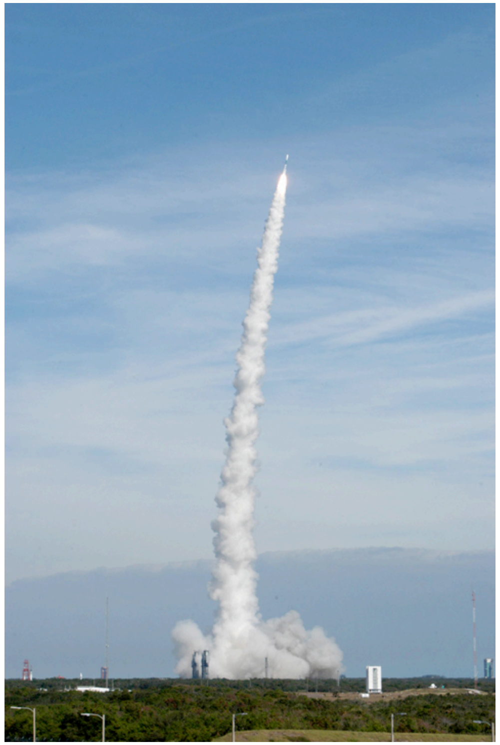
Probing the ISM of High z Galaxies with GRB Afterglows

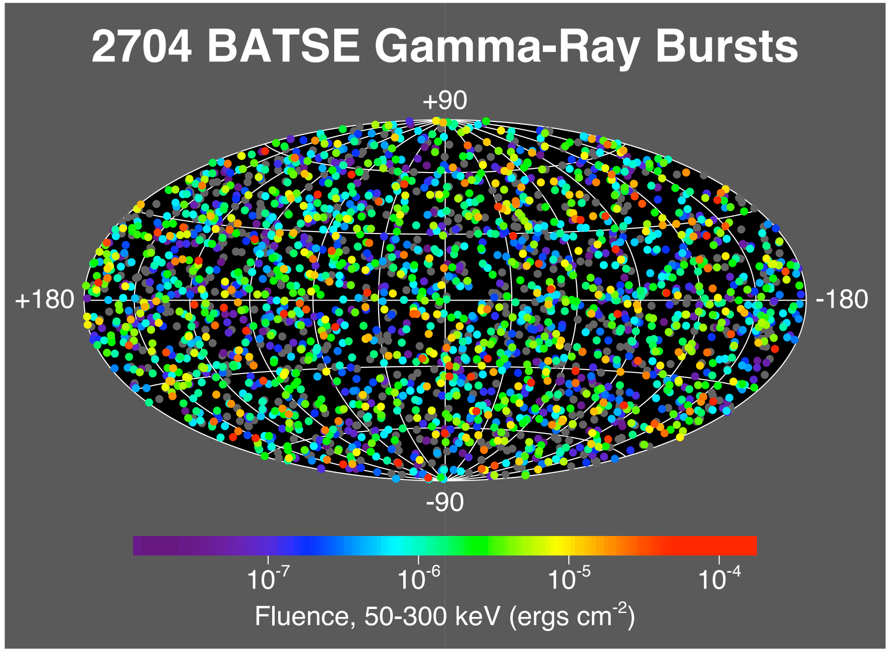
Jason X. Prochaska
UCO/Lick Observatory
(on behalf of GRAASP)

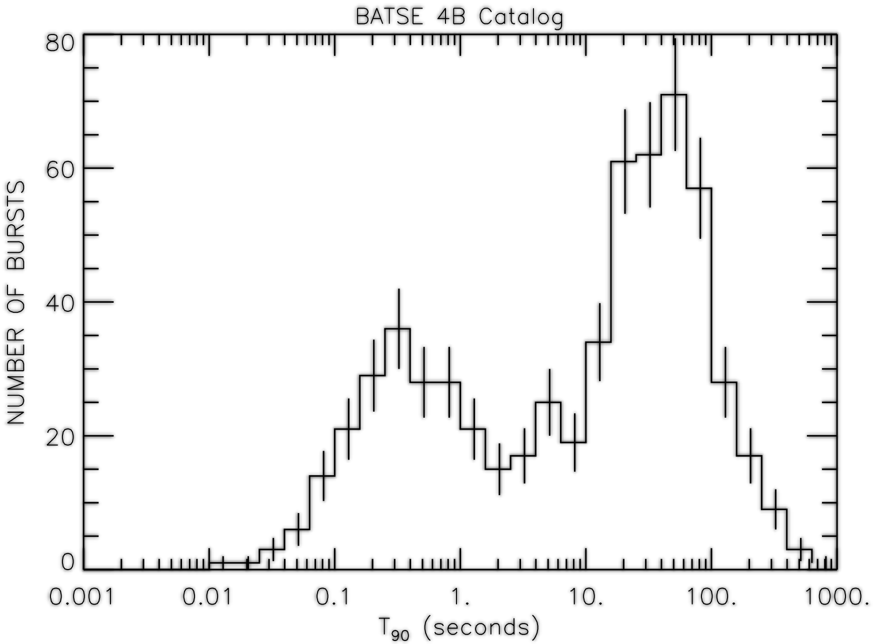


H.-W. Chen (University of Chicago)
M. Dessauges-Zavadsky (Obsv. Geneve)
J. S. Bloom (UC Berkeley)

Outline

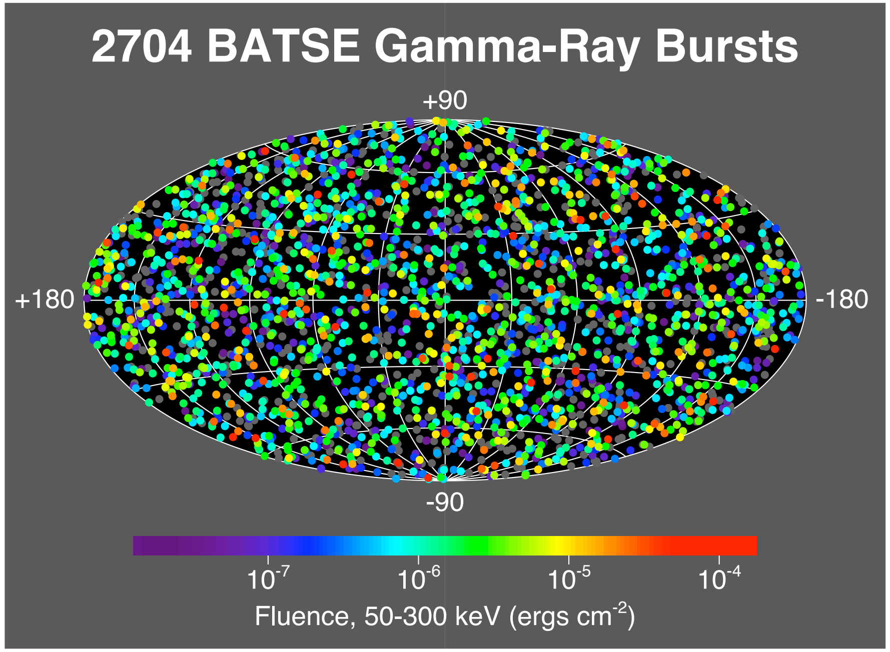
- Introduction
- HI and H_2 gas
  - Where is the fuel for SF?
  - Estimating the escape fraction
- Metal-line transitions
  - Resolving the distance of the gas
  - Metallicity measurements
- Velocity fields in High z Galaxies
  - Testing the standard paradigm
  - Examining outflow/inflow in 'normal' SF galaxies

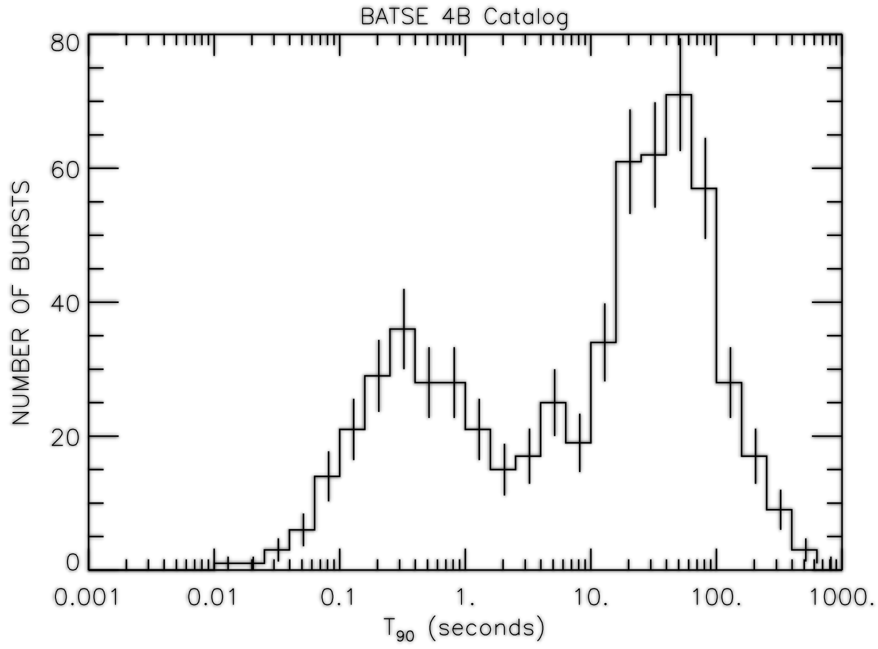




Gamma-ray Bursts: GRBs

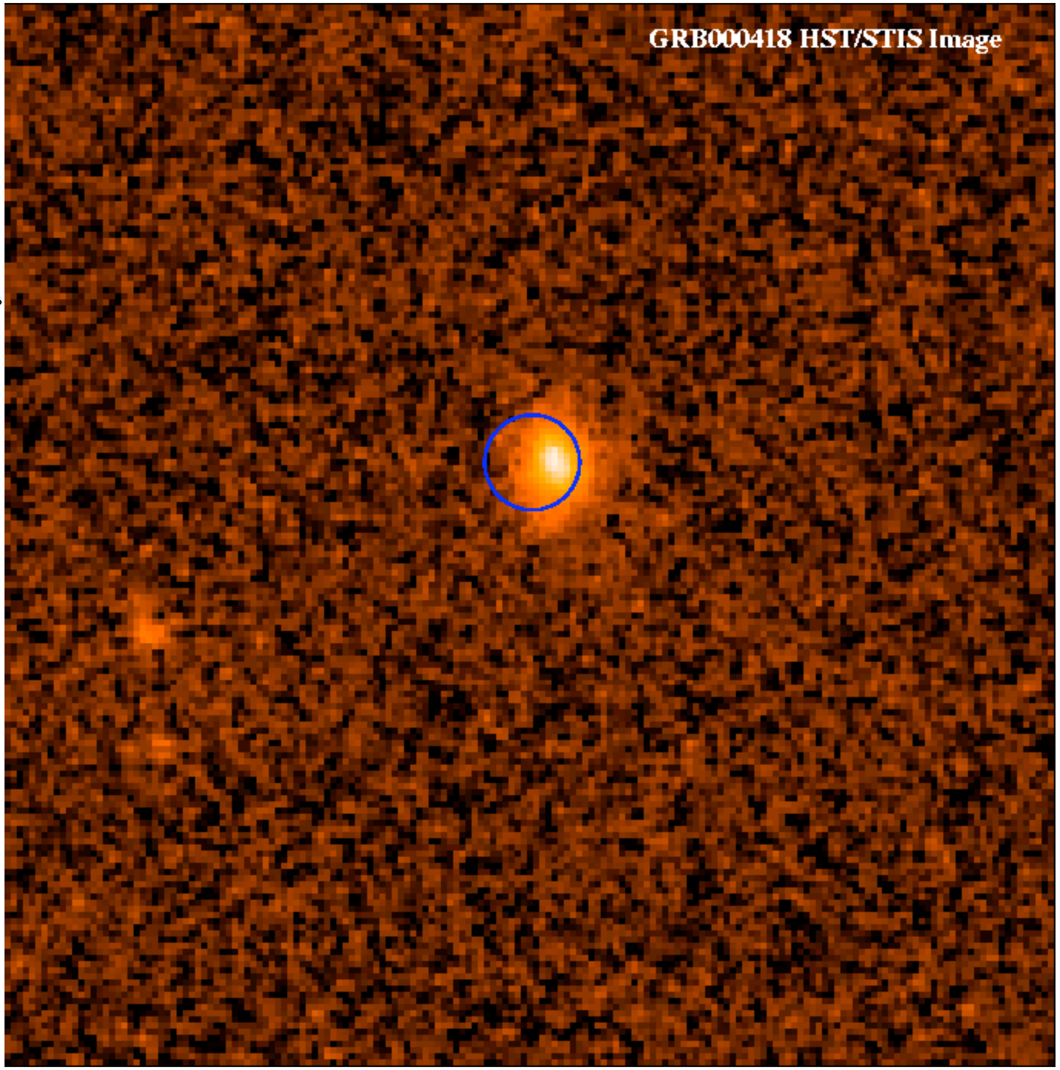
- BATSE All-sky survey
  - GRB are isotropically distributed on the sky
    - Strong support for cosmological origin
  - Localized to ~3 degrees
- Short and Long
  - t_{90} = time for 90% of energy
  - Bimodal population
    - Short-hard: t < 1s
    - Long-soft: t > 2s
  - <u>This talk will focus on the long duration bursts</u>





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)



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2 Mirabal

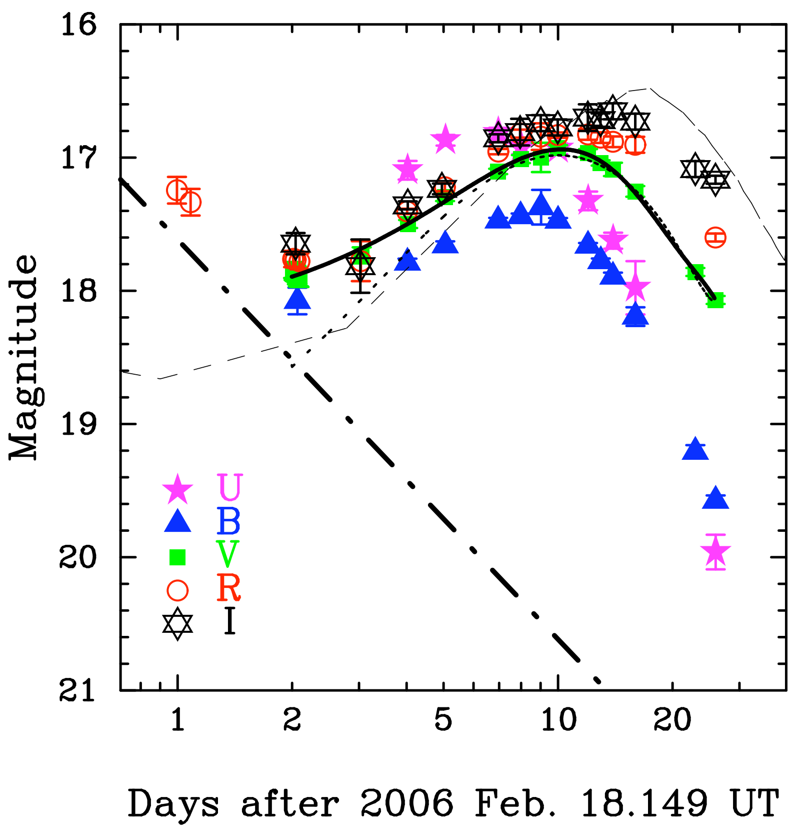

FIG. 1.— *UBVRI* data for GRB 060218, corrected for Galactic extinction and host-galaxy contamination. The *solid line* is a fit to the *V*-band light curve. The *dotted line* is a fit to the *V*-band light curve after subtracting an $\alpha = 1.2$ power-law decay (*dot-dashed line*) as justified in 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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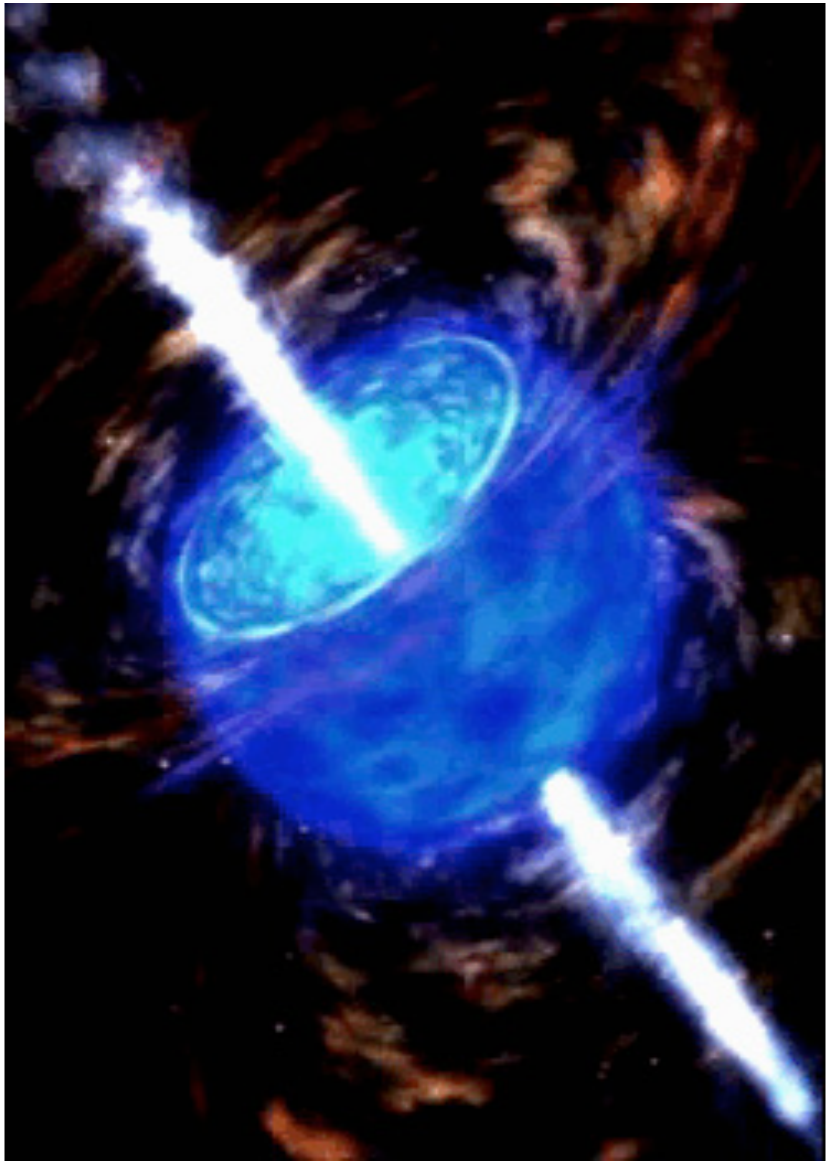
Long GRB Progenitors

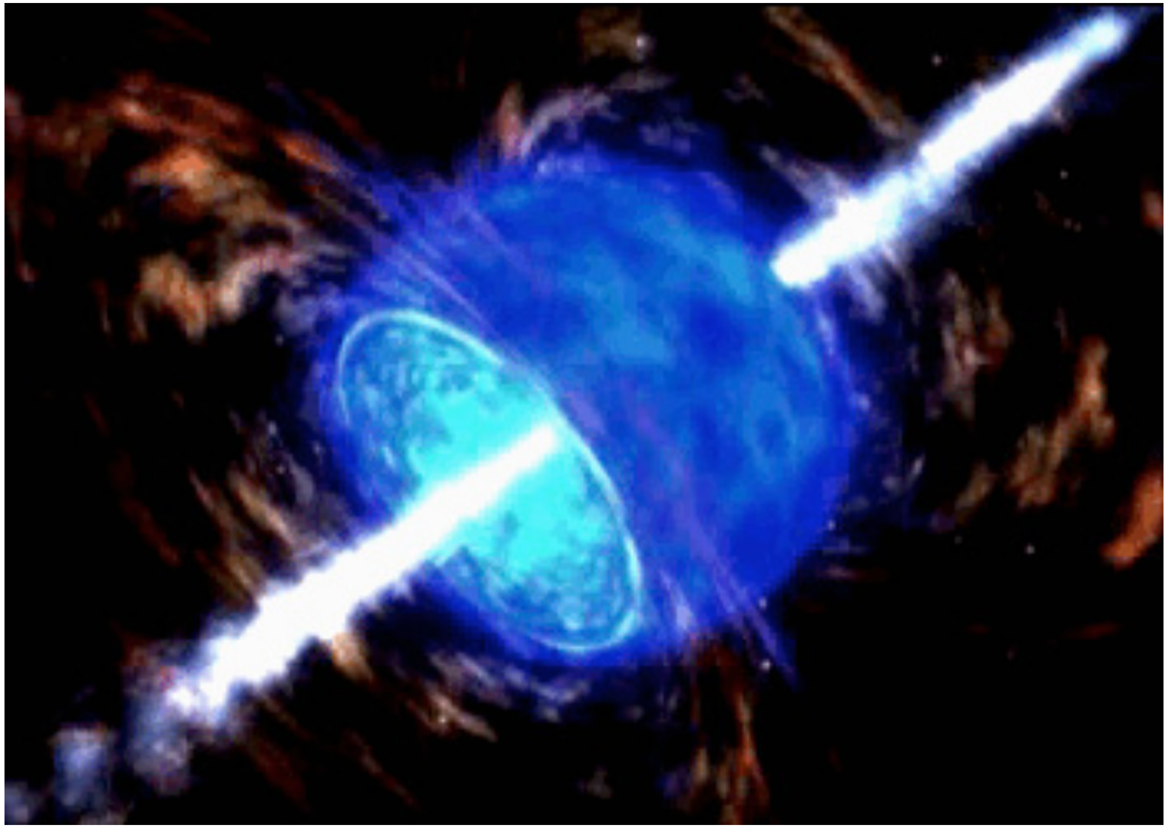
- Theory
  - Collapsar model
    - 15 Msol star
    - Collapse to black hole
    - Relativistic jet ensues
  - Afterglow
    - Jet deaccelerates as it interacts with surrounding gas (10^{16} cm)
    - Synchrotron radiation



Woosley (1993)

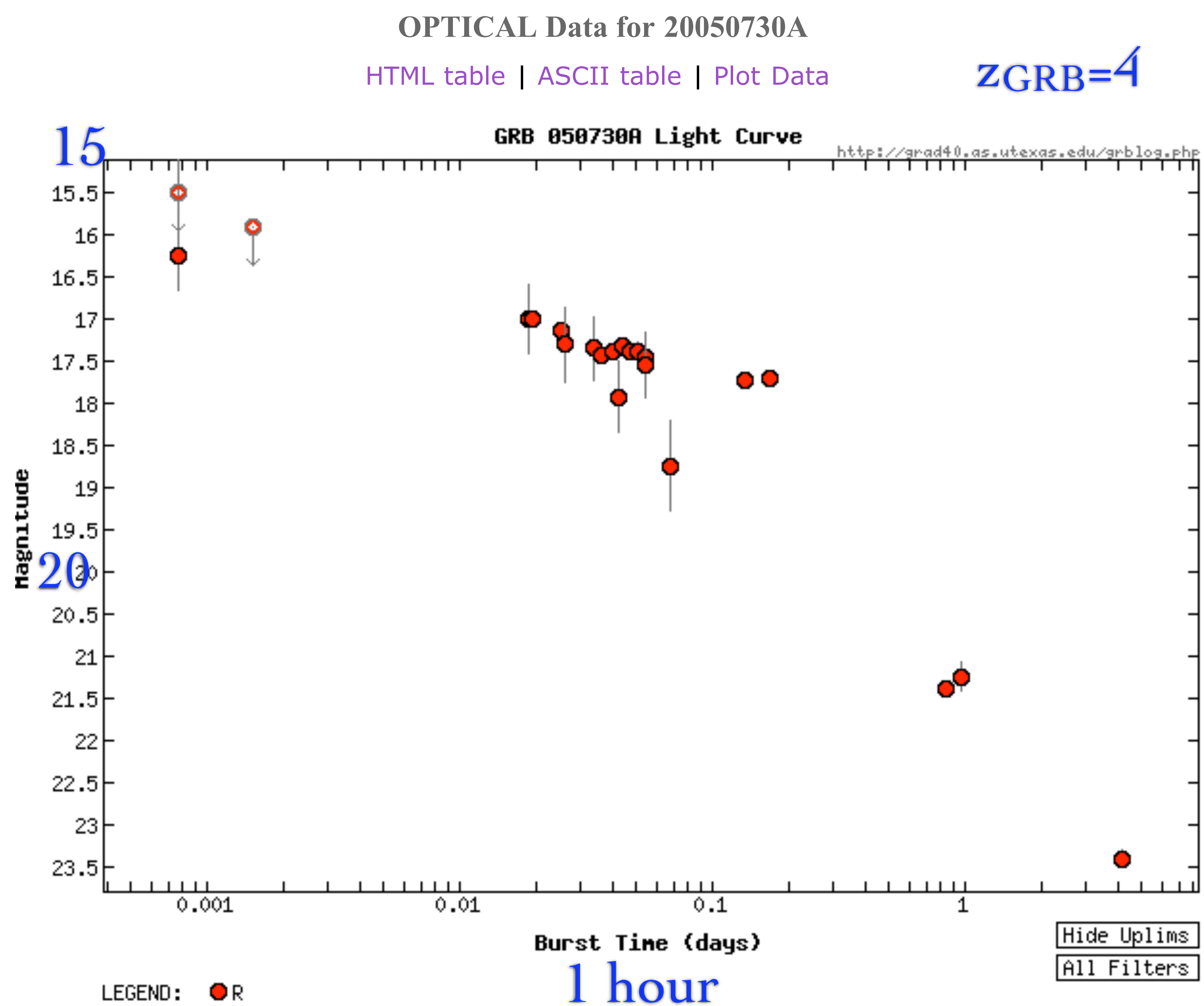
Long GRB Progenitors are massive stars

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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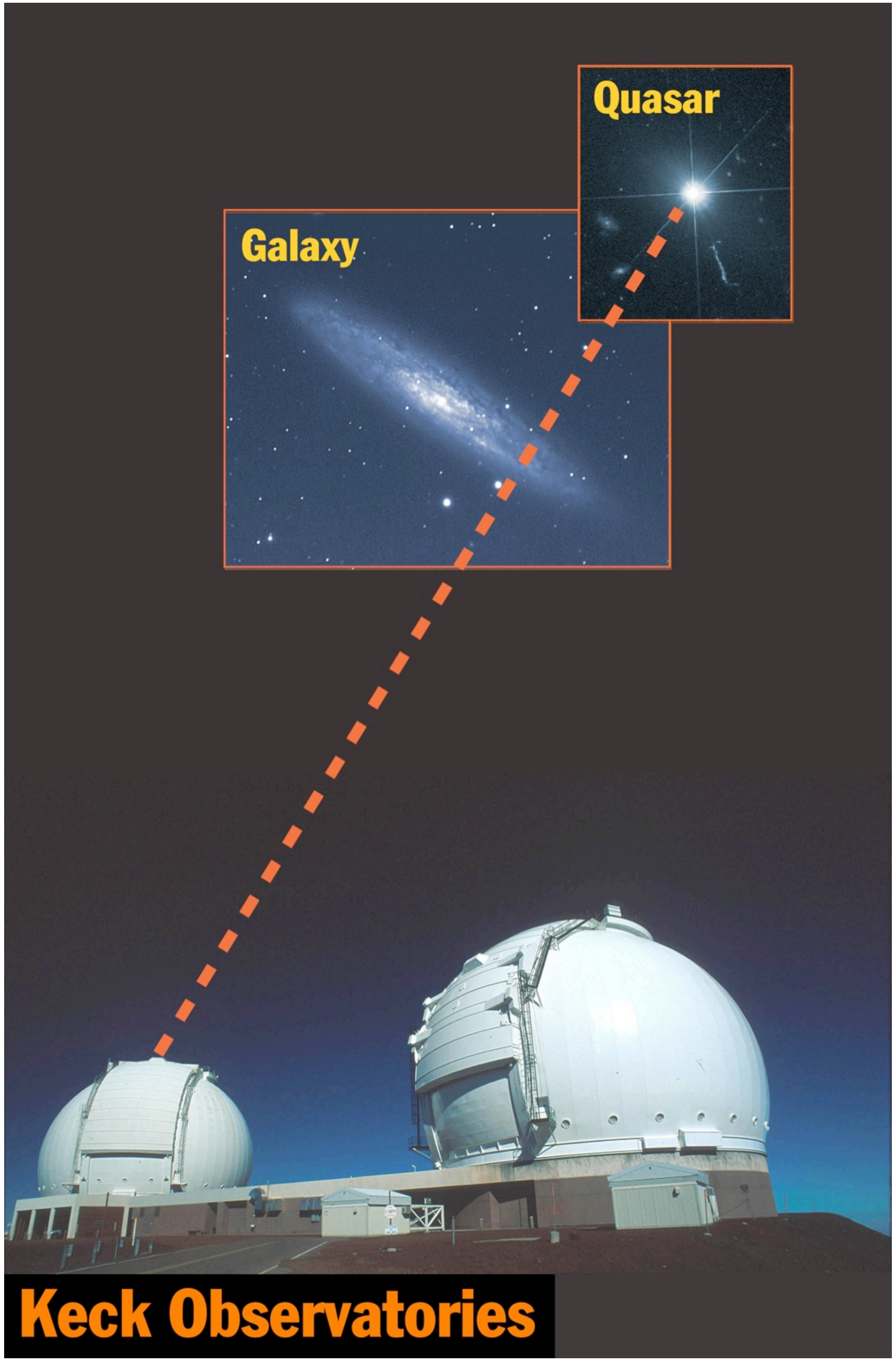

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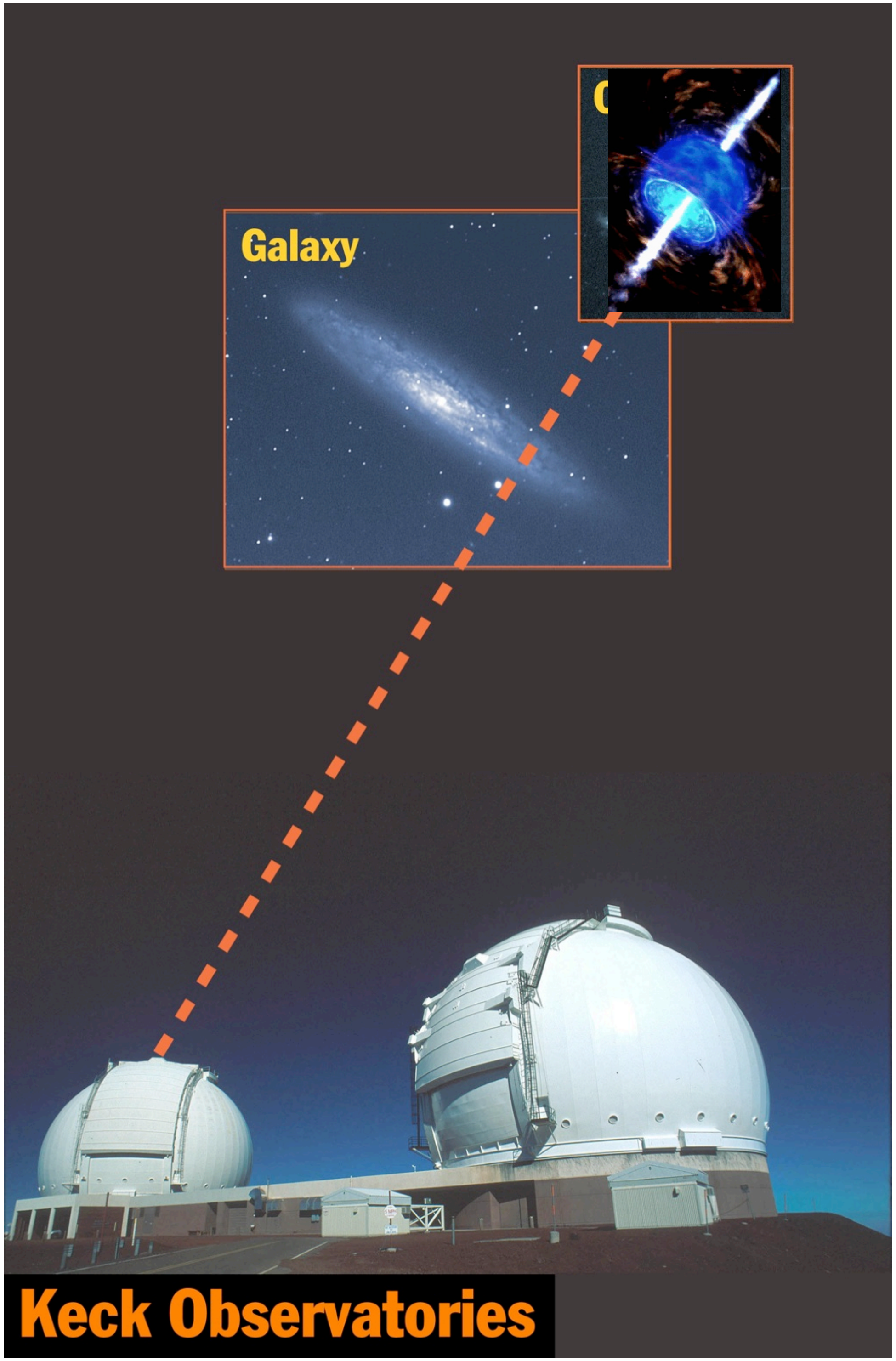
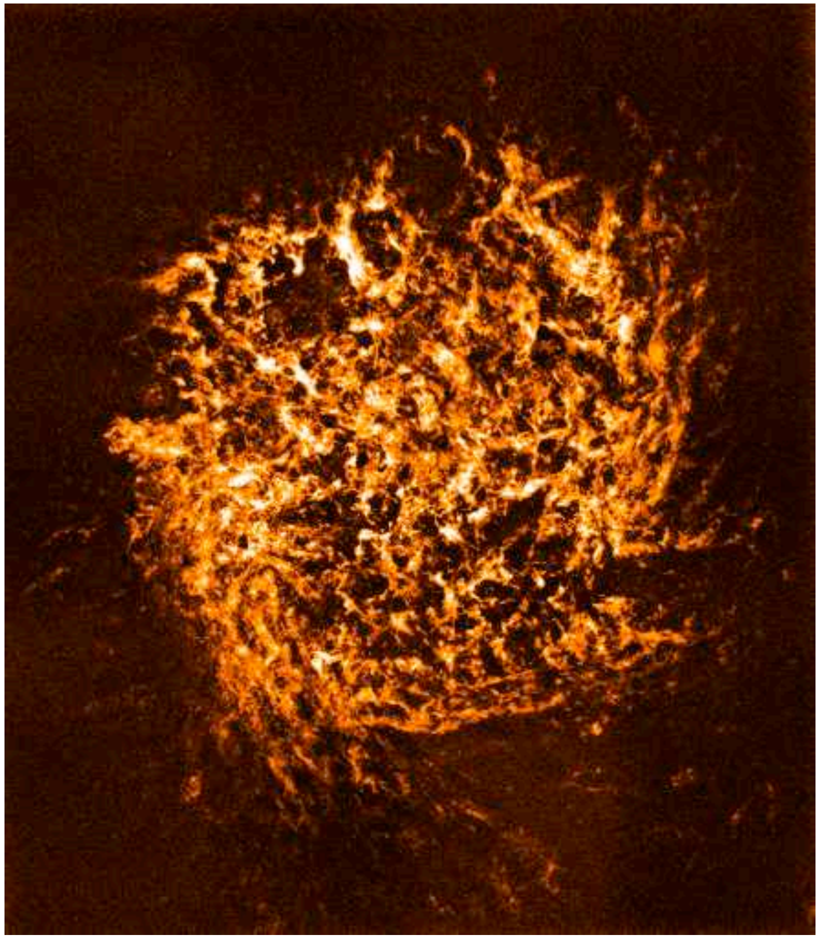
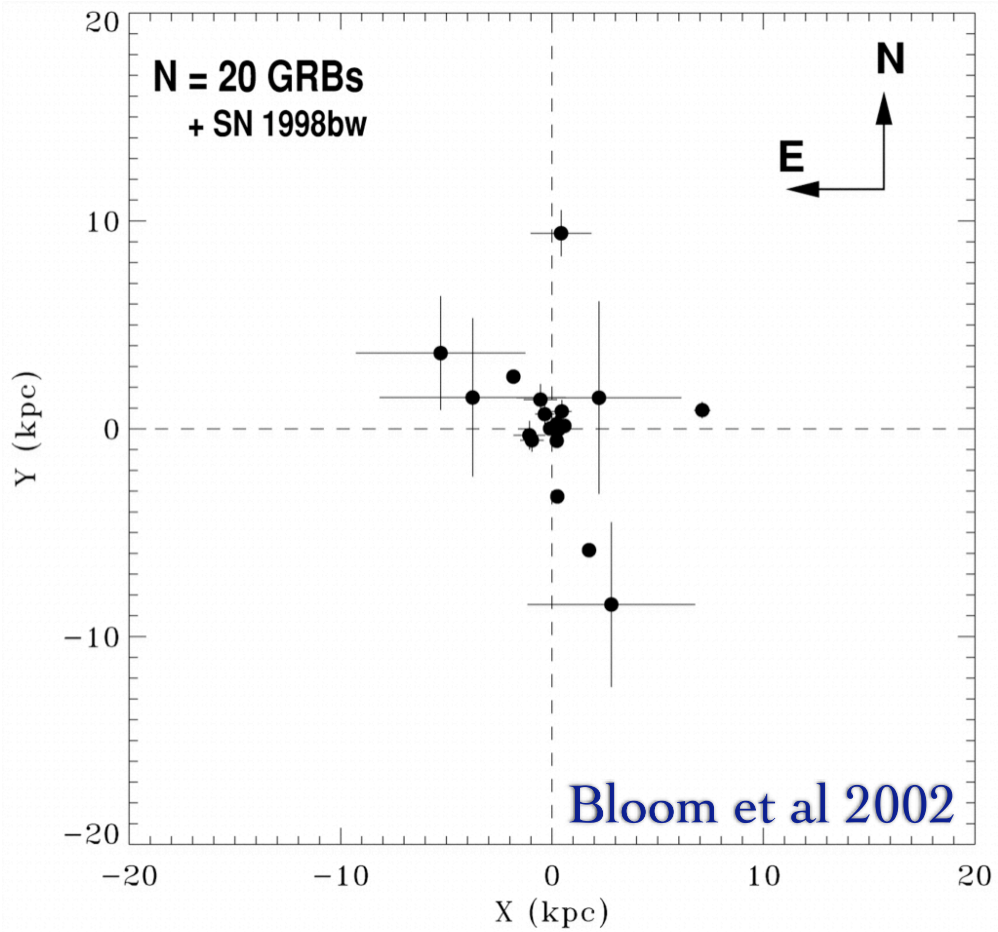


QSO vs GRB as Probes of the ISM





Damped Lya System

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

GRB

- All within 10 kpc
- >50% within 2 kpc
- Probe star-forming regions

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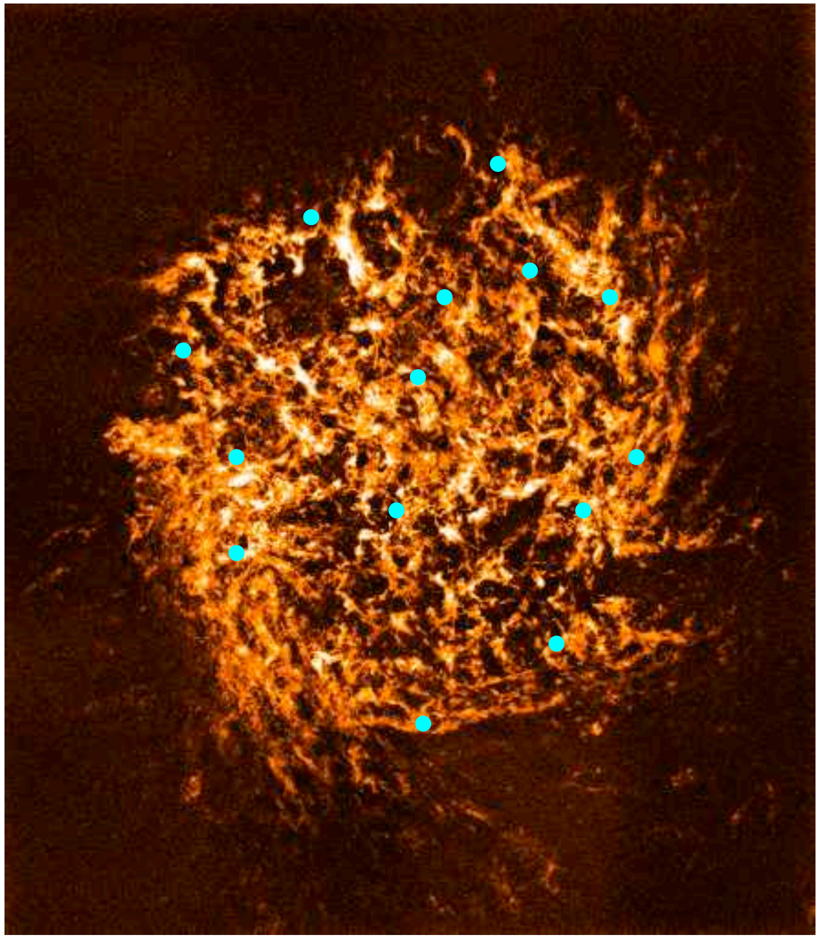

