The N_{HI} Distribution Function at High z

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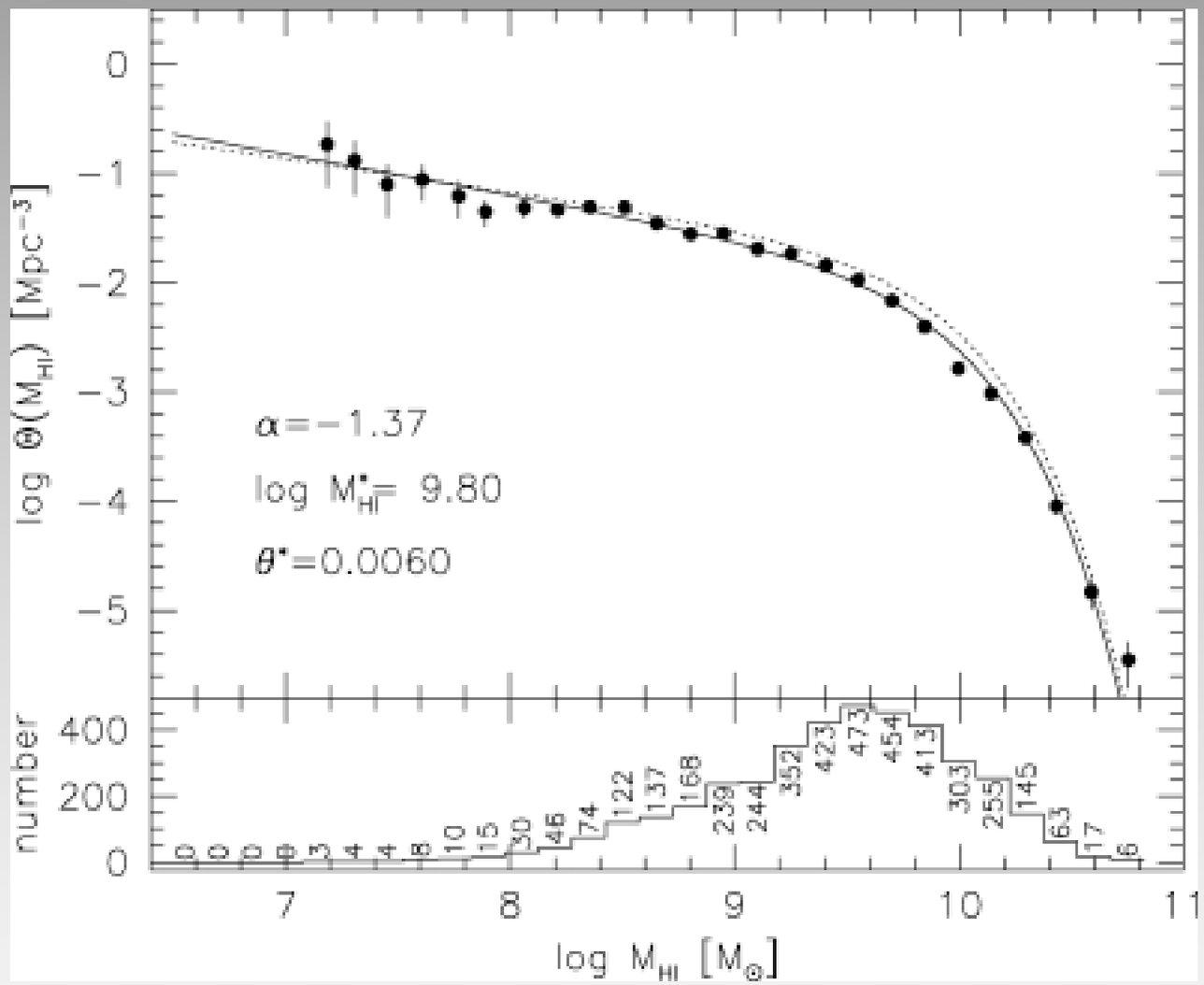
$f(N_{HI})$ Defined

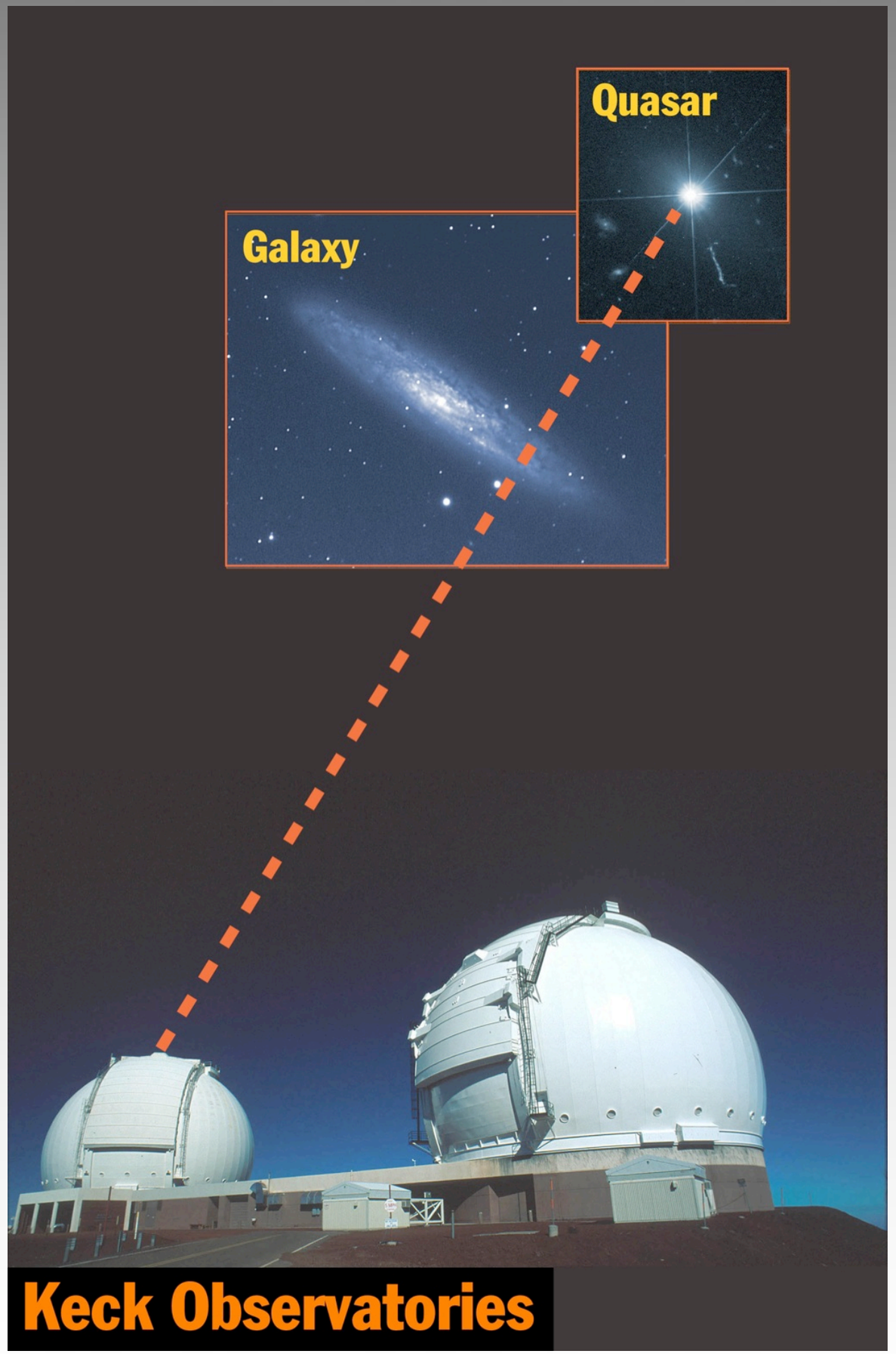
- N_{HI} frequency distribution
  - Akin to a luminosity or mass function
- Definition $f(N_{HI},X)$
  - Number of lines within (N, N+dN) and (X, X+dX)
  - X is defined to give a constant line density with redshift
    - If n and σ are constant
    - Cosmology dependent
- Moments
  - Zeroth: Line density $\ell(X)$
  - First: Mass density Ω



$$f(N,X) = \frac{m_{DLA}(N, N+\Delta N)}{\Delta X}$$

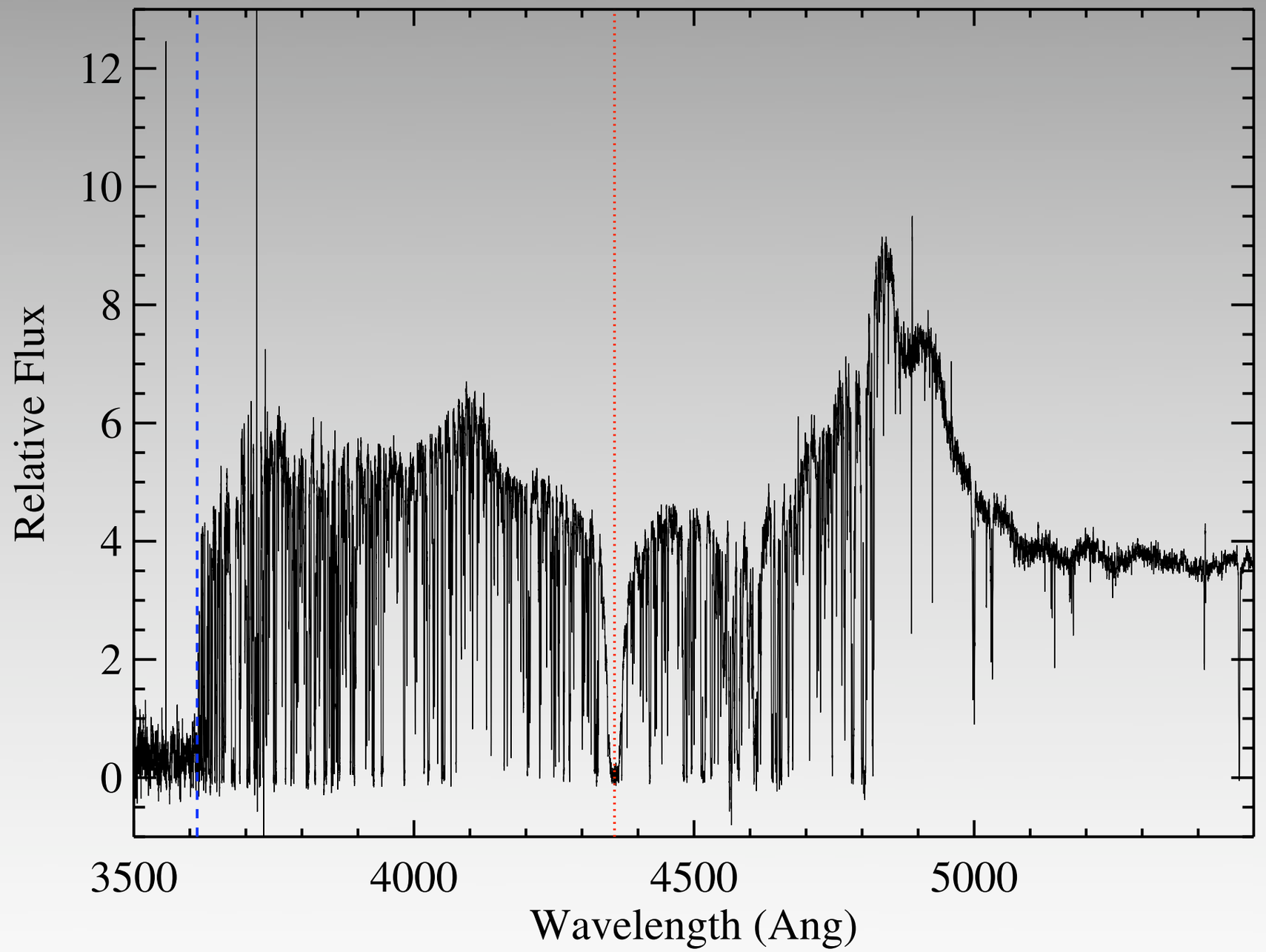
The Experiment

- Observe a quasar
  - ✦ typically bright (V<19)
  - ✦ Generally z>2
- Study the gas between us and the QSO
  - ✦ Properties of the QSO are largely unimportant
  - ✦ Absorption-line spectroscopy
    - Akin to Galactic ISM studies using O and B stars



QAL Systems: Classify by N_{HI}

- **Lyα forest**
  - $N_{HI} < 10^{17}$ cm^{-2}
  - $\delta\rho/\rho < 10$
  - Lots o' science
- **Lyman Limit Sys**
  - $N_{HI} > 10^{17}$ cm^{-2}
  - $\delta\rho/\rho \sim 100$
  - Unexplored
- **Damped Lyα Sys**
  - $N_{HI} > 2\ 10^{20}$ cm^{-2}
  - $\delta\rho/\rho >> 100$
    - Galaxies
    - Neutral ISM



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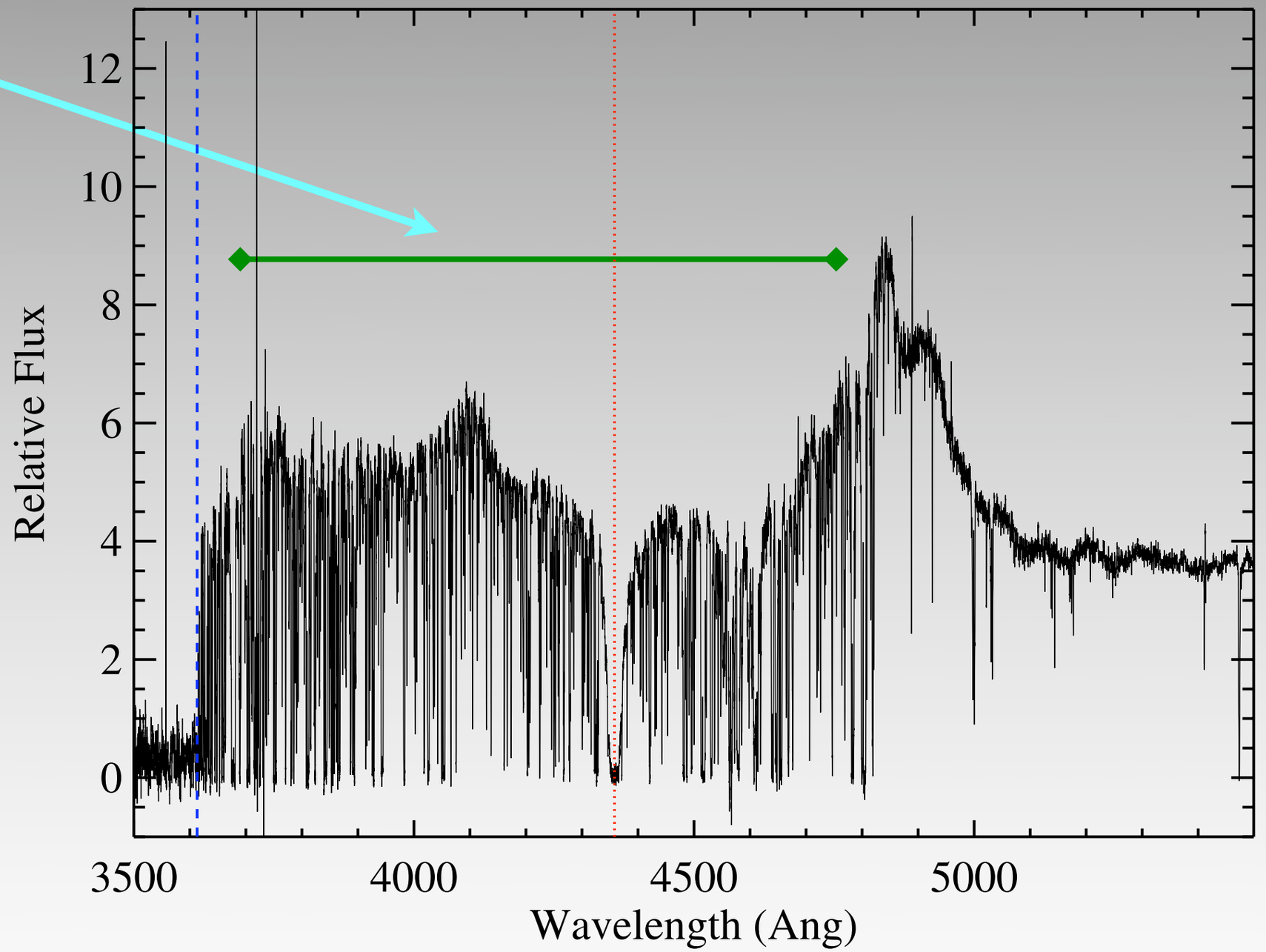

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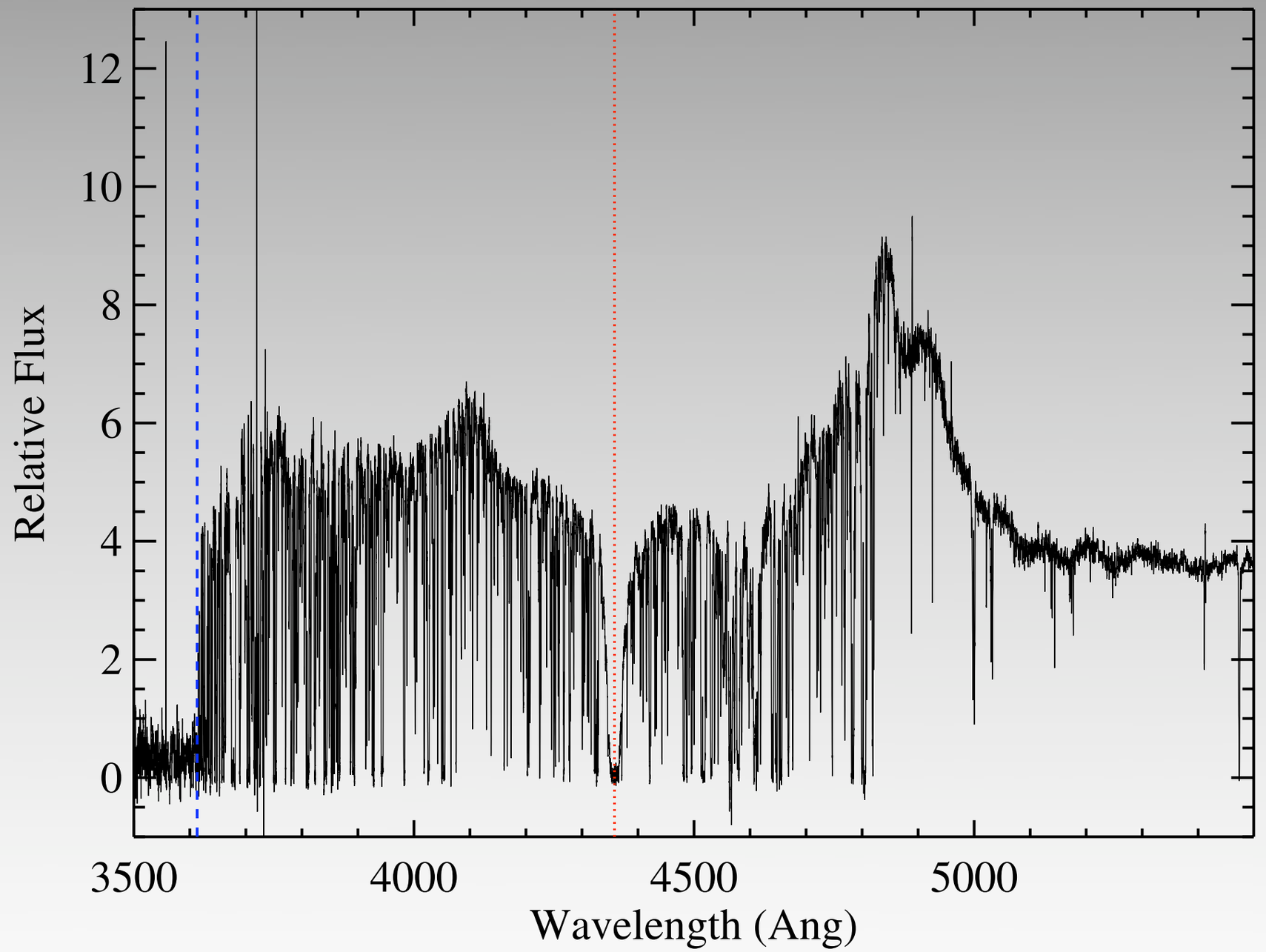

