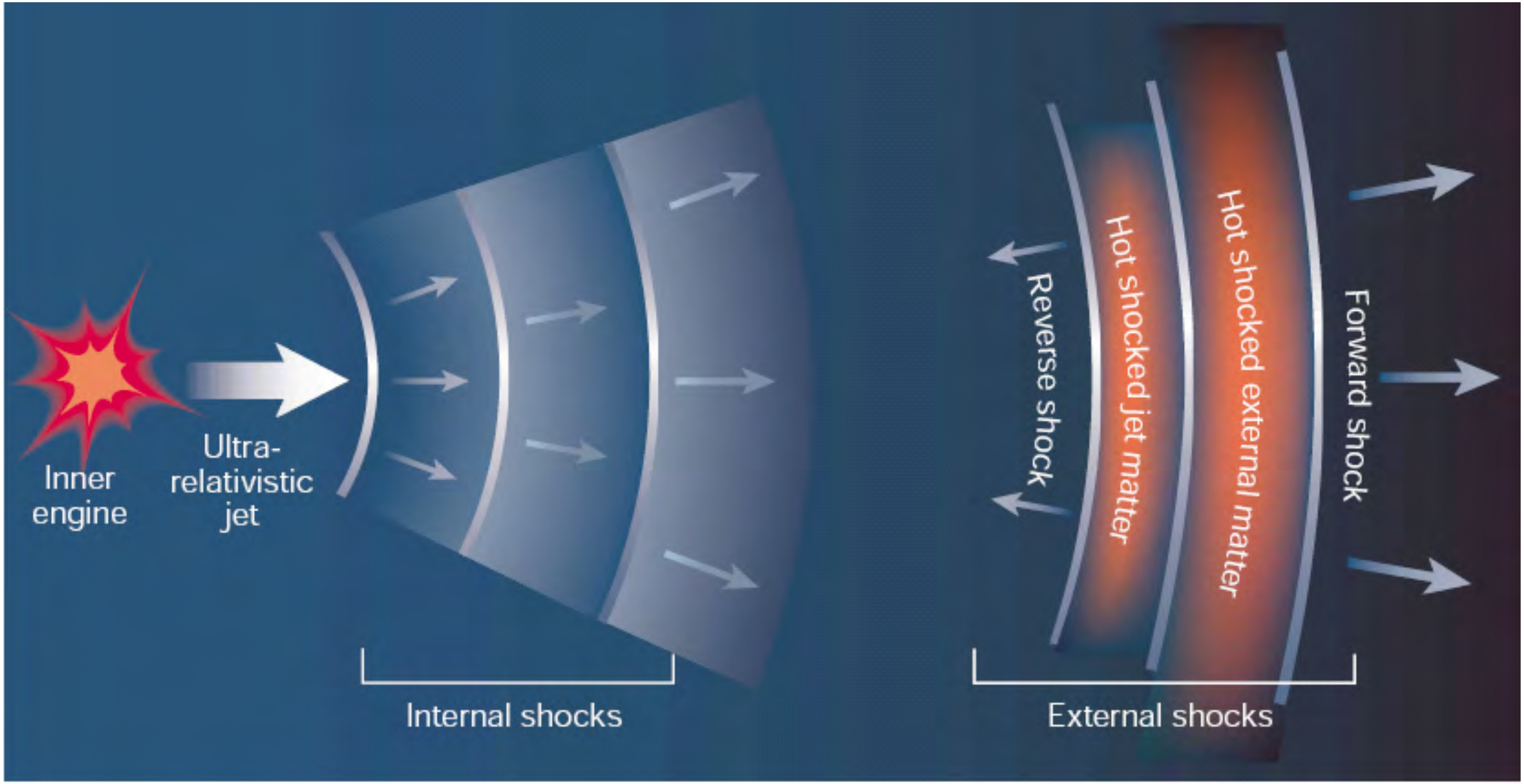
Associated with death of massive stars

- "Collapsar" – relativistic jet launched at core collapse of a massive star
- Occur exclusively in star forming galaxies
- Supernova spectral component seen in GRB030329

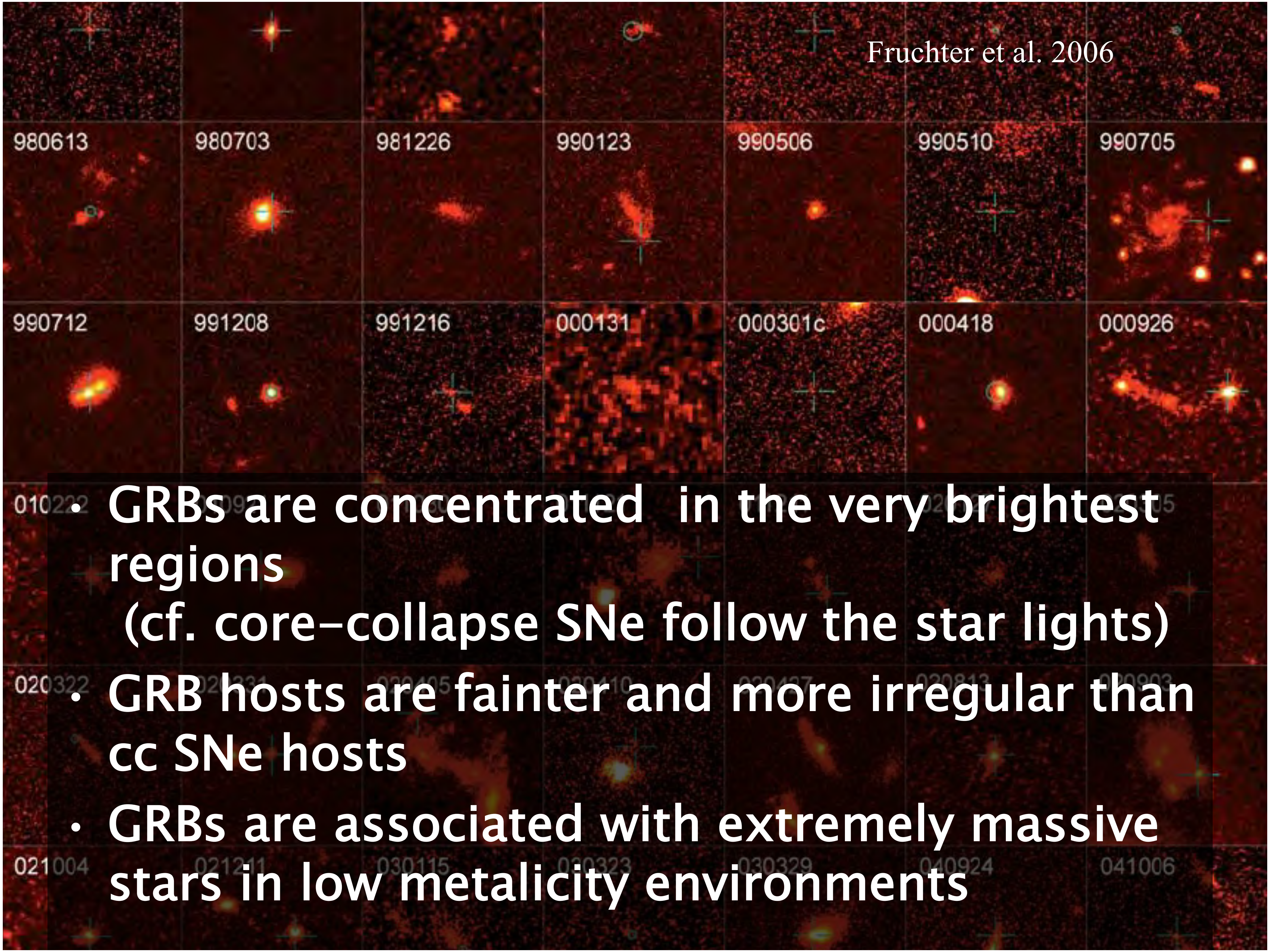
- GRB rate
  - Measure of star formation rate
  - Cosmic chemical evolution
- Single star can produce large luminosity
  - First star
- Illuminate the host galaxy from inside
  - Probe the environment

Fireball scenario of GRBs

Paczynski, Meszaros, Rees, Sari, Piran, …



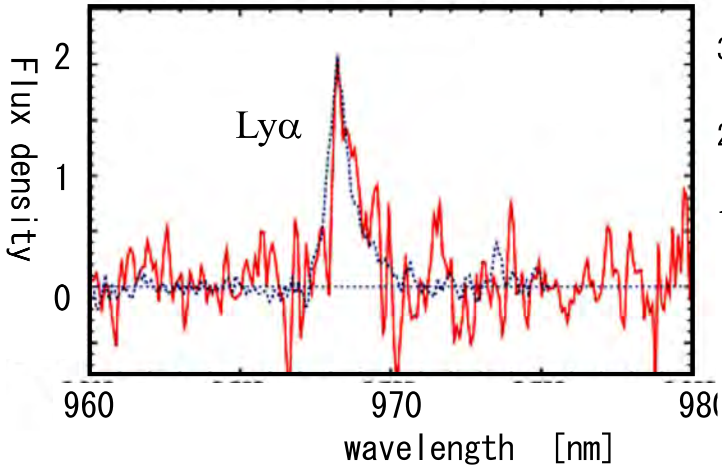
Piran 2003



- GRBs are concentrated in the very brightest regions
  (cf. core-collapse SNe follow the star lights)
- GRB hosts are fainter and more irregular than cc SNe hosts
- GRBs are associated with extremely massive stars in low metalicity environments

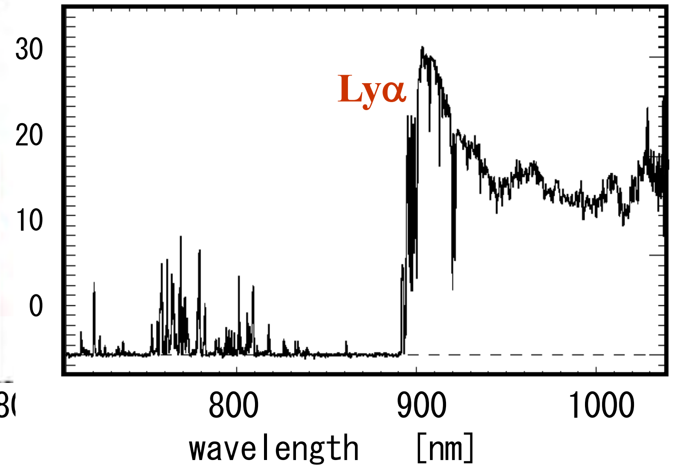
optical/NIR spectra of highest-z objects

Galaxy
z = 6.96



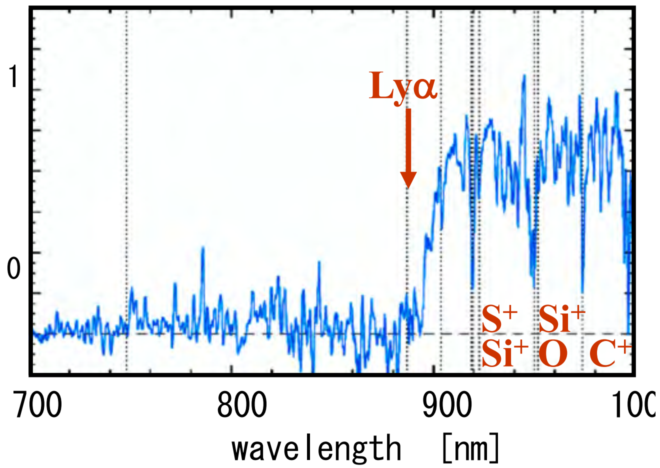
- Lyman alpha emitter
- can be found with systematic wide-field narrow band survey + spectroscopy
- little information in spectra (e.g. metal?)
- luminosity selected

Quasar
z = 6.4



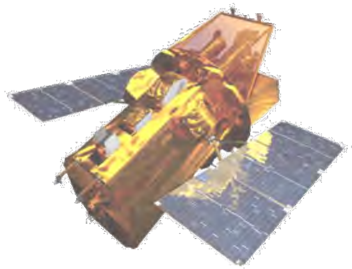
- very rare: only 10 at z>6 in SDSS
- steadily bright
- complicated spectra: difficult to interpret
- proximity effect
- luminosity-selected

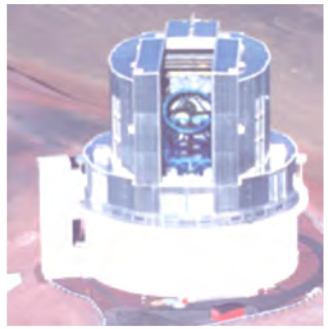
GRB
z = 6.3



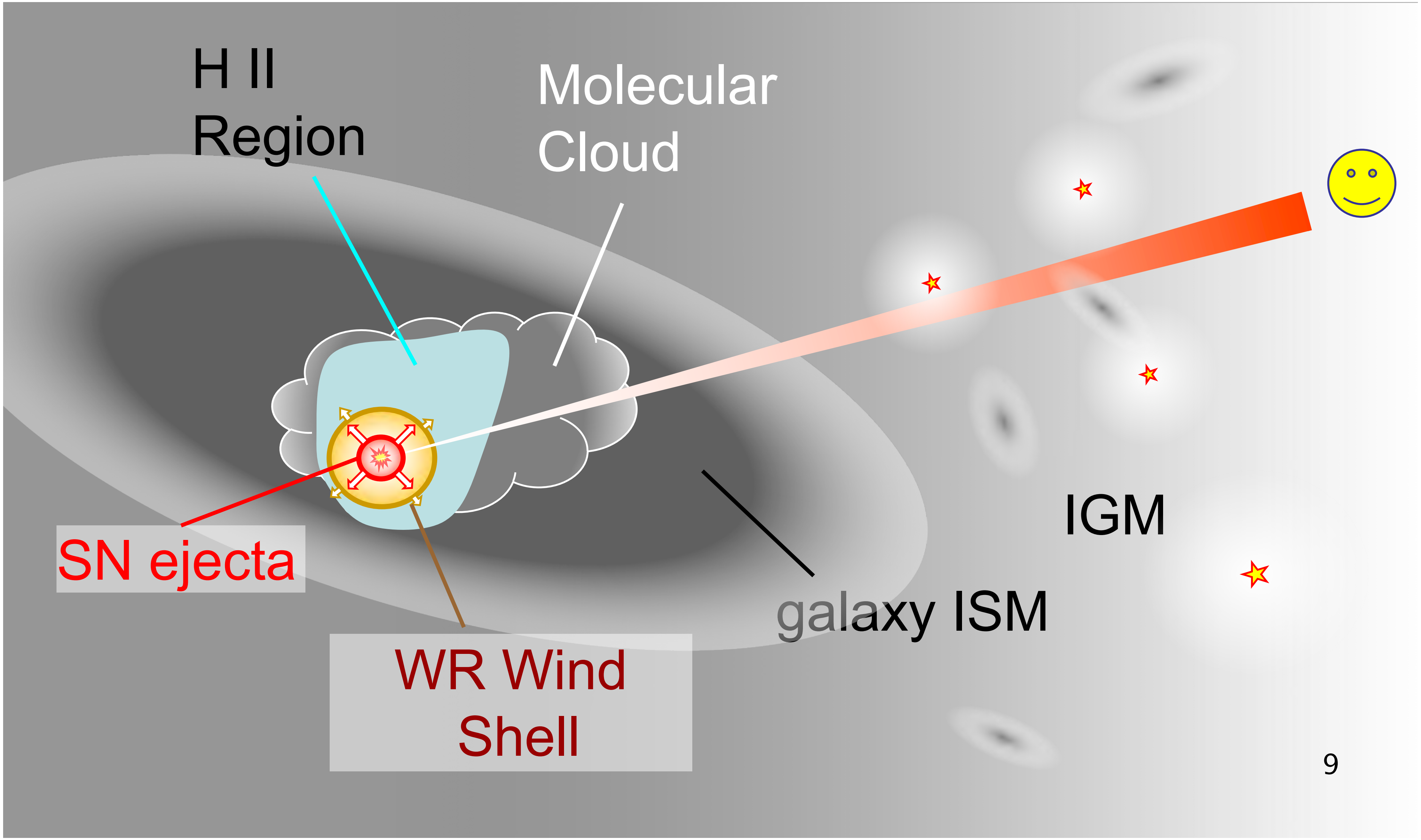
- rare: ~<5% at z>6 ?
- bright at early phase
- simple intrinsic spectra: abundant information
- no proximity effect
- sampling normal star-forming glaxy

