What the D/O ratio tells us about the interstellar abundance of deuterium?

Guillaume HÉBRARD
Institut d'Astrophysique de Paris

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D/O as D/H proxy

Timmes et al. (1997), Hébrard & Moos (2003)

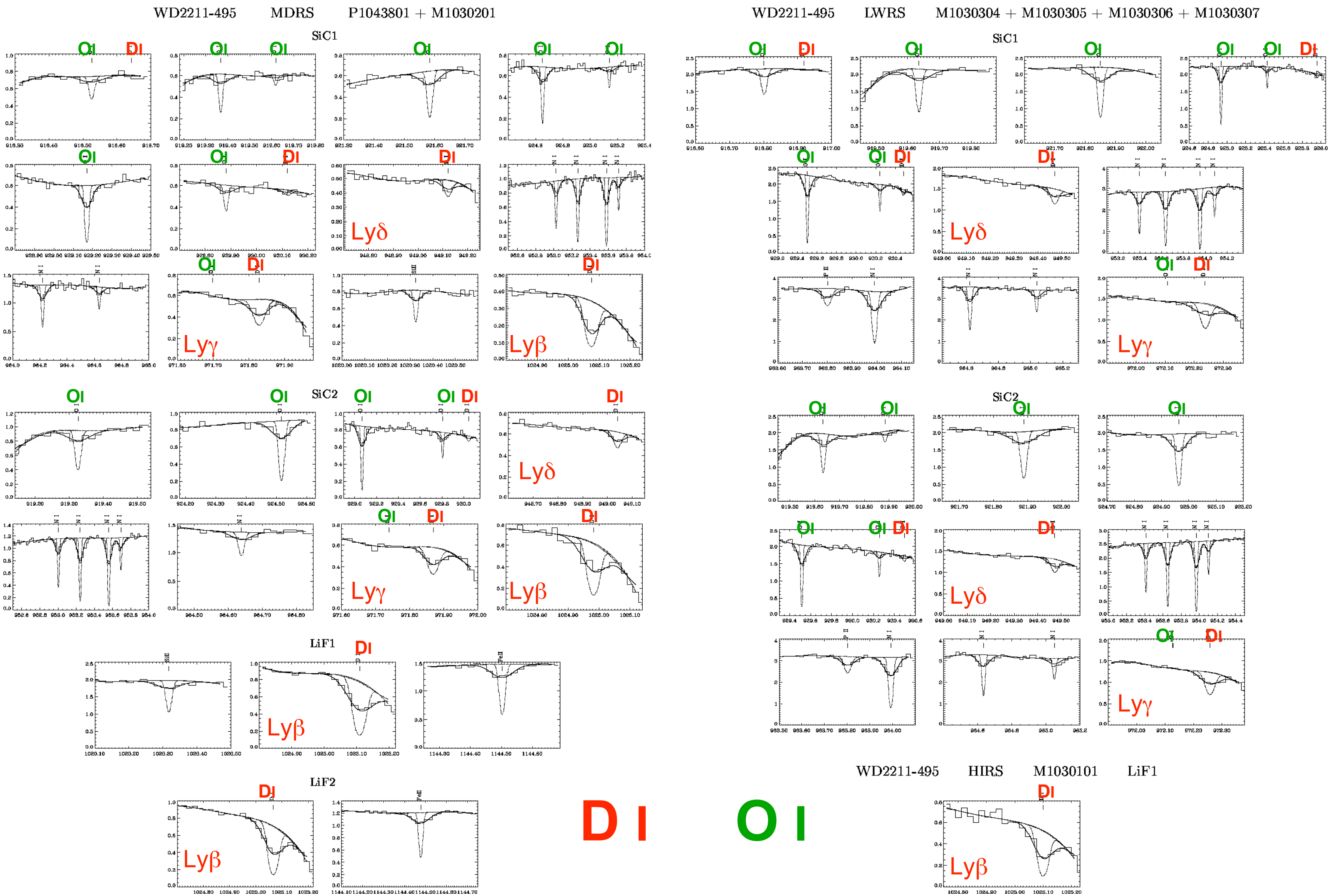
- *N*(D I) and *N*(H I): 5 orders of magnitude;
  N(D I) and *N*(O I): less than 2 orders of magnitude
  $\rightarrow$ less systematics for D/O than for D/H?

- O I is a good tracer of H I in the diffuse ISM
  (Meyer et al. 1998; André et al. 2003; Cartledge et al. 2004; Oliveira et al. 2005).

- D/O is particularly sensitive to astration.

- Numerous D I and O I transitions in the *FUSE* band pass,
  with a large range of *f*-values.

D/O as D/H proxy



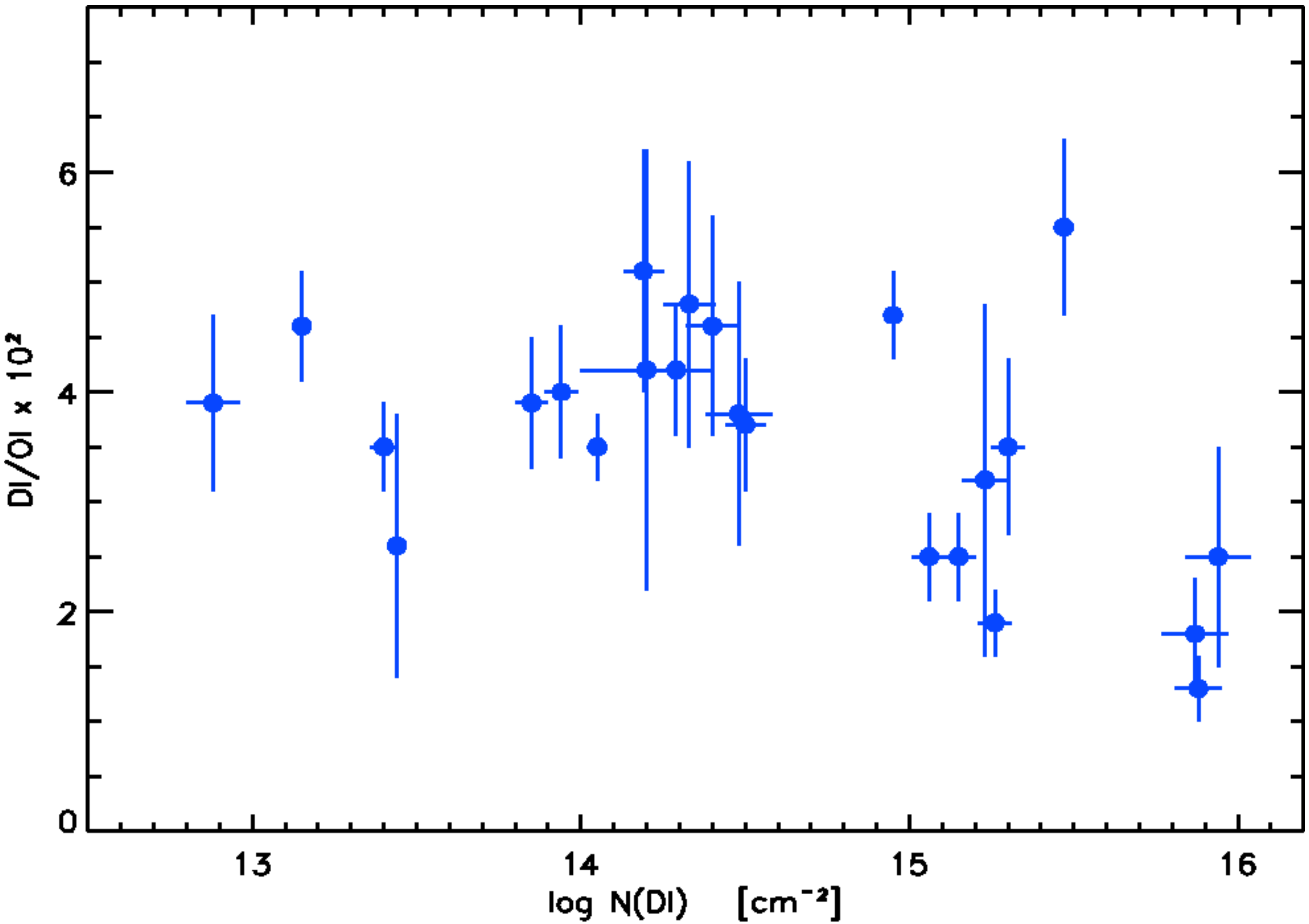
D/O as D/H proxy

Target	Sp.	l (°)	b (°)	d (pc) [a]	log N(D I) [b]	log N(N I) [b]	log N(O I) [b]	D/N ×10	D/O ×10^2
Sirius B	DA2	227.2	−8.9	2.64 ± 0.01 [h]	12.88 ± 0.08	13.35 ± 0.03	14.29 ± 0.05	3.4 ± 0.7	3.9 ± 0.8
HZ 43 A	DA1	54.1	+84.2	68 ± 13 [p]	13.15 ± 0.02	13.51 ± 0.03	14.49 ± 0.04	4.4 ± 0.4	4.6 ± 0.5
G191−B2B	DA1	155.9	+7.1	69^{+19}_{-12} [h]	13.40 ± 0.04	13.87 ± 0.04	14.86 ± 0.04	3.4 ± 0.4	3.5 ± 0.4
Capella	G8III+	162.6	+4.6	12.9 ± 0.2 [h]	13.44 ± 0.01	13.86 ± 0.09	15.02 ± 0.16	3.8 ± 0.8	2.6 ± 1.2
WD 0621−376	DA1	245.4	−21.4	78 [p]	13.85 ± 0.05	14.34 ± 0.05	15.26 ± 0.04	3.3 ± 0.5	3.9 ± 0.6
WD 2211−495	DA1	345.8	−52.6	53 [p]	13.94 ± 0.05	14.30 ± 0.03	15.34 ± 0.04	4.4 ± 0.6	4.0 ± 0.6
WD 1634−573	DO	329.9	−7.0	37 ± 3 [h]	14.05 ± 0.03	14.62 ± 0.04	15.51 ± 0.03	2.7 ± 0.3	3.5 ± 0.3
WD 2331−475	DA1	334.8	−64.8	82 [p]	14.19 ± 0.06	14.53 ± 0.05	15.48 ± 0.06	4.6 ± 0.9	5.1 ± 1.1
α Vir	B1III-IV	316.1	+50.8	80 ± 6 [h]	14.20 ± 0.20	14.66 ± 0.05	15.58 ± 0.10	3.5 ± 1.8	4.2 ± 2.0
GD 246	DA1	87.2	−45.1	79 [p]	14.29 ± 0.05	14.75 ± 0.03	15.67 ± 0.04	3.5 ± 0.5	4.2 ± 0.6
WD 2004−605	DA1	336.6	−32.9	52 [p]	14.33 ± 0.08	14.84 ± 0.08	15.65 ± 0.08	3.1 ± 0.8	4.8 ± 1.3
HZ 21	DO2	175.0	+80.0	115 [p]	14.40 ± 0.08	14.77 ± 0.04	15.74 ± 0.05	4.3 ± 0.9	4.6 ± 1.0
WD 1631+781	DA1	111.3	+33.6	67 [p]	14.48 ± 0.10	15.28 ± 0.10	15.90 ± 0.09	1.6 ± 0.6	3.8 ± 1.2
CPD−31 1701	sdO	246.5	−5.5	131 ± 28 [h]	14.50 ± 0.06	15.33 ± 0.04	15.93 ± 0.04	1.5 ± 0.2	3.7 ± 0.6
BD +28° 4211	sdO	81.9	−19.3	104 ± 18 [h]	14.95 ± 0.02	15.52 ± 0.05	16.28 ± 0.03	2.7 ± 0.4	4.7 ± 0.4
δ Ori A	O9.5II	203.9	−17.7	280 ± 80 [h]	15.06 ± 0.05	15.79 ± 0.04	16.67 ± 0.05	1.9 ± 0.3	2.5 ± 0.4
γ Cas	B0IVe	123.6	−2.1	190 ± 20 [h]	15.15 ± 0.05	16.06 ± 0.04	16.76 ± 0.04	1.2 ± 0.2	2.5 ± 0.4
Lan 23	DA	107.6	−0.6	122 [p]	15.23 ± 0.07	15.73 ± 0.07	16.72 ± 0.17	3.2 ± 0.8	3.2 ± 1.6
ϵ Ori	B0Ia	205.2	−17.2	450 ± 200 [h]	15.26 ± 0.05	16.45 ± 0.20	16.98 ± 0.05	0.7 ± 0.4	1.9 ± 0.3
ι Ori	O9III	209.5	−19.6	410 ± 150 [h]	15.30 ± 0.05	15.99 ± 0.07	16.76 ± 0.09	2.0 ± 0.4	3.5 ± 0.8
Feige 110	sdOB	74.1	−59.1	179^{+265}_{-67} [h]	15.47 ± 0.03	16.51 ± 0.10	16.73 ± 0.05	0.9 ± 0.3	5.5 ± 0.8
LSS 1274	sdO	277.0	−5.3	580 ± 100 [p]	15.87 ± 0.10	16.73 ± 0.05	17.62 ± 0.08	1.4 ± 0.4	1.8 ± 0.5
HD 195965	B0V	85.7	+5.0	800 [p]	15.88 ± 0.07	16.85 ± 0.03	17.77 ± 0.03	1.1 ± 0.2	1.3 ± 0.3
HD 191877	B1Ib	61.6	−6.5	2200 [p]	15.94 ± 0.10	16.88 ± 0.05	17.54 ± 0.10	1.1 ± 0.4	2.5 ± 1.0

D/O survey with 24 targets

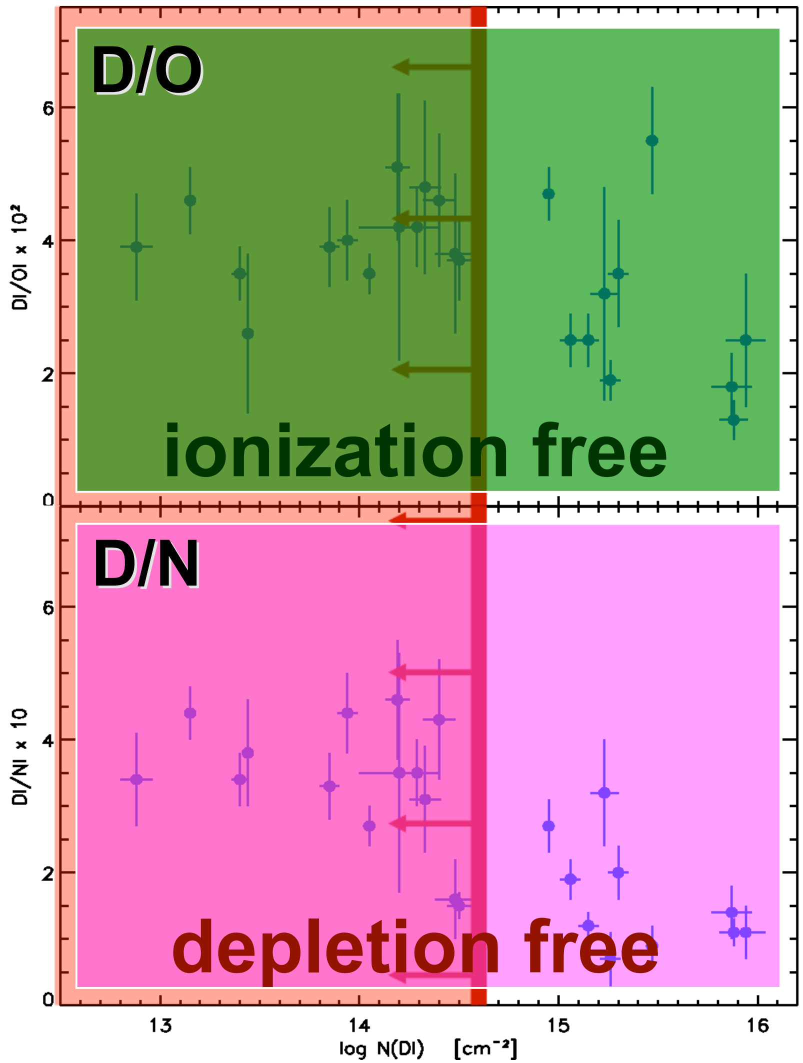
Hébrard & Moos (2003)

D/O



Hébrard & Moos (2003)

D/O *vs.* D/N



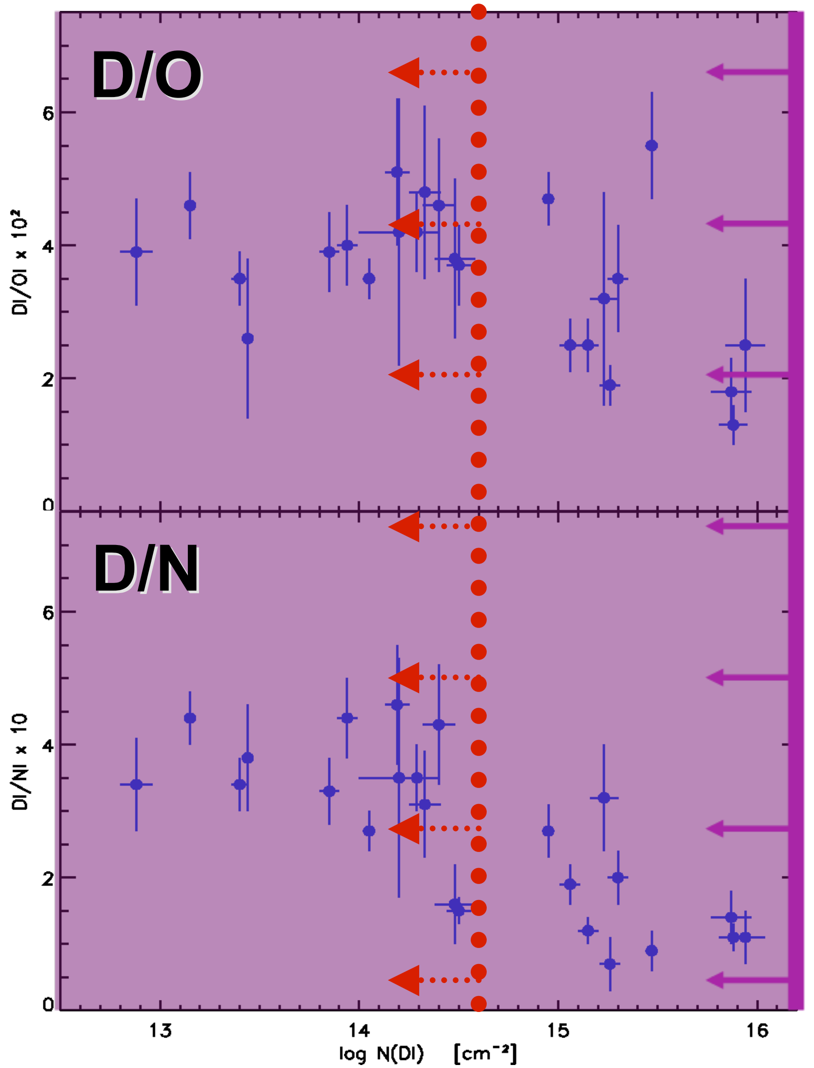
χ^2 = 8.4 for 13 d.o.f.

χ^2 = 37.3 for 13 d.o.f.

Hébrard & Moos (2003)

d.o.f. = degrees of freedom

D/O *vs.* D/N



χ^2 = 8.4 for 13 d.o.f.

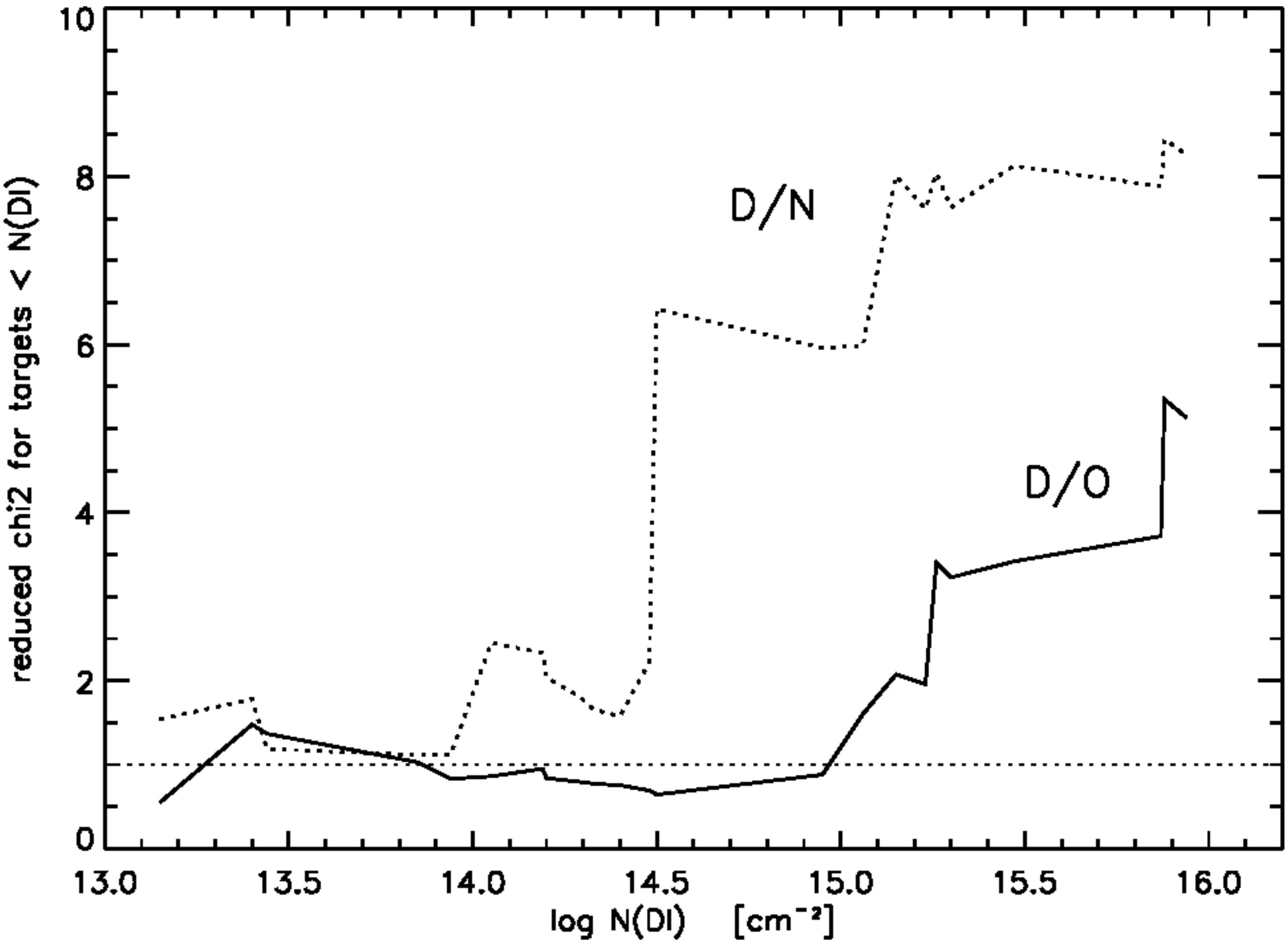
χ^2 = 117.9 for 23 d.o.f.

χ^2 = 37.3 for 13 d.o.f.

χ^2 = 189.9 for 23 d.o.f.