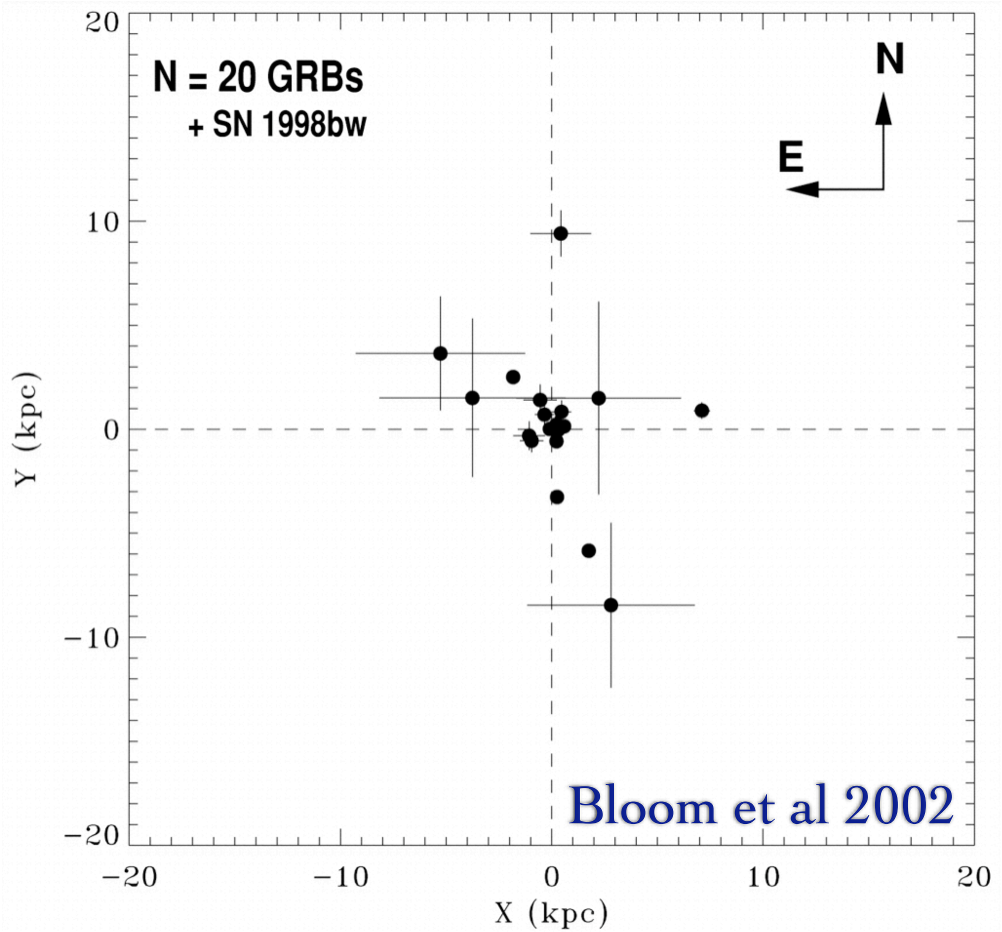

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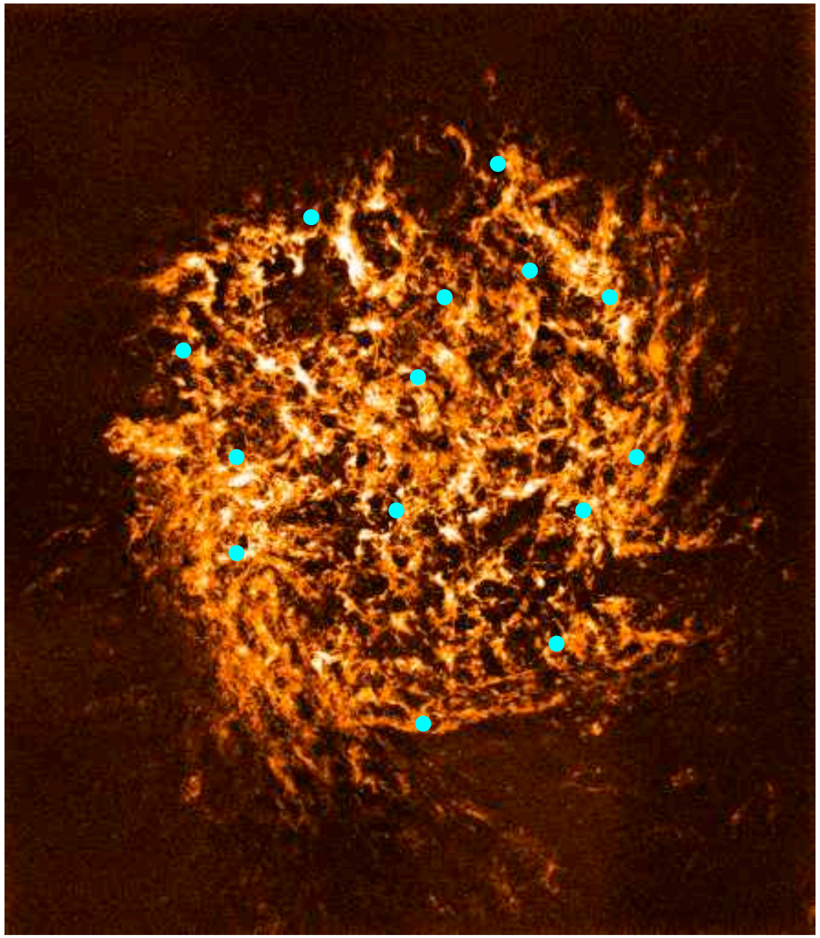

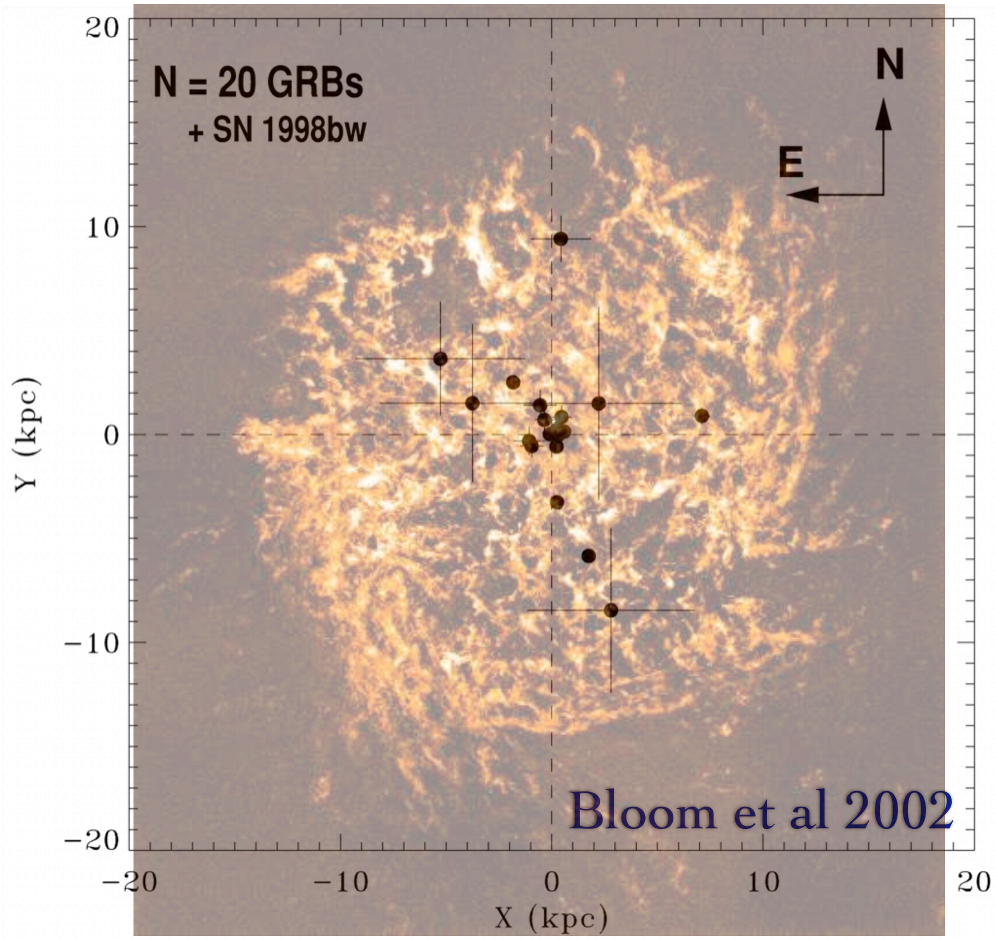

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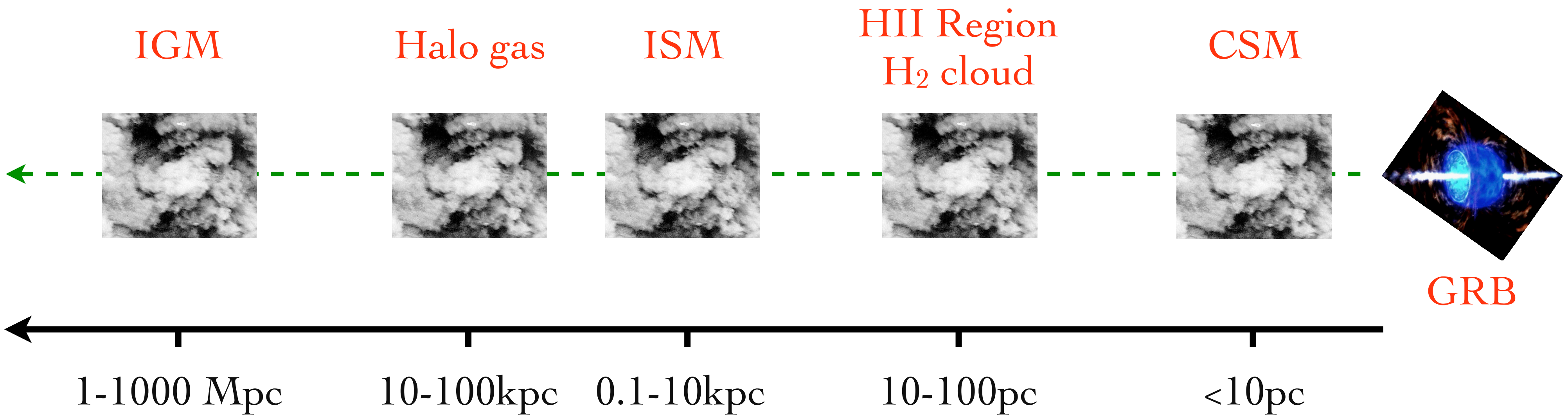
The Experiment

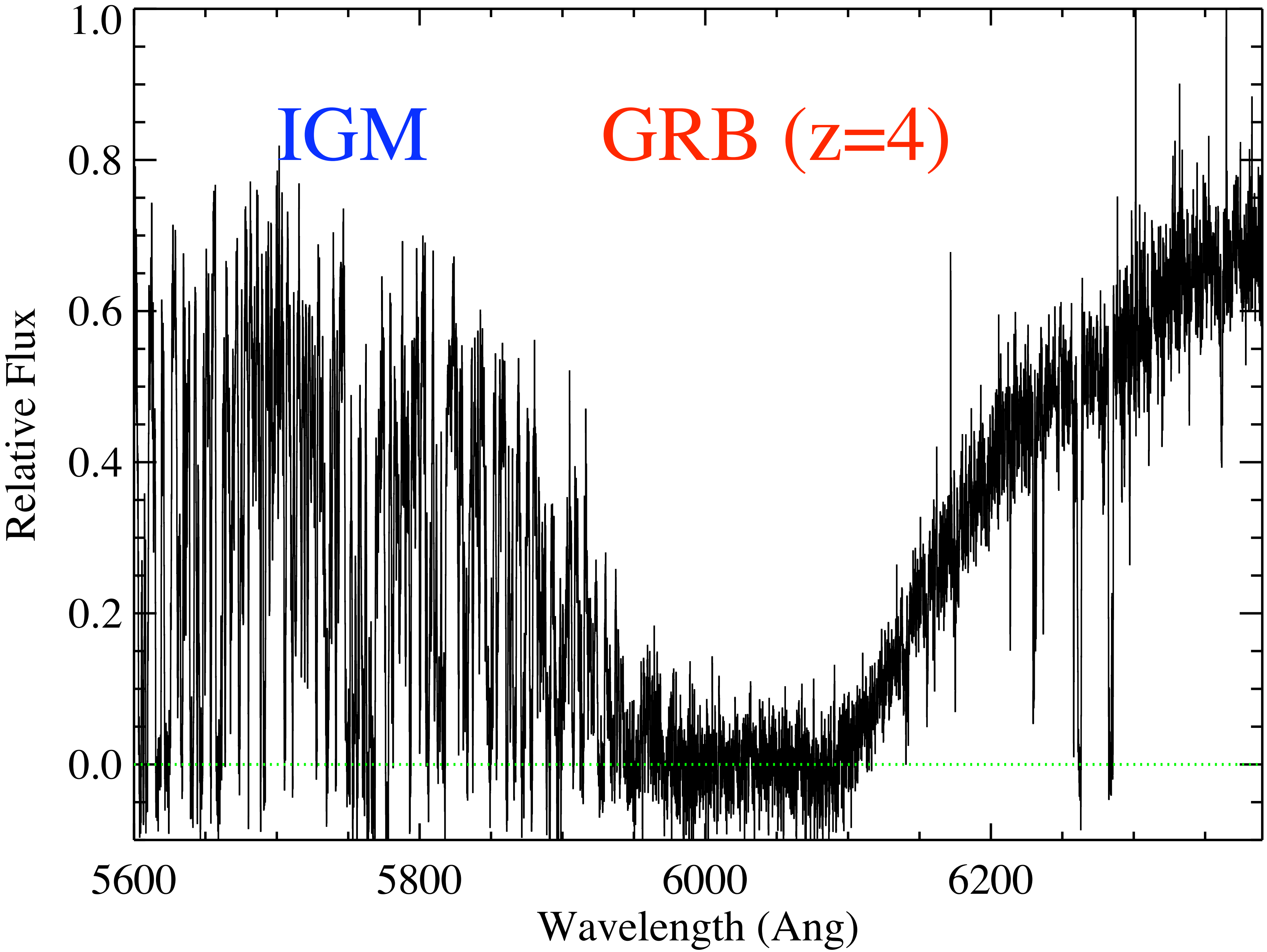
Acquire spectra of GRB afterglows to study gas in the galaxy hosting the GRB (its interstellar medium, ISM) and gas between Earth and the GRB (the intergalactic medium, IGM)



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

GRB Afterglow Spectrum

GRB 050730 (MIKE) CHEN ET AL. (2005) $R_{PEAK} \sim 15$



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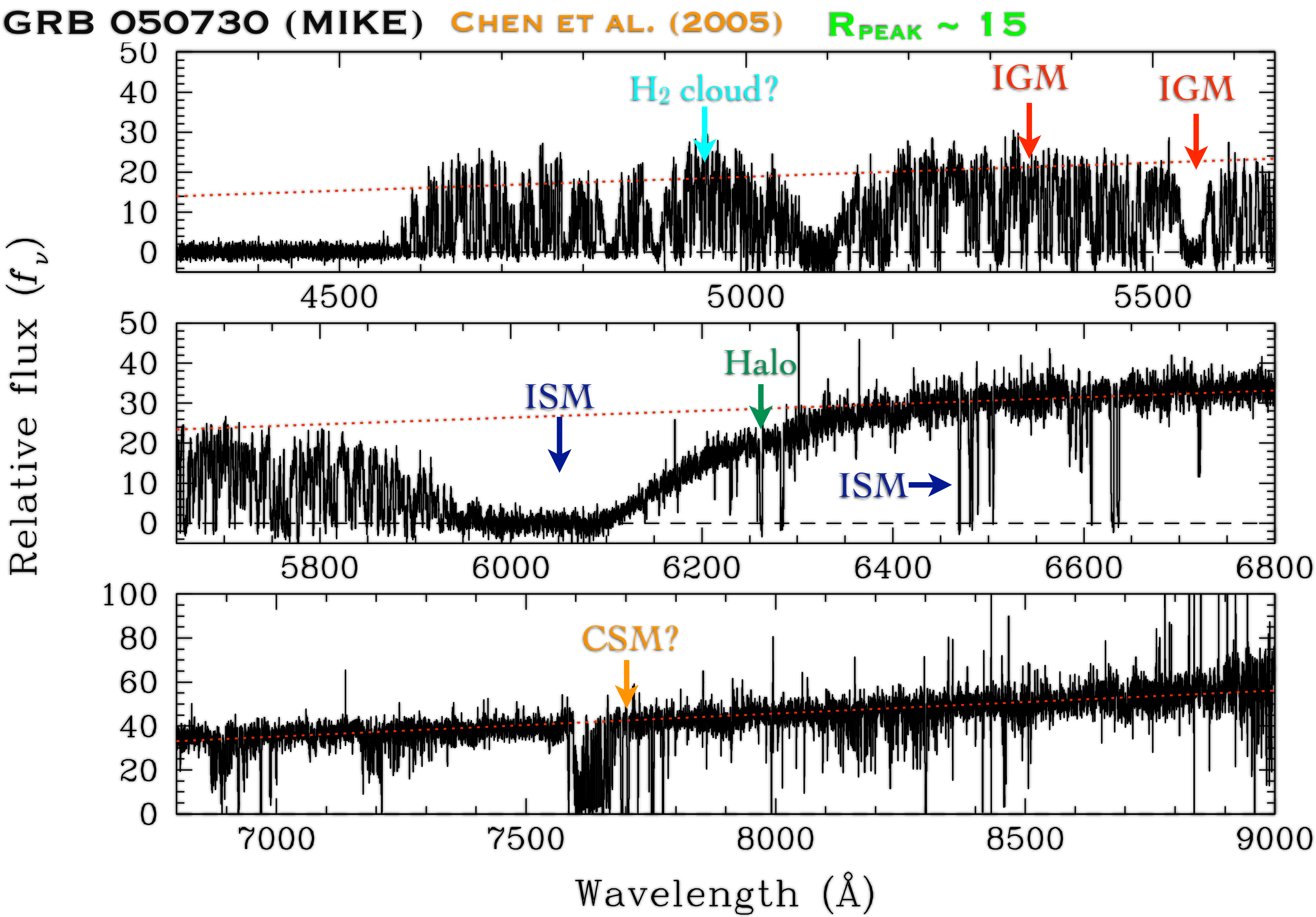

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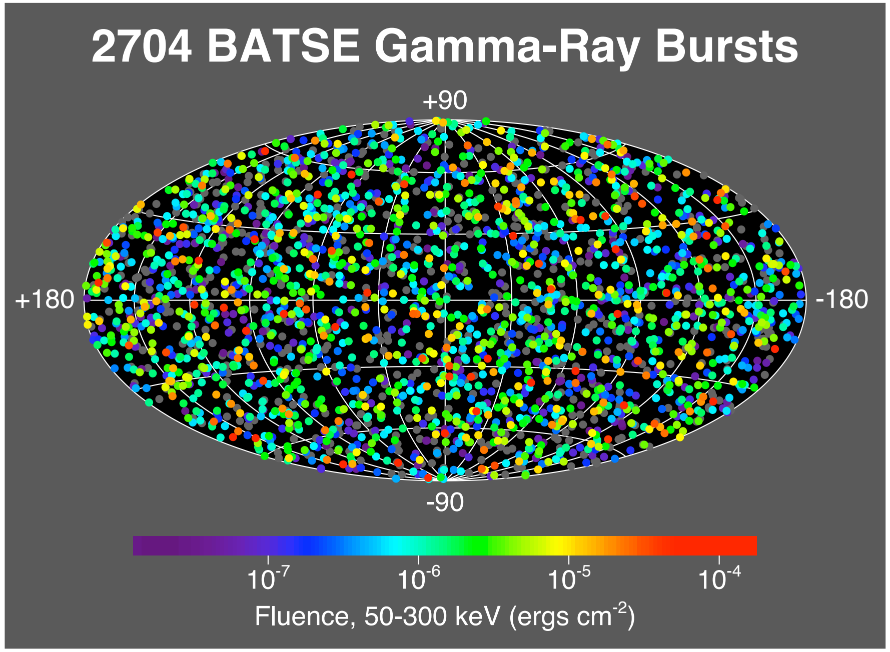

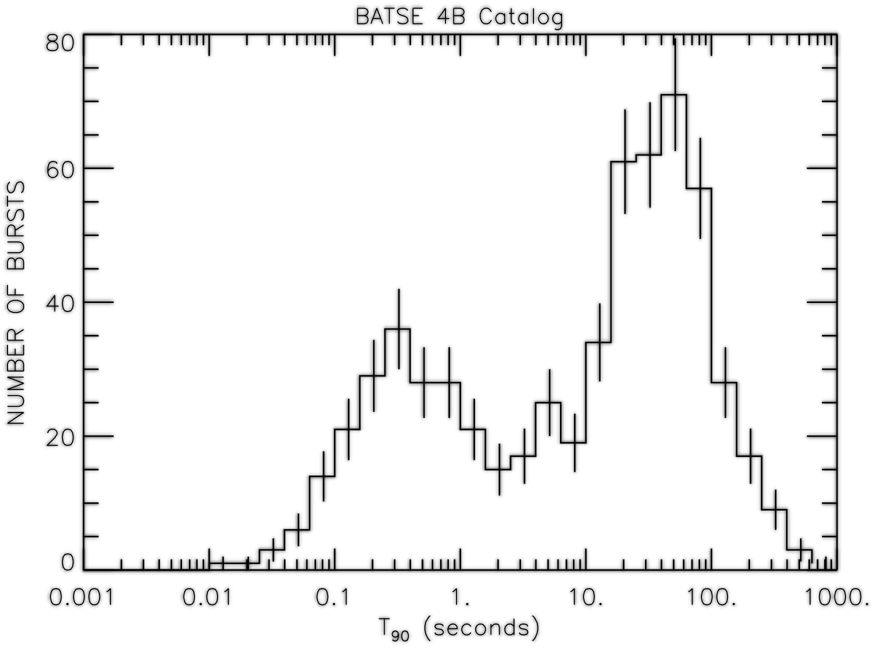

The Experiment: H gas

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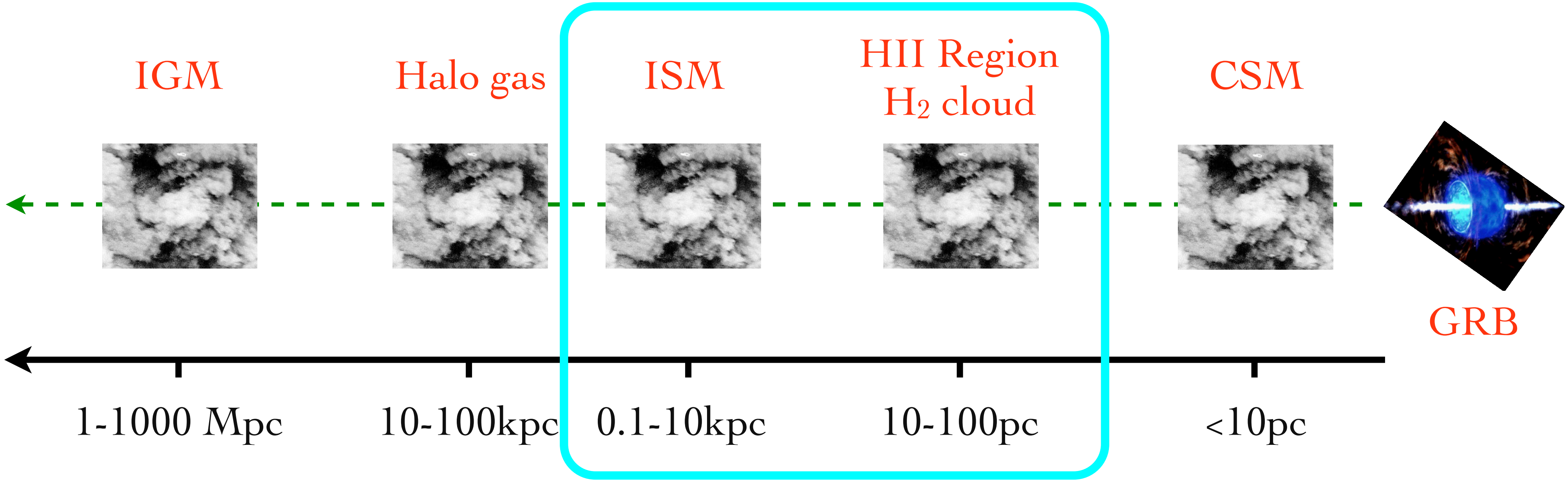

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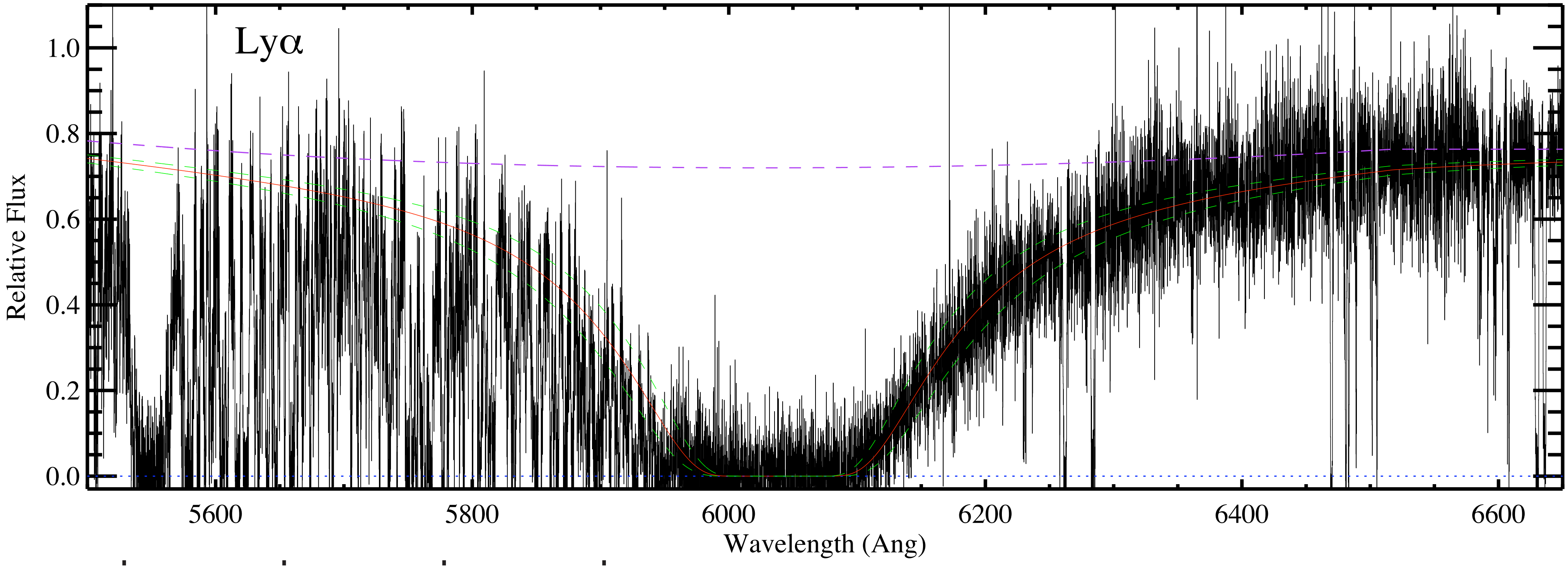
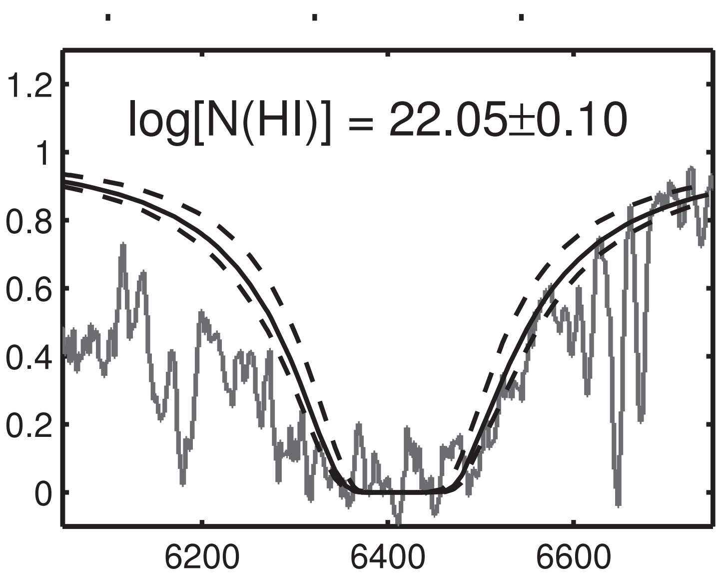
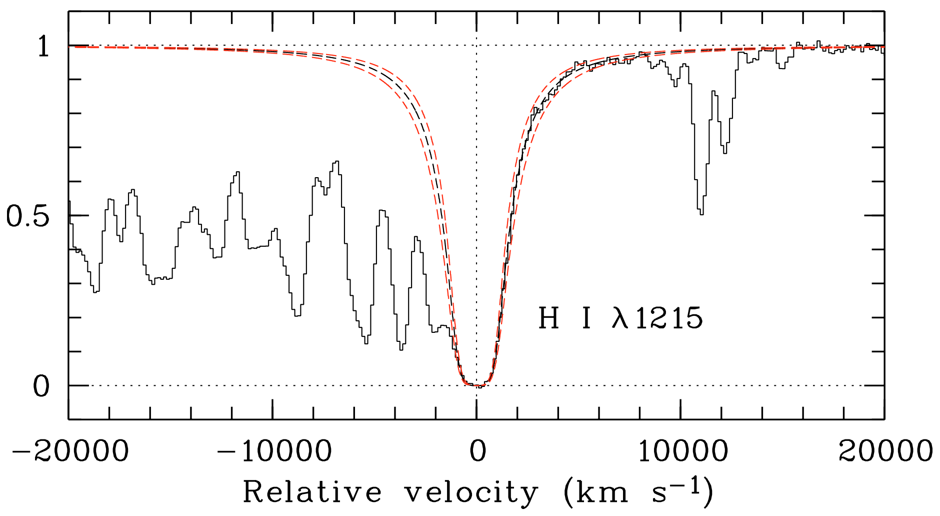
Large HI Column Densities



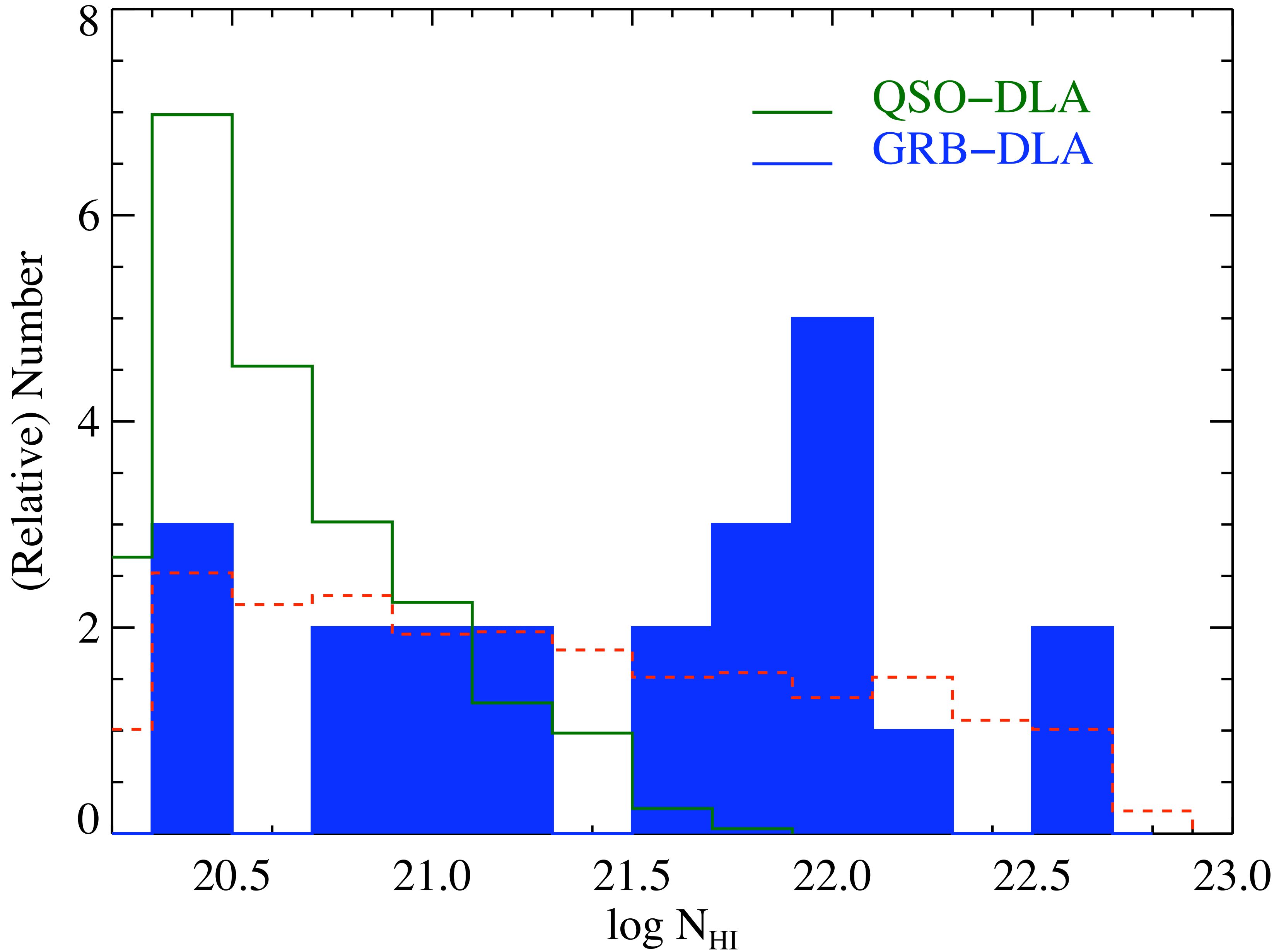




HI Column Densities

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

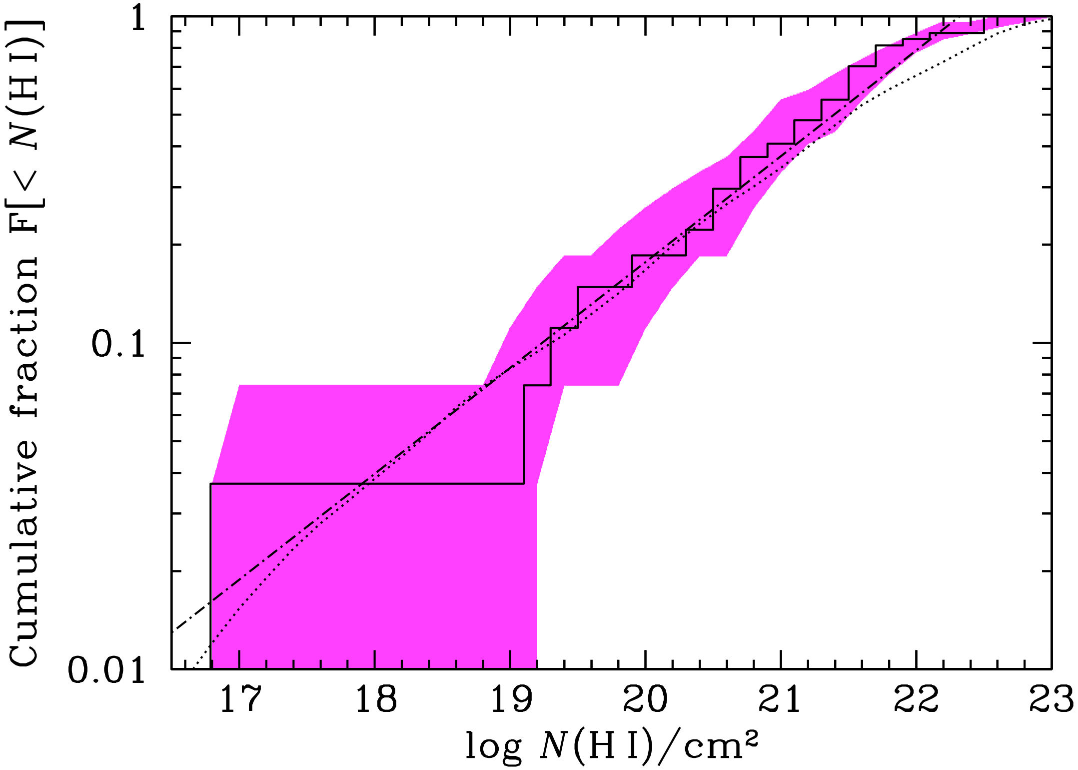
Large N_{HI} due to a SF Region?



