Measurements of Deuterium in the Milky Way

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Deuterium and the Big Bang

- Most of the deuterium in the Universe was created in the Big Bang with an abundance D/H ~ 26-28 ppm [BBN: H, ^{4}He, D, ^{3}He, ^{7}Li]

Nucleosynthesis

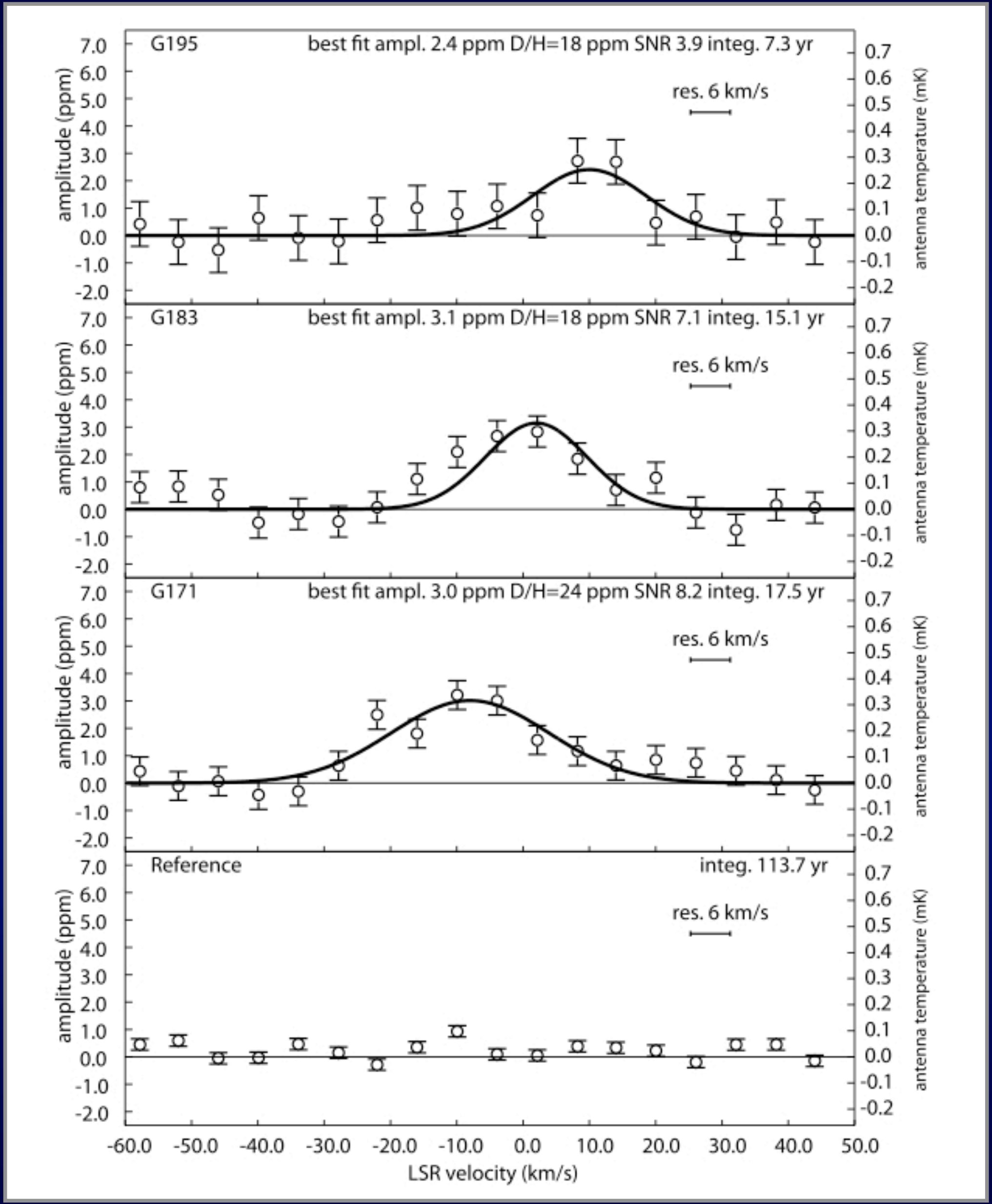
At kT ~ 1 MeV (1 second)	$n + e^+$	$\leftrightarrow$	$p + \nu_e$
	$p + e^-$	$\leftrightarrow$	$n + \nu_e$
	n	$\leftrightarrow$	$p + e^- + \nu_e$
At kT ~ 0.3 MeV	$p + n$	$\rightarrow$	$D + \gamma$
	$D + D$	$\rightarrow$	$^3He + n$, $^3H + p$
At kT ~ 0.1 MeV (100 second)	$^3He + D$	$\rightarrow$	$^4He + p$
	$^3H + D$	$\rightarrow$	$^4He + n$
	$^3H + {}^4He$	$\rightarrow$	$^7Li + \gamma$
	$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$
	$^7Be + n$	$\rightarrow$	$^7Li + p$
	$^7Li + p$	$\rightarrow$	$^4He + {}^4He$

D I Hyperfine Structure Transition

- D I hyperfine structure transition at 327.38 MHz (92 cm)
  - Weinreb 1962 (Nature, 195, 367)
  - Wineland & Ramsey 1972 (PhysRevA, 5, 821)
  - Anantharamaiah & Radhakrishnan 1979 (A&A, 79, L9)
  - Blitz & Heiles 1987 (ApJ, 313, L95)
  - Lubowich et al. 1989 (ApJ, 345, 770)
  - Heiles et al. 1993 (ApJS, 89, 271)
  - Chengalur, Braun, & Burton 1997 (A&A, 318, L38)

<u>General result</u>: N(D I) / N(H I) < $(4\text{-}8)\times10^{-5}$

  - Rogers et al. 2005 (ApJ, 630, L41)
  - Rogers et al. 2007 (AJ, 133, 1625)

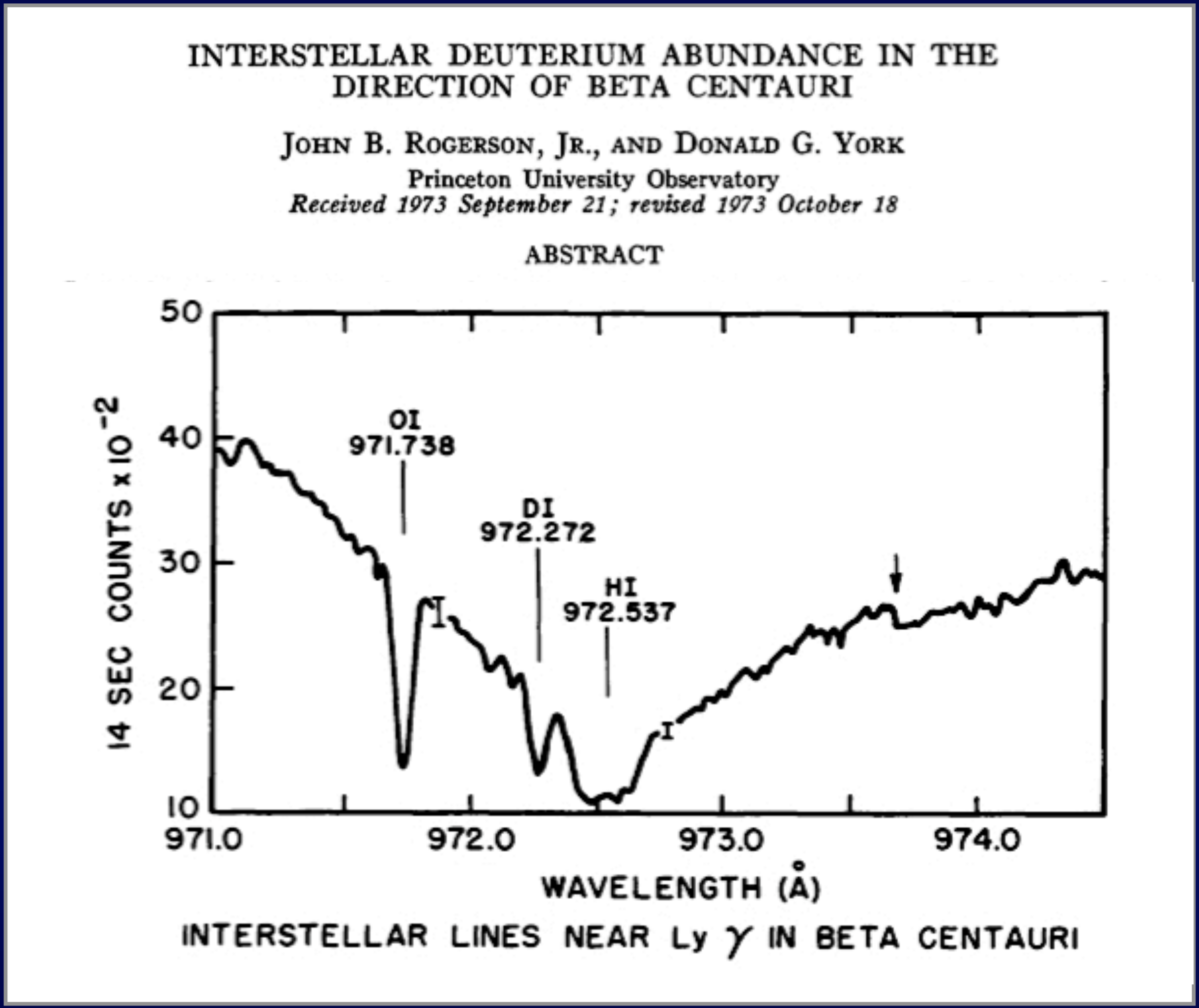


Rogers, Dudevoir, & Bania 2007
AJ, 133, 1625

Look in direction of Galactic anti-center

Array of 24 antennae built specifically to look for D I 327 MHz emission

FUV Lyman Series Absorption



INTERSTELLAR DEUTERIUM ABUNDANCE IN THE DIRECTION OF BETA CENTAURI

John B. Rogerson, Jr., and Donald G. York
Princeton University Observatory
Received 1973 September 21; revised 1973 October 18

ABSTRACT

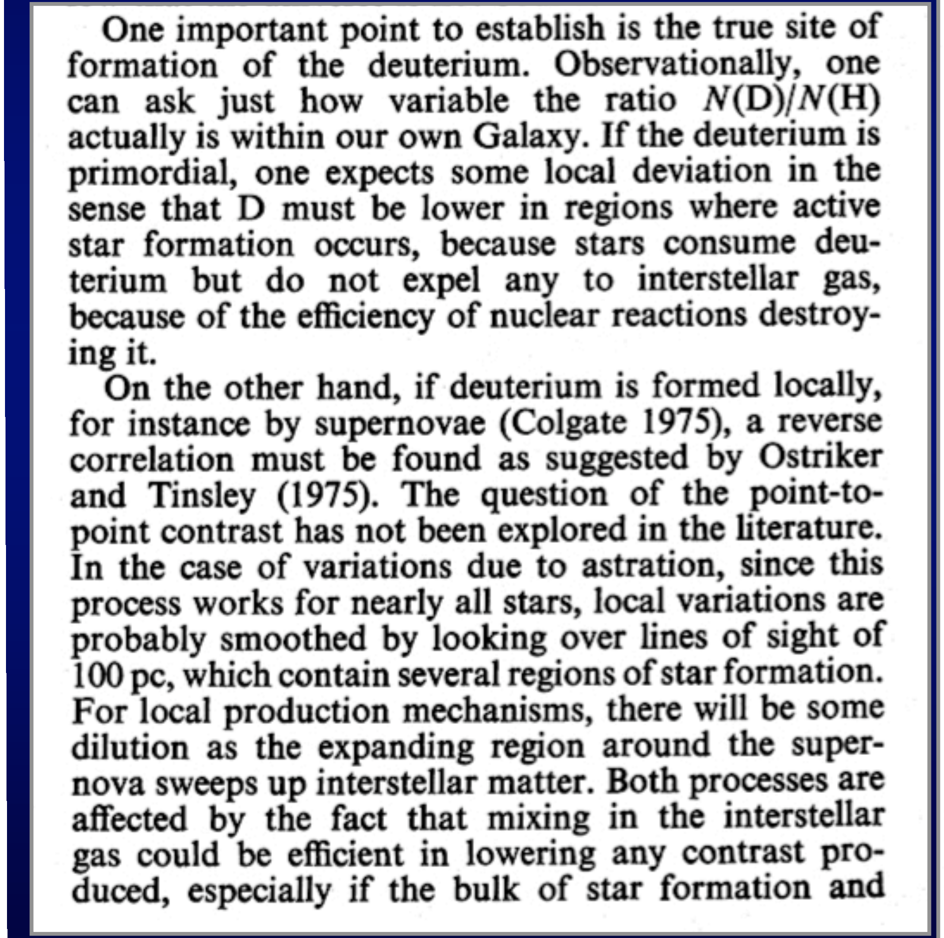
INTERSTELLAR LINES NEAR Ly γ IN BETA CENTAURI

1973
ApJ, 186, L95

Followed soon thereafter by York & Rogerson (1976, ApJ, 203, 378)

