Image: B. Premkumar

ABSORBING GALAXIES

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OUTLINE

- The high-*z* galaxy zoo: Damped Lyman-α absorbers (DLAs).
- What can HI 21cm absorption studies do for you?
- An N(HI) threshold for CNM formation in the Milky Way.
- HI 21cm absorption studies of high-*z* DLAs and MgII absorbers.
- The hosts of high-*z* DLAs and HI 21cm absorbers.
- Summary.

THE HIGH-z GALAXY ZOO

- Ideally, uniformly-selected high-z galaxy samples, without any bias. In reality, selection biases, from the detection method!

- Emission-selected samples ⇨ Brighter galaxies (strong bias)! e.g. quasars, sub-mm galaxies, Lyman-break galaxies, ultra-luminous infrared galaxies, Lyman-α emitters, BzK galaxies, radio galaxies …

(e.g. Chambers et al. 1987; Hu et al. 1996; Hughes et al. 1998; Steidel et al. 1999; Daddi et al. 2006; Fan et al. 2003)

- Absorption-selected samples ⇨ No bias towards bright galaxies! e.g. DLAs, MgII absorbers.

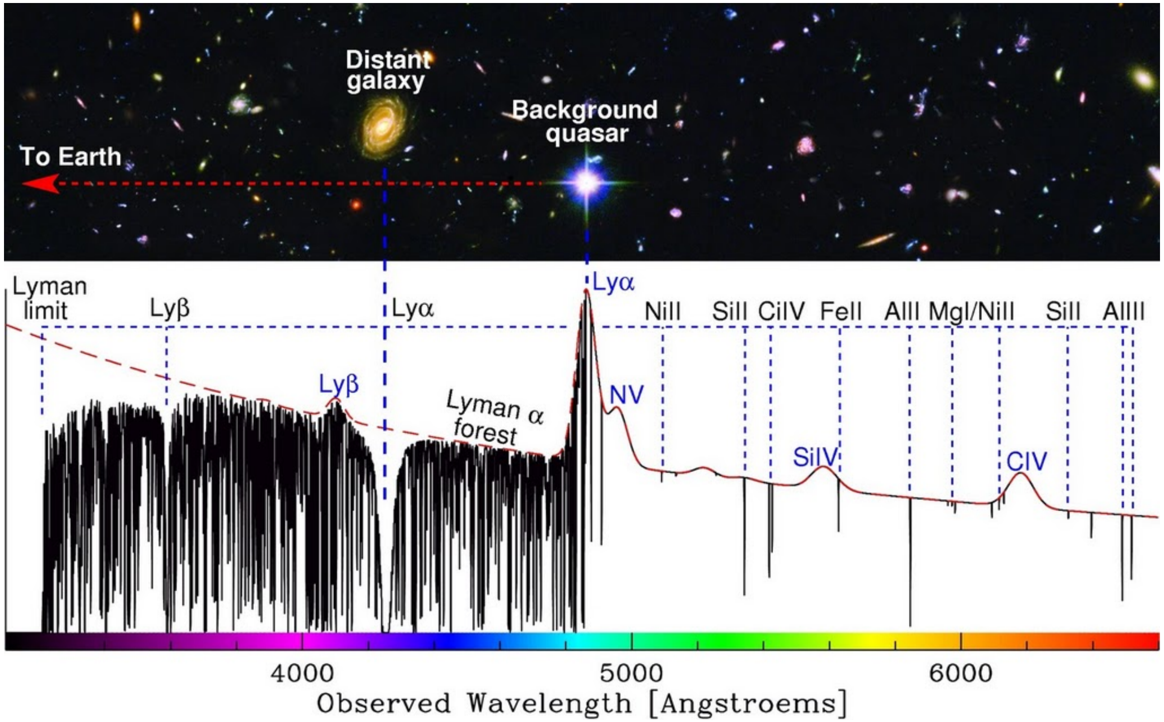
(e.g. Wolfe et al. 1986; Sargent et al. 1988)

DAMPED LYMAN-α ABSORBERS (DLAs)

(e.g. Wolfe et al. 2005)

- Damped Lyman-α wings ⇨ High $N(\mathrm{HI}) \geq 2 \times 10^{20}\ \mathrm{cm}^{-2}$, similar to the Milky Way!
- No luminosity bias ⇨ “Normal” gas-rich galaxies!
- SDSS-DR12: >10,000 DLAs at $z > 2$. Only ~60 at $z < 1.7$!

(e.g. Rao et al. 2006; Noterdaeme et al. 2012)



- Quasar absorption spectroscopy: Abundances, metallicity, H_2 fraction.

  ⇨ Low metallicities, ~0.03 solar at $z \sim 2$, increasing to lower z.

(e.g. Prochaska et al. 2003; Rafelski et al. 2013)

- Little information on the host galaxies: Optical imaging and spectroscopy difficult due to the bright background QSO.
- What galaxies are DLAs ? Mass, size, SFR, gas temperature, …

THE HI 21CM SPIN TEMPERATURE

- HI 21cm absorption studies of gas towards compact sources:

  Multi-phase medium: $N(\mathrm{HI}) = 1.8 \times 10^{18} \times [\langle T_s \rangle / f] \times \int \tau_{21}\, dV$

  $\langle T_s \rangle$: Column-density-weighted harmonic mean of T_s values.

- N(HI) from Lyman-α absorption or HI 21cm emission ⇨ Infer $\langle T_s \rangle$.