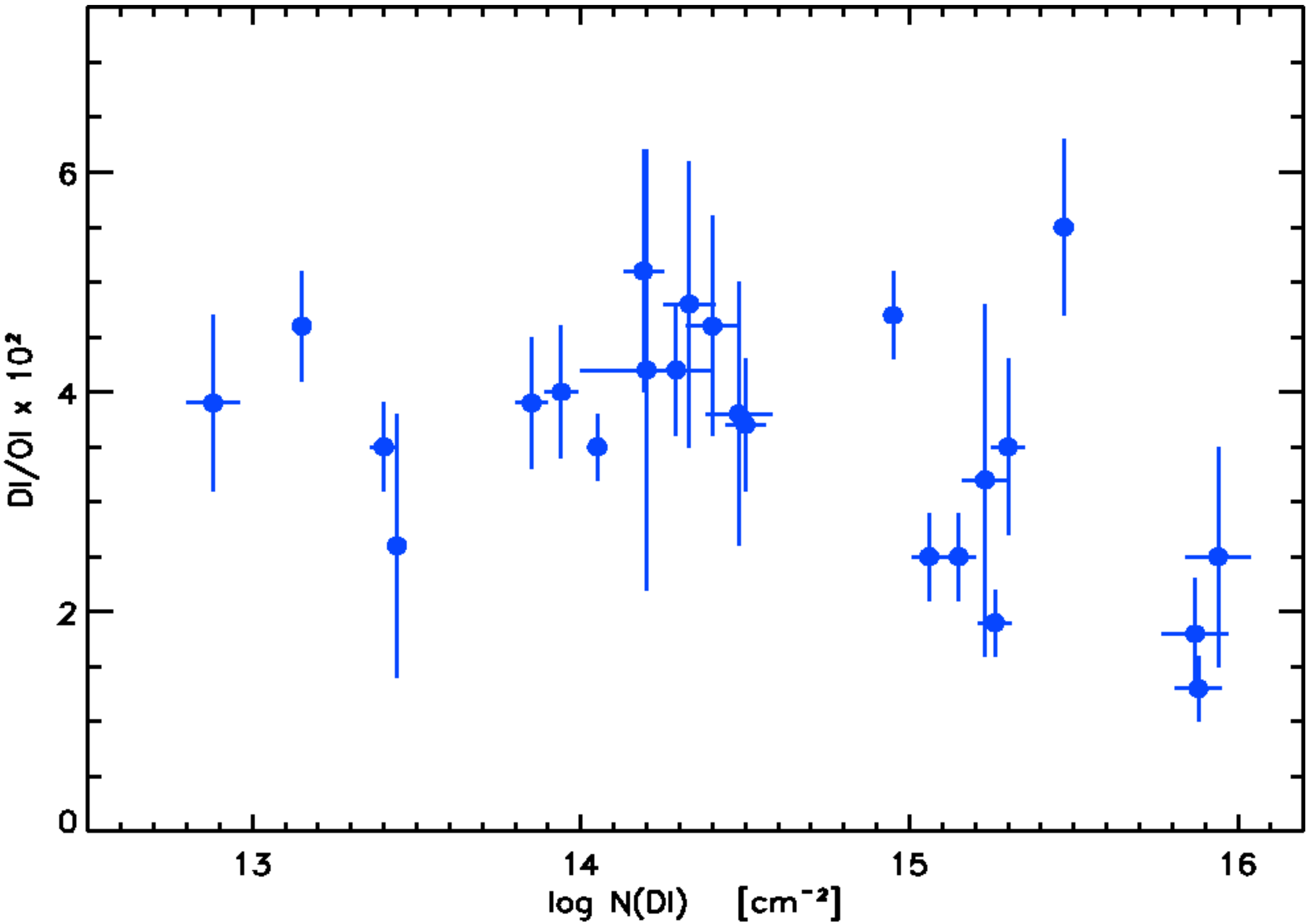
Hébrard & Moos (2003)

d.o.f. = degrees of freedom



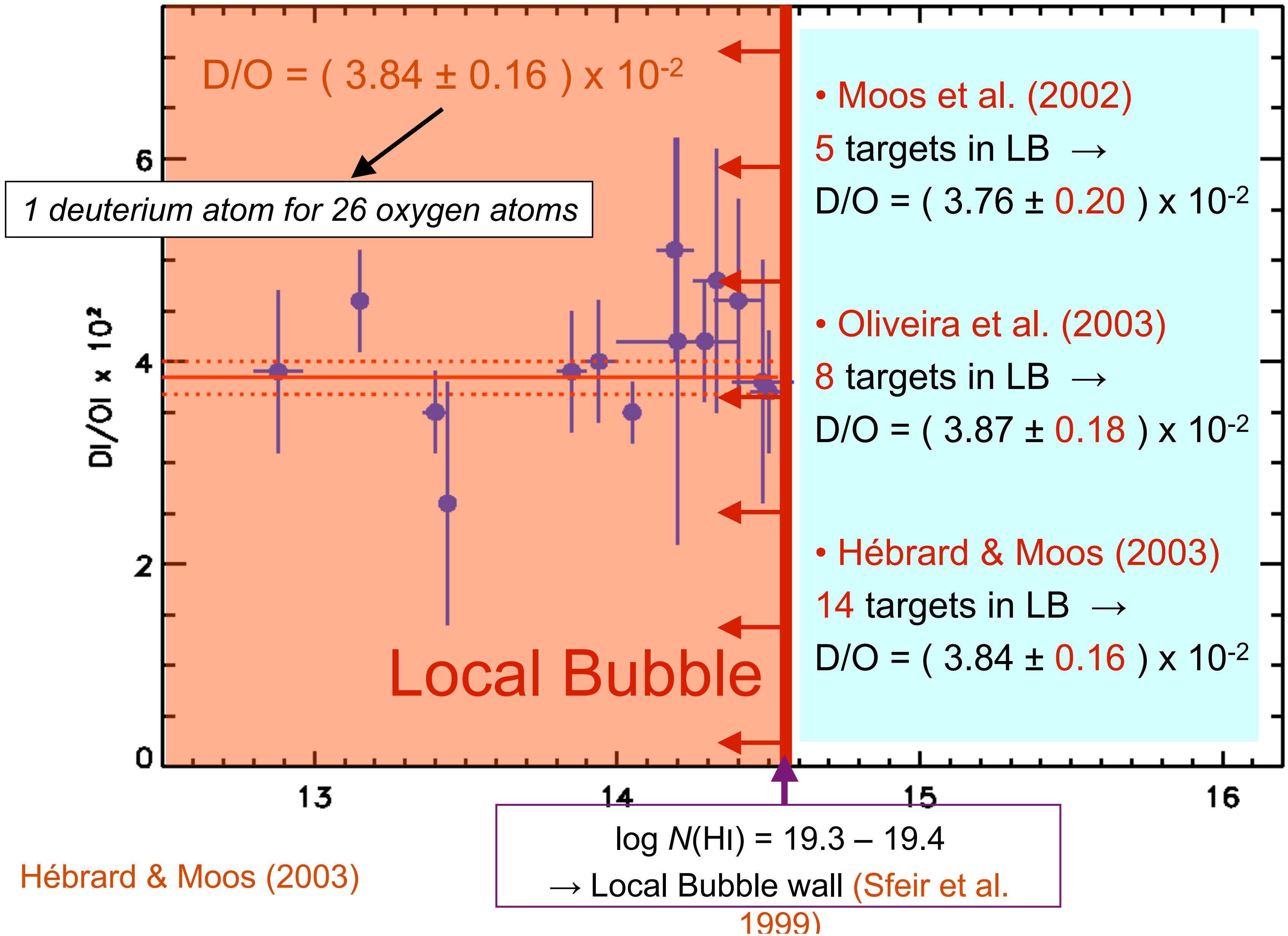
Hébrard & Moos (2003)

D/O



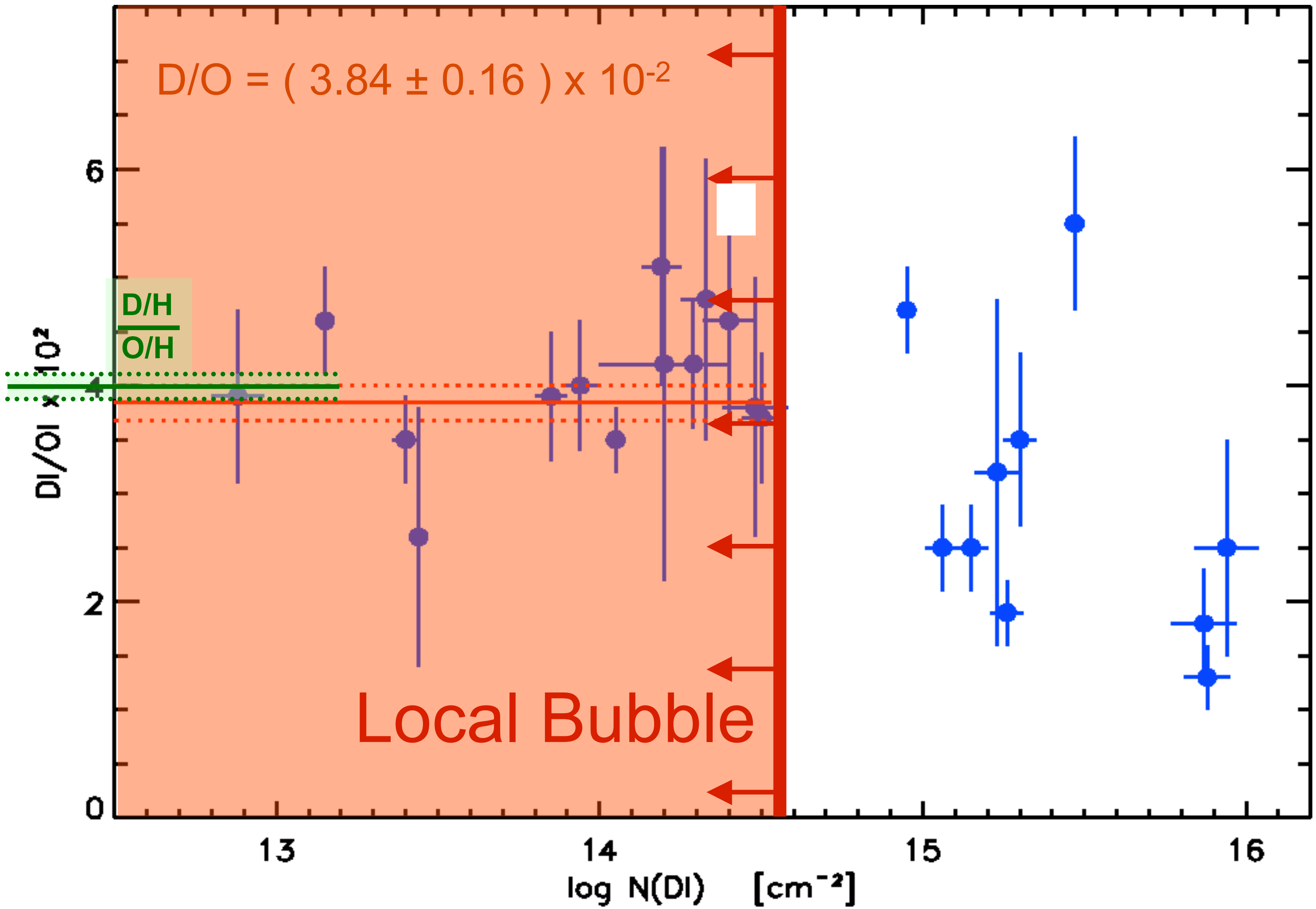
Hébrard & Moos (2003)

D/O



Hébrard & Moos (2003)

D/O in the Local Bubble



Hébrard & Moos (2003)

D/O in the Local Bubble

- D/O = (D/H) / (O/H)

D/O is homogeneous in the LB

⇒ **D/H and O/H homogeneous in the LB**

- If D/O = $3.84 \pm 0.16 \times 10^{-2}$,

  with O/H = $3.43 \pm 0.15 \times 10^{-4}$ (Meyer 2001)

  ⇒ D/H = $1.32 \pm 0.08 \times 10^{-5}$

- If D/H = $1.56 \pm 0.04 \times 10^{-5}$ (Wood et al. 2004),

  with O/H = $3.43 \pm 0.15 \times 10^{-4}$

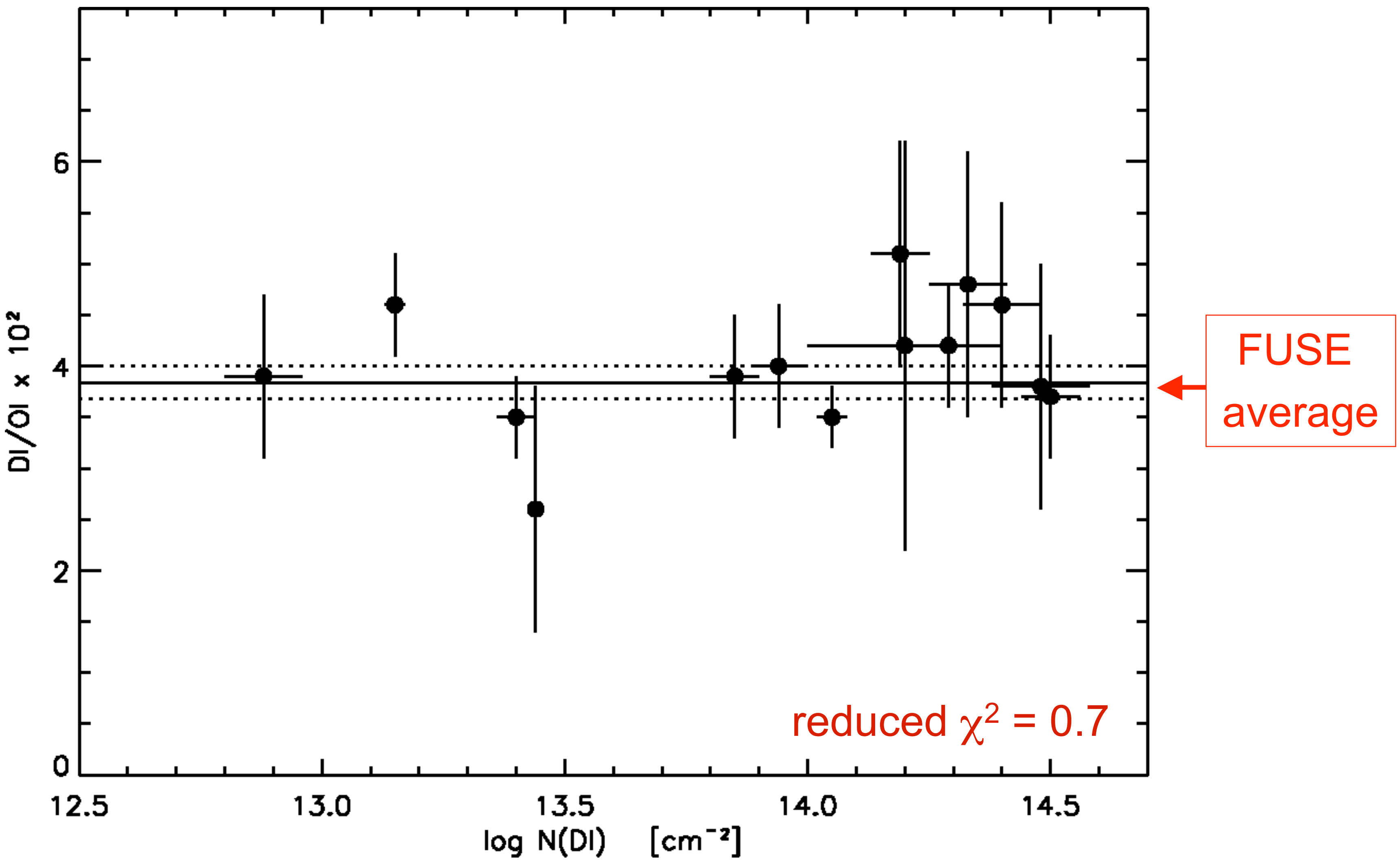
  ⇒ D/O = $4.55 \pm 0.23 \times 10^{-2}$

$(O/H)_{LB} = (3.45 \pm 0.19) \times 10^{-4}$

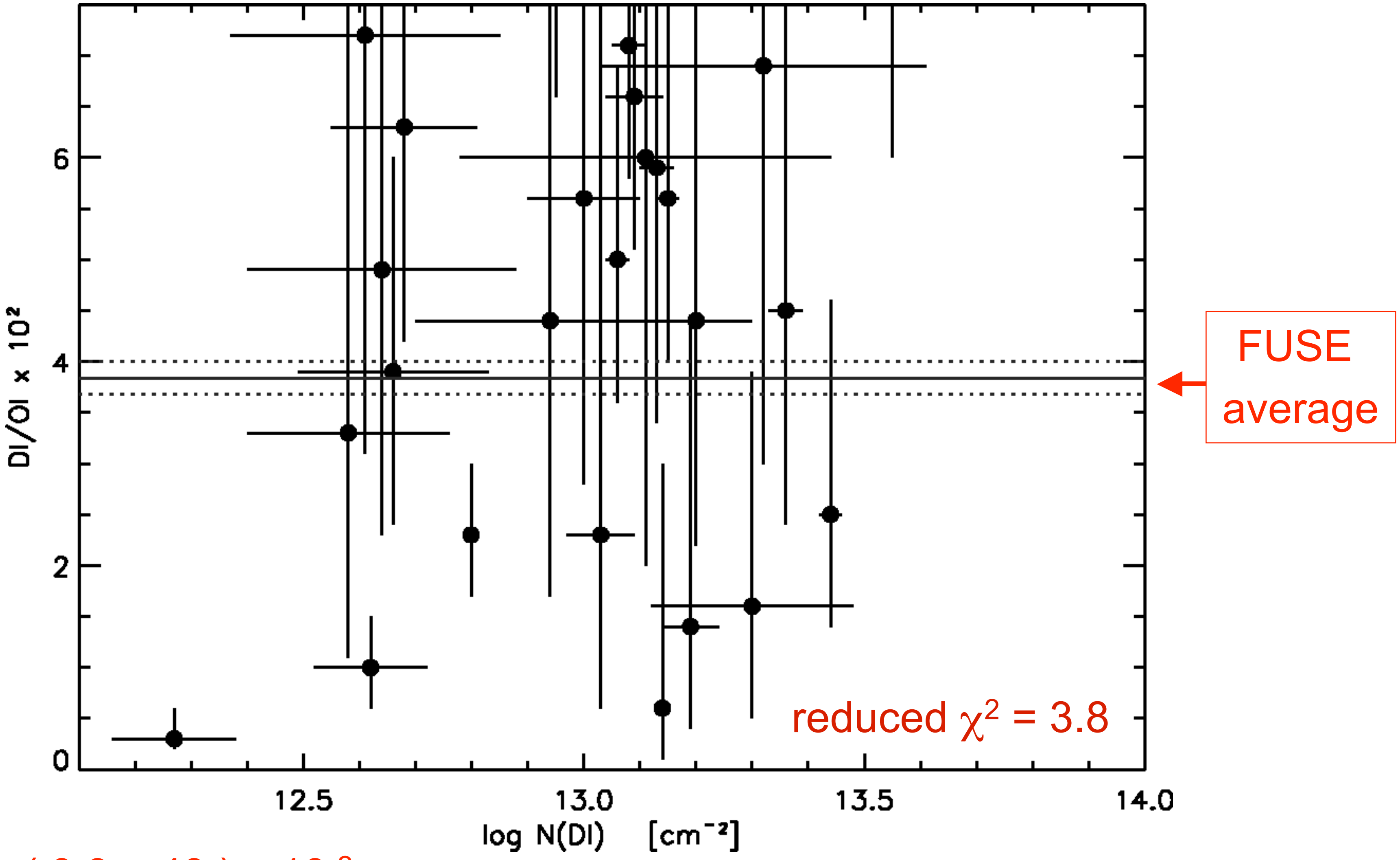
(Oliveira et al. 2005)

Hébrard & Moos (2003)

D/O in the Local Bubble with FUSE



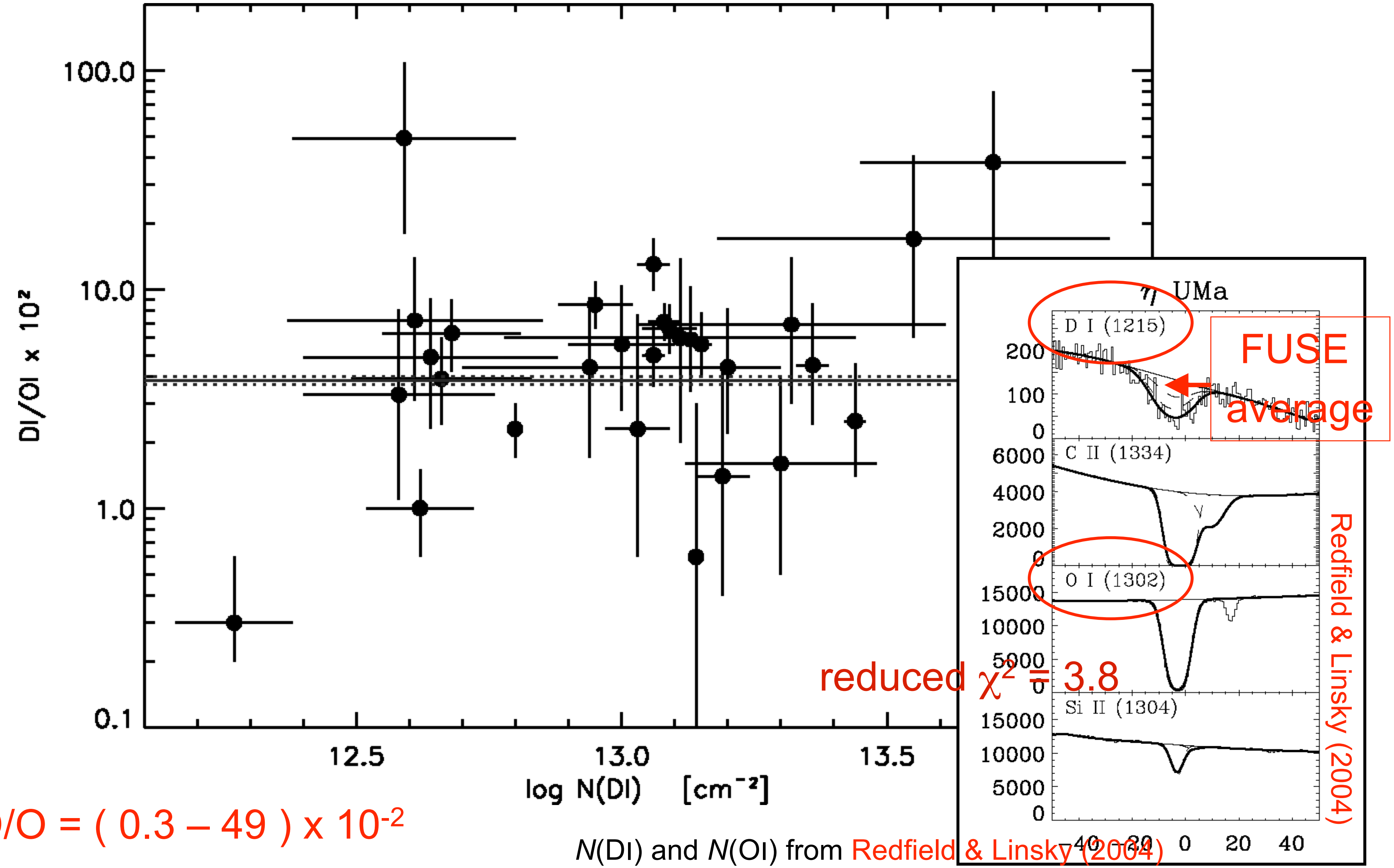
D/O in the Local Bubble with HST



D/O = (0.3 – 49) x 10^{-2}

N(DI) and *N*(OI) from Redfield & Linsky (2004)

