# Cold Gas at High Redshift: CO and CII-158μm Studies of Damped Lyman-α Absorbers


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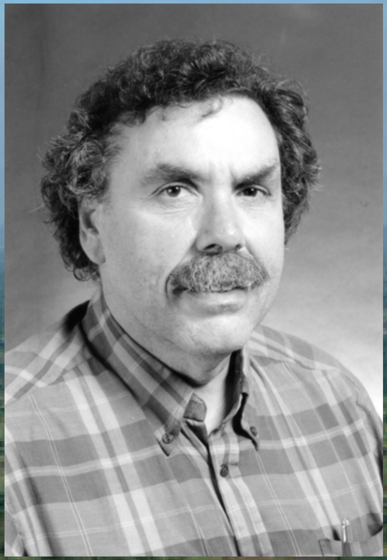


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Image: B. Premkumar

# Outline

- The high-$z$ galaxy zoo (i.e. why do folks care about DLAs?).
- The host galaxies of DLAs.
- Gas in galaxies: The CO and CII-158μm emission lines.
- CO emission studies of DLAs at $z \sim 0.1 - 2.5$.
- CII-158μm emission studies of DLAs at $z \sim 4$.
- 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 (selected based on luminosity) ⇨
  Strong bias toward bright galaxies!
  e.g. Quasars, Sub-mm galaxies, Lyman-break galaxies,
  Lyman-$\alpha$ emitters, BzK galaxies, radio galaxies, etc.
  (e.g. Chambers et al. 1987, Nature; Hu et al. 1996, Nature; Hughes et al. 1998, Nature; Steidel et al. 1999, ApJ; Daddi et al. 2006, ApJL; Fan et al. 2003, ApJ)

- Absorption-selected samples (selected based on absorption lines in QSO spectra) ⇨ "Normal" galaxies! (weak bias toward large galaxies)
  e.g. Damped Lyman-$\alpha$ absorbers (DLAs), MgII absorbers.
  (e.g. Wolfe et al. 1986, ApJS; Sargent et al. 1988, ApJ)

# Damped Lyman-α Absorbers (DLAs)

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

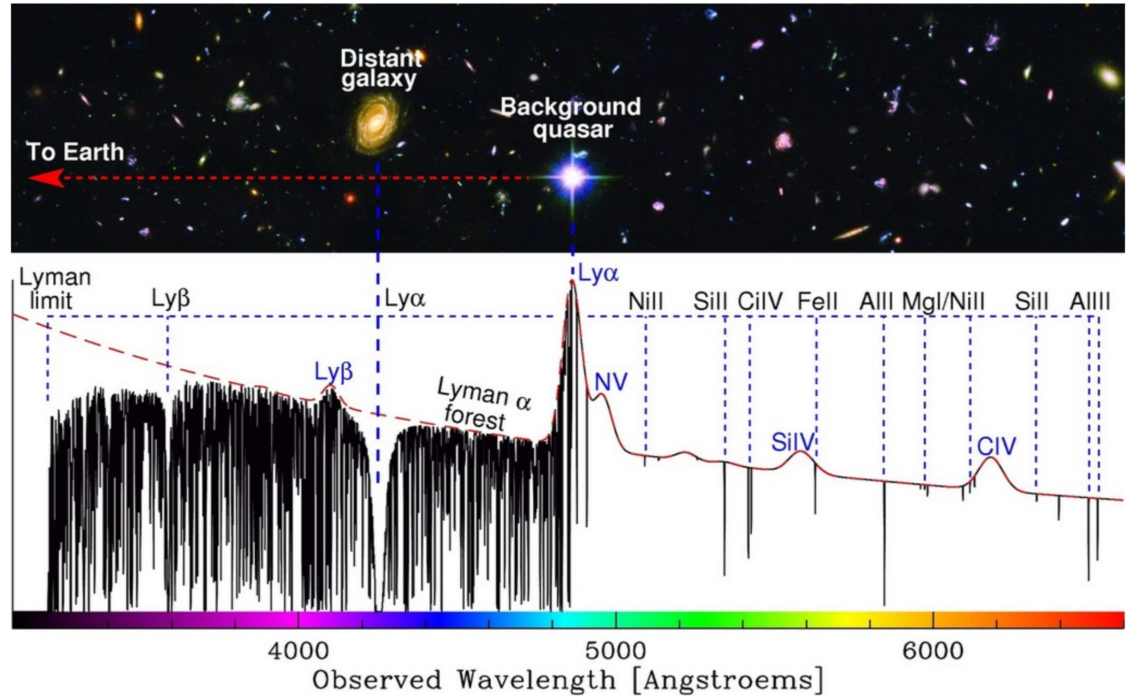
- High N(HI) $\geq 2 \times 10^{20}$ cm$^{-2}$.

  (Wolfe et al. 1986, ApJS)

- No luminosity bias: Normal gas-rich galaxies!

- SDSS-DR12: ~10,000 DLAs at $z > 2$. Only ~ 60 at $z < 1.7$!

  (e.g. Noterdaeme et al. 2012, A&A)




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

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

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

- HI 21cm absorption studies: High spin temperatures, >~ 1000 K.

  $H_2$ absorption studies: Low $H_2$ fractions: N($H_2$)/N(HI) <~ $10^{-6}$.

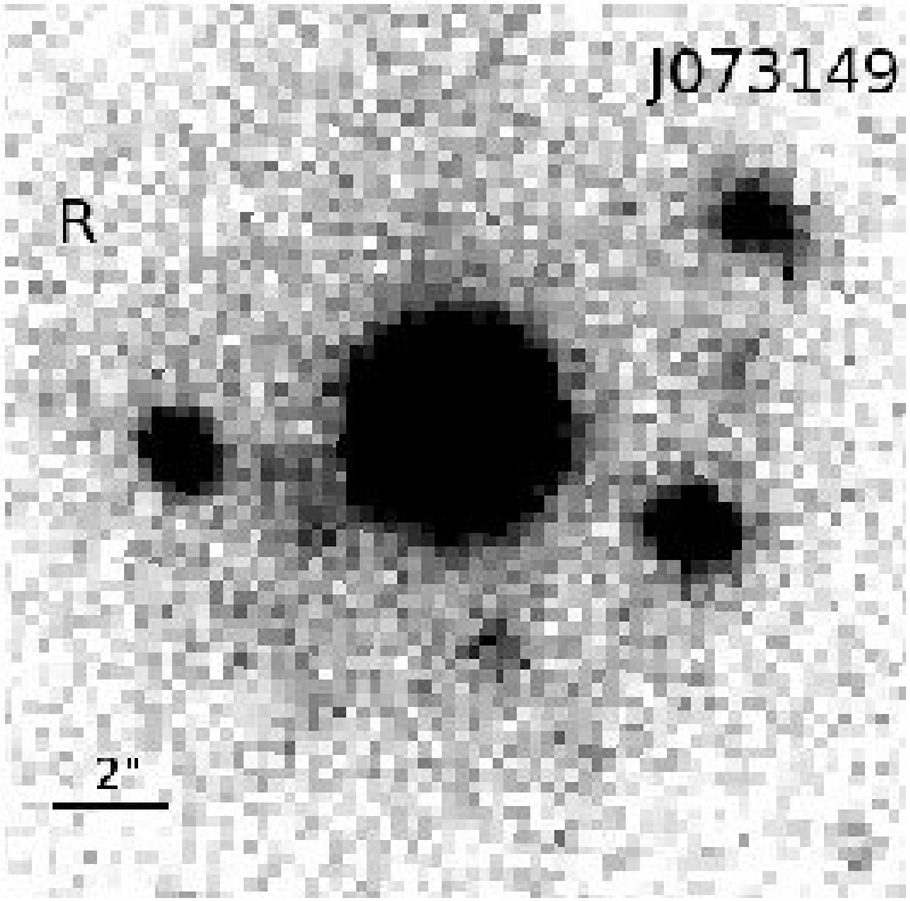
  (e.g. Noterdaeme et al. 2008, A&A; NK et al. 2014, MNRAS)