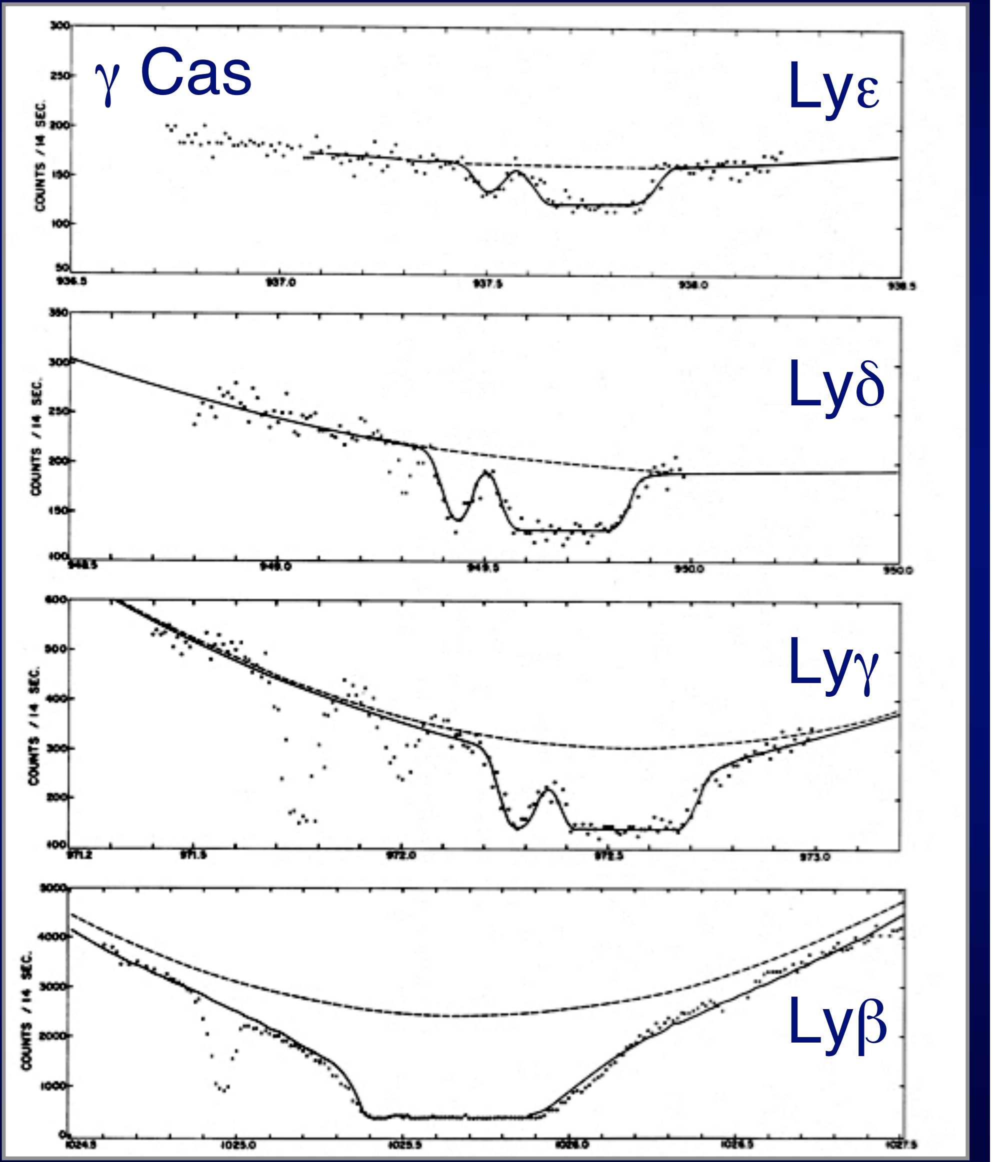
FUV Lyman Series Absorption

Vidal-Madjar et al. 1977
(ApJ, 91, 211)



One important point to establish is the true site of formation of the deuterium. Observationally, one can ask just how variable the ratio $N(\mathrm{D})/N(\mathrm{H})$ actually is within our own Galaxy. If the deuterium is primordial, one expects some local deviation in the sense that D must be lower in regions where active star formation occurs, because stars consume deuterium but do not expel any to interstellar gas, because of the efficiency of nuclear reactions destroying it.

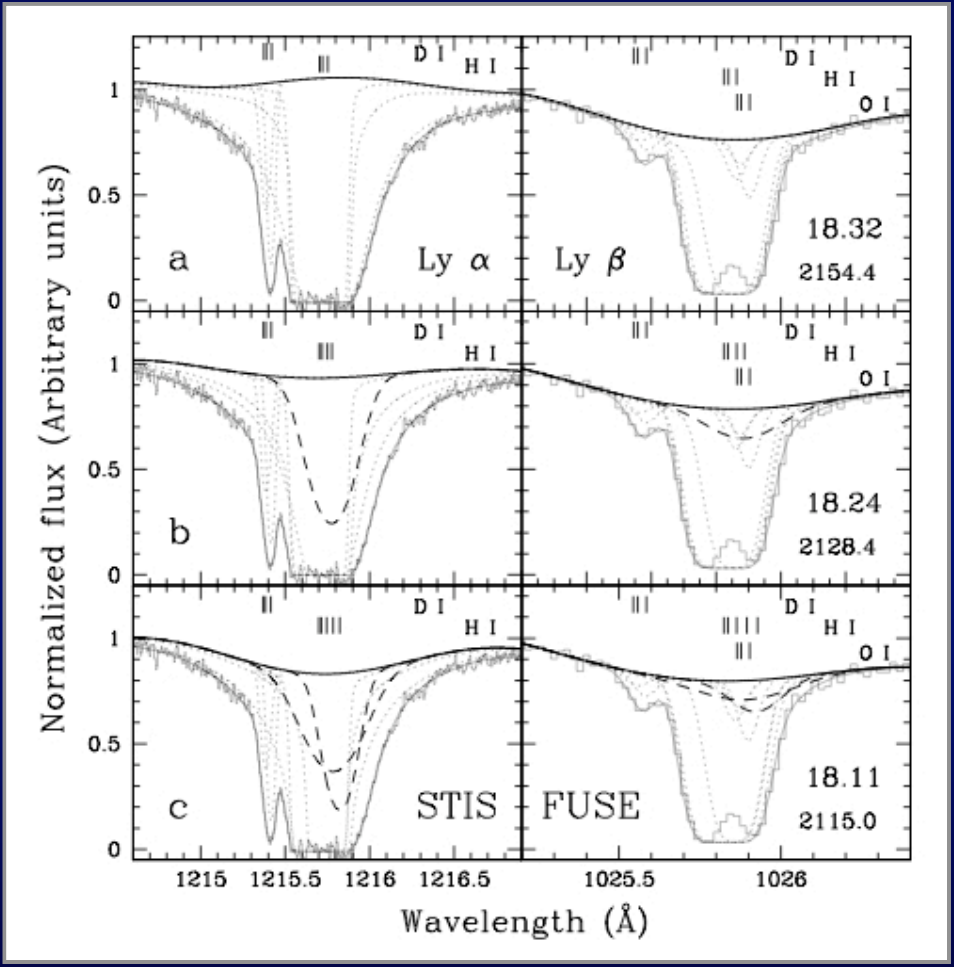
On the other hand, if deuterium is formed locally, for instance by supernovae (Colgate 1975), a reverse correlation must be found as suggested by Ostriker and Tinsley (1975). The question of the point-to-point contrast has not been explored in the literature. In the case of variations due to astration, since this process works for nearly all stars, local variations are probably smoothed by looking over lines of sight of 100 pc, which contain several regions of star formation. For local production mechanisms, there will be some dilution as the expanding region around the supernova sweeps up interstellar matter. Both processes are affected by the fact that mixing in the interstellar gas could be efficient in lowering any contrast produced, especially if the bulk of star formation and



FUSE Observations of D/H and D/O

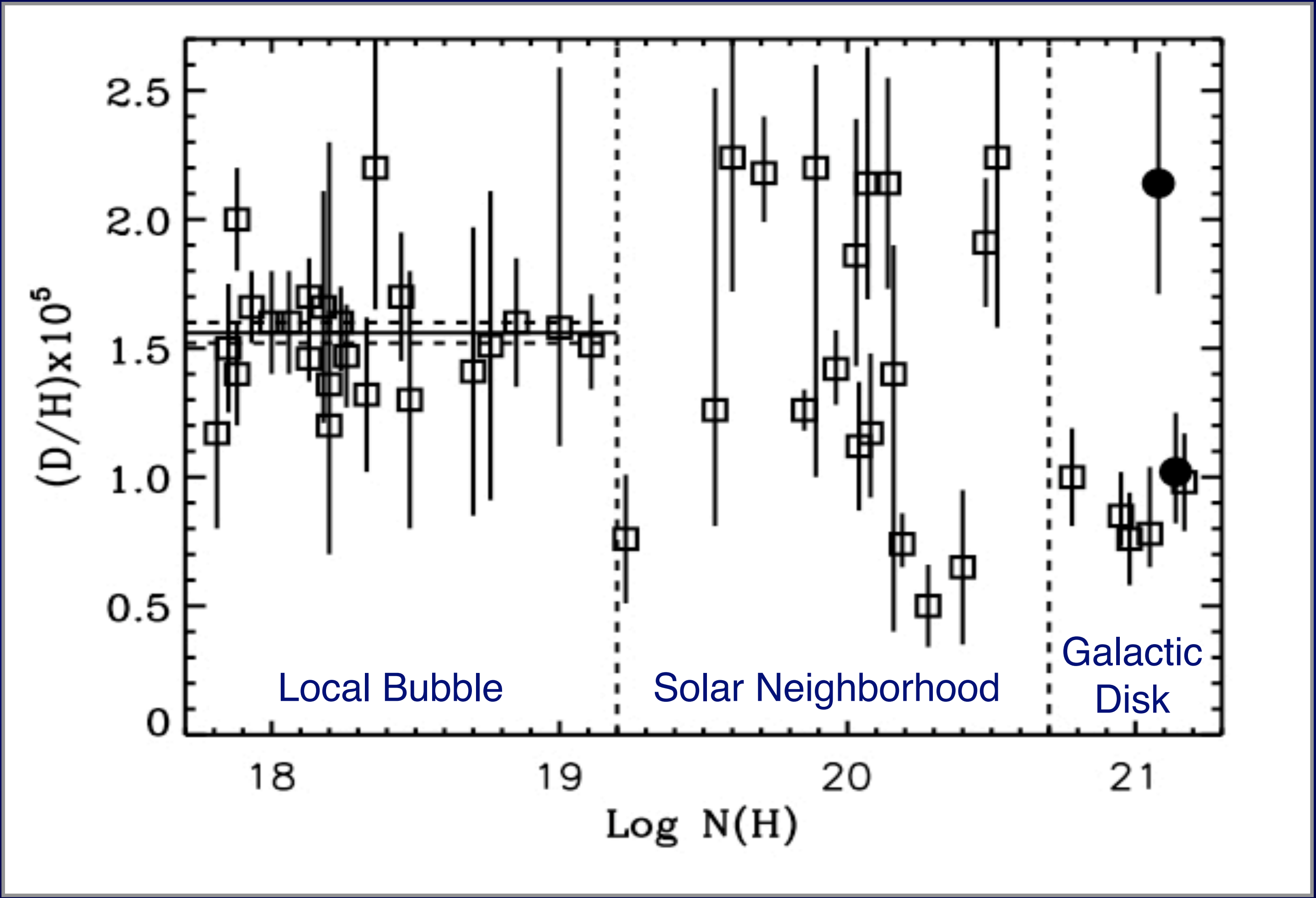
2002 ApJS v.140 Special Issue
First Results from FUSE
on the
Galactic Deuterium Abundance

Moos et al.
Kruk et al.
Friedman et al.
Sonneborn et al.
Lemoine et al. →
Lehner et al.
Wood et al.
Hébrard et al.

