# Cosmology with DLA absorption systems

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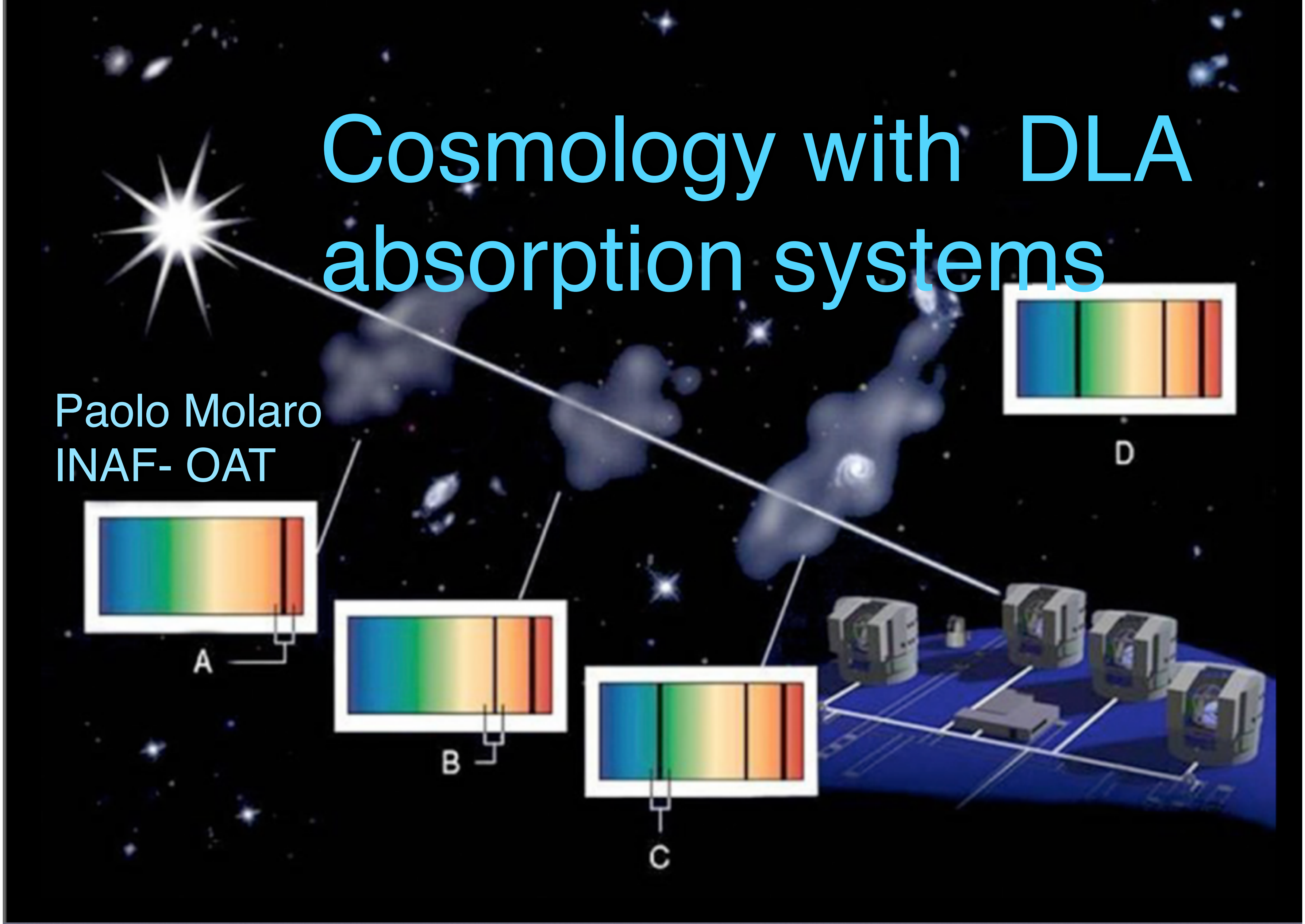


# outline

## I

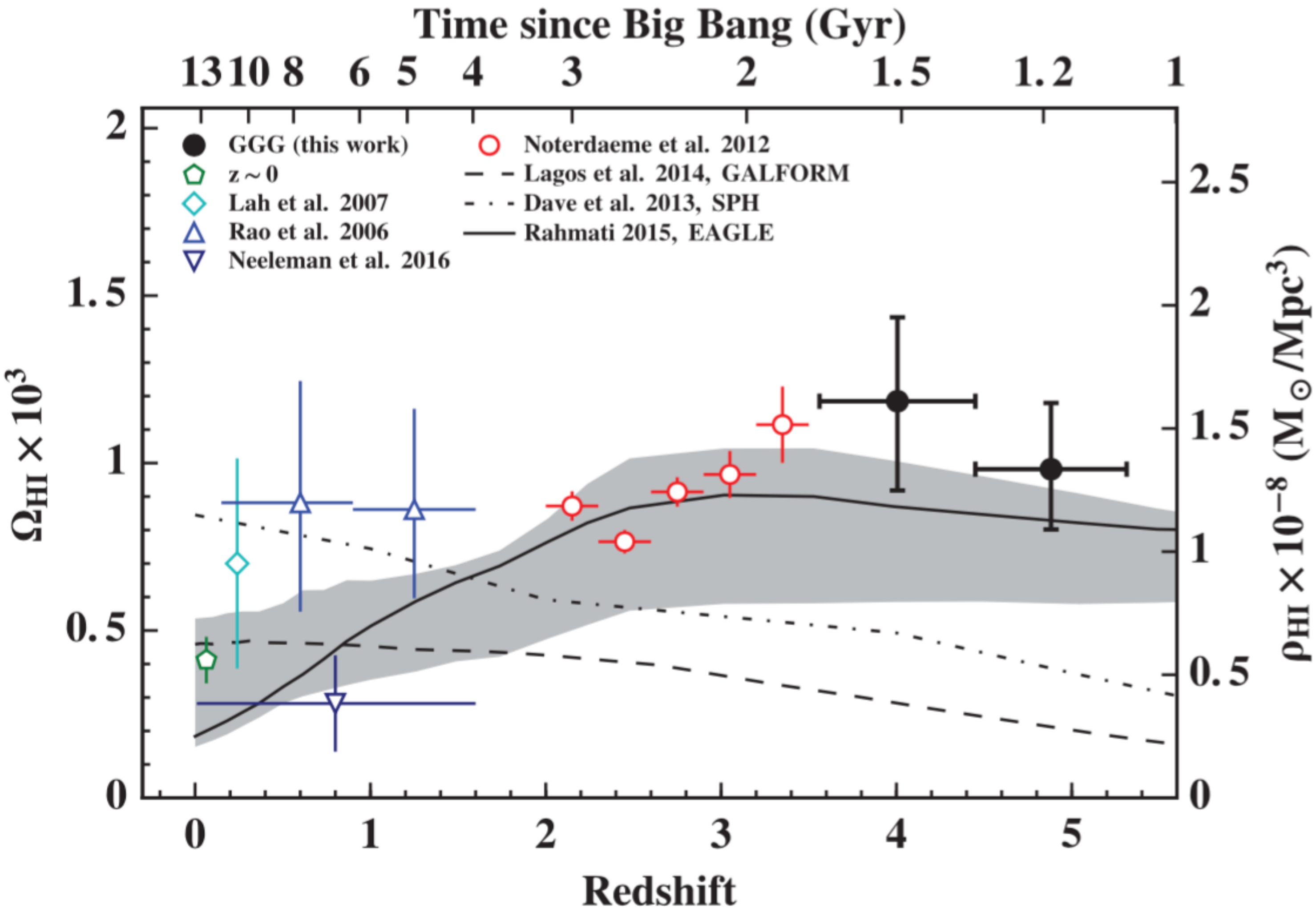
- What are the DLAs?
- The neutral gas content of the Universe
- Chemical abundances, dust, chemical patterns.
- DLA and First stars

## II

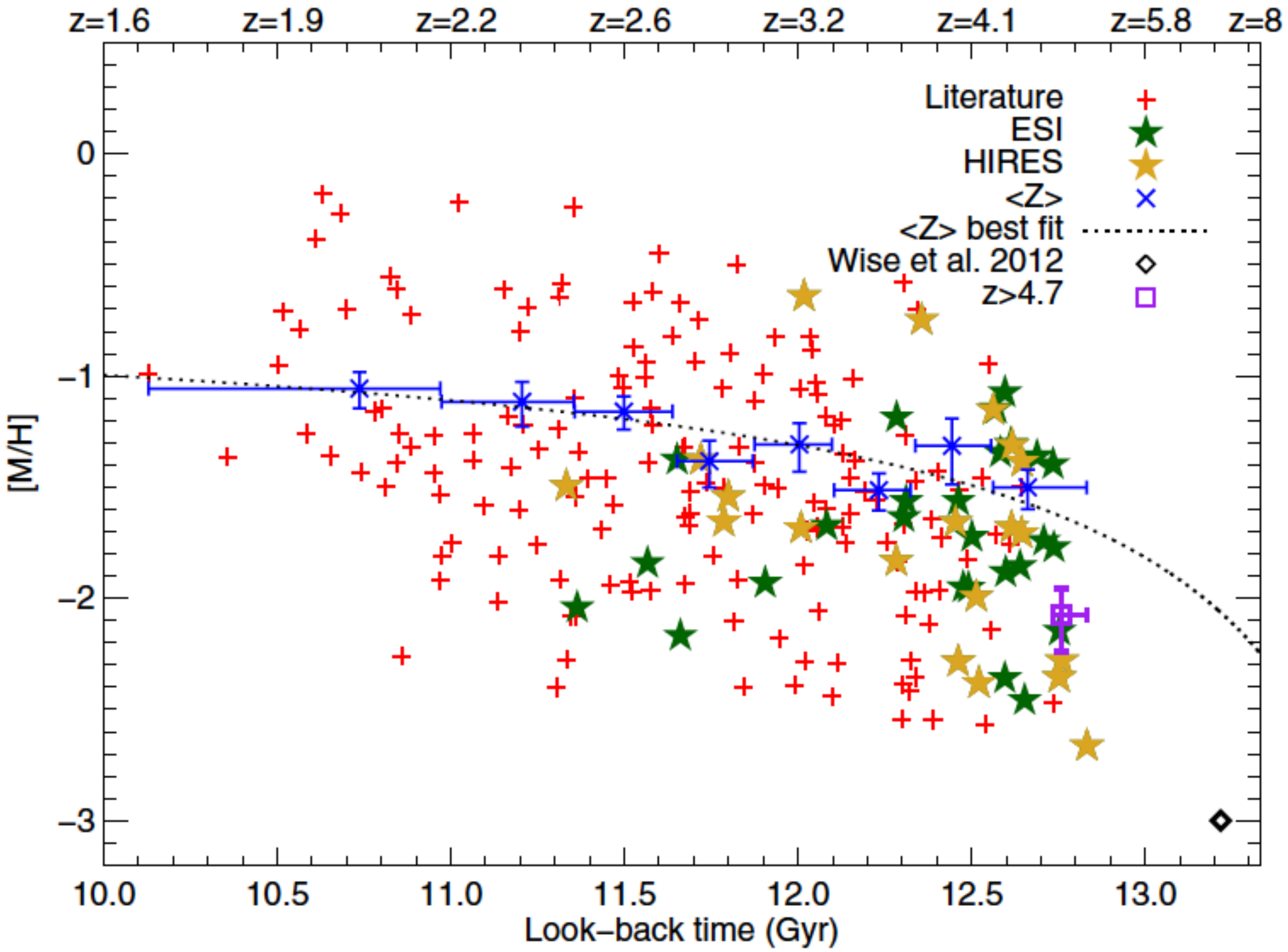
- Primordial Deuterium
- Molecules gas in DLAs: $H_2$, HD, CO
- $T_{CMB}$ (z)

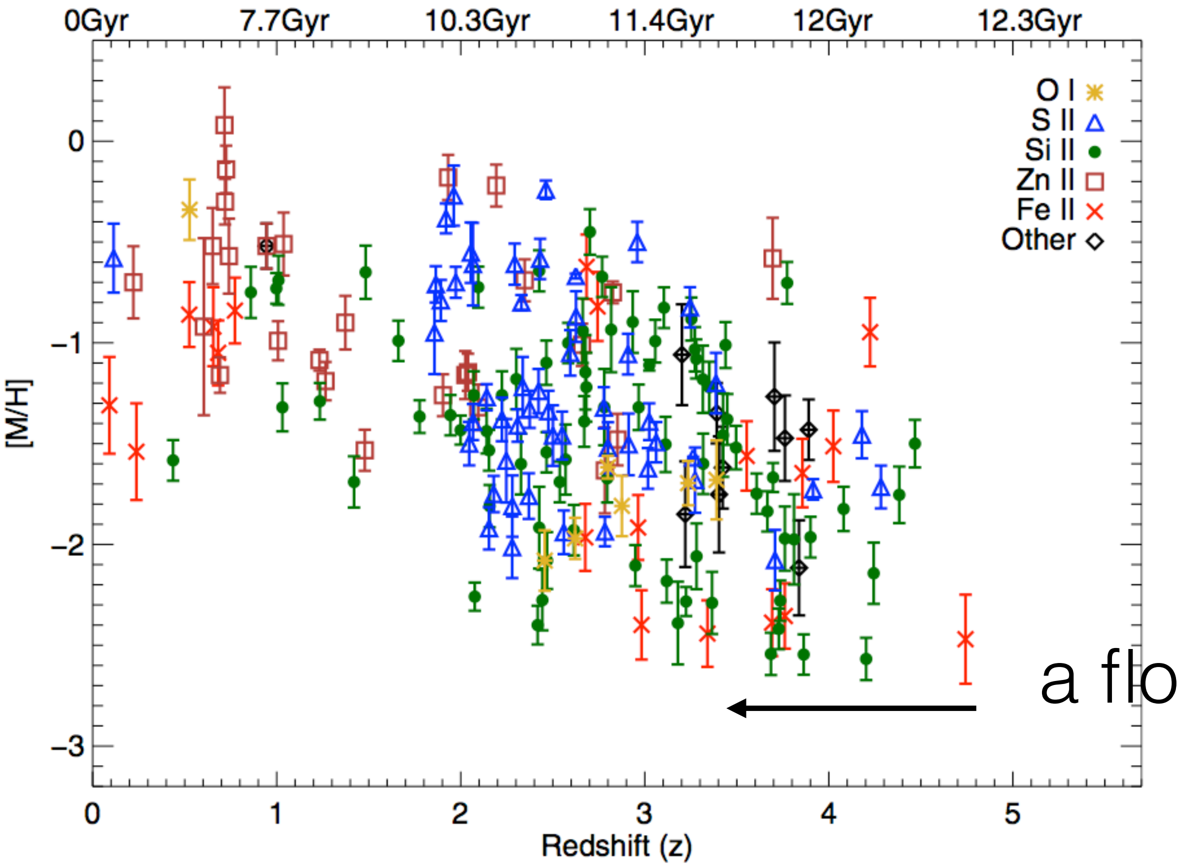
# DLA: LogN(H) > 20.3

6839 candidates



# ~250 DLA


z=1.6
z=1.9
z=2.2
z=2.6
z=3.2
z=4.1
z=5.8
z=8
Literature
ESI
HIRES
<Z>
<Z> best fit
Wise et al. 2012
z>4.7
0
−1
−2
−3
[M/H]
10.0
10.5
11.0
11.5
12.0
12.5
13.0
Look−back time (Gyr)



a floor??

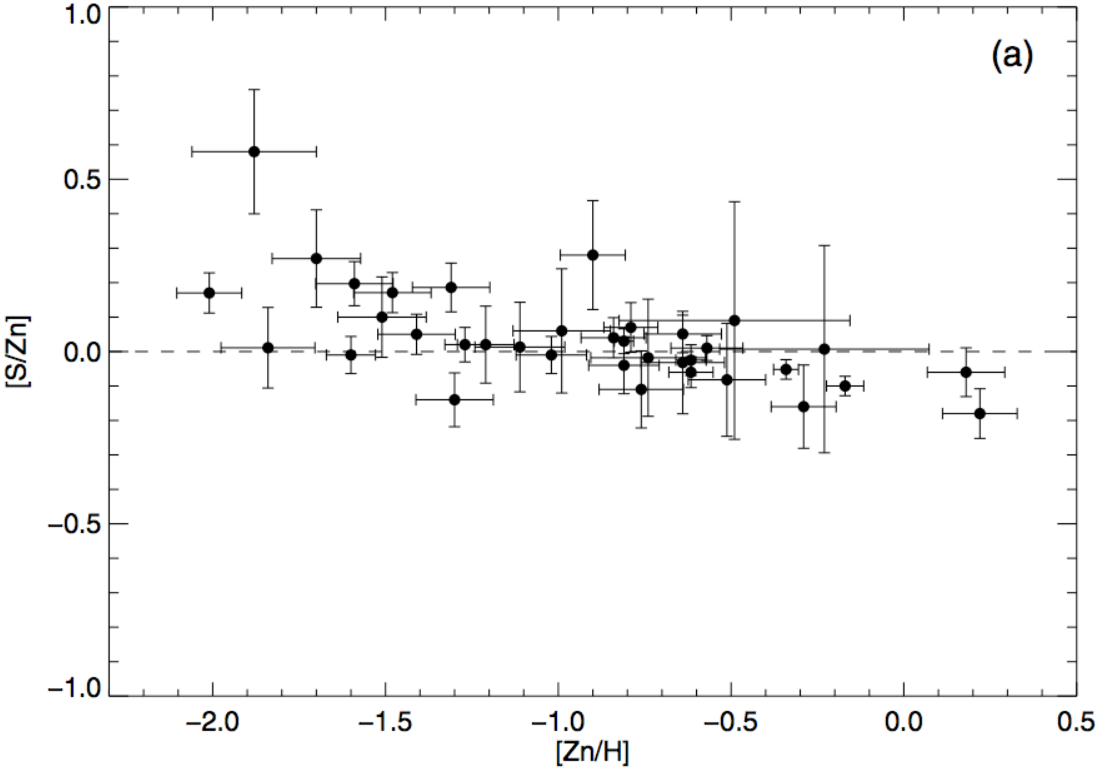
several stars with [C/H]< -3.0

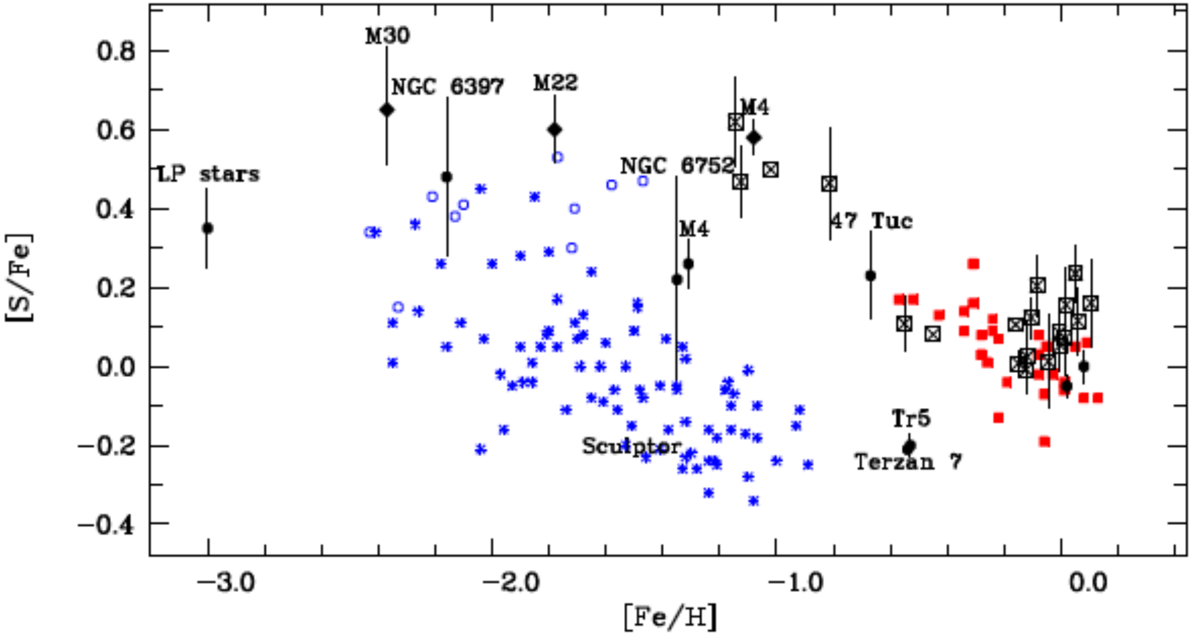
QSO J0903+2628

[C/H] = -3.43
[O/H] = -3.05
[Si/H] = -3.21

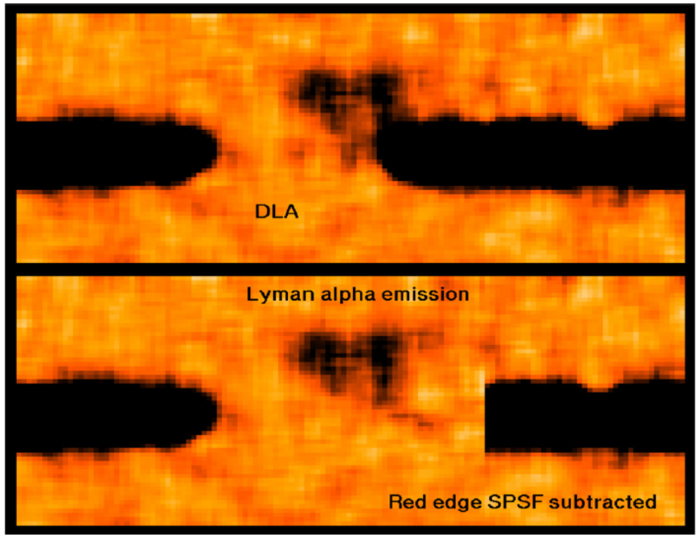
**20.5 $M_\odot$ POPIII**

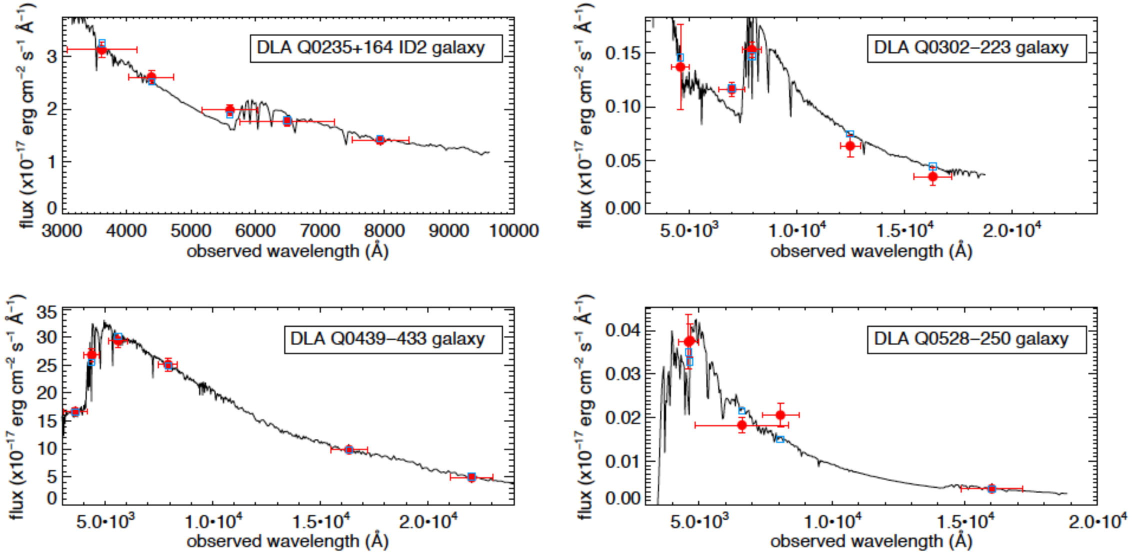
[N/H]~ -4.0





DLA ~ Dwarf Galaxies



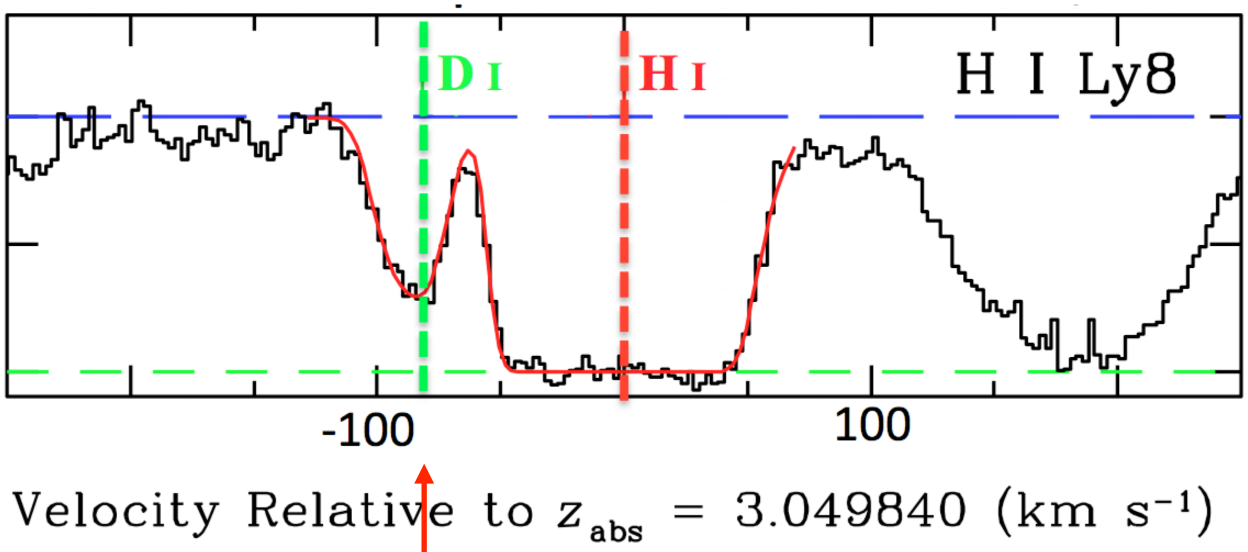


- $M_{DLA}$ span from $10^6$ to $10^{11}$ , with average $10^8\ M_\odot$
- $L_{DLA}$ span from the $L_{LBG}$ down for 8 mag
- $SFR_{DLA}$ from 0.1 to 10 $M_\odot\ yr^{-1}$ (possibly lower)

# Deuterium

Adams (1976), first suggested primordial D could be measured in QSO absorption lines

D isotope is blueshifted respect to HI by -83 km s$^{-1}$



or HI interloper?

