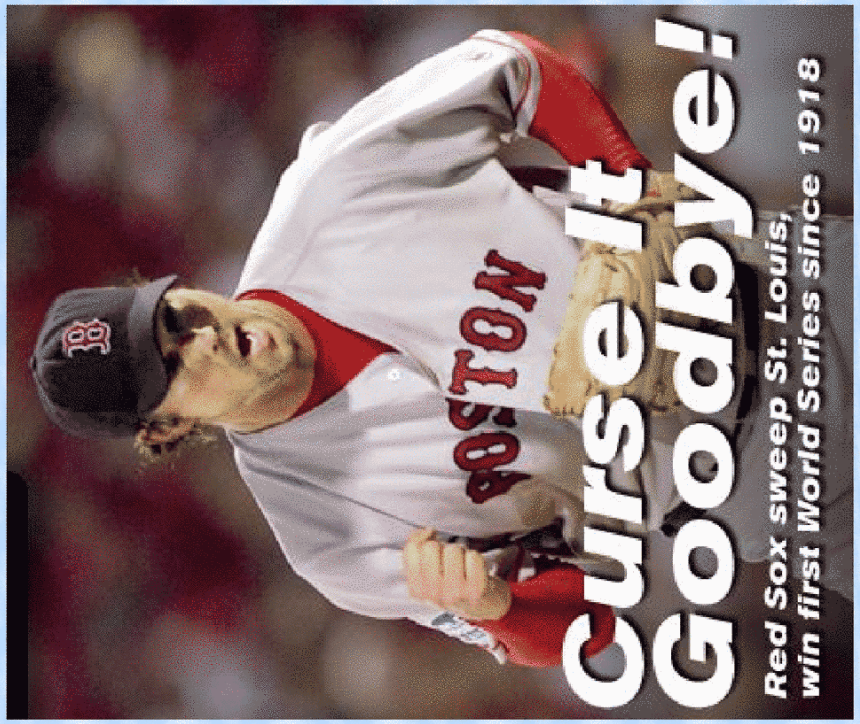
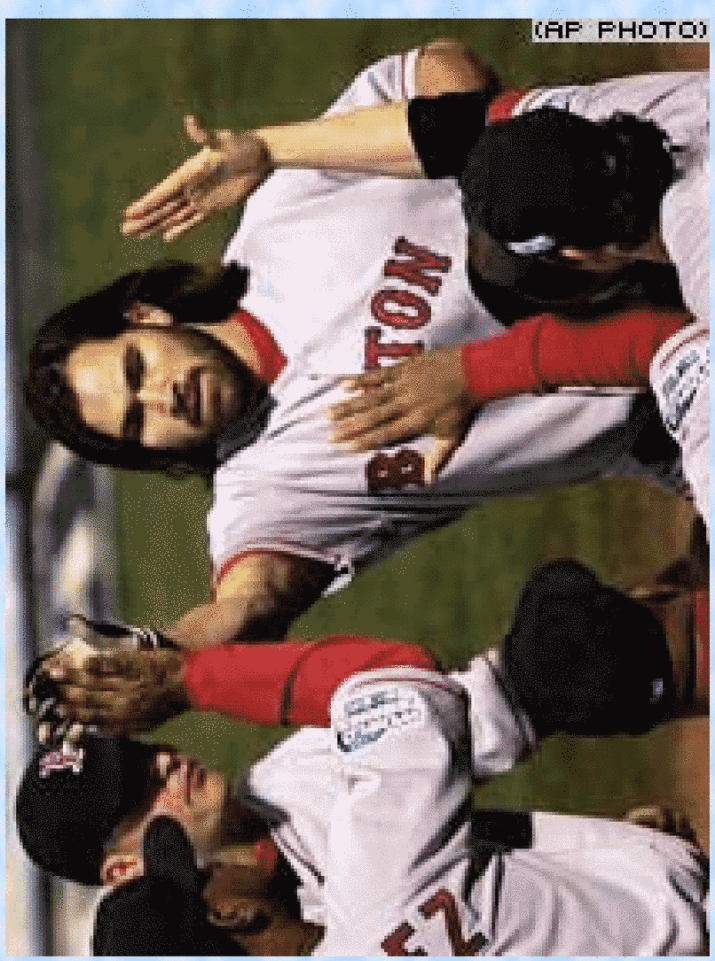
Investigating the IGM/Galactic Interface with QAL Systems

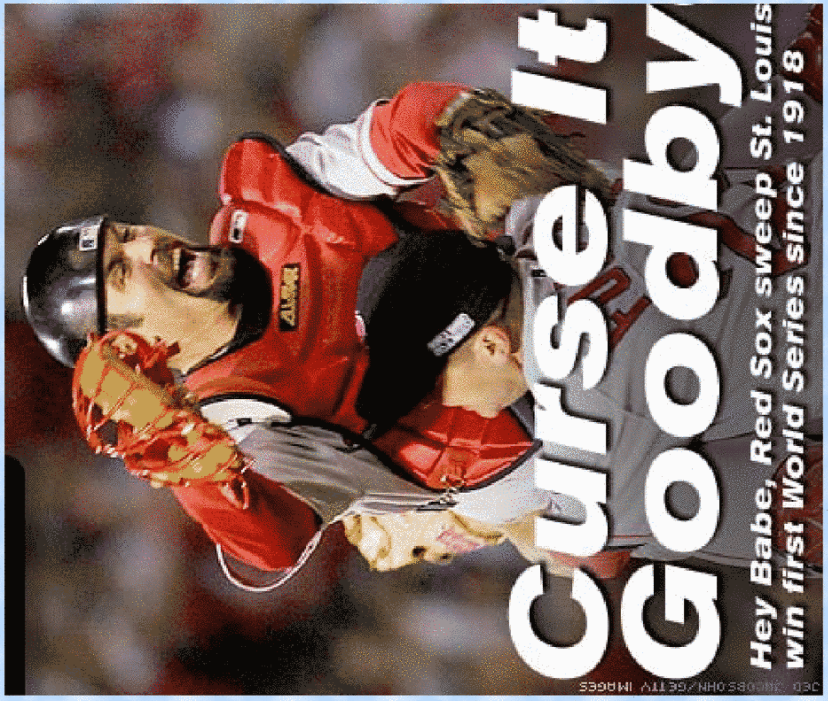
Jason X. Prochaska

UCO/Lick Observatory
UC Santa Cruz


BOSTON
Curse It Goodbye!
Red Sox sweep St. Louis, win first World Series since 1918


AP


(AP PHOTO)
STON


Hey Babe, Red Sox sweep St. Louis
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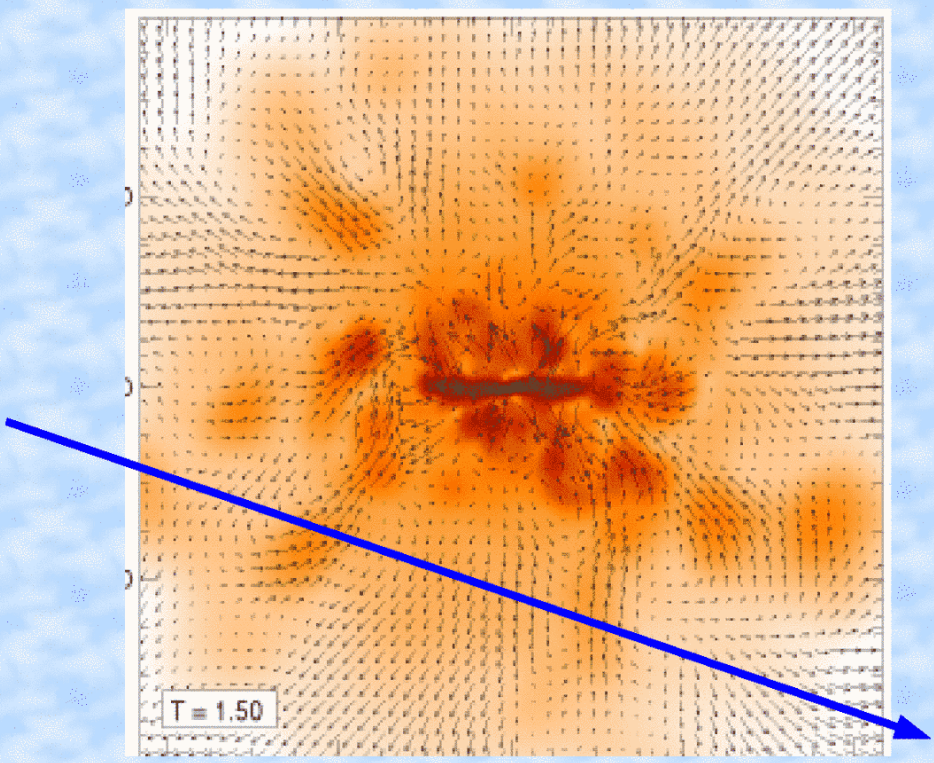