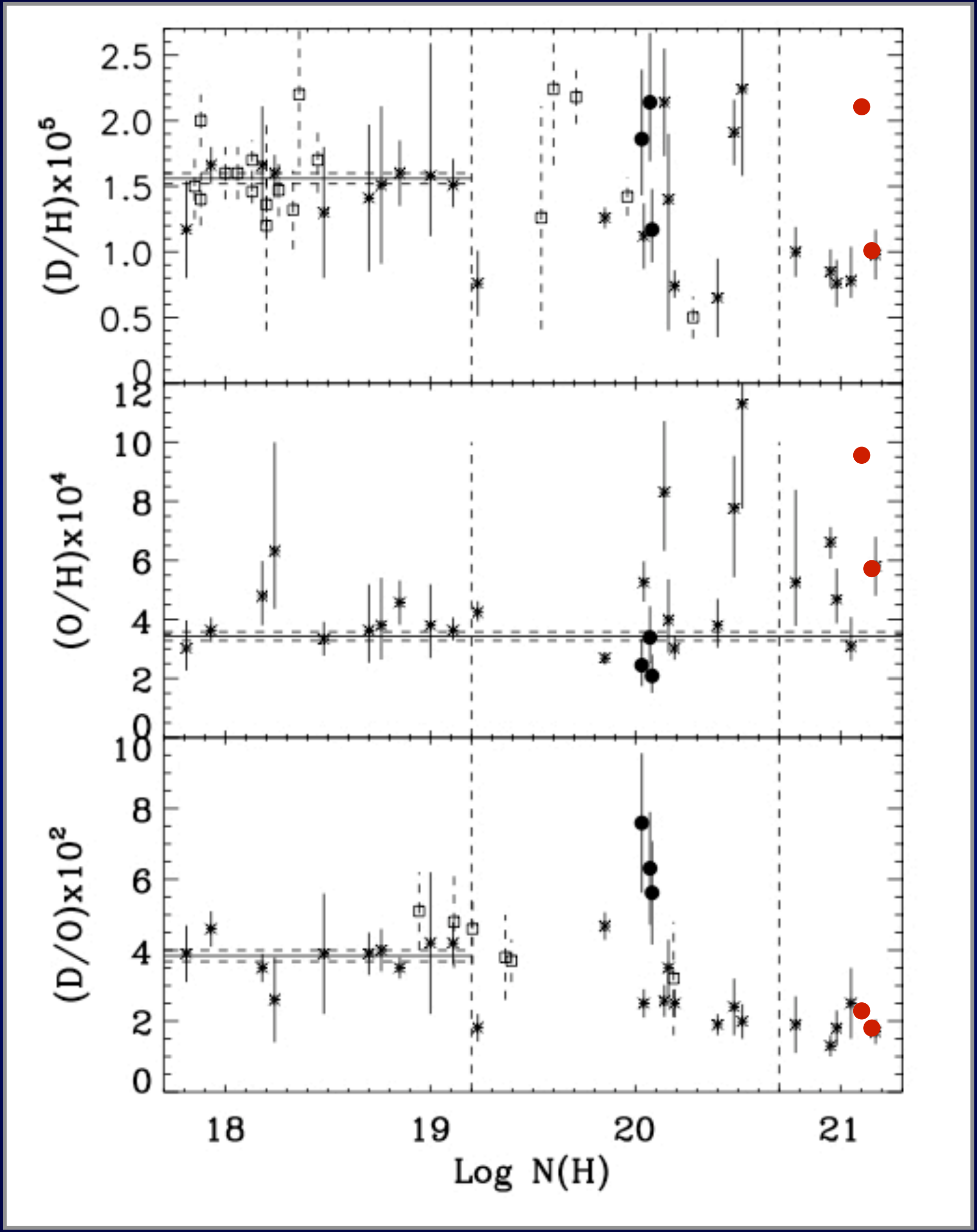


Variations in D/H

D I absorption measured by Copernicus, HST, IMAPS, and FUSE

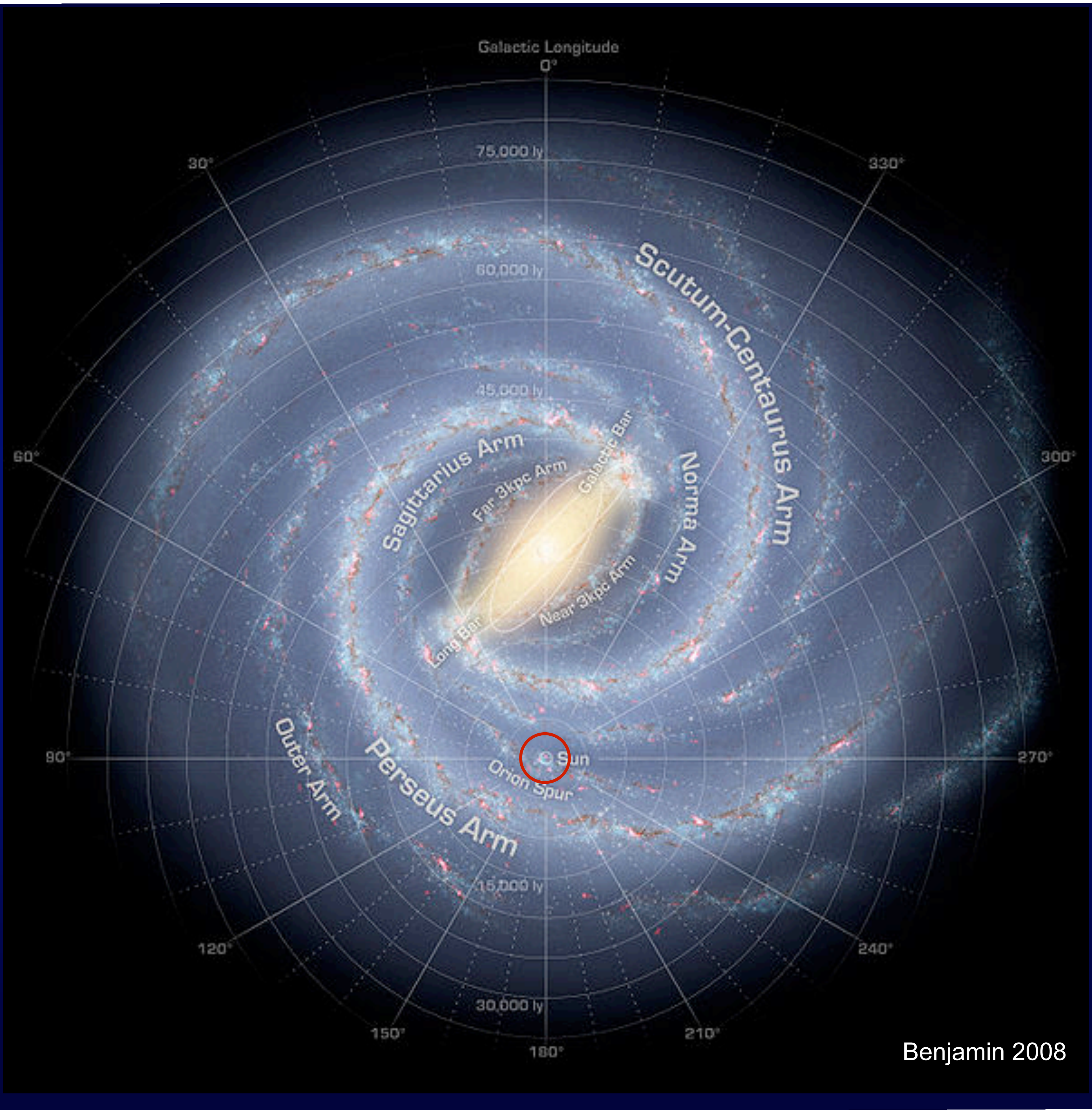


Oliveira & Hébrard 2007, ApJ, 653, 345
Linsky et al 2006, ApJ, 647, 1106

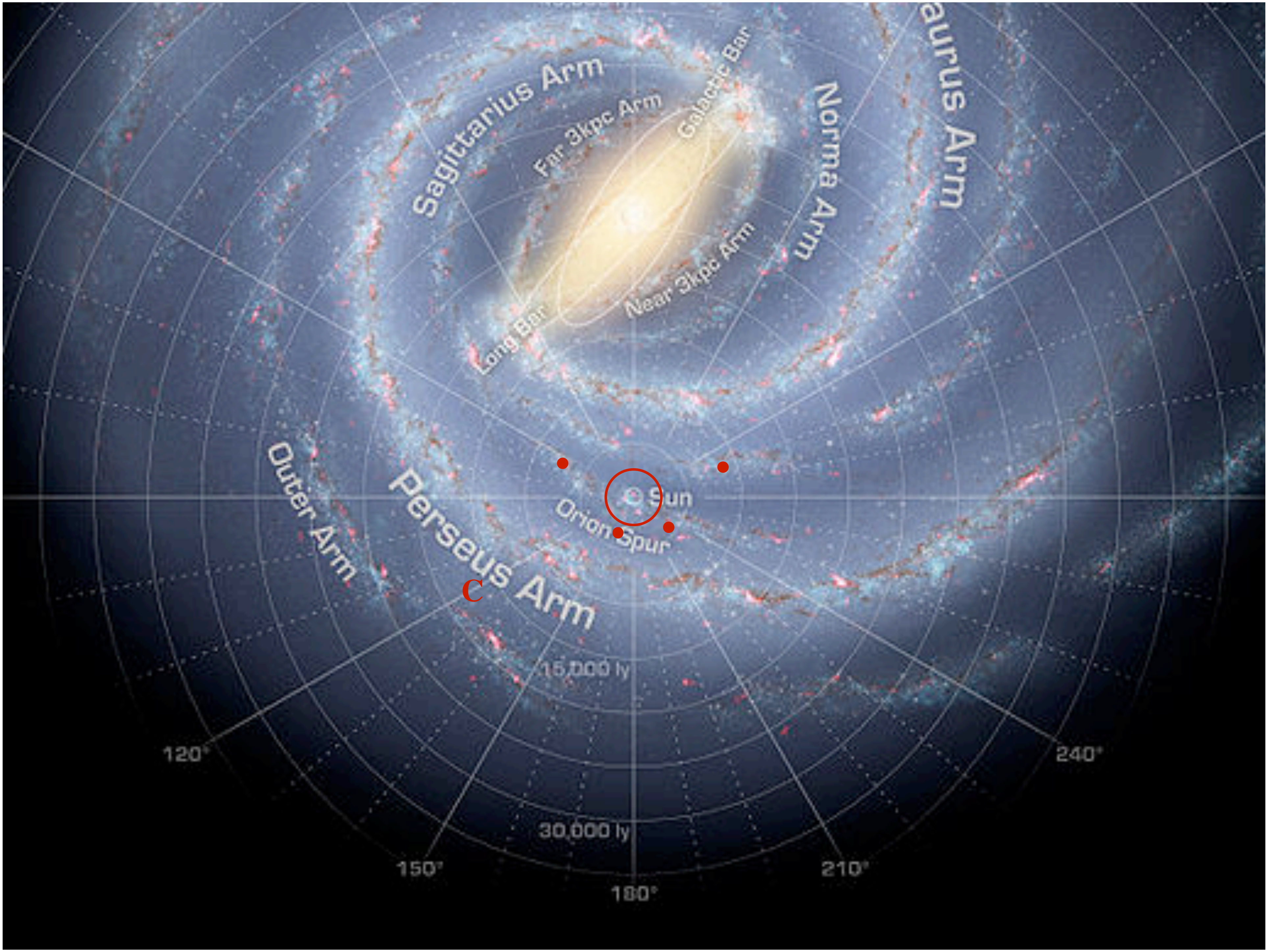


D/H, O/H, and D/O
From Oliveira et al. 2006

● HD 41161 and HD 53975 from Oliveira & Hébrard 2007



Benjamin 2008


Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
aurus Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
C
15,000 ly
30,000 ly
120°
150°
180°
210°
240°

Variations in the Deuterium Abundance

- Incorporation of D into carbonaceous grains (PAHs → PADs)
  (Jura 1982; Tielens 1983; Draine 2004, 2006)
  - Incorporation of D occurs in molecular clouds
    - Extreme deuteration (factor of >10,000) is necessary, possible
  - D released back to gas-phase at later times
  - Expect correlation of D/H with [X/H], where X = refractory element

- Chemical chemical evolution (astration) of D
  (Steigman, Tosi, Romano, Prodanovic, Fields, Chiappini, Matteucci, ...)
  - Constrained by stellar and gas-phase abundances, star-formation rate, IMF, etc.
  - Often include effects of infalling (usually pristine) gas
  - Generally find astration factors of $1.4 < f_D < 1.8$

Simple D Chemistry in Molecular Clouds

- This can get complicated quickly....
  - Watson 1976 (Rev. Mod. Phys., 48, 513)
  - Dalgarno & Lepp 1984 (ApJ, 287, L47)
  - Parise et al. 2009 (A&A, in press)

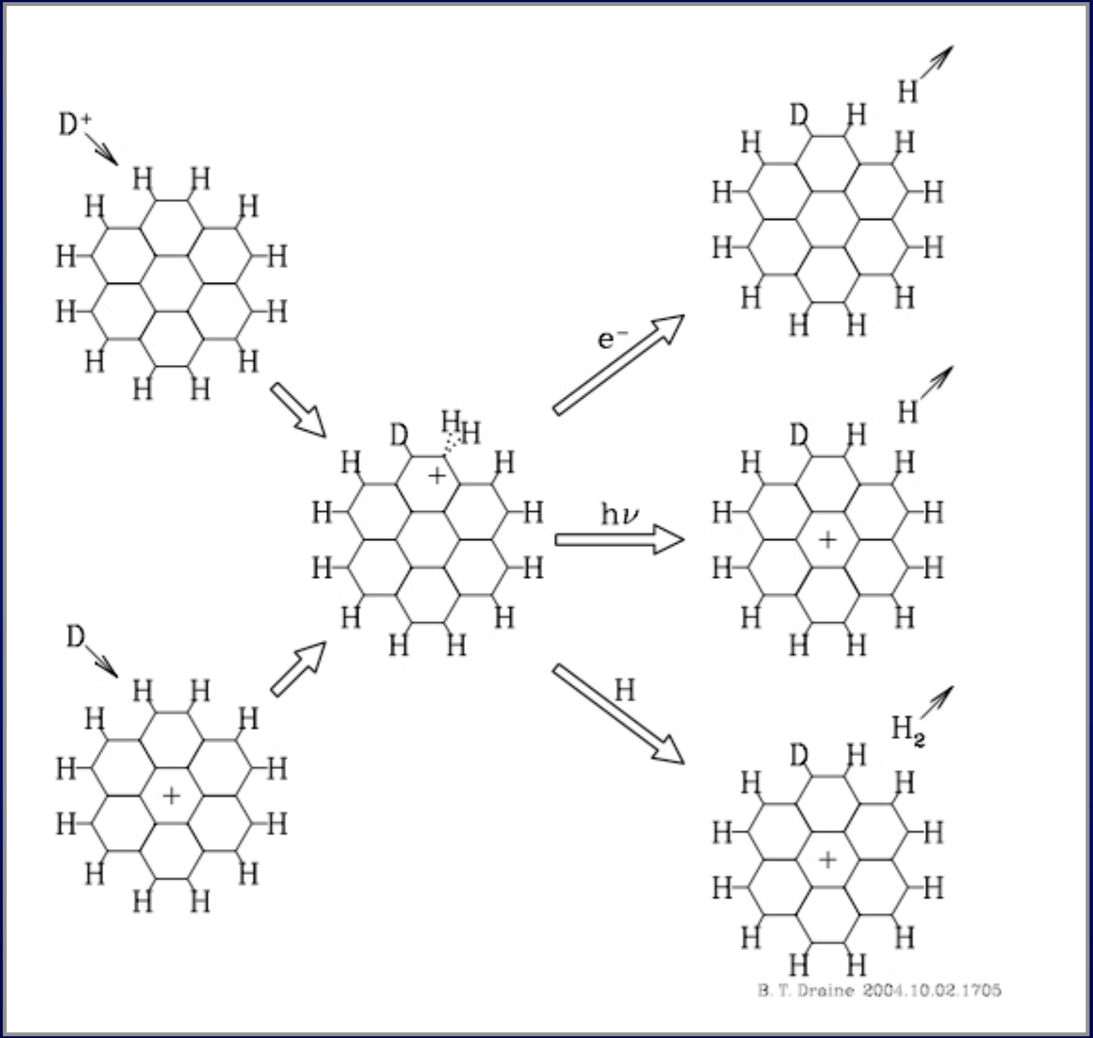
$D + \text{grain} \rightarrow HD$
$H^+ + D \rightarrow D^+ + H$
$D^+ + H_2 \rightarrow H^+ + HD$
$H_3^+ + D \rightarrow H_2D^+ + H$
$H_3^+ + HD \rightarrow H_2 + H_2D^+$
$H_2D^+ + e^- \rightarrow HD + H$ (or $H + H + D$) (or $H_2 + D$)

$H_3^+ + CO \rightarrow HCO^+ + H_2$
$H_2D^+ + CO \rightarrow DCO^+ + H_2$
$H_2D^+ + CO \rightarrow HCO^+ + HD$

$CH_3^+ + HD \rightarrow CH_2D^+ + H_2$
$C_2H_2^+ + HD \rightarrow C_2HD^+ + H_2$

- Chemical fractionation makes it difficult to determine D/H from molecular observations in most dark cloud environments.