- What galaxies host DLAs? Big disks or small merging galaxies? Are they similar to emission-selected galaxies?

  (e.g. Prochaska & Wolfe 1997, ApJ)

# The Host Galaxies of DLAs

- What galaxies host DLAs? Mass, morphology, size, SFR, …
  Optical identification difficult due to the bright background QSO!




(Fumagalli et al. 2010, MNRAS)

- "Some" information on the stellar properties of ~ 15 DLA hosts at $z \sim 2$.
  ⇨ Relatively low SFRs, <~ 1 – 10 $M_\odot$/yr, in high-metallicity DLAs.
  Relatively low impact parameters, <~ 10 kpc.

(e.g. Krogager et al. 2017, MNRAS)

# GAS IN HIGH-$z$ GALAXIES: TRACERS

- Best probes of gas in local galaxies: HI 21cm, CO, and CII-158μm lines. Weakness of the HI 21cm line ⇨ Detected in only 5 DLAs, at $z < 0.1$.
  (e.g. Bowen et al. 2001, A&A; NK et al. 2018, MNRAS)

- CO mm-wave rotational lines: Best tracer of diffuse molecular gas. Good probe of kinematics in the star-forming disk of a galaxy. CO-to-$H_2$ conversion factor depends on galaxy type, metallicity: For spirals, $\alpha_{CO} \sim 4$; for ULIRGS, $\alpha_{CO} \sim 1$; for dwarfs, $\alpha_{CO} > 10$.
  (e.g. Bolatto et al. 2013, ARA&A; Carilli & Walter 2013, ARA&A)

- CII-158μm emission (~ 1.9 THz): Strongest cooling line in most galaxies! Traces atomic & molecular gas, and photo-dissociation regions. CII-158μm line luminosity correlates with SFR. Optically thin, so provides a good probe of galaxy kinematics!
  (e.g. Stacey et al. 1991, ApJ; de Looze et al. 2011, A&A)

- Before ALMA: Low mm-wave sensitivity ⇨ Few CO searches in DLAs. Atomic THz fine structure lines (e.g. CII, OI): *Terra incognita*.
  (e.g. Frayer et al. 1994, ApJ; Wiklind & Combes 1995, A&A; Ivison et al. 1998, MNRAS)

# CO Emission from DLAs at $z \sim 0.1 - 2.5$

- 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, ApJL)

- 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.
(Møller et al. 2018, MNRAS; NK et al. 2018, ApJL)

- Pushed to $z \sim 2$ in Cycle-4: First high-$z$ CO J = 3 – 2 detection, at $z \sim 2.2$. Second CO detection, from a companion (*not* the DLA host!) at $z \sim 2.5$.
(Neeleman, NK et al. 2018, ApJL; Fynbo et al. 2018, MNRAS)

- Observing 10 high-metallicity DLAs at $z \sim 2$ in ALMA Cycle-5, and 6 northern DLAs at $z \sim 2$ with NOEMA: Four new ALMA CO J = 3 – 2 detections two weeks ago!

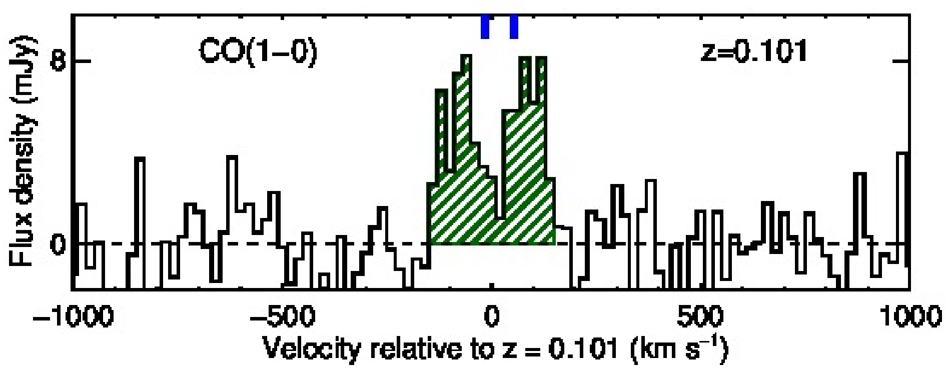
# THE $z \sim 0.101$ SUB-DLA TOWARDS 0439-433

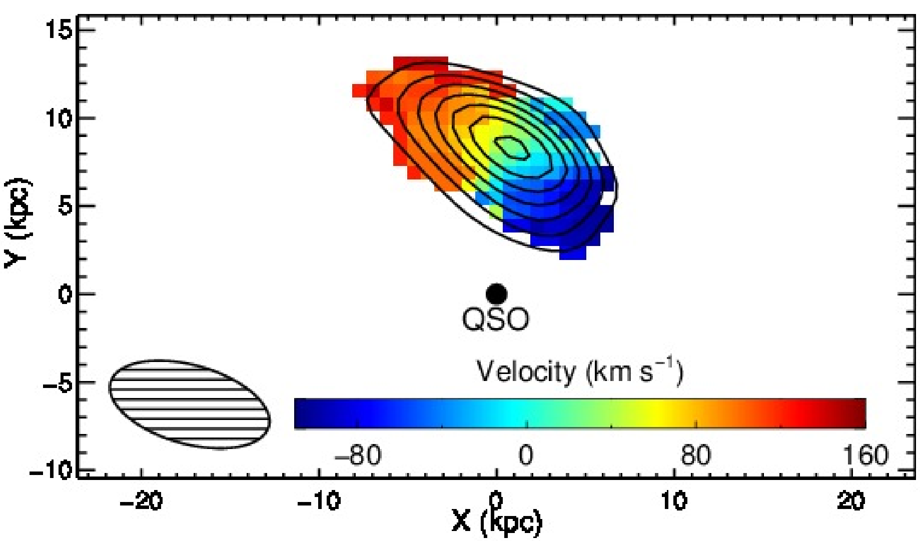
(Neeleman et al. 2016, ApJL)