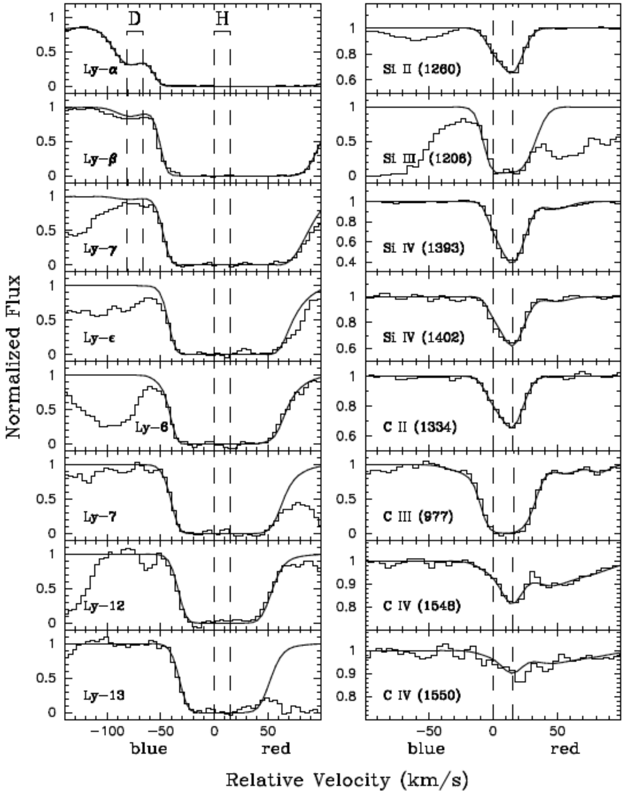
- **High D/H ~ $10^{-4}$** Songaila et al (1994), Carswell et al (1994), Rugers & Hogan (1996)

(in agreement with $^{7}$Li and $^{4}$He!)

- **Low D/H ~ $10^{-5}$** Tytler et al (1996), Burles & Tytler (1998) Molaro et al (1999) ,Kirkman et al 2000

QSO 1937 1009 $z_{abs}$=3.572

Tytler et al (1996)

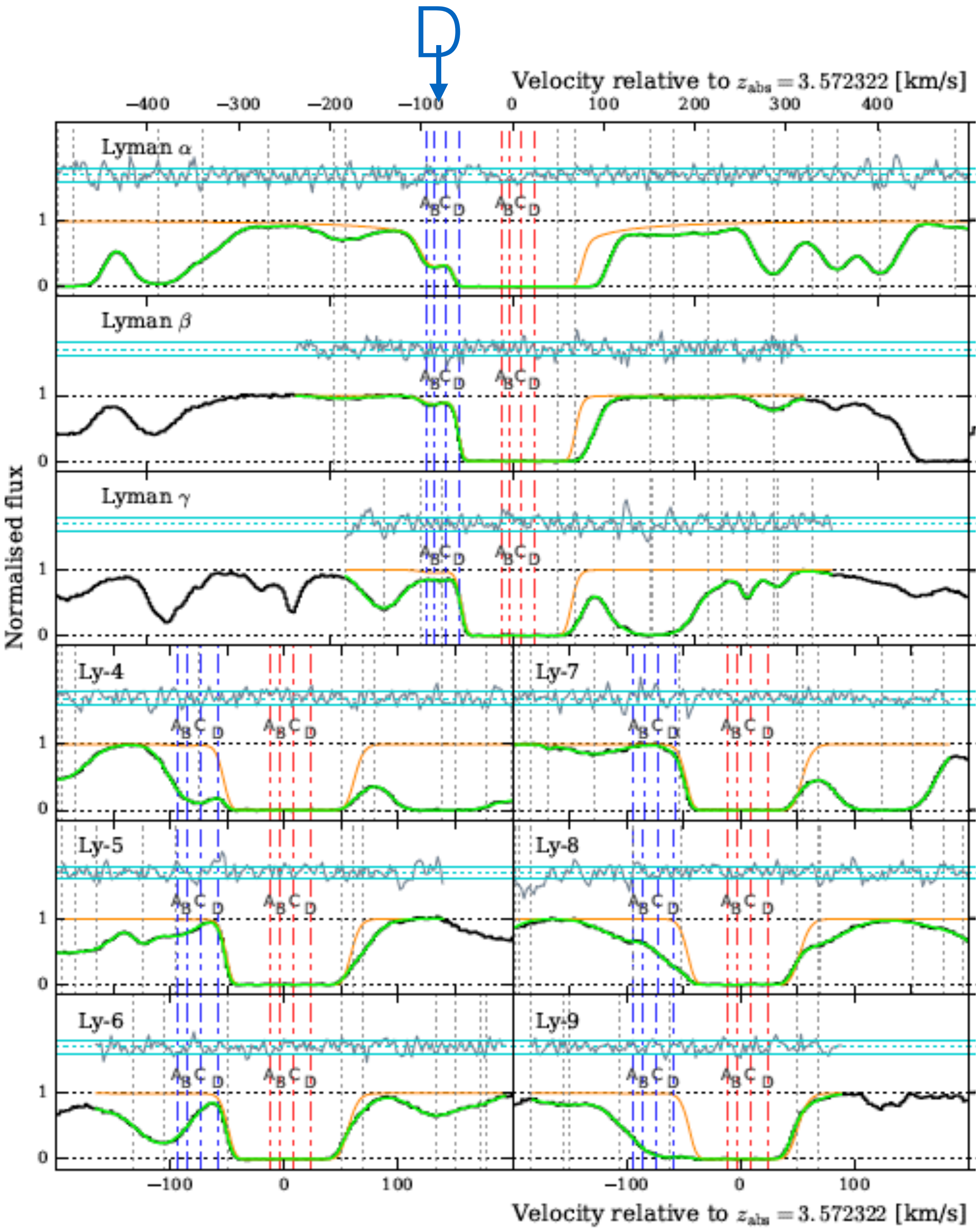


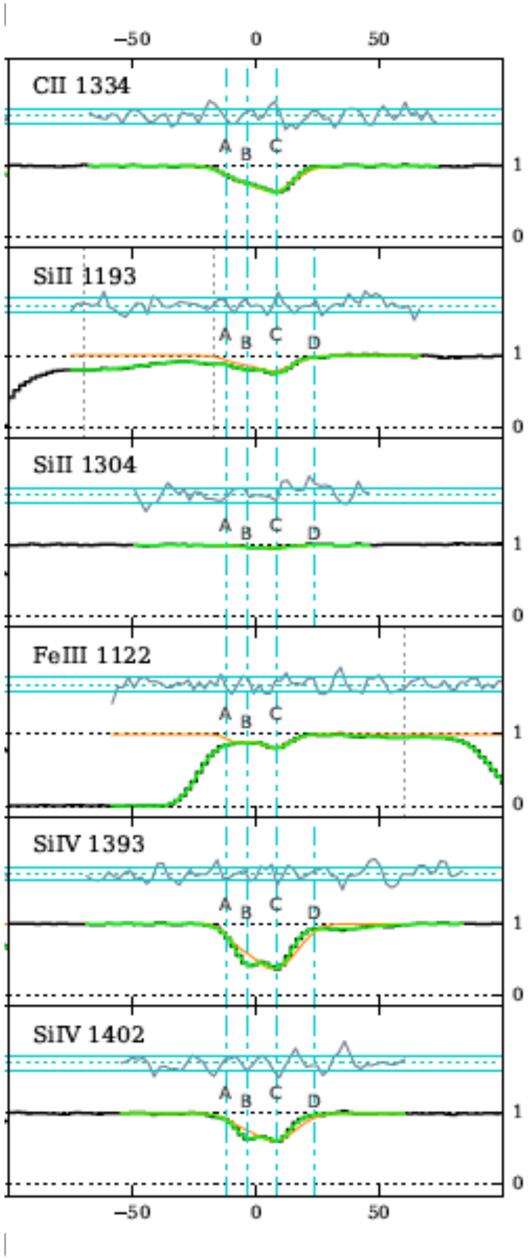
LLS: Log N(HI) =17.9

$10^{5}$ D/H= 2.3 ± 0.6

# Riemer-Sorensen et al (2017)

orange Tytler et al (1996) model

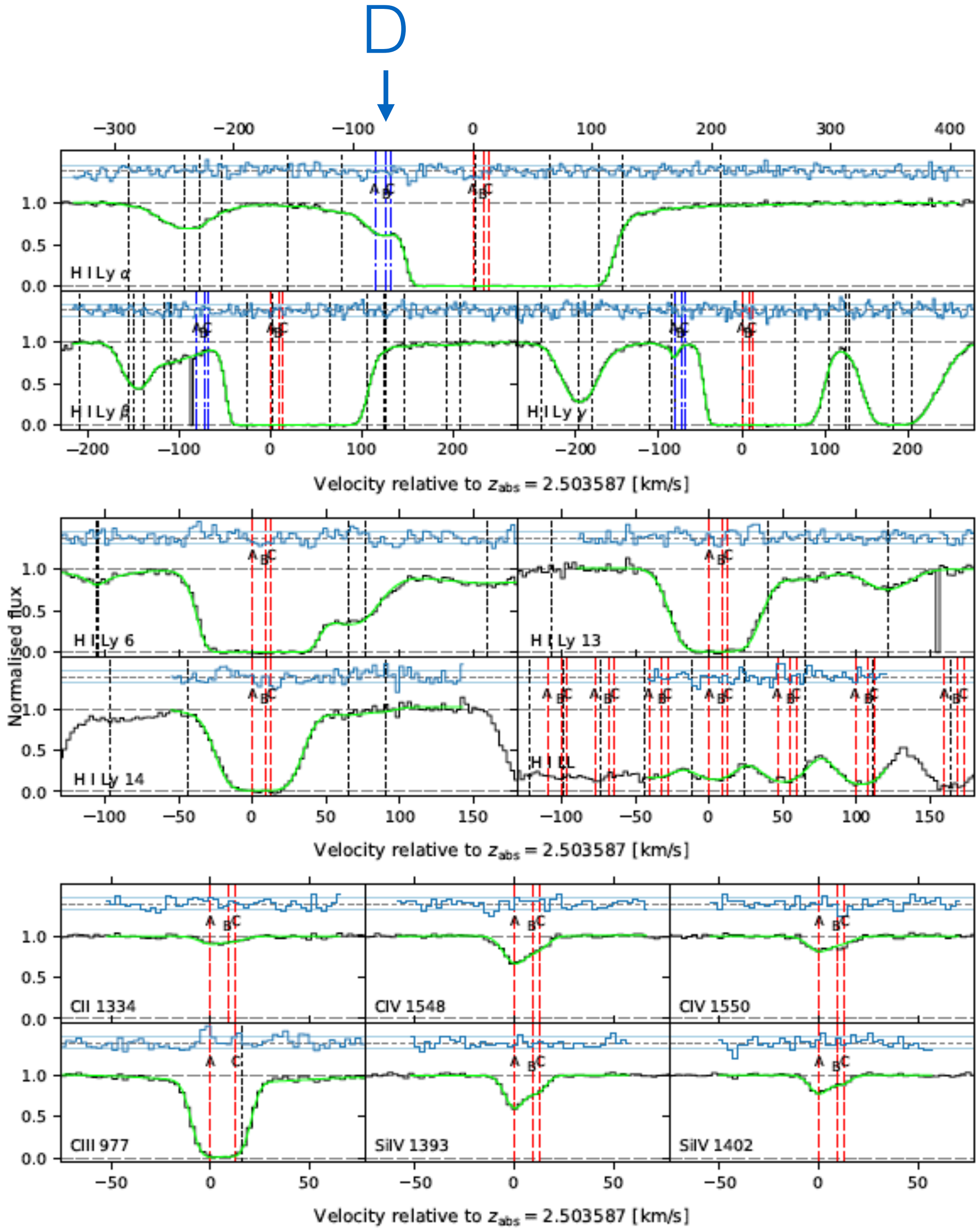




$10^5$D/H= 2.62 ± 0.05

one dex lower error!

# Burles &Tytler (1998) **Q1009+2956 $z_{abs}$ =2.504 LogN(I)=17.4 $10^5$D/H = 4.0 ± 0.7**



**Zavarygin et al (2017)**

S/N ~147 (from 60)

=>Ly 14 small contamination in the Ly-α

$10^5$D/H=3.16 ± 0.6

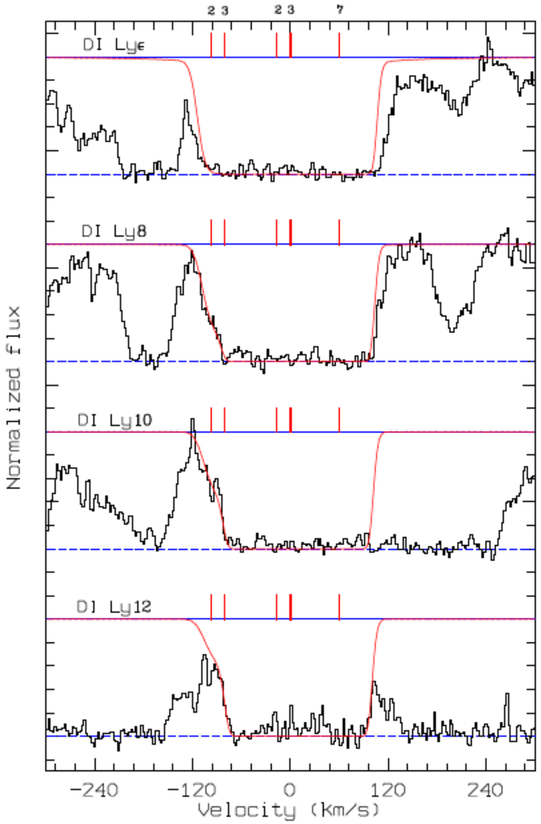
- **in LLS hydrogen is ionized => large error**
- **in a DLA the D line is hidden in the HI line**

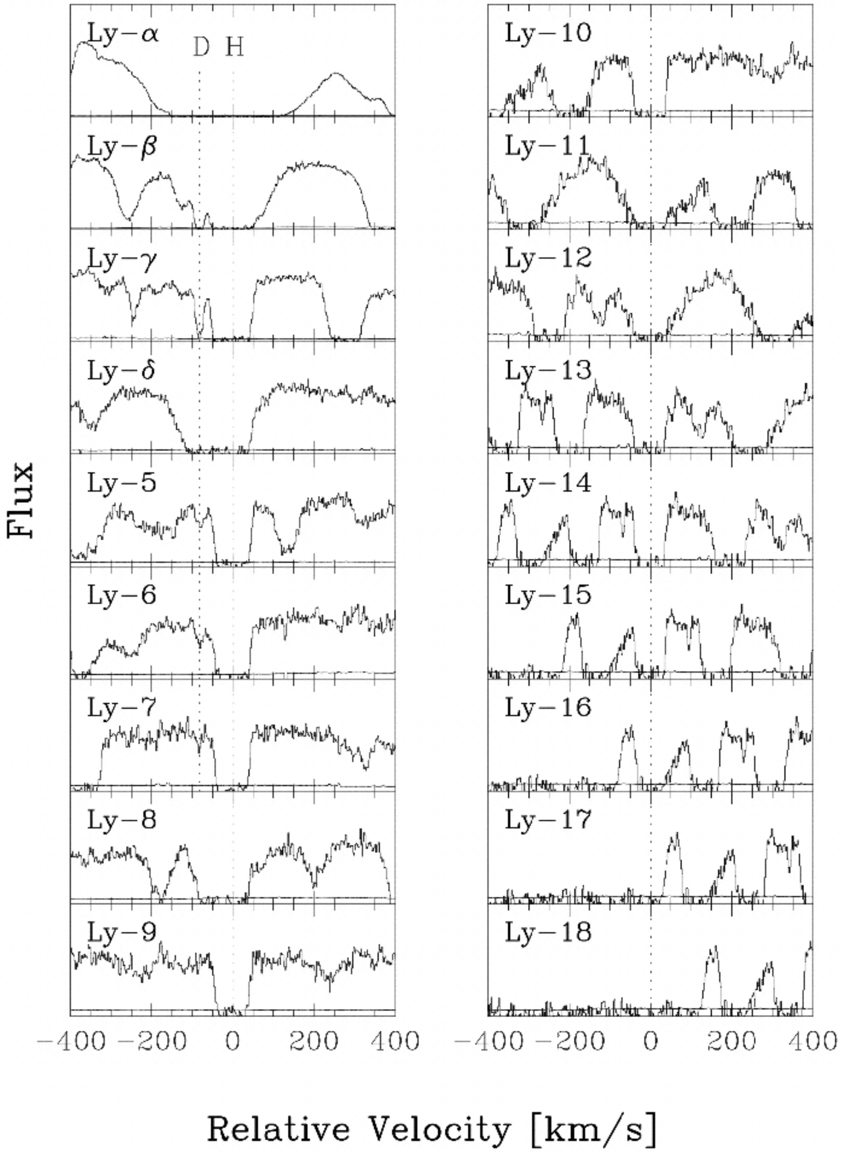
# D in DLAs

QSO 0347-3819 $z_{abs}$=3.0
UVES, LogN(I)=6.3 ± 1.3 $10^{20}$
D/H=2.24±0.67 $10^{-5}$; D' Odorico et al 2001

O'Meara et al 2001
HS 0105+1619 $z_{abs}$ 2.53
Sub-DLA Log(HI)=19.4 [M/H]= -1.8

Ly-8, Ly-10, Ly-12





QSO 2206-199 $z_{abs}$=2.0, LogN(I)=20.5
D/H=1.65±0.25 $10^{-5}$ Pettini & Bowen (2001)

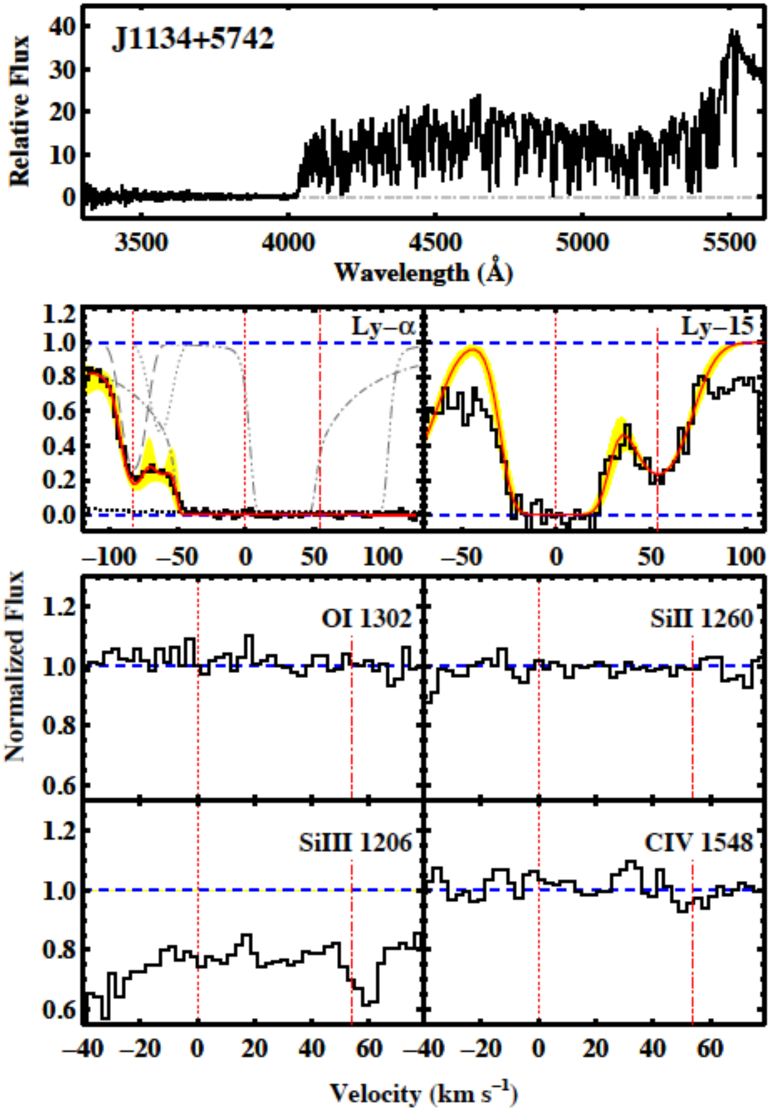
# in the most pristine gas

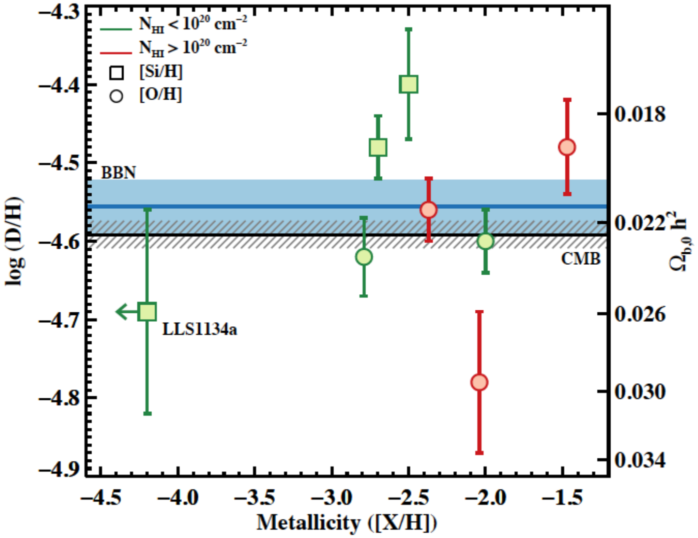
Fumagalli O'Meara Prochaska (2011)

LogN(HI)=17.95+/-0.05

[Si/H]<-4.2

2003 Kirkman et al
2004 Crighton et al PKS 1937-1009 **Riemer Sorensen et al 2015**
2006 O'Meara et al QSO J1558-0031 **Cooke et al 2014**
2008 Pettini et al Q0913+072 **Cooke et al 2014**
2011 Fumagalli et al
2012 Noterdaeme et al
2012 Pettini & Cooke J1419+0829 **Cooke et al 2014**





