The Gas Mass and Star Formation Rate of Star-Forming Galaxies at $z \sim 1.3$

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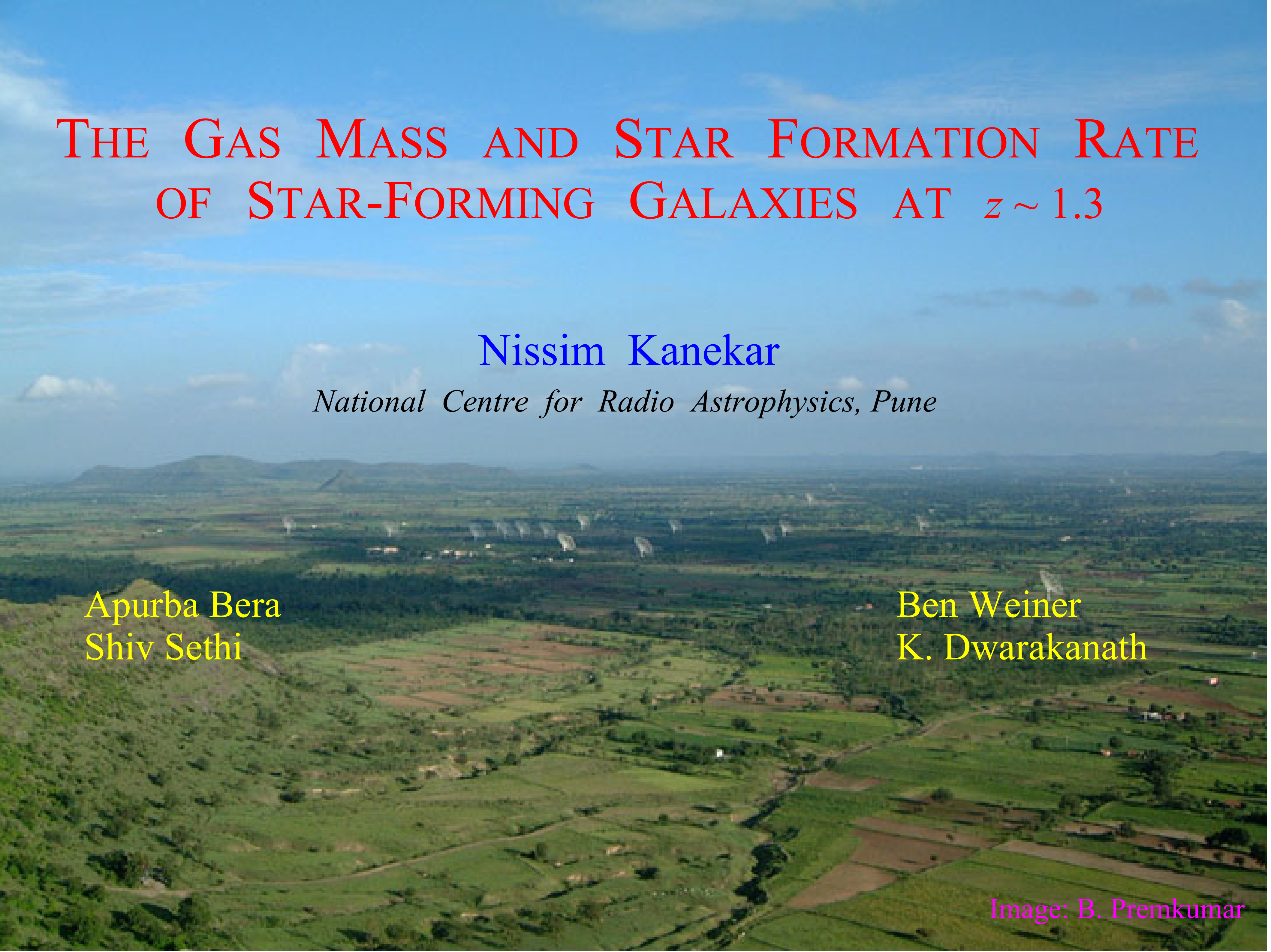


Image: B. Premkumar

Outline

- High-redshift galaxies: The deep fields.
- HI 21cm emission studies: The atomic gas mass.
- The Keck-DEIMOS DEEP2 survey.
- A Giant Metrewave Radio Telescope survey of the DEEP2 fields.
- The future: the Wide-Field Optical Spectrograph.

High-Redshift Galaxies: The Deep Fields

- Galaxy evolution: Must understand both the stars and the gas!

- Emission-selected galaxies from fields with deep multi-band optical imaging (e.g. GOODS-N/S, COSMOS, etc). Typically, follow-up imaging in radio, X-ray, near-IR, mid-IR, ... wavebands. Follow-up optical spectroscopy for a subset of the galaxies.

(e.g. Giavalisco et al. 2004, ApJL; Scoville et al. 2007, ApJ)

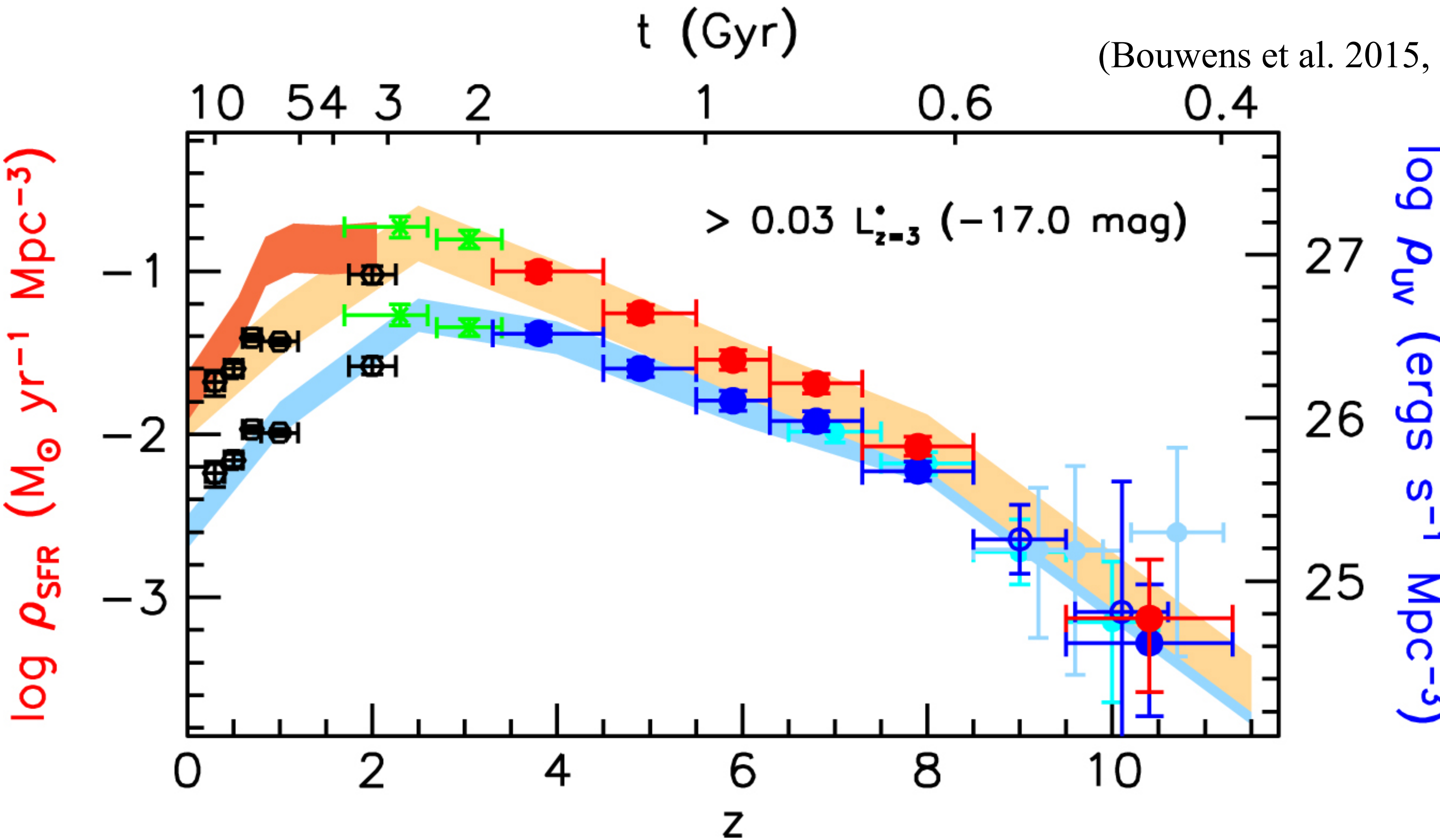
- Deep fields: Galaxy redshifts, luminosities, SFRs, stellar masses, …

- Redshift evolution of the cosmological SFR density and galaxy luminosity functions, the "main sequence" relation between SFR and stellar mass, …

(e.g. Hopkins & Beacom 2006, ApJ; Noeske et al. 2007, ApJL; Bouwens et al. 2011, 2015, ApJ)

The Star Formation Rate Density

(Bouwens et al. 2015, ApJ)



- The SFR density increases by an order of magnitude over $z \sim 0-1$, is flat at $z \sim 1-4$, declines at $z > 4$, and declines steeply at $z \sim 8$.