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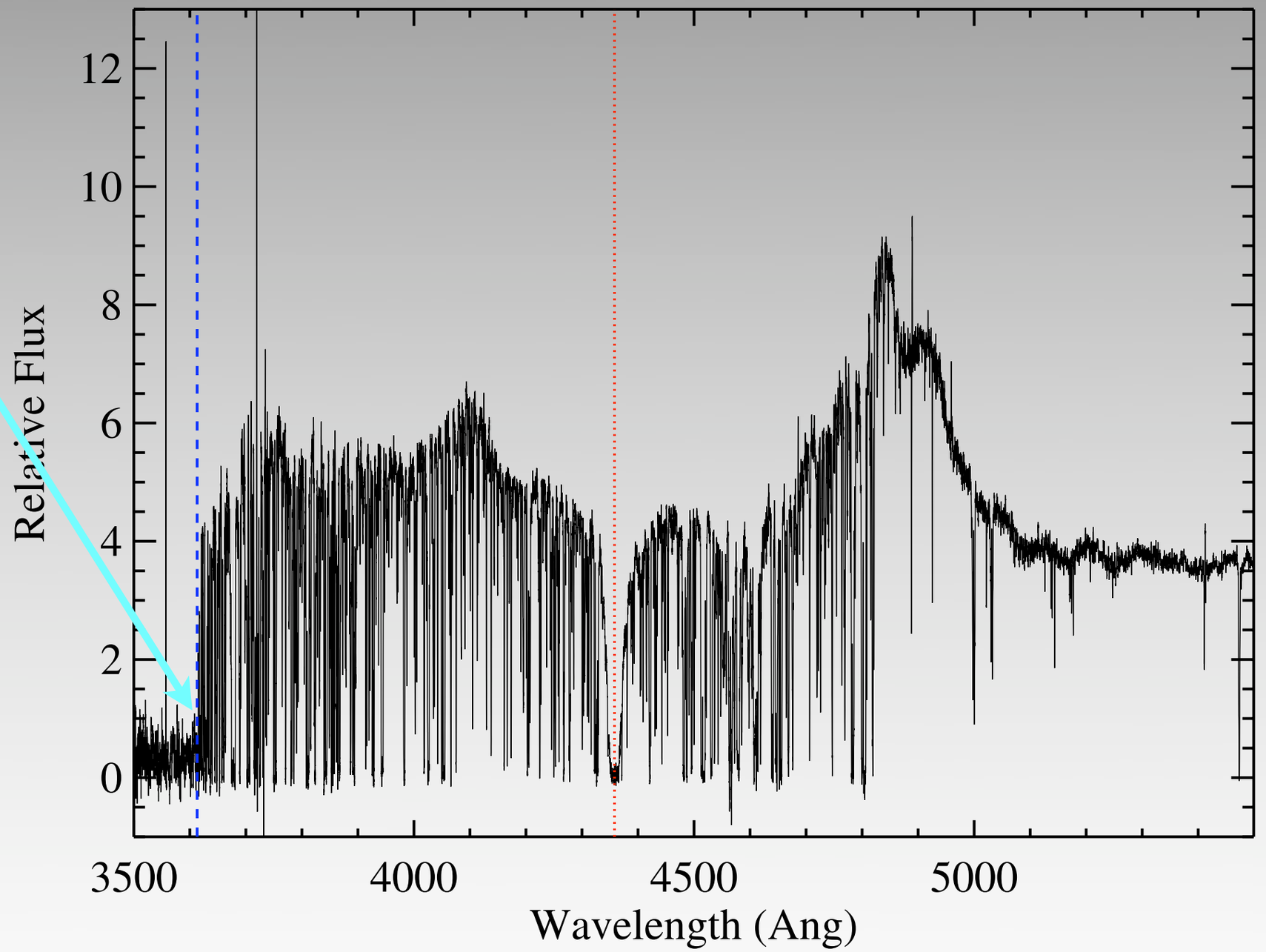

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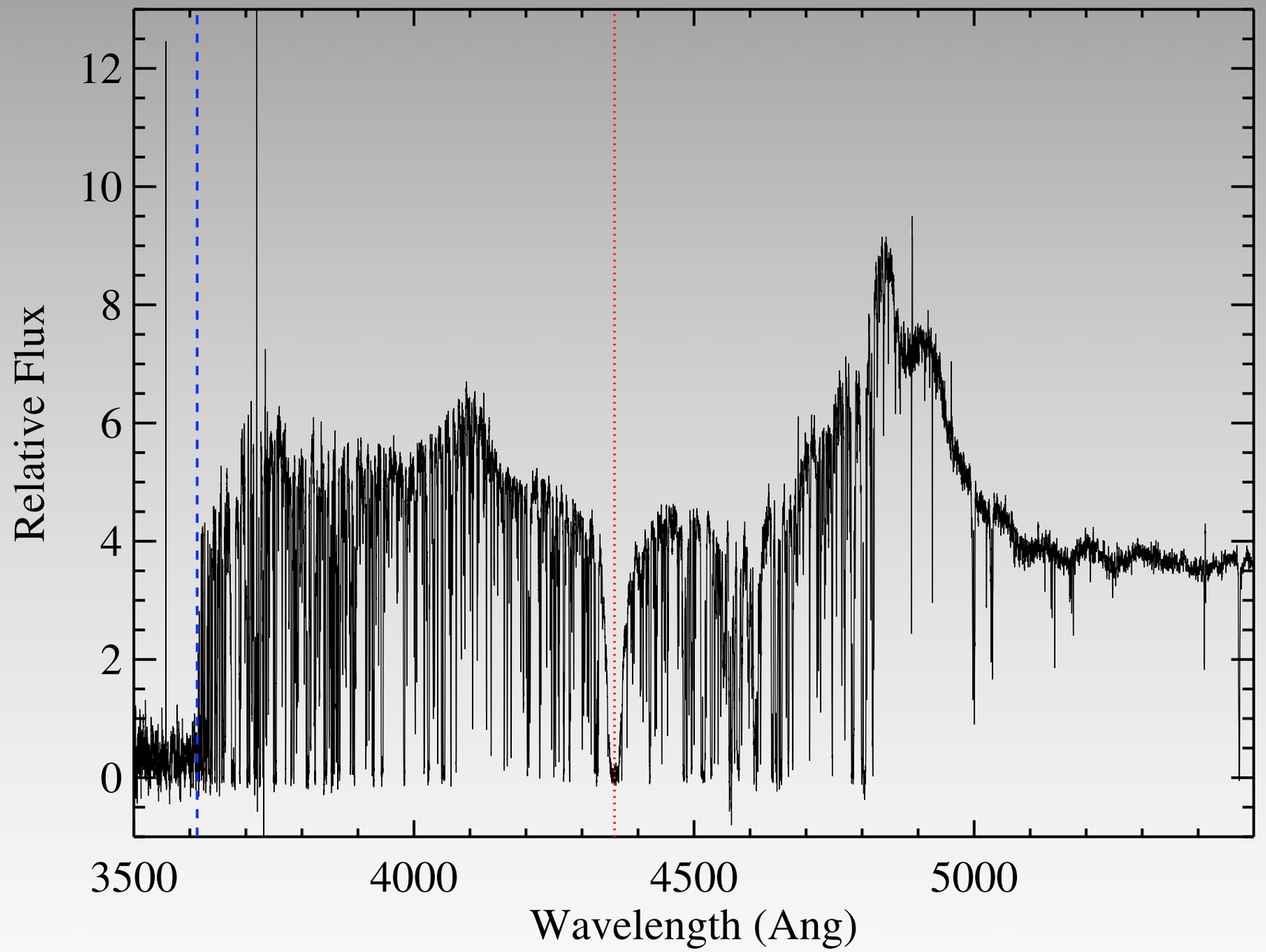

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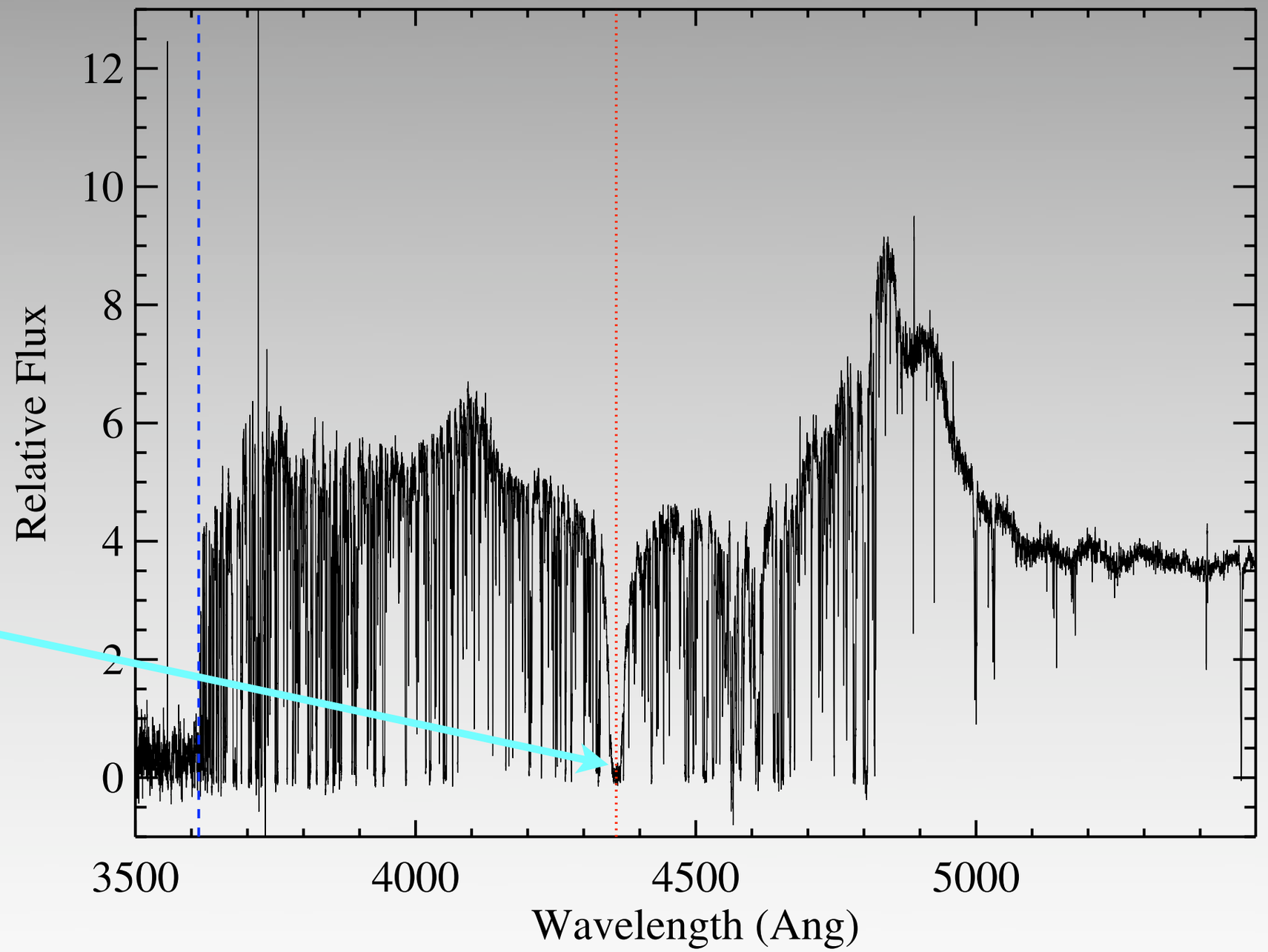

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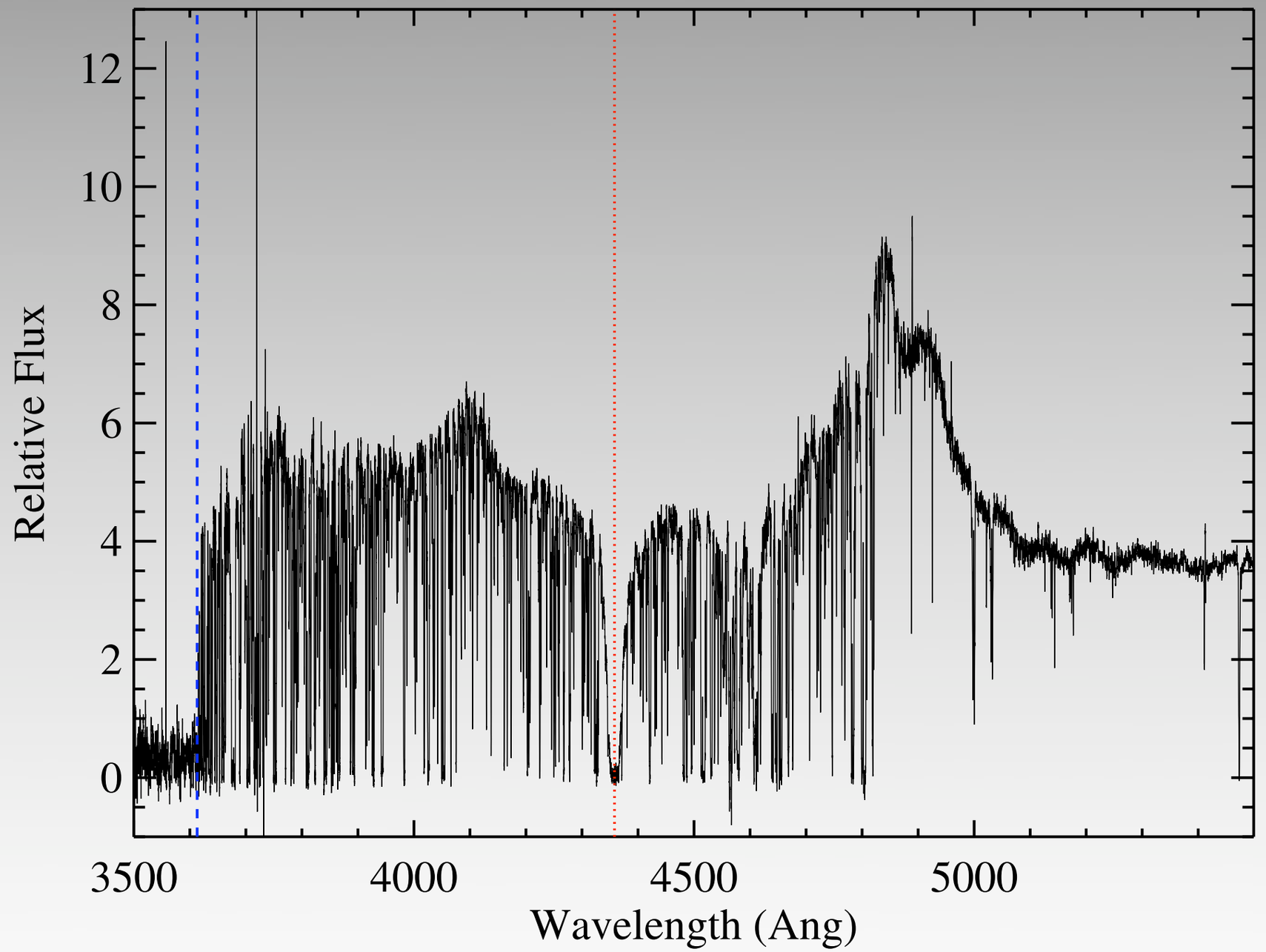
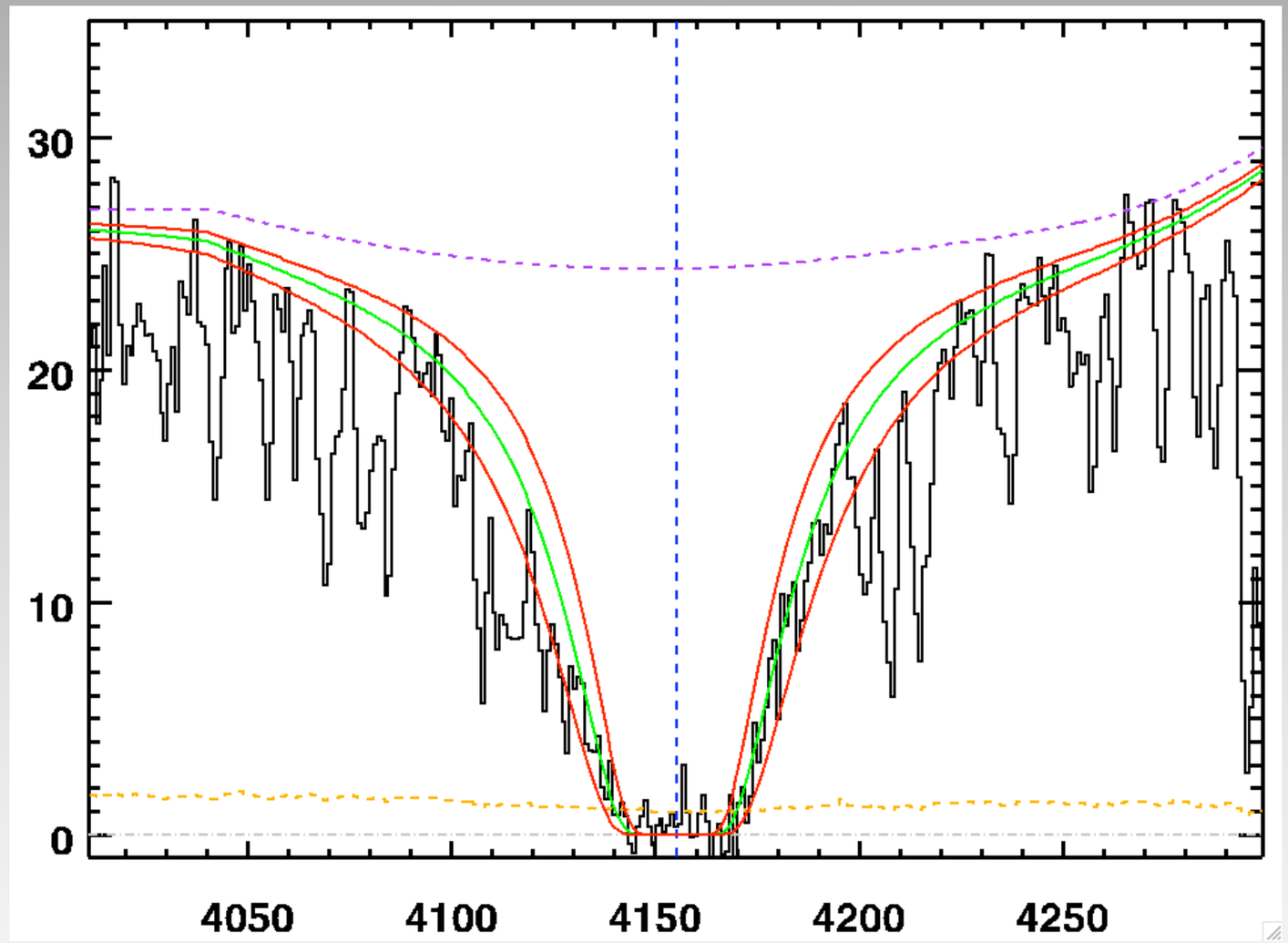


