THE SPIN TEMPERATURES OF THE GALAXY & HIGH-z DAMPED LYMAN-α SYSTEMS

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Outline

- The HI-21cm spin temperature.
- Galactic HI-21cm absorption studies: An N(HI) threshold for CNM formation ?
- Damped Lyman-α absorbers (DLAs).
- HI-21cm absorption studies of a large sample of DLAs.
- A metallicity – spin temperature anti-correlation in DLAs.

THE HI-21CM SPIN TEMPERATURE

- For HI-21cm absorption studies of compact sources:

$$N(HI) = 1.8 \times 10^{18} \times \int T_s \times \tau_{21} \, dV.$$

$T_s \equiv$ "Spin" temperature: $[n_2/n_1] \propto e^{(-h\nu/kT_s)}$

- N(HI) from Lyman-α absorption or HI-21cm emission.

(e.g. Wakker et al. 2011, ApJ)

- Single cloud ⇨ Infer T_s by measuring $\int \tau_{21} \, dV$.

- Multi-phase medium: Infer $\langle T_s \rangle$, column-density-weighted harmonic mean of T_s in the warm and cold phases.

$T_C \sim 100$ K ⇨ $n_W \sim n_C \sim 0.5$ ⇨ $\langle T_s \rangle \sim 200$ K.

$T_W \sim 8000$ K ⇨ $n_W \sim 0.9, n_C \sim 0.1$ ⇨ $\langle T_s \rangle \sim 1000$ K.

- $\langle T_s \rangle$(Galaxy) ~ 100 – 300 K; $\langle T_s \rangle$(SMC) >~ 450 K.

(e.g. Heiles & Troland 2003, ApJS; Dickey et al. 2000, ApJ)

An N(HI) Threshold for CNM Formation ?

(NK et al. 2011, ApJL)

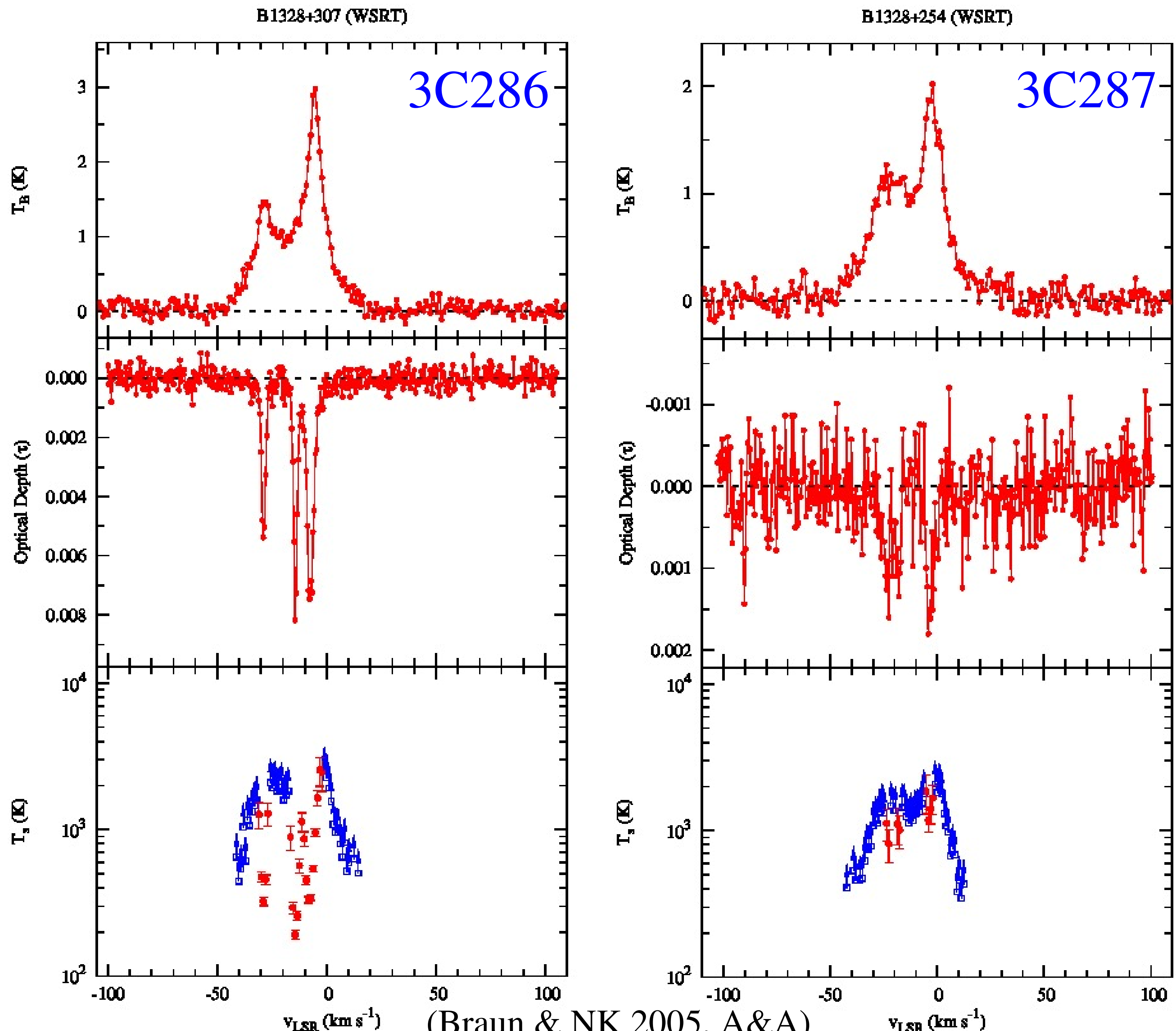
- Interferometric Galactic HI-21cm absorption survey with the ATCA, the GMRT and the WSRT (10 – 24 hours per target).

- Bandpass calibration with frequency-switching every 5m. Two sources observed with WSRT+GMRT to test quality.

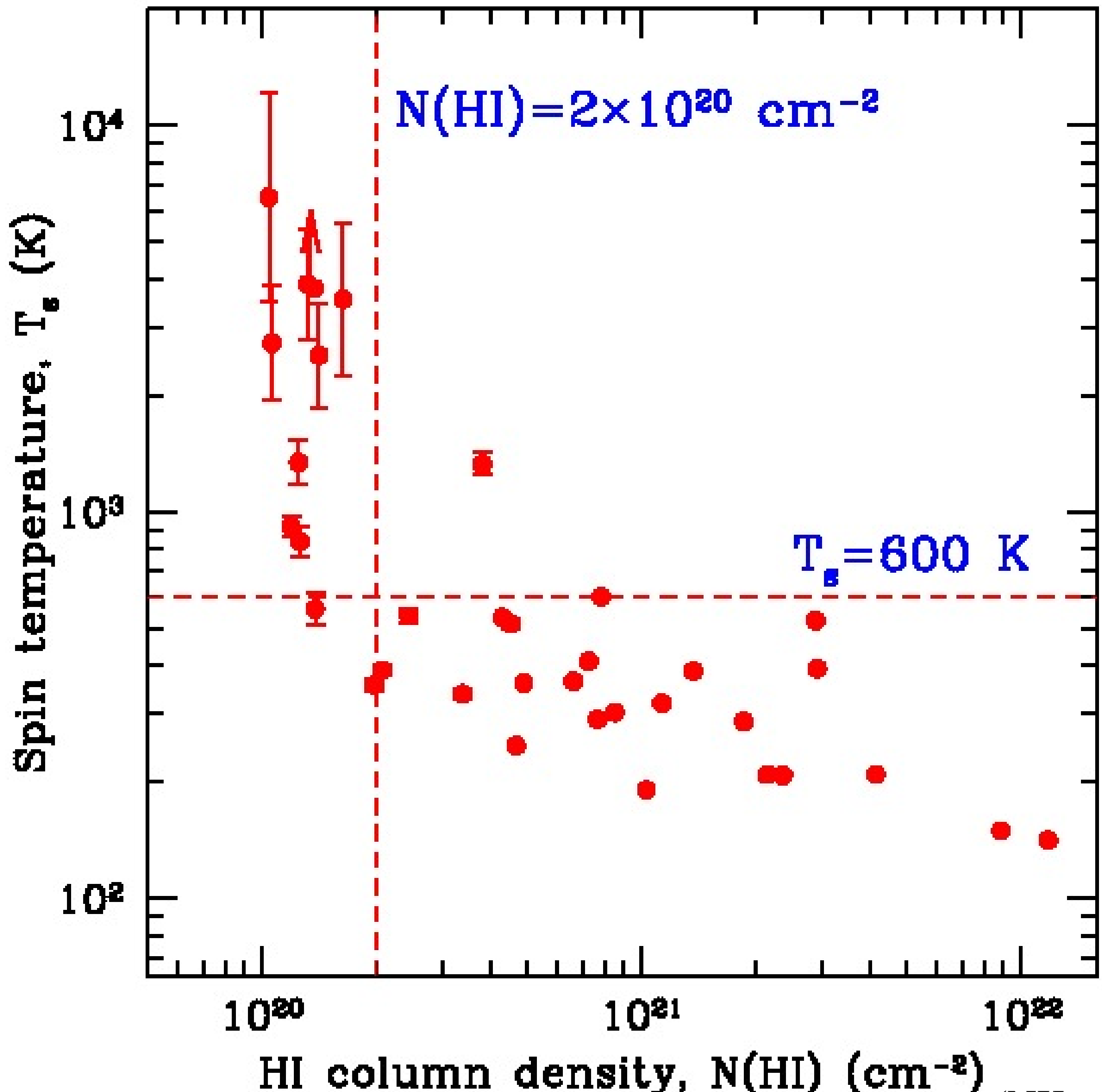
- 34 compact quasars, mostly at Galactic latitude >> 10°. Optical depth sensitivity ~ 0.0003 – 0.001 per 0.3 – 0.5 km/s N(HI) ~ 10^{20} cm^{-2} – 10^{22} cm^{-2} .

- HI-21cm absorption detected against 33 of 34 quasars. N(HI) measured from the LAB HI-21cm emission survey.

(NK et al. 2003, MNRAS-L;
Braun & NK 2005, A&A-L; Roy et al. 2013, in prep.)



(Braun & NK 2005, A&A)



(NK et al. 2011, ApJL)

An N(HI) Threshold for CNM Formation ?

(NK et al. 2011, ApJL)

- Low spin temperatures, ~ 250 K, for N(HI) $\geqslant 2 \times 10^{20}$ cm^{-2}.
- Sightlines with low N(HI) have systematically higher T_s.
  ⇨ Sharp drop in CNM fraction at N(HI) $< 2 \times 10^{20}$ cm^{-2}.
- Inefficient self-shielding against soft X-ray / UV photons ?
- Possibly *four* phase "transitions" in the ISM:

(1) N(HI) ~ 10^{17} cm^{-2} : HII → HI.

(2) N(HI) ~ 2×10^{20} cm^{-2} : Warm HI → Warm + Cold HI.

(3) N(HI) ~ 5×10^{20} cm^{-2} : HI → HI + H_2. (Savage et al. 1977, ApJ)

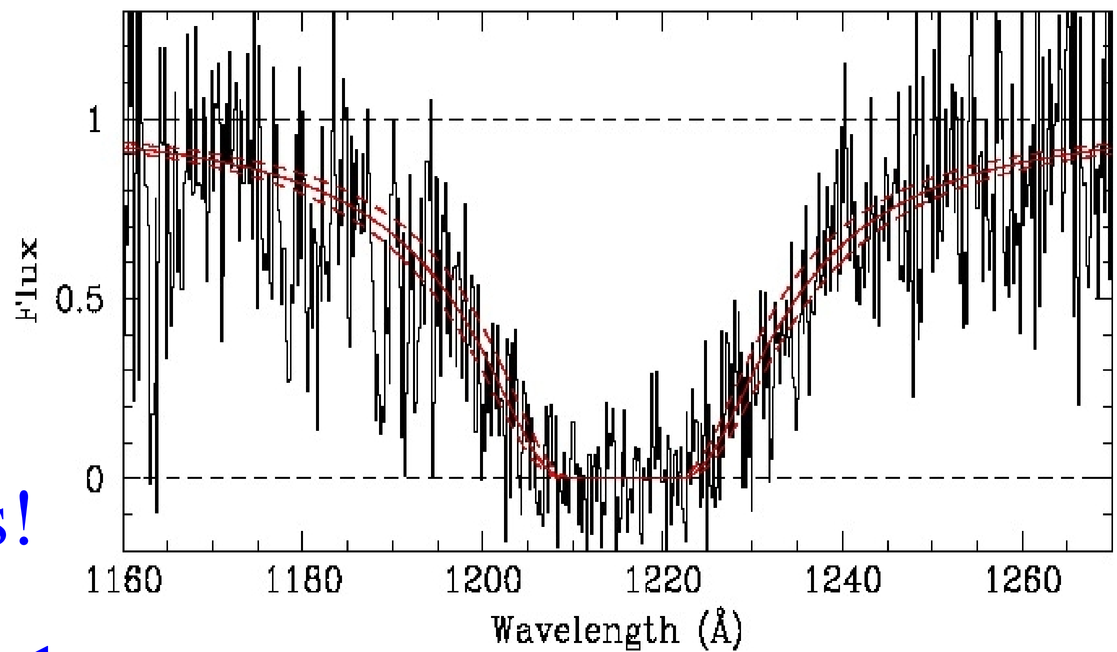
(4) N(HI) ~ 10^{22} cm^{-2} : HI → H_2.

