The SDSS-DR3 Damped Lyα Survey

(and a fast review of DLA abundances)

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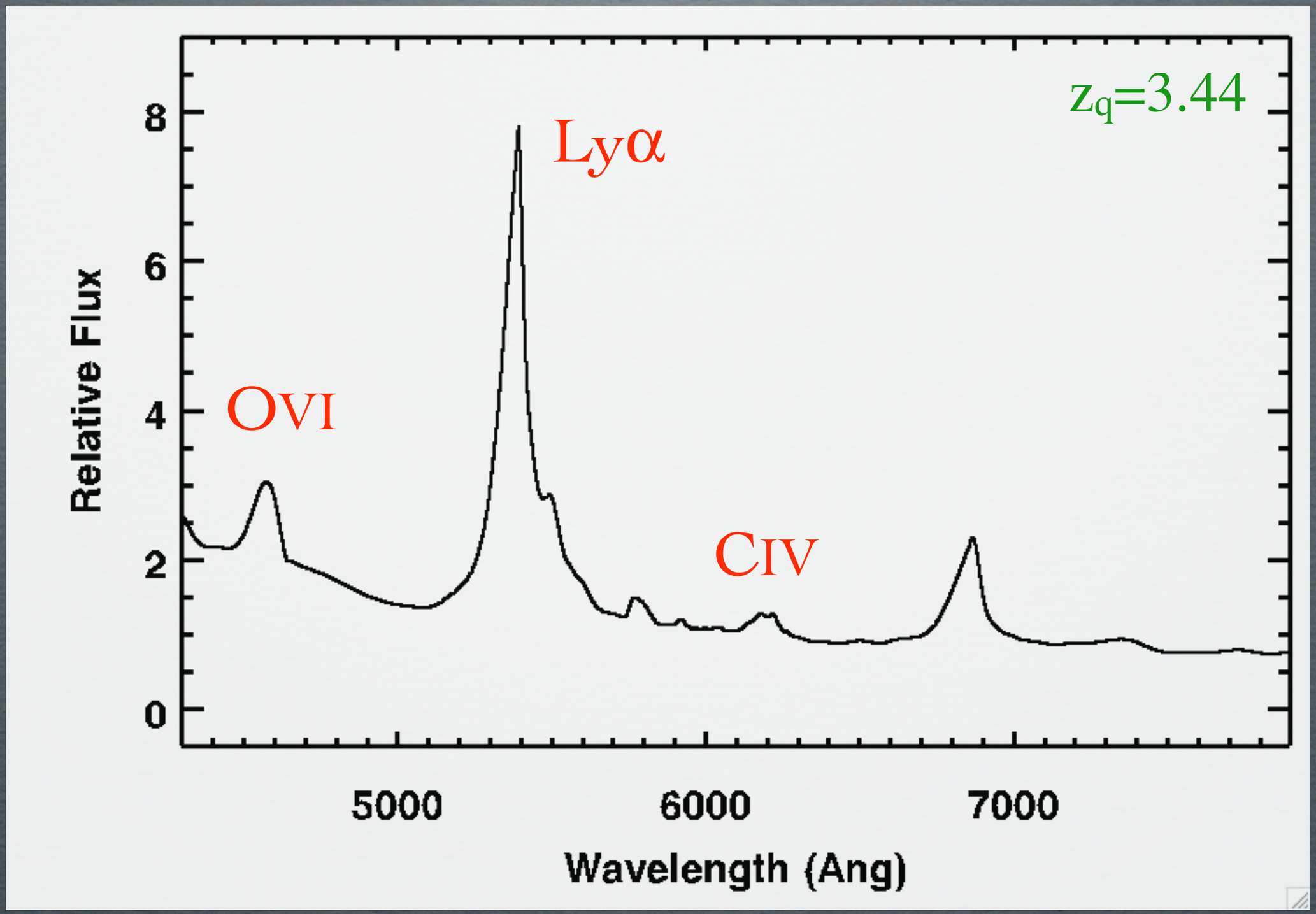
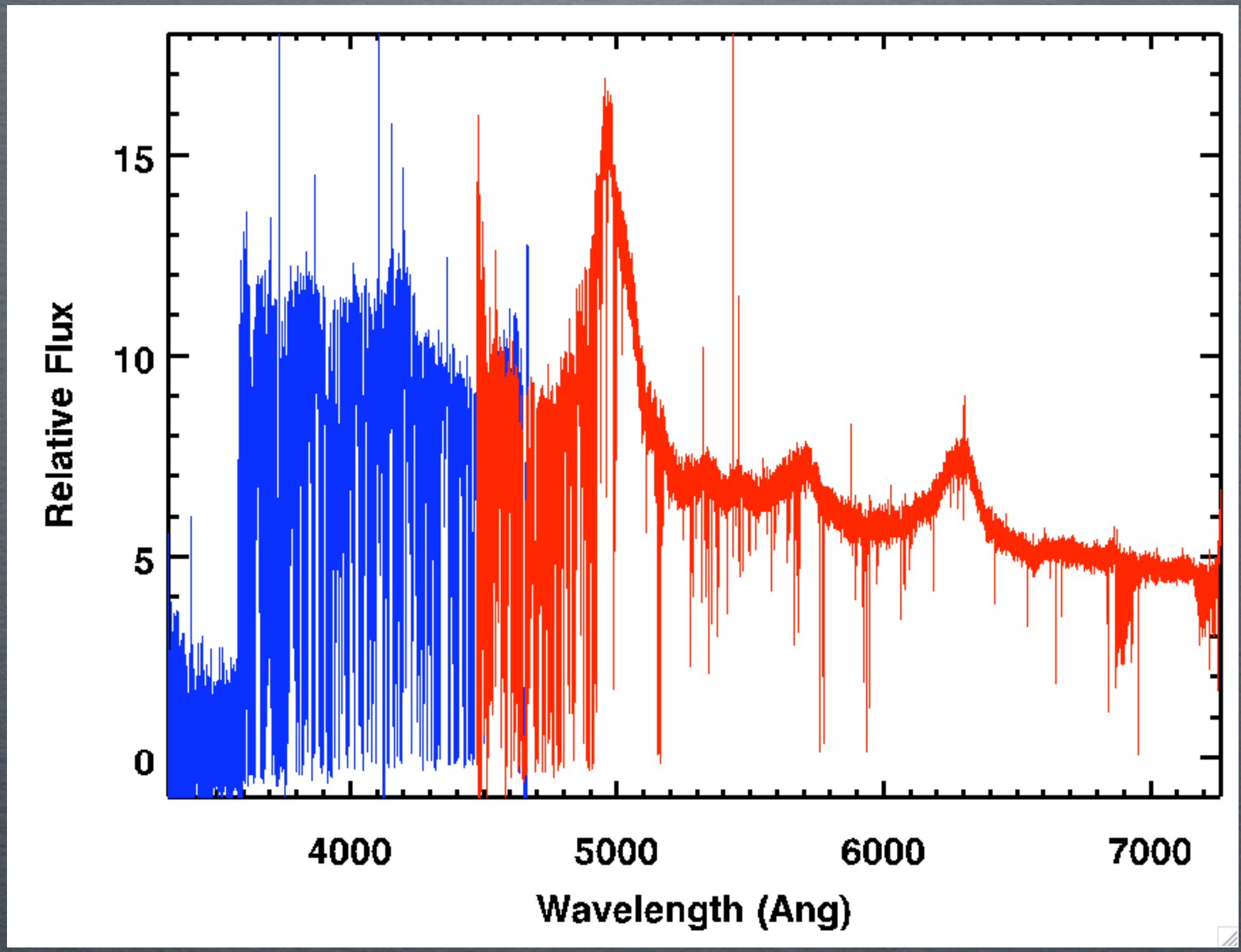
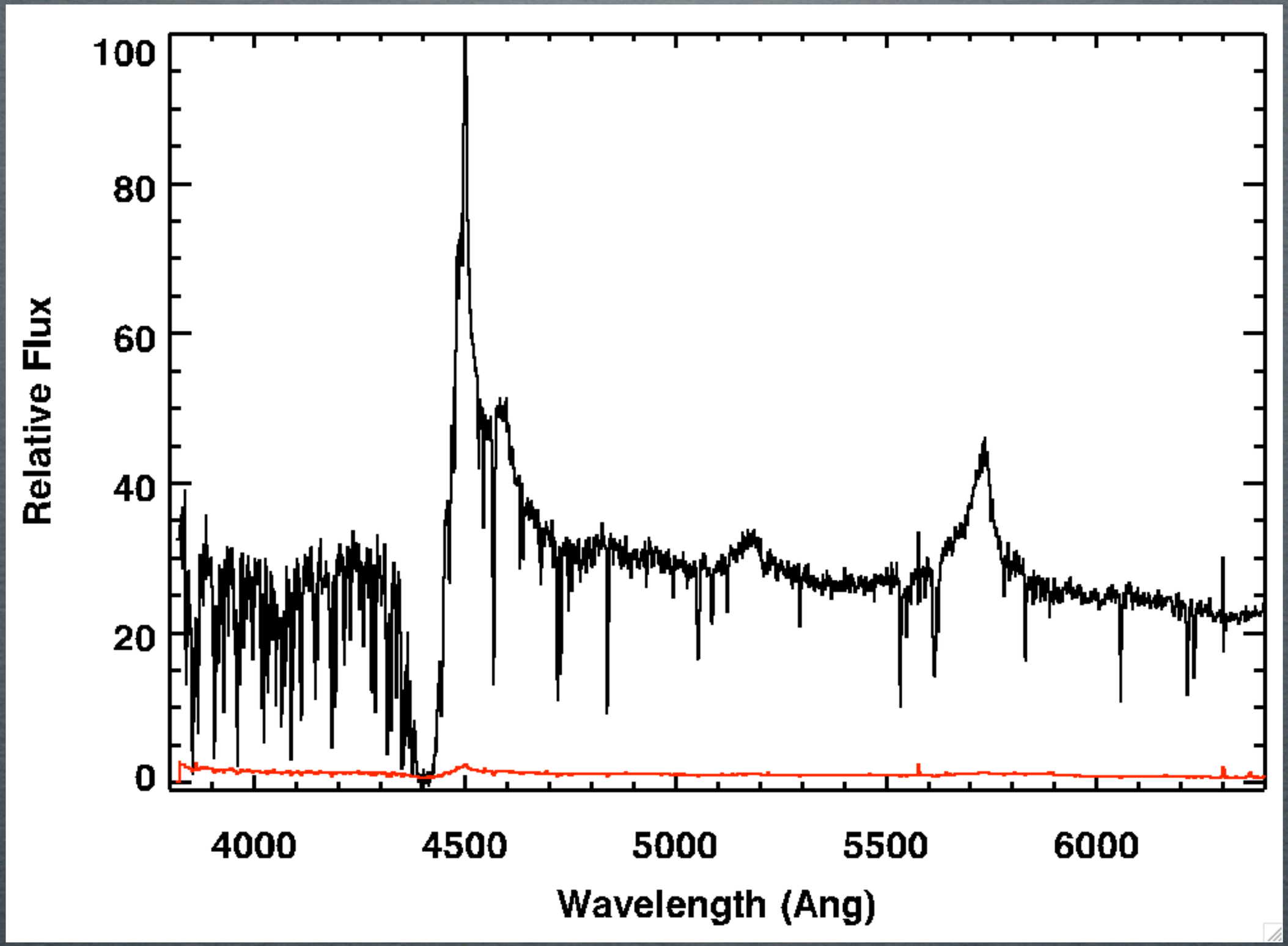
Quasar Continuum