GRB 050904
Gamma-Ray Burst at a high redshift



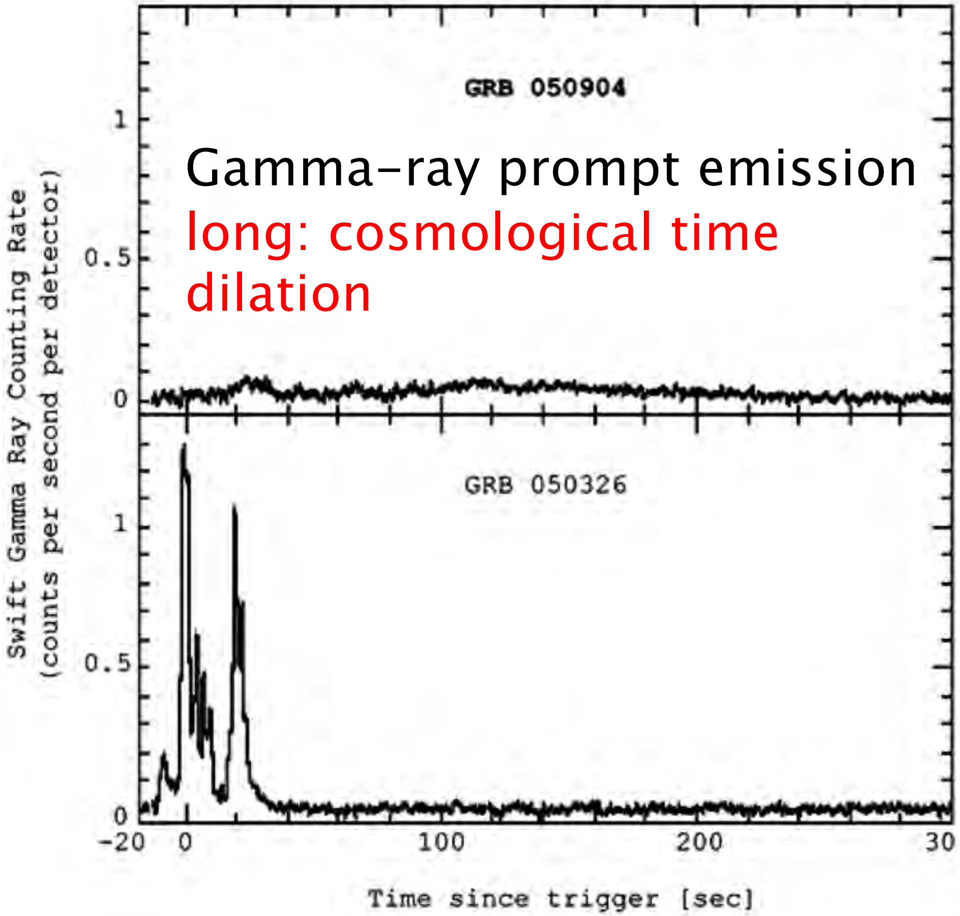


GRB Environment



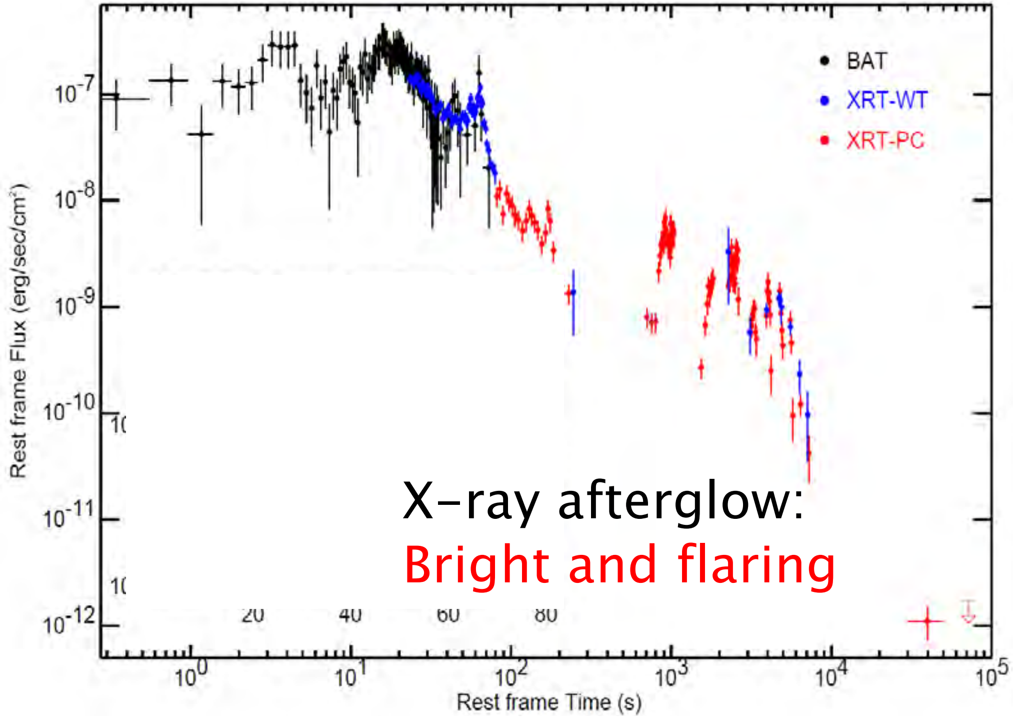
GRB 050904

Cusumano et al. 2006

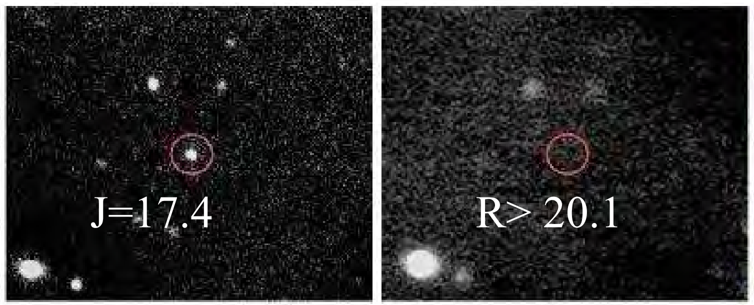


Gamma-ray prompt emission
long: cosmological time dilation

Long GRB (duration T90 = 225 s) detected by ***Swift*** on 4 September 2005, 01:51:44 UT,



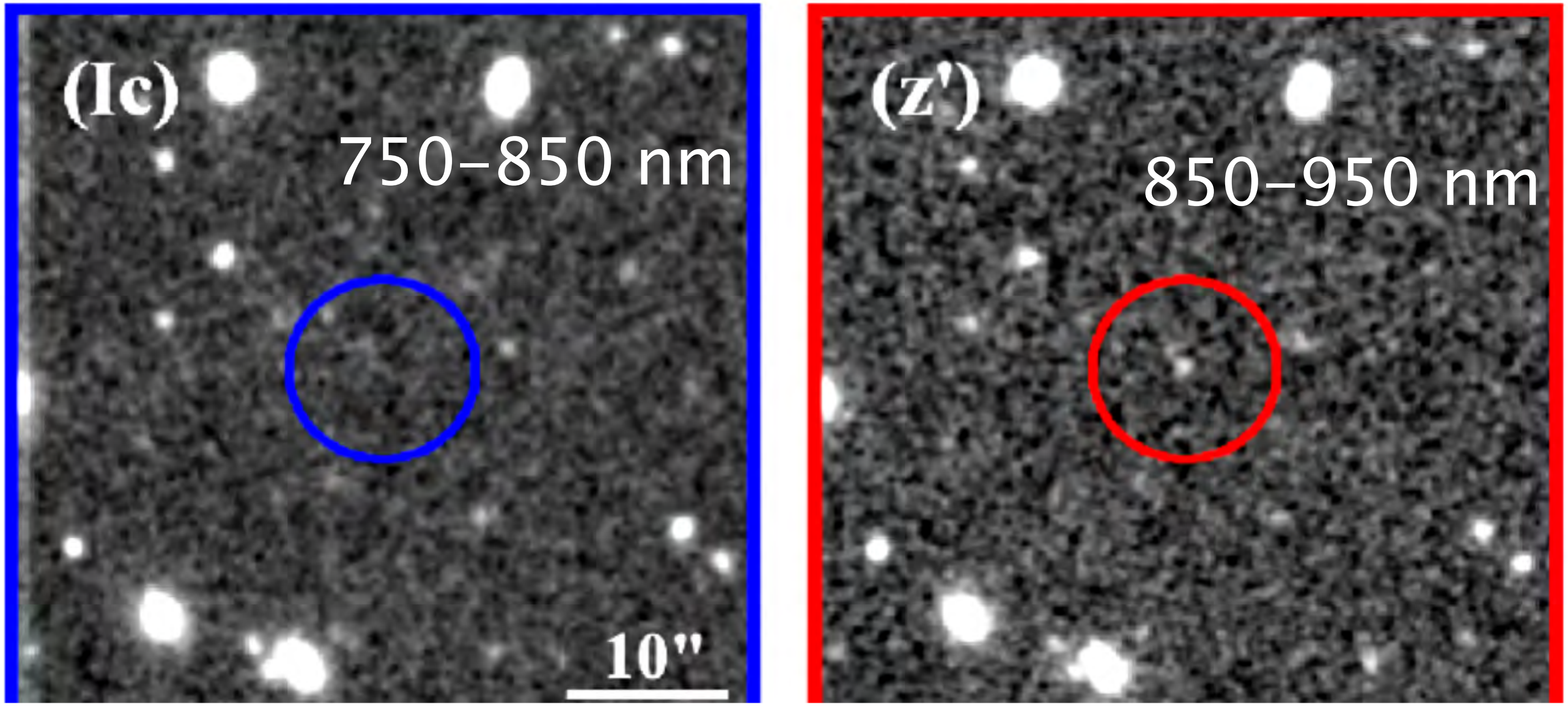
X-ray afterglow:
Bright and flaring



Bright in infrared, but dark in the optical band

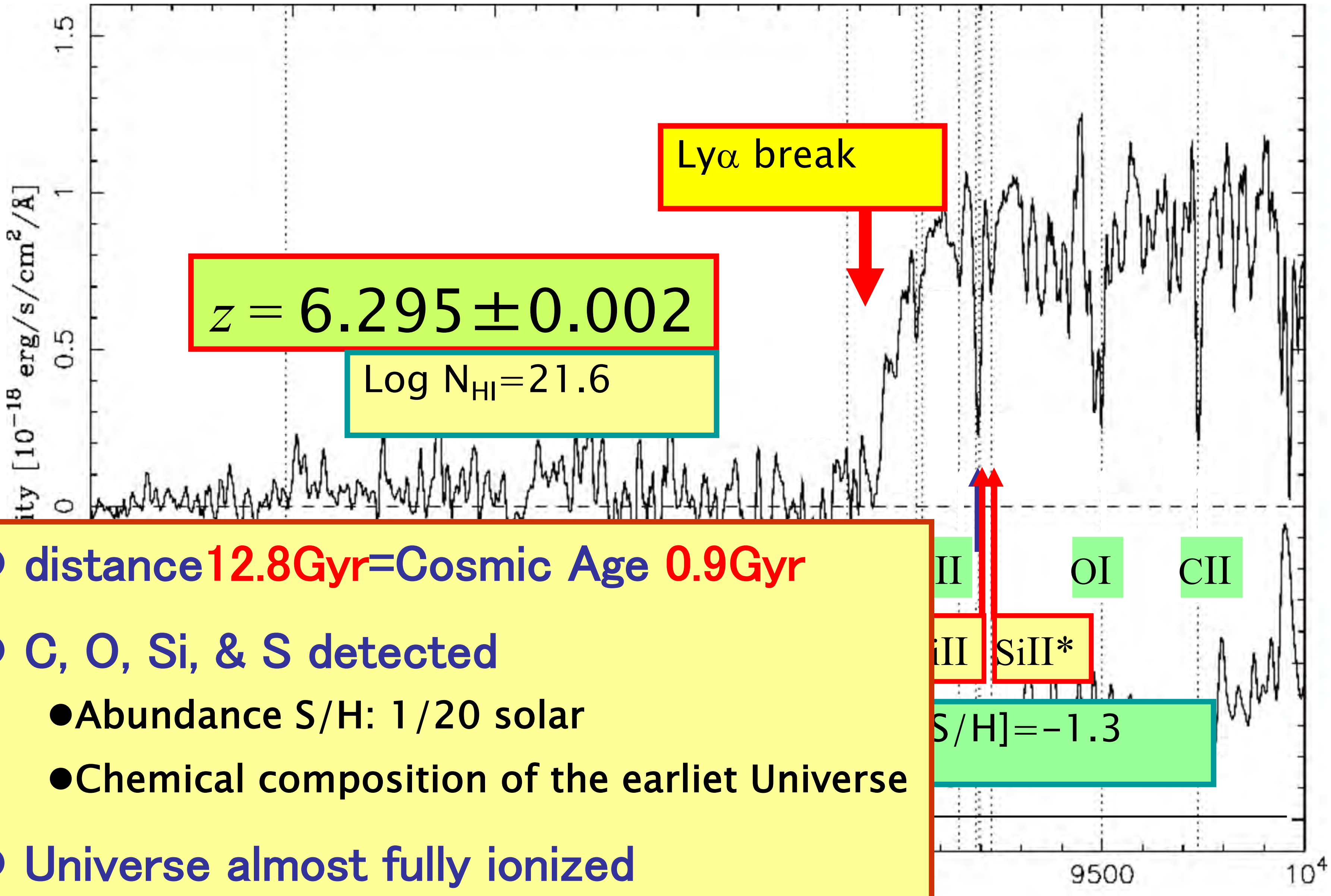
Haislip et al. 2006

Subaru Images (t_0+3 days)



- z'(AB) = 23.71 ± 0.14 mag,
- No detection in Ic band.
- → Ly break at 8500–9000 A°   .

GRB 050904 at t=3.4 d

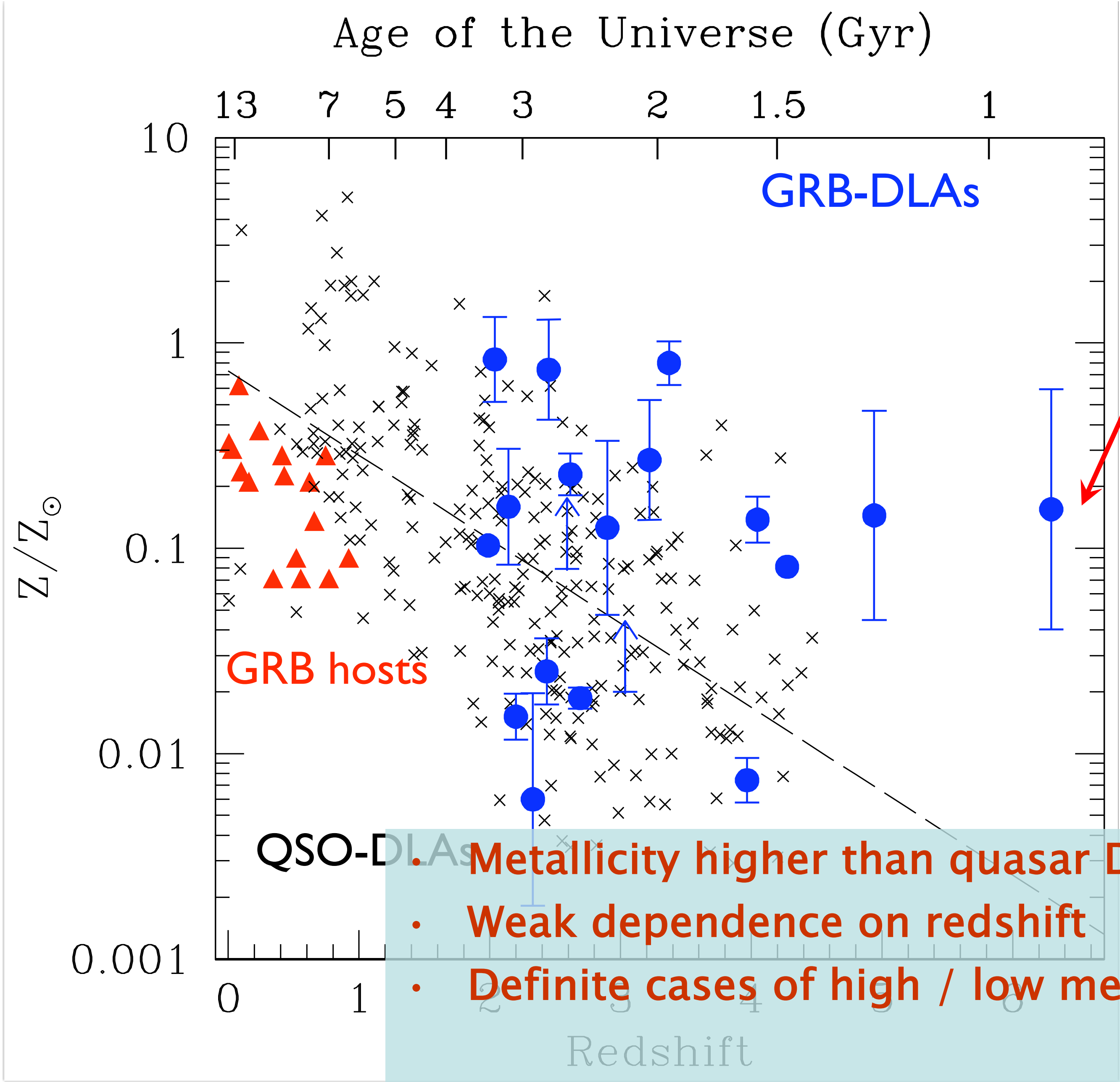


- **distance 12.8Gyr=Cosmic Age 0.9Gyr**
- **C, O, Si, & S detected**
  - **Abundance S/H: 1/20 solar**
  - **Chemical composition of the earliet Universe**
- **Universe almost fully ionized**
  - **Later than the “First Stars”**