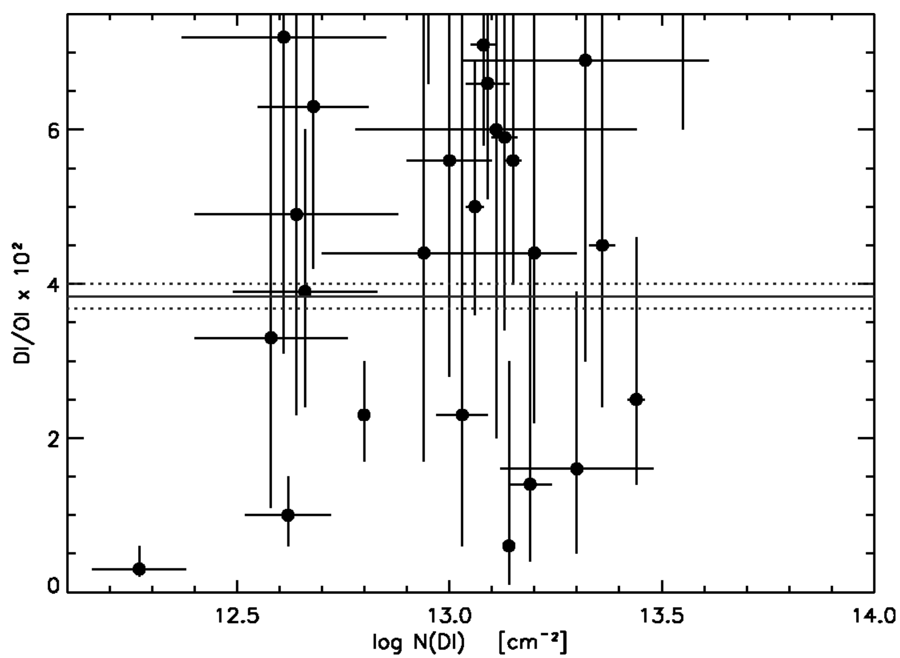
D/O in the Local Bubble with HST



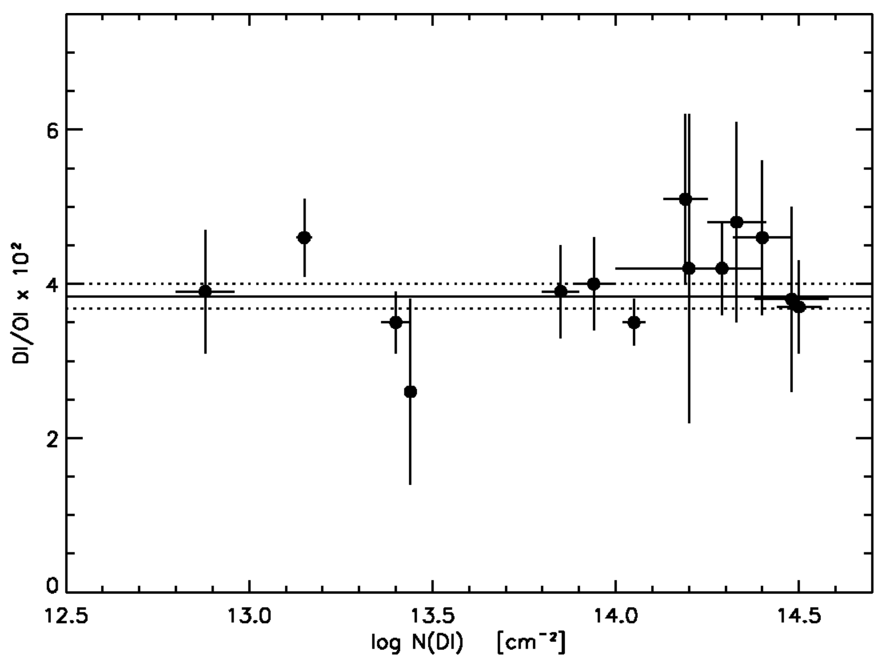
D/O = (0.3 – 49) x 10^{-2}

N(DI) and *N*(OI) from Redfield & Linsky (2004)

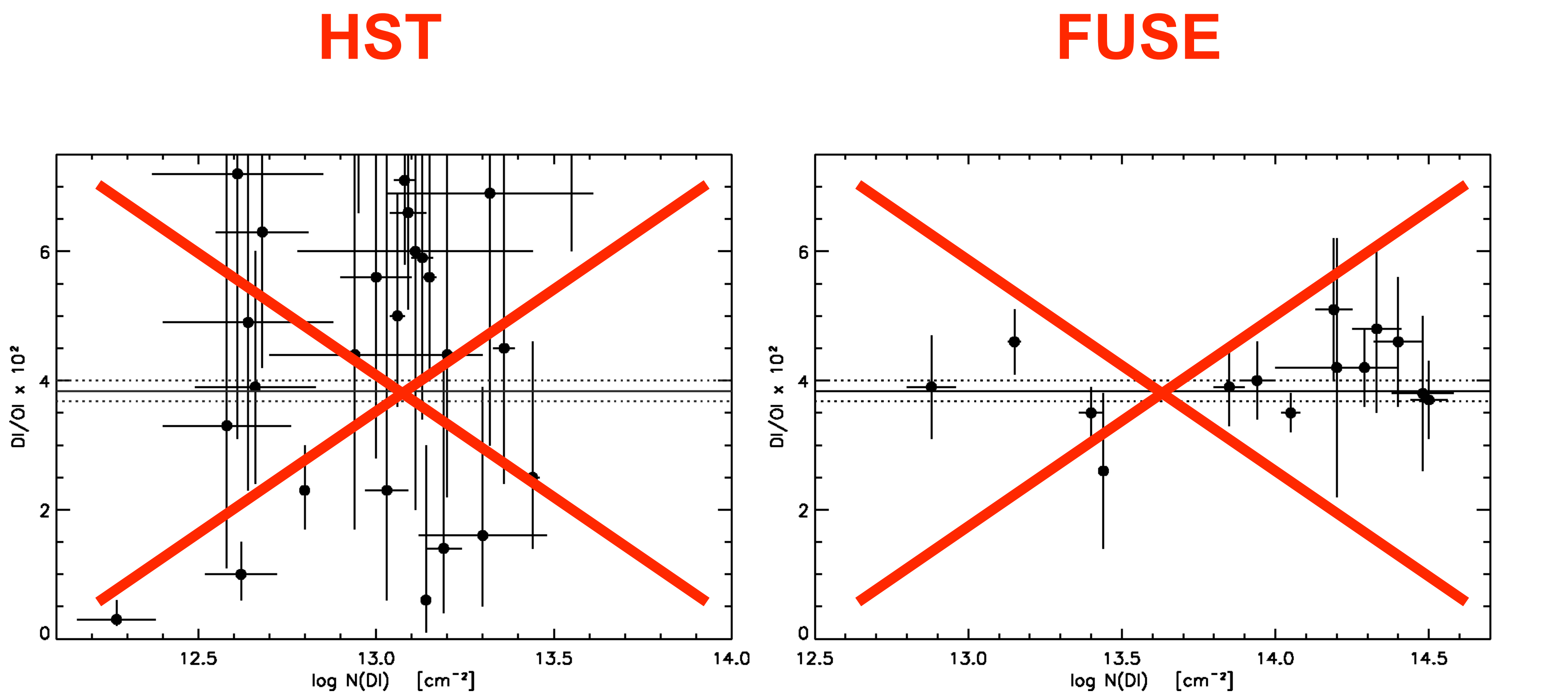
HST



FUSE

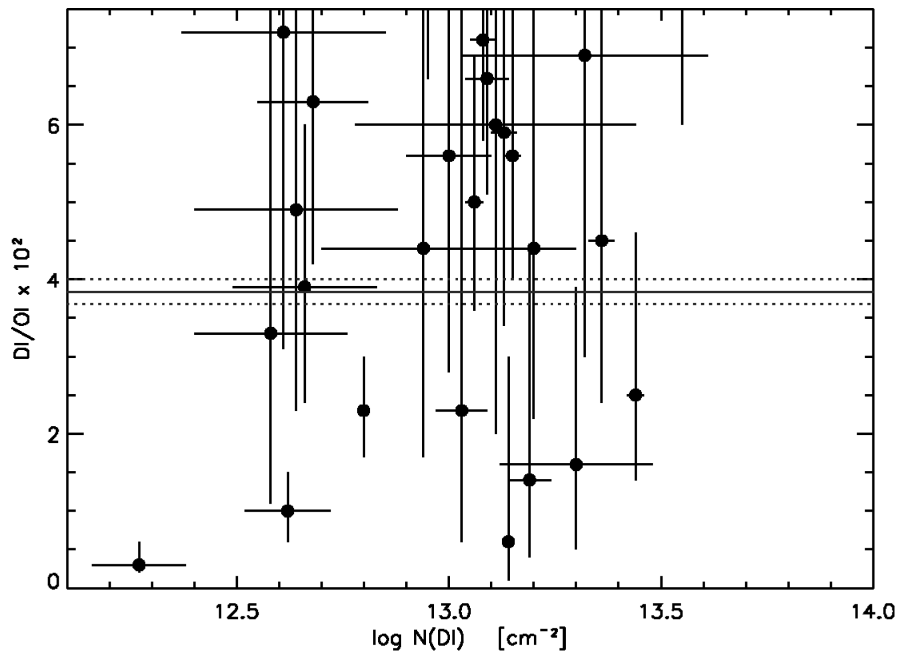


Where is the misunderstanding?

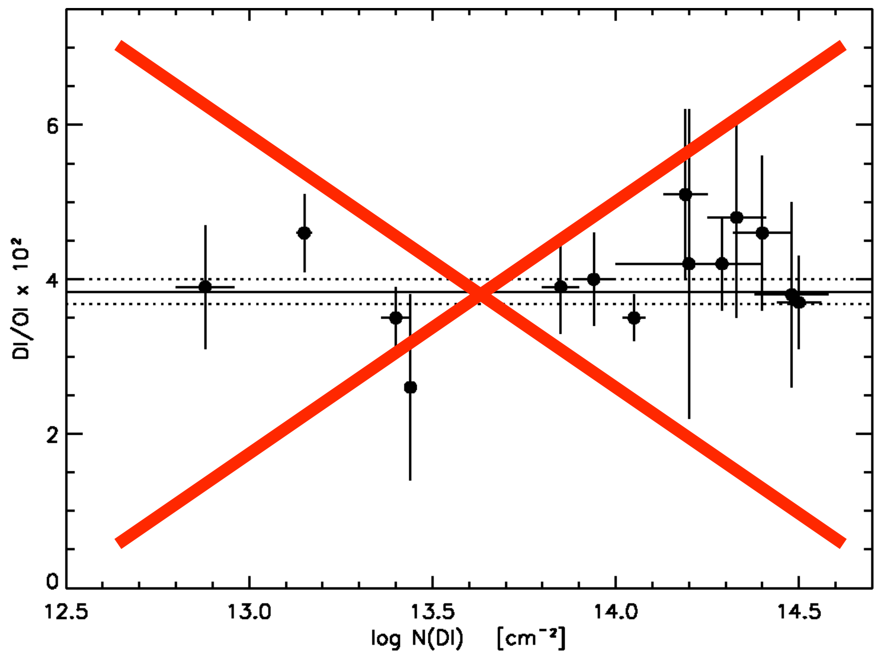


Maybe all is wrong…

HST



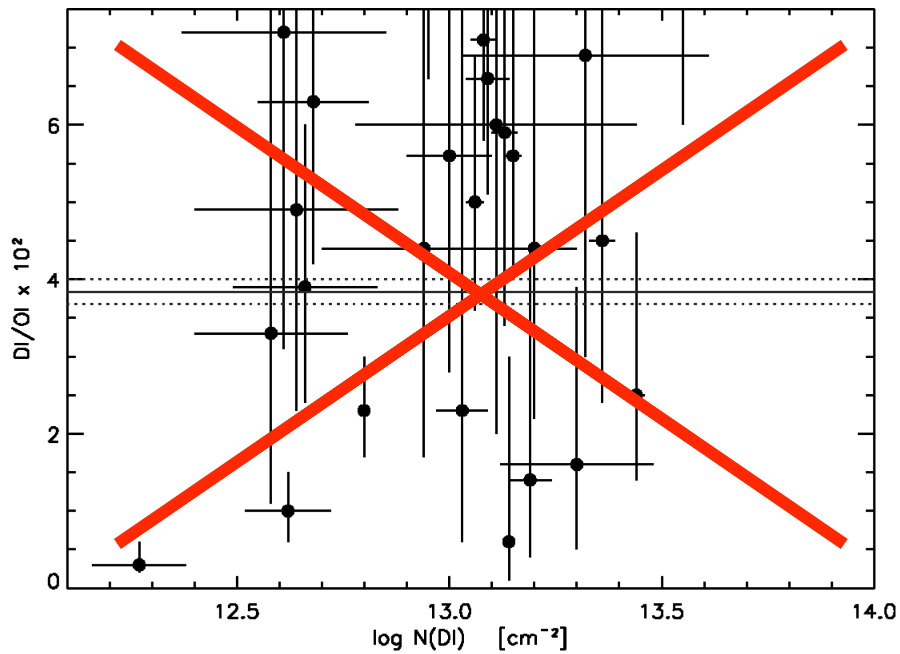
FUSE



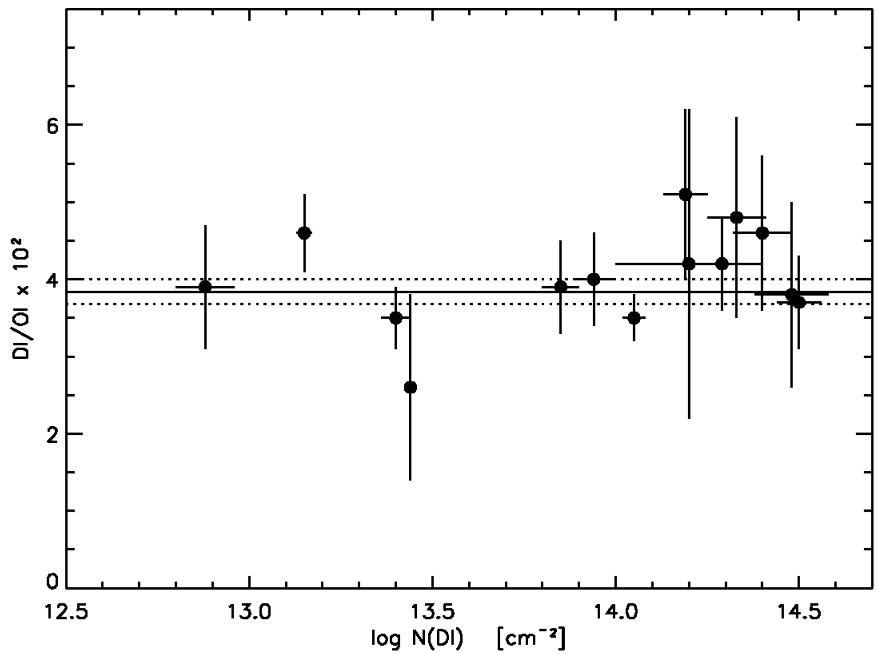
FUSE result is erroneous: D/O does vary in the Local Bubble, and thus D/H does vary in the Local Bubble too.

→ Some systematic effects disturb the FUSE D/O measurements in a way that erase variations. → These effects have to be particularly malicious!

HST



FUSE

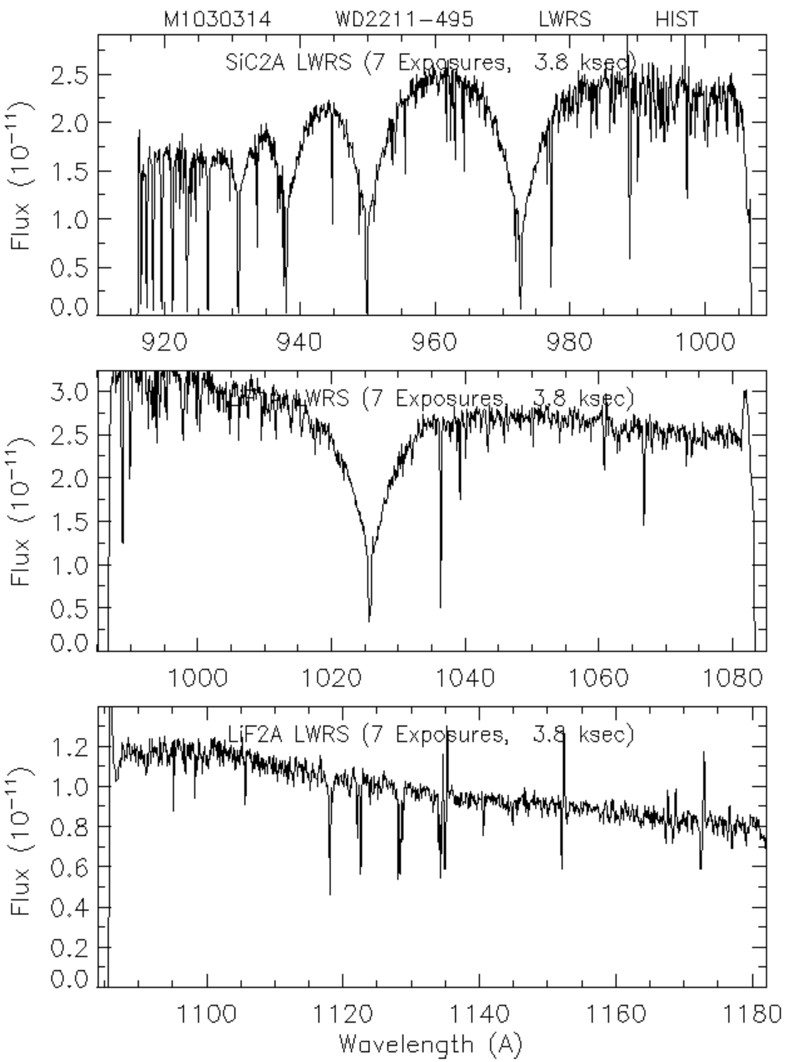


HST result is erroneous: D/O does not vary in the Local Bubble.

→ Some systematic effects disturb the HST D/O measurements in a random way. → saturation of the OI line at 1302 Å

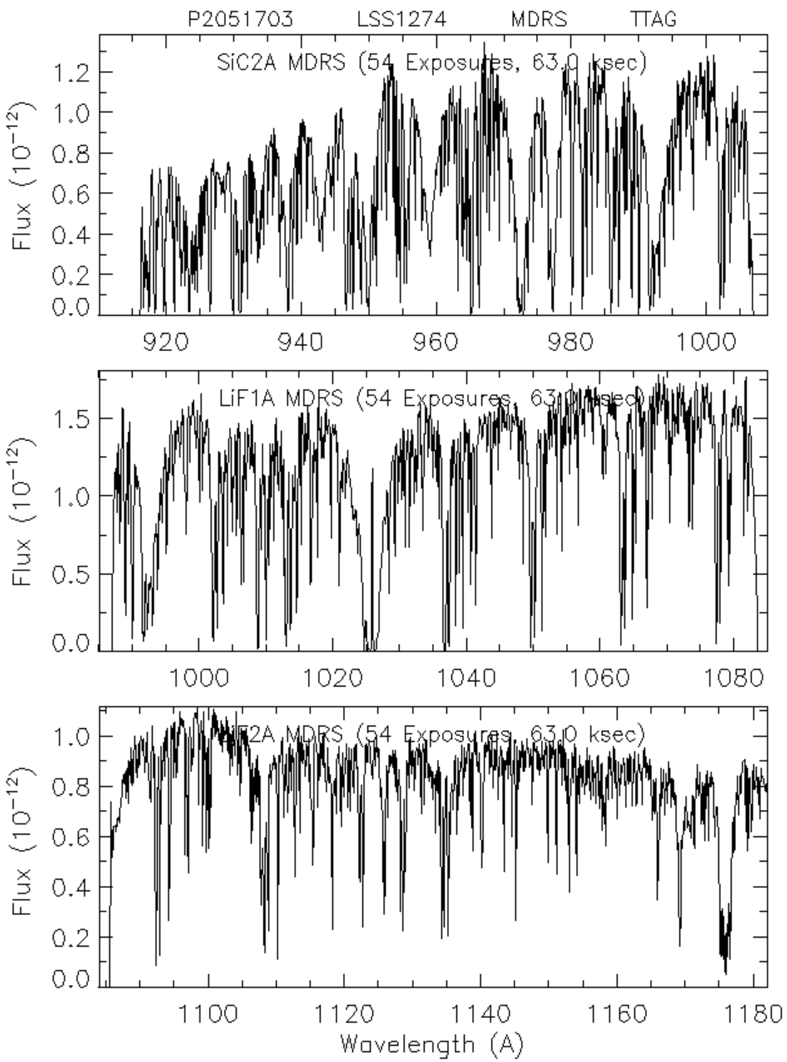
Most local ISM

(white dwarfs)

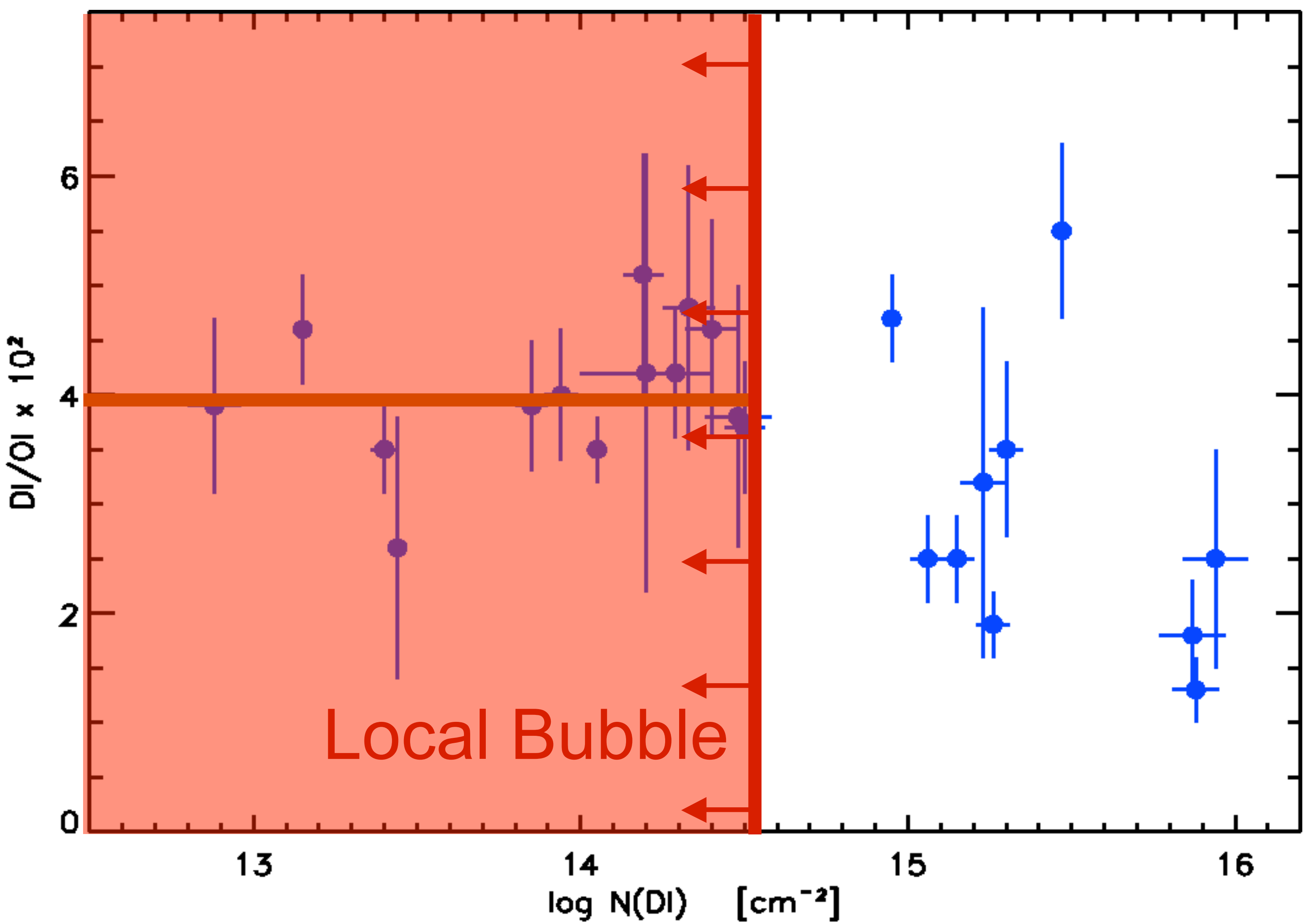


More distant ISM

(subdwarfs)

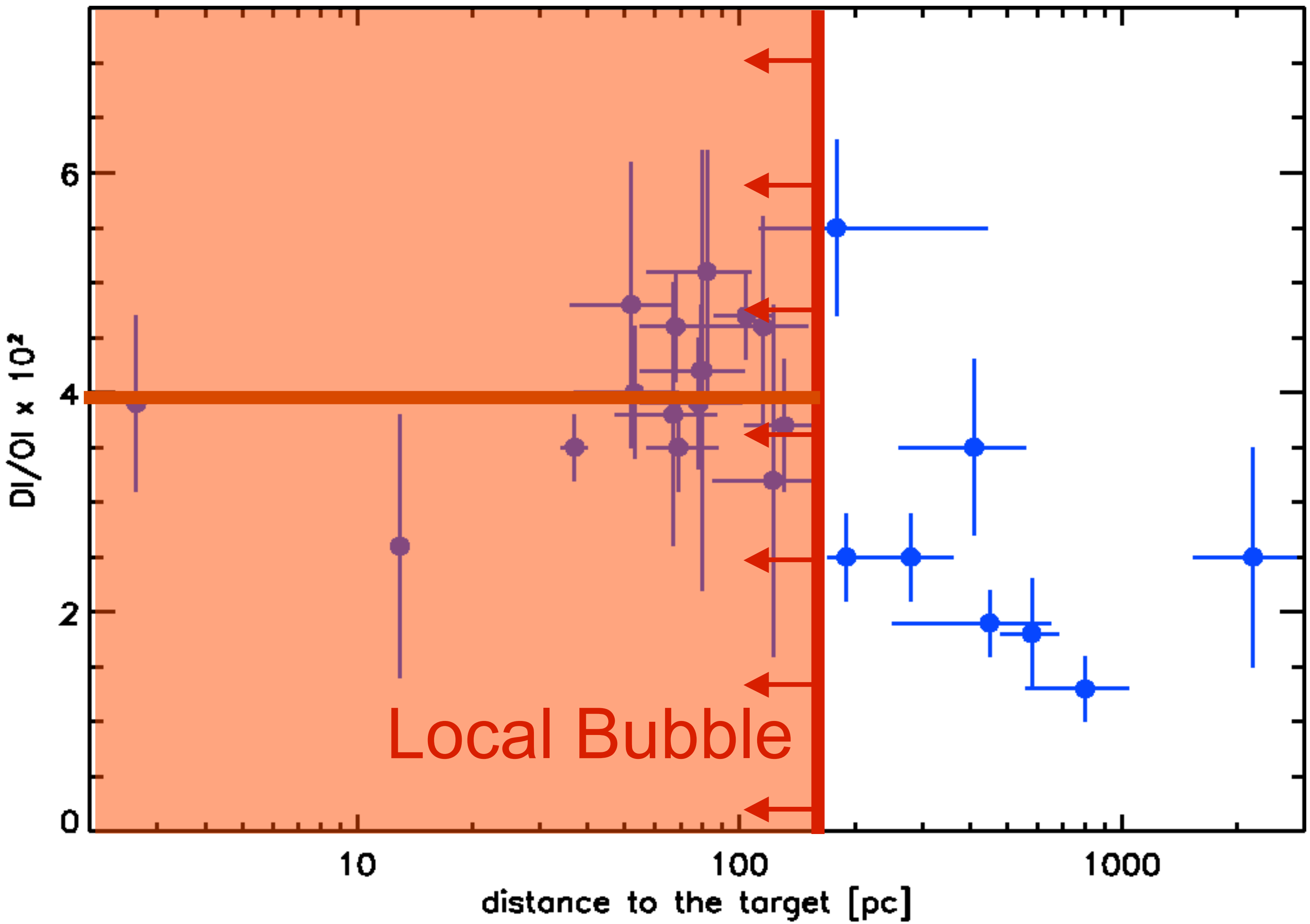


Which value for D/O is representative of the present epoch?