  (e.g. Wakker et al. 2011)

- Low $\langle T_s \rangle$ ⇨ High cold gas (CNM) fraction.

  High $\langle T_s \rangle$ ⇨ High warm gas (WNM) fraction.

- 50% CNM (~100 K) + 50% WNM (~8000 K) ⇨ $\langle T_s \rangle \sim 200$ K;

  10% CNM (~100 K) + 90% WNM (~8000 K) ⇨ $\langle T_s \rangle \sim 900$ K!

- $\langle T_s \rangle$(Galaxy, M31) ~100 – 300 K; $\langle T_s \rangle$(SMC) $\gtrsim$ 450 K.

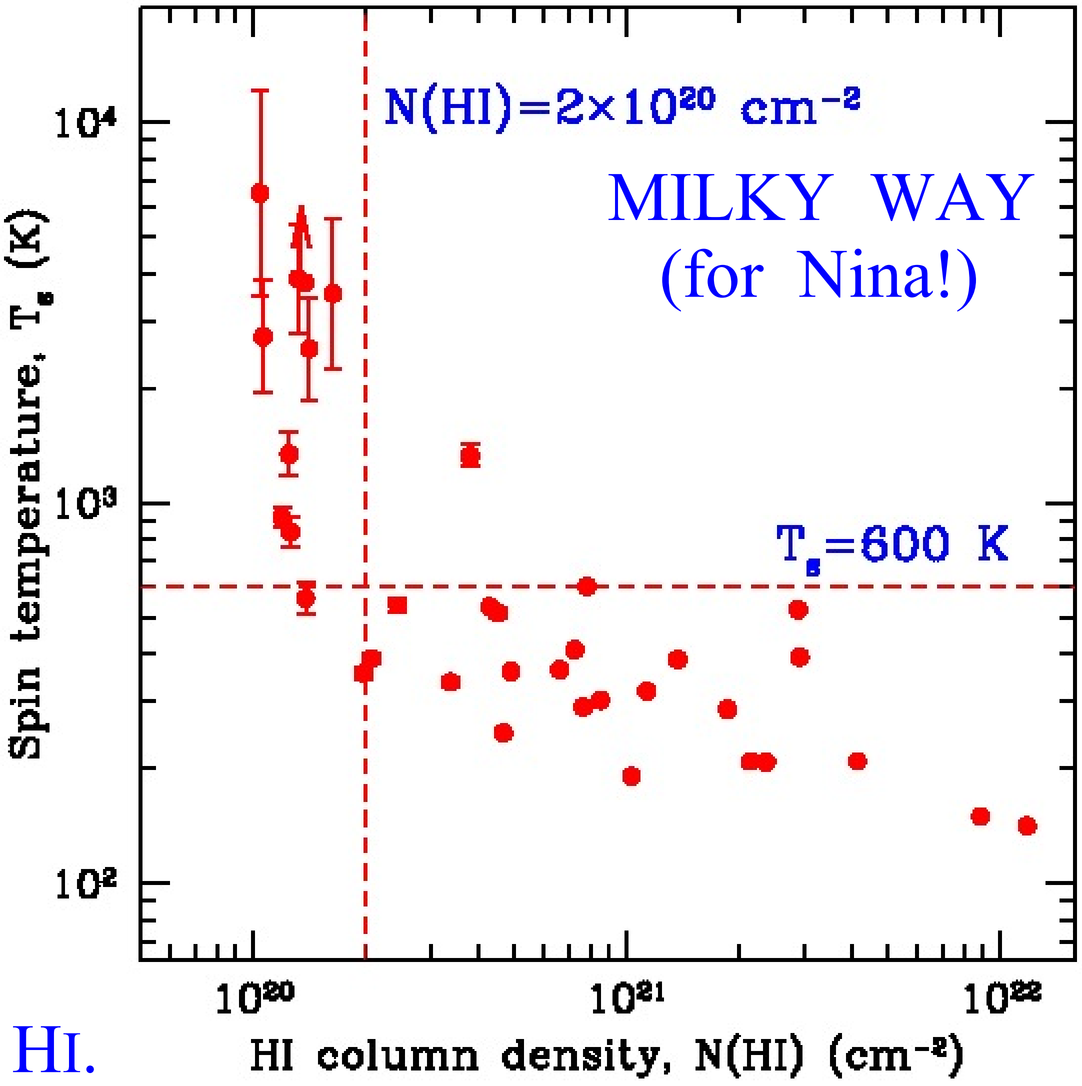
  (e.g. Braun & Walterbos 1992; Dickey et al. 2000; but see Lister's talk!)

- HI 21cm absorption studies of DLAs towards compact radio QSOs

  ⇨ Redshift evolution of the spin temperature in normal galaxies.

AN N(HI) THRESHOLD FOR CNM FORMATION

(NK et al. 2011)



- Median spin temperature:
  ~ 340 K: N(HI) $\gtrsim 2 \times 10^{20}$ cm^{-2},
  ~ 2500 K: N(HI) $< 2 \times 10^{20}$ cm^{-2}.

- Sharp drop in CNM fraction
  for N(HI) $< 2 \times 10^{20}$ cm^{-2}.

- Inefficient self-shielding against soft X-ray / UV photons ? Or vertical dynamical equilibrium yielding WNM-only sightlines ?

(Kim et al. 2014)

- *Four* ISM phase transitions ?

