Probing the ISM of High z Galaxies with GRB Afterglows

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UCO/Lick Observatory
(on behalf of GRAASP)

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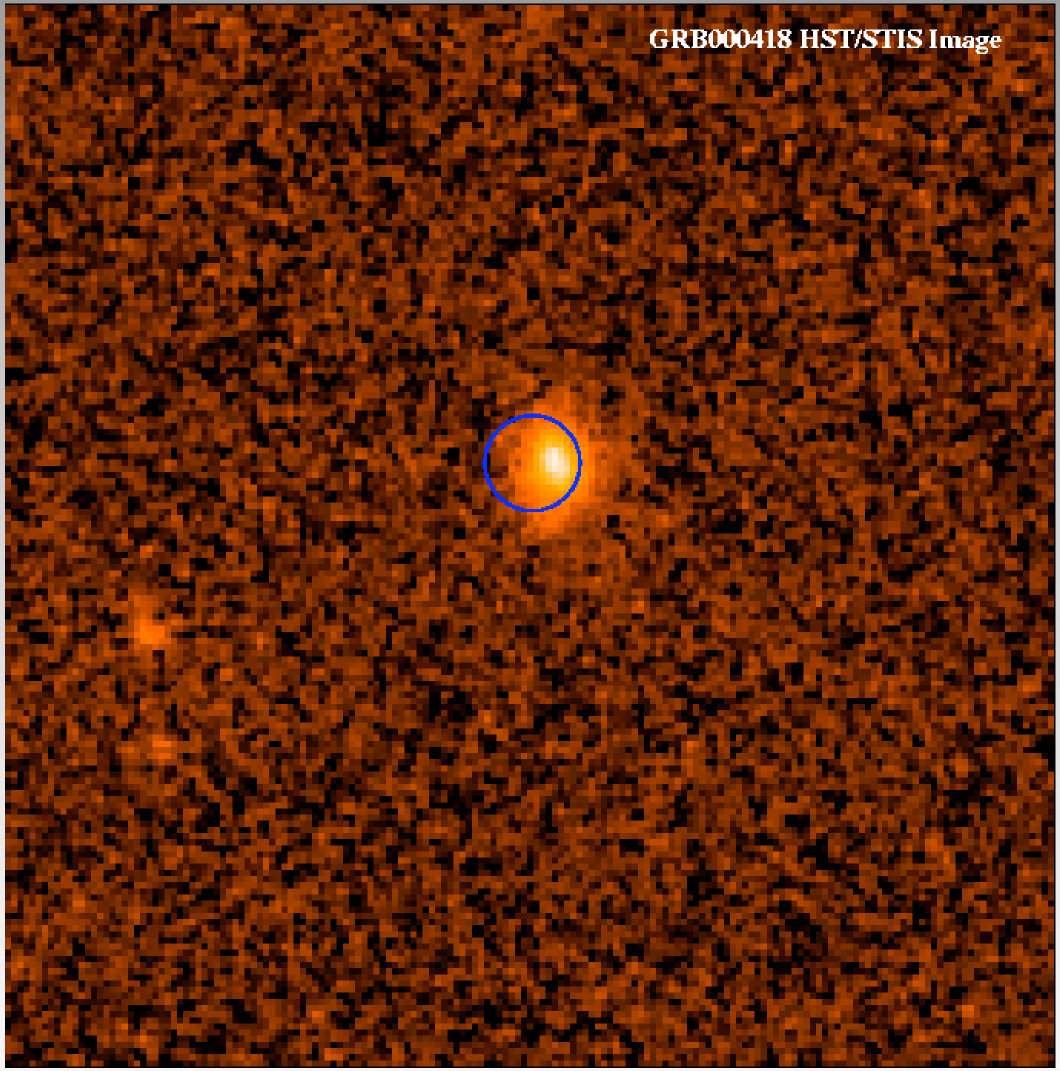
J. S. Bloom (UC Berkeley)

Long GRB Progenitors

- Host galaxies
  - Blue, star forming
    - Generally low luminosity
  - GRB located within few kpc of the galaxy center
- SN connection
  - Low z events
  - SN spectrum
    - Bright, TypeIc SN
    - Metal-poor, blue host galaxy
      - (Mirabal et al. 2003)
- Theory
  - Collapsar model
    - 15 Msol star
    - Collapse to black hole
    - Relativistic jet ensues
  - Afterglow
    - Jet deaccelerates as it interacts with surrounding gas (10^{16} cm)
    - Synchrotron radiation



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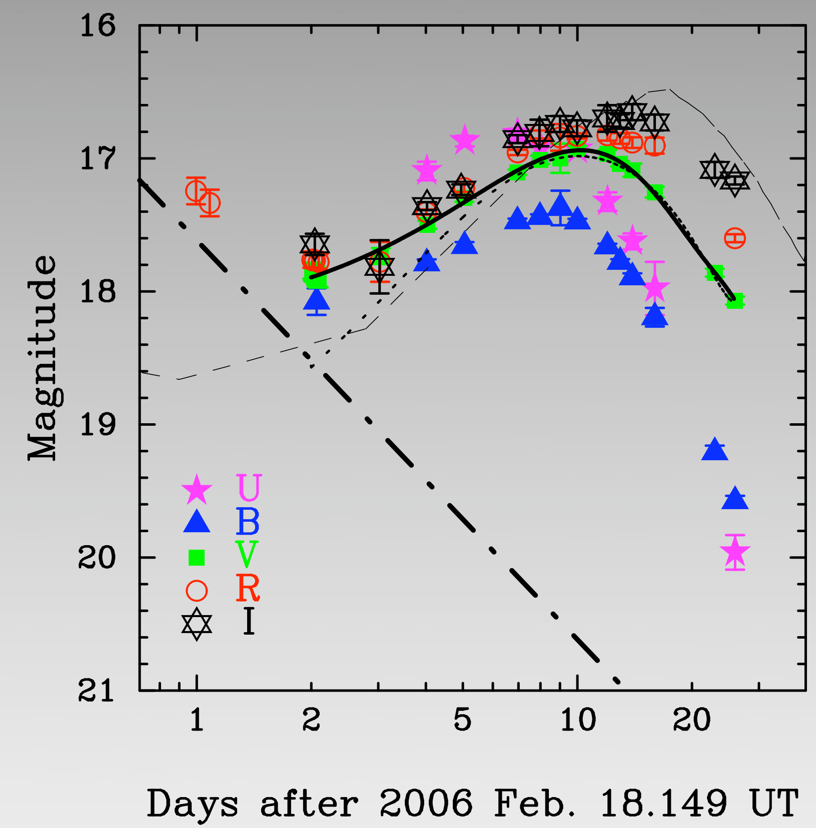

Fig. 1.— *UBVRI* data for GRB 060218, corrected for Galactic extinction and host-galaxy contamination. The *solid line* is a fit to the V-band light curve. The *dotted line* is a fit to the V-band light curve after subtracting an $\alpha = 1.2$ power-law decay (*dot-dashed line*) as justified in the text. The *dashed line* is a template of the V-band light curve of SN 1998bw (Galama et al. 1998) shifted to $z = 0.0335$. [*See the electronic edition of the Journal for a color version of this figure.*]

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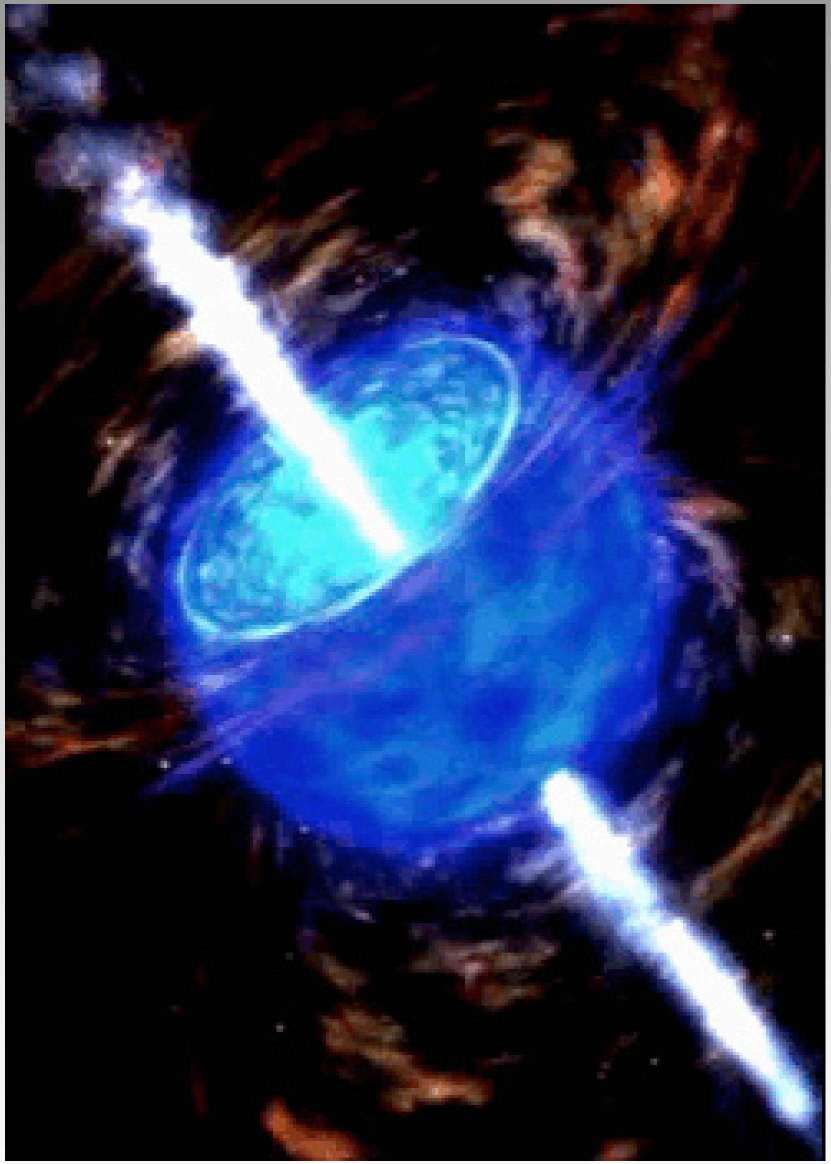
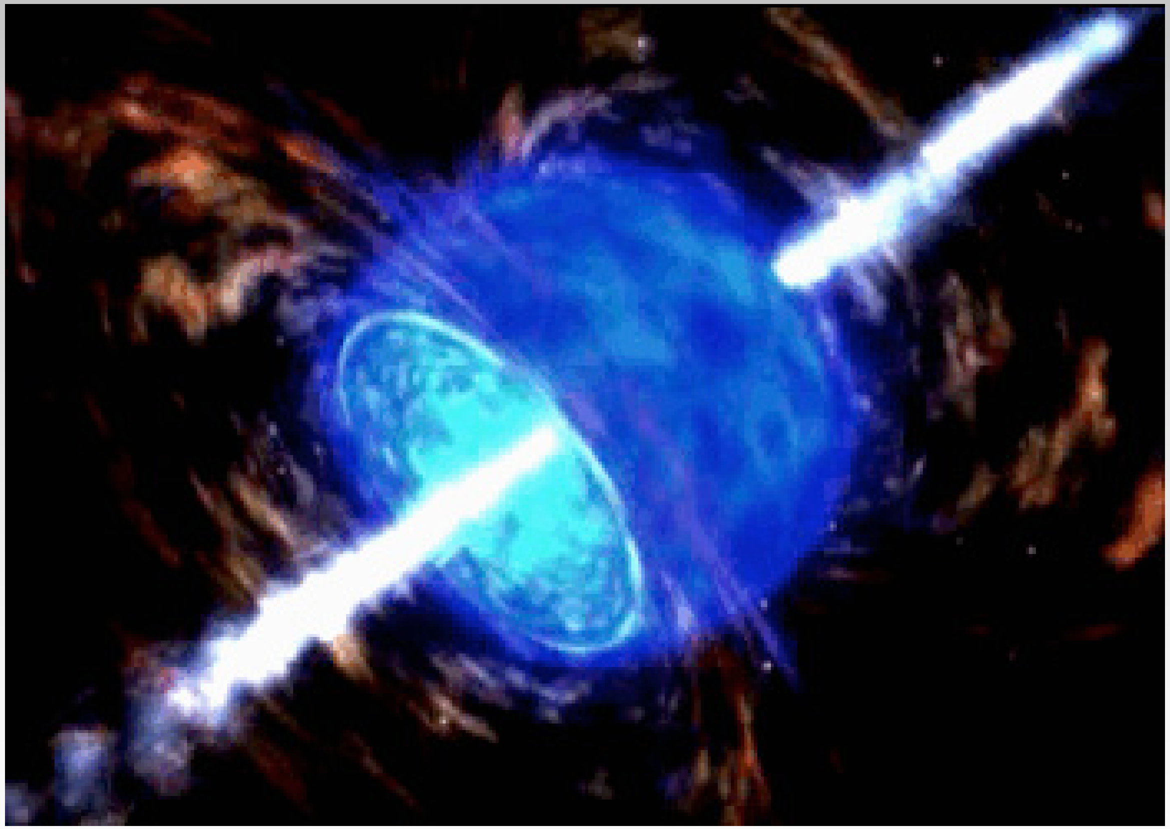


Woosley (1993)

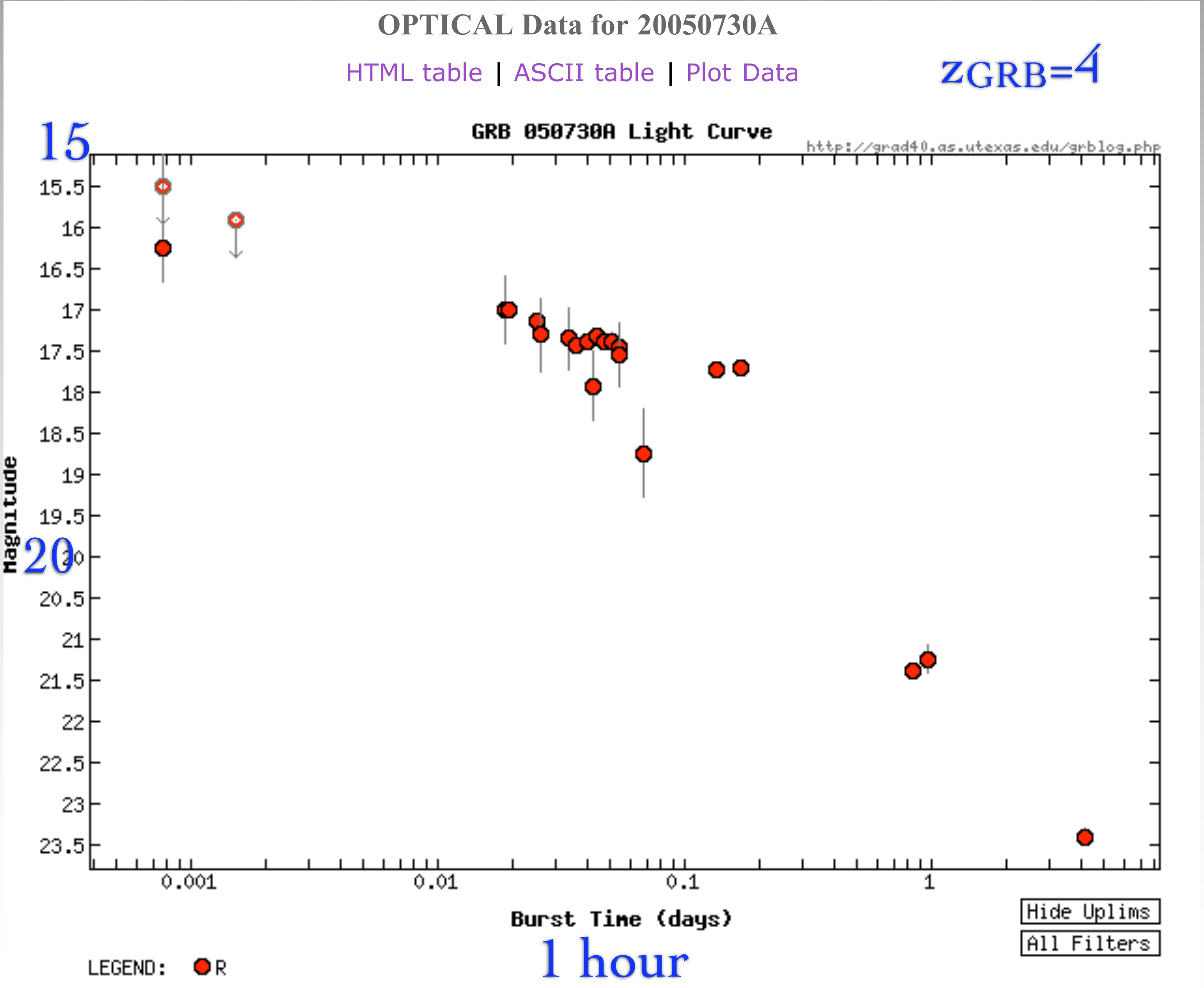
Long GRB Progenitors are massive stars

Presumably arising in star-forming regions



Woosley (1993)

GRB Afterglows are often very bright



GRB Experiment

- GRB
  - Swift telescope
  - ToO Optical observations
    - Similar instruments and analysis
- Analysis
  - Probe ISM of the GRB Host galaxy
  - Probe IGM at high z
  - Probe reionization?

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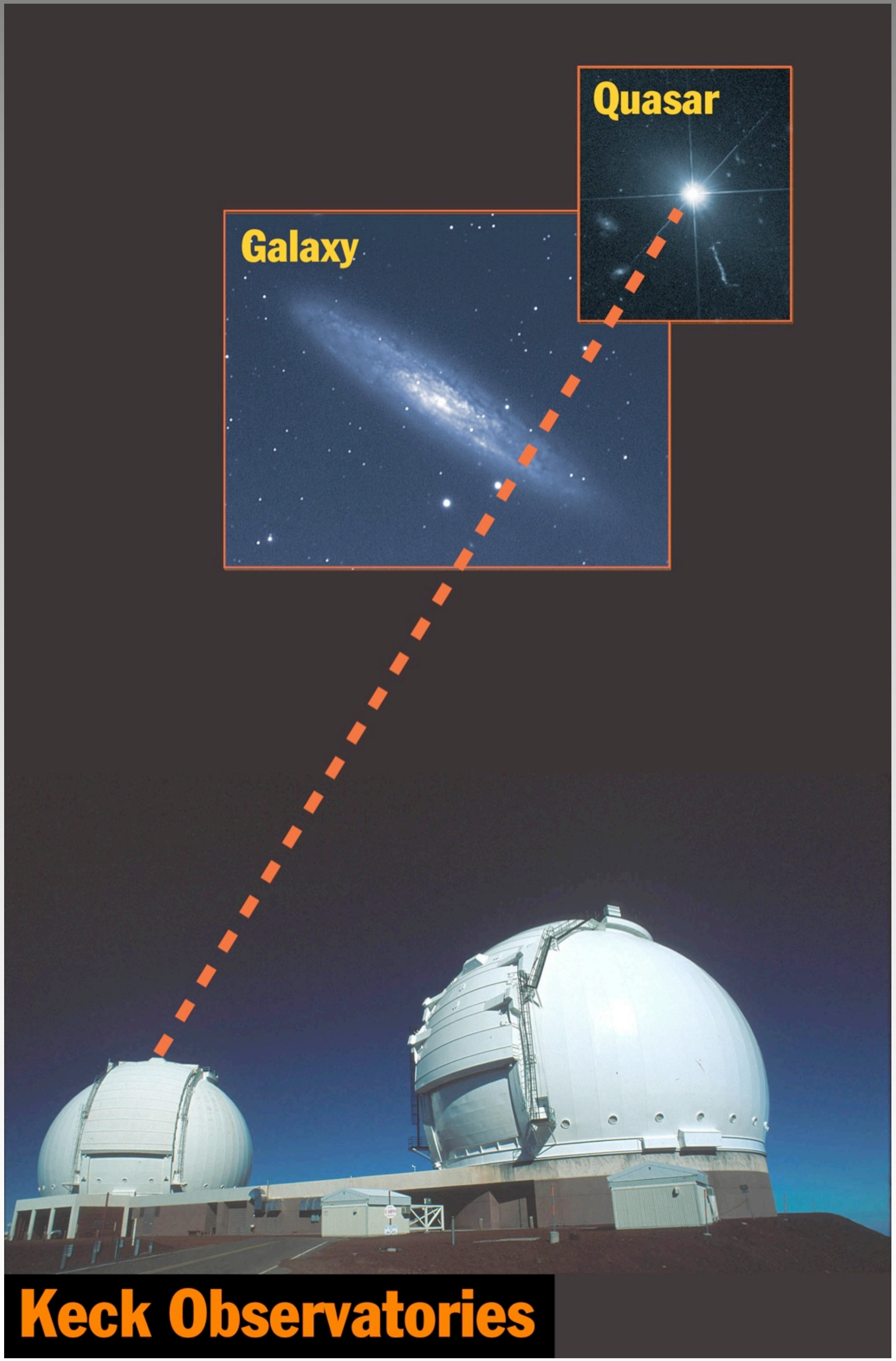

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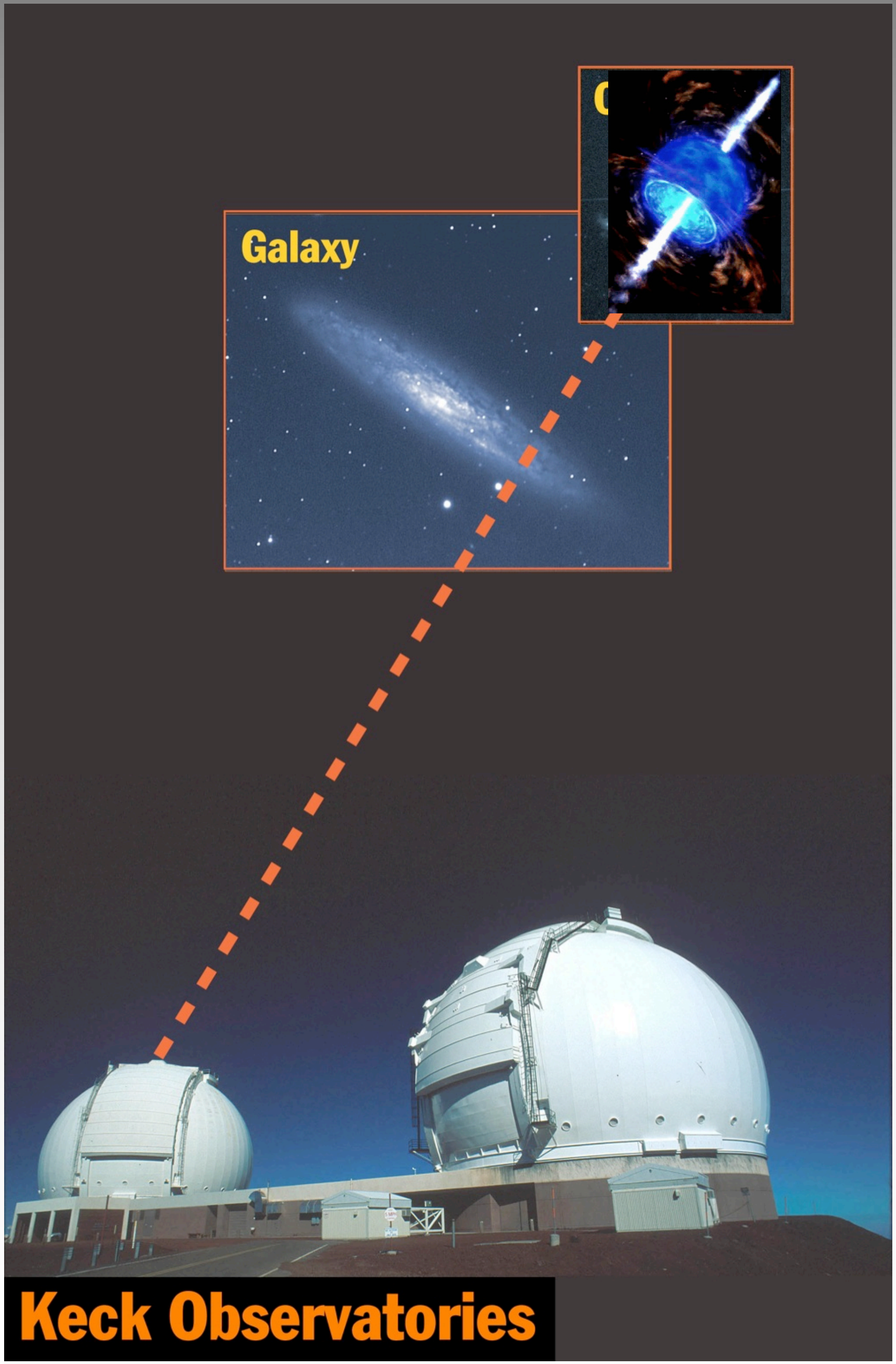

The Experiment

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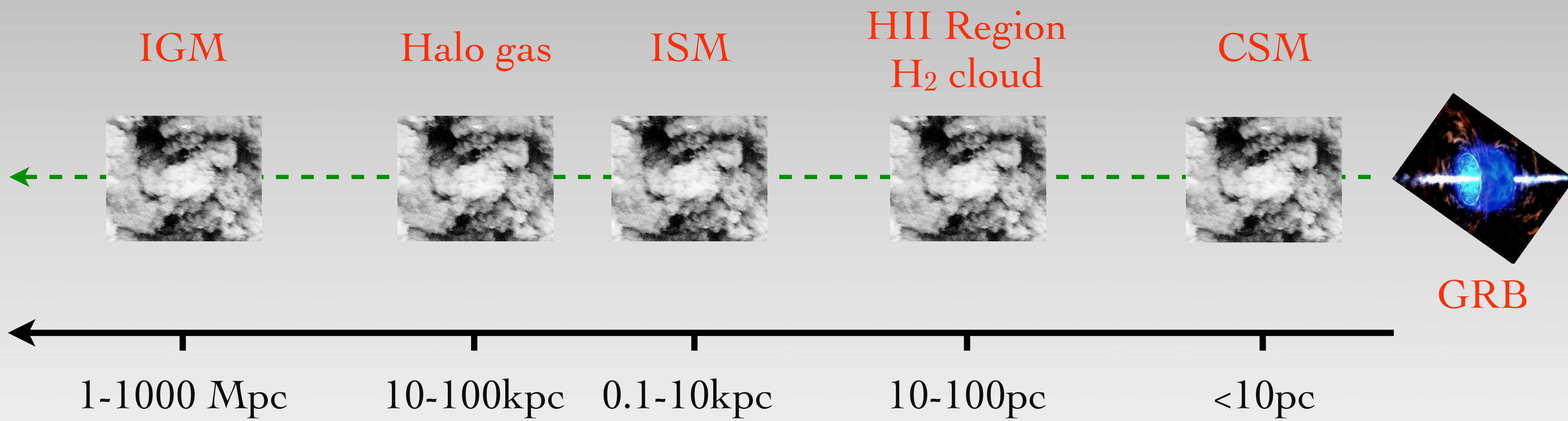

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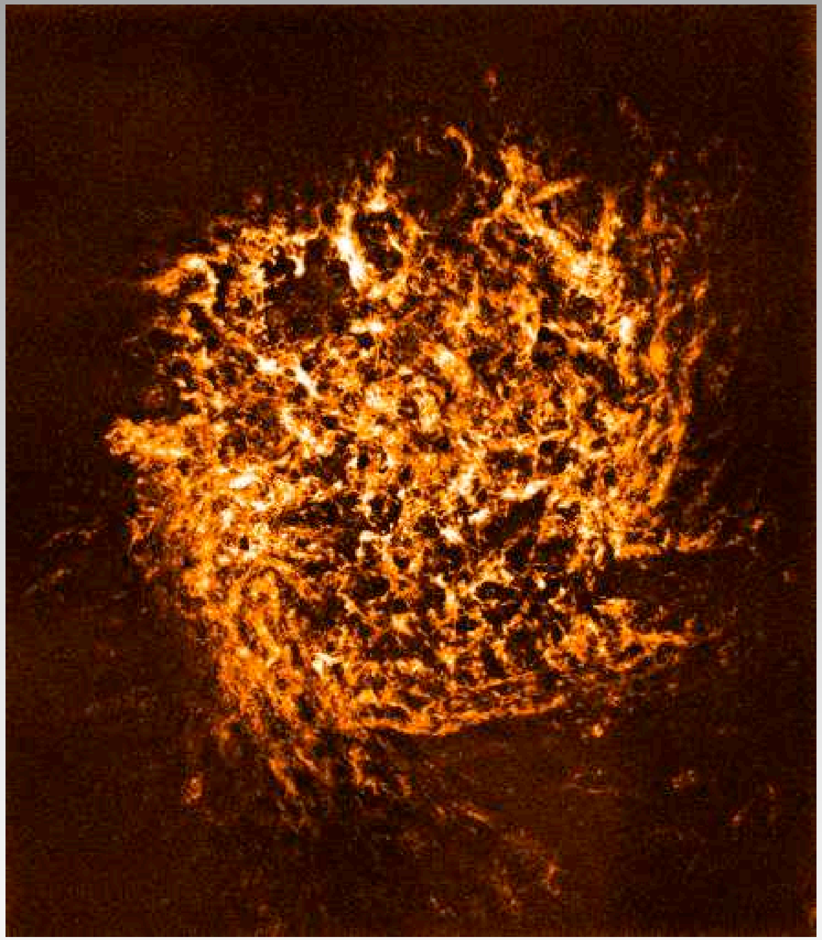
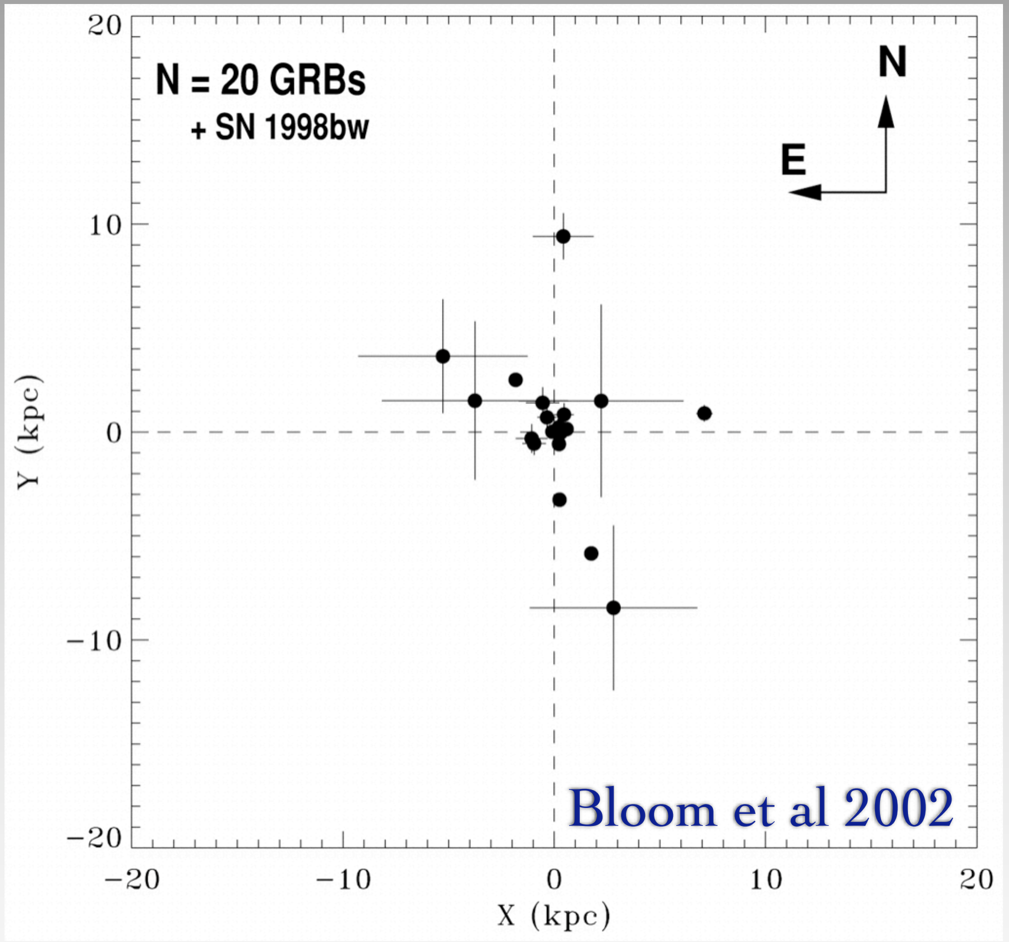
QSO vs GRB as Probes of the ISM





Damped Lya System

- Quasar abs system
- HI cross-section
- Expect sightlines at ϱ > 5kpc

GRB

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- >50% within 2 kpc
- Probe star-forming regions

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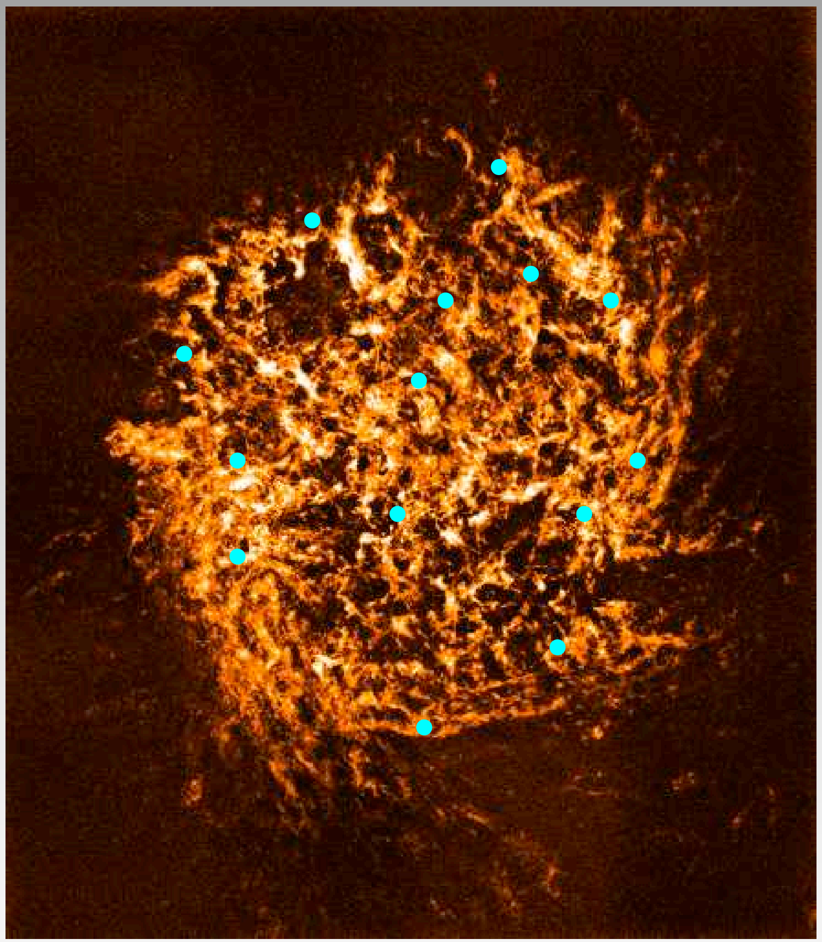

