The Total Deuterium Abundance in the Local Galactic Disk: Decisions and Implications

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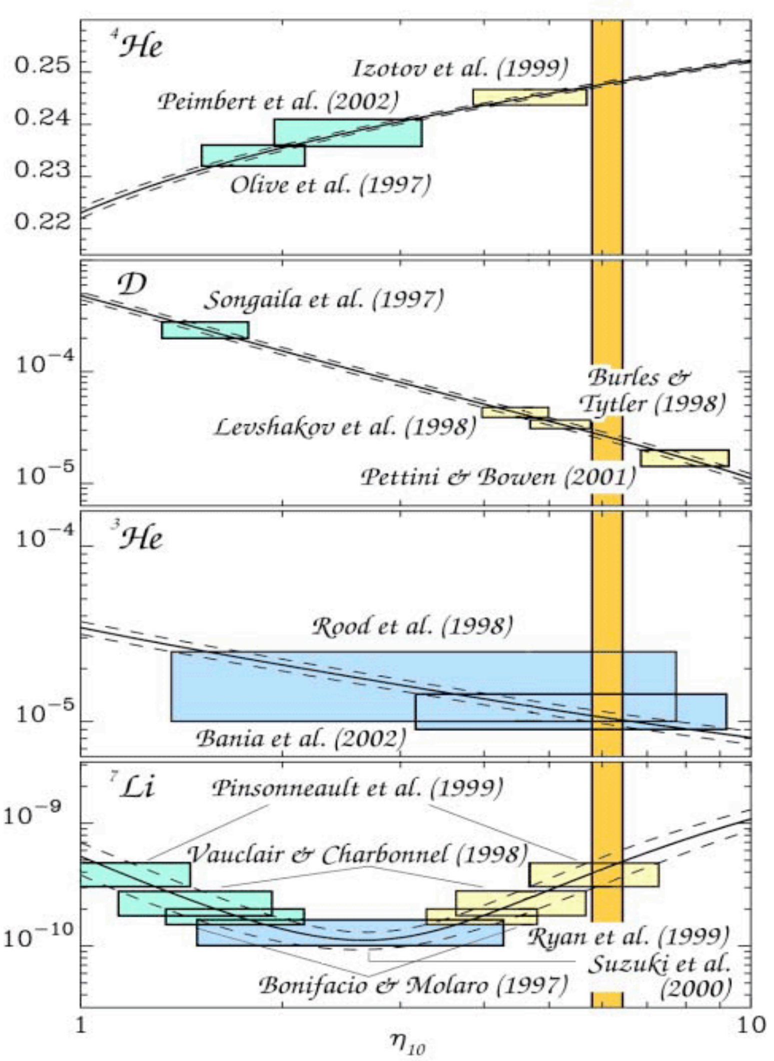
Why study D/H by concentrating on D and H and not other elements?

- D is the best baryometer: only one source (BBNS) and only destruction in stars; steep dependence on η; directly measurable by UV and FUV spectroscopy; H and D have same ionization potentials.
- Comparison with other elements (e.g., O, C, N) introduces more information but more assumptions (depletion, ionization, different chemical evolution, etc.)

Big Bang Nucleosynthesis

- Solid lines are theoretical predictions (with standard assumptions) from Fiorentini et al. (1998).
- Dashed lines are ±1σ.
- Abundances (linear for He and log for others) are relative to H.
- η=baryons/photons
- Horizontal blue boxes are observational results.
- Vertical band is the WMAP range in $\eta_{10} = 6.14 \pm 0.25$.
- Figure from Romano et al (2003) MN 346, 295.



Coauthors for the D/H Study

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- Bruce Draine
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- Brian Wood
- Cristina Oliveira
- William Blair
- Scott Friedman
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- Seth Redfield
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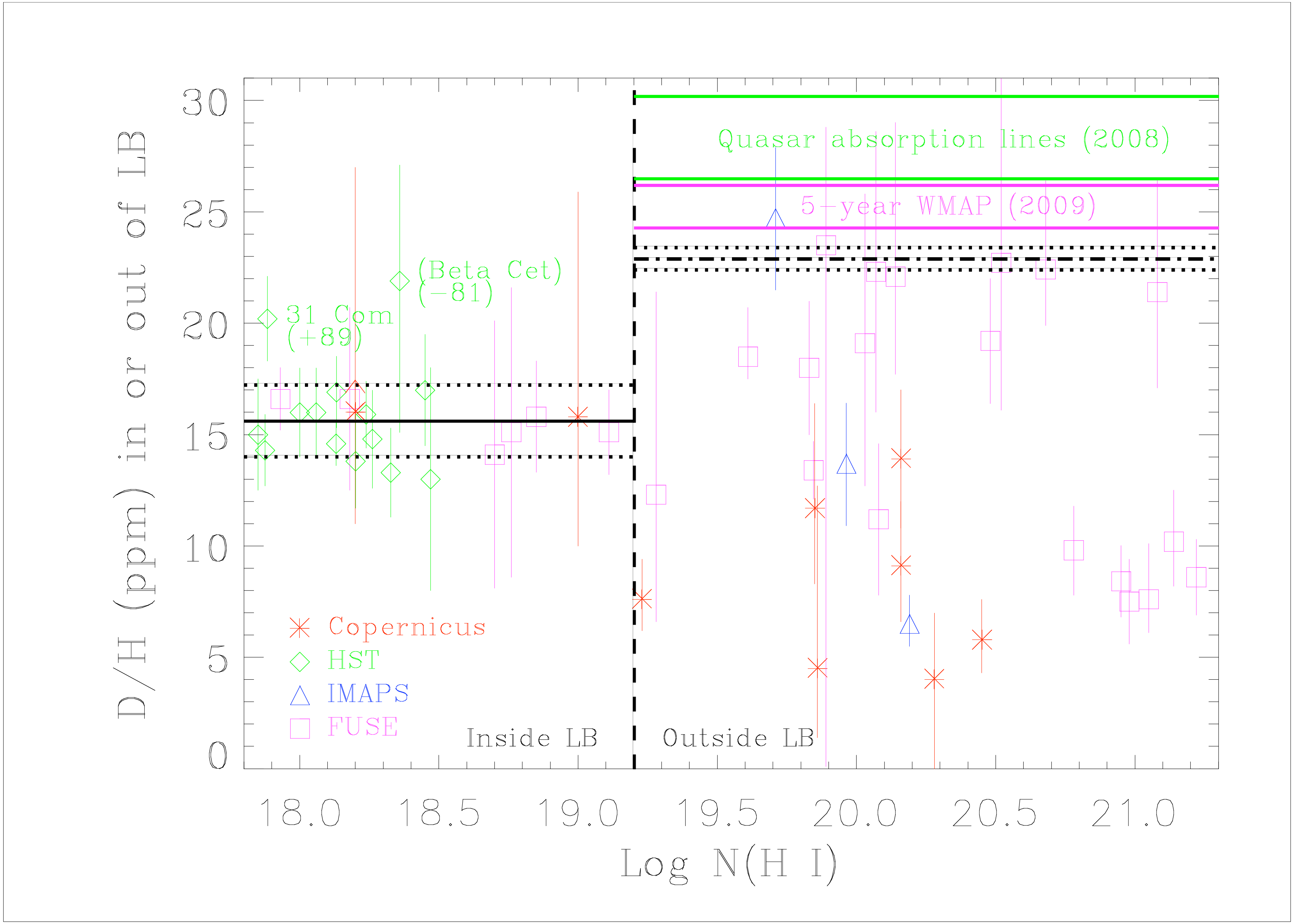
- Gerard Williger

