Probing the *Dark Side* of Galaxy Formation with Absorption Spectroscopy

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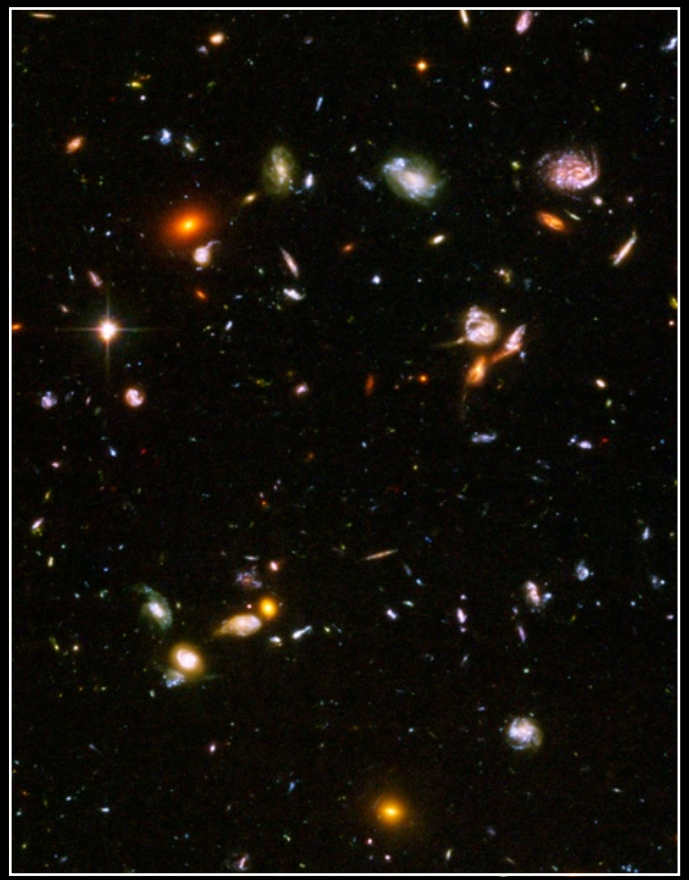
Baryon Accounting

the empirical lumpy universe



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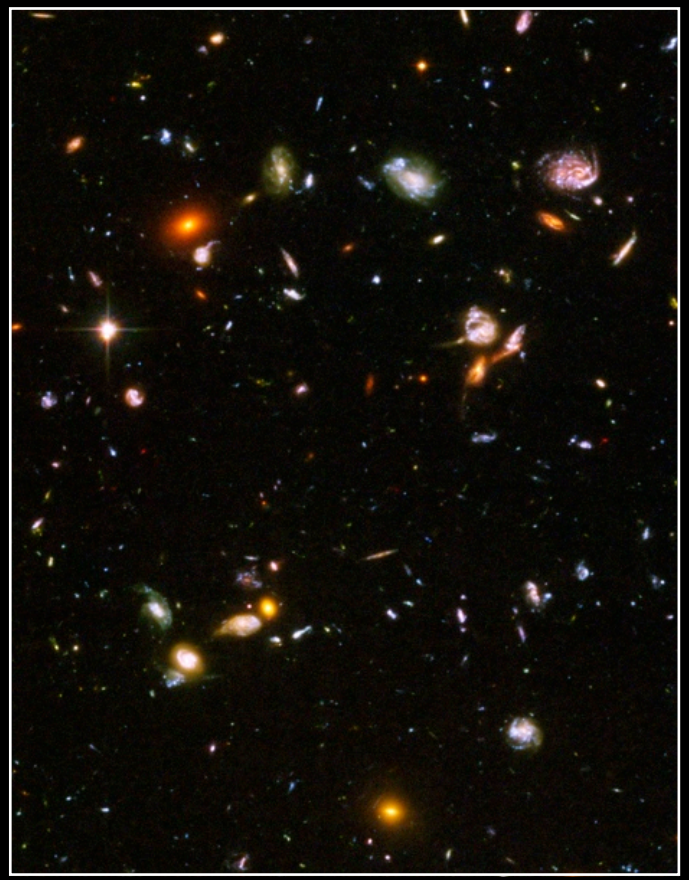

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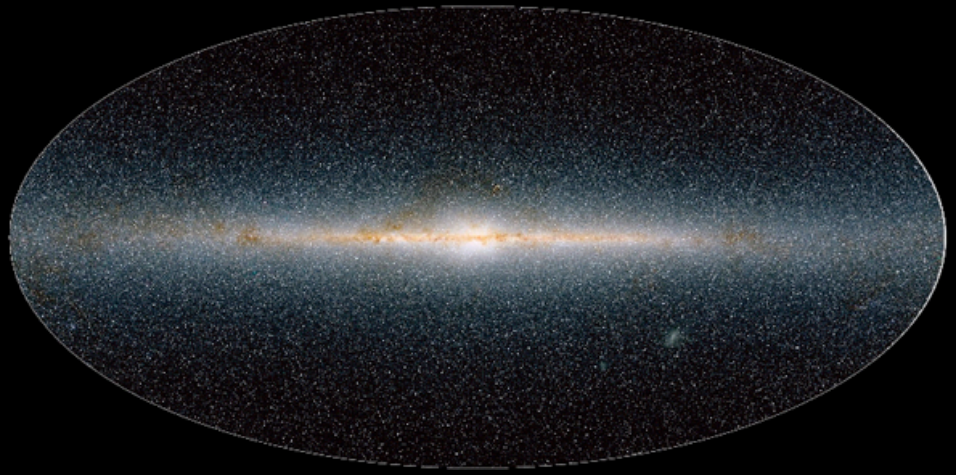
Known Baryon Content of the Milky Way



- total stellar mass : $\sim 5 \times 10^{10}\ M_\odot$
- total neutral gas mass : $\sim 9 \times 10^{9}\ M_\odot$
- total baryonic mass : $\sim 6 \times 10^{10}\ M_\odot$
- total dynamic mass : $\sim 10^{12}\ M_\odot$

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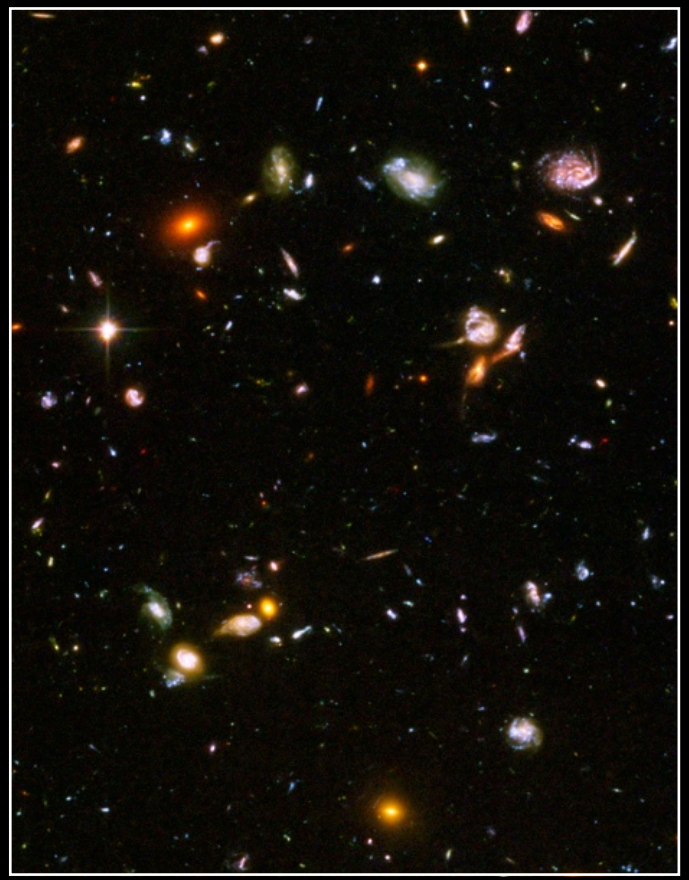

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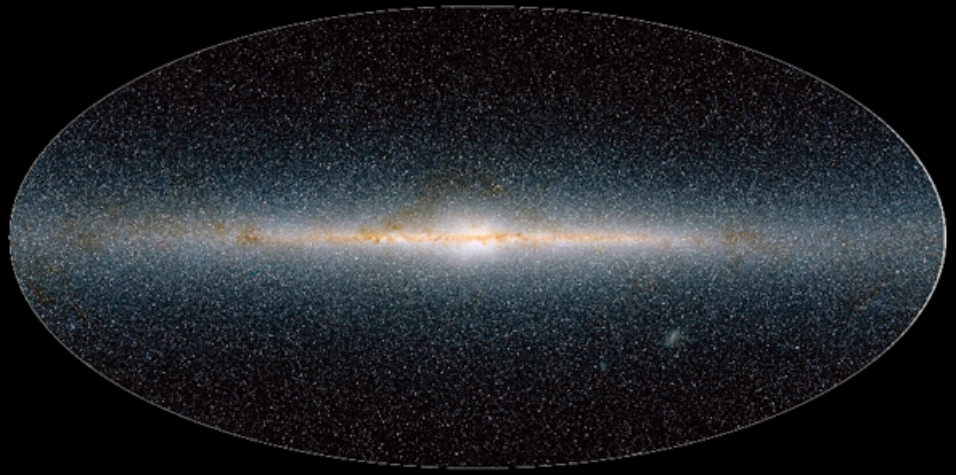

- **total stellar mass : ~ 5 x 10^{10} $M_\odot$**
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cf. **the cosmic baryon to dark matter ratio** $f_b \equiv \frac{\Omega_b}{\Omega_{\rm M}} = 0.176^{+0.008}_{-0.013}$

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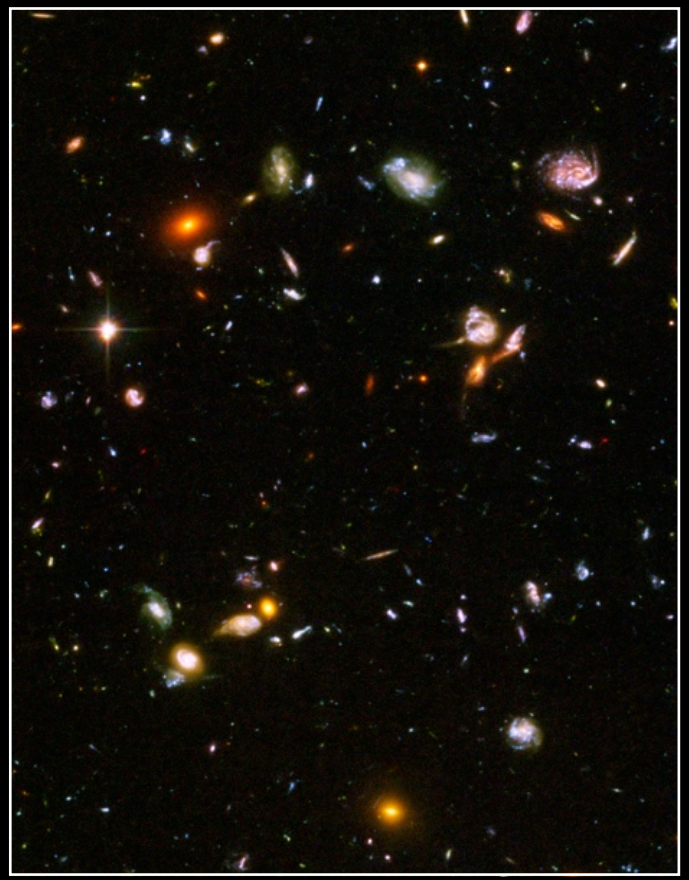

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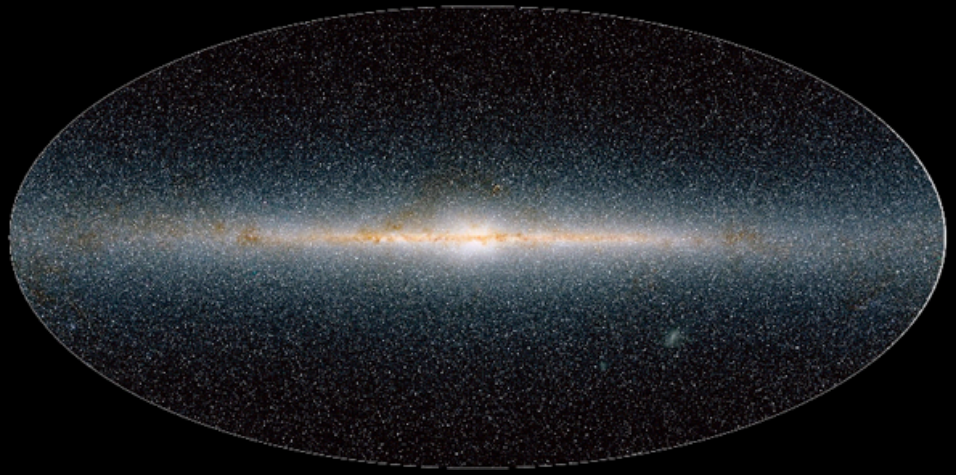

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- on-going star formation rate : ~ 3 $M_\odot$ yr^{-1}

Baryon Accounting

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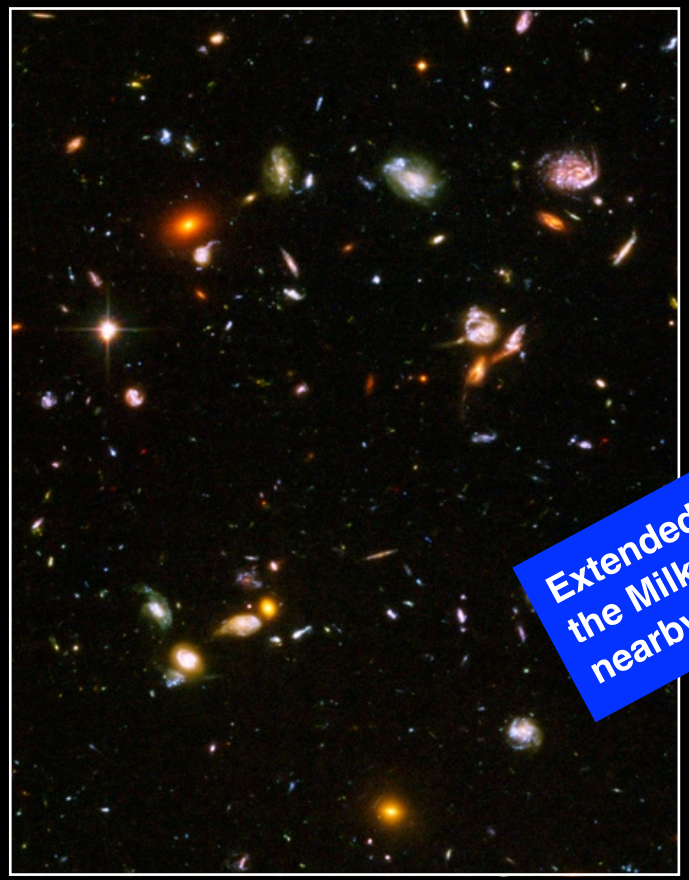

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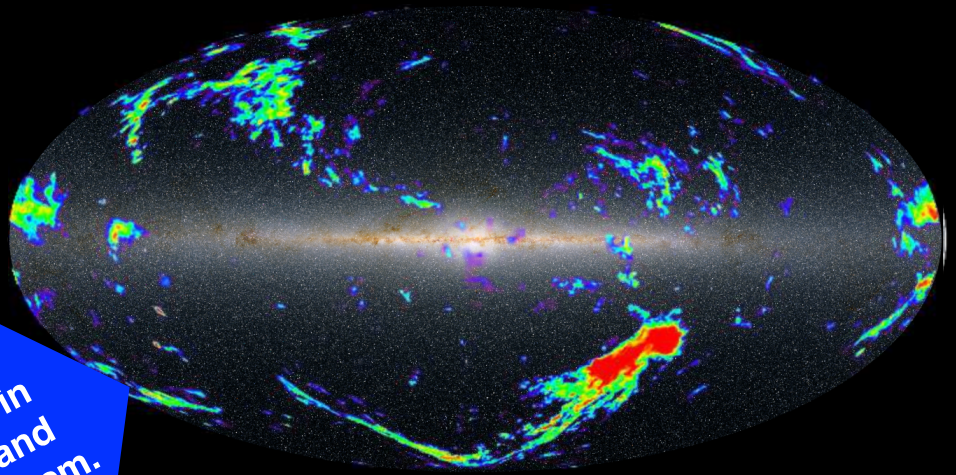

Extended gas is seen in the Milky Way Halo (and nearby galaxies) in 21cm.

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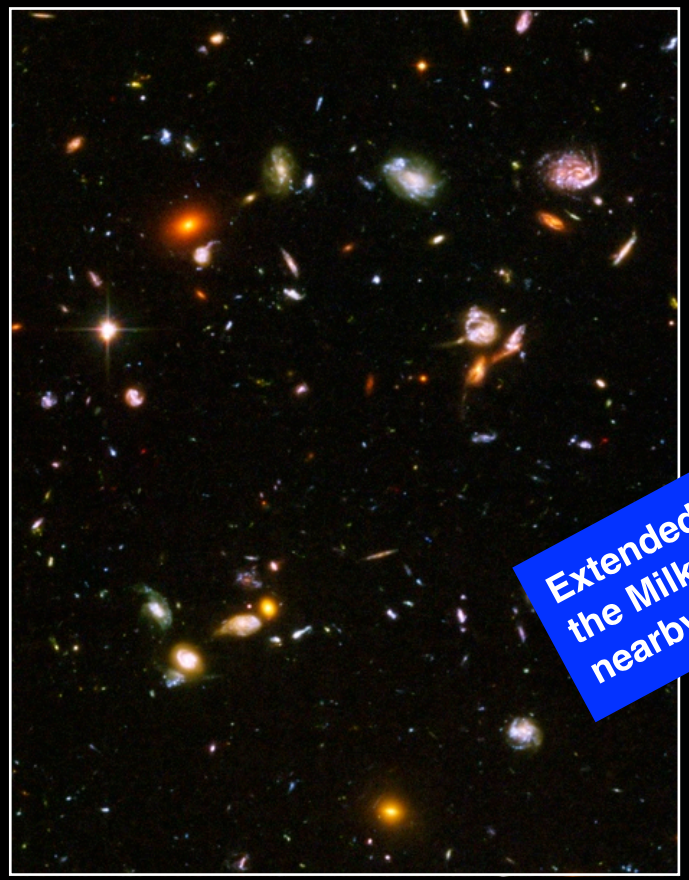

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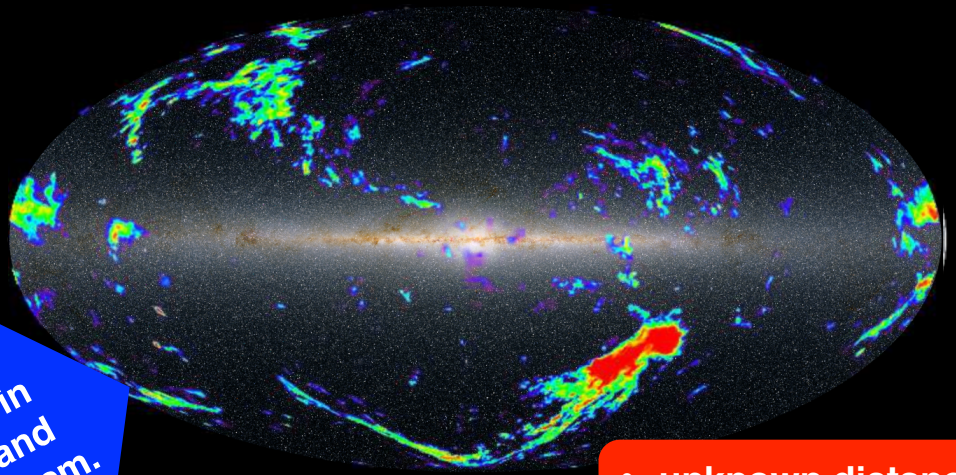

Extended gas is seen in the Milky Way Halo (and nearby galaxies) in 21cm.

- unknown distances
- ambiguous origin

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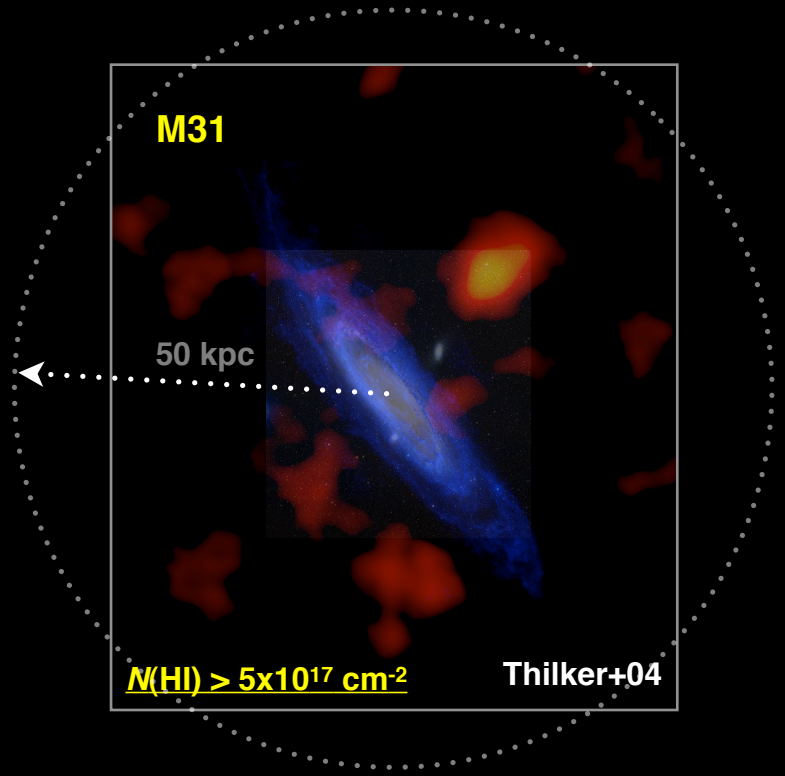
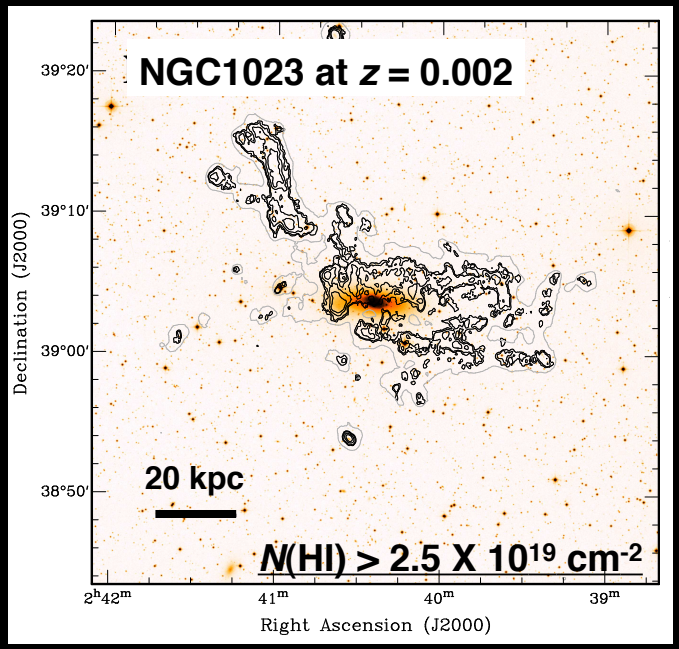
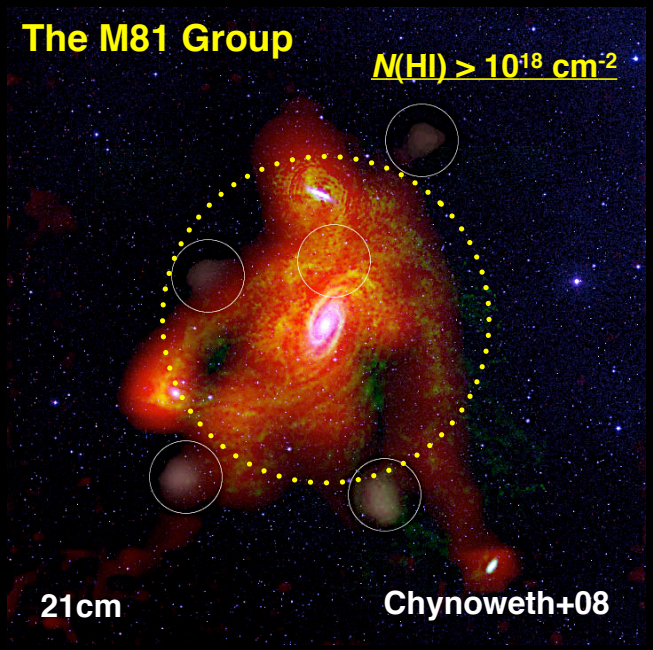
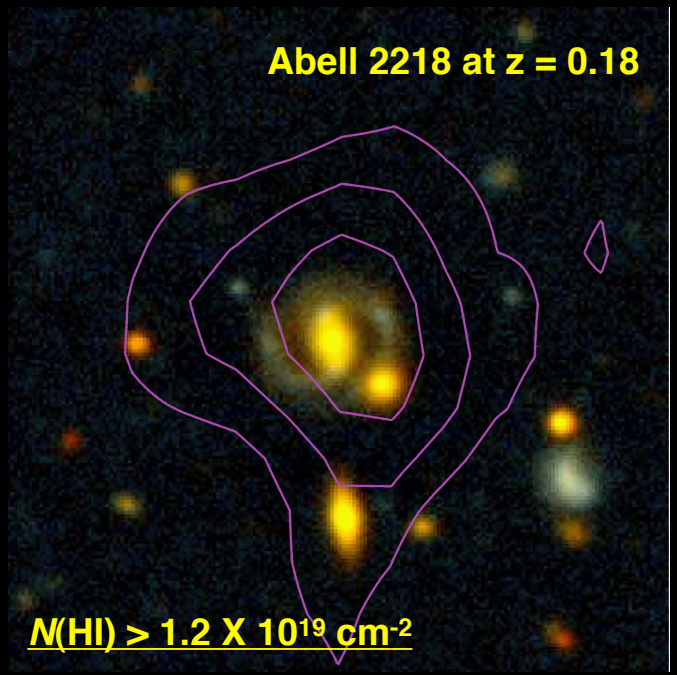
Extended Gas Around External Galaxies





Sancisi et al. (1984); Morganti et al. (2006)





Zwaan et al. (2001)

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What is the correlation between stars and gas?

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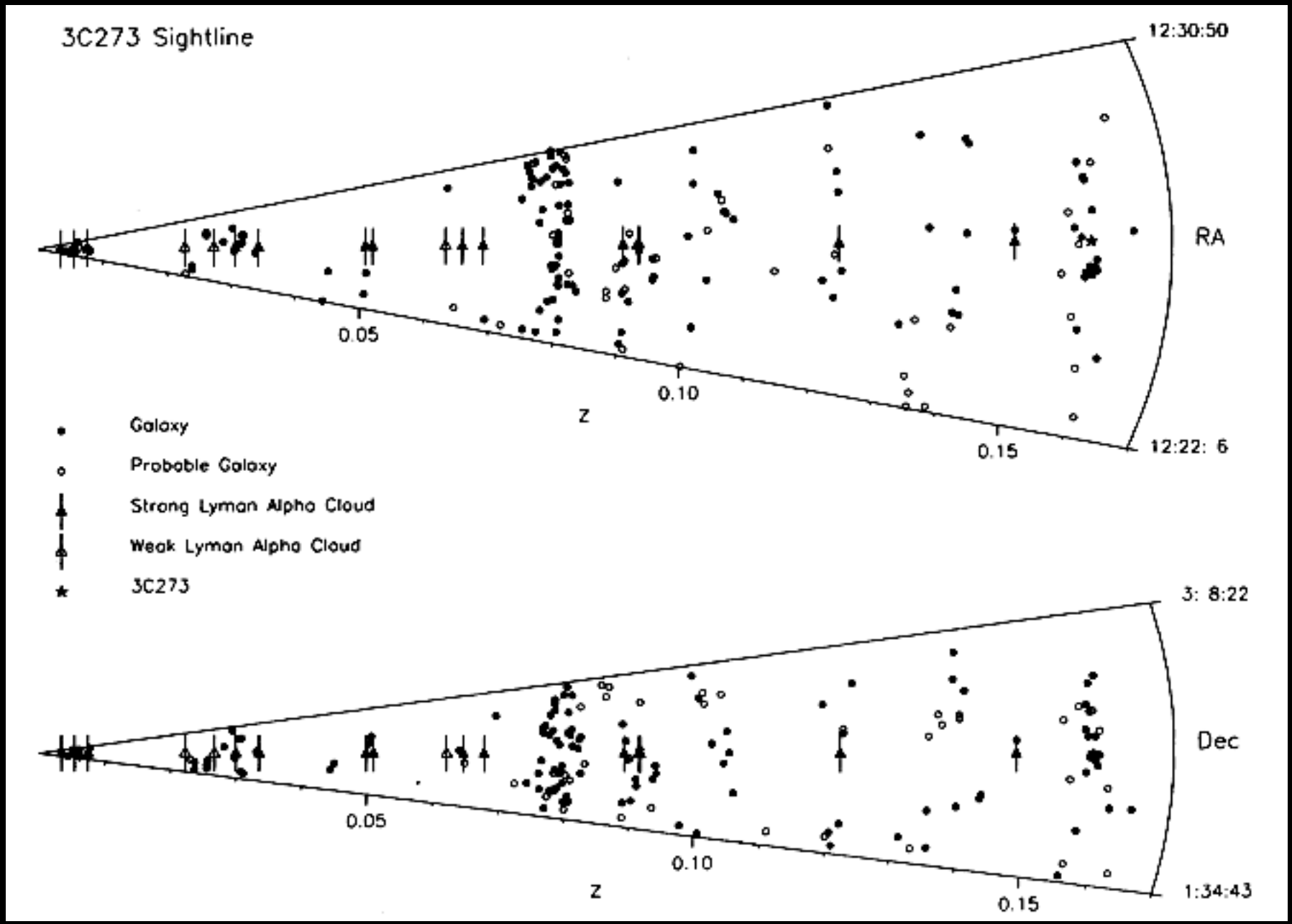
What is the correlation between stars and gas?

How can we apply known absorber properties for constraining the growth of galaxies?

Galactic Environment of QSO Absorption-line Systems



Morris et al. (1993)

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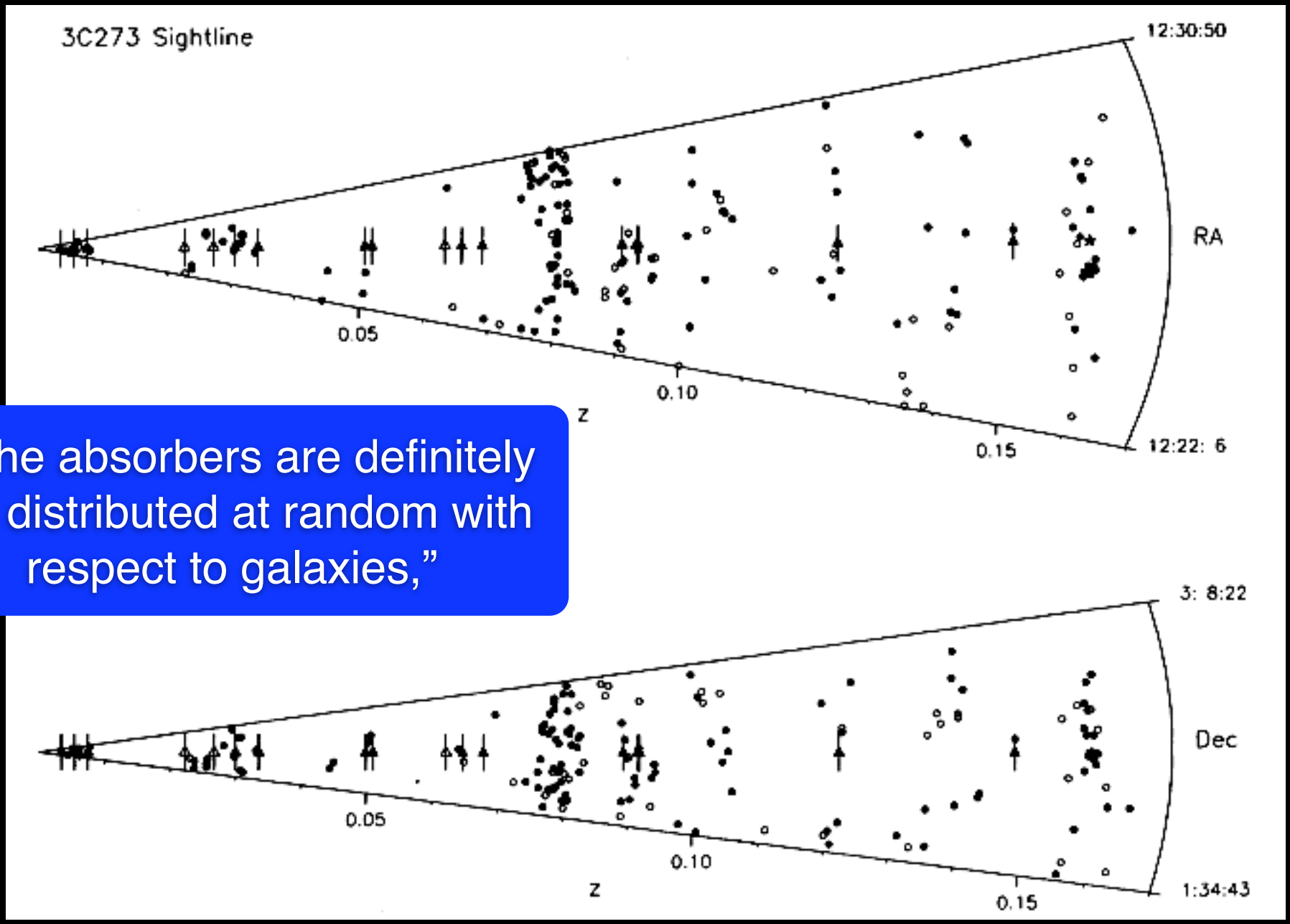
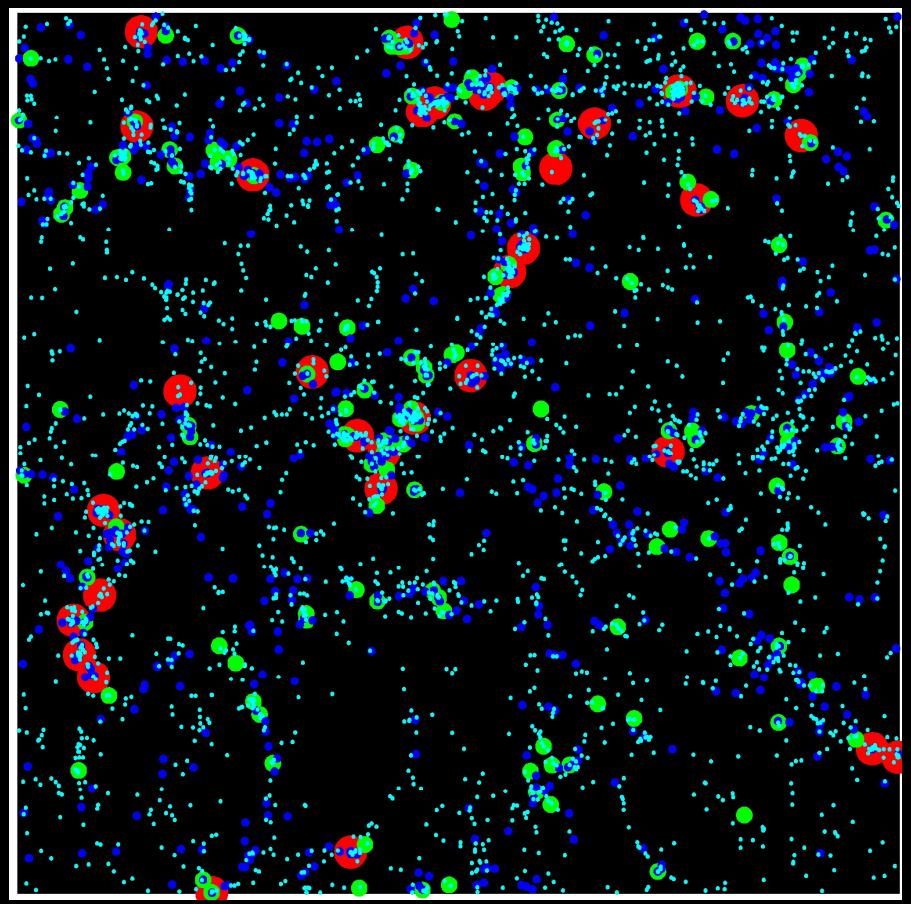
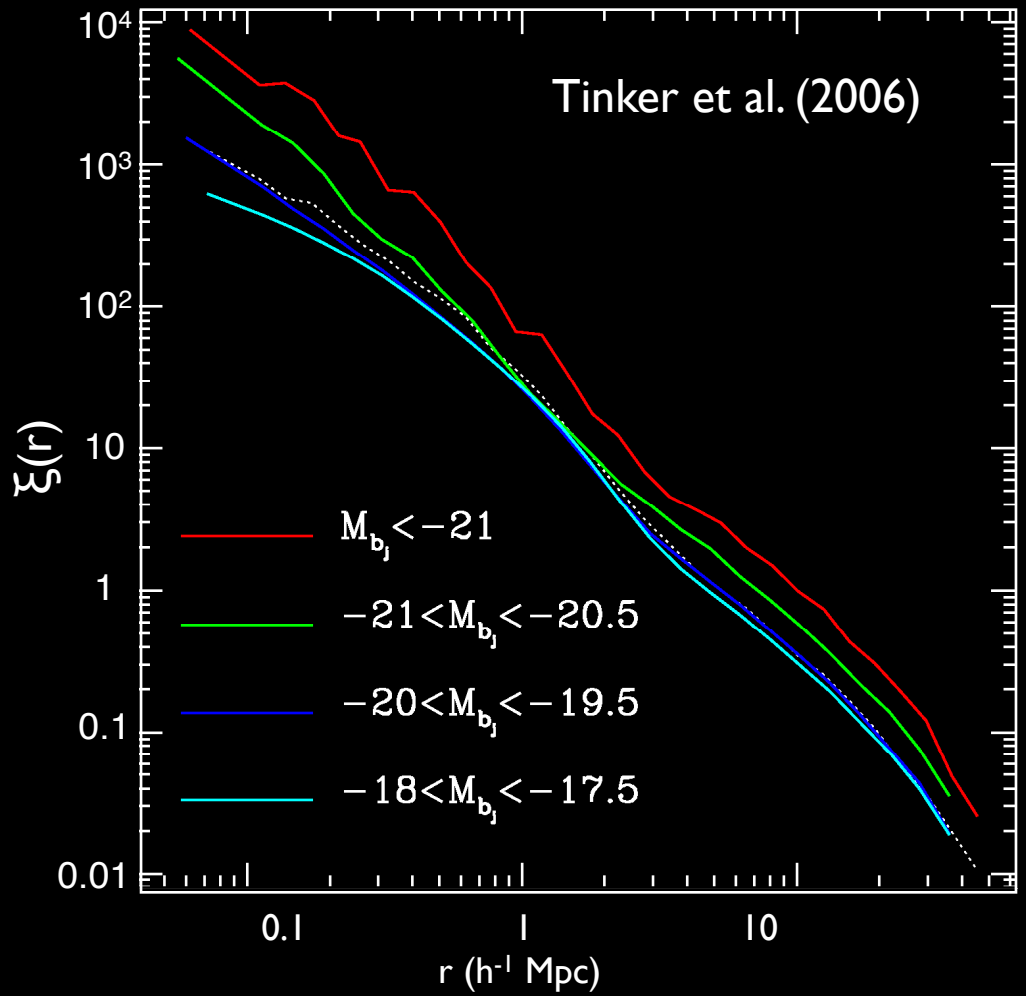