(e.g. Schaye 2001, ApJL; Krumholtz et al. 2009, ApJ;
But see Braun 2012, ApJ)

Damped Lyman-α Systems (DLAs)

(e.g. Wolfe et al. 2005, ARA&A)

- High HI column density, $N(HI) \geq 2 \times 10^{20}$ cm^{-2}.
- Absorption-selected ⇨ No luminosity bias.
- "Normal" gas-rich galaxies!
- Low metallicities, $[Z/H] < -1$.



(Ellison et al. 2012, MNRAS)

- Optical imaging difficult due to the background QSO.

What galaxies are DLAs at different redshifts ?

Typical mass, kinematics, physical conditions ?

- HI-21cm absorption *directly* probes the HI in DLAs!

Note: HI-21cm emission studies near-impossible at high *z*.

HI-21CM ABSORPTION STUDIES OF DLAS

- Until 1998, 3 detections at $z > 0.7$, 4 at $z < 0.7$, few limits.

(e.g. Wolfe & Davies 1979, AJ; Wolfe et al. 1985, ApJL)

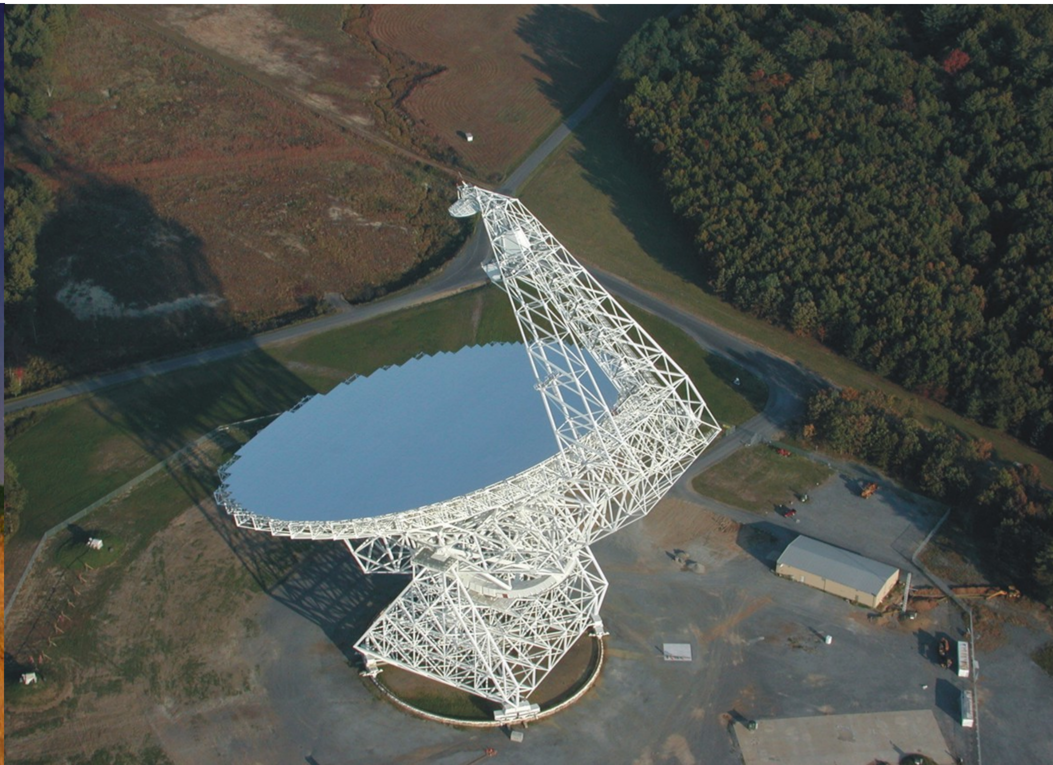
- Reasons: Poor frequency coverage, low sensitivity, RFI !

Giant Metrewave Radio Telescope

30 dishes, 45-m diameter.
$z \sim 0 - 0.6, 1.1 - 1.5, 2.9 - 3.6.$

Green Bank Telescope

110-m dish, $z \sim 0 - 3.6.$



HI-21cm Absorption Searches in DLAs

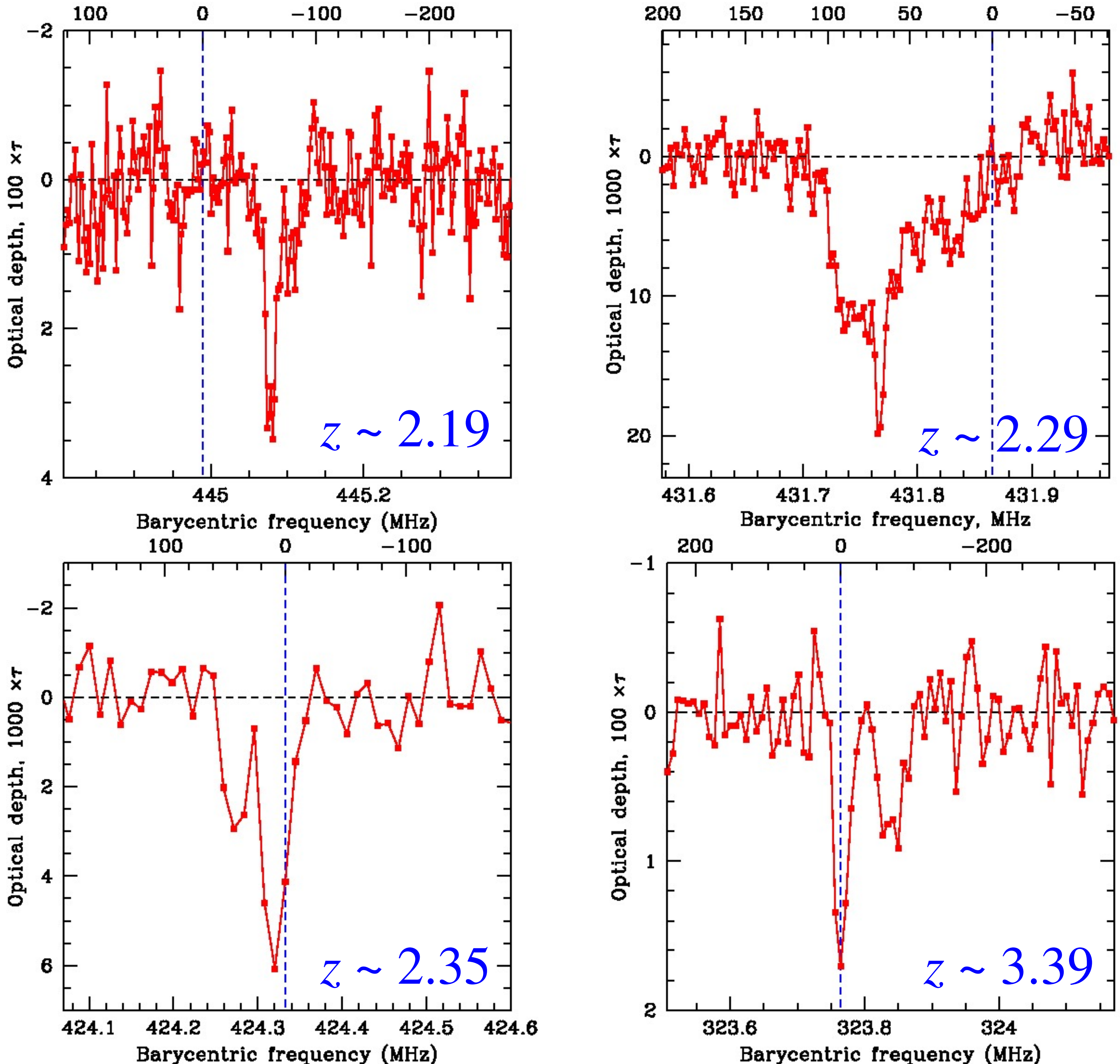
- VLT, Gemini & WHT optical survey of radio-loud QSOs to find DLAs for follow-up HI-21cm spectroscopy.
  (Ellison et al. 2008, MNRAS)

- 45 DLAs & 90 MgII absorbers observed with the GBT and the GMRT; roughly one-third wiped out by RFI !

- ~25 new HI-21cm absorption detections, at $1.1 < z < 3.4$.
  25 strong lower limits on the spin temperature, >~ 1000 K.
  (NK et al. 2006, 2007, 2013a,b, MNRAS; Ellison et al. 2012, MNRAS; York et al. 2007, MNRAS)

- 39 spin temperature estimates in DLAs, 27 at $z > 1$.

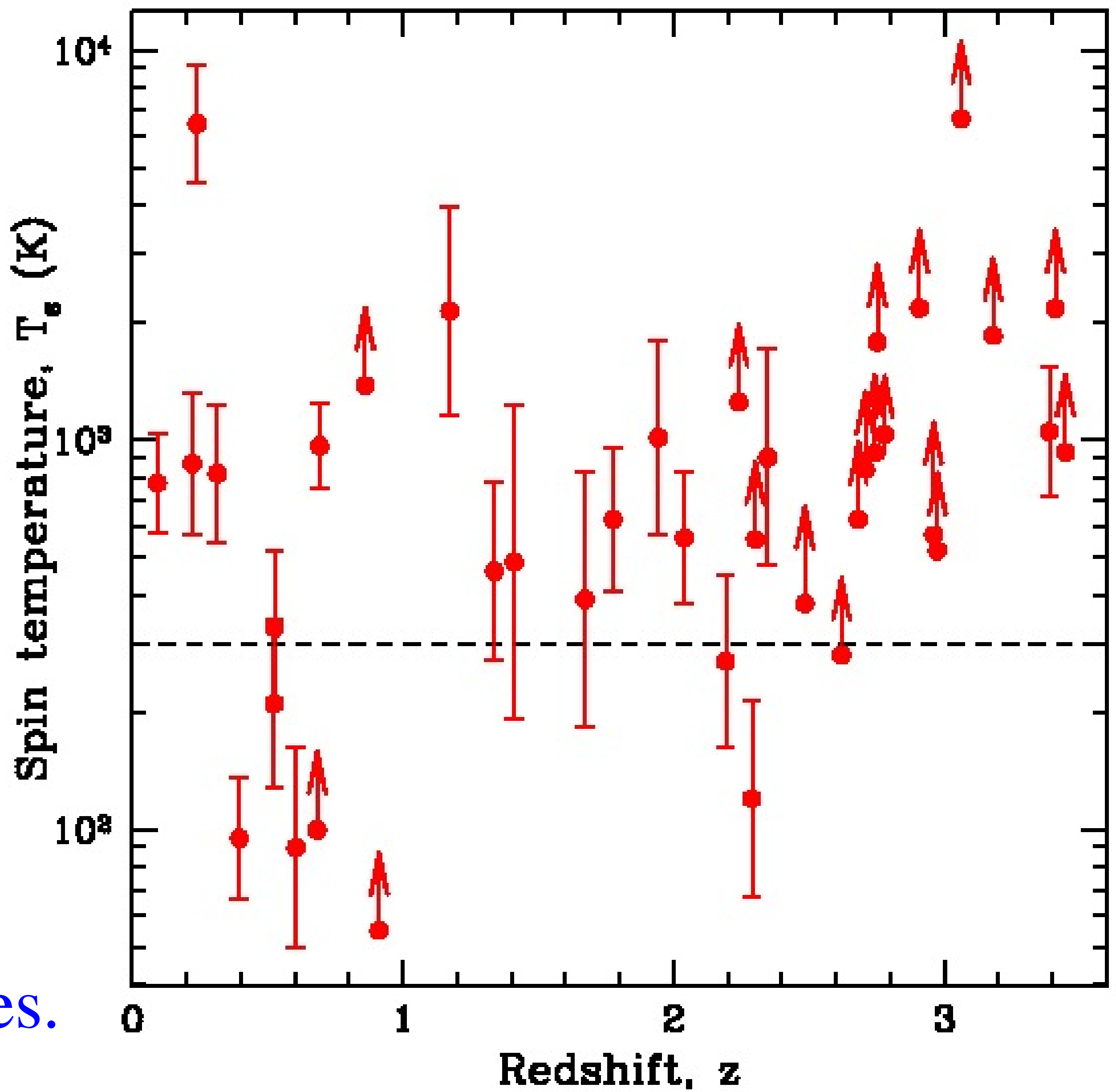
- 20 of 22 DLAs at $z > 2$ have high T_s ; typically > 1000 K.