Subaru FOCAS 4.0 hrs, $\lambda/\Delta\lambda \approx 1000$

Kawai et al. (2006)
Totani et al. (2006)

Cosmic Chemical Evolution

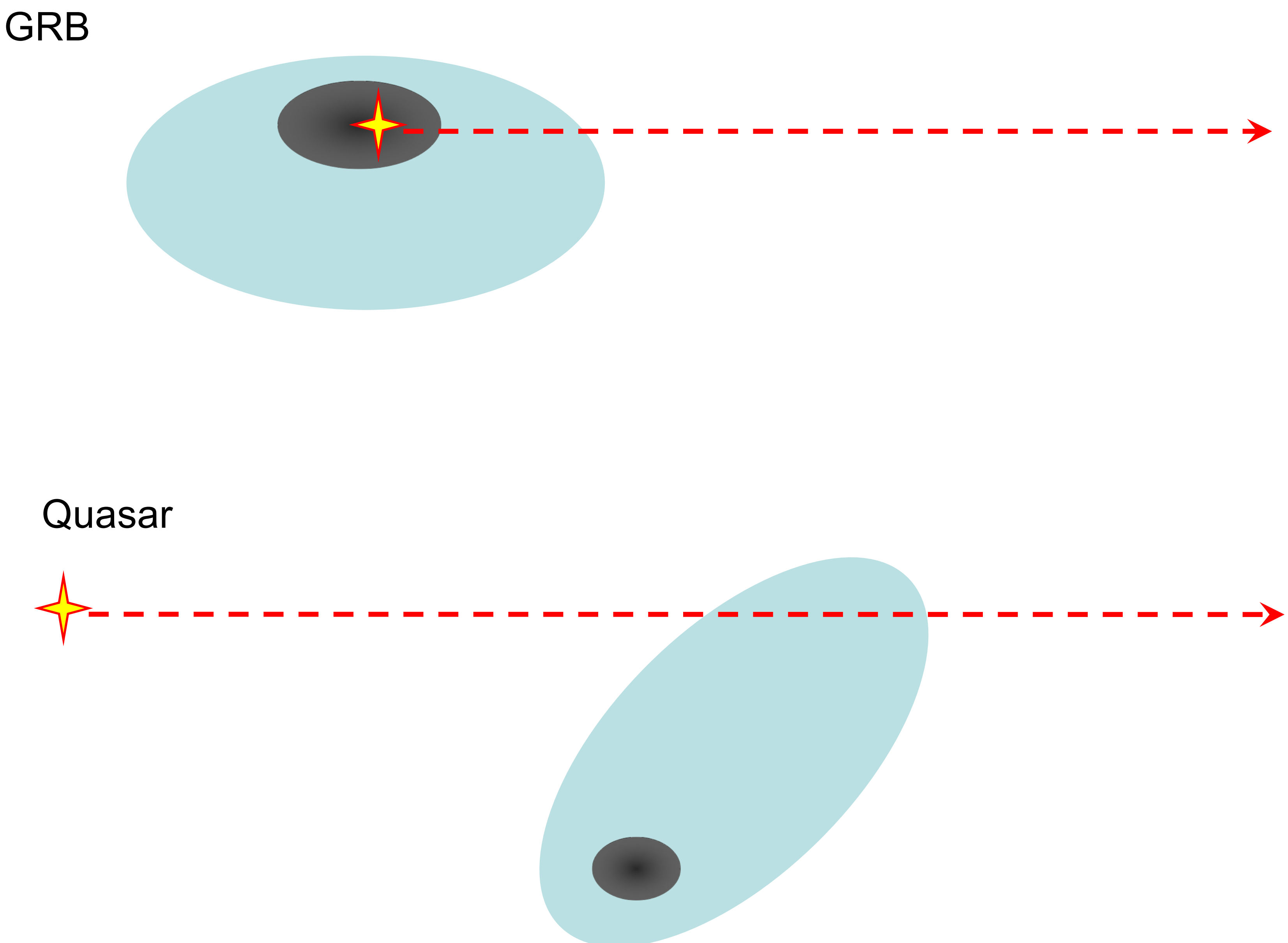


GRB 050904
NK+ 2006

Fynbo et al. 2006
Prochaska et al. 2003
Sollerman et al. 2005
Savaglio, et al. 2009

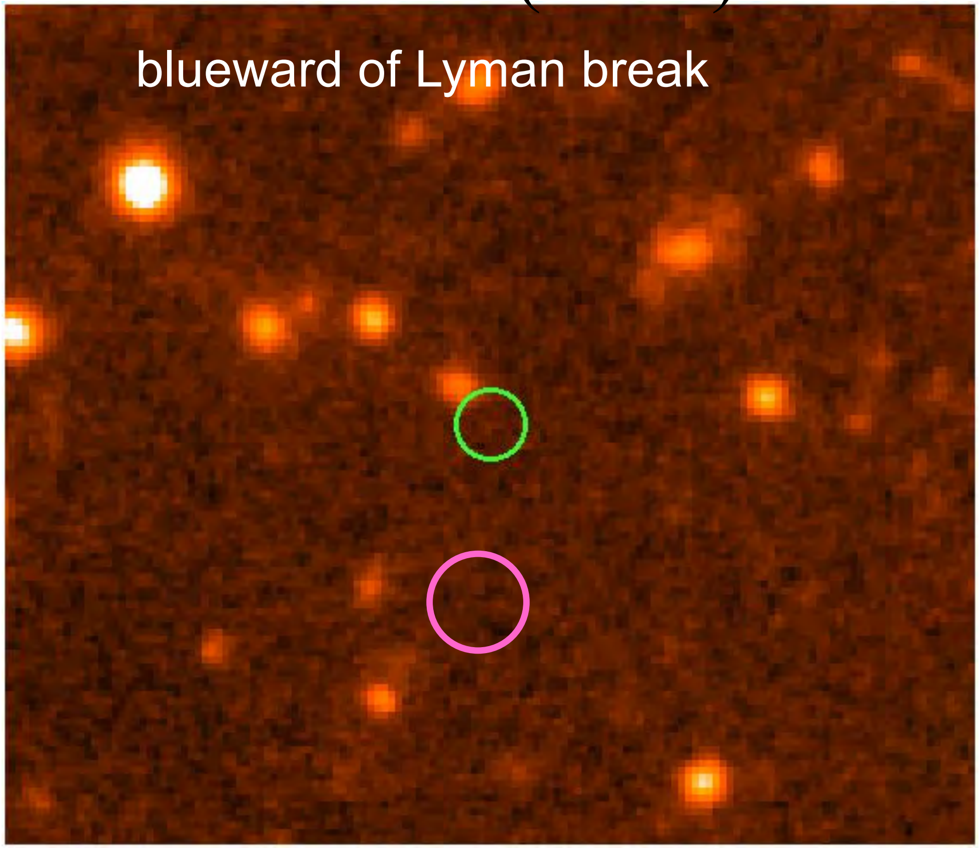
- Metallicity higher than quasar DLA
- Weak dependence on redshift
- Definite cases of high / low metallicities

DLA in GRB and Quasar



GRB 050904 Host galaxy

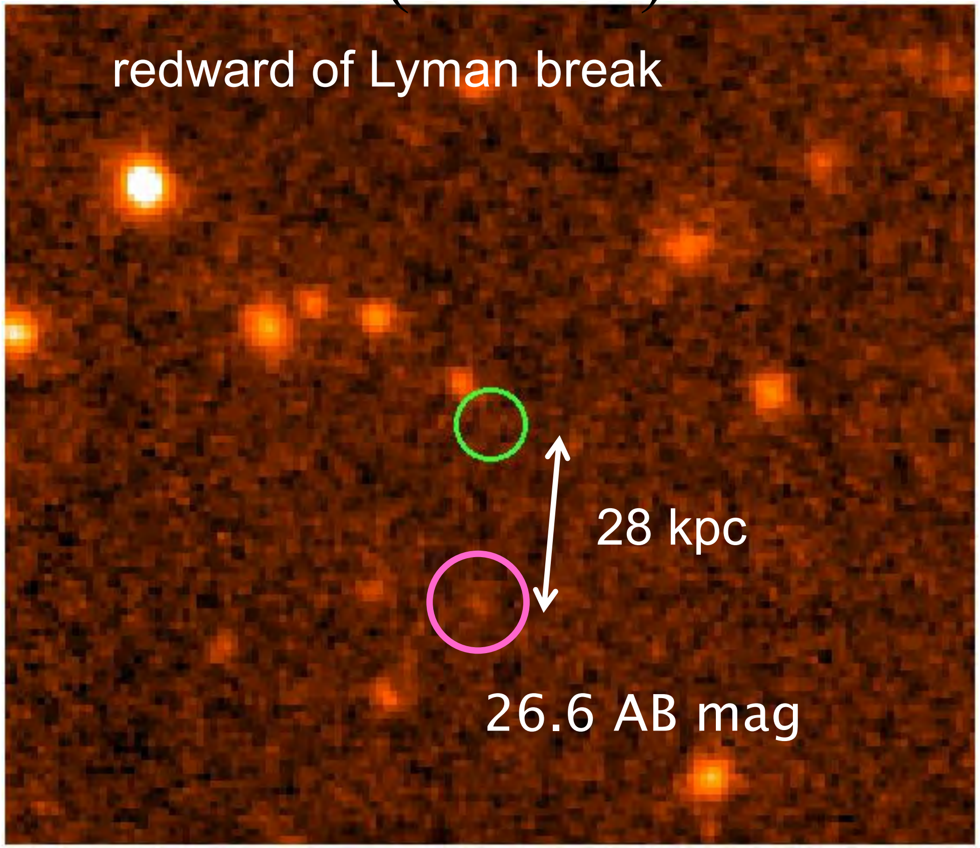
i'-band (24 ks)



Dec 27 '05--Jan 01 '06
(t_0+115~119d)

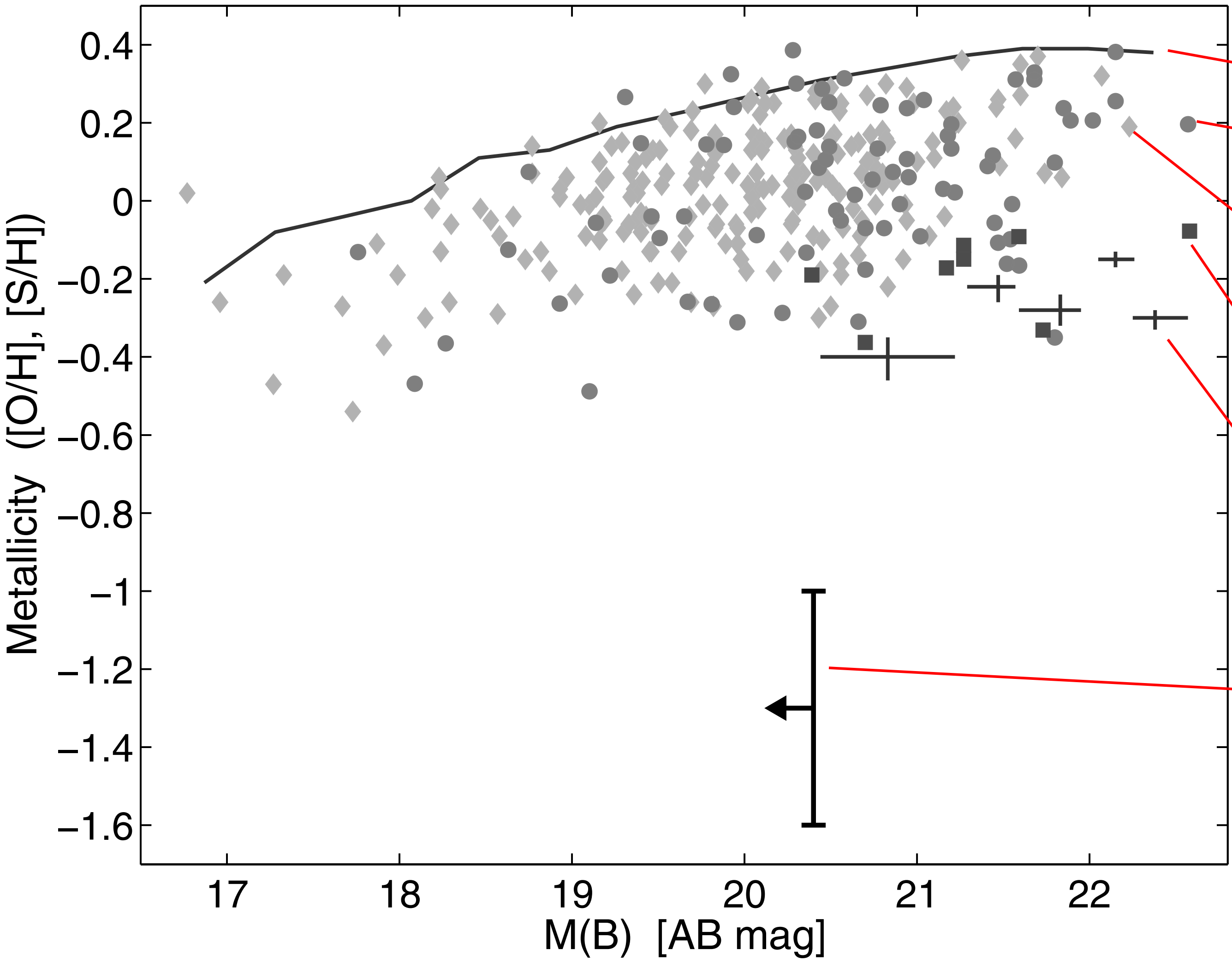
Aoki et al. 2006

NB921 (56.7 ks)