"... the absorbers are definitely not distributed at random with respect to galaxies,"

Morris et al. (1993)

Luminosity Dependence in Galaxy Clustering

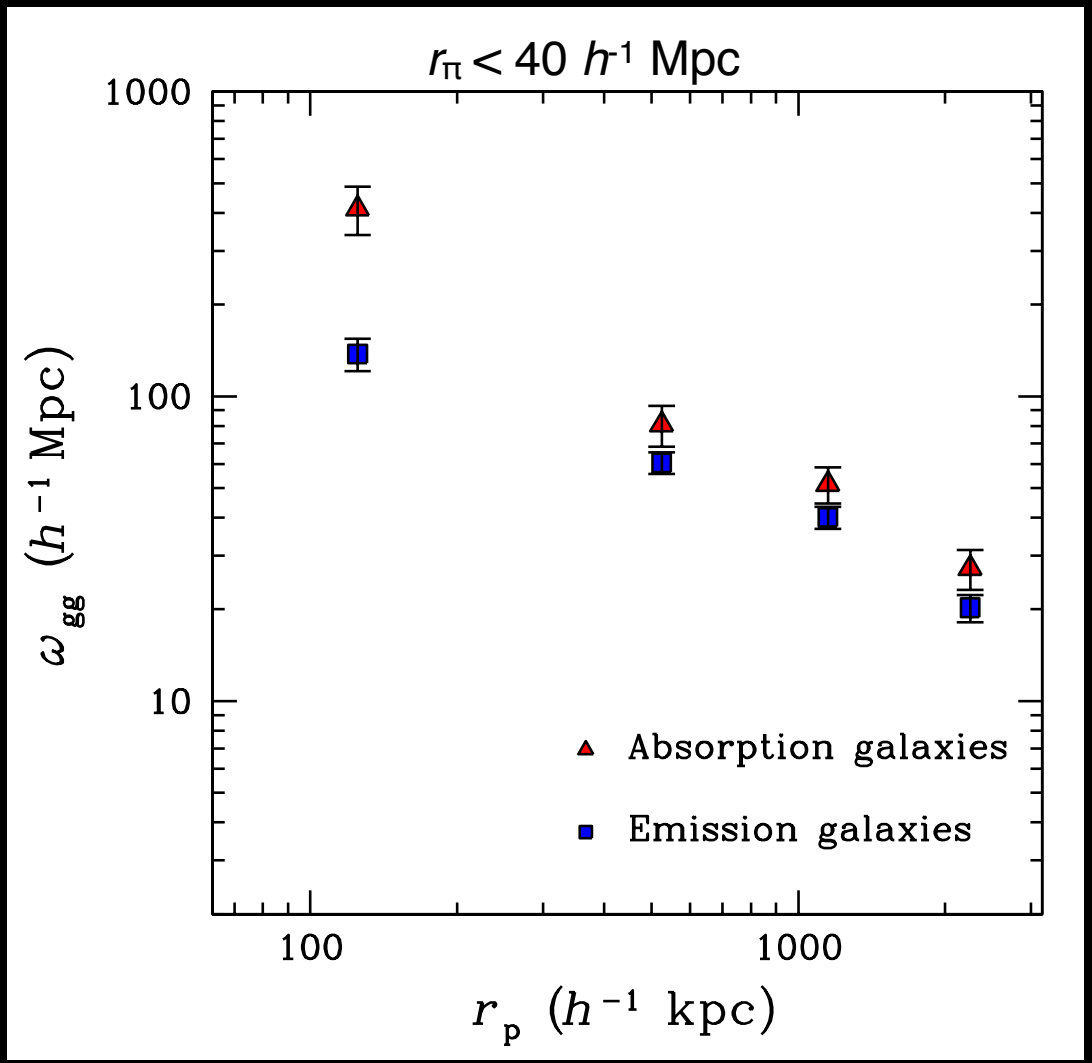




Clustering properties of QSO absorbers at z < 1

Wide-field surveys of faint galaxies in QSO fields

-- the galaxy auto-correlation function



Chen & Mulchaey (2009)

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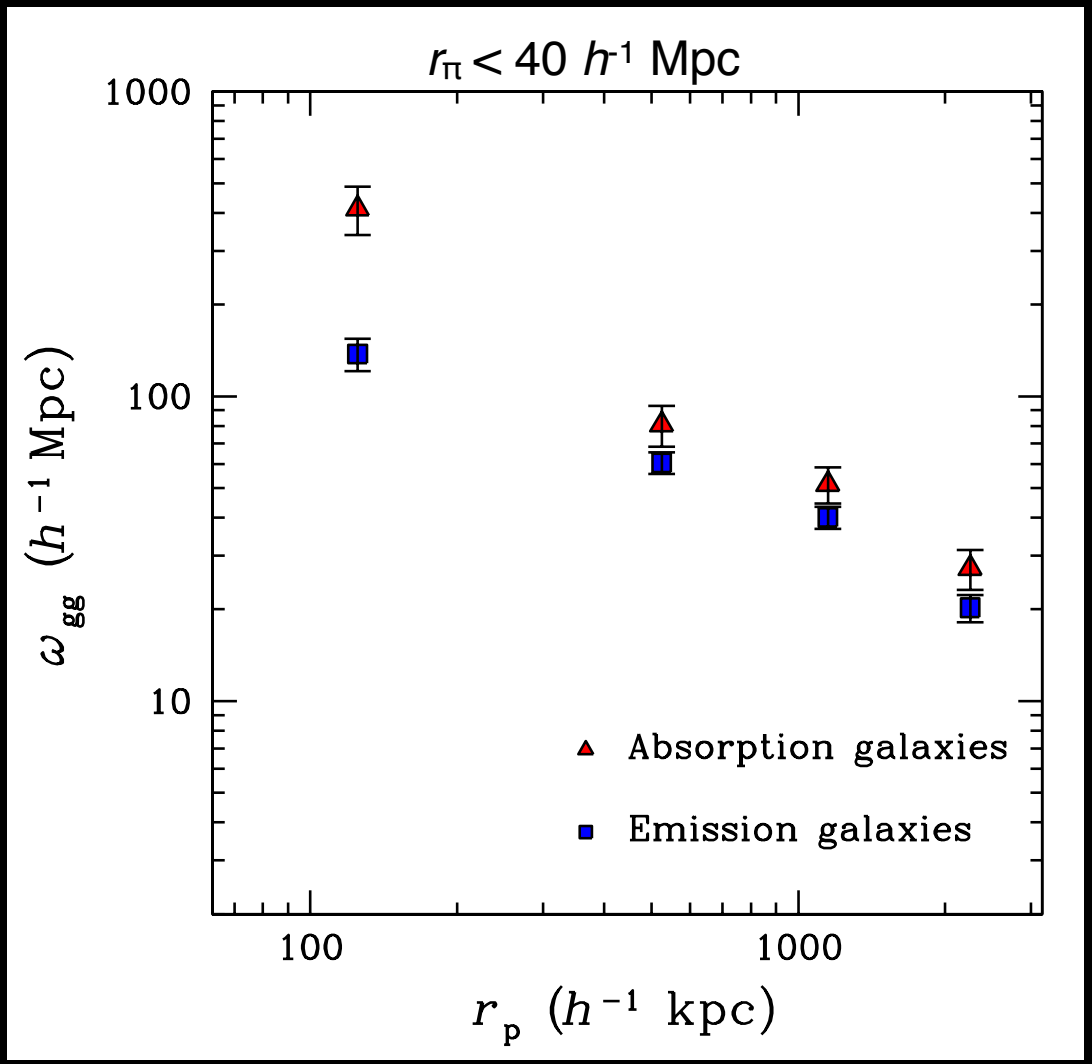

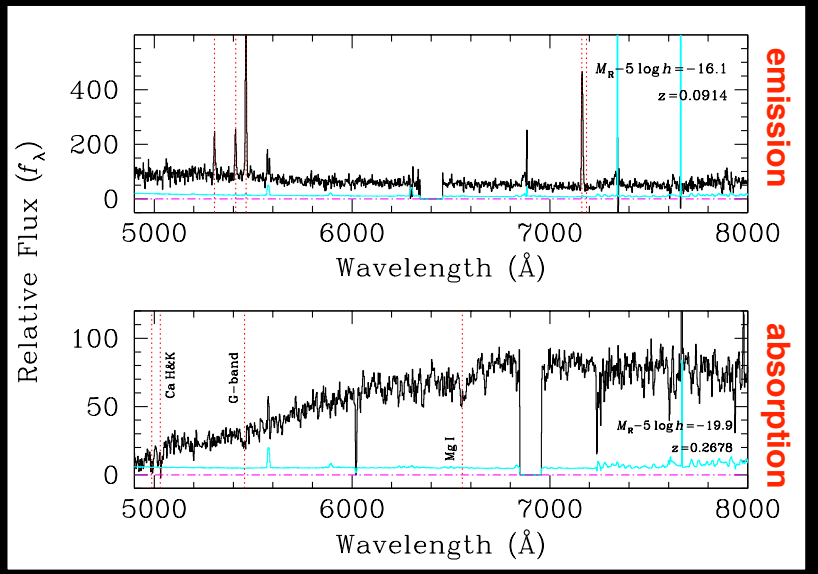

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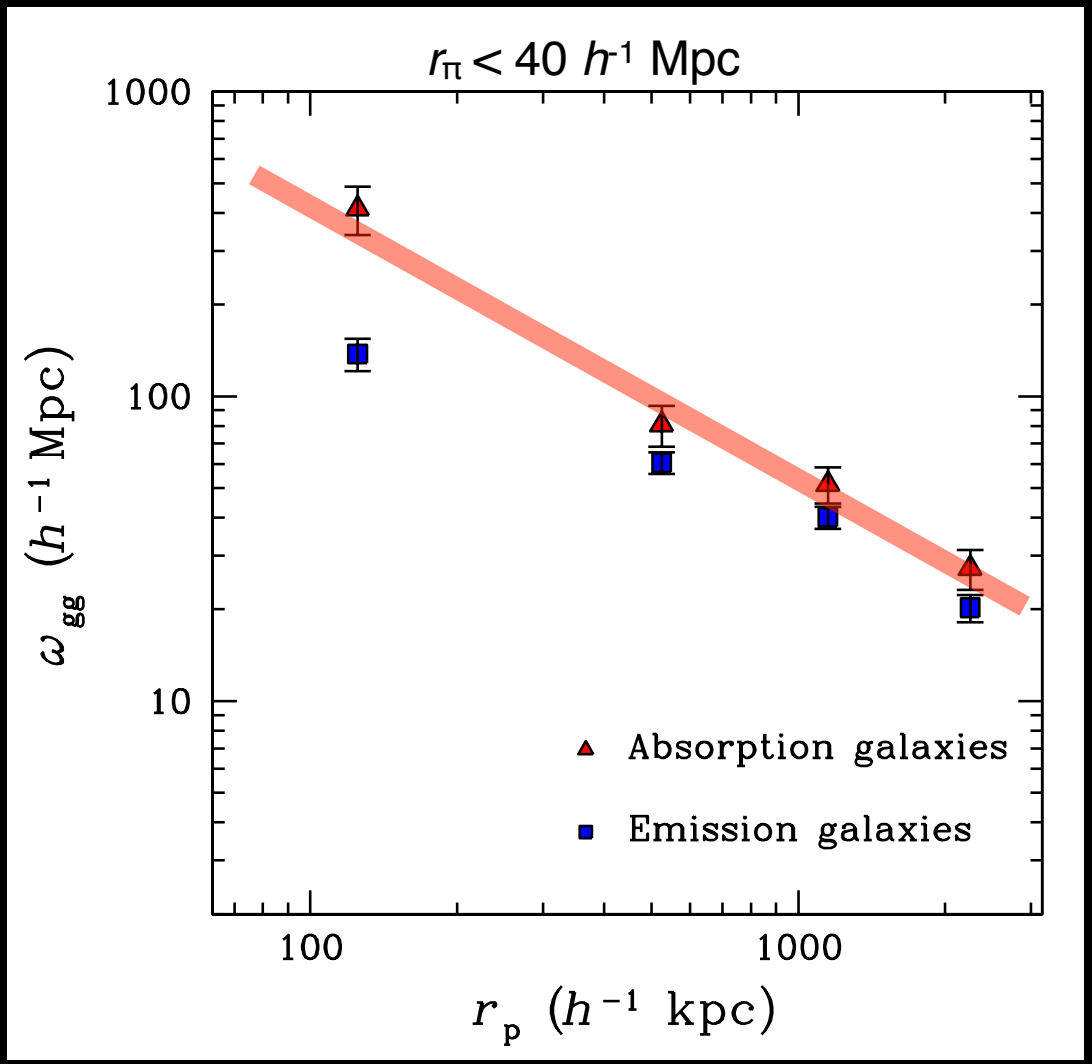

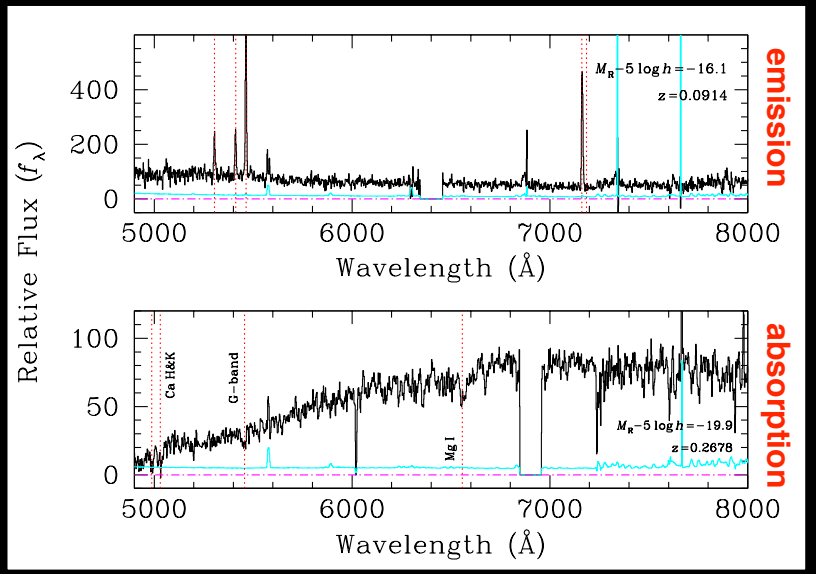

older/redder galaxies cluster more strongly than younger ones

Chen & Mulchaey (2009)

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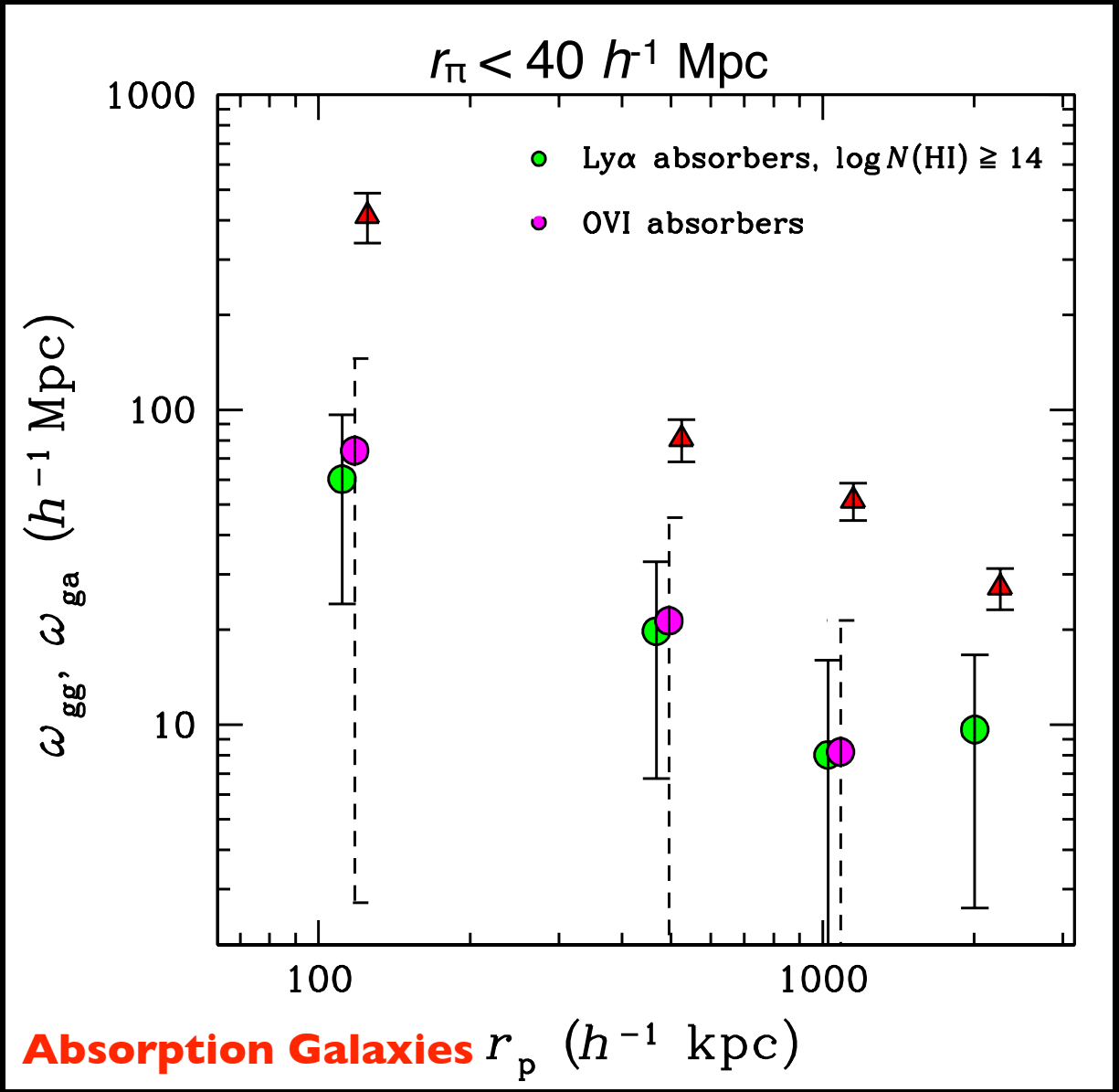

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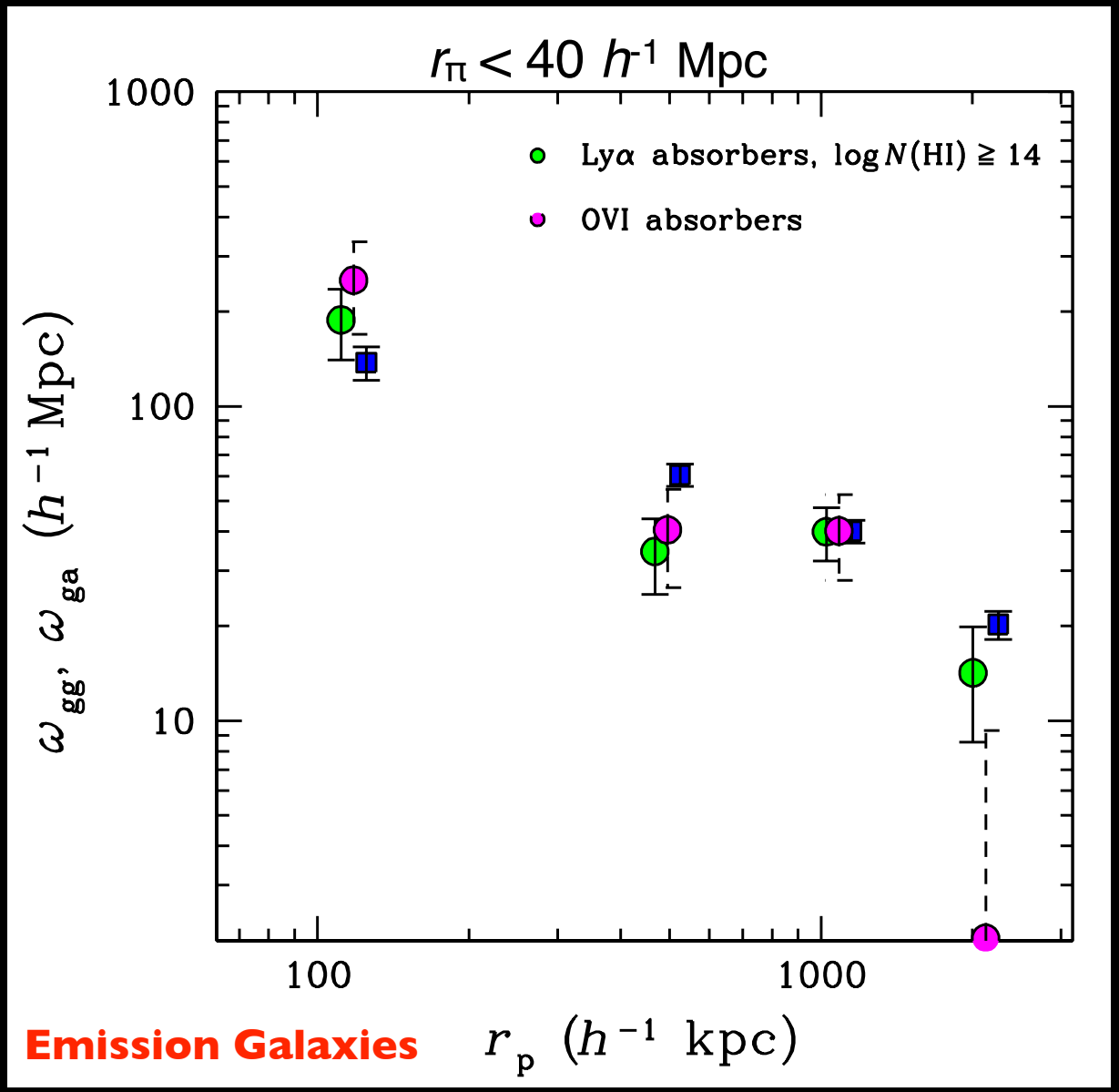

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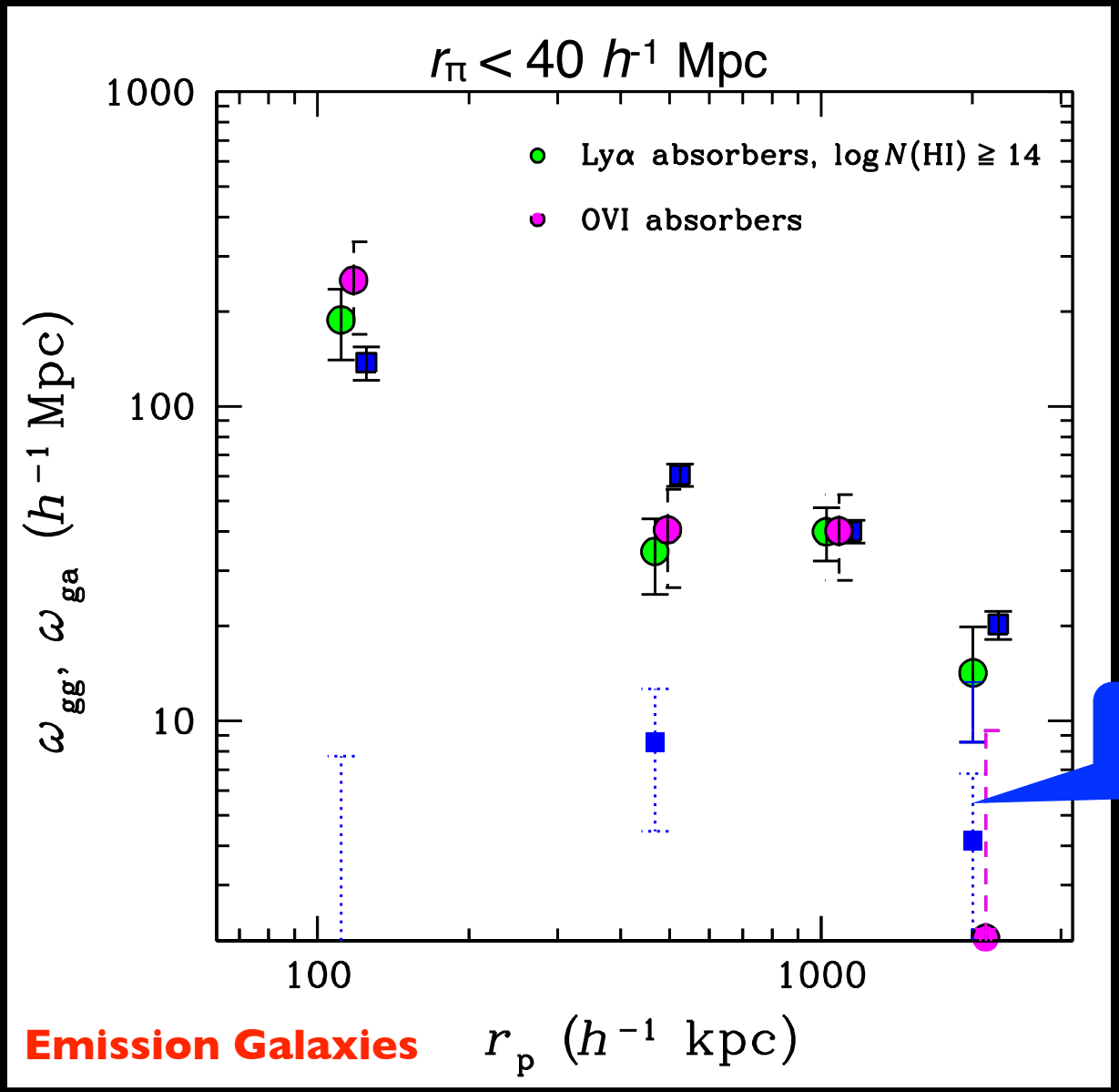

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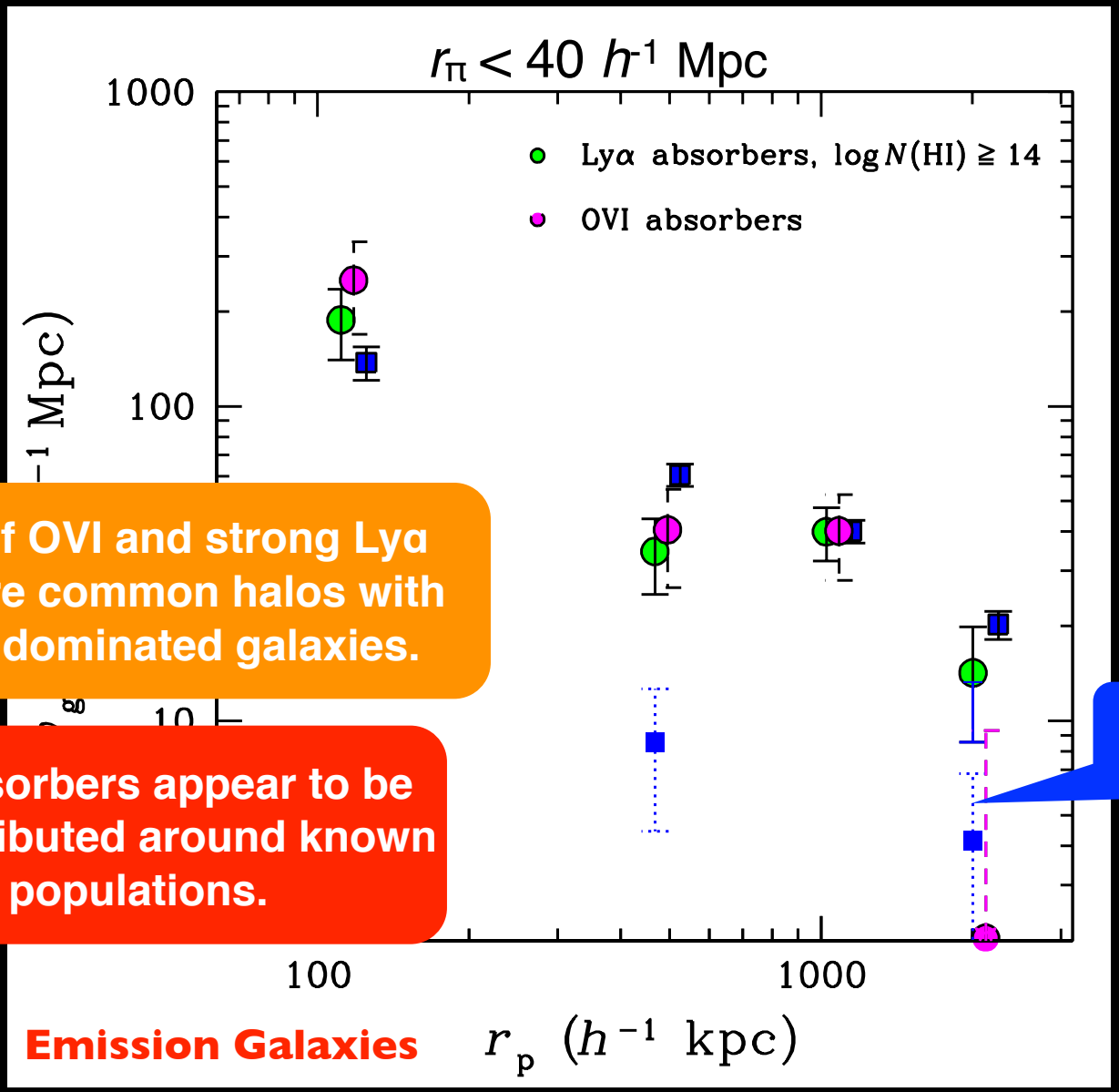


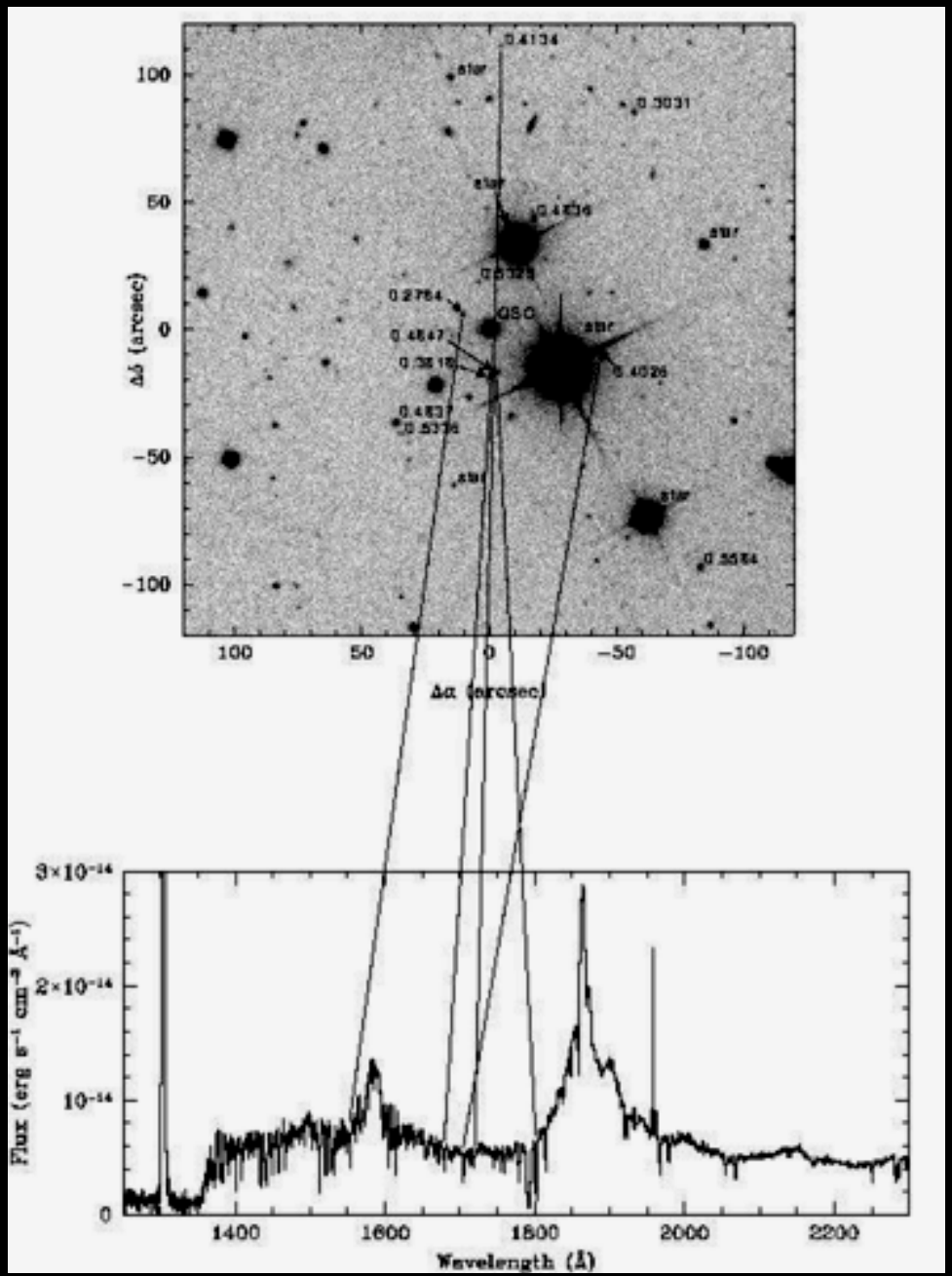
The majority of OVI and strong Lyα absorbers share common halos with emission-line dominated galaxies.

Weak Lyα absorbers appear to be randomly distributed around known galaxy populations.