z ~ 2.19
Optical depth, 100 ×τ
Barycentric frequency (MHz)
z ~ 2.29
Optical depth, 1000 ×τ
Barycentric frequency, MHz
z ~ 2.35
Optical depth, 1000 ×τ
Barycentric frequency (MHz)
z ~ 3.39
Optical depth, 100 ×τ
Barycentric frequency (MHz)

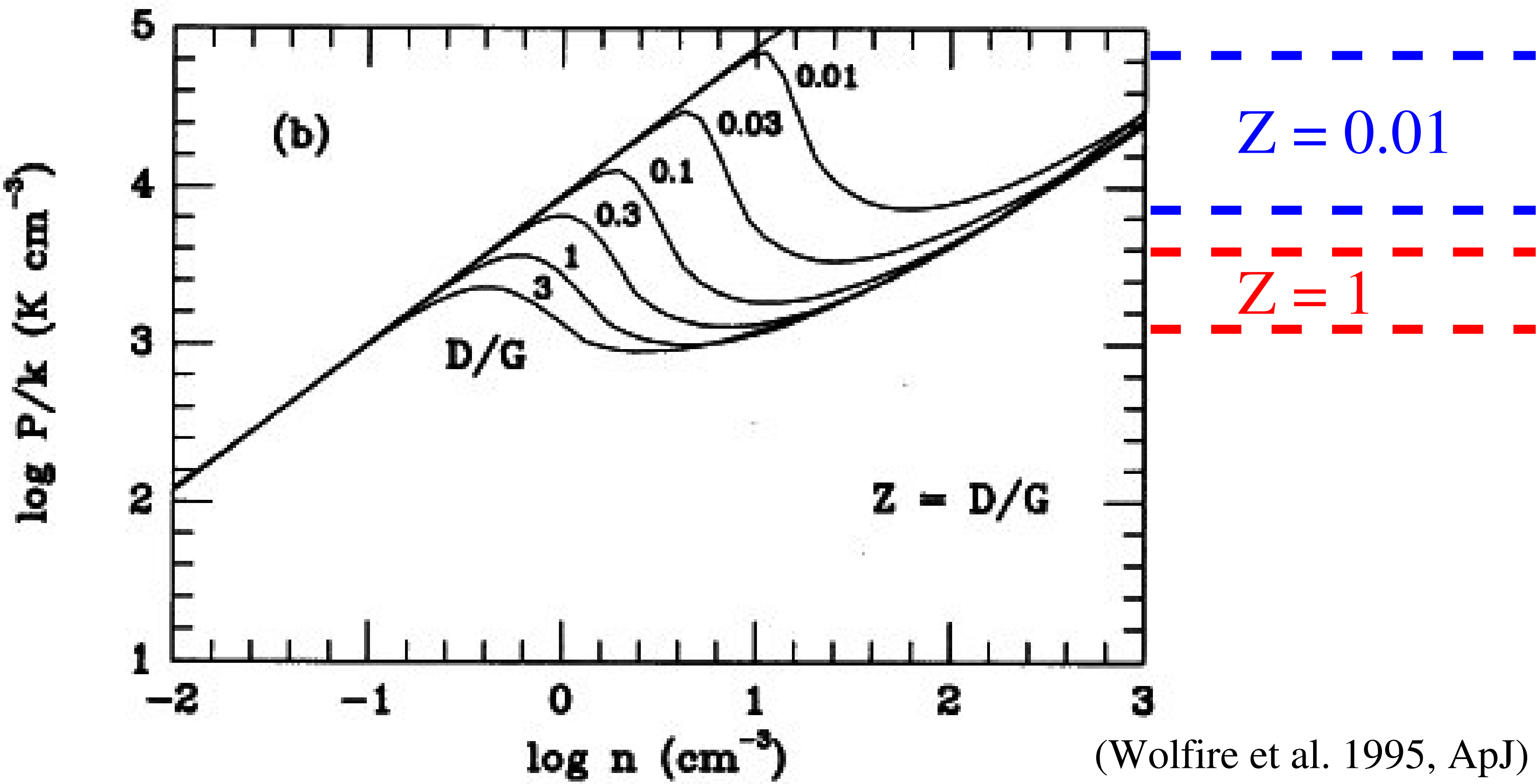
Spin Temperatures in DLAs

- 39 T_s estimates in DLAs, 22 at $z > 2$.
- 20/22 DLAs at $z > 2$ have high T_s.
- High T_s values ⇨ High WNM fraction in high-z DLAs.
- 4.2σ evidence for redshift evolution in DLA spin temperatures.



- T_s in DLAs and the Galaxy different at 6σ significance.

(NK et al. 2013, MNRAS)



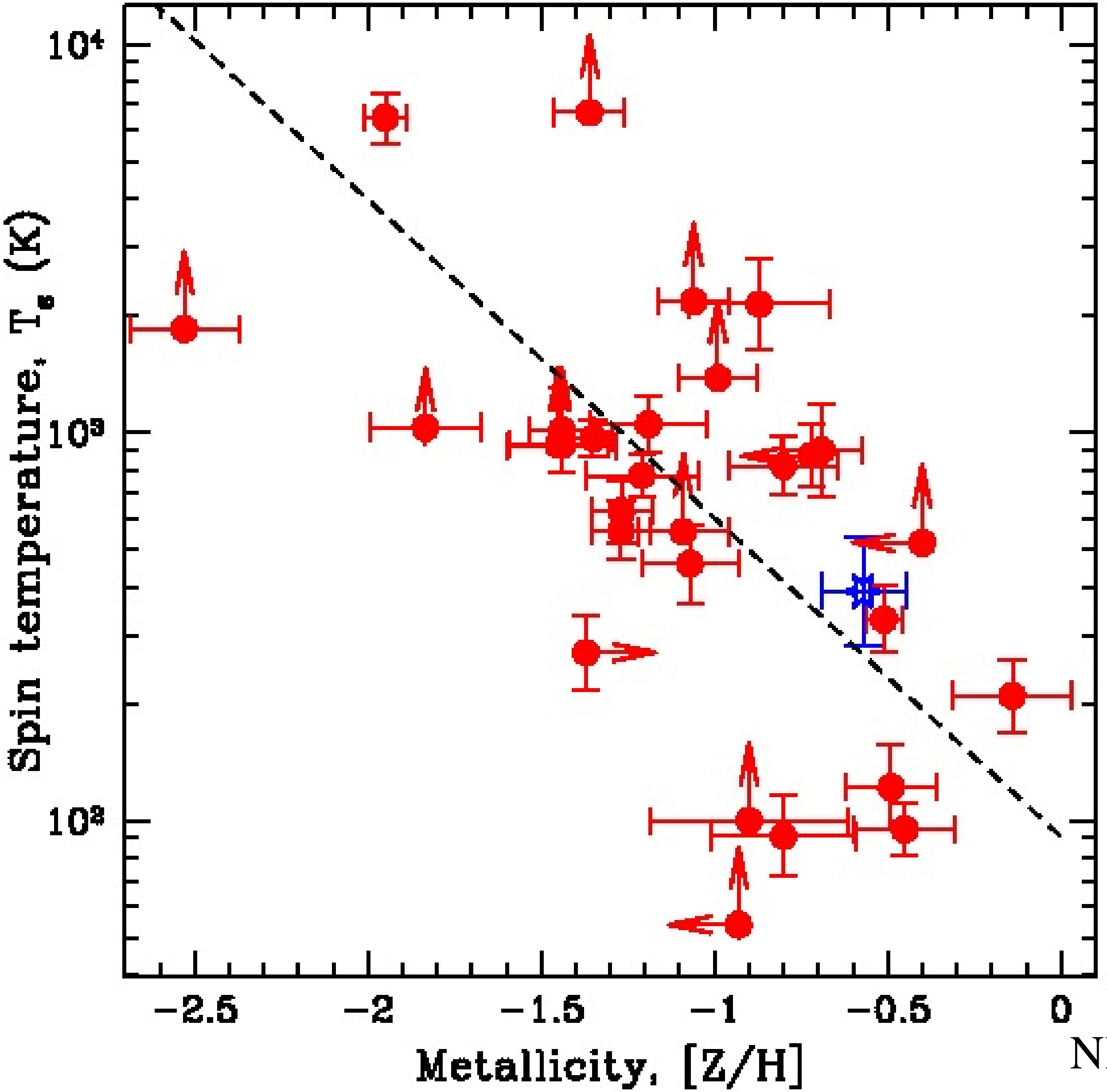
(Wolfire et al. 1995, ApJ)

- Higher metallicity, Z ~ 1 ⇨ More CNM ⇨ Low T_S
  Lower metallicity, Z < 0.1 ⇨ Less CNM ⇨ High T_S.

- High T_S due to low DLA metallicities and a paucity of cooling routes ? ⇨ Anti-correlation between T_S and [Z/H]!

(NK & Chengalur 2001, A&A)

DLA Spin Temperature vs. Metallicity



(NK et al. 2009, ApJL;
NK et al. 2013, MNRAS)

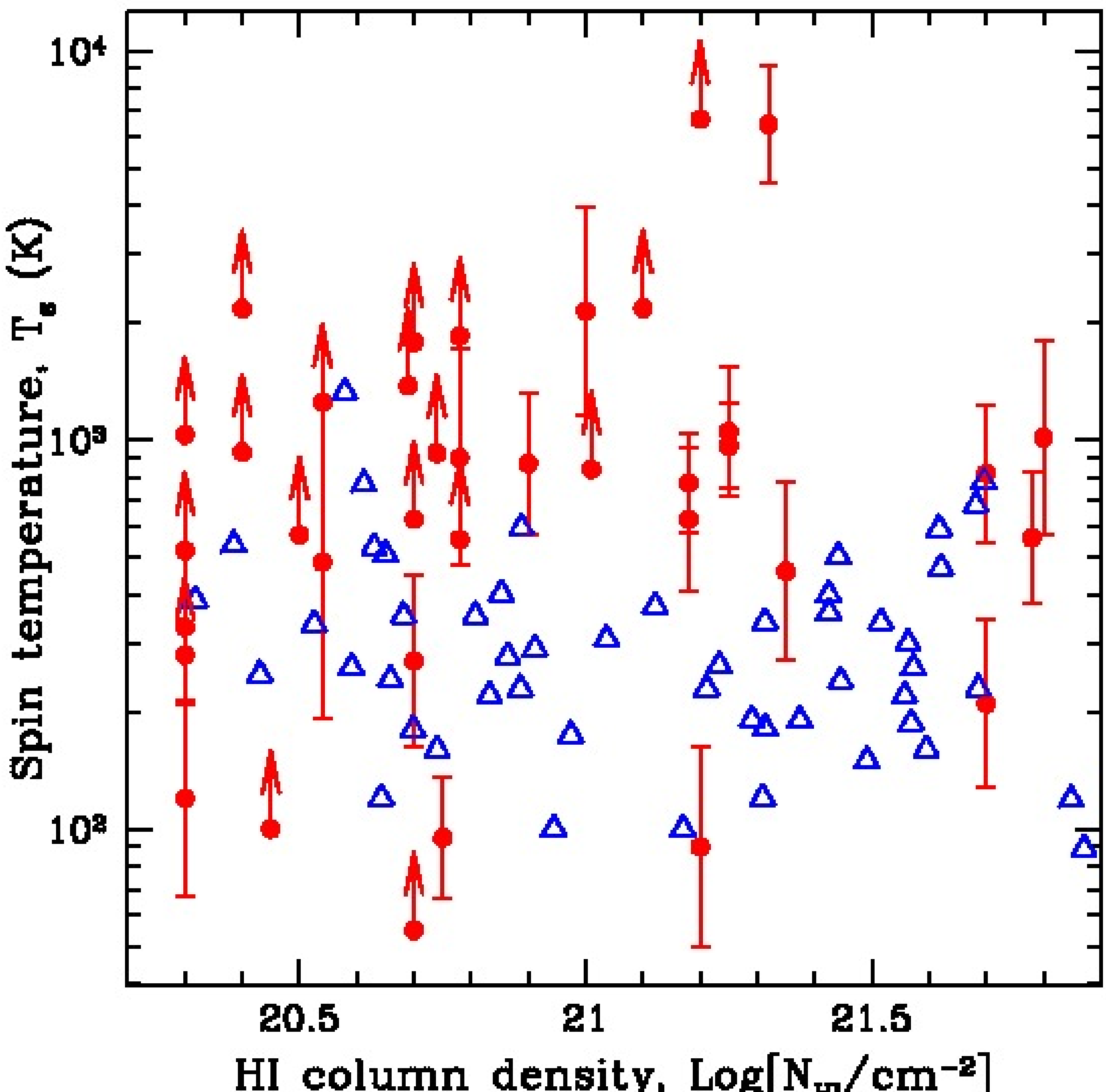
Non-parametric Kendall–τ test ⇨ 4σ anti-correlation!