> 26.4 AB mag (3σ)
M_{1260} > −20.4 mag → $L < L_*$
SFR < 7.5 M_{sun}/yr

GRB 050904 Host galaxy

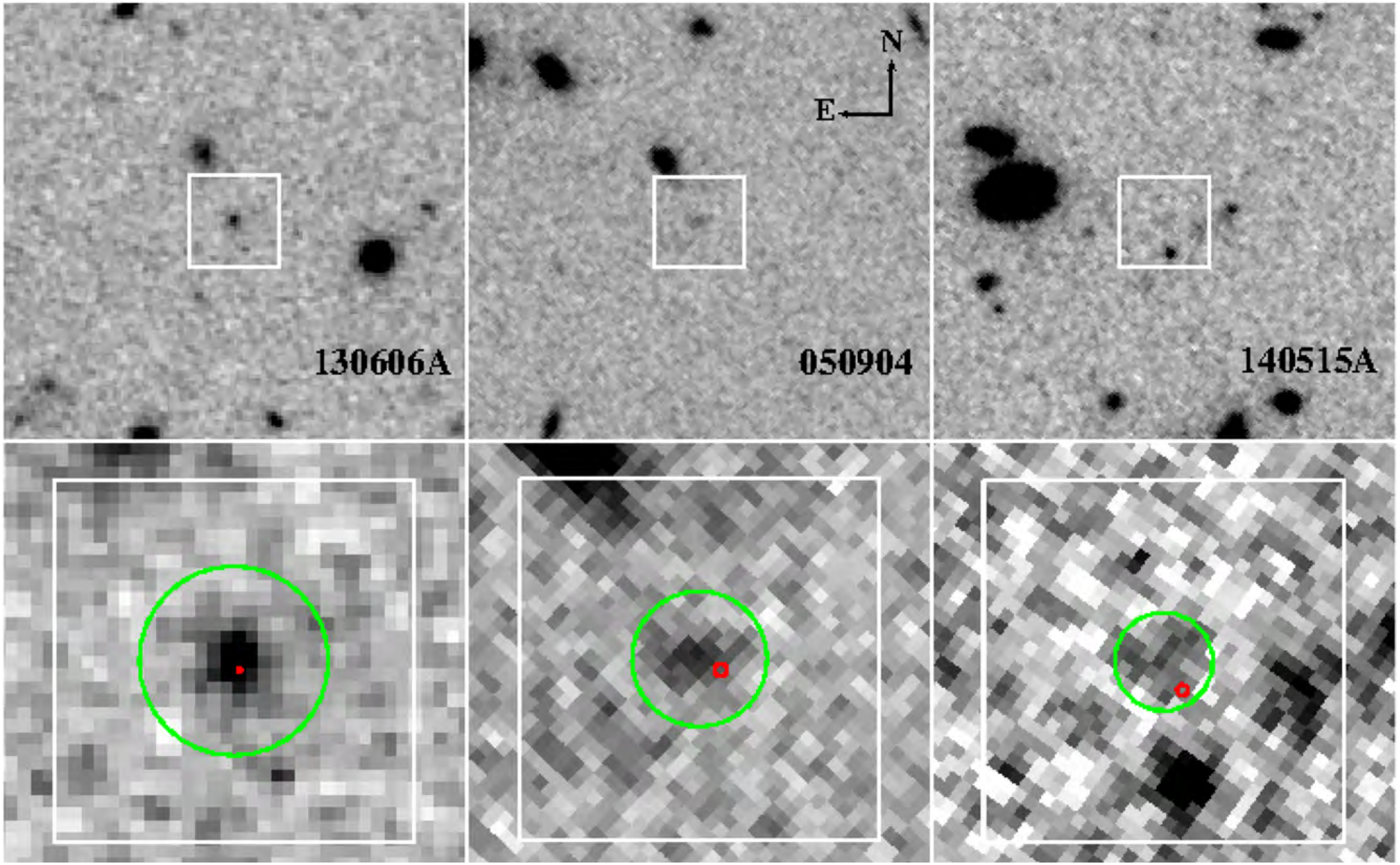


$M_{2200} > -20.3$ mag → $L \leq L_*$

SFR < 5.7 M_{sun}/yr

Berger et al. 2007

High-z GRB Host galaxy

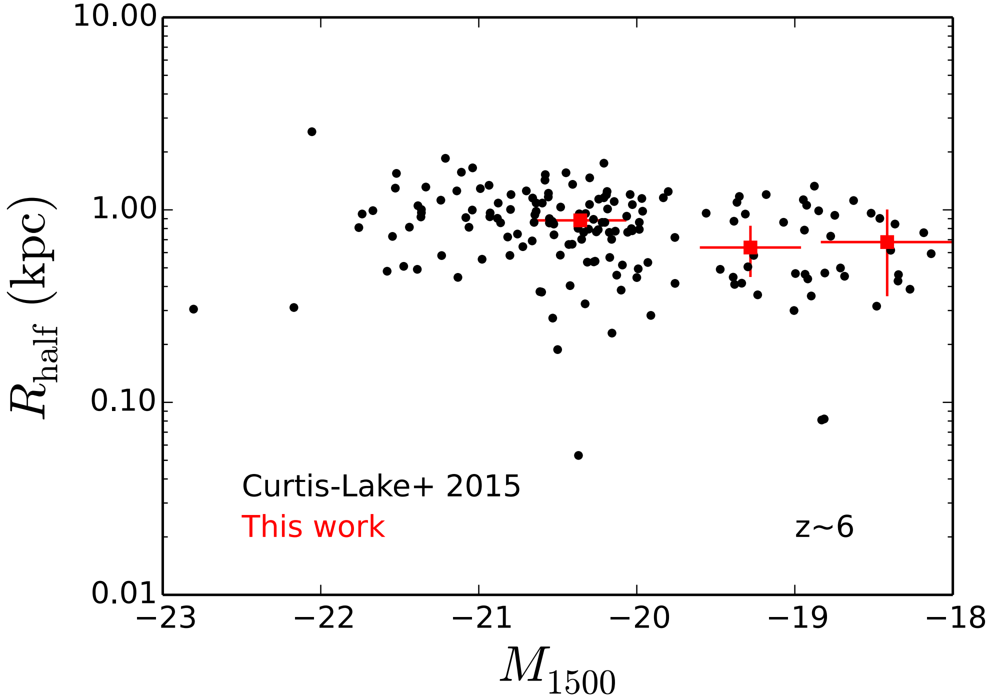


m_{AB} = 26.34+0.14−0.16 | 27.56+0.18−0.22 | 28.30+0.25−0.33
z = 5.913 | z = 6.295 | z = 6.327
GRB 130606A | GRB 050904 | GRB 140515A

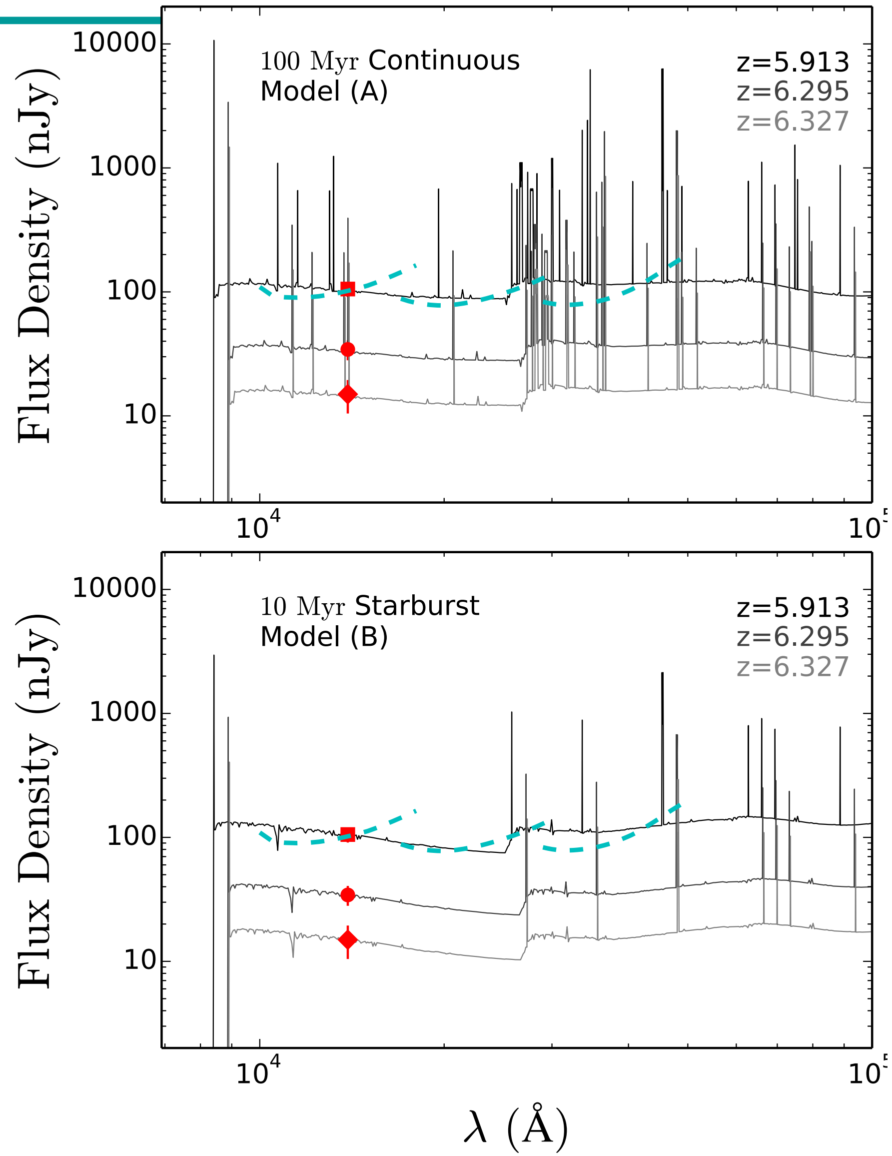
HST WFC3 F140 (~1.4um) 10791s, 13488s, 10791s

McGuire et al. 2016

High-z GRB Host galaxy



half light radius compared with LBGs



SED models vs. NIRSpec sensitivity
(R=1000, S/N=3, 10ks)

McGuire et al. 2016

GRB 140515A (z=6.327)

GTC +14.2 hr, 1800s x 3, R=1600

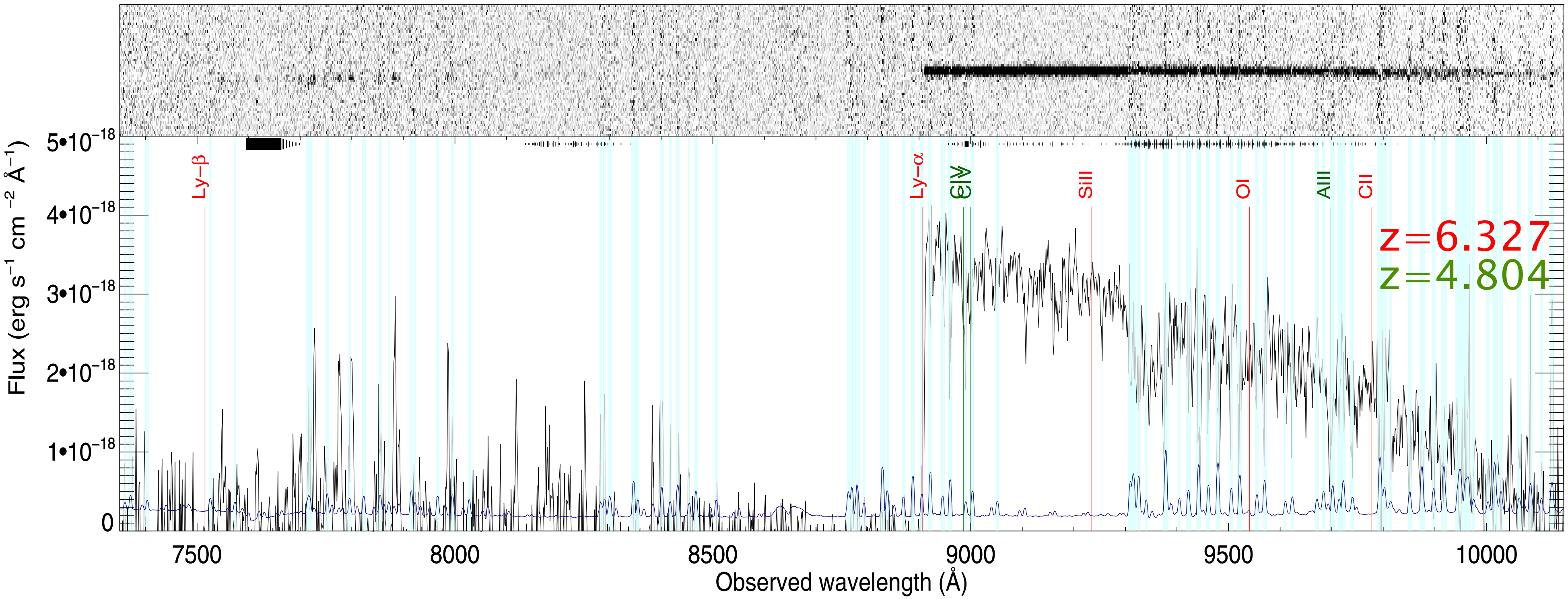


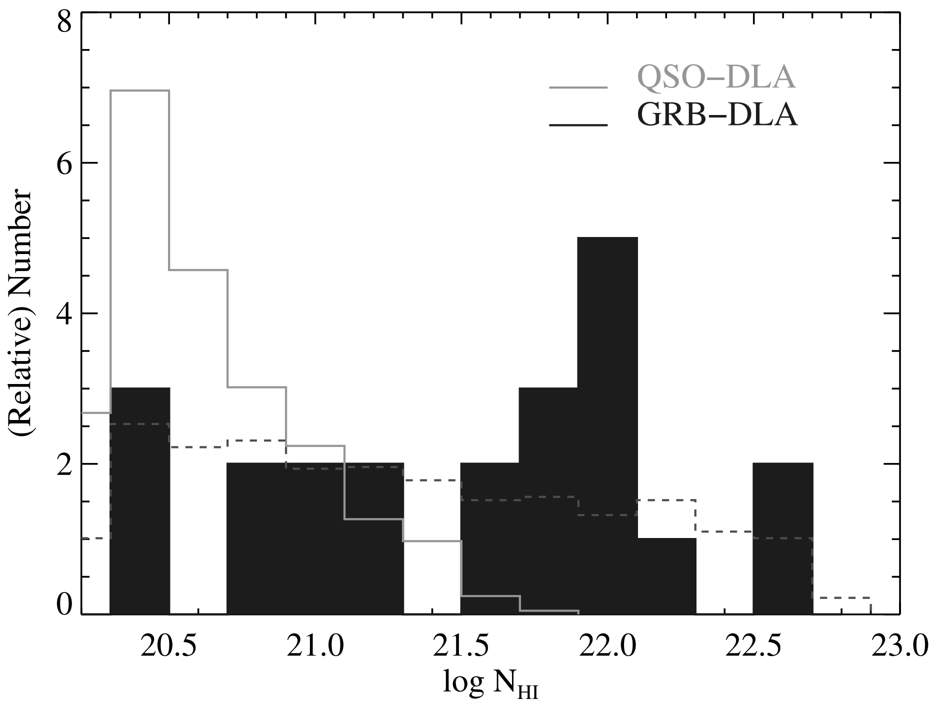
Fig. 3. Flux-calibrated GTC spectrum: Lyα lines at z = 6.327 are shown in red, while the lines of the intervening system at z = 4.804 are shown in green. Black lines at the *top of the panel* mark telluric absorptions, with the thickness of the line indicating the absorption strength. At the *bottom* the error spectrum is shown (blue), while the parts of the spectrum where the strength of the sky emission lines is strong enough to leave significant residuals have been masked with light blue columns. The spectrum has been smoothed with a Gaussian filter.

Si II λ1260, O I λ1302, C II λ1334 upper limits

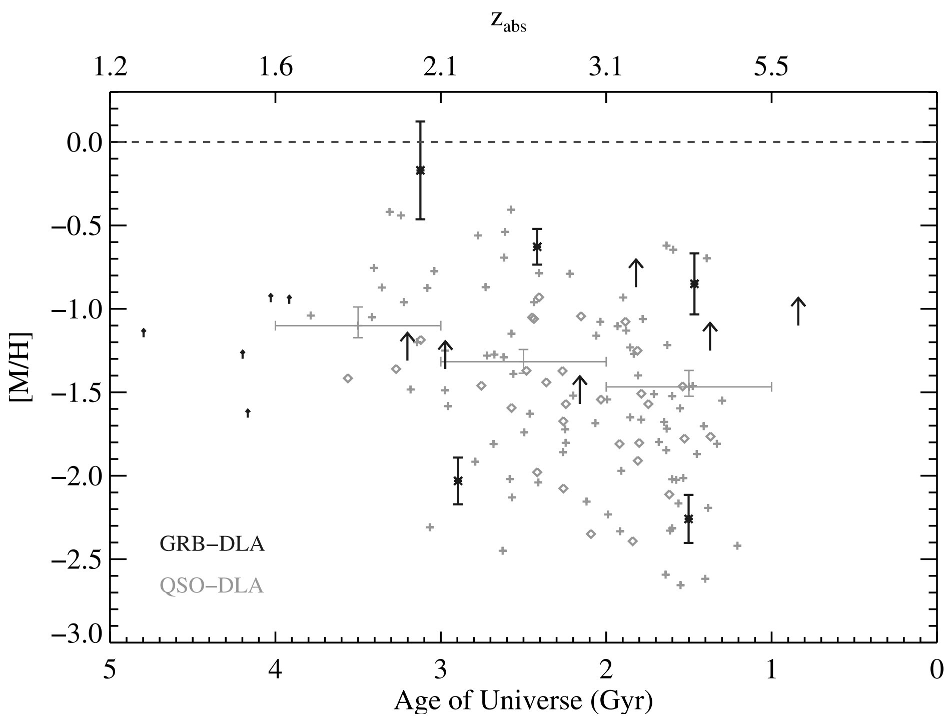
➔ [Si/H] ≤ −1.4, [O/H] ≤ −1.1, [C/H] ≤ −1.0.