QAL Technique and HI Studies

- **Advantages**
  - Sensitivity to very low column densities
    - $N_{HI} < 10^{12}$ cm^{-2}
  - Probes HI directly at high redshift
  - Excellent statistics
- **Disadvantages**
  - Restricted to z > 1.6 when using the optical
  - Difficult to connect gas with galaxies, filaments
    - QSO glare
  - Subject to biases related to QSO samples

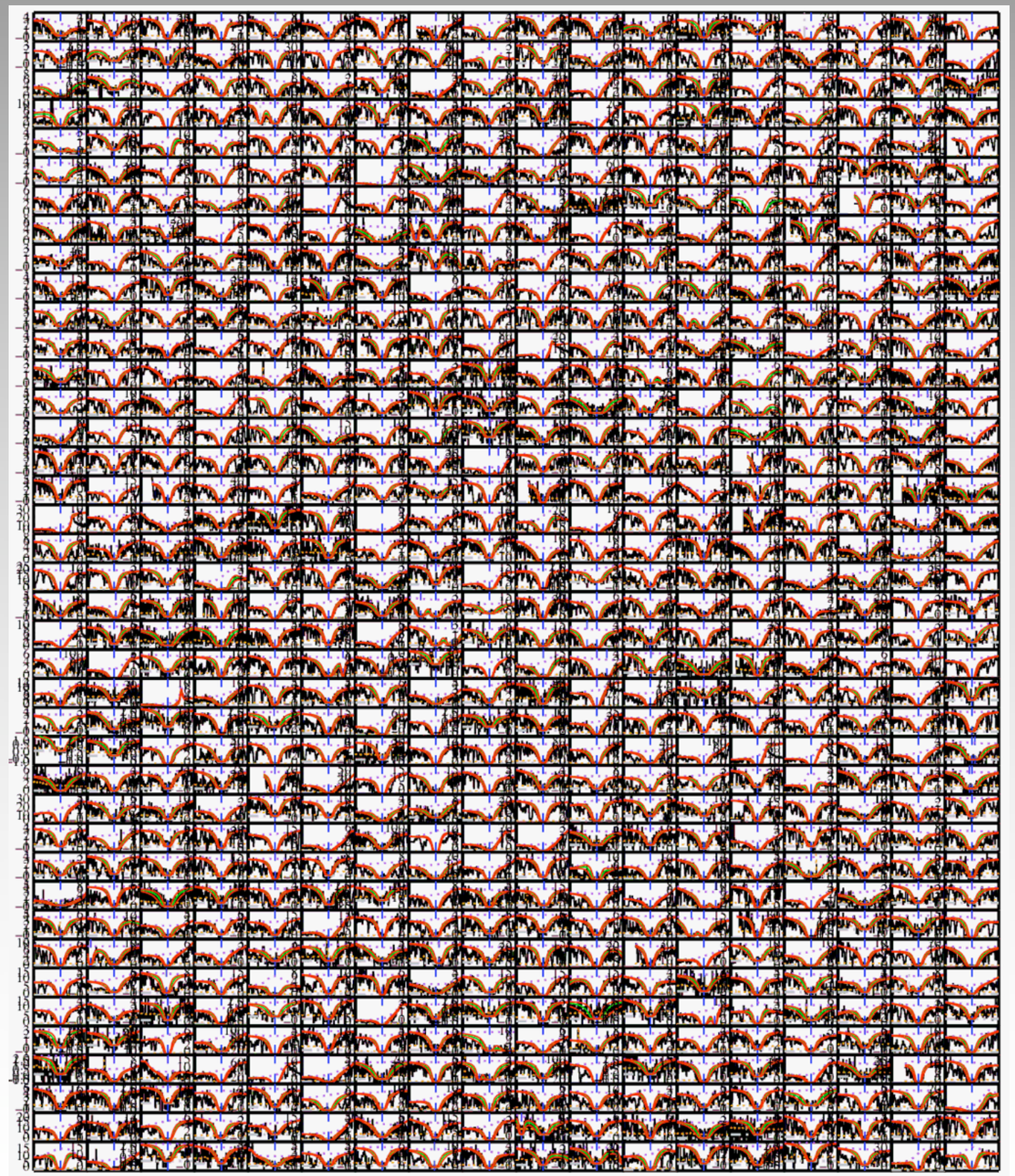
Damped Lyα System Defined

- $N_{HI} > 2 \times 10^{20}$ cm^{-2}
  - Dominant reservoir of neutral gas
  - Large N_{HI} => $\delta\rho/\rho >> 100$
  - ISM of the Progenitors of modern galaxies



SDSS DLA Sample

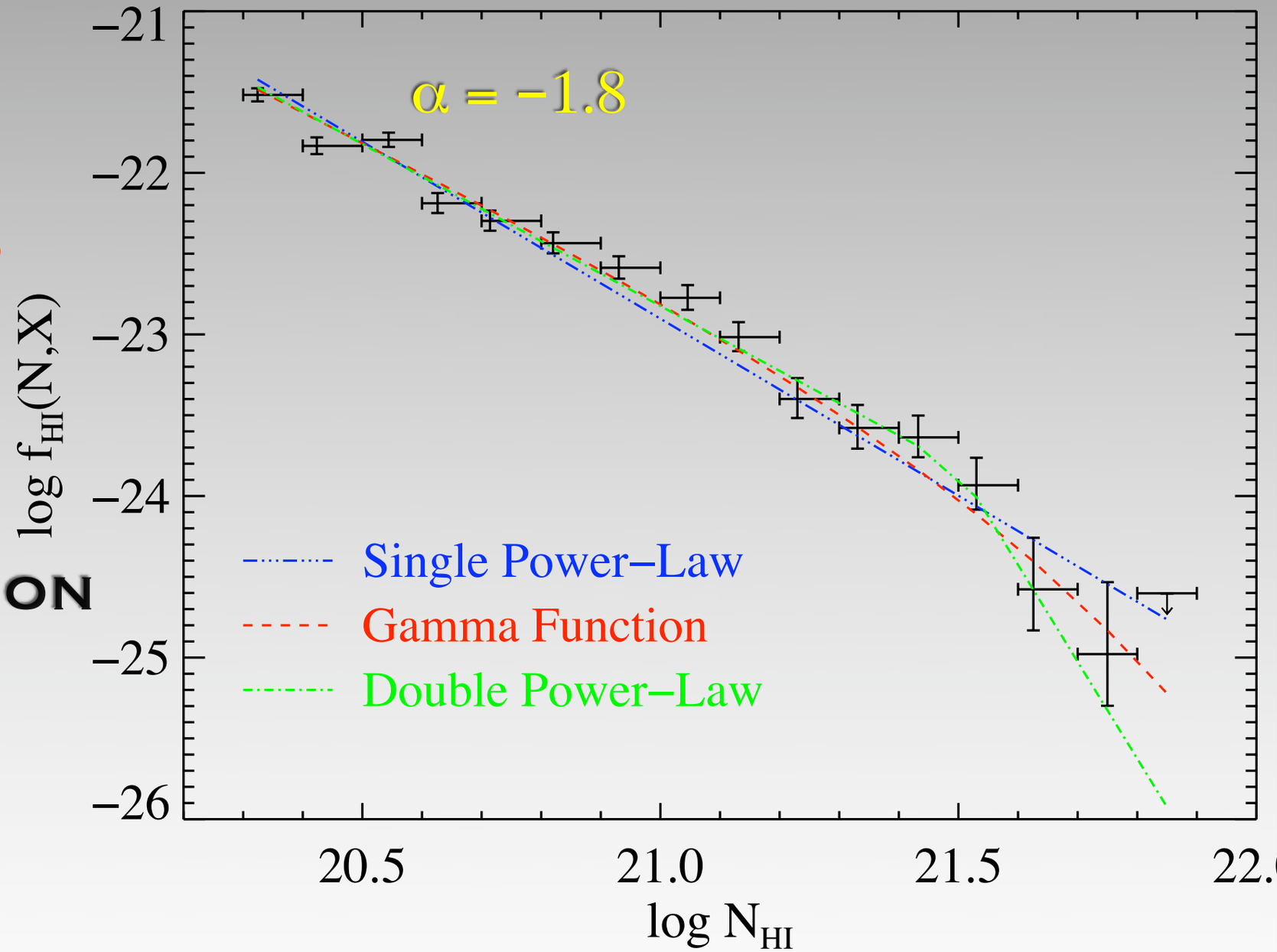
- Homogenous dataset
  - Color selected QSOs
  - Complete to i = 19.5
  - Uniform spectra
    - R~2000
    - λ = 3800 to 9200A
- Current data release
  - >1000 DLAs
  - z>2.2
- Auto DLA search
  - Simple algorithm
  - Visual verification
  - By-hand Lyα analysis



f_{HI}: N_{HI} Frequency Distribution

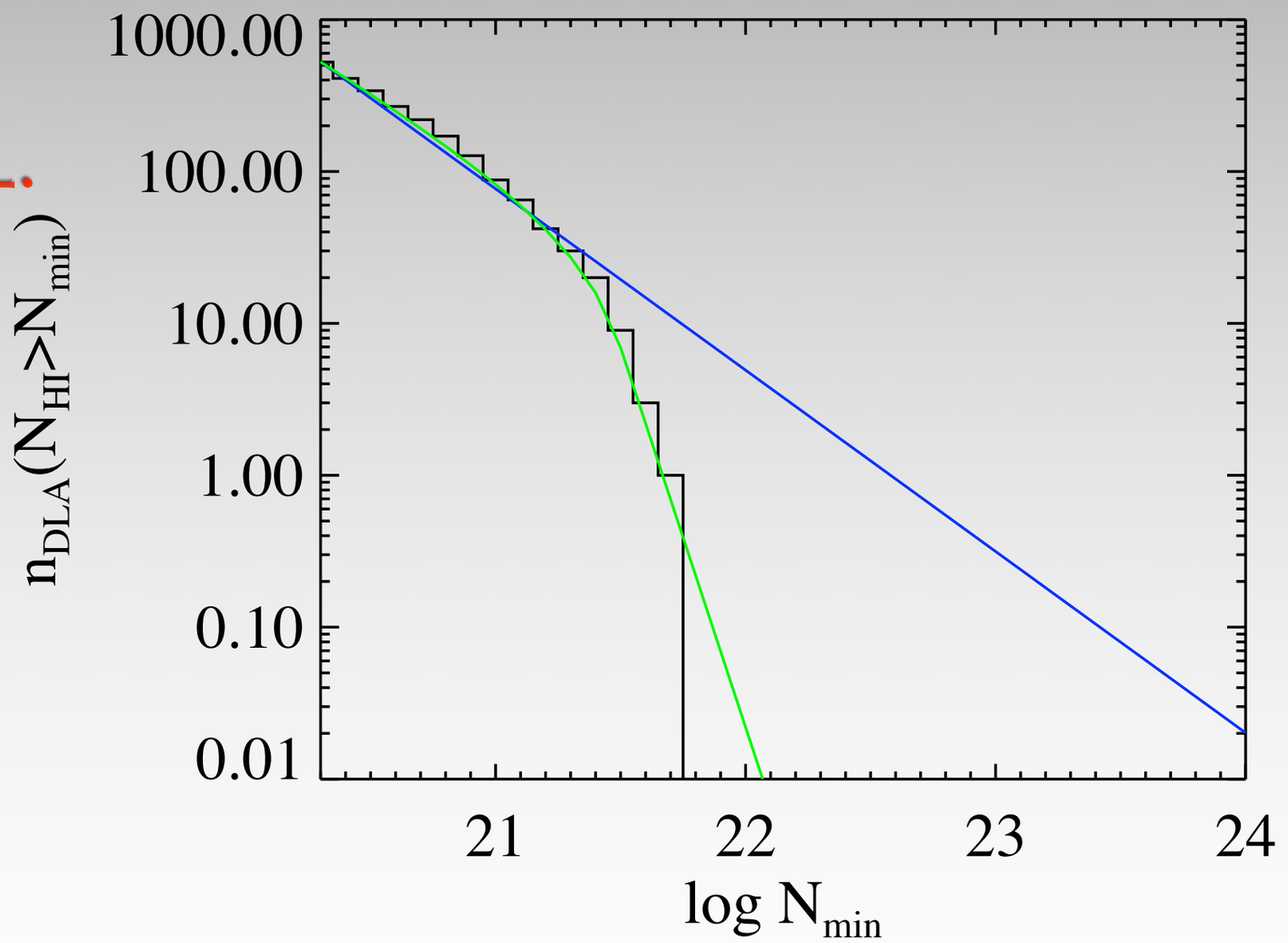
- $f(N_{HI})$ of DLAs
  - ‘Faint’ end: $\alpha \sim -2$
  - Break at $N_{HI} \sim 21.5$
  - ‘Bright’ end
    - Steeper than -3
    - Conversion to H_2?
    - Ω_g converges!!
- Redshift evolution
  - Shape is invariant
  - Normalization increases with z

Prochaska, Herbert-Fort, & Wolfe (2005)



The Break: Significance

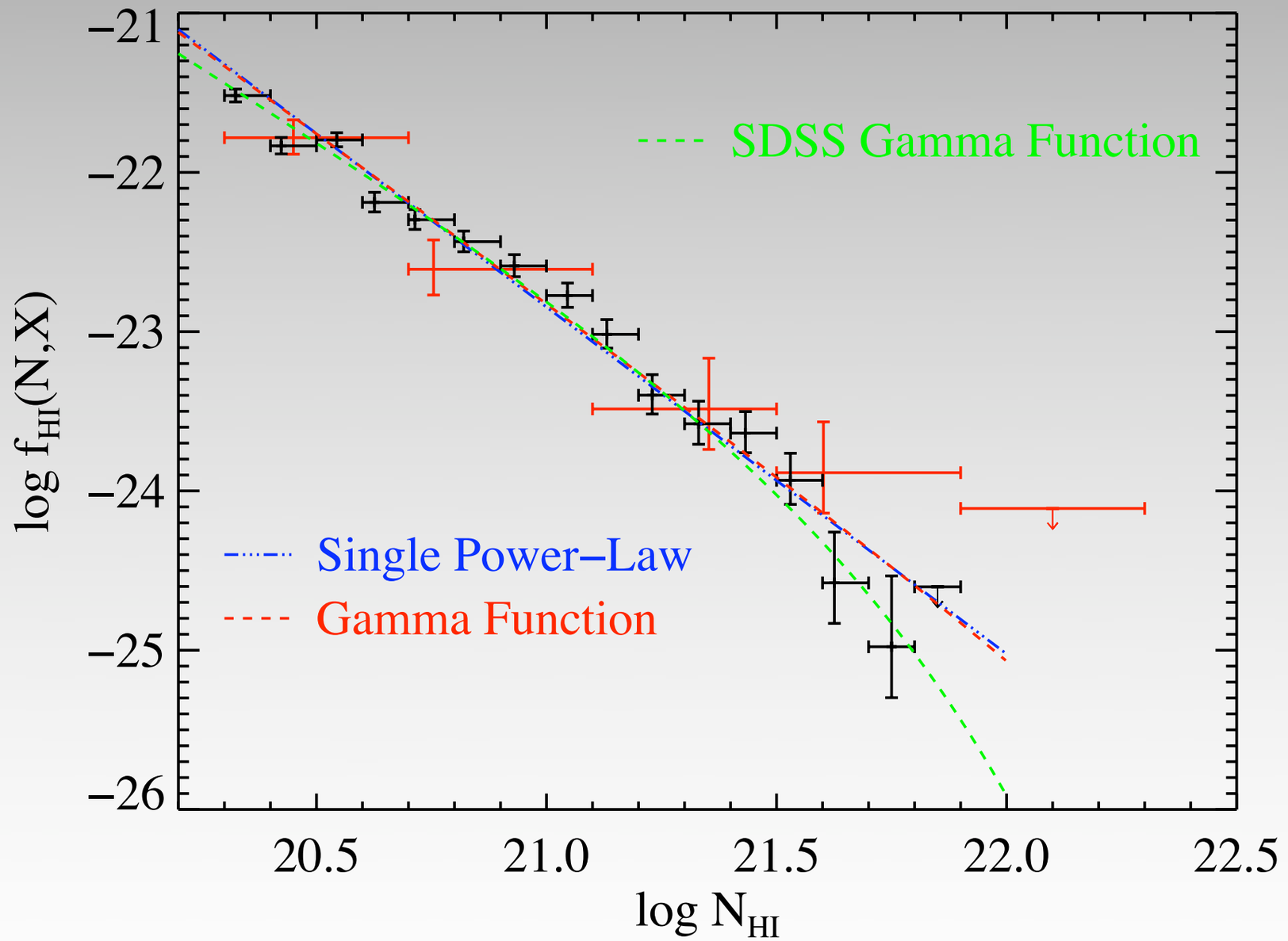
- **Single-power law**
  - $\alpha \sim -2$ from low N_{HI}
  - Ruled out at >99% c.l.
  - Overpredicts the incidence of DLAs with $N_{HI} > 21.7$ substantially
- **Slope at large N_{HI}**
  - Steeper than -2
  - Best fit is -6



The Break: Dust?

- Extinction
  - ✦ Magnitude limited QSO sample
  - ✦ Large N_{HI}
    - Large dust column
- Tests for dust
  - ✦ Radio surveys
    - CORALS, UCSD
    - Reproduce α=-2 at low N_{HI}
    - Small sample implies wiggle room for the break
  - ✦ Minimal Reddening
    - Murphy et al.
    - Vladilo et al.

