An HST/COS survey of H_2 in DLAs & sub-DLAs at z <1

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Motivations

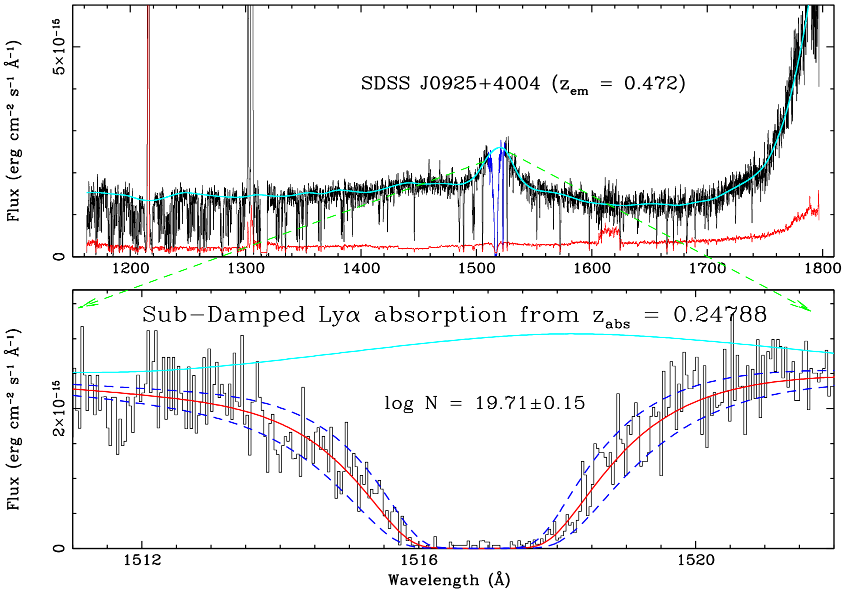
- Cold gas is important – raw materials for star-formation!!
- **Molecular hydrogen (H_2) is a sensitive tracer of cold gas**

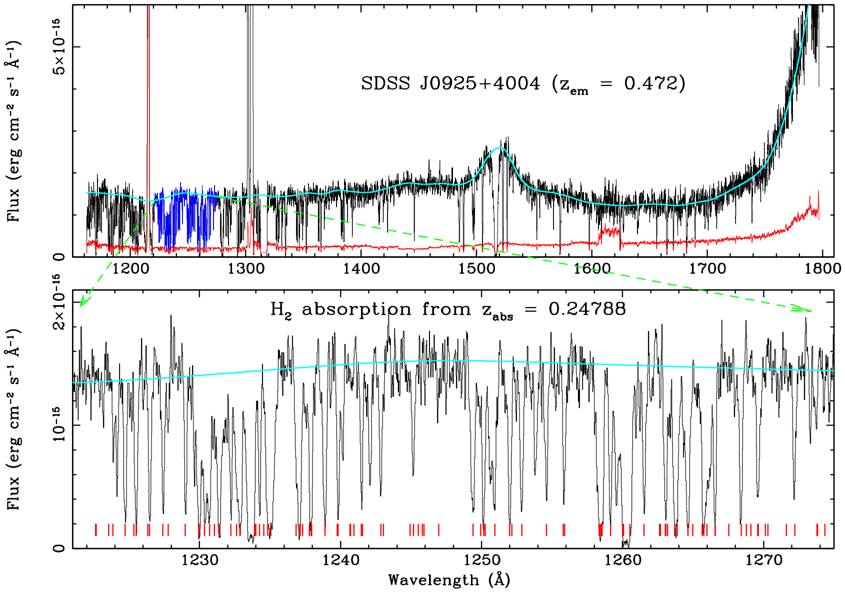
Role of the HST/COS

- Unprecedented FUV sensitivity of COS: large number of QSO spectra in the archive
- Spectral coverage 1150 – 1800 Å: allows us to study H_2 below the atmospheric cutoff

Our study

- We have searched nearly 400 archival HST/COS spectra (before March 2014)
- Built the first-ever sample of H_2 systems at $z < 1$ (Muzahid+15, MNRAS, 448, 2840)
- Only 3 H_2 systems were known before (Crighton+13, Oliveira+14, Srianand+14)