HIGH SPIN TEMPERATURES IN DLAs ?

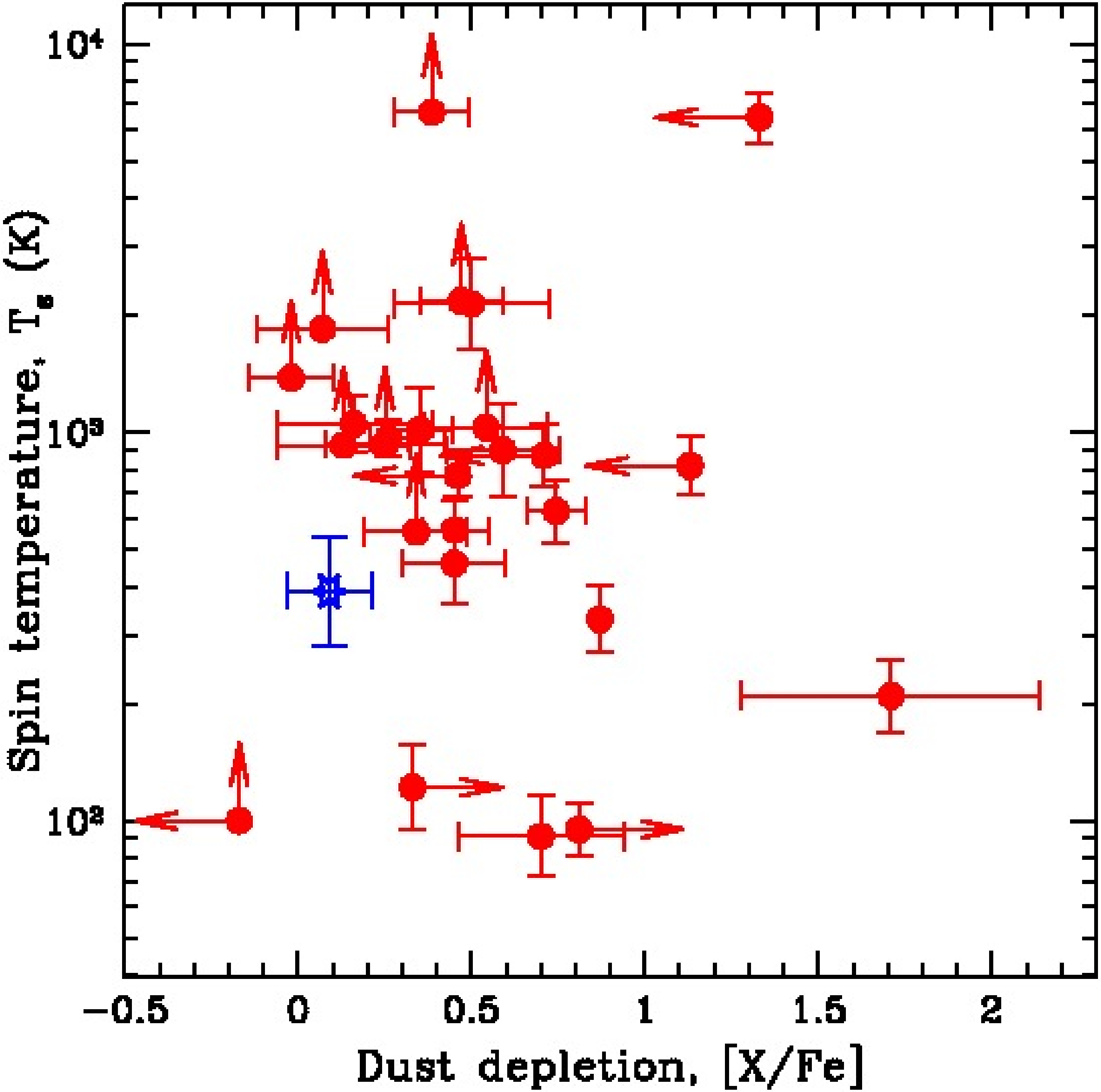
- Gas distribution in a 2-phase medium depends on the metallicity and pressure.
  Higher metallicity, pressure ⇨ More CNM ⇨ Low T_S
  Lower metallicity, pressure ⇨ Less CNM ⇨ High T_S
  (Wolfire et al. 1995, ApJ)
- High-*z* DLAs have low metallicities: median [Z/H] ~ -1.5.
  (Rafelski et al. 2012, ApJ)
  ⇨ *The HI in most high-z DLAs is mainly in the WNM.*
  (NK et al. 2013, MNRAS)
- Dwarfs ⇨ Low pressure, star formation, metallicity
  ⇨ More WNM ⇨ High spin temperature.
  ⇨ *Most high-z DLAs are likely to be small galaxies.*
- But... High-*z* DLAs have large velocity spreads, ~ 90 km/s.

SUMMARY

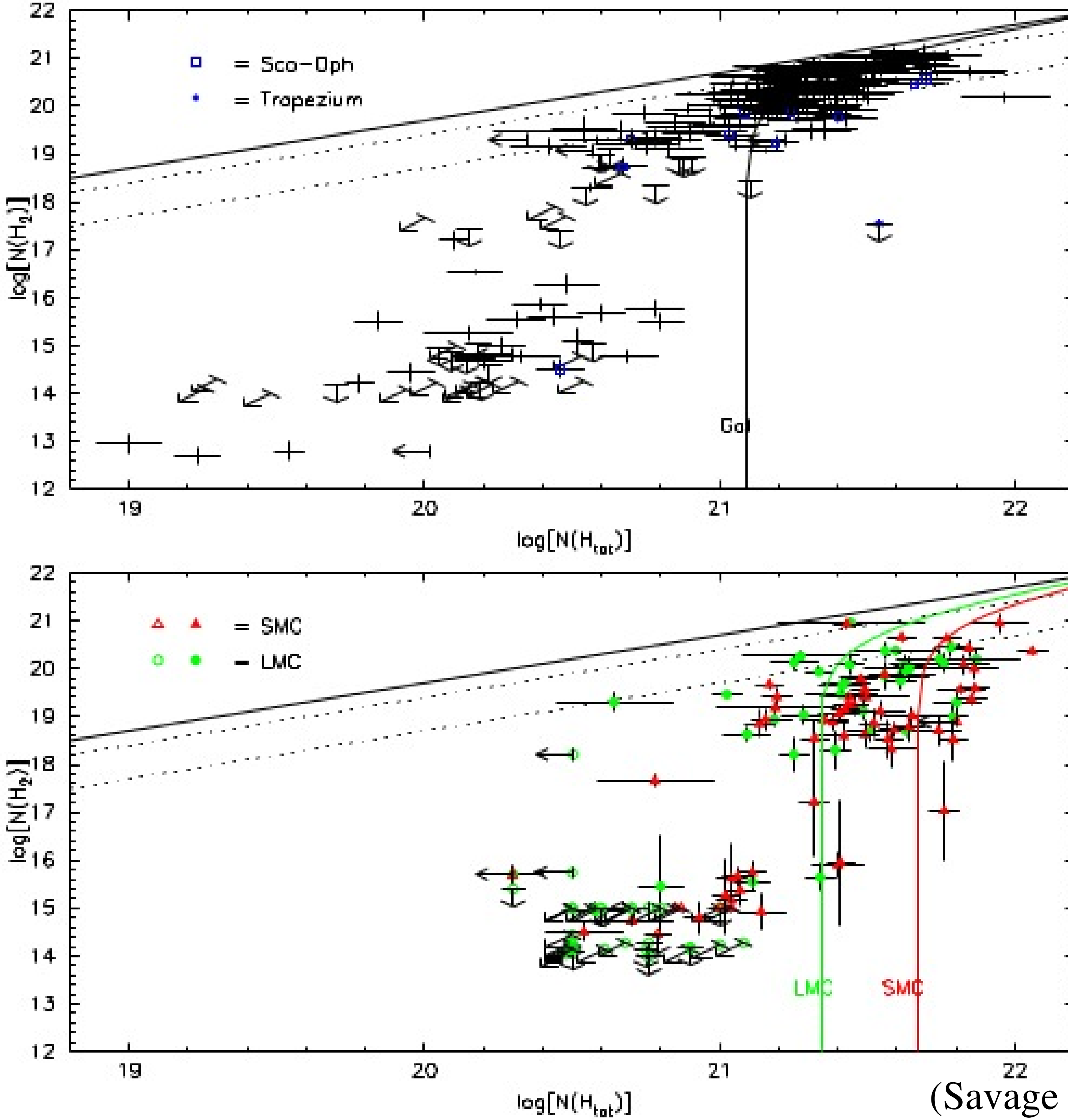
- Spin temperature measurements in the Galaxy:
  $T_S \sim 240$ K for $N(HI) \geqslant 2 \times 10^{20}$ cm^{-2}.
  $T_S > 1000$ K for $N(HI) < 2 \times 10^{20}$ cm^{-2}.
- A column density threshold for CNM formation ? A third phase transition in the ISM ?
- A physical difference between DLAs and sub-DLAs ?
- 39 T_S estimates in DLAs, with 22 at $z > 2$. Most high-z DLAs have high spin temperatures ($\gtrsim$ 1000 K).
- 4σ anti-correlation between T_S and metallicity [Z/H]
  ⇨ High T_S in DLAs is due to a high WNM fraction.
  ⇨ Most of the HI in high-z DLAs is in the WNM.



Spin temperature, T_s (K)
10^4
10^3
10^2
20.5
21
21.5
HI column density, Log[N_{HI}/cm^{-2}]



10^4
10^3
10^2
Spin temperature, T_s (K)
−0.5
0
0.5
1
1.5
2
Dust depletion, [X/Fe]



(Savage et al. 1977, ApJ;
Welty et al. 2012, ApJ)

HI-21CM ABSORPTION STUDIES: A BRIEF HISTORY

- 1973: HI-21cm absorption at $z \sim 0.692$ towards 3C286.

  (Brown & Roberts 1973, ApJL)

- z_{21cm} vs. z_{UV} at $z \sim 0.524$ ⇨ Fundamental constant evolution!

  (Wolfe et al. 1976, PRL)

- 1979-1985: Three absorbers at $z \sim 1.776, 1.944, 2.040$ ⇨ First evidence for high spin temperatures in high-z DLAs.

  (e.g. Wolfe & Davies 1979, AJ; Wolfe et al. 1985, ApJL)

- 1983: HI-21cm absorption survey targetting MgII absorbers.

  (Briggs & Wolfe 1983, ApJ)

- 1997: Tentative detection at $z \sim 3.4$; not confirmed later.

  (Briggs et al. 1997, AJ; NK & Chengalur 1997, MNRAS)

- Until 1998, 3 detections at $z > 0.7$, 4 at $z < 0.7$, few limits.

- Reasons: Poor frequency coverage, low sensitivity, RFI !