Lya absorbers of log N(HI) < 13.5

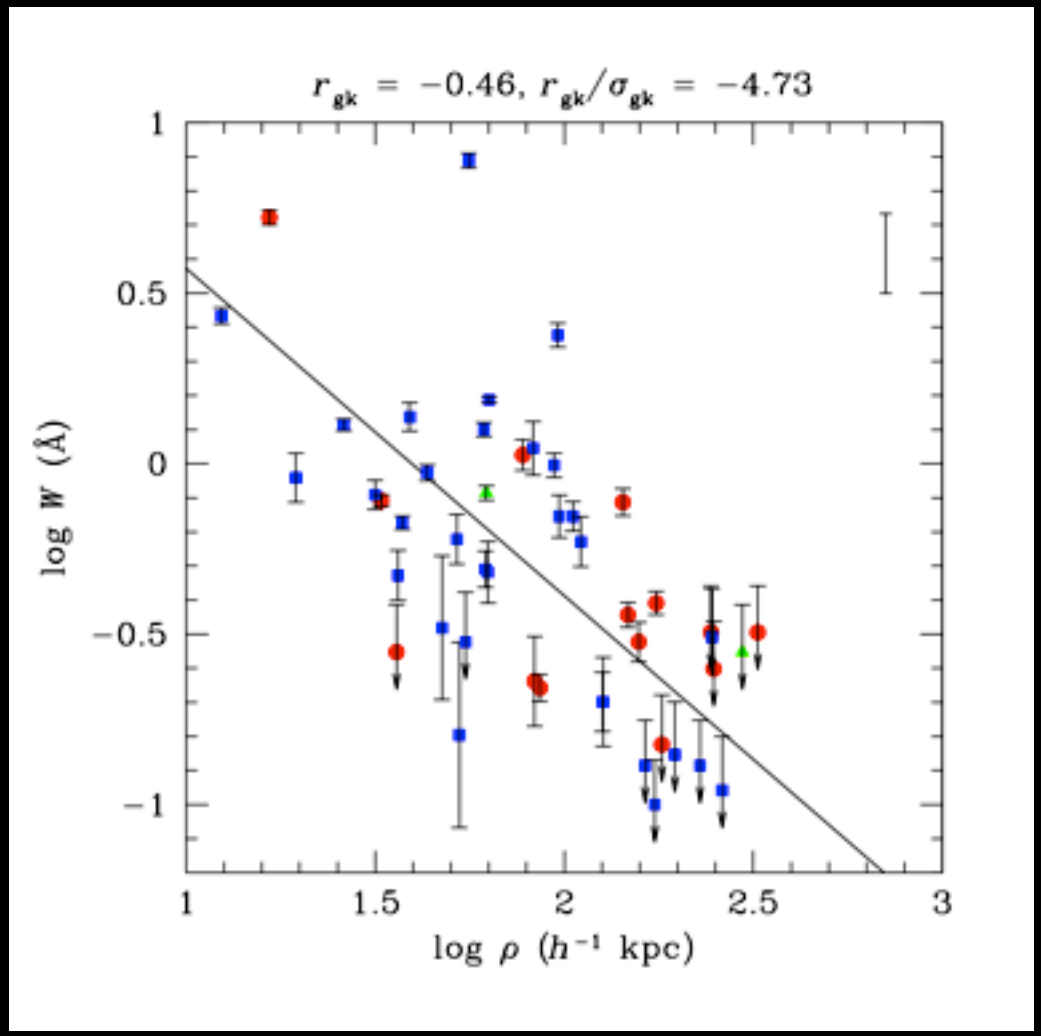
Chen & Mulchaey (2009)

Circumgalactic Medium at z < 1

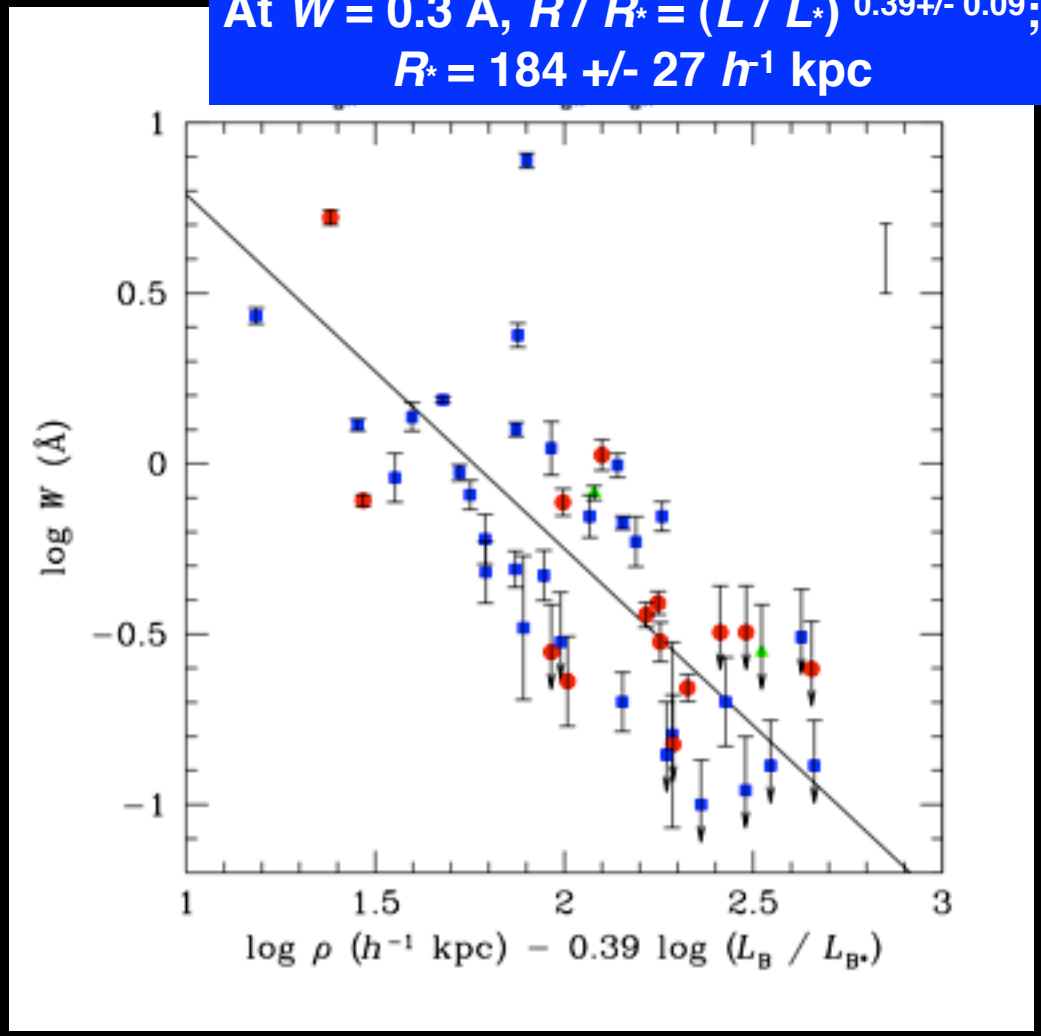


Circumgalactic Medium at z < 1

Lyα Absorbers



At W = 0.3 A, $R / R_* = (L / L_*)^{0.39+/-0.09}$;
R_* = 184 +/- 27 h^{-1} kpc



Chen et al. (1998, 2001a)

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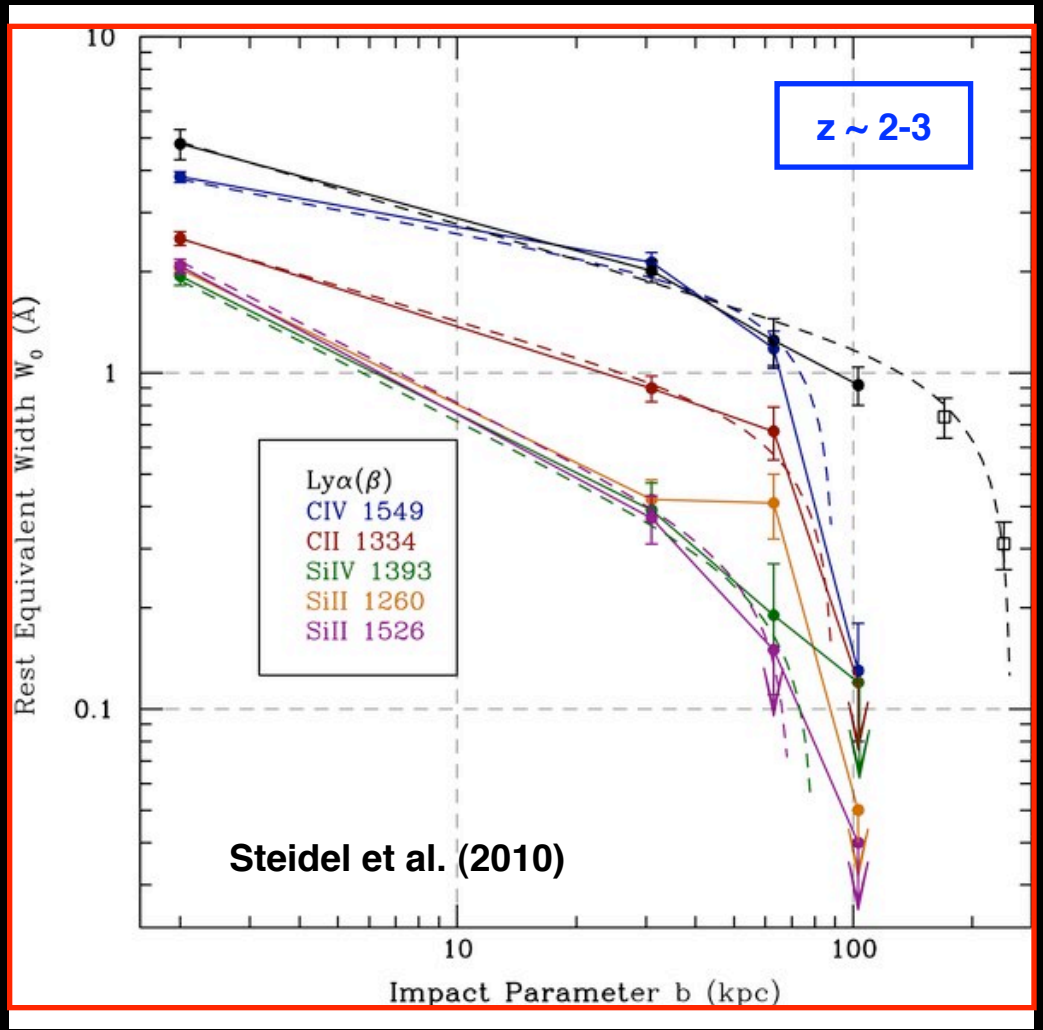

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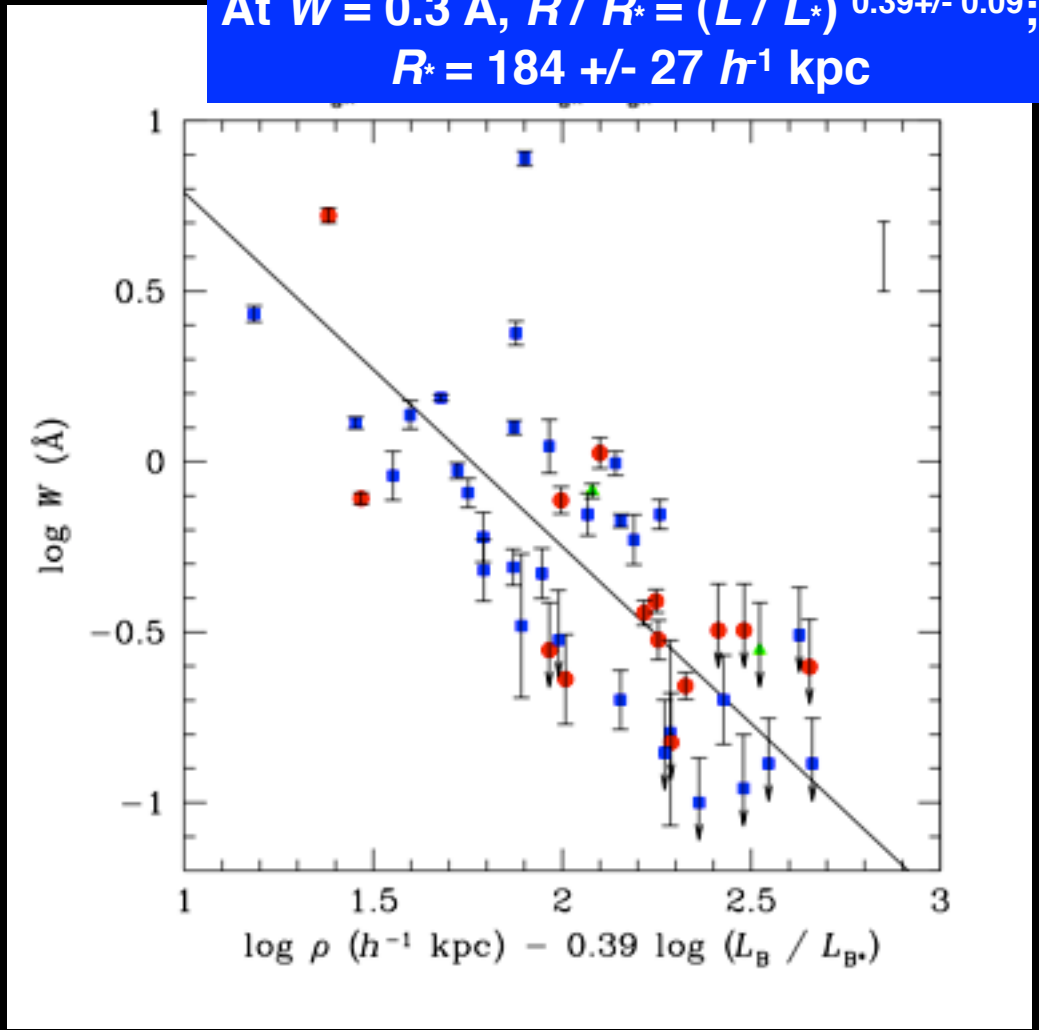

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Circumgalactic Medium at z < 1

CIV Absorbers

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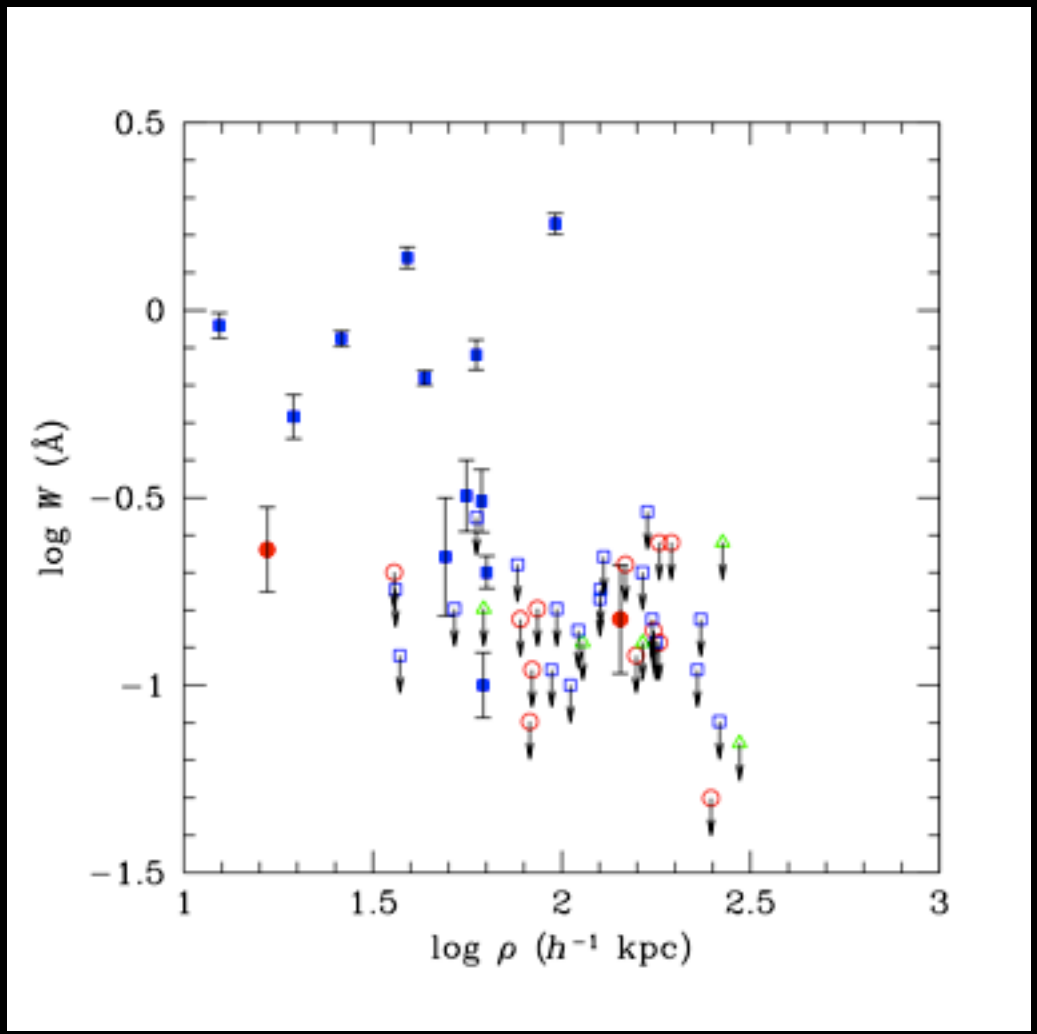

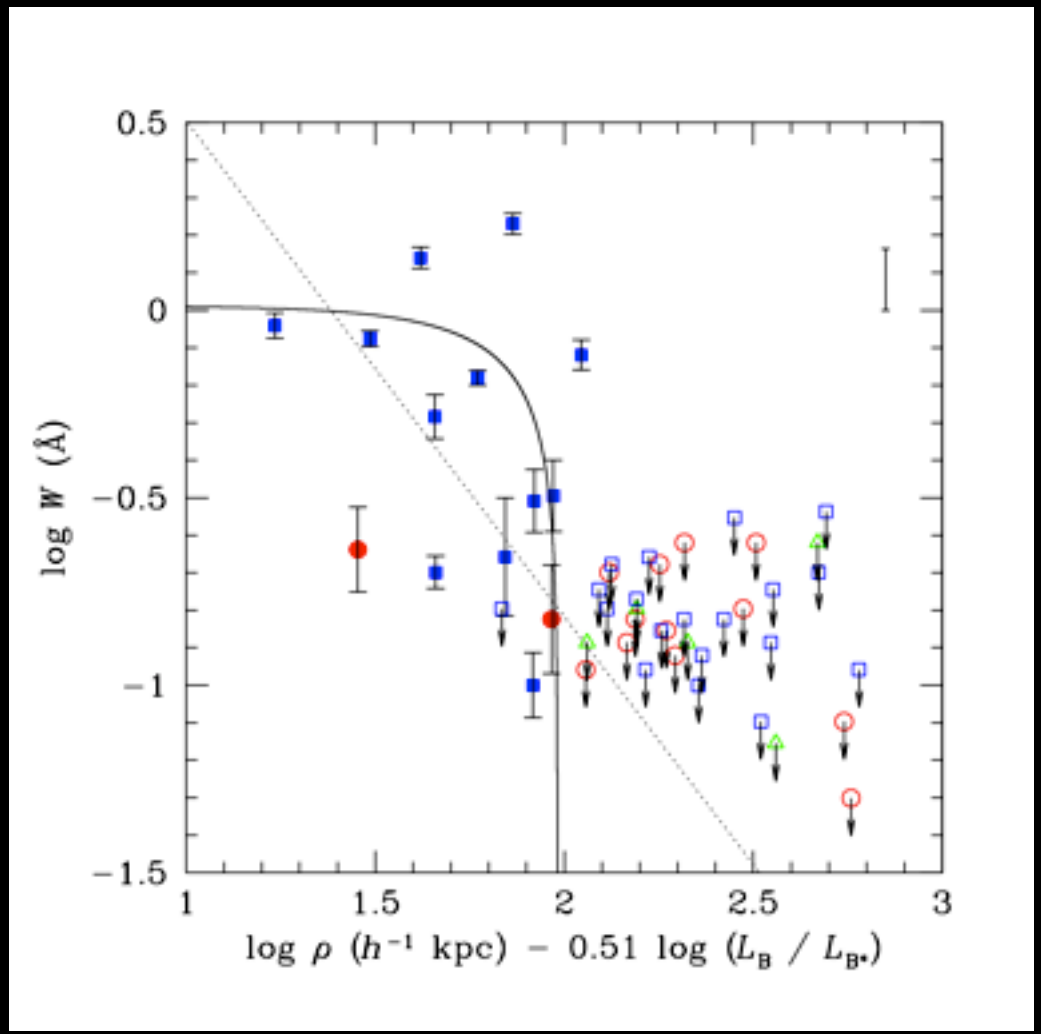

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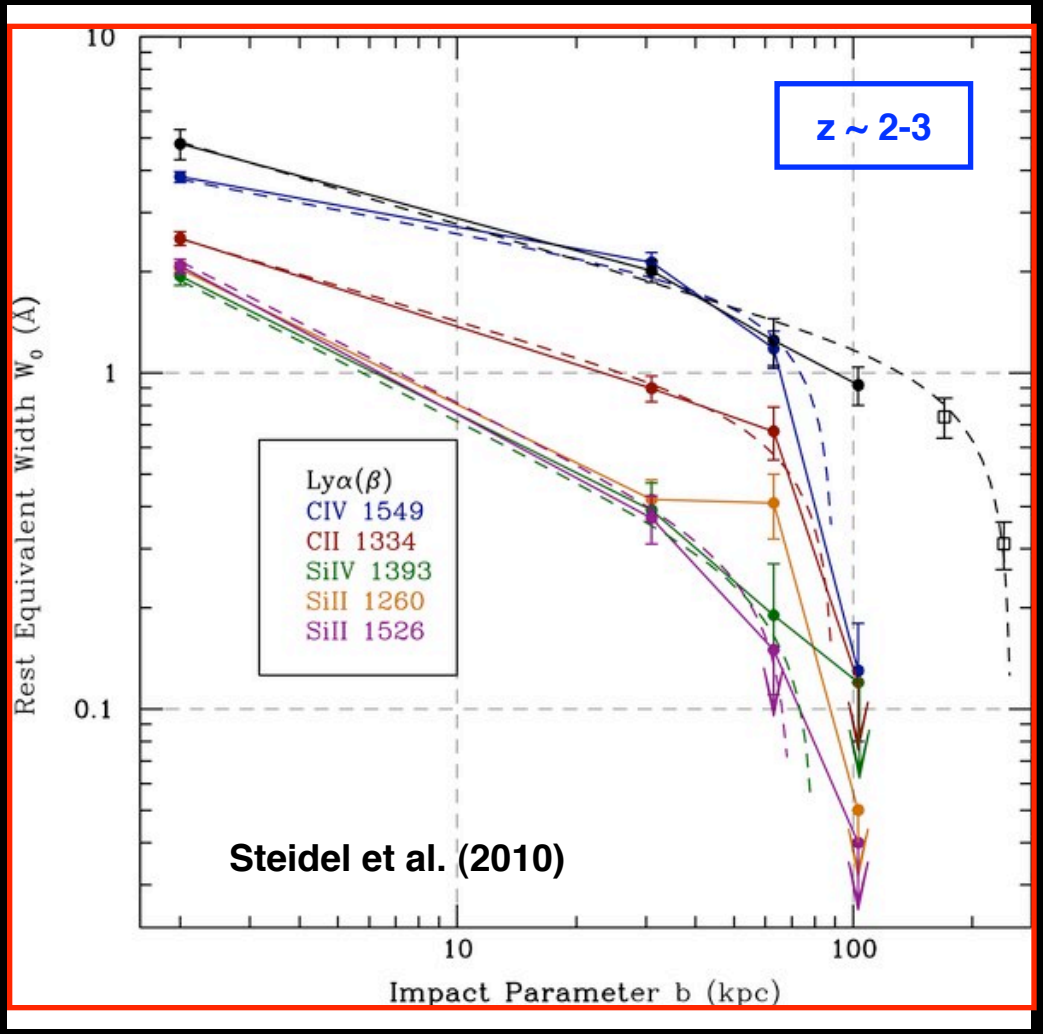
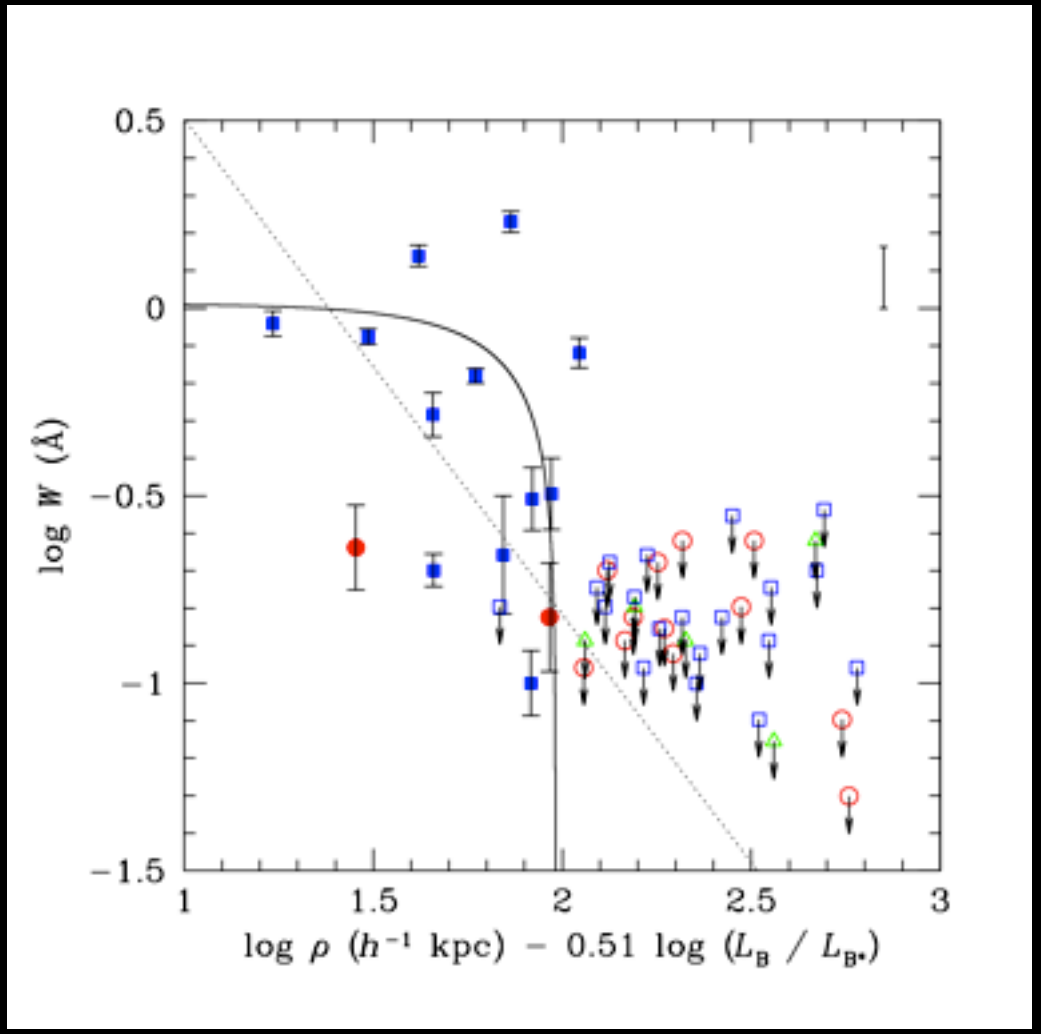
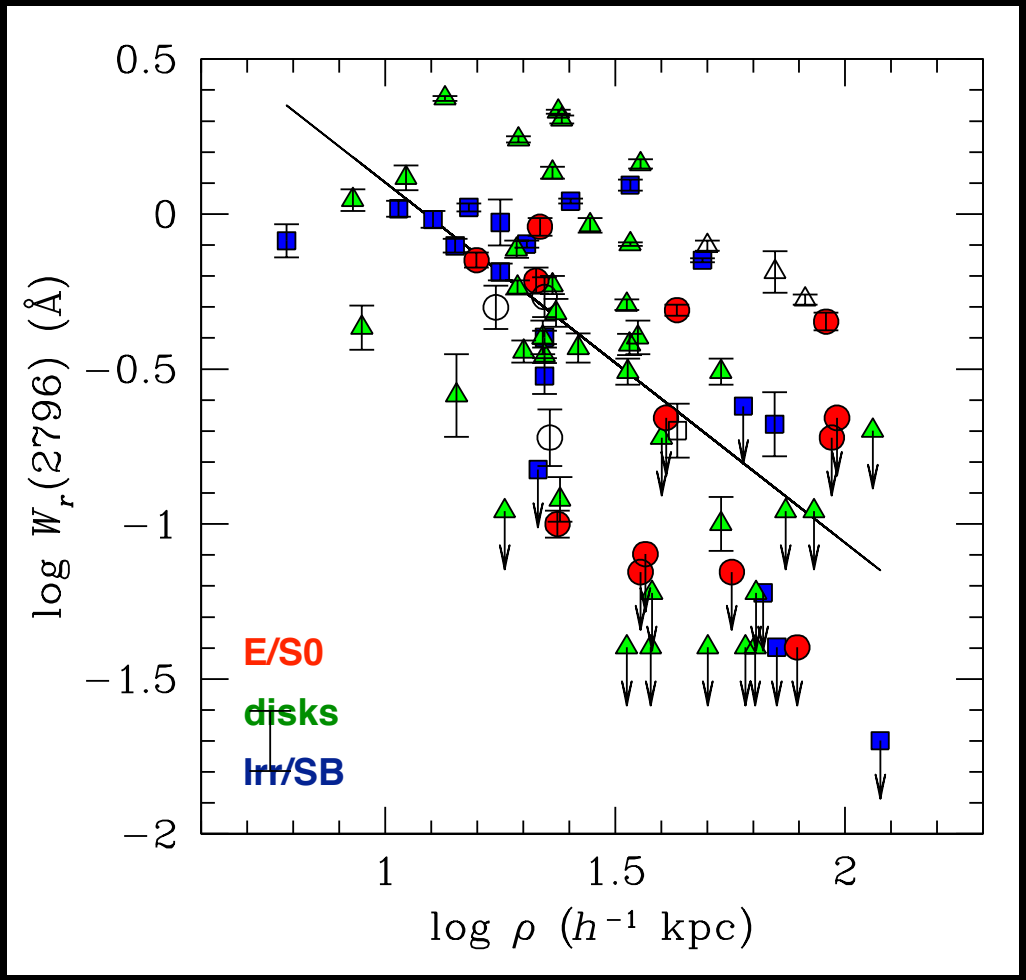


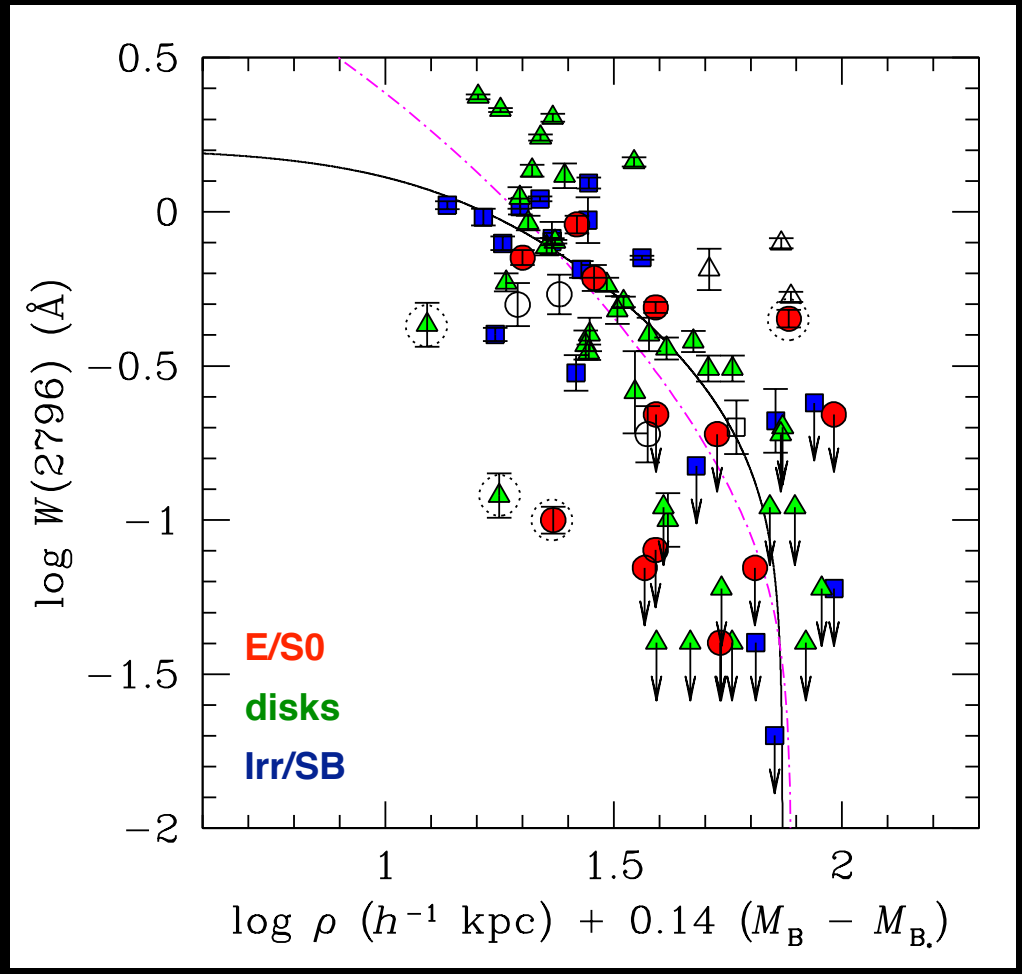


Chen et al. (2001b)

Circumgalactic Medium at z < 1

MgII Absorbers



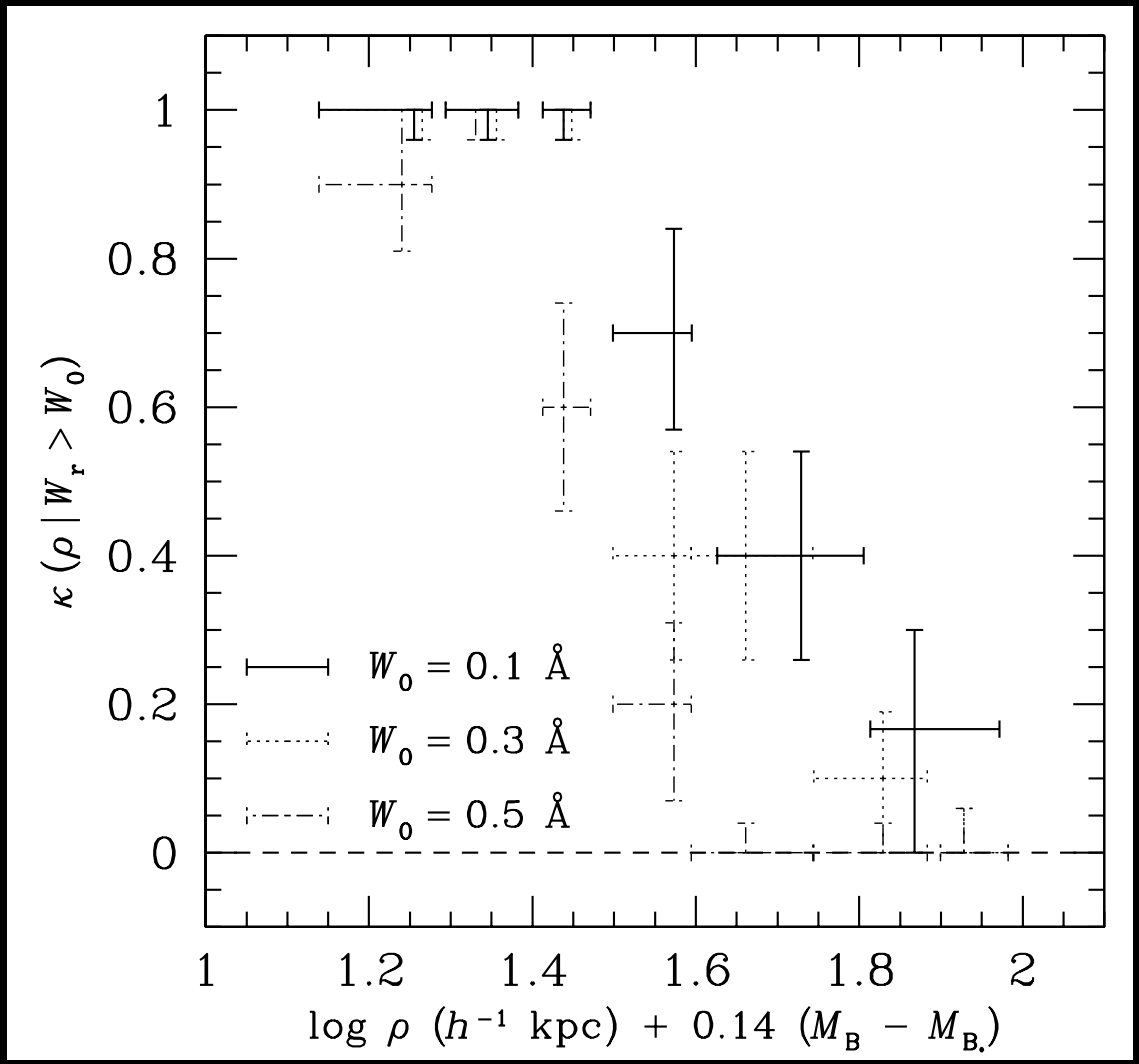


Chen et al. (2010a,b)

Circumgalactic Medium at z < 1

Incidence of *Cool Gas* in Galactic Halos

Covering Fraction of MgII Absorbers vs. Radius



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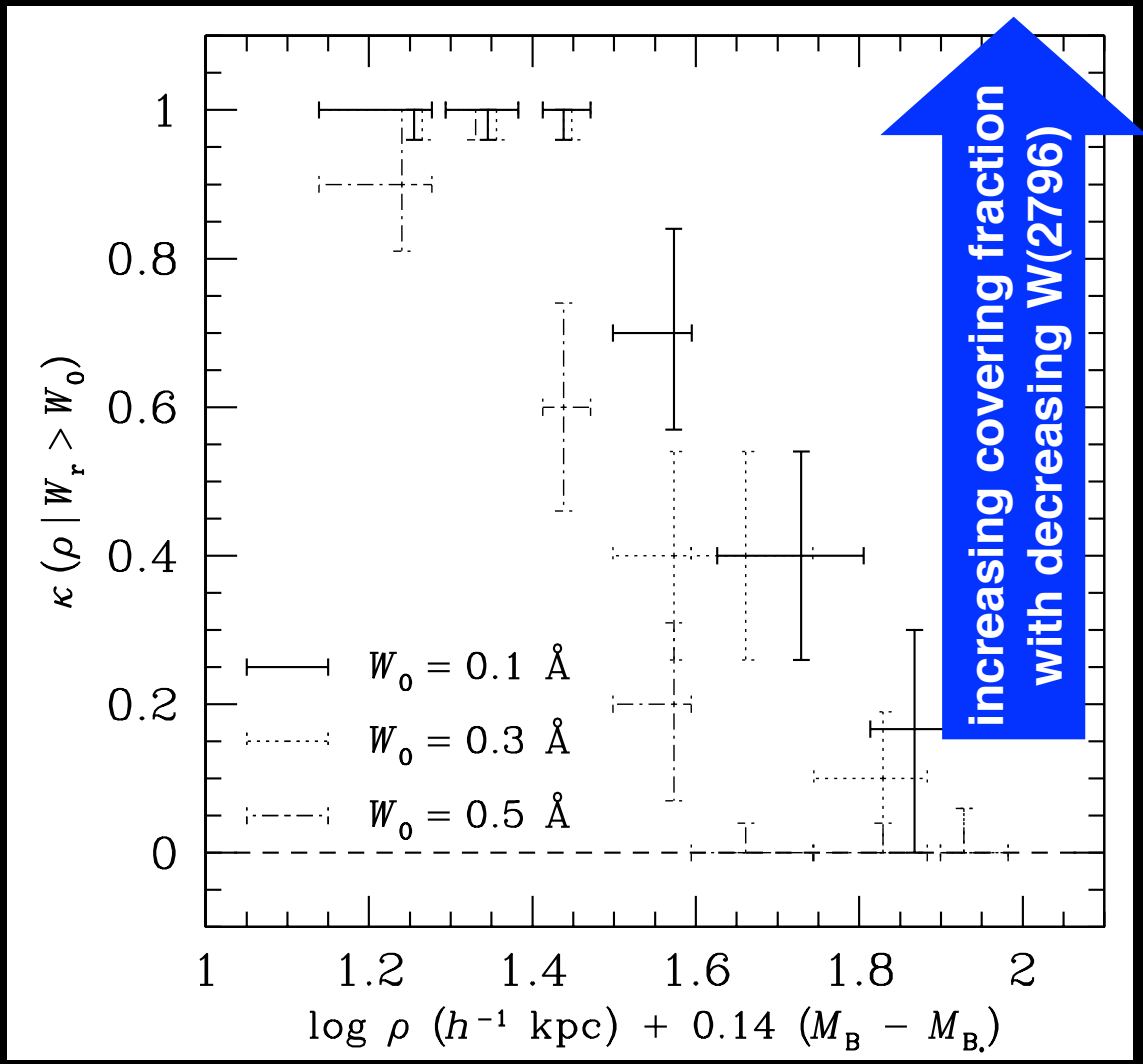