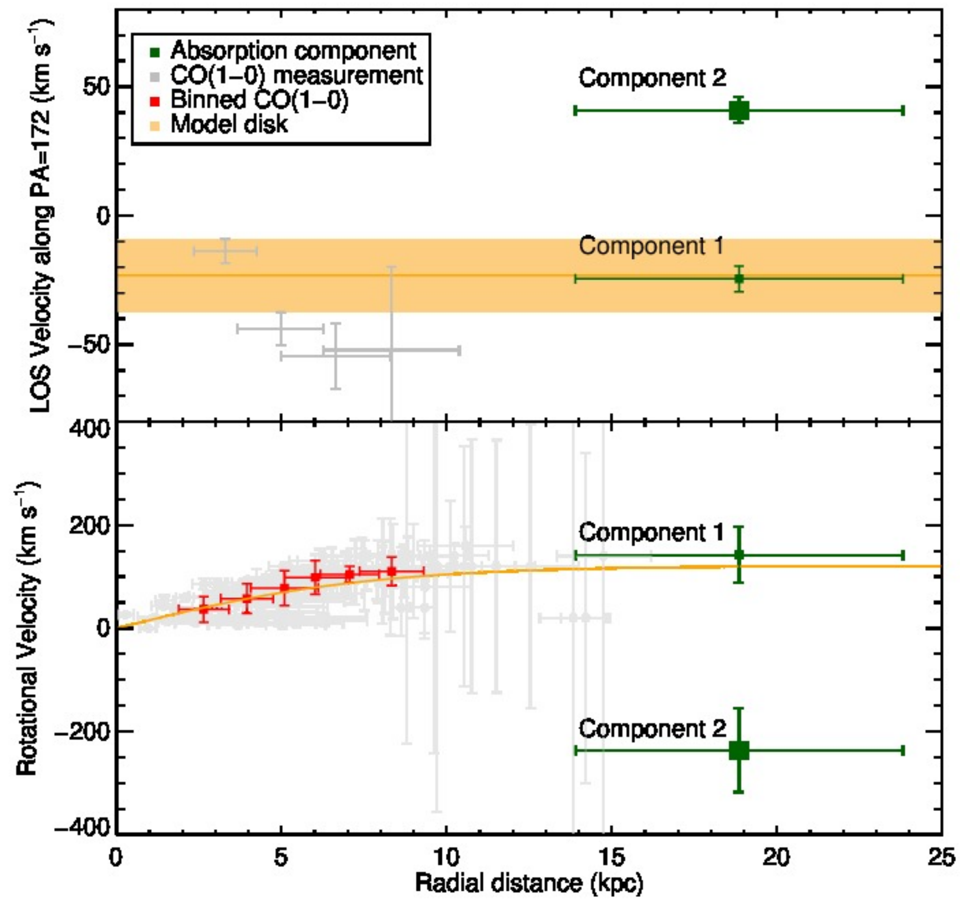
- First detection of CO emission in an absorption-selected galaxy. Molecular gas mass $\sim 4.2 \times 10^9\ M_\odot$, larger than limit on the HI mass!

(NK et al. 2001, A&A-L)

- Clear rotating molecular disk, extending out to ~ 15 kpc. Strong ultraviolet $H_2$ absorption arises from the circumgalactic medium!