Lyα Forest

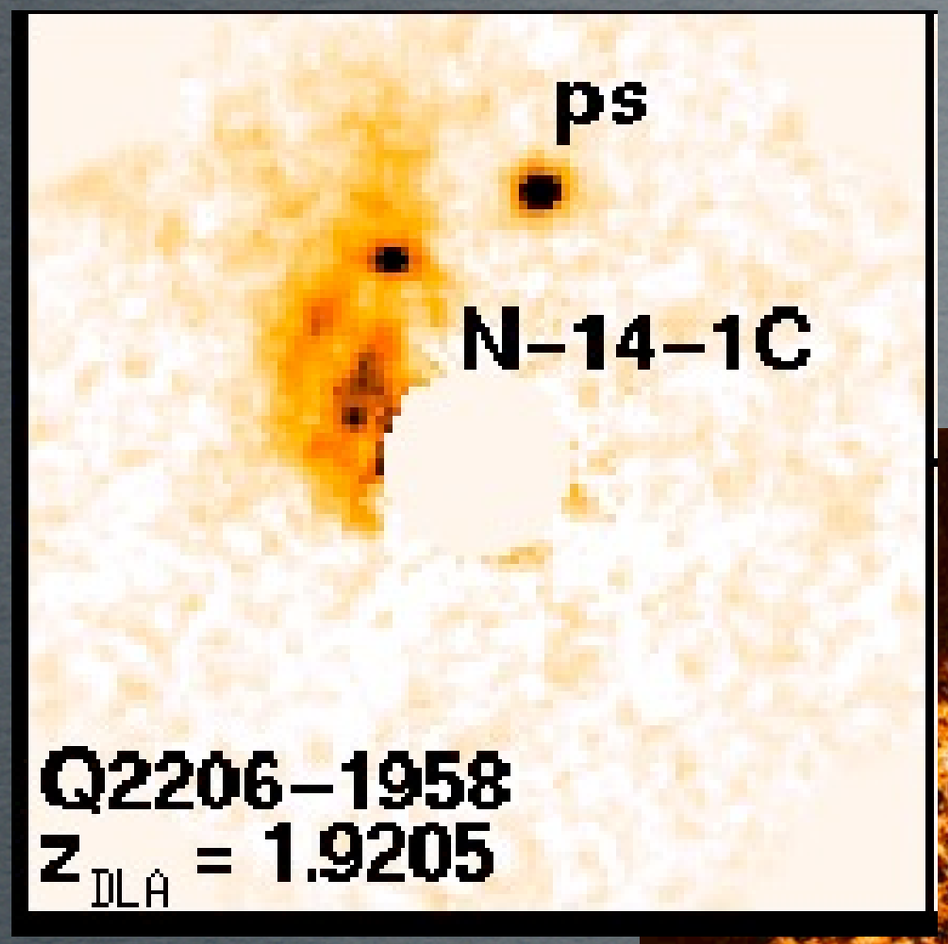


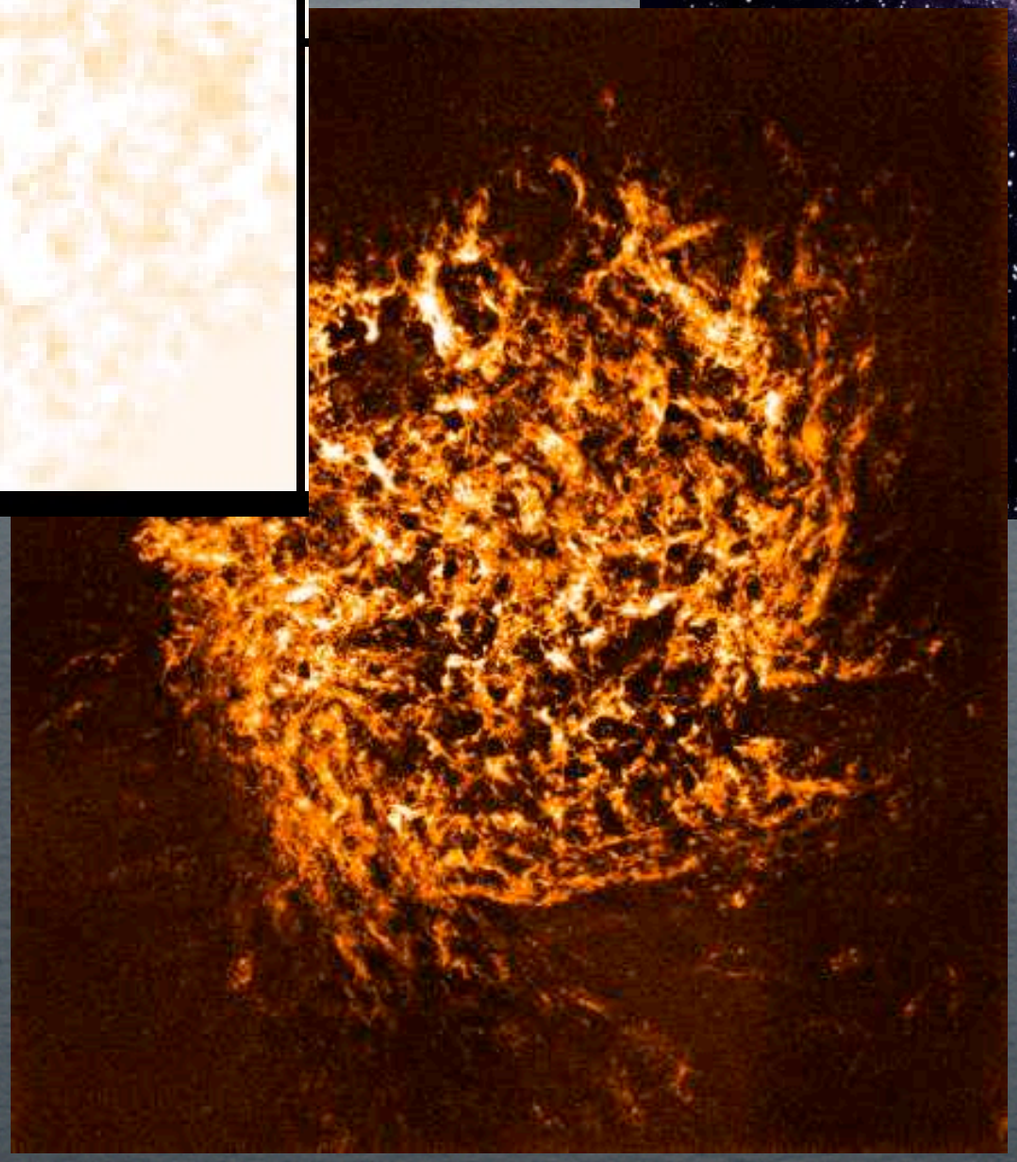
Damped Lyα System

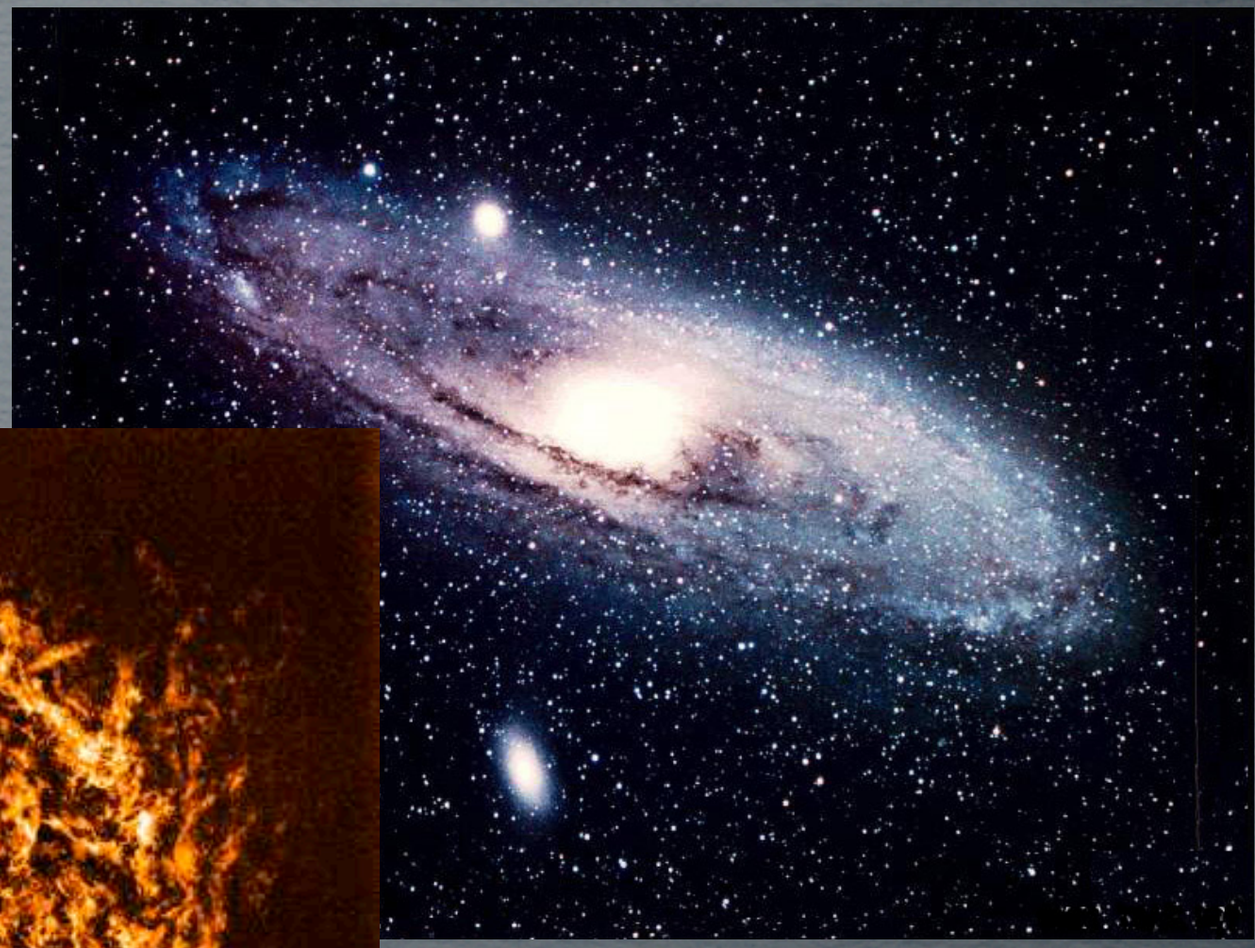


The Godfather

DLA Images

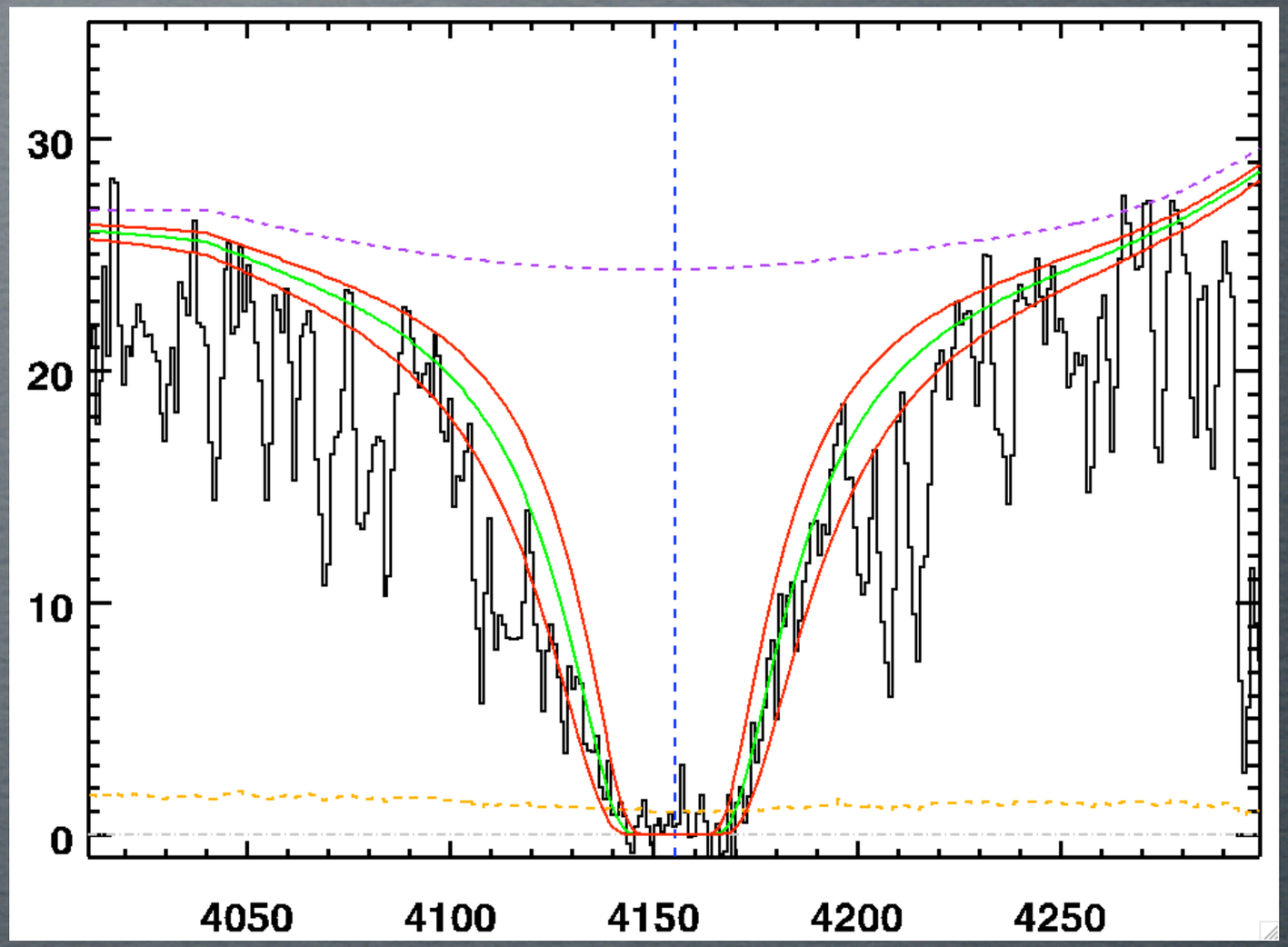






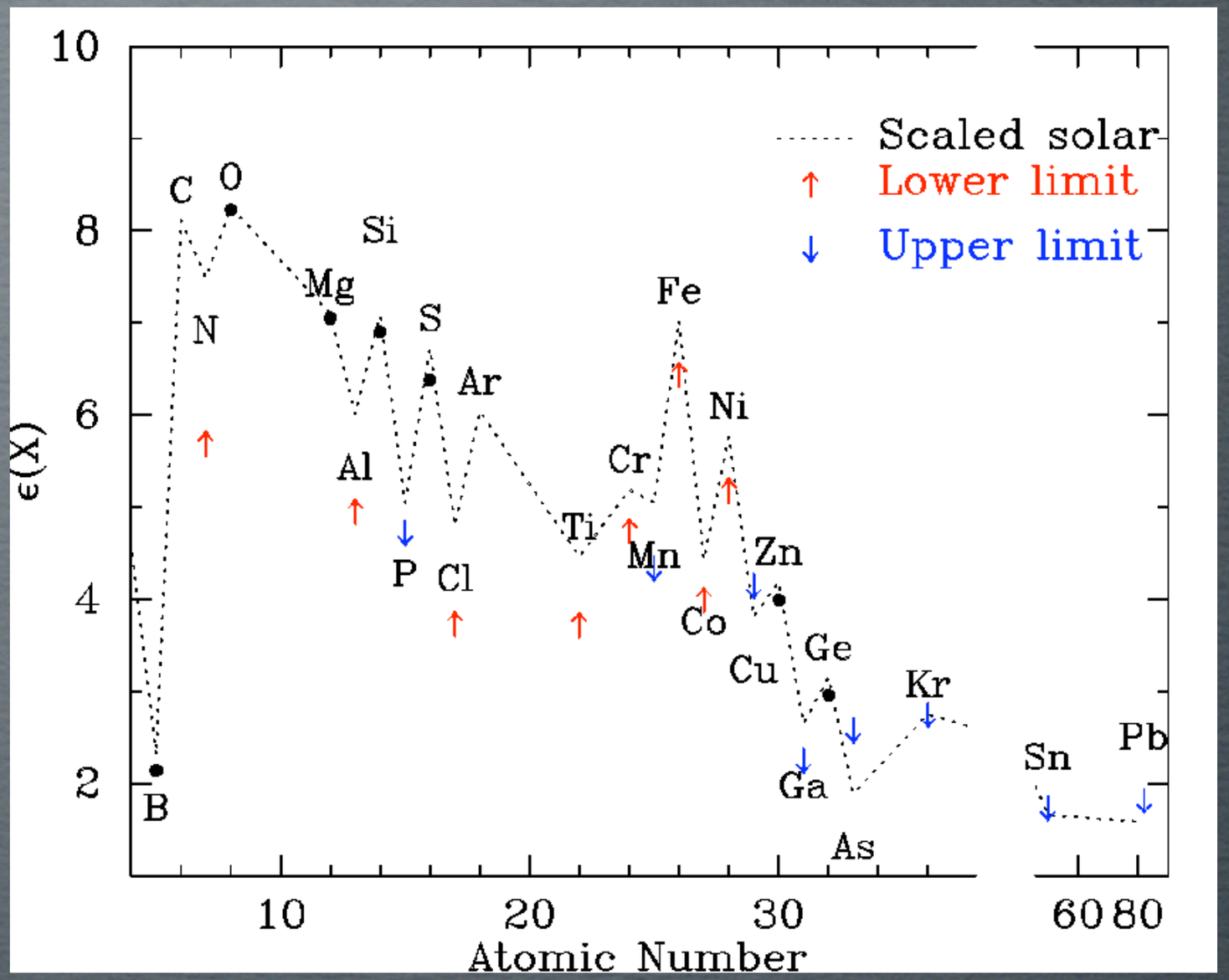
Damped Lyα System Defined

- N(HI) > 2 x 10^{20} cm^{-2}
  - ✦ Dominant reservoir of neutral gas
  - ✦ Large N(HI) => $\delta\rho/\rho >> 100$
  - ✦ Progenitors of modern day galaxies
- Identified in Absorption
  - ✦ Optical depth weighted $\tau \sim n\,\sigma$
  - ✦ Not restricted to the bright end
  - ✦ => Greater diversity of mass, luminosity,



Today's Talk

- Intro
- Quick review of DLA Abundances
  - ✦ Chem evolution
  - ✦ Abundance ratios
  - ✦ Metal strong DLA
- SDSS survey
  - ✦ 500+ DLA
  - ✦ Incidence of gas 'disks'
  - ✦ Mass density of neutral gas



Measuring DLA Abundances

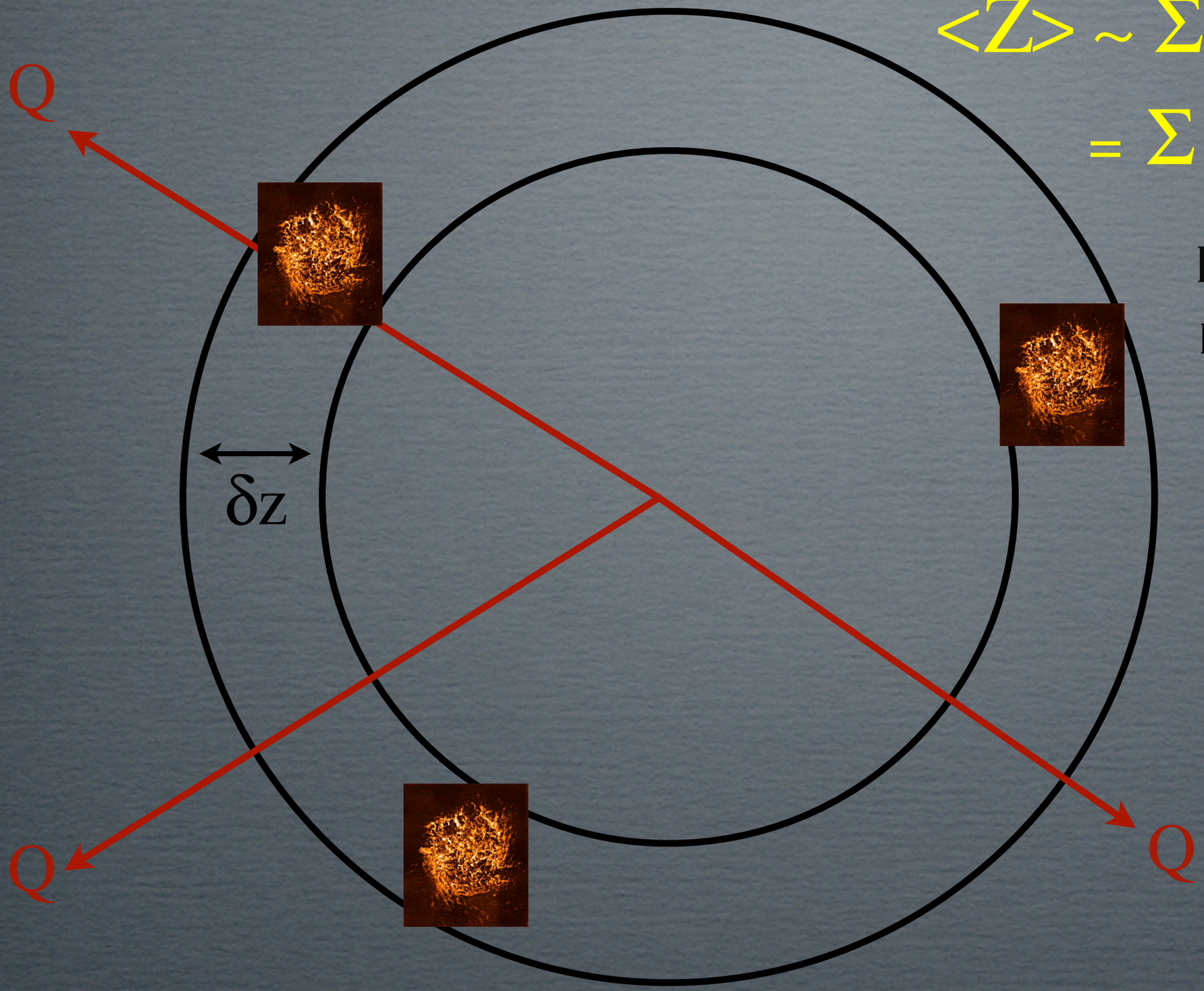
- **Observations**
  - ✦ High resolution
    - ◗ Echelle (HIRES, MIKE, UVES): R > 30000
    - ◗ Echellette (ESI, XSHOOTER?): R~10000
  - ✦ SNR > 20 per pixel
- **Gas-Phase abundances**
- **Dust**
  - ✦ Depletion: Adsorption onto dust grains
  - ✦ Obscuration: Selection bias
- **Ionization**
  - ✦ Generally unimportant
    - ◗ e.g. (Vladilo et al.)
  - ✦ <u>BUT</u>, >10% DLA are significantly ionized
    - ◗ e.g. Q1759 (Prochaska et al. 2001)
    - ◗ e.g. Q0450-13 (Dessauges-Zavadsky et al.)

Cosmological Mean Metallicity

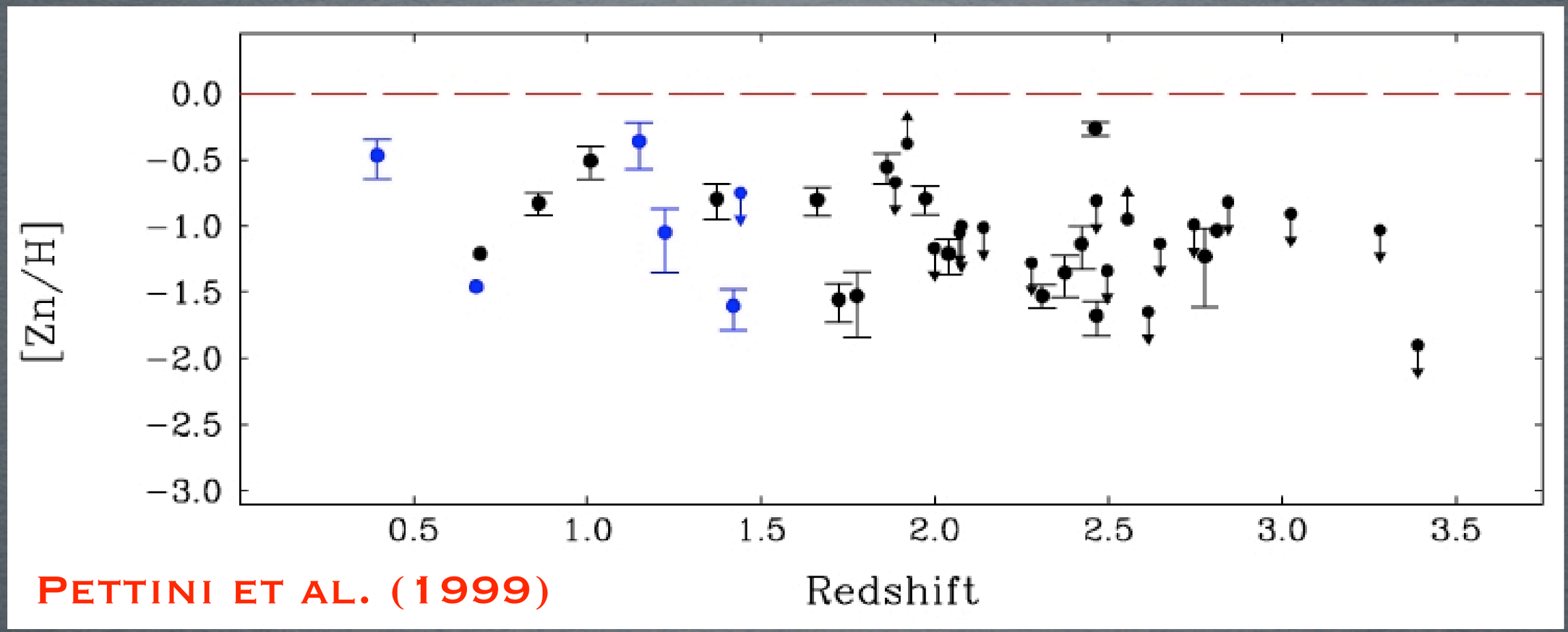
$$\langle Z \rangle \sim \Sigma\,(\mathrm{mtl}) / \Sigma(\mathrm{gas})$$

$$= \Sigma\, N(M) / \Sigma\, N_{HI}$$

Restricted to neutral gas!!



Chem Evolution (1999)

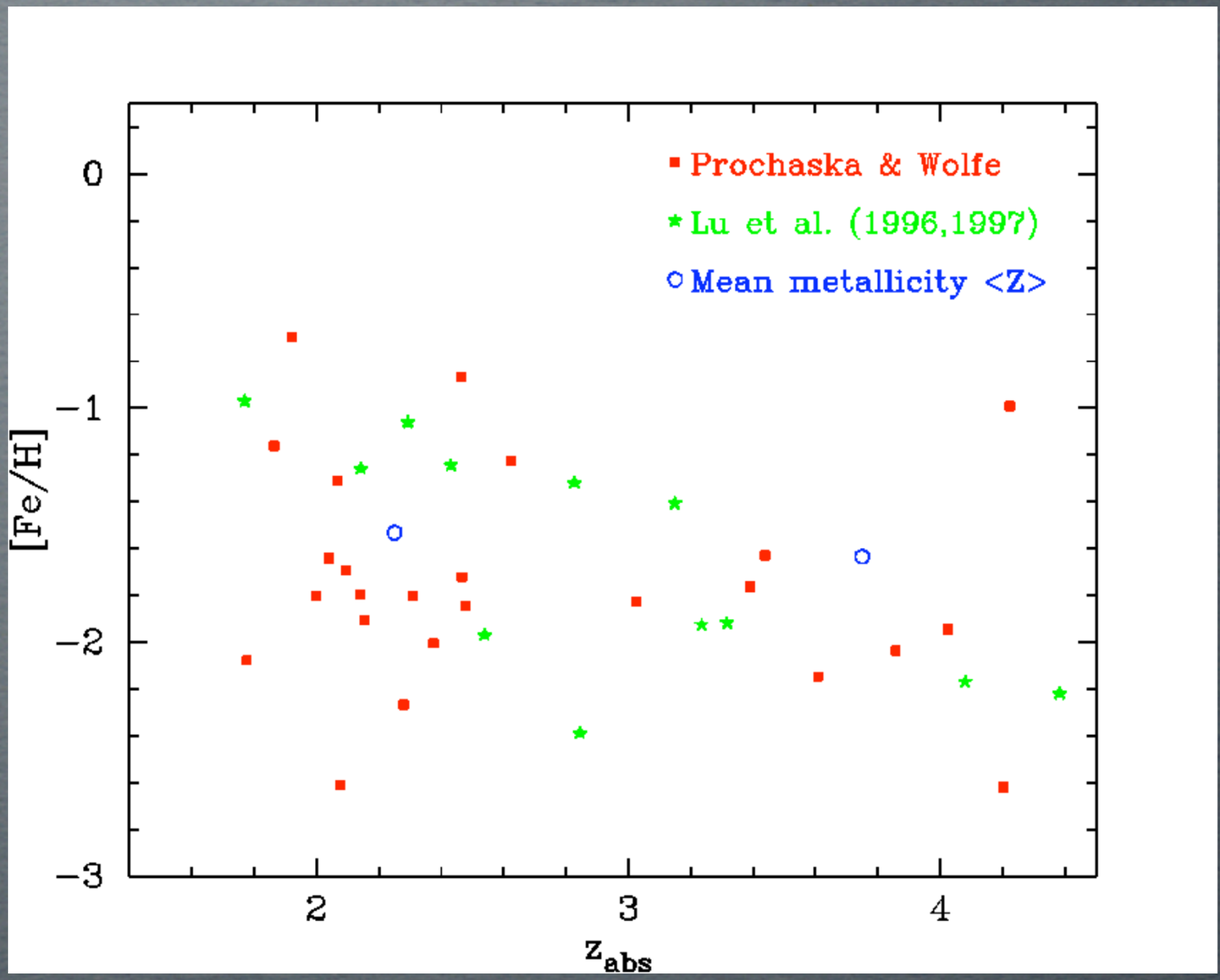


Pettini et al. (1999)

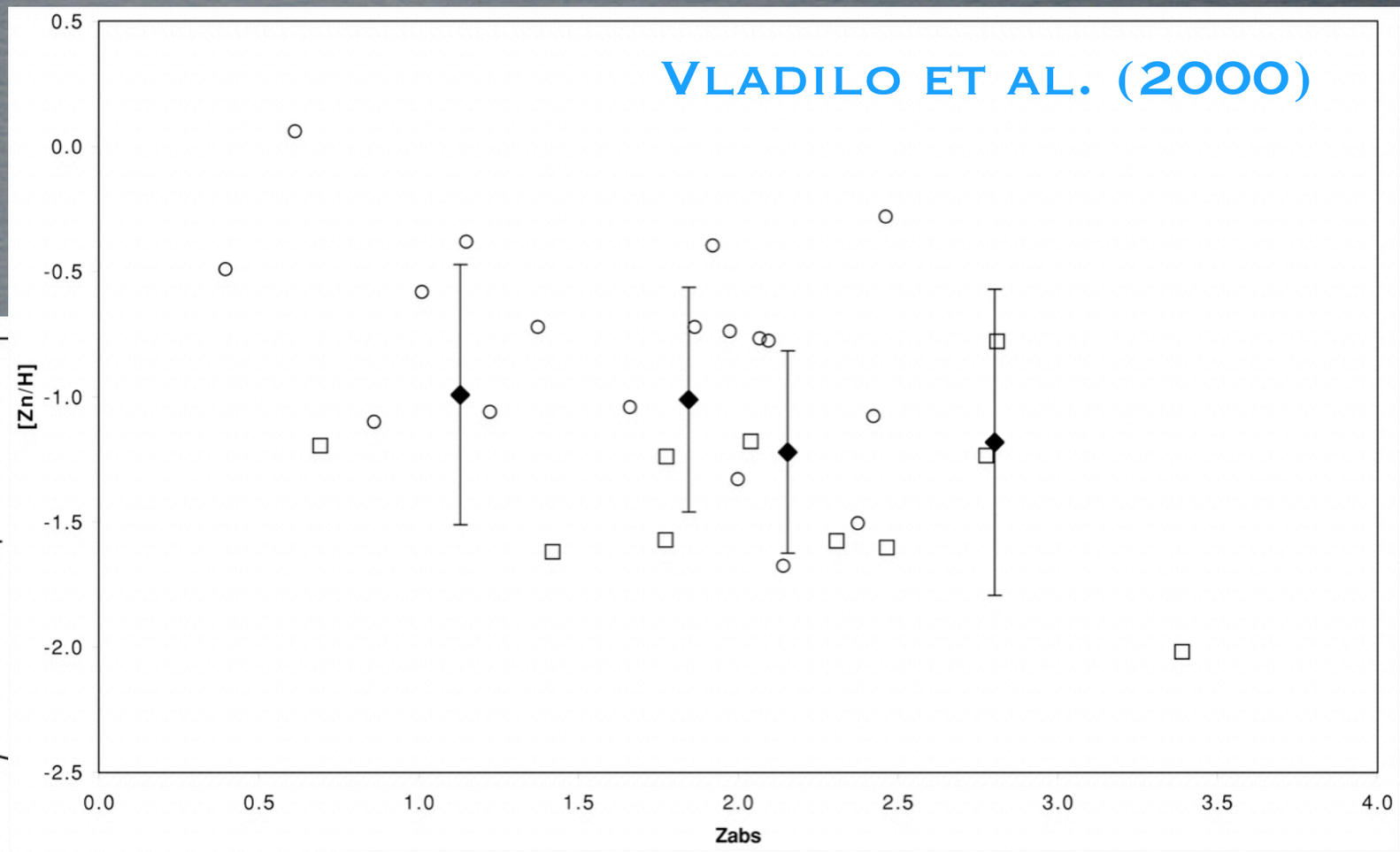
- Primarily 4m class
  - Restricted to Zn
  - Many upper limits
- N=18 detections
  - <Z> ~ -1
  - Large scatter
- Evolution at z>1 ??

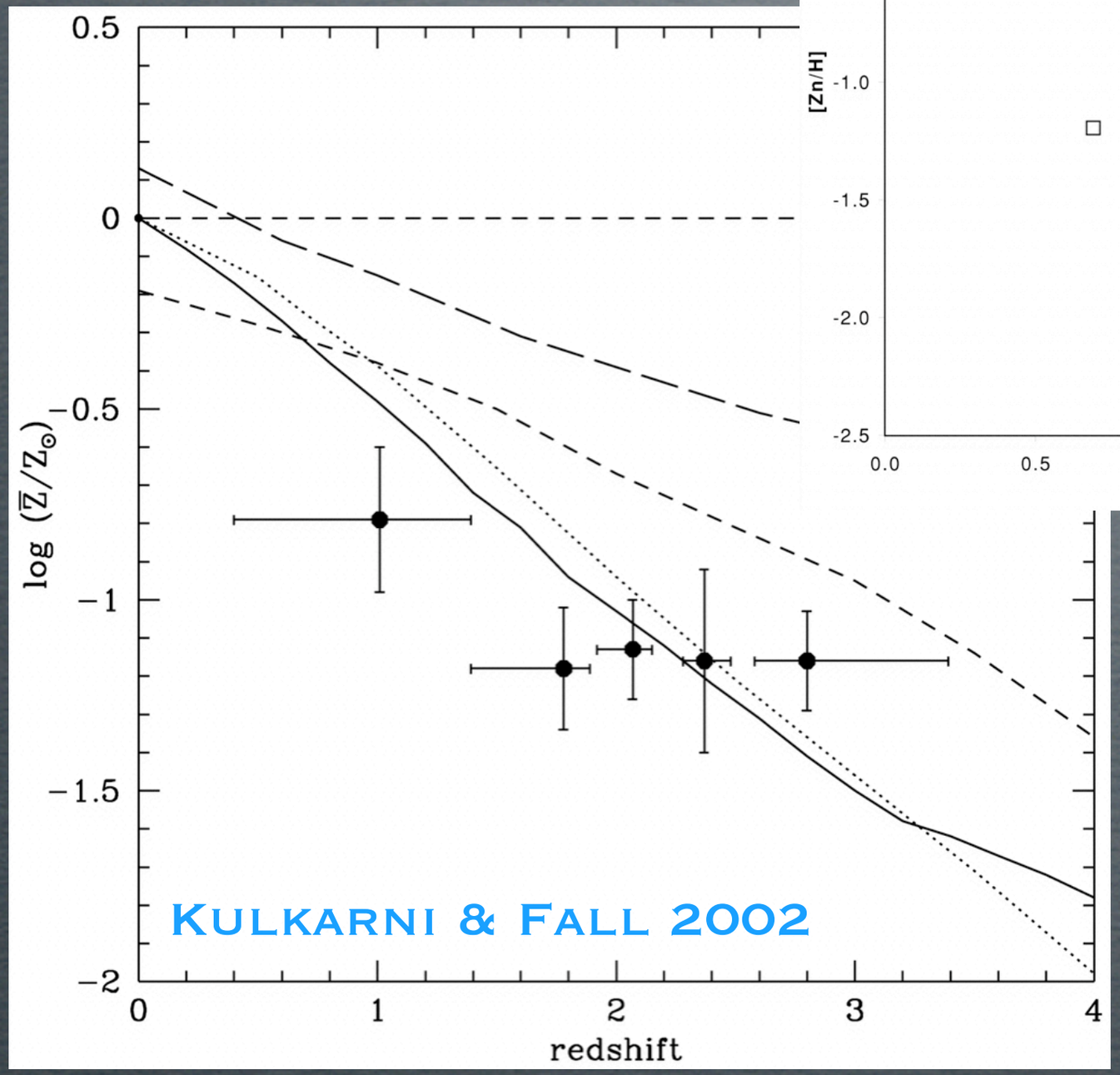
Chem Evolution (2000)

- Keck/HIRES
  - [Fe/H] measurements
  - High precision
- Results
  - Low metallicity
    - Consistent with [Zn/H]
  - No statistically significant evolution
  - Floor to [Fe/H] at -3



Chem Evol (2000-2)