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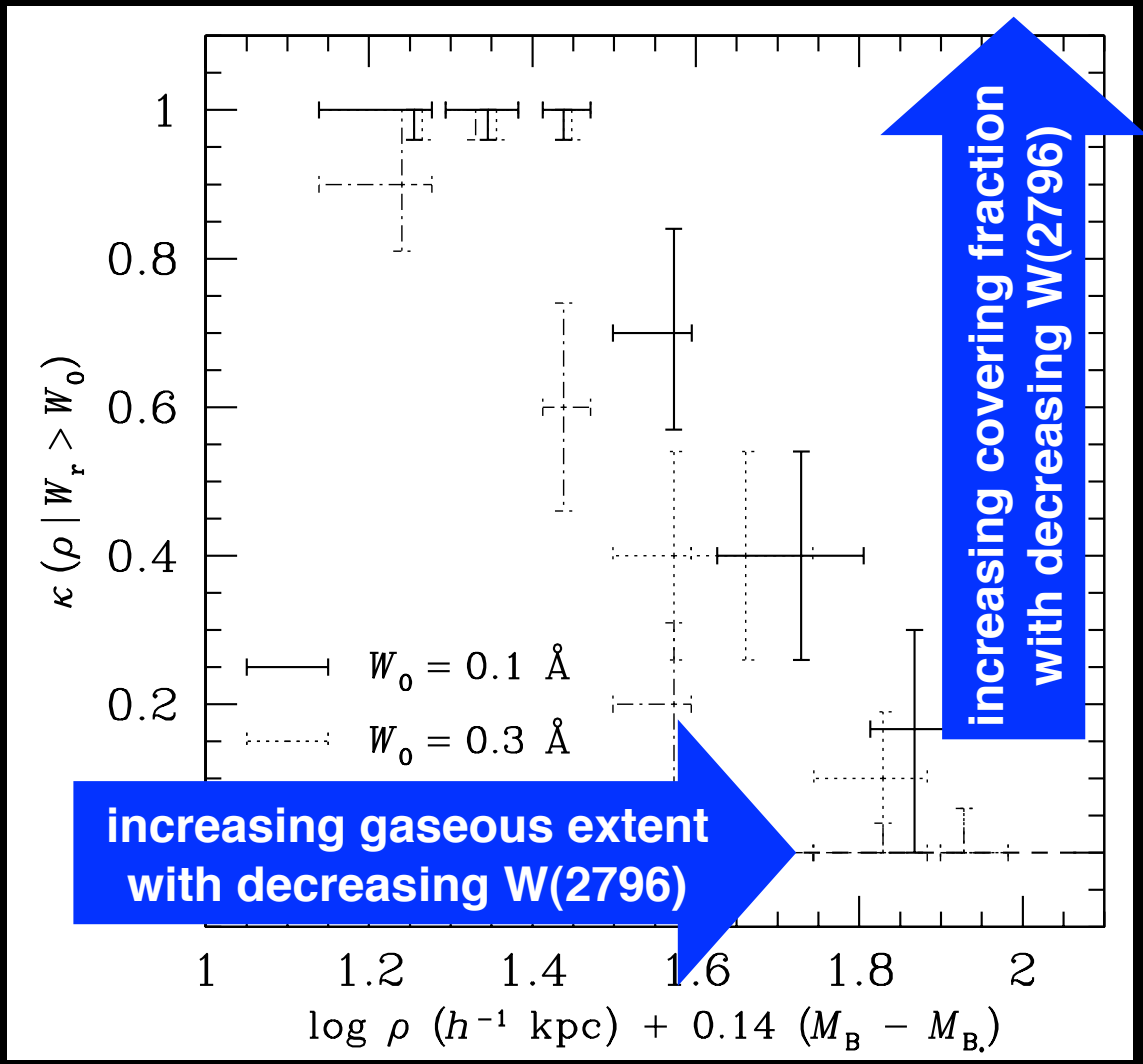

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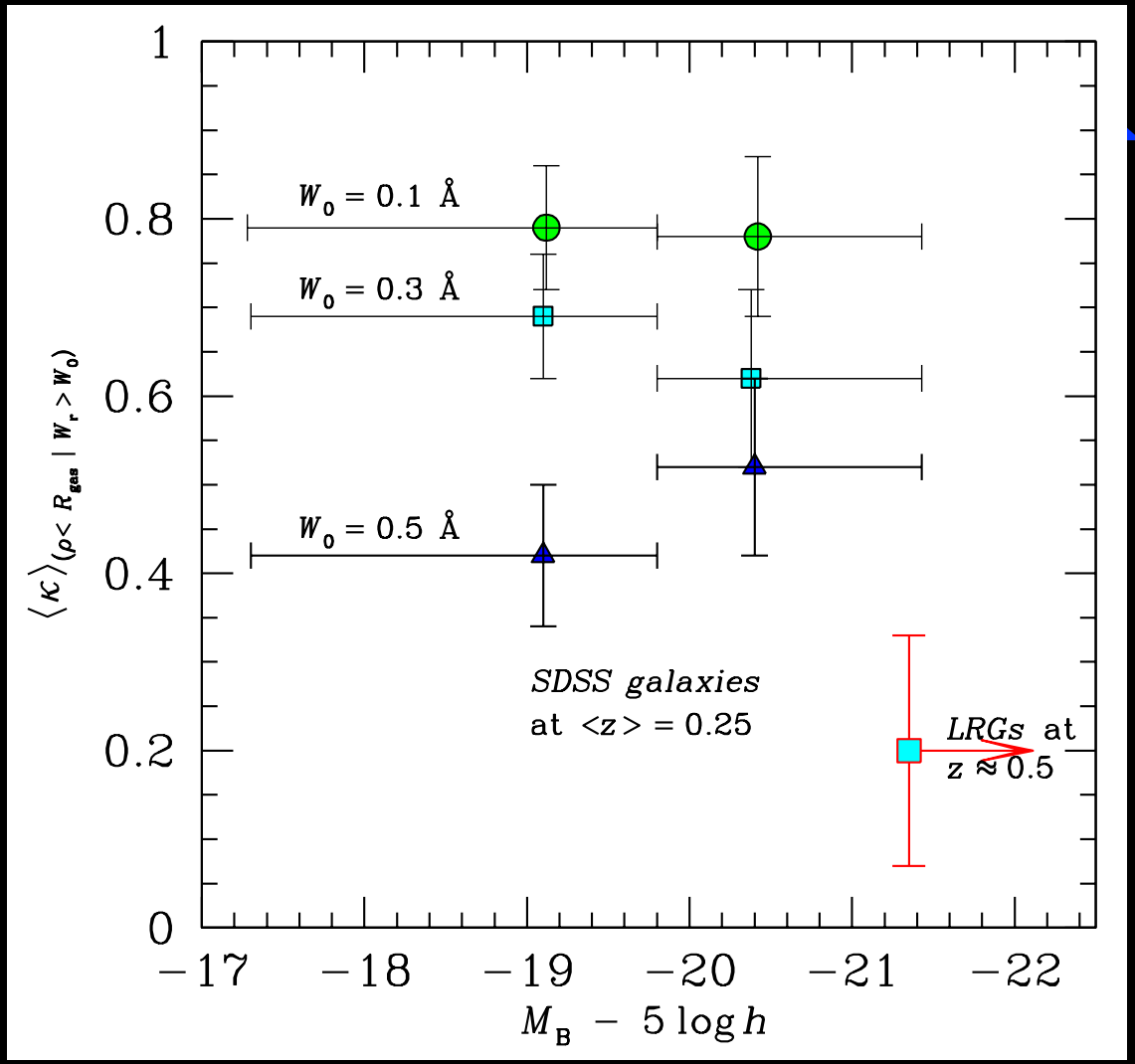
Covering Fraction of MgII Absorbers vs. Luminosity



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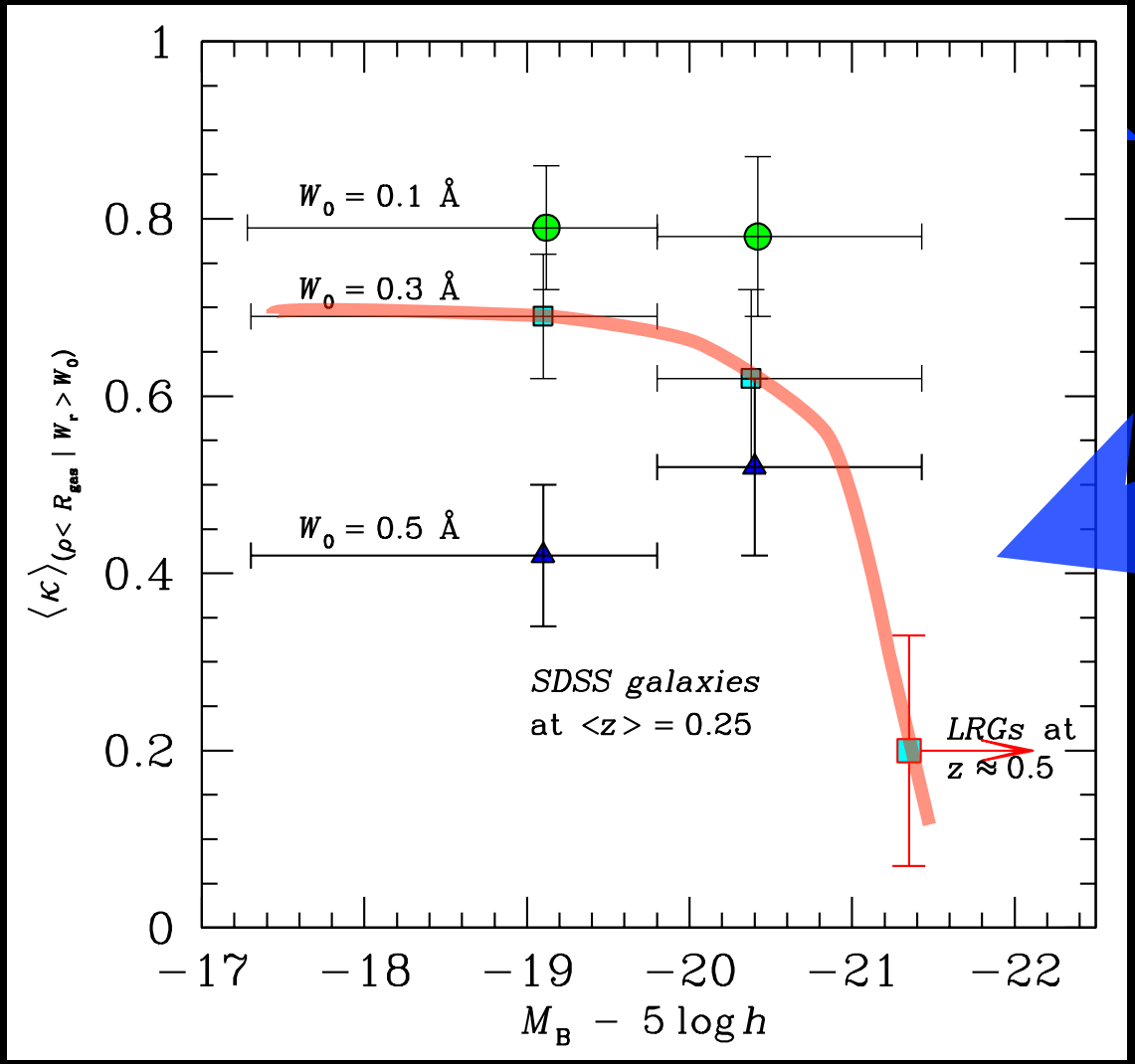
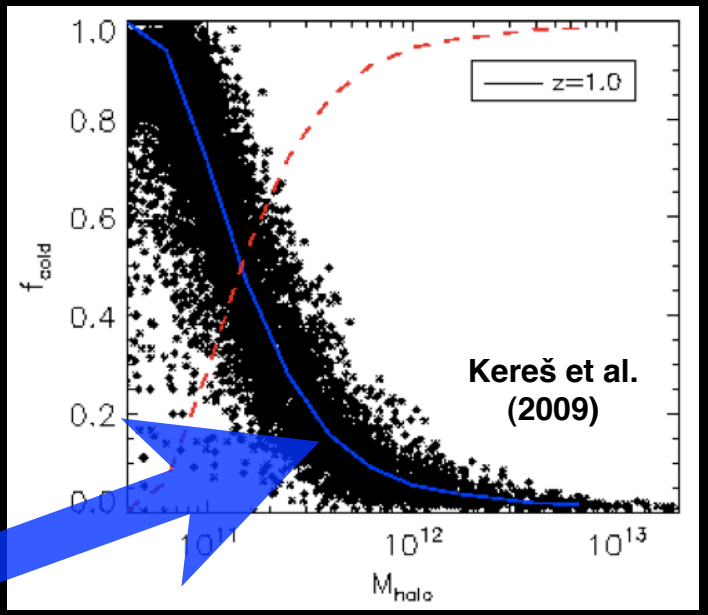
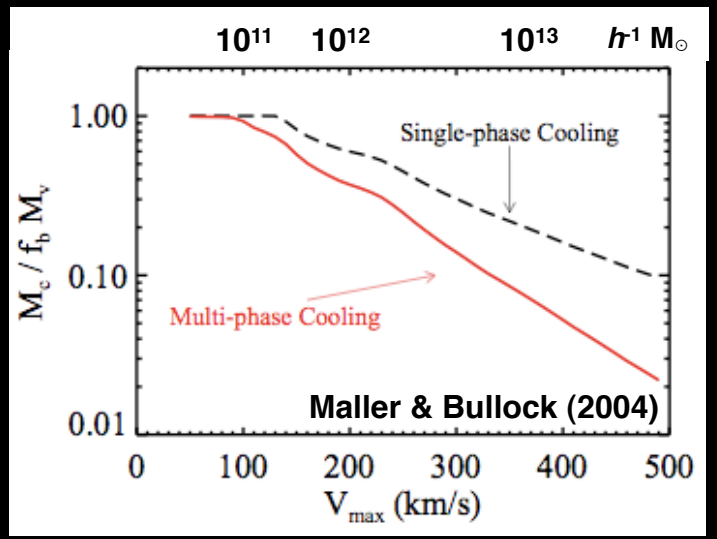


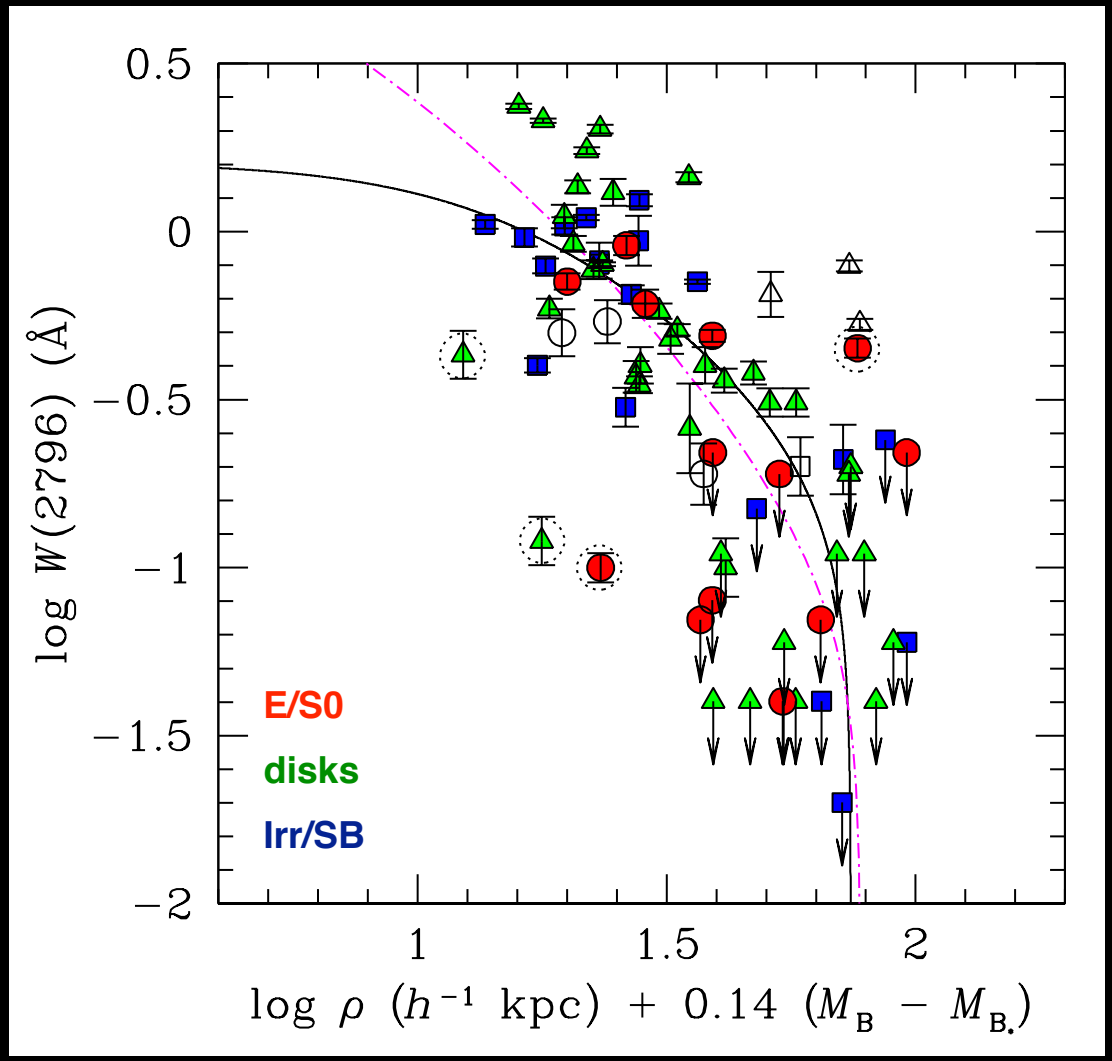




Chen et al. (2010); Gauthier et al. (2010), Gauthier & Chen (2011)

Circumgalactic Medium at z < 1

Total Cool Gas Mass in Galactic Halos



Chen et al. (2010a)

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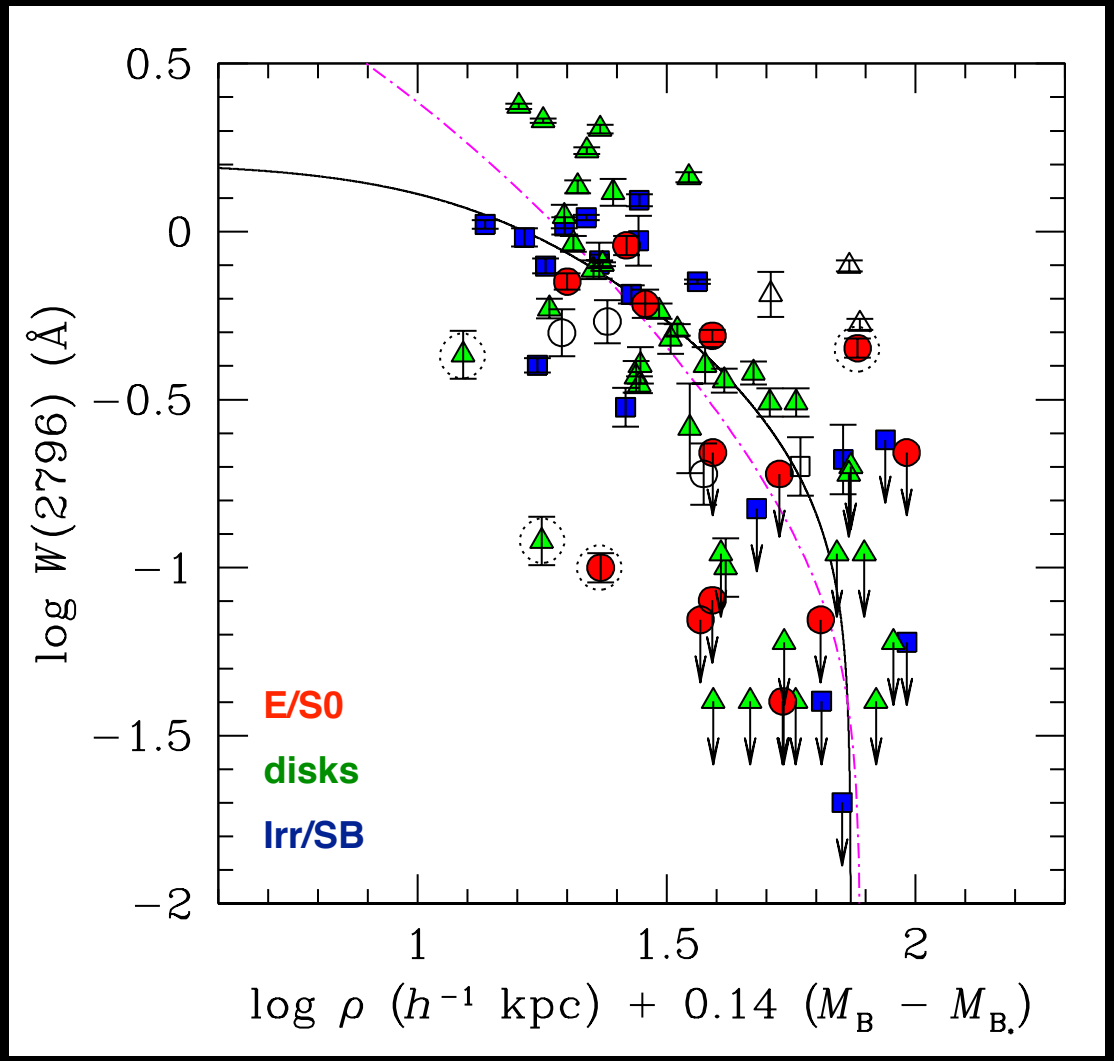

Chen et al. (2010a)

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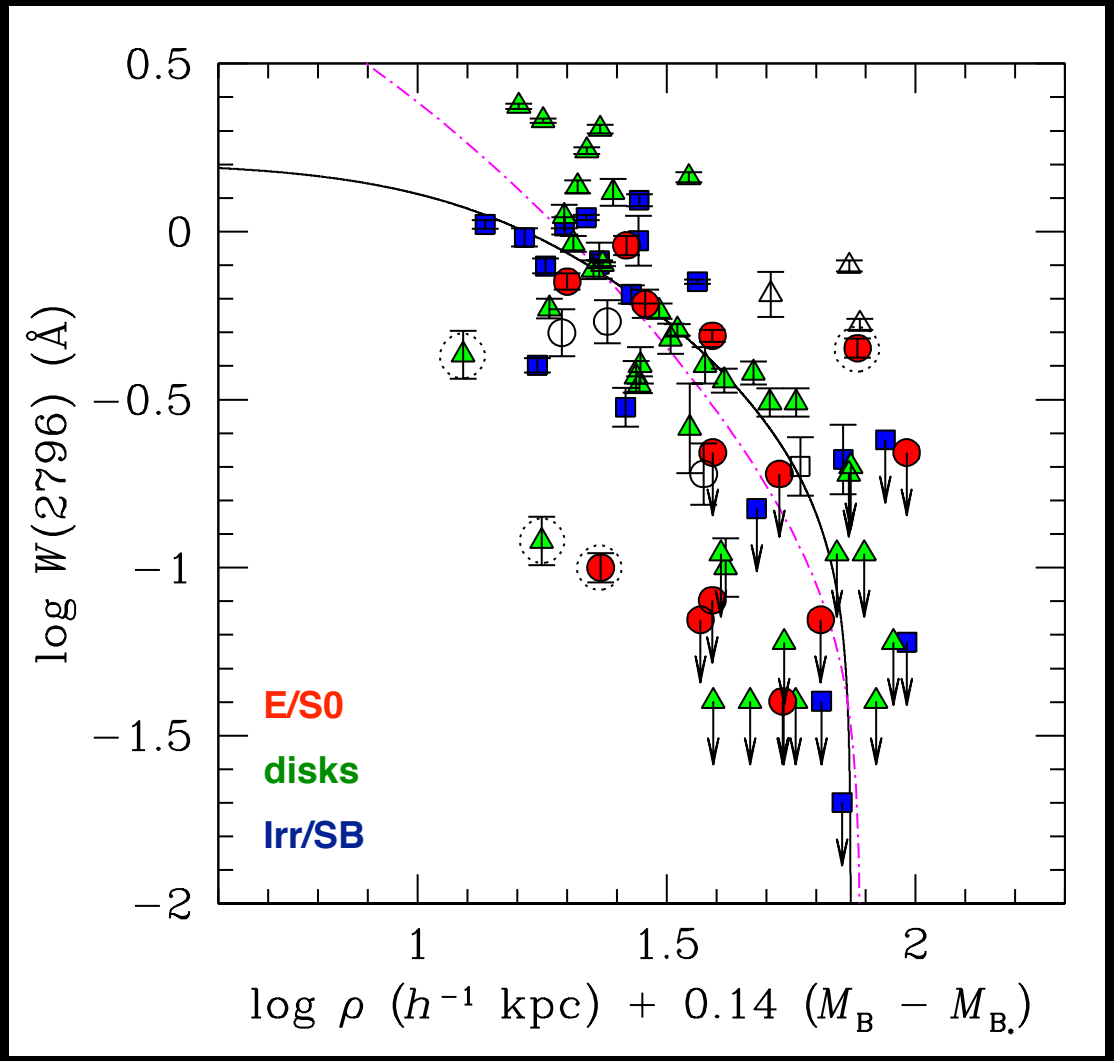

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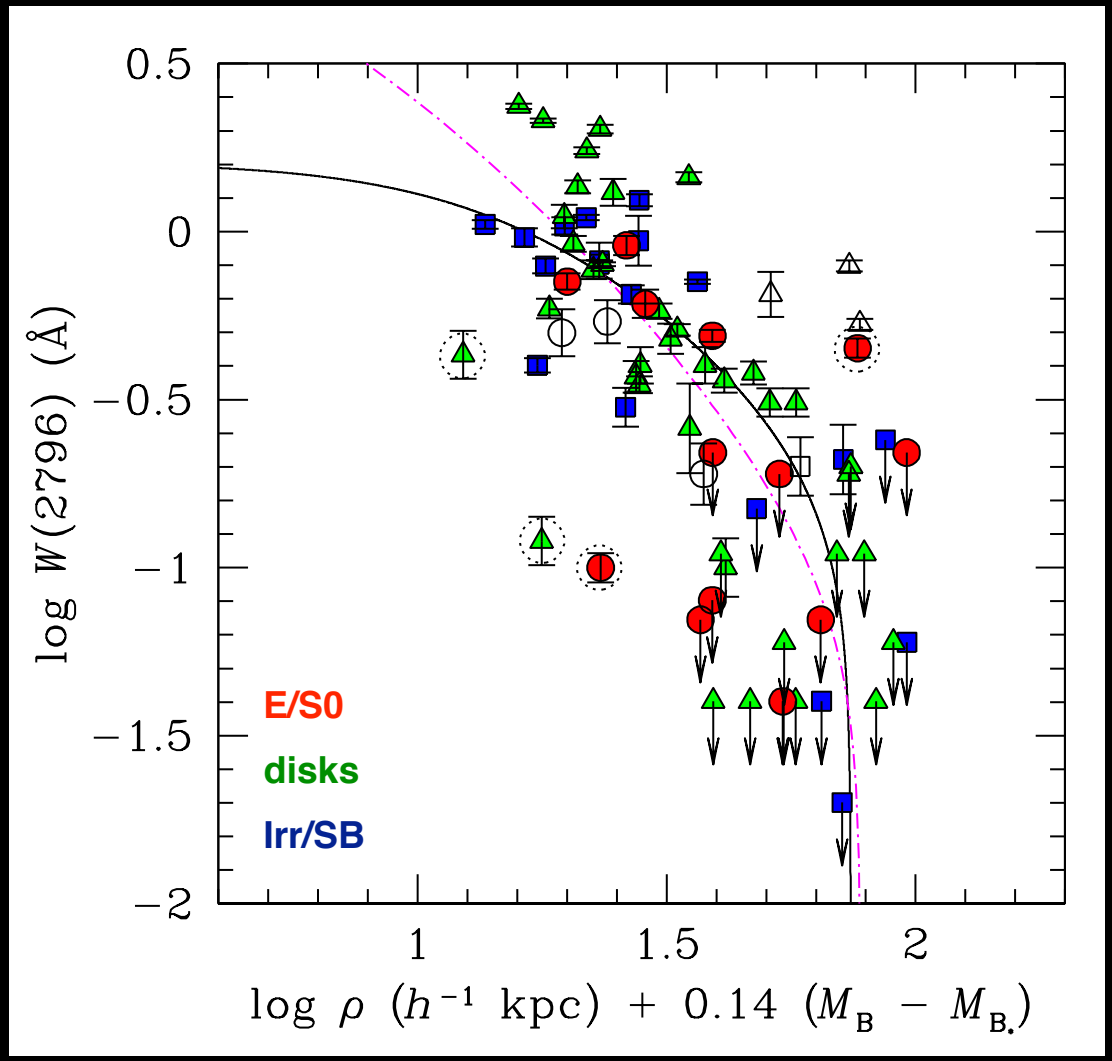

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Origin of Metal Absorbers Around Distant Galaxies

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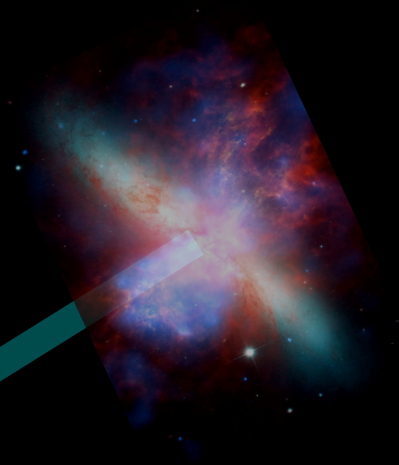
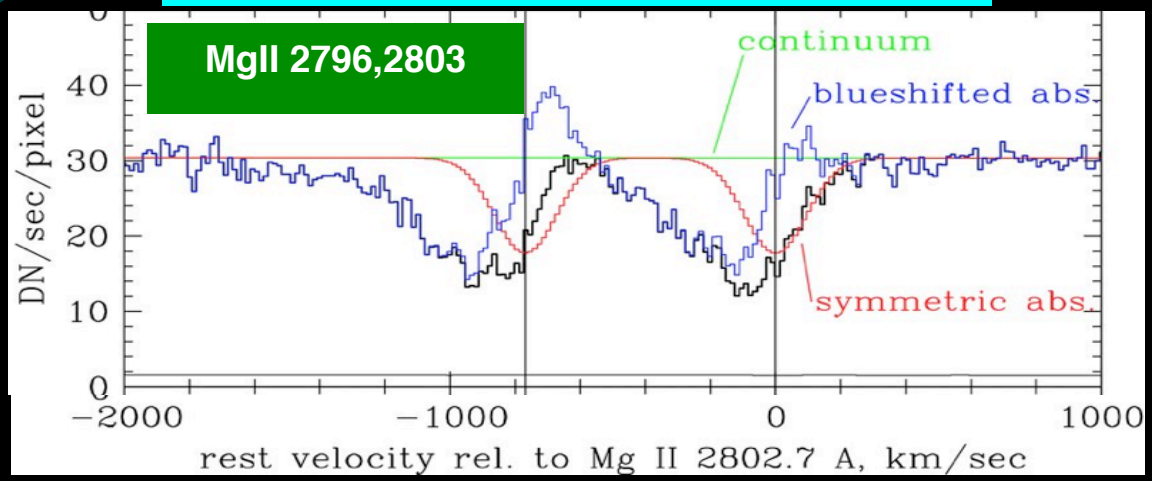


self-absorption against star-forming regions



Weiner+ ’09; Martin & Bouche ’09; Rubin+’10

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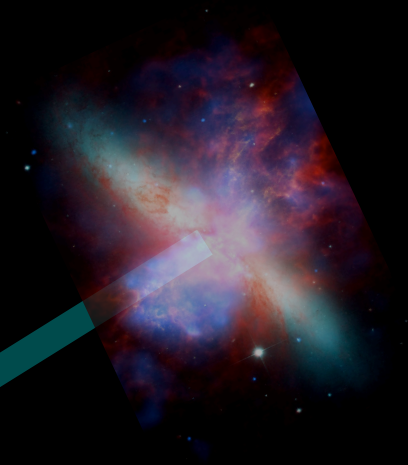

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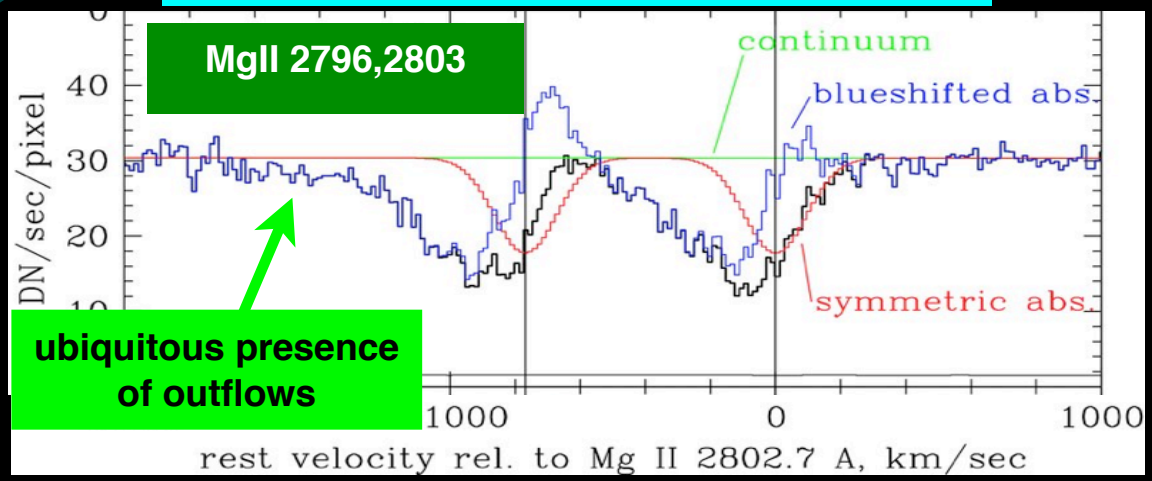

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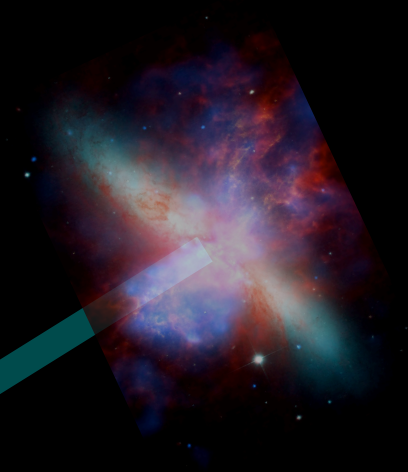

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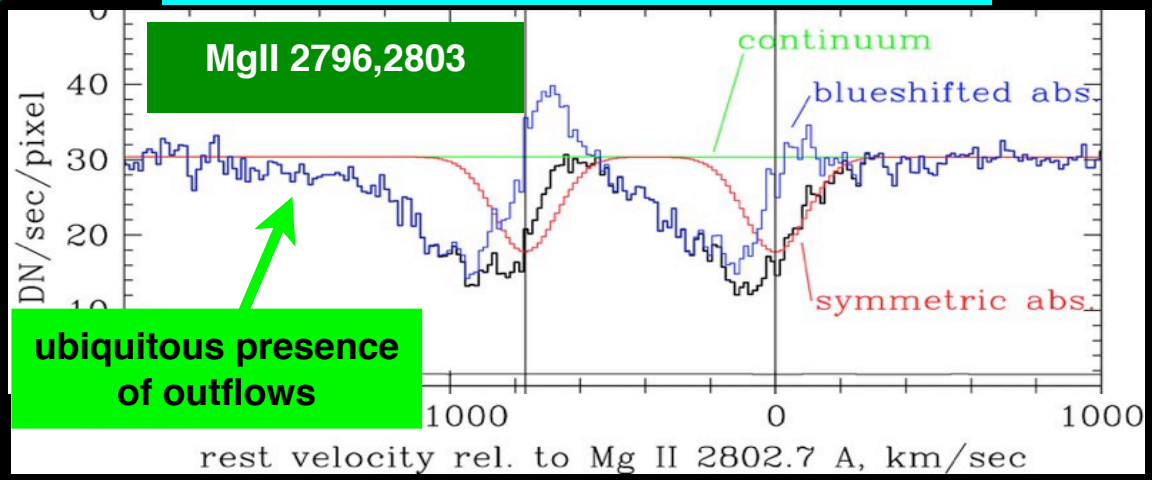

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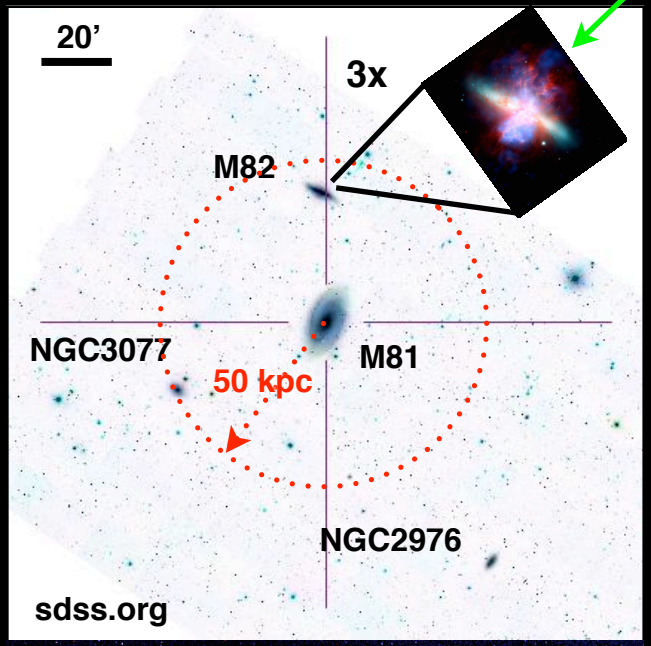

