The Gas Mass of Galaxies in *and after* the Epoch of Galaxy Assembly

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21cm emission at $z \sim 1.3$

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CO emission at $z \sim 0.7$

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Xavier Prochaska
Martin Zwaan
Lise Christensen …

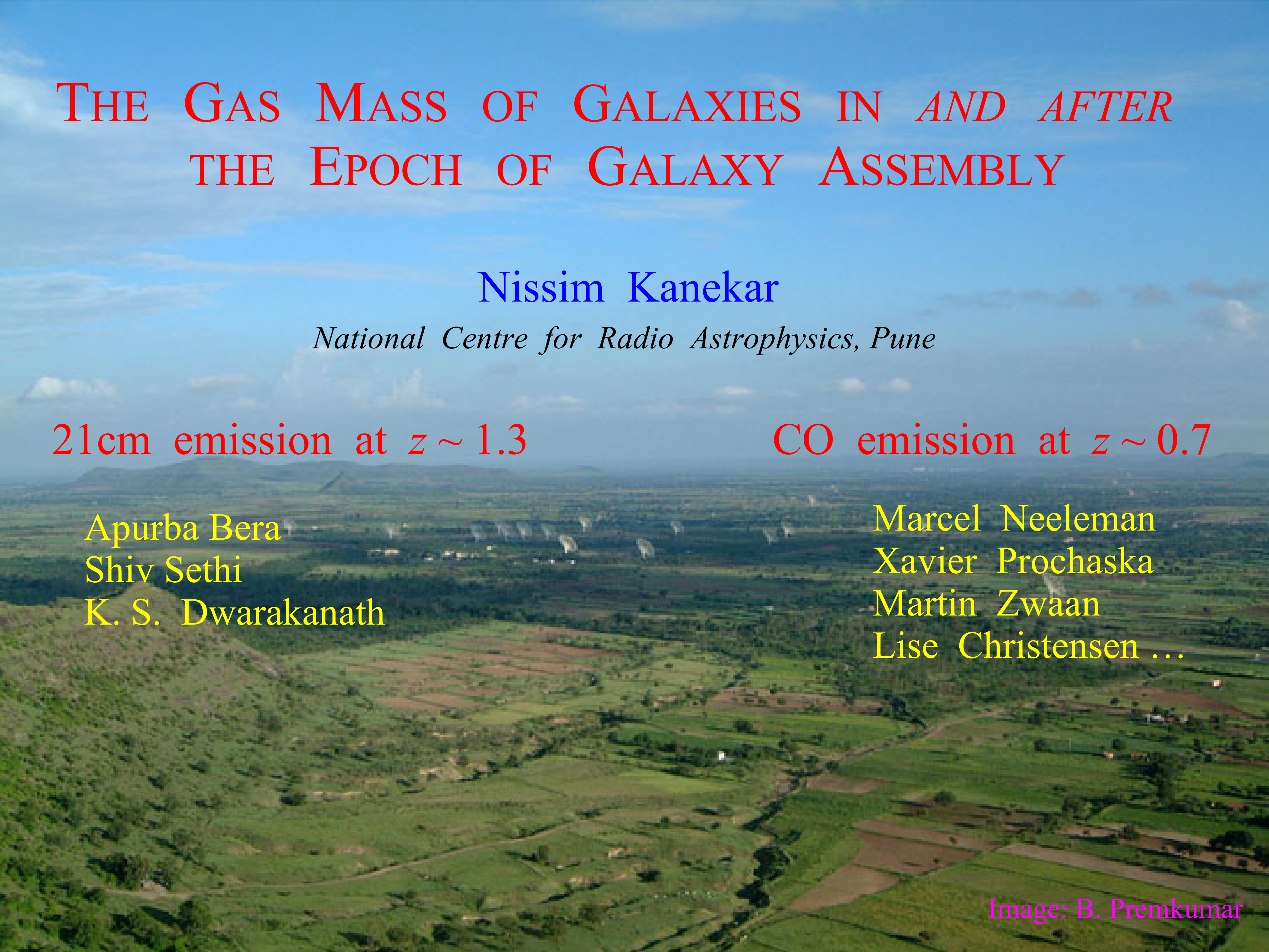
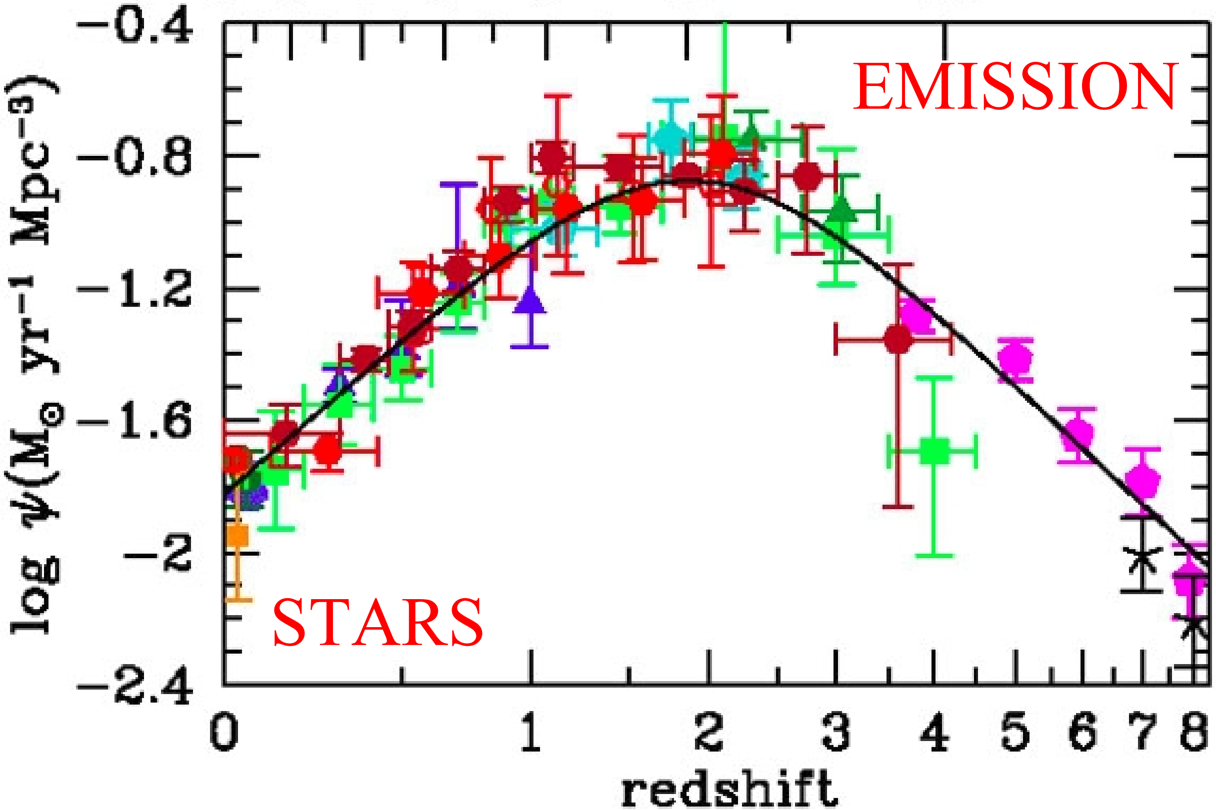
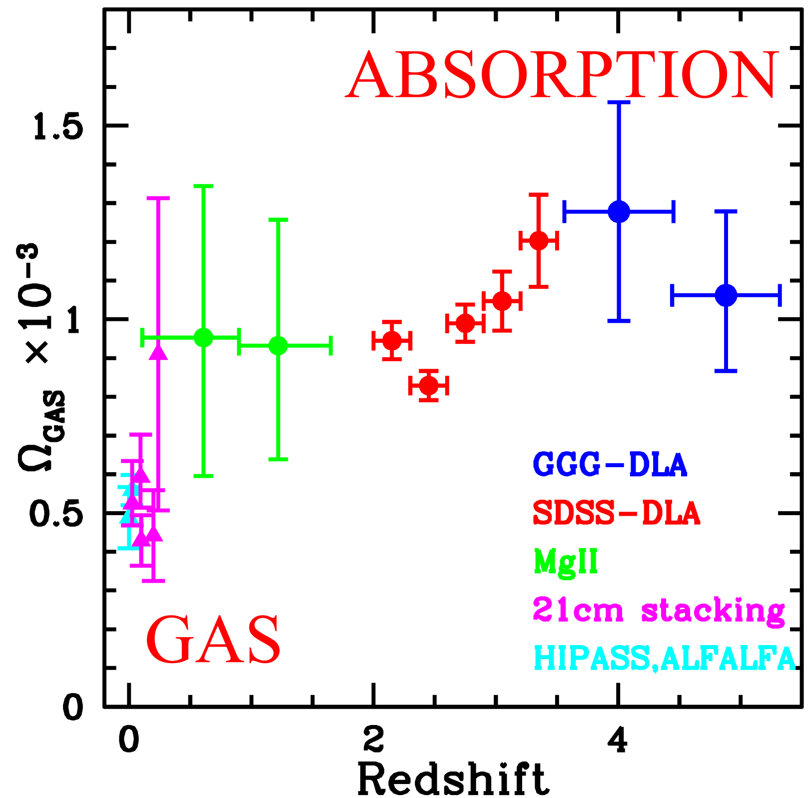


Image: B. Premkumar

EMISSION AND ABSORPTION SELECTION





(Madau & Dickinson 2014, ARA&A; Crighton et al. 2015, MNRAS)

- Emission-selected galaxies ⇨ Cosmic SFR density, Main sequence, …
  CO studies: Large molecular gas reservoirs; H_2 depletion time ~ 0.7 Gyr.
  No information on the atomic gas mass at $z > 1$!

(e.g. Bouwens et al. 2011, 2015, ApJ; Tacconi et al. 2013, 2018, ApJ)

- Absorption-selected galaxies ⇨ Cosmic gas mass density, column densities.
  No information on the atomic or molecular gas mass at $z >\sim 0.1$!

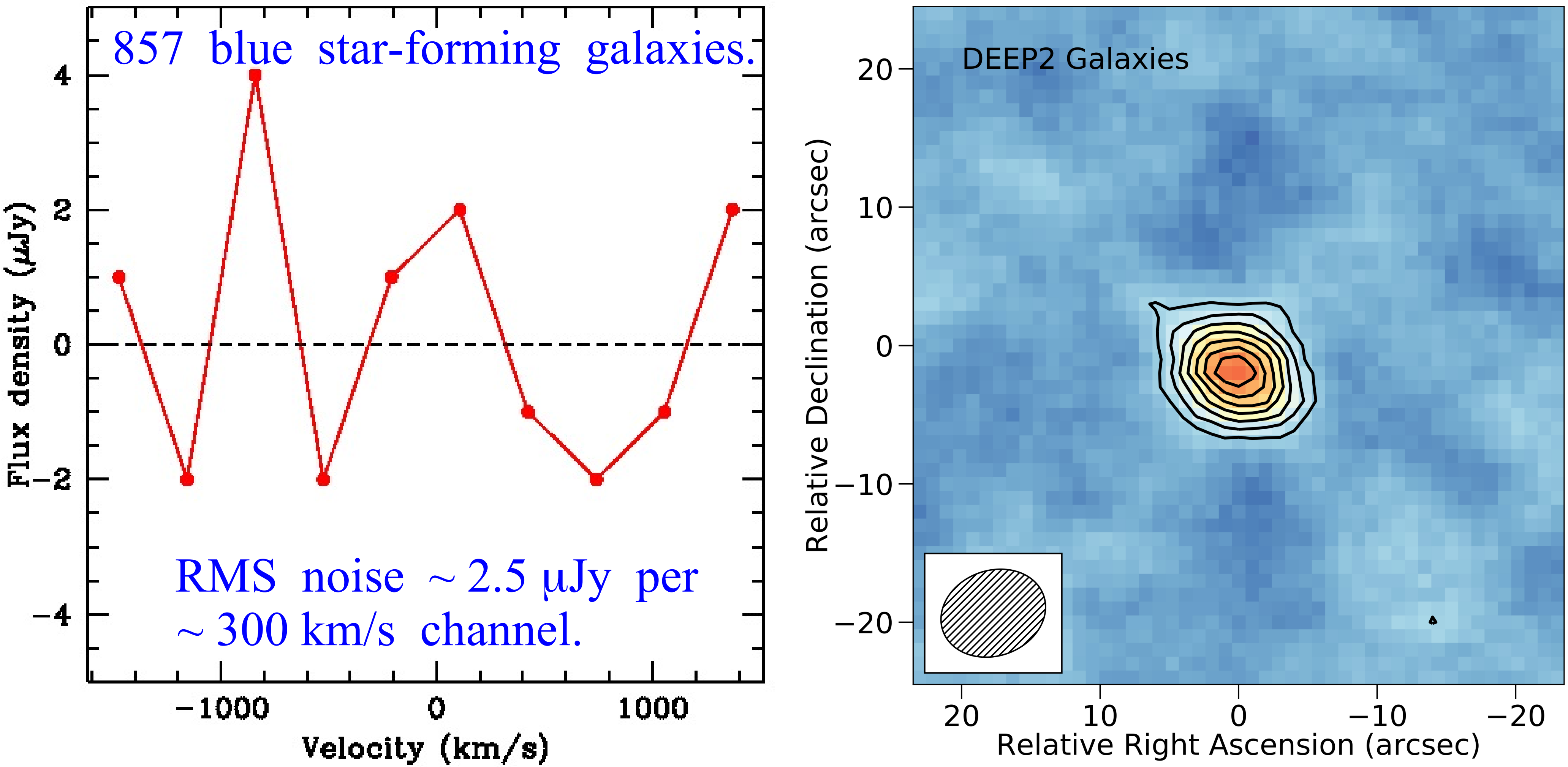
(e.g. Noterdaeme et al. 2012, A&A; Krogager et al. 2017, MNRAS)