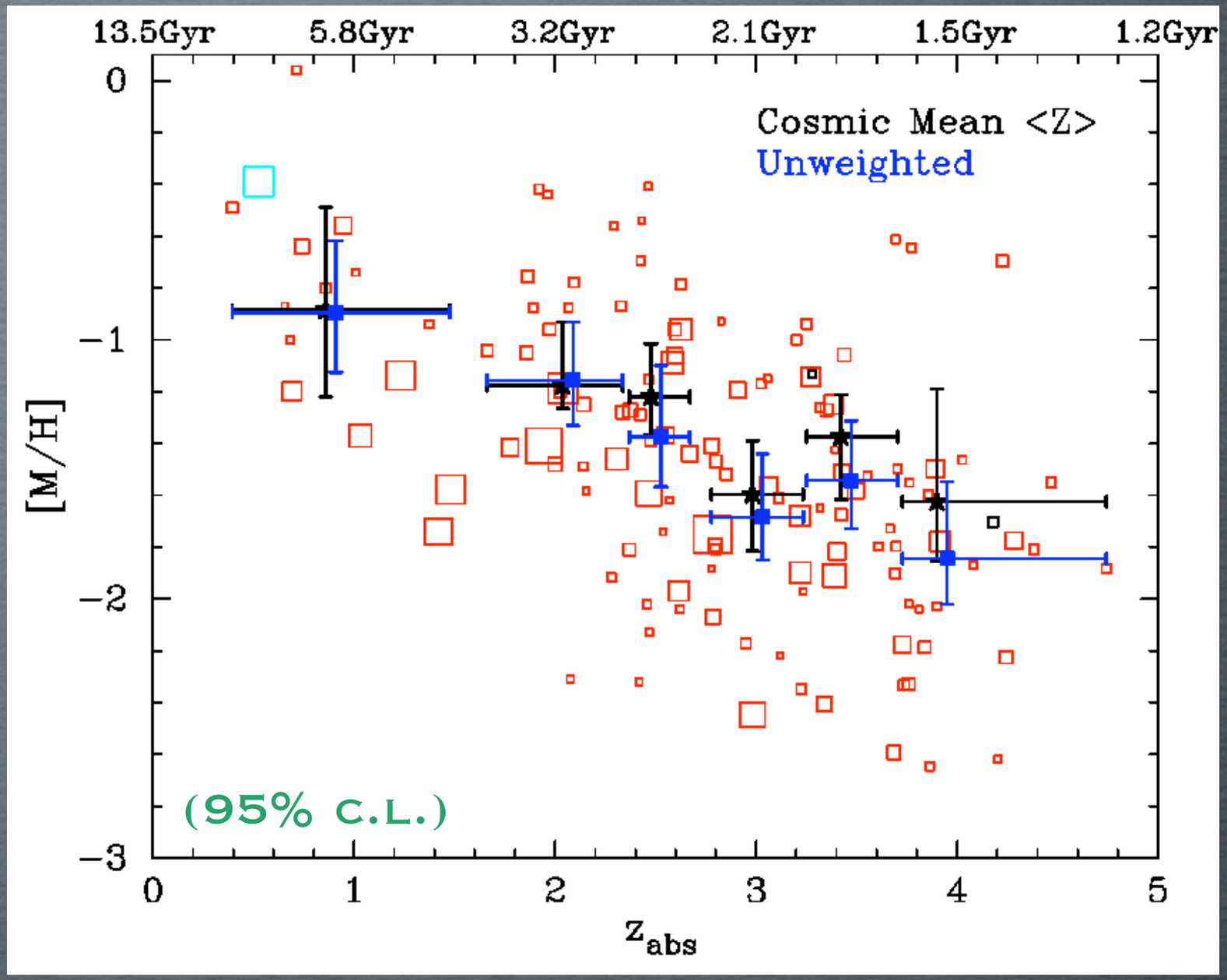


Claims for evolution

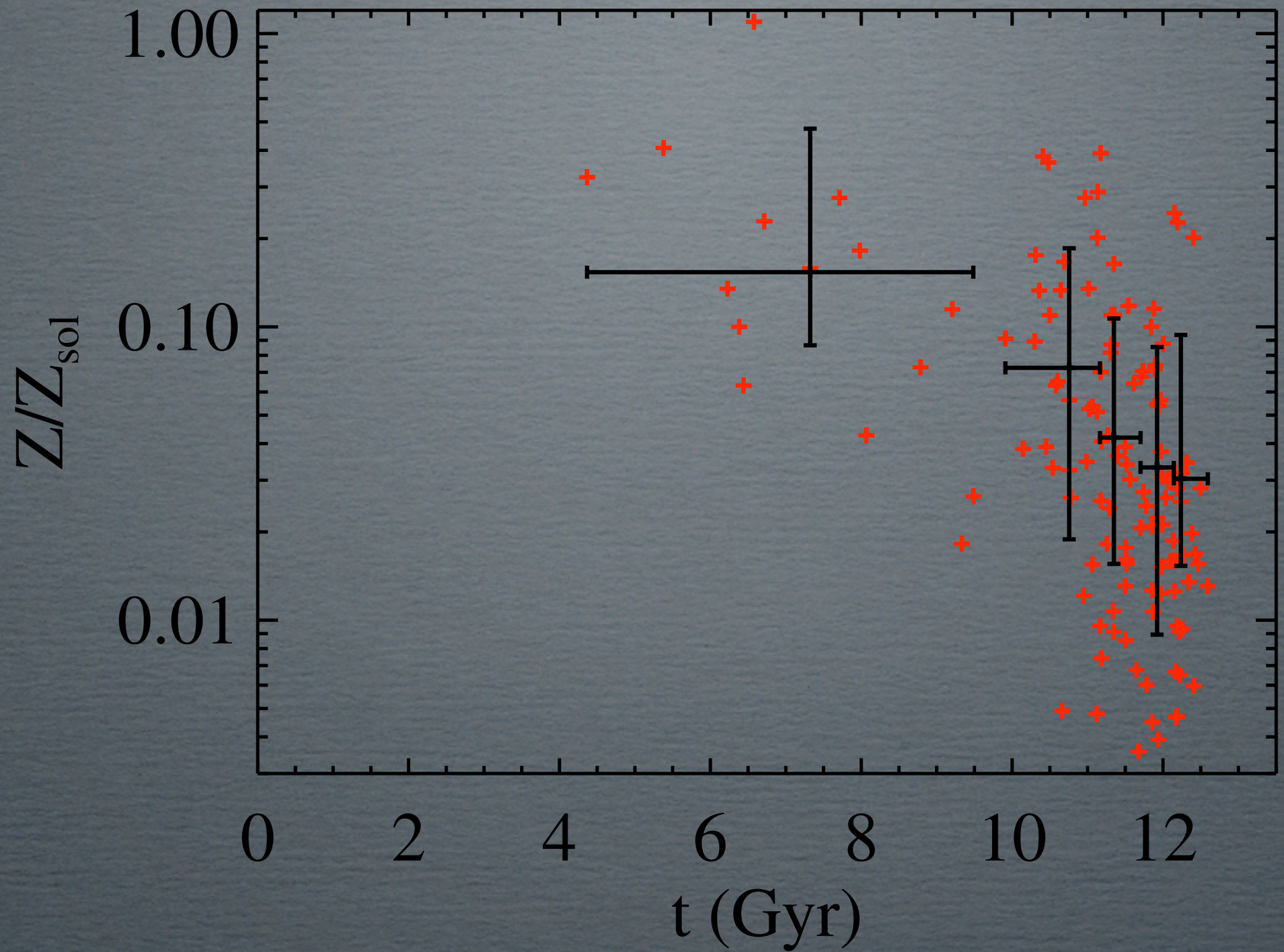
ESI + Keck Telescope

Chem Evol (Today)

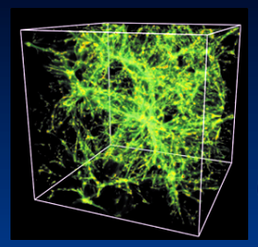
- >120 DLA
  - Evolution in both unweighted and <Z>
  - -0.26 dex per Δz
  - About 2x per Gyr
- Scatter
  - Roughly constant with z
  - Uniform population?
- Metallicity floor
  - [M/H] > -2.6
  - DLA are linked to current or recent SF



Chem Evolution (Time)



Next UV Frontier



The Baryonic Structure Probe

Characterizing the Cosmic Web of Matter Through Ultraviolet Spectroscopy

Mission Objective:
Detect, map, and characterize the cosmic web, its inflow into galaxies, and its enrichment with the products of stellar and galactic evolution

Origins Concept Study Goals:

- Define absorption and emission properties of the WHIM through numerical simulations
- Develop a mission concept capable of testing these predictions in detail
- Design a roadmap for investments in enabling technologies

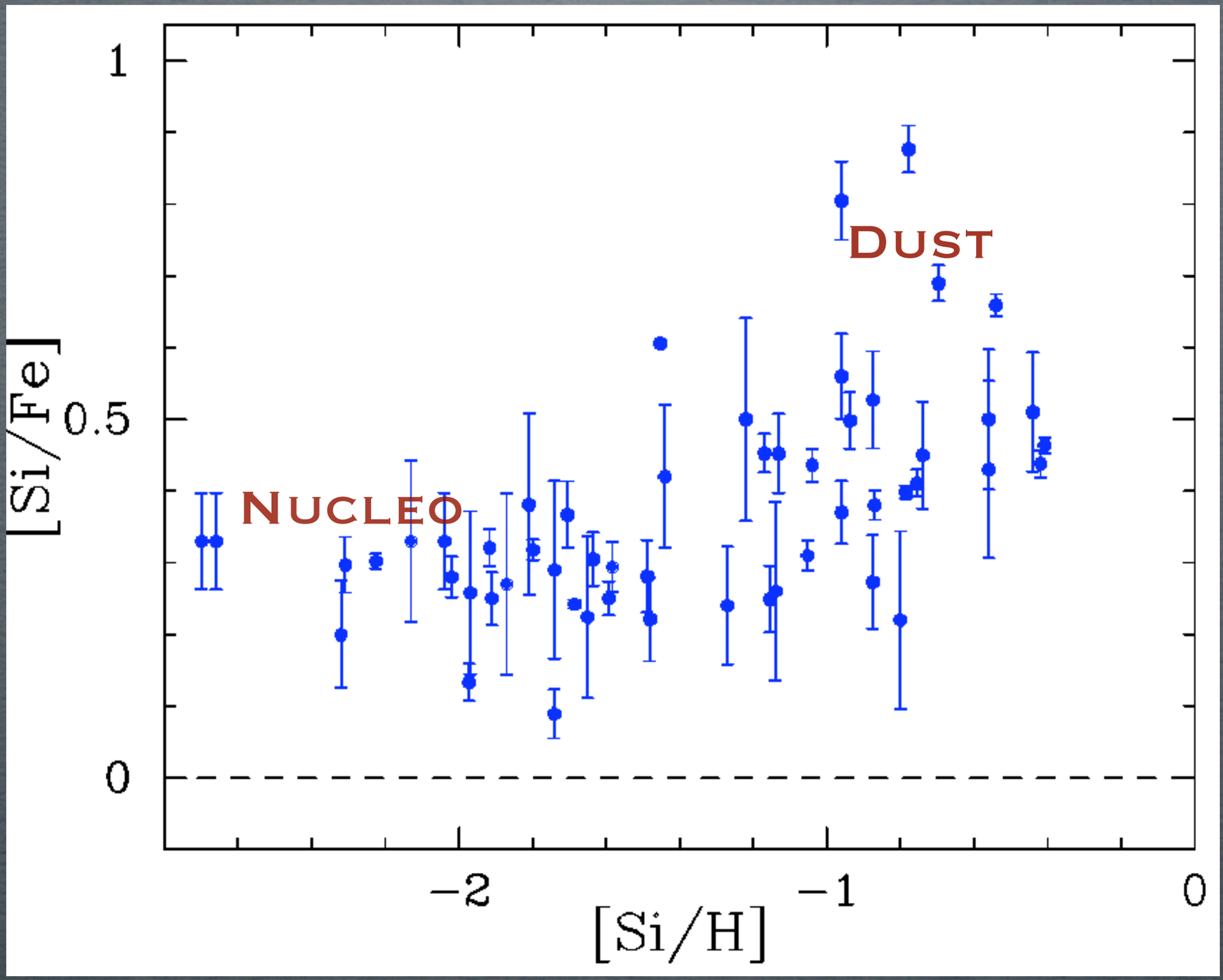
High-Throughput Spectroscopy:
Point source *and* spectral imaging
$\lambda \sim 1000 - 3000$ Å
$R \geq 30{,}000$ (absorption), $R \geq 3000$ (emission)
Spectral imaging over ~ 30-60 arcmin FOV

Concept Study Team

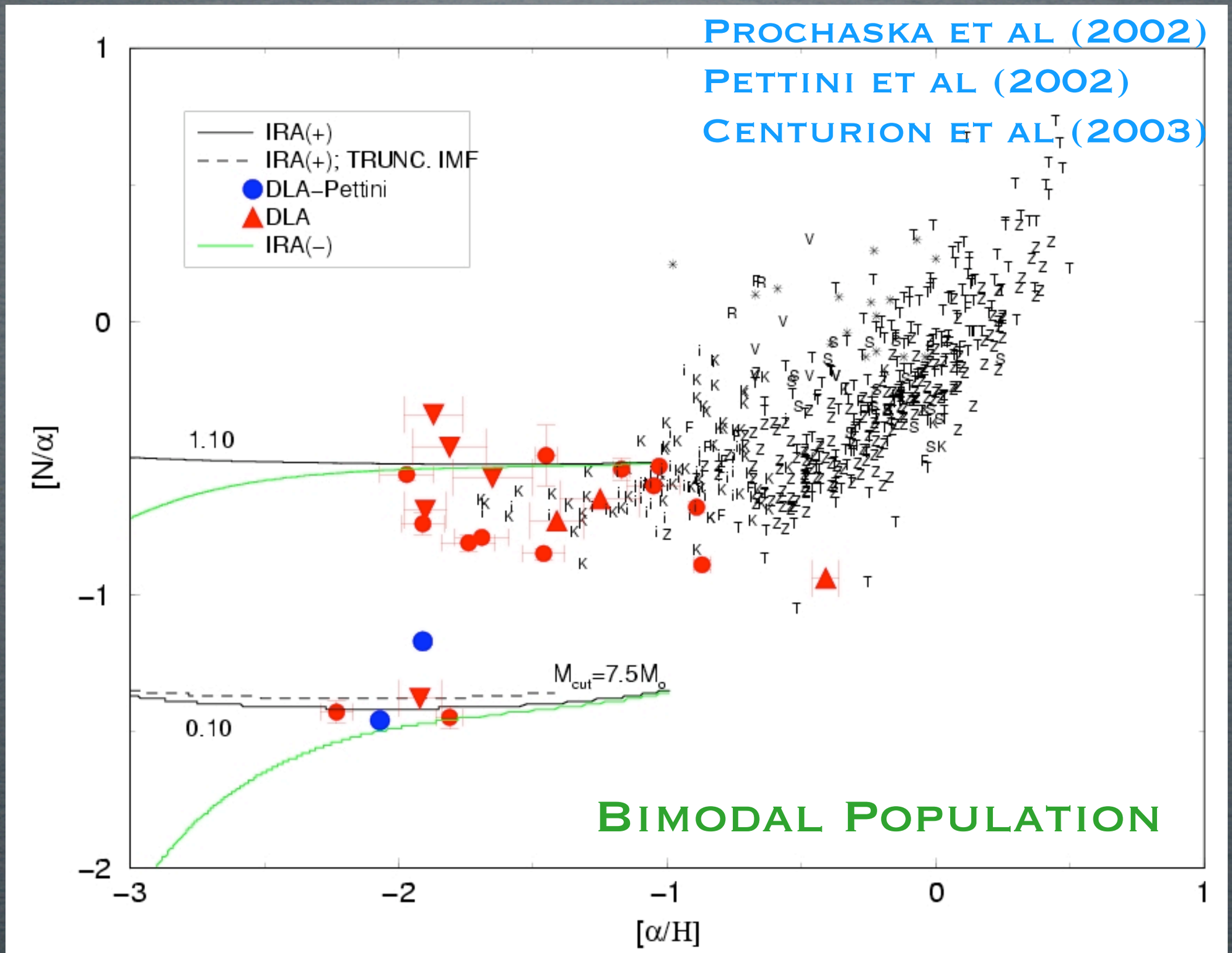
Renyue Cen	Princeton U.
Timothy Cook	Boston U.
Romeel Davé	U. Arizona
Megan Donahue	Mich. State U.
Dennis Ebbets	BATC
James Green	U. Colorado
Edward B. Jenkins	Princeton U.
William R. Oegerle	NASA/GSFC
Jeremiah P. Ostriker	Princeton U.
Jason X. Prochaska	U.C. Santa Cruz
Blair D. Savage	U. Wisconsin
Kenneth R. Sembach (PI)	STScI
J. Michael Shull	U. Colorado
H. Philip Stahl	NASA/MSFC
Todd M. Tripp	U. Mass.

Baryon: a heavy subatomic particle composed of three quarks (examples: protons, neutrons)

Relative Abundances

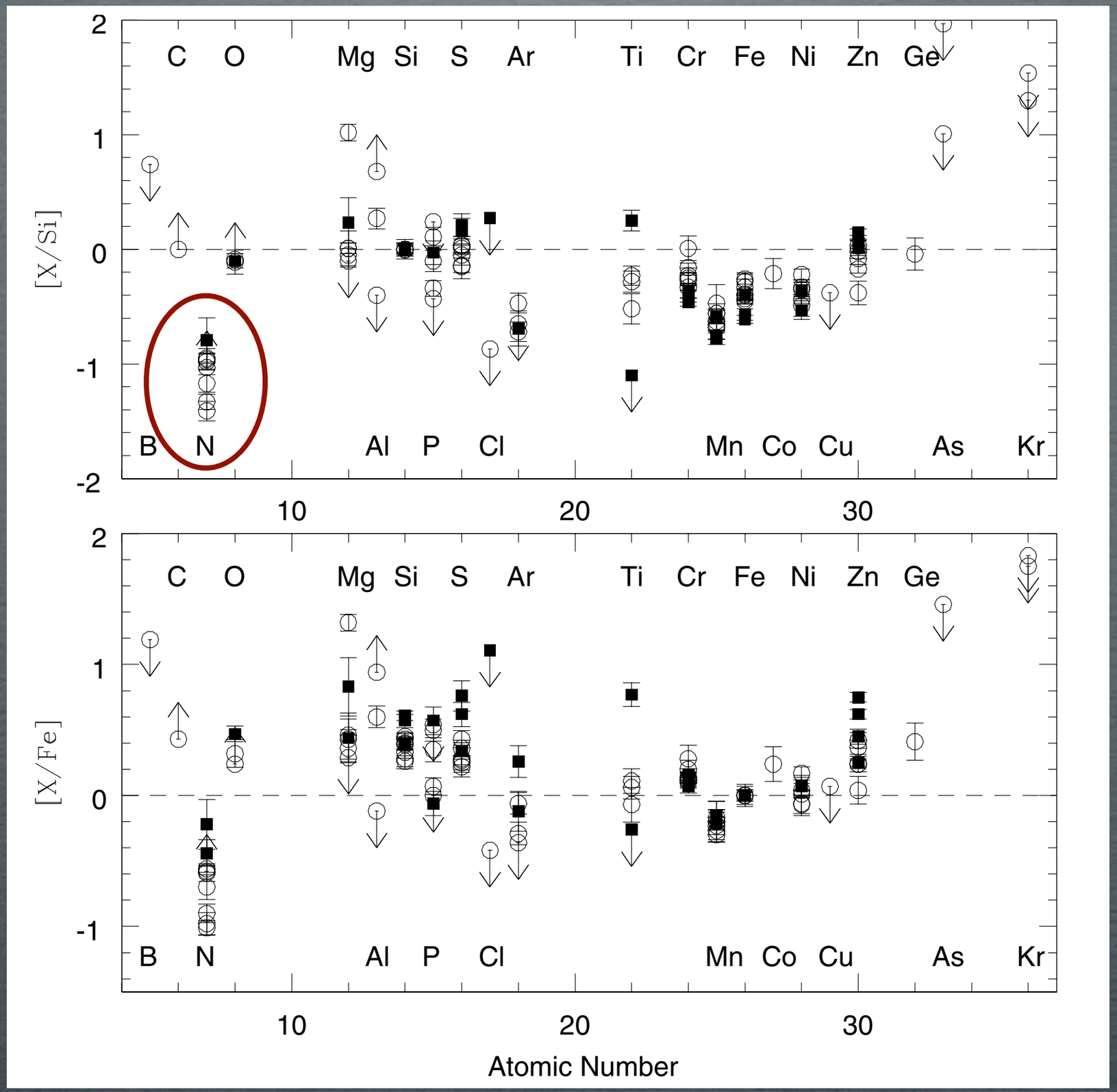


Nitrogen in the DLA



Uniformity

Dessauges-Zavadsky et al. (2005)

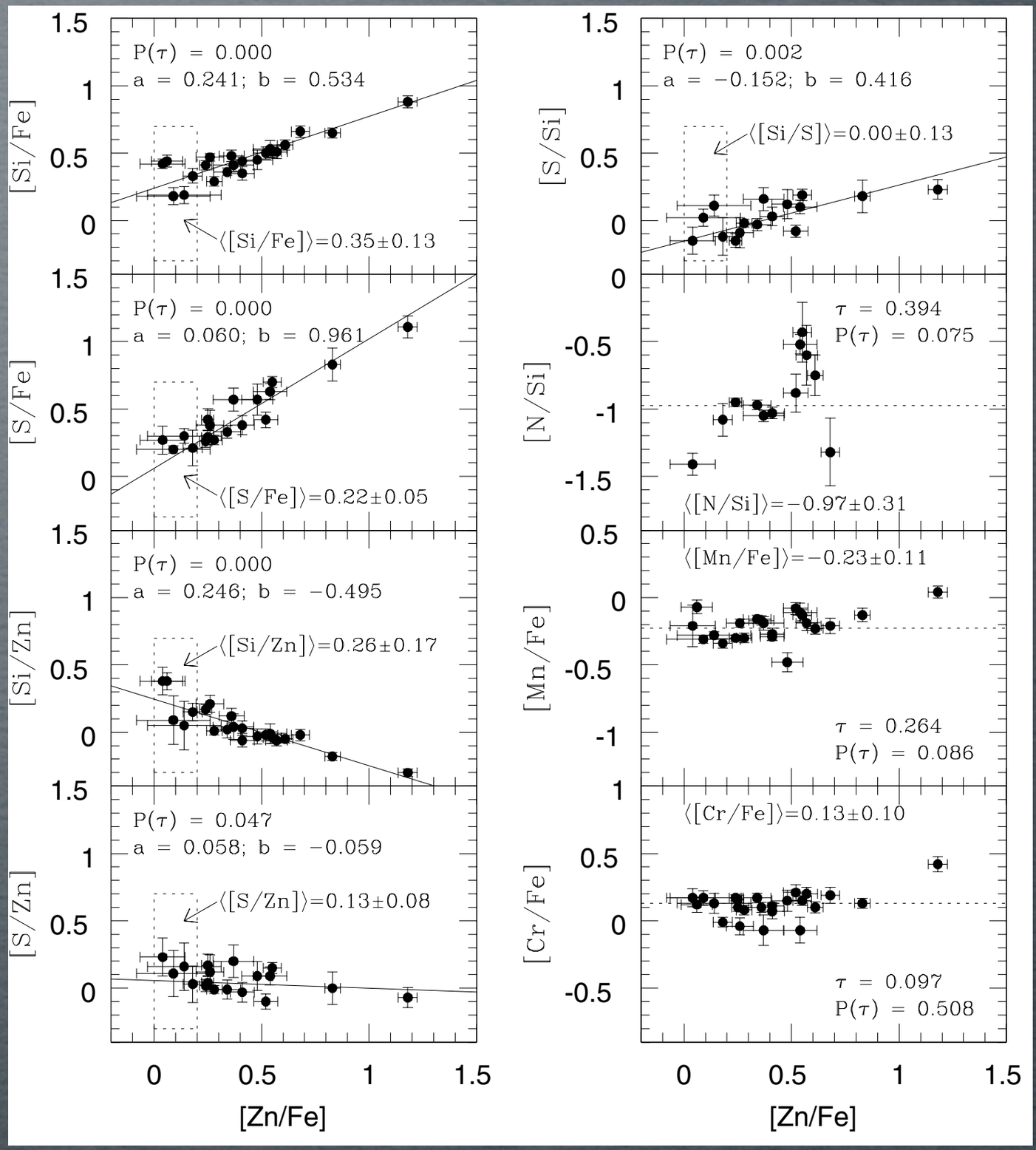


Nucleosynthesis

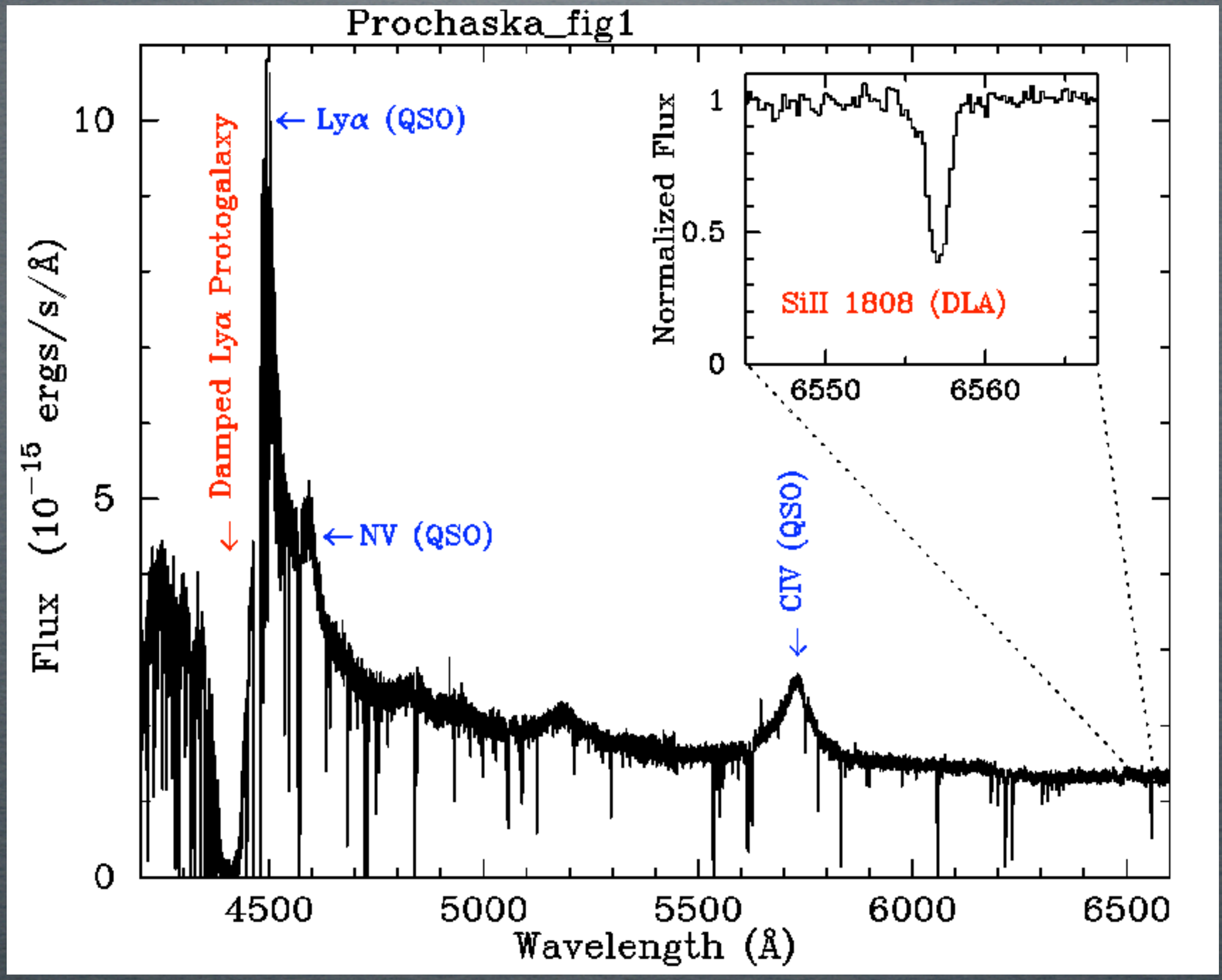
- Minimize dust effects
  - Focus on DLA with low [Zn/Fe]
  - Measure abundances
- Results (~5 DLA)
  - [Si/Fe] ~ +0.25
  - [S/Fe] ~ +0.2
  - [Si/Zn] ~ +0.25
  - [S/Zn] ~ +0.13
  - [Si/S] ~ 0.0