SDSS J0925+4004 (z_{em} = 0.472)
Flux (erg cm^{-2} s^{-1} Å^{-1})
5×10^{-15}
0
1200
1300
1400
1500
1600
1700
1800
Sub−Damped Lyα absorption from z_{abs} = 0.24788
log N = 19.71±0.15
Flux (erg cm^{-2} s^{-1} Å^{-1})
2×10^{-15}
0
1512
1516
1520
Wavelength (Å)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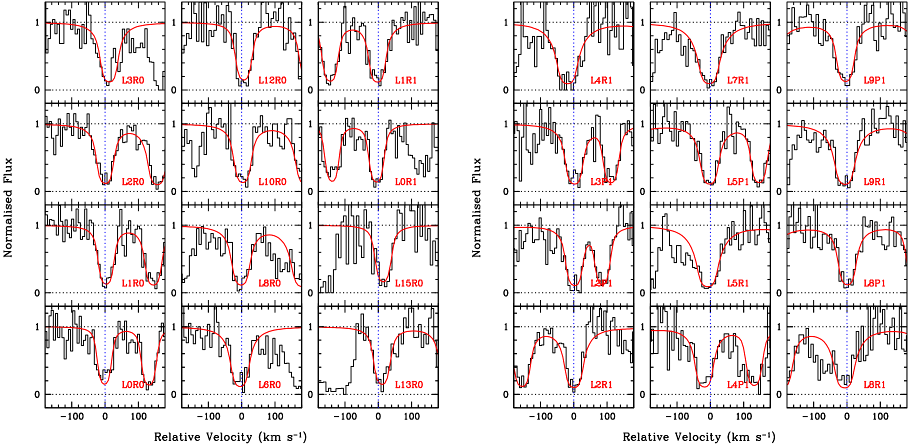
5×10^{-15}
0
1200
1300
1400
1500
1600
1700
1800
2×10^{-15}
10^{-15}
0
1230
1240
1250
1260
1270
Wavelength (Å)

H_2 AT LOW-Z: MEASUREMENTS

⊛ H_2 absorption from $z_{abs} = 0.24788$ system towards SDSS J0925+4004 ⊛

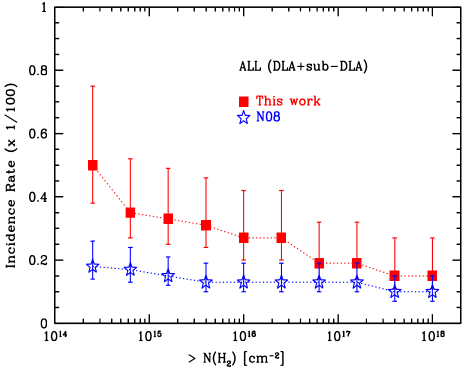


- We identify each absorption line originating from different rotational (J) levels
- Perform Voigt profile fits for all the identified unblended lines simultaneously
  - This gives best fitting H_2 column densities for different J levels

H_2 at low-z: Detection Rate

- 10 out of 27 DLAs/sub-DLAs at low redshift show H_2 absorption
- 3/5 DLAs (log N(H I) > 20.3) and 7/22 sub-DLAs show H_2

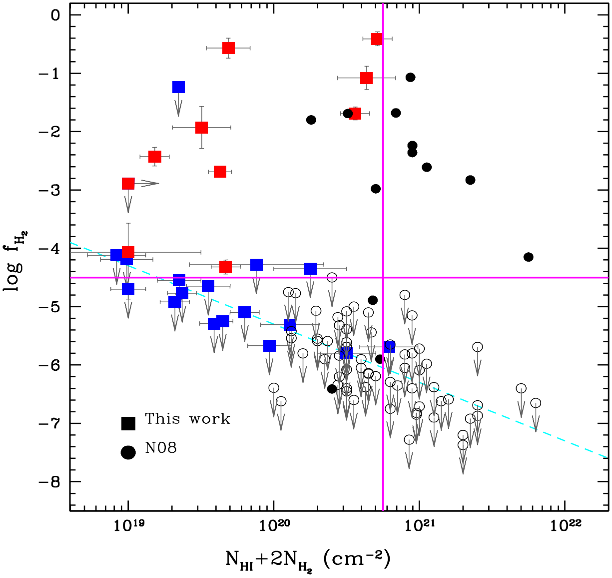
- 13 out of 77 DLAs/sub-DLAs at high redshift ($z > 1.8$) show H_2 (Noterdaeme+08, N08)