Melandri et al. 2015

GRB DLA vs QSO DLA —Gas, Metals, and Dust



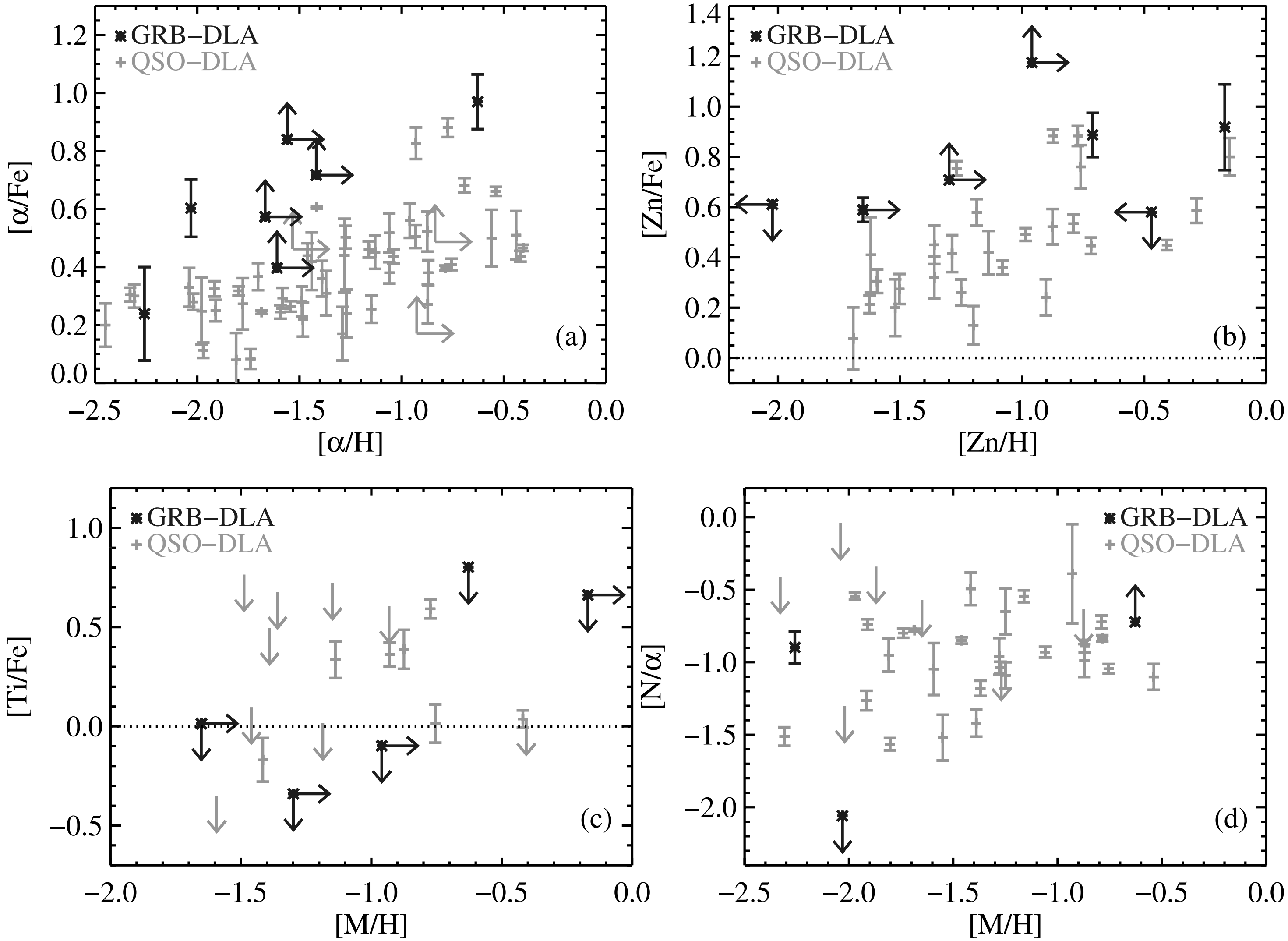
Larger N_H



Diverse metallicity,
no evidence for being metal-rich
(but GRB lines often saturated)

Prochaska et al. 2007

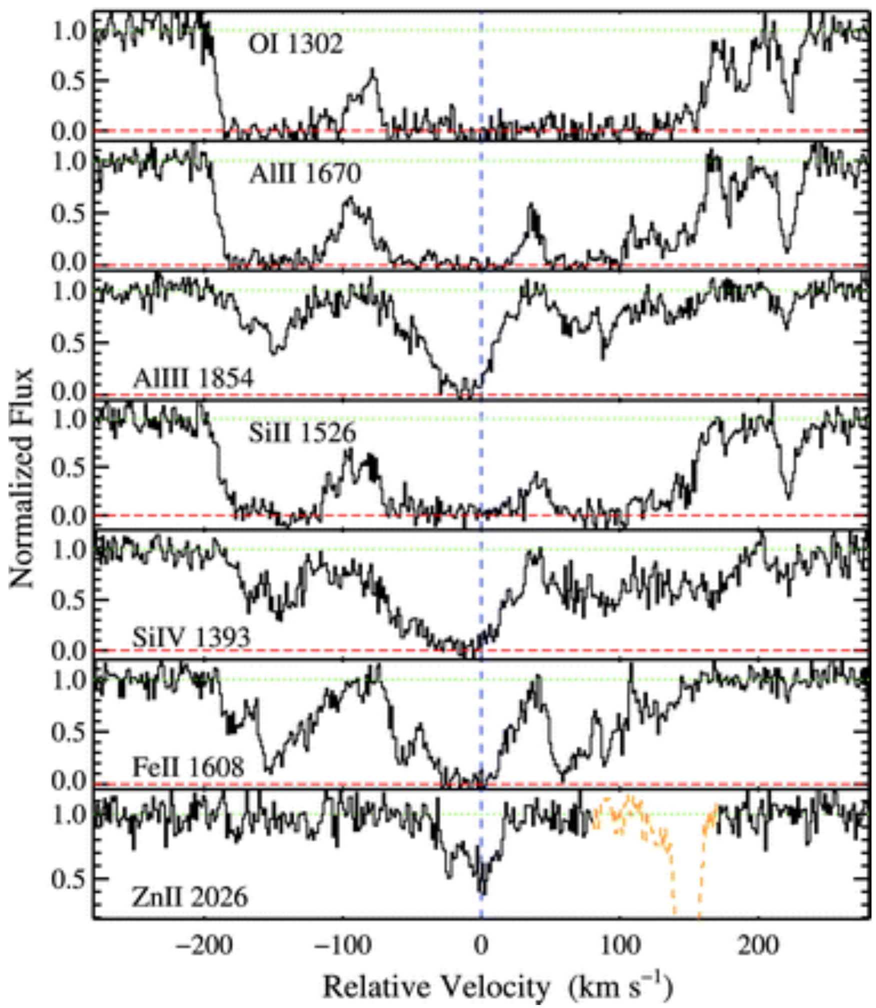
GRB DLA vs QSO DLA —Gas, Metals, and Dust



- Large [α/Fe], [Zn/Fe]➔ Enhanced by nucl. synth. of massive stars
- Low [Ti/Fe] ➔ Refractory metals depleted on dust grains
- Diverse [N/ α] ➔ diverse SF history

Prochaska et al. 2007

GRB DLA vs QSO DLA —Velocity fields

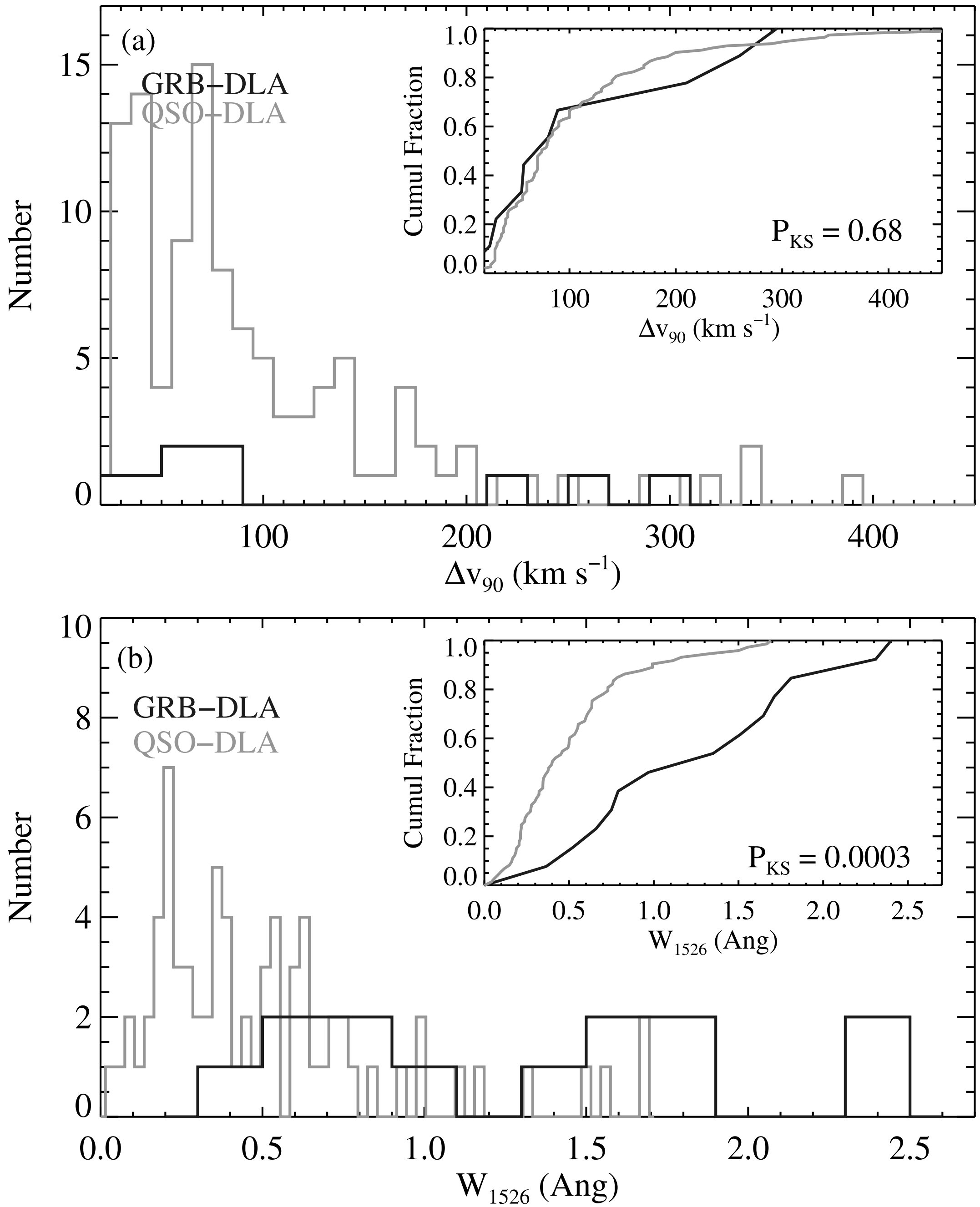


GRB 050820 (z=2.61469)

GRB 050820 (z=2.61469)

Prochaska et al. 2008

GRB DLA vs QSO DLA —Velocity fields

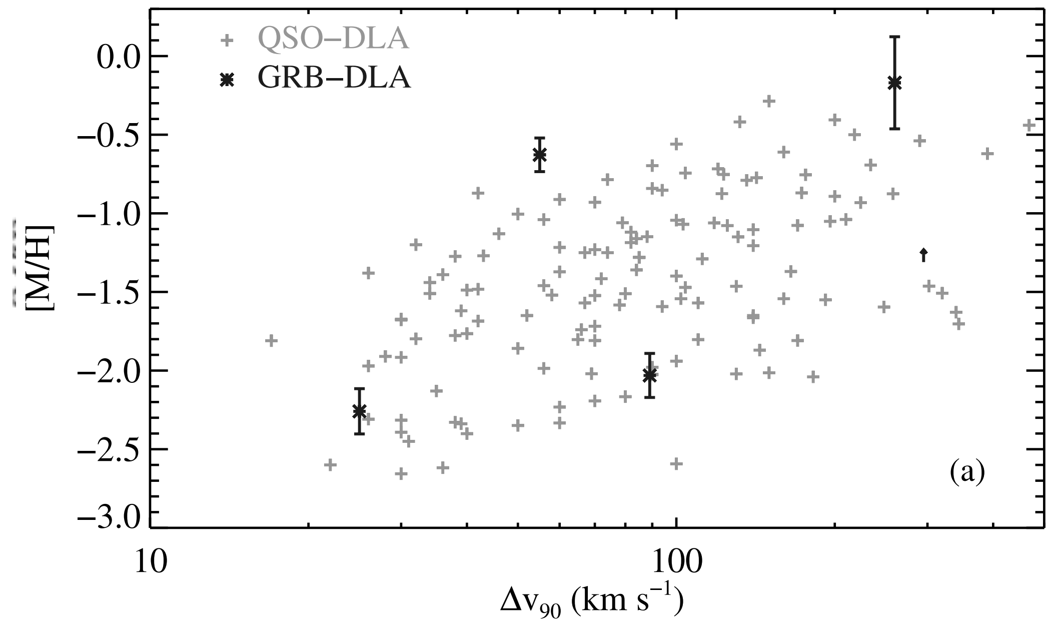


- The distributions of Δv_{90} values similar
- median $\Delta v_{90} \approx$80 km/s
- Significant tail >200 km/s

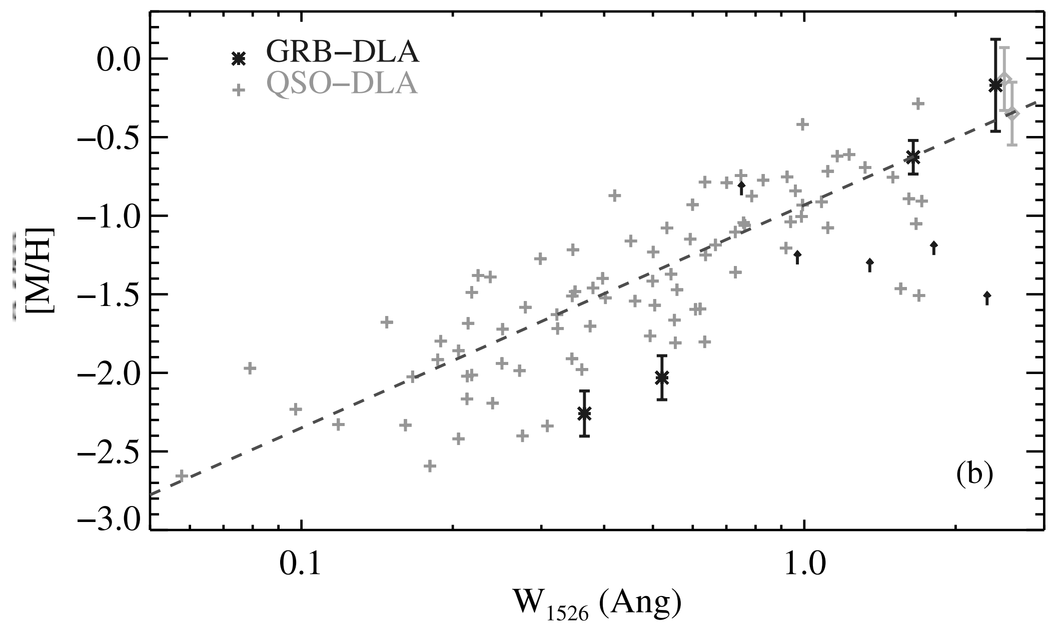
- GRB-DLAs: significantly larger EW of Si II 1526