(e.g. Hopkins & Beacom 2006, ApJ; Schiminovich et al. 2005, ApJL; Magnelli et al. 2009, 2011, A&A; Bouwens et al. 2011, 2015, ApJ)

- SFR estimates from optical/UV data ⇨ Dust corrections critical!

HIGH-REDSHIFT GALAXIES: THE GAS ???

- Galaxy evolution: Must understand both the stars and the gas!

- Main local gas tracers: HI 21cm (atomic) and CO (molecular) lines.

- PHIBSS CO studies at $z \sim 1 - 2$: Large molecular gas reservoirs. Molecular fraction ~ 0.33. H_2 depletion times ~ 0.7 Gyr.

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

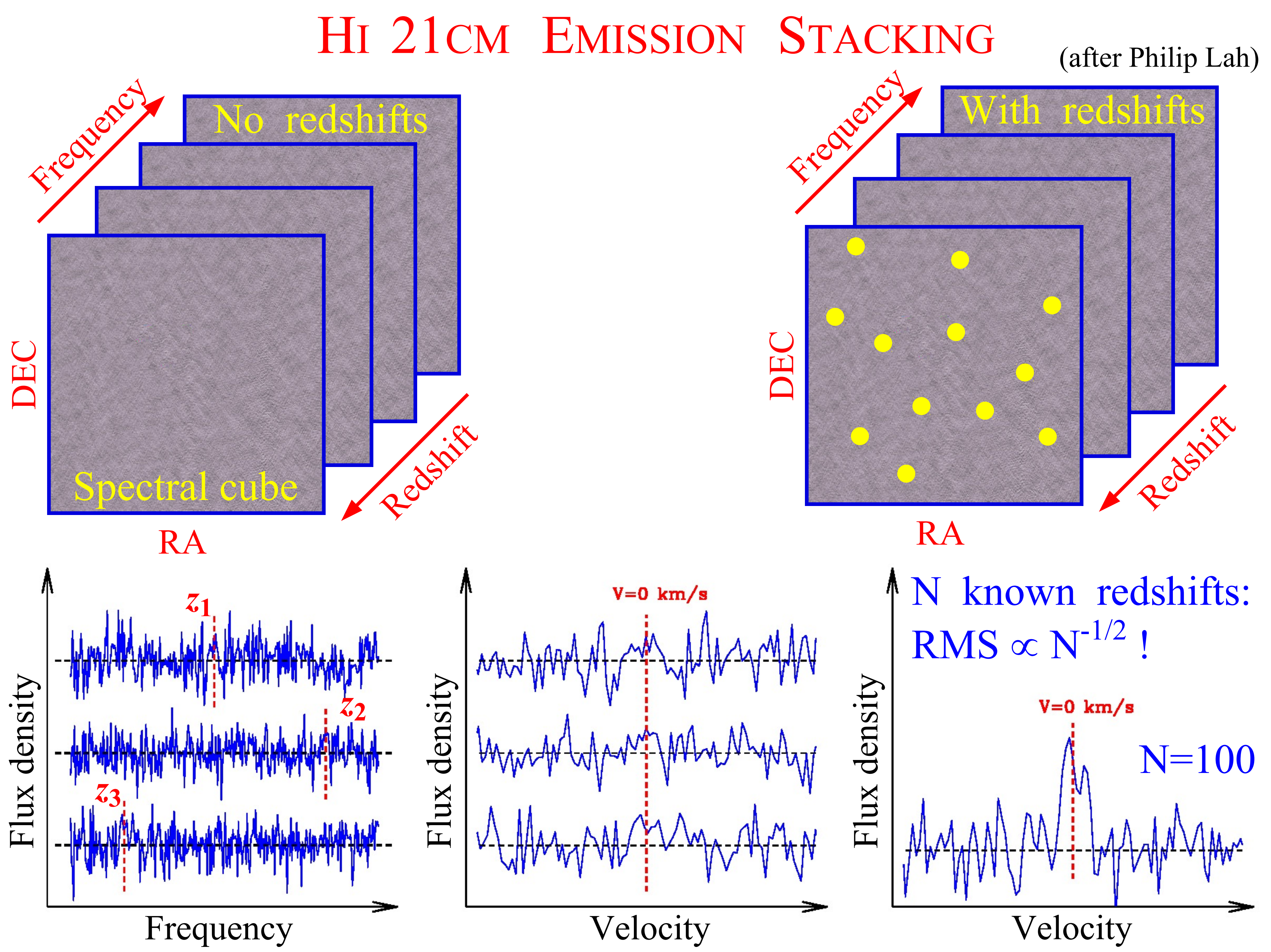
- But… No information on the neutral atomic gas in high-z star-forming galaxies!

- The HI 21cm line is weak: Very tough to detect at $z > 0.25$! Current $z_{MAX} \sim 0.376$, from the VLA-CHILES survey.

  (e.g. Catinella & Cortese 2015, MNRAS; Fernandez et al. 2016, ApJL)

- *Stacking* of HI 21cm emission signals from galaxies with known redshifts ⇨ The average HI mass of the stacked galaxies!

  (Chengalur et al. 2001, A&A; Zwaan 2000, Ph.D.)



HI 21CM EMISSION STACKING
(after Philip Lah)
Frequency
No redshifts
DEC
Spectral cube
RA
Redshift
Frequency
With redshifts
DEC
RA
Redshift
Flux density
z_1
z_2
z_3
Frequency
V=0 km/s
Flux density
Velocity
N known redshifts:
RMS $\propto$ N$^{-1/2}$!
V=0 km/s
N=100
Flux density
Velocity

The Atomic Gas Mass: HI 21cm Emission

- *Stacking* of HI 21cm emission signals from galaxies with known redshifts ⇨ The average HI mass of the stacked galaxies!

(Chengalur et al. 2001, A&A; Zwaan 2000, Ph.D.)

- Can also be used to measure the cosmological gas mass density!

- HI 21cm emission stacking of ALFALFA galaxies: Reproduces dependences of average properties on stellar mass, environment.

(Fabello et al. 2011, 2012, MNRAS)

- HI 21cm emission stacking so far done at $z \sim 0.1 - 0.3$. Would like to push to the epoch of galaxy assembly, $z \sim 1 - 3$!

(e.g. Lah et al. 2007, 2009, MNRAS; Delhaize et al. 2013, MNRAS)

- Stacking best done with a radio *interferometer* (e.g. GMRT, VLA), which combines a wide field of view (i.e. many galaxies in a single pointing) and good resolution (to separate different galaxies).

The Galaxy Sample: The DEEP2 Survey

- (1) High-sensitivity, low-frequency radio interferometer: The GMRT!

  (2) 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, over ~ 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)

- 90 Keck nights, covering galaxies at $z > 0.7$, with $R < 24.1$.

- 38,000 galaxies with "good" redshifts. Redshift accuracy ~ 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