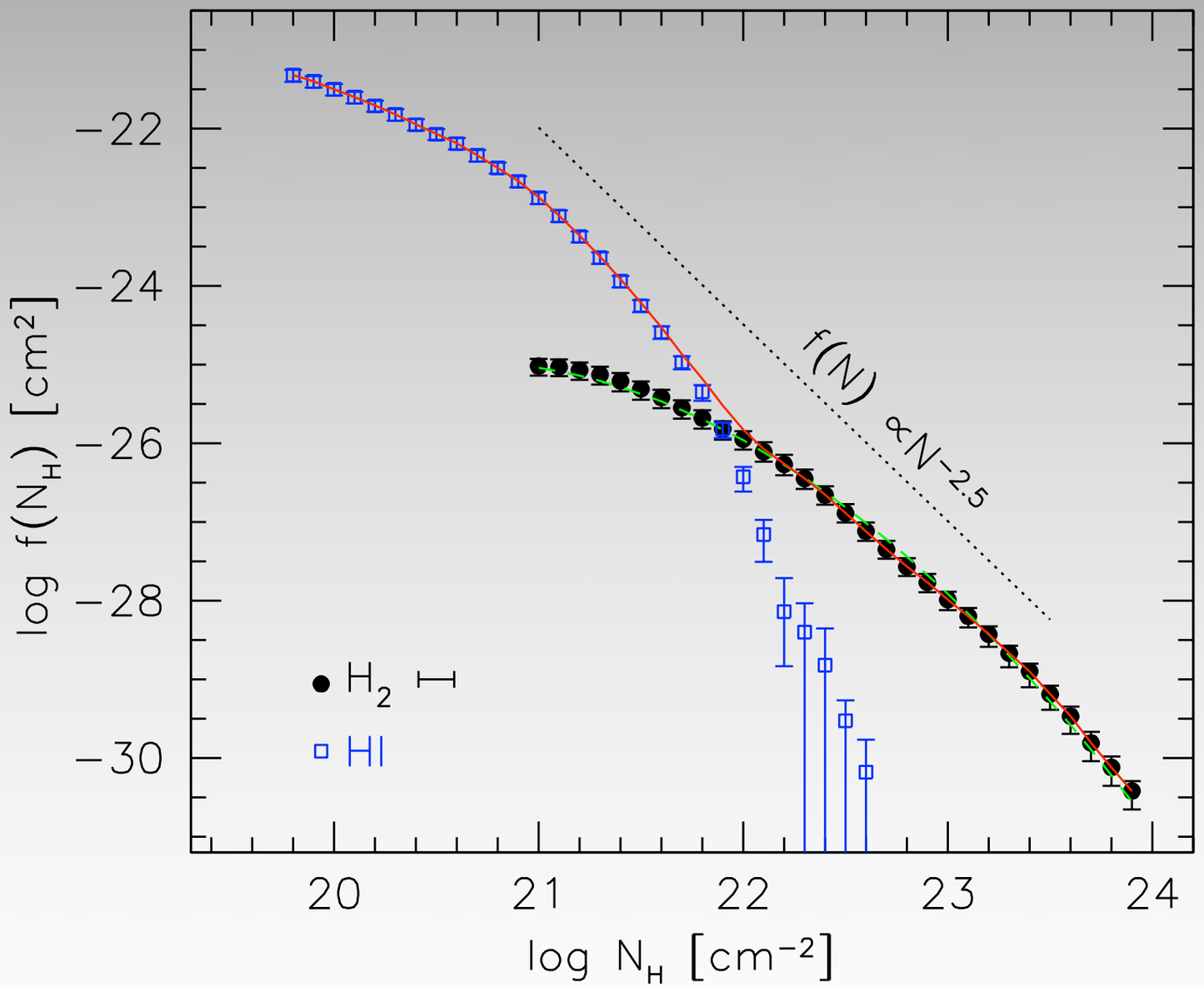
Jorgensen et al. (2006)



The Break: H_2

- **Molecular phase**
  - **At large surface density, HI -> H_2**
    - Extinction facilitates H_2 cloud formation
    - e.g. Schaye (2001)
- **Local f(N)**
  - **HI: Break at N_{HI} ~ 21.5**
    - Transition to H_2?
  - **CO maps**
    - BIMA survey of local galaxies
    - Weight by luminosity
  - **$f(N_{H2})$ extends off the HI distribution**
    - Plausible explanation
    - Incidence of large $N(H_2)$ clouds is very small

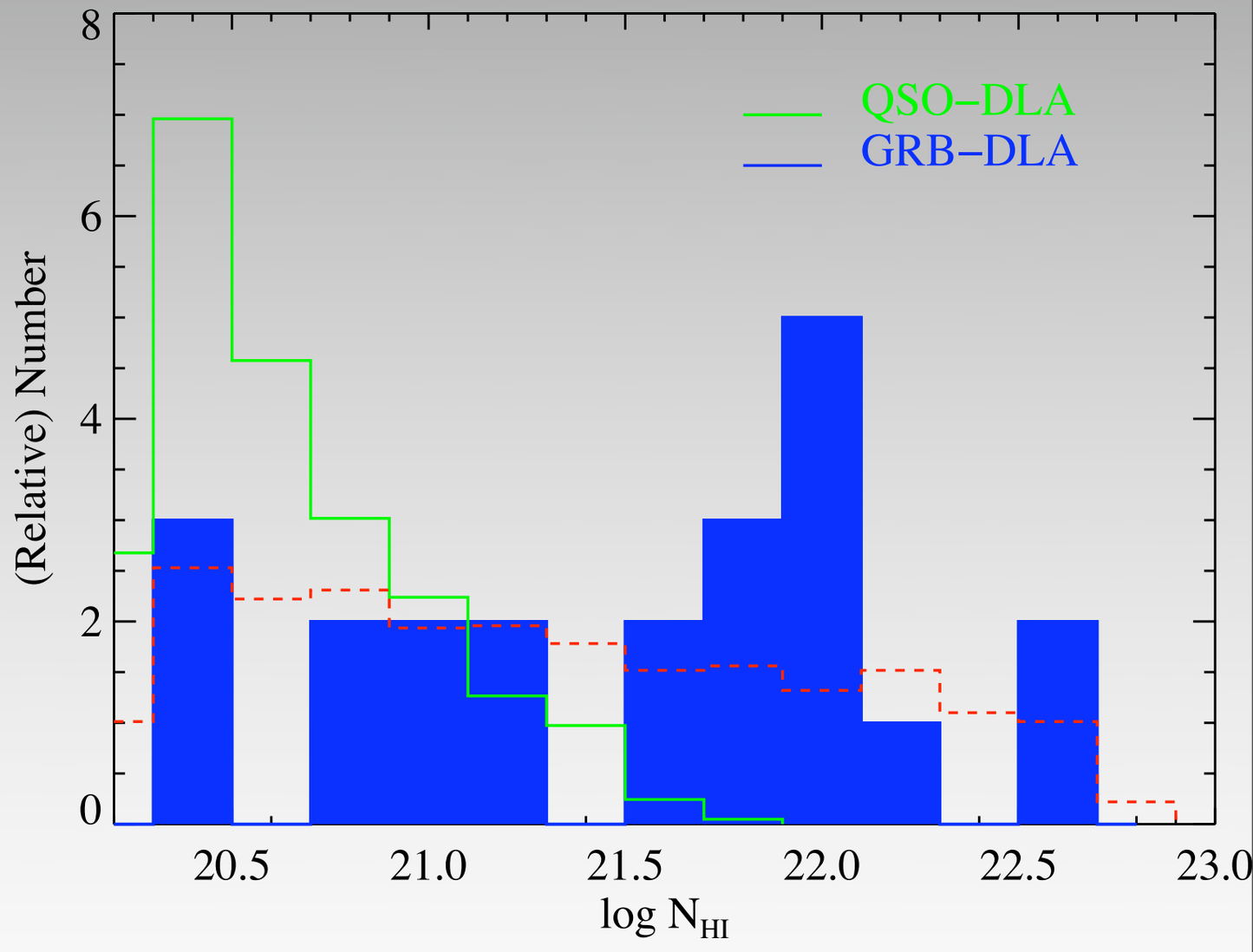
Zwaan & Prochaska (2006)



The Break: GRBs!

- **GRB afterglow**
  - Generally exhibit a large DLA at $z=z_{GRB}$
    - Includes $N_{HI} > 22$!!
  - Measure metallicity, depletion, H_2 content
- **Extinction?**
  - A_V = 0.05 to 0.2 mag
    - QSO surveys would include most GRB sightlines
- **H_2?**
  - Very low molecular fraction in GRB DLAs
  - $f(H_2) < 10^{-5}$
    - Destroyed by local SF?

Prochaska et al (2007)



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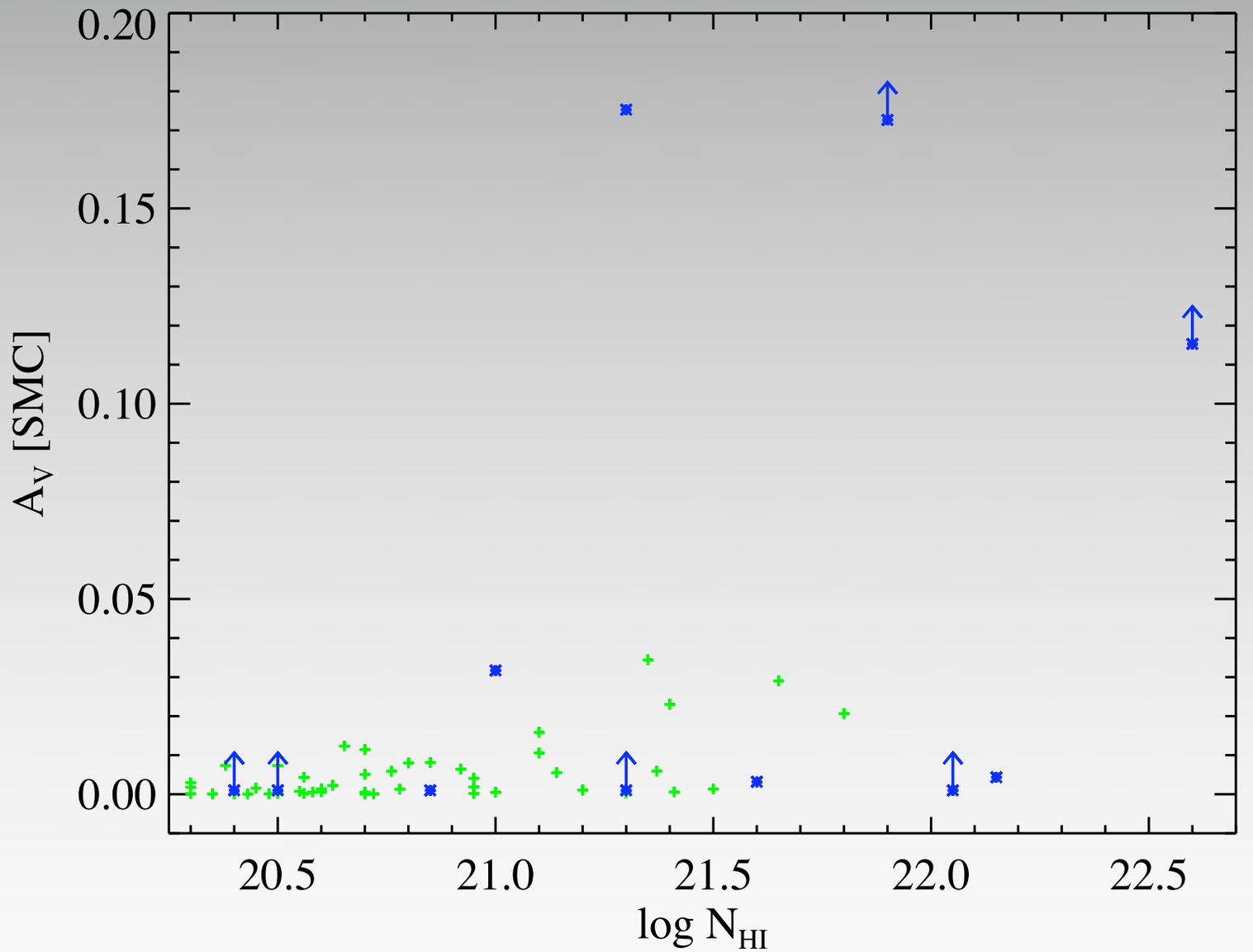

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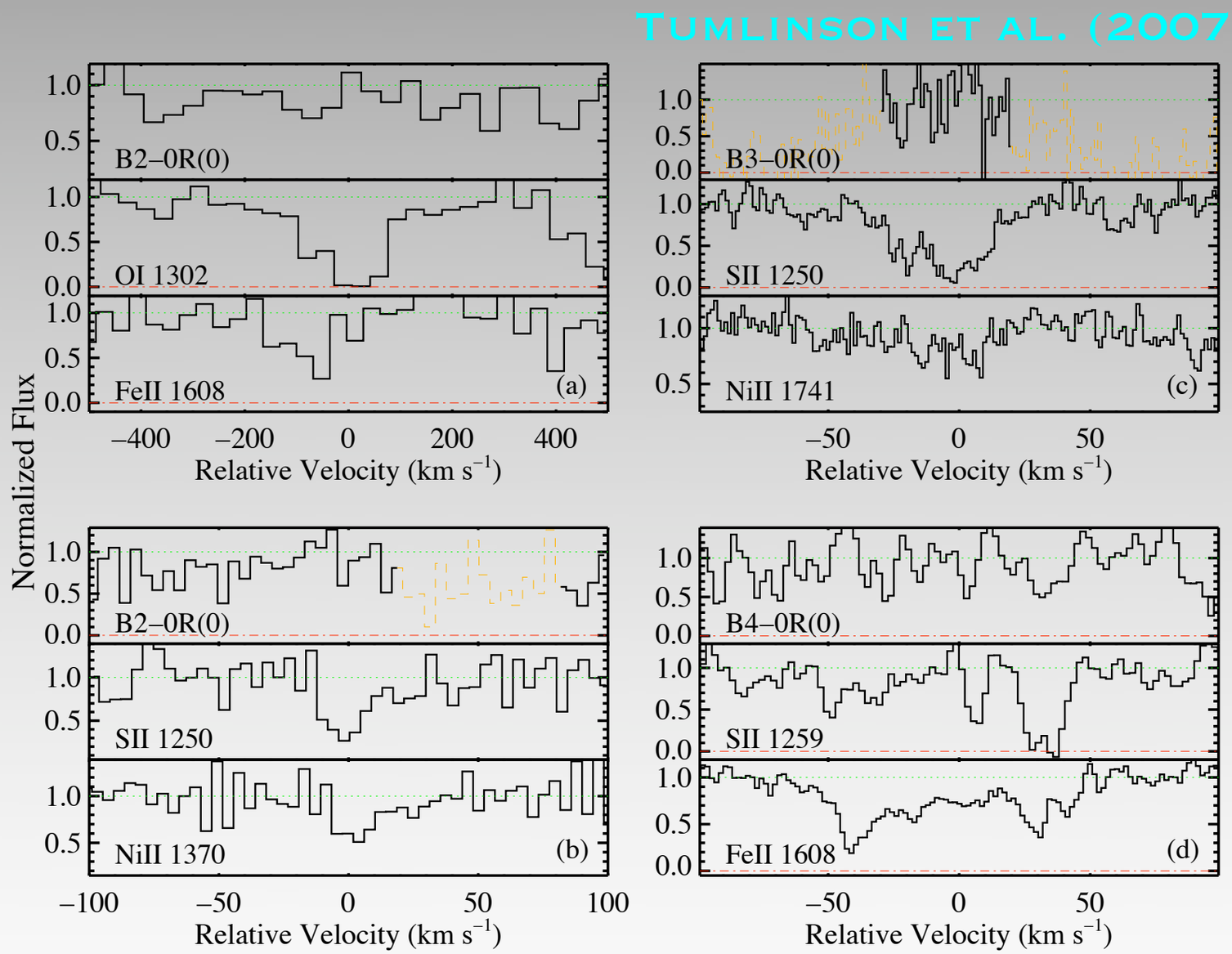
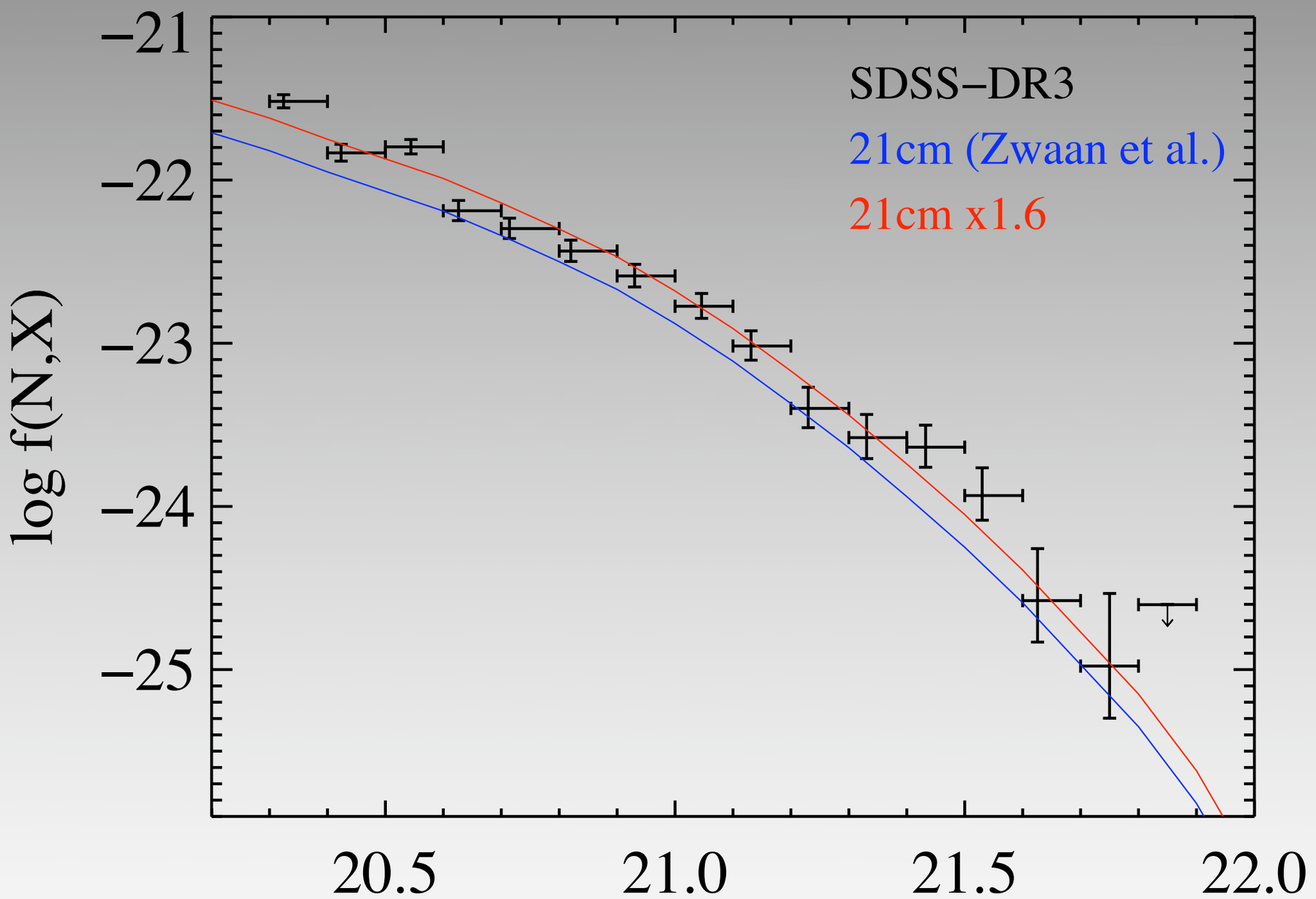