Prochaska et al. 2008

GRB DLA vs QSO DLA —Velocity fields



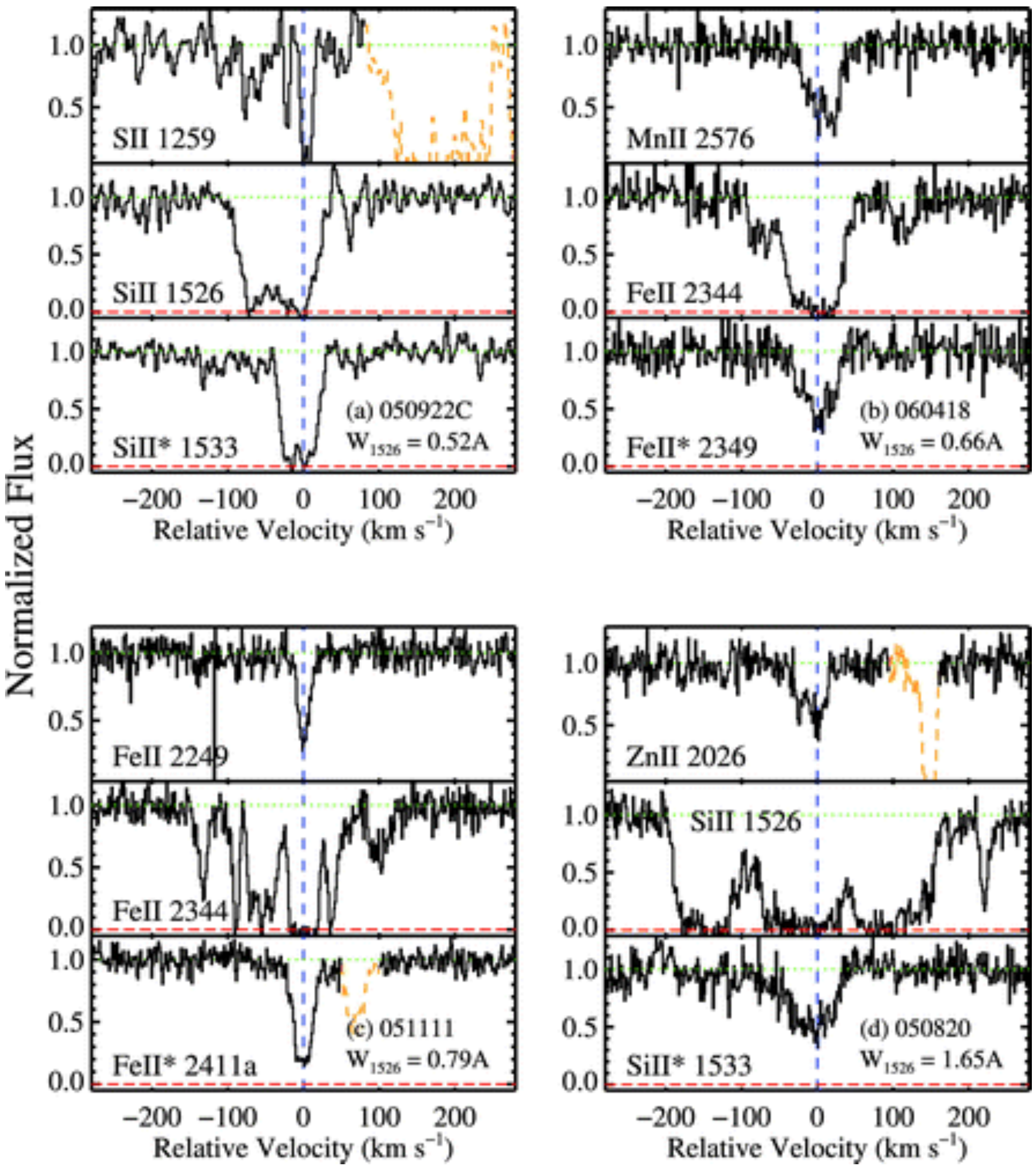
- QSO-DLA:
  Δv_{90} – [M/H] correlation



- QSO-DLA: tight correlation W1526 – [M/H]
  - Mass-metallicity → halo dynamics
- GRB-DLA: similar correlation, maybe steeper
  - → Galactic-scale outflow

Prochaska et al. 2008

GRB DLA vs QSO DLA —Velocity fields

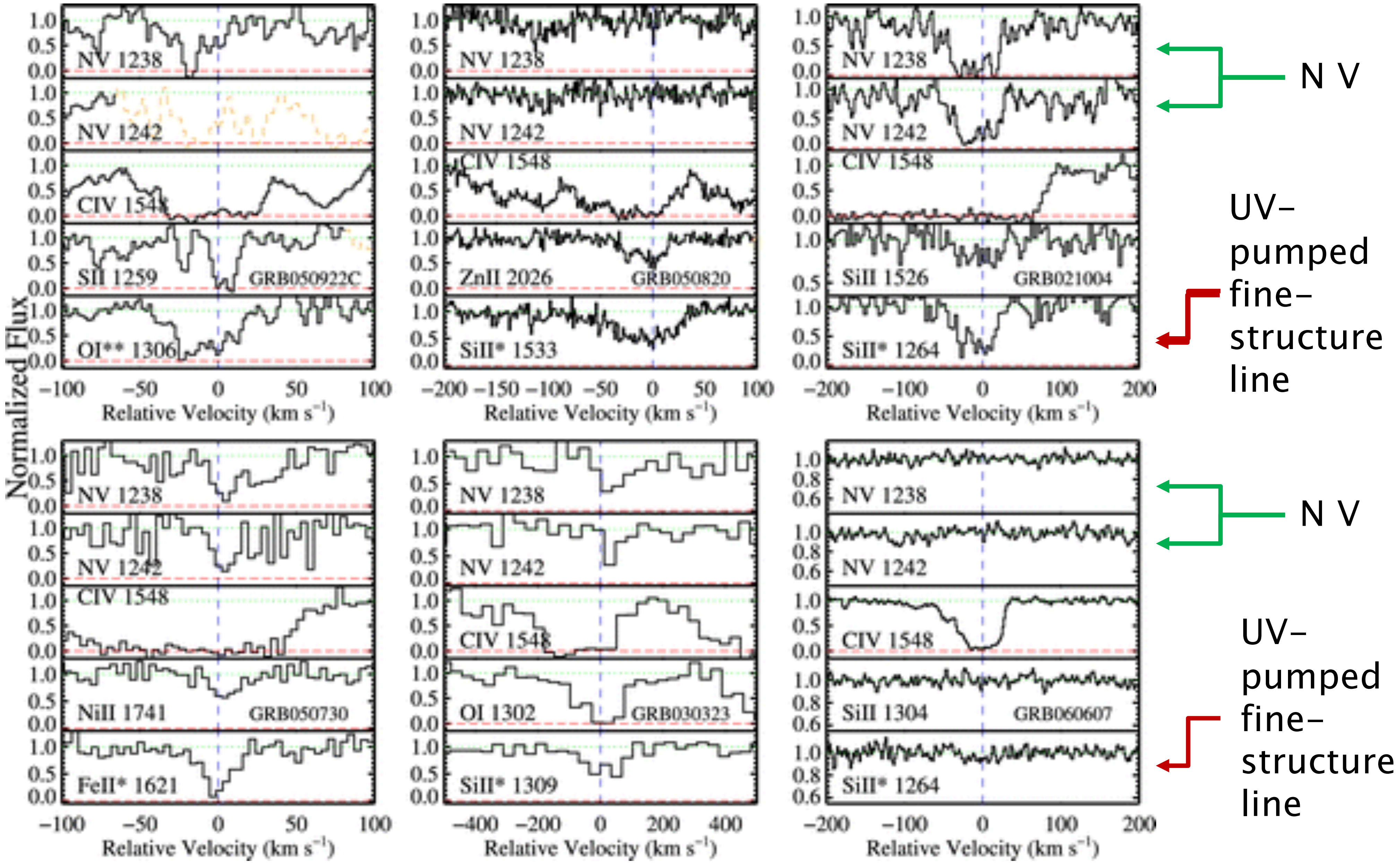


- 4 GRB-DLAs
  - Top: weak line
  - Middle: strong line
  - Bottom: fine structuire line (at <1kpc of GRB)

- Fine structuire line:
  - UV pumping at <1kpc of GRB
- Strong line:
  - Velocity components at > 1 kpc
  - Outflow and inflow on galactic scale