D/H=2.04±0.61 $10^{-5}$

# Precision measurements

J1358+6522

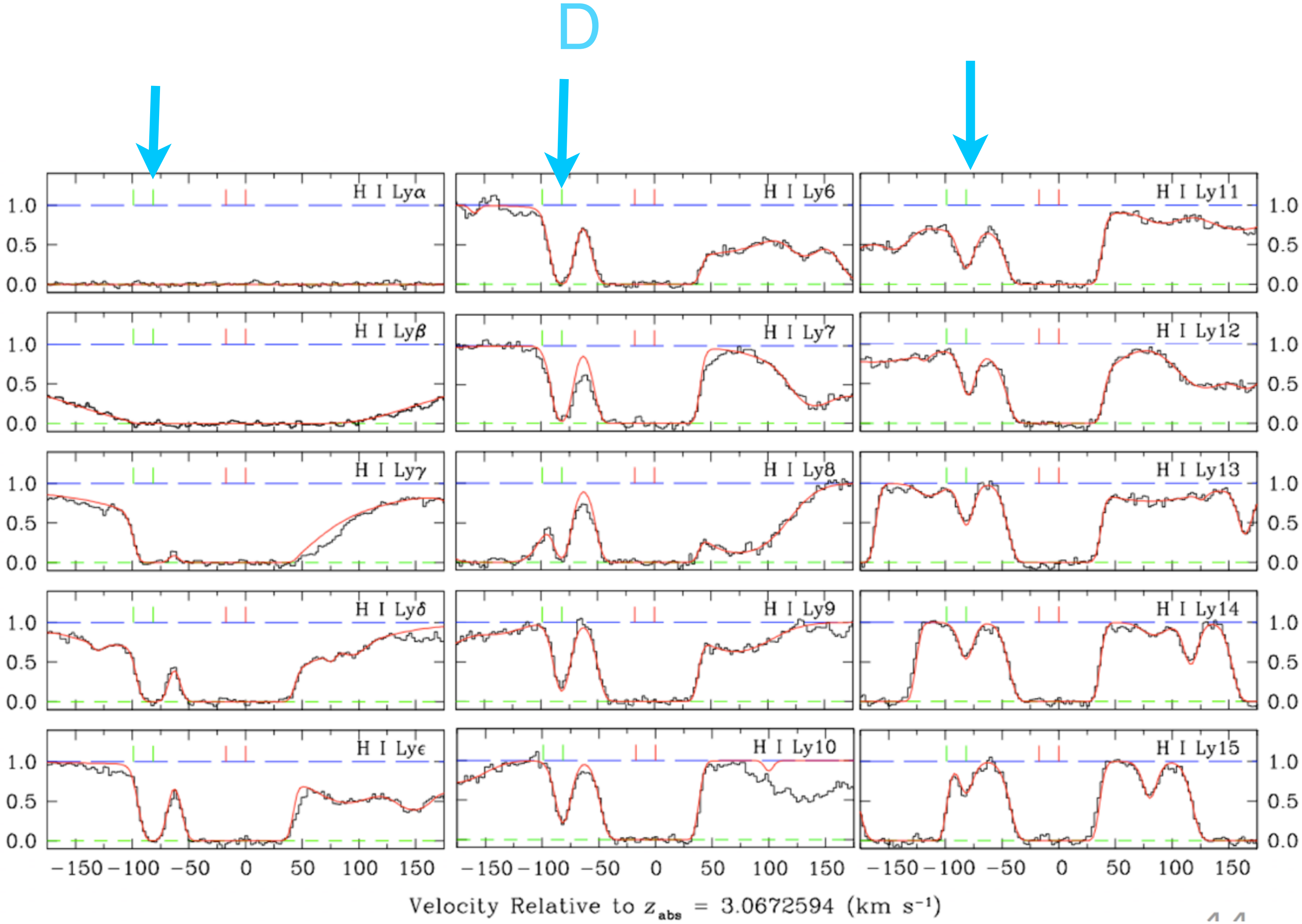
$z_{abs}$ = 3.067, LogN(HI)=20.5, [Fe/H] = -2.84

simple system: two components b=8-9 km/s

13 resolved DI Ly lines in the lyman serie!

Cooke et al (2014)

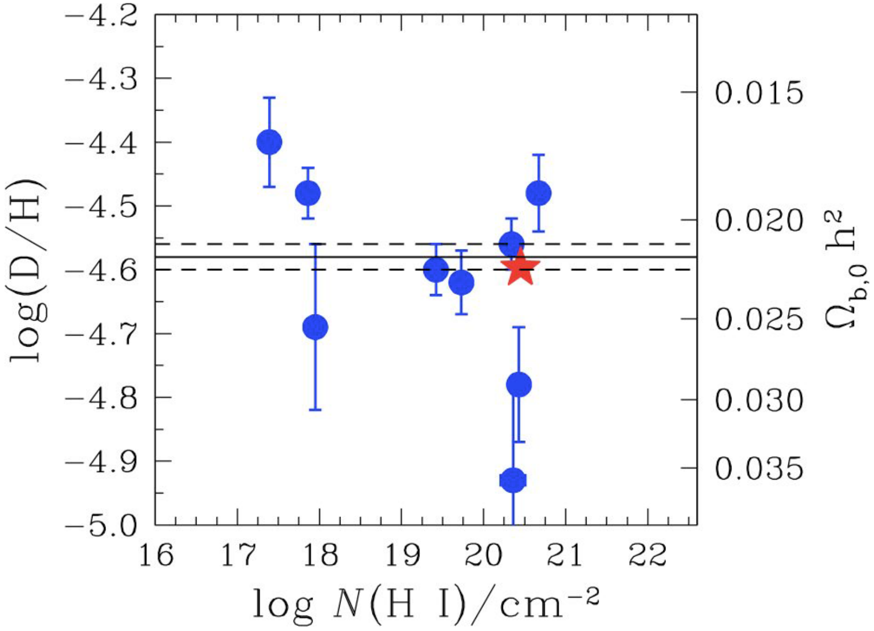
$10^{-5}$ D/H=2.58±0.07



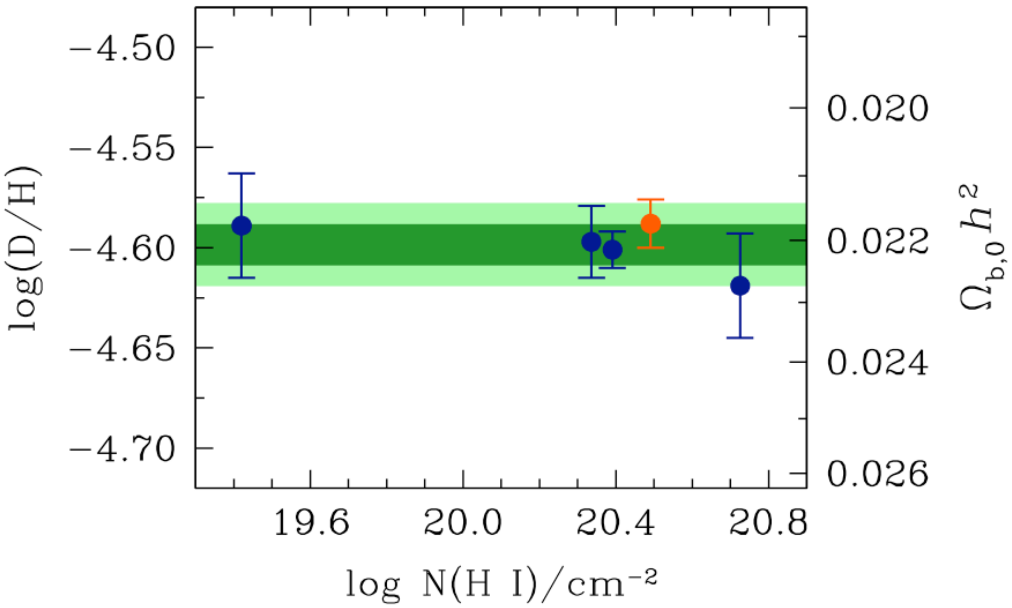
# dispersion?

Cooke et al 2014

10 measurements before 2014



sub-sample of the best 5 systems (4 DLA +1 subDLA) with several resolved DI lines i.e. less contamination by Ly-α forest



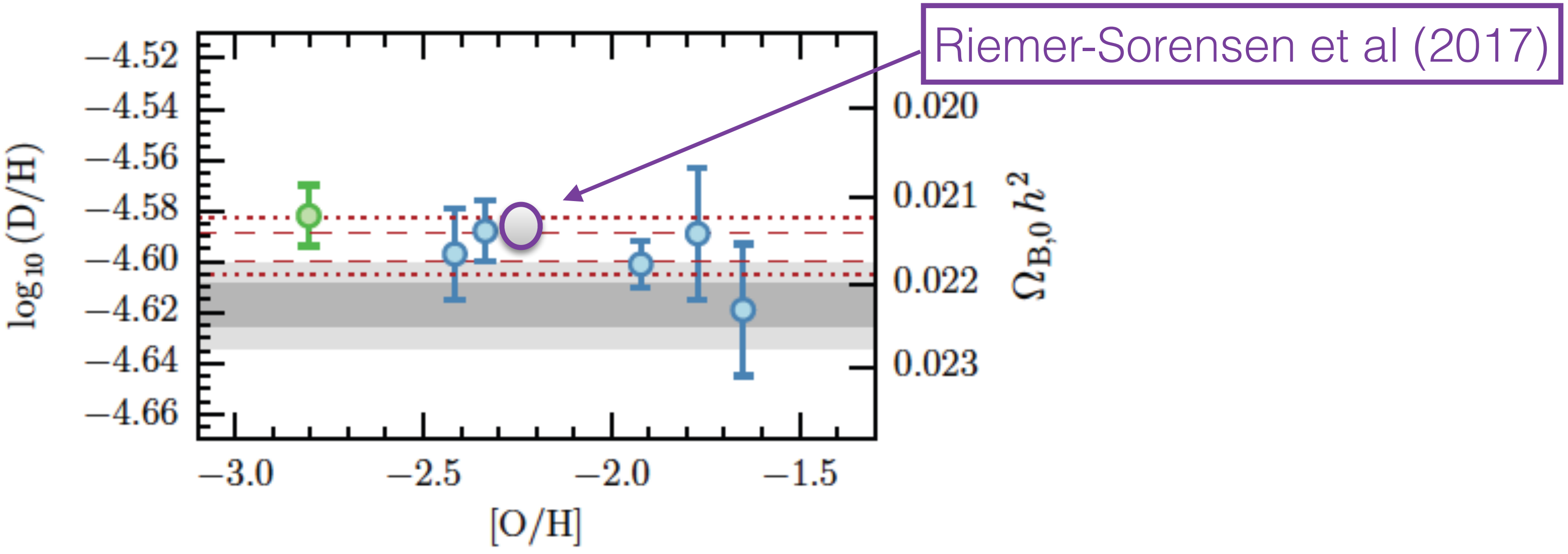
# Updated Precision sample

All systems after 2014: 10 systems:

5 DLA systems Cooke et al 2014
3 re-determination: Zavarygin et al (2017); Riemer-Sorensen et al (2015, **2017**)
2 new determinations: Cooke et al 2016, Balashev et al 2017

$$10^5(\mathrm{D/H}) = 2.569 \pm 0.027$$

**~ 1% error!!!**

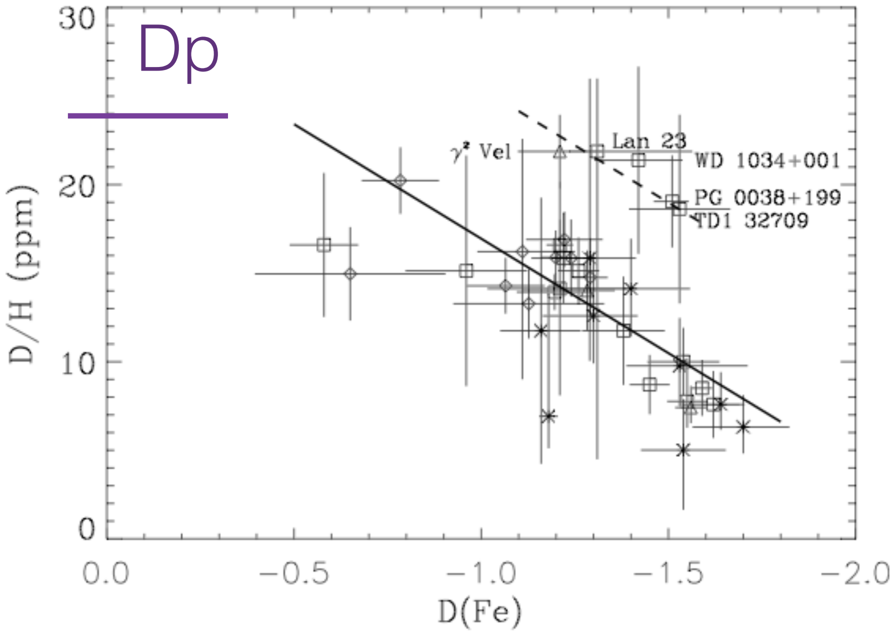

Riemer-Sorensen et al (2017)

- no dispersion (the two not plotted have large errors)
- no dependence on HI
- no dependence on metallicity

# D depletion

Local measurement D/H and chemical evolution

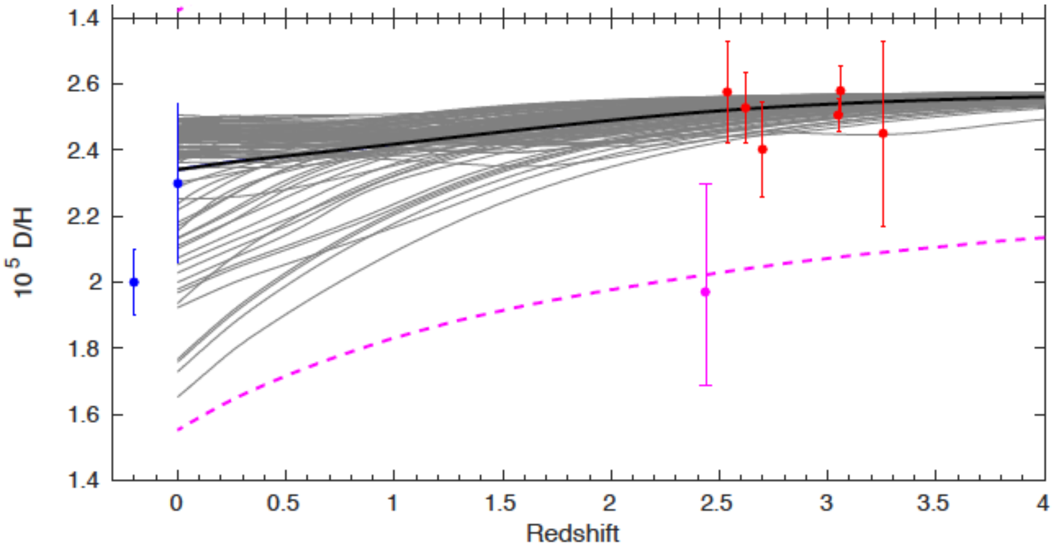
Evidence of D depletion in dust from FUSE observations (Linsky 2006)



Dvorkin et al (2016)

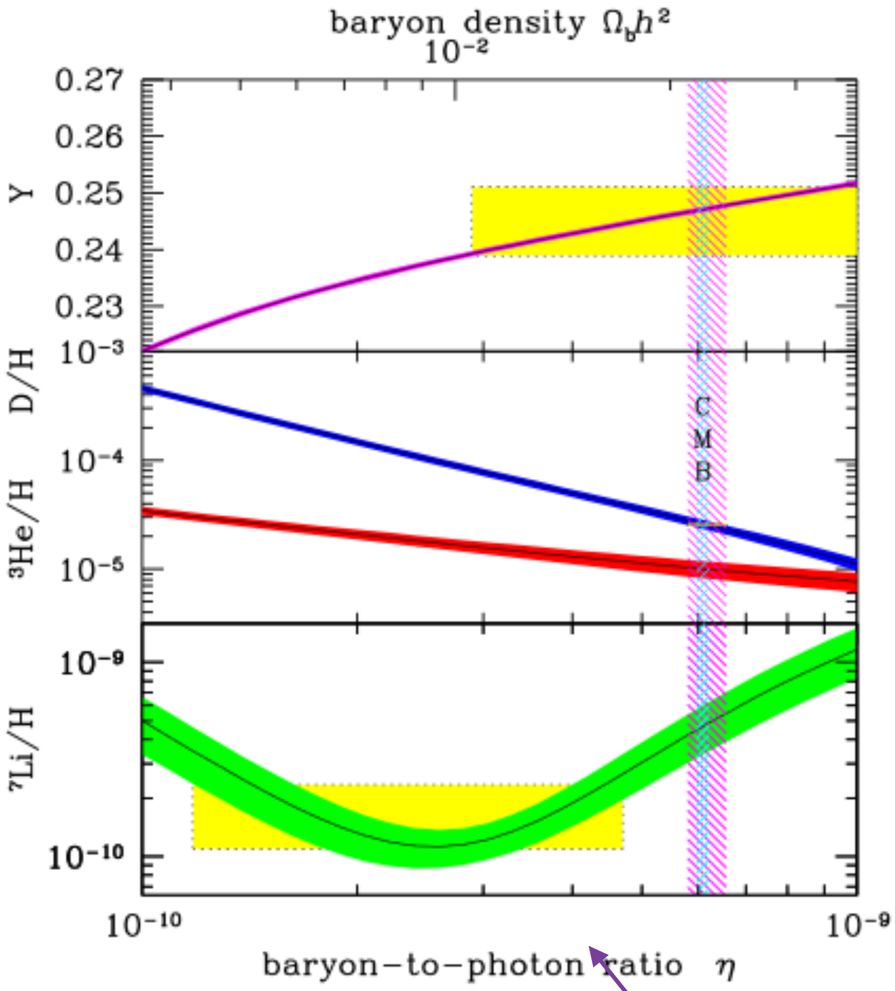
D/H in the context of cosmological structure formation

$10^5$Dp =2.58



- no dust in the DLA (when measured)
- small depletion is expected for [Fe/H]~ -2

# D the “baryometer” of choice



- D ~ **not** sensitive to expansion rate
- strong sensitivity to eta.
- BB only astronomical source (spallation minor) , stars destroy D

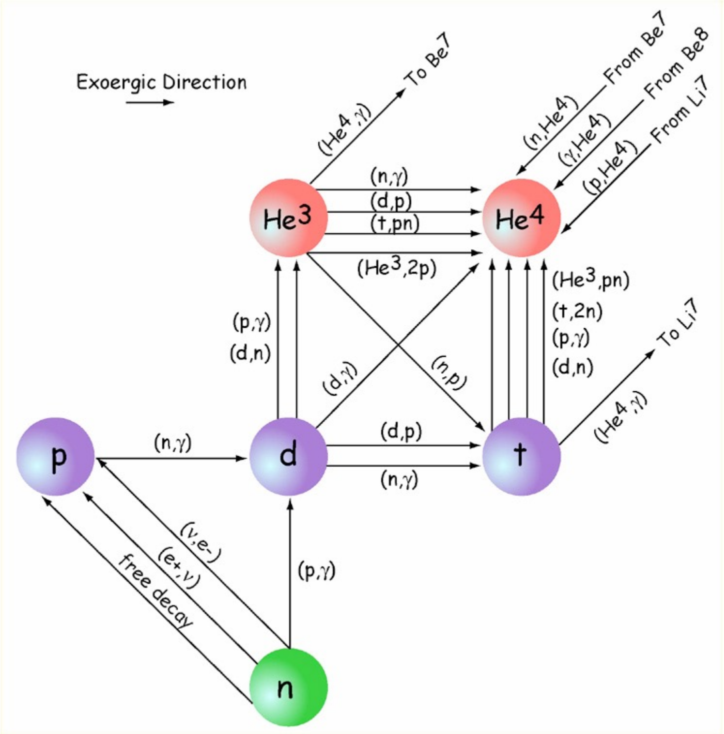
Fields et al (2018)

$^4$He extragalactic HII regions (Peimpert et al 2017)
$^7$Li: Halo stars
D: DLAs

$10^5$(D/H)= 2.569 ± 0.027

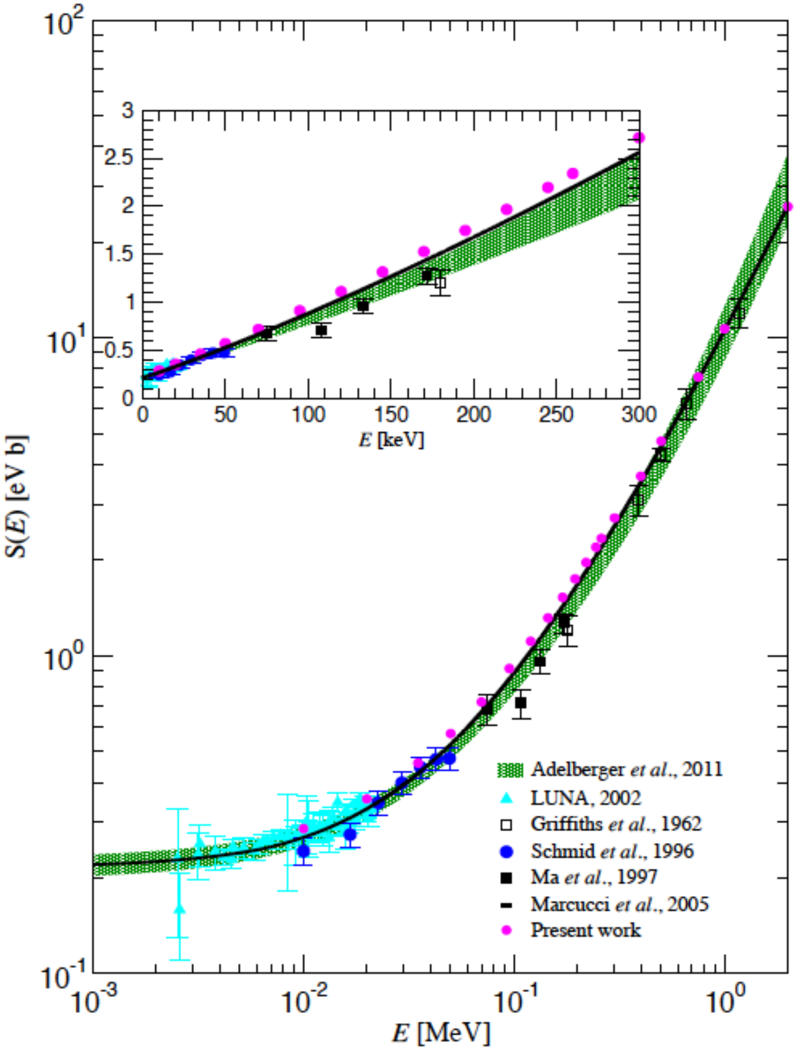
Li problem

# D Nucleosynthesis



Theoretical S(E) have uncertainties ~ 1% error.
D/H can shift by 4.5% (Marcucci et al 2016)

S(E) factor D(p,g)$^3$He

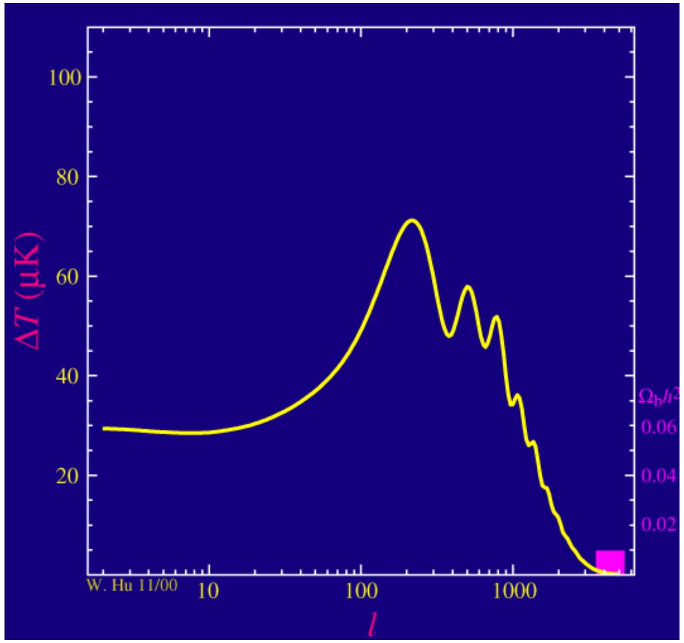


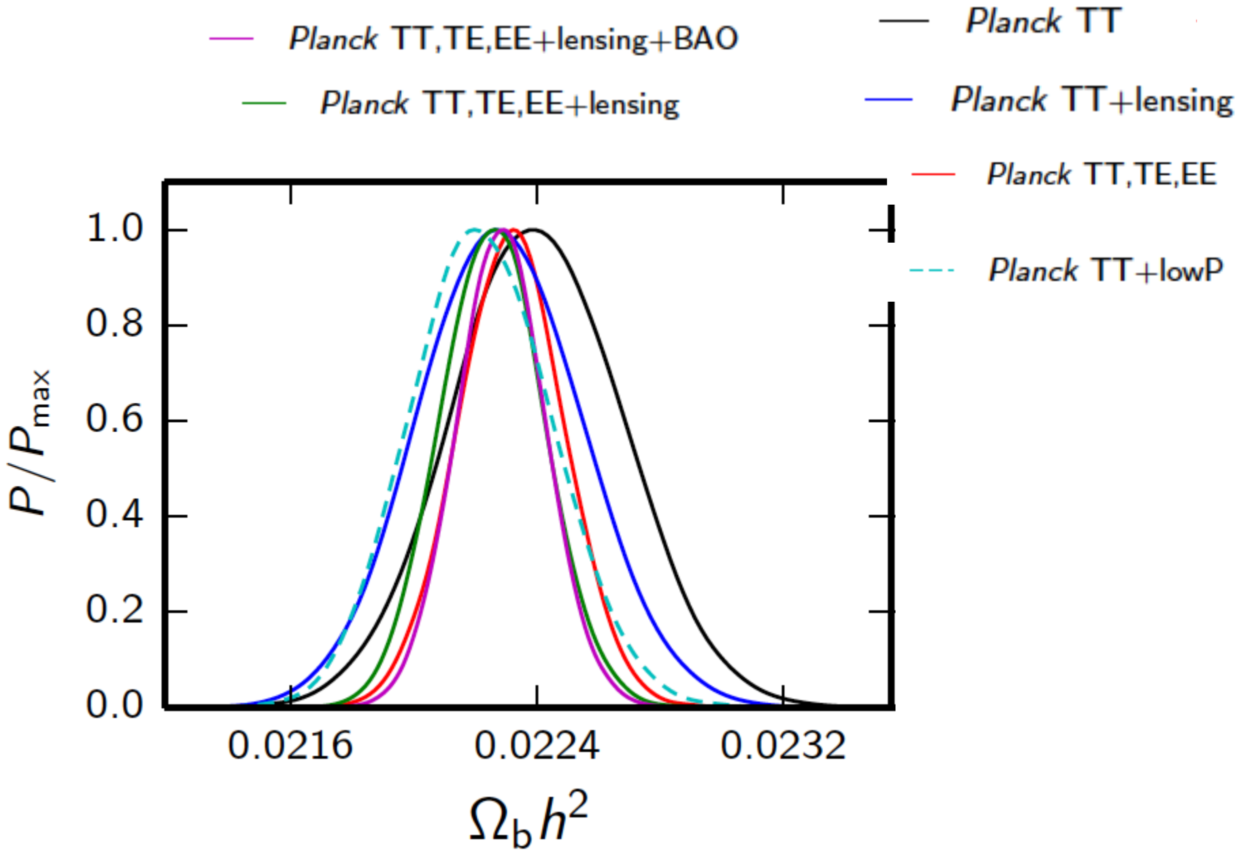
leading reactions:

| Reaction | Rate Symbol | $\sigma_{D/H} \cdot 10^5$ |
|---|---|---|
| $p(n,\gamma)^2H$ | $R_1$ | ±0.002 |
| $d(p,\gamma)^3He$ | $R_2$ | ±0.062 |
| $d(d,n)^3He$ | $R_3$ | ±0.020 |
| $d(d,p)^3H$ | $R_4$ | ±0.0013 |

# CMB & SBBN

The odd acoustic peaks in the power spectrum are enhanced over the even as we increase the baryon density.