THE GAS MASS OF STAR-FORMING GALAXIES AT $z \sim 1.3$

- Tough to detect 21cm emission at $z > 0.2$; $z_{\mathrm{MAX}} \sim 0.376$ (JVLA-CHILES).
  (Fernandez et al. 2016, ApJL; Jacqueline's talk)
- *Stacking* of 21cm emission from galaxies with known redshifts ⇨ The average HI mass! For a complete volume-limited sample, ⇨ Ω_{GAS}!
  (Chengalur et al. 2001, A&A; Zwaan 2000, Ph.D.)
- GMRT & WSRT at $z \sim 0.15 - 0.37$; GBT cross-correlation at $z \sim 0.8$.
  (e.g. Lah et al. 2007, MNRAS; Chang et al. 2010, Nature)
- Push to epoch of galaxy assembly, $z \sim 1 - 3$: Need (1) A sensitive interferometer (GMRT), & (2) A galaxy sample with accurate redshifts & positions, at the "right" redshifts, matched to telescope primary beam.
- Keck DEEP2 survey: 38,000 galaxies with R ⩽ 24.1 and $z \sim 0.7 - 1.45$. Upper end, $z \sim 1.1 - 1.4$: Good match to GMRT 610 MHz coverage. Sub-fields: 36' × 30': Good match to 44' GMRT 610 MHz primary beam.
  (Newman et al. 2013, ApJS)
- GMRT 60-hour pilot survey, covering $z \sim 1.18 - 1.36$ on 4 sub-fields.
- Also stack the radio continuum, to measure the average *total* SFR!

Gas Mass, SFR, Depletion Time

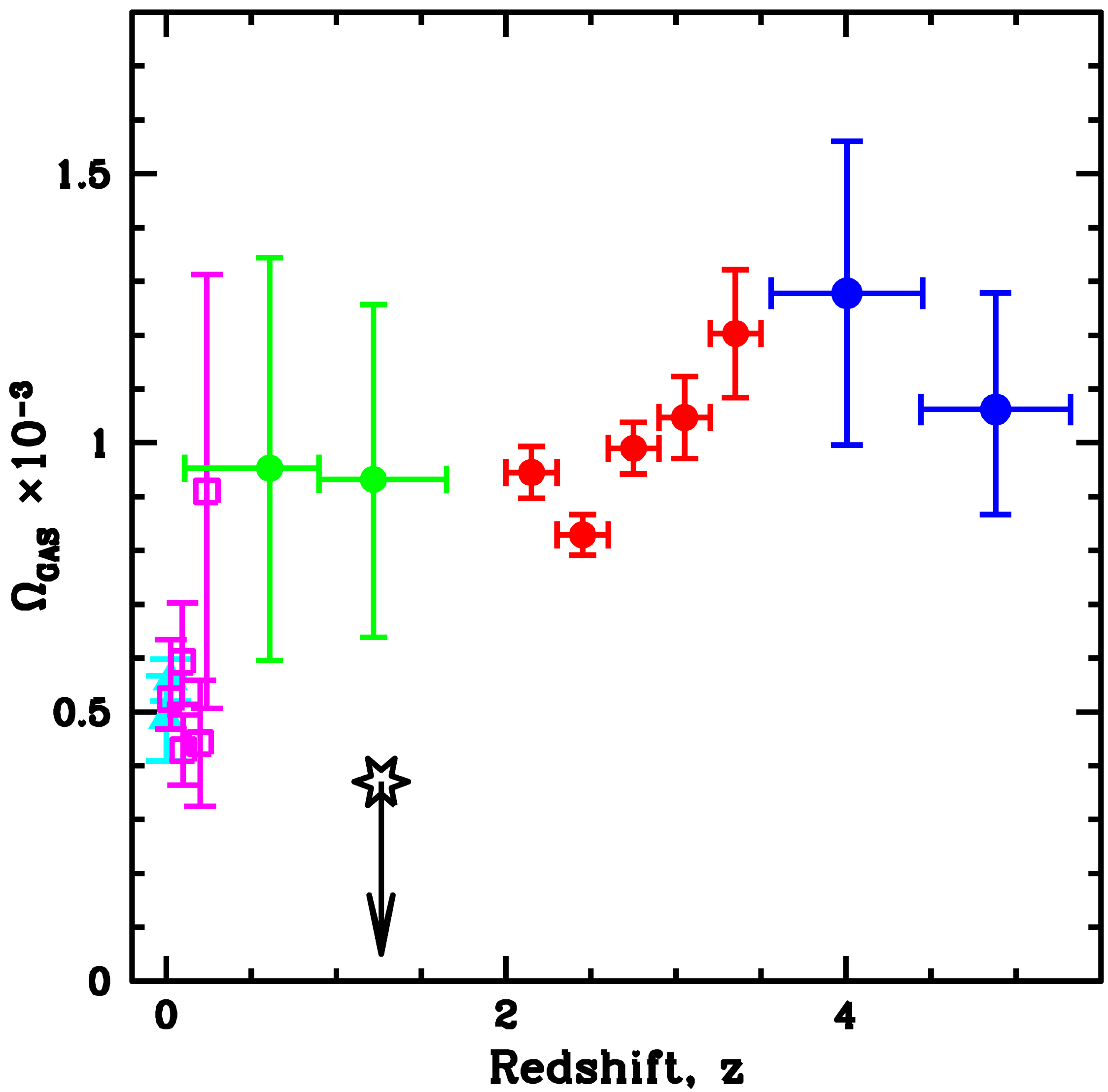
(NK et al. 2016, ApJL; Bera, NK et al. 2018, ApJ)



- Average HI mass, $M(\mathrm{HI}) \leq 2.1 \times 10^{10}\, M_\odot$ (3σ) ⇨ $M(\mathrm{HI})/M_* <\sim 0.5$.
- Median SFR ~ 24.2 $M_\odot$/yr ⇨ HI depletion time < 0.87 Gyr (3σ).
  Comparable to molecular gas depletion time, ~ 0.7 Gyr, in similar galaxies.

(Tacconi et al. 2013, ApJ)

The Cosmological Gas Mass Density



(e.g. Zwaan et al. 2005;
Rao et al. 2006;
Lah et al. 2007;
Martin et al. 2010;
Prochasa et al. 2005;
Noterdaeme et al. 2012;
Delhaize et al. 2013;
Rhee et al. 2013;
Crighton et al. 2015)

- The gas mass density in star-forming galaxies at $z \sim 1.3$ is Ω_{GAS}(SF) < 0.00037, lower than Ω_{GAS} at higher and lower redshifts!

⇨ The bulk of the HI at $z \sim 1.3$ is *not* in star-forming galaxies !!??

(NK et al. 2016, ApJL)

Damped Lyman-α Absorbers (DLAs)

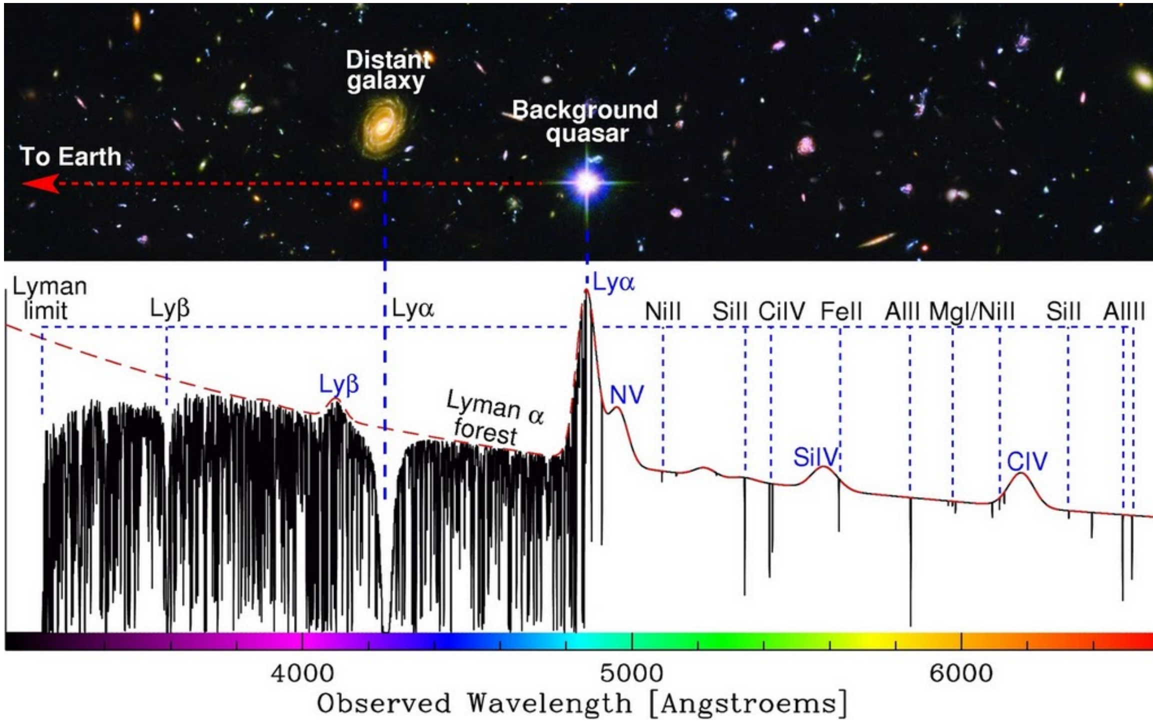
(e.g. Wolfe et al. 2005, ARA&A)

- Damped Lyman-α wings ⇨ High $N(HI) \geq 2 \times 10^{20}$ cm^{-2}, similar to the Milky Way!

- No luminosity bias ⇨ "Normal" gas-rich galaxies!

- Quasar absorption spectroscopy: DLA metallicity, H_2 fraction …
  ⇨ Low metallicity, ~ 0.03 solar at $z \sim 2$, increasing to lower z.

(e.g. Rafelski et al. 2012, ApJ)



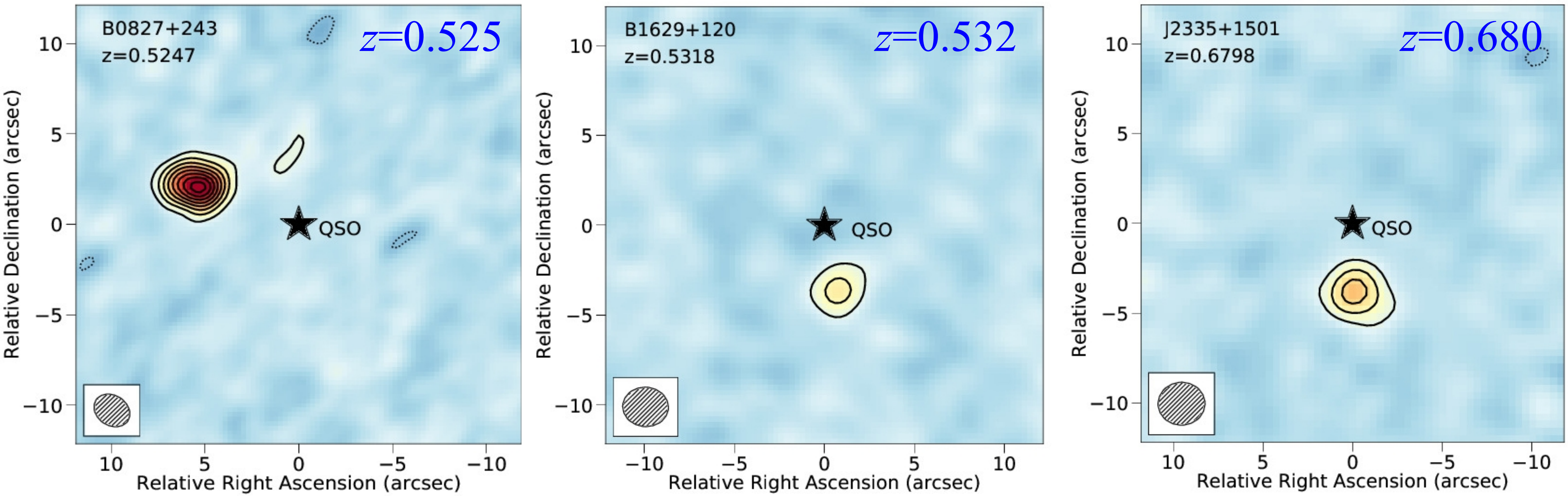
- Optical "host" galaxy ID's for ~20 DLAs at $z < 1$, and ~20 at $z \sim 2$. Five 21cm emission detections at $z < 0.1$; no CO emission detections.