N(HI) ~ 10^{17} cm^{-2} : HII → HII + HI.
N(HI) ~ 2×10^{20} cm^{-2} : Warm HI → Warm HI + Cold HI.
N(HI) ~ 5×10^{20} cm^{-2} : HI → HI + H_2.

(Savage et al. 1977)

N(HI) ~ 10^{22} cm^{-2} : HI → H_2.

(e.g. Schaye 2001; Krumholtz et al. 2009)

HI 21CM ABSORPTION STUDIES OF DLAs

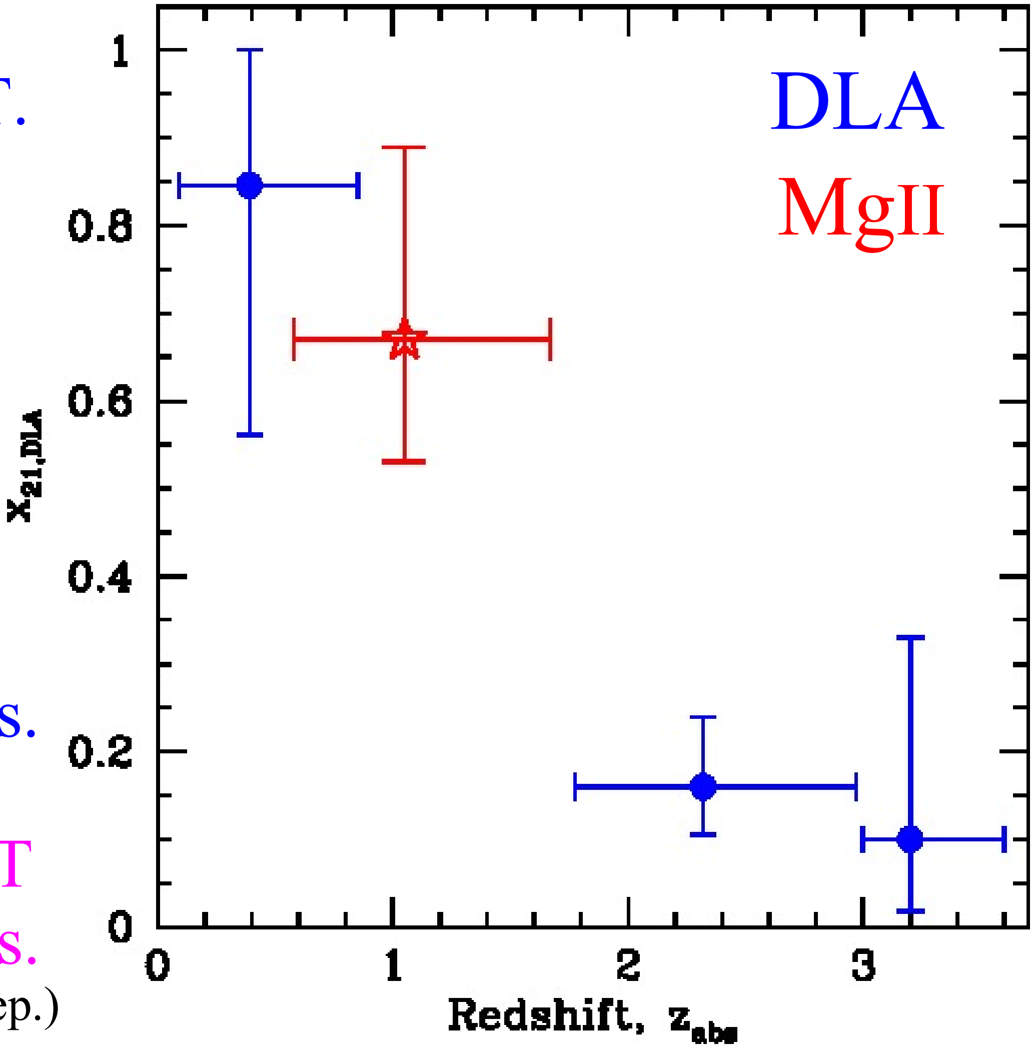
- Searched ~ 50 DLAs and ~120 MgII absorbers with GBT, GMRT.
- ~ 35 new HI 21cm absorption detections, at $0.09 < z < 3.39$.

  ~ 30 lower limits on T_s, > 700 K.

  (NK et al. 2006, 2007, 2014; York et al. 2007)
- Keck, VLT, Gemini, & HST spectroscopy for DLA metallicities.
- 40 DLAs at $z > 1.9$ with u-GMRT 250 – 500 MHz band: 3 detections.

  (Murthy et al., in prep.)