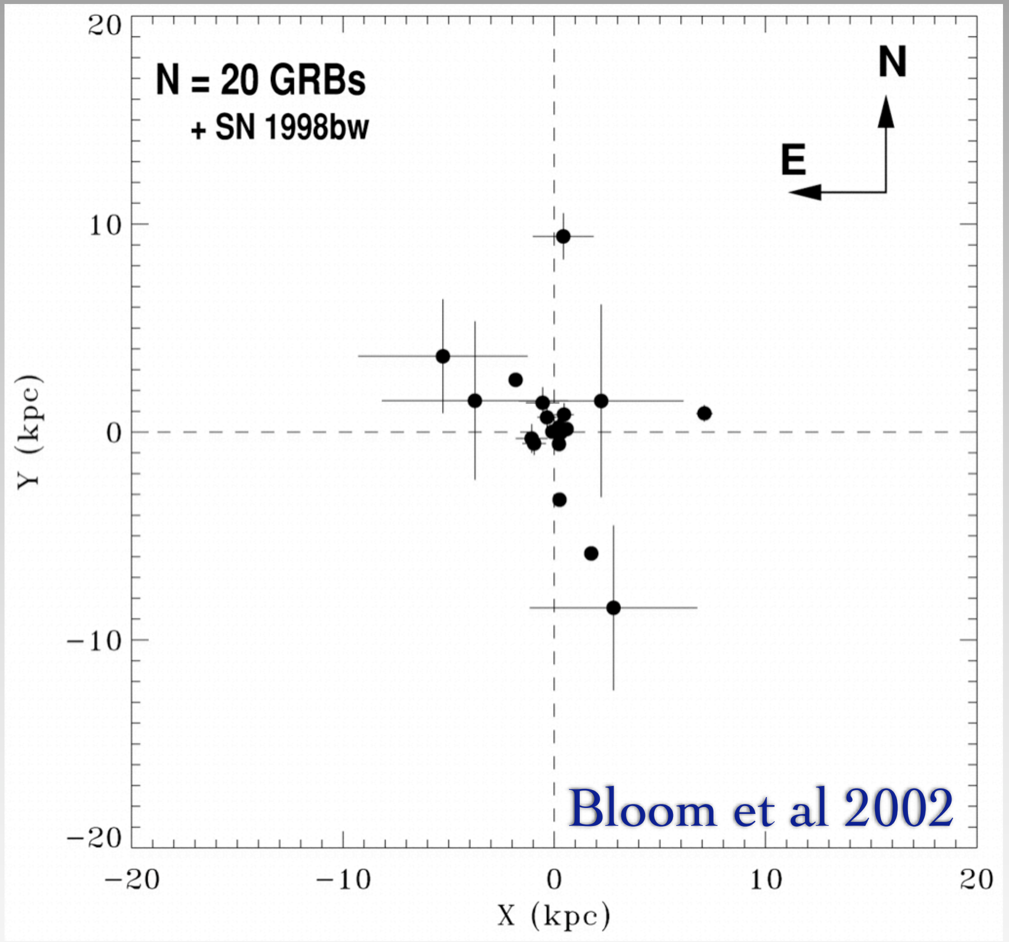

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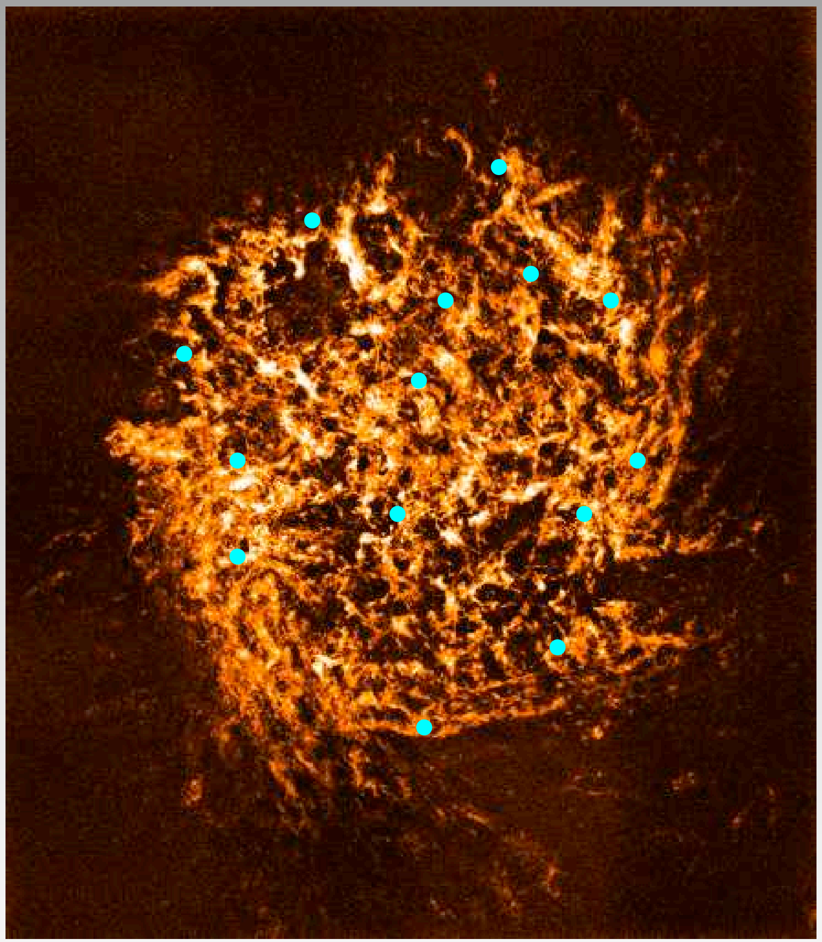

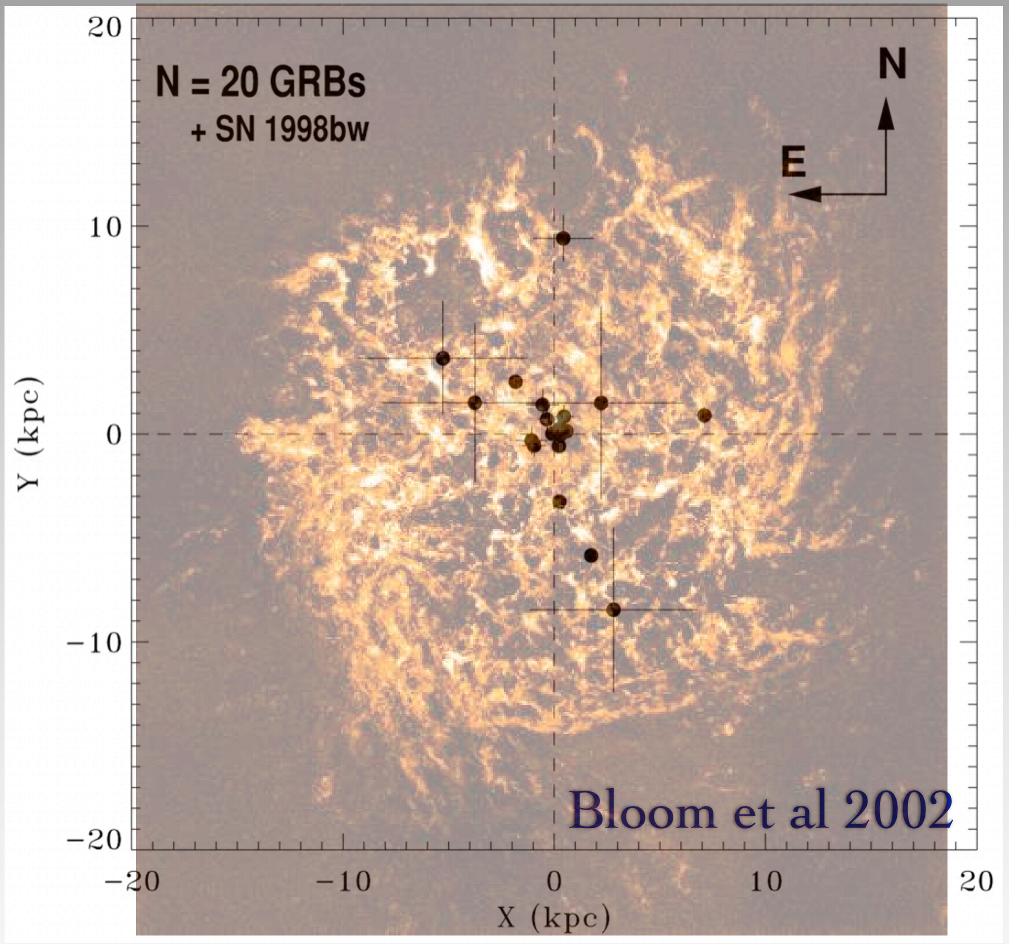

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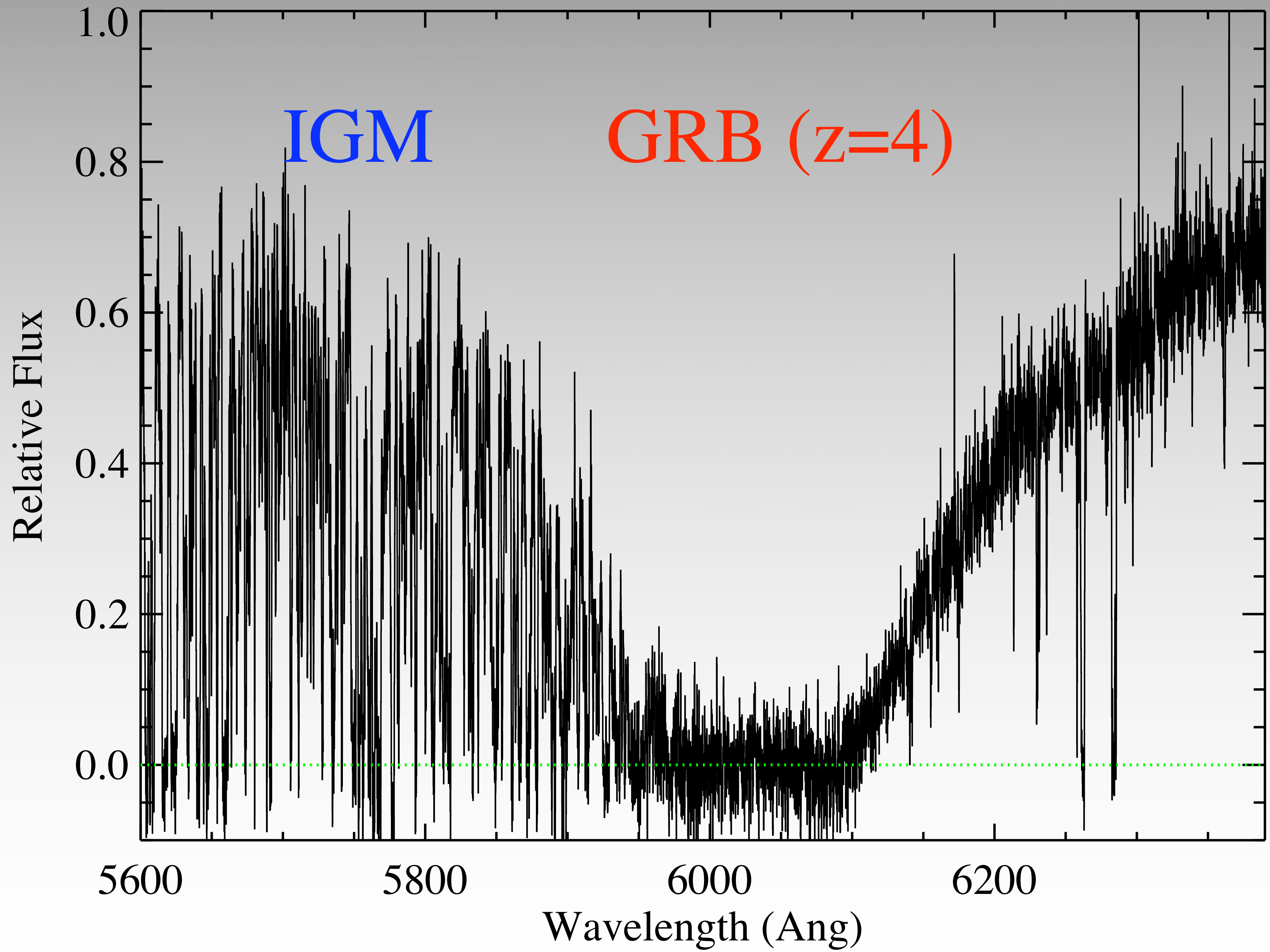
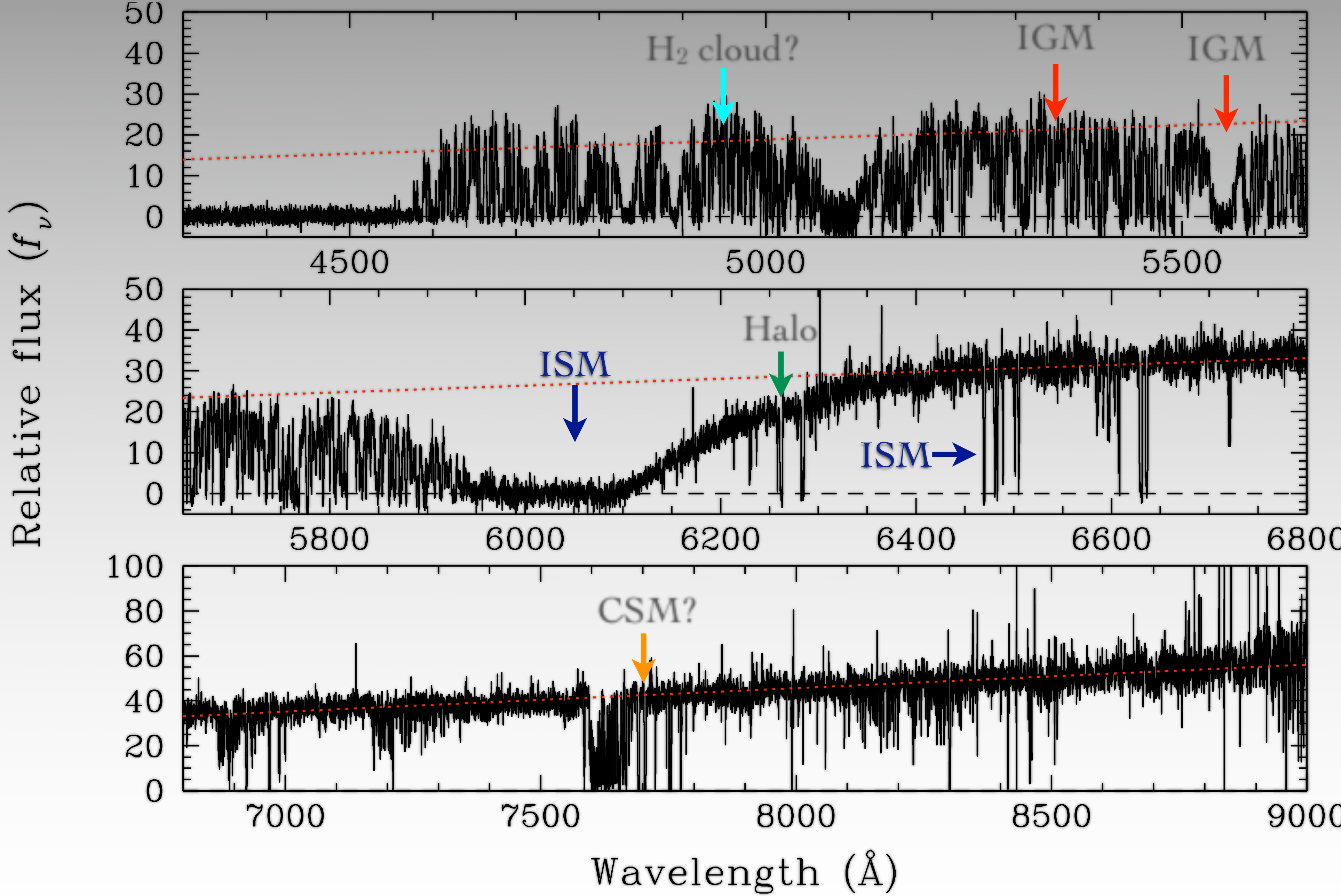
GRB Afterglow Spectrum

GRB 050730 (MIKE) Chen et al. (2005) $R_{PEAK} \sim 15$



GRB Afterglow Spectrum

GRB 050730 (MIKE) Chen et al. (2005) R_{peak} ~ 15



The Experiment: H gas

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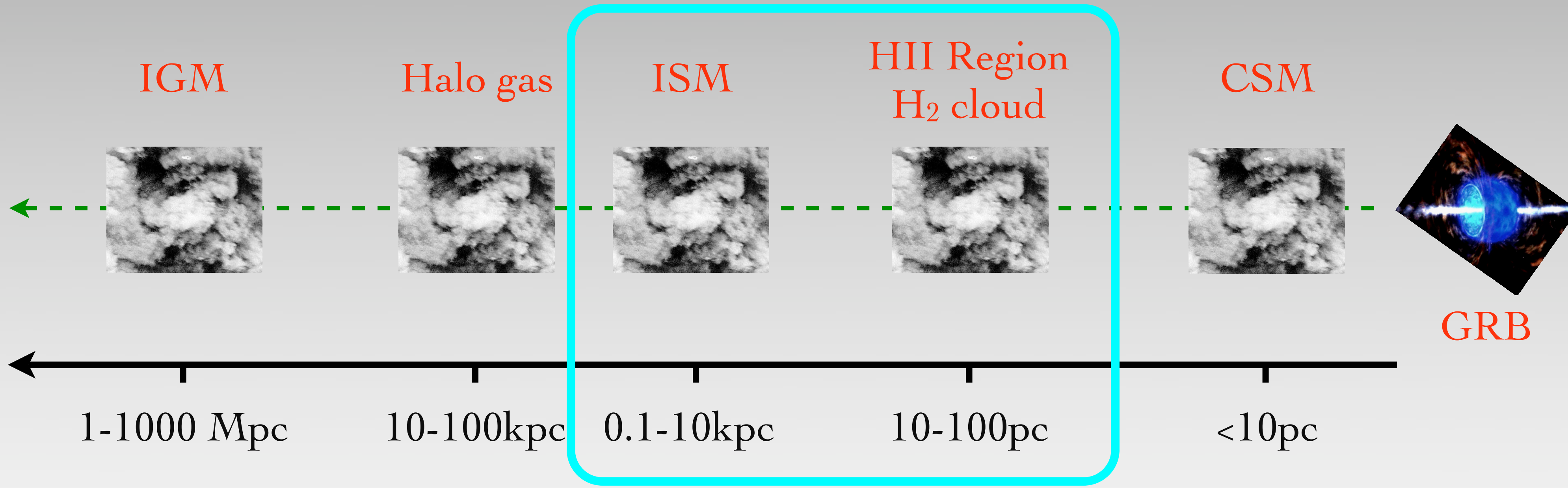

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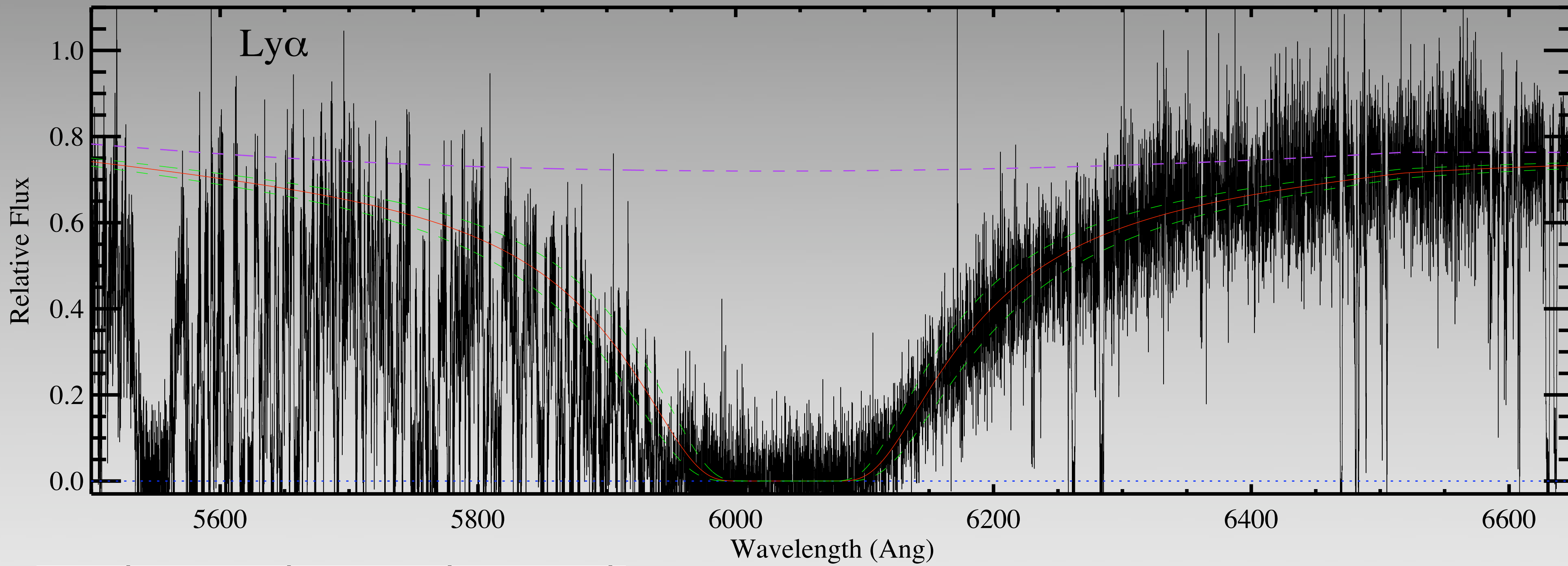
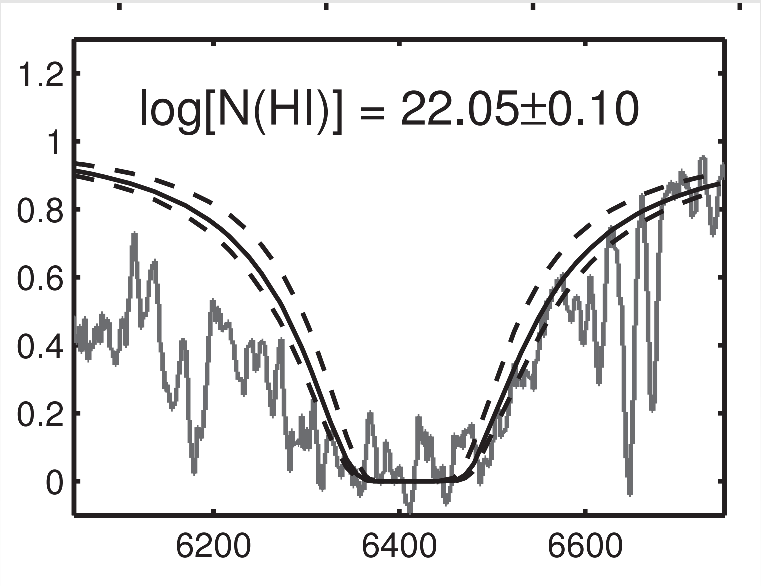
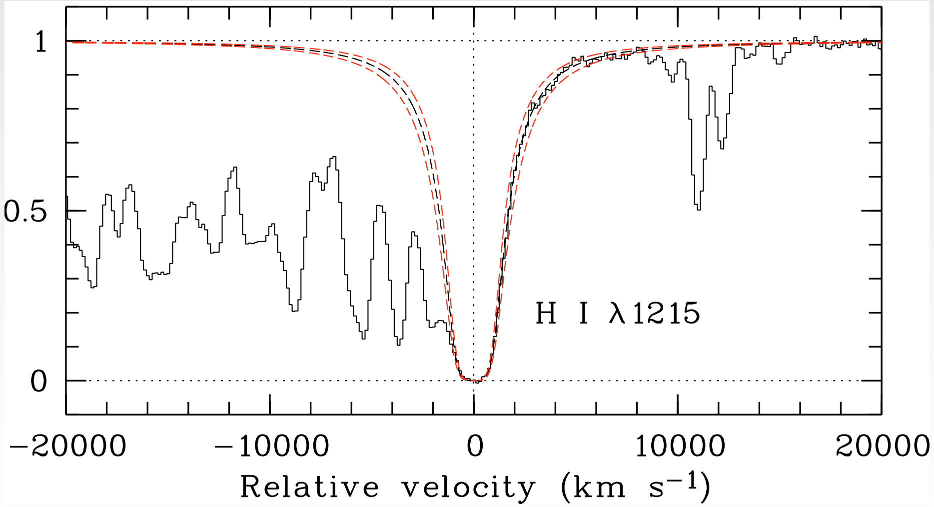
Large HI Column Densities



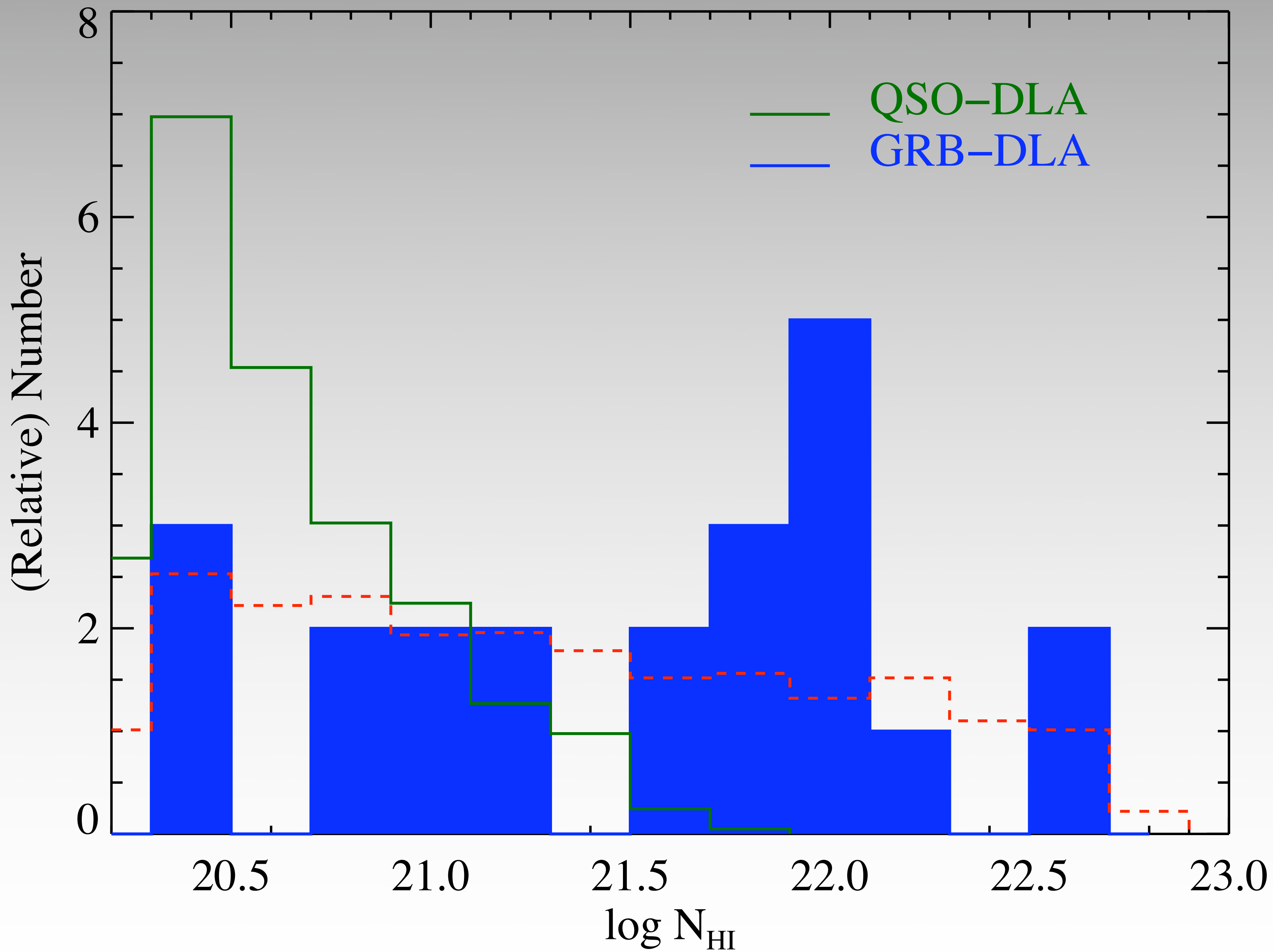




HI Column Densities

Jakobsson et al. (2006)
Prochaska et al. (2007)

Large N_{HI} due to a SF Region?



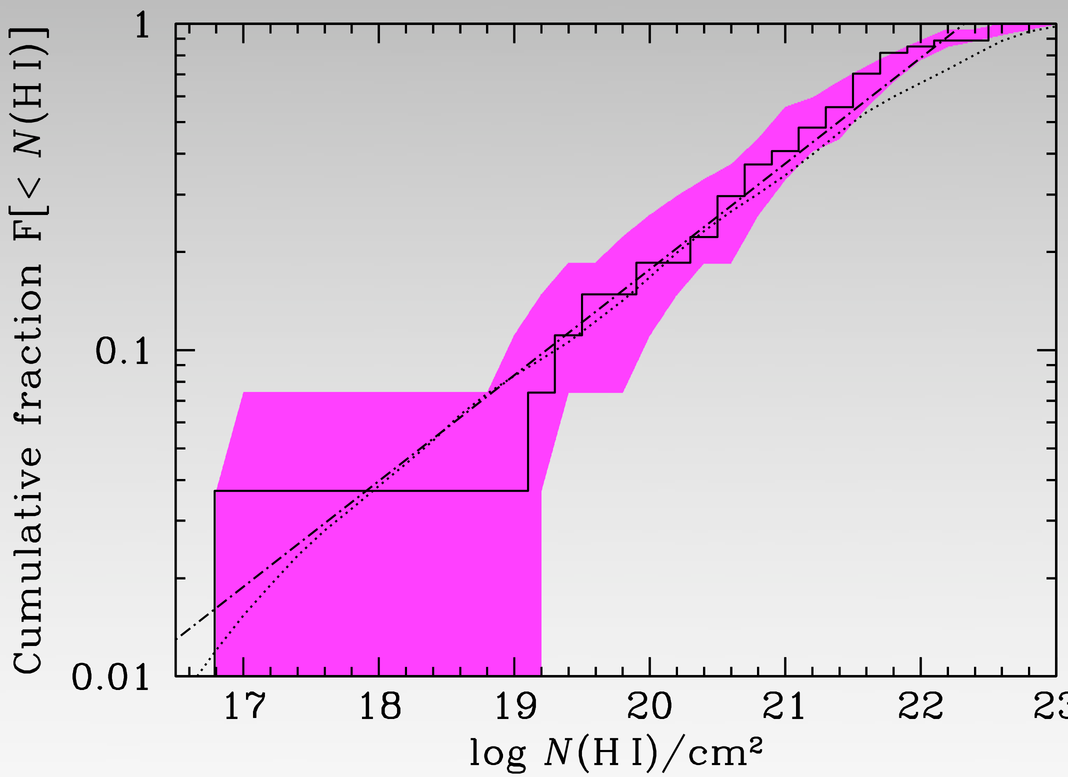
Escape Fraction

- GRB sightlines originate in SF regions
  - Trace massive stars
    - i.e. Dominant UV sources
  - Assume random orientations
- Survey GRB sightlines
  - Measure the rate of optically thin sightlines

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

  - Not restricted to the brightest galaxies at z>2
- Current results
  - 1 sightline in 30
  - f_{esc} < 0.08 (95% c.l.)
  - Dominate bright SF galaxies

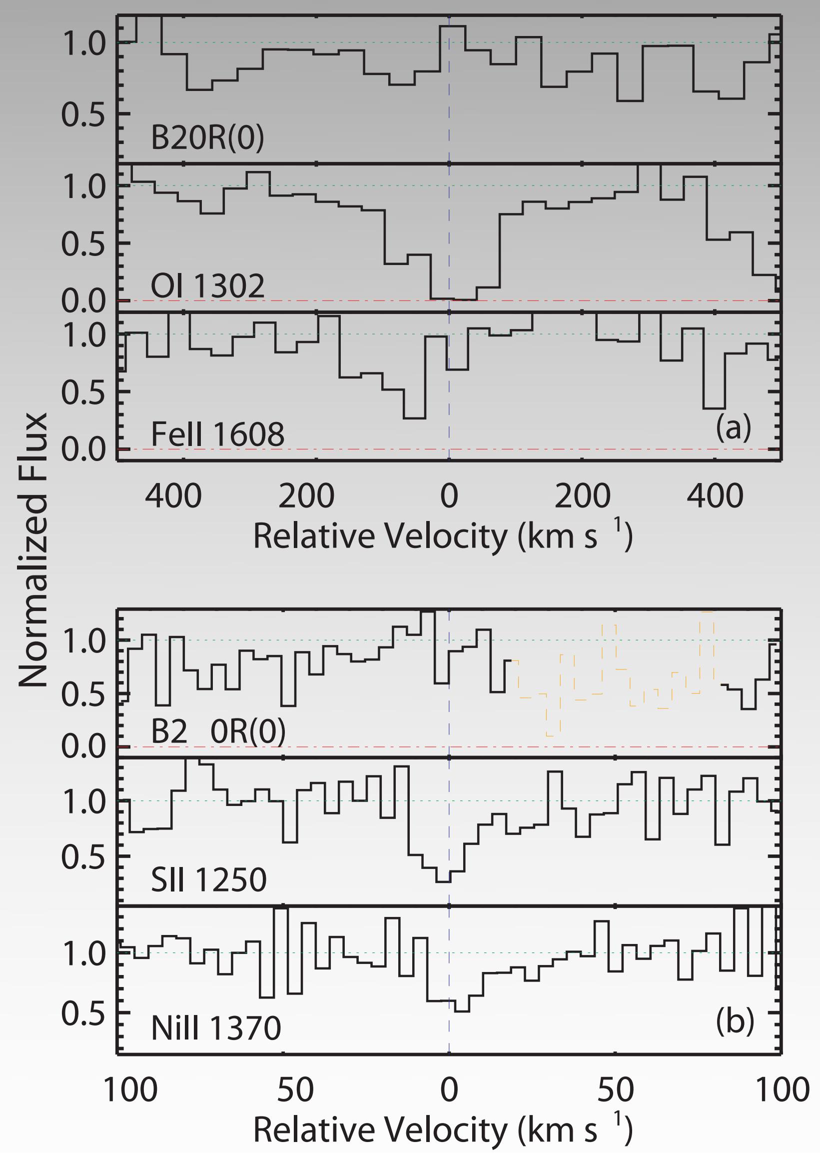
Chen, Prochaska, & Gnedin (2007)



H_2 in SF Galaxies?