What have we learned since the 1996 paper?



Four regions of the D/H plot: Local Bubble, Galactic halo, low values of D/H in ISM outside of LB, high values of D/H and comparison with primordial D/H.

Measuring N(HI) and N(DI) against the stellar Lyα emission line (logN(HI)<18.9)

- Shape of the stellar emission line core not important unless a large radial velocity difference between star and ISM.
- Edge of ISM Lyman-α core measures N(HI) because line on flat part of curve of growth.
- Stellar Lyman-α line shape can be scaled from other stellar emission lines.
- Lyman-α horizon at N(HI)~7×10^{18} cm^{-2}.
- This N(HI) corresponds to what thickness at density of air in this room? n(HI) = 0.2 cm^{-2} in local ISM.

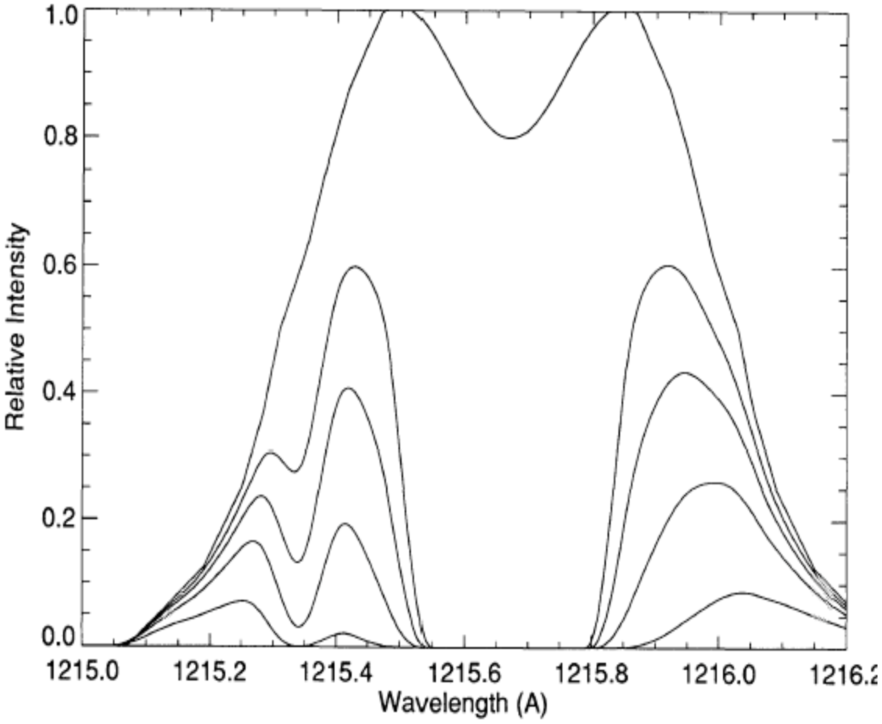
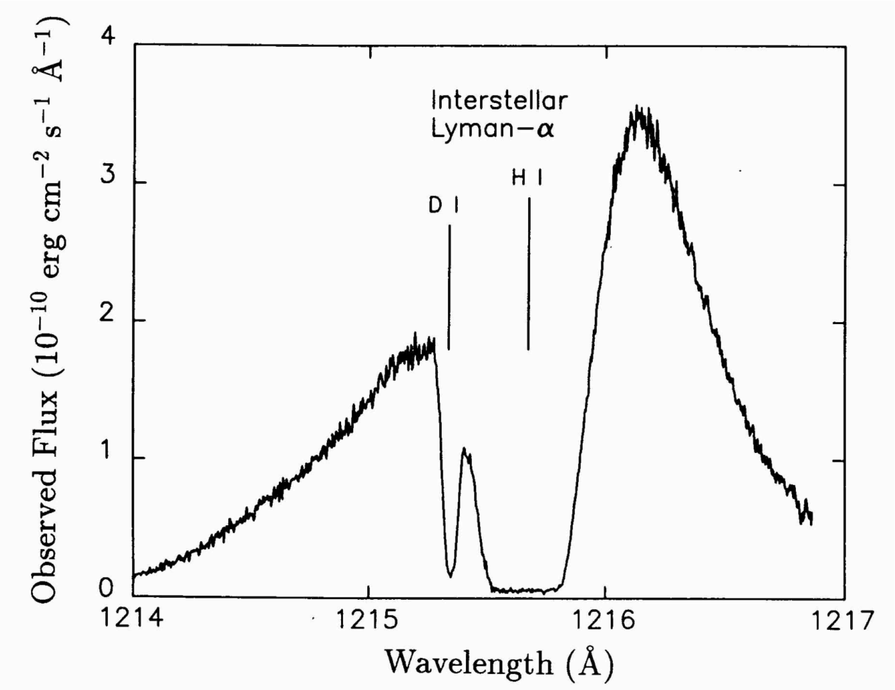


FIG. 2.—A model solar Lyα profile is shown as it would appear if observed through H I column densities of 0, 0.5, 1, 2, and 5×10^{18} cm^{-2}.