Deuteration of PAHs



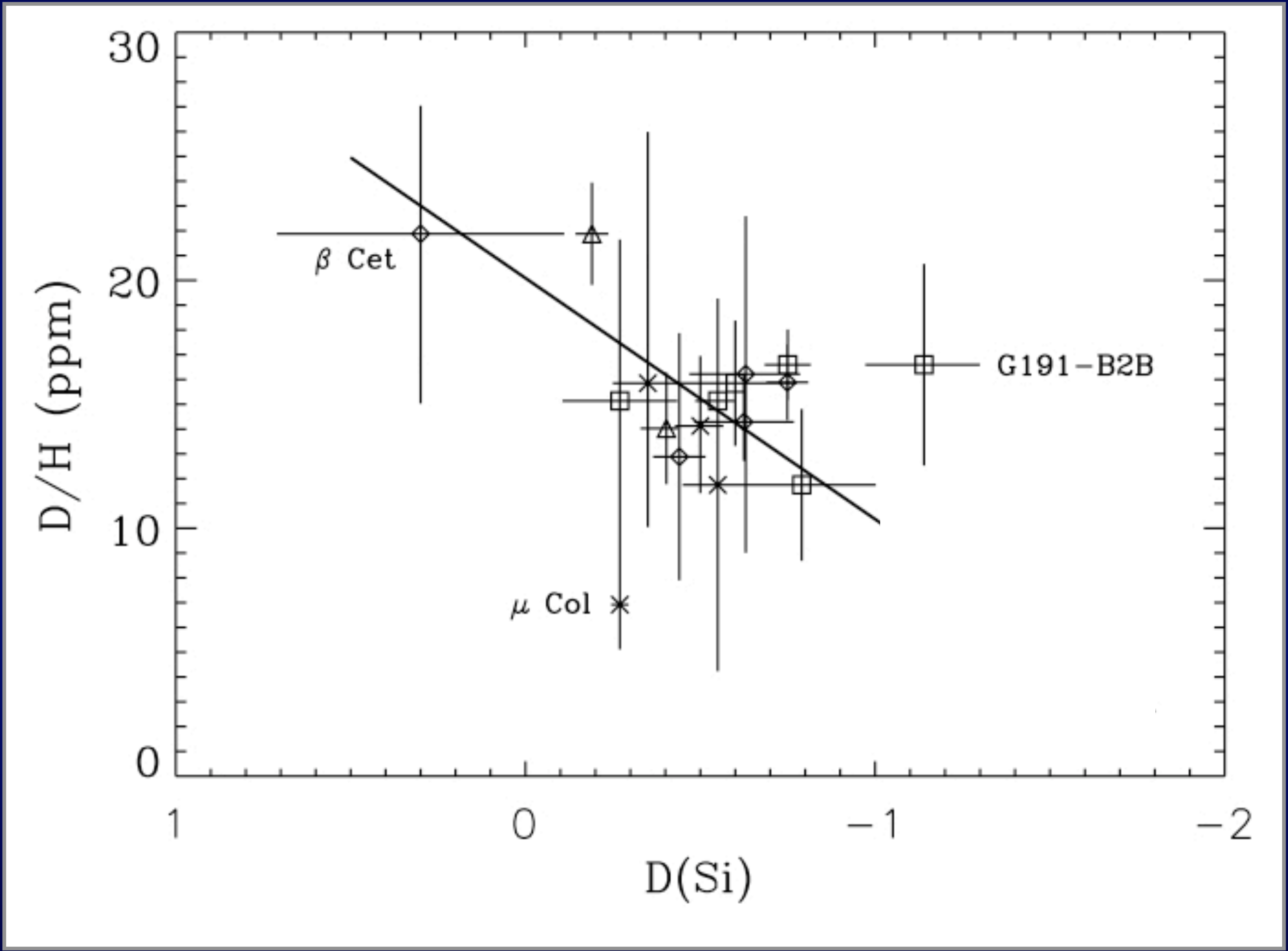
In the CNM:

$D^+ + PAH \rightarrow H\text{-}PAD^+$
$D + PAH^+ \rightarrow H\text{-}PAD^+$

$H\text{-}PAD^+ + e^- \rightarrow PAD + H$
$H\text{-}PAD^+ + \gamma \rightarrow PAD^+ + H$
$H\text{-}PAD^+ + H \rightarrow PAD^+ + H_2$

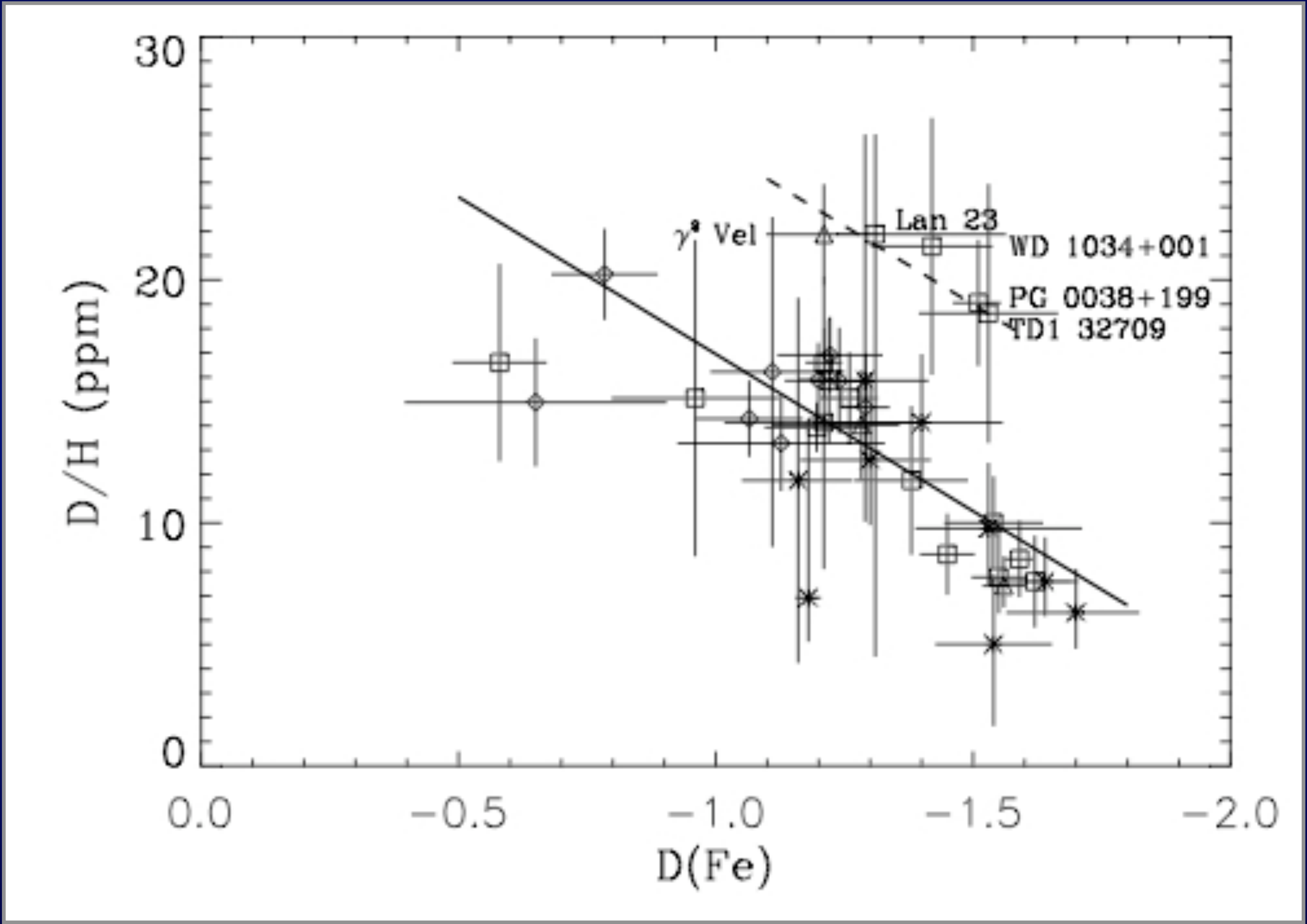
Draine (2006)