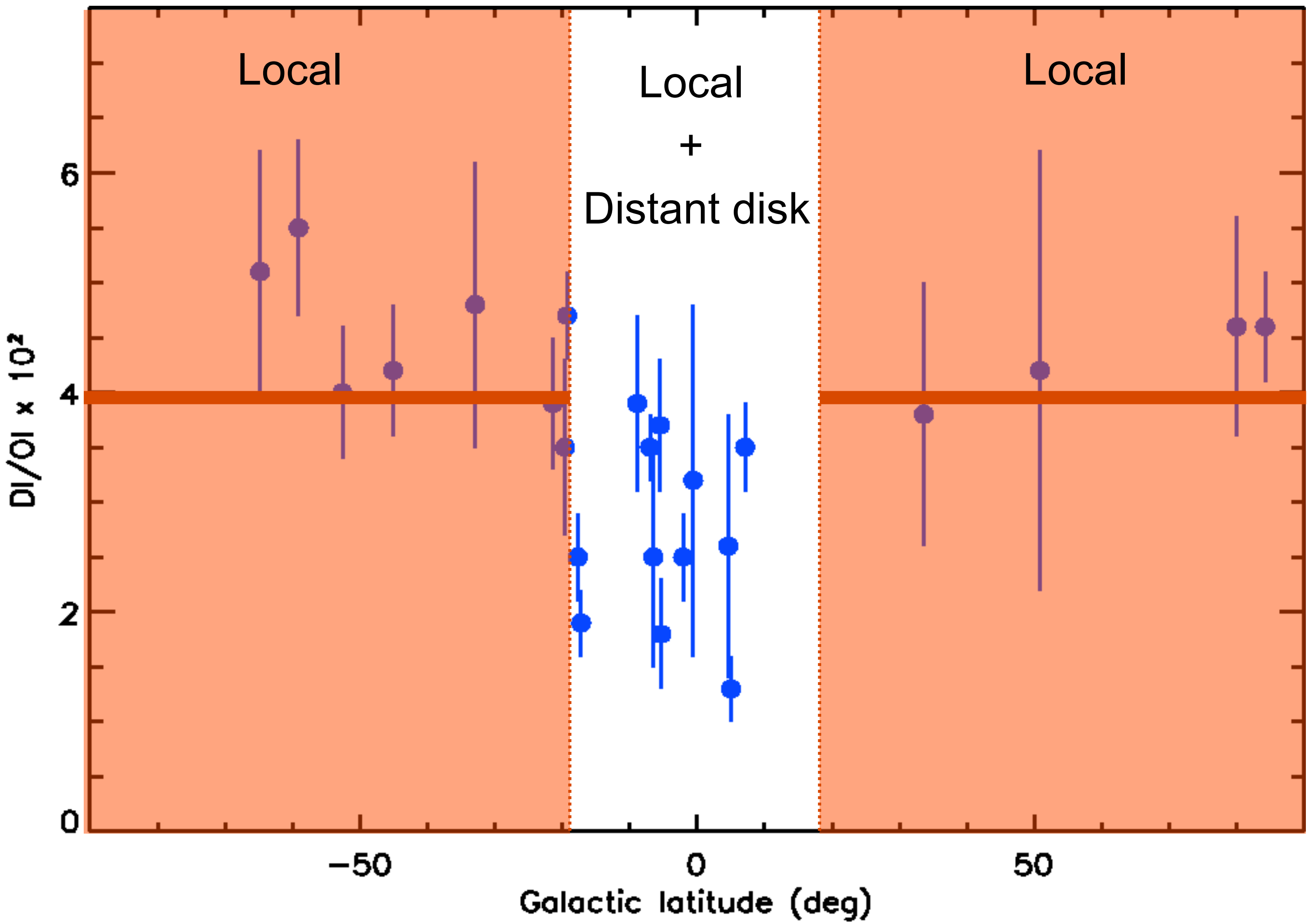
Hébrard & Moos (2003)

D/O



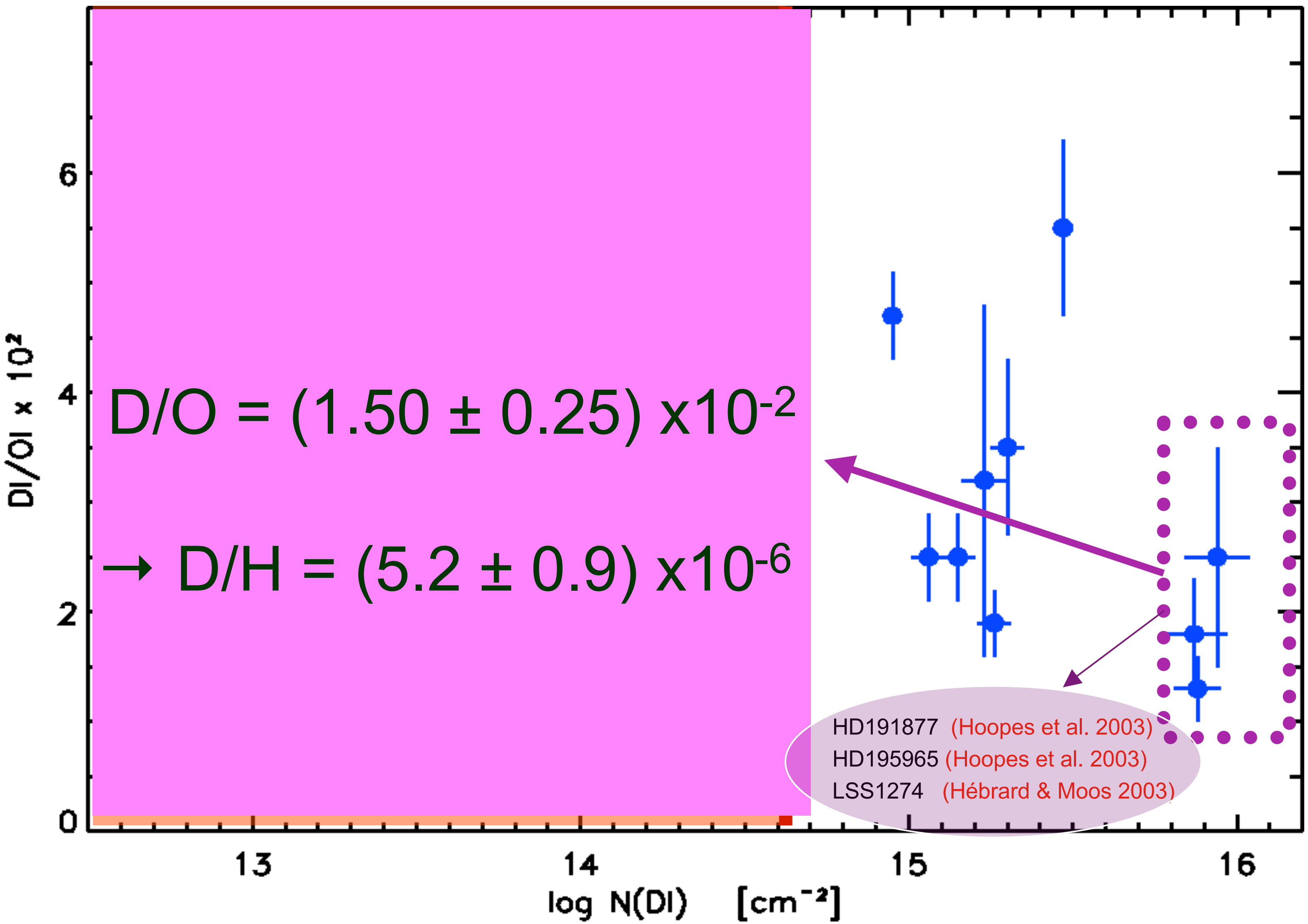
Hébrard & Moos (2003)

D/O



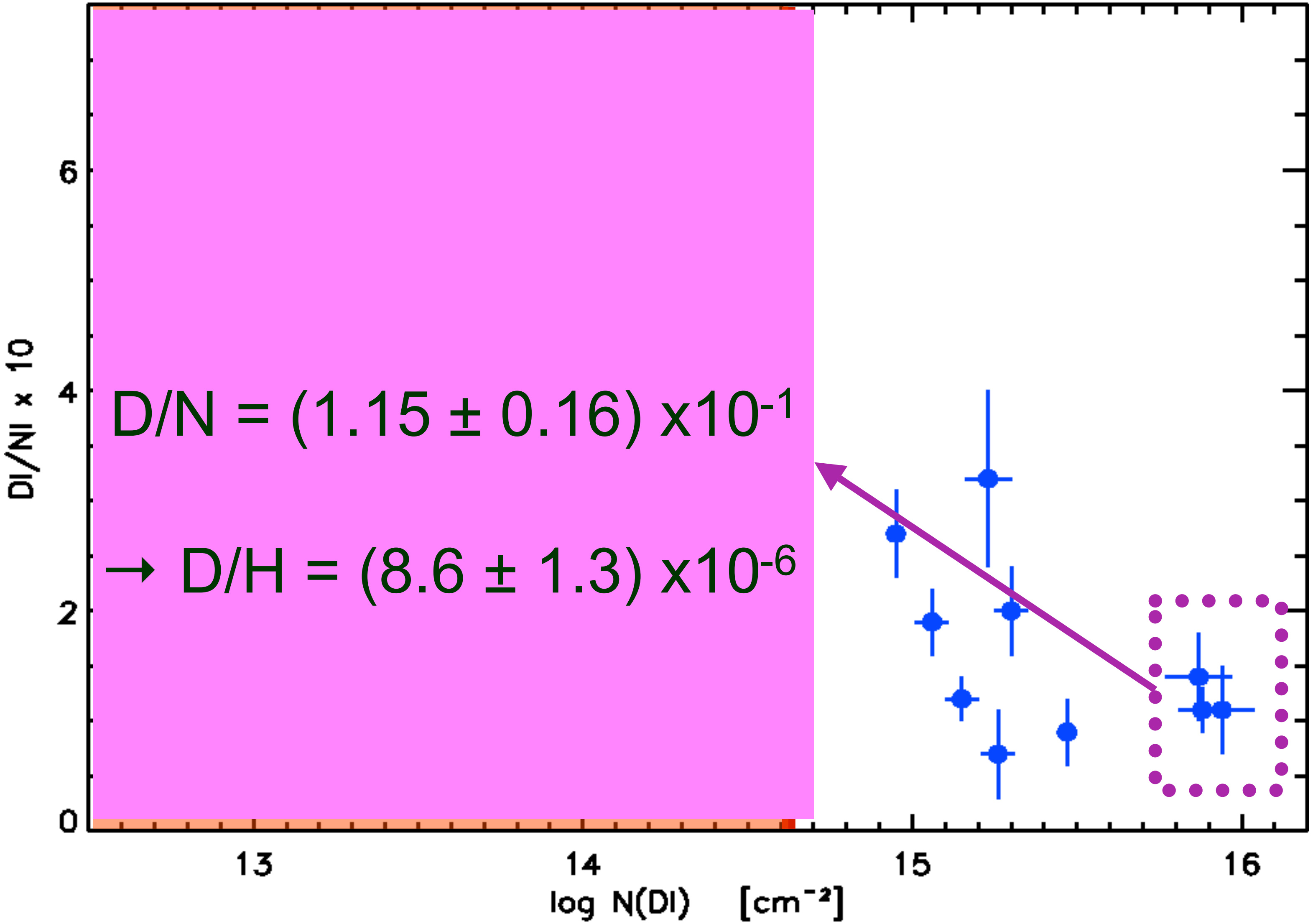
Hébrard & Moos (2003)

D/O



Hébrard & Moos (2003)

D/N



Hébrard & Moos (2003)

- D/H likely has a single value in the Local Bubble.

- $(D/H)_{LB}$ is in the range $(1.3 – 1.5) \times 10^{-5}$.

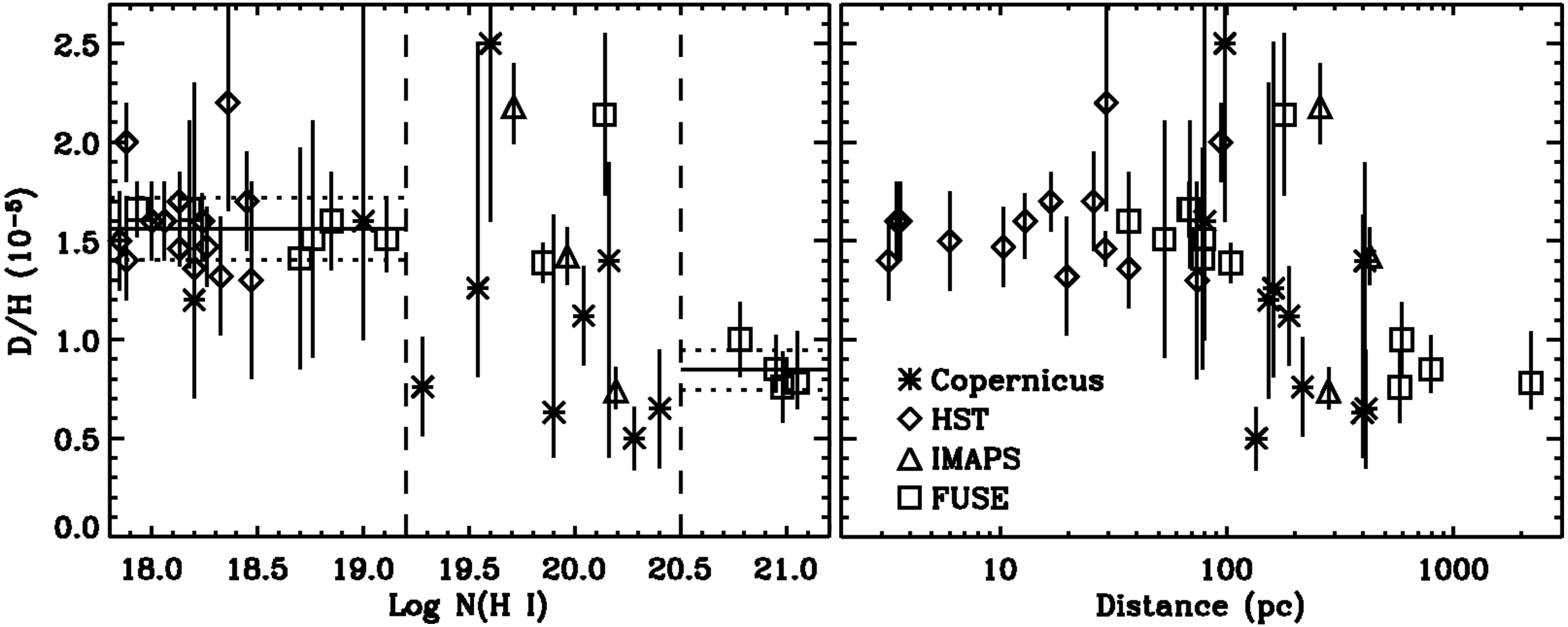
- Distant D/O, D/N, and D/H suggest a canonical present epoch value $(D/H)_{PE}$ in the range $(0.5–1.0)\times10^{-5}$.

- $(D/H)_{LB}$ is an abnormal D/H value (not canonical).

Hébrard & Moos (2003)

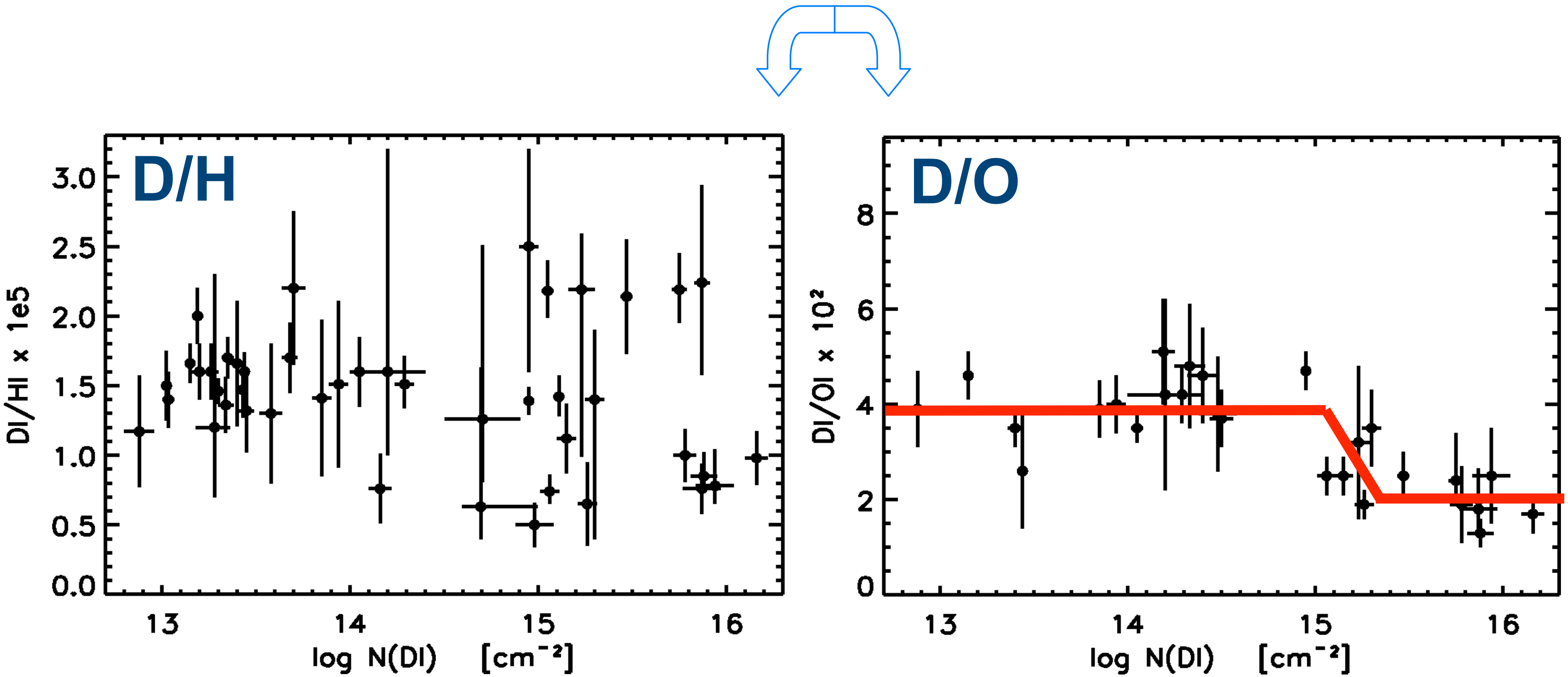
D/H in the interstellar medium

Wood et al. (2004)

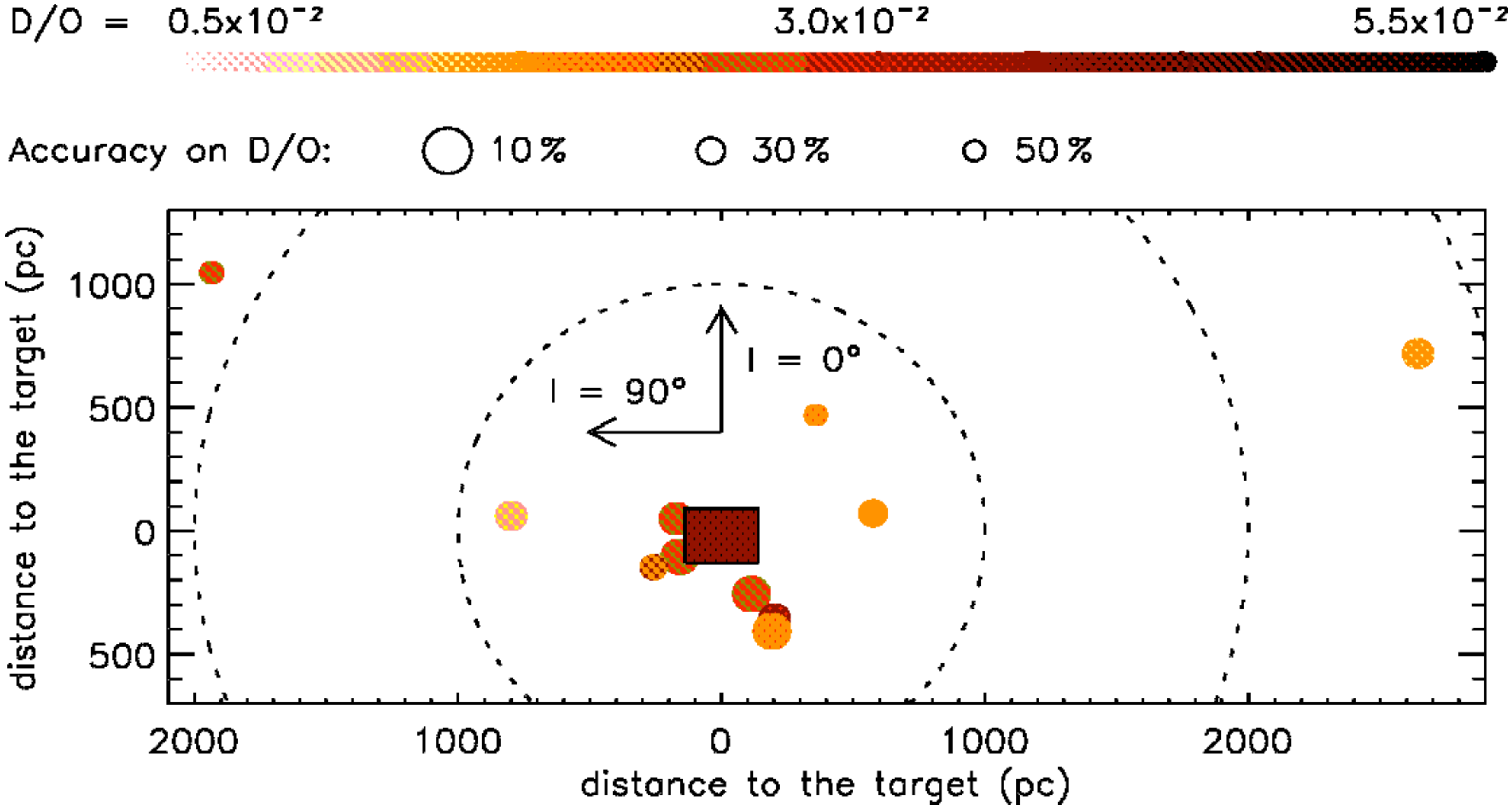


D depletion in dust? → D/H ≥ 2.3 x 10^{-5} (Linsky et al. 2006)