See also papers by Hou et al

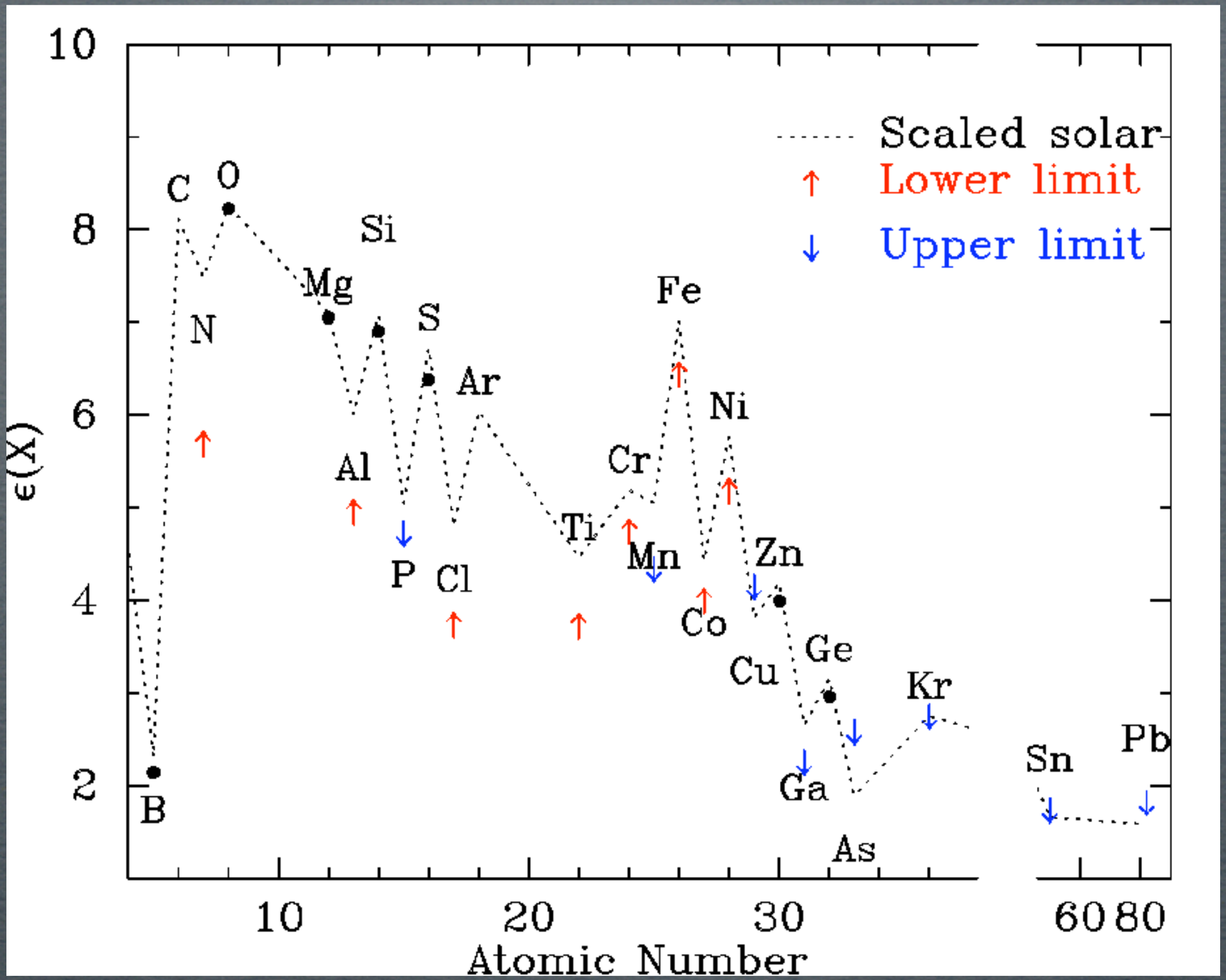
Dessauges-Zavadsky et al. (2005)



Metal-Strong DLA



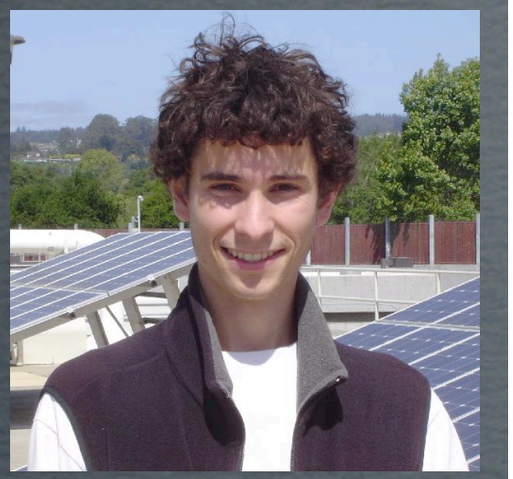
Metal-strong pattern



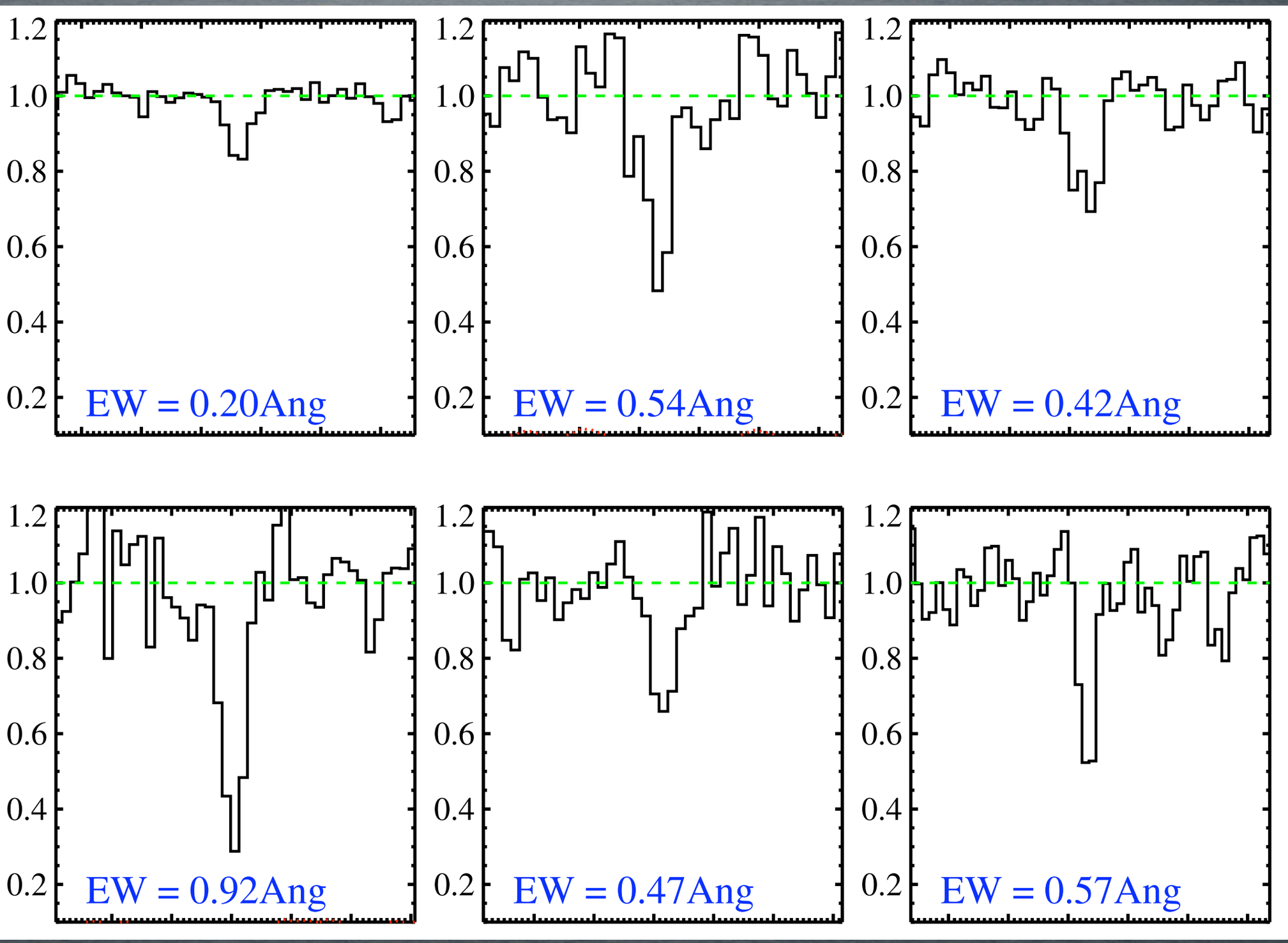
Prochaska, Howk, & Wolfe (2003)

Mining the SDSS

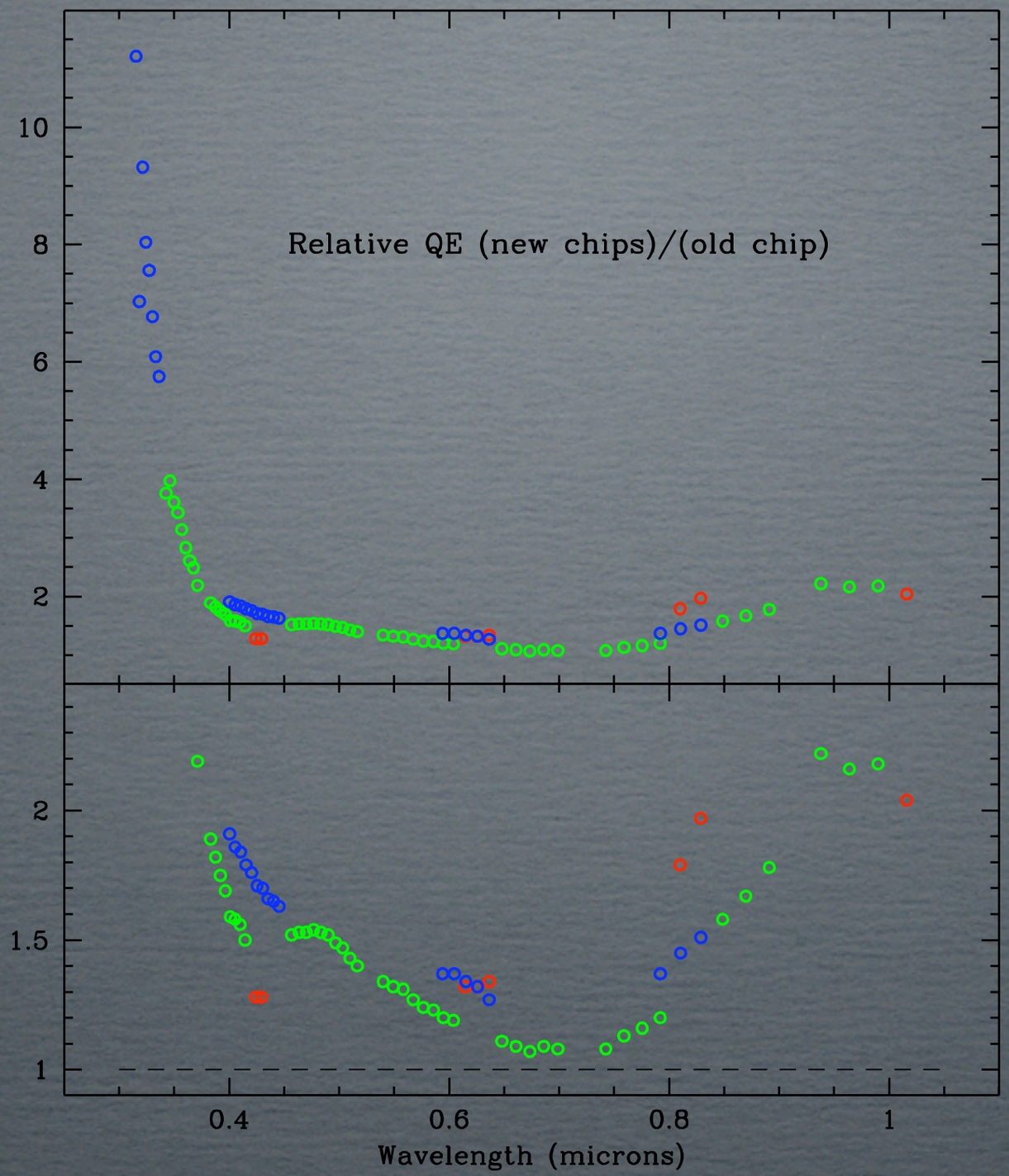
SiII 1808 Profiles



Stéphane Herbert-Fort



HIRES Upgrade



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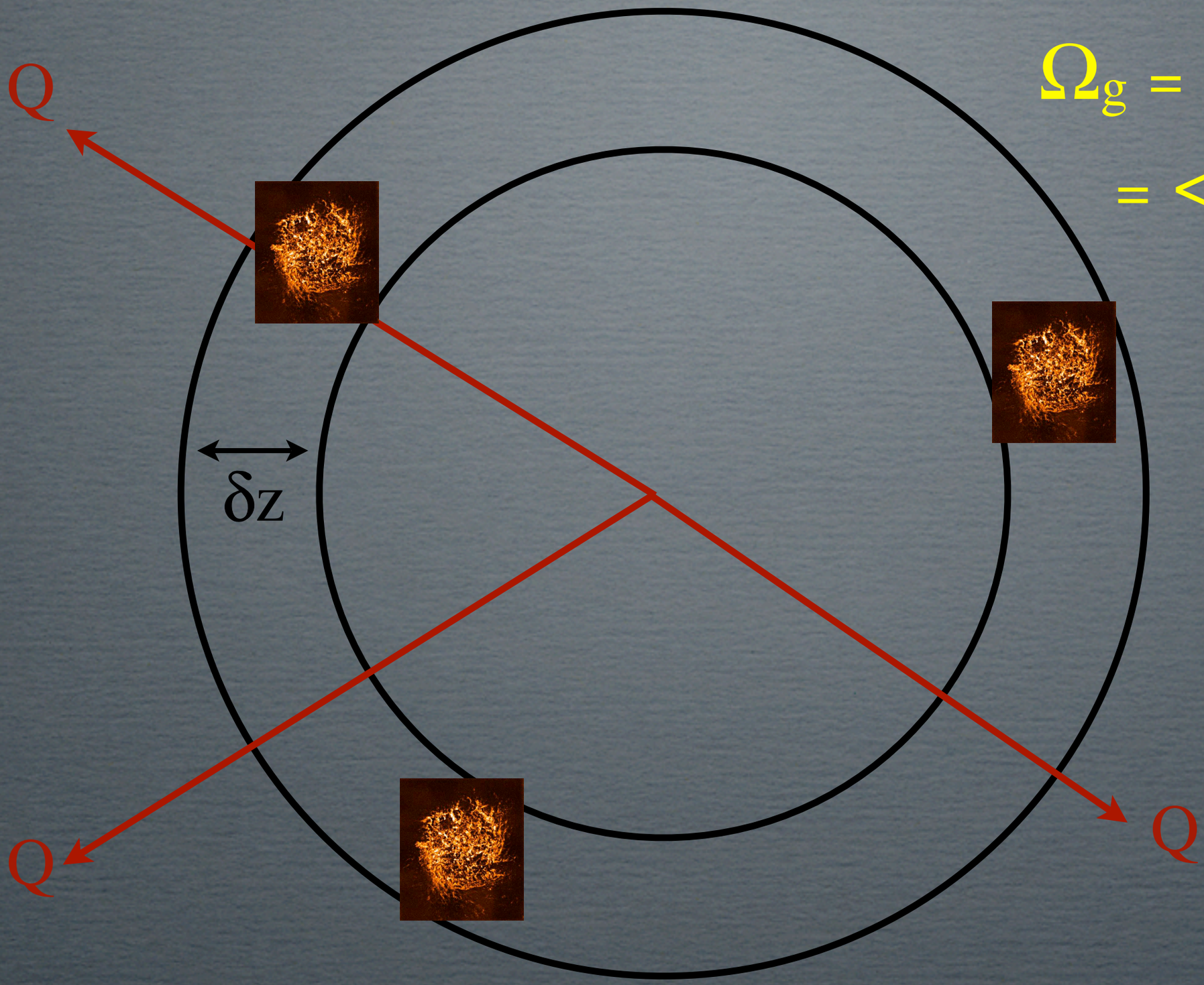
  - ✦ 500+ DLA
  - ✦ Incidence of gas 'disks'
  - ✦ Mass density of neutral gas

Submitted to ApJ

Gas Mass Density

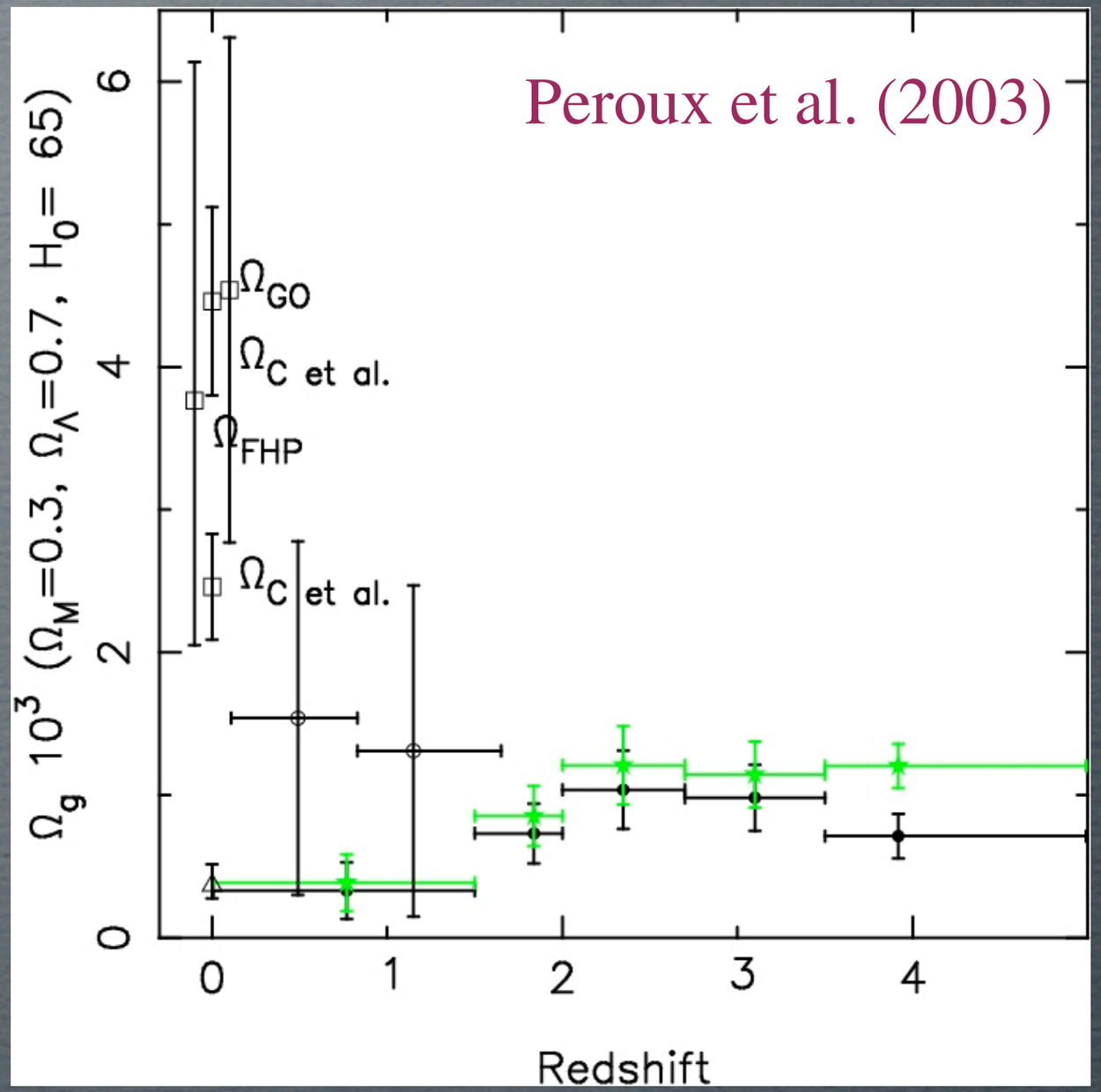


$$\Omega_g = \Sigma\,(\text{gas}) / V$$

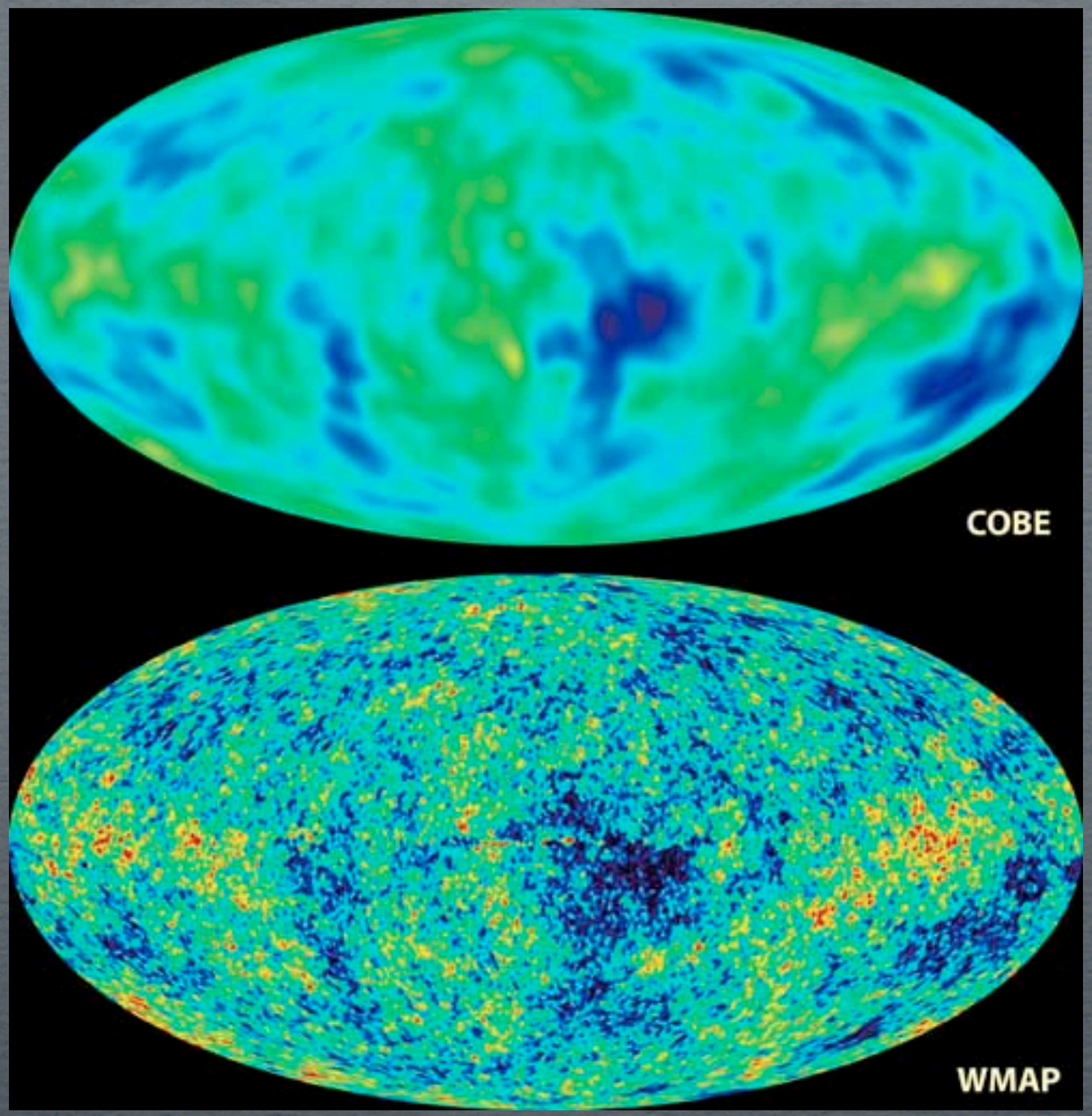
$$= \langle N \rangle / \delta z$$

Ω_g circa 2003

- Observations
  - 4m class telescopes
  - Heterogeneous surveys
  - >5 observers
- Sample
  - ~100 DLA with z>2
- Results
  - Ω_g shows little evolution
    - Decline at z>3?
  - Error bars are >30%
  - Systematics??