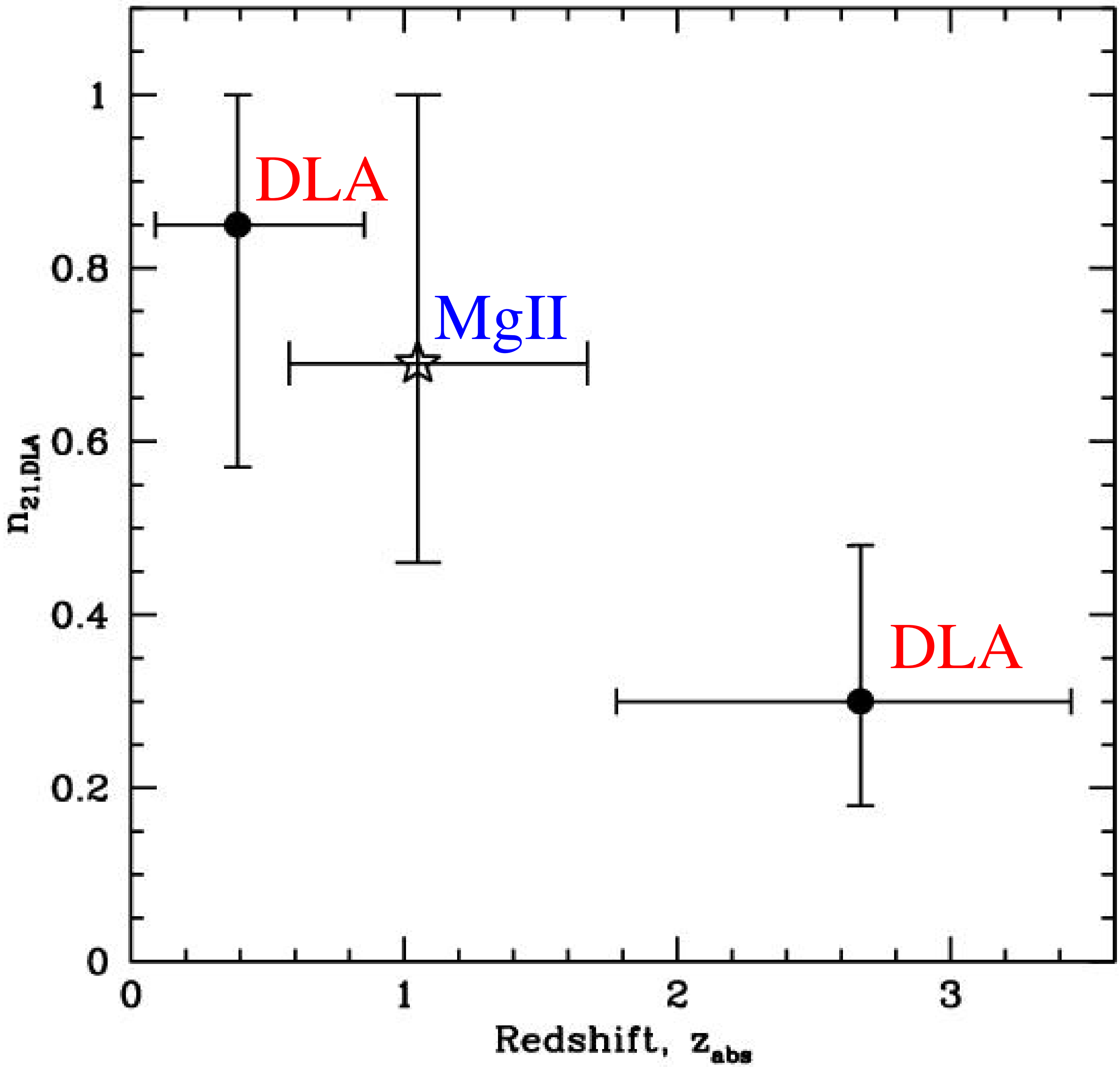
HI-21cm Absorption at Low Redshifts

- Low-z DLA surveys require large amounts of HST time.
- HI-21cm absorption only detectable in DLAs ⇨ Find DLAs via HI-21cm surveys in strong MgII absorbers.

(Rao et al. 2006, ApJ)

- 38 MgII absorbers at $0.6 < z < 1.7$; $W_{\mathrm{MgII,\,FeII}} > 0.5$ Å. Either 21cm detections or strong limits on the HI-21cm optical depth ($\tau_{21} < 0.013$).
- 9 (16) detections of 21cm absorption, at $1.07 < z < 1.67$ ⇨ 21cm detection rate in DLAs ~ 69^{+31}_{-23} %.
- Detection rate at $z \sim 1$ comparable to that at low z ⇨ Significant amounts of cold HI present by $z \sim 1$.

(NK et al. 2009, MNRAS)



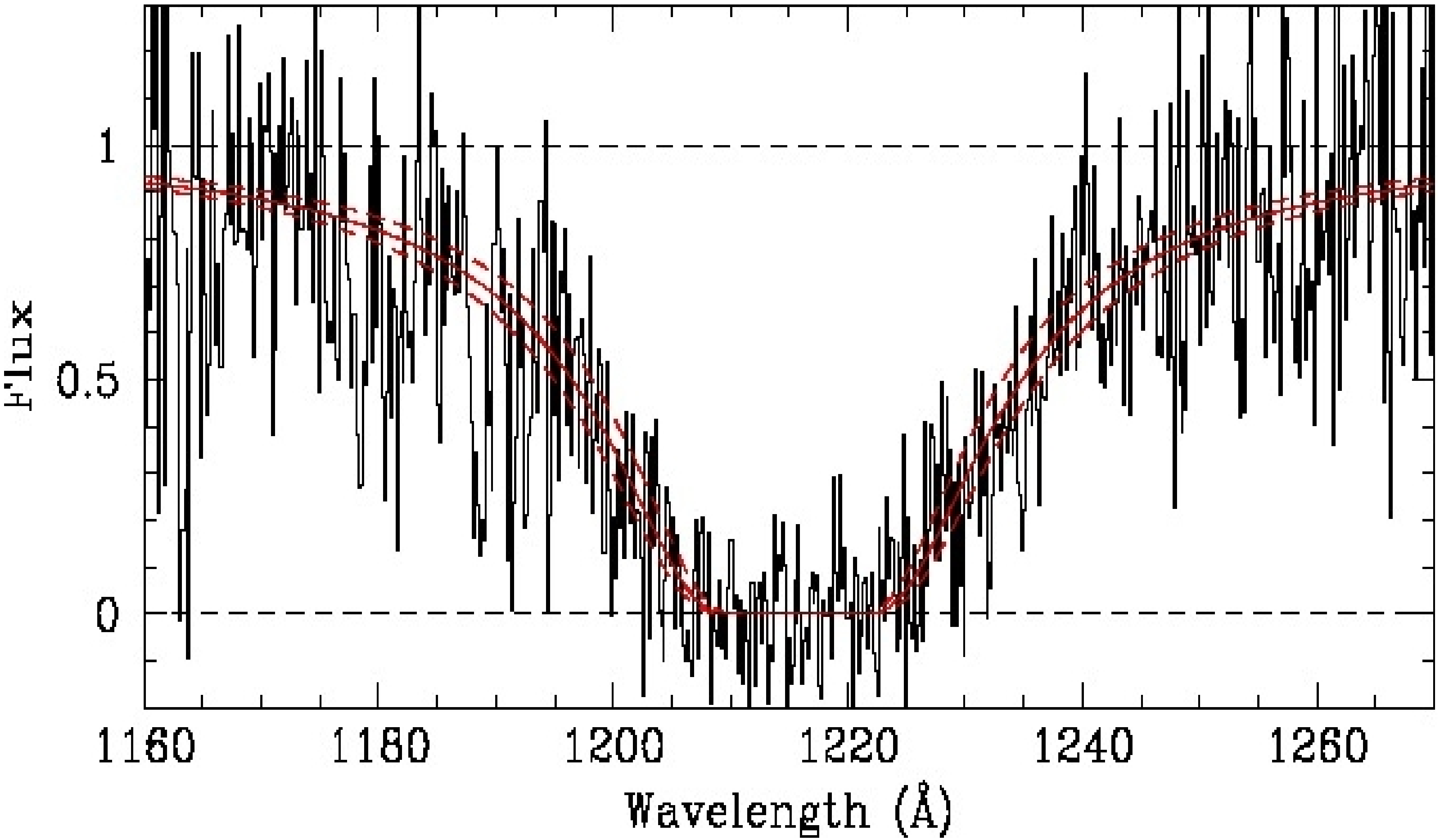
(NK et al. 2009. MNRAS)

HI-21CM ABSORPTION STUDIES: MOTIVATION

- HI-21cm emission is very difficult to detect ($z_{MAX} \sim 0.25$). Even for the SKA, ~360 hours to detect M^*_{HI} at $z \sim 2$!
- HI-21cm absorption *directly* probes conditions in the neutral atomic ISM in high-z galaxies.
- DLAs towards *extended* radio sources ⇨ Transverse size & kinematics.
- DLAs towards *compact* radio-loud QSOs ⇨ DLA spin temperatures ⇨ Evolution of the temperature of the neutral ISM with redshift.
- Strong MgII absorbers at $z < 1.7$ ⇨ Finding low-z DLAs.
- z_{21cm} versus z_{UV} , z_{OH} ⇨ Fundamental constant evolution.

• COS spectroscopy of the z~1.371 system toward UM305.

(Ellison et al. 2012, MNRAS)

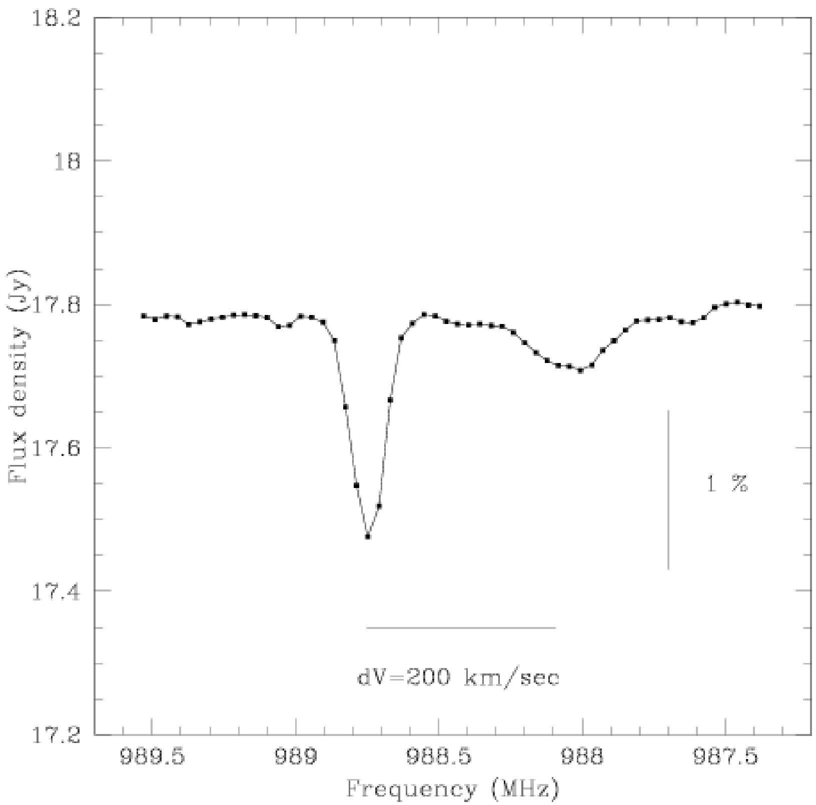


$$N_{HI} = (6 \pm 1) \times 10^{21}\ \mathrm{cm}^{-2}$$

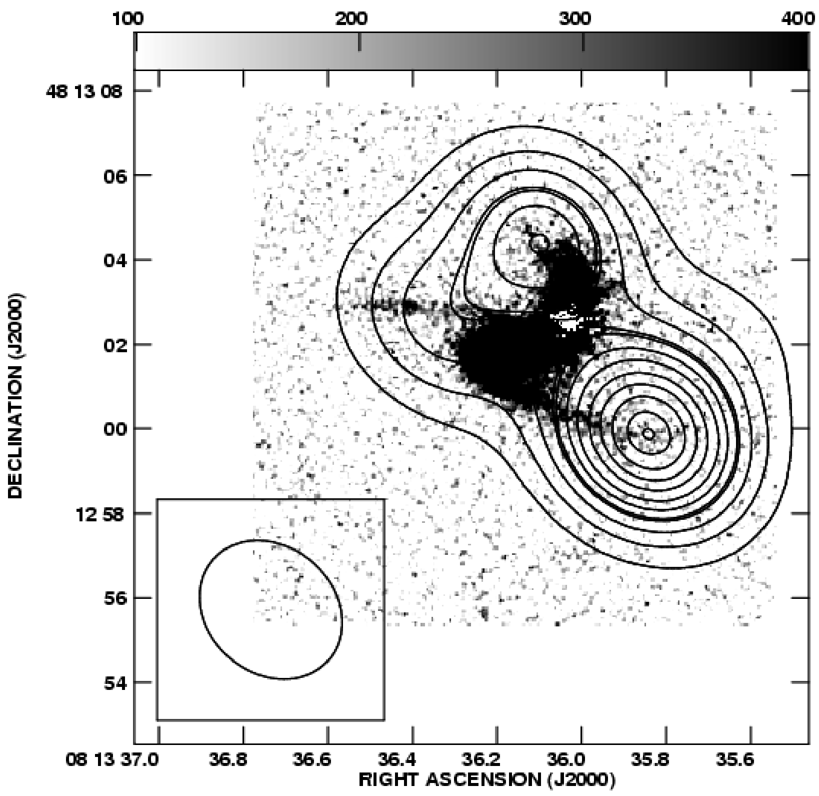
$$\Rightarrow \quad T_s = (1000 \pm 150)\ \mathrm{K}.$$

Mapping High-z HI-21cm Absorption

- Can measure the size and velocity field of DLAs lying towards extended radio sources (e.g. radio galaxies).
- Long-baseline interferometers for high spatial resolution!
- Best target: the $z \sim 0.437$ DLA towards 3C196.