Landsman & Simon
ApJ 408, 305 (1993))

Measuring Interstellar Hydrogen and Deuterium Absorption

- The D Lyman lines are Δv= -82 km/s relative to H.
- τ_0(H)=667,000τ_0(D)
- Analysis is complicated due to uncertain intrinsic profile, flat curve of growth for H, multiple velocity components.
- To Capella log N(HI)=18.24.
- Profiles of FeII and MgII lines contain important information on central wavelenths and line widths.
- High resolution required (3 km/s very useful).
- We greatly need the on orbit fix for STIS (high spectral resolution)!
- H wall absorption (Sun and stars).
- FUSE needed to go beyond the Lyα horizon (log N(HI)=18.7). E.g., λ(Lyβ)=1025Å.

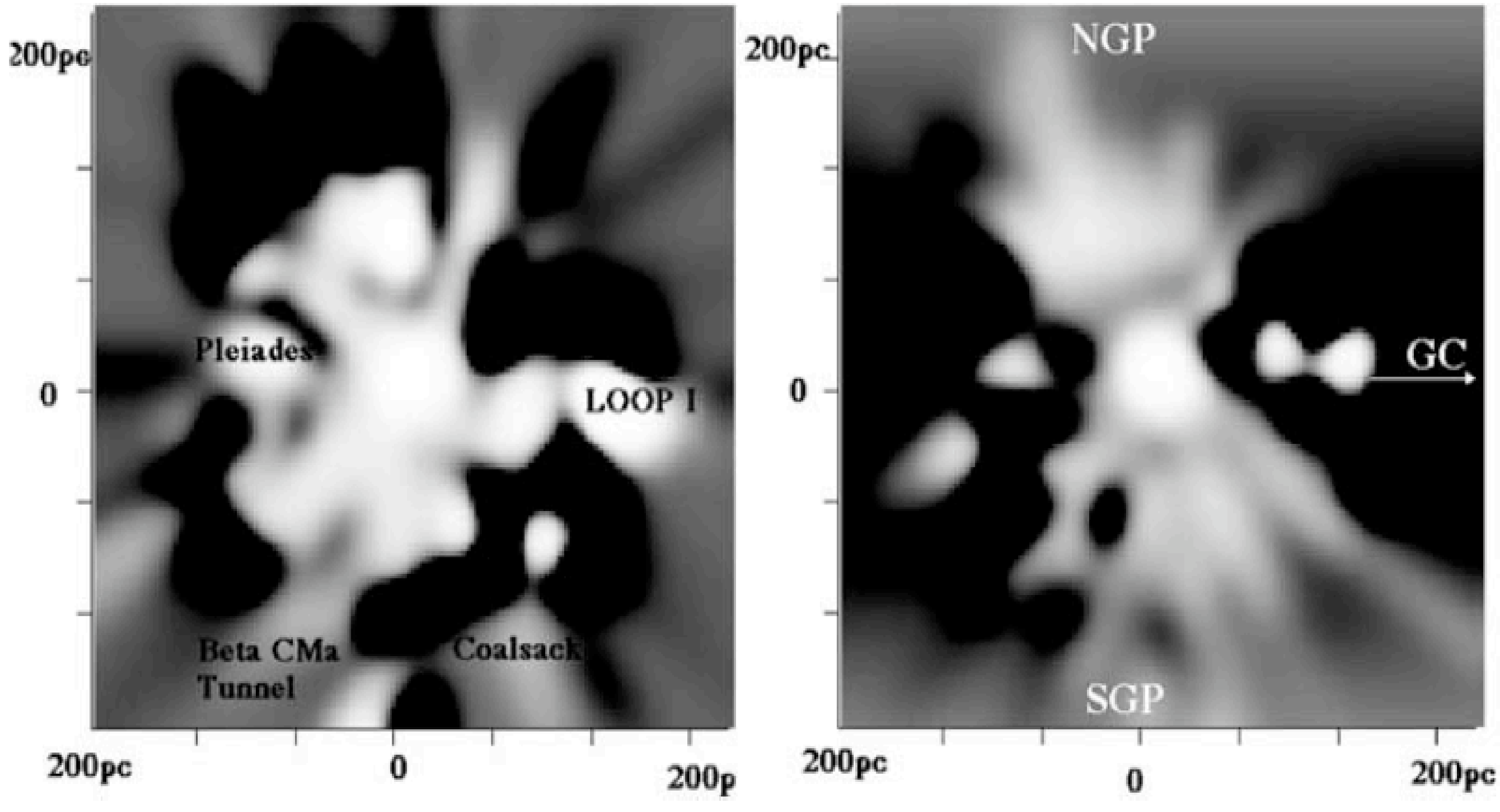


HST/GHRS observation of the star Capella (α Aurigae).