(e.g. Krogager et al. 2017, MNRAS; NK et al. 2018, MNRAS)

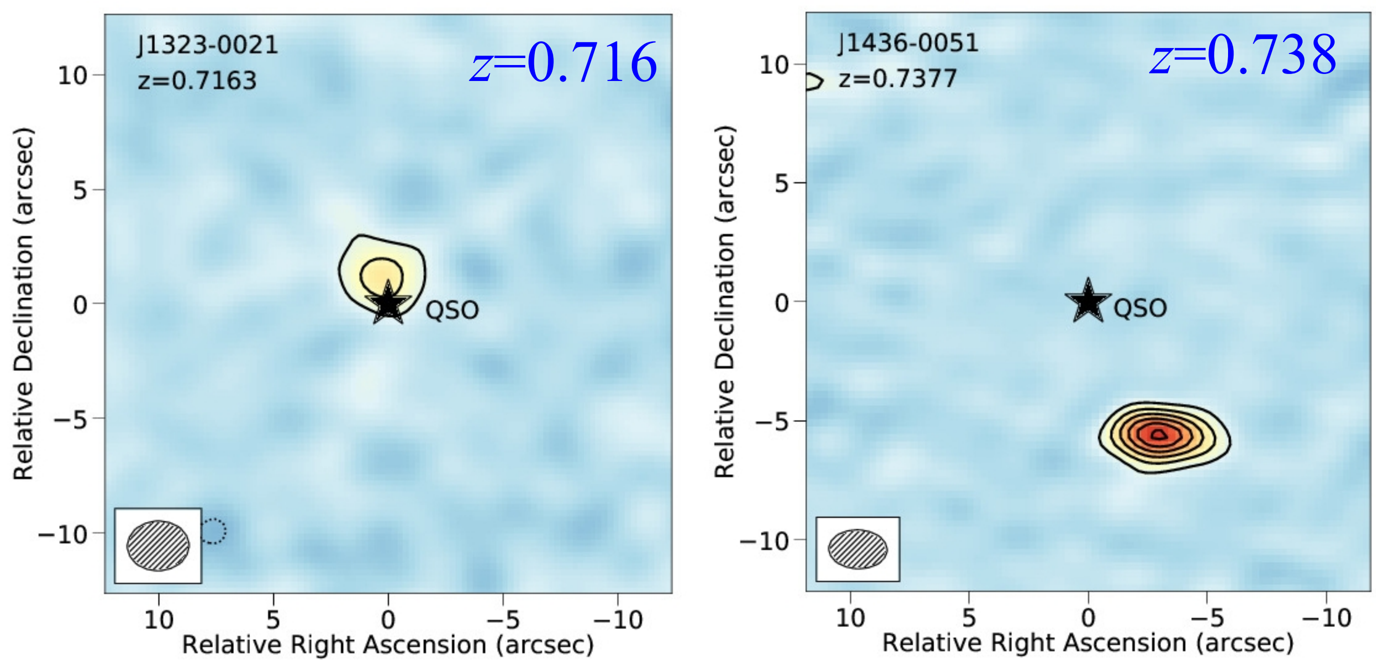
- And then ALMA came along:
  (1) CO emission from DLA hosts at $z < 1$: 6 detections so far.
  (2) CO emission from DLA hosts at $z \sim 2$: 5 detections so far.
  (3) CII-158 μm emission from DLA hosts at $z \sim 4$: 6 detections so far.

(e.g. Neeleman, NK et al. 2017, Science; Neeleman, NK et al. 2018, ApJL)

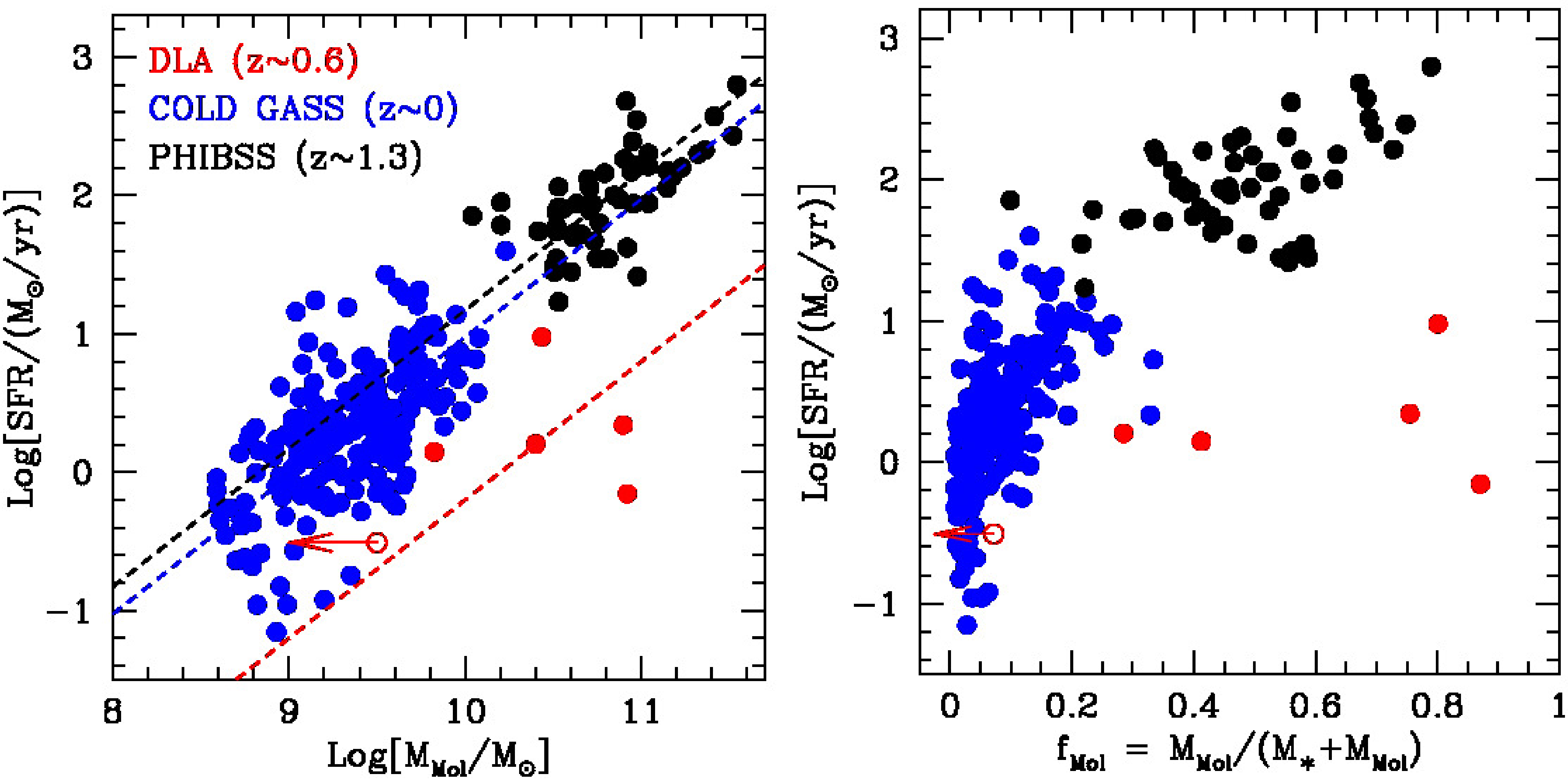
CO Emission from Intermediate-z DLAs



- High gas masses: $(0.6 - 8) \times 10^{10}$ $M_\odot$! Assumes $\alpha_{CO} = 4.3$.
- 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)

- DLAs appear to be "normal" main-sequence galaxies in optical properties. But large gas depletion times, ~10 Gyr, & large molecular 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 is the absorption selection picking out "different" galaxies?

(NK et al. 2018, ApJL)

SUMMARY

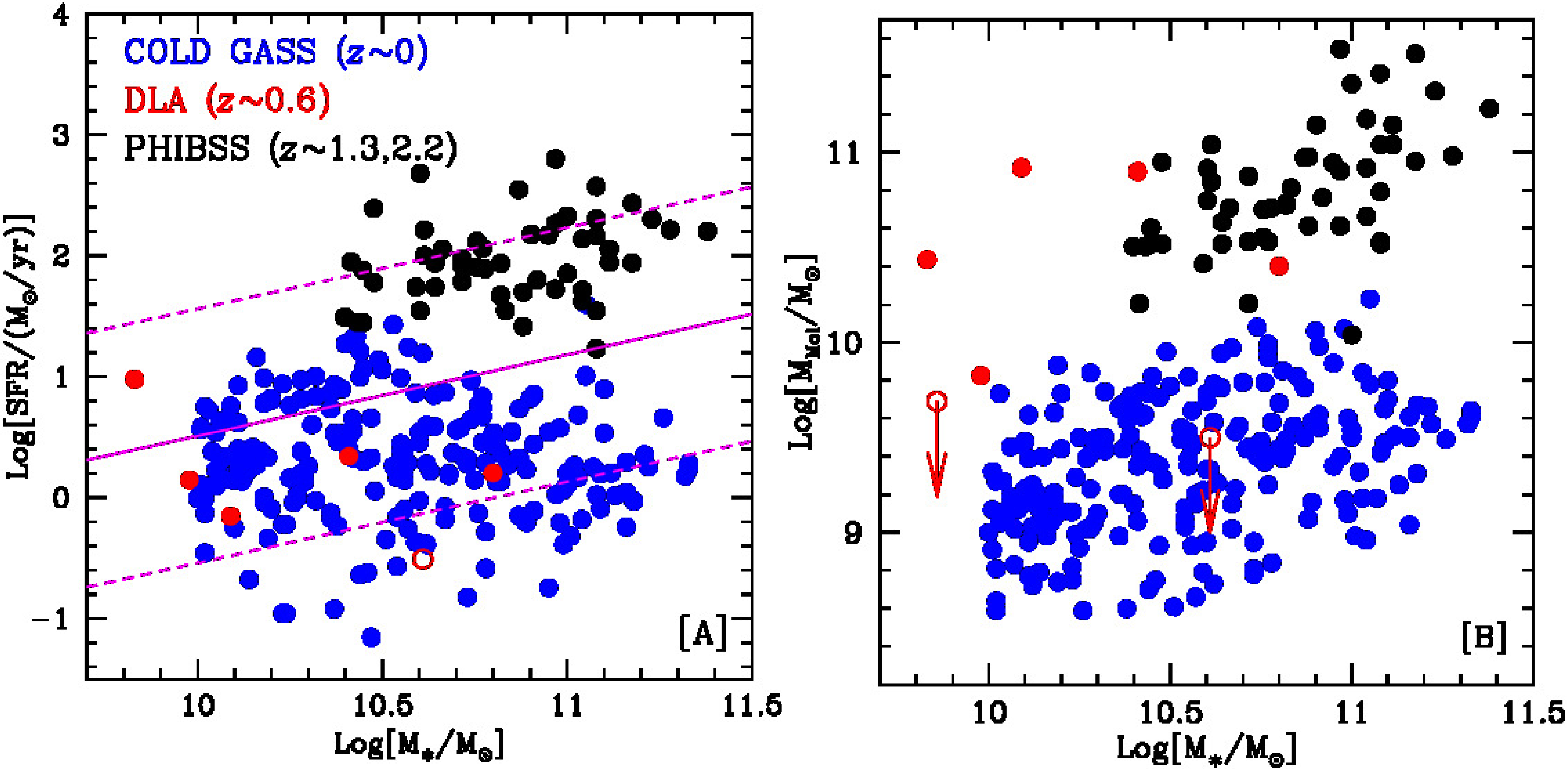
- Finally getting atomic gas mass estimates in high-z star-forming galaxies, molecular gas mass estimates in high-z DLAs.

- Stacked the GMRT 21cm spectra of 857 DEEP2 galaxies at $z \sim 1.3$:
  - ⇨ Average HI mass $\leq 2.1 \times 10^{10}$ $M_\odot$ (3σ) at $z \sim 1.3$.
  - ⇨ Gas fraction < 0.5 at $z \sim 1.3$ for galaxies, with SFR ~ 24 $M_\odot$/yr. HI depletion time < 0.87 Gyr (3σ): HI appears to be a transient phase.

- The cosmological atomic gas mass density in star-forming galaxies Ω_{GAS}(SF) < 0.00037 at $z \sim 1.3$, lower than Ω_{GAS} at $z \sim 0$, $z \sim 2-4$!
  - ⇨ The bulk of the neutral atomic gas is *not* in star-forming galaxies.