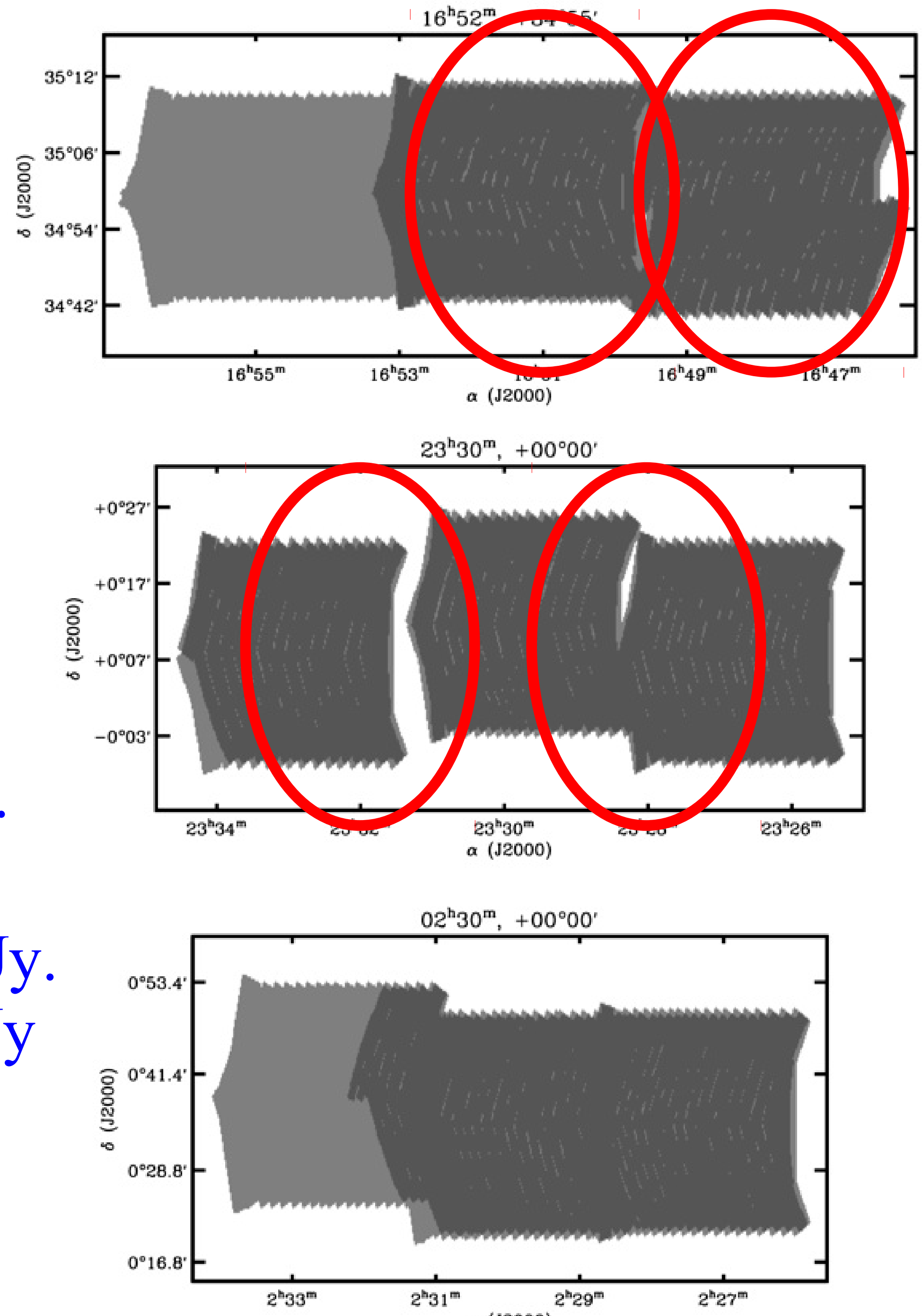
- DEEP2 sub-fields ~ 36' × 30':
  Excellent match to 44' GMRT 610 MHz primary beam.

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

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

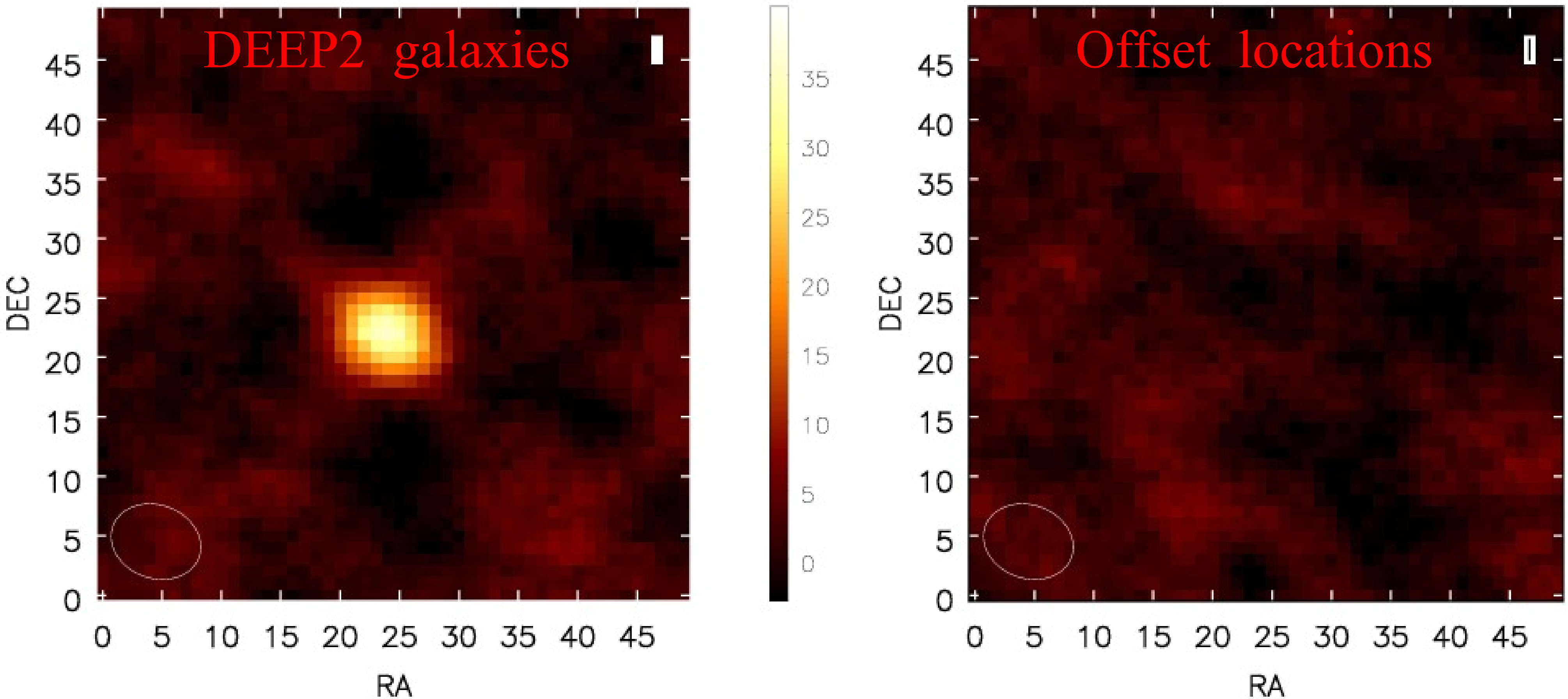


(Newman et al. 2013, ApJS)

1.4 GHz Radio Continuum Stacking

(Bera et al. 2017, in prep.)

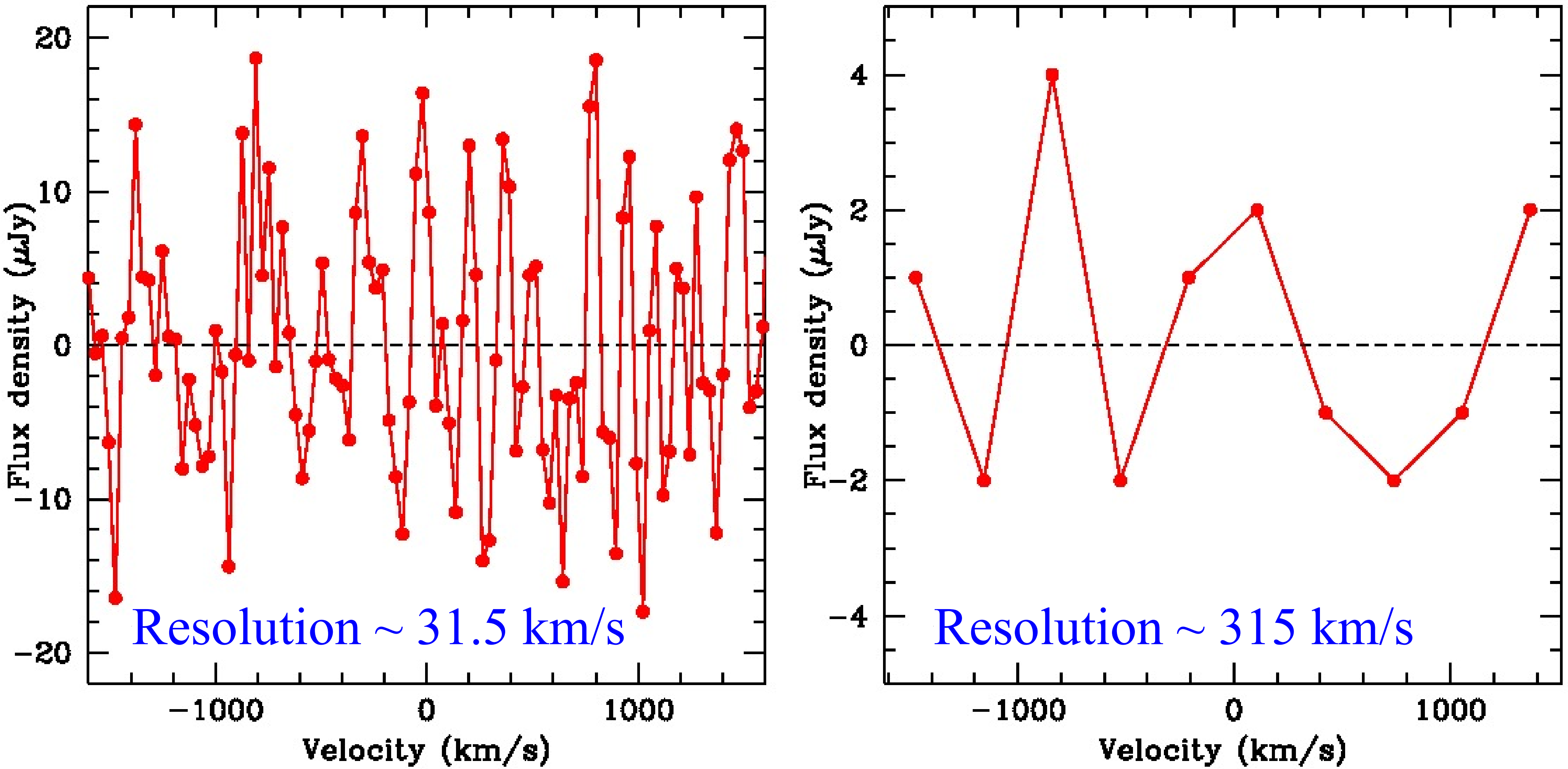
- FIR-radio correlation, at $z <\sim 4$ ⇨ SFR from 1.4 GHz luminosity!
- Stacked 1.4 GHz continuum emission from 4002 blue galaxies with $M_B \leqslant -20$ at $z \sim 0.7 - 1.4$.