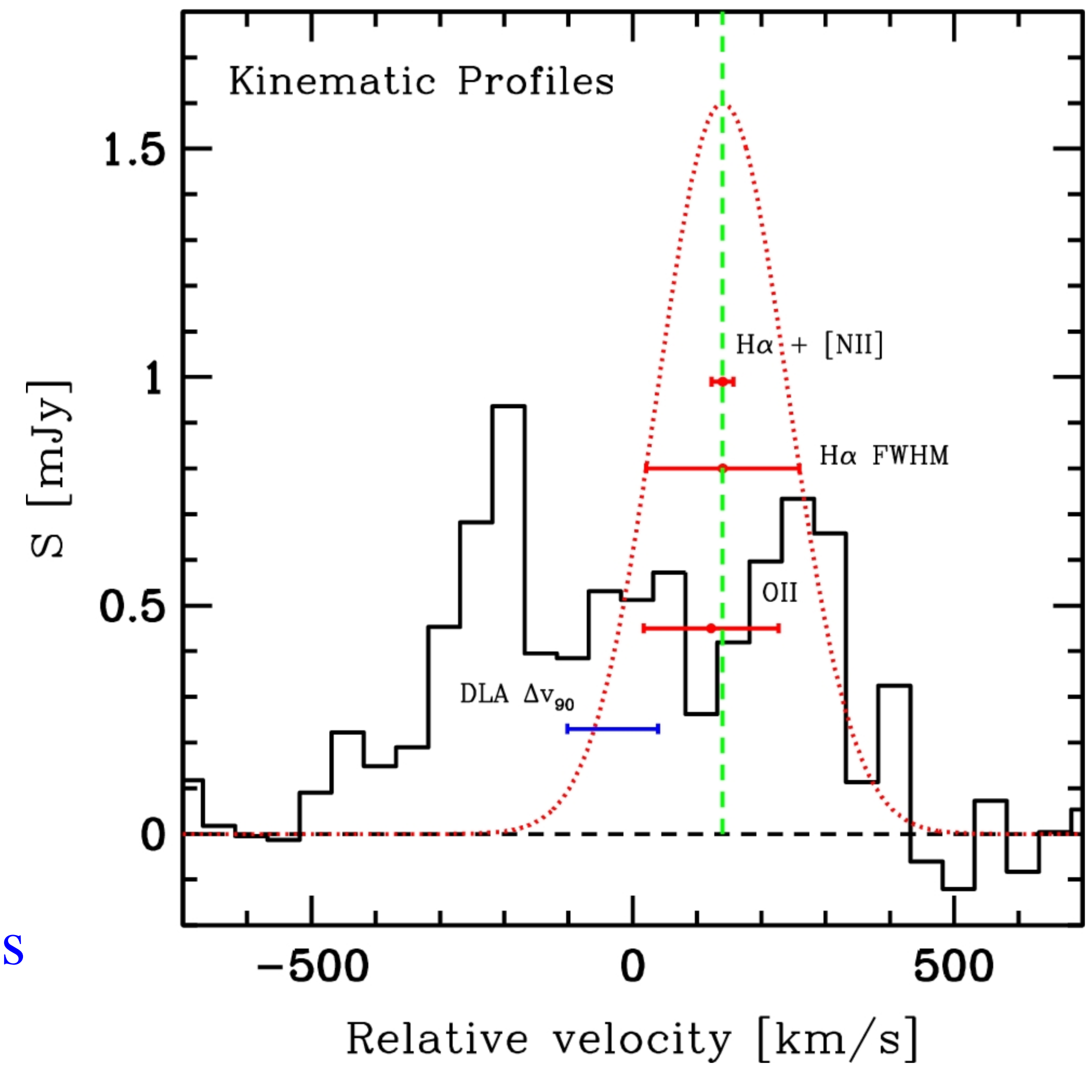



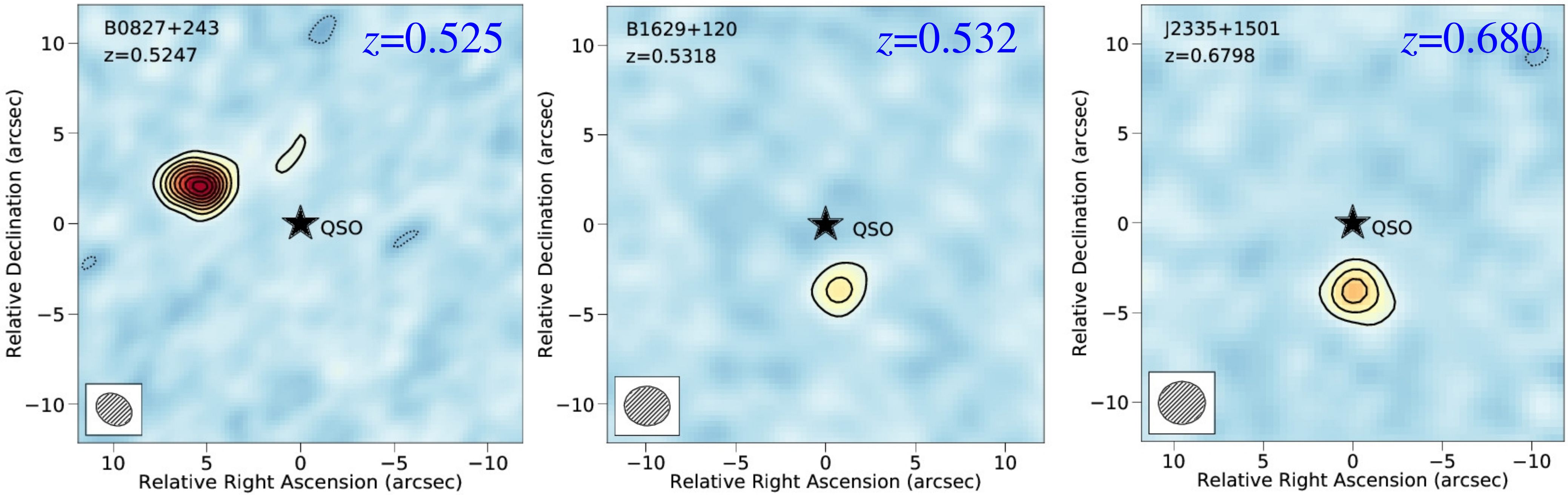
# THE $z \sim 0.716$ DLA TOWARDS J1323-0021

(Møller et al. 2018, MNRAS)

- High molecular gas mass, $2.3 \times 10^{10}\ M_\odot$ (assuming $\alpha_{CO} \sim 4.3$).
- Very wide CO emission, ~ 800 km/s between 20% points.
- VLT FORS2, SINFONI coverage: OII and Hα emission lines!
- Optical emission, UV absorption from only one CO component. "Dark" second CO component!
- Low SFR: $1.6\ M_\odot$/yr (Hα line);
  : $4.5\ M_\odot$/yr (Far-IR).
- High stellar mass, $7 \times 10^{10}\ M_\odot$.
- Very low SFR for the stellar mass and the gas mass!



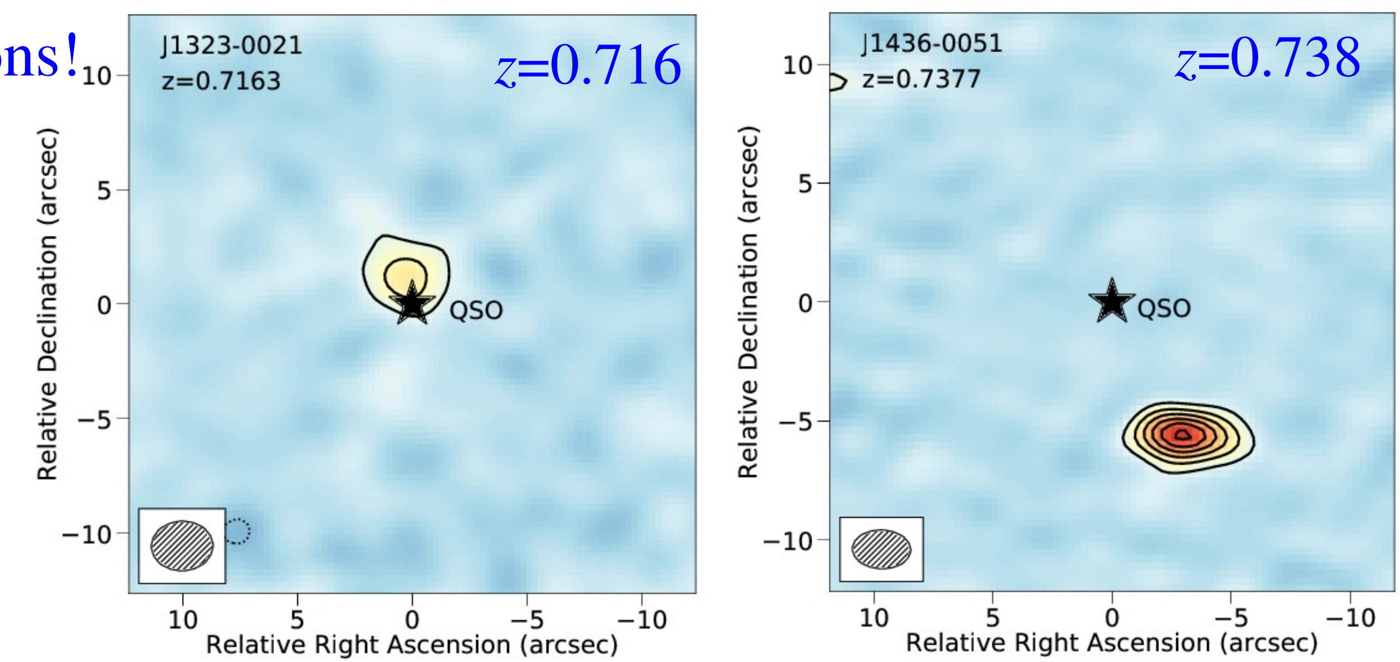
# CO Emission from Intermediate-$z$ DLAs