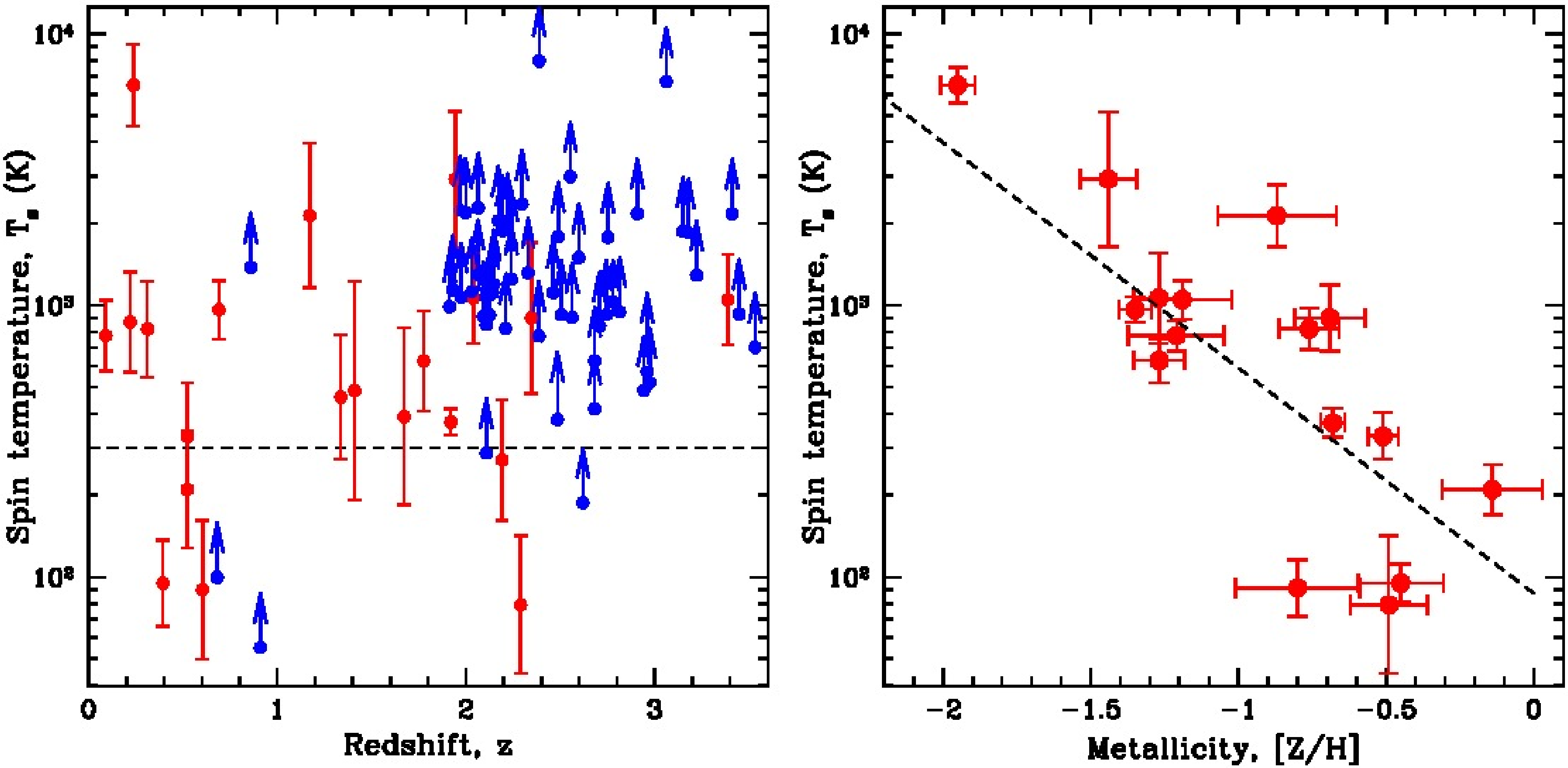
(NK et al. 2009; Murthy et al., in prep.)



- Higher HI 21cm detection rate ⇨ Higher CNM fraction.
- Increasing HI 21cm detection rate with decreasing redshift ⇨ Increasing CNM fraction. Substantial CNM in DLAs by $z \sim 1$.

SPIN TEMPERATURES IN DLAs

(NK et al. 2014; Murthy et al., in prep.)



- Most high-*z* DLAs have high T_s, >> 300 K ⇨ Low CNM fraction, due to low metallicity in high-*z* DLAs: Lack of cooling routes.

(NK & Chengalur 2001; NK et al. 2009)

- Low SFR & metallicity, high T_s: Are most high-*z* DLAs dwarfs ?

THE HOST GALAXIES OF HIGH-*z* DLAs: CO STUDIES

- Chose to initially target high-metallicity DLAs, as the expected low CO-to-H_2 conversion factor gives the best chance of a detection.

- ALMA Cycle-2: Four high-metallicity DLAs at $z \sim 0.1 - 0.8$, in the CO $J = 1 - 0$ or $J = 2 - 1$ lines: First detection, at $z \sim 0.101$.

(Neeleman et al. 2016)

- Used ALMA in Cycles 2 and 3 to target 7 high-metallicity DLAs at $z \sim 0.5 - 0.8$, in the $J = 2 - 1$ line: Five new CO detections. New estimates of stellar mass, SFR: Gas fractions, depletion times.