D/H inside the Local Bubble

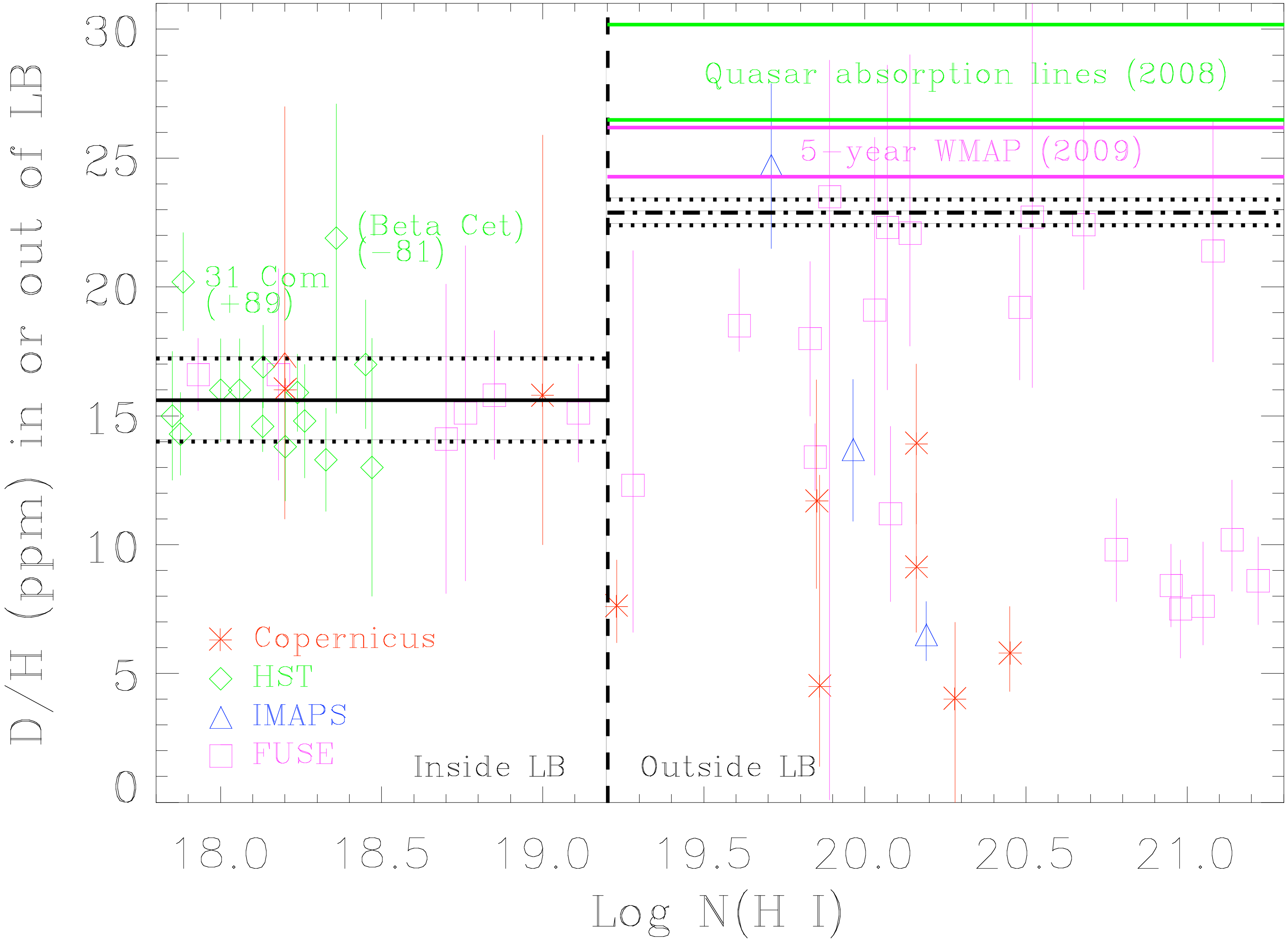
- Local Bubble a region with a common history formed by SN explosions and hot star winds from the Sco-Cen Association.
- Extends to log N(HI)≈19.2 (about 100 pc) with warm gas clouds, hot? gas in between and surrounded by cold gas.
- (D/H)gas = 15.6±0.4 ppm (Linsky et al. ApJ 647, 1106 (2006)).
- But not so simple.

Maps of the Local Bubble (white: warm or hot gas; dark: cold NaI absorption) from Lallement et al. A+A 411, 447 (2003). Left: as seen from NGP. Right: as seen from Galactic plane.



$(D/H)_{gas}$ in Galactic halo

- Galactic halo gas in line of sight to QSO HE 0226-4110 shows $(D/H)_{gas}=22^{+8}_{-6}$ ppm (Savage et al. ApJ 659, 1225 (2007)).
- Galactic halo gas in line of sight to HD 93521 shows $(D/H)_{gas}=18.5^{+2.2}_{-1.0}$ ppm (Kruk et al. ASP 348, 85 (2006)).
- High velocity cloud Complex C shows $(D/H)_{gas}=22\pm7$ ppm (Sembach et al. ApJS 150, 387 (2004)).
- Toward 31 Com (b=89) $(D/H)_{gas}=20.2\pm1.9$ ppm.
- Toward β Cet (b=-81) $(D/H)_{gas}=21.9^{+5.2}_{-6.8}$ ppm.

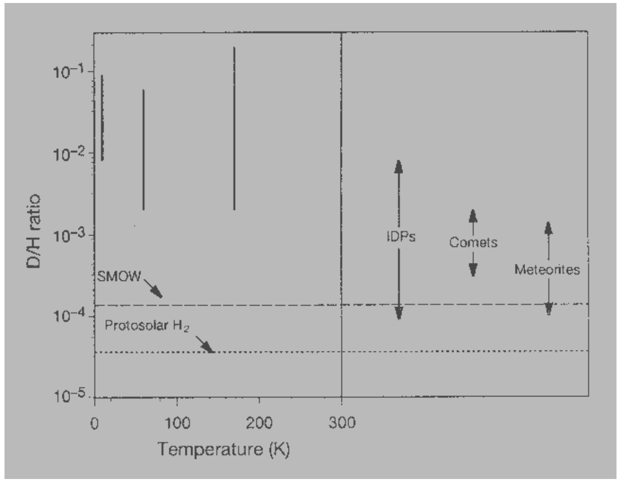

D/H (ppm) in or out of LB
0
5
10
15
20
25
30
Log N(H I)
18.0
18.5
19.0
19.5
20.0
20.5
21.0
Quasar absorption lines (2008)
5-year WMAP (2009)
(Beta Cet)
(-81)
31 Com
(+89)
Copernicus
HST
IMAPS
FUSE
Inside LB
Outside LB

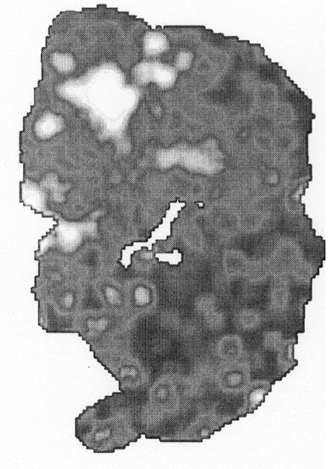
Theoretical Justification for Deuterium Depletion onto Grains

- The binding energy for C-D is 0.092 eV larger than for C-H.
- The binding energy for H-D is 0.035 eV larger than for H-H.
- In thermodynamic equilibrium: $(D/H)_{dust}/(D/H)_{tot} = e^{[(0.092-0.035eV)/kT]} > 10^4$ for $T_{dust} < 70$ K.
- Dust is usually cold, $T_{dust} \sim 20$ K.
- Enough C in interstellar grains to reduce $(D/H)_{gas}$ by ~10 ppm.
- But the ISM is dynamic and generally out of thermodynamic equilibrium.
- See papers by Draine (2003, 2004) and Jura (1982).
- Likely scenario: D depletion when ISM is undisturbed (cools), but dust evaporates when strong shocks or near a hot star.
- Timescale for D capture by grains in cold neutral clouds (30 cm^{-3}) is ~2 Myr. For warm neutral medium (0.3 cm^{-3}) is ~50 Myr.