Toward Measuring the EUVB

- EUVB
  - Extragalacitc UV Background radiation field
- Fundamental measure for many IGM applications
  - Power spectrum from Lya forest
  - Baryonic budget
  - Metal enrichment of the IGM
- Current estimates
  - Primarily indirect methods
    - e.g. Source counting
  - Uncertainty: 100% or more

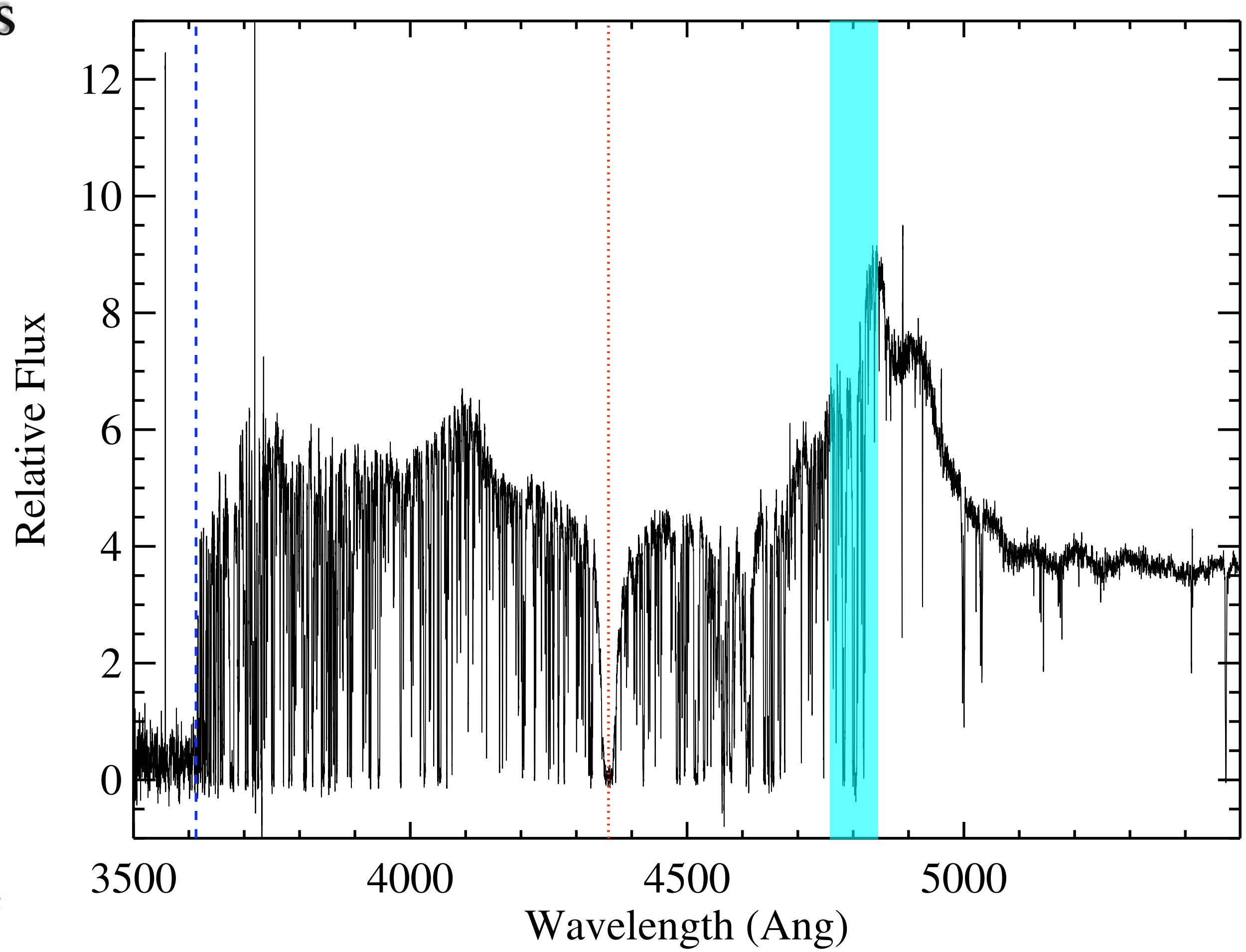
Chen, Prochaska, & Gnedin (2007)



Measuring Γ: Proximity effect

- Definition
  - Over-ionization of the gas near a QSO
    - Along its sightline
  - Measurement of Γ
    - IGM attenuation is relative
    - Analysis gives Γ/L_{QSO}
- Challenges
  - Small sample size
  - QSOs occur in highly biased environments
    - Enhanced absorption
    - Compromises the technique

Carswell et al. (1987)
Scott et al. (2000)

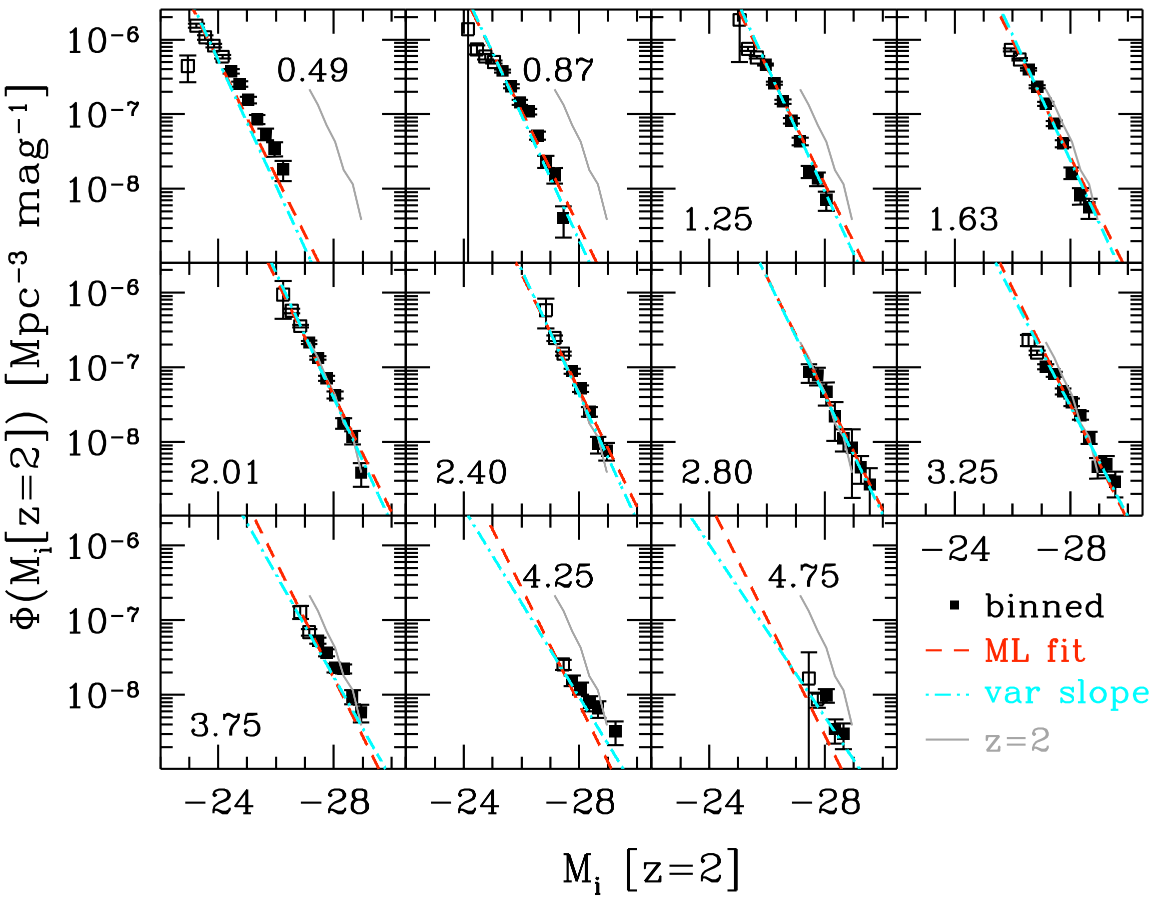


Pascarale et al. (2000)
Faucher-Giguere et al (2007)

Measuring Γ: Photon counting

- Quasars
  - Well-determined luminosity function at z=3
    - ✦ With well characterized spectra
  - Escape fraction?
    - ✦ Observed to be high
- IGM opacity
  - Lyman limit systems (SDSS)
- Galaxies
  - Good UV luminosity func.
    - ✦ At least to 0.1 L*
    - ✦ Steep: $\alpha < -1.6$
      - ➡ Low L galaxies may be key
  - Escape fraction
    - ✦ Poorly constrained

Richards et al. (2005)



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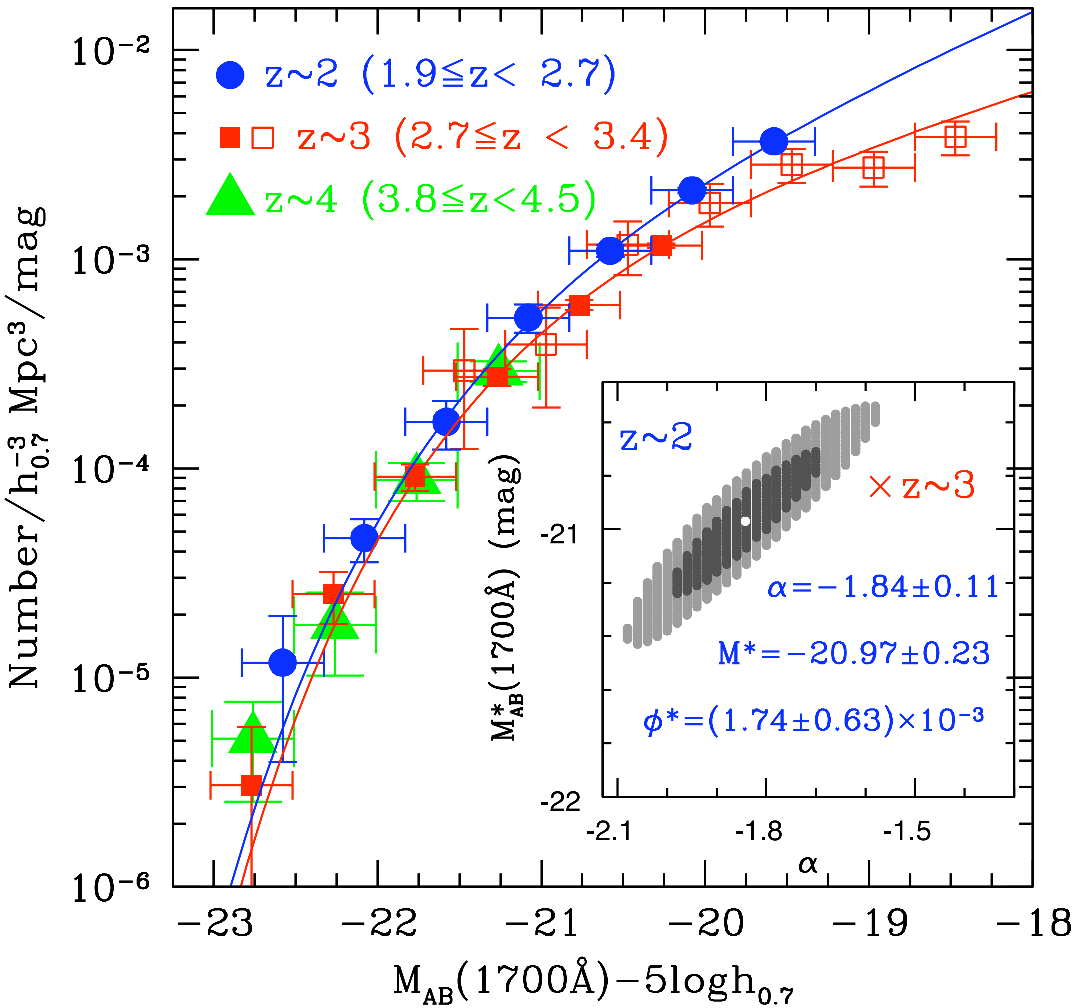
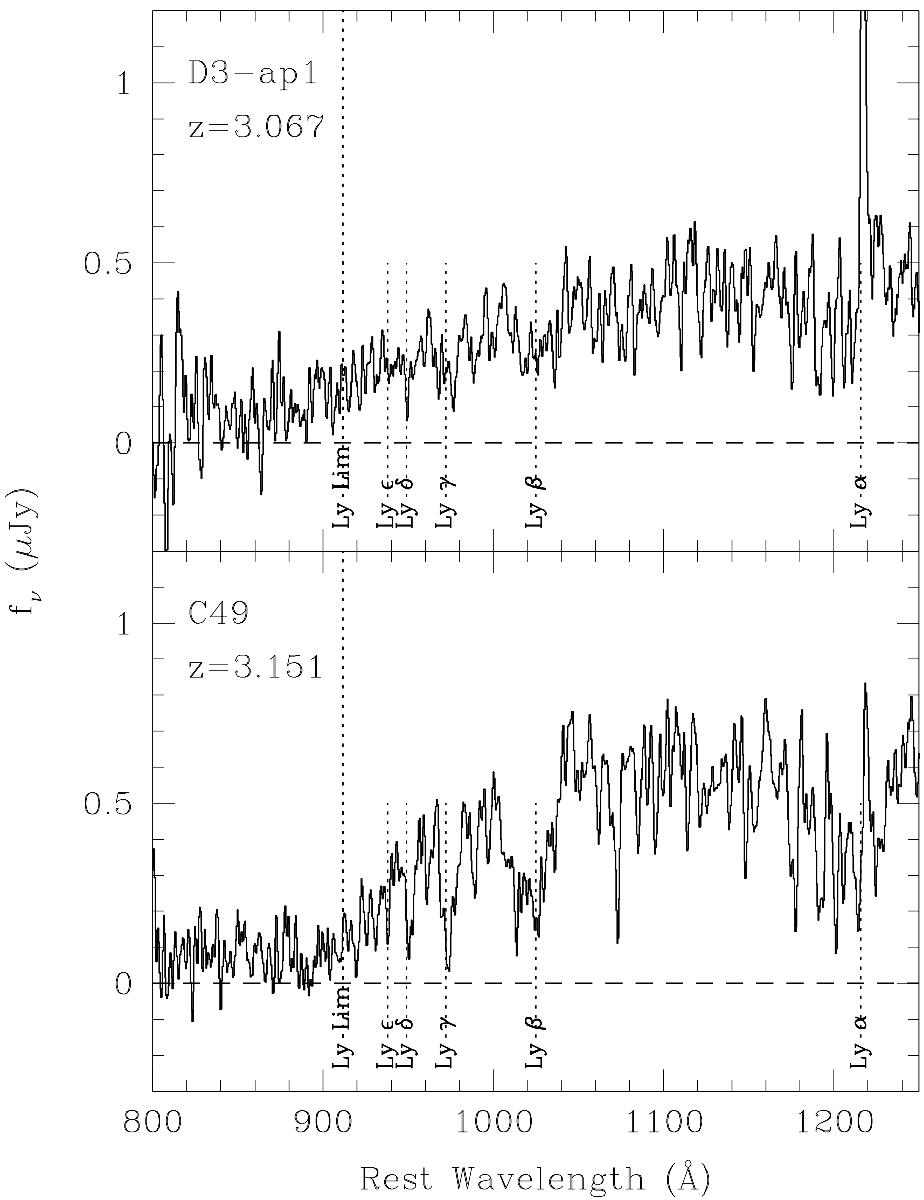
Reddy et al. (2007)



Galactic Escape Fraction

- Lyman break galaxies
  - IGM => Spectra required
  - Current results:
    - L>L* galaxies
    - Small fraction detected (2 of 14)
      - ➡ Too rare to dominate Γ
- z=1.3 galaxies
  - ACS UV imaging
    - (IGM sufficiently weak)
  - Sub L* galaxies
    - $f_{esc} < 10\%$

Shapley et al. (2006)



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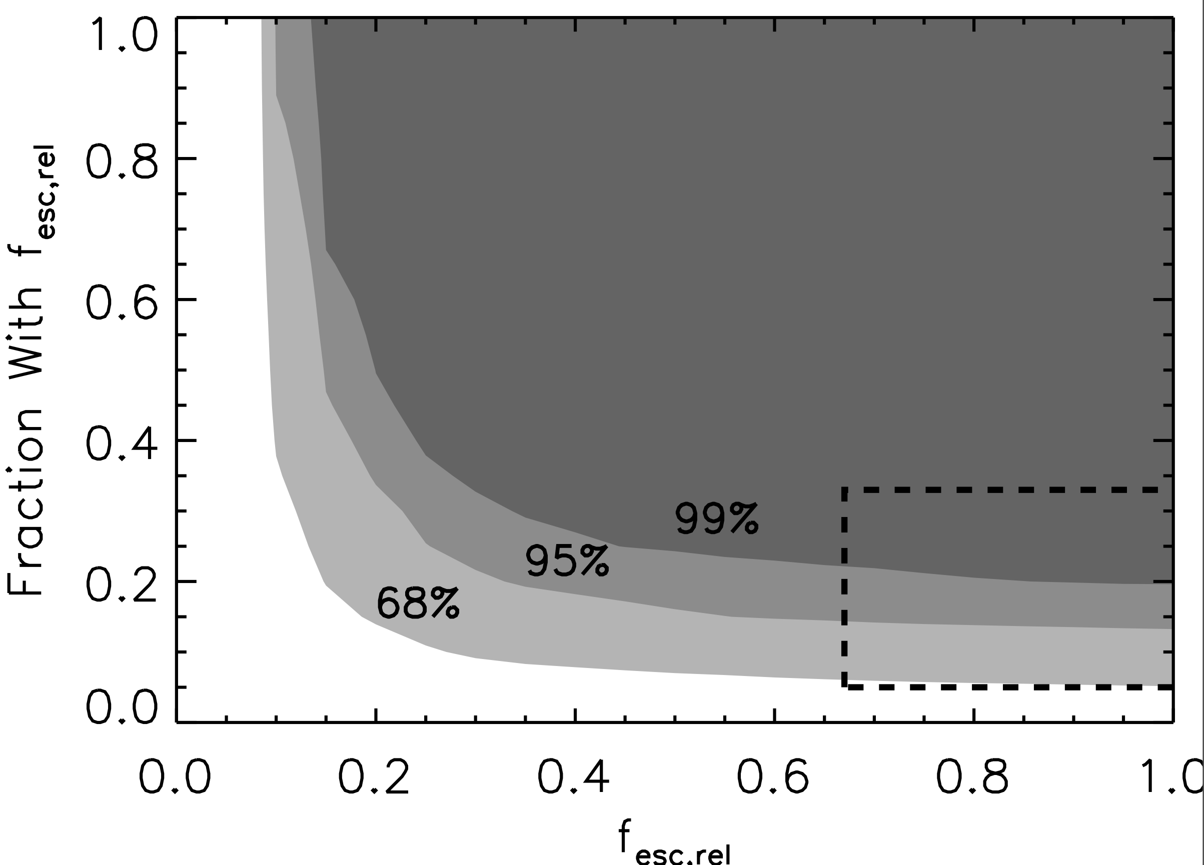
Siana et al. (2007)

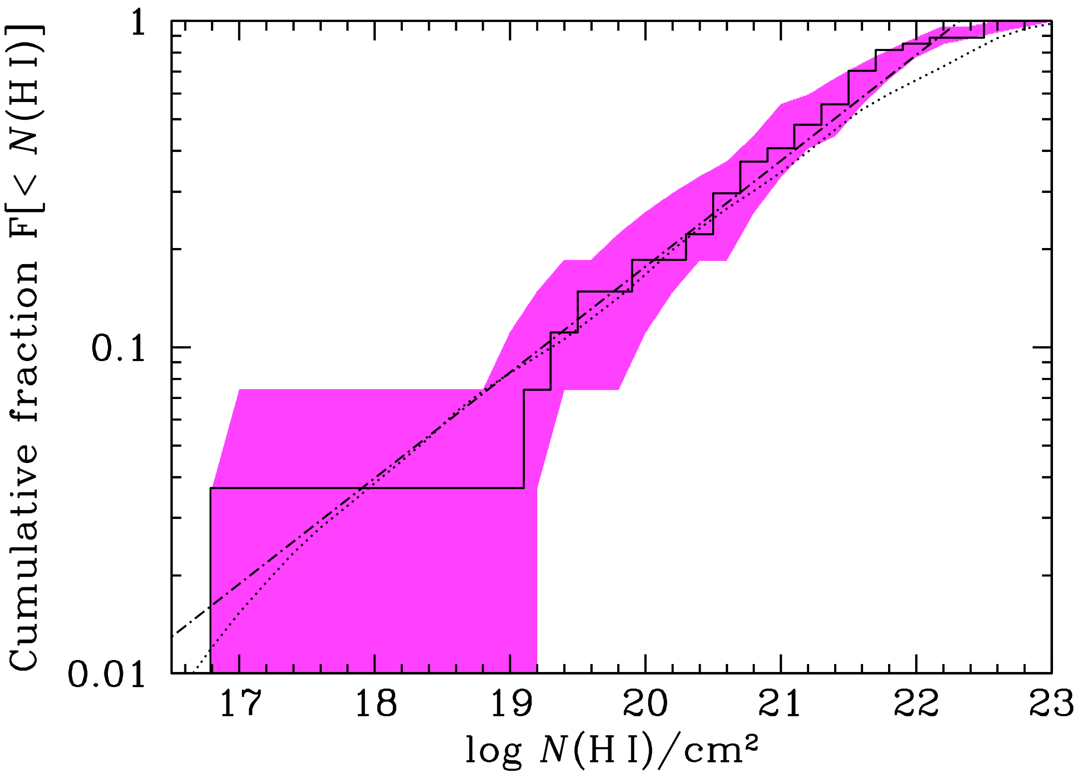


Escape Fraction from GRBs

- GRB sightlines originate in SF regions
  - Trace massive stars
    - i.e. Dominant UV sources
  - Assume random orientations
- Survey GRB sightlines
  - Not restricted to the brightest galaxies at z>2
  - Measure the rate of optically thin sightlines

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

Chen, Prochaska, & Gnedin (2007)



- Current results
  - 1 optically thin sightline in 30
  - $f_{esc} < 0.08$ (95% c.l.)
    - But this may easily dominate bright, SF galaxies

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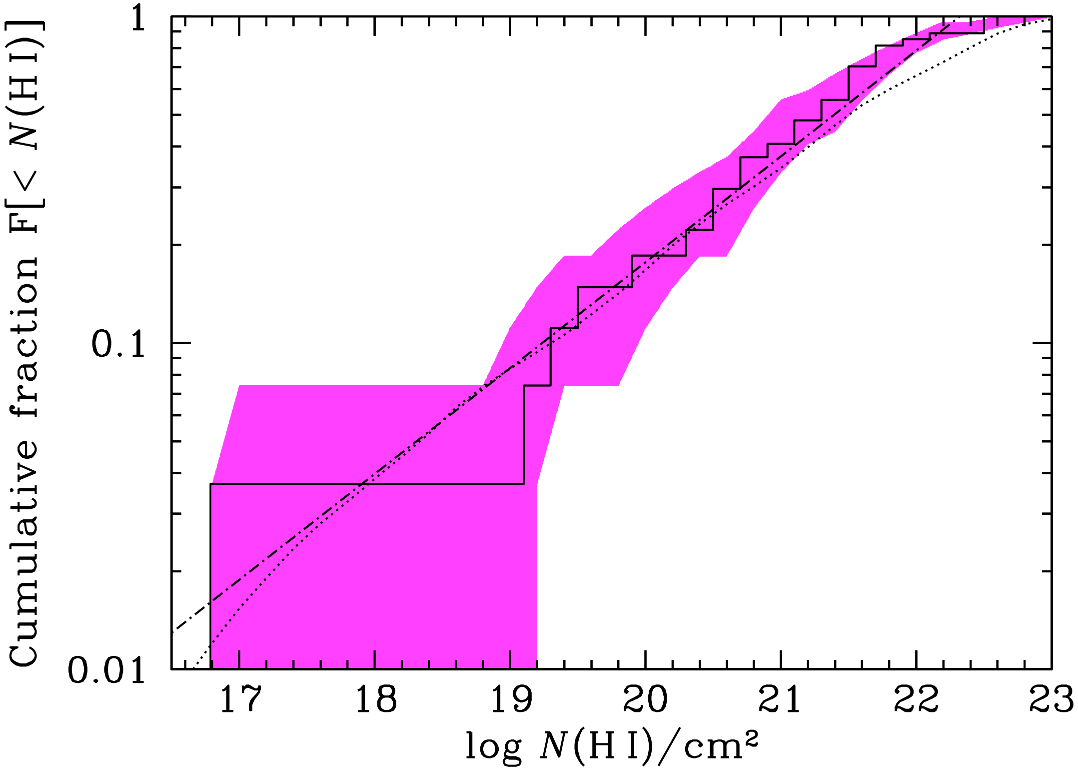

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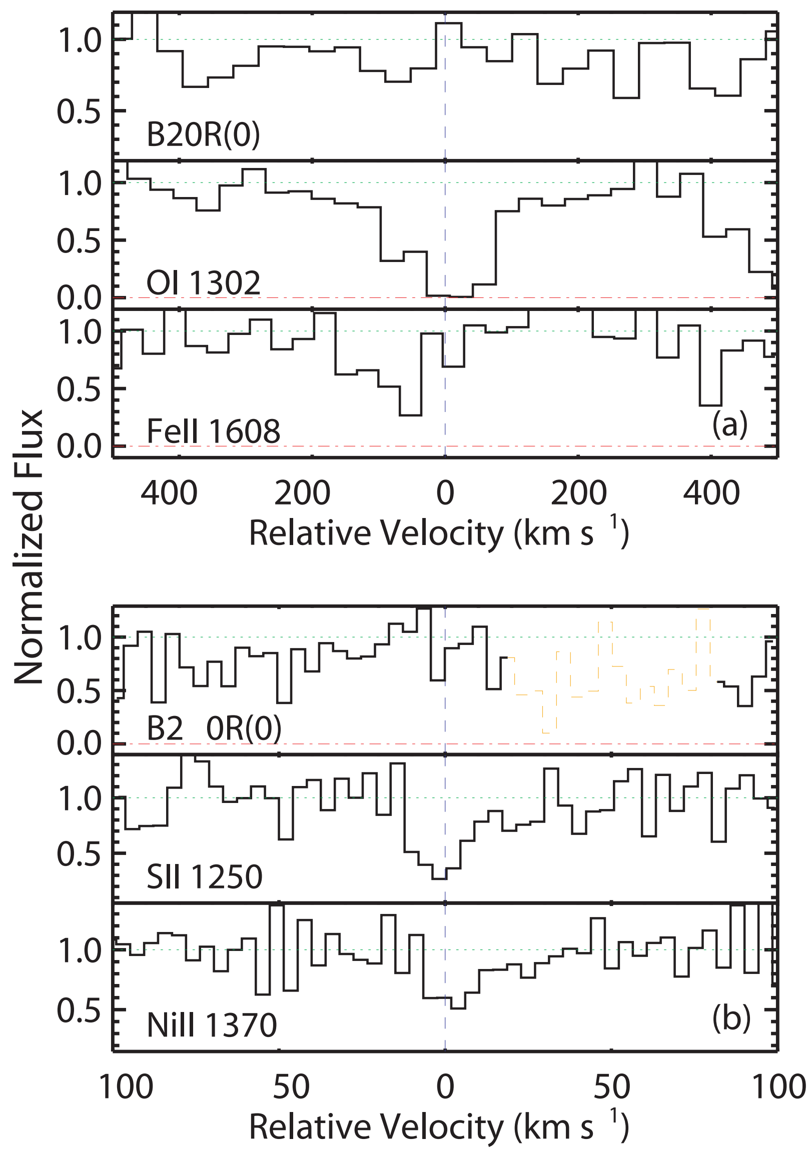
H_2 in SF Galaxies?

Tumlinson et al. (2007)

- 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



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)

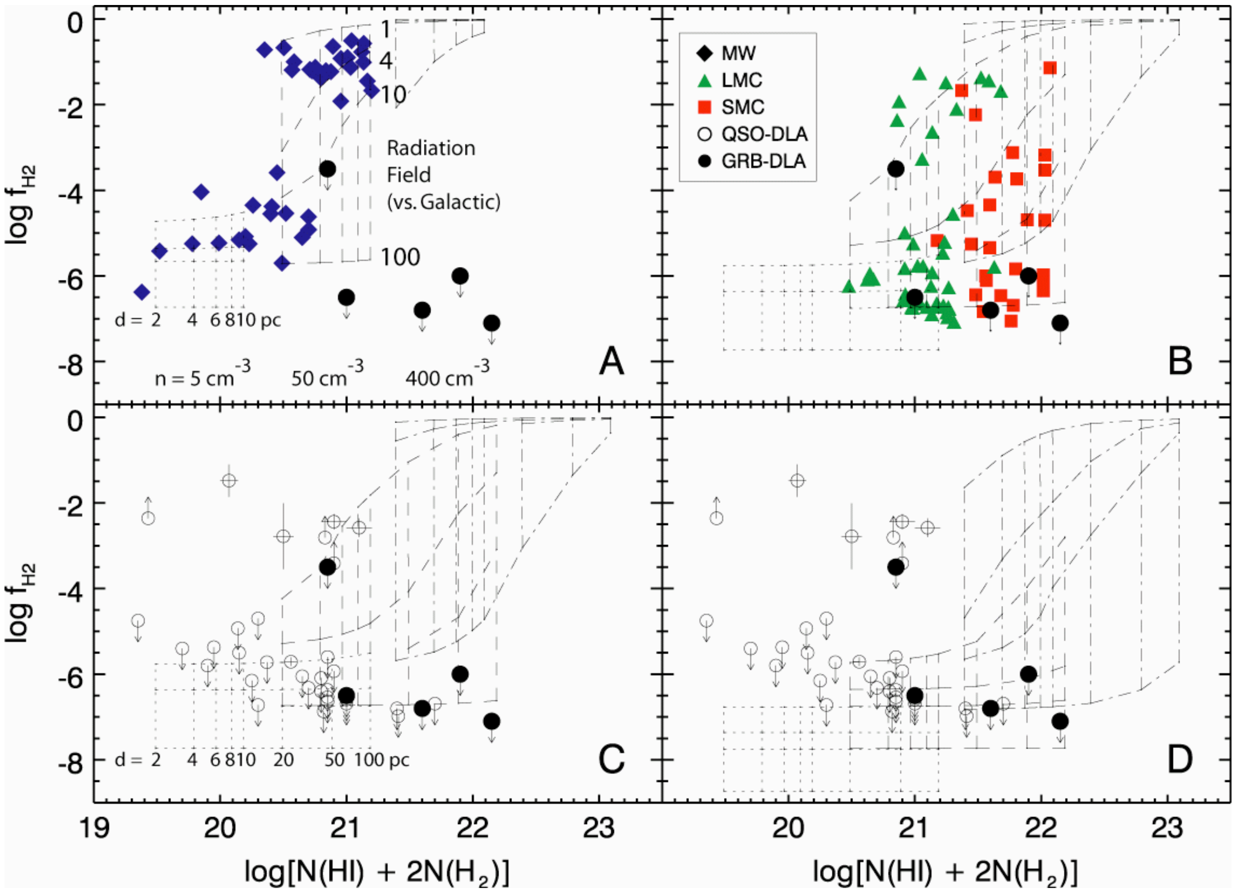
[a]Metallicity derived from Si, S, or Zn abundance (see Prochaska et al. 2007a).
[b]See Prochaska et al. (2006).
[c]With the exception of 060206, the values represent 4σ statistical upper limits.
[d]Upper limit (4σ) based on non-detection of either L0-3P(1) at 1276.82 Å or L0-3R(2) at 1276.33 Å (see 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
  - No H_2
- 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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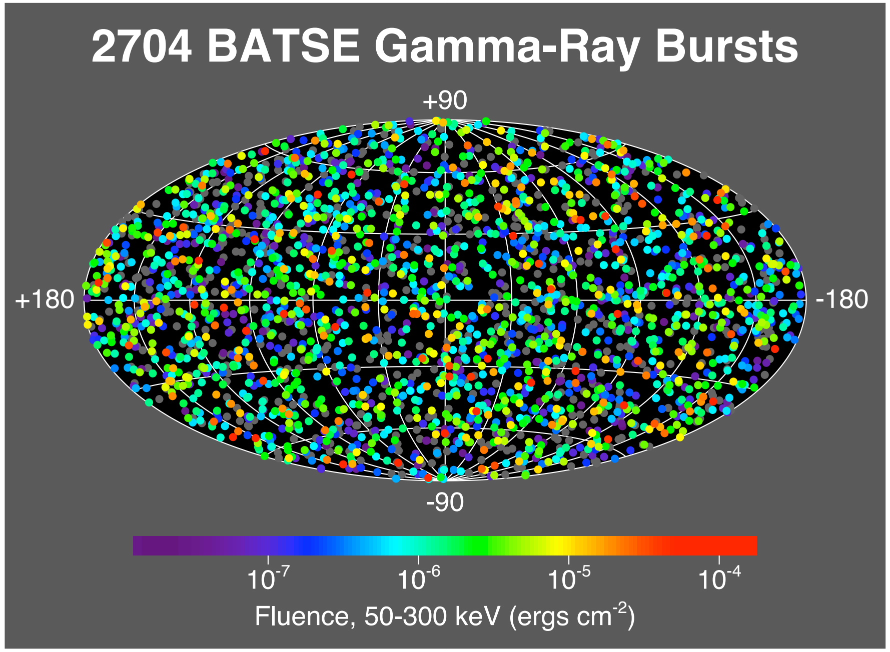

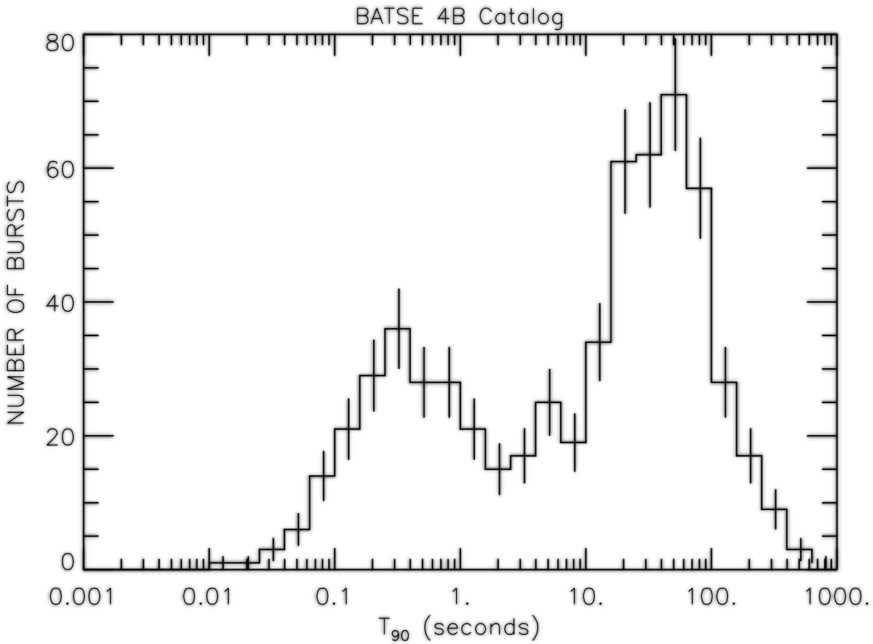

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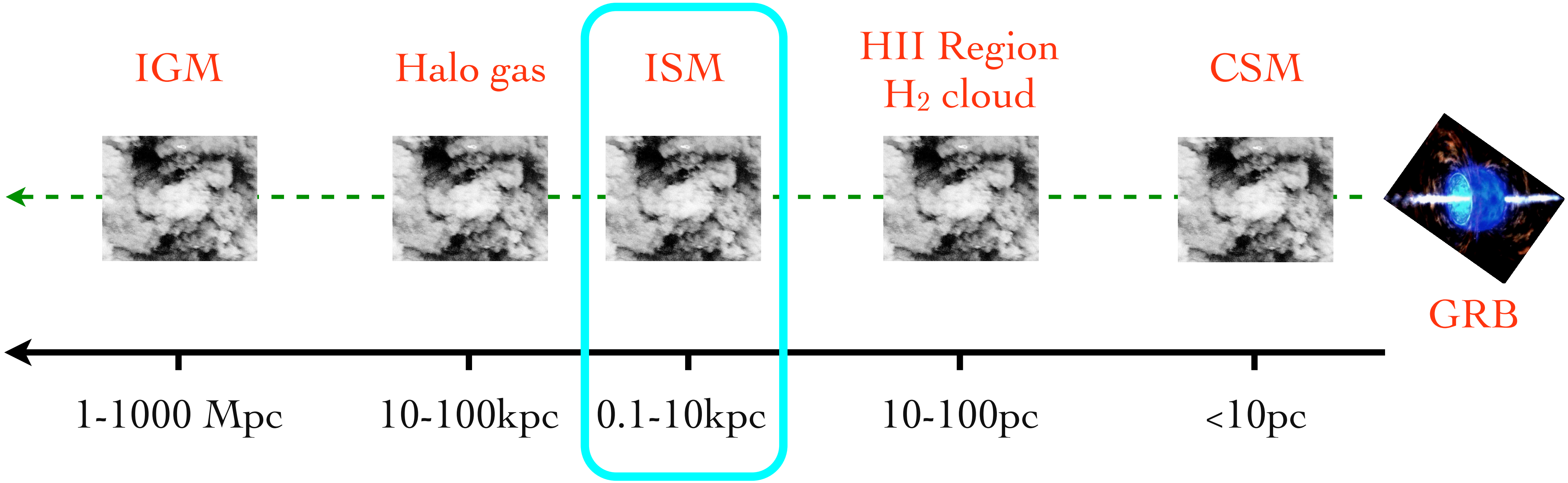

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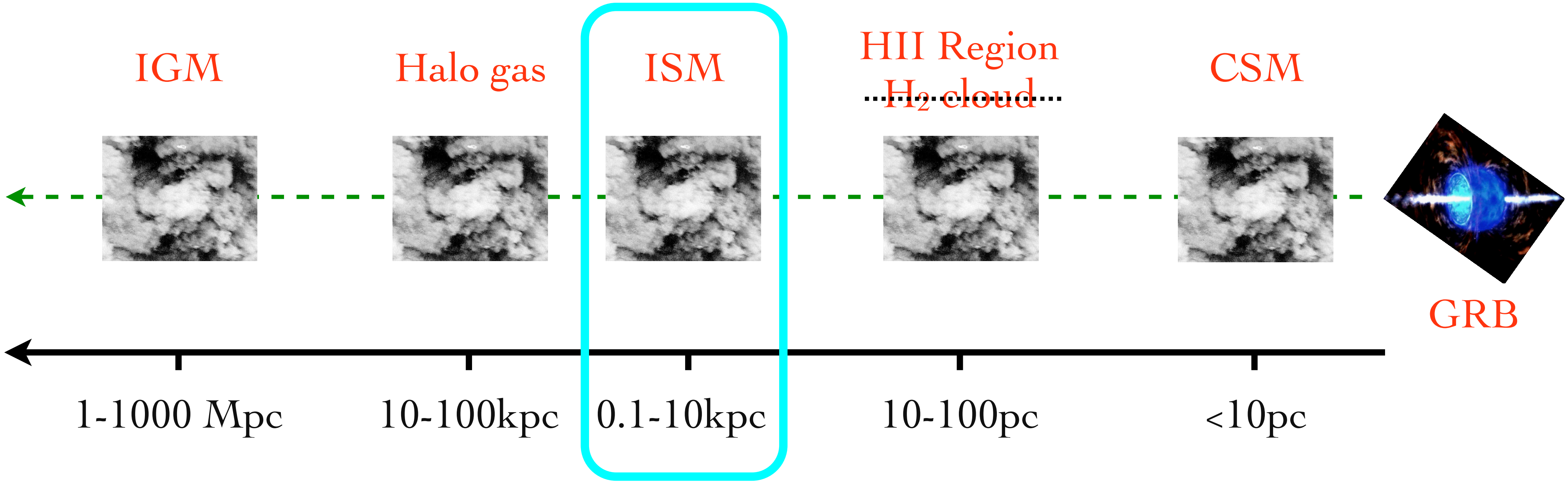

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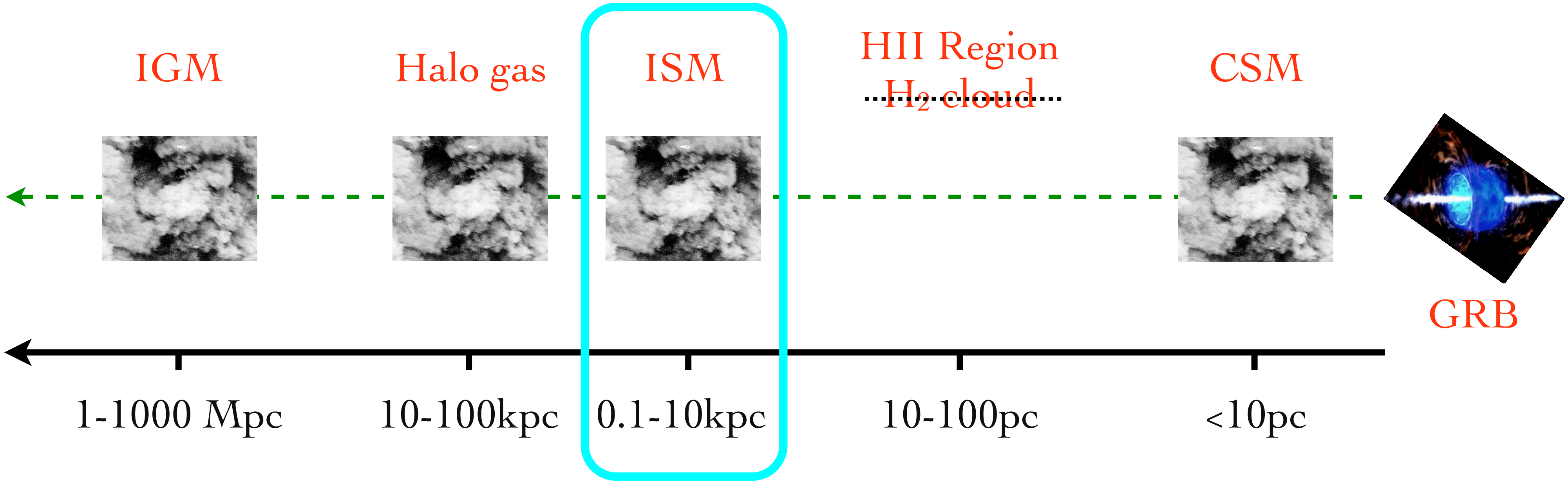

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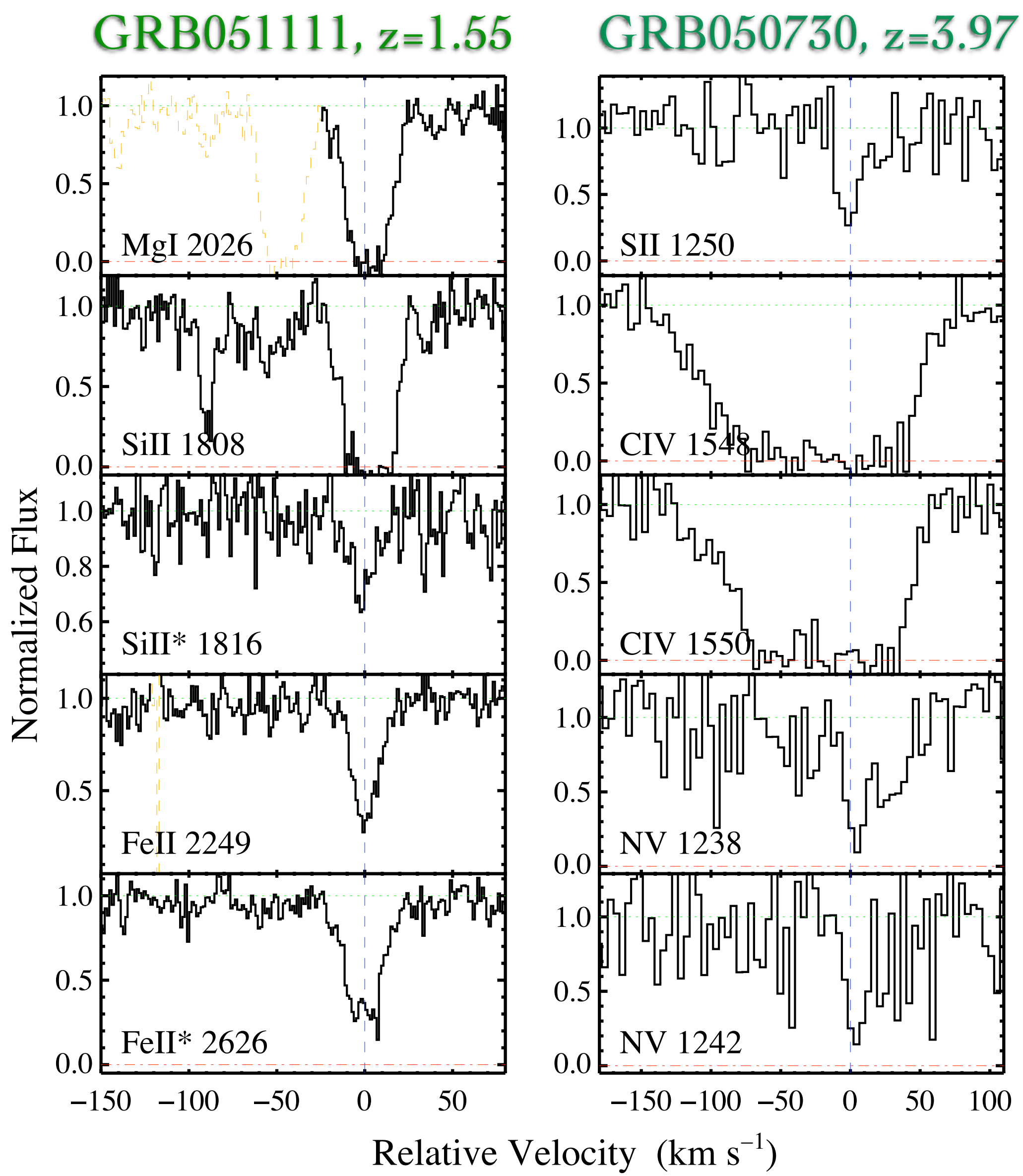
Metal-line Transitions