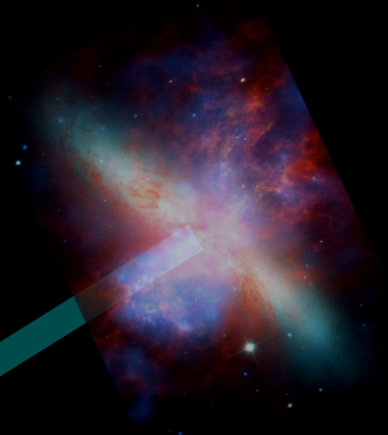

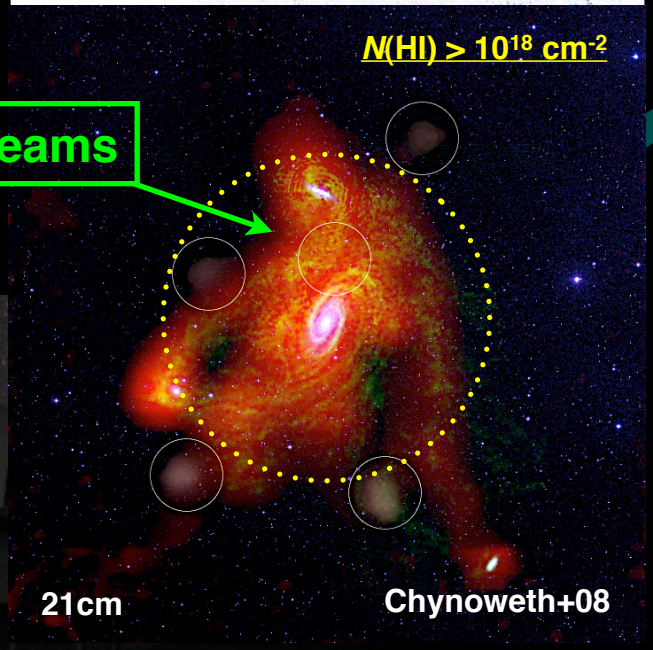

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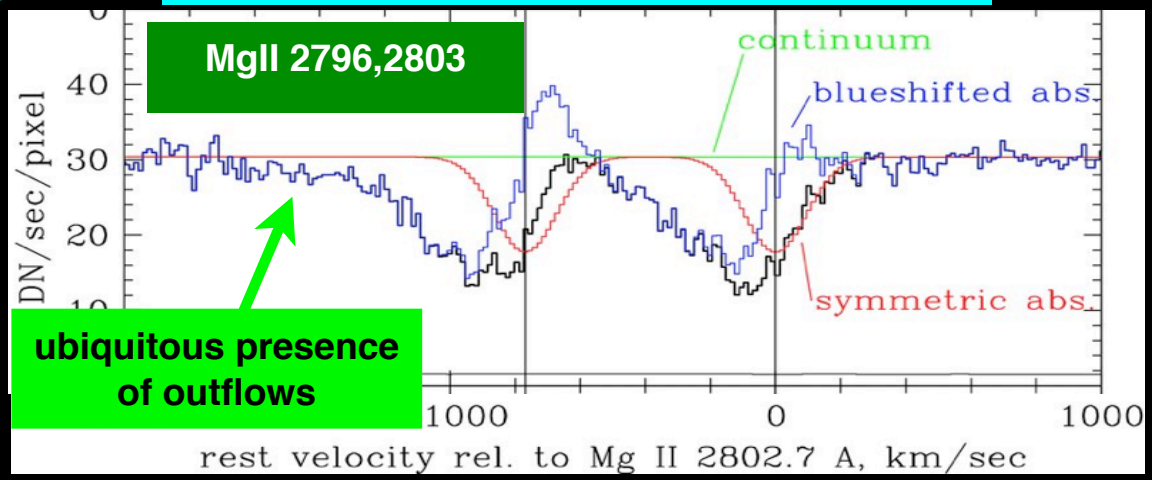

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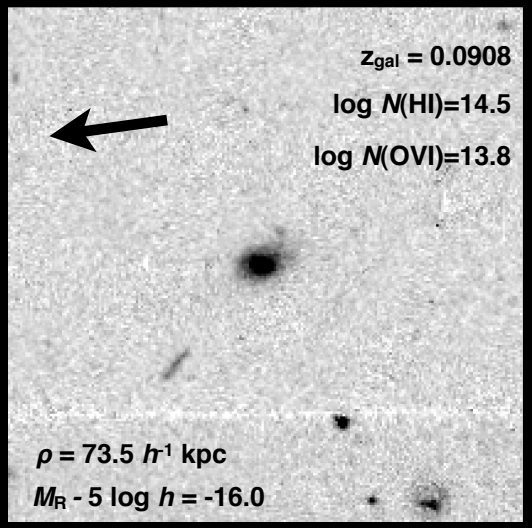
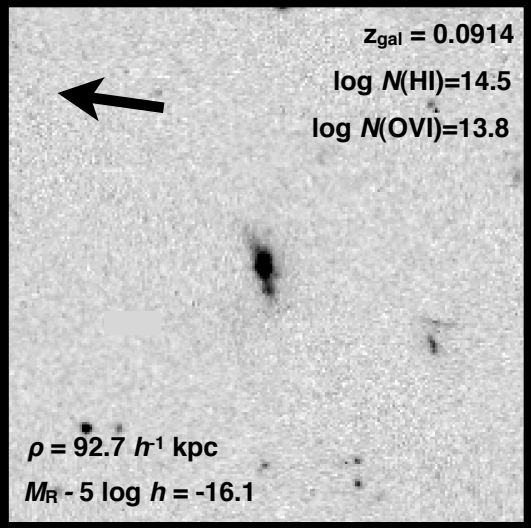
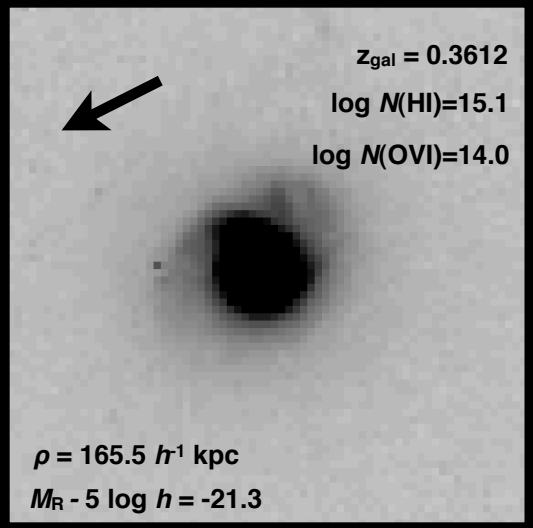
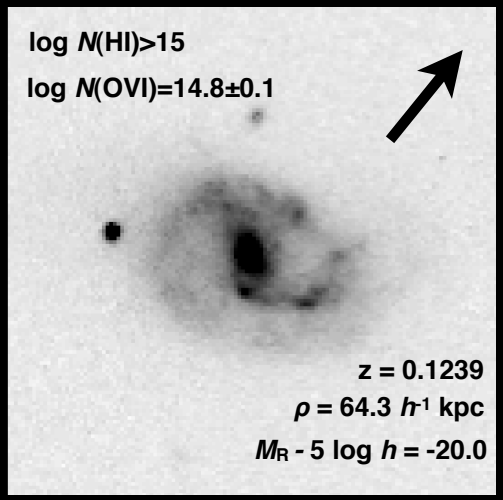
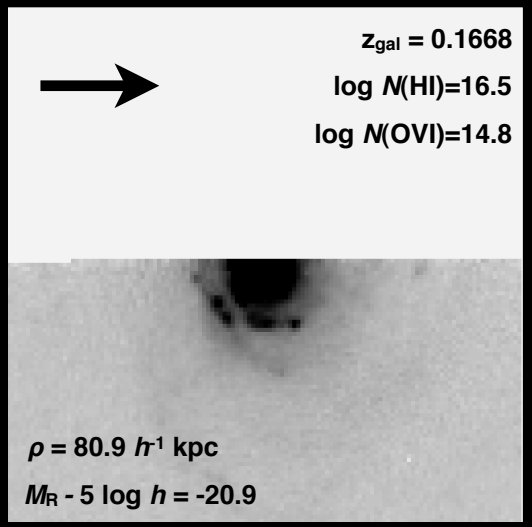
HST/WFPC2 images of seven OVI galaxies Chen & Mulchaey (2009)

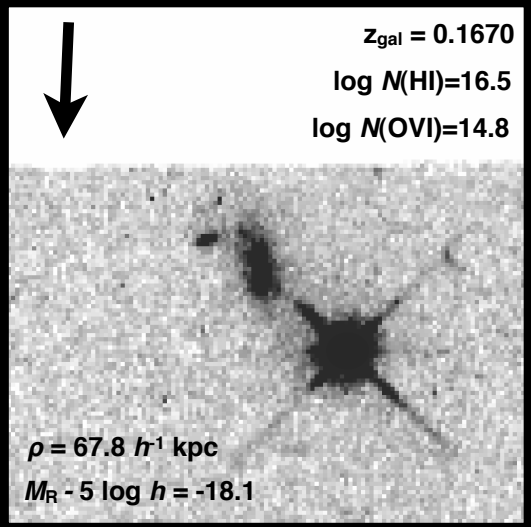


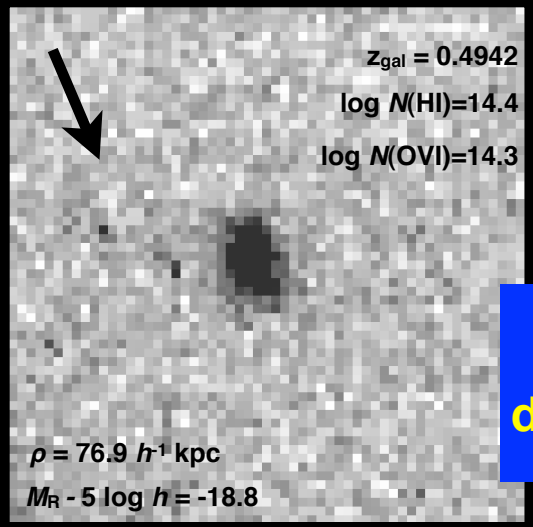












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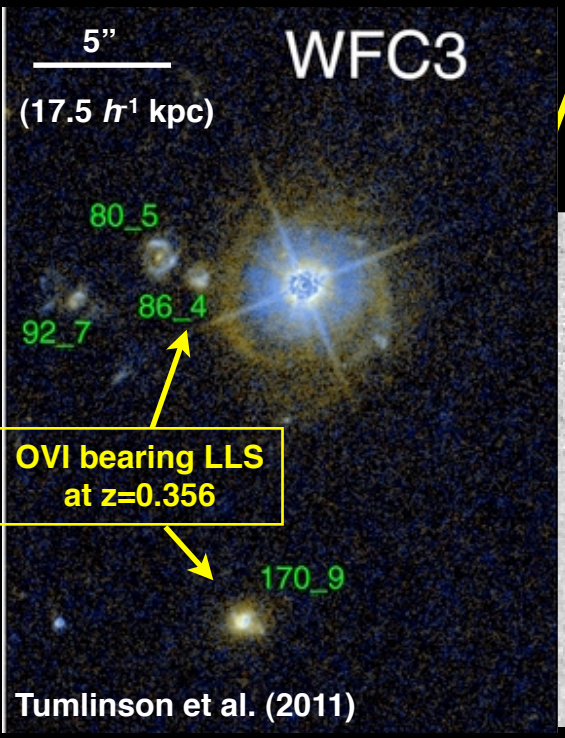

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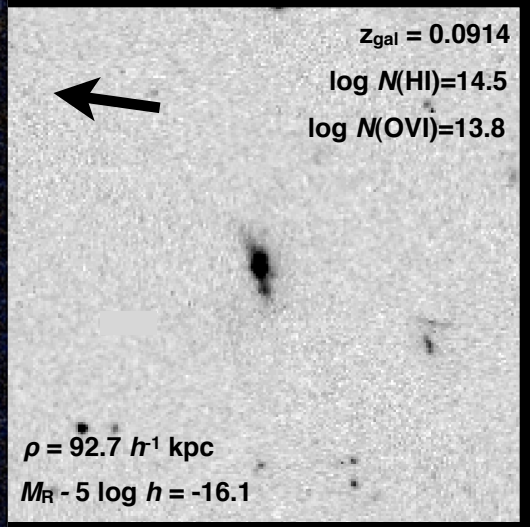

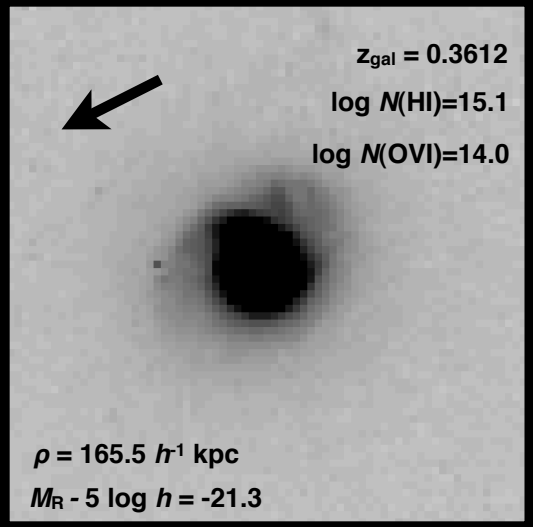

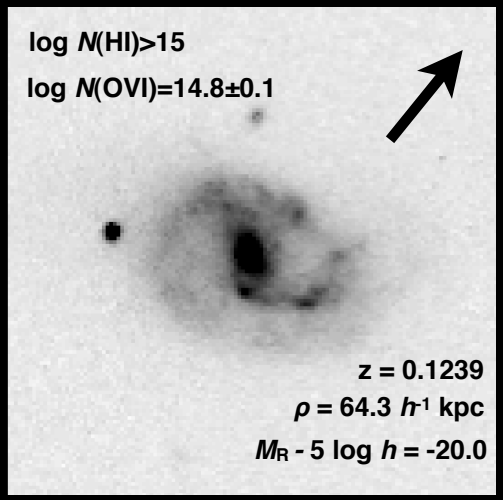

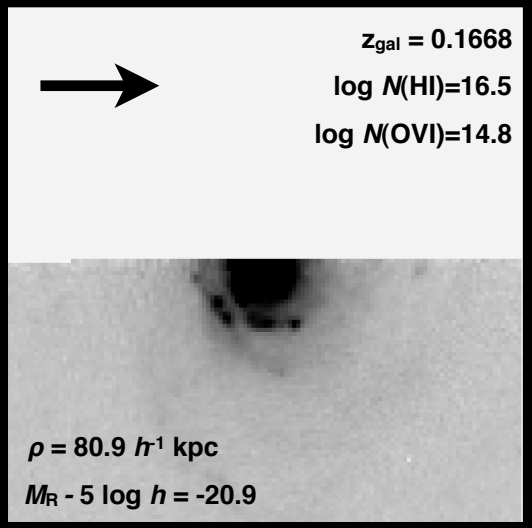

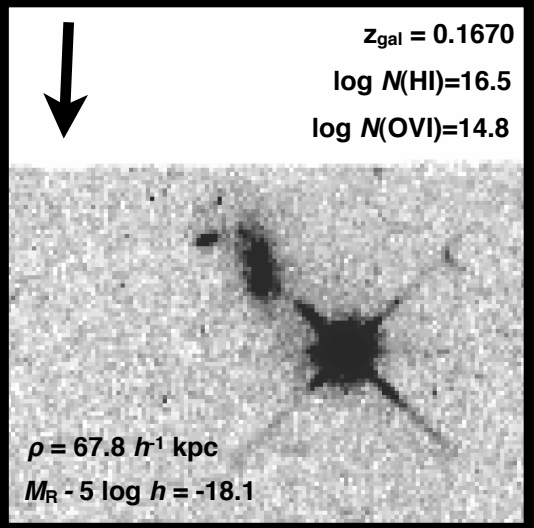

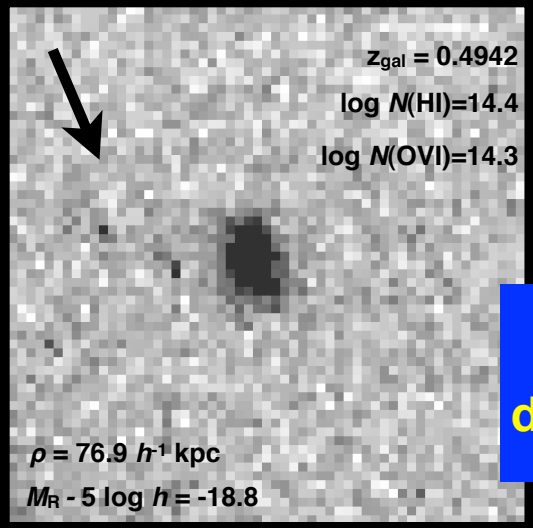

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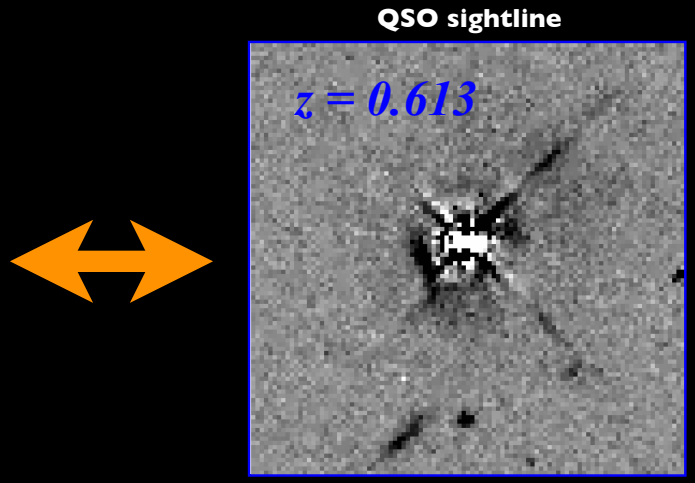
GRB Afterglows as Cosmic Probes

- **transient phenomenon**
  - does not interfere imaging follow-up



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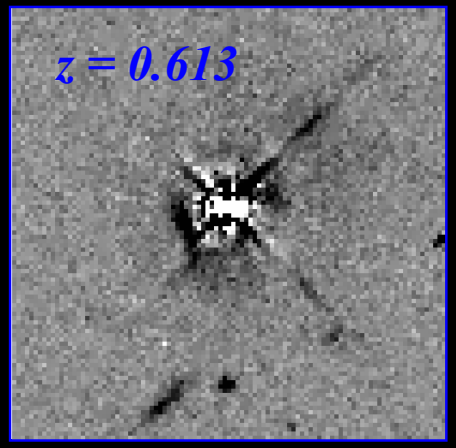

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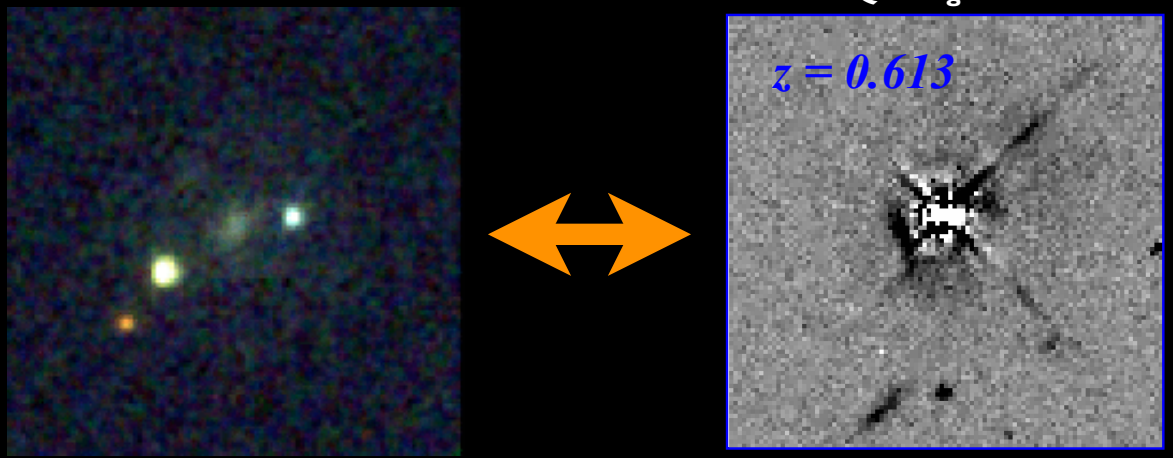

- **simple power-law spectral shape**
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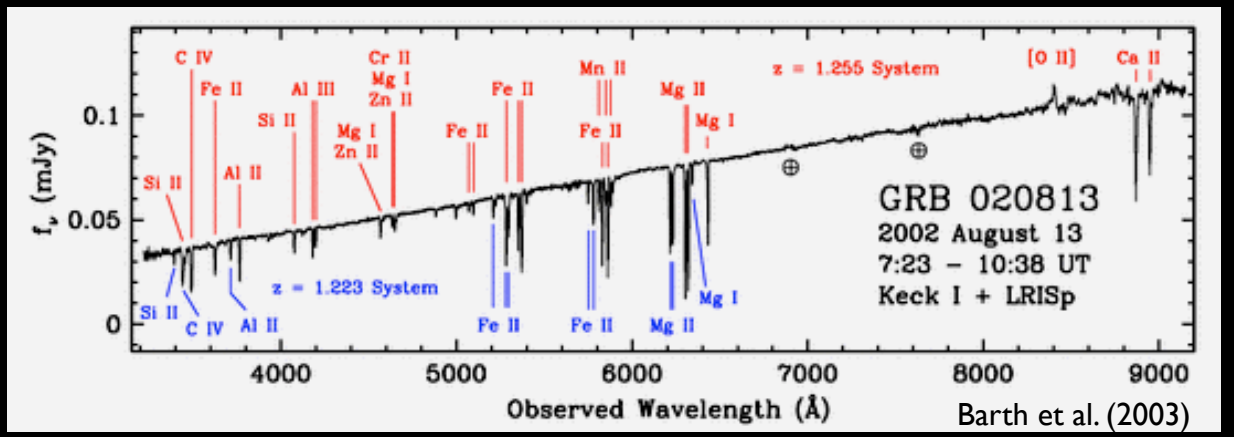

Barth et al. (2003)

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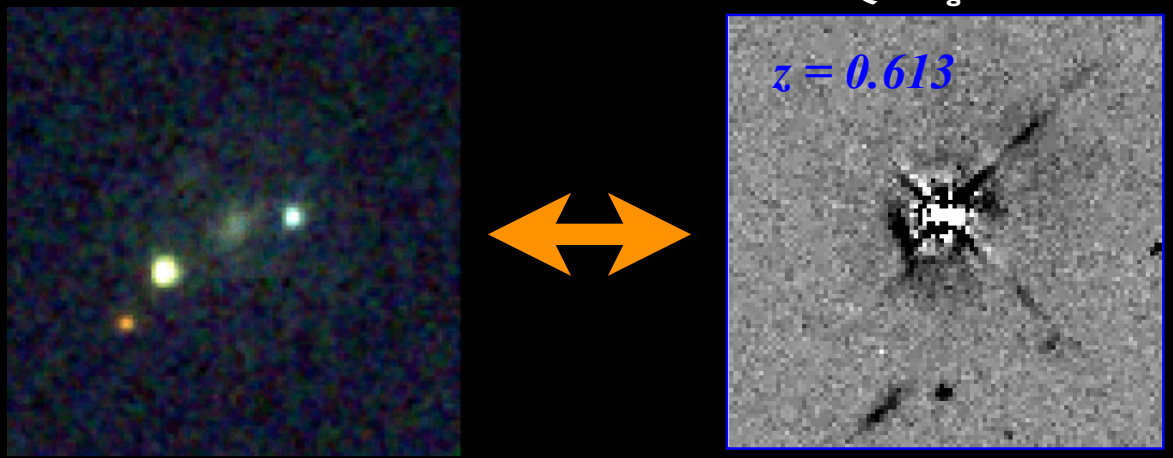

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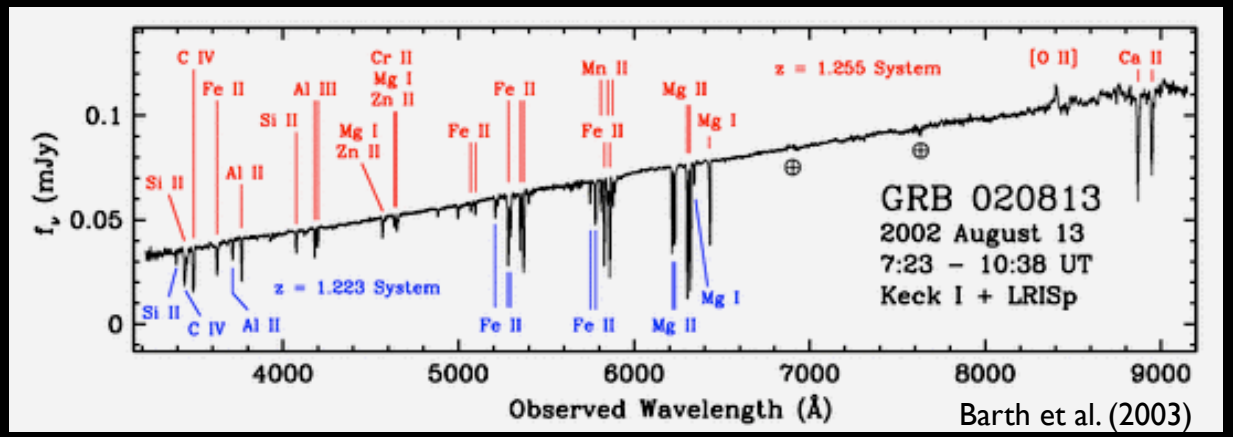
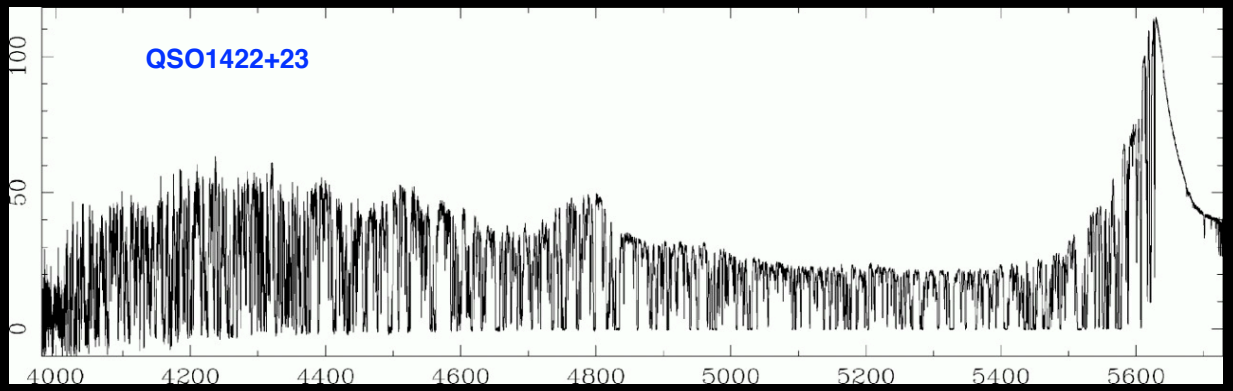


Barth et al. (2003)

- **c.f. QSO spectra with bumps/wiggles**



Rauch (1998)

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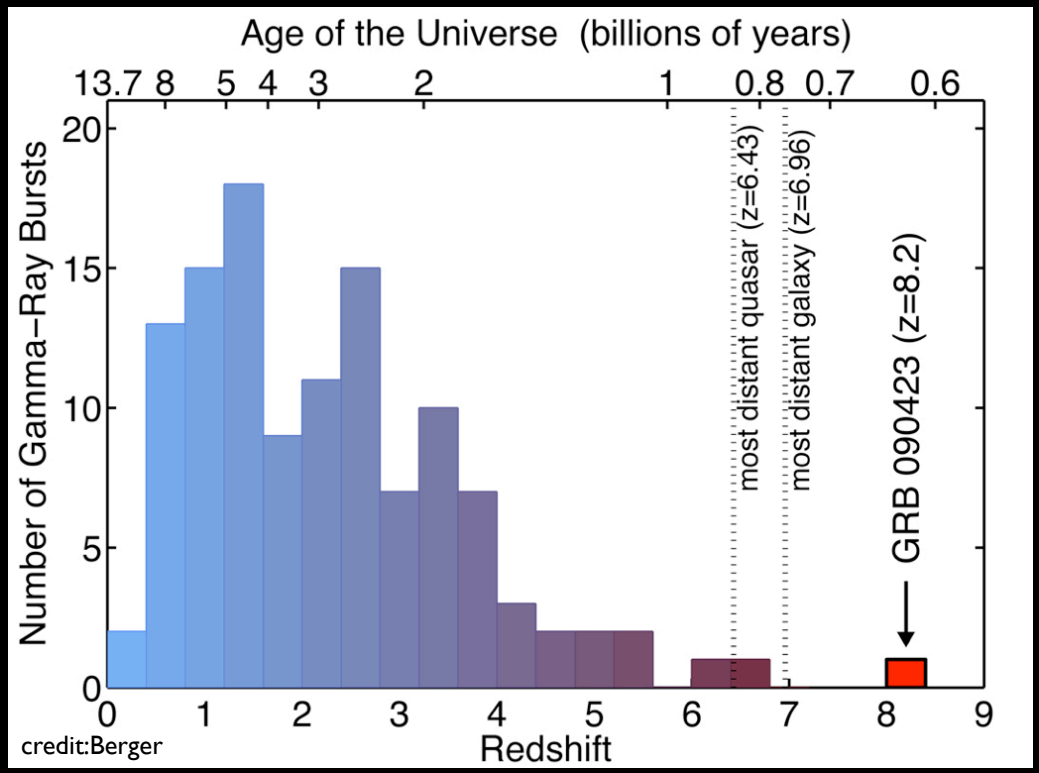
- **Pushing into the epoch of re-ionization**



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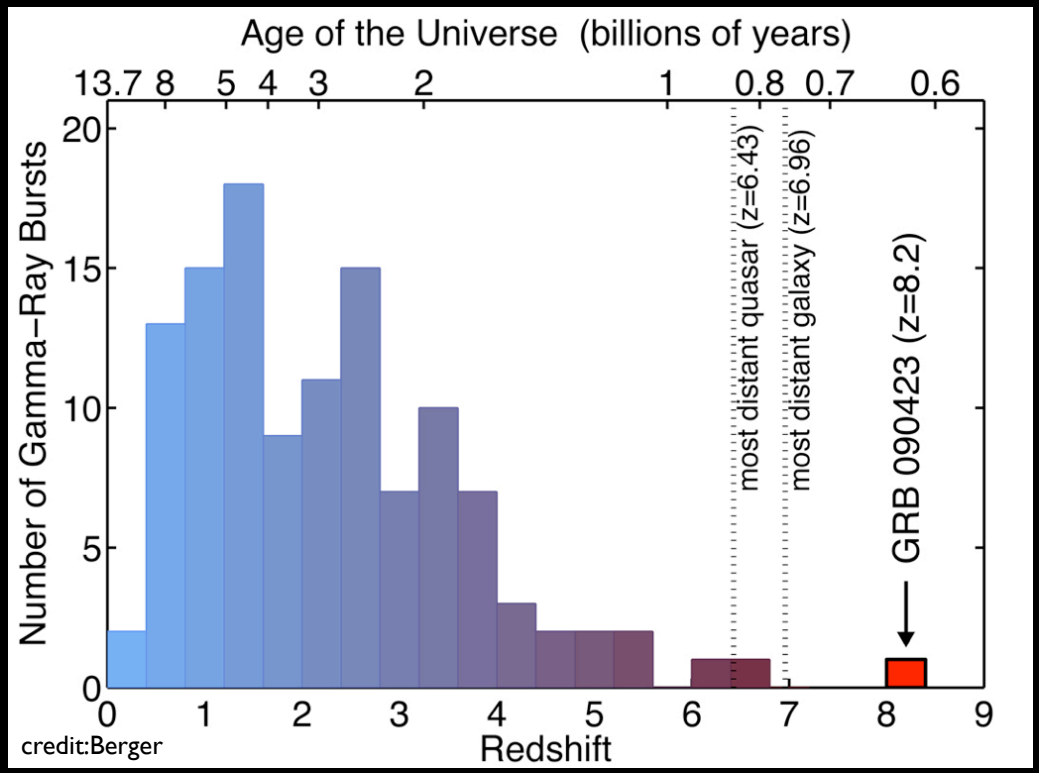

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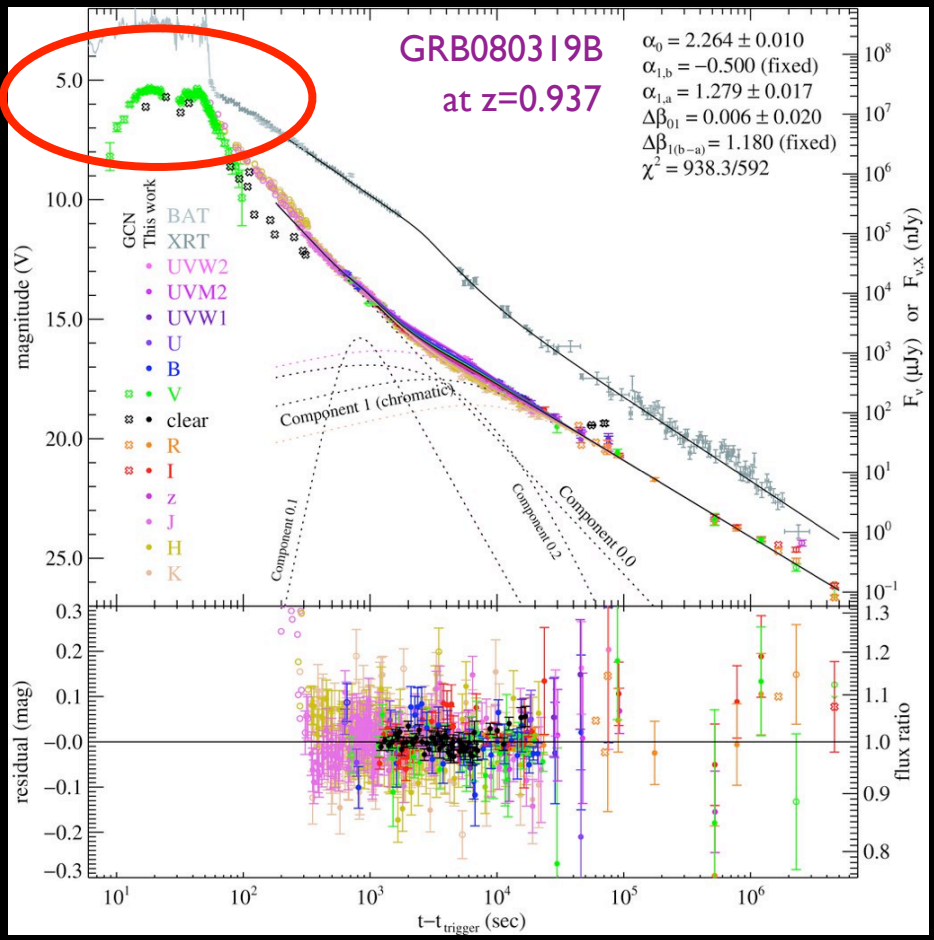

Bloom et al. (2009)

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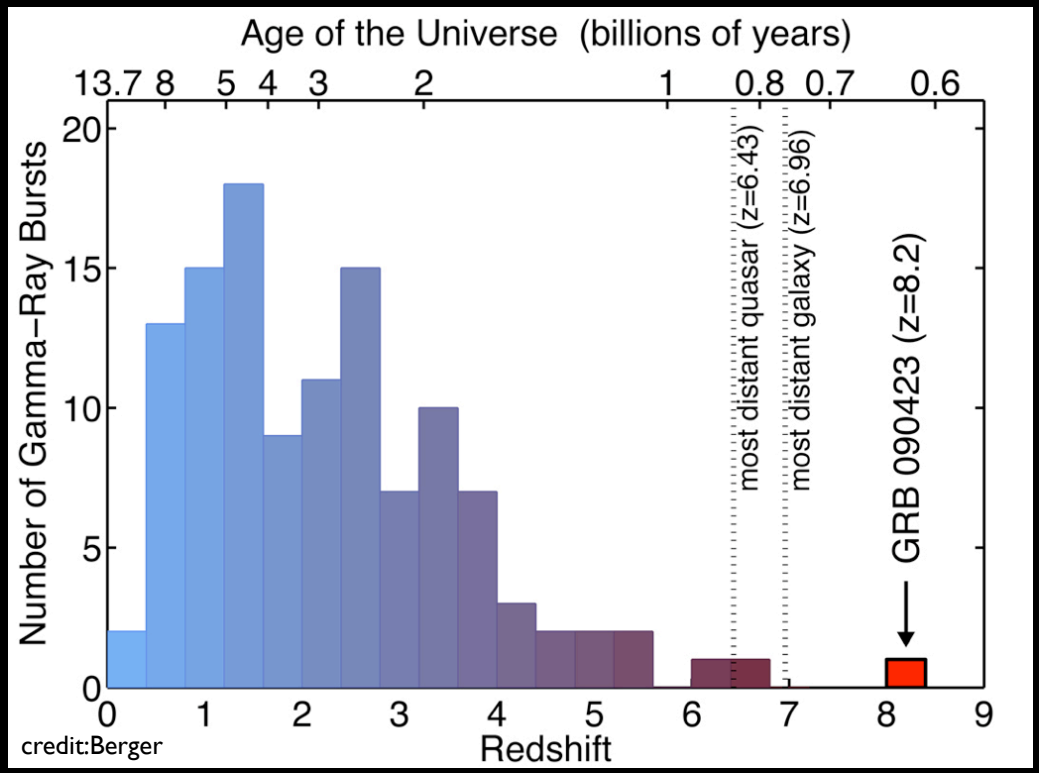