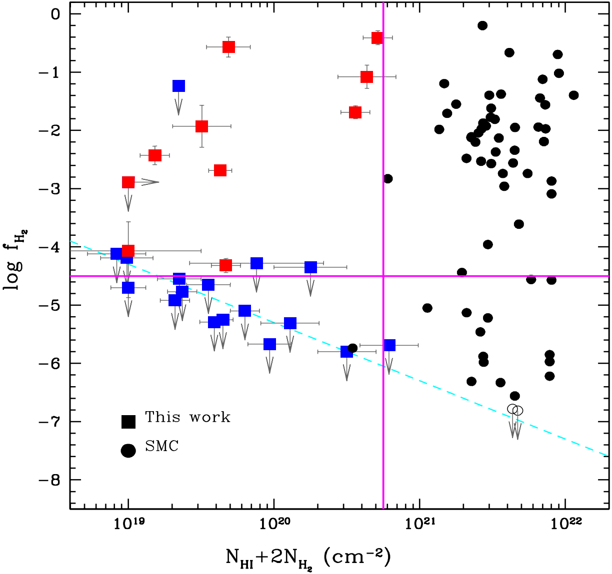
★ **For log N(H_2)>14.4, D.R(low-z) = 50^{+25}_{-12} % and D.R(high-z) = 18^{+8}_{-4} %**

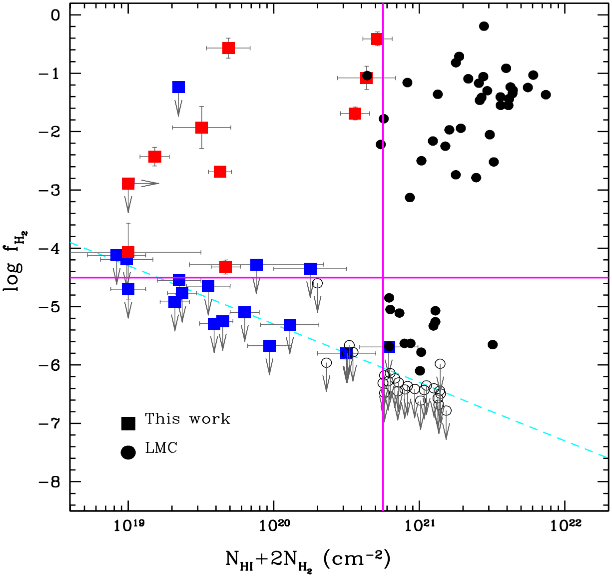
★ **Detection rate is $\geqslant 2$ times higher at low-z (at $\sim 2\sigma$ level)**

H_2 at low-z: $N_H - f_{H_2}$ (Low-z and High-z)



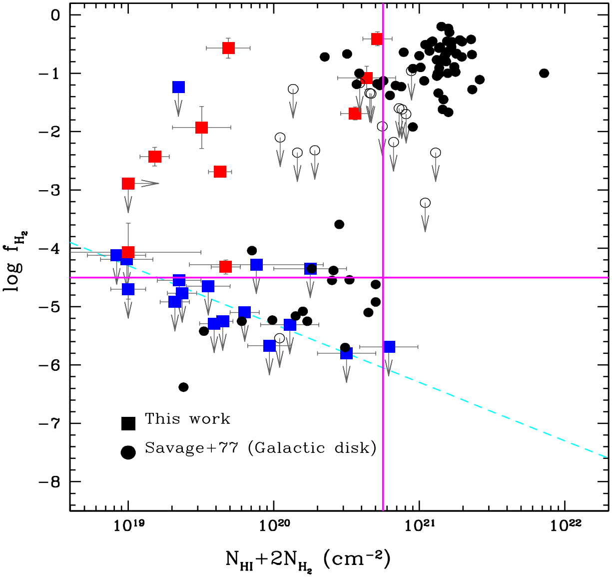
H_2 AT LOW-Z: $N_H - f_{H_2}$ (LOW-Z AND SMC)