- Massive stars
  - Observed to form in H_2 clouds locally
  - Chicken/egg: Unclear if H_2 is required or a by-product
- UV Spectroscopy
  - Lyman-Werner bands
    - Most sensitive probe of H_2 for astronomers
    - Requires high-resolution, blue data

Tumlinson et al. (2007)



H_2 'Survey'

TABLE 1
Data Summary

Tumlinson et al. (2007)

GRB	z_{GRB}	$\log N_{HI}$	[M/H][a]	[M/Fe]	Strong Mg[b]	Exc. Fe[b]	$\log f^c_{H2}$	$\log N(H^*_2)^d$	Ref.
030323	3.3720	21.90	> -0.87	>1.53	Y	N	< -6.5	< 13.9	1
050730	3.9686	22.15	-2.26	0.25	?	Y	< -7.1	< 13.6	2, 3
050820	2.6147	21.00	-0.63	0.97	N	N	< -6.5	< 12.9	3
050922C	2.1990	21.60	-2.03	0.75	W	Y	< -6.8	< 13.5	4
060206	4.0480	20.85	-0.85	...	?	?	< -3.6	...	5

References. — 1: Vreeswijk et al. (2004); 2: Chen et al. (2005); 3: Prochaska et al. (2007a); 4: Piranomonte et al. (2007); 5: Fynbo et al. (2006)

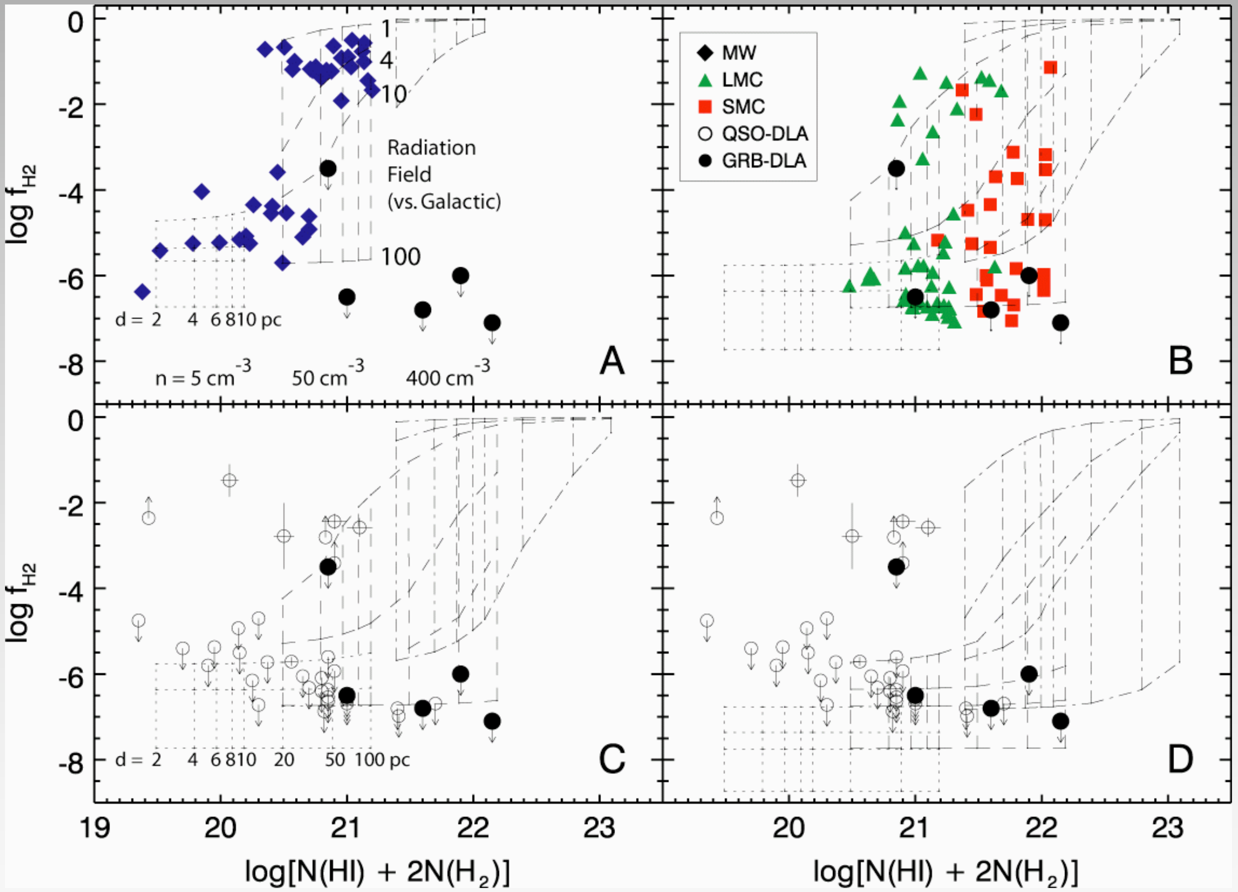
[a] Metallicity derived from Si, S, or Zn abundance (see Prochaska et al. 2007a).
[b] See Prochaska et al. (2006).
[c] With the exception of 060206, the values represent 4σ statistical upper limits.
[d] Upper limit (4σ) based on non-detection of either L0-3P(1) at 1276.82 Å or L0-3R(2) at 1276.33 Å (see Draine & Hao 2002).

- Results
  - 5 GRBs at z>2
  - No H_2
    - Not even a trace
    - $f(H_2) < 10^{-6}$
- ISM properties
  - Large HI column
  - Modest metallicity
  - Modest dust-to-gas
- SMC+LMC
  - Similar ISM and H_2

Implications from Absence of H_2

- Results
  - 5 GRBs at z>2
  - No H_2:
    - Not even a trace
    - $f(H_2) < 10^{-6}$
- Implications
  - H_2 cloud hosting the GRB was destroyed prior to the burst
    - PDR together with HII region
  - H_2 formation is suppressed in ISM
    - Intense FUV field
    - O+B stars related to the star-forming region?

Tumlinson et al. (2007)



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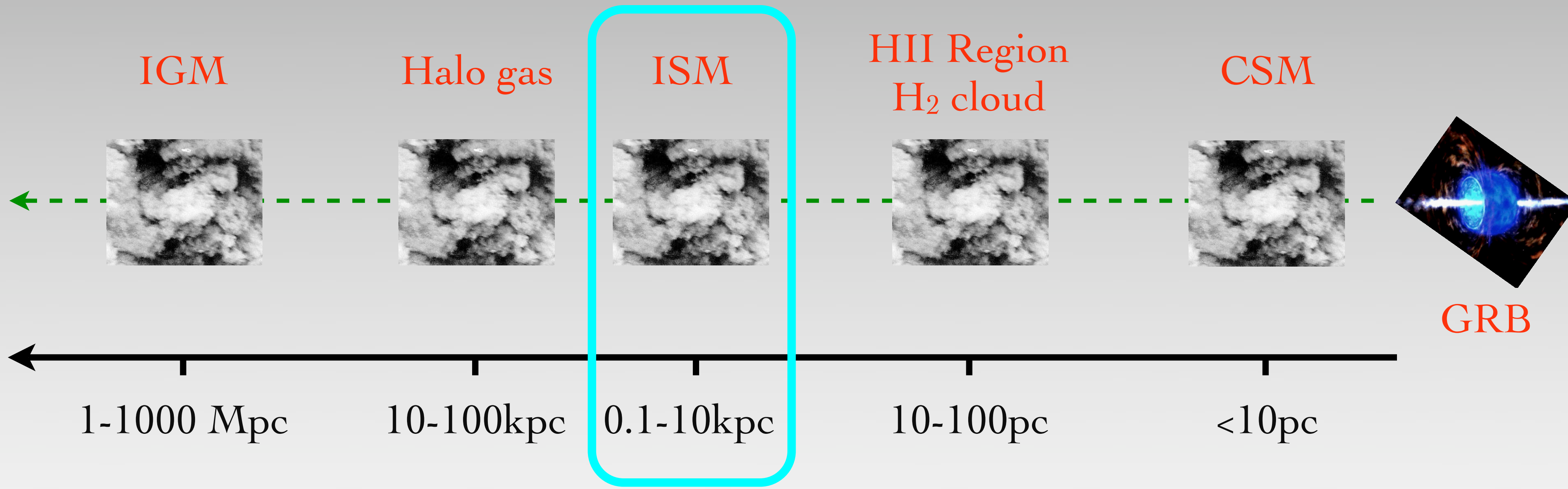

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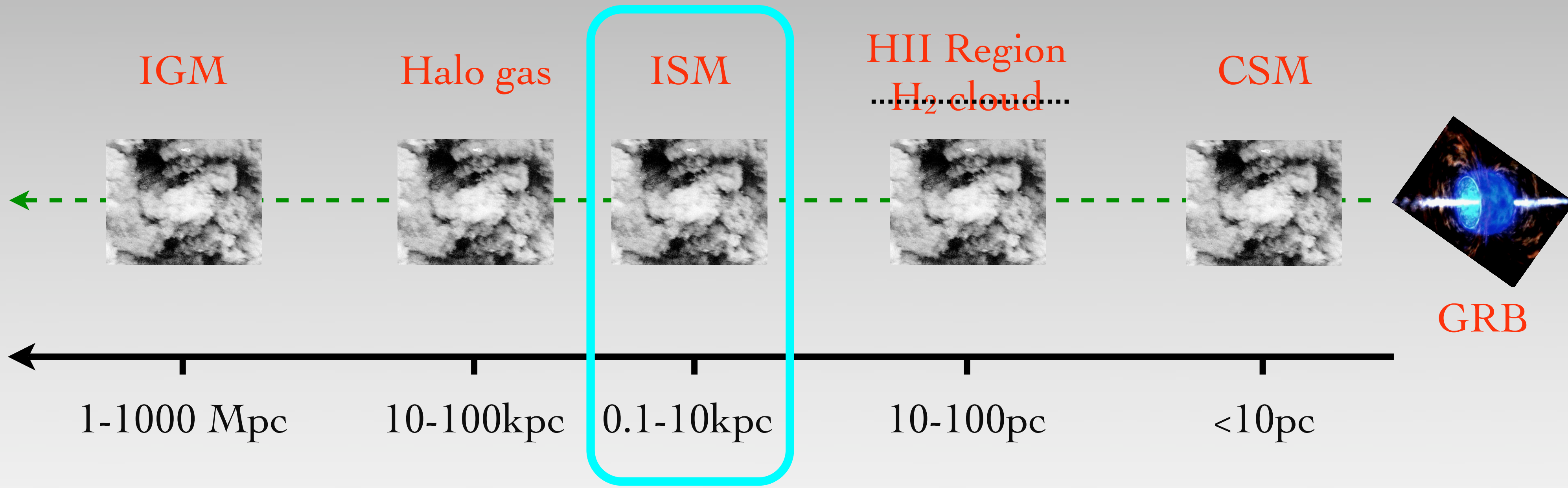

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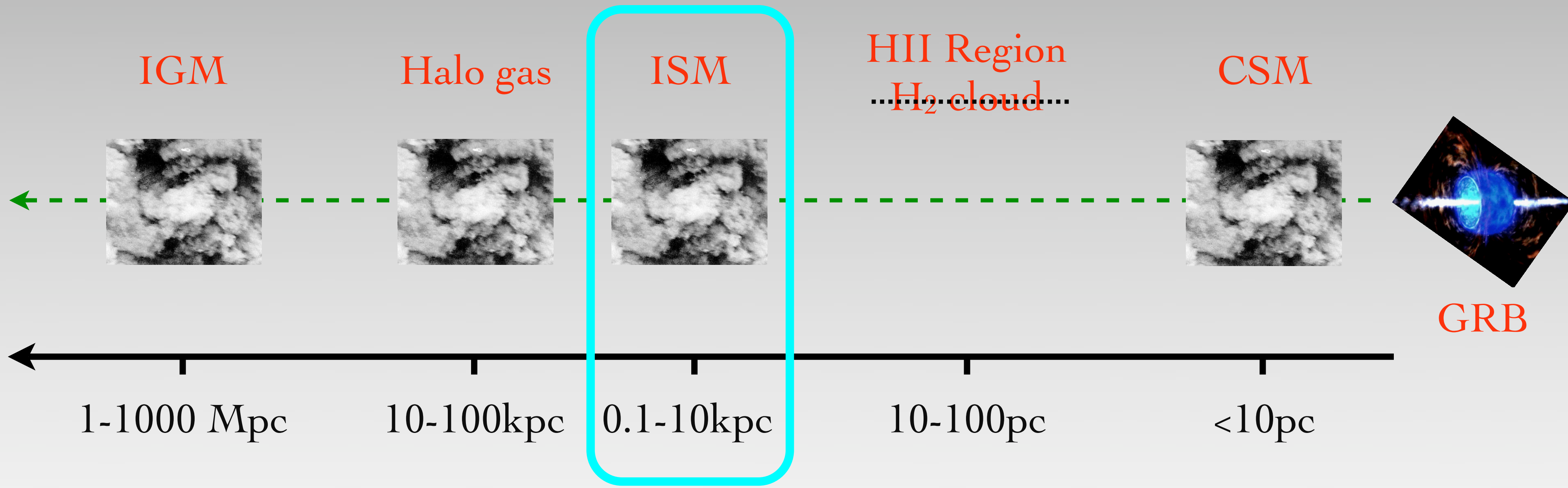

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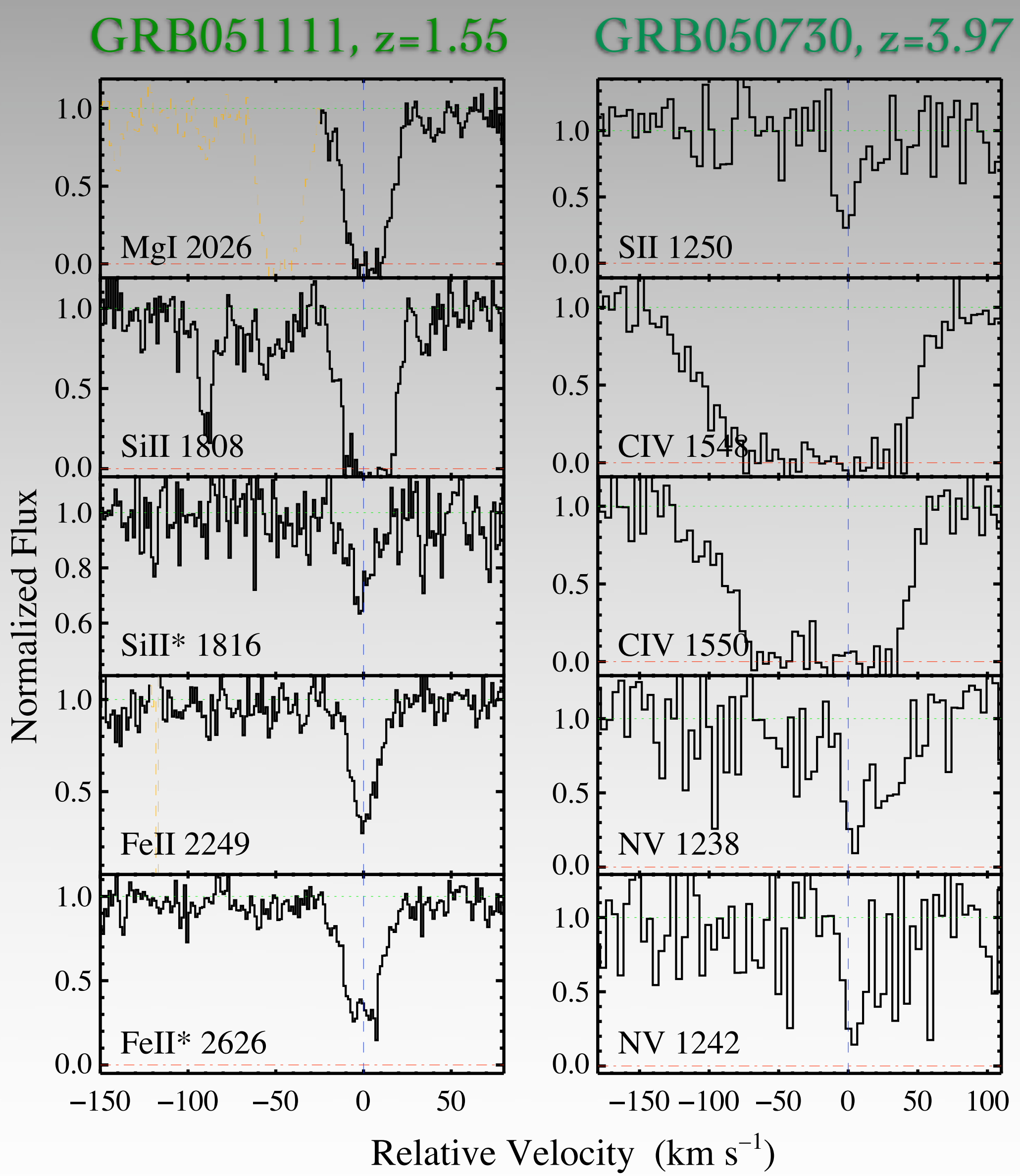
Metal-Line Transitions

- Very strong lines
  - Follows from large N_{HI}
  - Echelle data preferred
- Distance diagnostics
  - MgI: Atomic Mg
  - FeII*: Fine-structure lines
- Metal abundances
  - Unsaturated resonance
  - Low-ion transitions
  - Dust depletion, too
- HII Regions, CSM?
  - High-ion states
  - Could be halo/ISM gas



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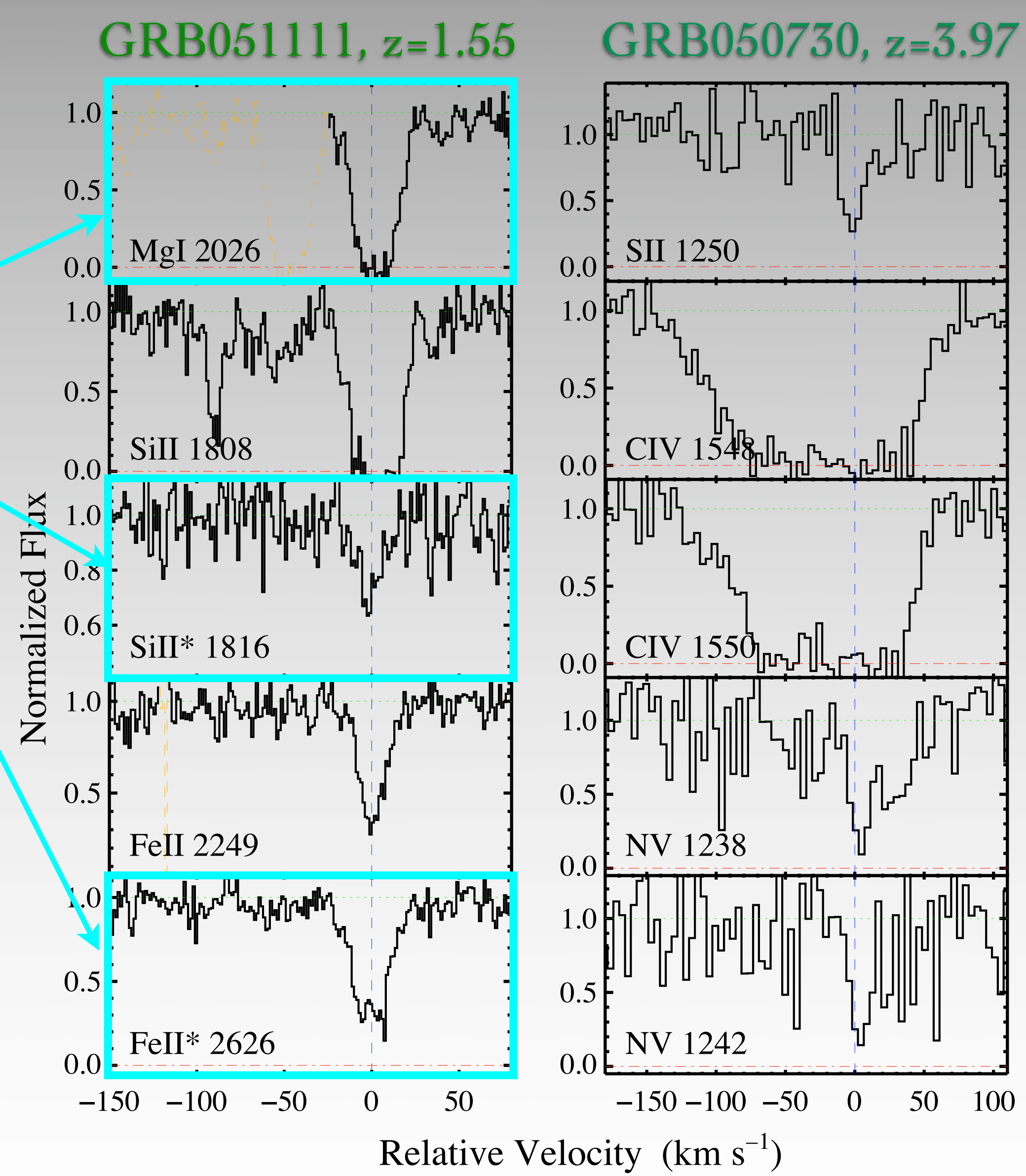

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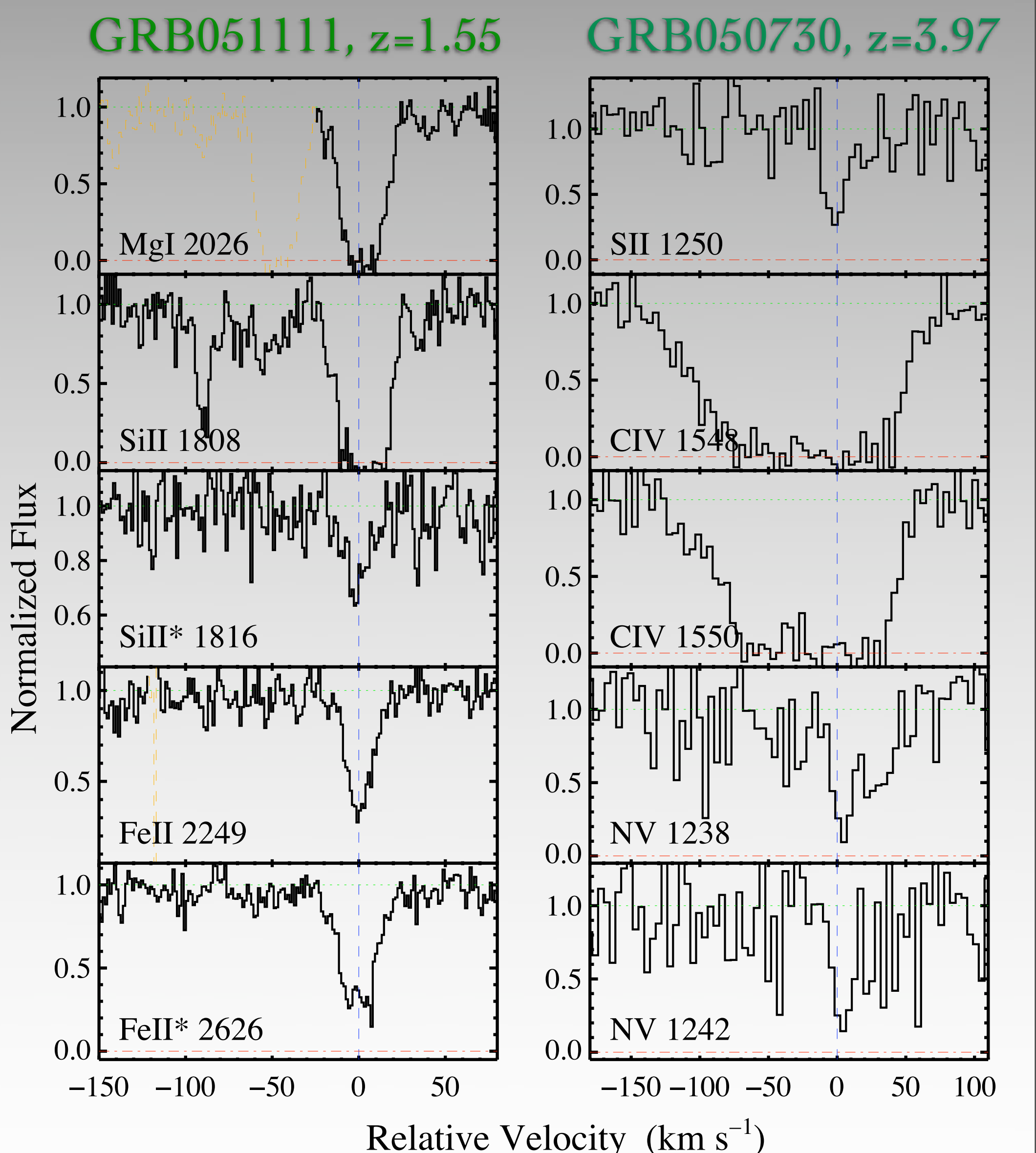

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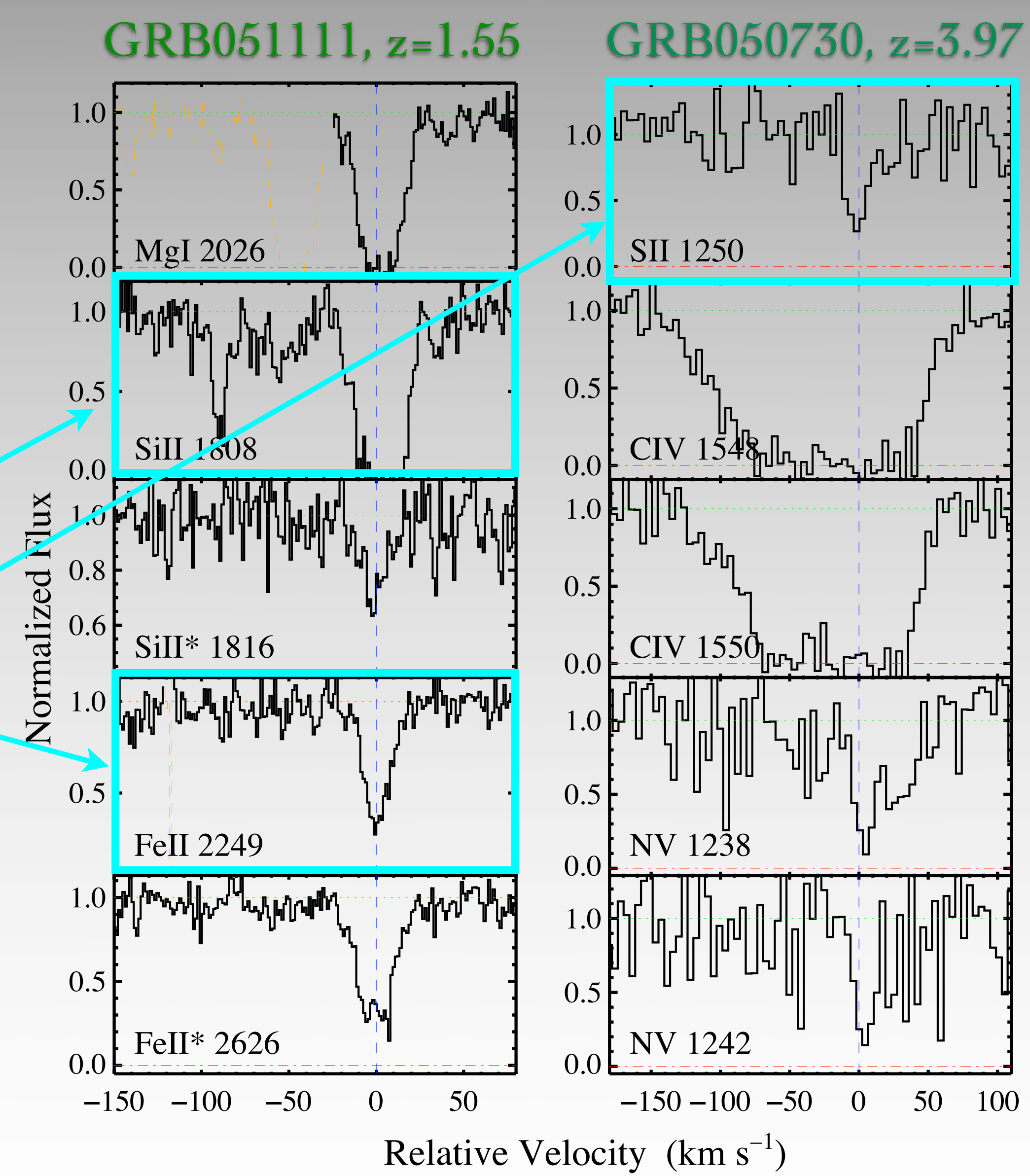

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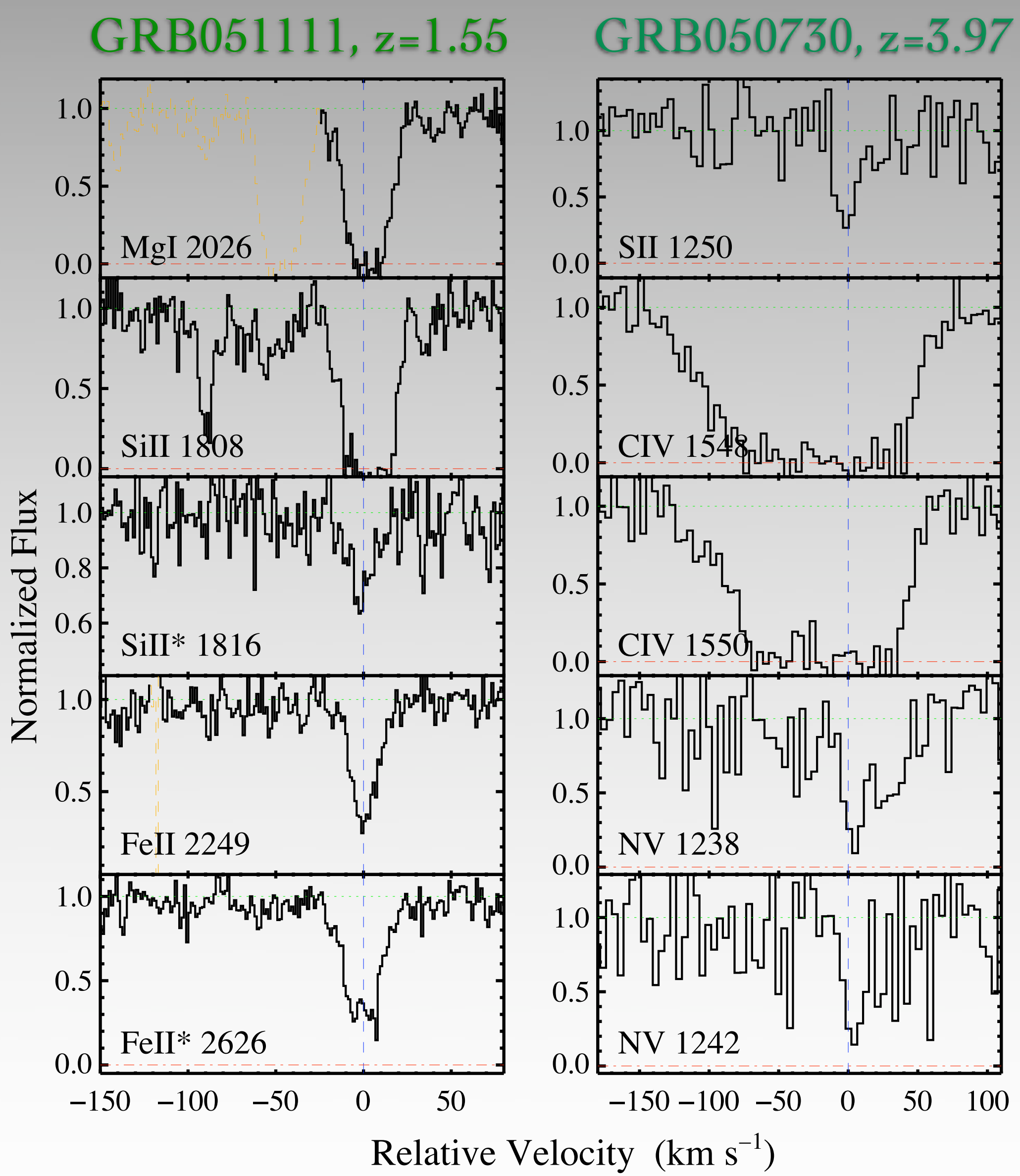