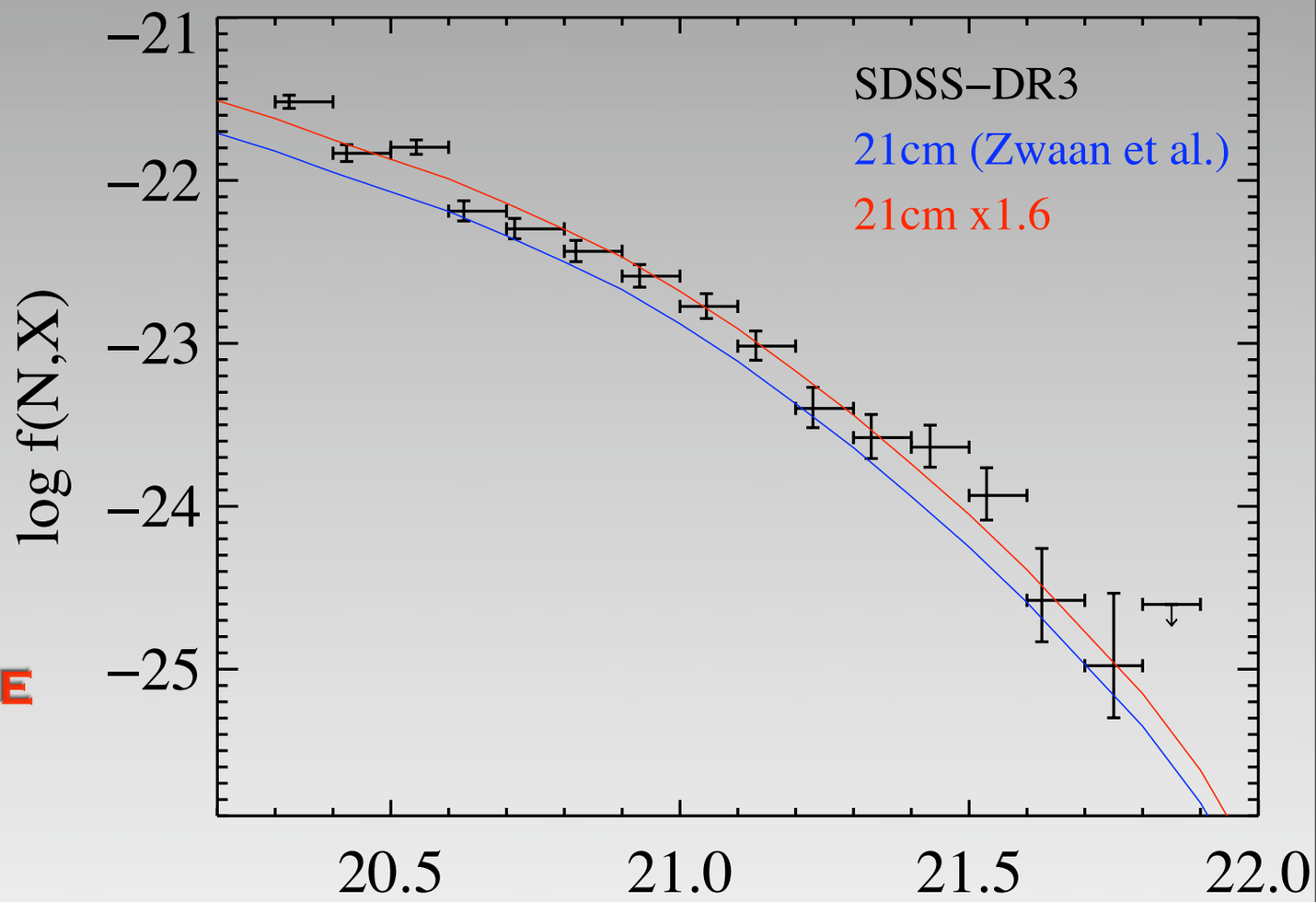
Comparison with z=0



Very similar results from very different techniques

Comparison with z=0

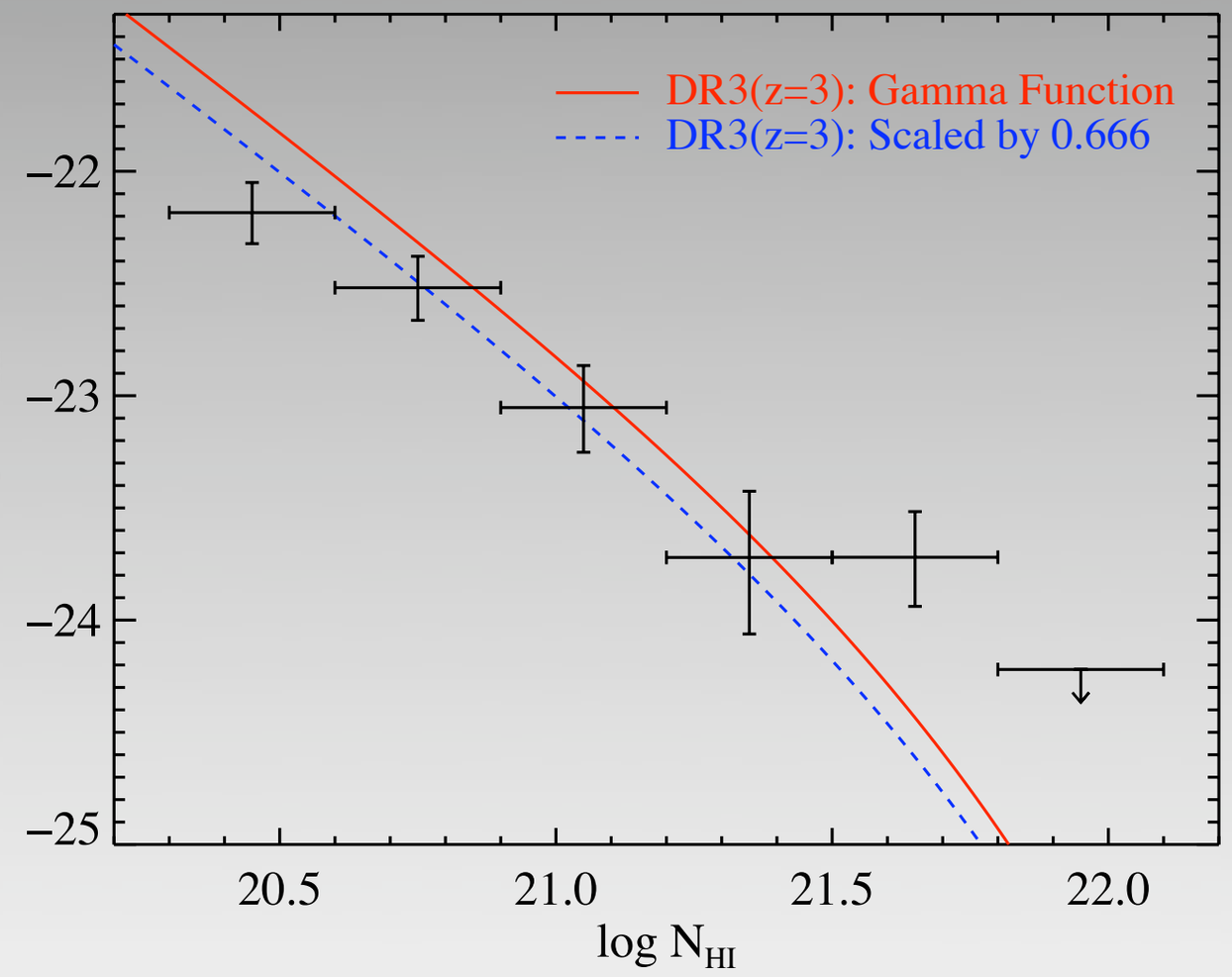
- Coincidence?
  - z~3 Galaxies
    - Lower average DM mass
    - Lower metallicity
    - Higher HI fraction?
    - Disks? Clumps??
- Statement about galaxy formation?
  - SF regulate the HI surface density profile
    - Consumption of gas
    - H_2 formation
    - Feedback
  - Similar average 'disk' mass?
    - $M_{HI} \sim 2\pi N_{HI} R_d^2 \sim 4 \times 10^9 M_{sun}$



Comparison with z=1

- z=1 'DLA' Survey
  - MgII Survey (SDSS)
  - HST bootstrap
    - Rao et al. (2006)
    - Average N_{HI} of MgII absorbers
- $f(N_{HI})$ Results
  - $f(N_{HI})$ contradicts measurements at z=0 and 2
    - Only the NHI ~ 21.7 bin
  - z=1 $f(N_{HI})$ is non-physical
    - More cross-section in HI disks at NHI = 21.7 than 21.35
    - Find one galaxy (real world or simulation) where this holds
  - Explanations
    - Small number stats?
    - Lensing?

Rao et al. (2006)



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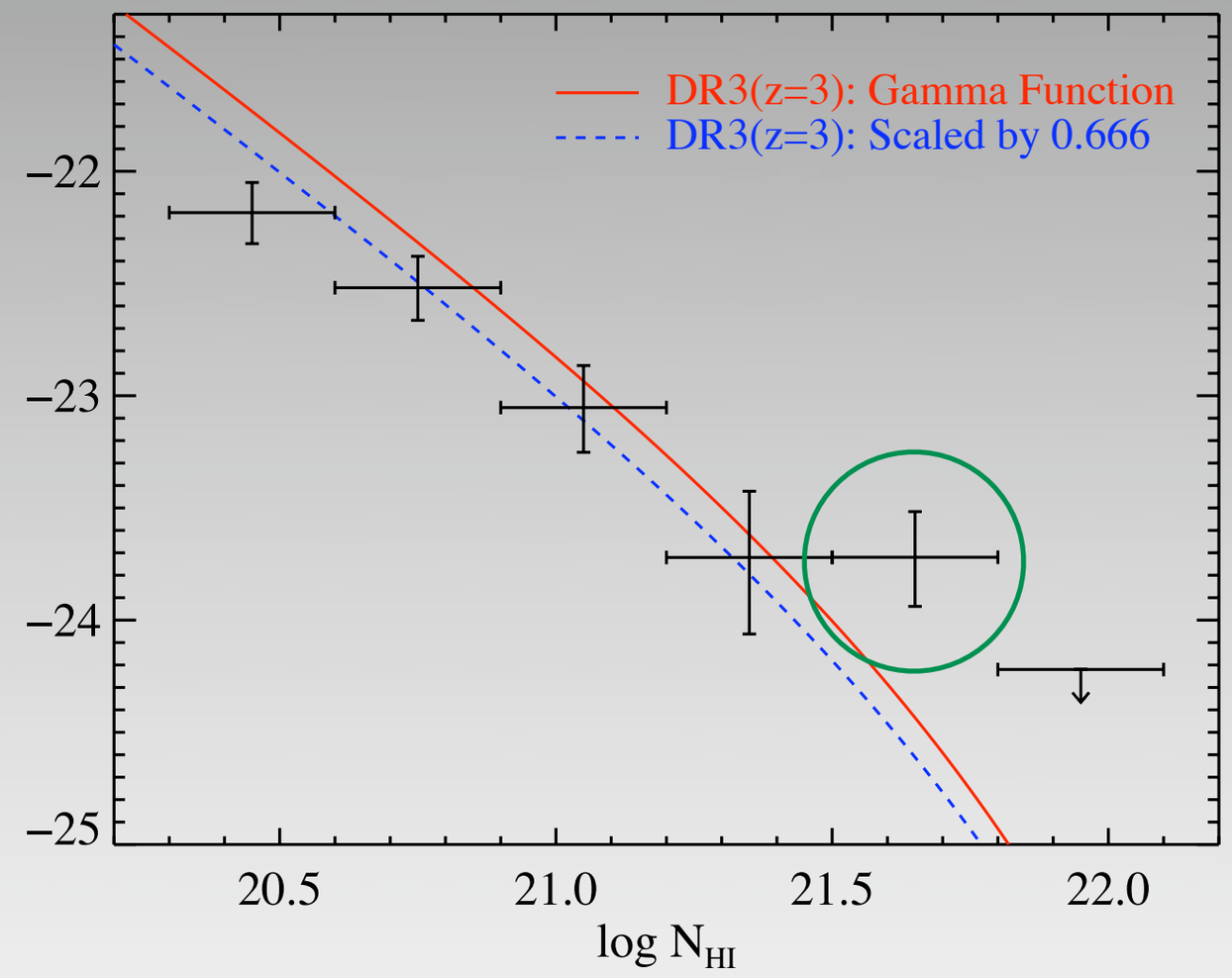
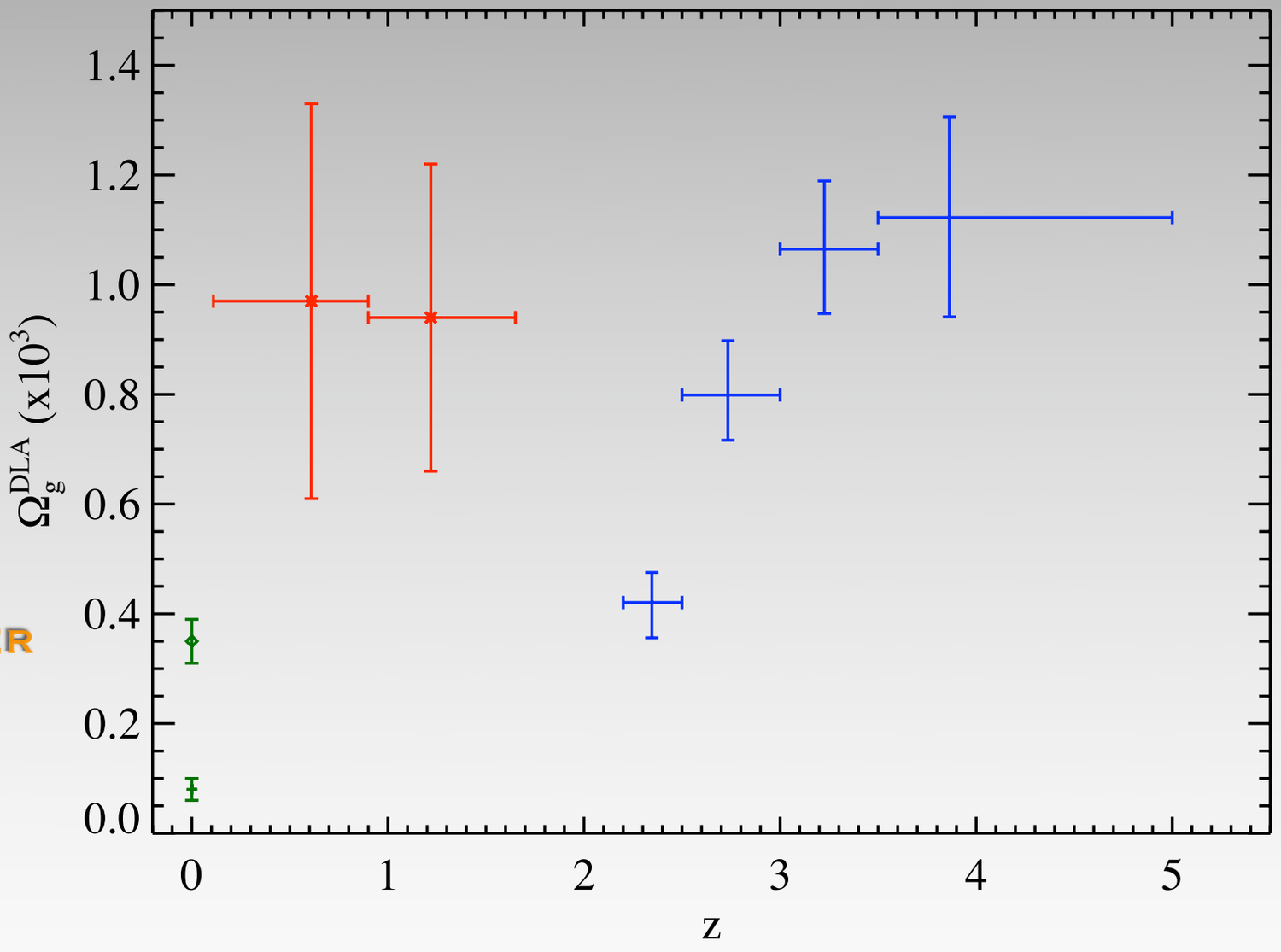


HI Mass Density from DLA

- Ω_g
  - Mass density of the universe in atomic gas
  - Units of ρ_c
- Redshift evolution
  - z>2 (SDSS)
    - Decline by ~2 from z=4 to 2
    - Coincidence of z=0 and z=2
    - HI mass density is far larger than dwarf galaxies at z=0
  - z=0 (21cm)
    - Reasonable agreement with z=2
  - z=1 (MgII)
    - Total disconnect
    - Reasonable with 0.666 scaling