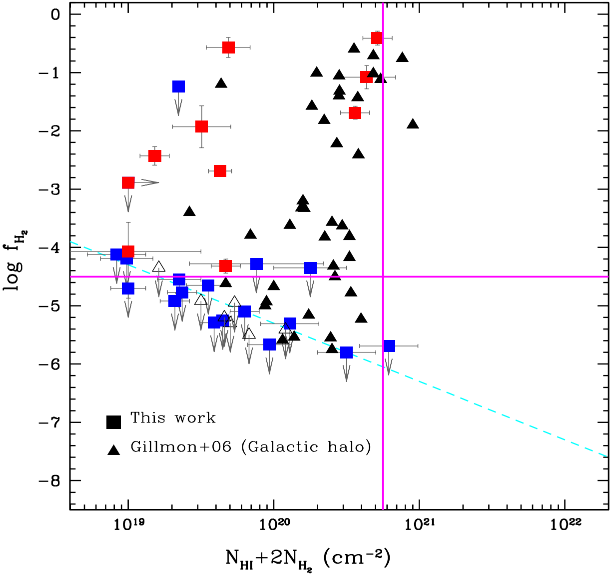


0
−1
−2
−3
−4
−5
−6
−7
−8
log f_{H_2}
10^{19}
10^{20}
10^{21}
10^{22}
$N_{HI}+2N_{H_2}$ (cm^{-2})
This work
LMC

H_2 at low-z: $N_H - f_{H_2}$ (Low-z and MW Disk)



H_2 at low-z: $N_H - f_{H_2}$ (Low-z and MW Halo)



H_2 at low-z: $N_H - f_{H_2}$ (Low-z and MW Halo)

★ **Origin(s)/physical conditions of molecular gas in low-z DLAs/sub-DLAs are similar to that of the Milky Way halo gas!(?)**

★ **Even with systematically lower N_H values, most of our low-z systems show a considerably large molecular fraction**
$\Longrightarrow$ **Very high density?**
$\Longrightarrow$ **Weak radiation field?**

$N_{HI}+2N_{H_2}$ (cm^{-2})

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$\Longrightarrow$ **Very high density?**
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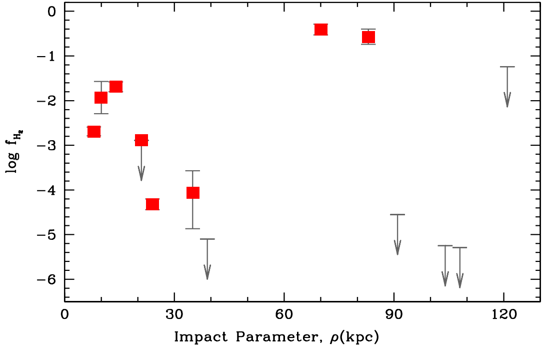
★ **Density cannot be much higher than $\sim$ 10 - 100 cm^{-3}**
$\Longrightarrow$ **Absence of HD/CO and C I* and C II***

★ **Using Photoionization models we found that:**
$\Longrightarrow$ **The radiation field prevailing in the low-z H_2 systems cannot have an appreciable stellar contributions for densities of $\sim$ 10 - 100 cm^{-3}**
$\Longrightarrow$ **Absence of $J \geqslant 4$ transitions of H_2 also strongly suggests that**

★ **H_2 bearing gas must be located away from SF disks** ★

$N_{HI}+2N_{H_2}$ (cm^{-2})

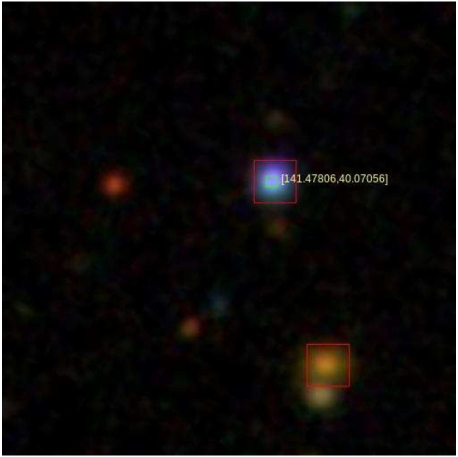


- **Impact parameter are typically large ($\rho > 10$ kpc)**
- **Presence of molecular gas at large ρ (> 20 kpc) is intriguing**