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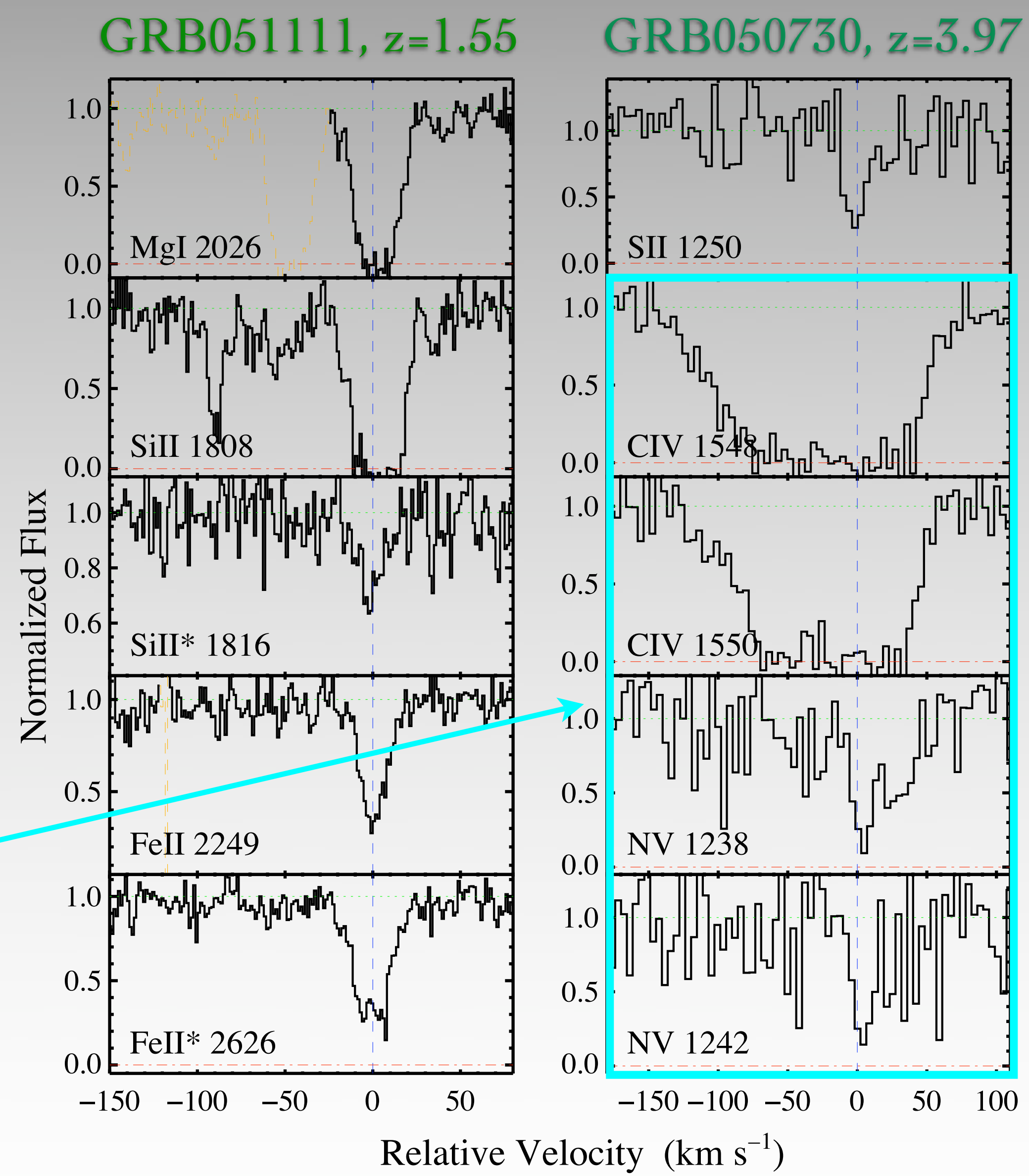

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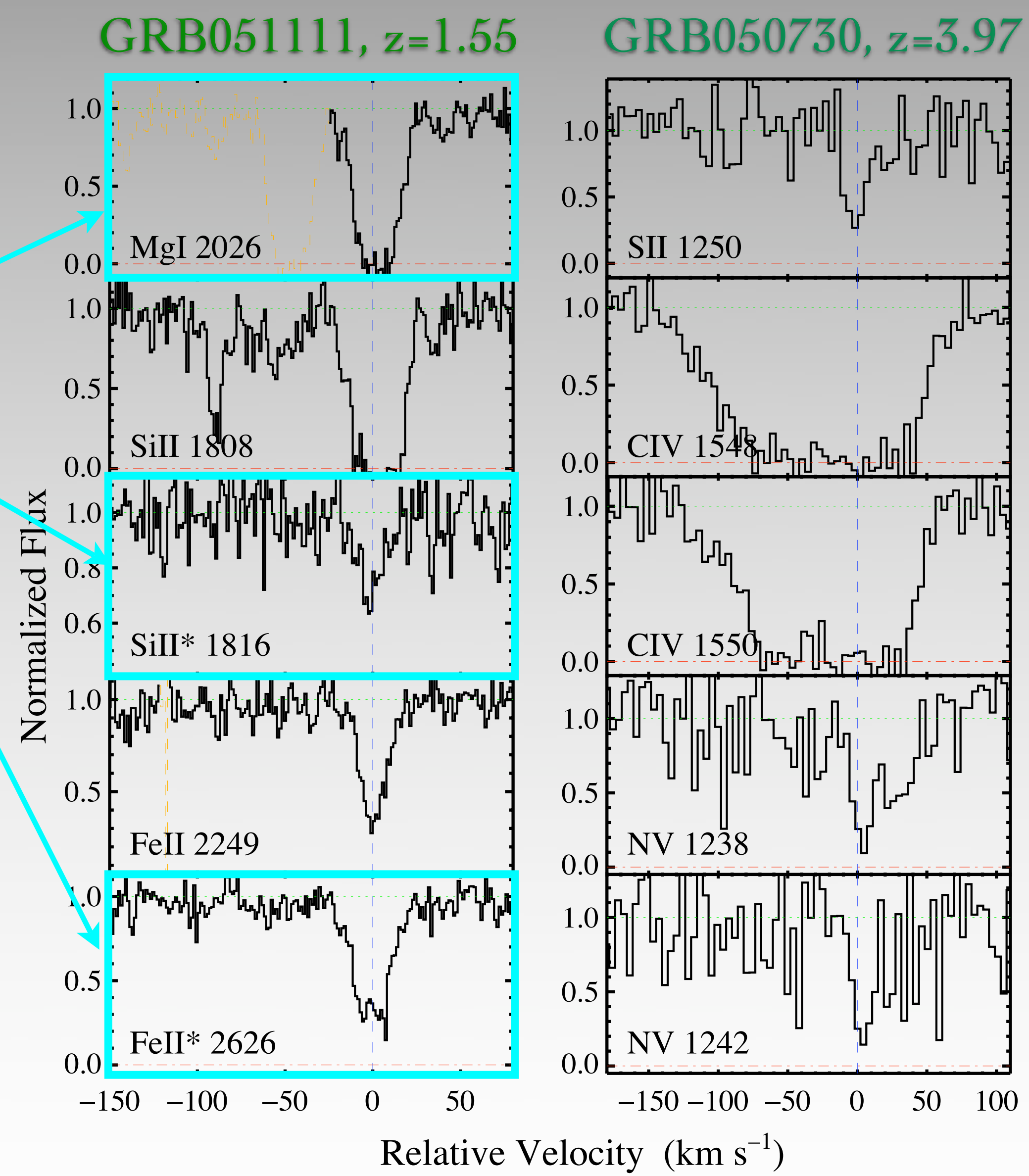
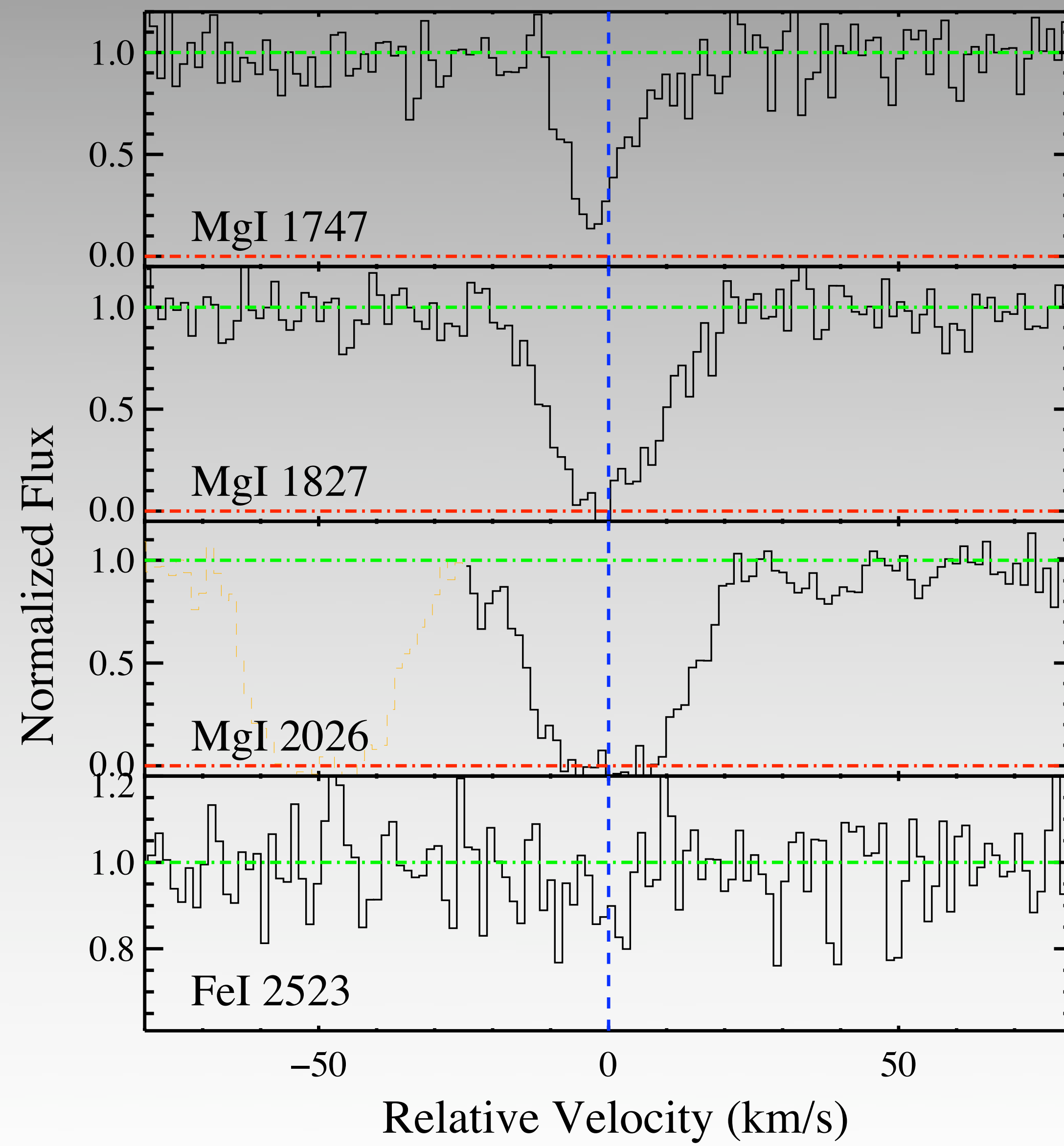


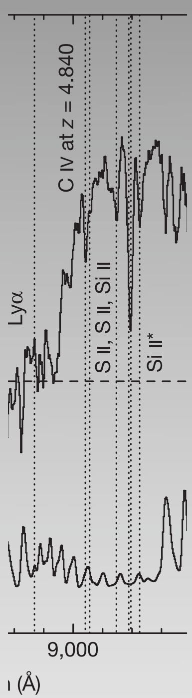
MgI Detection

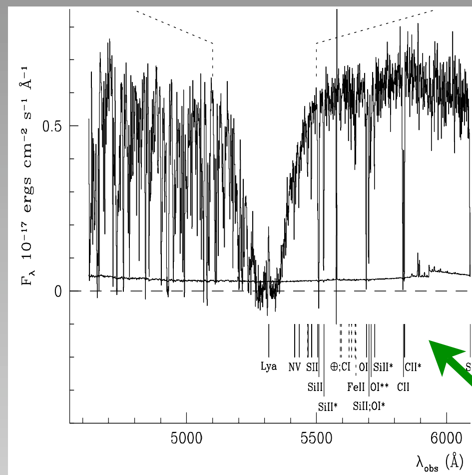
- Very large Mg^{0} column
  - Detected in several transitions
  - $N(Mg^{0}) = 10^{14.7}$ cm^{-2}
- $IP(Mg^{0}) = 7.7$ eV
  - The galaxy is optically thin at this energy
  - Caveat: Dust
- At r=50pc, 99.99% of MgI is ionized in <1000s
  - Generic result for GRB
  - Detection of MgI places the neutral gas at >50pc
  - variations in $N(Mg^{0})$?
    - None found: r>80pc

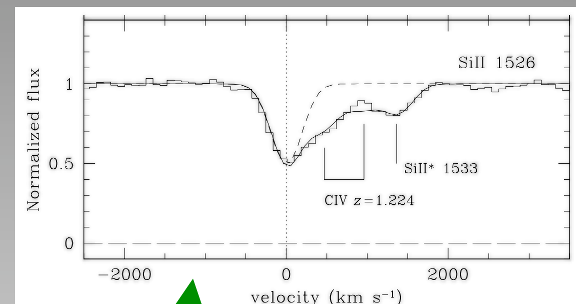


Prochska, Chen, & Bloom (2006)

Fine-structure is ubiquitous







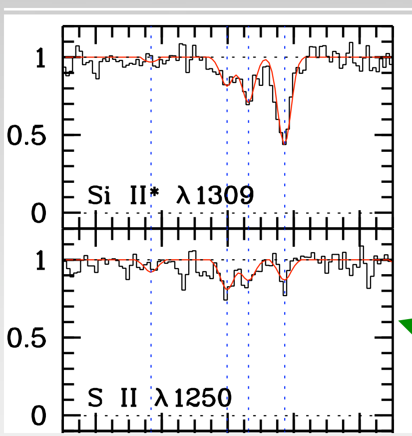
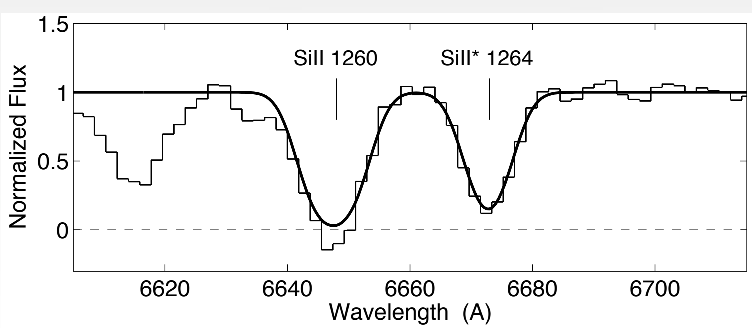
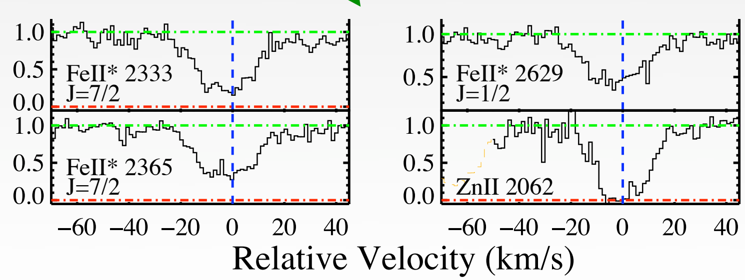
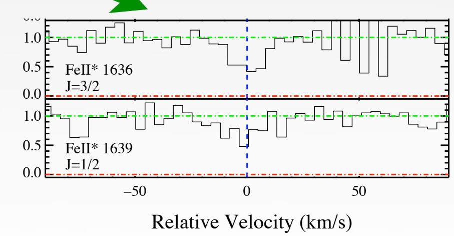


Table 3. Constraints on Circumburst Distances of Observed Neutral Gas

GRB	z	α	β	Ref	$\log L_\nu^a$ (cgs)	r_{MgI}^b (pc)	r_{excite}^c (pc)
010222	1.477	0.80	0.89	1	31.39	40	190
020813	1.254	0.85	0.92	2	31.09	30	140
021004	2.328	1.05	1.05	3	32.21	140	620
030323	3.372	1.56	0.89	4	32.85	540	2330
030329	0.169	1.10	1.00	5	31.38	60	250
050408	1.236	0.79	1.30	6	29.93	10	40
050730	3.969	0.30	1.80	7	32.16	70	340
050820	2.615	0.95	1.00	8	31.97	100	430
051111	1.549	0.87	0.60	9	31.32	40	180
060206	4.048	1.01	0.51	10	32.41	170	730

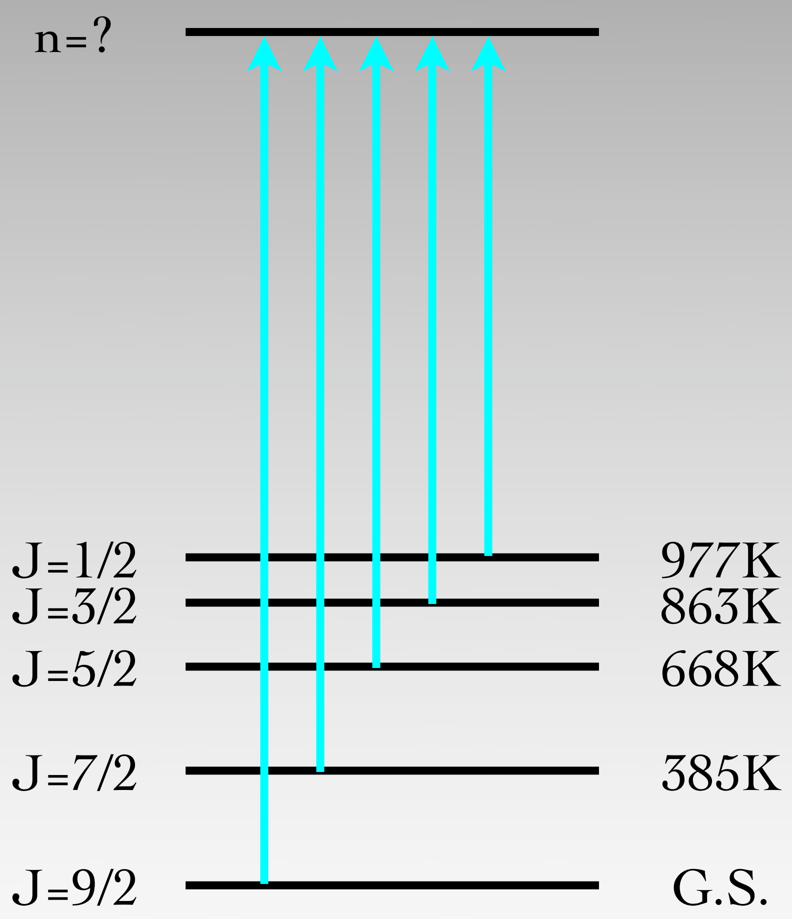






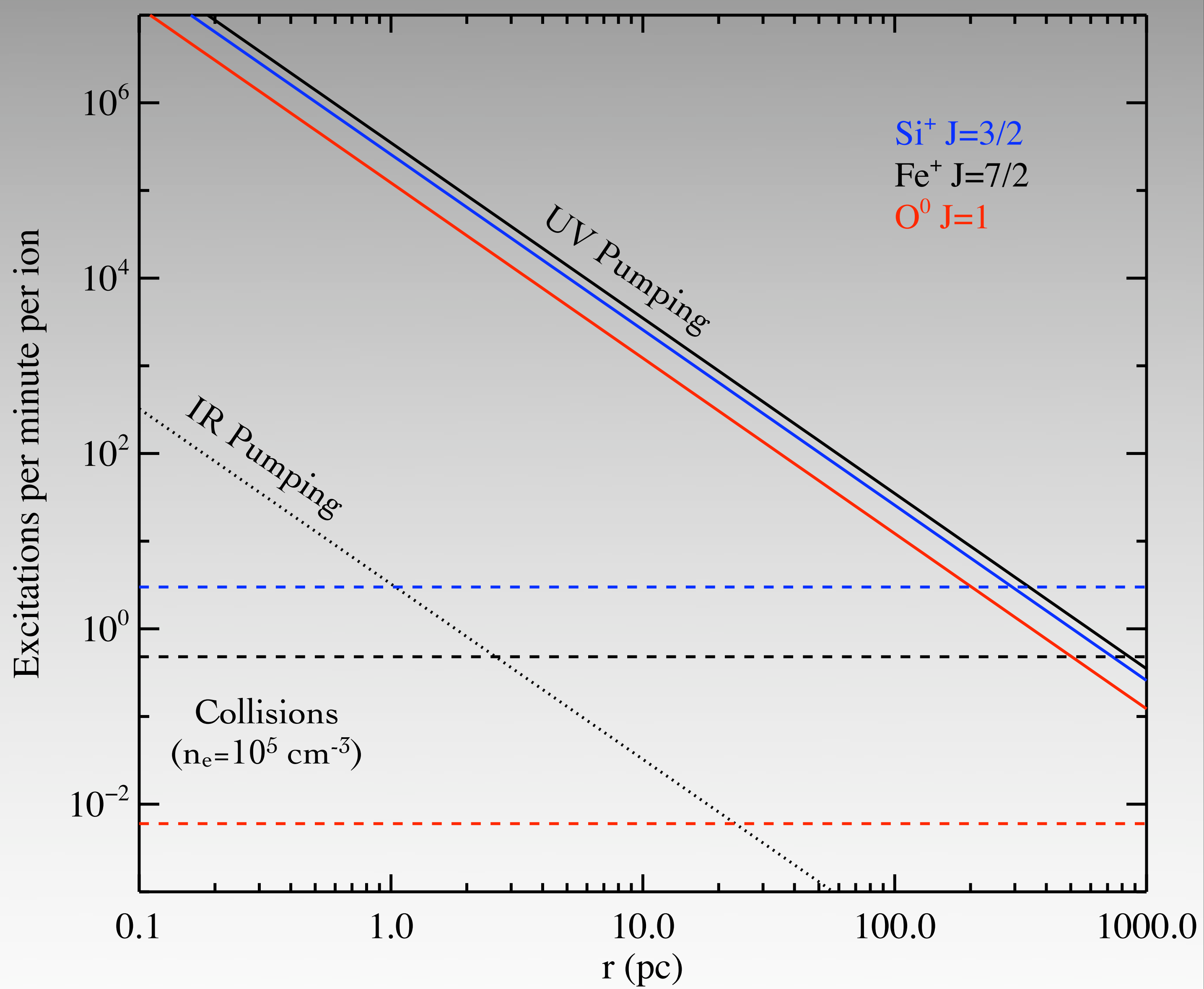
Fine-Structure Excitation

- Indirect pumping
  - UV transition to upper level
  - Cascade down to excited state
  - Electric-dipole forbidden
    - Multiple generations?
- Direct Pumping
  - IR transition from J=9/2
  - Magnetic-dipole transition
    - J=9/2 to 7/2
    - J=7/2 to 5/2
    - etc
  - Possible, but unlikely
- Collisional excitation
  - Electrons should dominate
  - Neutral rates not calculated to high precision



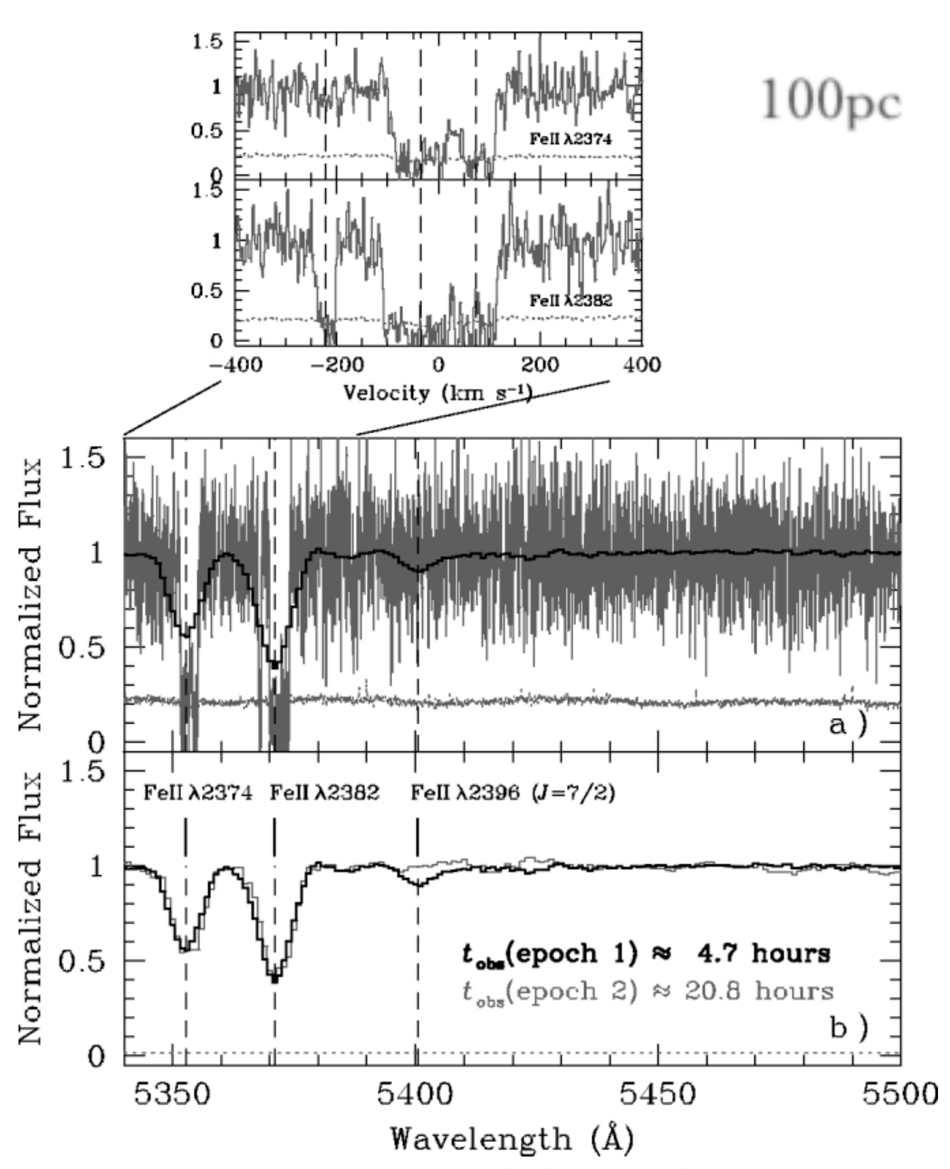
UV Pumping Dominates

- UV dominates over collisions and IR pumping
  - The gas is not high density CSM
  - The gas must arise within ~1kpc of the GRB



Implications of UV Pumping

- Rules out previously claimed CSM features
  - Highly ionized? Chen et al. (2007)
  - Absent altogether?
- Line variability
  - Lines should appear
    - Timescale of <few min
  - Lines should decay
    - $t(Fe^{+}) \sim 1$ hr
- Distance constraint
  - d = 100pc to 2 kpc



Dessauges-Zavadsky et al. (2006)

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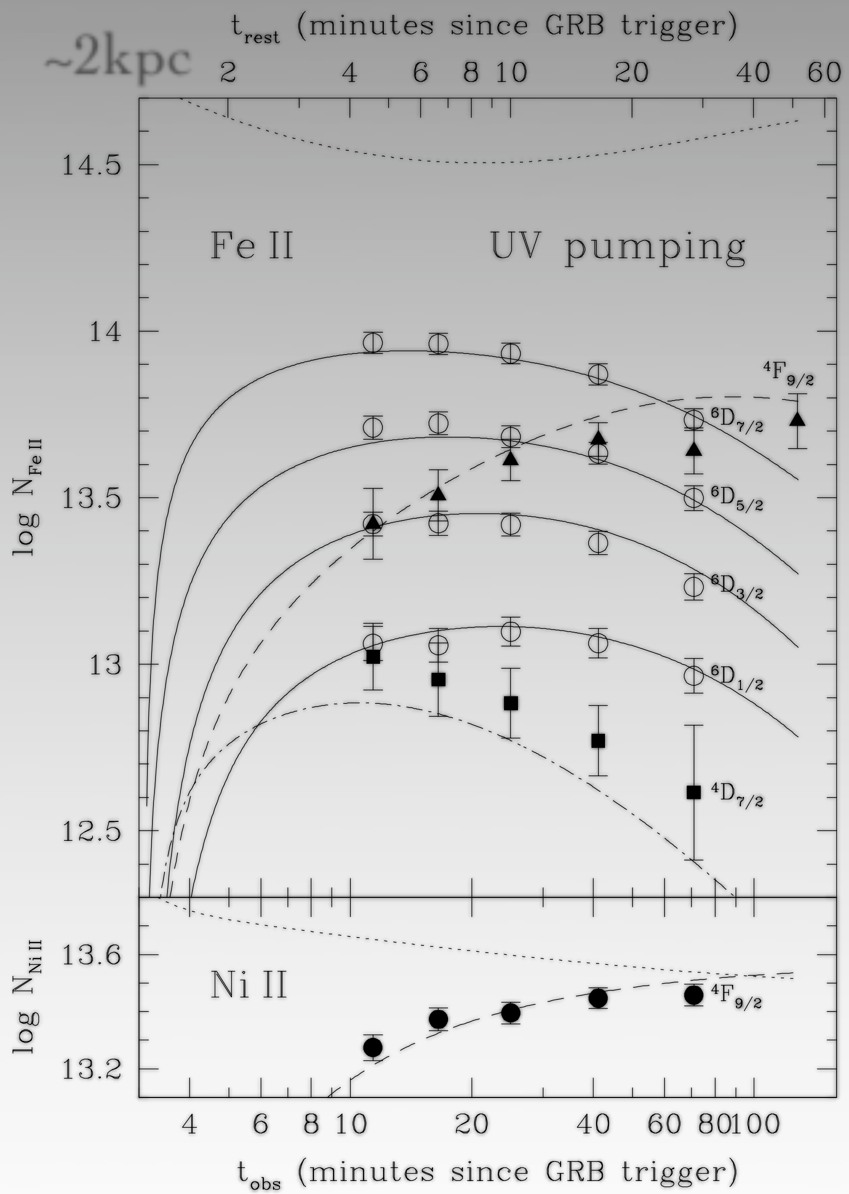

Vreeswijk et al. (2007)

Poor man's animation

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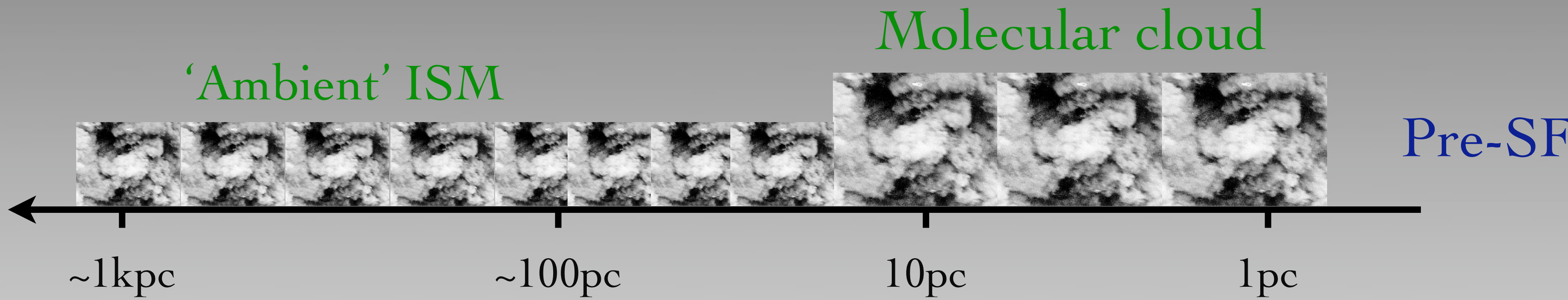

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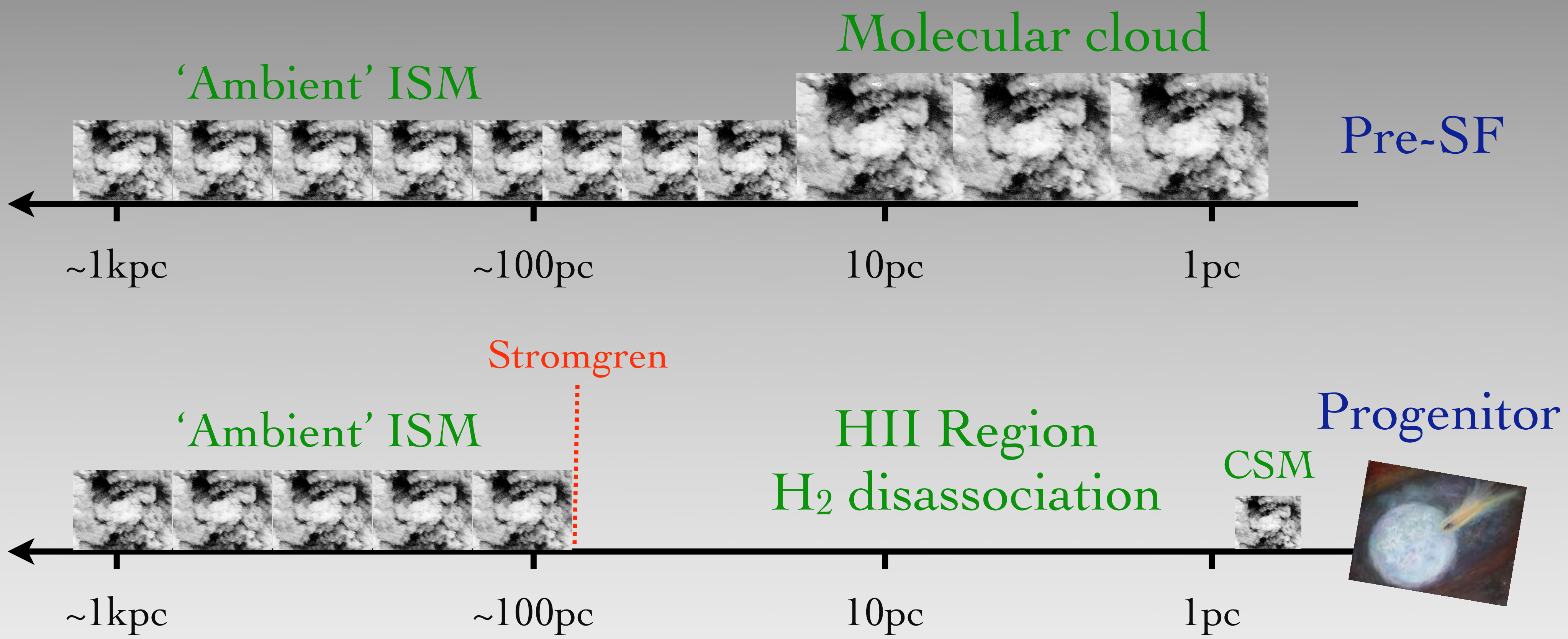