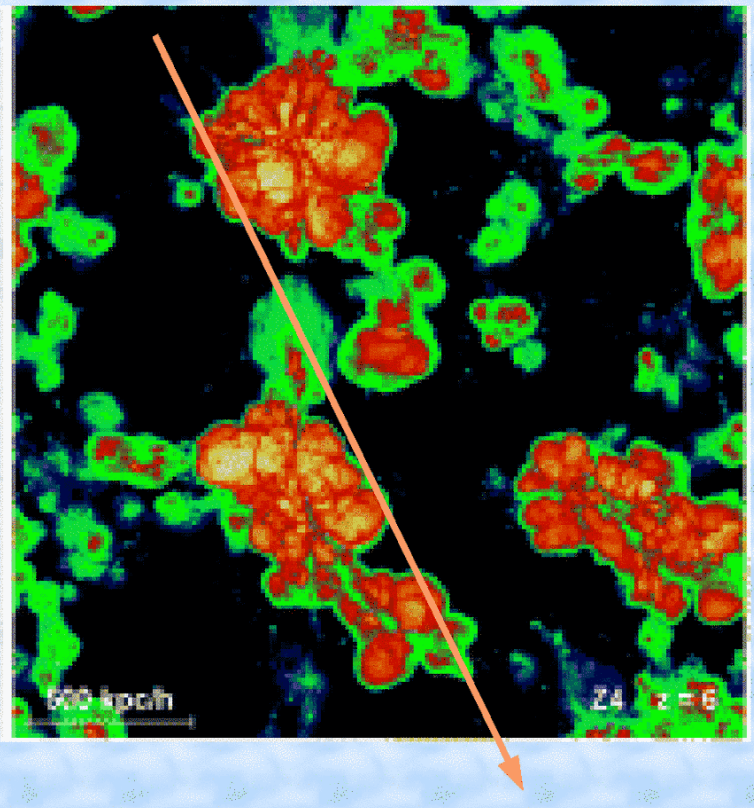

Outline

- Lyman Limit Systems at z~2
  - Ionization of the IGM
  - Metal enrichment
  - Accretion, SF feedback

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  Burles (MIT)
  Bernstein (U Michigan)
- Strong MgII Systems at z~1
  - Superwinds, superbubbles?
  - Clumps in DM Halos?

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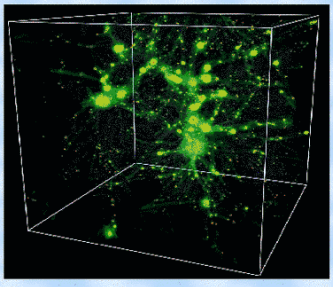
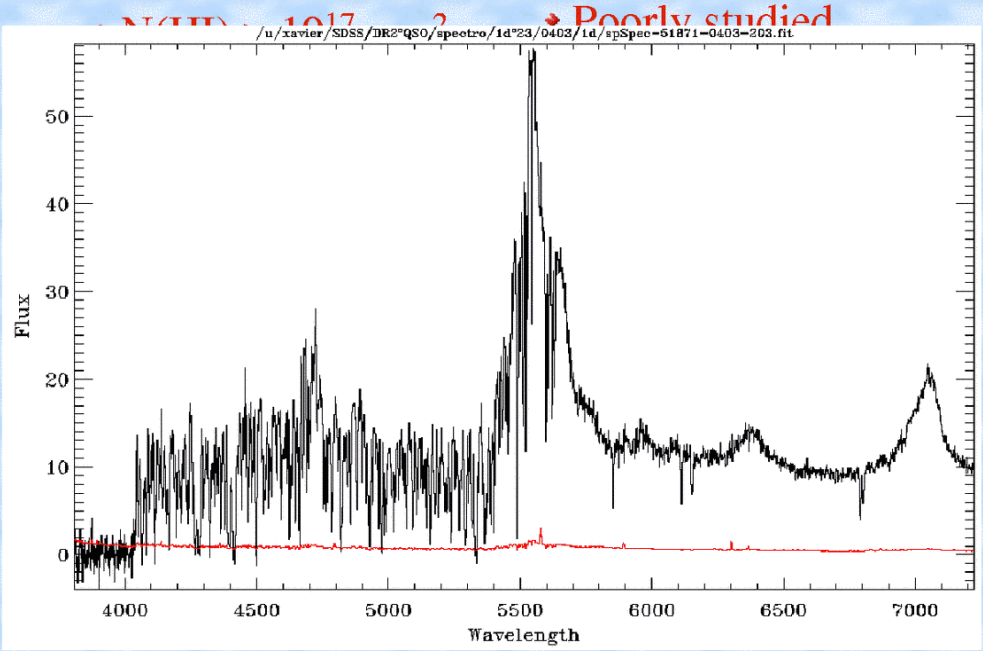
- Metal-line Systems at z~0
  - Metal Enrichement
  - N(H) Constancy

  Cooksey (UCSC)
  Chen (MIT)
  Howk (UC San Diego)



Lyman Limit System

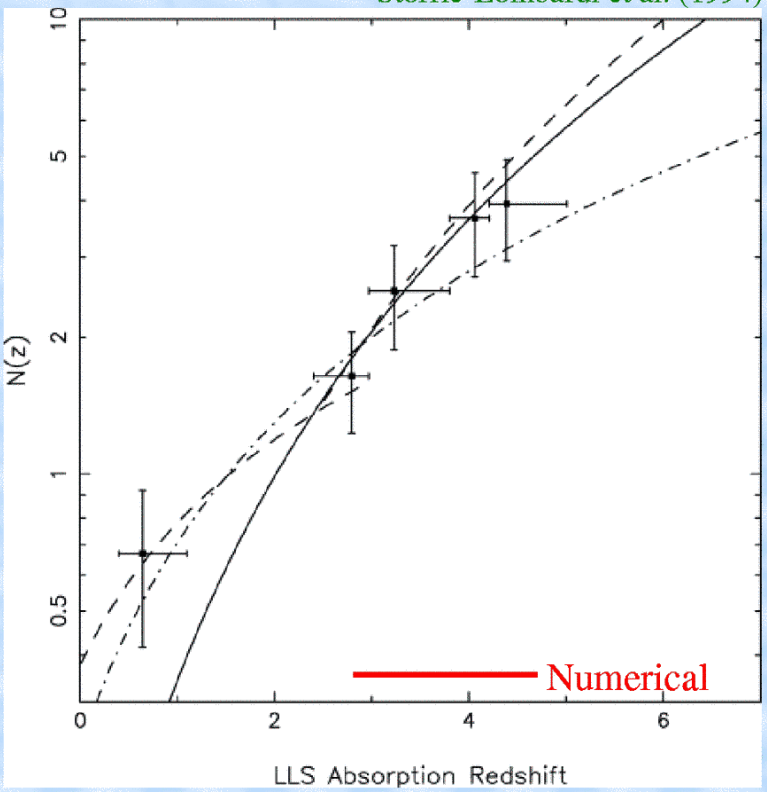
- Definition
  - $912 > 1$
  - $N(HI) > 10^{17}$ cm^{-2}
- Trivial to identify
  - Well surveyed
  - Poorly studied

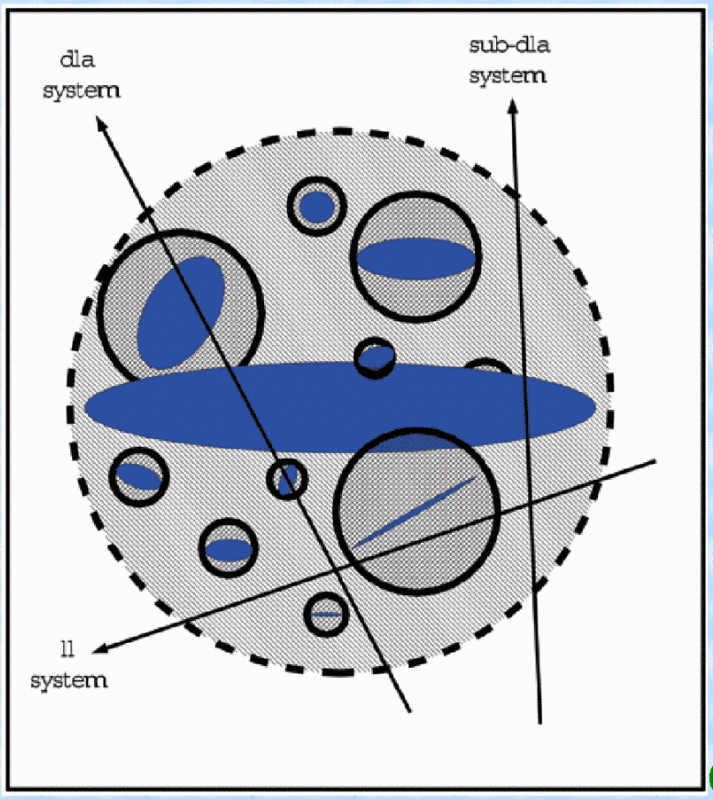


LLS dN/dz

- Observations
  - Low resolution spec
  - Large sample size
    - Gardner et al. 2001
- Numerical sim
  - 10x too few LLS
    - Unresolved galaxies?
    - Large-scale struct?
- Semi-Analytic
  - 'Mini'-halos (v_c<30)?
  - Photoionization is a serious problem
    - Abel & Mo
    - Maller et al.
    - Kepner et al.