- ALMA CO $(2-1)$ emission in five of seven DLAs at $z \sim 0.5-0.8$:
  - ⇨ Large molecular gas masses, $(0.6-8) \times 10^{10}$ $M_\odot$, for $\alpha_{CO} = 4.3$.
  - ⇨ Large gas depletion times, ~ 10 Gyr.

- Transition in the nature of star formation at intermediate redshifts? Or is the absorption selection picking out "different" galaxies from the emission selection? Or just the usual small-number statistics?

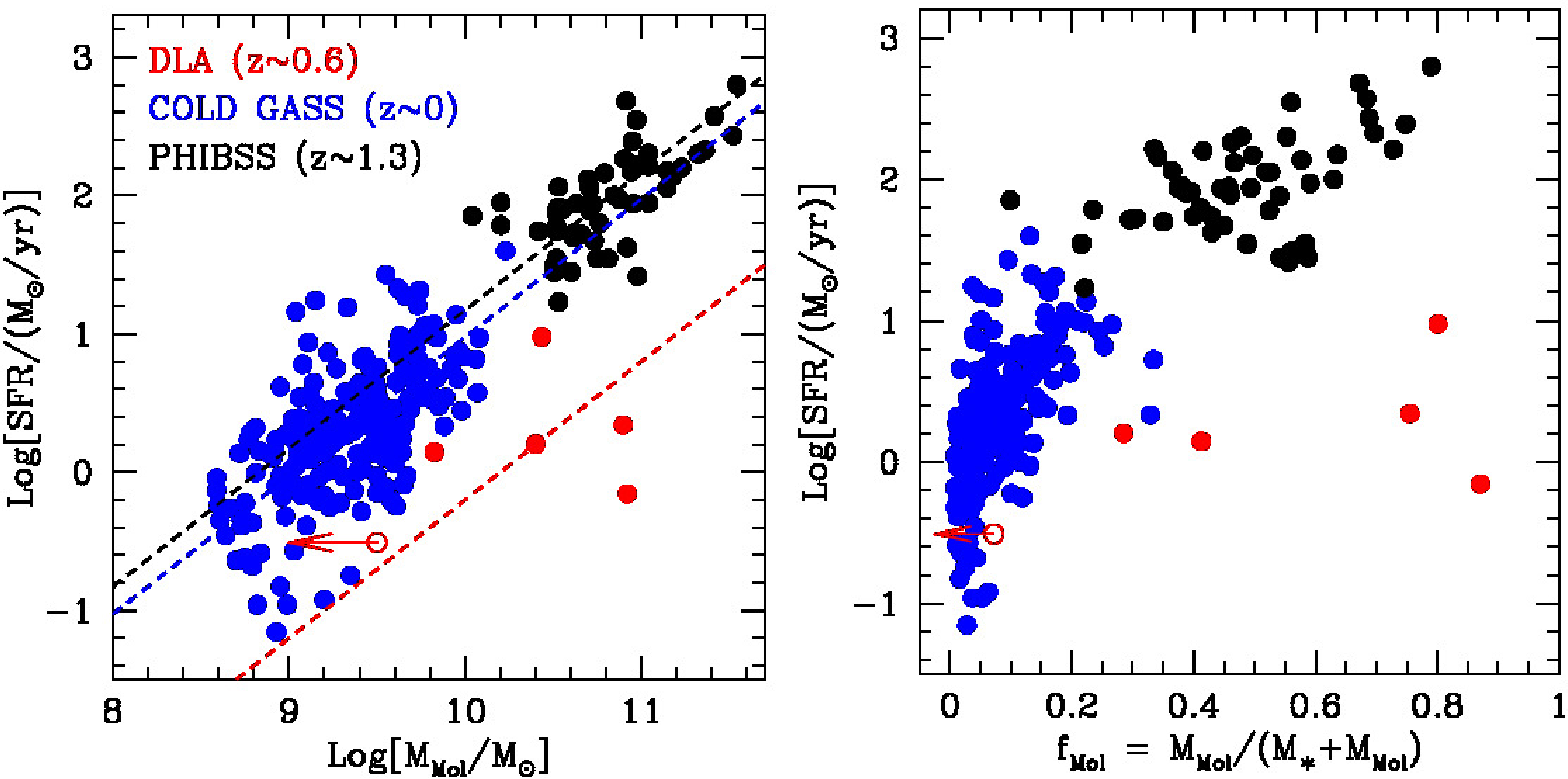


(Saintonge et al. 2011, ApJ; Tacconi et al. 2013, MNRAS)

- Low SFRs, $\sim 0.3 - 9.5\ M_\odot$/yr, & 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 at 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 $z \sim 1.3$!

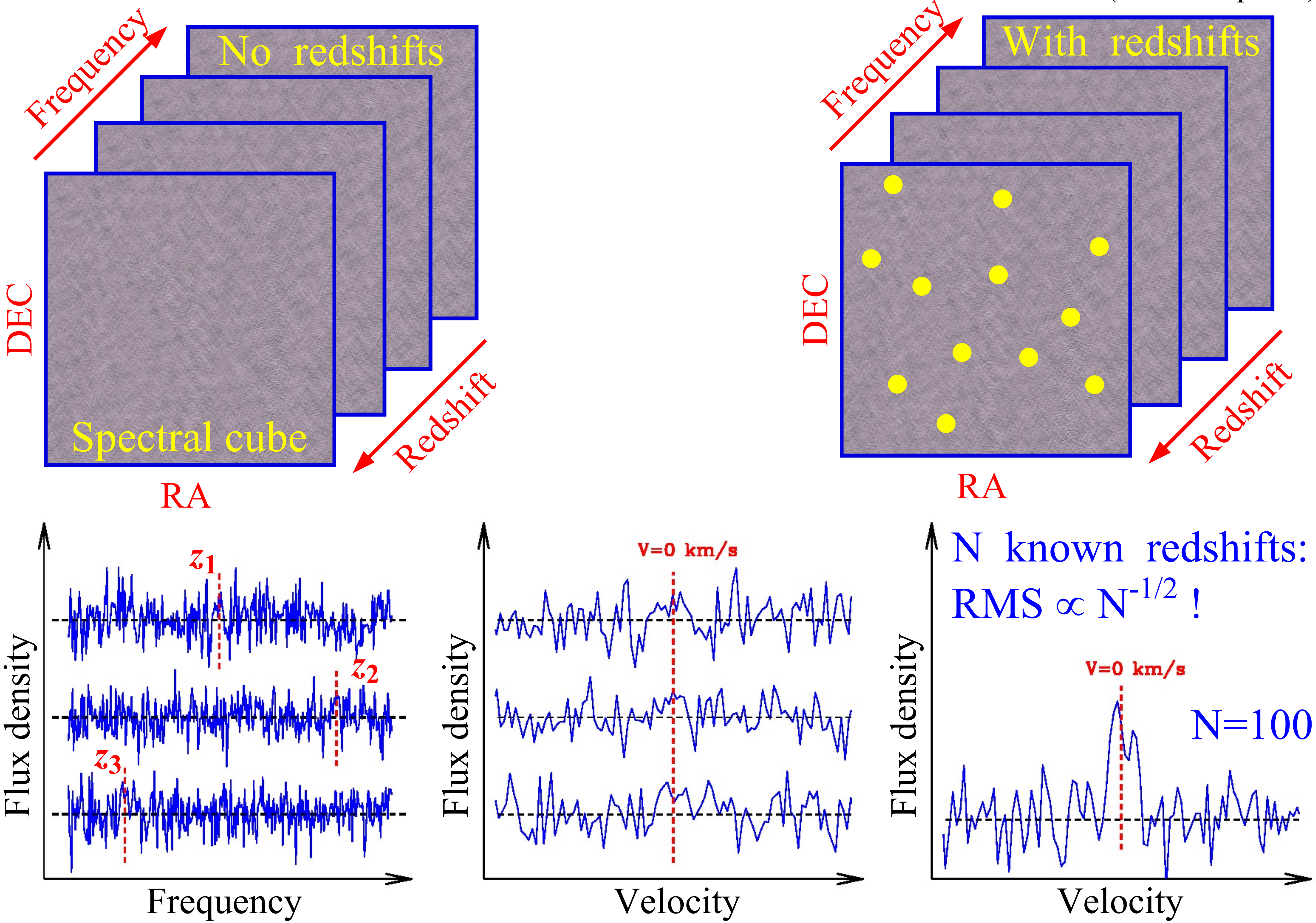
(Saintonge et al. 2011, ApJ; Tacconi et al. 2013, MNRAS)

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

(NK et al. 2018, ApJL)

HI 21cm Emission Stacking

(after Philip Lah)



Radio Continuum Studies: Galaxy SFRs

(Yun et al. 2001, ApJ)

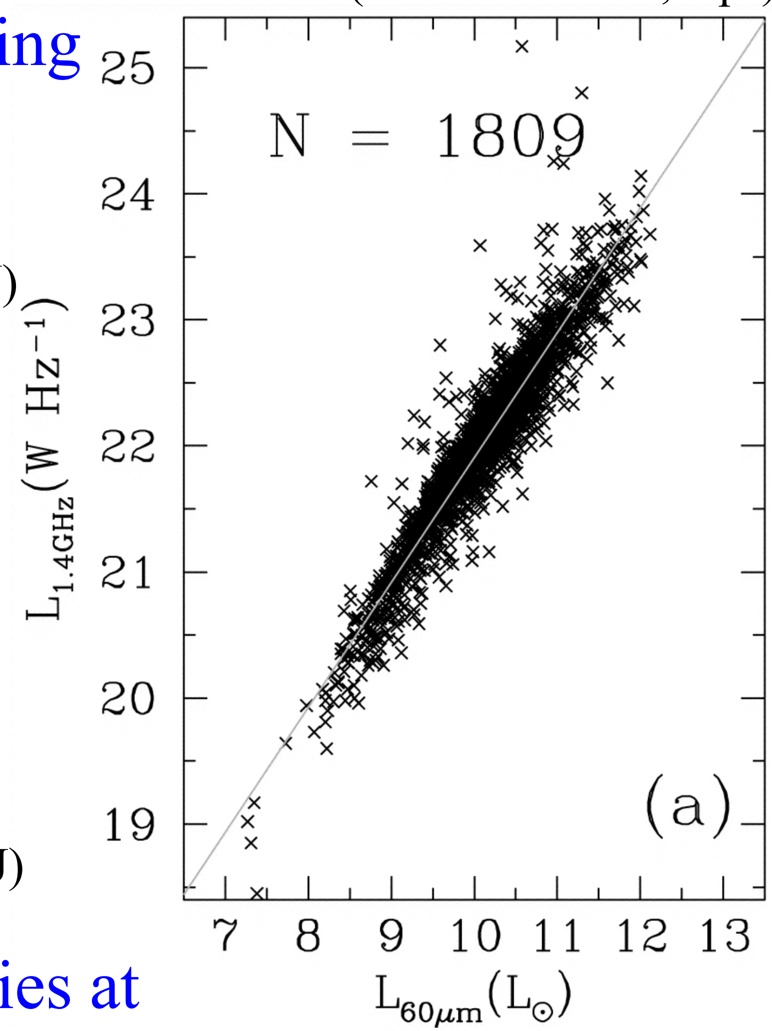
- Far-infrared (FIR) emission from star-forming galaxies: Dust heated by massive stars. FIR luminosity ⇨ The *total* SFR!

(e.g. Kennicutt 1998, ARA&A; Calzetti et al. 2010, ApJ)

- 1.4 GHz radio emission from star-forming galaxies comes from supernova remnants & HII regions, powered by massive stars.

- Tight FIR-radio correlation, out to $z \sim 4$: Estimate SFR from 1.4 GHz luminosity!

(e.g. Condon 1992, ARA&A; Pannella et al. 2015, ApJ)



- 1.4 GHz emission from star-forming galaxies at $z > 1$ too faint for a direct detection: *Stacking* of 1.4 GHz emission from galaxies with known positions ⇨ The average *total* SFR!

- Radio continuum stacking done in a few VLA fields, at 1.4 GHz, for galaxies at $z \sim 1 - 4$.

(e.g. Carilli et al. 2007, ApJ; Pannella et al. 2009, ApJL; 2015, ApJ)

The Galaxy Sample: The DEEP2 Survey

- (1) A high-sensitivity low-frequency radio interferometer: GMRT!

  (2) A galaxy sample in a region matched to the telescope beam, with accurate redshifts and positions, and at the "right" redshifts.

- Few spectroscopic surveys cover $z \sim 1 - 1.5$: The "redshift desert"!

- DEEP2 survey: 3.5 sq. degrees of multi-band optical imaging, in 4 fields, 3 of size $2^o \times 0.5^o$, & the Extended Groth Strip $(2^o \times 0.25^o)$.