- Clear (~14σ) detection! SFR = 20.9 ± 1.6 $M_{\odot}$/yr.

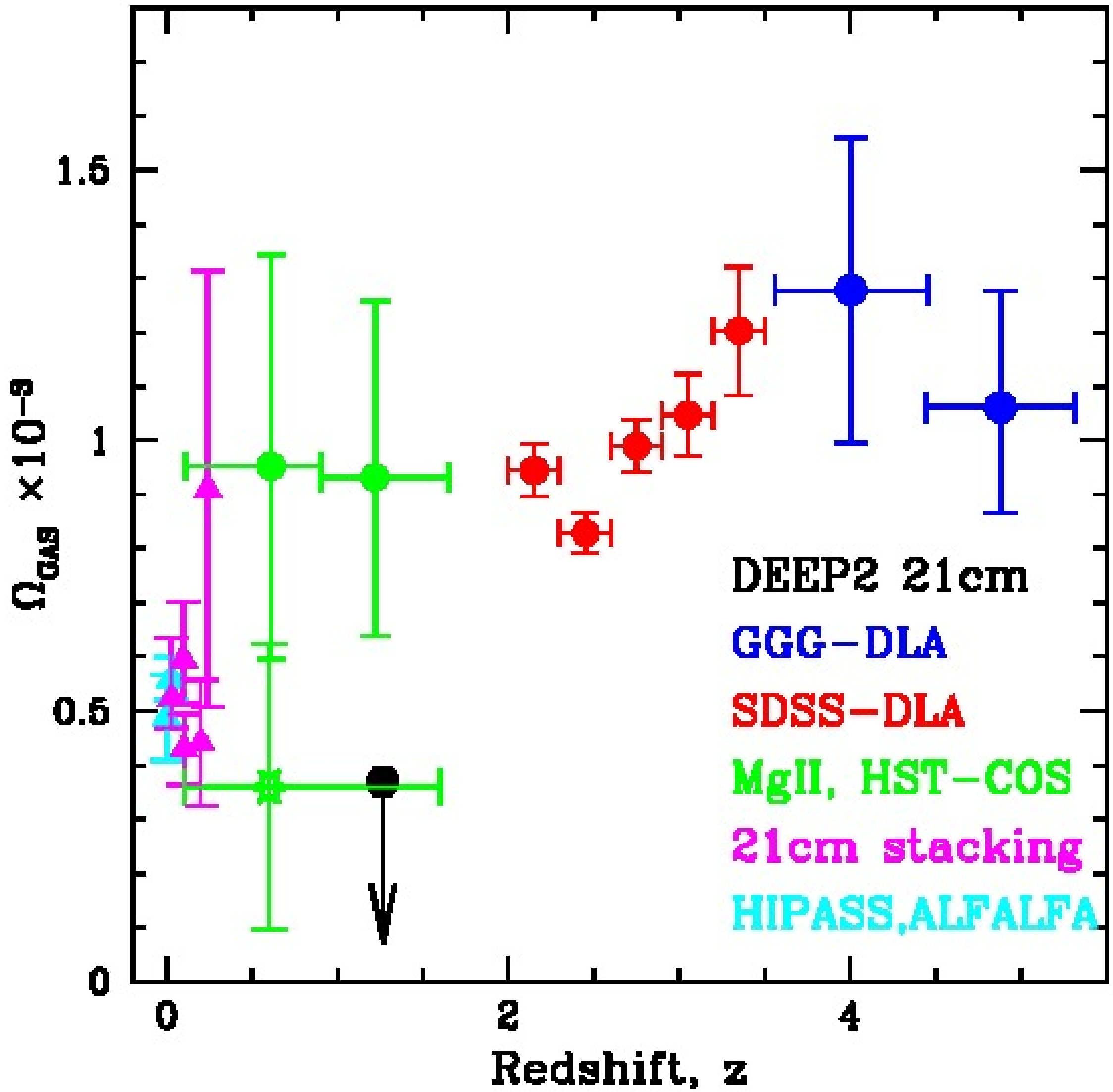
  Inferred SFR ~ 2.5 times higher than optical estimates!

HI 21CM LINE STACKING (NK et al. 2016, ApJL)



- Stacked HI 21cm emission from 857 galaxies within beam FWHM: Final stacked RMS noise ~ 2.5 μJy per 315 km/s channel!
- Average HI mass, M(HI) ≤ 2.1×10^{10} $M_\odot$ (3σ). M(HI)/M_* < 0.5.
- Median SFR ~ 24.2 $M_\odot$/yr ⇨ Gas depletion time < 0.87 Gyr (3σ).

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 Ω_{GAS}(SF) < 0.00037, 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: WFOS on TMT

- 400-hour GMRT project covering all DEEP2 sub-fields: HI mass sensitivity better by a factor of ~ 3, to $< 10^{10}\,M_\odot$.

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

- HI 21cm stacking will remain important in the SKA & TMT era! SKA1-Mid 300-hour integration: M*(HI) $\sim 10^{10}\,M_\odot$ out to $z \sim 0.5$!

- Critical: Wide-field, multi-object spectrograph, with R >~ 5000.

- Wide-field Optical Spectrograph: Wavelength range: 0.31 – 1 μm; R ~ 1500 – 5000; Field of view ~ 40 arcmin^2; 200 objects at a time.

- (1) Slicer-WFOS: R~5000 for 25 targets; R~1600 for 100 targets. (2) Fiber-WFOS: R~5000 for ~ 700 targets, 10′ diameter field!

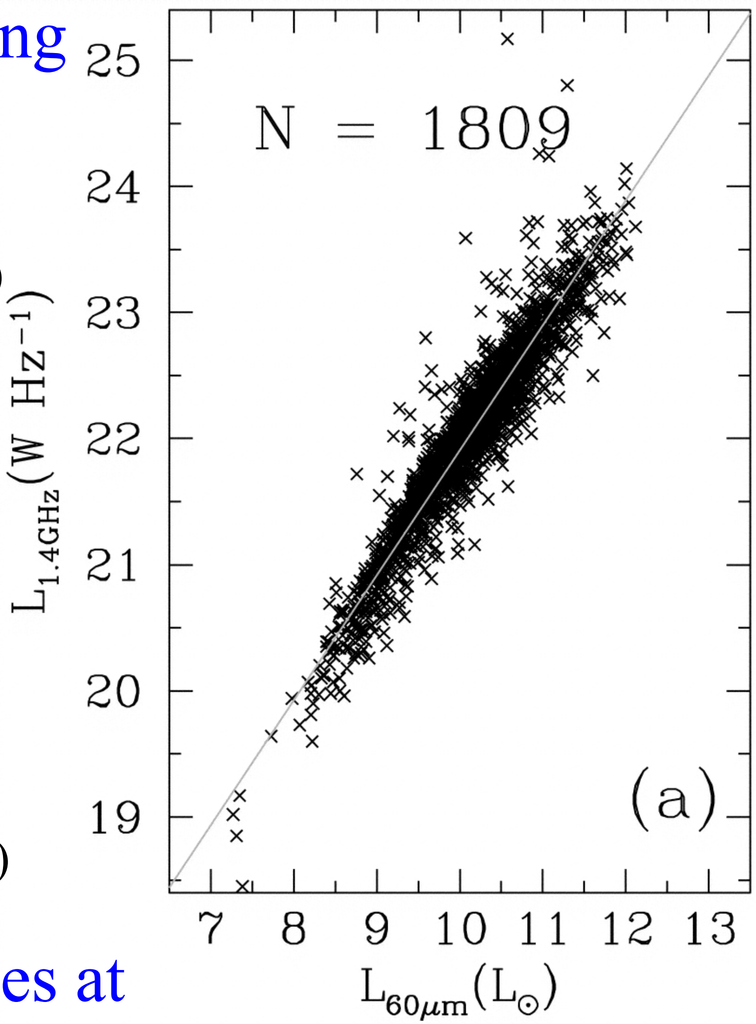
- Clear preference for Fiber-WFOS for HI 21cm emission stacking!