D/H vs. Depletion of Si



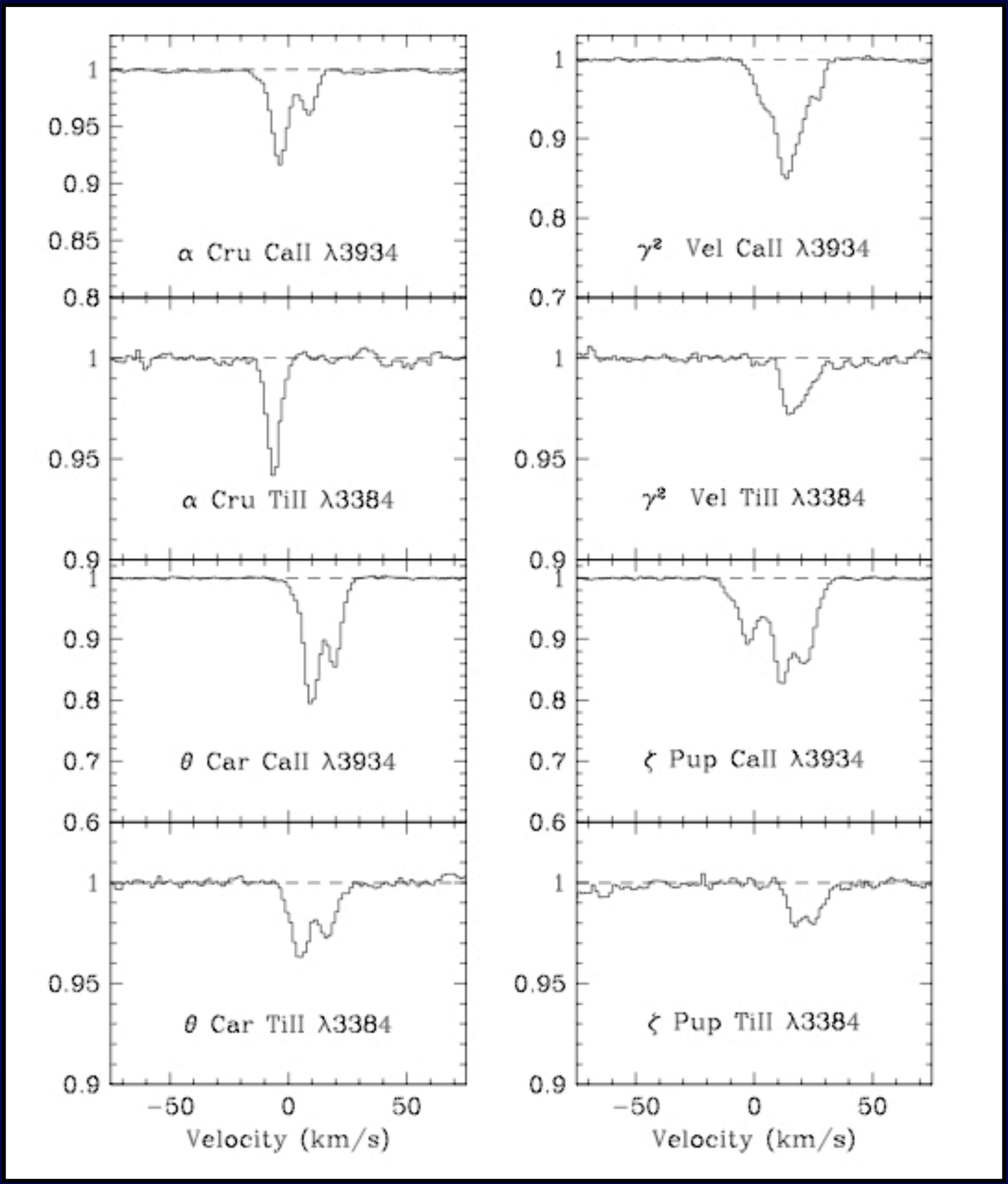
Linsky et al. 2006

D/H vs. Depletion of Fe



Linsky et al. 2006

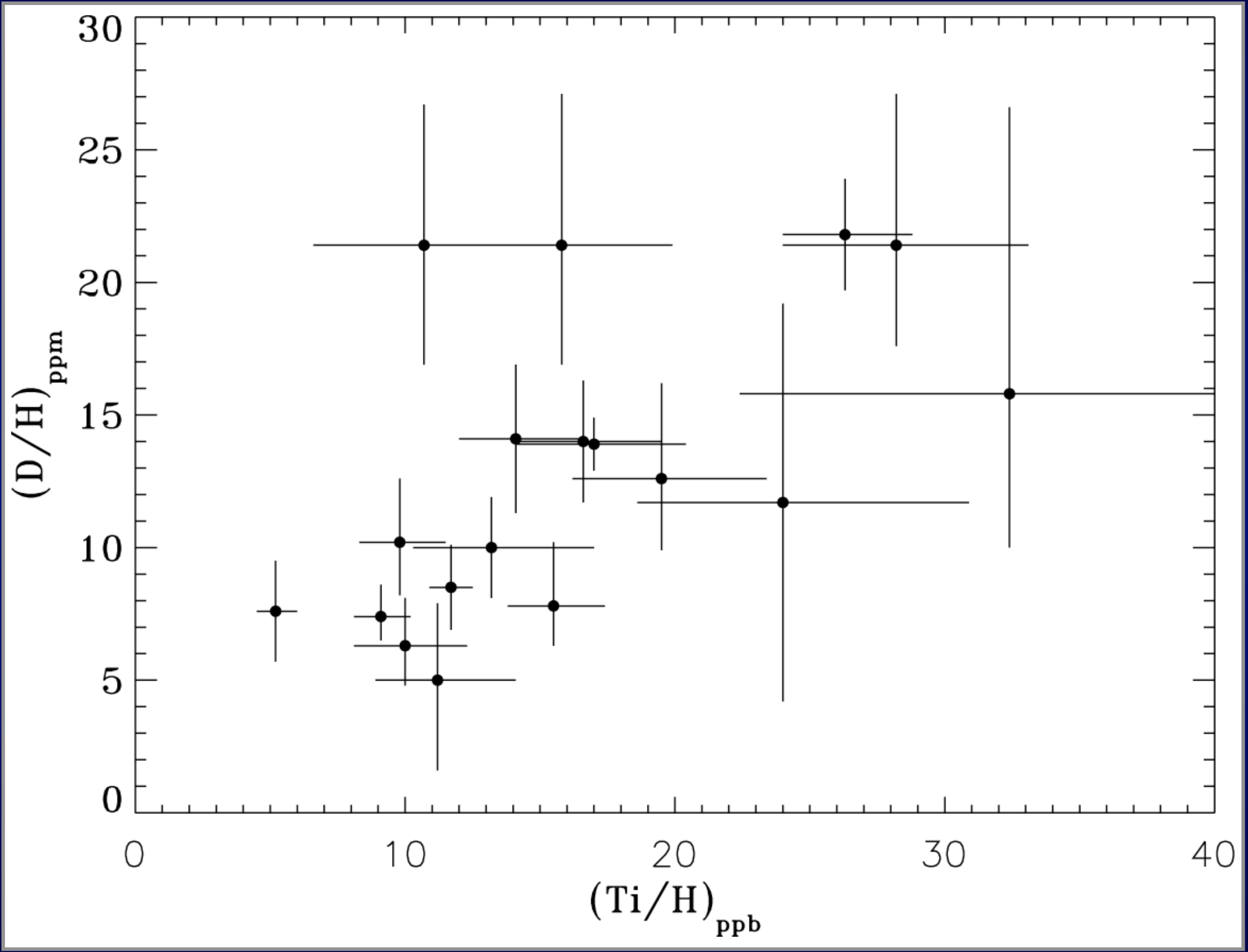
Ti II Profiles



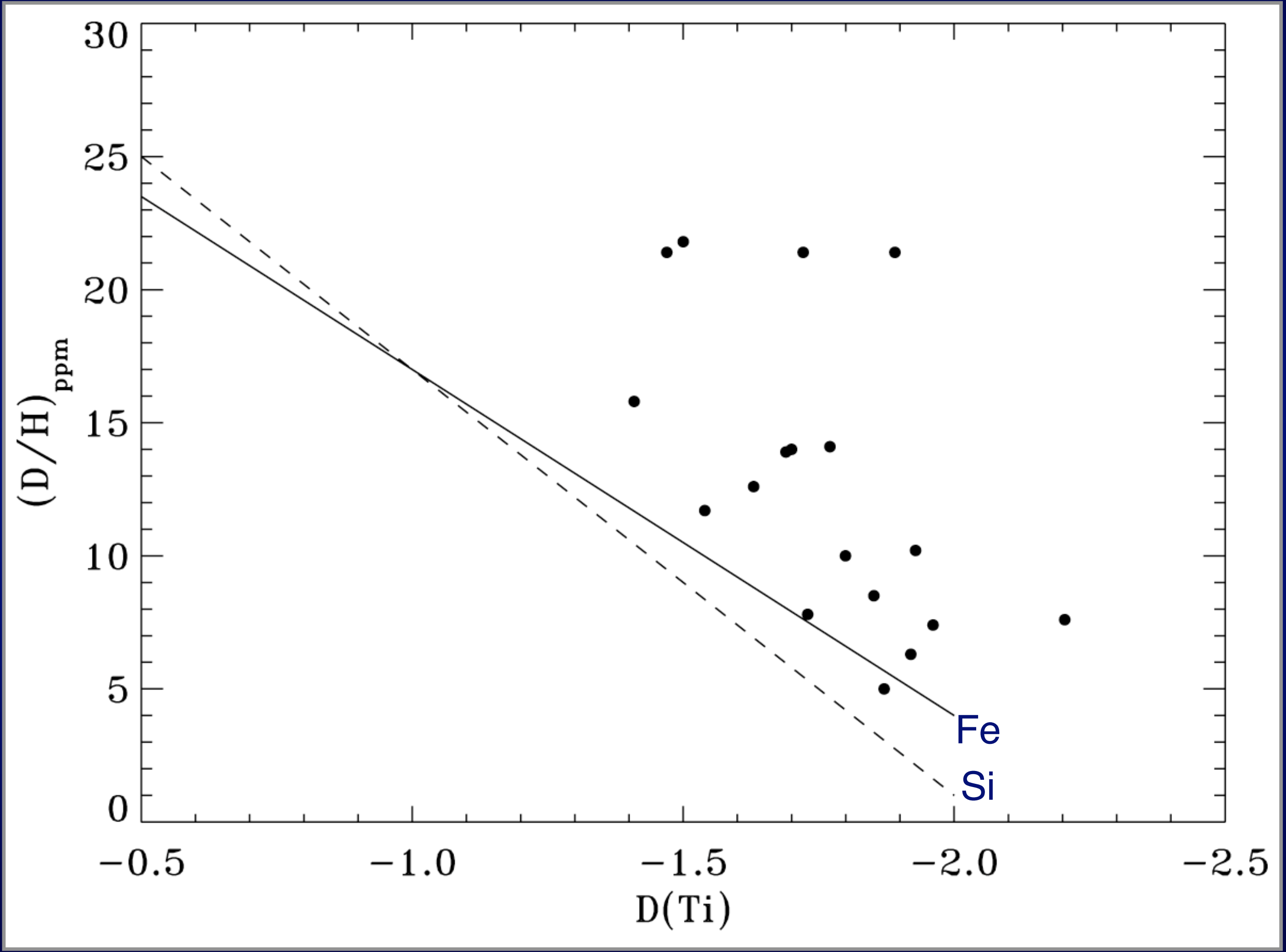
<u>Note</u>:
Narrow features
Line blending
Ca II vs. Ti II