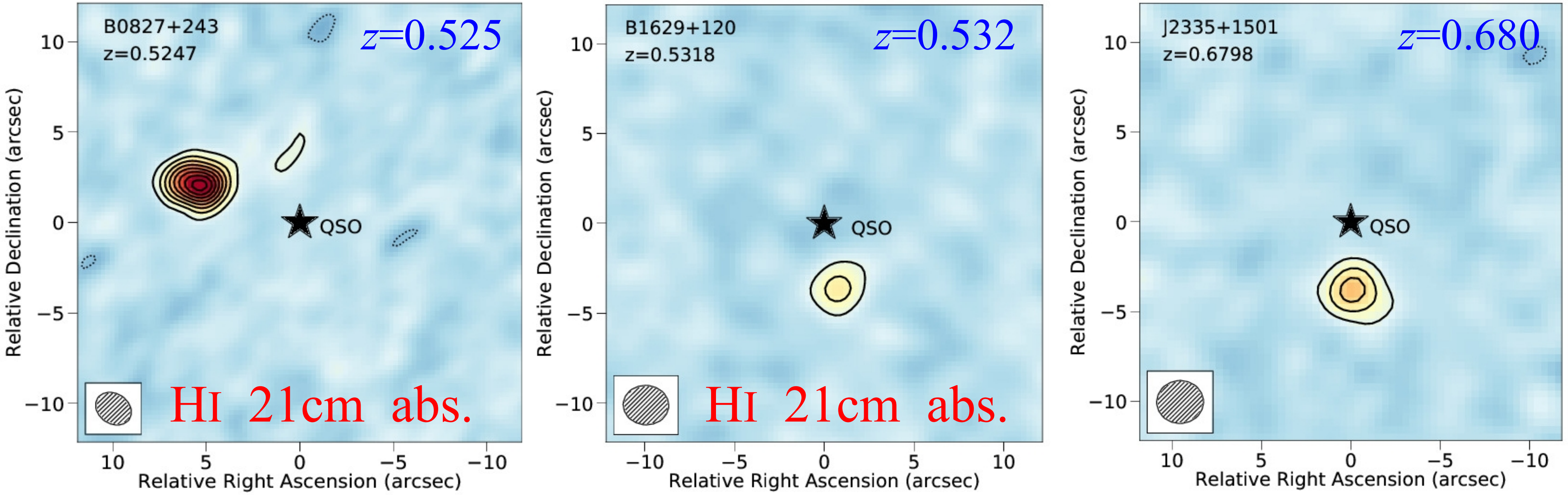
(Moller et al. 2018; NK et al. 2018)

- Pushed to $z \sim 2$ in Cycle-4: First high-*z* CO detection, at $z \sim 2.2$.

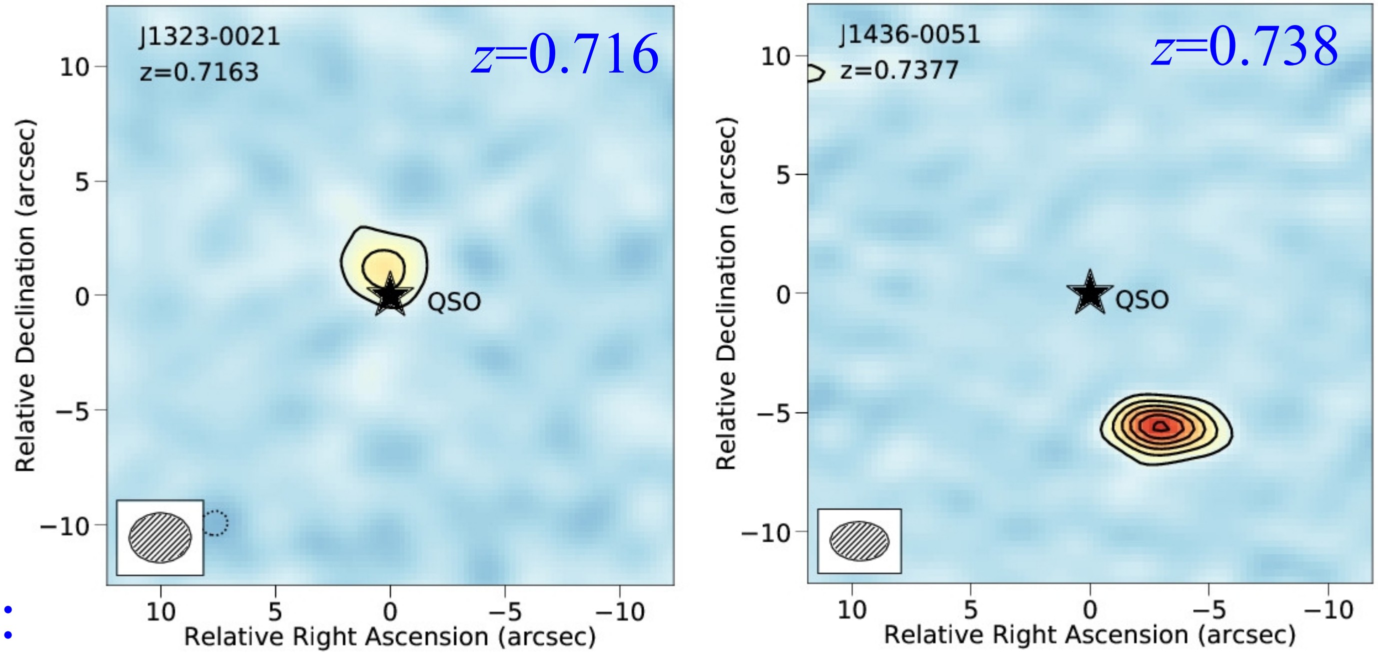
(Neeleman, NK et al. 2018)

- Observing 10 high-metallicity DLAs at $z \sim 2$ in ALMA Cycle-5, and 6 northern DLAs at $z \sim 2$ with NOEMA: Three more CO detections last week!