Summary

- Possible to measure the average gas mass and SFR of galaxies at $z > 1$ via GMRT HI 21cm stacking! DEEP2 fields best for this.
- Clear detection of the median-stacked radio continuum emission from blue DEEP2 galaxies, with $M_B \leqslant -20$: SFR = $20.9 \pm 1.6\ M_\odot$/yr.
- Stacked spectra of 857 DEEP2 galaxies: No detection of emission.
  ⇨ Average HI mass $\leq 2.1 \times 10^{10}\ M_\odot$ (3σ) at $z \sim 1.3$.
  ⇨ Gas fraction $M(\mathrm{HI})/M_* < 0.5$ at $z \sim 1.3$.
  HI depletion time < 0.87 Gyr (3σ): HI may be a transient phase!
- The cosmological atomic gas mass density in star-forming galaxies, $\Omega_{GAS}(\mathrm{SF}) < 0.00037$ at $z \sim 1.3$, is lower than the total Ω_{GAS} at $z \sim 0 - 4$! ⇨ The bulk of the gas is *not* in star-forming galaxies!
- HI 21cm stacking will remain important in the TMT & SKA era: Clear preference for Fiber-WFOS, due to higher resolution, more simultaneous targets, and wider field of view.

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)

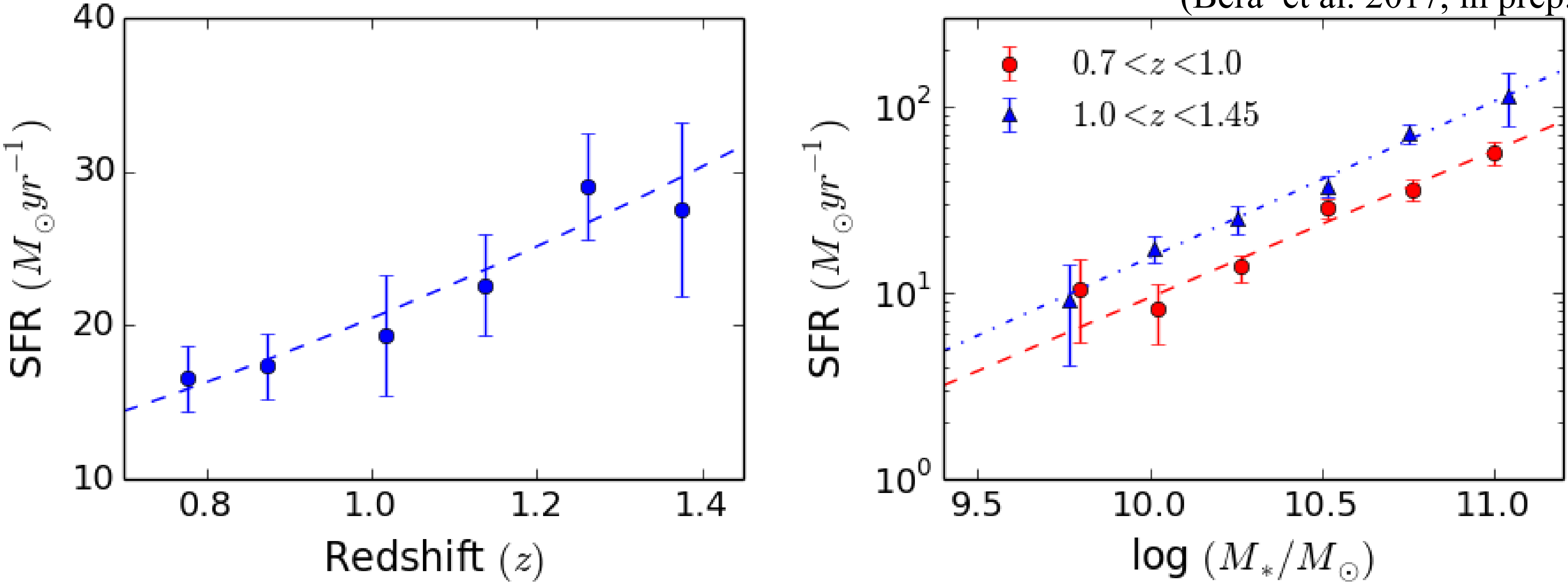
- 1.4 GHz emission from star-forming galaxies at $z > 1$ too faint for a direct detection: *Stacking* of 1.4 GHz emission from galaxies with known positions ⇨ The average *total* SFR!

- 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)

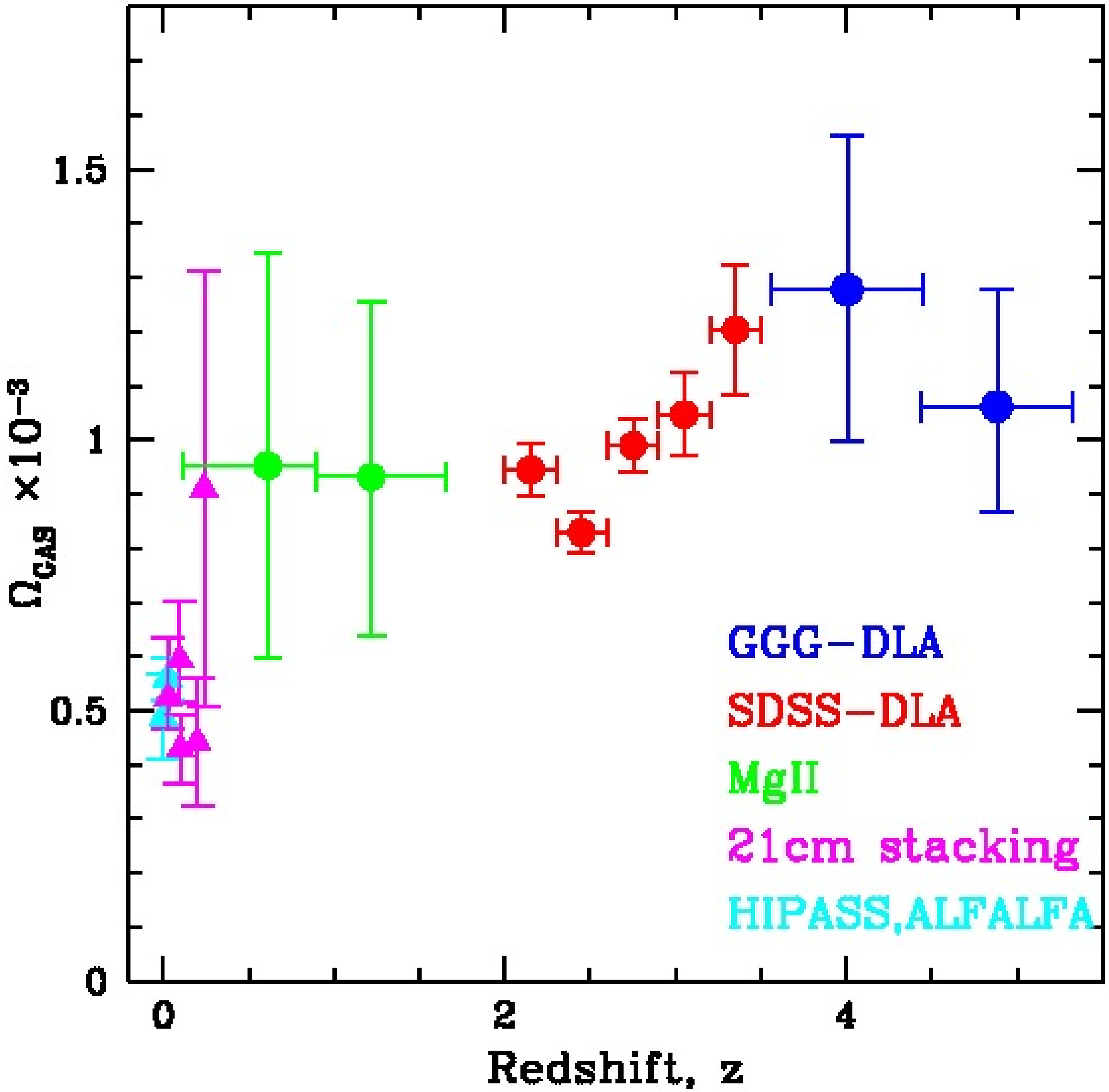
1.4 GHz Radio Continuum Stacking

(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_*.