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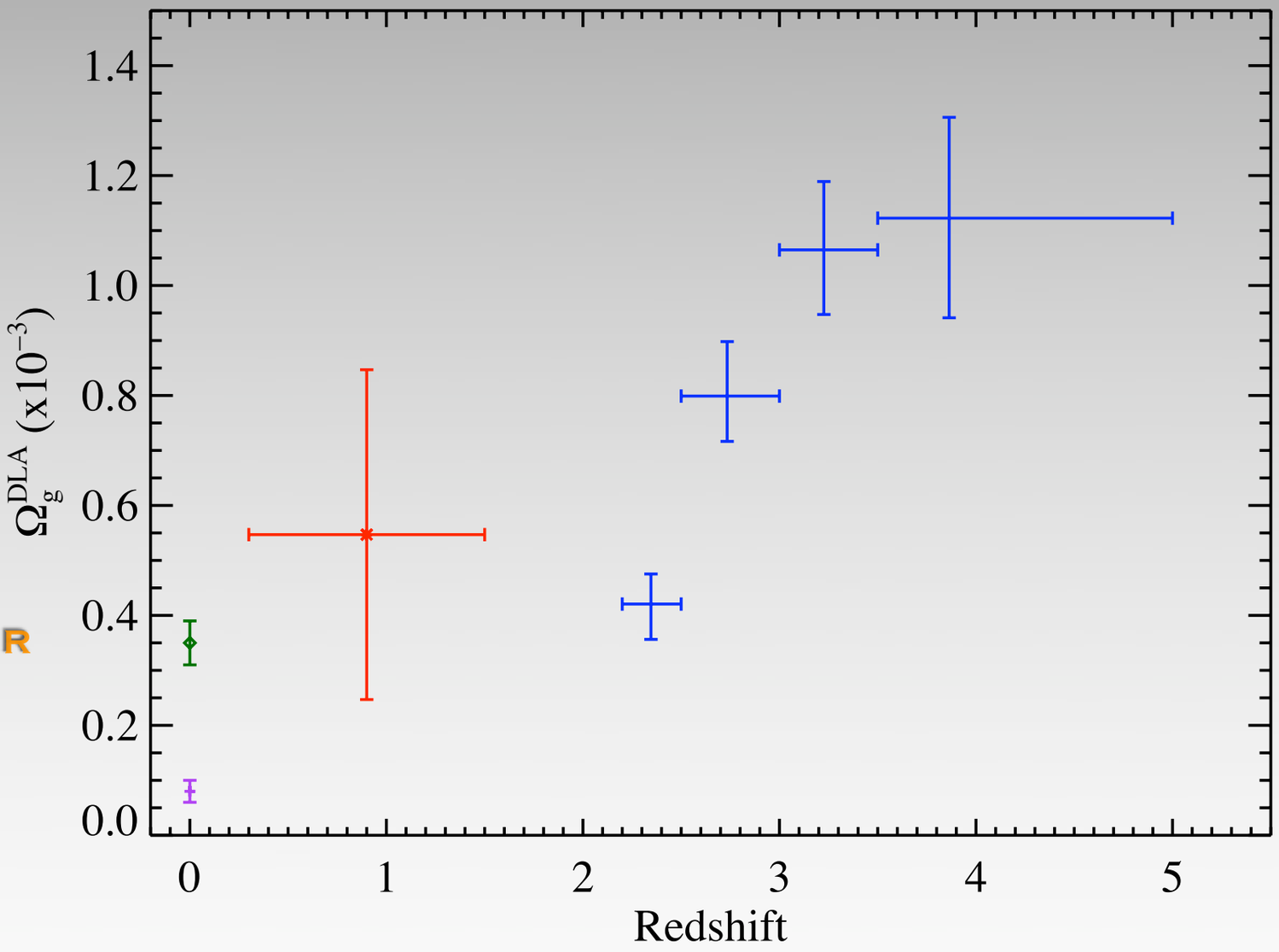
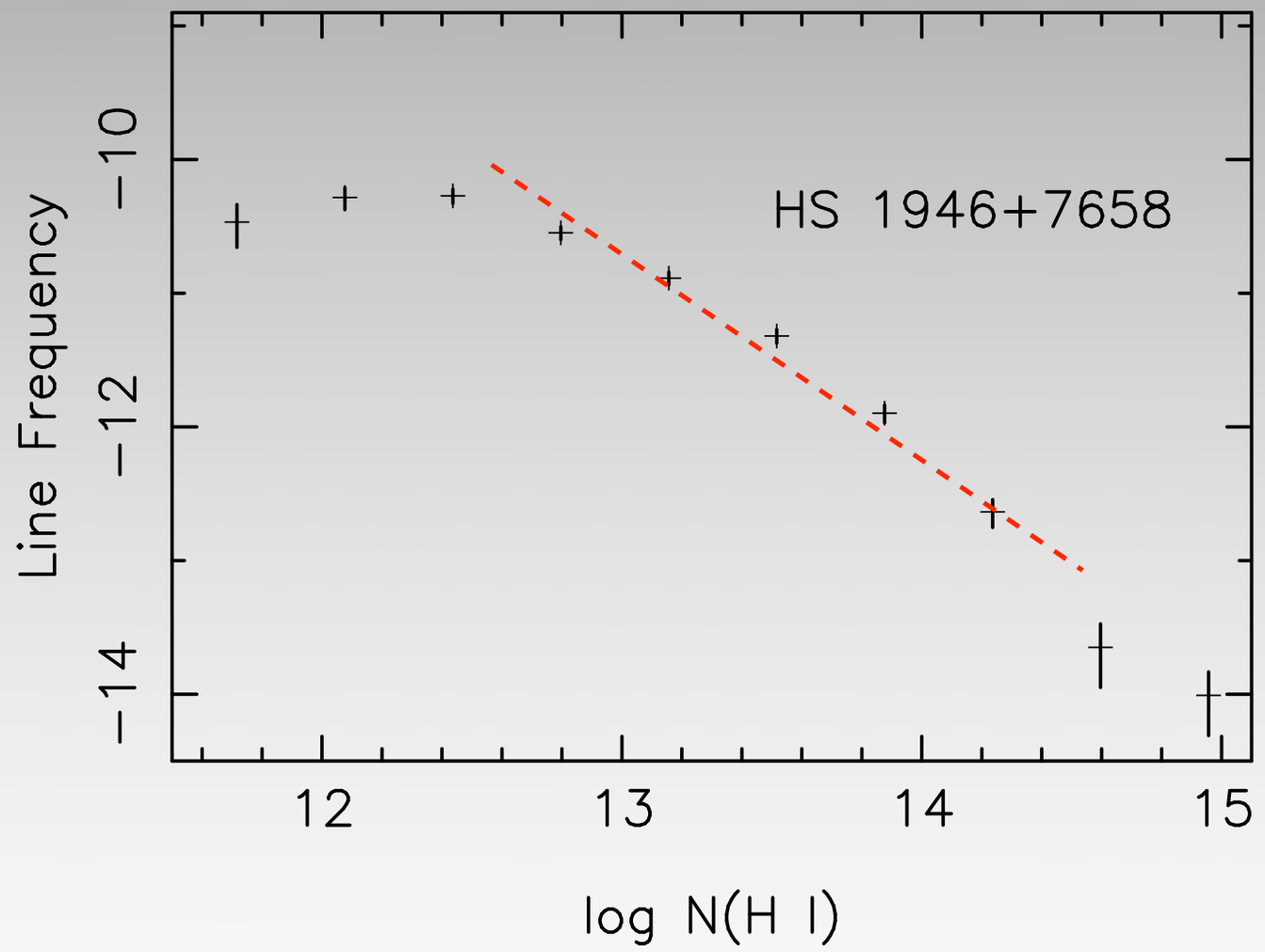


$f(N_{HI})$ of the Lya Forest

- Lya Forest
  - Even a single sightline can suffice
  - e.g.
    - Kirkman & Tytler (1997)
    - Kim et al. (2002)
- Result
  - $f(N_{HI}) \sim N_{HI}^{-1.5}$
    - $N_{HI} \sim 10^{12.5}$ to $10^{14.5}$
    - Incomplete at $<10^{12.5}$?
  - Perhaps, this is a very limited description
    - Or even, incorrect
- Big 'gap'
  - LLS
    - 4+ orders of magnitude in N_{HI}
    - Observational challenge



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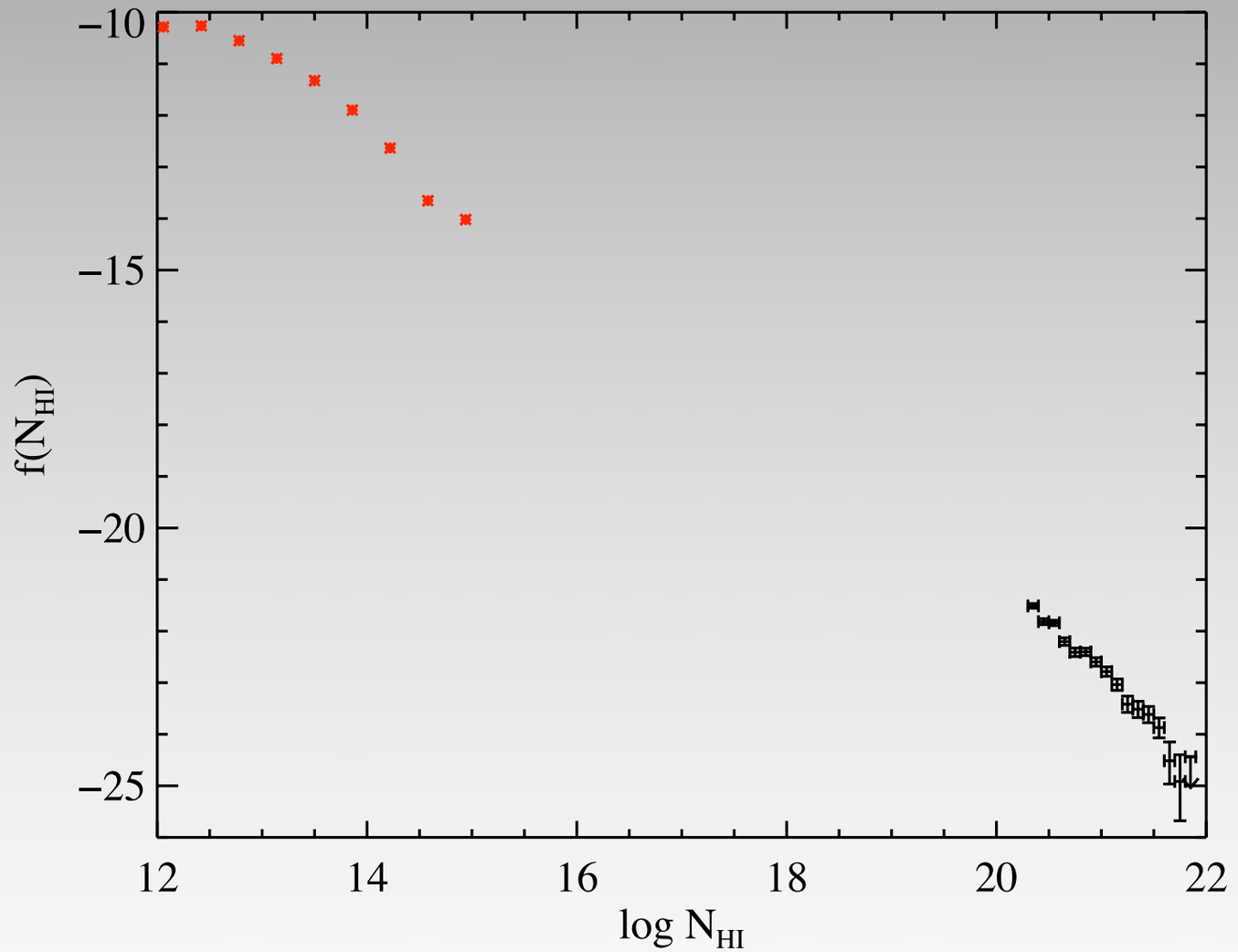
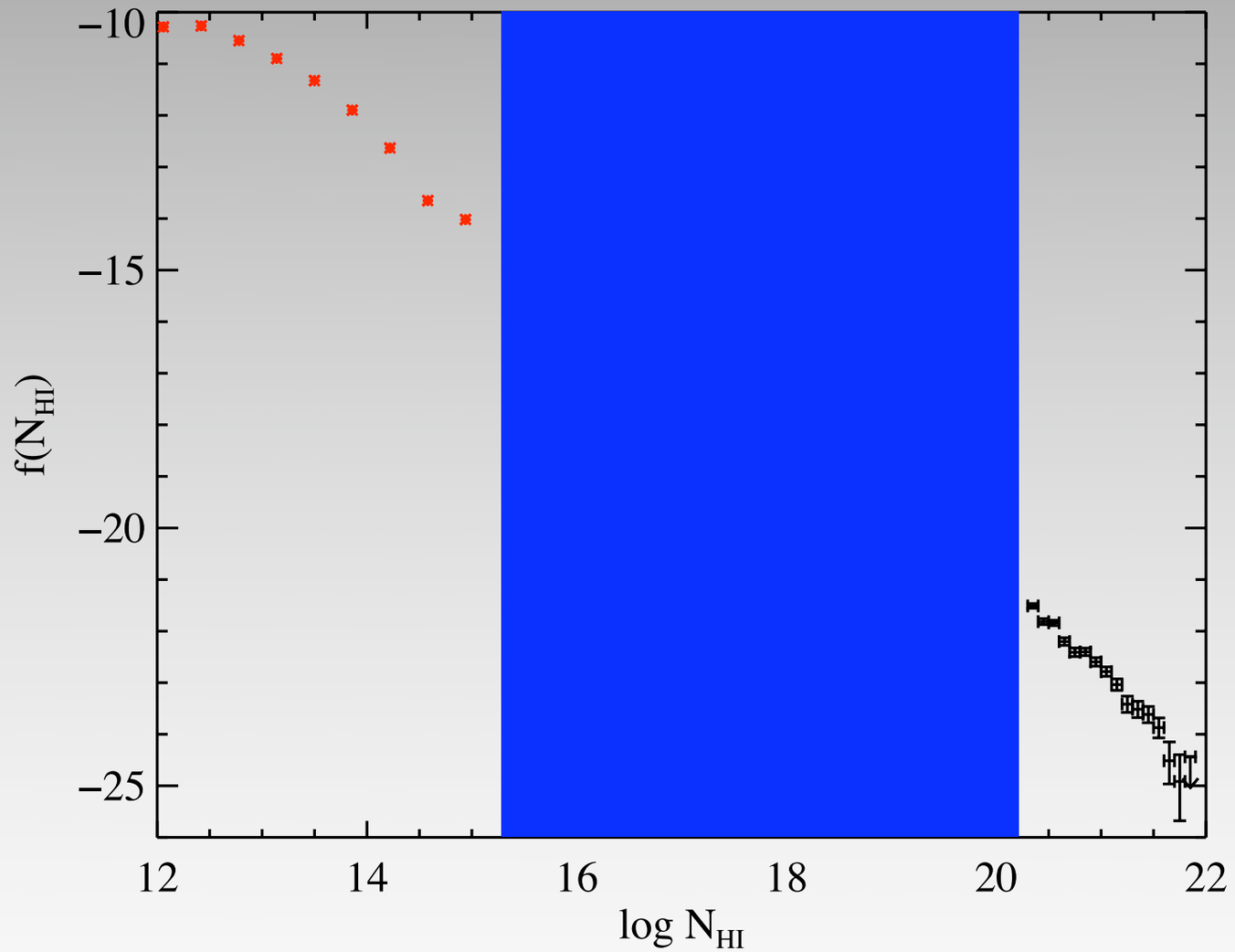


$f(N_{HI})$ of the Lya Forest

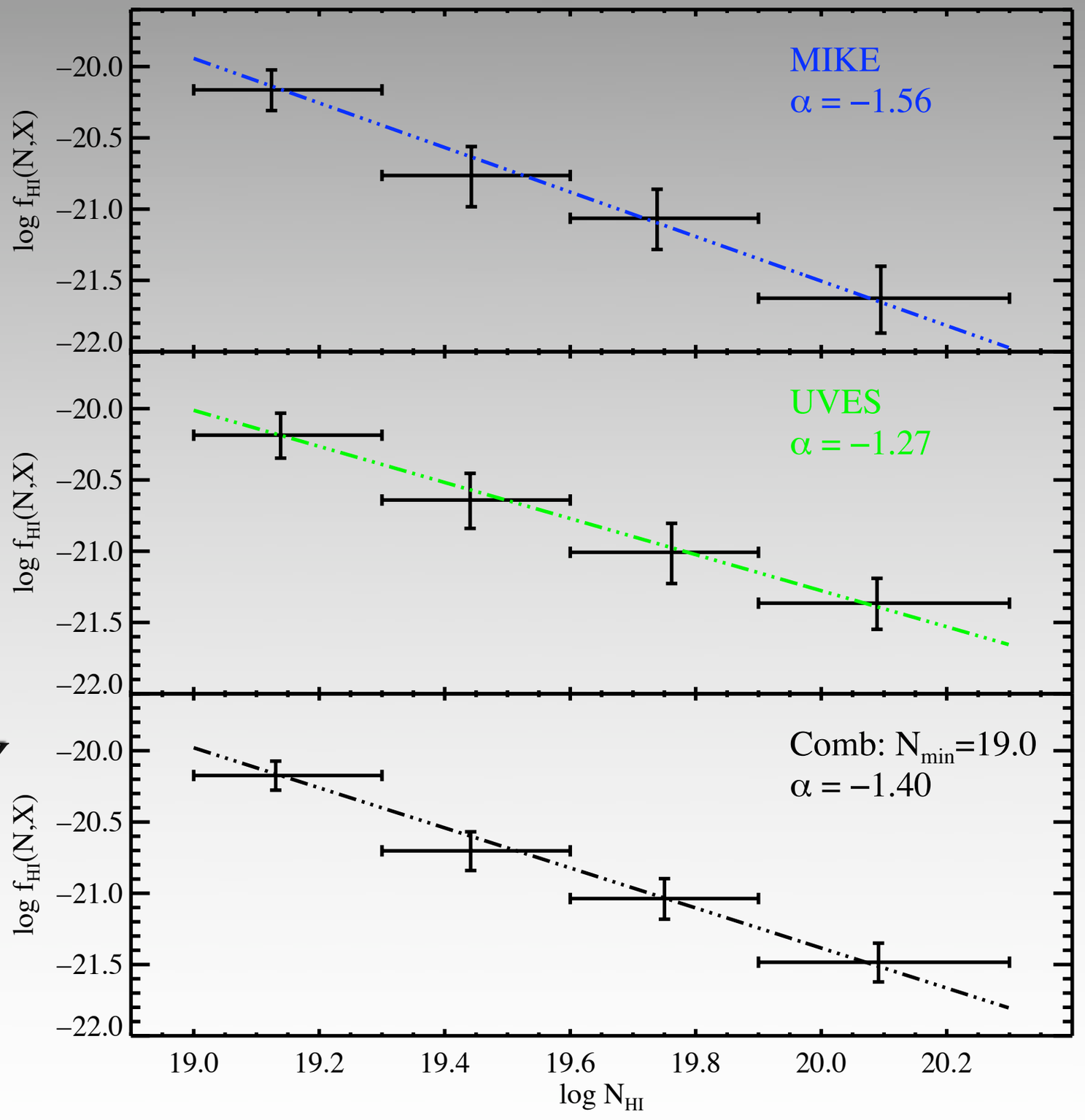
- Lya Forest
  - Even a single sightline can suffice
  - e.g.
    - Kirkman & Tytler (1997)
    - Kim et al. (2002)
- Result
  - $f(N_{HI}) \sim N_{HI}^{-1.5}$
    - $N_{HI} \sim 10^{12.5}$ to $10^{14.5}$
    - Incomplete at $<10^{12.5}$?
  - Perhaps, this is a very limited description
    - Or even, incorrect
- Big 'gap'
  - LLS
    - 4+ orders of magnitude in N_{HI}
    - Observational challenge



Super LLS

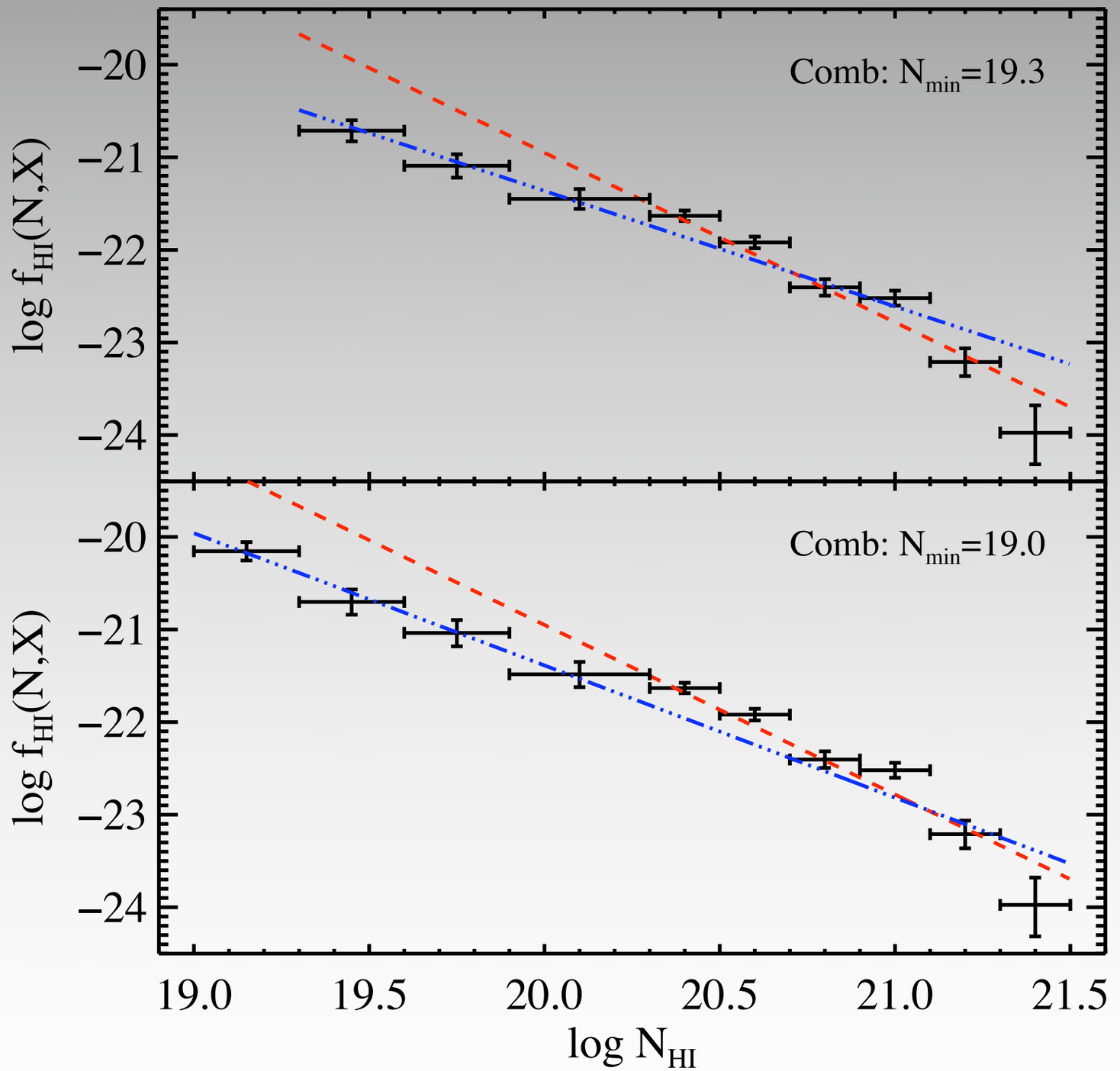
- $N_{HI} > 10^{19}$ cm-2
  - a.k.a. "sub-DLA"
  - But more LLS than DLA
    - Ionized gas
  - Damping wings of Lya
    - Require high-res spectra
- First survey
  - UVES
    - Dessauges-Zavadsky et al.
    - Peroux et al.
- Keck/Magellan Survey
  - MIKE, ESI
  - 50 SLLS at z>2