Storrie-Lombardi et al. (1994)



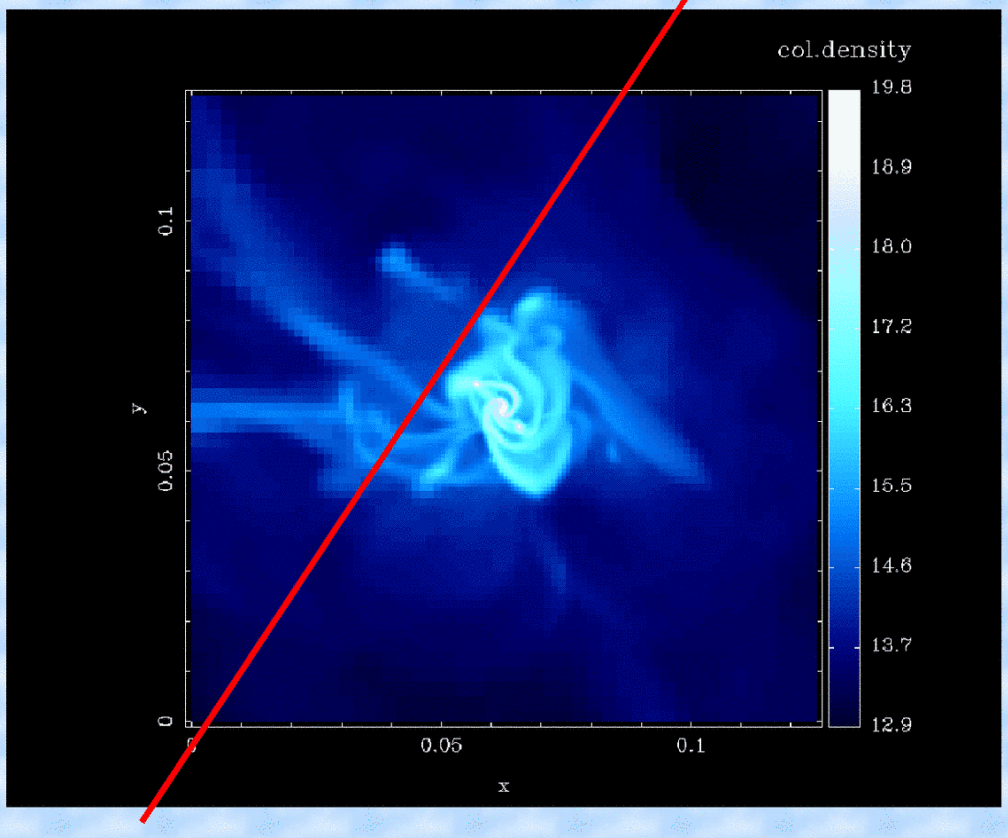


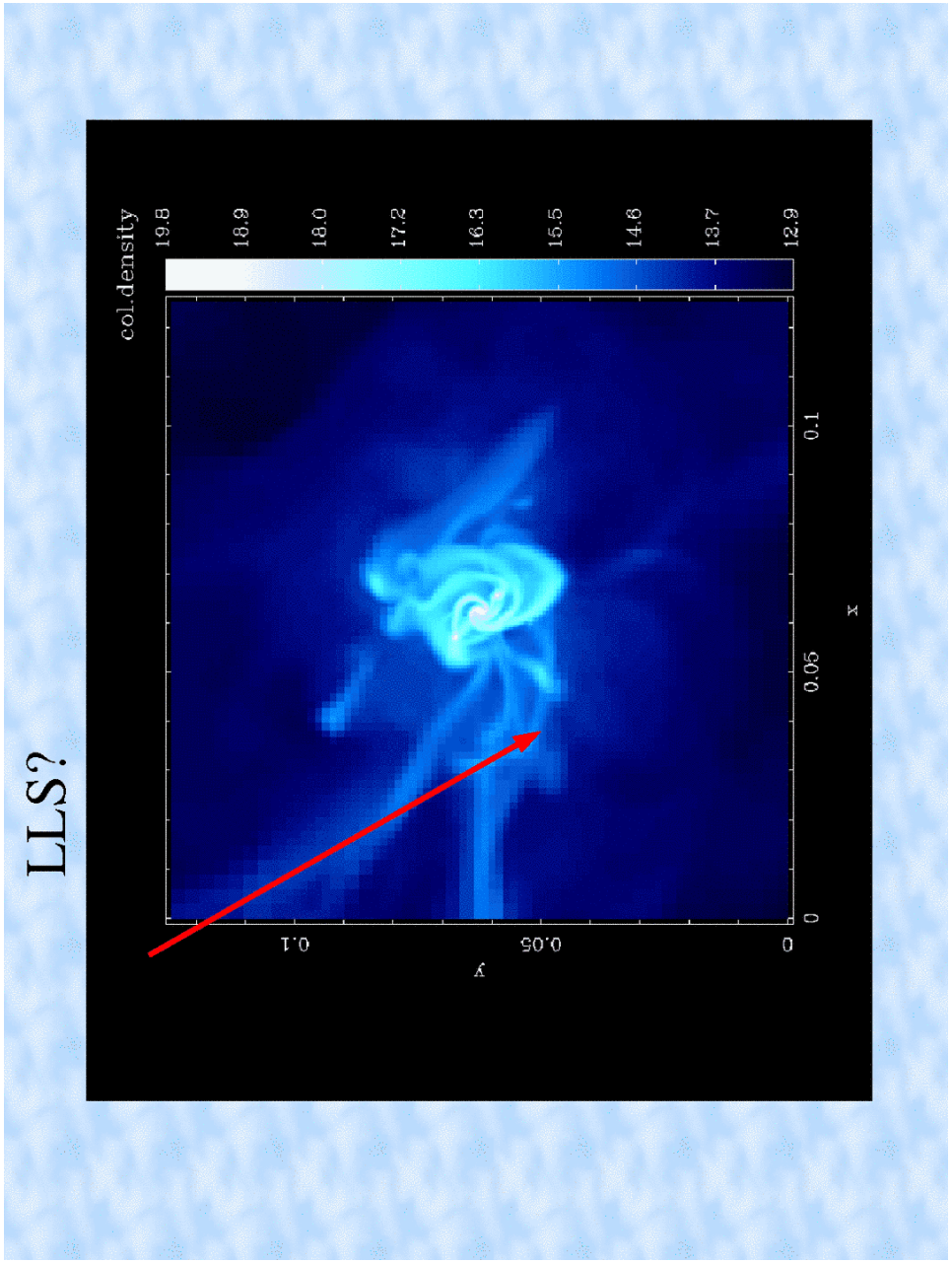
QAL Metal-Line Systems

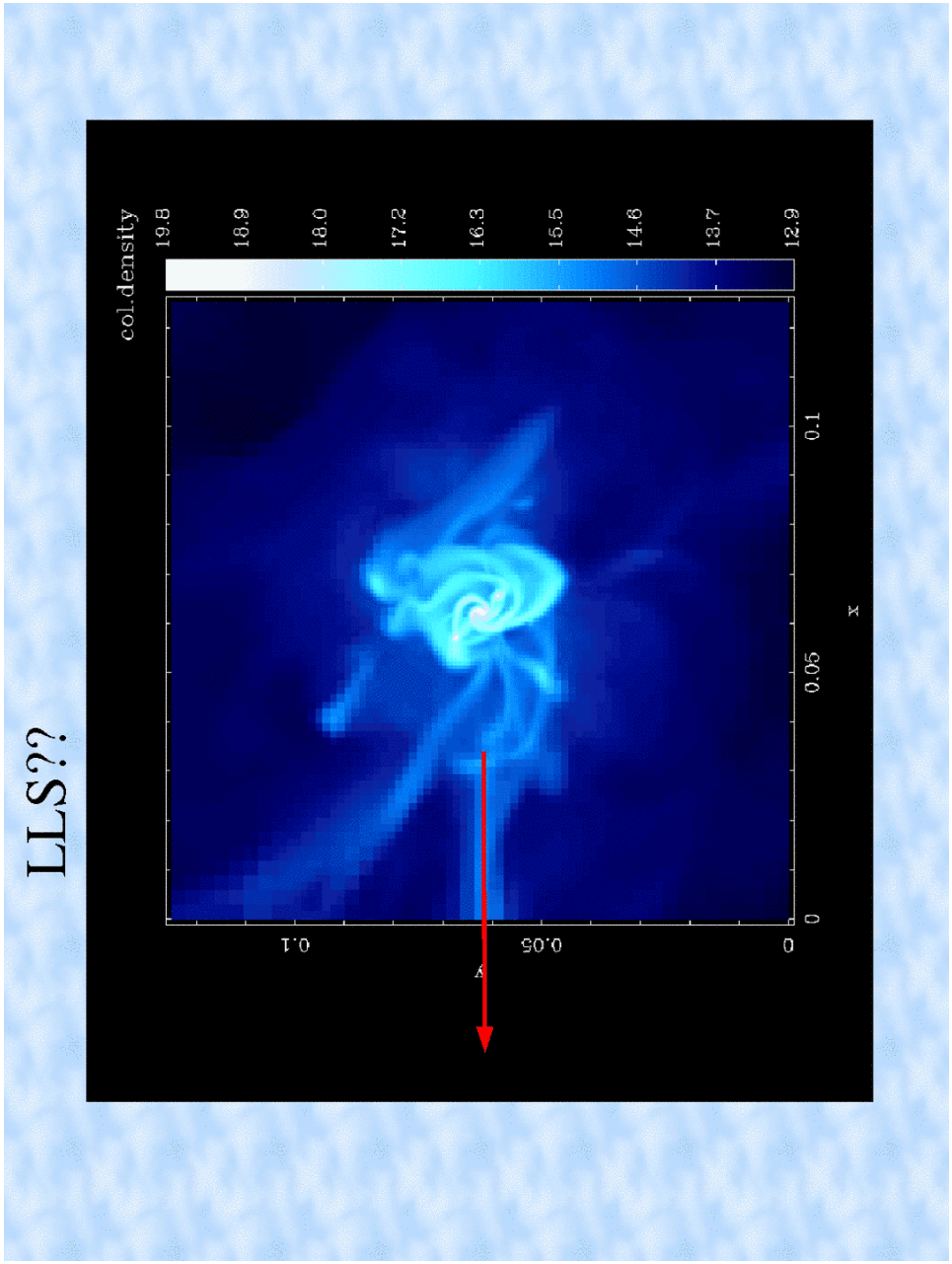
Is this the right picture??