$100\ \Omega_{b,o} h^2 = 2.226 \pm 0.023$ also at ~1%

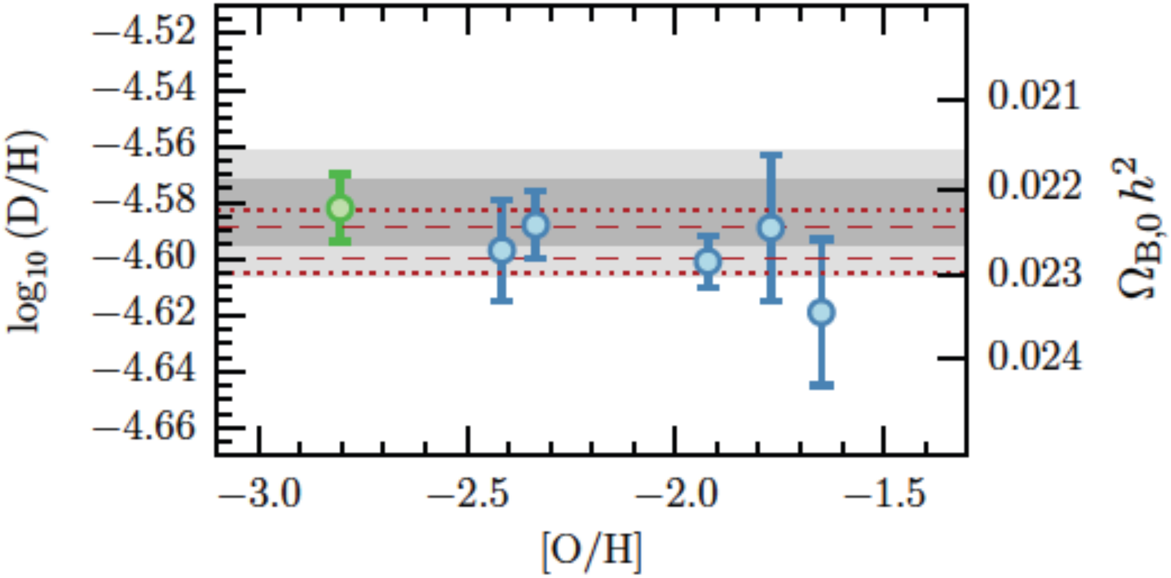
$$\eta_{10} = 273.9\, \Omega_{b,0}\, h^2$$

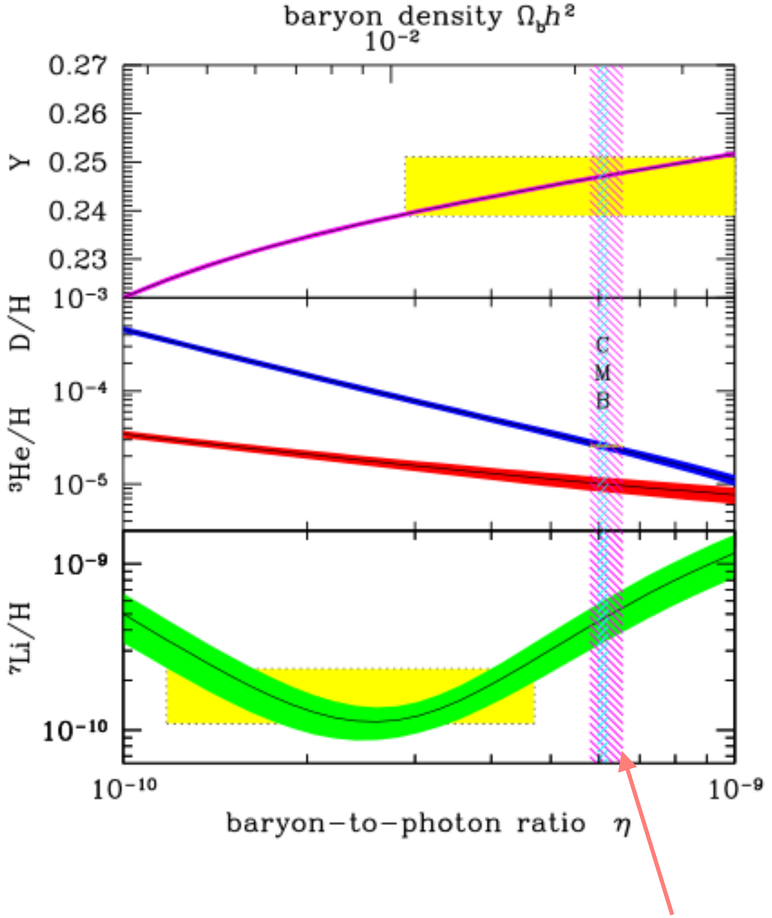
( for Yp, CMBT=2.7258 K, Steigman 2006,)

# Cooke et al (2016)

100 $\Omega_{b,o}h^2$ = 2.260 ± 0.018 ± 0.029   exp S(E)

100 $\Omega_{b,o}h^2$ = 2.226 ± 0.023





(with D/H=25.69 ±0.27: $100\Omega_b$ $\Omega_{b,o}h^2$ ~ 2.245 ± 0.015 ± 0.029 (preliminary!)

perfect agreement!

- no need for new physics beyond the SM.

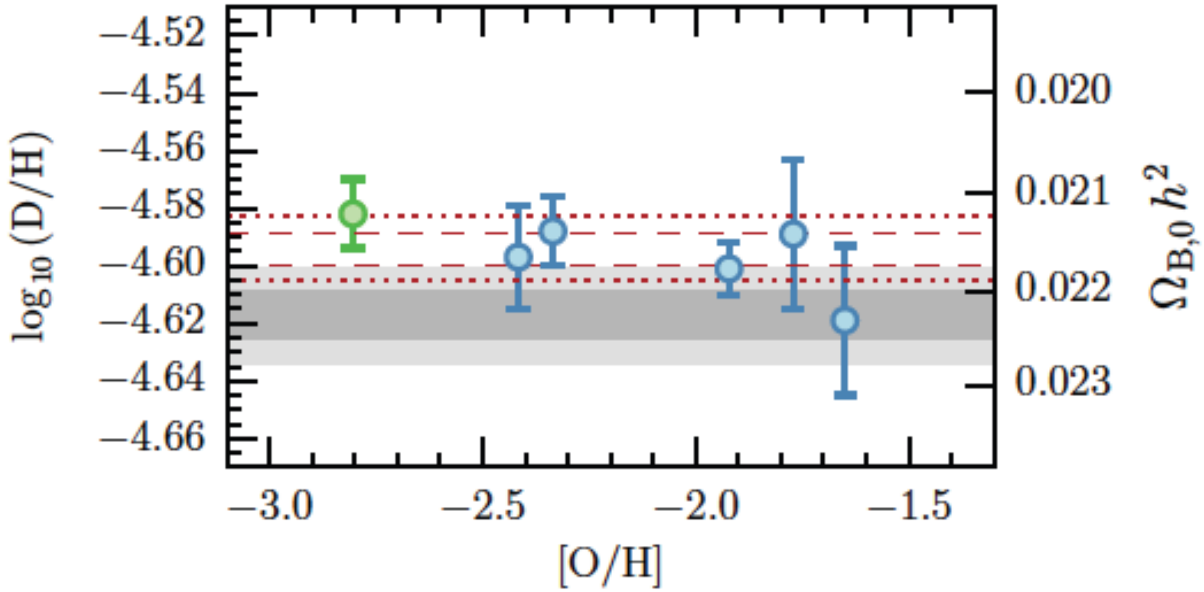
$$N_{\text{eff}} = 3.046\,(1 + \Delta N_\nu/3)$$

# theoretical S(E) (Marcucci et al 2016): lower $D_p$ (~ 4.5%), lower eta, and lower Ω

$$10^5\,(\mathrm{D/H})_\mathrm{P} = 2.47\,(1 \pm 0.01)\,(6/\eta_\mathrm{D})^{1.68}$$

$$\eta_\mathrm{D} = \eta_{10} - 1.08\,(S - 1)\,(1.1\,\eta_{10} - 1)$$

$$S = \left(1 + \frac{7\Delta N_\nu}{43}\right)^{1/2}$$



$100\ \Omega_{b,o}h^2 = 2.156 \pm 0.017 \pm 0.011$ new S factor Cooke et al (2016)

$100\ \Omega_{b,o}h^2 = 2.226 \pm 0.023$ Planck

small tension (~ 2.3 sigma or more)

with $10^5 \mathrm{D/H} = 2.569 \pm 0.027 \Rightarrow 100\ \Omega_{b,o}h^2 = 2.140 \pm 0.015 \pm 0.011$ (preliminary!)

# LUNA experiment  Gran Sasso

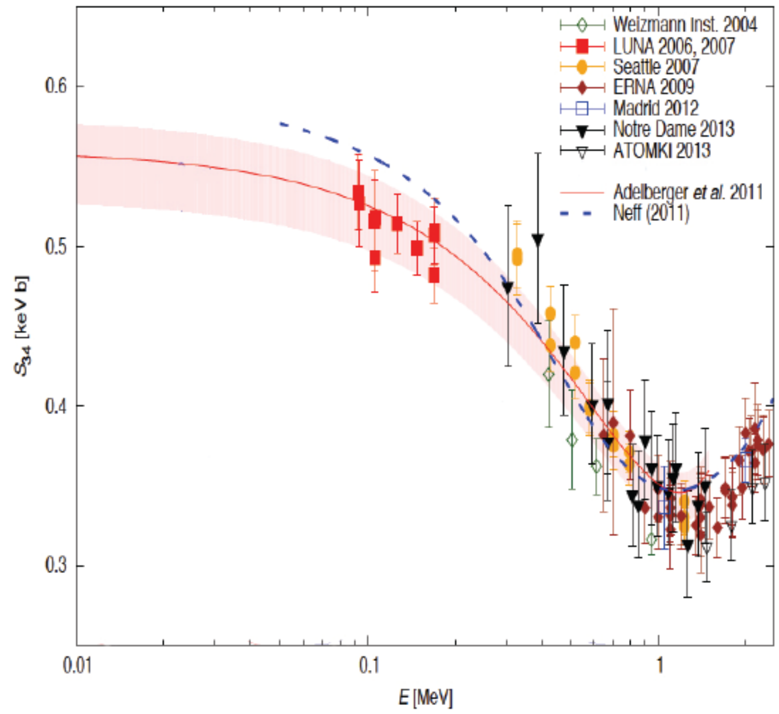
Gustavino (2017)

$^{2}H(p,\gamma)^{3}He$

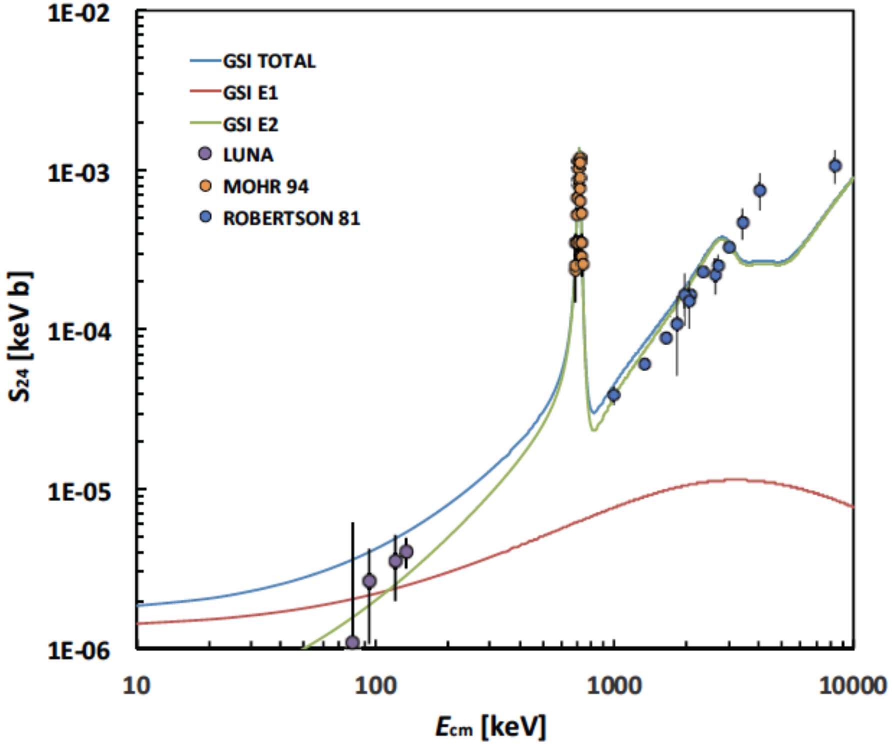
$^{3}He(\alpha,\gamma)^{7}Be$

$^{2}H(\alpha,\gamma)^{6}Li$

$^{3}He(\alpha,\gamma)^{7}Be$



$^{2}H(\alpha,\gamma)^{6}Li$



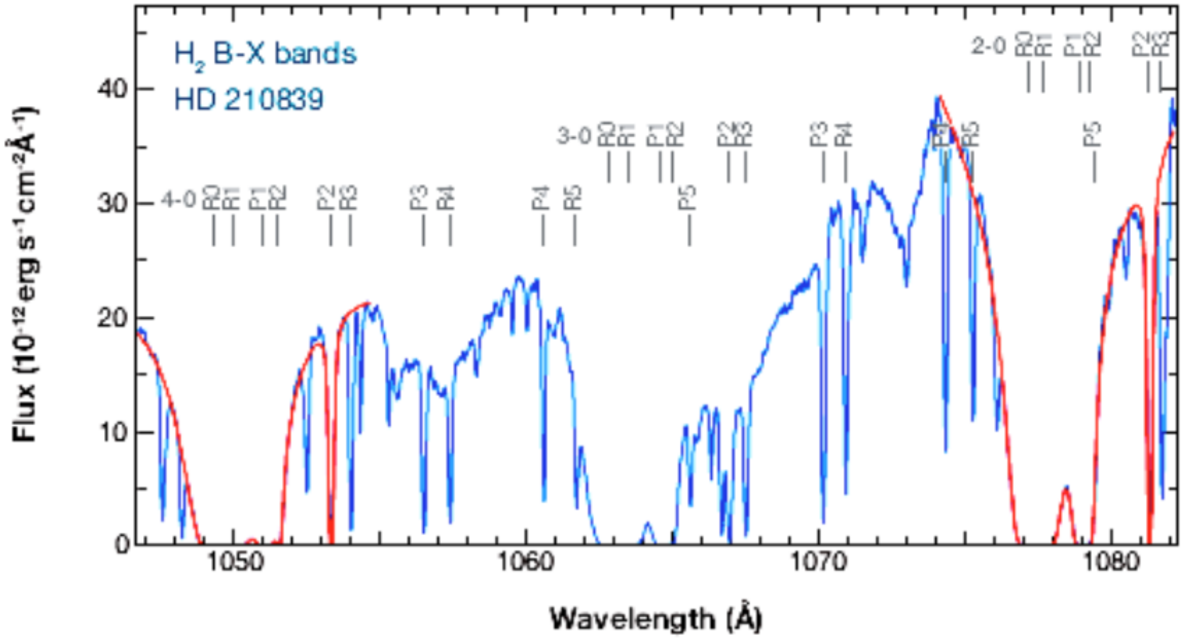
- $^{7}$Li predicted by SBBN is  OK, no nuclear fix to the Li problem
- $^{6}$Li not produced in the SBBN enhanced

# Molecular hydrogen

$H_2$ is stable at low temperatures, but difficult to predict: formes on dust grains, photodissociated by hv> 14 ev,

In the Milky Way. Lyman and Werner bands (~ 1000 A ) first detected in a rocket experiment (Carruthers 1967), then Copernicus and FUSE.

## Fuse FUV Lyman Band lines

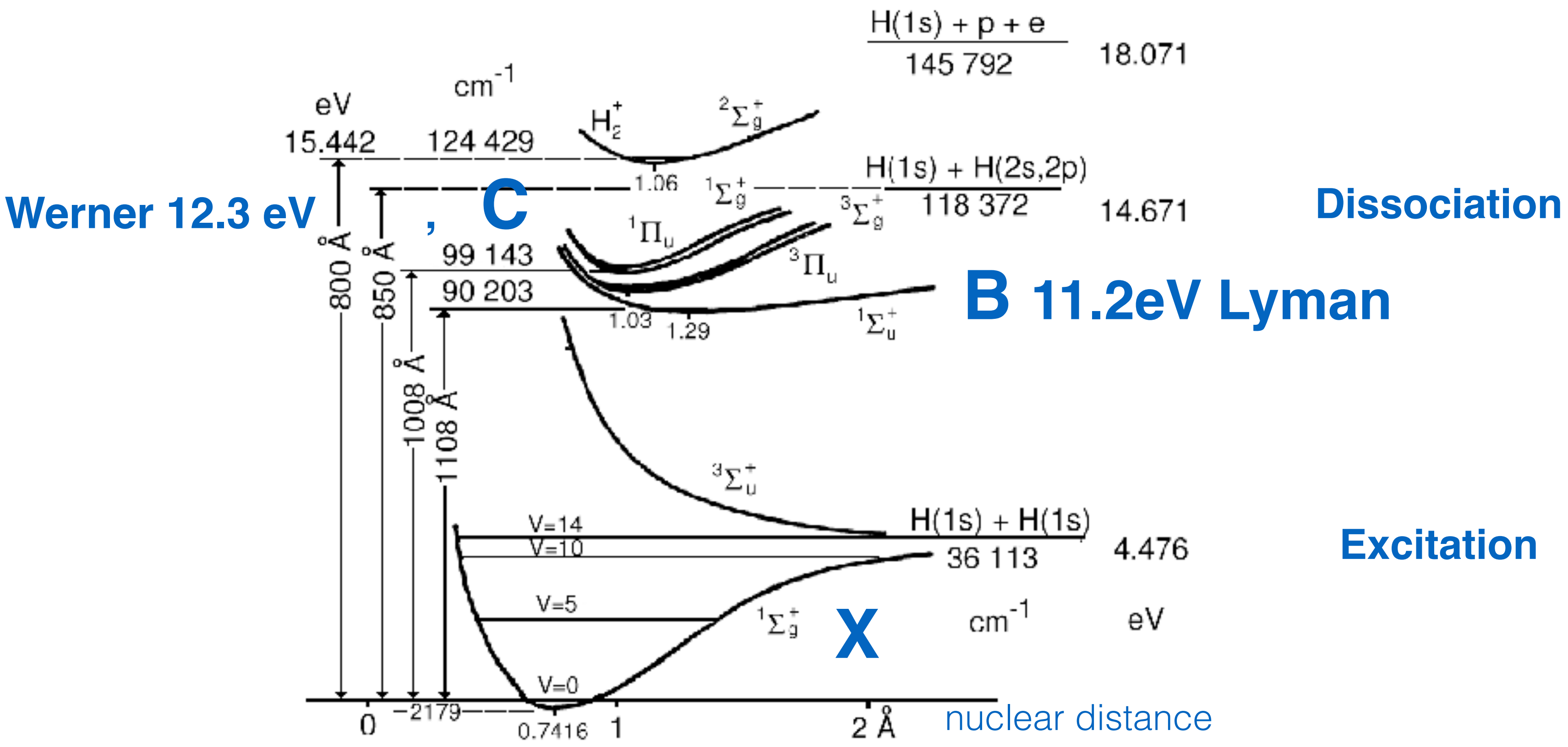


- $H_2$ in ~ 90% of l.o.s the Milky Way (Savage et al.1977
- $f(H_2) > 10^{-2}$

$$f = 2N(H_2)/[2N(H_2) + N(\text{H I})]$$

# Electronic level diagram

from Field et al (1966)



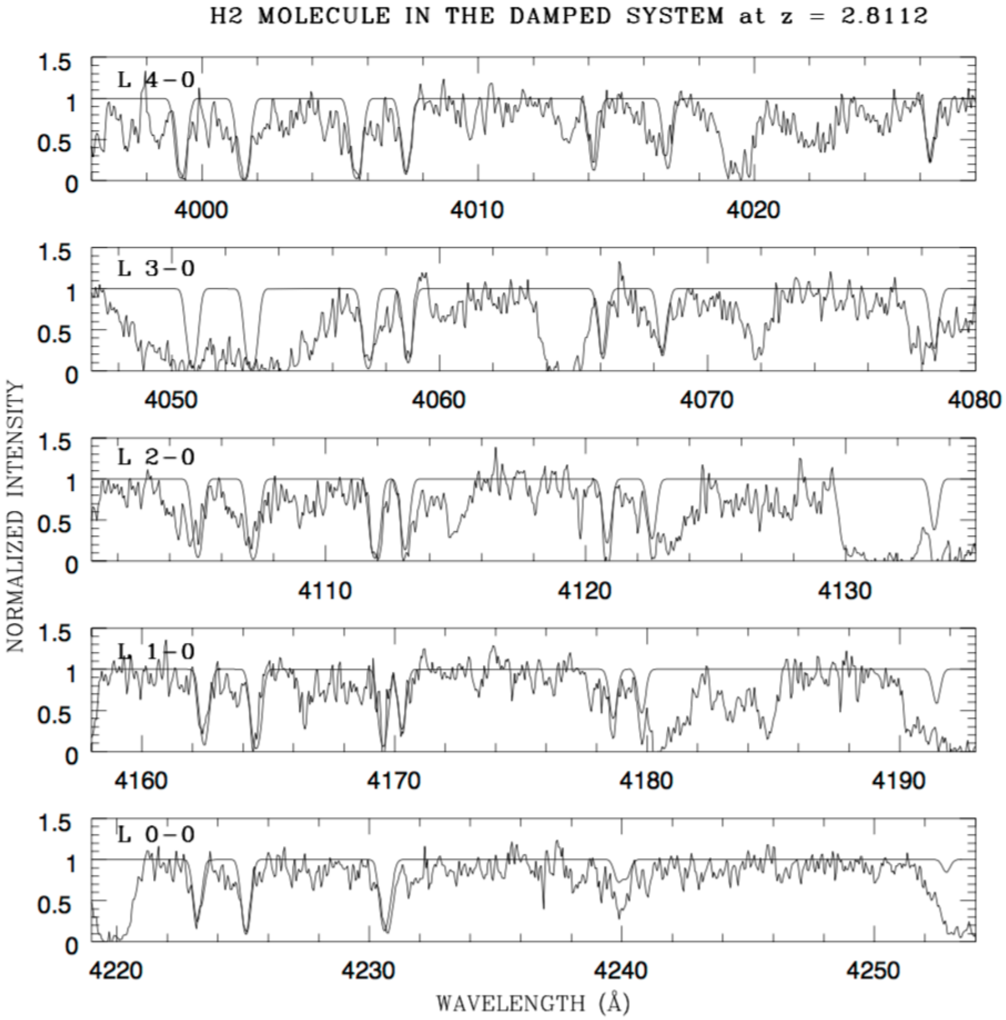
- Ground state is X. It has 30 vibrational levels, each with an infinite number of rotational states.