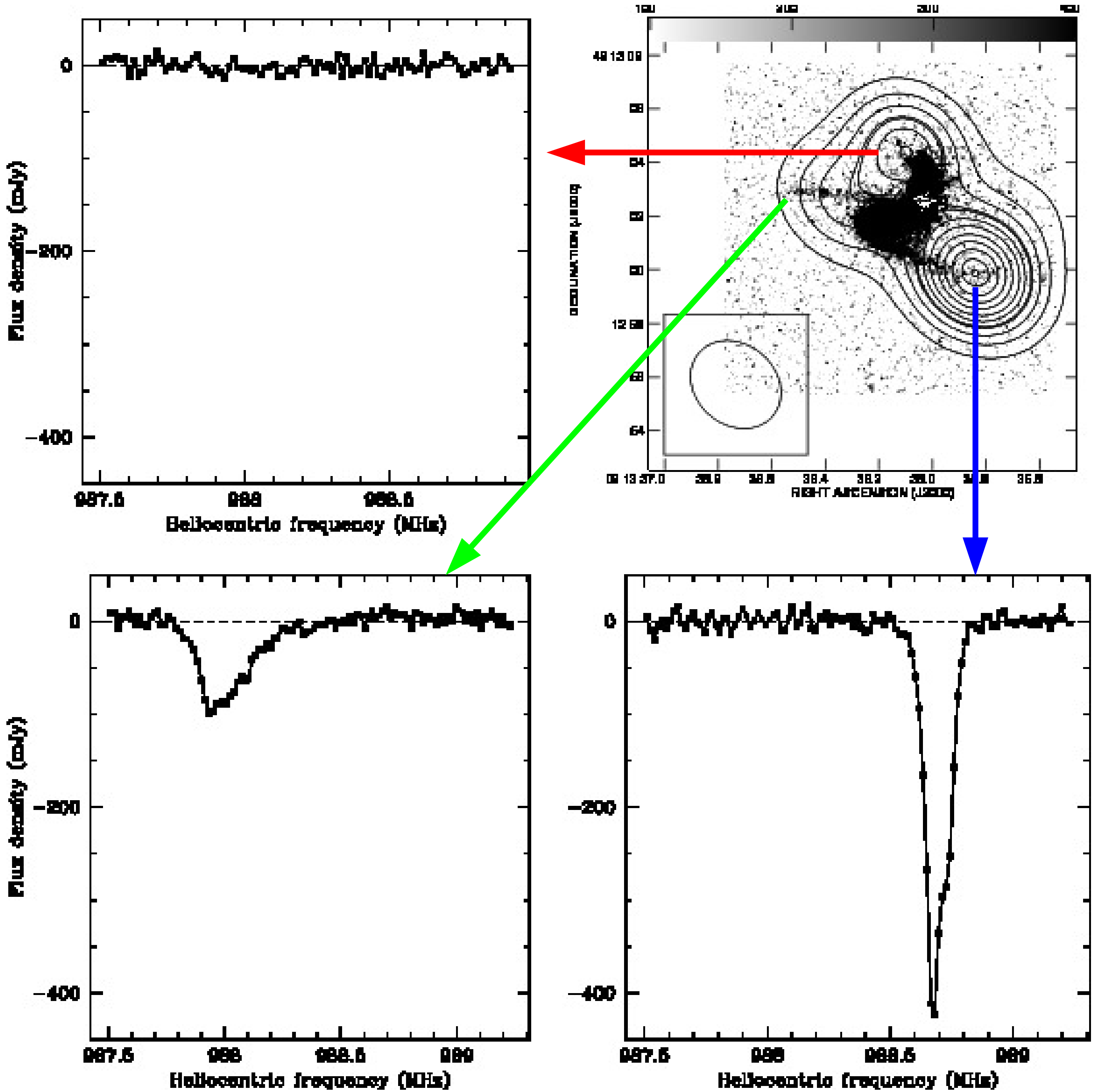


(Briggs et al. 2001, A&A)



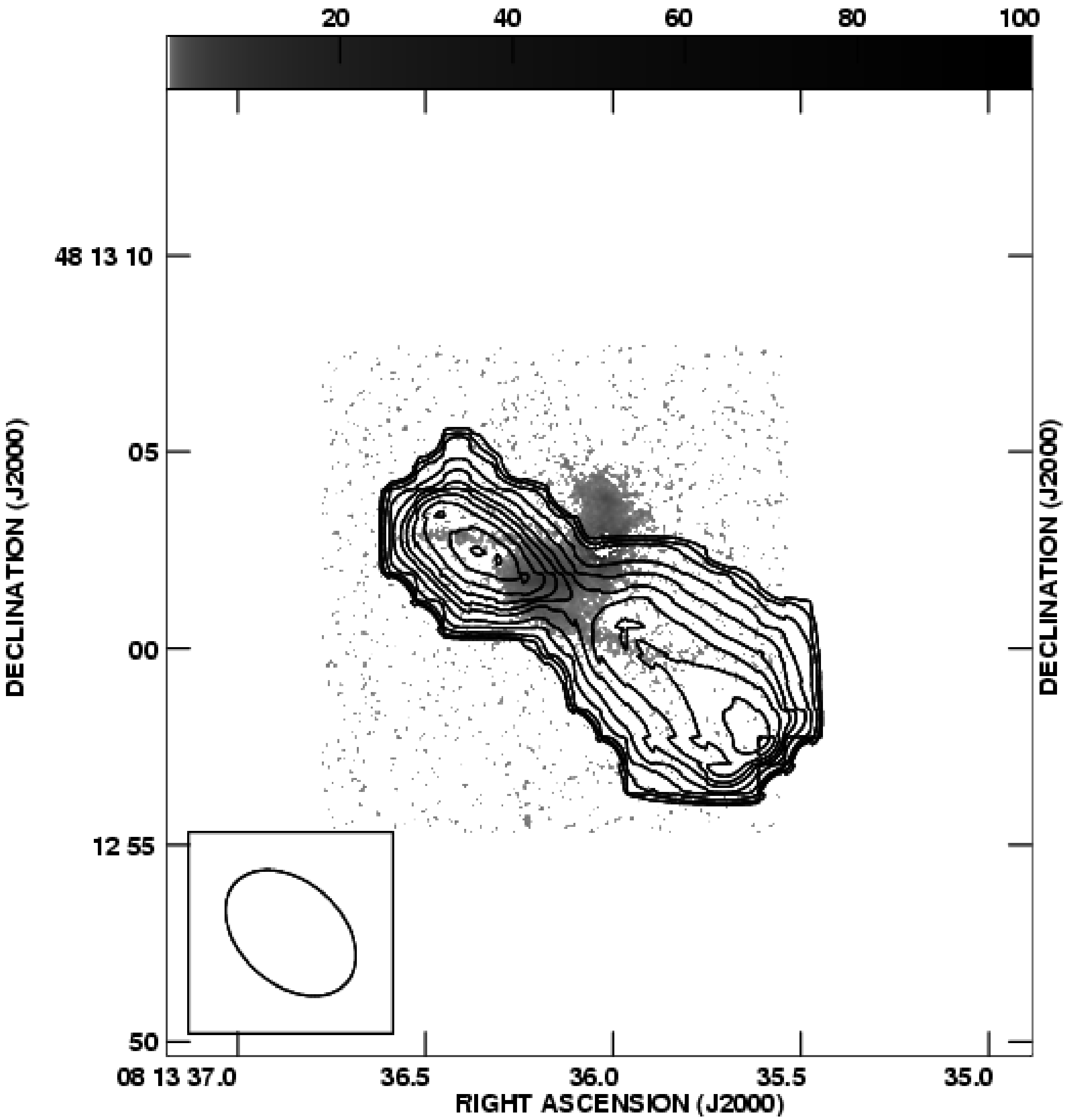
(Ridgway & Stockton 1997, AJ)