O'Meara et al. (2007)



Super LLS

- **SLLS $f(N_{HI})$**
  - $f(N_{HI}) \sim N_{HI}^{-1.4}$
  - **Shallower power-law slope than the DLAs**
    - **Phase-transition, i.e. Zheng & Miralda-Escude (2002)**
    - **Neutral to ionized**
  - **Akin to HI edges in local galaxies**
- **Shallow but not shallow enough**
  - **Still too many LLS**
  - **α=-1 is likely at $N_{HI} <\sim 10^{19}$ cm^{-2}**
- **Closing the gap...**



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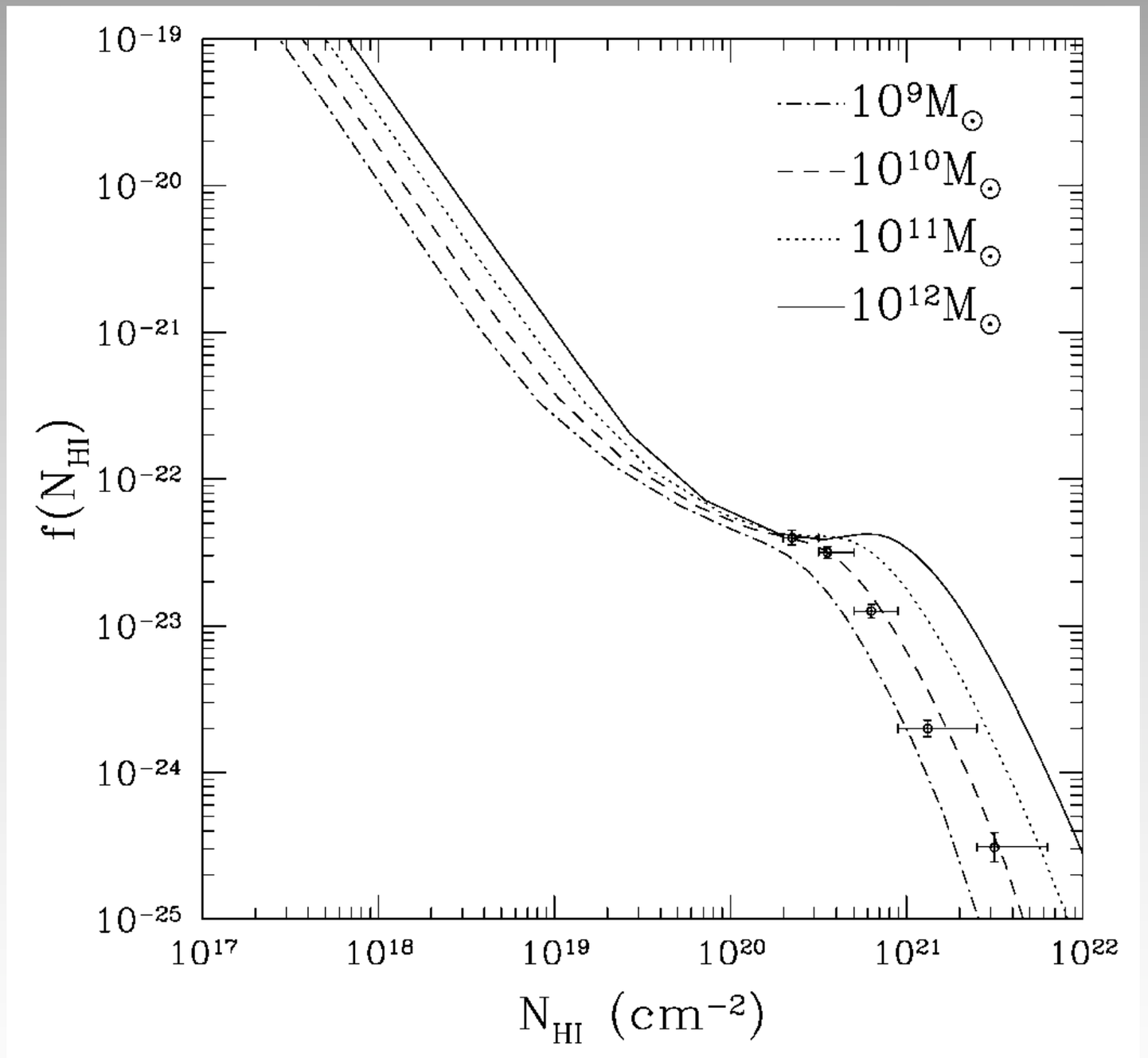

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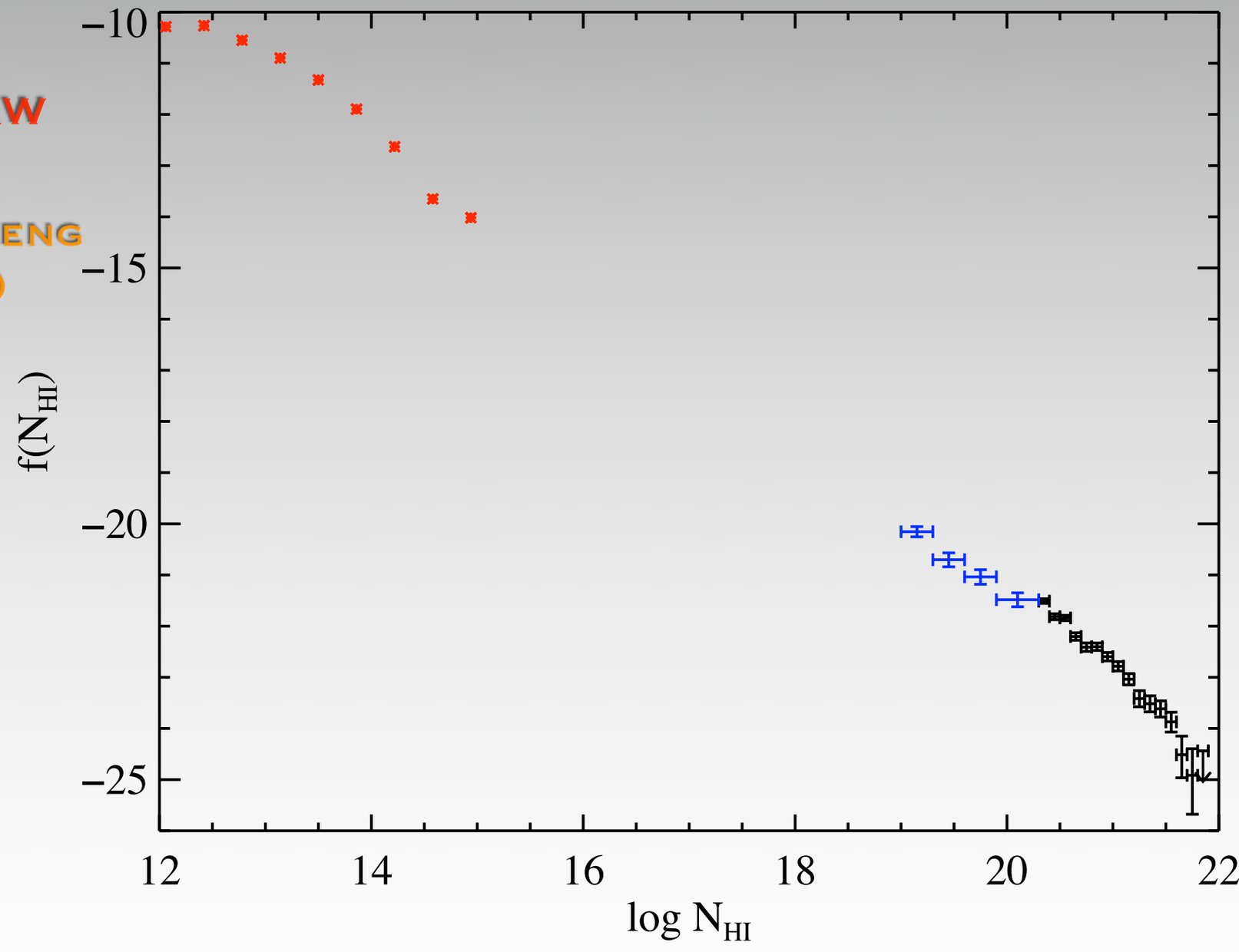
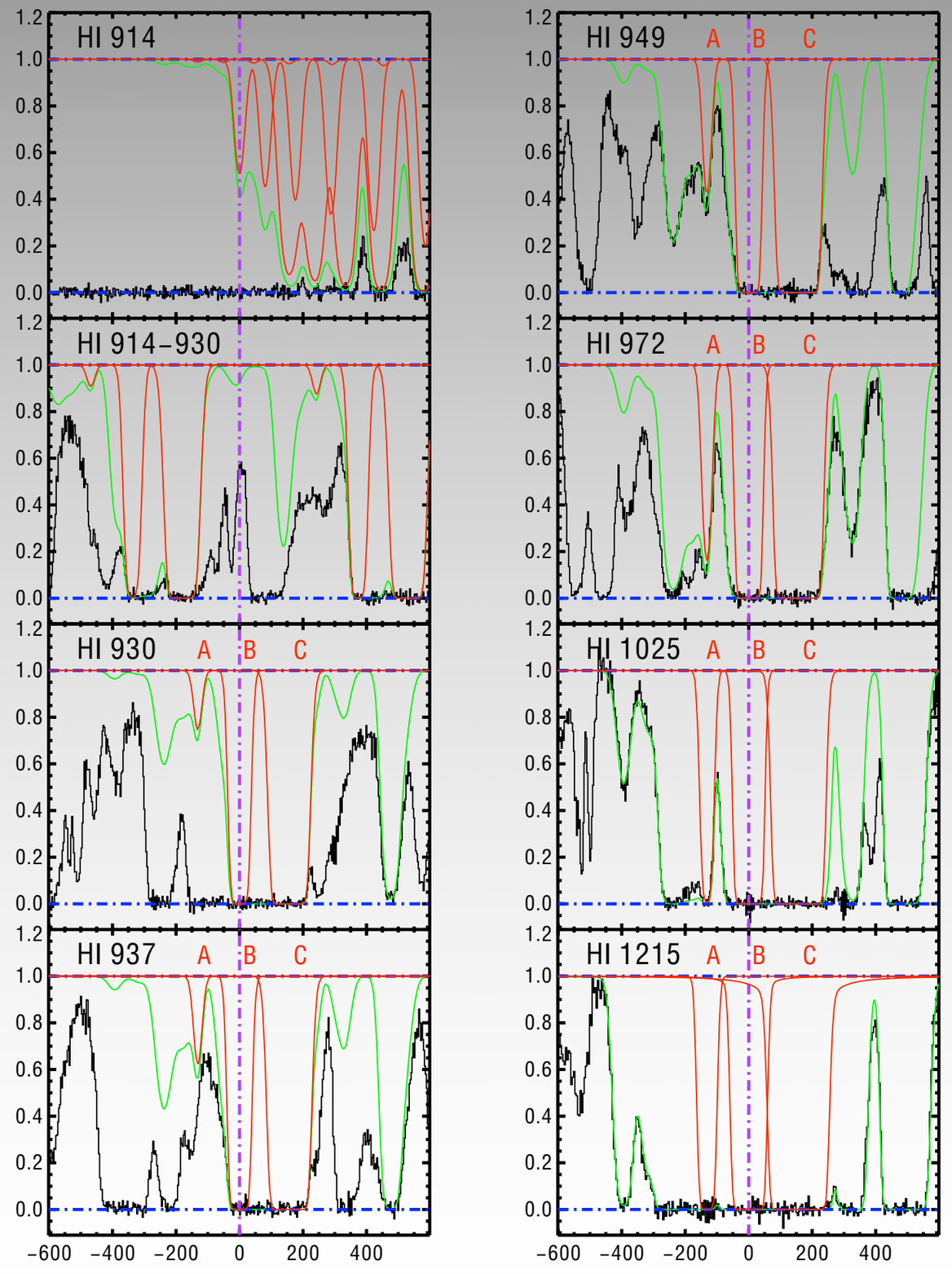


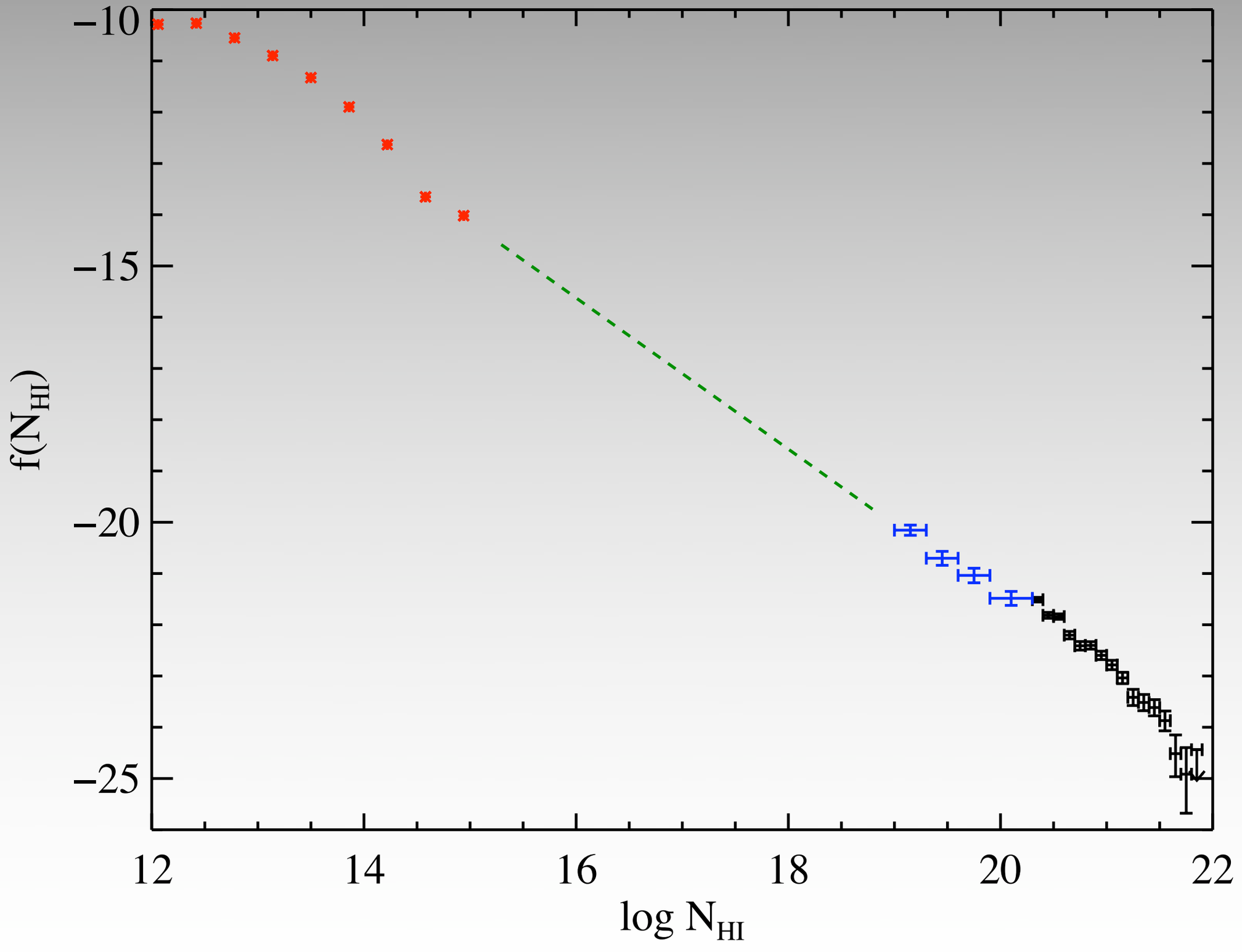
LLS

Procther et al. (2007)

- LLS
  - Echelle spectra of full Lyman series
  - z>2.7
    - Blue spectra
    - MIKE, HIRES upgrade
- Keck/Magellan survey
  - ~100 LLS
  - Selected on the basis of Lyman limit only
  - Primarily SDSS quasars
- Challenging analysis
  - Ongoing work
  - See Prochter et al. (2007)

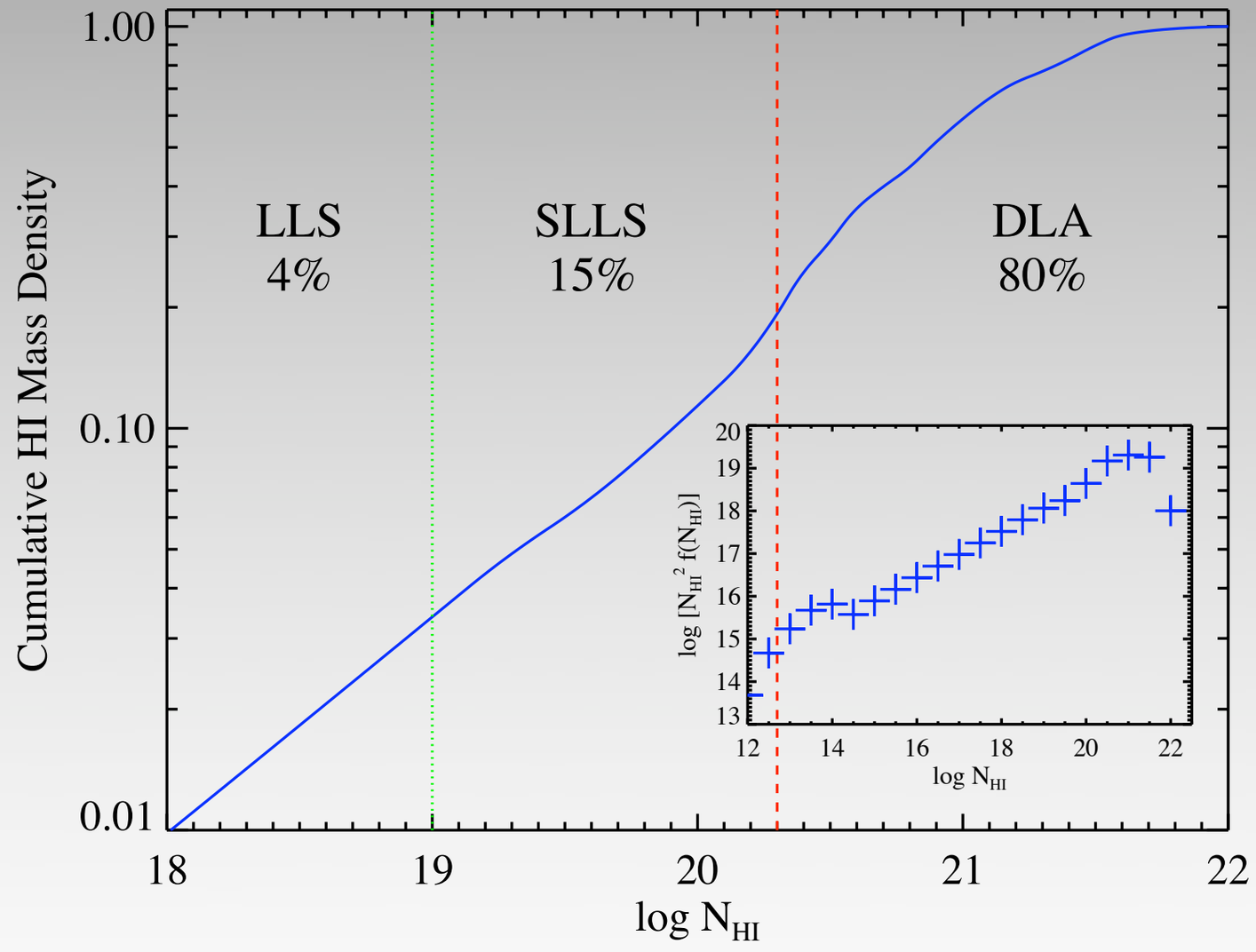


z~3 Summary of $f(N_{HI})$



Where is the HI Gas?