- The next two singlet levels are B C, connected to ground X by allowed electric-dipole transitions (analogs of HI Ly-alpha). Lyman and Werner bands start at 1108 Å and 1040 Å, and are spread to the HI Lyman edge at 911.7 Å

# Extragalactic

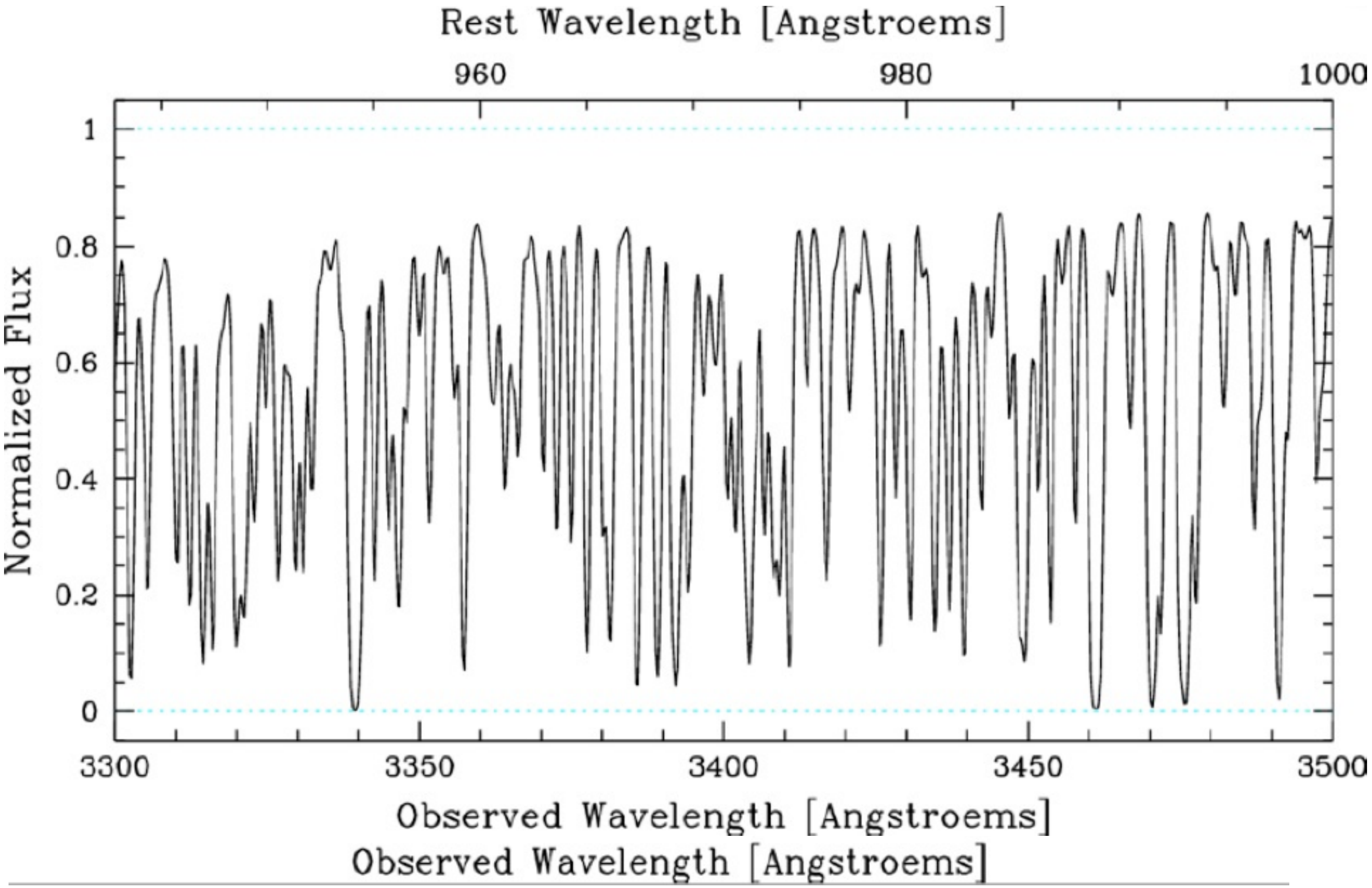
- Levshakov & Vershalovich 1985 on a spectrum of PKS 0528-250 by Morton et al 1980 taken at the 3.9 Anglo-Australian Telescope
- Confirmation: Foltz et al 1998, Srianand & Petijean 1998, Gee & Betchold 1999

PKS 0528-250



# $H_2$ lines fall within the Lyman forest

## $H_2$ z~ 2

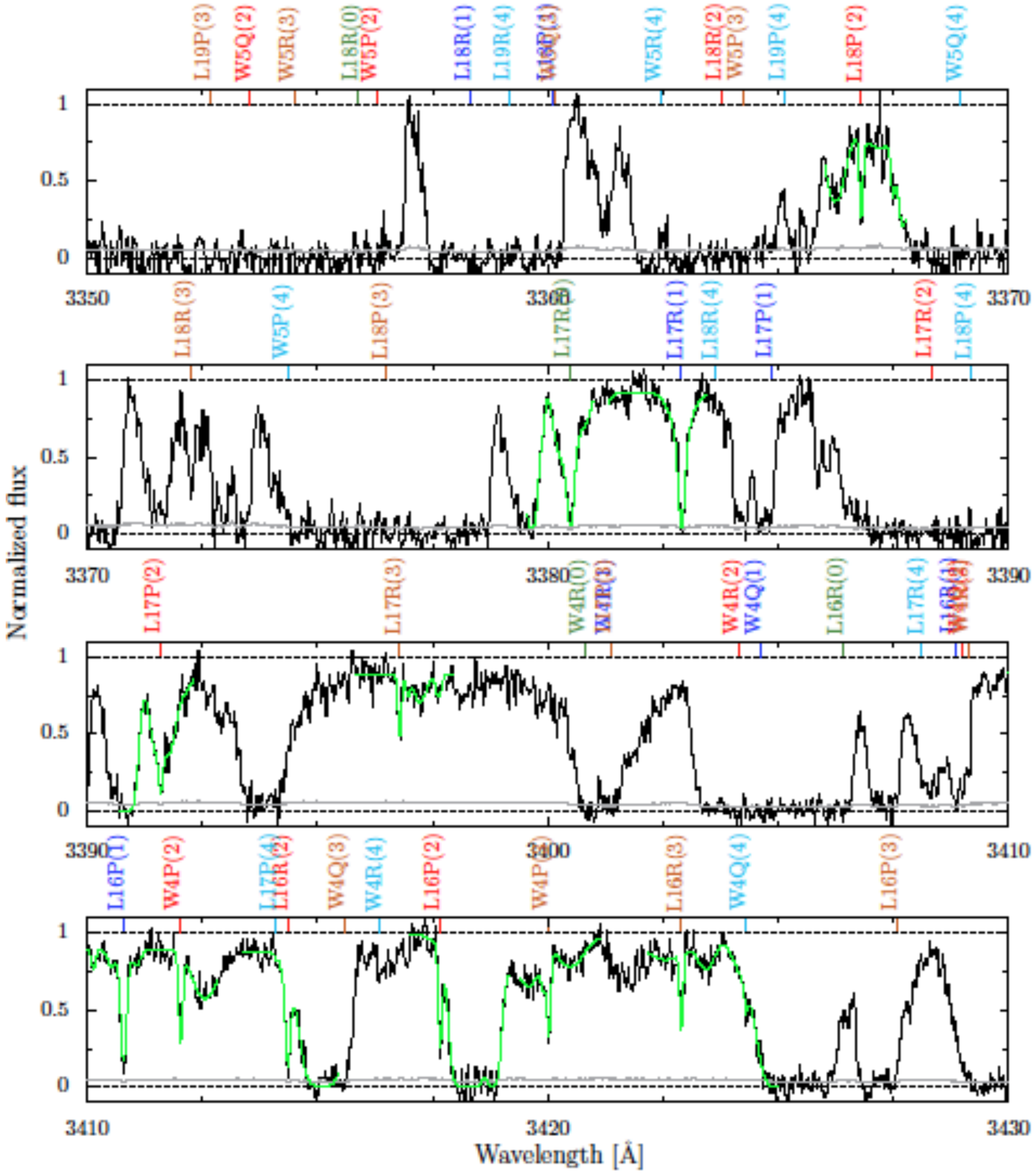


courtesy Regina Jorgenson

# B 0642-5038

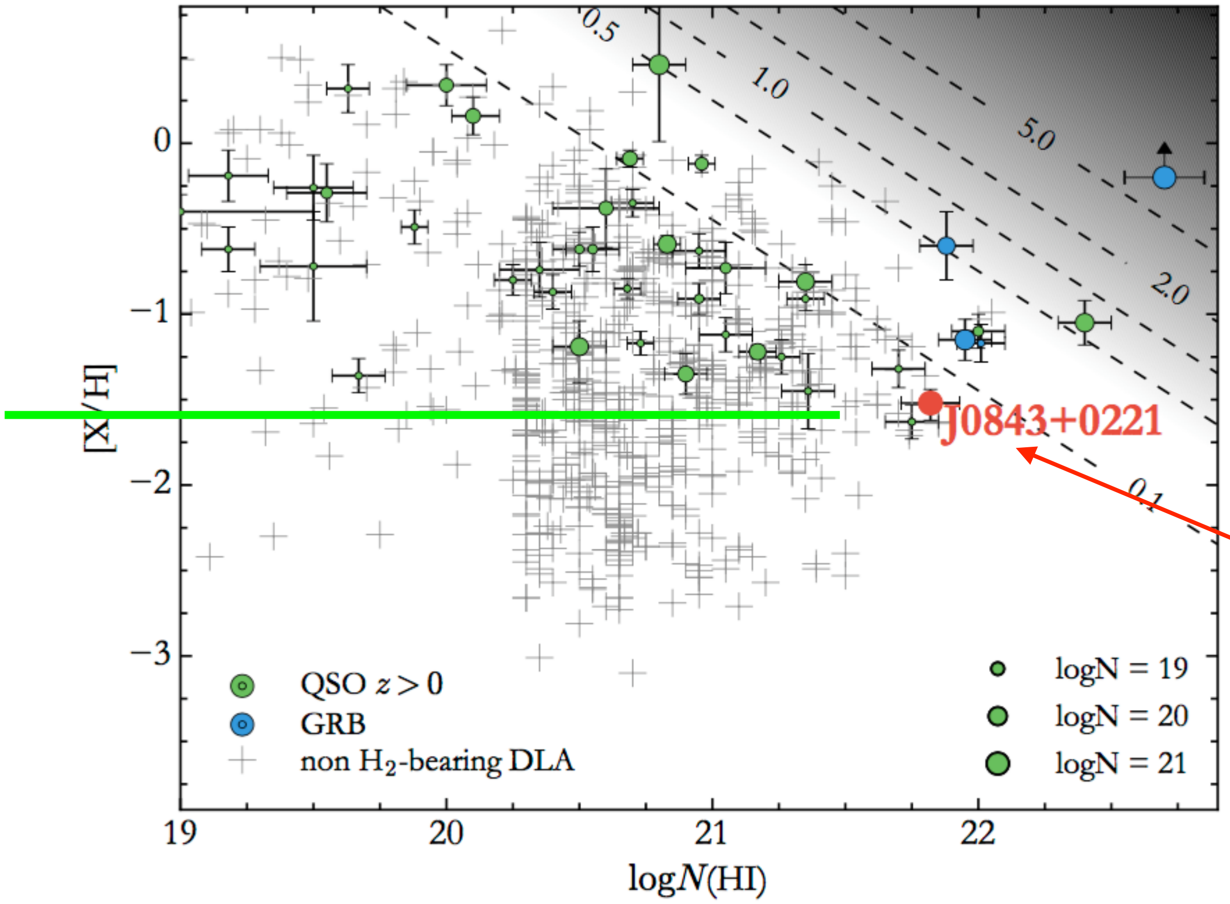
Bagdonaite (2013)

$z_{abs}$~2.66



# $H_2$ and DLA metallicity

40 measurements



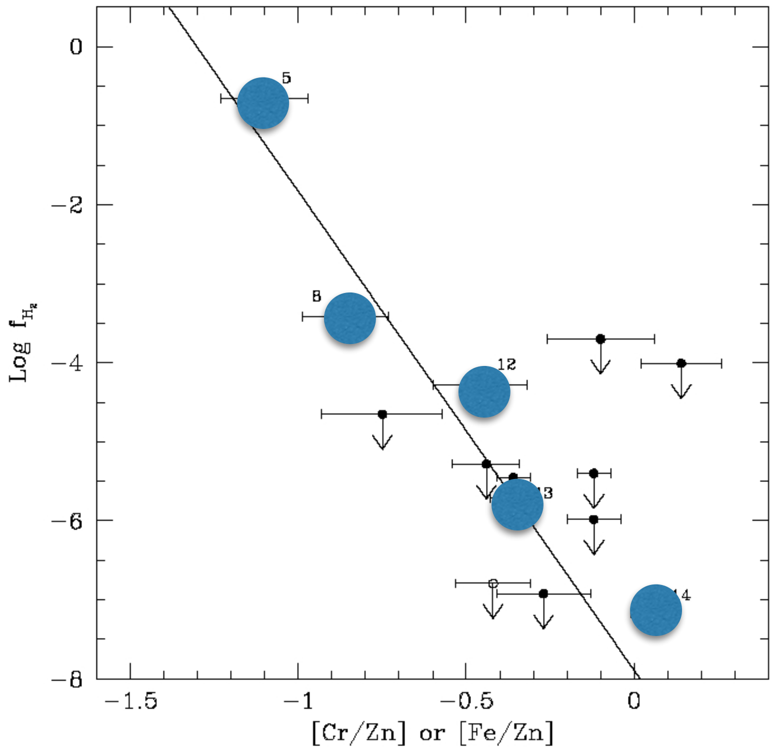
**[Fe/H]~ -1.5**

Balashev et al 2017

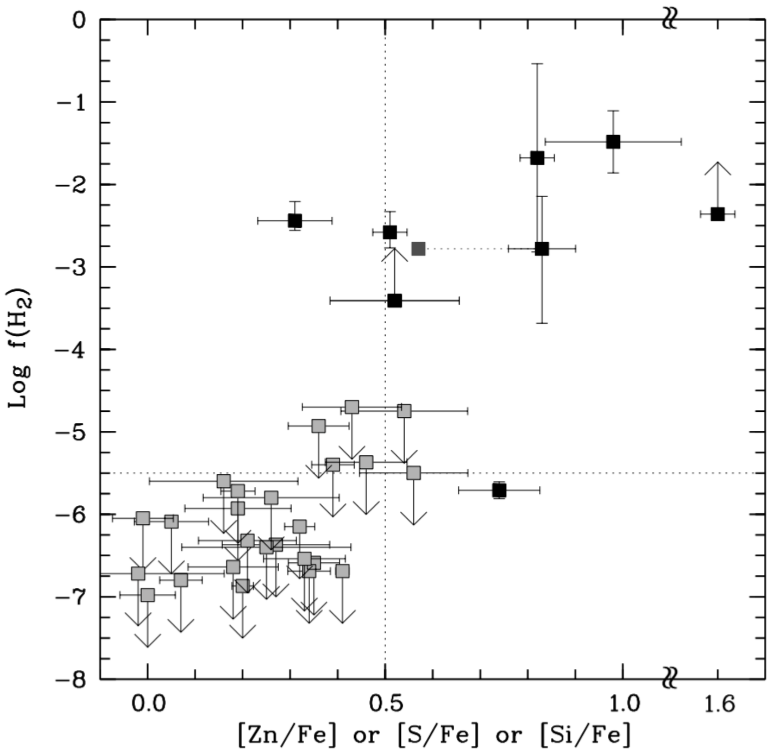
- $H_2$ is found preferentially in high metallicity systems
- less abundant in high redshift DLA

# $H_2$ and dust

Levshakov et al. 2001



Ledoux et al 2003

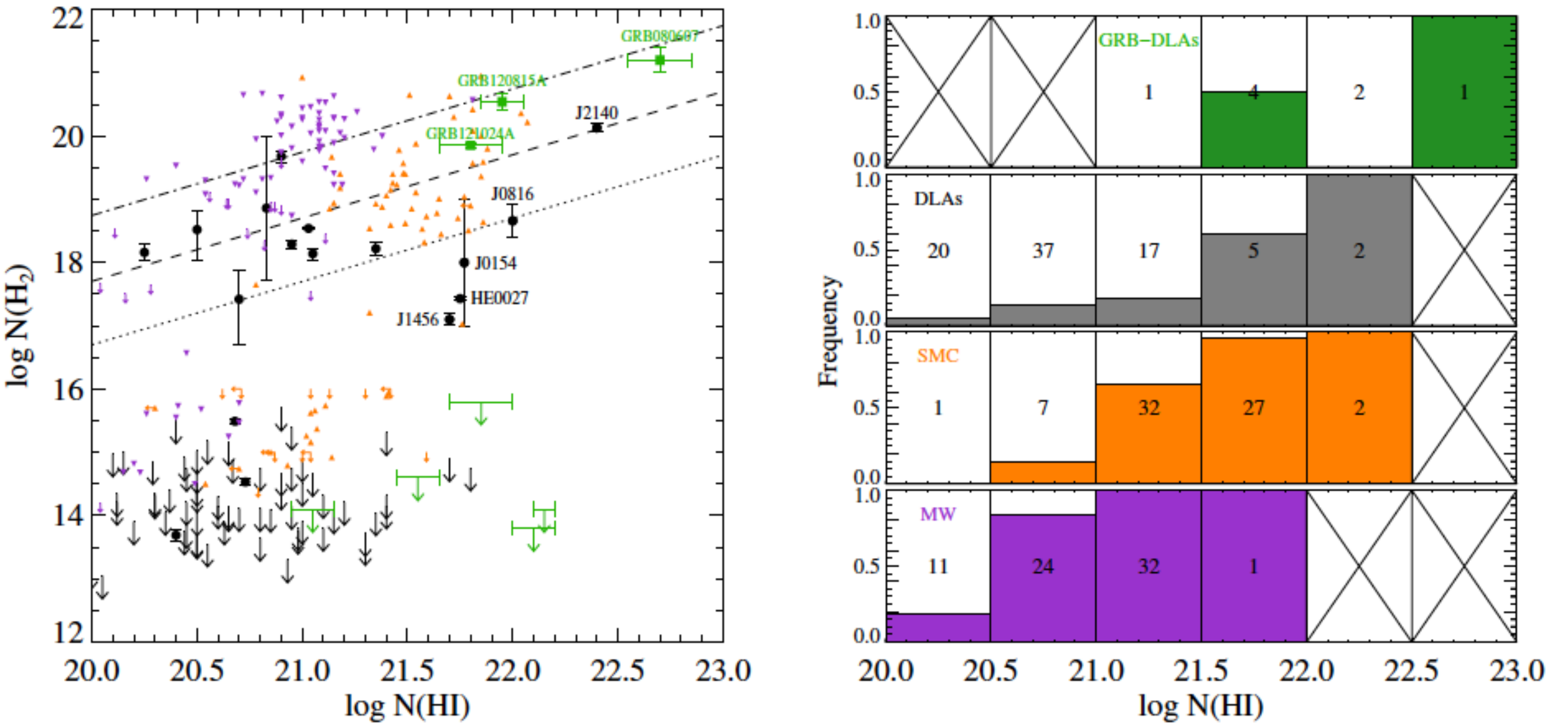


- f($H_2$) correlates with dust depletion $f = 2N(H_2)/[2N(H_2) + N(\mathrm{H\,I})]$
- $H_2$ formation needs dust, and dust needs metals

# H2 & LogN(HI)

## dependence on the LogN(HI) ?

Noterdaeme et al (2015) study of the few log H(I) ~ 22



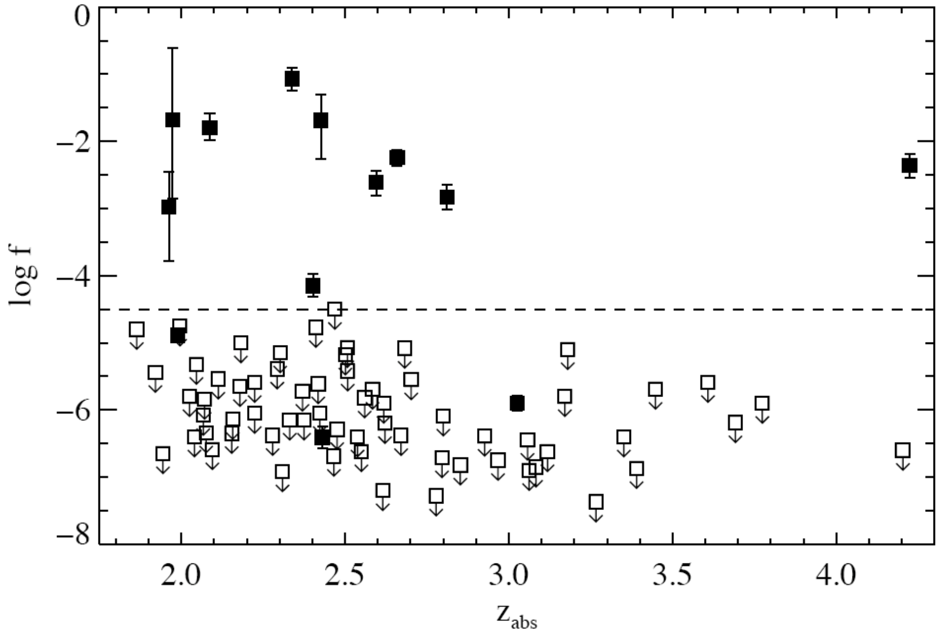
- At Log H(I)~22 the incidence is higher but the molecular level ($f(H_2)\sim 10^{-4} - 10^{-2}$) remains low.
- No evidence for dense molecular clouds

# Surveys of $H_2$

- 2003: Ledoux et al. on **33 DLAs**, **detection rate: 13 – 20%.** Preselection: dusty systems
- 2008: Noterdaeme et al., on **77 DLA,detection rate: 10 – 18%** . Preselected
- 2013 Jorgenson ~**100** z ≥ 2.2 DLA **detection rate** 1-5%. Unbiased, blind survey.
- 2014 Balashev et al. High logN( $H_2$) candidates from SDSS (z>2.3) spectra (logN($H_2$) > 19.5), **100 candidates found, 8 studied 8 systems** ( 100% success)
- 2015 Noterdaeme, detection rate <10% . Preselection of strong CI lines from SDSS (or 2175 A bump)