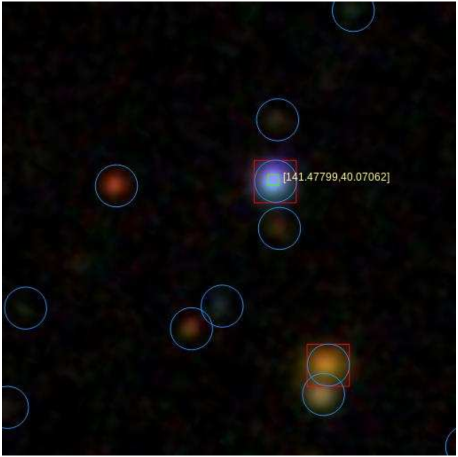
$\Longrightarrow$ **molecular gas is probably located in the extended halo of the host-galaxy**

$\Longrightarrow$ **Faint dwarf galaxies at lower ρ??**

★ Deep imaging is essential ★



- **SDSS image of J0925+4004 field**
- $\rho = 83$ **kpc, SFRH**$\alpha < 0.57$ $M_\odot$ **yr**$^{-1}$**, L = 1.5L**$_*$ **"COS-Halos" (Werk+12)**
- **log N(H I) = 19.7, log N(**H_2**) = 18.8, log** $f_{H_2} = -0.7$**,** $T_{01} = 156$ **K**



- **Two galaxies at the same redshift! ($\rho = 92$ kpc, SFR(Hα) $= 0.86$ M$_\odot$ yr^{-1})**

$\Longrightarrow$ Single galaxy or Group??

- **Two faint photometric objects at 5" ($\rho < 20$ kpc)**

Take-home Messages!

- **H_2 is detected in half of the DLAs/sub-DLAs at low-z with log $N(H_2) > 14.4$**
- **They trace diffuse atomic/molecular gas with density $\sim 10 - 100$ cm^{-2}**
- **The prevailing radiation field can't have a considerable stellar contribution**
- **Impact parameters of the candidate host-galaxies are typically large (>10 kpc)**

We conjecture that the low-z H_2 bearing gas is not related to star-forming disks but stems from self-shielded, tidally stripped or ejected disk-material in the extended halo

T H A N K S

???

H_2 at low-z: Higher Detection Rate

- Under equilibrium conditions: $f_{H_2} = \dfrac{2N(H_2)}{N(H\,I) + 2N(H_2)} = \dfrac{2Rn_{H\,I}}{D}$

$\Longrightarrow$ R (cm^{-3} s^{-1}) is the formation rate coeff. $\propto \kappa \propto Z$
$\Longrightarrow$ D (s^{-1}) is the photo-dissociation rate $\propto$ ionizing radiation

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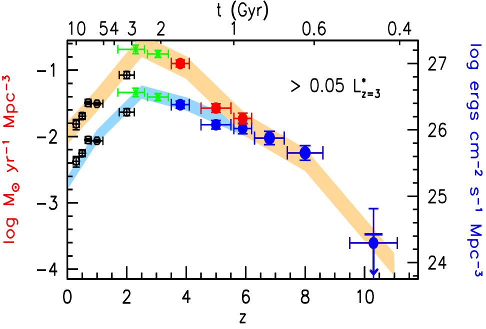
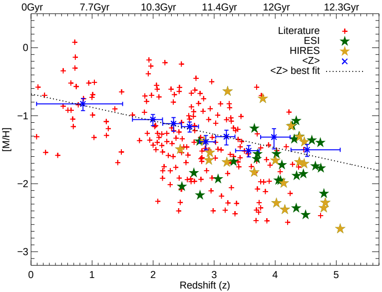
- Ionizing radiation field decreases with time ($z = 3 \rightarrow 0$)
  $\Longrightarrow$ Lower D at low-z, easier to retain molecular phase!

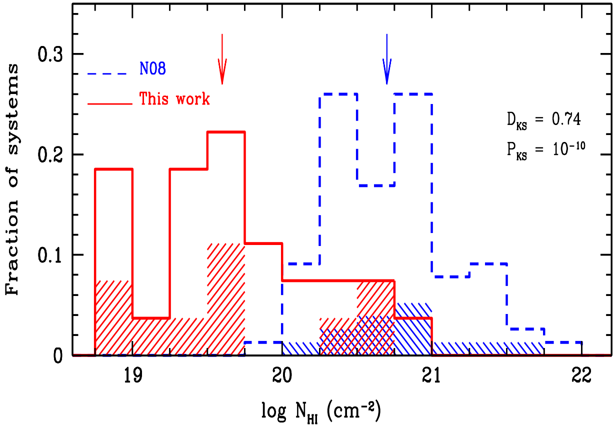
- Probability of finding a metal-rich DLA/sub-DLA at low-z is higher than at high-z
  $\Longrightarrow$ metal-rich DLAs/sub-DLAs are more H_2 prone! (Petitjean+96, N08)