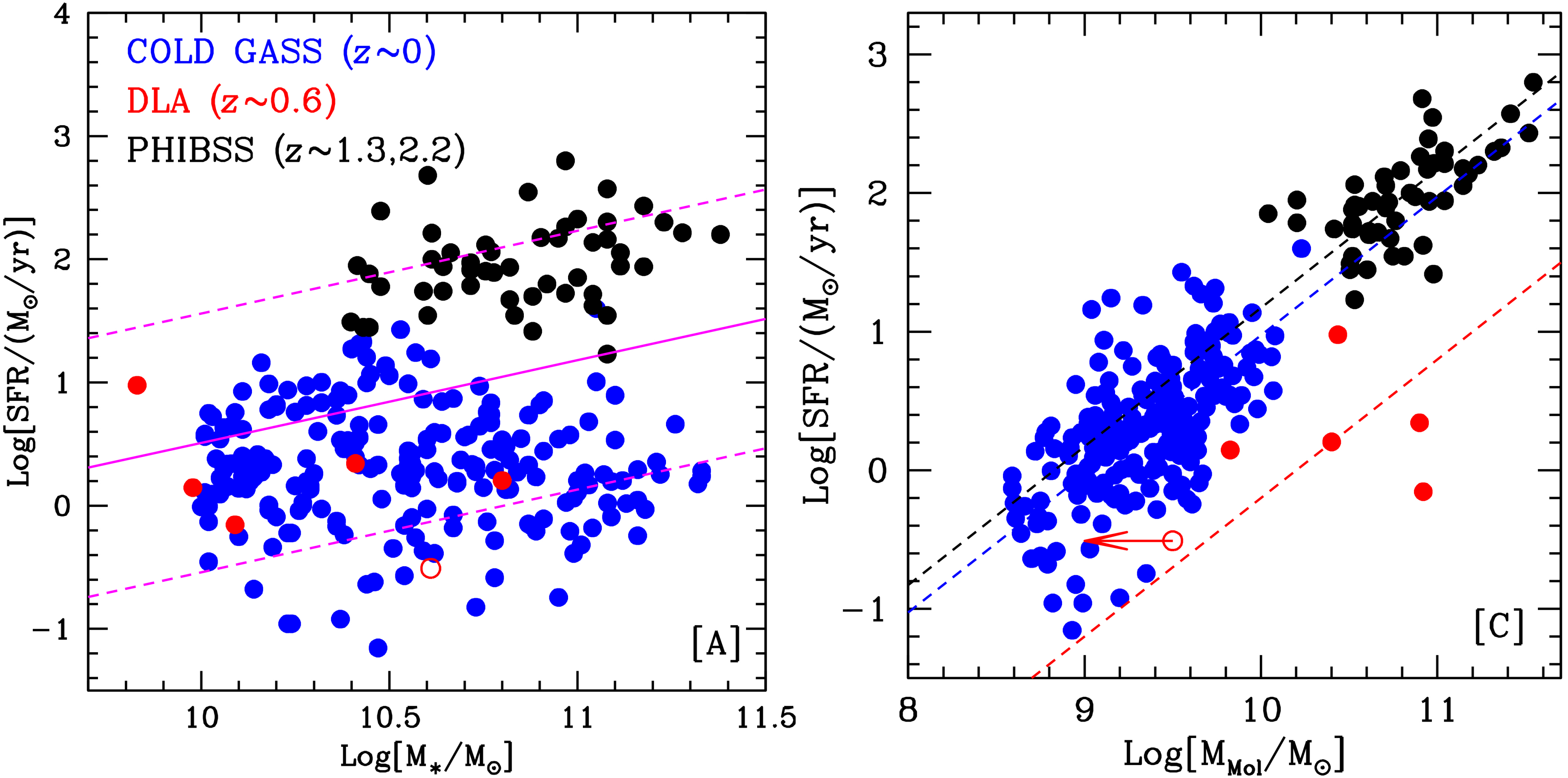
CO EMISSION FROM INTERMEDIATE-z DLAS



- Five CO detections! High gas masses: $(0.6 - 8) \times 10^{10}\ M_{\odot}$!
- Optical images show normal disk galaxies.
- Extended emission in four DLAs (> 15 kpc): Big galaxies!



(NK et al. 2018)



(Saintonge et al. 2011; Tacconi et al. 2013)