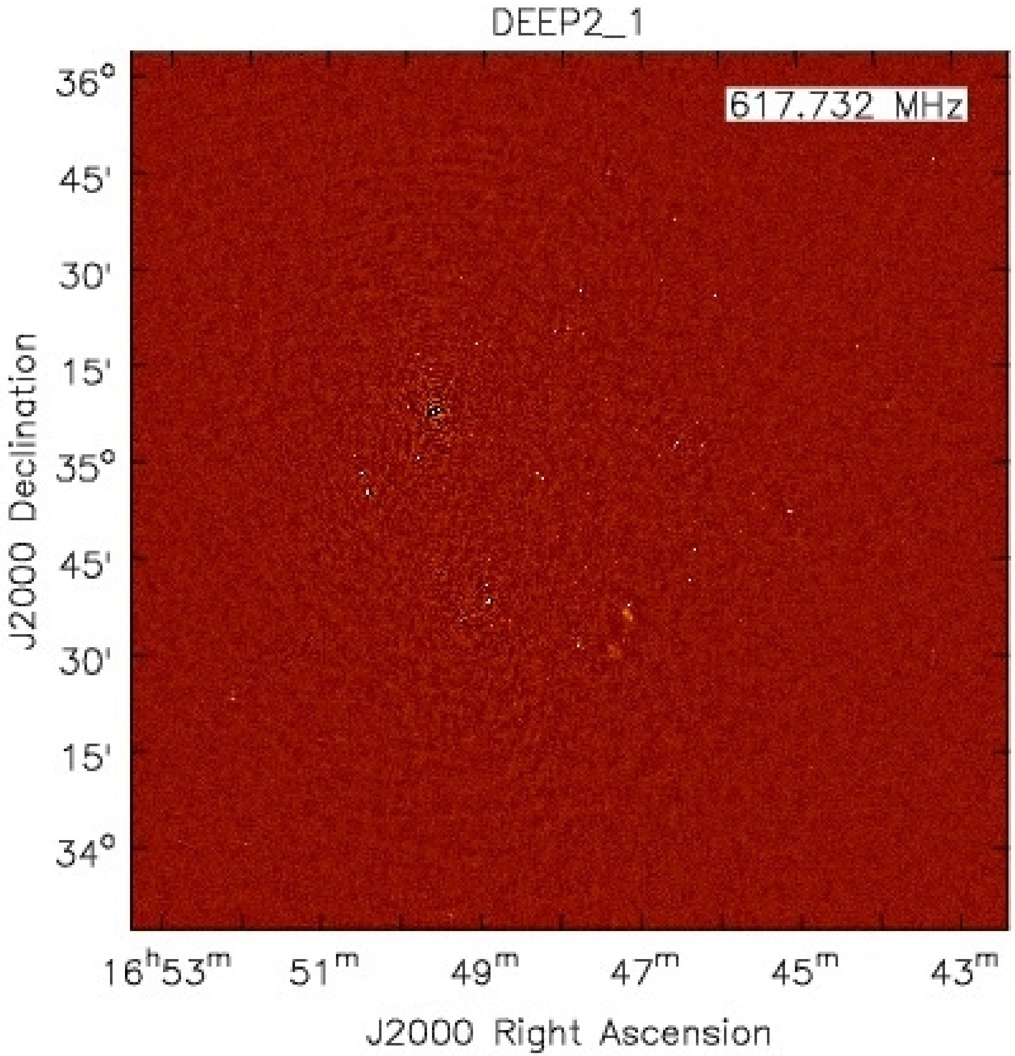
The Cosmological Gas Mass Density

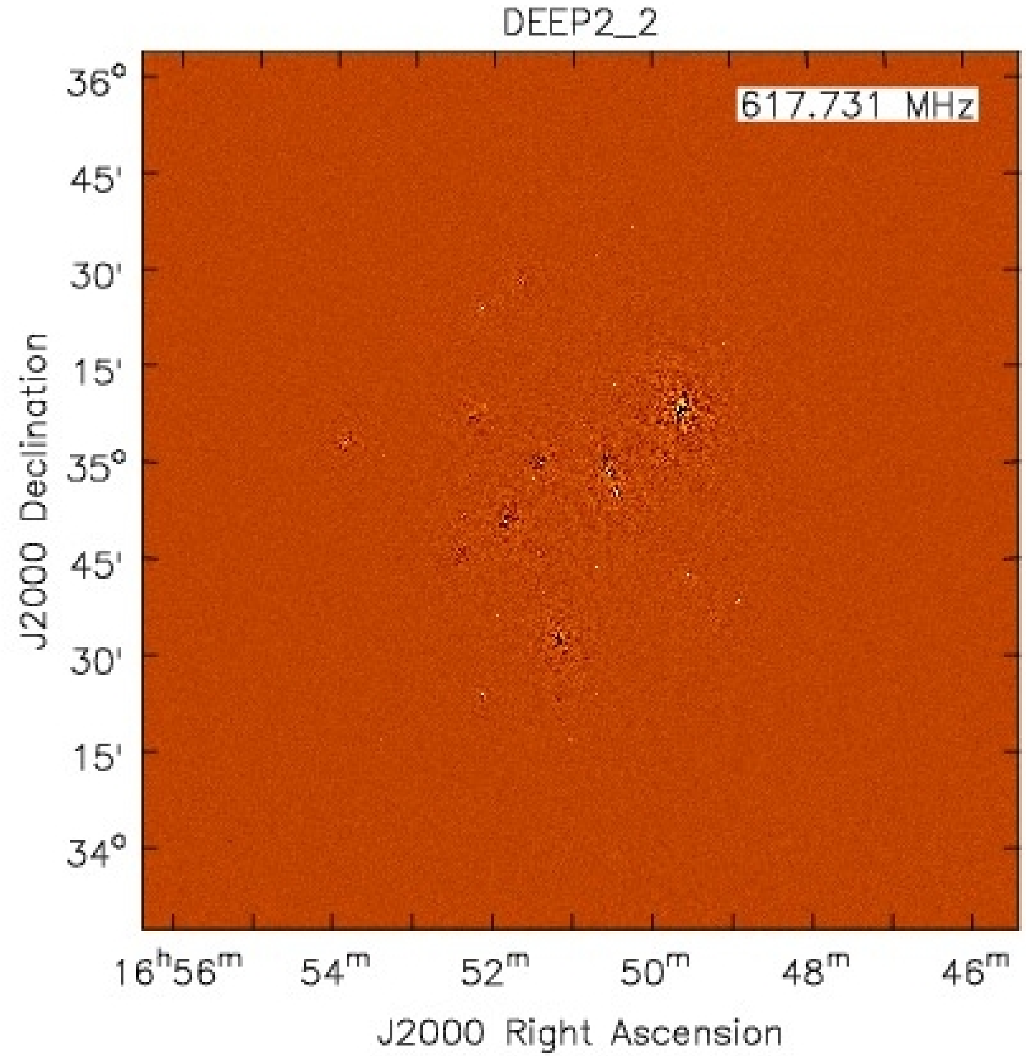


(e.g. Zwaan et al. 2005;
Rao et al. 2006;
Lah et al. 2007;
Martin et al. 2010;
Prochaska et al. 2005;
Noterdaeme et al. 2012;
Delhaize et al. 2013;
Rhee et al. 2013;
Crighton et al. 2015)

- The gas mass density declines by a factor of ~ 2.5 from $z \sim 3$ to $z \sim 0$. Little information in the redshift range $z \sim 0.2 - 2$.