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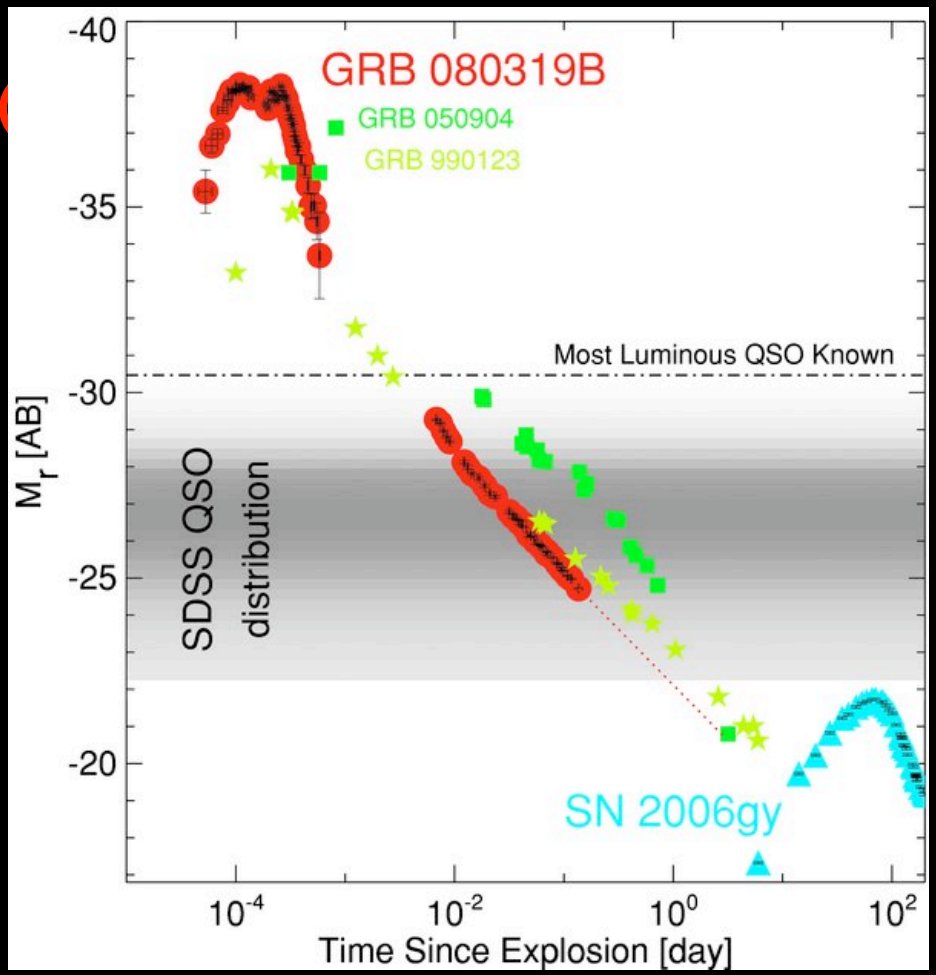
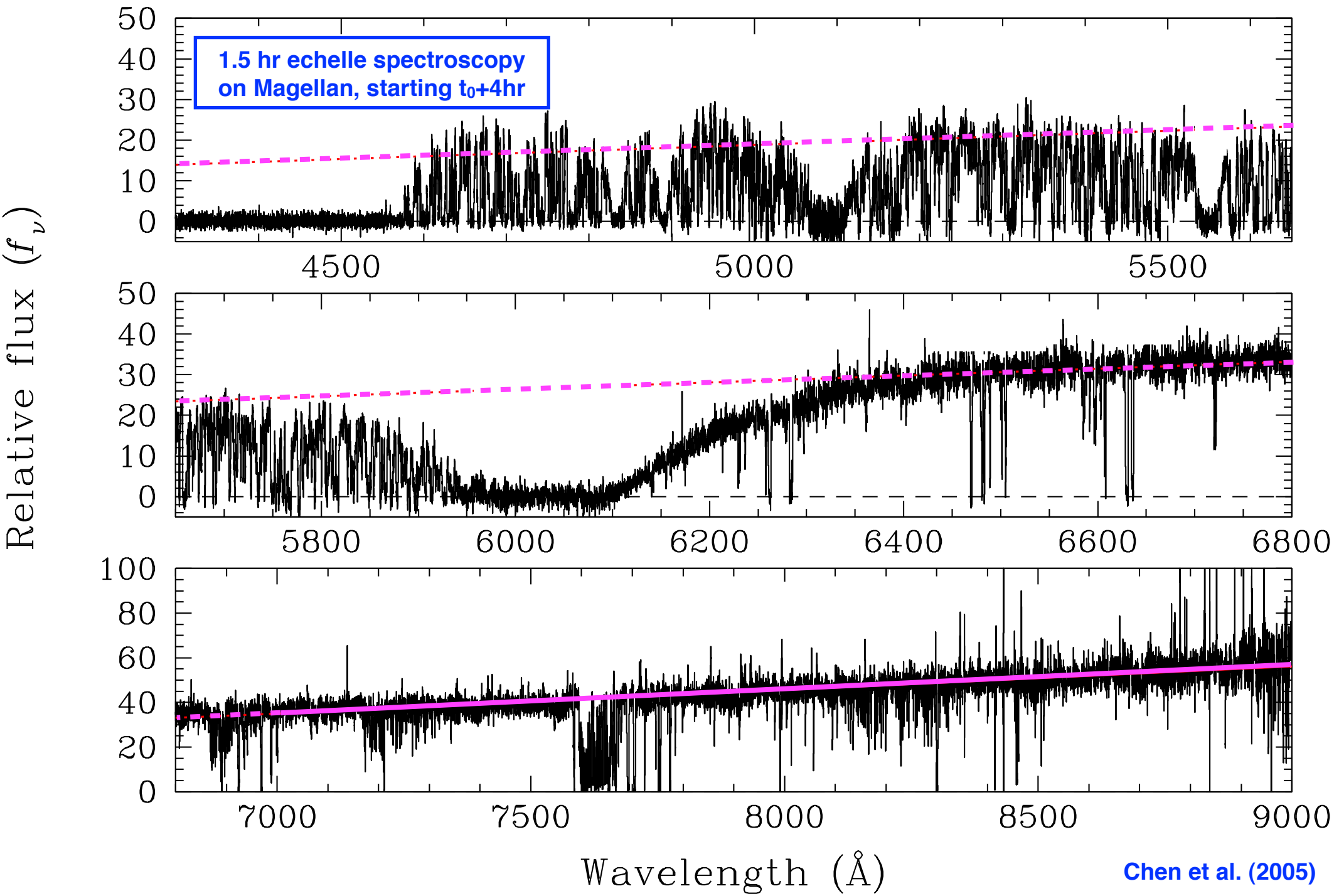


Bloom et al. (2009)

Early-time Afterglow Spectroscopy



Chen et al. (2005)

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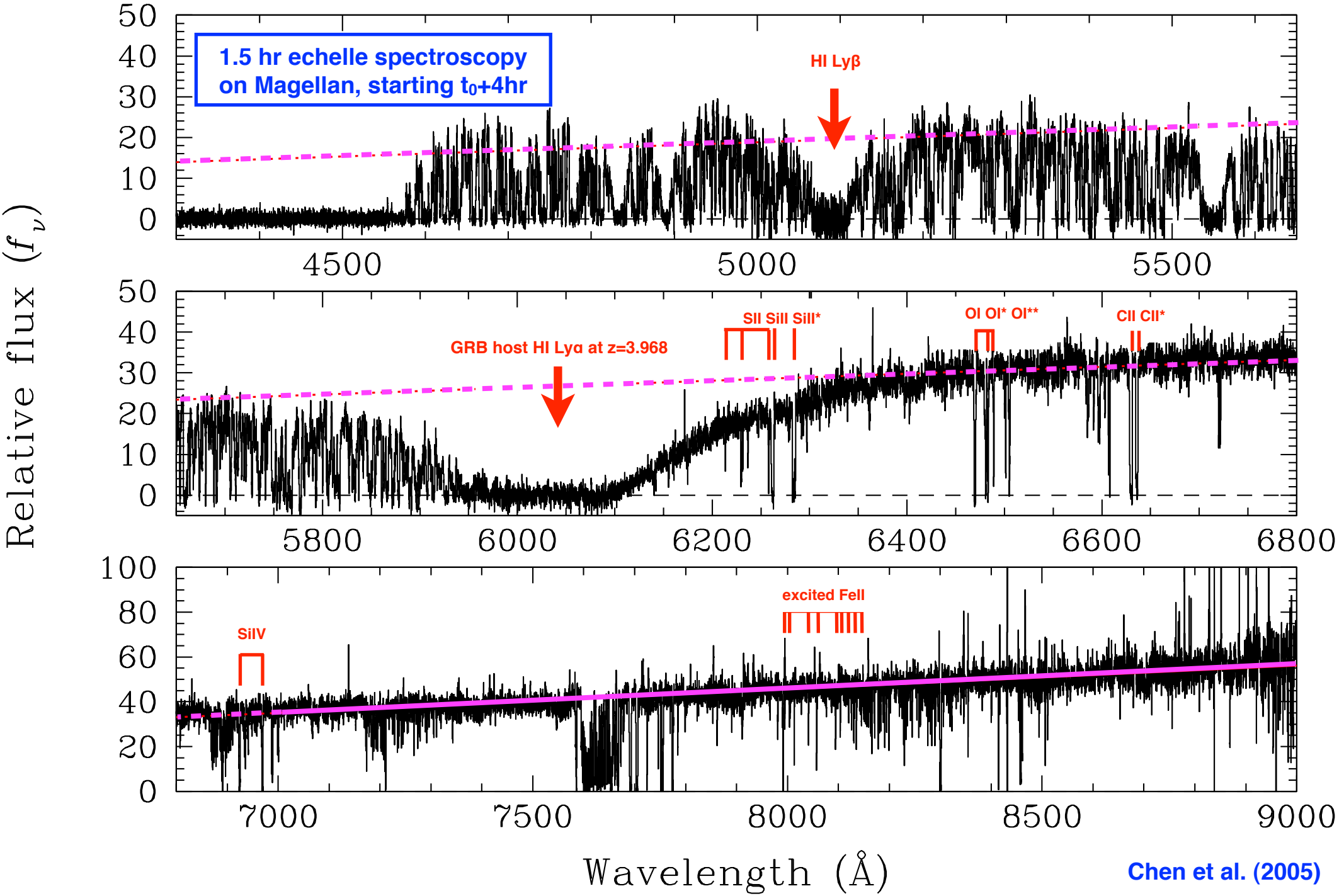

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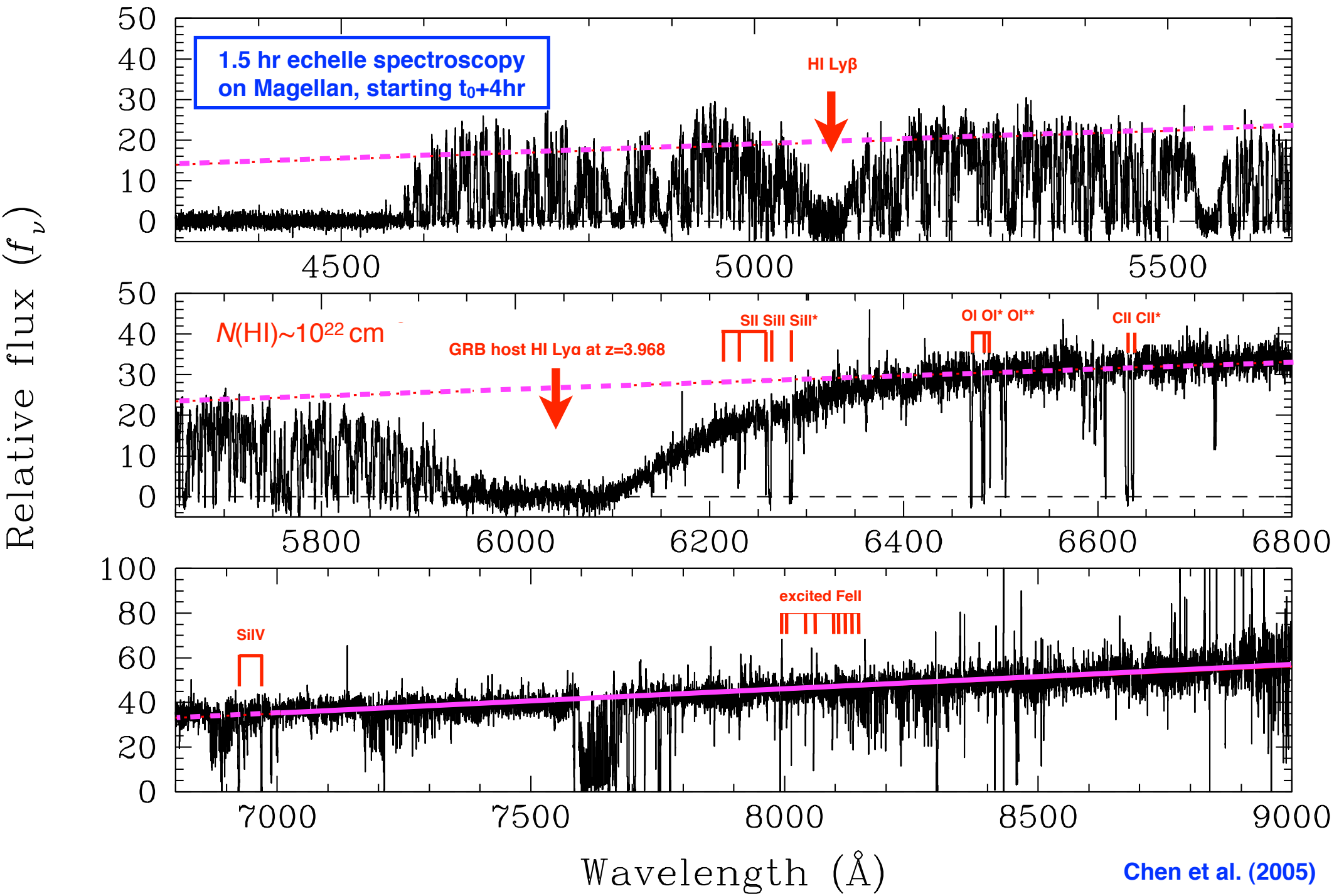

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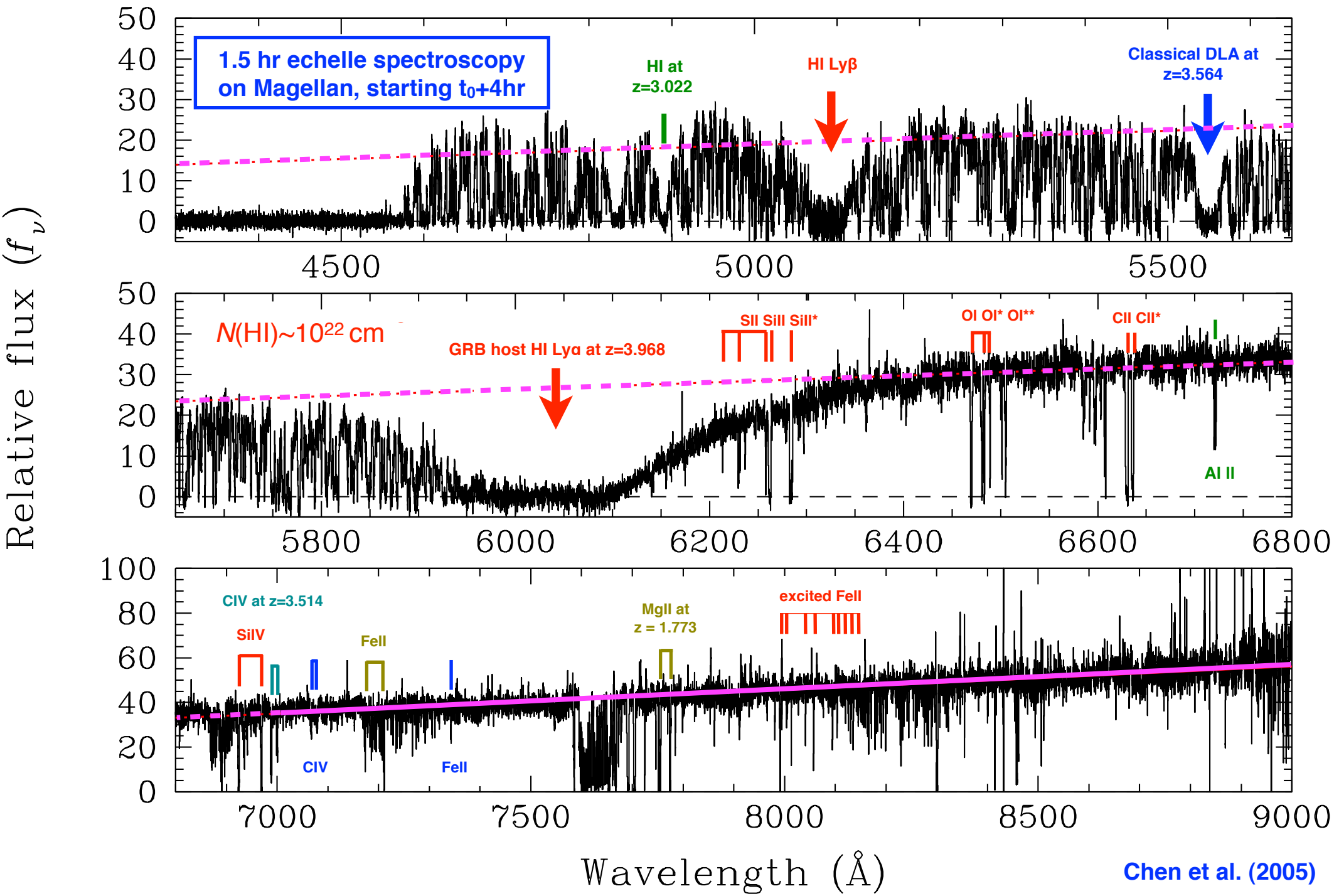

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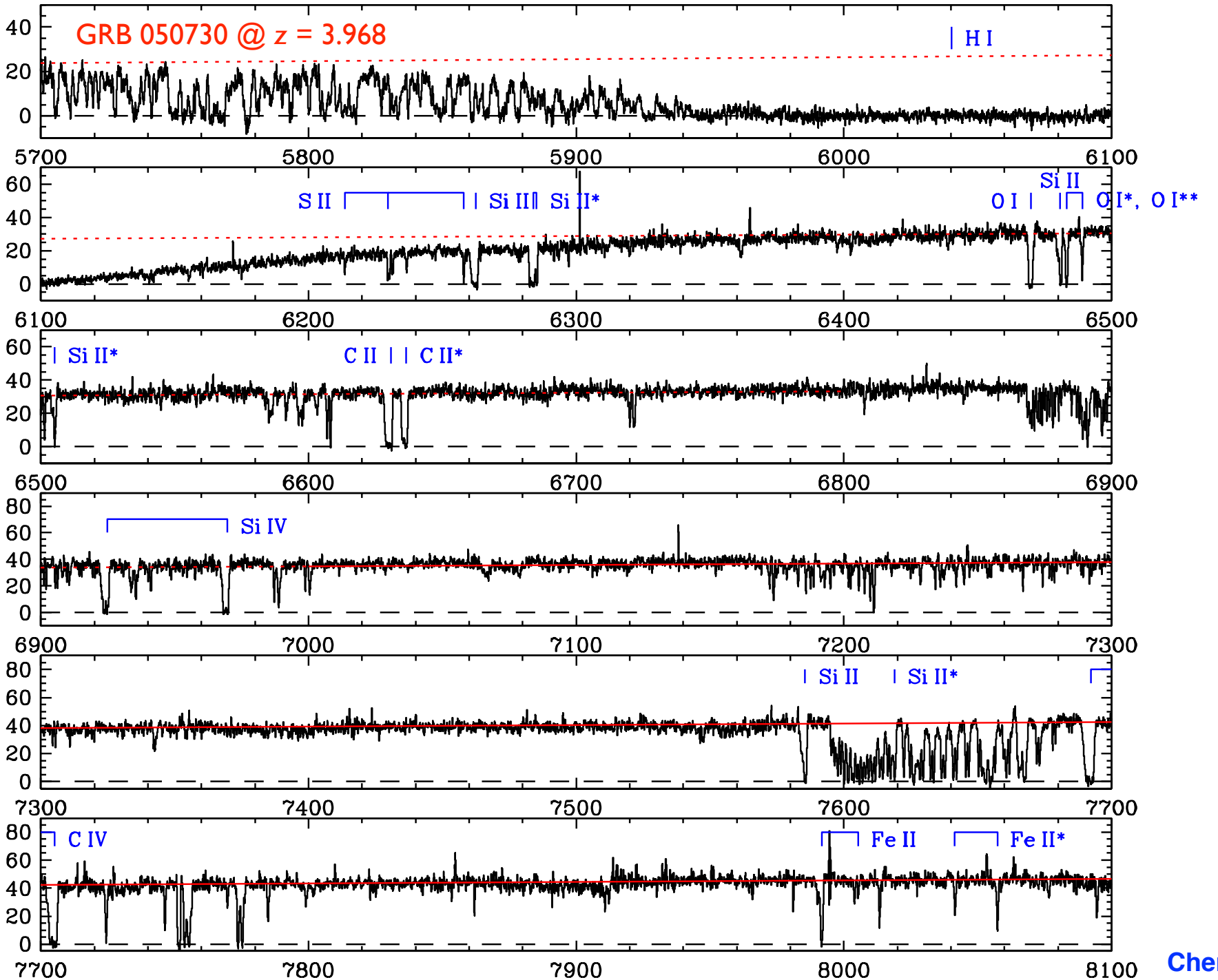

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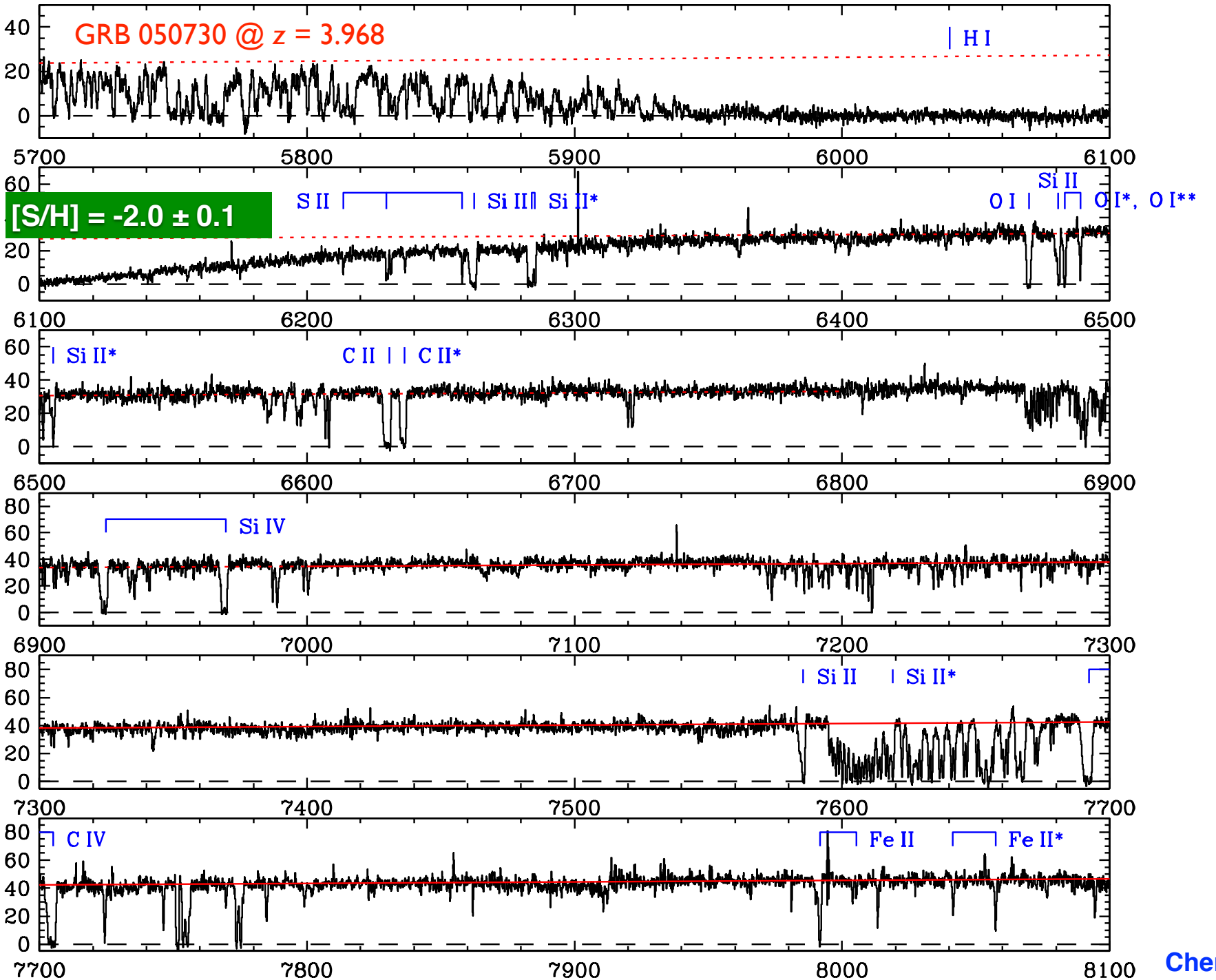

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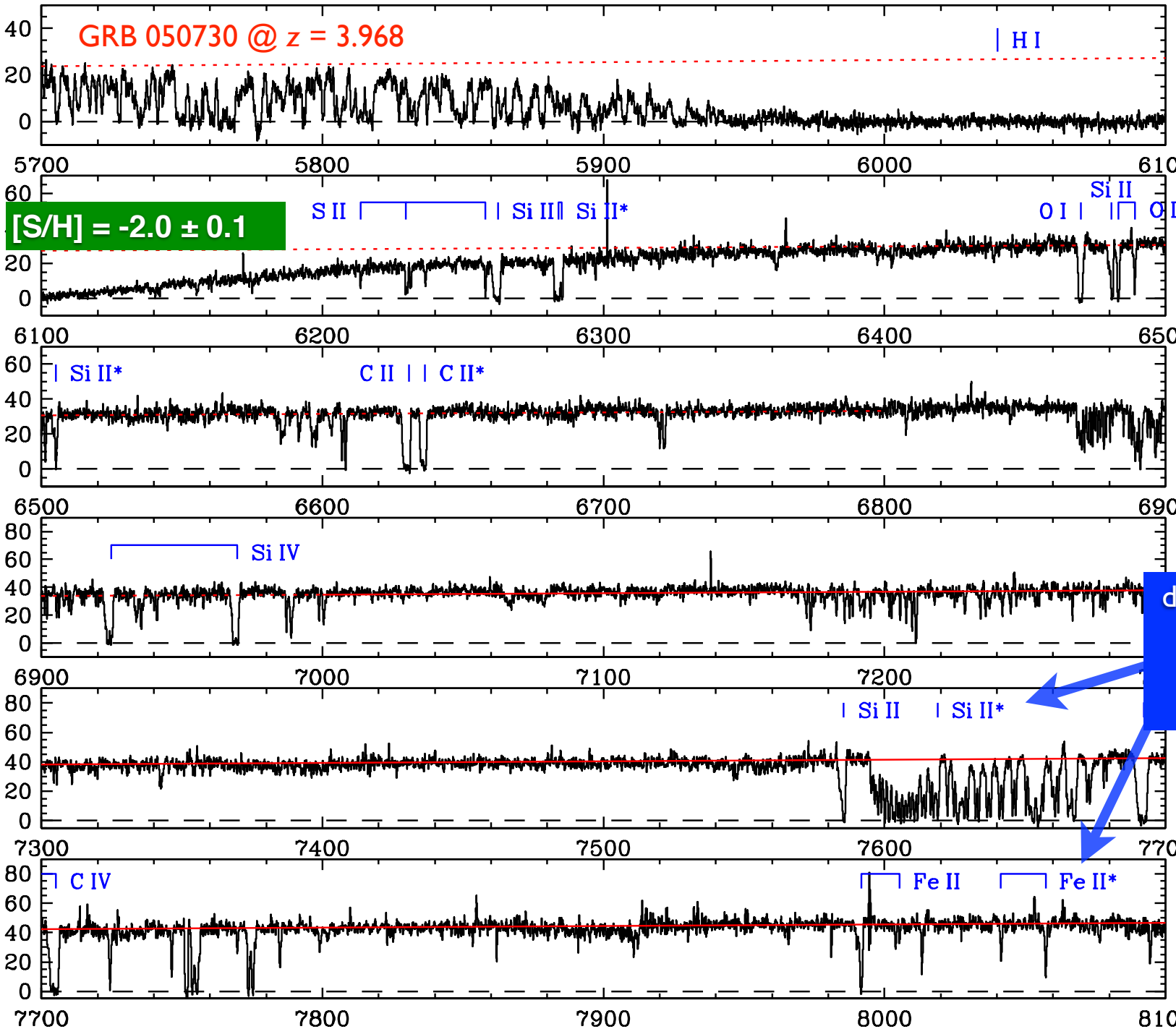
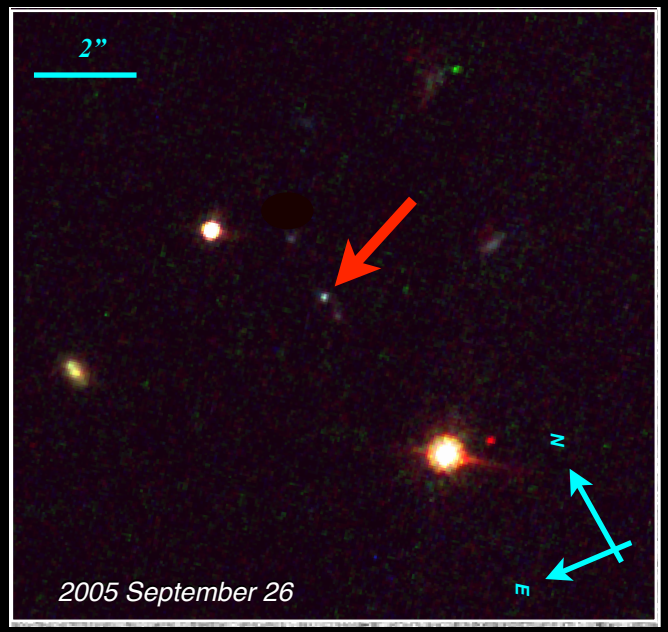


diminishing strength as the afterglow fades, allowing distance constraints

Chen et al. (2005)

Insights into Galactic Environment of Distant Star-forming Galaxies from GRB Afterglow Spectroscopy

GRB050820A @ z = 2.61



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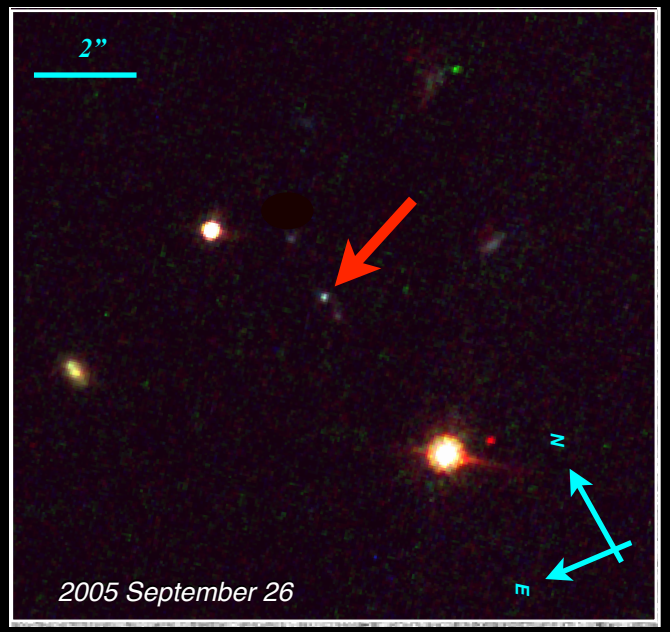
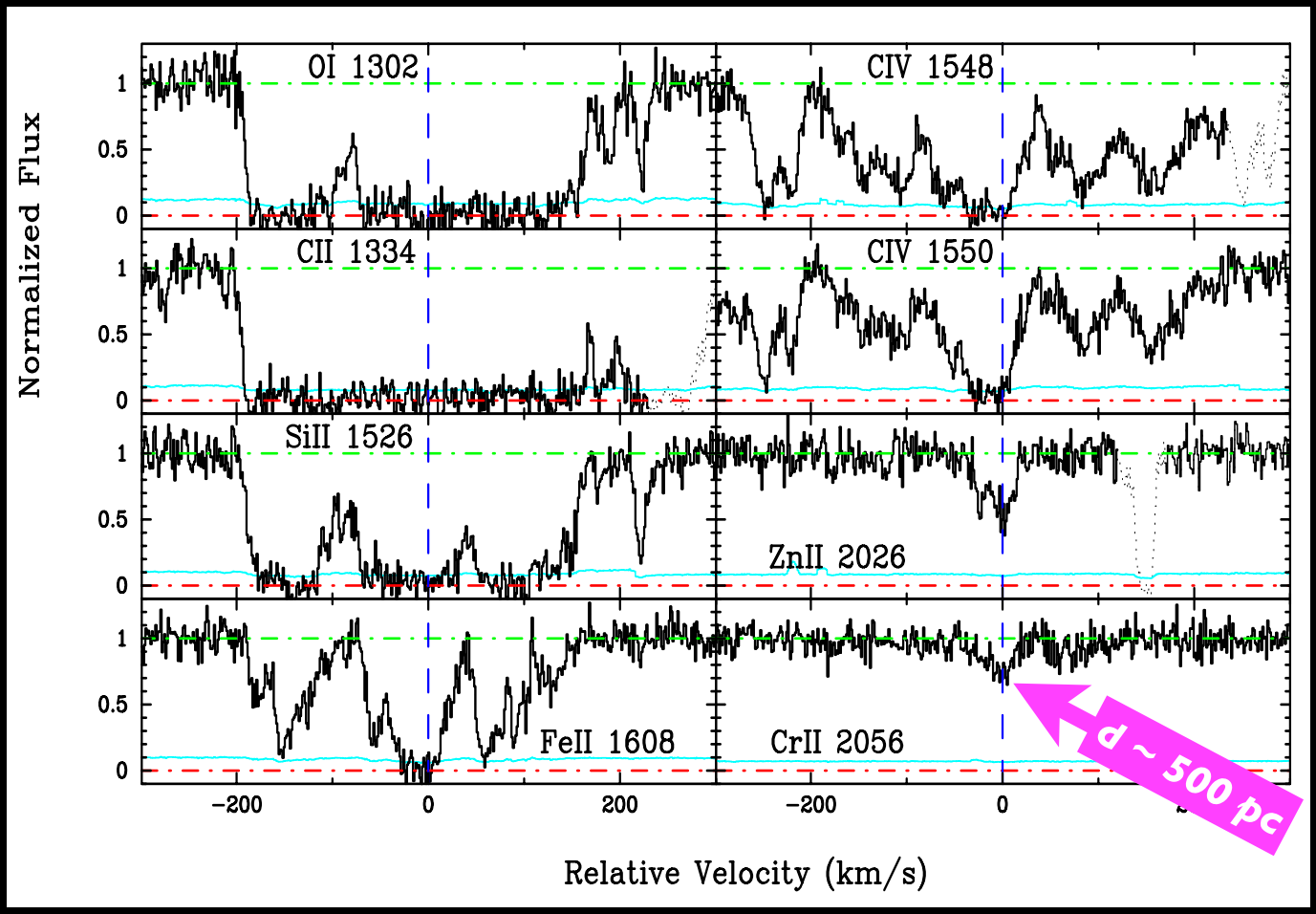


- log *N*(HI) = 21.0 ± 0.1
- [S/H] = -0.63 ± 0.11
- [Fe/H] = -1.6 ± 0.1
- A_V = 0.08
- $f_{H2} < 10^{-6.5}$



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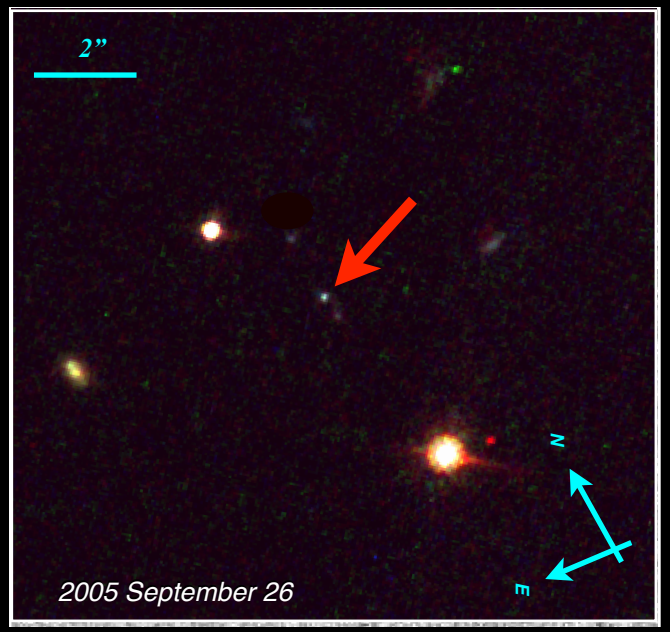