(Maller et al. 2003)

LLS?




LLS?
col.density
19.8
18.9
18.0
17.2
16.3
15.5
14.6
13.7
12.9
0
0.05
0.1
y
0
0.05
0.1
x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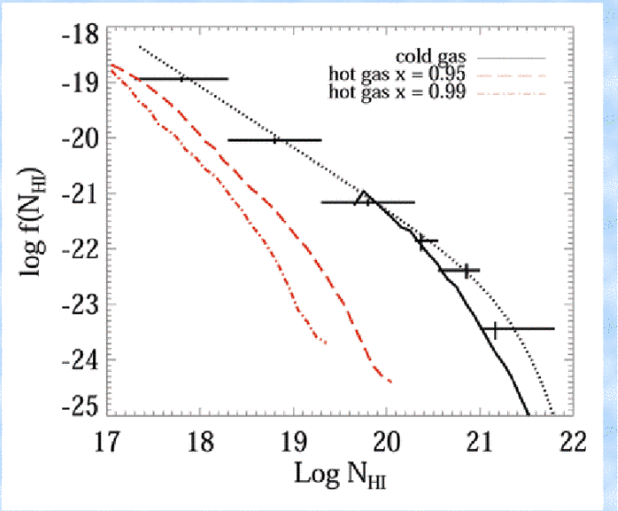
y
0
0.05
0.1
x

Galaxy/IGM Interface

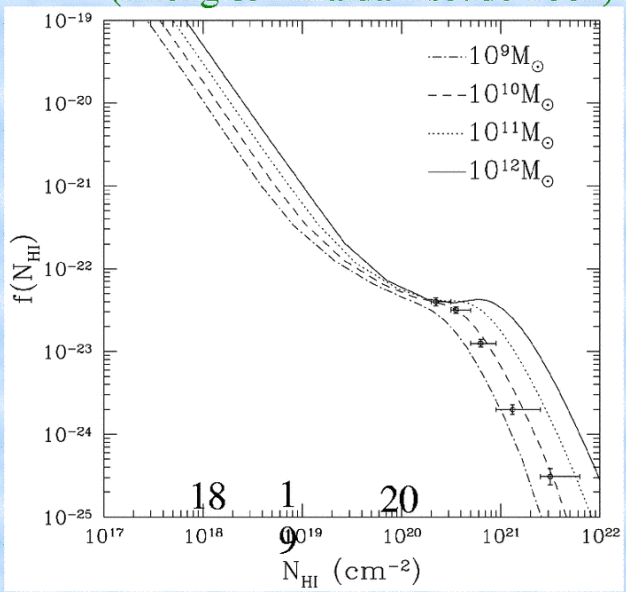
- Intensity, shape of UV background
  - $f(N_{HI})$
  - Metal-line ratios
- Gas distribution of halos, filaments
  - Constrain models of radiative transfer
- Kinematics
  - Dynamics of outflows
  - Accretion?
- Chemical enrichment

LLS HI Frequency Distribution



(Maller et al. 2003)

(Zheng & Miralda-Escude 2002)

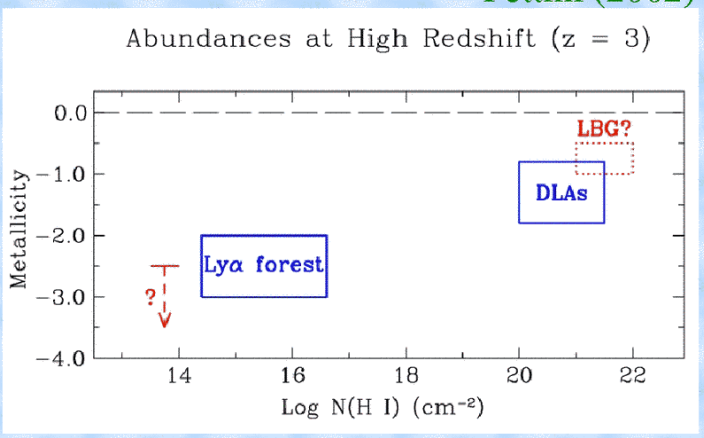


- $f(N_{HI})$
  - Ly: $N^{-1.5}$
  - DLA: N^{-2}
  - LLS: ??

LLS: Major metal reservoir?

Pettini (2002)

- DLA
  - $m_D = _g Z_{DLA}$
  - $m_D \sim 2 \times 10^{-6} \ll \odot^*$
- LLS
  - $m_L = _{LLS} Z_{LLS}$
  - Expect $_{LLS} >\sim _g$

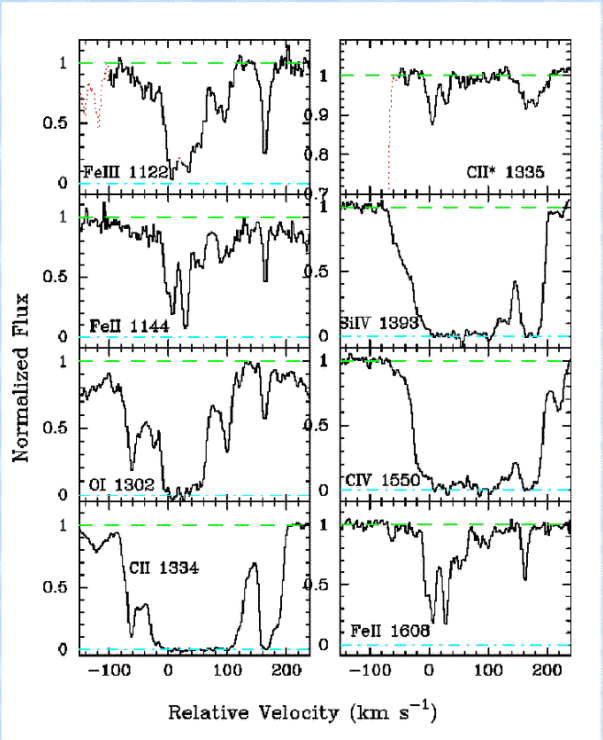


$$\frac{m_L}{m_D} \sim \frac{Z_{LLS}}{Z_{DLA}}$$

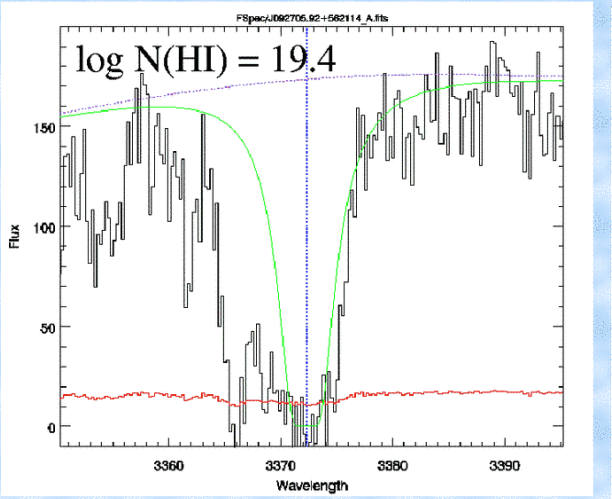
LLS Metal-Lines

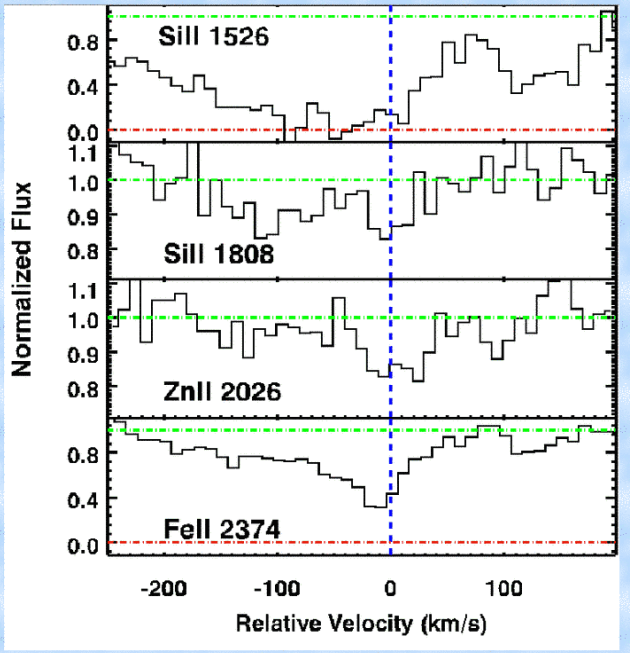
- Multiple ioniz states
  - Low-ions: OI, FeII
  - Intermediate: FeIII, AlIII
  - High-ions: SiIV,CIV,OVI
- Ionization corrections
  - 100% uncertainty in absolute abundance
- Results
  - x>95%
  - log N(H) ~ 20.7
  - 1/3 solar metallicity

Prochaska (1999)