(Bouwens+11)



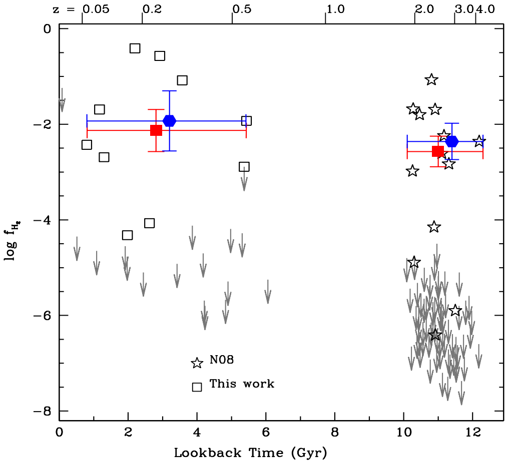
(Rafelski+12)



- **N(H I) distributions of our sample and N08 are significantly different**
- **N(H I) distributions for systems with and without H_2 are not different**
- **There is no preferential N(H I) for H_2 to be detected**
- **There is no significant correlation between N(H I) and N(H_2)**

★ **Search for H_2 in sub-DLAs at high-z and in DLAs at low-z is essential** ★

H_2 at low-z: (non)Evolution of f_{H_2}



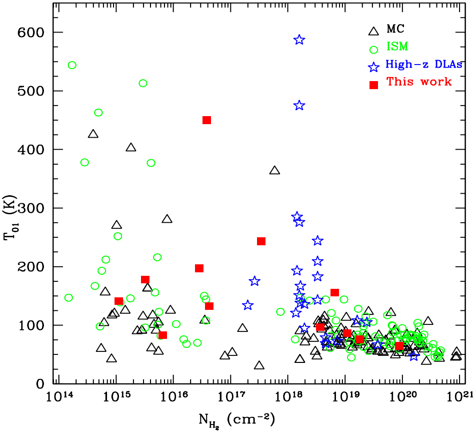
- **Median $f_{H_2} = -1.93 \pm 0.63$, for $\log f_{H_2} > -4.9$, at low-z is consistent with high-z**
- **A mild anti-correlation is suggested by the Kendall's τ test (with limits) ($\tau = -0.27$, 99.99% confidence)**

H_2 AT LOW-Z: THE EXCITATION TEMPERATURE, T_{01}

- Excitation temperature (T_{01}) is defined as:

$$\frac{N(J=1)}{N(J=0)} = \frac{g_1}{g_0}\exp(-170.5/T_{01}) \tag{1}$$

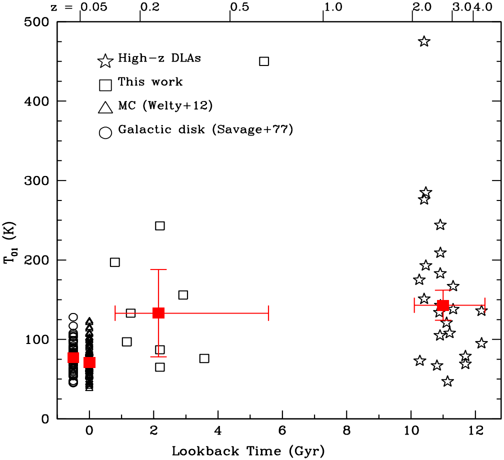
- When H_2 is sufficiently self-shielded, collisional processes dominate the populations of J=1 and J=0 levels, then $T_{01} \equiv T_{KE}$ (Snow+06, Roy+06)