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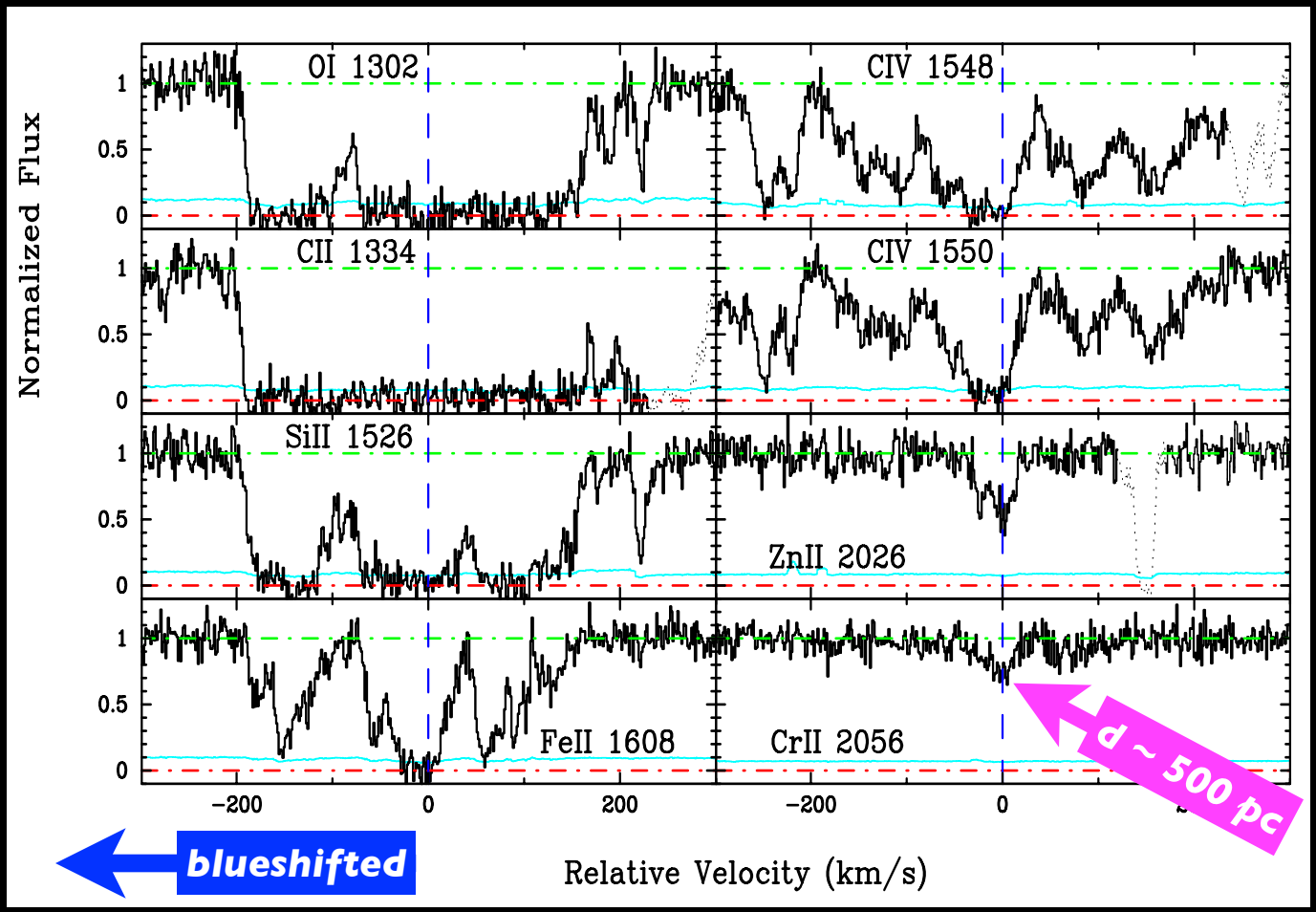

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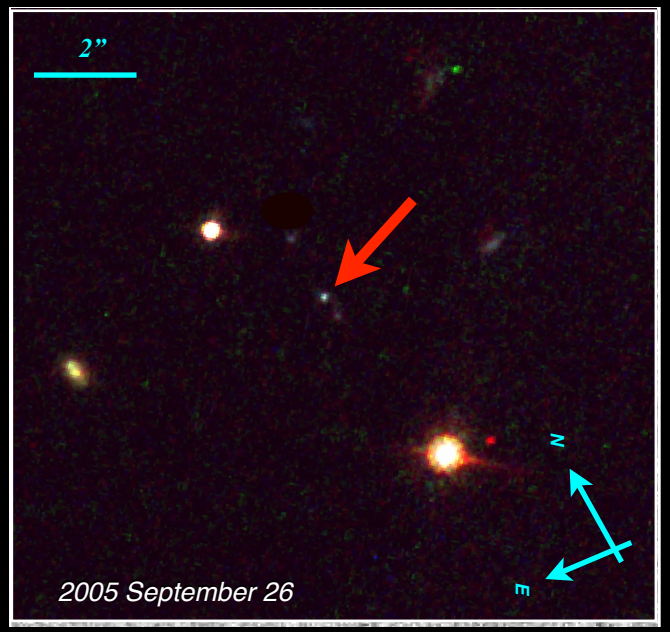

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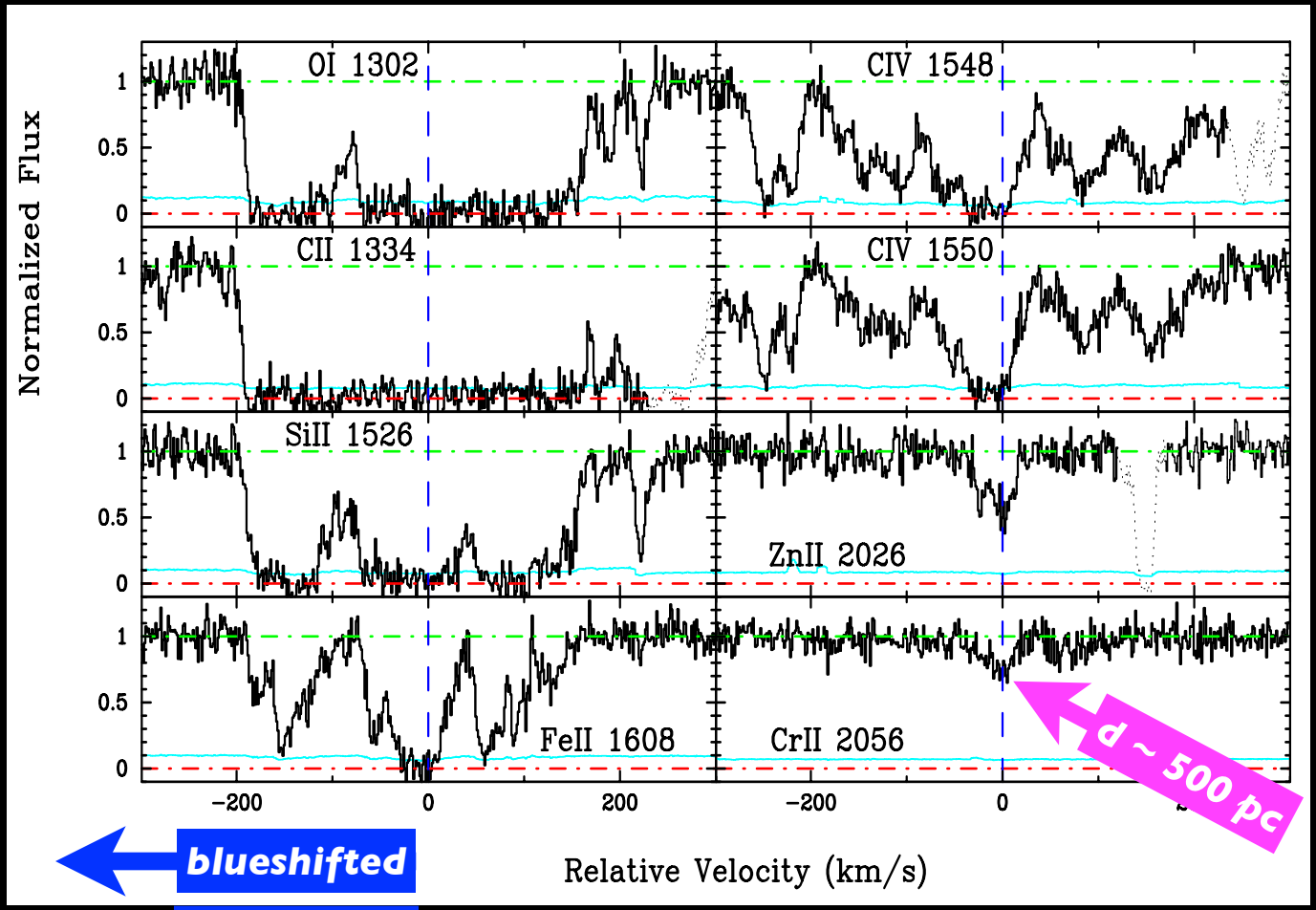

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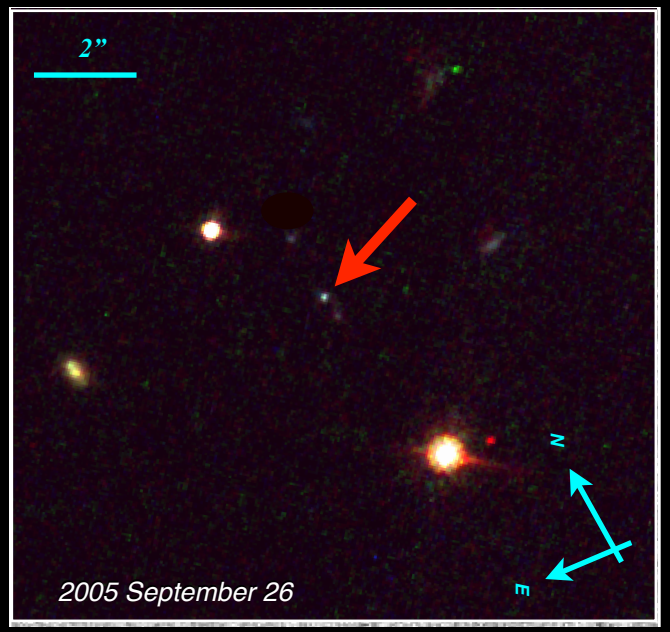

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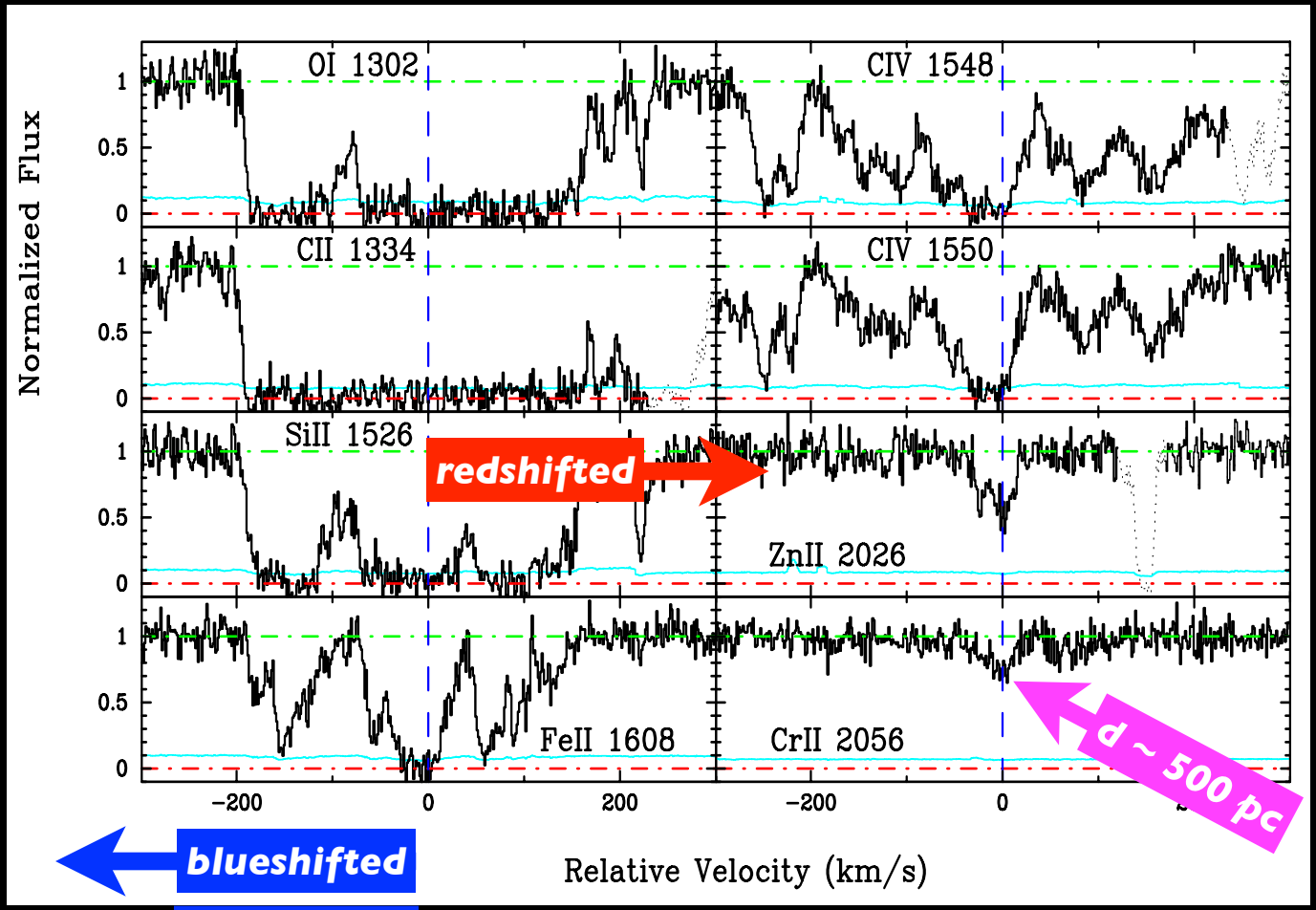

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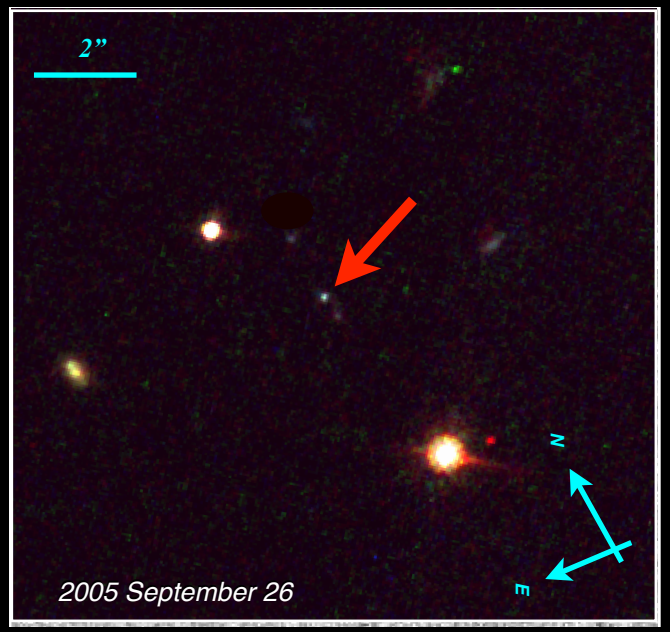

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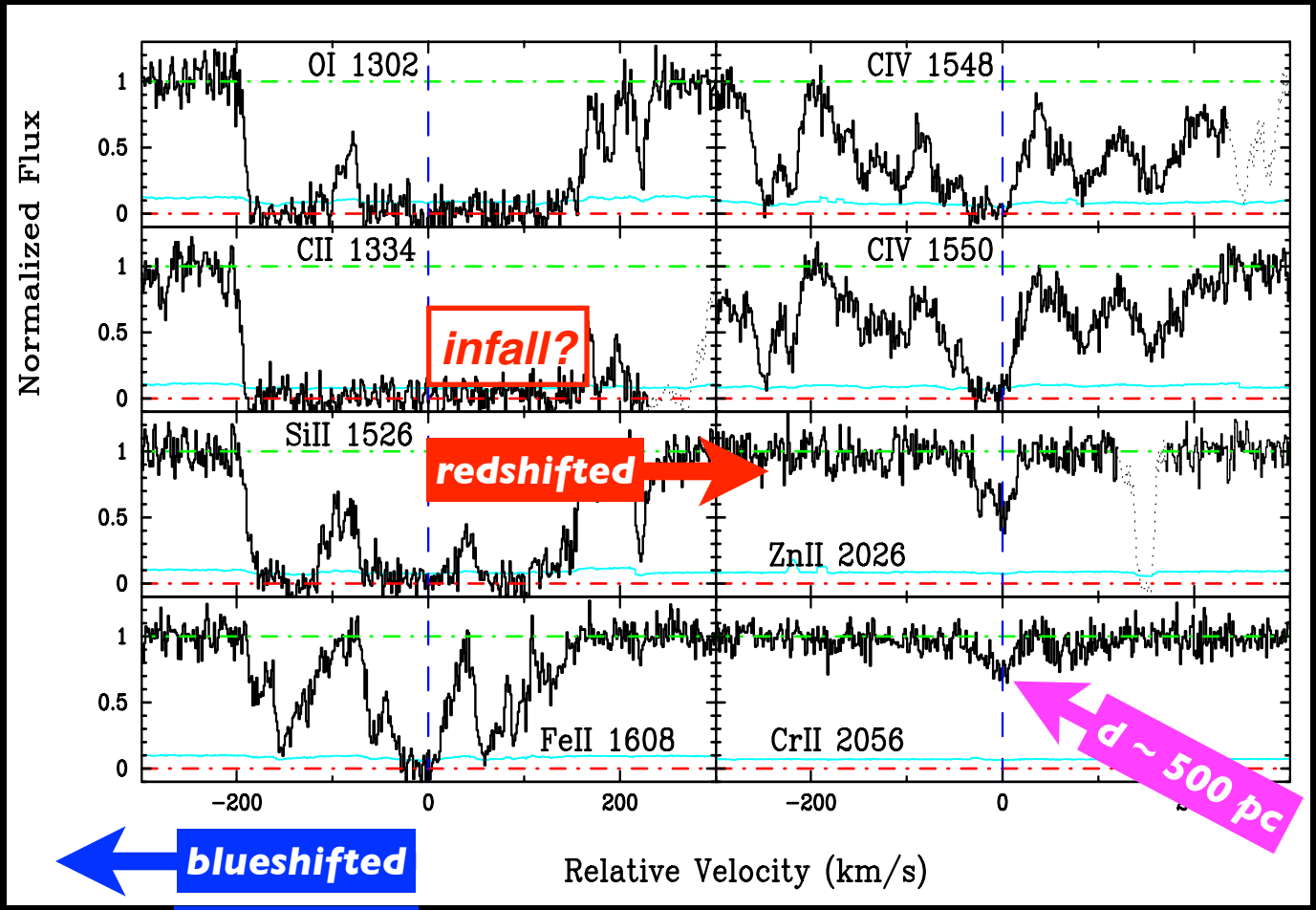

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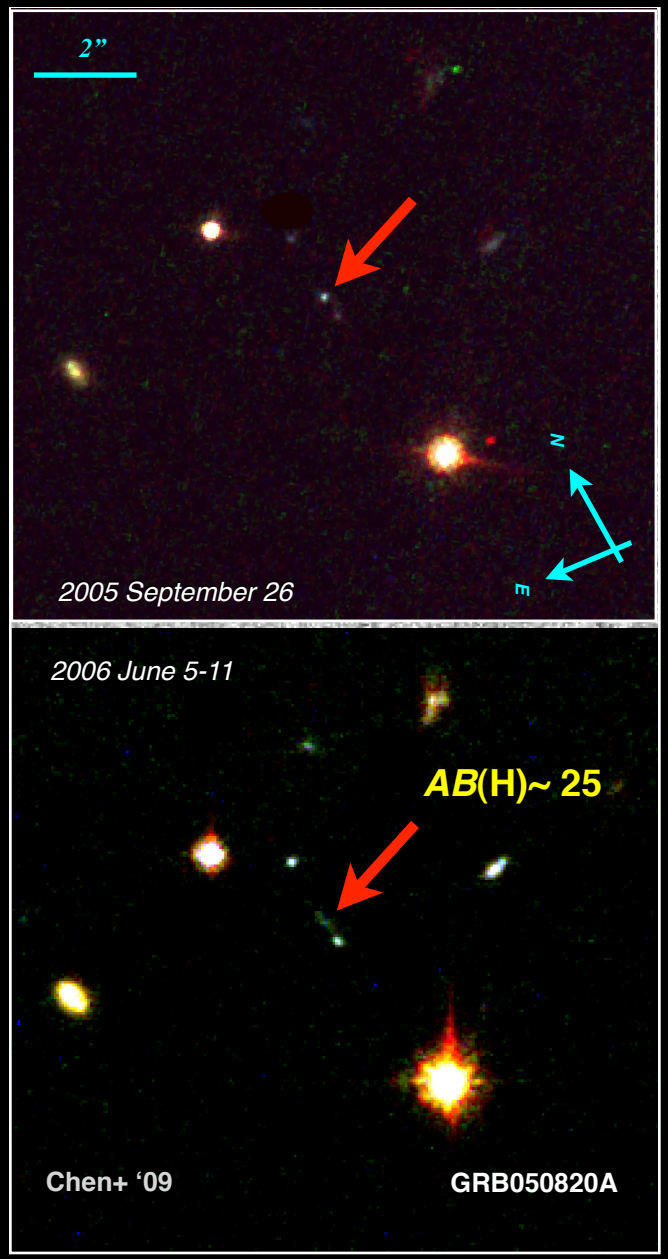

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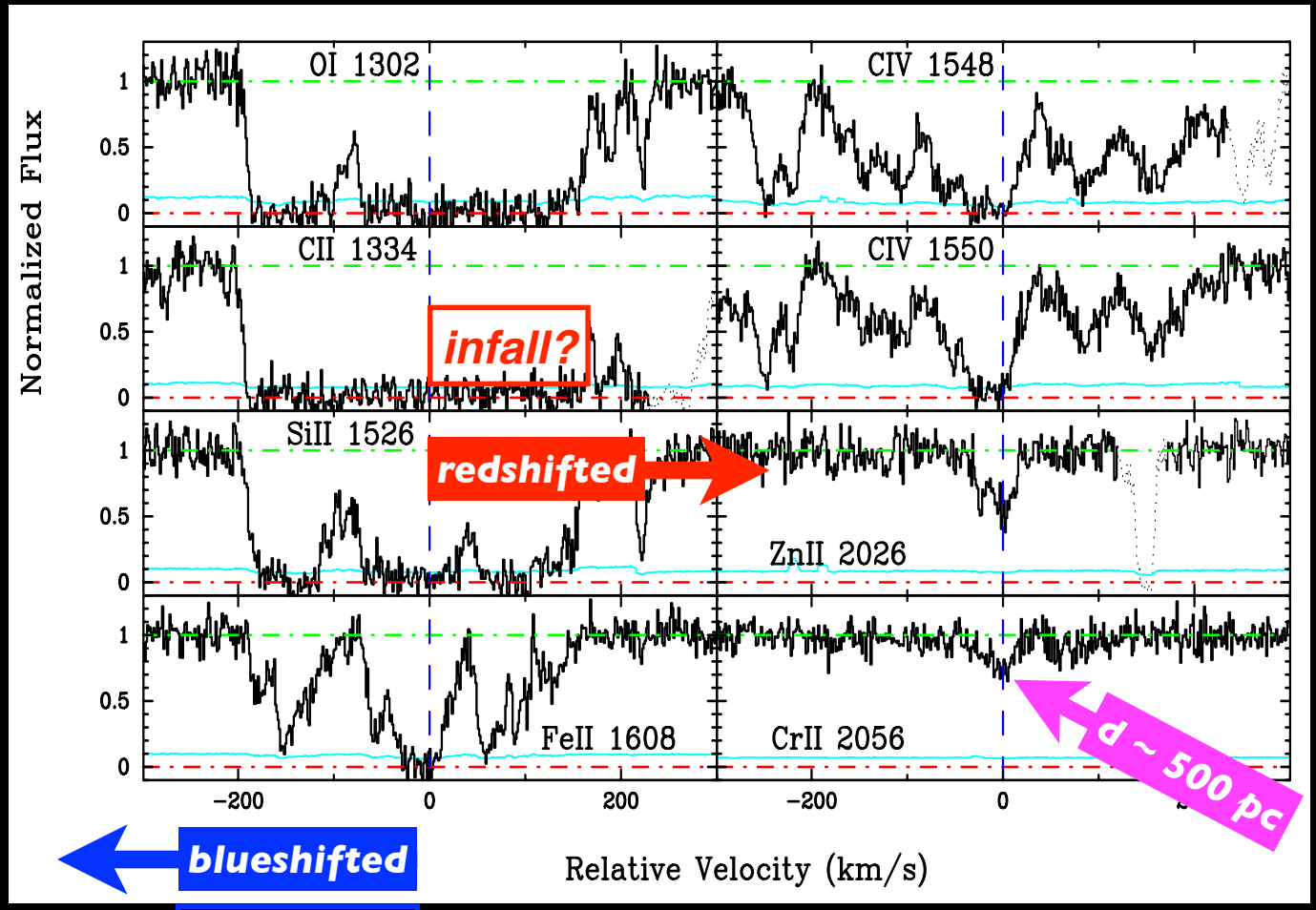

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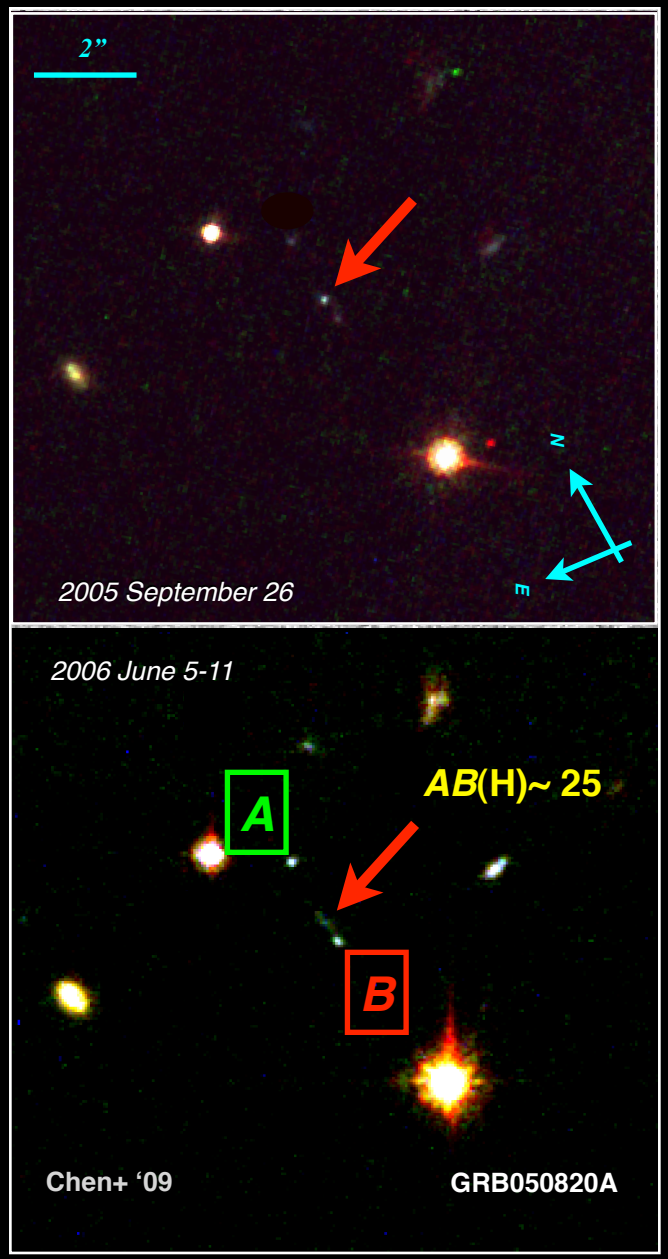

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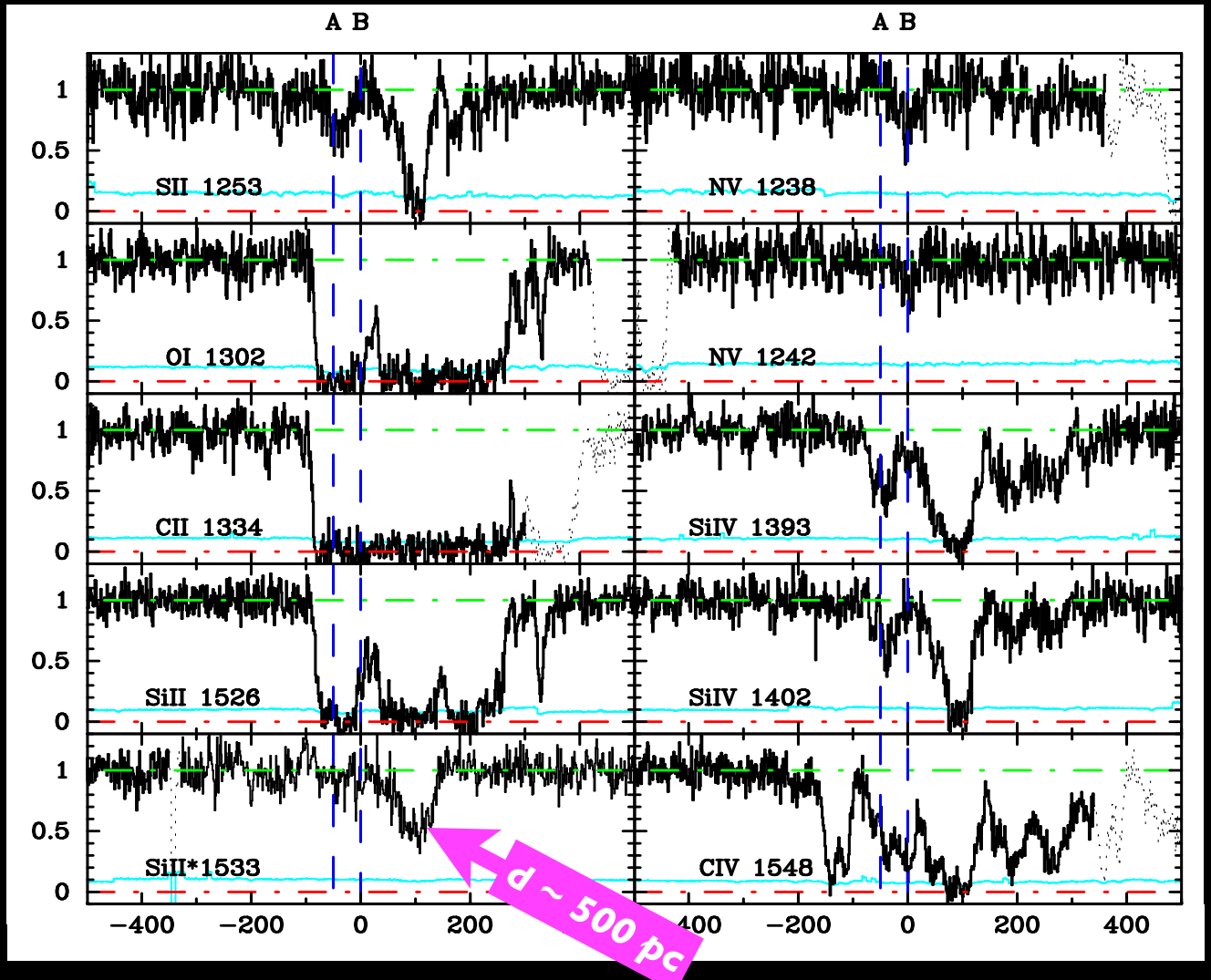

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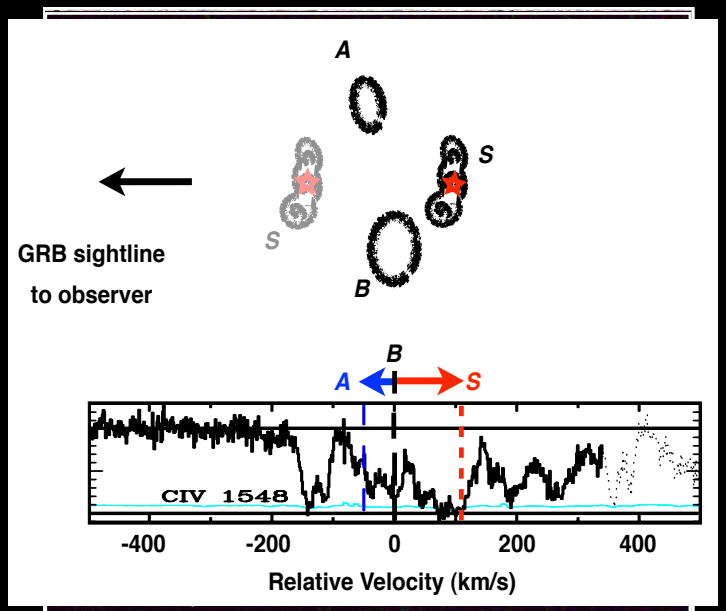

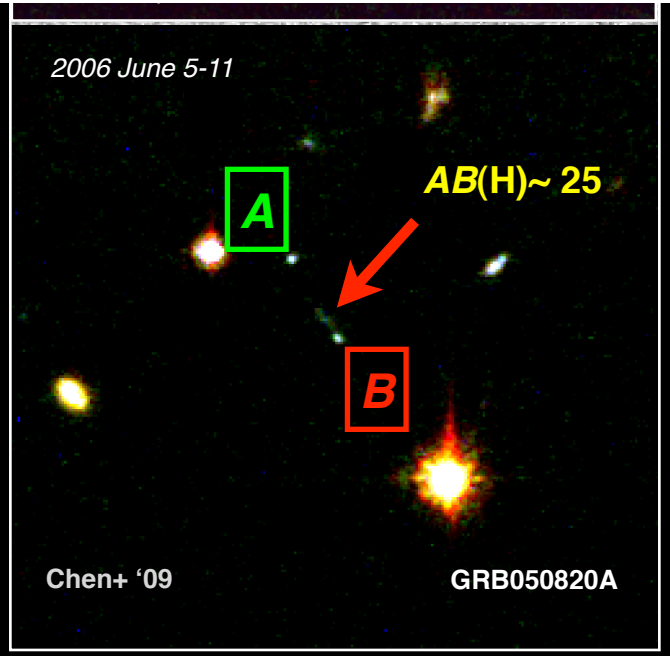

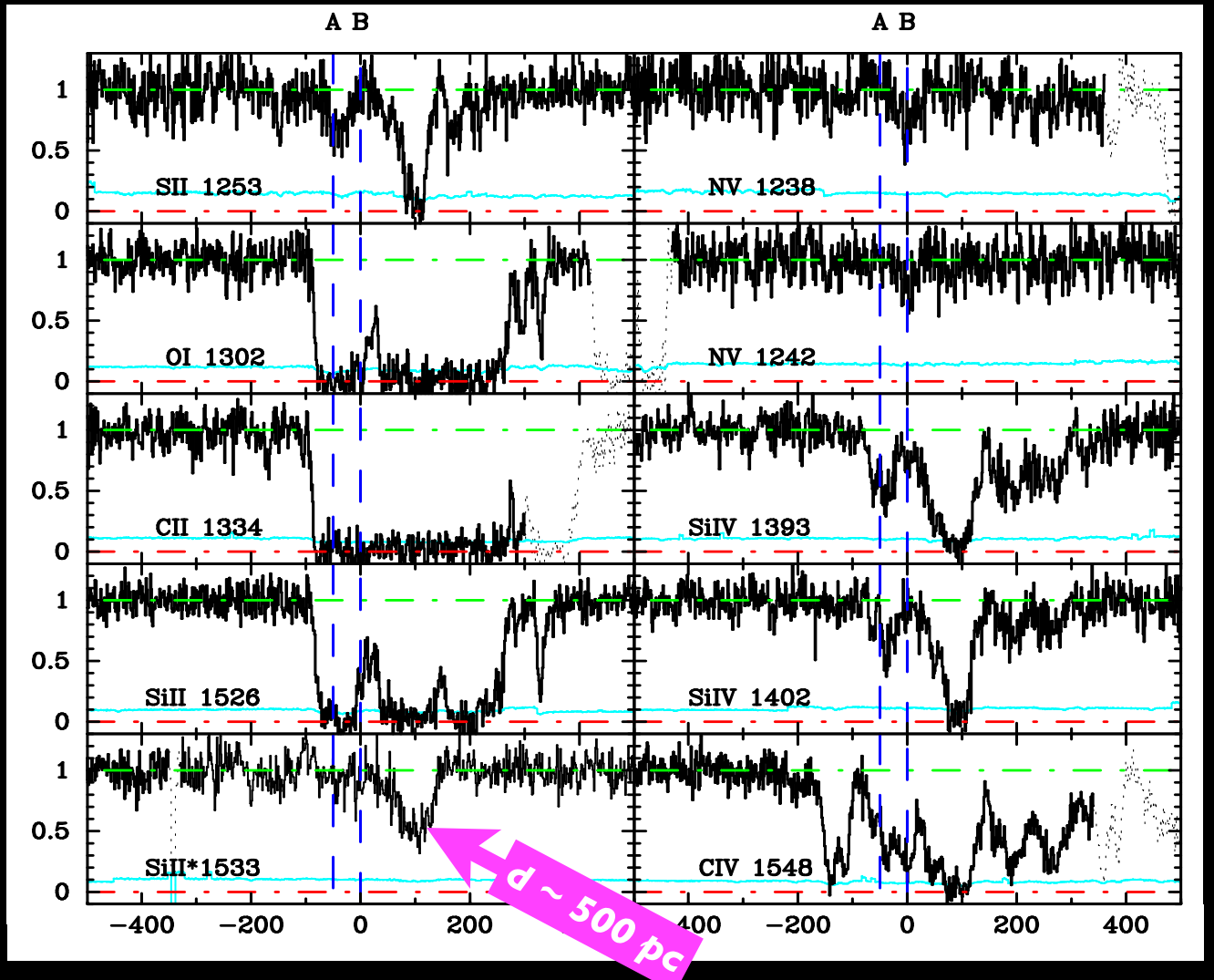

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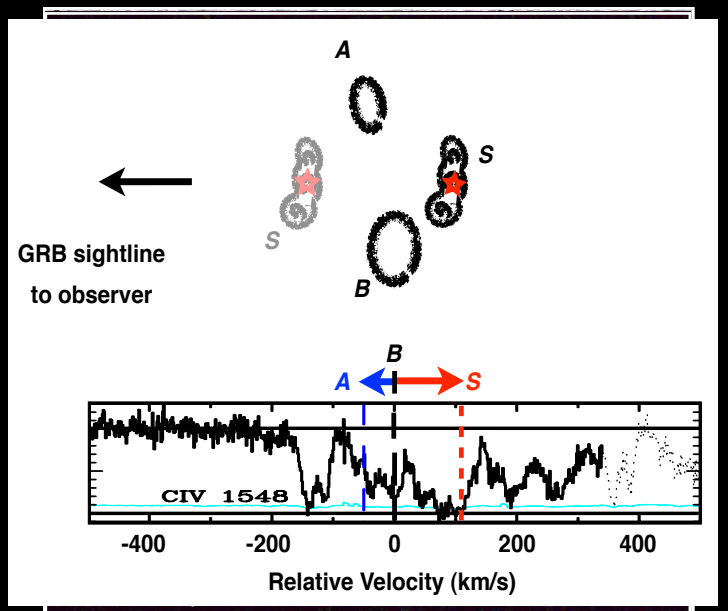
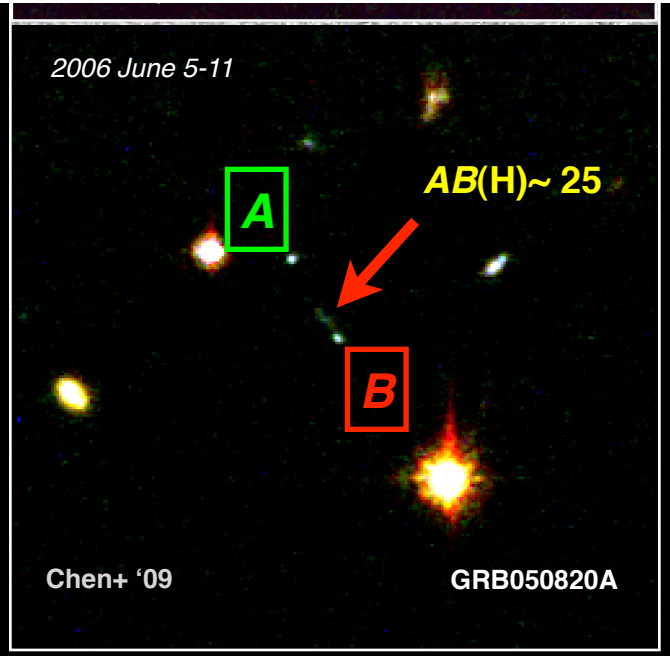
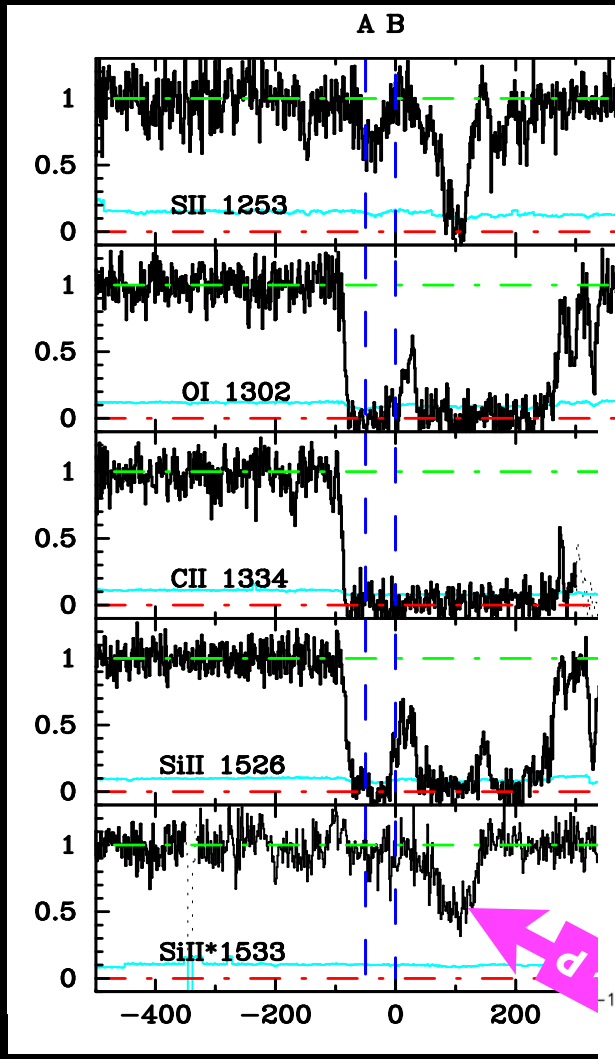
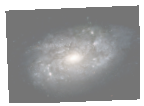