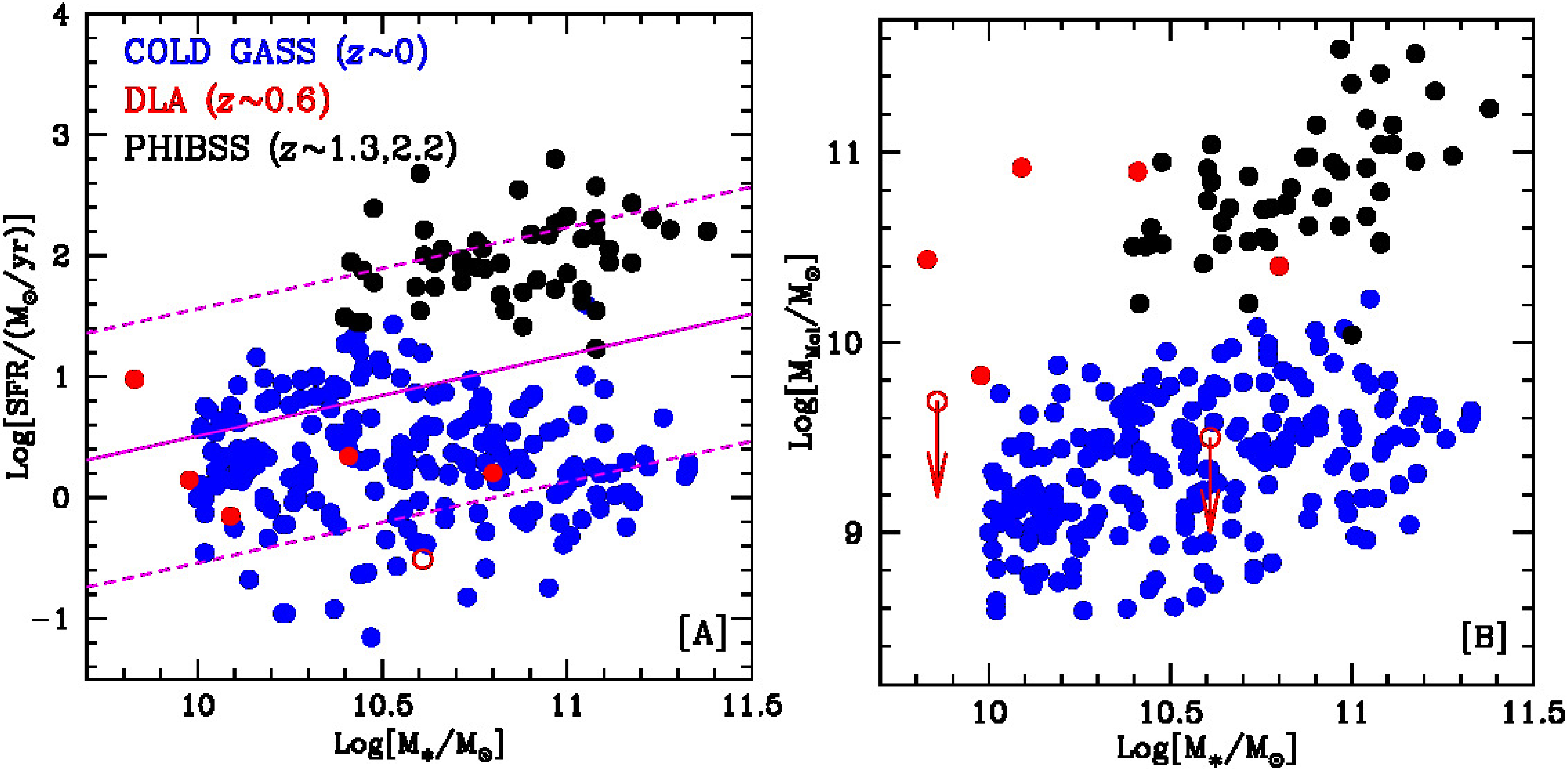

- Five CO (2 – 1) detections! High gas masses: $(0.6 – 8) \times 10^{10}$ $M_\odot$!

- Optical images show normal disk galaxies.

- Extended emission in four DLAs (> 15 kpc): Big galaxies!




(NK et al. 2018, ApJL)

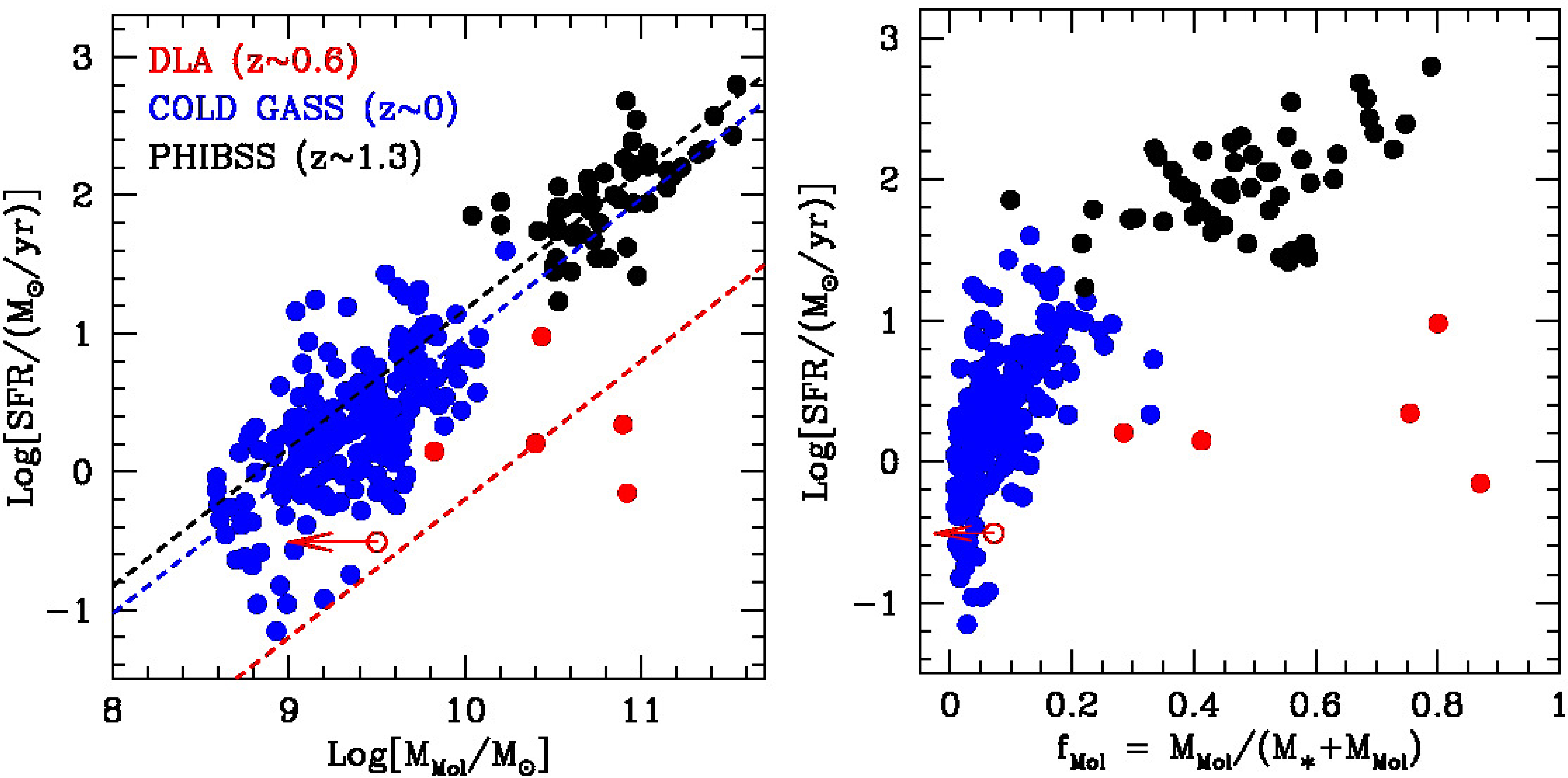



(Saintonge et al. 2011, ApJ; Tacconi et al. 2013, MNRAS)

- Low SFRs, $\sim 0.3 - 9.5\ M_\odot/yr$, & low stellar masses, $\sim (0.6 - 6) \times 10^{10}\ M_\odot$. Appear to be “normal” main-sequence galaxies in optical properties.