- 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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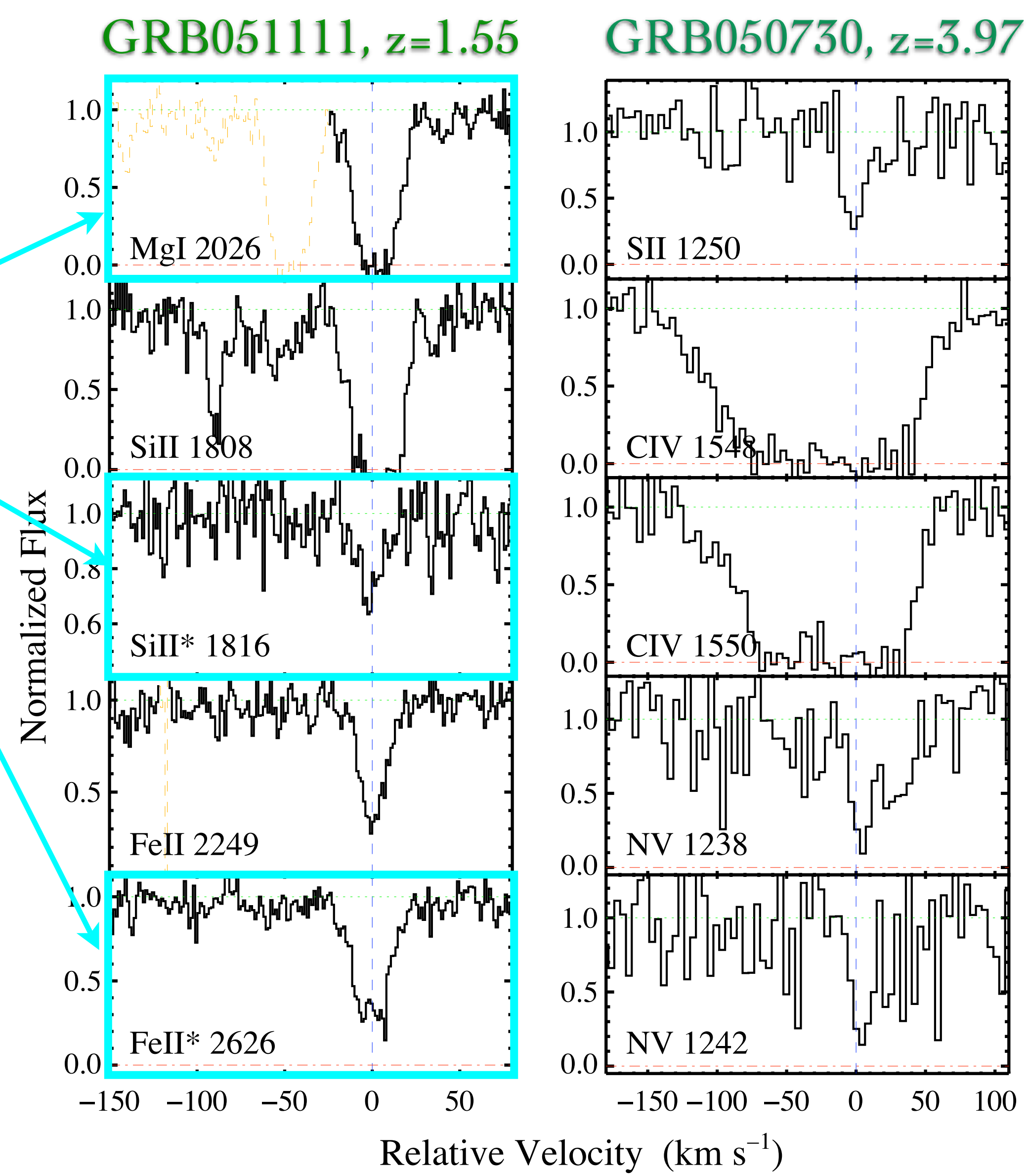

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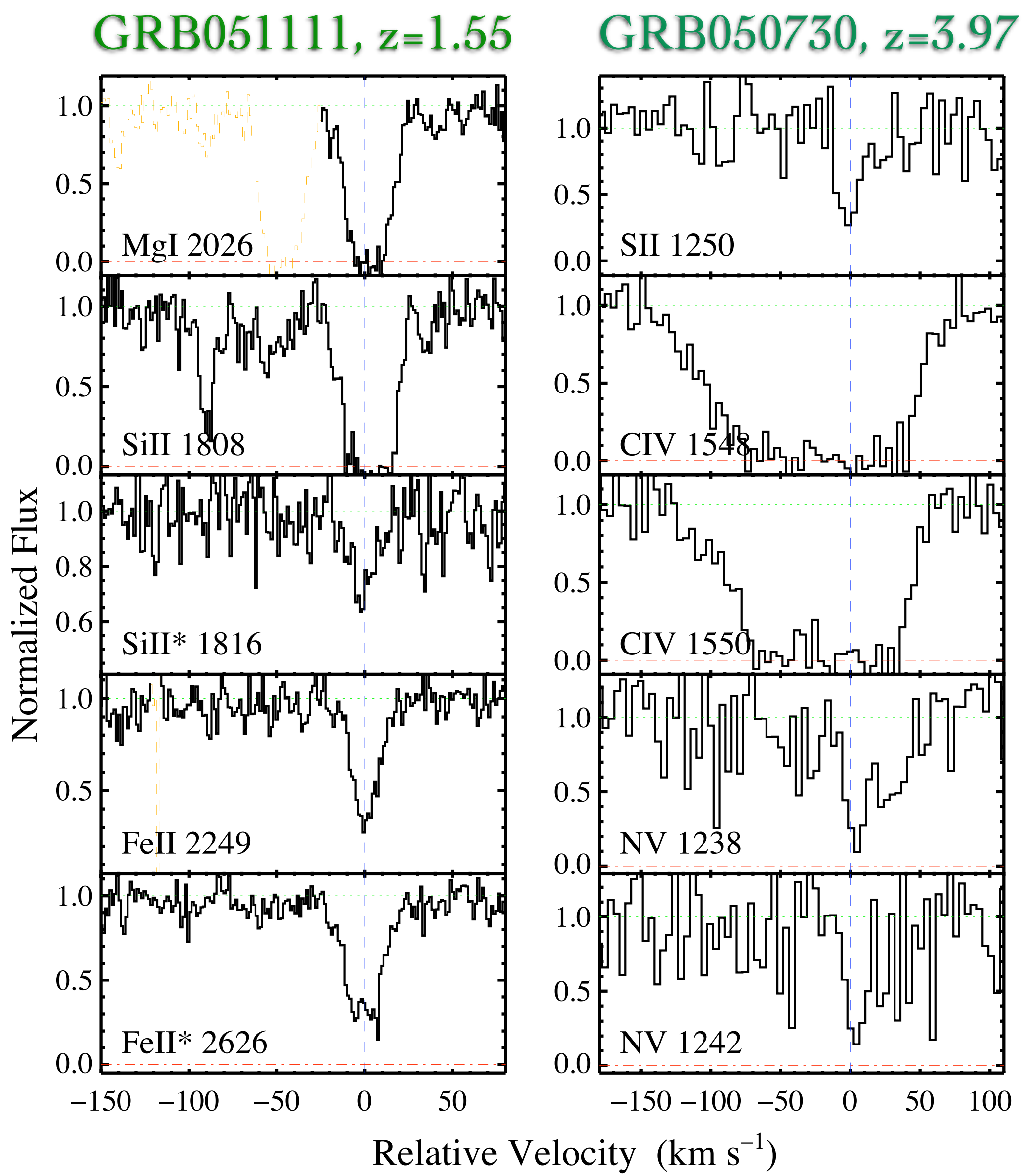

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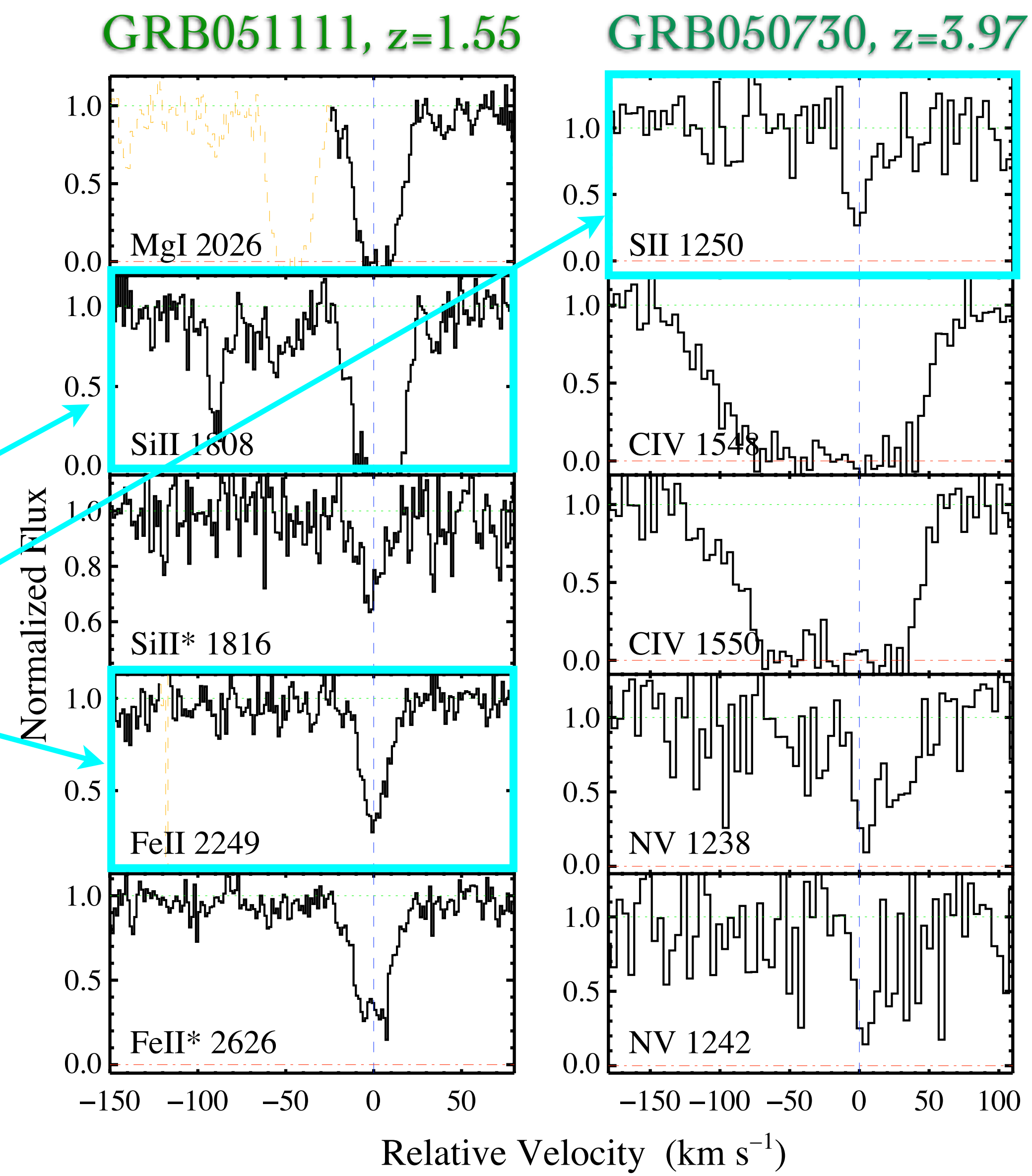

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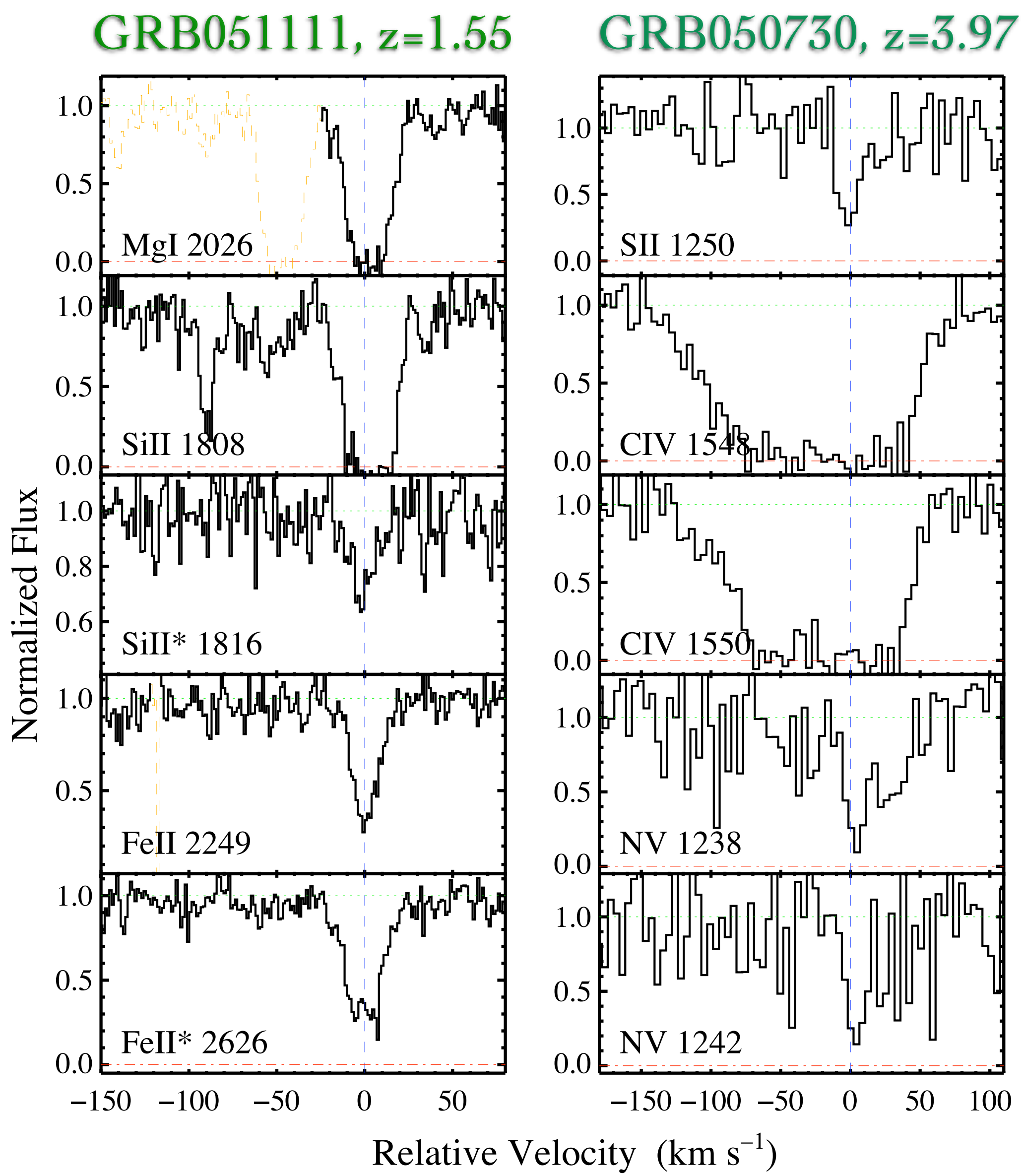

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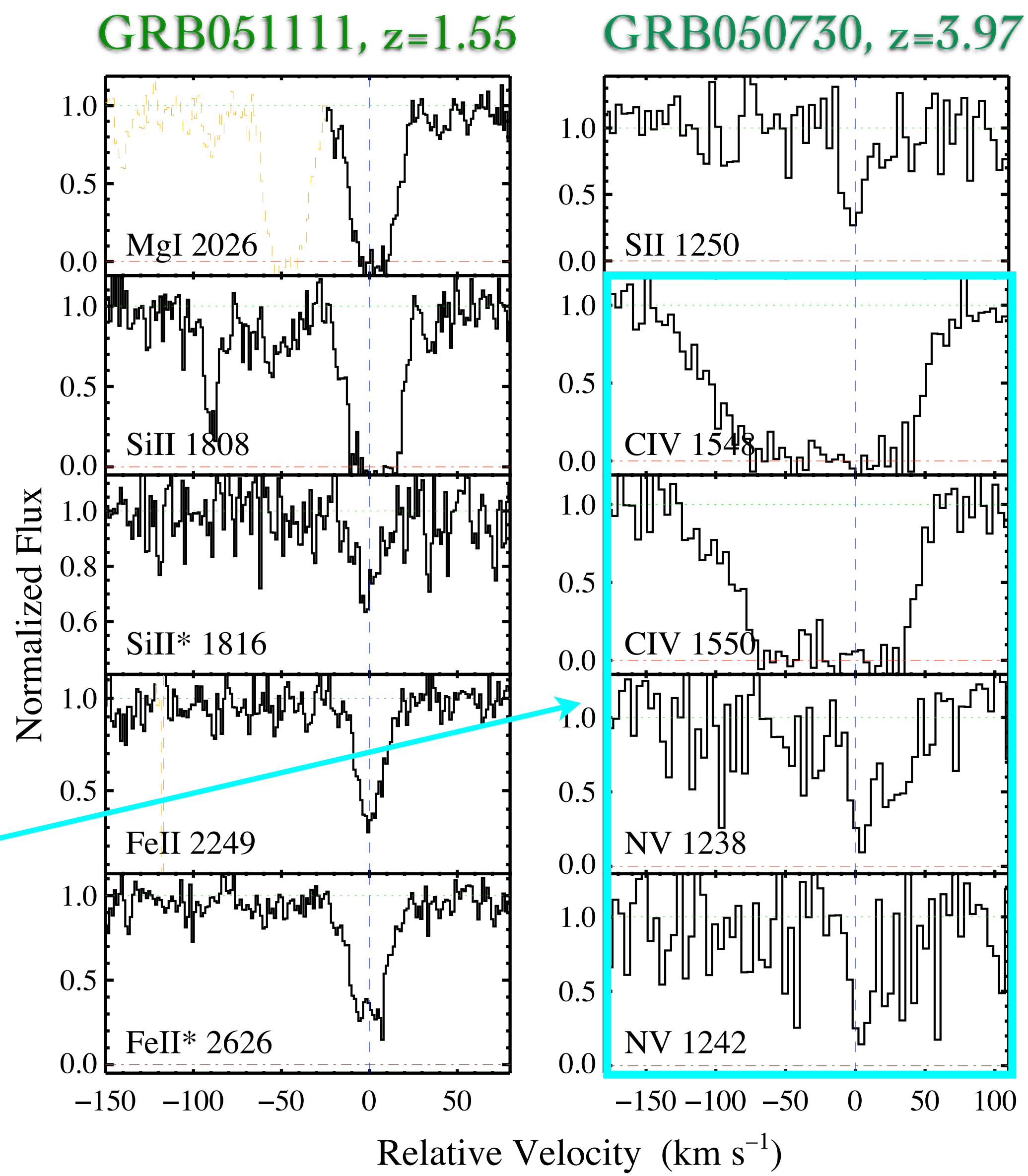

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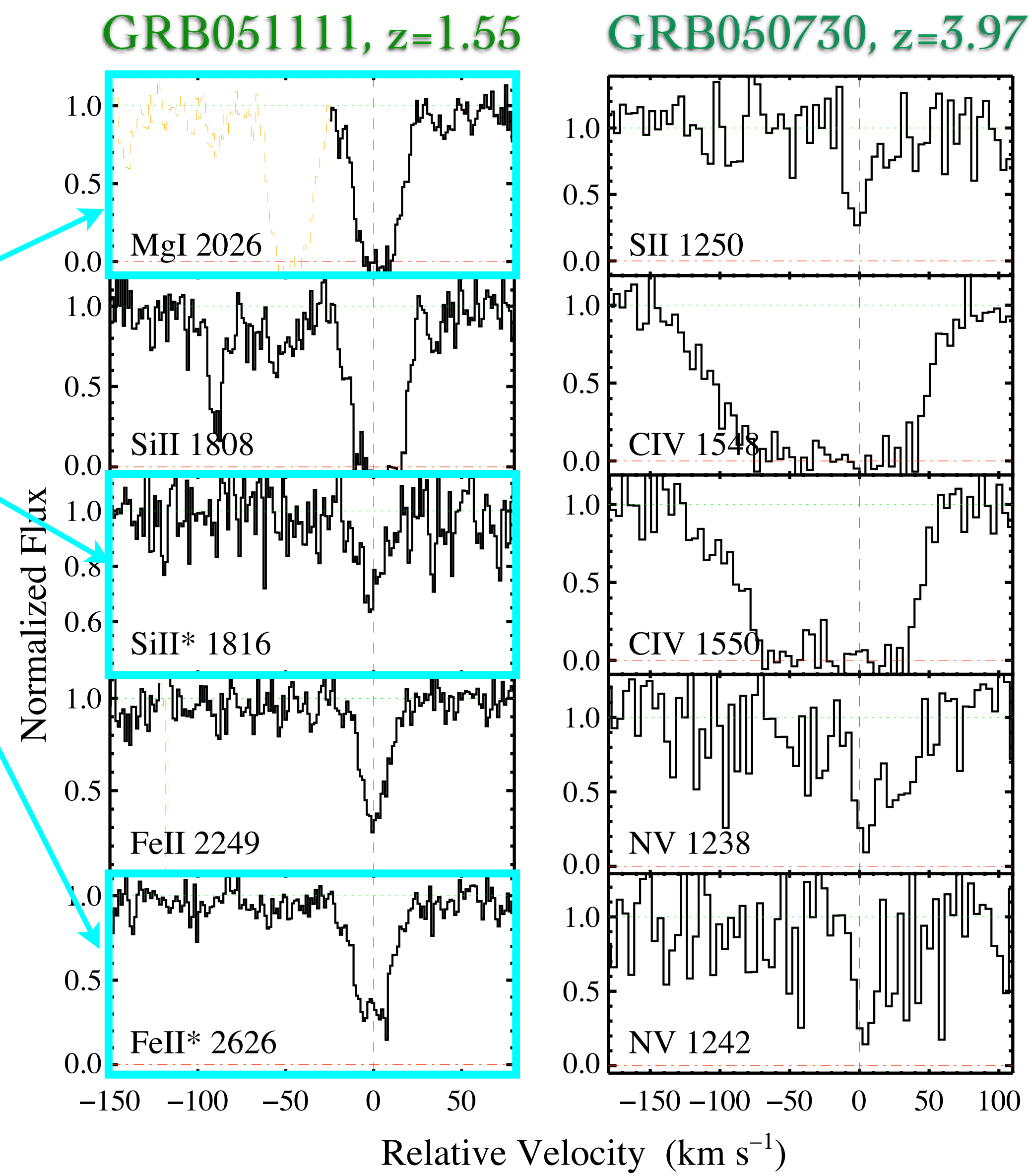
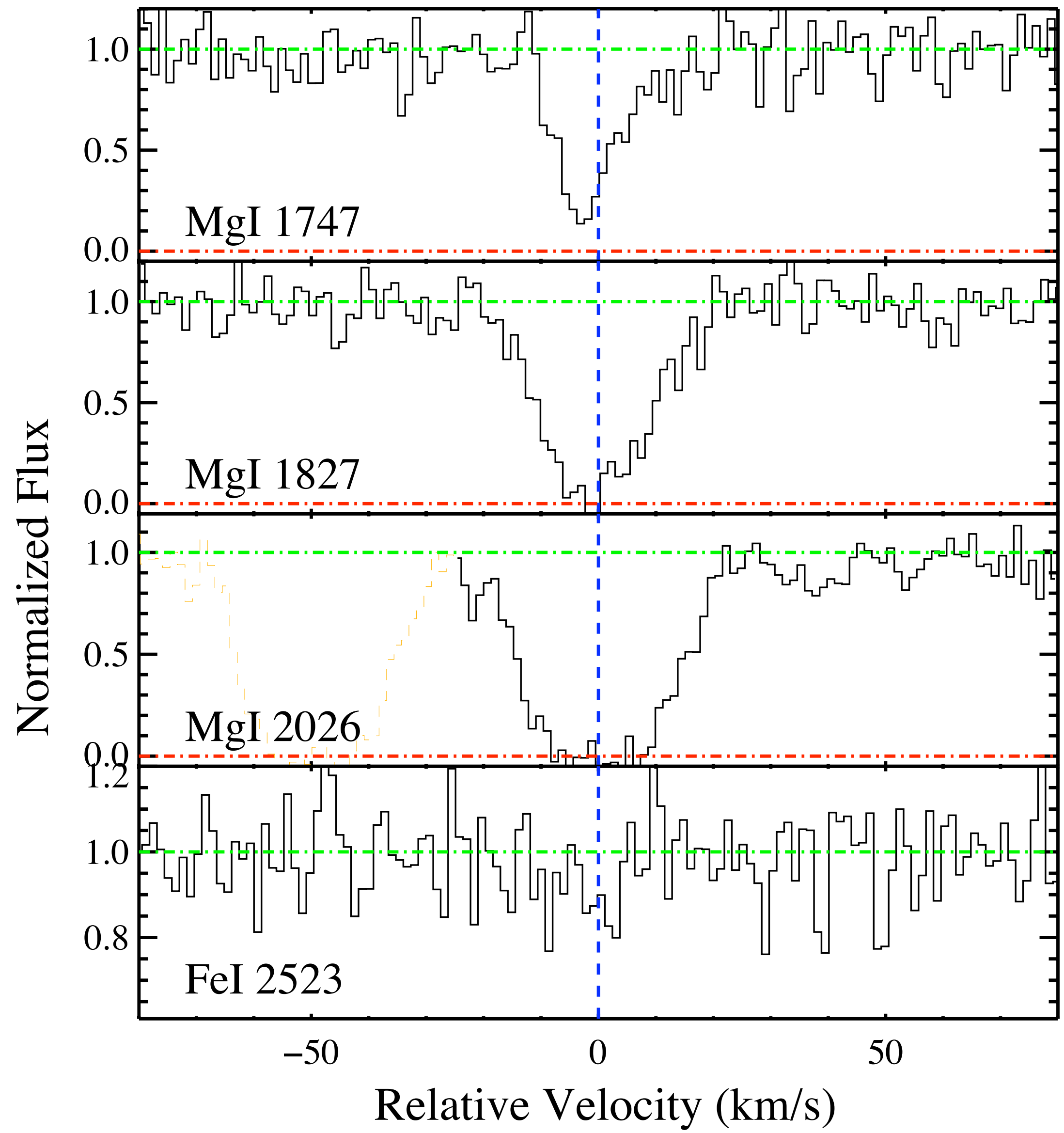


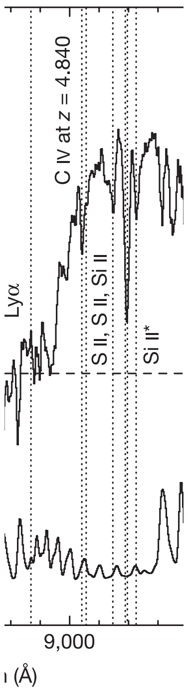
MgI Detection

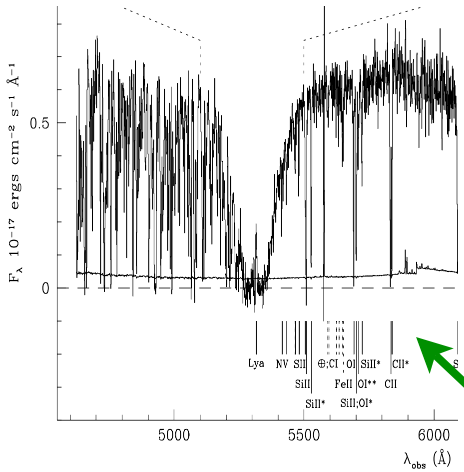
- Very large Mg$^{\circ}$ column
  - Detected in several transitions
  - N(Mg$^{\circ}$) = $10^{14.7}$ cm^{-2}
- IP(Mg$^{\circ}$) = 7.7 eV
  - The galaxy is optically thin at this energy
  - Caveat: Dust
- At r=50pc, 99.99% of MgI is ionized in <1000s
  - Generic result for GRB
  - Detection of MgI places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



Prochska, Chen, & Bloom (2006)

Fine-structure is ubiquitous





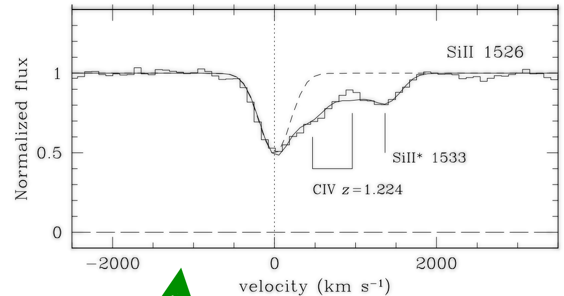
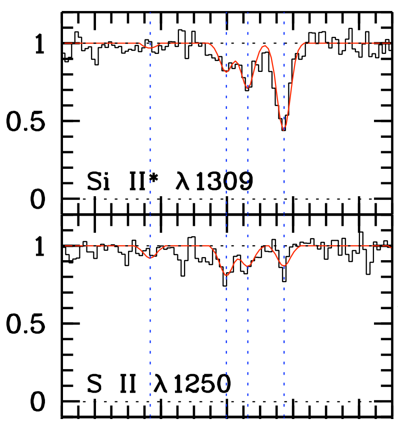
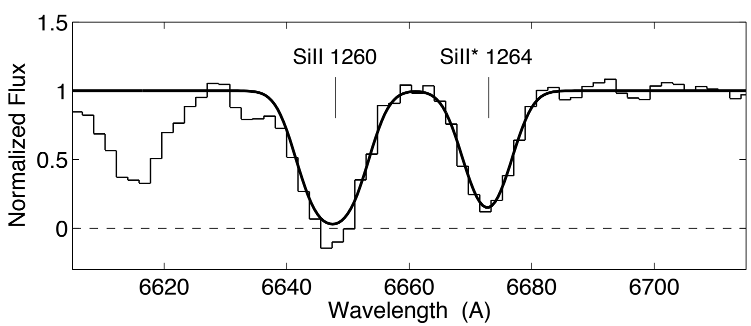
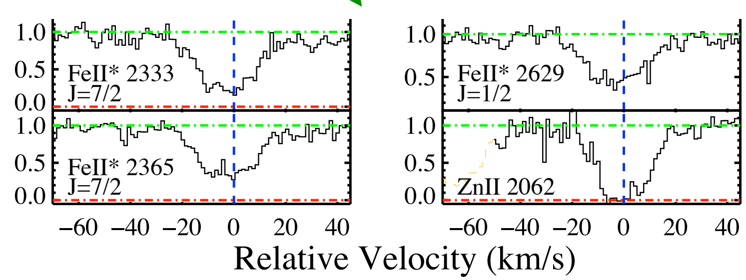


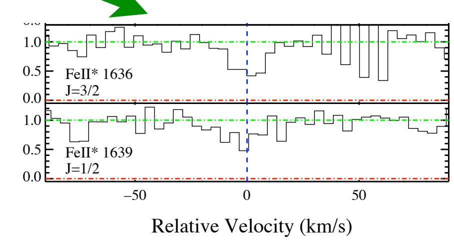
Table 3. Constraints on Circumburst Distances of Observed Neutral Gas

GRB	z	α	β	Ref	$\log L_\nu^a$ (cgs)	r^b_{MgI} (pc)	r^c_{excite} (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



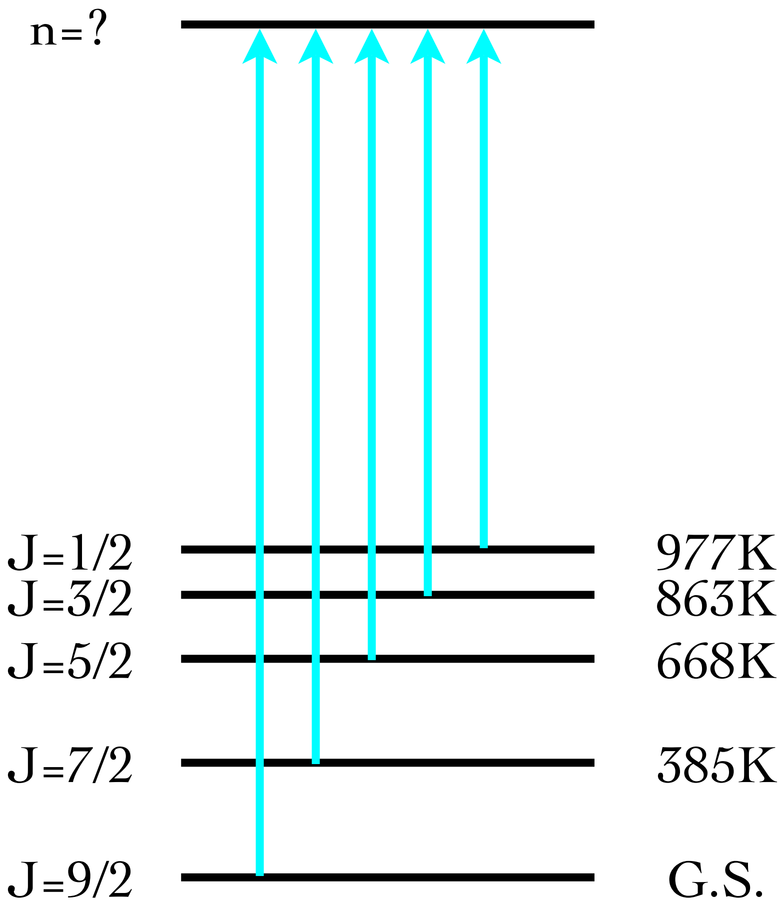






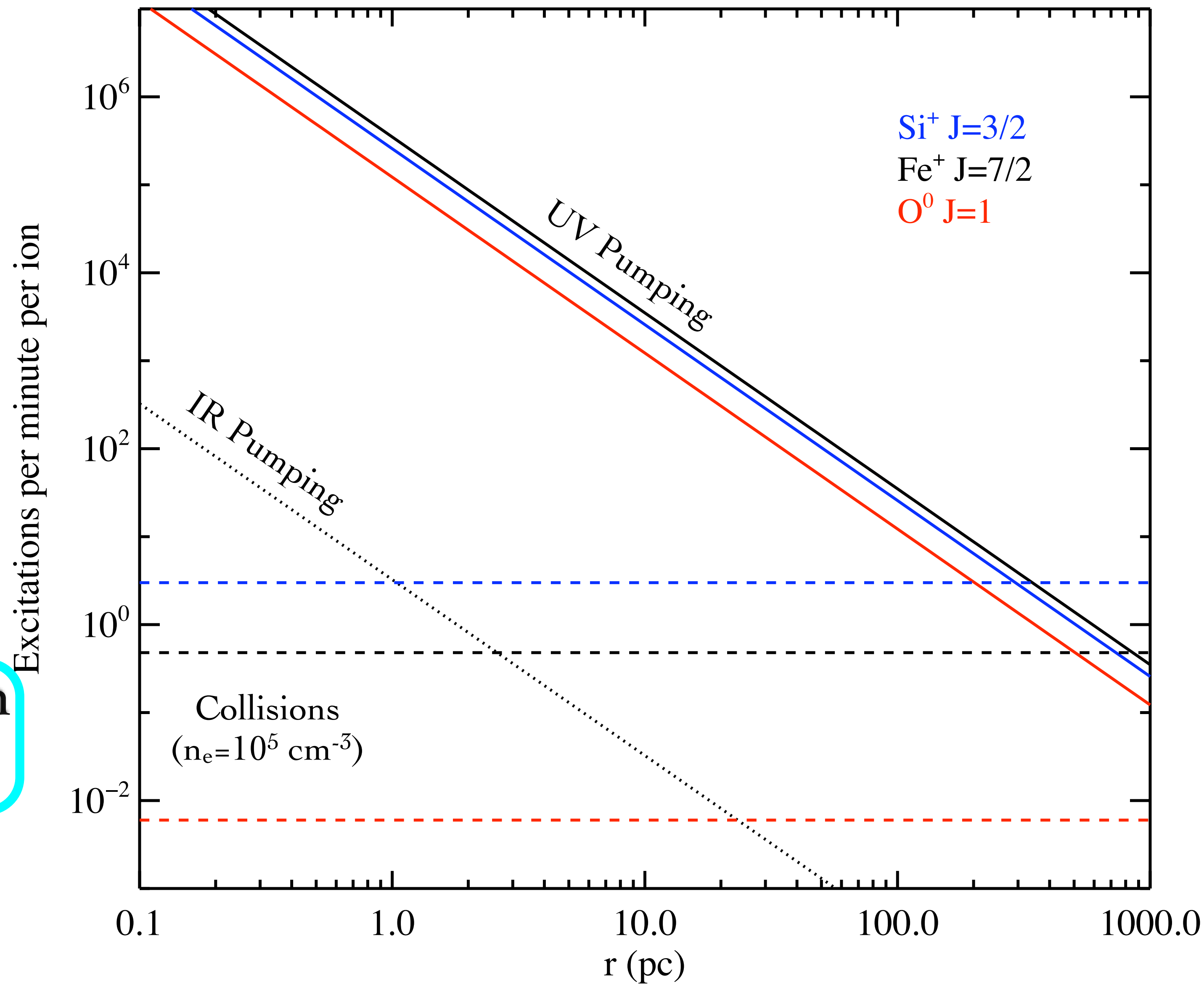
Fine-Structure Excitation

- 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
  - Key: Density and temperature



UV Pumping Dominates

- UV dominates over collisions and IR pumping
  - The gas is not high density CSM
- Turn the problem around
  - The gas arises within ~1kpc of the GRB

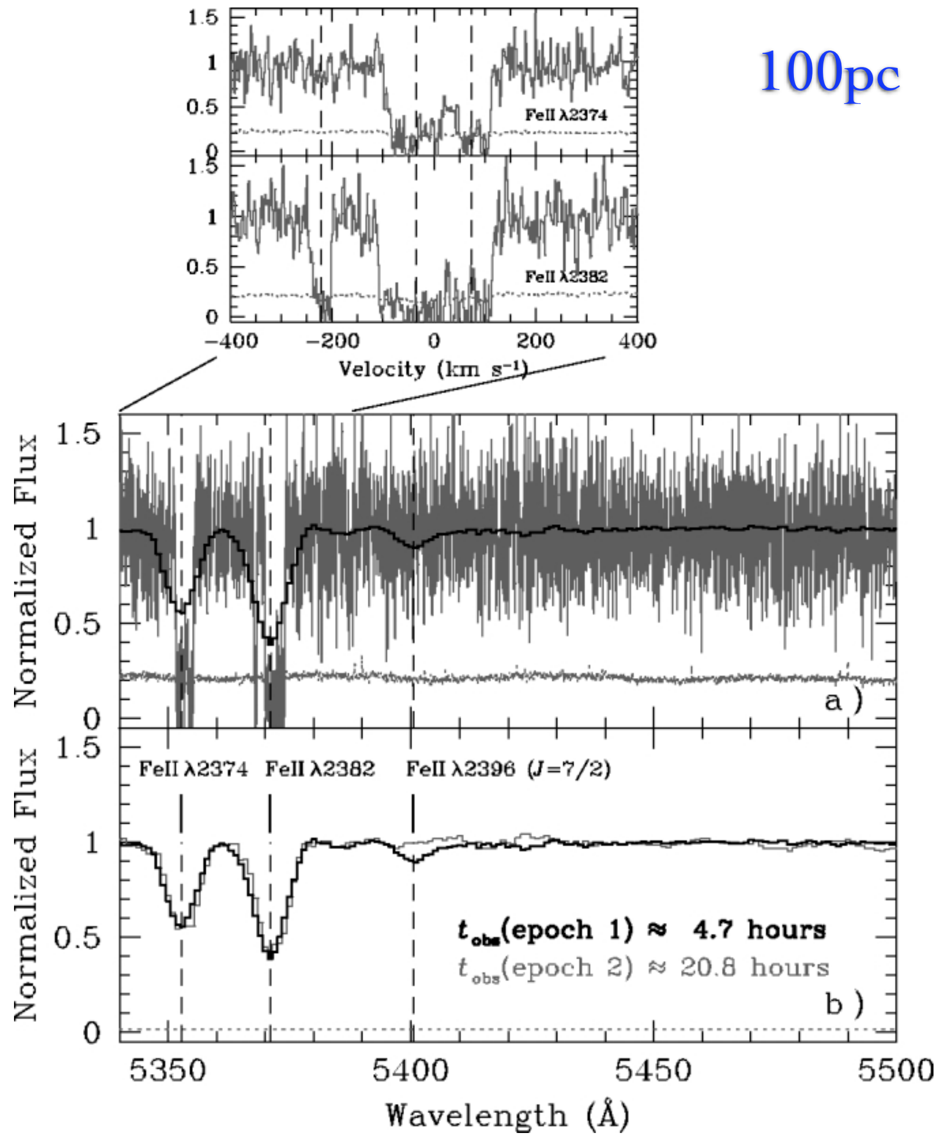


Implications of UV Pumping

- Rules out previously claimed CSM features
  - Highly ionized?
  - 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

Chen et al. (2007)

100pc



Dessauges-Zavadsky et al. (2006)

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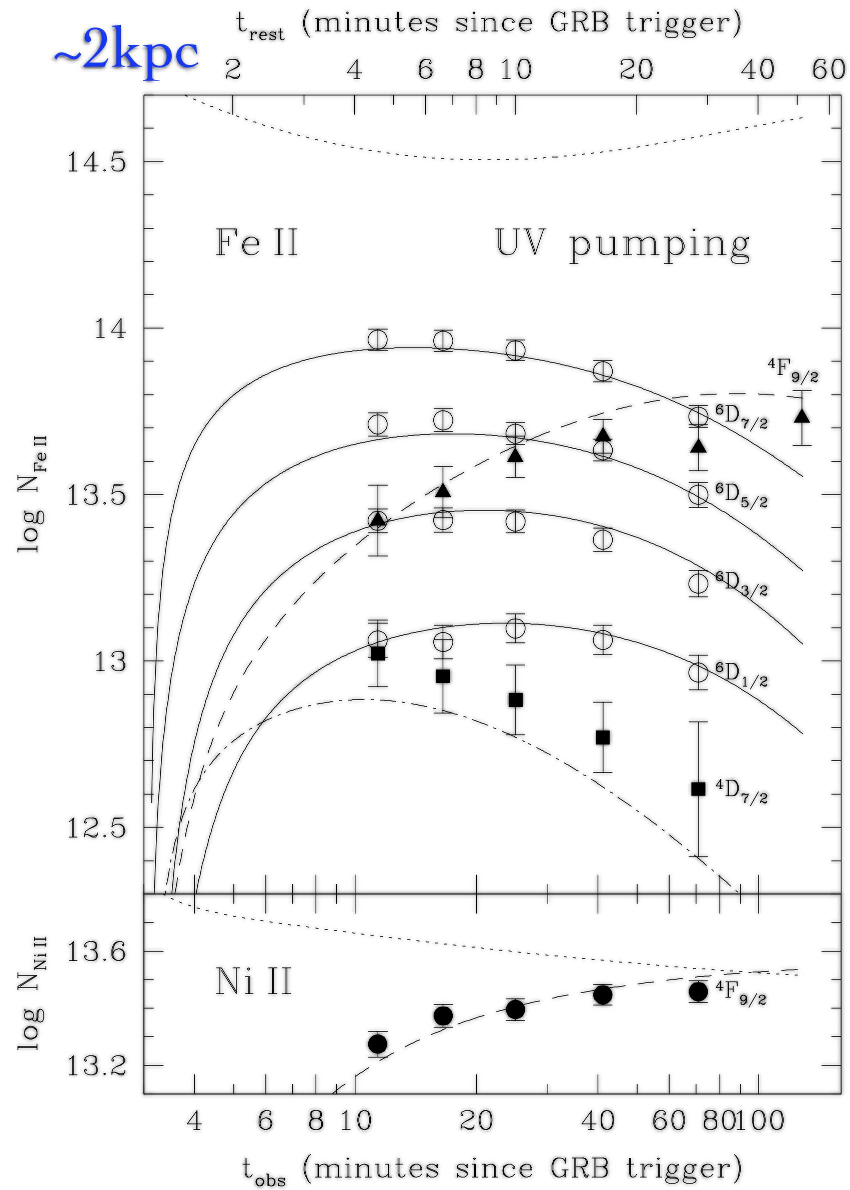