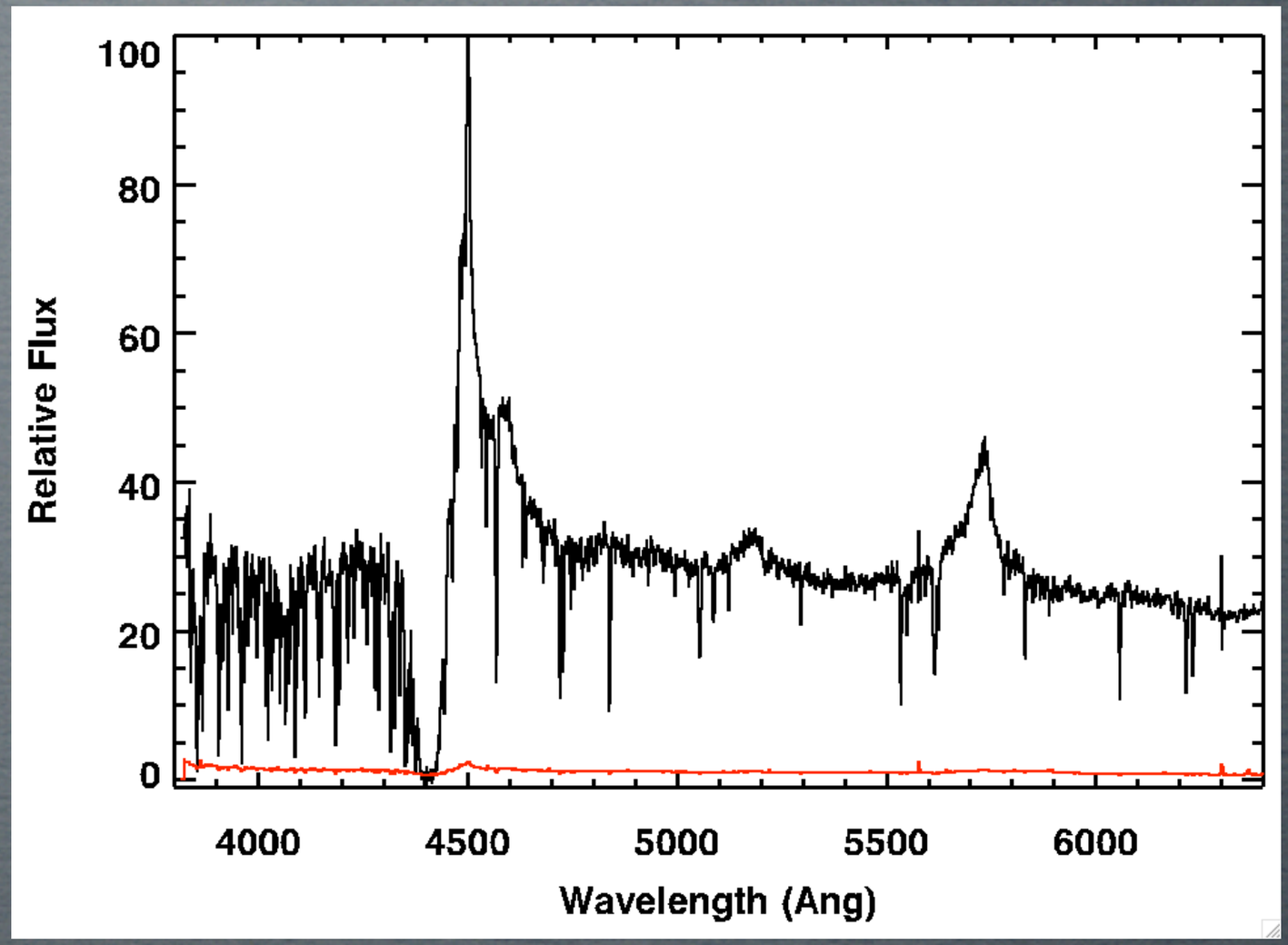
‘Precision’ Cosmology?



30% Errors are no longer acceptable!!

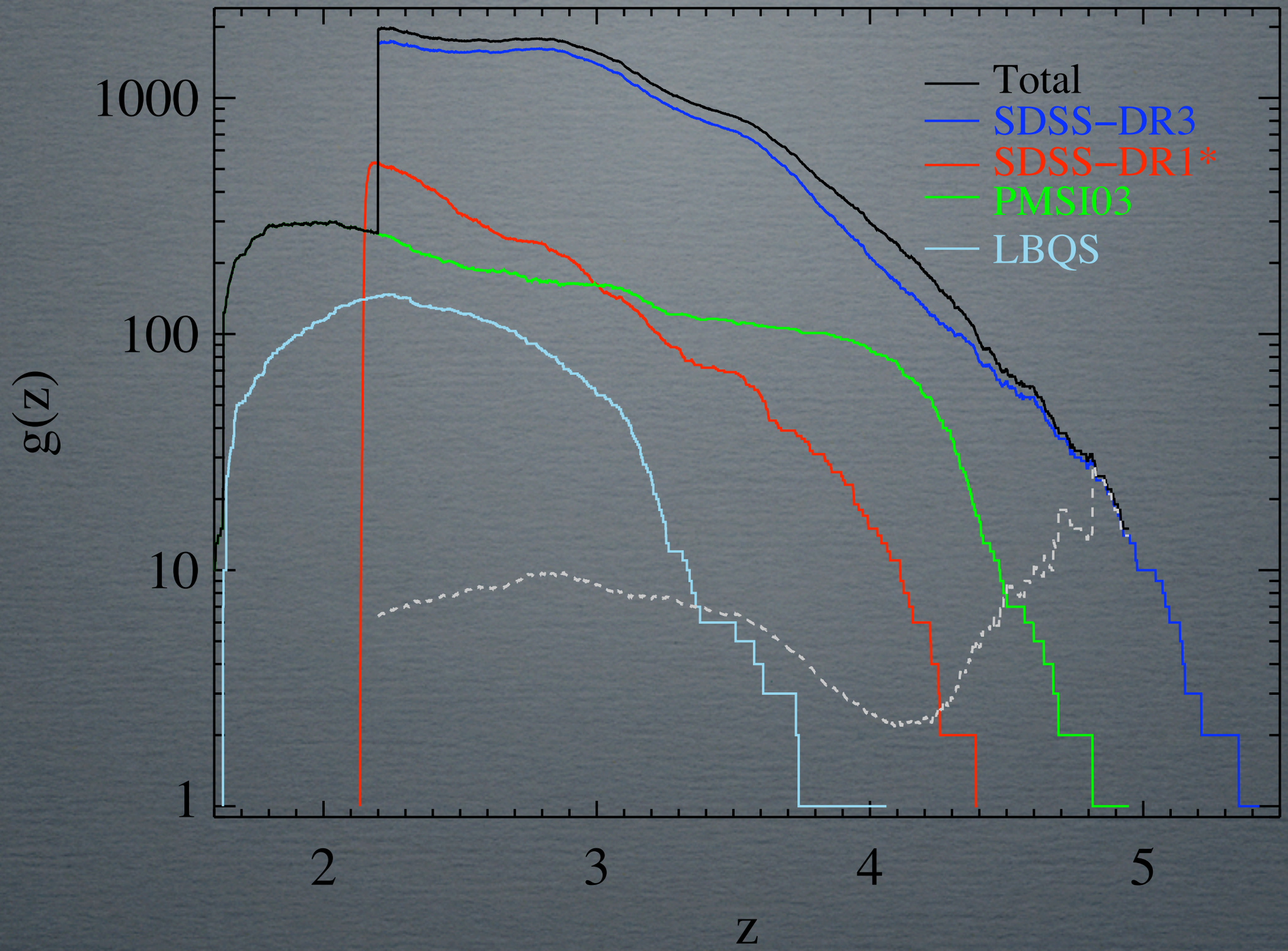
SDSS Database

- SDSS spectra
  - R~2000
  - λ = 3800 -- 9200 Ang
- Quasar sample
  - Color selected
  - Complete to i^* = 19.5
  - DR3: over 40000
  - z>2: 8000 quasars
- Auto DLA search
  - Simple algorithm
  - Visual verification
  - Careful Lyα analysis

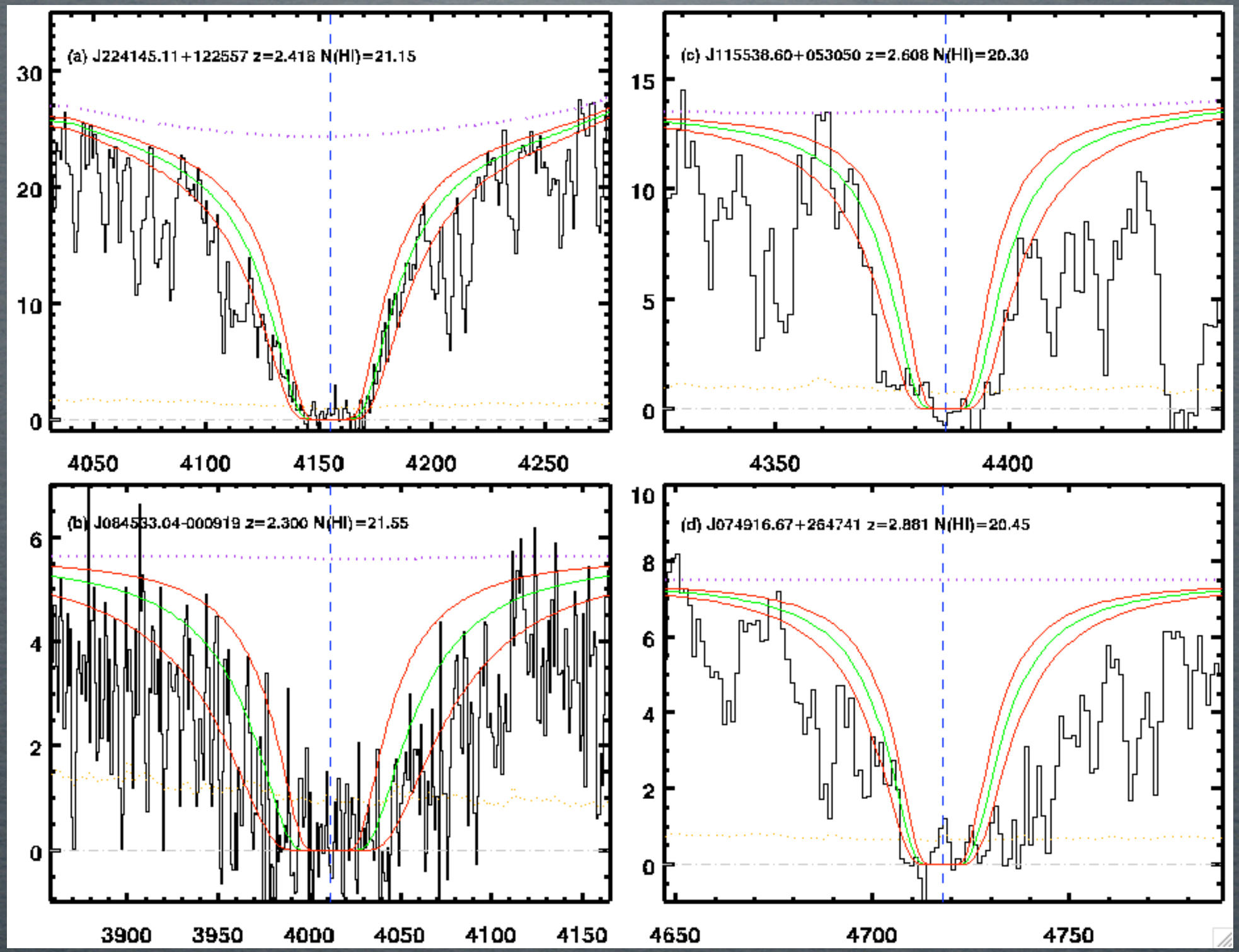


Prochaska & Herbert-Fort (2004)

Sensitivity Function

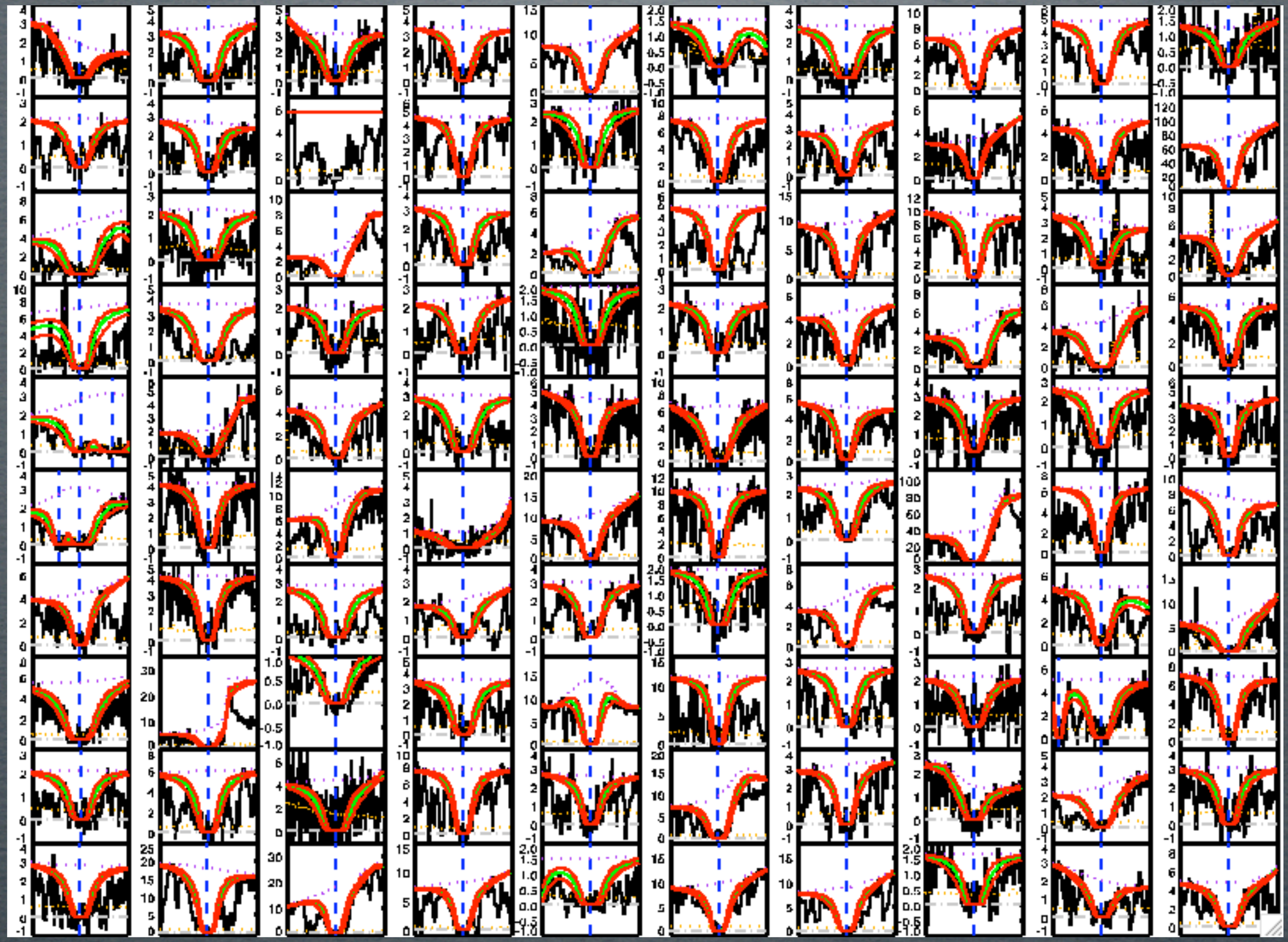


Example Lyα Fits



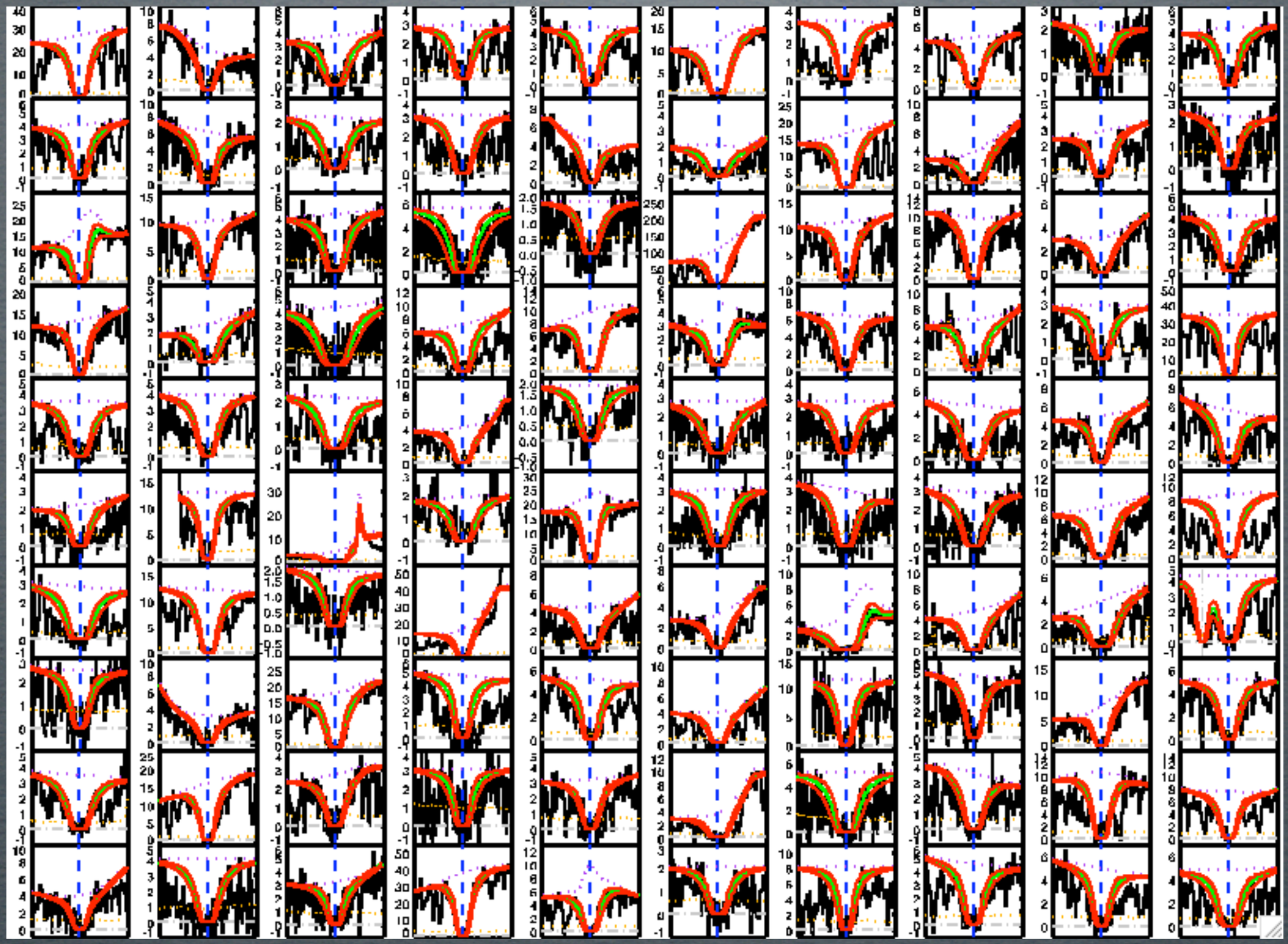
The fits...

1-100



The fits...

101-200



The fits...

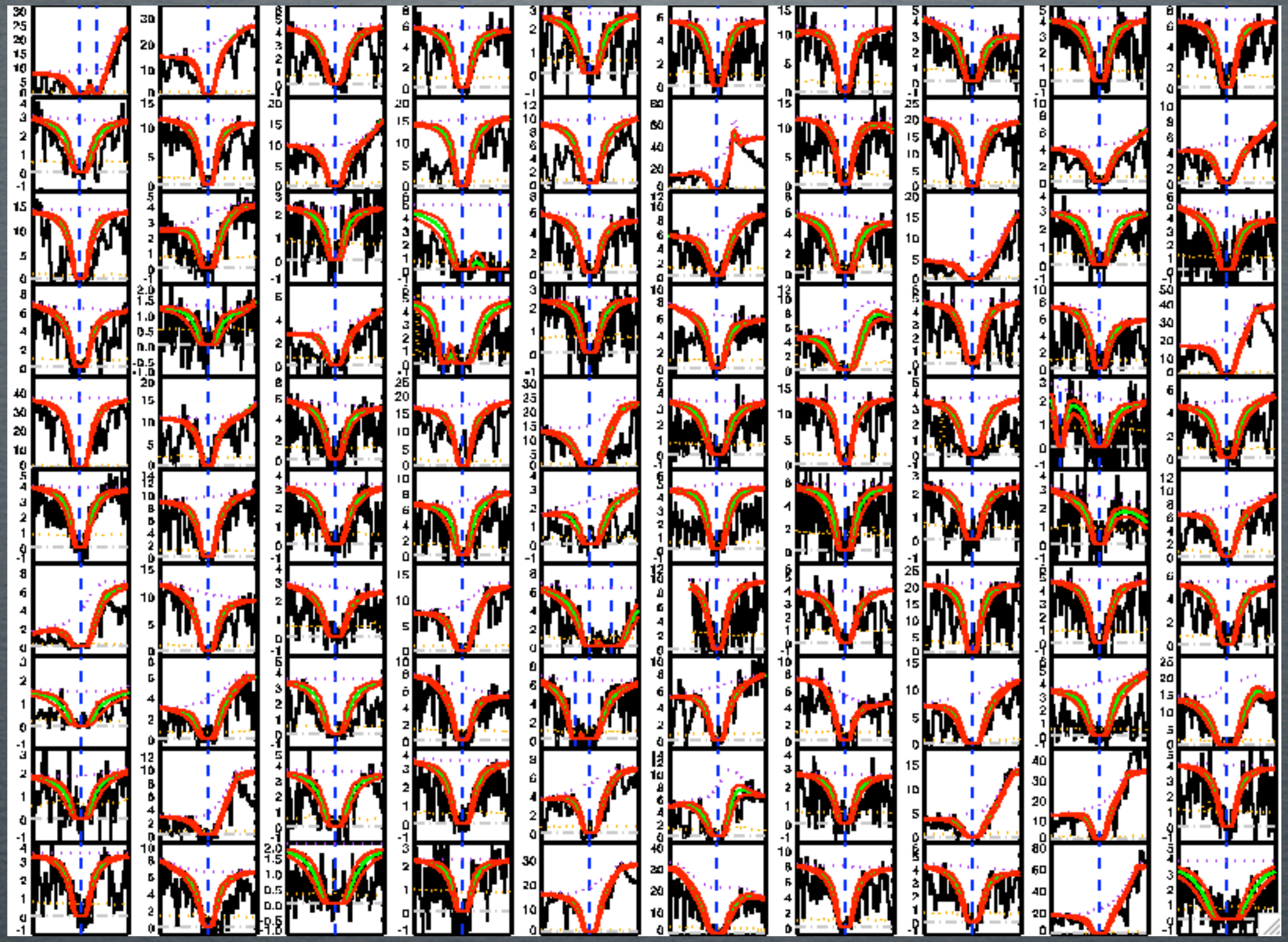
201-300

The fits...

301-400

The fits...