$H_2$ in DLA: ~ 40

GRBs: 4 (Prochaska et al 2009, Kruhler et al 2013, Friis et al 2015, D'Elia et al 2014)



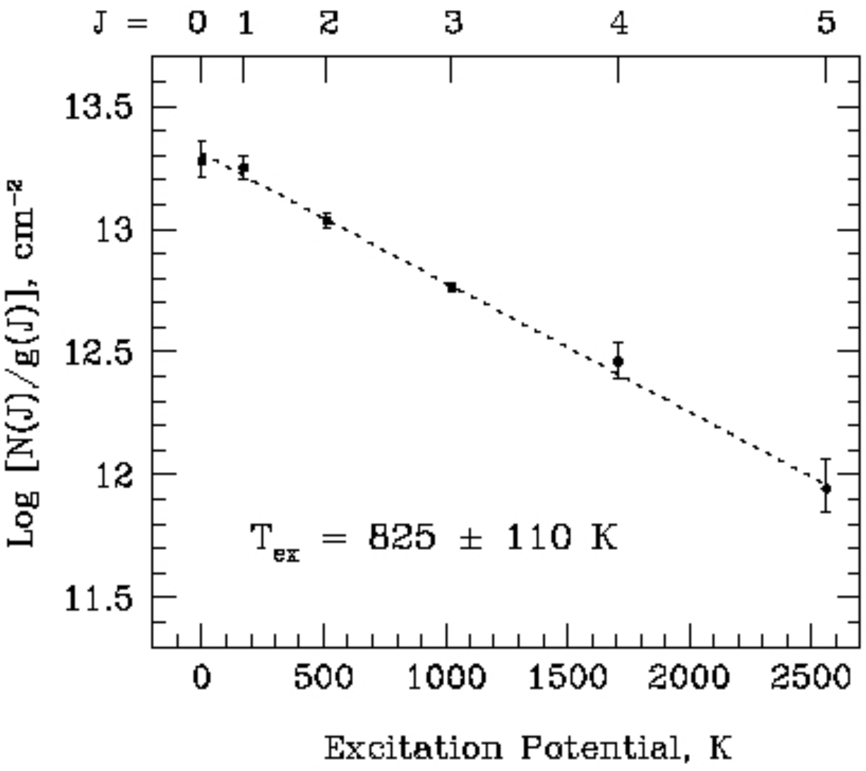
peak at z~ 2.5 (related to dust)

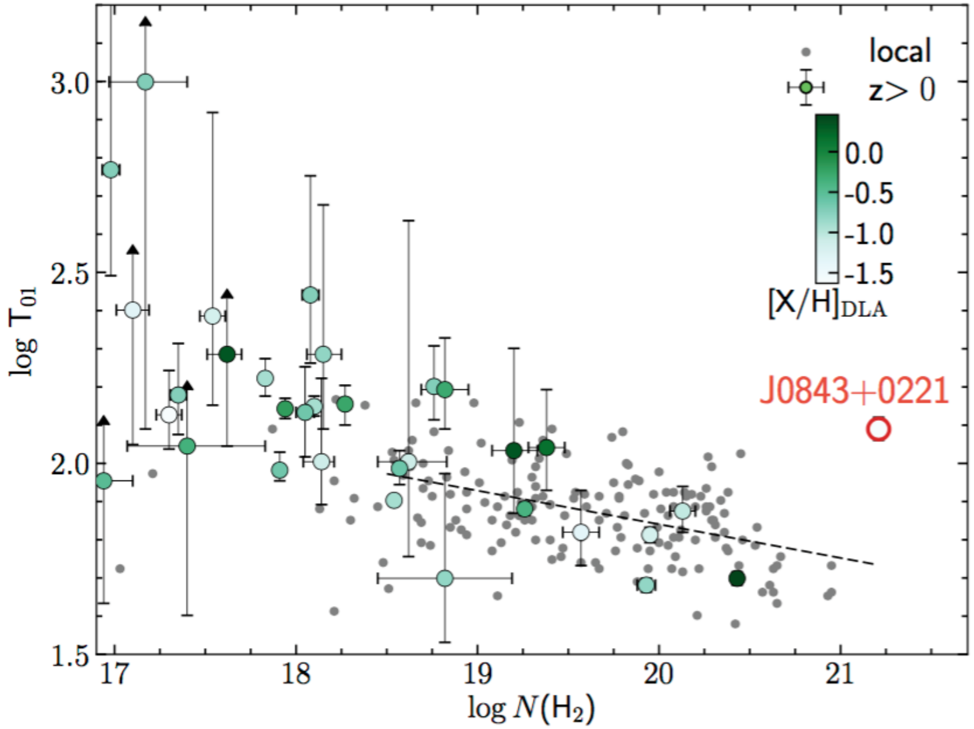
fraction 1-5% Jogerson et al (2013)

# physical state of the gas:

Balashev et al 2017

Excitation temperature:





From the population levels J

- ➡ $T_{exc}$: ~ 100 K
- ➡ density: n(H) ~ 50-60 $cm^{-3}$
- ➡ sizes: ~ pc

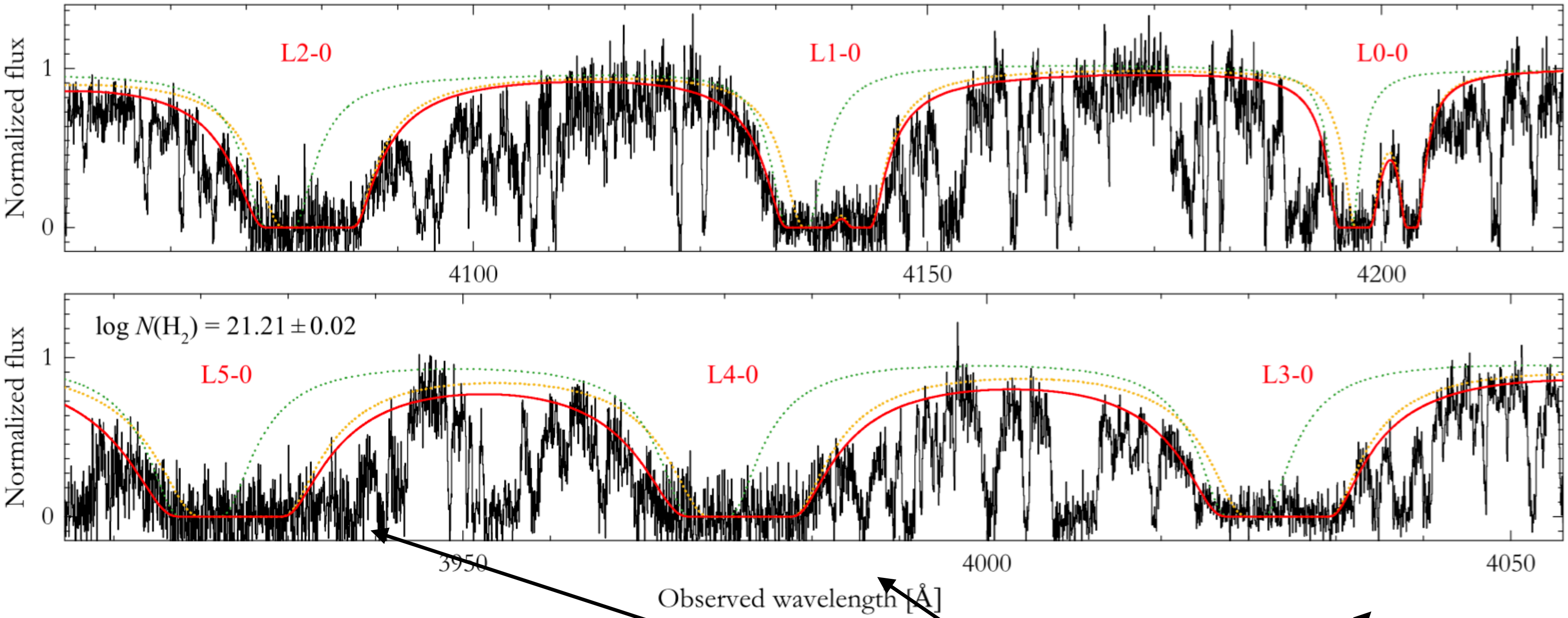
- like the Milky Way
- $T_{exc}$ decrease with $N(H_2)$

# The largest $H_2$ column density

J0843+0221, $z_{abs}$=2.786

logN(H)=21.82, **logN($H_2$)=21.21**,

Balashev et al 2017

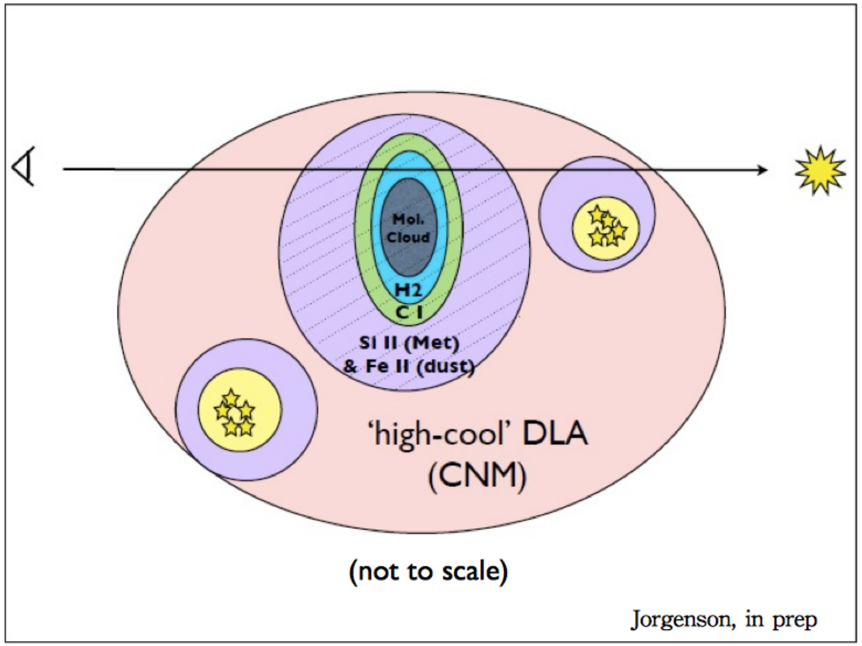


[Zn/H]=-1.5
$T_{exc}$=123 ± 9 K
n ~ 260-380 $cm^{-3}$

strongly saturated lines,
CI to resolve the structure

# Observational evidences:

- The incidence is 1-5% (possibly higher at high logNH(I)
- f($H_2$) in DLA is much lower than in the Galaxy
- $H_2$ correlates with metallicity and dust and no $H_2$ is detected for [Fe/H] < -2
- No dense $H_2$ cloud detected
- $T_{exc} \sim 10^{2,}$ n(HI)~ 50 $cm^{-3}$



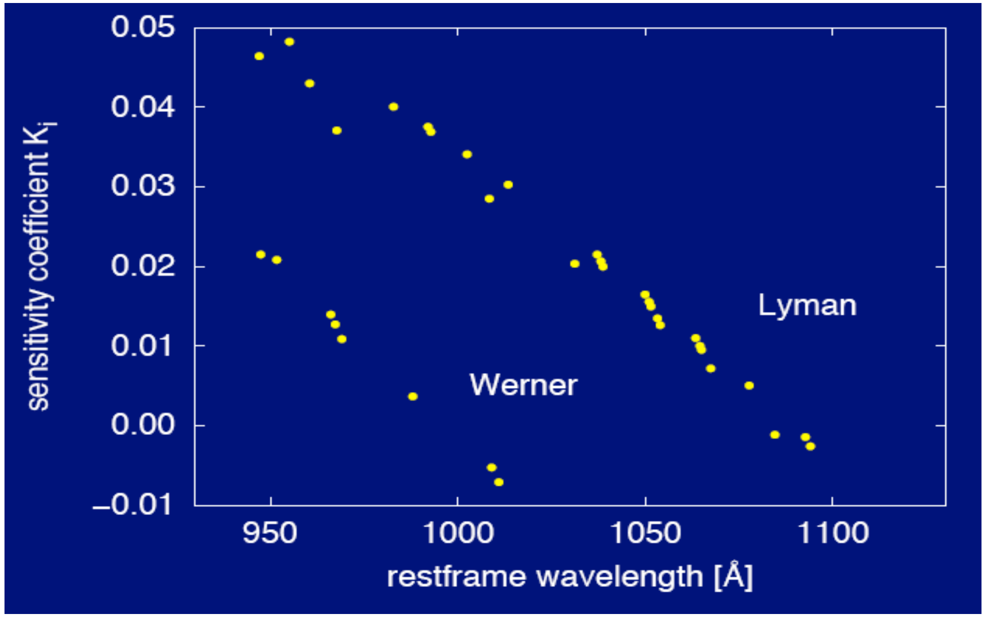
- $H_2$ are small cloudlets with low filling factor

# μ =Mp/Me

electron-vibro-rotational transitions have different dependence from the reduced $H_2$ mass.

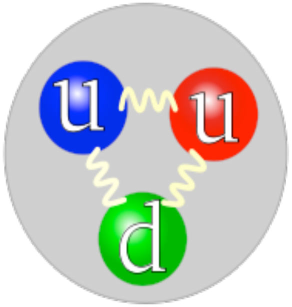
Rovibronic transitions

$$E_{molecule} = \underset{\underset{\propto const}{\nearrow}}{E_{elec}} + \underset{\underset{\propto \frac{1}{\sqrt{\mu}}}{\uparrow}}{E_{vibr}} + \underset{\underset{\propto \frac{1}{\mu}}{\nwarrow}}{E_{rot}}$$



$$\lambda_{obs} = \lambda_{rest}\,(1+z_{abs})(1+K_i\,\Delta\mu/\mu)$$

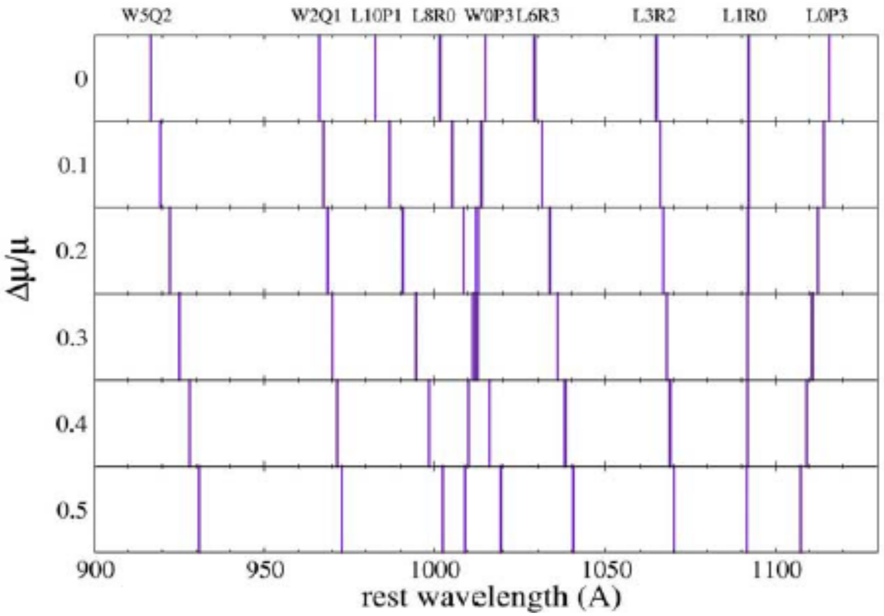
$$K_i = -\frac{\mu_n}{\lambda_i}\frac{d\lambda_i}{d\mu_n} = \frac{1}{E_e - E_g}\left(-\frac{\mu_n dE_e}{d\mu_n} + \frac{\mu_n dE_g}{d\mu_n}\right)$$



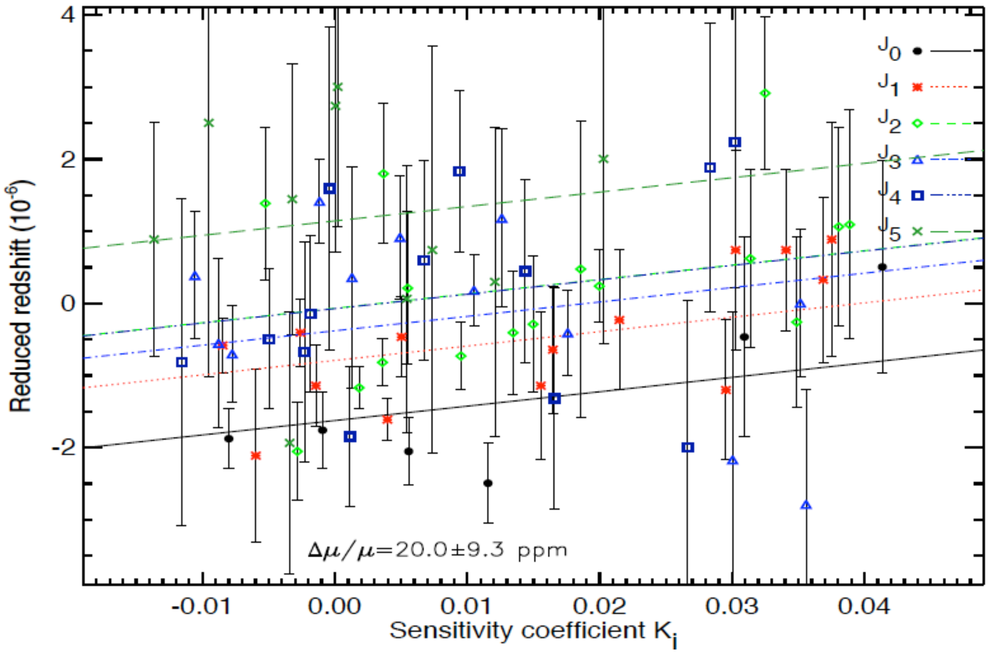
$m_p$ = 938 Mev = $(862_{QCD} + 74_q + 2_{QED})$ Mev $\propto \Lambda_{QCD}$ => strong forces

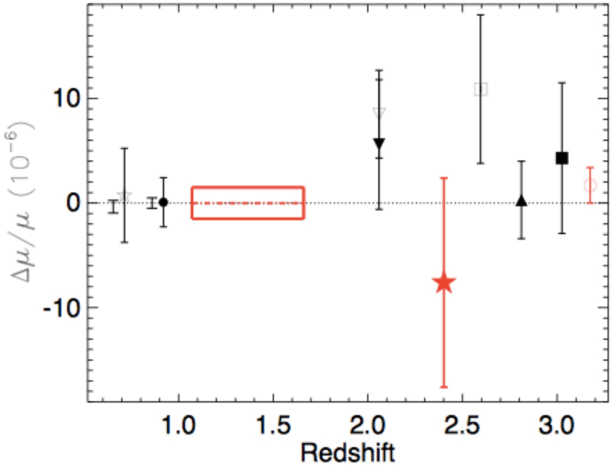
$m_e$= 0. 5 Mev ∝ the vacuum expectation value of the Higgs field => The weak scale (223

μ = strong/weak



highly exaggerated





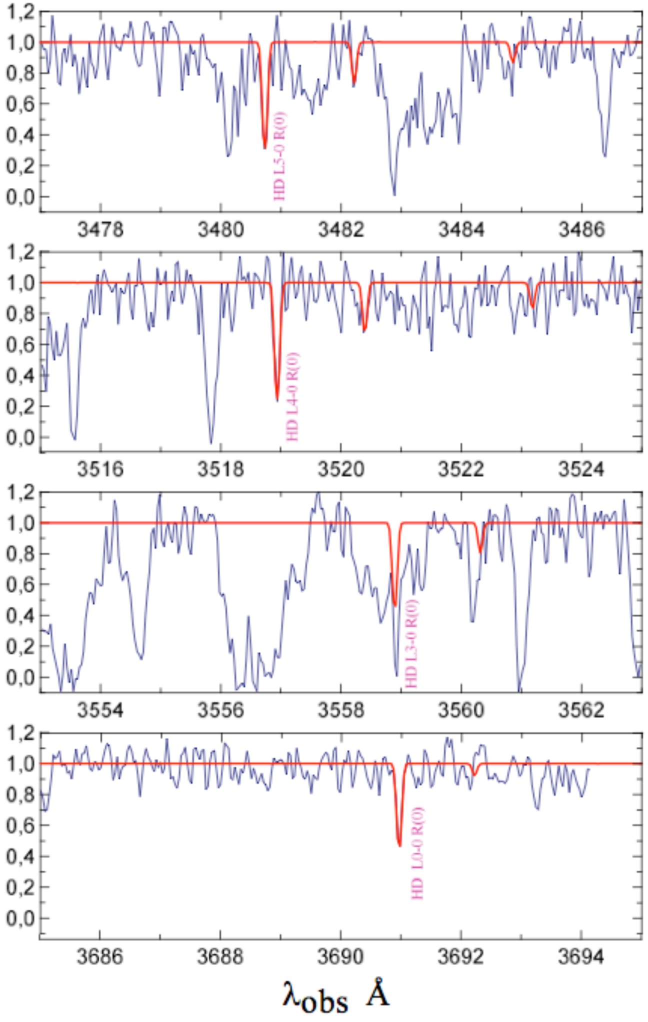
$H_2$ : <Δμ/μ> = 3.4 ± 2.7 ppm

# Deuterate Hydrogen

## 8 detections:

**Q1232+082 Varshalovich et al 2001**
J1439+1117 Srianand et al 2008
J2123-0500 Tumlison et al 2010
Q0812+32 Balashev et al 2010
Q1331+170 Balashev et al 2010
J1237+064 Noterdaeme et al 2010
J0000+0048 Noterdaeme et al 2017
J0843+0221 Balashev et al 2017

Q1232+082 $z_{abs}=2.3$



$HD/2H_2 \sim 10\text{-}80$ ppm

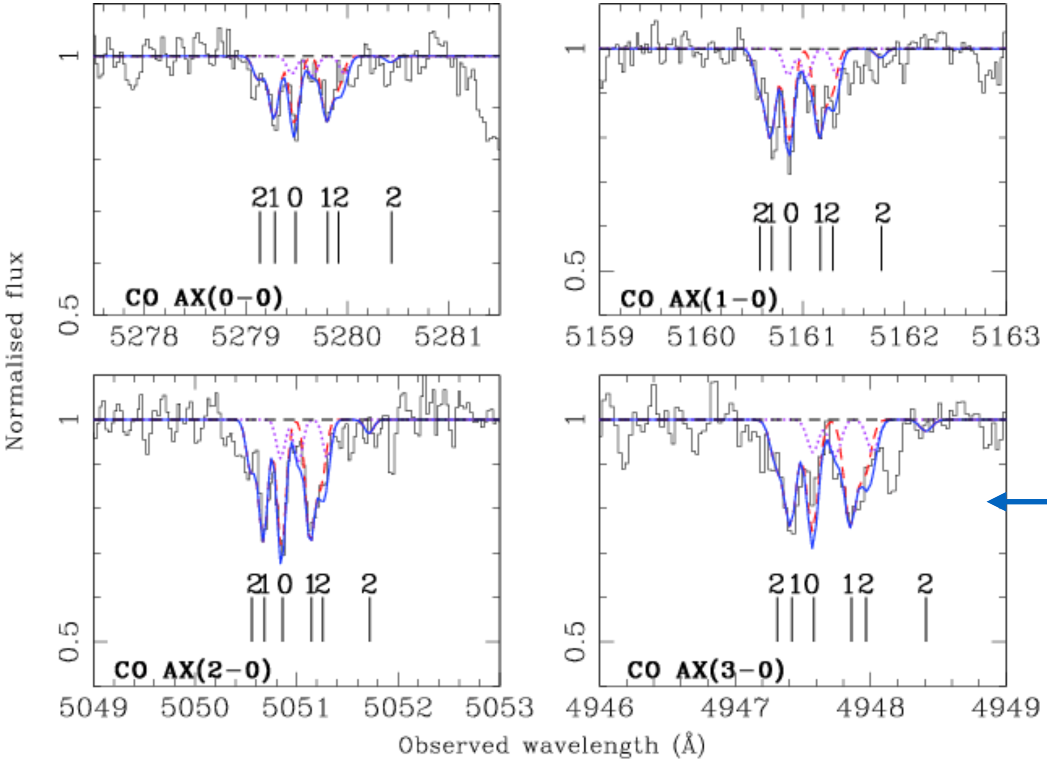
- greater than the MW ~ 1 ppm (Snow et al 2008),
- ~ (DH)p = 25 ppm