  (Coil et al. 2004, ApJ)

- Keck-DEIMOS multi-object spectroscopy: Resolution ~ 6000, covering ~ 6500 – 9100 Å (i.e. the OII-λ3727 doublet for $z \sim 0.7 - 1.45$).

  (Davis et al. 2007, ApJ; Newman et al. 2013, ApJS)

- 1-hr Keck integrations covering galaxies at $z > 0.7$ with $R < 24.1$.

- 38,000 galaxies with redshifts; a redshift accuracy of ~ 30 km/s.

  (Newman et al. 2013, ApJS)

- Optical SFRs and stellar masses from OII lines & SED fits.

  (Weiner et al. 2009, ApJ; Mostek et al. 2012, ApJ)

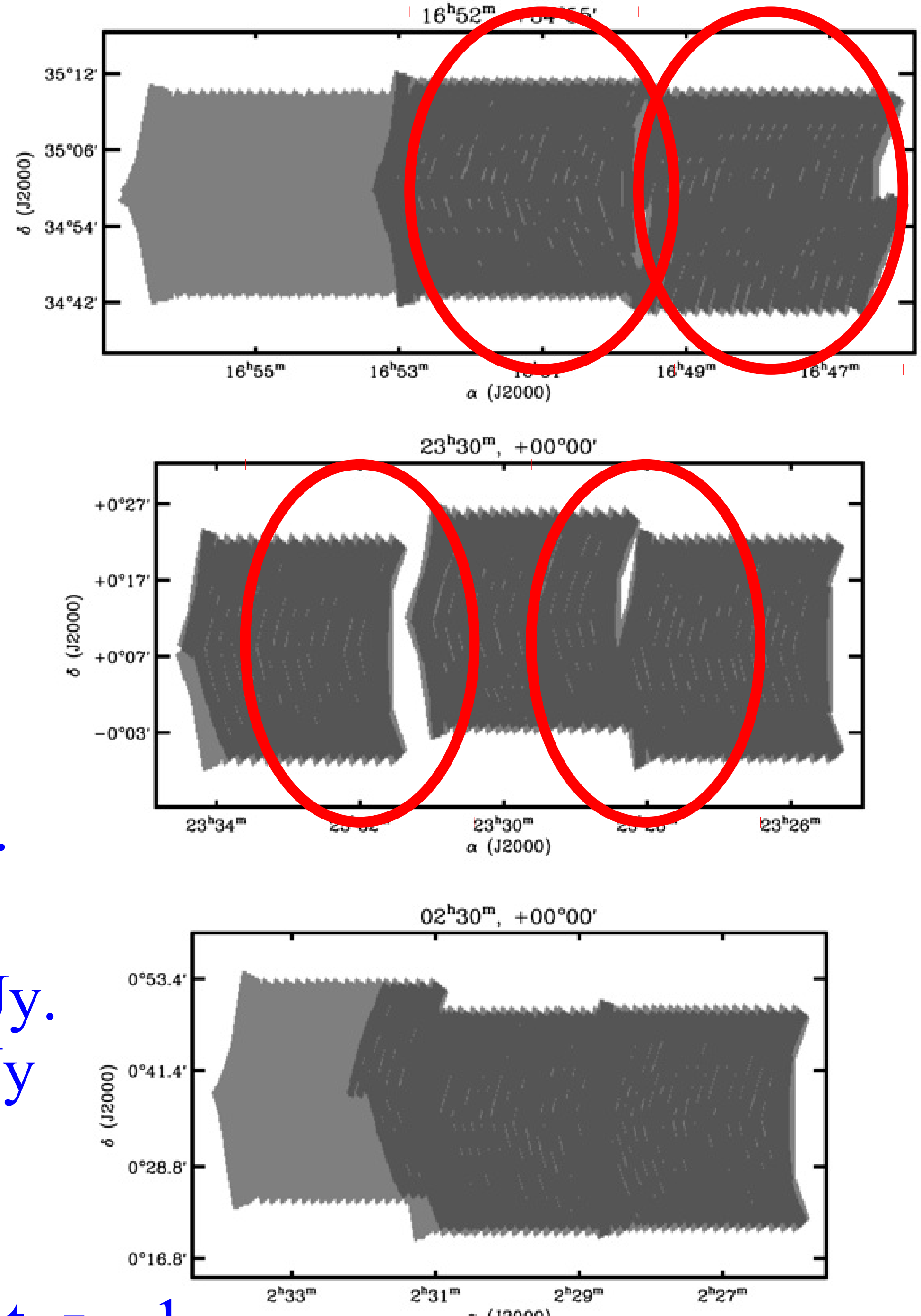
The GMRT DEEP2 Pilot Survey

- DEEP2 sub-fields ~ 36' × 30':
  Excellent match to 44' GMRT 610 MHz primary beam.

- Accurate redshifts, $z \sim 0.7 - 1.45$:
  Upper end matched to GMRT's 610 MHz frequency coverage.

- 10 – 15 on-source hours per field;
  33 MHz bandwidth, 512 channels.
  HI 21cm line from $z \sim 1.18 - 1.36$.

- Continuum RMS noise: 14 – 39 μJy.
  Spectral RMS noise: 240 – 300 μJy per 31.5 km/s channel.



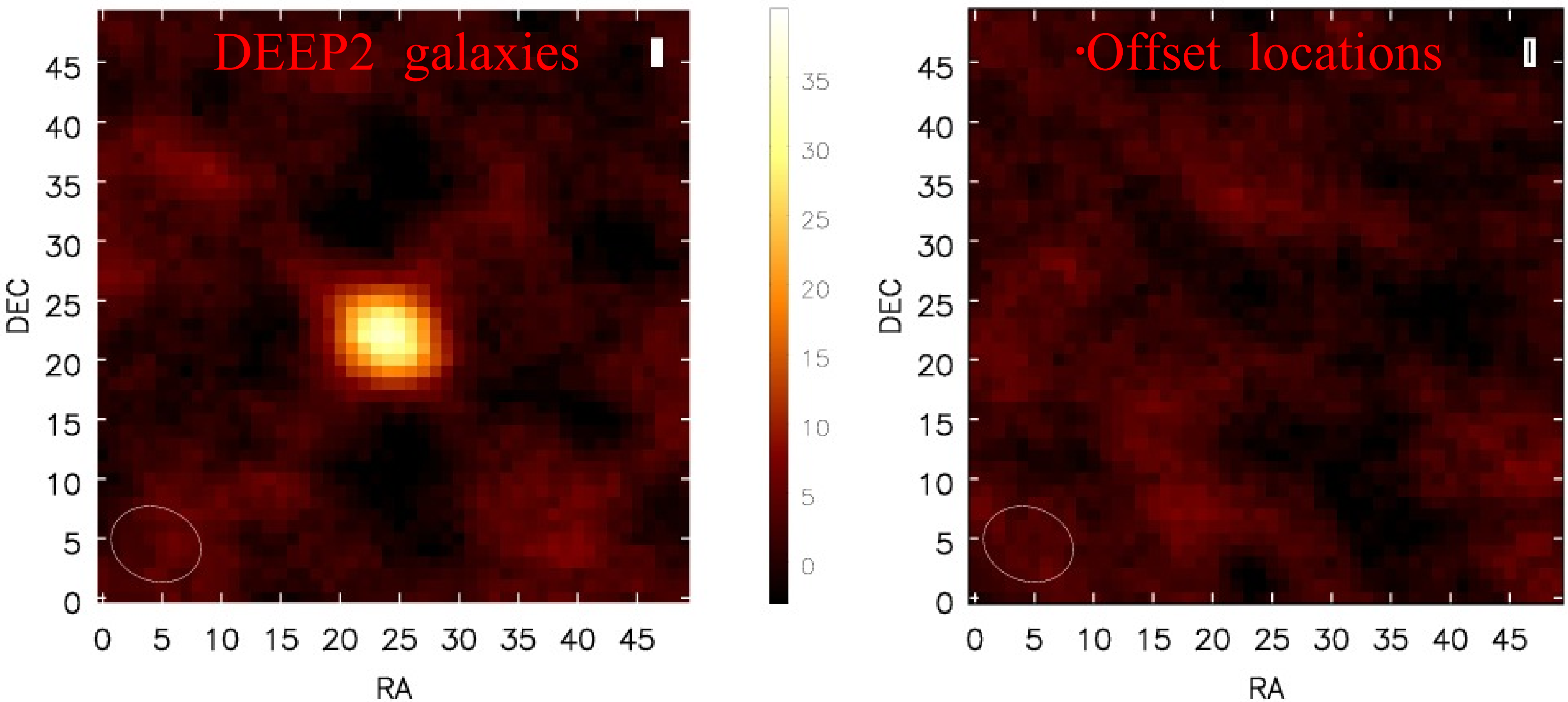
- Angular resolution ~ 6": ~ 50 kpc at $z \sim 1$.

(Newman et al. 2013, ApJS)

1.4 GHz Radio Continuum Stacking

(Bera et al. 2017, in prep.)

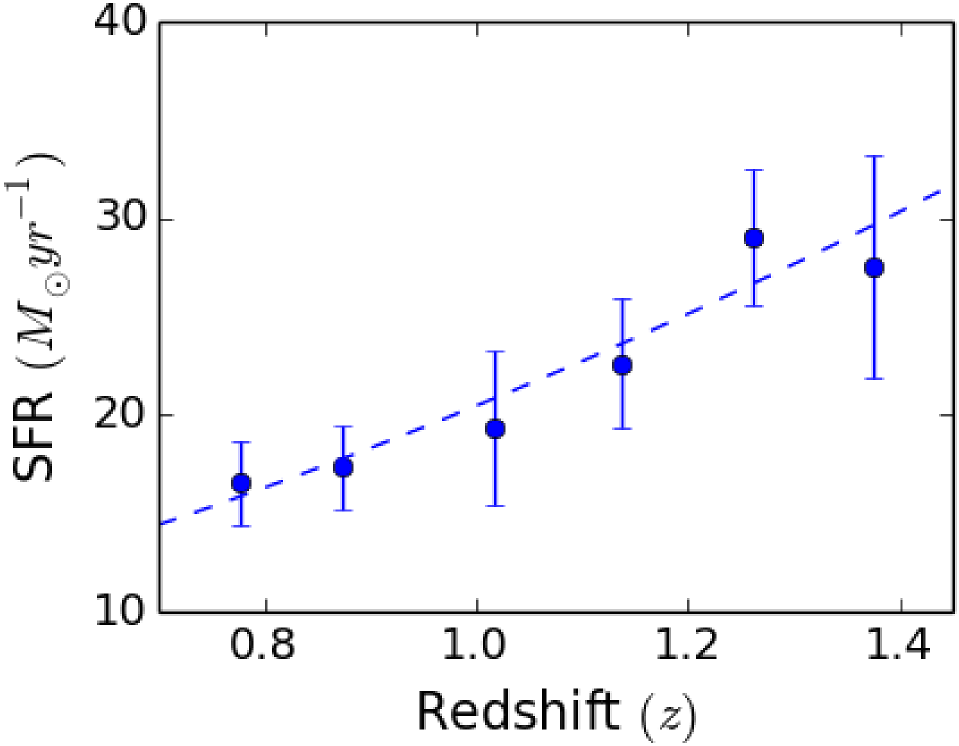
- Stacked 1.4 GHz continuum emission from 4002 blue galaxies with $M_B \leqslant -20$ at $z \sim 0.7 - 1.4$. Median stacking, in 1.4 GHz luminosity.

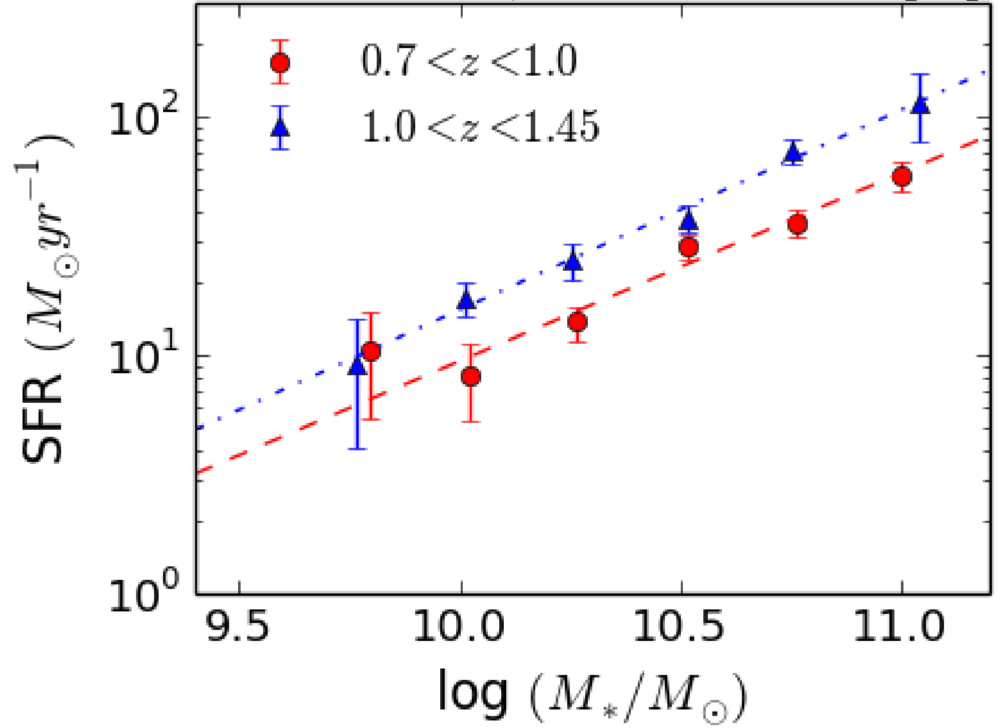


- Clear (~14σ) detection! SFR = 20.9 ± 1.6 $M_\odot$/yr; deconvolved size ≤ 1" (i.e. ≤ 8 kpc). No detection on stacking offset locations.