- Higher molecular gas mass in galaxies associated with DLAs than in galaxies with the same stellar mass at $z \sim 0$.

(NK et al. 2018, ApJL)



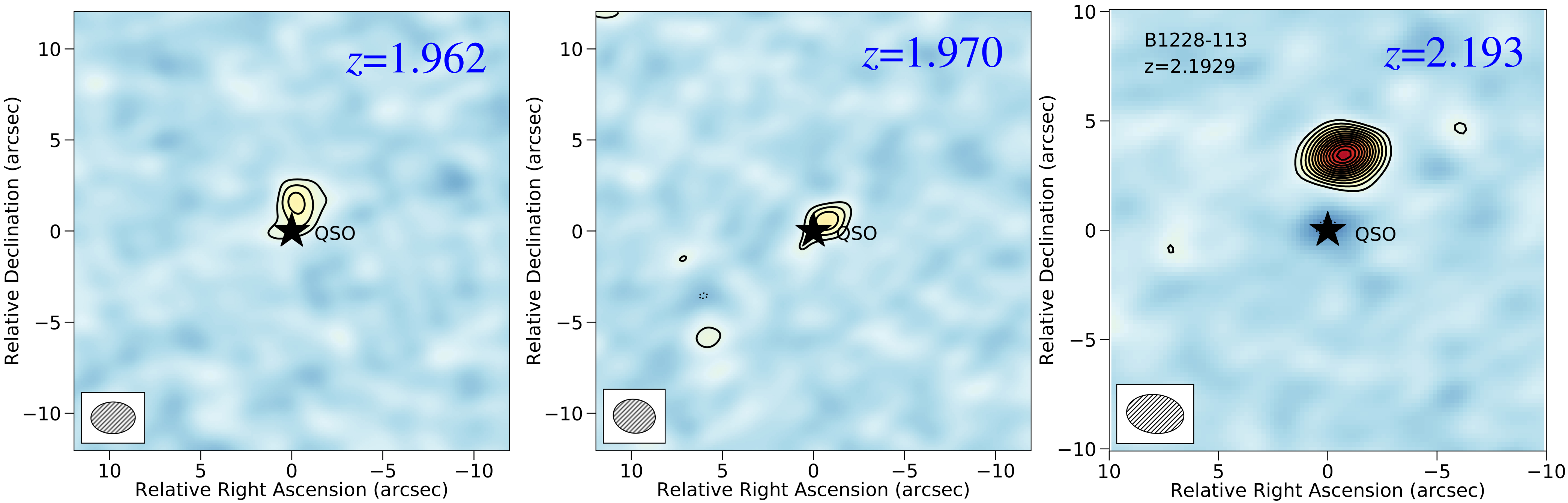

- But large gas depletion times, ~10 Gyr, and large gas fractions!
  Very different from star-forming galaxies at $z \sim 0$ and $z \sim 1.3$!
  (Saintonge et al. 2011, ApJ; Tacconi et al. 2013, MNRAS)

- Transition in the nature of star formation at intermediate redshifts?
  Or is the absorption selection picking out "different" galaxies?
  Milky Way SFR dropped by an order of magnitude ~ 8 – 10 Gyrs ago!
  (Haywood et al. 2016, A&A; NK et al. 2018, ApJL)

# CO Emission from High-$z$ DLAs

- Used ALMA to search for CO J=3 – 2 emission in high-metallicity DLAs.

- Six CO detections in nine DLAs at $z \sim 2$, all at $> 4.5\sigma$ significance!