THE RADIO CONTINUUM: GMRT 617 MHz IMAGES

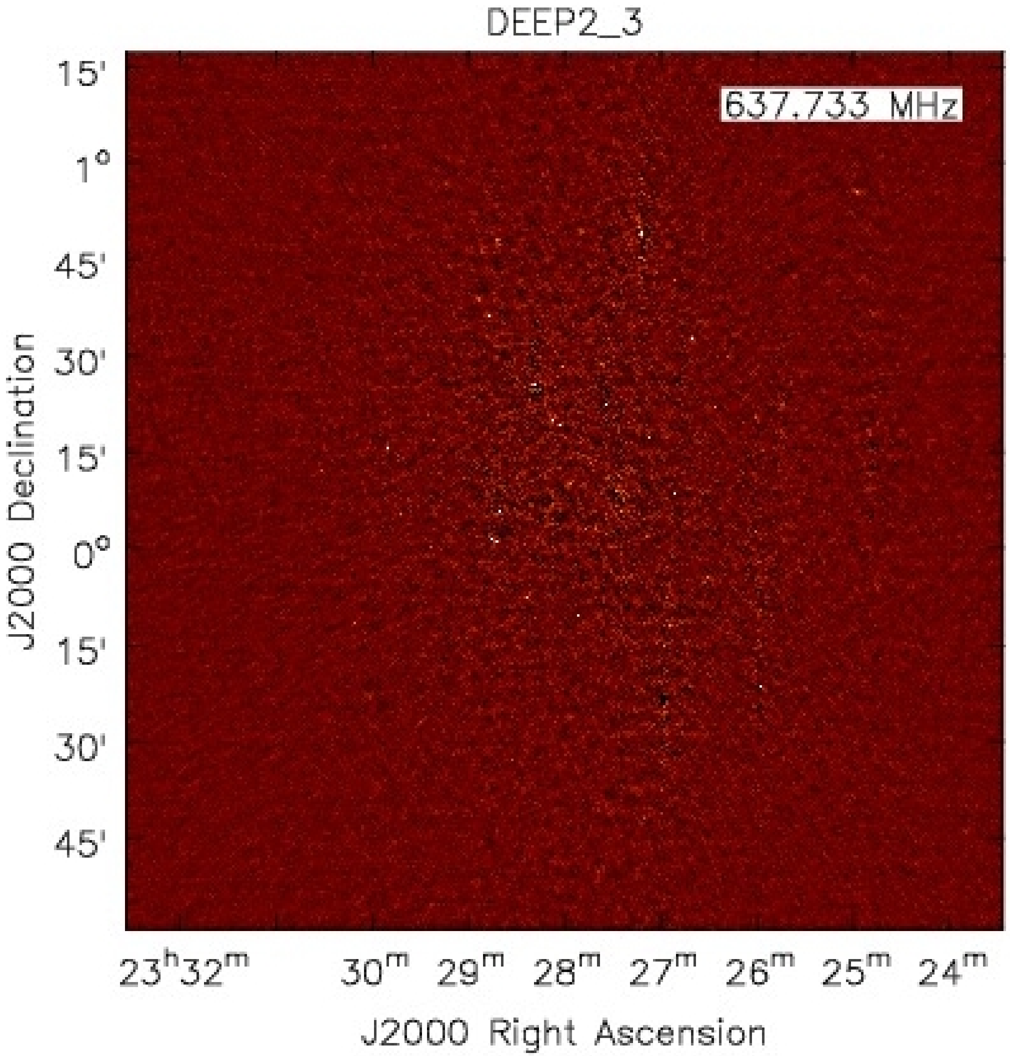


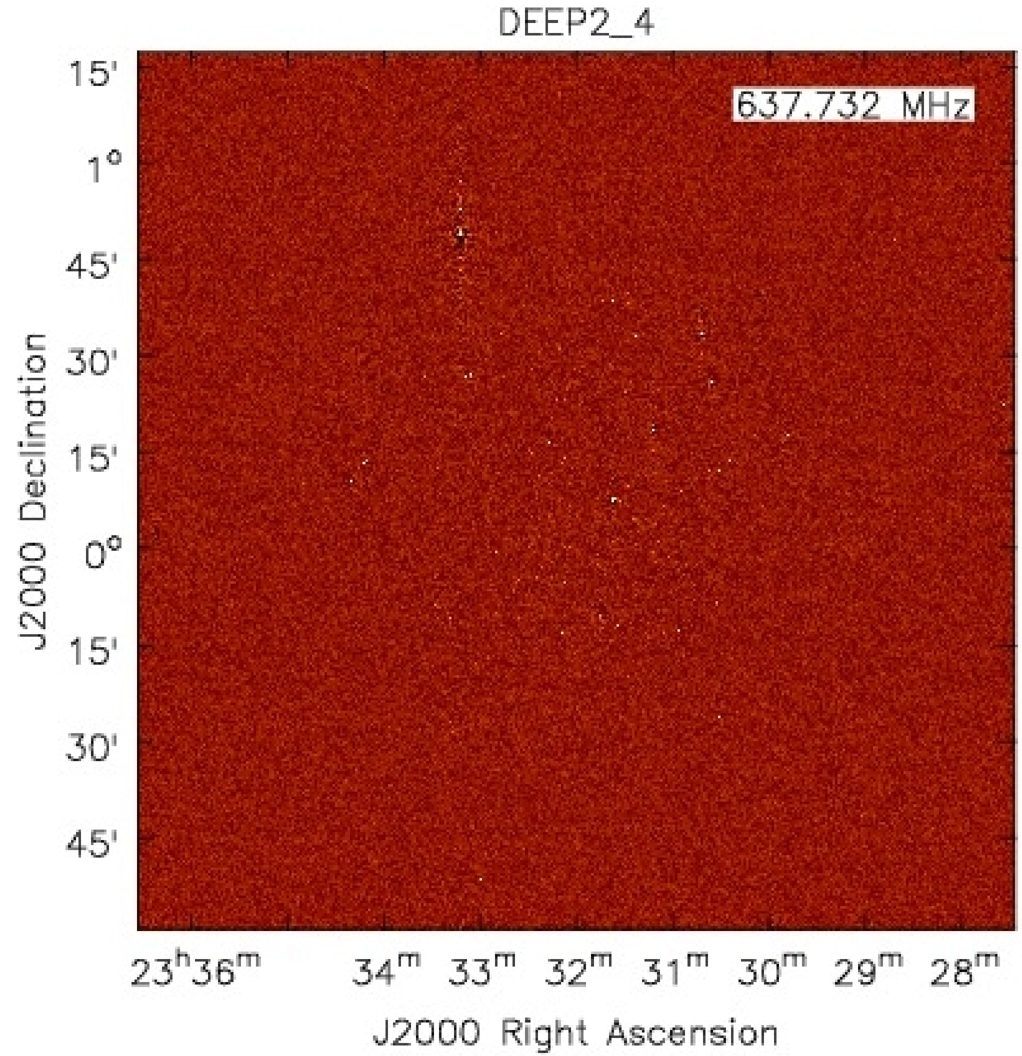


- Beam: 4.7" × 3.9".
- RMS noise ~ 21 μJy.
- 2006 galaxies $(0.70 < z < 1.45)$

- 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.

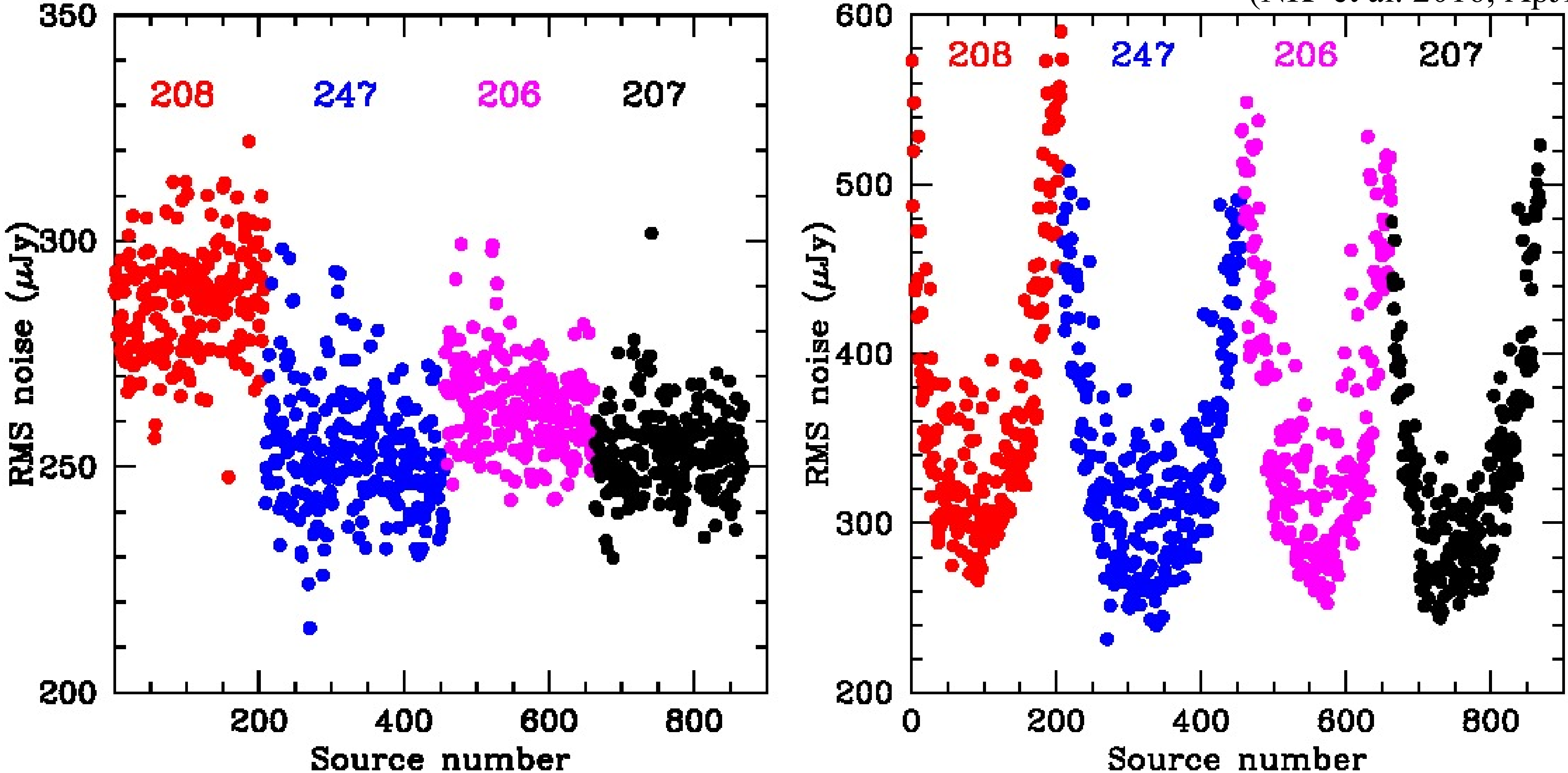
- Beam ~ 6.1" × 4.4".
- RMS noise ~ 14 μJy.
- 1844 galaxies.