Vreeswijk et al. (2007)

Poor man's animation

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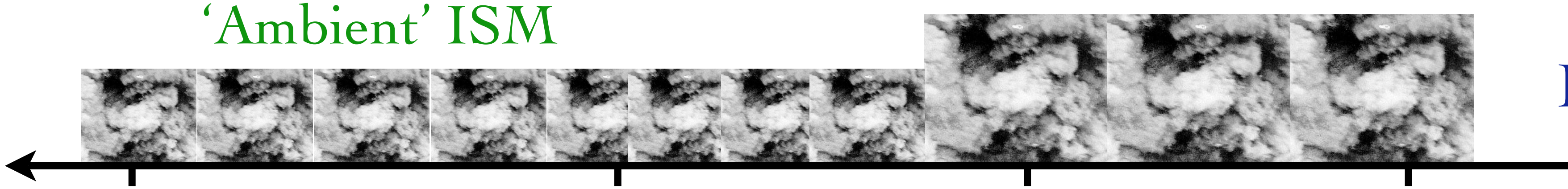

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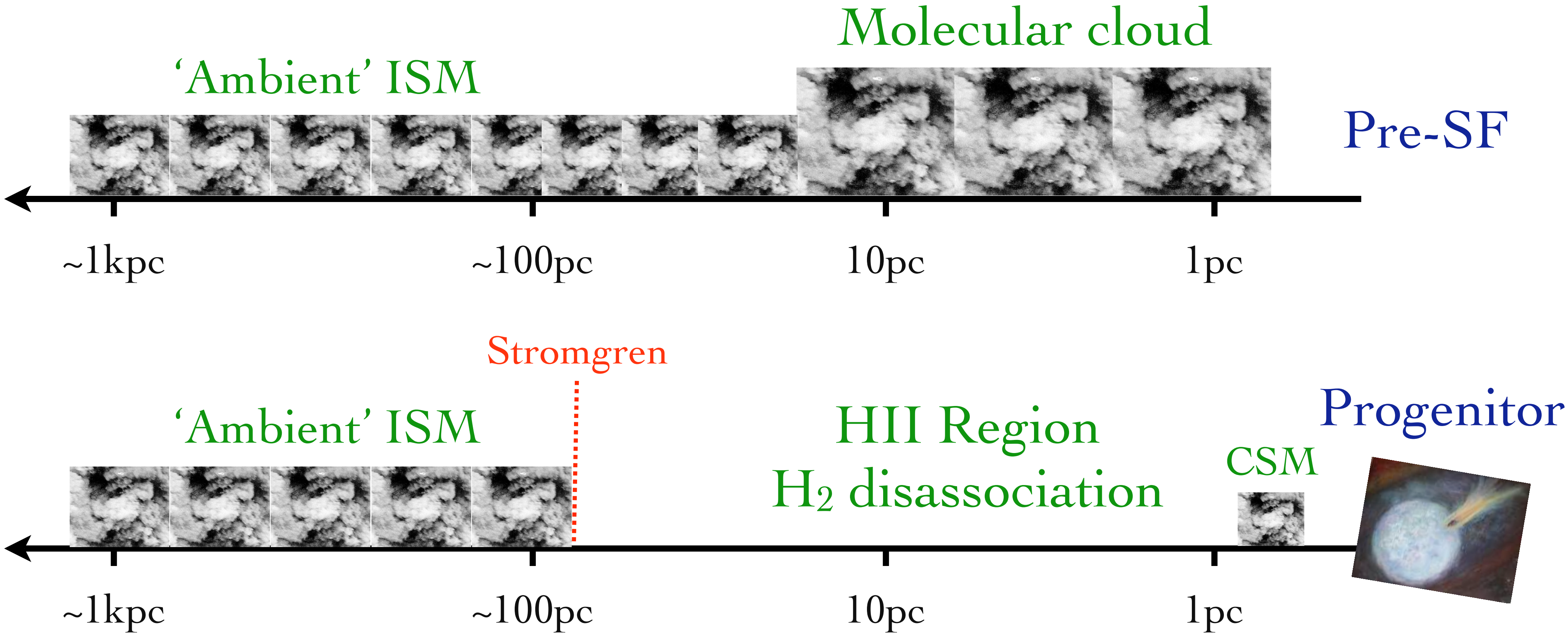

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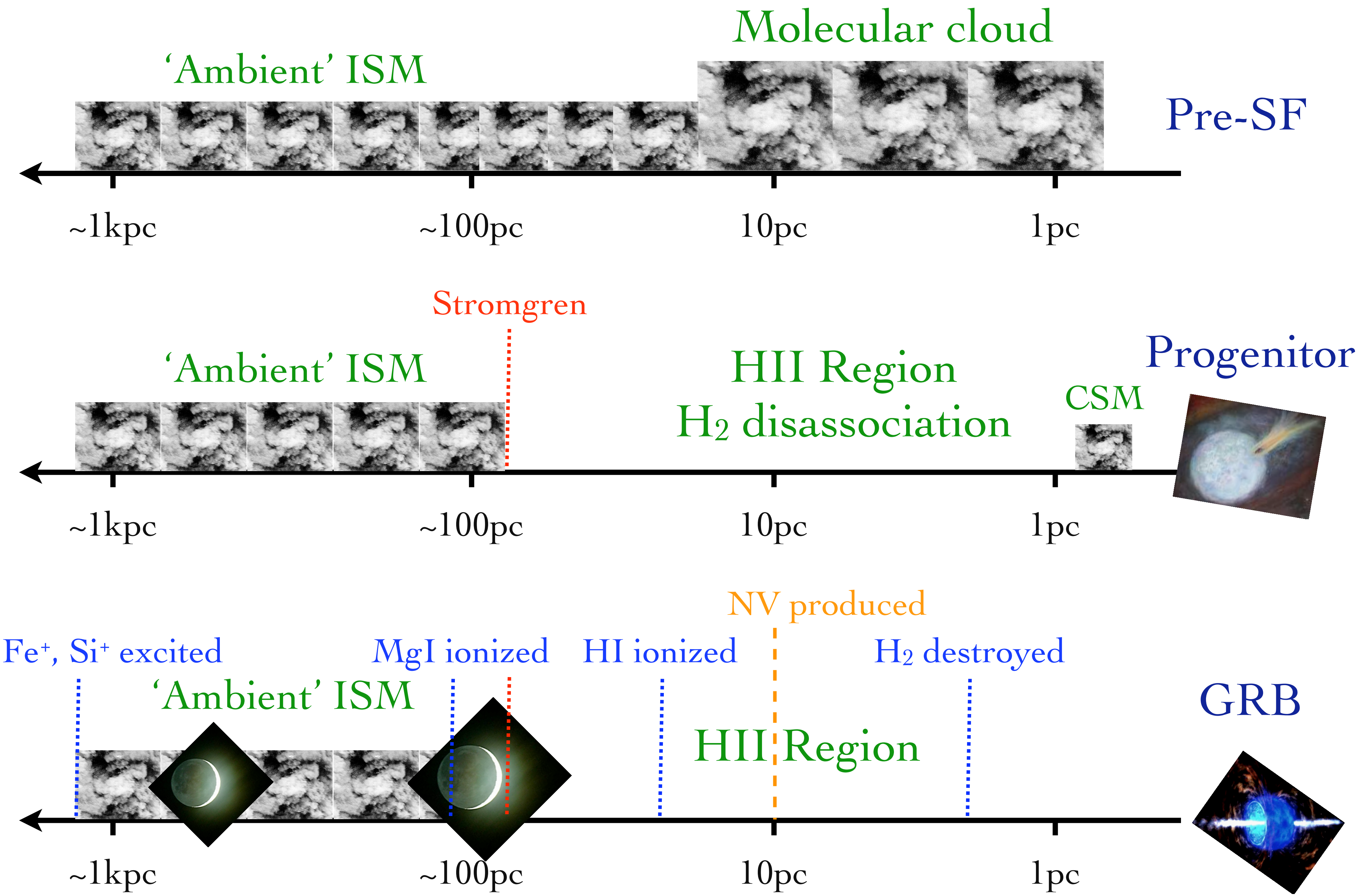
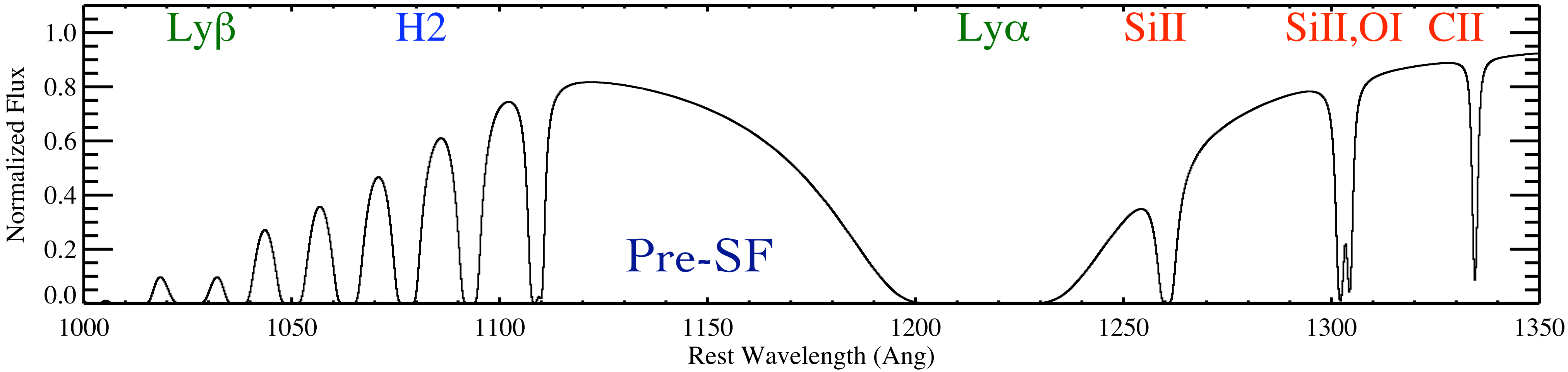
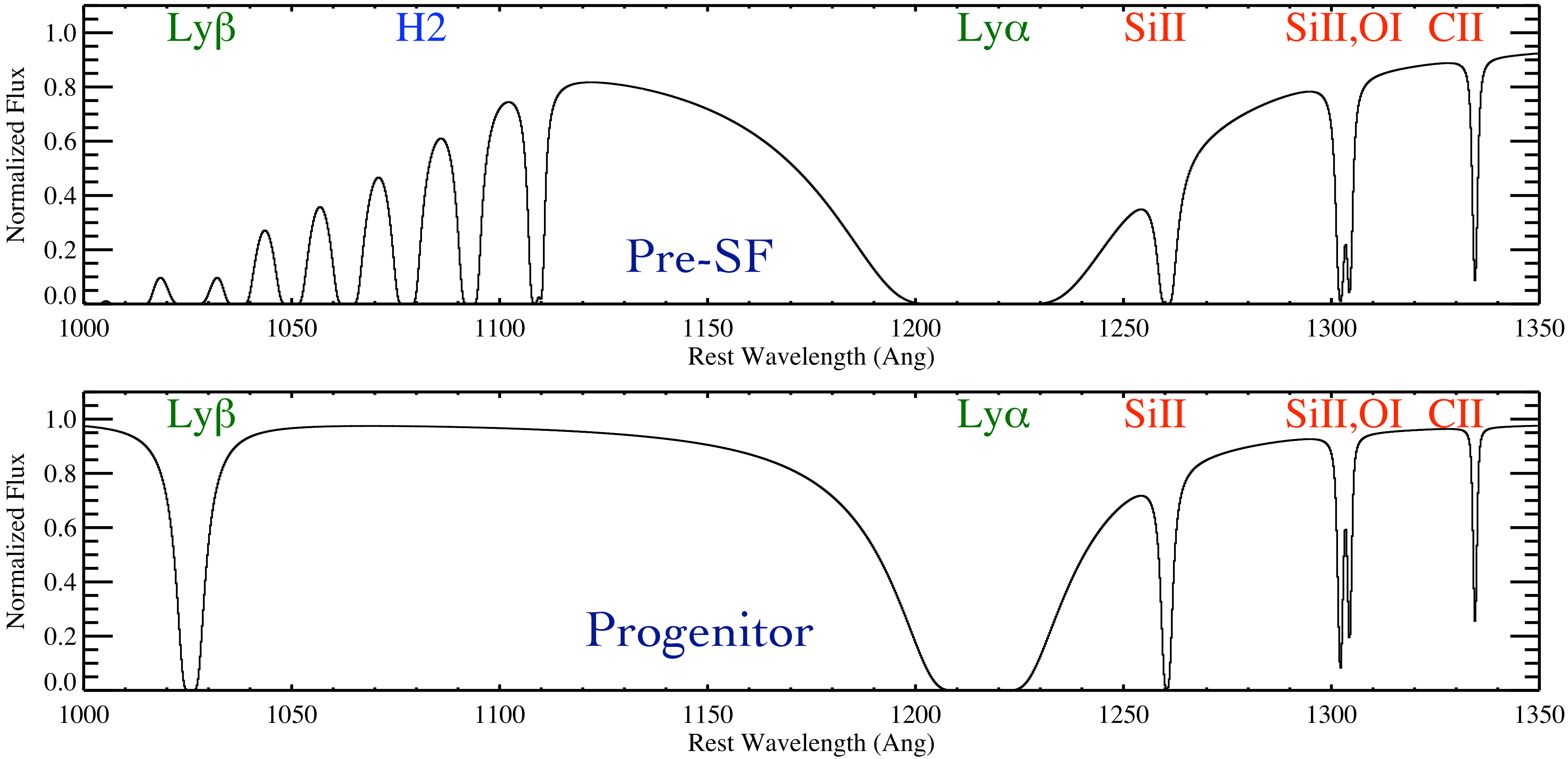




Lyβ
H2
Lyα
SiII
SiII,OI
CII
Pre-SF
Normalized Flux
Rest Wavelength (Ang)



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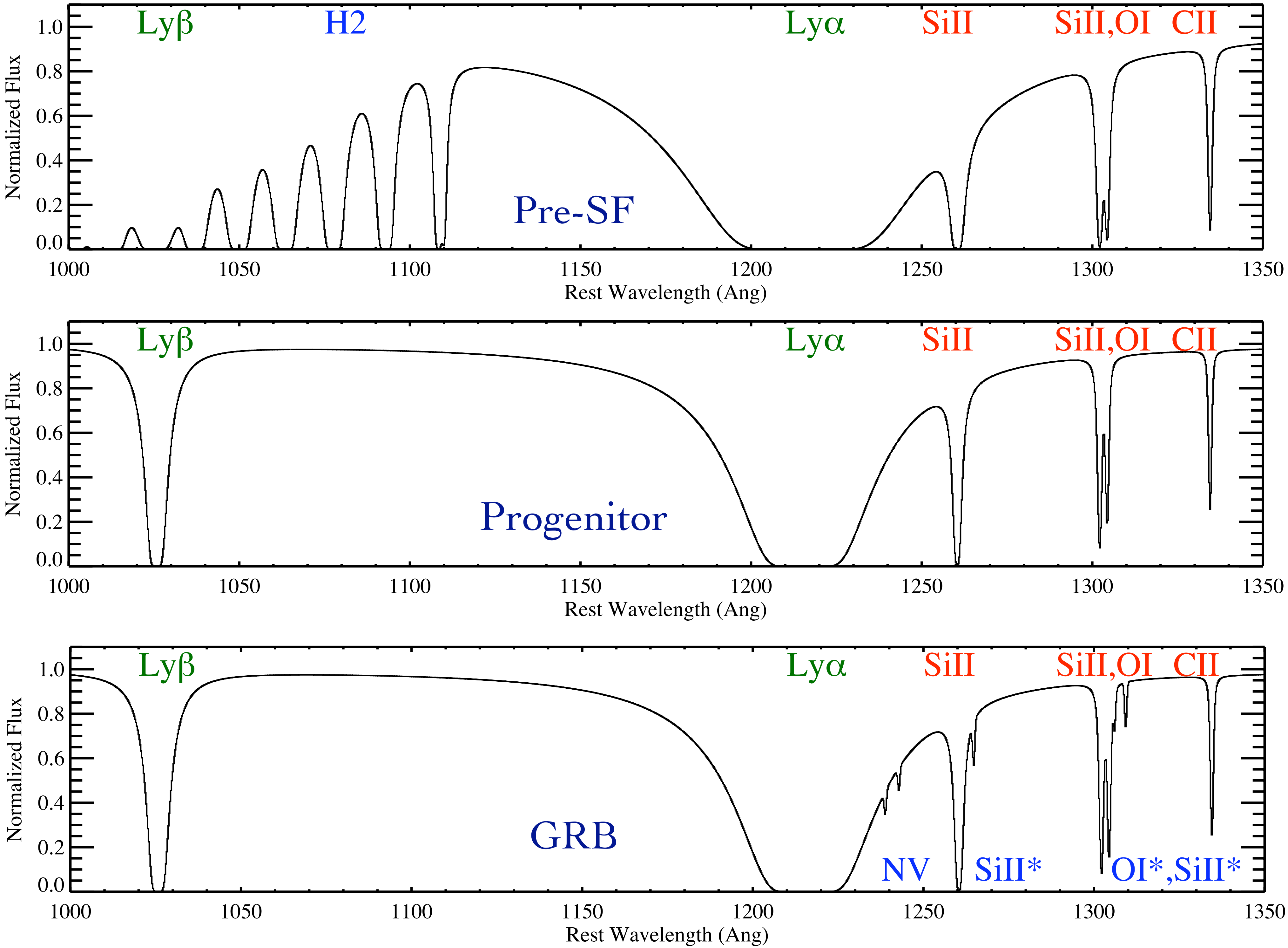

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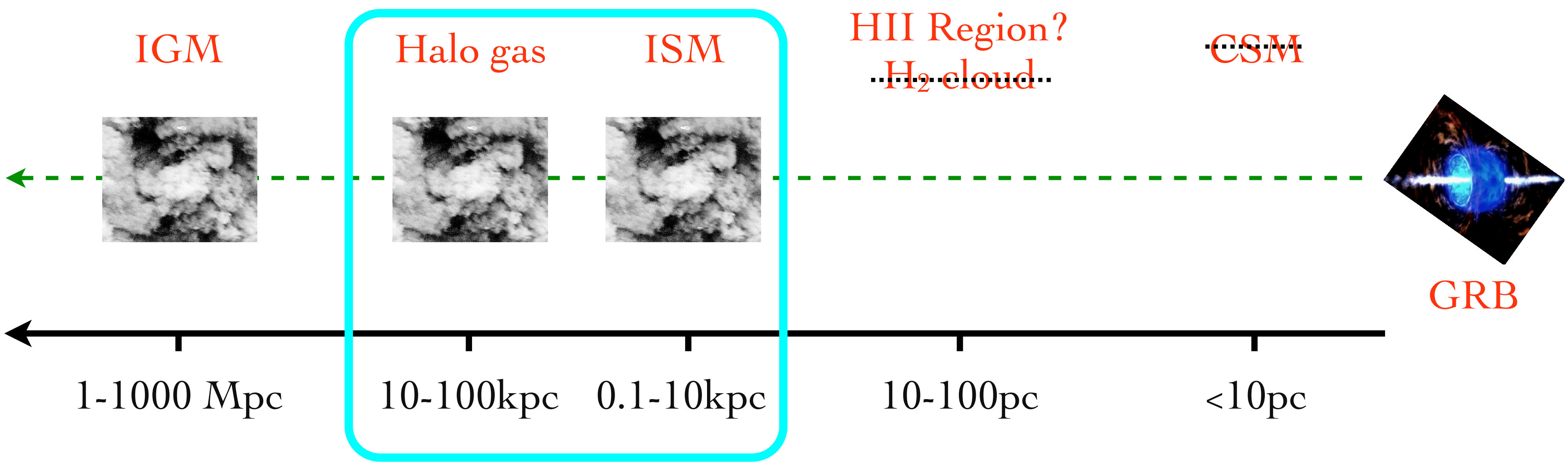

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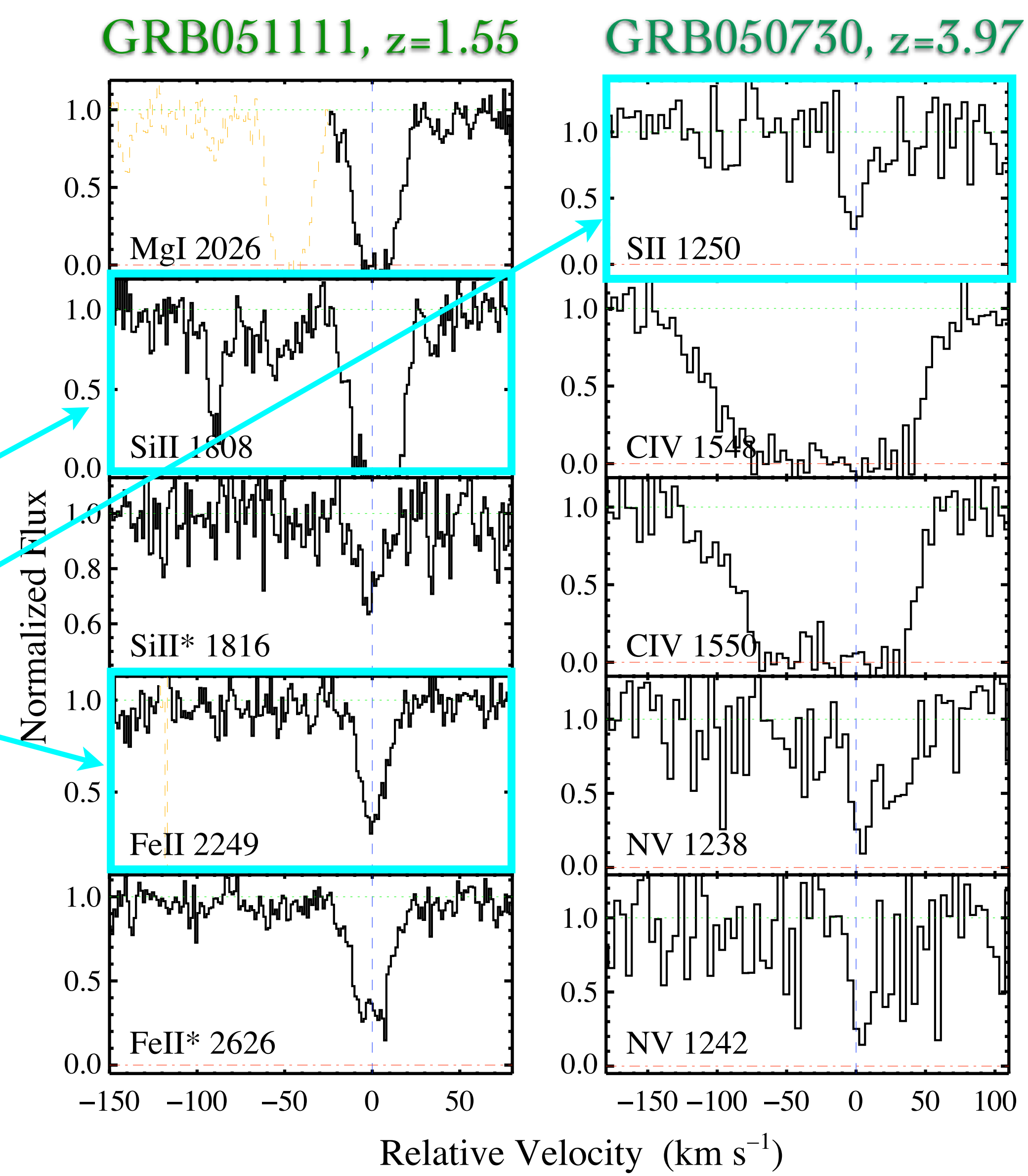
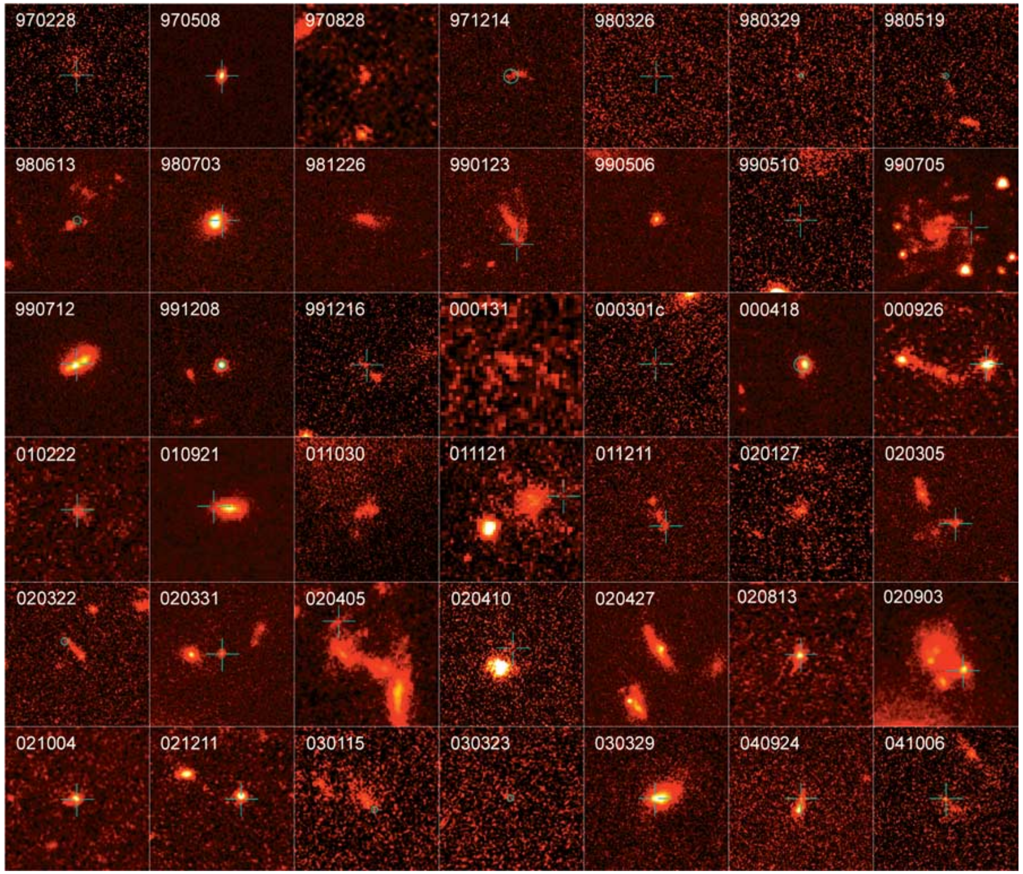


Abundances of Gas Near GRB

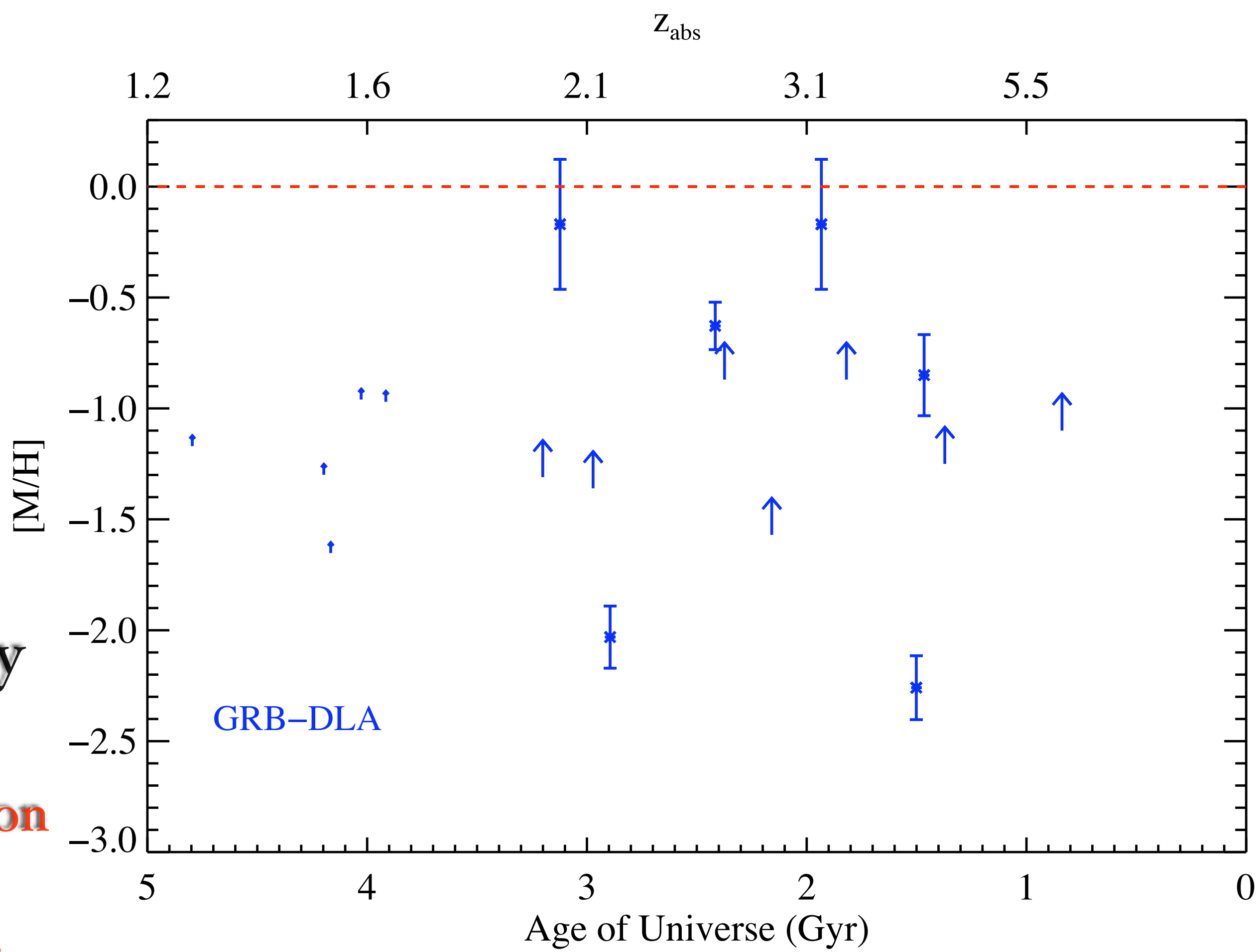
- GRB progenitor (theory)
  - Prefer low metallicity
    - Need to maintain a high angular momentum
    - Therefore, suppress the wind
  - e.g. Woosley & Heger 2006
- GRB hosts (observed)
  - Low luminosity
    - And, blue color
  - Expect low metallicity
    - (Mass-metallicity relation)
  - Observe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



Fruchter et al. (2006)

GRB ISM Abundances

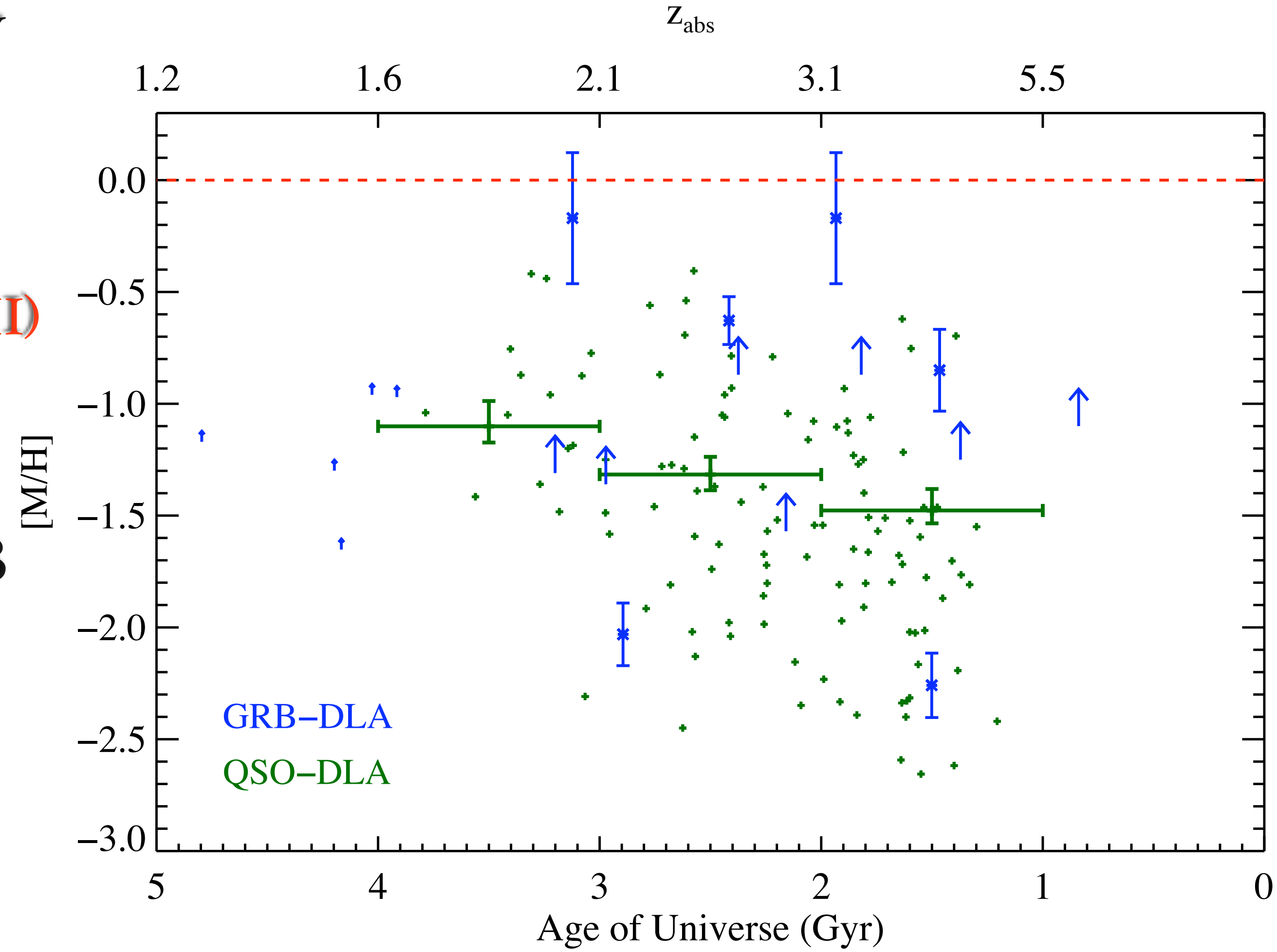
- Typical GRB
  - Large N_{HI}
    - Accurate measure
  - Large EW metal-lines
    - Desire high-res spectra
    - Often limited to lower limit values
- Keep in mind
  - The gas is not immediately local to the progenitor
    - ISM surrounding the SF region
  - Gas-phase
    - Far more accurate than nebular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



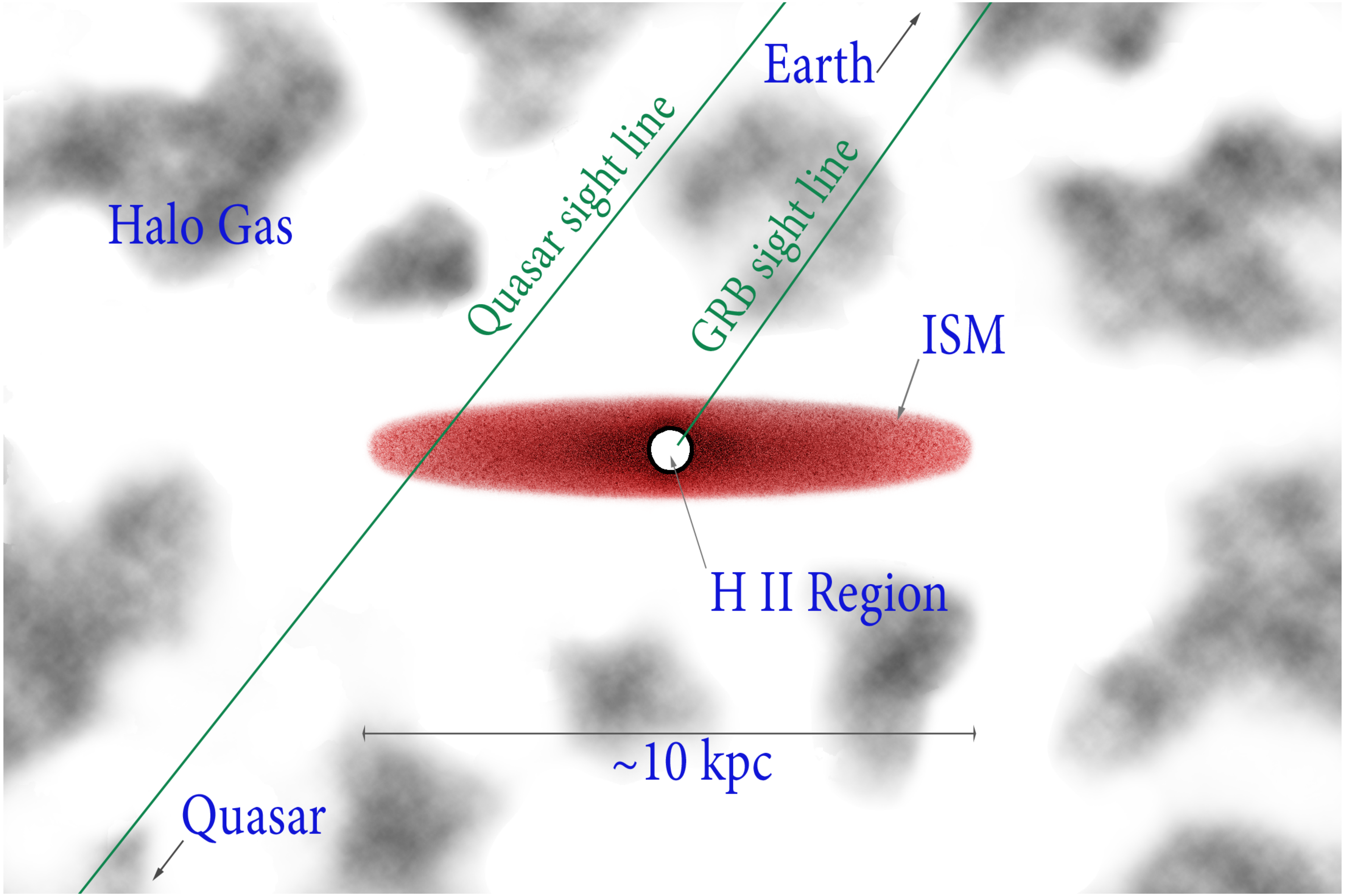
GRB vs QSO-DLA

- 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)



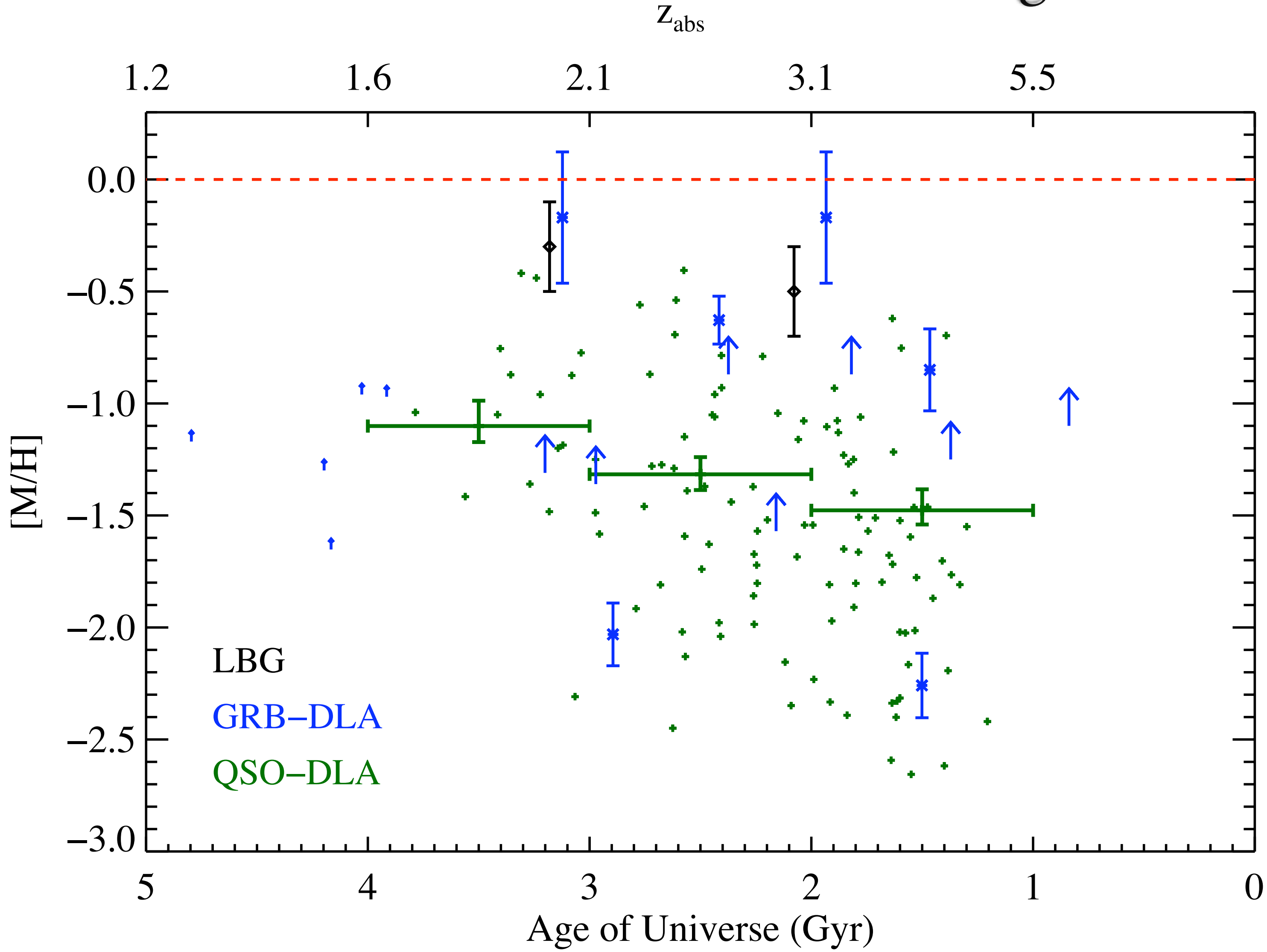
Cartoon Galaxy



Prochaska et al. (2007)

But aren't the GRB values a bit low?