1.4 GHz Radio Continuum Stacking

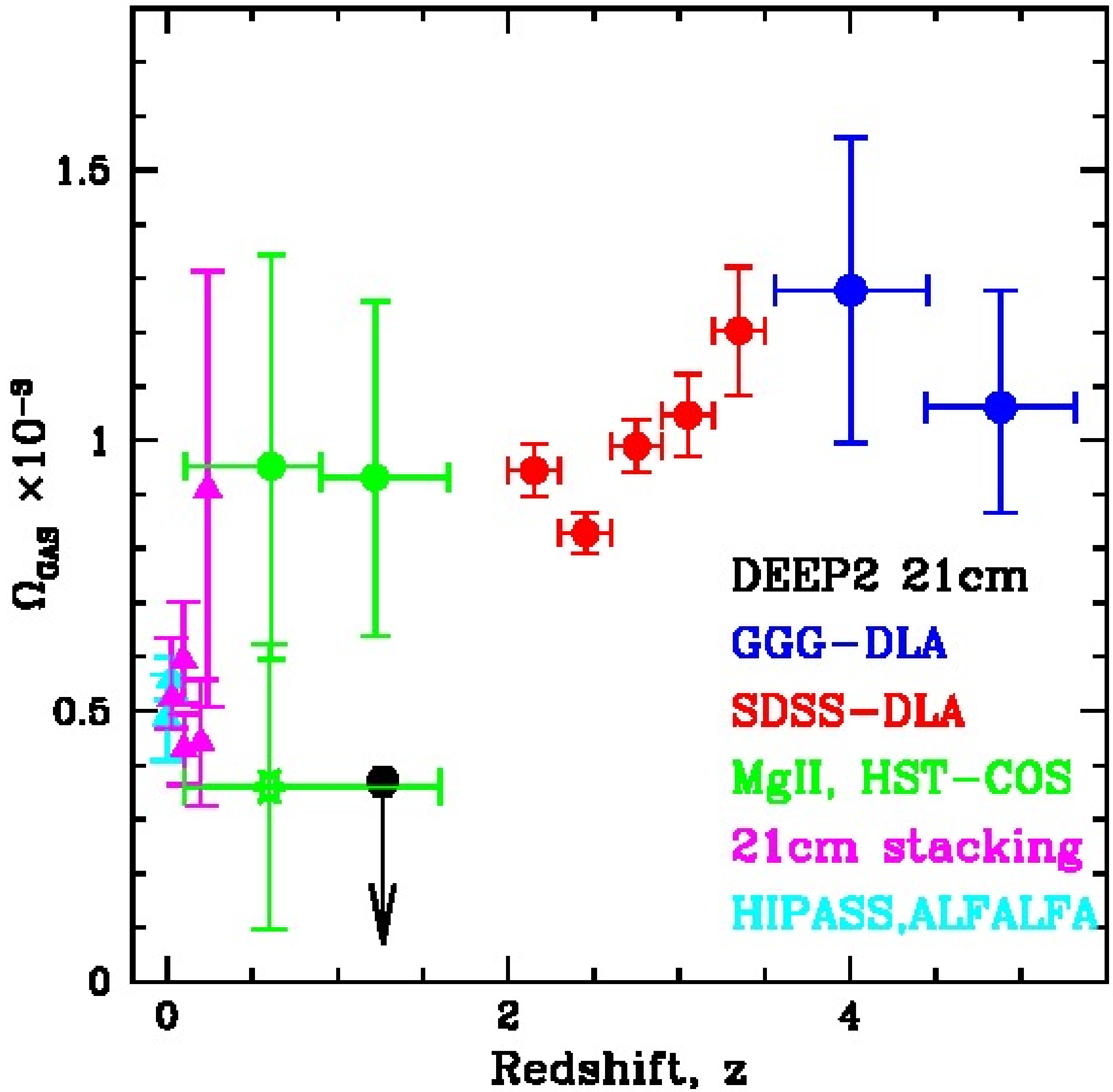
(Bera et al. 2017, in prep.)





- Stacked the 1.4 GHz emission in bins of redshift, stellar mass, ...
- SFR increases with increasing redshift: SFR $\propto (1+z)^{2.2}$.
- The main sequence: SFR $= 11.9 \times M_*^{0.79}$ $(0.7 < z < 1.4)$. Amplitude decreases with redshift; no discernible change in slope.
- Extinction factor = $SFR_{RAD.}/SFR_{OPT.} \sim 2.4$; increases with colour, M_*.

THE COSMOLOGICAL GAS MASS DENSITY



(e.g. Zwaan et al. 2005;
Rao et al. 2006;
Lah et al. 2007;
Martin et al. 2010;
Prochasa et al. 2005;
Noterdaeme et al. 2012;
Delhaize et al. 2013;
Rhee et al. 2013;
Crighton et al. 2015;
Neeleman et al. 2016)

- The gas mass density in star-forming galaxies at $z \sim 1.3$ is $\Omega_{GAS}(SF) < 0.00037$, far lower than the total Ω_{GAS} at $z \sim 0 - 4$!

⇨ The bulk of the atomic gas is *not* in star-forming galaxies ??!!

(NK et al. 2016, ApJL)

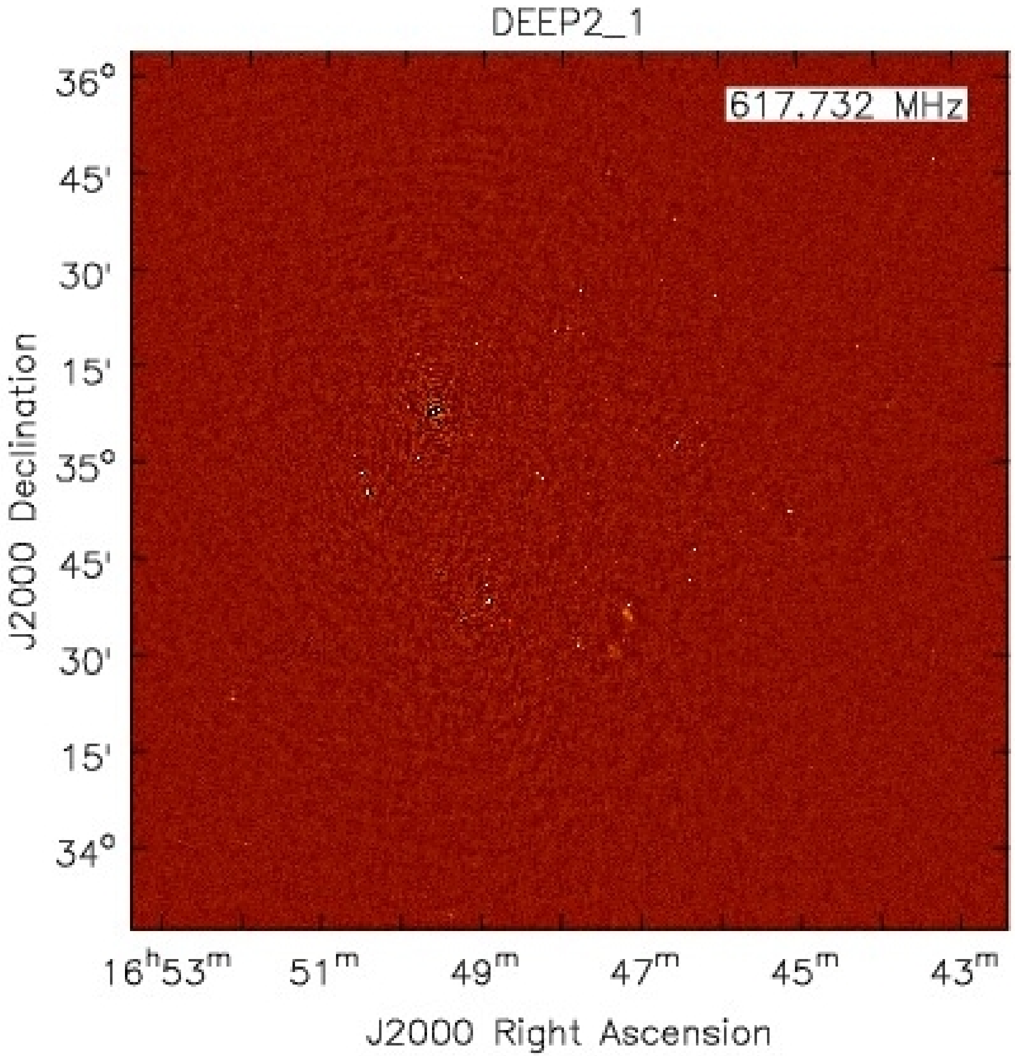
The "Future"

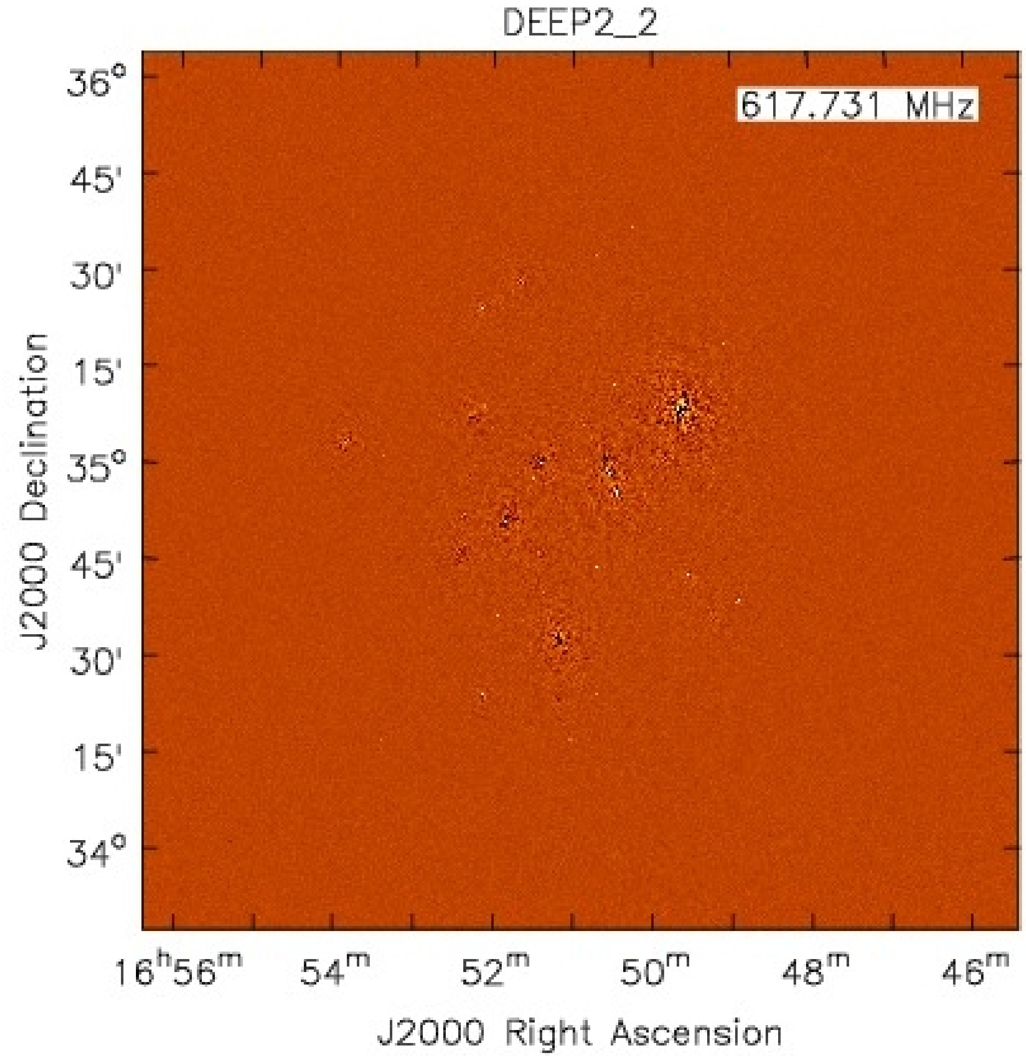
- Completed the observations of a 400-hour GMRT project to observe 7 DEEP2 sub-fields with spectroscopy to improve the HI mass sensitivity by a factor of ~ 3, to $< 10^{10}\,M_\odot$.