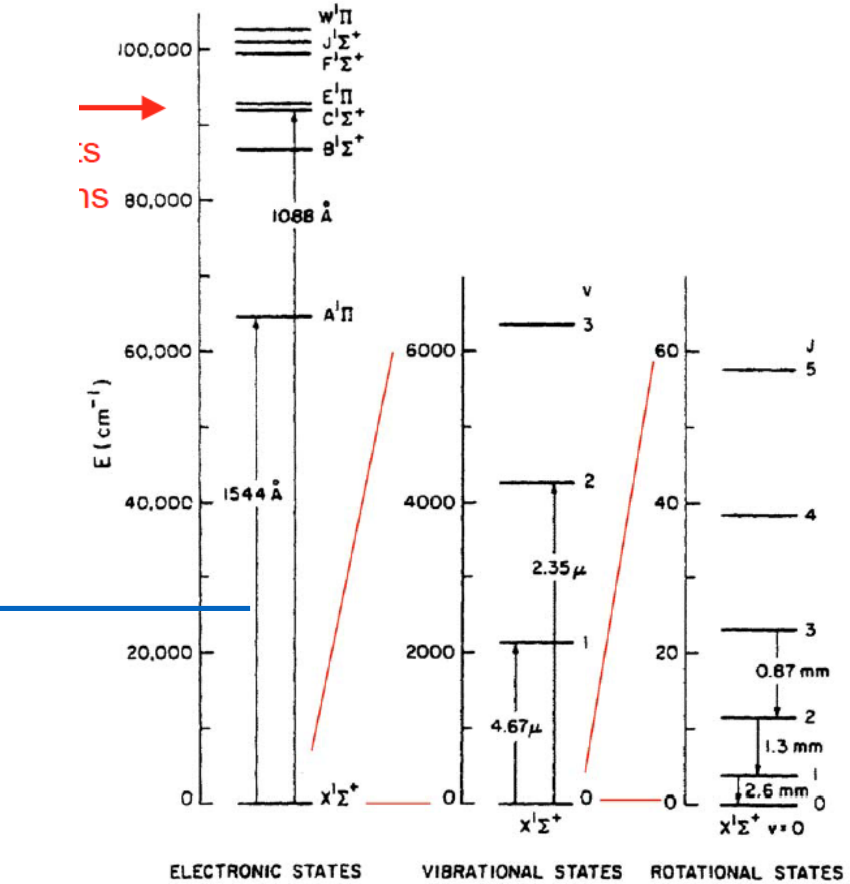
puzzling behaviour. HD chemistry: chemical fractionation and charge exchange processes:
$D^+ + H_2 \Rightarrow HD + H^+$ (Litz 2015)

# Carbon Monoxide

CO second molecule more abundant in the universe.
Elusive for more than a quarter of century Discovery: (Srianand et al 2008)

SDSS J1439+1117, DLA $z_{abs}$=2.4





# 6 detections

Srianand et al 2008,
Noterdaeme et al 2010, 2011,2017

**Q1439+113 at z = 2.42**

**Q1604+220 at z = 1.64**

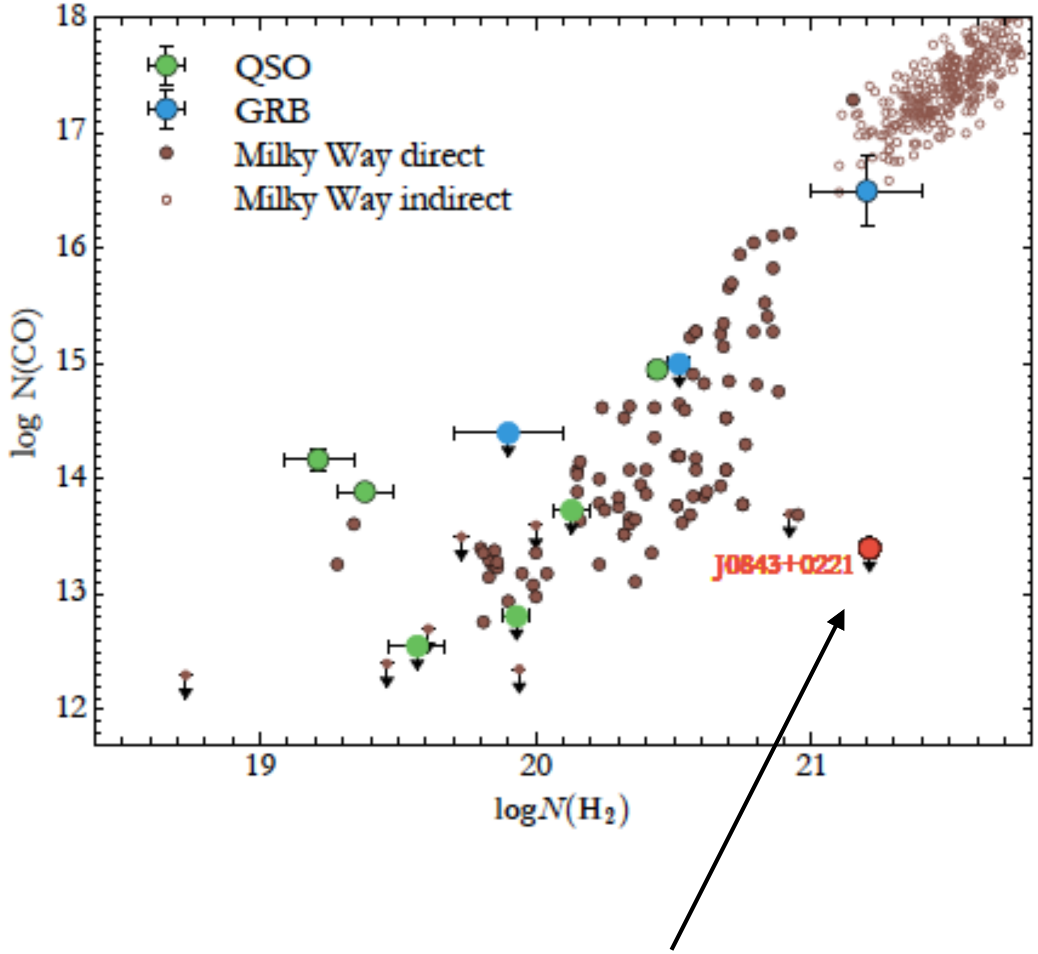
**J1237+064 at z = 2.69**

**J0857+18 at z = 1.73**

**J1047+205 at z = 1.77**

J0000+0048 z=2.52

CO and $H_2$

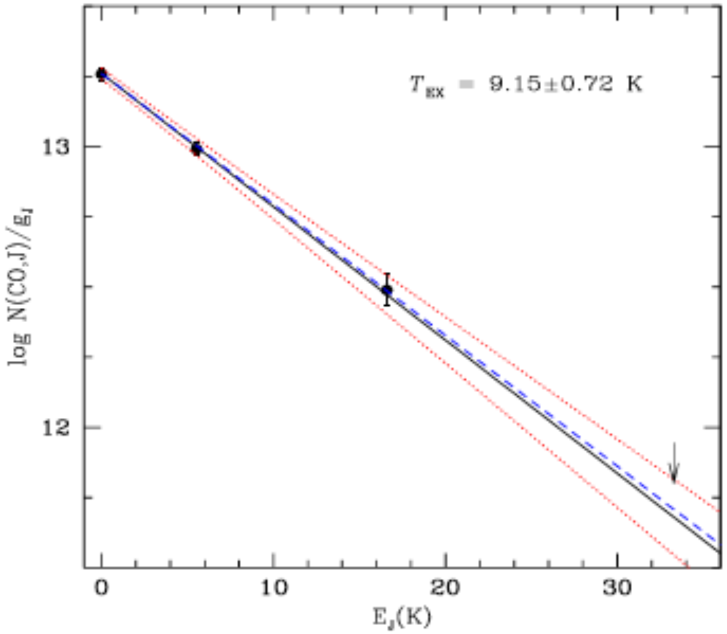


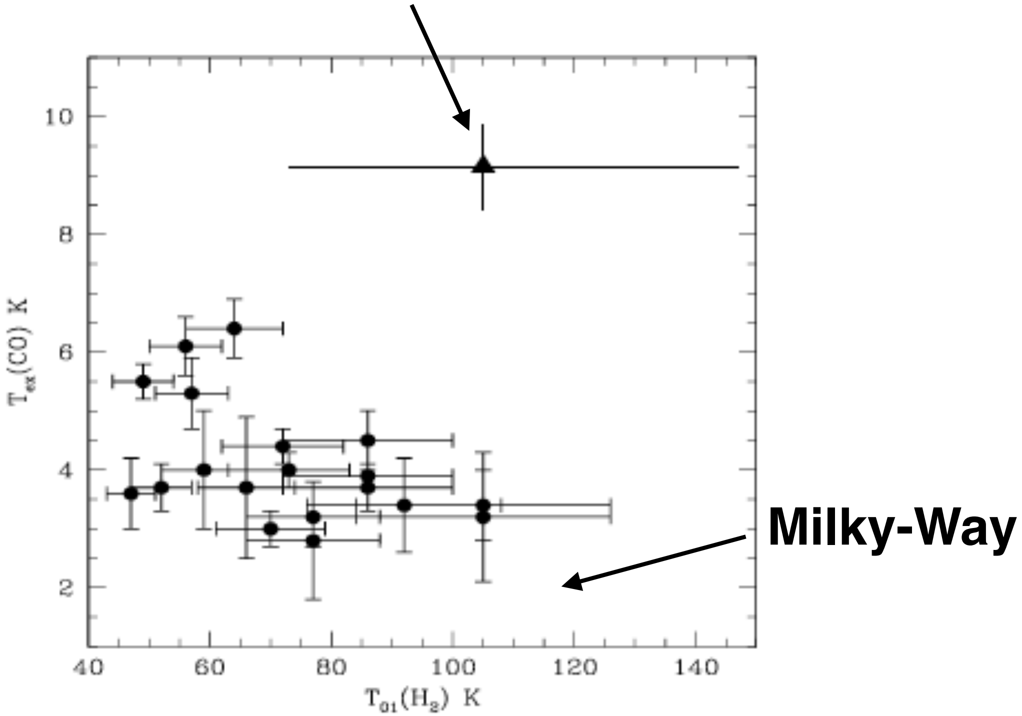
**non** detection in the system with the highest $H_2$
but [Zn/H] =-1.5 (Balashev et al 2017)

$X_{CO}$ conversion factor: CO-$H_2$ is not known

# $T_{exc}$

Srianand et al 2008




**J1439+1117, $z_{abs}$=2.418**

**Milky-Way**

provides a good measure of the $T_{CMB}$ energy between J and (J-1): $E_J = 5.54\,J$ K

$$T_r = 2.725(1 + z)$$

Excitation of atomic or molecular lines with transition energies ~ K $T_{CMB}$ ( z ) can be excited by $T_{CMB}$

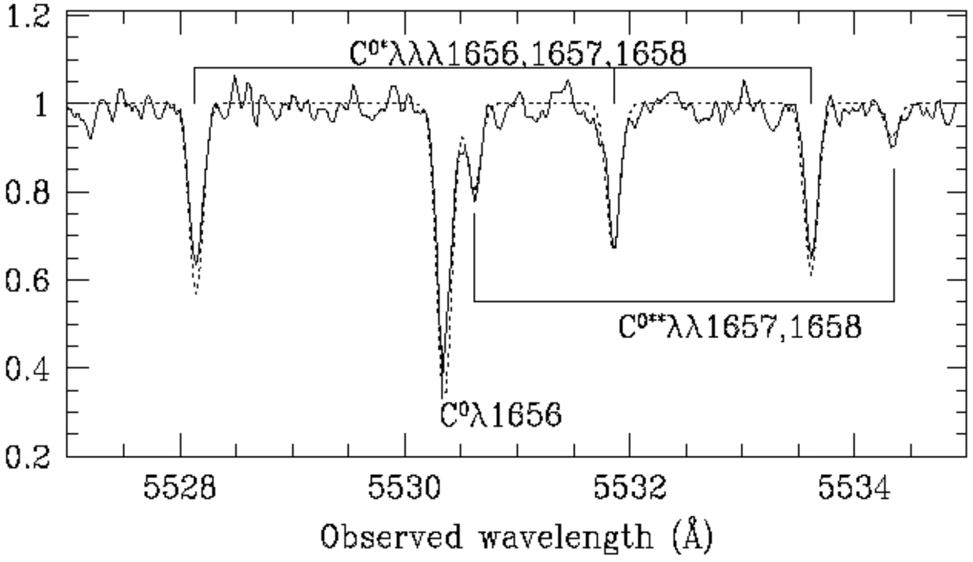
# CI* CII*

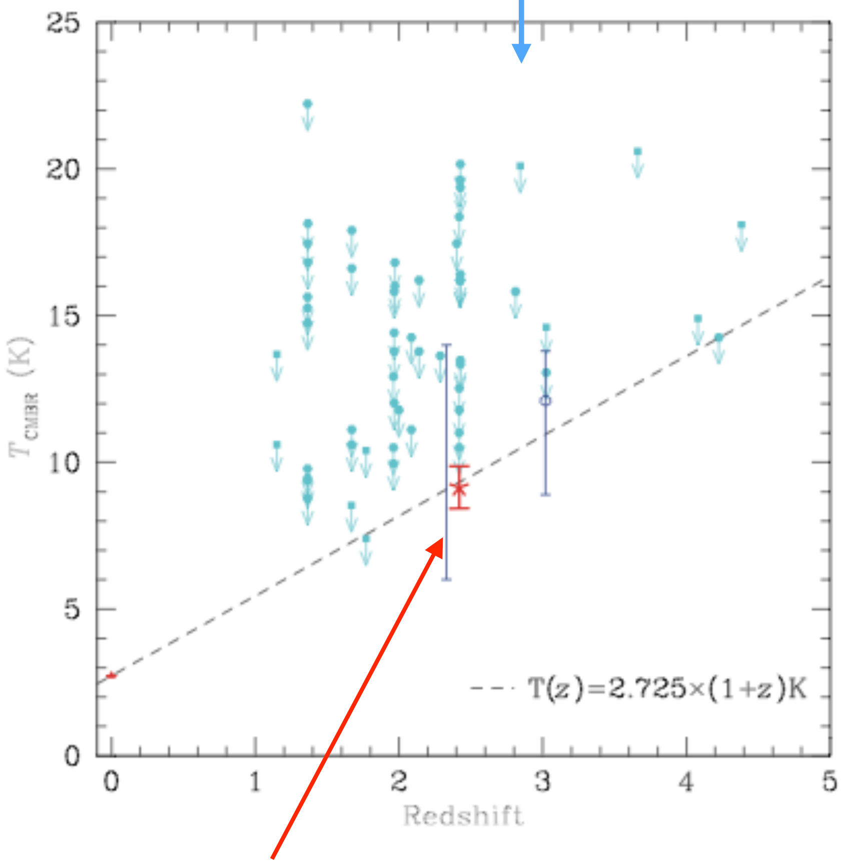
The population of fine-structure levels of the ground state of C I* or C II* depends mainly on (Bachall Wolfe 1968):

- Collisional excitation
- CMB radiation

Ignoring the collisional excitation => upper limits to TCMB.

Songaila et al (1994)
at z=1.776 measured < 8.2 K.



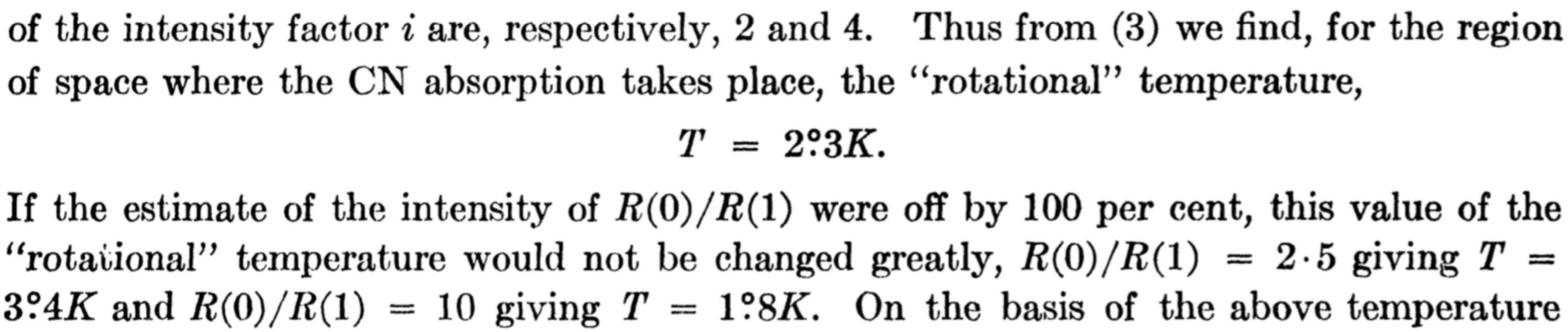


CI* CII*

Srianand et al 2008 on CO

# McKellar 1941

A. McKellar, *Molecular Lines from the Lowest States of Diatomic Molecules Composed of Atoms Probably Present in Interstellar Space*, in *Publications of the Dominion Astrophysical Observatory (Victoria, BC)*, vol. 7, 1941, pp. 251–272.



of the intensity factor $i$ are, respectively, 2 and 4. Thus from (3) we find, for the region of space where the CN absorption takes place, the "rotational" temperature,

$$T = 2^{\circ}\!.3K.$$

If the estimate of the intensity of $R(0)/R(1)$ were off by 100 per cent, this value of the "rotational" temperature would not be changed greatly, $R(0)/R(1) = 2\cdot 5$ giving $T = 3^{\circ}\!.4K$ and $R(0)/R(1) = 10$ giving $T = 1^{\circ}\!.8K$. On the basis of the above temperature

CN Molecules:

- CN, used in the Galaxy (Meyer &Jura 1985, Ritchey et al 2010.
- However, CN not yet detected in external galaxies

# CI* CII* + H2

$H_2$ provides simultaneous determination of **local density**, kinetic temperature and UV radiation, thus allowing to estimate the level of collisional excitation of CI* and CII*

Srianand et al. 2001 PKS 1232+0815, $z_{abs}$=2.3377

$T_{CMB}$ = 10 ± 4 K
$T_{CMB}(z)$ = 9 K

Molaro et al 2002 Q 0347-381 $z_{abs}$=3.0

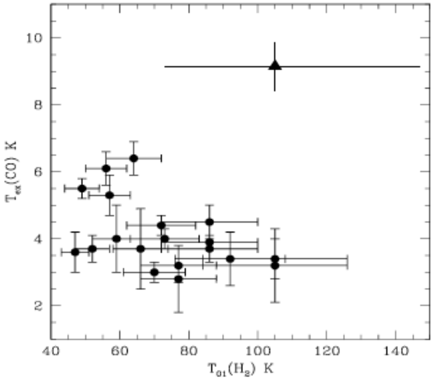
$T_{CMB}$=12.1(+1.7,-3.2) K
$T_{CMB}(z)$ = 10.5 K

Cui et al (2005) QSO 1331+170 $z_{abs}$=1.77

$T_{CMB}$= 7.2 ± 0.8 K
T(z) = 7.566 K

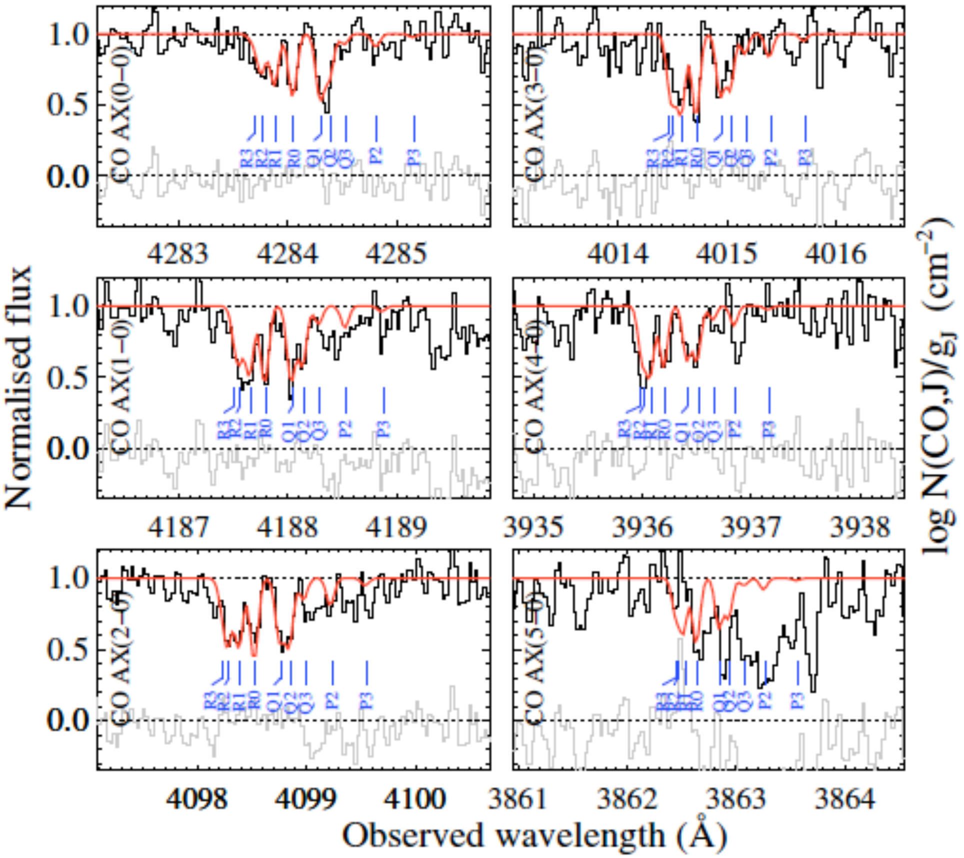
# CO

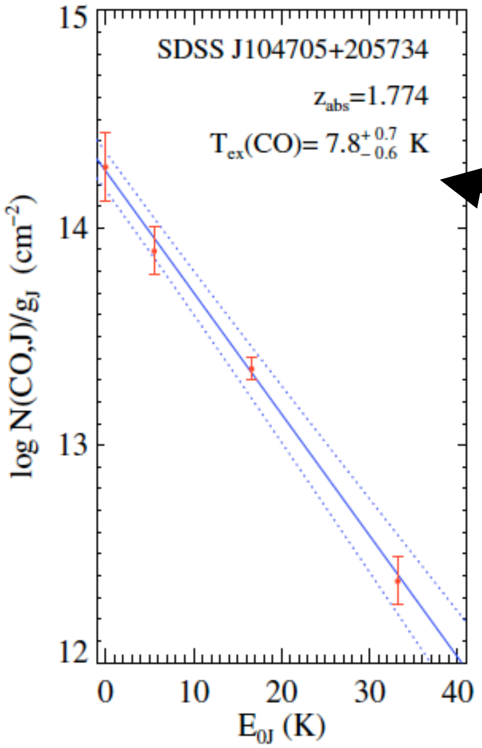
CO levels depend "*uniquely*" from CMB photons