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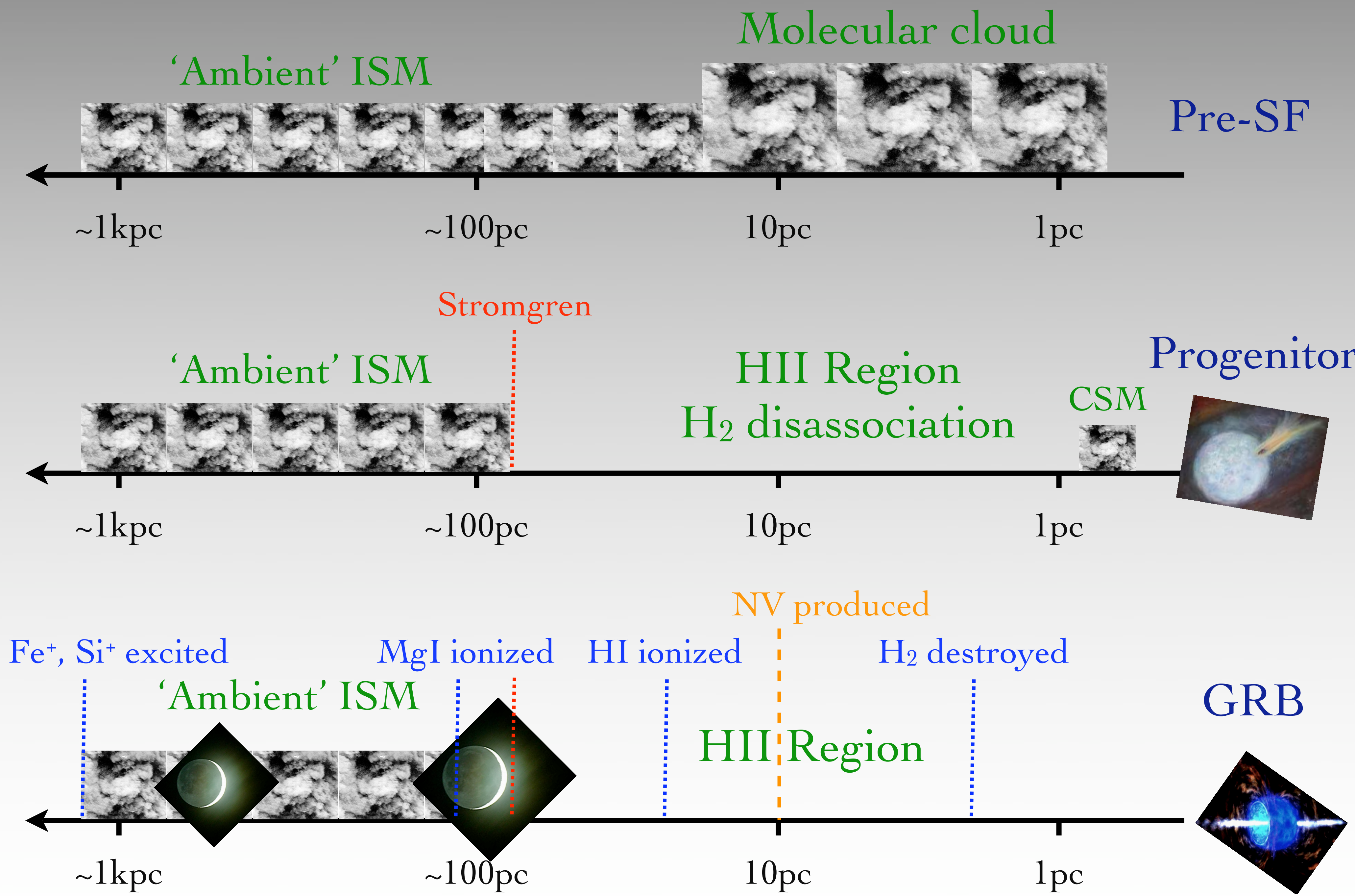
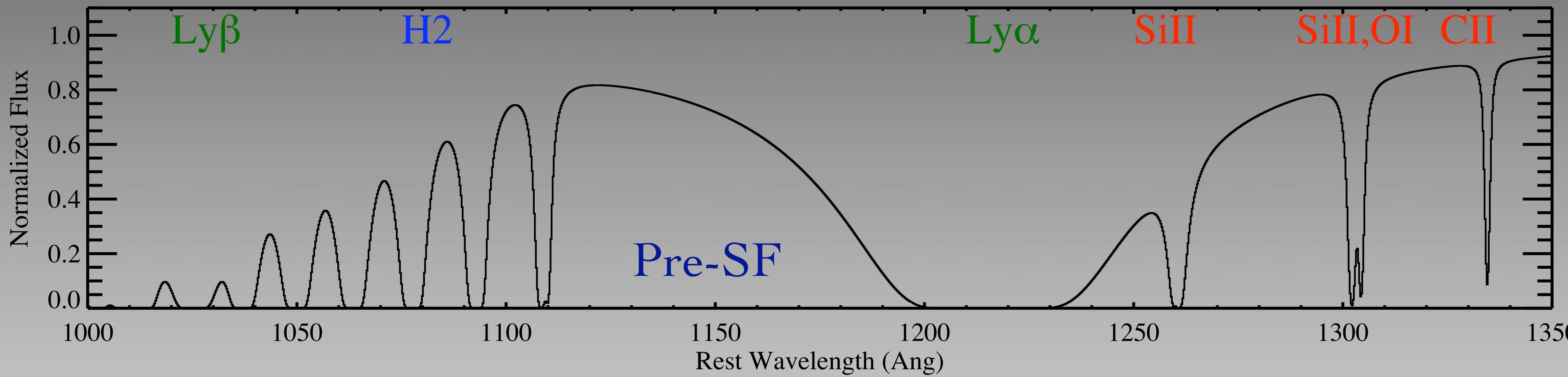
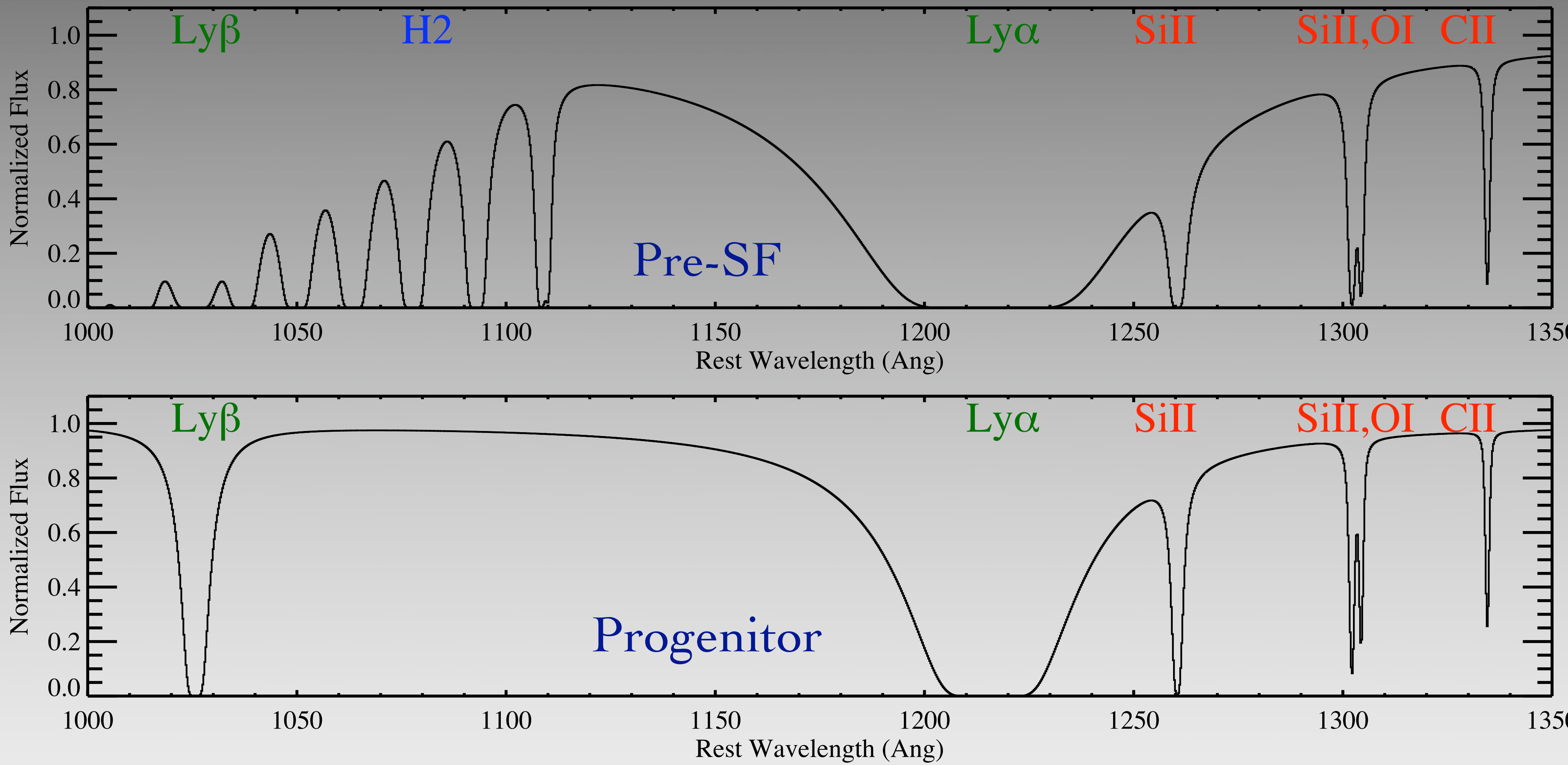




Lyβ
H2
Lyα
SiII
SiII,OI
CII
Pre-SF
Normalized Flux
Rest Wavelength (Ang)
0.0
0.2
0.4
0.6
0.8
1.0
1000
1050
1100
1150
1200
1250
1300
1350



Lyβ
H2
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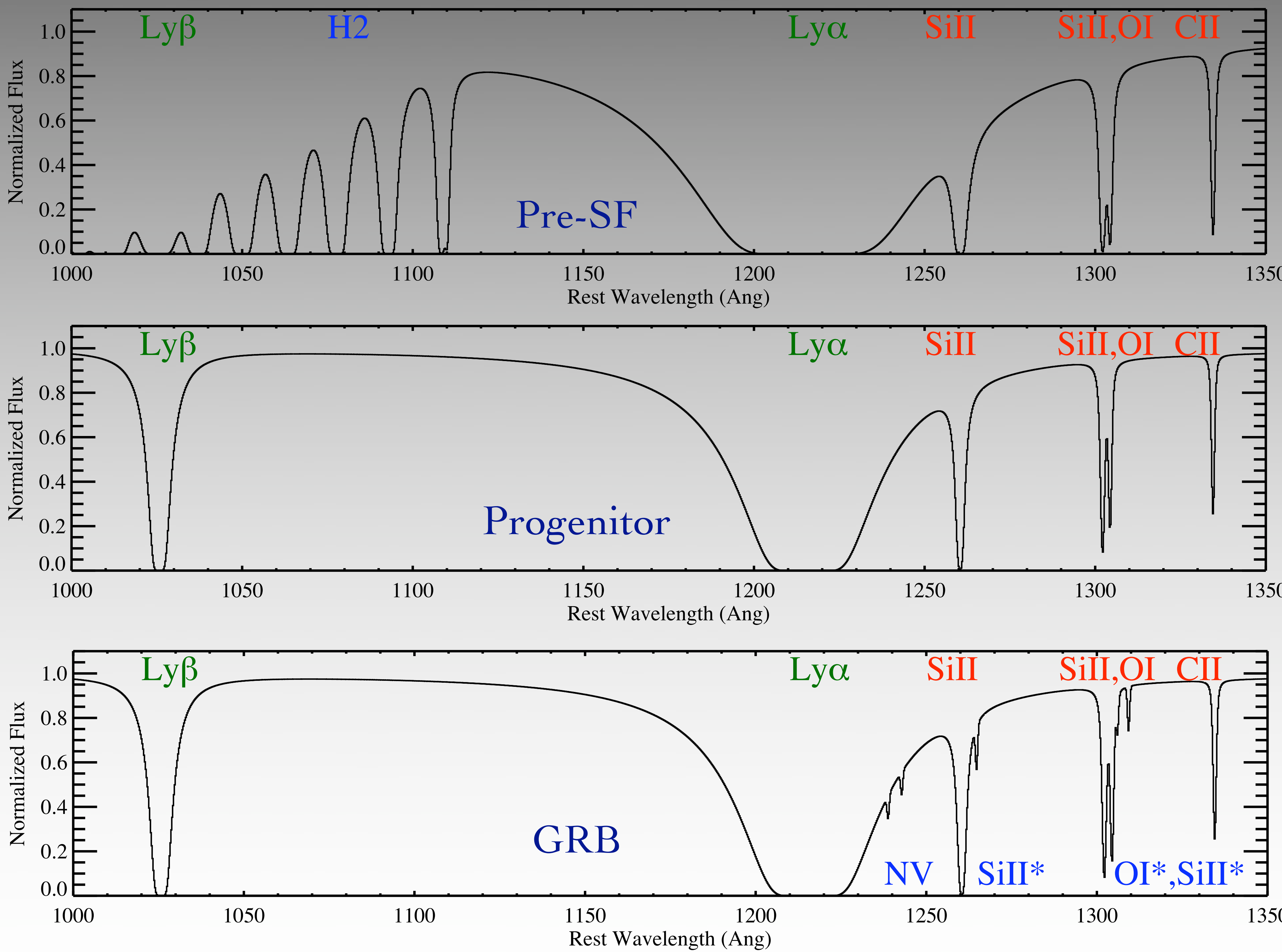
CII
Pre-SF
Normalized Flux
Rest Wavelength (Ang)
Lyβ
Lyα
SiII
SiII,OI
CII
Progenitor
Normalized Flux
Rest Wavelength (Ang)



Lyβ
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Normalized Flux
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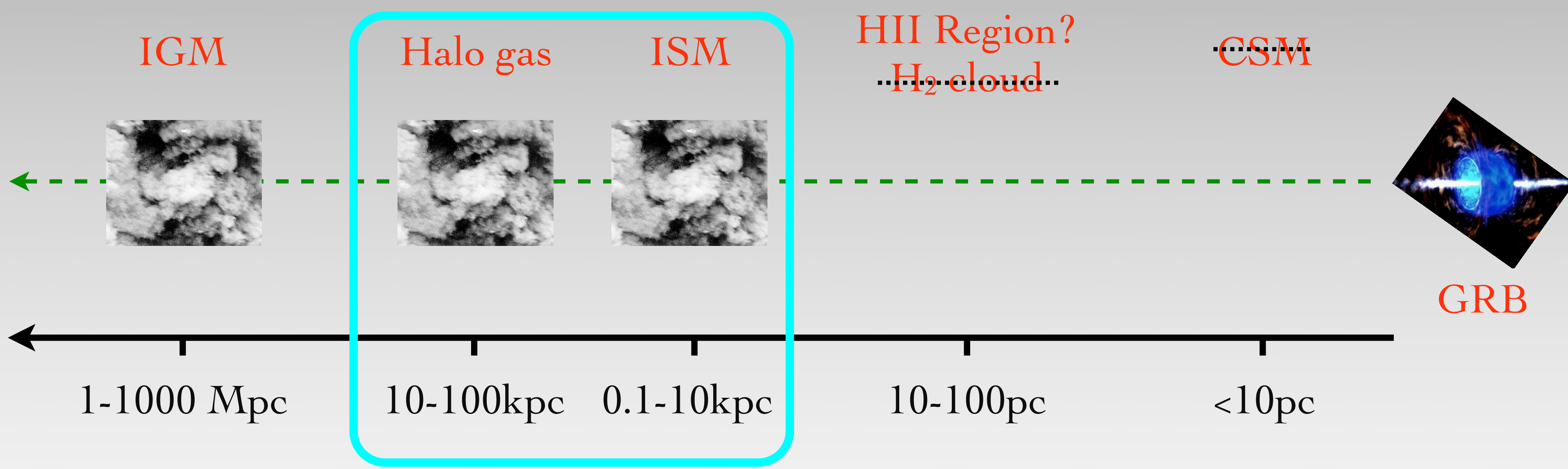
Progenitor
Normalized Flux
Rest Wavelength (Ang)
Lyβ
Lyα
SiII
SiII,OI
CII
GRB
NV
SiII*
OI*,SiII*
Normalized Flux
Rest Wavelength (Ang)

The Experiment

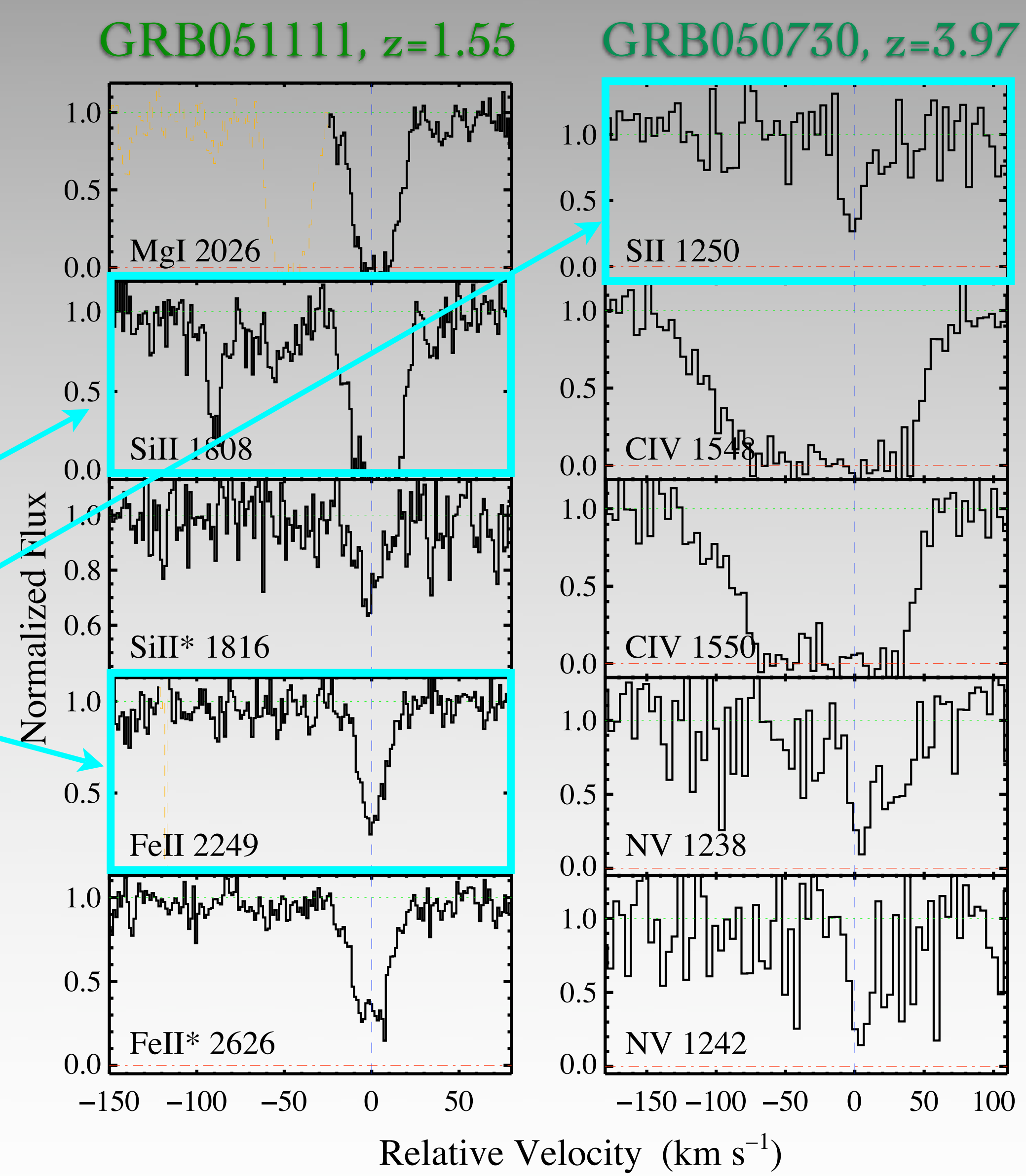
Acquire spectra of GRB afterglows to study gas in the galaxy hosting the GRB (its interstellar medium, ISM) and gas between Earth and the GRB (the intergalactic medium, IGM)



Keep in Mind: One measures directly the velocity of the gas, not its distance. Therefore, all of these regions are potentially mixed together in our spectrum

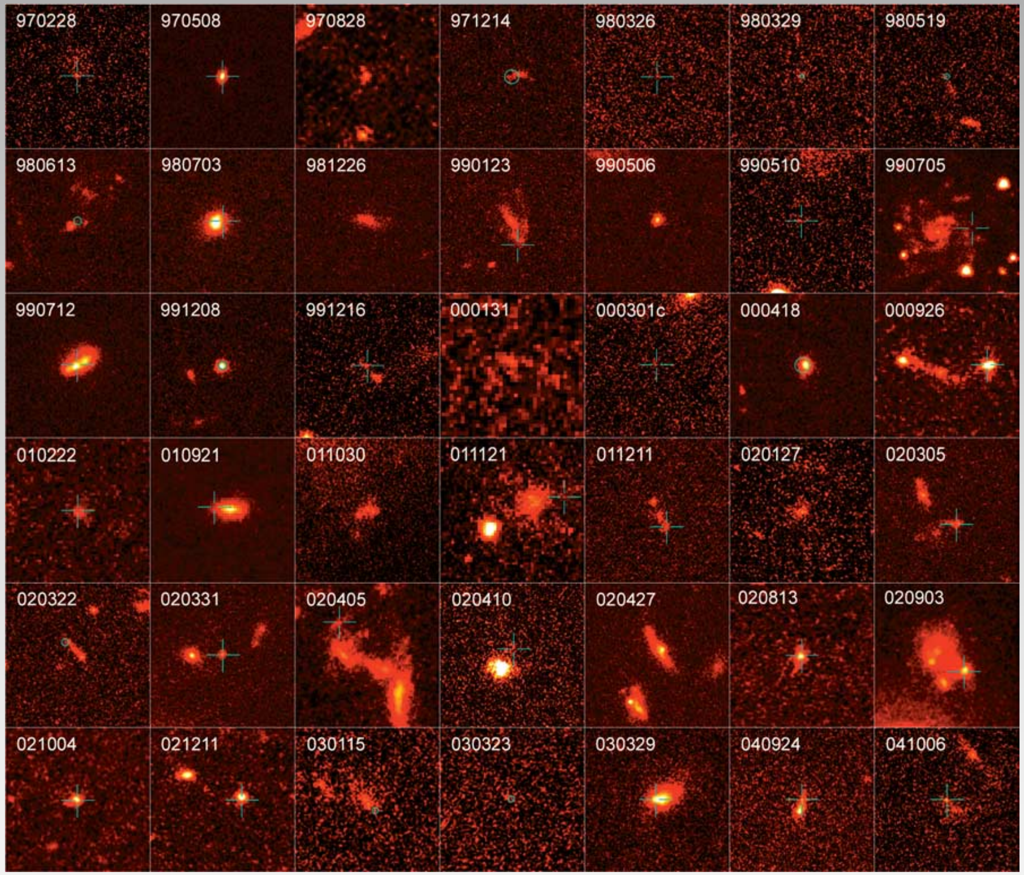
Metal-line Transitions

- Very strong lines
  - Follows from large N_{HI}
  - Echelle data preferred
- Distance diagnostics
  - MgI: Atomic Mg
  - FeII*: Fine-structure lines
- Metal abundances
  - Unsaturated resonance
  - Low-ion transitions
  - Dust depletion, too
- HII Regions, CSM?
  - High-ion states
  - Could be halo/ISM gas



Abundances of Gas Near GRB

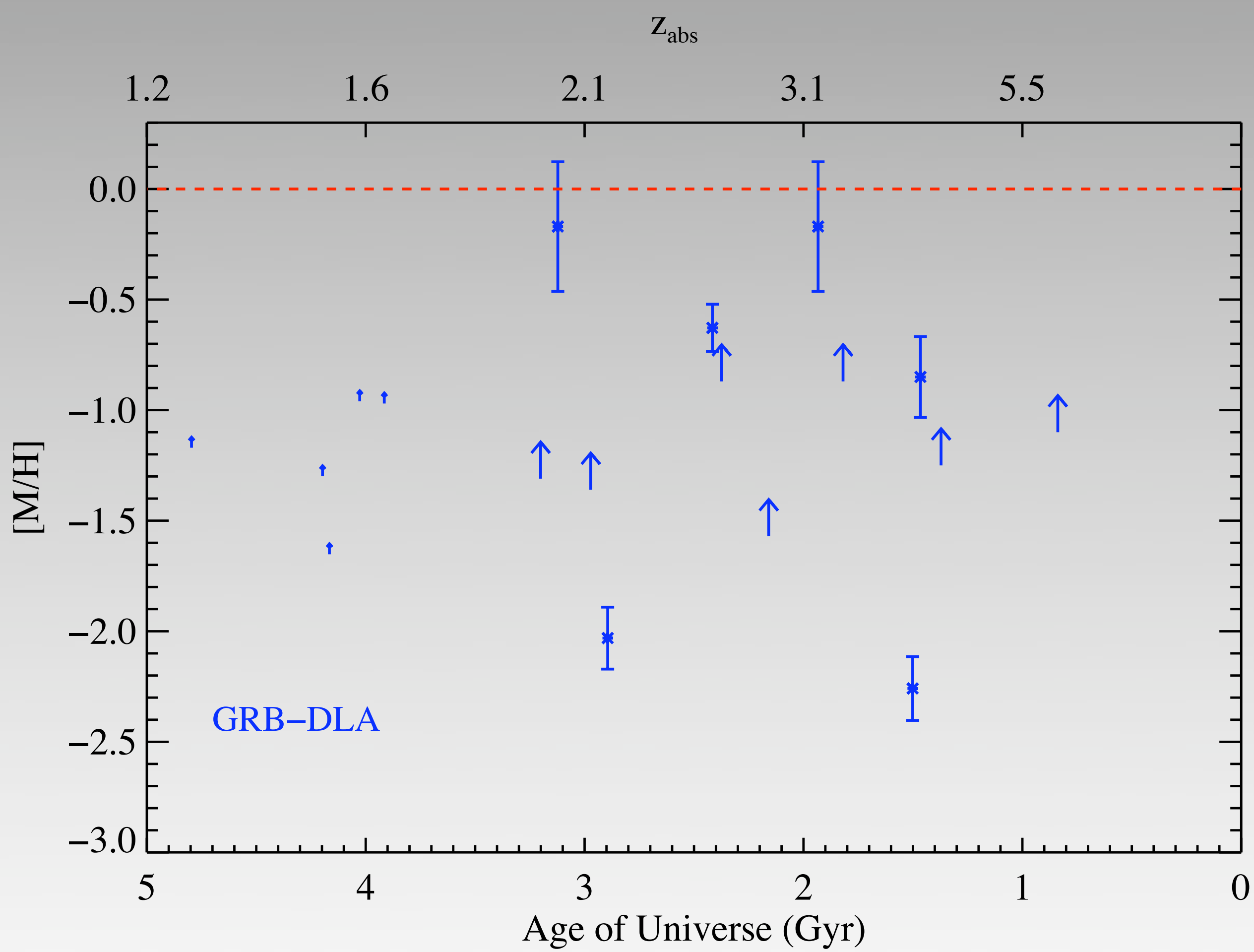
- GRB progenitor (theory)
  - Prefer low metallicity
    - Need to maintain a high angular momentum
    - Therefore, suppress the wind
  - e.g. Woosley & Heger 2006
- GRB hosts (observed)
  - Low luminosity
    - And, blue color
  - Expect low metallicity
    - (Mass-metallicity relation)
  - Observe sub-solar metallicity at z < 0.5
    - Special population?