- LBG vs GRB
  - Most GRB have metallicities below bright LBG



Are GRBs Unbiased Tracers of SFR?

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

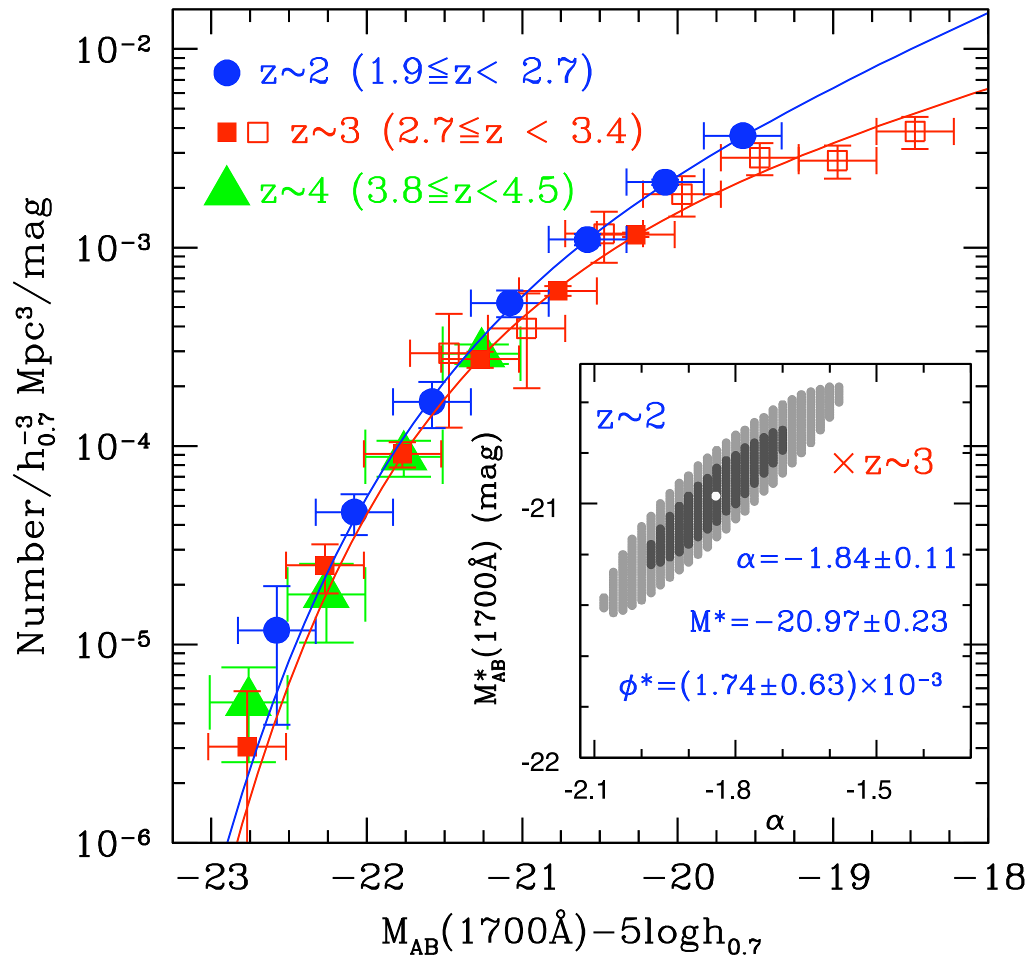
$$\phi(L_{UV}) \propto (L_{UV}/L_*)^{-1.6} \exp(-L_{UV}/L_*)$$

  - 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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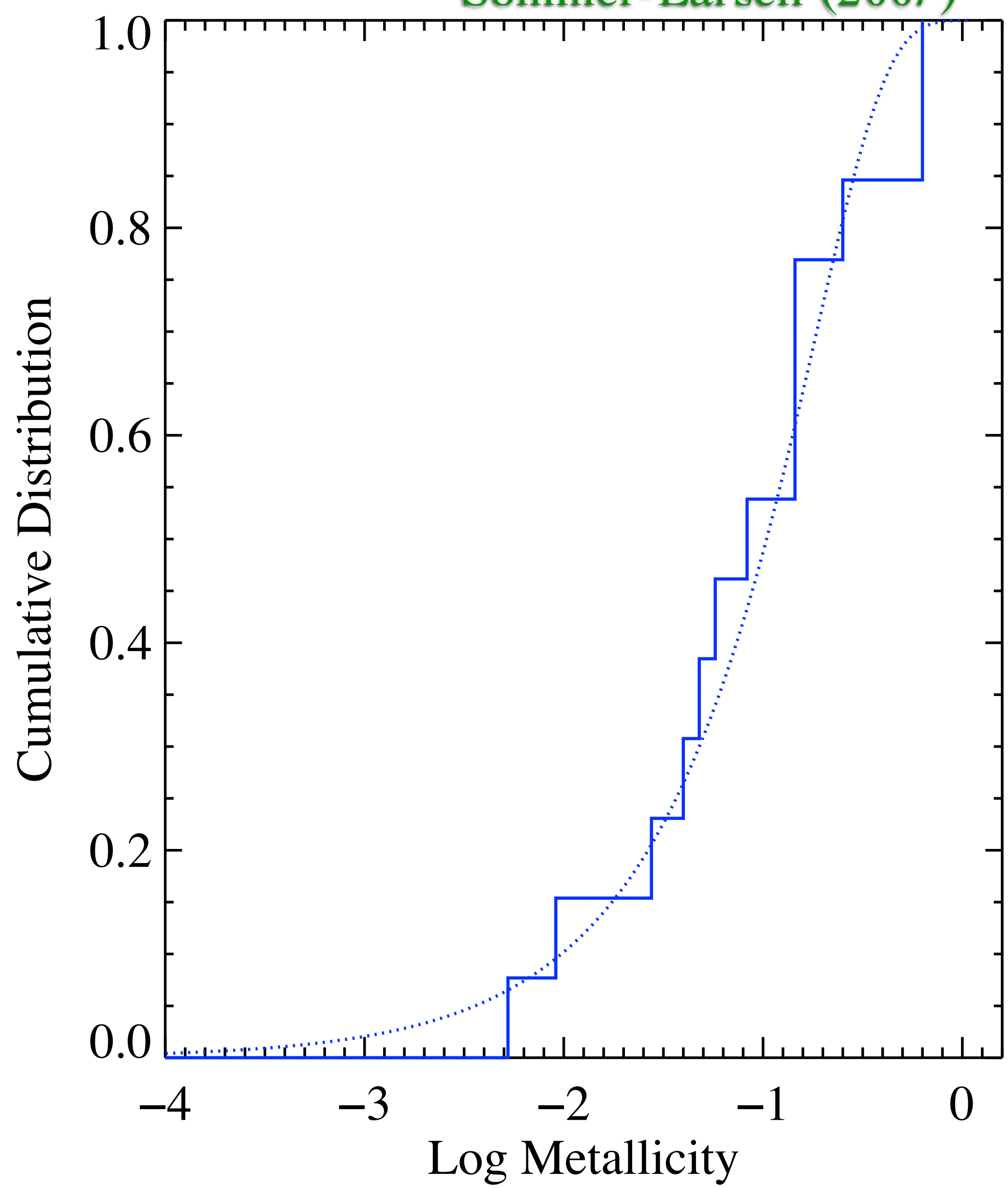
Fynbo, Prochaska, & Sommer-Larsen (2007)



Bright Galaxies are the Tip of the SF Iceberg

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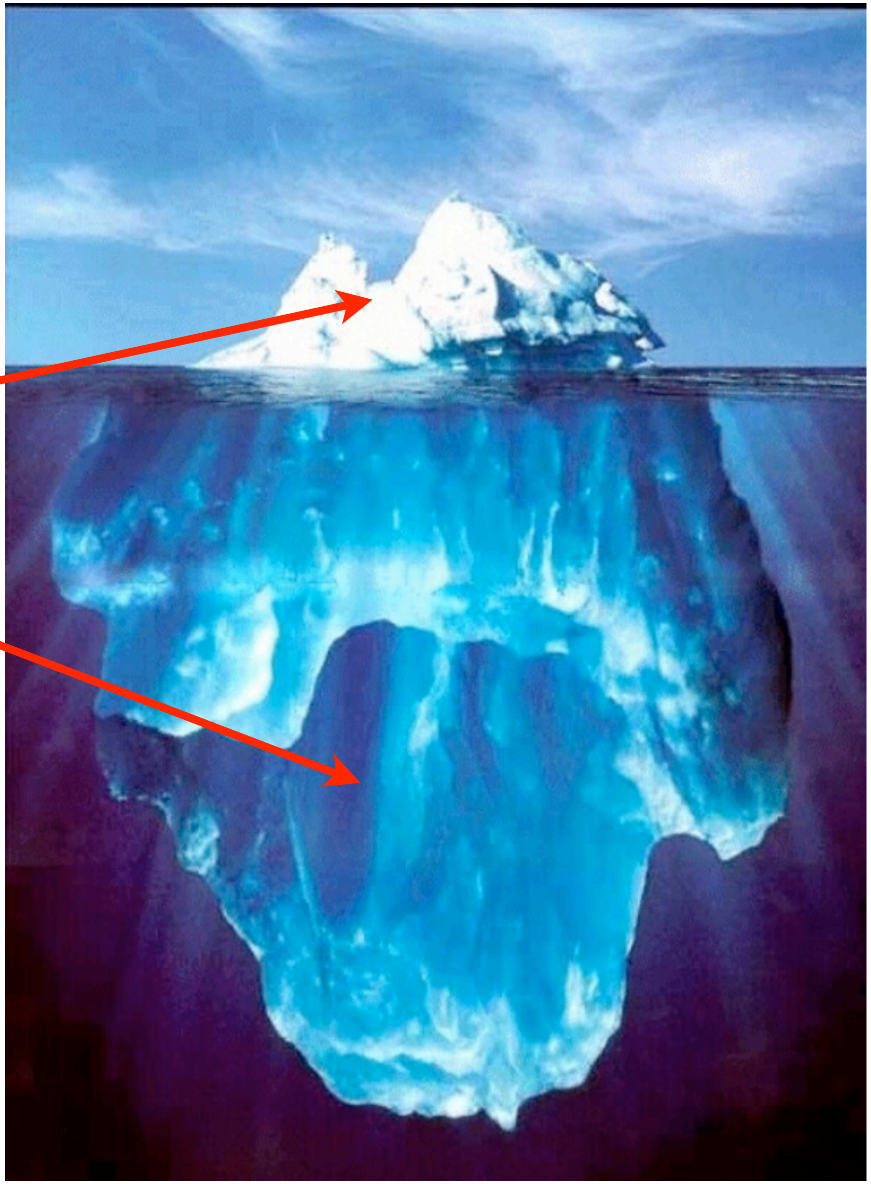
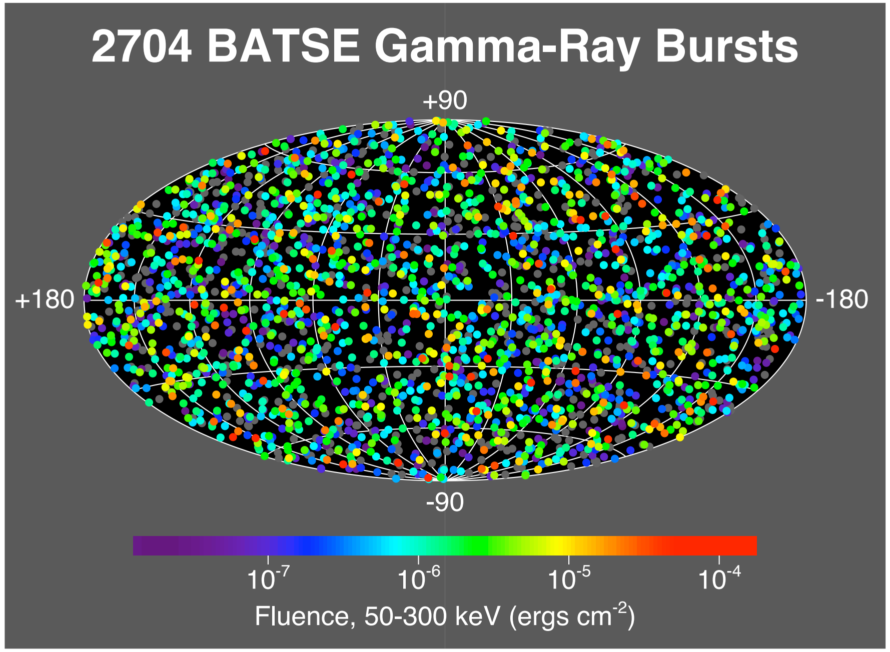
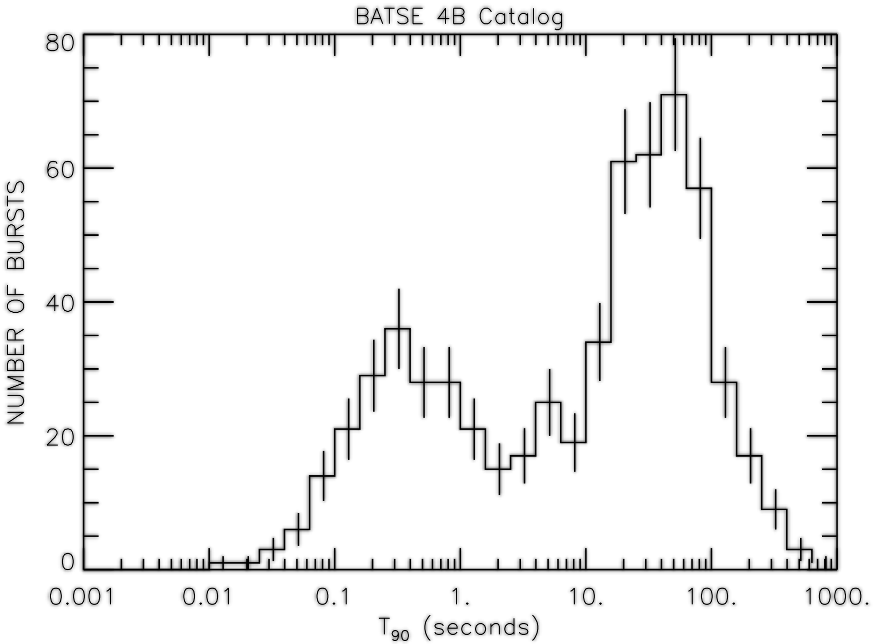


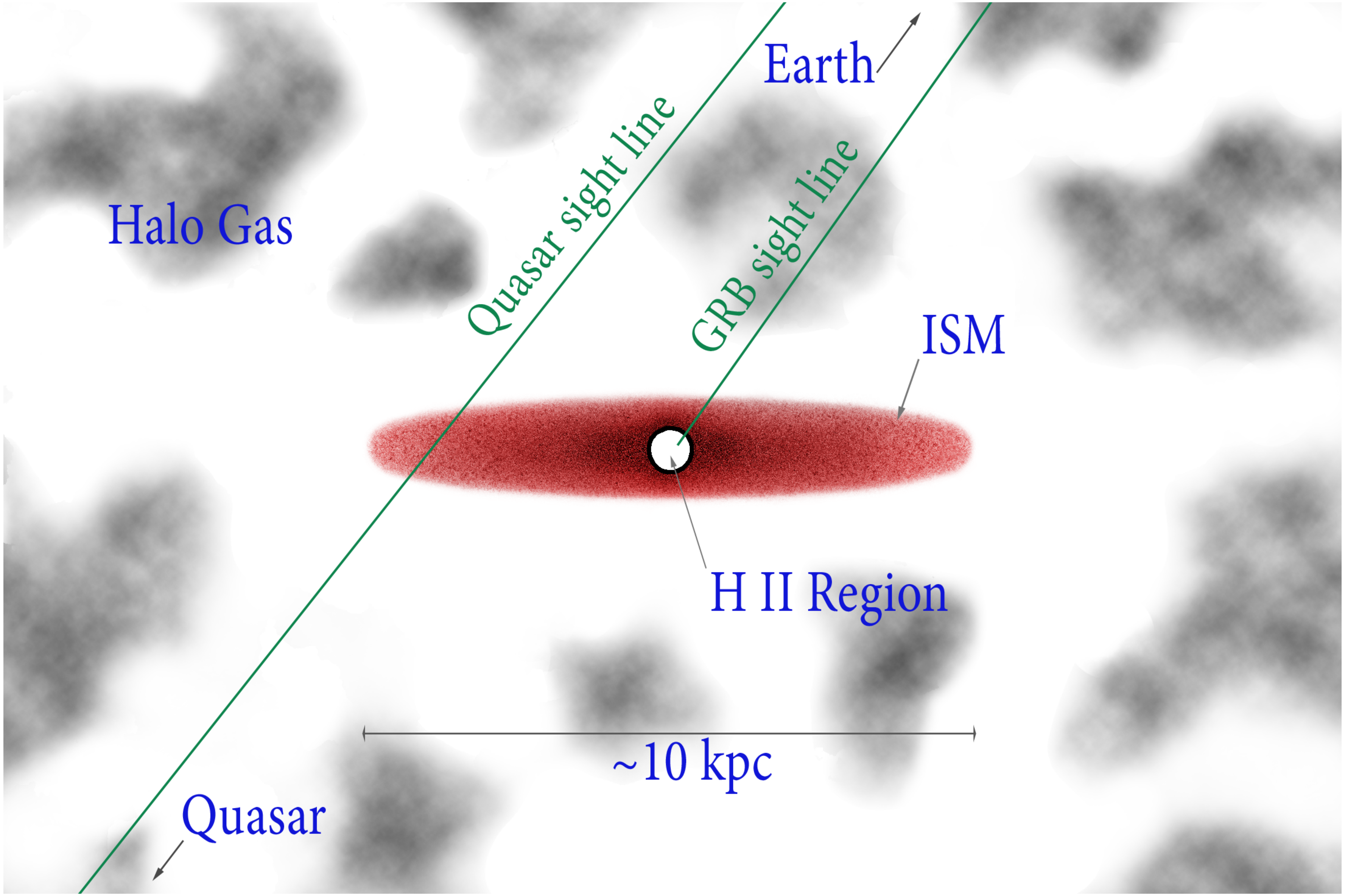
Outline

- Introduction
- HI and H_2 gas
  - Where is the fuel for SF?
  - Estimating the escape fraction
- Metal-line transitions
  - Resolving the distance of the gas
  - Metallicity measurements
- Velocity fields in High z Galaxies
  - Testing the standard paradigm
  - Examining outflow/inflow in 'normal' SF galaxies





Velocity Fields of High z Galaxies

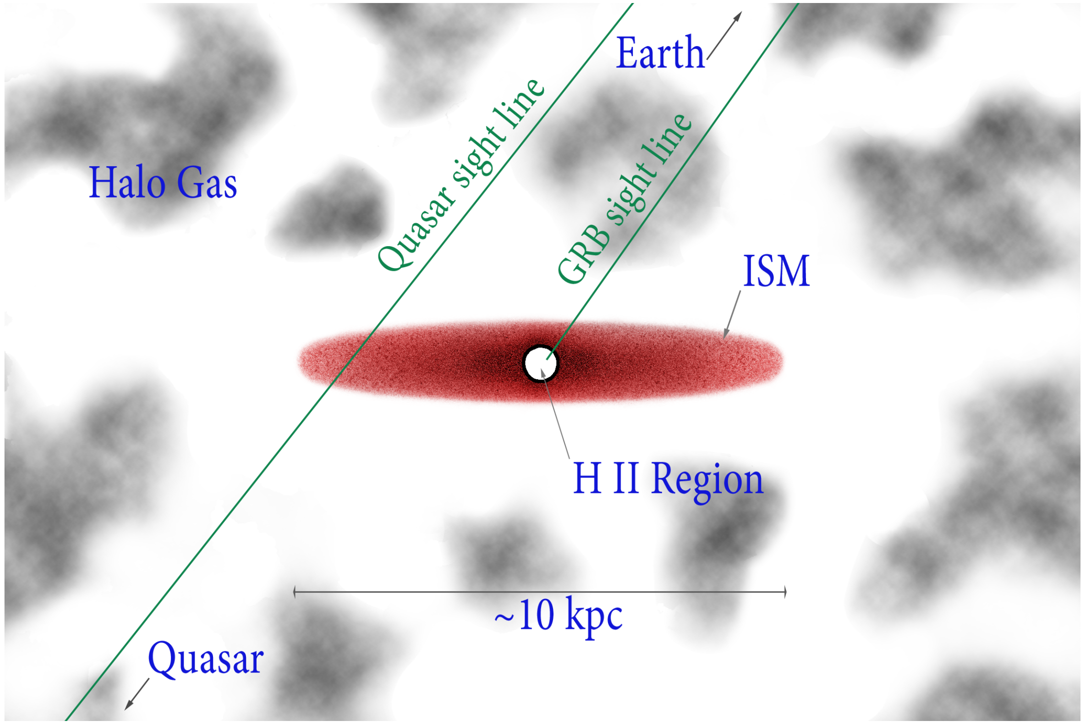


Prochaska et al. (2007)

GRB Sightlines

- Easy to do
  - Measure velocity widths
  - Probe multiple ionization states
- Doable
  - Break degeneracy of inflow vs outflow
  - Get the systemic velocity of the galaxy
  - Link velocities to distance
  - Probe SF regions

Prochaska et al. (2008)

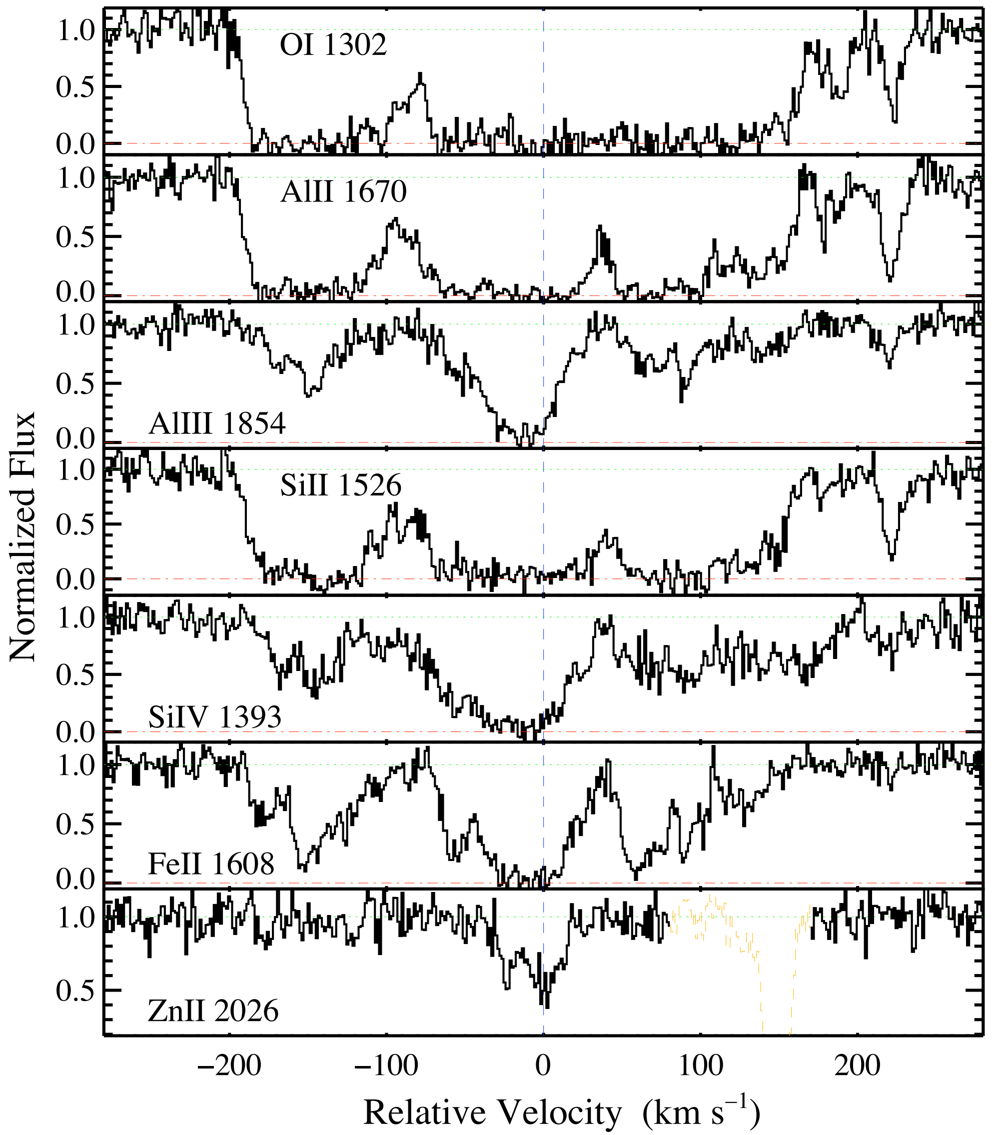


Key: Like LBGs, GRBs originate in galaxies, but do not affect the velocity fields.

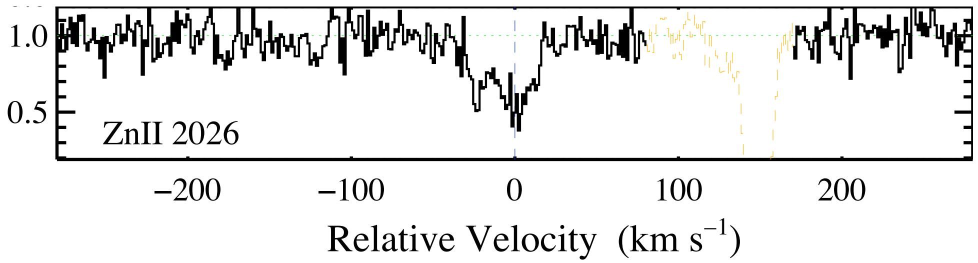
Kinematics: Data

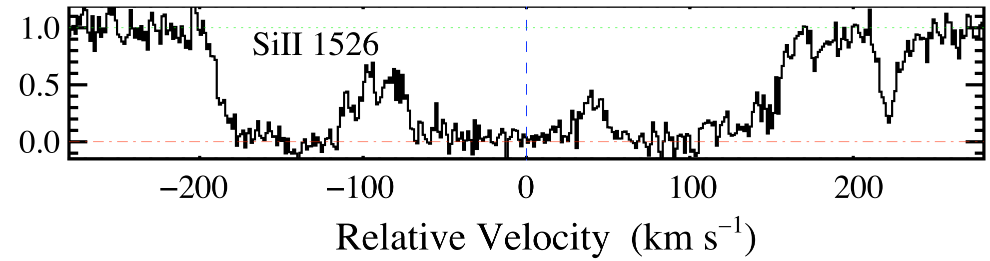
- Gas Velocity field
  - High-resolution data
    - Resolve features at <10 km/s
- Majority of gas?
  - Weak transitions
  - e.g. ZnII 2026
- Majority of velocity field?
  - Strong transitions
  - e.g. SiII 1526
- Neutral or Ionized gas?
  - Low-ion vs. high-ion
  - e.g. ZnII vs CIV

GRB 050820



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'
    - Akin to Δv_{99}
- Expectation
  - ISM may play a minor role
  - Additional velocity fields
    - Halo dynamics (infall, virial)
    - Galactic-scale outflows

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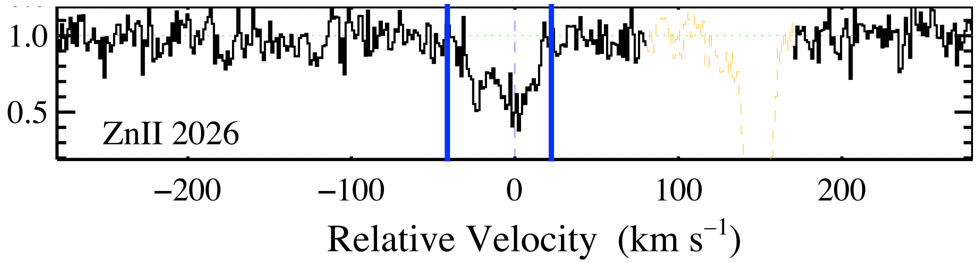

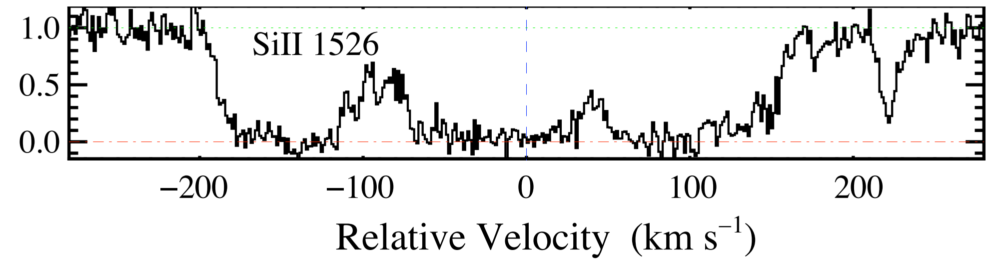

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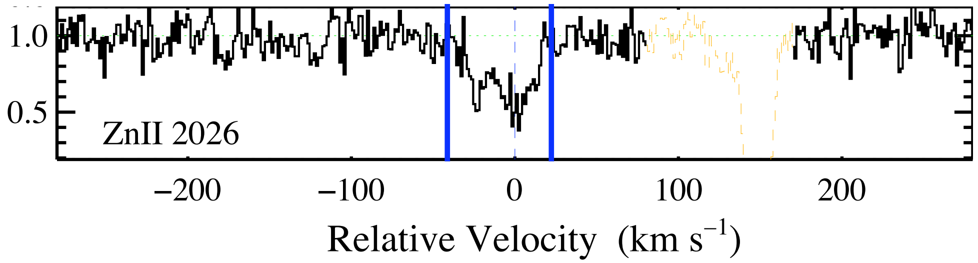

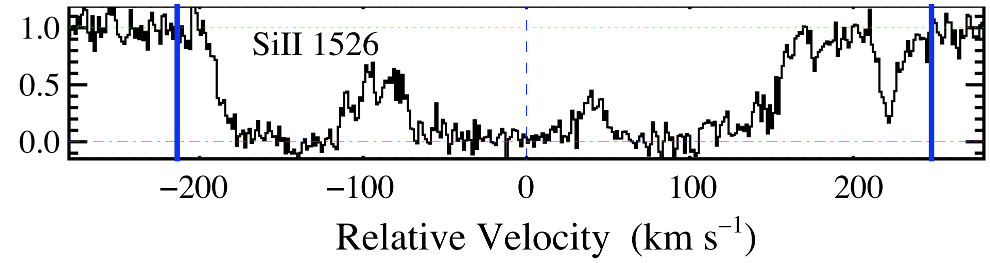

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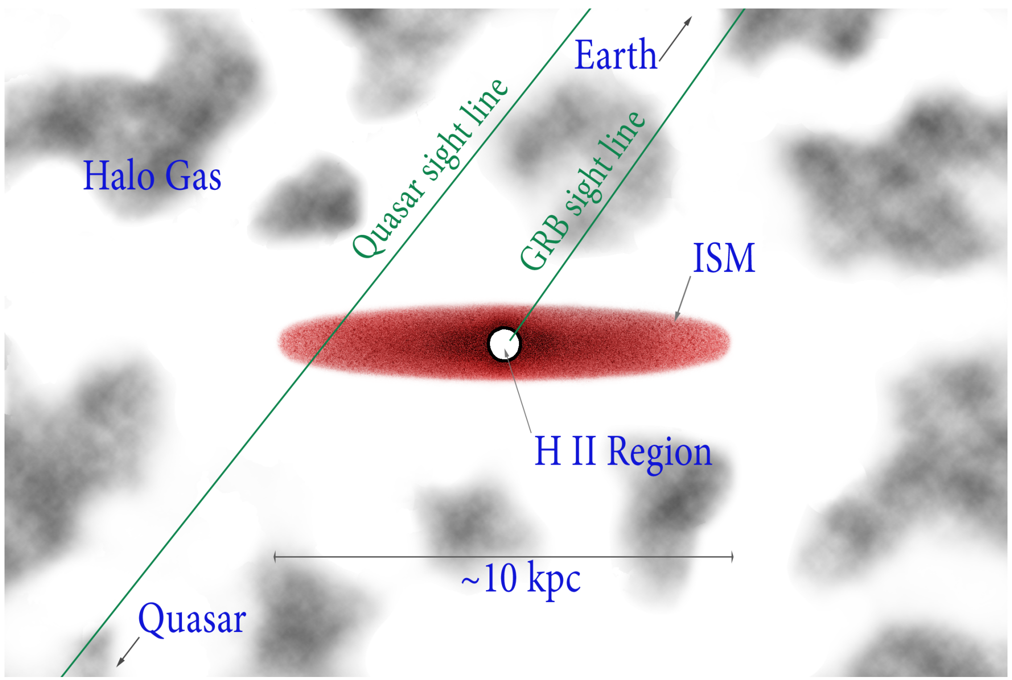
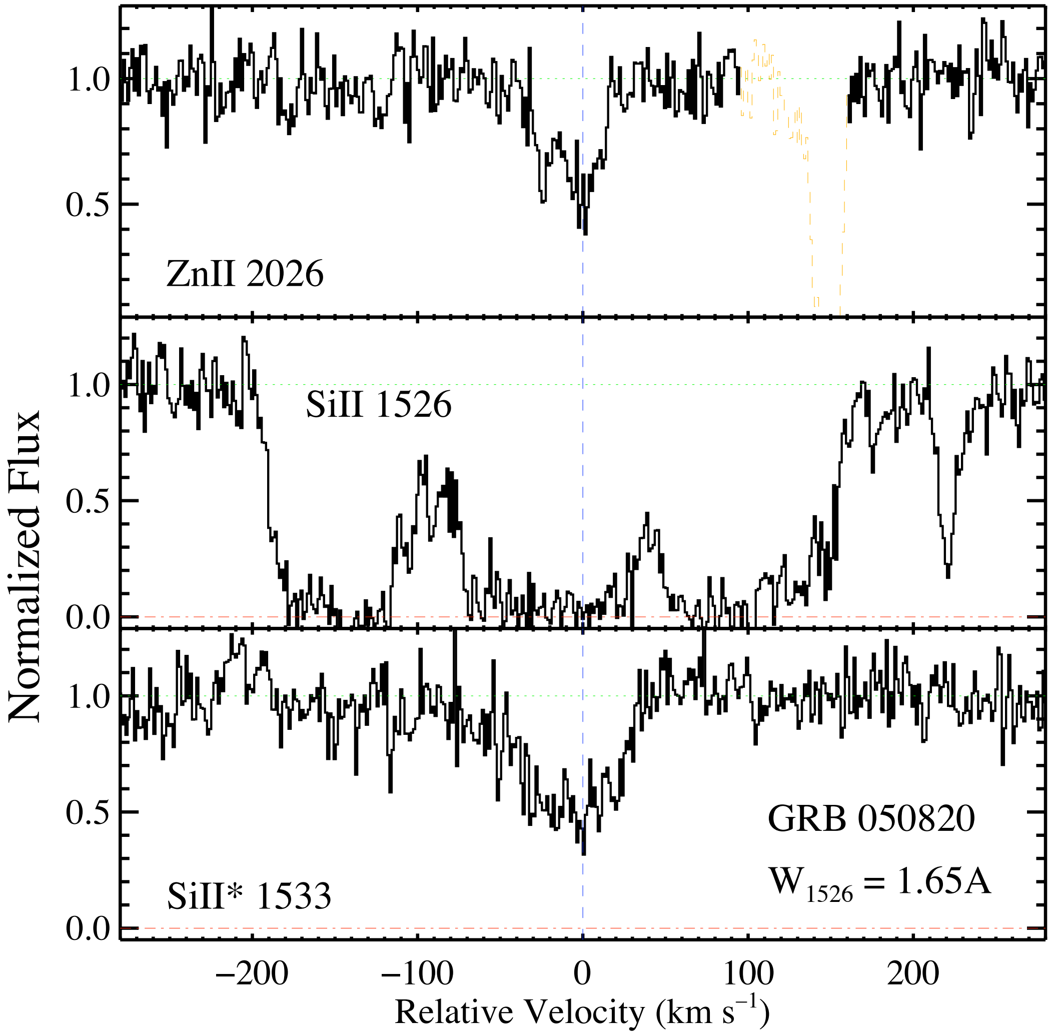
Origin and Nature of the Velocity Fields





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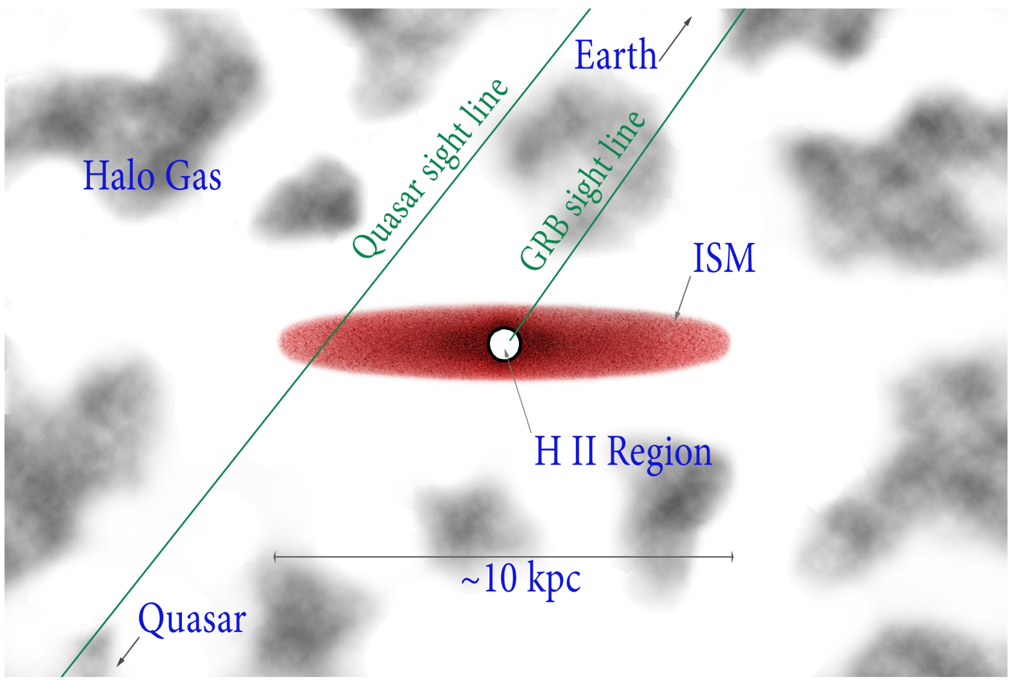