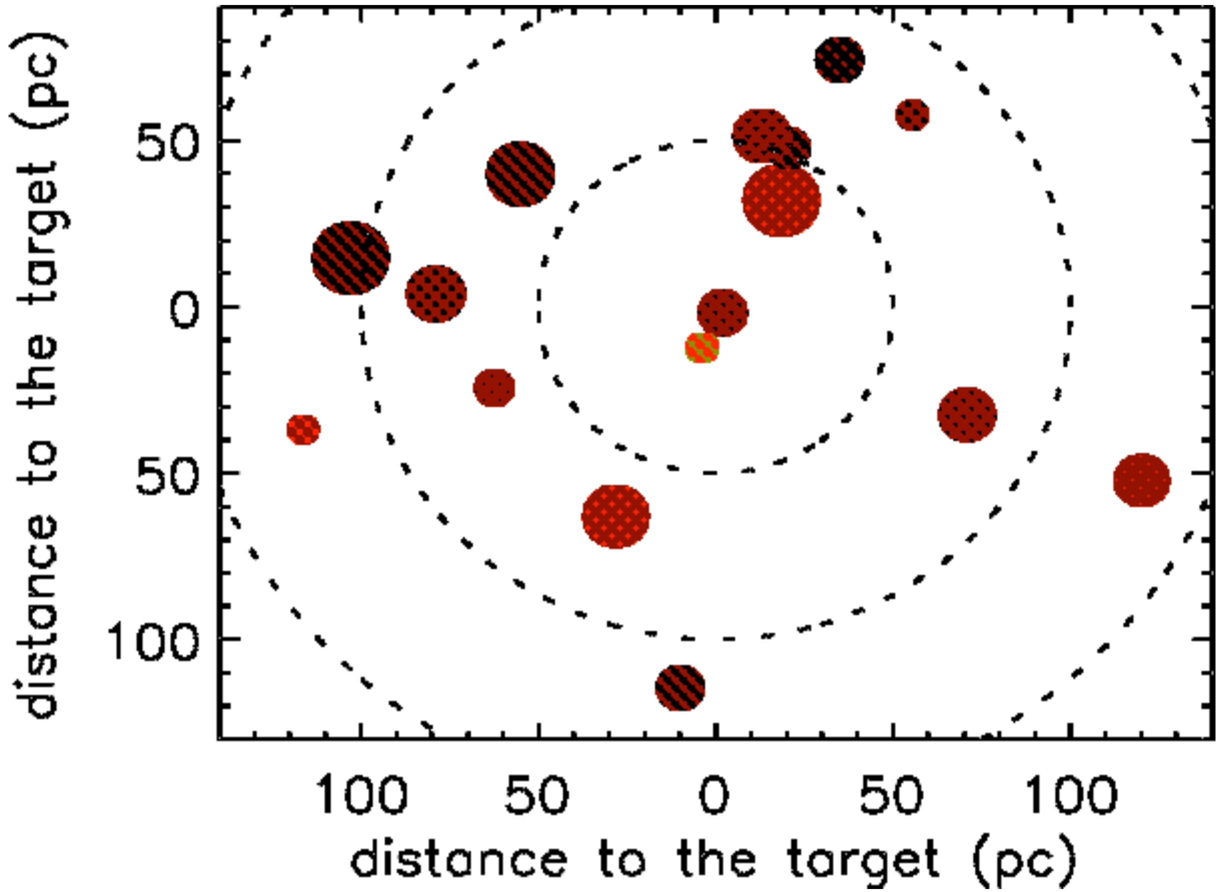
O/H = 3.43 x 10^{-4} (Meyer 2001)

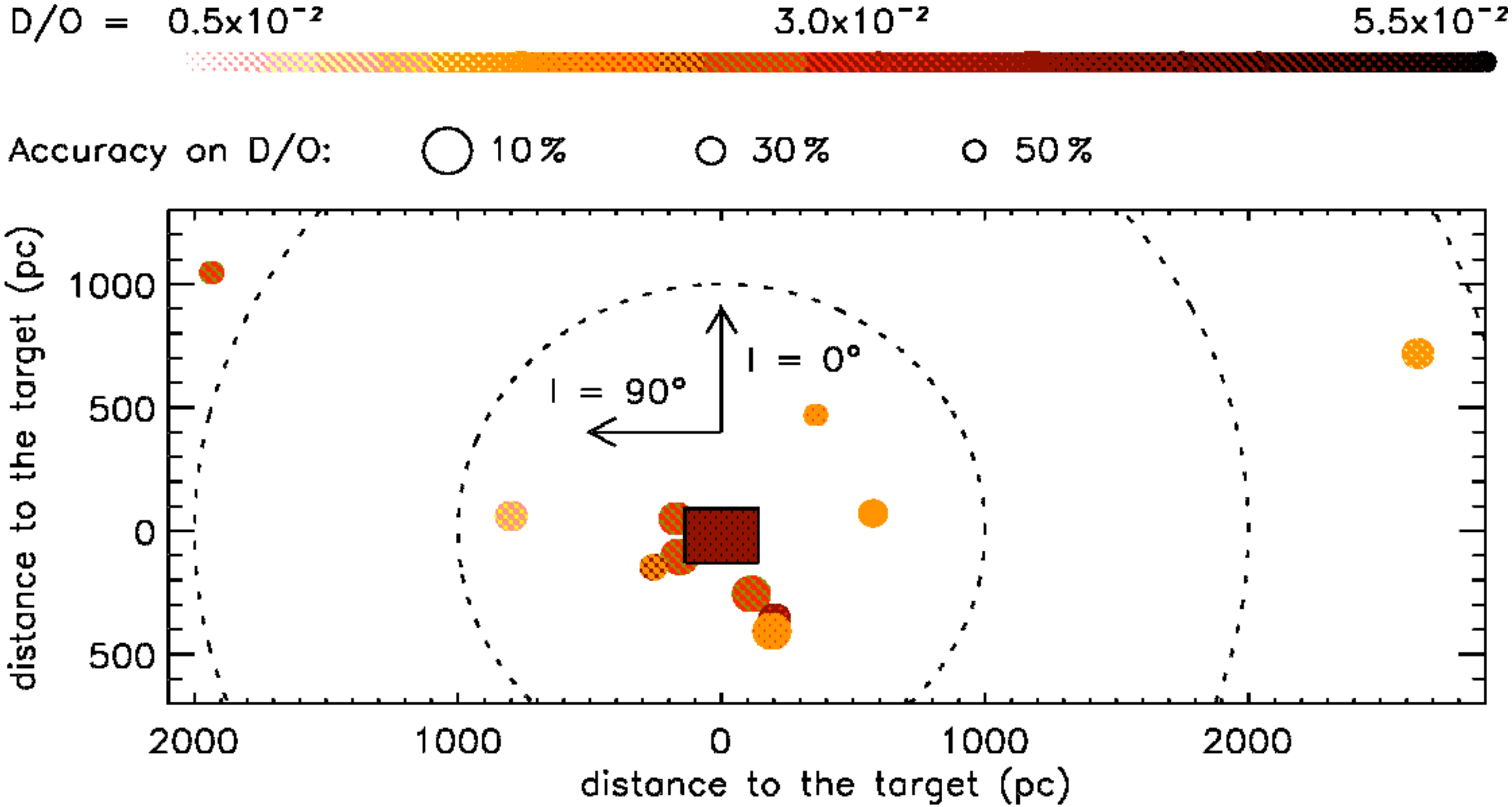


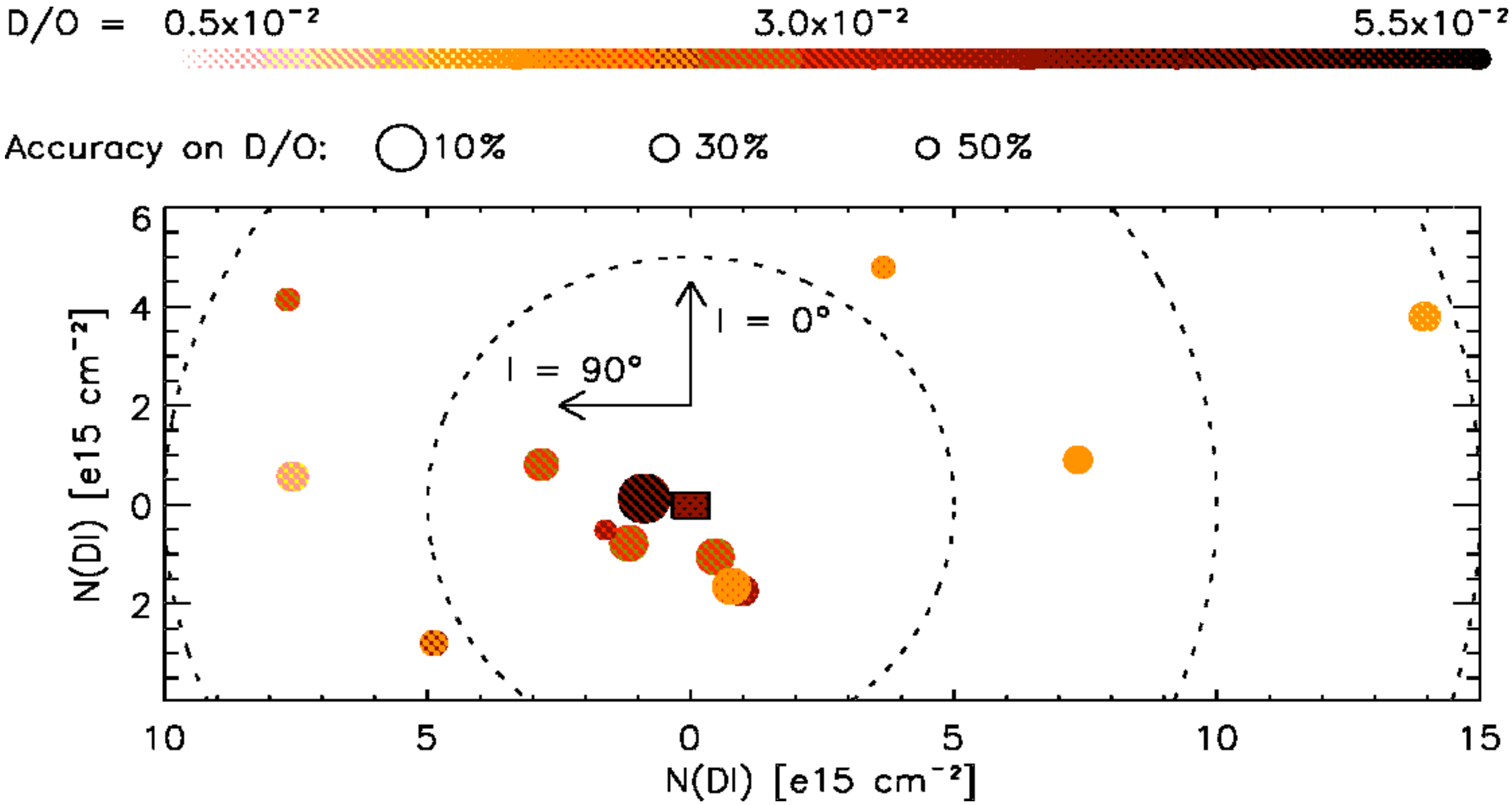
Hébrard et al. (2005)


D/O =
0.5x10⁻²
3.0x10⁻²
5.5x10⁻²
Accuracy on D/O:
10 %
30 %
50 %
l = 0°
l = 90°
1000
500
0
500
2000
1000
0
1000
2000
distance to the target (pc)
distance to the target (pc)

Local Bubble

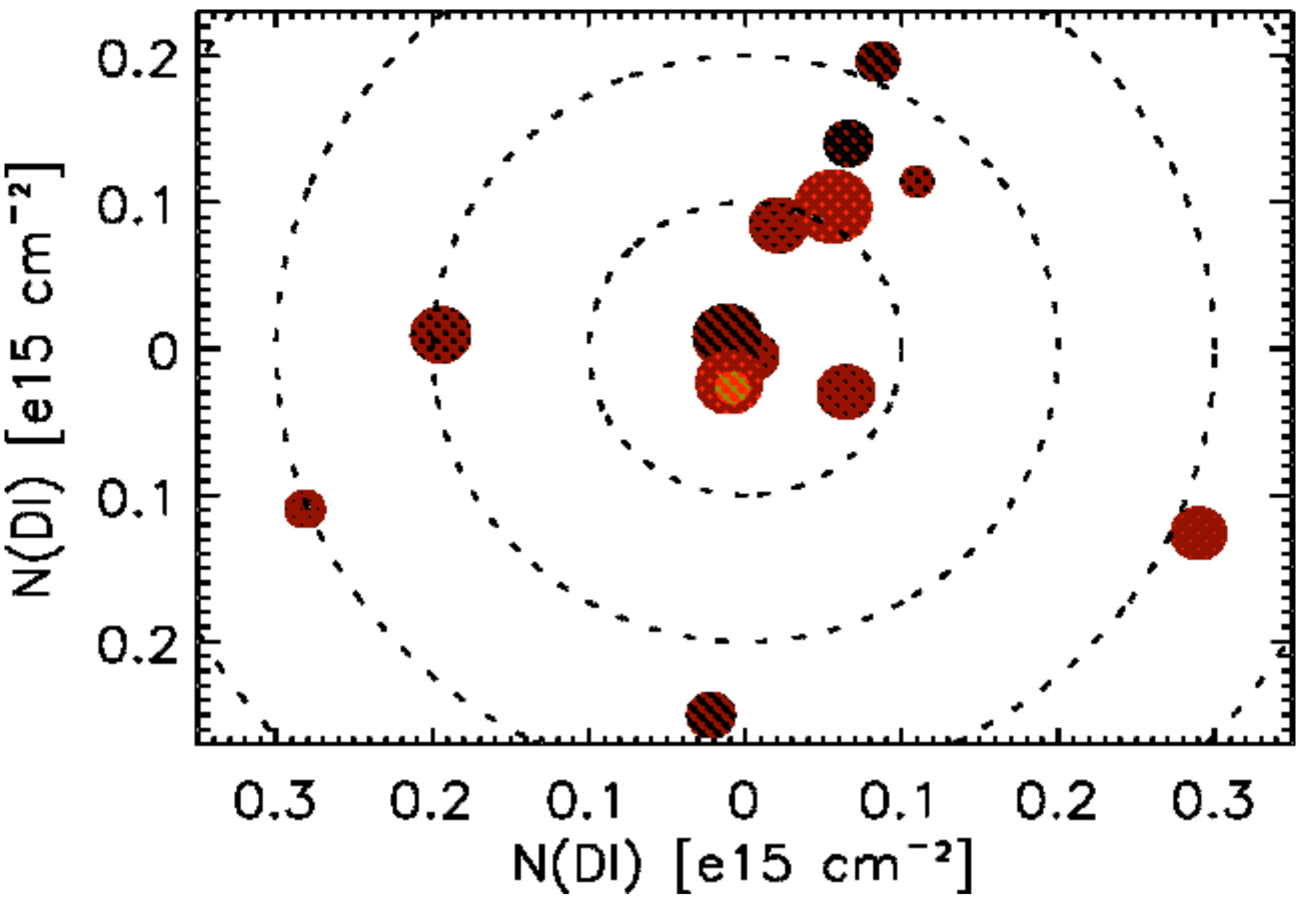


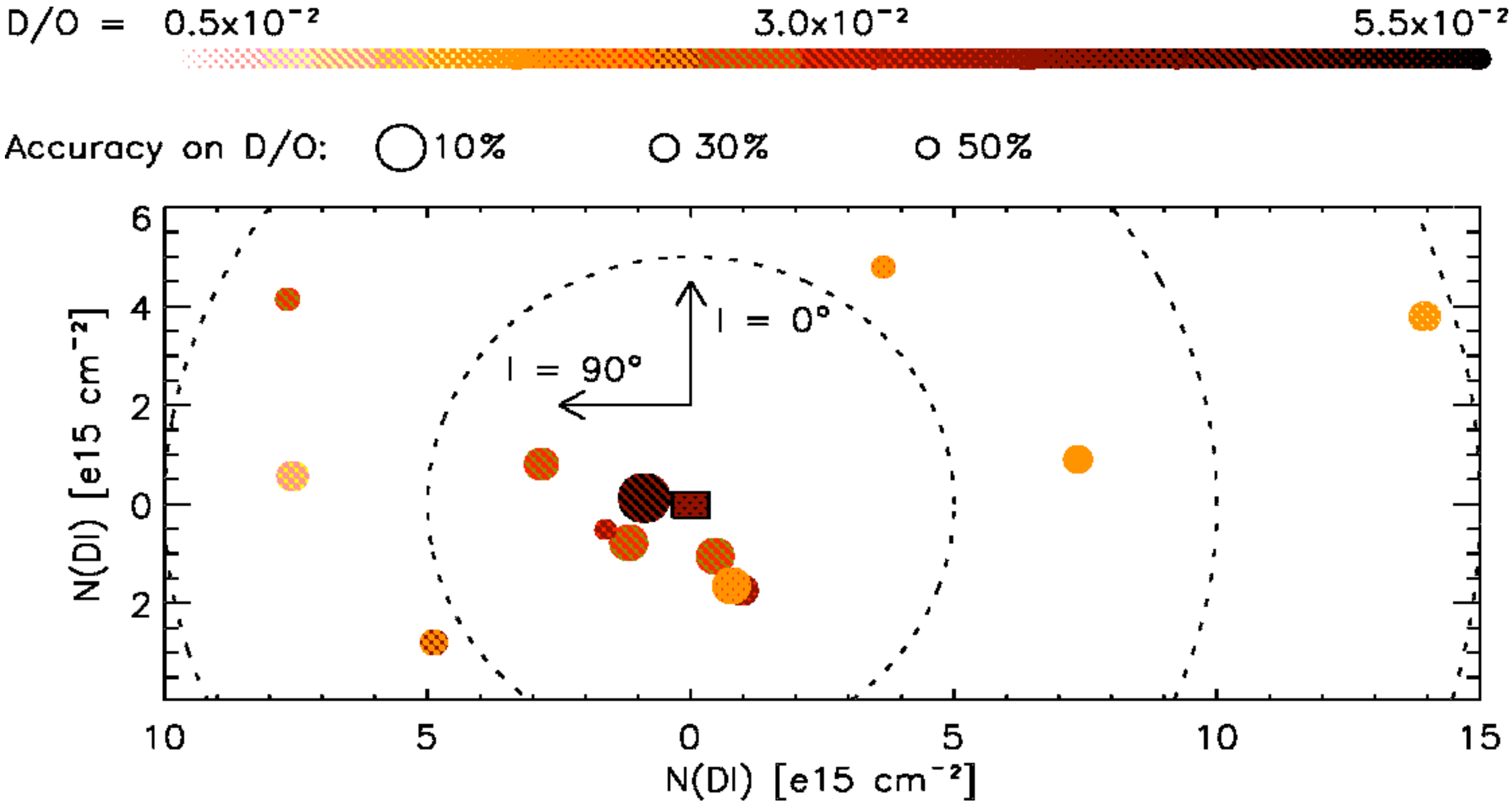

D/O = 0.5x10⁻² 3.0x10⁻² 5.5x10⁻²
Accuracy on D/O: 10% 30% 50%
l = 0°
l = 90°
1000
500
0
500
2000
1000
0
1000
2000
distance to the target (pc)
distance to the target (pc)



D/O = 0.5x10⁻² 3.0x10⁻² 5.5x10⁻²
Accuracy on D/O: 10% 30% 50%
l = 0°
l = 90°
N(DI) [e15 cm⁻²]
N(DI) [e15 cm⁻²]

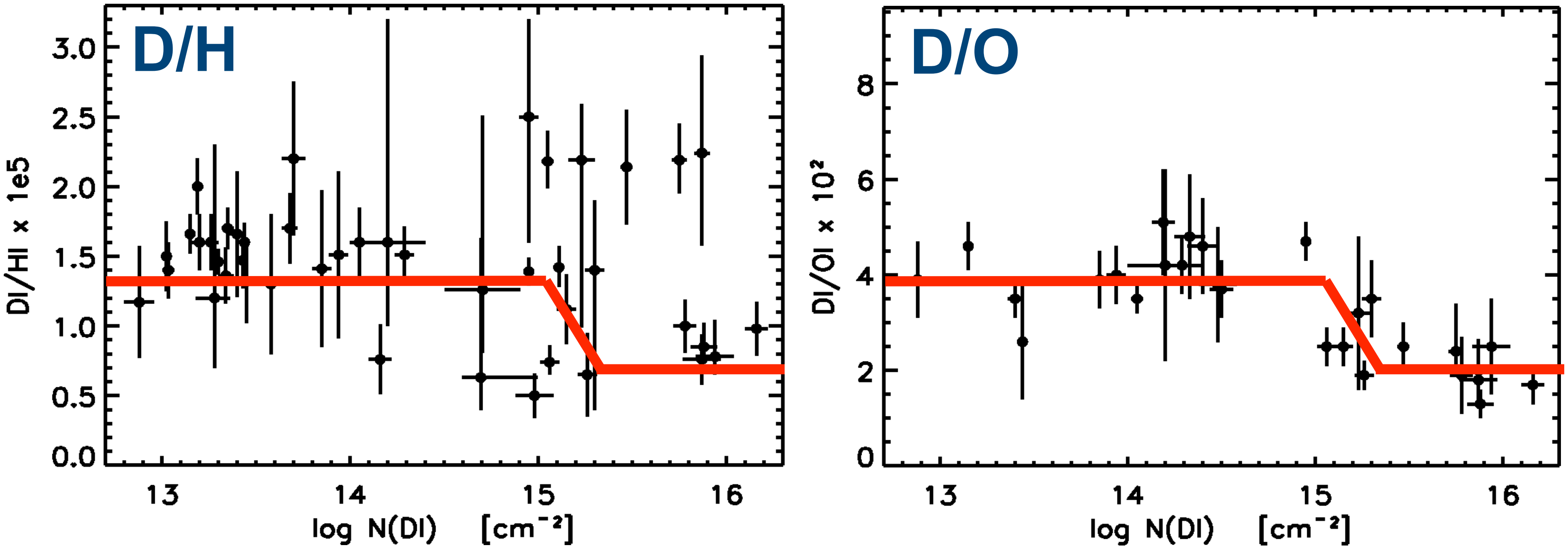
Local Bubble





D/O = 0.5x10⁻² 3.0x10⁻² 5.5x10⁻²
Accuracy on D/O: 10% 30% 50%
l = 0°
l = 90°
N(DI) [e15 cm⁻²]
N(DI) [e15 cm⁻²]

Where is the misunderstanding?