- 125-hour GMRT run on the Extended Groth Strip, covering $1000 - 1400$ MHz, i.e. $z = 0.0 - 0.4$ for the HI 21cm line. Should yield detections of both individual and stacked HI 21cm emission.

- New GMRT $550 - 900$ MHz receivers will yield coverage of $z \sim 0.7 - 1.5$ ⇨ Large survey of the DEEP2 fields from 2018.

THE RADIO CONTINUUM: GMRT 617 MHZ IMAGES

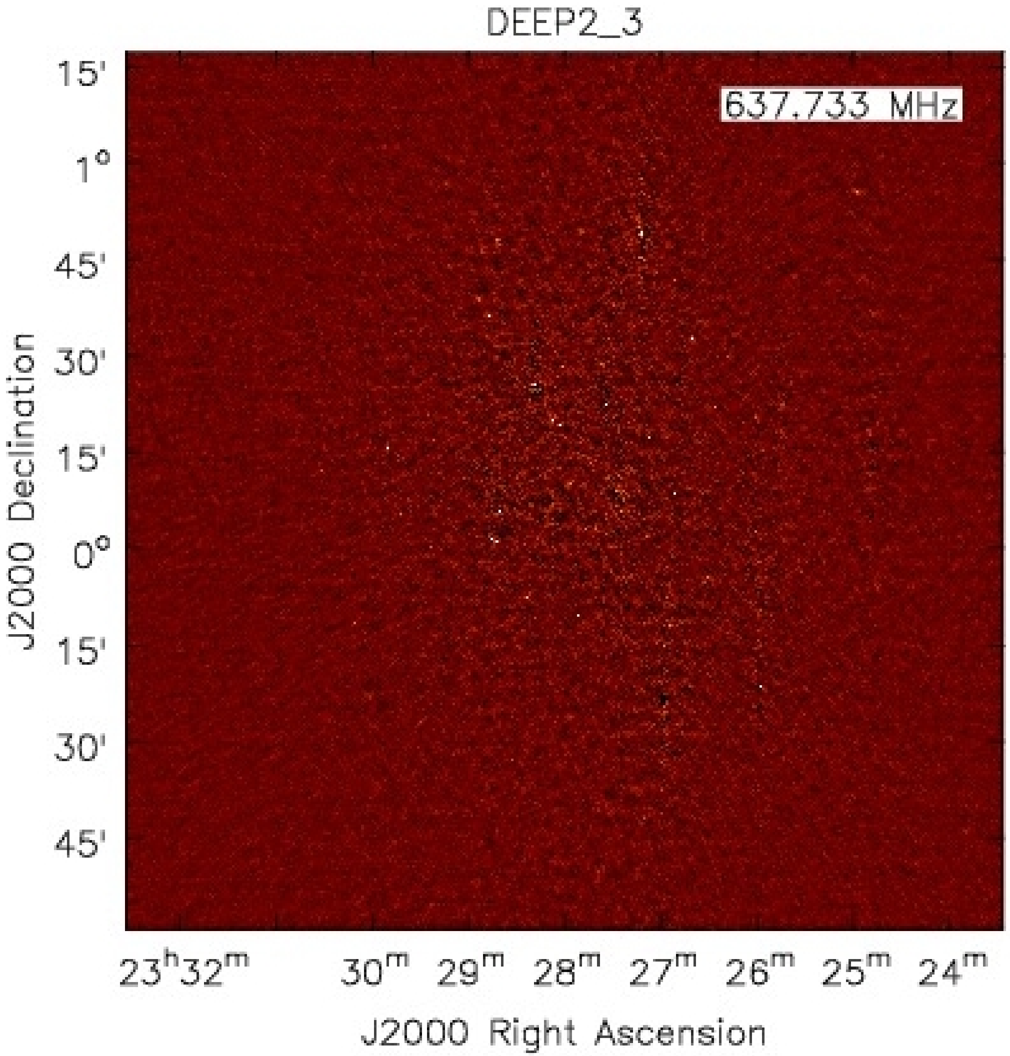


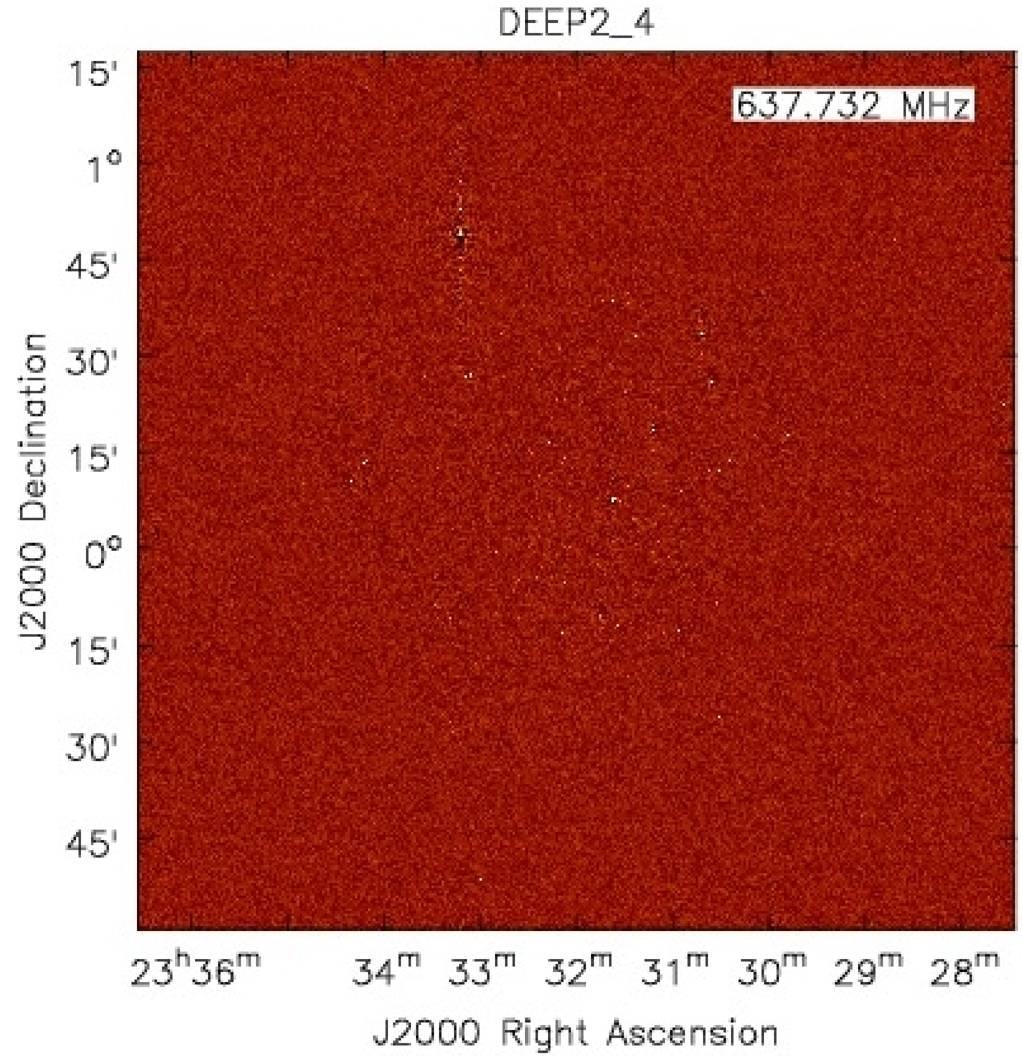


- Beam: 4.7" × 3.9".
- RMS noise ~ 21 μJy.
- 2006 galaxies (0.70 < z < 1.45)

- Beam: 5.2" × 4.3".
- RMS noise ~ 39 μJy.
- 2116 galaxies.

The Radio Continuum: GMRT 637 MHz Images





- Beam ~ 5.9" × 4.6".
- RMS noise ~ 22 μJy.
- 2105 galaxies.

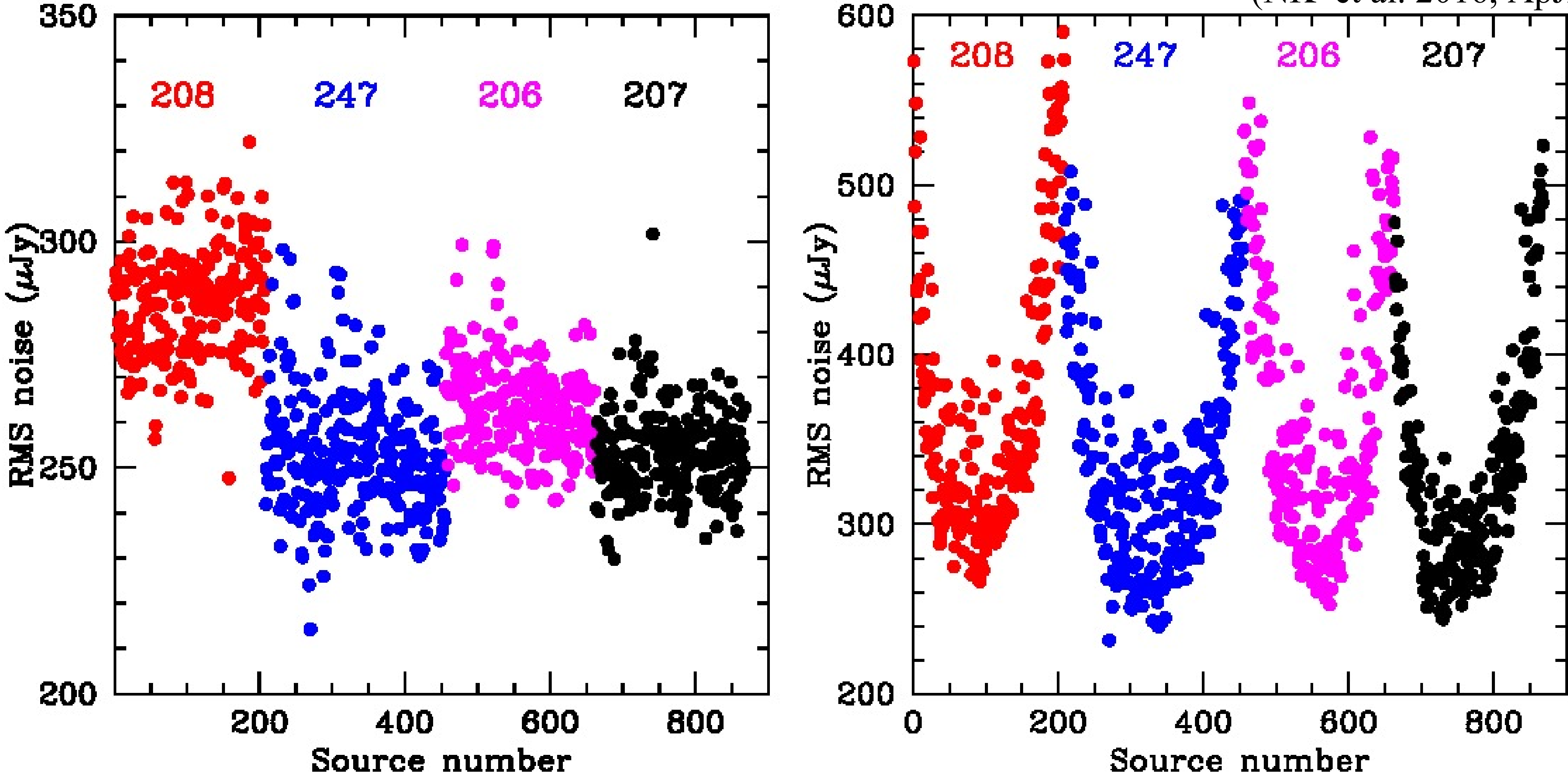
- Beam ~ 6.1" × 4.4".
- RMS noise ~ 14 μJy.
- 1844 galaxies.

Radio Continuum Stacking

- Excluded galaxies outside the 44' FWHM of the primary beam.
- Measured the local RMS noise around each DEEP2 galaxy, and excluded galaxies in the 10% tail of the RMS noise distribution.
- Excluded galaxies with pixels $\geq 5\sigma$ within 5" of the galaxy position to remove possible active galactic nuclei.
- Excluded "red" galaxies, with "colour" > 0.
- Final number of galaxies: 6845 "blue" systems at $z \sim 0.7 - 1.45$.
- Before stacking, smoothed all images to one resolution, $6.1'' \times 4.8''$.
- Used median stacking, to reduce sensitivity to outliers.
- Stacked in bins of redshift, stellar mass, optical SFR, and colour.