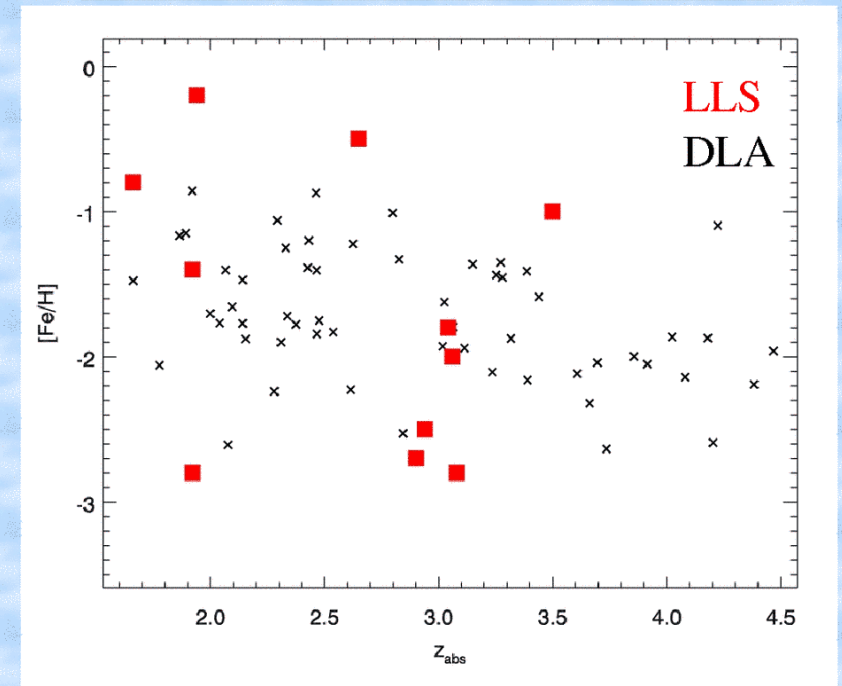
Super? Solar LLS





- 'Metal-strong' LLS
  - [Si^+/HI] ~ +0.6 dex
  - No ioniz corrections yet
  - N(SiII), N(ZnII) > 95% of DLA

Current LLS 'Sample'



Dominant reservoir of (detectable) metals at high z??

Ongoing LLS Survey

- Observational challenge
  - High resolution
  - Moderate S/N to ~ 3400A
- Keck/HIRES
  - CCD upgrade completed 8/04
  - Aim for 40 LLS
  - SDSS quasars
- Magellan/MIKE
  - CCD upgrade completed 5/04
  - Additional 40 LLS
- Current
  - 20 LLS with z>3.1

Prochter (UC Santa Cruz)
Burles (MIT)
Bernstein (U Michigan)

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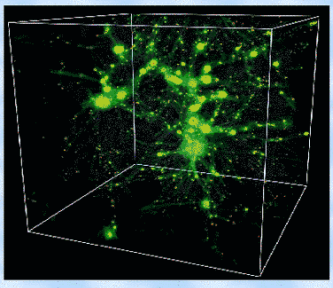
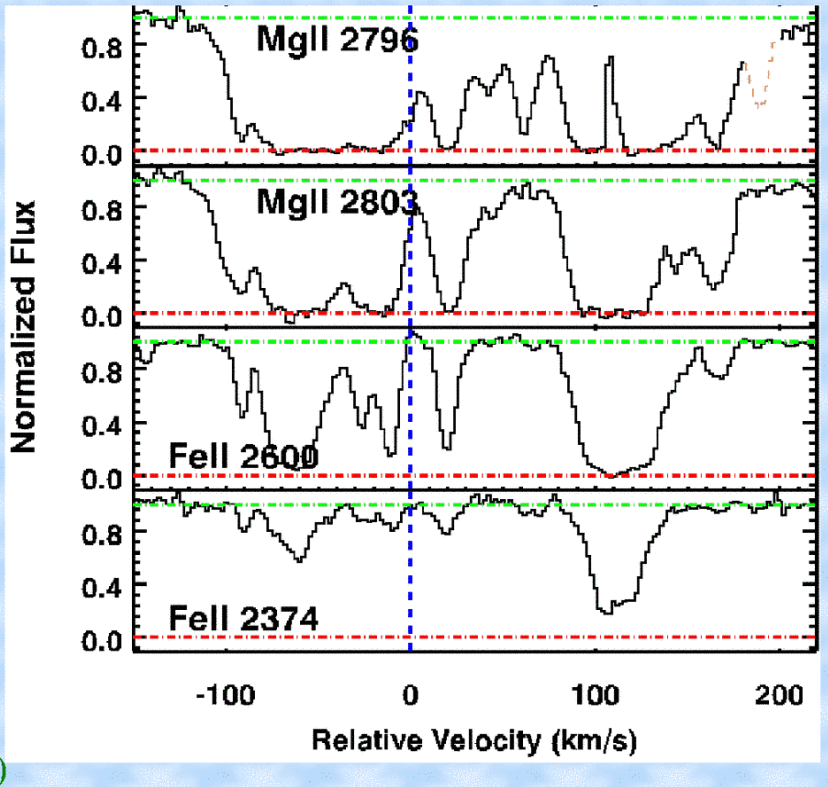


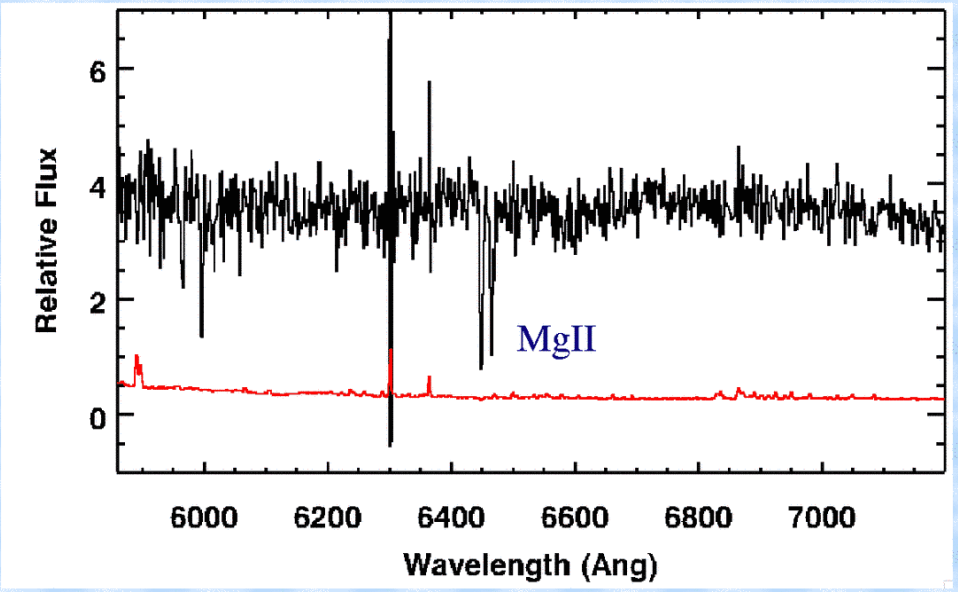
Strong MgII Absorbers

- Majority are LLS
- Superwinds?
  - Bond et al.
  - W > 1.8 Å
  - Feedback driven velocity field
- Massive galaxies
  - Mo & Miralda-E
  - Clouds falling in the DM halo
  - Motivated by optical counterparts (Lanzetta, Steidel, Bergeron)



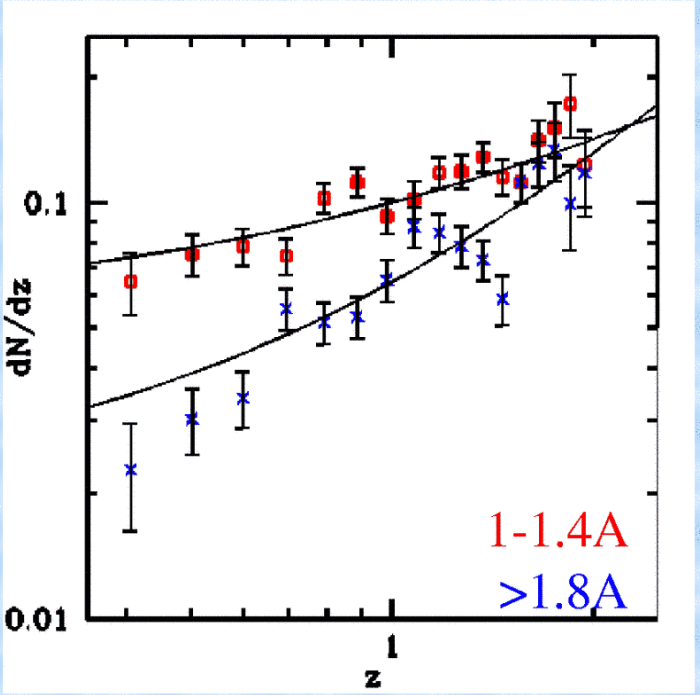
SDSS Search

- DR2
  - N > 10000 QSOs
  - 0.4 < z < 2.2
- Automated search
  - Verified by eye
  - >95% complete to W=1Å