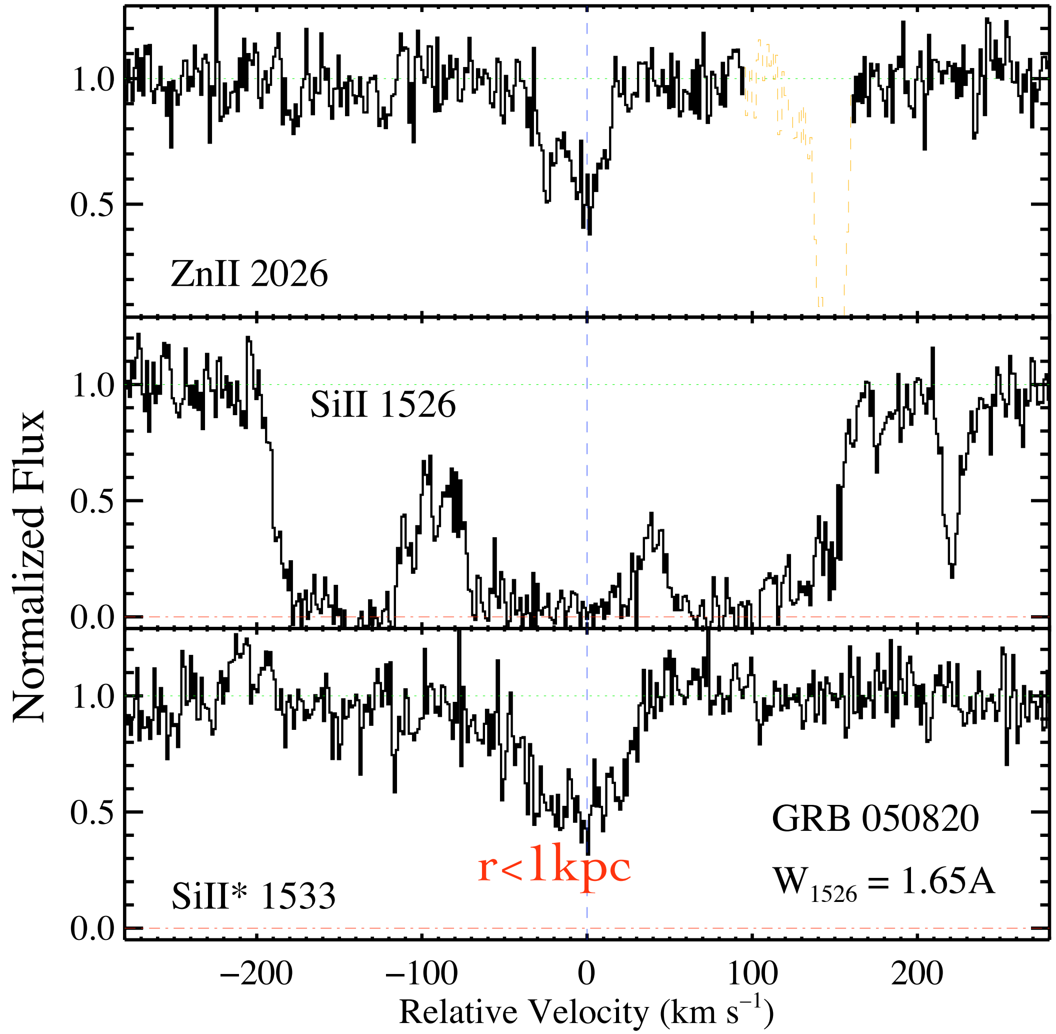

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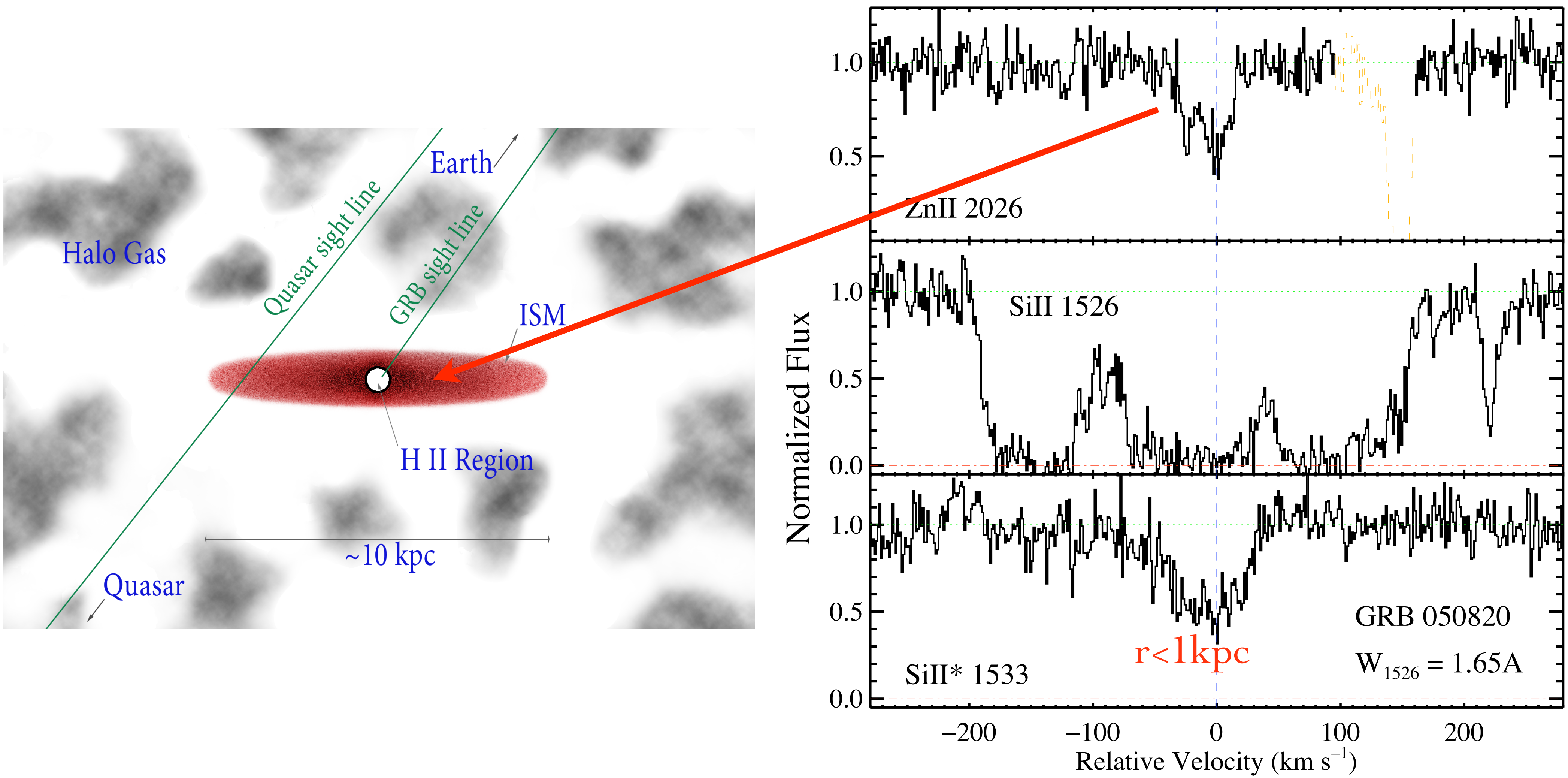

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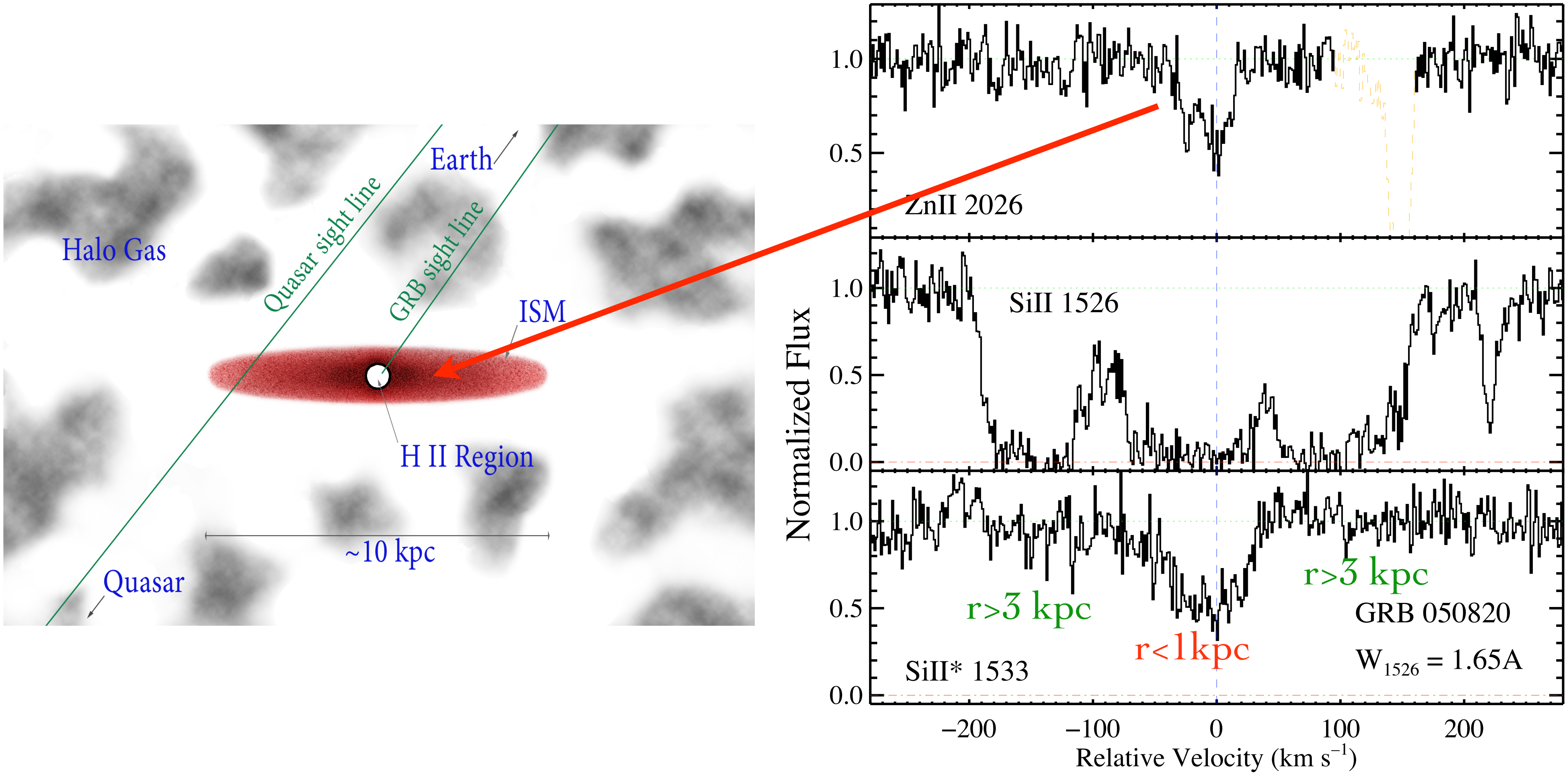

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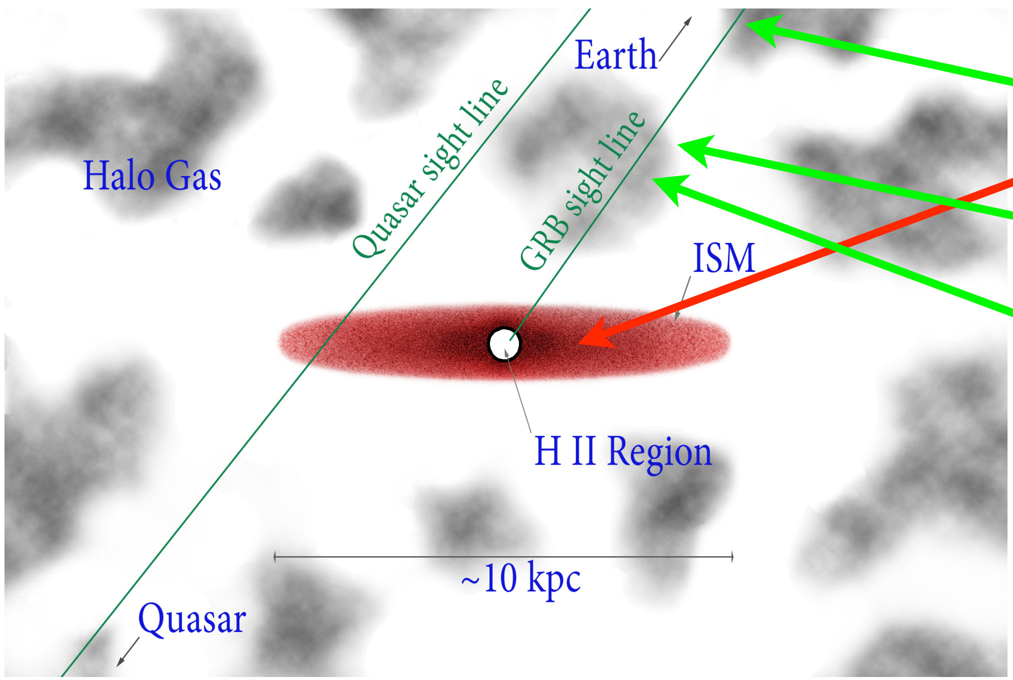
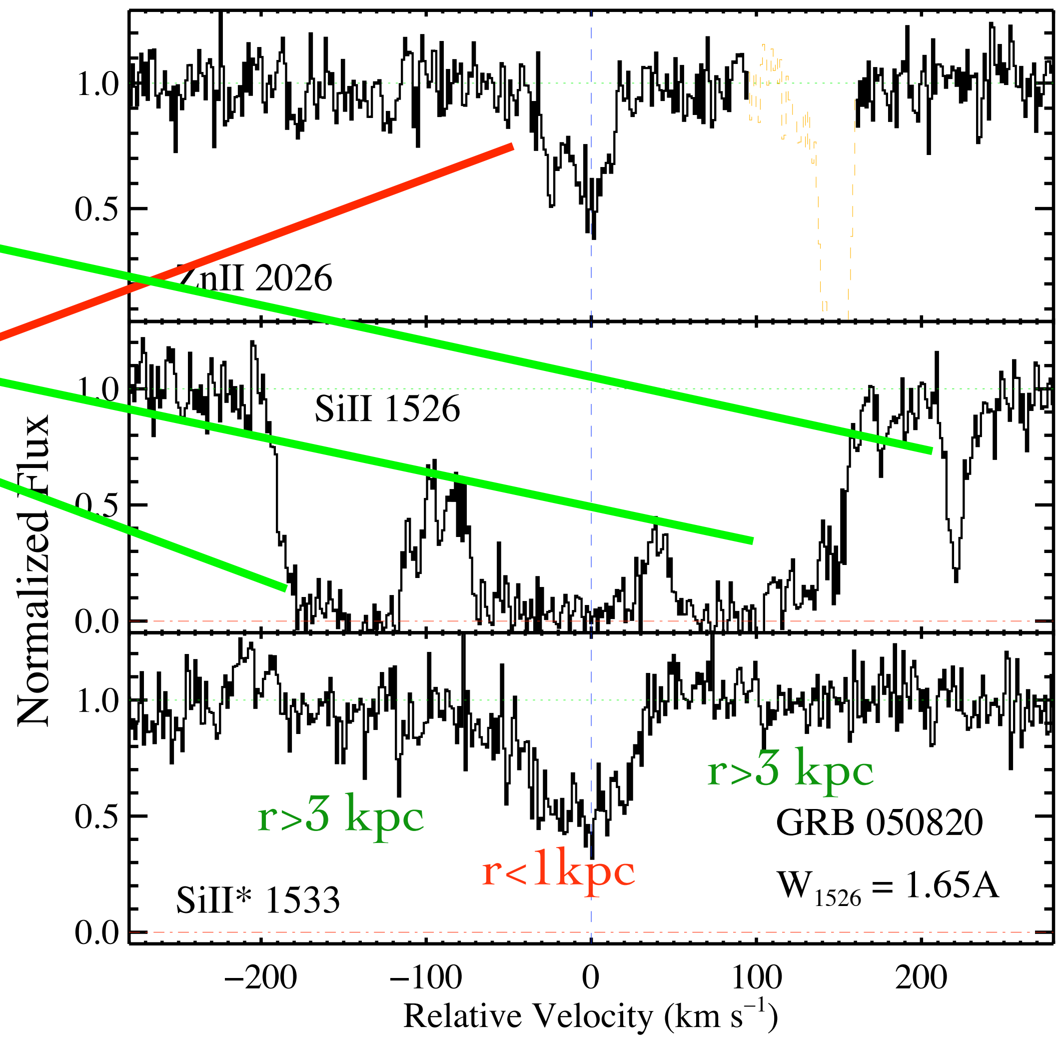
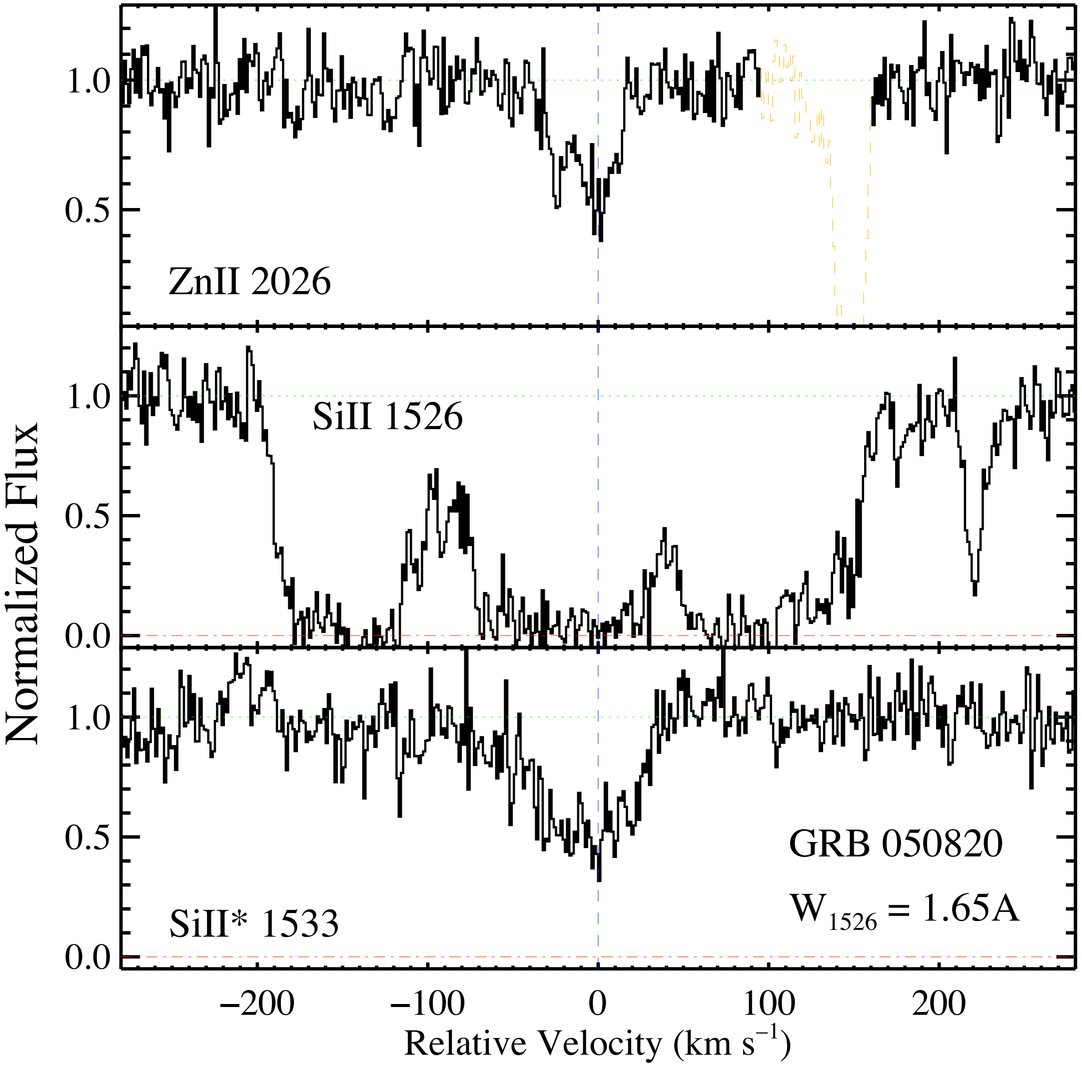




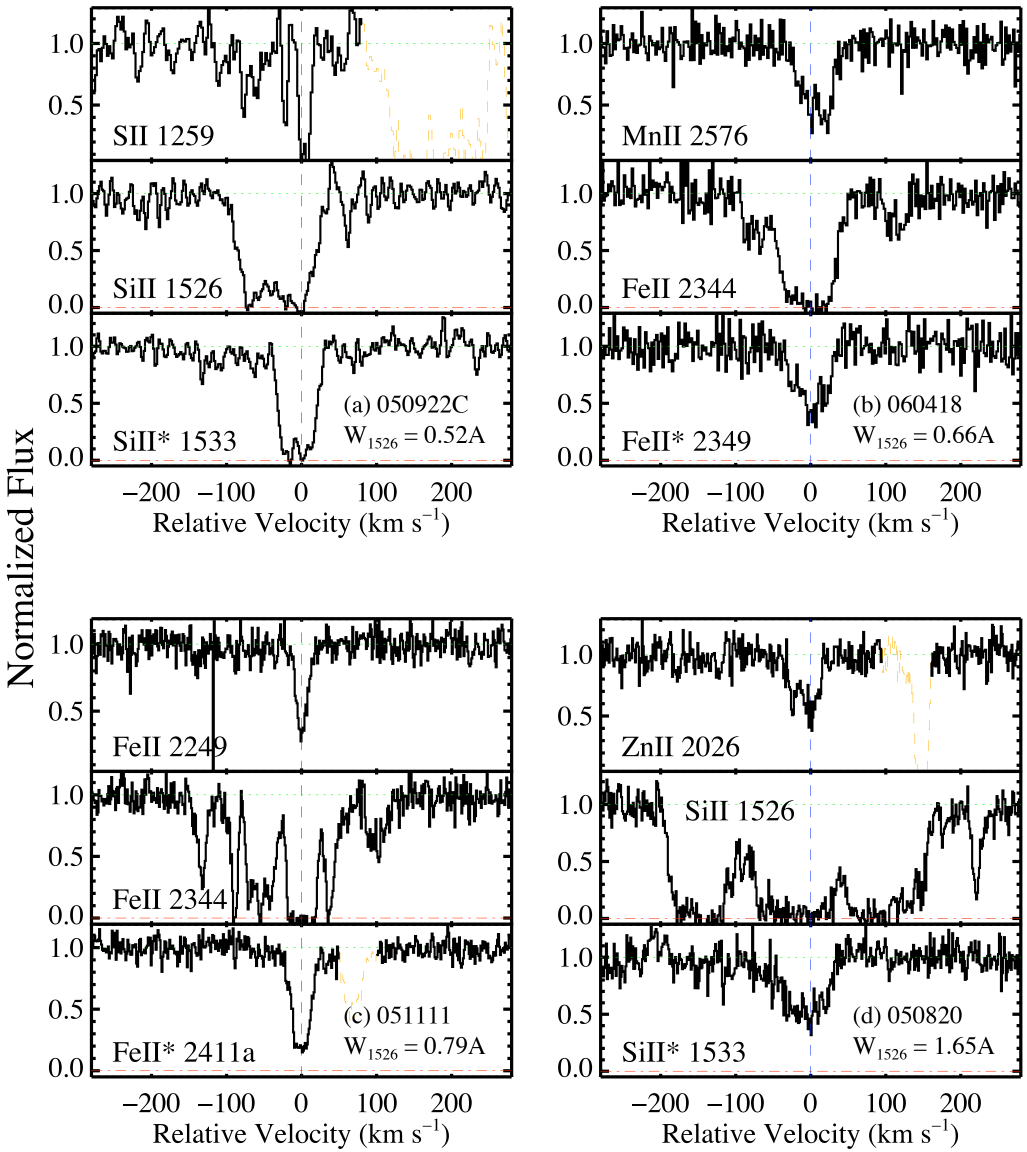
Origin and Nature of the Velocity Fields

- 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



Origin and Nature of the Velocity Fields

- Nature of the field
  - Fine-structure lines
    - Set ISM systemic (v=0) velocity
  - GRB sightline
    - Breaks the QSO symmetry
    - Velocity relative to the ISM
      - Negative => Outflow
      - Positive => Inflow
- Current Observations
  - 051111: Outflow (primarily)
  - 050820,060418:
    - In and out
    - First evidence for accretion!?
  - Origin of the fields
    - Virialized motions?
    - Galactic fountain in action?



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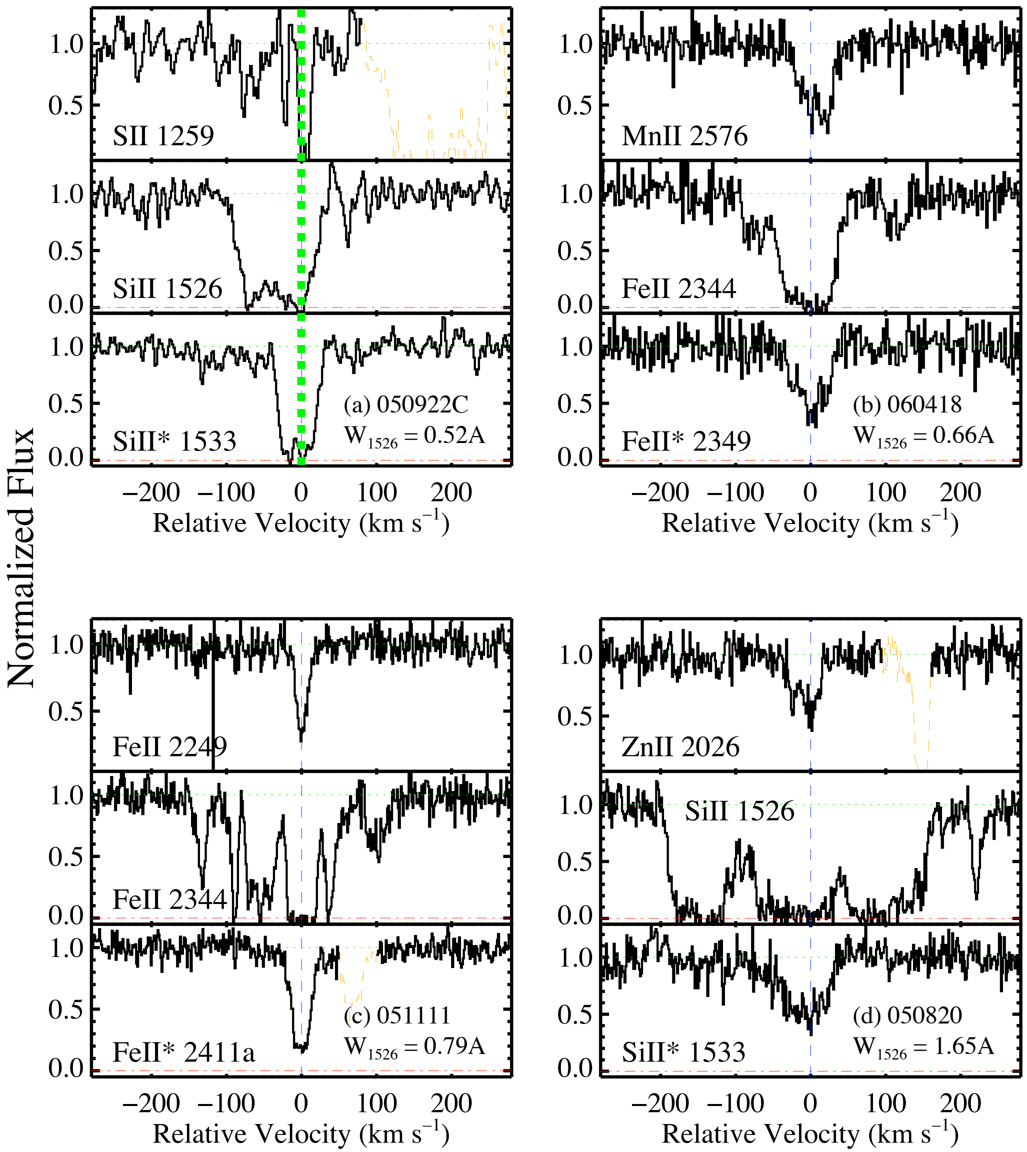

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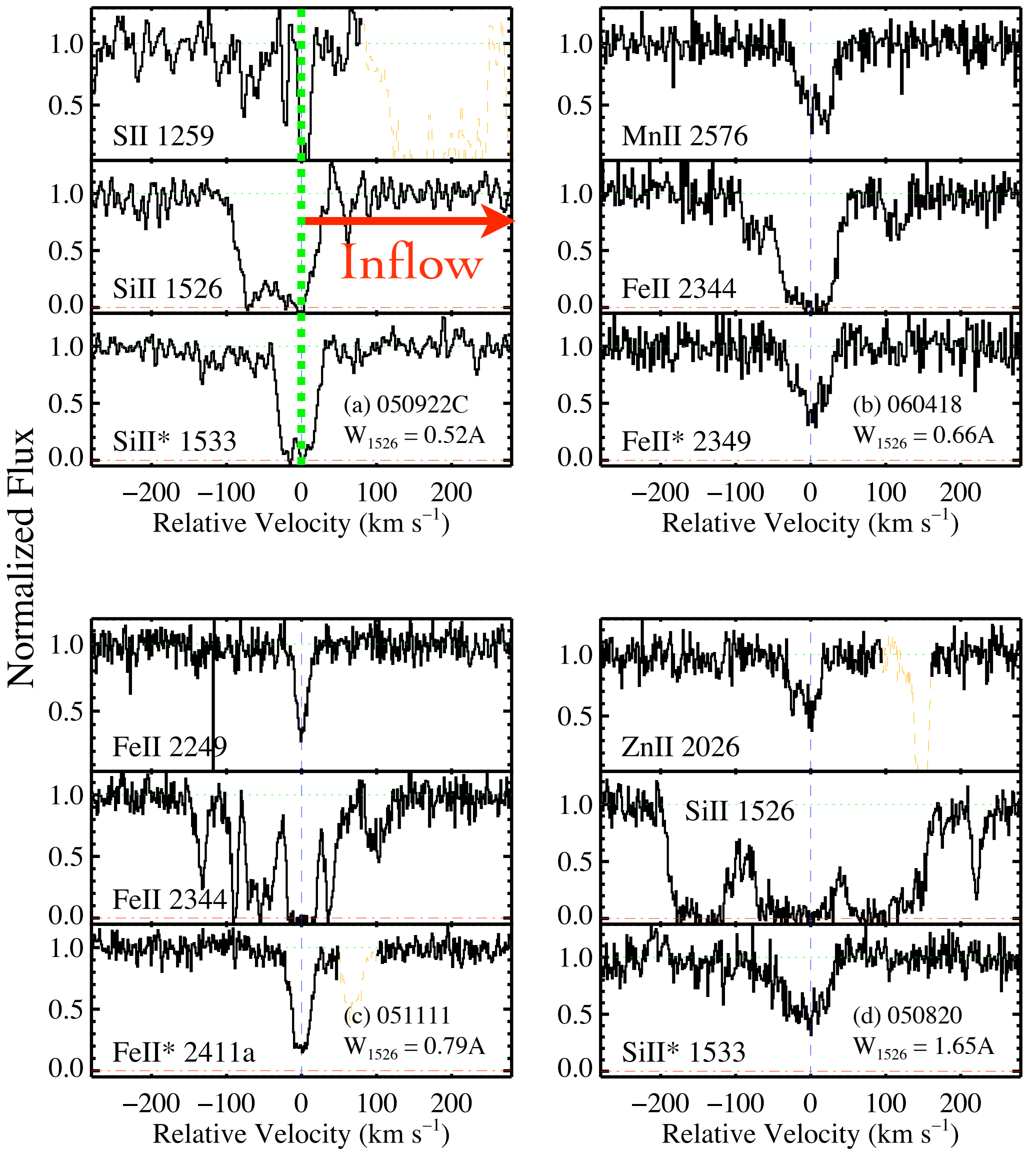

Origin and Nature of the Velocity Fields

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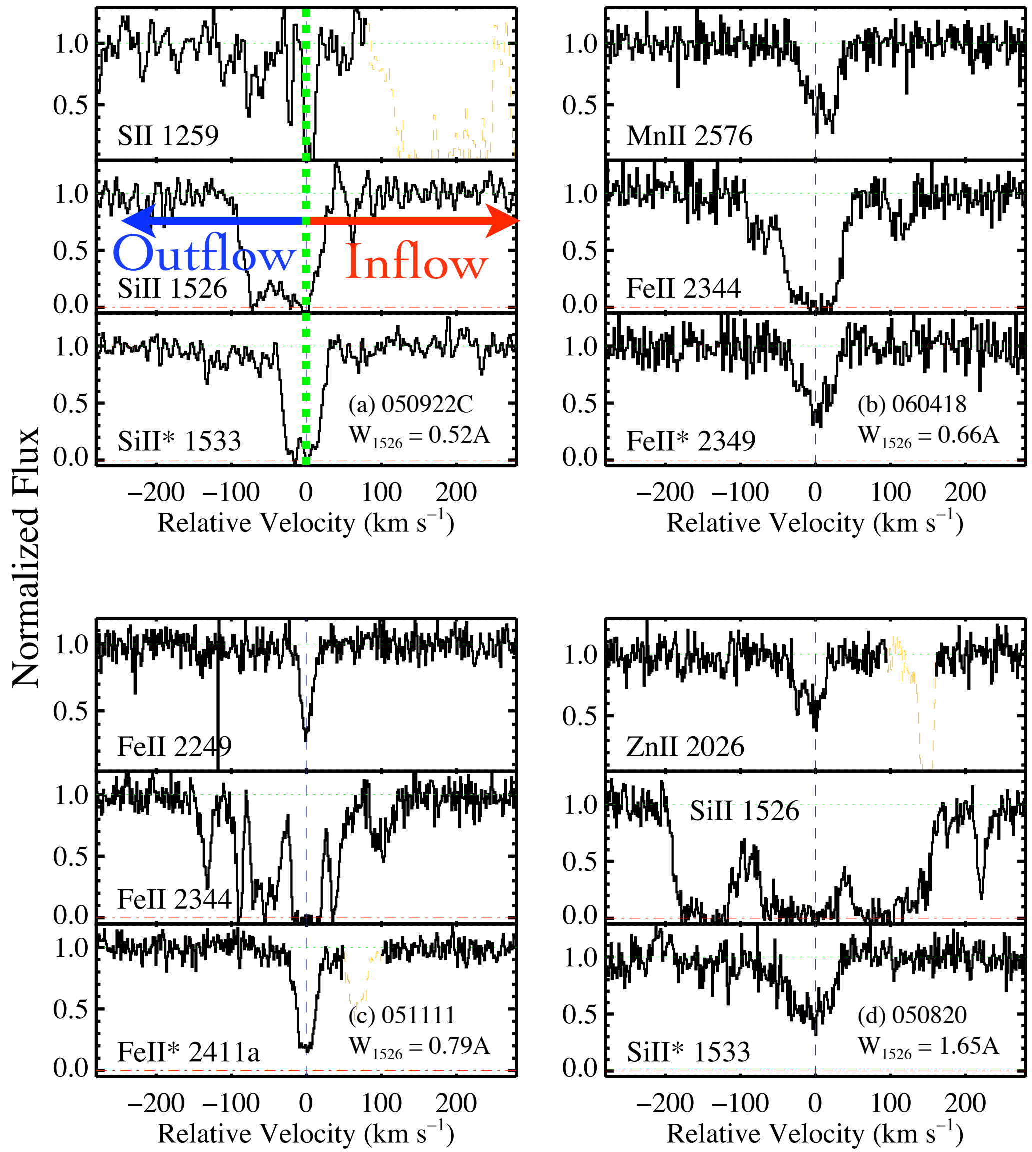
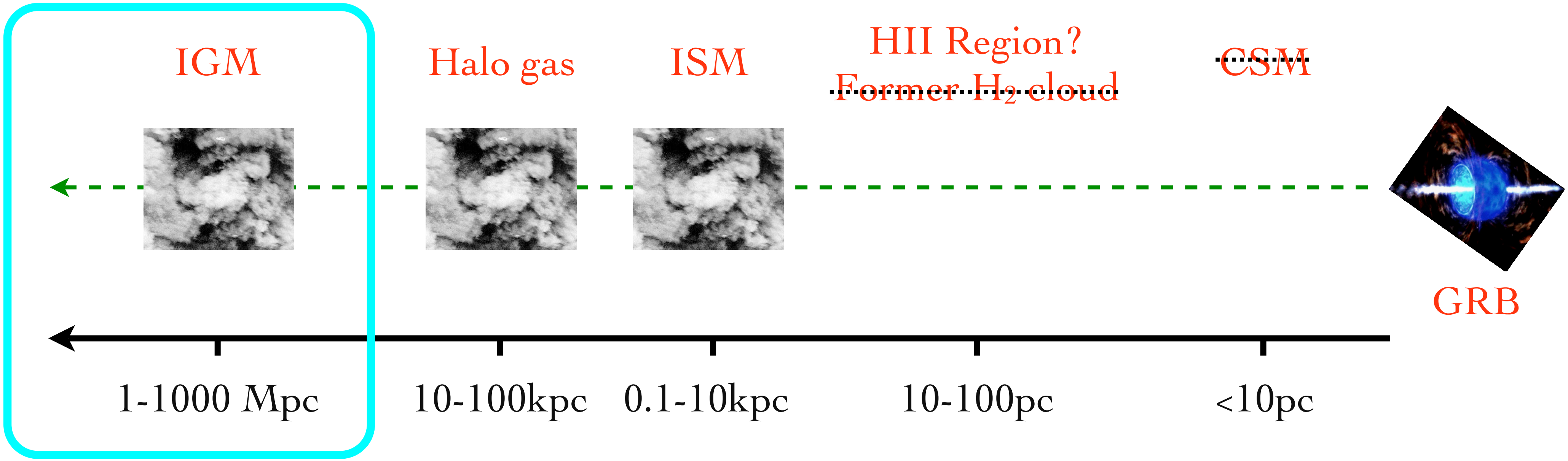


The Experiment

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)

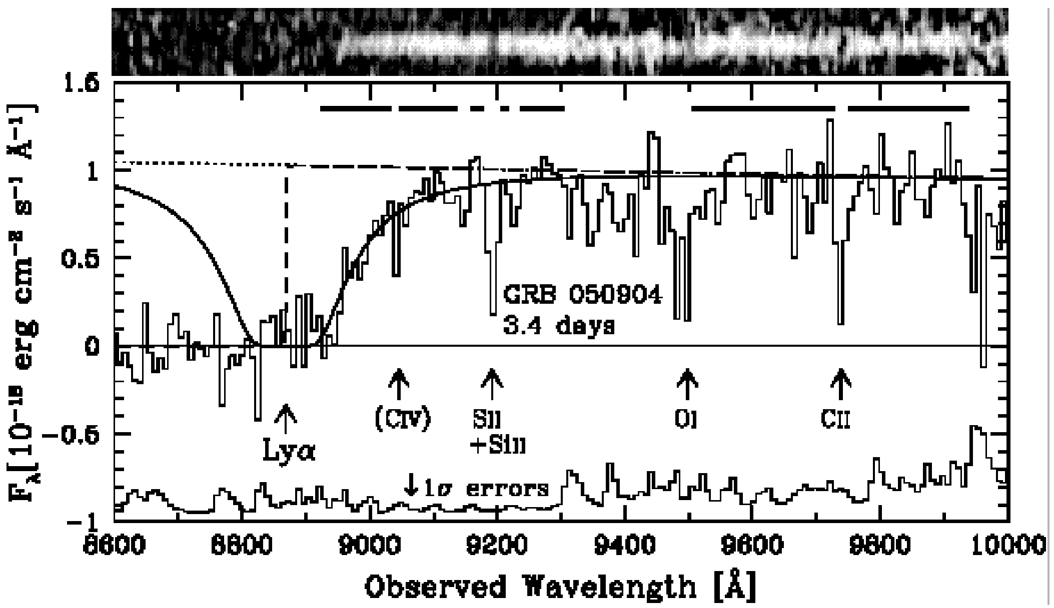


Keep in Mind: One measures directly the velocity of the gas, not its distance. Therefore, all of these regions are potentially mixed together in our spectrum

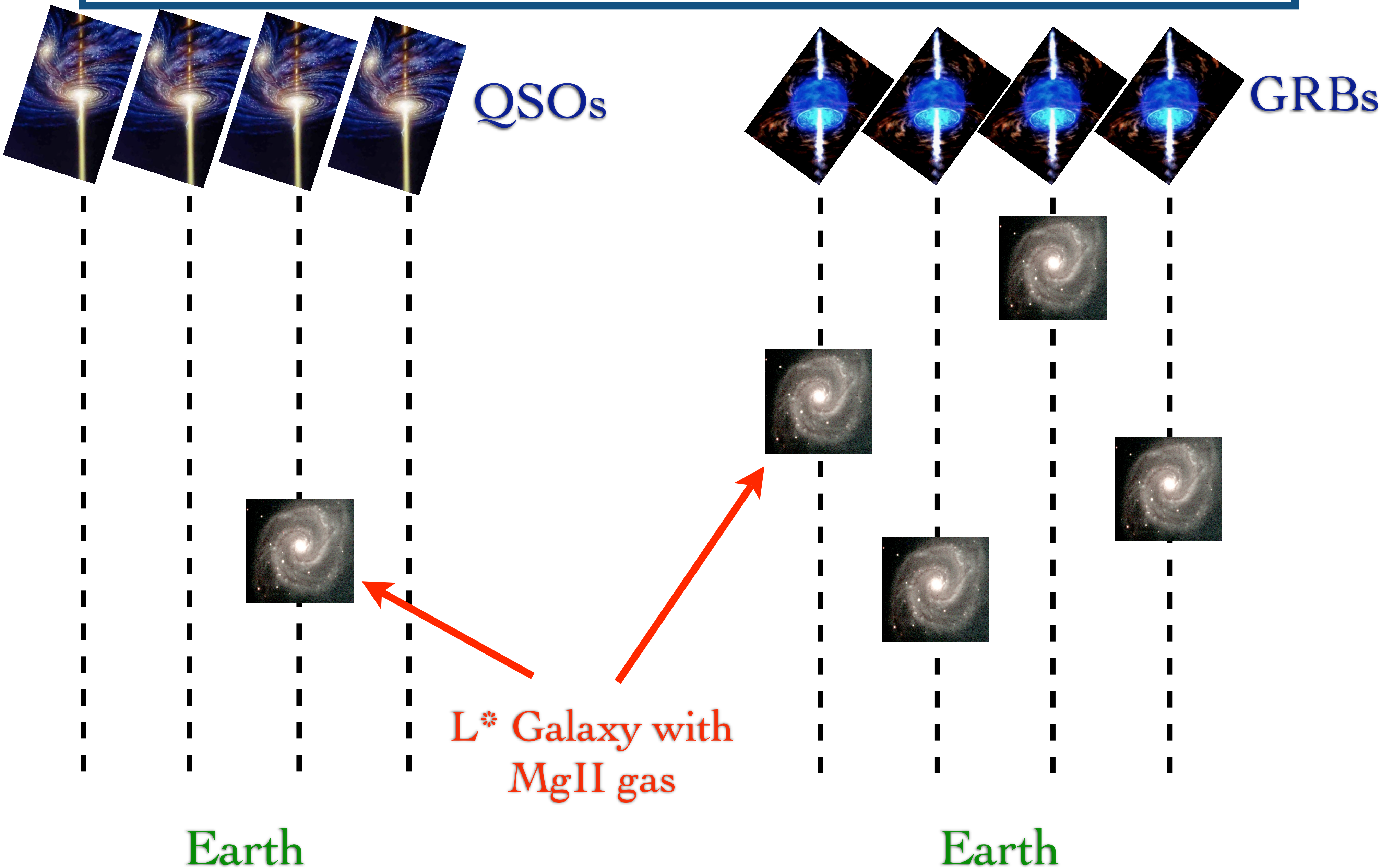
Probing Reionization with GRBs

- 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 constrain reionization
  - Going to need lots of patience and a bit of luck

Kawai et al. (2005)