MAPPING HI-21CM ABSORPTION AT $z \sim 0.437$

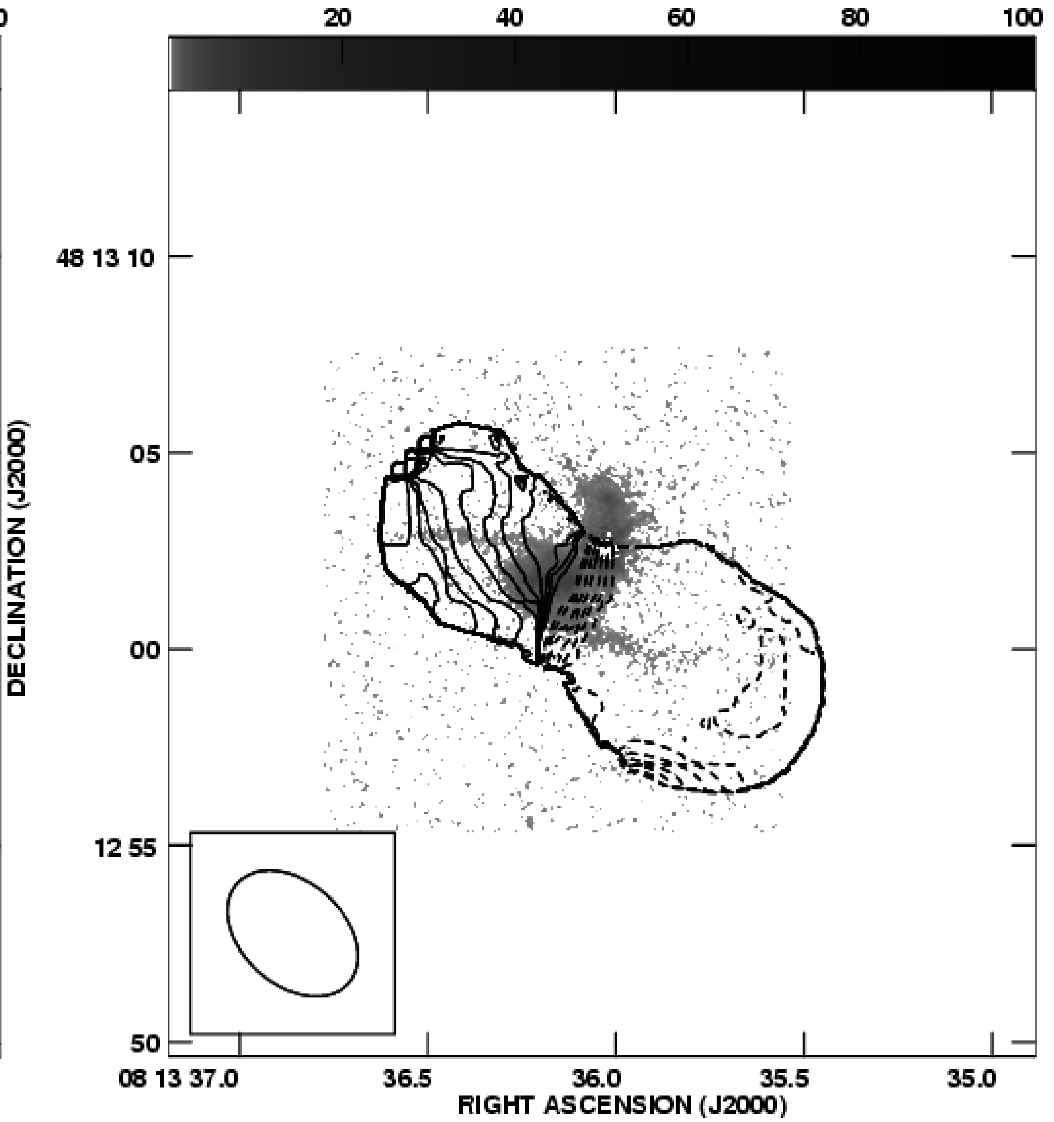


MAPPING HI-21CM ABSORPTION AT $z \sim 0.437$

Integrated optical depth



Velocity field

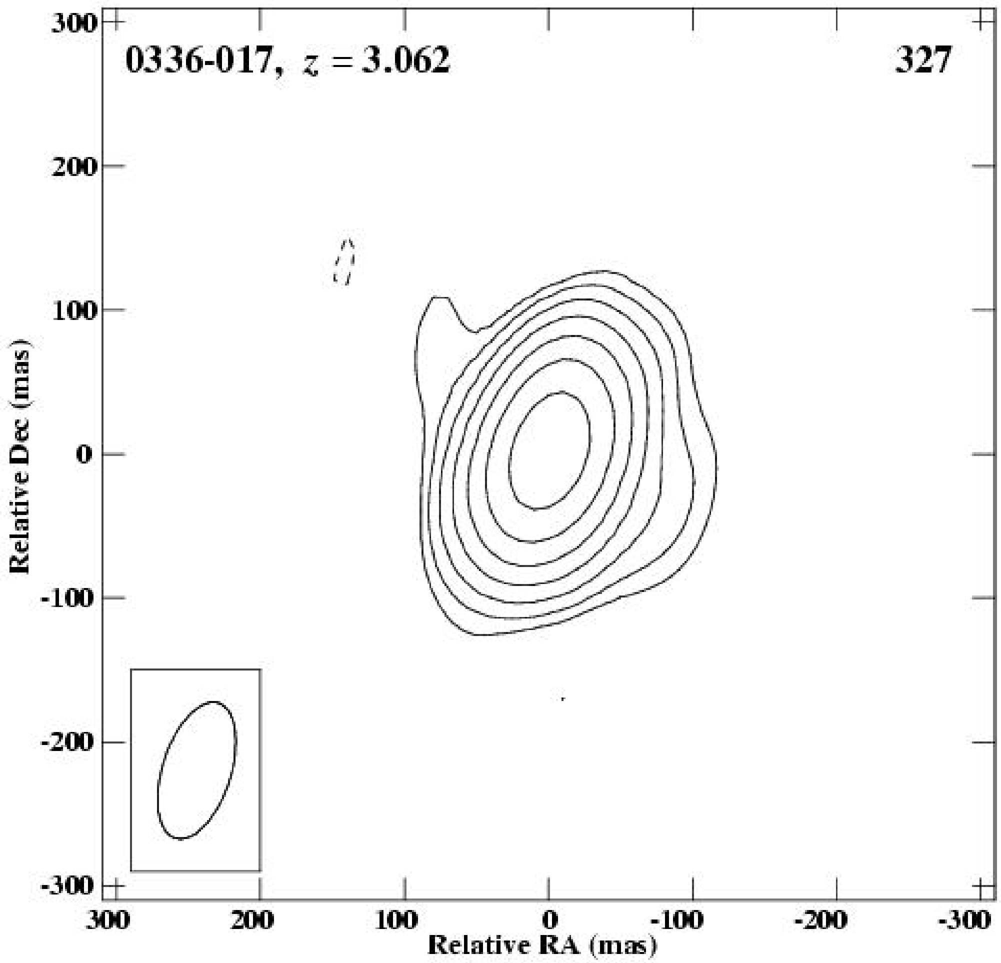


(NK & Chengalur, some day)