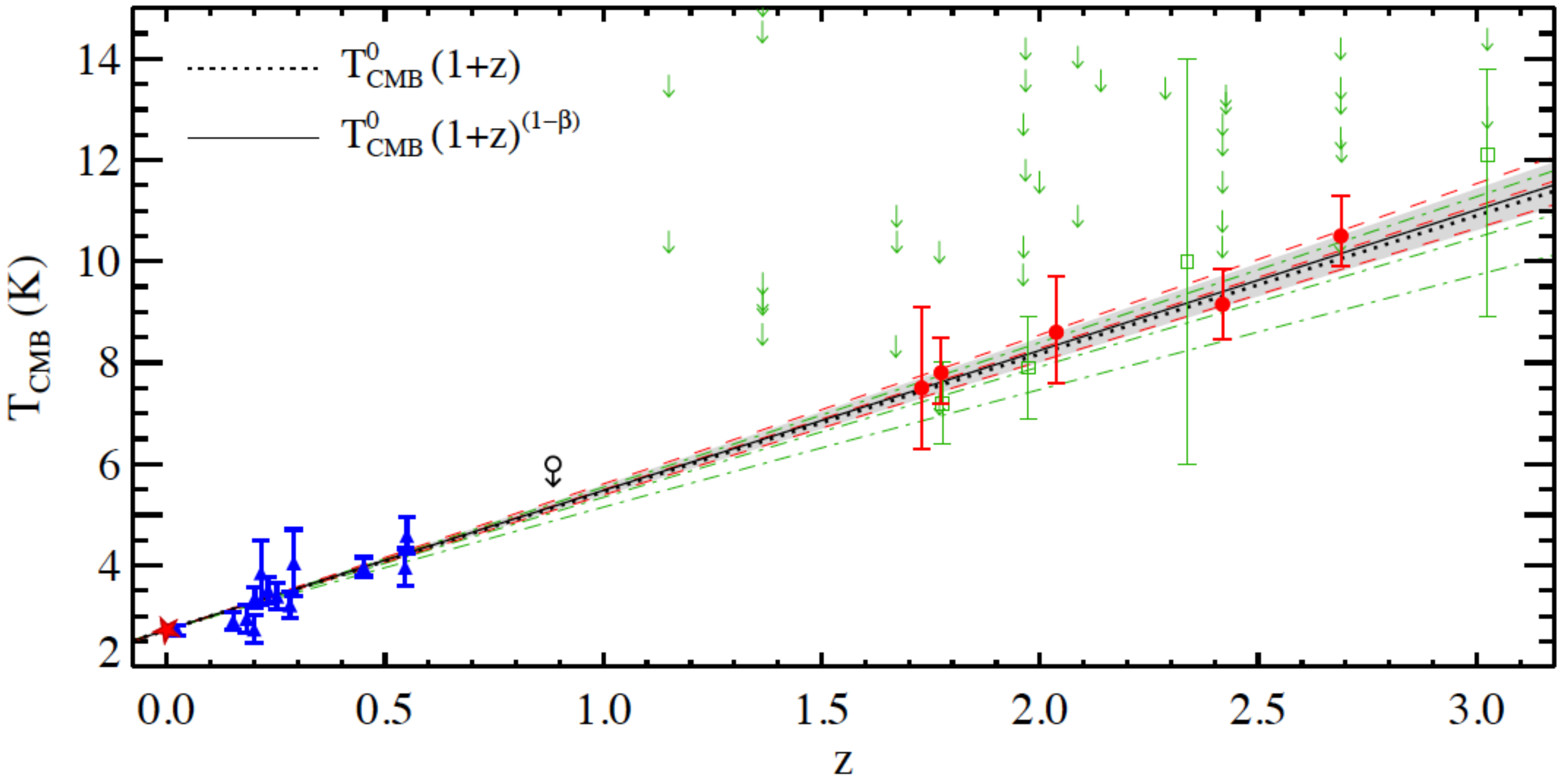
AX(0-0)-AX(4-0) band

Srianand et al 2008,
Noterdaeme et al 2010,2011





Noterdaeme et al 2011



$$T_{\rm CMB}(z) = (2.726 \pm 0.001) \times (1+z)^{1-\beta}\ {\rm K}$$

Constraint to non adiabatic expansion (.e. decaying D

| Data set | $\beta$ |
|---|---|
| S-Z | $+0.040 \pm 0.079$ |
| S-Z + atom. carbon | $+0.029 \pm 0.053$ |
| S-Z + CO | $-0.012 \pm 0.029$ |
| S-Z + atom. carbon + CO | $-0.007 \pm 0.027$ |

# CO theory

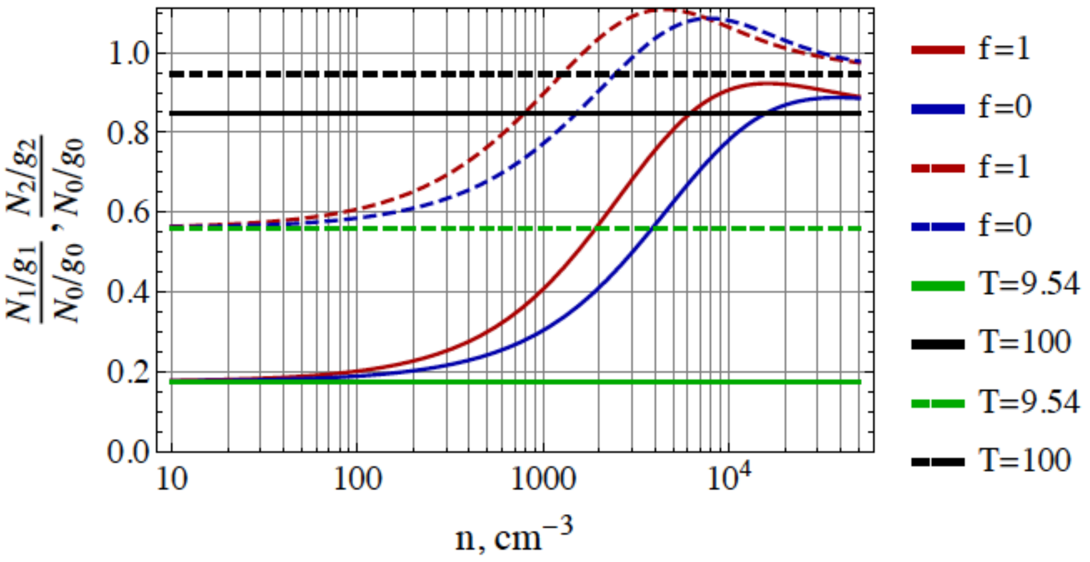
Sobolev et al 2015

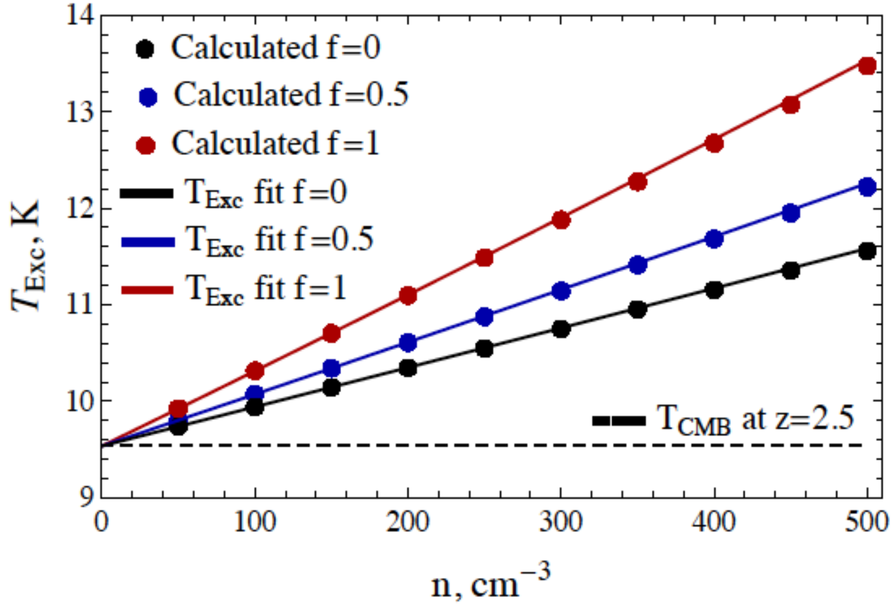
relative populations of CO levels function of: $T_{CMB}$, $T_{Kin}$, $n$, $f(H_2)$

$$W_{ij}^{\mathrm{tot}}(T_{\mathrm{CMB}}, T_{\mathrm{Kin}}, n, f) = \left\{ \frac{f}{2} \left[ \alpha_{para}(T_{\mathrm{Kin}}) W_{ij}^{H_{2para}}(T_{\mathrm{Kin}}) + (1 - \alpha_{para}(T_{\mathrm{Kin}})) W_{ij}^{H_{2ortho}}(T_{\mathrm{Kin}}) \right] \right.$$
$$\left. + (1 - f) W_{ij}^{H}(T_{\mathrm{Kin}}) + 0.083 \cdot W_{ij}^{He}(T_{\mathrm{Kin}}) \right\} \frac{n}{1.083 - f/2} + W_{ij}^{CMB}(T_{\mathrm{CMB}})$$

collisions with **$H_2$**, **H**

for $T_{kin}$=100 K

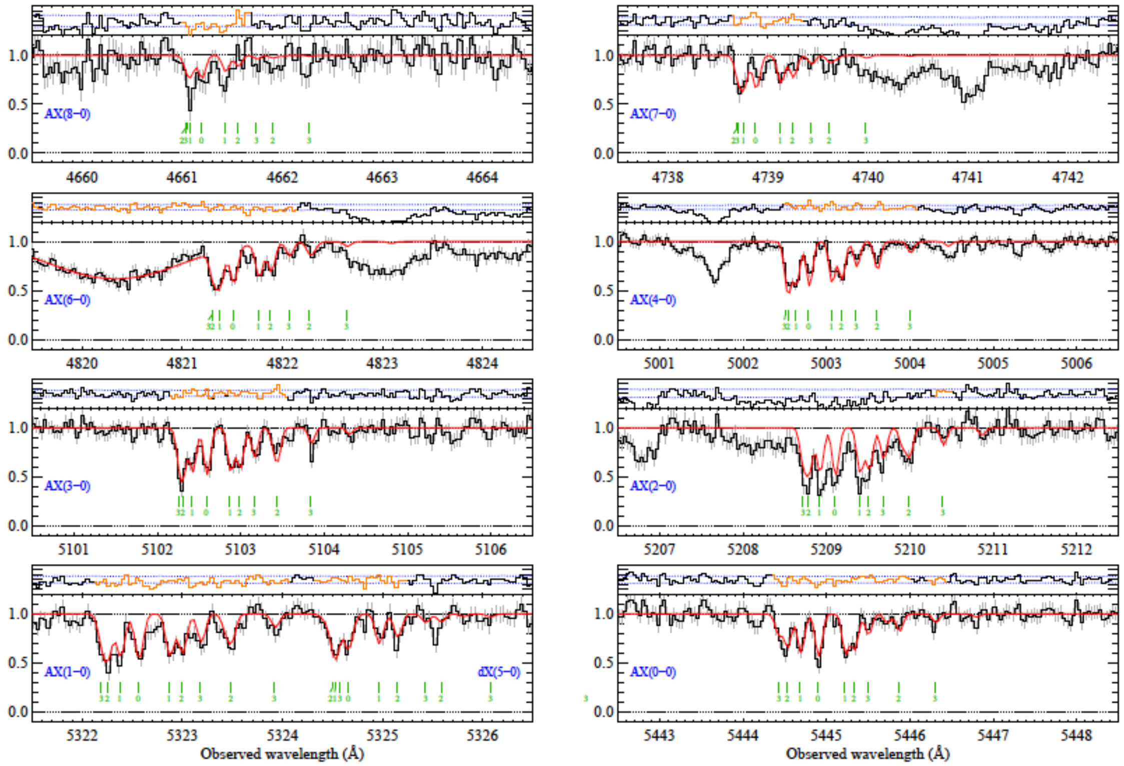


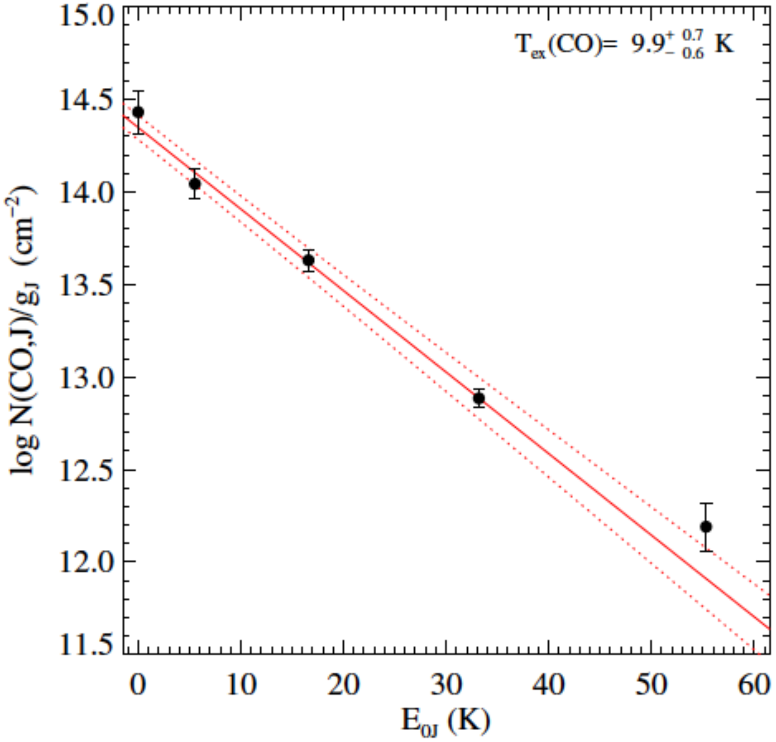


precision of a fraction of degree difficult to obtain at high z

# supersolar metallicity

Noterdaeme et al 2017





$f(H_2)=0.5$
$n_h = 50$ cm$^{-3}$
$T_{kin}=50$

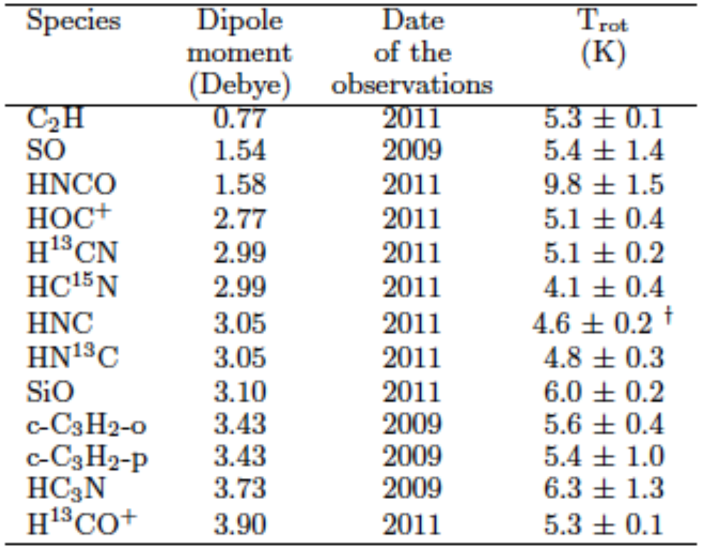
9.9 - 0.3 K=> 9.6 K

correction using the Sobolev 2015 formula

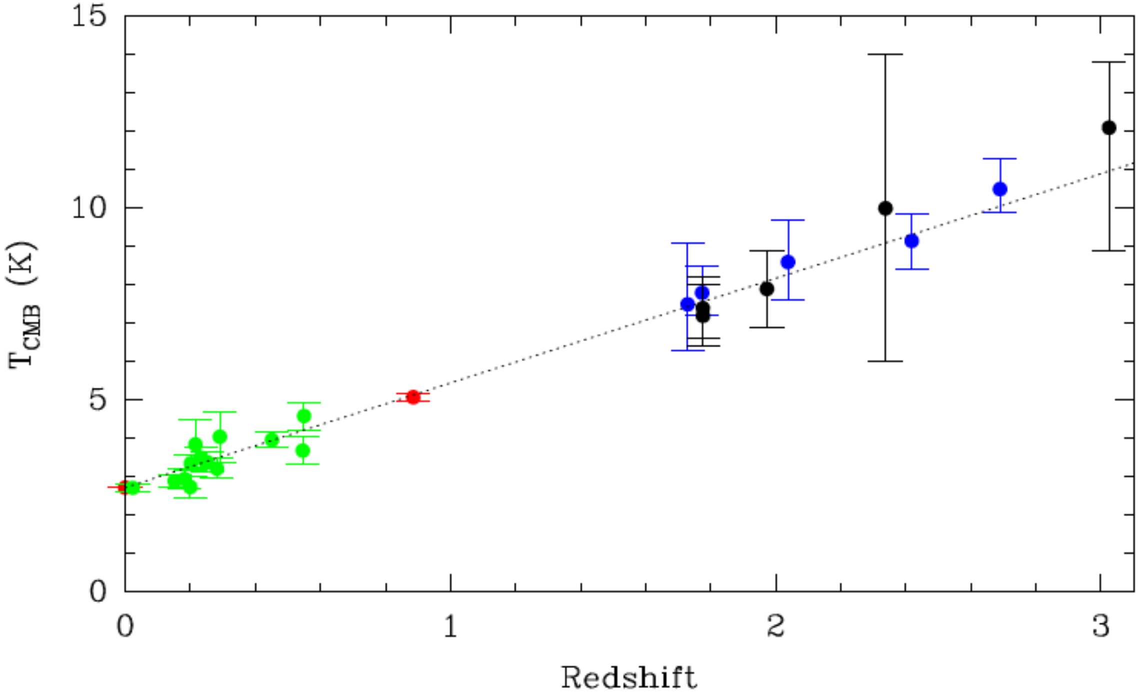
Muller et al 2013

PKS 1830-211

z~0.89, ATCA obs



| Species | Dipole moment (Debye) | Date of the observations | $T_{rot}$ (K) |
|---|---|---|---|
| $C_2H$ | 0.77 | 2011 | 5.3 ± 0.1 |
| SO | 1.54 | 2009 | 5.4 ± 1.4 |
| HNCO | 1.58 | 2011 | 9.8 ± 1.5 |
| $HOC^+$ | 2.77 | 2011 | 5.1 ± 0.4 |
| $H^{13}CN$ | 2.99 | 2011 | 5.1 ± 0.2 |
| $HC^{15}N$ | 2.99 | 2011 | 4.1 ± 0.4 |
| HNC | 3.05 | 2011 | 4.6 ± 0.2 † |
| $HN^{13}C$ | 3.05 | 2011 | 4.8 ± 0.3 |
| SiO | 3.10 | 2011 | 6.0 ± 0.2 |
| $c\text{-}C_3H_2\text{-}o$ | 3.43 | 2009 | 5.6 ± 0.4 |
| $c\text{-}C_3H_2\text{-}p$ | 3.43 | 2009 | 5.4 ± 1.0 |
| $HC_3N$ | 3.73 | 2009 | 6.3 ± 1.3 |
| $H^{13}CO^+$ | 3.90 | 2011 | 5.3 ± 0.1 |



$T_{CMB}$ = 5 **± 0.1** K

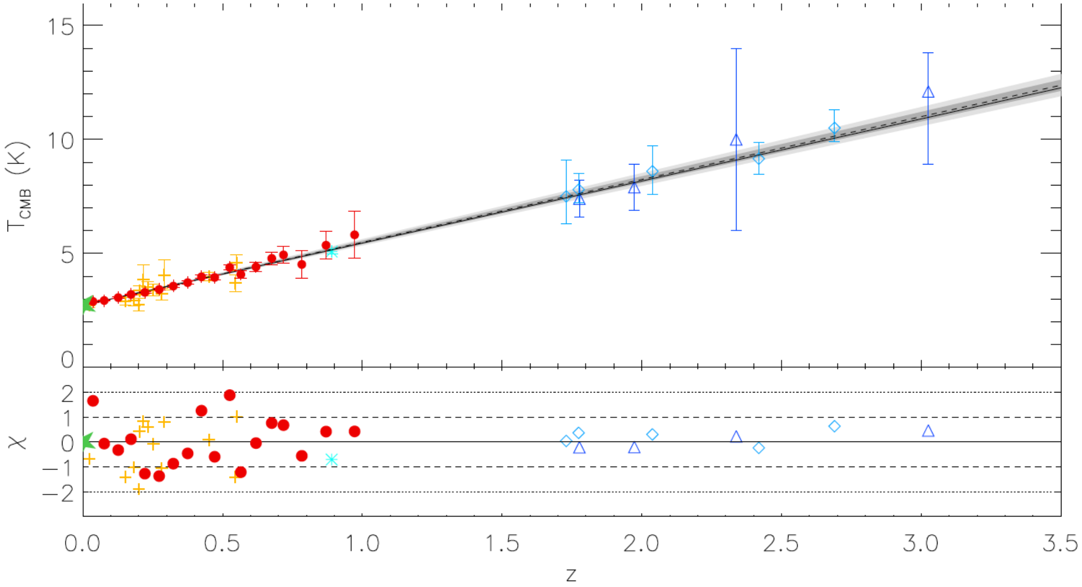
The most precise measure ever

# t-SZ

Sunyaev-Zeldovich (S-Z) effect: change in the spectral energy of the CMB towards clusters owing to inverse Compton scattering of the CMB photons by hot intra cluster gas.

Useful for z<0.6 (Fabbri et al 1978, Luzzi et al 2009)

## t-SZ from Planck Hurier et al 2014

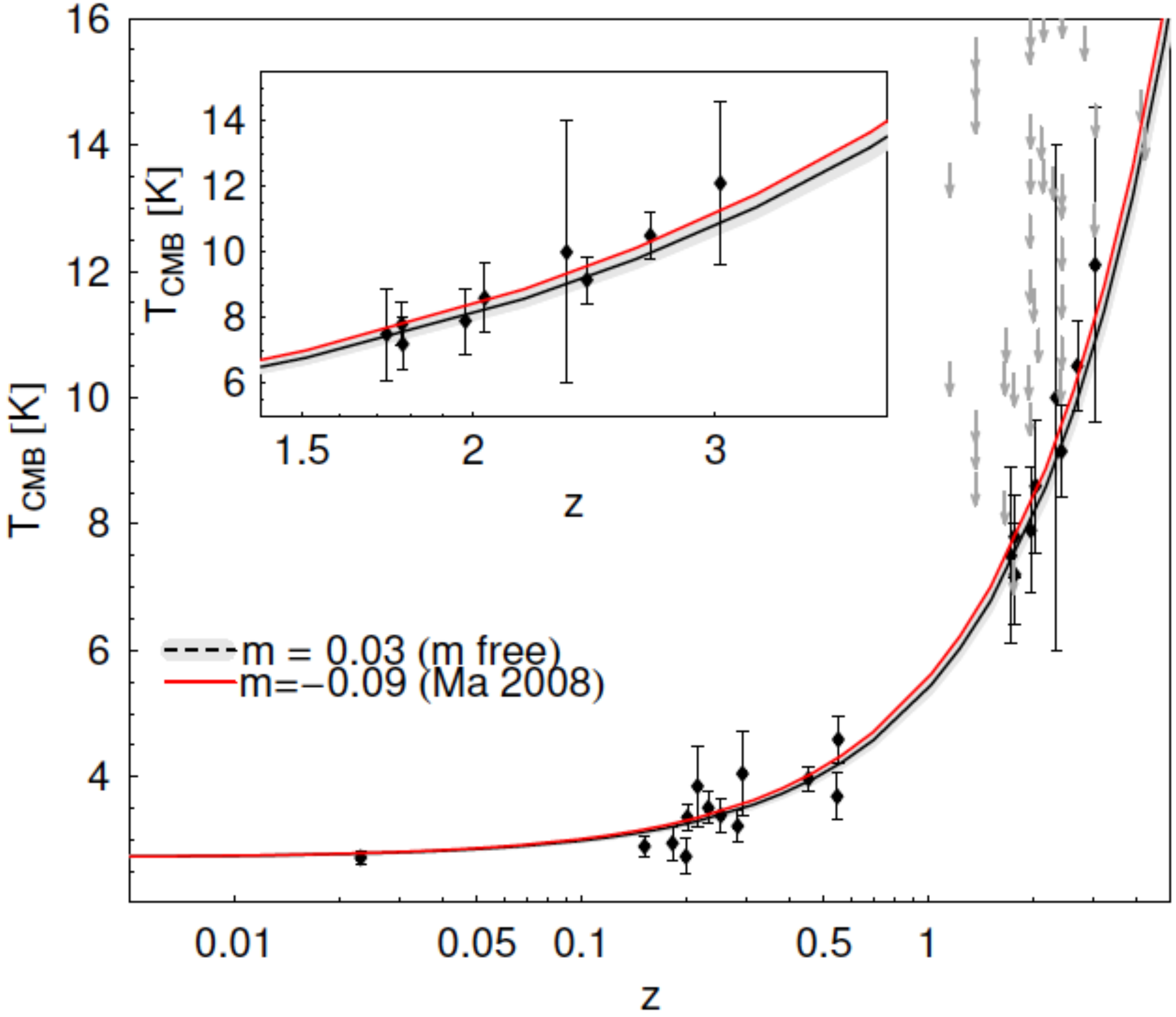


$\beta = 0.006 \pm 0.013.$ ~ 1% DT/T

also Saro et al 2014 using the South Pole Telescope

# Decaying Dark Energy

Ma 2008;
Jetzer et al 2011,2012



# summary:

DLA useful for:

- account of the neutral gas in the universe
- precise chemistry of 90% (up to z~ 5) of the universe
- universal chemical evolution
- smoking gun of the first stars
- nucleosynthesis of elements: nitrogen, carbon
- measure $D_p$ and the baryonic component at few % level
- probe the variability of alpha and $m_e/m_p$
- measure $T_{CMB}(z)$

# Thank You

and special thanks to:

Elsa,

Miguel

Catarina

Miguel

Carlos

et al

# Thank You

and special thanks to:
Elsa,
Miguel
Catarina
Manuel
Carlos
et al