401-500

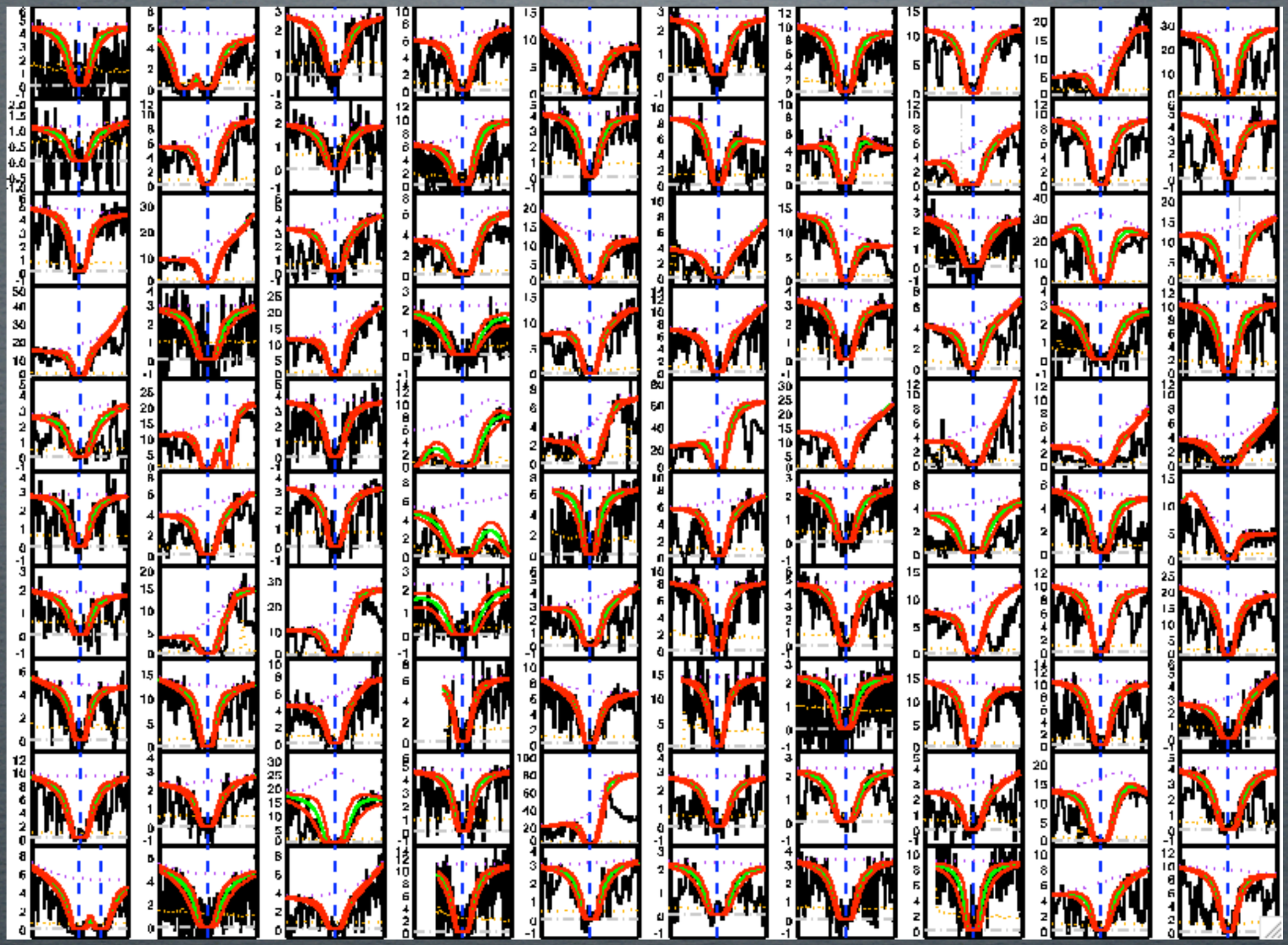


The fits...

501-600

The fits...

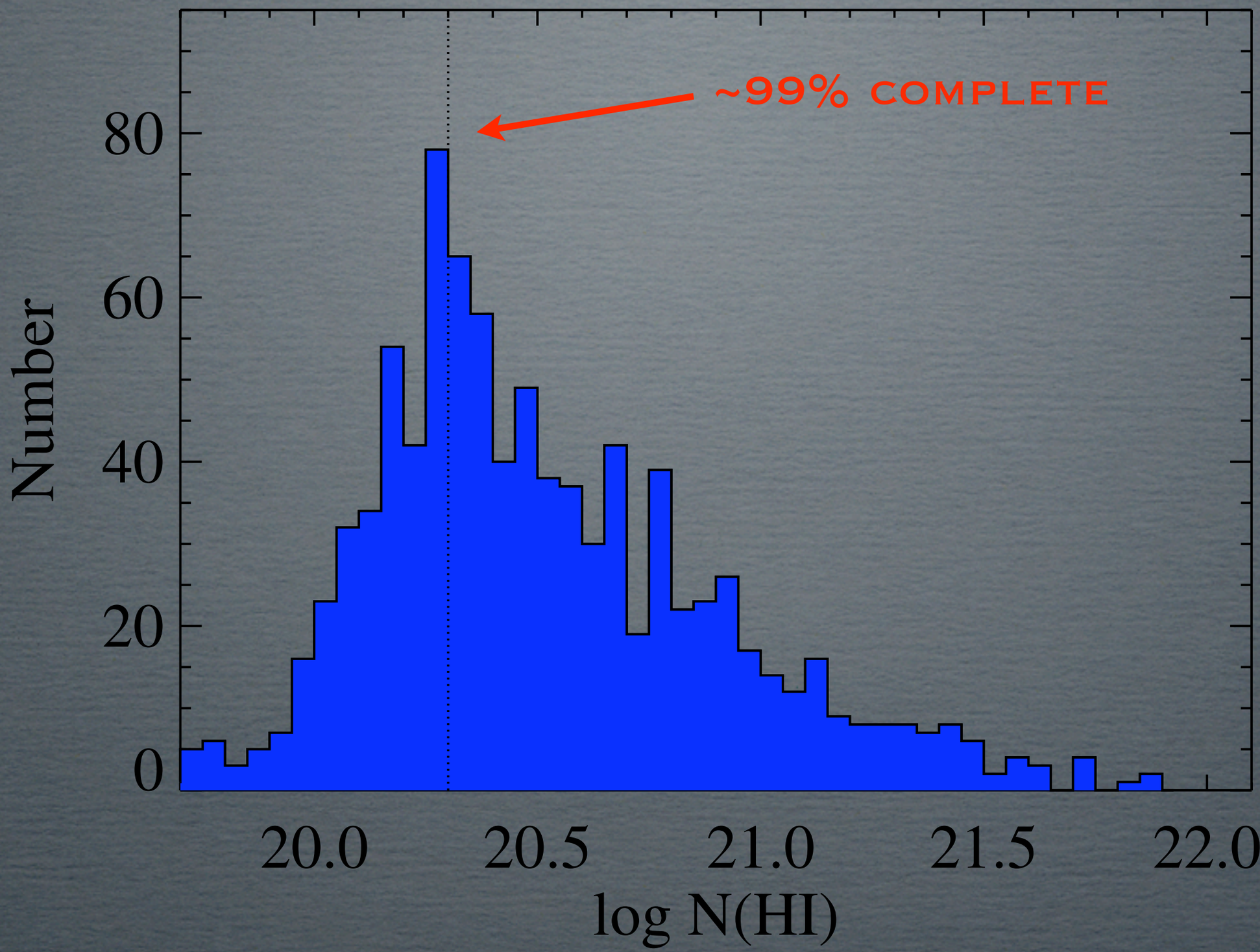
601-700



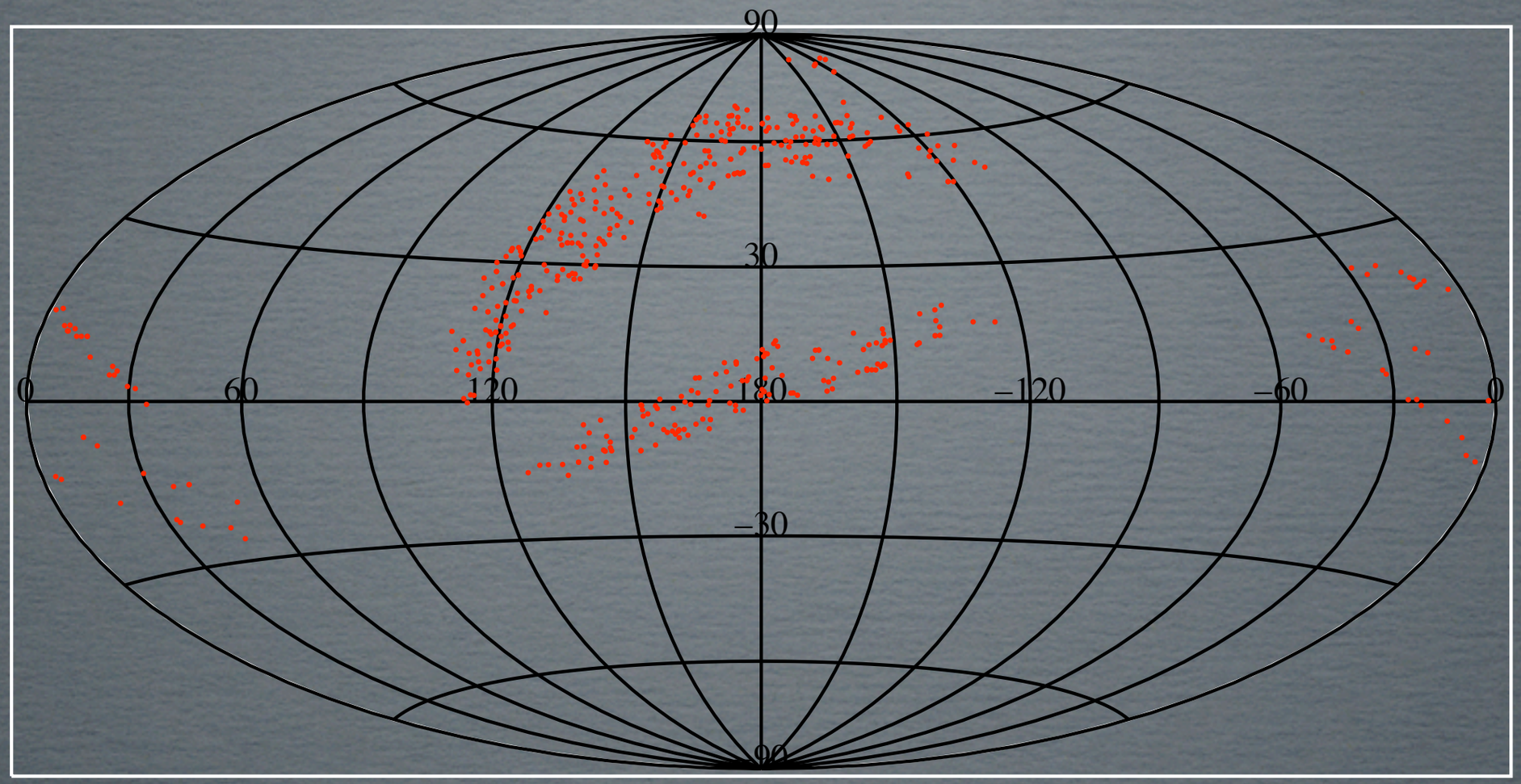
The fits...

701-739

N_{HI} Histogram



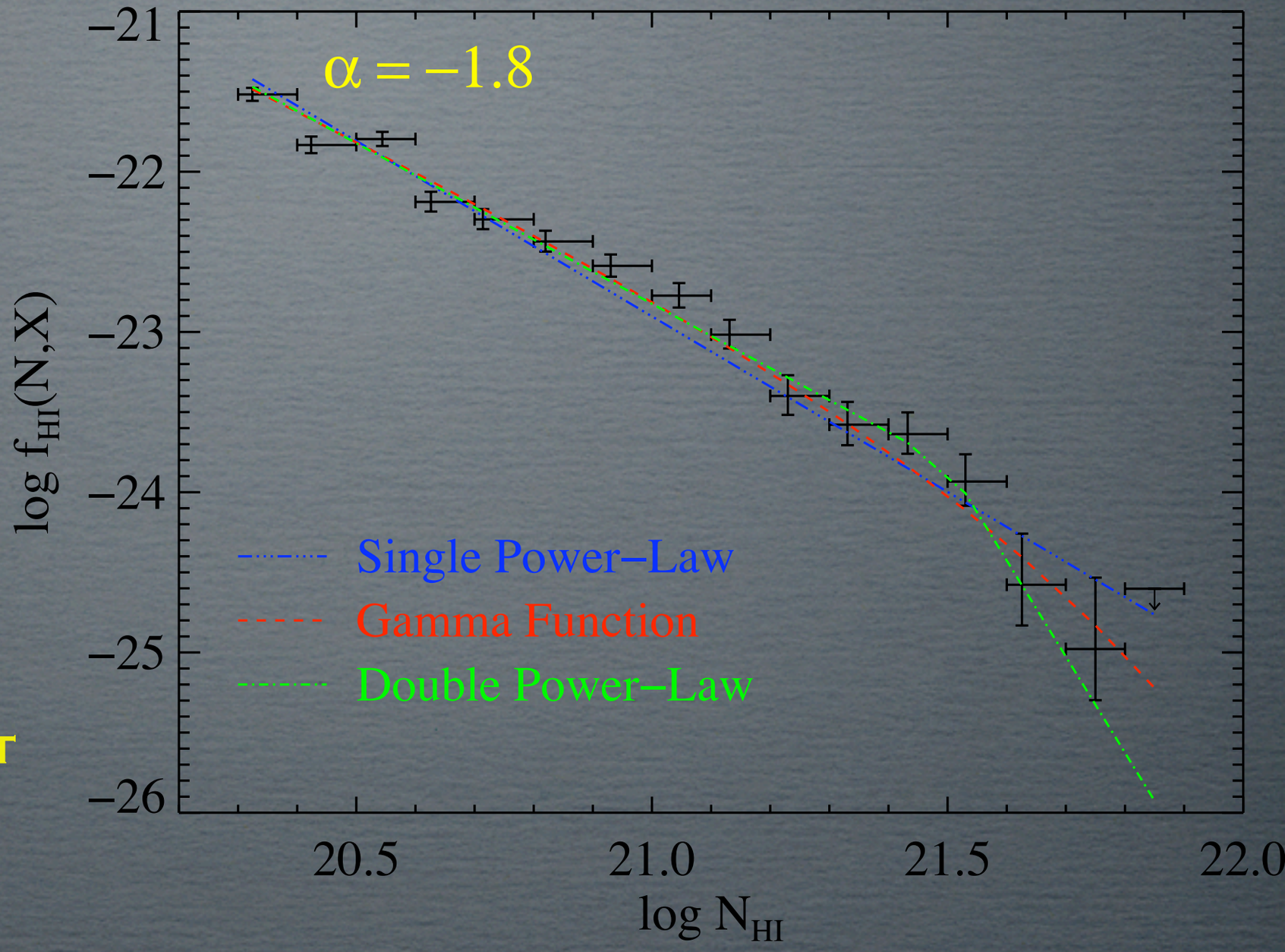
Sky plot



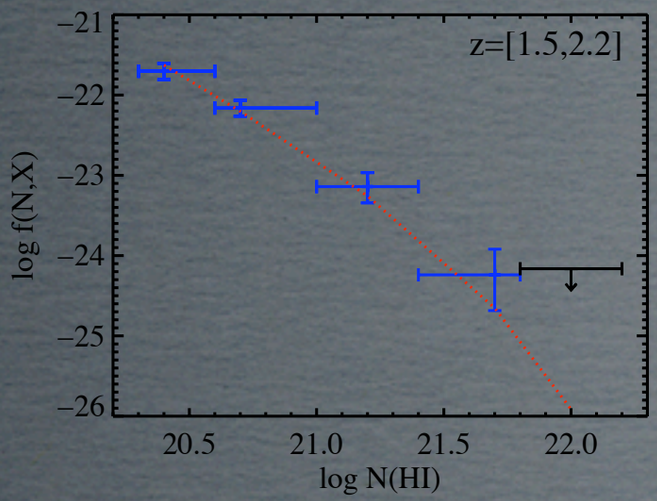
- Minimum separation
  - 3 arcminutes
  - $\Delta z = 0.1$
- Minimum separation with $\delta v < 1000$ km/s
  - 20 arcminutes
  - clustering analysis?

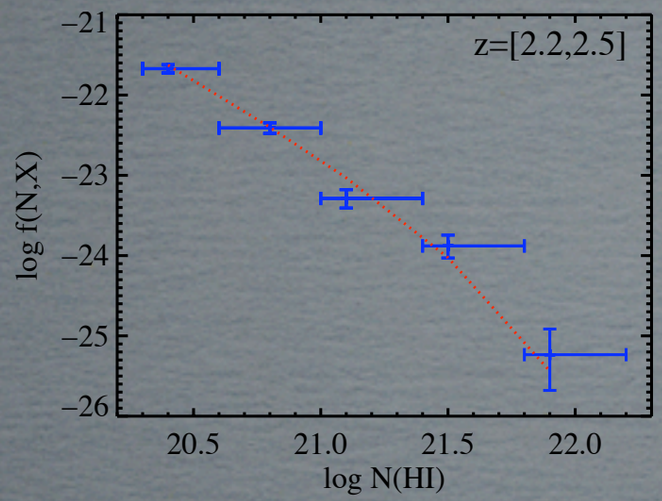
f_{HI}: N_{HI} Frequency distribution

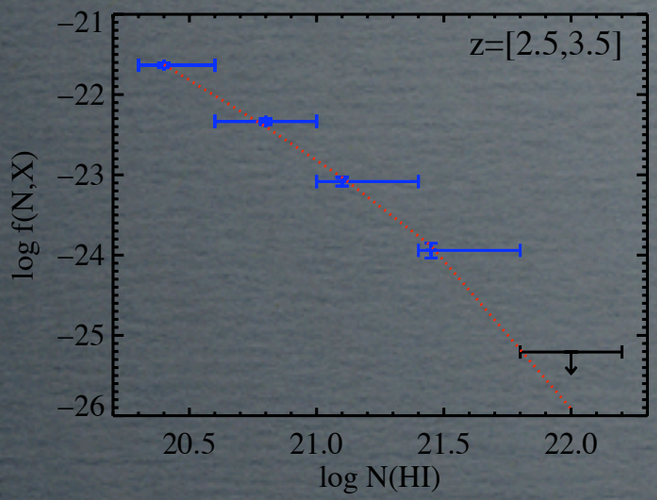
- $f_{HI}(N)$
  - 525 SDSS DLA
  - Single is poor
  - Break N_{HI}~21.5
    - Ω_g converges!!
    - Are you convinced?
  - 'faint' end: $\alpha \sim -2$
  - Bright end
    - Steeper than -3
- z evolution
  - Shape is invariant
  - Normalization increases with z

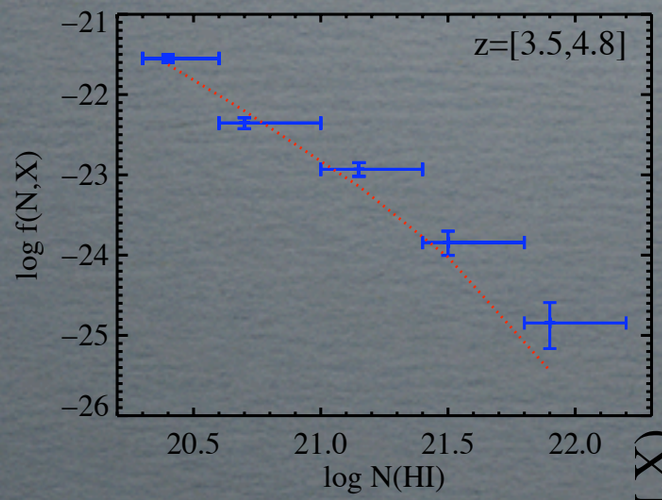


f_{HI} Evolution





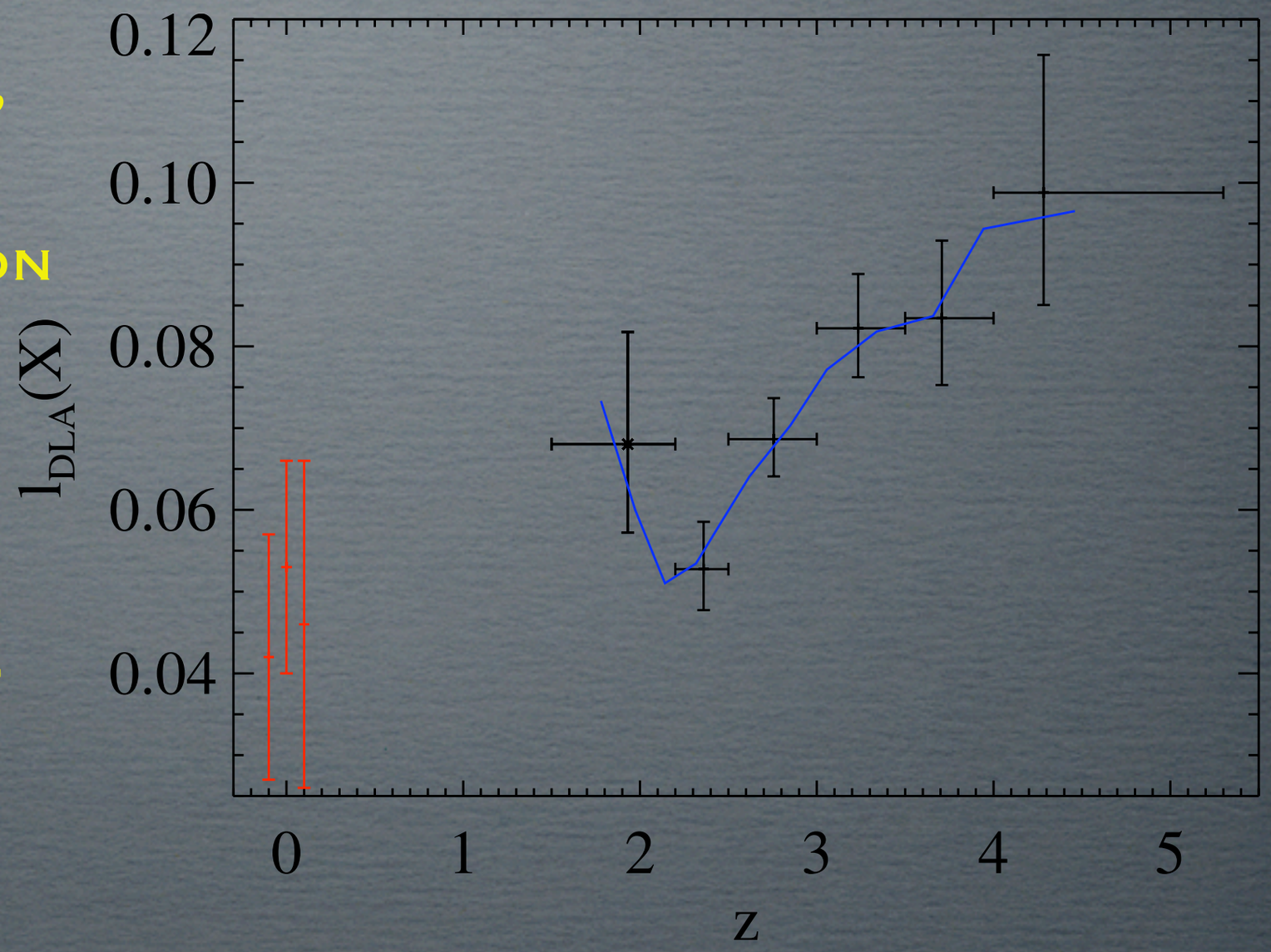




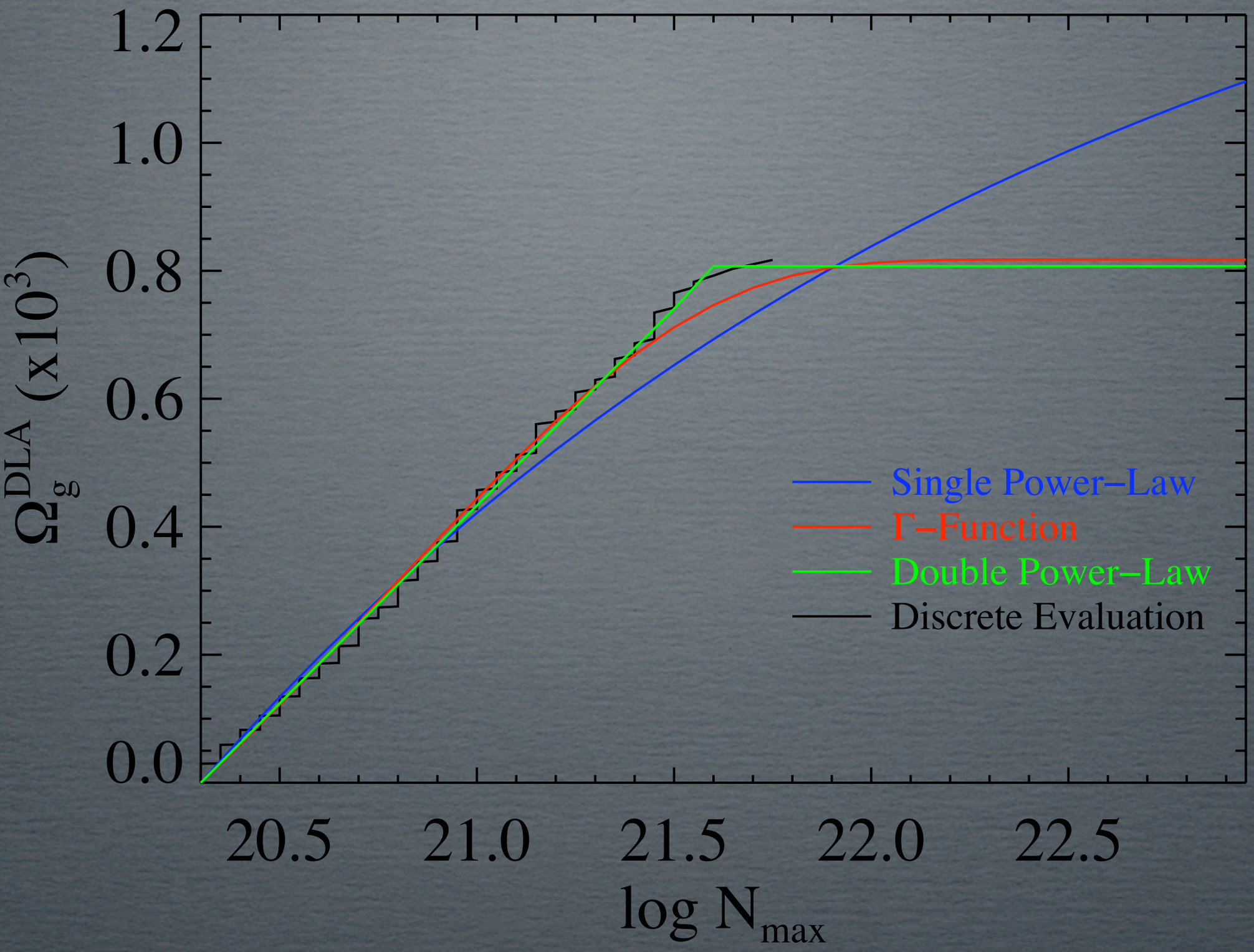
- No shape evolution
- Normalization evolves