Hébrard et al. (2005)

Feige 110 sight line

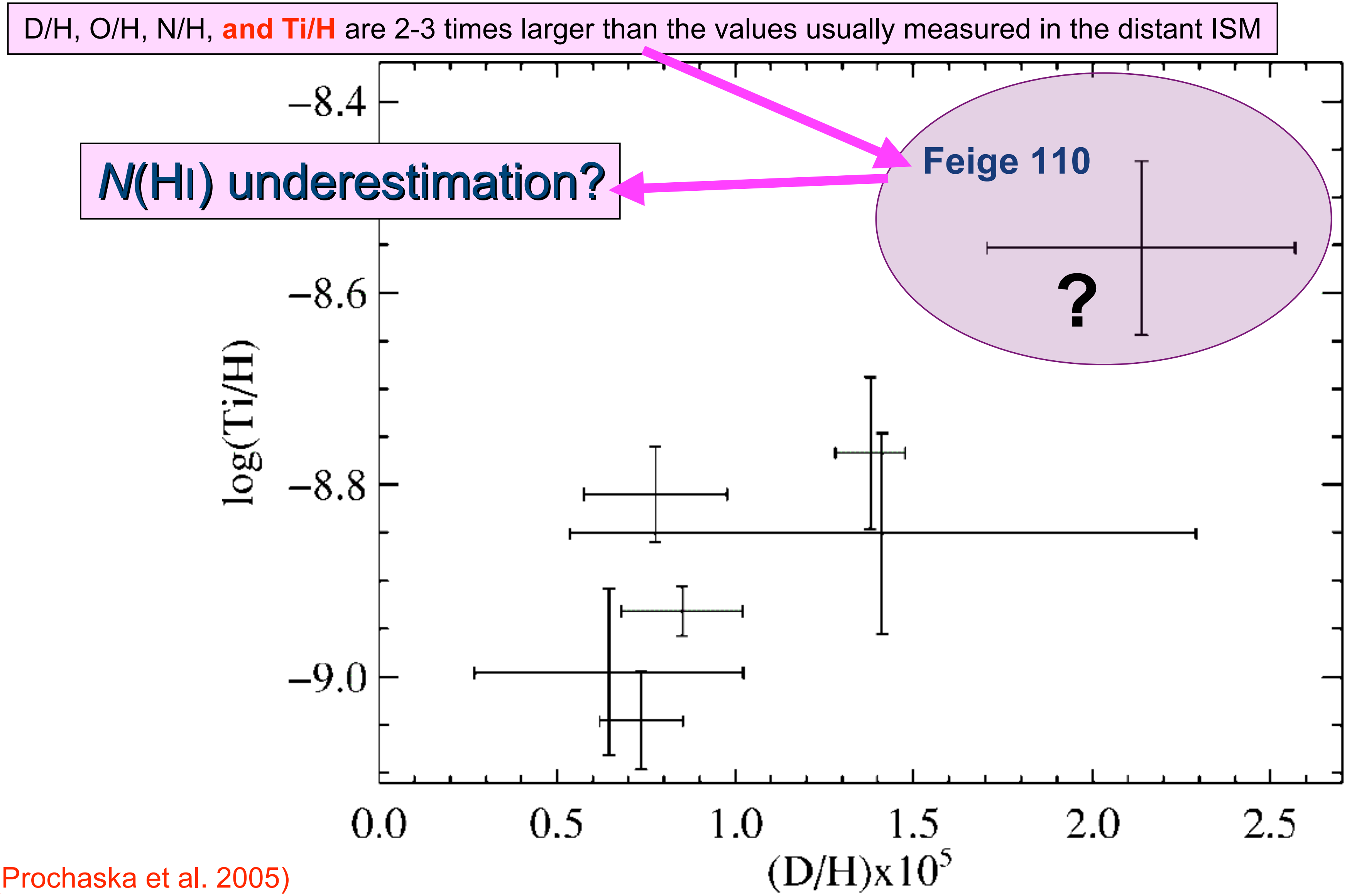
- D/H = $(2.1 \pm 0.4) \times 10^{-5}$: high
- O/H = $(8.3 \pm 2.3) \times 10^{-4}$: high
- N/H = $(2.4 \pm 0.8) \times 10^{-4}$: high

All those 3 ratios are 2-3 times larger
than the values usually measured in the distant ISM

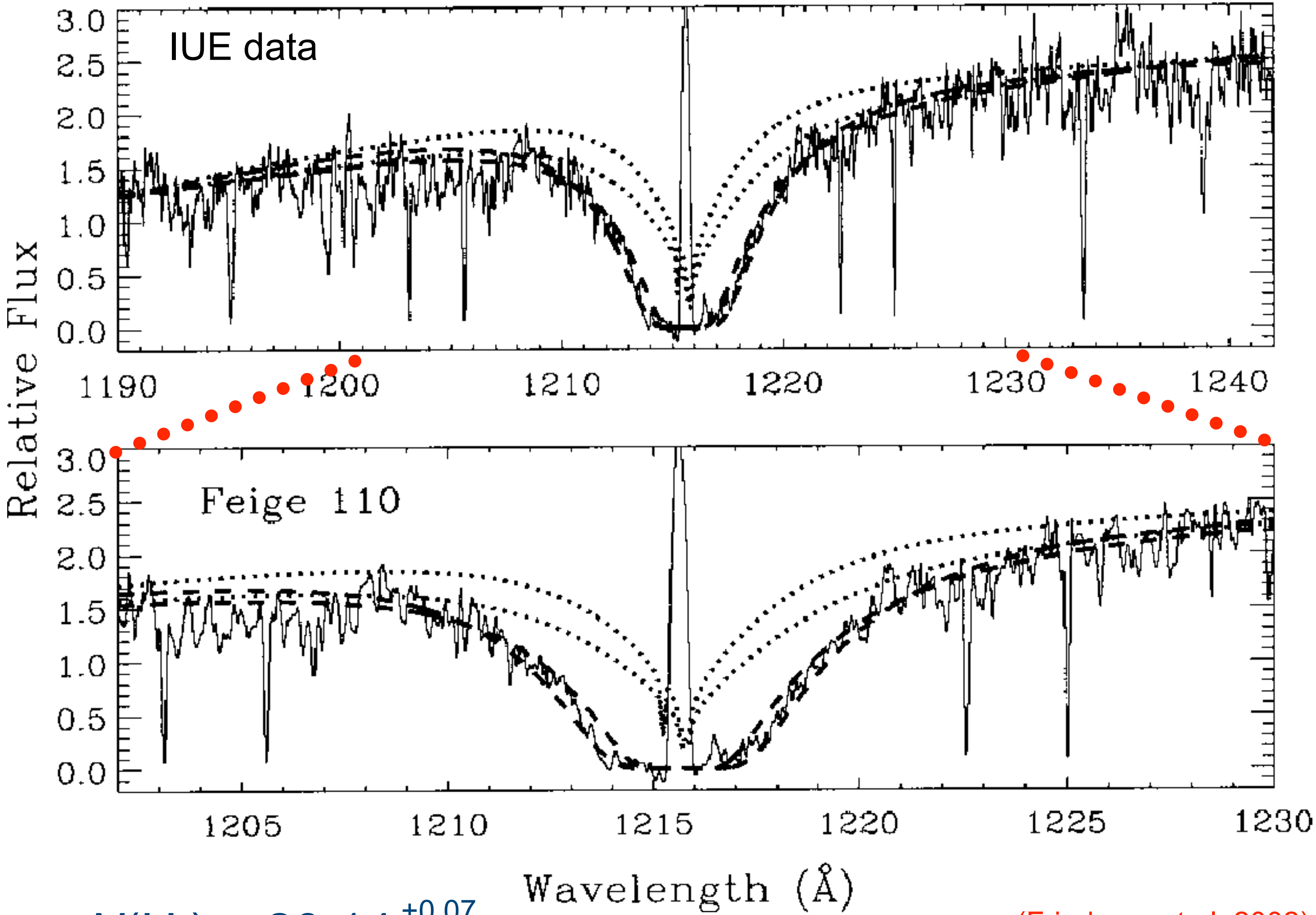
→ N(HI) underestimation?

(→ Might explain some correlations)

Evidence for correlated titanium and deuterium depletion?



(Prochaska et al. 2005)



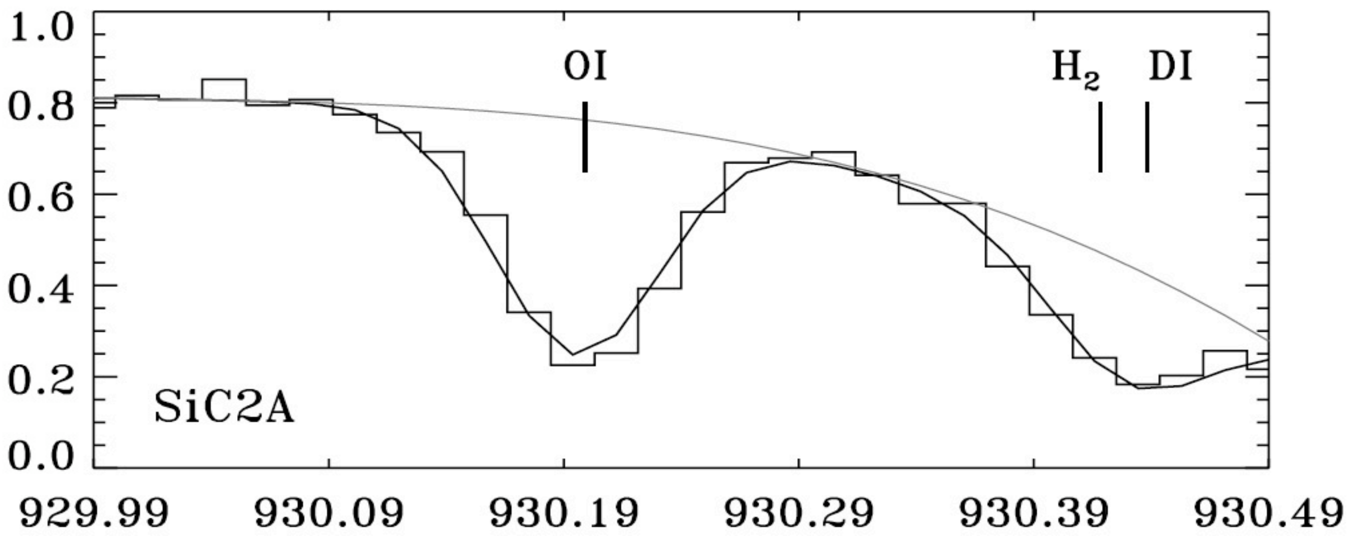
Log N(HI) = 20.14 $^{+0.07}_{-0.10}$

(Friedman et al. 2002)

Feige 110 sight line

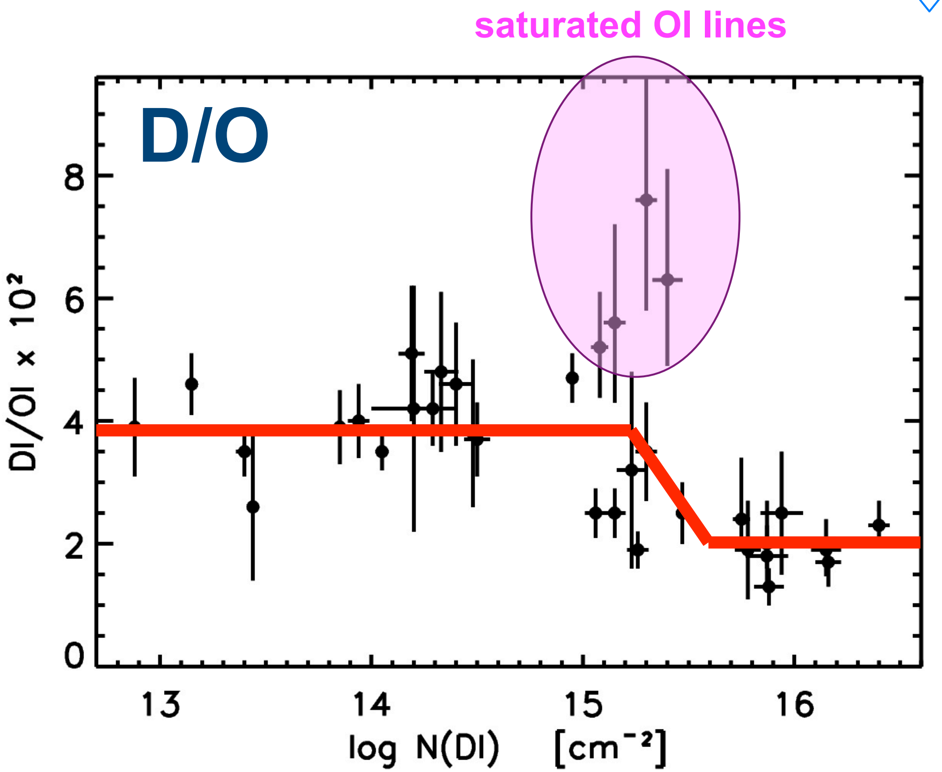
- D/O = $(5.5 \pm 0.7) \times 10^{-2}$: high

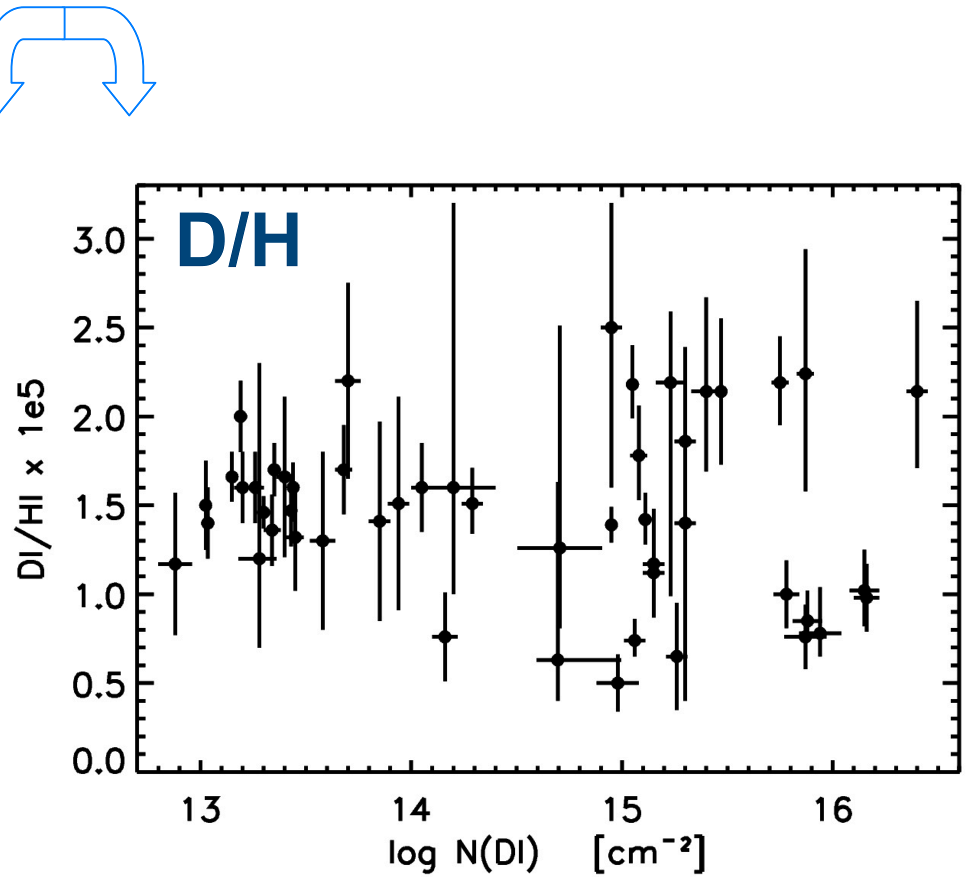
(Friedman et al. 2002)



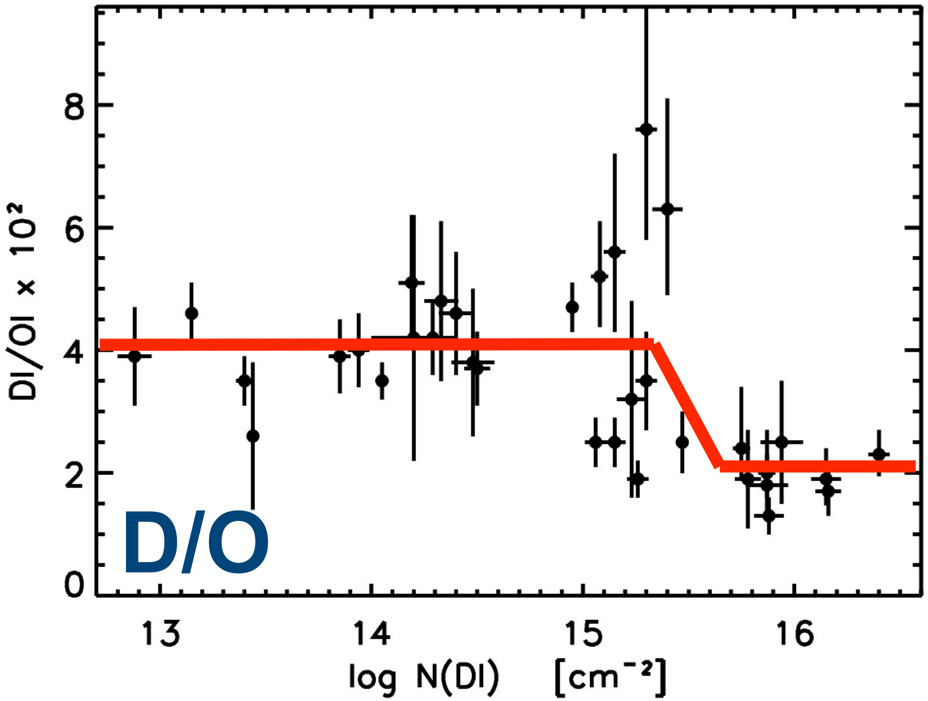
2009

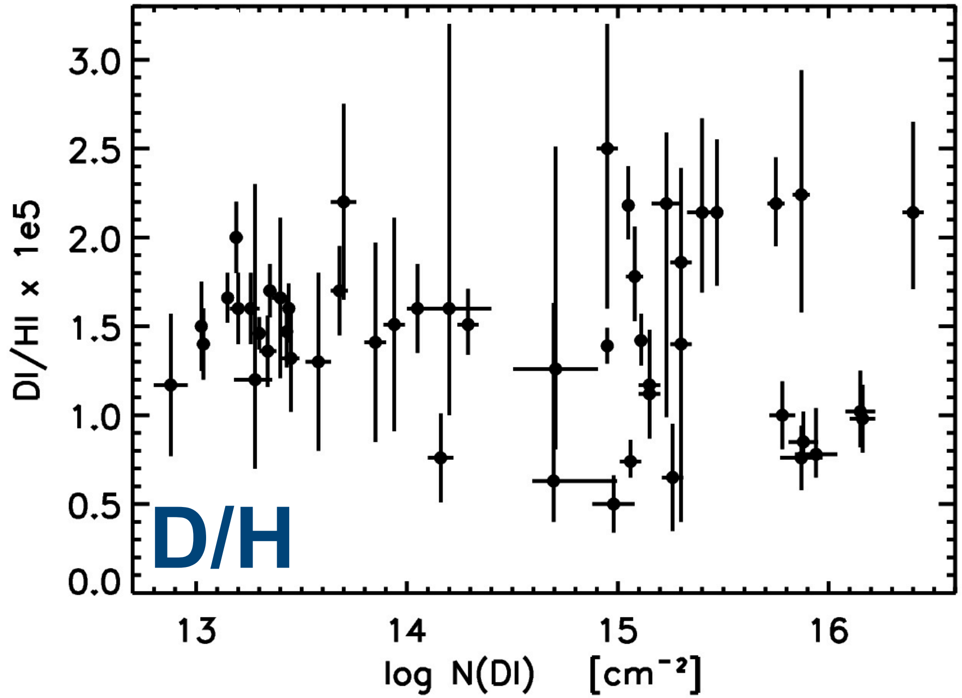
O/H = 3.43 x 10^{-4} (Meyer 2001)





2009





- D/H = 1.5 x 10^{-5} should no longer be considered as a canonical value.

- D/O shows less dispersion than D/H does.

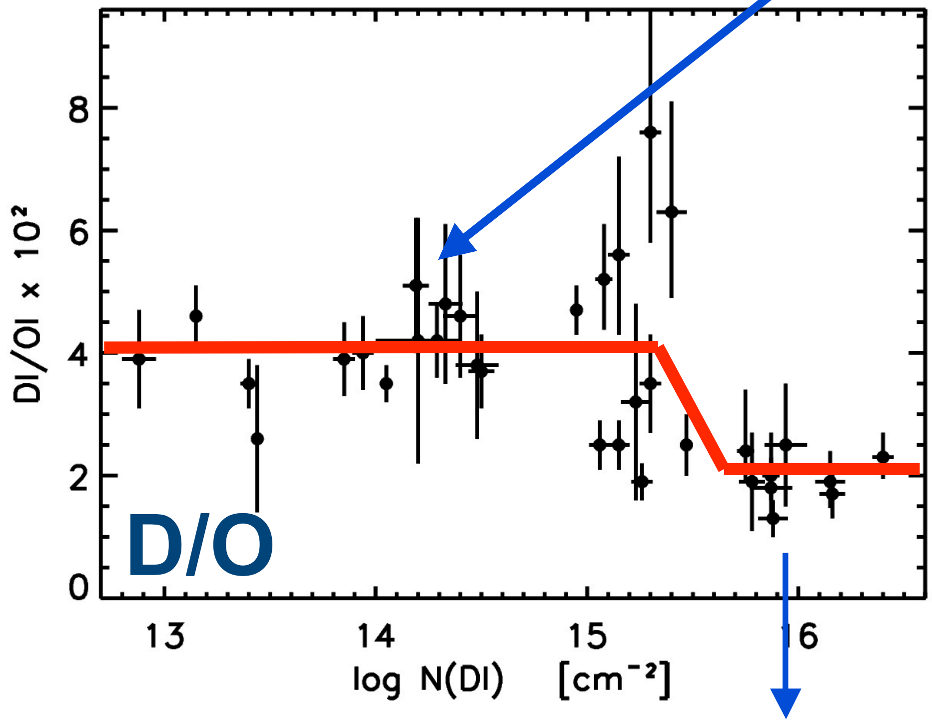
9 distant targets with available D/H and D/O: χ^2 = 35.8 for D/H and χ^2 = 5.9 for D/O

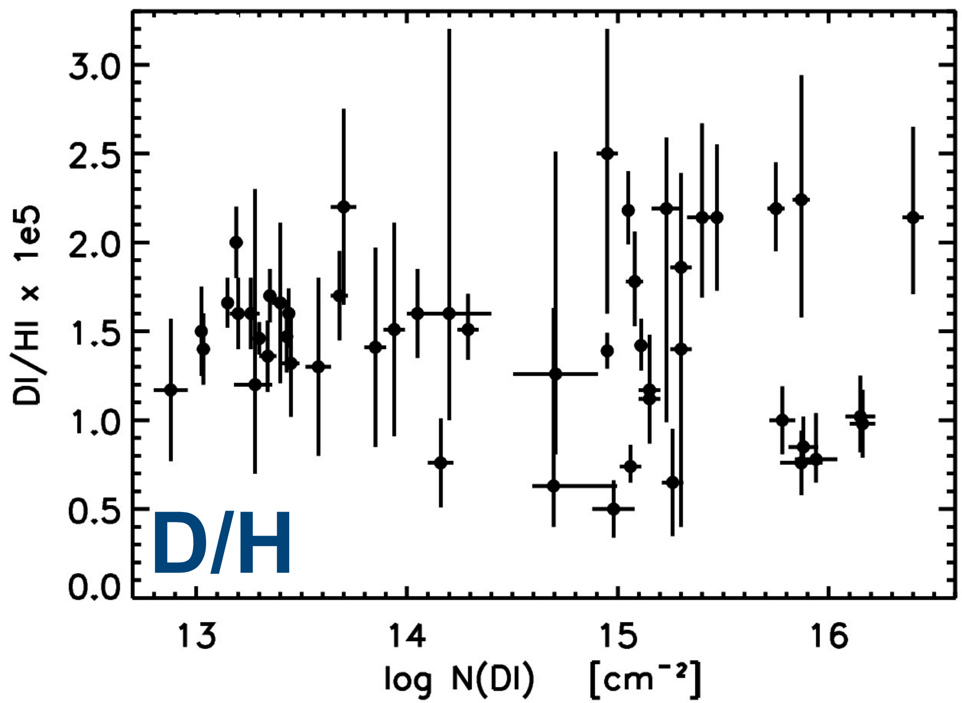
- D/H ≈ 2.3 x 10^{-5} would correspond to D/O ≈ 7 x 10^{-2}.

- D/O appears to be homogeneous and low in the distant ISM.