Evidence for high D/H in interstellar carbonaceous grains

- Interplanetary dust particles (IDPs) are presolar system material from the ISM.
- Carbon-rich dust grain inclusions have D/H up to 16,500 ppm (Keller et al JGR 105, 10397, 2000).
- Proof of concept that D can be depleted on to grains in the ISM.



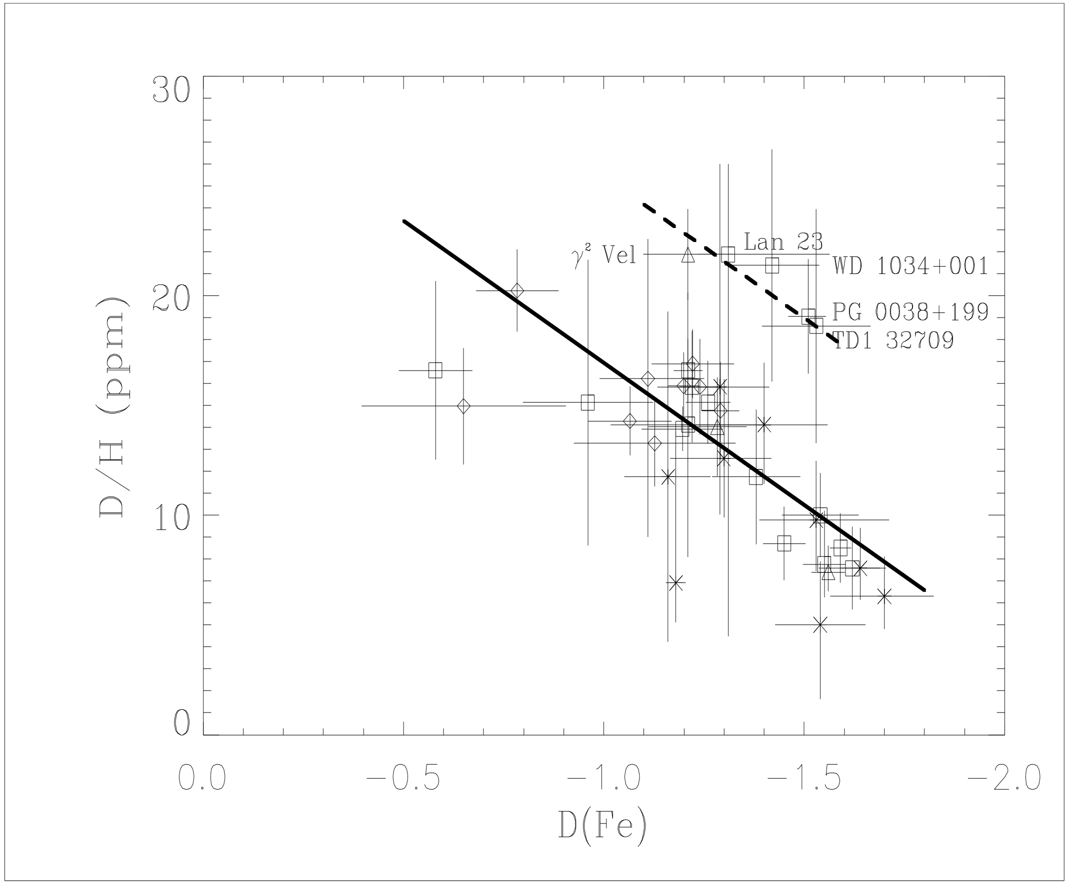


Empirical tests for the deuterium depletion scenario

- If D is depleted onto grains, then $(D/H)_{gas}$ should correlate with other elements that deplete onto grains like Fe, Si, and Ti.
- Grains more likely in dense regions, so $(D/H)_{gas}$ should correlate with density (Oliveira et al. ApJ 642, 283 (2006)).
- Warm gas indicates a recent shock or high radiation, so $(D/H)_{gas}$ should correlate with gas temperature, i.e., $T(H_2)$.
- γ^2 Vel located near a large H II region and near the Vela SNR (hot gas). So, expect D to be evaporated from grains and high $(D/H)_{gas}$.