Fruchter et al. (2006)

GRB ISM Abundances

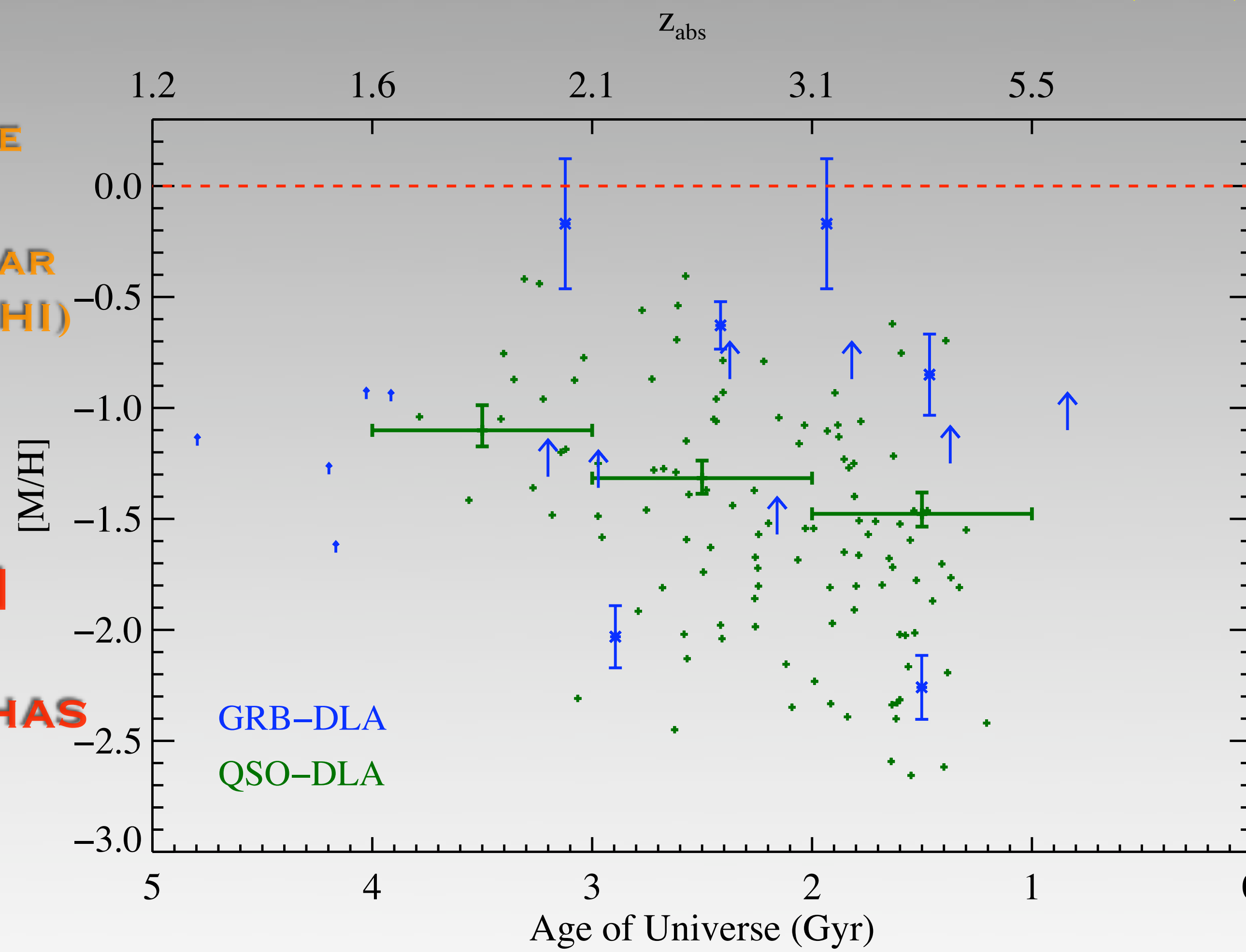
- Typical GRB
  - Large N_{HI}
    - Accurate measure
  - Large EW metal-lines
    - Desire high-res spectra
    - Often limited to lower limit values
- Keep in mind
  - The gas is not immediately local to the progenitor
    - ISM surrounding the SF region
  - Gas-phase
    - Far more accurate than nebular line measures



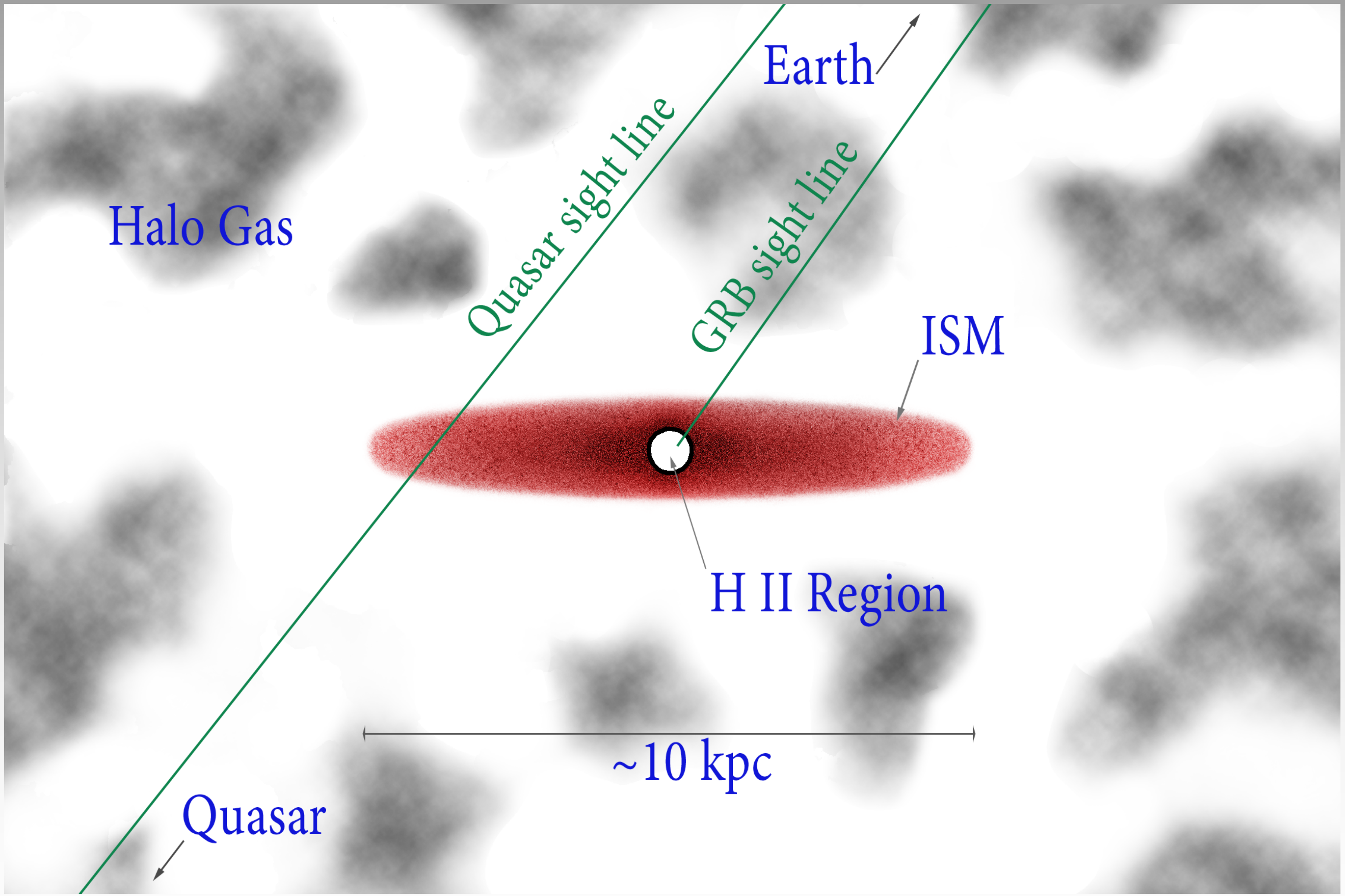
GRB vs QSO-DLA

- **Summary**
  - Large range of metallicity
    - 1/100 to solar abundance
  - Average GRB value
    - <[M/H]> exceeds 1/10 solar
    - Exceeds the cosmic ISM (HI) value of <M/H>
- **Implications**
  - Little evidence that GRB prefer low [M/H]
    - At high z
  - Gas near SF regions has enhanced metallicity
    - metallicity gradient is very likely at high z

Prochaska et al. (2007)



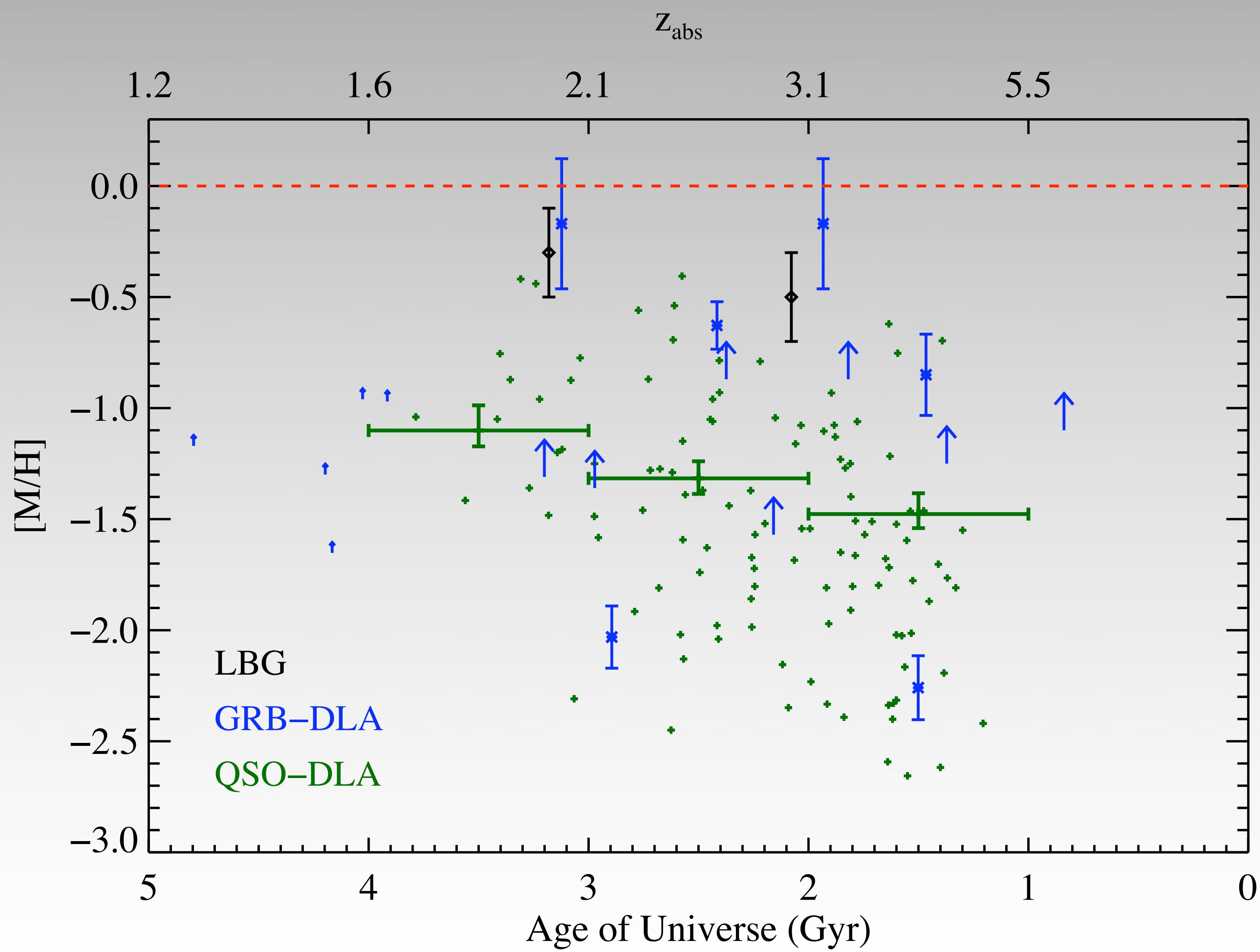
Cartoon



Prochaska et al. (2007)

But aren't the GRB values a bit low?

- LBG vs GRB
  - Most GRB have metallicities below bright LBG
    - Are they representative of SF galaxies at high z?



Are GRBs Unbiased Tracers of SFR?

- Metallicity distribution
  - ✦ Indirect
    - But worth a test for consistency
- UV Luminosity function

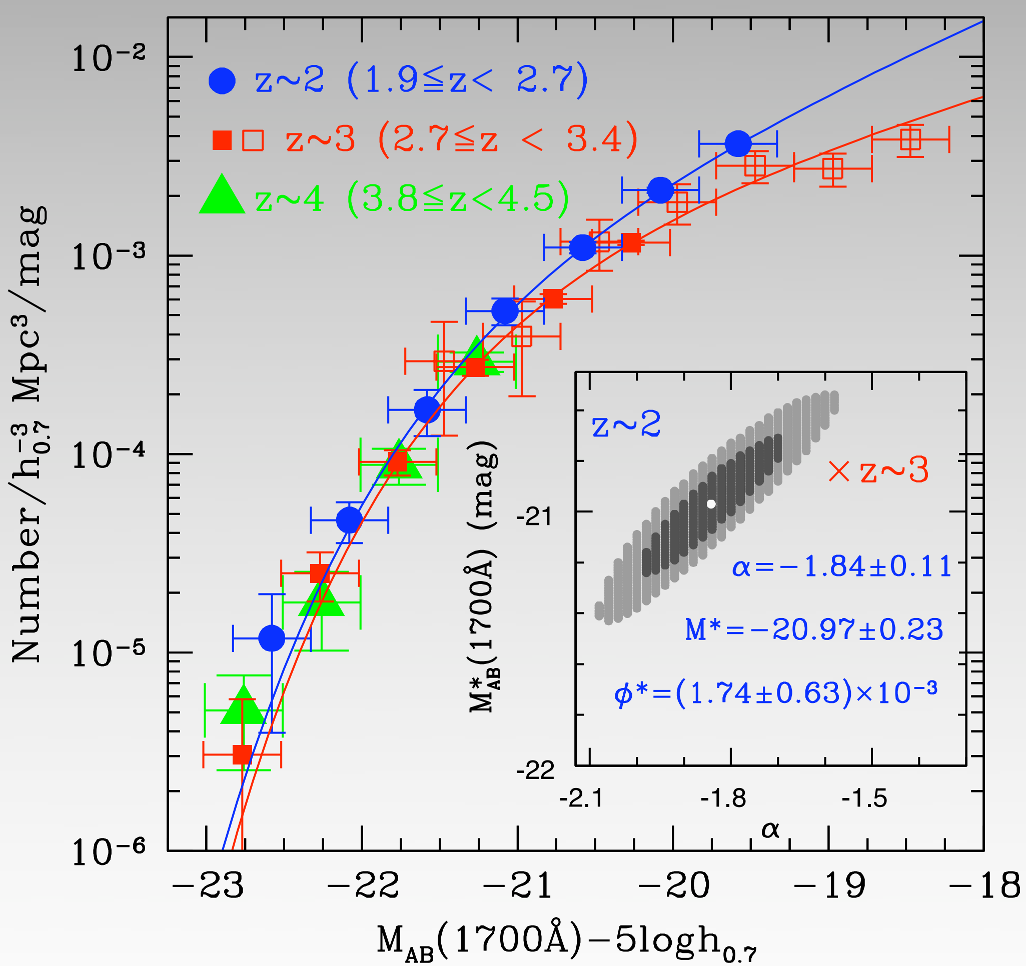
$$\phi(L_{UV}) \propto (L_{UV}/L_*)^{-1.6} \exp(-L_{UV}/L_*)$$

  - ✦ Assume SFR ~ L_{UV}
- Z/Luminosity Relation
  - ✦ Follow empirical relations

$$Z = Z_*(L/L_*)^{0.5}$$

  - ✦ Normalize by LBG values
    - $Z(L^*) = Z^* = 1/2$ solar
- Result
  - ✦ Excellent agreement
    - Small sample
  - ✦ Key: Bright LBGs are the tip of the iceberg

Reddy et al. (2007)



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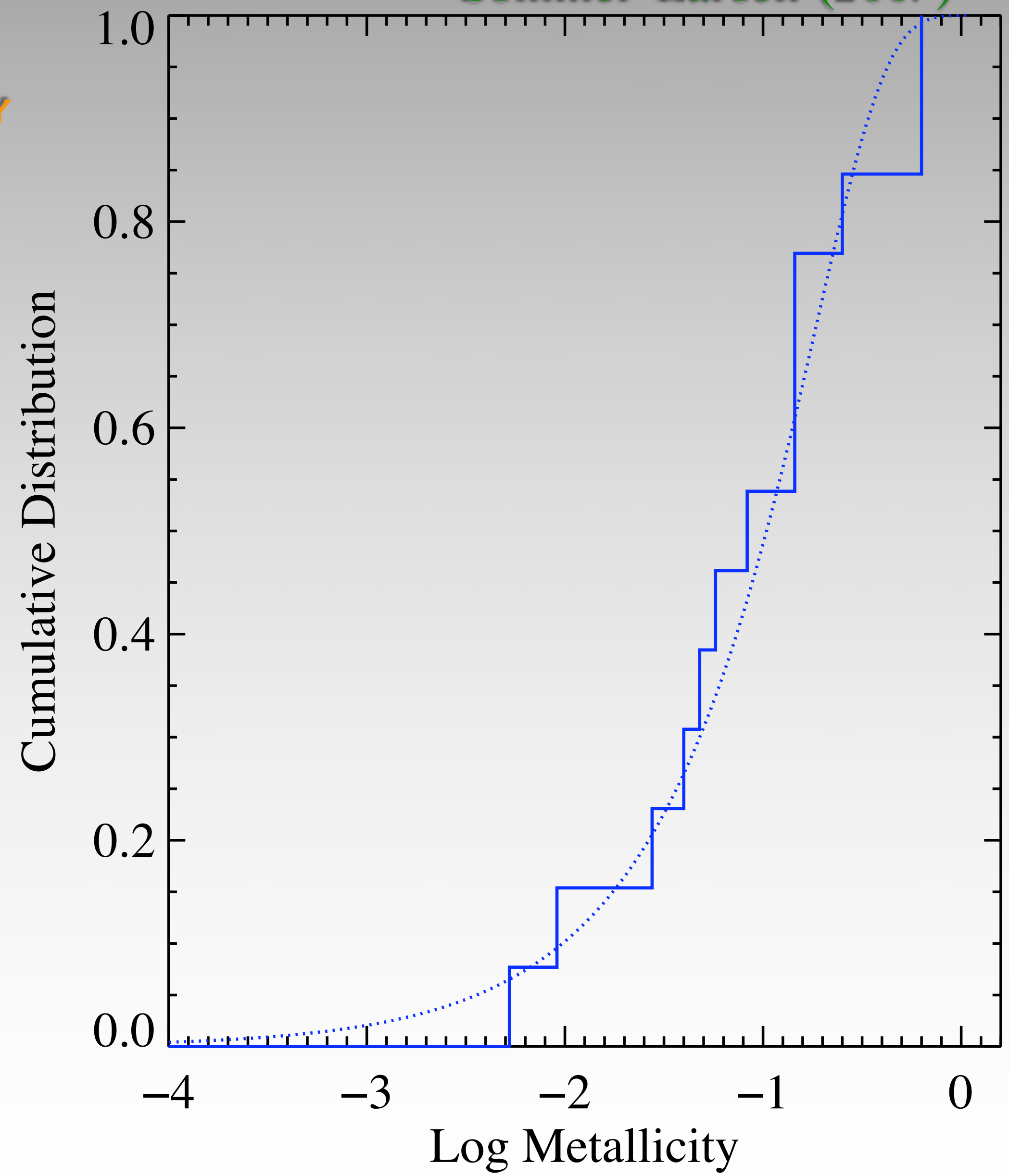
Fynbo, Prochaska, & Sommer-Larsen (2007)



Bright Galaxies are the Tip of the SF Iceberg

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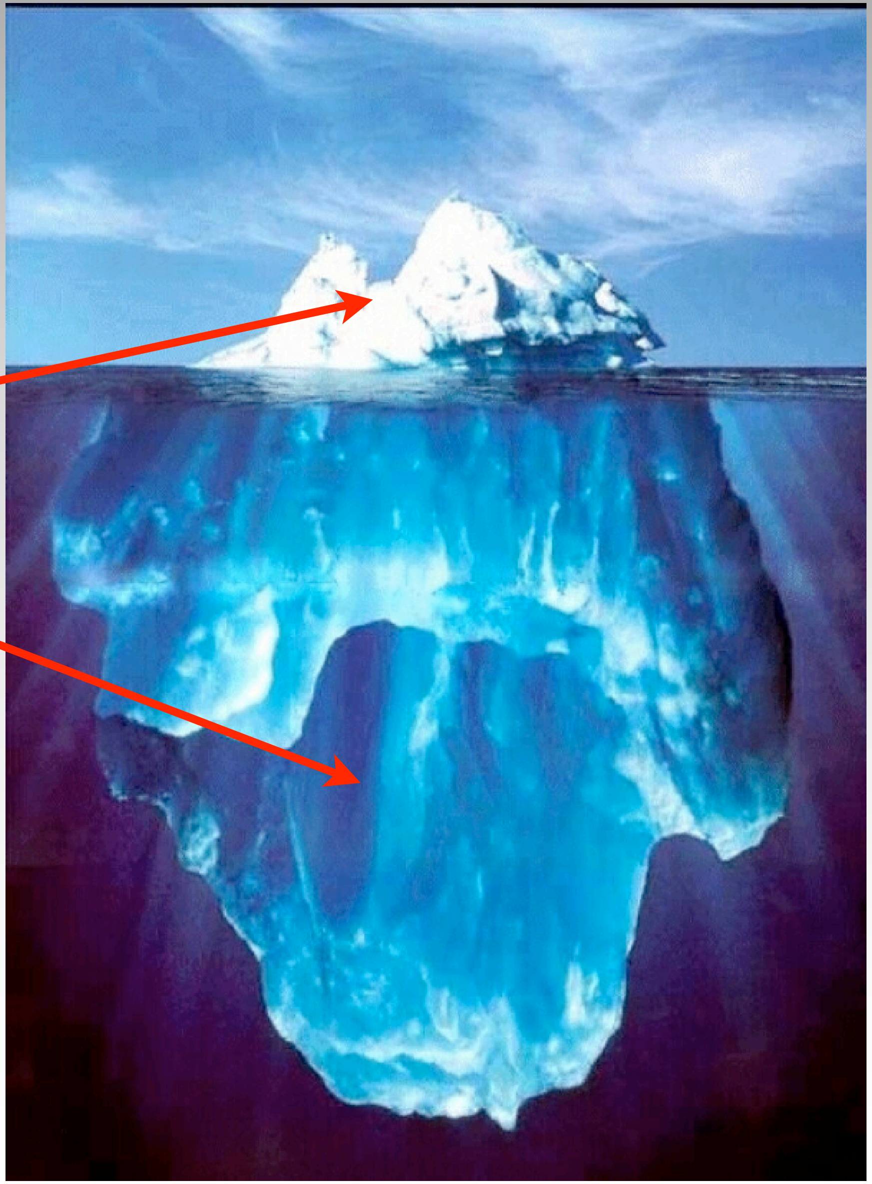
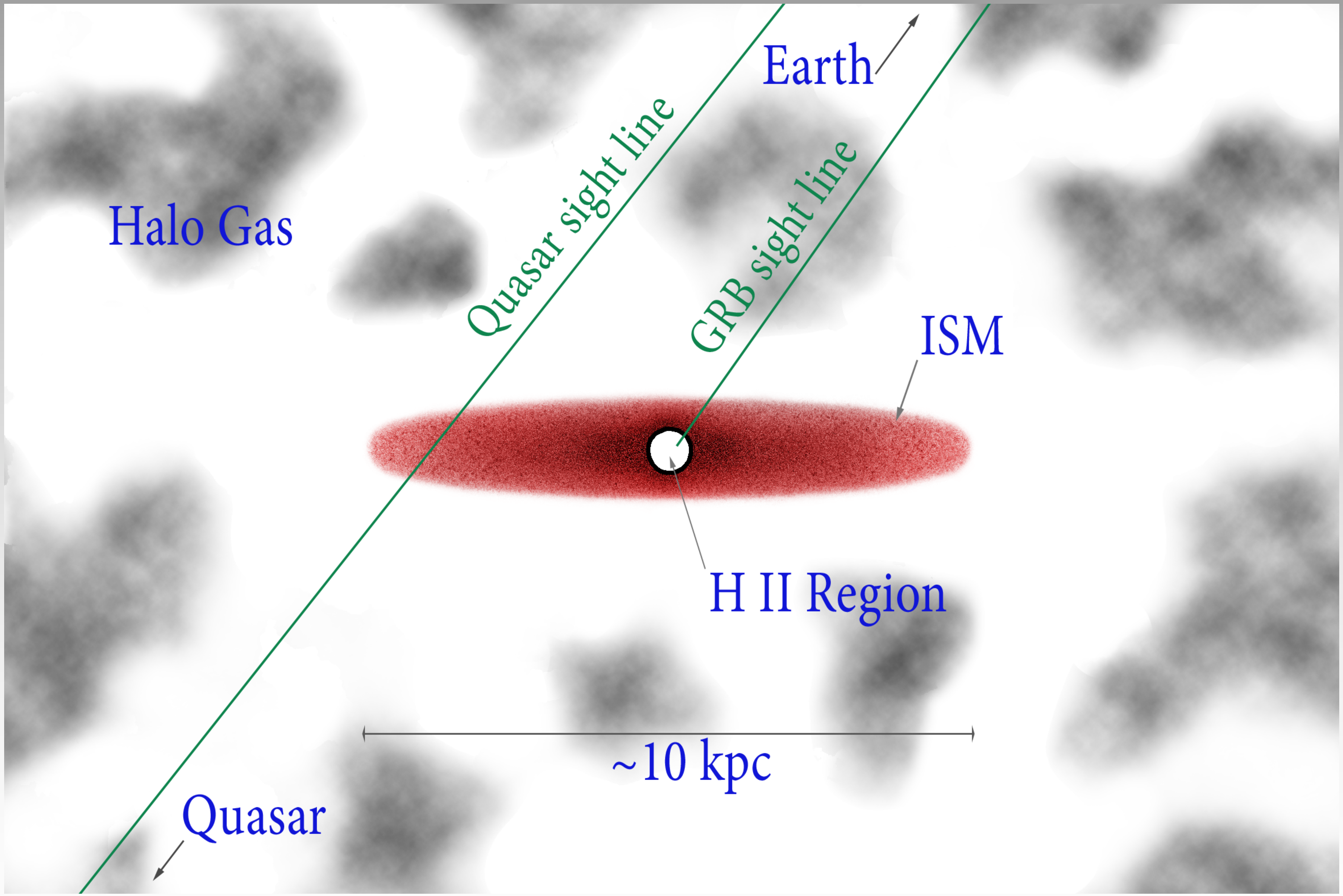


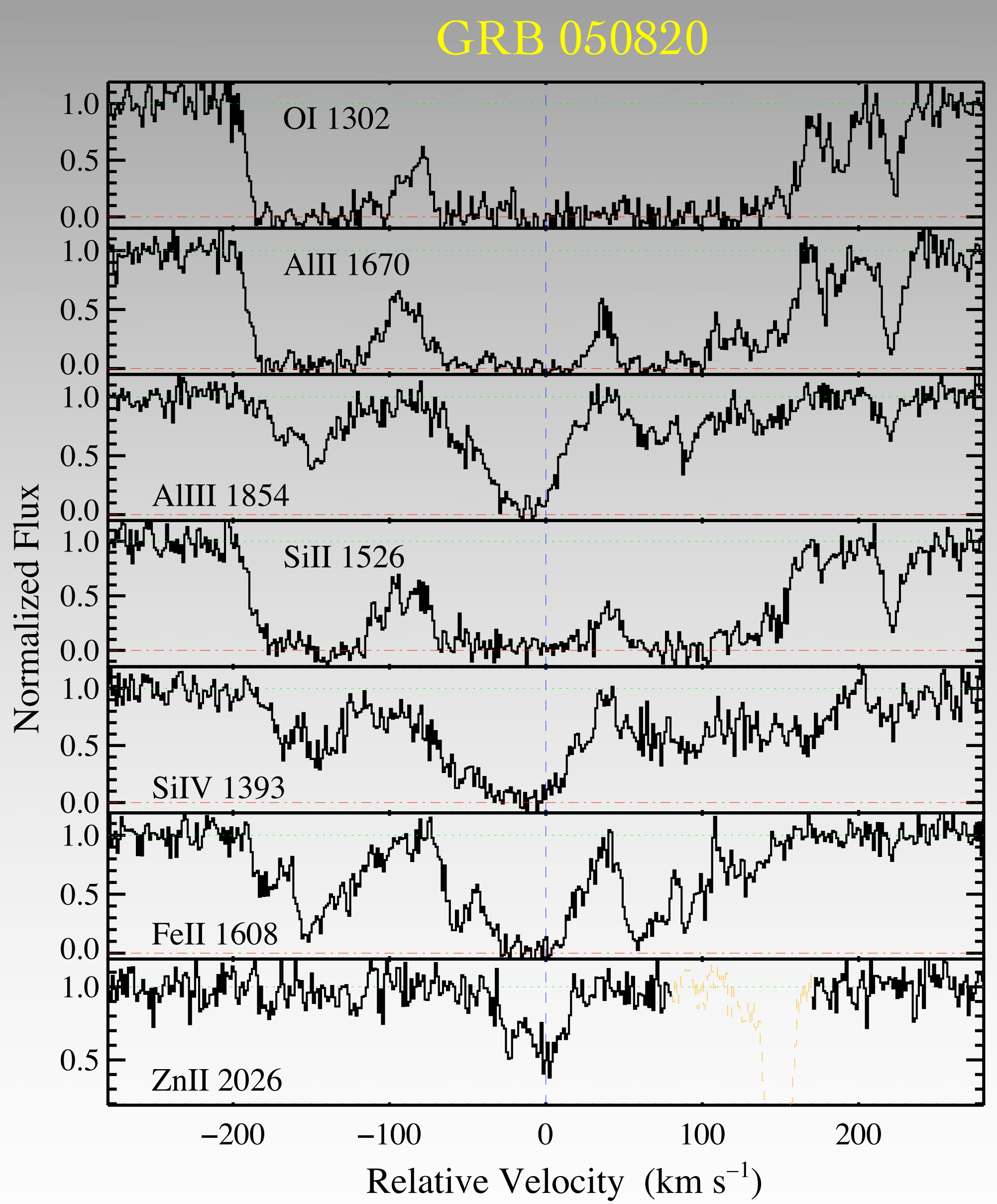
Velocity Fields of High z Galaxies



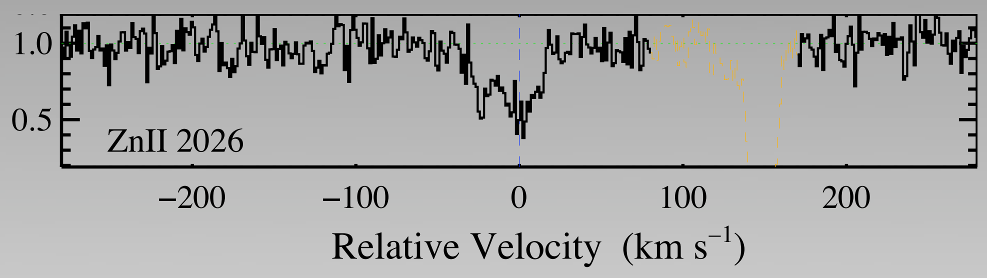
Prochaska et al. (2007)

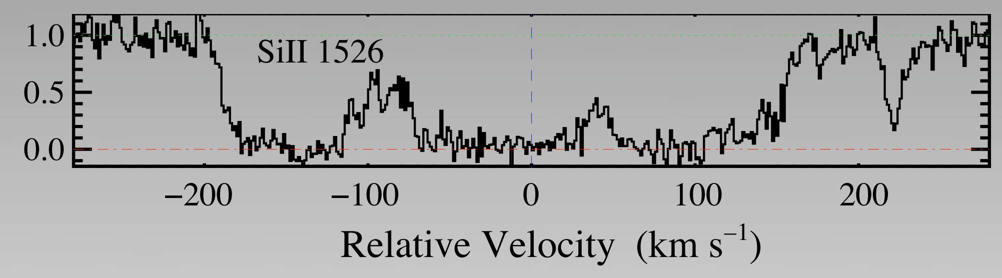
Kinematics: Data

- Gas Velocity field
  - High-resolution data
    - Resolve features at <10 km/s
- Majority of gas?
  - Weak transitions
  - e.g. ZnII 2026
- Majority of velocity field?
  - Strong transitions
  - e.g. SiII 1526
- Neutral or Ionized gas?
  - Low-ion vs. high-ion
  - e.g. ZnII vs CIV



Kinematics: Statistics





- Velocity width Δv_{90}
  - Physical quantity
    - Interval encompassing 90% of the optical depth
    - Velocity field of the majority of gas
- Expectation
  - Velocity field of the ISM
  - Rotation, mild turbulent motions
    - Dynamical Mass

- Equivalent width W_{1526}
  - Observational quantity
    - Width of absorption feature
    - Akin to MgII lines
  - Physical significance
    - Strong (optically thick) lines
    - Velocity field of weak 'clouds'
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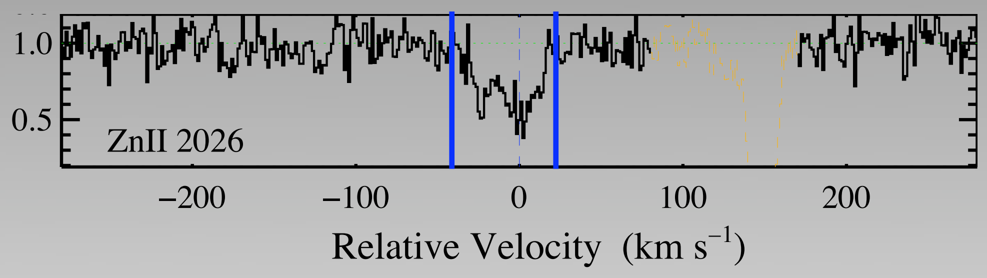

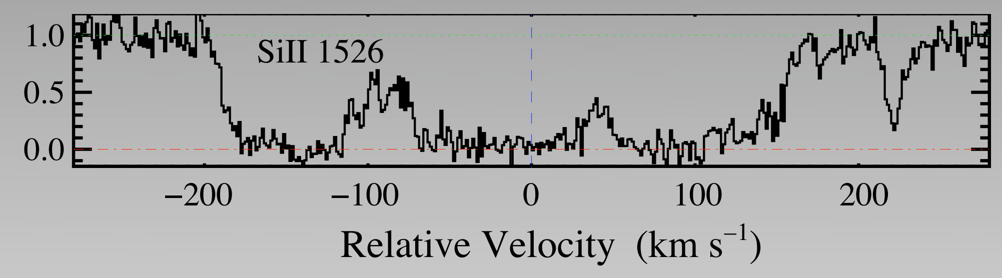

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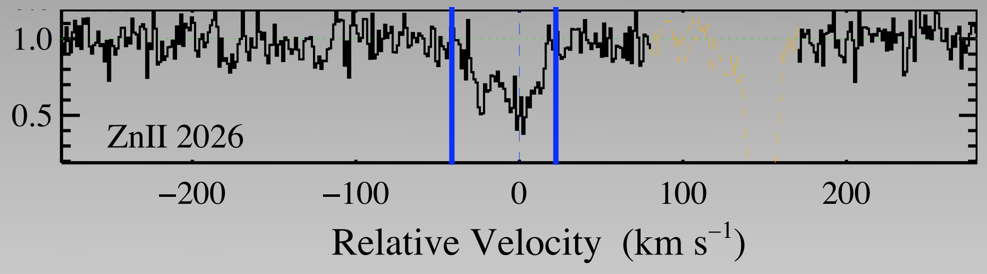

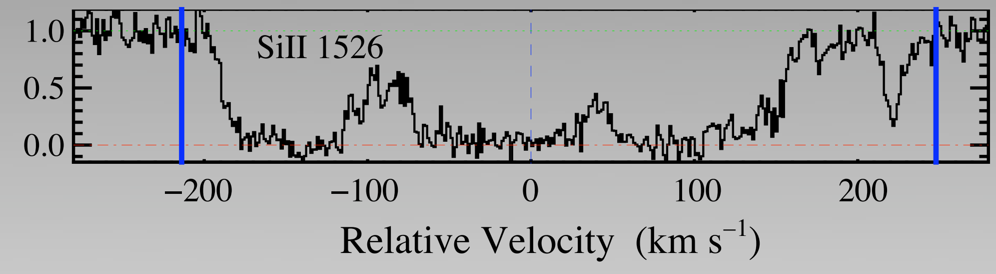

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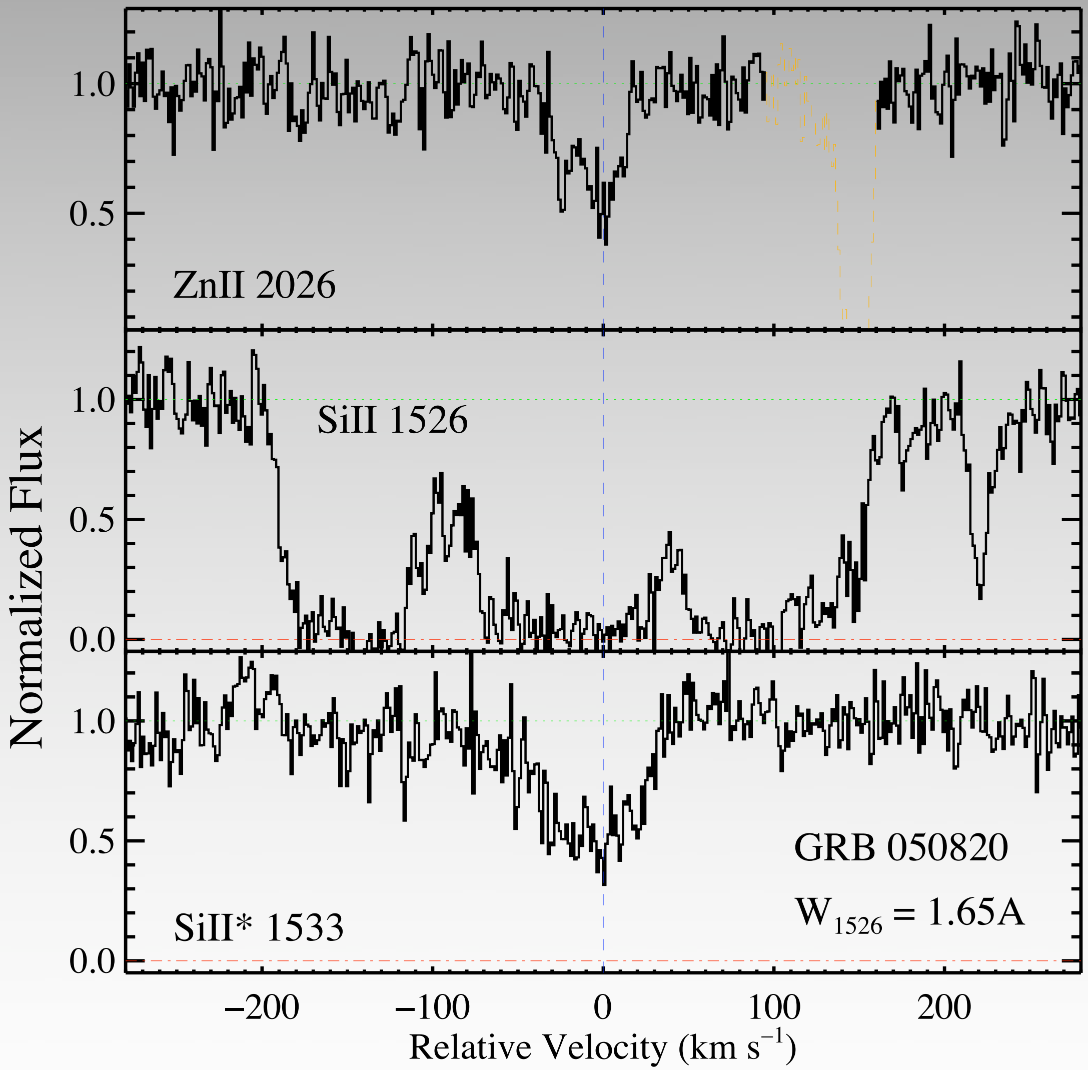
Origin and Nature of the Velocity Fields

- Δv_{90}
  - Traces fine-structure lines
    - Located within 1kpc of the GRB
    - 'Ambient' ISM of the galaxy
  - Rotation, turbulence
- W_{1526}
  - contributions from gas at Large distance (>1kpc)
    - Likely outside the ISM
    - Especially true for cases with large W_{1526} values
  - Halo gas or outflows?