Ellison, Prochaska, & Lopez 2007

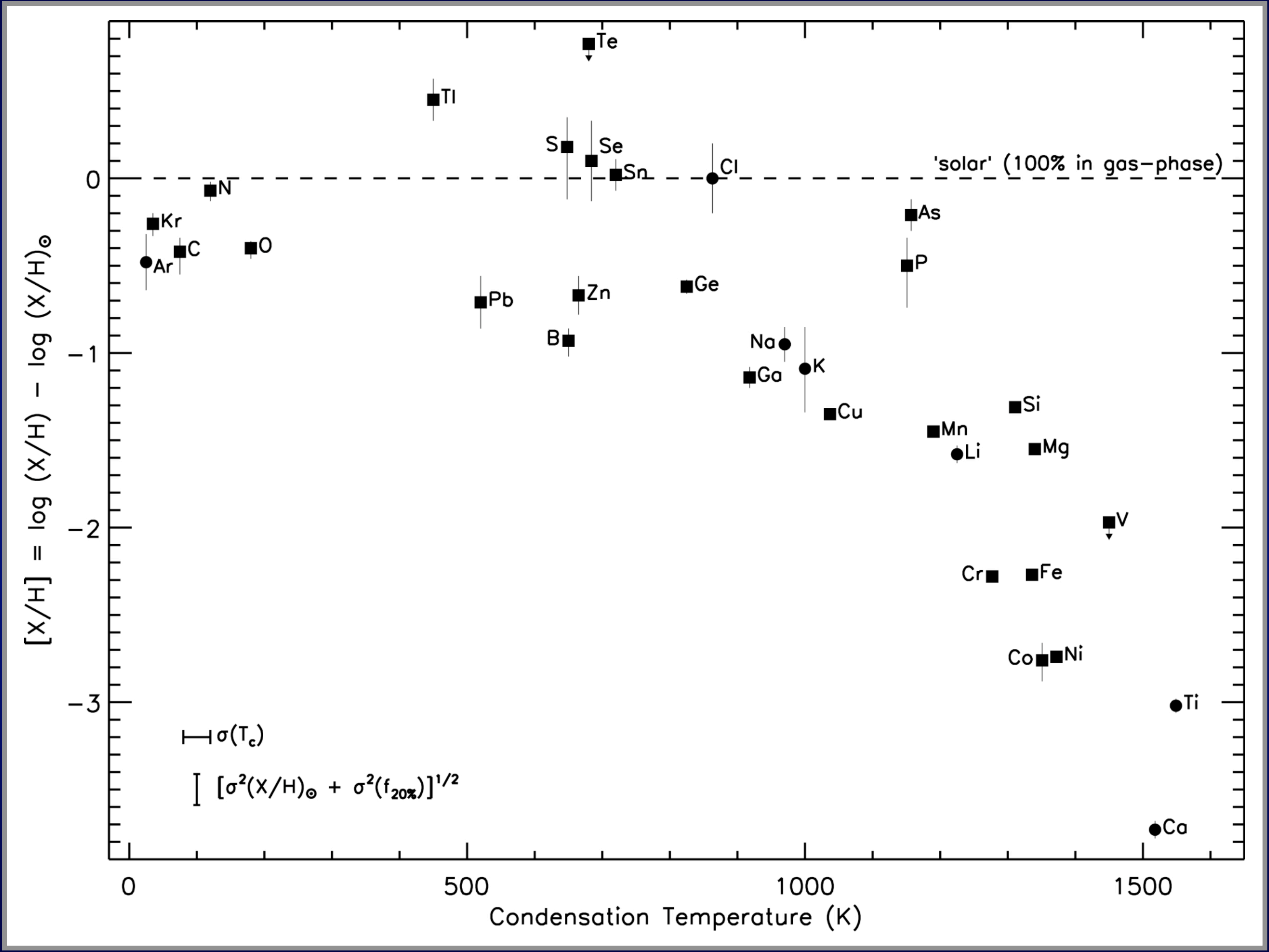
D/H vs. Ti/H



Lallement, Hébrard, & Welsh 2008

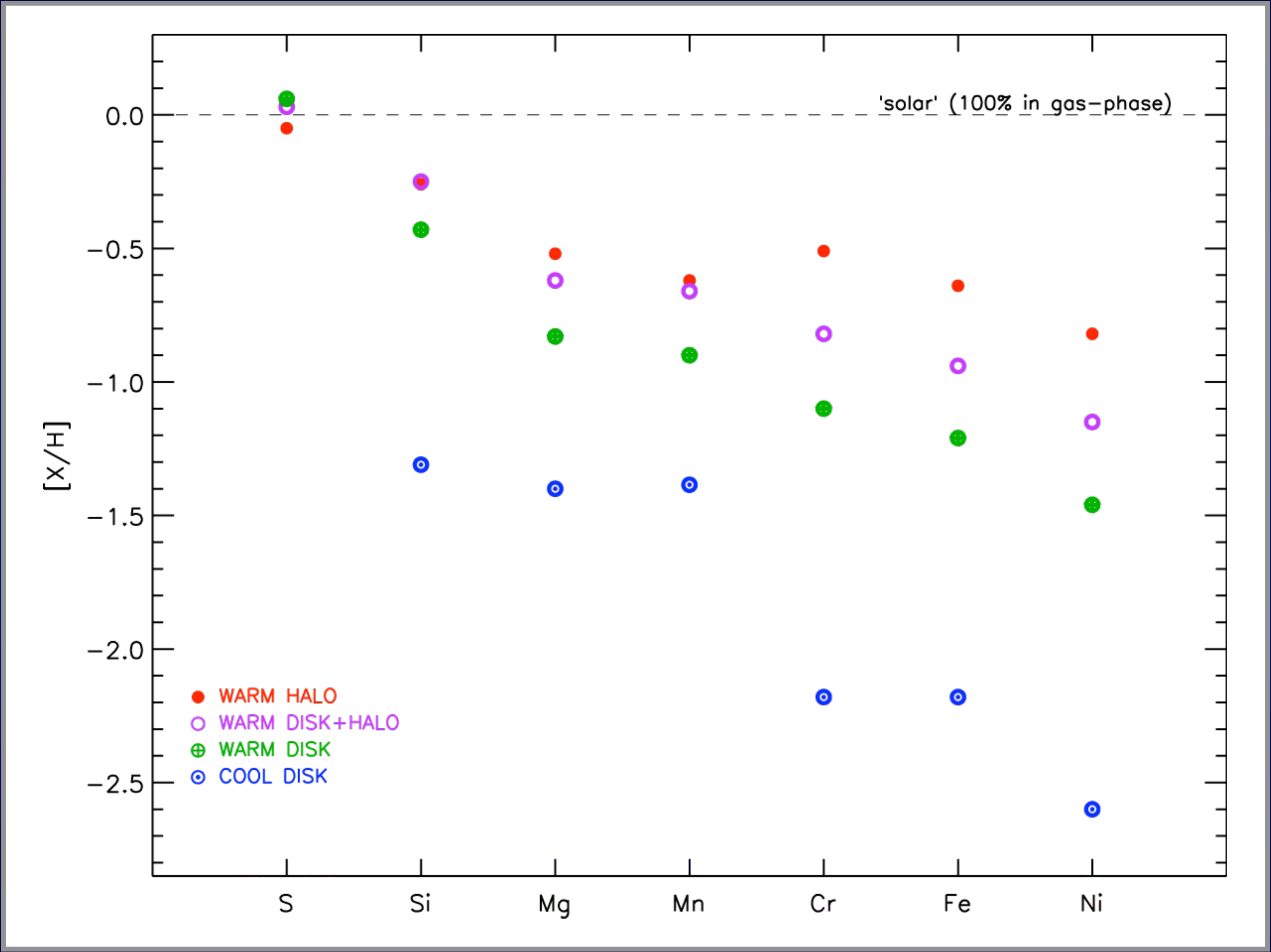

30
25
20
15
10
5
0
$(D/H)_{ppm}$
−0.5
−1.0
−1.5
−2.0
−2.5
D(Ti)
Fe
Si

ζ Oph – Diffuse Cloud Abundances

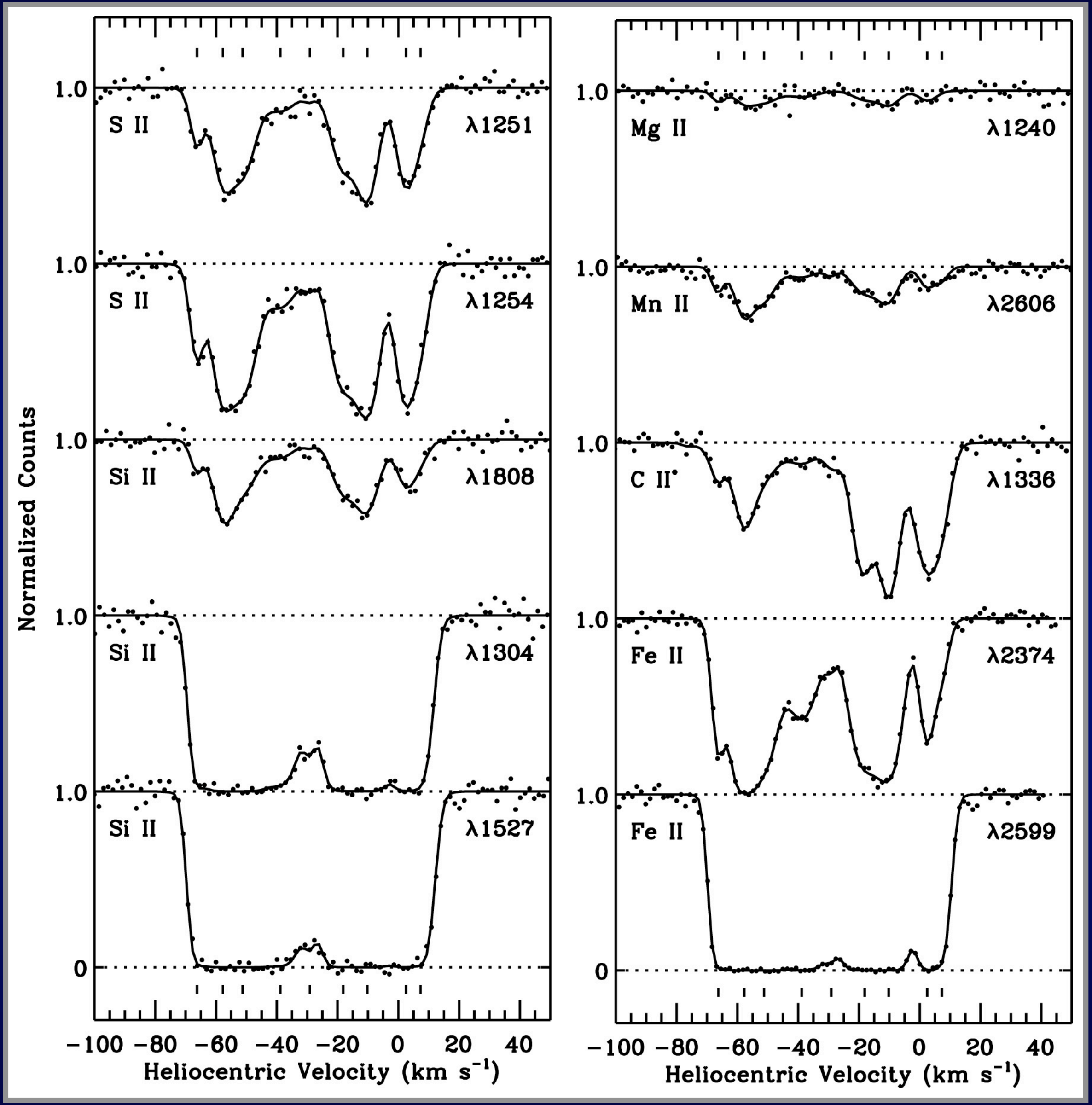


Savage & Sembach 1996 (ARA&A, 34, 279)

Milky Way Elemental Depletion Patterns - Disk and Halo

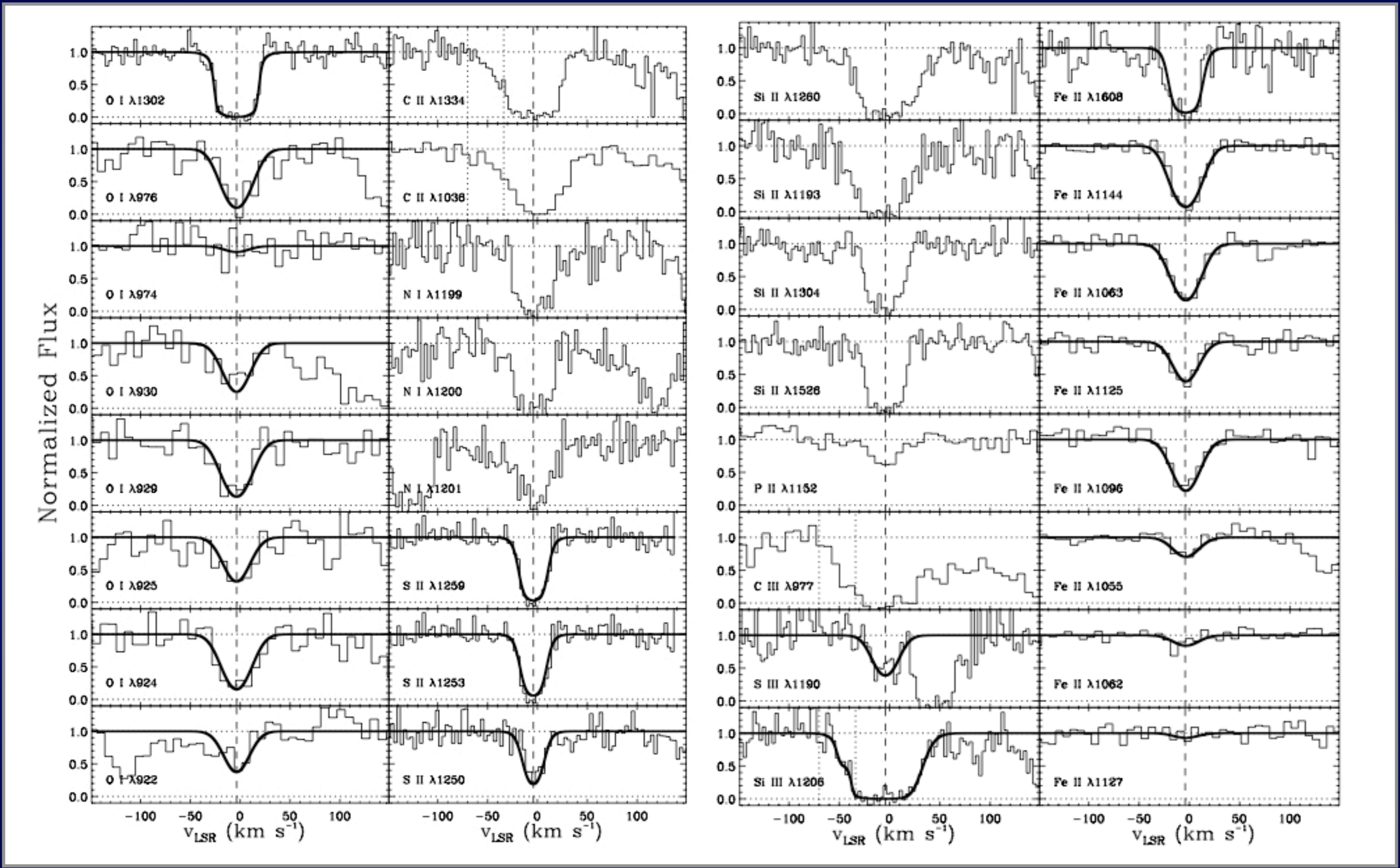


Savage & Sembach 1996 (ARA&A, 34, 279)



HD 93521: Spitzer & Fitzpatrick 1993 (ApJ, 409, 299)

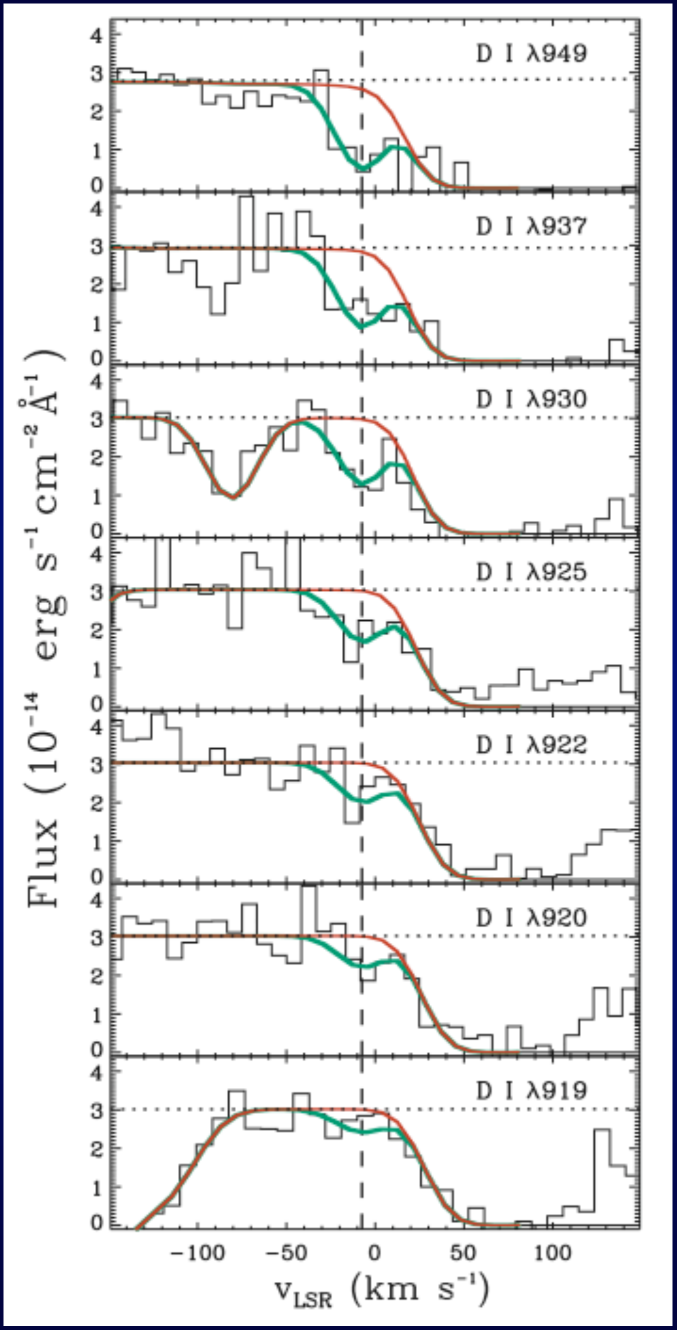
Halo Sight Line HE0226-4110



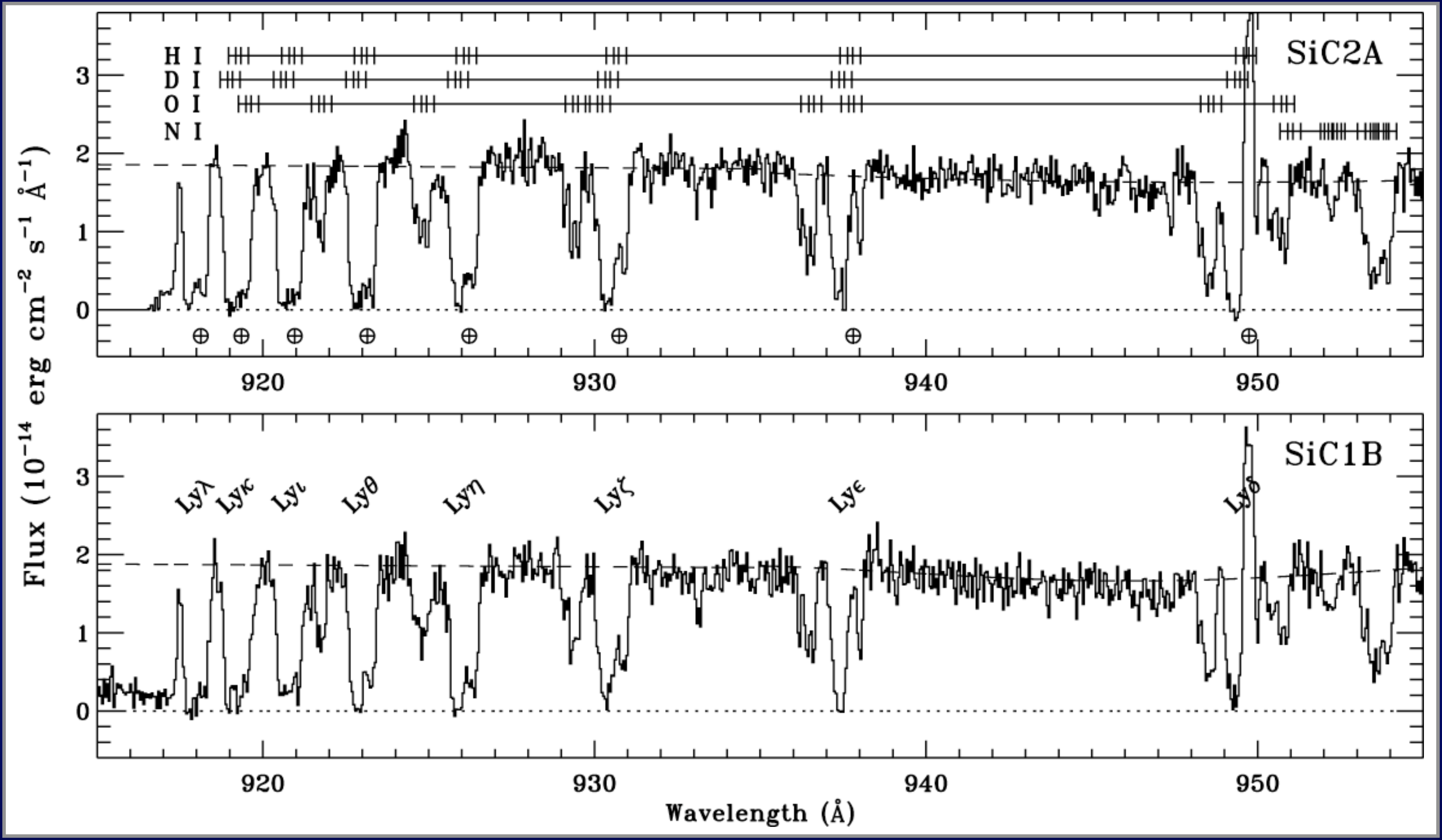
Savage et al. 2007, ApJ, 659, 1222

HE0226-4110

- Warm halo clouds
  - [O/H] = -0.1
  - [Fe/H] = -1.0
  - z ≈ few hundred pc
  - $N(H_2)/N(H\ I) \sim 3\times10^{-6}$
- $D/H_{ppm} = 21\pm(8,6)$
- LB contribution is small (~8%)