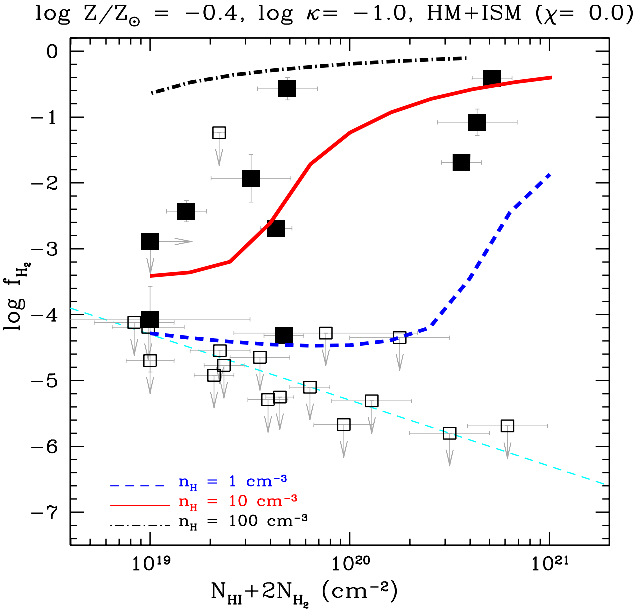


- **Large scatter at lower N(H_2)** • **T_{01} < 120 K for N(H_2) > 3×10^{18} cm^{-2}**

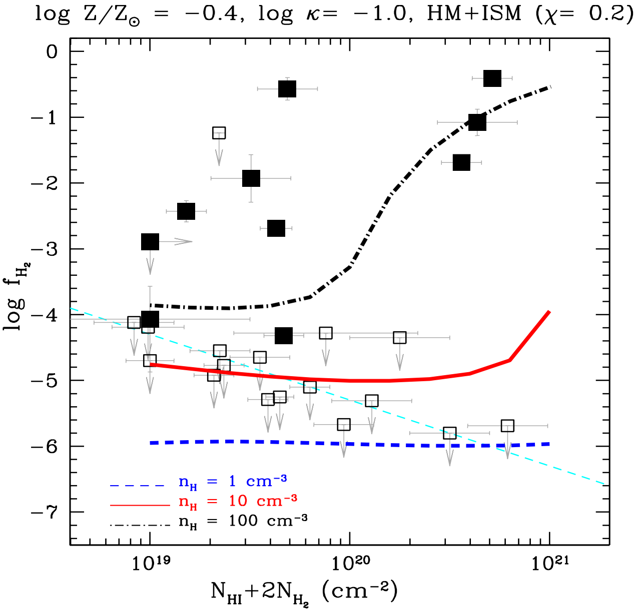
H_2 at low-z: (non)Evolution of T_{01}

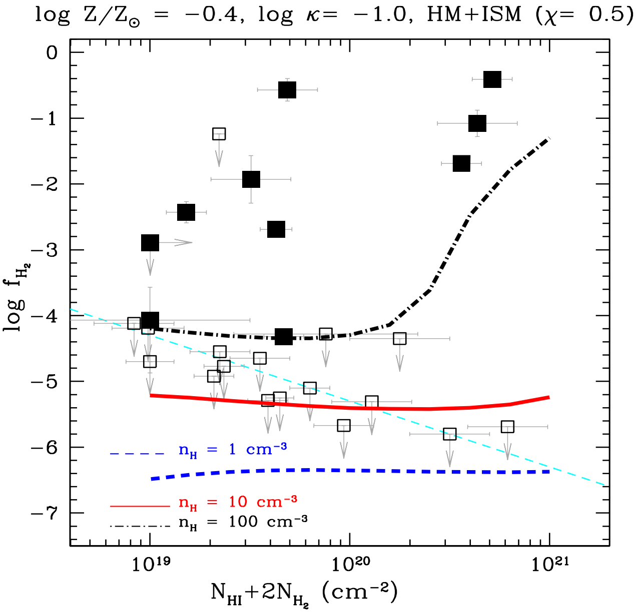
- **Median T_{01} = 133±55 K at low-z for log $N(H_2) > 16.5$**
- **Median T_{01} = 143±19 K at high-z**
- **Median T_{01} ~ 80 K for local measurements**




log Z/Z☉ = −0.4, log κ= −1.0, HM+ISM (χ= 0.0)
log f_H2
N_HI+2N_H2 (cm^-2)
10^19
10^20
10^21
0
−1
−2
−3
−4
−5
−6
−7
n_H = 1 cm^-3
n_H = 10 cm^-3
n_H = 100 cm^-3

H_2 at low-z: Ionization models

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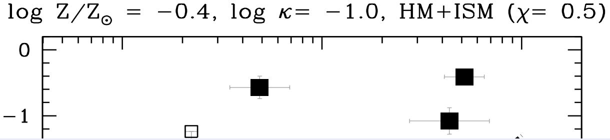

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