Line Density: $\ell_{DLA}(X)$

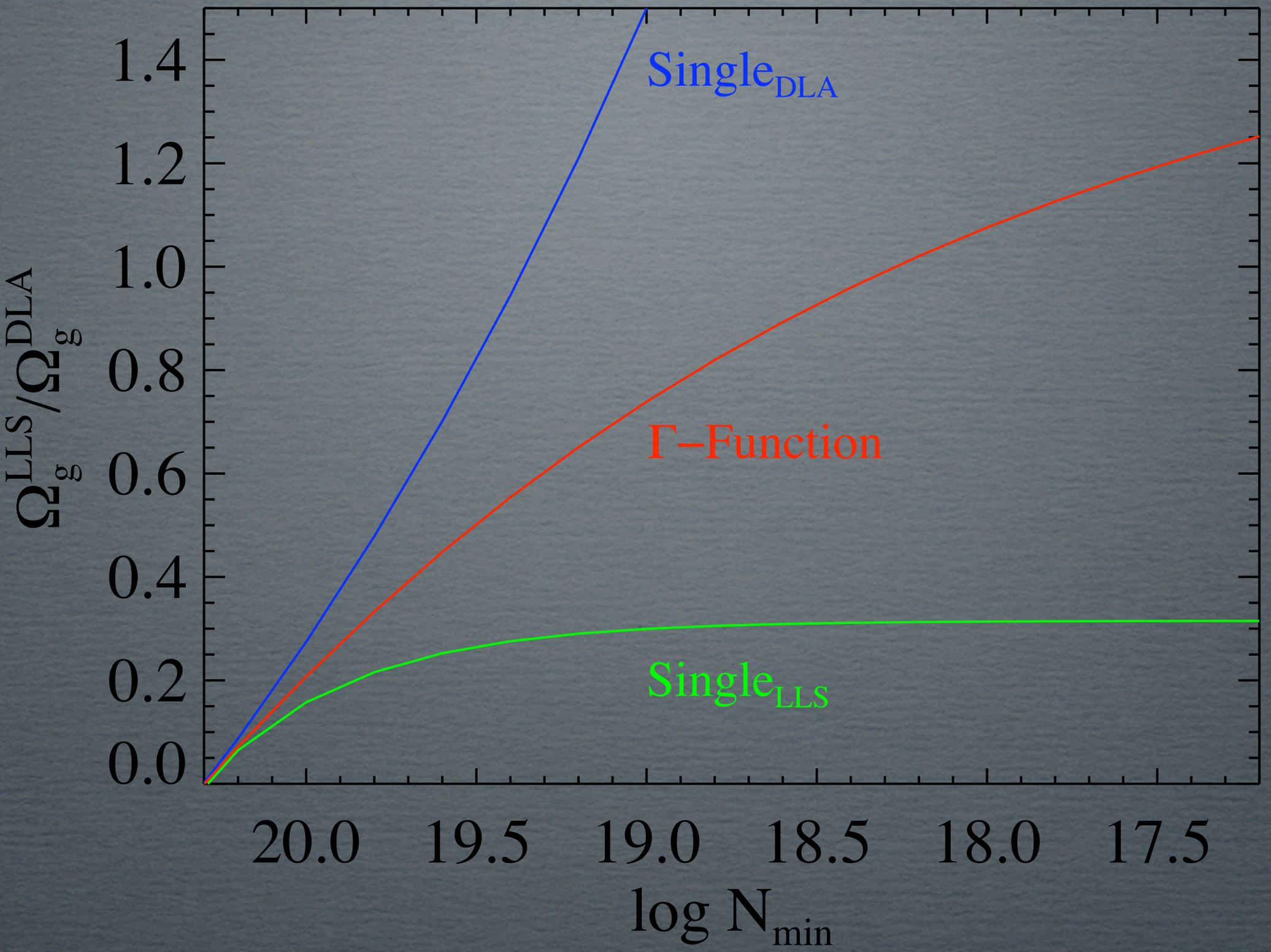
- $\ell(X)$
  - Incidence of DLA per 'absorption distance'
  - Often written dn/dX
  - DLA covering fraction $\ell \sim n A$
- Results
  - $\ell(X)$ decreases by 2x from z=3.3 to 2.3
  - Minimal evolution at endpoints
  - Is $\ell(X)$ flat from z=2 to today?!



Ω_g Convergence at high N_{HI}

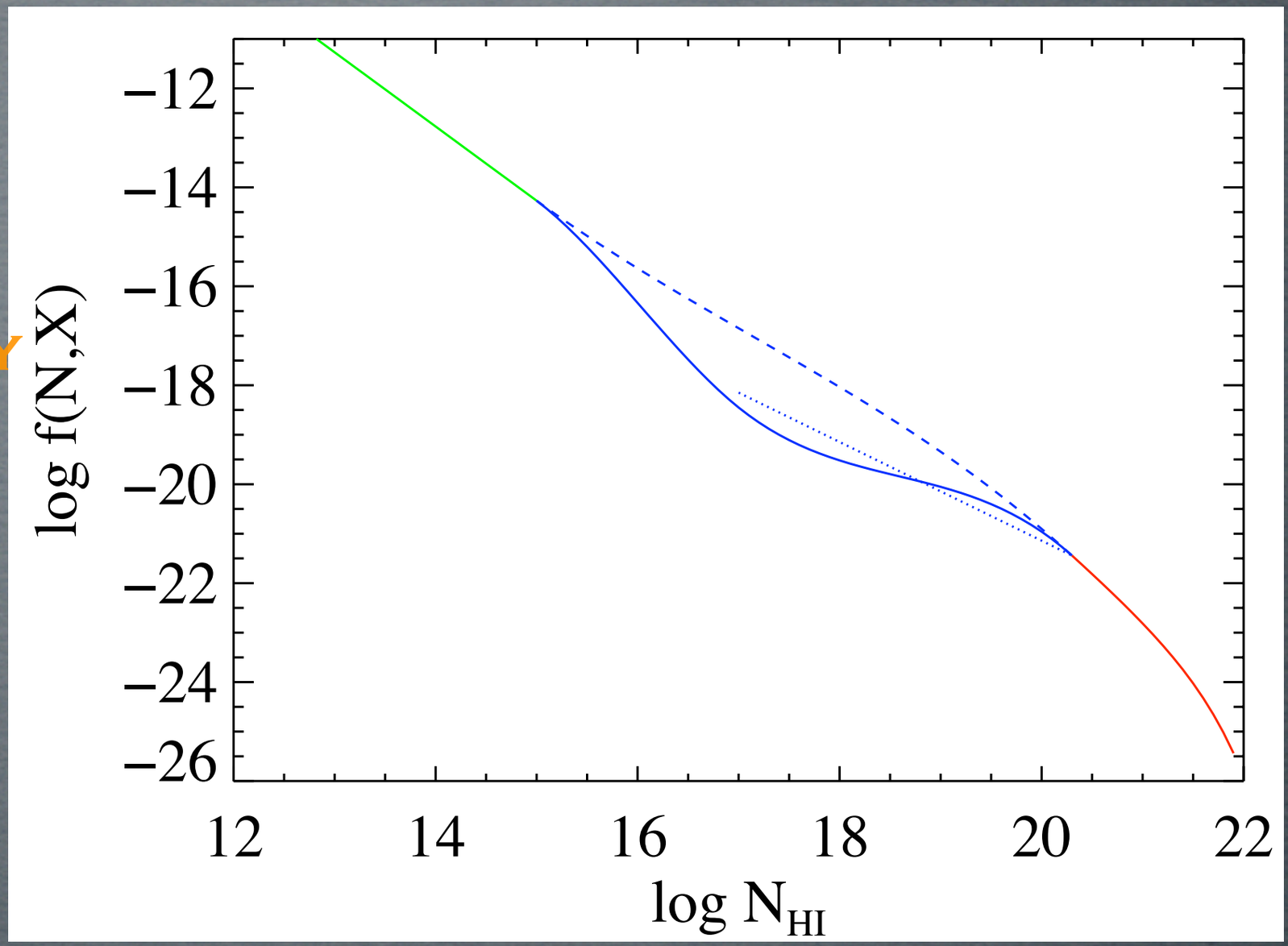


Ω_g Convergence at low N_{HI}



LLS Regime

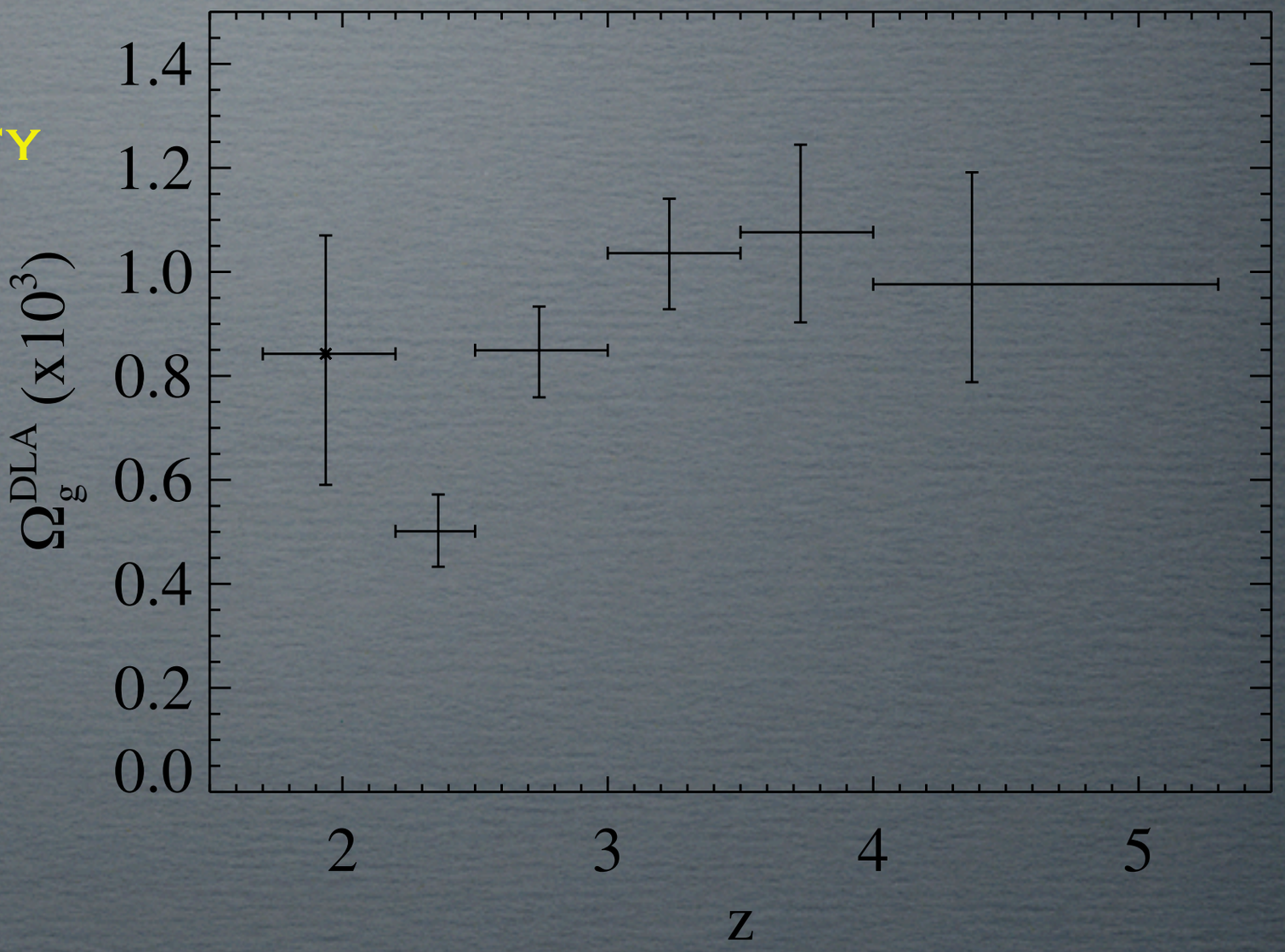
- **LLS**
  - Largely unexplored
  - $\alpha < -1$ somewhere!
  - Metallicity?
- **MIKE/HIRES survey**
  - 100+ LLS
  - High resolution
  - N_{HI}, [M/H], etc.



See posters by John O'Meara (MIT) and Gabriel Prochter (UCSC) + Scott Burles (MIT)

Neutral Gas Mass Density: Ω_g

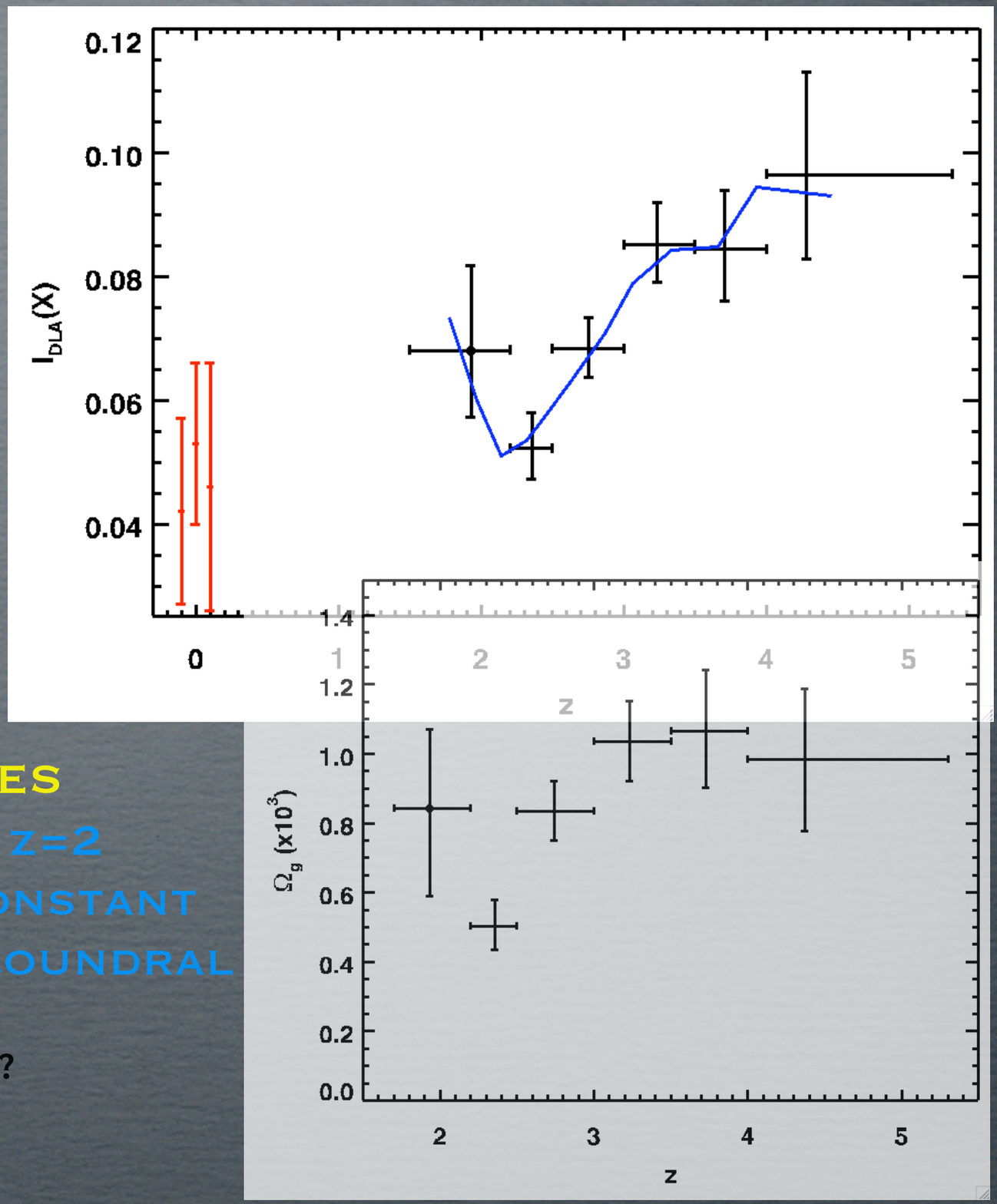
- Ω_g
  - Neutral gas density
  - Cosmological quantity
  - Reservoir for SF
- Results
  - First evidence for significant evolution
  - Also, a factor of ~2 decrease from z = 3.3 to 2.3



Theorists: Time to wake up!!

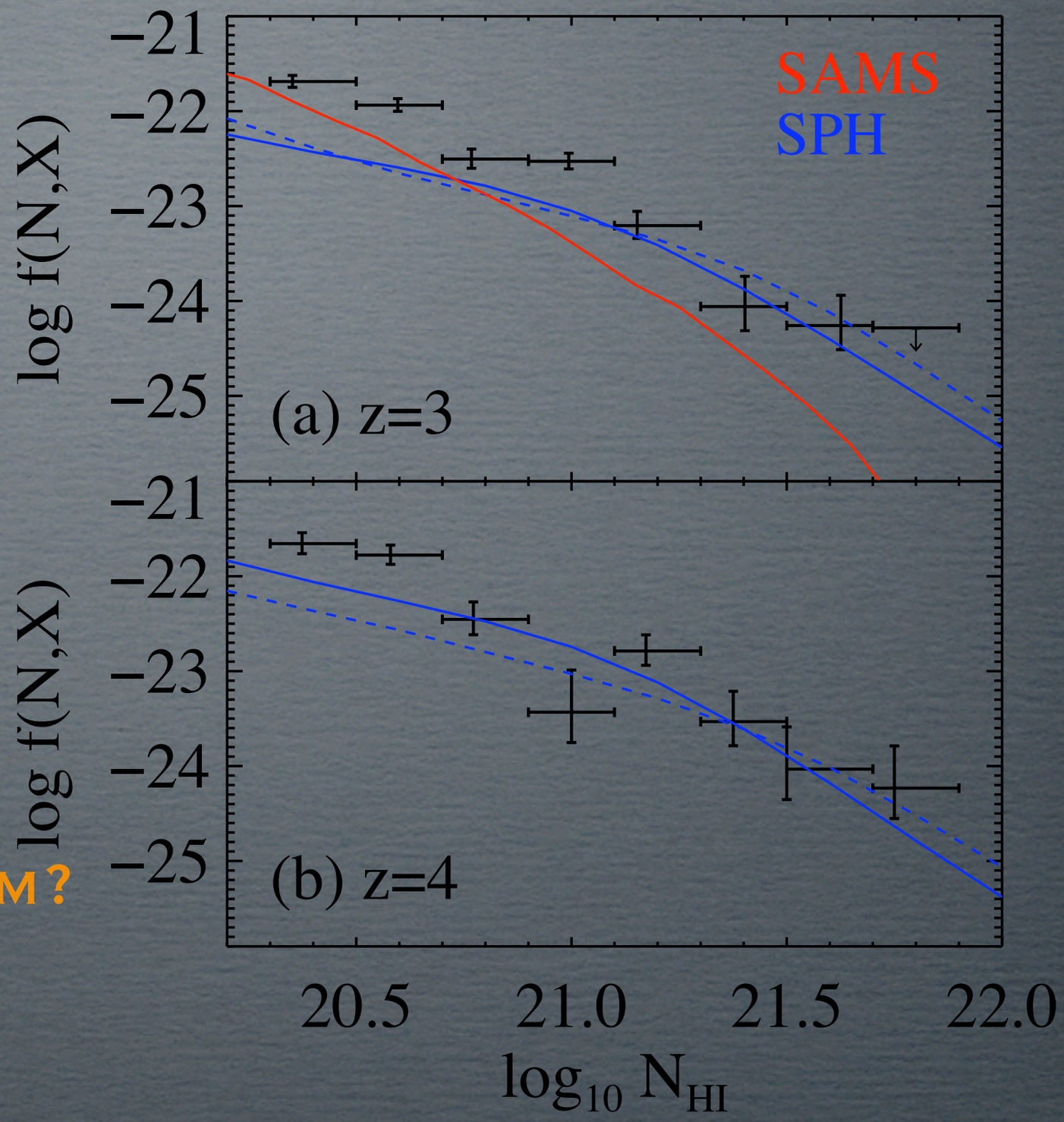
Implications of the Evolution

- **Line density**
  - ✦ Either n or A (or both) drops by 2 in <1 Gyr
  - ✦ Consider n
    - P-S: $M^* \sim 10^{10}\ M_{SUN}$ (z=3)
    - $M >> M^*$ have n increasing
    - $M << M^*$ have n nearly const
  - ✦ Therefore, A is changing
- Ω_g
  - ✦ Gas density drops by 2
  - ✦ Consider physical processes
    - SF: Unlikely, SF peaks below z=2
    - Ionization: Unlikely, EUVB constant
    - Feedback: Last resort of a scoundral
      - ➡ AGN, SF, Galactic winds?
      - ➡ Why would SFR peak below z=2.3?



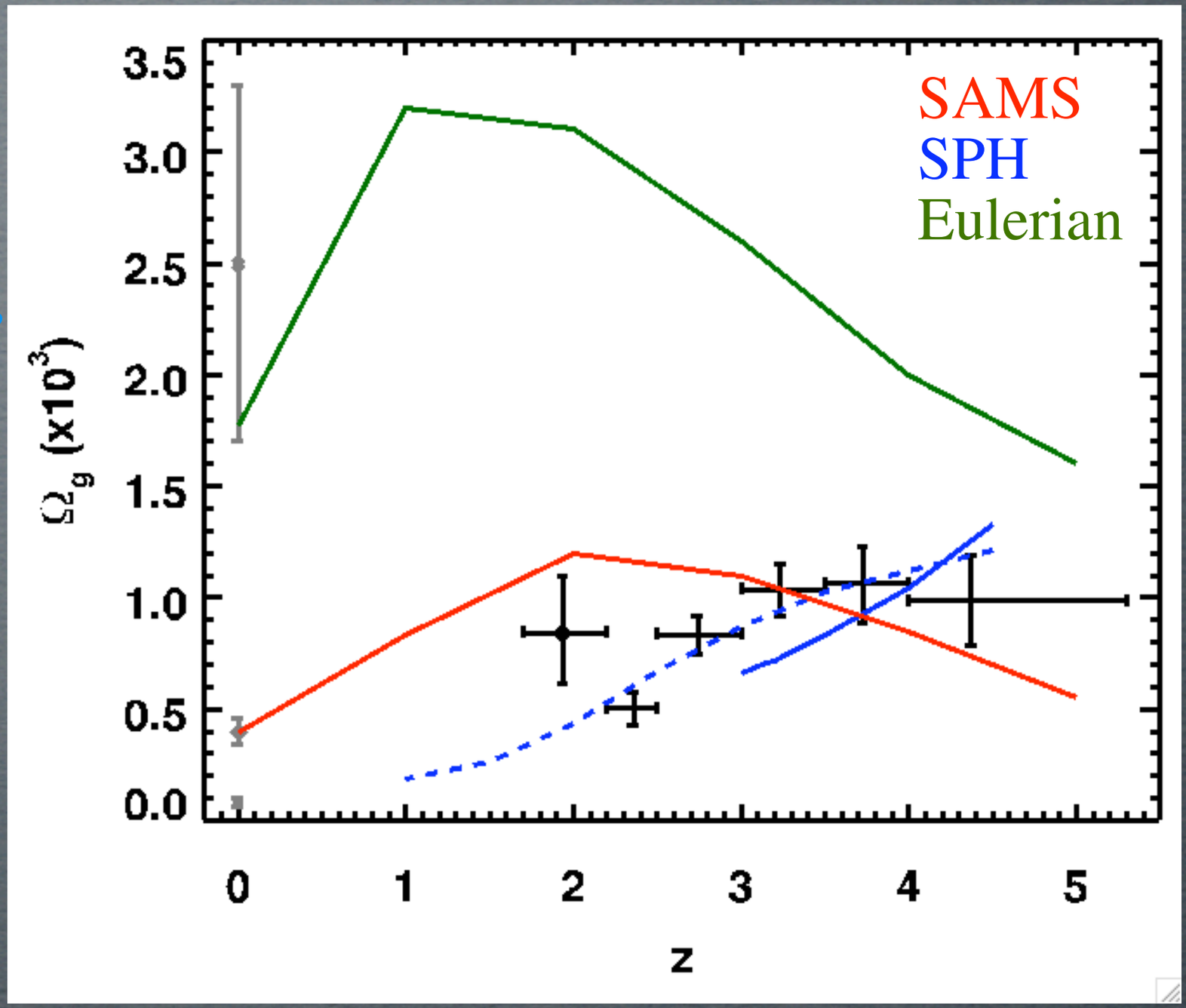
Comparison with CDM: I

- $f_{HI}(N)$: z=3
  - **SAMS:**
    - Correct shape
    - Low normalization
  - **SPH**
    - Good at high N_{HI}
    - Very low at low N_{HI}
    - Under predict $\ell(X)$
- $f_{HI}(N)$: z=4
  - **SPH**
    - Again, low at low N_{HI}
    - Partly observational?
- Fundamental problem?
  - $f_{HI}(N)$ vs kinematics