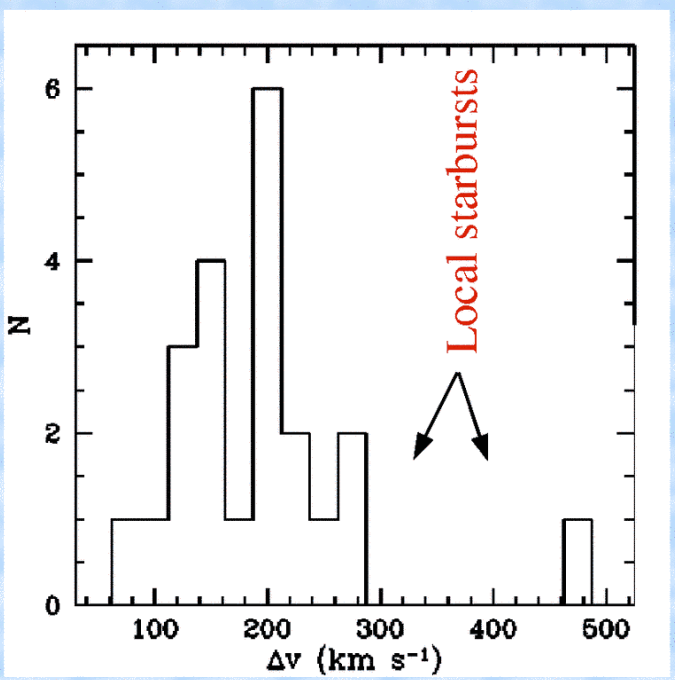
MgII dN/dz

- Power-law Fit (1+z)
  - W~1.2Å: = 0.9 +/- 0.2
  - W>1.8Å: = 1.8 +/- 0.1
  - Steepening w/ W
- Turnover at z~1.5 ??
- Problems for scenarios
  - MM: No turnover at z>2
  - Wind: < 3
- 'Realistic' Model
  - Both processes contribute
  - Data allows 4% of dN/dz in winds at z~1



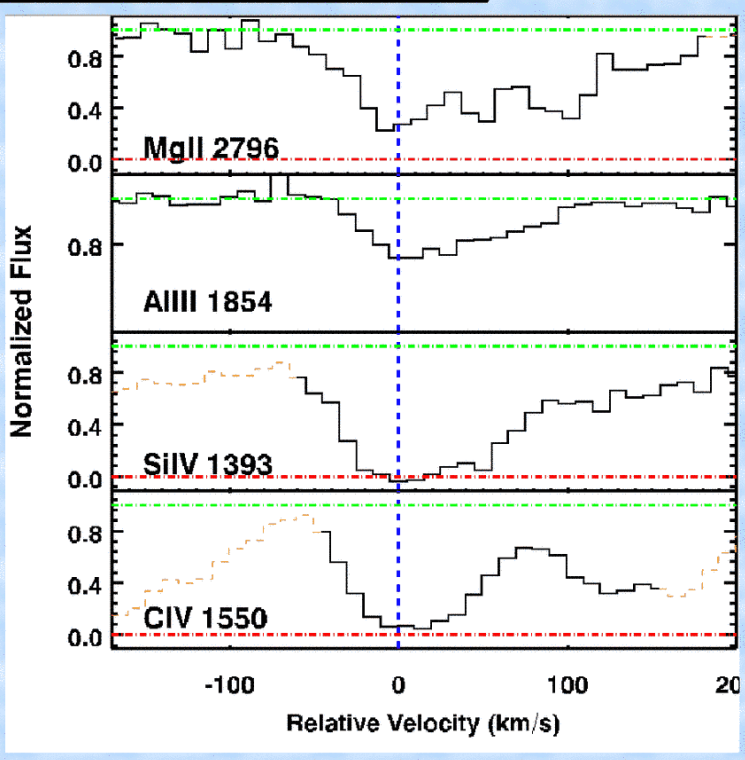
MgII Velocity Widths

- High resolution obs
  - ESI, HIRES
  - Sample of 22 absorbers
- v lower limit
  - W is set by kinematics
- Very few systems with v > 250 km/s
  - Contrary to winds locally
  - Contrary to winds in LBG
    - Smaller cross-section?



MgII vs. High-Ions

- ESI, HIRES Obs
- Compare CIV, AlIII with MgII, FeII
  - High-ions track MgII
  - Suggests ions share the same velocity field
- Challenge to wind scenarios??
  - Need further obs on W>1.8Å systems



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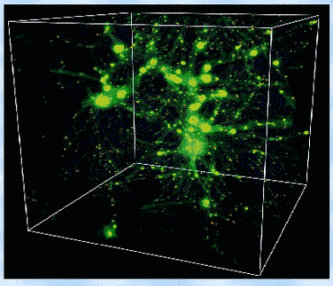
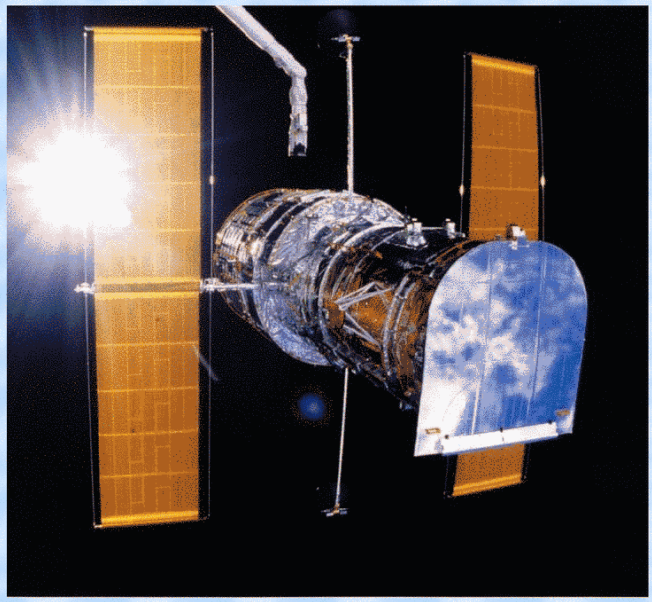
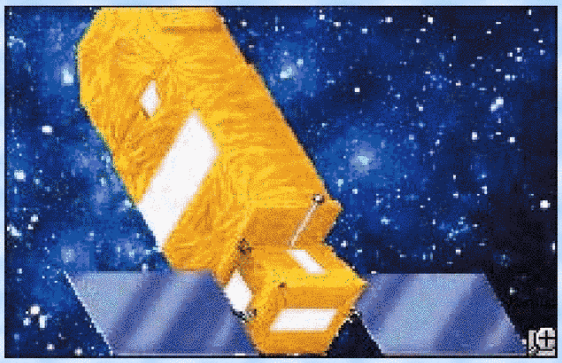


Low z IGM: UV Spectroscopy

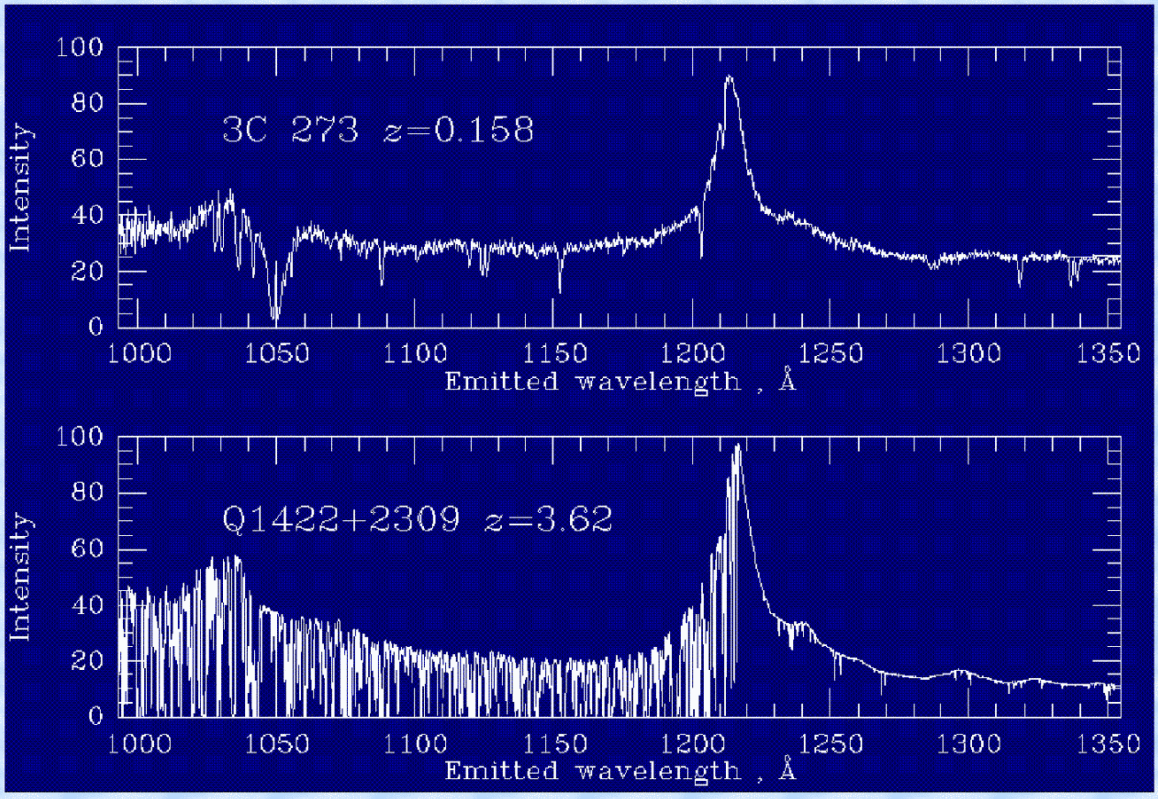


HST



FUSE

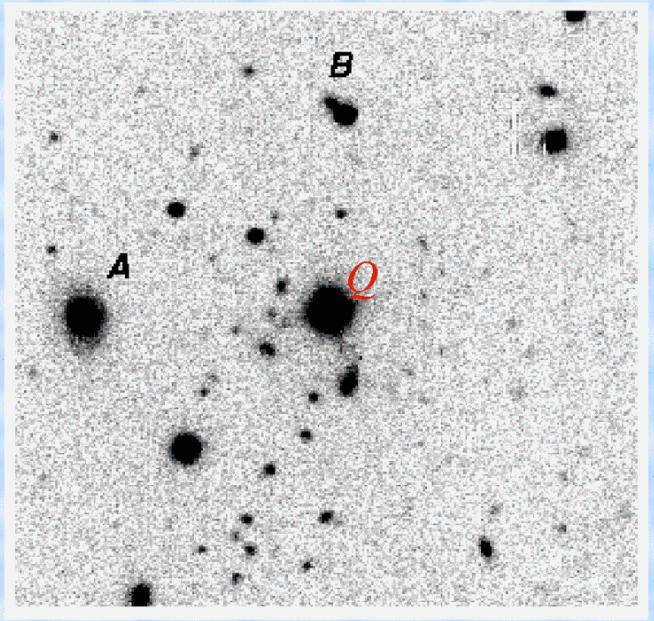
Low z vs. High z



PKS0405-123 (z=0.57)