HI 21cm Line Stacking

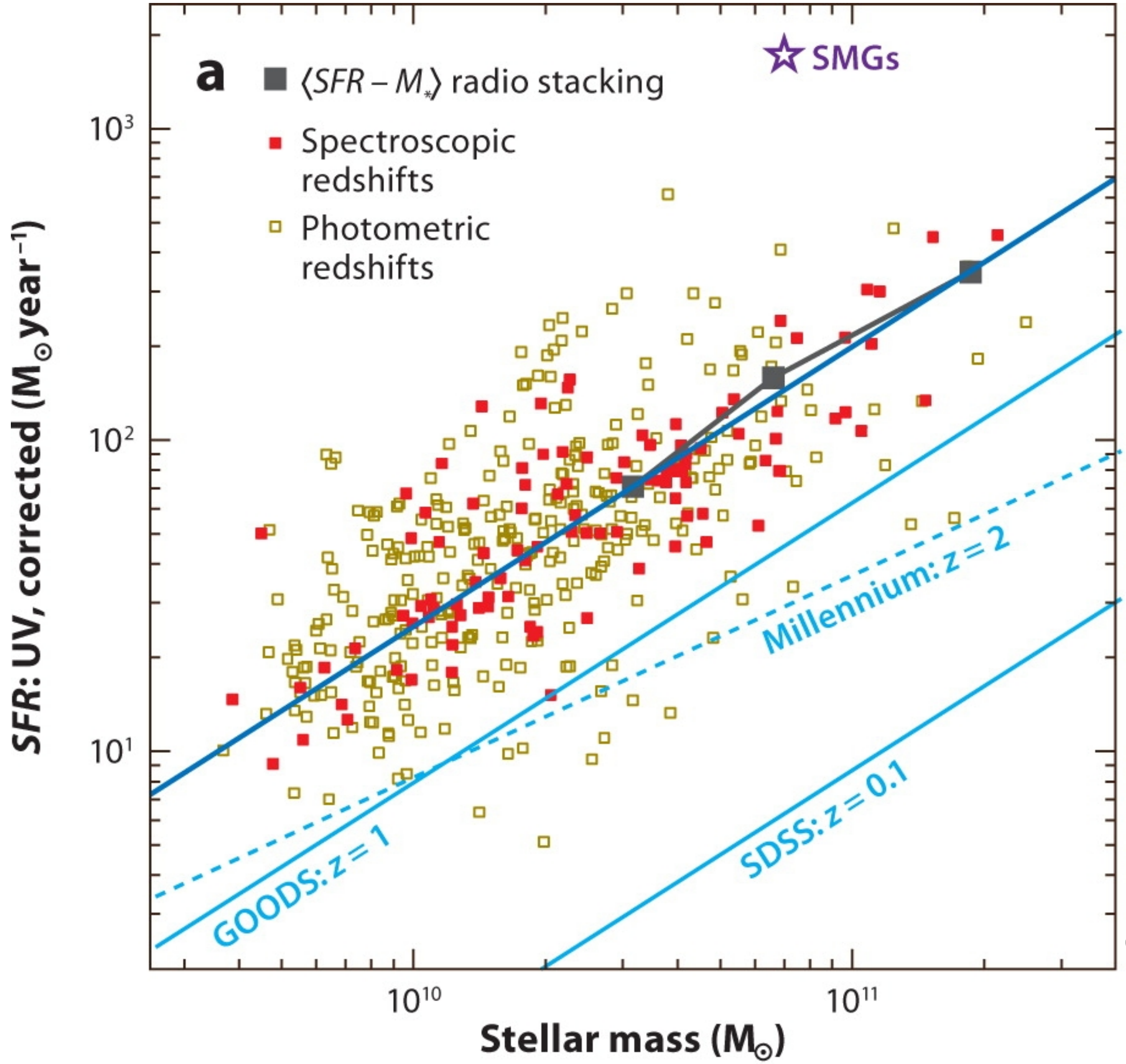
(NK et al. 2016, ApJL)



- Spectral RMS noise of ~ 240 – 300 μJy per 31 km/s channel.

- 868 DEEP2 galaxies within the beam FWHM, and with redshifts placing the HI-21cm line within 1500 km/s of the band edge. 857 spectra were stacked, after aligning in velocity space.

THE MAIN SEQUENCE



(Daddi et al. 2007, ApJL)

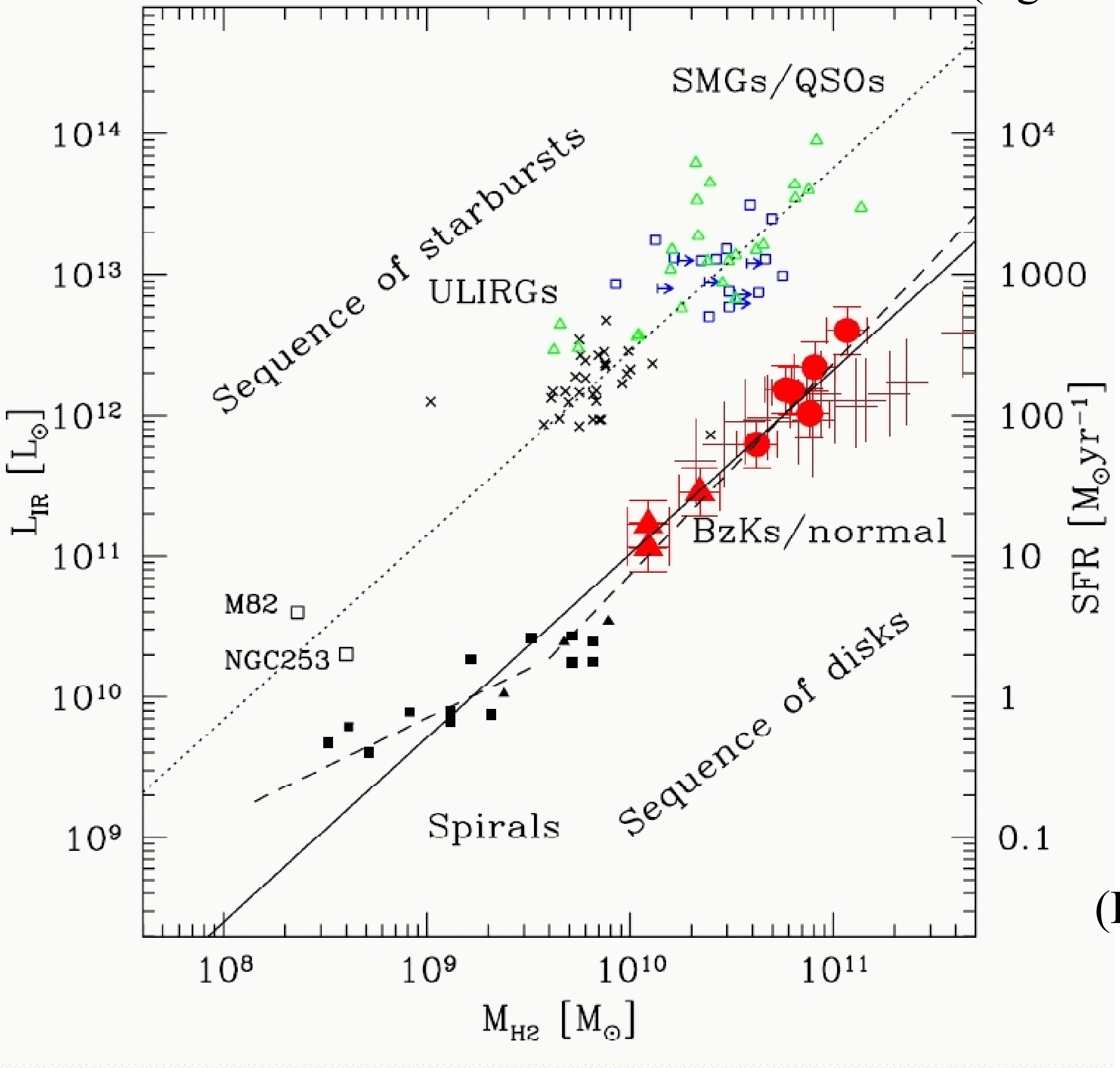
- Normal disk galaxies lie on a "main sequence", with the SFR increasing roughly linearly with the stellar mass. Star formation is much more efficient at higher redshifts, at a given stellar mass.

(e.g. Brinchmann et al. 2004, MNRAS; Noeske et al. 2007, ApJL; Daddi et al. 2007, ApJL; Rodighiero et al. 2011, ApJ)

The Main Sequence: Molecular Gas

- CO studies: Large molecular gas reservoirs, evidence for rotation.

(e.g. Tacconi et al. 2013, ApJ)



(Daddi et al. 2010, ApJ)

- "Main sequence" between SFR and molecular gas mass: SFR far higher in starbursts than in disks at a fixed gas mass.

(e.g. Daddi et al. 2010, ApJ)

Radio Continuum Studies: Galaxy SFRs

- The FIR-SFR and FIR-radio relations can be combined to infer the *total* SFR from the 1.4 GHz luminosity:

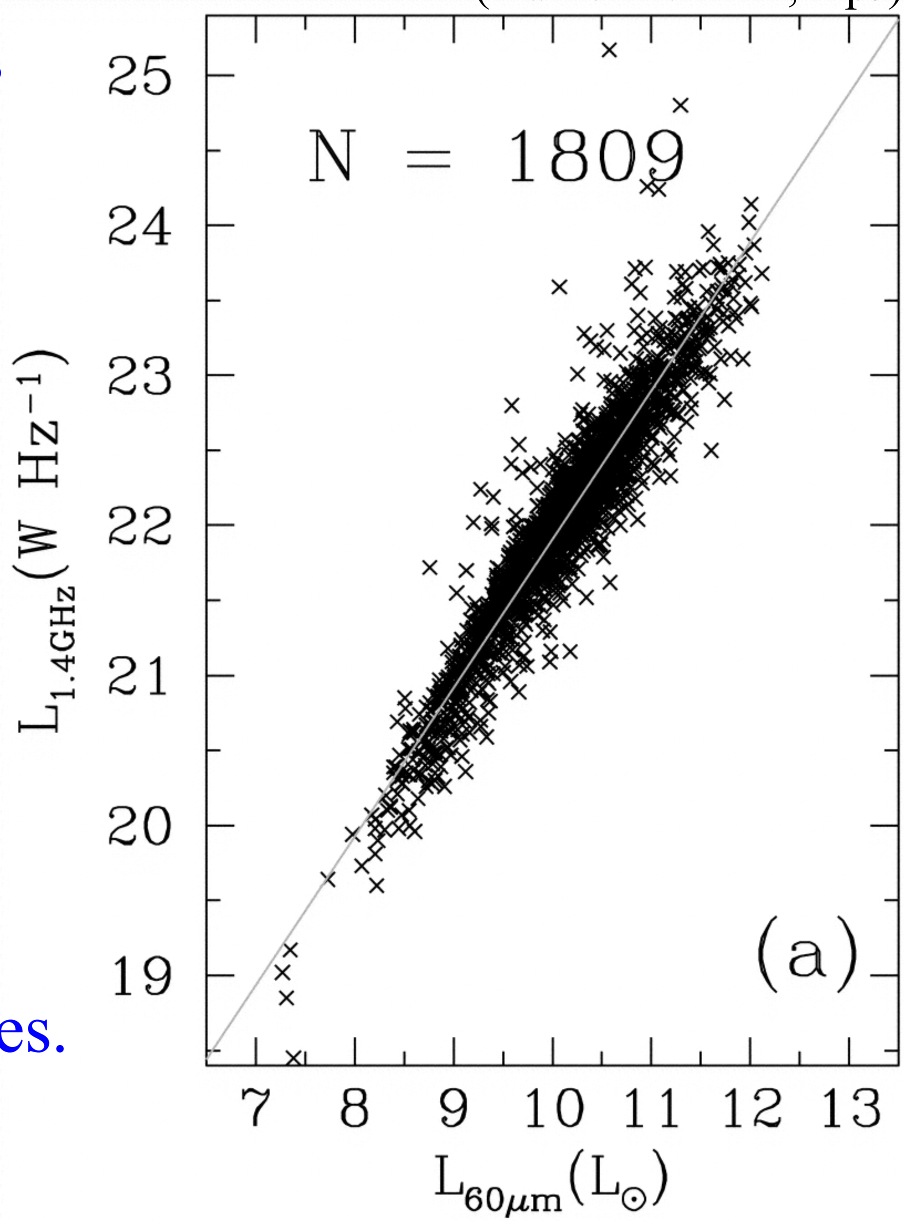
$$\mathrm{SFR} = (5.9 \pm 1.8) \times 10^{-22}\ L_{1.4\,\mathrm{GHz}}\,,$$

for a Salpeter initial mass function. The SFR is in ($M_\odot$/yr), while $L_{1.4\,\mathrm{GHz}}$ is in (W/Hz)

(Yun et al. 2001, ApJ)

- Radio continuum from star-forming galaxies at $z \sim 1$ too faint for a direct detection with today's telescopes.

(Yun et al. 2001, ApJ)



- *Stacking* of the radio continuum emission from galaxies with known positions ⇨ The average SFR of the stacked galaxies!