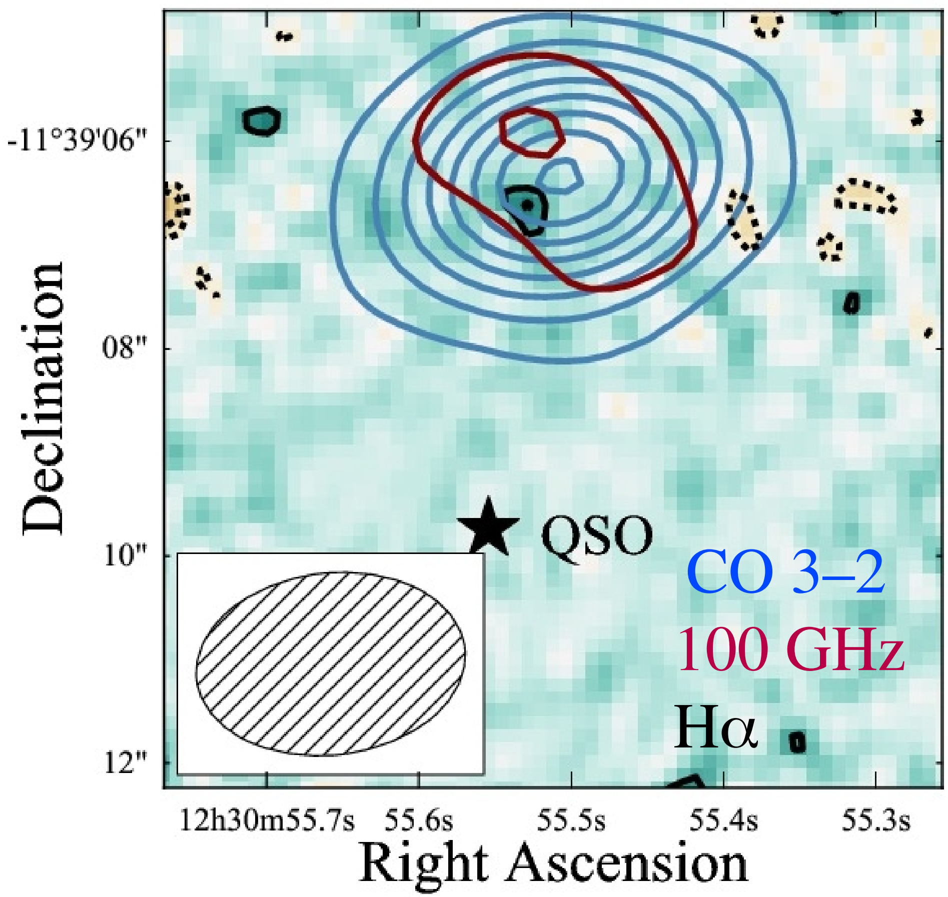


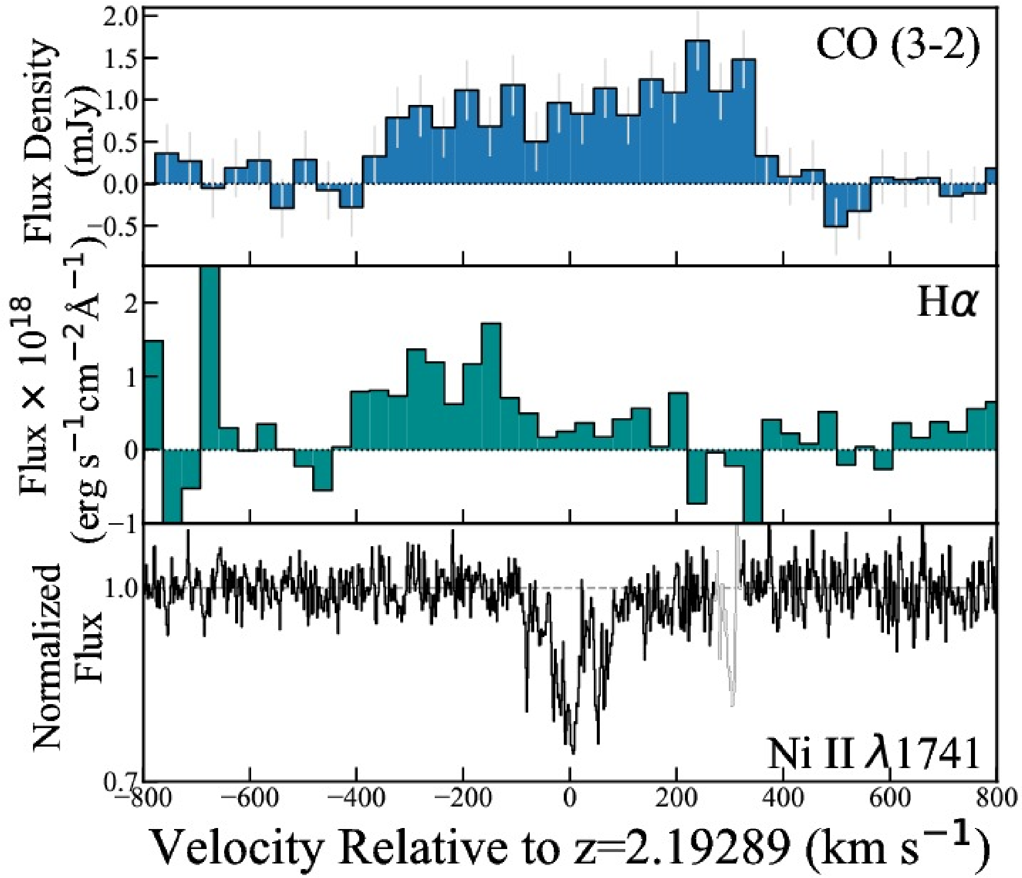

- Relatively large impact parameters: 10 – 30 kpc.
  High molecular gas masses: $2 - 20 \times 10^{10}\ M_\odot$.

- Next step: SFRs and stellar masses from optical imaging, spectroscopy.
  Extend to low-metallicity DLAs at similar redshifts.

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

(Neeleman, NK et al. 2018, ApJL)




- 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 GMRT HI 21cm absorption ⇨ DLA spin temperature > 1900 K!

# CII-158μm Emission from High-$z$ DLAs

- Chose to initially target high-metallicity DLAs (likely to have the highest SFR, and so the highest CII-158μm line luminosity).

- Lots of high-metallicity DLAs at $z \sim 2$. But would need ALMA Band-9 (~ 630 GHz!), i.e. outstanding weather conditions!

- Used ALMA in Cycle-1 to target 2 high-metallicity DLAs at $z \sim 2$: Relatively poor data quality; one tentative detection (PI: Wolfe!).

- Used Keck-HIRES to measure metallicities of a bunch of DLAs at $z \sim 4$.

- Used ALMA in Cycle-3 to target 3 high-metallicity DLAs at $z \sim 4$.

- Used ALMA in Cycle-5 to target seven high-metallicity DLAs at $z \sim 4.3$.

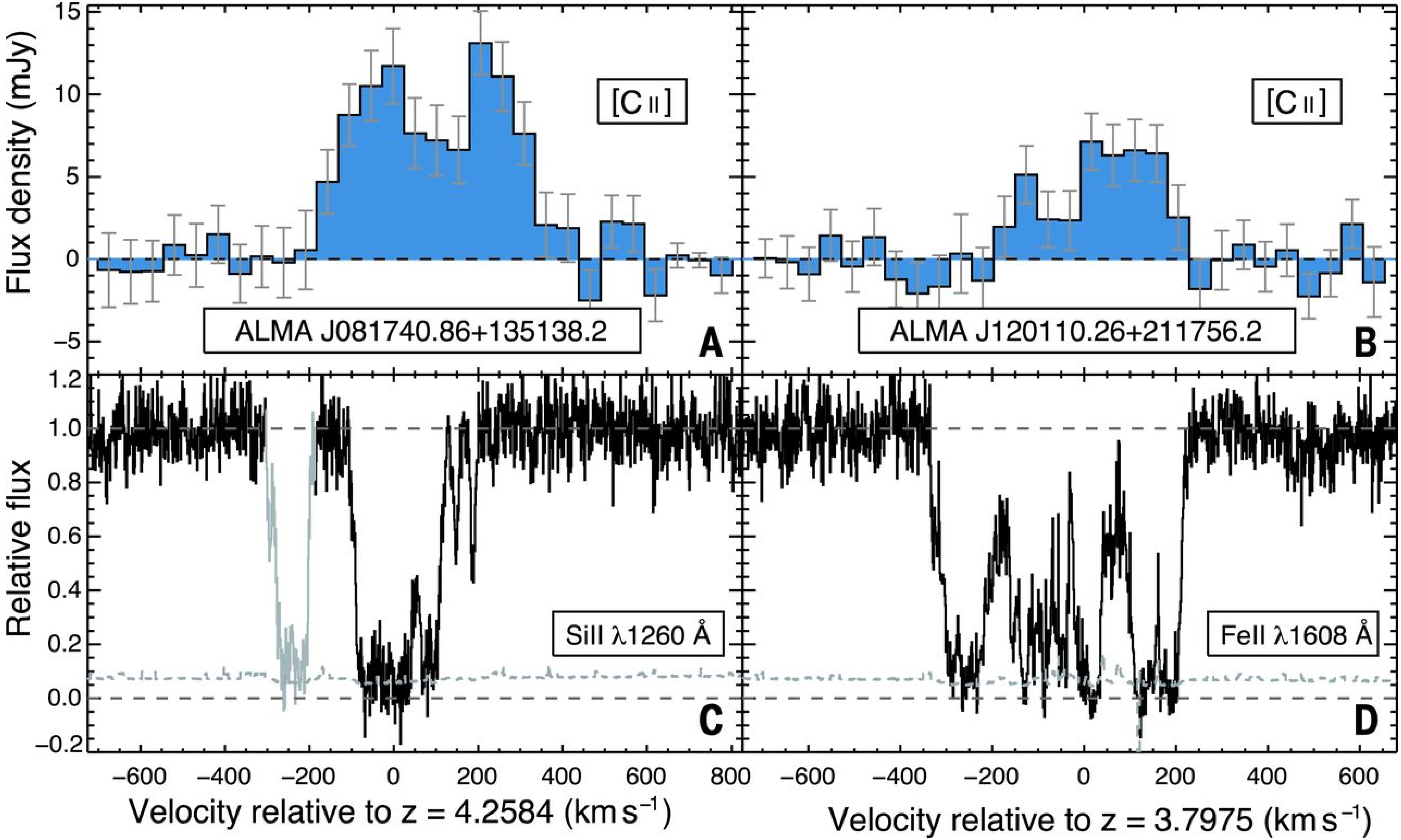
- Now using ALMA in Cycle-6 to target 9 DLAs at $z \sim 4.1 - 4.5$, covering *all* DLAs in this redshift range that are observable with ALMA.