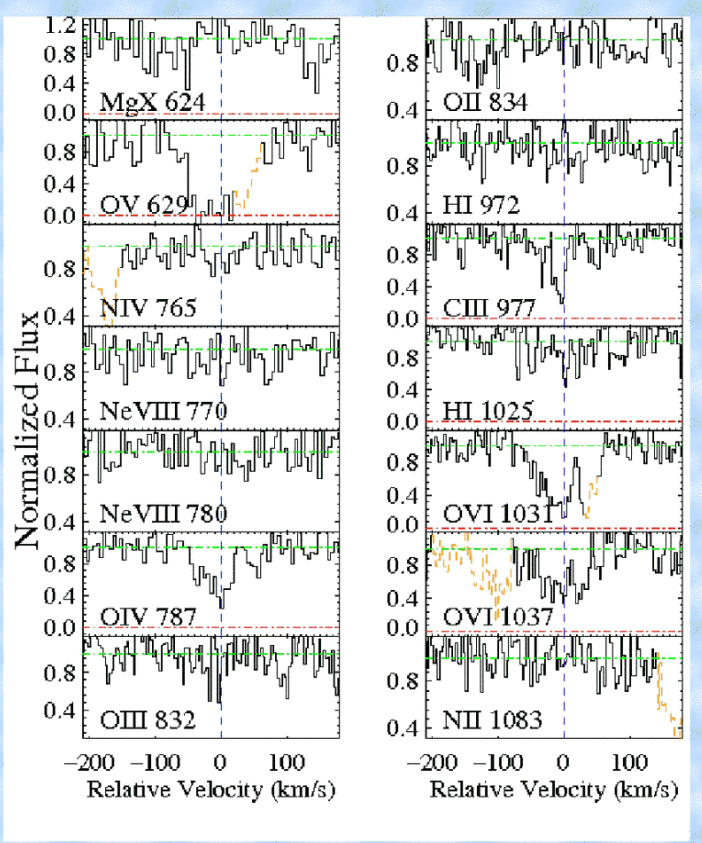
- FUSE
  - 72ks (+80 ks Cycle 4)
  - S/N ~ 15 per res (LiF1a)
    7 per res (SiC1a)
- HST/STIS
  - 10 orbits with E140M
  - = 1170 – 1700 Ang
  - R = 35,000

  - S/N ~ 7 per pixel
  - E230M (Cycle 13)
- ~7 metal-line systems



Metal-Line Systems

- Generic term
  - i.e. any Lya cloud with metals
  - O VI, Mg II, C IV, ...
- Analysis
  - Ionization state
  - Metallicity
  - Physical properties: N(H), n_H, T



Howk, Prochaska, & Chen (2005)

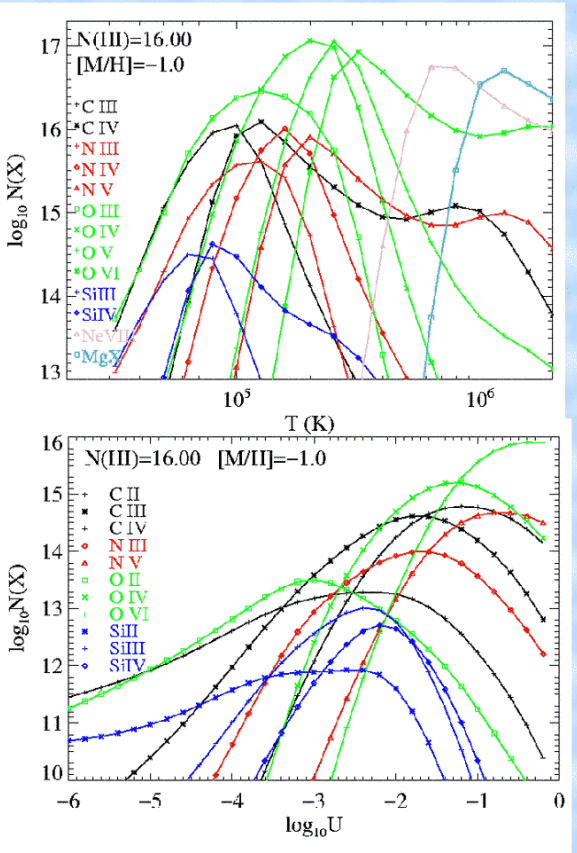
Ionization Modeling

- Simplest approach first
  - Assume equilibrium
  - Assume single phase
- Photoionization vs Collisional Ionization Equil.
- As required, consider more complex scenarios
  - Multi-phase
  - Non-equilibrium conditions

Caution: Results are accurate to a factor of 2 at best!!

Ionization Mechanisms

- Collisional ionization equil.
  - Single parameter: T
  - Assume equilibrium applies
- Photoionization
  - Ionization parameter: $U = n / n_H$
  - Assume Haardt-Madau (QSO)
  - Use Cloudy (Ferland 2002)
- Key: Distinguish between the processes and constrain T and/or U through metal-line observations



Metal system Summary

- Perform analysis for all 9 systems
  - Several have ambiguous ionization mechanisms
  - Results have >~0.3 dex uncertainty

			Photo			Collisional	
z	N(HI)	N(OVI)	U	[M/H]	n(H)	T	[M/H]
0.0918	14.5	13.8	-1.5	>-1.4	<2	>2.5 x 10^5	>-2.2
0.0965	14.7	13.7	-1.2	-1.5	1.2	--	--
0.1671	16.5	14.8	-2.9	-0.25	60	--	
0.1825	14.9	<13.8	--	--	--	> 3 x 10^5	<-1
0.1829	14.1	14	>-1	>-1.4	3	3 x 10^5	-1.5
0.3608	15.1	<13.3	-2	>-0.7	8		
0.3633	13.4	13.4	-1.4	0	2	--	
0.4057	14.9	<13.6	--	<-2			<-2.5
0.4951	14.4	14.3	-1.3	>-0.3	1.7	2.6 x 10^5	>-1

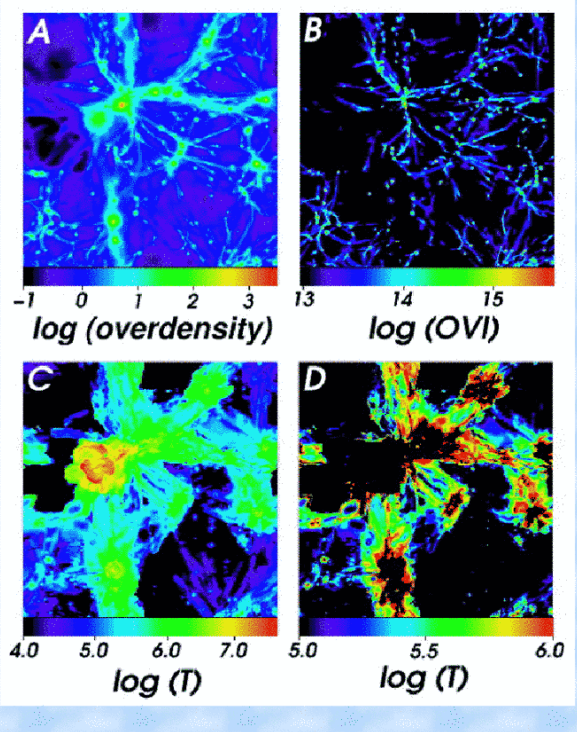
No metals

(4 other systems with N(HI) > 10^{14} cm^{-2} and no metals)