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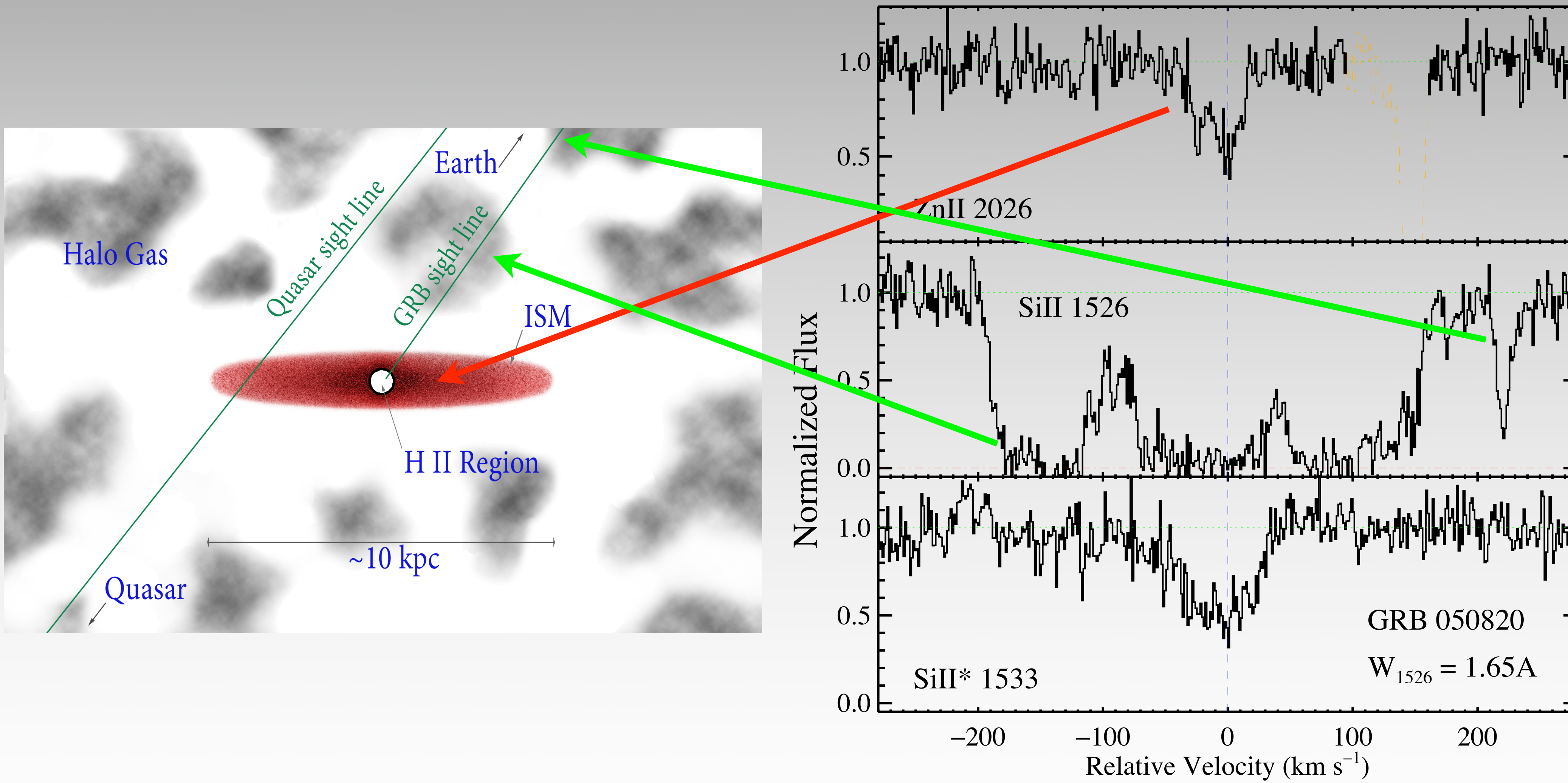
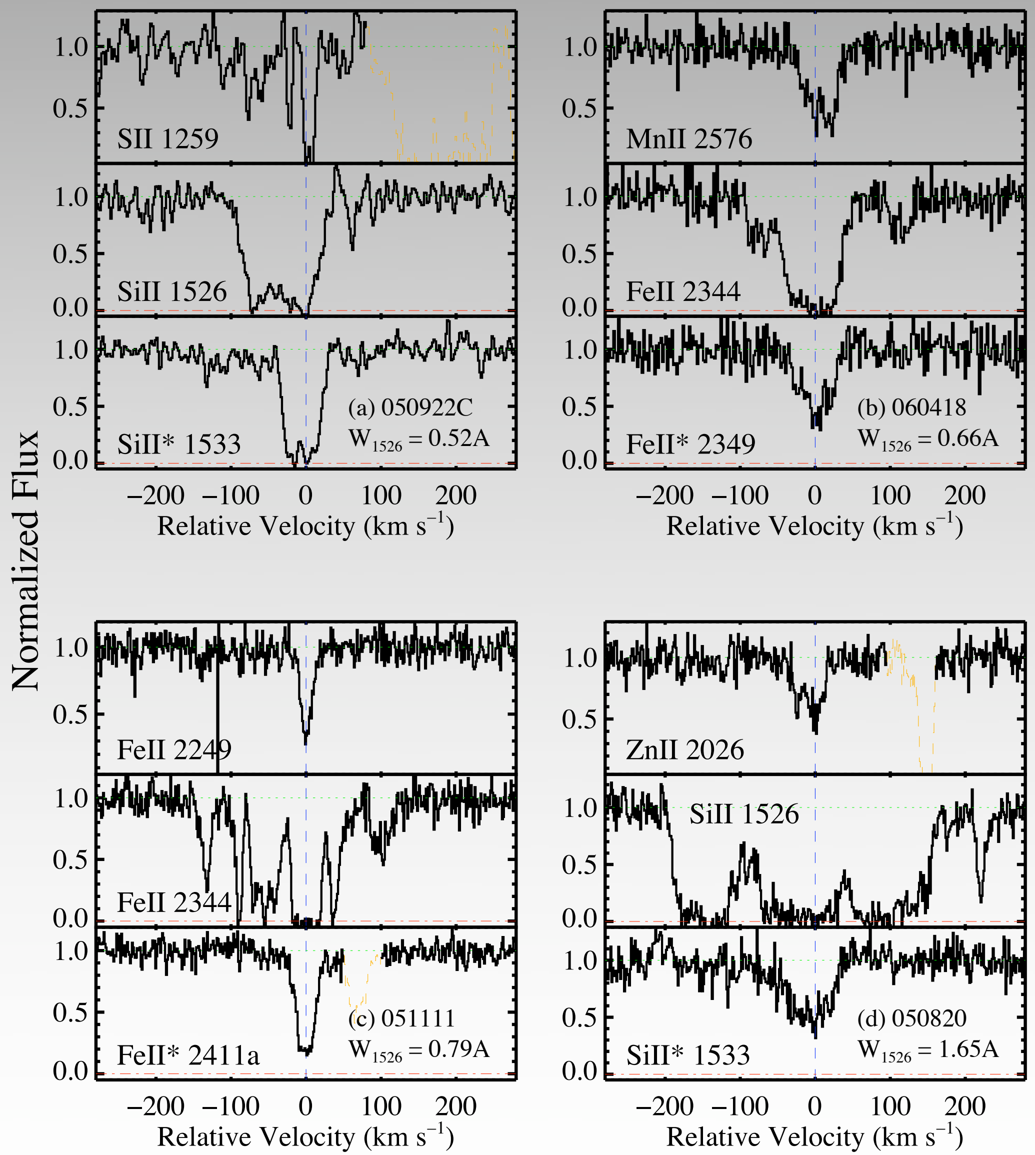


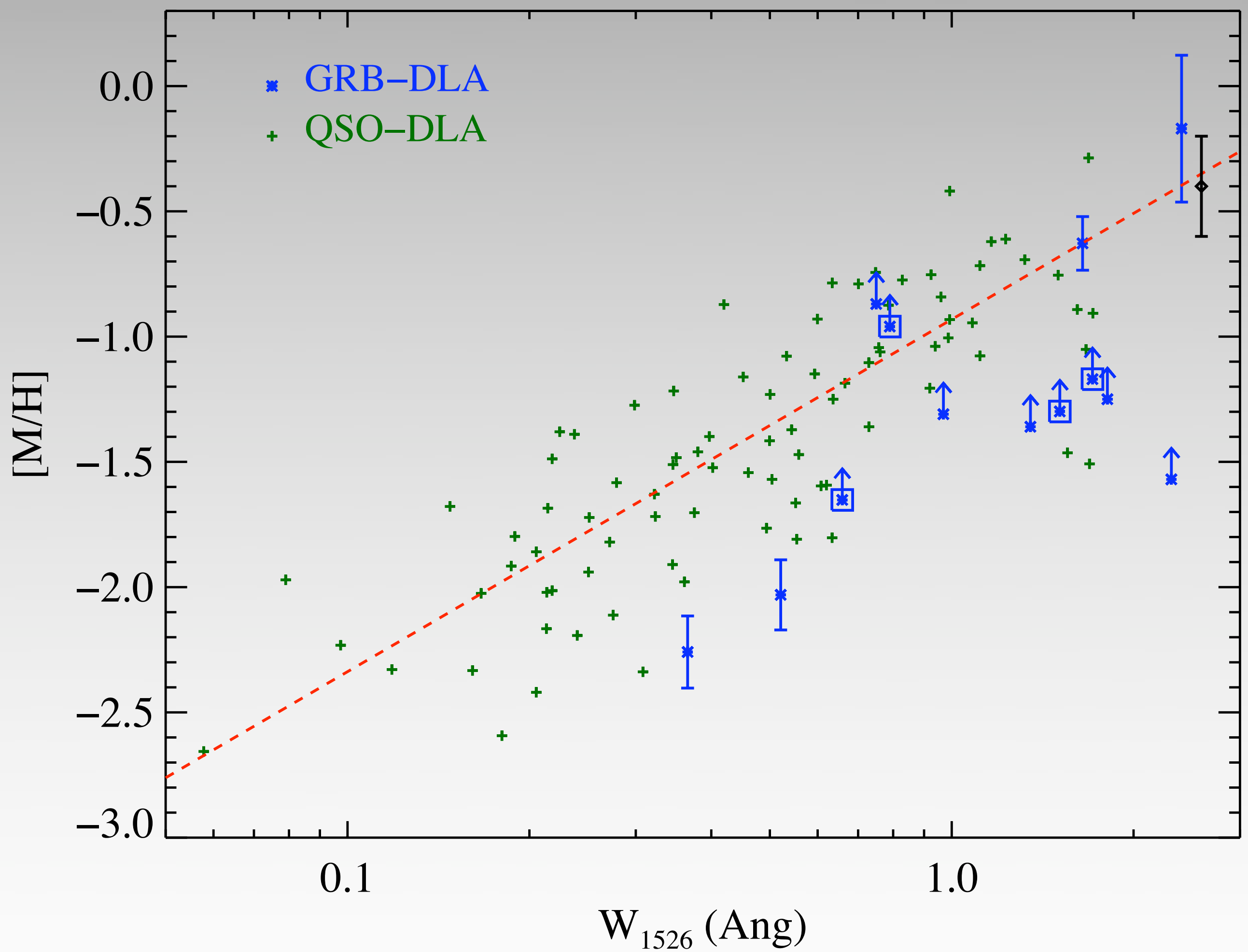
Origin and Nature of the Velocity Fields

- Nature of the field
  - Fine-structure lines
    - Set ISM systemic velocity
    - v=0 km/s
  - GRB sightline
    - breaks the QSO symmetry
    - Velocity relative to the ISM
      - Negative => Outflow
      - Positive => Inflow
- Current Observation
  - 051111: Outflow?
  - 050820,060418: In and out
    - Virialized motions?
    - Galactic fountain in action?



Mass-Metallicity Relation

- W_{1526} vs. [M/H]
  - Tight correlation!
    - see also Murphy et al.
  - Scatter
    - Mainly observational
    - Impact parameter
    - Clumpiness?
- Power-law fit
  - [M/H] ~ $W^{1.5}$
  - Same trend as dwarf galaxies locally
    - Dekel & Woo
    - $Z \sim v^{1.6}$
  - Mass-Metallicity
- GRB-DLA
  - Offset?
  - Similar physics



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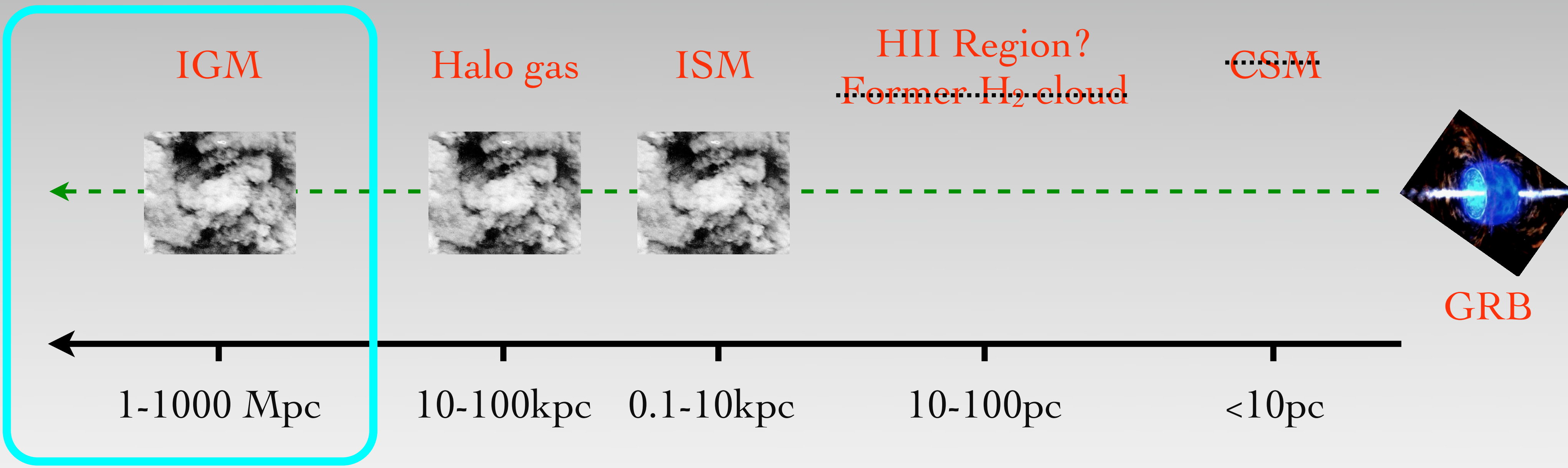
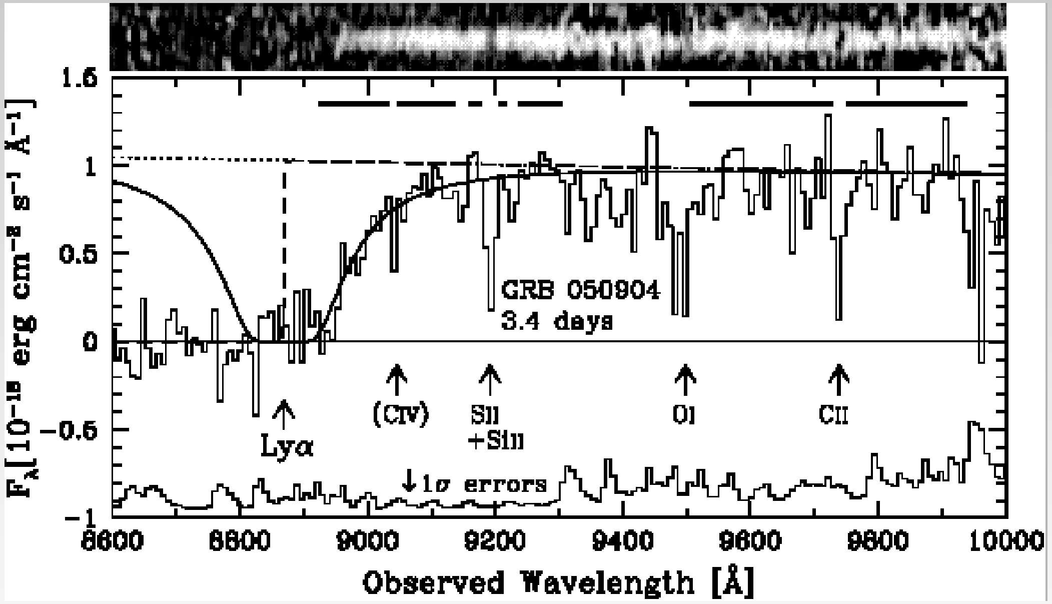


Keep in Mind: One measures directly the velocity of the gas, not its distance. Therefore, all of these regions are potentially mixed together in our spectrum

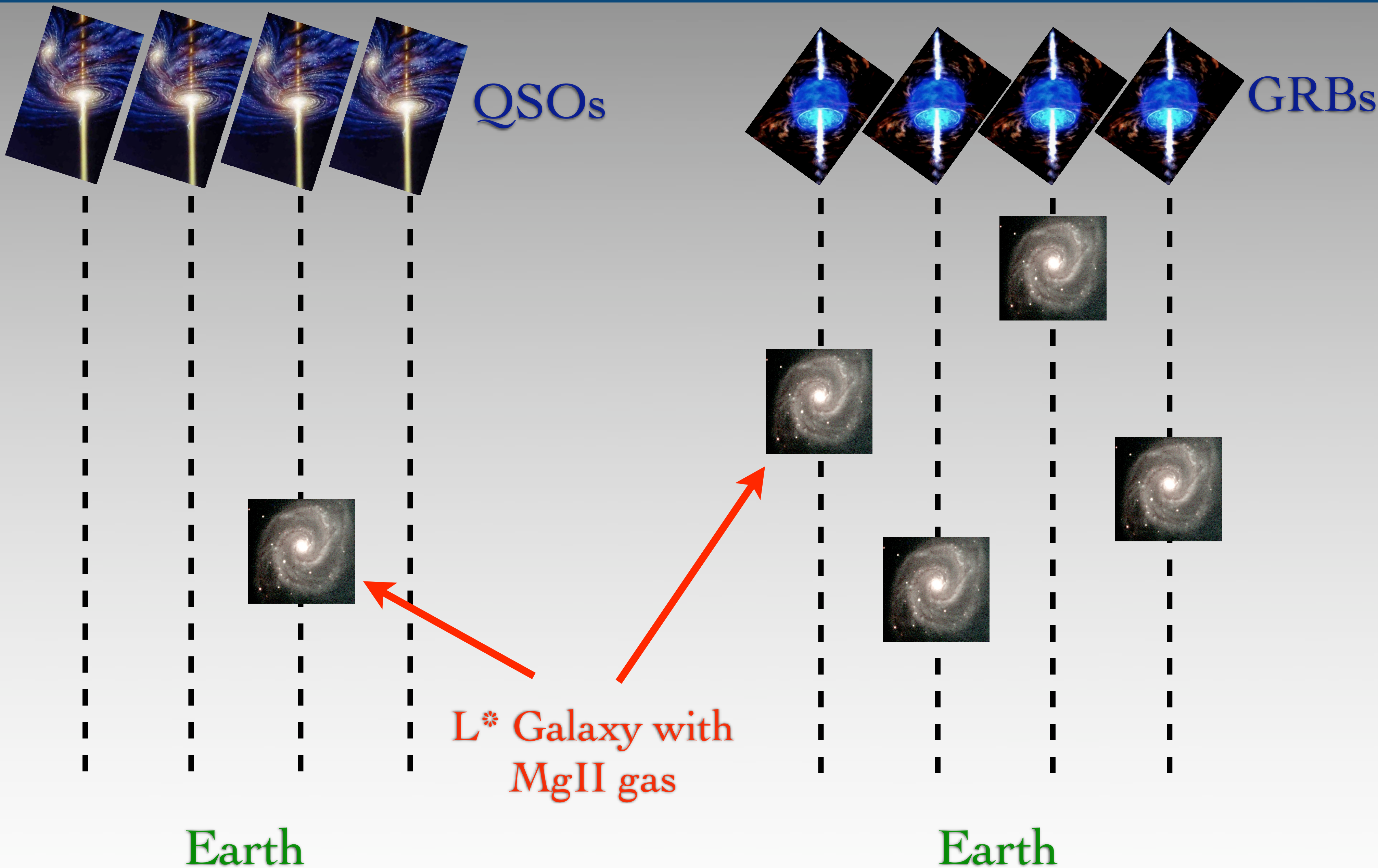
Probing Reionization with GRBs

- Some GRBs are brighter than QSOs at z>6
  - Simple scaling of z=5 GRBs
  - Decline of QSO lum function
- Lya signature
  - Voigt profile of GRB host
  - Convolved Voigt profile of a neutral universe
    - Challenging to disentangle
- Progress to date
  - One z>6 GRB verified
    - S/N too low to significantly constrain reionization
  - Going to need lots of patience and a bit of luck

Kawai et al. (2005)

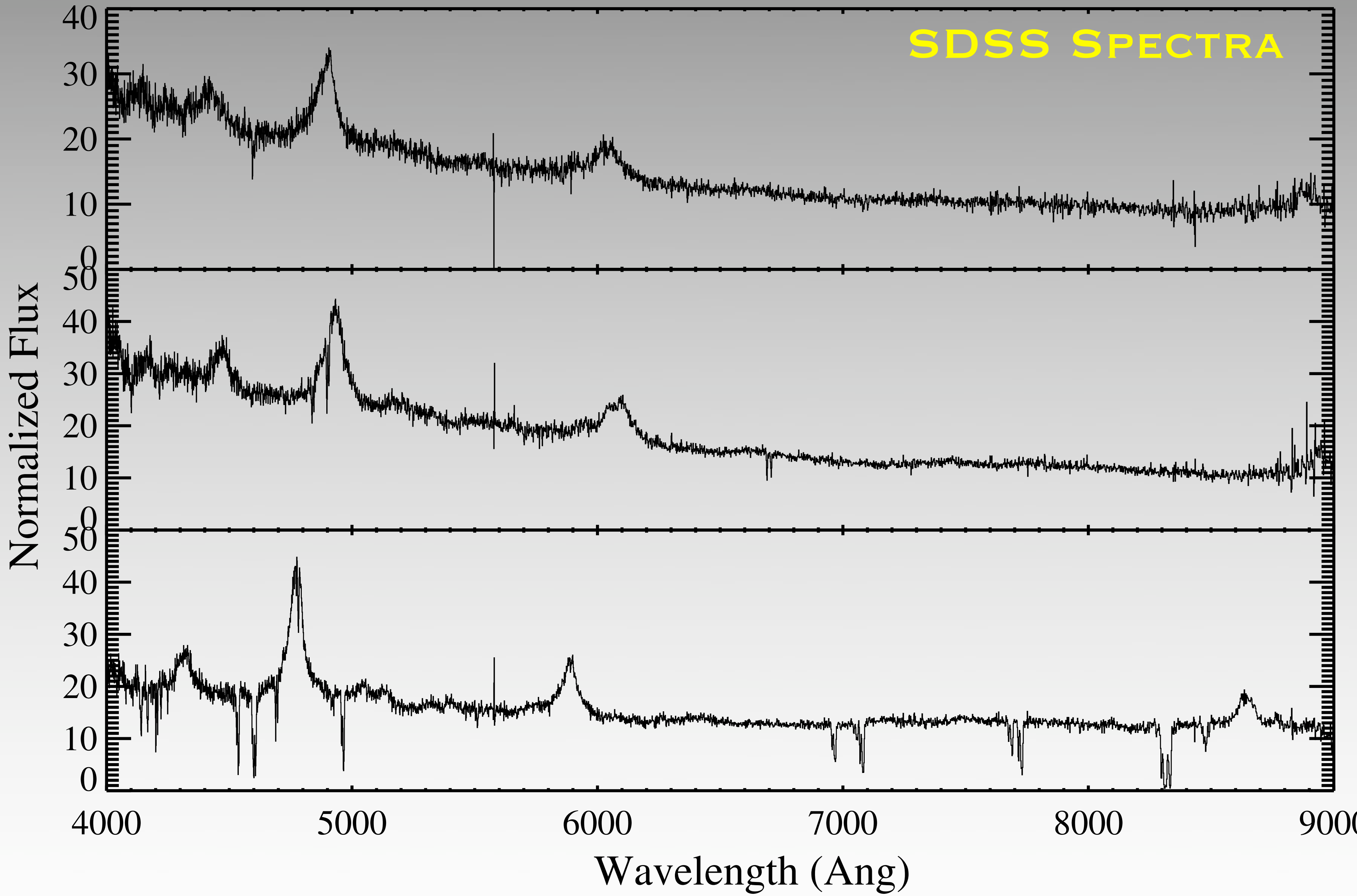


A 'Spooky' MgII Enhancement

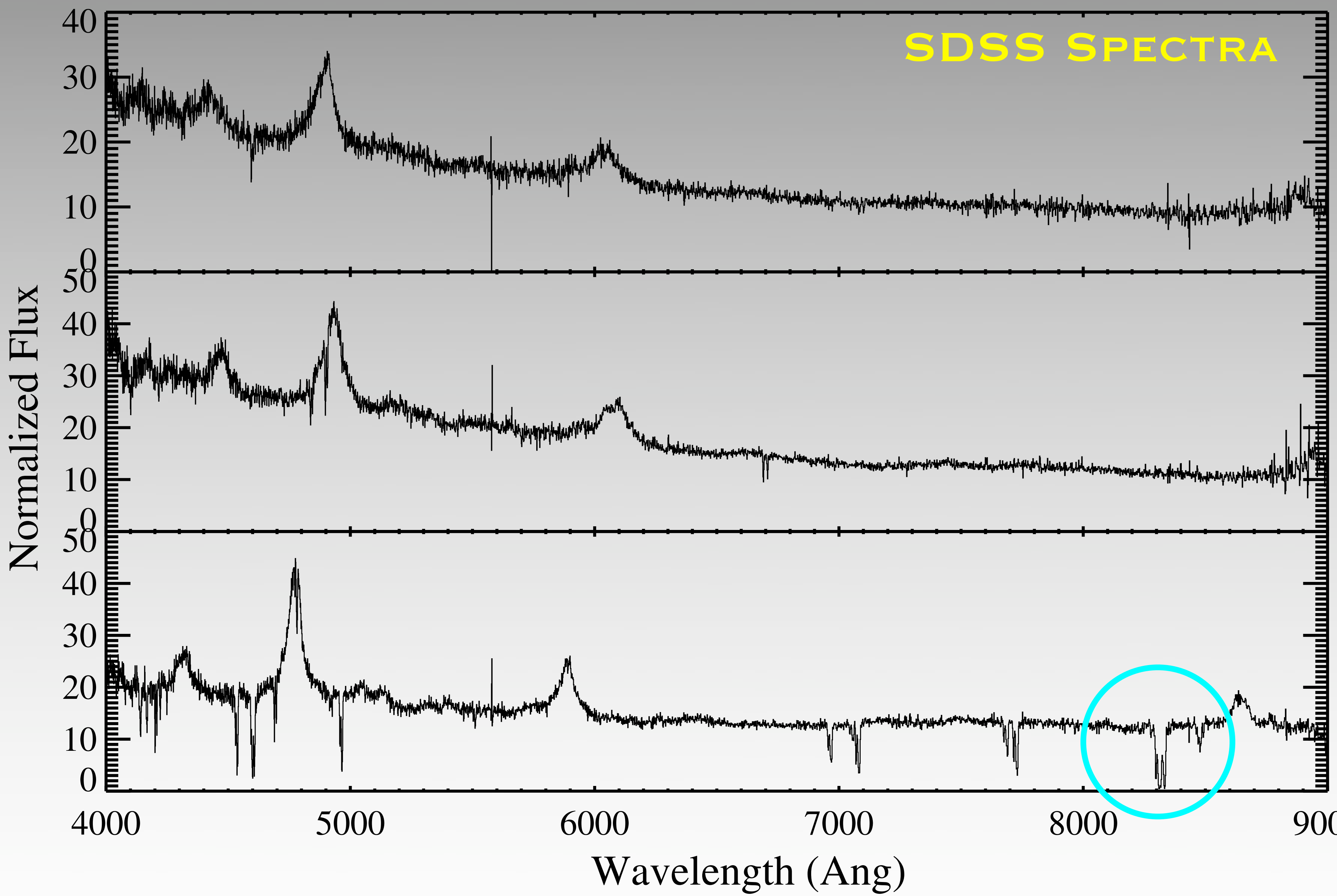


Prochter et al. (2006)