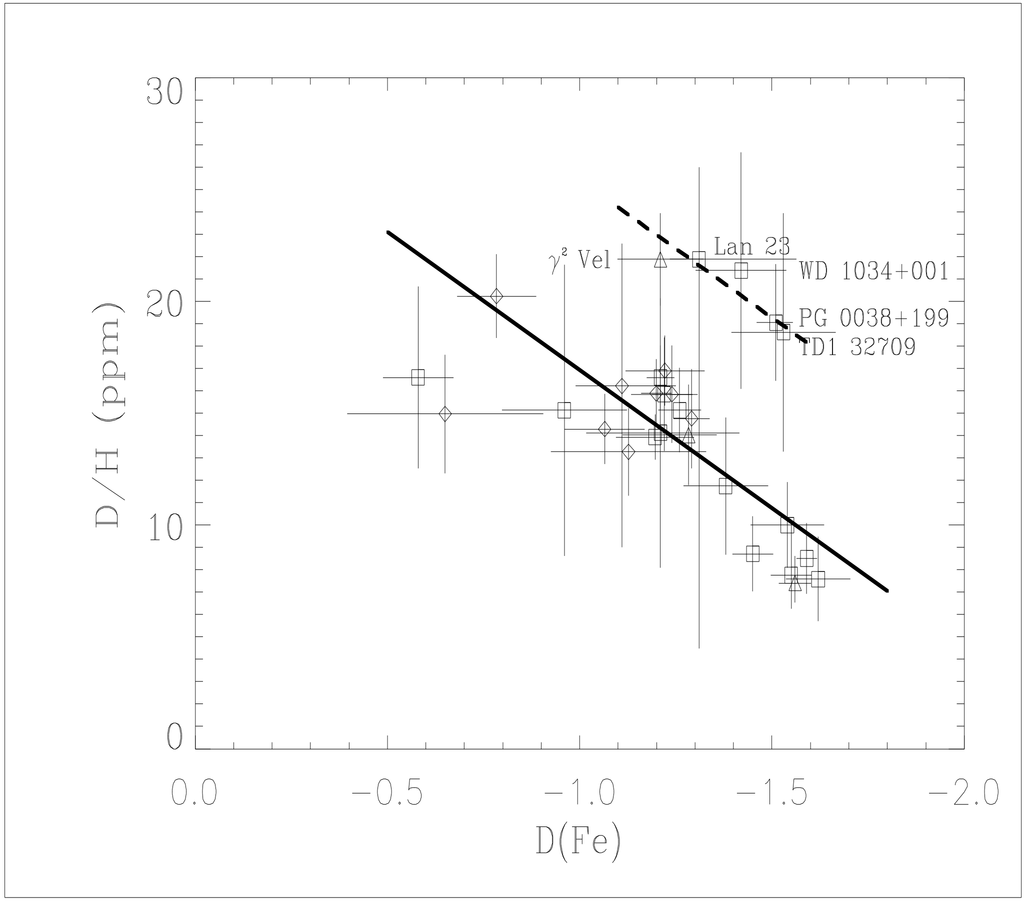
Test No.1: $(D/H)_{gas}$ vs Fe depletion

- Spearman test rejects no correlation at 99.8% (2.9σ).
- Excellent correlation with a few high points.
- Fe likely in grain cores and hard to vaporize.
- D in mantles of carbon grains.



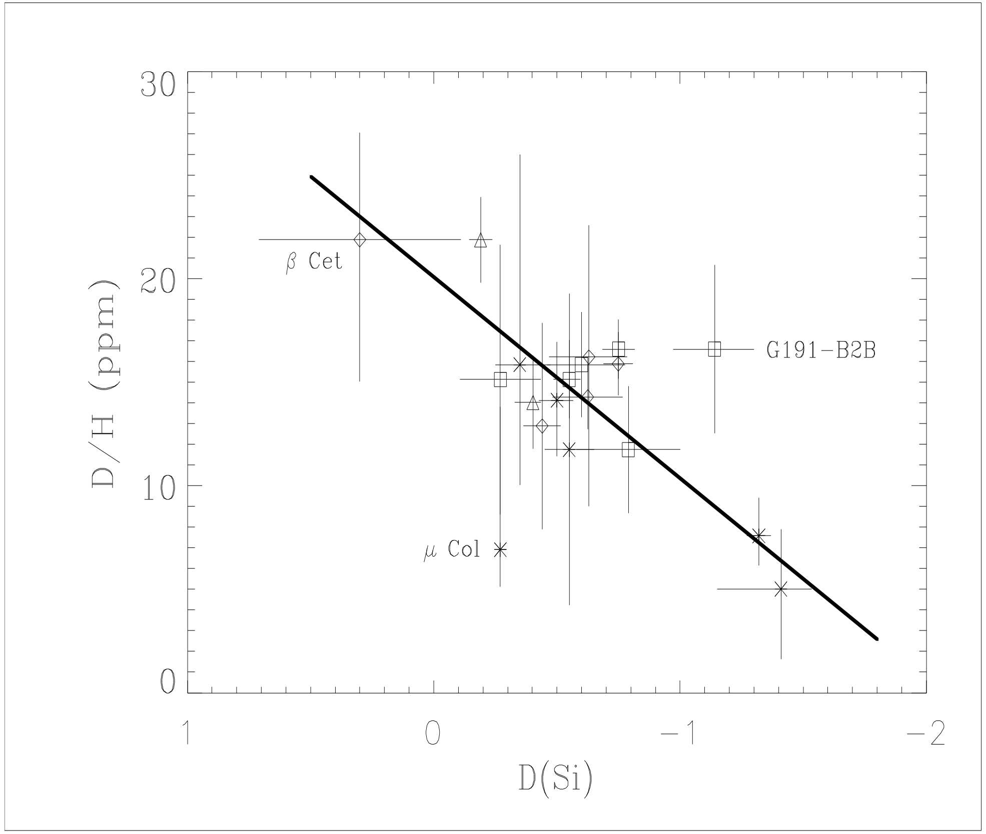
(D/H)$_{gas}$ vs Fe depletion using only STIS, GHRS, IMAPS, and FUSE data

- Spearman test rejects no correlation at 96.8% (2.1σ).
- Removal of the old Copernicus data points does not change the results.



Test No. 2: $(D/H)_{gas}$ vs Si depletion

- Spearman test rejects no correlation at 84.3% confidence (1.4σ).
- De(Si)>0.0 likely due to H being partially ionized (β Cet).
- $(D/H)_{gas}$ low where D depleted onto grains.