Results I: WHIM

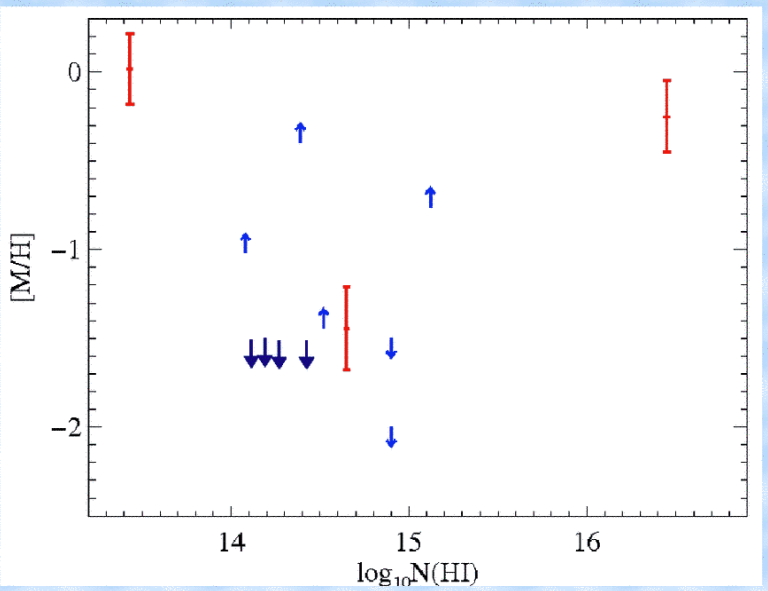
- O VI: dN/dz = 16 (+9 -6)
  - Implies a large baryon reservoir
  - Consistent with previous results (Savage et al. 2002)
- 50% of O VI sys. show CIII
  - Suggests photoionization and also multi-phase or non-equil
  - Contrary to the canonical WHIM?
- Metallicity: ~1/10 solar
- Ne VIII Survey
  - Excellent ion for T > 10^6 K
  - dN/dz < 40 (for EW > 80mA)

Fang & Bryan



Results II: IGM Enrichment

- Restrict analysis to $N(HI) > 10^{14}$ cm^{-2}
  - 6 out of 12 show metals
  - Several 'misses' may show metals
- Key results:
  - Median [M/H] > -1.5
  - Large scatter (~1dex)
  - No correlation with N(HI), b, H, etc.
- Much higher metallicity than z>3 IGM
  - Suggests enrichment during the past 10 Gyr
  - Contrast with constant metallicity at z>2



Schaye et al. 2003
Madau et al. 2003

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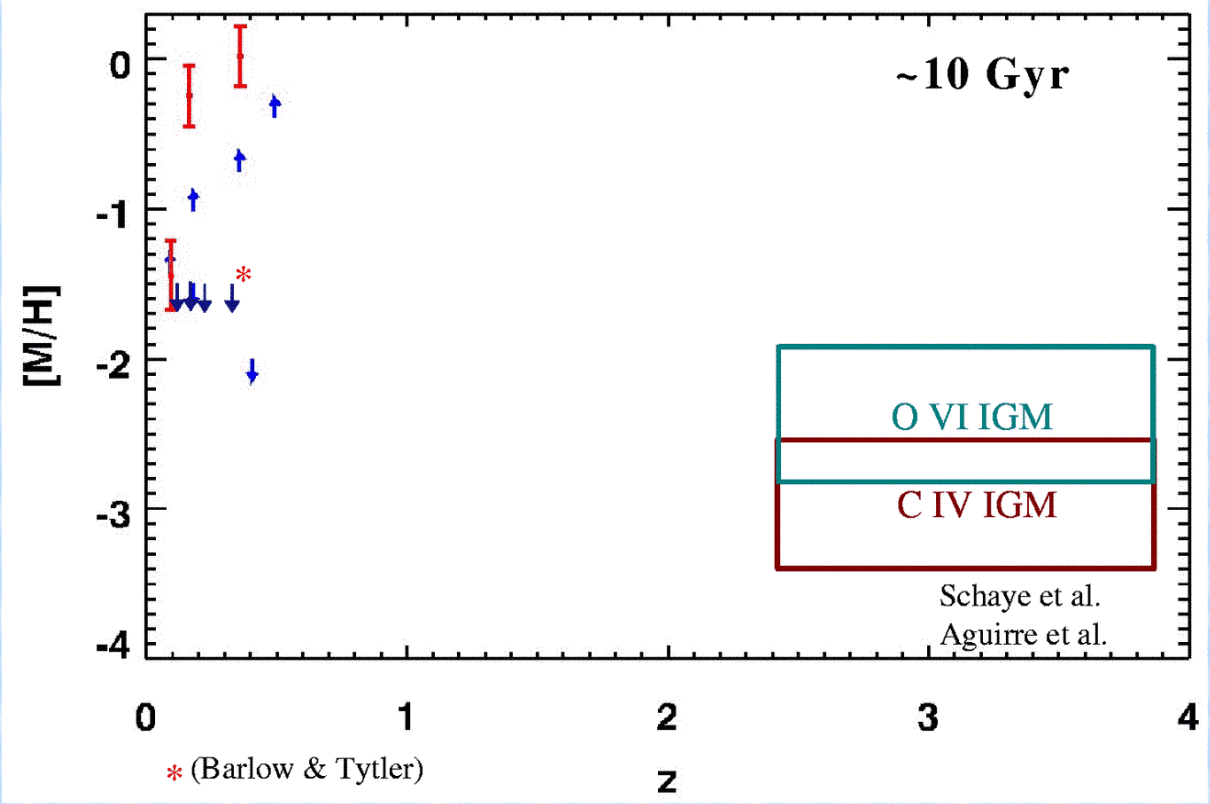
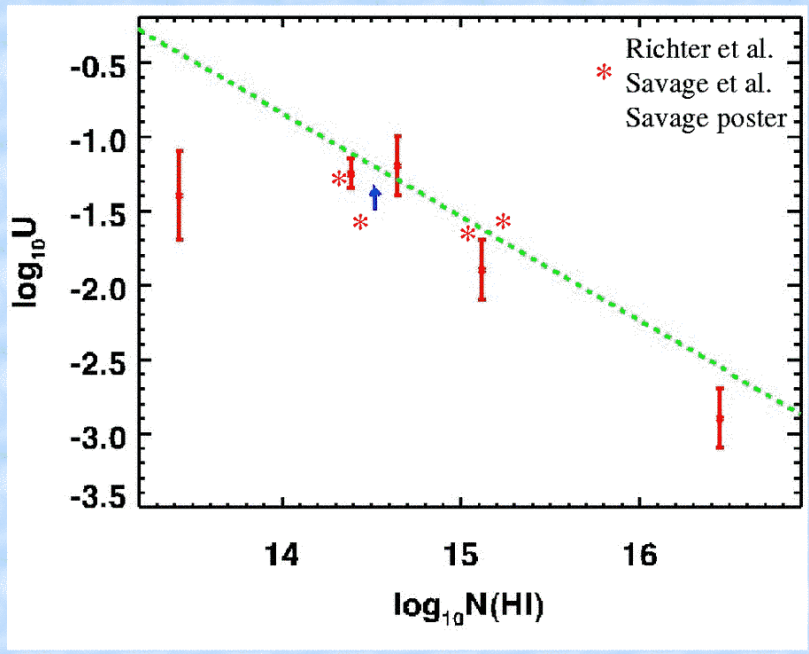


Results III: Ionization Parameter

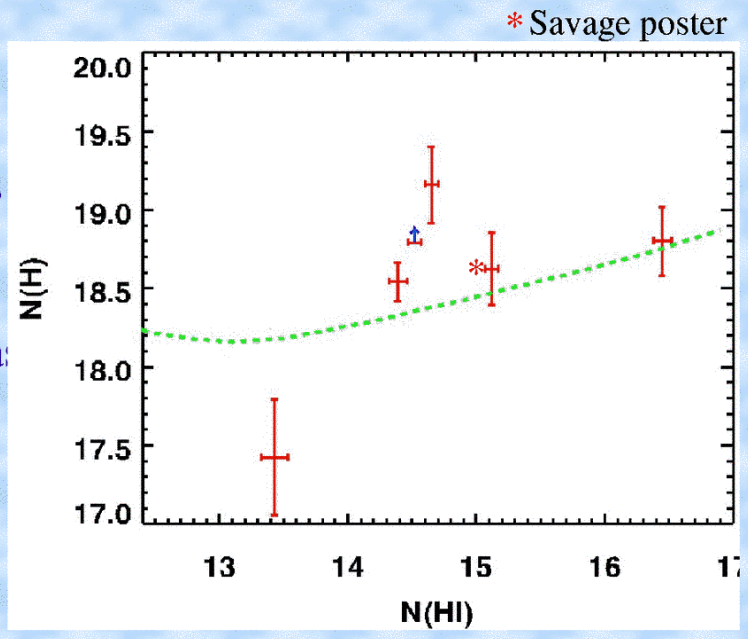
- U vs. N(HI) correlation
  - Restrict to photoion systems
  - ~3 result (without *)
- Theory
  - /<> ~ $N(HI)^{0.7}$
  - Assume J = constant
  - $U \sim n_H^{-1} \sim N(HI)^{-0.7}$
  - Normalization set by EUVB intensity

Dave et al. 1999
Dave & Tripp 2001



Results III: N(H) Conspiracy

- Calculate ionization correction
  - N(HI) => N(H)
  - N(H) is nearly constant!?
- Implication
  - Majority of Ly forest has a characteristic N(H)
  - N(H) ~ 10^{19} corresponds to l~20 Mpc at z=0
  - Does this length scale correspond to a velocity?
  - Do numerical simluations support this?



(See also Schaye 2002)

Summary

- LLS probe the IGM/Galactic interface at z~3
  - Ionization intensity and shape
  - Metal enrichment
  - Kinematics of outflow and inflow
- Strong MgII systems at z~1
  - dN/dz suggests mix of L* galaxies and superwinds
  - Kinematics suggest large v are rare
- Low IGM
  - For N(HI) ~ 10^{14}, [M/H] ~ -1.5
  - U, N(HI) anti-correlation 'predicted' by simulations
  - Constancy of N(H) ?!