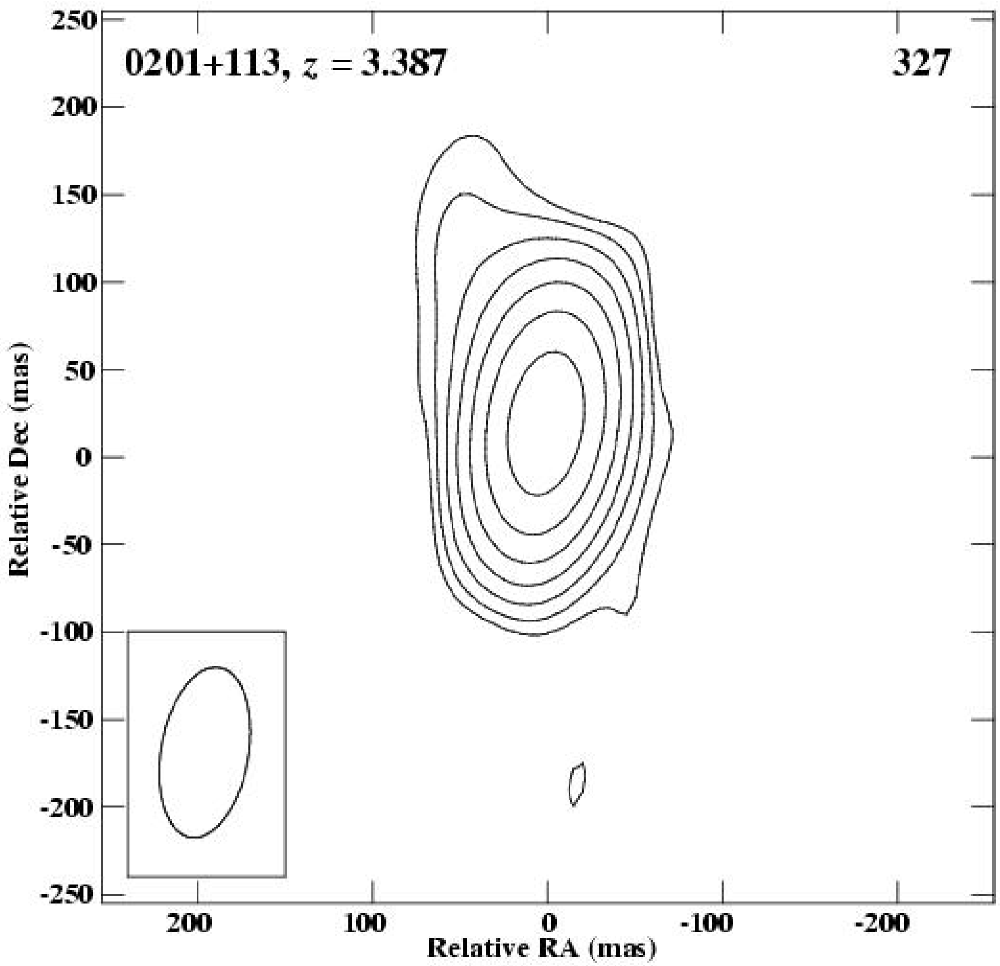
VLBA Imaging ⇨ DLA covering factors

30 QSOs observed at 327, 610 or 1420 MHz.

0336-017, $z \sim 3.062$, $f \sim 0.68$



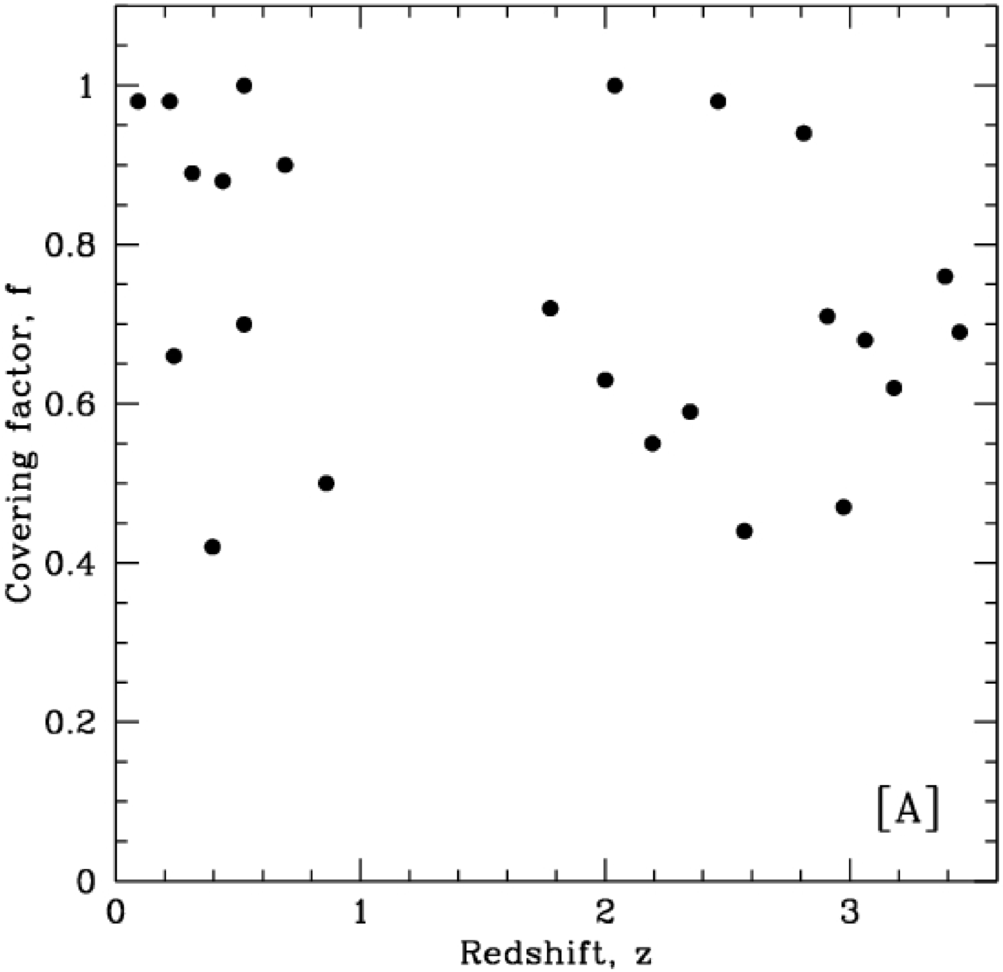
0201+113, $z \sim 3.387$, $f \sim 0.76$

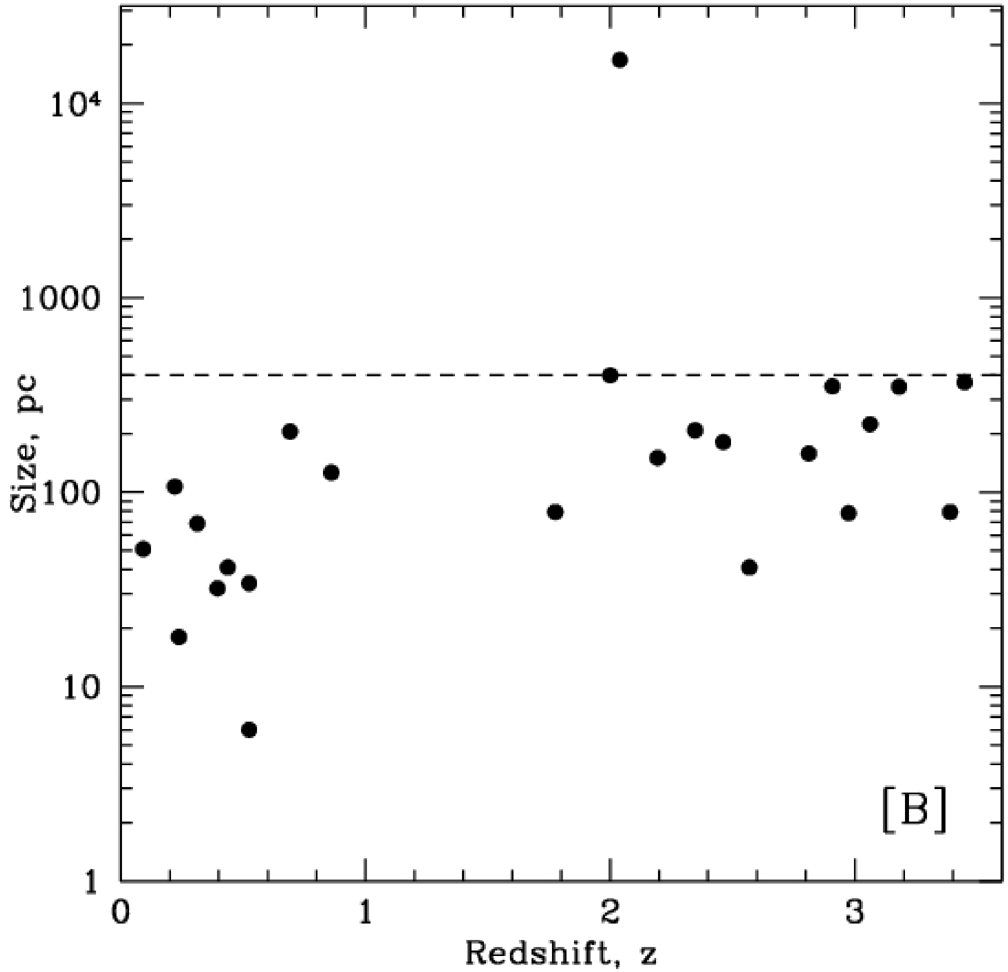


39 QSOs with covering factor measurements.

Covering factor vs. redshift

Transverse size vs. redshift





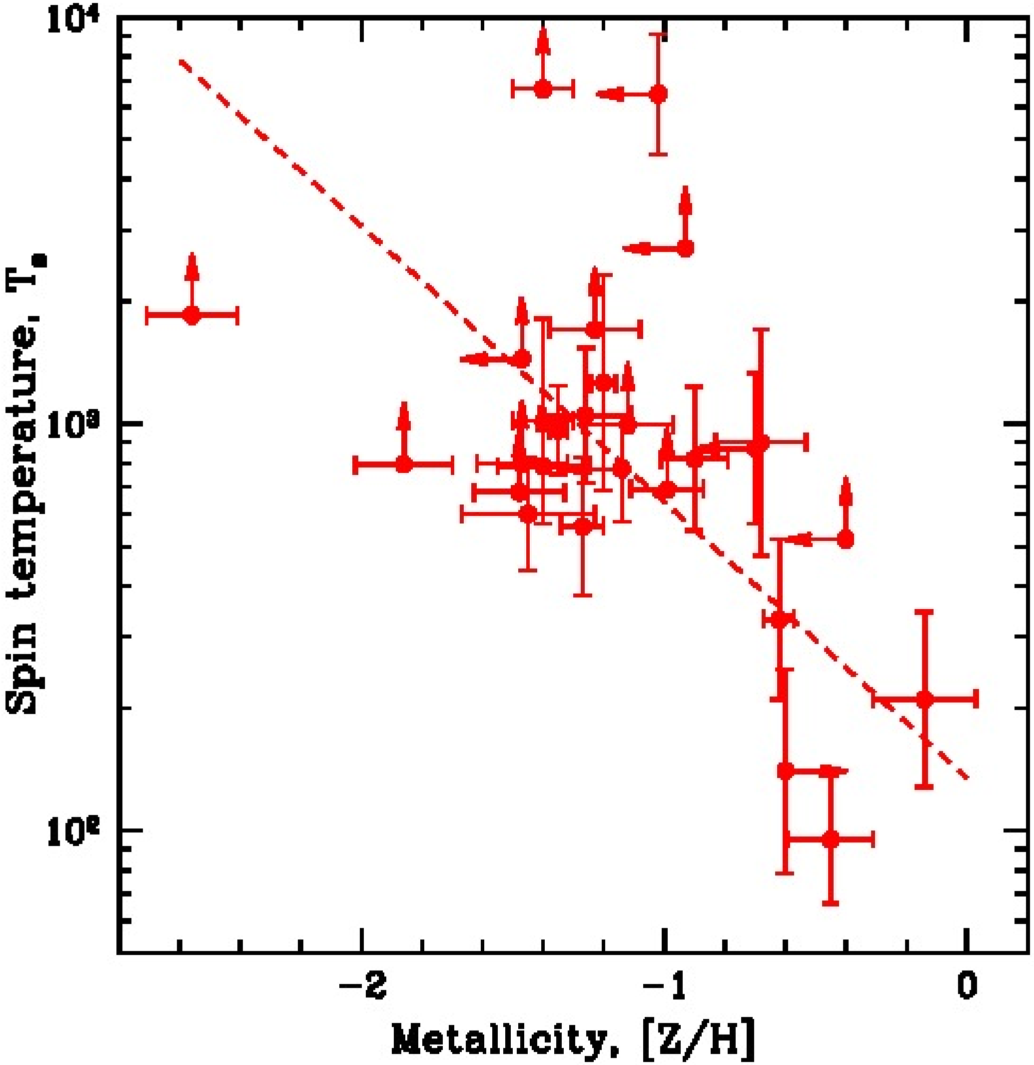
⇨ Similar covering factors at all redshifts, $0.4 < f < 1$

⇨ Covering factor effects not significant.

(NK et al. 2009, MNRAS-L)

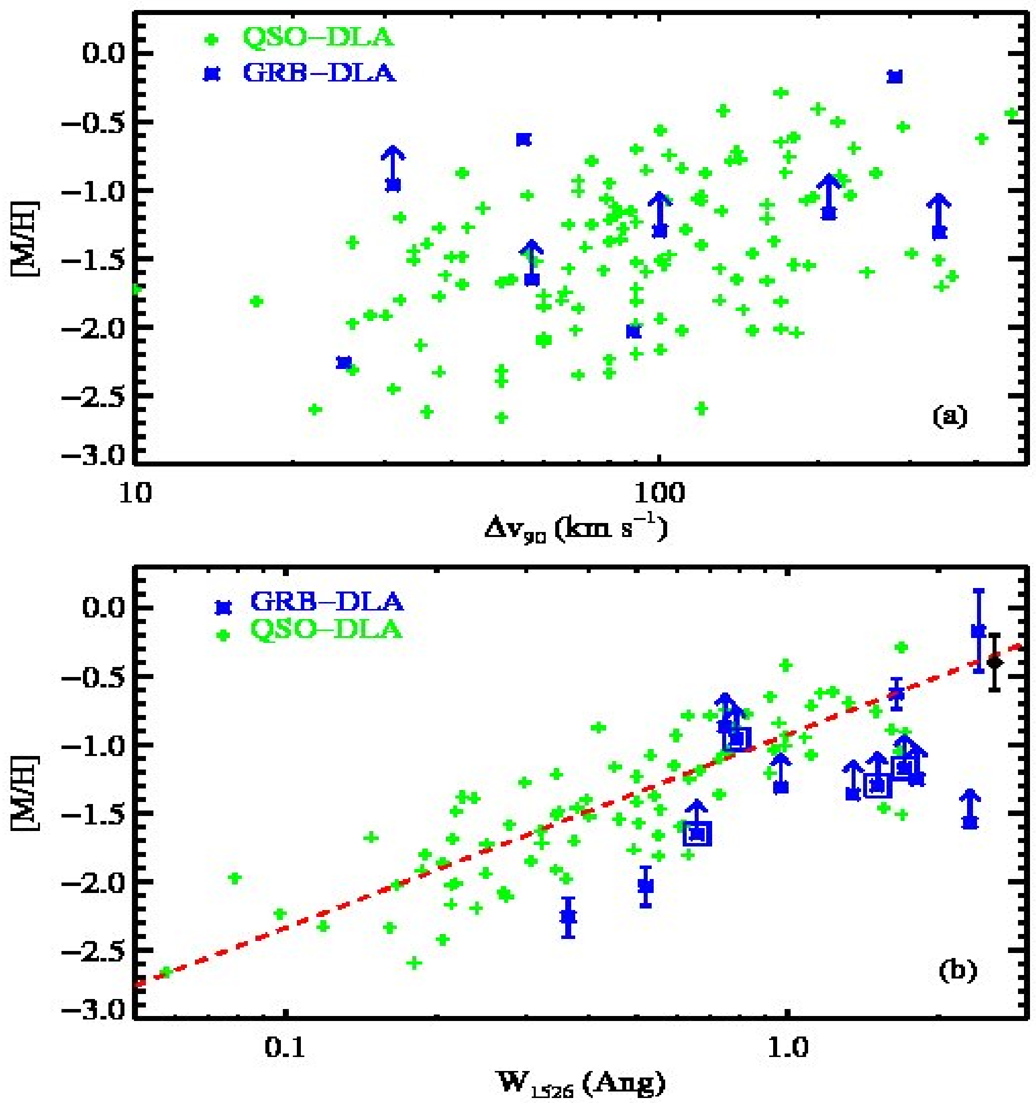
T_s - [Z/H] anti-correlation

(NK et al. 2009, ApJL)

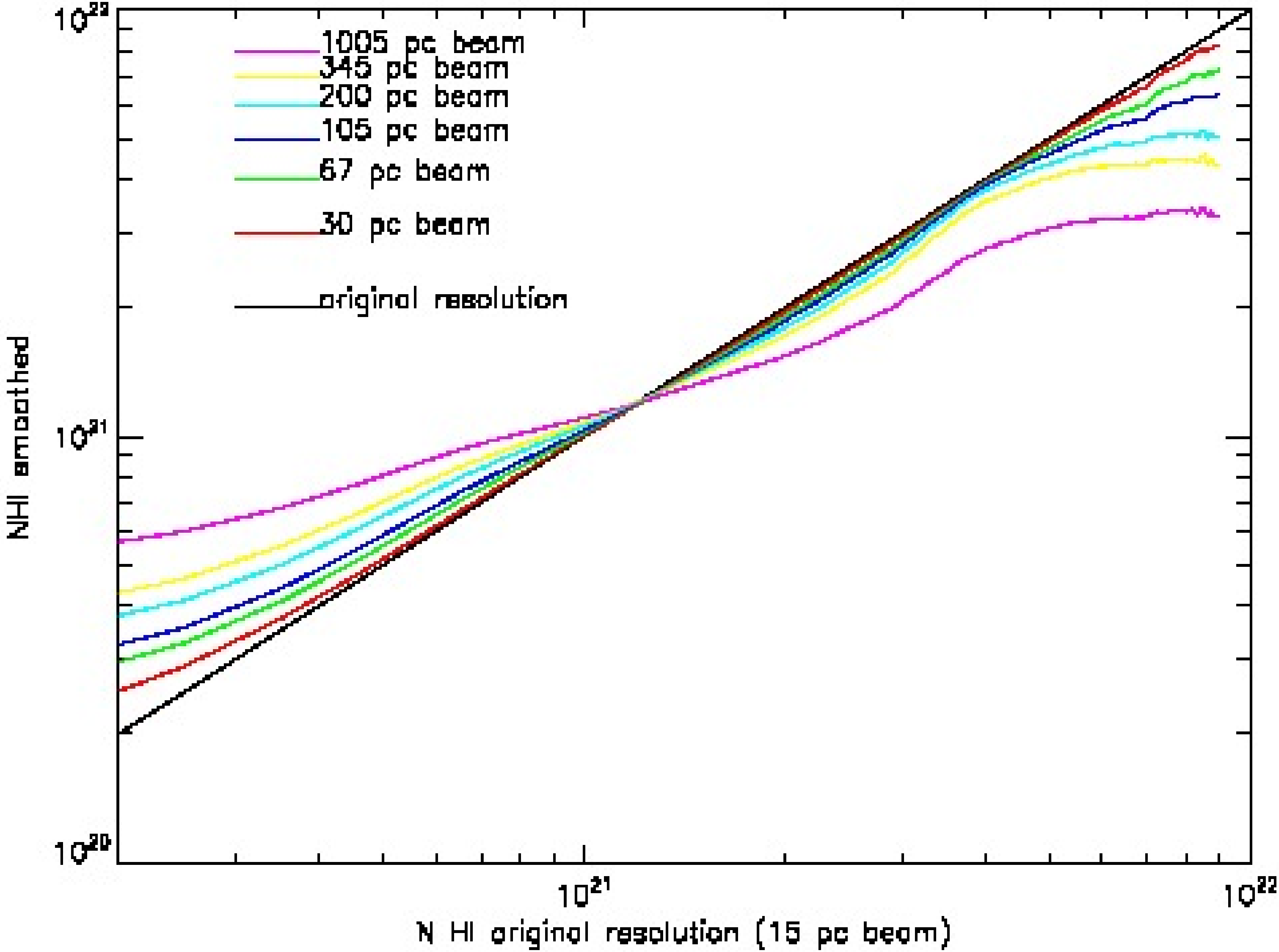


[Z/H] - ΔV correlation

(Prochaska et al. 2007, ApJ)



- Consistent picture if high-*z* DLAs are typically small galaxies, with low SFR, metallicity and CNM fraction.


1005 pc beam
345 pc beam
200 pc beam
105 pc beam
67 pc beam
30 pc beam
original resolution
10^{22}
10^{21}
10^{20}
NHI smoothed
10^{21}
10^{22}
N HI original resolution (15 pc beam)