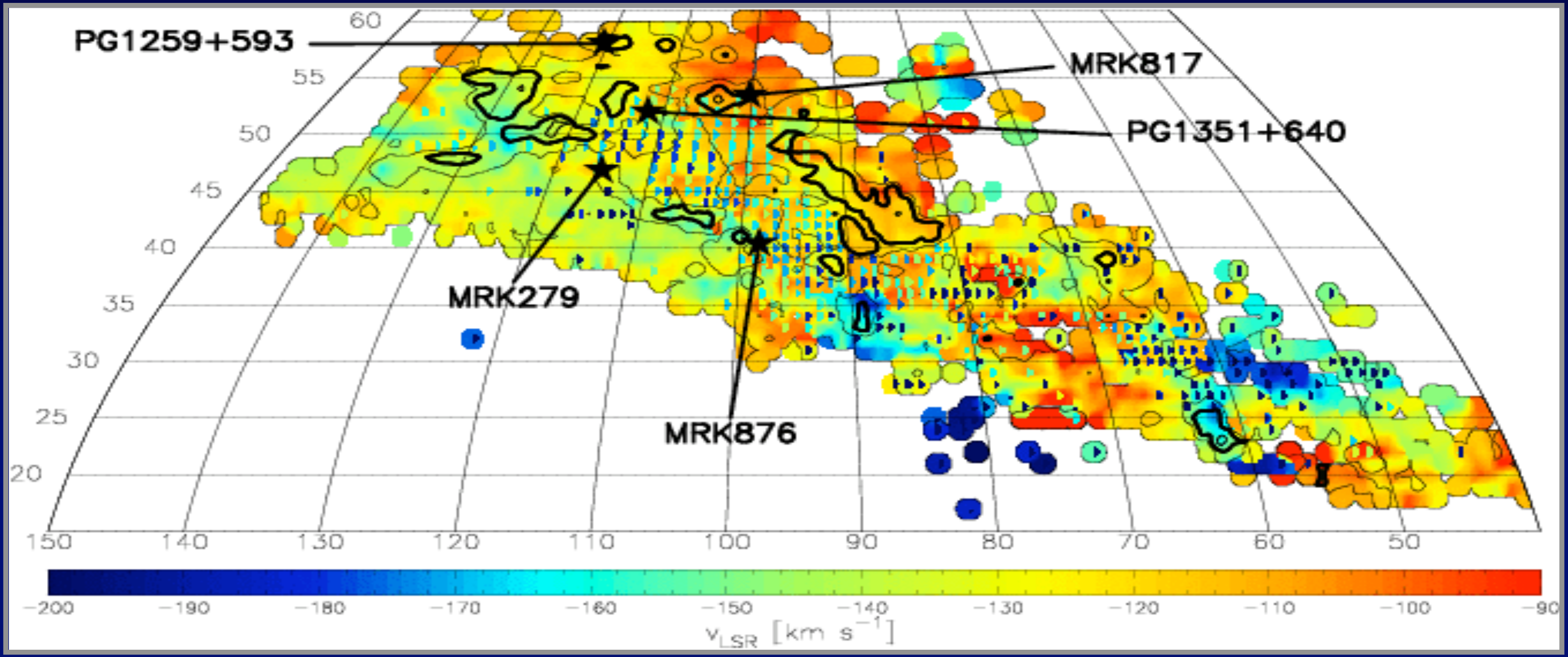


What about D/H in High Velocity Clouds?



Sembach et al. 2004, ApJS, 150, 387

High Velocity Cloud Complex C



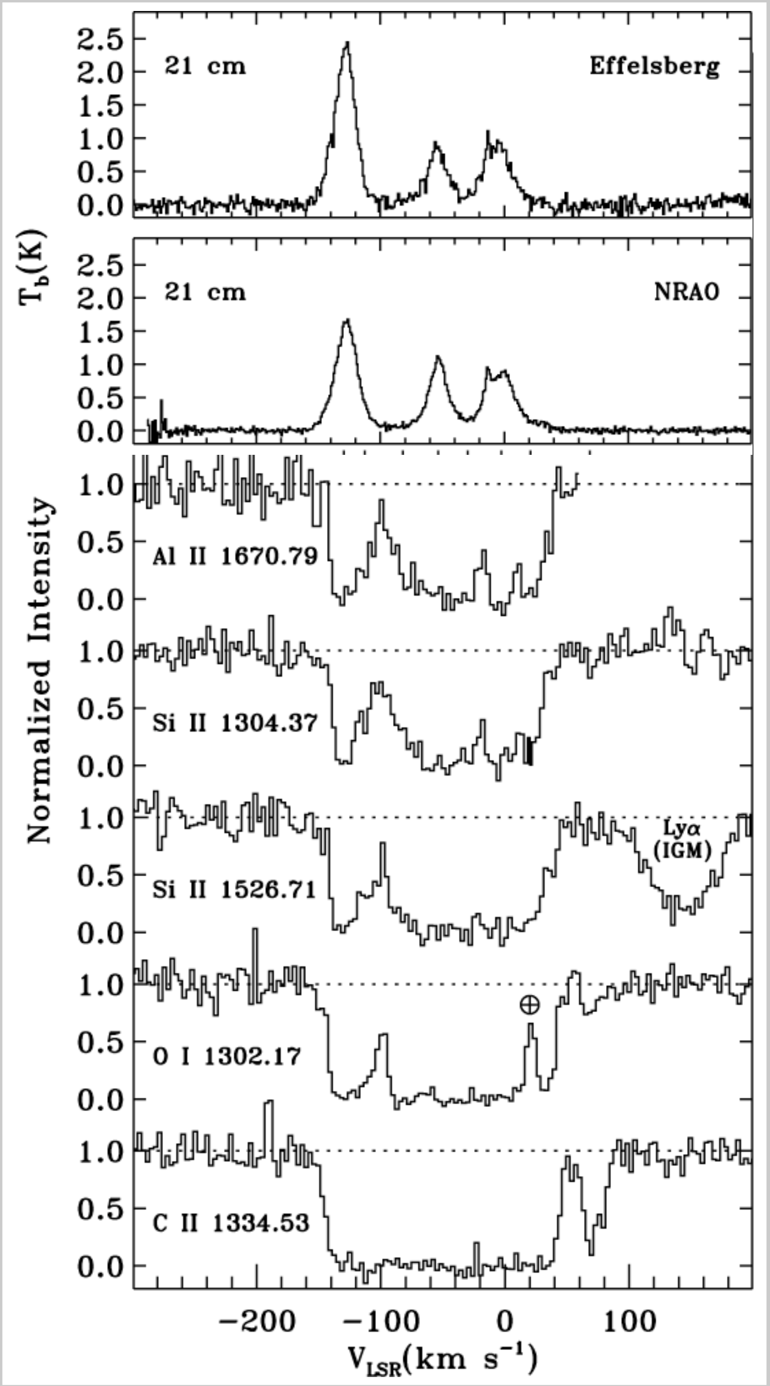
Metallicity: Z/Z_o ~ 0.1 – 0.25 (FUSE + HST + 21cm)

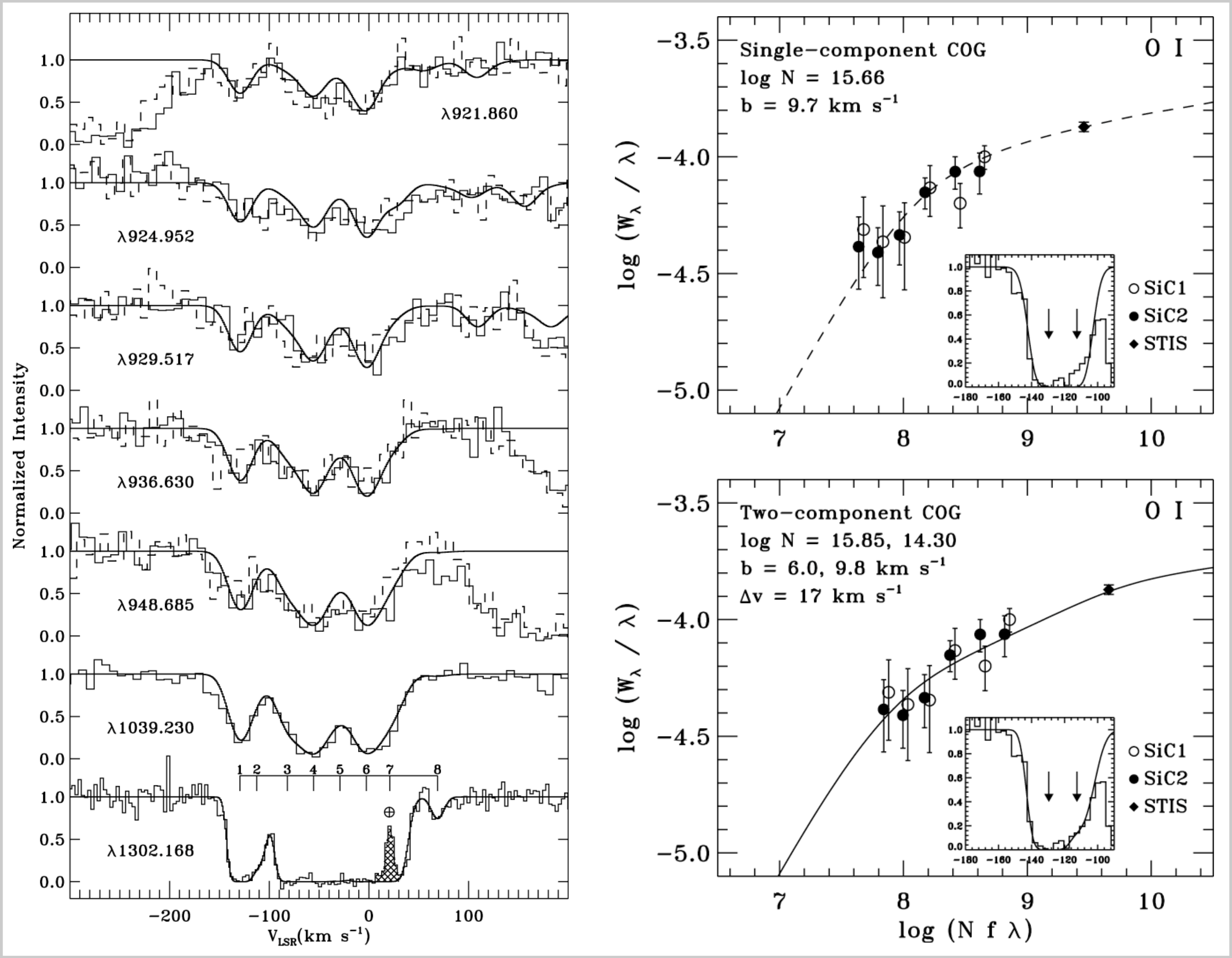
(Wakker et al. 1999; Gibson et al. 2002; Collins et al. 2003; Sembach et al. 2004)