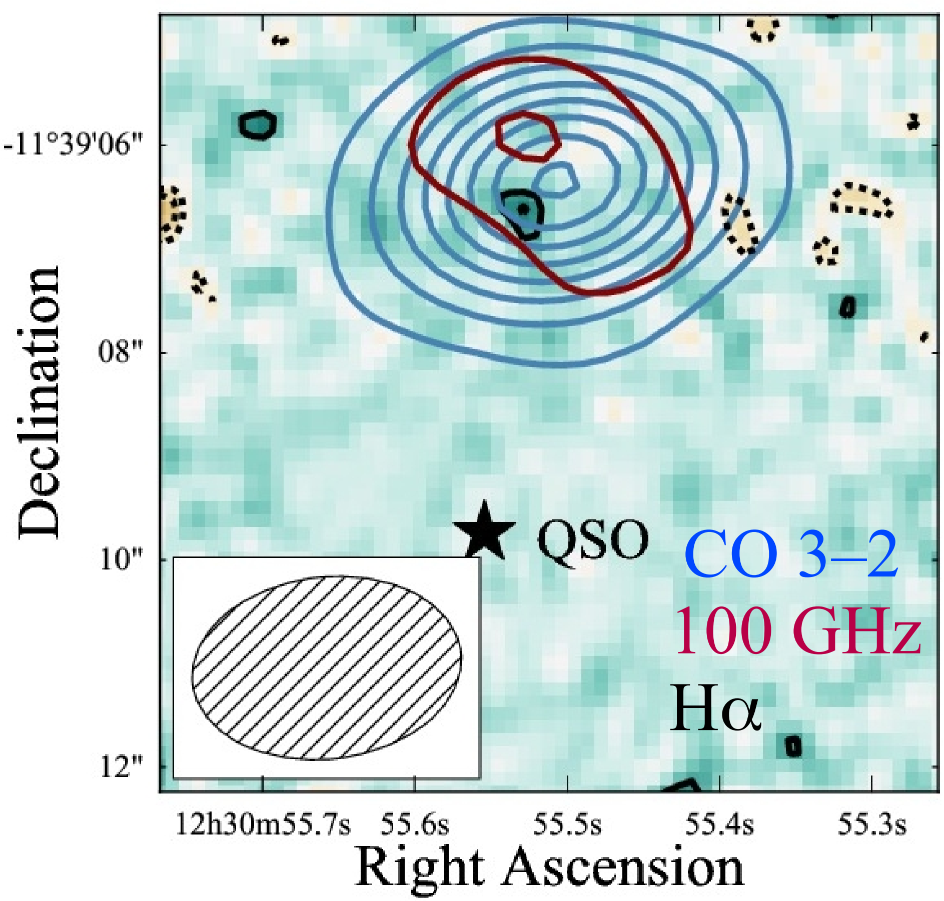
- Appear to be "normal" main-sequence galaxies in optical properties. But large gas depletion times, ~10 Gyr, and large gas fractions! Very different from star-forming galaxies at $z \sim 0$ and $z \sim 1.3$!

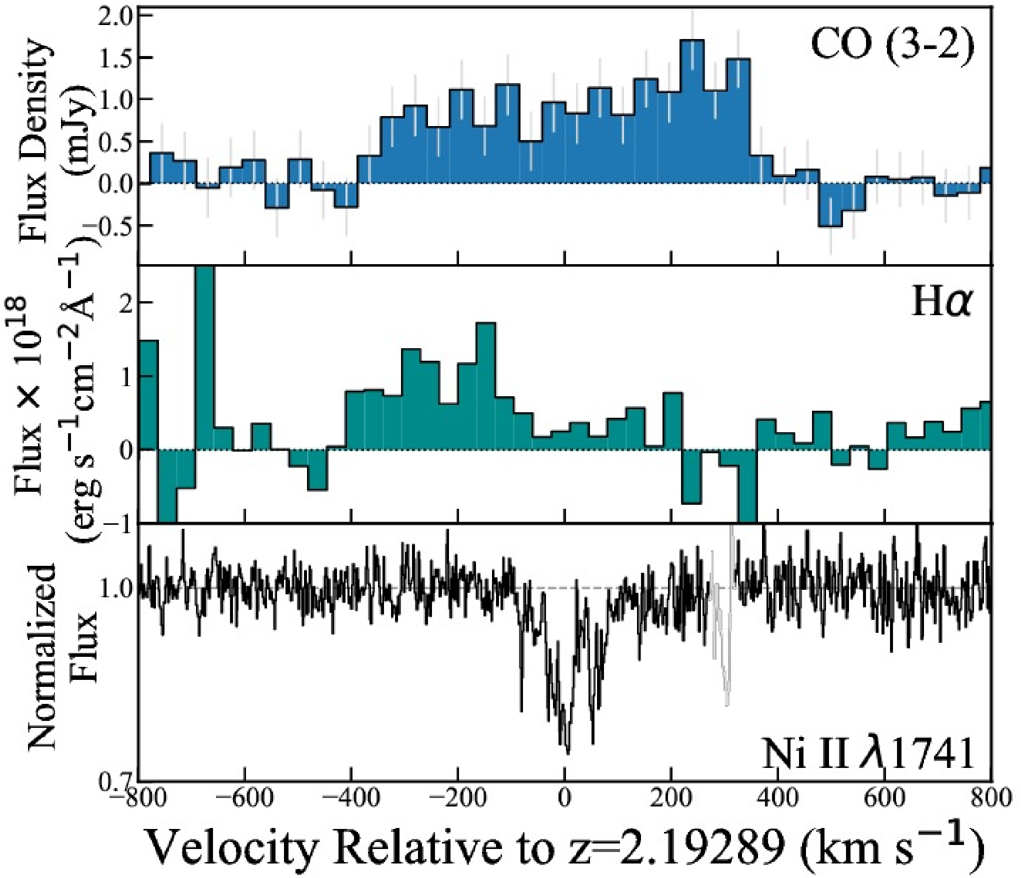
- Transition in the nature of star formation at intermediate redshifts? Or does absorption selection pick out "different" galaxies?

(NK et al. 2018)

THE $z \sim 2.193$ DLA TOWARDS B1228-113

(Neeleman, NK et al. 2018)





- Very high molecular gas mass: $1.9 \times 10^{11}\ M_\odot$, for $\alpha_{CO} \sim 4.3$!
  SFR (Hα) ~ 3.9 $M_\odot$/yr. SFR (100 GHz) ~ 110 $M_\odot$/yr ⇨ Dusty galaxy!
  Large impact parameter ~ 30 kpc. Gas depletion time ~ 1.8 Gyr.