# CII-158μM EMISSION FROM HIGH-$z$ DLAs

(Neeleman, NK, et al., 2017, Science)

- Wide CII-158μm emission, 400 – 600 km/s between nulls.

J0817+1315, $z = 4.258$ J1201+2117, $z = 3.788$

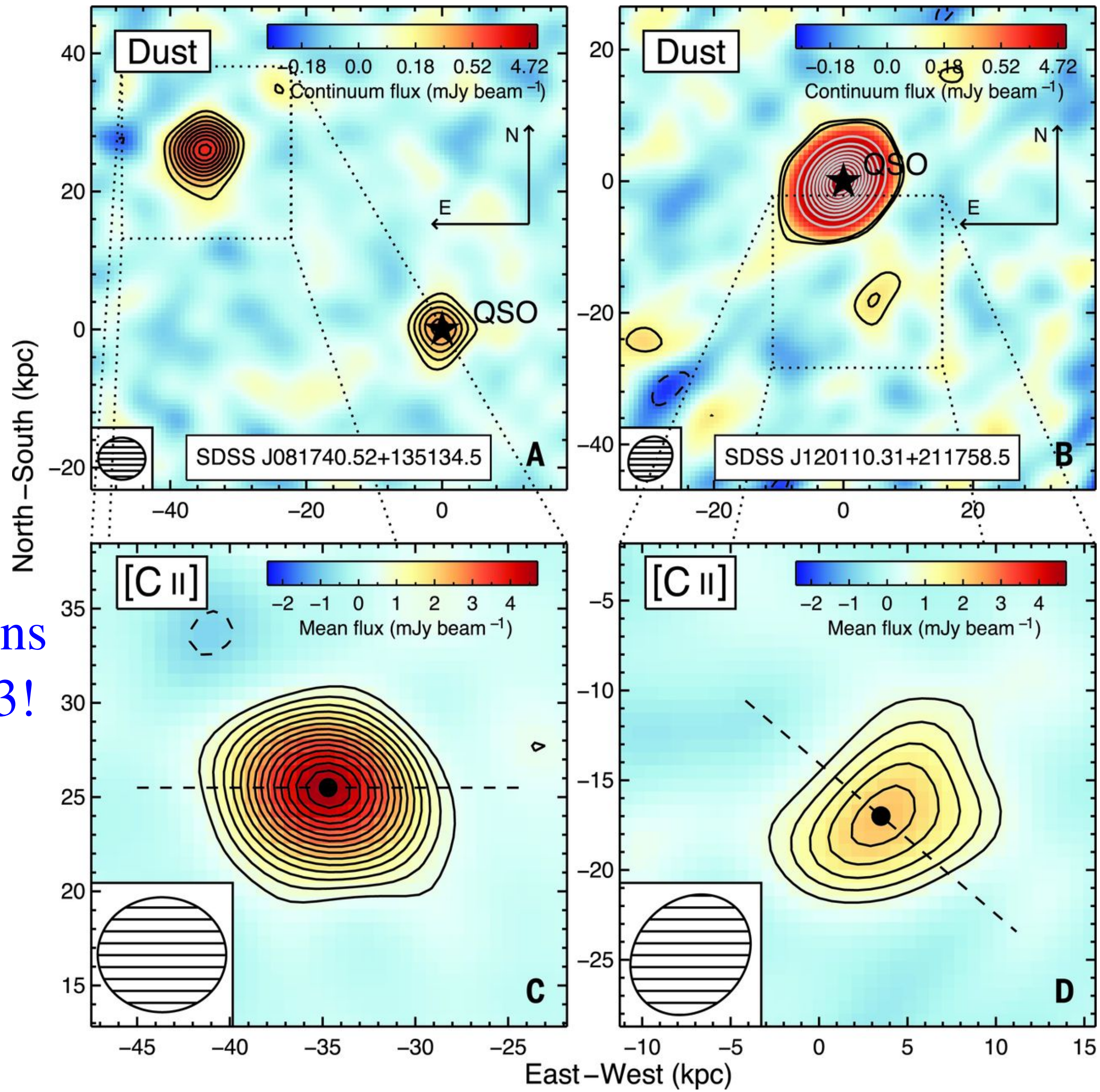


# CII-158μm Emission from High-$z$ DLAs

(Neeleman, NK, et al., 2017, Science)

- Detections of CII-158μm line emission and the 160 μm dust continuum!
- SFRs ~ 24, 110 $M_{\odot}$/yr from the dust continua.
- Large impact parameters: 25, 45 kpc.
- 3 new CII-158μm detections from four DLAs at $z \sim 4.3$!
- Large velocity spreads, high impact parameters, high SFRs:

Are high-metallicity DLAs massive disk galaxies?



# SUMMARY

- ALMA has opened 2 new windows on high-$z$ DLAs, allowing both the identification of the host galaxy, and estimates of size, gas mass, etc.

- CO emission from high-metallicity DLAs at $z \sim 0.5 – 0.8$: High molecular masses, gas fractions, low SFRs, large depletion times ⇨ Transition in the nature of star formation at intermediate redshifts?

- First identification of a DLA host galaxy via CO emission at $z \sim 2$! Massive object, $M(H_2) \sim 1.9 \times 10^{11}\ M_\odot$. SFR ~ 110 $M_\odot$/yr: "Normal" gas depletion timescale, ~ 1.8 Gyr. Large impact parameter ~ 30 kpc. Five new CO detetections in DLAs at $z \sim 2$: Massive galaxies!

- Five of 6 targetted DLAs at $z \sim 4.3$ detected in CII-158μm emission. High SFRs ~ 10 – 110 $M_\odot$/yr. Large impact parameters, ~ 15 – 45 kpc.

- Are high-$z$, high-metallicity DLAs massive, dusty galaxies?