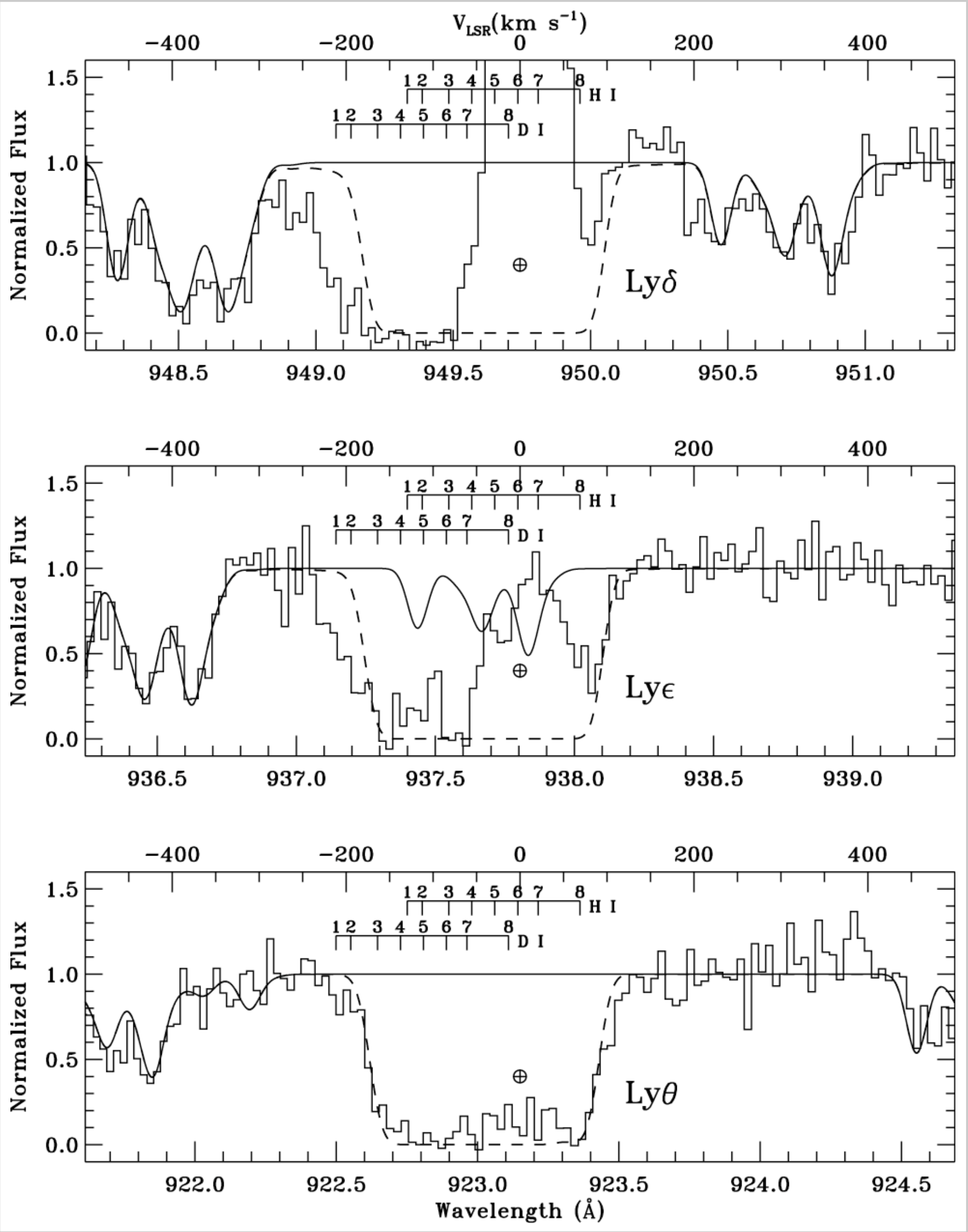
Distance: d = 10±2 kpc from the Galactic plane (Thom et al. 2008)

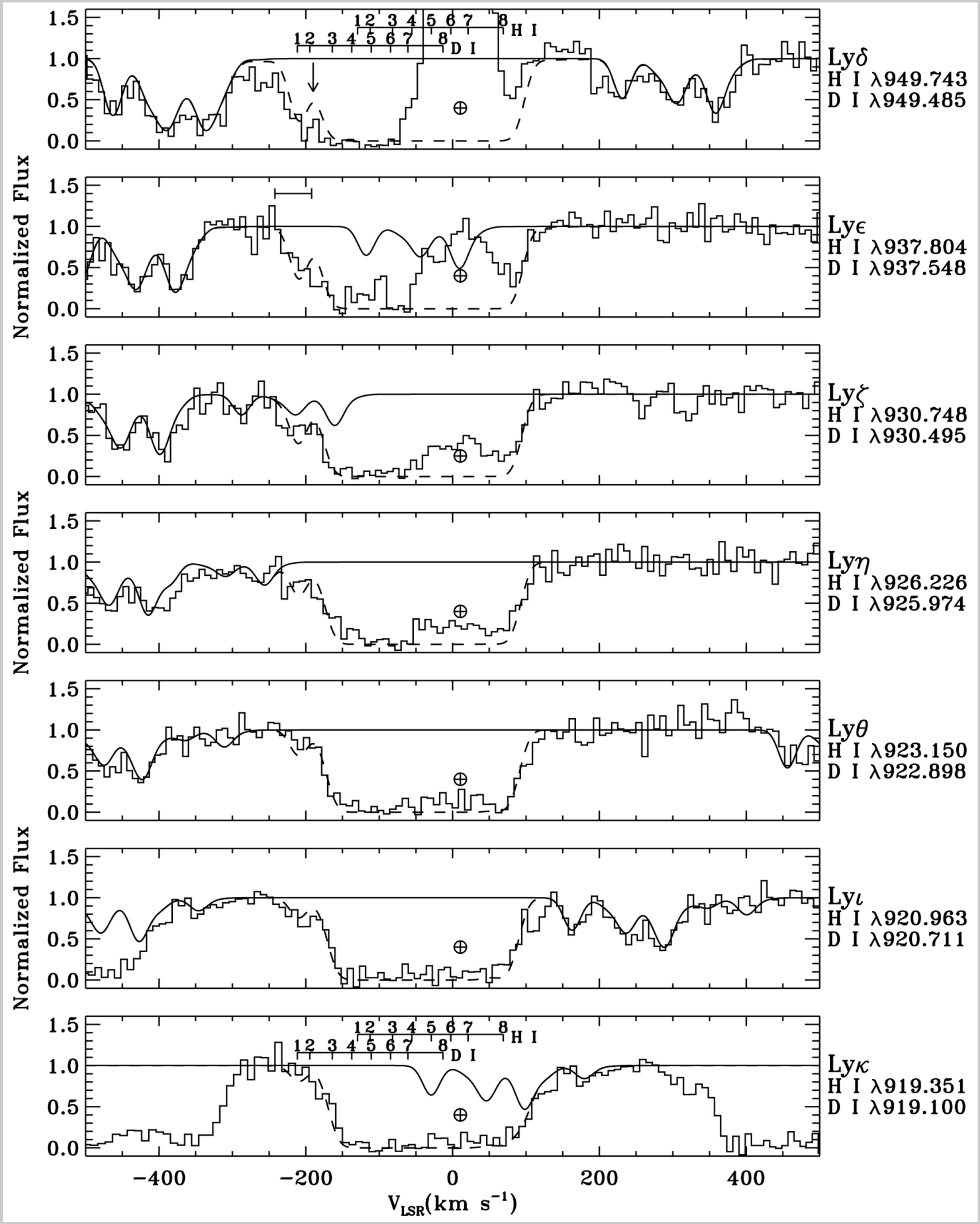
Mass: $M_{HI} \sim 10^7 M_o$

No dust or H_2 + low N abundance + high D/H (22±7 ppm) ⇒ chemically young

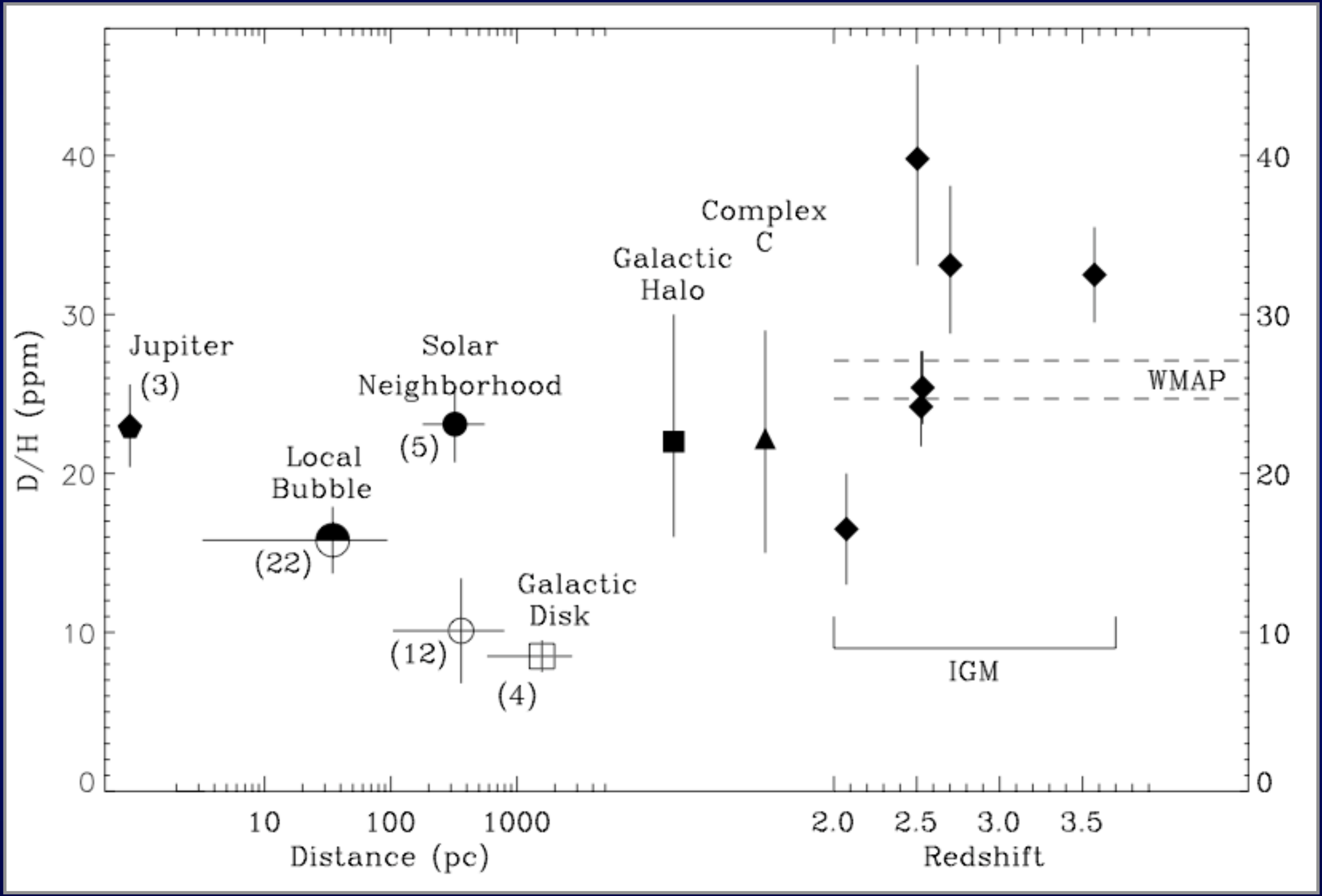

21 cm
Effelsberg
21 cm
NRAO
T_b(K)
2.5
2.0
1.5
1.0
0.5
0.0
Normalized Intensity
Al II 1670.79
Si II 1304.37
Si II 1526.71
Lyα (IGM)
O I 1302.17
⊕
C II 1334.53
−200
−100
0
100
V_{LSR}(km s^{-1})


Normalized Intensity
1.0
0.5
0.0
λ921.860
λ924.952
λ929.517
λ936.630
λ948.685
λ1039.230
λ1302.168
1 2 3 4 5 6 7 8
⊕
-200
-100
0
100
V_{LSR}(km s^{-1})
Single–component COG
log N = 15.66
b = 9.7 km s^{-1}
O I
log (W_λ / λ)
-3.5
-4.0
-4.5
-5.0
7
8
9
10
○ SiC1
● SiC2
◆ STIS
1.0
0.8
0.6
0.4
0.2
0.0
-180 -160 -140 -120 -100
Two–component COG
log N = 15.85, 14.30
b = 6.0, 9.8 km s^{-1}
Δv = 17 km s^{-1}
O I
log (N f λ)


V_LSR(km s^-1)
−400
−200
0
200
400
1.5
1.0
0.5
0.0
Normalized Flux
1 2 3 4 5 6 7 8 H I
1 2 3 4 5 6 7 8 D I
⊕
Lyδ
948.5
949.0
949.5
950.0
950.5
951.0
Lyϵ
936.5
937.0
937.5
938.0
938.5
939.0
Lyθ
922.0
922.5
923.0
923.5
924.0
924.5
Wavelength (Å)


1.5
1.0
0.5
0.0
Normalized Flux
12 3 4 5 6 7 8 H I
12 3 4 5 6 7 8 D I
⊕
Lyδ
H I λ949.743
D I λ949.485
Lyϵ
H I λ937.804
D I λ937.548
Lyζ
H I λ930.748
D I λ930.495
Lyη
H I λ926.226
D I λ925.974
Lyθ
H I λ923.150
D I λ922.898
Lyι
H I λ920.963
D I λ920.711
Lyκ
H I λ919.351
D I λ919.100
−400
−200
0
200
400
V_{LSR}(km s^{-1})

D/H in Different Environments



Savage et al. 2007

Deuterium Production

- Many different models have been proposed for the creation of deuterium in non-cosmological quantities. All invoke production through either:

  synthesis reactions involving fusing of free electrons into heavier nuclei

  Ex: $p + n \rightarrow D + \gamma$

  or dissociation reactions whereby particles more massive than deuterium are disrupted by energetic H or He atoms

  Ex: $^{4}He + p \rightarrow {}^{3}He + d$

  $p, He + C,N,O \rightarrow {}^{6,7}Li, {}^{9}Be, {}^{10,11}B$

- The main pitfall of synthesis reactions is that deuterium is easily destroyed by the same processes that create it.
- The main pitfall of photodisintegration/spallation is that the other light elements are more readily produced than deuterium

Possible Formation Mechanisms

- All methods of production require extreme environments or special conditions (see Epstein, Lattimer, & Schramm 1976; Jedamzik 2002)
    - Supernova shock waves
    - Accretion disks around black holes or neutron stars
    - Disrupted neutron stars
    - Pre-galactic cosmic rays
    - AGN jets (Famiano et al. 2001)
    - Stellar flares (Mullan & Linksy 1999; Prodanovic & Fields 2003)

General conclusion: While none of these process can account for the overall present-day abundance of deuterium, there is little evidence to suggest that they are not relevant in localized regions.

Some Things to Consider

- Selection effects
  - Small fraction of Galaxy sampled
  - Very specific types of sight lines (also cosmic confusion)
  - Velocity structure is unresolved
  - What about non-detections of D?
- Grains
  - PADs and “normal” (silicate, carbonaceous) grains may have very different histories
  - Gas-phase abundance of refractory elements can change dramatically as grains are destroyed
- Infall need not be pristine gas
  - We know the Milky Way is accreting material with subsolar abundances
- Localized sources of D
  - Difficult to test, but worth considering further

A Few (Obvious) Concluding Remarks

- Observations indicate that D/H varies among the sight lines so far measured
    - Difficult to define a “Galactic value” (for discussion later perhaps)
- Both GCE and depletion effects are likely contribute to this variation
    - No reason/evidence all variations are due to one or the other
- Further observational progress at FUV wavelengths is likely to be slow in coming