Implications for the High-z Universe

Escape of ionizing photons from star-forming galaxies at z > 2



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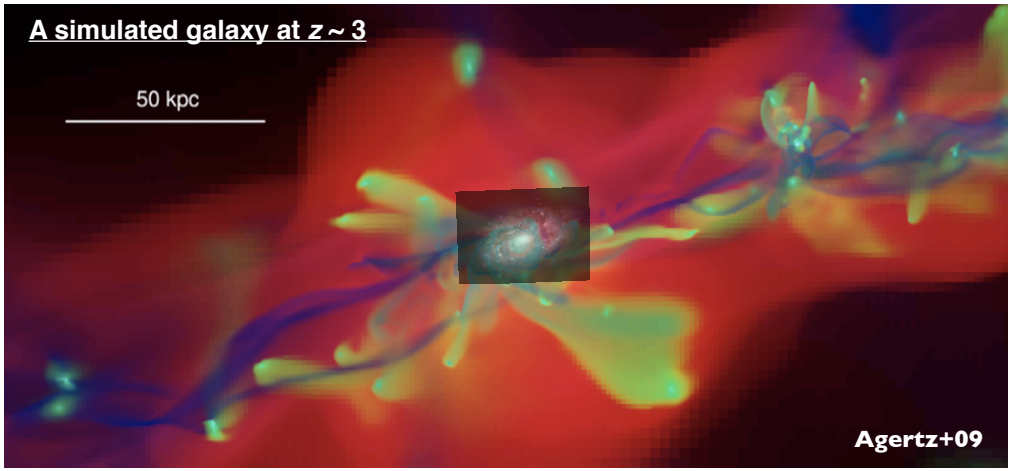

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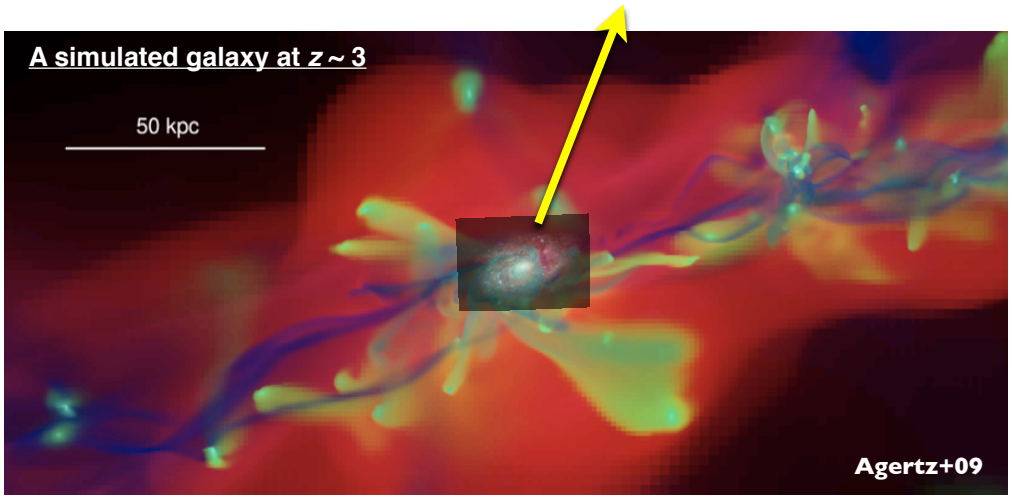
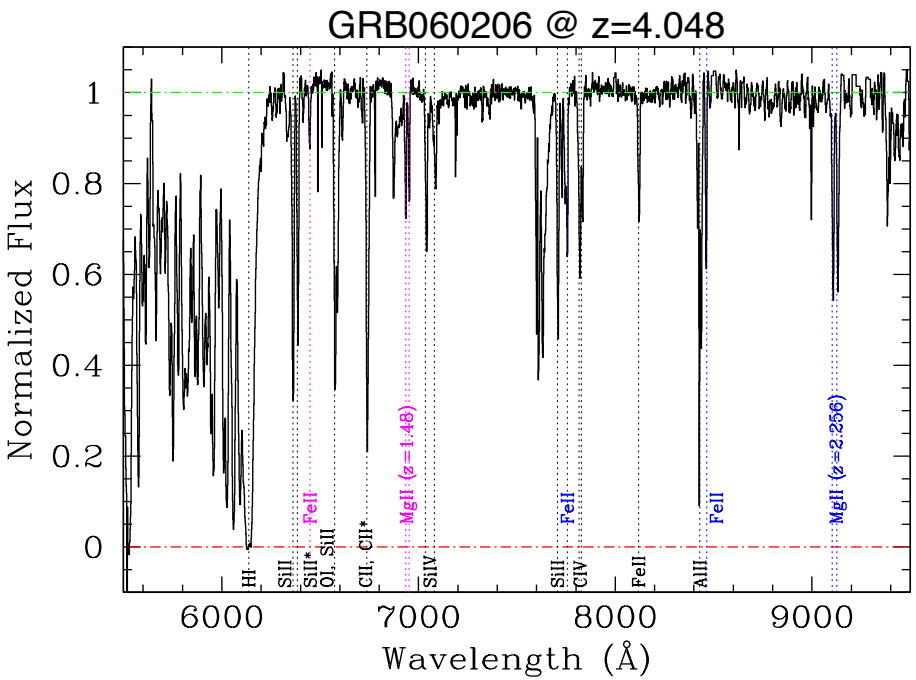


When a GRB occurs in a distant galaxy



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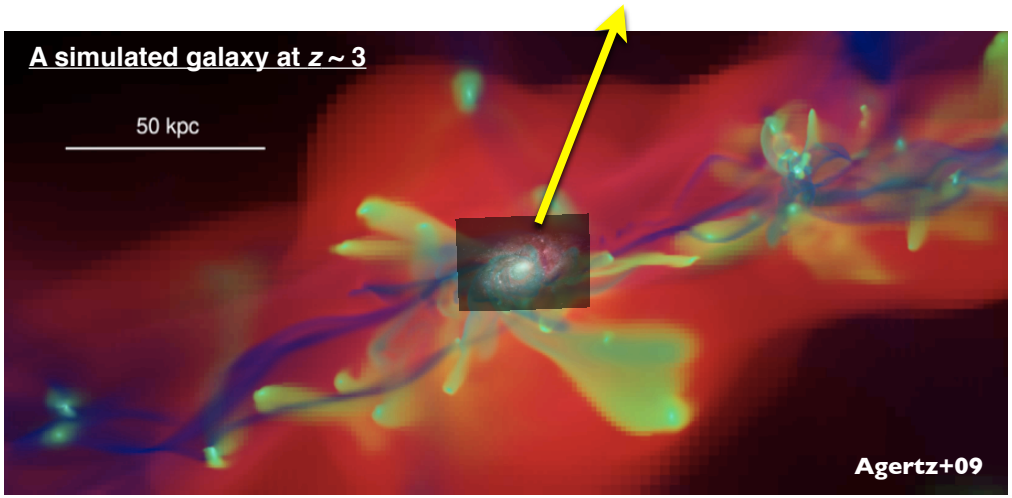

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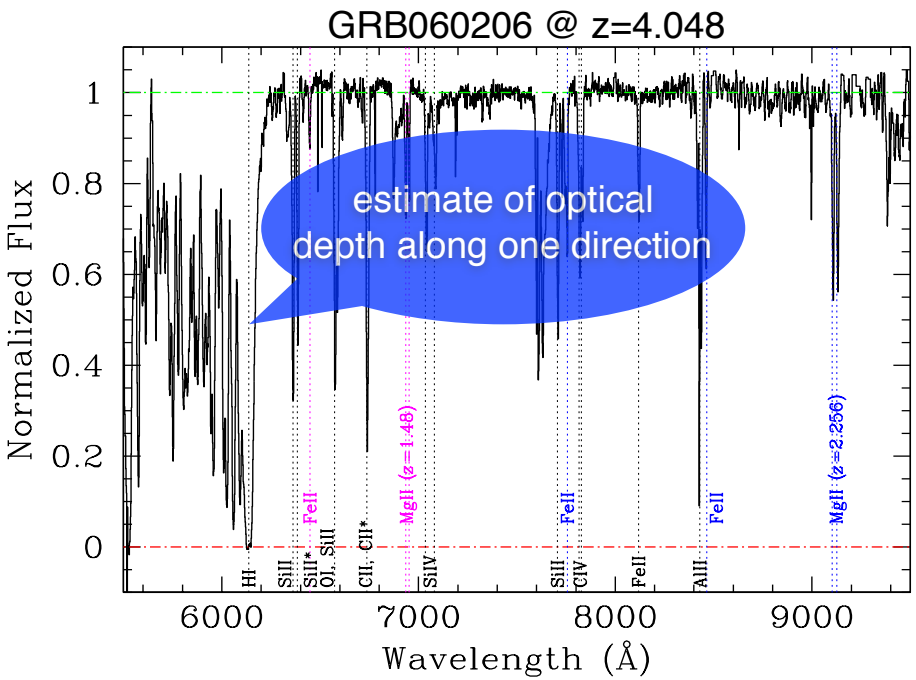

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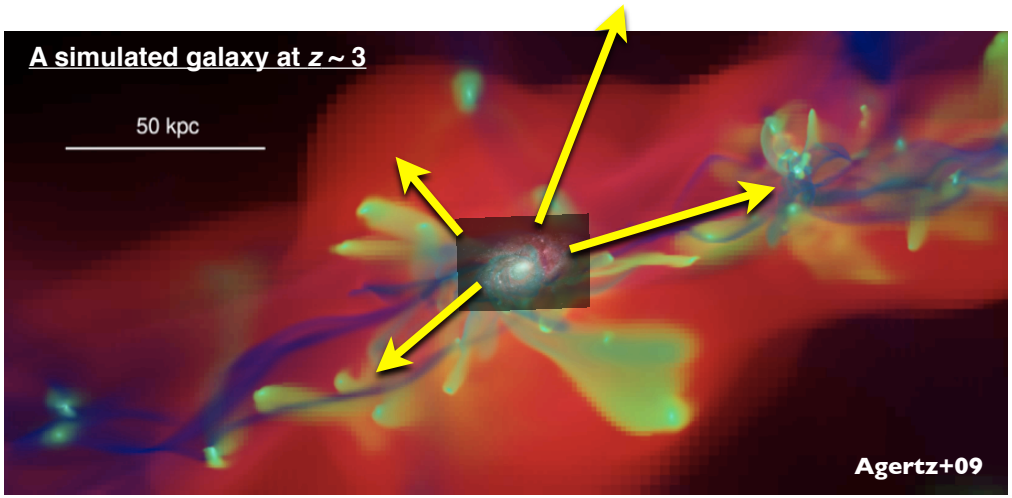

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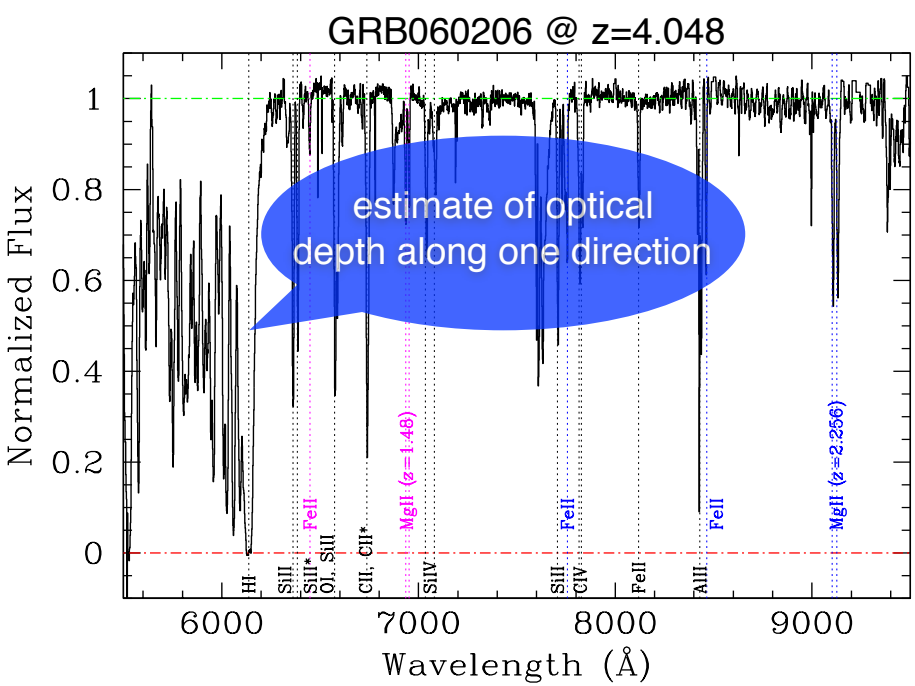
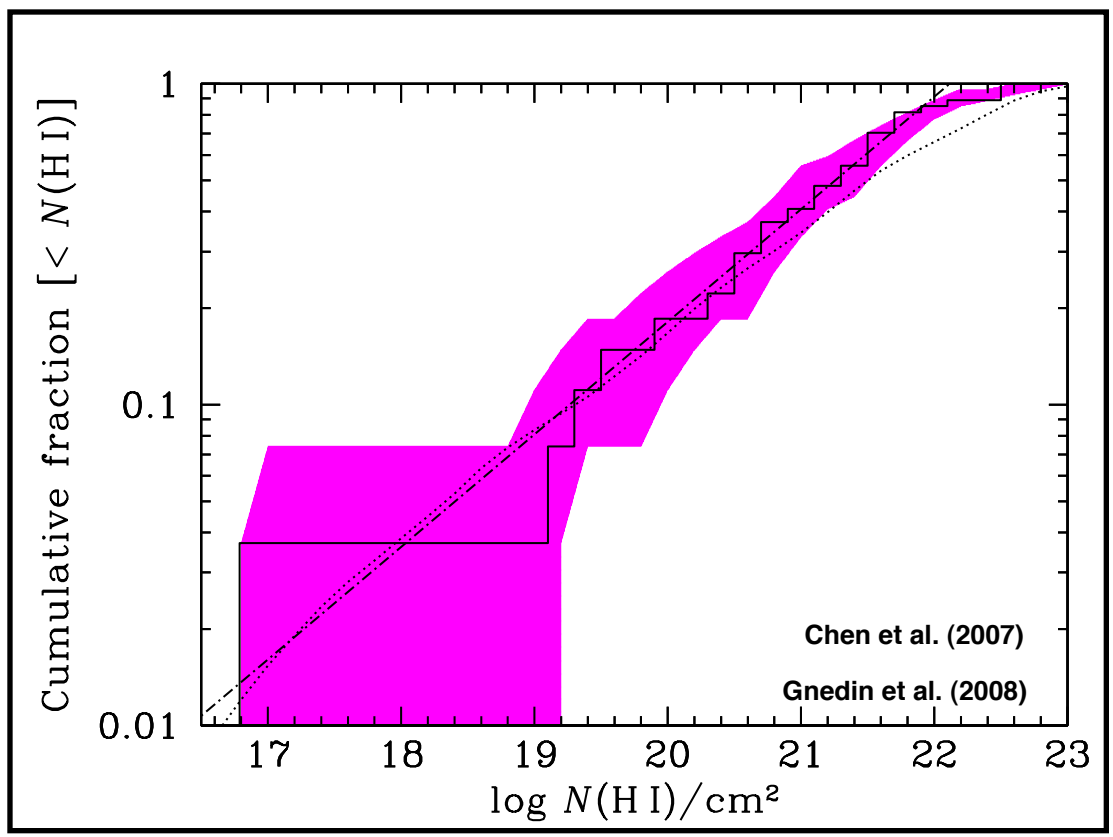


Angular distribution of optical depth around GRB host galaxies



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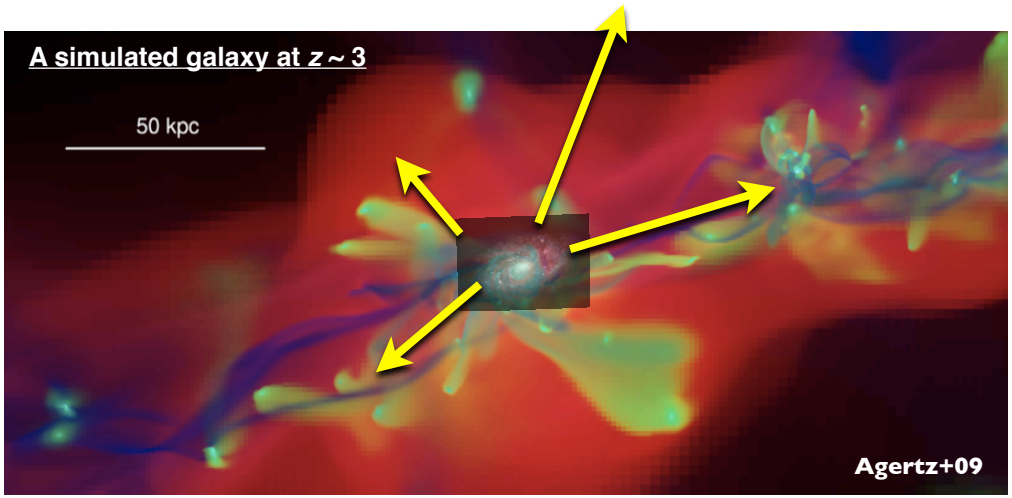

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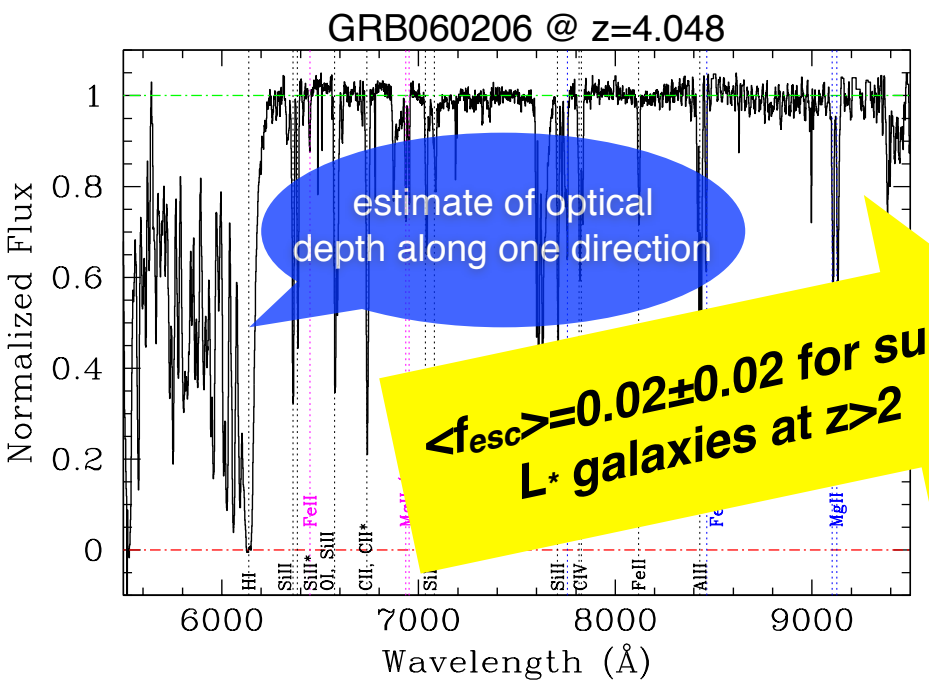

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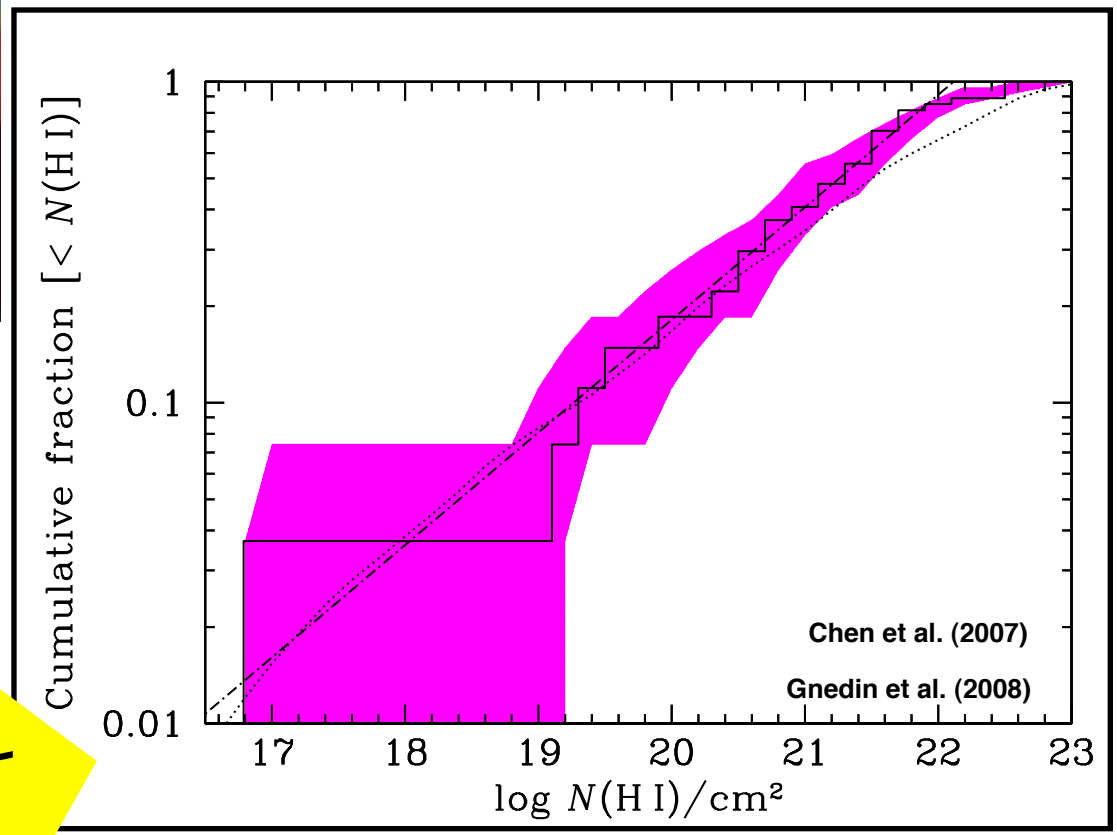
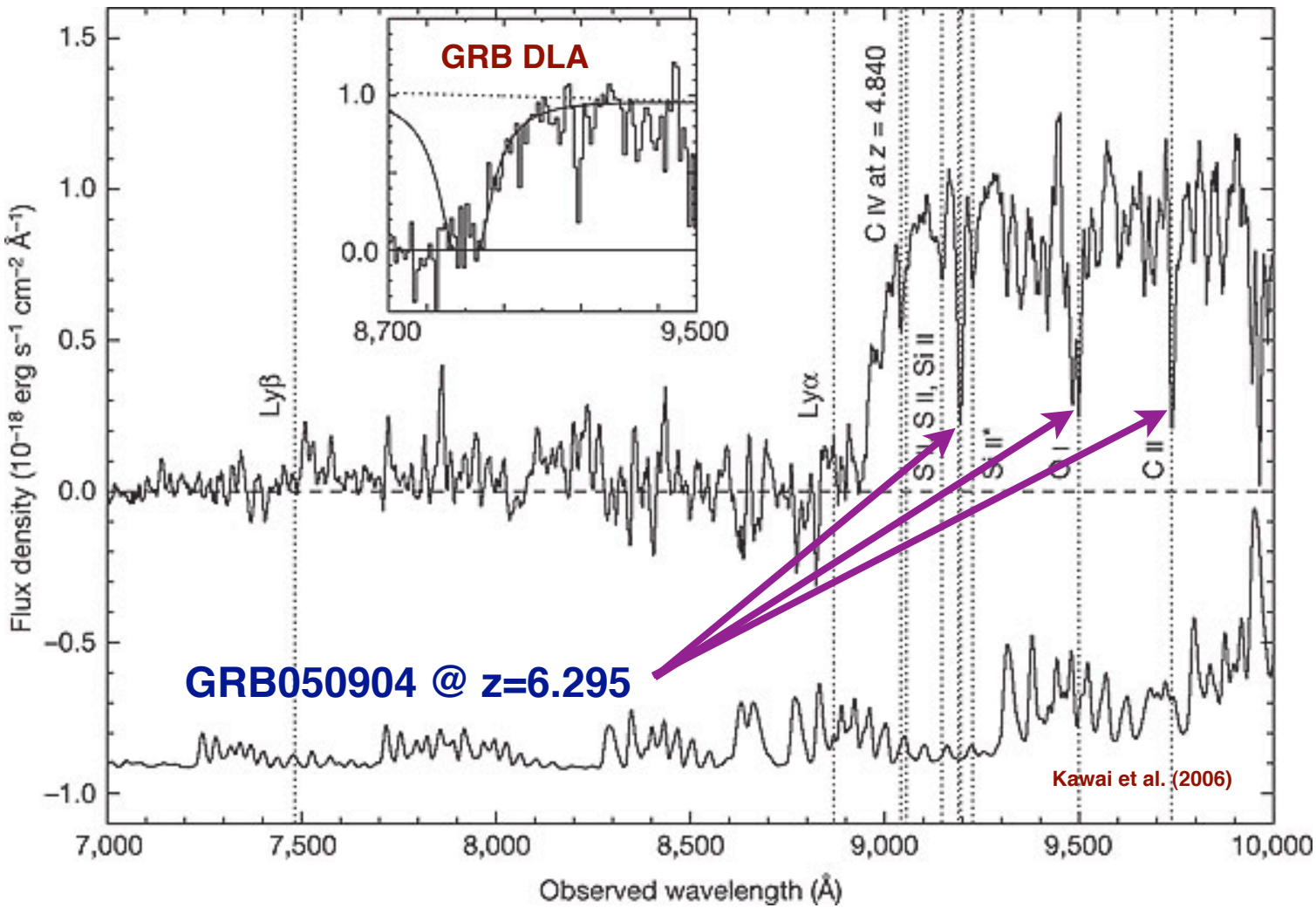


$$\langle f_{\rm esc} \rangle = \frac{1}{n} \sum_{i=1}^{n} \exp[-\sigma_{\rm LL} N_i({\rm HI})]$$

Implications for the High-z Universe

Probing the re-ionization epoch: ***searching for the red damping wing in GRB afterglow spectra***

$$\tau_\nu = N\sigma\Phi(\Delta\nu) = N\frac{\pi e^2}{m_e c} f_{jk} \frac{1}{\sqrt{\pi}\Delta\nu_D} H(a,x)$$



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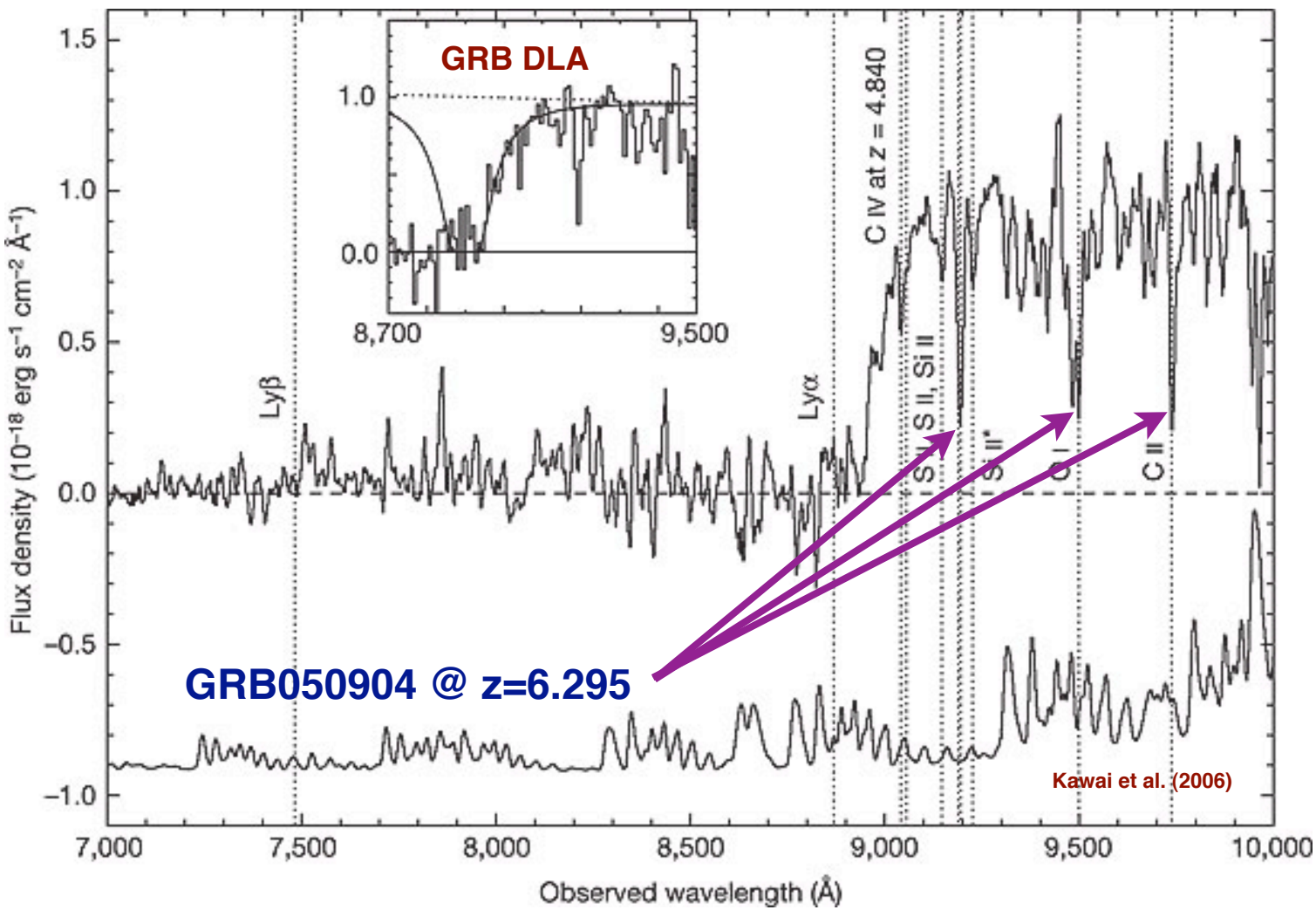
integrating over a cosmic distance



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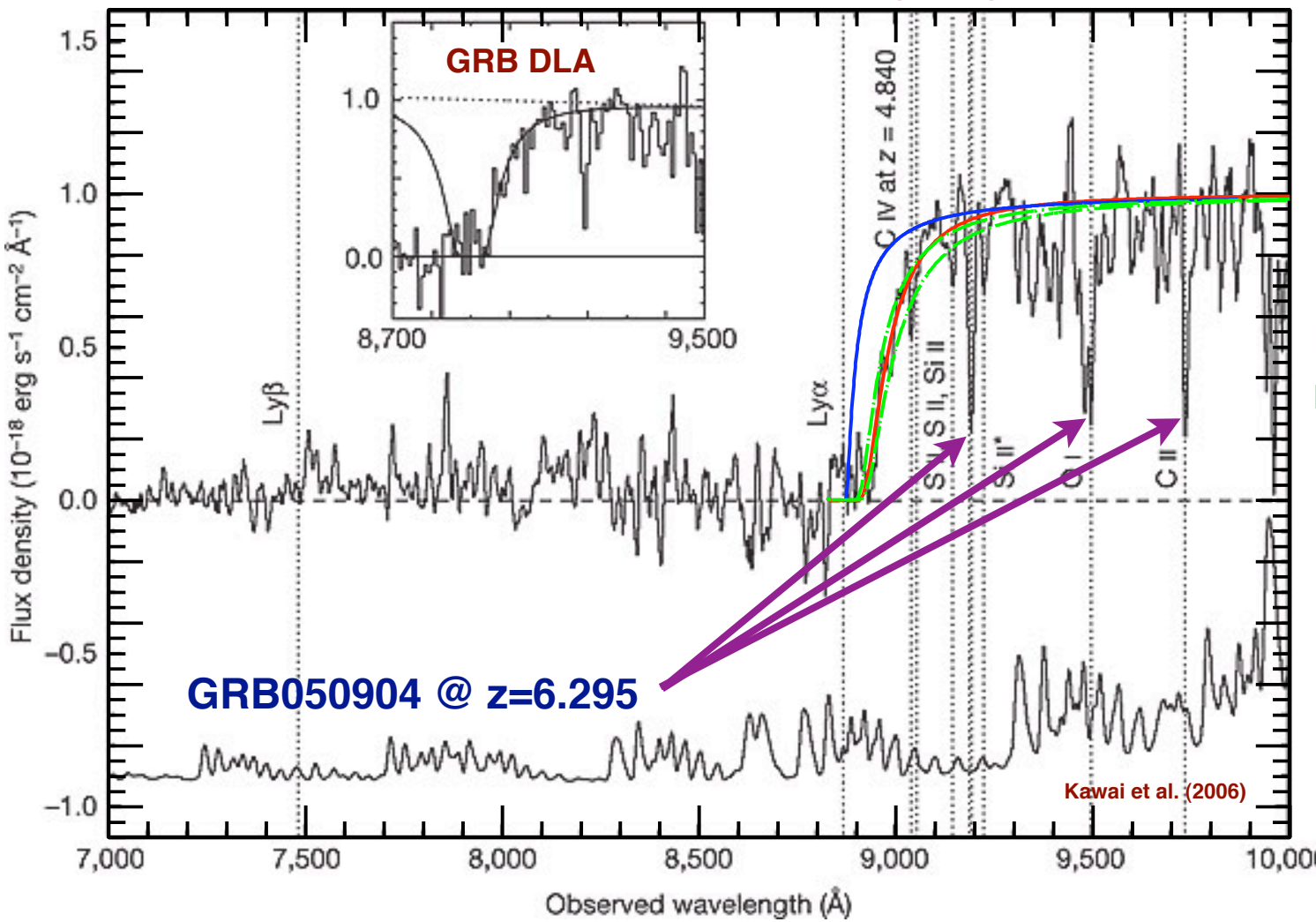

IGM only

logN(HI)=21.3, x_{HI}=1

logN(HI)=21.6

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