2009

Local infall? (see also Cartledge et al. 2004 about O/H)



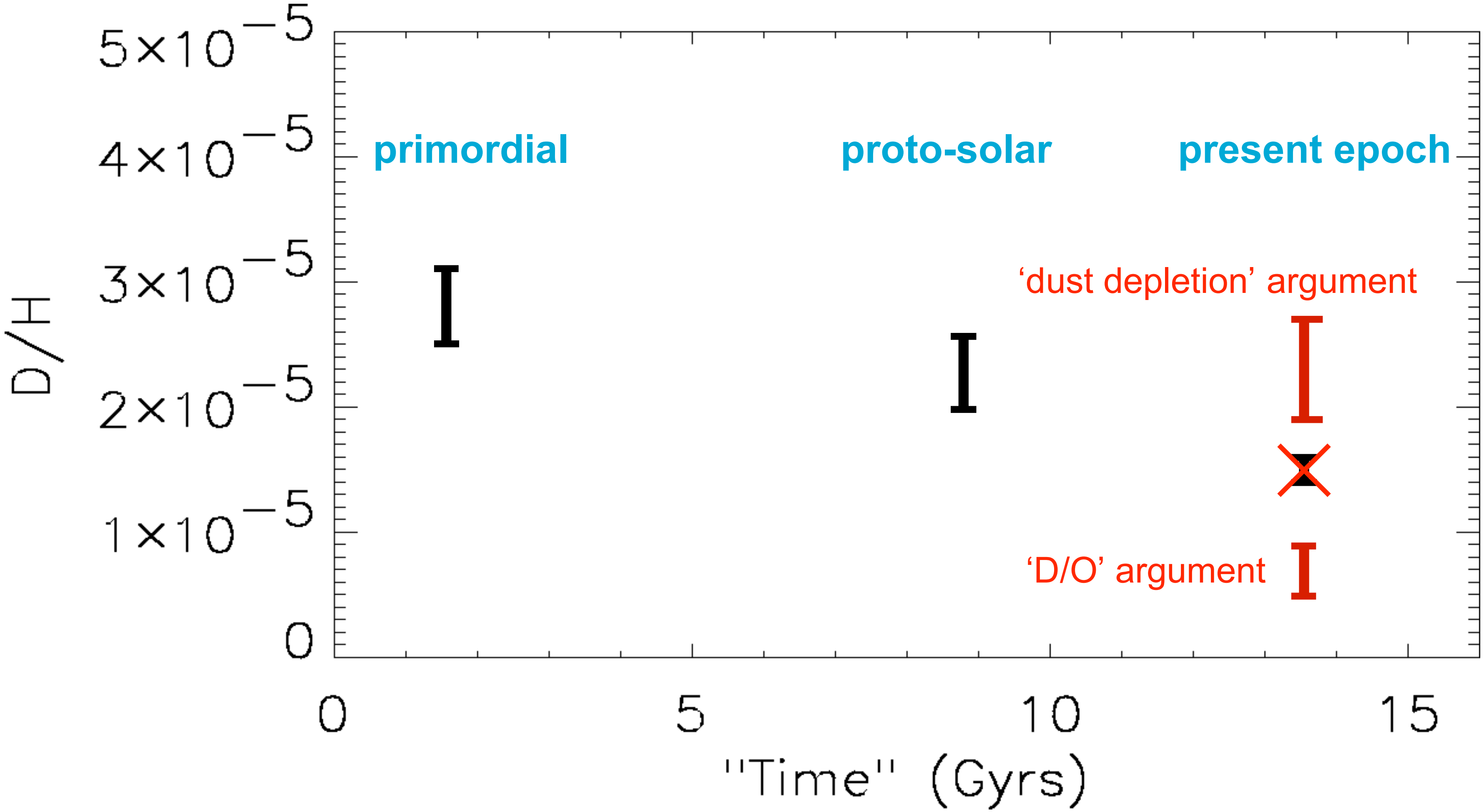


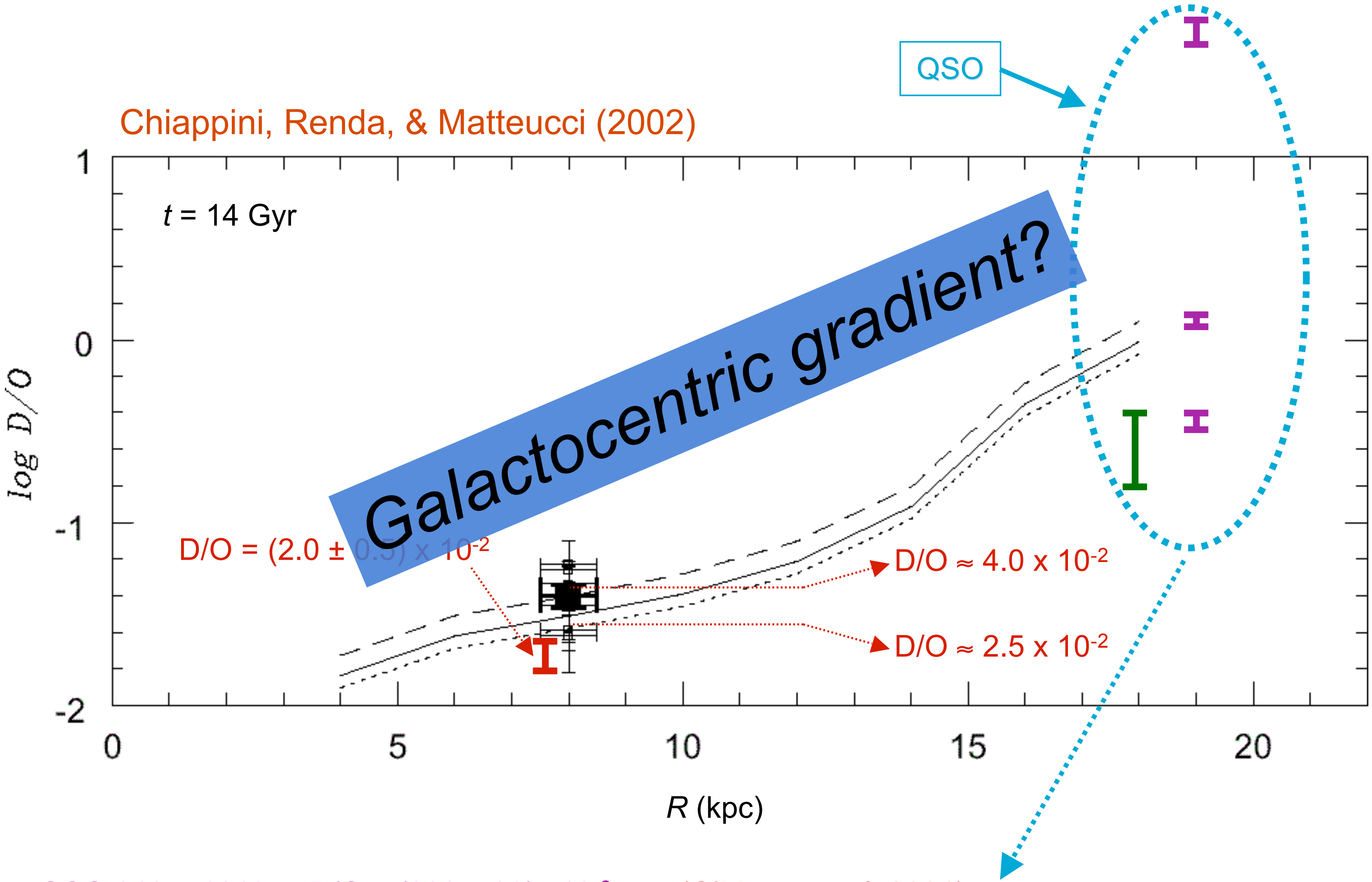
$(D/O)_{PE} = (2.0 \pm 0.5) \times 10^{-2}$

$(D/H)_{PE} = (7 \pm 2) \times 10^{-6}$

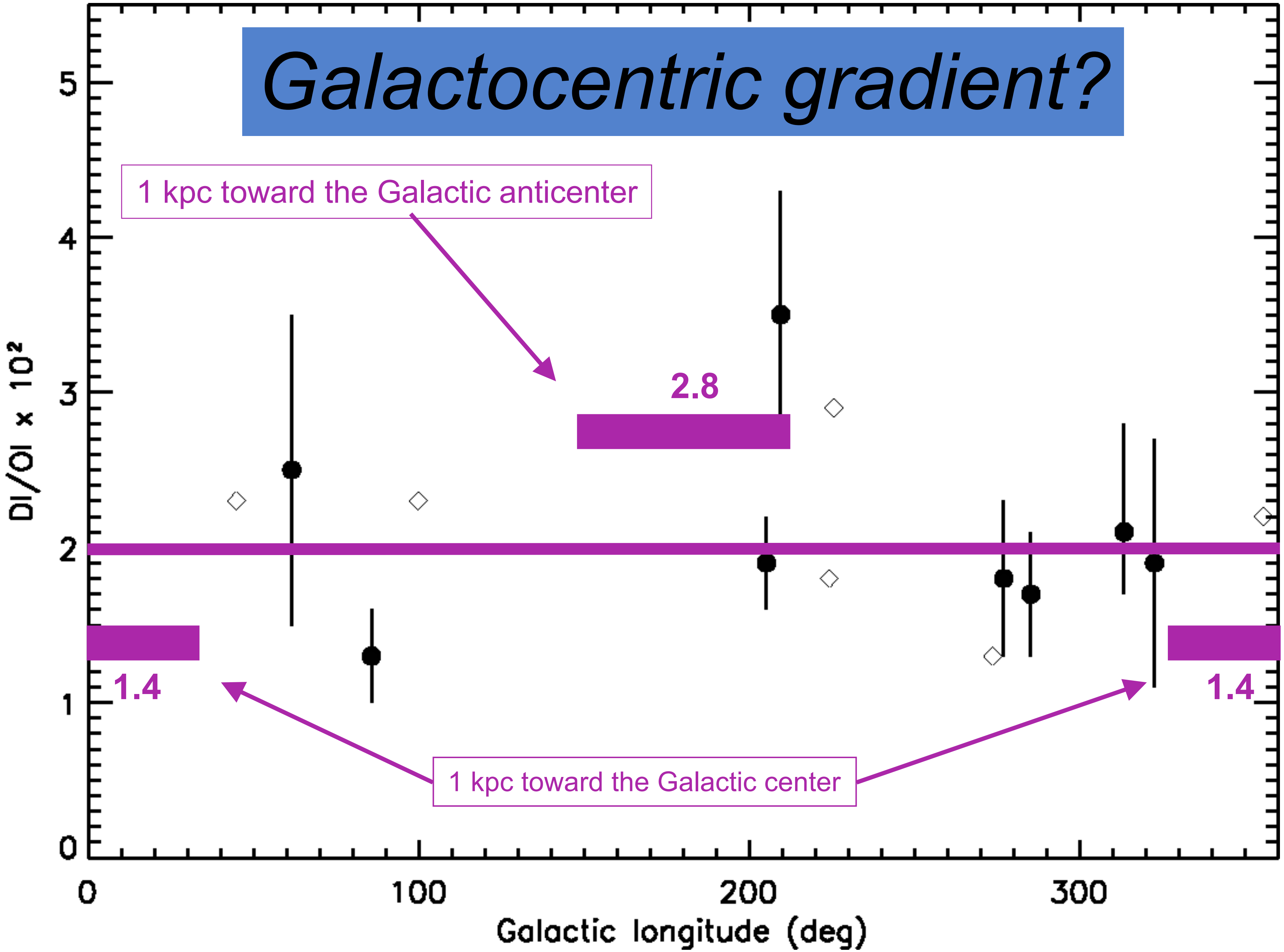
Canonical value representative of the present epoch?

Deuterium: tracer of chemical evolution





- QSO 0105+1619 : D/O = (280 ± 30) x10^{-2} (O'Meara et al. 2001)
- QSO 0347-3819 : D/O = (37 ± 3) x10^{-2} (Levshakov et al. 2002)
  = (21 ± 4) x10^{-2} (D'Odorico et al. 2001)
- QSO 1243+3047 : D/O = (3000 ± 300) x10^{-2} (Kirkman et al. 2003)
- Complex C : D/O = (28 ± 12) x10^{-2} (Sembach et al. 2004)



Galactocentric gradient?
1 kpc toward the Galactic anticenter
2.8
1.4
1.4
1 kpc toward the Galactic center
DI/OI x 10²
Galactic longitude (deg)
0
1
2
3
4
5
0
100
200
300

[redacted]

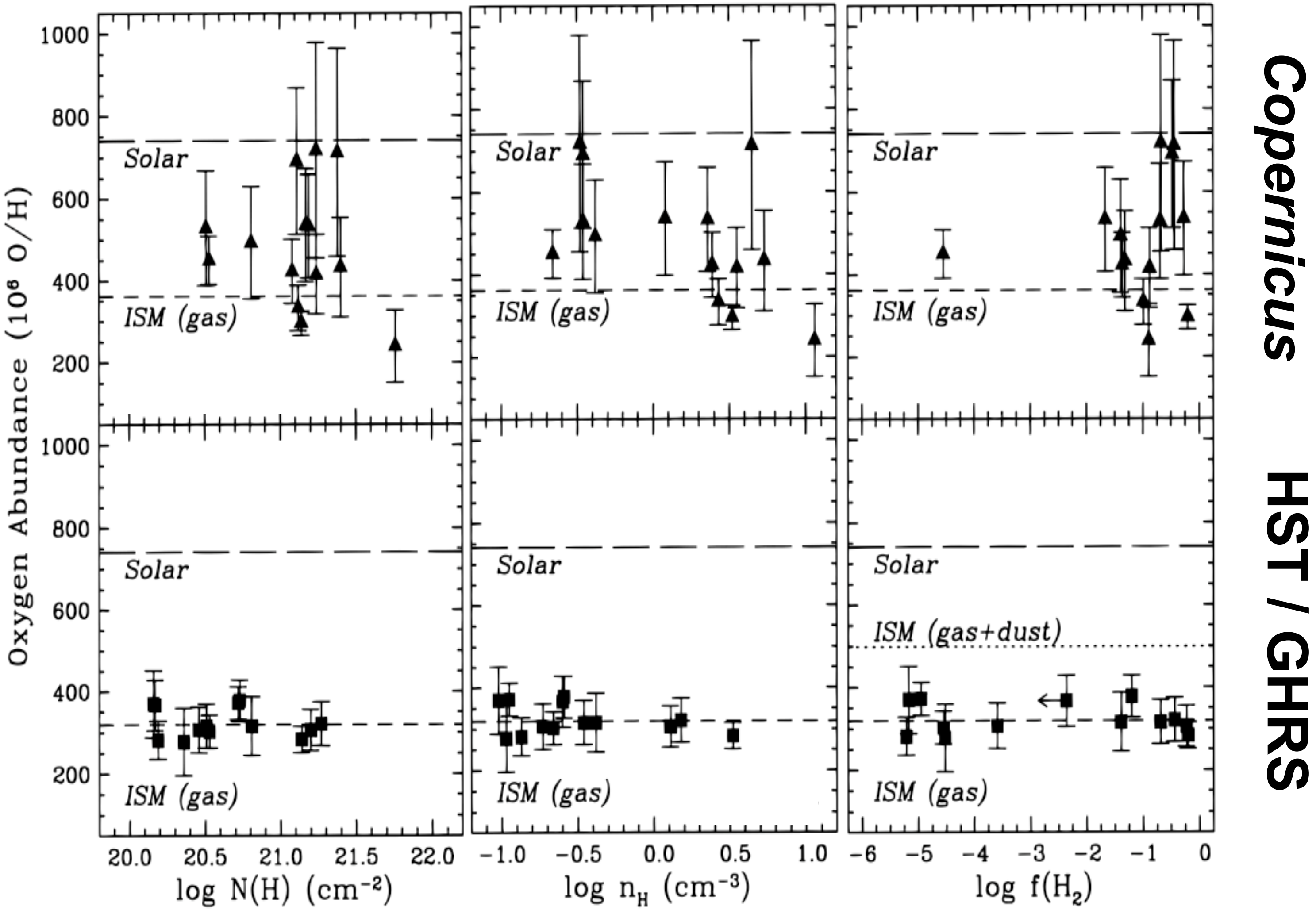
Distant D/H measurements before *FUSE*

- 2 high values (D/H > 2 $\times 10^{-5}$):
  - γ^2 Vel (Sonneborn et al. 2000): → D/H = (2.18 ± 0.20) $\times 10^{-5}$
  - Feige 110 (Friedman et al. 2002): → D/H = (2.14 ± 0.41) $\times 10^{-5}$

- 5 low values (D/H < 1 $\times 10^{-5}$):
  - δ Ori A (Laurent et al. 1979; Jenkins et al. 1999): → D/H = (0.74 ± 0.11) $\times 10^{-5}$
  - λ Sco (York 1983): → D/H = (0.76 ± 0.25) $\times 10^{-5}$
  - θ Car (Allen et al. 1992): → D/H = (0.50 ± 0.16) $\times 10^{-5}$
  - HD191877 (Hoopes et al. 2003): → D/H = (0.78 ± 0.20) $\times 10^{-5}$
  - HD195965 (Hoopes et al. 2003): → D/H = (0.85 ± 0.15) $\times 10^{-5}$

- 2 extra low values in Orion (*ISO*, HD molecule):
  - Orion molecular outflow (Bertoldi et al. 1999): → D/H = (0.76 ± 0.29) $\times 10^{-5}$
  - Orion Bar (Wright et al. 1999): → D/H = (1.0 ± 0.3) $\times 10^{-5}$

HST / GHRS

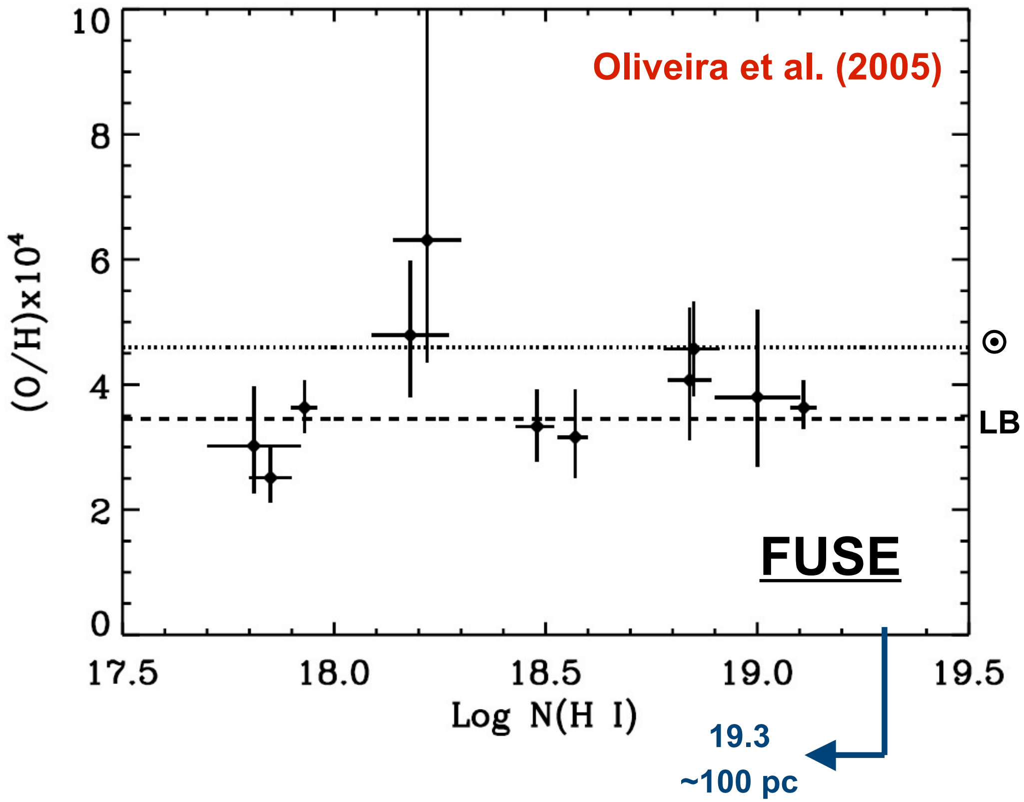


Meyer et al. (1998)

⇒ **Few echanges between dust and gas**

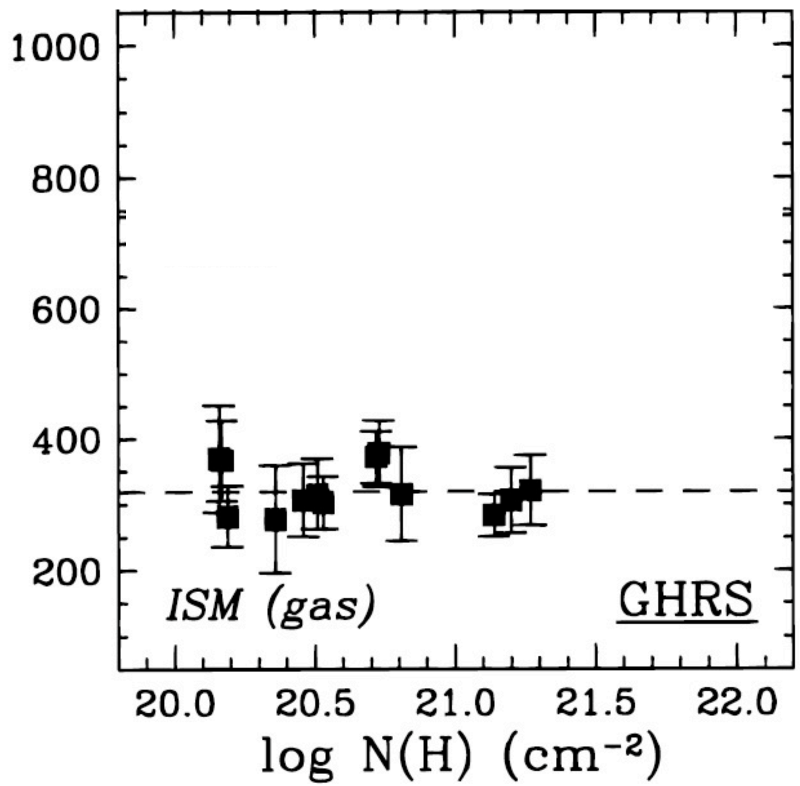
Oxygen in Local Bubble

$(O/H)_{LB} = (345 \pm 19) \times 10^{-6}$

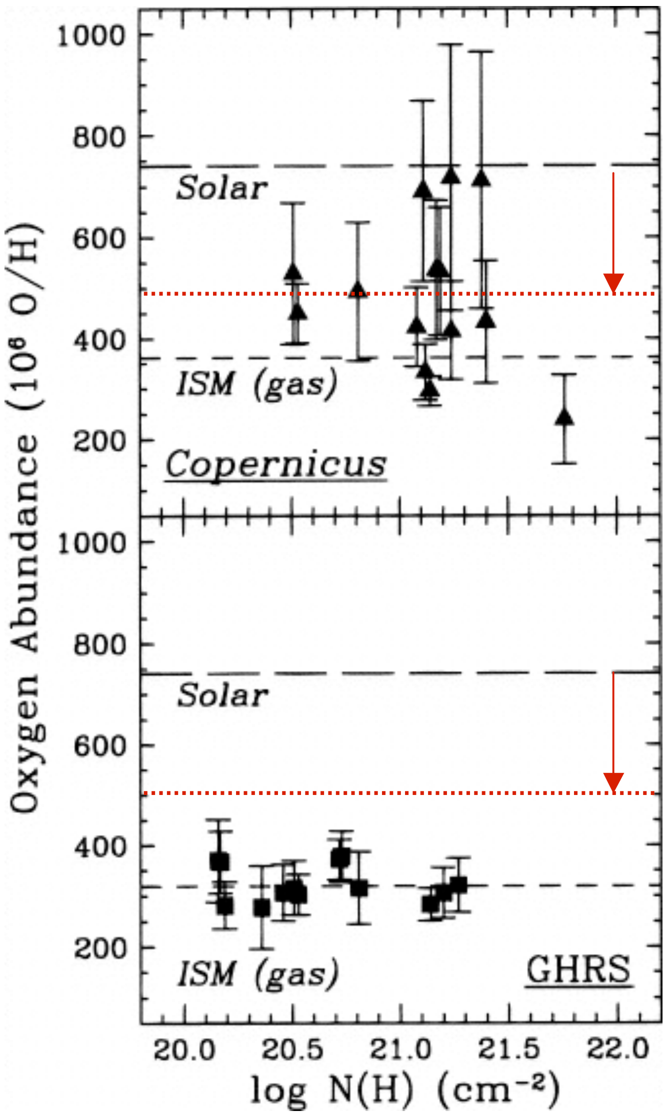


$(O/H)_{ISM} = (343 \pm 19) \times 10^{-6}$

Meyer (2001)