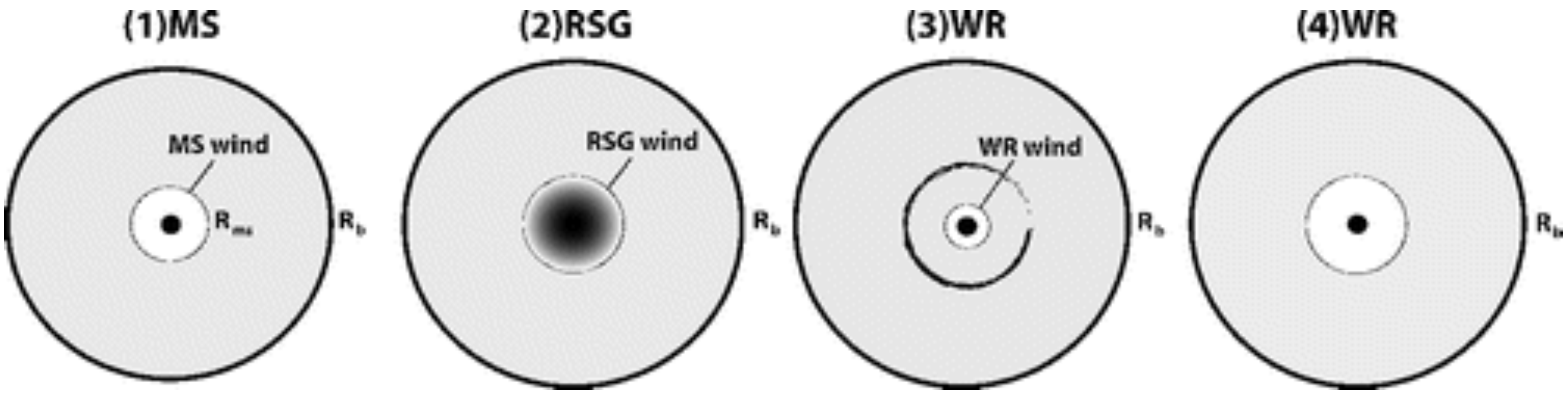
Prochaska et al. 2008

GRB N V absorption at $z \approx z_{GRB}$

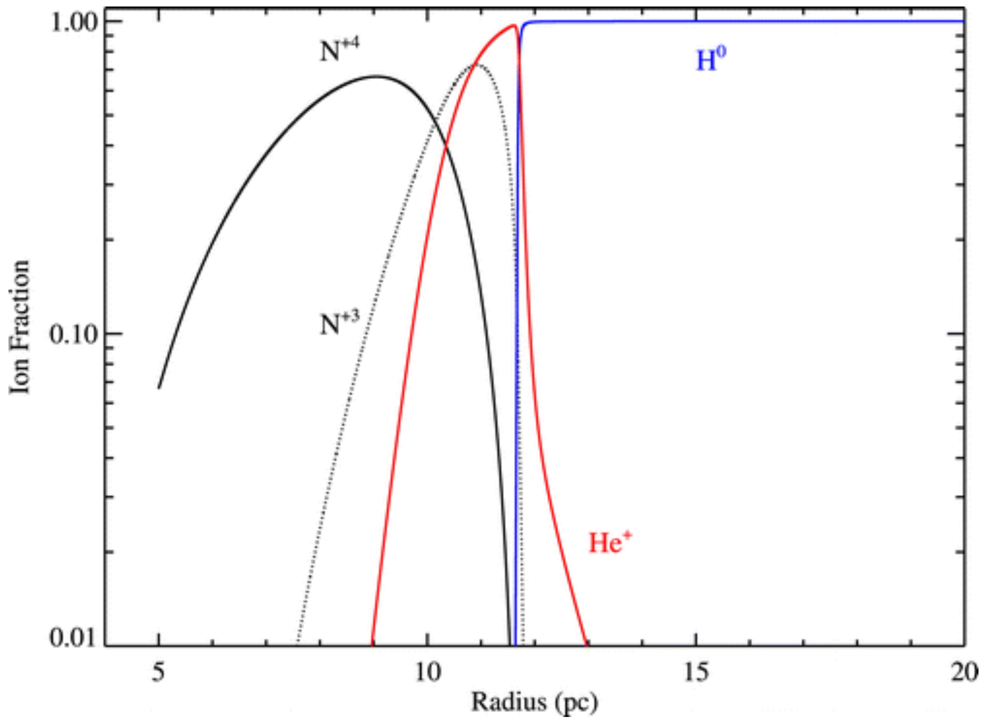


Prochaska et al. 2008b

GRB N V absorption at $z \approx z_{GRB}$



Stellar evolution: MS to WR shell



Ion fraction X_i/X vs. distance

- Constant density n = 10/cc
- L integrated t=10-1000 s

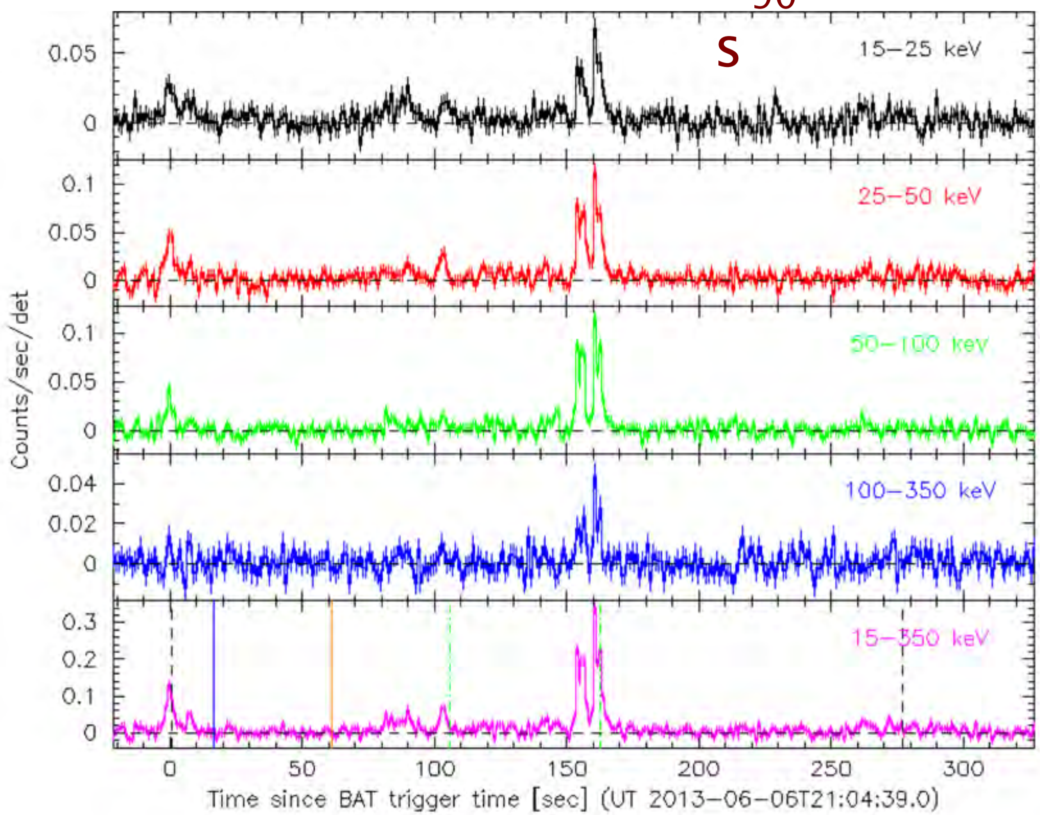
- → N v from r< 10 pc

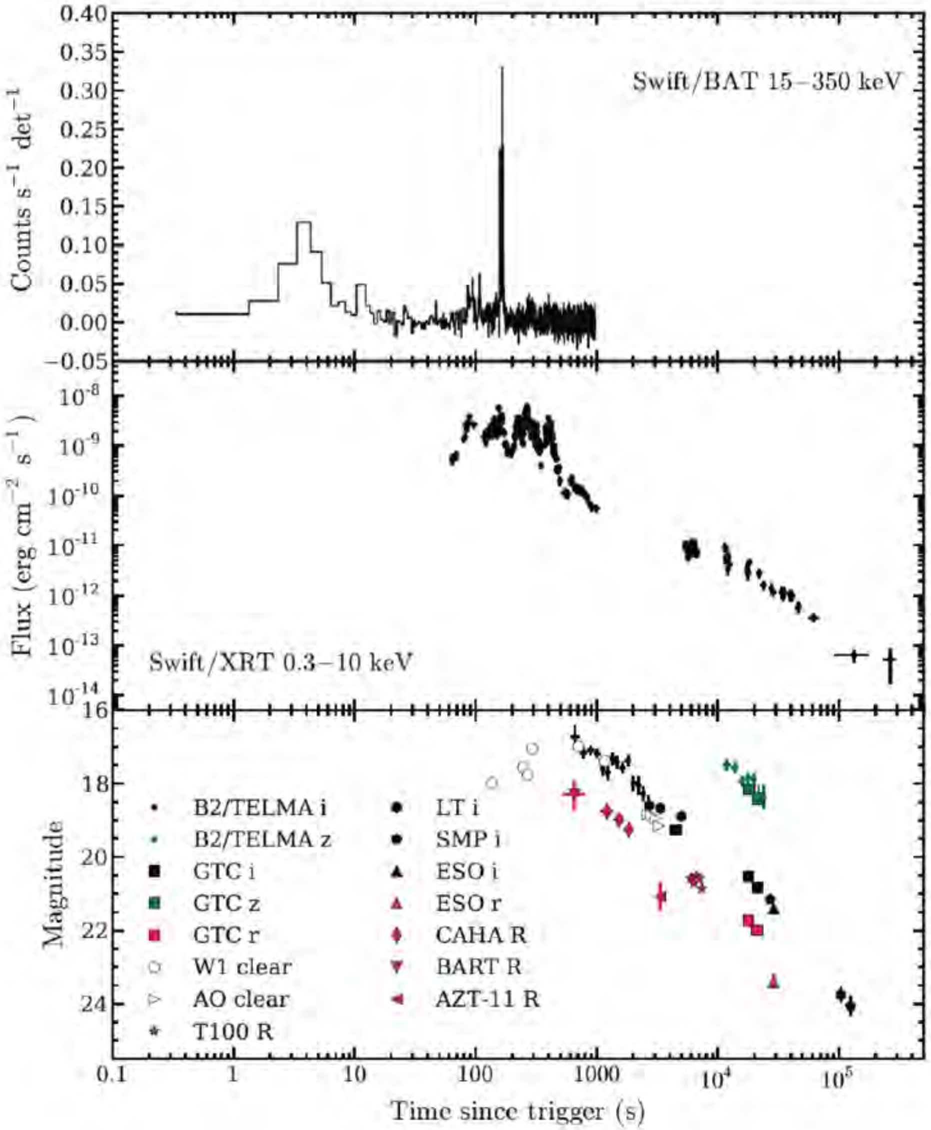
Prochaska et al. 2008b

GRB 130606A

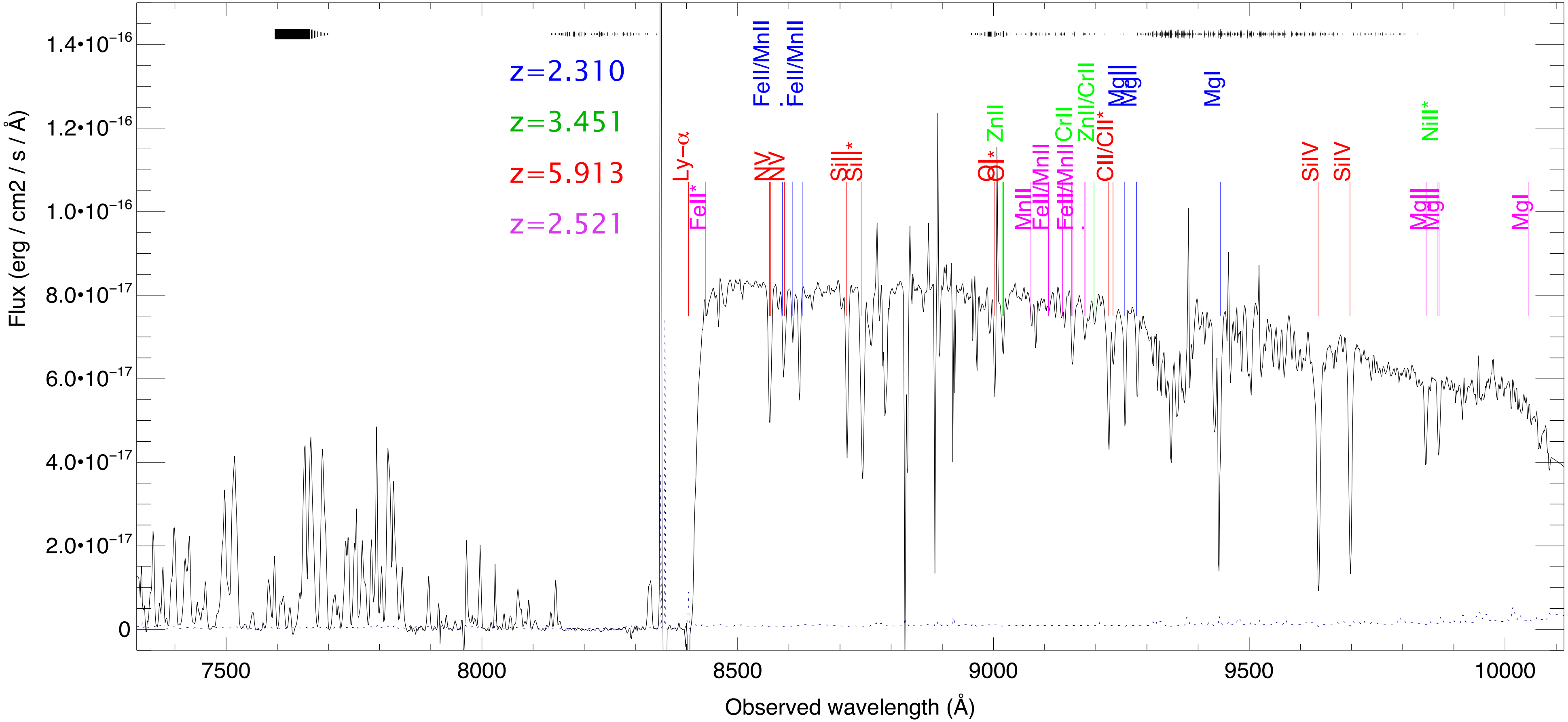
- Bright GRB at z=5.9
- Optical Afteglow spectroscopy

Swift BAT T_{90}=279 s



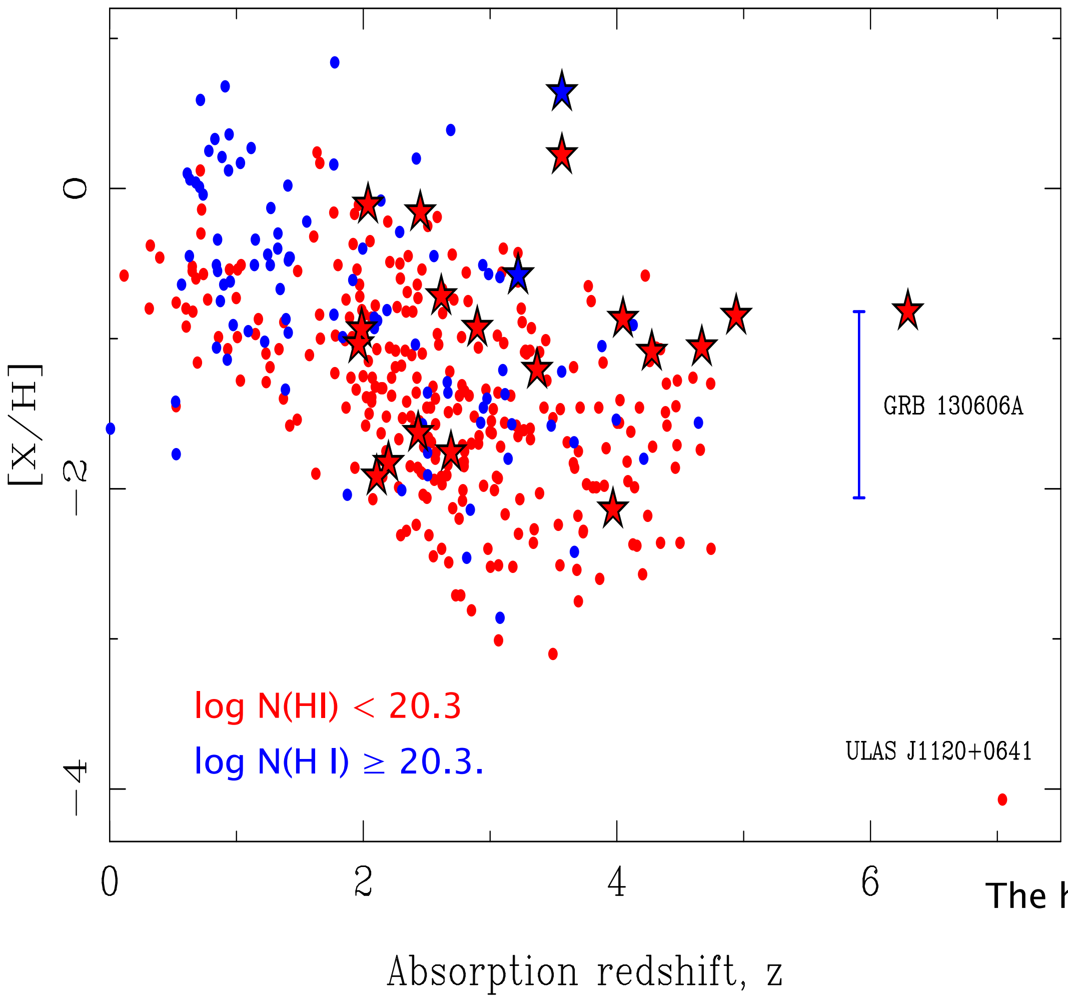


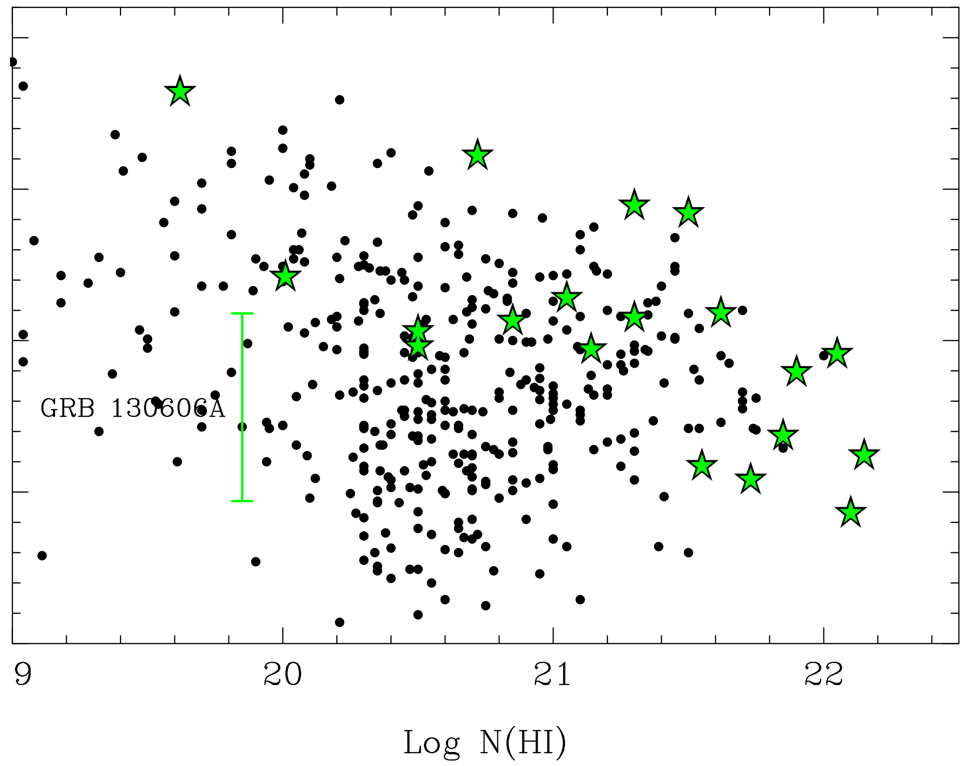
GRB 130606A GTC



Castro-Tirado et al. 2013

GRB 130606A

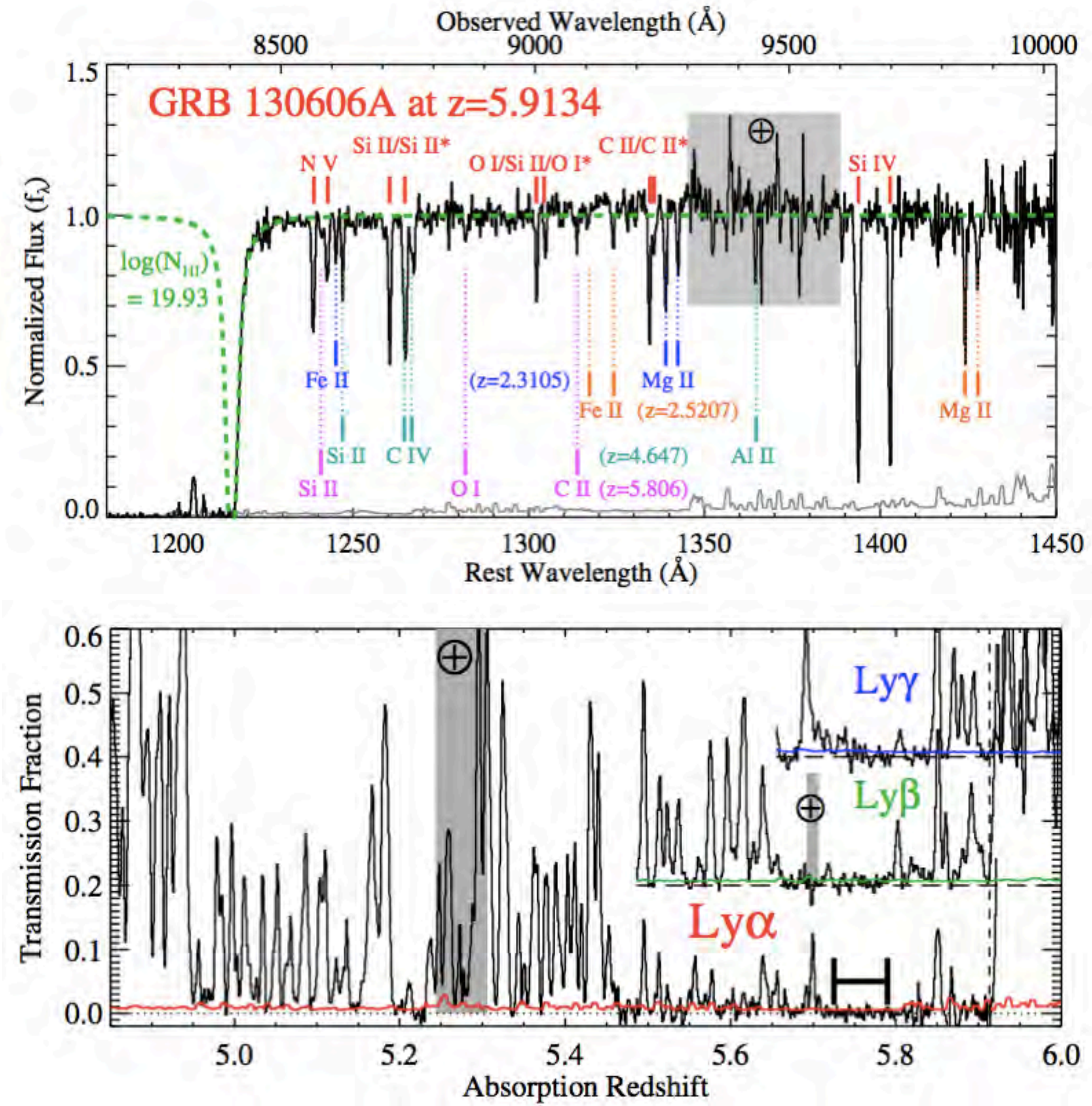




The host galaxy is a sub-DLA (log N (H I) = 19.85 ± 0.15)