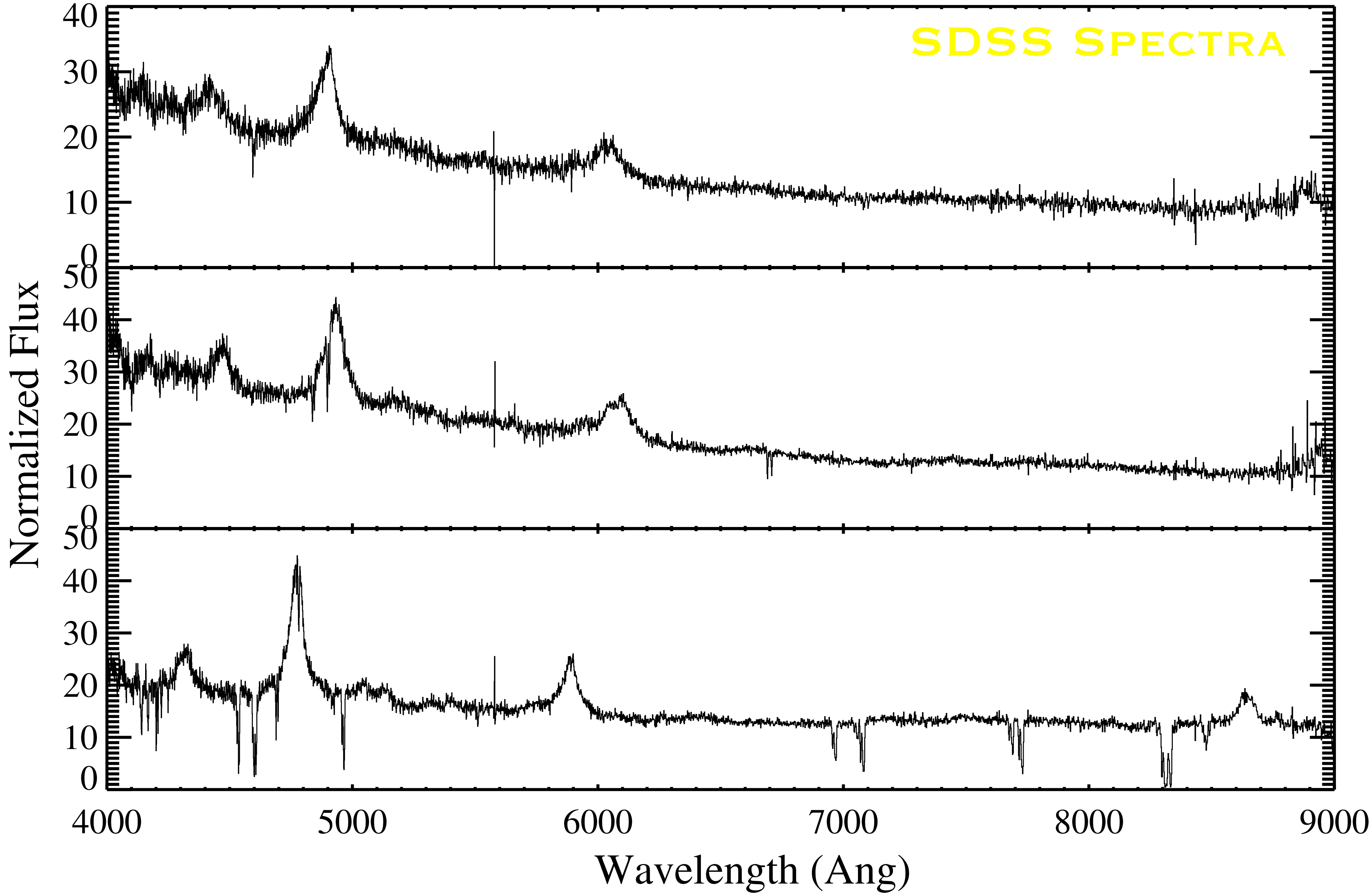


A ‘Spooky’ MgII Enhancement



Prochter et al. (2006)

MgII Search in QSO Spectra



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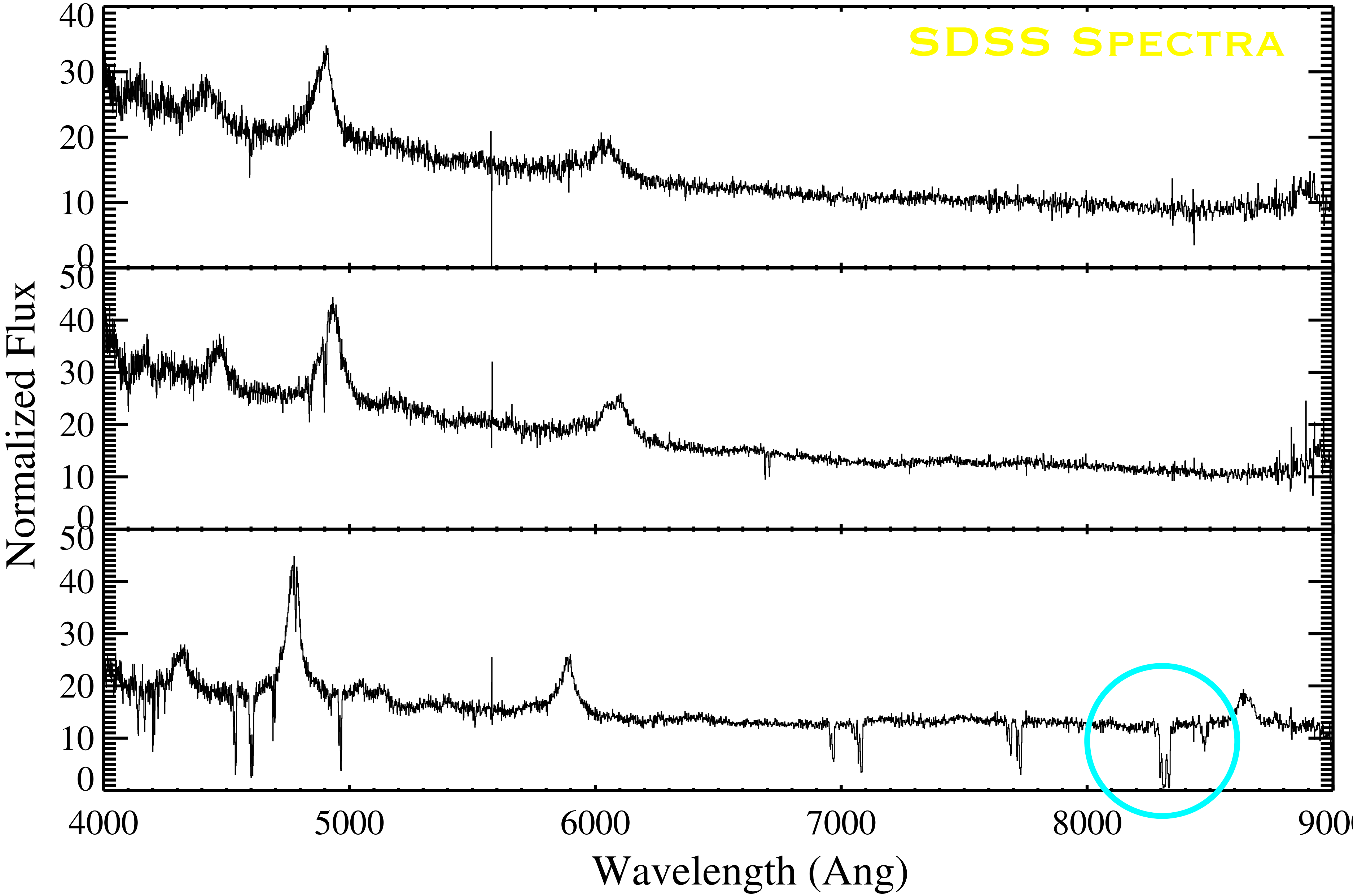

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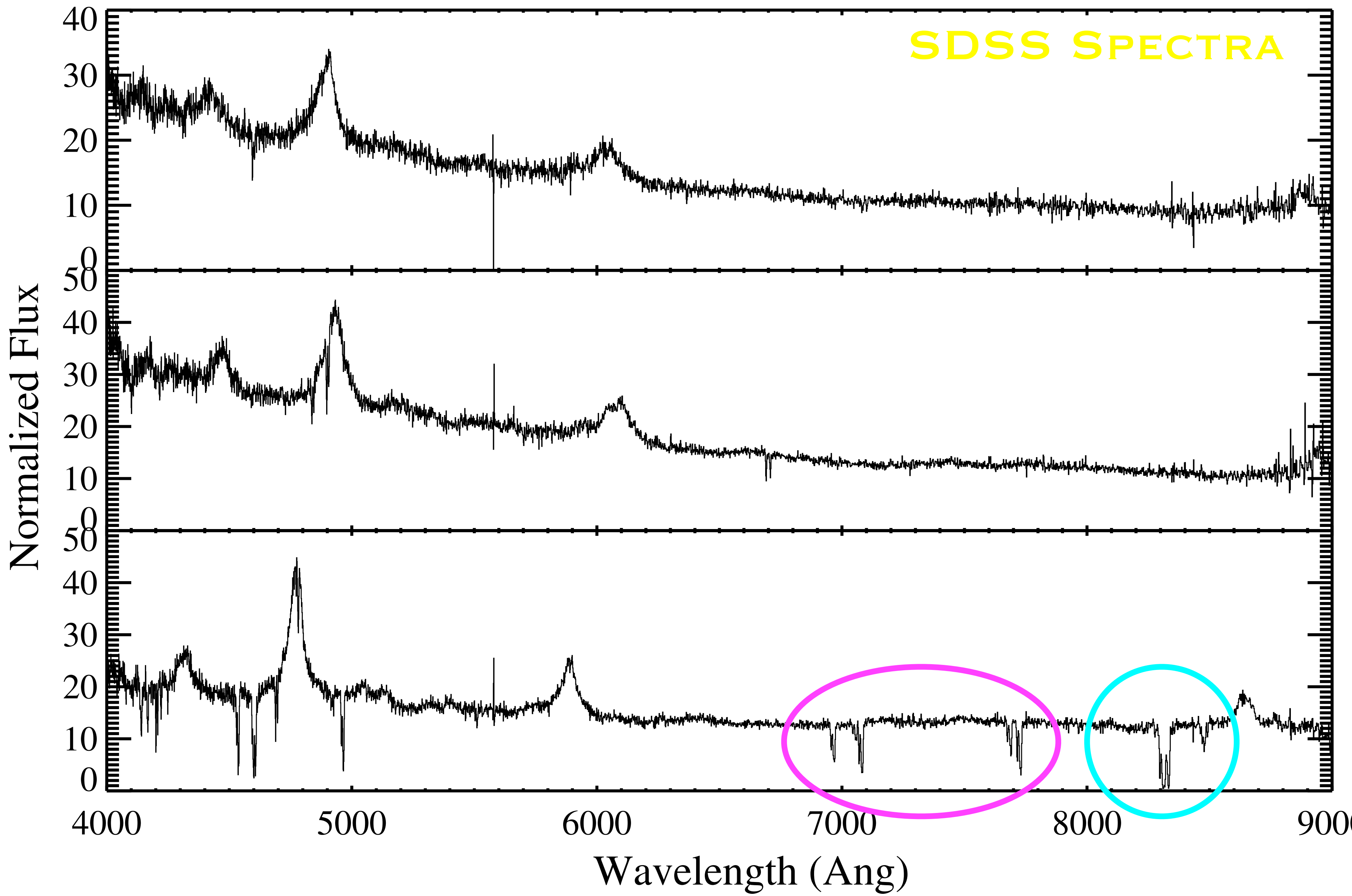
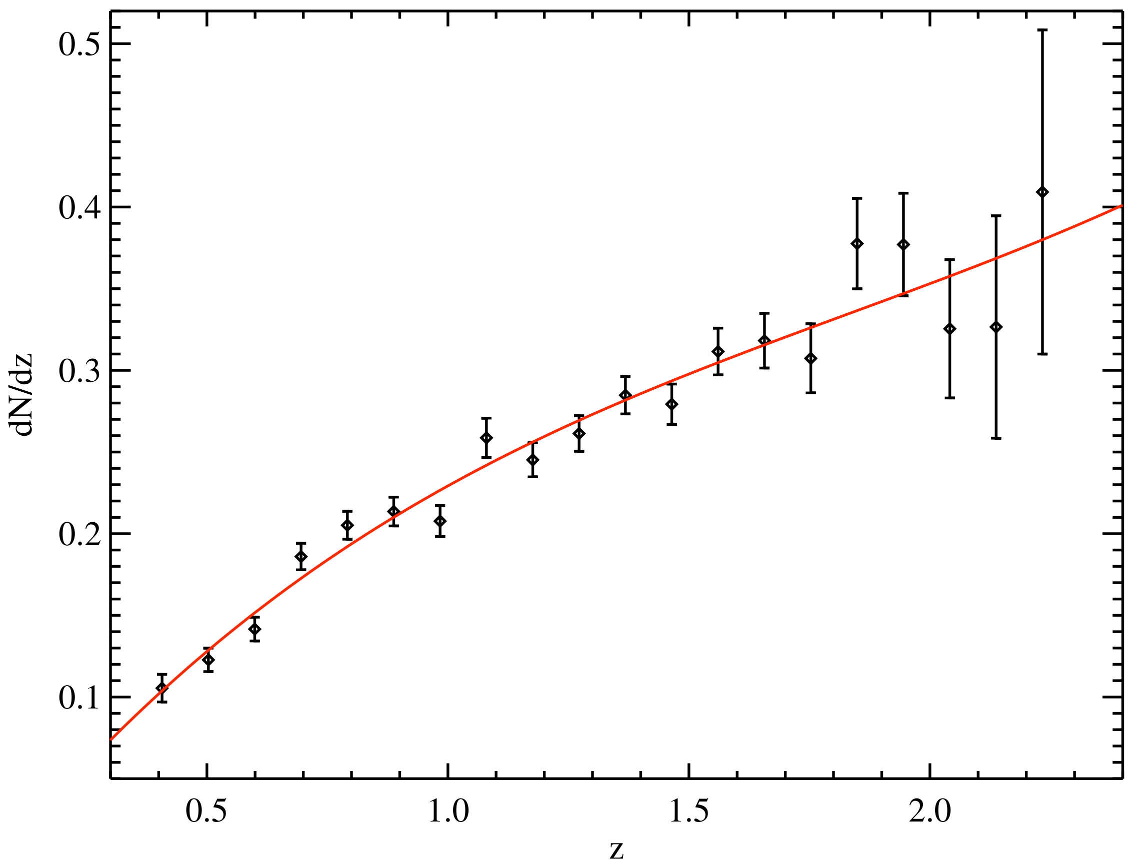


dN/dz of MgII

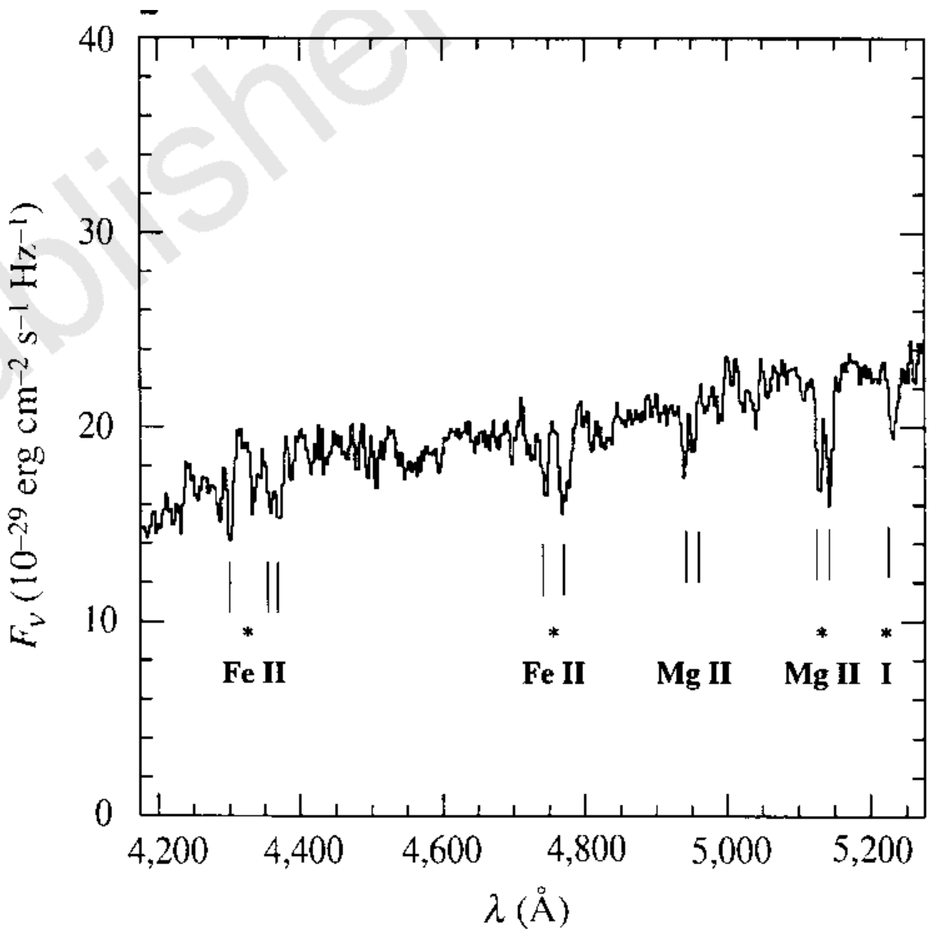
- *dN/dz*
  - Number of absorbers per unit redshift
  - Roughly, 1 QSO has 1 unit of redshift coverage
- SDSS
  - 20,000 quasars with sufficient SNR
    - Automatically identify 10,000 MgII systems
    - Stat sample is 7000 with Rest EW > 1A



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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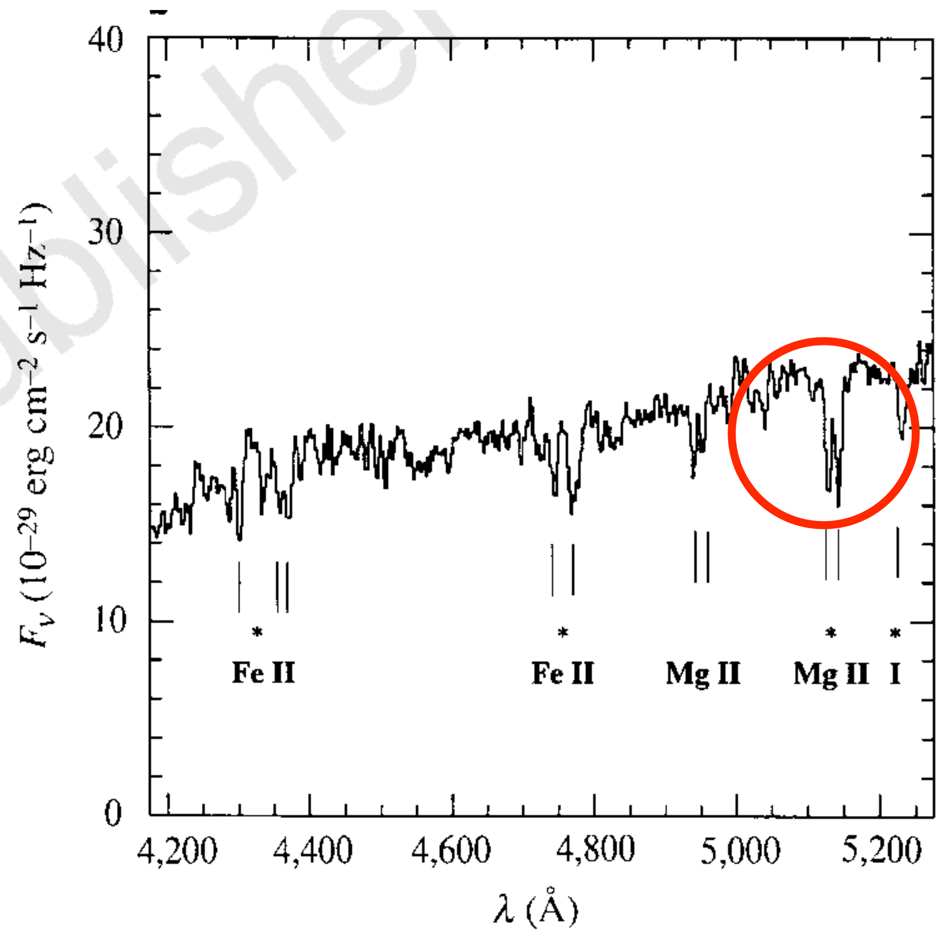

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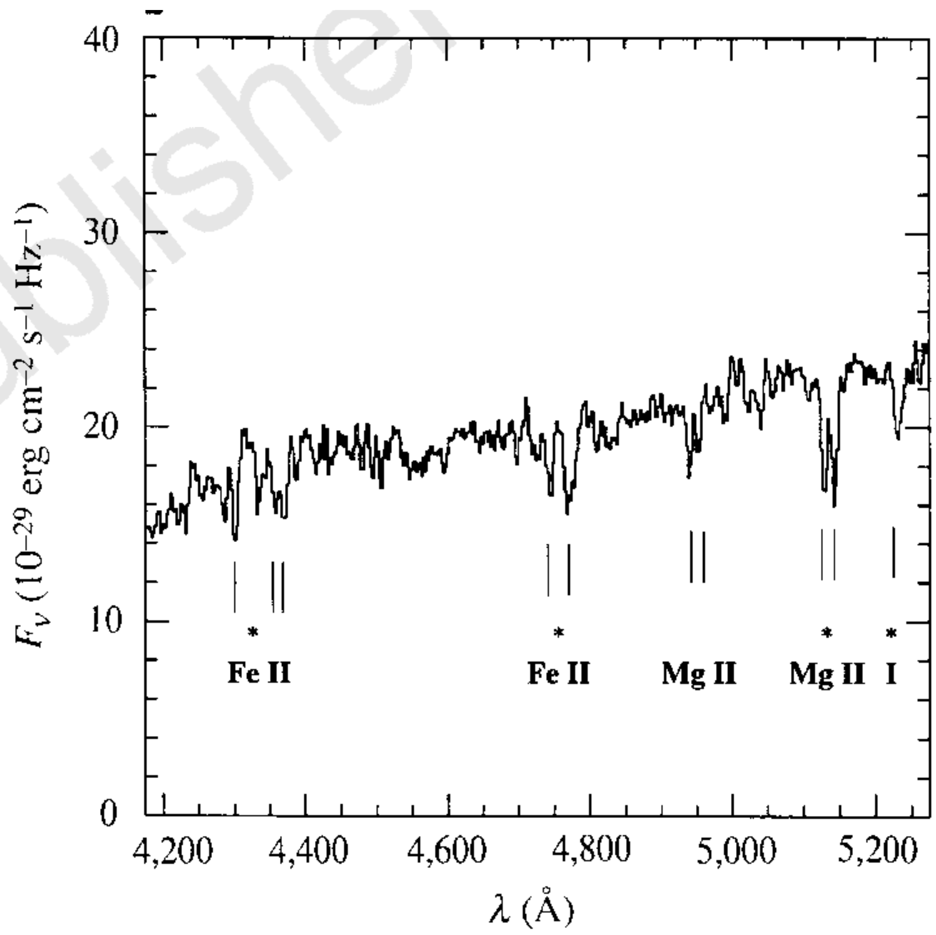

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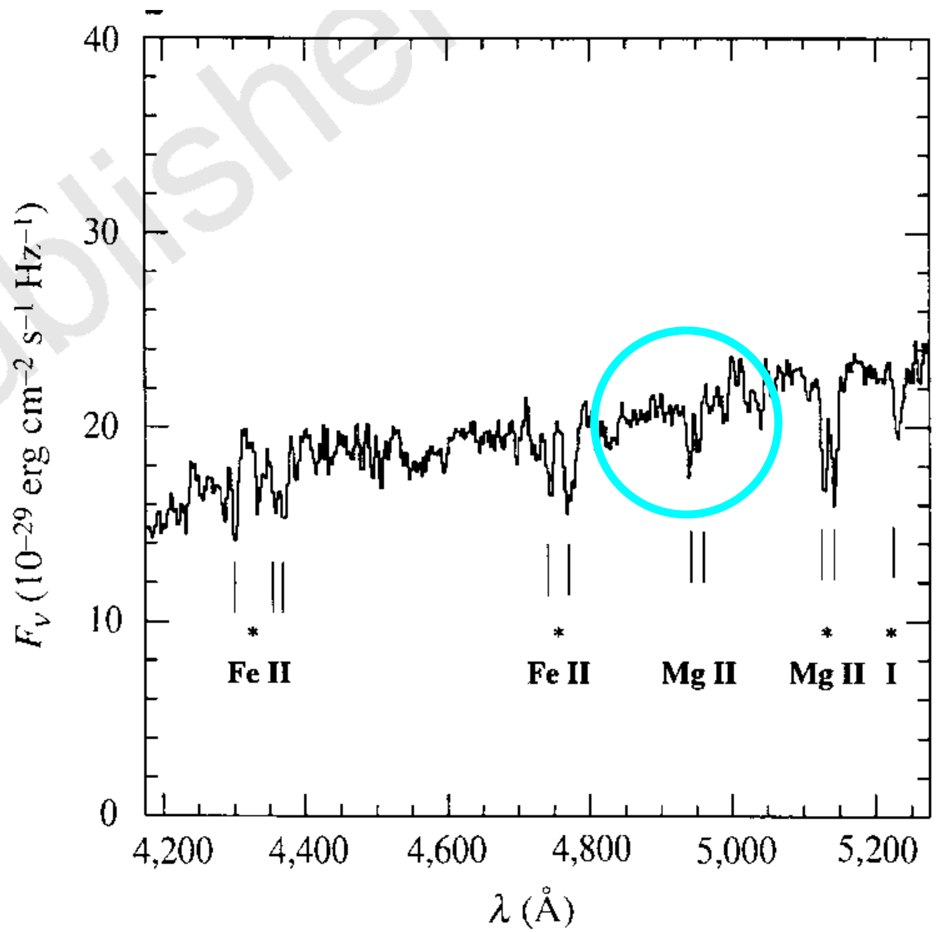
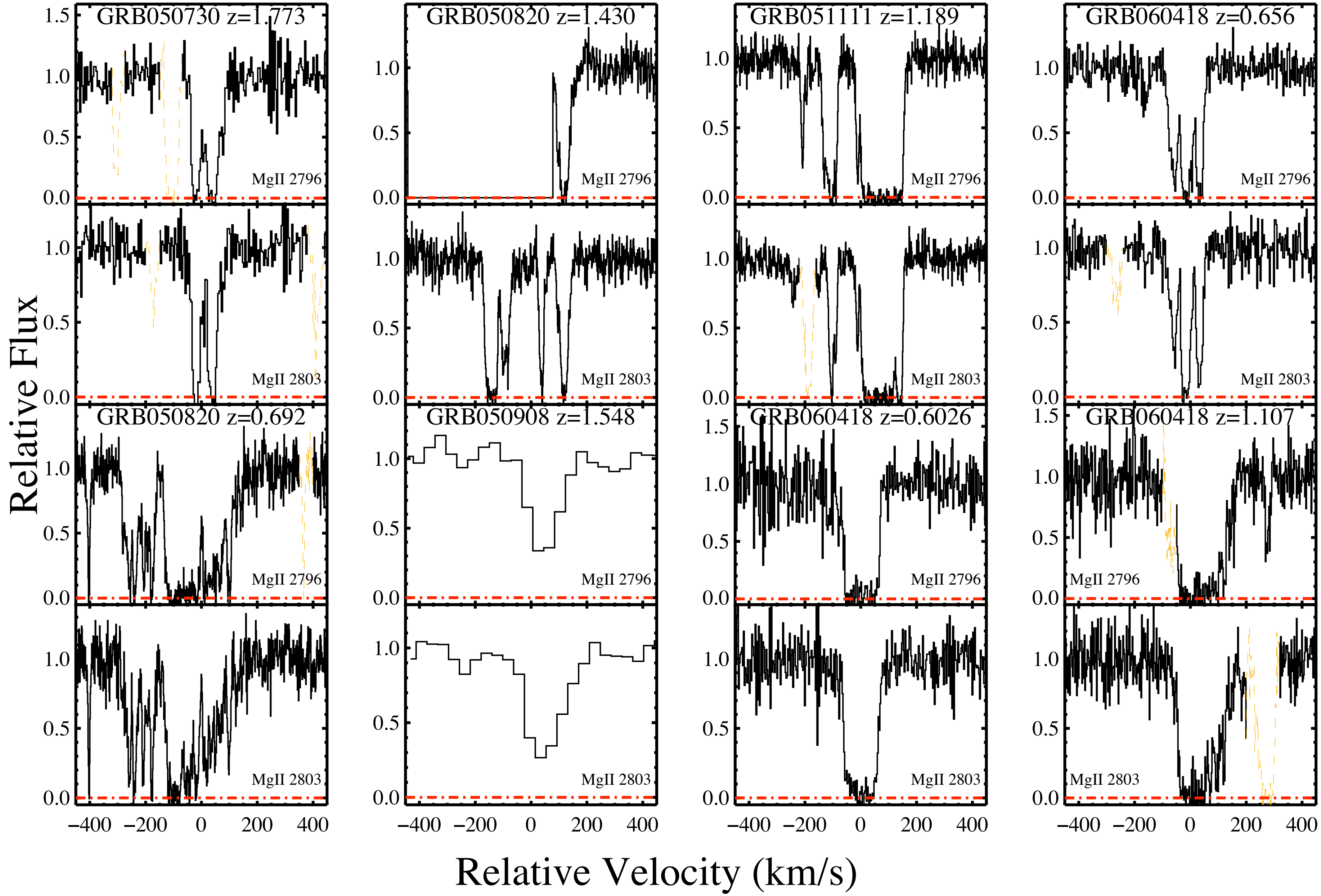


GRAASP Swift Sample



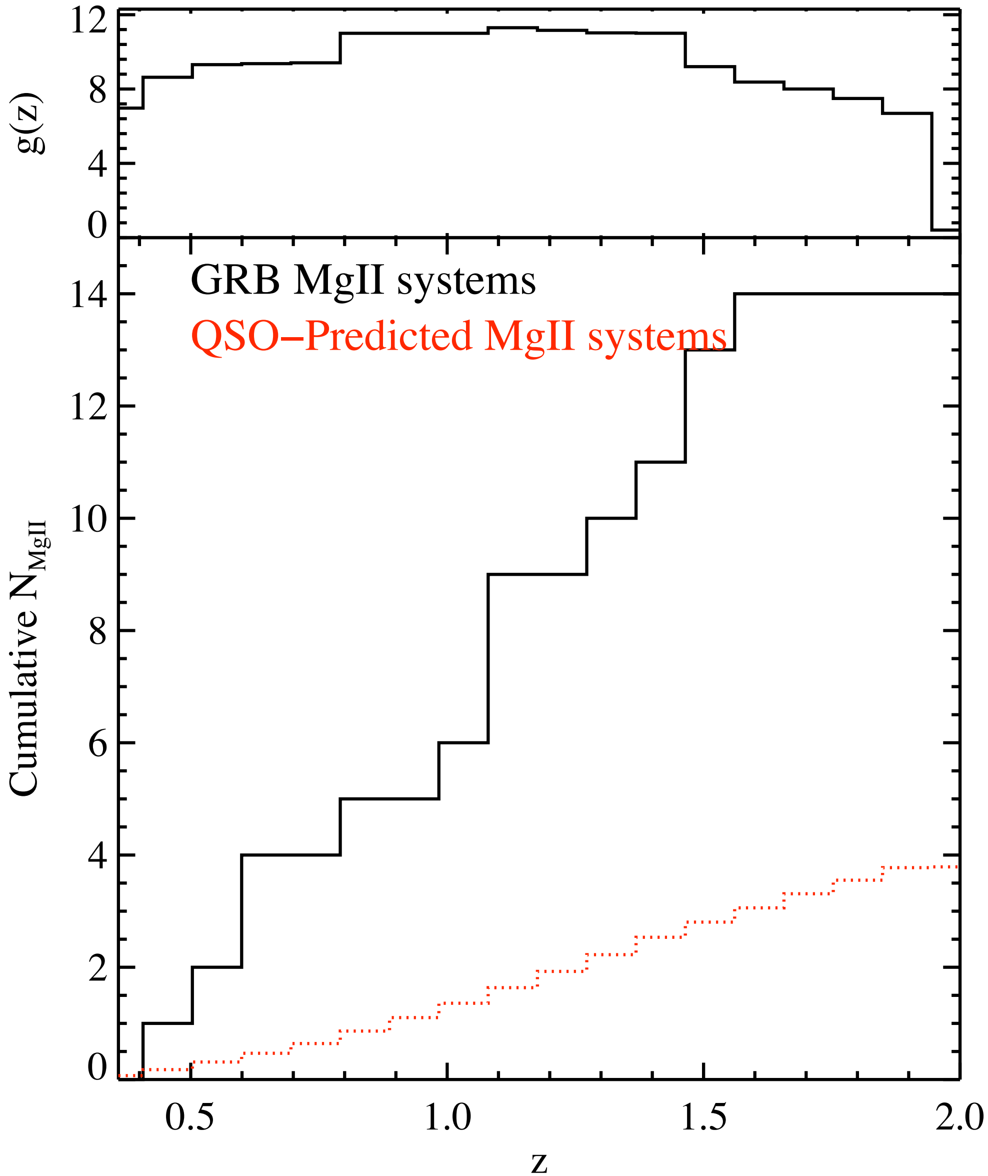
Prochter et al. (2006)

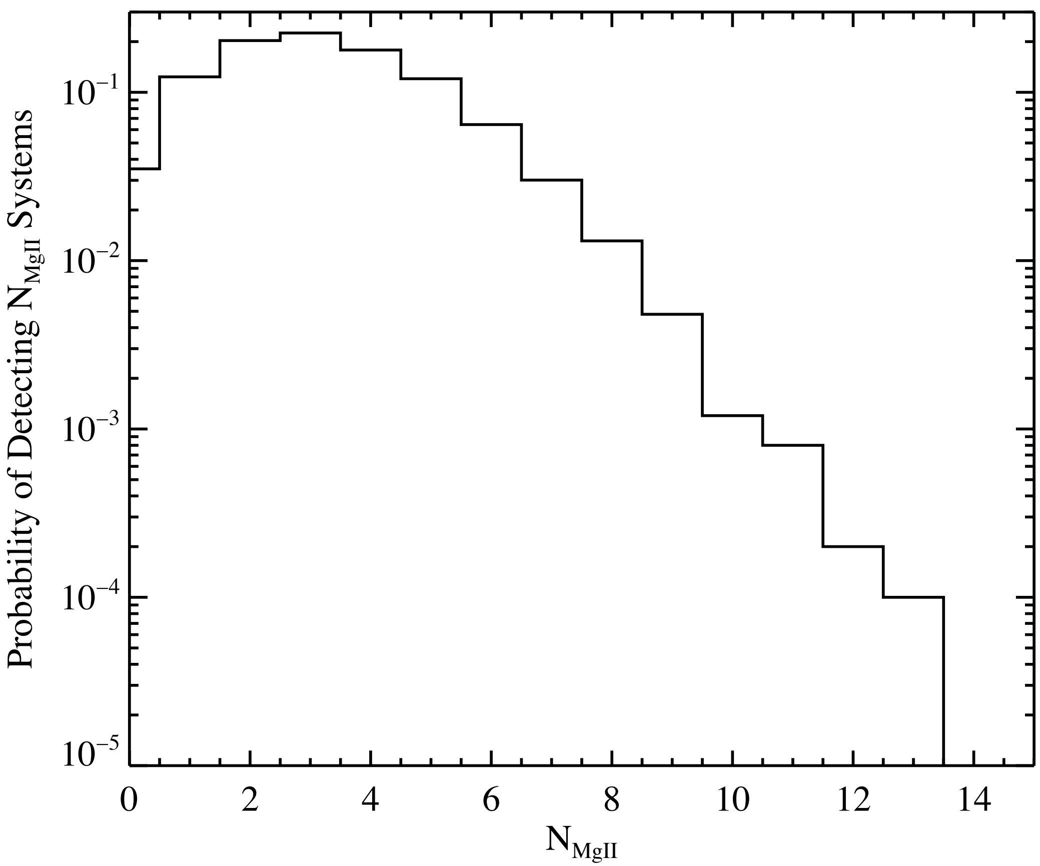
GRB MgII Sample

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 Strong Result

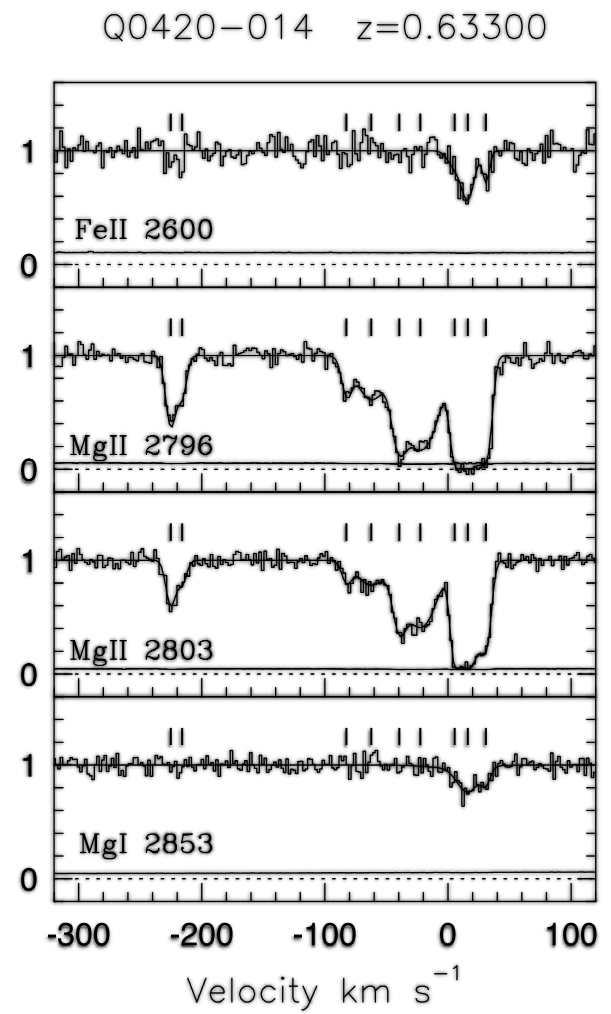




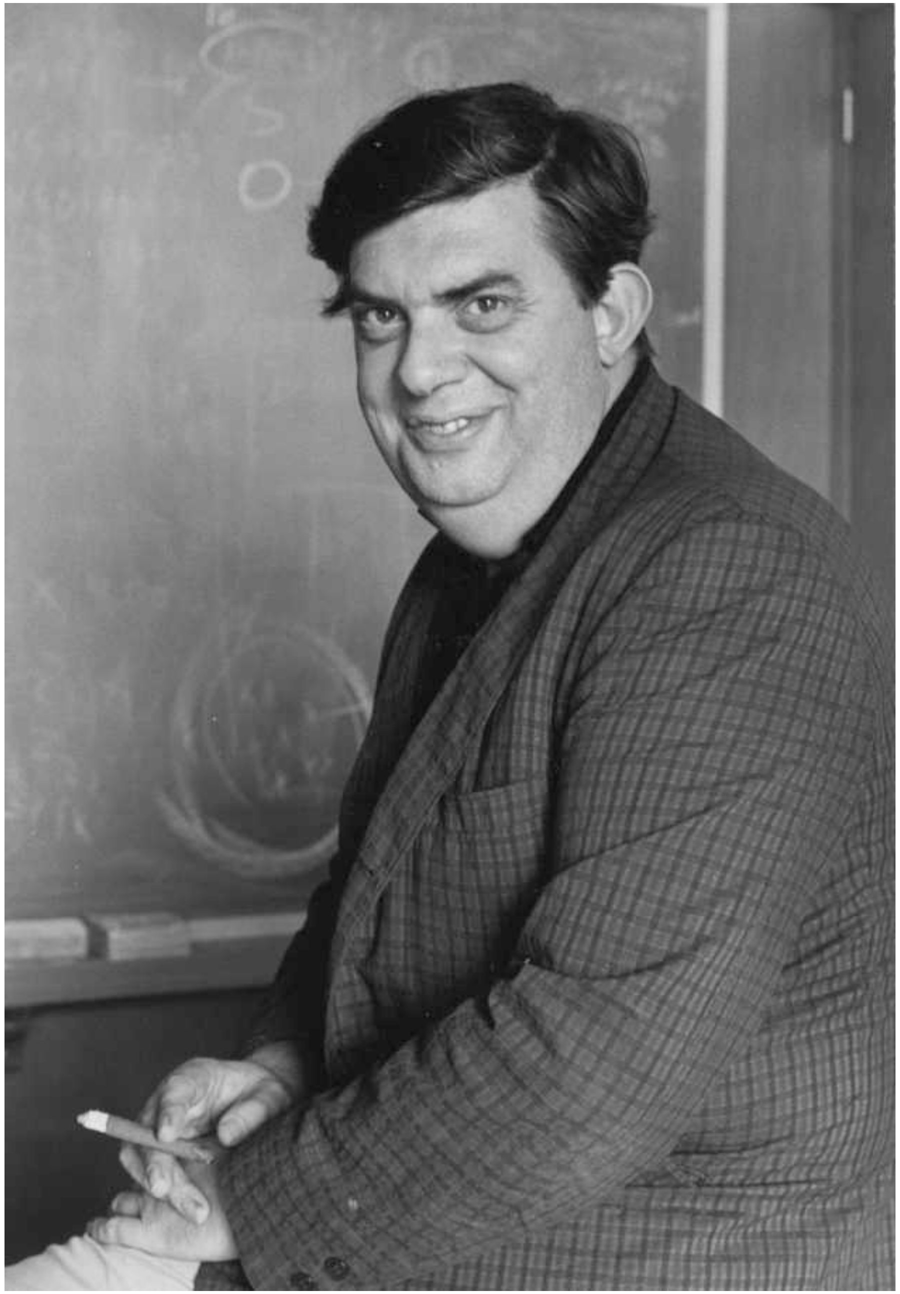
Chance result?
Less than 1 in 10,000

Possible Explanations

- Dust obscuration?
  - MgII absorbers contain dust
    - 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
- Beam size? (Frank et al.)
  - No partial covering observed
  - No difference in QSO emission lines
    - Pontzen et al. (2007)



Bizzare (fundamental?) result



Summary

- GRB Afterglow spectroscopy 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?
- IGM
  - z>6 Universe? I grow pessimistic (for now)
  - 'Spooky' MgII enhancement still awaits an understanding