- But, no u-GMRT HI 21cm absorption ⇨ Spin temperature > 1900 K!

AND… CII-158μM EMISSION FROM HIGH-*z* DLAS

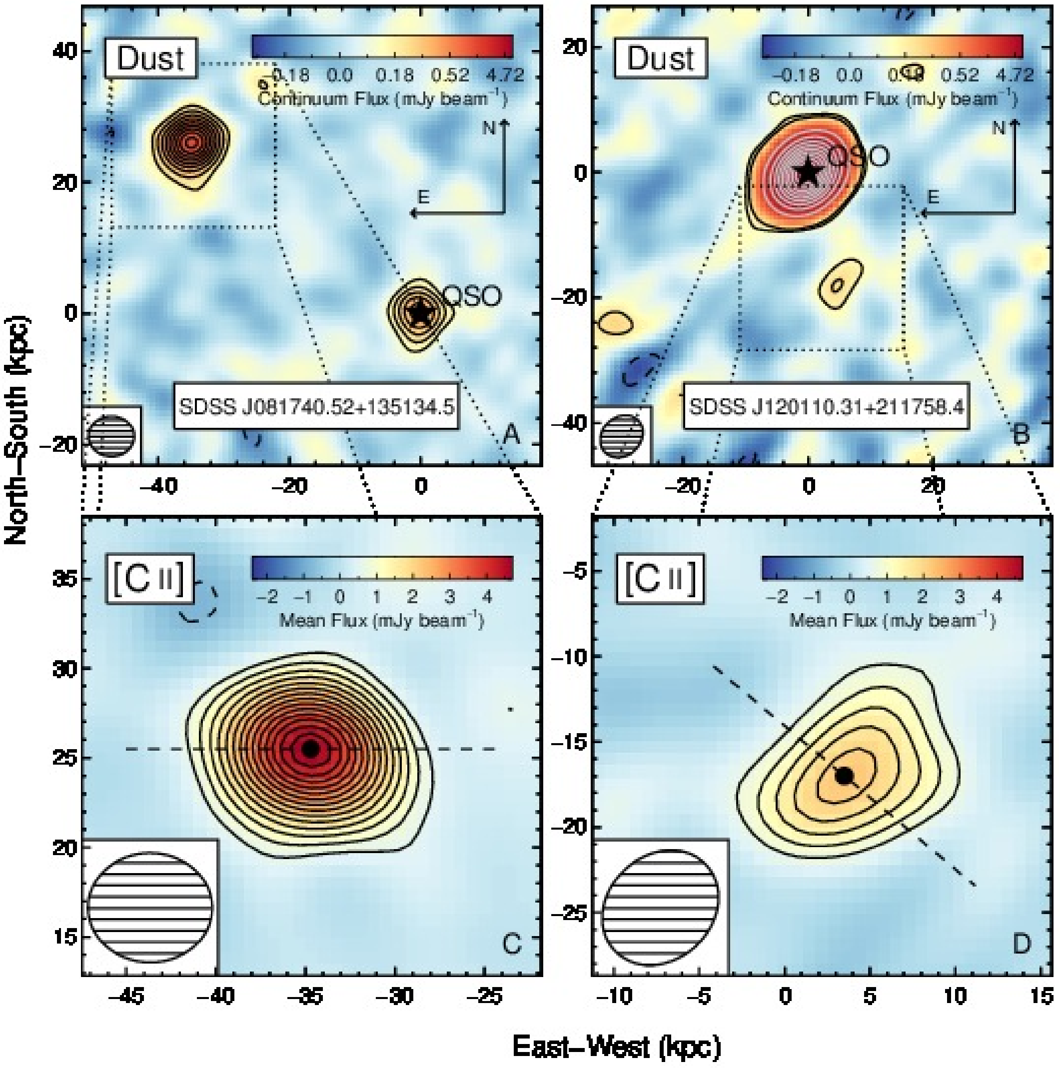
(Neeleman, NK, et al., 2017; NK et al., in prep.)

- ALMA detections of CII-158μm emission in 5 of 6 DLAs at $z \sim 4$, selected to have a high metallicity (~ 0.1 solar)!

- SFRs ~ 10 – 110 $M_\odot$/yr from the dust continua.

- Impact parameters: 15 – 45 kpc!

- Optically faint: Dusty galaxies? Recent weak HST detection of one system.



SUMMARY

- An N(HI) threshold, at $N(\mathrm{HI}) = 2 \times 10^{20}$ cm^{-2}, for CNM formation.

- HI 21cm absorption searches in ~ 90 DLAs, ~ 200 MgII absorbers:
  - Detections: ~15 at $z < 1$ ~25 at $1 < z < 2$
    5 at $2 < z < 3$ 2 at $z > 3$.

- Clear increase of HI 21 cm detection rate with decreasing redshift. High spin temperatures in DLAs at $z > 2$, typically >~ 1000 K. HI in typical high-z DLAs appears to be predominantly warm. Just 7 detections of absorption in ~ 50 DLAs at $z > 2$.

- High-metallicity DLAs at $z \sim 0.7$ have low SFRs for their gas mass. Transition galaxies at intermediate redshift? Or does the absorption selection pick out "different" galaxies?

- Large molecular gas masses in high-metallicity DLAs at $z \sim 2$.

- First detections of CII-158μm emission in DLAs at $z \sim 4$! Two mapping studies so far: One rotating disk, one messy system.