Castro-Tirado et al. 2013

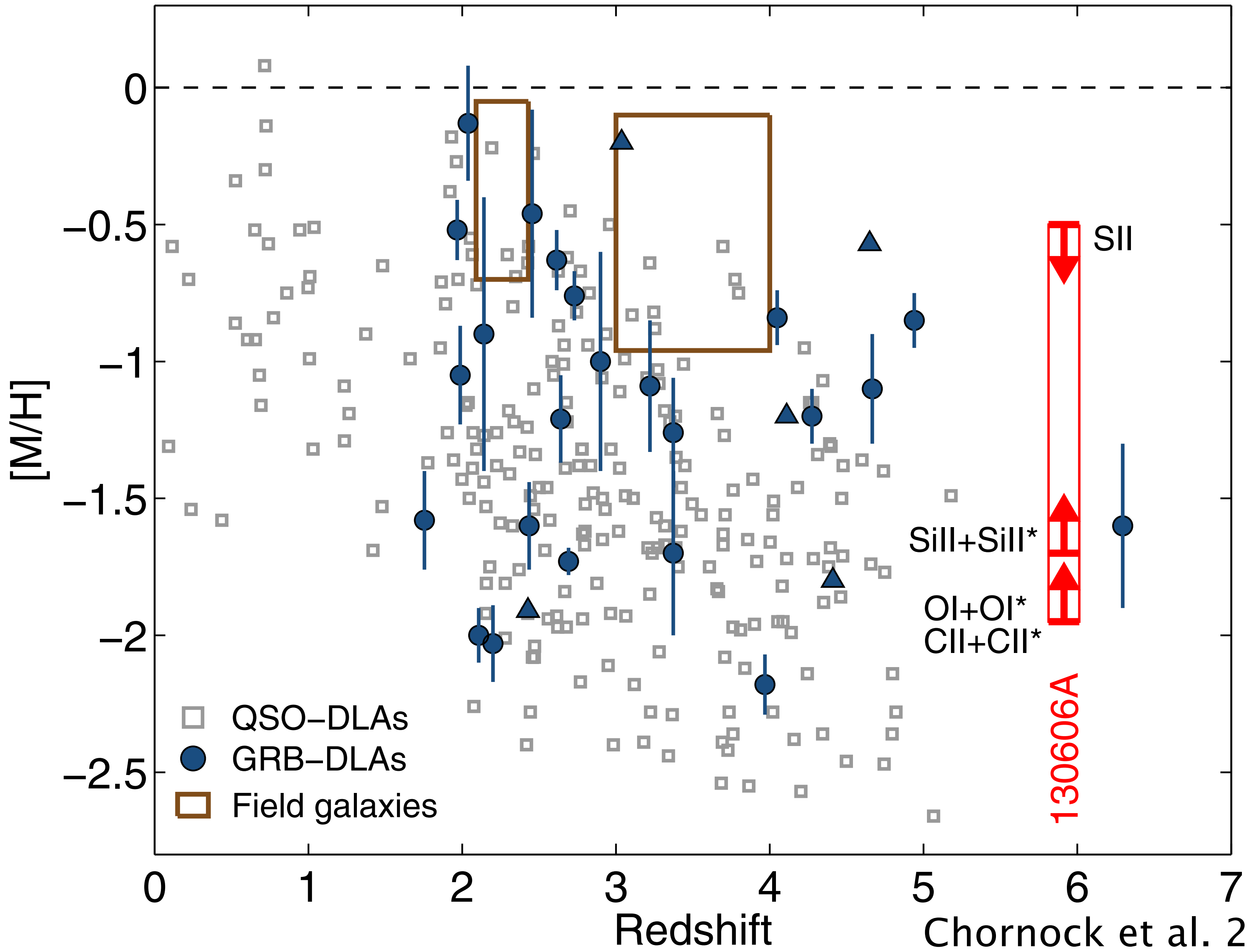
GRB 130606A — GMOS



- **ultra-high S/N spectra taken by Gemini, GTC, Magellan, Subaru, ...**
- **host HI at most $N_{HI} < 10^{19.8}$ cm^{-2}, good for IGM study!**
  - c.f. $10^{21.6}$ for GRB 050904

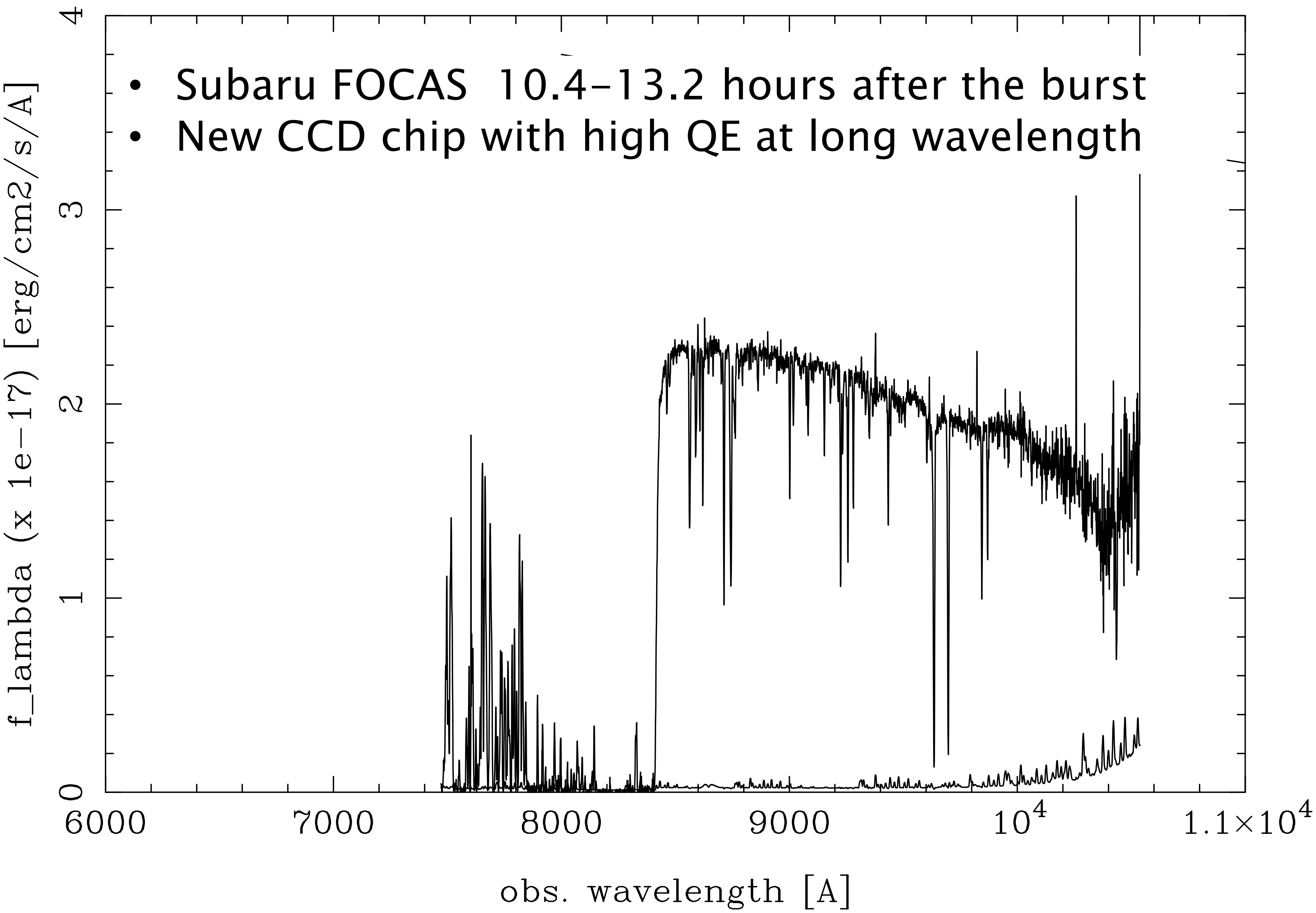
Chornock et al. 2013

GRB 130606A



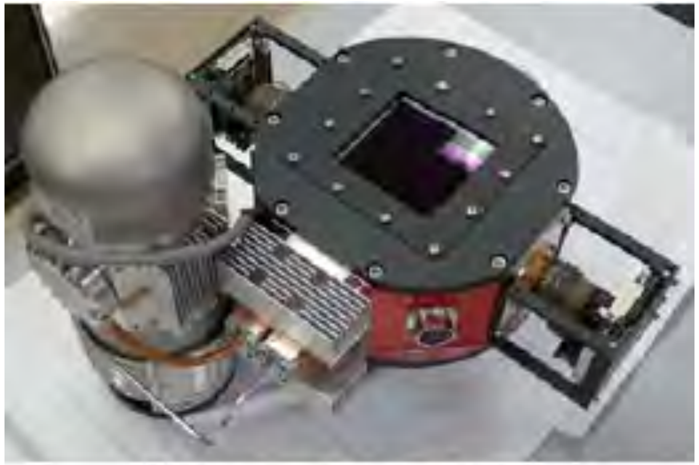
Chornock et al. 2013

GRB 130606A – Subaru FOCAS



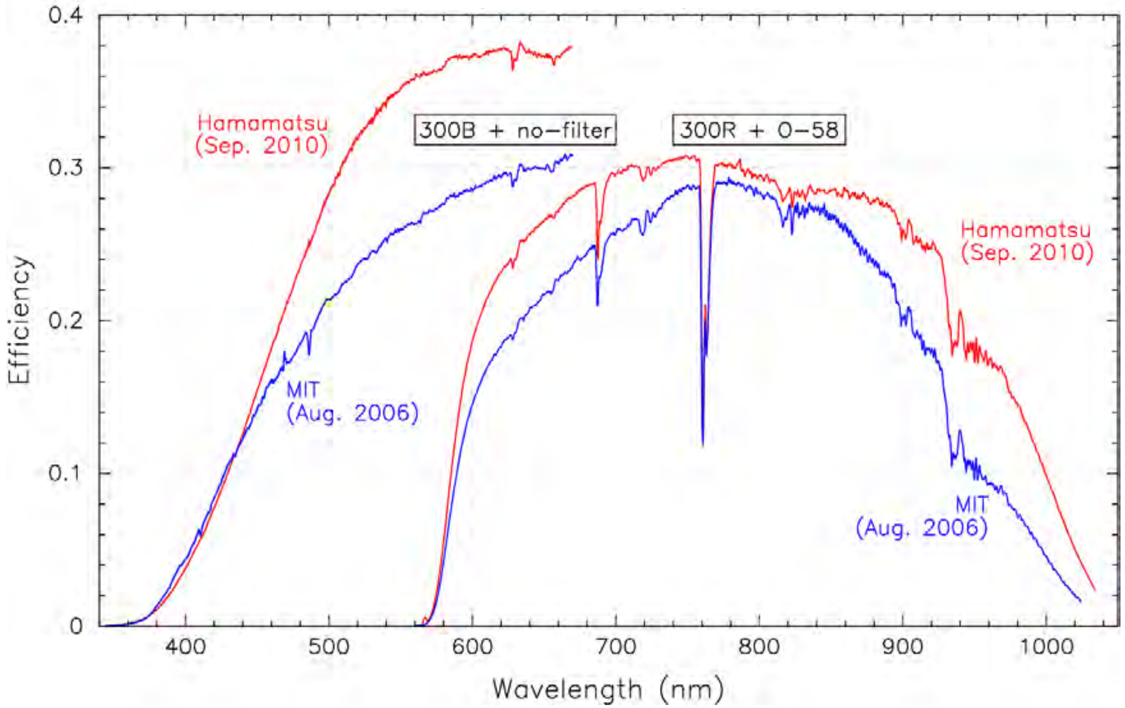
科研費重点領域「ガンマ線バーストで読み解く太古の宇宙」
FOCAS　CCD　upgrade　（太田）

新CCDの導入（浜松フォトニクス）
特に0.9-1μm付近での感度が大幅向上
High-z天体観測に威力　0.5umで1.3倍、1.0umで2倍
他に、フリンジの減少、読出速度の向上（約4倍）、cosmetics改善



新CCDシステム

大気、望遠鏡、装置を含めた効率



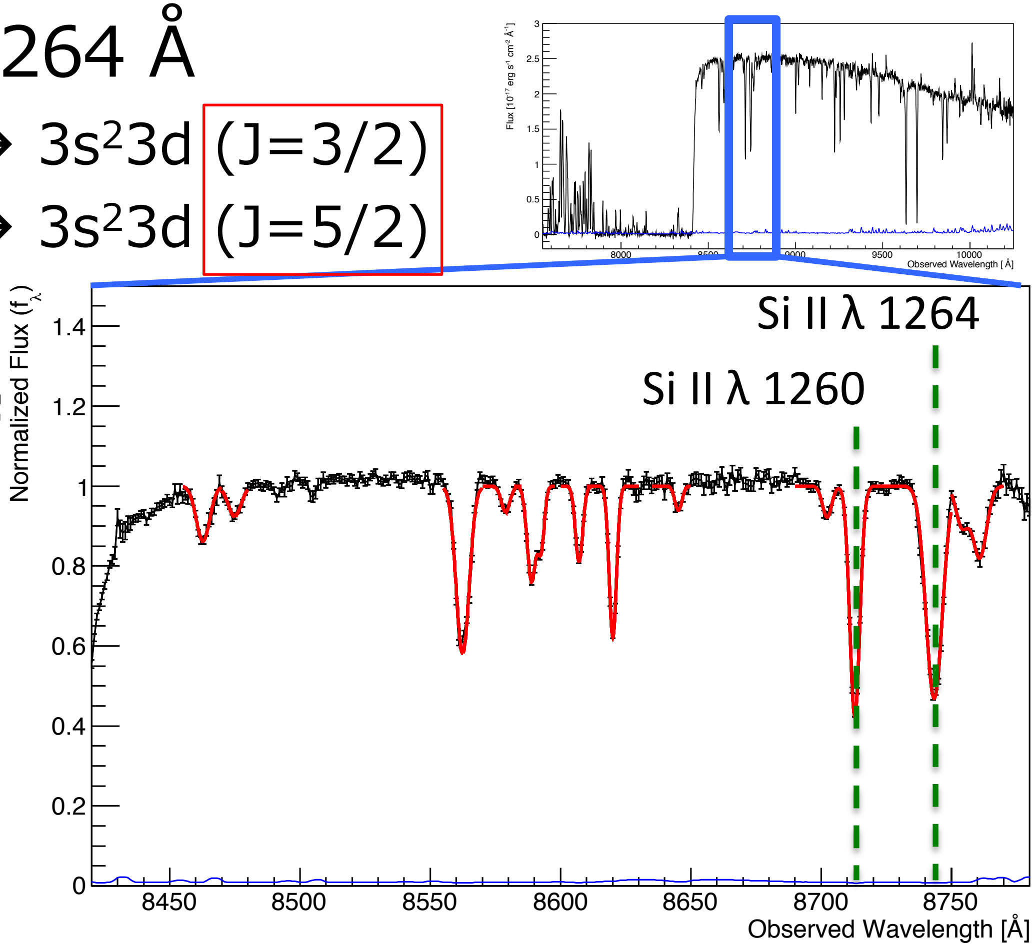
写真・図　提供：服部

Hamamatsu (new)　MIT (old)

Fine-struc… の利用

Si I : 中性のSi
Si II : 一回電離のSi
Si III : 二回電離のSi
…

- Fine-struc…
  - 電子の軌… スピン角運動量が違うエネルギー状態間の遷移…対応し、近い波長で複数本観測できるライン
- 具体例 : Si II λλ 1260, 1264 Å
  - 1260 Å : $3s^2 3p$ (J=1/2) → $3s^2 3d$ (J=3/2)
  - 1264 Å : $3s^2 3p$ (J=3/2) → $3s^2 3d$ (J=5/2)
- 有名なfine-structure line
  - Si IV λλ 1294, 1403 Å
  - O I λλ 1302, 1304 Å
  - C II λλ 1335, 1336 Å
  - Mg II λλ 2796, 2803 Å



まとめ

- GRB 130606AをSubaru/FOCASで分光観測し、41本の吸収線の同定をした。
- フィッティングから等価幅および柱密度の計算をした。
- 5台の大型望遠鏡による分光観測結果を比較し、GRB近傍の物質の柱密度に時間変化があることを確認した。
- 原子の励起が電子との衝突で起きていると仮定すると、星風によって電離水素が供給されている場合が考えられる。
- GRB 130606A近傍では、星風によって$n_e \sim 10^3 cm^{-3}$の電子が分布しているのでなければ、光子との衝突によって原子の励起が起きていると推察できる。