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.

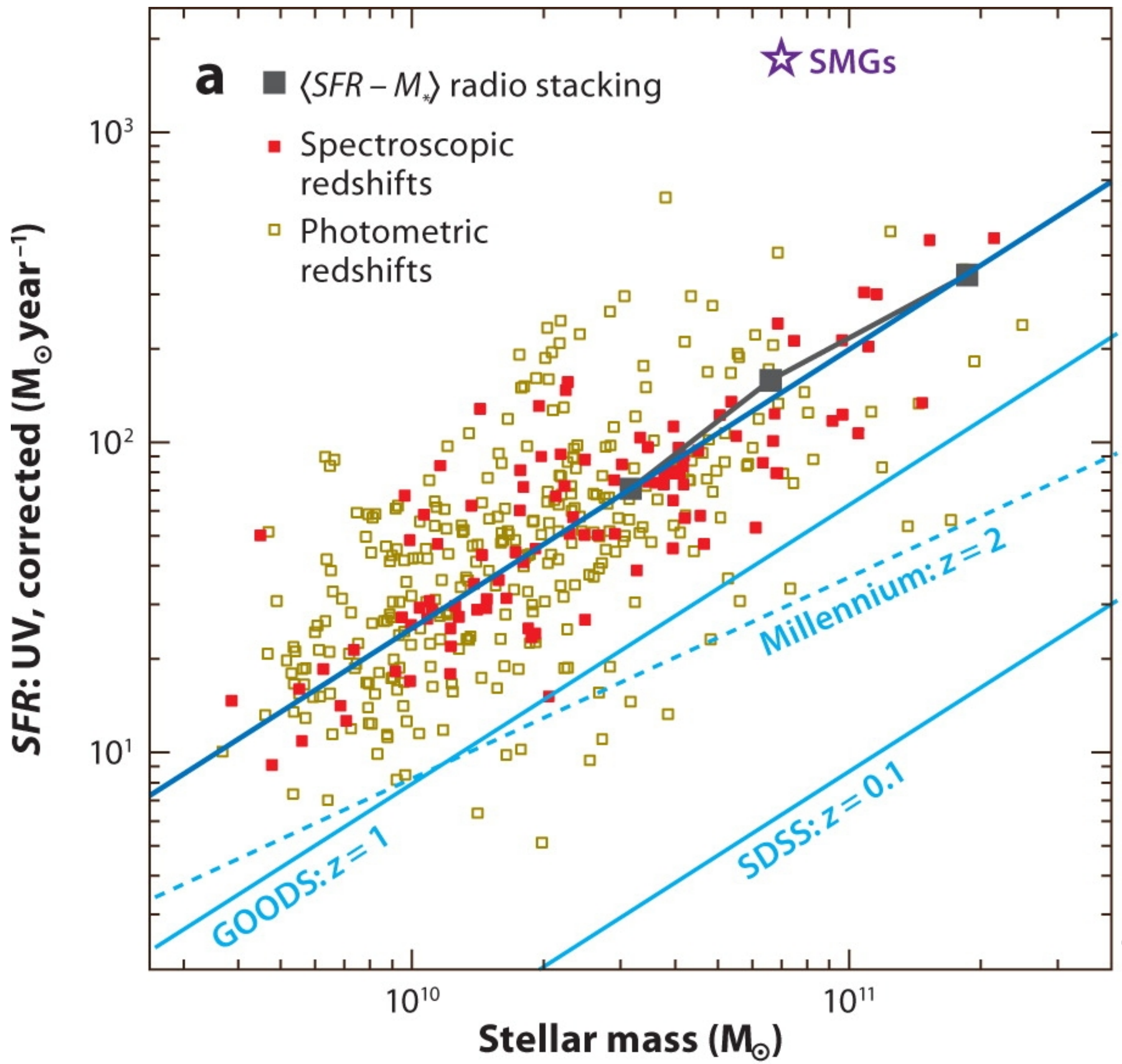
HI 21cm Line Stacking

(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)

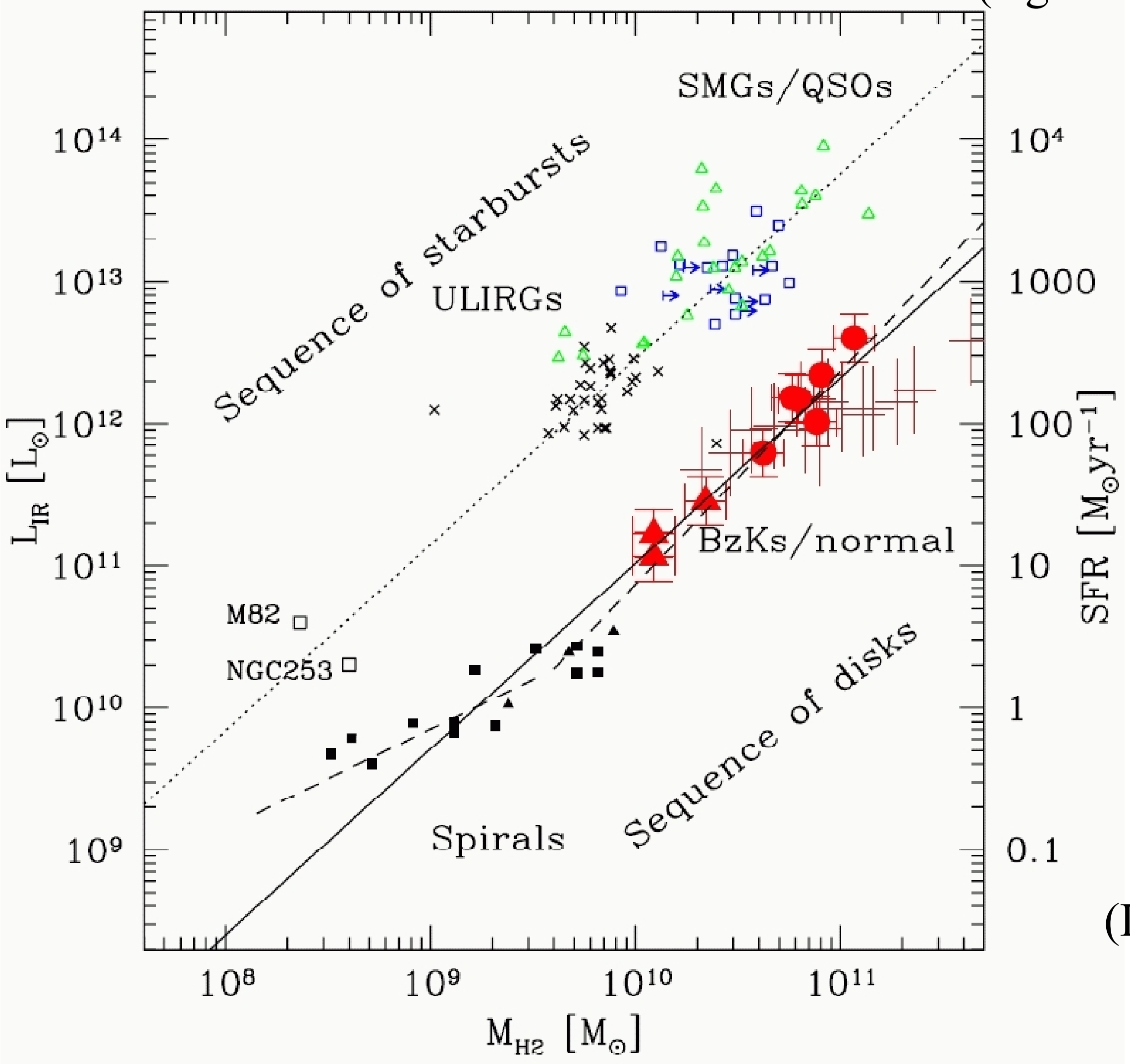
- Normal disk galaxies lie on a "main sequence", with the SFR increasing roughly linearly with the stellar mass. Star formation is much more efficient at higher redshifts, at a given stellar mass.

(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

(Yun et al. 2001, ApJ)

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

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

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

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