- Census of HI atoms
  - Integrate f(N)NdN
  - DLAs dominate the census
    - SLLS contribute ~15%
- predominantly (x < 0.5) neutral gas
  - Lya forest = 0%
  - LLS ~ 5% (estimate)
  - DLAs ~ 95%
    - Expect >90% of this gas to occur in star-forming galaxies
    - i.e. same as z=0 (Briggs et al.)
    - Remains to be shown



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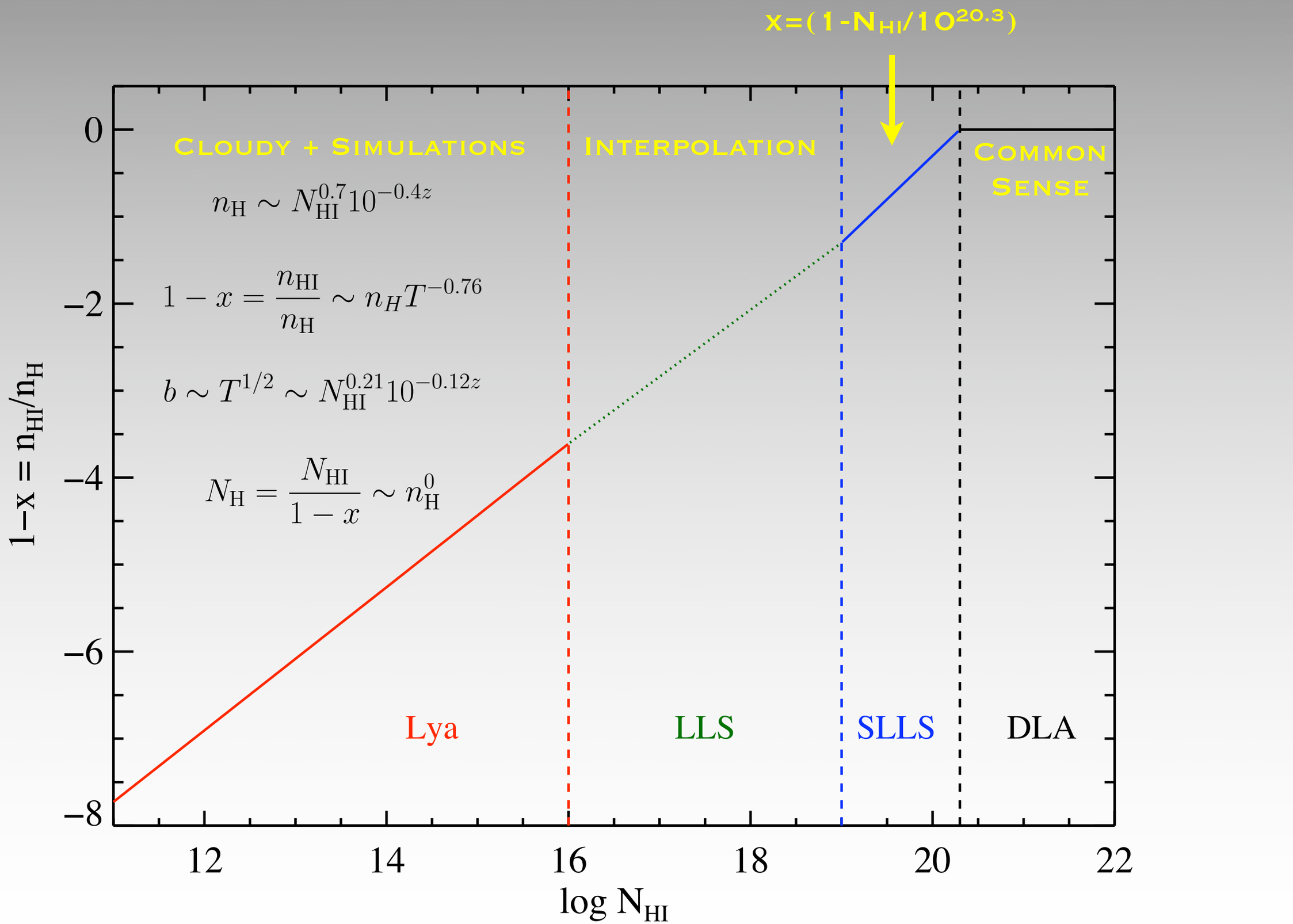

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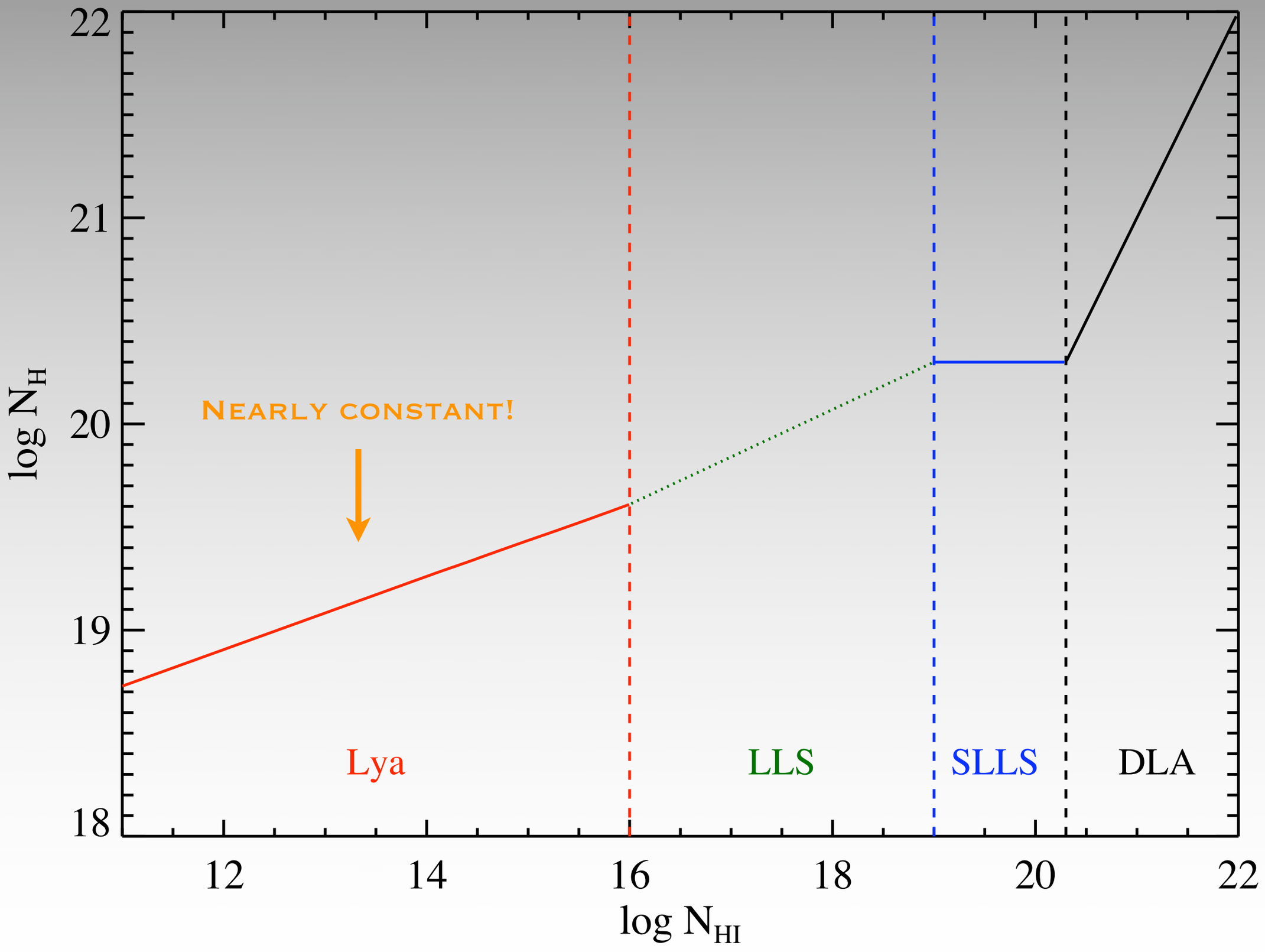

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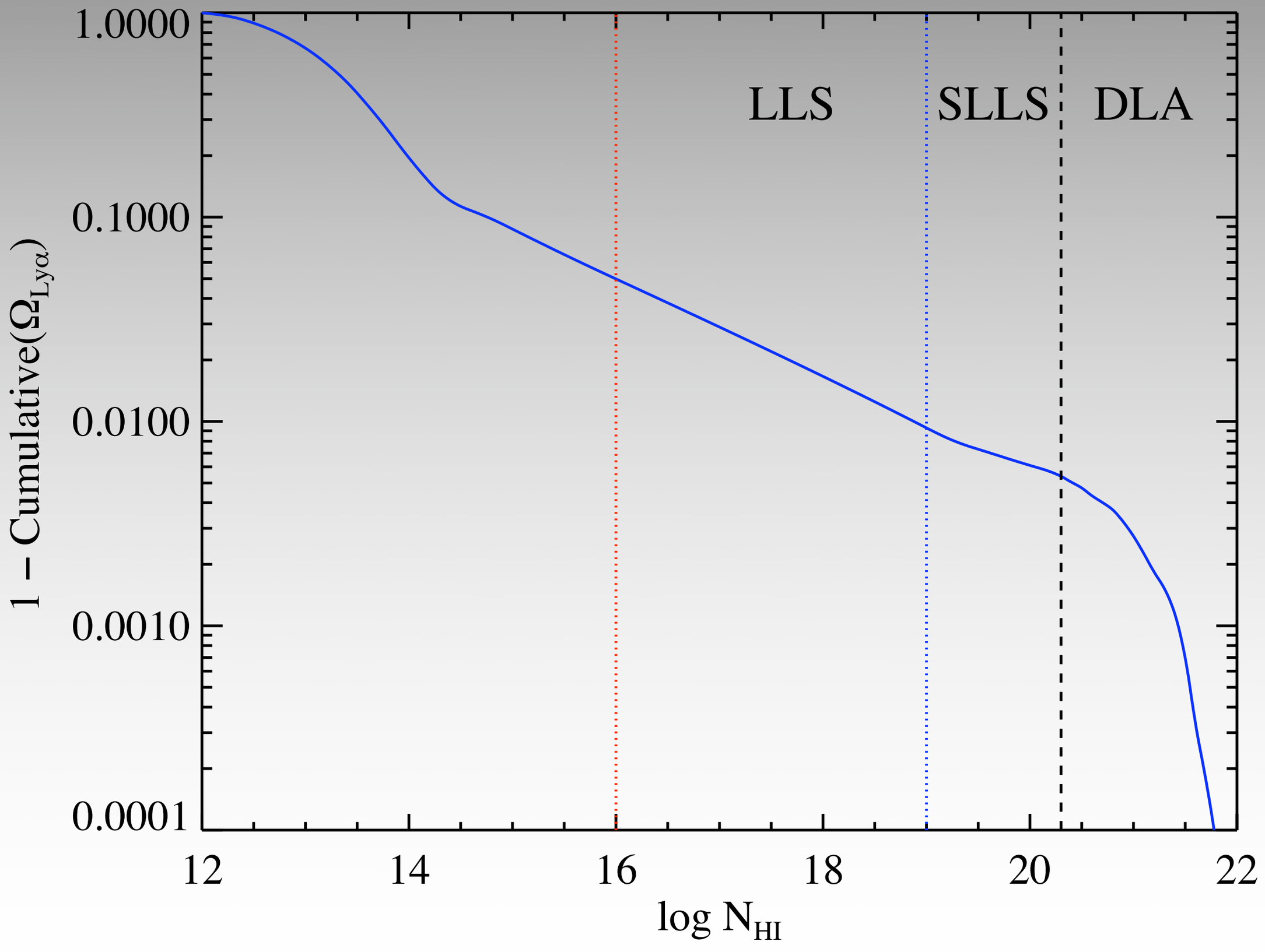
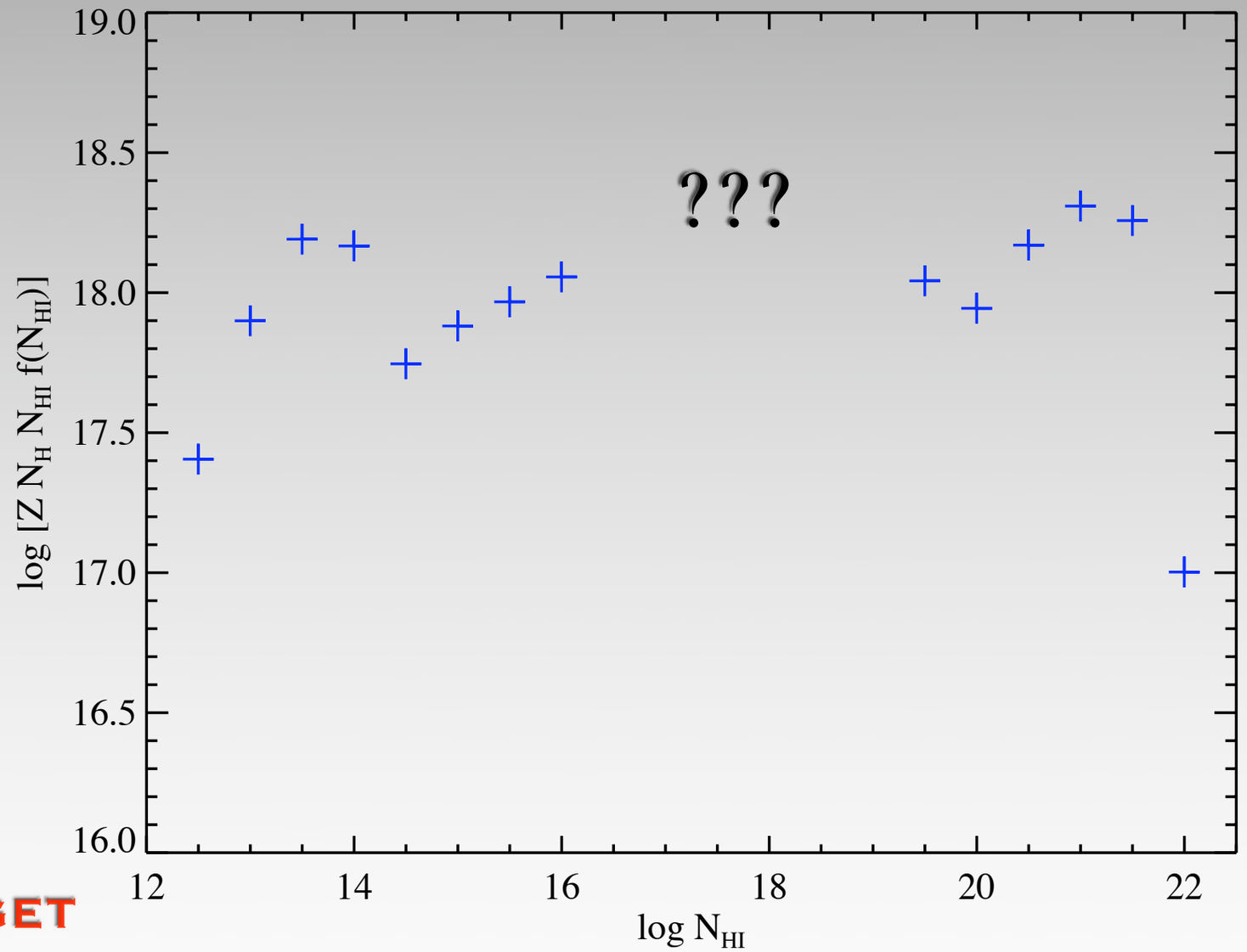


Where are the Metals?

- **Metallicities**
  - **DLAs: ~1/10 solar**
  - **LLS:**
    - **SLLS: 1/10 to 1/3 solar**
    - **LLS: ??**
  - **Lya Forest**
    - **< 10^{-2} solar**
    - **Schaye et al: [C/H] = -3.5 + 0.65*log(δ-0.5) + [O/C]**
- **Distribution**
  - **Near flat**
  - **Bounded**
    - **See next talk**
- **Integral (Sum)**
  - **Lower than metal budget expected from SFR**
  - **How about the LLS?**



Summary and Parting Questions

- $f(N_{HI})$ for DLAs
  - -1.8 faint-end slope
  - Break at log N_{HI} ~ 21.5
    - H_2 formation?
- $f(N_{HI})$ for LLS
  - Flattening for log N_{HI} ~ 19
  - Signature of photoionized 'disk' ?
- Baryon budgets
  - DLA: HI mass (i.e. galaxies)
  - Lya forest: Baryonic mass
  - Metals: Evenly distrubuted?
- What is $f(N_{HI})$ from 10^{15} to 10^{19} cm^{-2}?
  - What is the redshift evolution, e.g. due to the EUVB radiation field?
- What are the physical origins of the wiggles in $f(N_{HI})$?
- What is $f(N_{H2})$?