MgII Search in QSO Spectra



MgII Search in QSO Spectra



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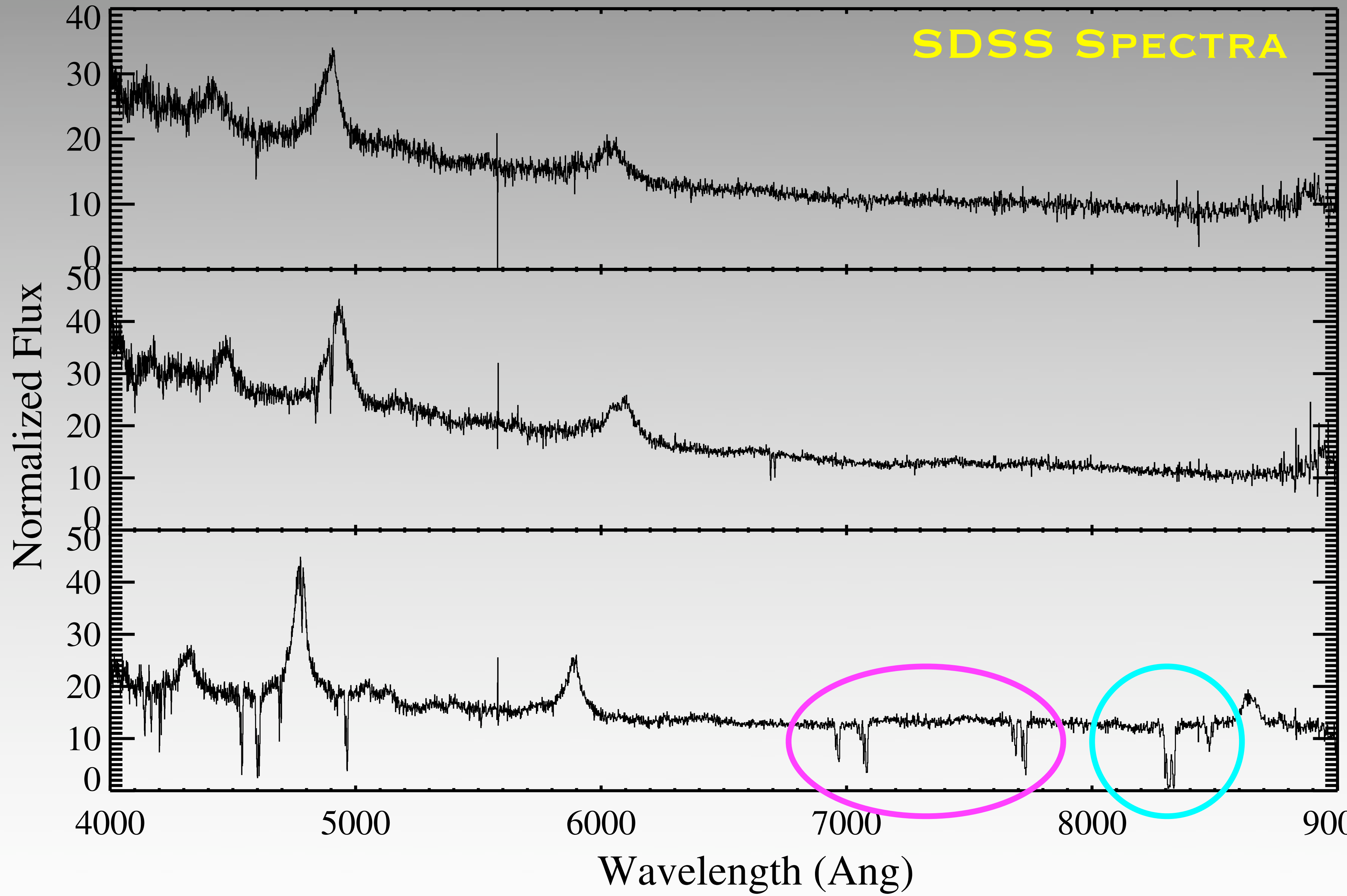
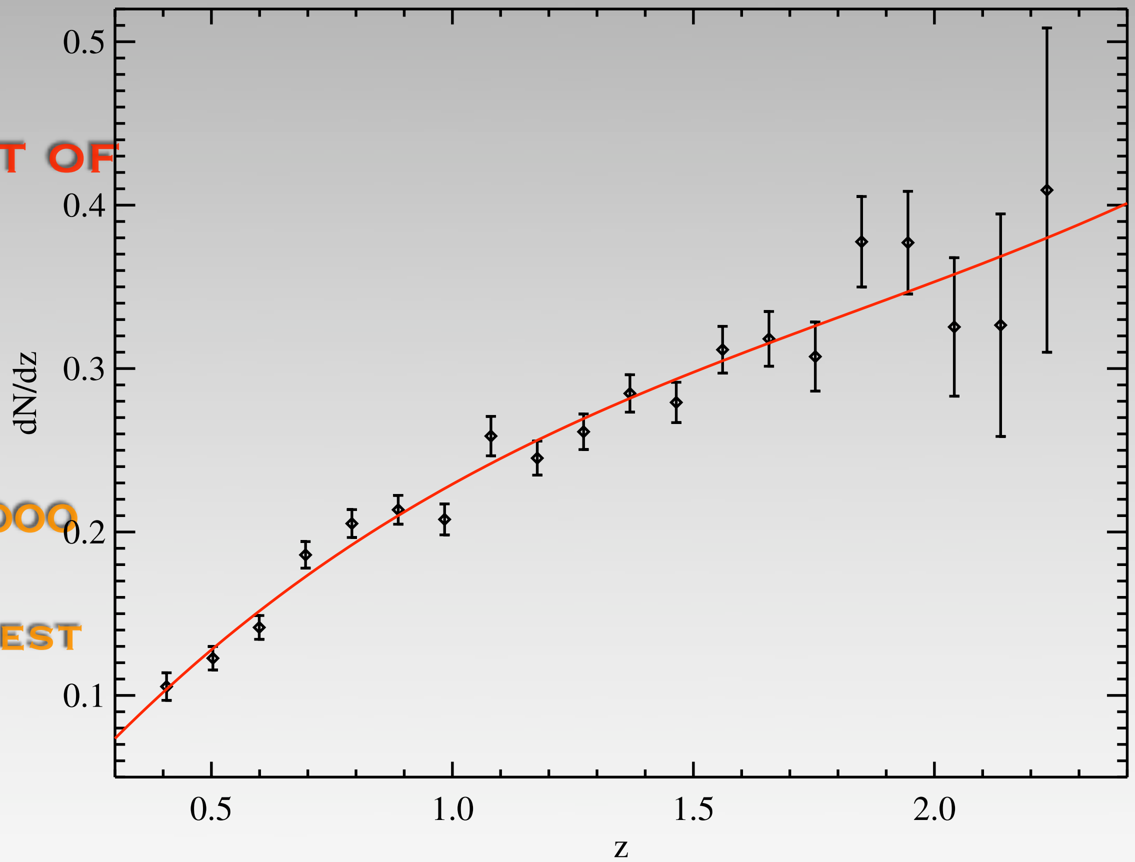


dN/dz of MgII

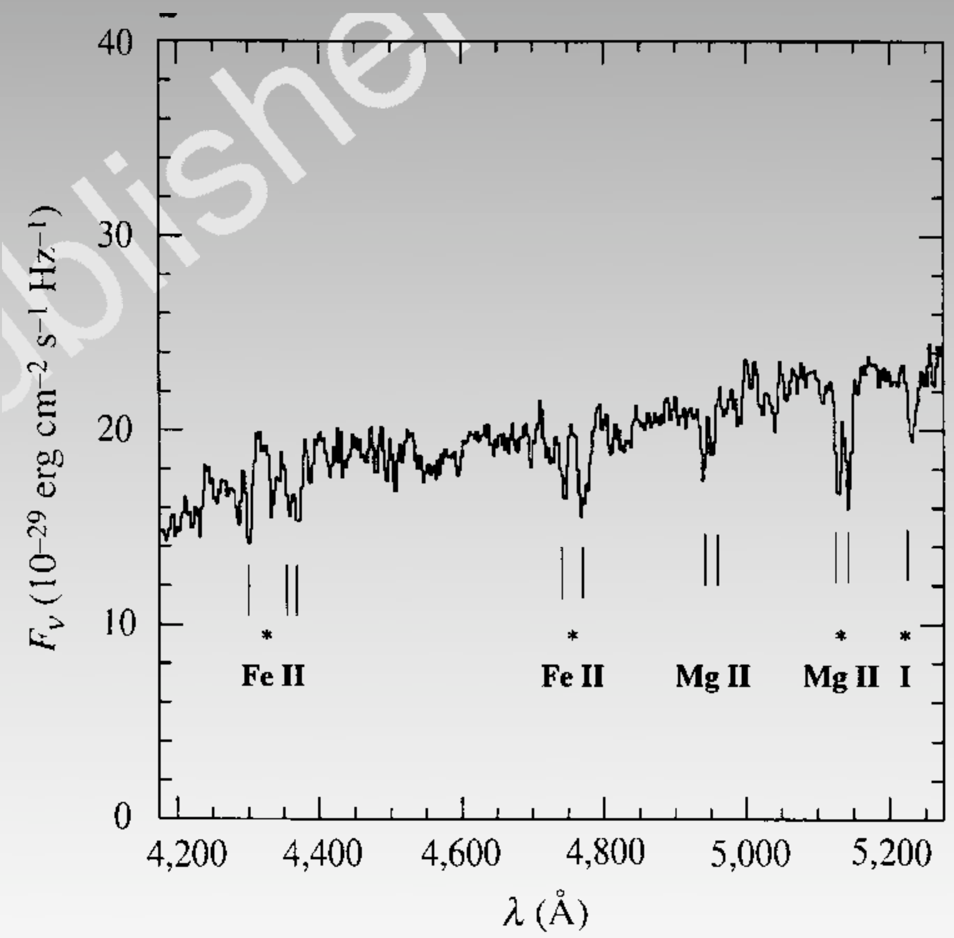
- dN/dz
  - Number of absorbers per unit redshift
  - Roughly, 1 QSO has 1 unit of redshift coverage
- SDSS
  - 20,000 quasars with sufficient SNR
    - Automatically identify 10,000 MgII systems
    - Stat sample is 7000 with Rest EW > 1A



Prochter et al. (2007)

GRB MgII

- MgII
  - Often establishes the GRB redshift (z<2.5)
    - Rest EW > 2A in most cases
- Intervening MgII
  - Easy to identify
    - Even with low-res data
  - Limited to large EW systems in many cases
- GRB 970508
  - Even an example in the first optical spectrum



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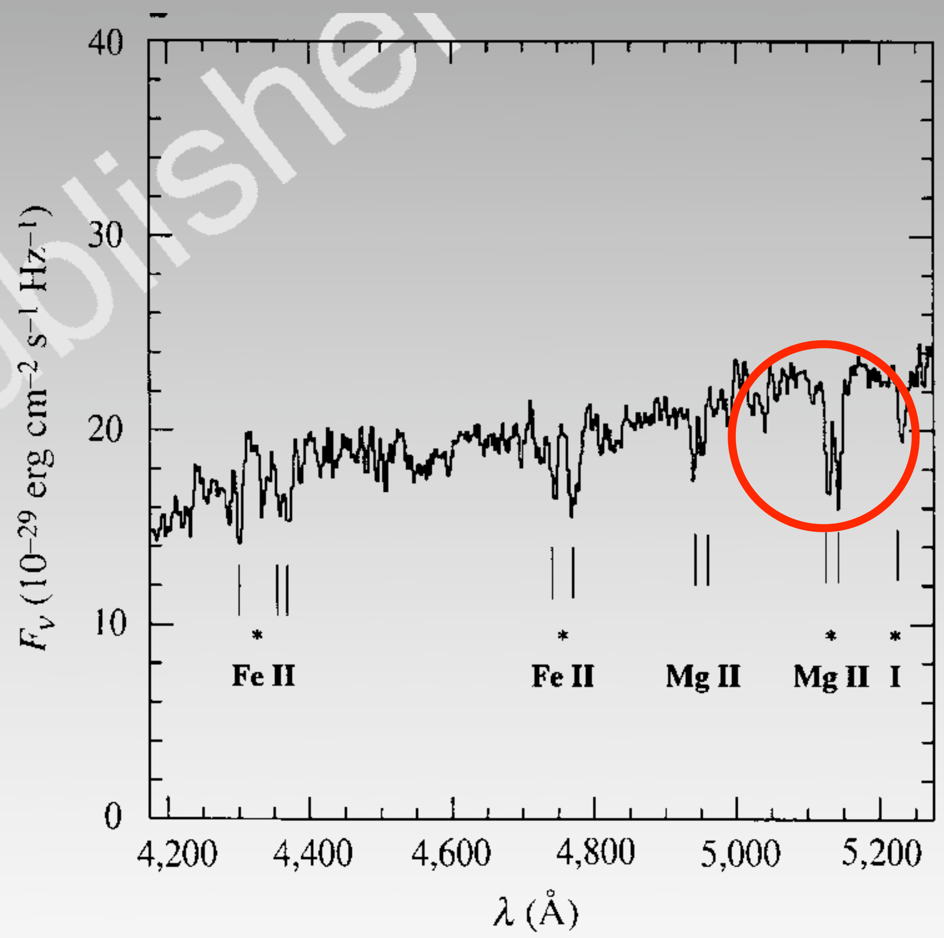

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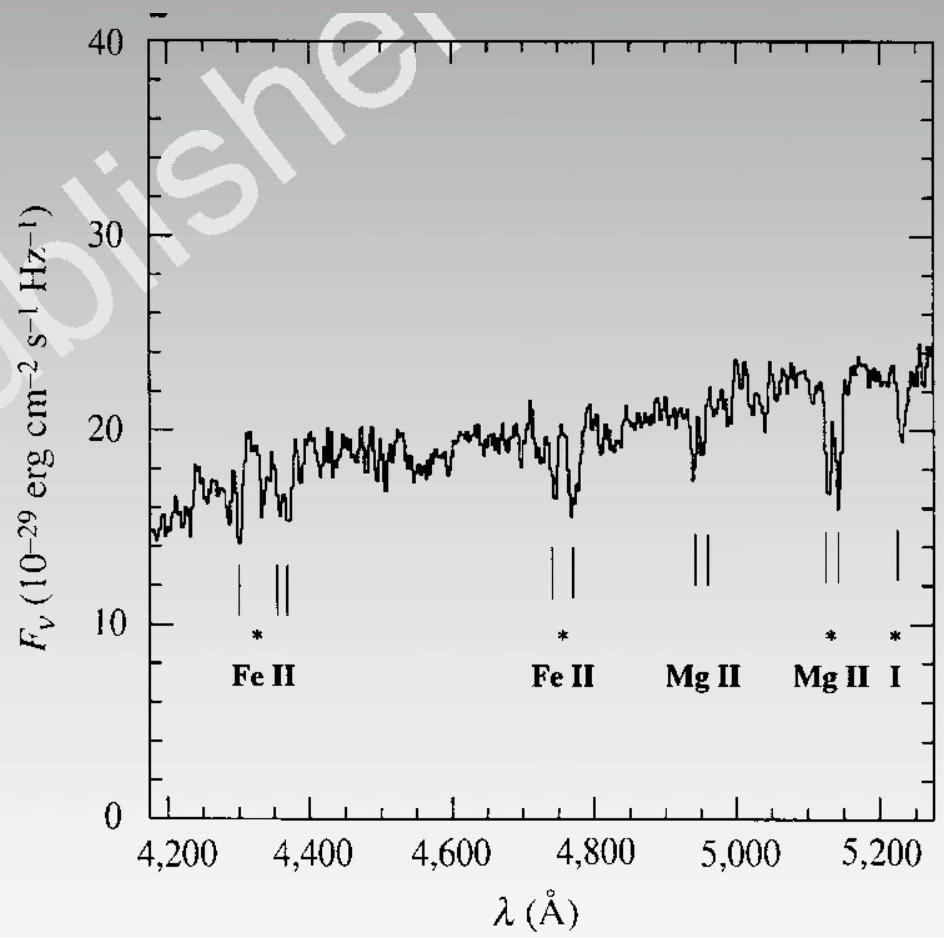

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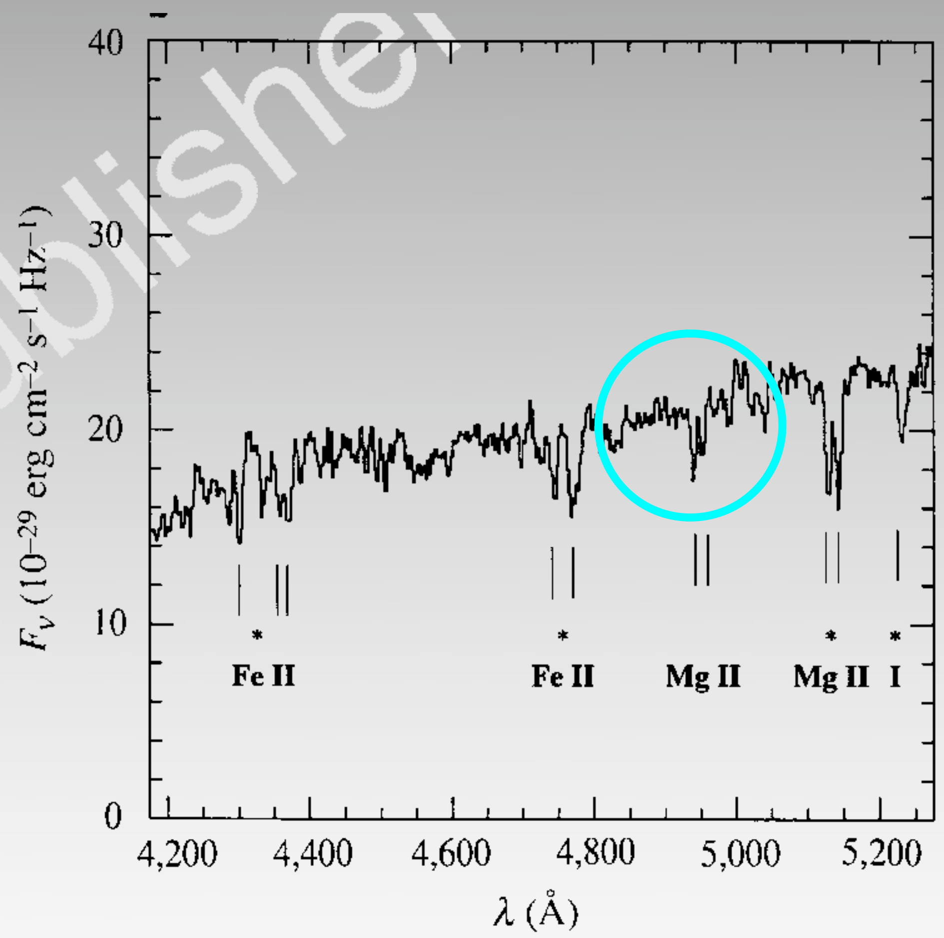
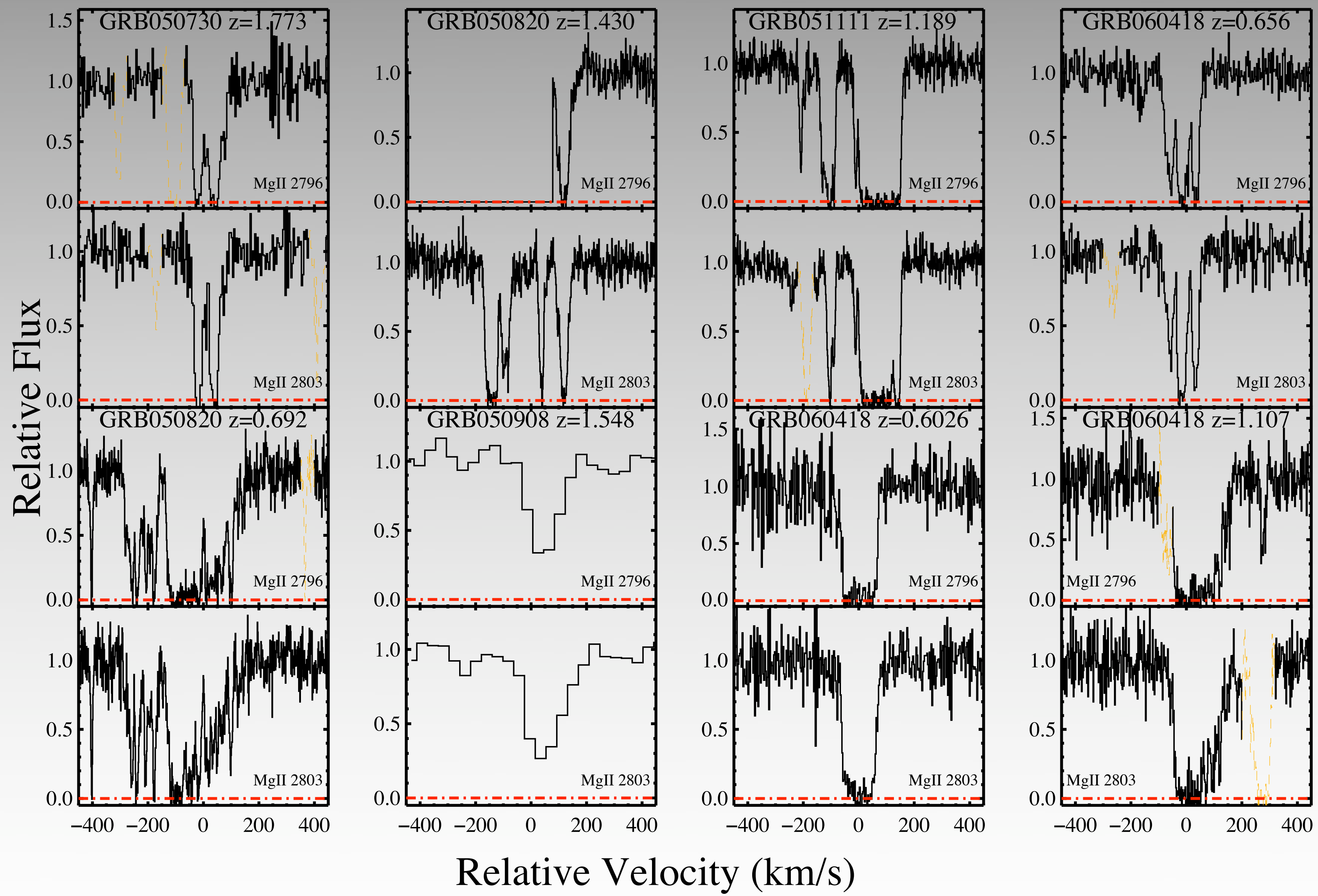


GRAASP Swift Sample



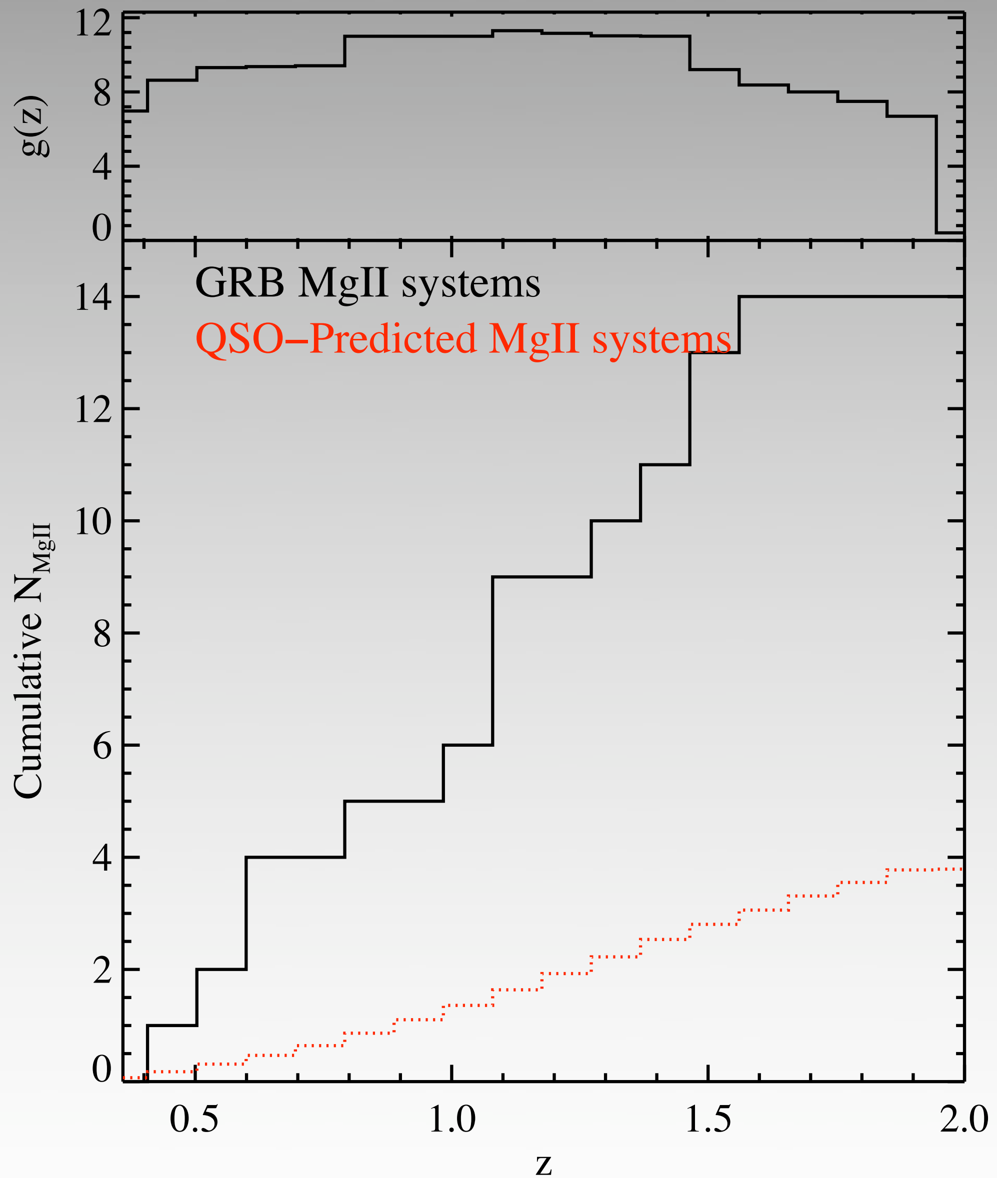
Prochter et al. (2006)

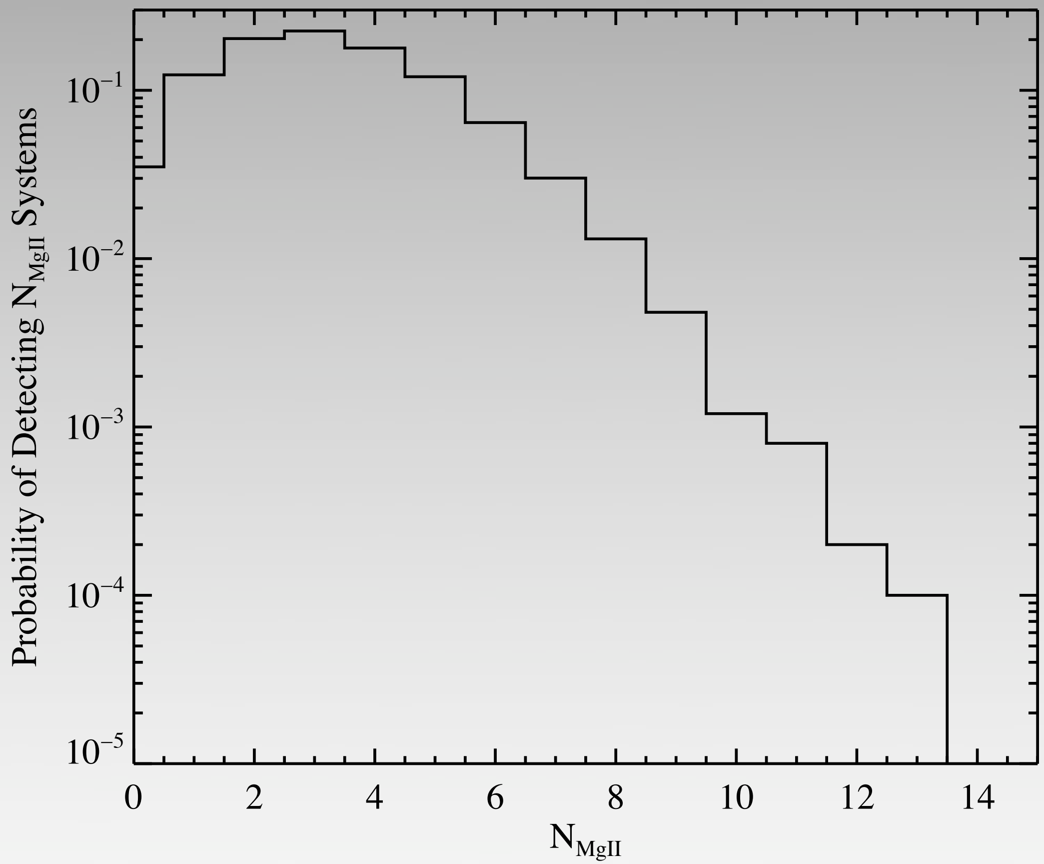
GRB MgII Sample

Table 1. Survey Data for Mg II Absorbers Along GRB Sightlines

GRB	z_{GRB}	z_{start}	z_{end}	z_{abs}	W_r(2796 Å)	Δv (km s^{-1})	Reference
$W_r(2796) \geq 1$ Å Mg II Statistical Sample							
000926	2.038	0.616	2.0				8
010222	1.477	0.430	1.460	0.927	1.00 ± 0.14	74,000	1
				1.156	2.49 ± 0.08	41,000	
011211	2.142	0.359	2.0				2
020405	0.695	0.359	0.684	0.472	1.1 ± 0.3	65,000	11
020813	1.255	0.359	1.240	1.224	1.67 ± 0.02	4,000	3
021004	2.328	0.359	2.0	1.380	1.81 ± 0.3	97,000	4
				1.602	1.53 ± 0.3	72,000	
030226	1.986	0.359	1.966				
030323	3.372	0.824	1.646				7
050505	4.275	1.414	2.0	1.695	1.98	176,000	6
050730	3.97	1.194	2.0				
050820	2.6147	0.359	1.850	0.692	2.877 ± 0.021	192,000	
				1.430	1.222 ± 0.036	113,000	
050908	3.35	0.814	2.0	1.548	1.336 ± 0.107	147,000	
051111	1.55	0.488	1.533	1.190	1.599 ± 0.007	45,000	
060418	1.49	0.359	1.473	0.603	1.251 ± 0.019	124,000	
				0.656	1.036 ± 0.012	116,000	
				1.107	1.876 ± 0.023	50,000	

Statistically Solid Result

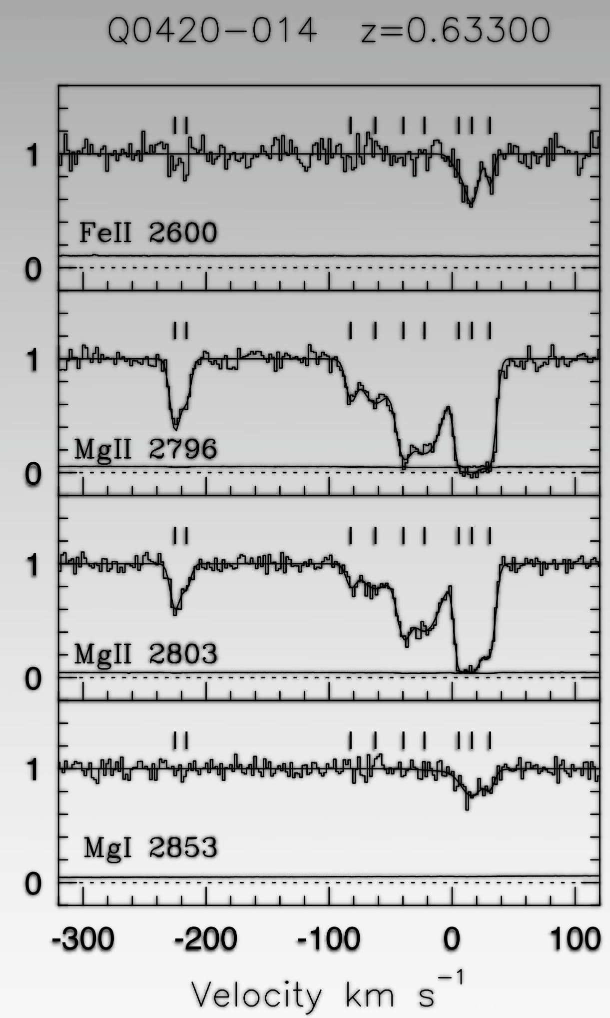




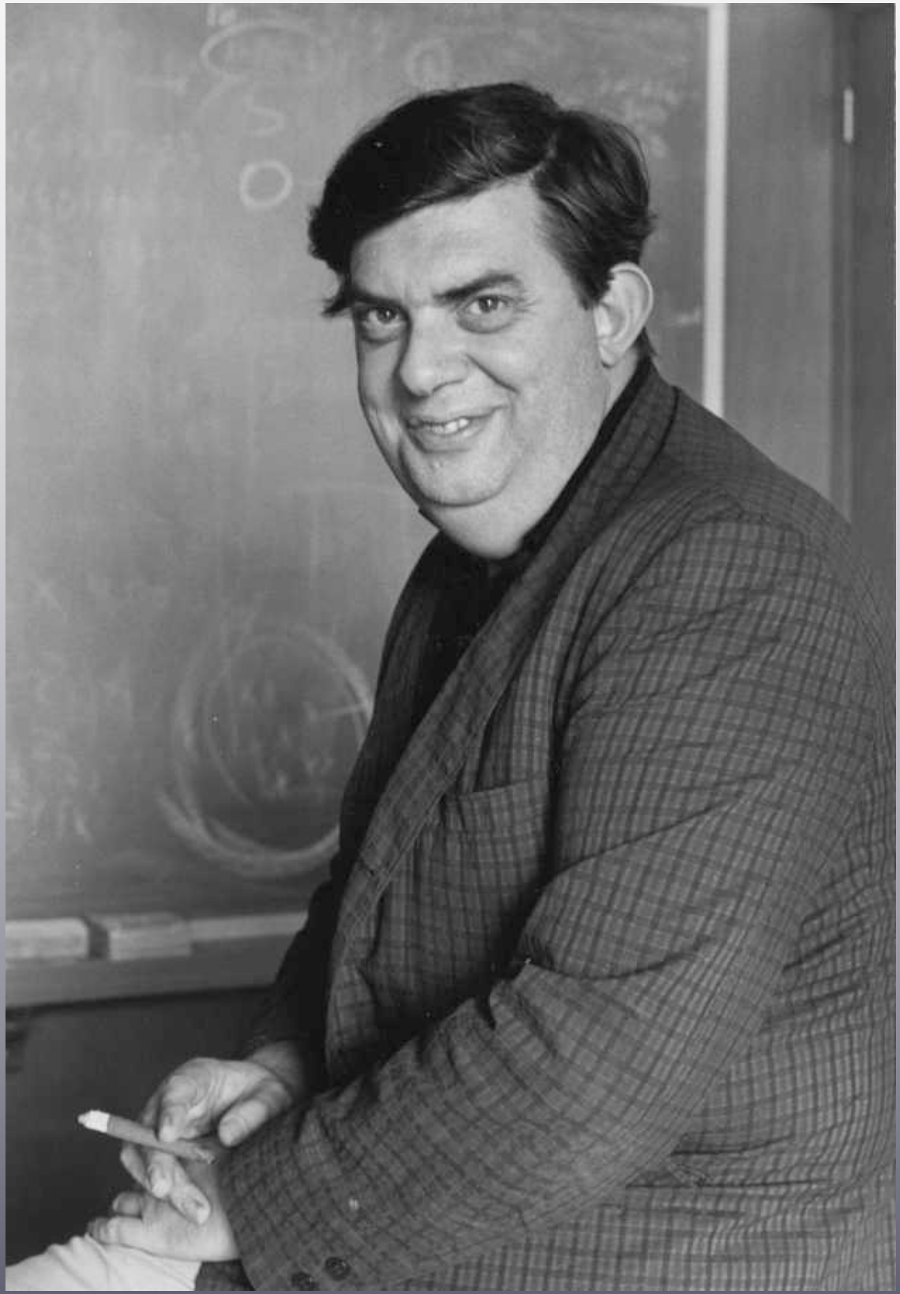
Chance result?
Less than 1 in 10,000

Possible Explanations

- Dust obscuration?
  - MgII absorbers contain dust
    - Could remove quasars from a magnitude limited sample
    - Underestimate *dN/dz*
  - But, dust content is low
    - Effect is small (Menard et al. 2007)
- Gas is intrinsic to the GRB?
  - v > 100,000 km/s !
  - Galaxies have been identified
- Gravitational lensing?
  - One MgII per sightline
    - Double lens enhancement
  - But, flux counts are flat
    - No GRB 'pairs'?
- Beam size? (Frank et al.)
  - No partial covering observed
  - No difference in QSO emission lines
    - Pontzen et al. (2007)



Bizzare (fundamental?) result



Summary

- GRB Afterflow spectroscopy effectively probes the High z Universe
- ISM in GRB Host Galaxies
  - Gas ionized to ~100pc (pre-existing HII region)
  - General properties
    - High N_{HI} surface densities
    - Moderate metallicities (Mean is 1/3 to 1/2 solar)
    - Dust depleted gas, but no molecules
  - Next phase -- study the galaxies hosting this gas
- Velocity fields
  - Majority of gas arises in neutral ISM
  - 'Halo gas'
    - contributes a few % of the optical depth
    - Significant velocity field: Gravitational/feedback?
  - 'Mass'/metallicity relation in place at z=3
- IGM
  - z>6 Universe? I grow pessimistic (for now)
  - 'Spooky' MgII enhancement