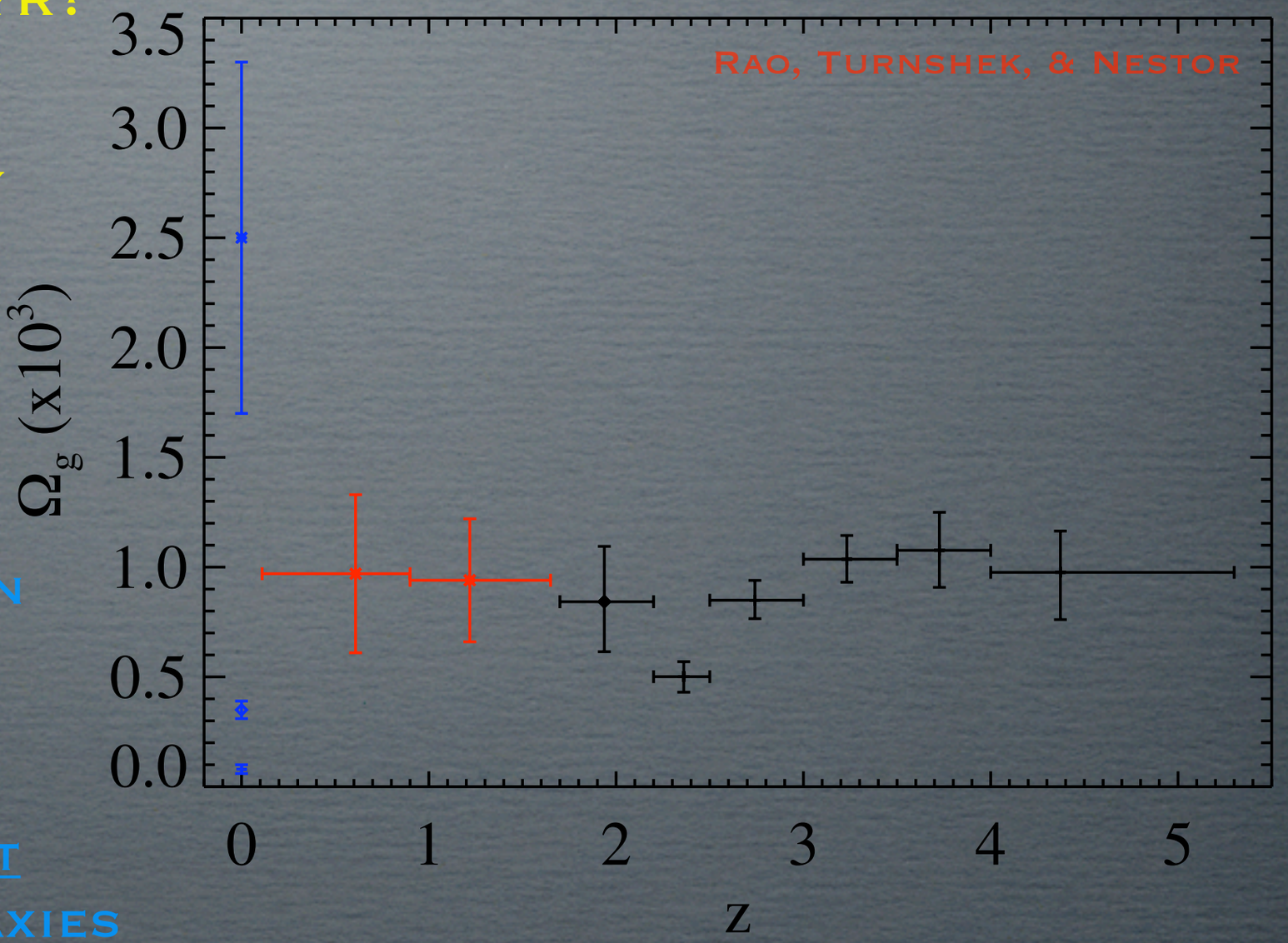
Comparison with CDM: II

- Ω_g
  - **SAMS:**
    - Fine at high z
    - Too high at low z?
    - Not enough feedback?
  - **SPH**
    - Low res is excellent
    - High res is too low
    - Problem?
  - **Eulerian**
    - Too much gas!
    - Dust obscuration?



Comparison with z=0

- $\ell(X)$
  - z=0 matches z=2
  - nA constant for 10Gyr?
- Ω_g
  - Stellar mass density
    - ~3x z=3.5 value
    - Every galaxy is (or was) a DLA
  - Gas mass density
    - z=2 matches z=0
    - SFR balances accretion
    - Kennicutt law?
  - Dwarf mass density
    - DLA are 10x higher
    - Majority of DLA cannot evolve into dwarf galaxies

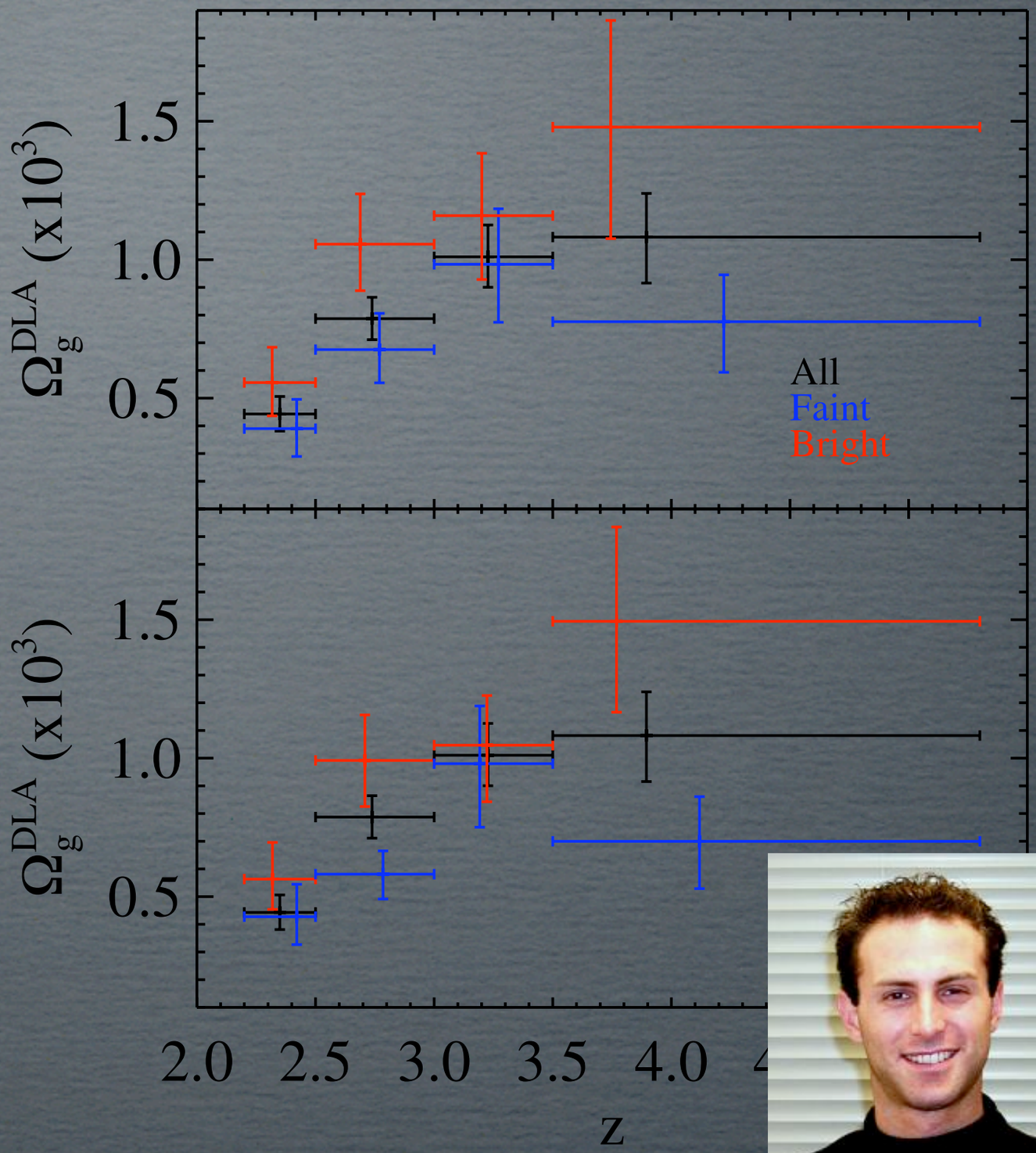


Redefine Ω_g

- Classical
  - Mass-density in gas of the DLA
  - Expectation was that this dominated over all the LLS
  - Observations focused on this quantity except at z=0
- New
  - The mass-density of predominantly neutral gas
  - Expect this is dominated by DLA
- z=0?
  - What does HIPASS give?

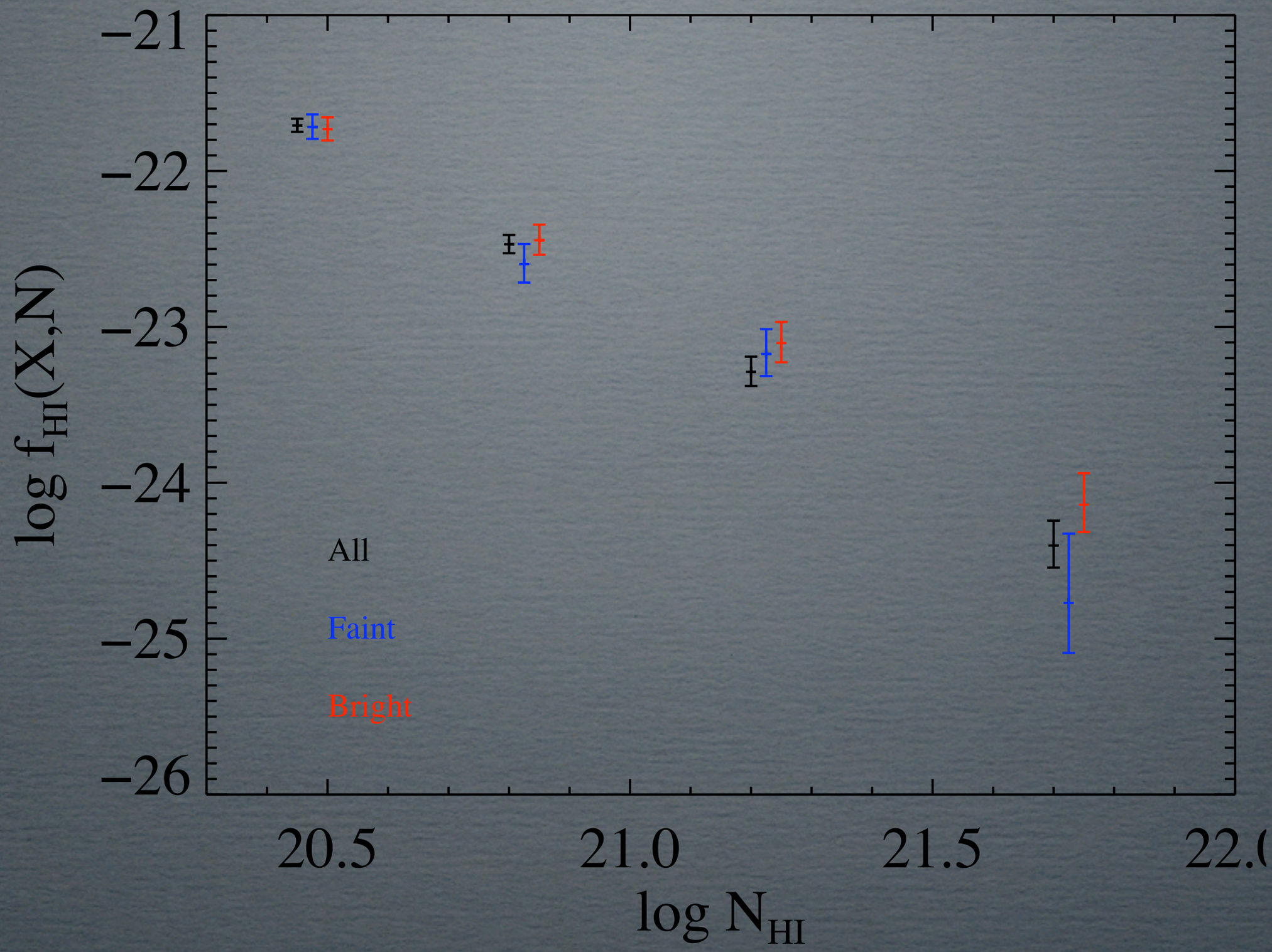
Systematic Error: III

- Ω_g
  - ✦ Higher toward brighter quasars!
  - ✦ Same is true for SNR
- Explanations:
  - ✦ Sample variance? No
  - ✦ Intrinsic? Unlikely
  - ✦ Missed DLA? Doubtful
  - ✦ Overestimate bright? No
  - ✦ Underestimate faint? Maybe
  - ✦ Dust obscuration? NO!!
  - ✦ Gravitational lensing? Quite possible!!



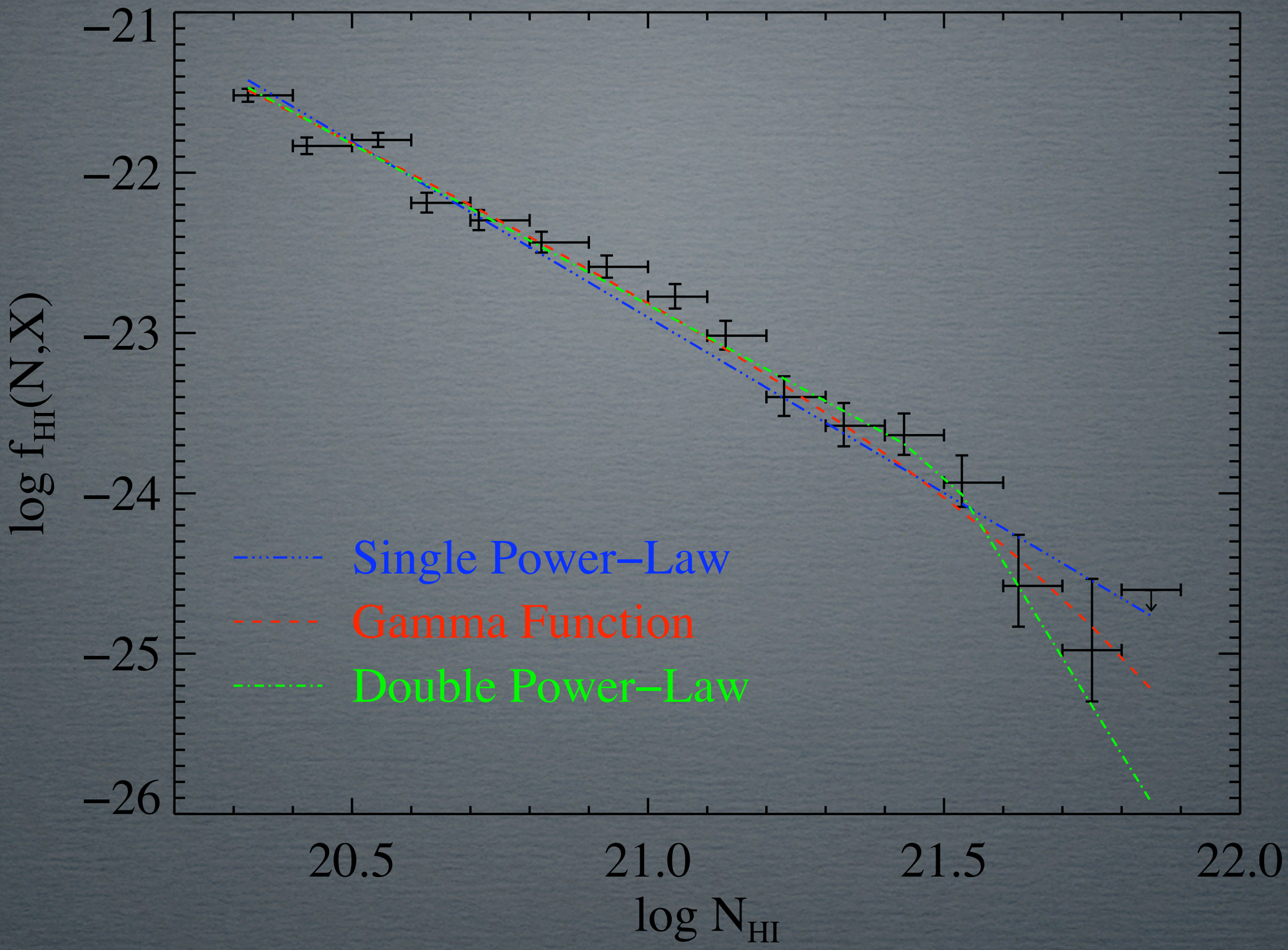
Michael Murphy (IoA)

f_{HI} for Bright/Faint



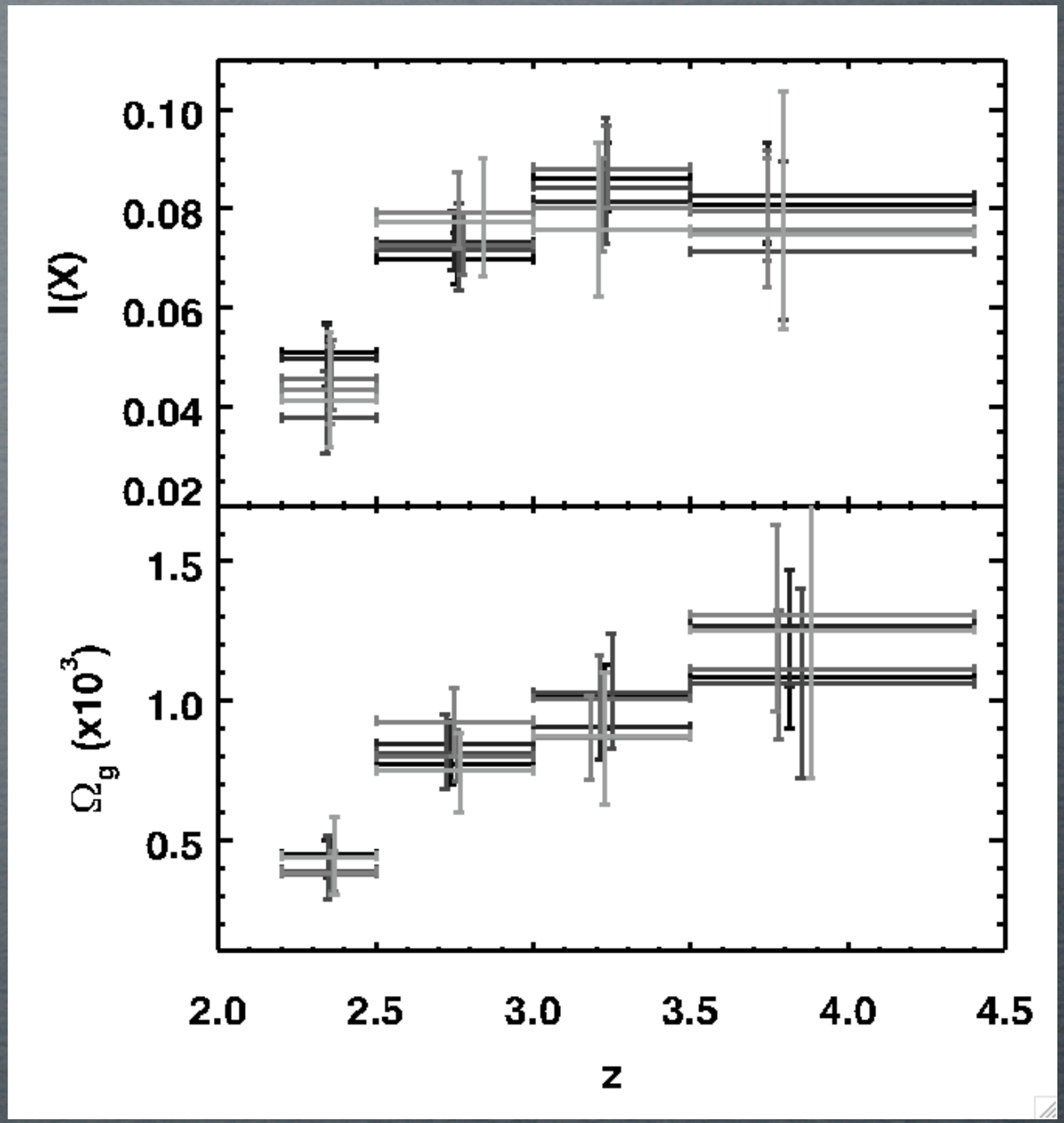
Summary

- DLA Chemical abundances
  - ✦ Mean metallicity of the universe
    - Increasing by 2x every Gyr at z>2
    - Approaching sensible values at z=0
  - ✦ Relative abundances (see next talks)
  - ✦ Metal-strong DLA
    - Excellent lab for nucleosynthesis
    - SDSS: Discovery of >20 new systems
- $f_{HI}(N)$
  - ✦ Shape is invariant
  - ✦ Normalization increases from z=2 to 3
- $\ell(X)$, Ω_g
  - ✦ Both decrease from z = 3.3 to 2.3
  - ✦ Suggests HI gas is 'removed'
  - ✦ Gravitational lensing?

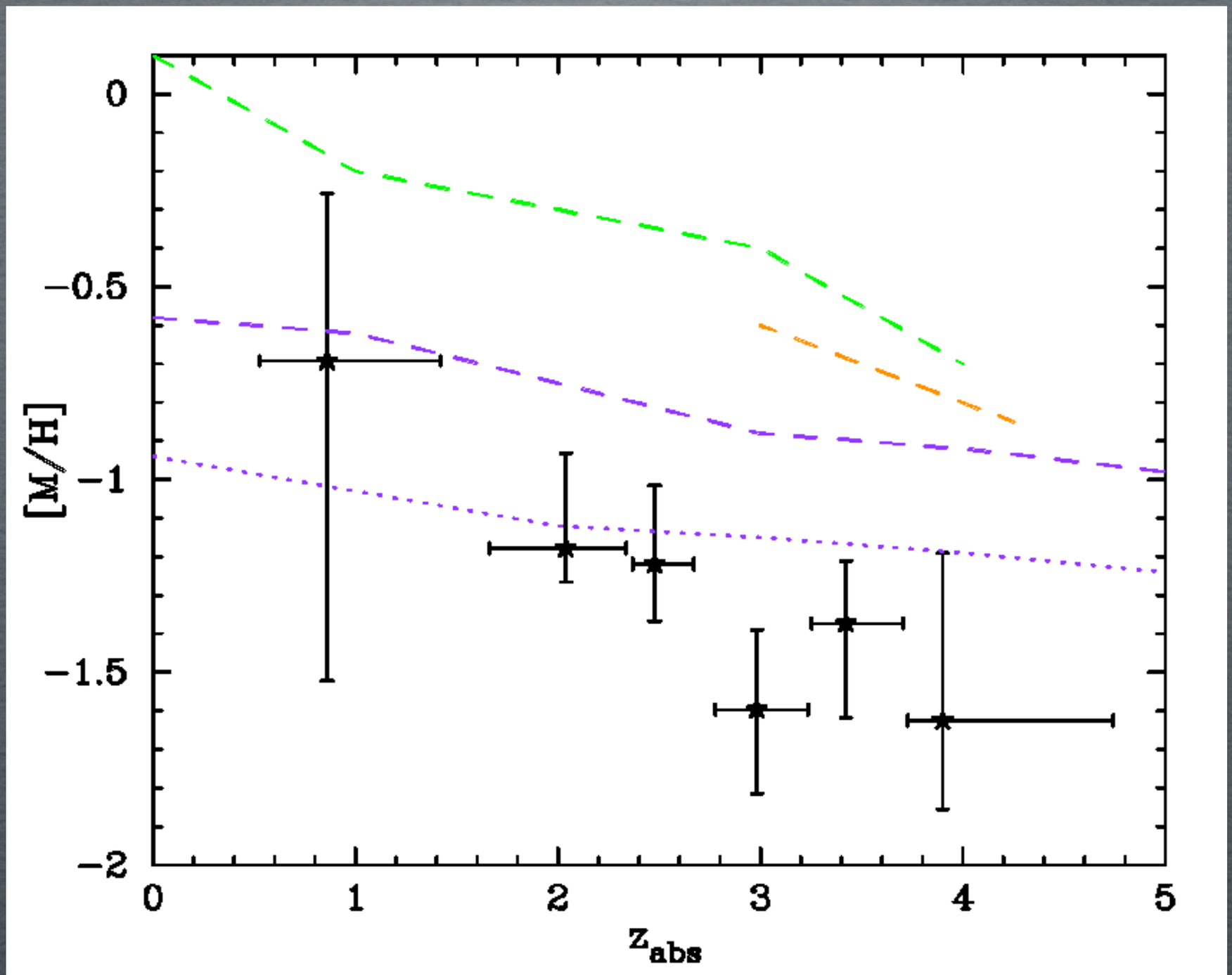

−21
−22
−23
−24
−25
−26
log $f_{HI}(N,X)$
Single Power−Law
Gamma Function
Double Power−Law
20.5
21.0
21.5
22.0
log N_{HI}

Systematic Error: I

- Minimum SNR
  - ✦ No effect
  - ✦ SNR>4 is fine
- Color criterion
  - ✦ Early days: uncertain
  - ✦ DR2+: Strict criteria
  - ✦ No effect



Chem Evol Models (missing metals)



Systematic Error: II

- $\ell(X)$
  - Mild effect with mag
  - Brighter show higher ℓ
- SNR?
  - Again, mild effect
  - Perhaps statistically significant