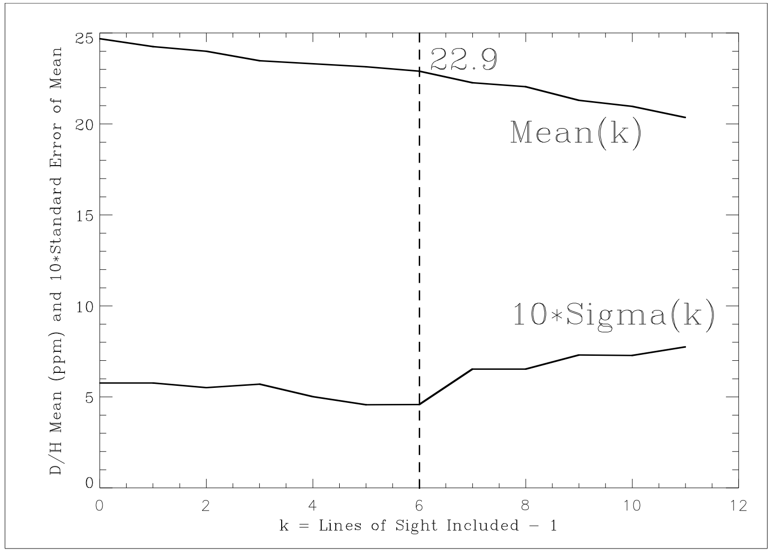


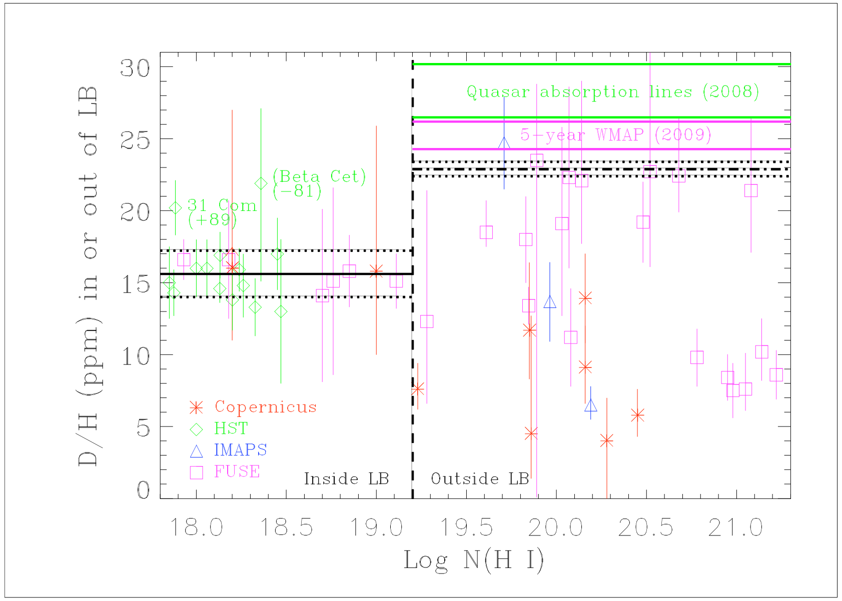
Possible causes of scatter in the correlation plots

- ISM is inhomogeneous – different quantities can be more/less important in different velocity components along LOS.
- Ionization effects – IP (Fe+, Si+, Ti+) > 13.6 eV, so H ionizes before they do. Could explain why De(Si)>0.0 and De(Fe)>-0.5 for some LOS.
- D likely condenses onto C grain mantles and easily vaporized while Fe, Si, and Ti in cores of other grains that hard to vaporize.
- Line saturation can lead to uncertain column densities.

If low values of $(D/H)_{gas}$ outside of the Local Bubble are due to depletion of D, then high values are for lines of sight with small D depletion

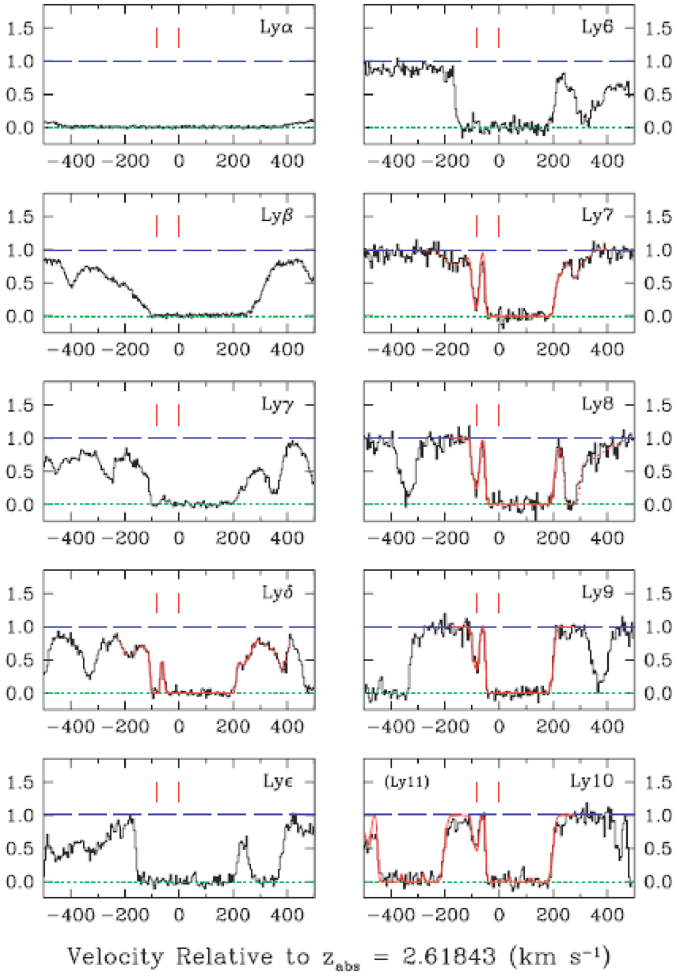
- What is best value of $(D/H)_{gas}$ for low depletion lines of sight?
- Upper plot is weighted mean and standard error of the weighted mean as a function of number of data points included starting with highest.
- Error smallest for 7 points included.
- $(D/H)_{gas} \geq 22.9 \pm 0.5$ ppm