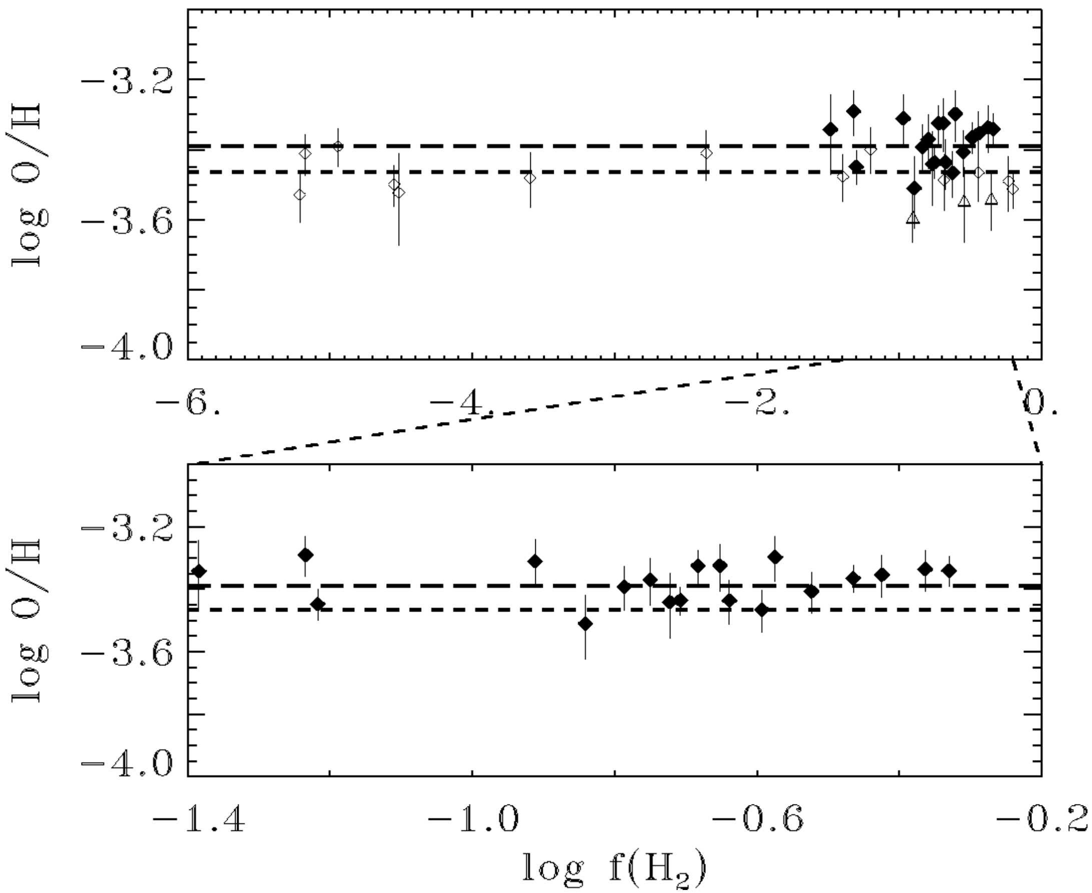


O/H: depletion



Meyer et al. (1998)

$$\left(\frac{D}{H}\right)_{gas} = \left(\frac{D}{O}\right)_{gas} \times \left(\frac{O}{H}\right)_{gas}$$

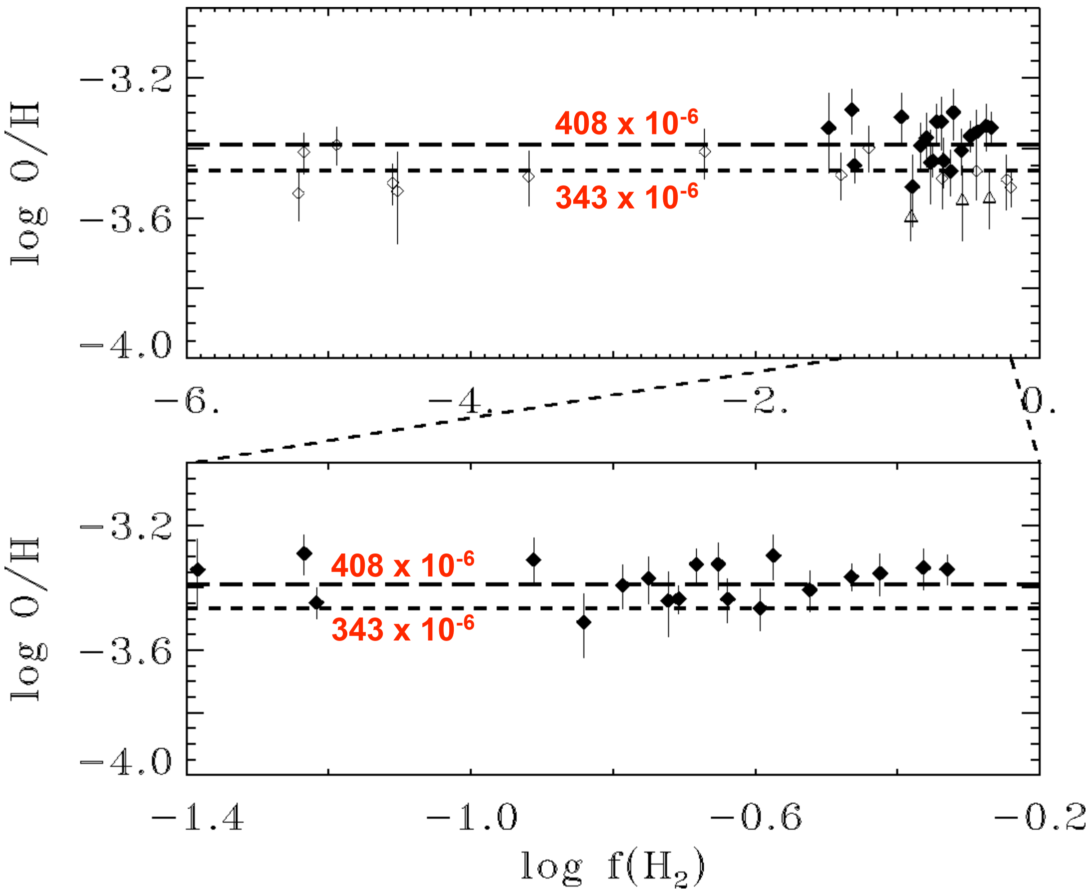


André et al. (2003)

HST / STIS

$(O/H)_{ISM} = (408 \pm 13) \times 10^{-6}$

up to 3.6 kpc



⇒ O/H homogeneous

André et al. (2003)

Hébrard et al. (2005)

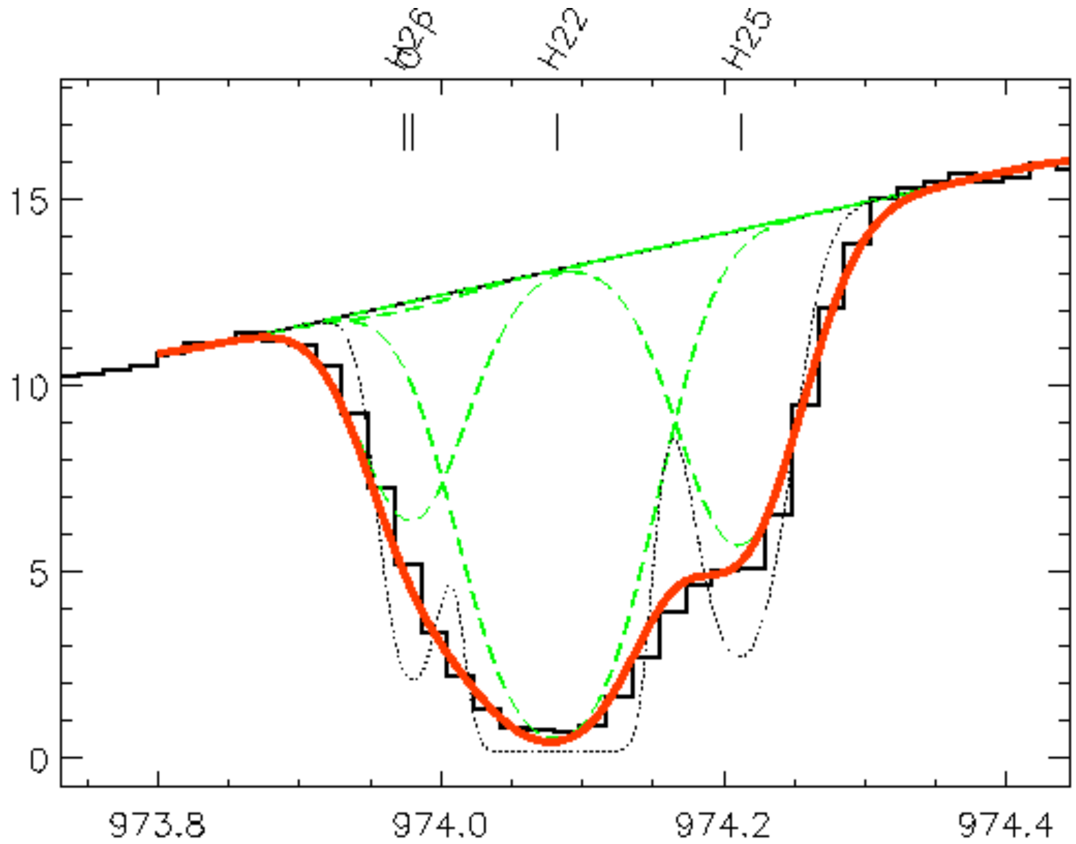


Figure 10: **Fit of the λ 974.07 Å as observed on *FUSE* spectra of HD 195965.** The value $N(\text{O I}) =$ 17.77 is in good agreement with those obtained by Hoopes et al. (2003) using the O I line at 1355.60 Å, namely 17.76. In addition, the case of BD +28°4211 shows that λ 974 Å is in agreement with the stronger O I lines available in the *FUSE* bandpass (Hébrard & Moos 2003). Thus, λ 974 Å presents no strong oscillator strength inconsistencies nor significant uncontrolled blends.

High-D/O targets? (Oliveira et al. 2006)

- BD+39 3226

  $D/H = (1.2 \pm 0.3) \times 10^{-5}$

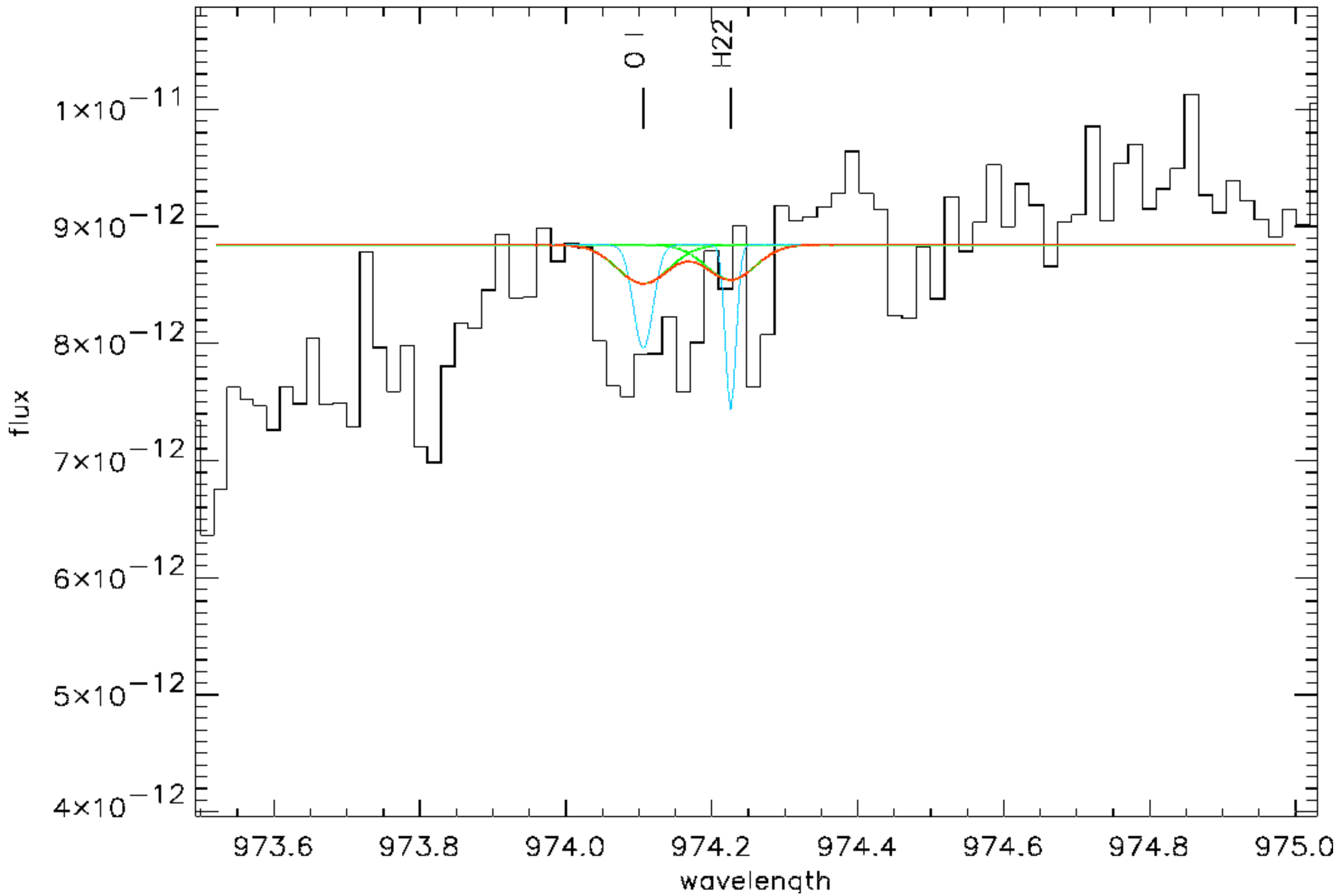
  $D/O = (5.6 \pm 1.5) \times 10^{-2}$

- TD1 32709

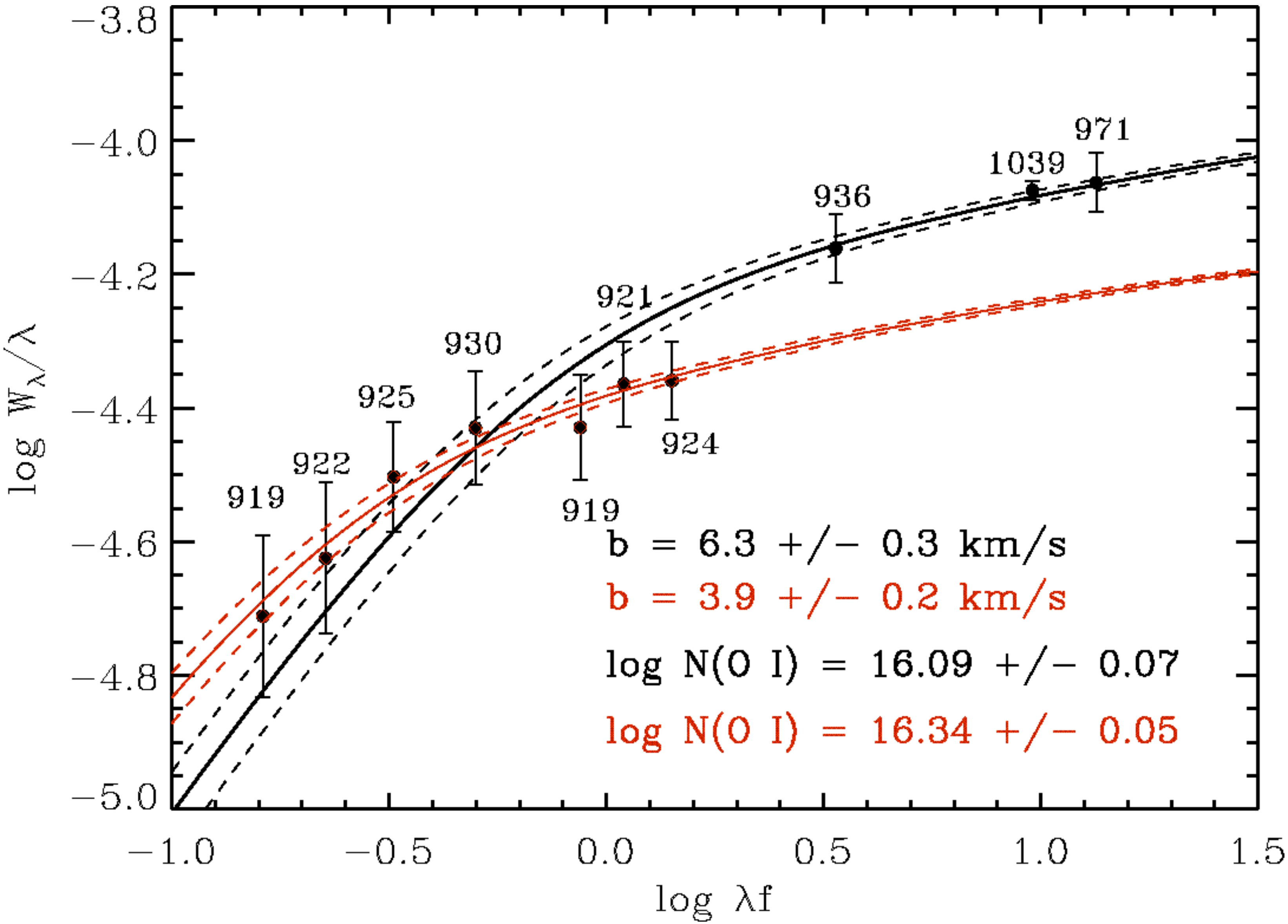
  $D/H = (1.8 \pm 0.5) \times 10^{-5}$

  $D/O = (7.6 \pm 2.0) \times 10^{-2}$

TD1 32709

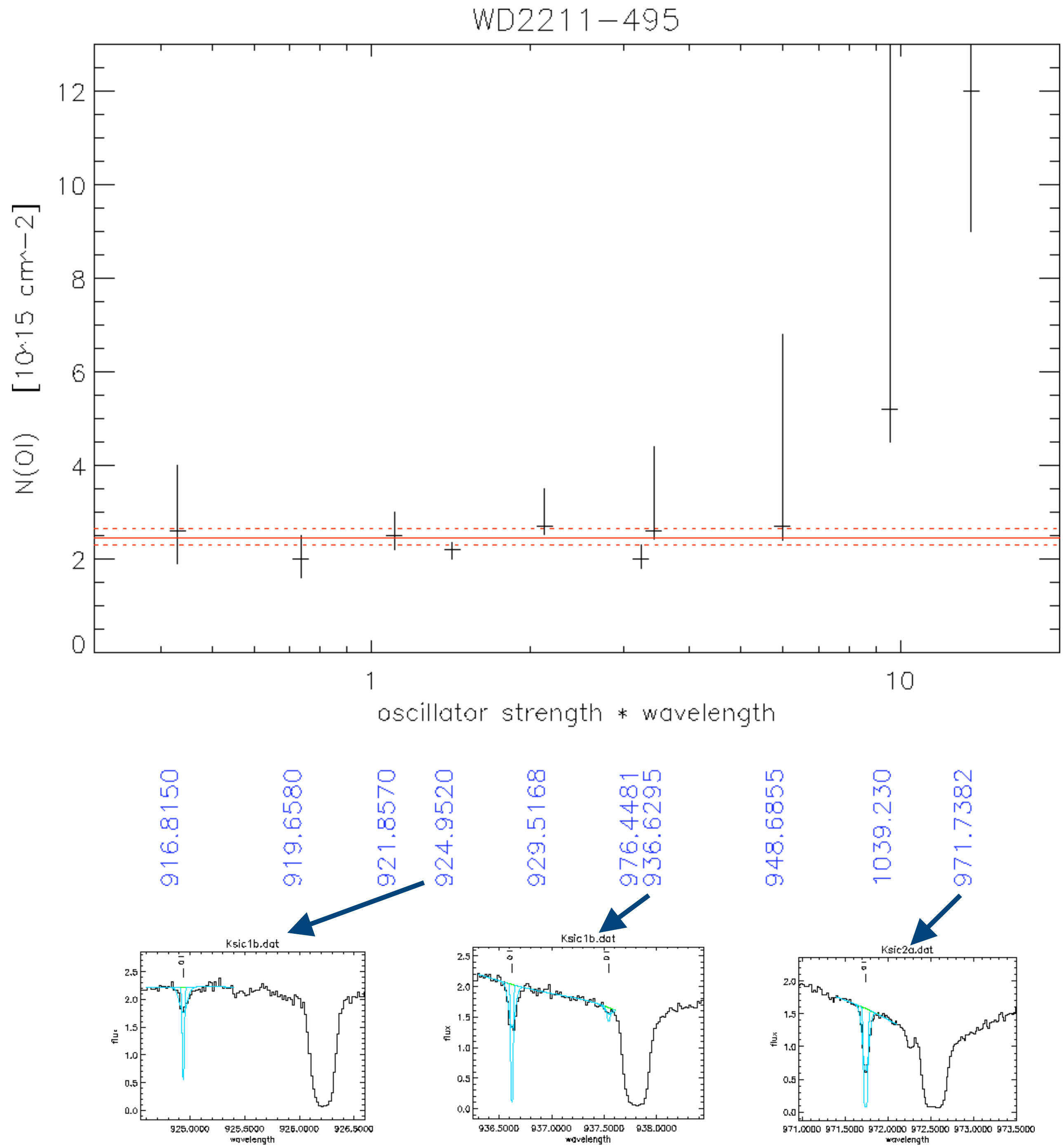


O I
H22
1×10^{-11}
9×10^{-12}
8×10^{-12}
7×10^{-12}
6×10^{-12}
5×10^{-12}
4×10^{-12}
flux
973.6
973.8
974.0
974.2
974.4
974.6
974.8
975.0
wavelength

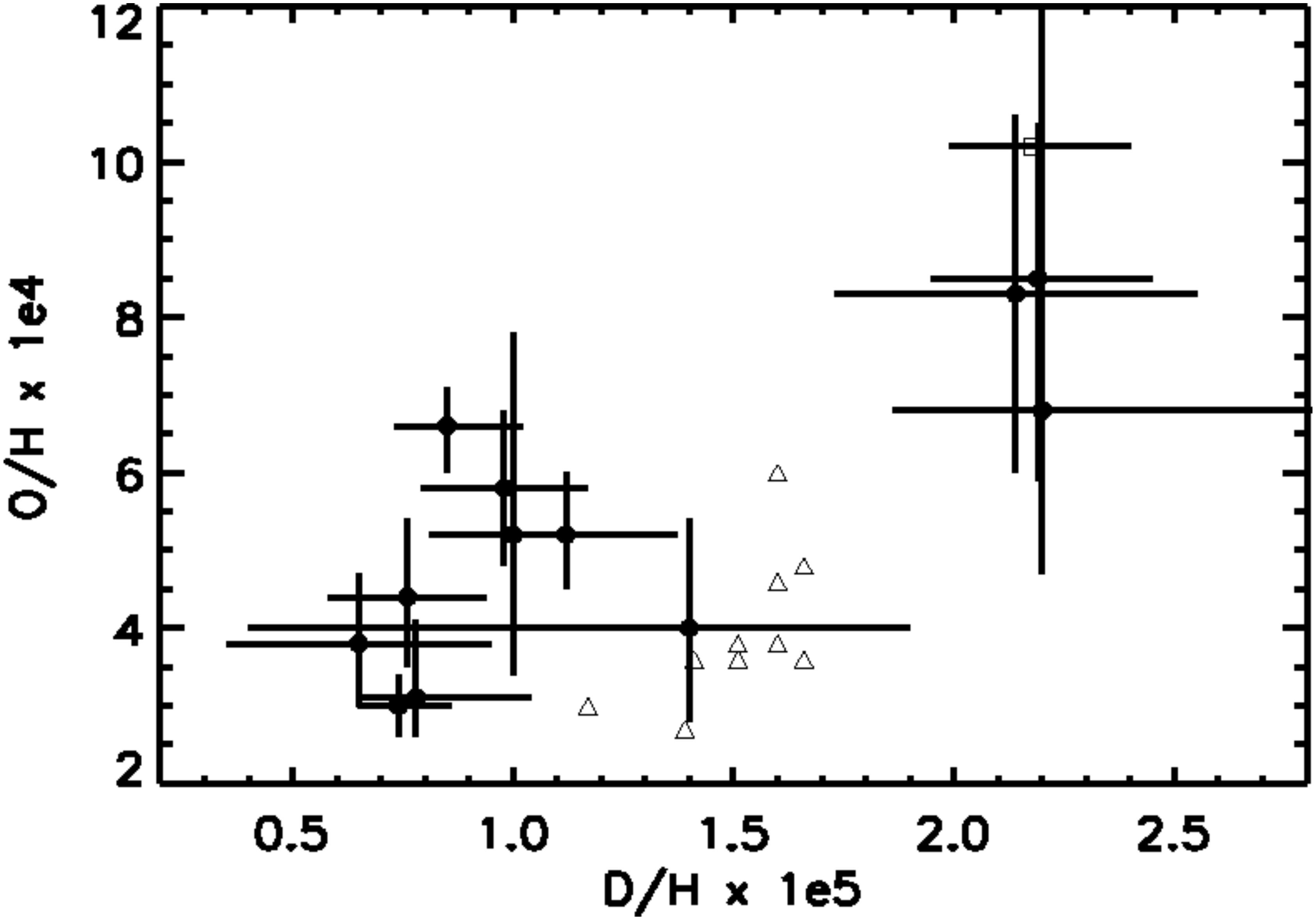


Oliveira (2003; PhD Thesis)

Saturation



Hébrard et al. (2004)



12
10
8
6
4
2
O/H x 1e4
0.5
1.0
1.5
2.0
2.5
D/H x 1e5