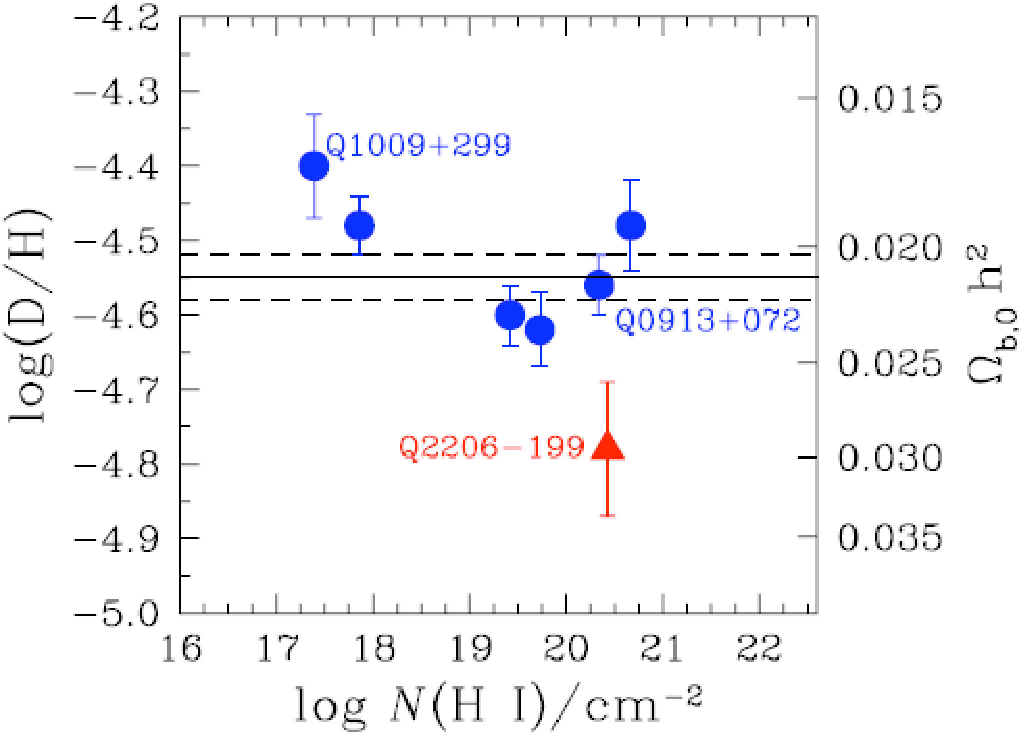
$(D/H)_{gas}$ from Lyman series quasar absorption lines (QAL)

- QSO 0913+072 (z_{abs}=2.61843) metal-poor system (1/250 solar).
- Pettini et al. (MNRAS 391, 1499 (2008)).
- Log N(DI)=15.78±0.02
- Log N(HI)=20.34±0.04
- Notes: N(HI) more uncertain than N(DI) and HI at -81 km/s will look like DI.



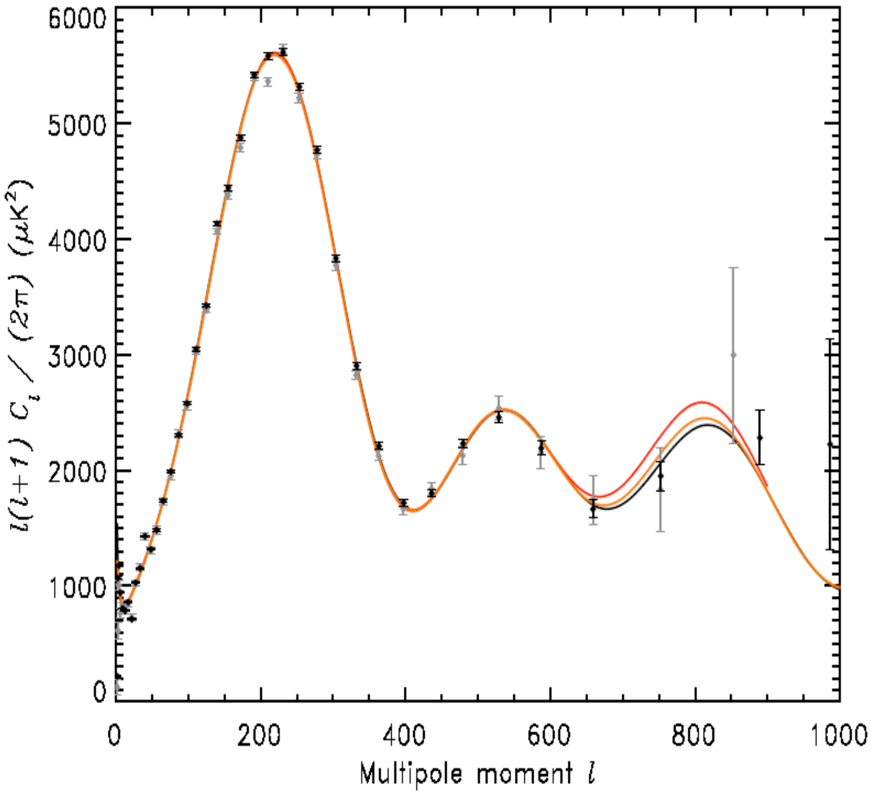
Summary of QAL studies of $(D/H)_{gas}$ from Pettini et al. (2008)

- $\log(D/H)_{qal}$ $= -4.55 \pm 0.03$
- $(D/H)_{qal}$ $= 28.2^{+2.0}_{-1.8}$ ppm
- $\Omega_{b,0}h^2(\mathrm{BBN})$ $= 0.0213 \pm 0.0009$
- $\eta_{10} = 5.84 \pm 0.27$
- Need more data!



Testing the standard model of cosmology with data from the Wilkinson Microwave Anisotropy Probe (WMAP) and other data sets

- Black data points are measured angular power spectrum from 3 years of WMAP data.
- Orange line is best fit to the WMAP and other microwave background data.
- Compare the primordial acoustic fluctuation data to predictions of cosmological models with a range of parameters (Ω_m, Ω_b, Ω_Λ, etc.).



Spergel et al. (ApJS 170, 377 (2007))

The Challenge for Galactic Chemical Evolution models

- If $(D/H)_{prim} = (D/H)_{qal} = 28.2^{+2.0}_{-1.8}$ ppm, then ≥81±7% of D atoms in the Galactic disk are unprocessed.
- If $(D/H)_{prim} = (D/H)_{WMAP} = 25.2 \pm 1.1$ ppm, then ≥91±6% of D atoms in the Galactic disk are unprocessed.
- Unprocessed means either initially present in the early Galaxy and accreted since then. Probably requires an accretion rate ~1M /yr (close to current star formation rate (Prodanovic & Fields JCAP 2008)

Is concordance possible?

Method	D/H (ppm)	$100\Omega_{b,0}h^2$	η_{10}
ISM (high 7)	$\geq 22.9 \pm 0.5$	$\leq 2.411 \pm 0.33$	$\leq 6.604 \pm 0.090$
QAL (7 LOS)	$28.2^{+2.0}_{-1.8}$	2.13±0.09	5.84±0.27
WMAP (5 years)	25.2±1.1	2.273±0.062	6.225±0.170